Pre-meeting Presentations

Participants were requested to provide ahead of the meeting. It is understood that all participants will diligently go through the presentations prior to coming to the meeting (preferably not on the meeting-bound airplane!). You have a choice of either viewing a consolidated file or individual files (below).

1. Fruitful returns from cadenced RV observations with SDSS (Badenes).
2. Introduction to ZTF: Surveys & Performance (Bellm). Presents the performance of ZTF and summarizes the surveys. Useful if you wish to use ZTF.
3. Finding interesting binaries from Gaia (Brandt).
4. Double Degenerates discovered with ZTF (Burdge).
   ZTF has discovered a clutch of short period detached eclipsing binaries some of which are the loudest signals for the LISA mission.
5. AGN Light curves (Graham).
6. ZTF as a modern time domain astronomy public survey (Graham).
   ZTF is unique in putting out LSST style, machine friendly, alerts.
7. Pulsating white dwarfs (Hermes).
8. TDA surveys and young stars (Hillenbrand).
9. The era of NRA TDA surveys begin. (Kasliwal).
   Hot results from cool transients
10. SDSS Phase V (Kollmeier).
    The next phase of SDSS aimed at "dynamic highly multiplexed stellar and interstellar" spectroscopy.
11. Other Exotic Stellar Binaries from ZTF (Kupfer).
12. Light Curves from TESS (Oelkers).
    Light curves & data products from TESS. Includes description of pipelines.
13. Limits to ground-based photometry & astrometry (pre-LSST) (Ofek).
14. ASAS-SN (Shappee).
15. ATLAS (pdf) | (ppt) (Tonry).
16. Tomo-e Gozen Observations of Pulsars (Ichicki).
    Observations of radio pulsars with sub-second framing Tomo-e-Gozen.
17. Tome-e-Gozen (Arima).
    The world's first wide-field sub-second framing optical camera (at Kiso Schmidt, Japan).
18. Application of Machine Learning for Stellar Binaries. (van Roestel).

```
# For Unix aficionados:
# Problem: how to automatically "build a book" from a website?
# (you can have any ordering by using sort but here it is by alpha)

# change directory where the pdf files are located

$ wkhtmltopdf ../PM_Presentations.html AAATable.pdf
$ pdfunite $(ls -1 *.pdf | xargs) ../PM_Presentations.pdf
```

Fruitful returns from cadenced RV observations with SDSS

Carles Badenes
University of Pittsburgh / PITT PACC

SDSS-V + ZTF
OCIW, May 3-4 2019

Framework

- Goal: find as many short-period binaries as possible, in order to
  - Constrain multiplicity statistics in the field.
  - Identify interesting systems for follow-up.
- Radial Velocities from SDSS-IV and SDSS-V: cadences, errors, and challenges.
- Main results so far: multiplicity statistics for binary WDs and field stars, discovery of a detached BH binary.
- Synergies with other data sets: Gaia, ASASS-SN, ZTF, ...

Open Questions

- **Multiplicity Statistics** only known at all P in the MS and in the Solar Neighborhood [Duchene & Kraus 13, Moe & DiStefano 17].

- Studies in stellar clusters (small samples) [Carney+ 03; Geller+ 08; Matijevic+ 11; Sana+ 12; Merle+ 17], but **no panoramic view of the interplay between multiplicity, stellar evolution, and stellar properties in the field**. Open questions:

  - Are our ideas about RLOF basically correct?

  - Stellar multiplicity vs. stellar properties and environment: Mass, age, metallicity, disk/halo... ⇔ SF theory [Machida+ 09, Bate 14], dynamics [Kroupa & Petr-Gotzens 11].

  - Rate of CE events in the MW? Rate of stellar mergers? Formation rate of short P systems? Can we help constrain BPS models for SNe, GW sources, etc.?

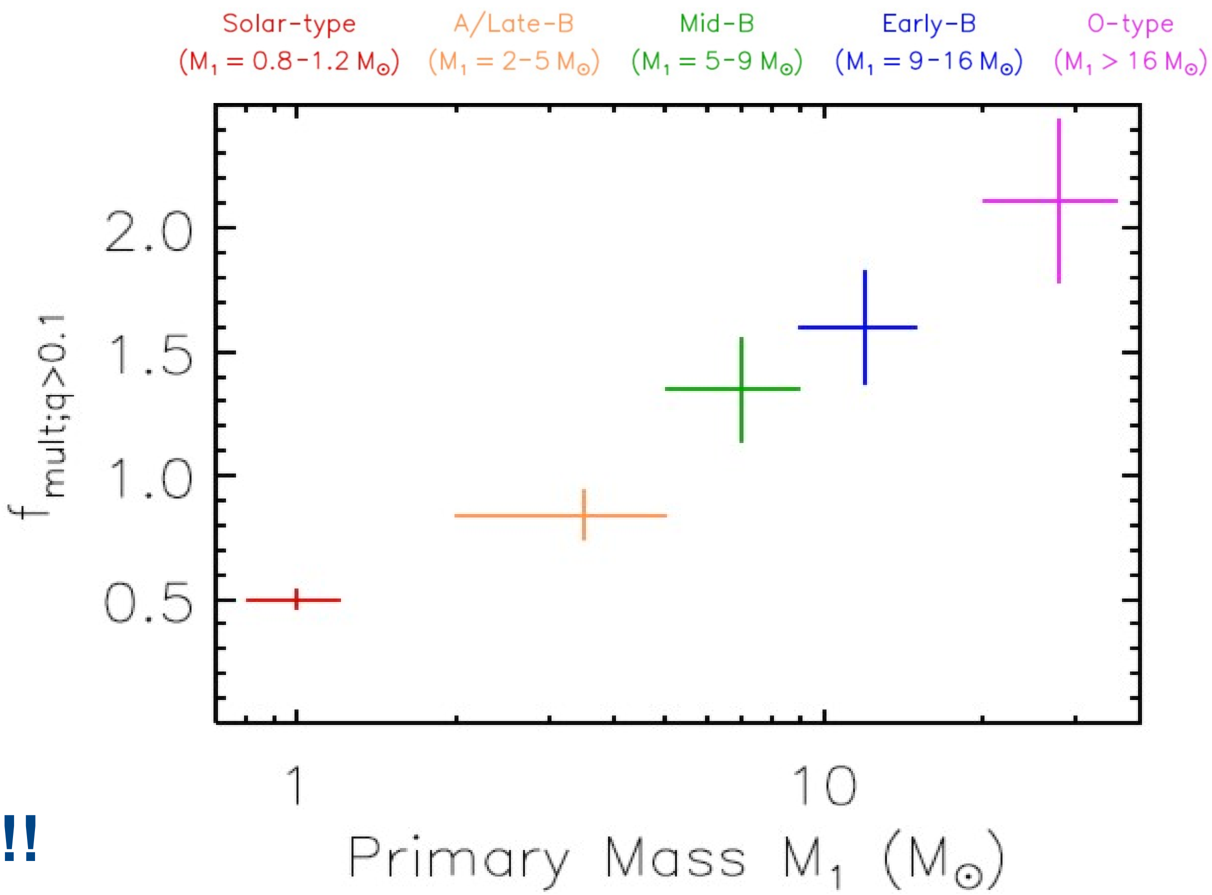
What are we looking for?

Carles Badenes
SDSSV+ZTF

- **Stellar Multiplicity Statistics** (well measured for Sun-like MS stars, D<25 pc) [Raghavan+ 10, Duchene & Kraus 13, Moe & DiStefano 17 (MD17)]:
  - Multiplicity frequency (f_m): dominated by M_1.
  - Period (P): ~lognormal.
  - Mass Ratio (q): ~flat, F_{twin}.
  - Eccentricity (e): tidal circularization, ~uniform.
- **These statistics are not independent of each other!!!!** [Sana+ 12, MD17].

$$f_m = \int f(P)dP$$

MD 17



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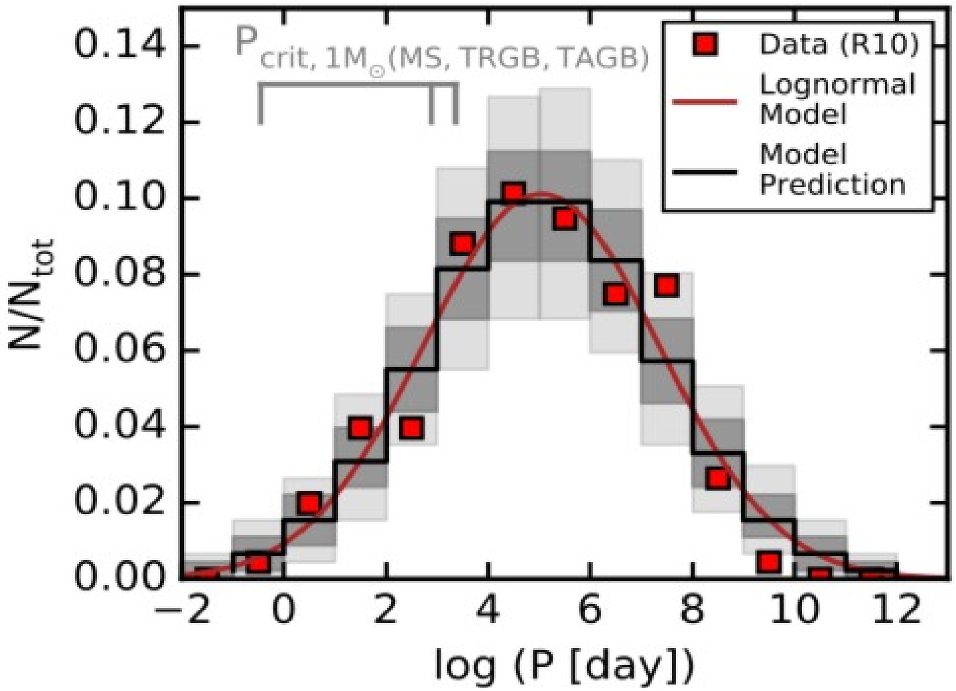
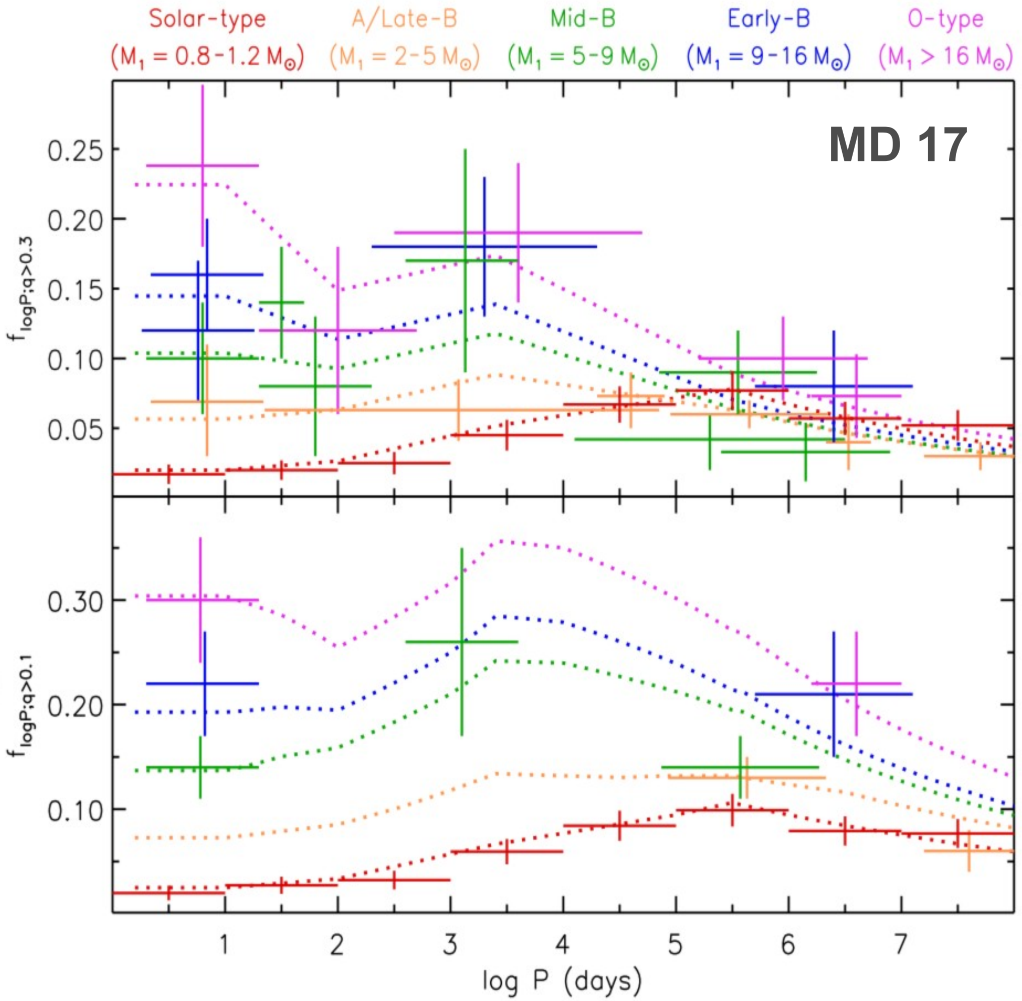
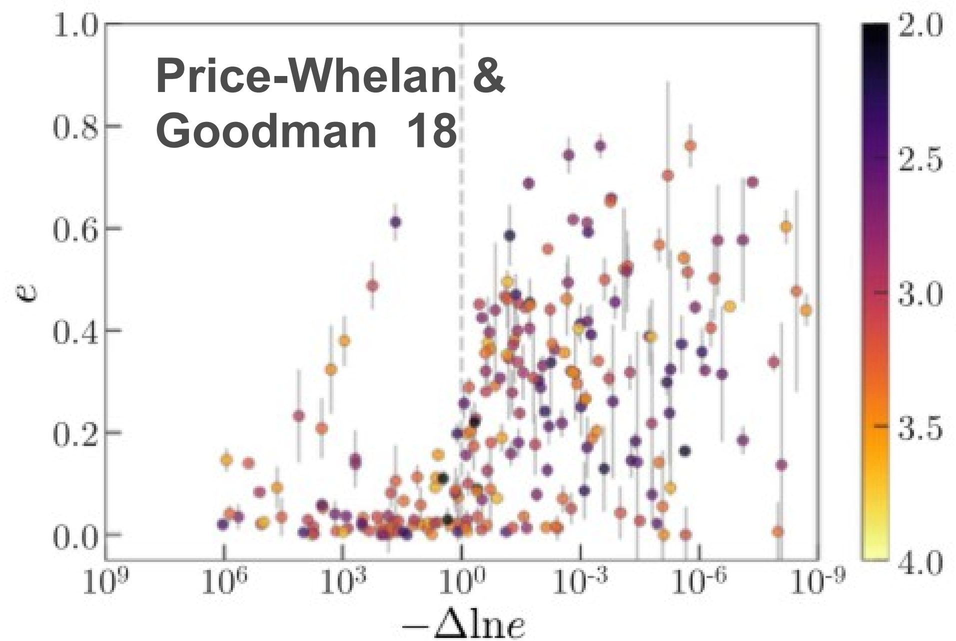


$$\mathbf{f(P,q,e) \neq f(P)f(q)f(e)}$$





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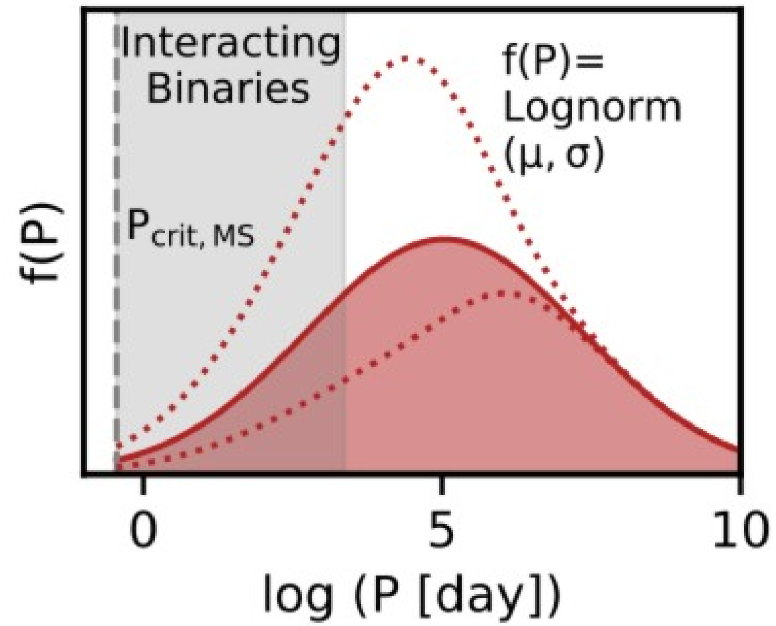
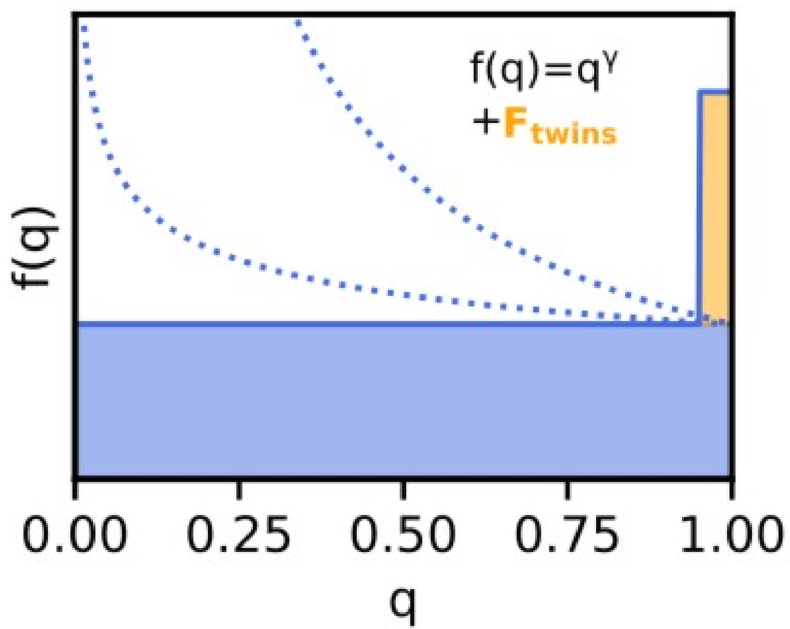
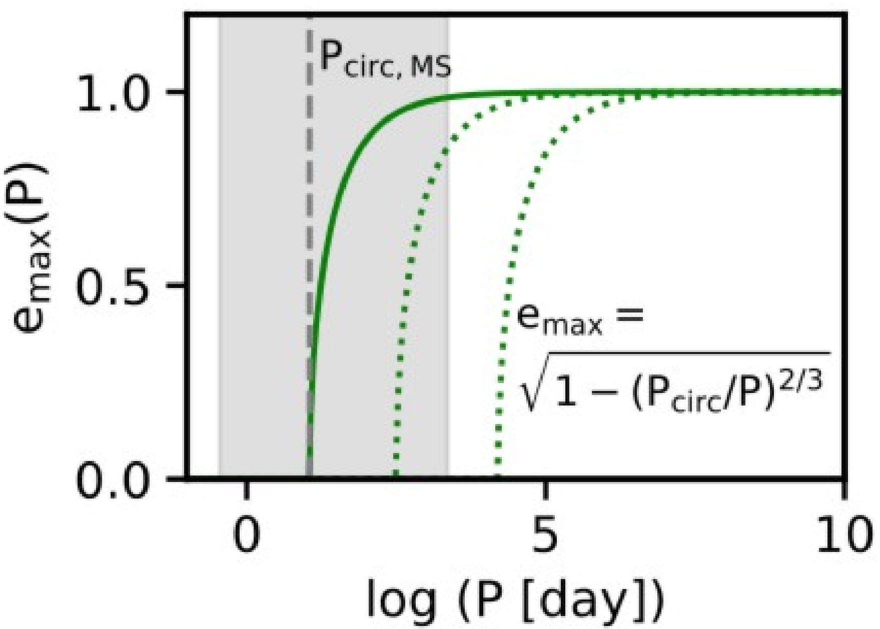






Multiplicity and Stellar Evolution

Carles Badenes
SDSSV+ZTF

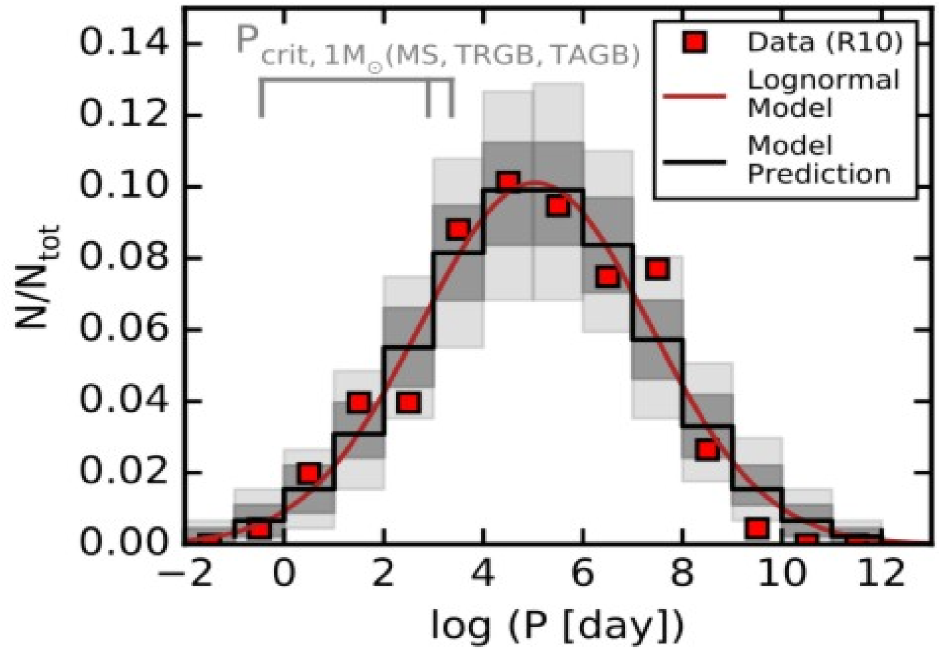
- Critical P for RLOF (q=1):

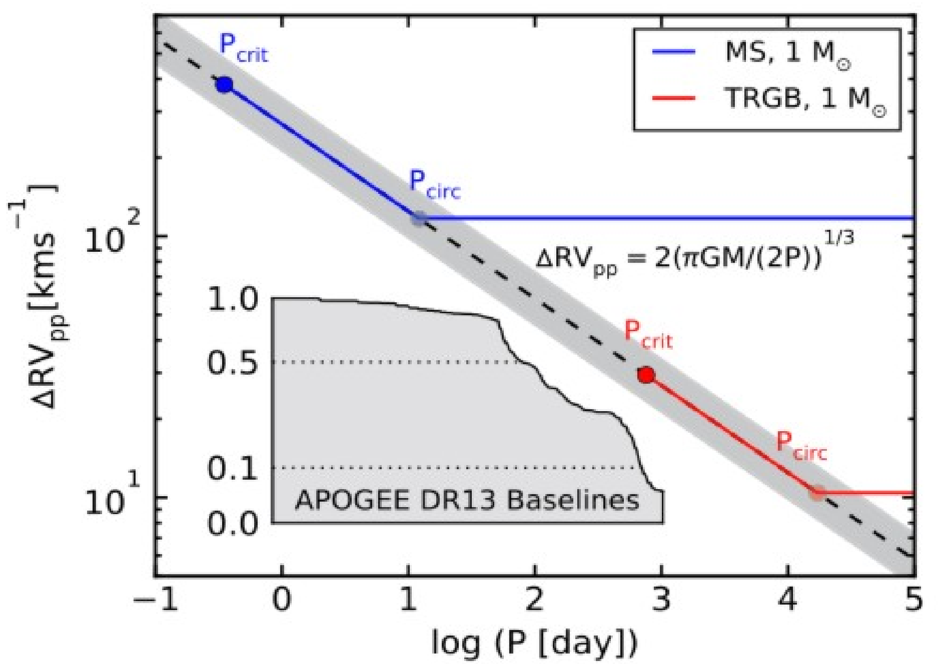
$$\mathbf{P_{crit} = 0.76(R^3/(GM))^{1/2}}$$

- Core H exhaustion ⇒ R↑ (RGB) ⇒ P_{crit}↑. log P_{crit} : -0.35 (MS) ⇒ 2.9 (TRGB) ⇒ 3.4 (TAGB).

- Case A (MS), B (RGB) and C (AGB) mass transfer. RGB (Case B) ⇒ Unstable [Pavloskii & Ivanova 15] ⇒ Common Envelope ⇒ merger or short P system.

- P_{crit} translates to maximum peak-to-peak RV: $\Delta RV_{PP}=2(\pi GM/(2P))^{1/3}$





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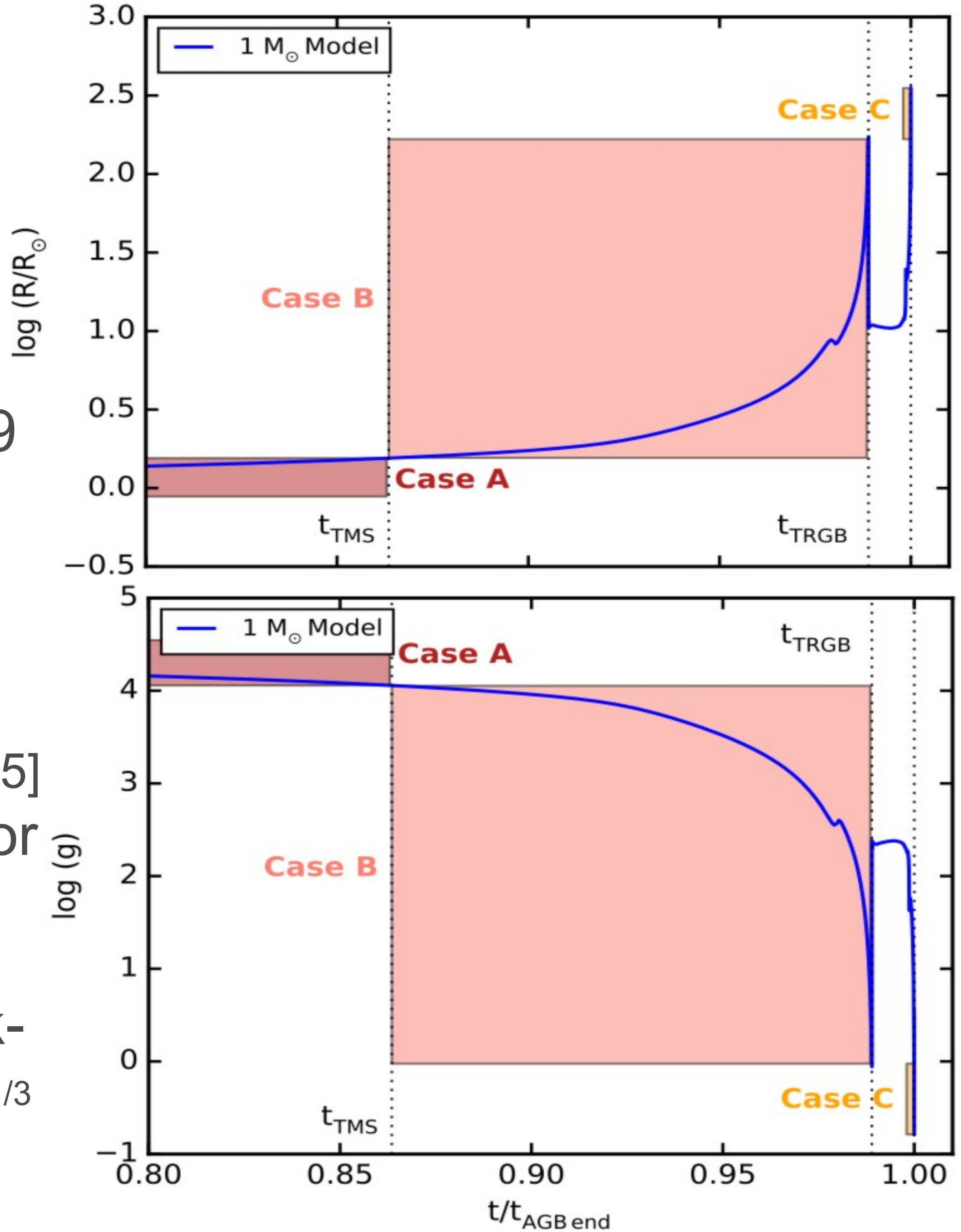
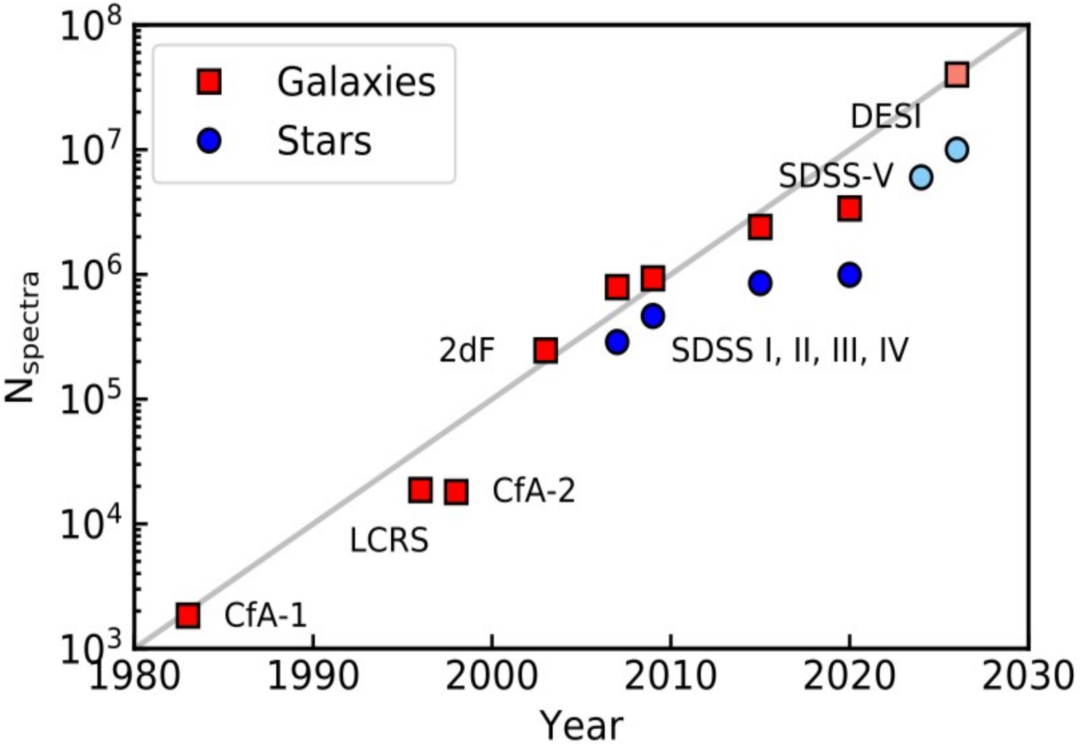


RVs in Large Spectroscopic Surveys

- **RVs**: most efficient probe of multiplicity for log P<4 ⇒ spectra.
- **Large spectroscopic surveys**: SDSS/SEGUE [Yanni+ 09], SDSS/APOGEE [Majewski+ 17], RAVE [Steinmetz+ 06], WEAVE [Dalton+ 14], MSE [Szeto+ 18].
- Well characterized (pipelines) ⇒ stellar parameters.
- Caveat: Orbital fitting requires ~10 RVs, good phase sampling ⇒ not for most targets.



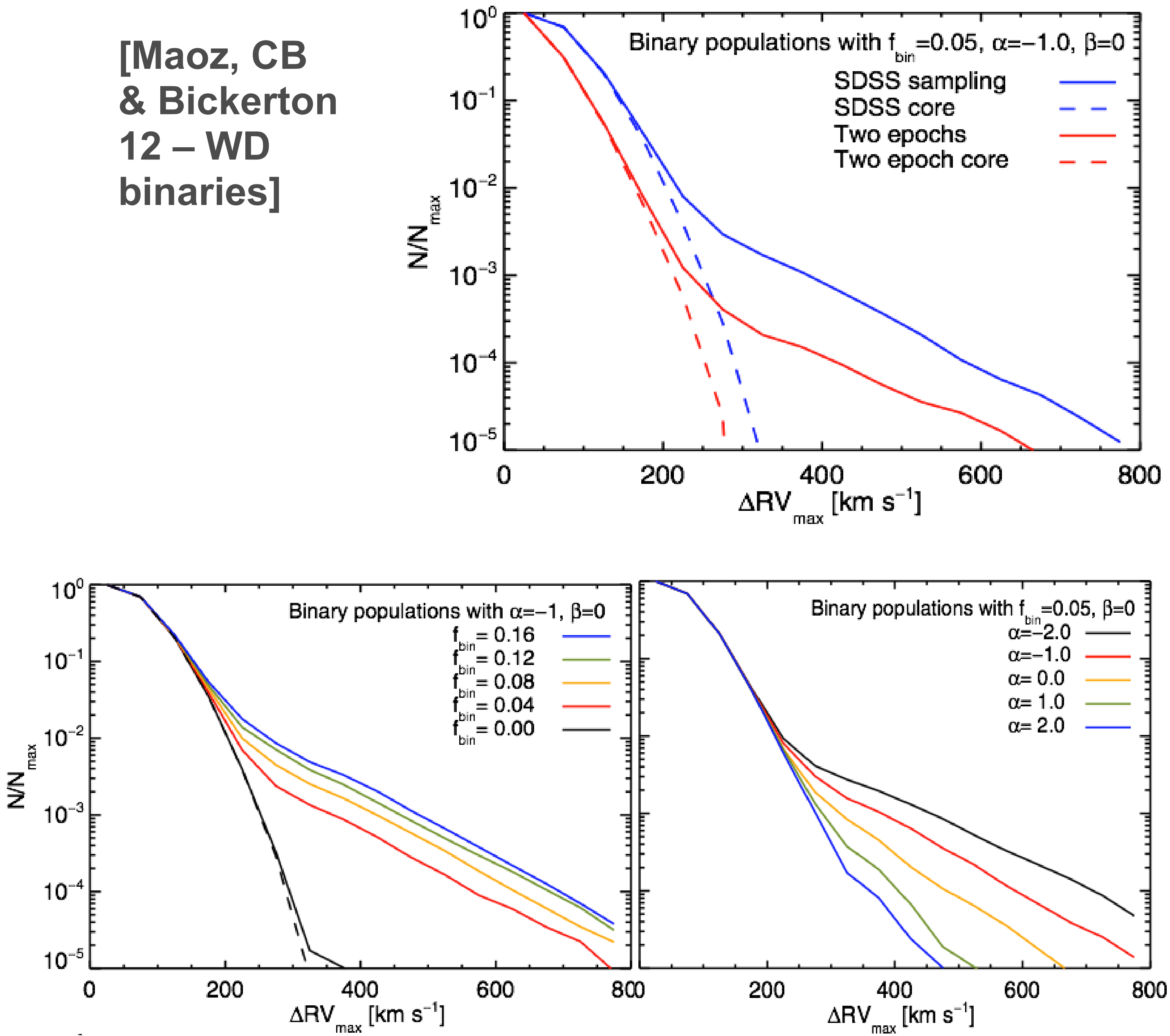
We don't need to fit the orbits to answer many of the open questions about stellar multiplicity!

RVs in Large Spectroscopic Surveys

Carles Badenes
SDSSV+ZTF

- Few epochs (4 or less) ⇒ ΔRV_{max} = $Max(RV_i)$ - $Min(RV_i)$
- RV errors ⇒ core of ΔRV_{max} distribution. Binaries ⇒ tail.
- Shape and height of tail ⇒ multiplicity statistics.
- Searches for RV variability ⇒ clear transition between core and tail.

[Maoz, CB & Bickerton 12 – WD binaries]

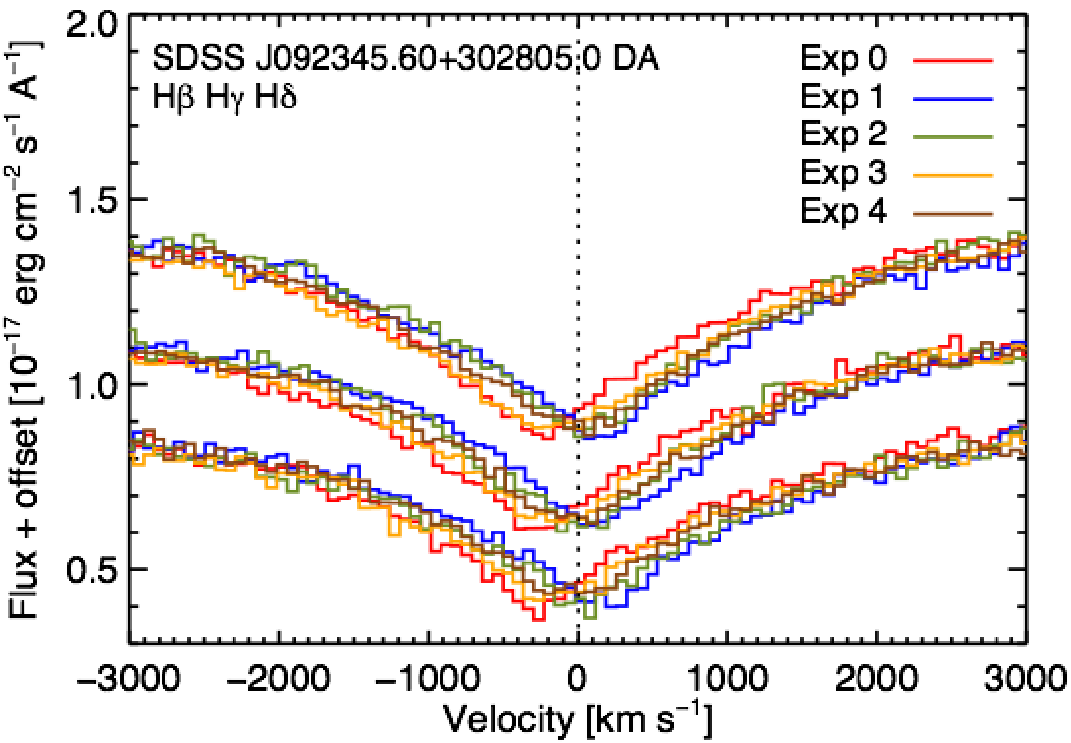


WD Binaries

Carles Badenes
SDSSV+ZTF

- Pre-merger WDs ⇒ P~hrs, RV~500 km/s, detectable at SDSS resolution (70 km/s/pixel) [Badenes+ 09, Mullally+ 09].
- ~4000 WDs in DR7 ⇒ ΔRV_{max} distribution ⇒ f_{bin}, f(P)⇒ WD merger rate.
- Complement w/ SPY survey (fewer WDs, higher R) [Maoz & Hallakoun 17].
- Enough WD mergers to explain SN Ia [Badenes & Maoz 12, Maoz+ 18]. LISA foreground!

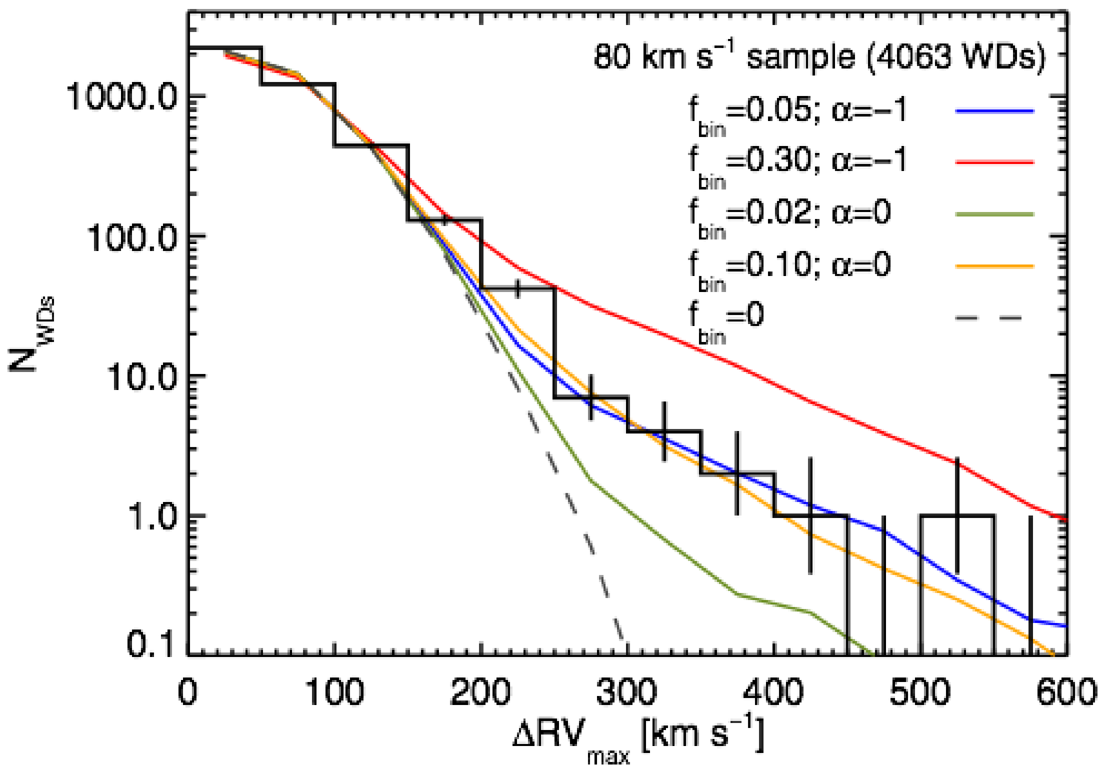
WD binary 'caught' by SDSS [Badenes+ 09]



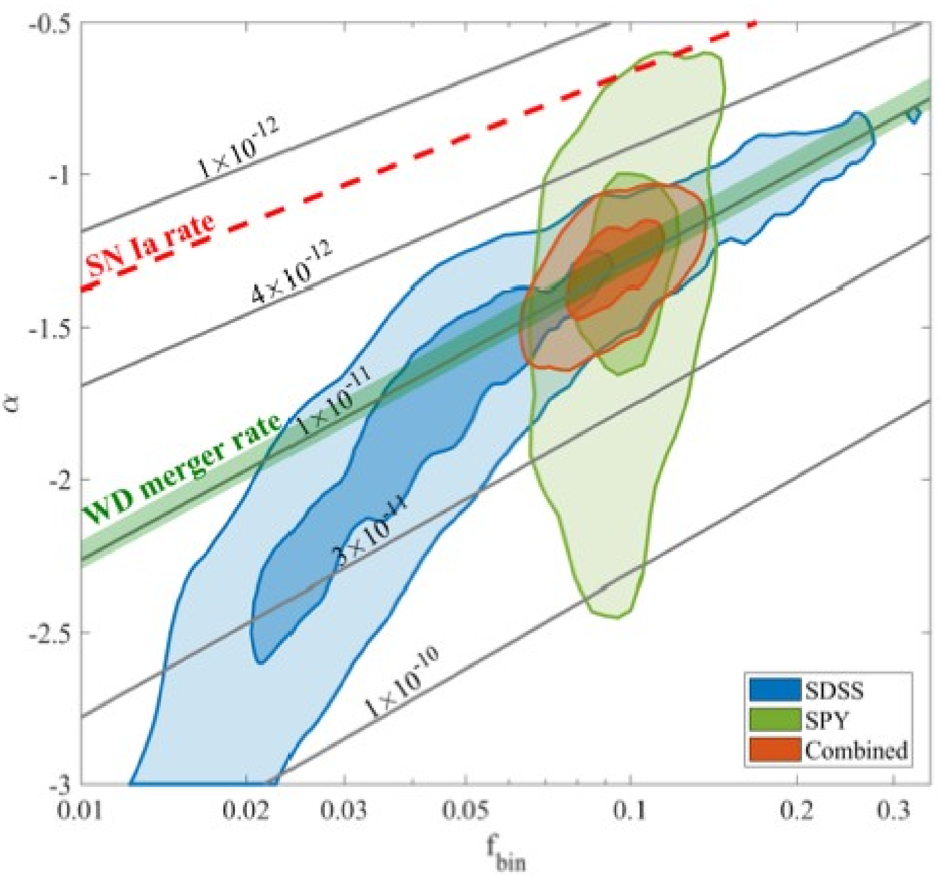
WD Binaries

Carles Badenes
SDSSV+ZTF

[Badenes & Maoz 12]



[Maoz, Hallakoun & CB 18]

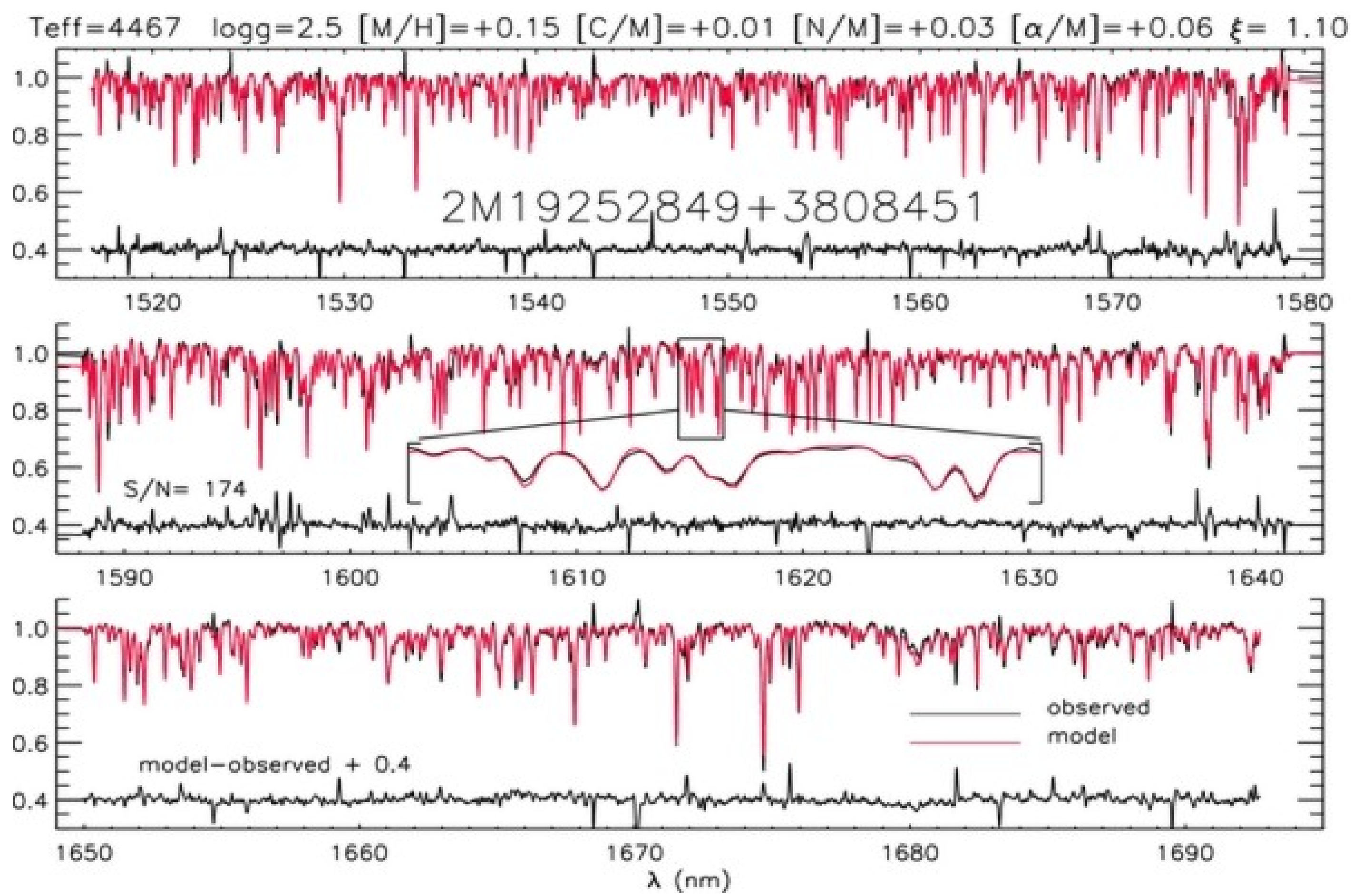


APOGEE

Carles Badenes
SDSSV+ZTF

- Galactic evolution: Multi-epoch IR spectra R~20,000, ~10^5 stars, high S/N [Majewski+ 17].
- MS, RG and RC stars, M~1 M_{Sun}, most of MW disk [Zasowski+ 13].
- ASPCAP [Perez+ 16] ⇒ T_{eff}, log(g), [Fe/H], **RVs**. RC catalog [Bovy+ 14]. The Cannon [Ness+ 15,16].

SDSS DR 10



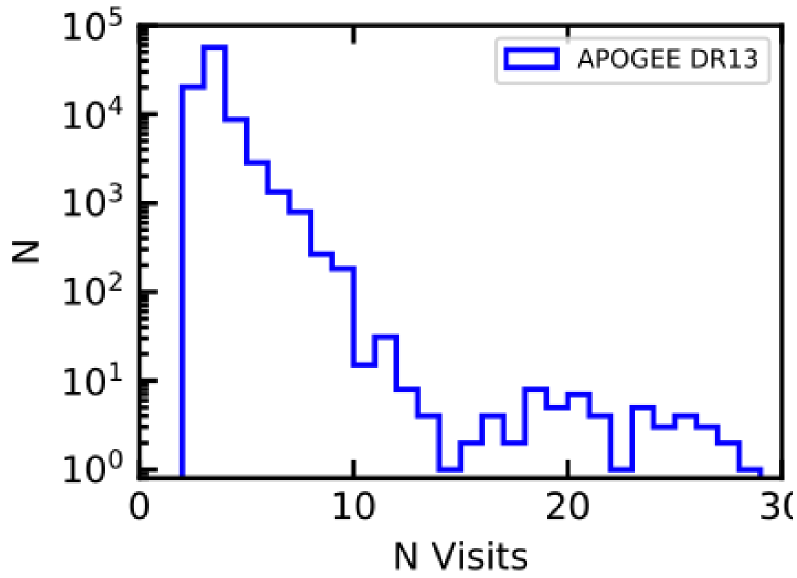
APOGEE: ΔRV_{max} vs. log(g)

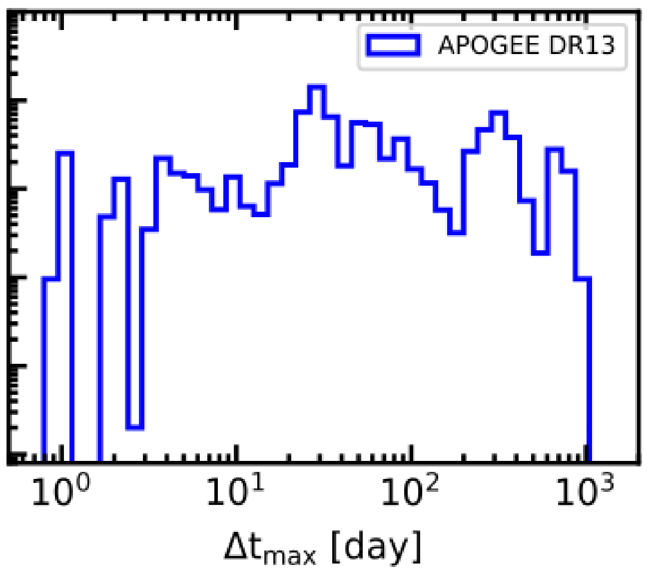
Carles Badenes
SDSSV+ZTF

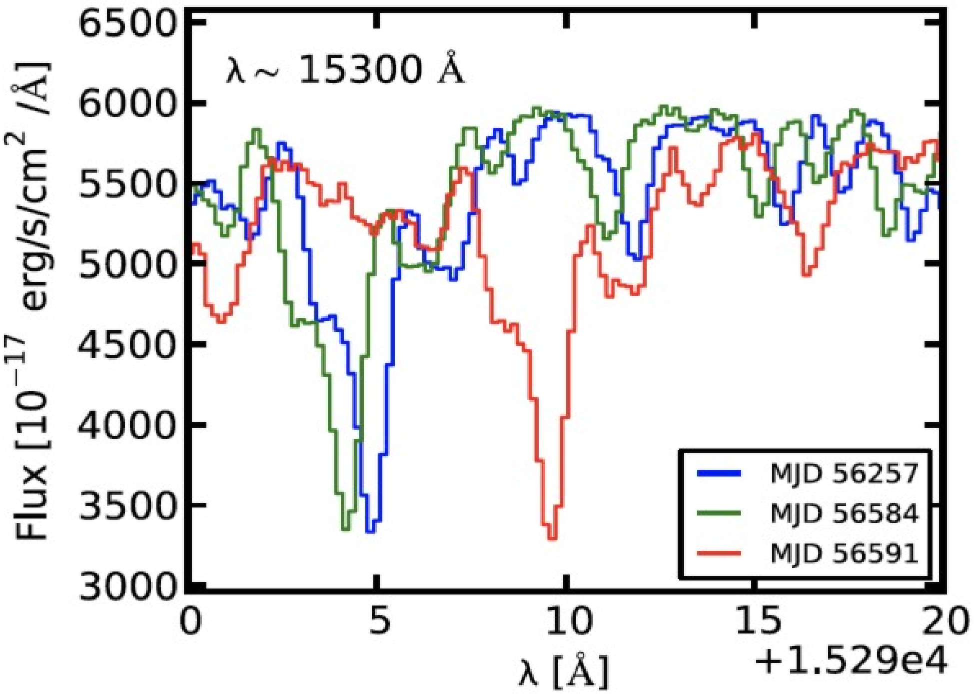
- Few RVs/star (median is 3) ⇒ no orbits! [but Troup+ 16]

- Figure of merit: **ΔRV_{max}**. Multiple systems ⇒ ΔRV_{max} > 10 km/s (> 2,000).

- Clear trend of ΔRV_{max} with log(g): stellar multiplicity meets stellar evolution.







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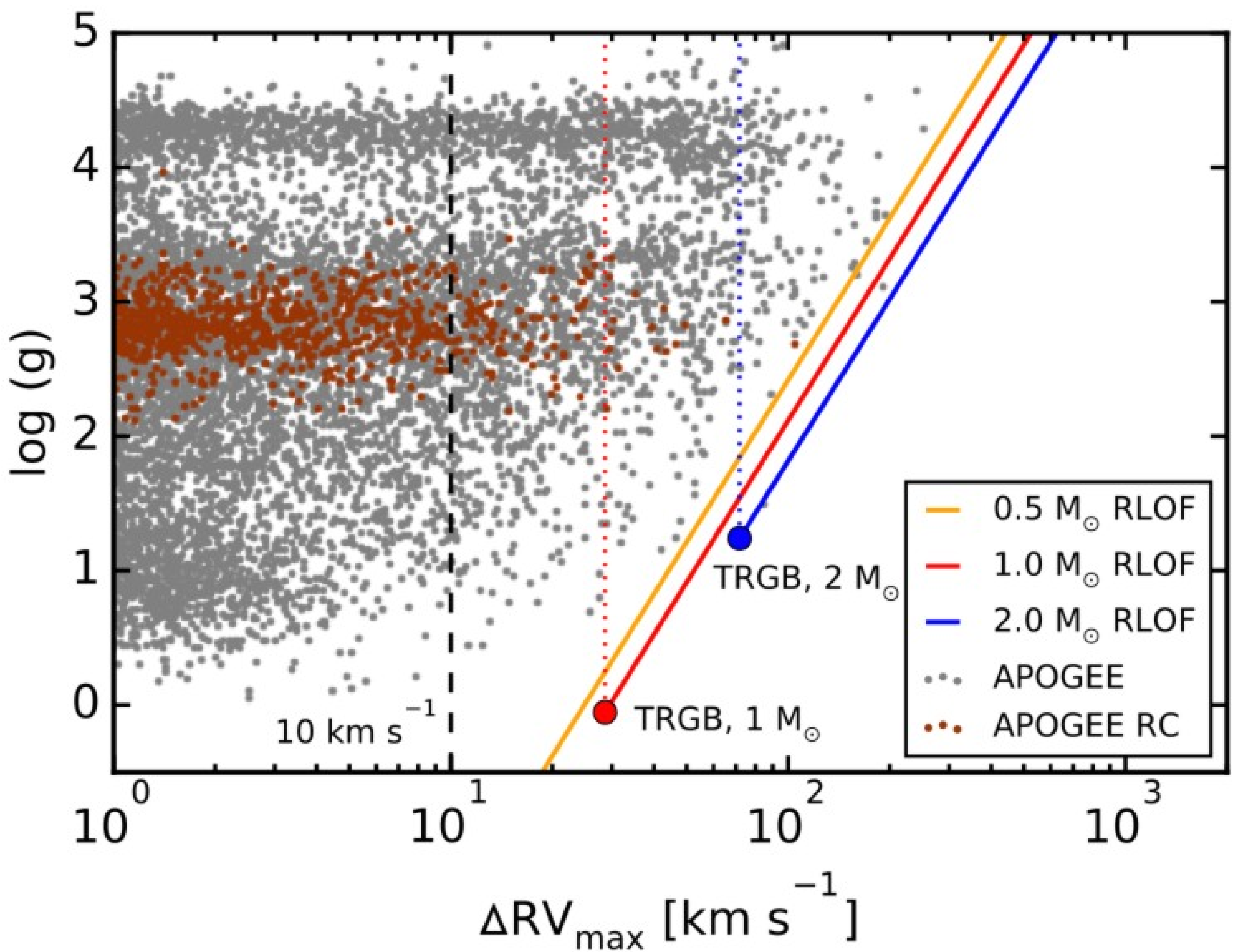

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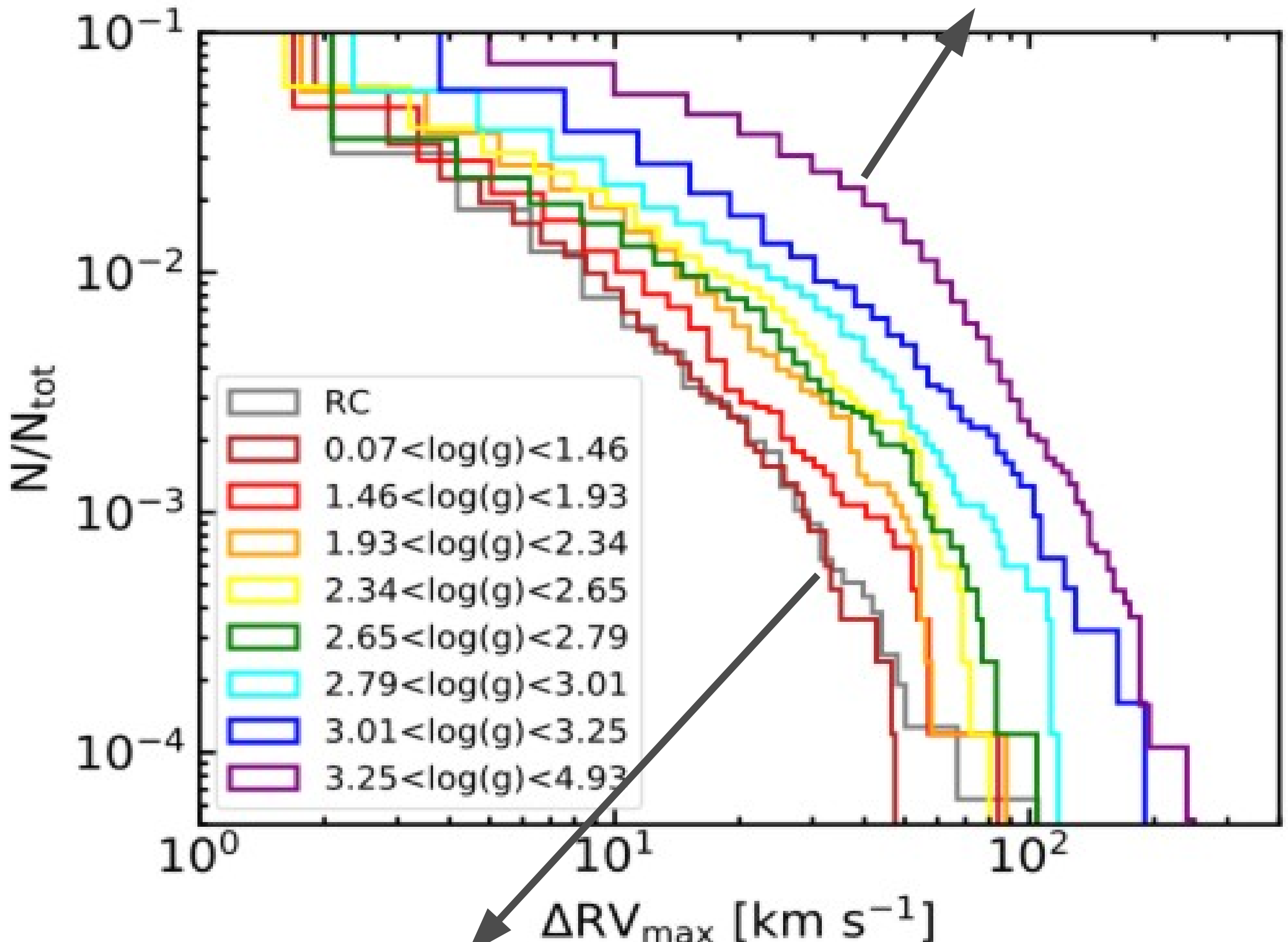
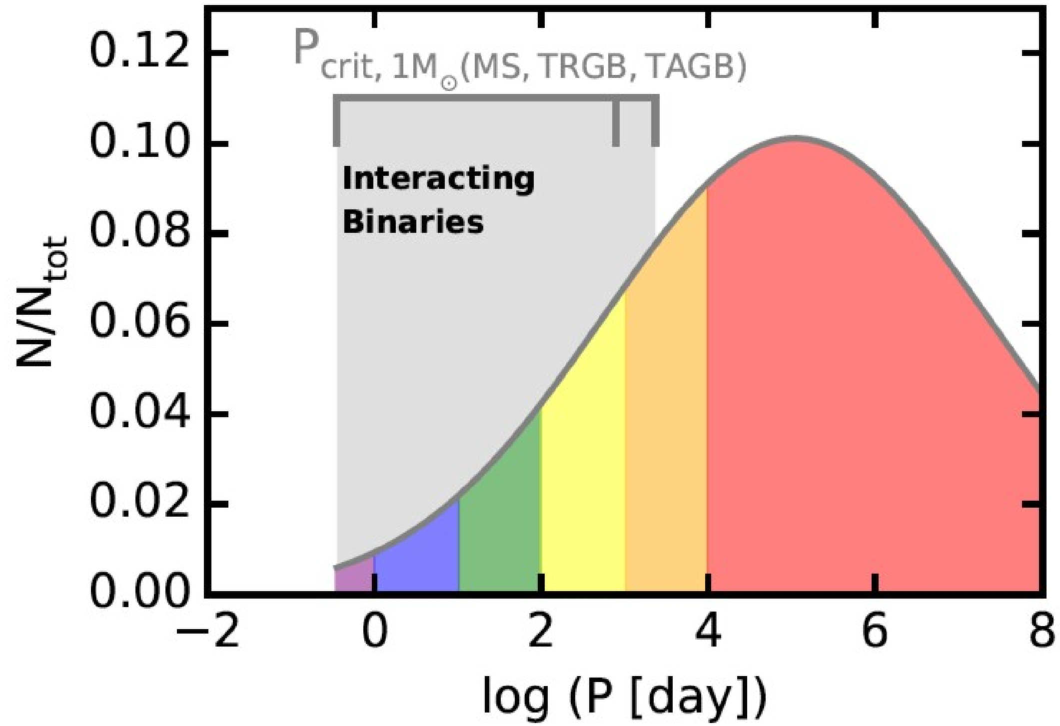
MS & subgiants: higher ΔRV_{max}

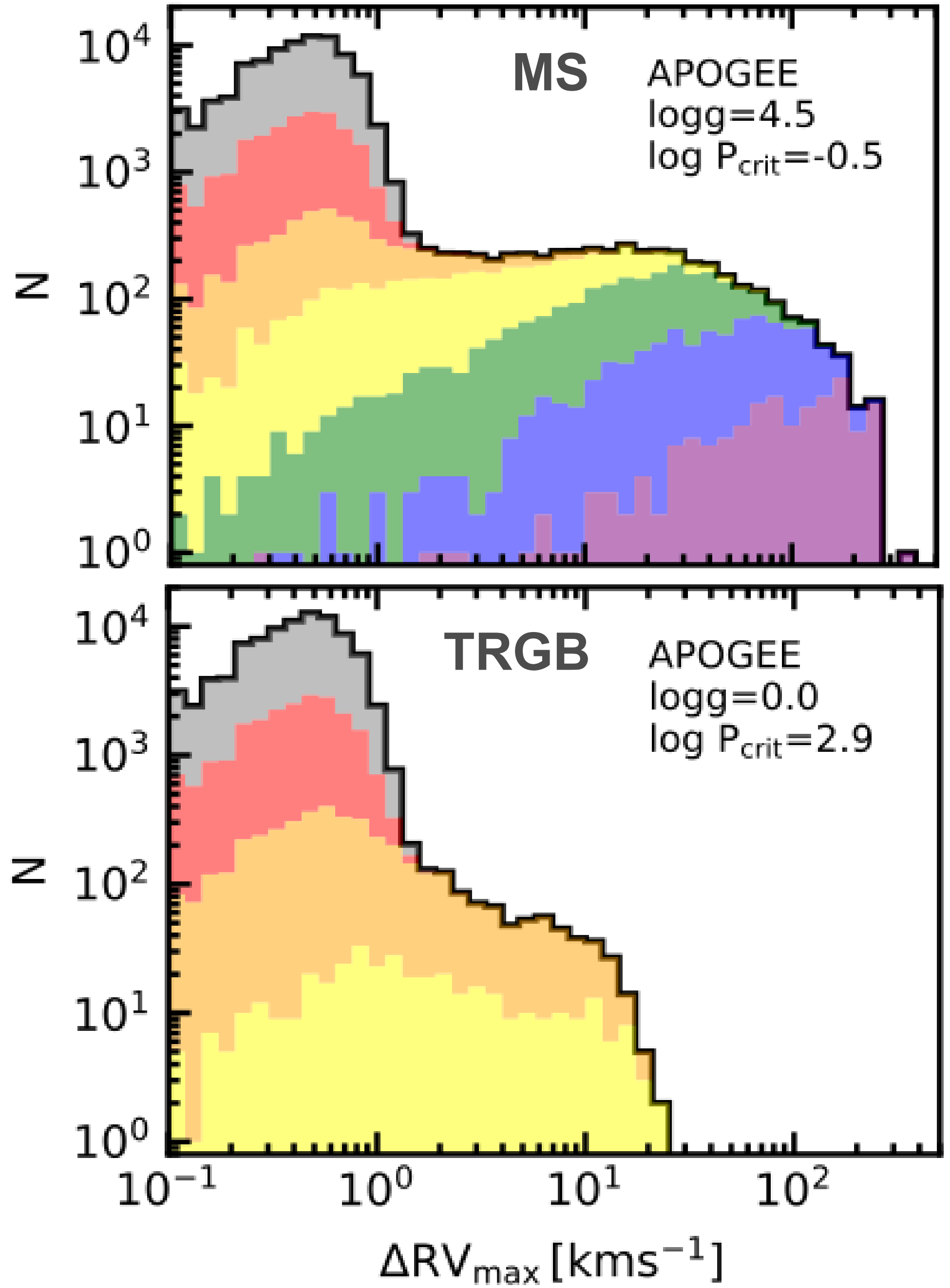


TRGB & RC: similar ΔRV_{max} distributions

APOGEE: Models for ΔRV_{max}

Carles Badenes
SDSSV+ZTF



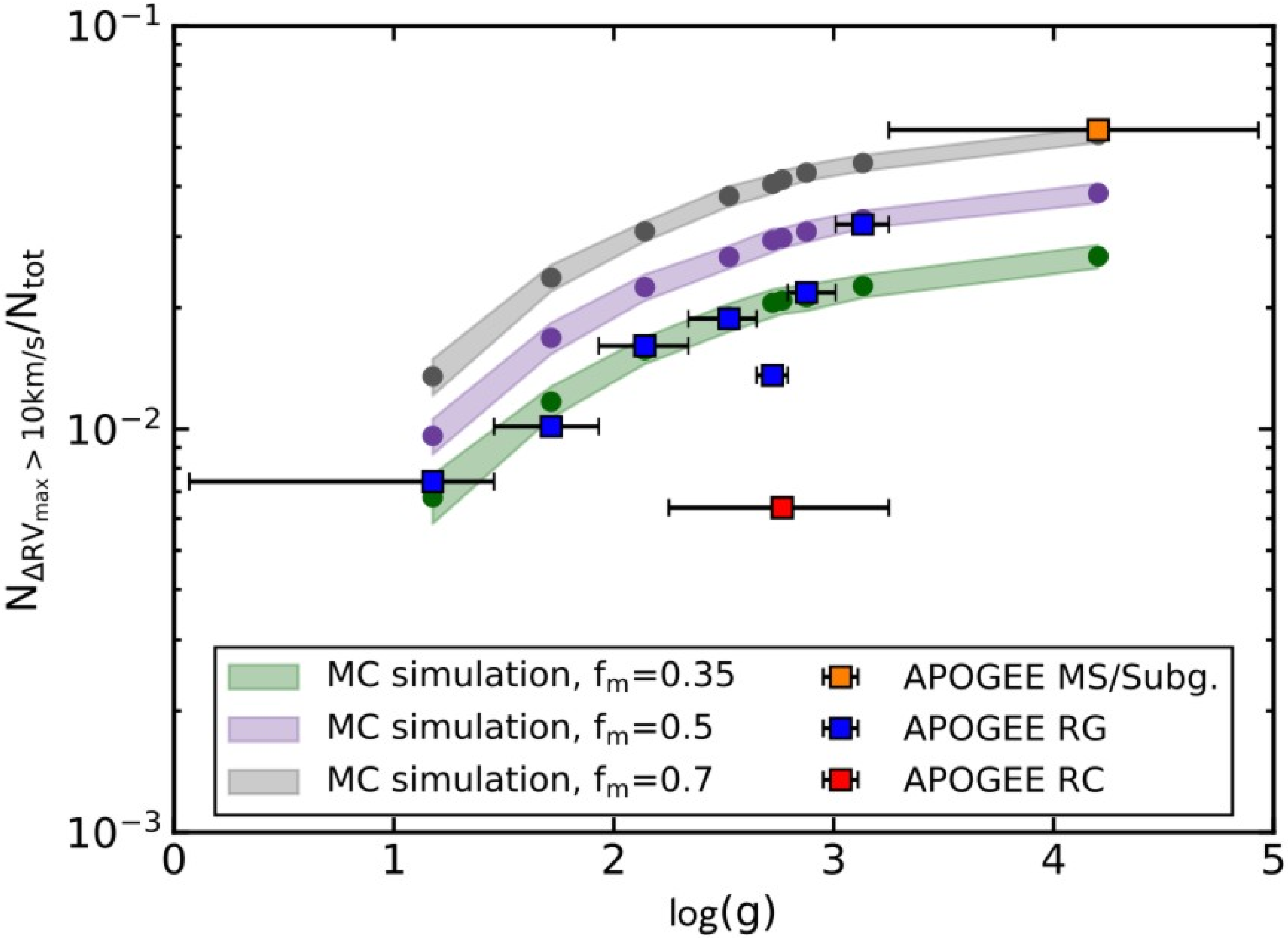


- Monte Carlo models for ΔRV_{max} [Badenes & Maoz 12, Maoz+ 12].
- Assume M = 1 $M_{Sun,}$ lognormal P, flat q, tidal circularization [Verbunt & Phinney 95]. Parameters: f_m, log(g) (⇒ P_{crit}), N.

APOGEE: ΔRV_{max} vs. log(g)

Carles Badenes
SDSSV+ZTF

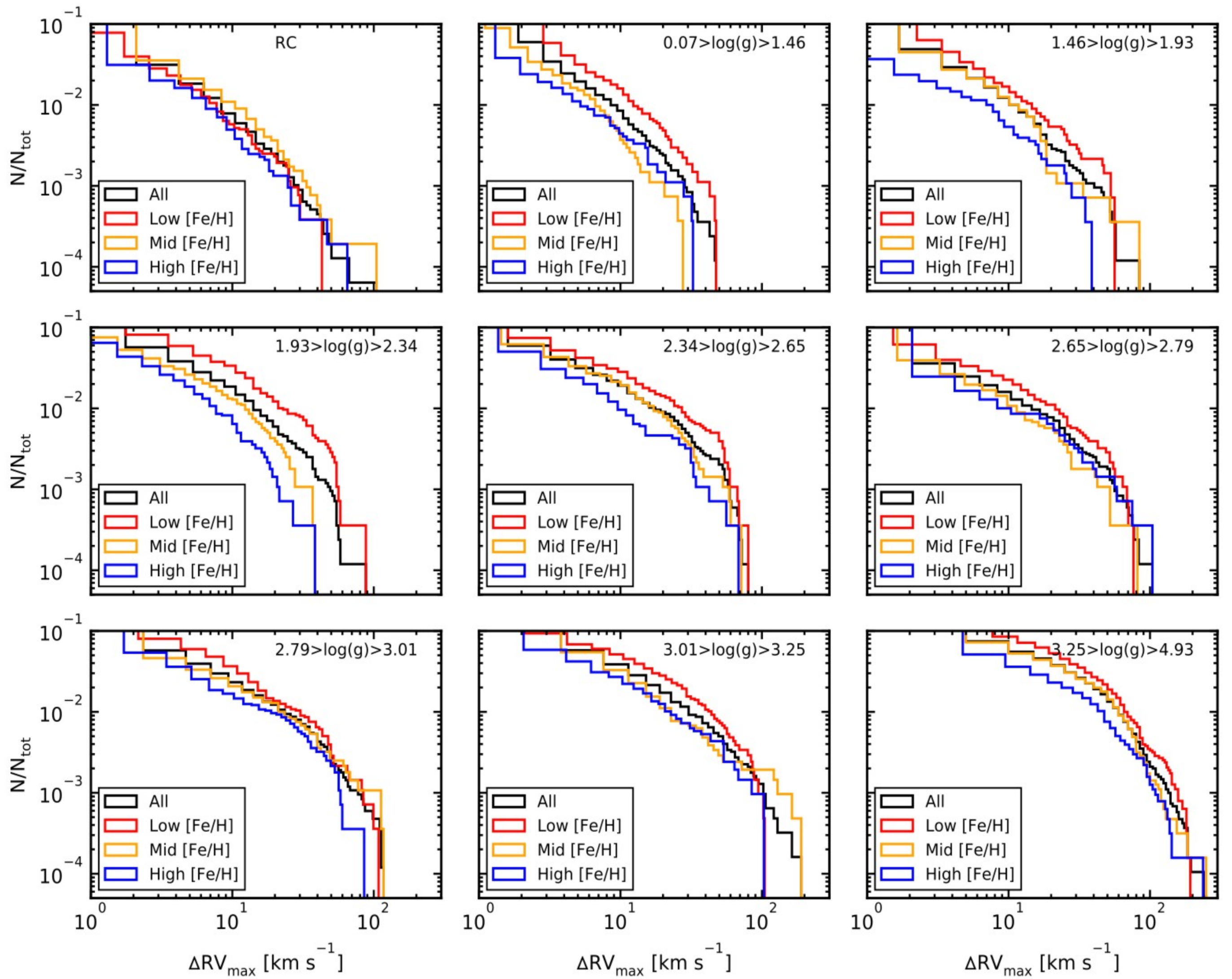
- Fraction of systems with ΔRV_{max} > 10 km/s.
- MC models work well in the RGB, but not at high log(g).
- Support for **lognormal P dist, truncated at P_{crit}**.
- Best-fit MC model in the RGB has f_m=0.35. Caveats: log P < 3.3, simple models, WD+RGB [MD 17].



APOGEE: ΔRV_{max} vs. [Fe/H]

Carles Badenes
NYU 4/16/19

- APOGEE view of MW disk ⇒ [Fe/H].
- ΔRV_{max} distribution in [Fe/H] terciles: low ~ -0.5; high ~0.0.
- ΔRV_{max} in low [Fe/H] clearly above high [Fe/H] in all non-RC samples.
- Consistent with **f_m a factor 2-3 higher at low [Fe/H]** for close (log P < 3.3) binaries.

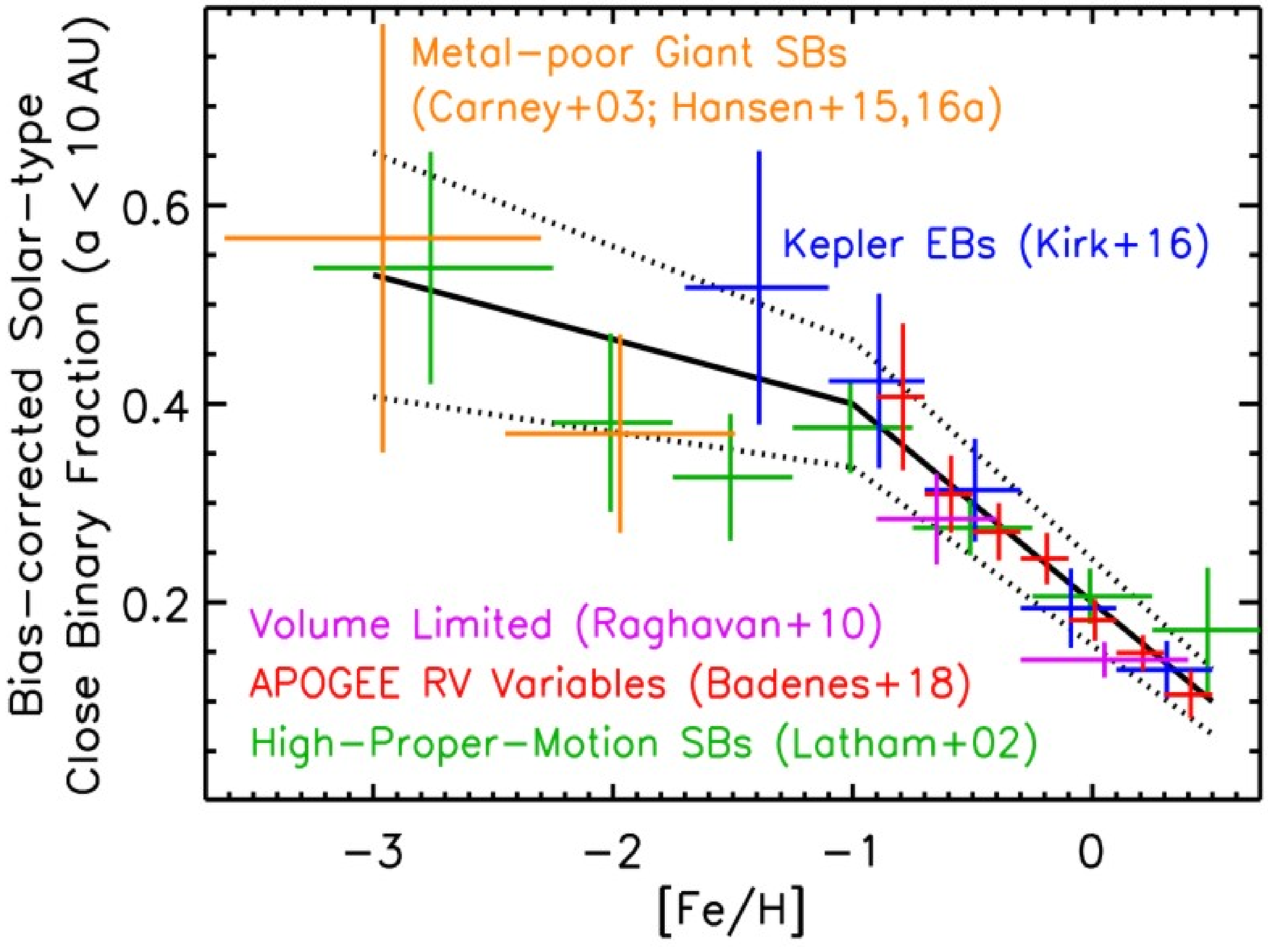


APOGEE: ΔRV_{max} vs. [Fe/H]

Carles Badenes
SDSSV+ZTF

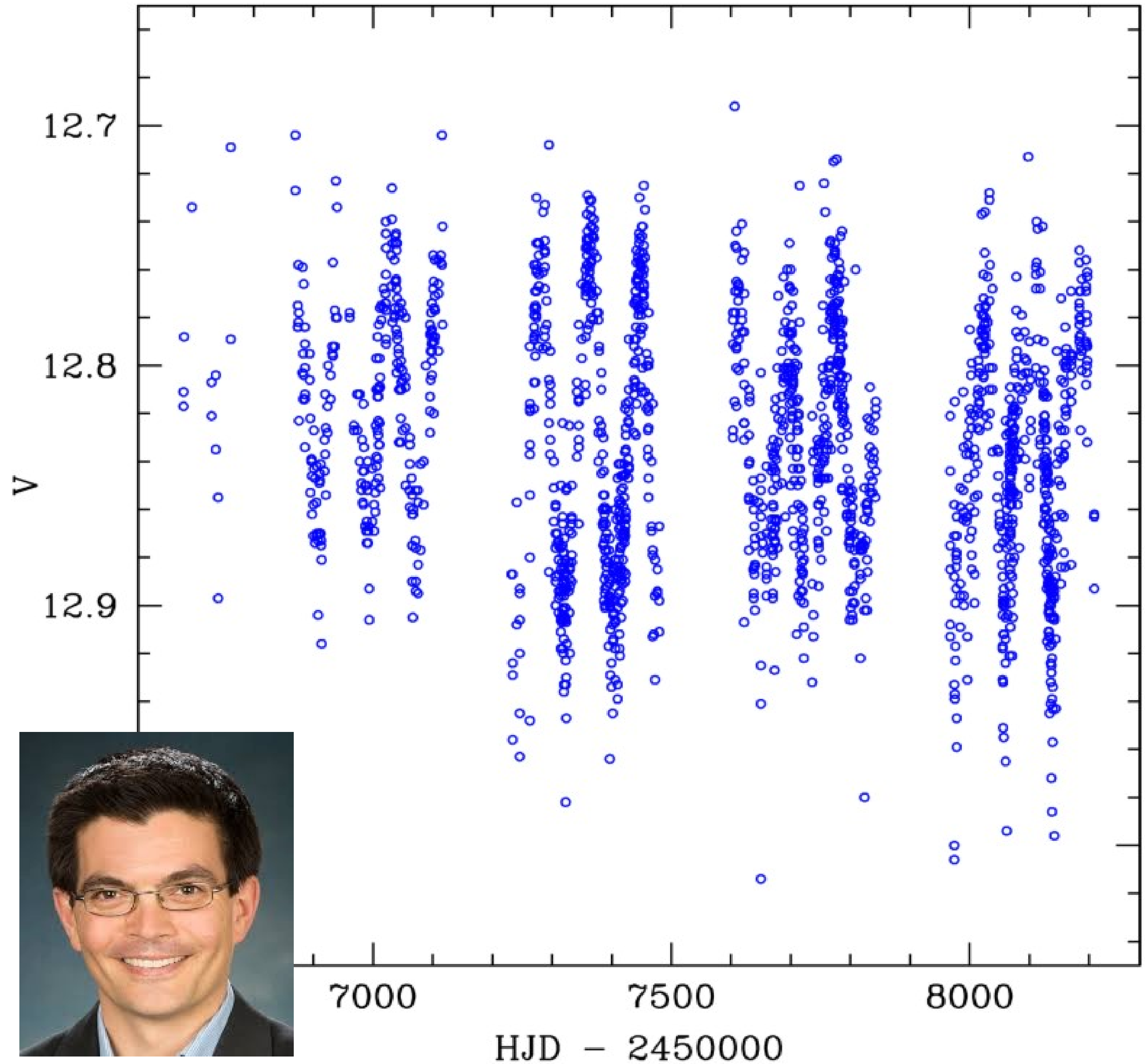
- Previous RV surveys did not find this effect!!!!
- Moe, Kratter & CB 18: explained by uncorrected biases.
- Bias-corrected meta-analysis: consistent picture: **f_m increase by a factor 6 across [Fe/H] range**.

Moe, Kratter & CB 18



Discovery of TAT-1

- Use APOGEE RVs to select systems with high mass function.
- TAT-1: photometric variable, P=83 days. Starspots. K = 45 km/s SB1.
- GAIA parallax: D>2.5 kpc, L>200 L_{Sun} ⇒ M_1 > 2 M_{Sun} ⇒ M_2 > 2.5 M_{Sun}.
- **Probably a BH!**



Thompson+ 19

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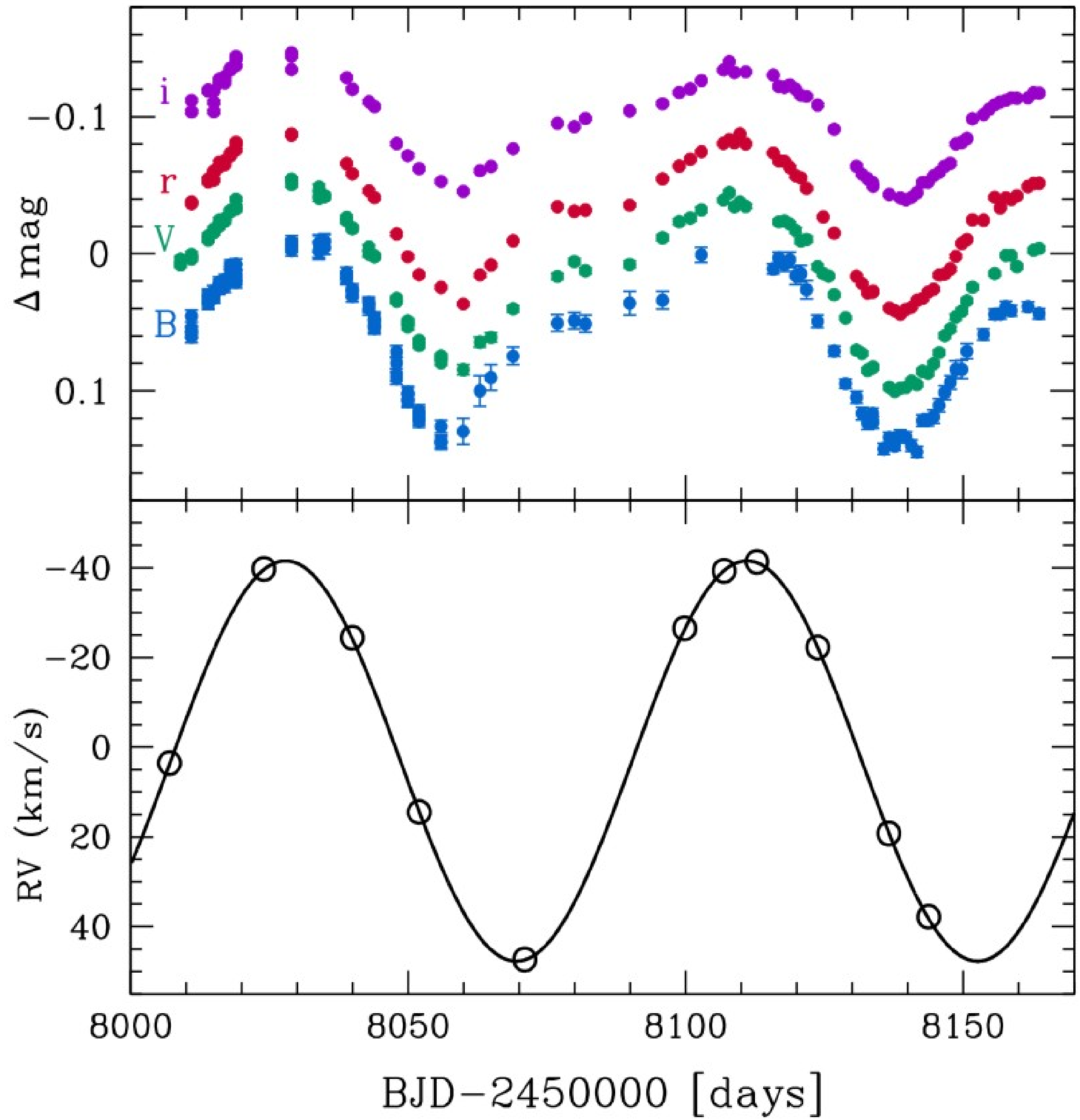

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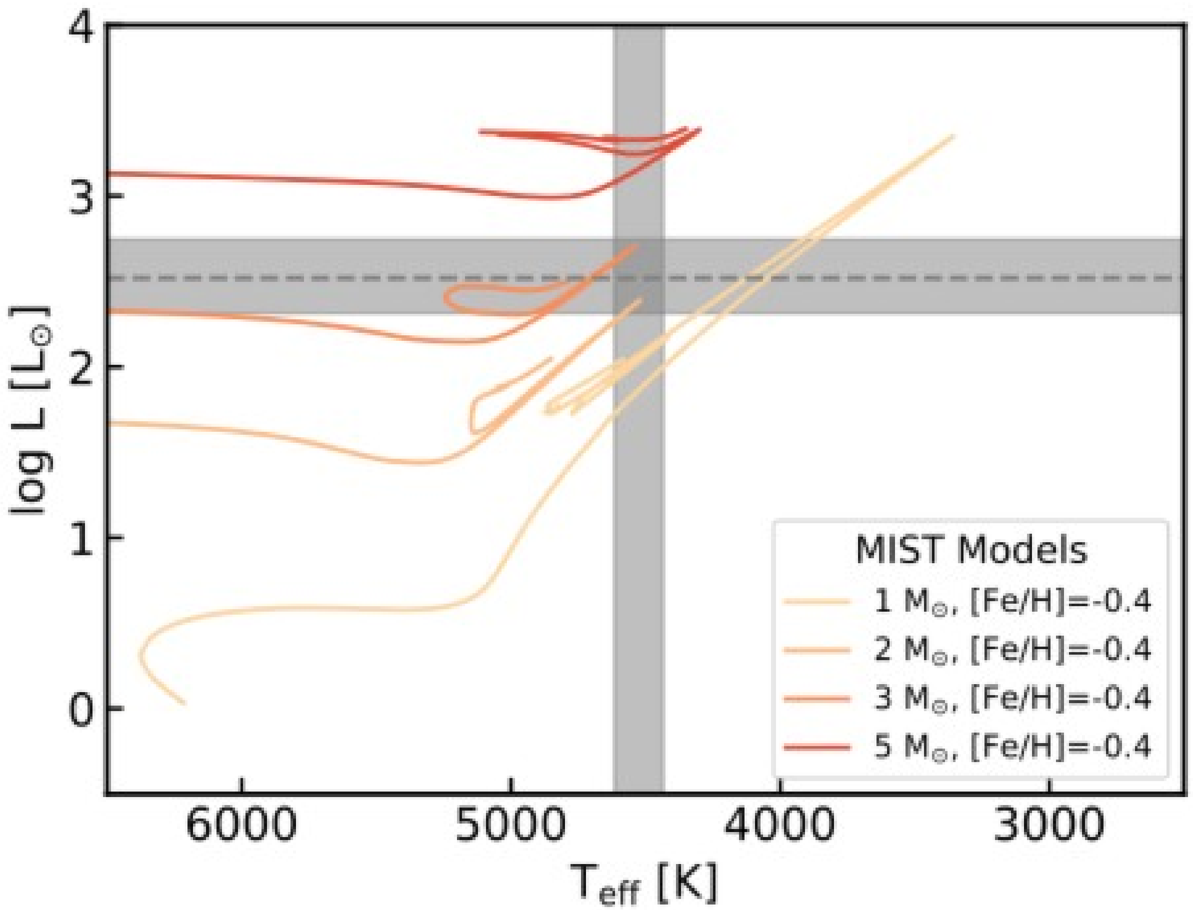

Thompson+ 19

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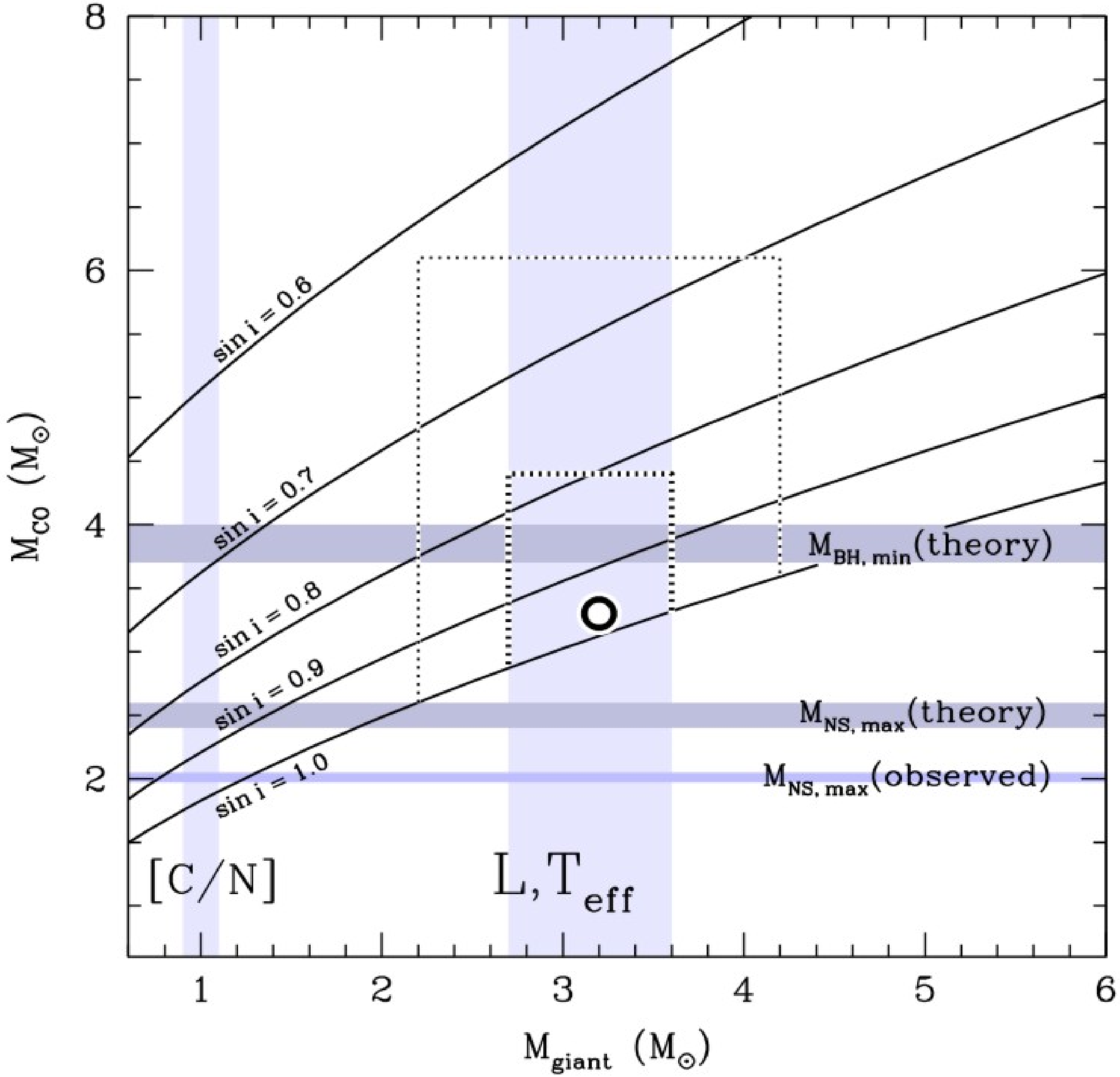

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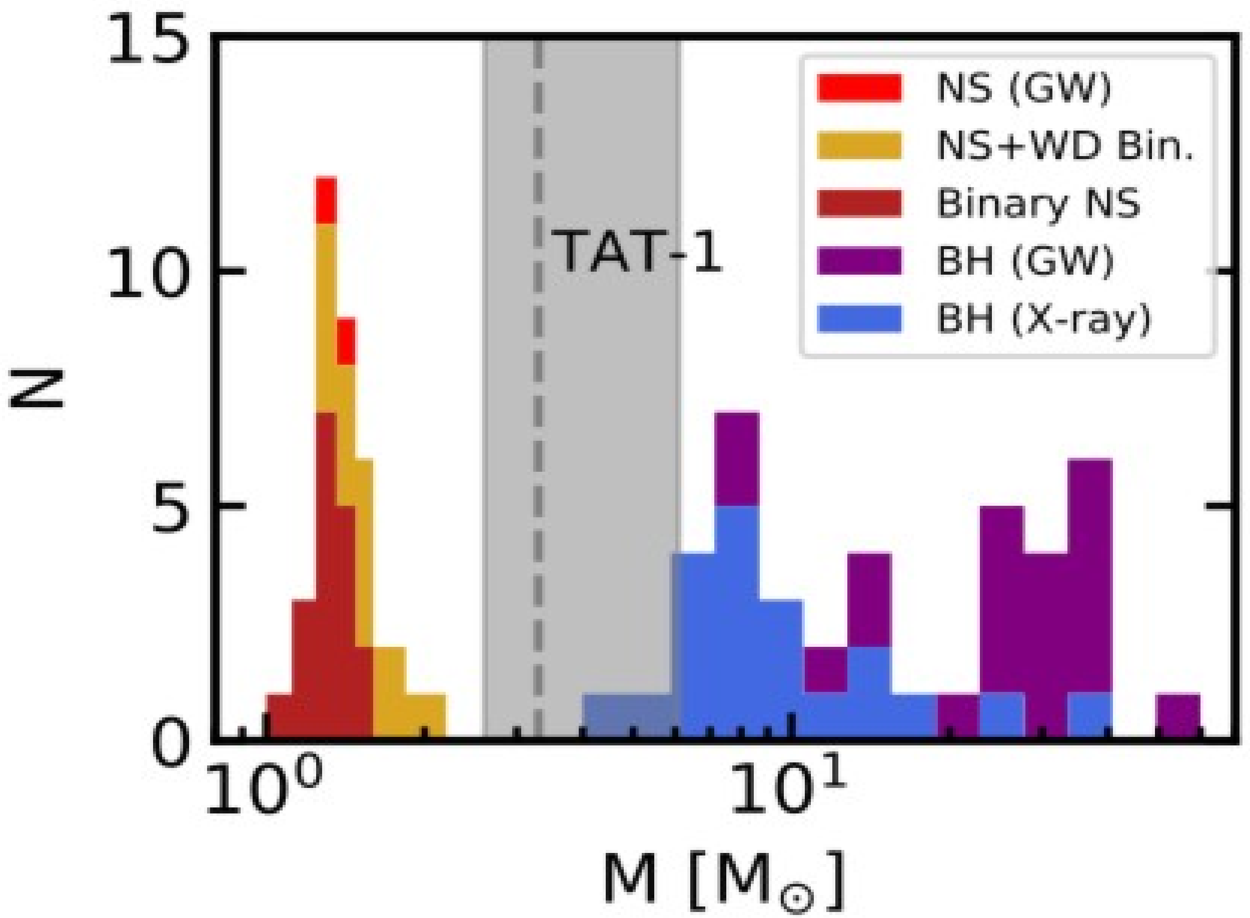
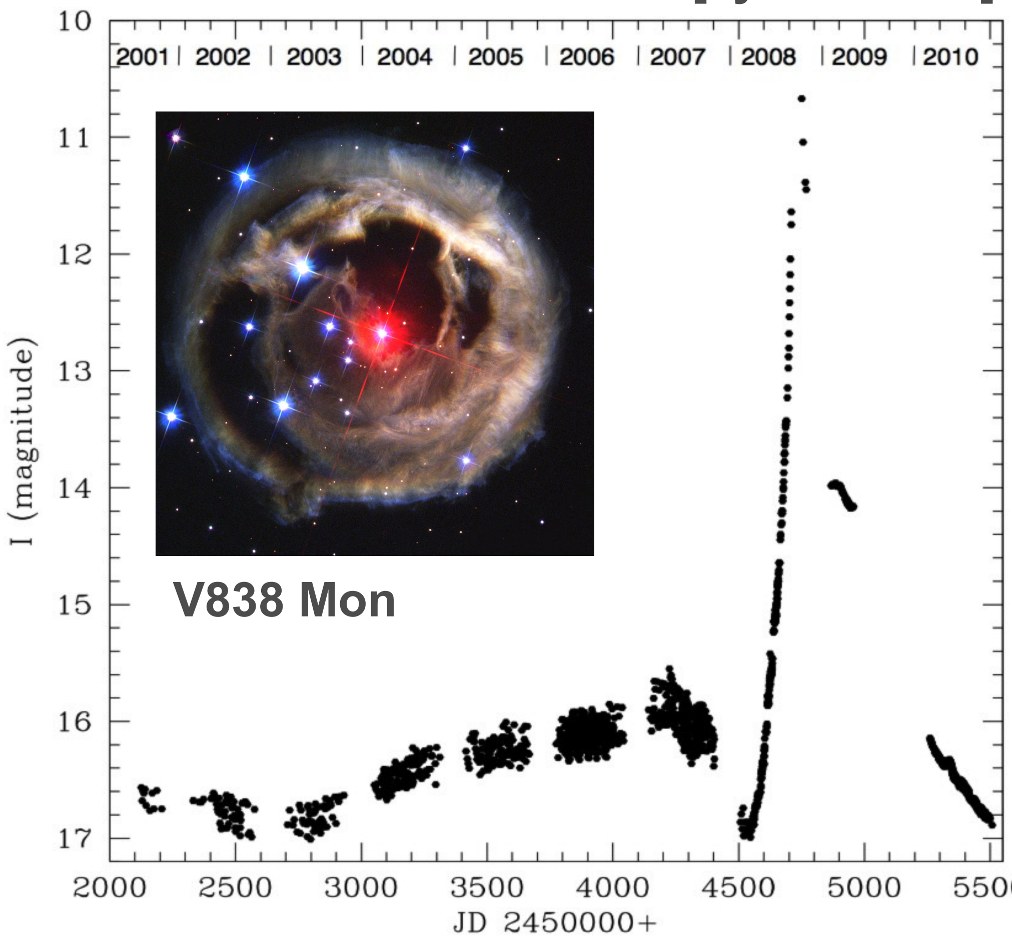


Thompson+ 19

Implications

- Case B mass transfer rate ⇒ CE events, stellar mergers (LRNe), birth rate of short P systems? [Tylenda+ 13, Kochanek+ 14].
- More close binaries at low [Fe/H] ⇔ SF theory [Machida+ 09, Bate 14].
- What about BPS models in different environments, redshift evolution? [de Mink & Belczynski 15]?
- Planet host metallicities ⇒ habitability [Johnson 10, Howard+ 12, Thompson+ 17, Guo+ 17].

V1309 Sco [Tylenda+ 13]



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Carles Badenes
SDSSV+ZTF

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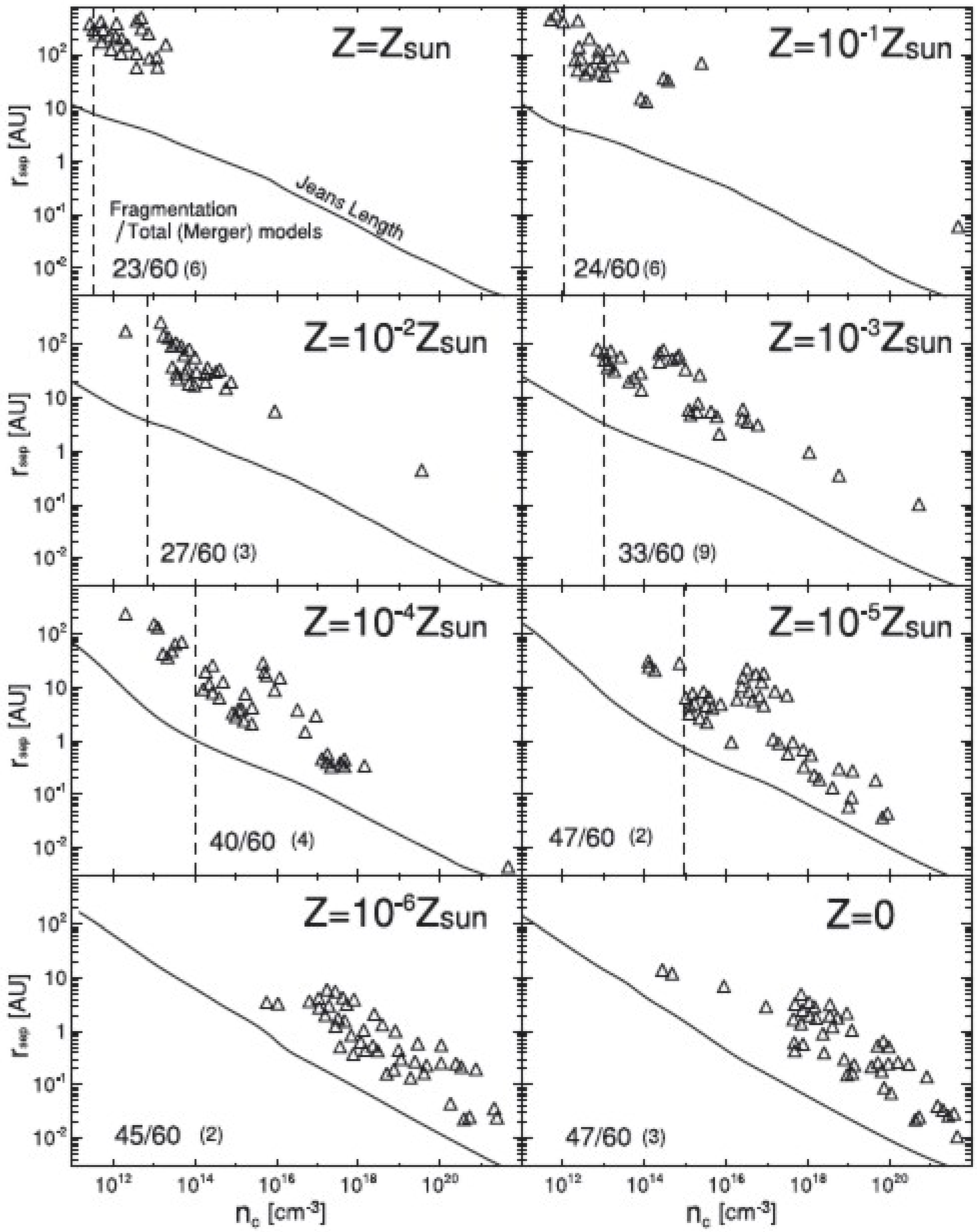
Machida+ 09



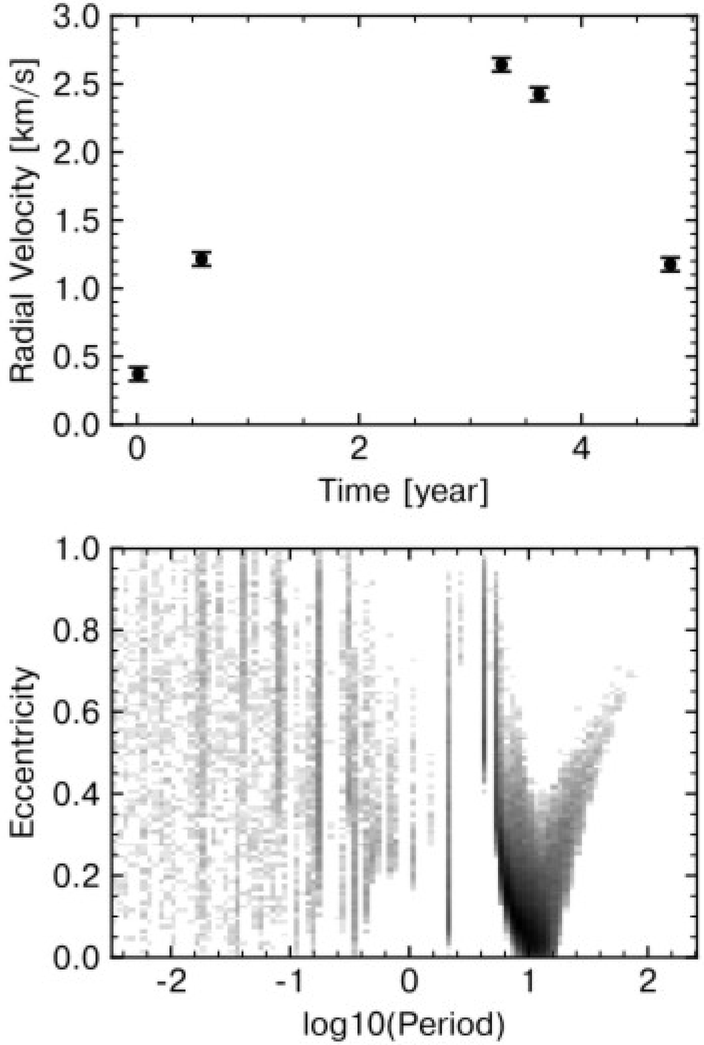
Summary

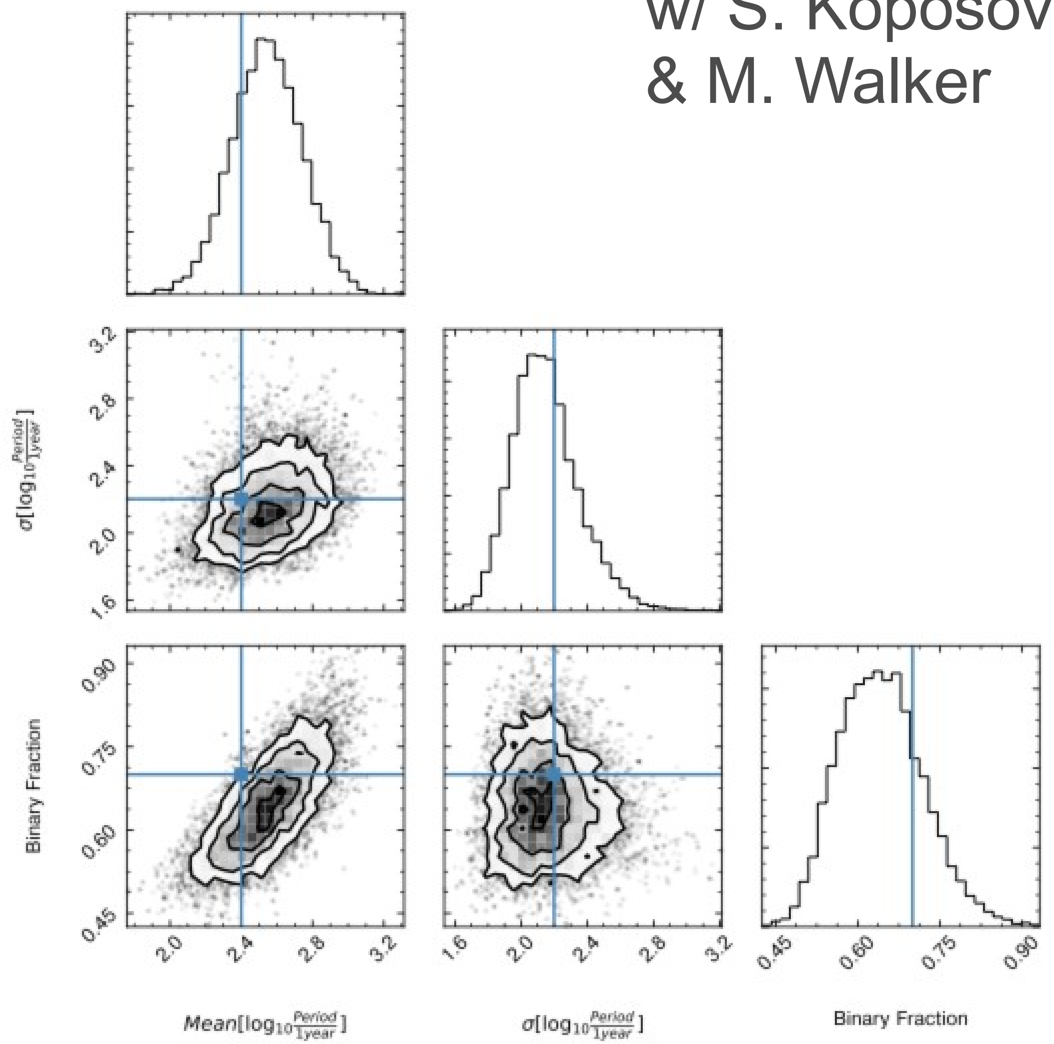
- APOGEE: high resolution, multi-epoch IR spectra of ~100,000 stars (Galactic archeology).
- Unique view of stellar multiplicity in the field, from the MS to the RC. Few-epoch spectra: no orbits ⇒ ΔRV_{max}.
- Attrition of high ΔRV_{max} (short P) systems as stars climb the RGB, consistent with lognormal P dist., truncated at P_{crit} ⇒ Case B mass transfer. ΔRV_{max} in RC stars ~ TRGB.
- Clear trend with [Fe/H]: lower [Fe/H] stars have higher ΔRV_{max} distributions ⇒ higher f_m at lower [Fe/H].
- Discovery of the first stellar mass non-accretting BH.
- Future work: Hierarchical Bayesian models, multiplicity statistics w/ age & Galactic location, GAIA, BPS, follow-up of interesting systems.

Hierarchical Bayesian Models

Carles Badenes
SDSSV+ZTF

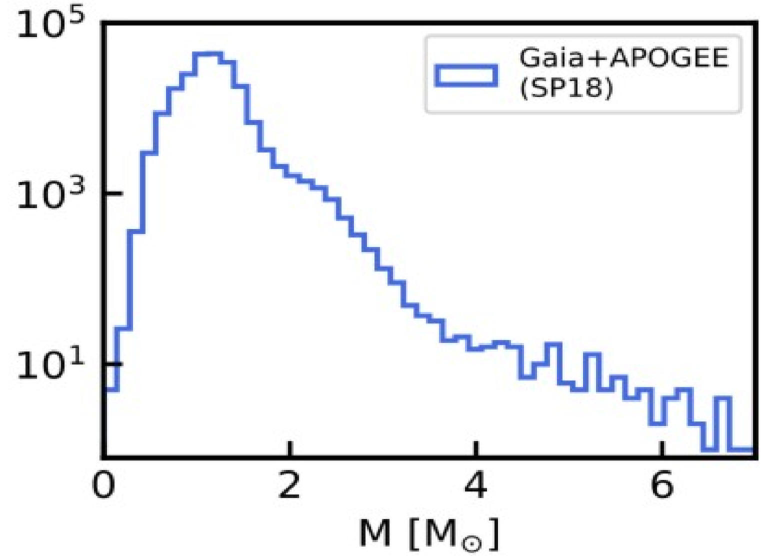
w/ S. Koposov
& M. Walker

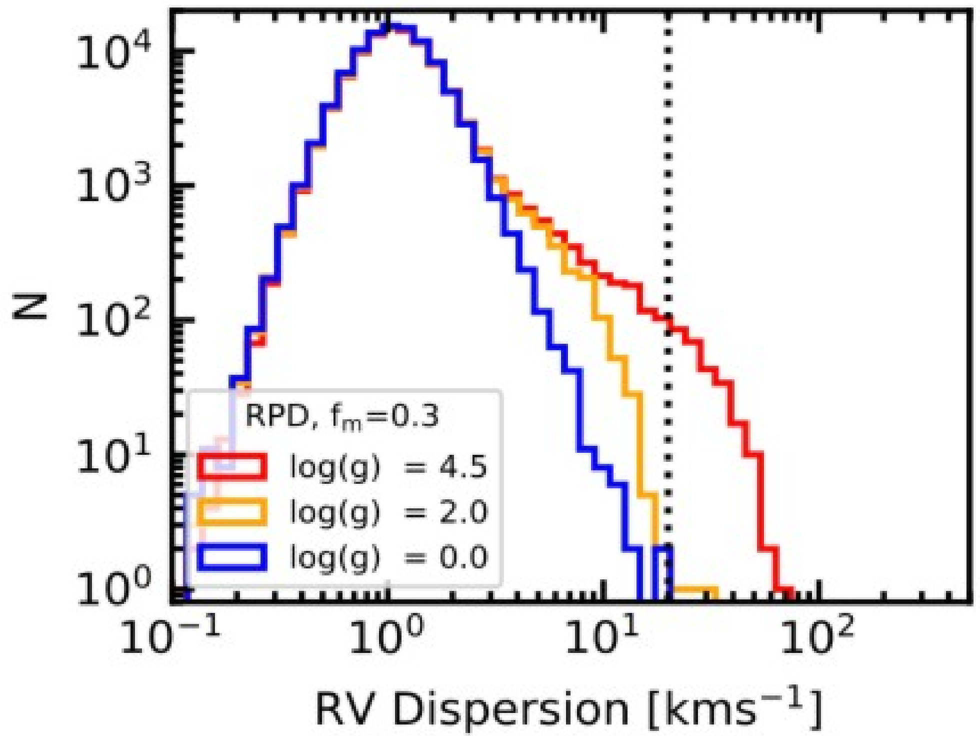


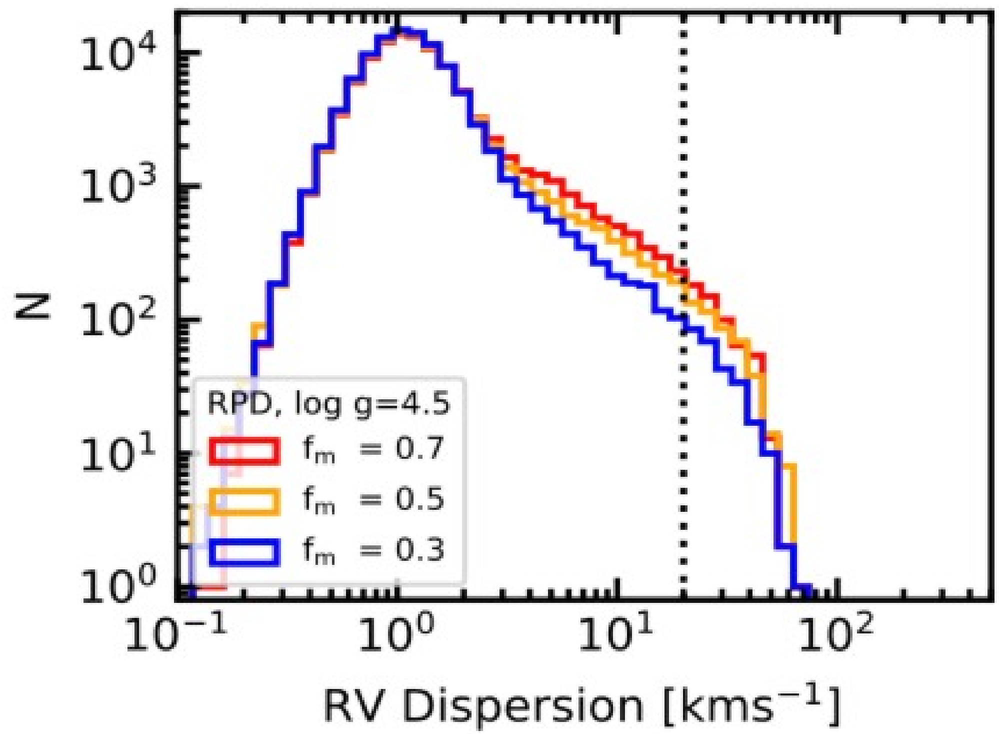


GAIA

Carles Badenes
SDSSV+ZTF

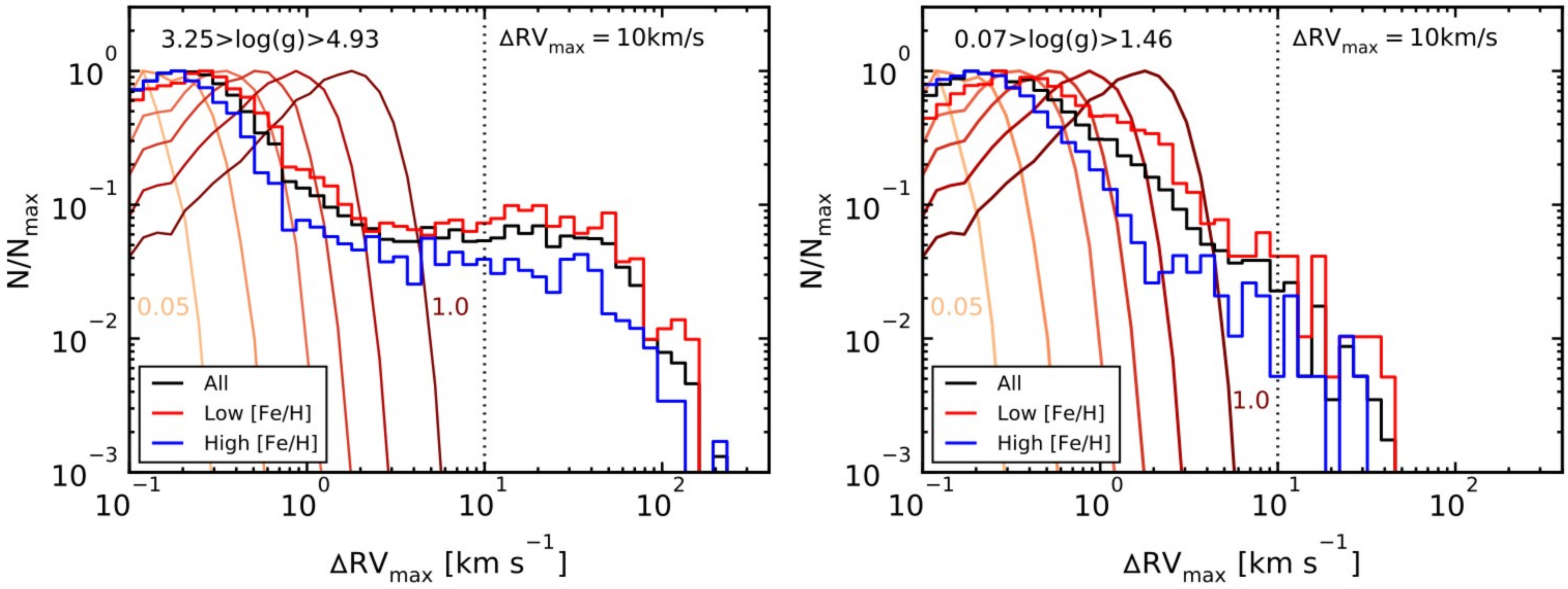






Additional Plots

Carles Badenes
SDSSV+ZTF



Finding interesting (accelerated and otherwise) binaries from *Gaia*

SDSS-V/ZTF

Timothy Brandt
Assistant Professor
University of California, Santa Barbara
with Trent Dupuy, Jackie Faherty, Brendan Bowler, G. Mirek Brandt, Daniel Michalik, Yiting Li, Daniella Bardalez-Gagliuffi, Mark Popinchalk

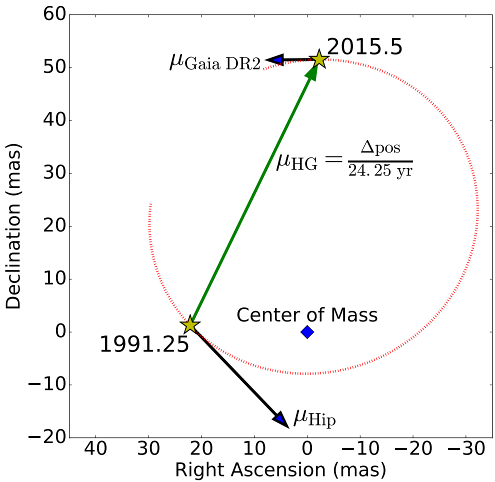
April 18, 2019

Part I: Astrometric Accelerators

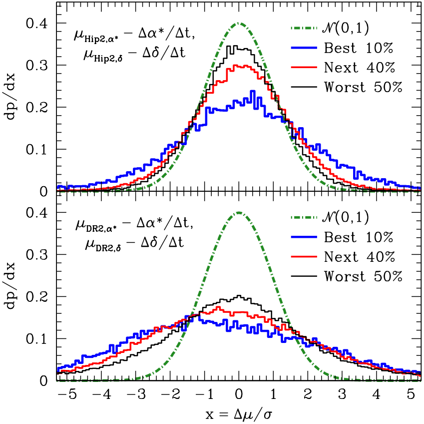
Need detectable acceleration, single-star astrometry

- Separations $\sim 2 - 100$ AU
- Large brightness difference
- Nearby: $\mathrm{d} \lesssim 200$ pc

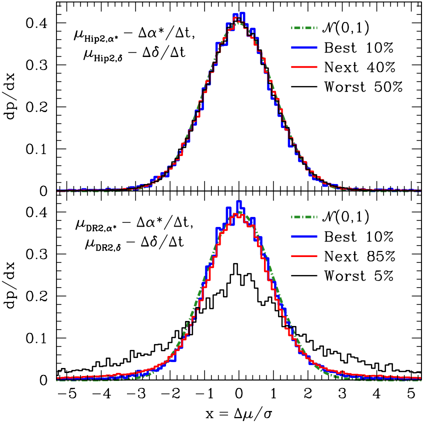
Basic idea: *Hipparcos* and *Gaia* can detect astrometric accelerations of a few μas/yr^2, a few m/s/yr at 50 pc. *Gaia* DR3 will improve this (ideal case: $\sigma_\mu \sim t^{-3/2}$).



Use of *Hipparcos* and *Gaia* for fitting orbits & identifying astrometric accelerators requires a *cross-calibration*.



Δpositions/Δt – proper motions, raw catalogs



Δpositions/Δt – proper motions, after cross-calibration

Full details of the cross-calibration are in Brandt (2018): The *Hipparcos*-*Gaia* Catalog of Accelerations

- Refinement of *Hipparcos* astrometry with *Gaia* parallaxes
- Propagation of all positions to their central epochs
- 60/40 linear combination of the two *Hipparcos* reductions outperforms either reduction individually at 150 σ significance
- Spatially variable calibration offsets and frame rotations between the catalogs
- Error inflation in quadrature for *Hipparcos*, spatially dependent multiplicative error inflation for *Gaia*
- Perspective acceleration included
- Three proper motions given on the DR2 reference frame

If we also have RV and relative astrometry from imaging, we can fit orbits even for long-period systems:

$$a_{\text{astrometric}} = \frac{GM_2}{r_{12}^2} \cos\varphi$$

$$a_{\text{RV}} = \frac{GM_2}{r_{12}^2} \sin\varphi$$

$$\rho_{\text{projected}} = r_{12} \cos\varphi$$

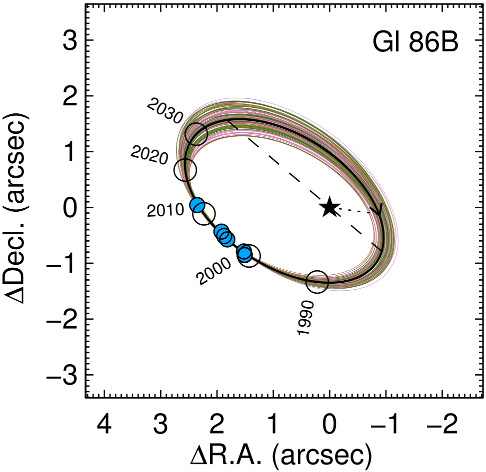
combine to determine the companion mass (though full orbital fits generally remain necessary).

Example: white dwarf companion to Gl 86

Proper Motion Difference	Significance
$\mu_{\alpha*,Hip} - \mu_{\alpha*,H\to G} = -14.98 \pm 0.43\ \mathrm{mas\,yr^{-1}}$	**35σ**
$\mu_{\alpha*,Gaia} - \mu_{\alpha*,H\to G} = -17.80 \pm 0.13\ \mathrm{mas\,yr^{-1}}$	**133σ**
$\mu_{\delta,Hip} - \mu_{\delta,H\to G} = 12.73 \pm 0.46\ \mathrm{mas\,yr^{-1}}$	**27σ**
$\mu_{\delta,Gaia} - \mu_{\delta,H\to G} = -3.53 \pm 0.12\ \mathrm{mas\,yr^{-1}}$	**31σ**

Orbital period is ~70 years, but we have a ~1% measurement of the astrometric acceleration!

RVs from UCLES/AAT, relative astrometry from *HST*



Orbit fit by Trent Dupuy: mass of the white dwarf Gl 86B improves from 0.5 ± 0.1 to 0.60 ± 0.01 $M_\odot$ (Brandt et al. 2018).

. . . and we can use the *Hipparcos* and *Gaia* scanning laws to fit individual observations, *even without the full epoch astrometry*. **Very important, especially for DR3.**

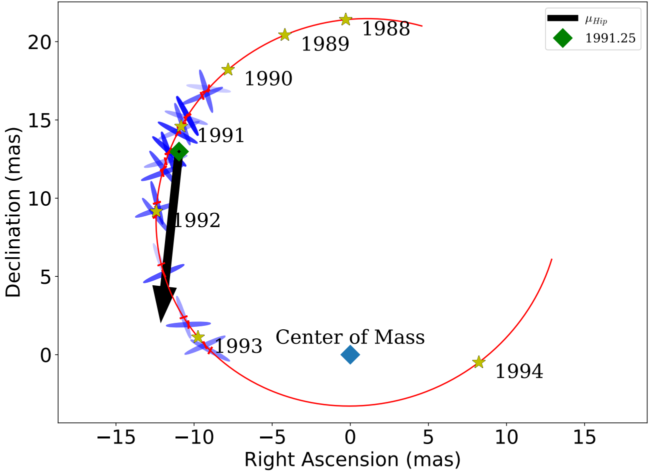


image by G. Mirek Brandt

Note that **DR3 will release accelerations, not orbits!** Fitting orbits to DR3 accelerations with the scanning law (epochs and scan angles) will be the only way to go.

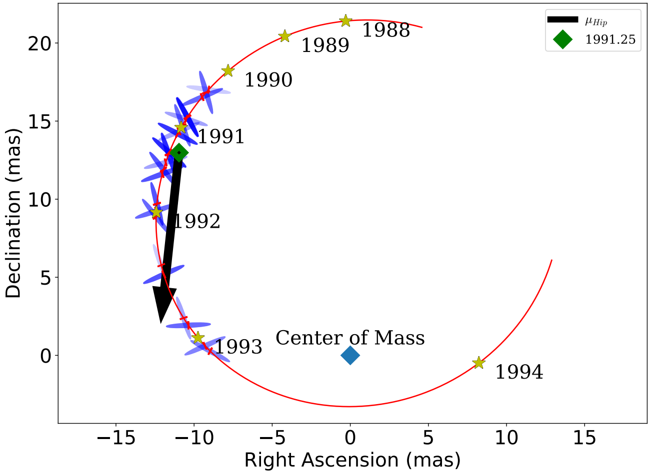


image by G. Mirek Brandt

Current work

with Trent Dupuy, Brendan Bowler, Jackie Faherty, G. Mirek Brandt, Yiting Li, Daniel Michalik, Daniella Bardalez-Gagliuffi, Mark Popinchalk

- Fitting exoplanet orbits, breaking $\sin i$ degeneracy
- Masses and orbits for long period brown dwarfs, low-mass stars, white dwarfs
- Searches for new companions, targets for RV and imaging follow-up

Great way to find and weigh Sirius-like binaries!

Even better for (heavier) non-interacting neutron stars and black holes?

Gaia DR3 will measure accelerations for millions of stars, but **confirmation** and **masses** really need RV curves. **Whence the RVs?**

SDSS-V Ideas:

- MARVELS for dark remnants. 100 $\mu\mathrm{as\,yr}^{-2}$ at 200 pc is 100 $\mathrm{m\,s}^{-1}\,\mathrm{yr}^{-1}$—not crazy.
- Can we find the nearest neutron star or black hole?
- Chemical compositions of main sequence stars with dark companions?

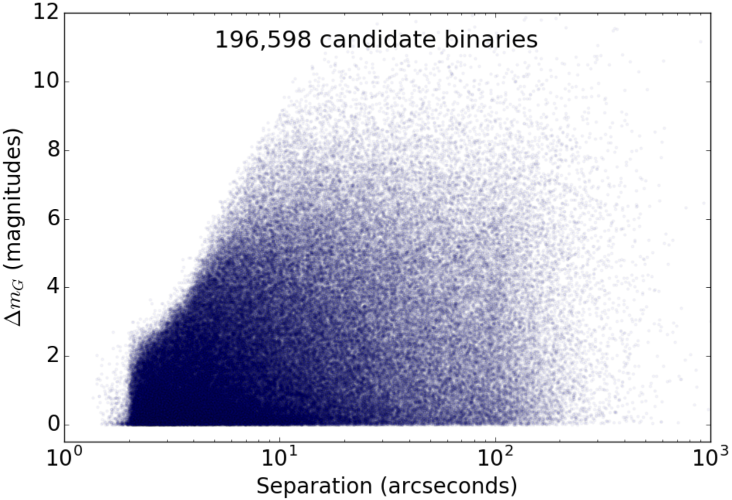
ZTF Idea:

- Gyrochonology+masses to constrain pre-main-sequence of low-mass stars, evolution of brown dwarfs and remnants? C.f. Lynne Hillenbrand's talk.

Part II: Non-Accelerating Binaries

- Wide: separations $\gtrsim$ 20 AU
- More distant: up to at least $\sim$500 pc
- Favors stars of comparable brightness
- Major credit to Kareem El-Badry!

~200,000 systems within 500 pc have compatible parallaxes and proper motions. Most are binaries.



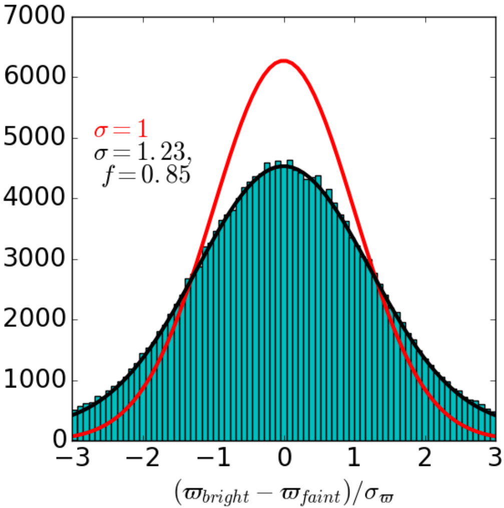
Sample from Kareem El Badry

So much about the distribution of stellar binaries is hidden in that sample!

- Mass ratio distribution
- Semimajor axis distribution
- Eccentricity distribution (isothermal???)
- Trends with age, metallicity?
- Hierarchical triples??

We can have it all . . . once we deal with *Gaia* systematics and underestimated uncertainties, and the *Gaia* selection function.

Example: DR2 parallax errors underestimated by 20–30%?



Really want more data—like RVs—to model orbits and back out *Gaia* systematics. Recall 100 μas/yr at 200 pc is ~100 m/s.

SDSS-V to the rescue?

~200,000 binaries would also be great for understanding scatter in gyrochronology.

Typical brightness of $G \sim 14$ mag is well-matched to the ZTF saturation limit.

Back to the title (my perspective):

- Interesting individually: the accelerators
- Interesting statistically: the wide binaries

A philosophical comment on "rare and/or interesting systems:" searching for **outliers** in a large survey like *Gaia* will inevitably uncover **pathologies** in the data.

Independent supporting measurements are vital!

- RVs and chemistry from SDSS-V!
- Light curves from ZTF!

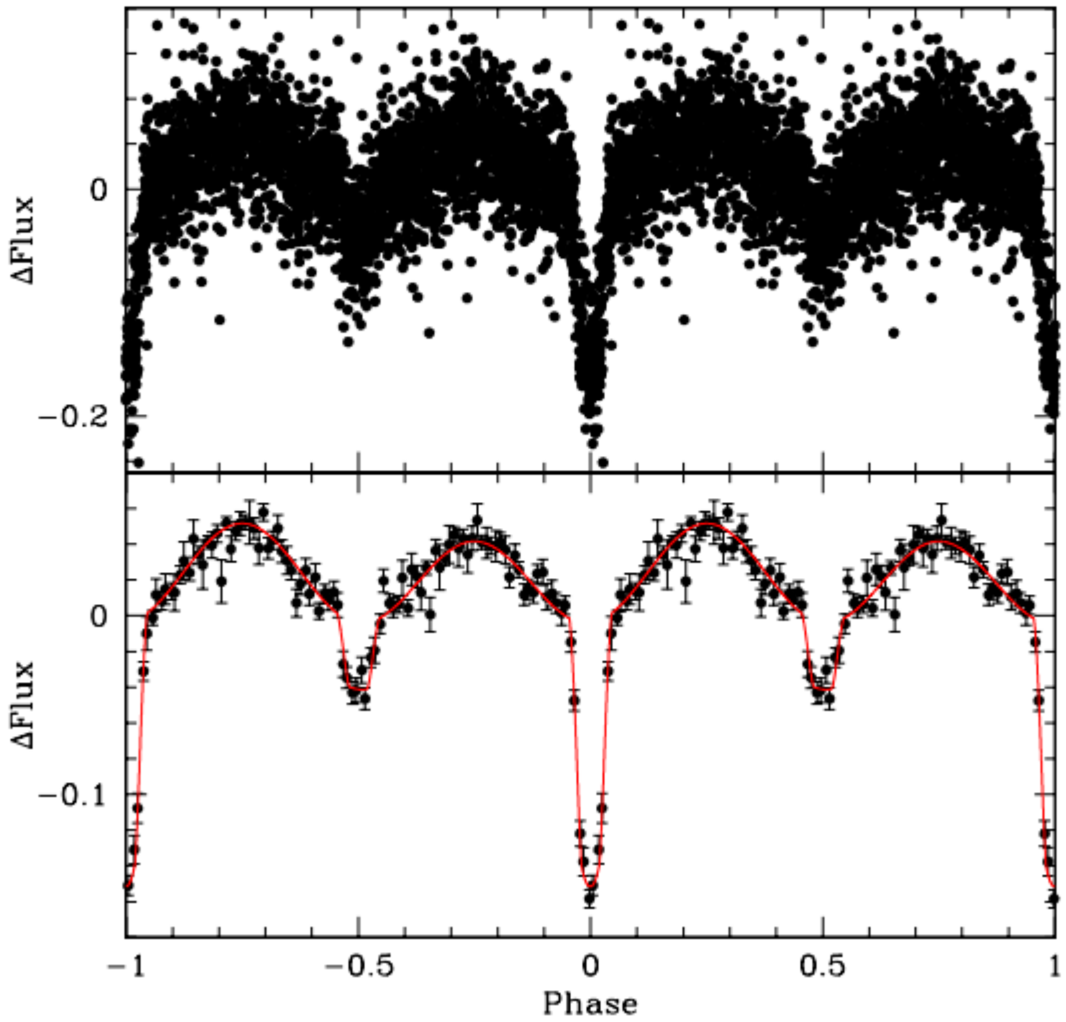
Status Report on Search for Double Degenerates with ZTF

Kevin Burdge

California Institute of Technology

How do we find White Dwarf Binaries

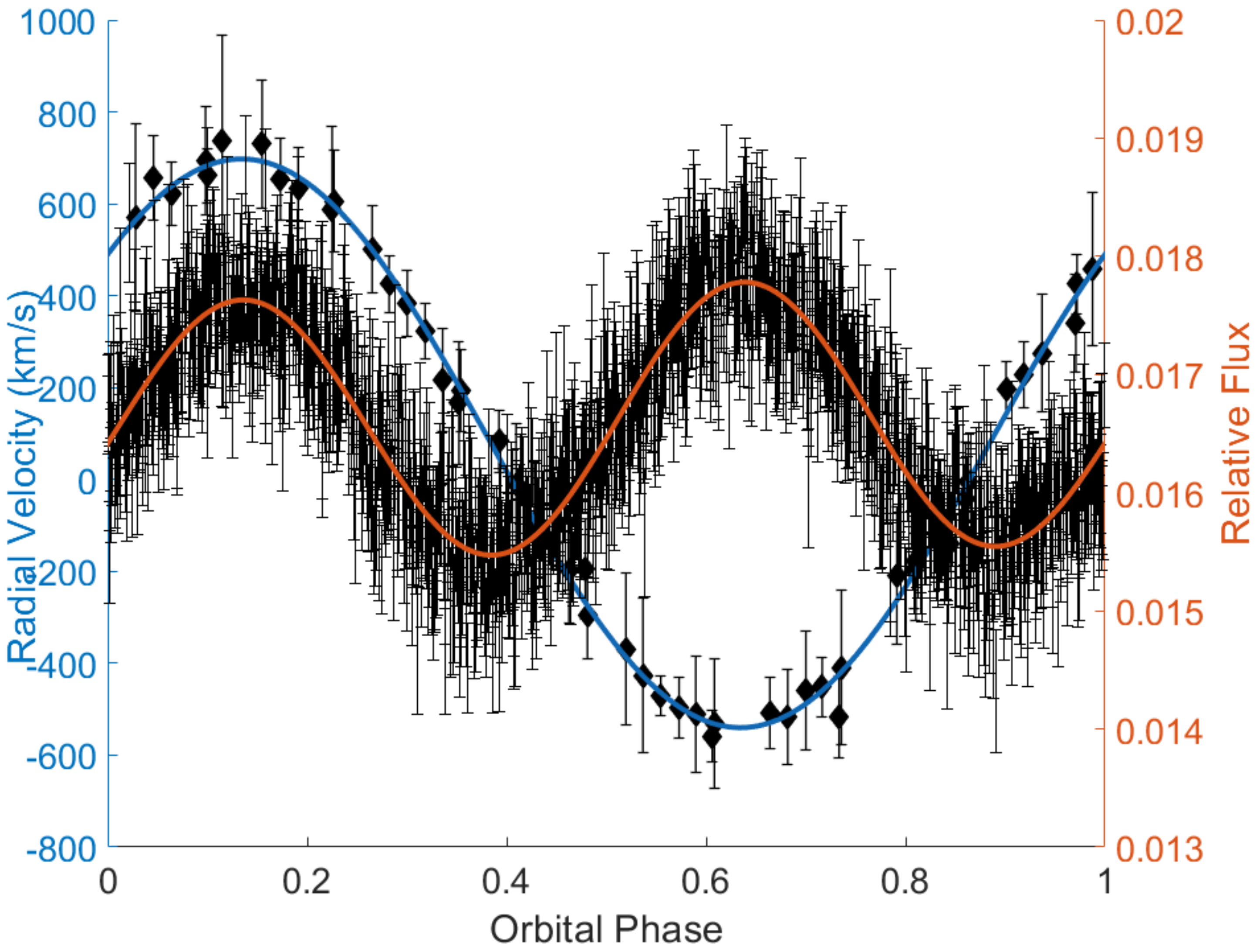
- Eclipses
- Ellipsoidal modulation
- Irradiation of companion



J0651, a 12.75 minute binary (Brown et al. 2011)

Before ZTF

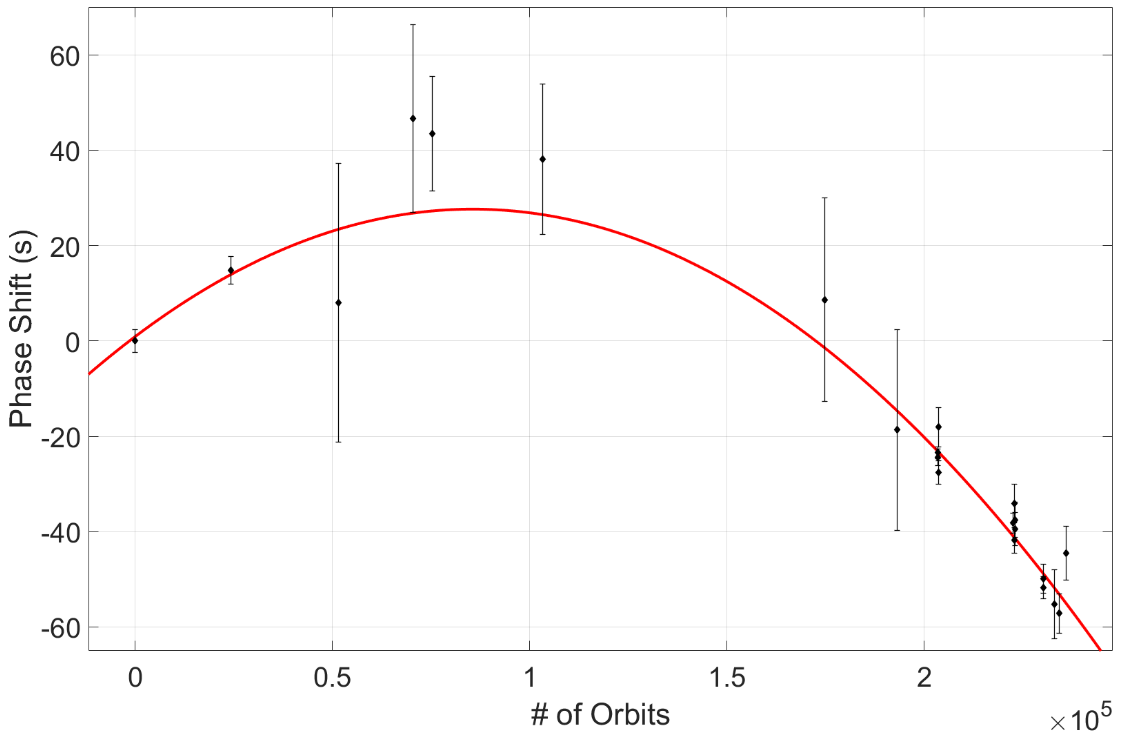
- Discovered one double degenerate in PTF
- The system exhibits a 20 minute orbital period, ellipsoidal modulation, Doppler boosting, and significant orbital decay



Orbital Decay

- After waiting 1.5 years, we have measured, with significance, the orbital decay of this system.

- The inferred chirp mass is rather large (~0.4 solar masses), indicating that this is likely a loud LISA source given its parallax measurement.



Technical Challenges and Solutions

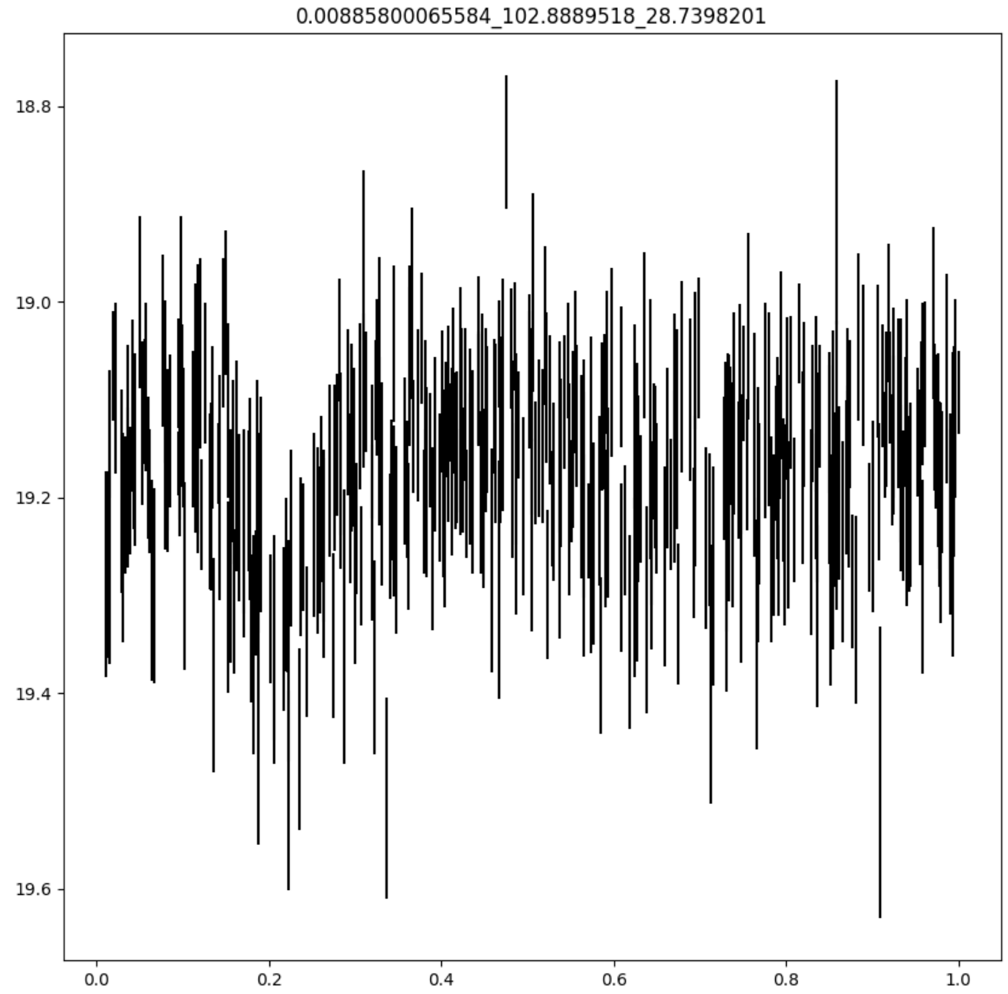
- Searching for short periods in long baseline data is computationally expensive
- Graphics Processing Units (GPUs) can largely outperform CPUs in such searches
- For the shortest orbital period systems, we must account for orbital period decay

Nvidia 1080 Ti GPU
(image from Nvidia.com)

Our Test Run with ZTF

- On the right, is a ZTF commissioning lightcurve of J0651, the 12.75 minute binary

- The primary eclipse is clearly visible

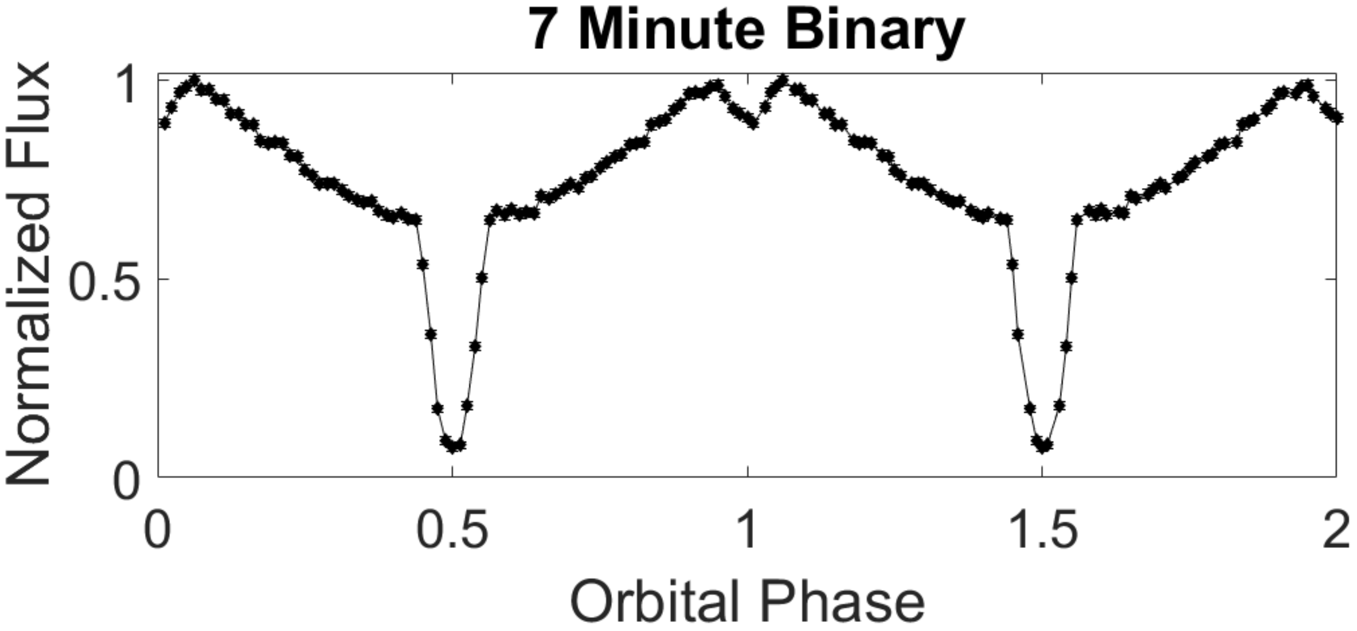


J0651 in ZTF

ZTF Science Results

- There are 6 published eclipsing detached DWDs
- So far with ZTF, we have discovered 5 new eclipsing systems (with a possible 6th candidate)
- In the remainder of this talk, we will highlight them

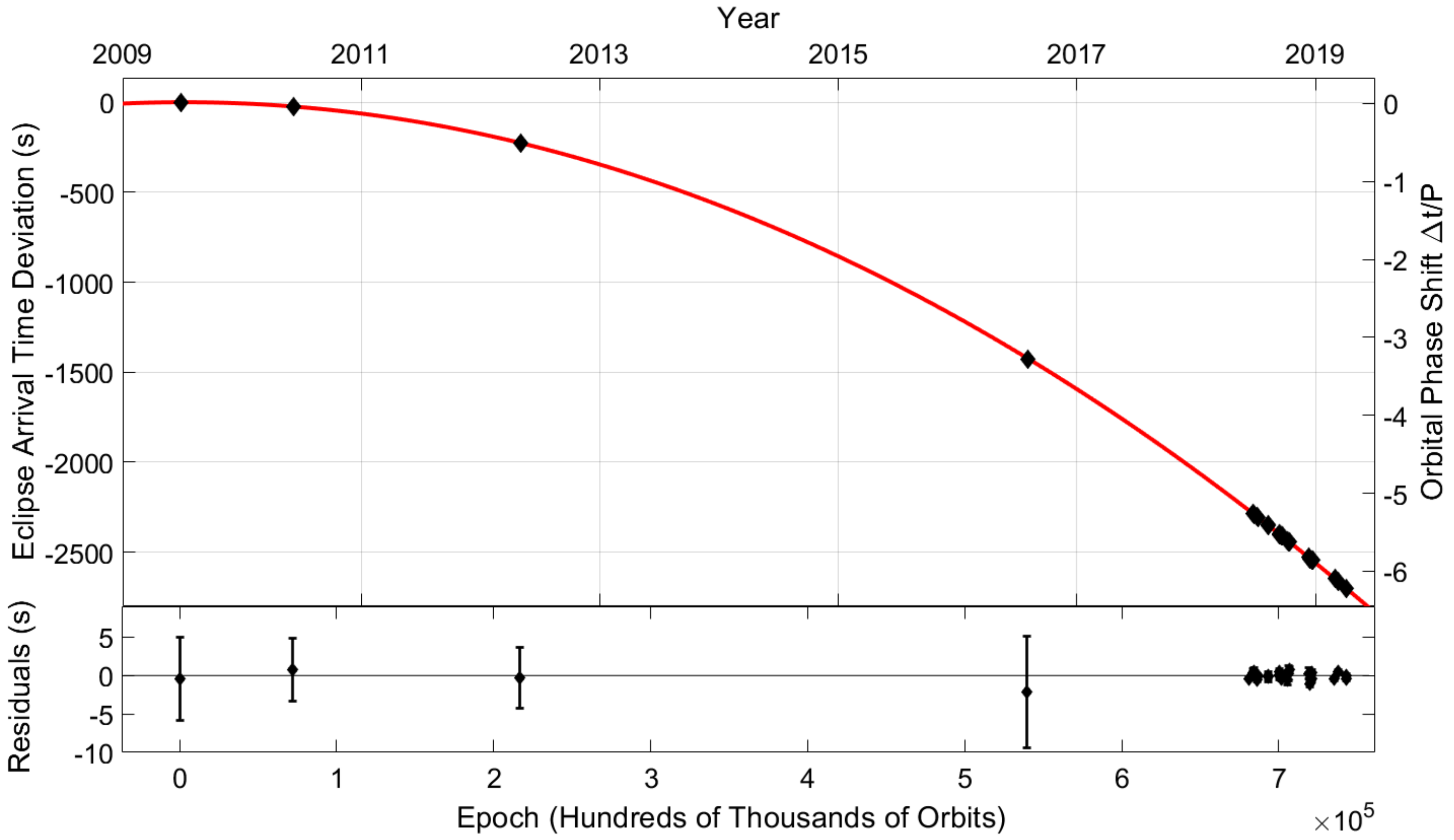
The 7 Minute Binary



- Paper submitted
- First candidate we found
- Exhibits strong reflection effect and eclipses

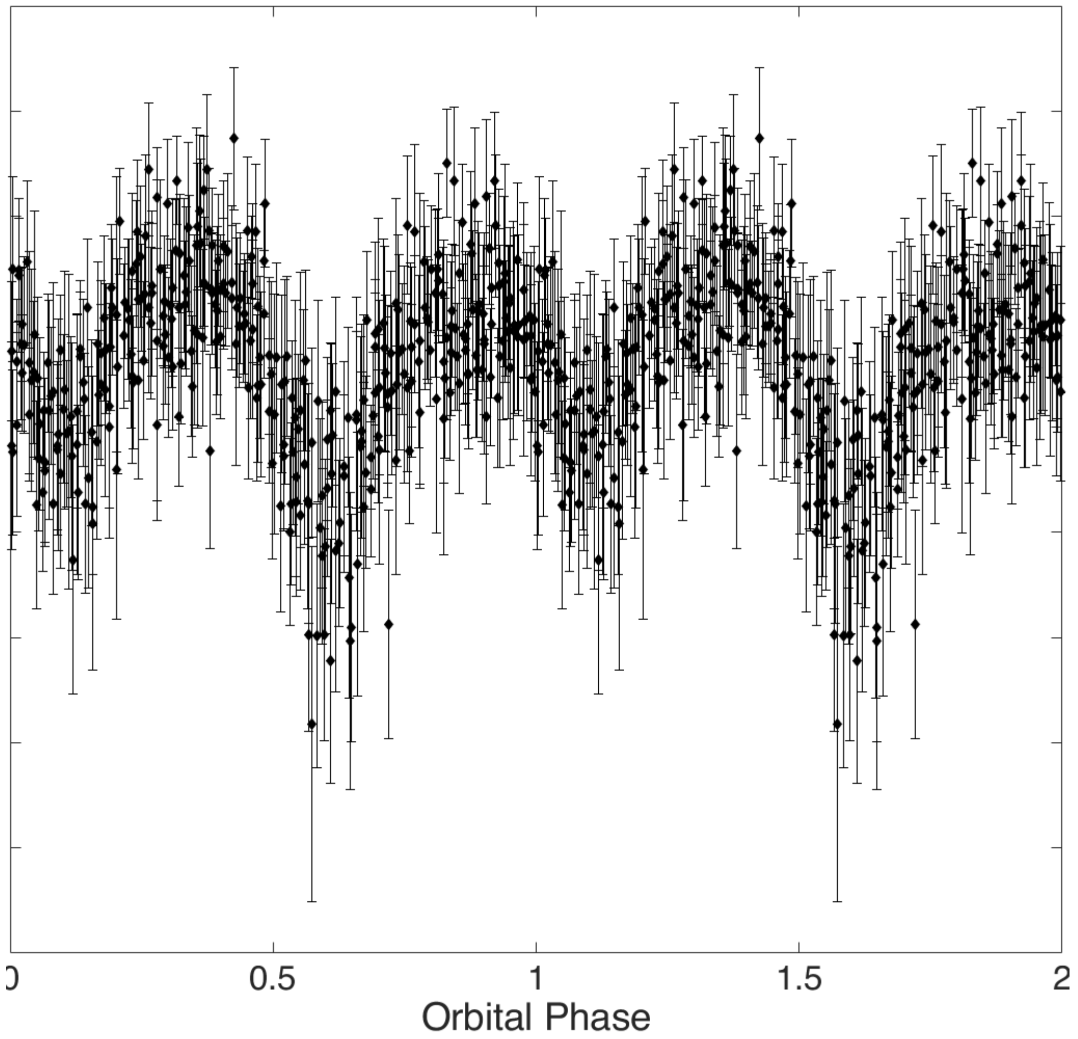
Orbital Decay Measurement on the 7-minute

- Using archival PTF data, we managed to make a highly precise measurement of the orbital decay due to GR in this system



A new candidate at ~8 minutes

- Appears likely to be a binary candidate based on position on HR diagram.
- More follow up still needed. If real, would be highest SNR LISA source known (has a reasonably good parallax measurement)

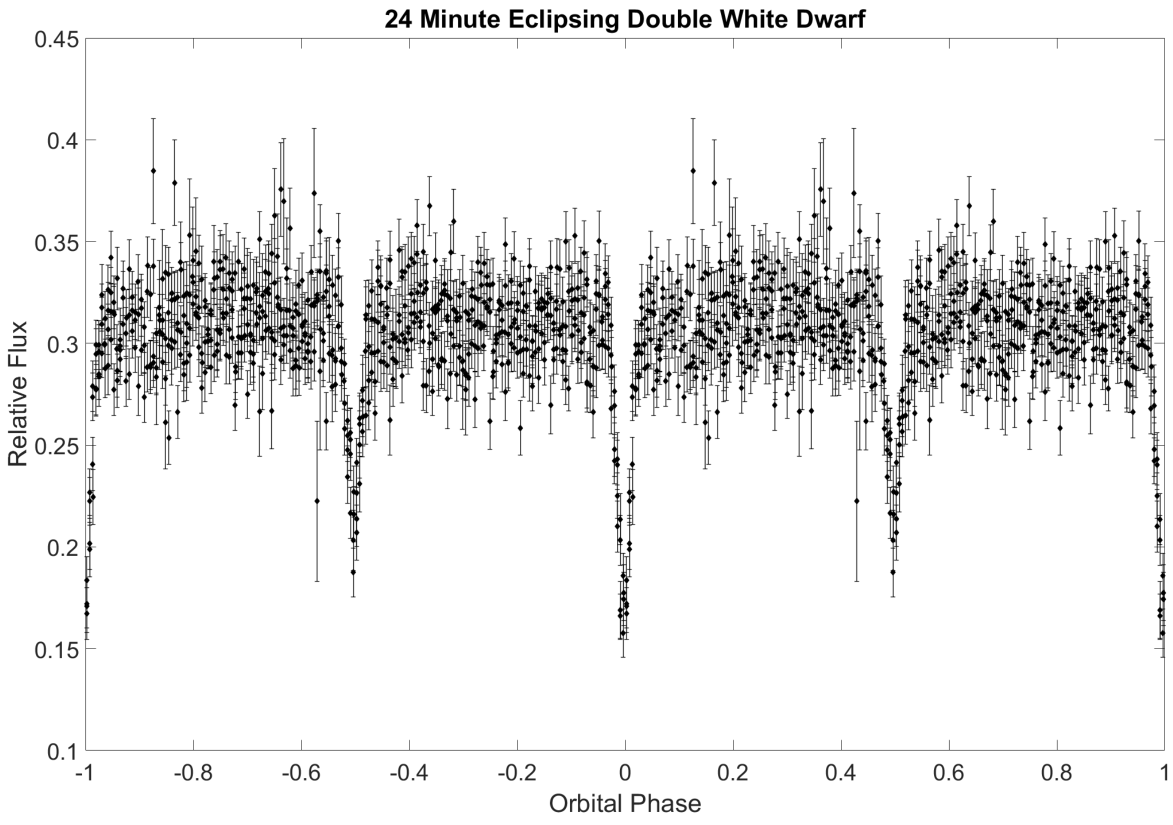


24 Minute Eclipsing System

- Eclipses are comparable depth, indicating that the two components contribute comparable luminosity

- Appears to be double lines from spectrum, but will be very challenging to fit due to two blended broad absorption lines

- Estimated LISA signal quite marginal

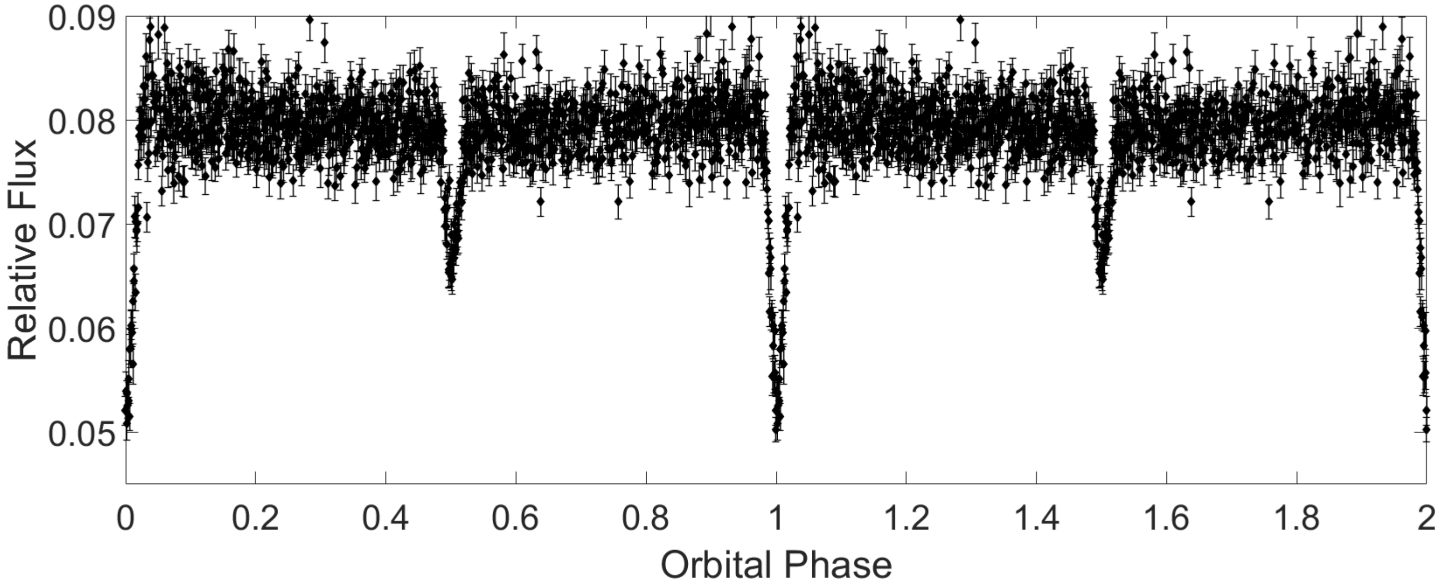


40 Minute Eclipsing System

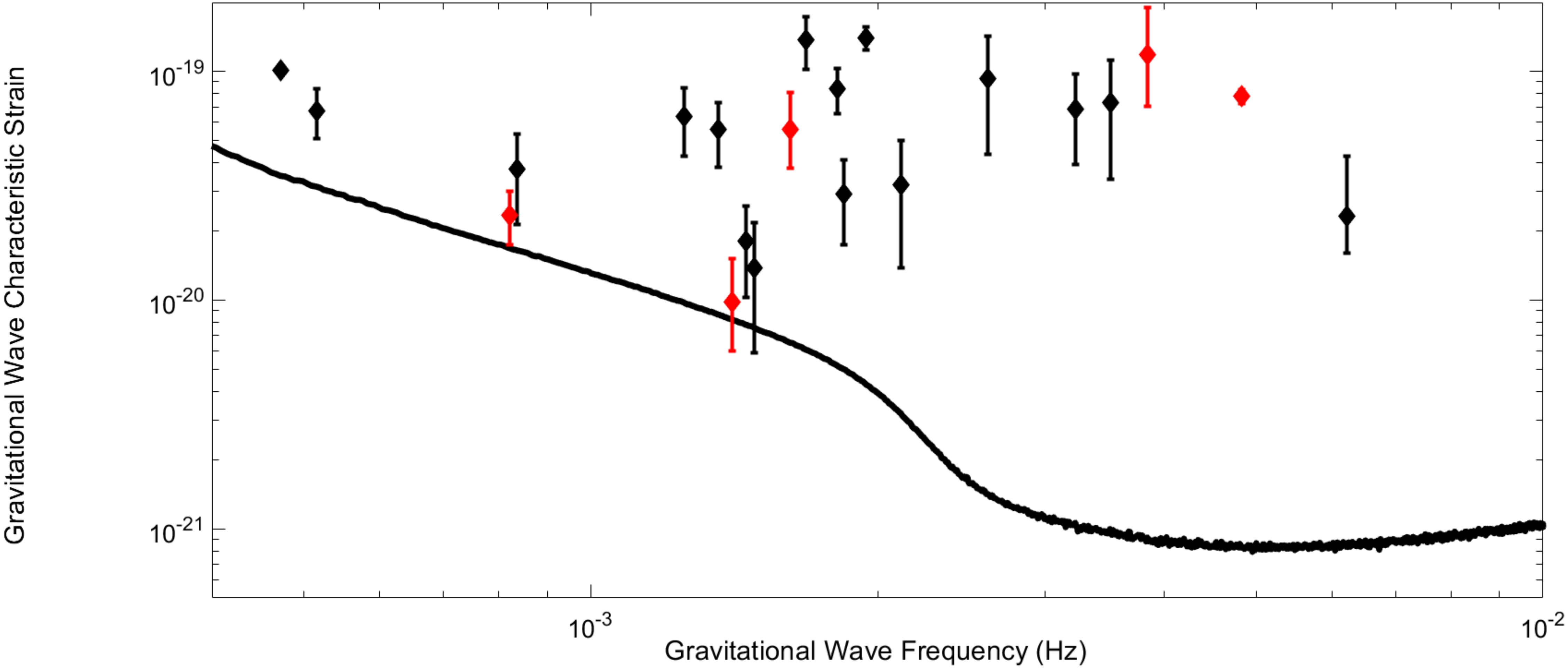
- Again, eclipses appear to be comparable in depth, suggesting comparable luminosity contribution

- No spectrum yet.

- Likely to have a marginal LISA signal



Where do these fall as LISA sources?



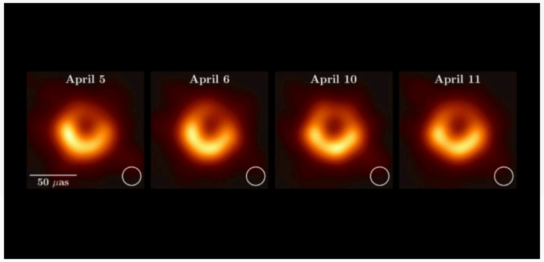
The future: SDSS V and Beyond

- Spectroscopic follow up of these systems is challenging. The 24 minute for example, because of its double lined nature, does not appear to have significant Doppler shifts, but rather seems to change in log(g) and Teff as the Balmer lines “widen” and “narrow”. This could perhaps be used to target such systems.
- Systems like the 20 minute binary, which are single lined, exhibit enormous radial velocity variations (620 km/s semi-amplitude in the case of this example). Even for low resolution surveys, this should be easy to resolve. However, exposures must be short.

Stellar/AGN photometric astronomy in the era of SDSS Phase V
Carnegie, May 3rd 2019

AGN: the most powerful variable sources in the Universe

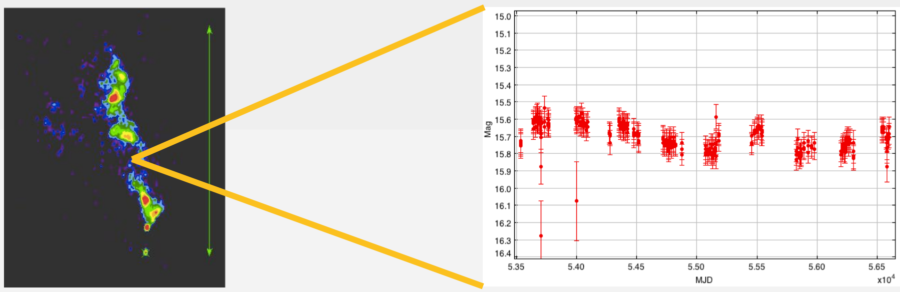
Matthew J. Graham
ZTF Project Scientist
mjg@caltech.edu



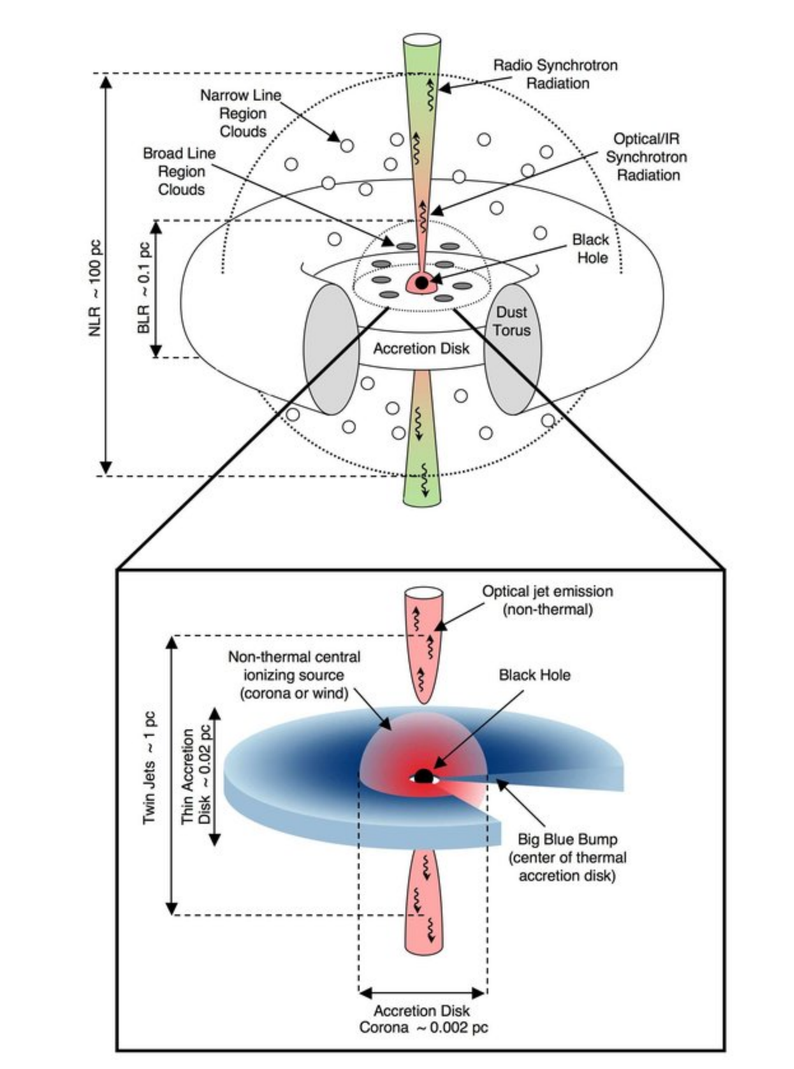
(EHT Collaboration)

Quasar variability

- First quasar identified 3C 48 – most striking feature was that the optical radiation varied

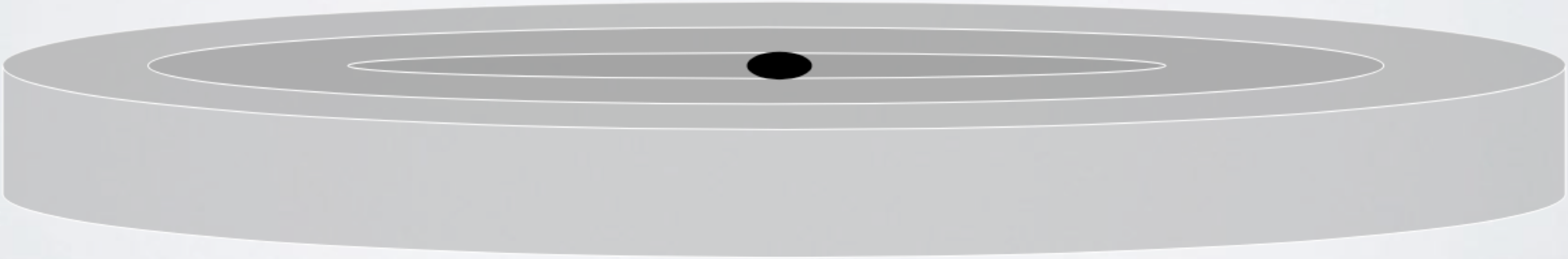


- Physical origin of photometric variability in optical/UV is unclear:
  - Instabilities in the accretion disk
  - Supernovae
  - Microlensing
  - Stellar collisions
  - Thermal fluctuations from magnetic turbulence



Physical timescales in AGN

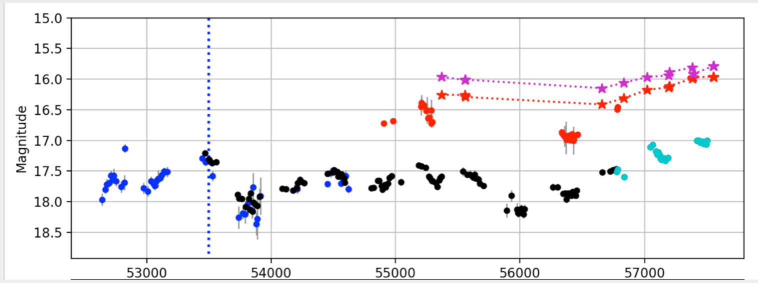
	Accretion Disk	Broad Line Region
Viscous (“radial drift”)	10,000 yr	-
Light travel	Hours	Days
Dynamical	Days	Years
Thermal	Days-years	-

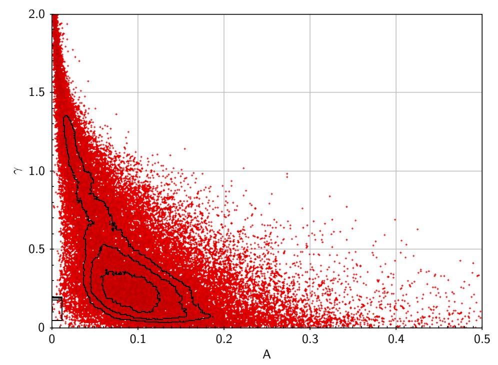


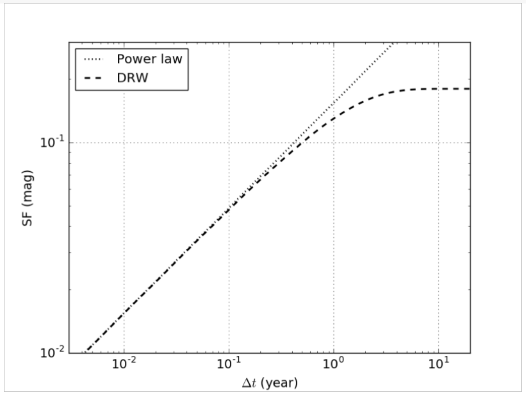
(C. MacLeod)

Describing quasar photometric variability

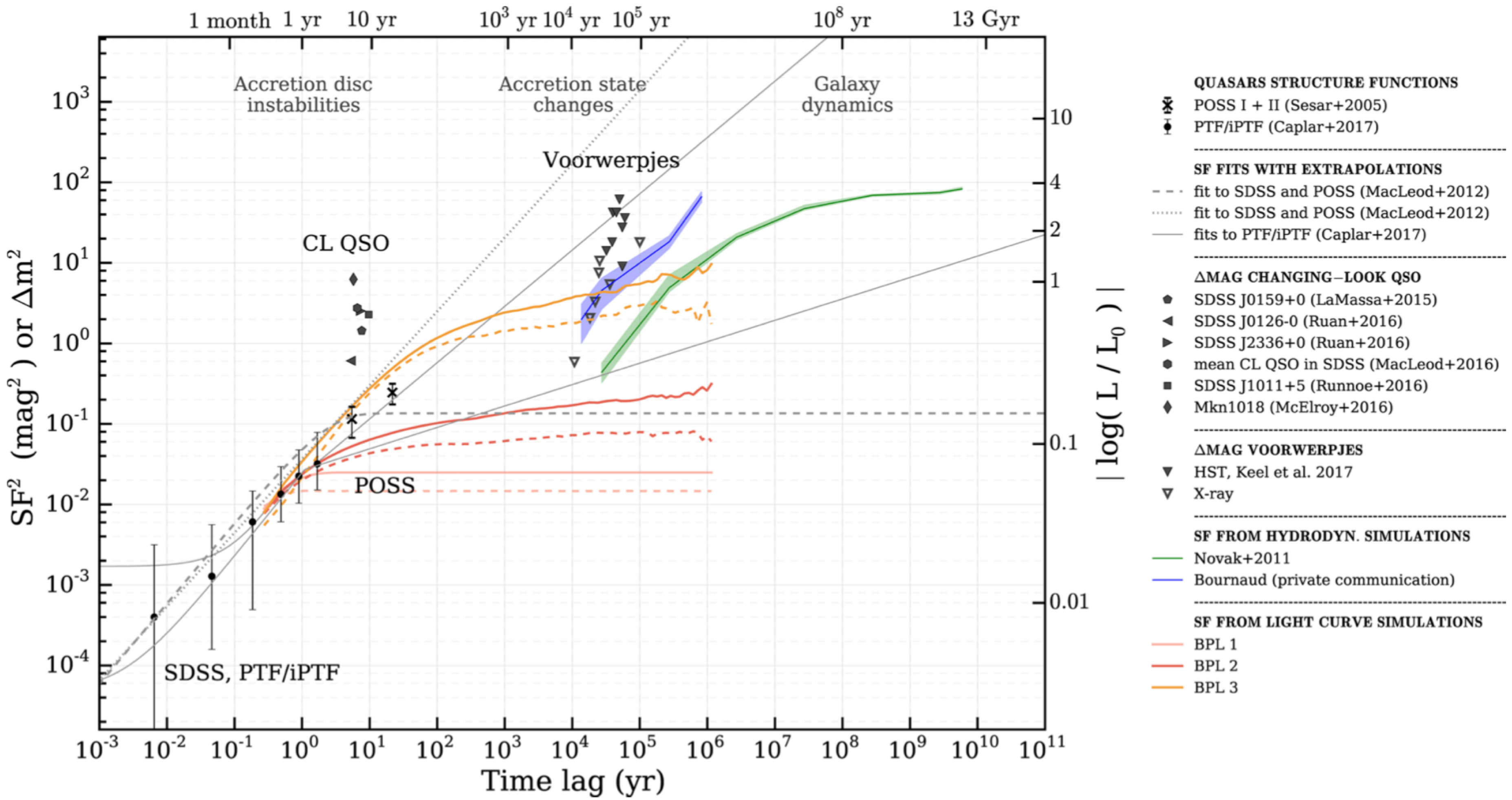
- $|\Delta m| > x$
  - DPOSS vs. SDSS (Stripe 82) vs. PS1
- Excess variability: χ^2
- Structure function
  - Variability amplitude as a function of the time lag between compared observations
  - Historic descriptor of variability and a variety of estimators
  - Not much information







Variability timescales

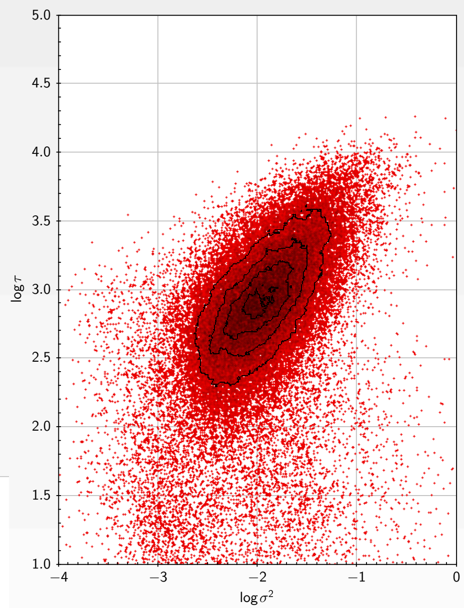


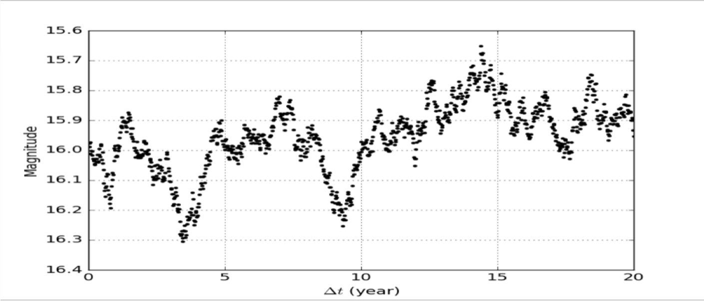
(L. Sartori)

Damped random walk (DRW/OU)

$$dX(t) = -\frac{1}{\tau}X(t)dt + \sigma\sqrt{dt}\,\varepsilon(t) + b\,dt \quad \tau,\sigma,t > 0$$

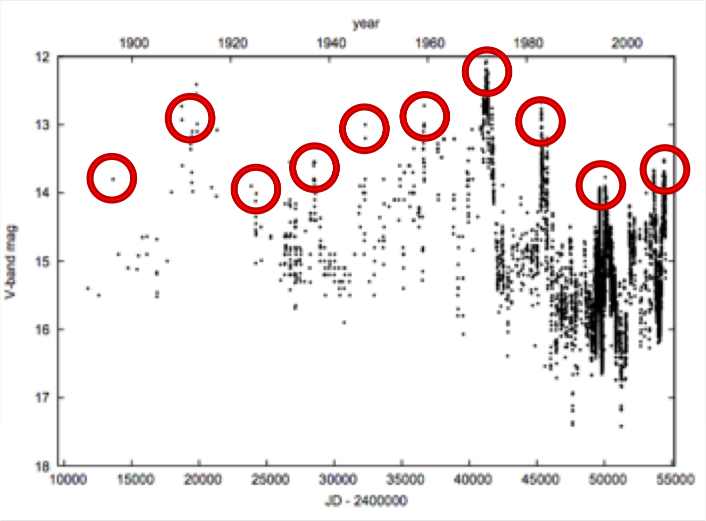
- Characterized by variability amplitude σ and timescale τ
- Basis for stochastic models of variability
- Deviations noted (e.g., Mushotzky 2011, Zu et al. 2013, Graham et al. 2014)
- Degenerate model – can be best fit for a non-DRW process (Kozlowski 2016)
- Need a baseline $\gtrsim 10\tau$ to recover τ

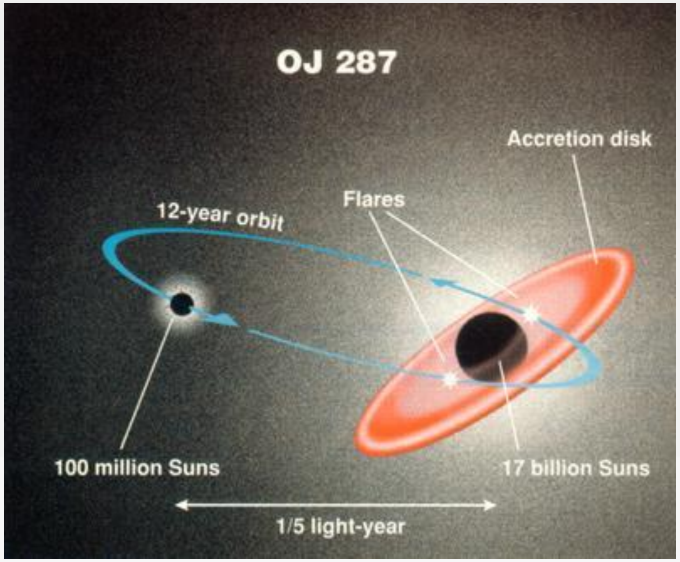


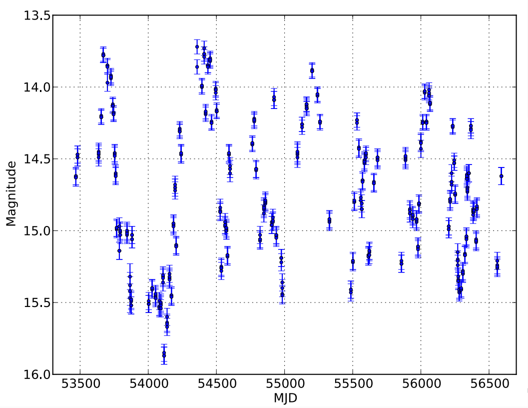


Are there periodic quasars?

- OJ 287 shows a pair of outburst peaks every 12.2 years for at least the last century







The physics of a SMBH binary merger

Stage I (> 1pc)

- SMBHs dissipate angular momentum through dynamical friction with surrounding stars

Stage II (0.01 – 1pc)

- Stalled phase due to stellar depletion (~10^6 – 10^7 yrs)

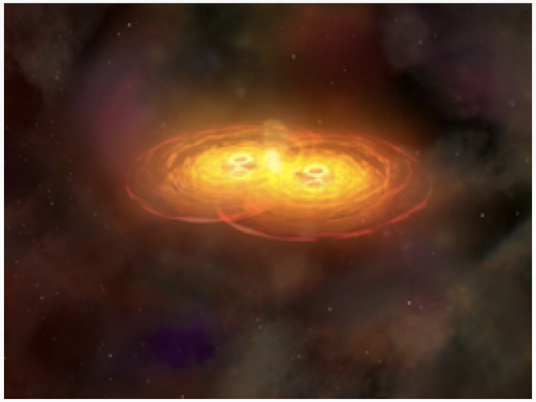
Stage III (< 0.01pc)

- Orbital angular momentum lost by gravitational radiation

Stage IV

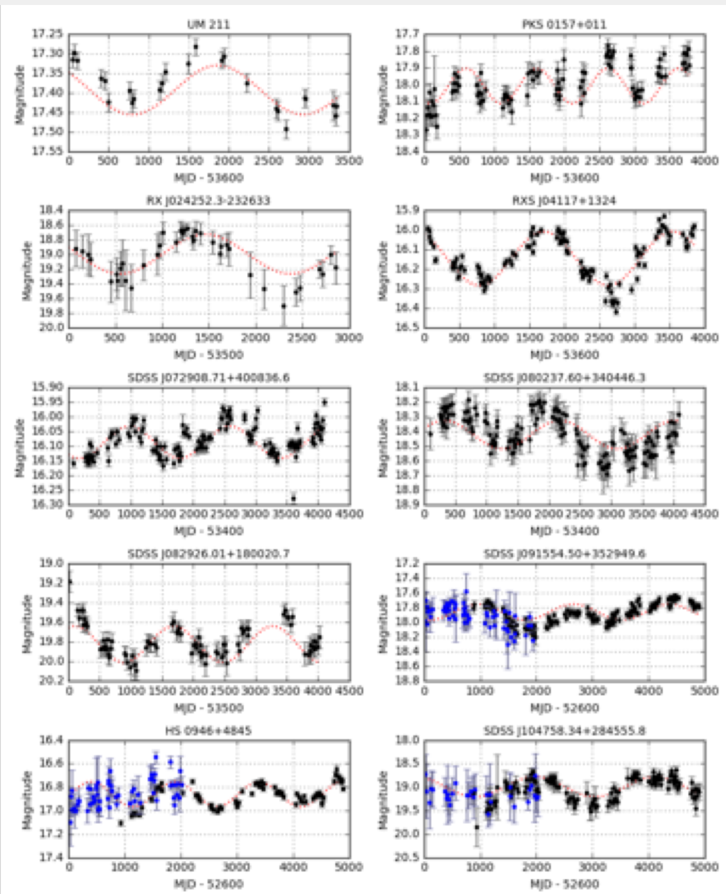
- Coalescence and recoil

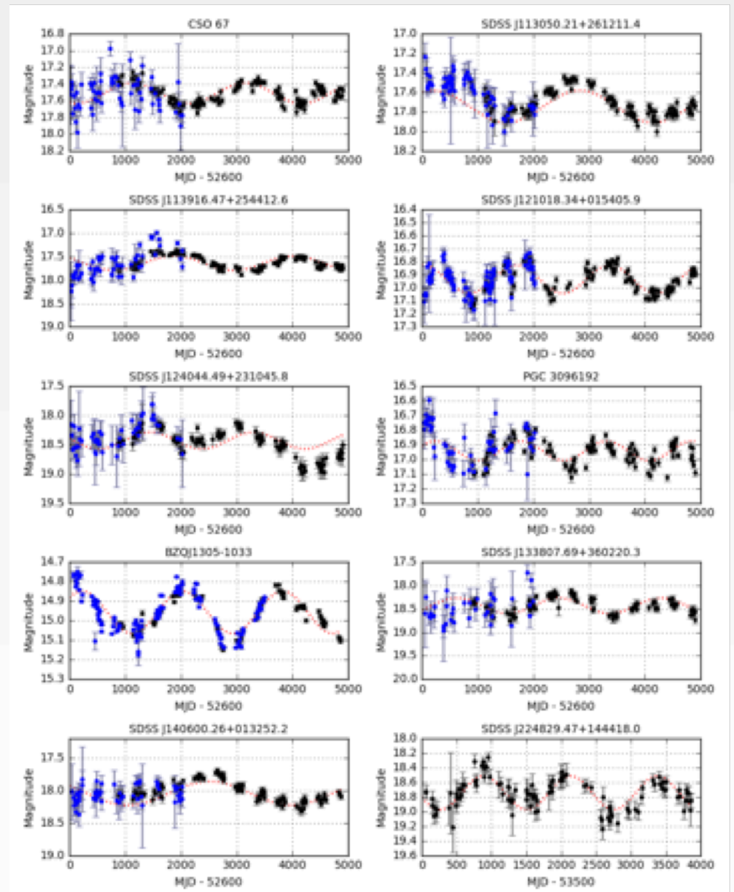
- The "final parsec" problem
- Subparsec systems are not resolvable
- PTA and potential LISA sources



Periodic quasars

- Graham et al. (2015a, b) identified 111 quasars with statistically significant periodicity (over stochastic models)



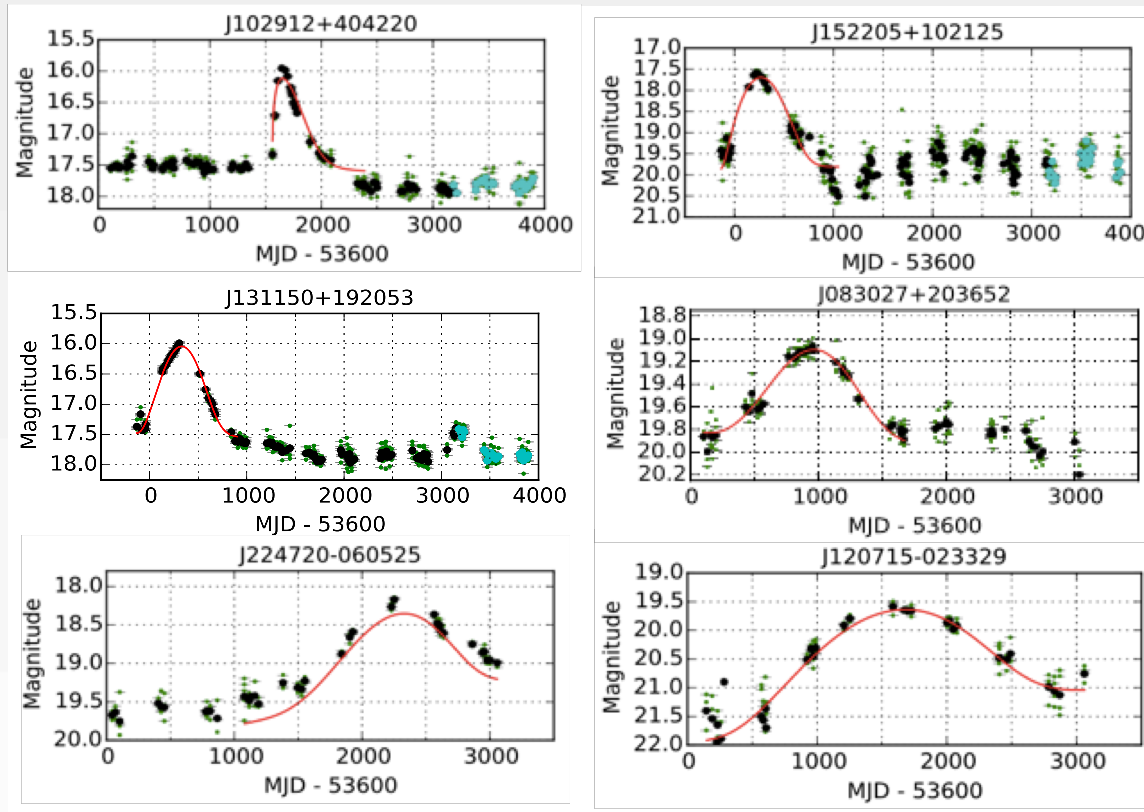


(Updated data Graham et al., in prep)

Major flares

A sample of 51 AGN with a significant flaring event inconsistent with DRW behavior

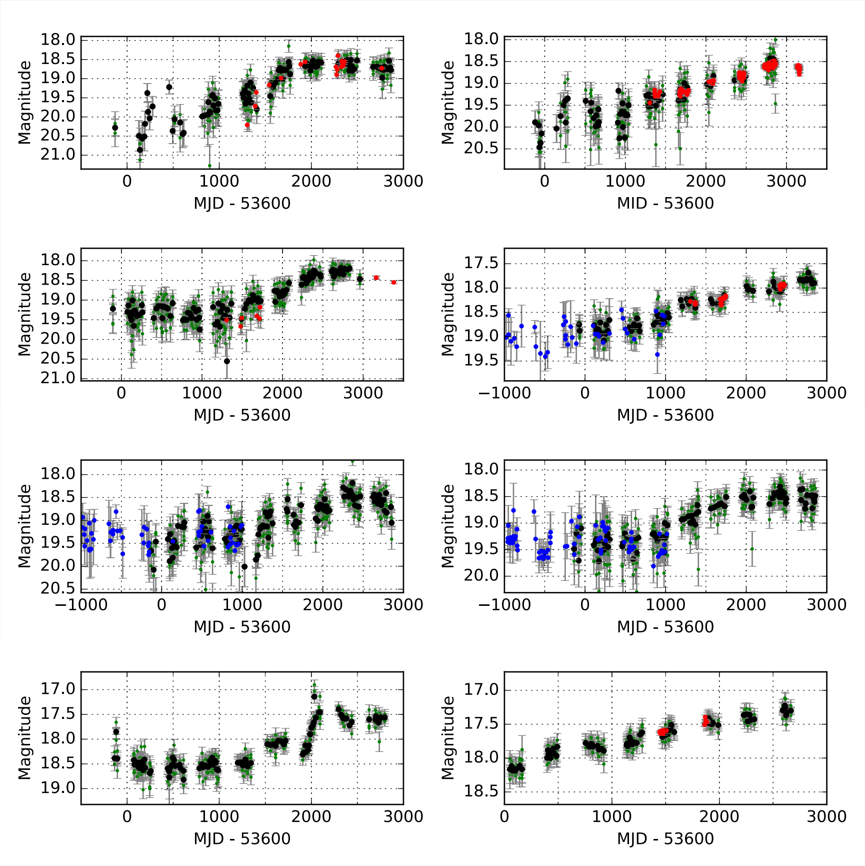
- Microlensing
- SLSN-II
- Slow TDEs
- SMBH merger in disk

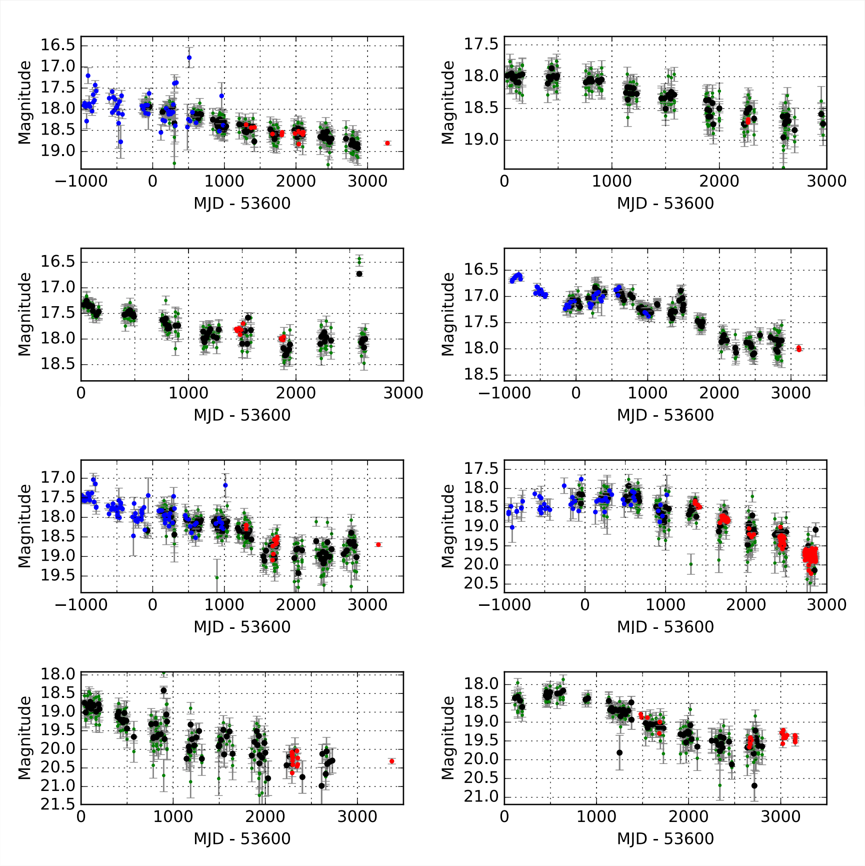


(Graham et al. 2017)

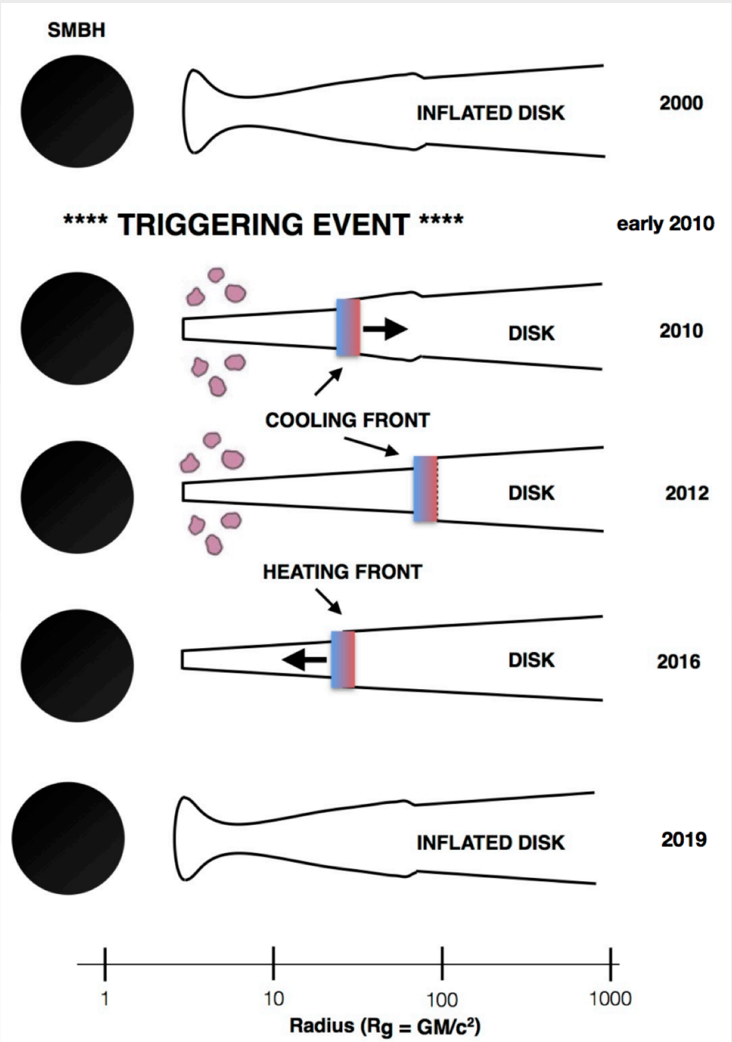
Changing look/state quasars

- Characterized by a smooth slow photometric rise/decline of ~1 mag over several years and some degree of spectral variability

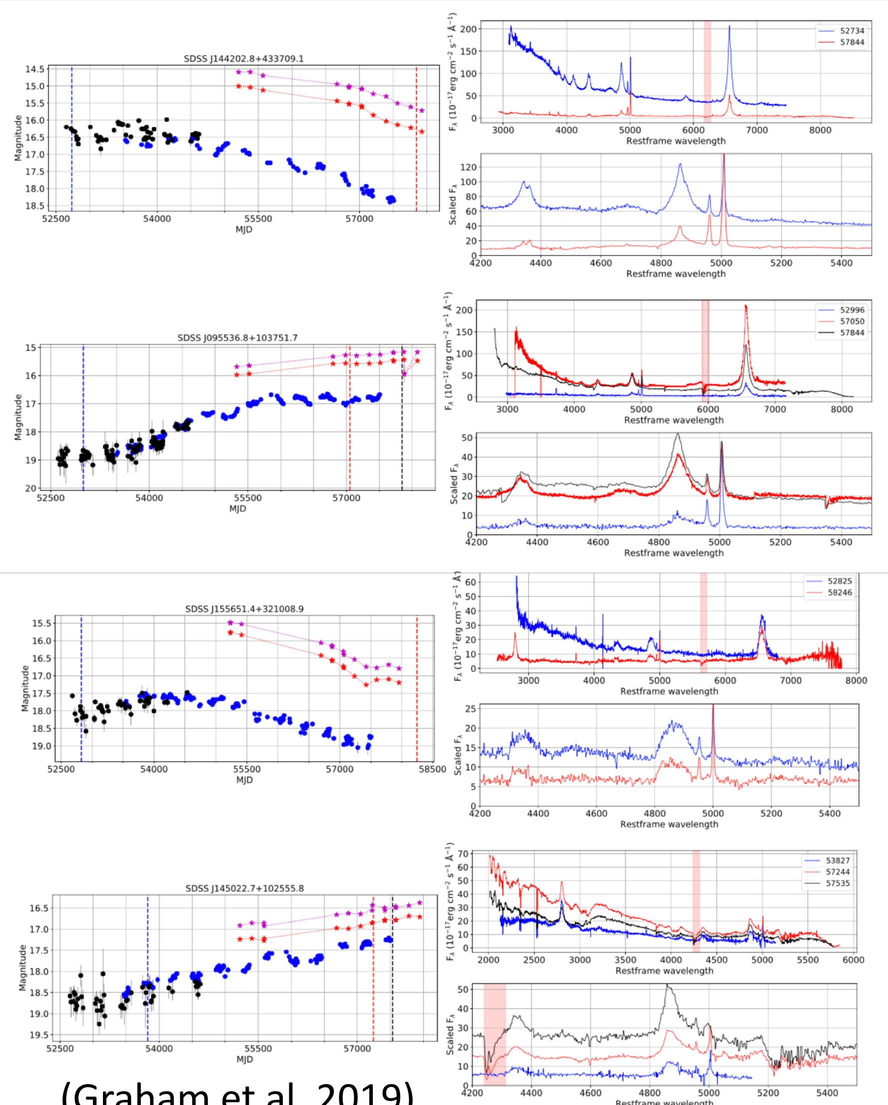




Propagating fronts as an explanation



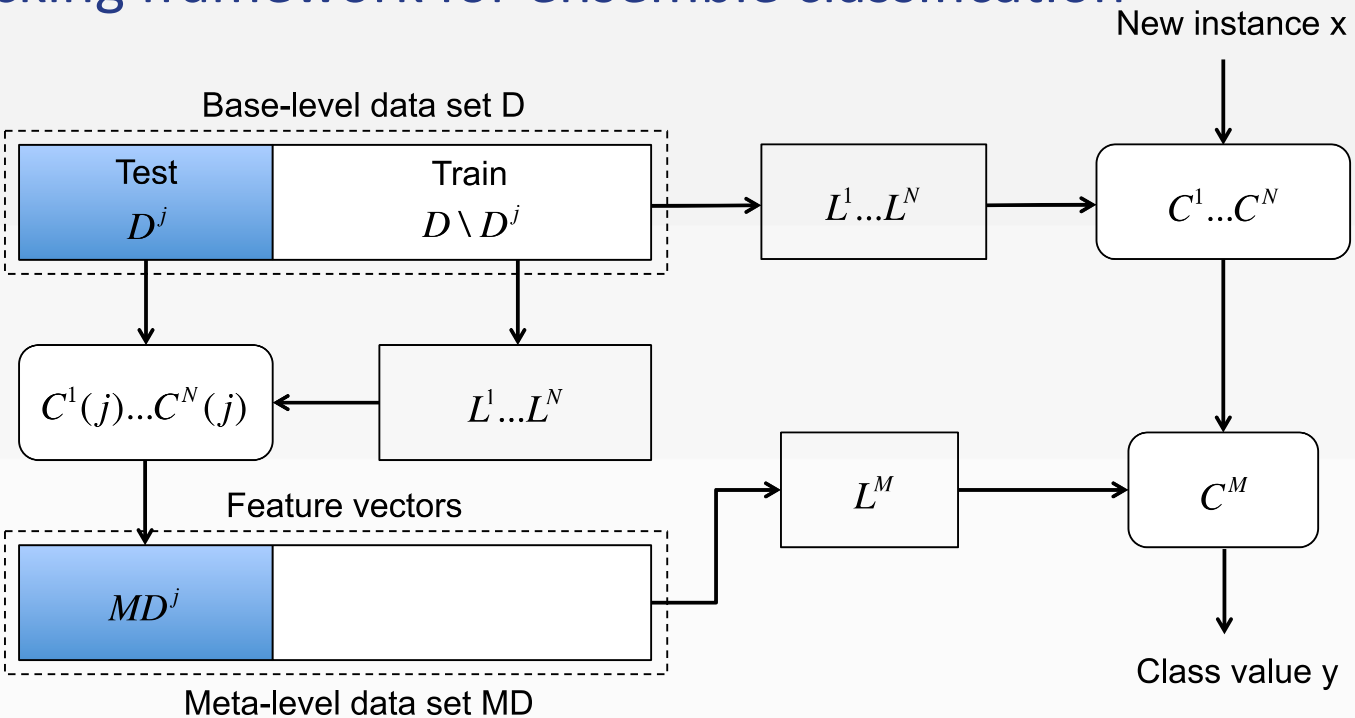
(Ross et al. 2018)



(Graham et al. 2019)

Variability, color, and zero motion-selected catalogs

- Feature set:
  - Variability characterizations
  - WISE colors (W1, W2, W1 – W2)
  - GAIA proper motions
- Stacking framework for ensemble classification

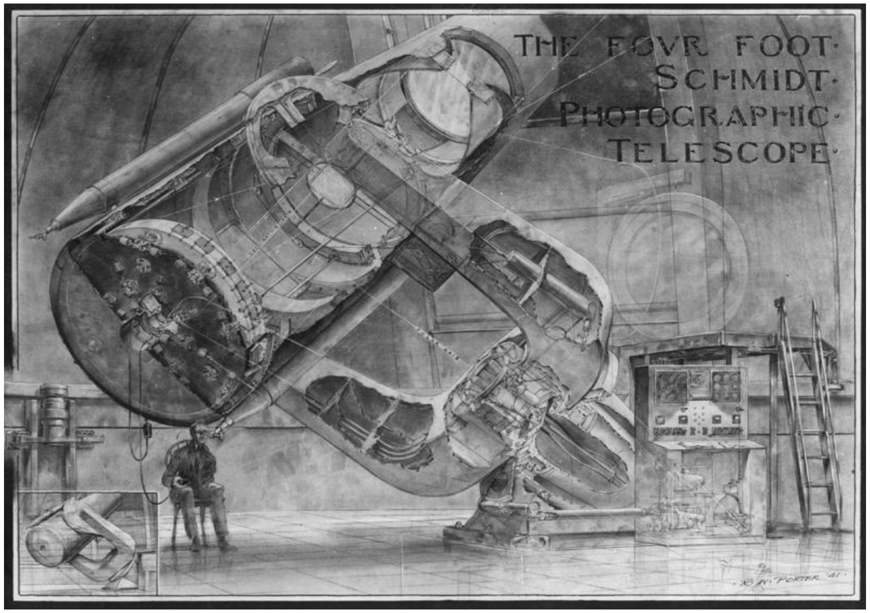


Stellar/AGN photometric astronomy in the era of SDSS Phase V
Carnegie, May 3rd 2019

ZTF as a public survey

Matthew J. Graham
ZTF Project Scientist
mjg@caltech.edu

The Palomar legacy

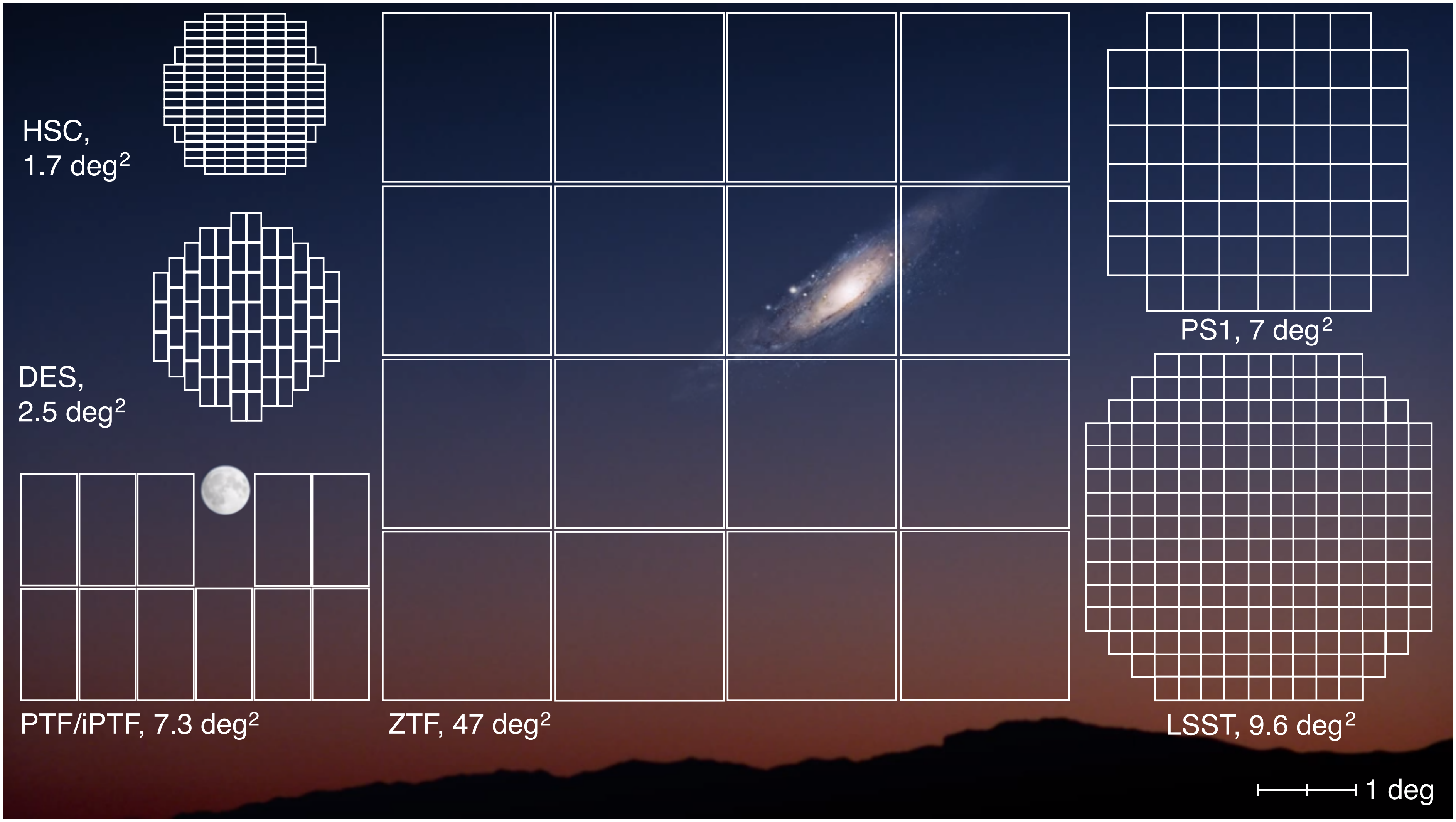


	Dates	Sky	Bands	Depth
POSS-I	1949-1956	Dec > -33	103a-O, 103a-E	22.0 (B)
POSS-II (DPOSS)	1985-1995	Dec > -22	IIIaJ, IIIaF, IVN	22.5-19.5
Palomar-Quest	2002-2009	Dec > -25	BVRI, griz	21 (V)
PTF	2009-2012		gr	20.5
iPTF	2013-2015	Dec > -30	gr	20.5
ZTF-I	2018-2020	Dec > -30	gri	20.5 (r)

The current landscape of sky surveys

	ATLAS	ASAS-SN	Pan-STARRS	ZTF	LSST
Total sources	-	10^8	10^{10}	10^9	37×10^9
Total detections	10^{12}	10^{11}	10^{11}	10^{12}	37×10^{12}
Annual visits/source	1000	180	60	3000	100
No. of filters	2	2	5	3	5
No. of pixels	10^8	4×10^6 (x 4)	10^9	6×10^8	3.2×10^9
CCD surface area (cm^2)	90	9	1415	1320	3200
Field of view (deg^2)	30	4.5	7	47	9
Hourly survey rate (deg^2)	3000	960	-	3760	1000
5σ detection limit in r	19.3	17.3	21.5	20.5	24.7
Nightly alert rate	-	-	-	10^6	10^7
Nightly data rate (TB)	0.15	-	-	1.4	15
Telescope (m)	0.5	4 x 0.14	1.8	1.2	6.5
No. of telescopes	2 (6)	5	2	1	1

Relative coverages

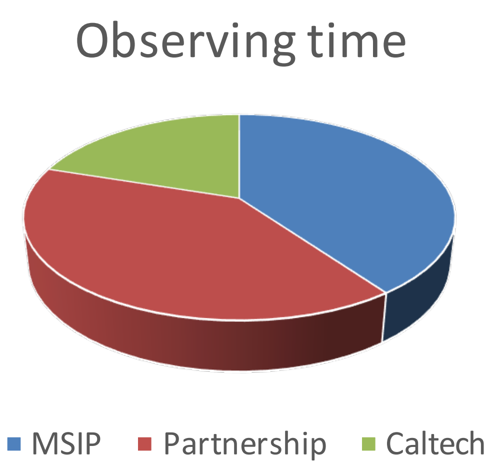


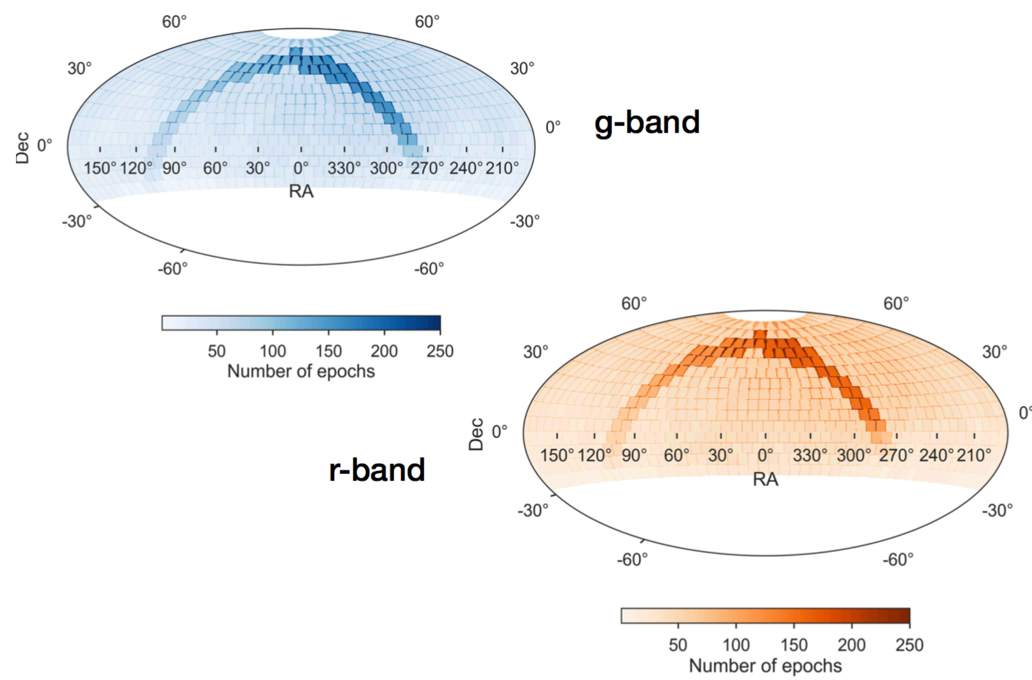
HEISING-SIMONS FOUNDATION

The public face of ZTF

Northern Sky Survey
- Two visits/night (g+r) for asteroid rejection => 3-day average
- 23,675 deg^2 total footprint; 85% time; 4325 deg^2 average/night

Galactic Plane Survey
- Nightly sweep of the Galactic Plane (|b|<7; nightly g+r)
- ~2,800 deg^2 total footprint; 15% time; 1475 deg^2 average/night

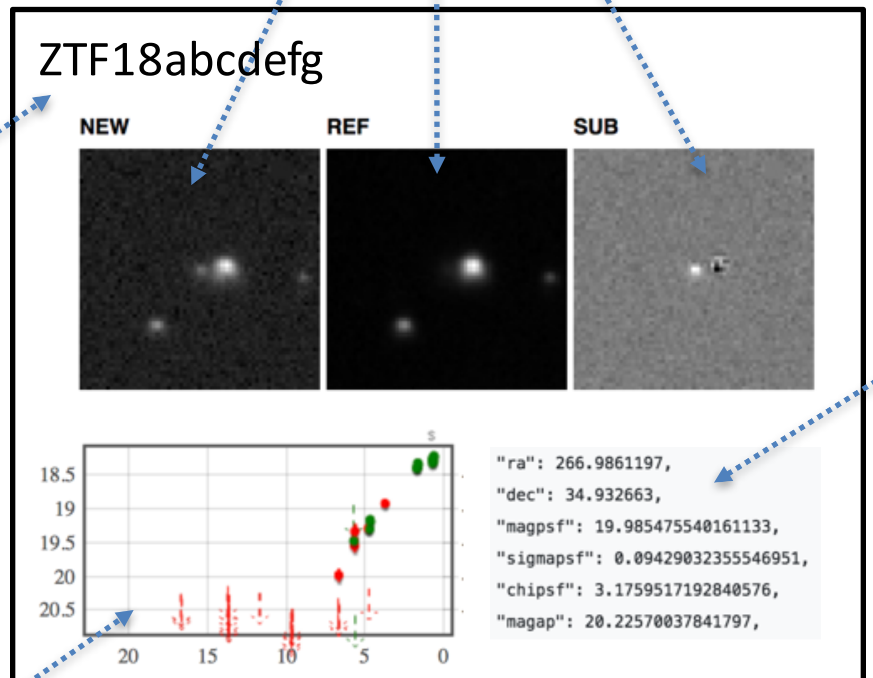




Alert structure: AVRO format

63 x 63 pixel 32-bit images

Unique spatially
matched alert name
(1.5” radius)



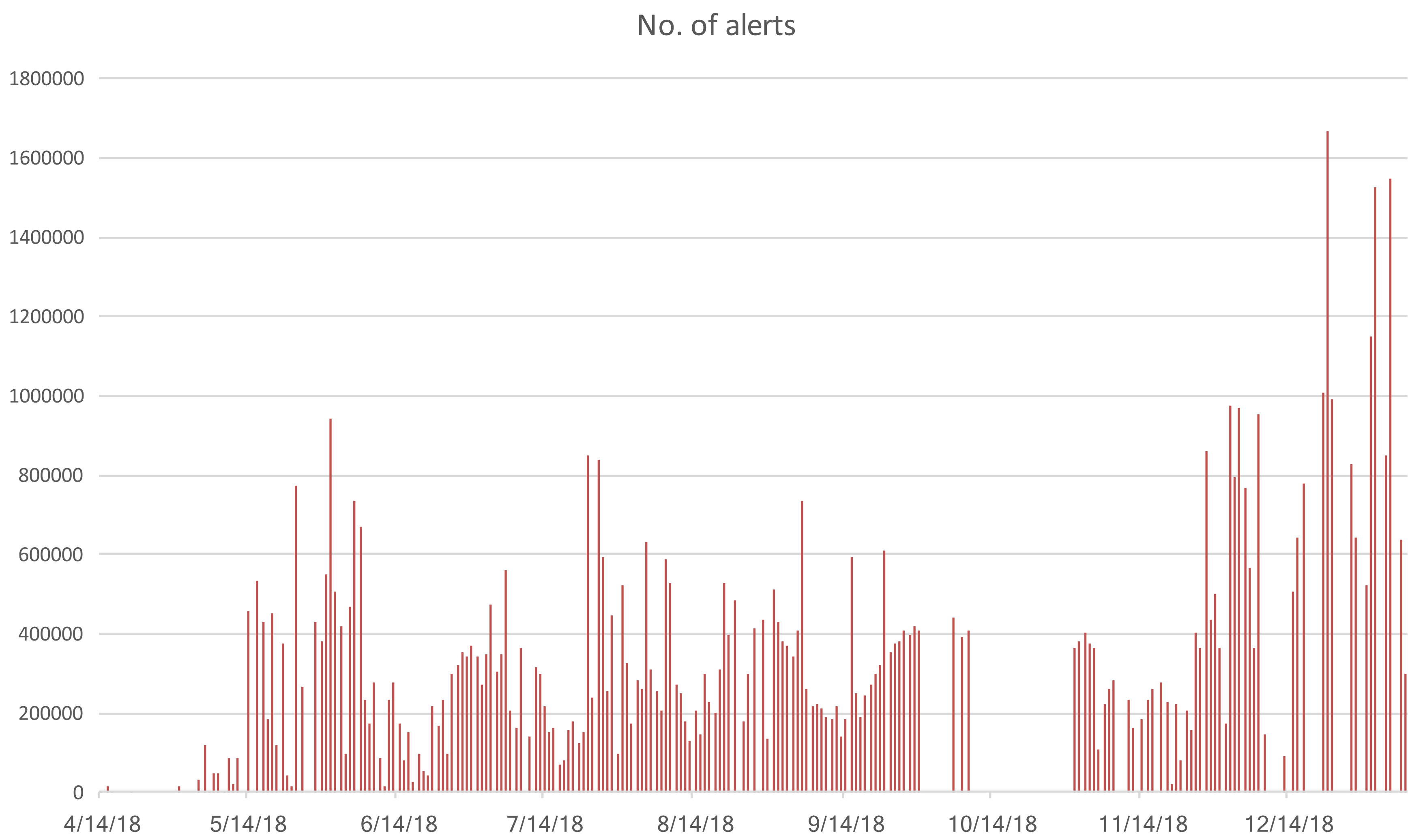
- ZOGY parameters
- Real-bogus score
- Star/galaxy score
- 3 nearest PS1 sources
- Nearest SS object
- Alert history

Rolling 30-day window
light curve

https://zwicky.tf/4t5

https://github.com/ZwickyTransientFacility/ztf-avro-alert

Alert statistics: 89,721,932 to 3/11/19



Where can I get alerts?

Service	Basic web search	User-defined filters	Notifications	Kafka streams	API	Bulk access
LCO MARS	Yes	No	-	No	JSON	No
ANTARES	No	Python	Slack	Yes	Python	(Yes)
LASAIR	Yes	SQL	-	No		No
UW	No	No	-	No	No	Yes
ALERCE	Coming soon					

ZTF Alert Archive

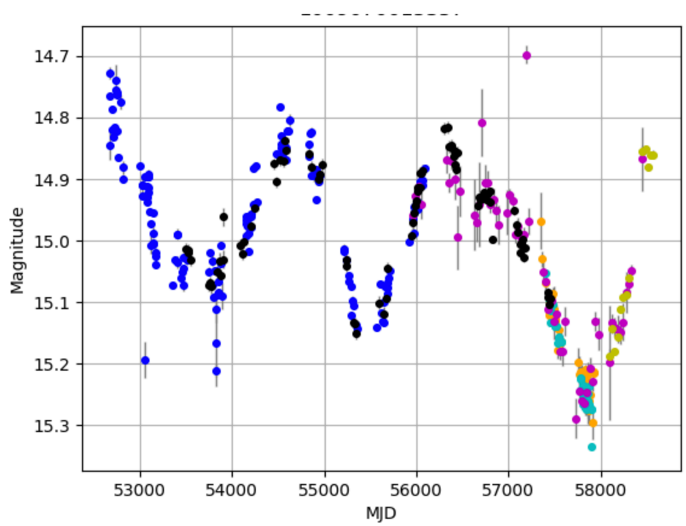
LCO MARS Make Alerts Really Simple

ANTARES

Lasair

The greater public legacy of ZTF

	Dates active	Magnitude limit	Mean Δt	Data available
LINEAR	1998-2007	18	22 d	Yes
CRTS	2003-2016	19.0-21.5	10 d	Yes
PTF/iPTF	2009-2015	20.5	77 d	Yes
ASAS-SN	2013-	18	1d	On demand
ATLAS	2016-	19	2d	No
ZTF	2018-	20.5	3 d	Yes



Why decadal baselines are important

- Quasars have a characteristic restframe variability timescale τ of 100s of days which scales with black hole mass
- Light curves need to cover at least 10τ for accurate estimates
- The bulk of the quasar population is $1 < z < 2$

=> observed frame data needs to cover at least 3000 days for just the least massive systems

Also for:

- Accurate periods for LPVs
- Period changes in close binary systems, Blazhko RR Lyrae, …

The predictable sky

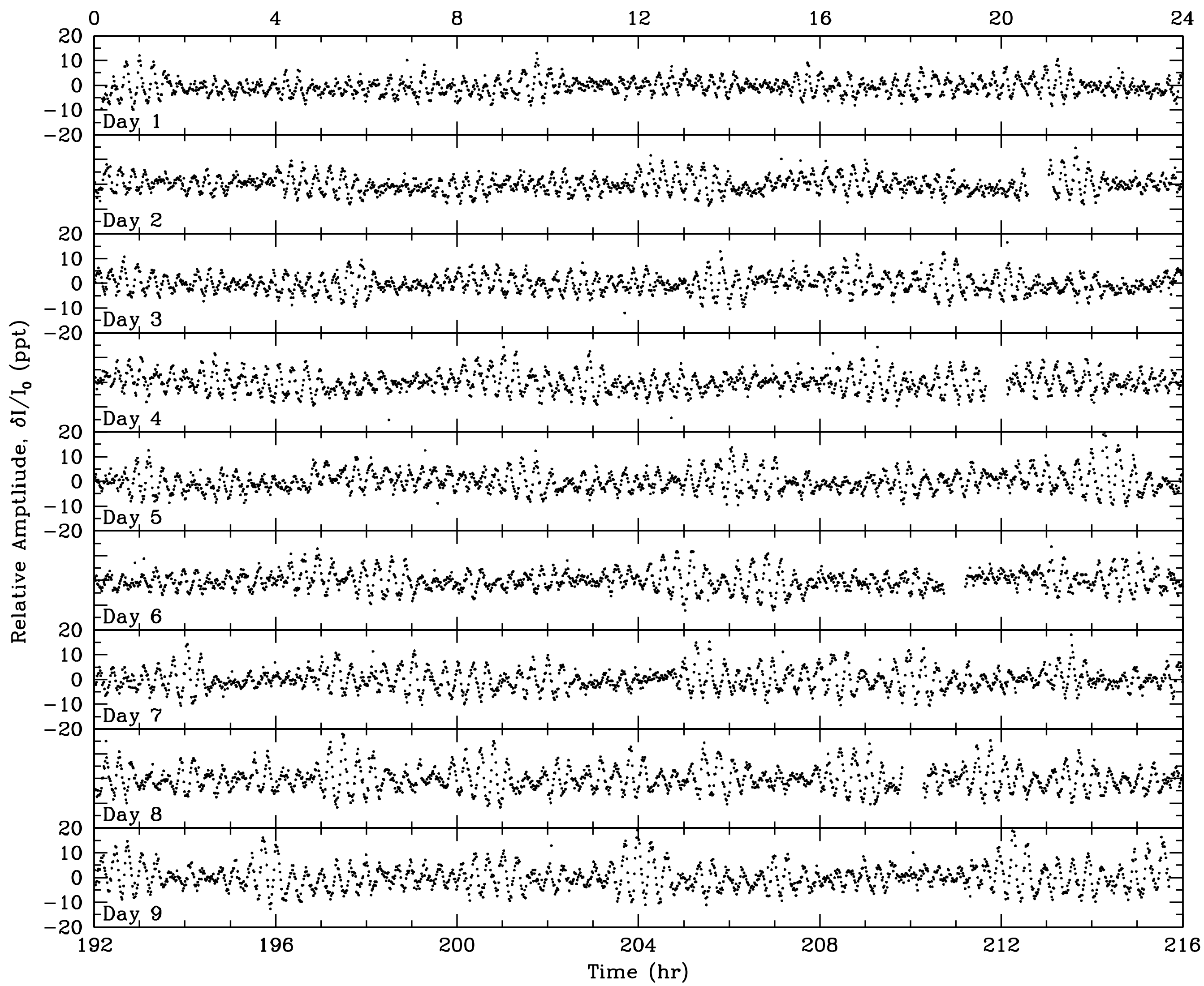
- Generative models of variability can be produced for every variable source in the sky
- Deep learning models are appropriate for both periodic sources and aperiodic or stochastic sources
- The expected behavior of each source could then be compared with the observed by ZTF
- This allows for much earlier detection of slow events such as:
  - Changing-look quasars
  - Microlensing
  - Slow flares/long-lived TDEs

Pulsating White Dwarfs from TDA Surveys

J.J. Hermes

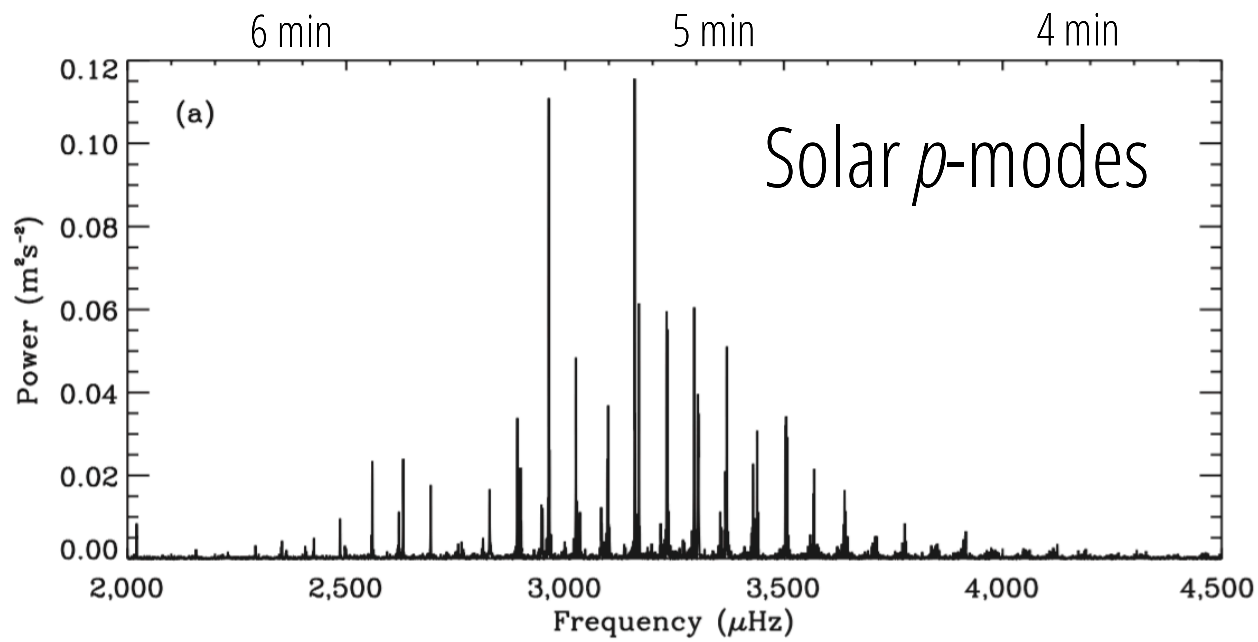
http://jjherm.es
@jotajotahermes

BOSTON UNIVERSITY

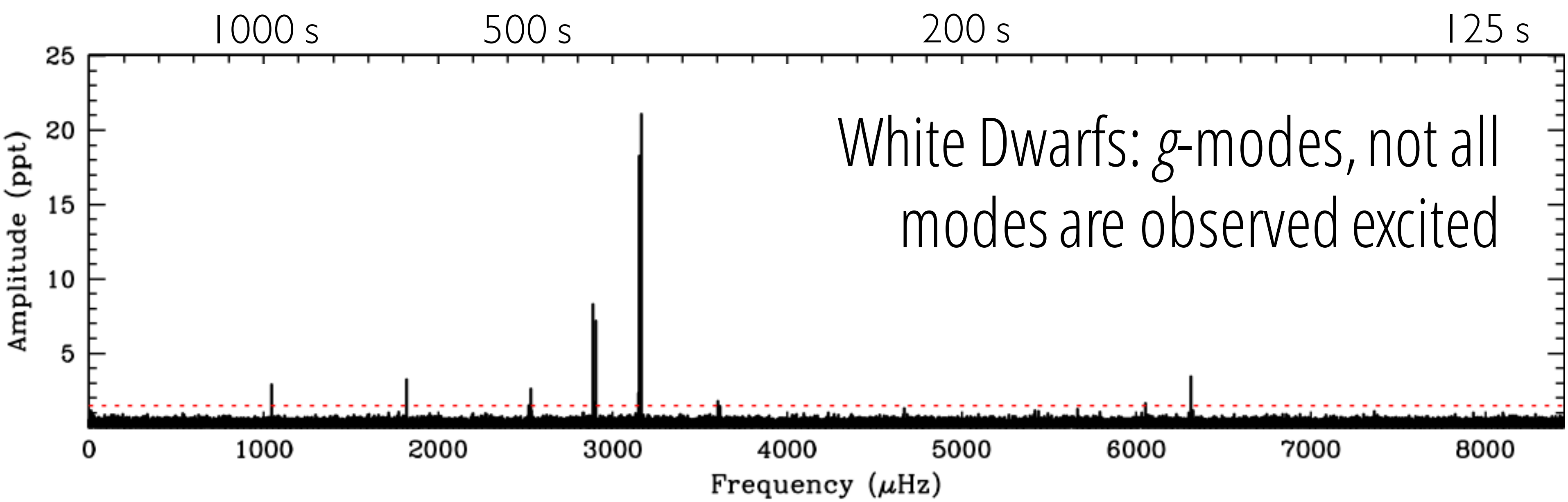


White dwarf pulsations:

Periods: 100-1500 s
Amps: 0.1-3% (and higher…)



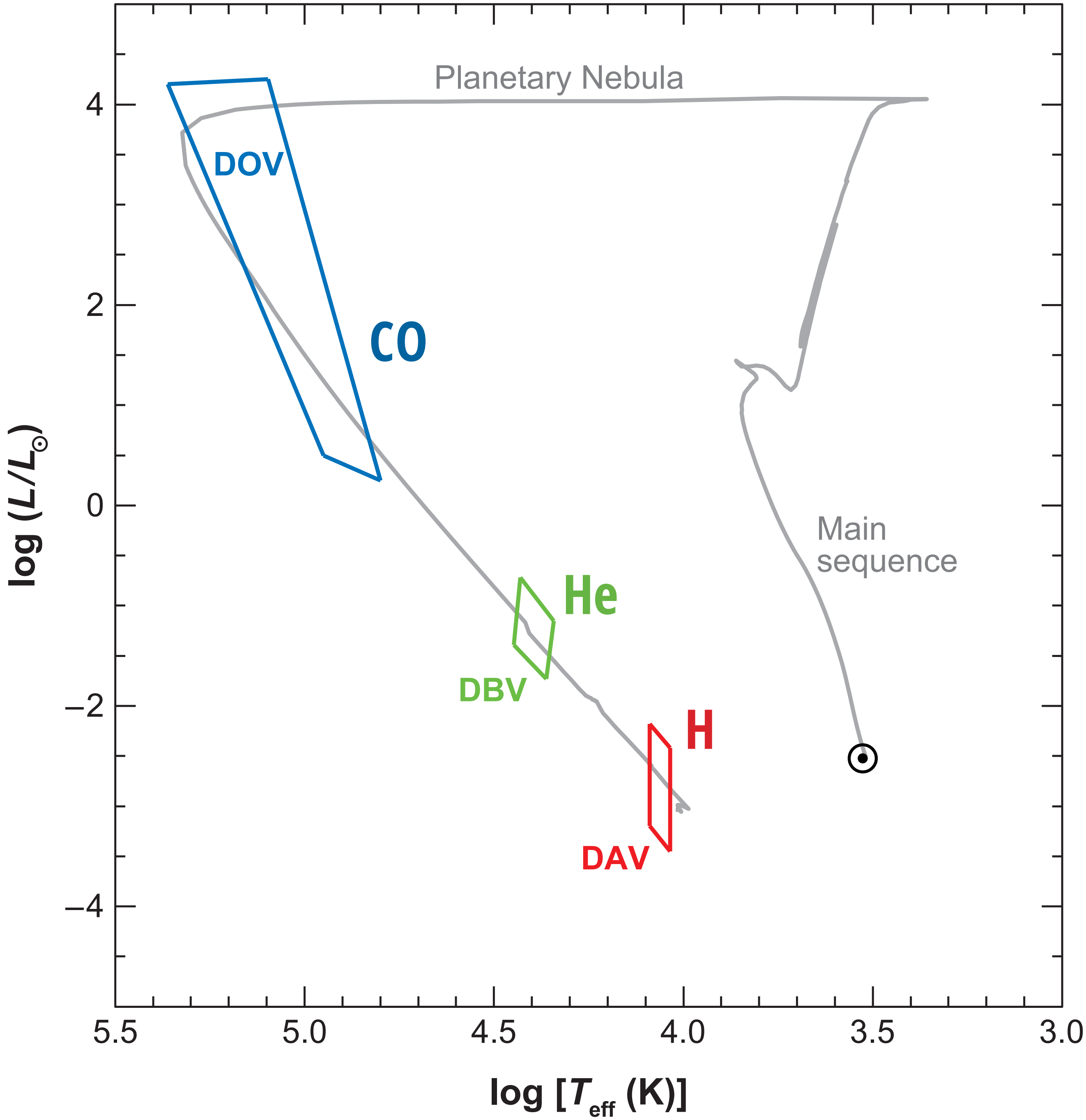
BiSON; Thompson et al. 2003



White dwarfs:

Peering 6 Gyr into our Sun's future…

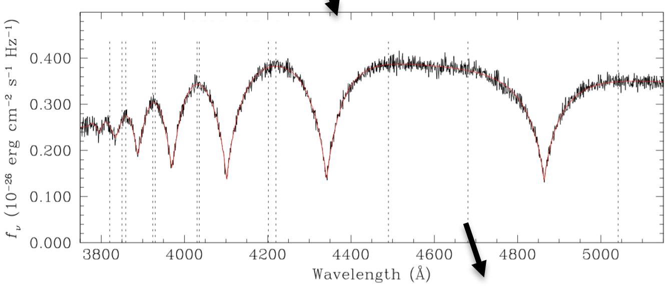
non-radial g-mode pulsations driven by partial ionization of **He** or **H**

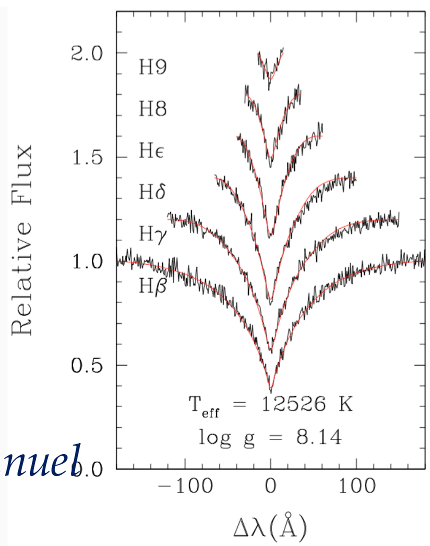


See reviews by:

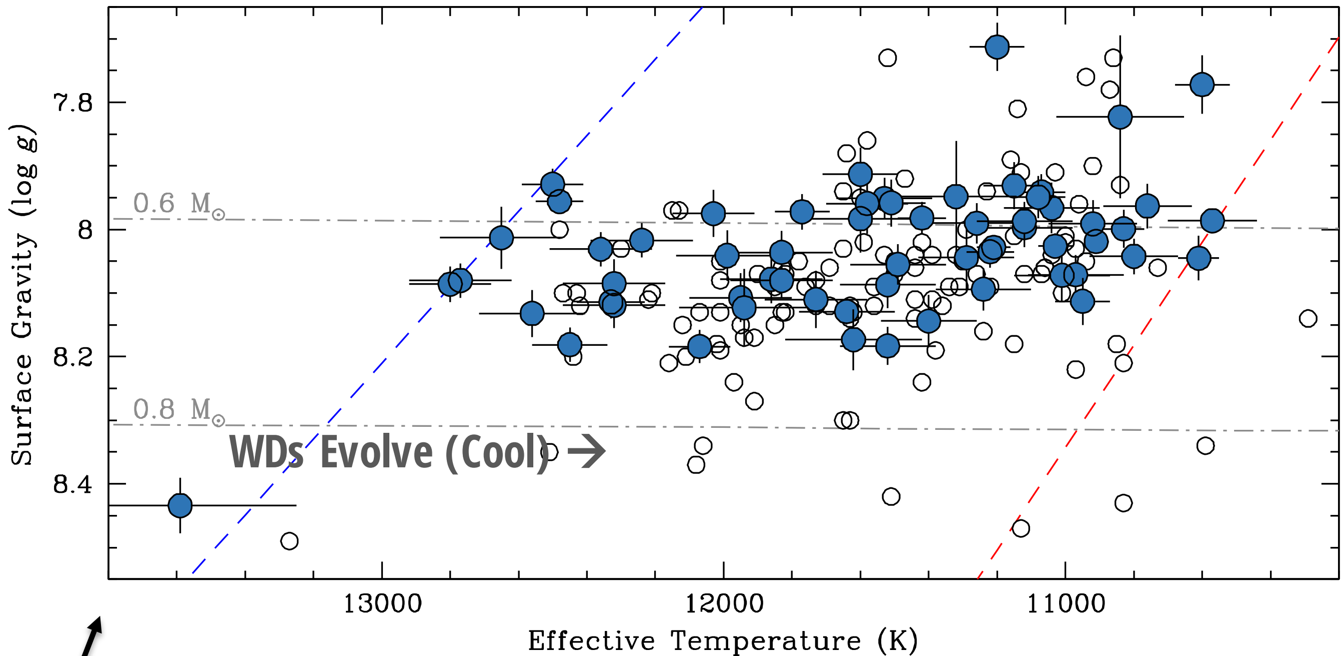
Winget & Kepler 2008
Fontaine & Brassard 2008
Althaus, Córsico, Isern & García-Berro 2010

Spectroscopy of DAs (H atm.) Yield Atmospheric Params.





fits via Pier-Emmanuel Tremblay



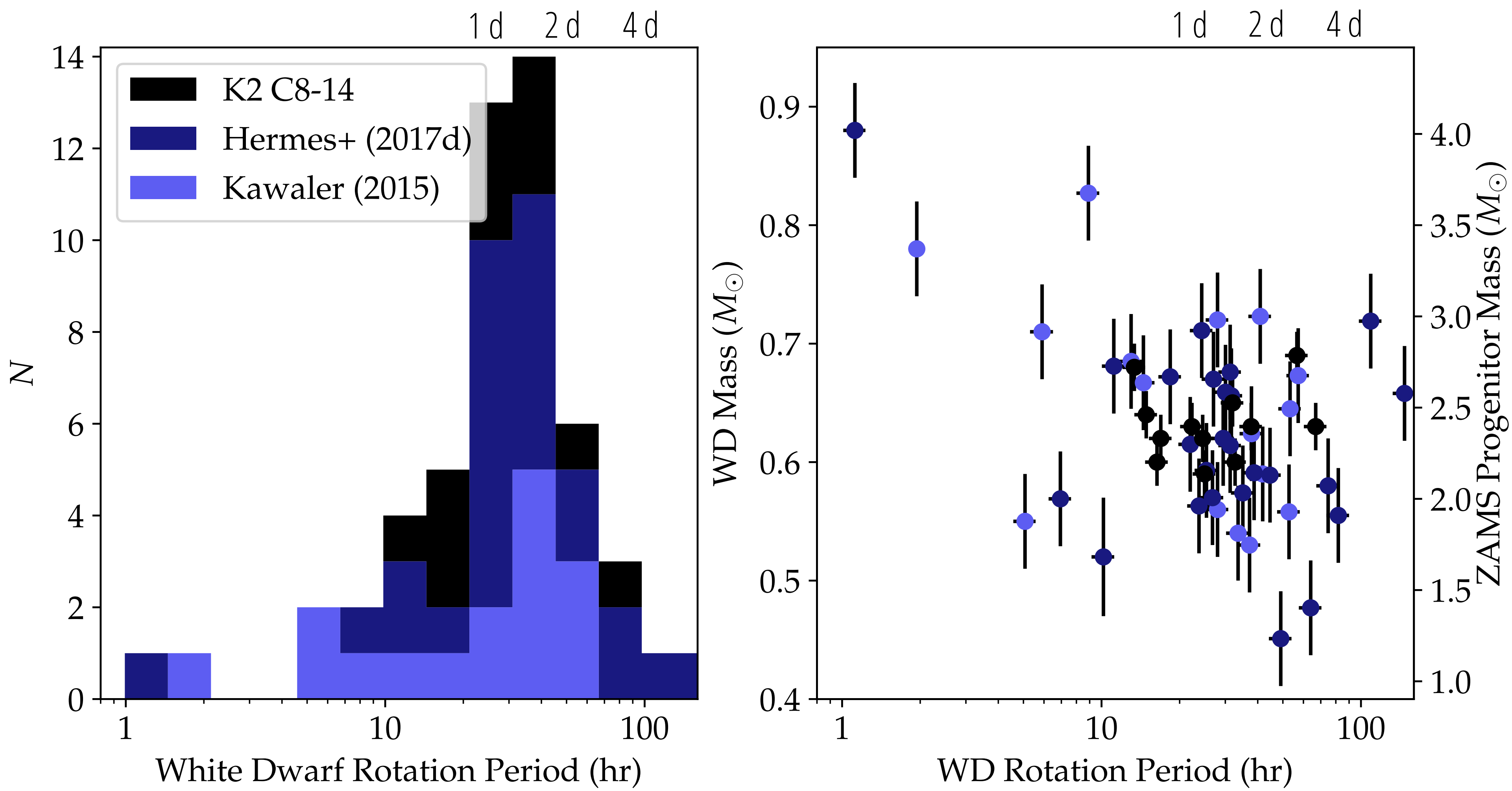
Blue: Observed by *Kepler*

Open: Ground-based

Note: Most white dwarfs: **0.55-0.70 $M_\odot$**

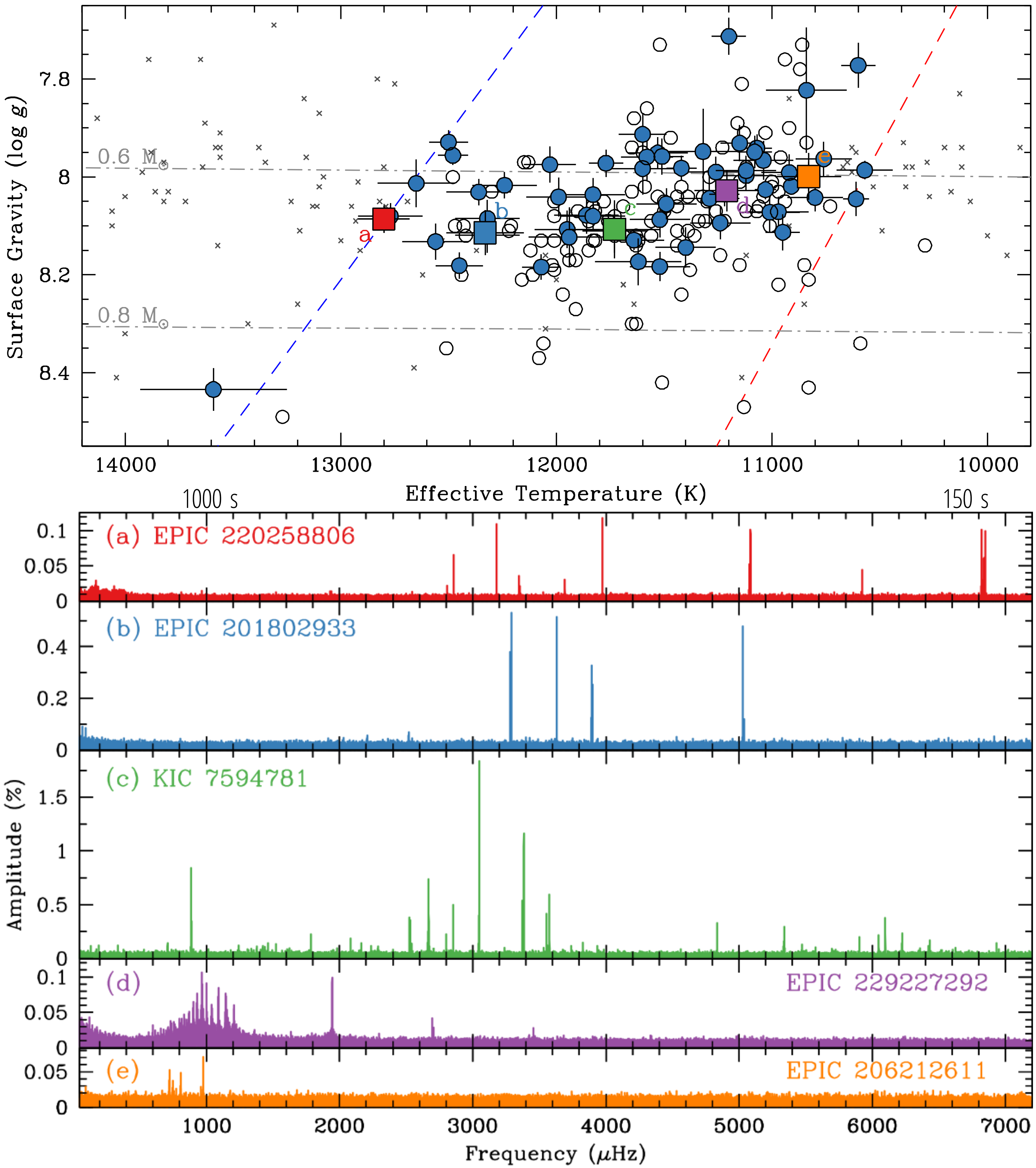
(evolved from 1.0-3.0 $M_\odot$ ZAMS)

Pulsations Give Rotational Splittings; Joined w/ Spectra We Finally Have WD Rotation Rates as Function of Mass



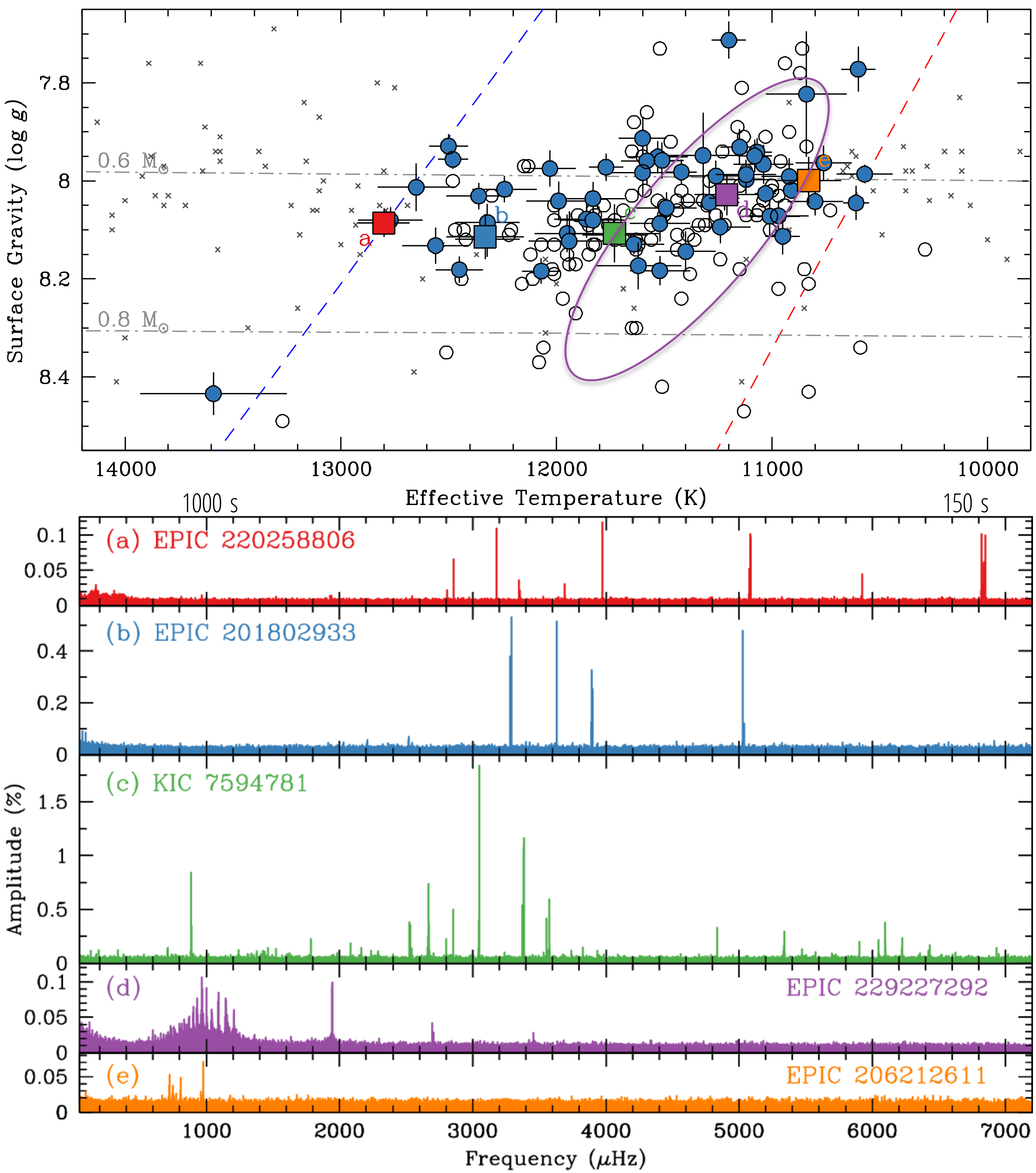
Most white dwarfs evolve from 1-3 $M_\odot$ ZAMS stars, and rotate with periods of 0.5-2.2 days

Hermes et al. 2017



as white dwarfs **cool**:

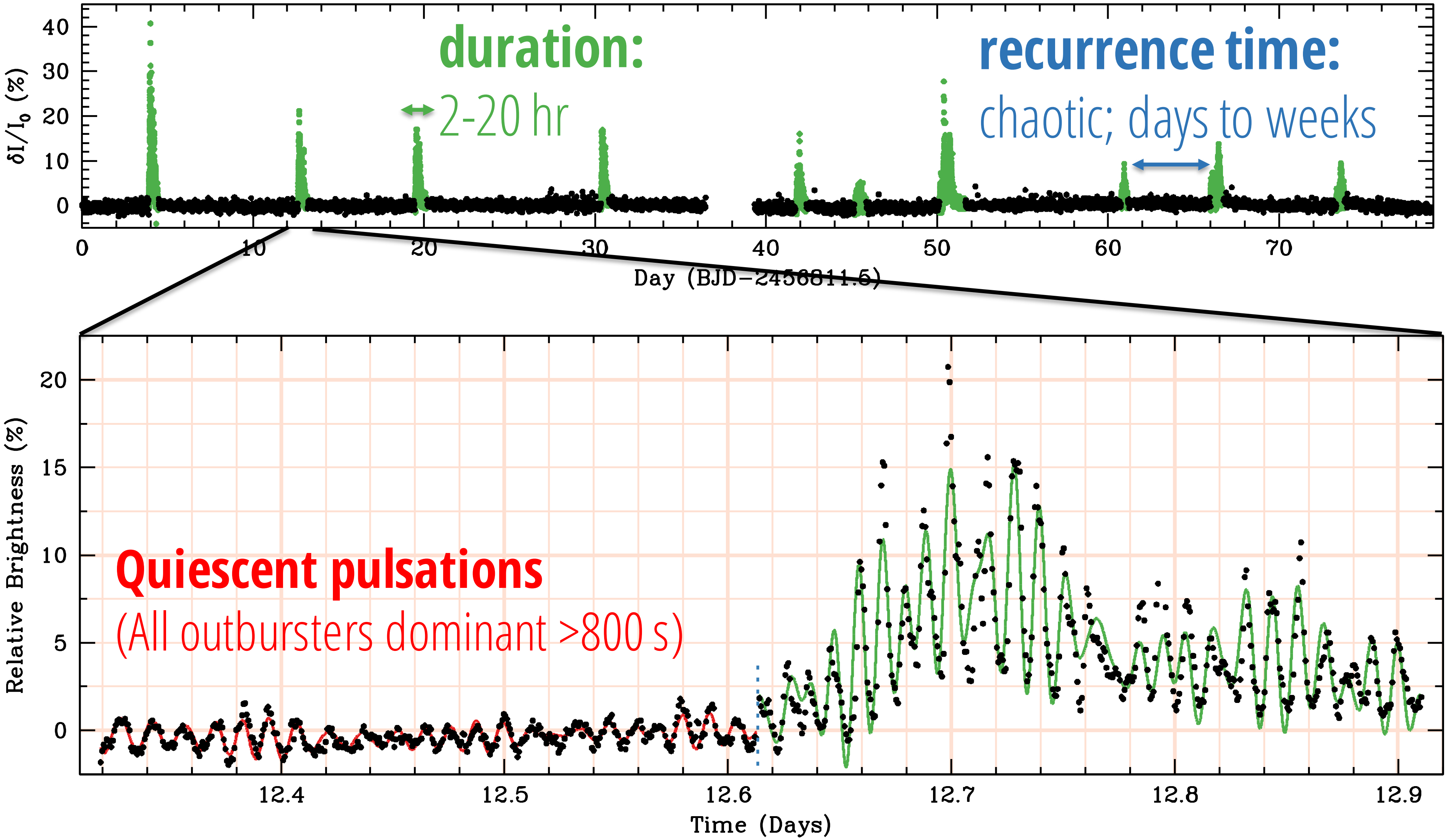
convection zone deepens and **longer-period** (higher-radial-order) pulsations driven



as white dwarfs **cool**:

convection zone deepens and **longer-period** (higher-radial-order) pulsations driven and **mode density** rapidly **increases**

Unexpected Outburst Phenomena in Pulsating WDs

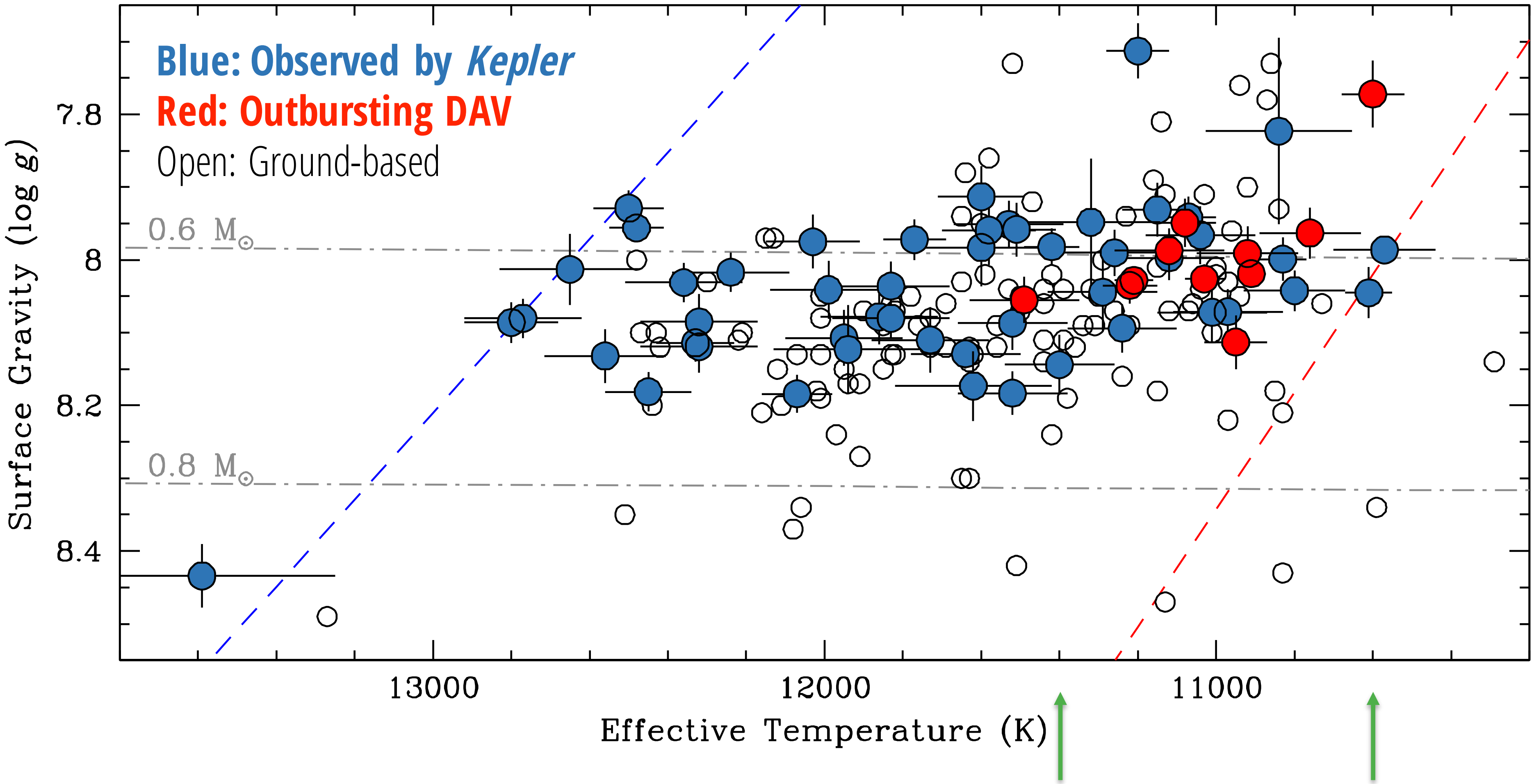


15% flux increase:
700 K T_{eff} increase

excess energy:
$10^{33\text{-}34}$ erg

PG 1149+057: Hermes et al. 2015b
see also Bell et al. 2015, 2016

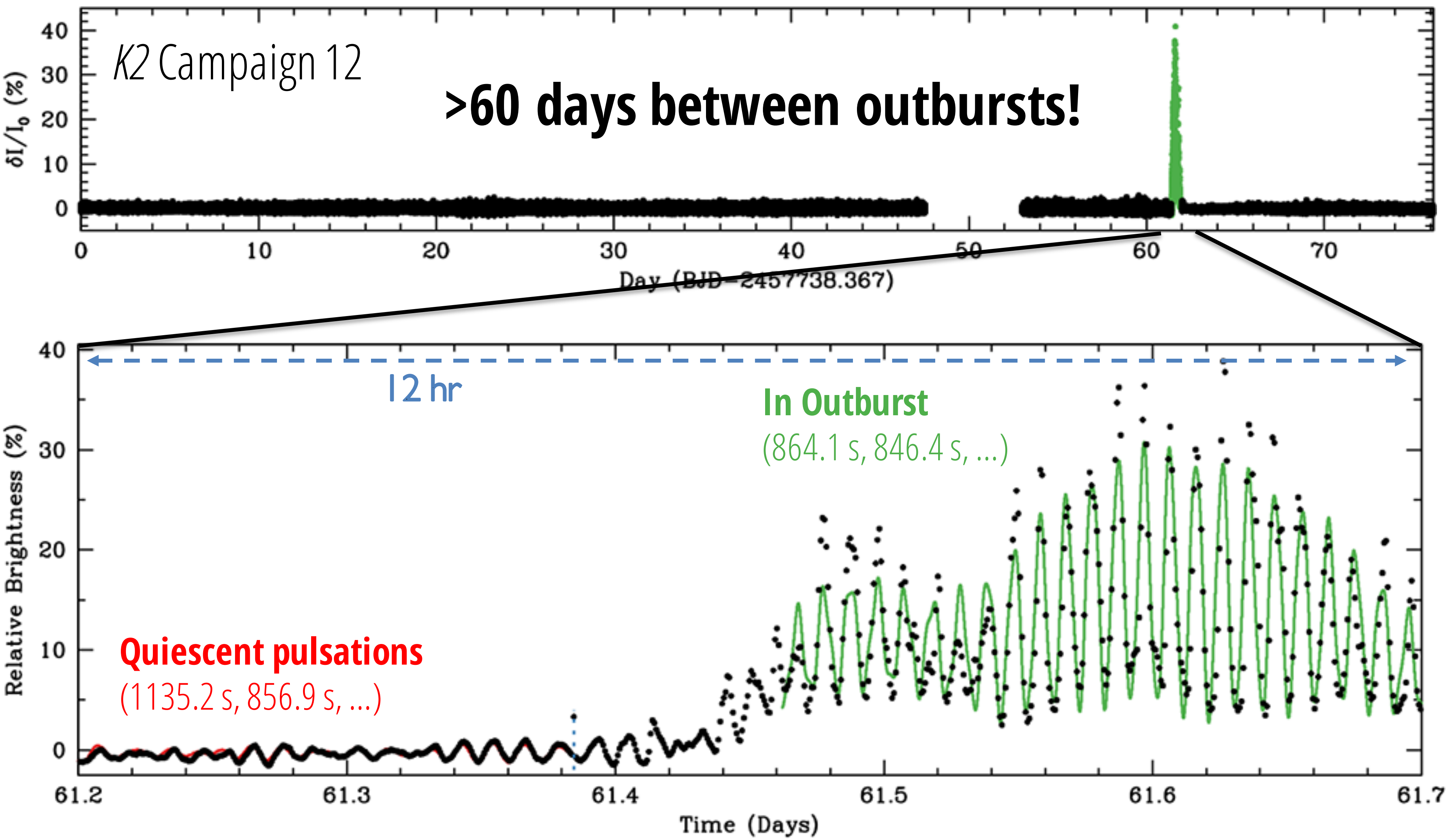
Outbursting DAVs are Among the Coolest DAVs



more than 50% of DAVs from 11,200-10,600 K show **outbursts** in ~70 days of K2 monitoring

16/71 (>20% of) DAVs with Kepler data show outbursts

GD 1212: The Brightest Outbursting White Dwarf



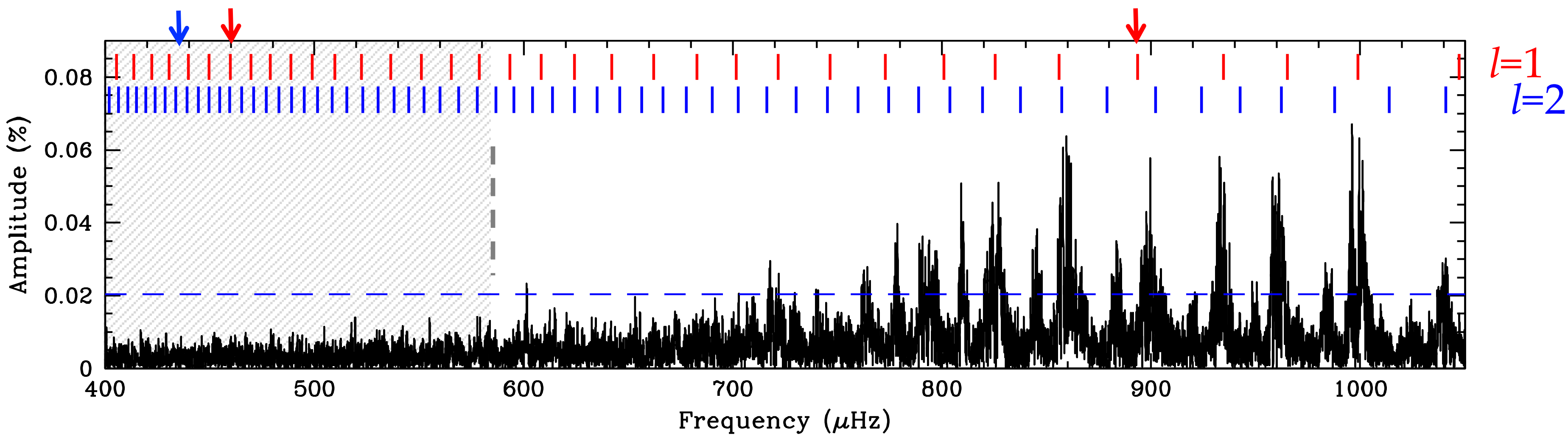
GD 1212 (g=13.2 mag): Hermes et al. 2019, in prep.

Outbursts: Mode Coupling via Parametric Resonance

outbursts are likely "**limit cycles** arising from sufficiently resonant **3-mode couplings** between **overstable parent modes** and pairs of radiatively damped **daughter modes**"

Luan & Goldreich 2018

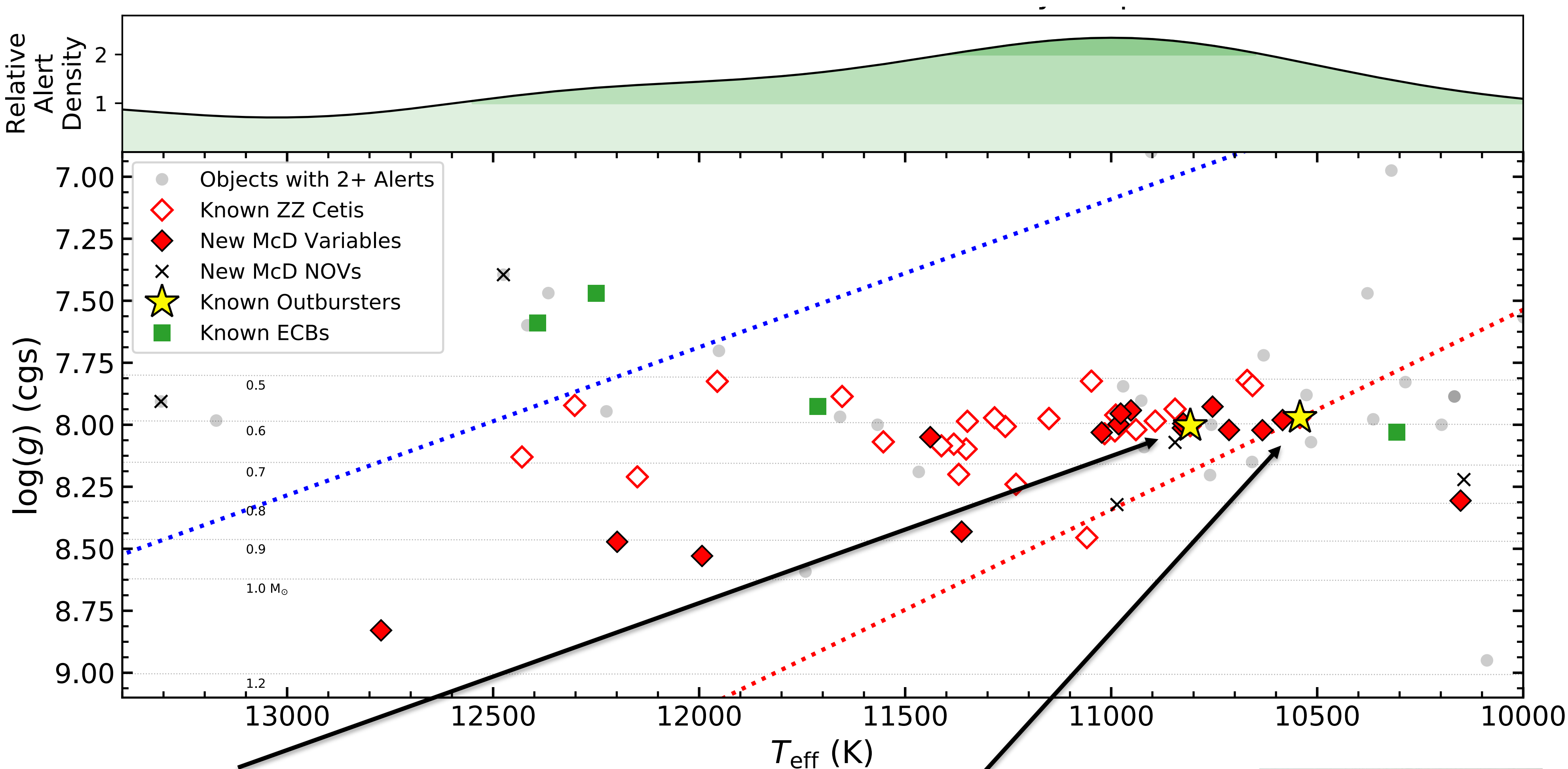
Radiative damping ← → Driving exceeds damping



Adiabatic Model: 11,245 K, 0.632 $M_\odot$, $10^{-4.12}$ M_H/M_{WD} (Romero et al. 2012)
Observed: 11,060(170) K, 0.64(0.03) $M_\odot$ (Gianninas et al. 2011)

What are surface temperatures and velocities in outburst?

Overdensity of ZTF Alerts Near Outbursting White Dwarfs

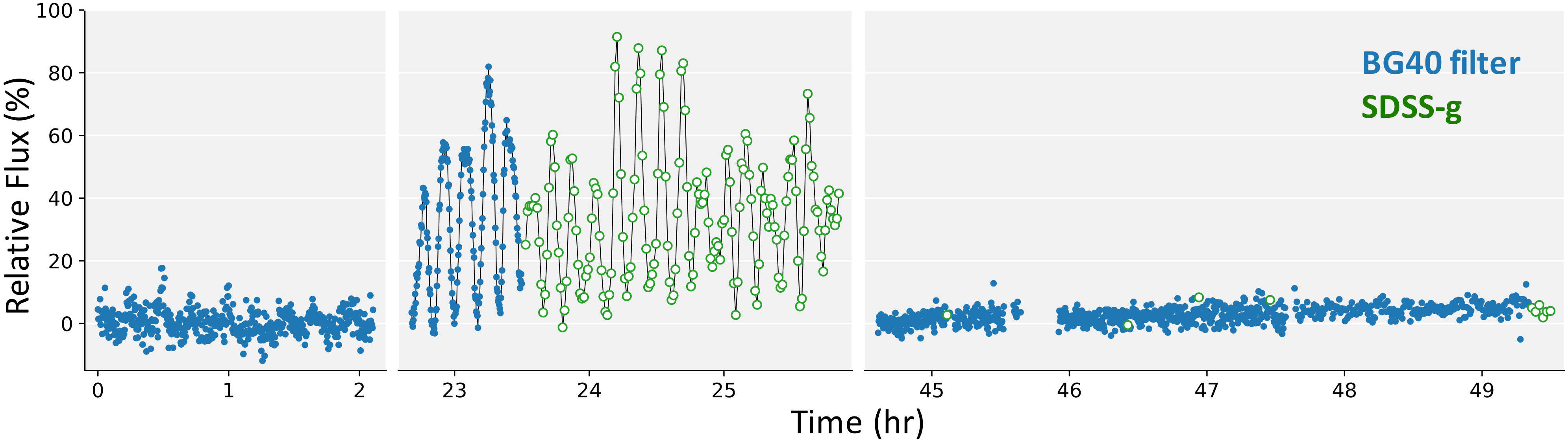


GD1212 (g=13.2 mag):
2 low-RB ZTF alerts

EPIC 229227292 (g=16.6 mag):
1 high-RB ZTF alert

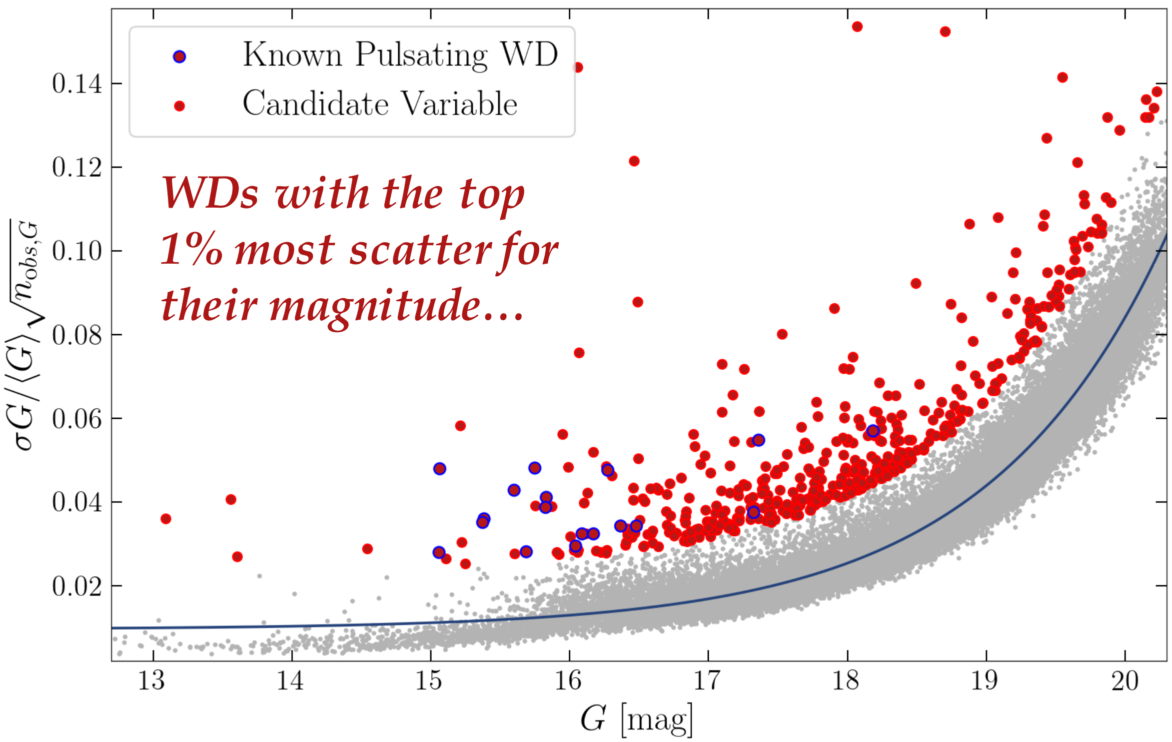
courtesy Zachary Vanderbosch (UT-Austin)

Outbursts Have Finally Been Detected from the Ground!

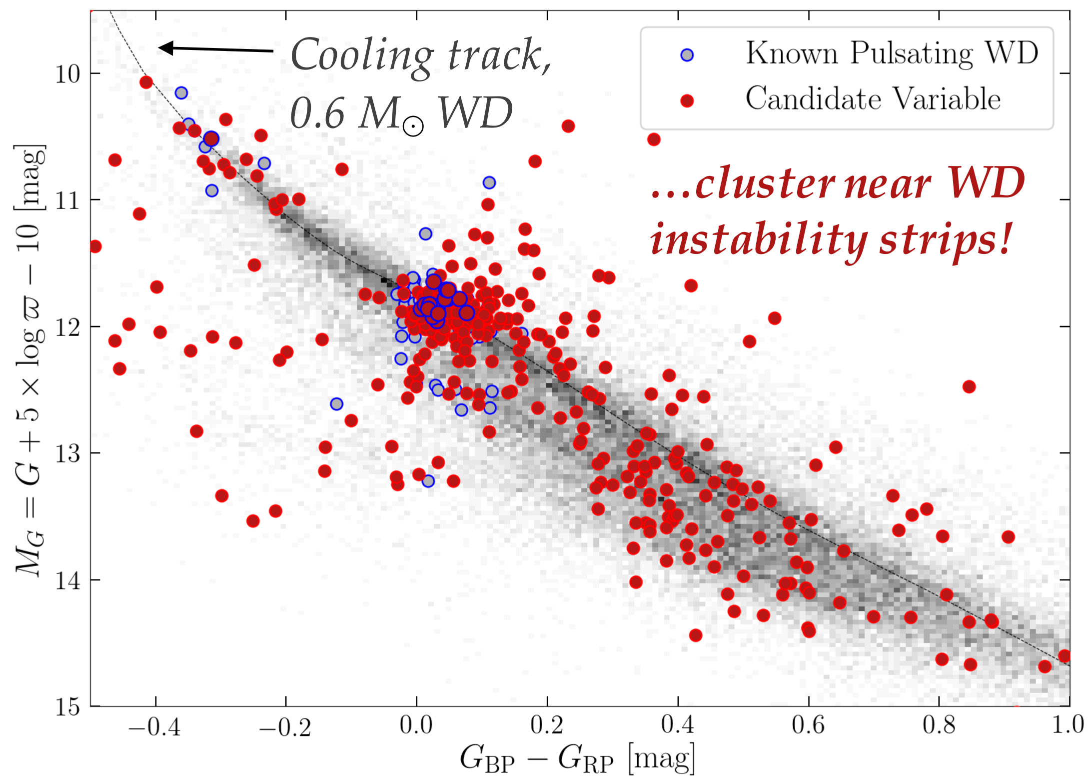


Vanderbosch et al. 2019, in prep.

Gaia Empirical Uncertainties Finds Variables!



>46,000 WDs within 200pc



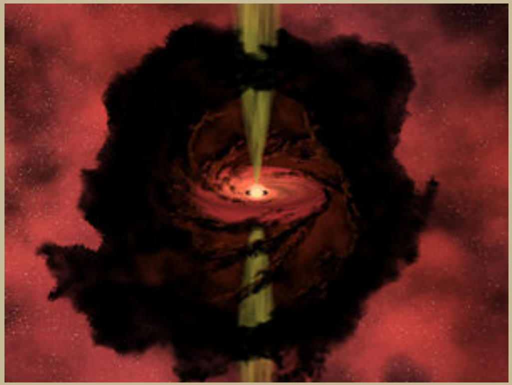
Hermes et al. 2018; 2019, in prep.

Time Domain Surveys and Young Stars

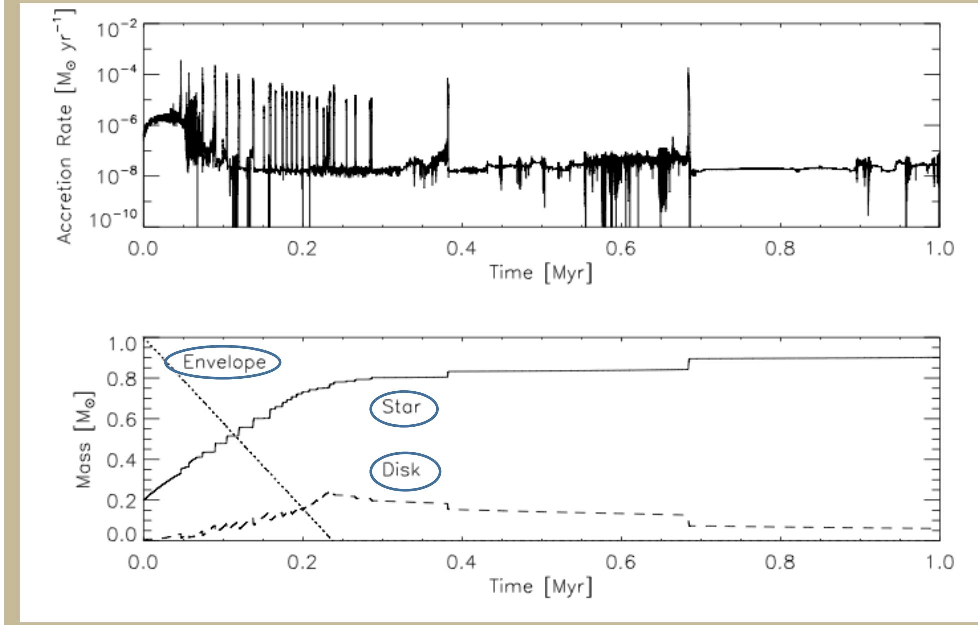
Lynne A Hillenbrand
Caltech

Not Only Stars, but Planets being Born “Today”

Disk Formation, Accretion, Evolution

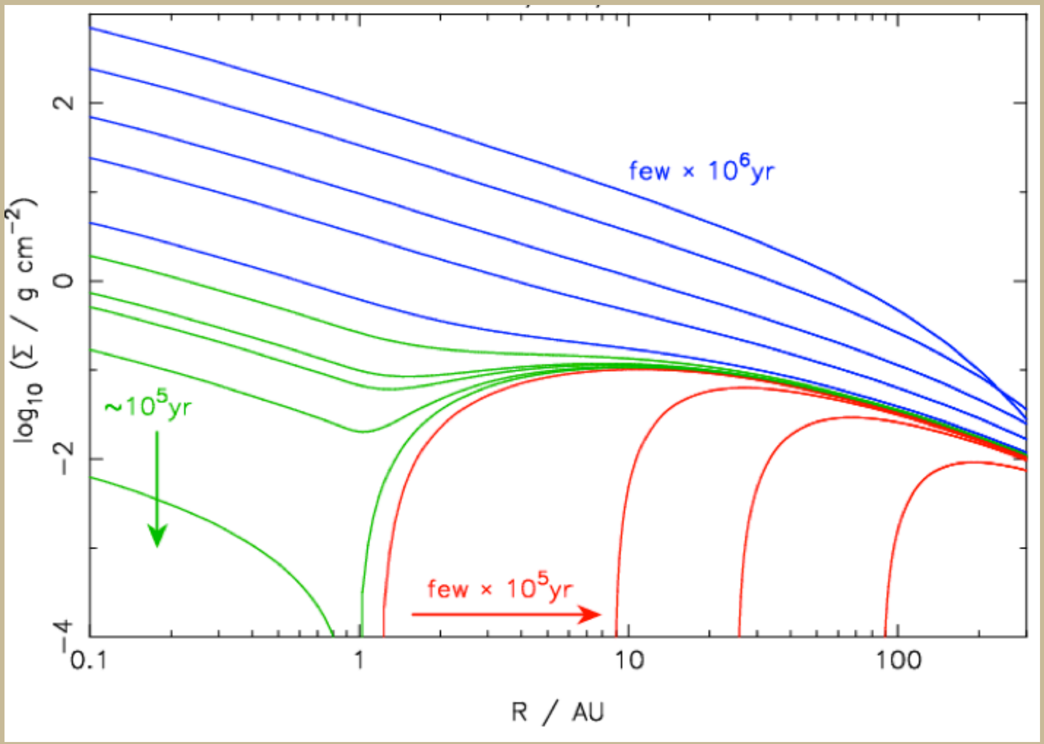


early accretion
(and outflow)



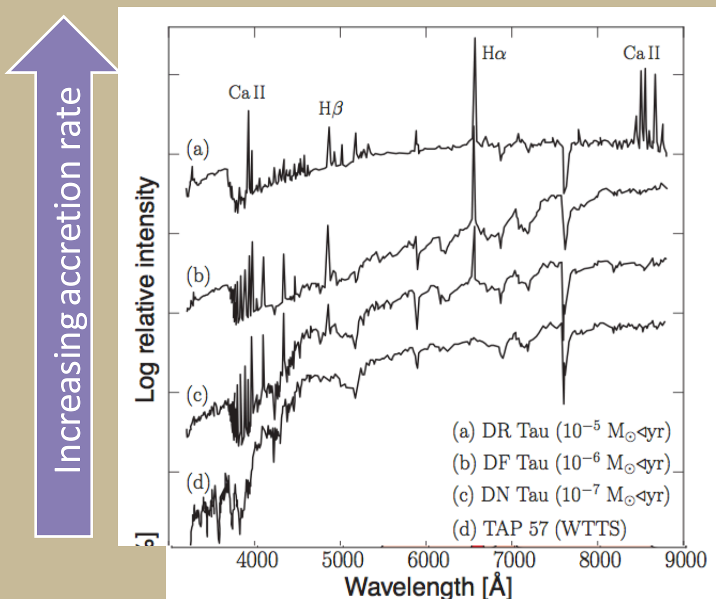
Bae et al. (2014)

later, viscous evolution and photo-evaporation

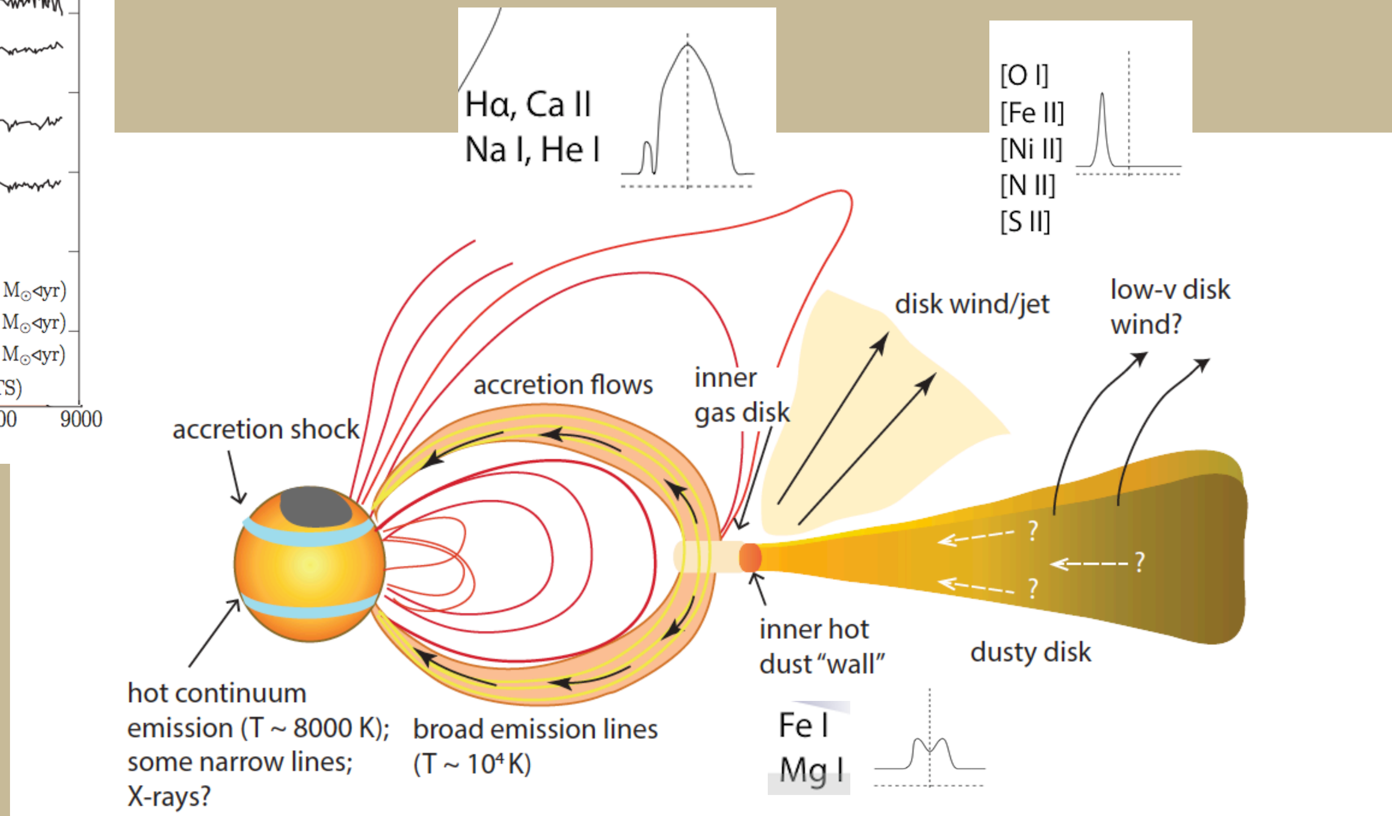


Alexander (2014)

Magnetospheric Accretion



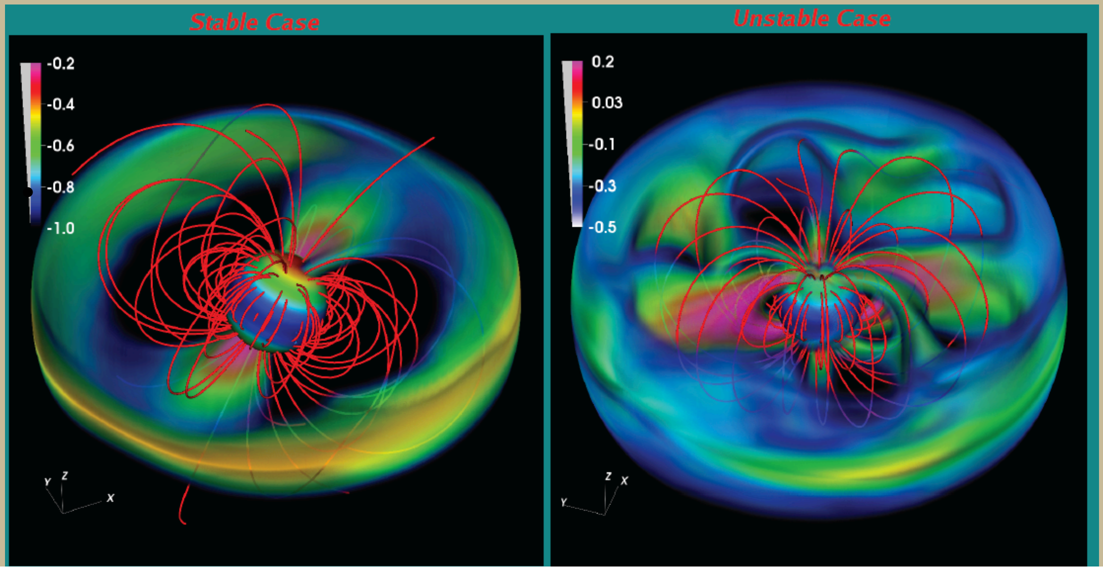
Barensten et al. 2013



Hartmann, Herczeg, Calvet 2016

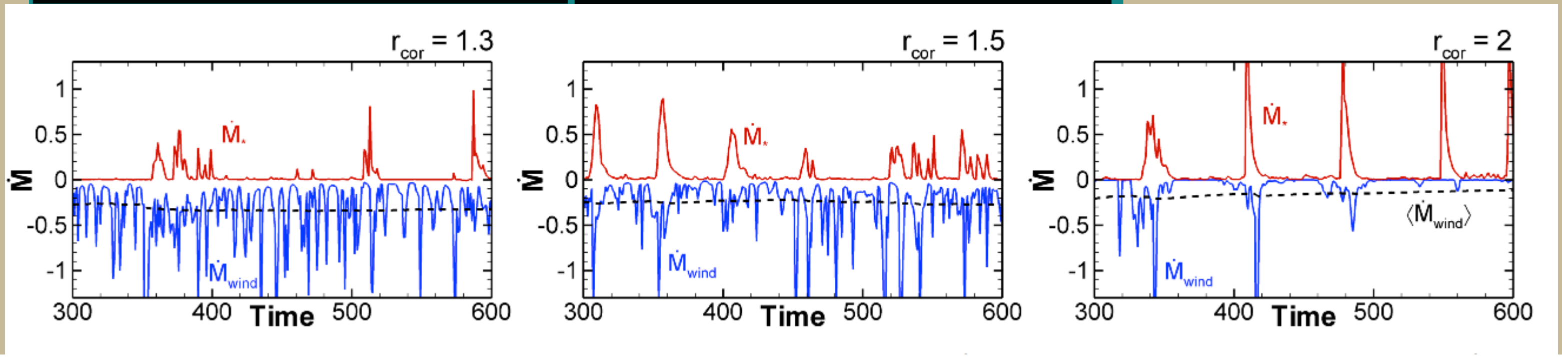
Innermost disk regions, r < 0.05 AU

- Dynamical time at the co-rotation radius ~1 week
- Infall time along magnetic field lines ~hours

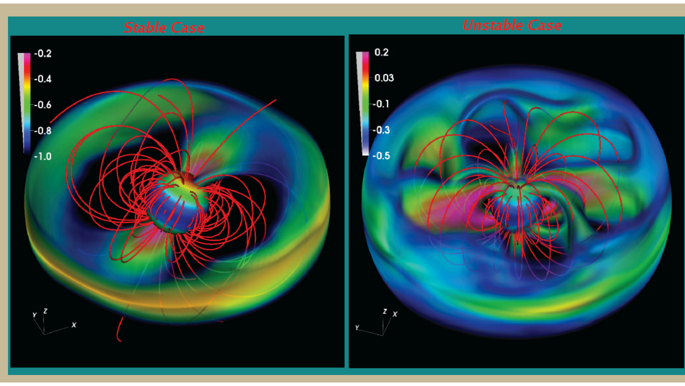


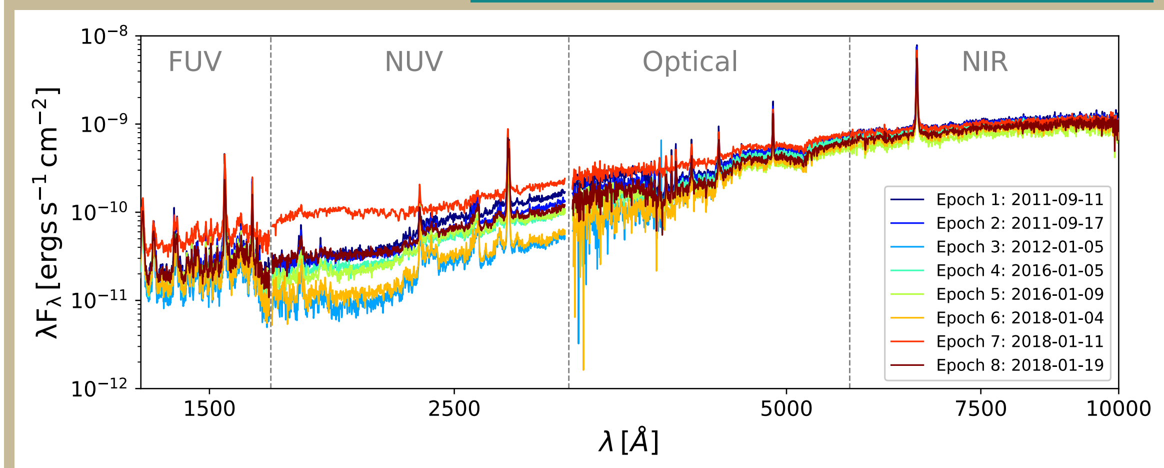
both accretion and ejection of material

Kurosawa, Romanova



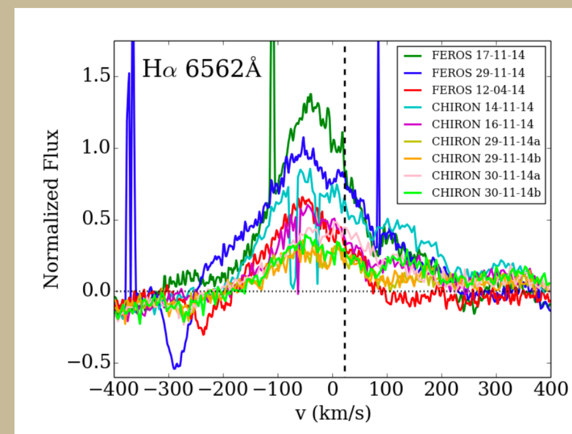
VARIABLE CONTINUUM

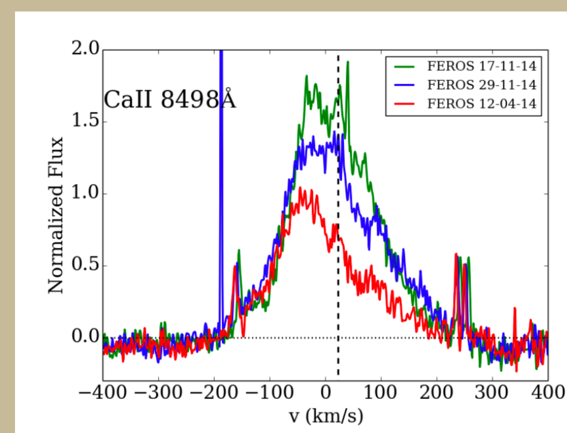




[Robinson et al. 2019]

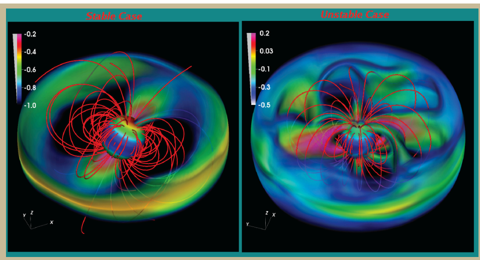
VARIABLE LINE PROFILES



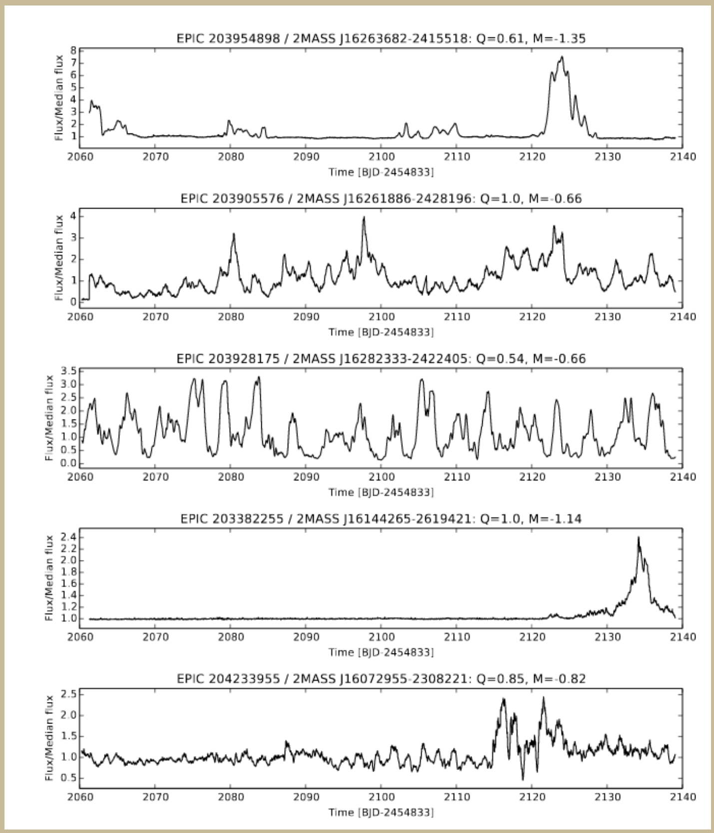


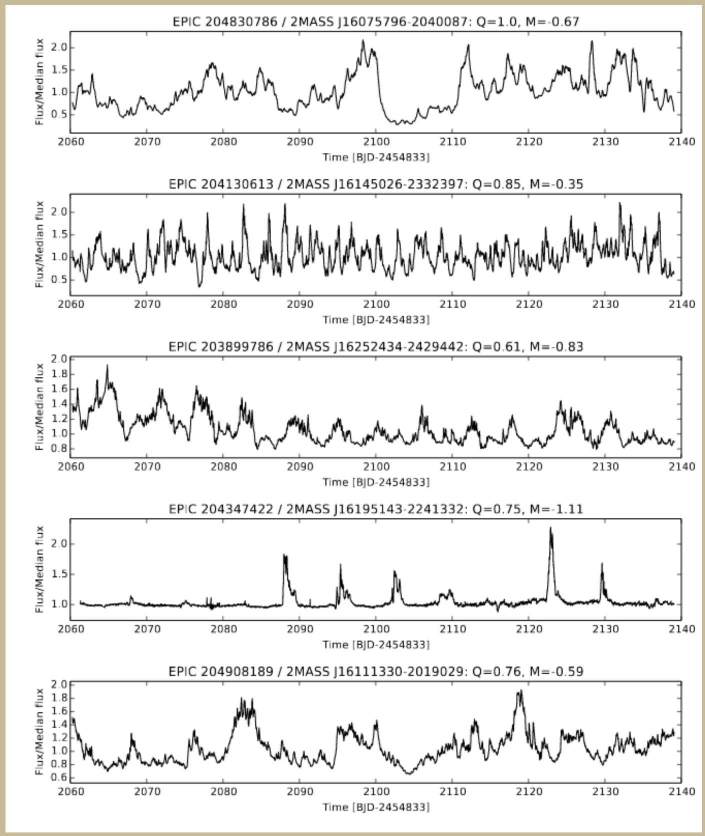
[Sicilia-Aguilar et al. 2017]

VARIABLE BROAD-BAND PHOTOMETRY: ACCRETION-DRIVEN BEHAVIOR



[Cody et al. 2017]





14% of the objects with disks exhibit with these types of lightcurves

A Range of Observing Strategies is Needed

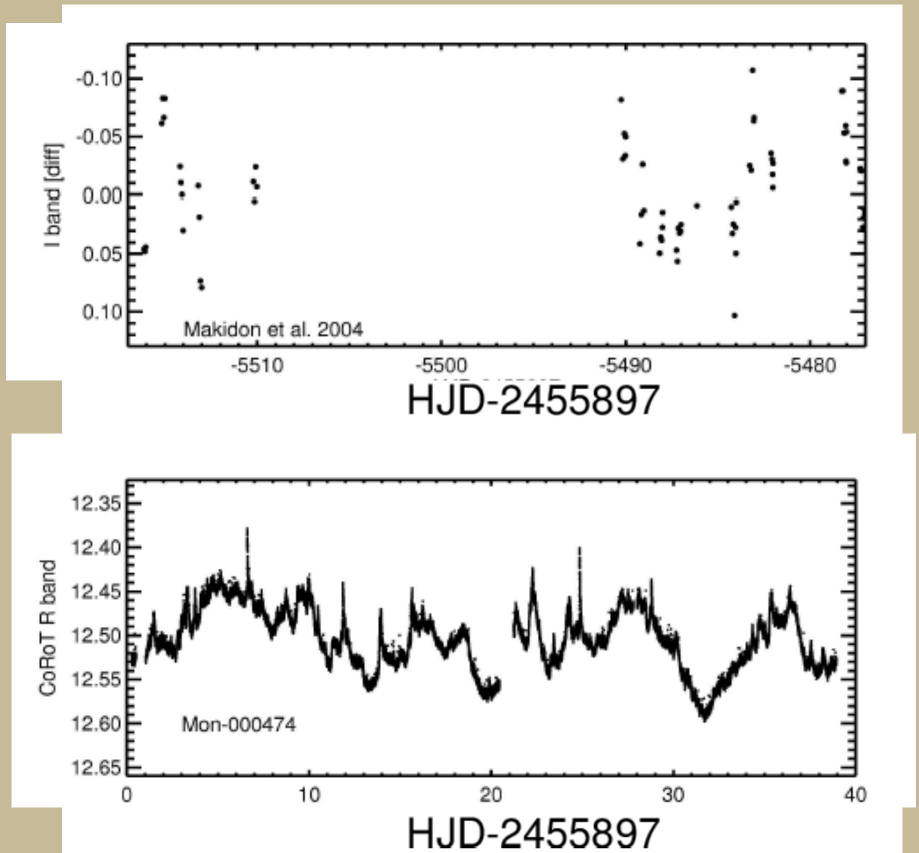
CoRoT
+
K2

PTF/ZTF
+
Gaia

Spitzer
+
NEOWISE

- High precision
  - Underlying stellar processes e.g. pulsations, spots, rotation
  - Details of accretion-driven and extinction-driven behavior
- High cadence
  - Resolve the time scales for accretion and/or inner disk geometry changes
- Long duration (can be lower precision)
  - Probe more dramatic accretion and disk morphology history
- Multiwavelength
  - Importance of dust extinction vs gas accretion processes
  - Importance of radiative vs dynamic processes

The Quality of Modern Data is Outstanding !



. *Ground (top) vs. space time series (bottom)*

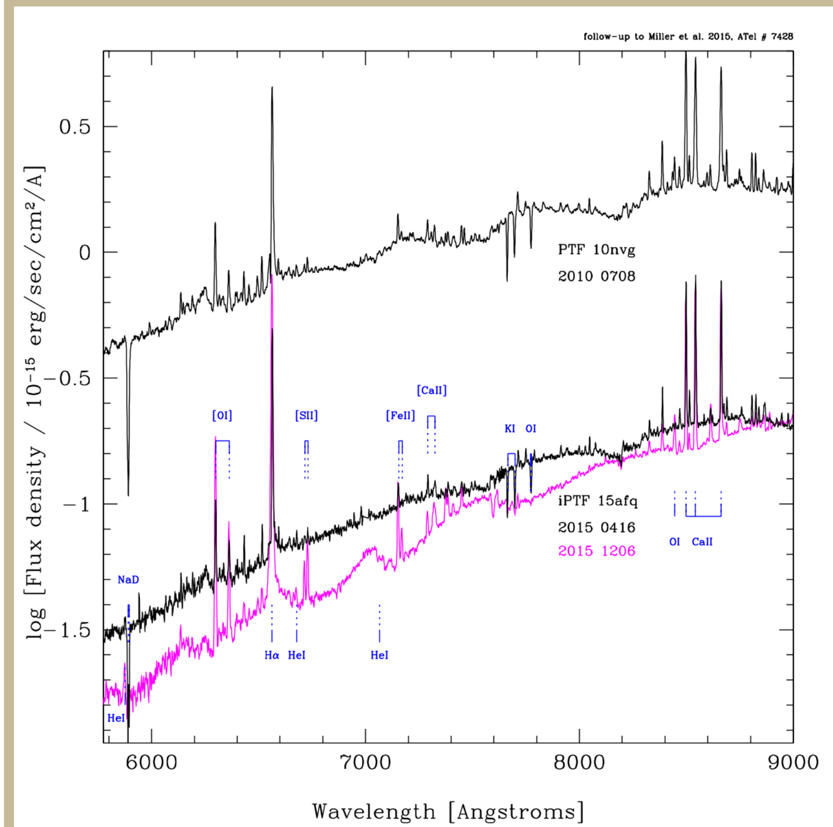
Ten to Fifteen years ago:

- ground-based
- precision-limited
- cadence-limited
- many gaps

Today:

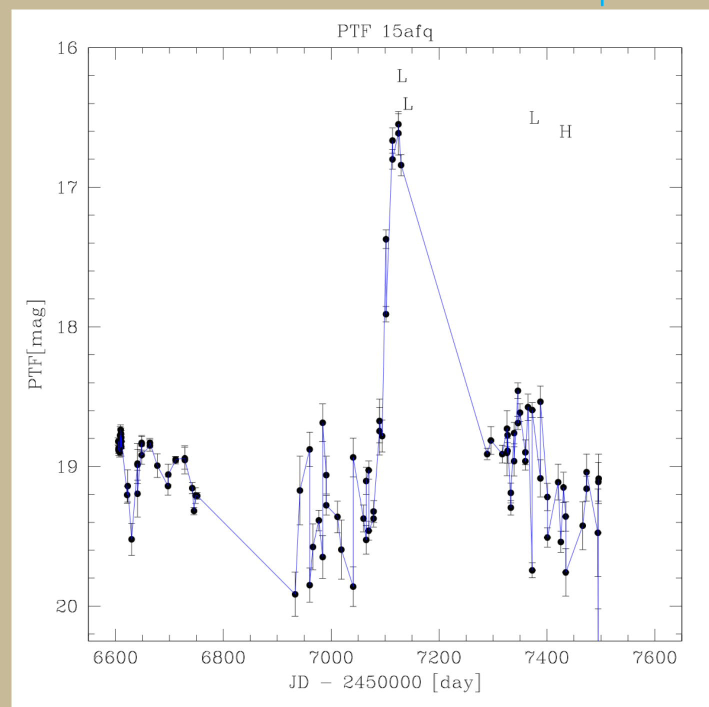
- space-based
- exquisite precision
- excellent cadence
- acceptable gaps

A LARGE SHORT-LIVED ACCRETION BURST



Increase in disk accretion rate caused ~3 mag brightening for several months accompanied by enhanced spectral veiling and TiO emission.

PTF 15afq



Miller et al. (2015)

A Somewhat Larger, Somewhat Longer-Lived, But Still Temporary Burst

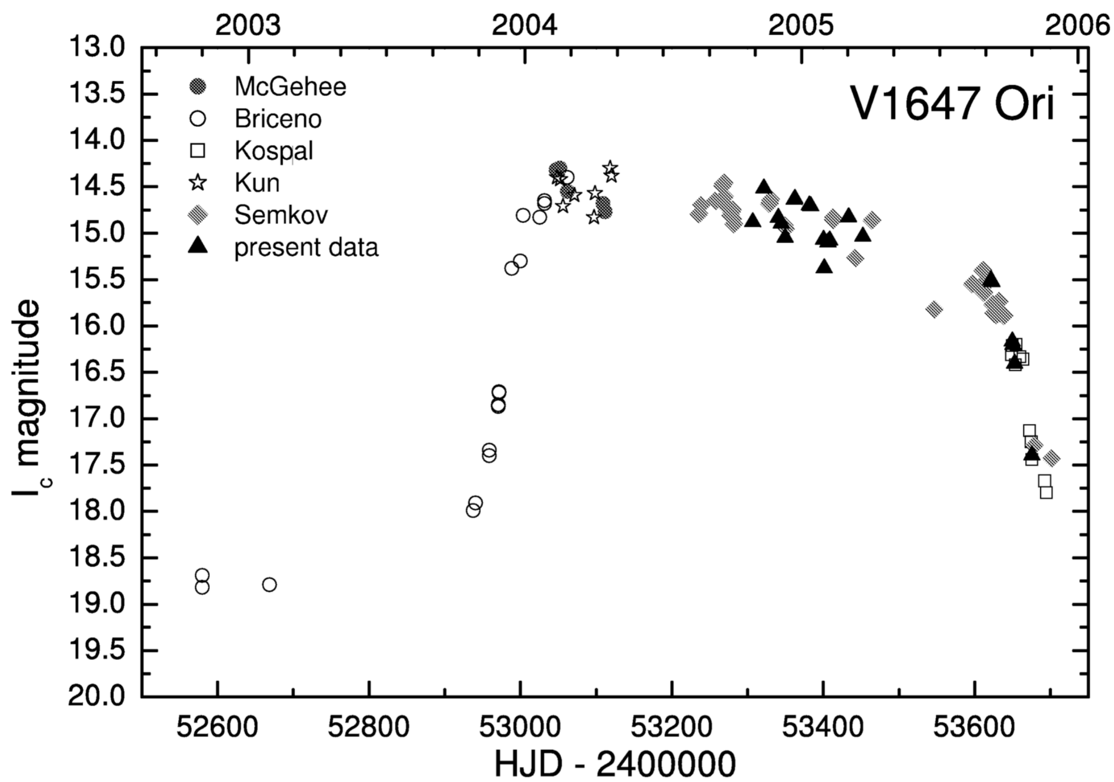


Figure 4. V1647 Ori light curve in the I_C passband. Our data and data from McGehee et al. (2004), Briceño et al. (2004), Kóspál et al. (2005), Kun et al. (2004) and Semkov (2004, 2006) were used.

Innermost Disk Instabilities

magnetospheric instability e.g. Goodson & Winglee (1999)

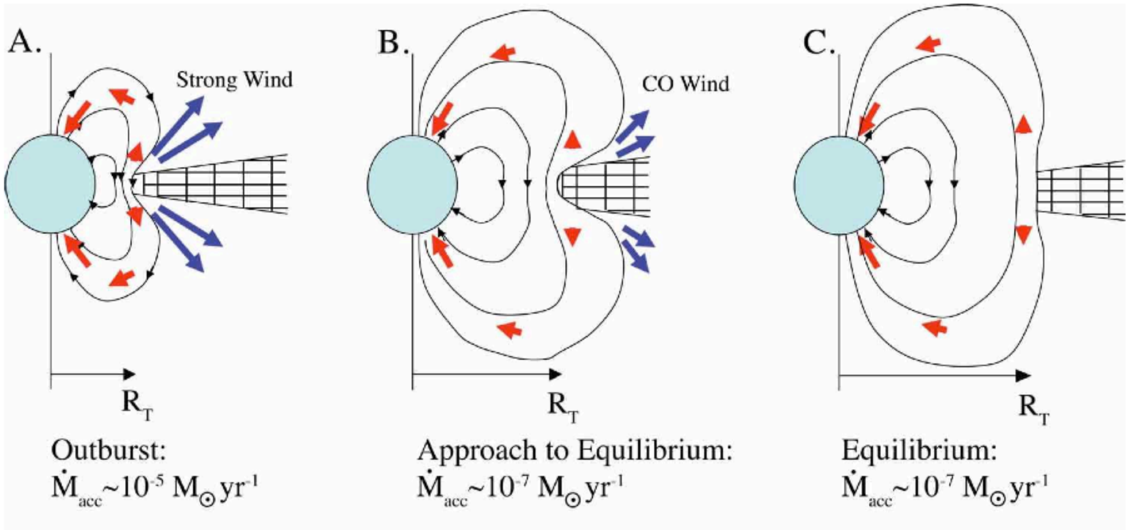
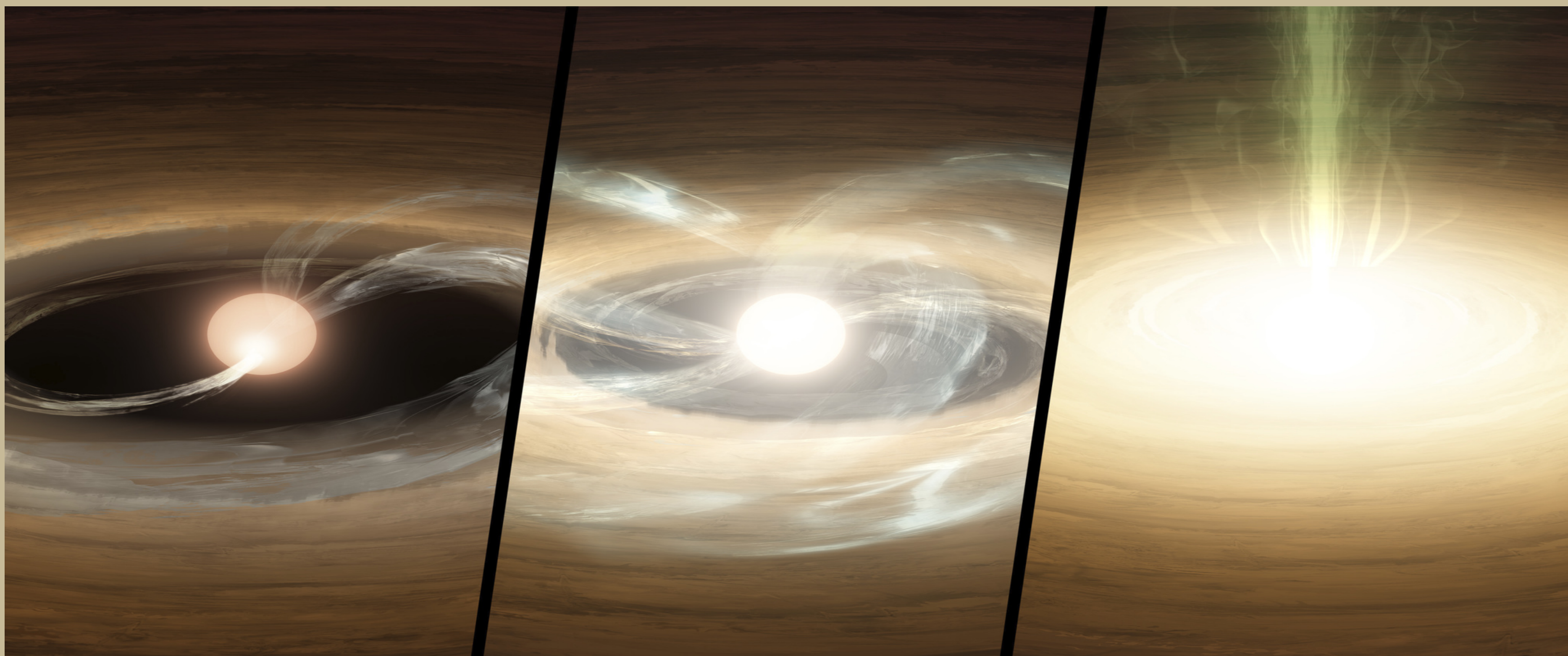


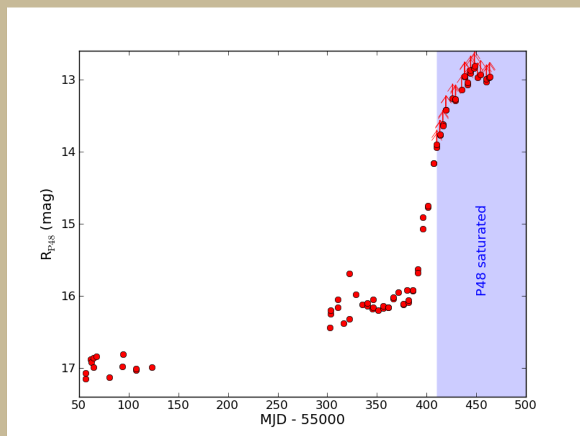
Fig. 6 Schematic model of an Exor V1647 Ori. During the outburst the accretion rate is enhanced so that the magnetospheric radius R_m decreases and the magnetic field lines were bunched (A). This results in a fast, hot outflow. As the accretion rate decreases, the disk moves outward and this results in a slower, cooler CO outflow (B). Further decrease in the accretion rate leads to a quiescence state where the production of warm outflows stops (C). From Brittain et al. (2007).

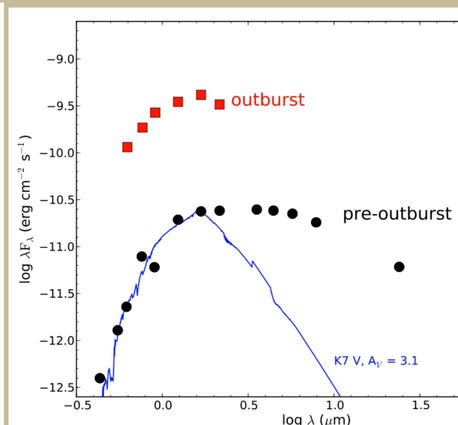
Extreme Outbursts = FU Ori Stars



Witnessing an FU Ori Outburst (PTF)

Miller et al. (2011)





PTF10qpf

=

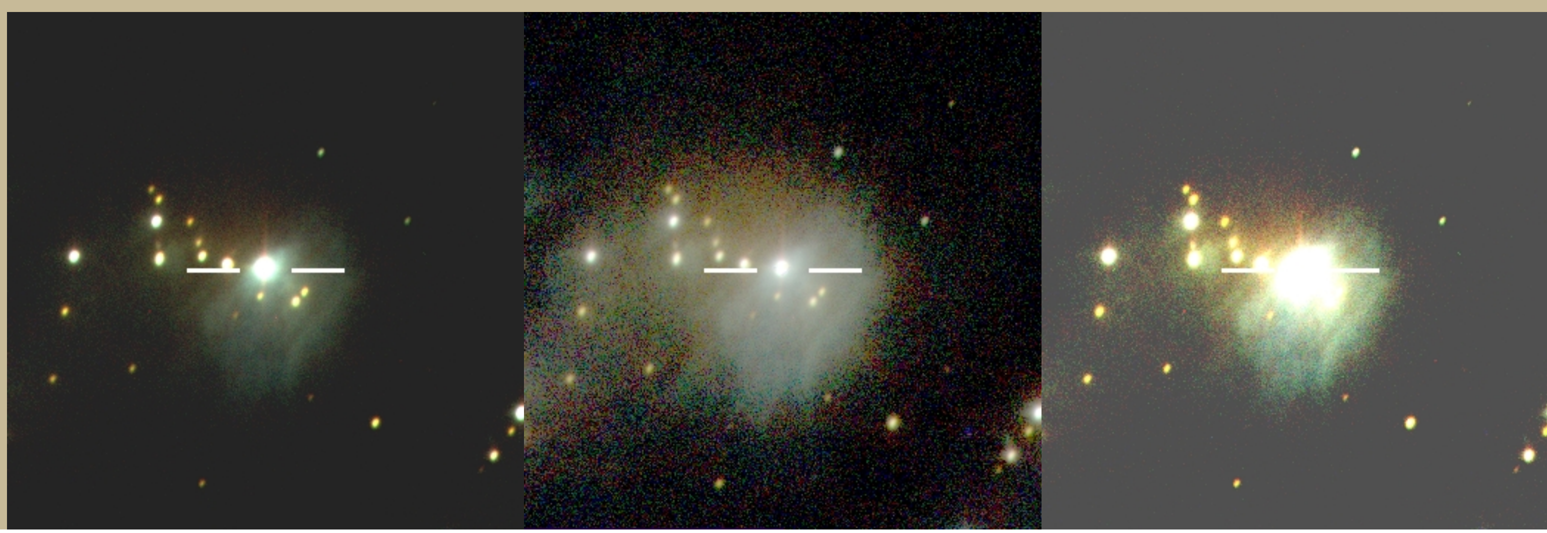
LkHa 188/G4

=

HBC 722

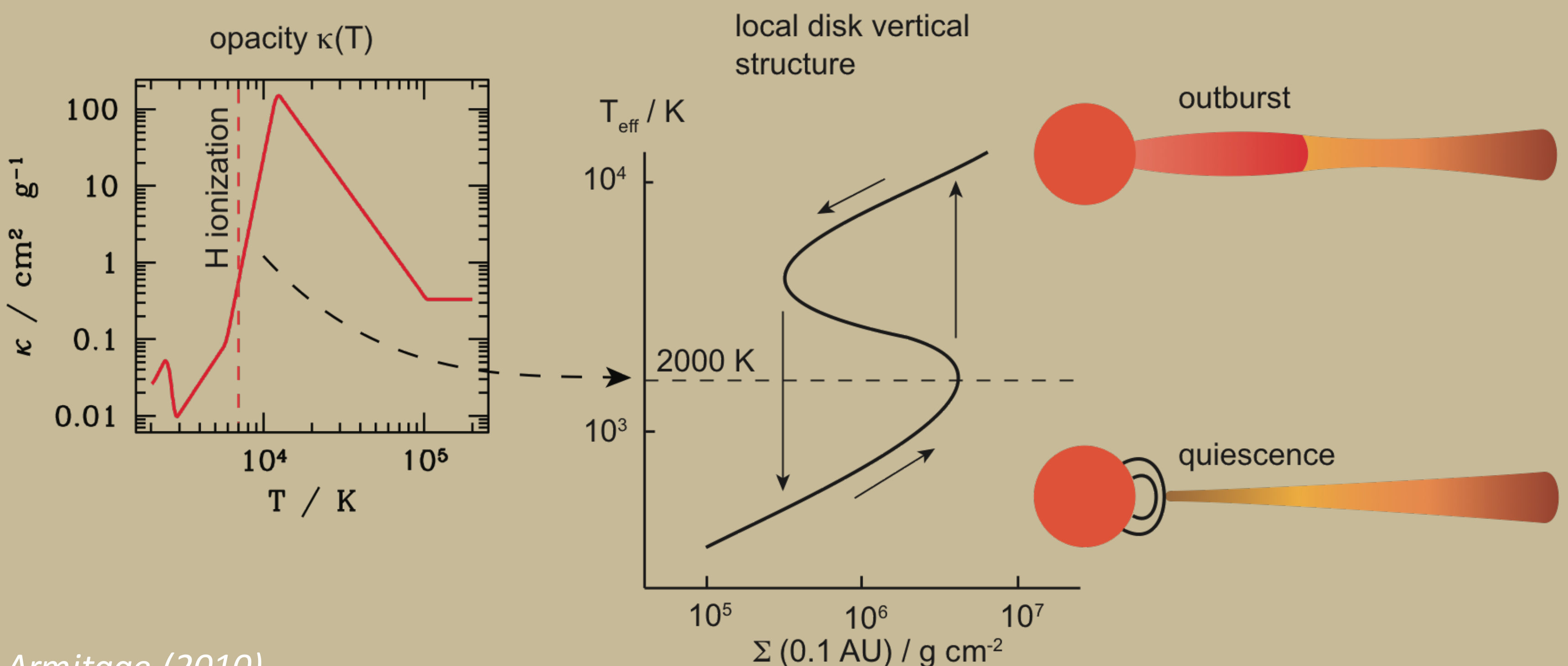
=

V 2493 Cyg



Broader Disk Instabilities

classical thermal instability driven by change in kappa e.g. Bell & Lin (1994)

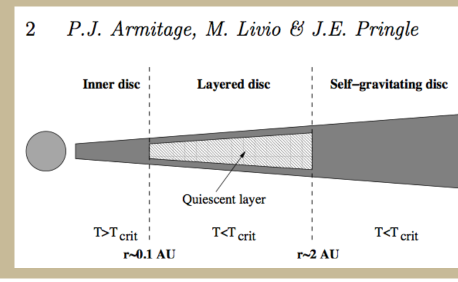


Armitage (2010)

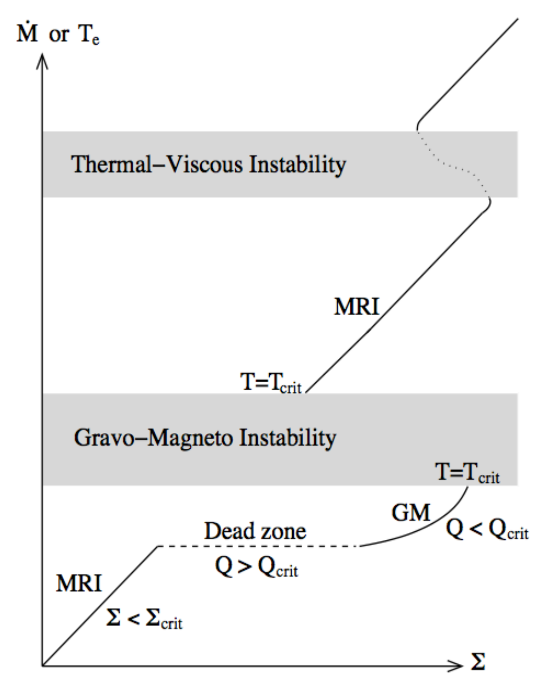
Broader Disk Instabilities

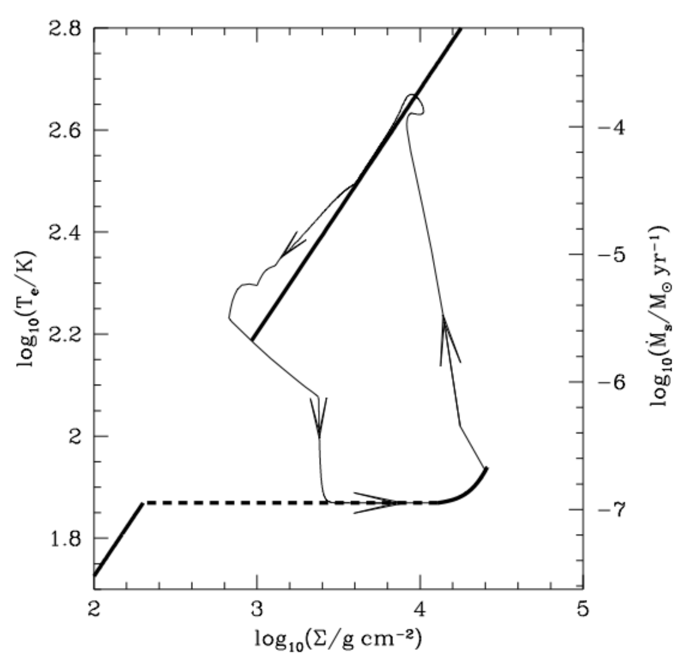
- Magneto-rotational instability, driven by
  - change in ionization e.g. Balbus & Hawley (1991)
  - change in alpha e.g. Zhu et al
- Gravitational instability driven by accumulation of mass

➔ Gravo-magneto instability studied by Martin & Lubow (2011)



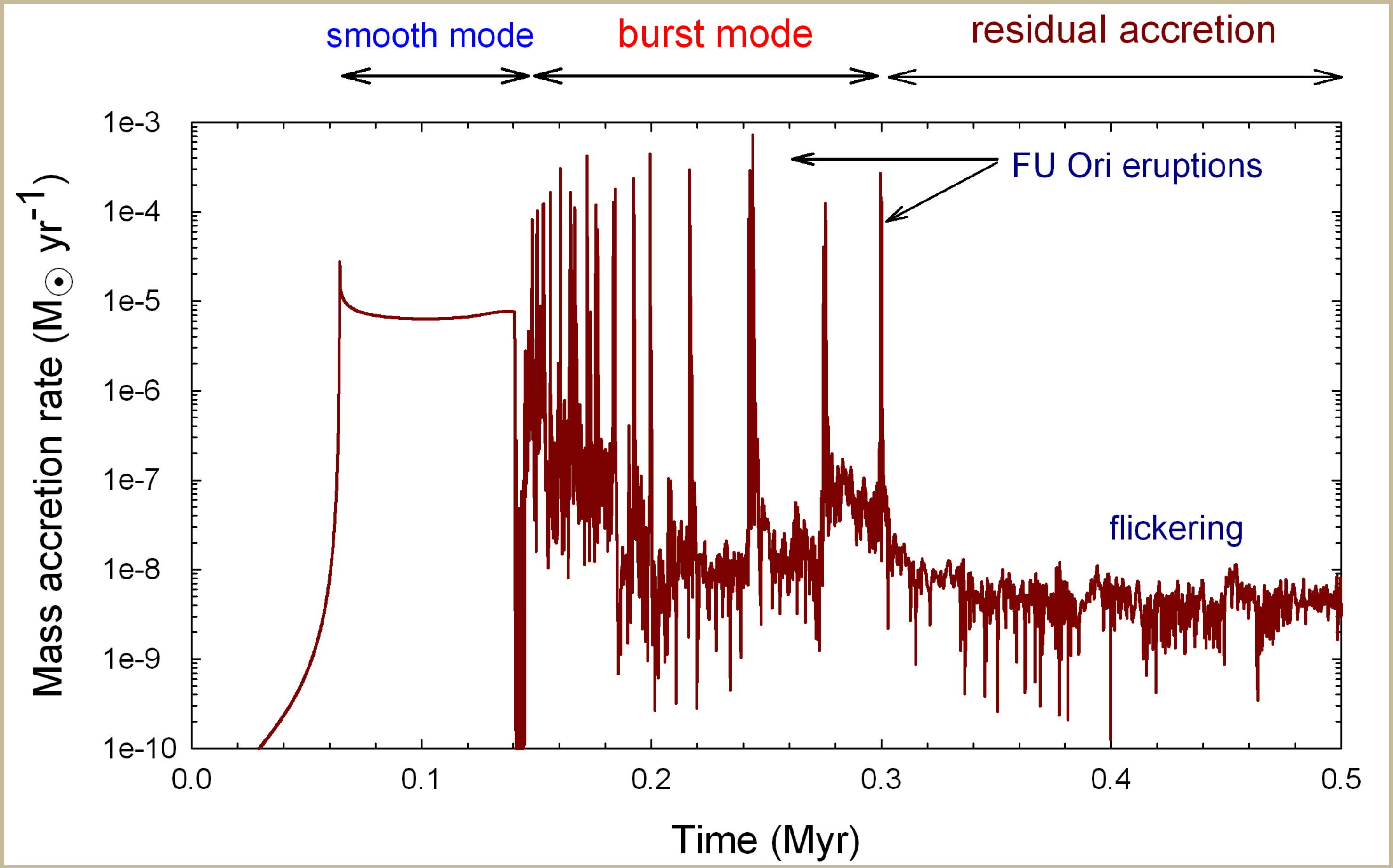
Armitage (2010)





...tic diagram of steady disk solutions in the Σ–$\dot{M}$ plane at some radius in

HOW FREQUENT ARE THE EXTREME OUTBURSTS?

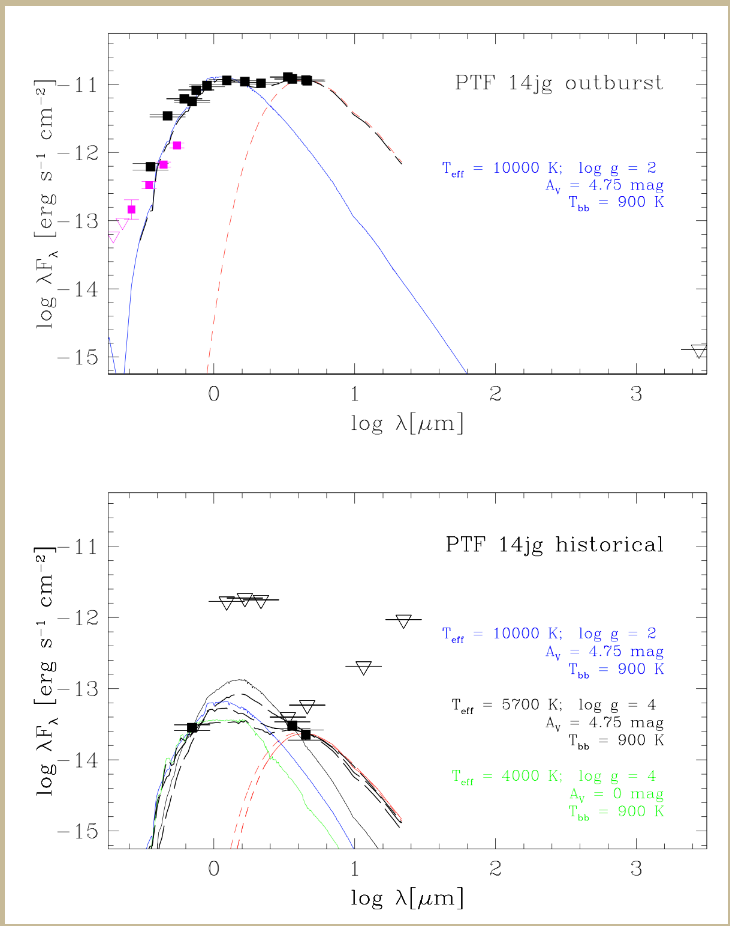


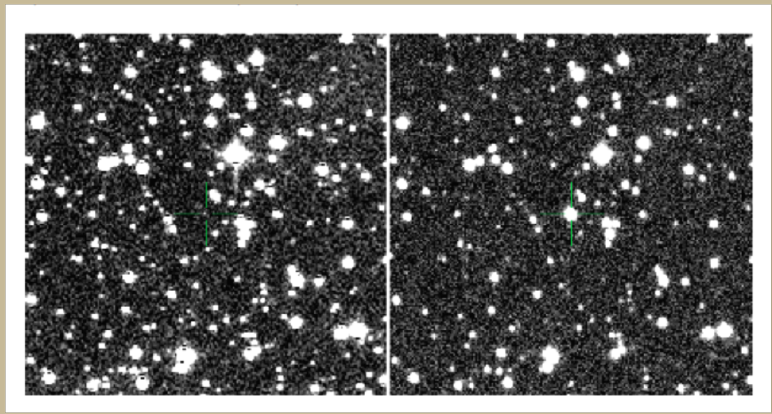
Vorobyov 2006

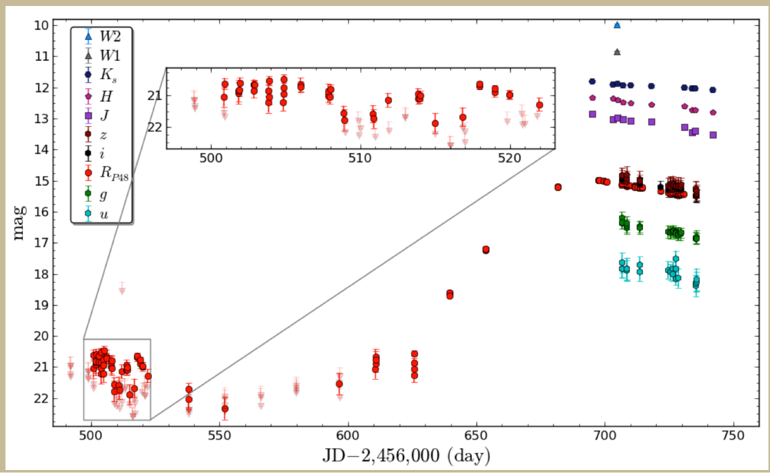
Another PTF-Discovered Likely FU Ori Event

Hillenbrand et al. (2019)

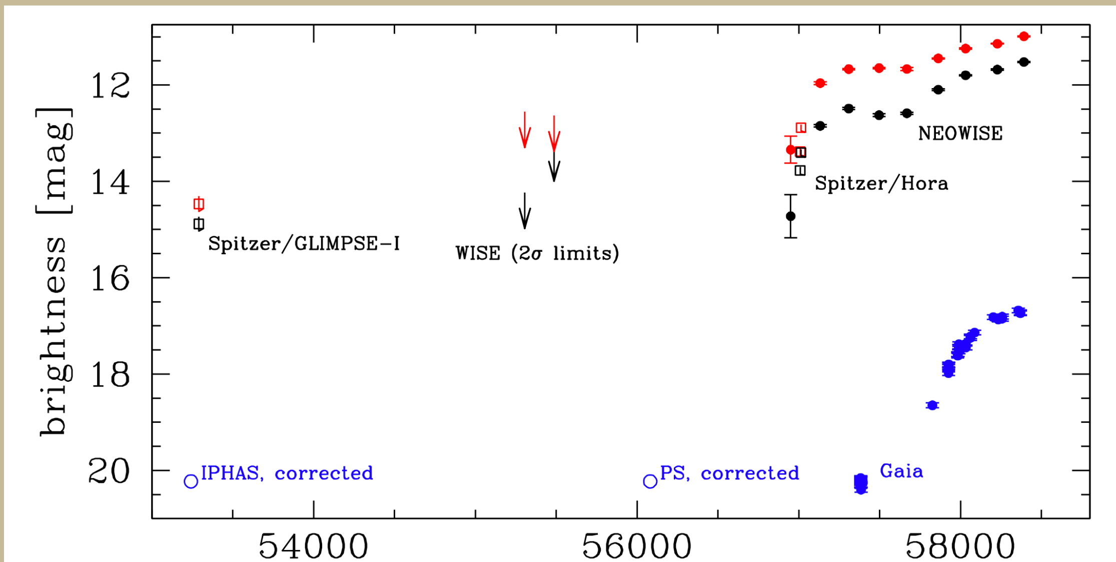
PTF14jg
(near W4 HII region)



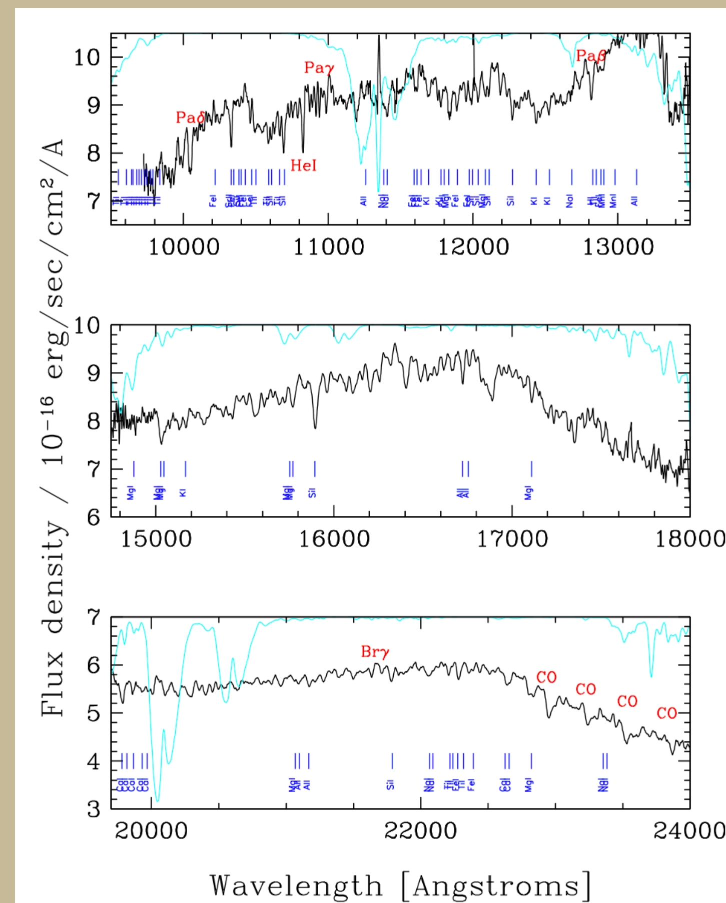


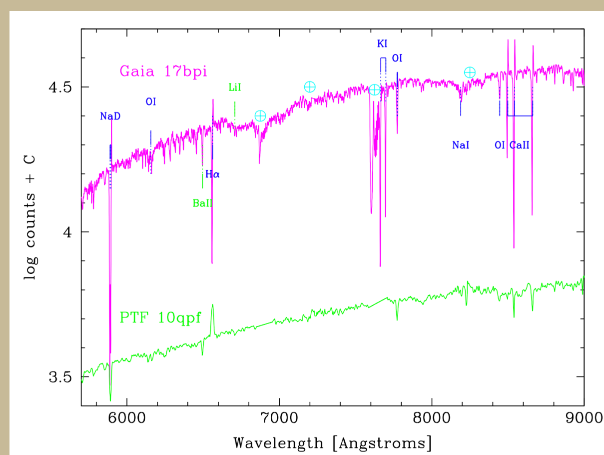


A Gaia-Discovered FU Ori Star



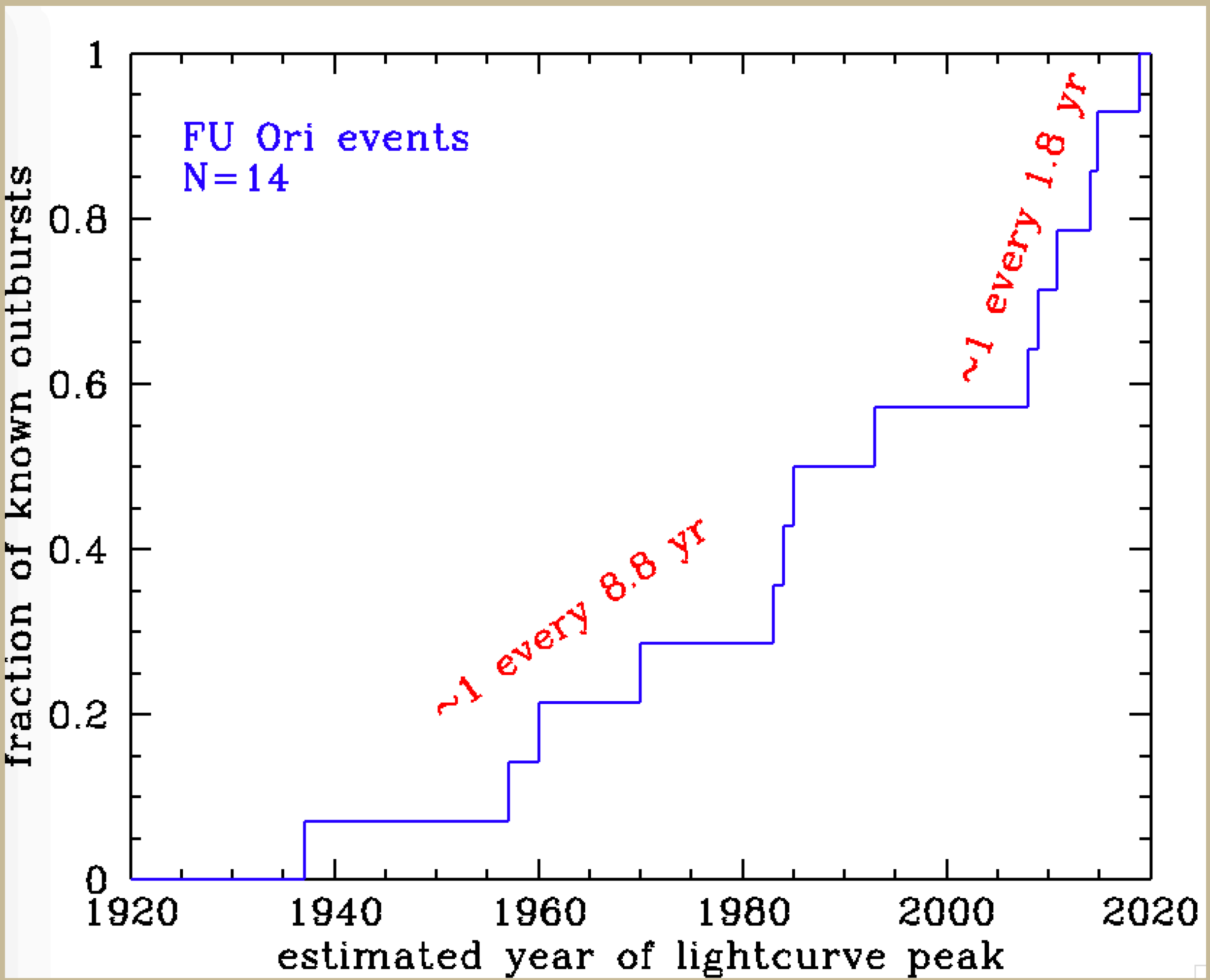
Gaia 17bpi
(in a relatively unstudied dark cloud)





Hillenbrand et al. (2018)

Extreme Outbursts – How Frequent?



Only 14 outbursts actually observed in the act (out of a total sample of only ~25 !)

- Though we appear to be getting better at noticing outbursting young stars, undoubtedly, we are not finding them all.
- In order to estimate the outburst rate – as distinct from the detection rate -- we need to understand our efficiency (or better stated, inefficiency).
- Rate estimation is difficult without more complete young star census information.

Compare to the Even More Intrinsically Rare Tidal Disruption Events

Theory:

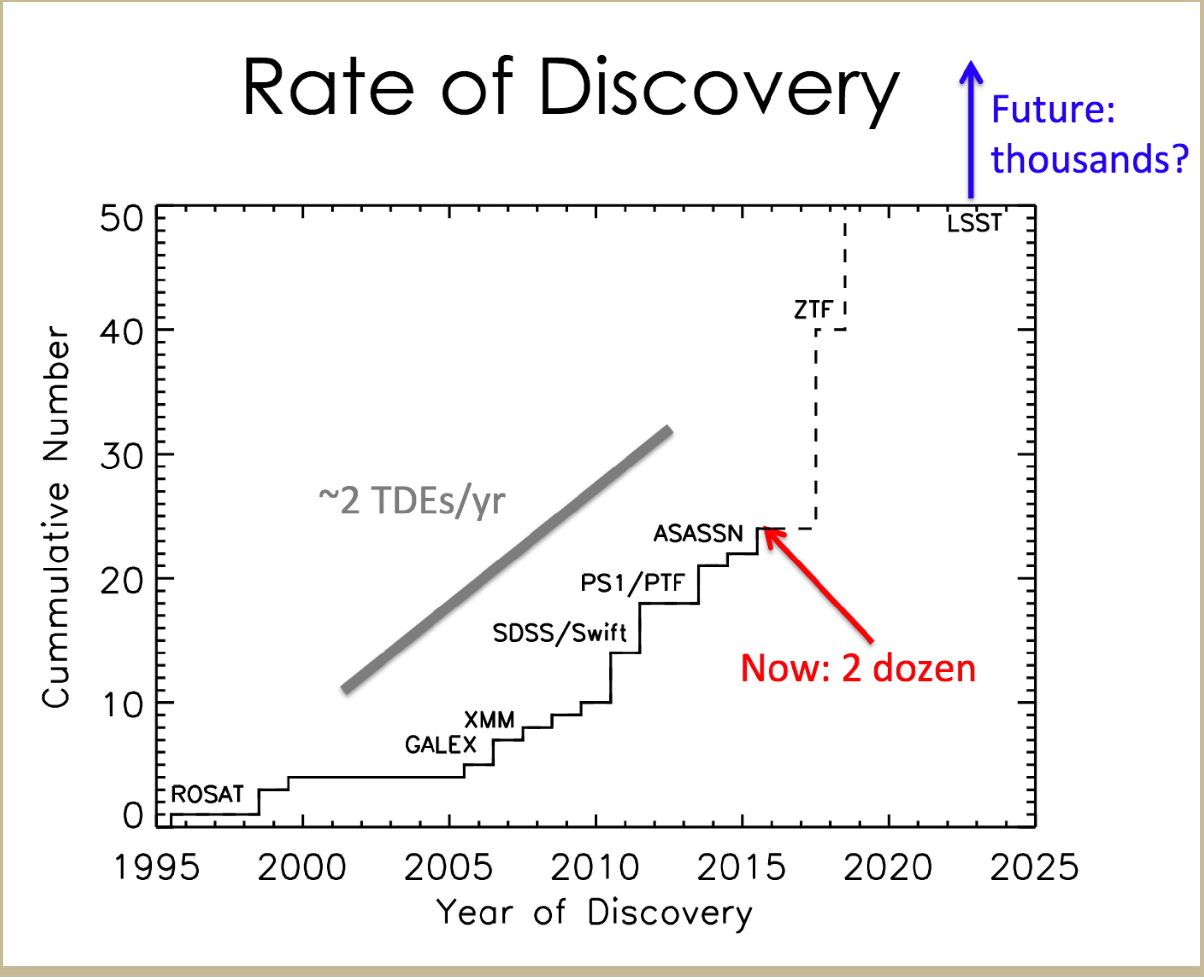
$\sim 10^{-5}$ to 10^{-4} / year / galaxy

Current Census:

~45

Young star researchers should be embarrassed!

plot from S. Gezari



Constraining the Rate of FU Orionis Outburst Events

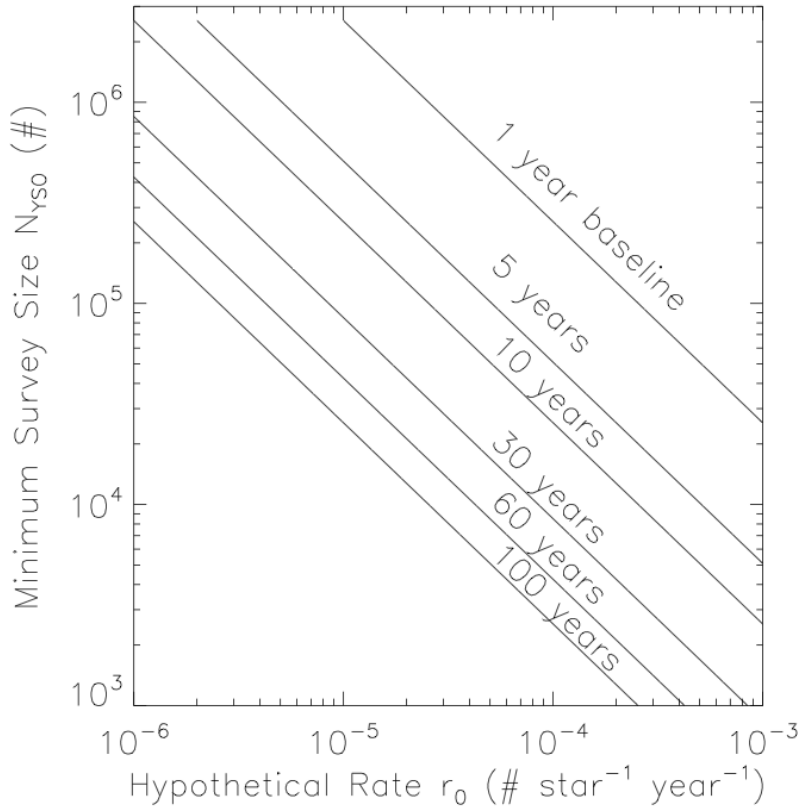


FIG. 2.— The survey size needed to have a 90% chance of constraining the outburst rate to a factor of 2 at 90% confidence, as a function of the true outburst rate r_0 (abscissa) and the time baseline (labels). One may reduce the needed survey size by choosing a longer time baseline, by admitting higher uncertainty than a factor of 2, or by requiring a lower confidence than 90%.

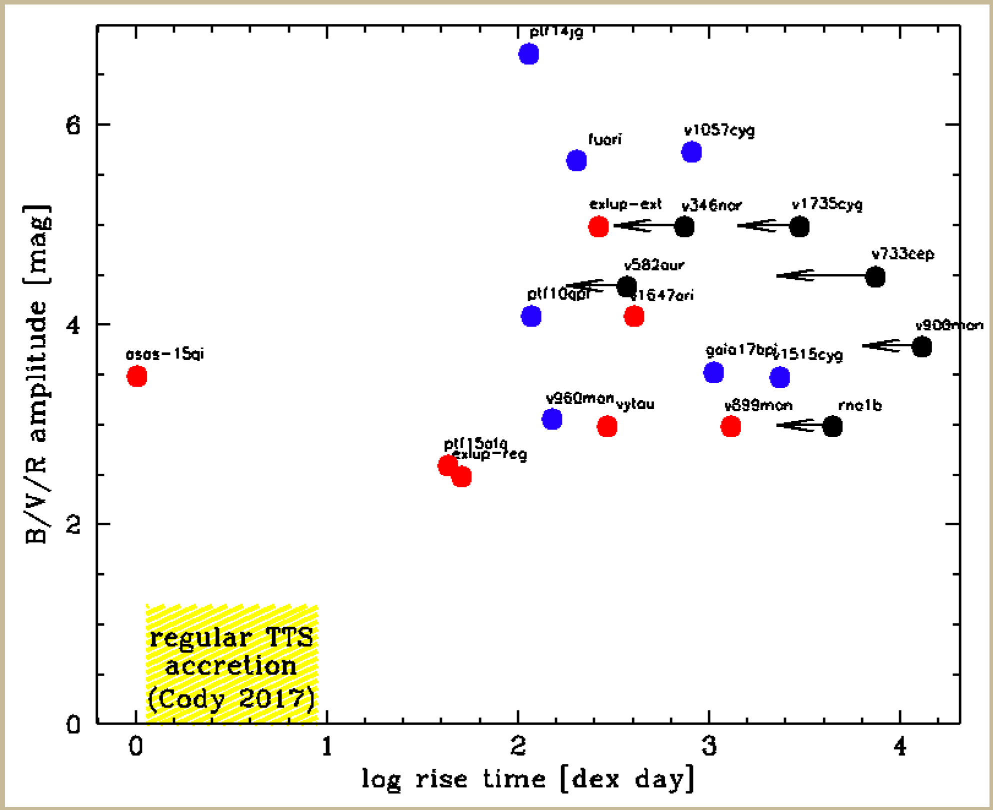
Need to know the numerator.

Need to know the denominator.

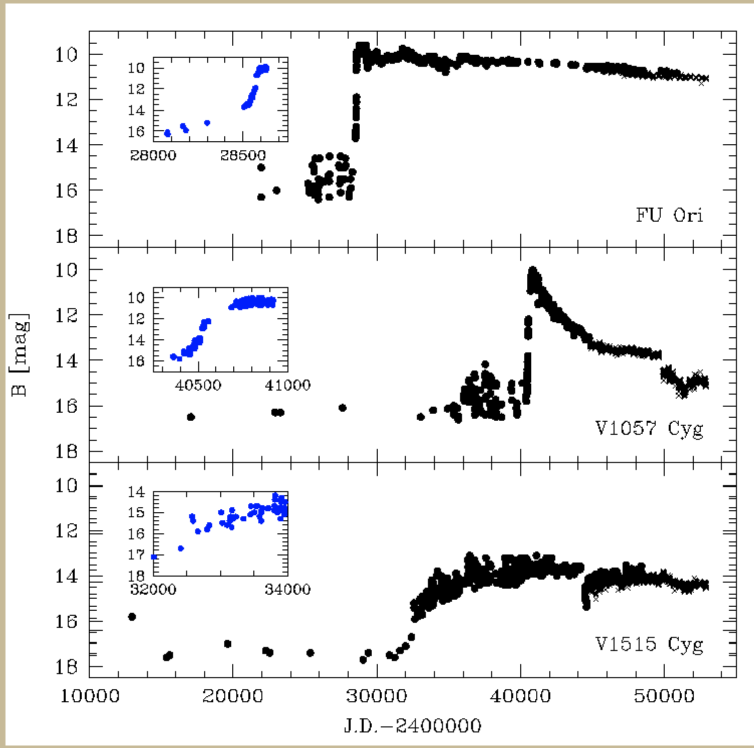
Need to have enough stars for meaningful statistics!

Hillenbrand and Findeisen (2015)

How Can we Recognize True FU Ori Events
vs
other Types of Young Star Outbursts ?



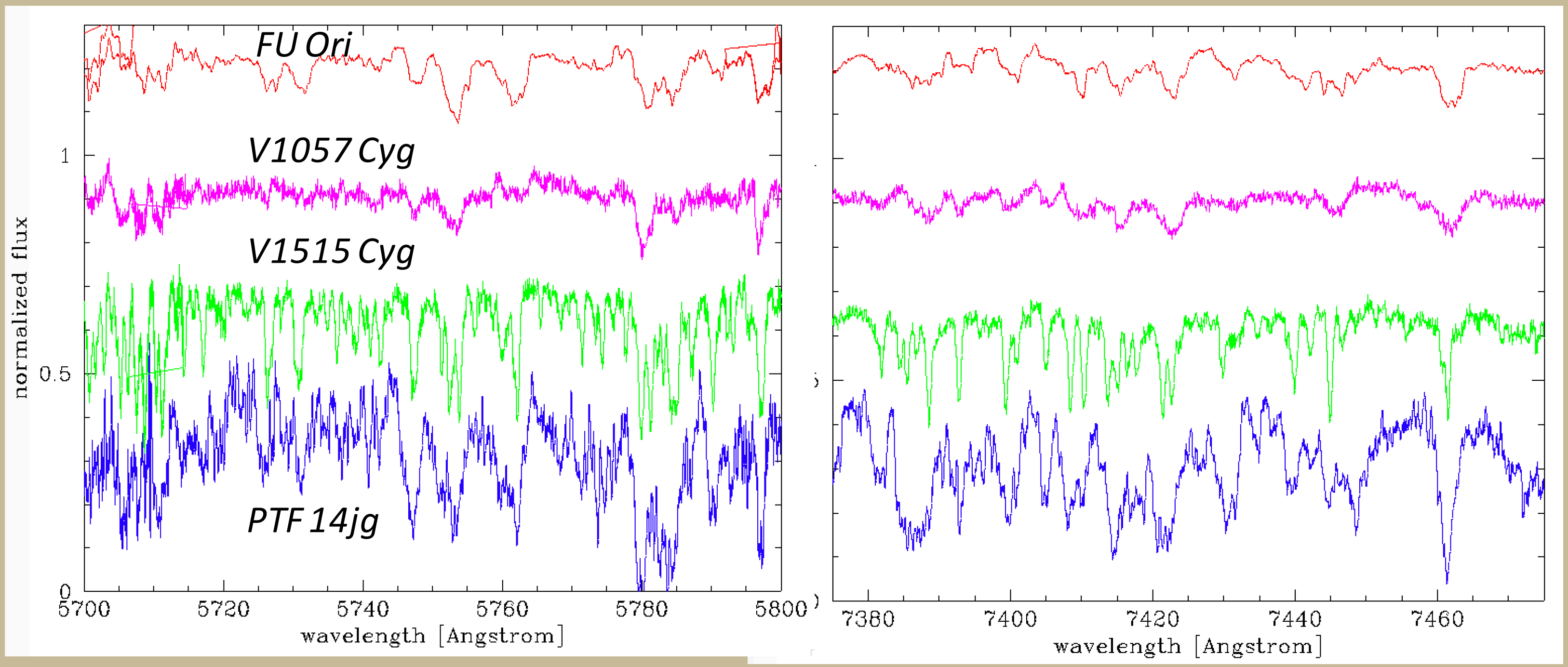
Hillenbrand (2019)



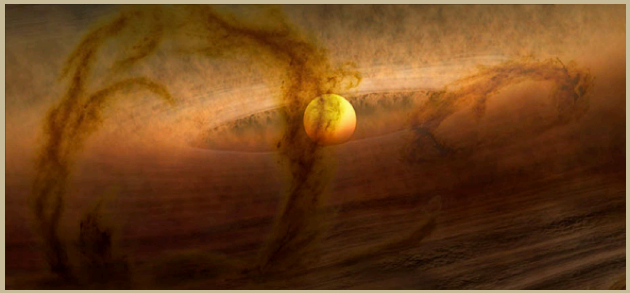
Measuring the duration of an outburst usually requires impatient people to wait….
- G. Herczeg

How Can we Recognize True FU Ori Events vs other Types of Young Star Outbursts ?

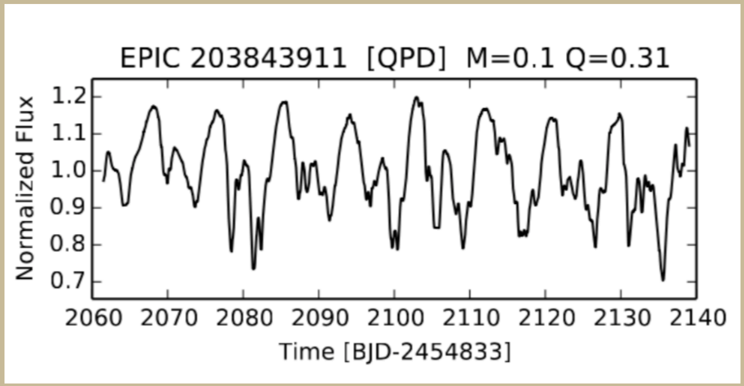
High Dispersion SPECTRA ➔ disk photosphere (composite, not single-temperature)

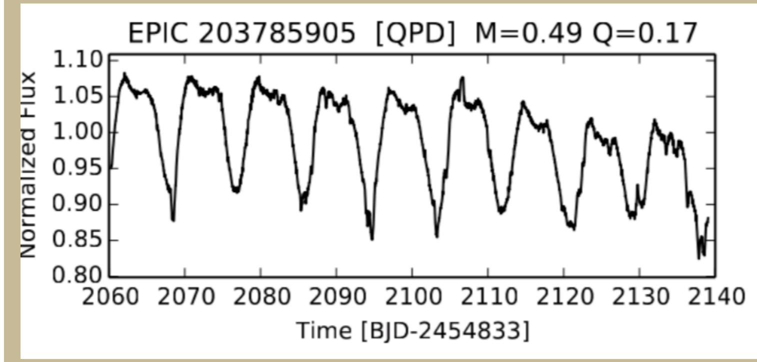


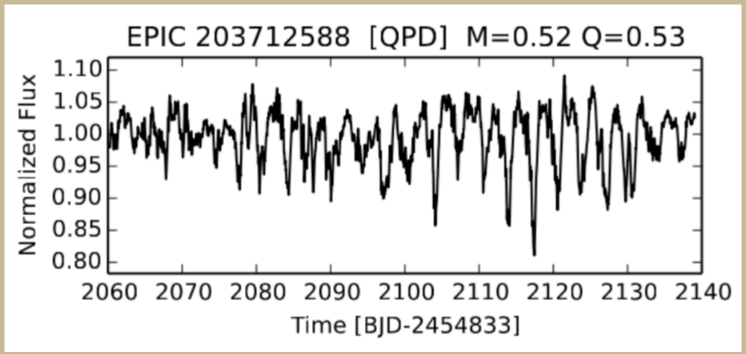
VARIABLE PHOTOMETRY: EXTINCTION-DRIVEN BEHAVIOR

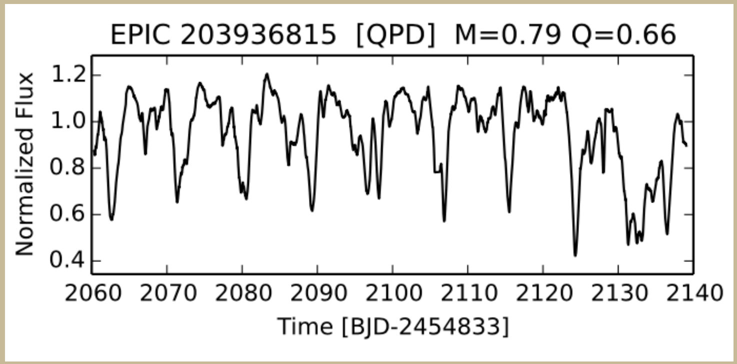


[Cody et al. 2018]





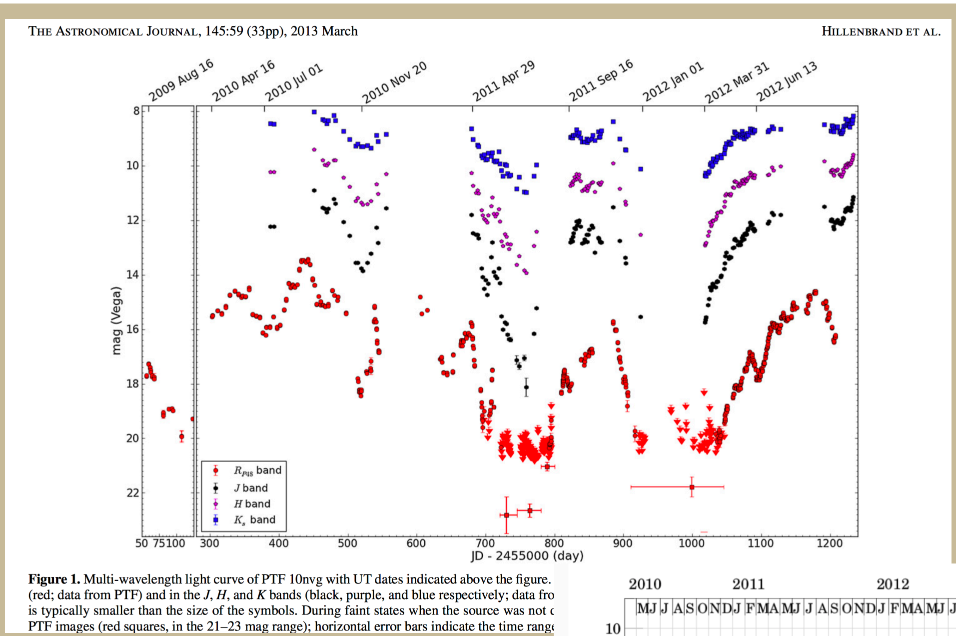




33% of the objects with disks exhibit with these types of lightcurves

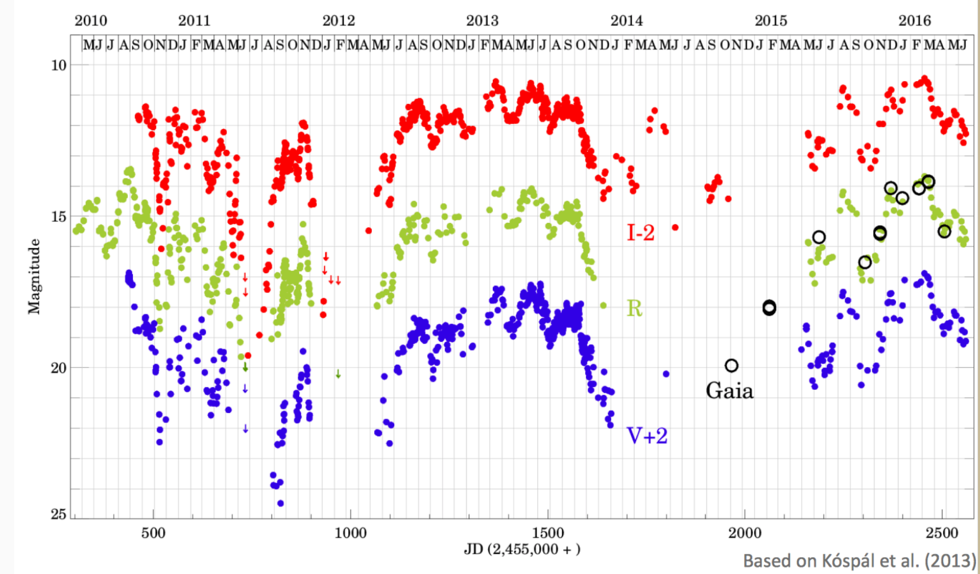
EXTREME EXTINCTION

Long-duration fades of 5-7 mag!



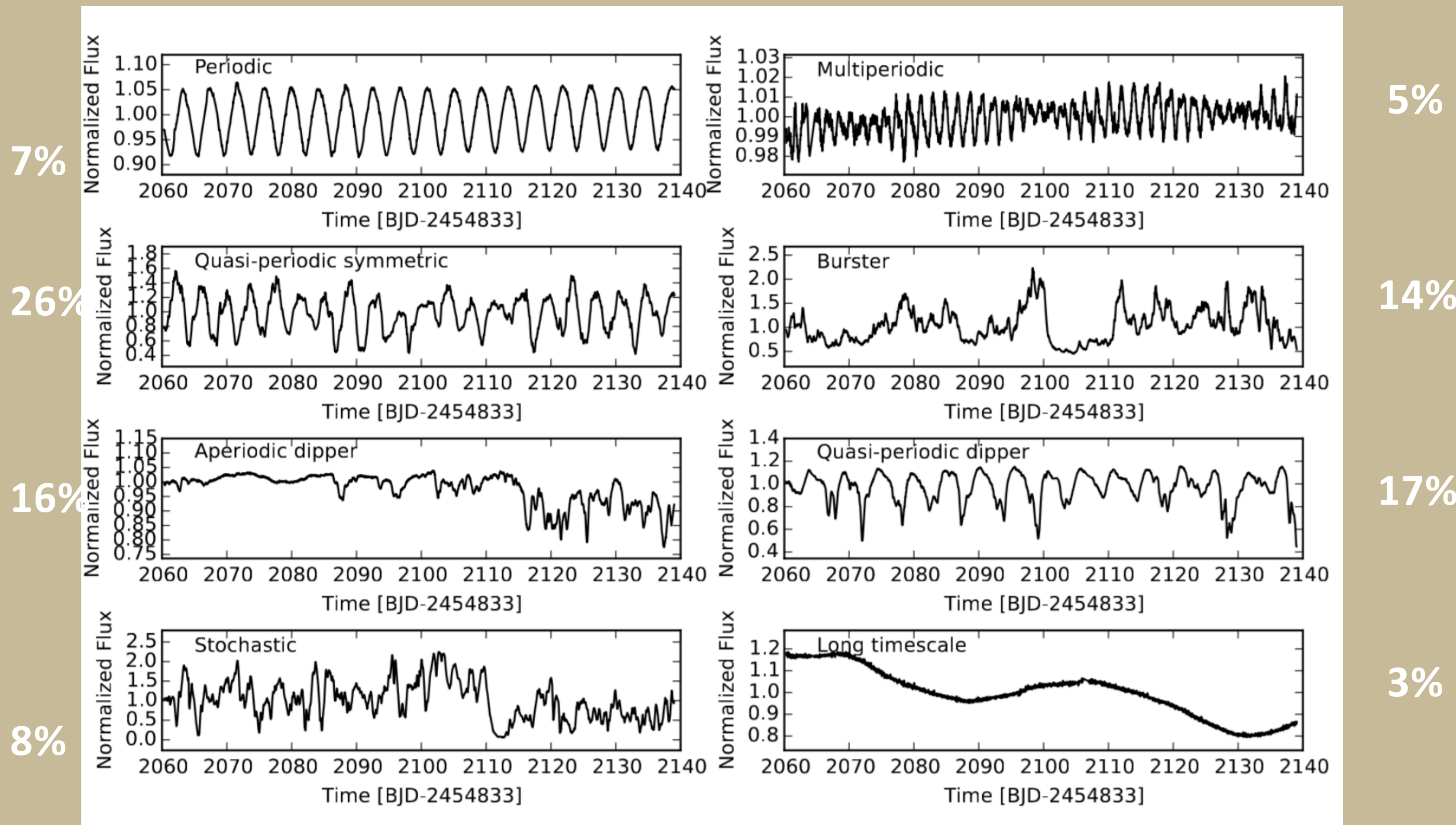
Catching this repeating cycle in a rising part of the phase might cause incorrect interpretation as an outburst event.

(see Gaia data points)



Ágnes Kóspál: Observational properties of outbursting sources

LIGHTCURVE MORPHOLOGY CLASSIFICATION



Cody and Hillenbrand

LIGHTCURVE MORPHOLOGY CLASSIFICATION

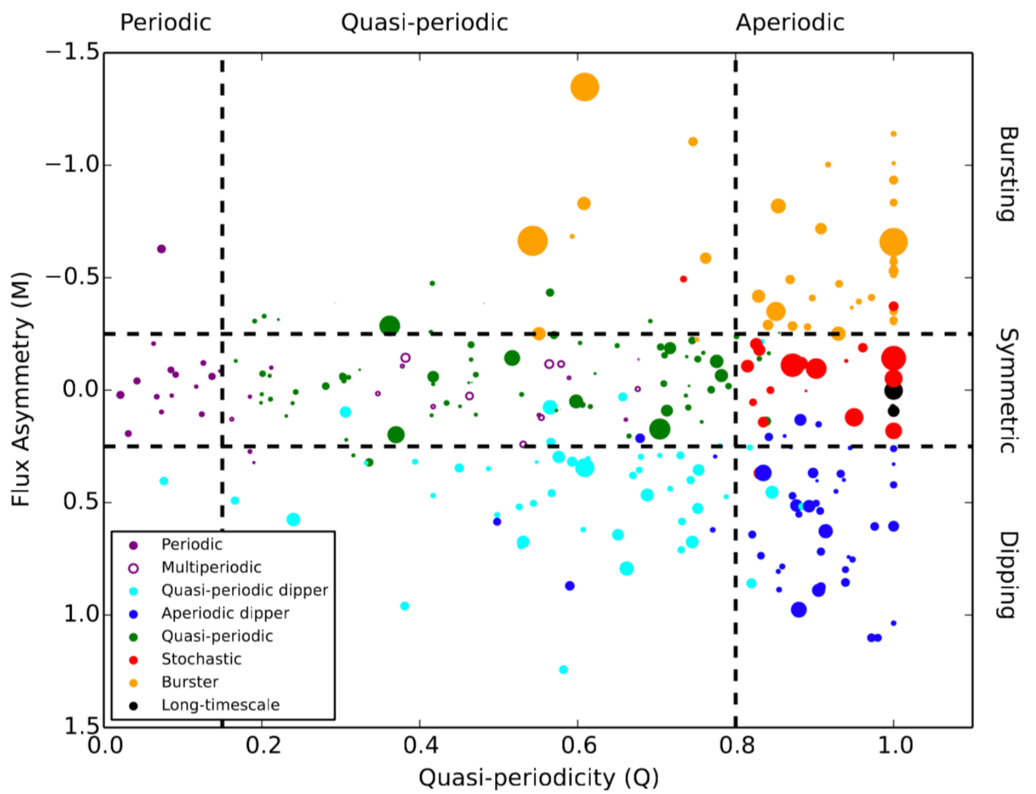
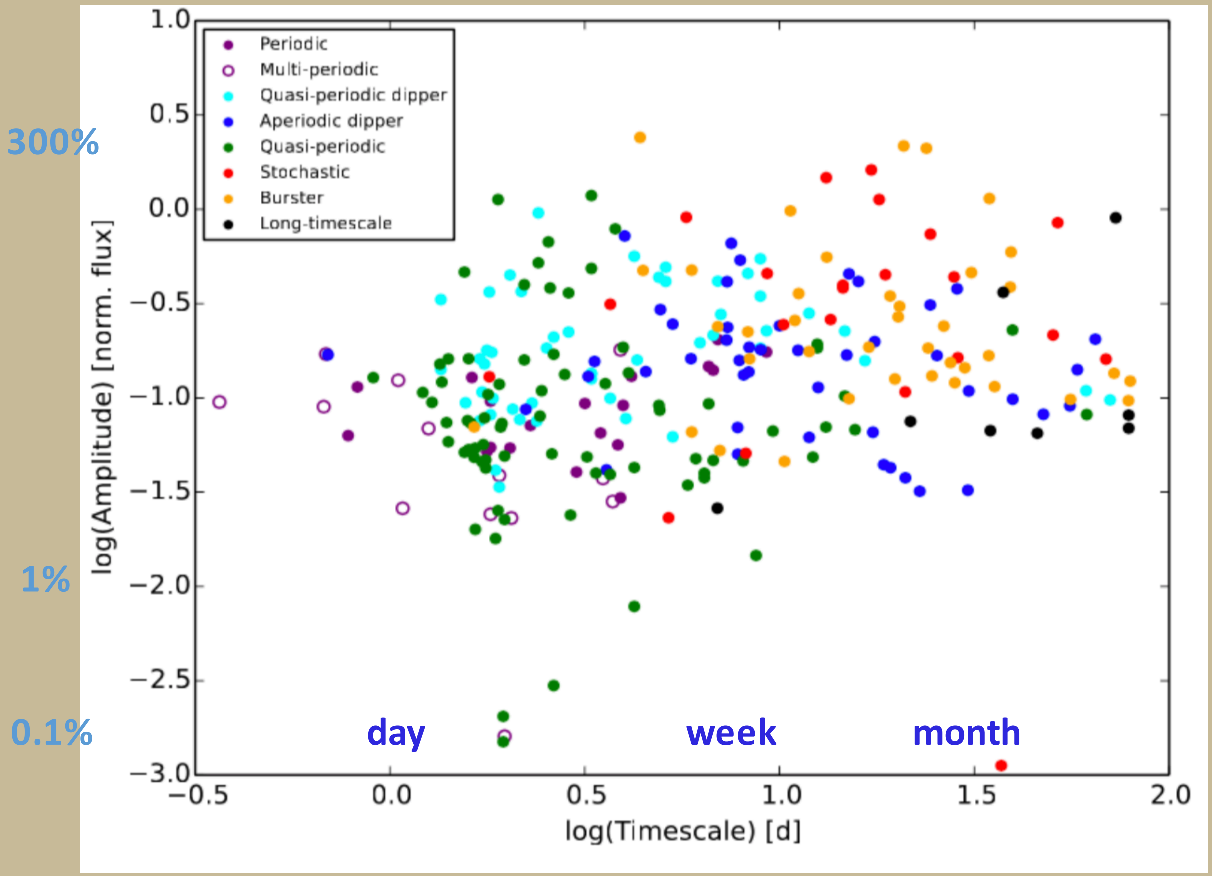


FIG. 6.— Q and M statistics for our sample of disk-bearing stars in Upper Scorpius and ρ Ophiuchus. Colors denote different types of variables, as identified by eye. Non-variable objects are excluded. Point sizes in this and subsequent plots are scaled according to variability amplitude.

Cody and Hillenbrand (2018)

TIMESCALES AND AMPLITUDES



Cody and Hillenbrand (2018)

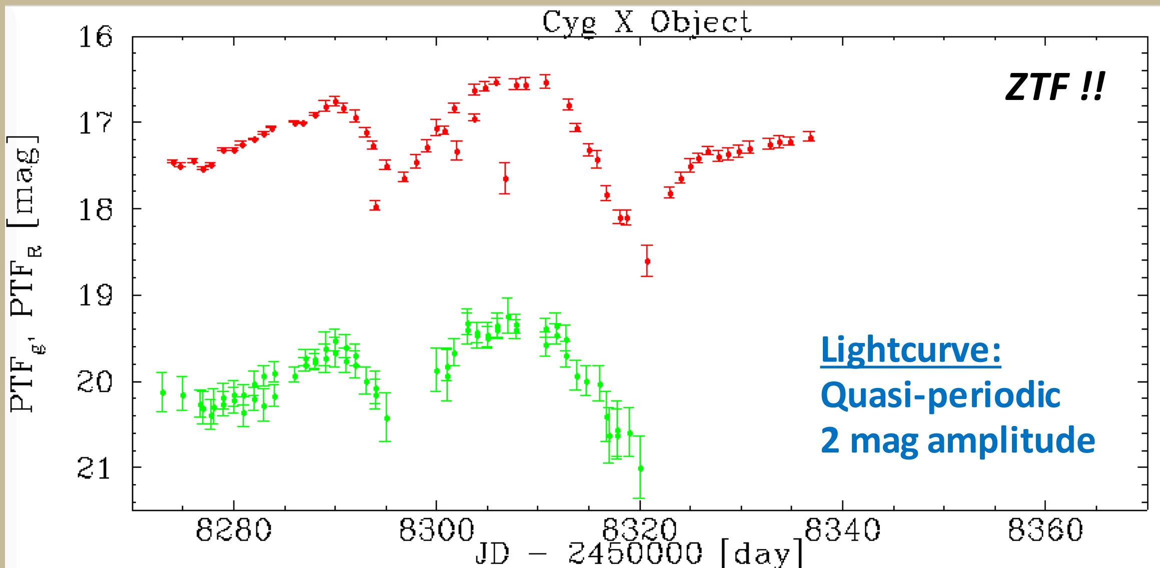
<u>Amplitude</u> ranges of most disk categories are similar.

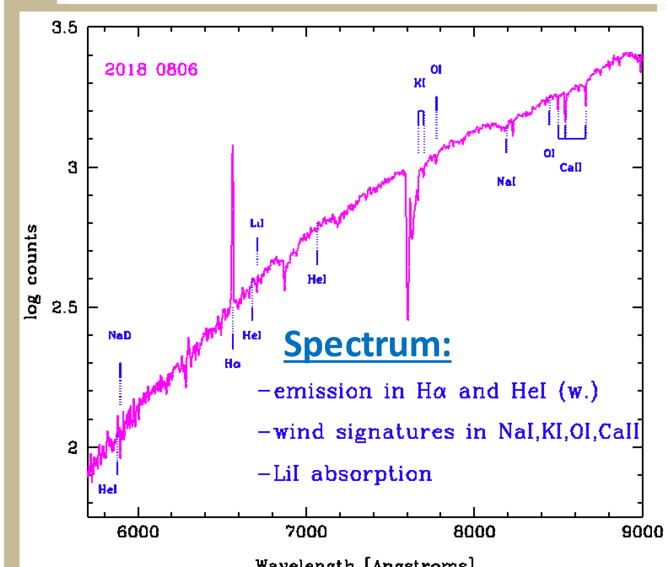
<u>Timescales</u> vary, however:

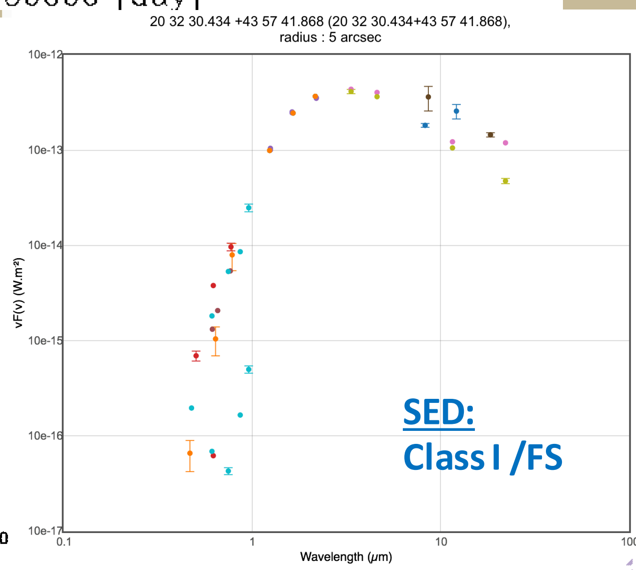
Long = Bursters, Stochastics
Aperiodic Dippers

Int = Quasi-periodic Dippers
Quasi-periodic Symm.

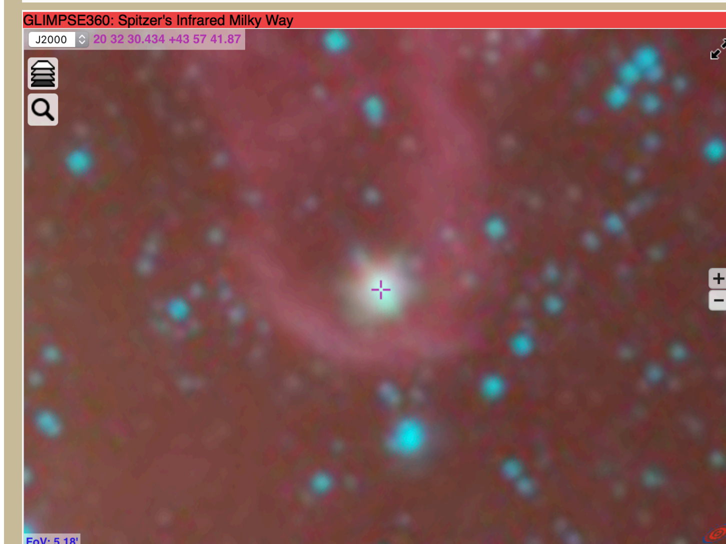
Short = Periodic
Multi-Periodic


Cyg X Object
ZTF !!
Lightcurve:
Quasi-periodic
2 mag amplitude
PTF_g' PTF_R [mag]
16
17
18
19
20
21
8280
8300
8320
8340
8360
JD − 2450000 [day]

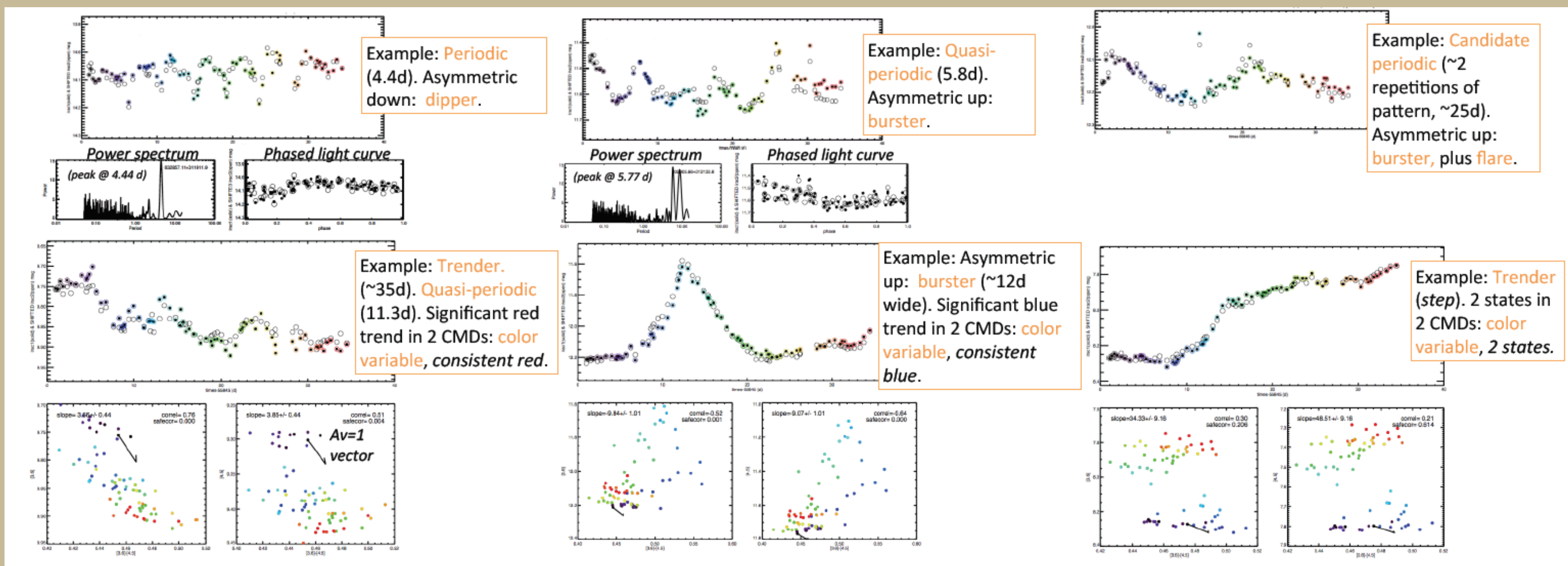

2018 0806
Spectrum:
−emission in Hα and HeI (w.)
−wind signatures in NaI,KI,OI,CaII
−LiI absorption
NaD
HeI
Hα
LiI
HeI
KI
OI
NaI
CaII
log counts
Wavelength [Angstroms]
6000
7000
8000
9000
2
2.5
3
3.5

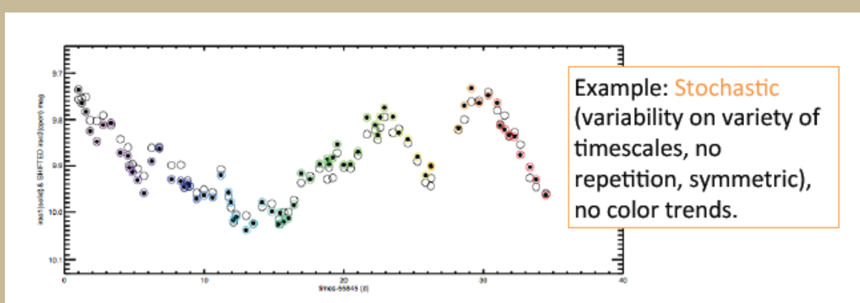

20 32 30.434 +43 57 41.868 (20 32 30.434+43 57 41.868),
radius : 5 arcsec
SED:
Class I /FS
νF(ν) (W.m²)
Wavelength (μm)
10e-12
10e-13
10e-14
10e-15
10e-16
10e-17
0.1
1
10
100


GLIMPSE360: Spitzer's Infrared Milky Way
J2000
20 32 30.434 +43 57 41.87
FoV: 55.75'


GLIMPSE360: Spitzer's Infrared Milky Way
J2000
20 32 30.434 +43 57 41.87
FoV: 5.18'

Infrared Variability Too (Spitzer)





[*Rebull et al 2014, 2015*]

~50% of identified variables also vary in color

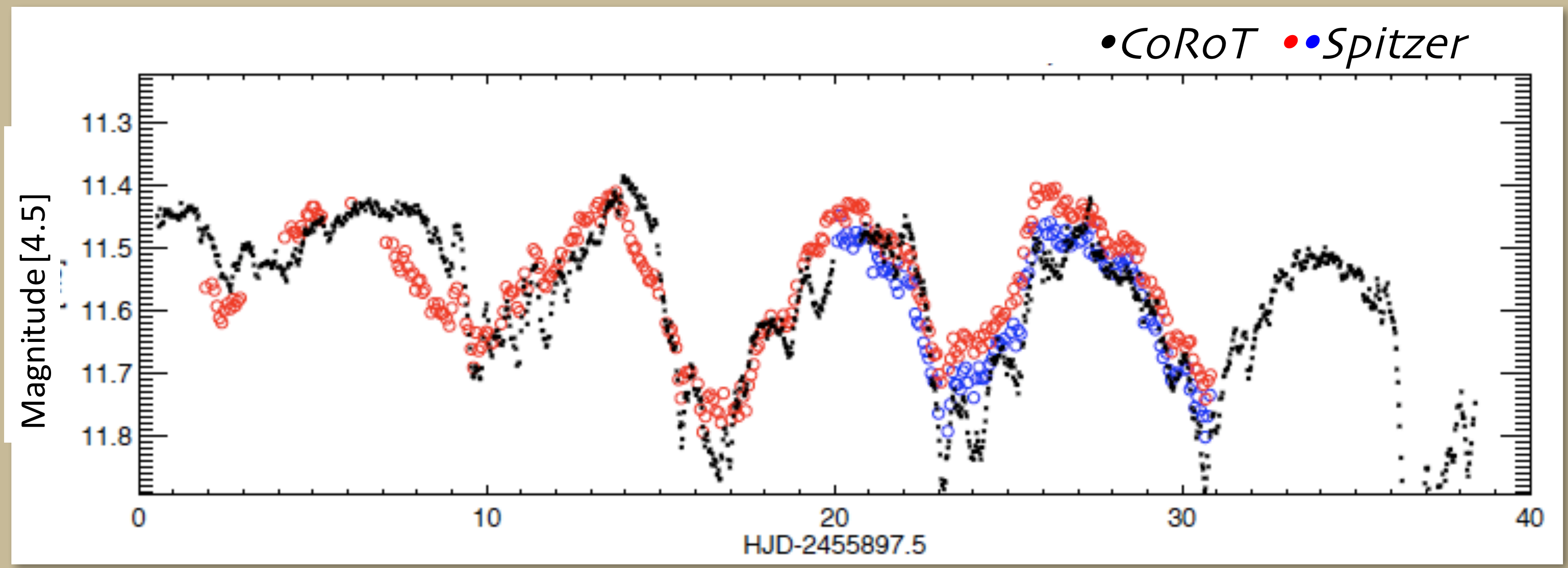
~33% are periodic

~25% "dip" and ~25% "burst"

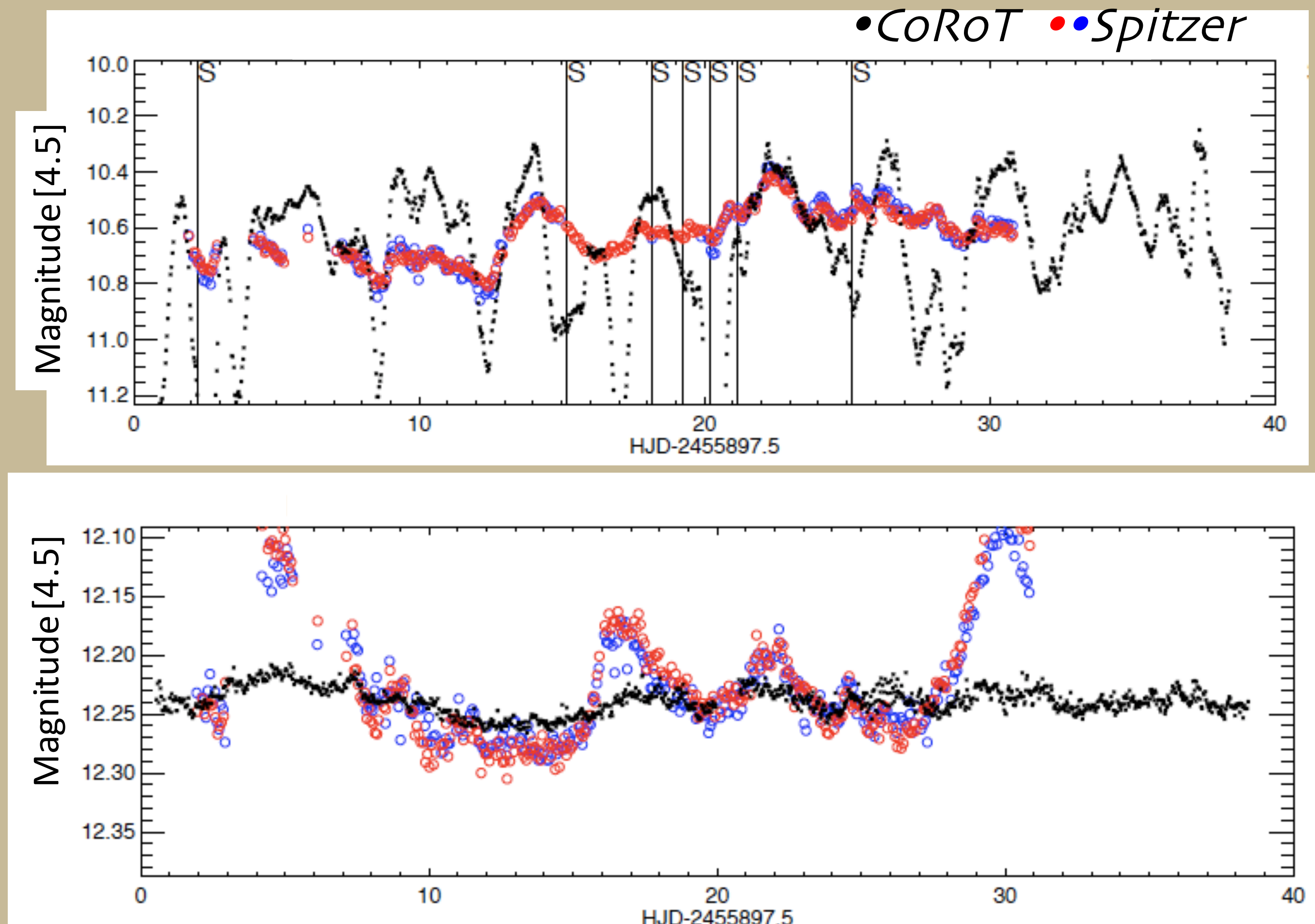
~50% "trend" over a month

~20% "stochastic"

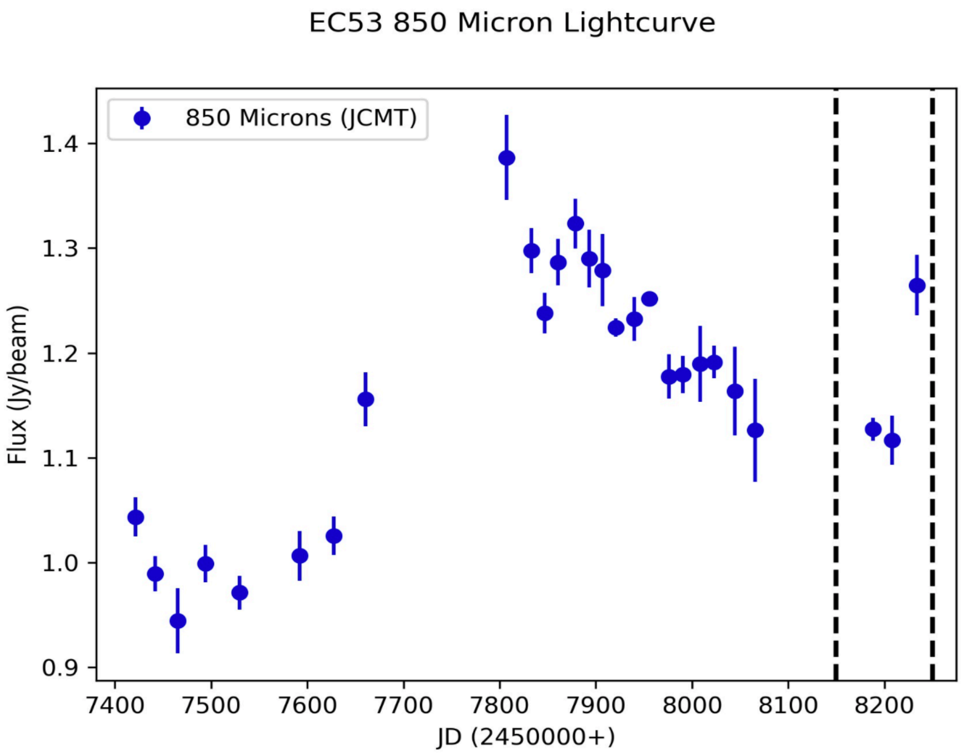
Optical and Infrared Sometimes Quite Similar



Sometimes Very Different



Even Sub-millimeter Variability is Observed!



The 850 micron light curve of EC 53 obtained by the Submillimetre COmmon User Bolometer Array 2 (SCUBA-2) at the JCMT. The dashed lines show the x-axis boundaries for the infrared data presented below. For more information about the variability of EC 53, see **Hodapp et al. 1996, ApJ: 468:861**, **Hodapp et al. 2012, ApJ: 744:56**, **Yoo et al. 2017, ApJ: 849:69**, and **Mairs et al. 2017, ApJ: 849:107**. For more information about the Transient Survey and how this light curve was generated, see **Herczeg et al. 2017, ApJ: 849:43**, **Mairs et al. 2017, ApJ: 843:55**, and **Johnstone et al. 2018, ApJ: 854:31**.

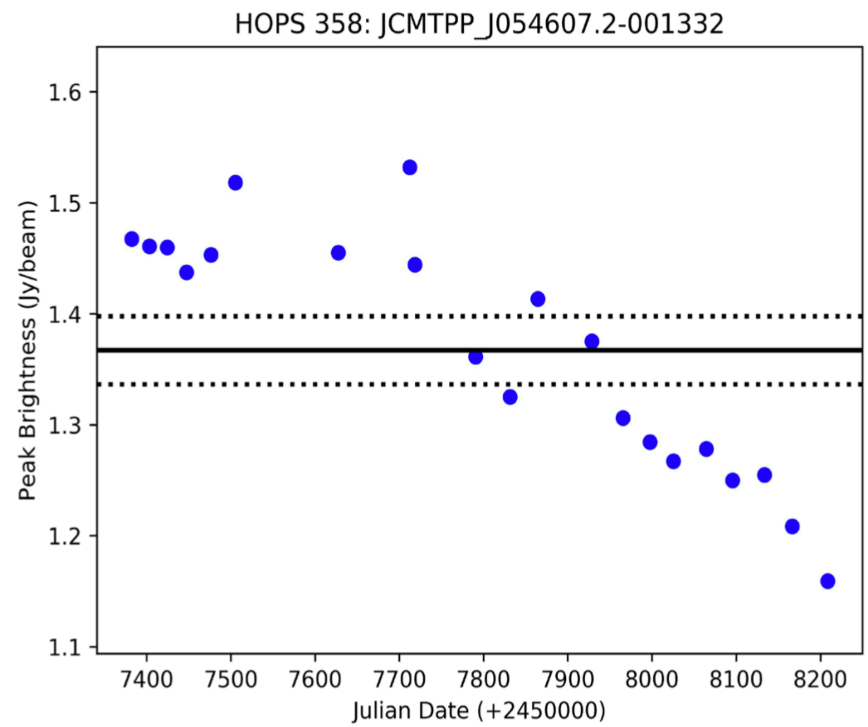
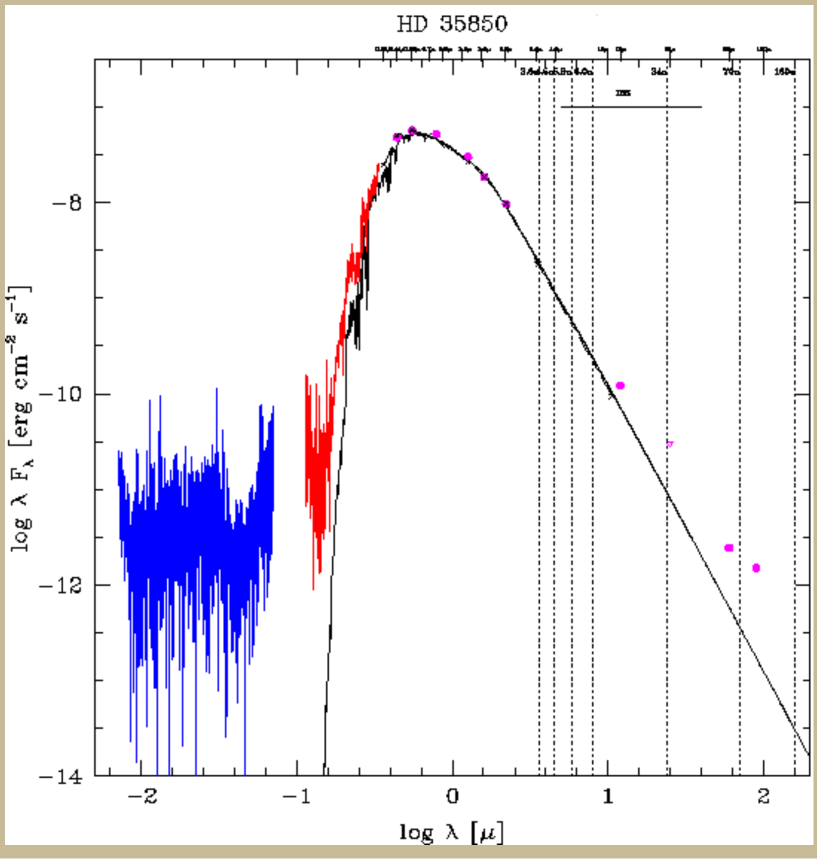
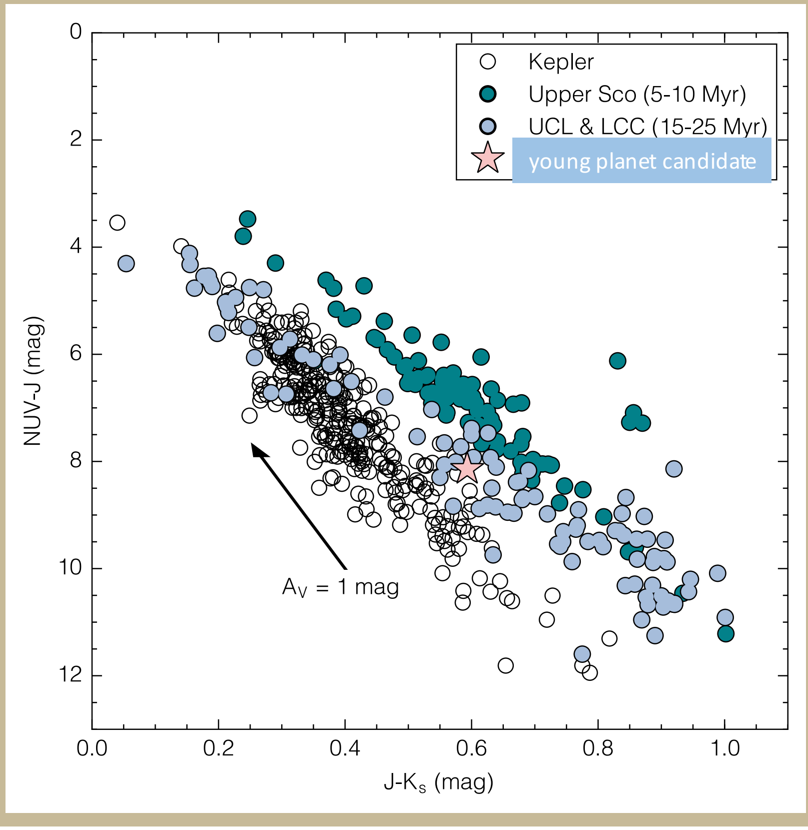


Figure 17. Secular Variables. Linear fits are performed for light curves and the significance of their slopes are tested by team members. HOPS 358 was the subject of a recent ATel released by the Transient Team (see text).

Post-Accretion Pre-Main Sequence Star SED



NUV excess ==> stellar youth up to ~100 Myr



Much larger ultraviolet variabiliy amplitudes compared to regular active late-type stars in the field (2-800x).

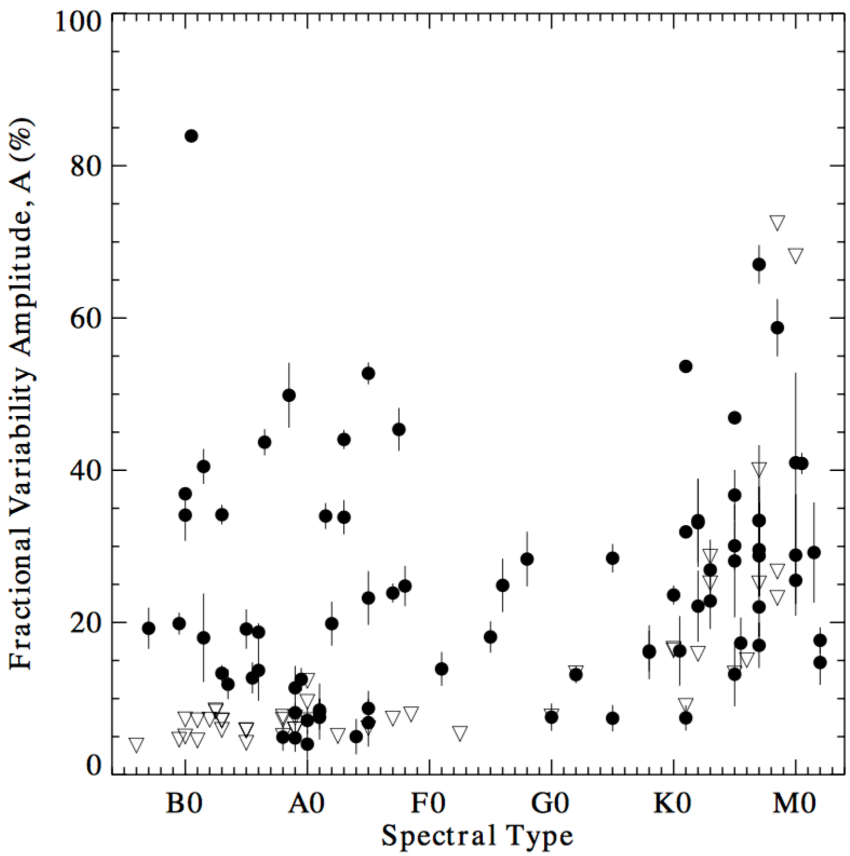
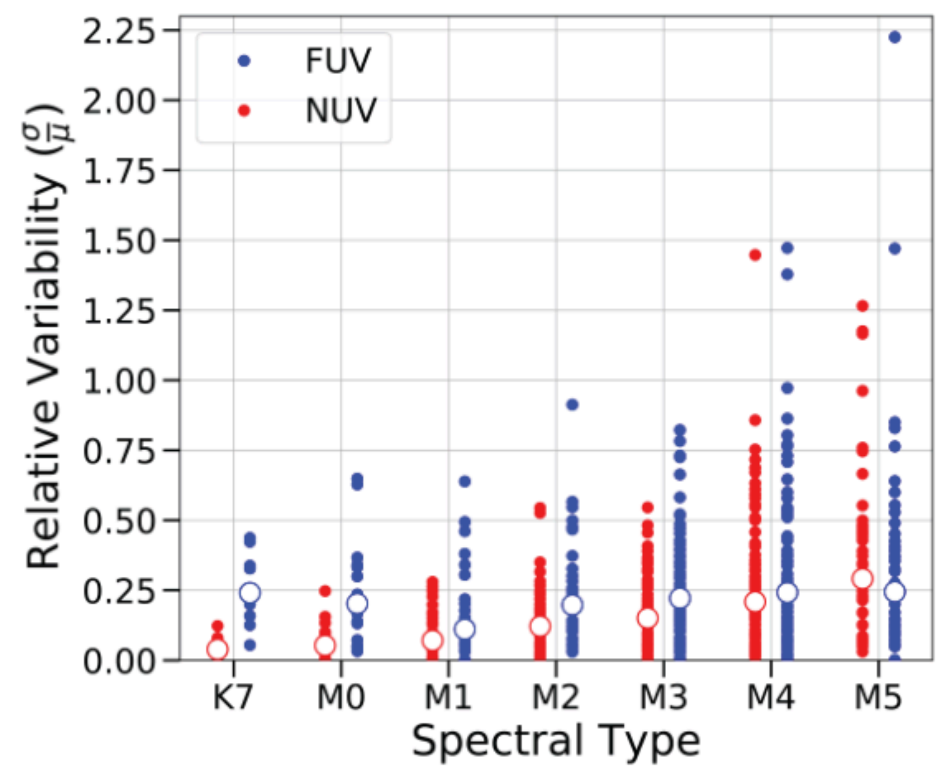
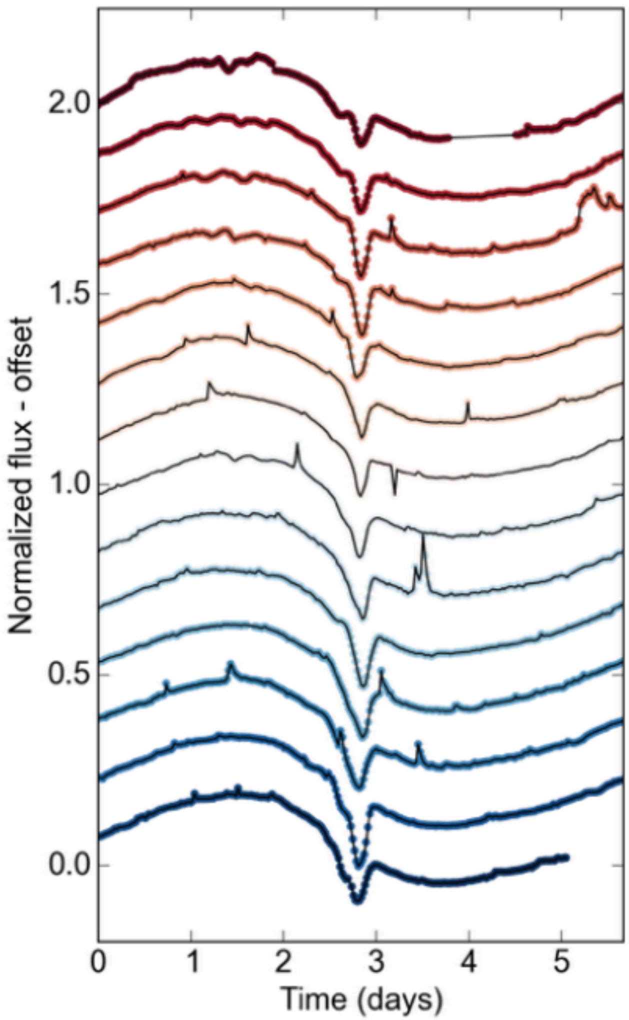


FIG. 9.—Mean deviation in 1900–3200 Å flux, relative to the global mean for all spectra of a given PMS star. Triangles indicate 2 σ upper limits. Only stars observed more than once by *IUE* are shown. Few PMS stars of spectral class F were observed by *IUE*, but LW data are adequate to show that they can vary significantly.



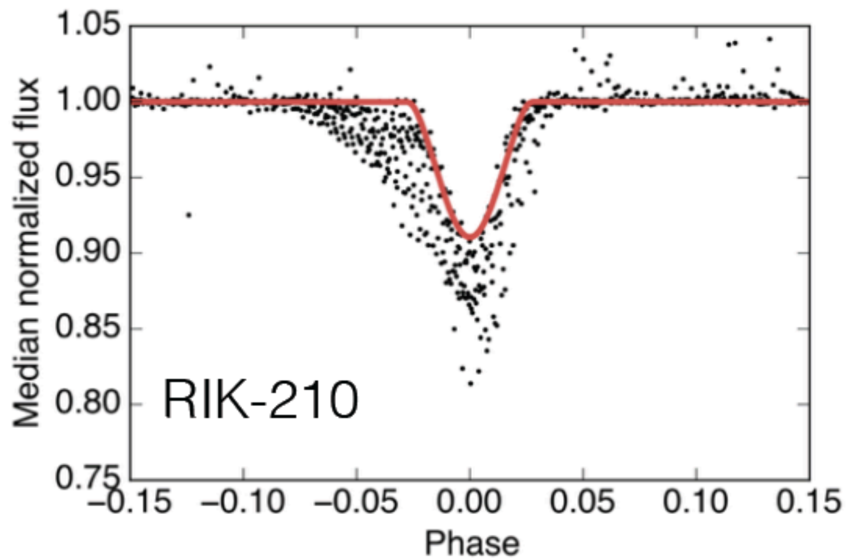
Shkolnik 2018

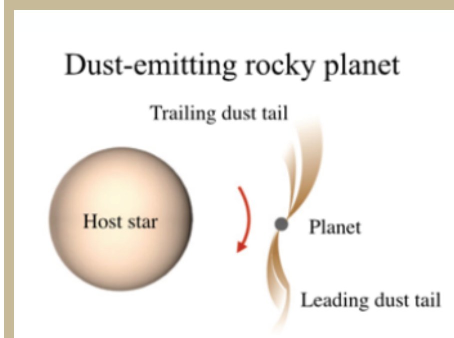


Transient dimming of a young star lacking a protoplanetary disk

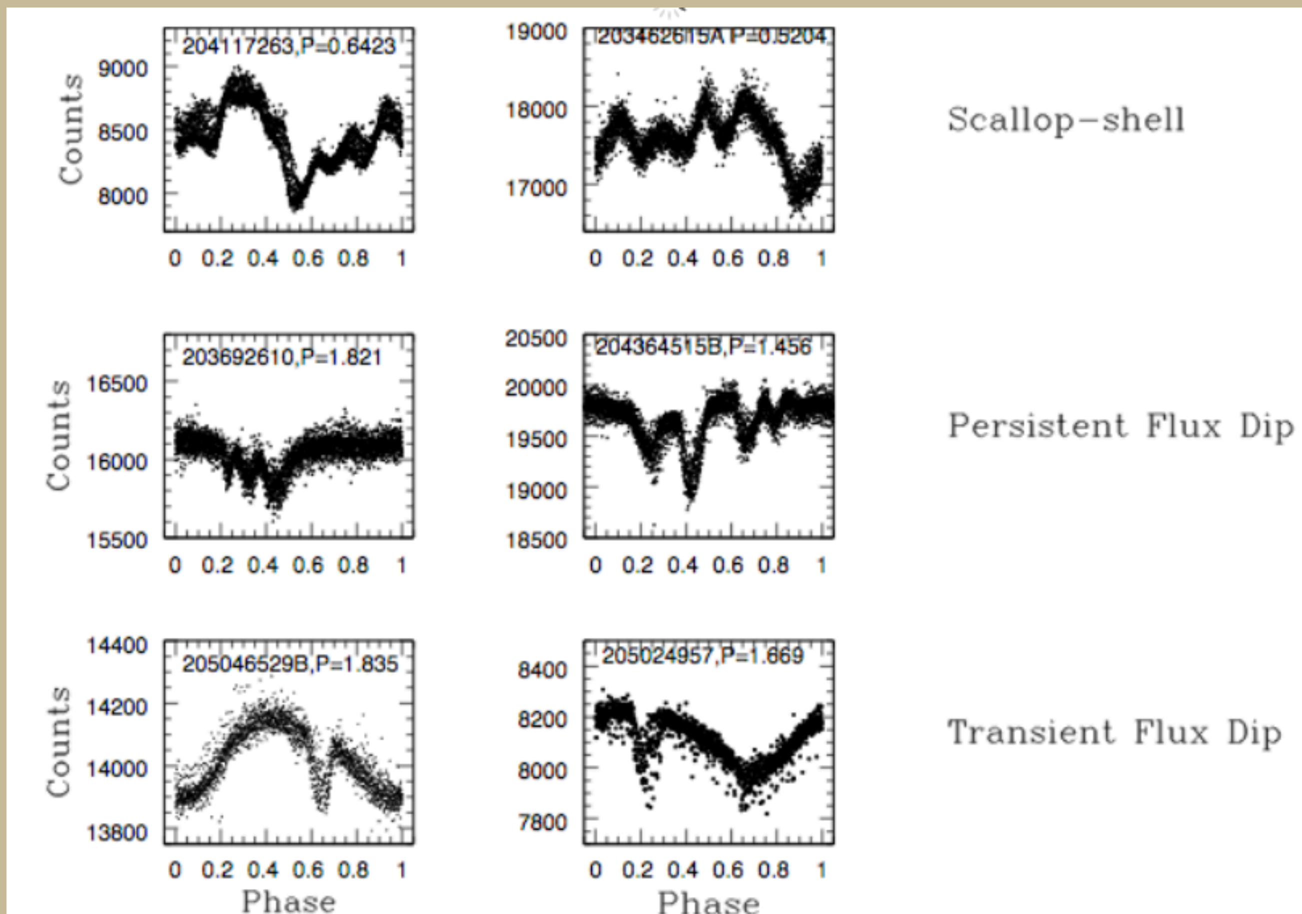
David et al. 2017, ApJ (arXiv:1612.03907)

magnetospheric clouds?
dusty accretion column?
corotating planetary debris?





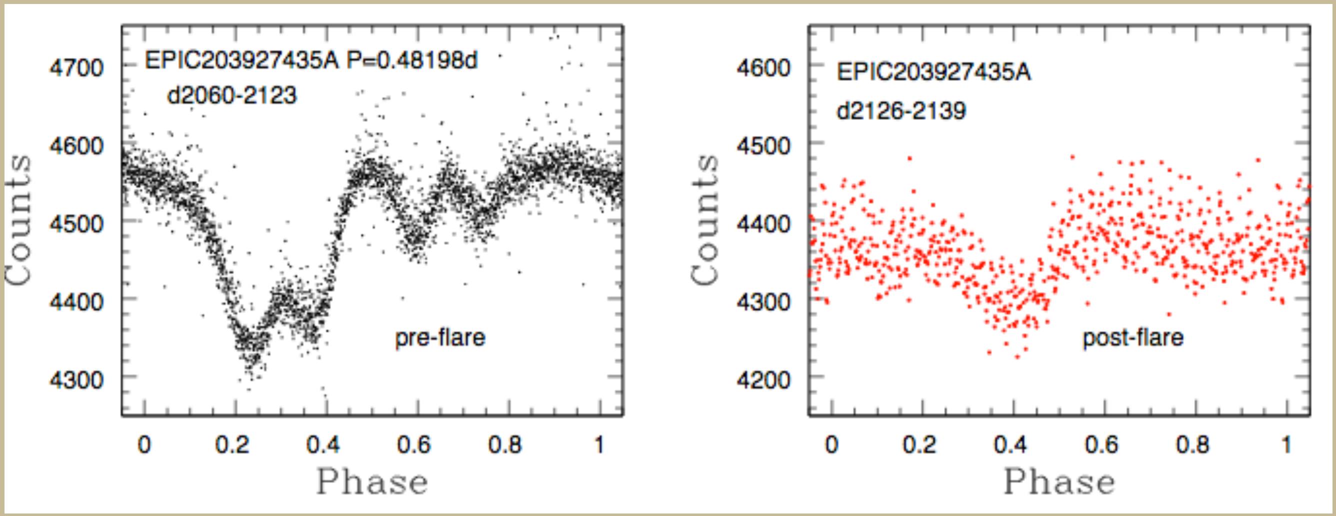
More Interesting Co-Rotating Structure



~9% of the objects <u>without</u> evidence for infrared excess (disks) exhibit these types of lightcurves

[Stauffer et al. 2017, 2018]

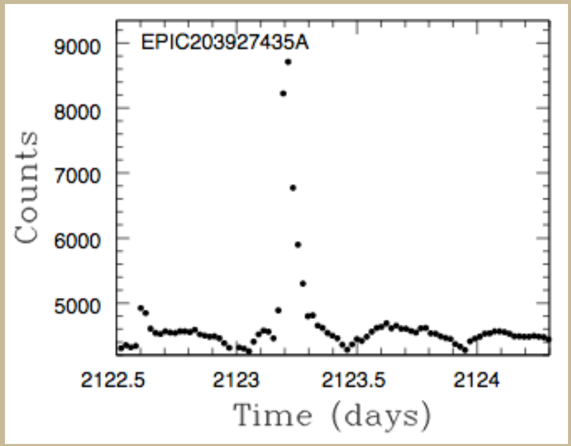
Waveform Can Change During the ~80 Day K2 Campaign

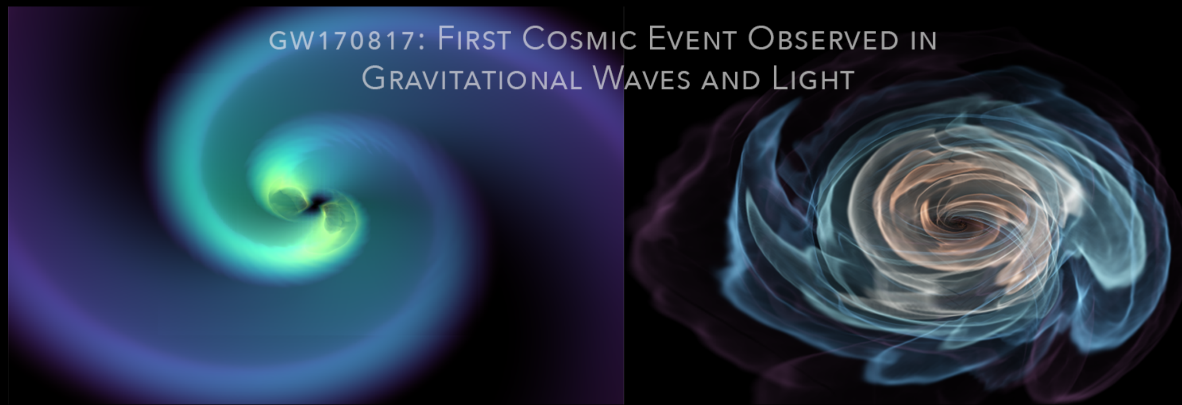


Orbiting Clouds of Material at or near the Keplerian Co-Rotation Radius in Late M Dwarfs WTTs of Upper Sco

[Stauffer et al. 2017]

changes seen at restricted phases, sometimes closely following detected flares.





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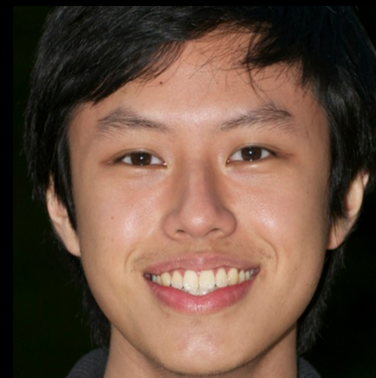
Kasliwal Research Group

Jacob Jencson
(Grad, 5^{th} Year)

Kishalay De
(Grad, 3^{rd} Year)



Samaporn Tinyanont
(Grad, joint w/ Mawet)

Shreya Anand
(Grad, joint w/ Weinstein)

Scott Adams
(Postdoc)

Matt Hankins
(Postdoc)

Christoffer Fremling
(Postdoc, joint w/ SRK)

Igor Andreoni
(Postdoc)

Alumni: Ragnhild Lunnan, Dave Cook, Ryan Lau, Nadia Blagorodnova,
Stephanie Kwan, Lindsey Whitesides, Viraj Karambelkar, Chris Cannella

Multi-Messenger Astrophysics Discovery Engines

Gravitational Waves: LIGO, Virgo, LIGO-India, Kagra, LISA, PTA

Neutrinos and UHECRs: Icecube, Pierre Auger, Antares, SuperK

Optical: Evryscope, ASASSN, HATPI, ZTF, KMTNet, CSS-II, PS2, Blackgem, ATLAS, DECAM, HSC (and soon, LSST)

Gamma-Rays Fermi, Swift, Integral

X-ray: MAXI, eROSITA

Radio: LOFAR, MWA, LWA, Apertif, Meerkat, Askap, CHIME, VLASS

MISSING: Wide-field Infrared and Ultraviolet

Why Infrared Fireworks?

I. Nuclear Physics

- Heavy Element Opacity cf Kilonovae & Gravitational Waves
- Line Blanketing cf He-shell detonations cf LISA GW

II. Enshrouded Stellar Fates

- Milky Way Dust cf Galactic Supernova & Neutrinos
- Mass-loss self-obscuration cf core-collapse supernovae

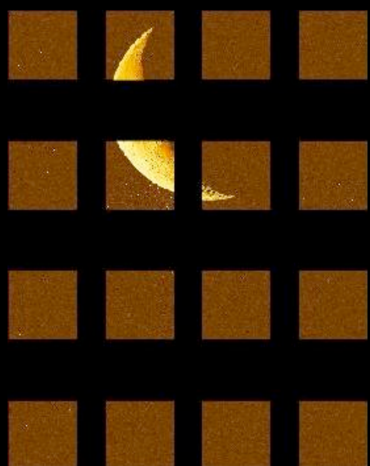
III. Cool Explosions

- Birth of Stellar Black Holes
- Stellar Mergers
- Shocks in Classical Novae

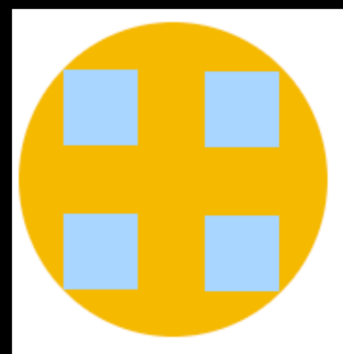
IV. The Unexpected

The Dynamic Infrared Sky is Relatively Pristine

No Wide-Field IR cameras?



VIRCAM on VISTA
0.6 deg^2 on 4m

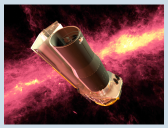
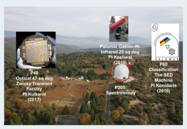
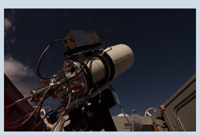
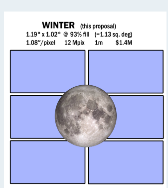


WFCAM on UKIRT
0.2 deg^2 on 4m

WIRCAM on CFH
0.13 deg^2 on 4m

Space

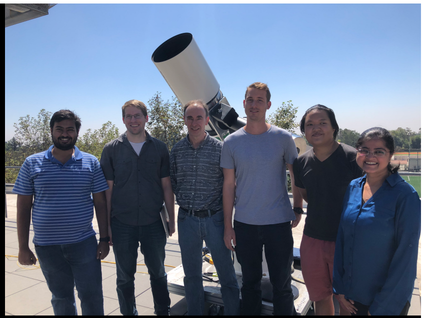
IR TDA Roadmap

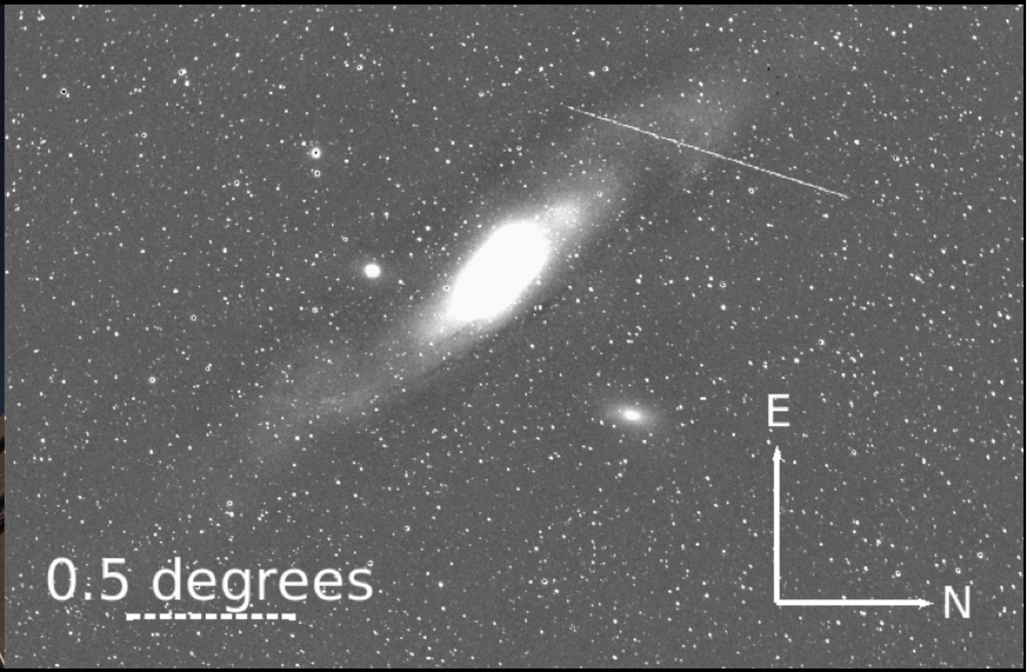
	Project	Description	Status
Phase I 	SPIRITS	Target 200 galaxies with the Spitzer Space Telescope	2014-2019 Ongoing
Phase II 	ZTF	Classify the reddest optical transients	2018-2020 Ongoing
Phase III 	Palomar Gattini-IR	15,000 sq deg every night in J-band to 16.4 mag	Sep 11, 2018 First Light
Phase IV 	WINTER	1 sq deg yJH camera on a 1 meter telescope	Summer 2020 Just Funded

And then perhaps, go to a Polar Location or Space…

Palomar Gattini-IR:

Opening up the dynamic infrared sky

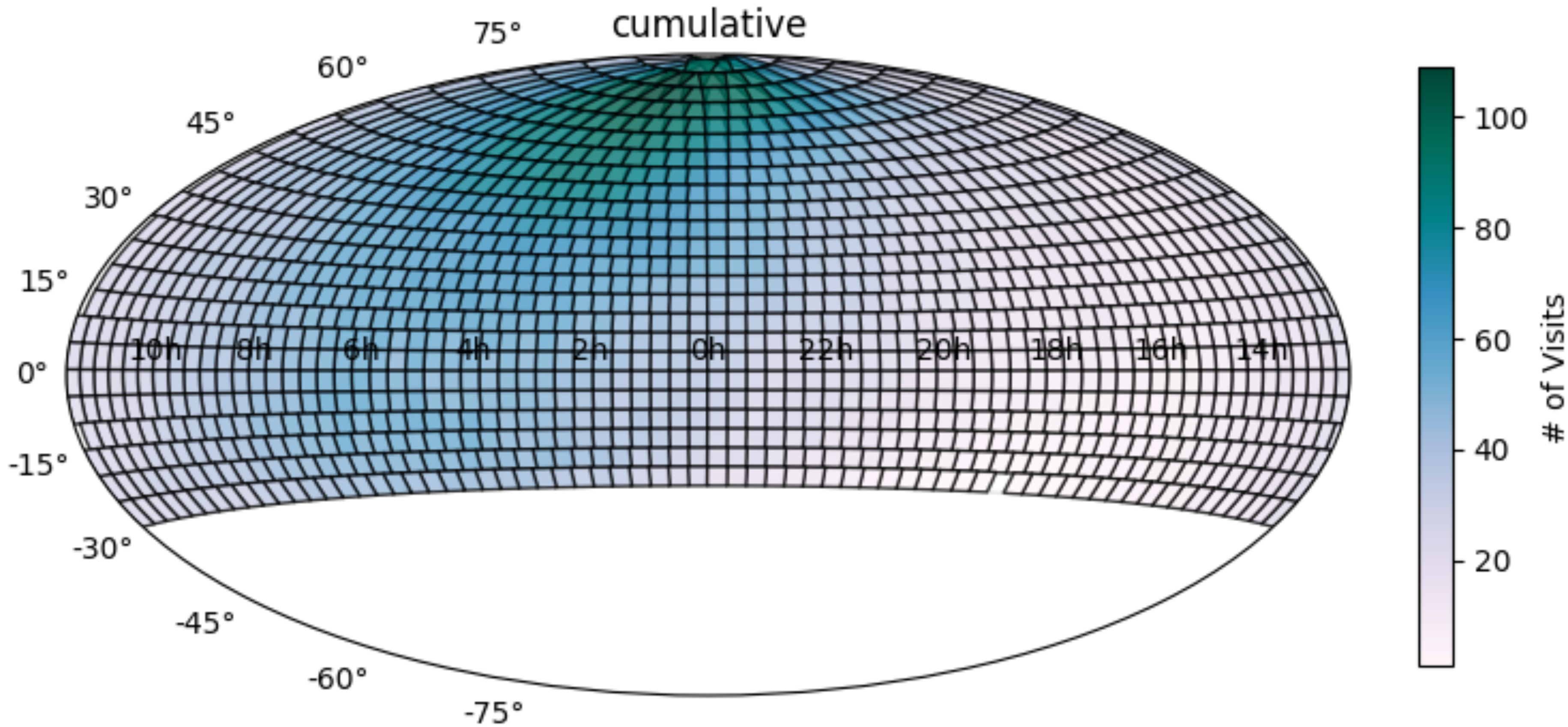




A robotic 30cm telescope with a 25 sq deg FoV camera
Surveys 9,000 sq deg to J < 15.4 mag every single night!
In partnership with Anna Moore (ANU)

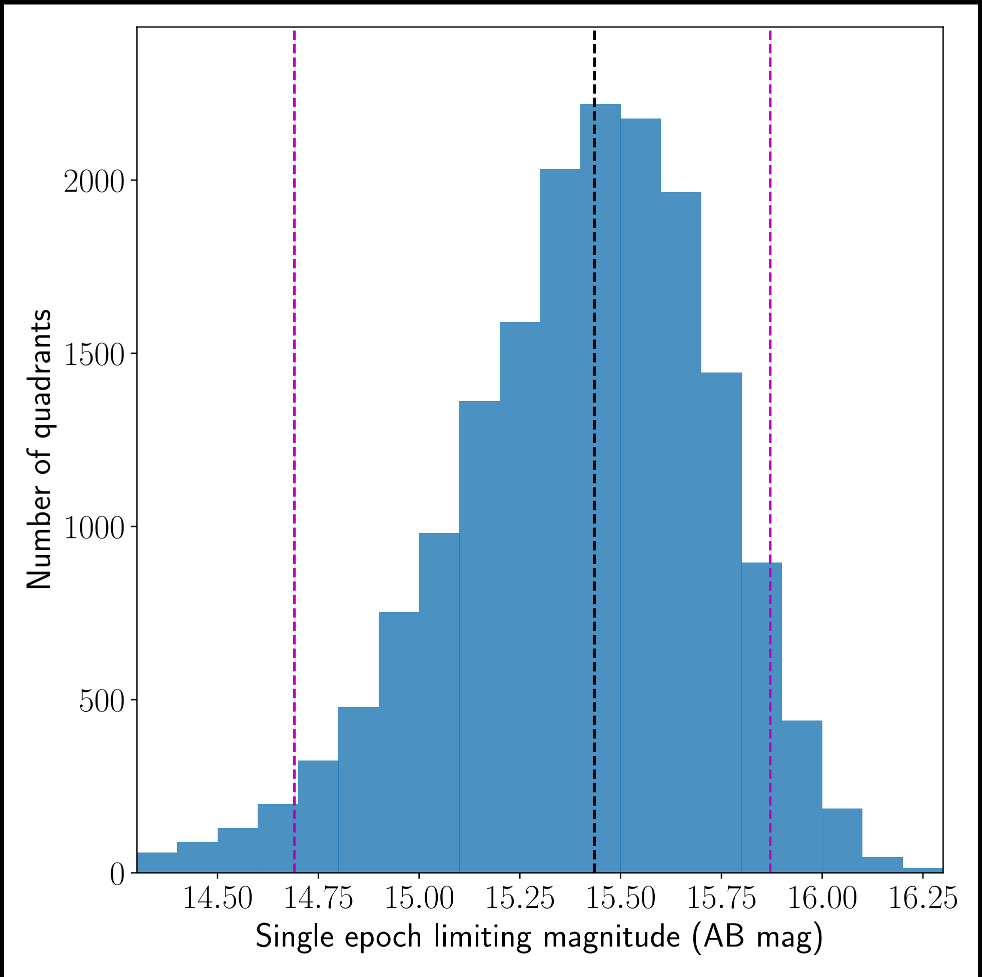
First light: September 11, 2018

Sky Coverage to date

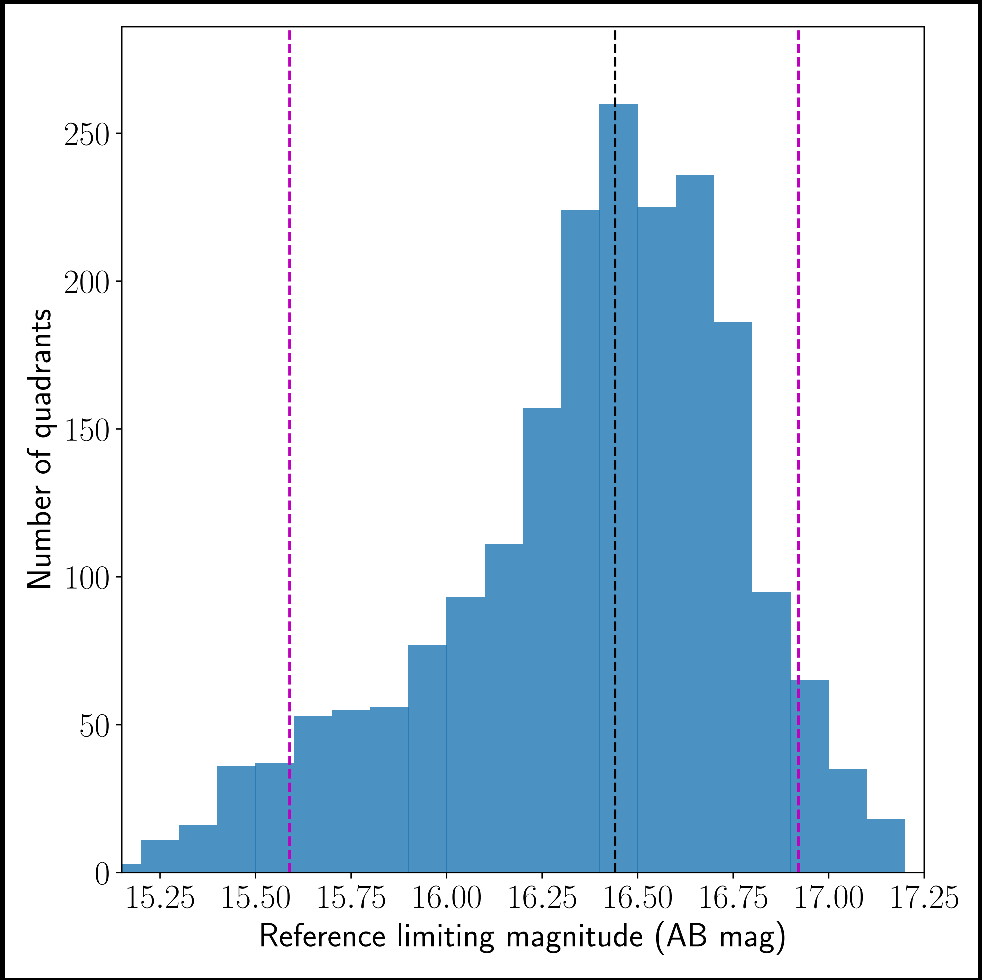


~9000 square degrees mapped every night!

Depth

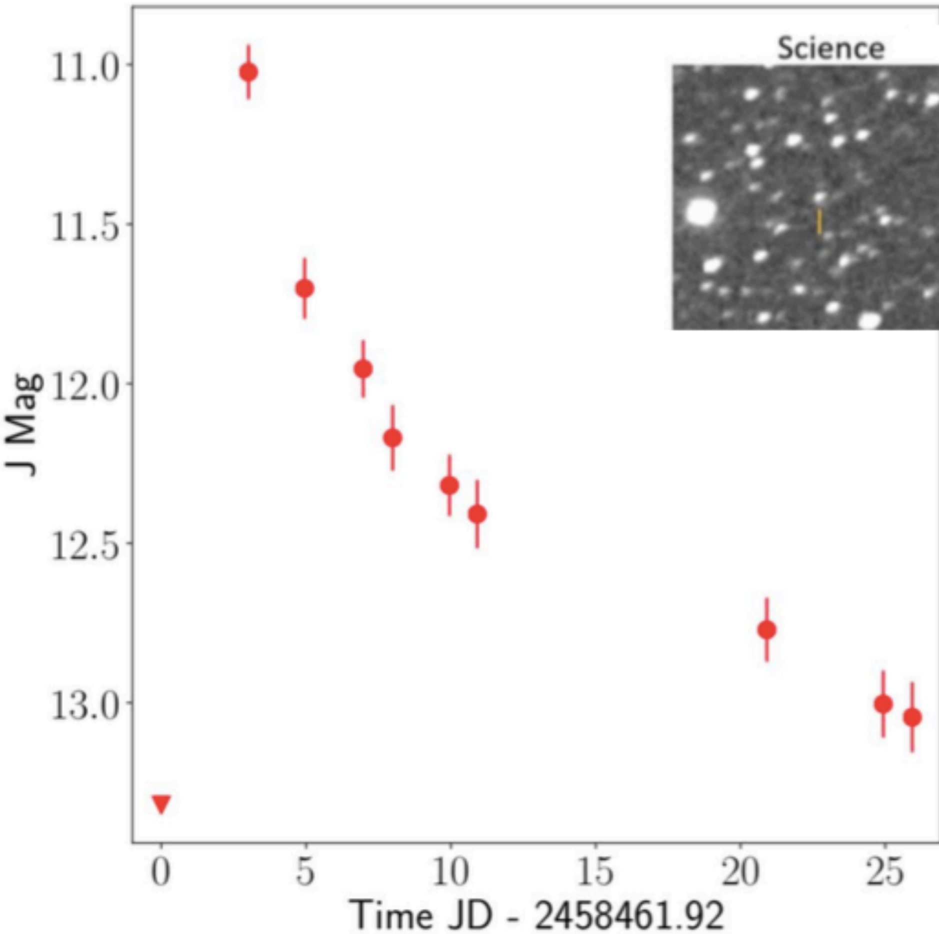


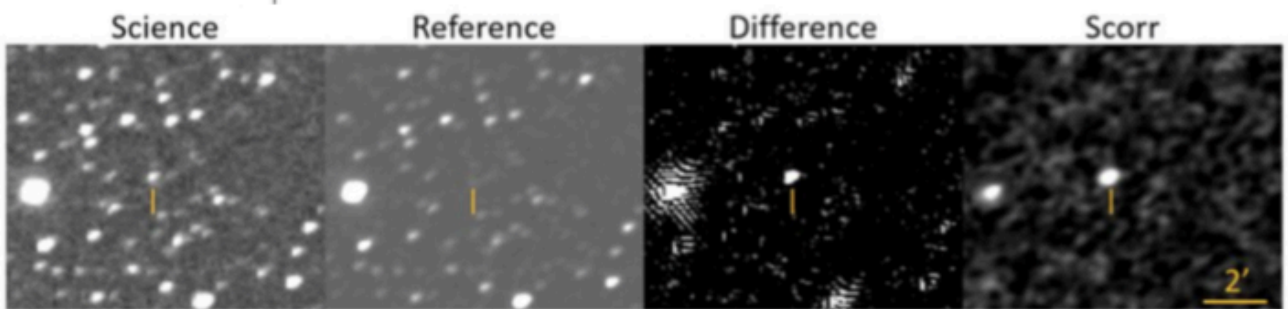
Nightly 5-sigma Depth



Stacked Reference Depth

Light curve of dwarf nova AT 2018jro



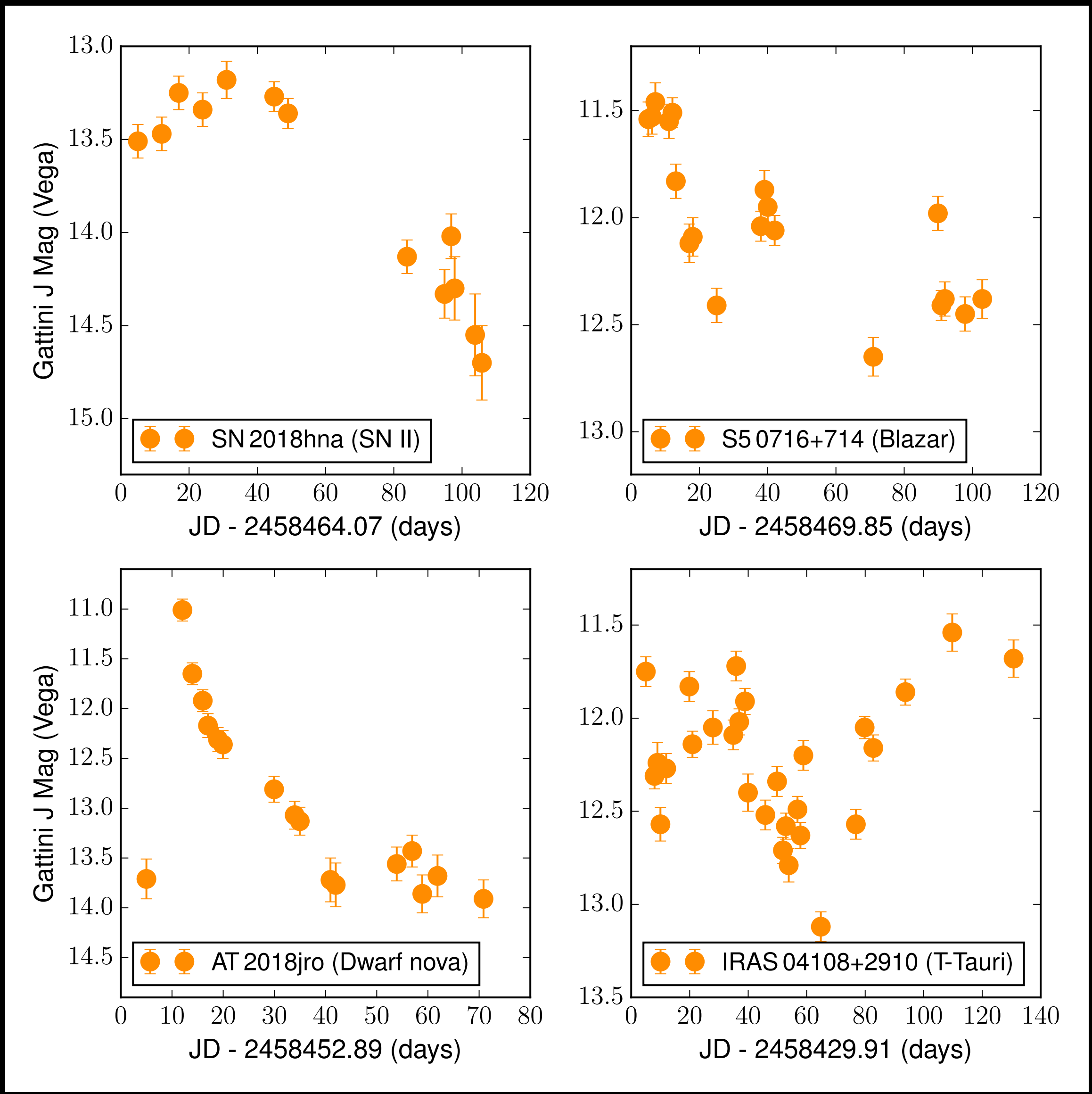


Palomar Gattini-IR J band detections of AT 2018jro

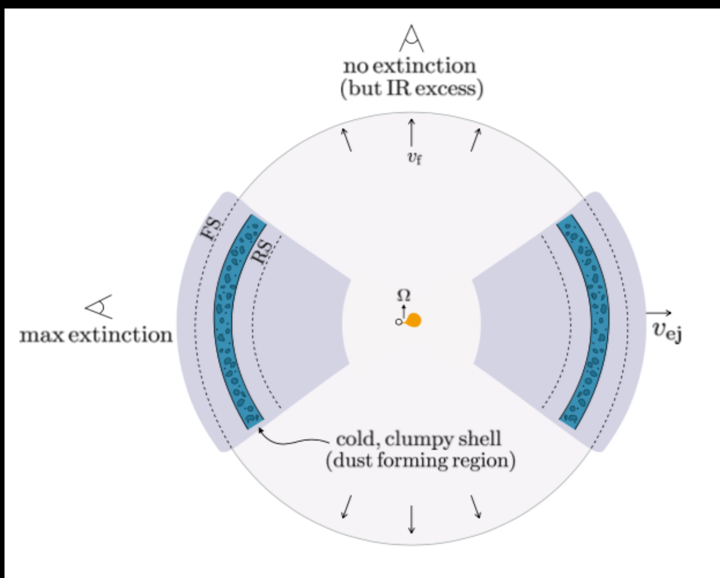
ATel #12305; *K. De (Caltech), M. Hankins (Caltech), M. M. Kasliwal (Caltech), A. Moore (ANU), S. M. Adams (Caltech), M. Ashley (UNSW), J. Burnham (SRL/Caltech), A. Delacroix (COO/Caltech), T. Greffe (COO/Caltech), D. Hale (COO/Caltech), R. Lau (JAXA), D. McKenna (COO/Caltech), E. O. Ofek (Weizmann), R. Smith (COO/Caltech), J. Sokoloski (Columbia), J. Soon (ANU), T. Travouillon (ANU)*
on ***18 Dec 2018; 03:33 UT***
Credential Certification: Kishalay De (kde@astro.caltech.edu)

Subjects: Infra-Red, Optical, Nova

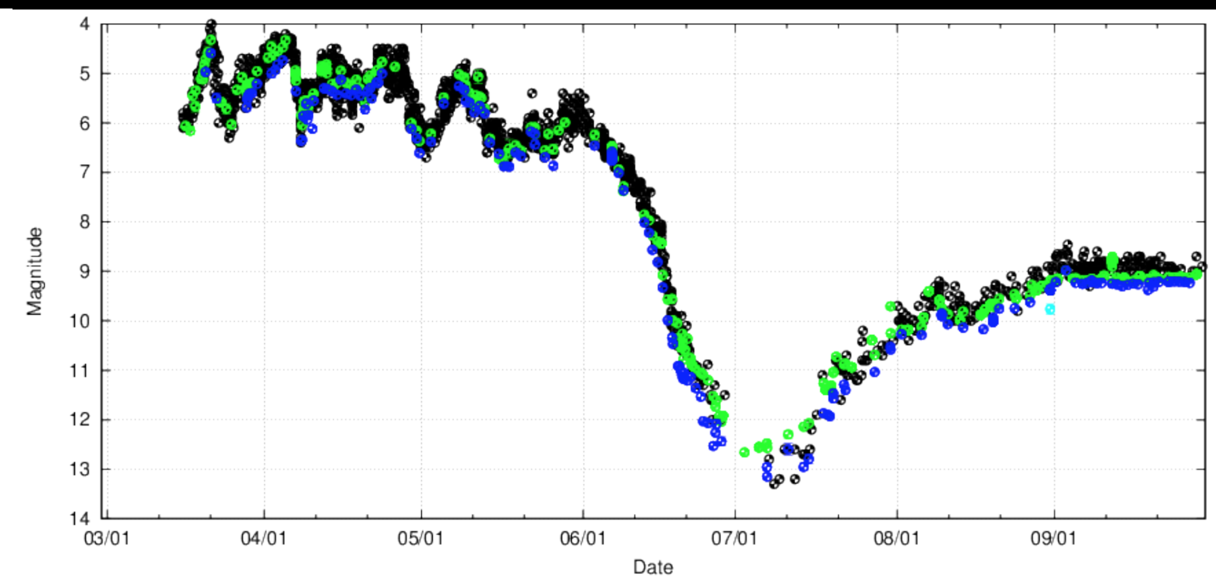
Collage of Palomar Gattini-IR light curves



Classical Novae: Shock-Dust Connection?



Derdzinski et al. 2016

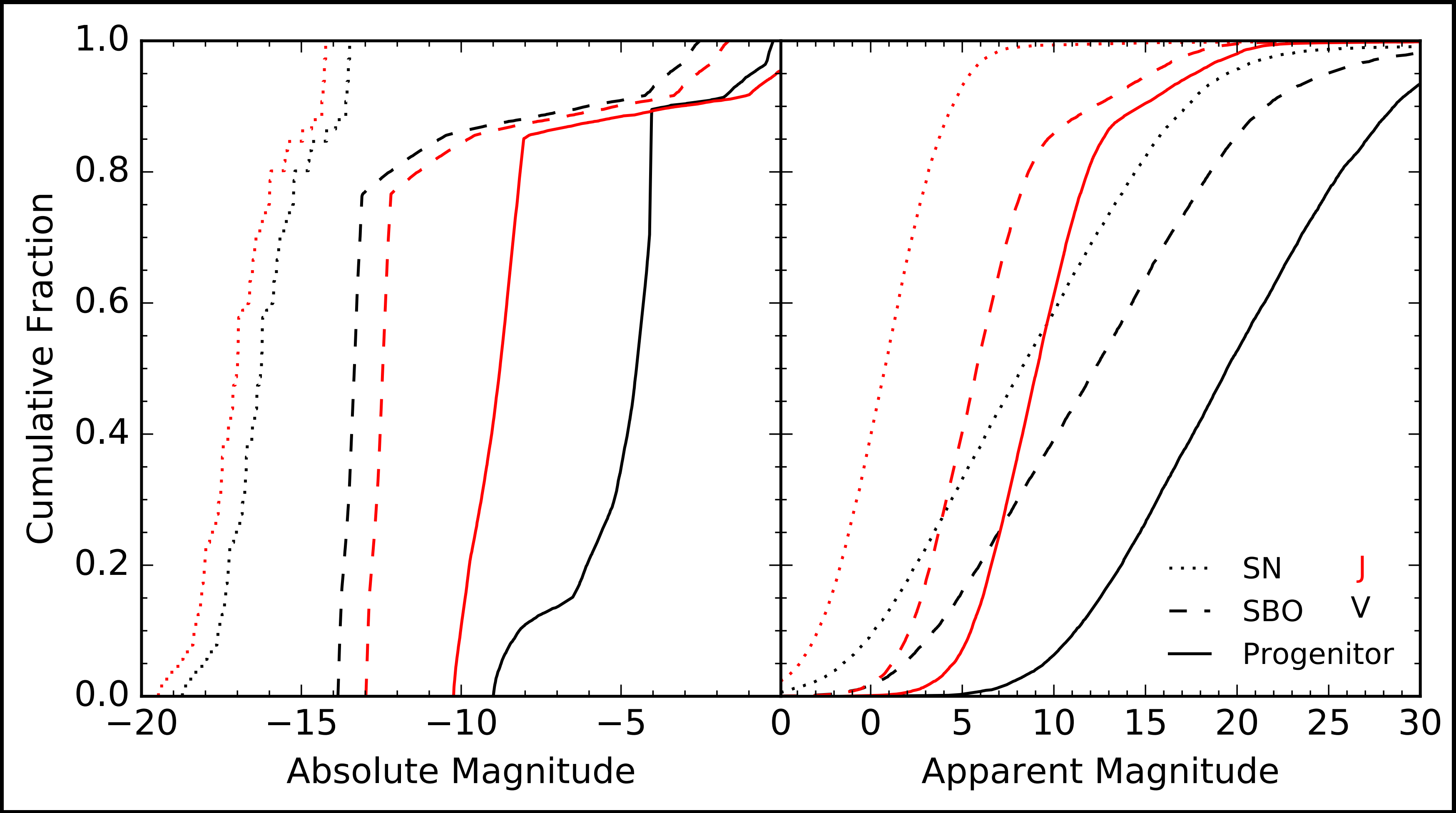


Dust Dip from V5668 Sgr/AAVSO

In partnership with Jeno Sokoloski.

HEISING-SIMONS FOUNDATION

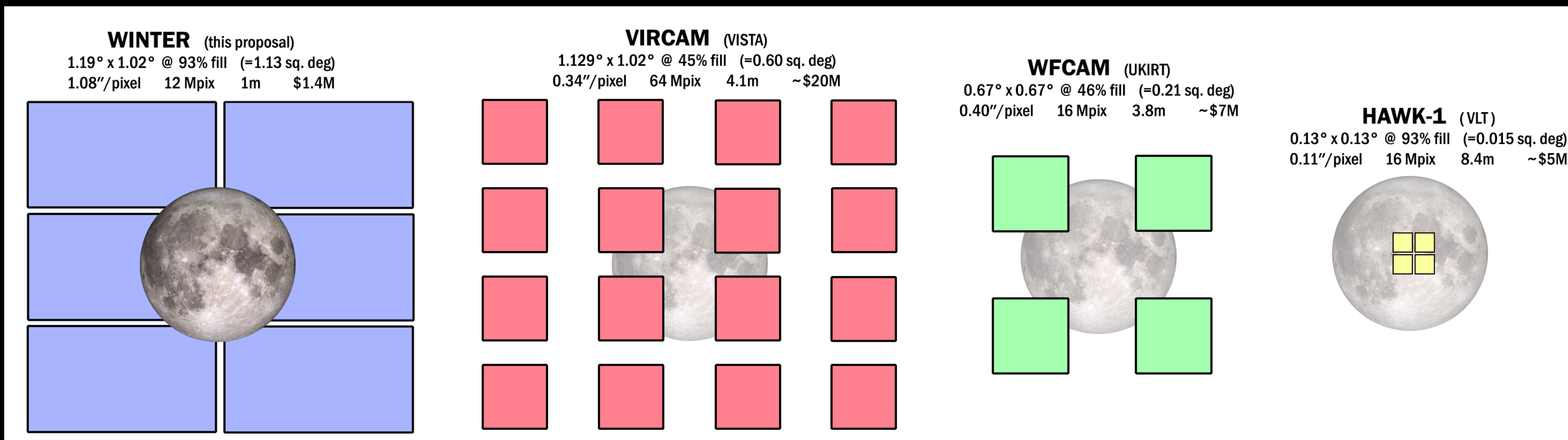
Supernova in the Milky Way

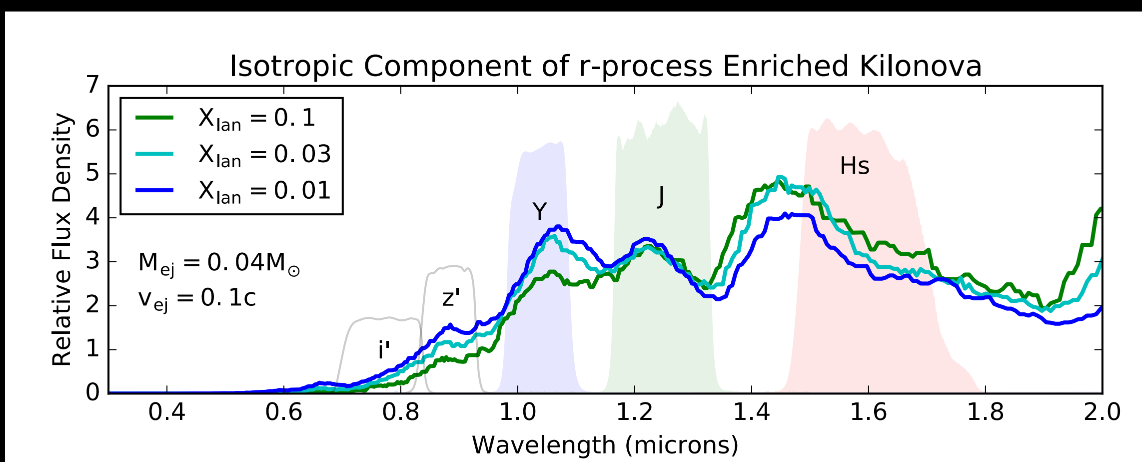


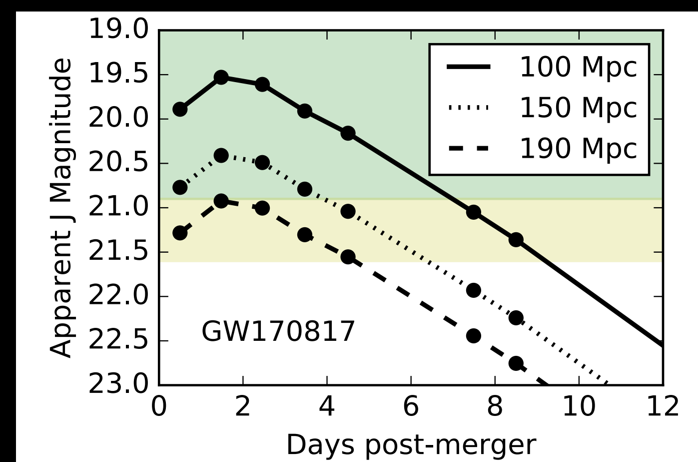
Adapted from Adams et al. 2013

WINTER @ Palomar

Alternative Semiconductor Technology



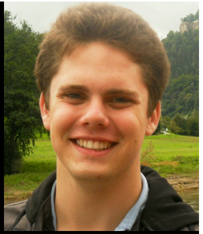




In Partnership with Rob Simcoe (MIT)

Now funded by NSF MRI + Packard; First light: Summer 2020

SPIRITS is discovering a wide range of IR transient sources.



Jacob Jencson

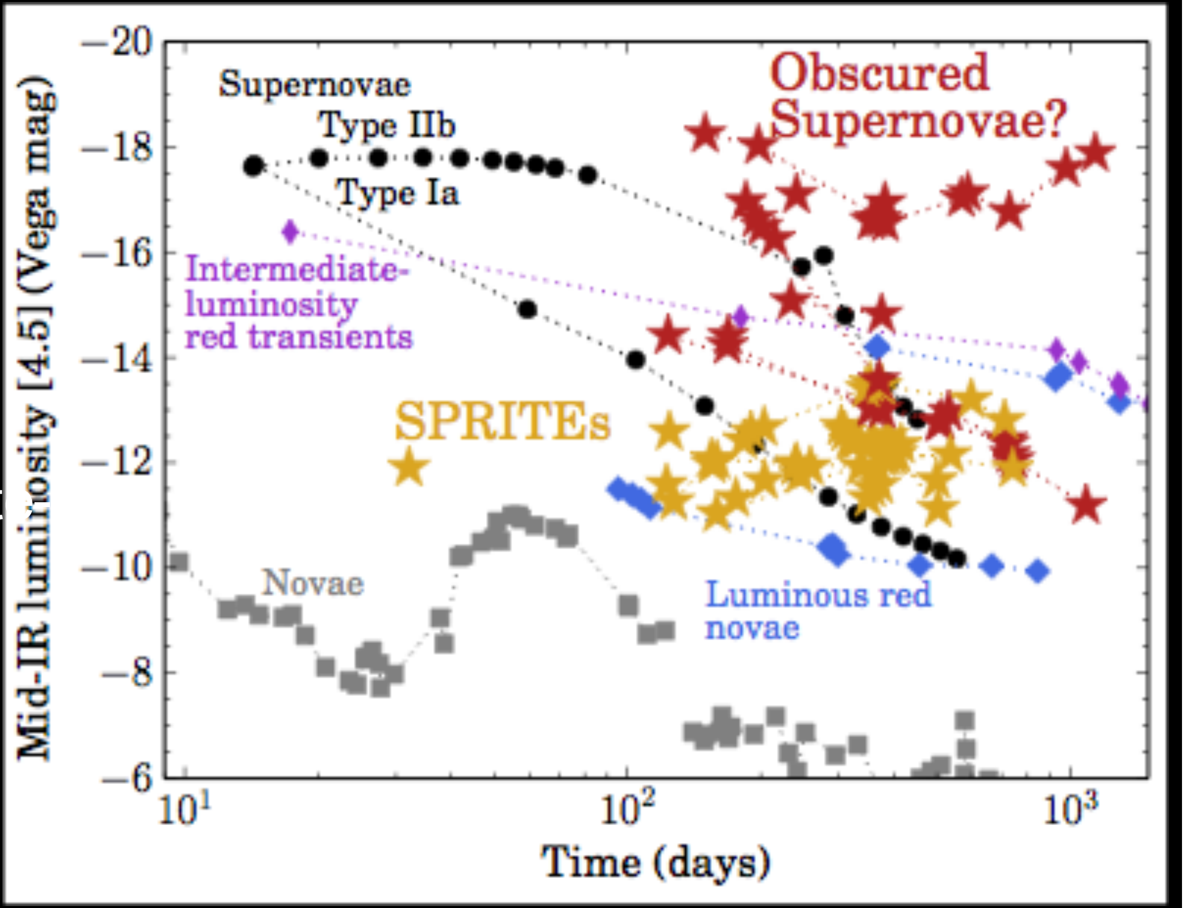
Identified 131+ transients

49 known supernovae

10 candidate obscured supernovae

8 likely classical novae

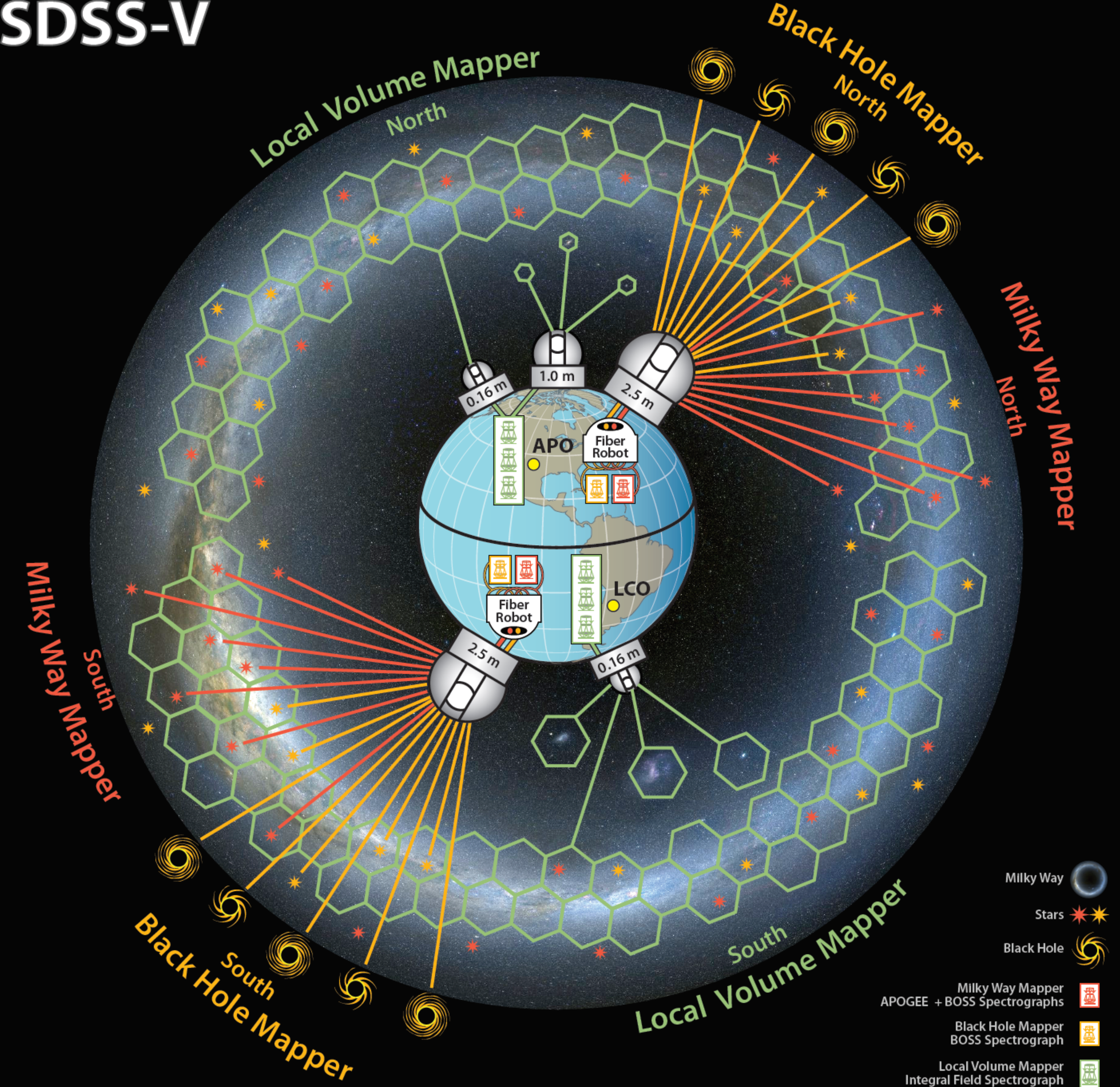
64 eSPecially Red Intermediate Luminosity Transient Events (SPRITEs)



The Dynamic Infrared Sky is Ripe for Exploration

SDSS-V UPDATE

SDSS-V


Local Volume Mapper
North
Black Hole Mapper
North
Milky Way Mapper
North
0.16 m
1.0 m
2.5 m
APO
Fiber
Robot
LCO
Fiber
Robot
2.5 m
0.16 m
Milky Way Mapper
South
Black Hole Mapper
South
Local Volume Mapper
South
Milky Way
Stars
Black Hole
Milky Way Mapper
APOGEE + BOSS Spectrographs
Black Hole Mapper
BOSS Spectrograph
Local Volume Mapper
Integral Field Spectrograph

SDSS-V's 3 "Mappers"

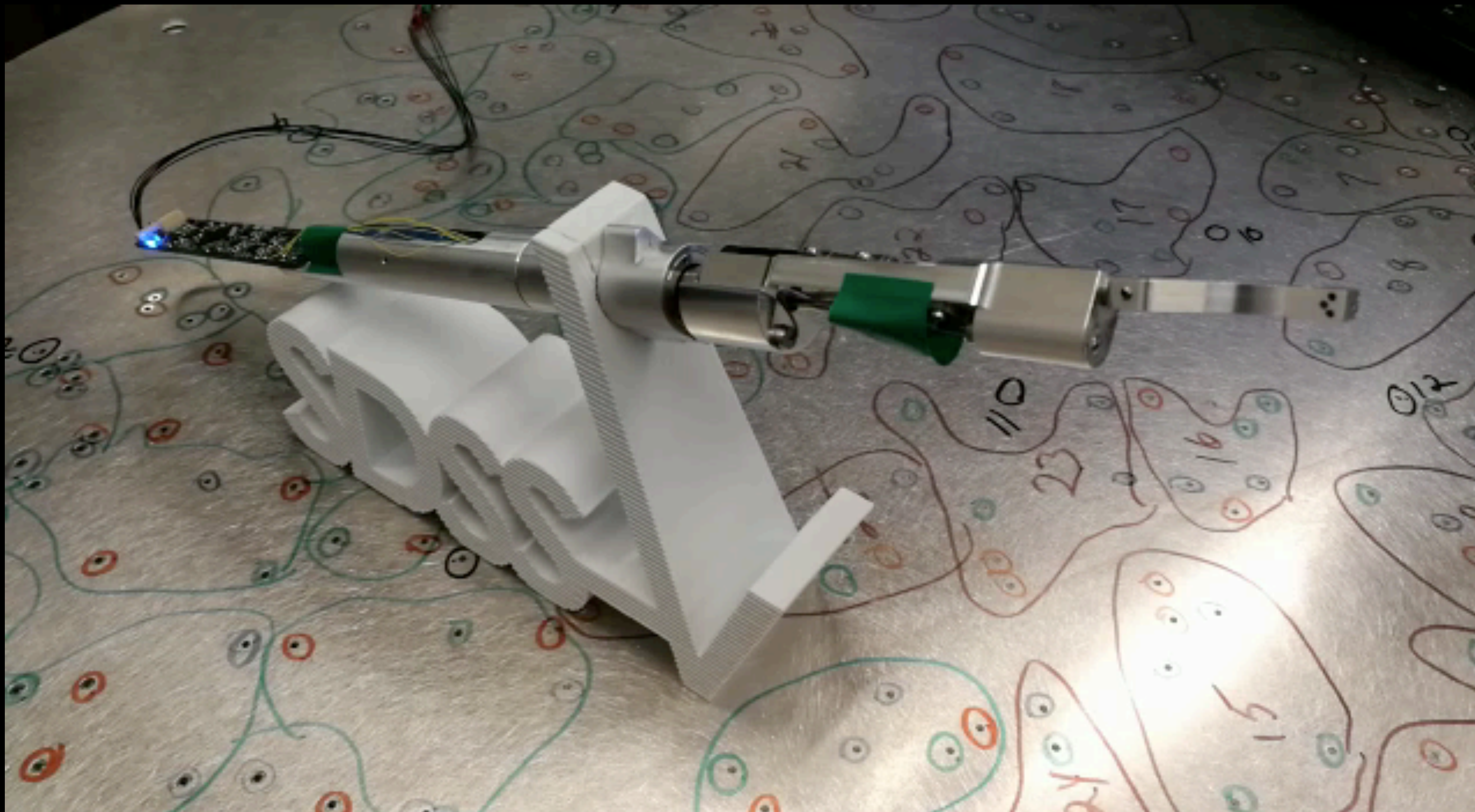
Program	Science Targets	N_{Objects} and/or Sky Area	Primary Spectral Range and Hardware	Primary Science Goals
Milky Way Mapper (MWM)	Stars across the Milky Way	>6M stars; all-sky	IR; APOGEE ($R \sim 22,000$) with fiber-positioning system	Understanding the formation of the Milky Way and the physics of its stars
Black Hole Mapper (BHM)	Primarily supermassive black holes	>400,000 sources; all-sky	Optical; e.g., BOSS ($R \sim 2000$) with fiber-positioning system	Probing black hole growth and mapping the X-ray sky
Local Volume Mapper (LVM)	ISM & stellar populations in the MW, Local Group, and nearby galaxies	>25M contiguous spectra over 3,000 deg^2	Optical; new integral field spectrographs covering 3600-10000Å at $R \sim 4000$	Exploring galaxy formation and regulation by star formation; feedback, enrichment, & ISM physics

Spectroscopic Surveys

Spectroscopic Survey Facilities around the Year 2020								
Survey (facility)	N_{target}	R_{spec}	N_{res}	$\overline{\lambda}[\mu m]$	Ω_{sky}	N_{epoch}	Timeframe	$m_{primary}$
SDSS-V	7×10^6	22,000 2,000	500	1.51-1.7 0.37-1	4π	$4-60$	2020-2024	$m_H \leq 12$ $m_G \leq 18$
Gaia (RVS)	2×10^6	8000	270	0.85-0.87	4π	~ 60	2013-2020	$m_G \leq 12$
Gaia-ESO	0.1×10^6	$17,000$	140	0.55& 0.85	0.02π	~ 1	2013-2018	$m_G \leq 17$
GALAH	0.8×10^6	$28,000$	400	0.40- 0.85	π $\lvert b\rvert \geq 10$	~ 1	2015-2020	$m_G \leq 13$
WEAVE	0.8×10^6	$5,000$& $20,000$	1000	0.37-0.9	$\sim \pi$	$\sim 1-2$	2018-2023	$m_G \leq 19$
DESI	8×10^6	$3,000$	5000	0.36-0.98	$\sim \pi$ $\lvert b\rvert \geq 25$	$\sim 1-2$	2019-2024	$m_G \leq 19$
LAMOST	8×10^6	$1,800$	4000	0.4-0.9	0.5π	~ 1	2010-2020	$m_G \leq 16$
4MOST	10×10^6	$5,000$& $20,000$	1600& 800	0.4-0.9	1.5π	$1-2$	2023-2028	$m_g \leq 21$ $m_V \leq 16$
APOGEE-1& -2	5×10^5	22,000	300	1.51-1.7	0.5π	~ 4	2011-2019	$m_H \leq 12$
PFS	1×10^6	$3,000$	2400	0.4-1.6	0.05π	1	2018-2021	$m_g \leq 22$
MOONS	2×10^6	$5,000$& $20,000$	1000	0.6-1.8	0.05π	1	2020-2025	$m_g \leq 22$ $m_H \leq 17$

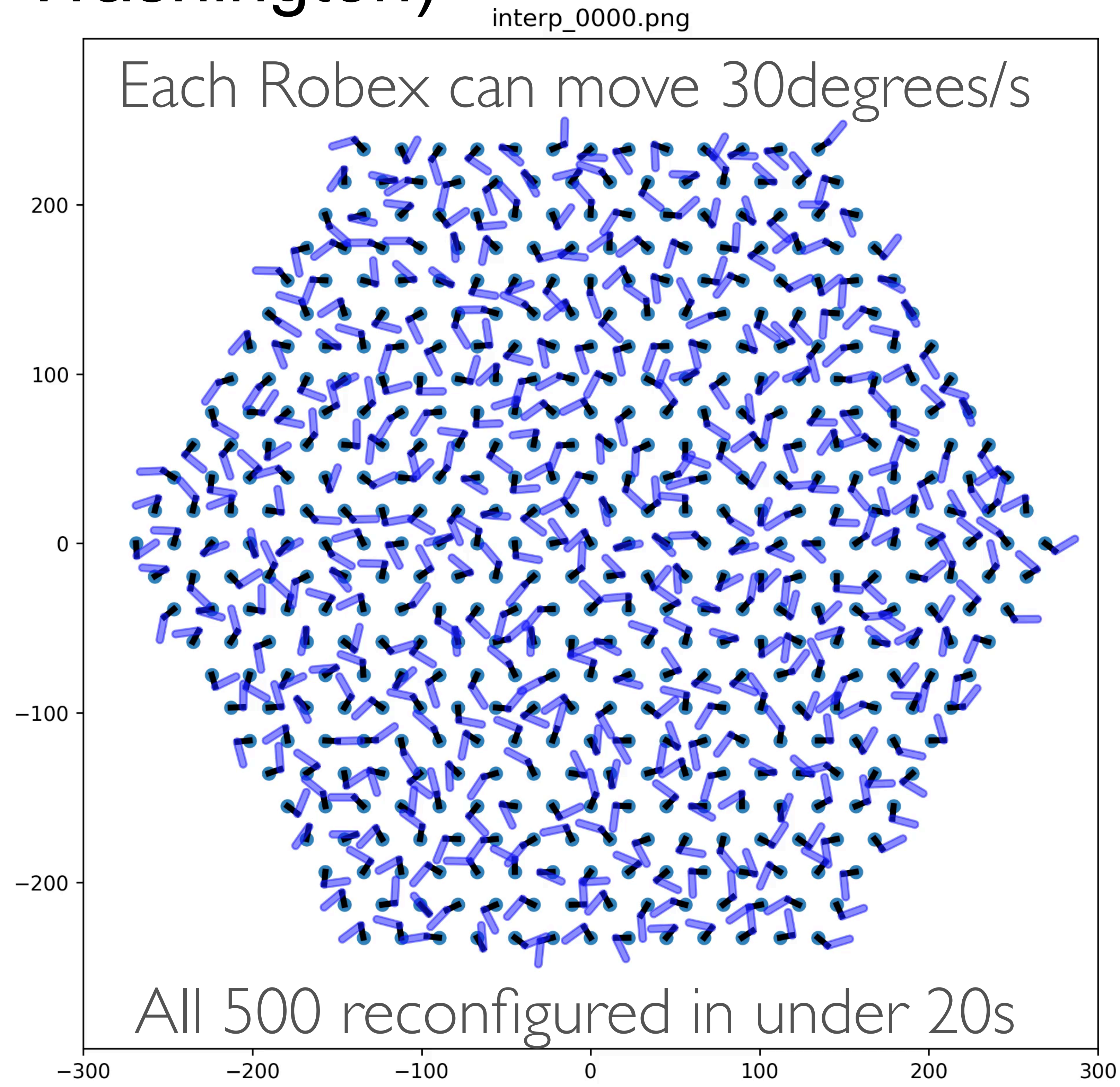
O + IR ; ALL SKY ; TIME DOMAIN!

SDSS-V PROTOTYPE0!

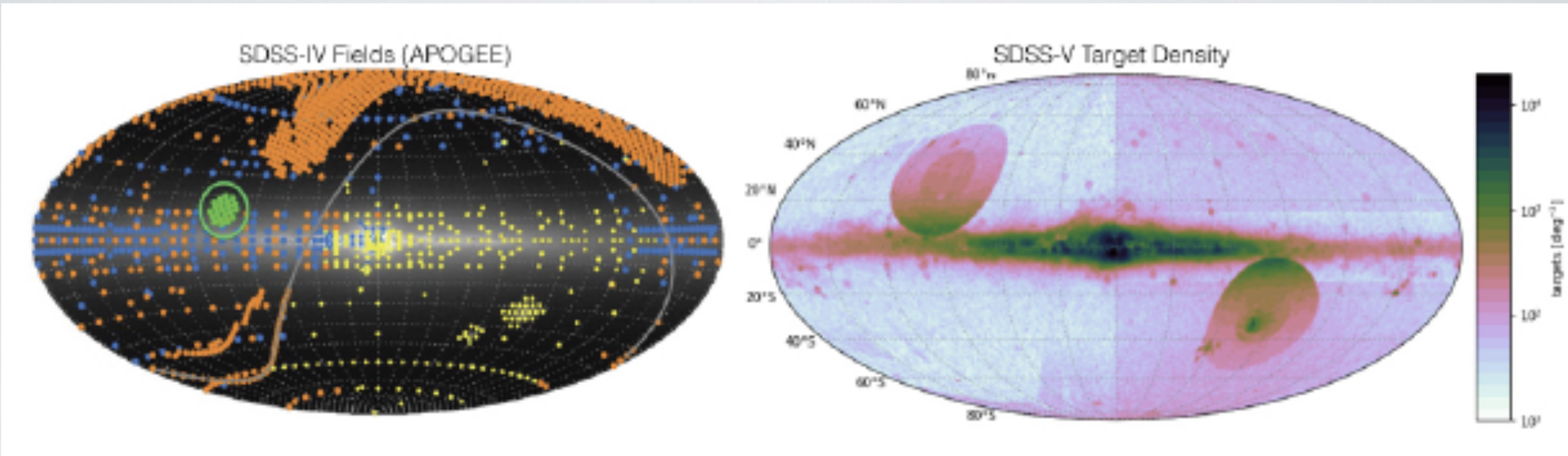


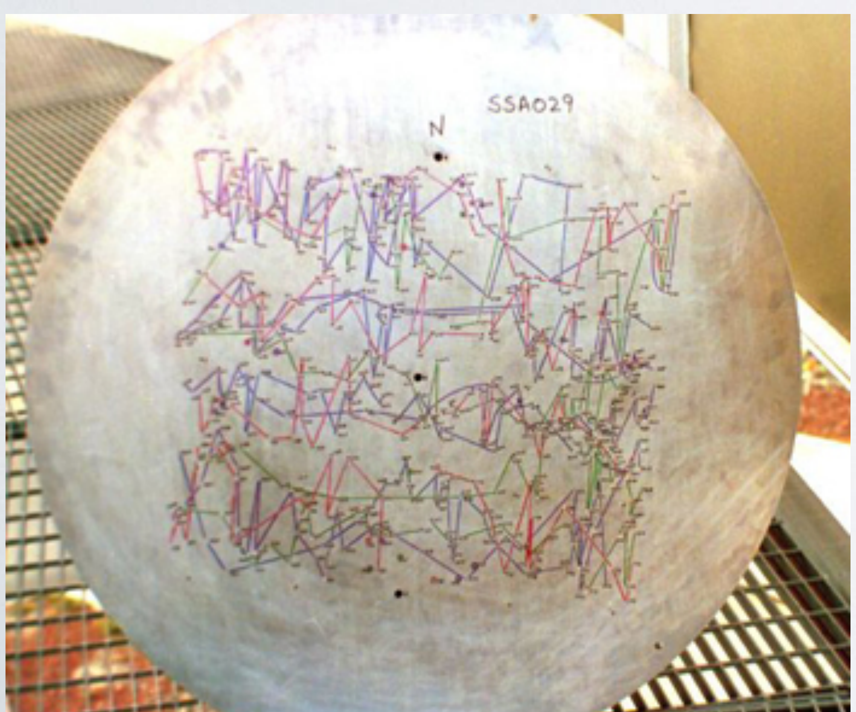
Courtesy J-P Kneib & EPFL Team

Kaiju: A Highly Efficient Collision Avoidance Algorithm for SDSS-V Robotic Fiber Positioners — Conor Sayres (U. Washington)

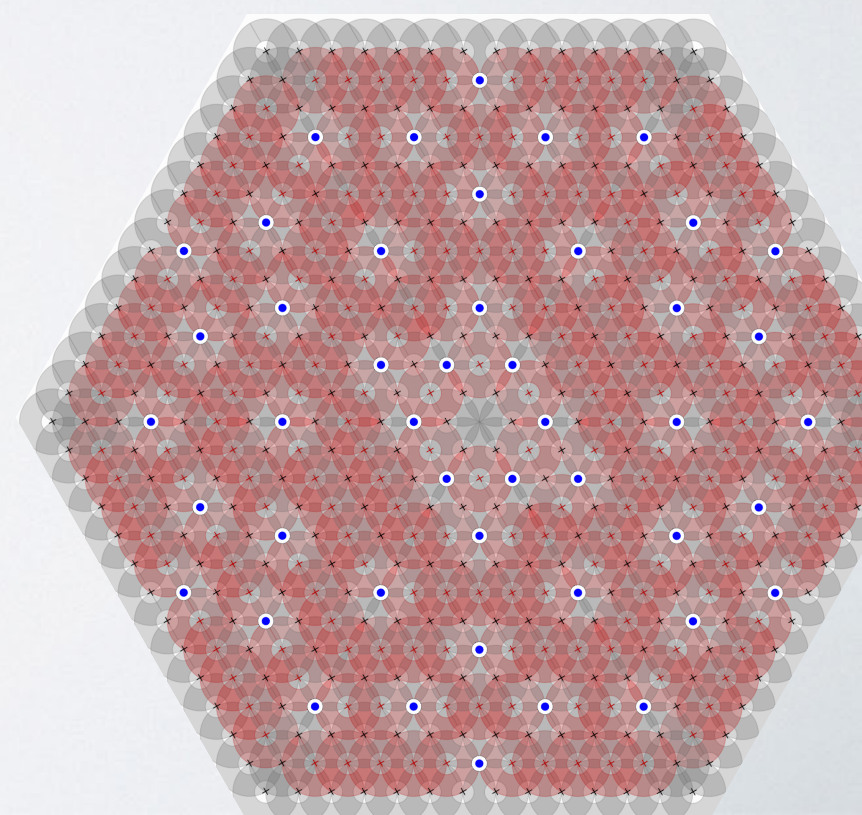


PLATES —> ROBOTS

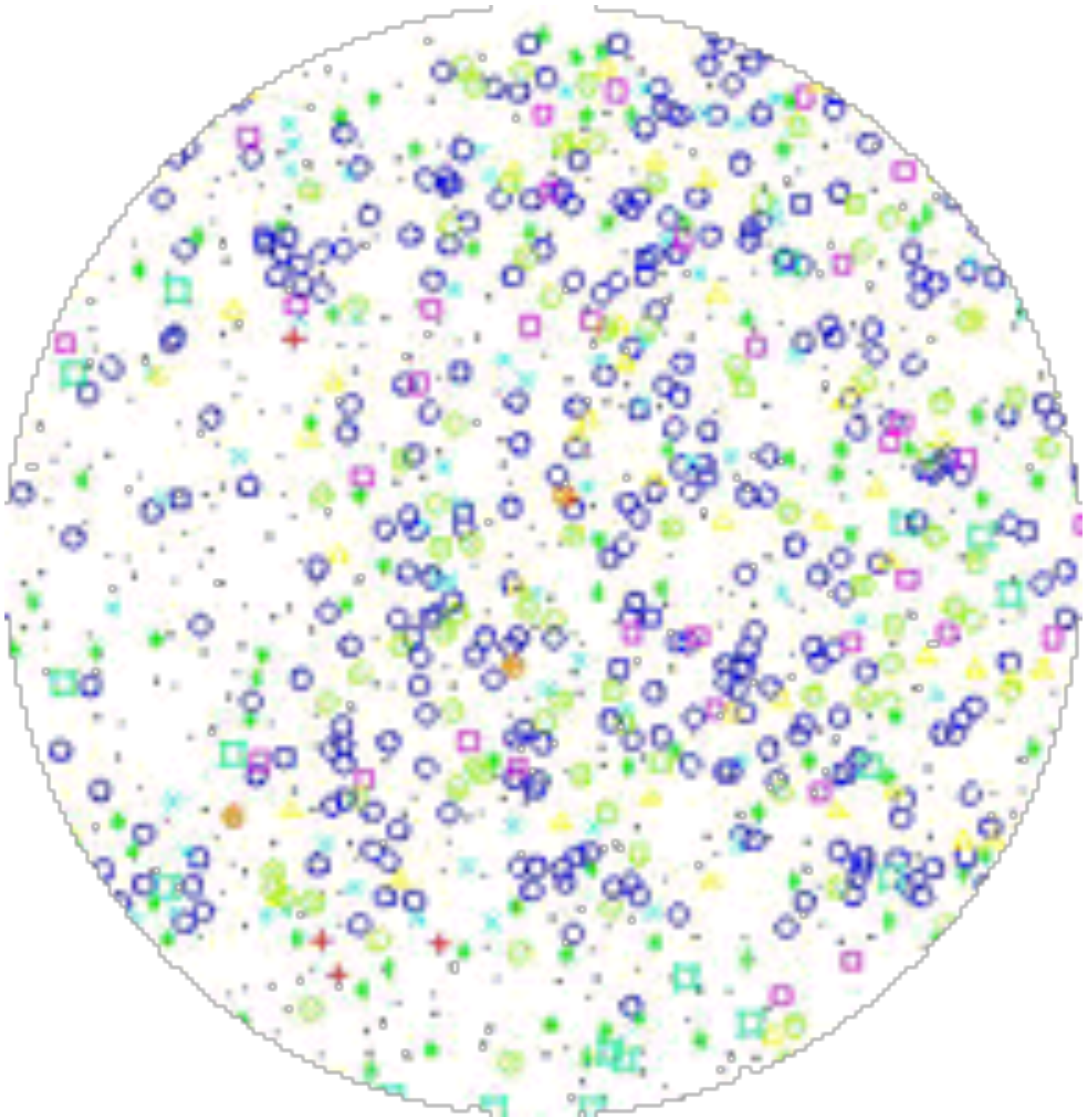


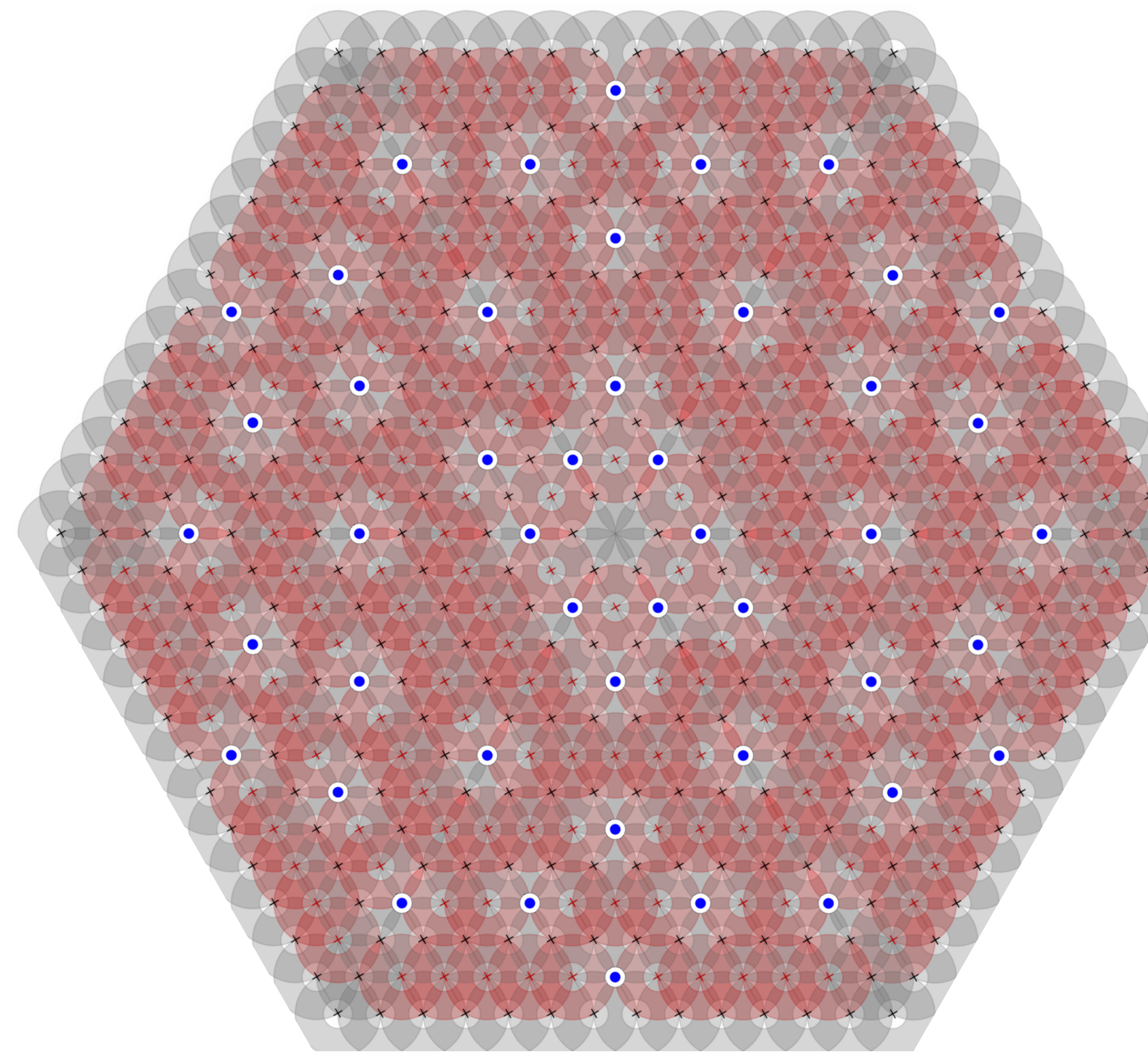


ALL Sky
Dust-Penetrating
Multi-epoch (1-60)
High-quality
spectroscopy



ROBOTIC FIBER POSITIONERS TO FEED SPECTROGRAPHS





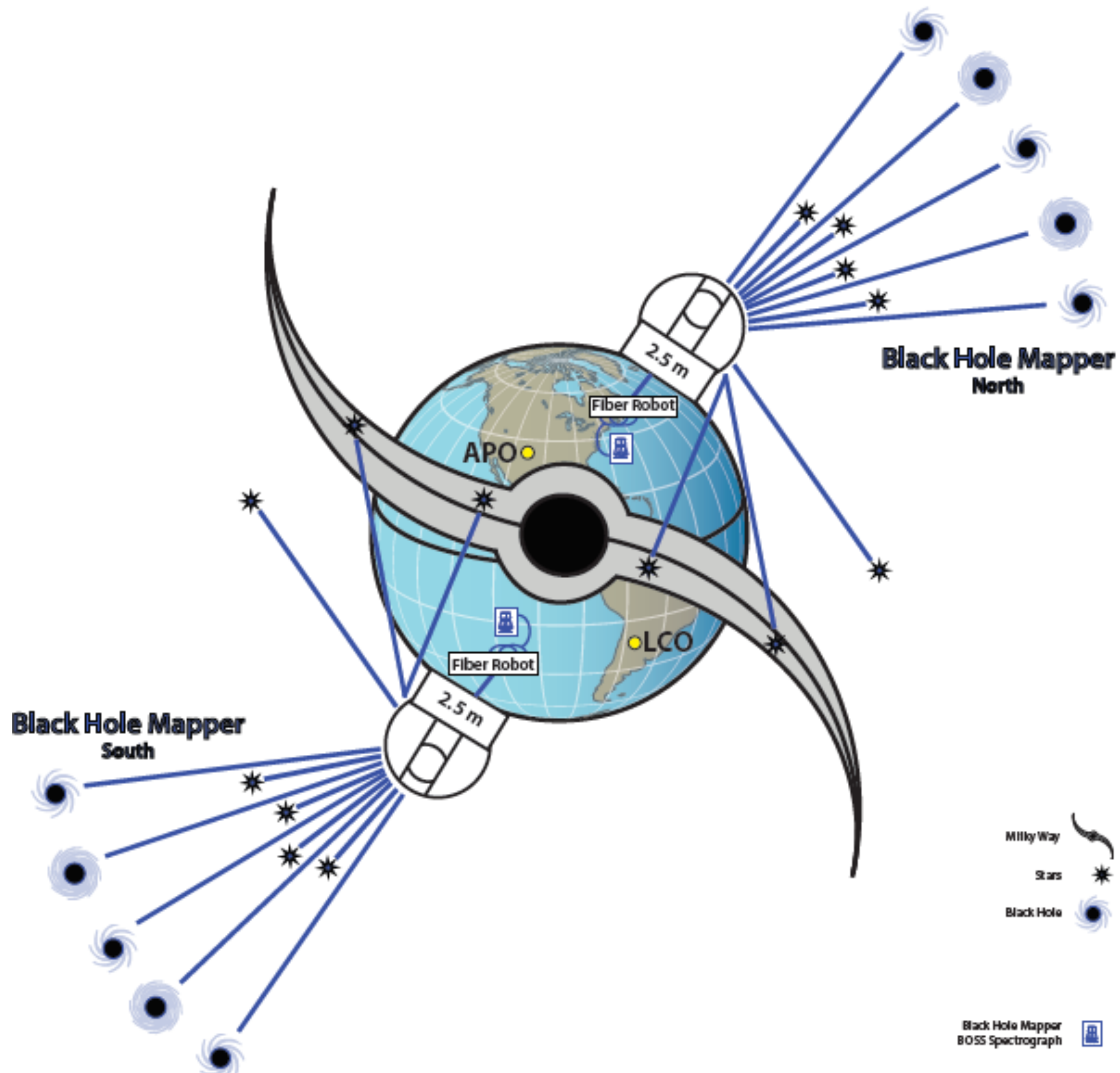
SDSS-V PROTOTYPE1!

- New prototypes tested in December/ January
- Fiber Positioning System successful PDR in November 2018
- Call of Tender for the robots has gone out (today!)

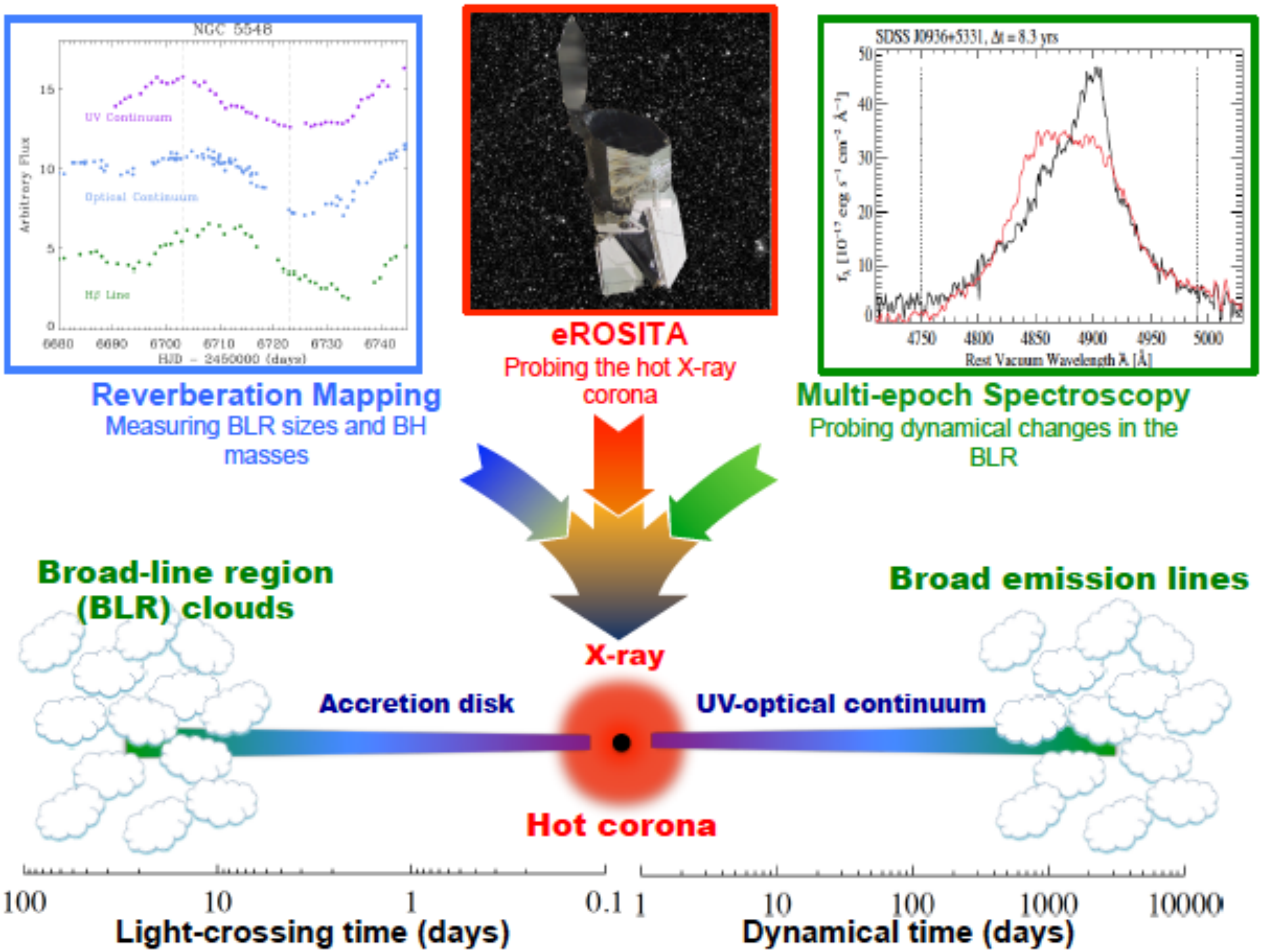
Final design review at the end of Q2!

Ready for "Robot Ridge" in mid-2020 will commission as soon as SDSS-IV completes

BLACK HOLE MAPPER: BHM



BLACK HOLE MAPPER:
UNDERSTANDING BLACK HOLE GROWTH



BHM Time-Domain Survey Outline

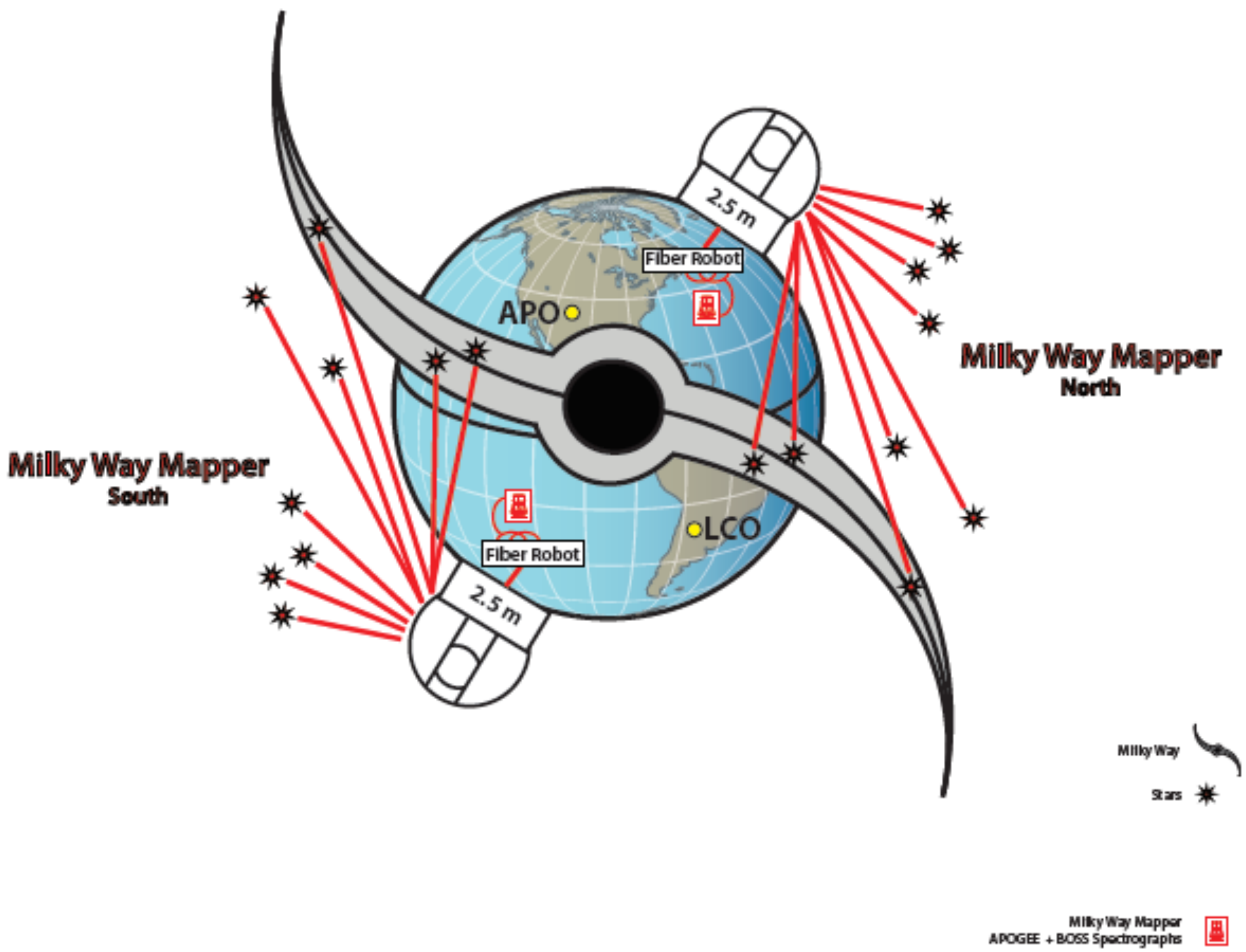
Spectral time-domain astrophysics of quasars: BH masses, binarity, accretion and events, BLR dynamics, outflows, etc. Broad range of time-sampling/cadence, days to decades.

- For >20,000 quasars, 2-3 epochs during AS4 plus earlier-epoch SDSS spectra, sampling ~1-10 year timescales, e.g., transition times of changing look quasars, BAL disappearance and emergence, etc. *(wide/low-cadence tier; ~3000 deg^2).*

- For >2000 quasars, 12 epochs during ~2 years of AS4, probing down to ~1-month to 1-year timescales, adding unfolding BLR structural and dynamical changes *(medium tier; ~300 deg^2)*.

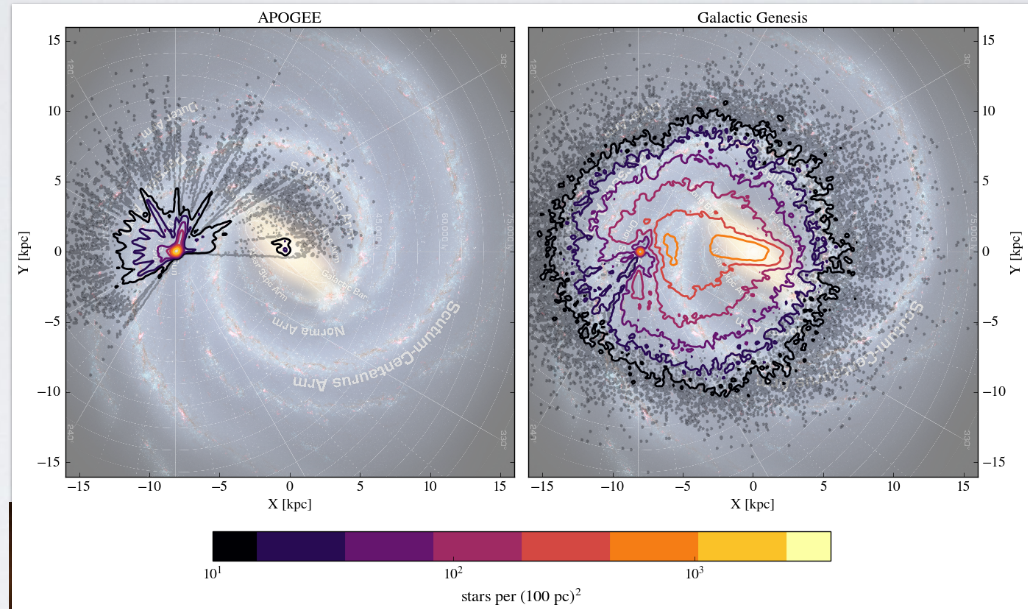
- Reverberation mapping (RM) for ~1000 quasars in 5 fields, >10^2 epochs, sampling down to days to weeks; lags between continuum and BLR emission yield BH masses; premier RM sample at high L, z. (high-cadence tier; ~30 deg^2)

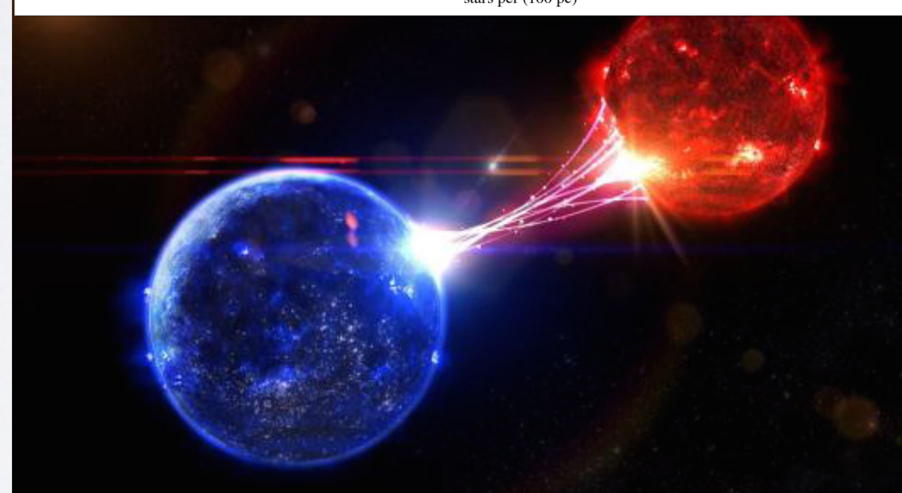
Milky Way Mapper: MWM

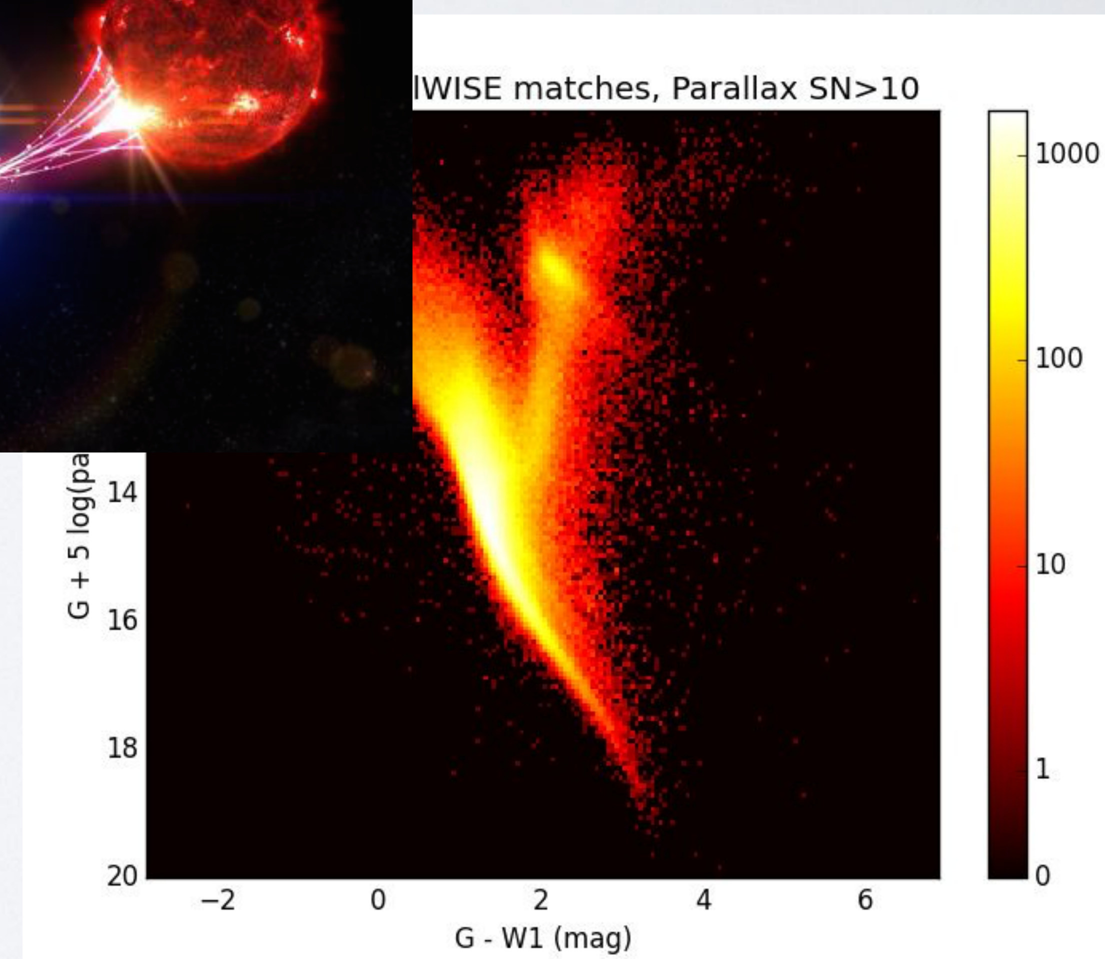


SCIENCE GOALS (GENERAL)

- **1) How did the Milky Way's disk form?**
- **2) How do stars live, evolve, and die (and affect transient/GW universe)?**
- **3) What stars host planets?**
- **4) What IS the stellar multiplicity across the HR diagram? Role of binaries in Stellar Evolution**
- **5) Origin of Supernovae and the heavy elements**



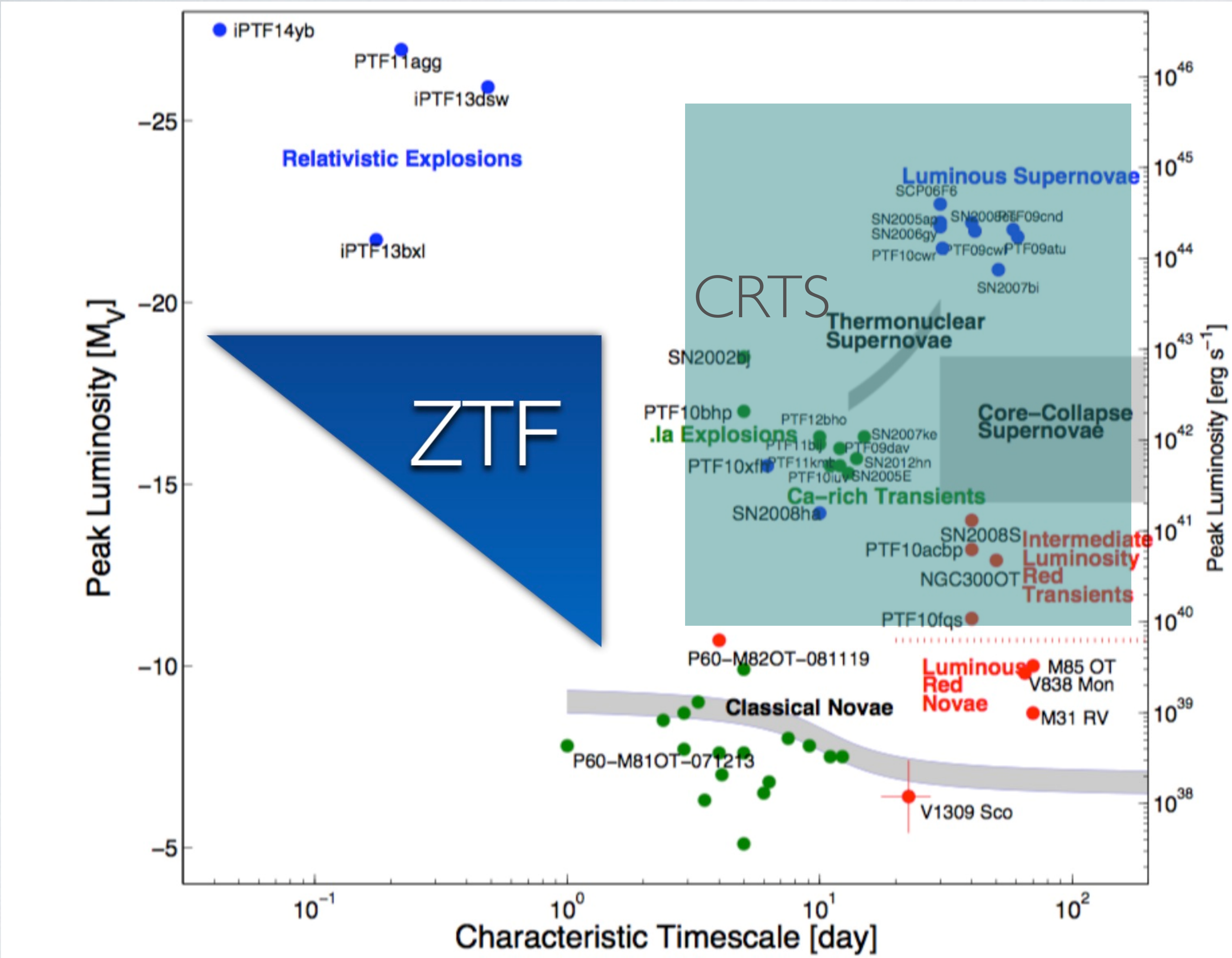




From D. Lang

Galactic Genesis & Stellar Astrophysics Targeting Classes				
Instrument	**Selection**	$\mathbf{N_{Targets}}$	$\mathbf{N_{Epochs}}$	**Comments**
Galactic Genesis Survey: mapping the dusty disk				
APOGEE	$H<11$, $G-H>3.5$	4,800,000	1	dust-extinguished disk
APOGEE	$\lvert z\rvert < 200$ pc, $H<11$, d<5 kpc	125,000	1	to complete high-res ISM map
Binaries with Compact Objects: enumerating the populations of binaries with white dwarfs, neutron stars, or black holes, selected by variability				
BOSS	PTF, ZTF, *Gaia* variability	30,000	3	binaries with WDs, NSs, and BHs
BOSS	*Gaia* parallaxes	30,000	1	wide WD+MS/RGB binaries
Solar Neighborhood Census: observing all stars within 100 pc, giving the best probe of low-mass stars, whether in single or binary systems				
APOGEE, BOSS	d<100 pc, $G<20$, $H<12$	400,000	2	1000× increase in volume & stars
White Dwarf Chronicle: using white dwarfs and their evolved companions to measure the SFH and age-metallicity relation				
BOSS	$G<20$	300,000	3	15× increase in sample size
TESS Exoplanet Host Candidates: observing all TESS short-cadence targets in the CVZs				
APOGEE	$H \leq 13.3$	300,000	1–8	all short-cadence targets & planet hosts
Binaries Across the Galaxy: measuring environmental dependence of binary fraction in the disk, bulge, halo, and stellar clusters; probing the brown-dwarf desert beyond solar-type stars				
APOGEE	$H<13.4$, $N_{Epoch} \geq 6$ by the start of SDSS-V	60,000	6–18	gives orbits with 24–40 epochs for all targets with long APOGEE baselines
Gaia Astrometric Binaries: characterizing rare systems that have good astrometric orbits but limited other information, from *Gaia*'s sample of > 10 million stars				
APOGEE, BOSS	$d<3$ kpc	200,000	1	rare types of systems
TESS Red Giant Variability: measuring spectroscopic properties for red giants in TESS that have seismic and/or granulation lightcurve signatures				
APOGEE	$H<12.5$	250,000	1	stars with at least 80 days of TESS observation
Massive, Convective Core Stars: combining dynamic and asteroseismic measurements of binary OBAF stars in the TESS CVZs and characterizing their multiplicity				
APOGEE	$H<12$	200,000	2	detection of single vs. binary systems
APOGEE		500	25	>10× increase in current sample size
Young Stellar Objects: quantifying the stellar populations in star-forming regions, including identifying sources of ionizing radiation and characterizing the binary frequency				
APOGEE	$H<12$, $d<1$ kpc	20,000	12	nearby star-formation regions
APOGEE	$H<12$	3,500	8	high-mass star-formation regions
APOGEE	$H<12$, $\lvert b\rvert<2°$	10,000	2	massive young stars in the Galactic Plane
APOGEE	$H<13$	10,000	2	Central Molecular Zone

TRANSIENTS!



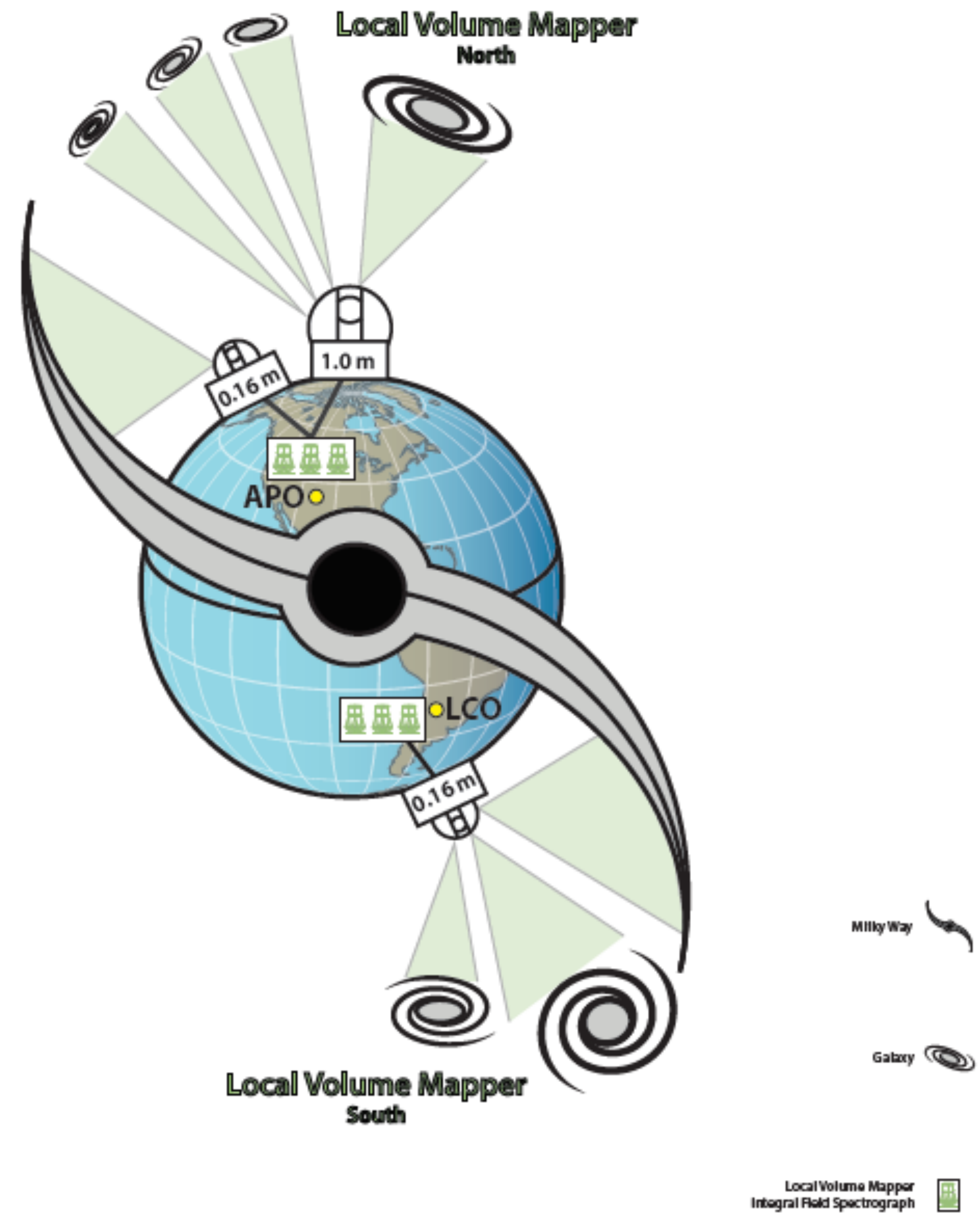
Wouldn't it be nice to settle BASIC questions like: What are Type Ia SNe (and what are they NOT)?

B. Penpraese

Local Volume Mapper: LVM

Using different telescope sizes of and an array of IFU-coupled spectrographs at $R\sim4000$ and 3600-10000Å, we survey

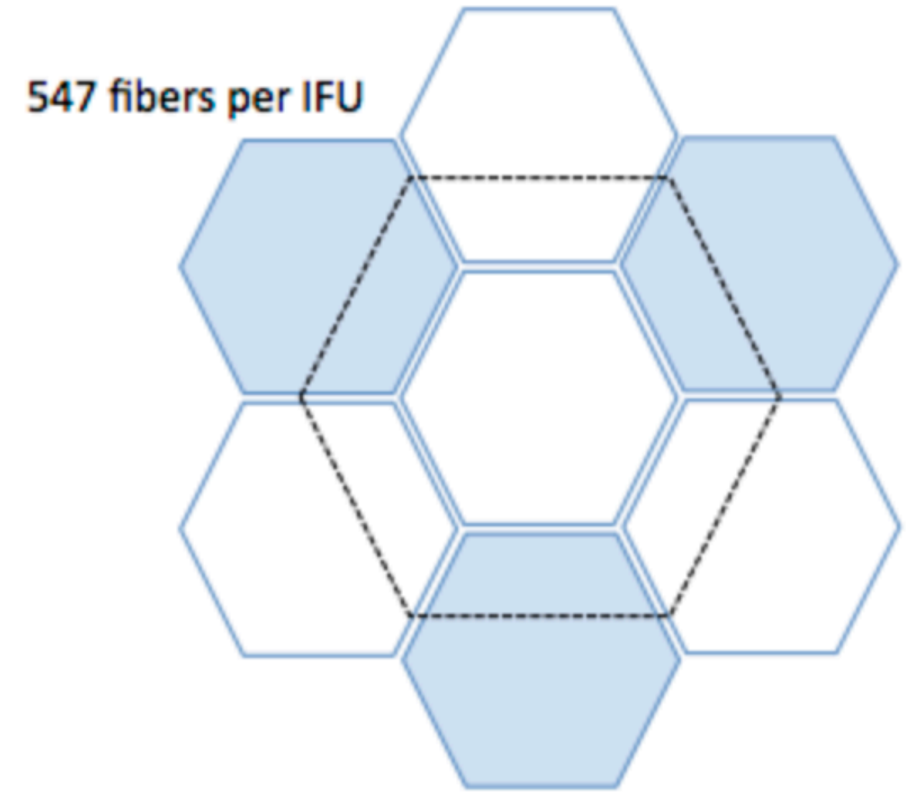
- 2800 sq. deg. in the MW @ 0.1-1 pc resolution,
- 300 sq. deg. in the MW 10x deeper,
- LMC & SMC @ 10 pc resolution,
- M31 & M33 @ 20 pc resolution, and
- 12 nearby galaxies (D≲5 Mpc) @ 50 pc resolution

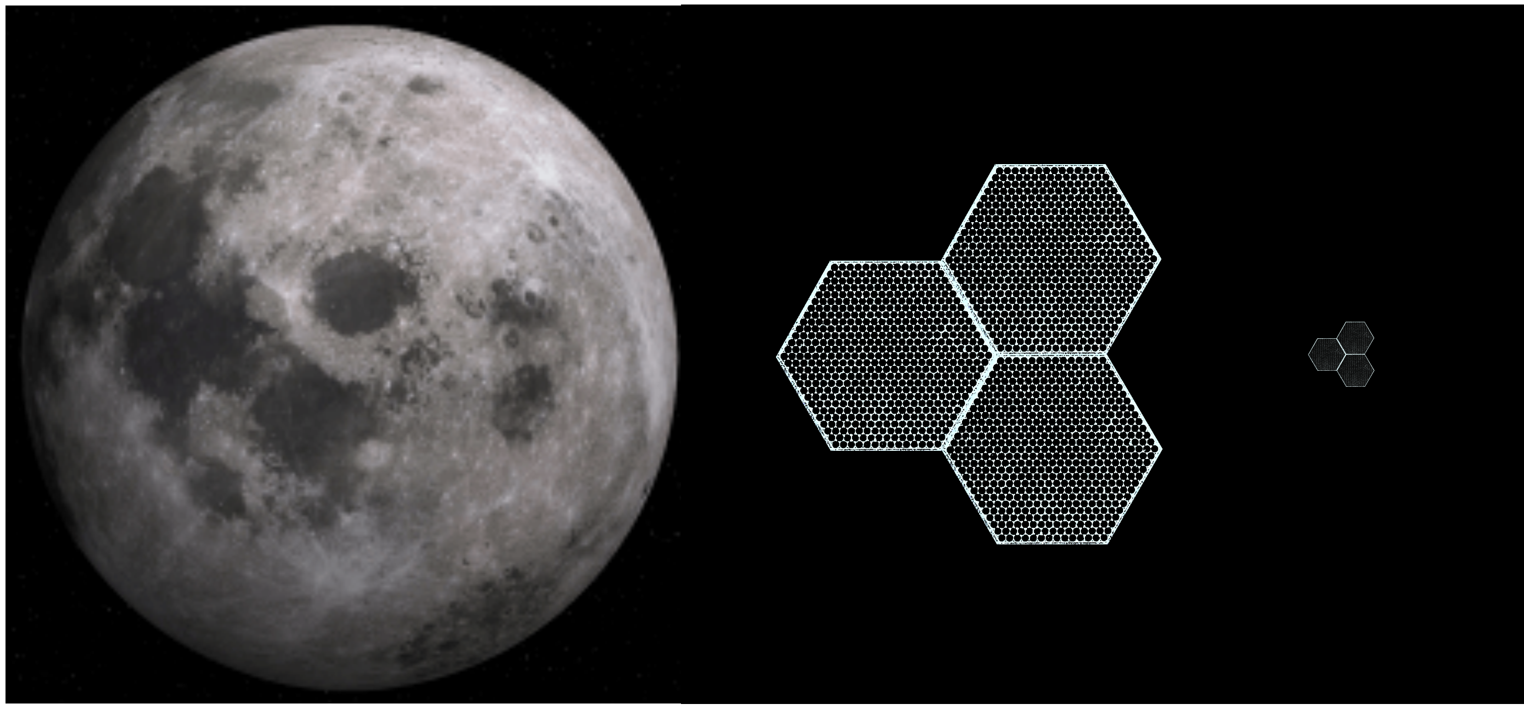


LVM hardware

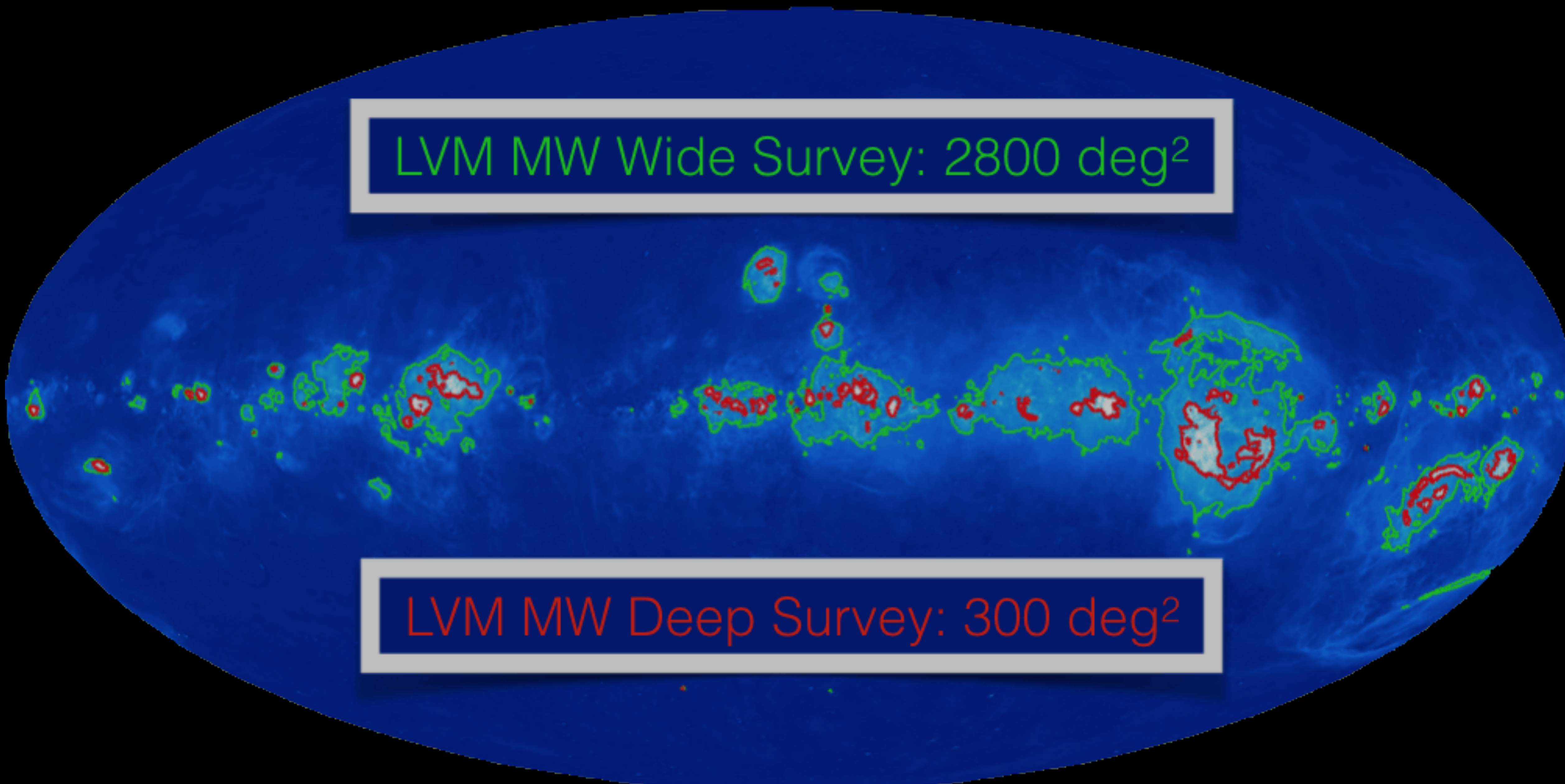
IFU design

* 3 x 547 hexagonal non-abutted lenslet coupled IFUs arrays.
* 309 calibration fibres.
* Based on highly-successful MaNGA design.
* 490 arcmin2 @ 0.16 m
* 12 arcmin2 @ 1 m





OBSERVING GALAXIES AT THE "ENERGY INJECTION SCALE"



Cosmological Zoom-In Observations!

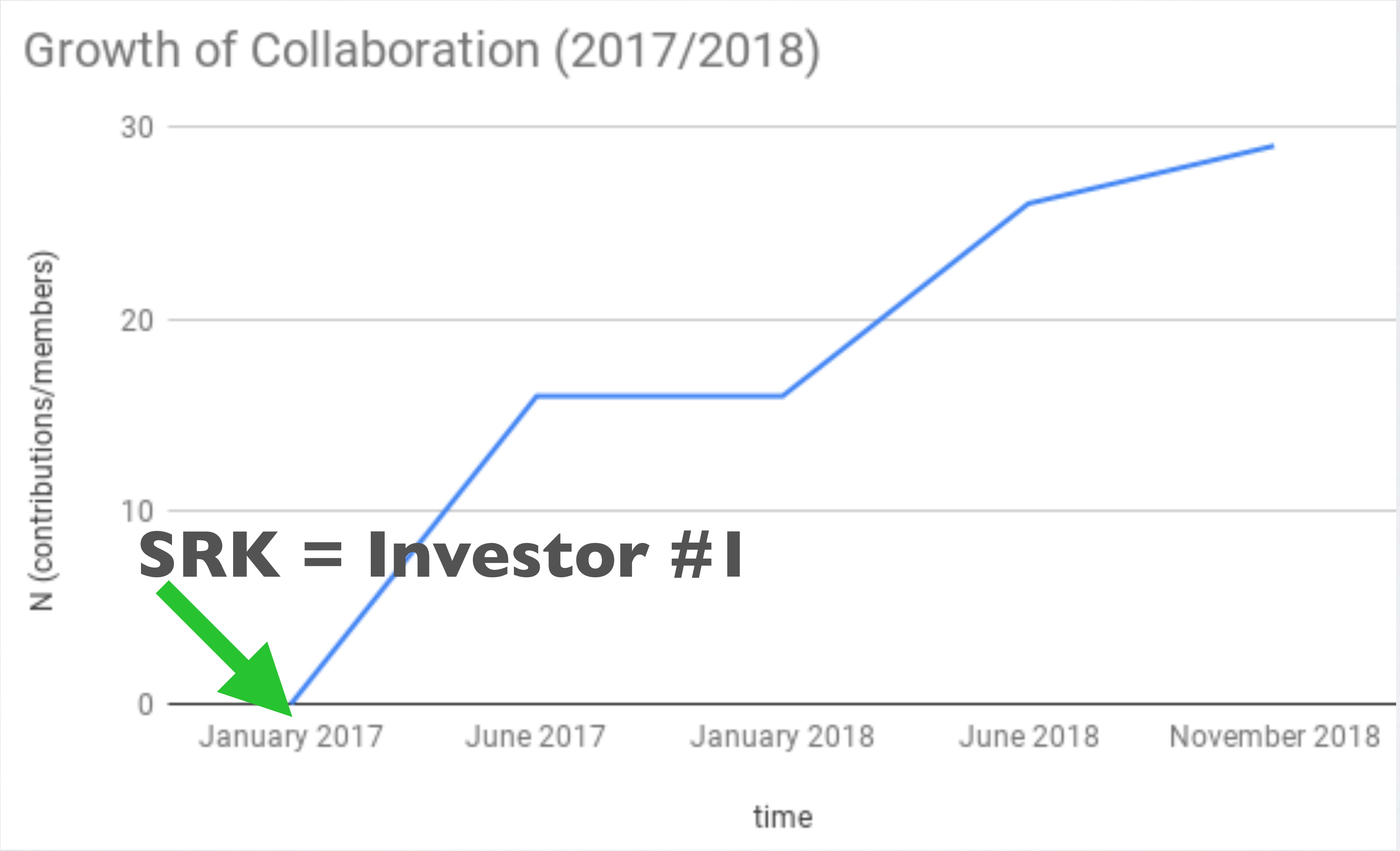
Orion

- M42 0.07 pc / spaxel
- APOGEE stars (yellow)
- Combine information from gas and stars to map the interaction between stars and ISM
- Have Teff, L, Z, [X/H], f_{UV}, (age) for each star
- Gas: temperature, density, kinematics, abundances

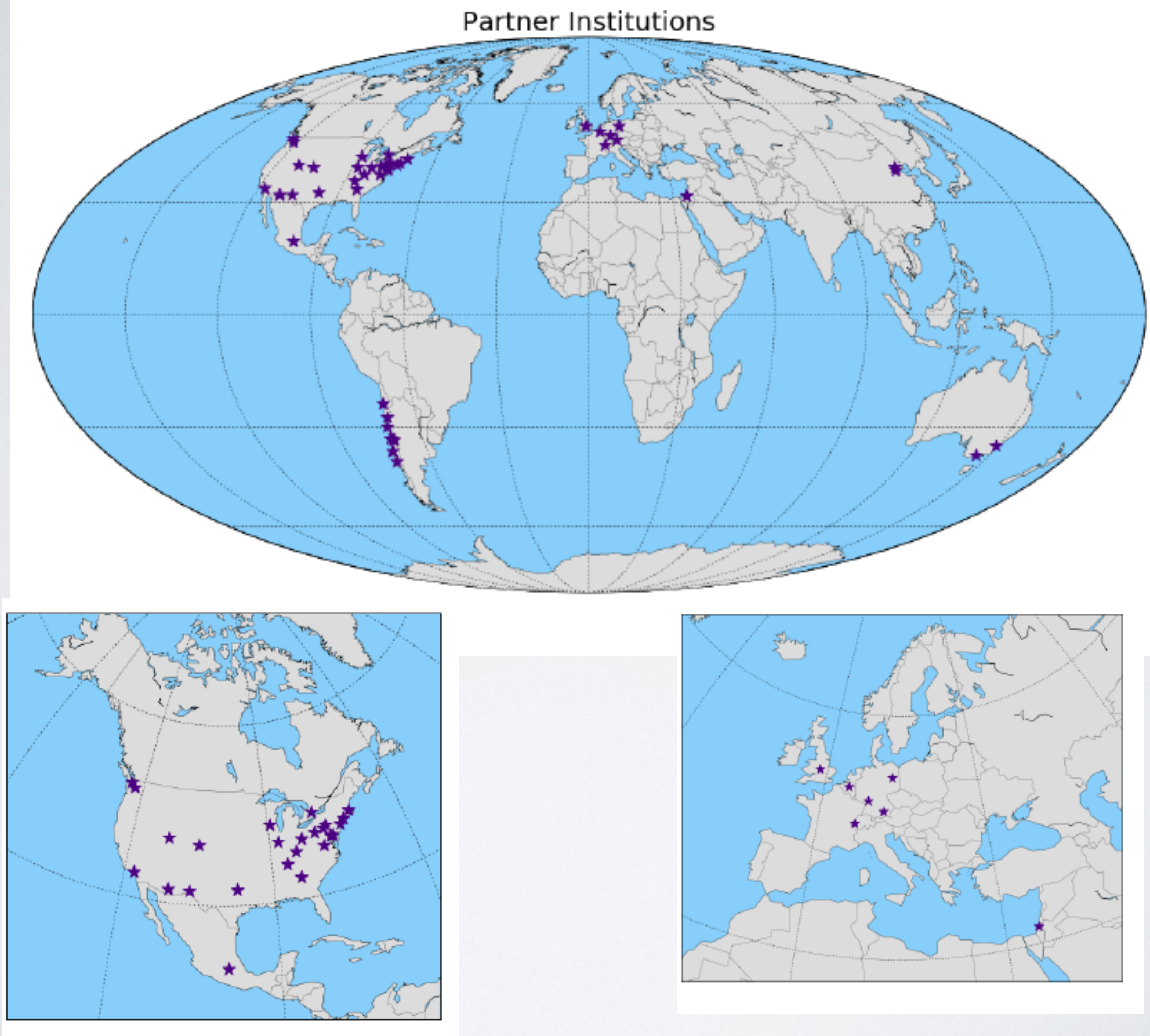
Images: ESO 2.2m

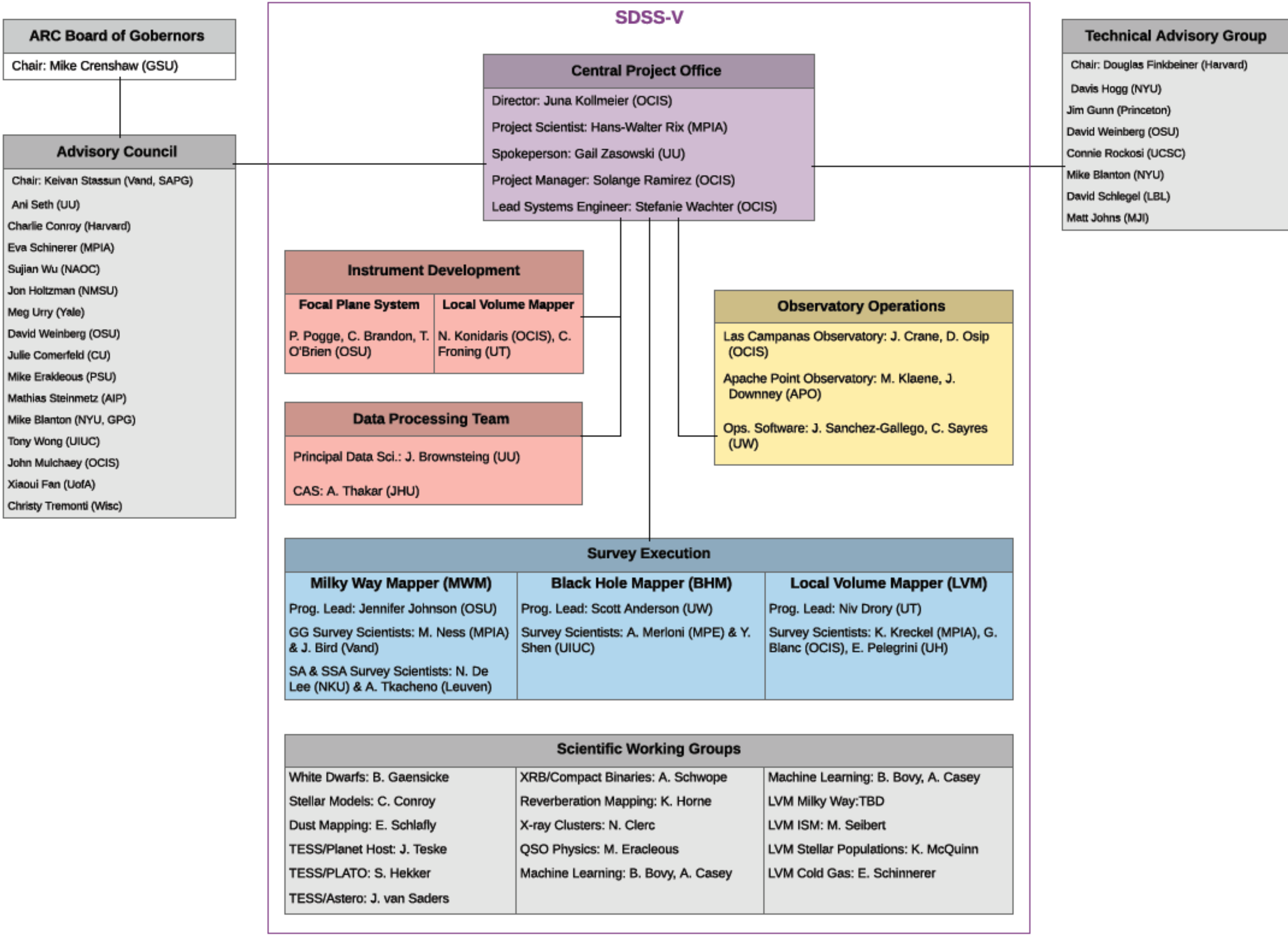
INSTITUTIONAL PARTNERSHIP

GROWTH OF COLLABORATION



SDSS Collaboration Matrix	MOU Signed/Out for Signature	MOU in Draft/Iteration	Prospective Institutions
FULL MEMBERS	CU Boulder Harvard MPE MPIA NMSU OSU NAOC Yale CNTAC	Carnegie Wisconsin STSCI UofA JHU UNAM U of Toronto SAO	NOAO INAF
3 Slot Members	AIP PSU Flatiron UIUC	UVA	Caltech MIT
Individual (1/2) slot Members	University of Washington (2) TCU, TAU (2) Vanderbilt, KIAA, U. Warwick, NYU, KU Leuven, Columbia, U. Penn,York University, University of Victoria, U. Pittsburgh, Georgia State	Monash University EPFL ANU	Oxford St. Andrews Nanjing U. SHAO


Partner Institutions


ARC Board of Gobernors
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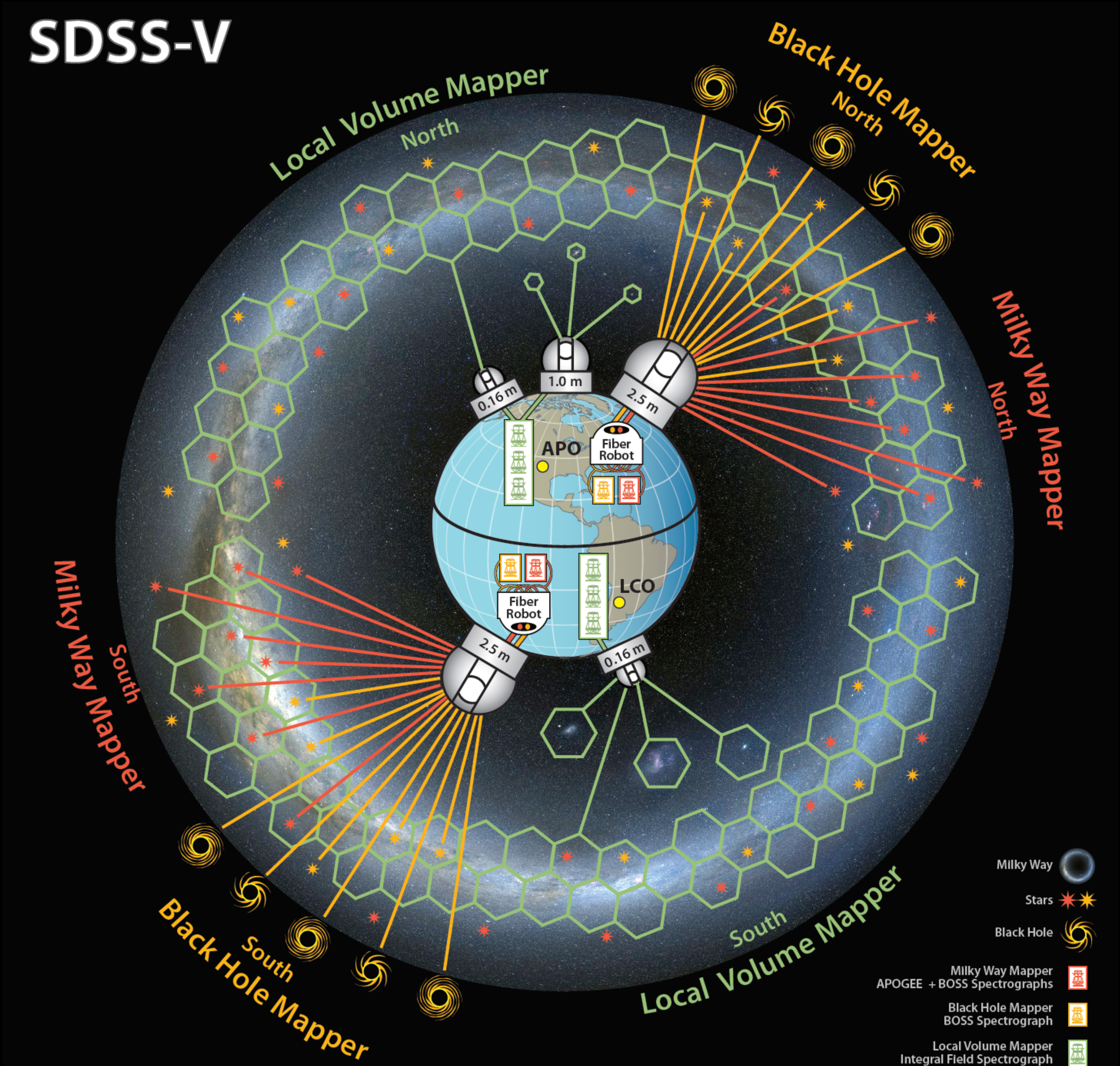
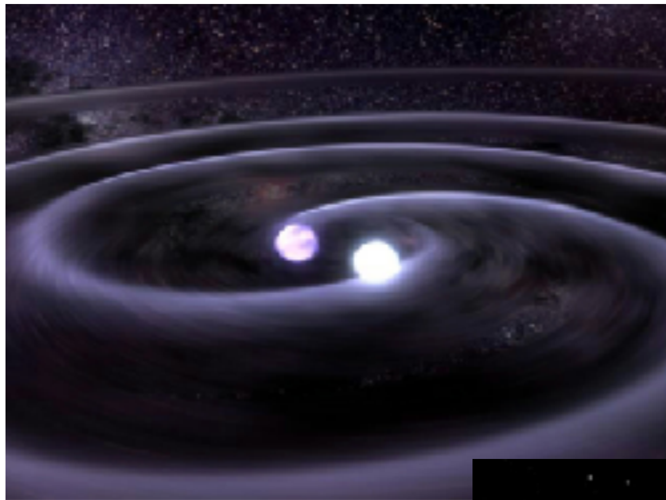
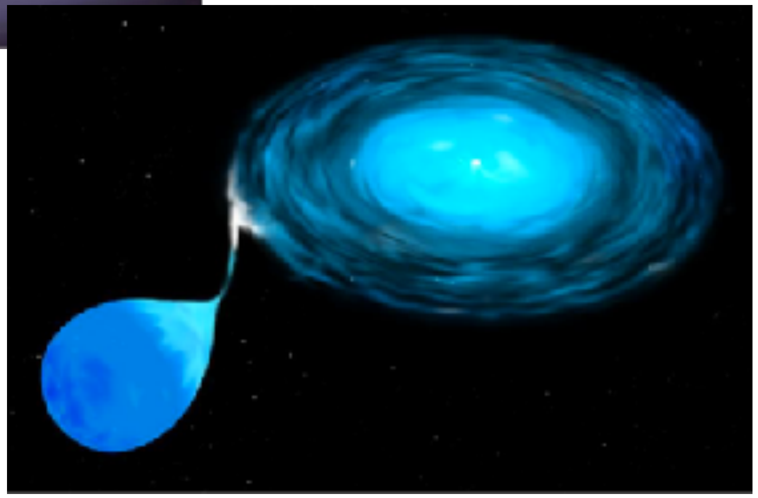
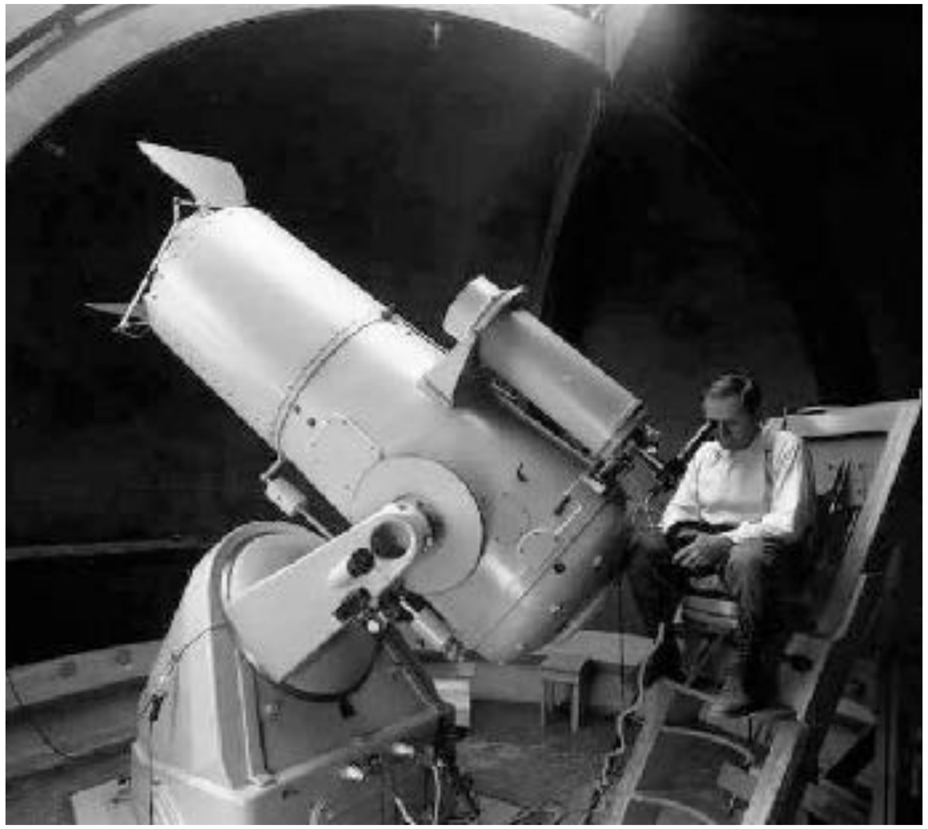
Survey Execution
Milky Way Mapper (MWM)
Prog. Lead: Jennifer Johnson (OSU)
GG Survey Scientists: M. Ness (MPIA) & J. Bird (Vand)
SA & SSA Survey Scientists: N. De Lee (NKU) & A. Tkacheno (Leuven)
Black Hole Mapper (BHM)
Prog. Lead: Scott Anderson (UW)
Survey Scientists: A. Merloni (MPE) & Y. Shen (UIUC)
Local Volume Mapper (LVM)
Prog. Lead: Niv Drory (UT)
Survey Scientists: K. Kreckel (MPIA), G. Blanc (OCIS), E. Pelegrini (UH)
Scientific Working Groups
White Dwarfs: B. Gaensicke
Stellar Models: C. Conroy
Dust Mapping: E. Schlafly
TESS/Planet Host: J. Teske
TESS/PLATO: S. Hekker
TESS/Astero: J. van Saders
XRB/Compact Binaries: A. Schwope
Reverberation Mapping: K. Horne
X-ray Clusters: N. Clerc
QSO Physics: M. Eracleous
Machine Learning: B. Bovy, A. Casey
Machine Learning: B. Bovy, A. Casey
LVM Milky Way:TBD
LVM ISM: M. Seibert
LVM Stellar Populations: K. McQuinn
LVM Cold Gas: E. Schinnerer


SDSS-V
Local Volume Mapper
North
Black Hole Mapper
North
Milky Way Mapper
North
0.16 m
1.0 m
2.5 m
APO
Fiber Robot
LCO
Fiber Robot
2.5 m
0.16 m
Milky Way Mapper
South
Black Hole Mapper
South
Local Volume Mapper
South
Milky Way
Stars
Black Hole
Milky Way Mapper
APOGEE + BOSS Spectrographs
Black Hole Mapper
BOSS Spectrograph
Local Volume Mapper
Integral Field Spectrograph

Exotic variables from ZTF







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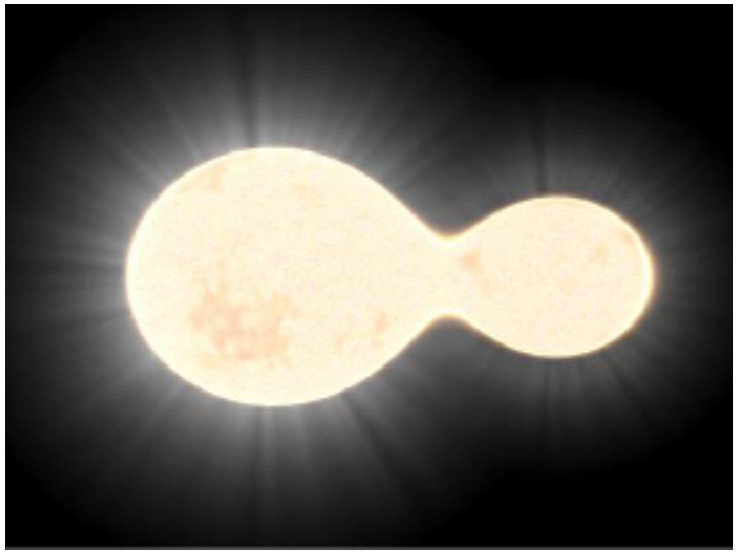
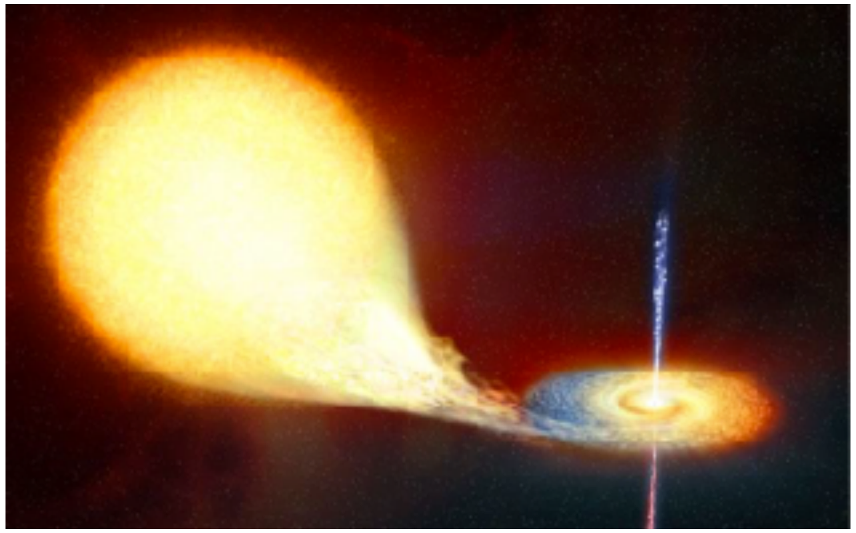
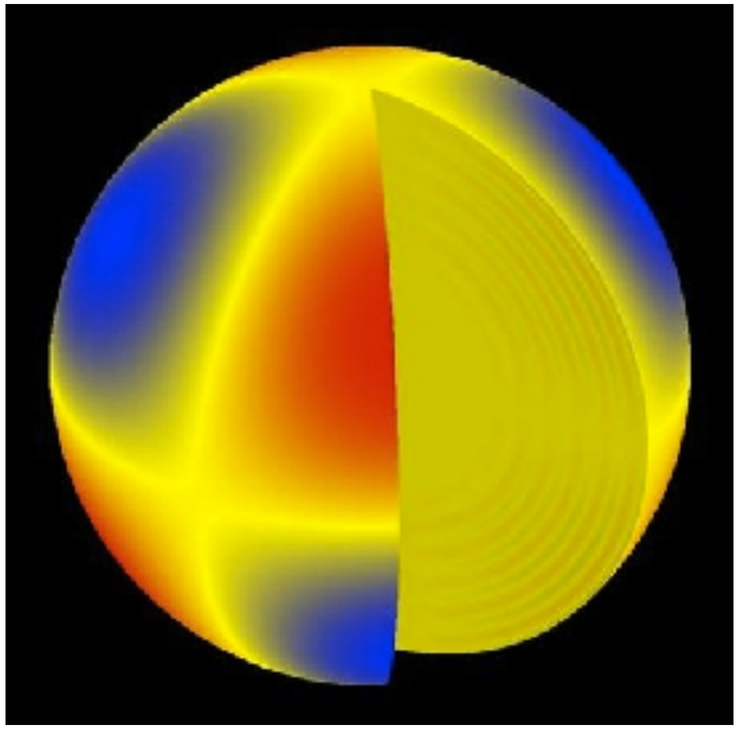
University of California, Santa Barbara

Zwicky Transient Facility

Stellar variability is very common







How did we find them

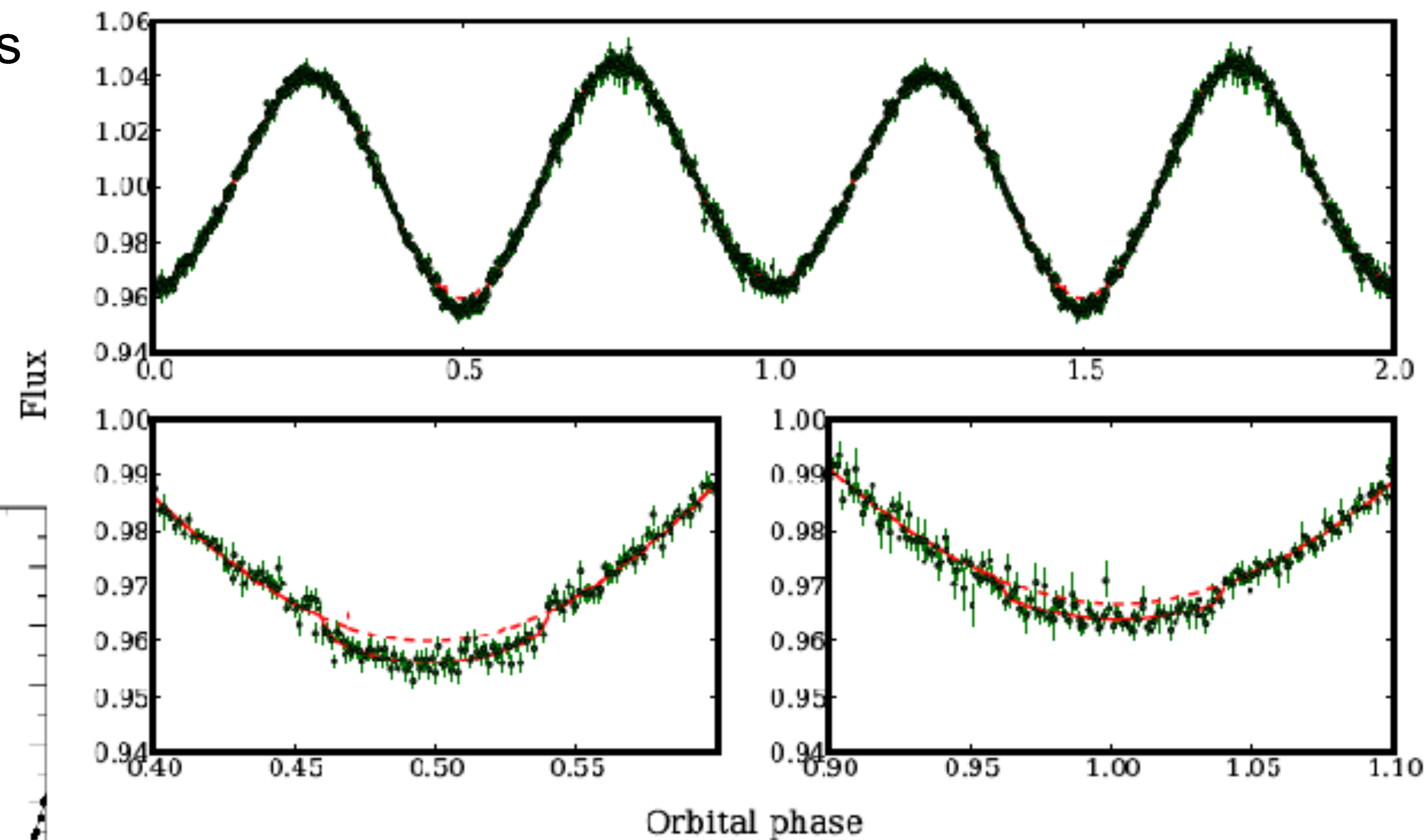
CD-30 11223 - SN Ia progenitor candidate (P_{orb} = 70min) - found completely serendipitously

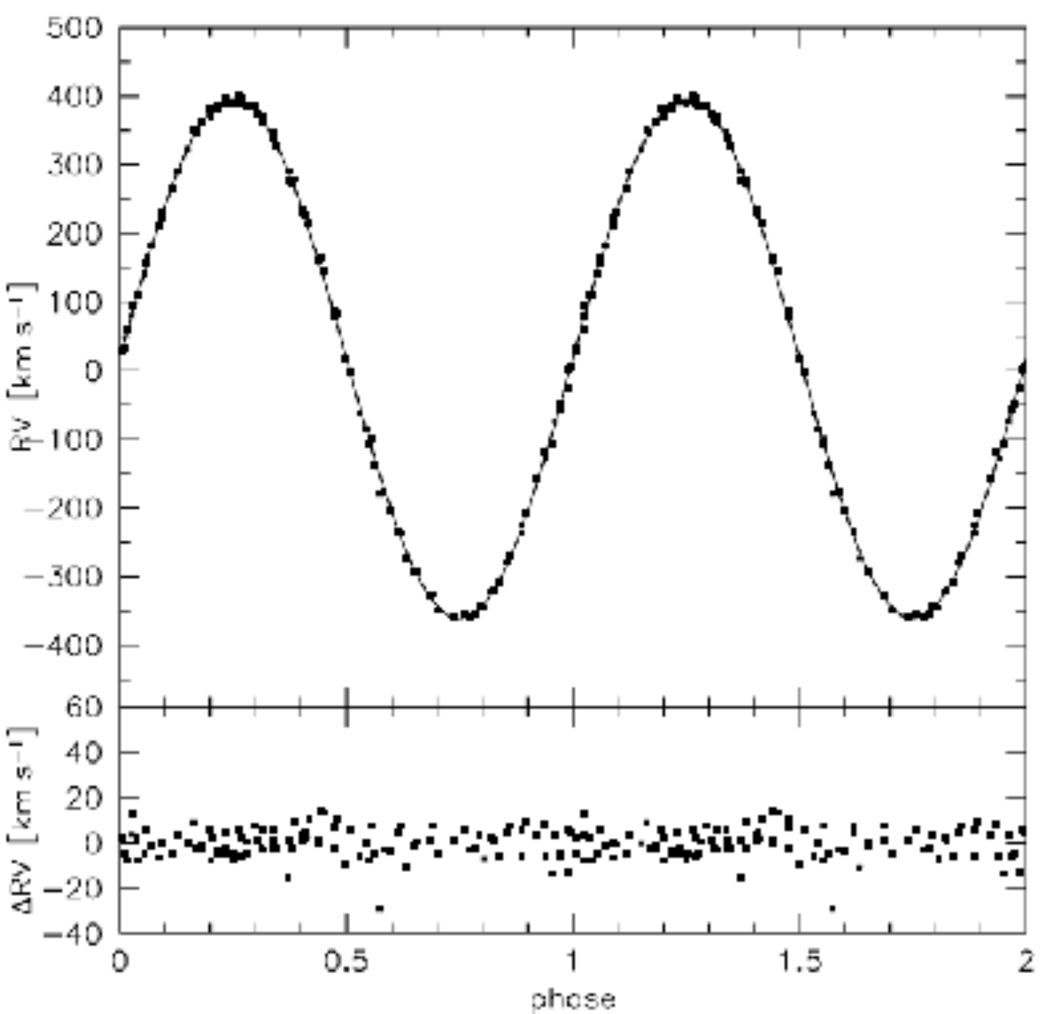
- Lightcurve shows weak eclipses
- Analysis gives:

M_{sdB} = 0.54 M_{sol}; M_{WD} = 0.74 M_{sol}

=> Progenitor system most likely

3 + 4 M_{sol} binary





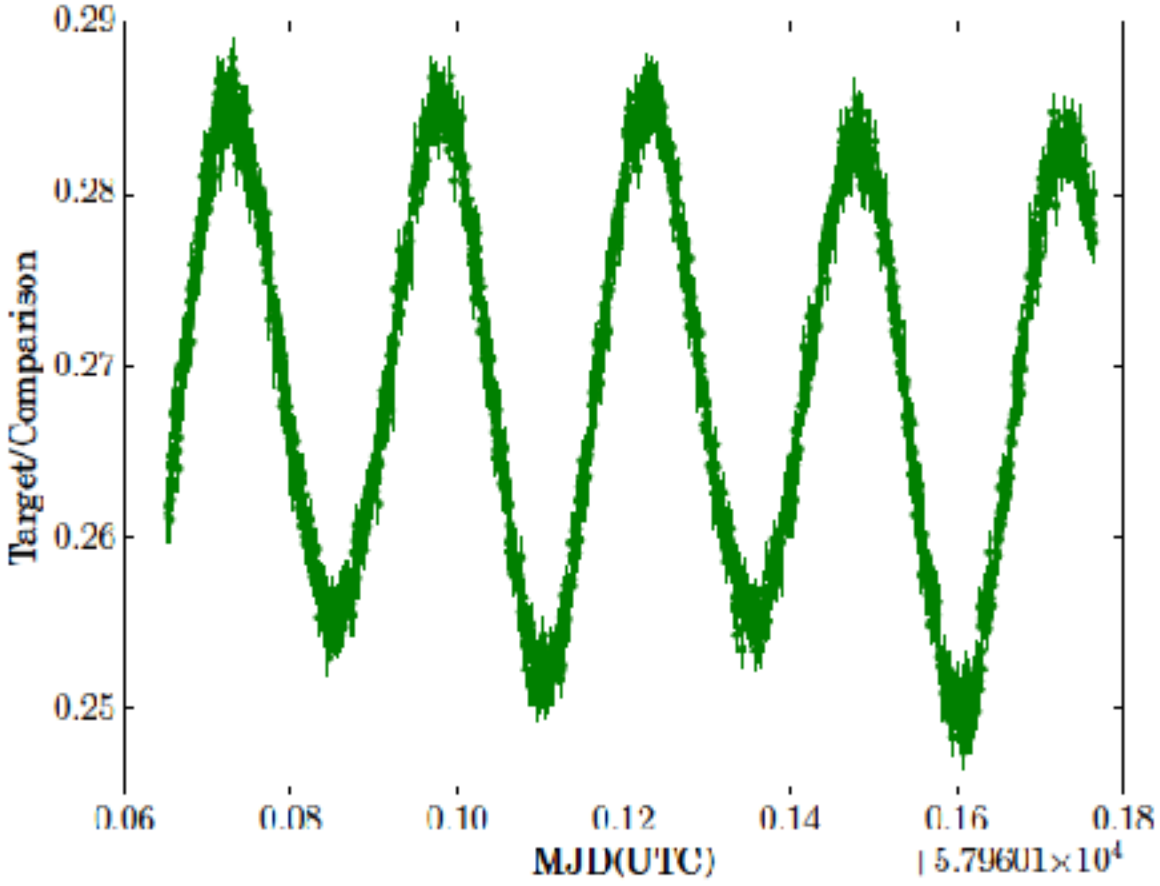
Will get in contact in about 40 Myr

Will probably explode as SN Ia??

Look for the freaks

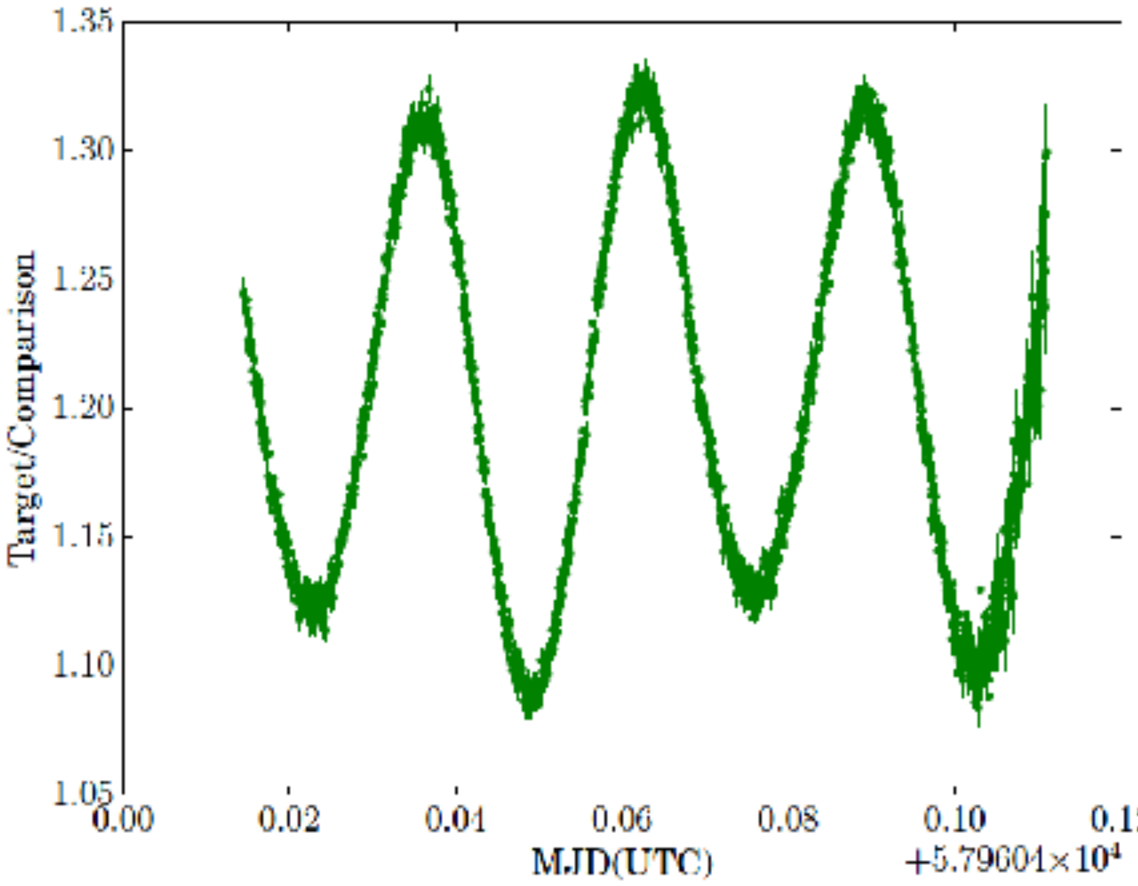
Two new CD-30 like systems from PTF - Parameter (very preliminary)

PTFS1 J1821 (b=13.9deg)



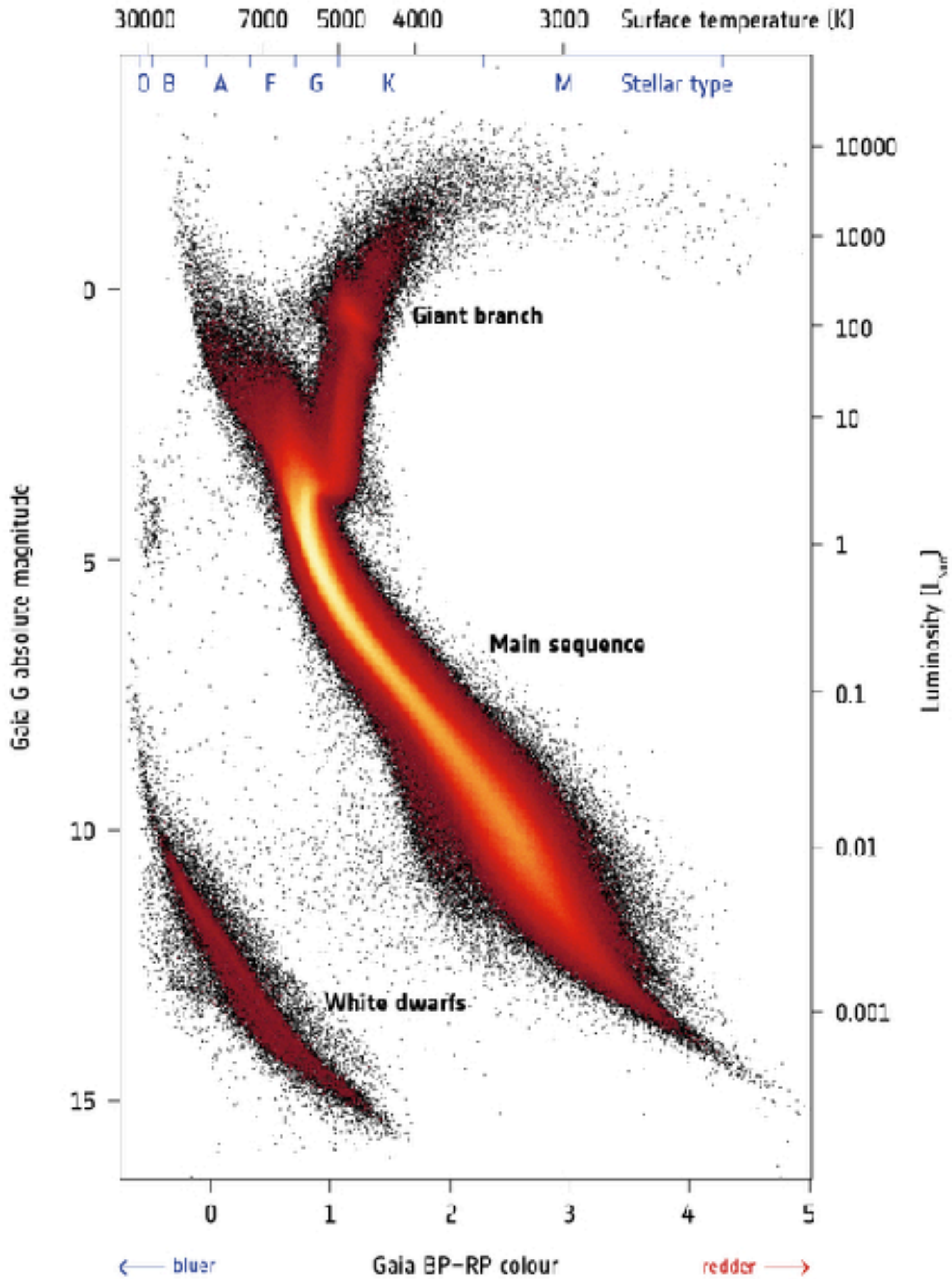
- **P_{orb} = 72.1 min**
- M_{sdB} ~ 0.40 M_{sun}
- M_{WD} ~ 0.65 M_{sun}

PTFS1 J2238 (b=8.9deg)



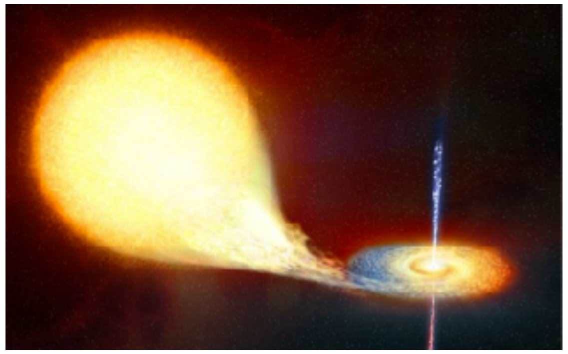
- **P_{orb} = 76.3 min**
- M_{sdB} ~ 0.35 - 0.4 M_{sun}
- M_{WD} ~ 0.7 - 0.8 M_{sun}

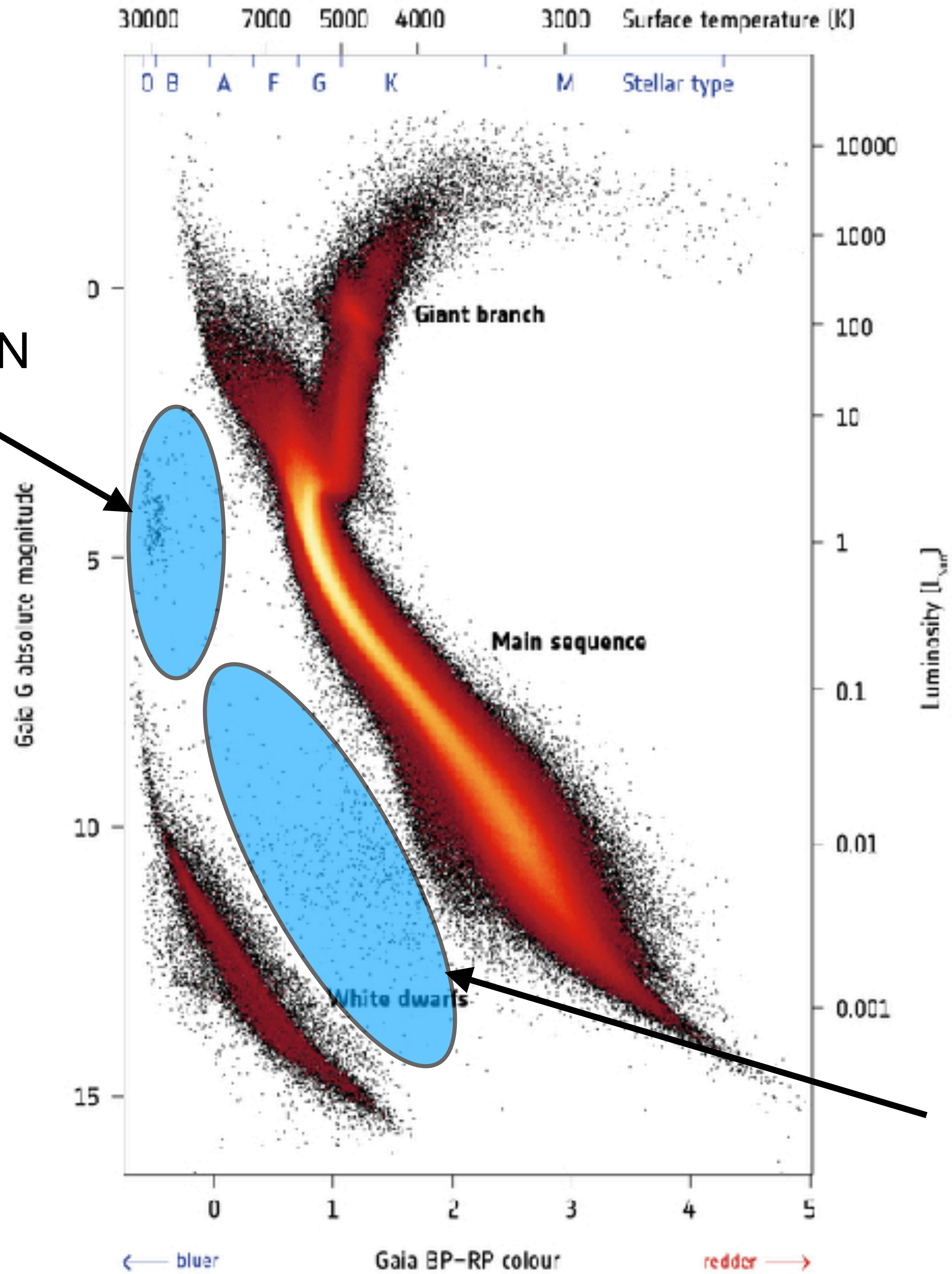
Look for the freaks

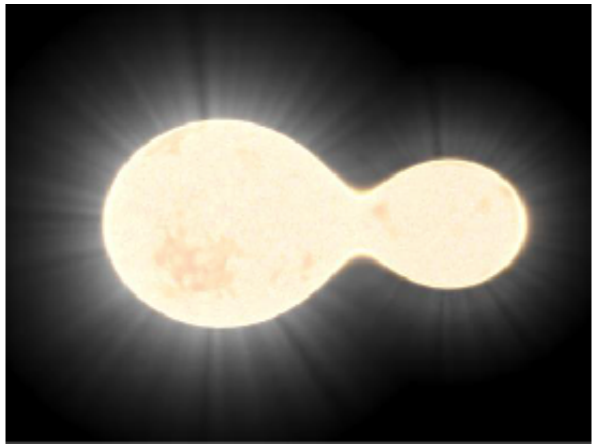


The population of freaks

- hot subdwarfs
- post AGB stars
- AMCVns
- hot pre-WDs
- central stars of PN



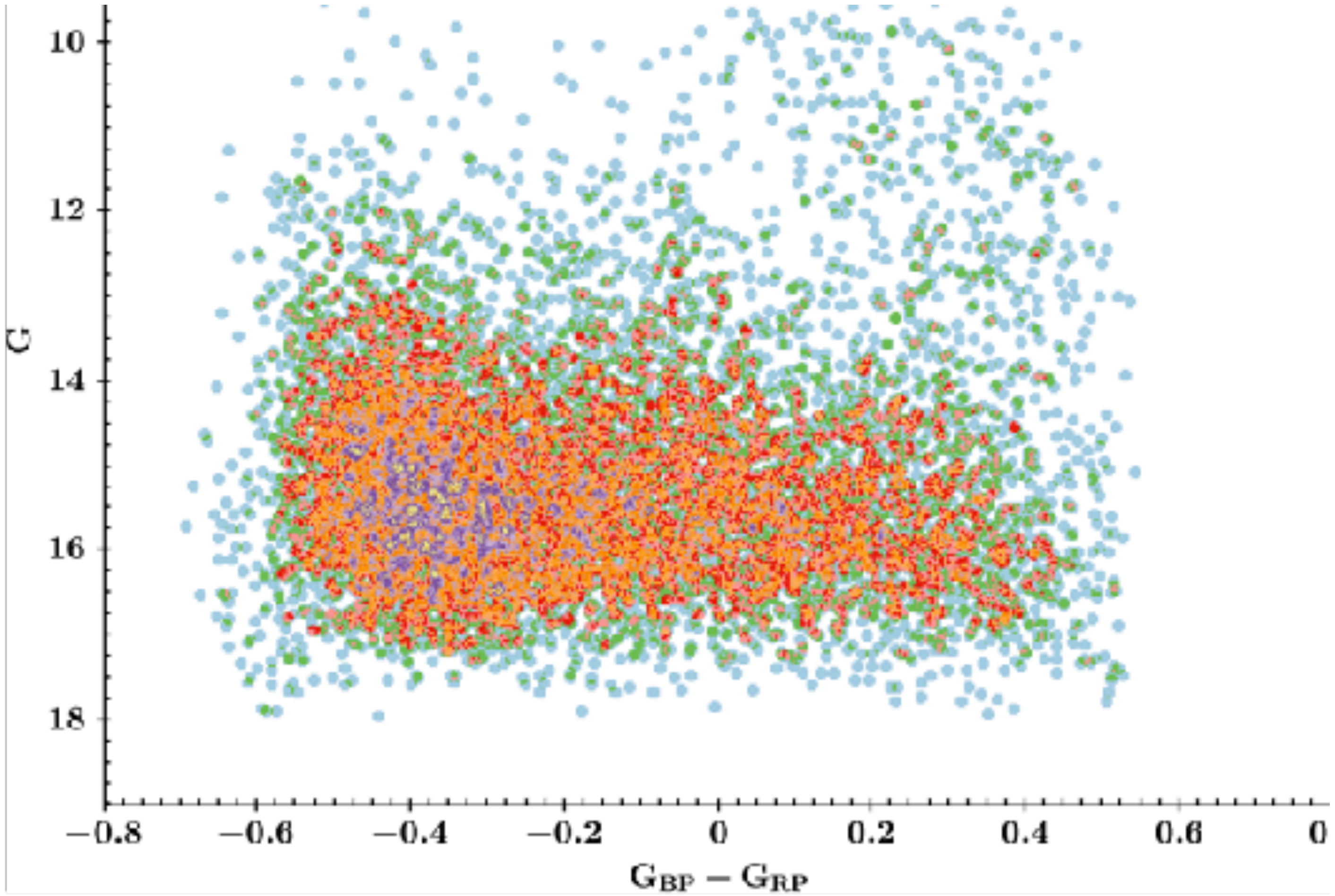


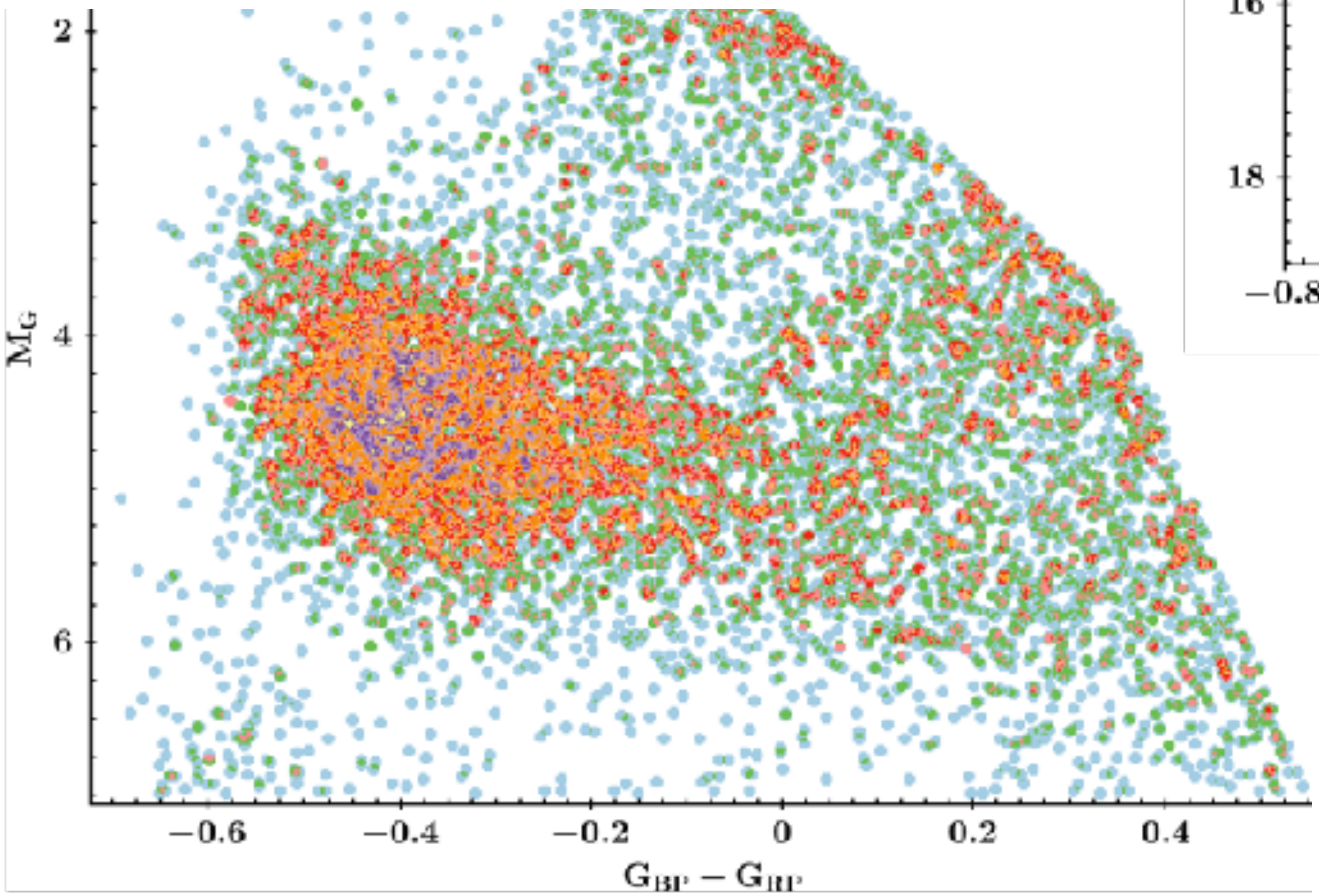


- cataclysmic variables
- extremely low mass WDs
- SN Ia(x) remnants

The sample of hot subdwarf stars

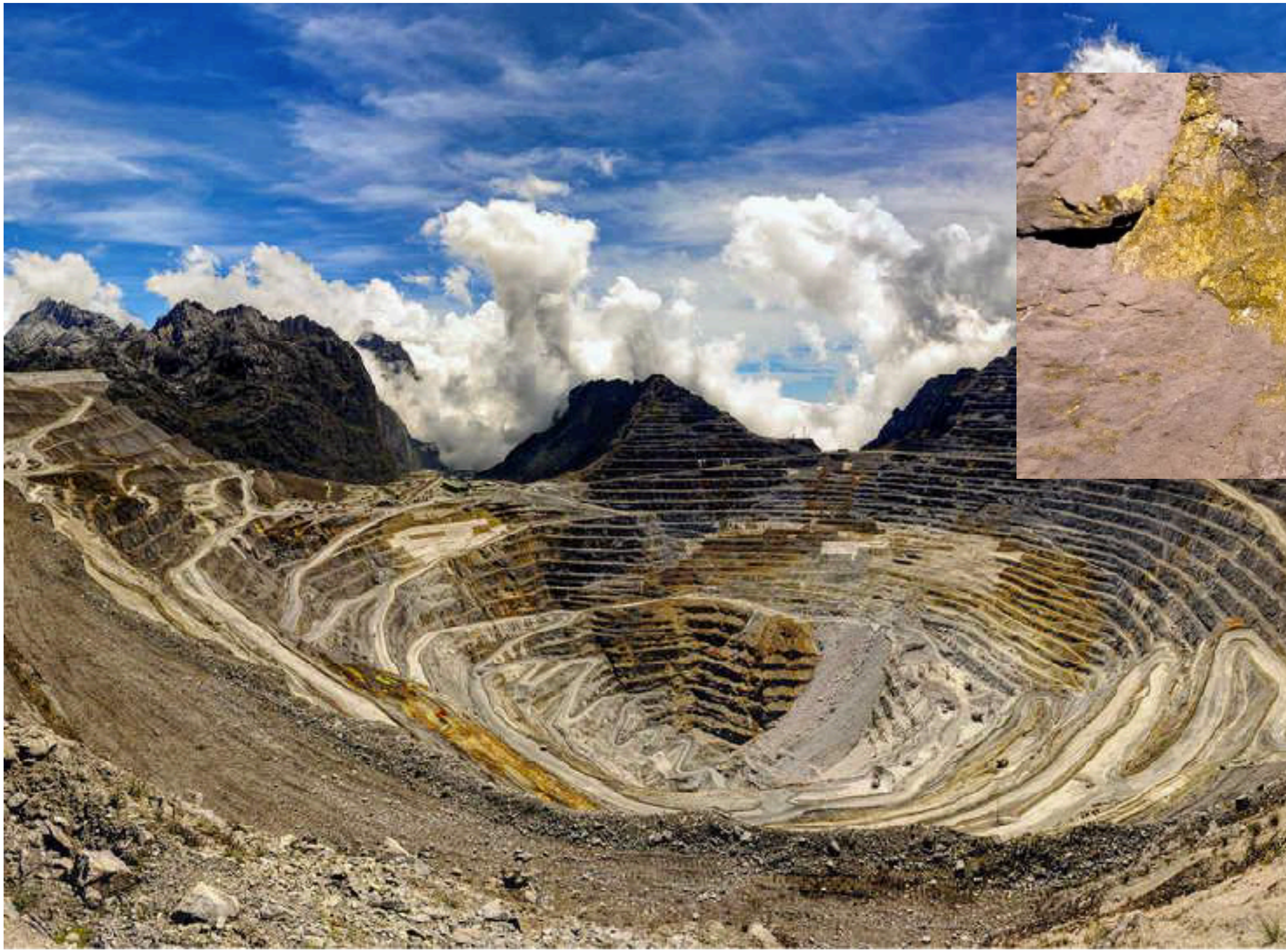
- **Selection based on:**
  - previously classified
  - parallax
  - reduced proper motion

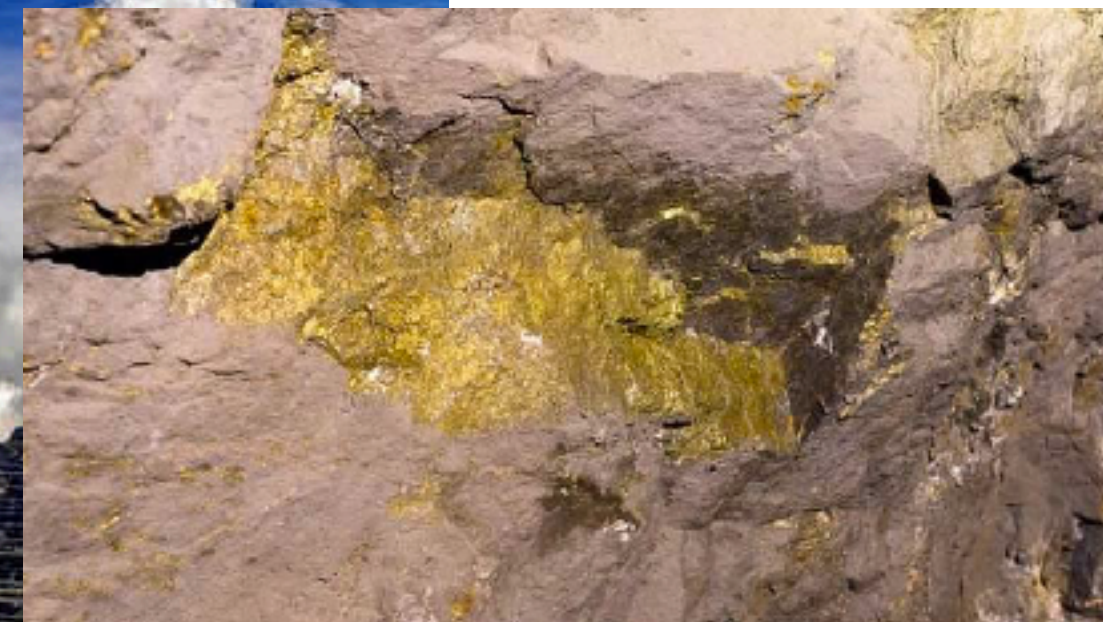




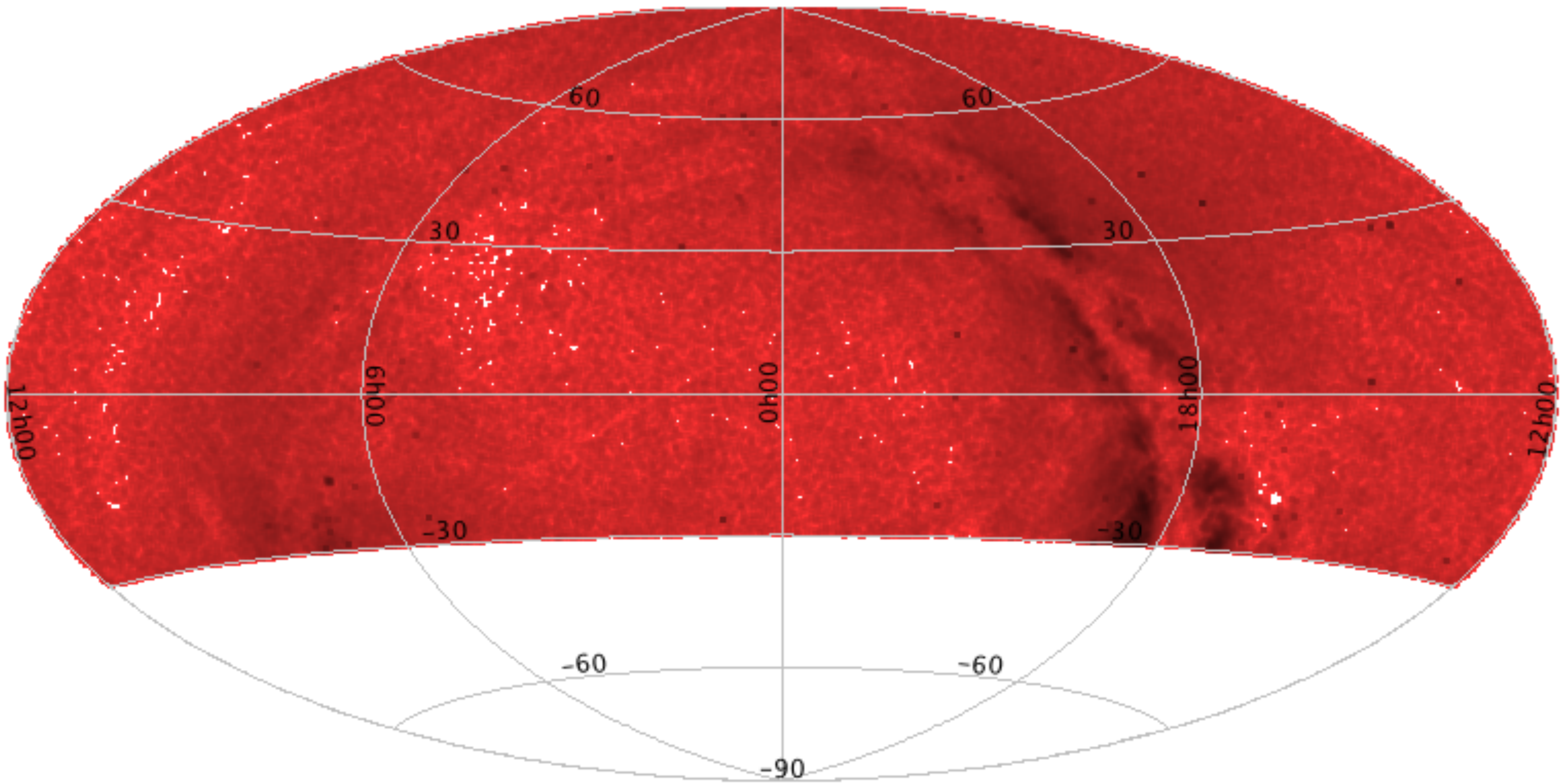
- **Numbers:**
  - about 9000 selected on parallax
  - Total sample ~40 000

Data mining





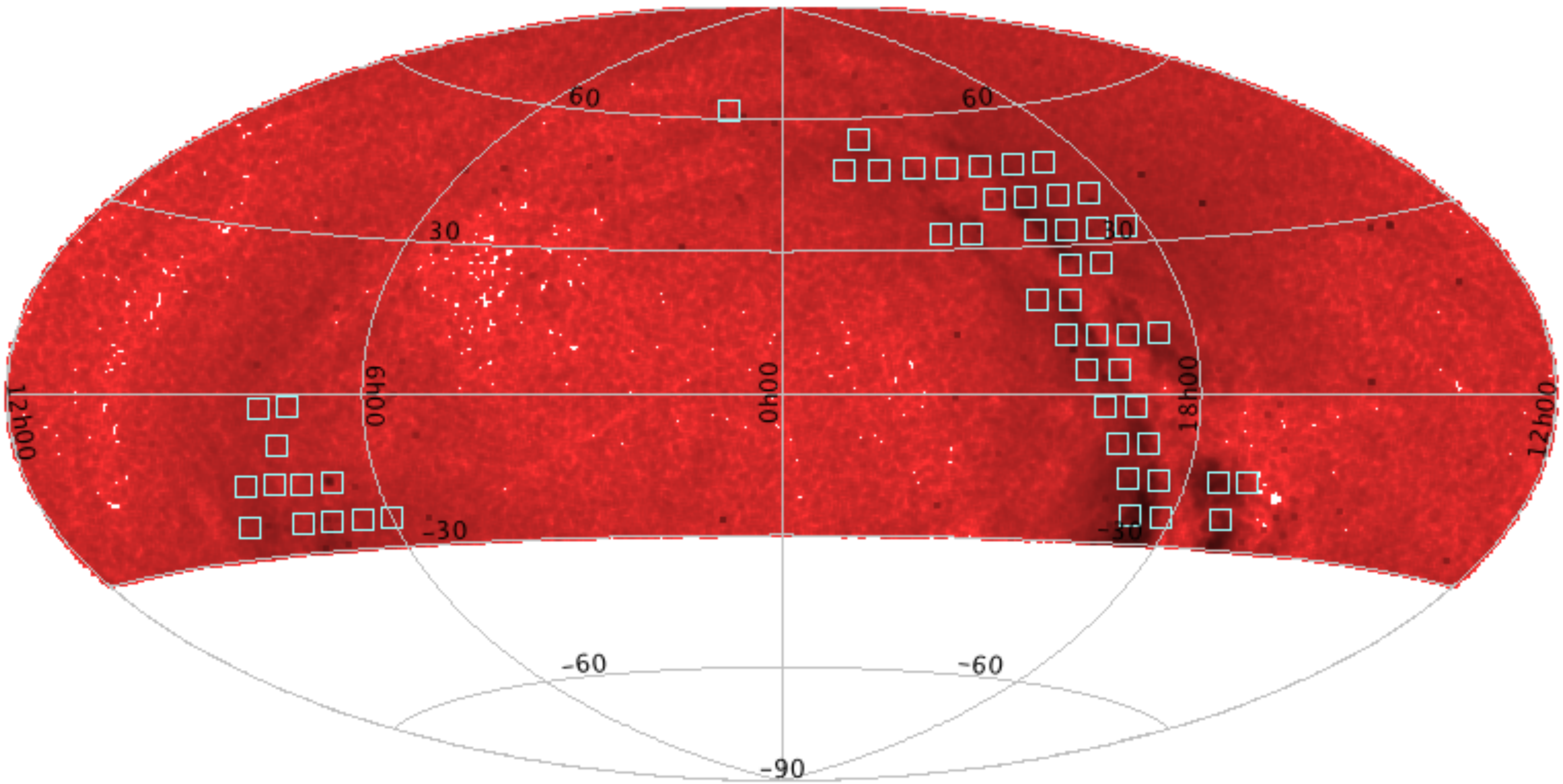
The ZTF high-cadence Galactic Plane survey



The fast and the furious - A fast cadence survey of the Galactic Plane

- **Time period:** mid 2018 - mid 2019
- **Cadence:** continuous for 2 - 3 hrs
- **Coverage:** ~2500 square degrees

The ZTF high-cadence Galactic Plane survey

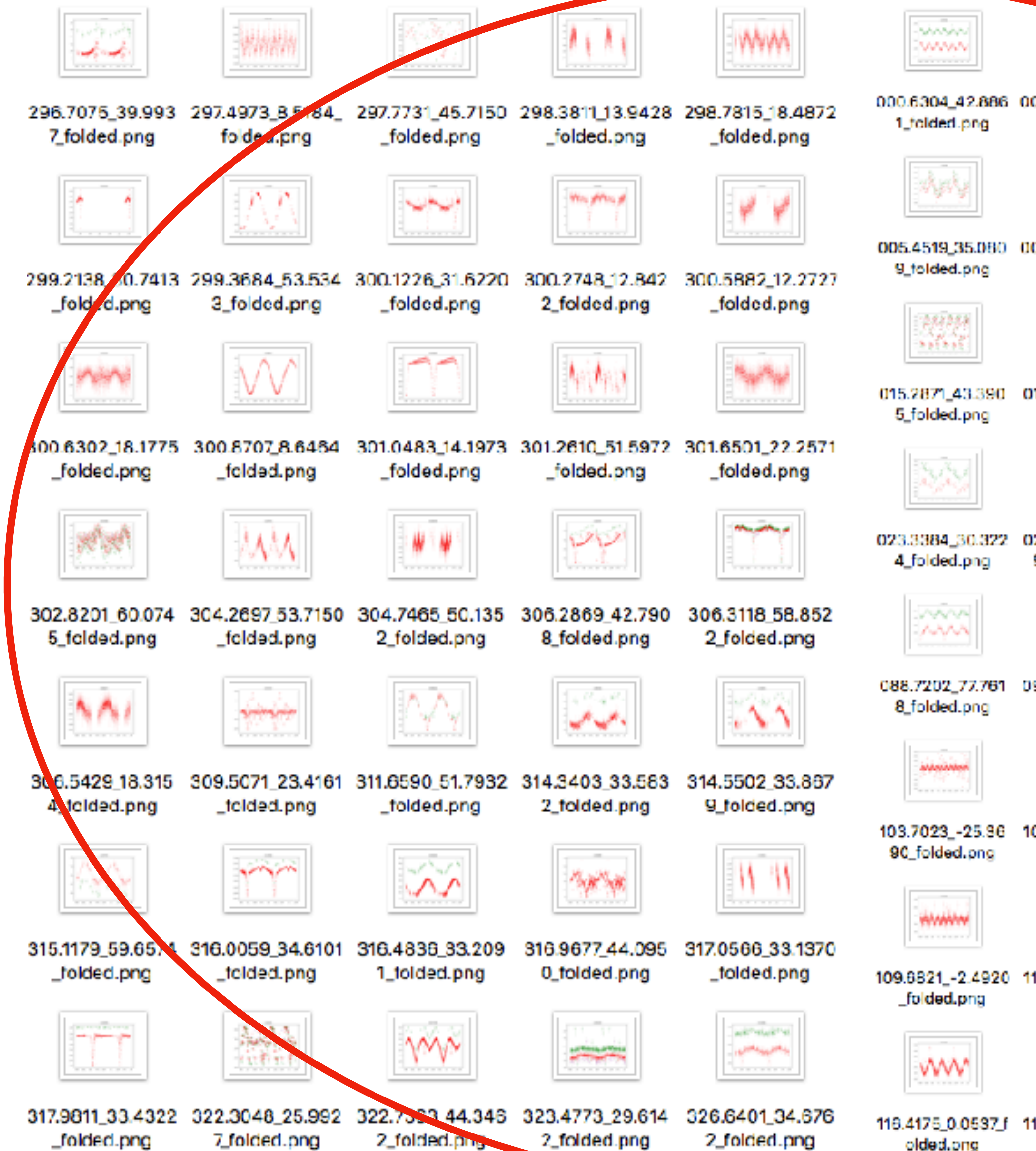


The fast and the furious - A fast cadence survey of the Galactic Plane

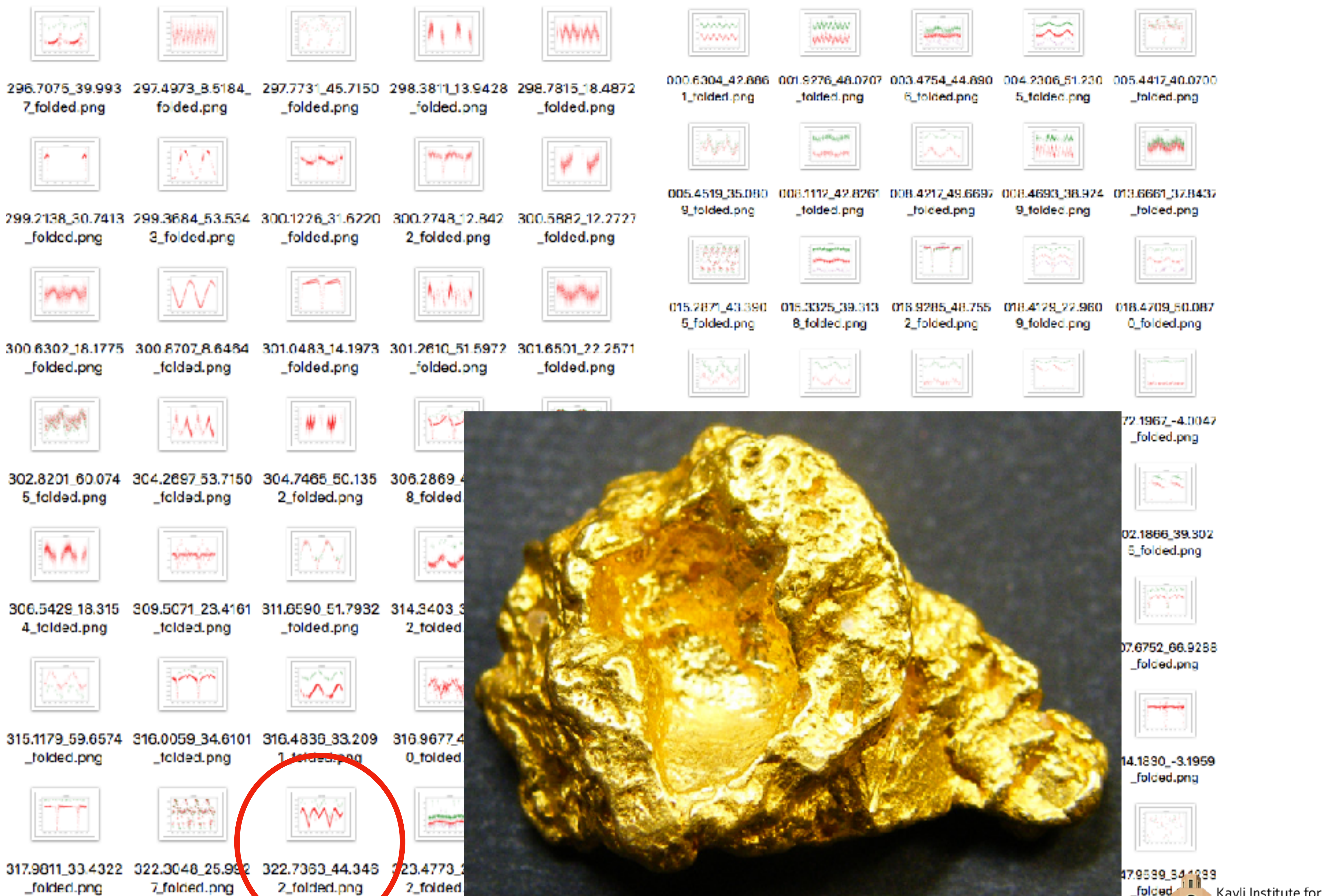
- **<u>Time period:</u>** mid 2018 - mid 2019
- **<u>Cadence:</u>** continuous for 2 - 3 hrs
- **<u>Coverage:</u>** ~2500 square degrees

Include time-domain information

Include time-domain information



Include time-domain information



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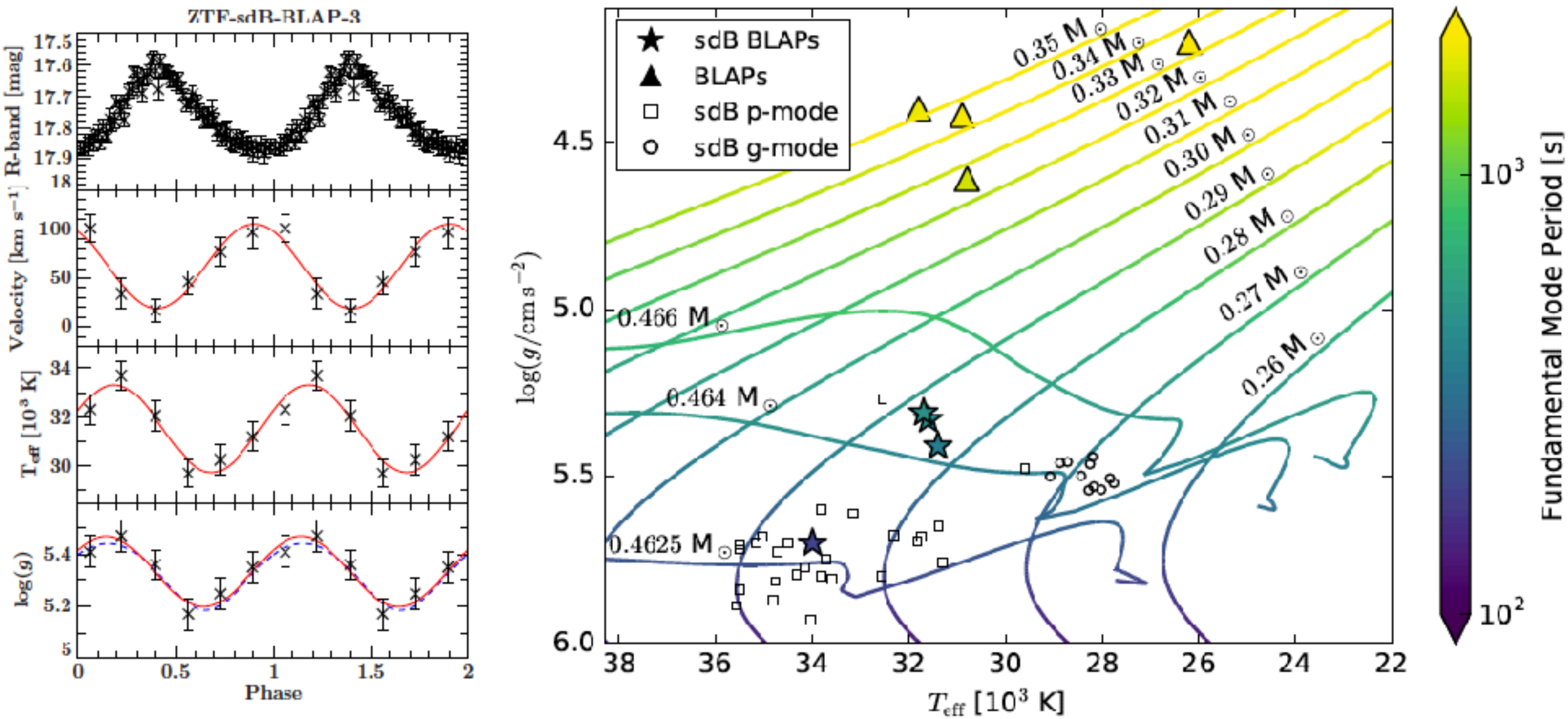
A new class of radial mode hot subdwarf pulsators



- Large amplitudes (photometry, velocity, Teff, surface gravity)
- 4 candidates, periods 3-8 min
- Observed mass and period is best consistent with cooling low mass helium white dwarf models with mass around 0.25 - 0.30 M_{sun}
- Low mass He-core burning stars cannot be fully excluded

Thomas Kupfer **Kupfer et al. in prep.**

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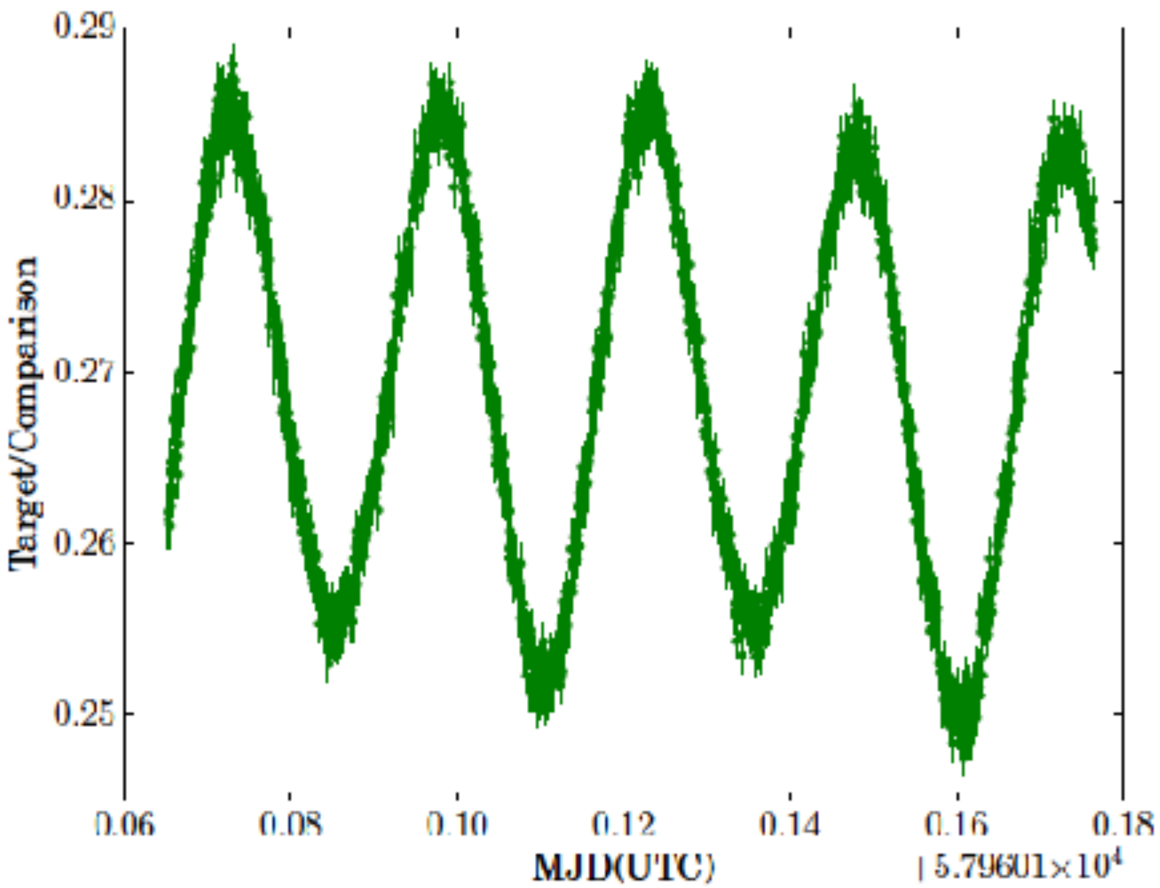
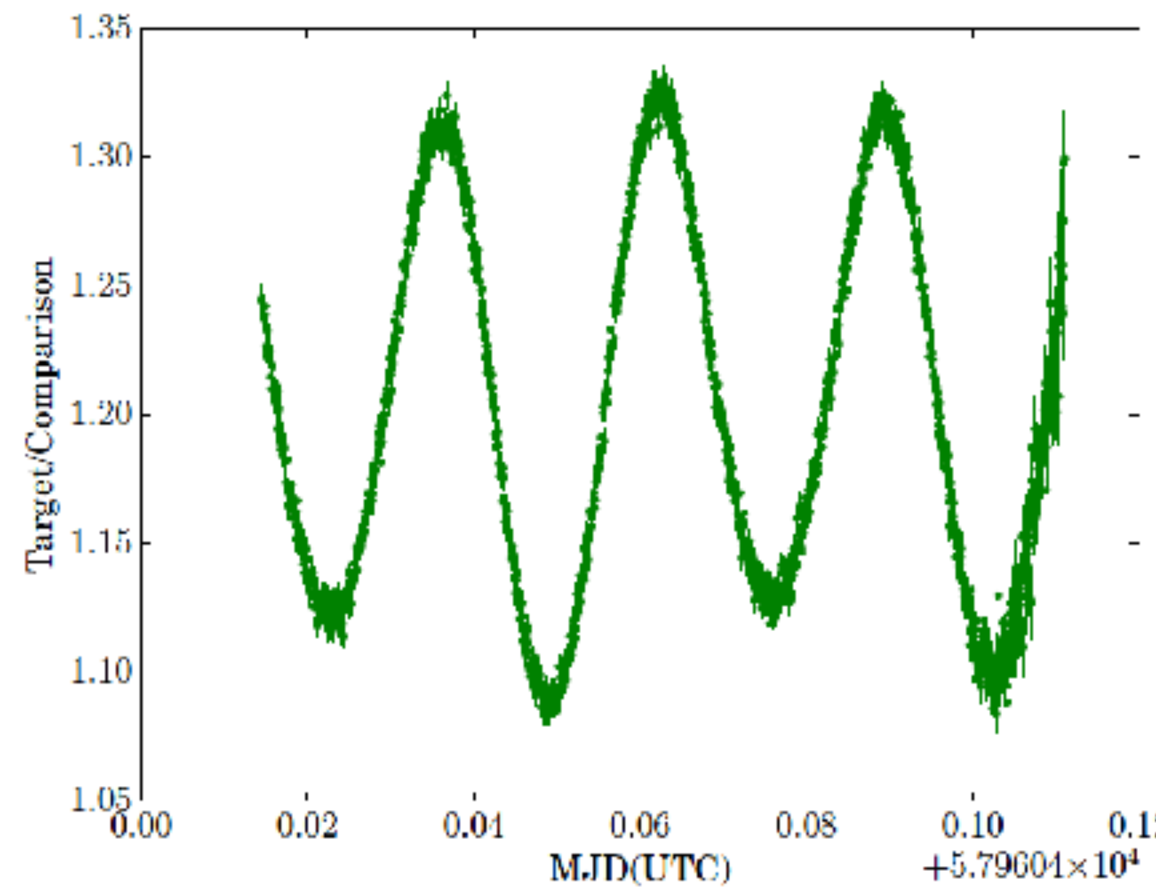
Two new CD-30 like systems - Parameter (very preliminary)

PTFS1 J1821 (b=13.9deg)



- **P_{orb} = 72.1 min**
- M_{sdB} ~ 0.40 M_{sun}
- M_{WD} ~ 0.65 M_{sun}

PTFS1 J2238 (b=8.9deg)



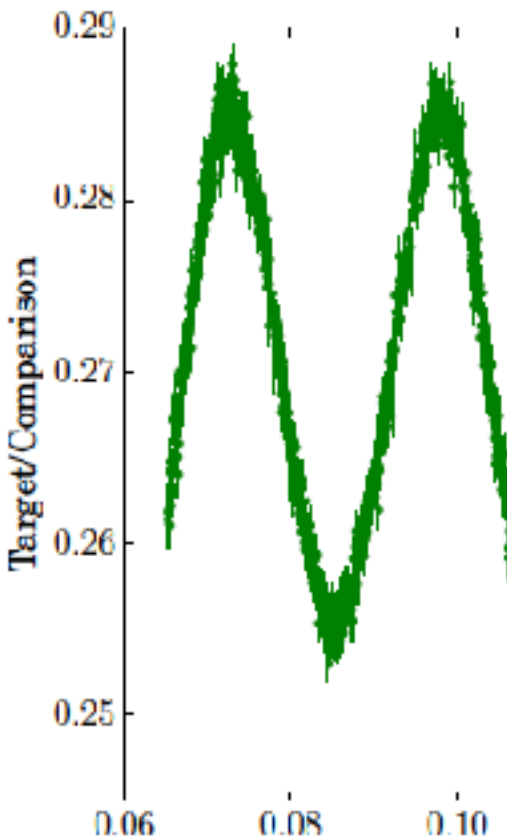
- **P_{orb} = 76.3 min**
- M_{sdB} ~ 0.35 - 0.4 M_{sun}
- M_{WD} ~ 0.7 - 0.8 M_{sun}

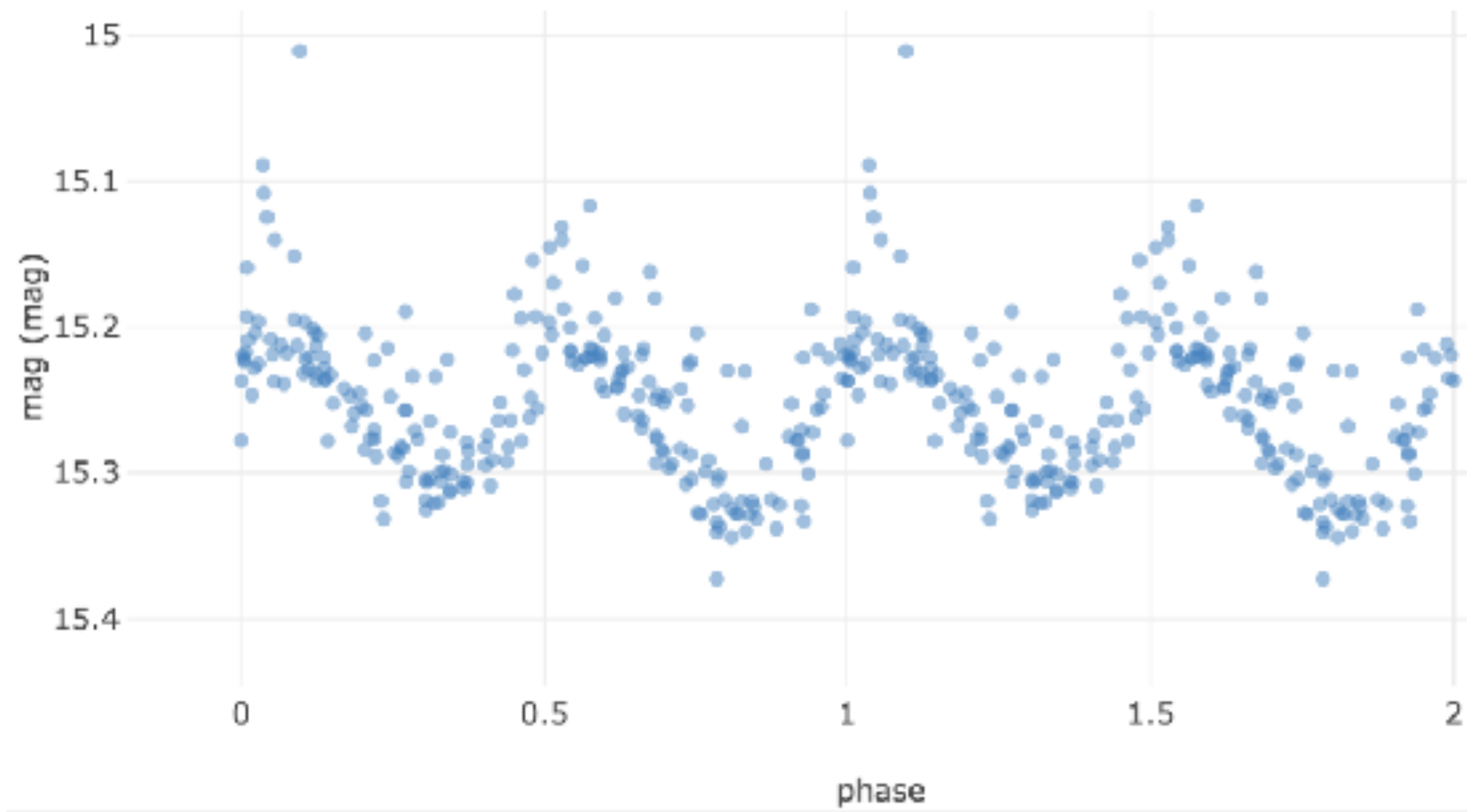
Two new CD-30 like systems - Parameter (very preliminary)

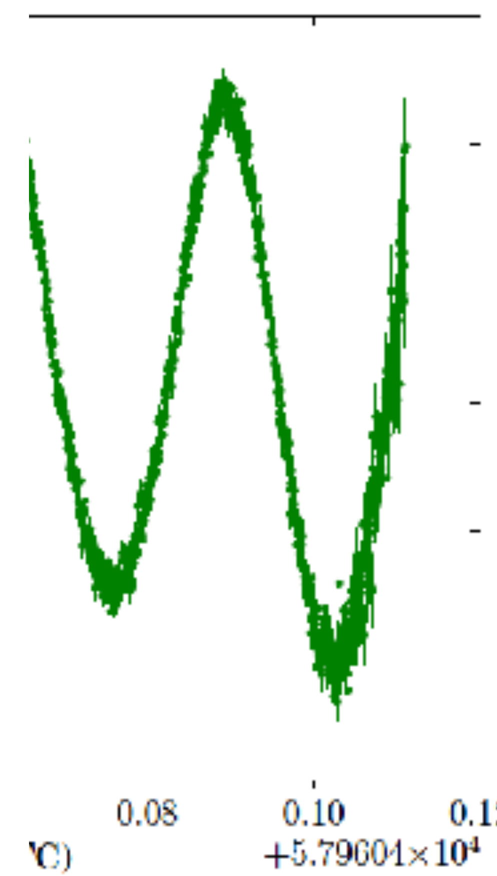
<u>ZTFJ0007</u> (b=-14.6deg)

<u>PTFS1 J182</u>

(b=8.9deg)







- <u>P_{orb} = 72.1</u>
- M_{sdB} ~ 0.40
- M_{WD} ~ 0.65

- <u>P_{orb} = 108 min</u>
- typical sdB but no full RV curve yet

!

4 M_{sun}

M_{sun}

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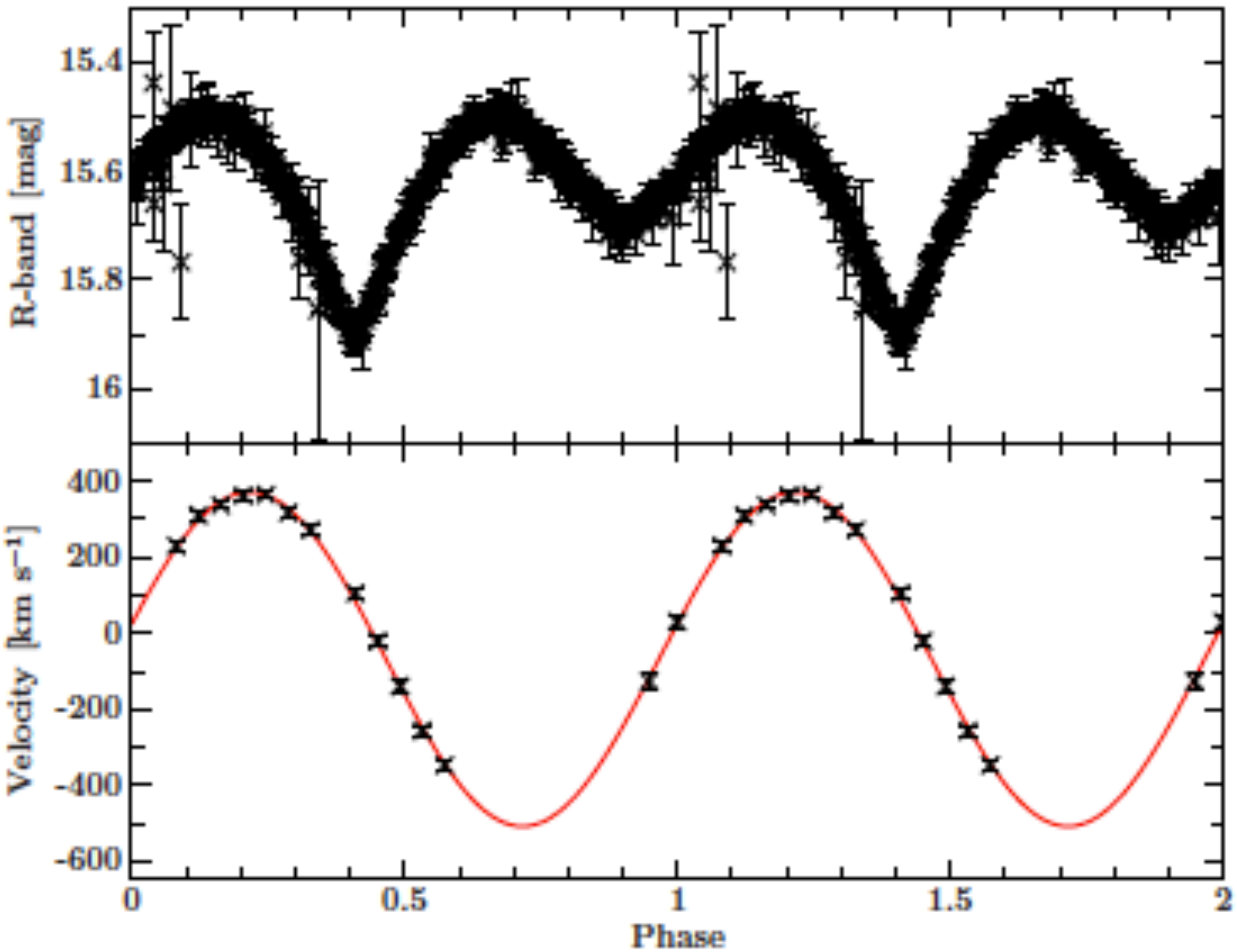
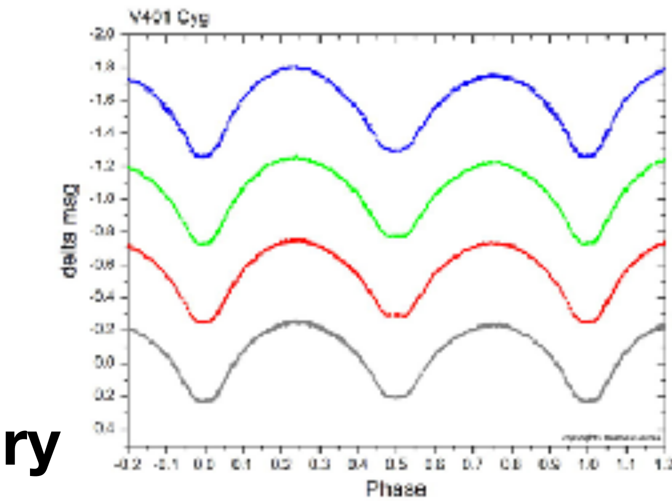
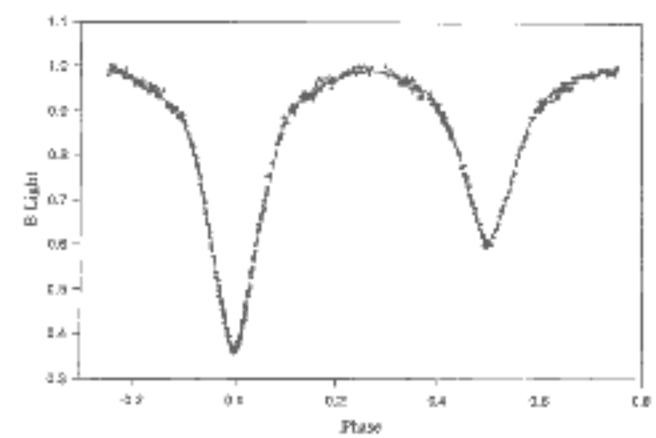
ZTF J2130 - The most compact hot subdwarf binary



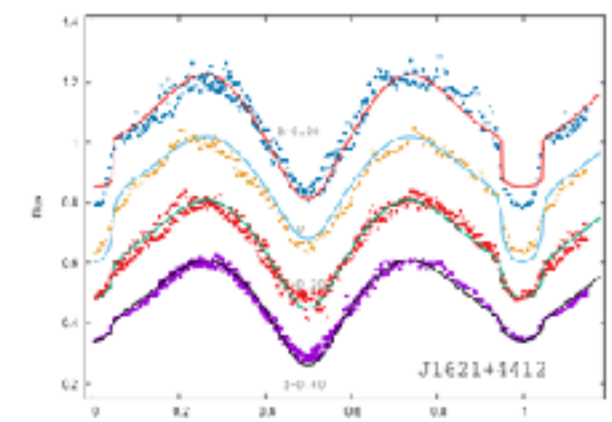
Contact binary



Algol type binary



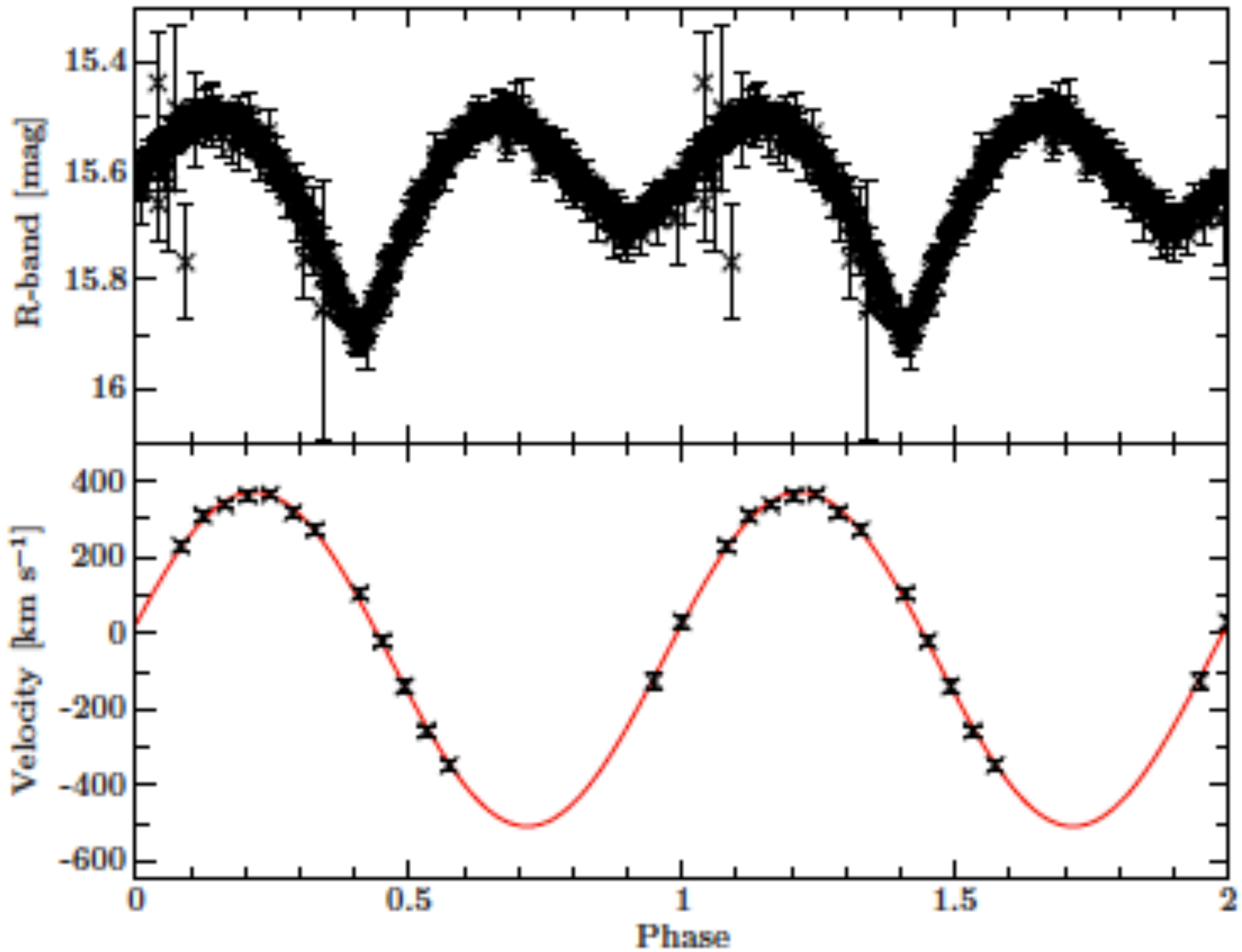
CV

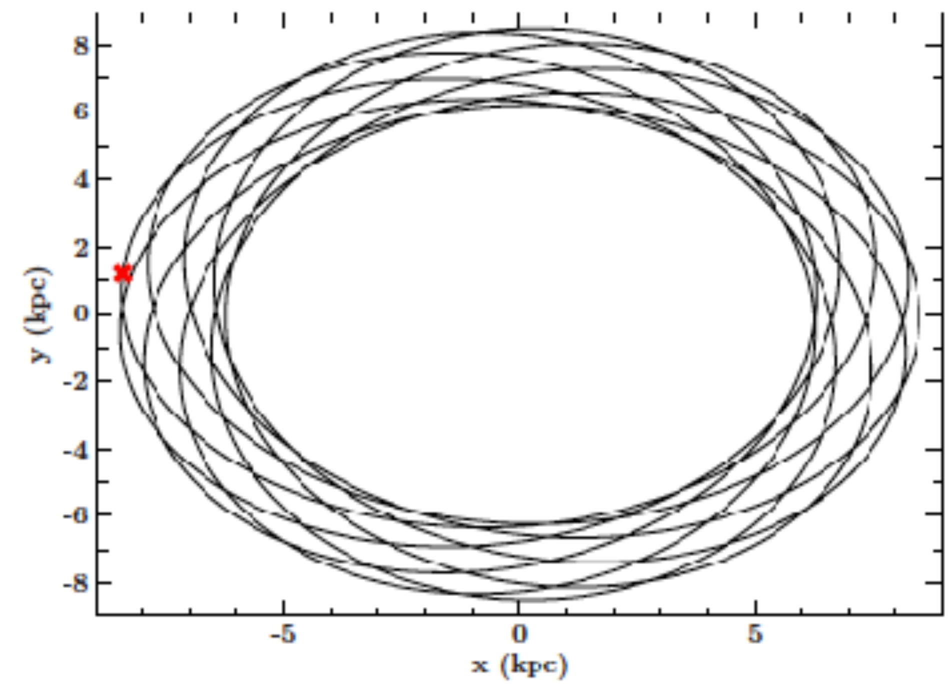


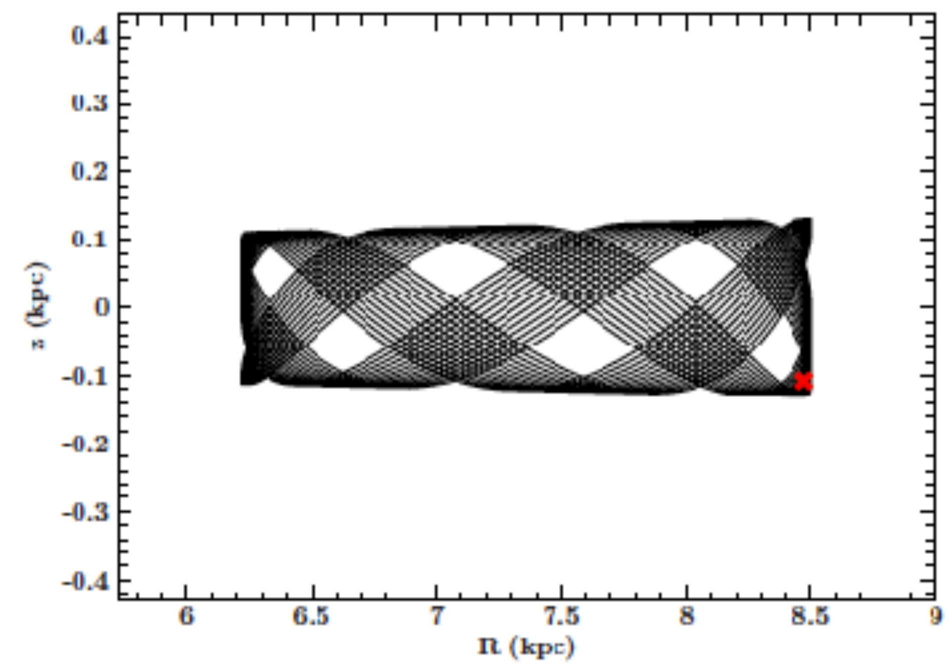
<u>One object stood out</u>

- very short orbital period: 39min
- velocity and phase shows that this is the shortest period hot subdwarf known
- The lightcurve is remarkable and inconsistent with a simple detached ellipsoidal system

ZTF J2130 - The most compact hot subdwarf binary



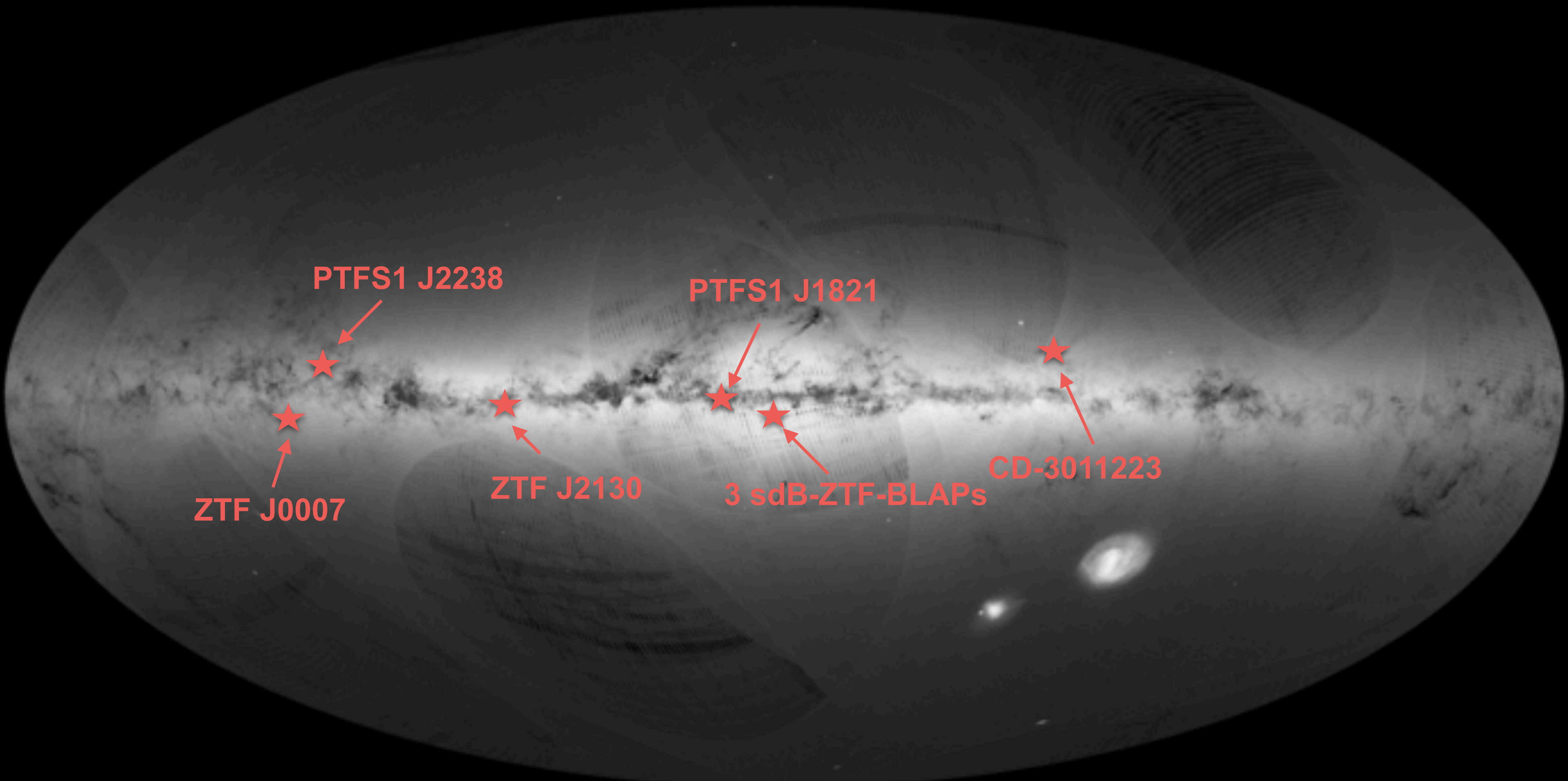




<u>One object stood out</u>

- very short orbital period: 39min
- velocity and phase shows that this is the shortest period hot subdwarf known
- The lightcurve is remarkable and inconsistent with a simple detached ellipsoidal system
- Kinematics shows its a member of the thin disc population

The sky location of the presented 'exotic' variables



- All systems are located at low Galactic latitudes

Summary

- 'Exotic' objects can teach us a lot about stellar evolution and stars in general

- Combining many catalogs allow us to select 'exotic' from more 'normal' objects
  - In particular Gaia was a game changer

- Combing with time-domain surveys reveal even more information (e.g. binaries, pulsators)

- Bottleneck now is follow-up (in particular spectroscopy)

- Hot subdwarf catalog has about 1 star per square degree.
  - Perfect filler for multi-object spectrographs
    - **Little price <-> high return**

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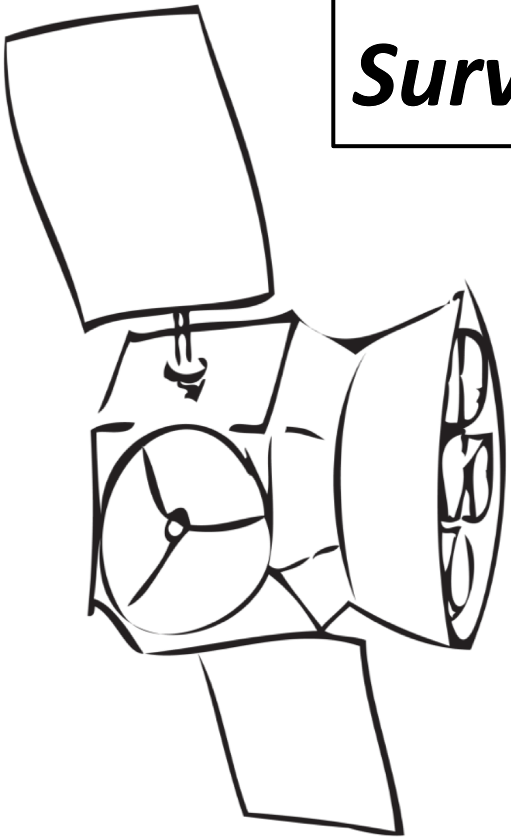
Light Curves and Data Products from the Transiting Exoplanet Survey Satellite (TESS)

Ryan J. Oelkers
Vanderbilt University | Rice University

Carnegie Observatories 2019
Stellar/AGN Photometric Astronomy in the Era of SDSS-V



The Transiting Exoplanet Survey Satellite (TESS)

TESS is an all-sky, wide-field survey of solar-type and cooler stars for Earth and Neptune-sized planets.

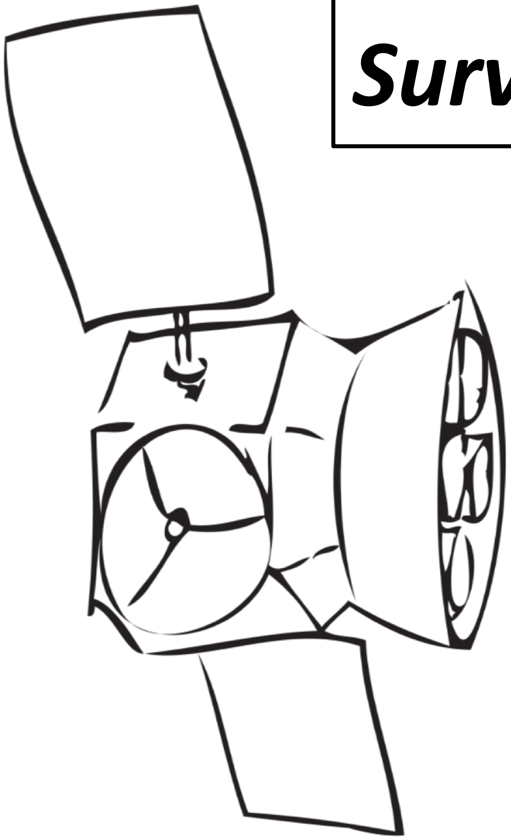
- → The survey expects to find ~2000 candidates (300 Earth-sized objects) using the transit method.

There are 4 cameras, each with 4 CCDs, for a combined field-of-view of 24° x 96° per pointing.

- → 100 mm effective pupil
- → 16.7 megapixel cameras
- → 600-1000 nm bandpass

Ricker et al. 2014, Sullivan et al. 2015

The Transiting Exoplanet Survey Satellite (TESS)



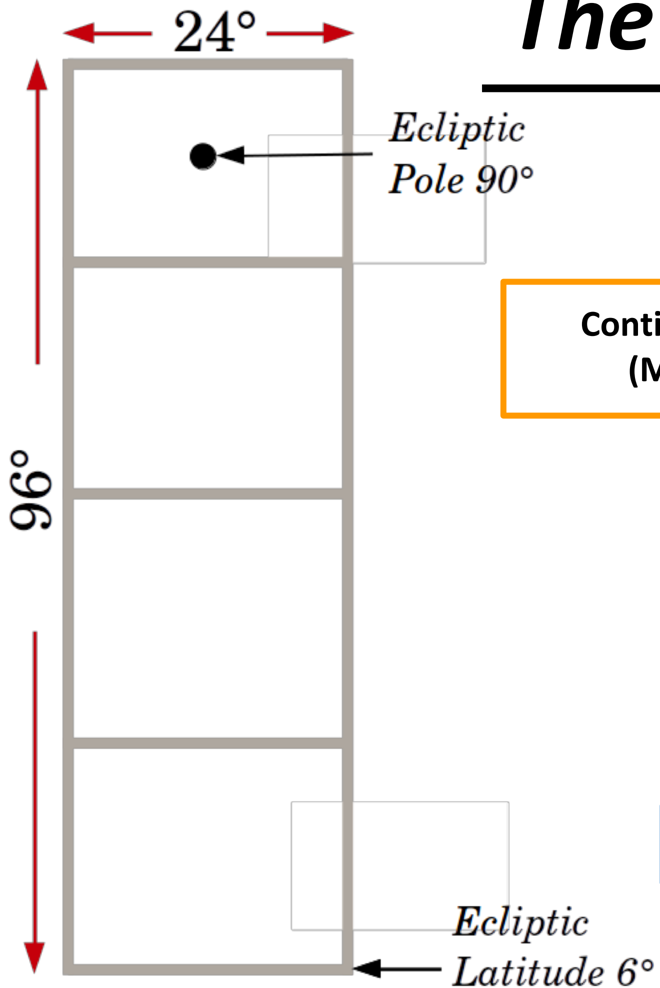
200,000-400,000 stars will be observed every 2 minutes, and nearly 420 million stars will be observed every 30 minutes.

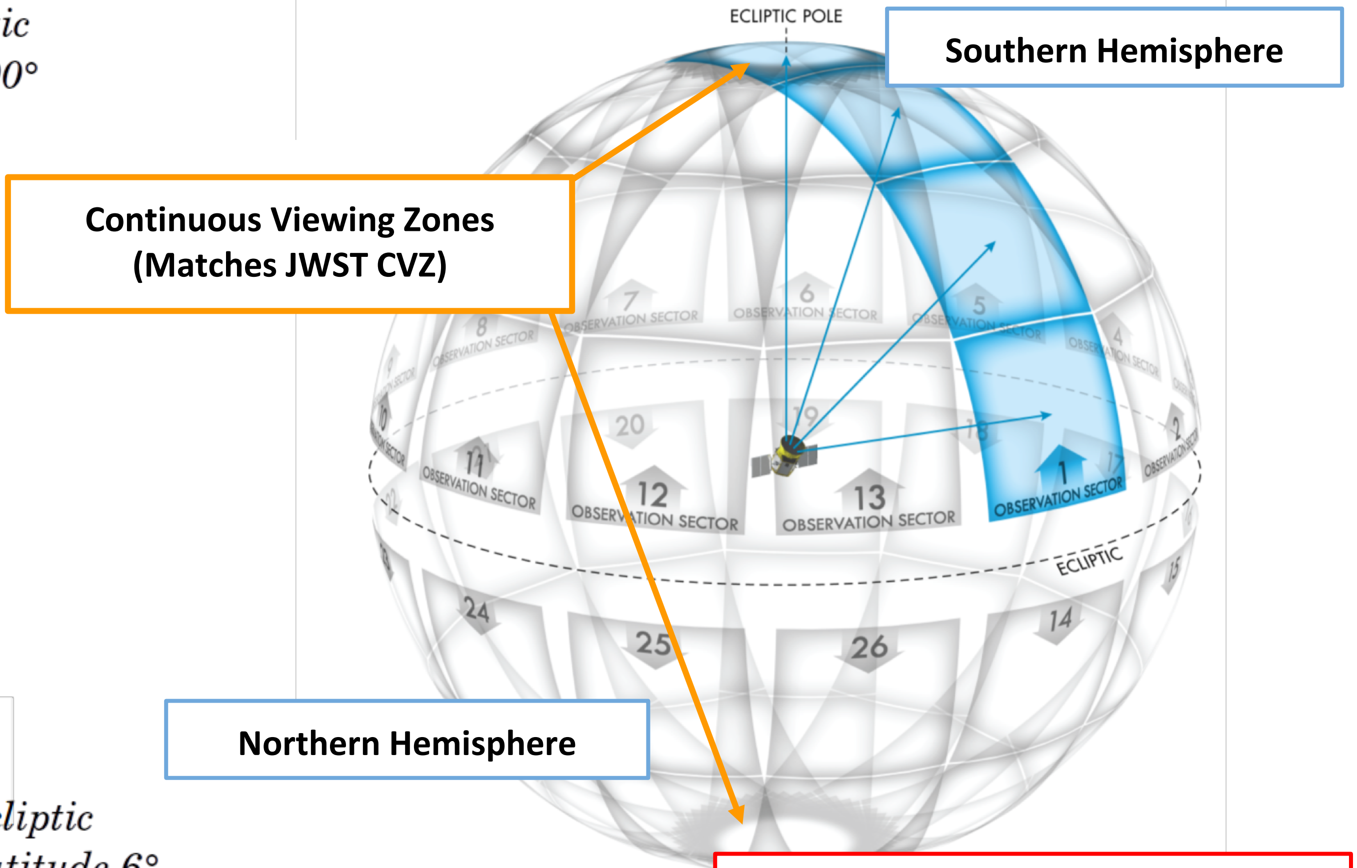
→ The stars observed every 30 mins will not have light curves provided by the mission, instead NASA will provide full-frame-images.

There is no proprietary period on the data, and most data products will be available ~4-6 months after downlink. First release was in December, as of early April, 7 Sectors have been released.

Ricker et al. 2014; Sullivan et al. 2015; Stassun et al. 2018

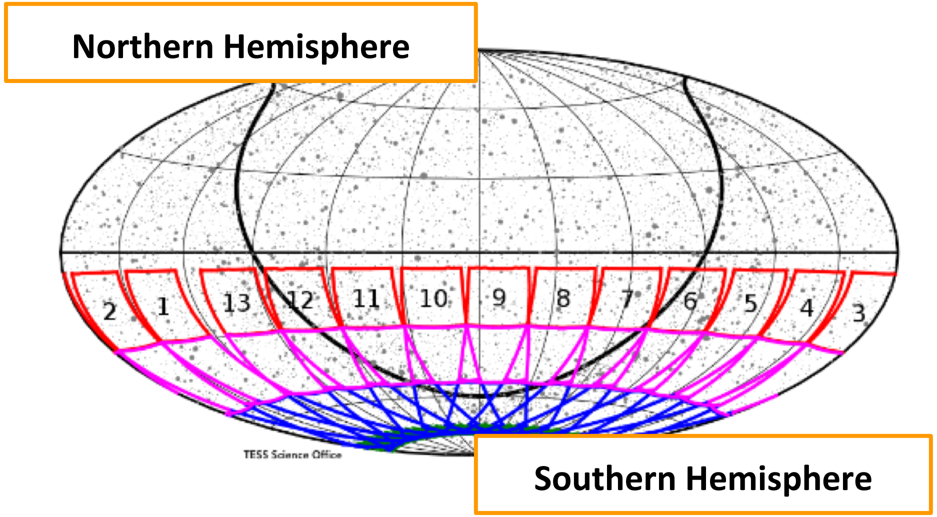
The TESS Observing Strategy





Ricker et al. 2014, Sullivan et al. 2015

Current Observations



Where is TESS pointed now?

TESS has begun observing Sector 10 in Orbit 27. The pointing direction of the instrument during Sector 10 is:

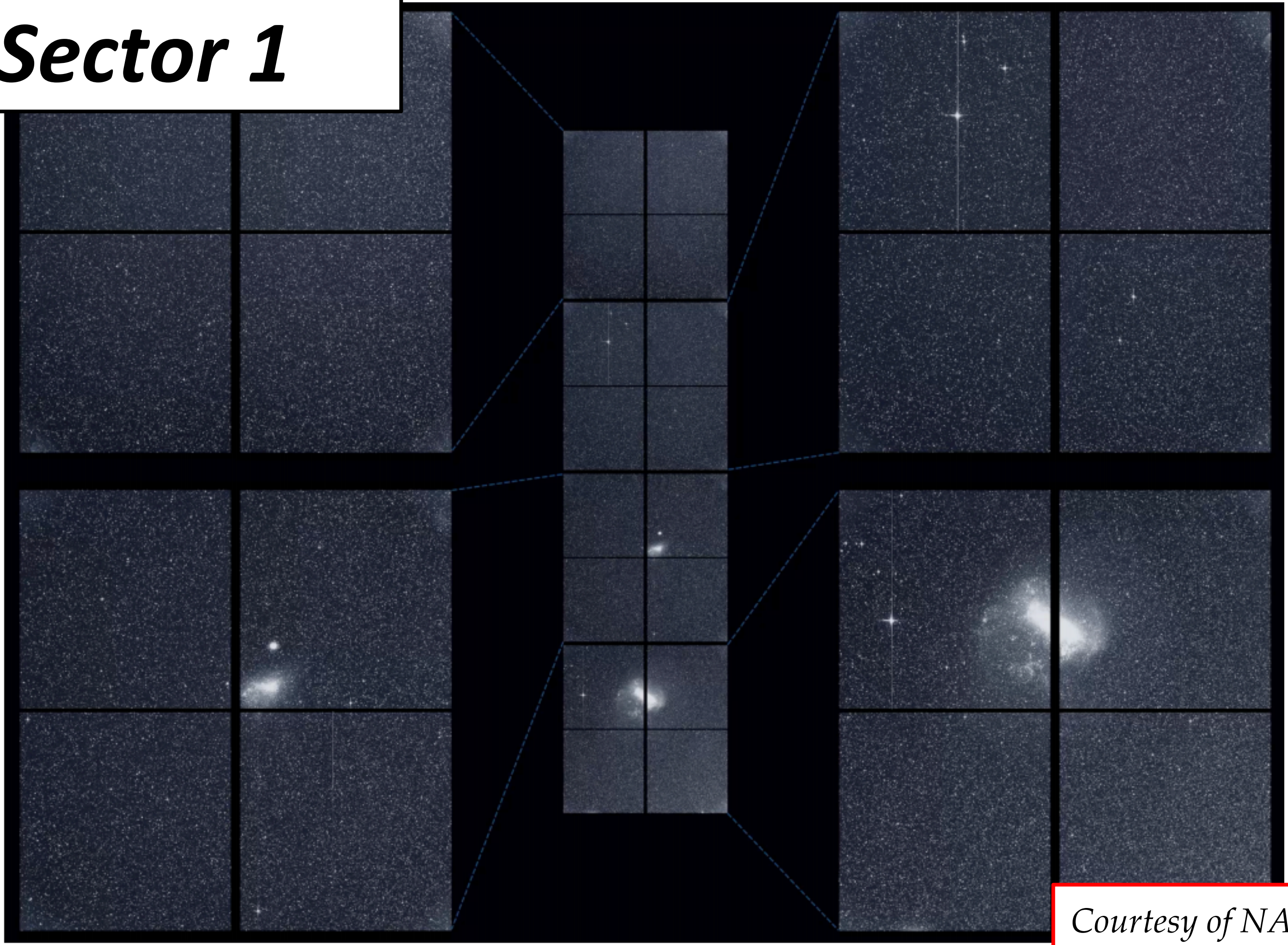
Ecliptic Longitude (J2000): 199°
Ecliptic Latitude (J2000): -54°

RA (J2000): +165°
Dec (J2000): -54°
Roll (deg): 139°

As of 4/13/2019, TESS has completed 9 sectors, with 7 sectors released to the public. The spacecraft is currently observing Sector 10. Northern observations start in July, 2019.

Courtesy of tess.mit.edu/pointing

TESS Sector 1



Courtesy of NASA-TESS; MIT

‘Primary’ TESS Data Products

2-minute cadence light curves: ~15,000 stars per each sector (for a total near 400,000 stars) will receive 2 minute cadence, and have light curves produced by NASA.

30-minute cadence FFIs: All stars in the TESS FoV receive 30-minute cadence in the form of full-frame-images. These are *not* reduced to light curve form. Many groups are producing light curves for the community at large.

***TESS* Input Catalog:** Stellar parameters, and a nearly full spectrum of magnitudes for more than 250 million stars -- 1.5 billion stars exist in the TIC with various measured quantities.

‘Primary’ TESS Data Products

2-minute cadence light curves: ~15,000 stars per each sector, for a total near 400,000 stars, receive 2 minute cadence, and have light curves produced by NASA.

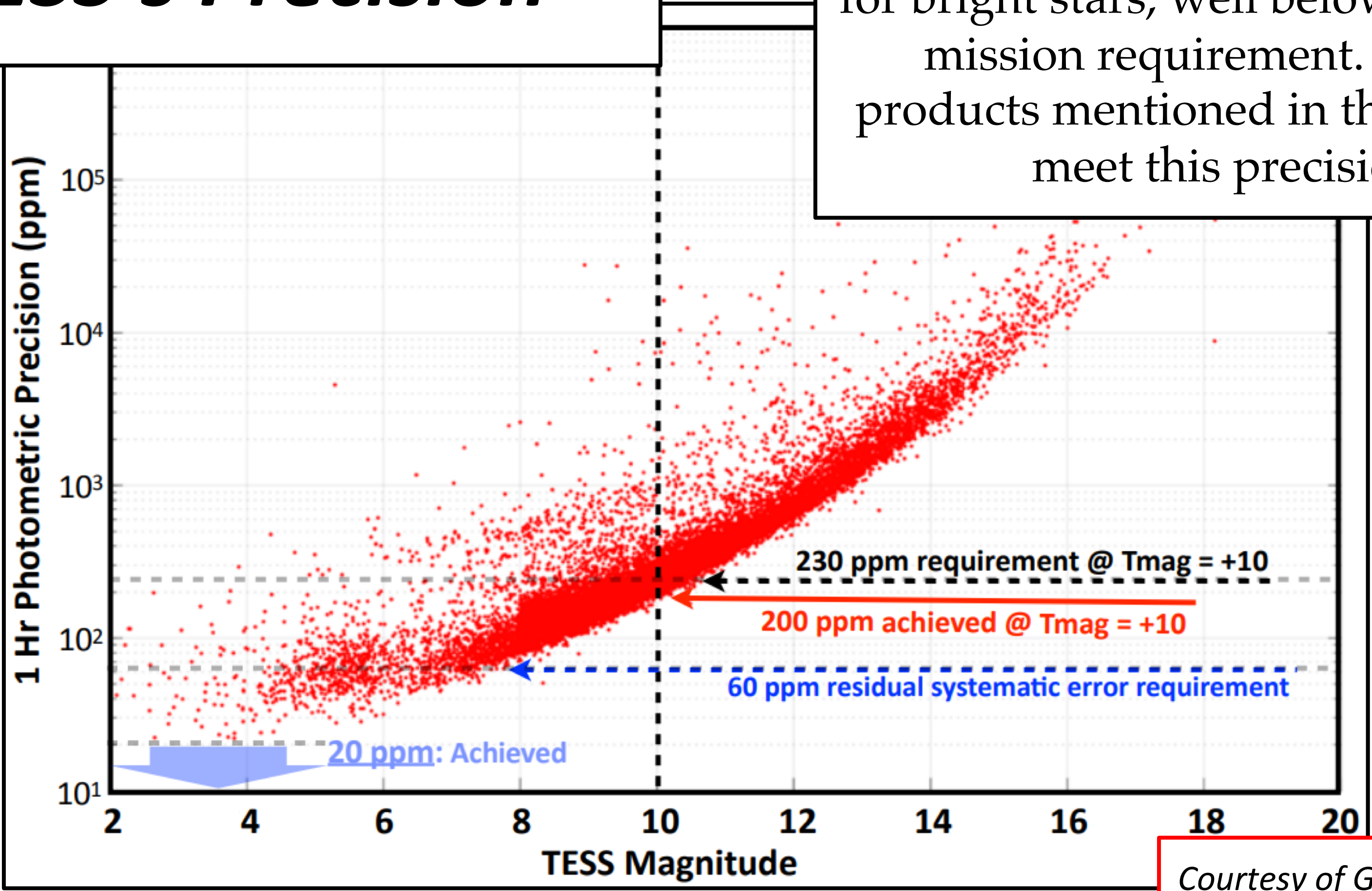
30-minu … 0-minute cadence … uced to light cur … n their own.

Many more types of data are available through MAST.

***TESS* Input Catalog:** Physical stellar parameters, and nearly full spectrum magnitudes for more than 250 million stars -- 1.5 billion stars exist in the TIC with various measured quantities.

TESS's Precision

Currently *TESS* can achieve *20 ppm* for bright stars, well below the *60 ppm* mission requirement. All data products mentioned in this proposal meet this precision.



Courtesy of George Ricker

A Variety of Official & Community-led Pipelines are Available to Access the Data

MAST: Primary location of most mission data products, and provides a variety of tools to access the data.

NASA: Official NASA-SPOC data to produce all *NASA-TESS* data products (Jenkins et al. 2016)

Eleanor: Open access PSF-fitting pipeline led by University of Chicago (Feinstein et al. 2019)

Filtergraph: Open access difference imaging pipeline led by Vanderbilt University (Oelkers & Stassun (2018 & 2019)

LightKurve: A package for Kepler & TESS time-series analysis (Barensten et al. 2019)

Quick-Look Pipeline (QLP): Aperture photometry pipeline led by MIT (Huang et al. 2018)

TASOC Pipeline: PSF photometry data reduction pipeline led by the TESS Asteroseismic Consortium

A Variety of Community-led Pipelines are Available to Access the Data

MAST: Primary location of most mission data products, and provides a variety of tools to access the data.

Eleanor: (

Filtergra... iversity

LightKu...

There may be many more pipelines I have missed!

NASA: Aperture based pipeline with 2-minute cadence

Quick-look Pipeline: Aperture photometry pipeline led by MIT

TASOC: PSF photometry data reduction pipeline led by the TESS Asteroseismic Consortium

TESS Data on MAST

http://archive.stsci.edu/tess/all_products.html

Bulk Downloads

1- 2-minute cadence light curves
2- 30-minute fill frame images (both calibrated, and un-calibrated)
3- Target pixel files for 2-minute data
4- Data validation files (TCE summary and full reports)
5- Co-trending basis vectors
6- Simulated data (ETE-6)
7- The TESS Input Catalog

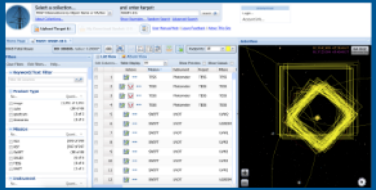
Data interaction tools

1- Search through data: MAST portal, exo.MAST, Astroquery.MAST
2- Make FFI cut-outs: TESScut

Slides adapted from a presentation by Scott Fleming http://archive.stsci.edu/tess/

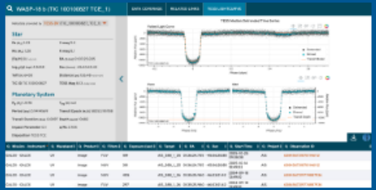
Search Tools

All Search Options TESS Search Tutorials



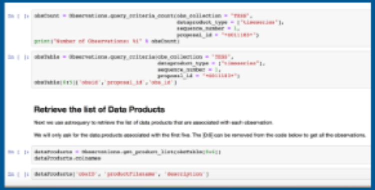
MAST Portal

Download light curves, target pixel files, and data validation files for a few targets. Download full frame images for a few CCDs. Conduct small searches within the TIC or CTL. Find data from other missions for your target.



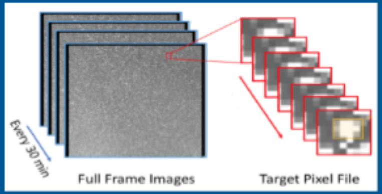
exo.MAST

Find MAST data (including TESS) for known planets or TCE's, matched to orbital phase. Plot sector-stitched DV light curves. Access exoplanet parameters with references.



MAST Astroquery

Search for, and retrieve, TESS data products programmatically based on a list of coordinates or target names. Interact with observational data, TIC, and CTL catalogs in programs you write.



TESScut

Create time series pixel cutouts from the TESS full frame images. Find out what sectors/cameras/detectors a target was observed in.

Bulk Downloads

Download all light curves or target pixel files for a given sector or GI program. Download all full frame images for a given sector. Download the entire TCE table for a given sector. Download versions of the TIC and CTL.

Amazon Web Services

Access all the publicly available TESS data directly in the AWS cloud. Calibrated and uncalibrated full frame images, two-minute cadence target pixel and light curve files, and co-trending basis vectors, and FFI cubes available on Amazon S3. Also accessible using astroquery.mast.

Slides adapted from a presentation by Scott Fleming

Official NASA-SPOC Data

Stars provided in the official releases:

1- The main data product from NASA-SPOC are light curves for 2-minute cadence targets.

2- Typically there are ~15,000 stars per sector which receive 2-minute cadence. These stars were selected based on priority in the candidate target list (CTL) of the TIC, the Asteroseismic Target List (ATL), GI/GO targets, and other special target lists.

3- The pipeline is heavily based on the *Kepler* pipeline.

Data Products: Hosted on MAST **(DATA available through Sector-7 as of 4/13/19)**

1- 2-minute light curves

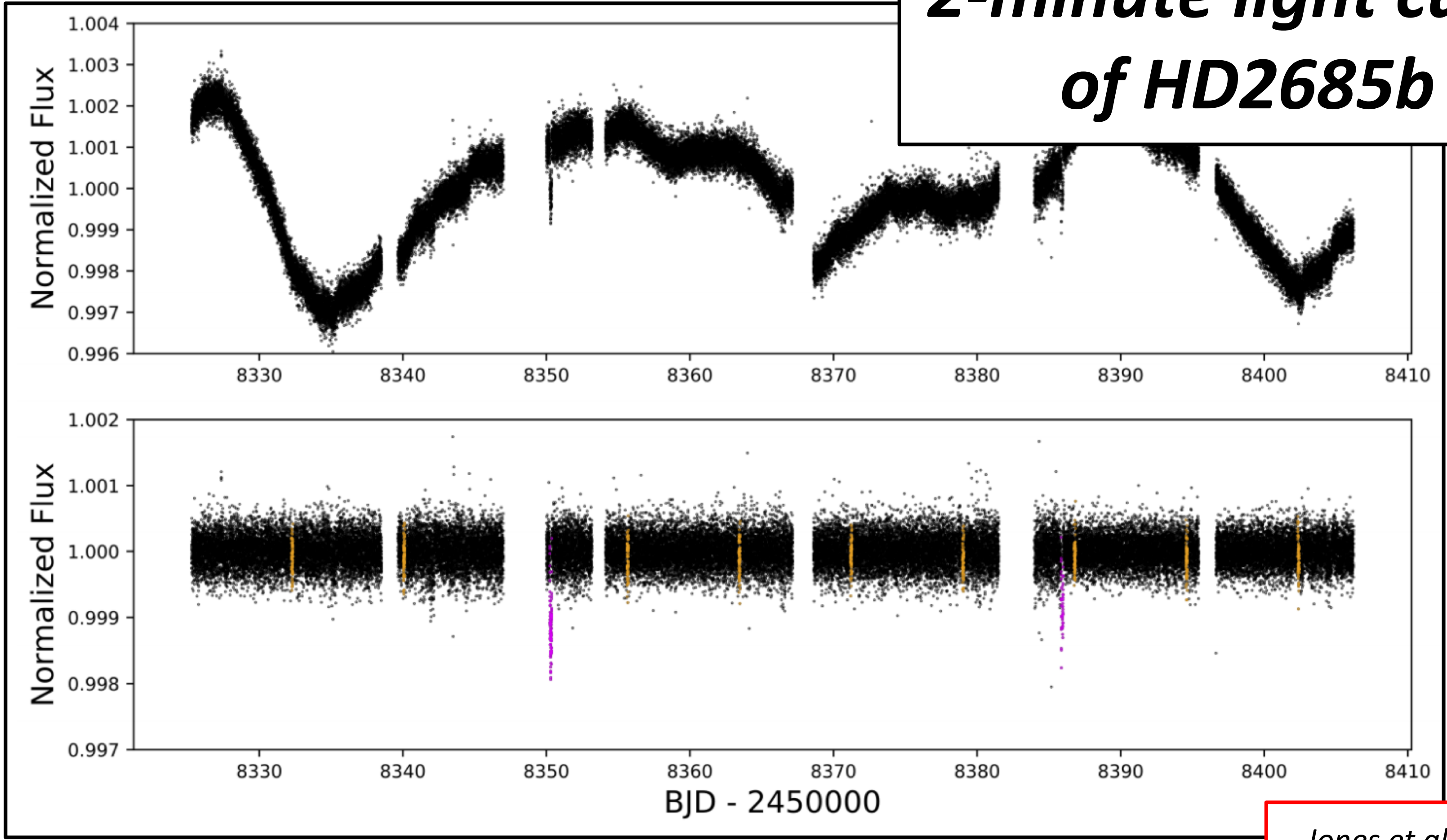
2- Data validation reports and TCE reports

3- 30-minute (un-)calibrated Full Frame Images

4- Co-basis detrending vectors

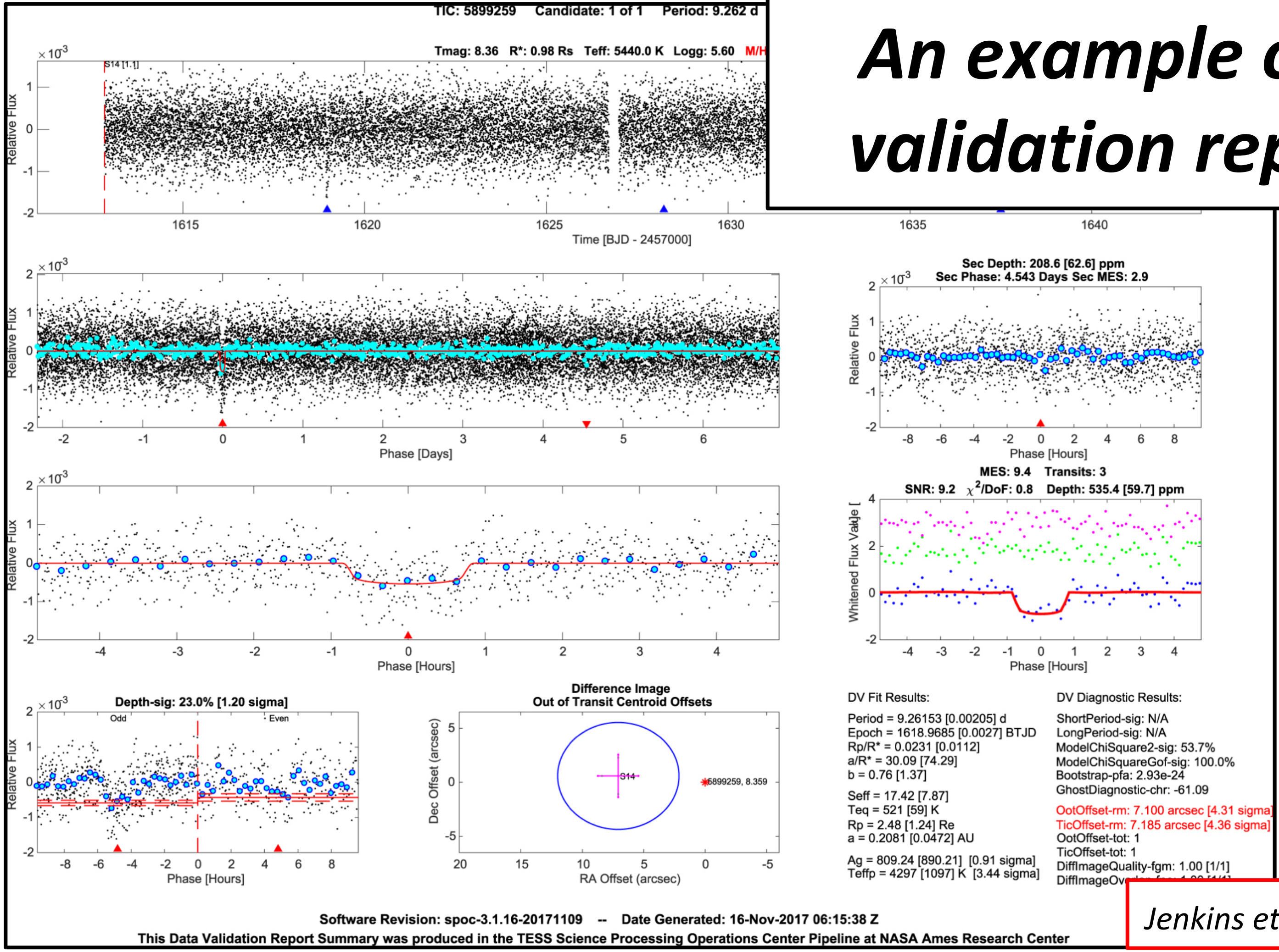
Jenkins et al. 2016 & 2018

2-minute light curve of HD2685b



Jones et al. 2019

An example of a validation report



Jenkins et al. 2018

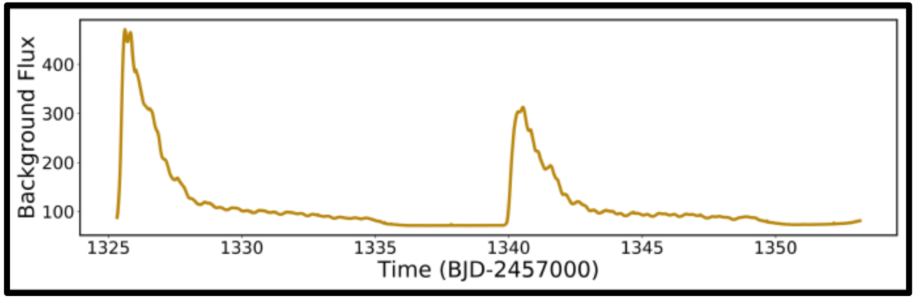
Community Generated Light Curves and Ancillary Data Products

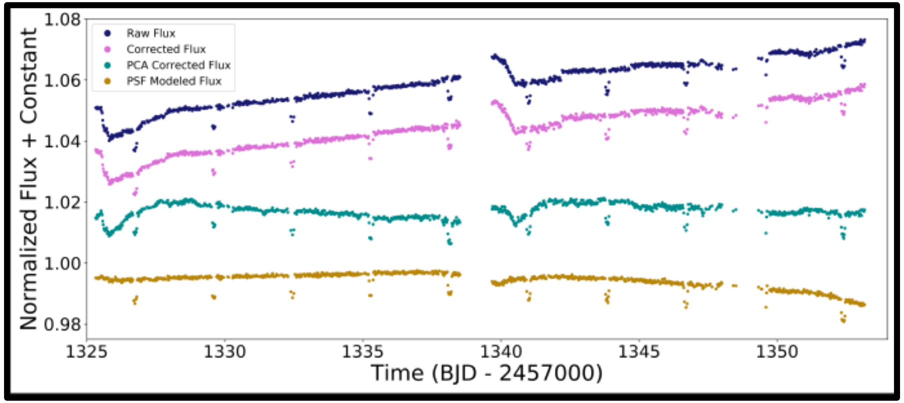
Courtesy of Adina Feinstein

ELEANOR Pipeline

(Feinstein, Montet, Bedell, Christiansen, Foreman-Mackey, Hedges, Luger, Saunders, Cardoso)

- Creating light curves for all stars < 16 magnitude in the FFIs and searching them for exoplanets
- Open-source software and light curves for Sector 1 are ready for use for all your time-series photometry needs.
- We remove noticeable background noise
- Principal Component Analysis of thousands of stars enables contending to remove shared Systematics.
- PSF modeling is also available

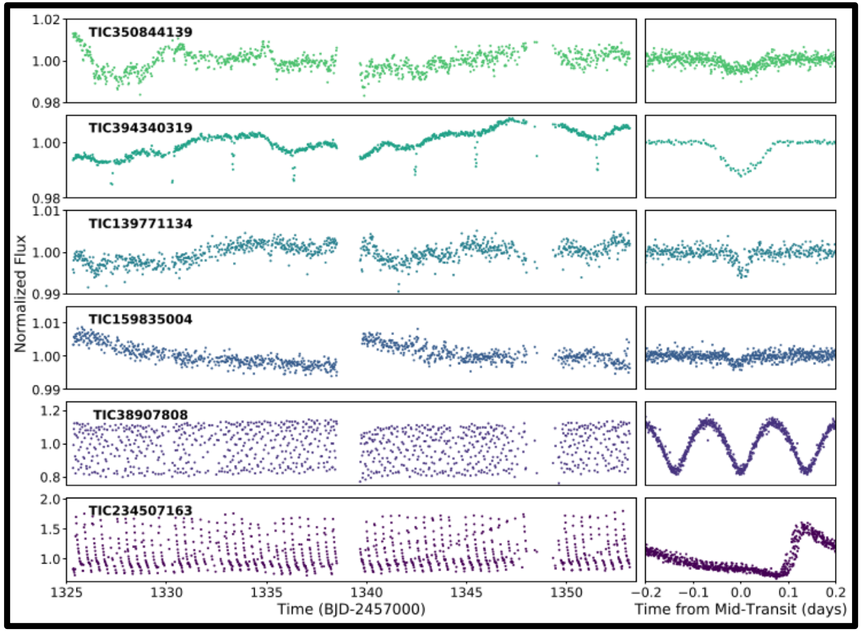




Courtesy of Adina Feinstein

ELEANOR Pipeline

- We already have new exoplanet, eclipsing binary, and other candidates!
- Light curves will be hosted on MAST soon
- New exoplanet candidates are already being uploaded to ExoFOP-TESS!



Can't wait until the light curves are uploaded? ***Make your own!***

pip install eleanor
https://adina.feinste.in/eleanor

Filtergraph Pipeline (Oelkers & Stassun)

Pipeline Availability: *https://github.com/ryanoelkers/DIA/*

1- Difference imaging C-code

2- Wrappers and various routines for background subtraction, alignment, master frame combination, de-trending and photometry.

Data Products: *https://filtergraph/tess_ffi/* **(DATA available through Sector-5)**

1- *TESS* Input Catalog information (Stassun,Oelkers+2018)

2- Variability metrics and basic periodicity information

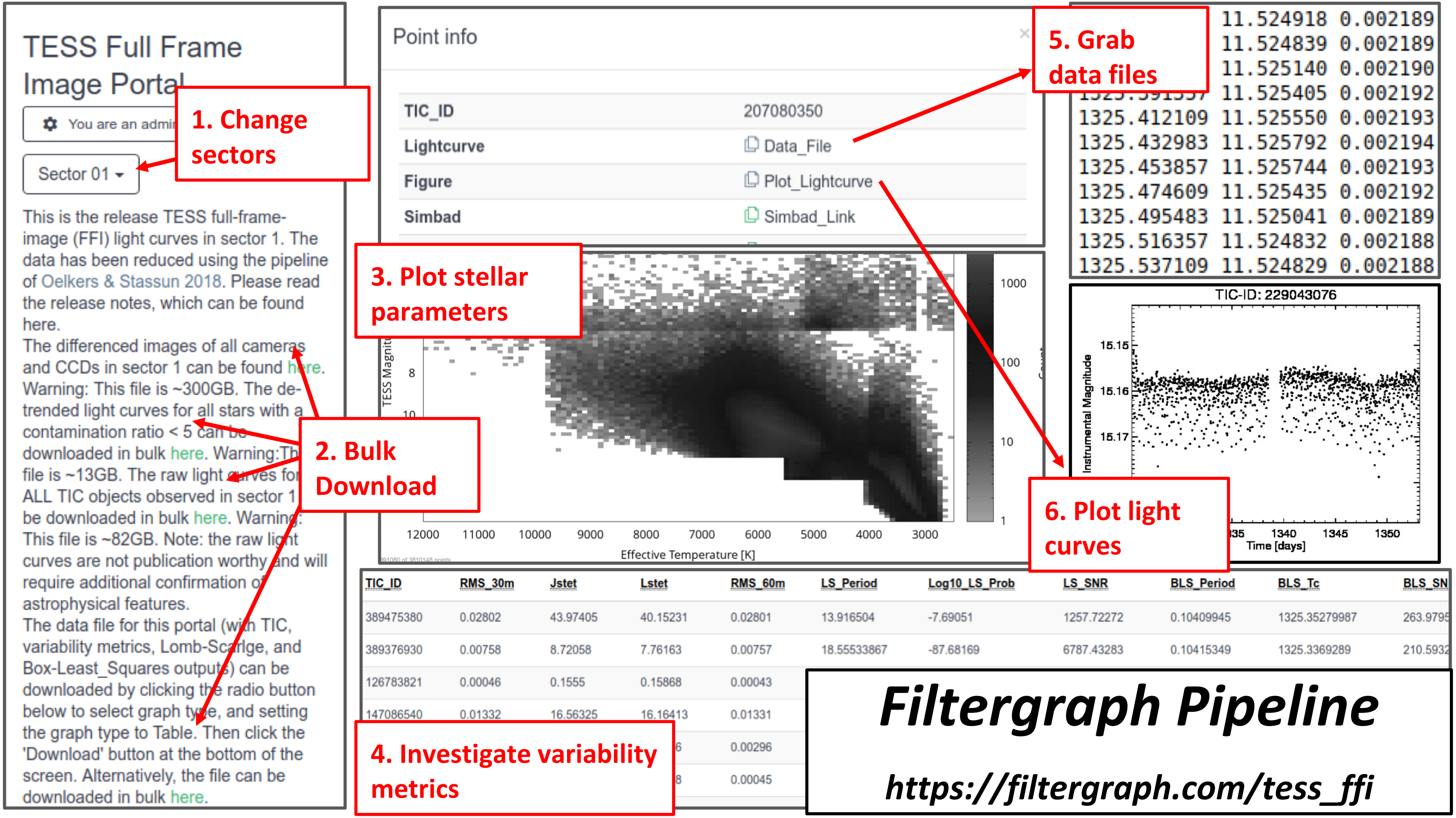
- ➔ Box-Least-Squares output from `VARTOOLS` (Kovacs+2002; Hartman & Bakos 2016)
- ➔ Lomb-Scargle output from `VARTOOLS` (Lomb 1976; Scargle 1982; Hartman & Bakos 2016)
- ➔ Welch-Stetson J & L metrics and rms on 30m and 60m timescales (Stetson 1996; Oelkers+2018)

3- Light curves

- ➔ Raw light curves for every star, cleaned light curves for a subset of low-contamination stars

4- Differenced images

- ➔ Useful for discovering transients, and/or variable stars previously unknown.


TESS Full Frame Image Portal
You are an admin
Sector 01
This is the release TESS full-frame-image (FFI) light curves in sector 1. The data has been reduced using the pipeline of Oelkers & Stassun 2018. Please read the release notes, which can be found here.
The differenced images of all cameras and CCDs in sector 1 can be found here. Warning: This file is ~300GB. The de-trended light curves for all stars with a contamination ratio < 5 can be downloaded in bulk here. Warning: The file is ~13GB. The raw light curves for ALL TIC objects observed in sector 1 can be downloaded in bulk here. Warning: This file is ~82GB. Note: the raw light curves are not publication worthy and will require additional confirmation of astrophysical features.
The data file for this portal (with TIC, variability metrics, Lomb-Scargle, and Box-Least_Squares outputs) can be downloaded by clicking the radio button below to select graph type, and setting the graph type to Table. Then click the 'Download' button at the bottom of the screen. Alternatively, the file can be downloaded in bulk here.
1. Change sectors
2. Bulk Download
Point info
TIC_ID 207080350
Lightcurve Data_File
Figure Plot_Lightcurve
Simbad Simbad_Link
3. Plot stellar parameters
TESS Magnitude
Effective Temperature [K]
Count
4. Investigate variability metrics
TIC_ID RMS_30m Jstet Lstet RMS_60m LS_Period Log10_LS_Prob LS_SNR BLS_Period BLS_Tc BLS_SN
389475380 0.02802 43.97405 40.15231 0.02801 13.916504 -7.69051 1257.72272 0.10409945 1325.35279987 263.9795
389376930 0.00758 8.72058 7.76163 0.00757 18.55533867 -87.68169 6787.43283 0.10415349 1325.3369289 210.5932
126783821 0.00046 0.1555 0.15868 0.00043
147086540 0.01332 16.56325 16.16413 0.01331
0.00296
0.00045
5. Grab data files
1325.412109 11.525550 0.002193
1325.432983 11.525792 0.002194
1325.453857 11.525744 0.002193
1325.474609 11.525435 0.002192
1325.495483 11.525041 0.002189
1325.516357 11.524832 0.002188
1325.537109 11.524829 0.002188
TIC-ID: 229043076
Instrumental Magnitude
Time [days]
6. Plot light curves
Filtergraph Pipeline
https://filtergraph.com/tess_ffi

Filtergraph Pipeline

TOI-150b

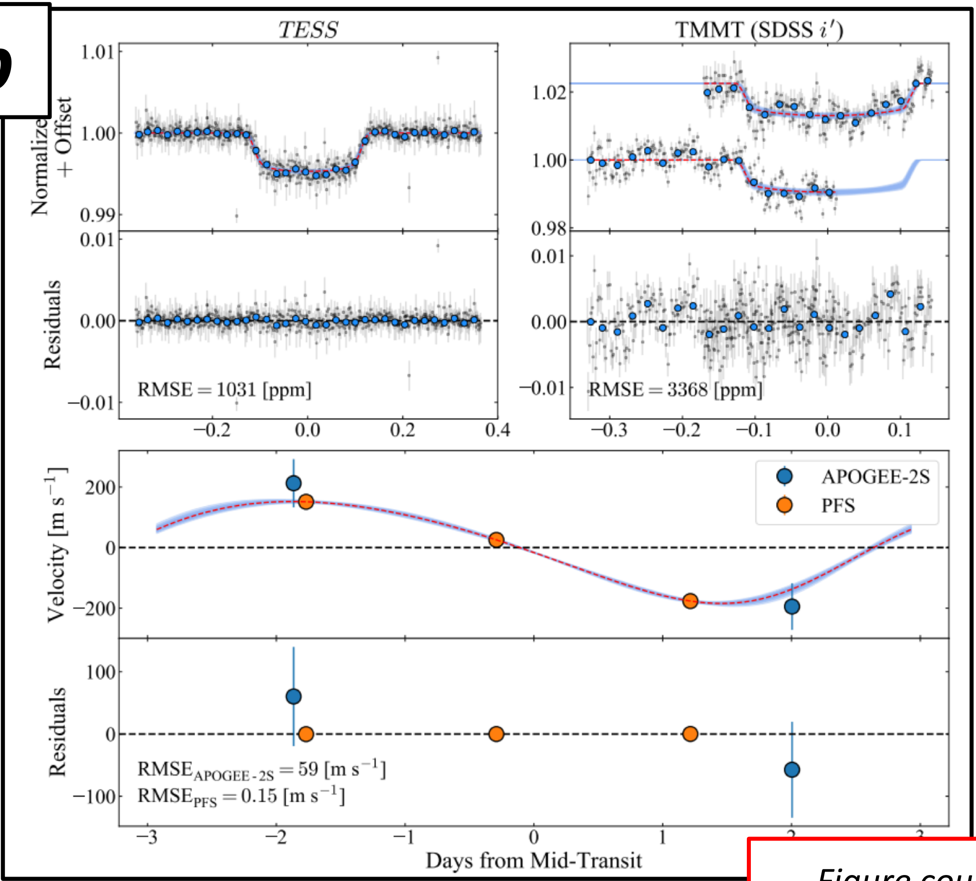


Figure courtesy of Canas et al. 2019

LightKurve Package

(Cardoso, Barentsen, Cody, Hedges, Gully-Santiago, Barclay, Mighell, Bell, Zhang, Tzanidakis. Sagear, Turtelboom, Coughlin, Berta-Thompson, Sundaram, Hall, Saunders, Lerma, Evensberget, Gosnell, Williams, Elkins, Davies, Foreman-Mackey, Hey)

Availability: *https://docs.lightkurve.org/index.html*

→ Lightkurve provides a user-friendly, low-barrier-to-entry, method of interacting with data from *Kepler* and *TESS*.

→ Written in `PYTHON` it can be installed, and used quickly.

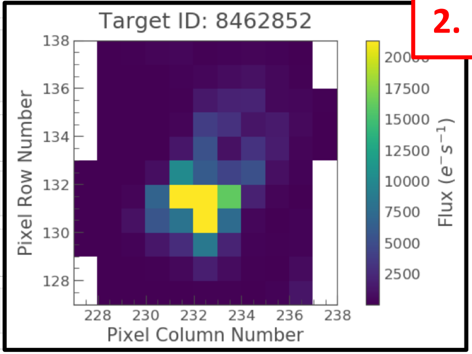
→ Provides users opportunities to access *Kepler* and *TESS* data, plot light curves, correct for systematics, identify trends, and find periodic signals.

Slide adapted from https://docs.lightkurve.org/

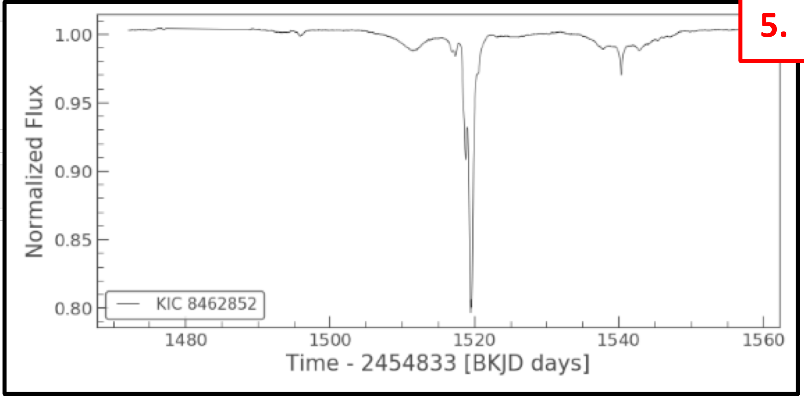
LightKurve Package

```
[1]: from lightkurve import search_targetpixelfile
     pixelfile = search_targetpixelfile(8462852, quarter=16).download(quality_bitmask='hardest');

[2]: pixelfile.plot(frame=1);

[3]: lc = pixelfile.to_lightcurve(aperture_mask='all');

[4]: lc.time, lc.flux

[4]: (array([1472.11777934, 1472.13821223, 1472.15864492, ..., 1557.89718798,
            1557.9380561 , 1557.95849016]),
      array([258645.03, 258660.05, 258690.08, ..., 258929.86, 258884.66,
            258865.6 ], dtype=float32))

[5]: lc.plot();
```

2.



5.



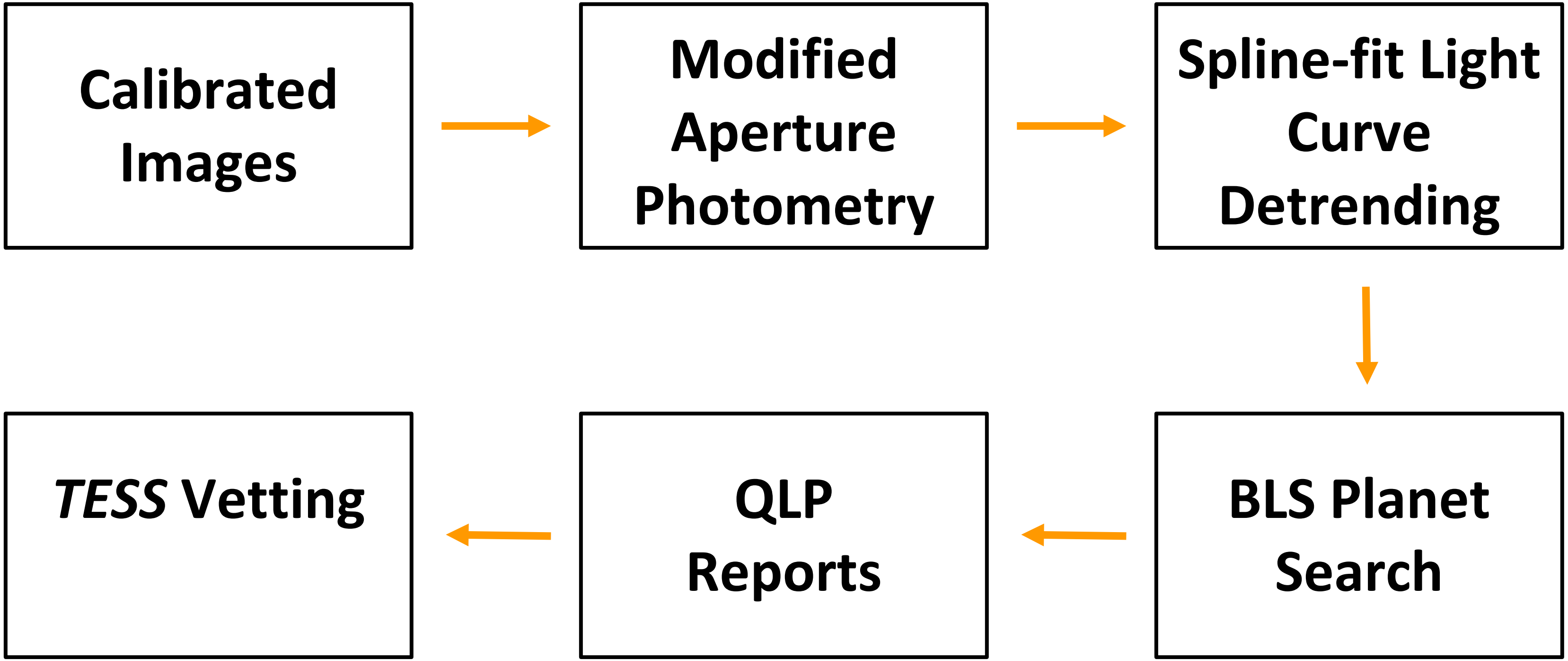
Slide adapted from https://docs.lightkurve.org/quickstart.html

TASOC Pipeline

TASOC Pipeline

MIT Quick-Look Pipeline (QLP)

(Huang, Pál, Vanderburg, Yu, Fausnaugh, Shporer, and the TESS team)

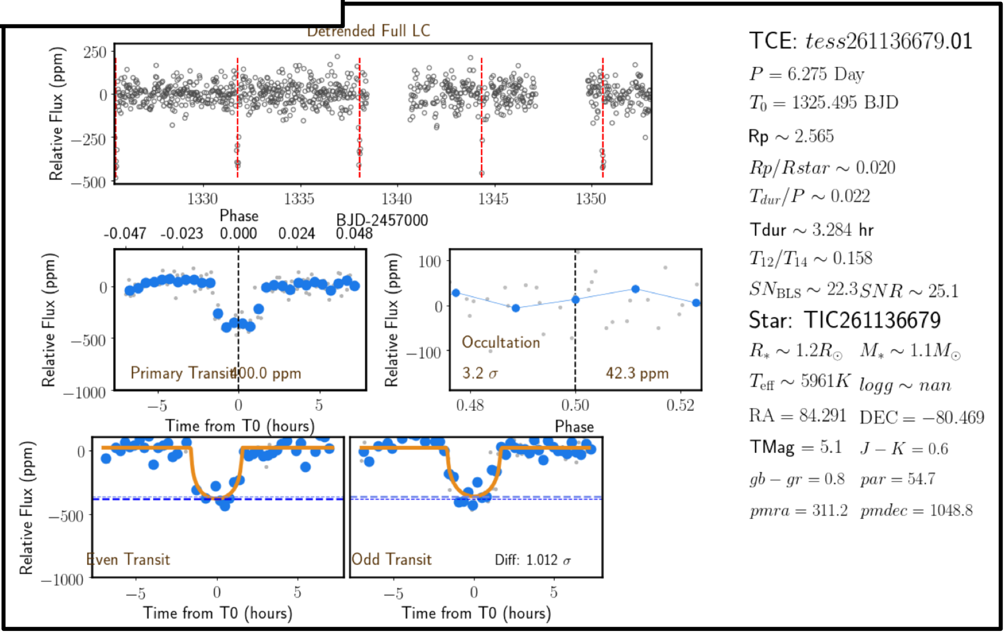


Huang et al. 2018; Slides adapted from a presentation by Lizhou Sha

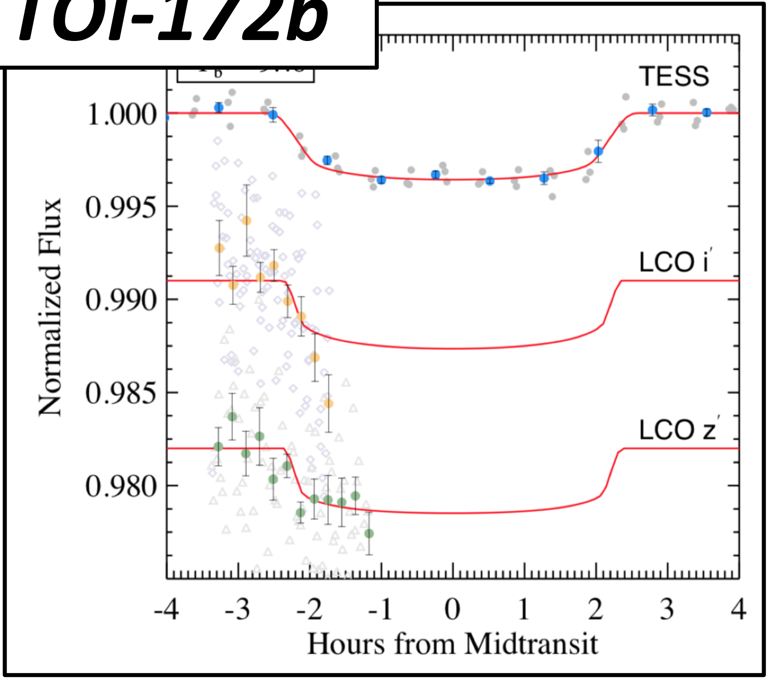
MIT Quick-Look Pipeline (QLP)

π Men c: Huang et al. 2018; TOI-271b: Rodriguez at el. 2019

π Men c

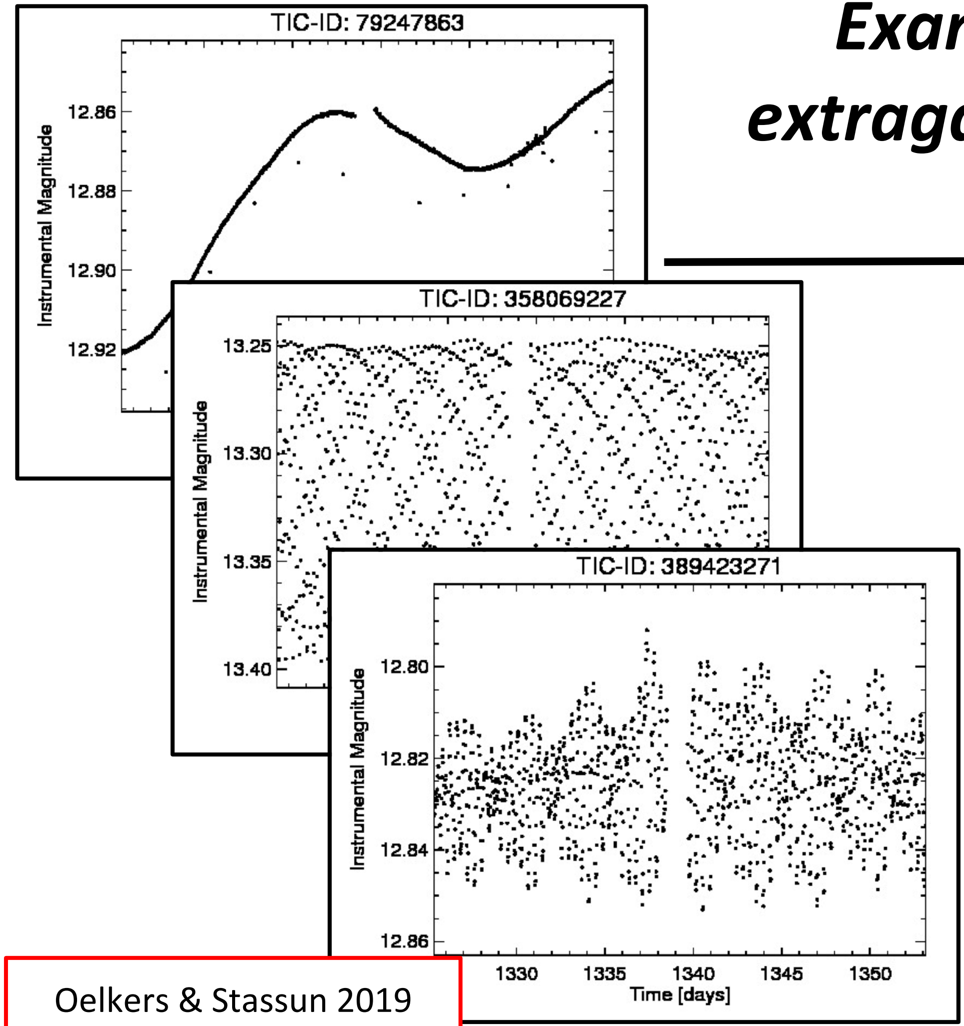


TOI-172b



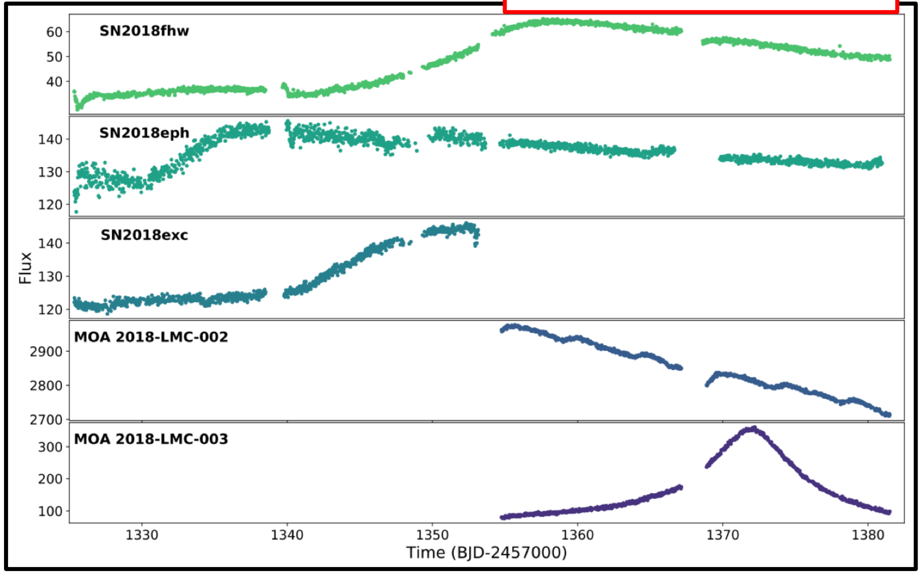
Slides adapted from a presentation by Lizhou Sha

Examples of TESS stellar and extragalactic light curves showing variability

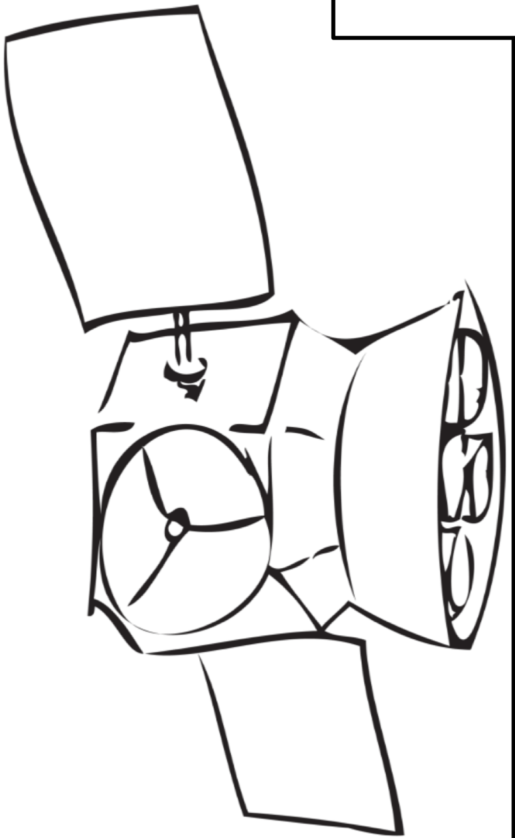


Oelkers & Stassun 2019

Feinstein et al. 2019



Summary



TESS is currently observing in Sector 10, with 7 sectors of data already released.

Most of the available data products can be found on MAST.

- → 2-minute light curves
- → 30-minute full frame images
- → TESS Input Catalog
- → Data validation reports

There are numerous community-led pipelines, already producing data light curves for 30-minute full frame images.

TESS has shown capabilities of detecting variability in stars and extra-galactic sources!

Towards precision Astromety & photometry from the ground

Eran Ofek

Weizmann Institute of Science

With: N. Segev, O. Springer, D. Polishook, B. Zackay, J. Lu, A. Goobar, E. Waxman, I. Arcavi



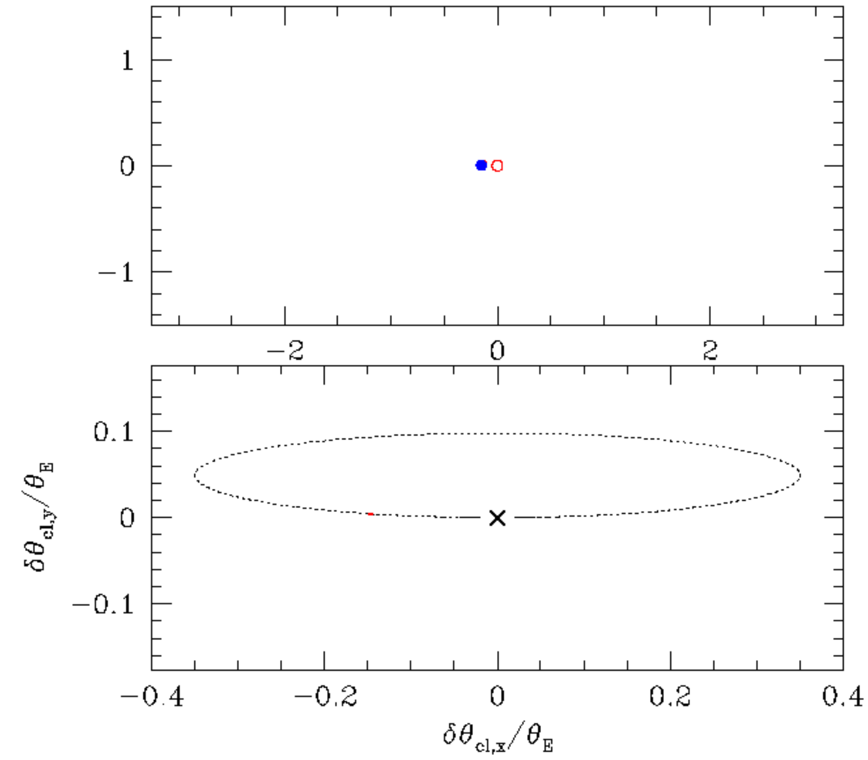





Outline

- Motivation for astrometry & photometry
  - Search for isolated stellar-mass BH
  - Binary asteroids
  - Lensed quasars and time delay
  - GW170817 jet
  - exoplanets
- Ground based astrometry
  - Limitations
  - Progress
- Ground based photometry
  - Limitations
  - Progress

Astrometric microlensing



Credit: S. Gaudi

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{ls}}{d_s d_l}}$$

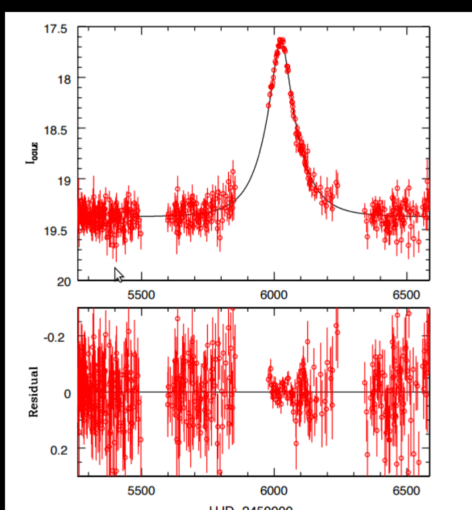
Search for compact objects

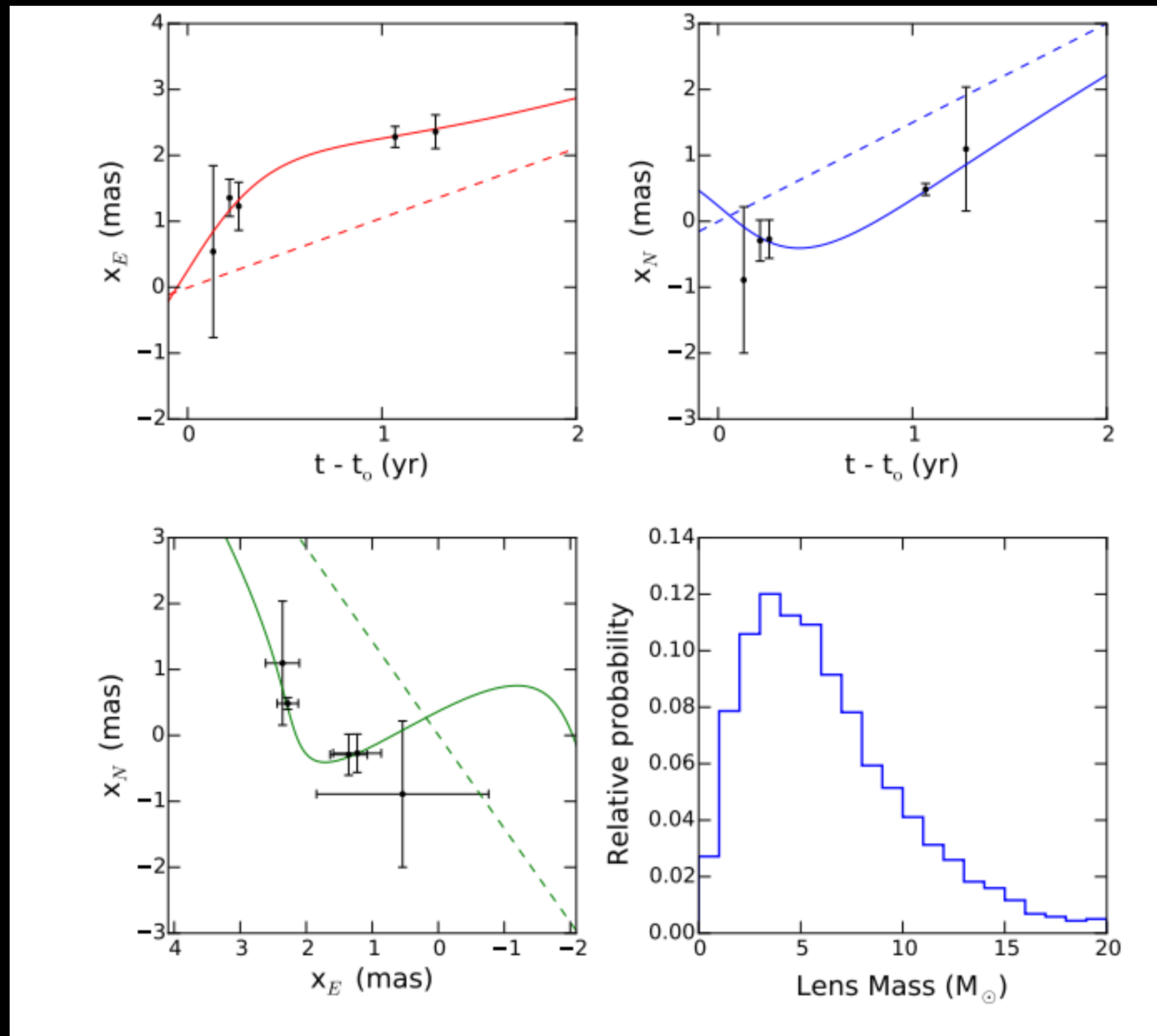
- Stellar-mass isolated BH/NS: product of stellar evolution
- Counting, and mass-function -> stellar death, GW,...

- Targets:
  - ML surveys (w/ long duration) i.e., Lu et al. (2016)
  - GAIA predictions (e.g., Bramich+2018, Ofek 2018)
  - High gal. lat blind surveys (e.g., ZTF)

A search (with: J. Lu+)

- OB120169
- Best fit:
- First 5 yr

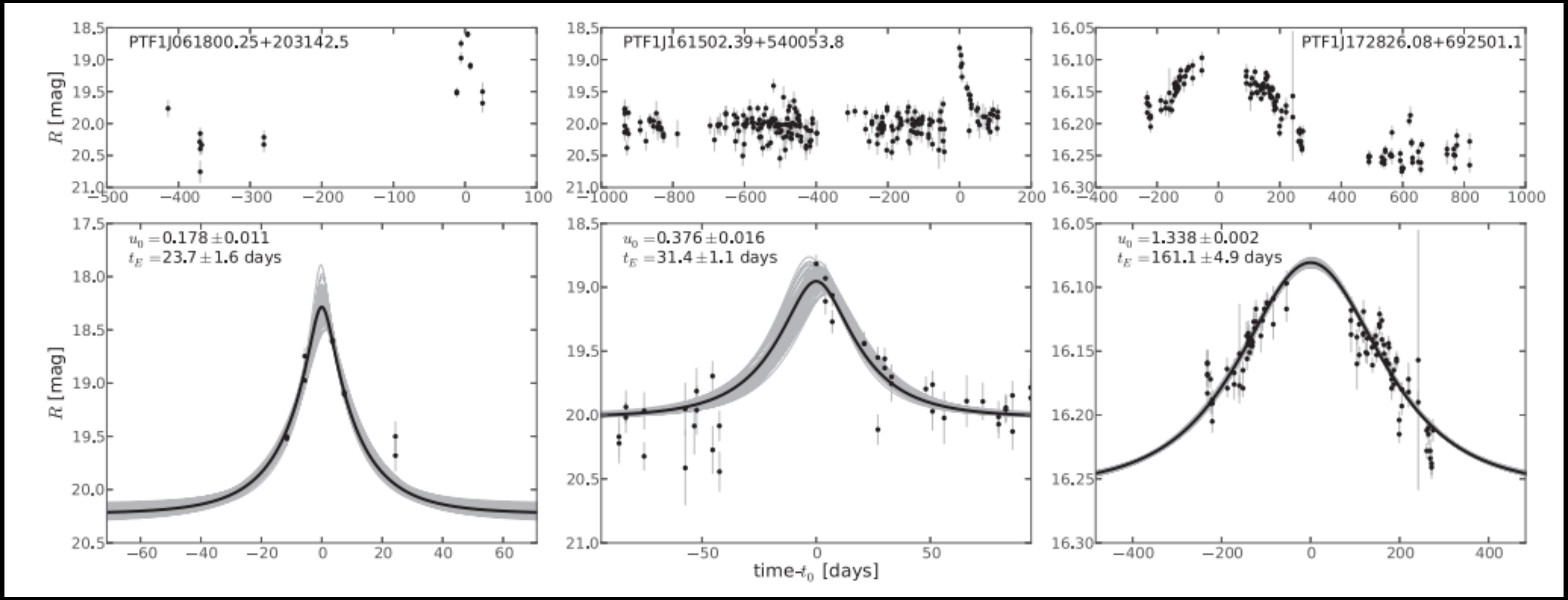




Lu et al. 2016 ApJ 830, 41

Relative Astrometry with ZTF

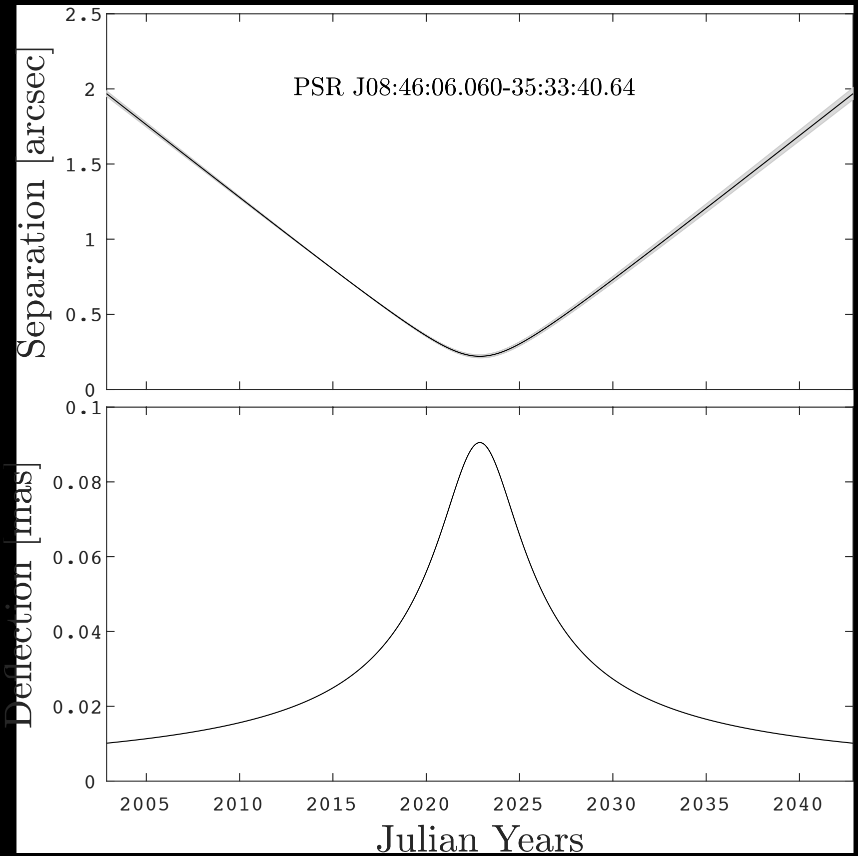
- ZTF can find (very rare) high Galactic latitude ML events (nearby->large θ_E)
- Candidates from PTF:



Price-Whelan et al. 2014

Lensing by pulsars

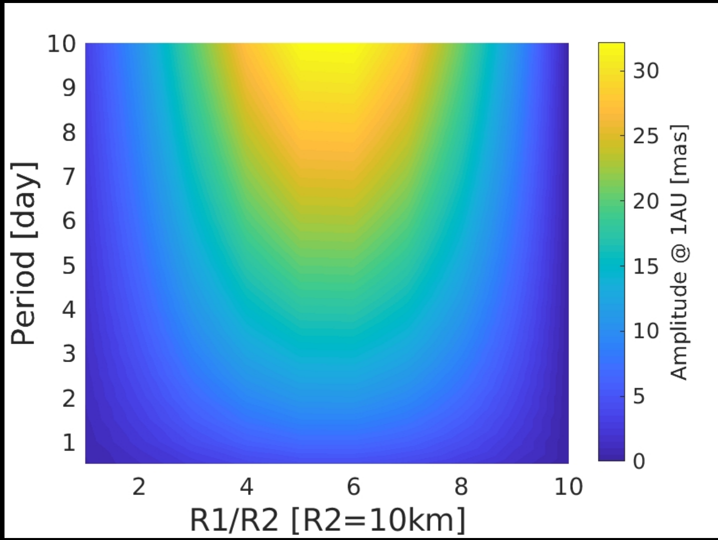
- Another possibility: detecting astrometric lensing of known pulsars on background stars



Ofek 2018, ApJ

Binary asteroids

- Characterizing binary asteroids is important for understanding the YORP effect
- Methods: radar, light curves, imaging,...
- Detection using the Center of light motion (Segev et al., in prep.)



Lensed quasars / time delays

- Time delay measurements of lensed quasars offers an independent method for measuring H_0.
- Hindered by: model dependent and systematics - requires large sample.
- Expensive!

- Springer+ in prep. - using Astrometry...

Why not GAIA?

- Cadence is too sparse for some applications
- Missing some objects (e.g., GW170817)

Precision photometry motivation

- Search for transiting exoplanets
- Debris around WDs
- Role of massive spectroscopy: radial velocities

Sub mas astrometry from the ground?

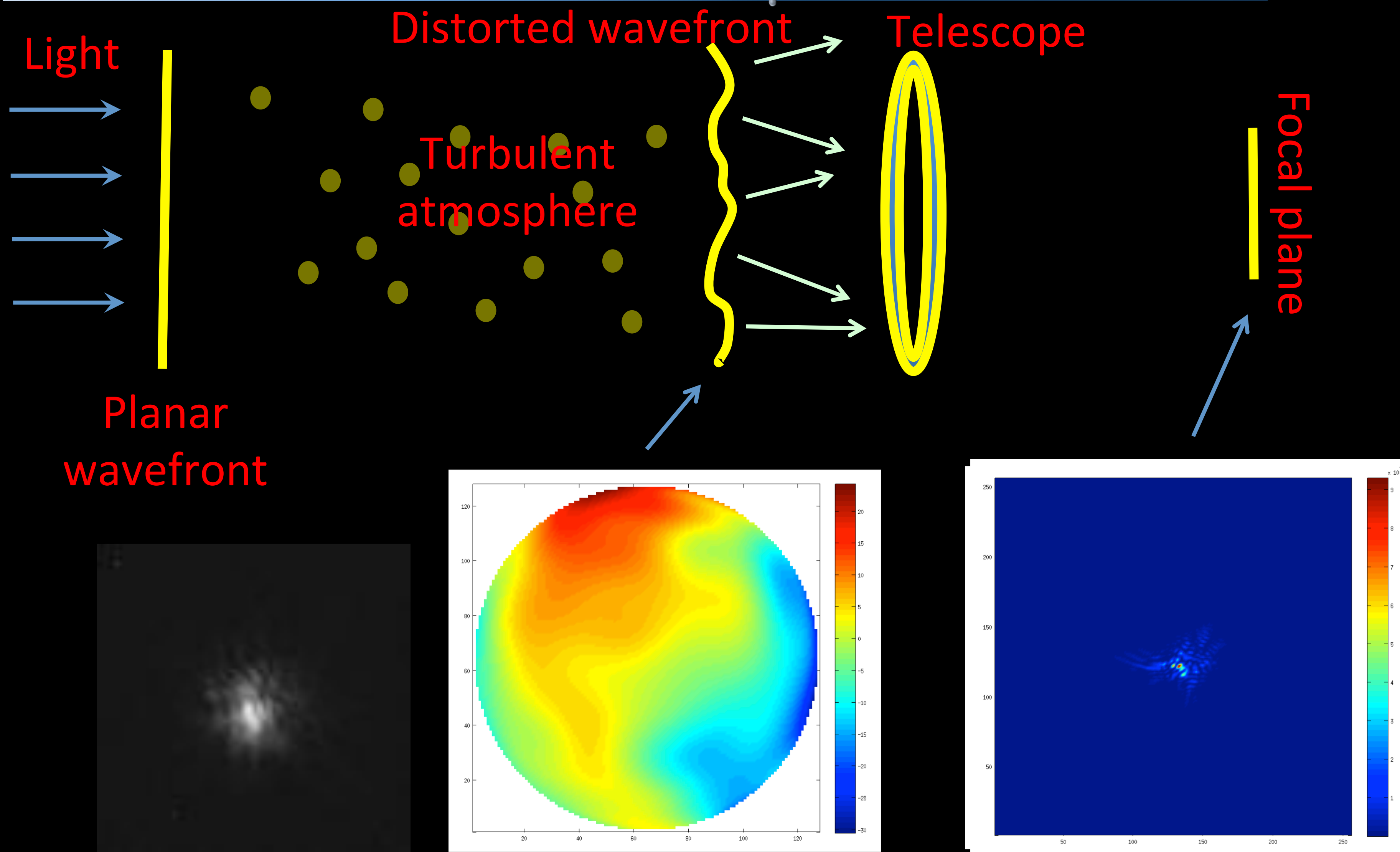
- With AO 100-200 μas is possible
- With GRAVITY ~tens μas is doable
- For seeing limited Monet (1983) claimed 1 mas parallax accuracy, but…
- All methods are likely limited by systematics(!)

Astrometry - limiting factors

- Poisson noise: FWHM/$\sqrt{}$/N_{ph}~1 mas
- Optical distortions: ~1"/deg
- Atmospheric refraction: ~2"/deg
- Color refraction: ~a few mas
- Aberration of light: 0.5"/deg
- Grav. Deflection: ~0.1 mas/deg
- At. scintillation: FWHM/(Exp/τ_{sc})~20mas
- Systematics:
  - My leading suspect - non uniformities in detectors - a few milipixel(?)

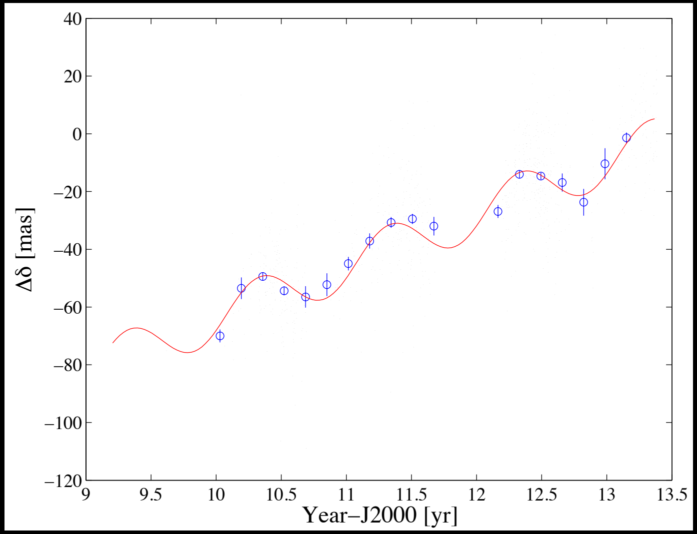
Have model

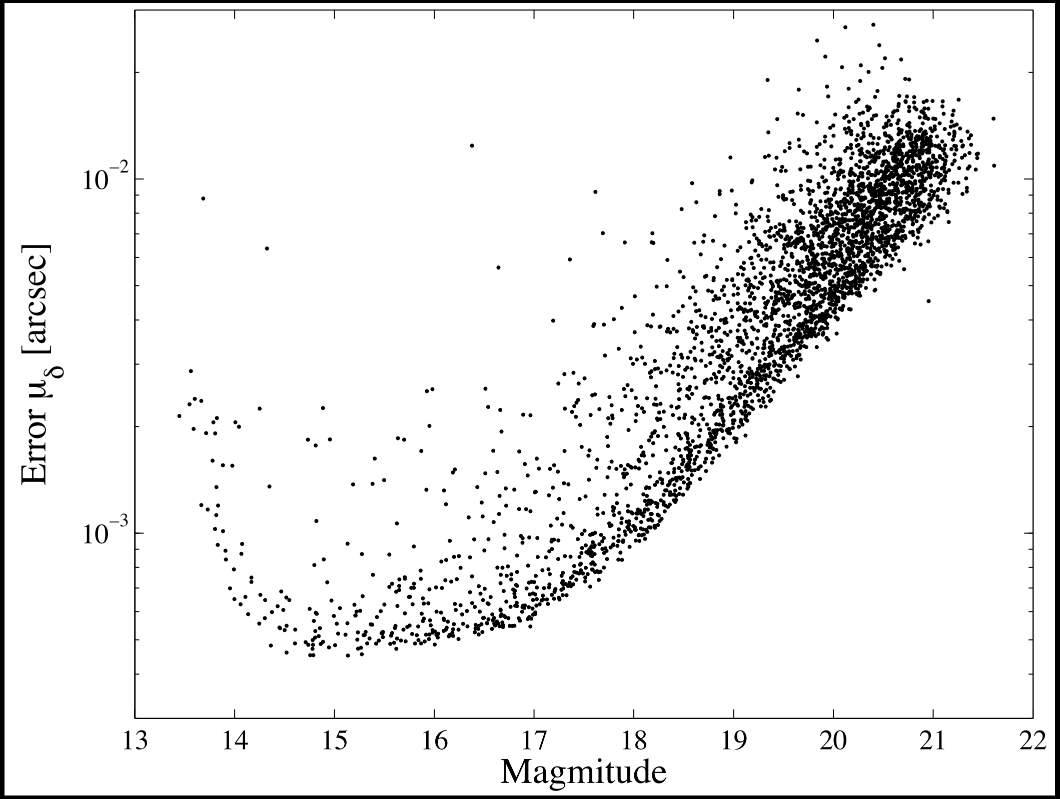
The turbulent atmosphere & the PSF



Before GAIA...

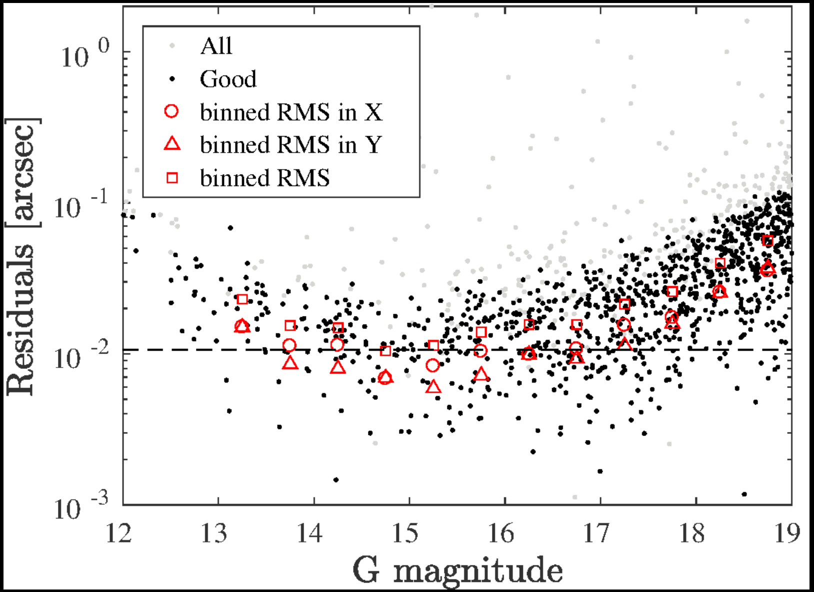
- Relative astrometry w/PTF
- Problem: difficult to estimate if the results are biased





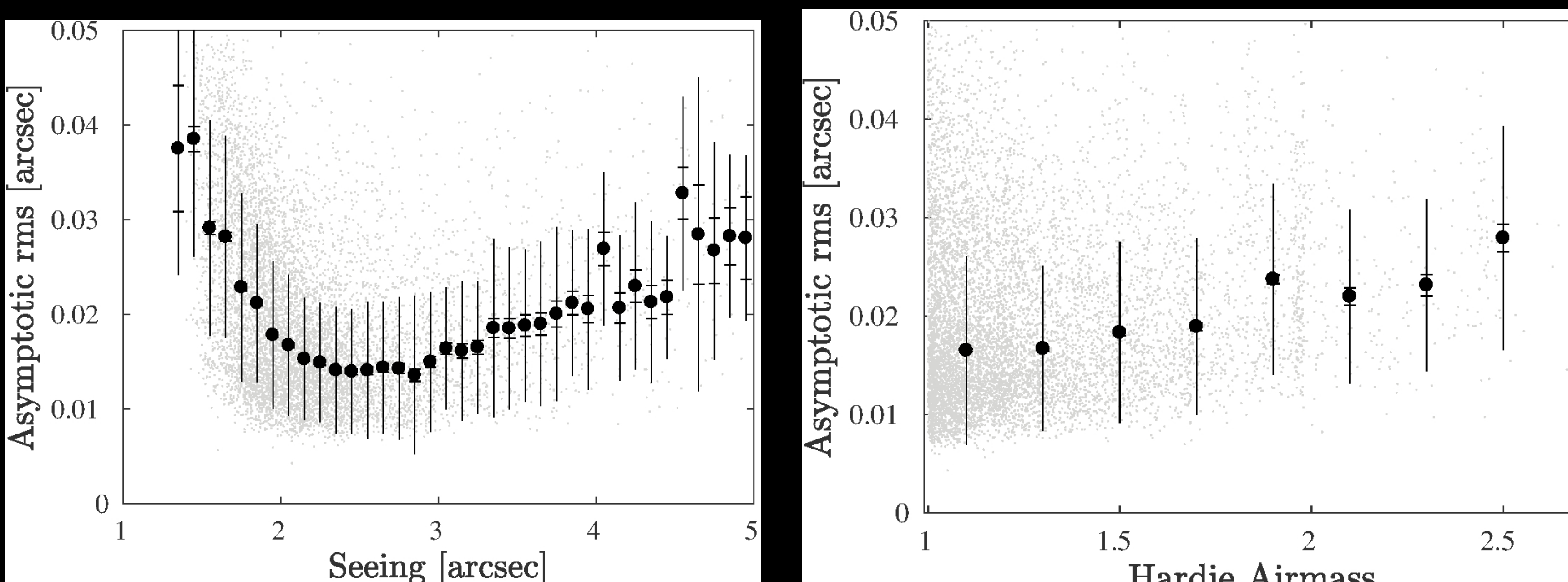
Astrometry relative to GAIA

- New astrometry code – performances:
- Failure rate ~<1 in 50,000
- Typical rms w/PTF: 14 mas (2 axes comb.)
- ~2-3 times better than ZTF pipeline



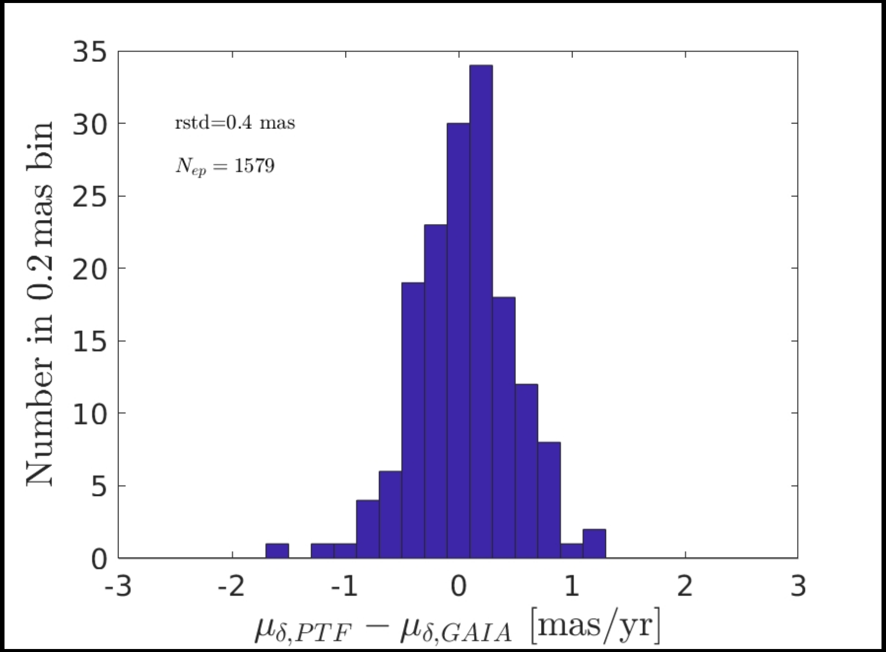
Astrometry relative to GAIA

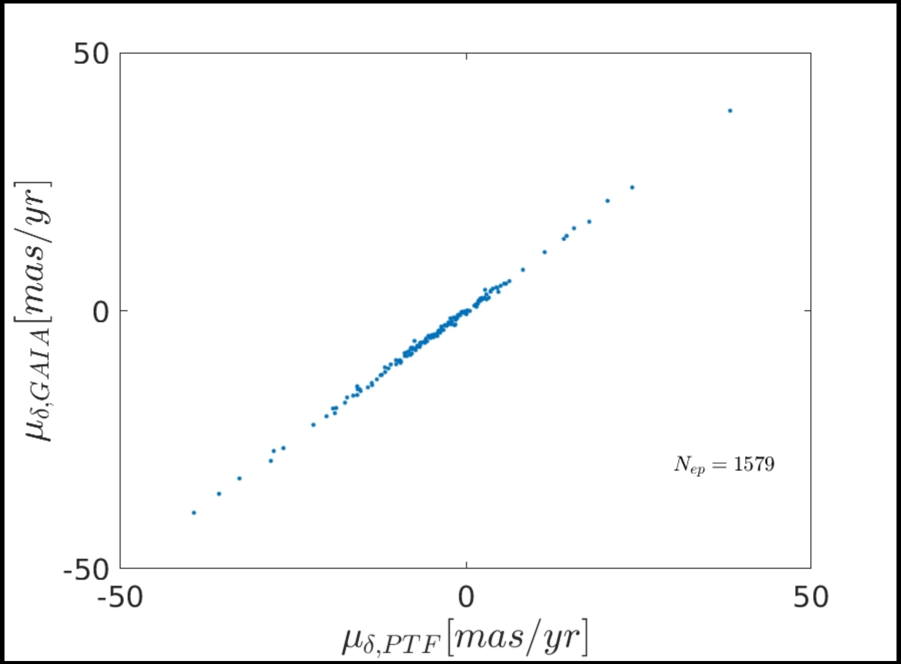
- New astrometry code – performances:



Comparison w/GAIA

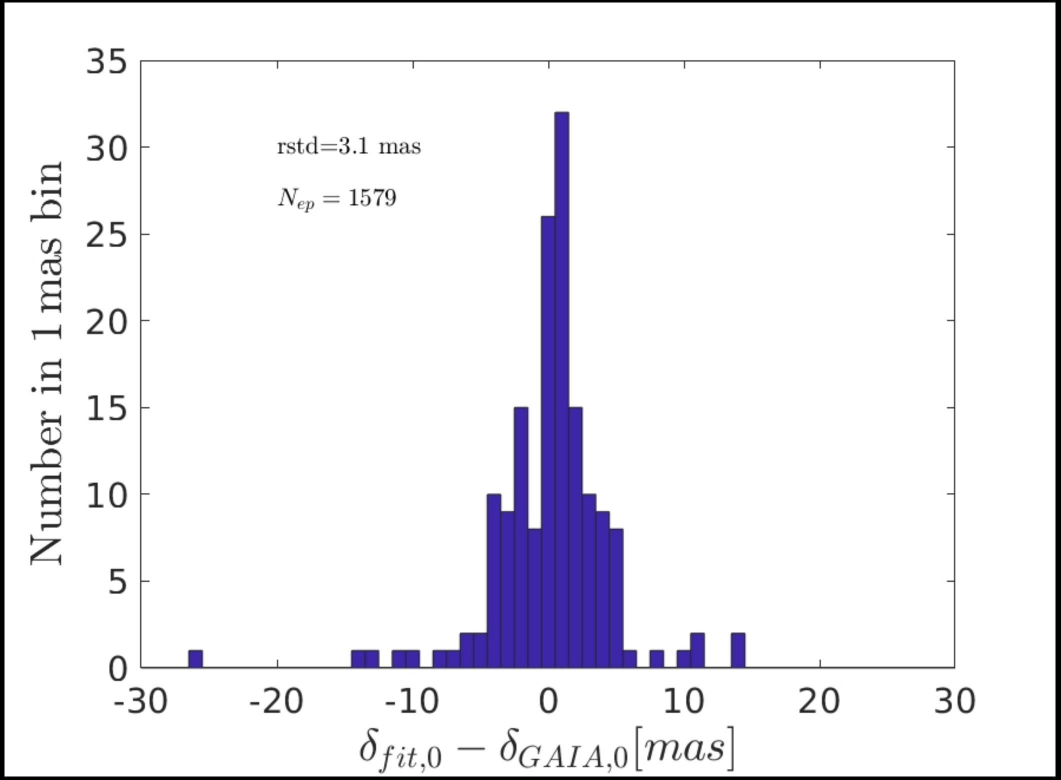
- Use GAIA to verify results
- ~0.4 mas/yr in PM over 7 years





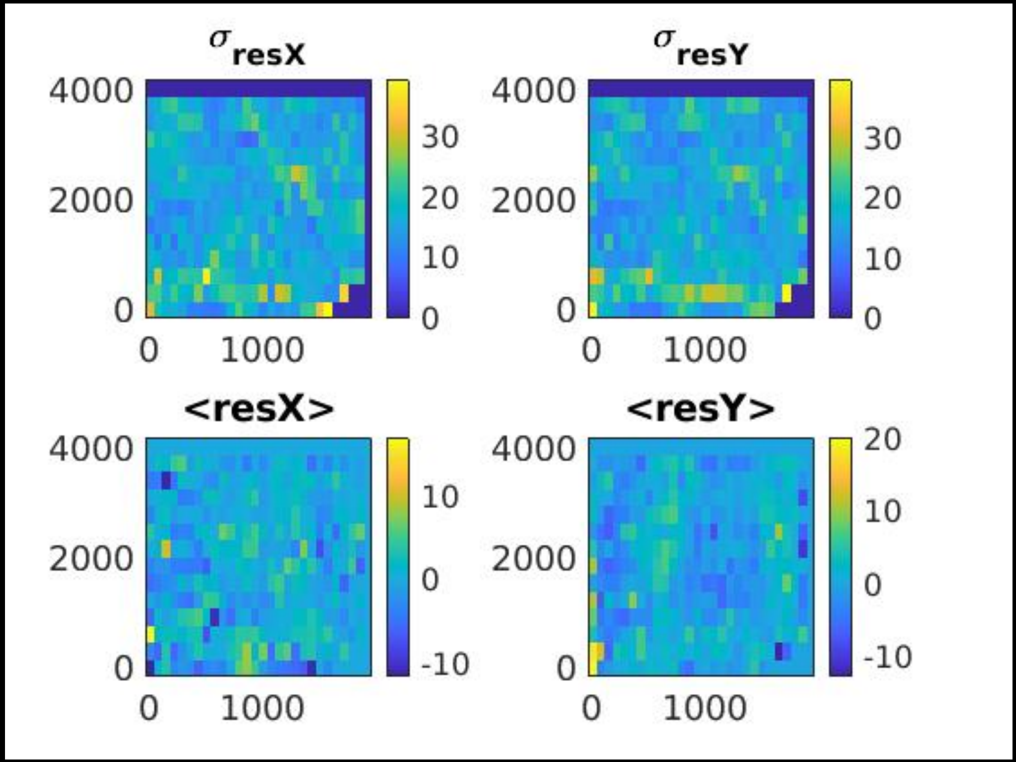
Comparison w/GAIA

- but ~3mas error in positions (w/1500 images)
- Predicted Poisson noise: 14/sqrt(1500)~0.4 mas
- Systematics!



Searching for systematics

- Pixel size variations?
- Requires simultaneous solution



Conclusion / Astrometry

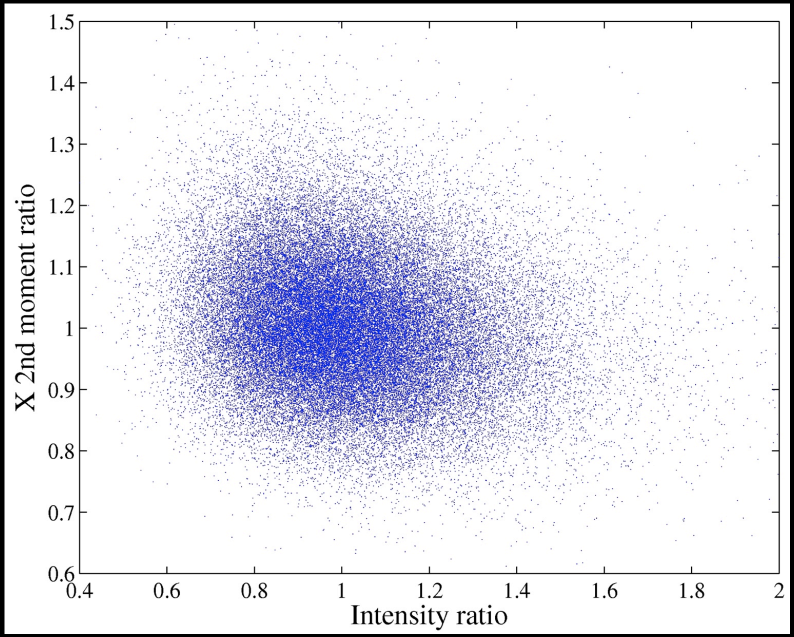
- Ground based seeing limited astrometry is useful
- We currently able to measure stellar positions to accuracy of about 3mas
- We are limited by systematic noise
- Next: trying to beat the systematics

Precision photometry / Limitations

- Flat fielding errors
  - Separate scattered light
  - Color dependency
- Scintillations
  - Intensity scintillations
  - Phase scintillations
- Transparency
  - Correlated noise

Precision photometry / Mitigation

- Flat fielding errors
  - TDI
  - Out of focus / small pixels
  - Keep star on the same pixel (hard)
- Scintillations
  - ML?
  - Aperture corrections
  - Fast imaging!
- Transparency [progress]
  - Model and filtering
  - Fast imaging!



End

Optimal Image coaddition

Transparency

Image

Noise

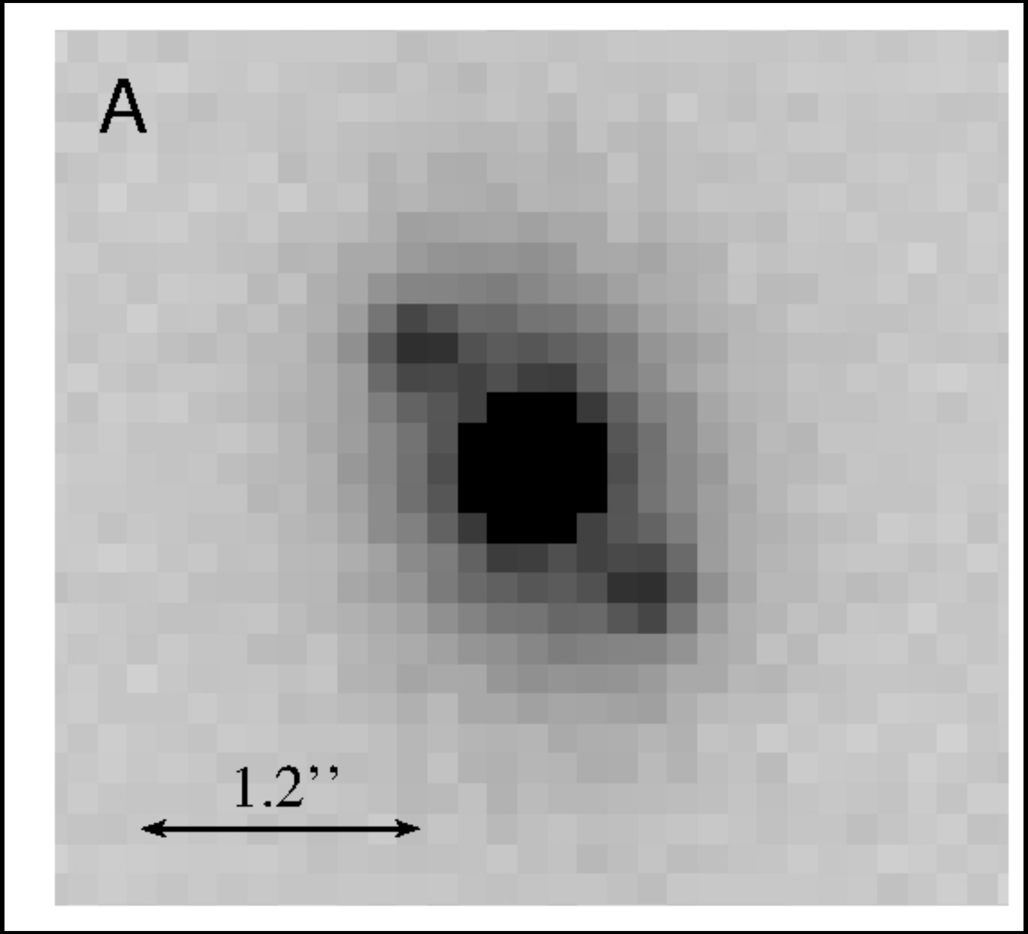
PSF of M_j

$$\hat{R} = \frac{\sum \frac{F_j}{\sigma_j^2} \hat{M}_j \bar{\hat{P}}_j}{\sqrt{\sum \frac{F_j^2}{\sigma_j^2} \left|\hat{P}_j\right|^2}}$$

$$\hat{P}_R = \sqrt{\sum \frac{F_j^2}{\sigma_j^2} \left|\hat{P}_j\right|^2}$$

Zackay & EO 15a; 15b

Coaddition: Tests on real images



Zackay & Ofek 2015b

The All-Sky Automated Survey for SuperNovae (ASAS-SN or "Assassin")

Benjamin J. Shappee

University of Hawai'i

UNIVERSITY·OF·HAWAI'I
MA LAMA MA LAMA
1907
MĀNOA

INSTITUTE FOR ASTRONOMY
UNIVERSITY OF HAWAI'I

ASAS-SN Approach:

- Monitors the entire sky every 20 hours in real-time
- g-band limiting magnitude ≈ 18.5
- Use commercially available Telephoto lenses and CCDs
- Find supernovae in a minimally biased search
- Announce discoveries **publicly**

ASAS-SN Is a Global Partnership

B. J. Shappee, M. Tucker, A. Payne, A, Do, K. Hart (University of Hawaii)

C. S. Kochanek, K. Z. Stanek, T. A. Thompson, J. F. Beacom, J. Brown, T. Jayasinghe, G. Simonian P. Vallely, Josh Shields (Ohio State)

T. W.-S. Holoien (Carnegie Observatories)

J. L. Prieto (Diego Portales), D. Bersier (LJMU)

Subo Dong, Ping Chen, S. Bose (KIAA-PKU)

M. Stritzinger, Simon Holmbo (Aarhus University)

L. Chomiuk, J. Strader (Michigan State)

Anna Franckowiak (DESY); Katie Auchettl (DARK)

Ondřej Pejcha, Michał Pawlak (Charles University)

Xinu Dai (University of Oklahoma);

David Martinez-Delgado (Heidelberg);

P. R. Wozniak (LANL), E. Falco (CfA)

N. Morrell (Carnegie Observatories)

J. Brimacombe (Coral Towers Observatory)

G. Pojmanski (Warsaw University)


GORDON AND BETTY MOORE FOUNDATION
ASAS-SN
THE OHIO STATE UNIVERSITY
Late-2019
NSF
CCAPP
PEKING UNIVERSITY
AARHUS UNIVERSITY
MICHIGAN STATE UNIVERSITY Founded 1855
MOUNT CUBA ASTRONOMICAL FOUNDATION
DESY
CASSACA

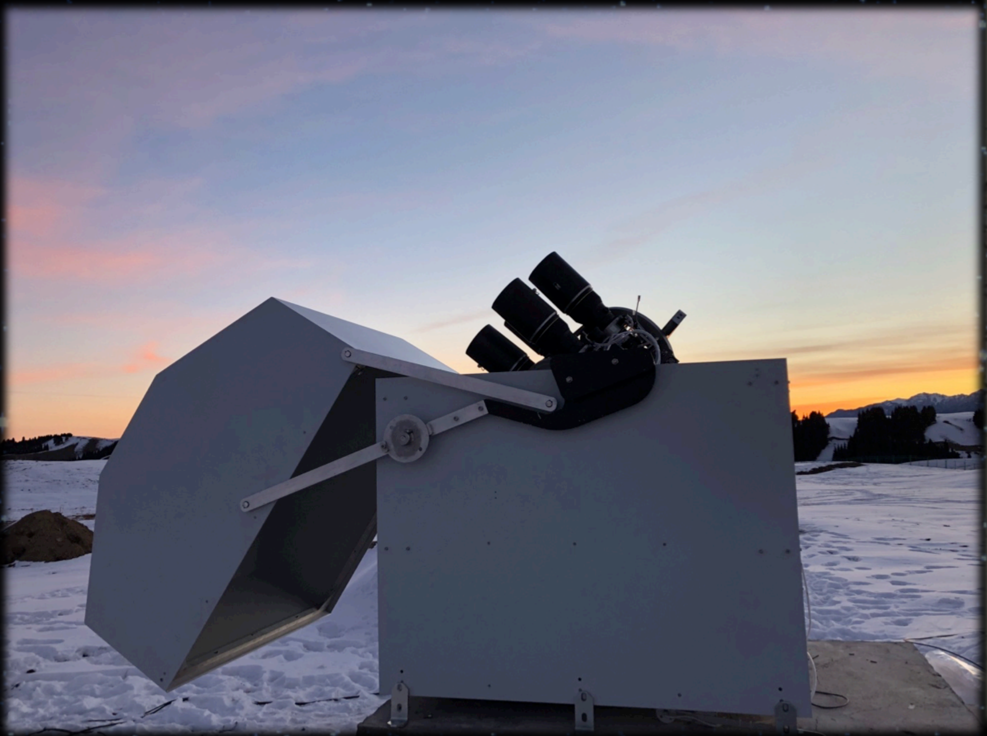
ASAS-SN units

- 4 telescopes per mount
- 14cm lens, 2k × 2k thinned CCDs
- 4.47 × 4.47 degree field-of-view
- 7.8" pixel scale
- *g*-band filters
- limiting magnitude ≈ 18.5
- ≈6500 images per night
- 40,000 square degrees per night

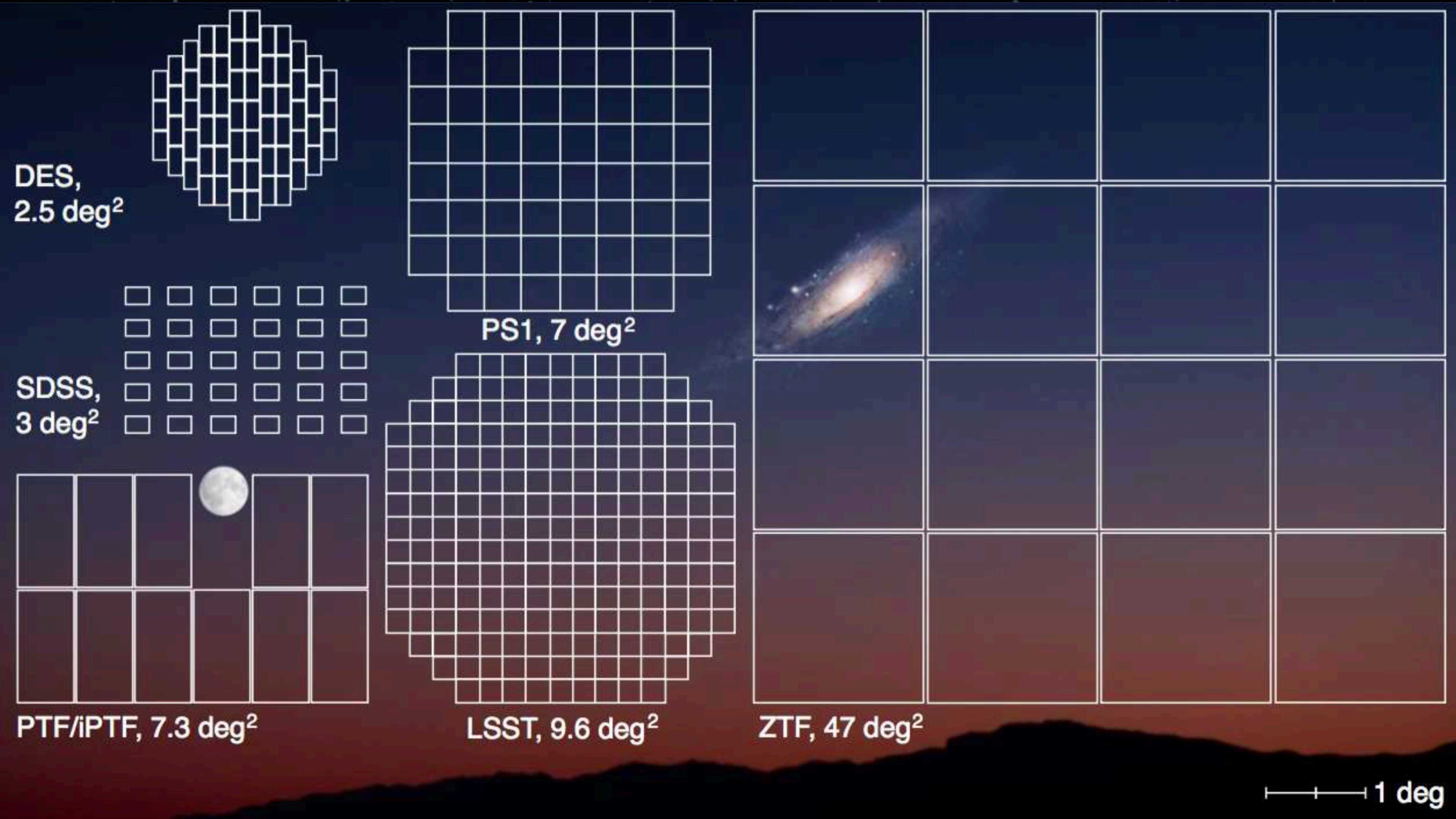
Picture Courtesy of Jon De Vera

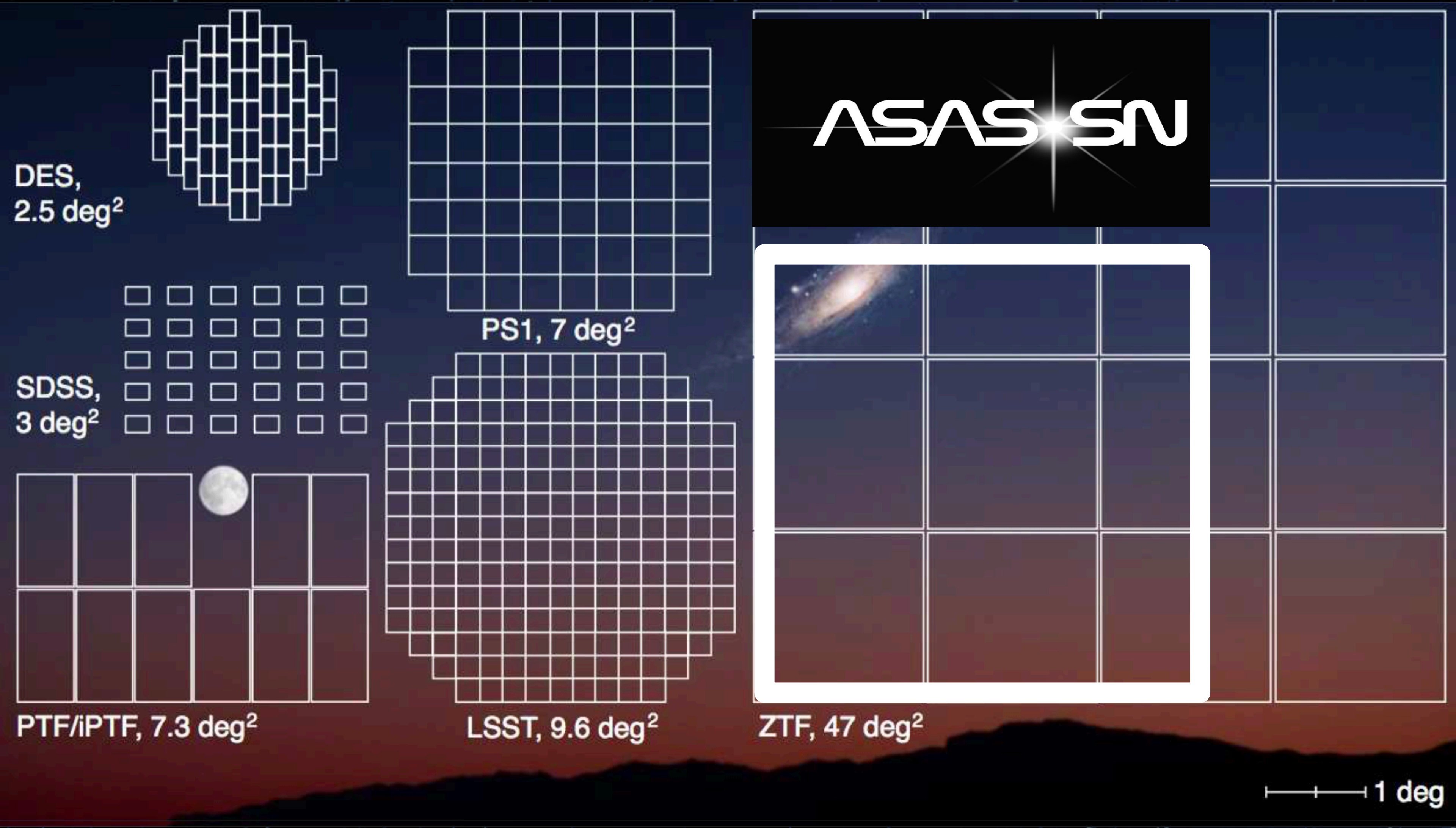
ASAS-SN "Tian Shan"

- 6th unit by the end of 2019
- 4 more telescopes
- Nanshan Station of Xinjiang Astronomical Observatory
- Funds from Peking University using the government funding "Double First Class University Plan"

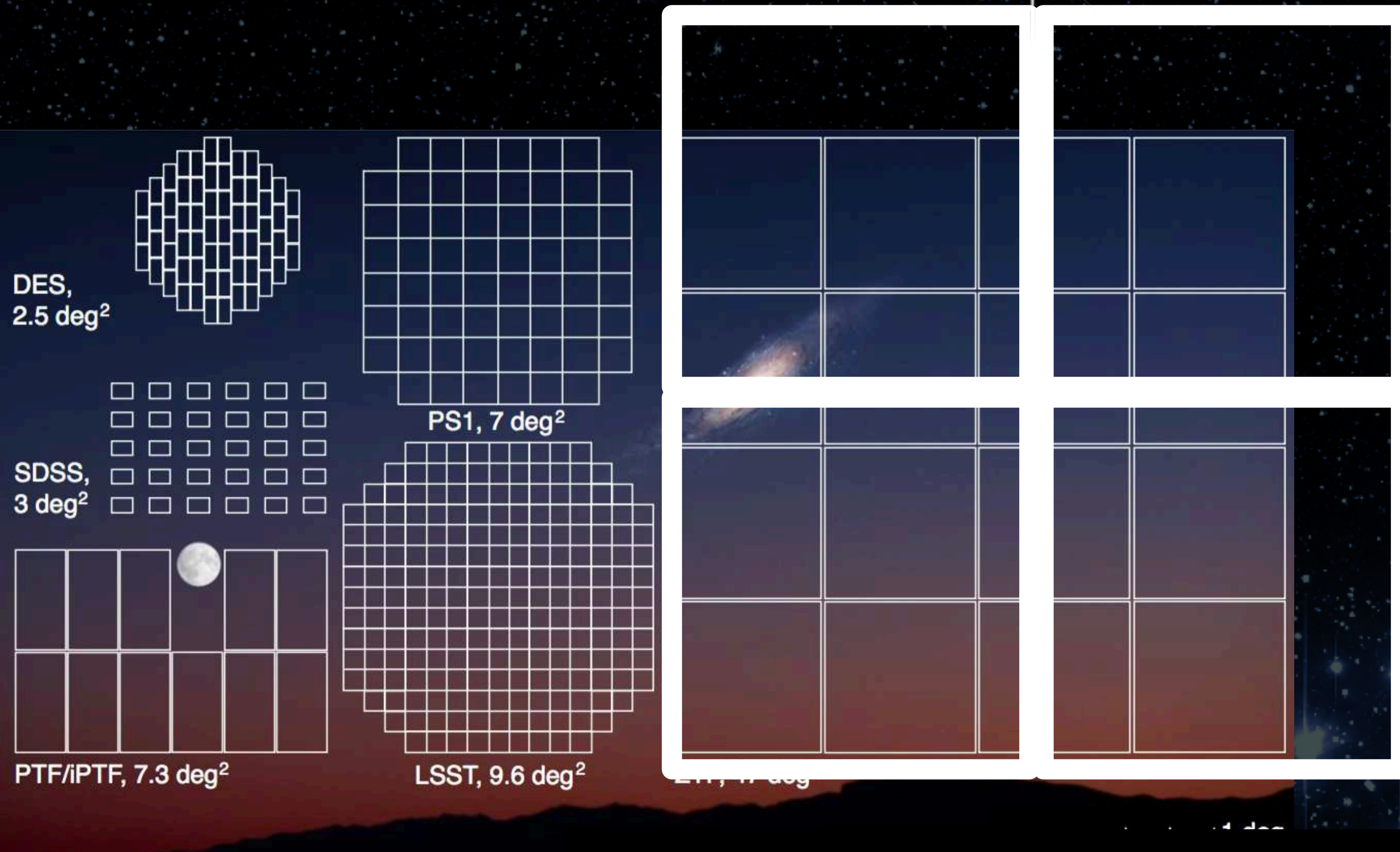


Pictures Courtesy of Xinjiang Astronomical Observatory and wikicommons


DES,
2.5 deg²
PS1, 7 deg²
SDSS,
3 deg²
PTF/iPTF, 7.3 deg²
LSST, 9.6 deg²
ZTF, 47 deg²
1 deg


ASAS-SN
DES,
2.5 deg²
PS1, 7 deg²
SDSS,
3 deg²
PTF/iPTF, 7.3 deg²
LSST, 9.6 deg²
ZTF, 47 deg²
1 deg

ASAS-SN



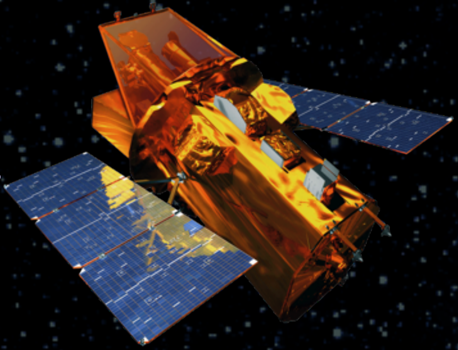
4 cameras per unit = 80 deg^2

ASAS-SN

Currently 5 units = 400 deg^2

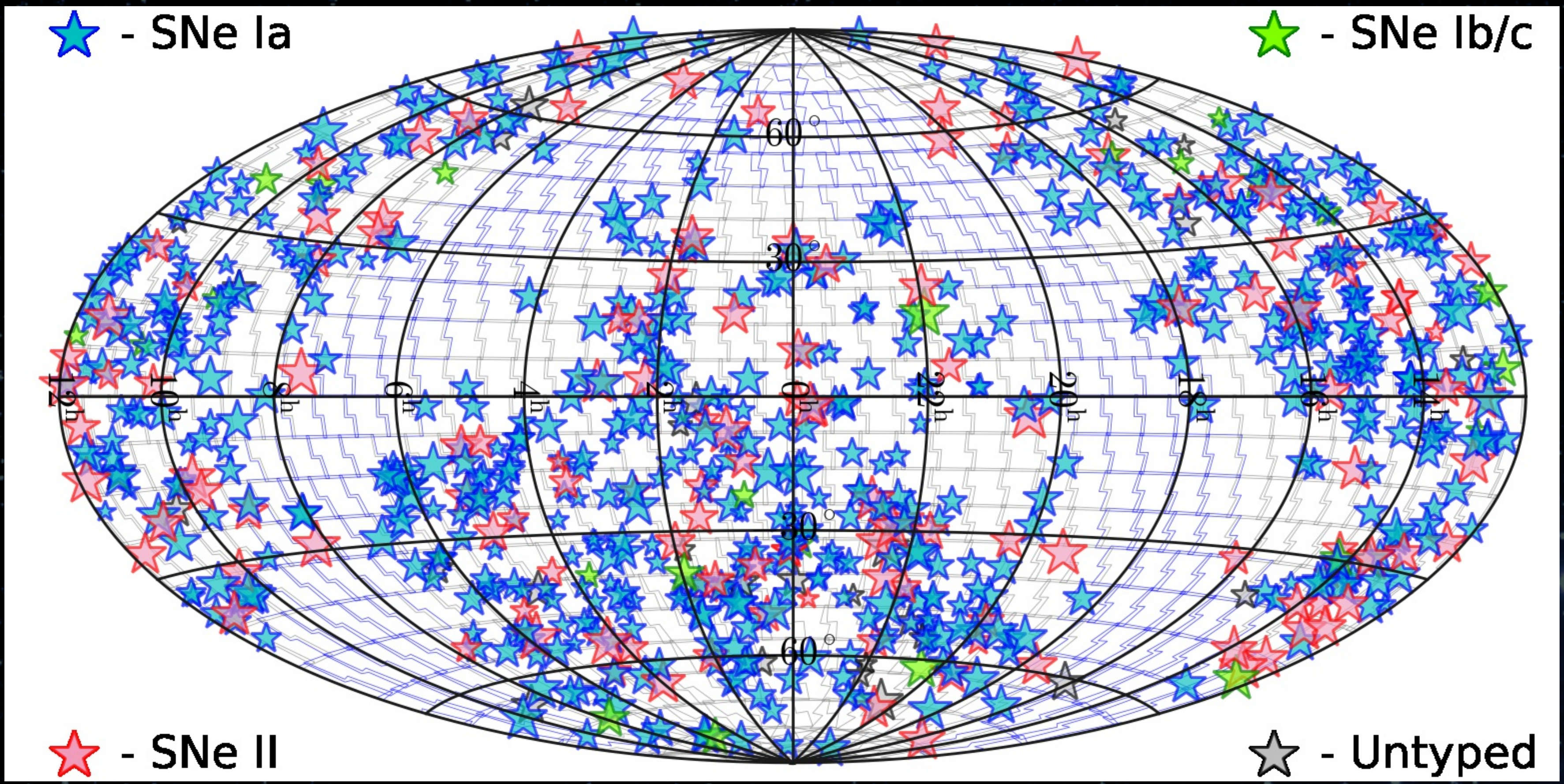
Follow-up Facilities

- UH88
- Keck
- LCOGT 1 meters
- Magellan 2 x 6.5 meter
- LBT 2 x 8.4 meter
- Du Pont 2.5 meter
- MDM 2.4 meter
- Liverpool Telescope 2 meter
- Swift satellite
- many others (SALT, FLWO 1.5m, NOT 2.5m, Faulkes, HST, Chandra, VLA …)

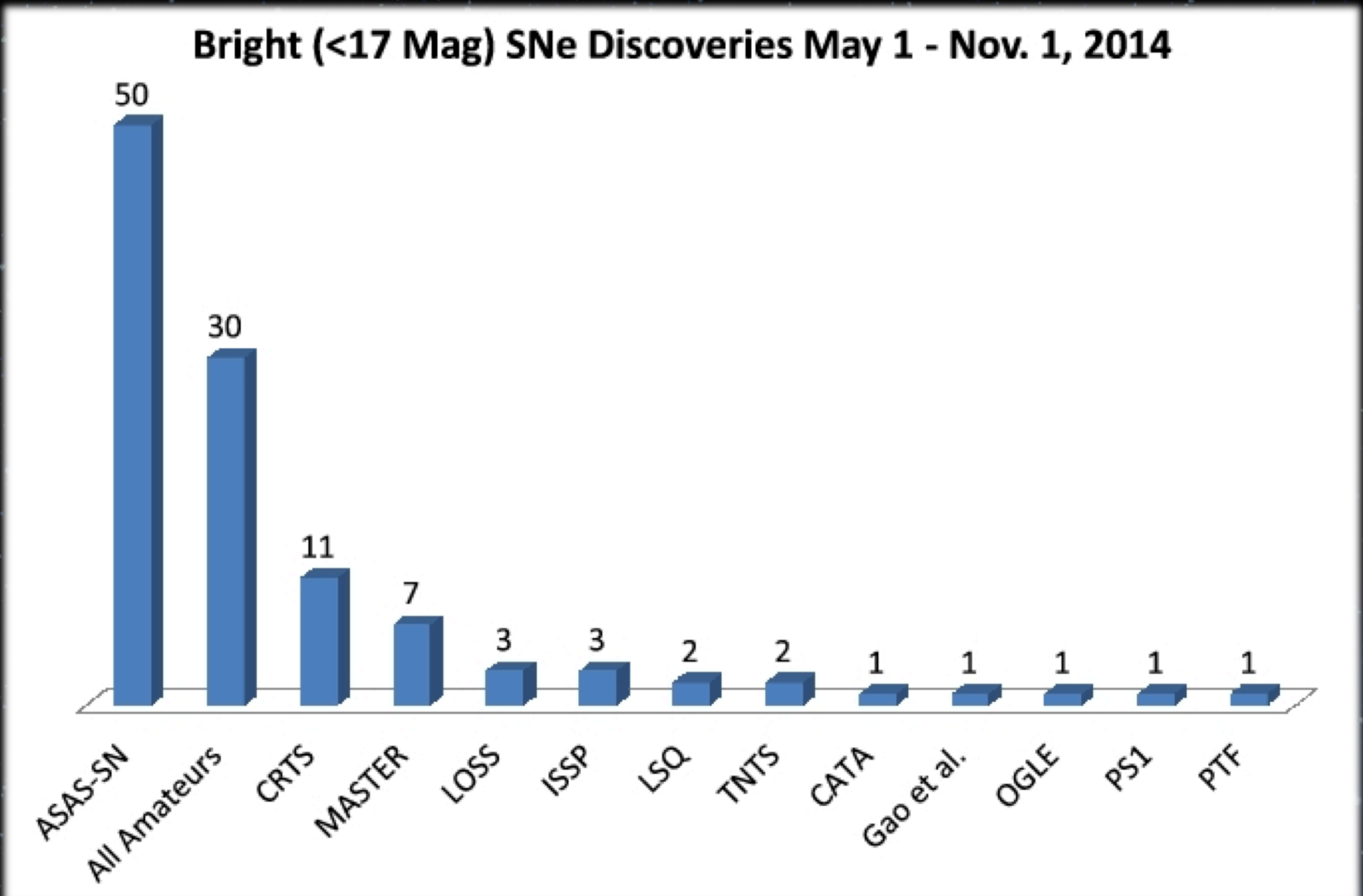


ASAS-SN Supernovae Discoveries

800+ Supernovae

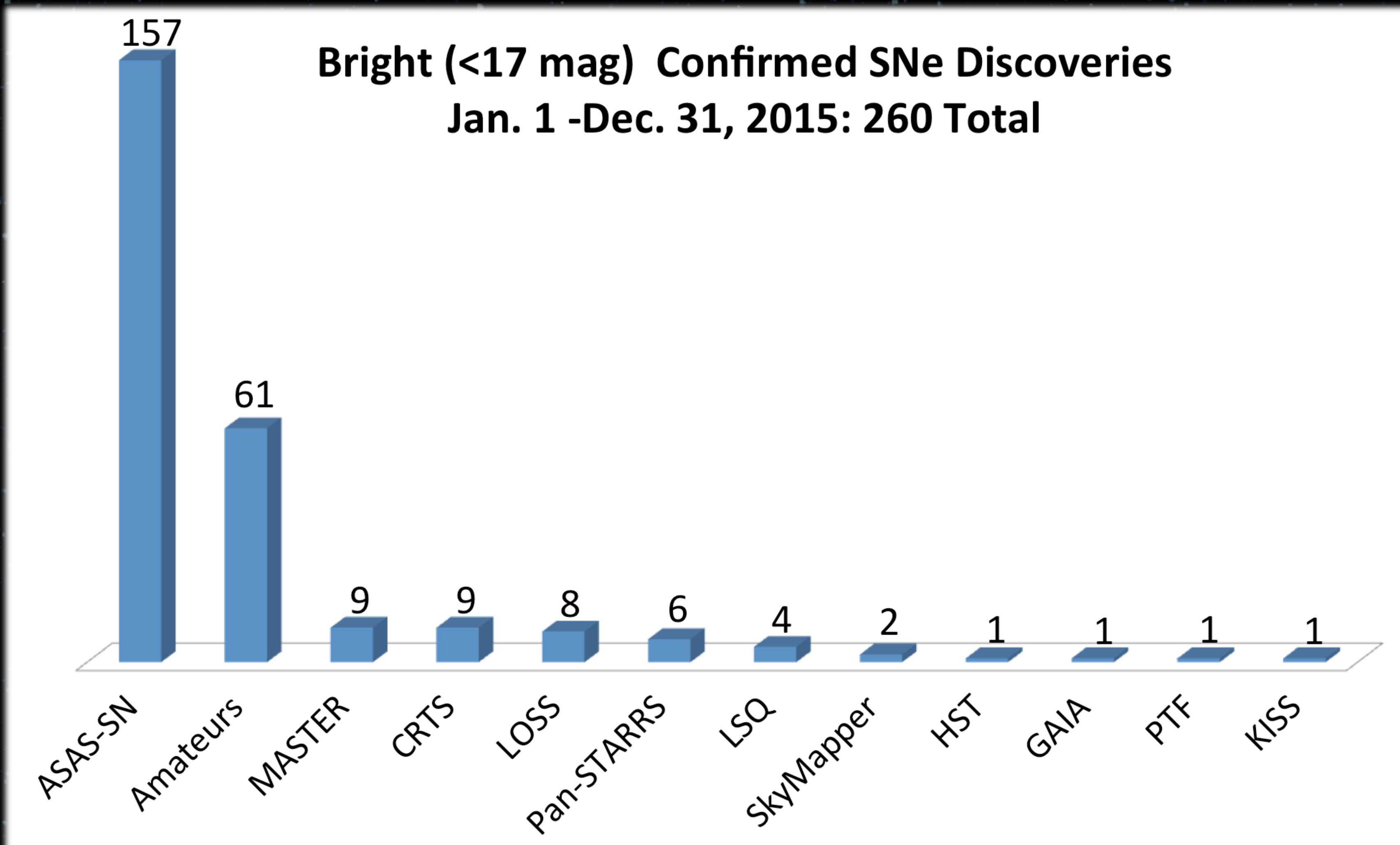


Nearby SNe

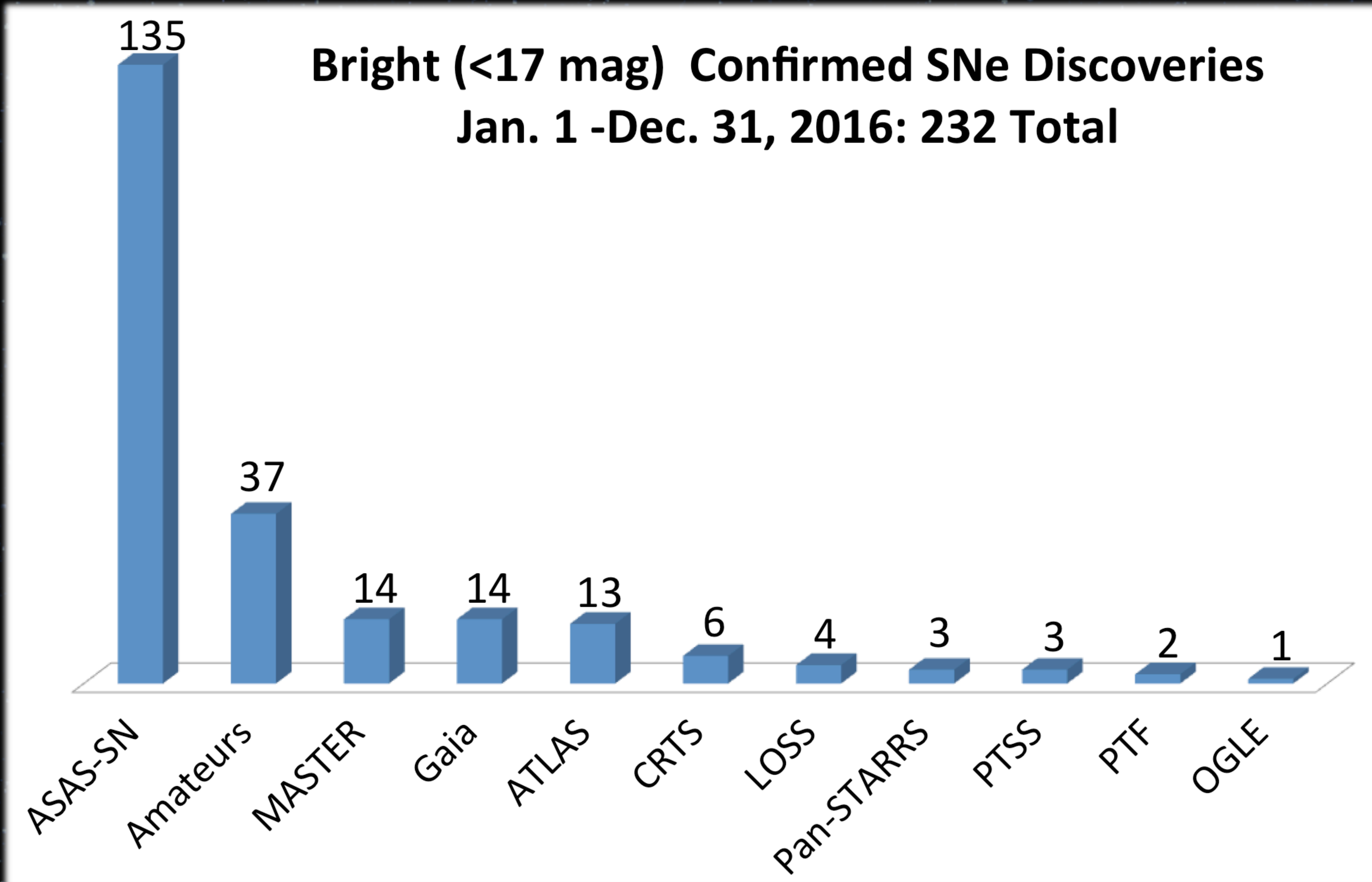


Bright (<17 Mag) SNe Discoveries May 1 - Nov. 1, 2014
50
30
11
7
3
3
2
2
1
1
1
1
1
ASAS-SN
All Amateurs
CRTS
MASTER
LOSS
ISSP
LSQ
TNTS
CATA
Gao et al.
OGLE
PS1
PTF

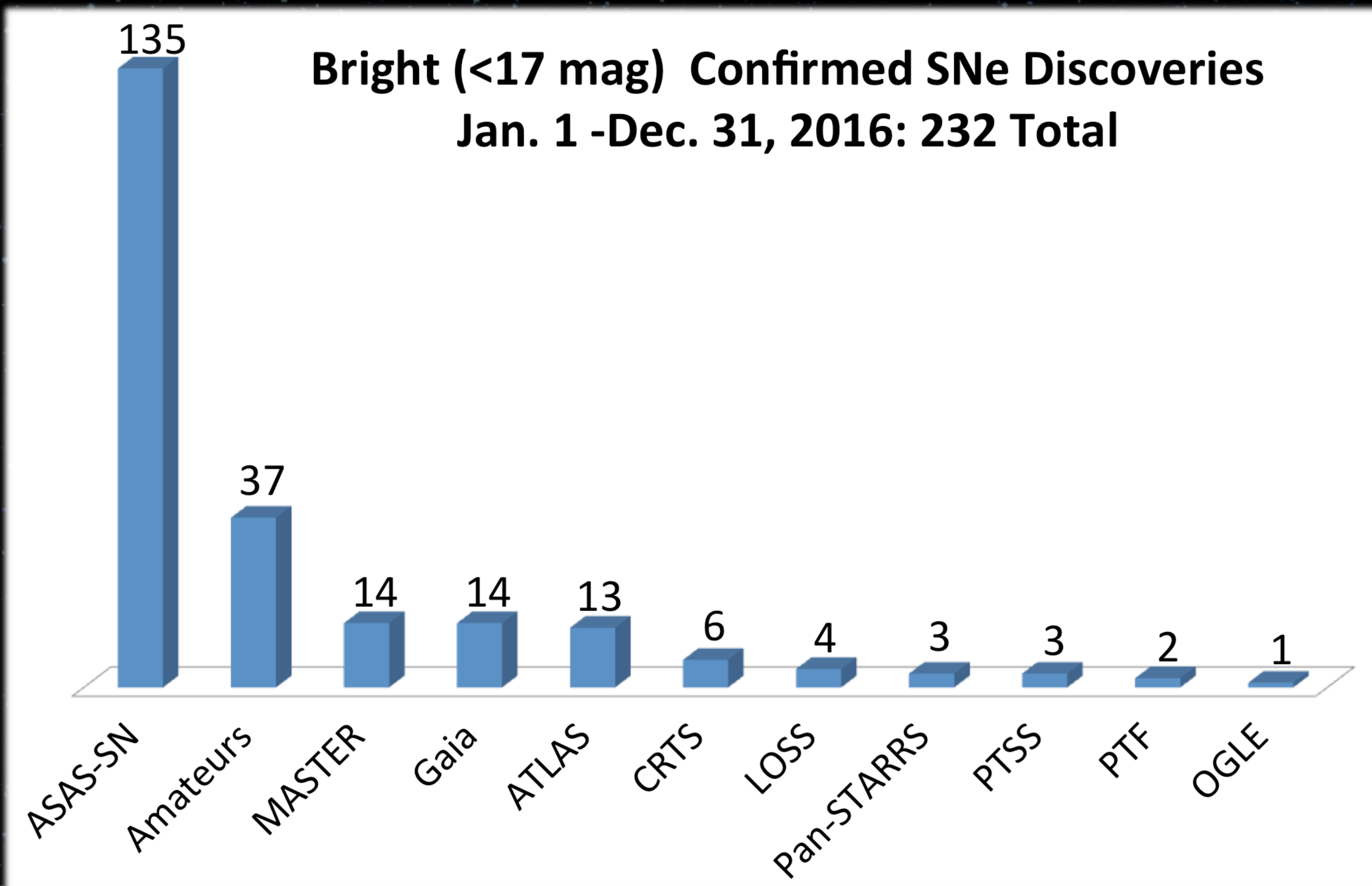
Nearby SNe


Bright (<17 mag) Confirmed SNe Discoveries
Jan. 1 -Dec. 31, 2015: 260 Total
157
61
9
9
8
6
4
2
1
1
1
1
ASAS-SN
Amateurs
MASTER
CRTS
LOSS
Pan-STARRS
LSQ
SkyMapper
HST
GAIA
PTF
KISS

Nearby SNe

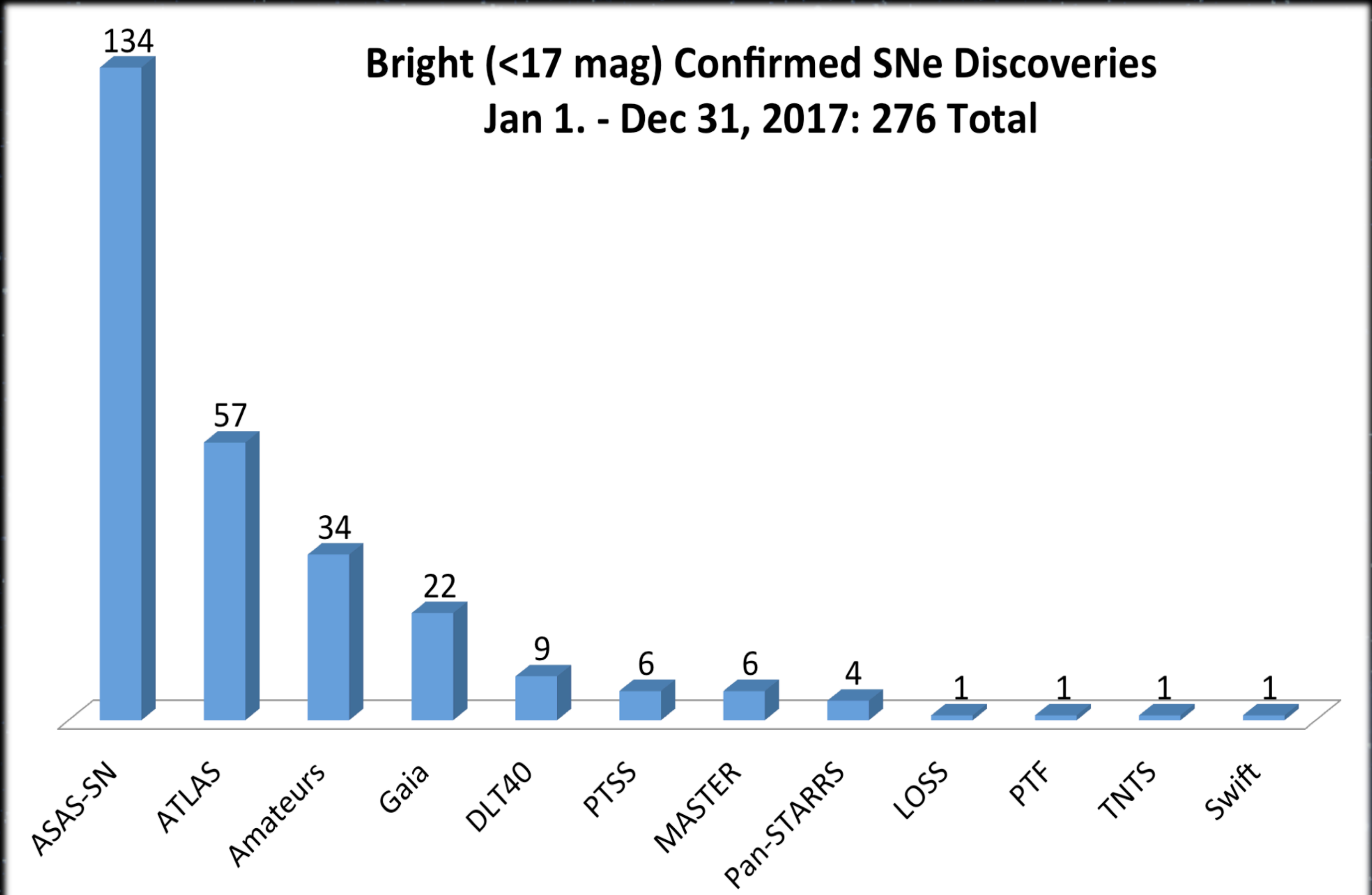

Bright (<17 mag) Confirmed SNe Discoveries
Jan. 1 -Dec. 31, 2016: 232 Total
135
37
14
14
13
6
4
3
3
2
1
ASAS-SN
Amateurs
MASTER
Gaia
ATLAS
CRTS
LOSS
Pan-STARRS
PTSS
PTF
OGLE

Nearby SNe



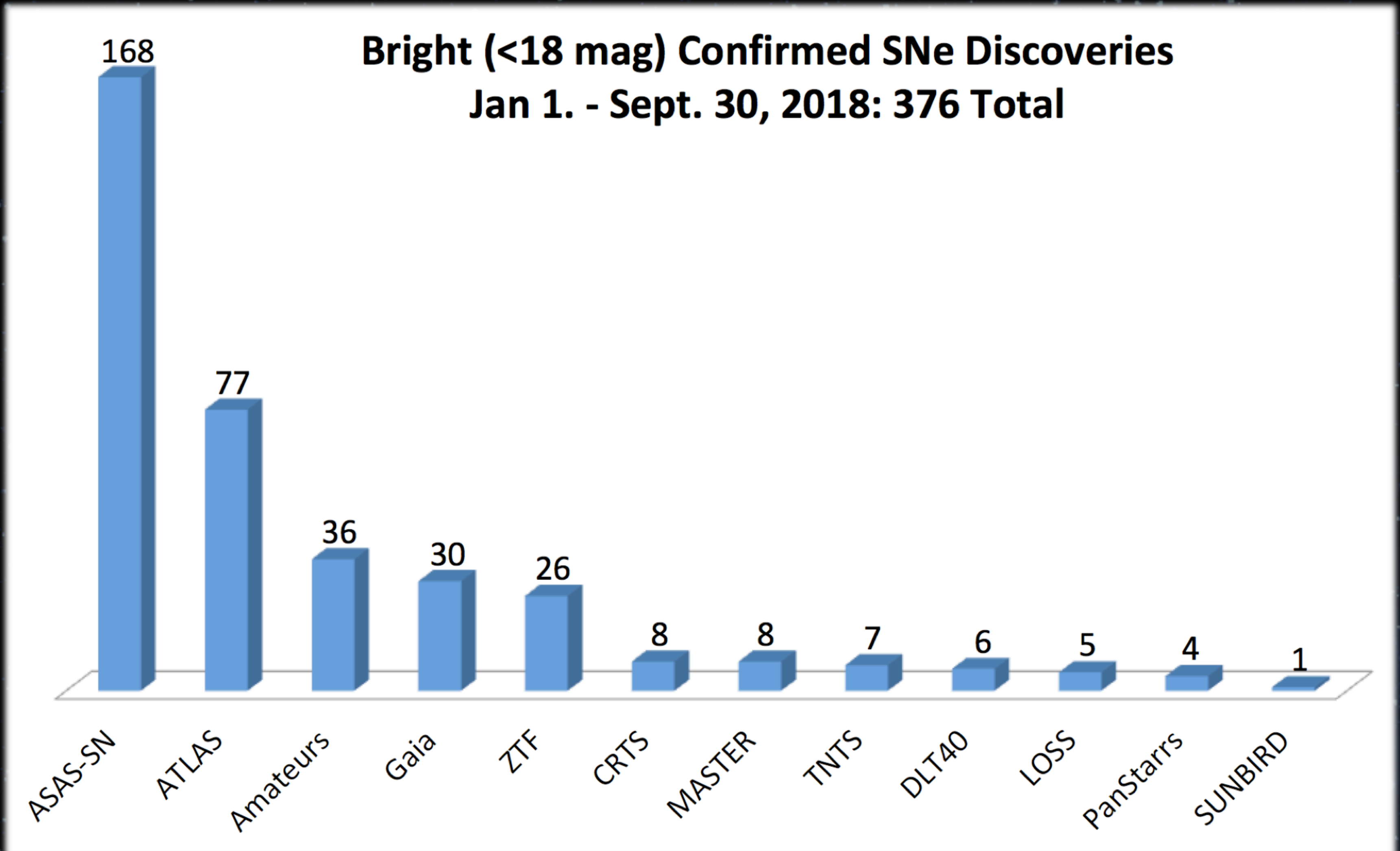
Bright (<17 mag) Confirmed SNe Discoveries
Jan. 1 -Dec. 31, 2016: 232 Total
135
37
14
14
13
6
4
3
3
2
1
ASAS-SN
Amateurs
MASTER
Gaia
ATLAS
CRTS
LOSS
Pan-STARRS
PTSS
PTF
OGLE

Nearby SNe



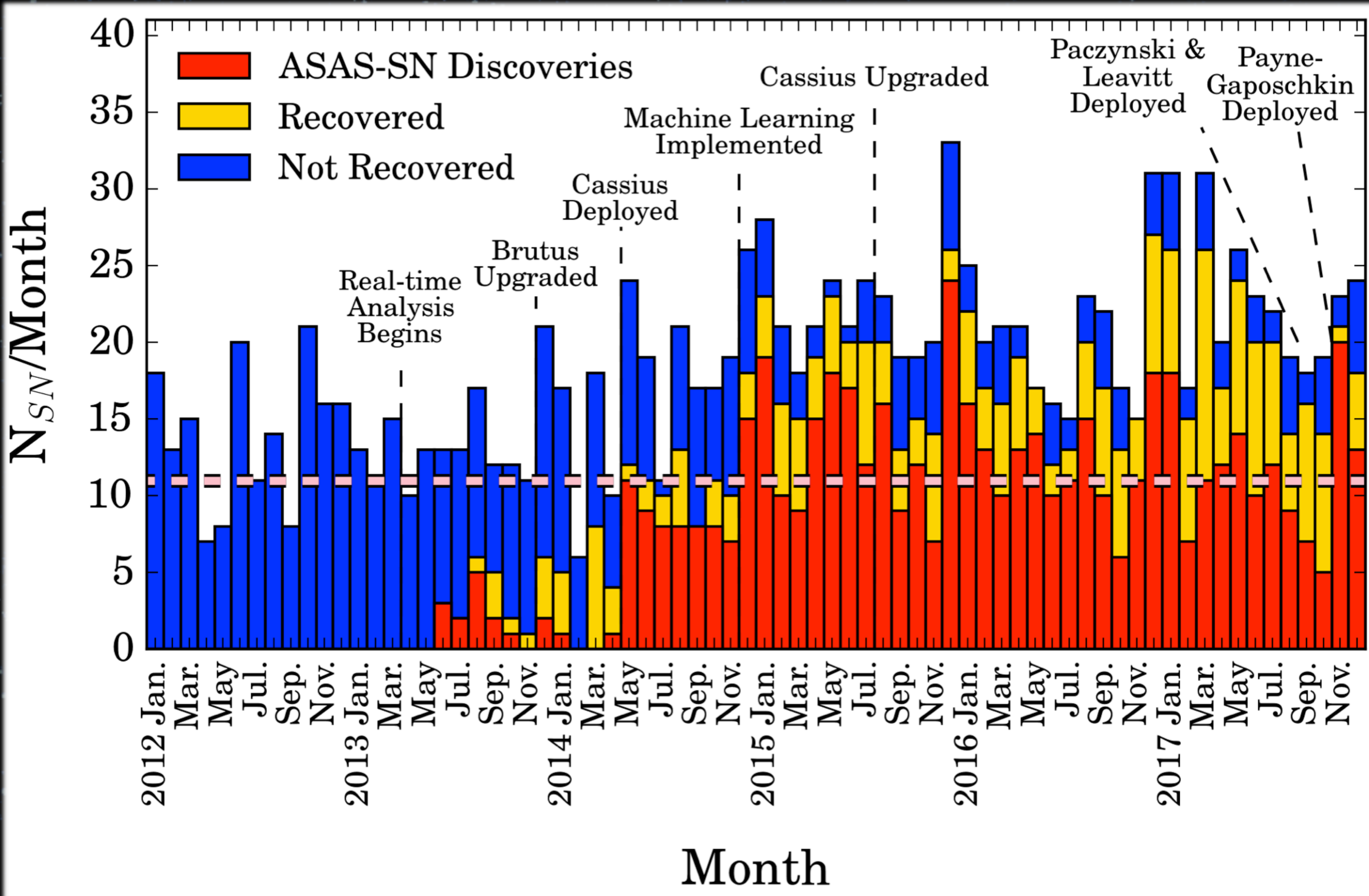
Bright (<17 mag) Confirmed SNe Discoveries
Jan 1. - Dec 31, 2017: 276 Total
134
57
34
22
9
6
6
4
1
1
1
1
ASAS-SN
ATLAS
Amateurs
Gaia
DLT40
PTSS
MASTER
Pan-STARRS
LOSS
PTF
TNTS
Swift

Nearby SNe



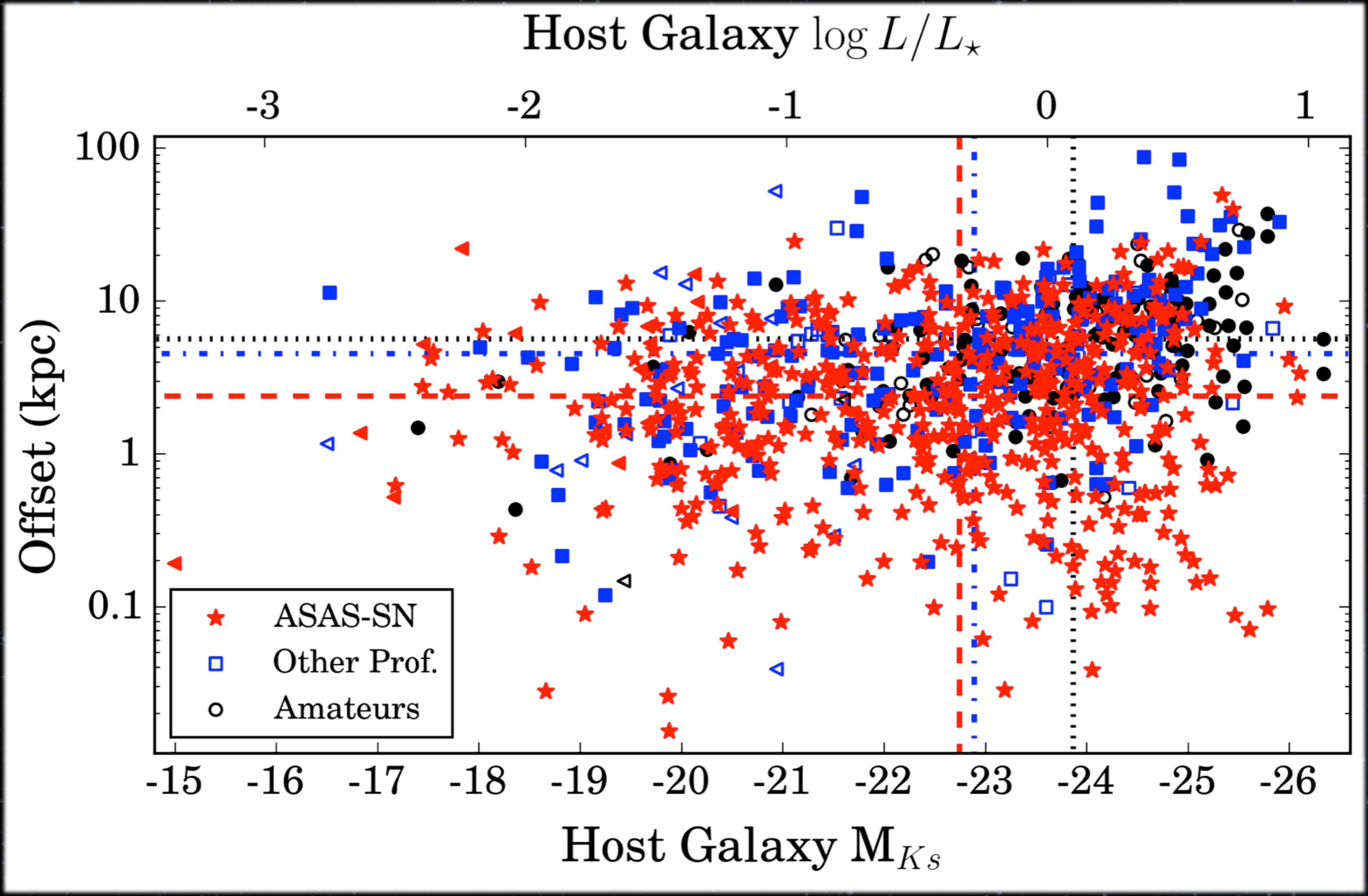
Bright (<18 mag) Confirmed SNe Discoveries
Jan 1. - Sept. 30, 2018: 376 Total
168
77
36
30
26
8
8
7
6
5
4
1
ASAS-SN
ATLAS
Amateurs
Gaia
ZTF
CRTS
MASTER
TNTS
DLT40
LOSS
PanStarrs
SUNBIRD

We are more complete, unbiased.



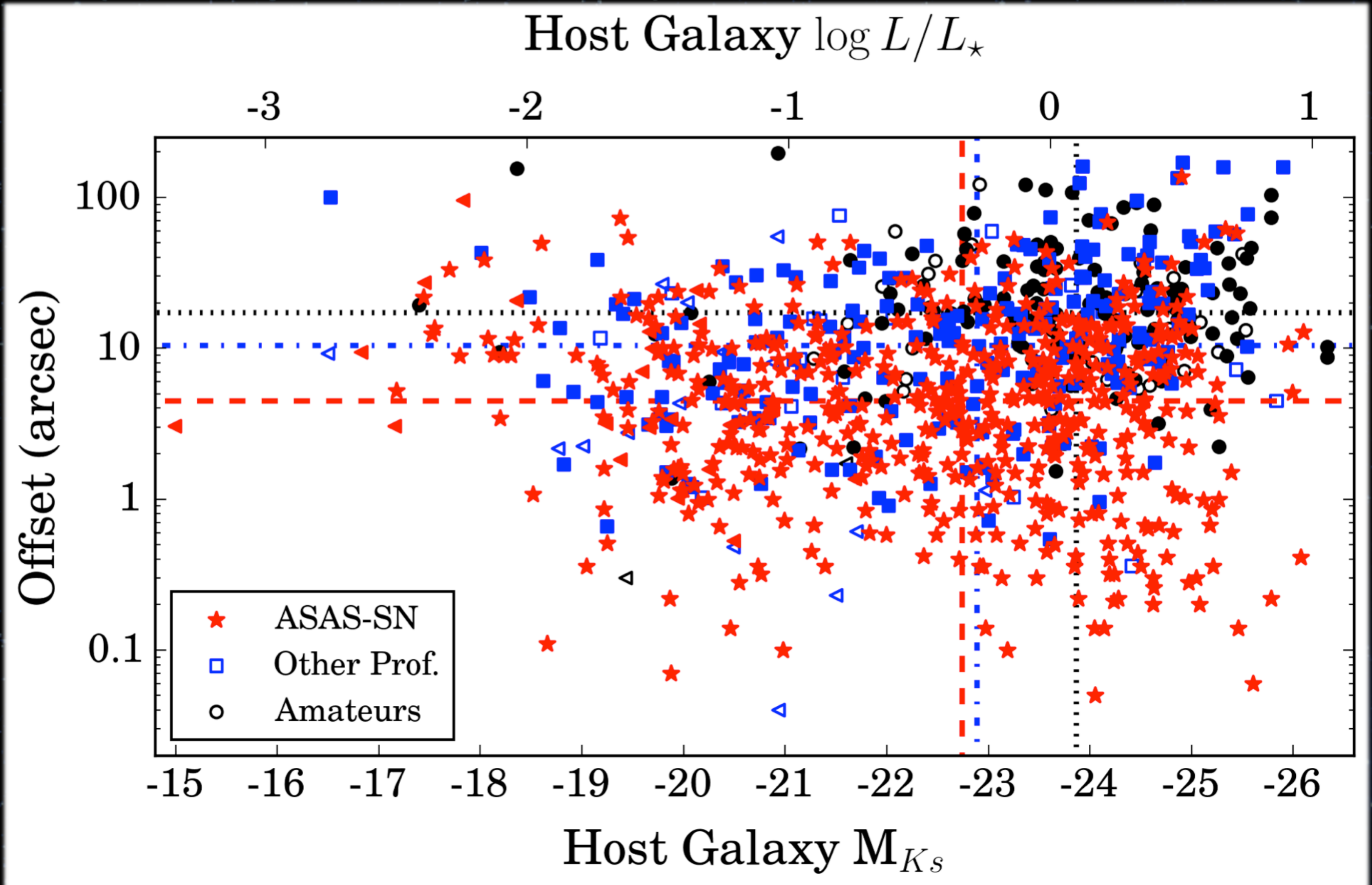
Holoien et al. (incl. Shappee) 2017b

The first unbiased supernova sample



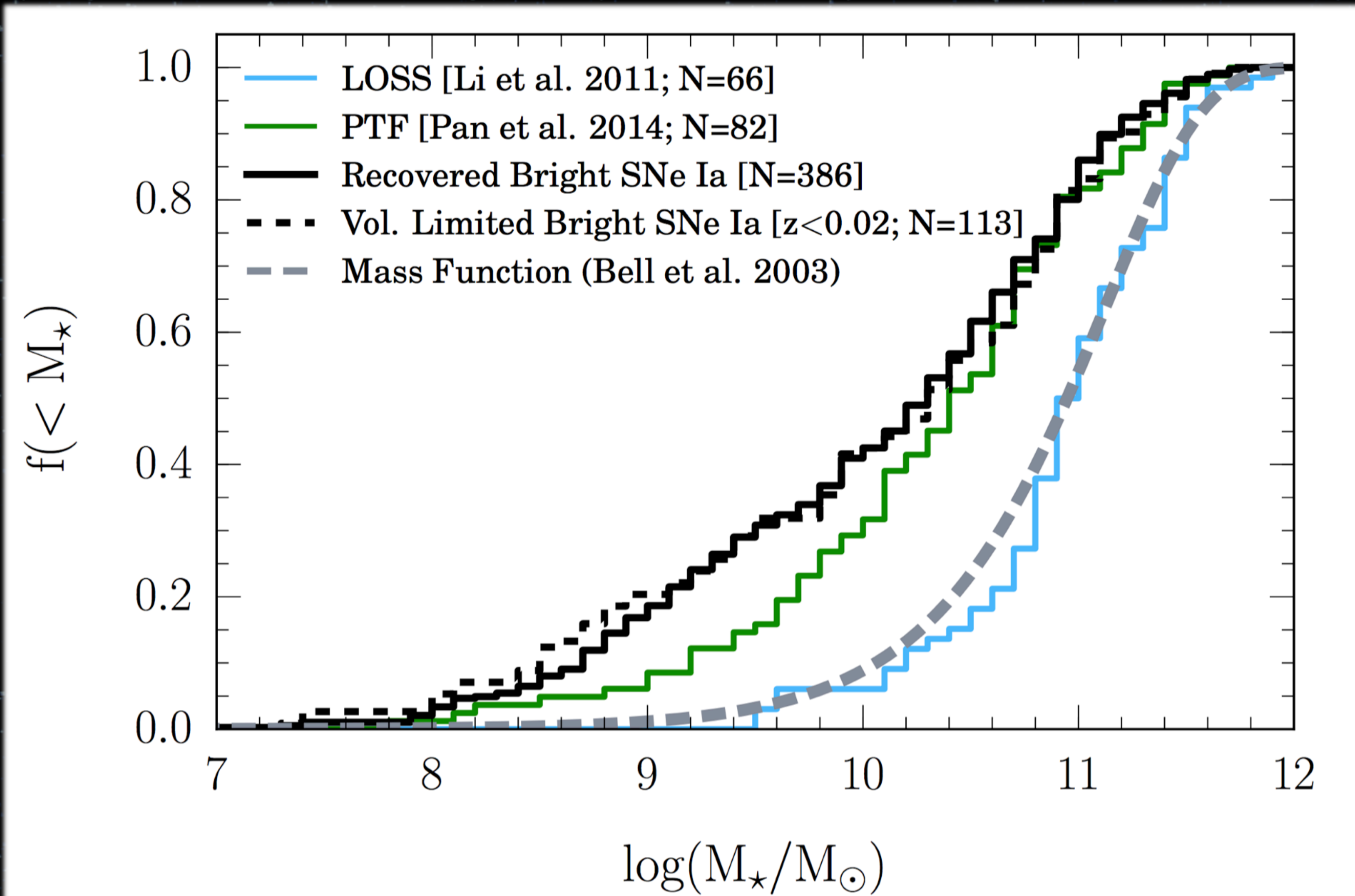
Holoien et al. (incl. Shappee) 2018c

The first unbiased supernova sample



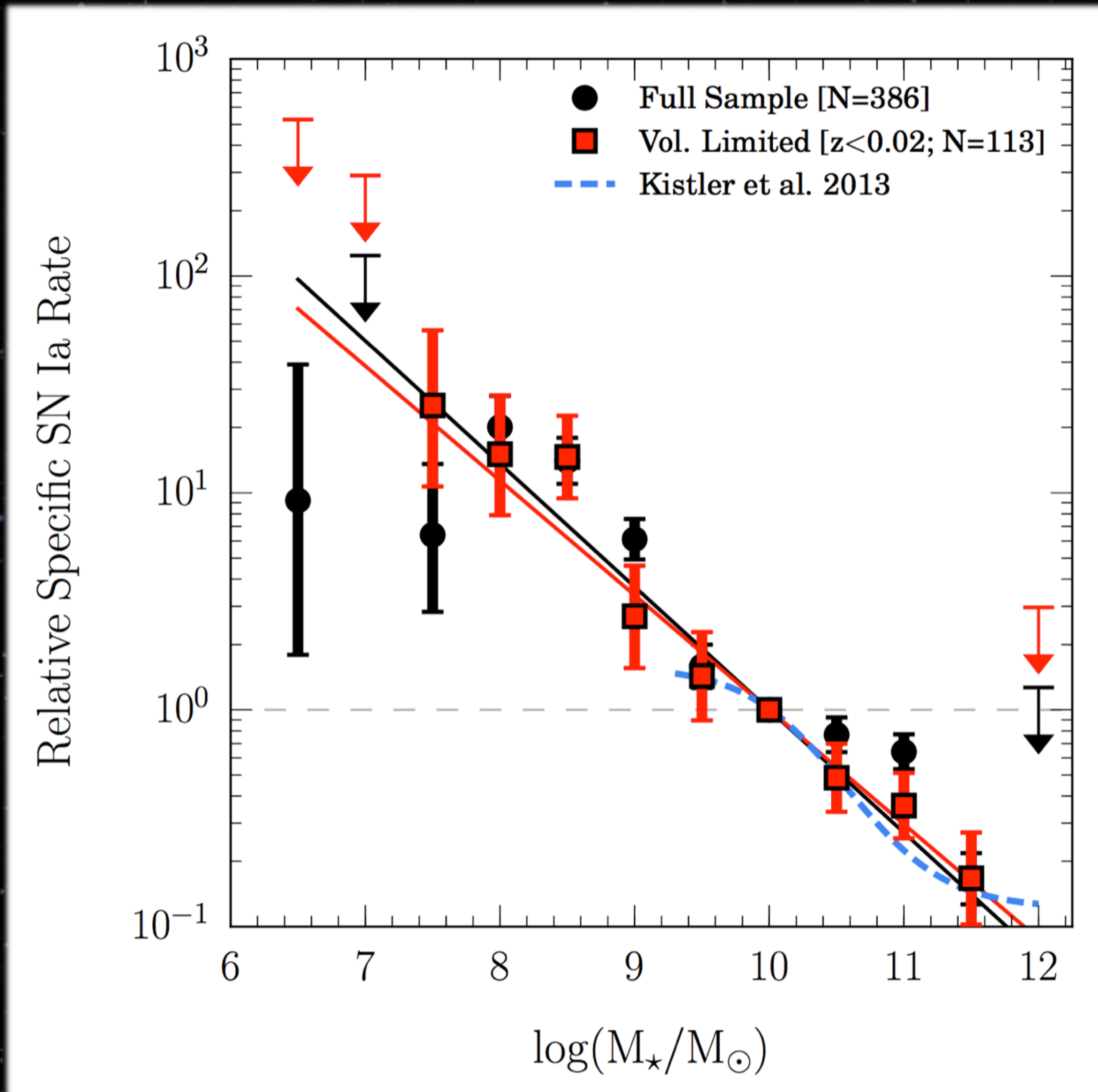
Holoien et al. (incl. Shappee) 2018c

Unbiased rate measurement



Brown et al. (incl. Shappee) 2018

Unbiased rate measurement



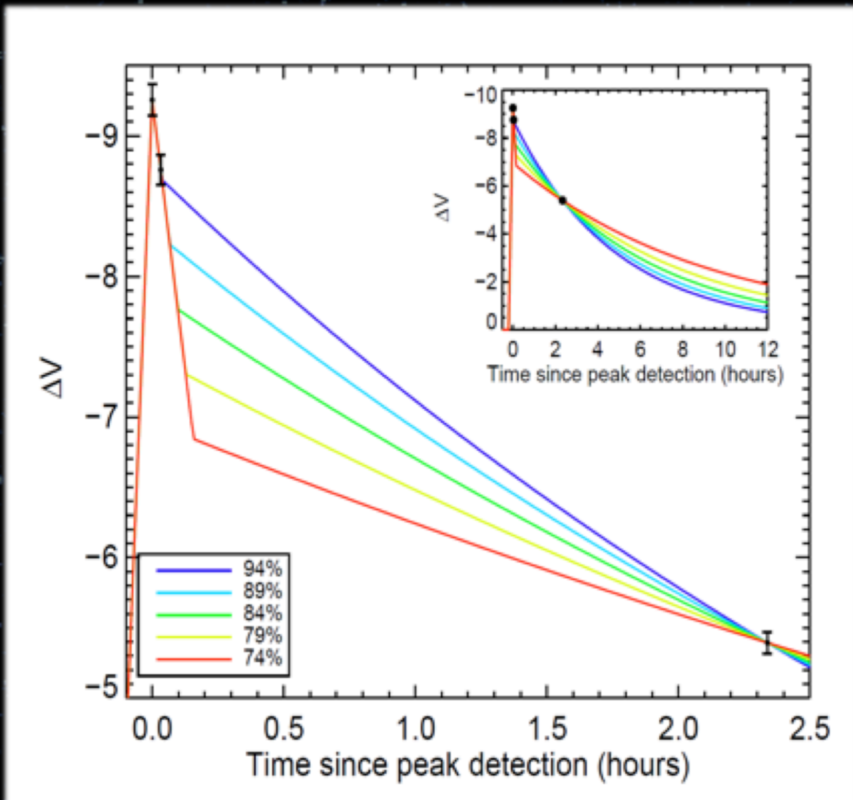
Brown et al. (incl. Shappee) 2018

Other science highlights so far

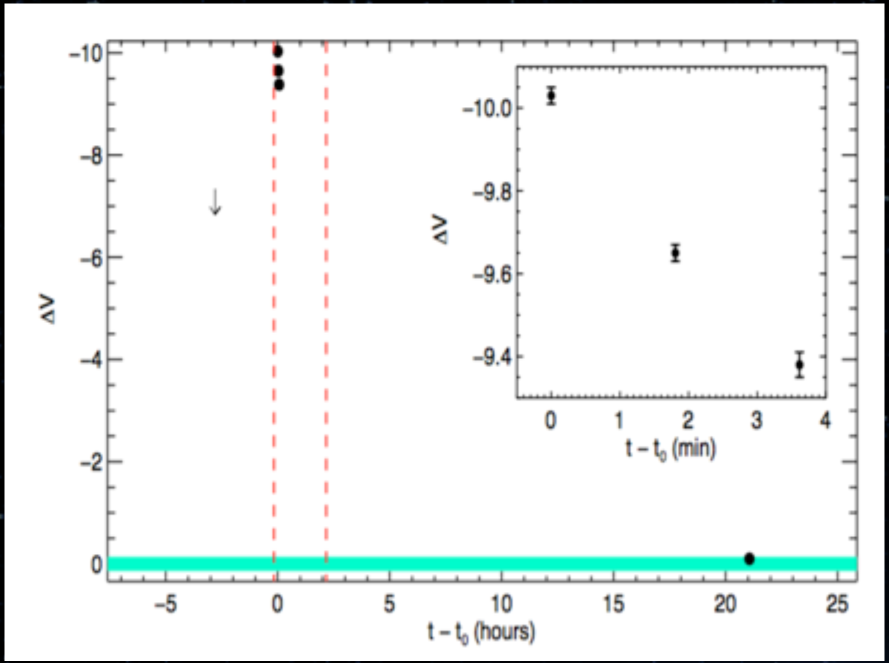
50+ publications,
750+ ATels,
1000+ new cataclysmic variable,
novae search,
2 comets,
and growing.

Dramatic Stellar Flares in ASAS-SN

ASASSN-13cb



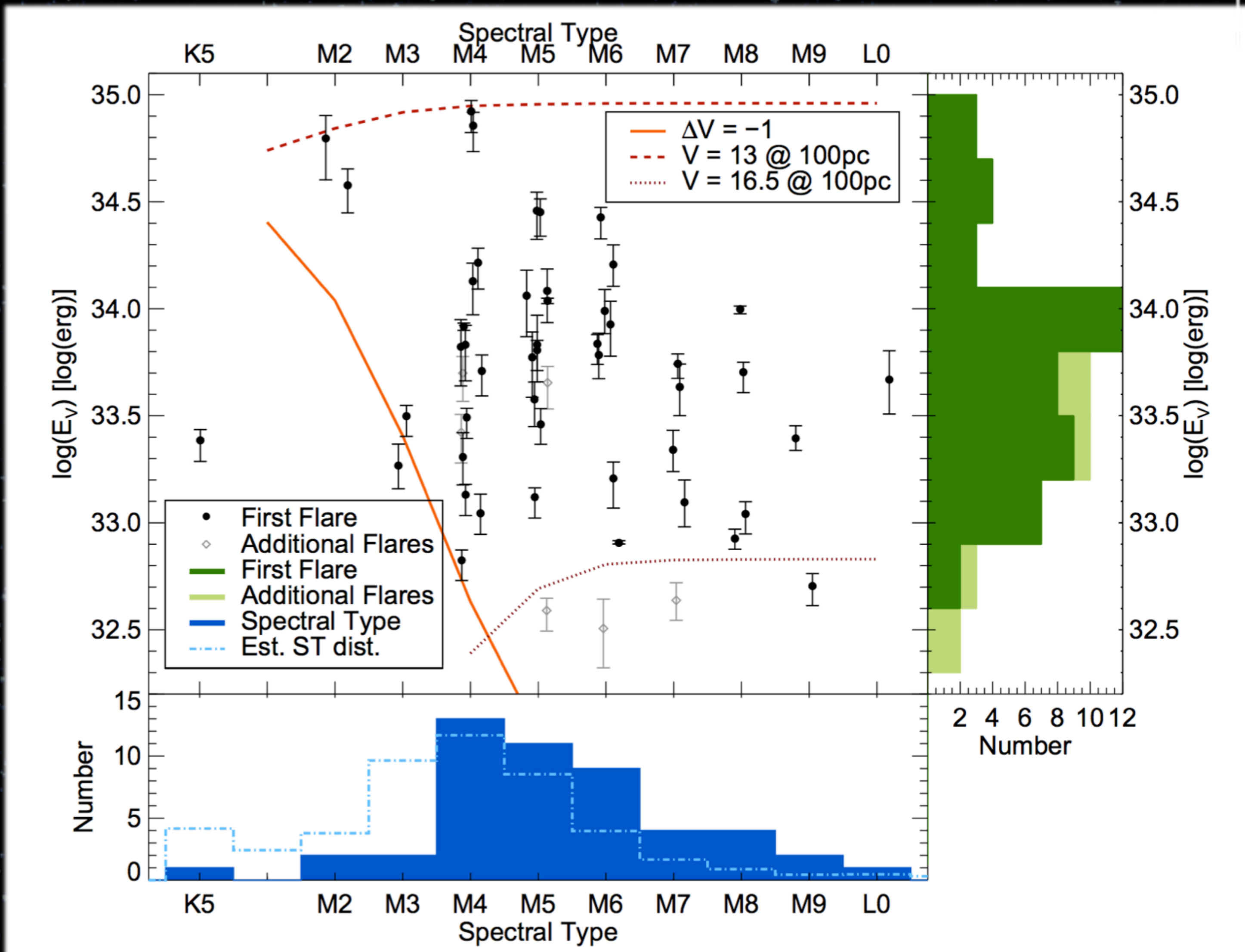
ASASSN-16ae



Schmidt et al. (incl. Shappee) 2016

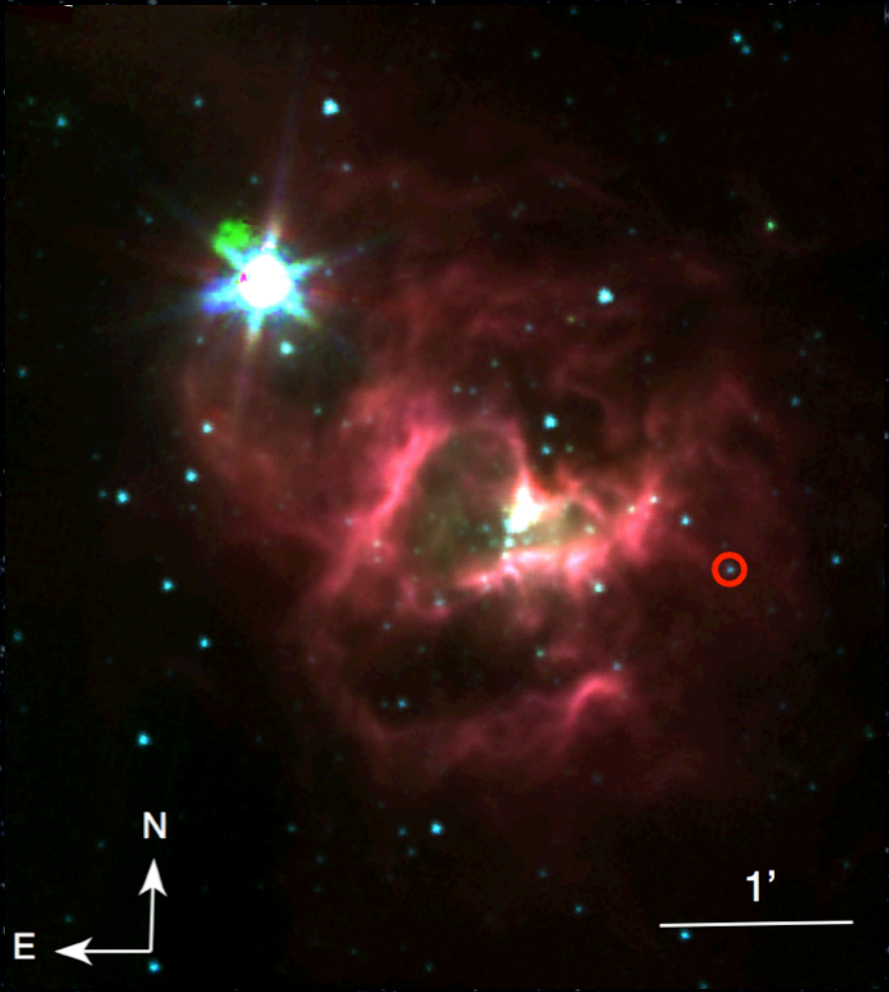
Schmidt, Shappee et al. 2016

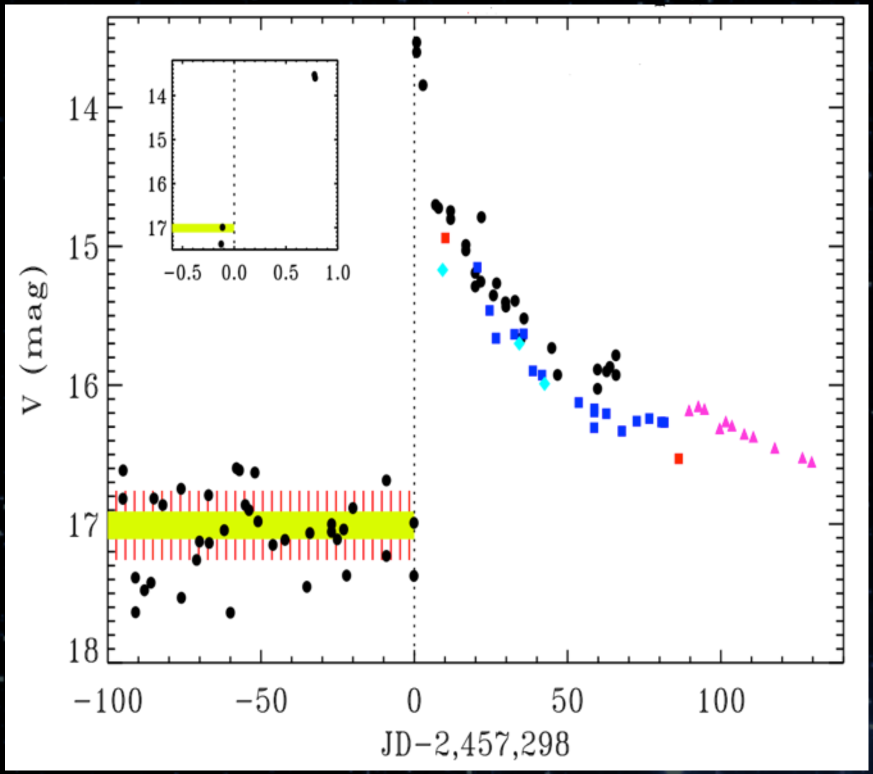
Dramatic Stellar Flares in ASAS-SN



Schmidt, Shappee et al. 2018

Outbursts from Young Stellar Objects



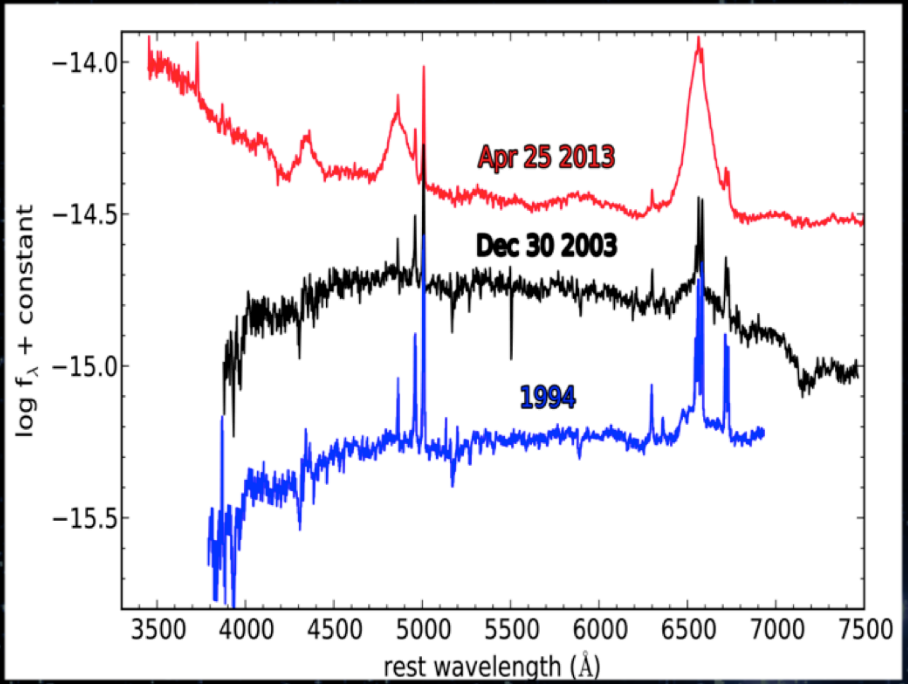


ASASSN-15qi

Herczeg et al. (incl. Shappee) 2016

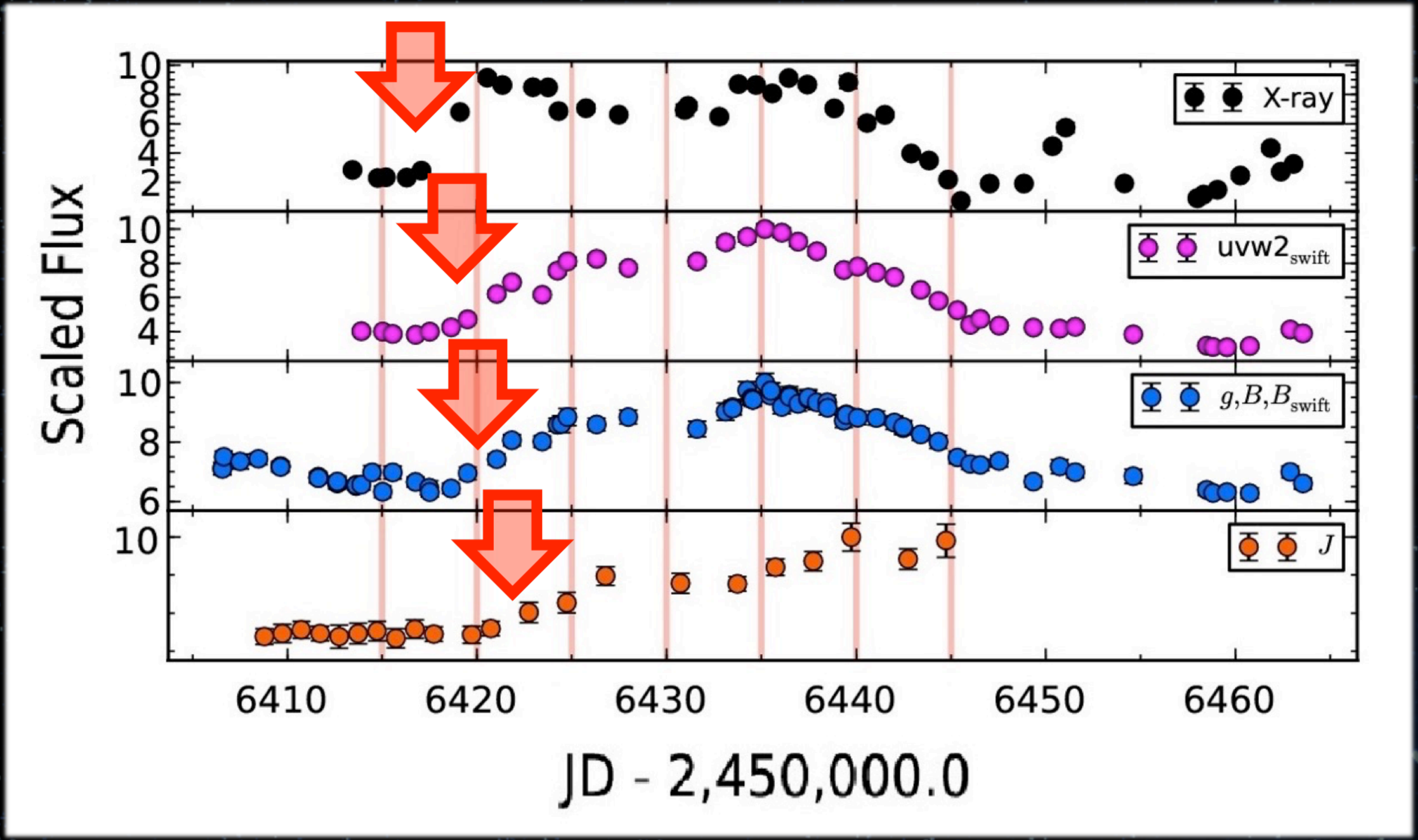
“Changing look” AGN: NGC 2617

- ASAS-SN triggered on a 10% increase in flux from AGN + host
- Follow-up imaging showed AGN continued to brighten by 1.3 mag
- Follow-up spectroscopy showed that the AGN changed from a Seyfert type 1.8 to 1.0



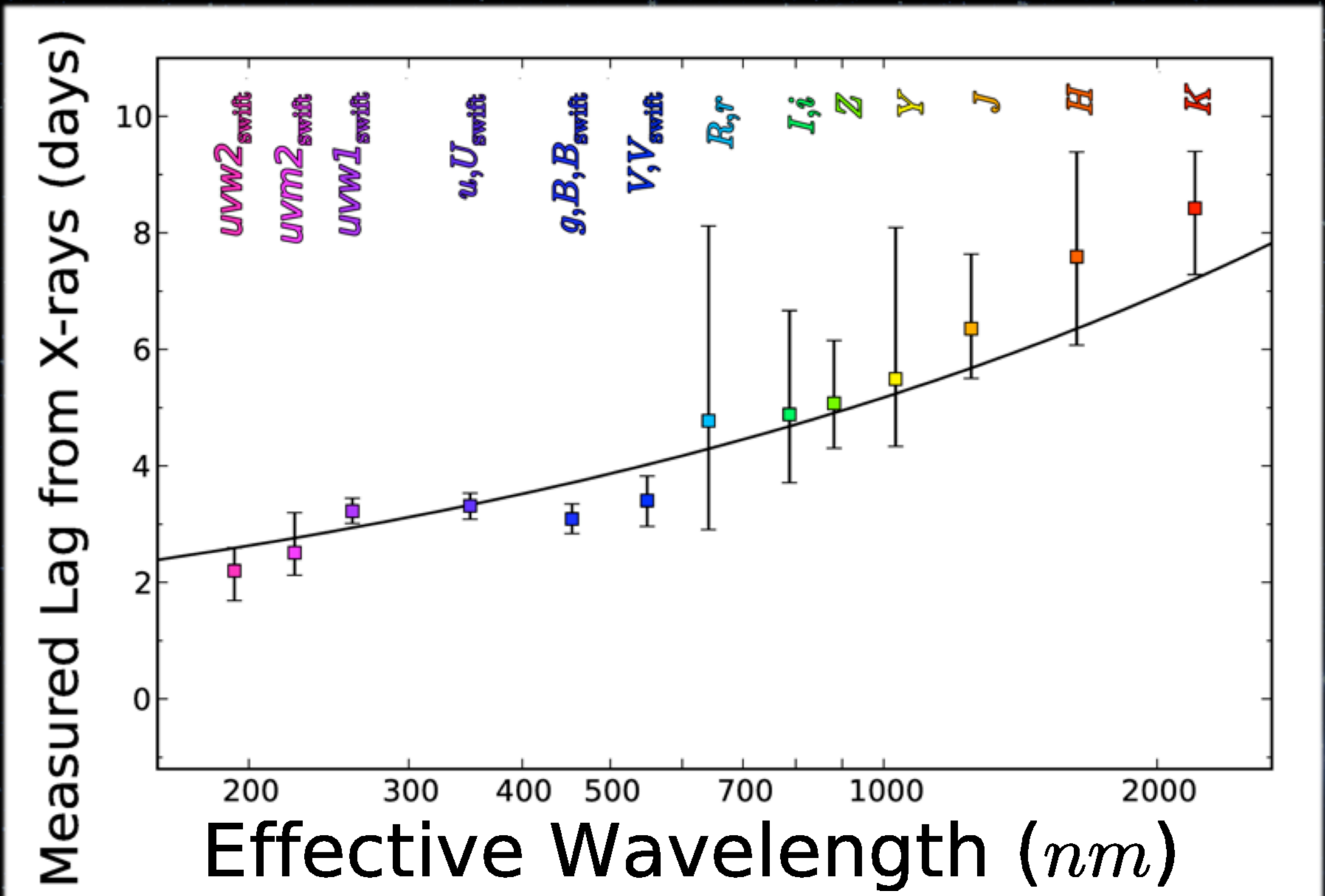
Shappee et al. 2014

NGC 2617 X-ray–NIR light curves



Shappee et al. 2014

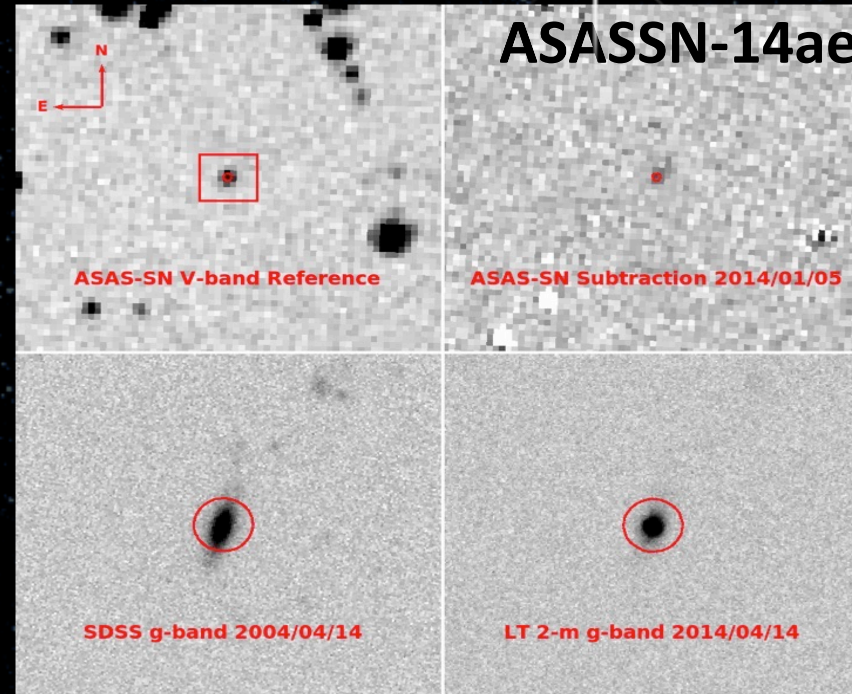
NGC 2617 Photometric Lags

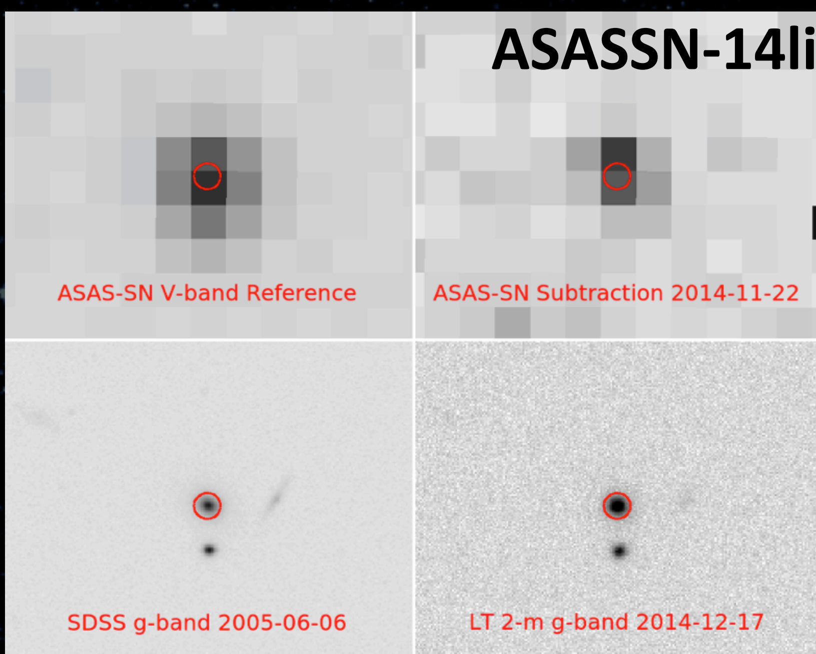


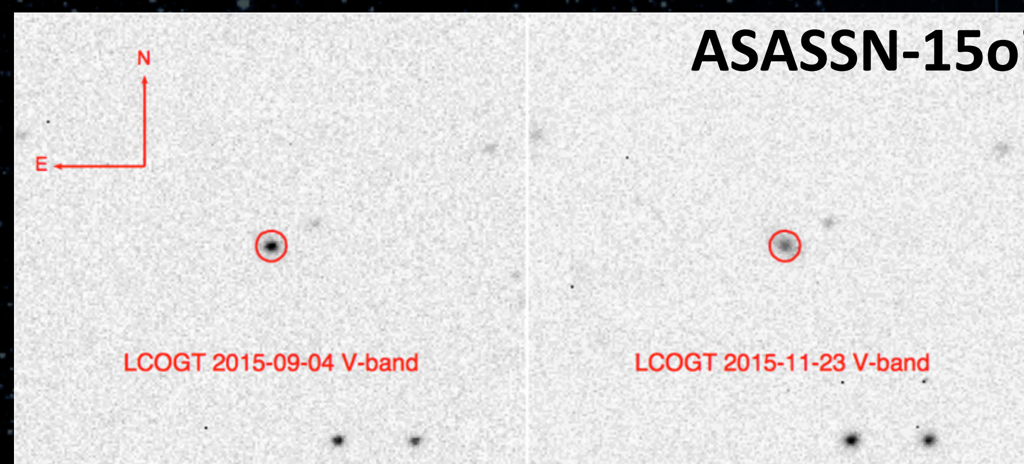
Shappee et al. 2014

Tidal Disruption Events in ASAS-SN

- 7 of the *brightest* and *(arguably) best-studied*
- ASAS-SN seems to be more complete than previous surveys
- Rates closer to theoretical rates

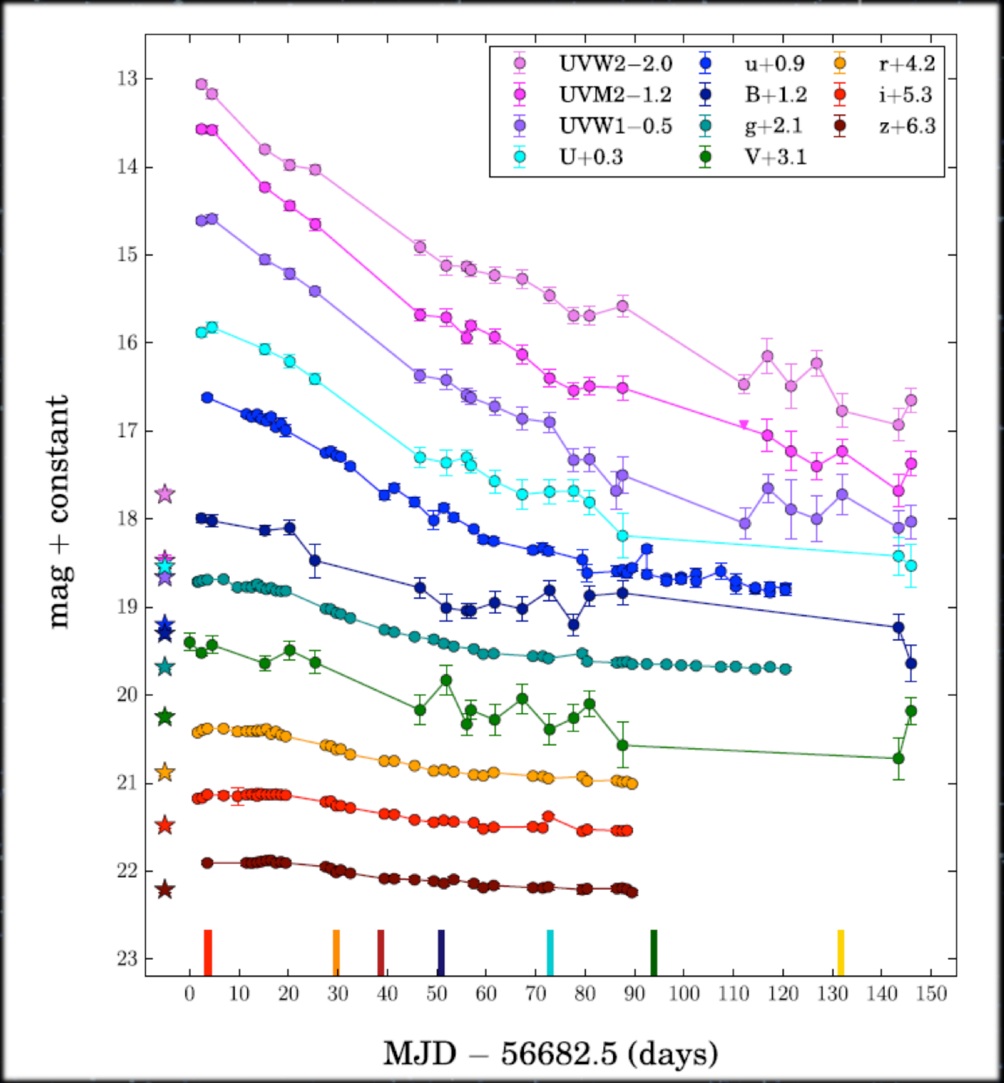


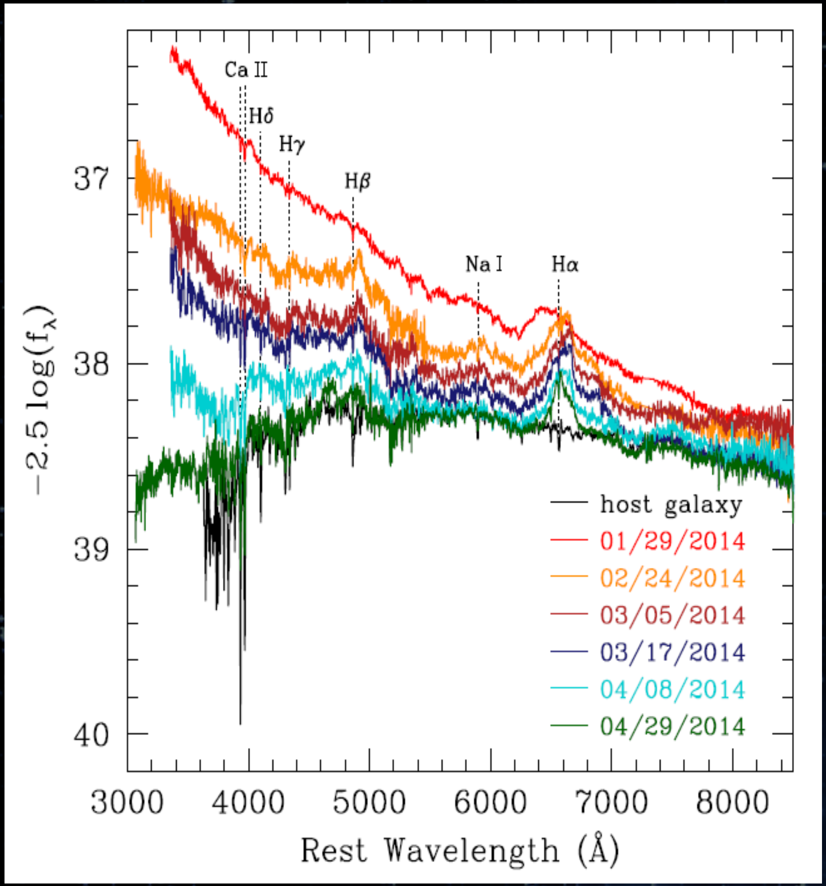




Holoien et al. 2014a,b, 2016

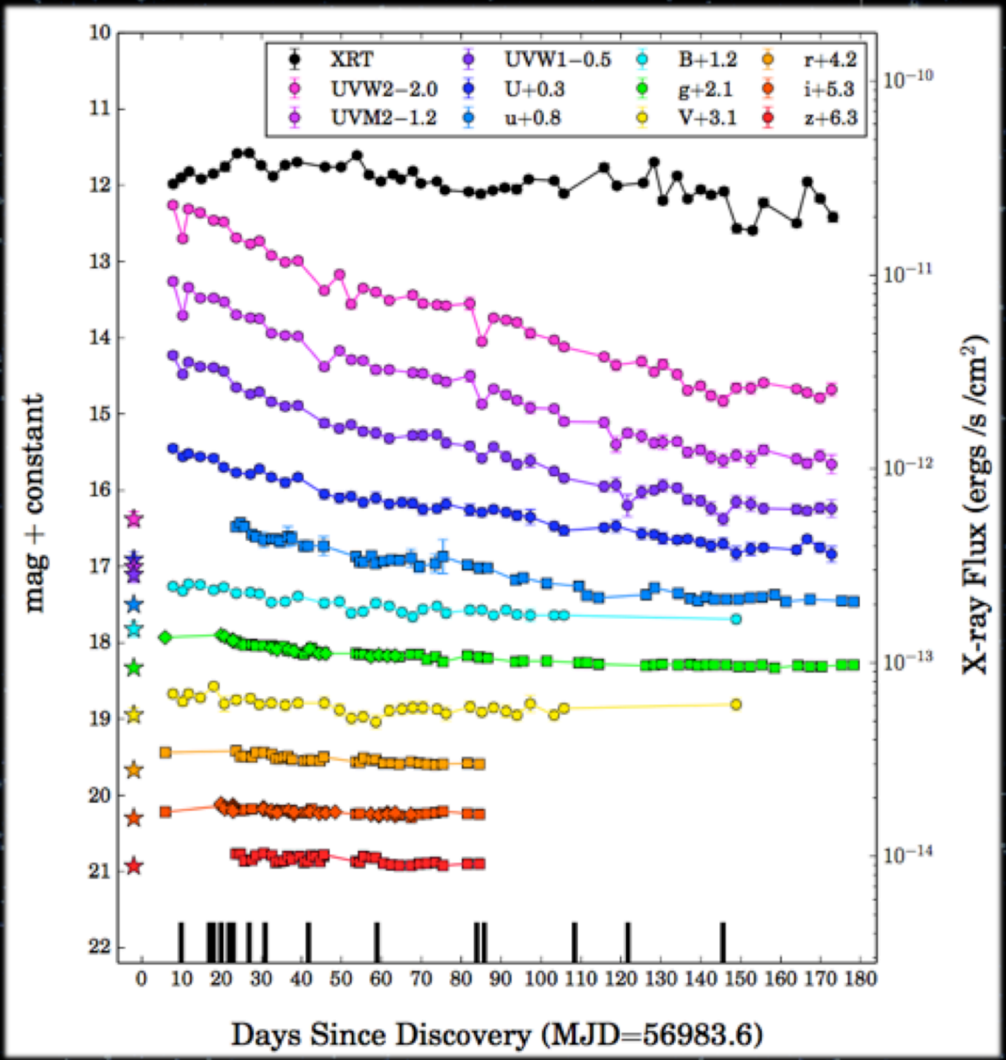
ASAS-SN-14ae

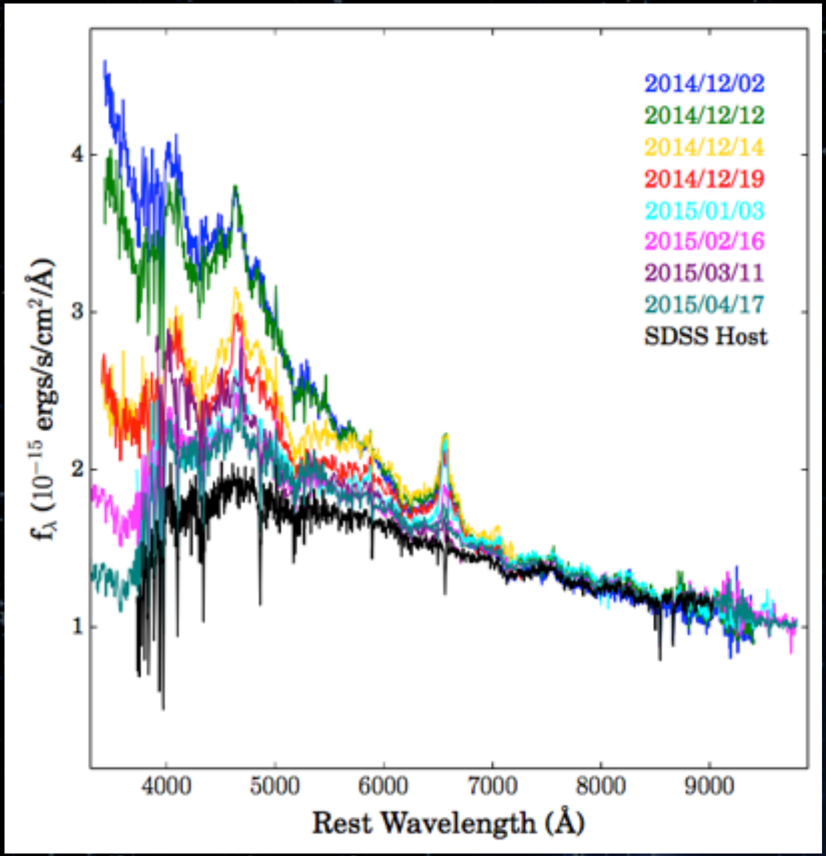




Holoien et al. (incl. Shappee) 2014b

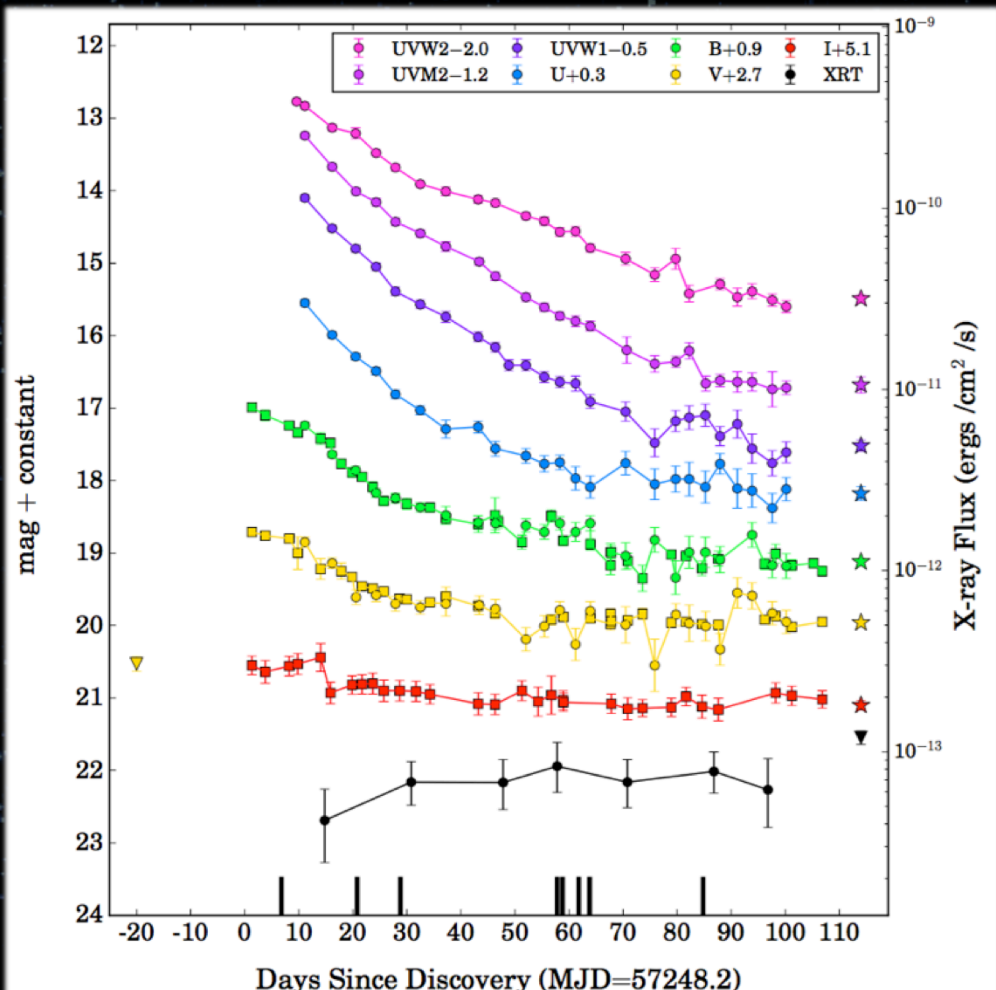
ASAS-SN -14li

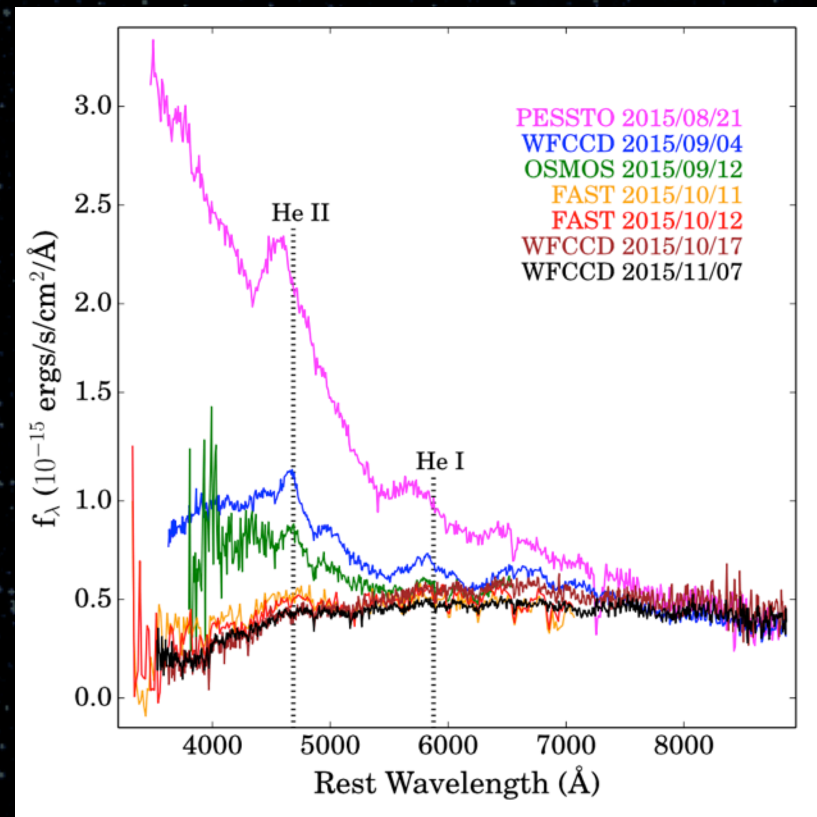




Holoien et al. (incl. Shappee) 2016

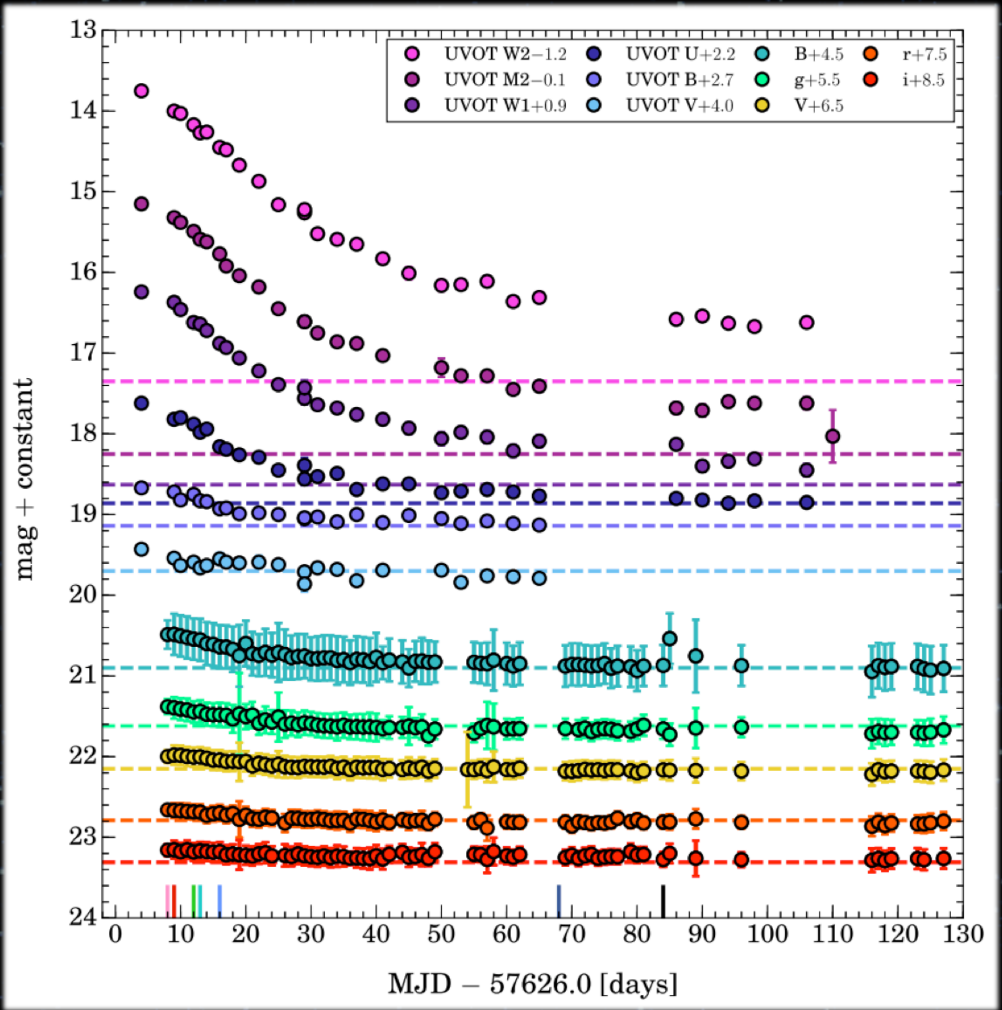
ASAS-SN-15oi

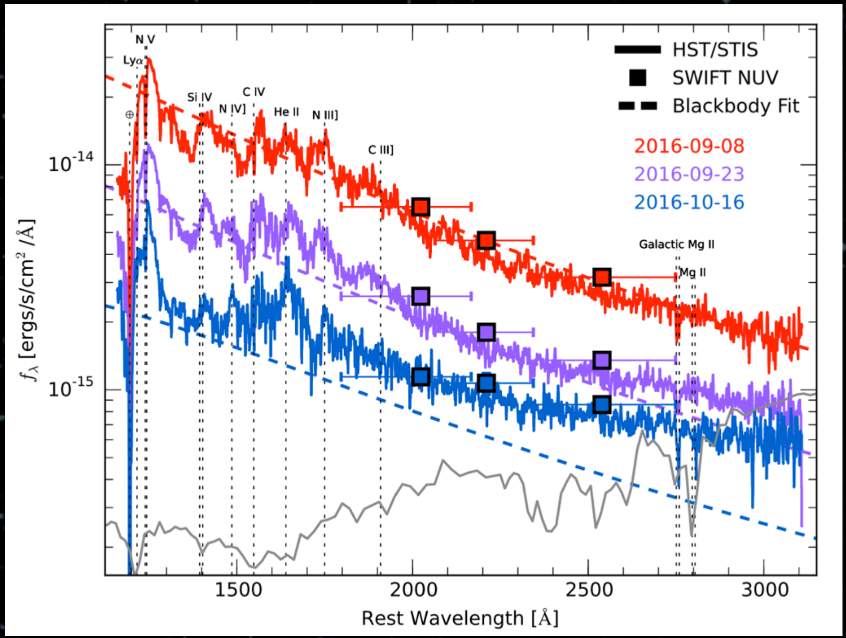


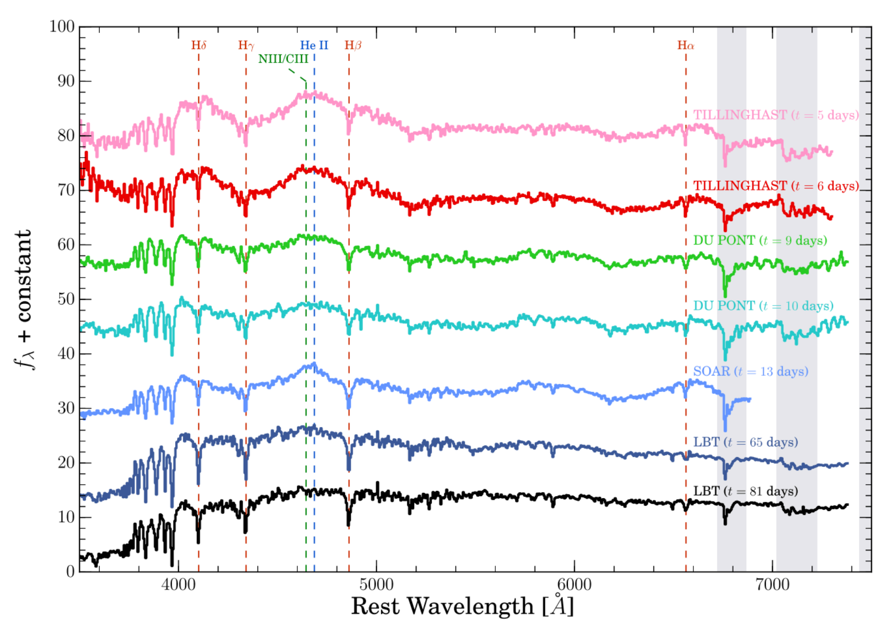


Holoien et al. (incl. Shappee) 2016b

iPTF 16fnl

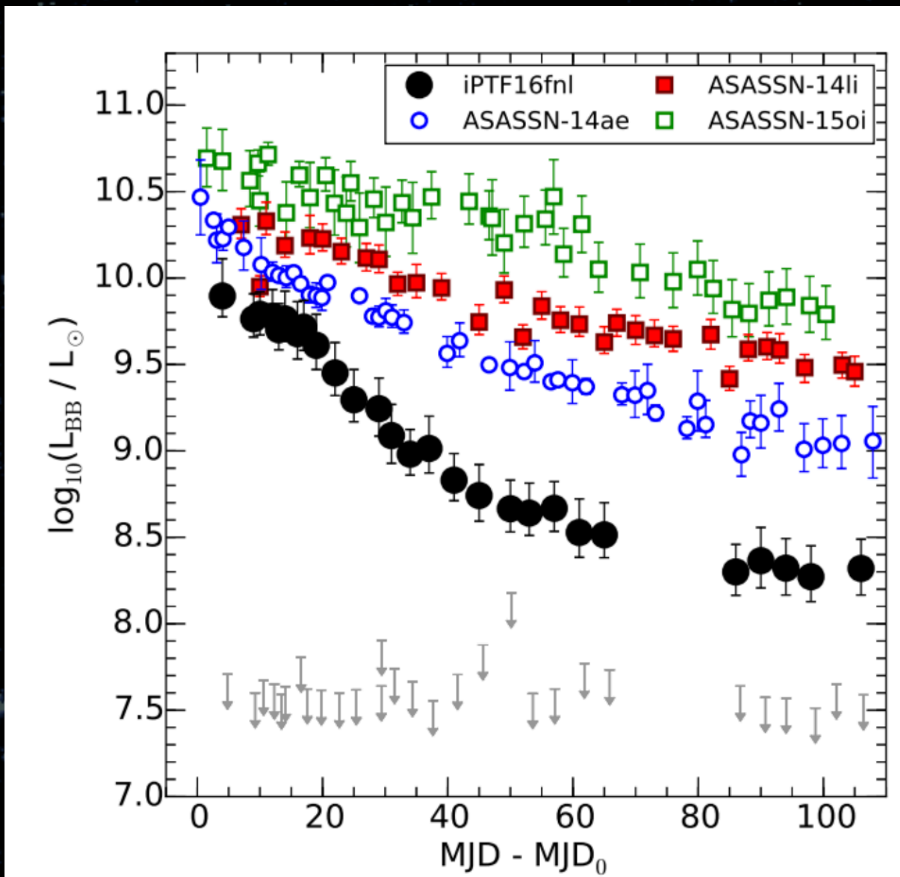


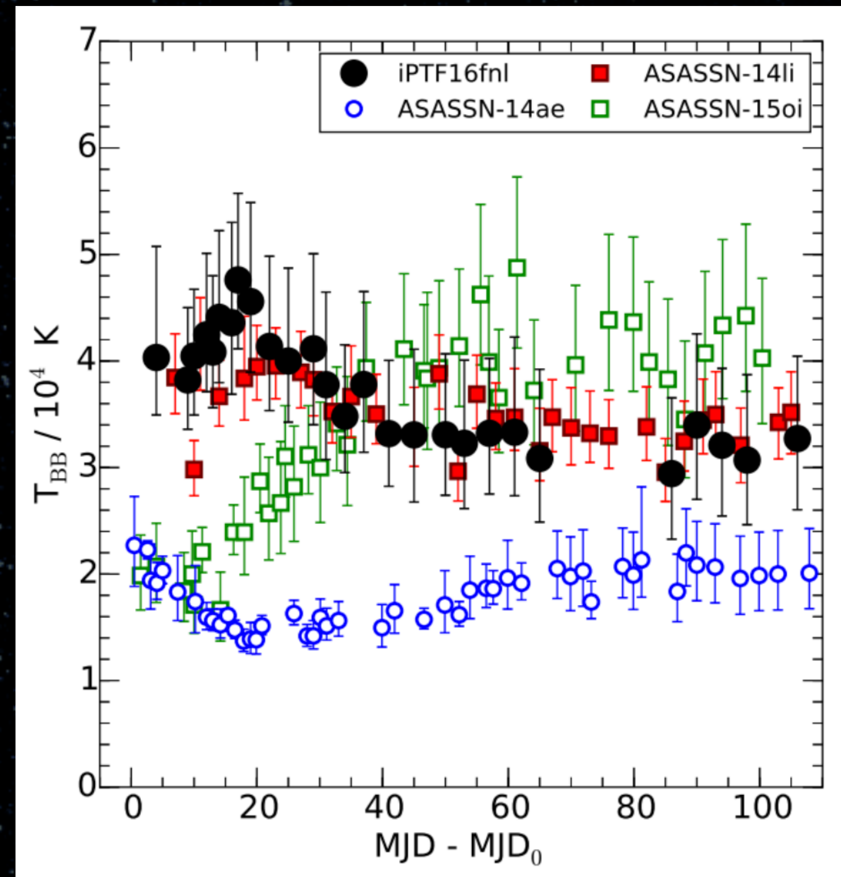




Brown et al. (incl. Shappee) 2017

Tidal Disruption Events in ASAS-SN

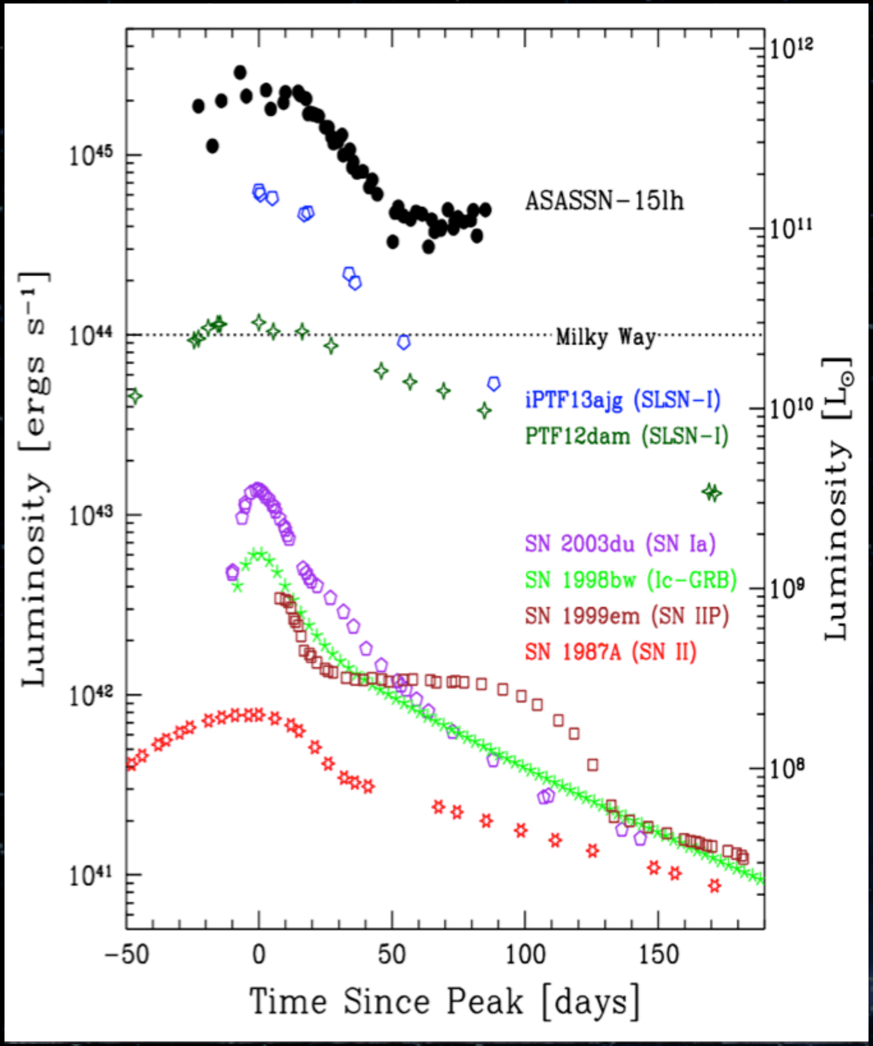




Brown et al. (incl. Shappee) 2017

The most luminous supernova(?)

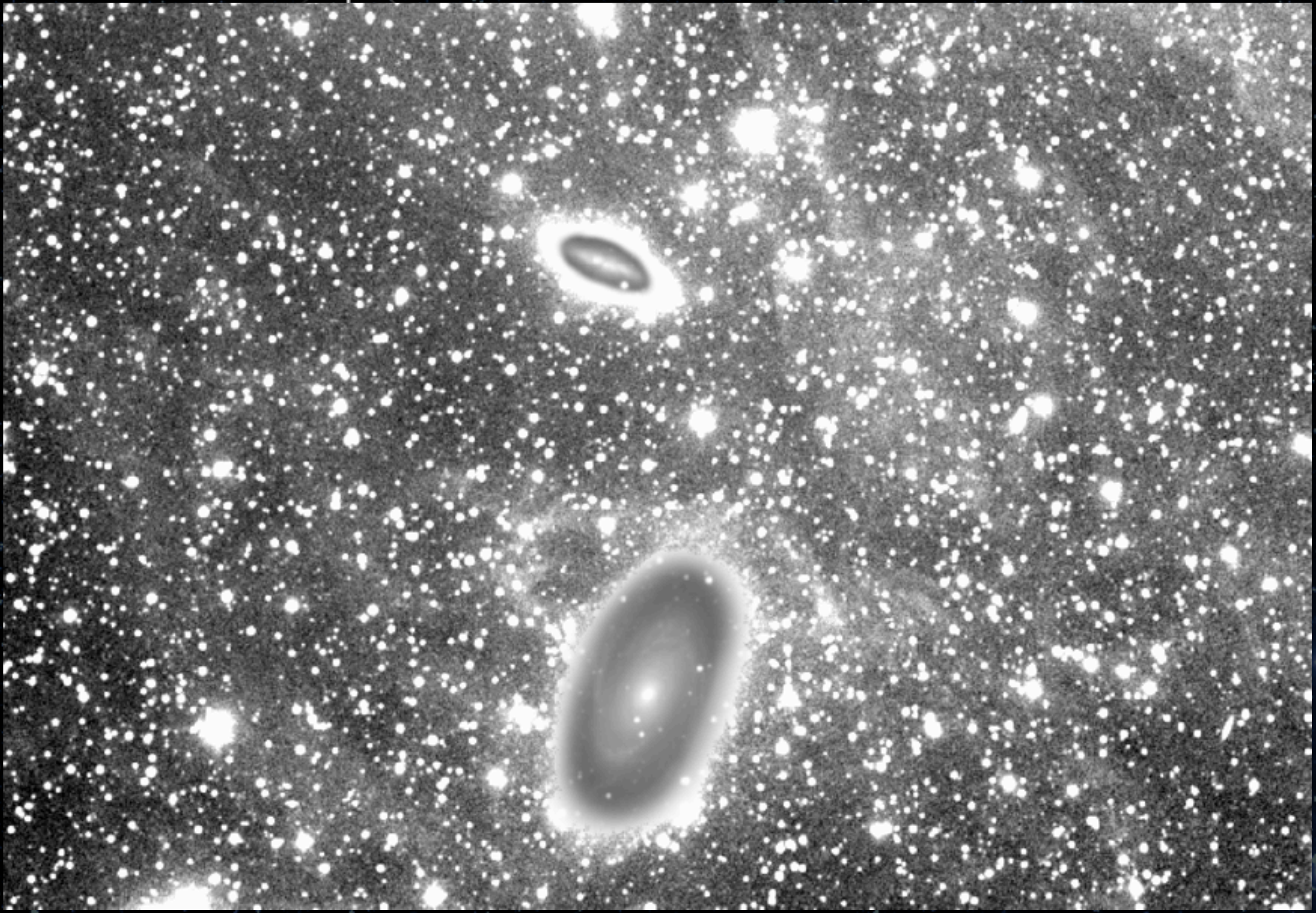
- Nuclear transient, massive host
- The most luminous SN ever discovered?
  Dong, Shappee, Prieto et al. 2016
- Magnetar powered supernova? (most energy possible?)
  Metzger et al. 2015
- TDE like no other?
  Leloudas et al. 2016
- Extreme events challenge all models, unbiased survey



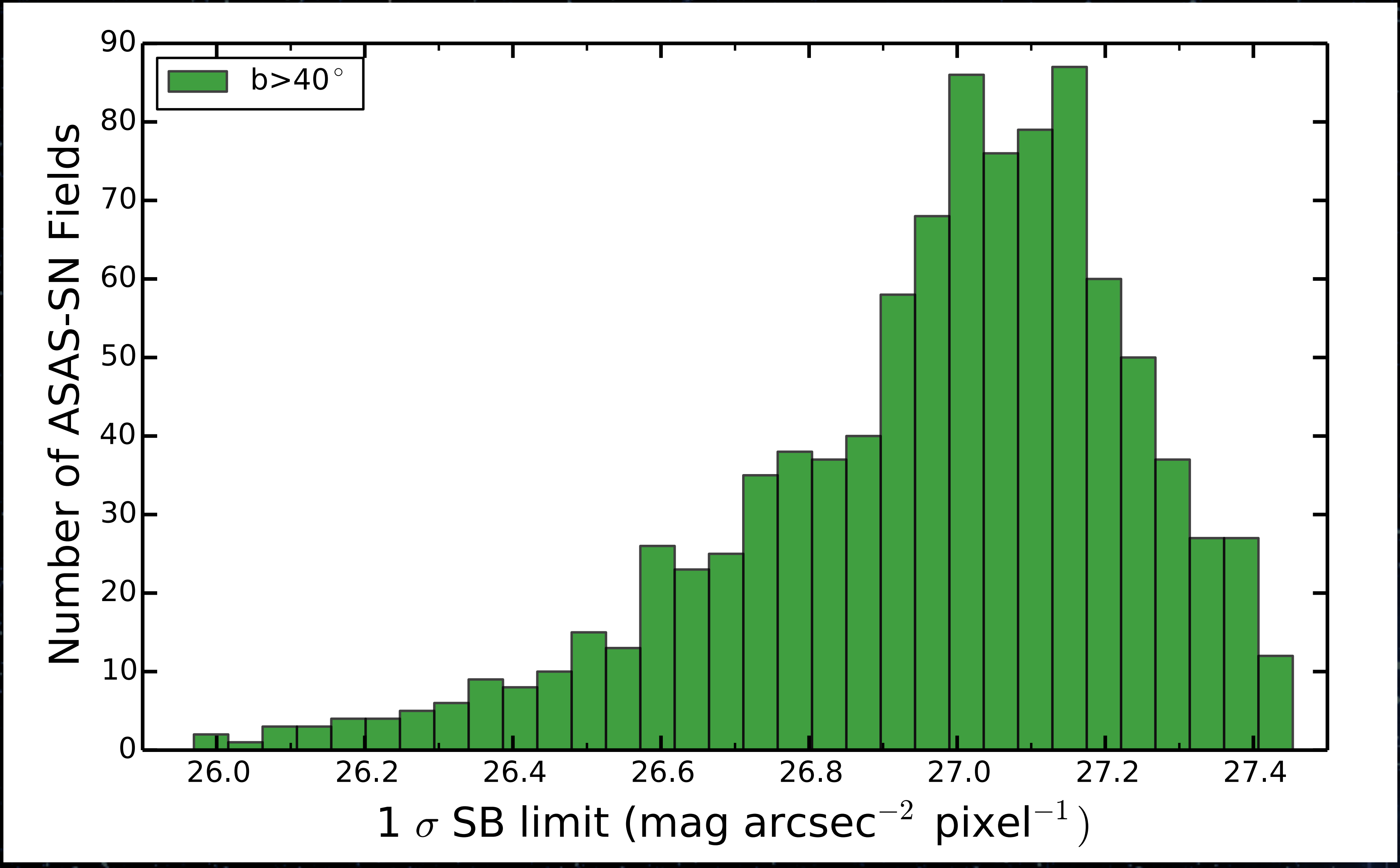
Dong, Shappee et al. 2016

New science with ASAS-SN !

ASAS-SN: Low Surface Brightness



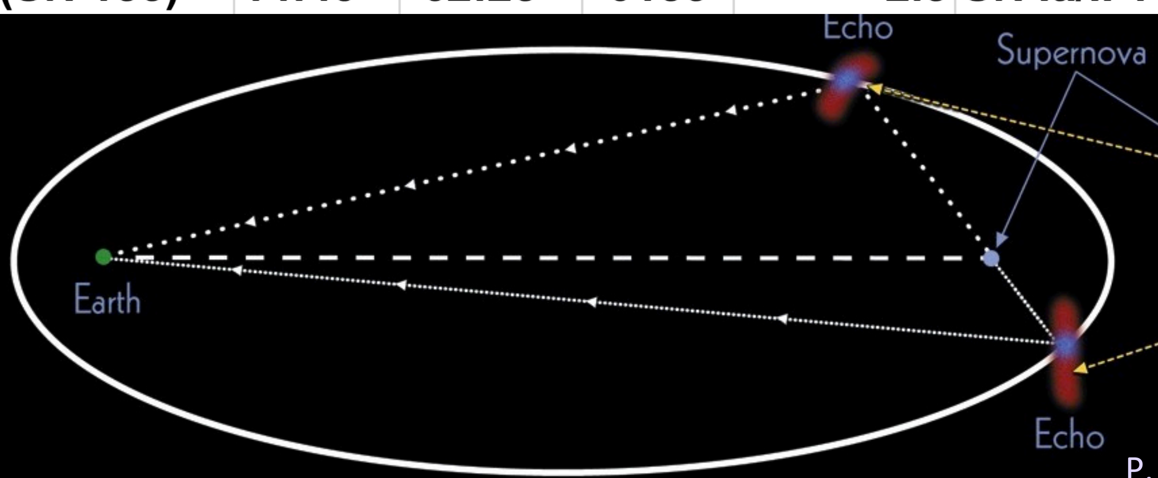
ASAS-SN: Low Surface Brightness



Light echoes, Time machines.

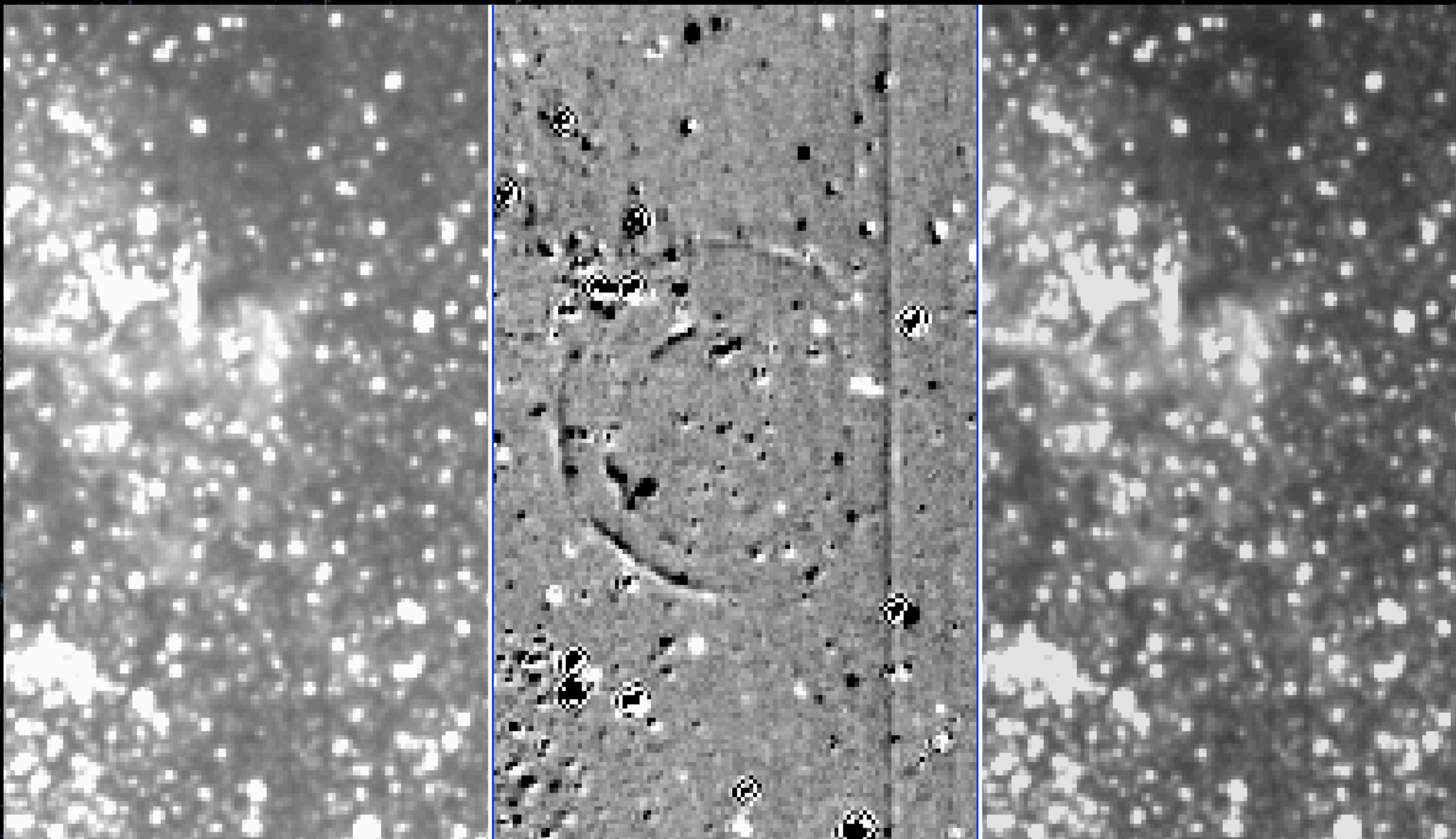
SN Name	RA	Dec	Date	Distance (kpc)	Type	Search Area (square deg)
Cas A	23:23	+48:58	1680	3.2	SN IIb	66
Tycho	00:25	+64:09	1572	2.3	Norm. SN Ia	287
Eta Car	10:45	-59:41	~1840	2.4	Great Eruption	36
SN 1181	02:05	+64:49	1181	2.6	?	2400
P Cygni	20:17	+38:02	1600	1.6	Great Eruption	3000
Crab Nebula	05:34	+22:01	1054	1.9	SN II?	3000
W49B	19:11	+09:06	1000	8	Core-Collapse?	113
Kepler	17:30	-21:29	1604	2.9	Pec. SN Ia?	140
SN 1006	15:02	-42:06	1006	2.2	Norm. SN Ia?	2300
RCW 86 (SN 185)	14:43	-62:28	0185	2.8	SN Ia/II ?	6000

Table adapted from Armin Rest

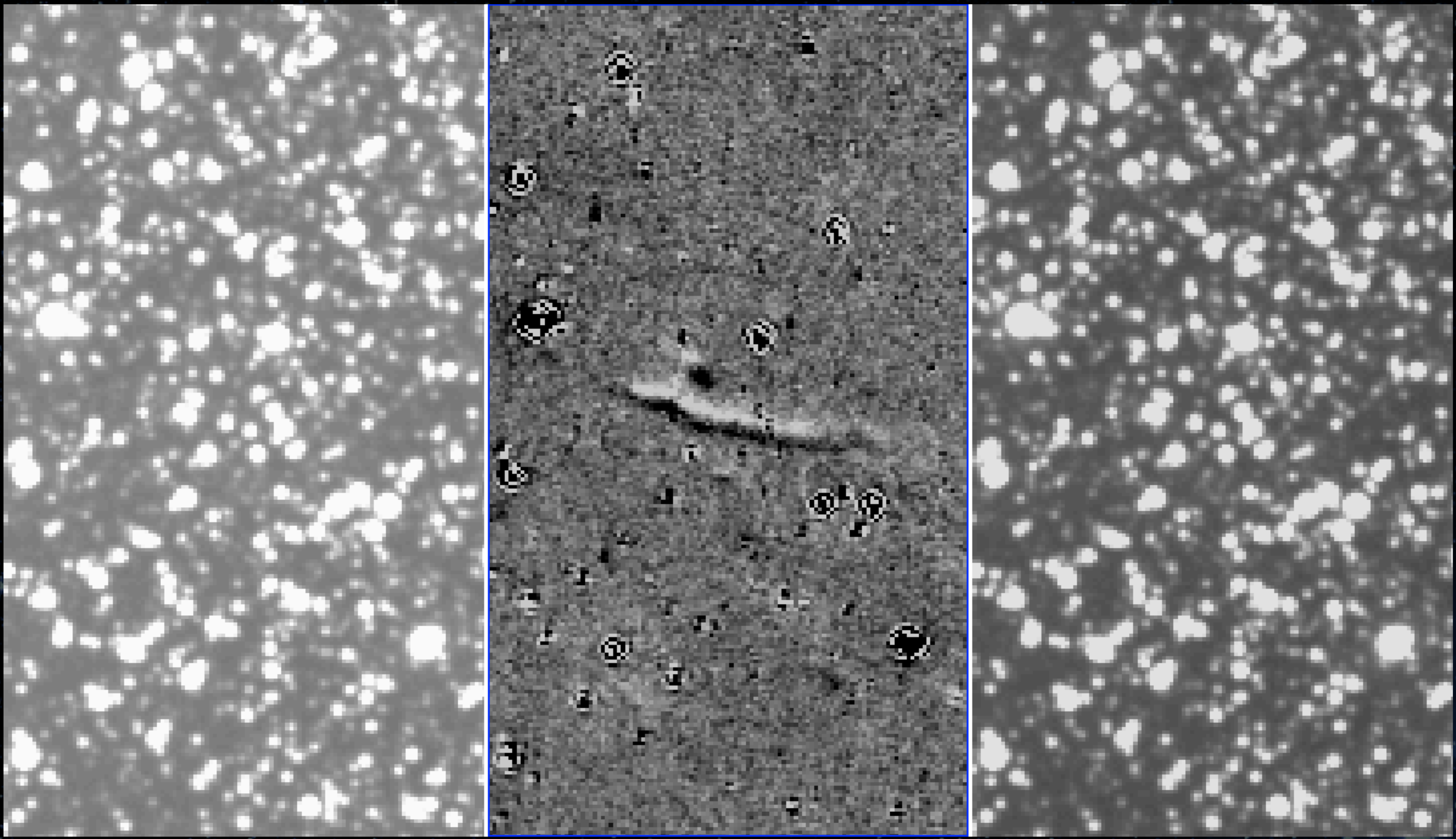


P. Marenfeld and NOAO/AURA/NSF

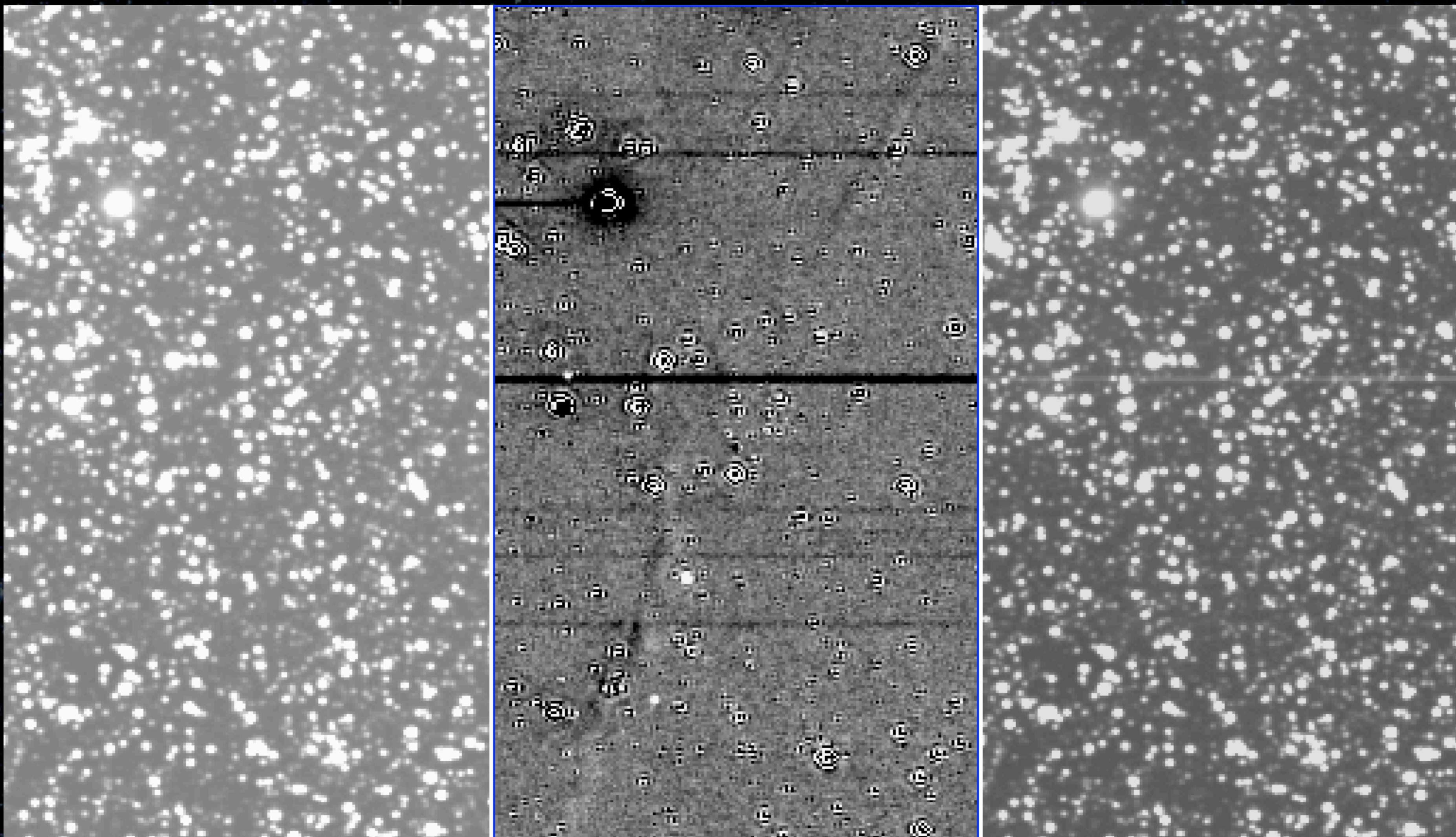
ASAS-SN: SN 1987A light echoes



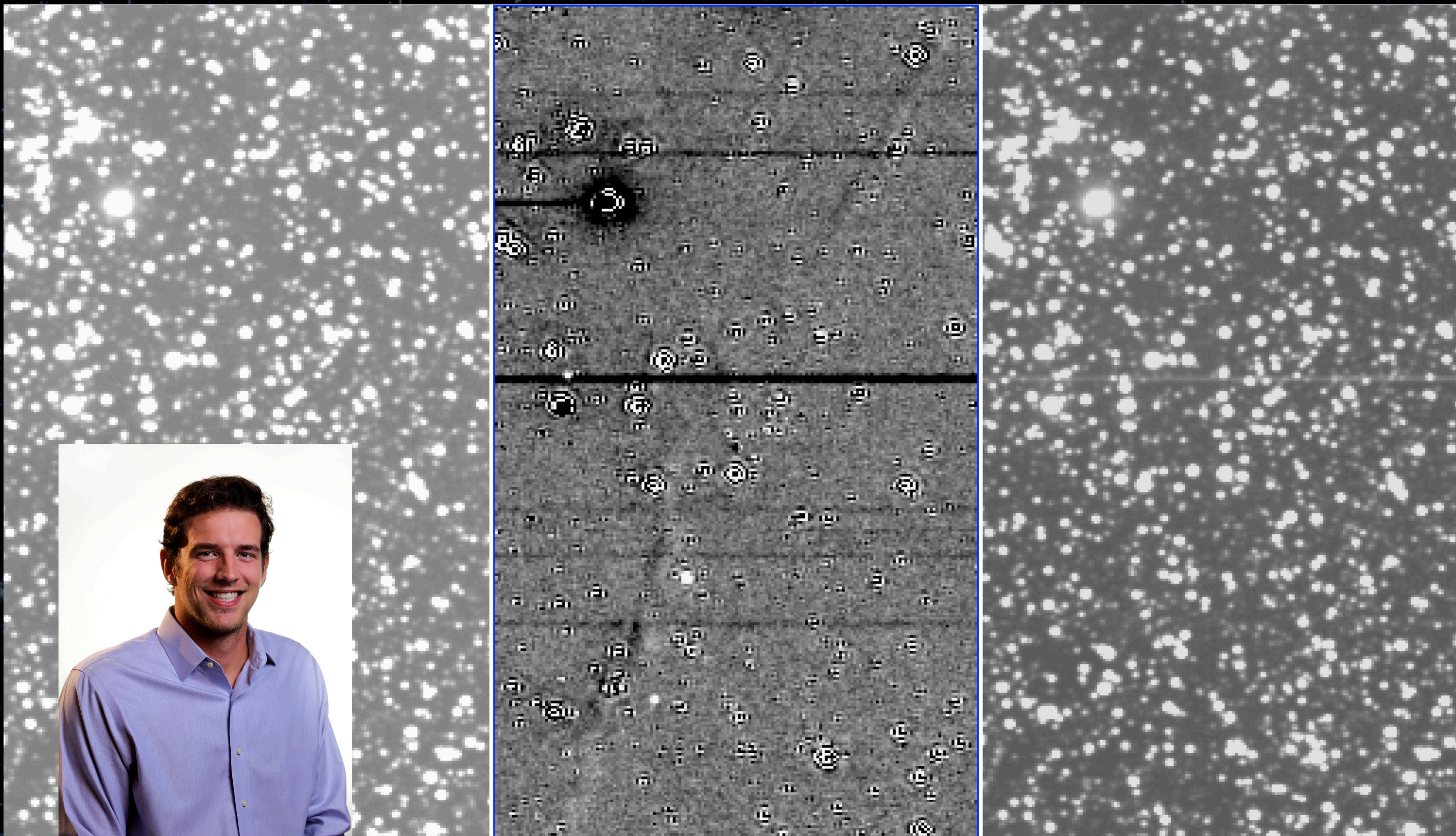
ASAS-SN: Tycho light echoes



ASAS-SN: Cas A light echoes

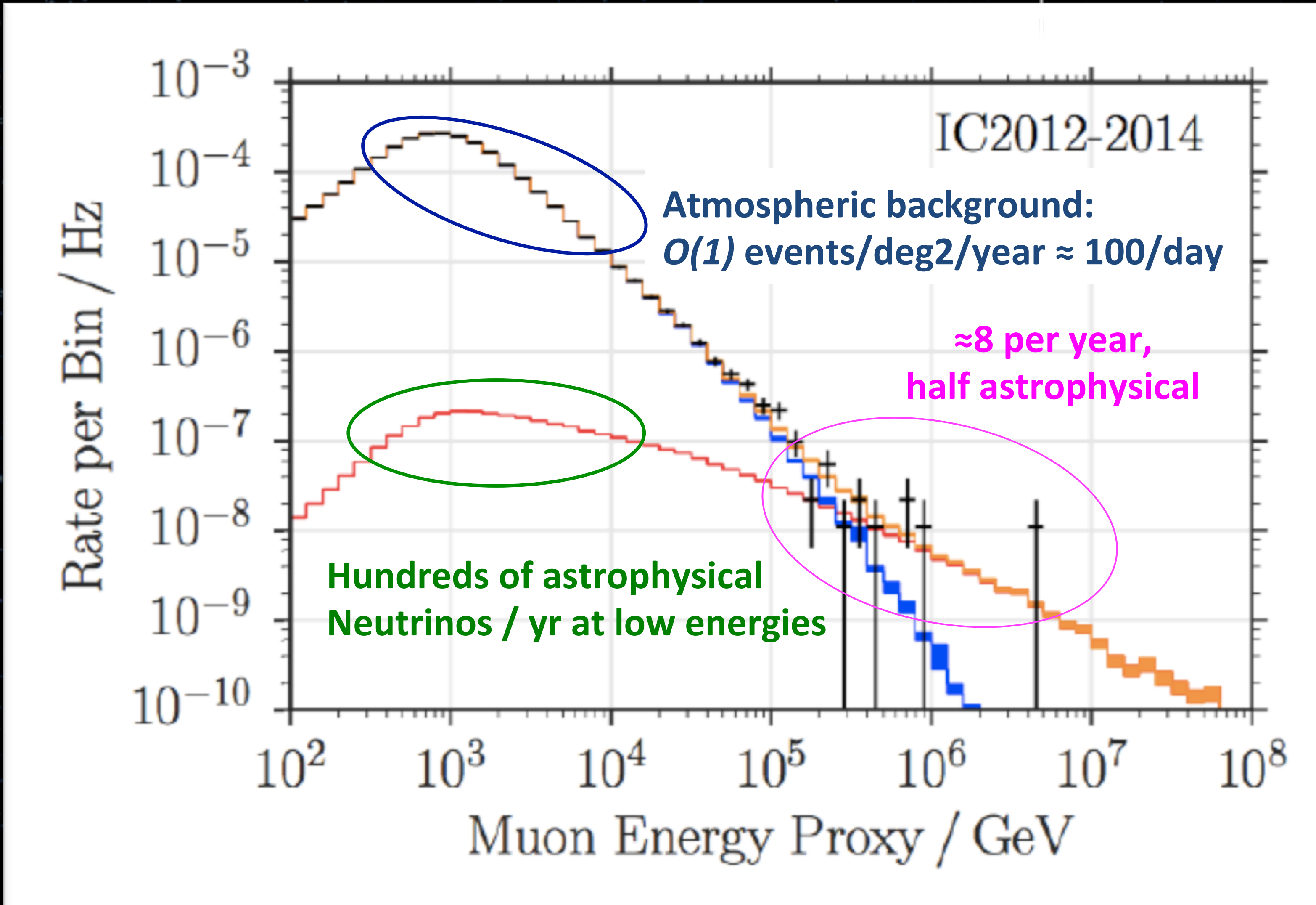


ASAS-SN: Cas A light echoes



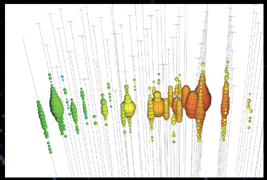
Grad student Michael Tucker

IceCube + ASAS-SN



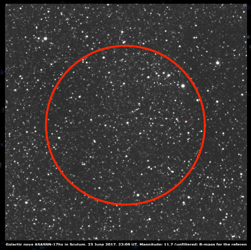
Slides courtesy of Anna Franckowiak and Robert Stein

Two Approaches To Correlate Neutrinos

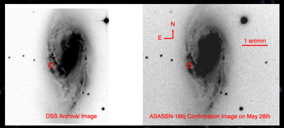


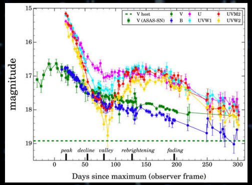
neutrino arrives

ASAS-SN observes neutrino error circle

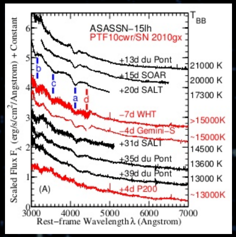


discovery of transient



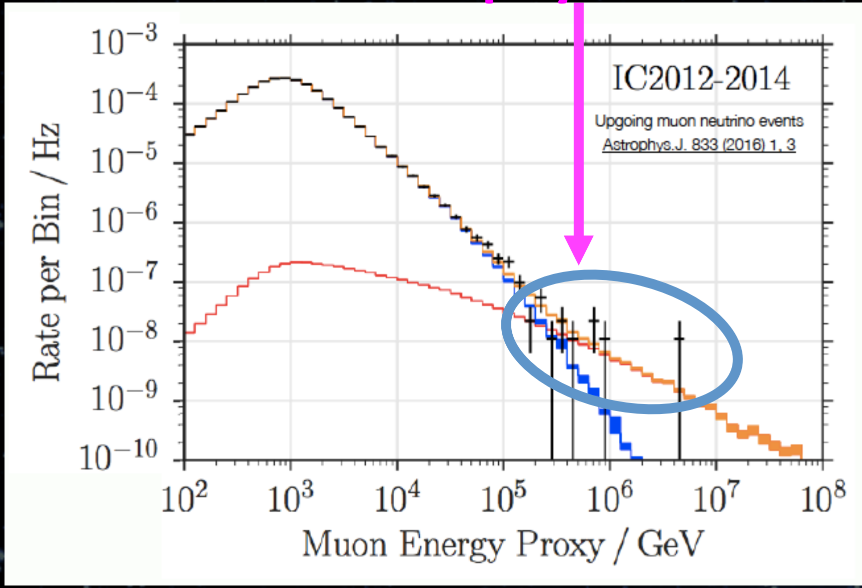


identification of transient



calculate p-value (how significant is detection?)

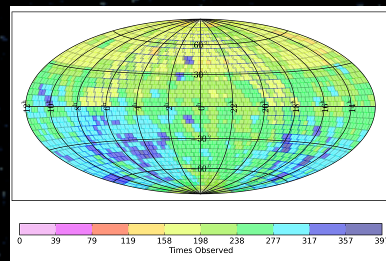
Roughly 8 per year, half astrophysical



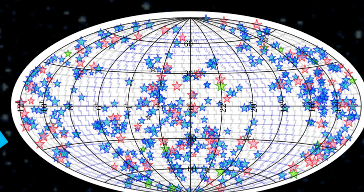
Slide courtesy of Anna Franckowiak and Robert Stein

Two Approaches To Correlate Neutrinos

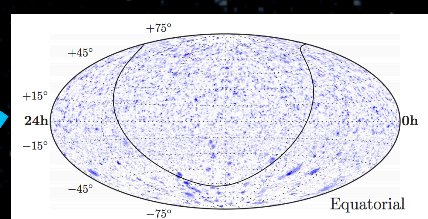
ASAS-SN scans entire sky



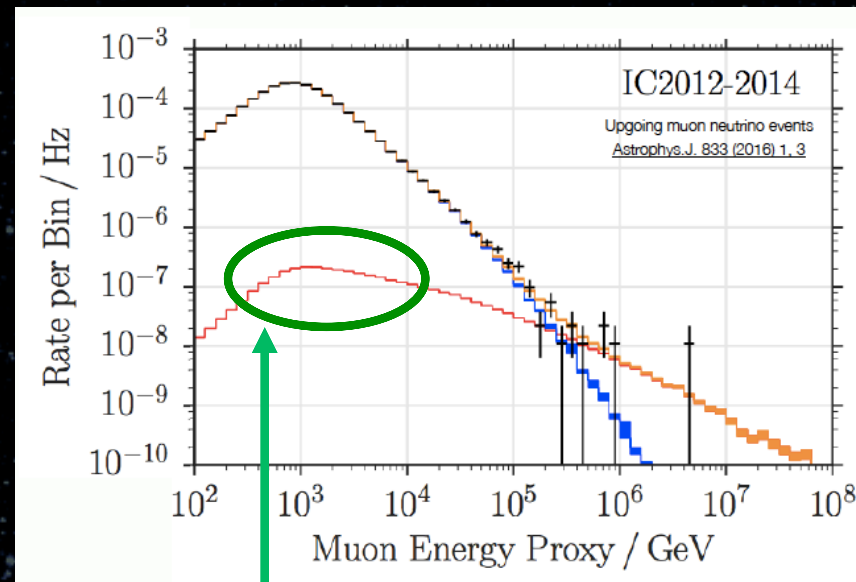
ASAS-SN finds many transients



After ≈1year:
Cross-correlate with neutrinos
search for statistically significant excess



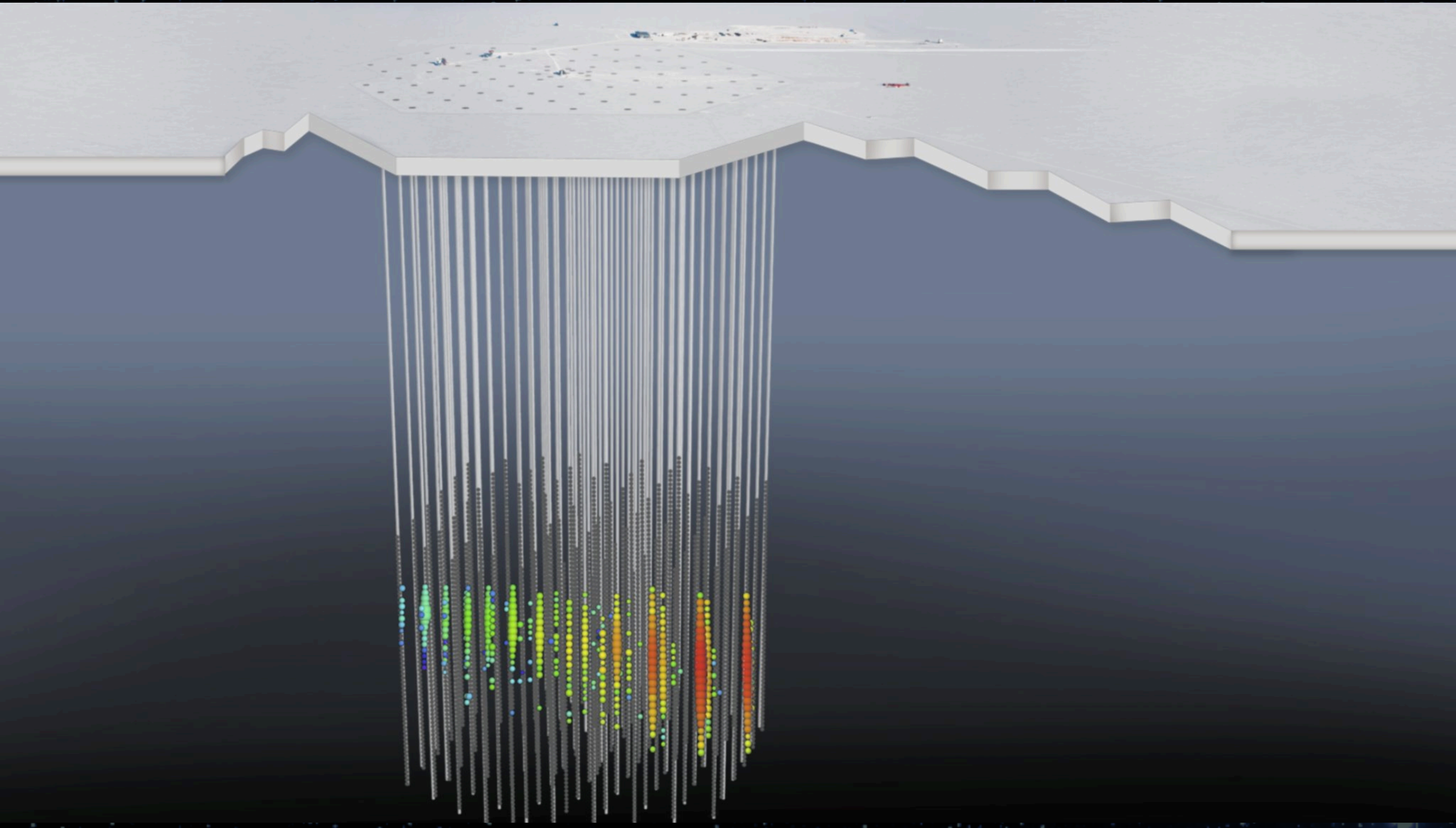
IceCube detects ≈100 neutrinos per day



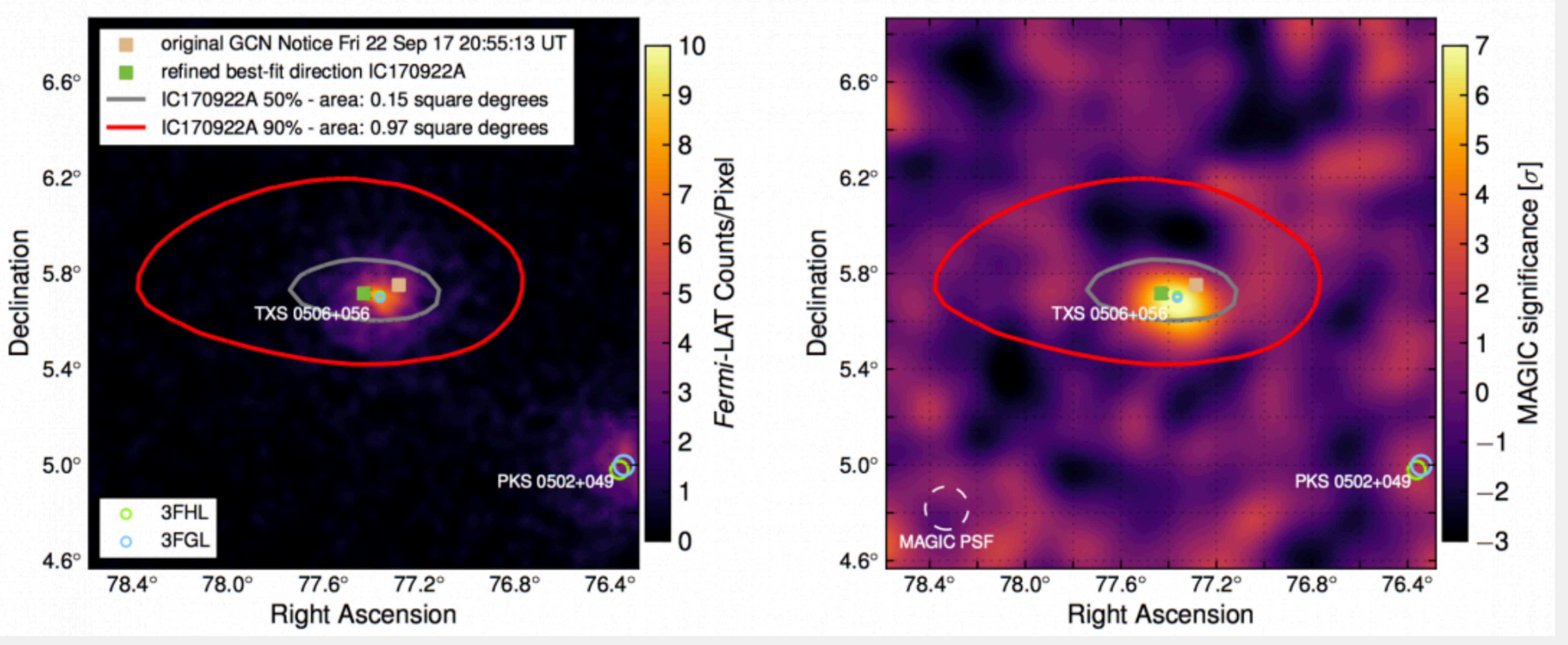
Hundreds of astrophysical Neutrinos per year at low energies

Slide courtesy of Anna Franckowiak and Robert Stein

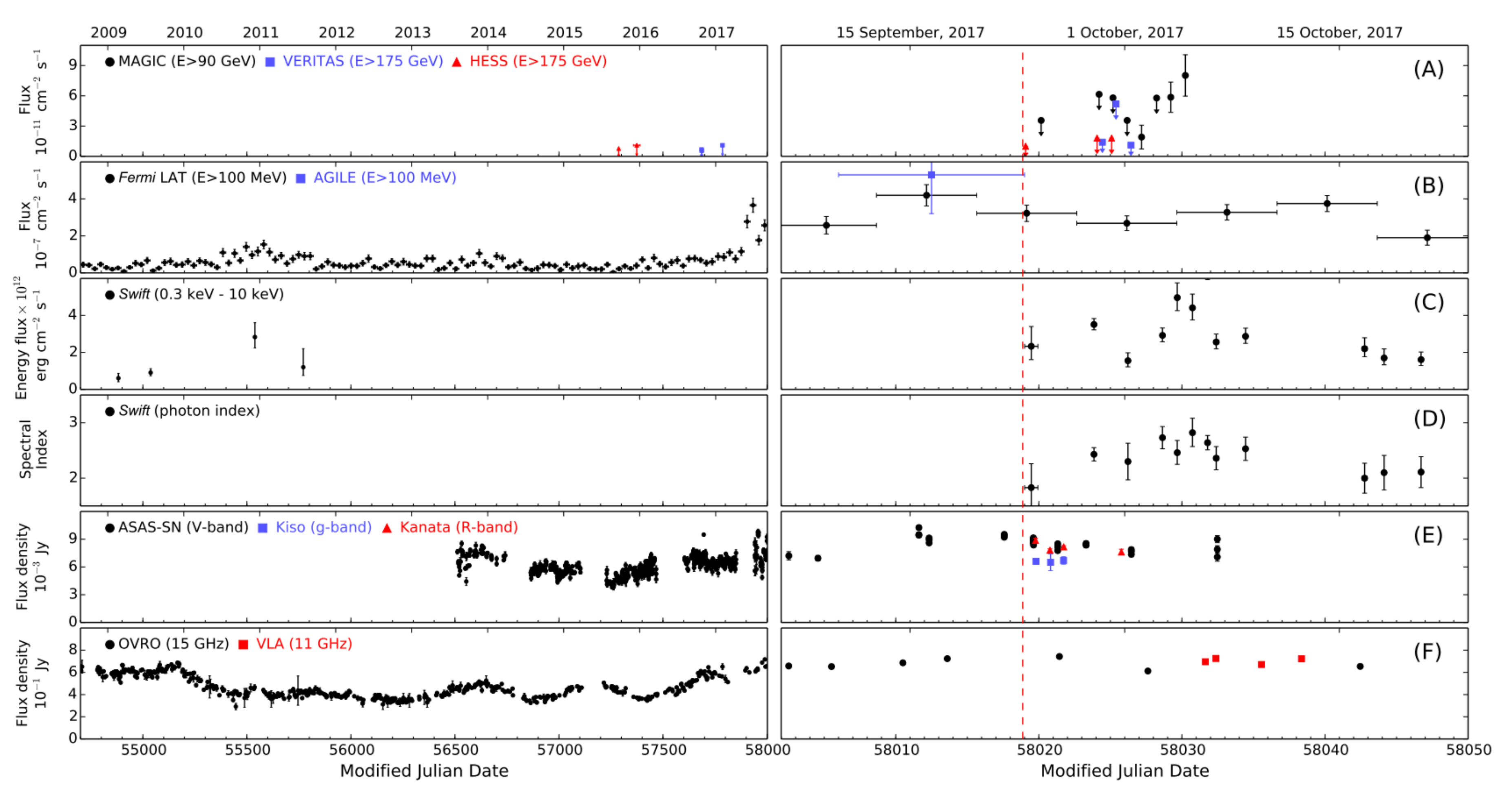
IceCube-170922A



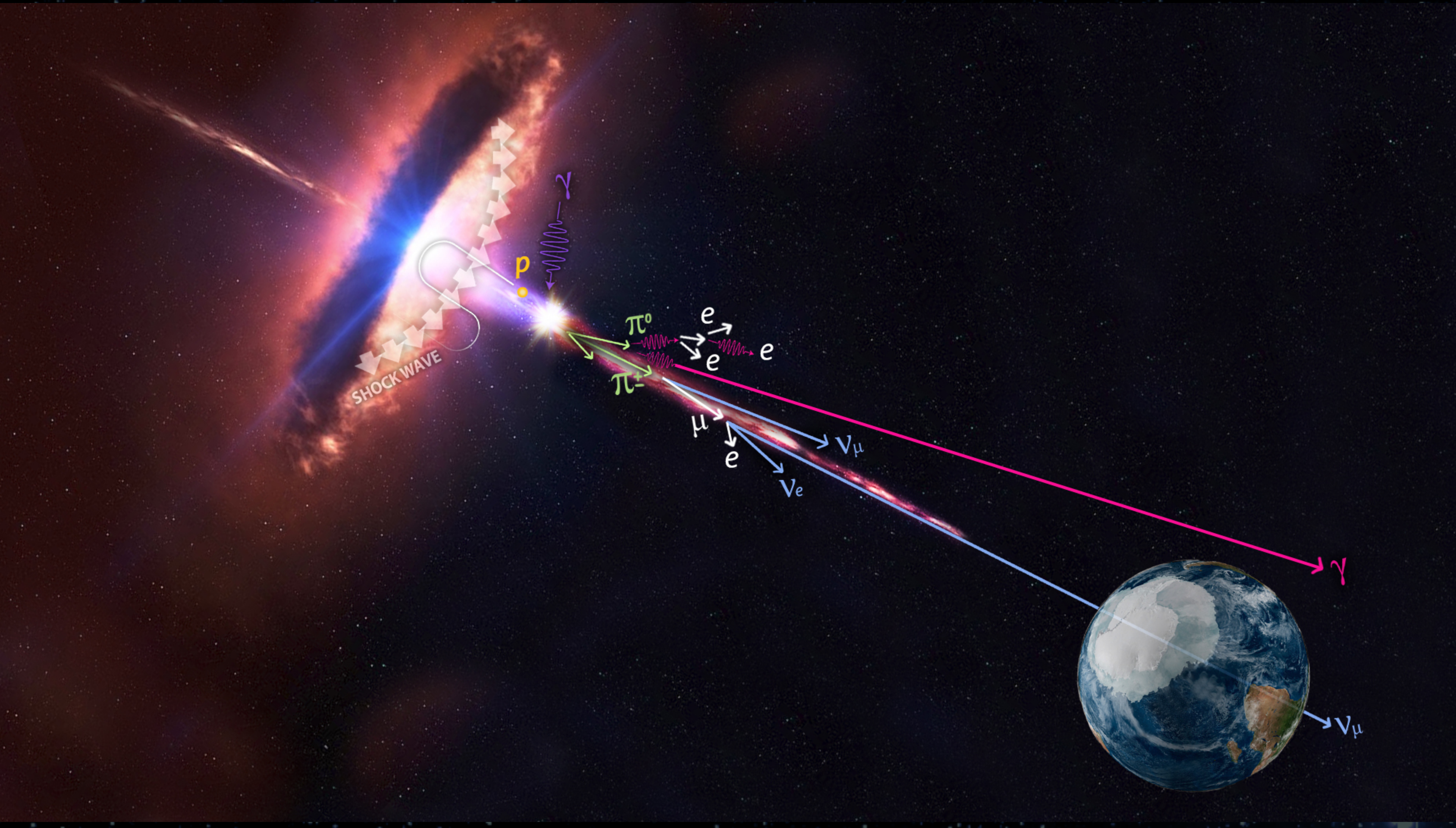
IceCube-170922A



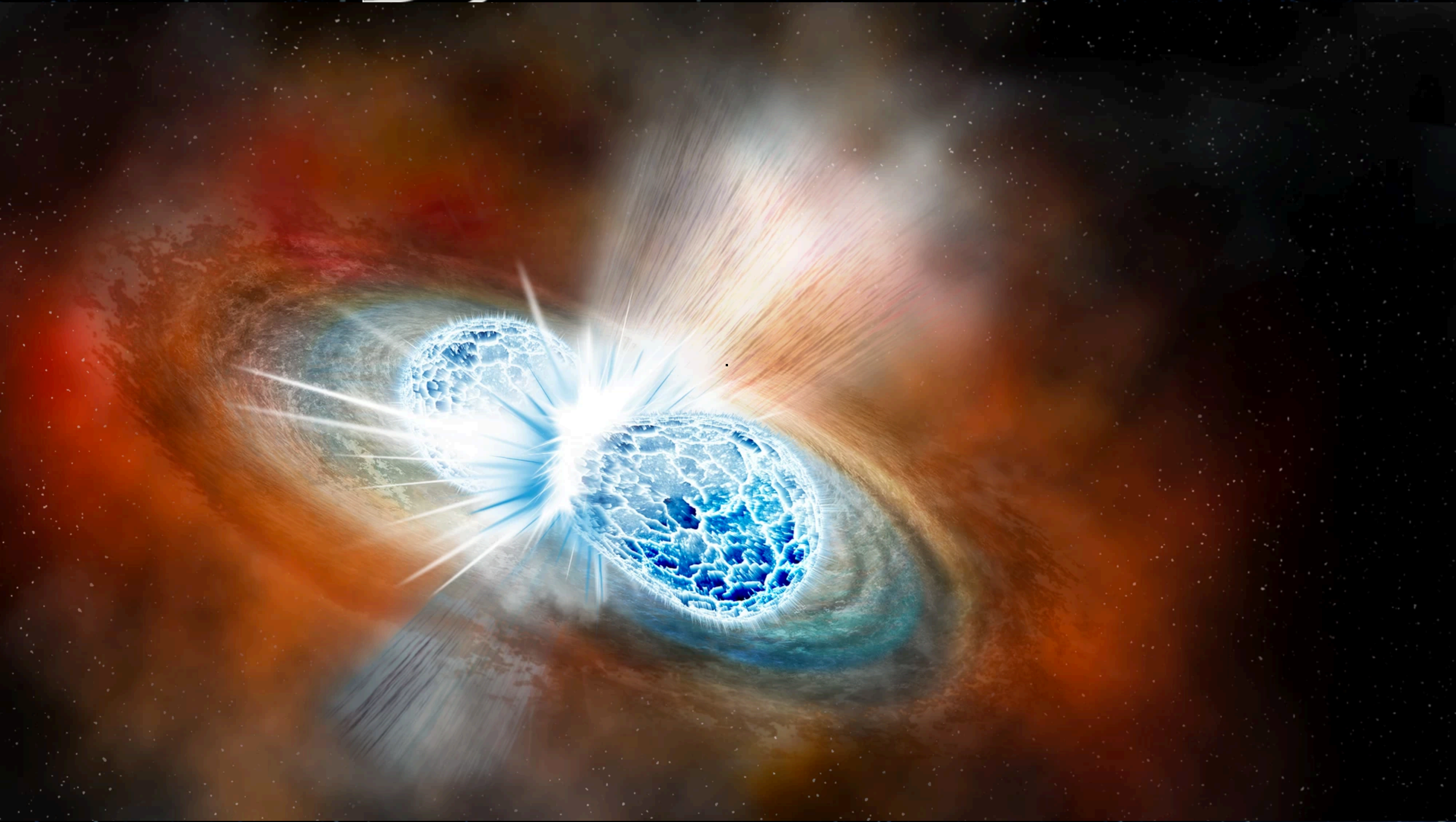
IceCube-170922A



IceCube-170922A



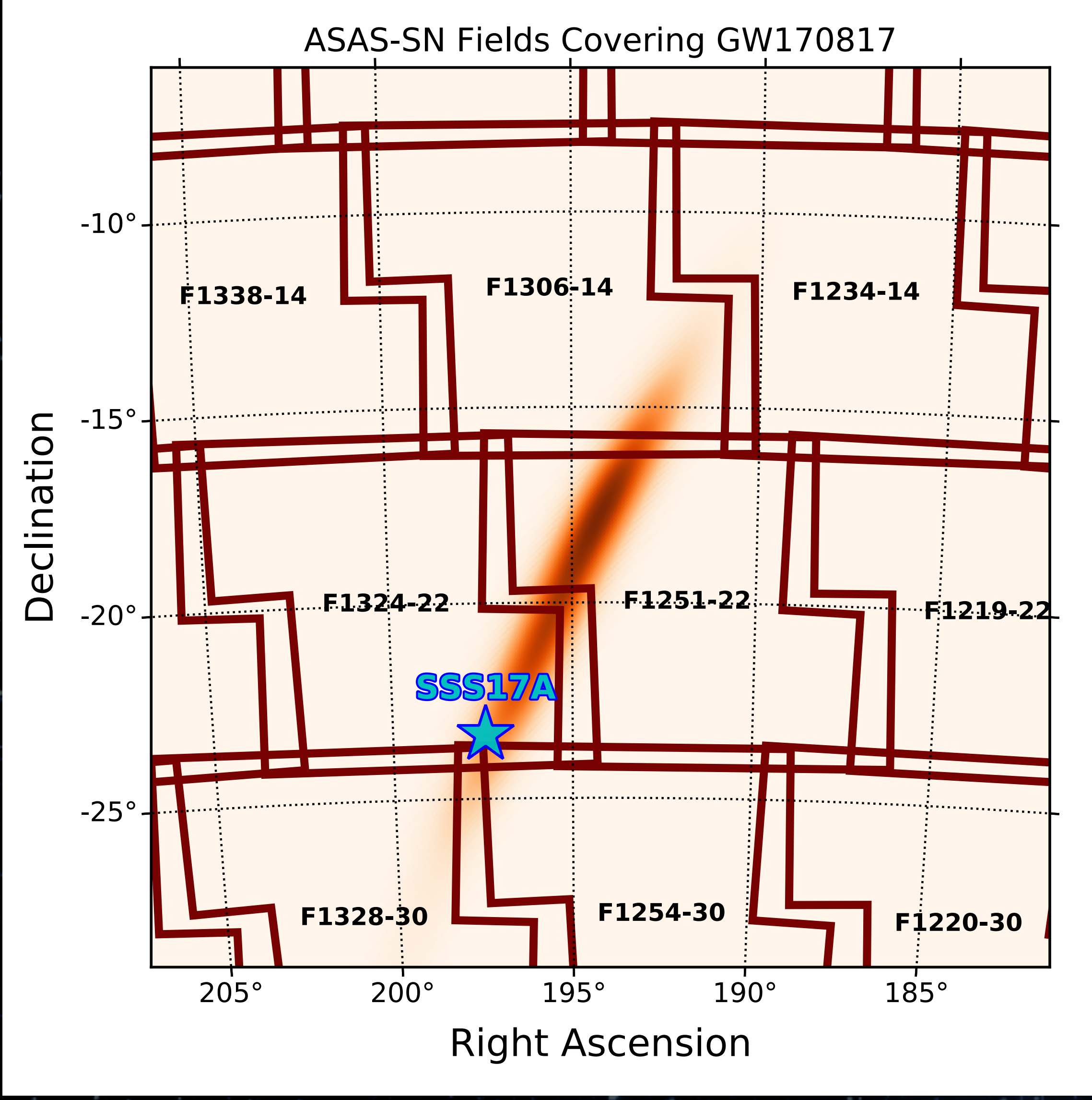
LIGO + ASAS-SN



LIGO + ASAS-SN

LIGO + ASAS-SN

- ASAS-SN automatically triggers in ≈ 30 seconds
- GW170817 would have taken 2 fields from *South Africa*
- ASAS-SN distribution around the globe is a major advantage.



High speed mode of Tomo-e Gozen: Application for Optical Pulsars

May. 3-4, A.D.2019 Carnegie Observatories

ICHIKI Makoto

(2nd year doctor course student, UTokyo, Japan)

Contents

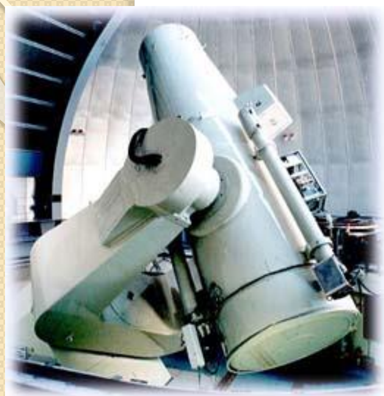
・About Tomo-e Gozen Camera
・About Optical Pulsars

・The result of test obs. for Crab pulsar
・Optical Pulsar Survey plan by Tomo-e
・Simultaneous obs. with Radio/X-ray

Tomo-e Gozen Camera

Tomo-e Gozen Camera

Extremely wide field CMOS camera

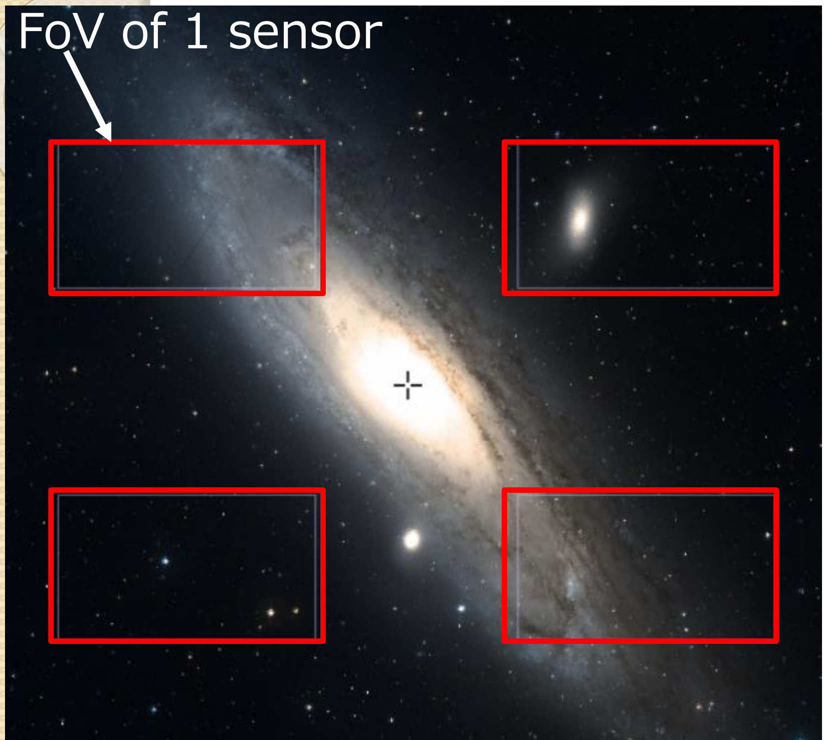


Telescope	Kiso Schmidt (aperture105cm, seeing~4”)
Filed of view	22 deg^2 in ϕ 9 deg
Sensor	CMOS (1k x 2k) x 84
Frame rate	2 frame / sec (0.5sec/frame)
Read out time	<0.5sec
Wavelength	optical

Full frame mode of Tomo-e can see
≳seconds time scale events

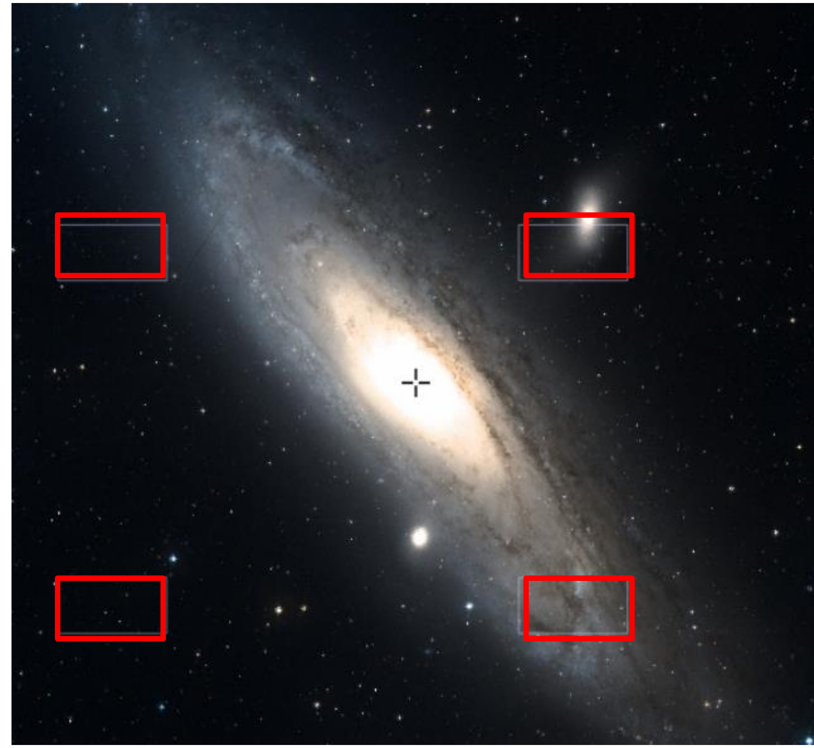
Partial mode (high speed mode) of Tomo-e

Full frame mode



$2000 * 1200$ pix^2 each
-> 0.5 sec cadence

Partial frame mode

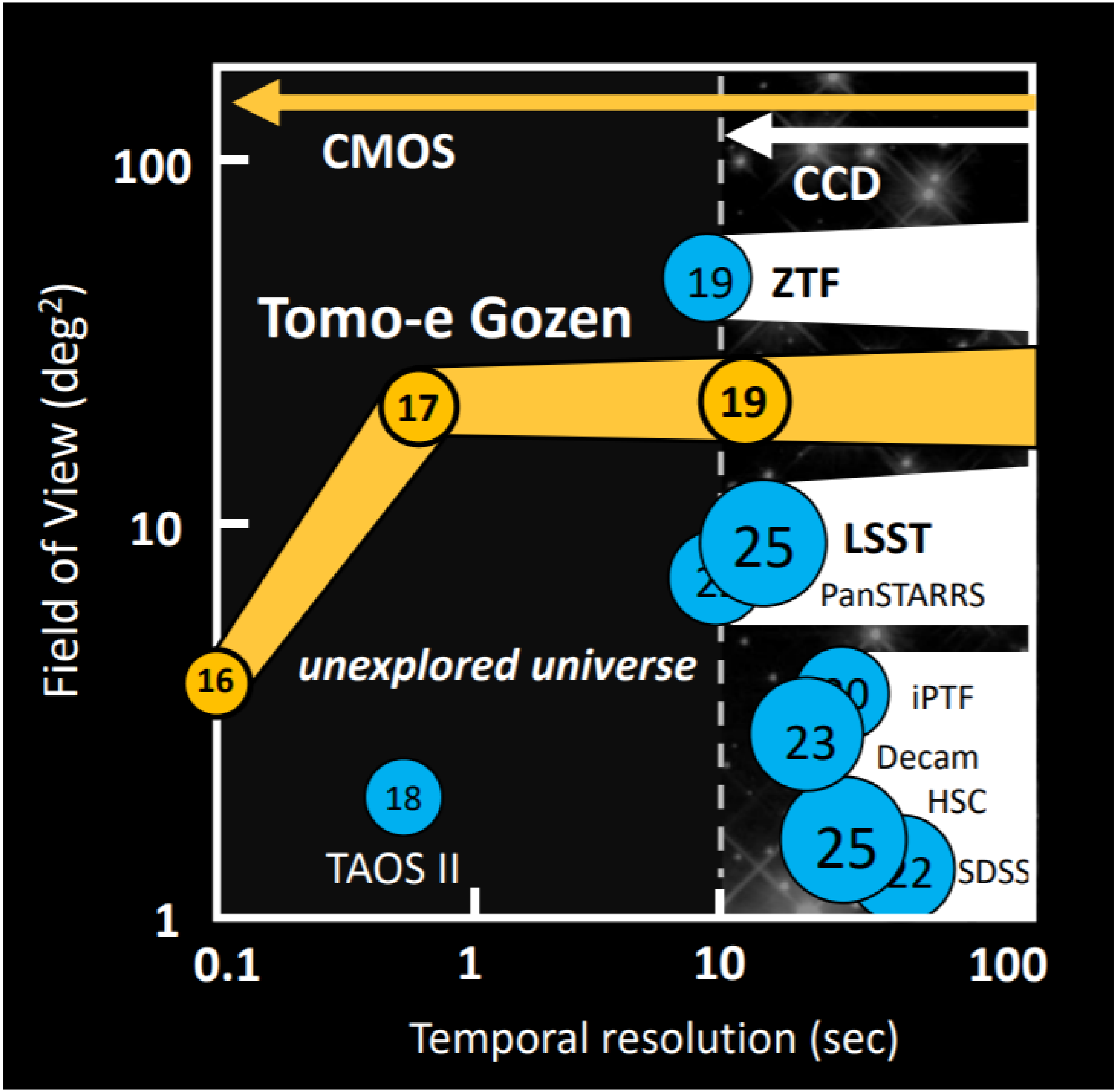


$1000 * 500$ pix^2 each
-> 0.12 sec cadence

Partial mode of Tomo-e can see
sub-seconds time scale events

Survey power for transients

Limiting magnitudes are showed in the circles

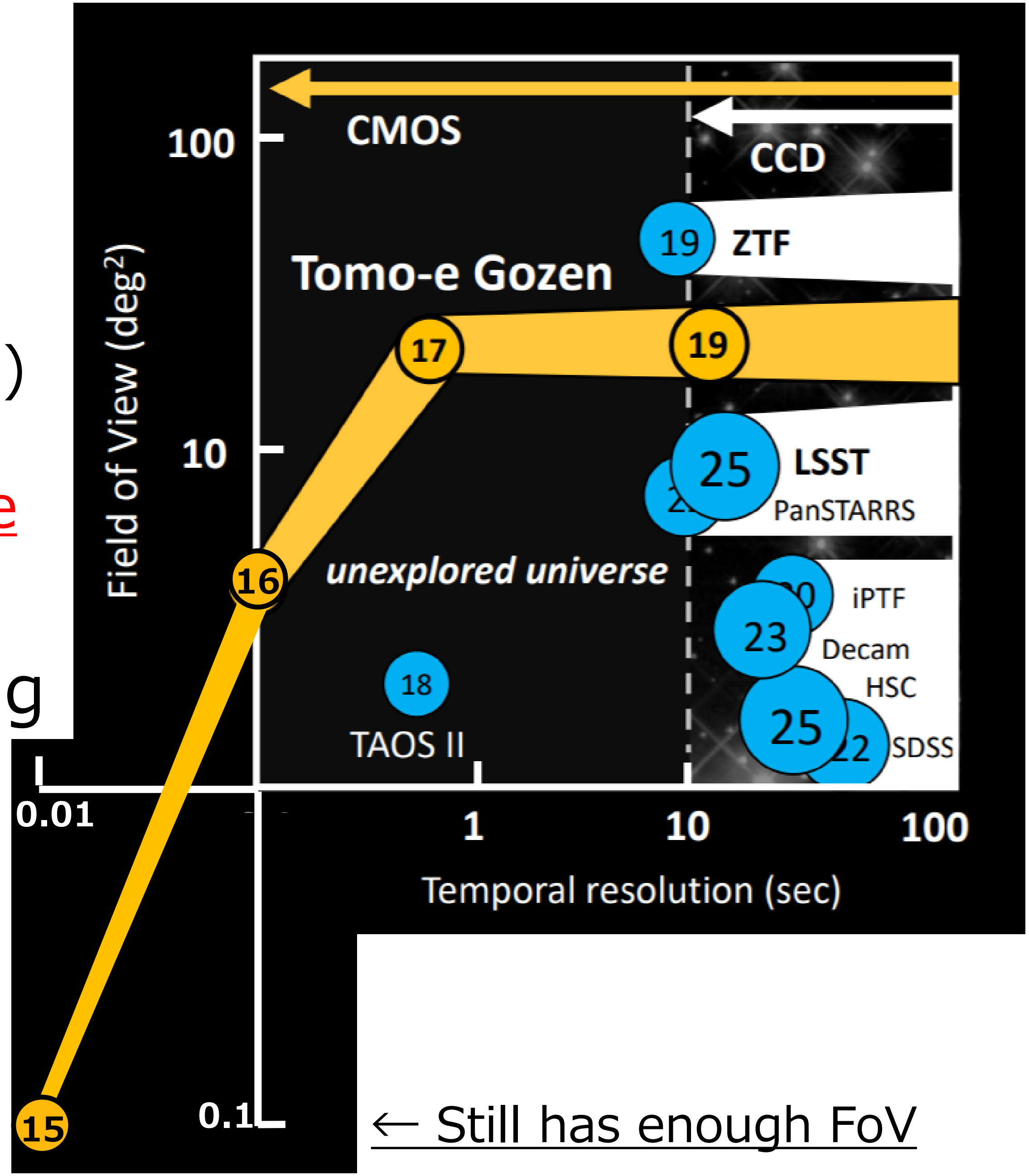


slide:
Shigeyuki Sako

Survey power for transients

280 * 24 pix^2
(FoV = 0.05 deg^2)
->
5.2 msec cadence

Transient or Pulsating Objects that have ~10msec time scale can be searched by Tomo-e

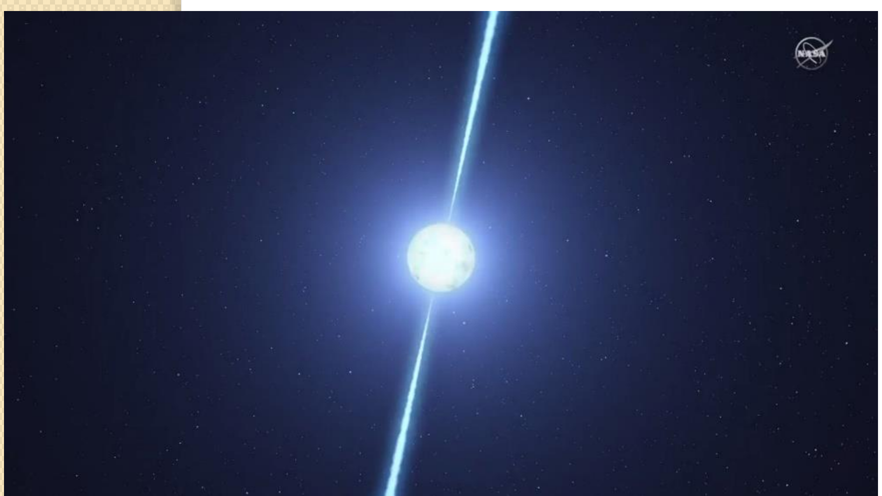


← Still has enough FoV

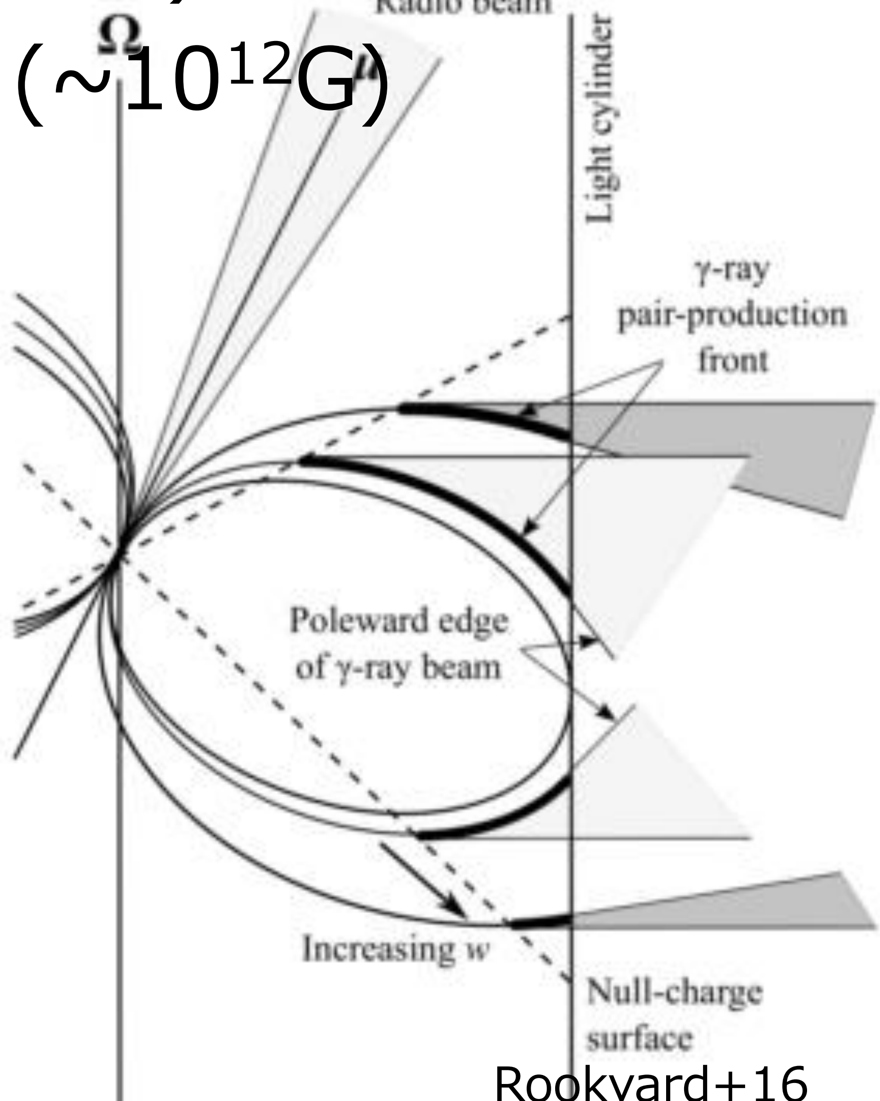
About Pulsars

What is pulsar?

- Pulsed emission (due to beaming effect)
- Fast Rotation (Period≲sec)
- Strong magnetic field (~10^{12}G)
- Neutron Star

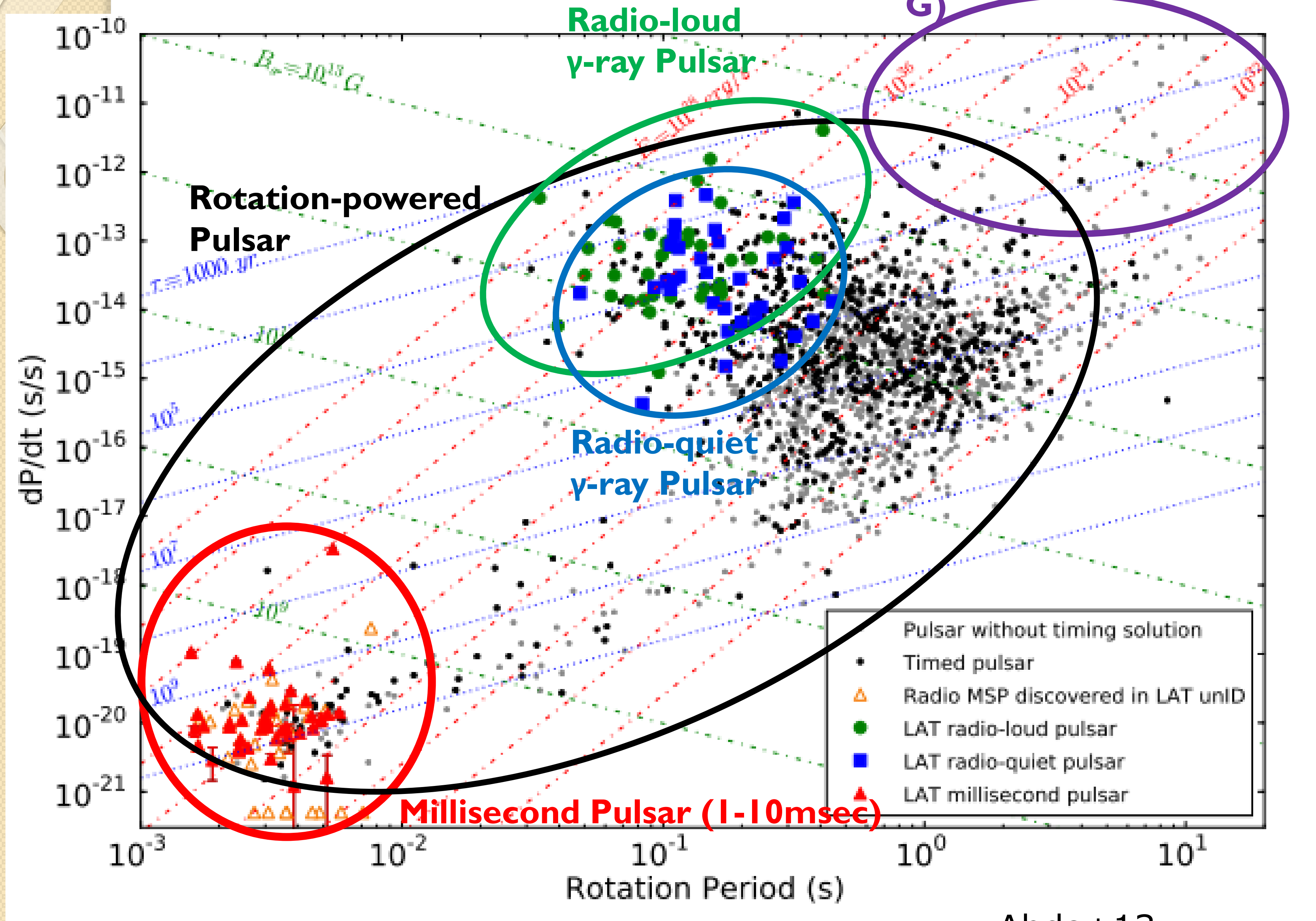


Neutron star…
Radius ~ 10km
Mass ≳ 1.4 solar mass
Only visible Nuclear matter



Rookyard+16

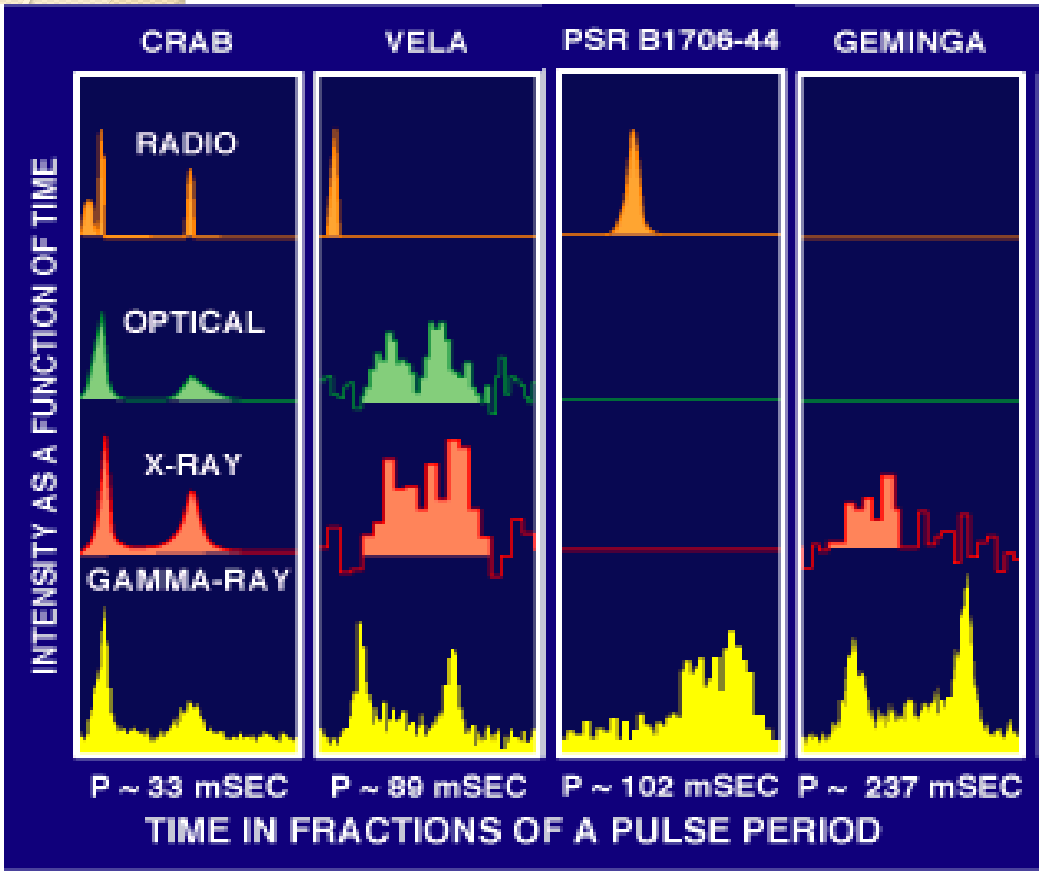
Diversity of pulsars



Abdo+13

Current status of optical observations for Pulsars

Diversity of light curve in a period



Thompson 04

in Radio,
~2000 pulsars
are detected.

In X-ray
~400 pulsars

In γ-ray
~200 pulsars

In optical bands,
<u>only 5</u> phase-resolved pulsars are detected.

All optical pulsars have been detected
only by follow-up observation for Radio/X・γ-ray survey.

Pulsar observation by Tomo-e

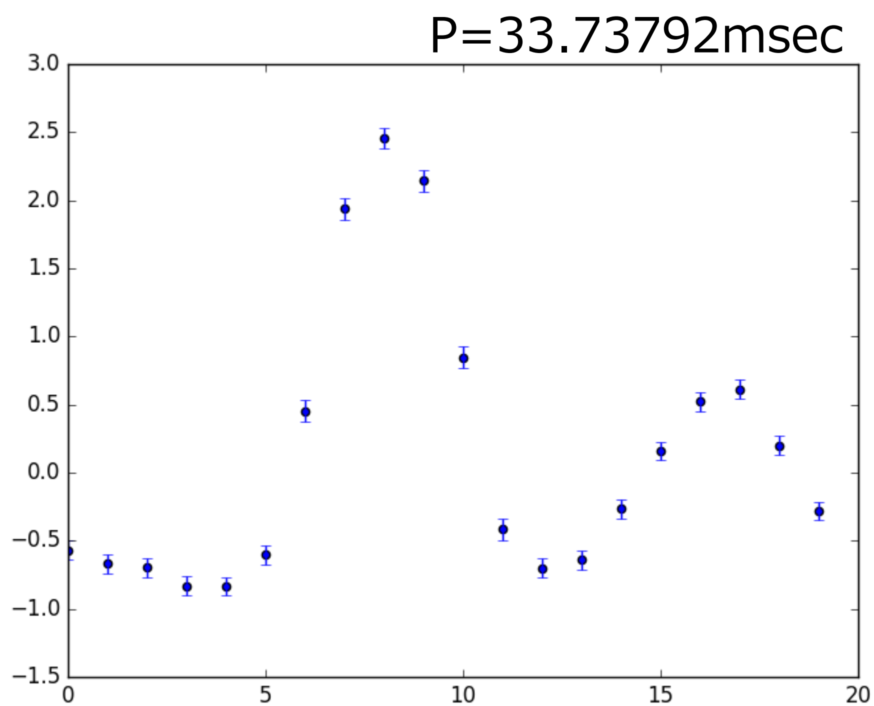
Test Observation for Crab Pulsar

Test observation for Crab pulsar

Oct. 2017 by Tomo-e Q0

↓Mean image for 50000 frames (322 sec)

↓ "Mean image of Peak 10000 frames" – "Off-peak 40000 frames"



frames	Pulses	SD	S/N
100	~20	0.73	8
300	~70	0.46	13
1000	~200	0.27	22
3000	~700	0.19	30
10000	~2000	0.13	50

Relation between
number of frames and S/N

Sufficient S/N for
pulsar survey

Optical pulsar survey plan
by Tomo-e Gozen

Survey Parameters

Conditions

- FoV of Tomo-e Gozen (180Hz): $\underline{0.04\ deg^2}$
- Time for Telescope moving: 6 sec

Parameters

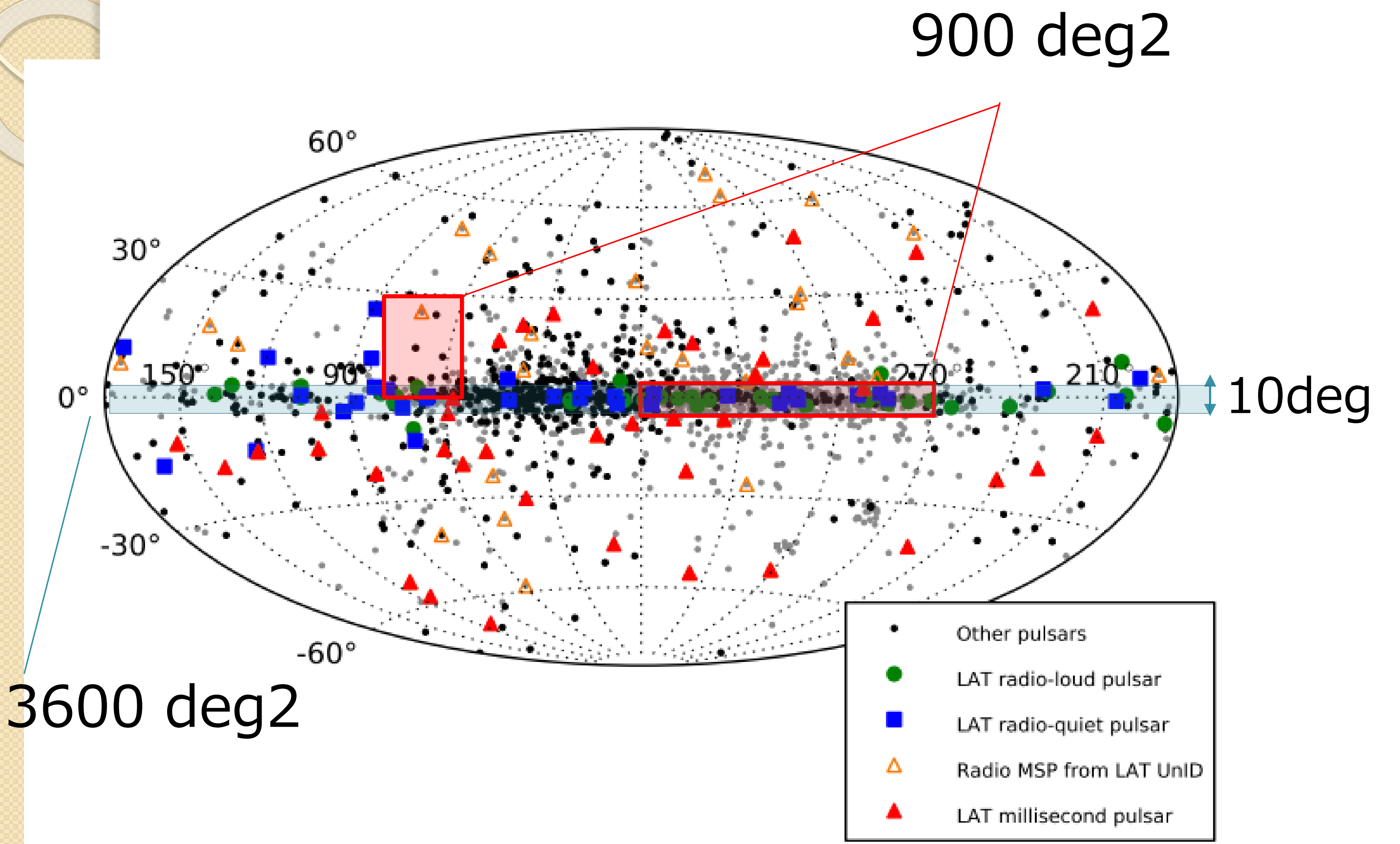
- Total Exposure time
- Total Observation time

e.g. Observation of 6 sec/FoV for 10 nights

gives 950 $\underline{deg^2}$

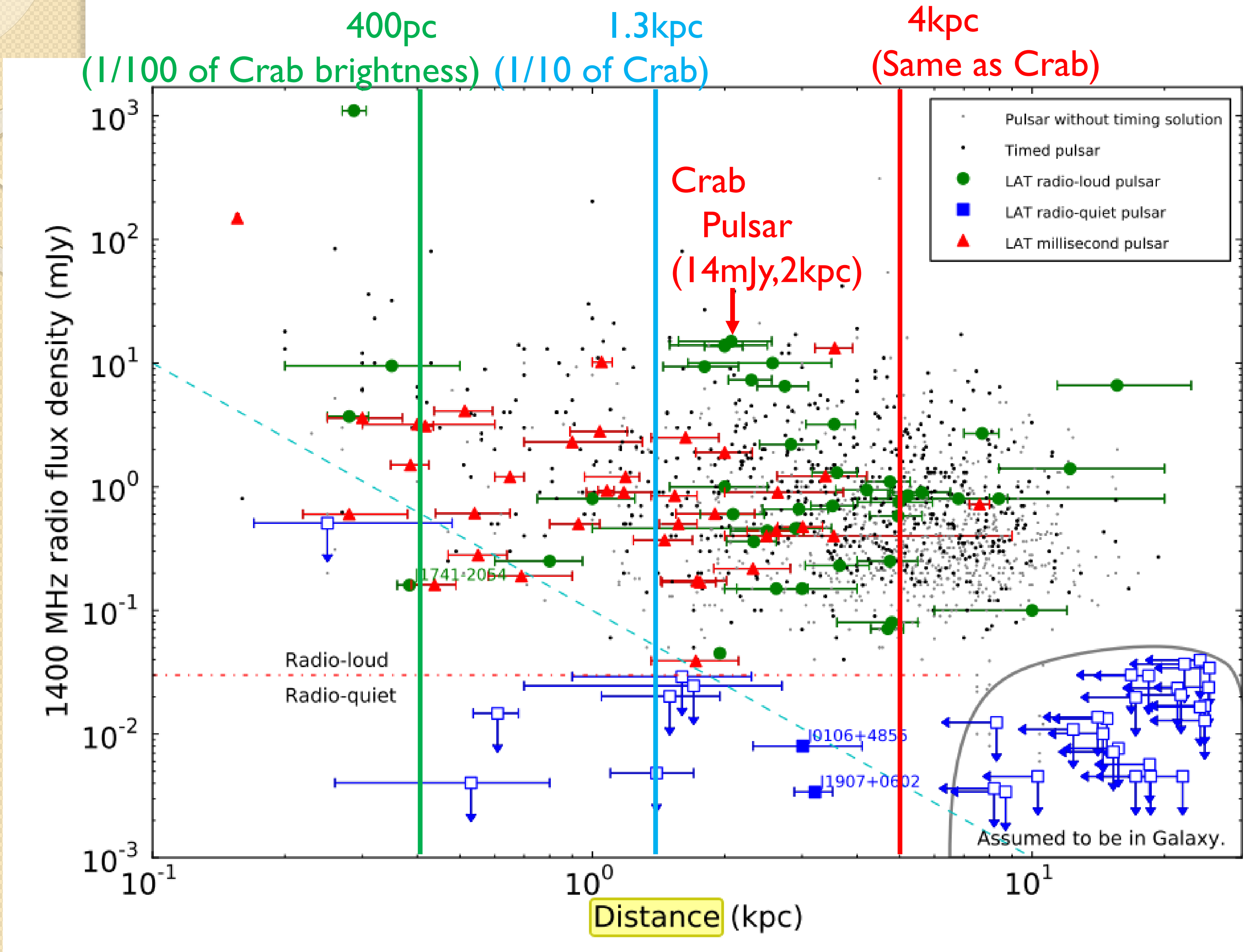
(x 4 season = 3800 $\underline{deg^2}$)

Survey Area



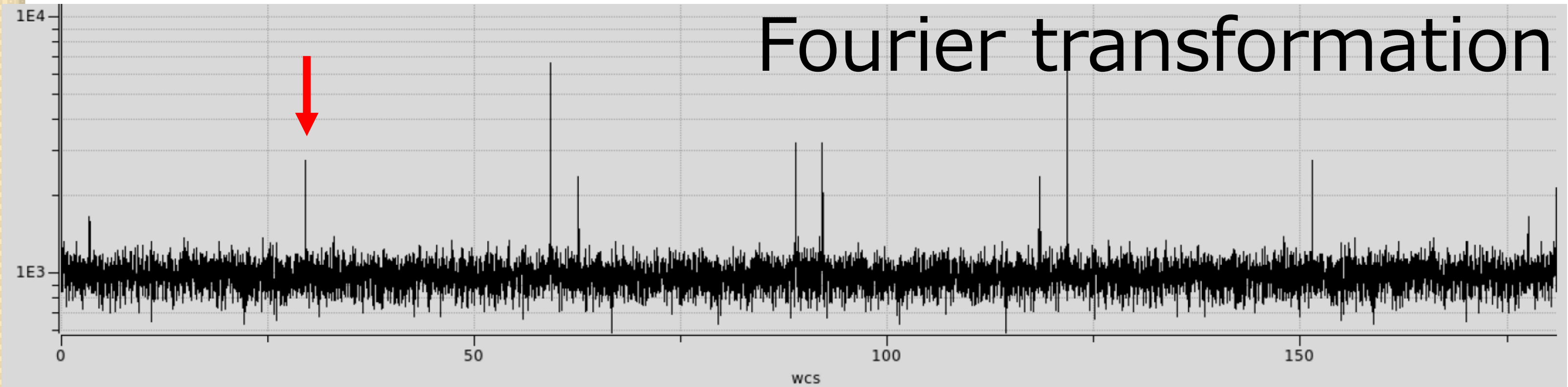
900 deg2
60°
30°
0°
-30°
-60°
150°
90°
270°
210°
10deg
3600 deg2
Other pulsars
LAT radio-loud pulsar
LAT radio-quiet pulsar
Radio MSP from LAT UnID
LAT millisecond pulsar

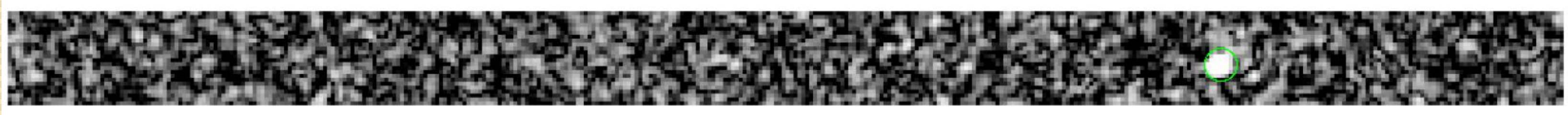
Survey depth (for 6 sec /FoV)



- Detecting pulsars that have unknown periods can be done with Fourier Transformation.

(Father studies)





Simultaneous observations with Radio and X-ray

- In Crab Pulsar, it is reported that its optical pulses are ~3% enhanced when Giant Radio Pulses occur.

Simultaneous observations have been done by Tomo-e with Radio (Kashima NICT) and X-ray (NICER)

2018/03/13-14

2018/04/07

2018/12/26-30

Now under analysis

One of the good points of Tomo-e for this obs. is that its wide field allows us to use reference stars for comparing different obs. periods.

Thank you!

Optical Fast Observations with the Wide-Field CMOS Sensor Camera: Tomo-e Gozen

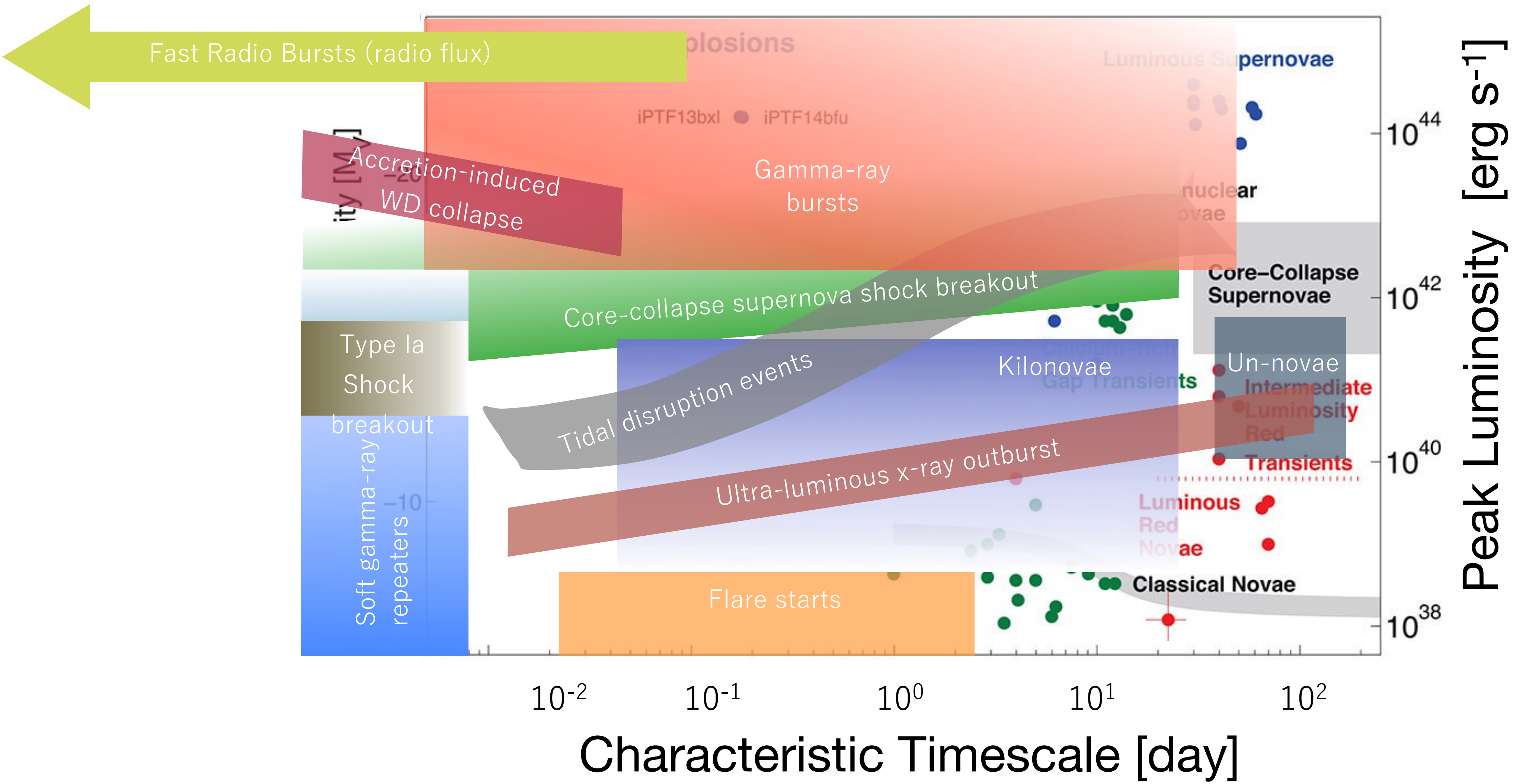
Noriaki Arima (Univ. of Tokyo)
Shigeyuki Sako(PI), Ryou Ohsawa, Hidenori Takahashi, Yuto Kojima, Tomoki Morokuma, Mamoru Doi, et al.

Contents

- Introduction: Scientific Background
- Tomo-e Gozen
    - Kiso Observatory & Telescope
    - The Performances
- Transient Survey w/ Tomo-e Gozen
- Summary

Time Domain Astronomy

The phase space of optical transients



Time Domain Astronomy

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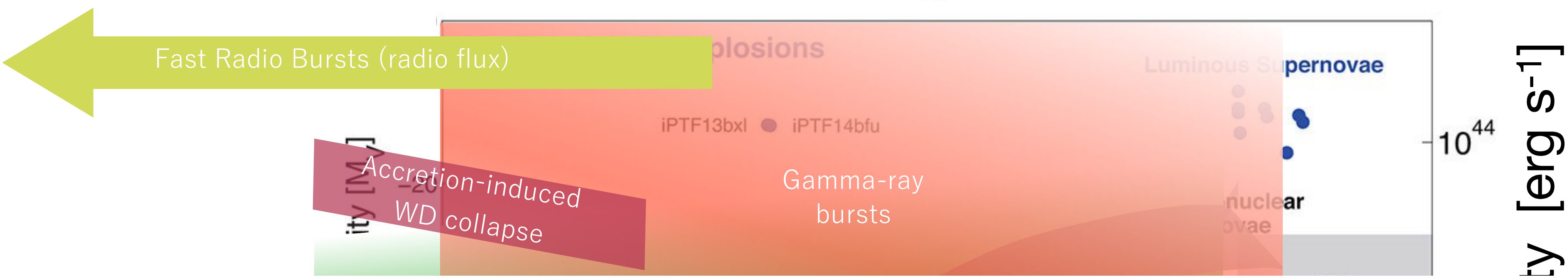
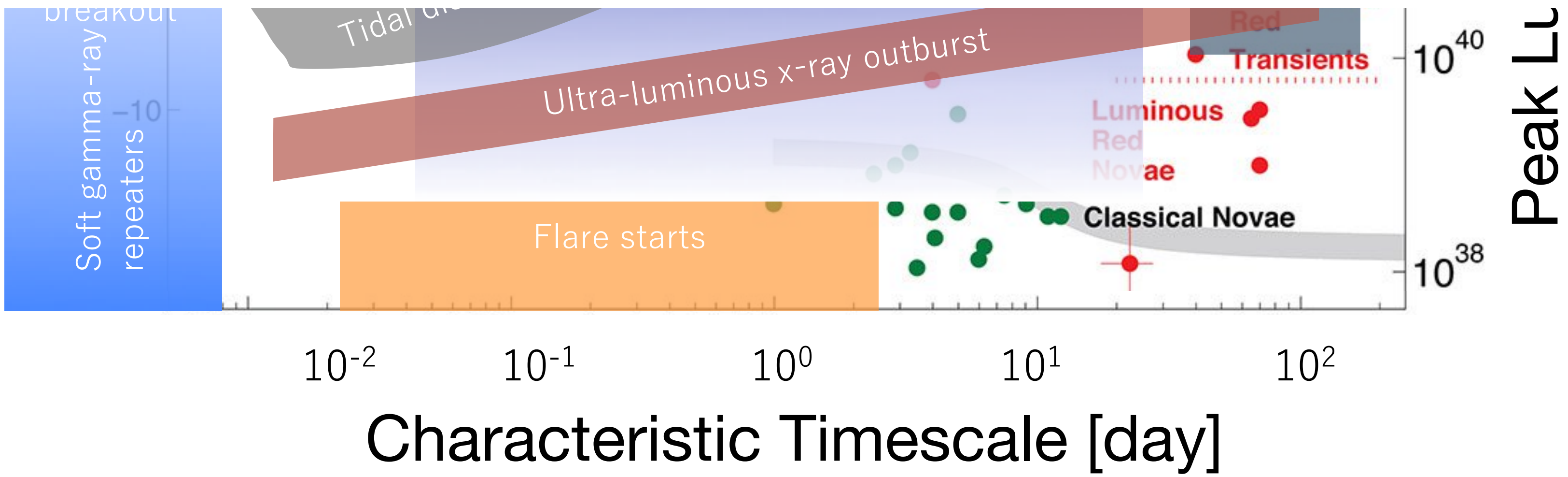


The Universe with **HOURS scale** is **less surveyed**.

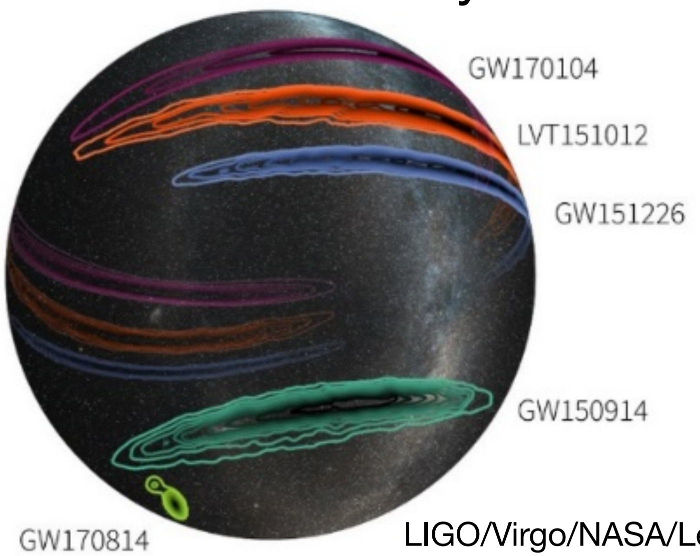
The Universe with **SECONDS scale** is **still unknown**.



Multi-messenger astronomy

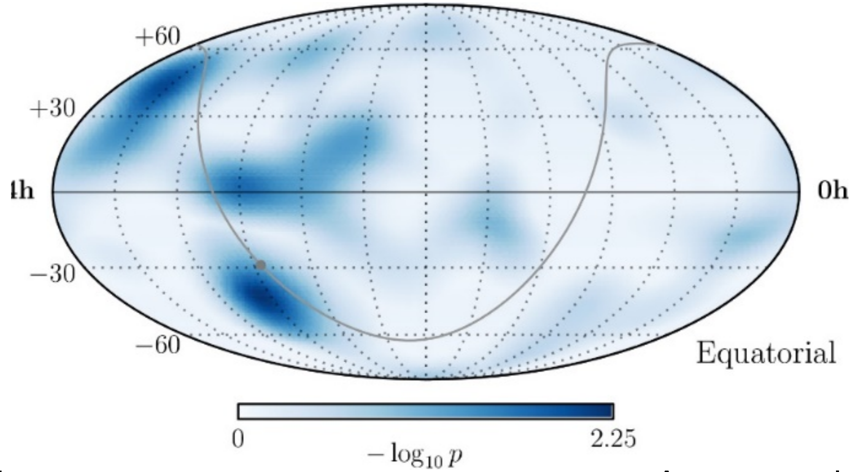
- Gravitational waves were detected from a black hole-black hole merger in 2015.
- The new astronomy with EM and non-EM radiations has begun.

GW events detected by LIGO/Virgo



LIGO/Virgo/NASA/Leo Singer

Neutrino cascade events detected by IceCube



Aartsen et al. 2017

In both case, typical localization error is 10 – 100 deg2

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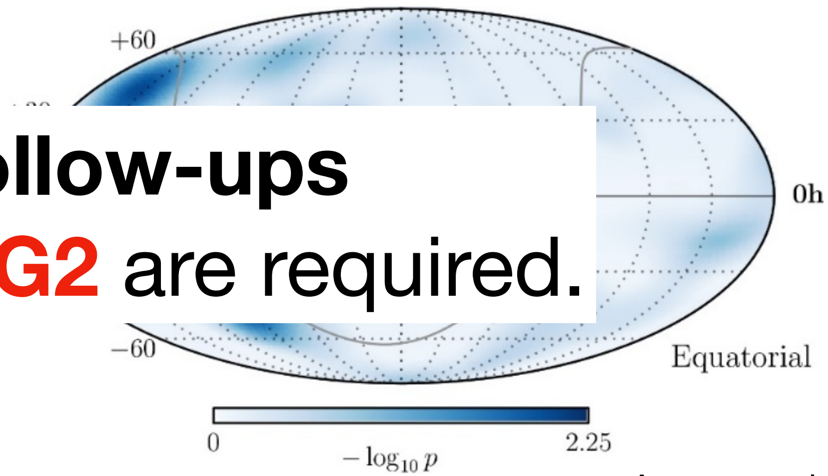


Aartsen et al. 2017

QUICK optical follow-ups
with **a few 10 DEG2** are required.

In both case, typical localization error is 10 – 100 deg2

Tomo-e Gozen

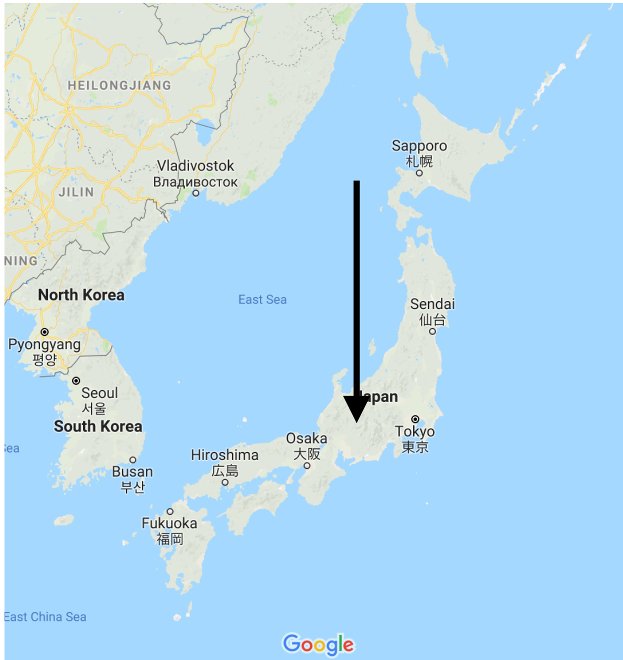

The Tomo-e Gozen
is named after
Tomo-e Gozen
(Lady Tomo-e), who
is a woman warrior
born in the Kiso
region, Japan in the
12th century.
Image: TNM Image Archives

Telescope

http://www.ioa.s.u-tokyo.ac.jp/kisohp/top_e.htm

- 1m Kiso Schmidt telescope
  - Operated by U. Tokyo since 1974
  - 9 deg diameter FOV

137.6283,+35.7940 (EL=1130 m)



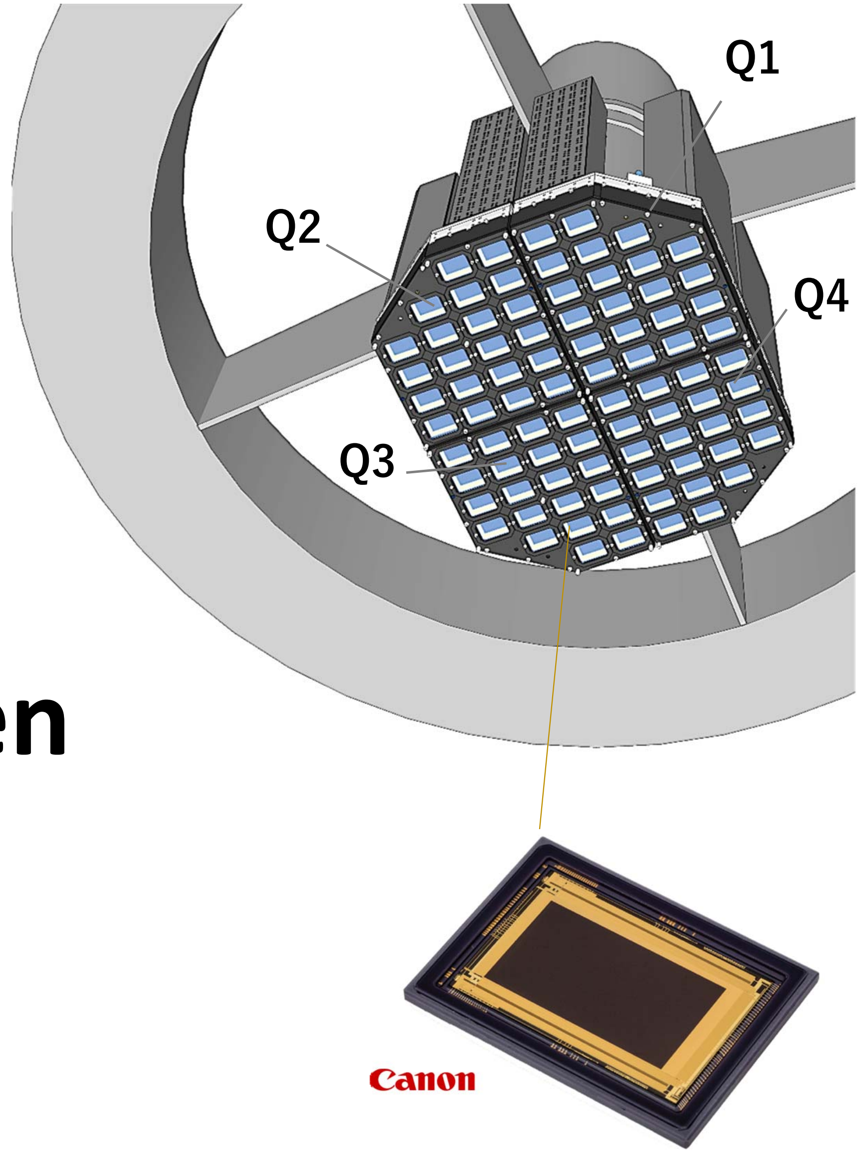
Camera

http://www.ioa.s.u-tokyo.ac.jp/tomoe/about.html

Sako et al. 2018, SPIE
Kojima et al. 2018, SPIE
Osawa et al. 2016, SPIE

the first wide-field CMOS camera

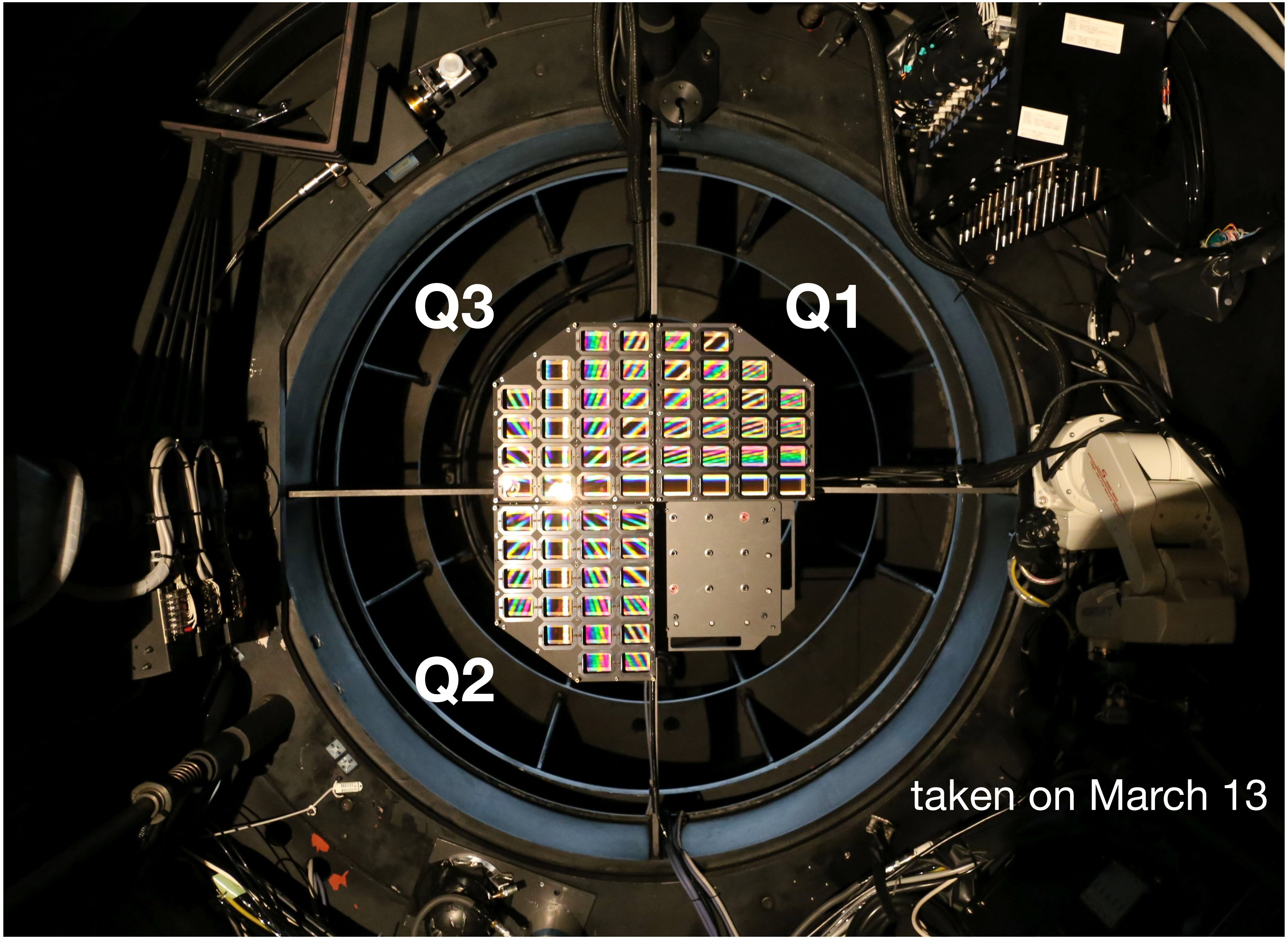
The Tomo-e Gozen



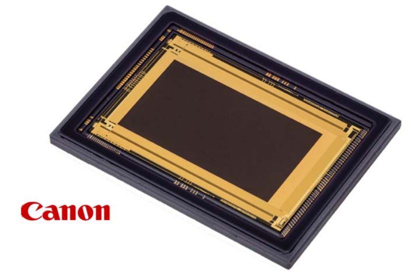
- FoV of 20 deg^2 in ϕ 9 deg
- 84 chips of CMOS, 1k x 2k pixels
- Consecutive frames in 2 fps (max)
- Big movie data of 30 TB/night (max)

Slide courtesy of Shigeyuki Sako

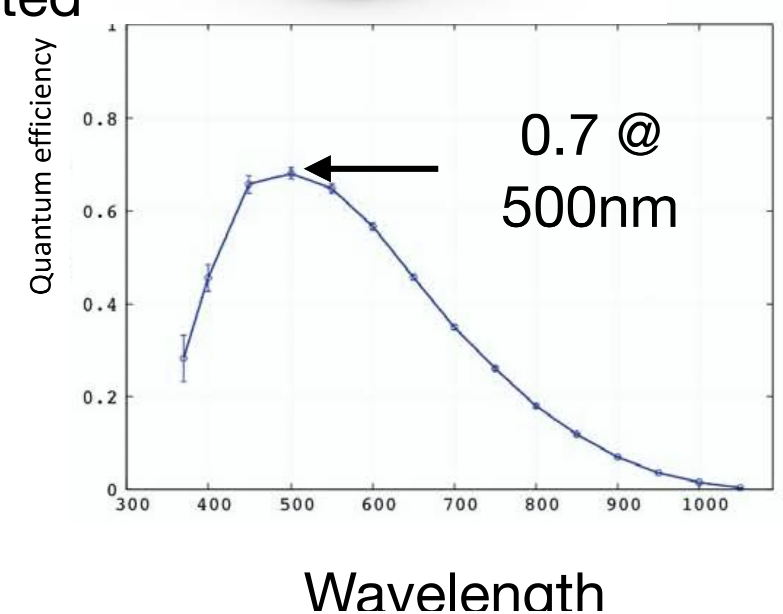
Q1+Q2+Q3 on focal plane

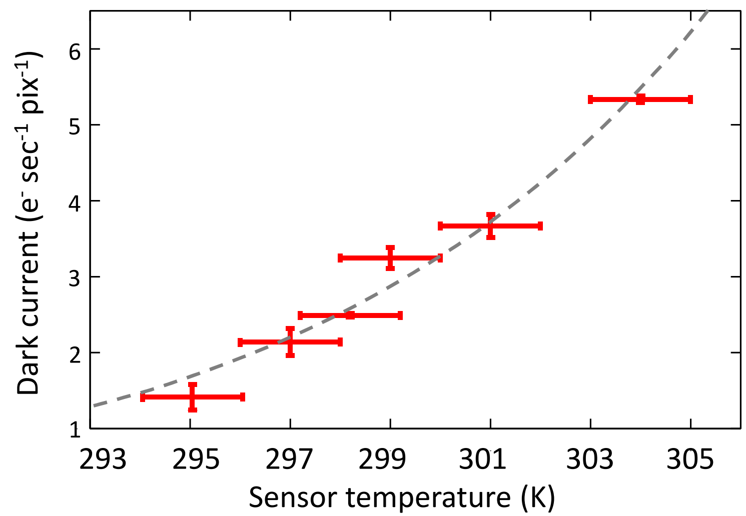


Sensor



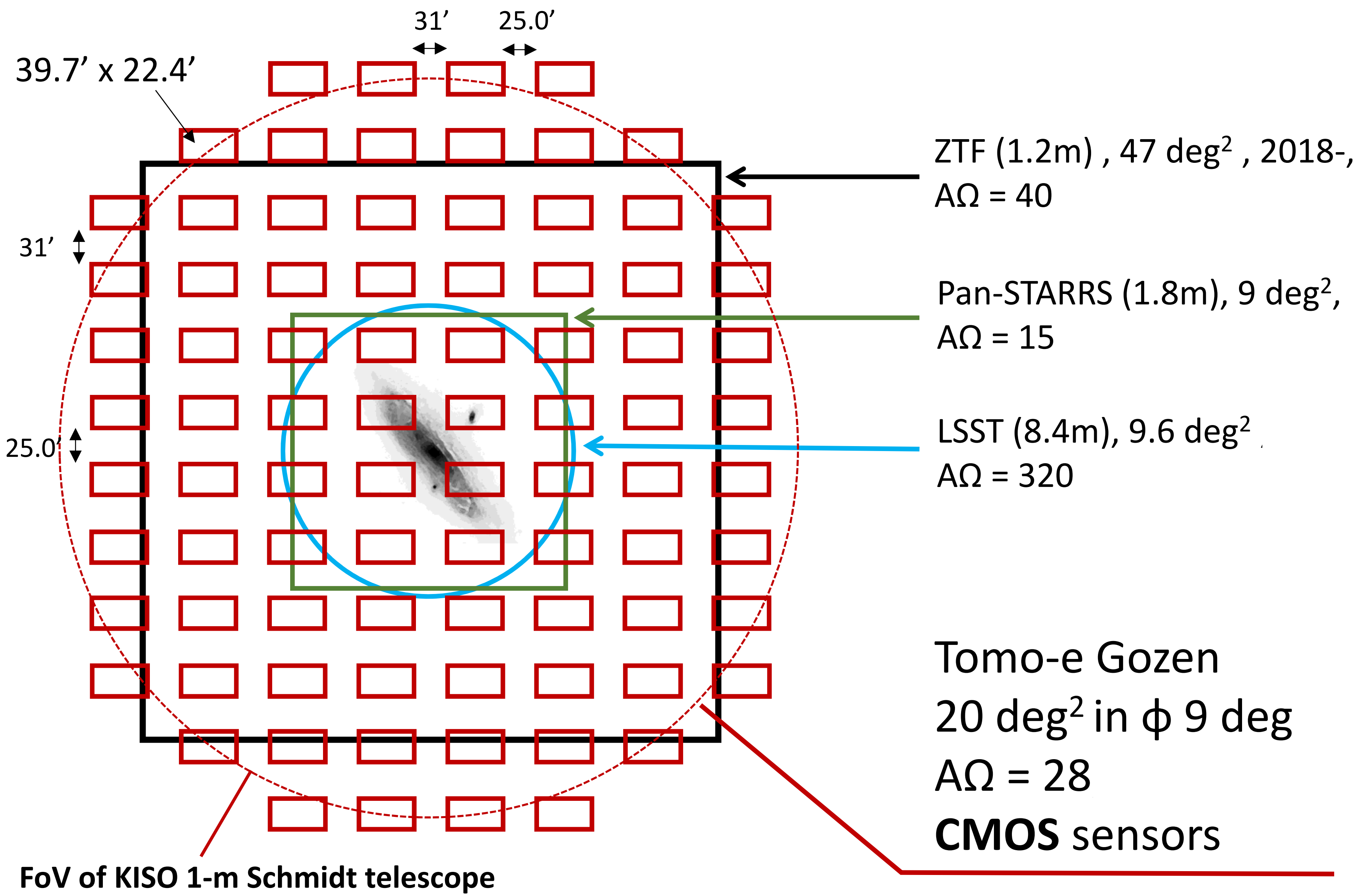
- **Large pixel CMOS sensor by Cannon**
  - 2000 x 1128 pixels, front side illuminated
  - 19 um/pix (= 1.198 arcsec/pix)
  - Sensitive at 370-730 nm
  - Readout noise: 2.0 e^-
  - Dark current: 6e^- sec^{-1} @ 305K (sky 50 e^- sec^{-1} pix^{-1} at Kiso)





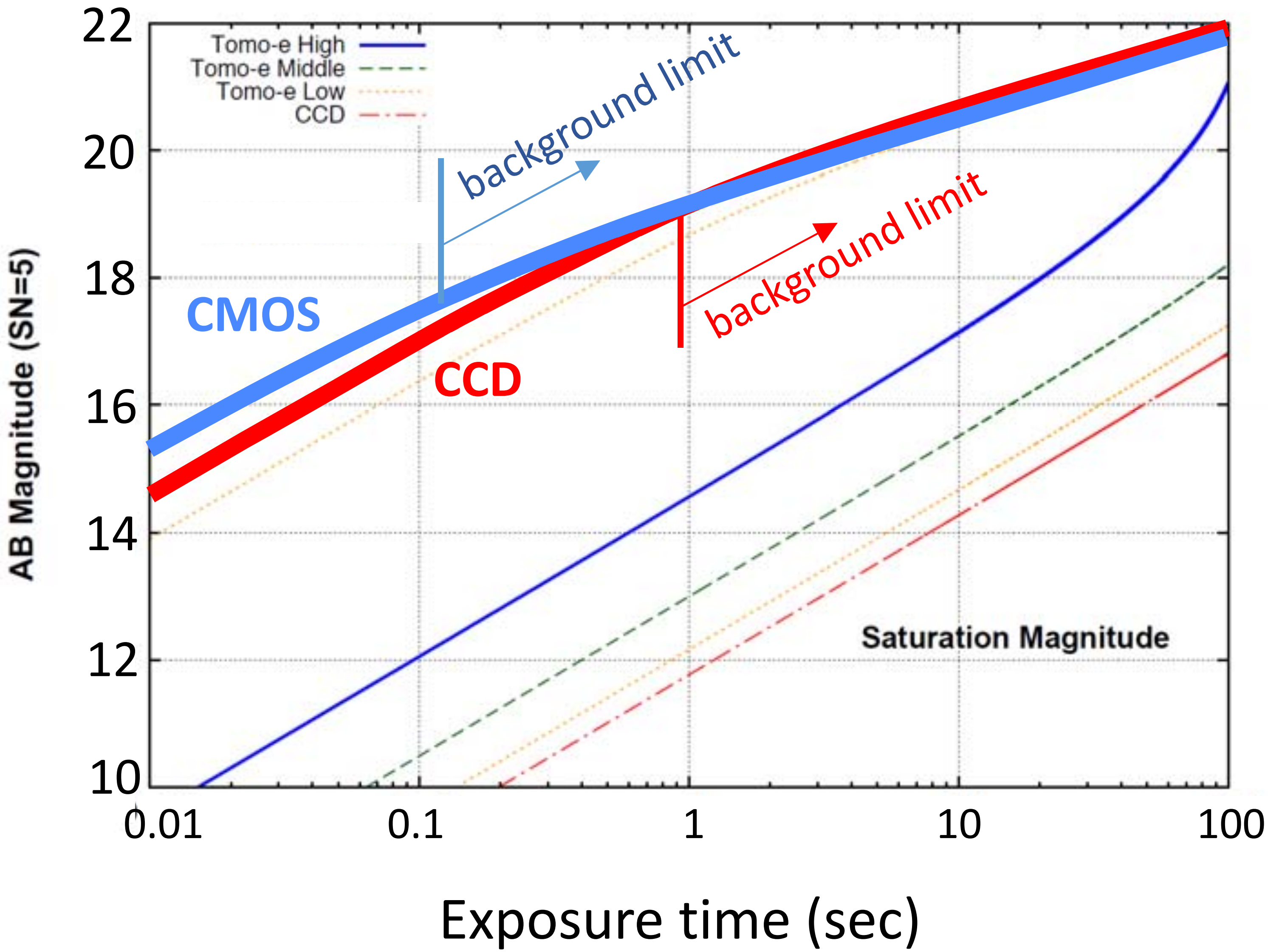
Kojima, Sako, Ohsawa et al. 2018, SPIE

Field of view



Slide courtesy of Shigeyuki Sako

Limiting magnitudes



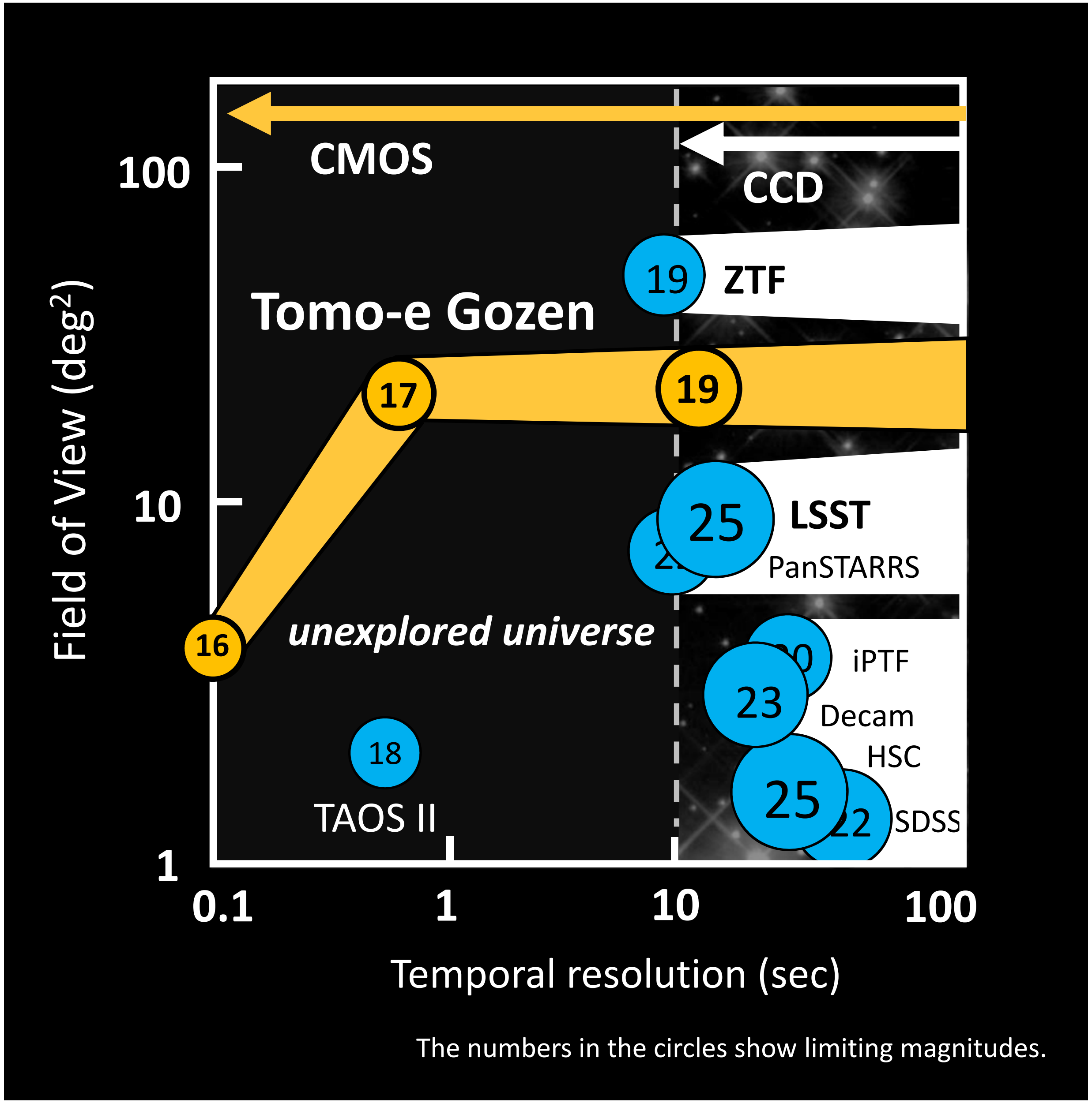
Kojima, Sako, Ohsawa et al. 2018, SPIE

Slide courtesy of Shigeyuki Sako

Transient sky in second timescale

Default observing mode:
imaging with 2 Hz (2fps)

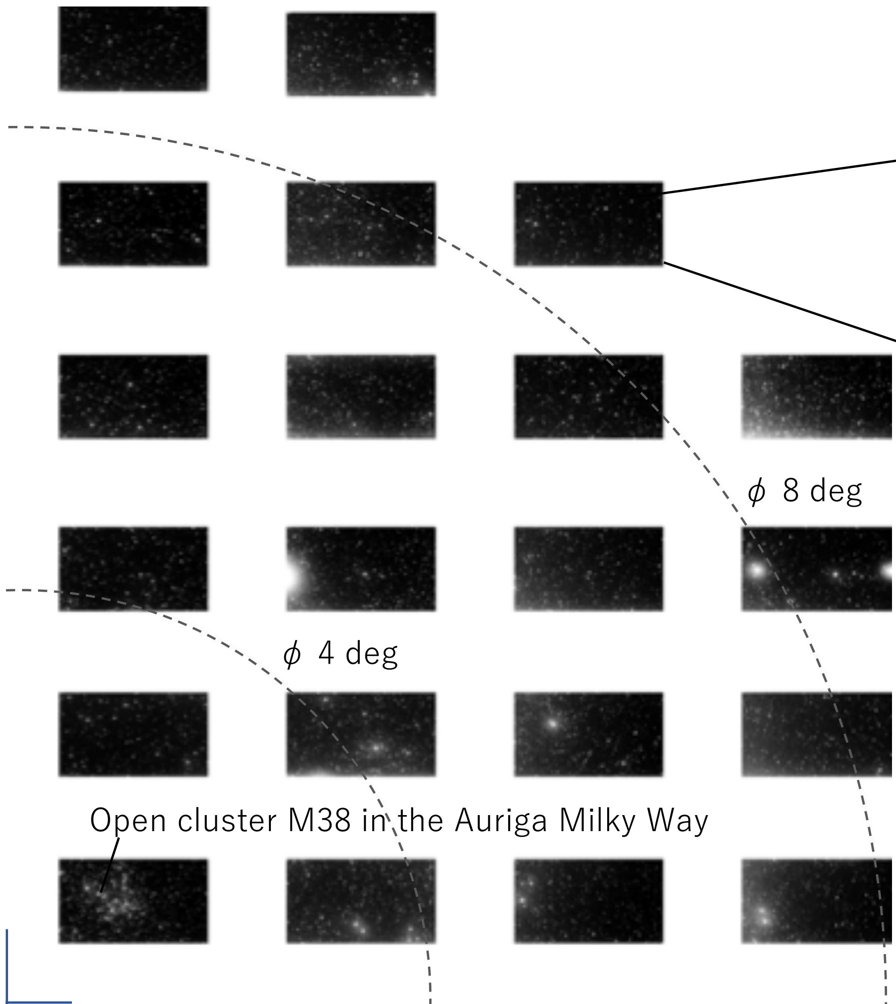
- ~17 mag in 0.5 sec
- ~30 TB/night



By Shigeyuki Sako


Transient Survey
w/ Tomo-e Gozen

Data acquisition started from Feb. 2018 with Tomo-e Q1 (21 sensors)

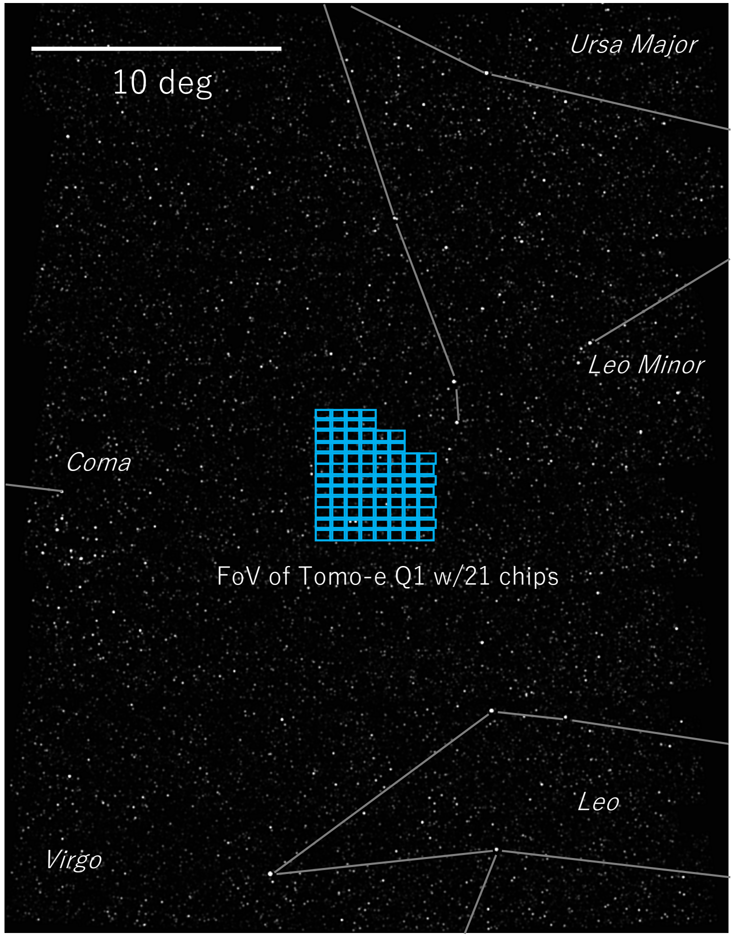


Sample movie data taken with Tomo-e Q1

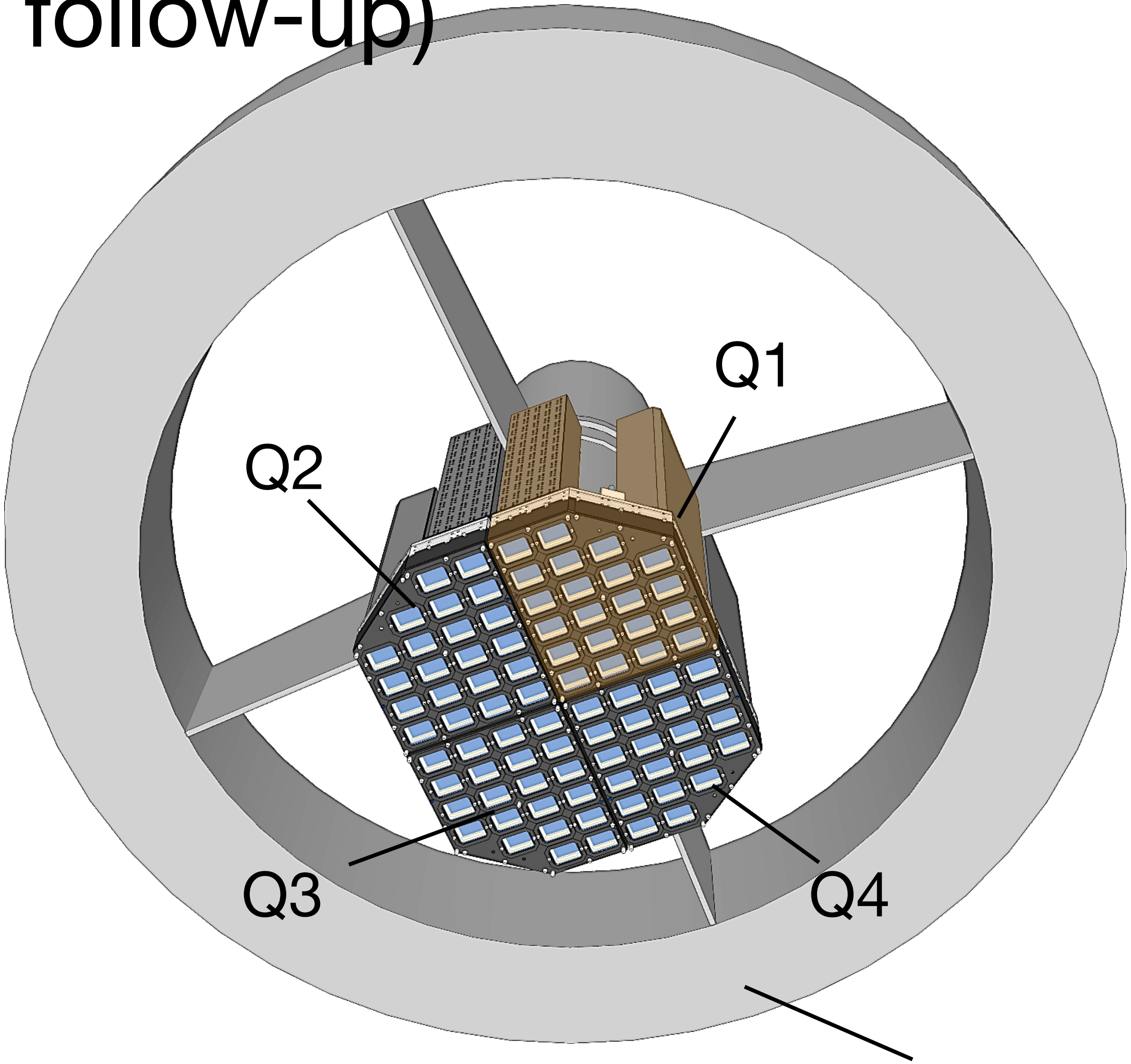
Movie data obtained in 2-fps, consecutive 6 frames every pointing

- 100 kilo-objects / frame, 2.3 G-records / night
- 5-σ limiting mag: 18.7 mag @ t_{exp} = 0.5 sec
- Seeing limited PSF (~3 arcsec) in all frames
- Photometric accuracy: ~10 millimag @ time scale < 5 sec

Very wide-field transient survey
(Supernova, GW follow-up)



produced from Tomo-e Gozen Q1



By Shigeyuki Sako

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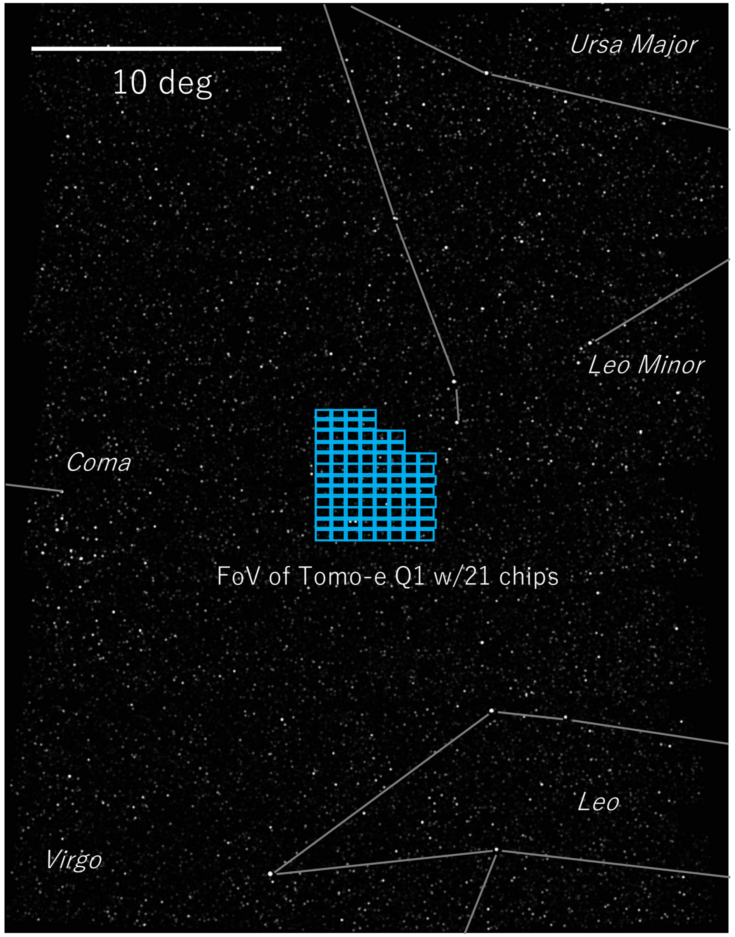
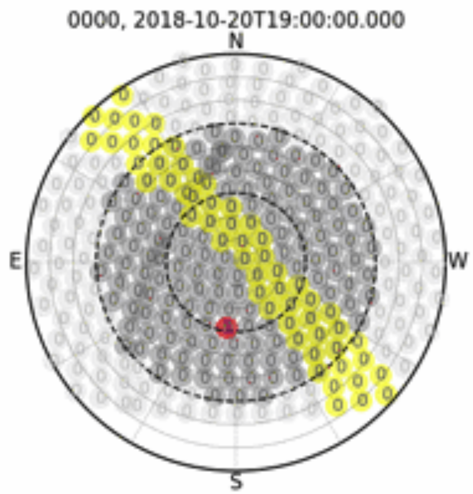


Q1 tests for the Northern sky survey

- Survey area: Elv > 40 deg → 7,000 deg^2 in 84 chips
- Survey pattern: 2 x 2 dithering
- Exposure: on-source 6 sec/pos (5-s 20 mag)
  → 0.5sec x 12 frames/pos
- Beam switching: ~ 8 sec
- Elapsed time: 2 hours



Estimated new detections

- Supernovae 1 - 2 events/night
- Other transients > 100 events/night
- Meteors > 1.000 events/night
- Artificial objects > 1,000 events/night

Simulation of northern sky survey
- Each circle: FoV with Φ9 deg
- Yellow: Milky way

produced from Tomo-e Gozen Q1

produced from Tomo-e Gozen Q1

By Shigeyuki Sako

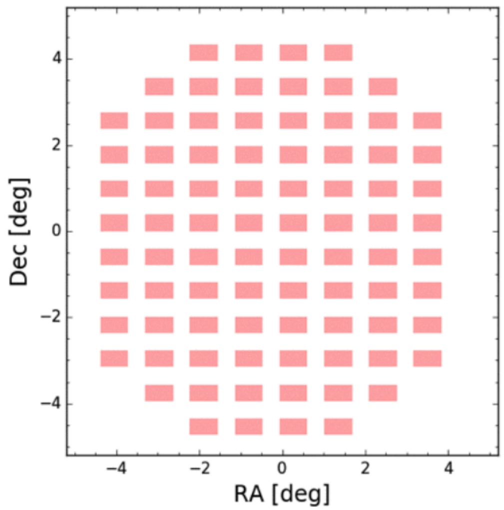
Northern sky transient survey

PI: Tomoki Morokuma

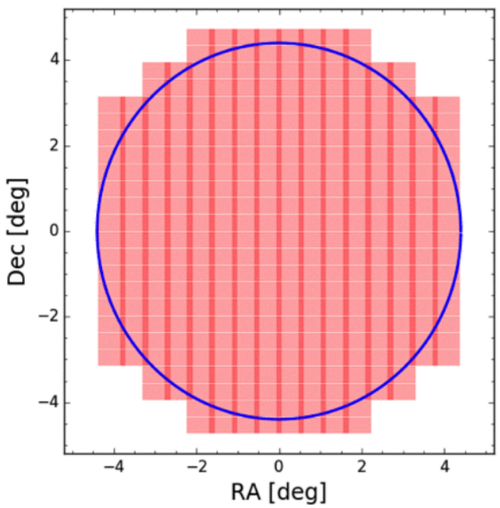
- **Survey plan: 7000 deg² - 2hr cadence - 18 mag**
  - 1 “visit” = 60 deg² in 1 min
    - 12 x 0.5 sec = 6 sec (~18 mag depth)
    - 2 x 2 dithering (to fill the gap)
  - 2 hr cadence (= 120 visits)
    => ~7000 deg² in total (elevation > 40 deg)
  - No filter (effectively g + r)
  - Keep detection information of 2 Hz images

- **Schedule**
  - 2018 November - (Q1, FOV 5 deg²)
  - 2019 April - (Q1-4, FOV 20 deg²)

1 exposure

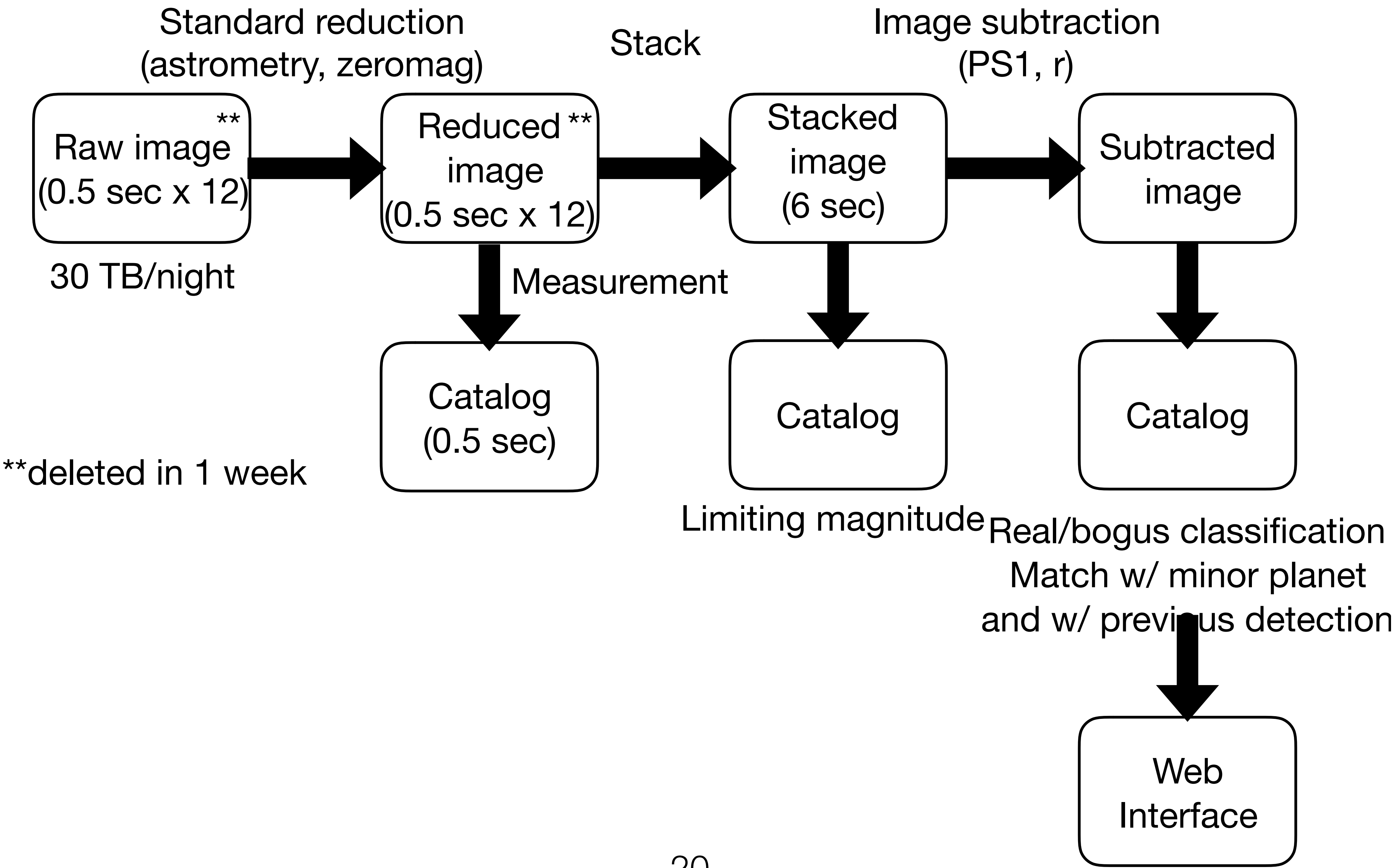


2 x 2 dithering



By Tomoki Morokuma

Data flow


Standard reduction
(astrometry, zeromag)
Stack
Image subtraction
(PS1, r)
Raw image **
(0.5 sec x 12)
Reduced image **
(0.5 sec x 12)
Stacked image
(6 sec)
Subtracted image
30 TB/night
Measurement
Catalog
(0.5 sec)
Catalog
Catalog
**deleted in 1 week
Limiting magnitude
Real/bogus classification
Match w/ minor planet
and w/ previous detection
Web Interface

Transient detection in the test run

= AT 2018leh (2018-12-31)
= ZTF18adbmrug (2018-12-30)

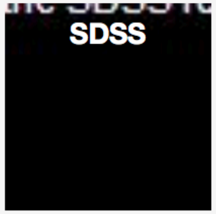
Tomo-e transient server | List | Object | Account | Logout

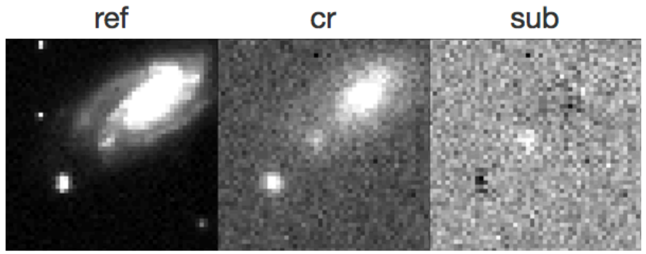
previous

19monv

Transient ID: 220736 Variable_id: 1021301

Number of detections: 3 (paramcand)





58496.5133 17.74 +- 0.07

2019-01-11

Tags Click a tag for removal | Insert tags

No tag assigned.

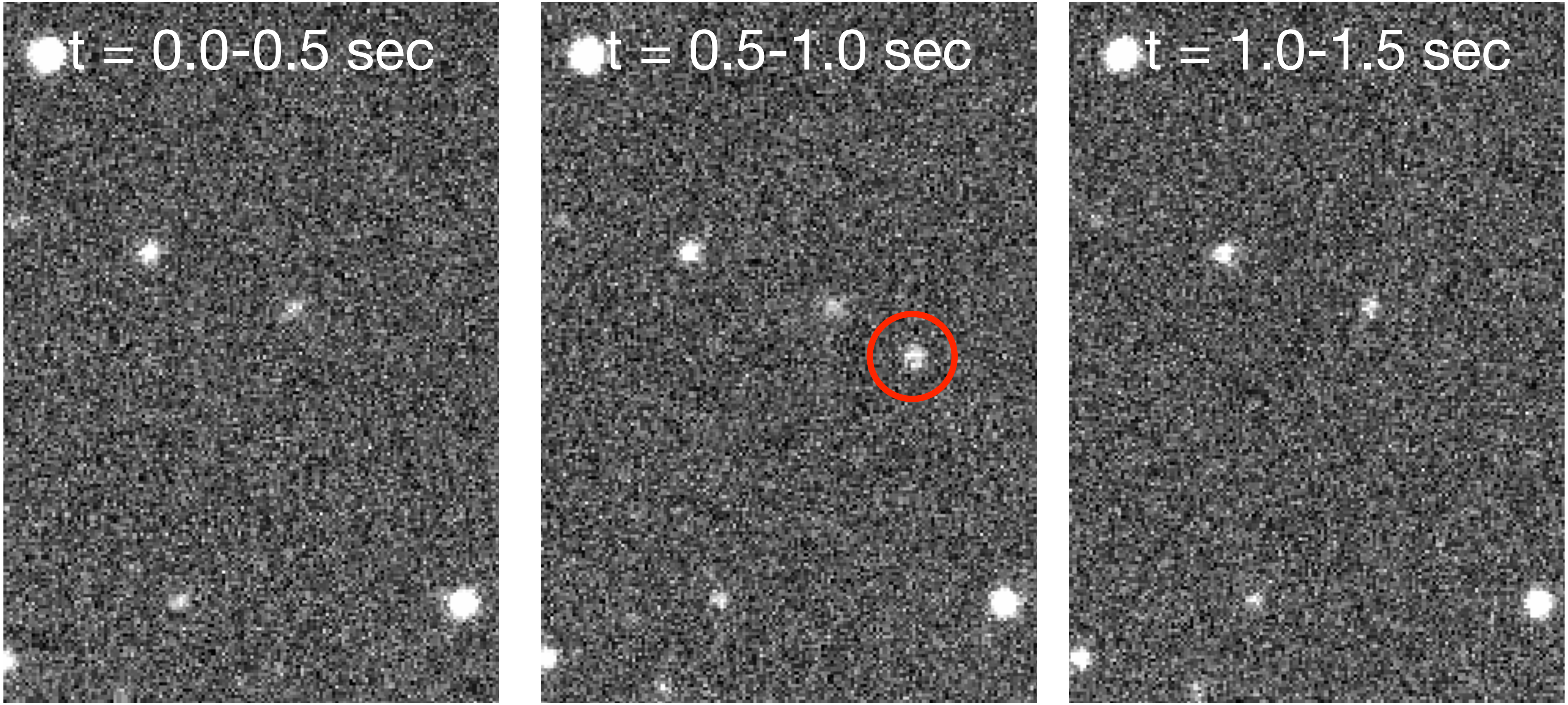
Rapid | Young? | SN | AGN | MP? | Unclear | Bogus | or | submit

SN? | AGN? | Variable?

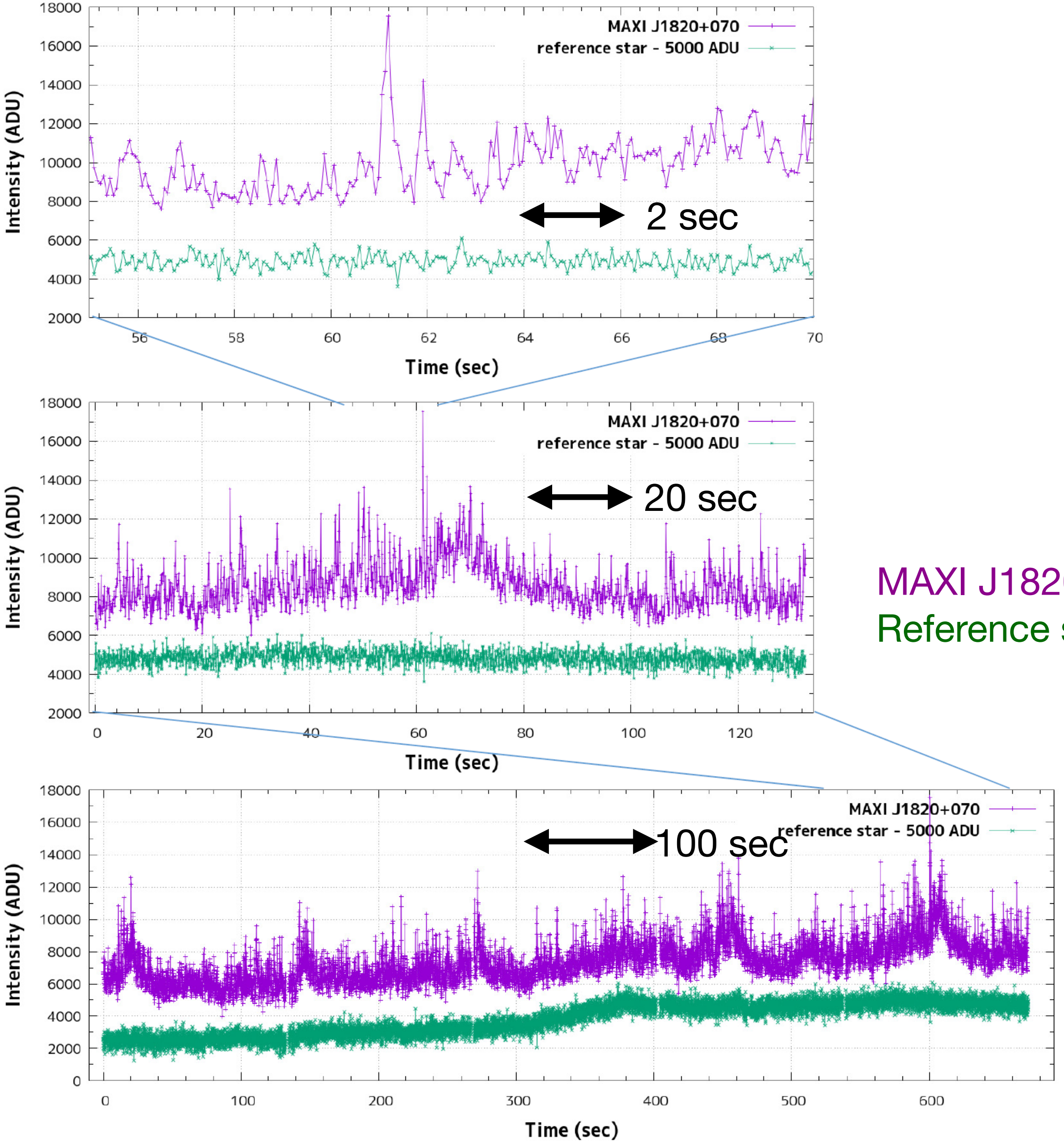
Ra, Dec (Decimal)	**Ra, Dec**	**Detector ID**	**x,y**
61.26379 , 25.26215	04:05:03.31, +25:15:43.8	134	0.00 , 0.00 0.00 , 0.00

Relavant links	SDSS	PS1	TNS	MPChecker	Visibility (local site: 137.6283 35.7942 1130 +9)
fits files	Ref	Sub			

Very rapid transient in 2Hz imaging mode



Rapid variability of X-ray transient (MAXI J1820+070)



MAXI J1820+070
Reference star

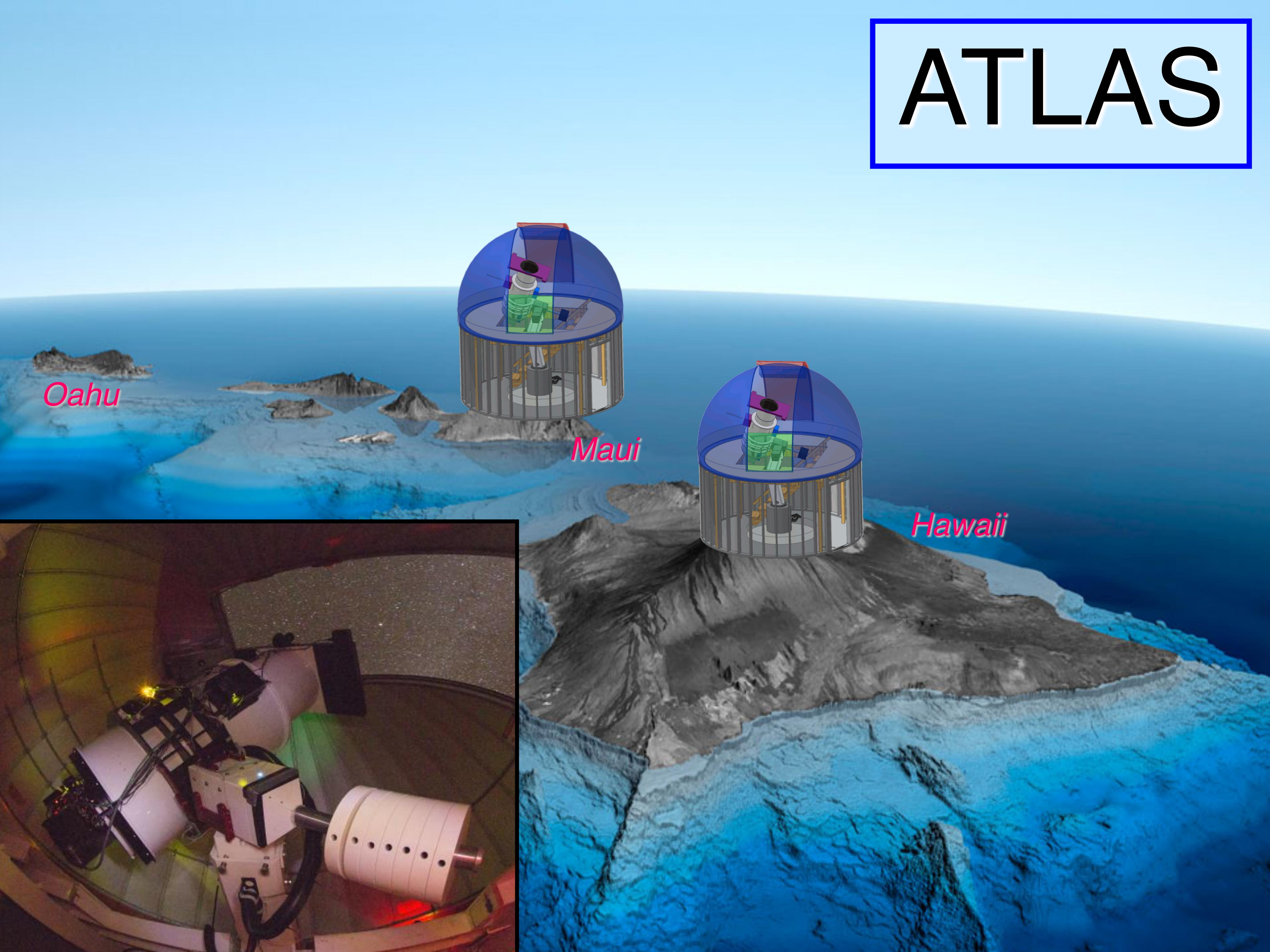
Sako et al. 2018, ATel, 11426

http://www.ioa.s.u-tokyo.ac.jp/tomoe/MAXIJ1820+070/MAXIJ1820+070.html

Tomo-e Gozen: summary

- **Instrument (PI: Shigeyuki Sako, U. Tokyo)**
  - 1m Kiso Schmidt telescope
  - 84 CMOS chips (1k x 2k)
  - 20 deg^2 FOV
  - Imaging with 2 Hz (2 fps)
  - ~17 mag in 0.5 sec exposure
  - 30 TB/night (raw data are deleted in 1 week)

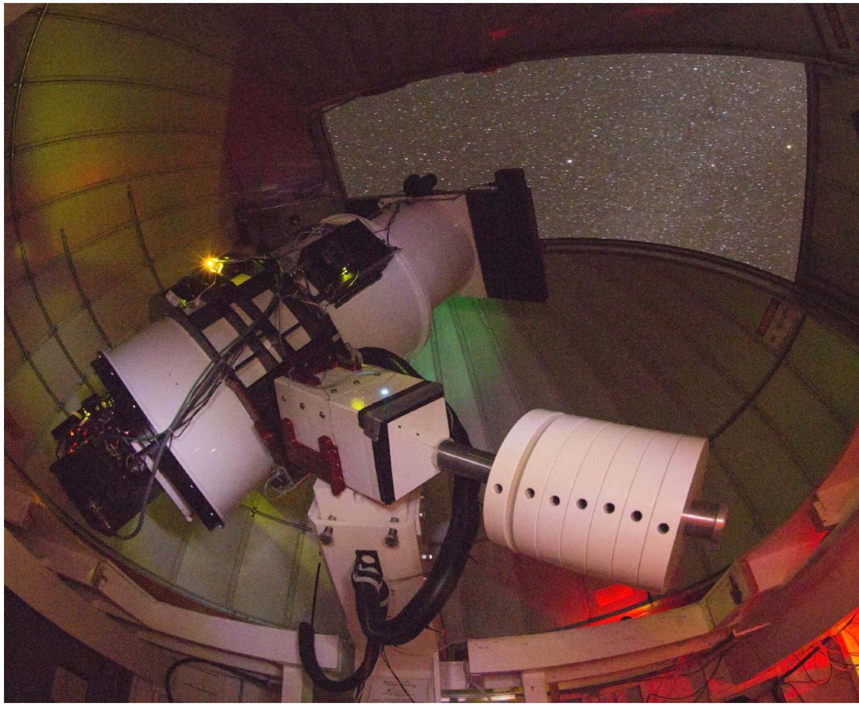
- **Survey (PI: Tomoki Morokuma, U. Tokyo)**
  - 7000 deg^2 - 2 hr cadence - 18 mag (6 sec exposure)
  - No filter
  - 2018 November - (FOV 5 deg^2), 2019 April - (FOV 20 deg^2)


ATLAS
Oahu
Maui
Hawaii

Why Survey the Sky?

- Because we can.
  - In the past 10 years silicon technology capacity and capability has exceeded the information content available from the sky! OMG!
- Unknown unknowns.
  - Pure discovery of weird phenomena that enrich our appreciation of what goes on in nature. E.g. QSOs, gravitational lensing, SS433, exoplanets, LIGO optical counterparts, etc.
  - Do stars ever disappear? What flashes in the sky at m~8?
- Known unknowns.
  - Greater understanding of rare things. E.g. GRBs, weird- hyper- kilo- novae, gravitational lenses, etc.
- Known knowns (that are useful).
  - Standard candles such as RR Lyrae, Cepheid, M giants, SNIa for mapping dust, cosmology, etc.

ATLAS in a Nutshell



- Domes (Ash) on HKO, MLO
- German mounts (APM)
- 0.5m telescopes (DFM)
  - f/2 Schmidt
  - 8 filters (co, uvgri, BVRI, Hα,[OIII])
- 10k cameras (IFA/STA)
  - 1.86" pixels, 5.4°x5.4° field of view
- 50Mb/s ethernet
- 50,000 deg^2/nt (4xsky/2) to m~19.5 in c (g+r) or o (r+i)
- Computers totaling >1PB, 2TB, 500 core
- Portable (?!) software

MLO telescope

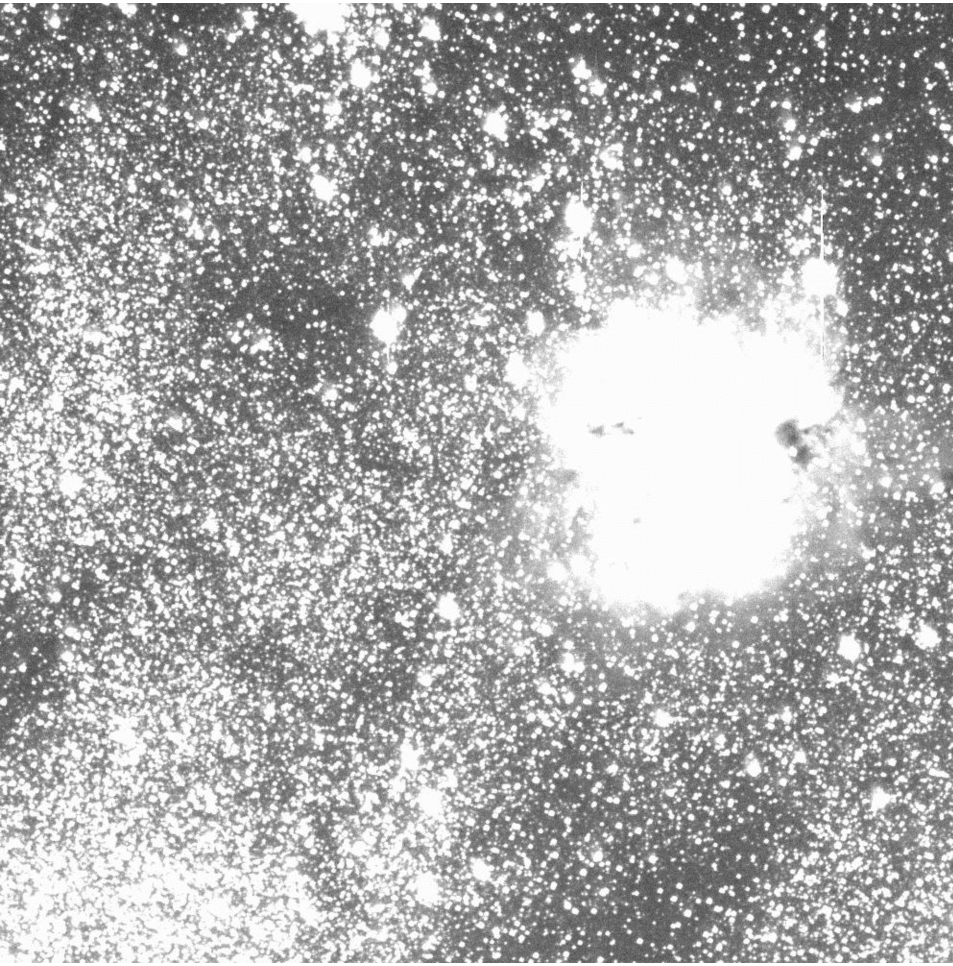
(HKO telescope, DR1)

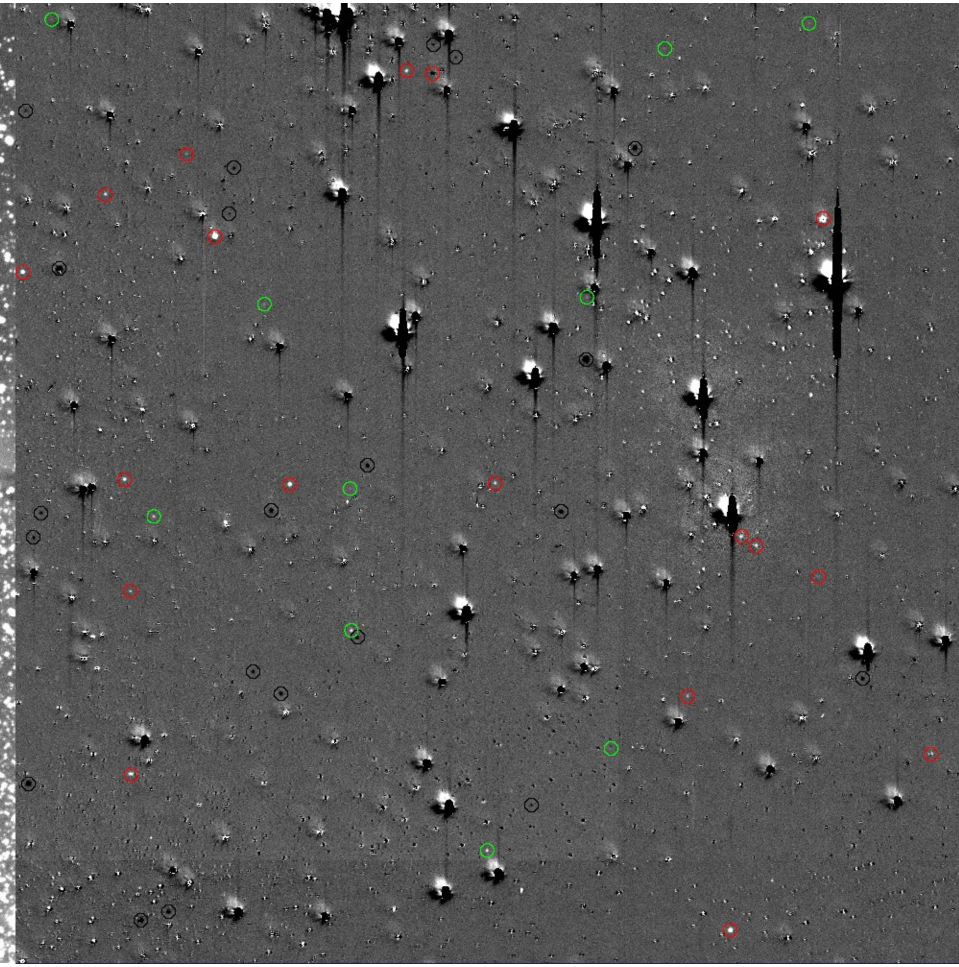
HKO telescope

2015 2016 2017 2018

Tonry et al. 2018, PASP.
arXiv:1802.00879

Autonomous operation, reduction, and analysis

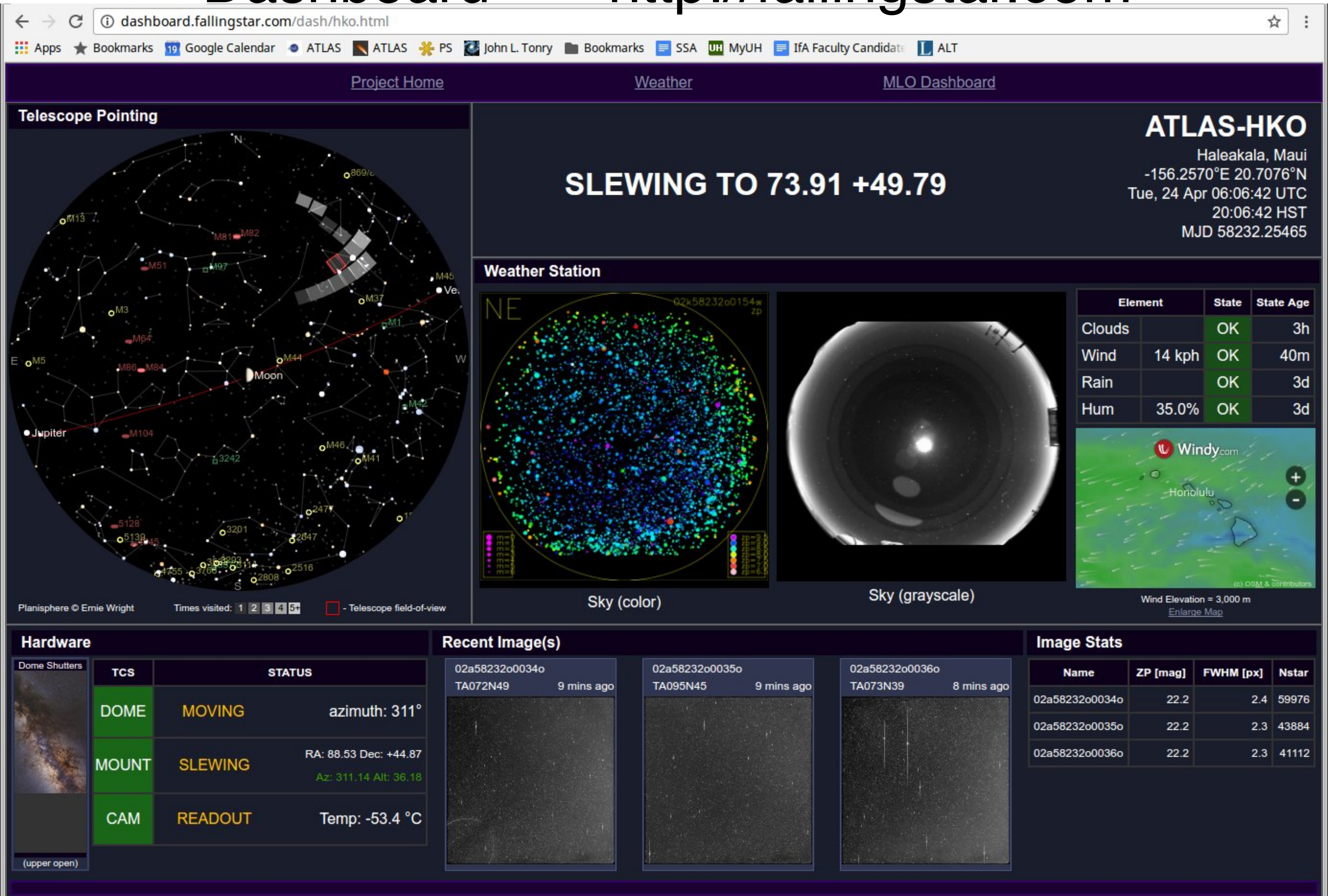




- 2 x 1,000 image = 0.5 TB per night
- 700,000 images to date
- Fully robotic system
- Gaia astrometry, Pan-STARRS photometry

Known asteroid
Variable (pos)
Variable (neg)

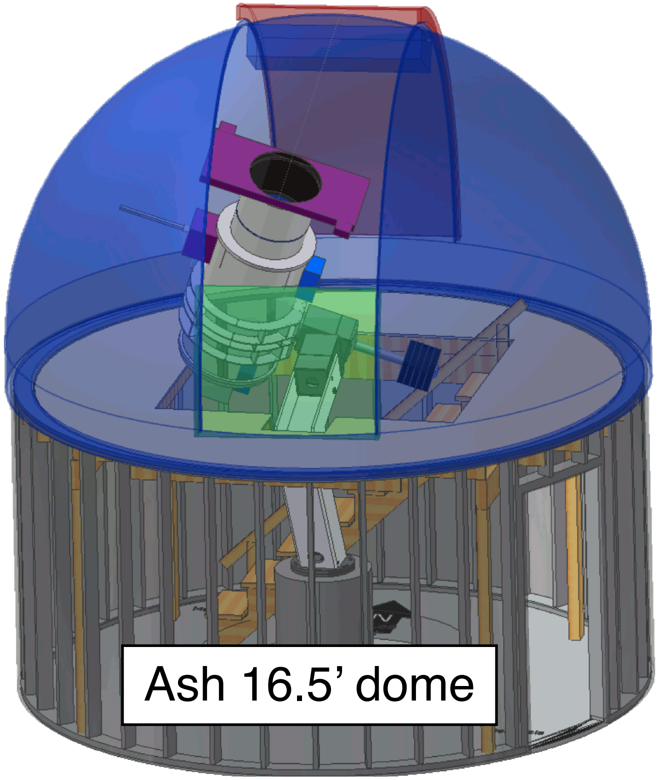
Dashboard - http://fallingstar.com

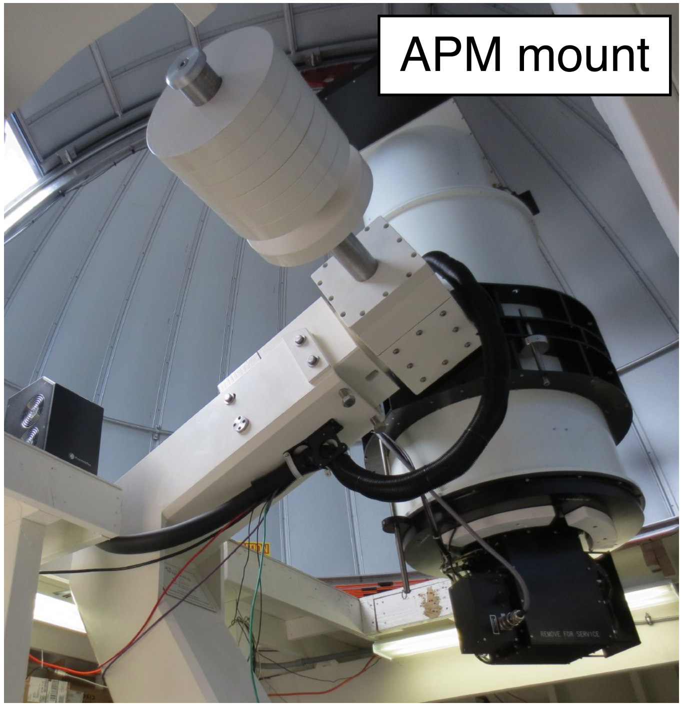


ATLAS DETAILS

Lots of details about hardware and software

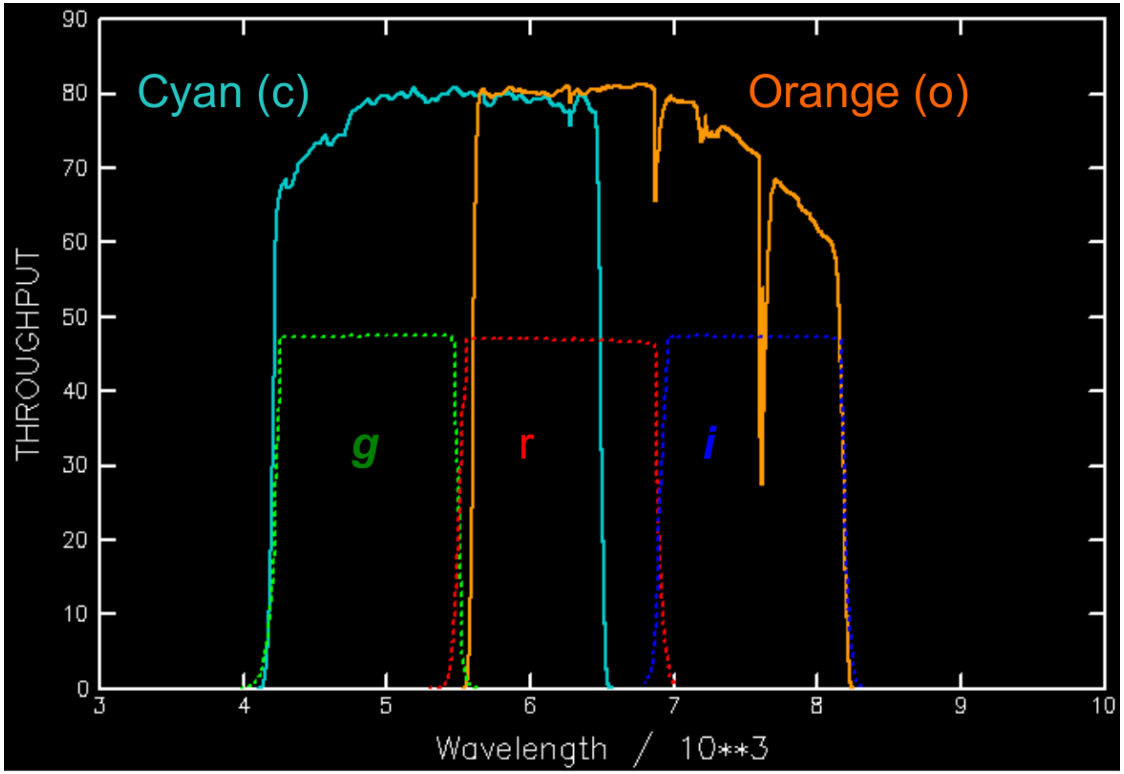
Enclosures and Mounts





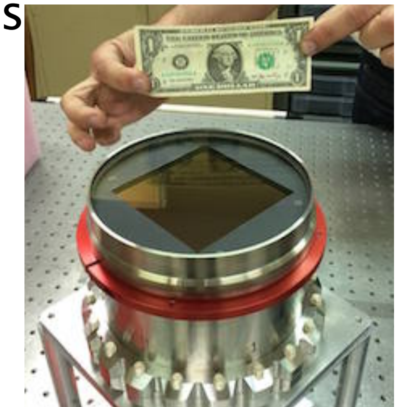
Filters

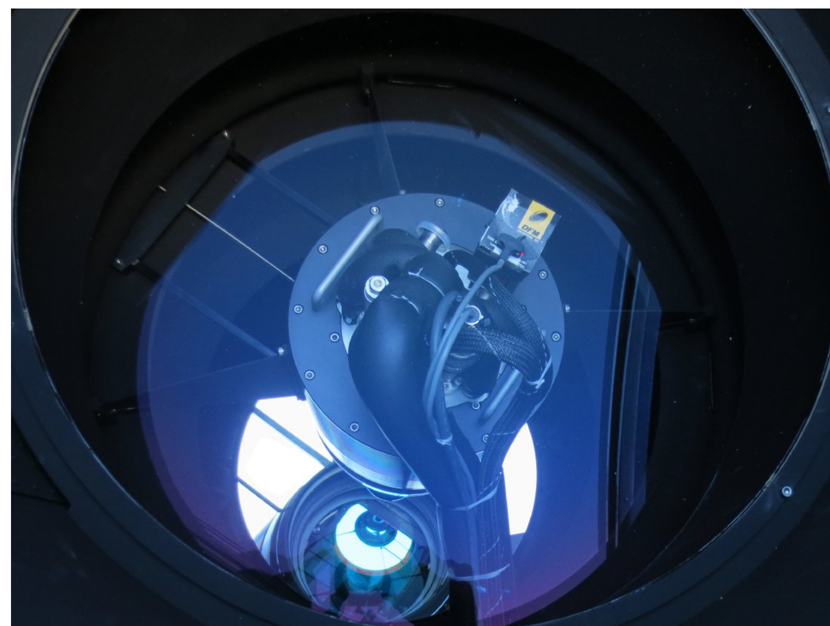
- ATLAS c, o, t
- SDSS/Pan-STARRS/SkyMapper u,v,g,r,i,z
- Johnson/Cousins B,V,R,I
- Narrow band Hα,[OIII]



Telescopes and Cameras

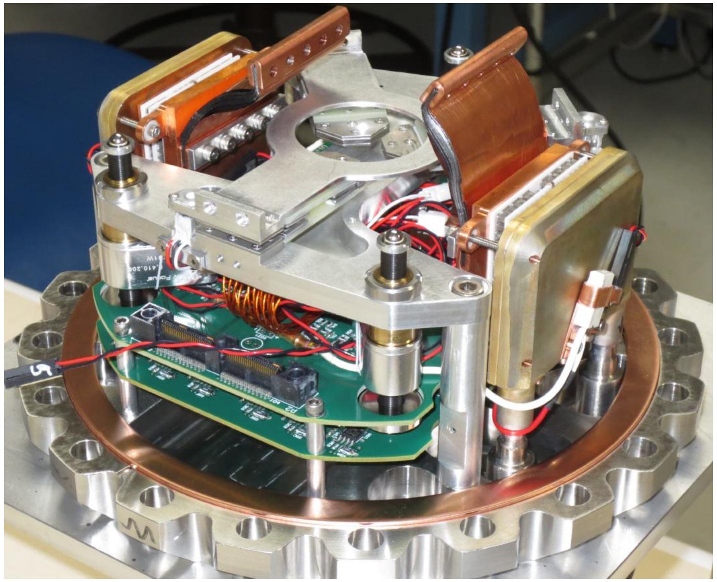
- DFM telescopes
  - 0.5m f/2 Schmidt telescope gives 1.86" per pixel over 8° field without vignetting
  - PSF is ~2 pixels; m_{lim}~19.5 in 30 sec exposure
- Acam
  - STA-1600: 110 Mpixel, 10e- read noise, ~8 sec readout, good QE, good cosmetics
  - TEC cooling to <-50°C, negligible dark current
  - Permanent vacuum
  - Sub-um positioning of detector in piston, tip, tilt (necessary for an f/2 system)
  - >1,000,000 images so far…

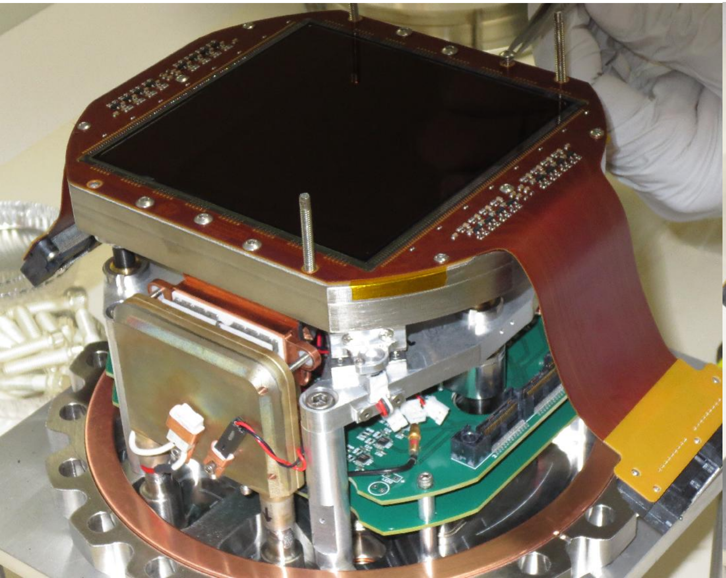


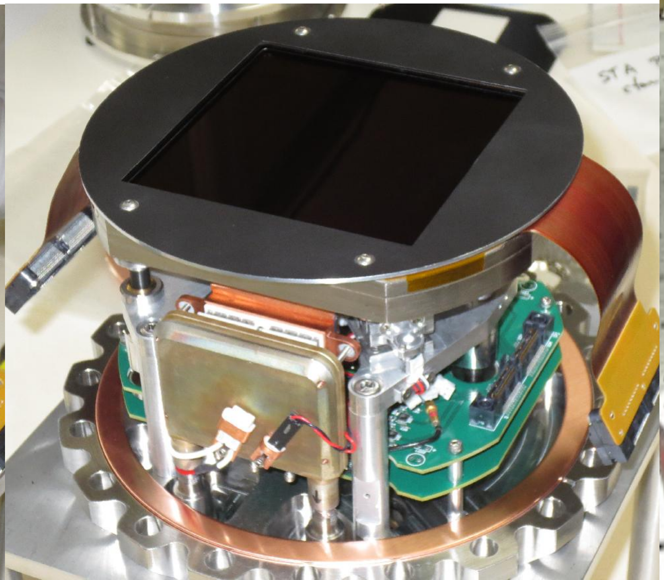


Acam

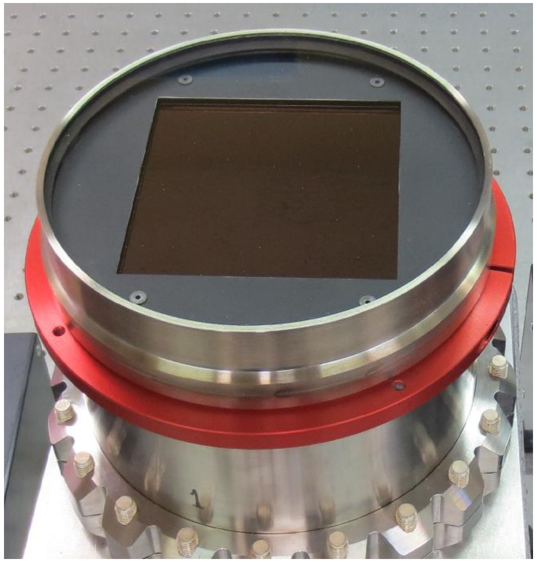
- All metal: no pumping required
- Buffer PCBs: no interference
- TEC cooling
- Picomotors
- Large area to volume ratio

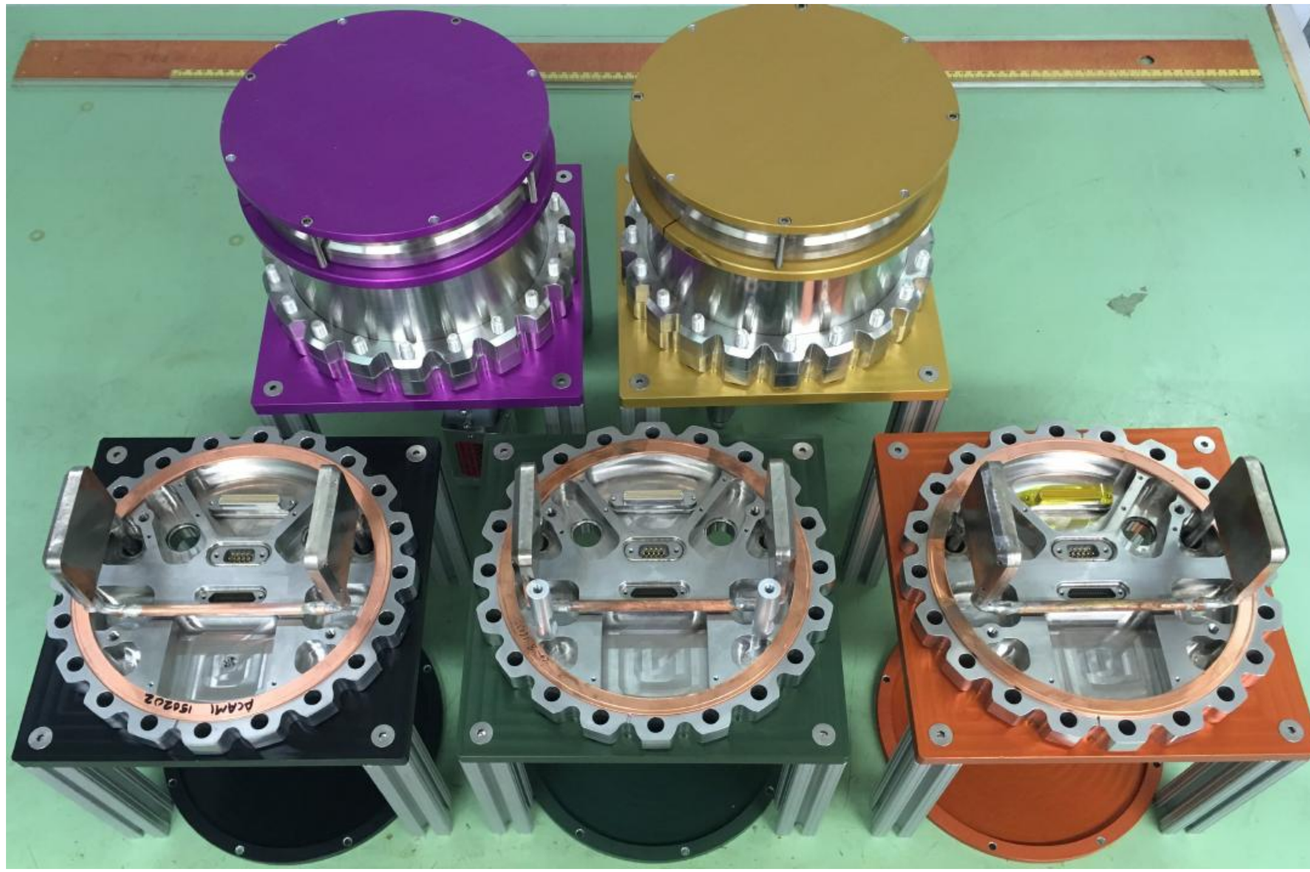




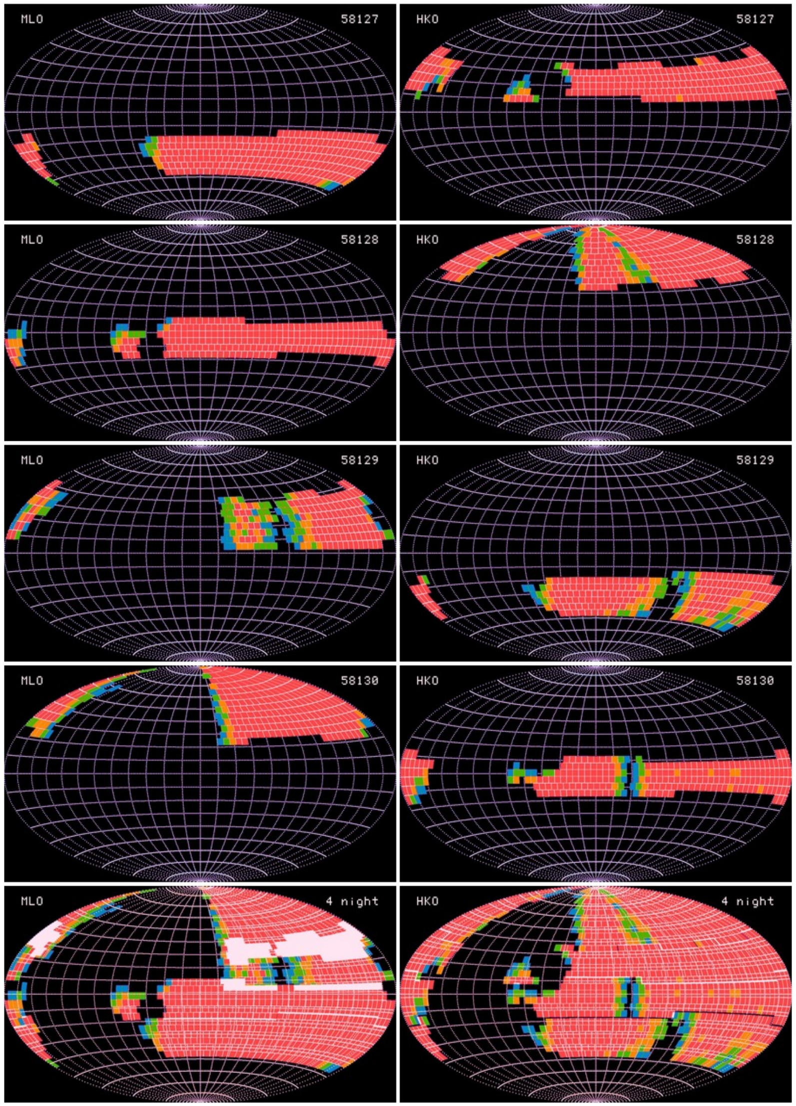


Five More Cryostats Ready for a Home…





Survey Strategy



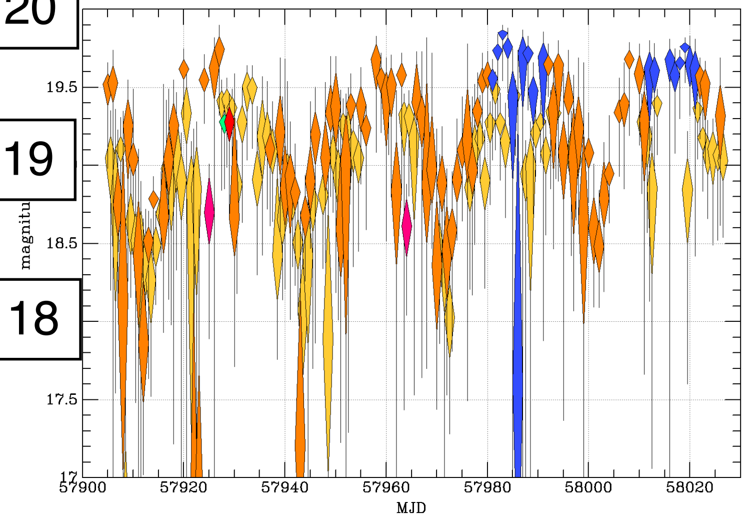
4 Nights MLO
(red=4 visits)

4 Nights HKO
(red=4 visits)

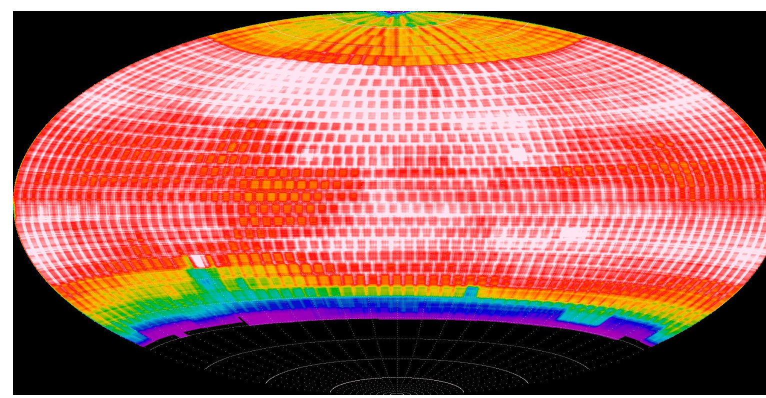
20

19

18



Limiting Magnitude (4 months)



Sky coverage to date
(red=500 visits)

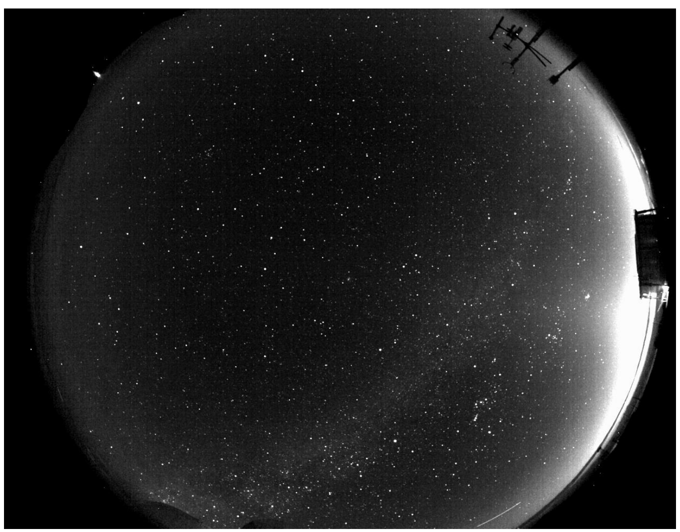
Auxiliary Camera #1

- Each telescope also has a Canon 5DII with 135mm f/2 lens taking simultaneous exposures.
  - 300,000 deg^2/nt at m_{lim}~14, m_{sat}~6
  - Fully reduced and quantified (WCS good to ~1" and photometry good to ~0.03 mag)
  - RGB color retained but not currently reduced

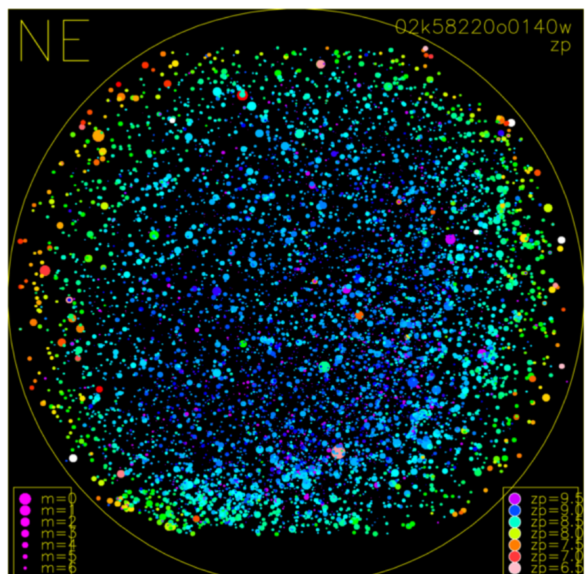
Auxiliary Camera #2

- Each site has a Canon 5DIII with 10mm f/4 lens taking continous exposures
  - All sky every 40 sec at m_{lim}~7, m_{sat}~0
  - Fully reduced and quantified (WCS good to ~30” and photometry good to <0.1 mag)
  - RGB color retained but not currently reduced

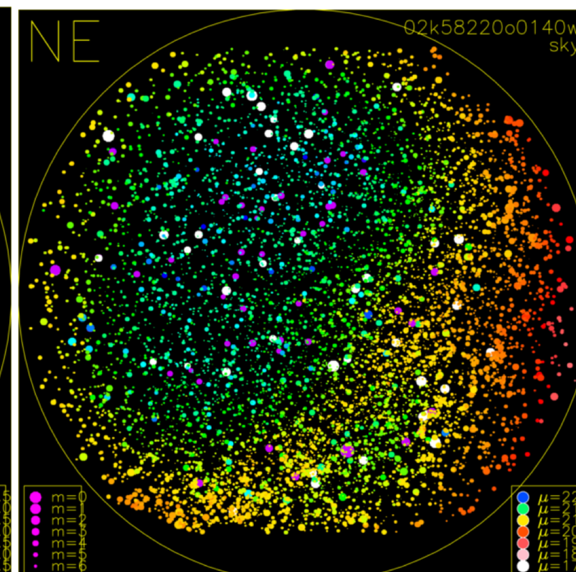
Image



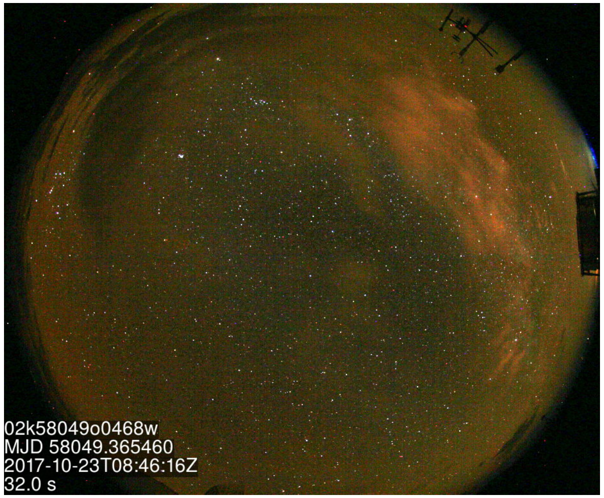
Zeropoint

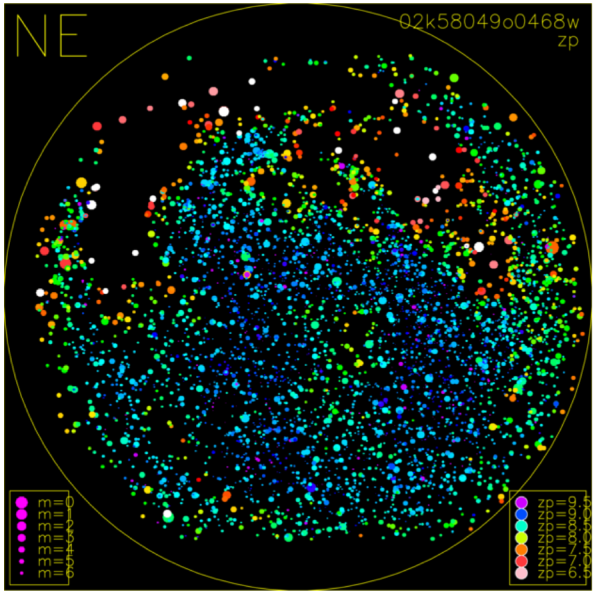


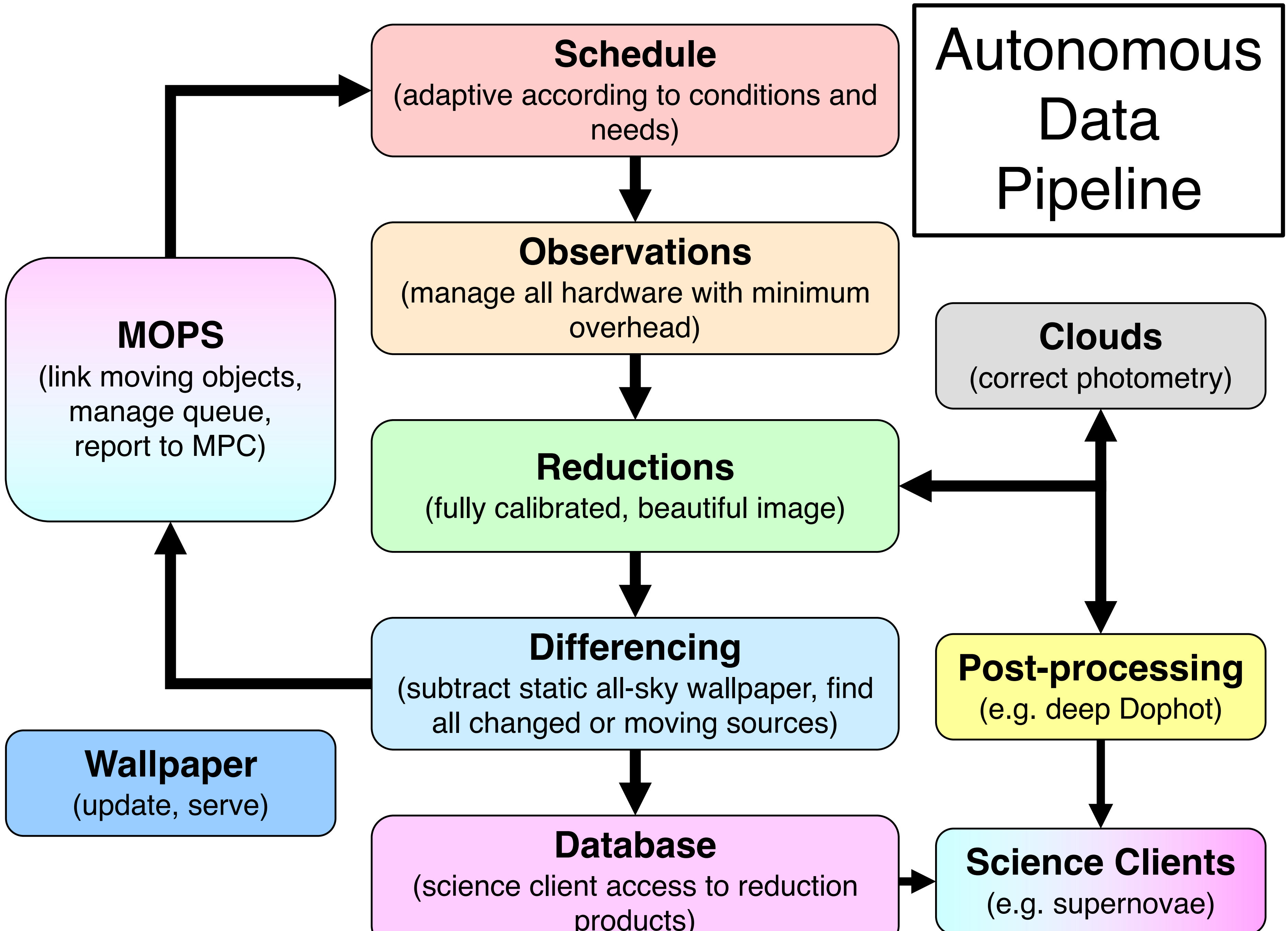
Sky Brightness



Photometric all-sky measurement






Autonomous Data Pipeline
Schedule
(adaptive according to conditions and needs)
Observations
(manage all hardware with minimum overhead)
Reductions
(fully calibrated, beautiful image)
Differencing
(subtract static all-sky wallpaper, find all changed or moving sources)
Database
(science client access to reduction products)
MOPS
(link moving objects, manage queue, report to MPC)
Wallpaper
(update, serve)
Clouds
(correct photometry)
Post-processing
(e.g. deep Dophot)
Science Clients
(e.g. supernovae)

Processing Time and Latency

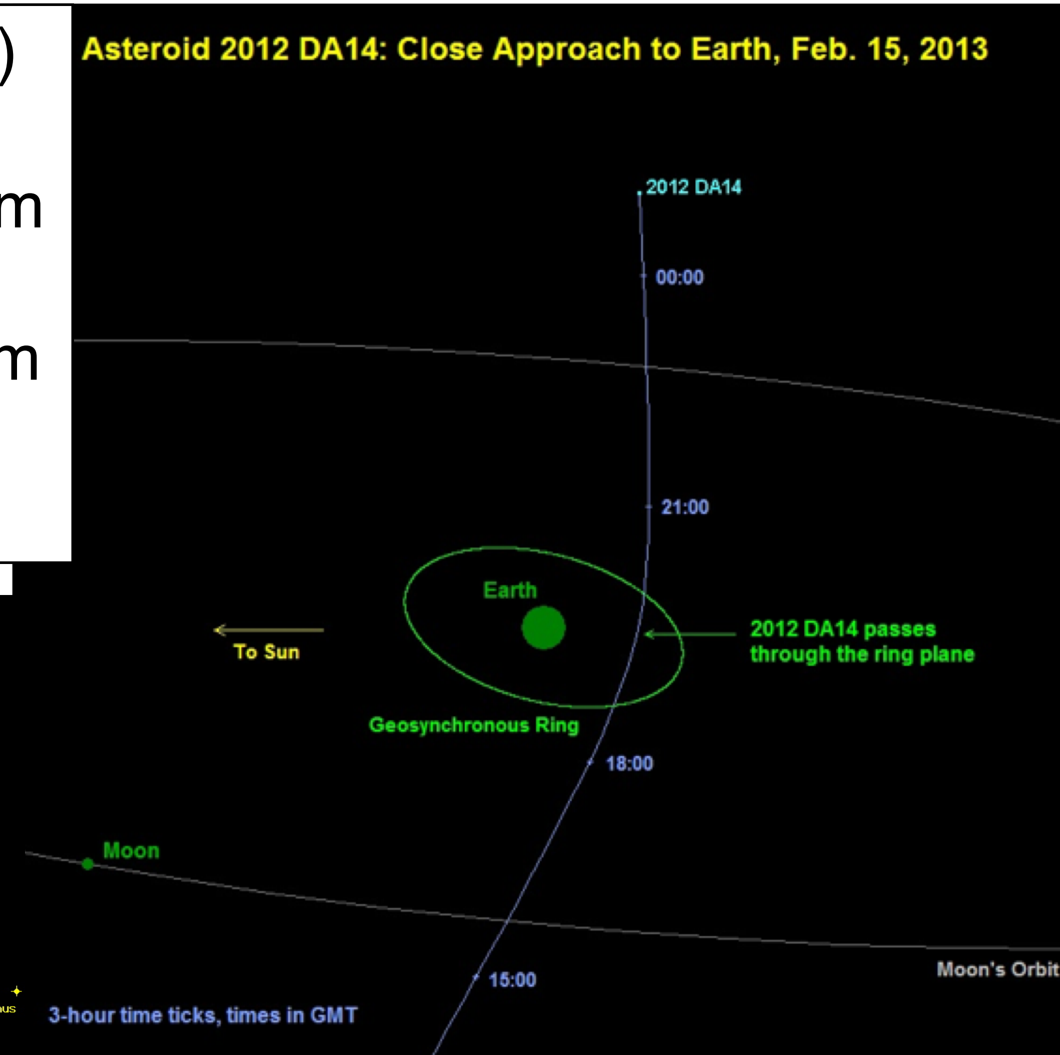
- Latency from shutter open to final results ~30 minutes
- Latency from start of quad exposure to asteroid warning ~90 minutes

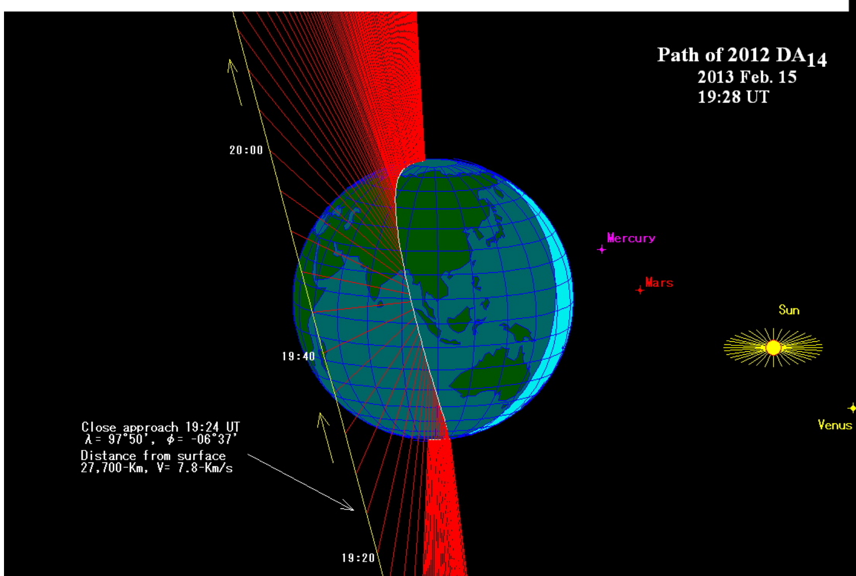
CPU	Elapsed	Stage
40	40	take exposure, save to disk as a raw image
40	80	flatten image
500	250	measure the brightest ∼60,000 stars (dophot)
20	270	find initial astrometric solution (Lang et al. 2010)
10	280	determine final astrometric and photometric solution
20	300	perform cloud detection and correction
10	310	calculate auxiliary metadata, compress and save image
....	....	....
250	560	produce wallpaper template matching image
600	1160	subtract wallpaper from image (hotpants)
750	1410	detect sources in difference image to 3σ, trim to 5σ (tphot)
180	1590	classify sources, write final detection table
120	1710	run primary science client MOPS to detect moving objects
900	610	measure $\sim 10^5$ to $\sim 2 \times 10^6$ stars (depending on galactic latitude) to 5σ (dophot)

2012 DA 14: 2013-Feb-15

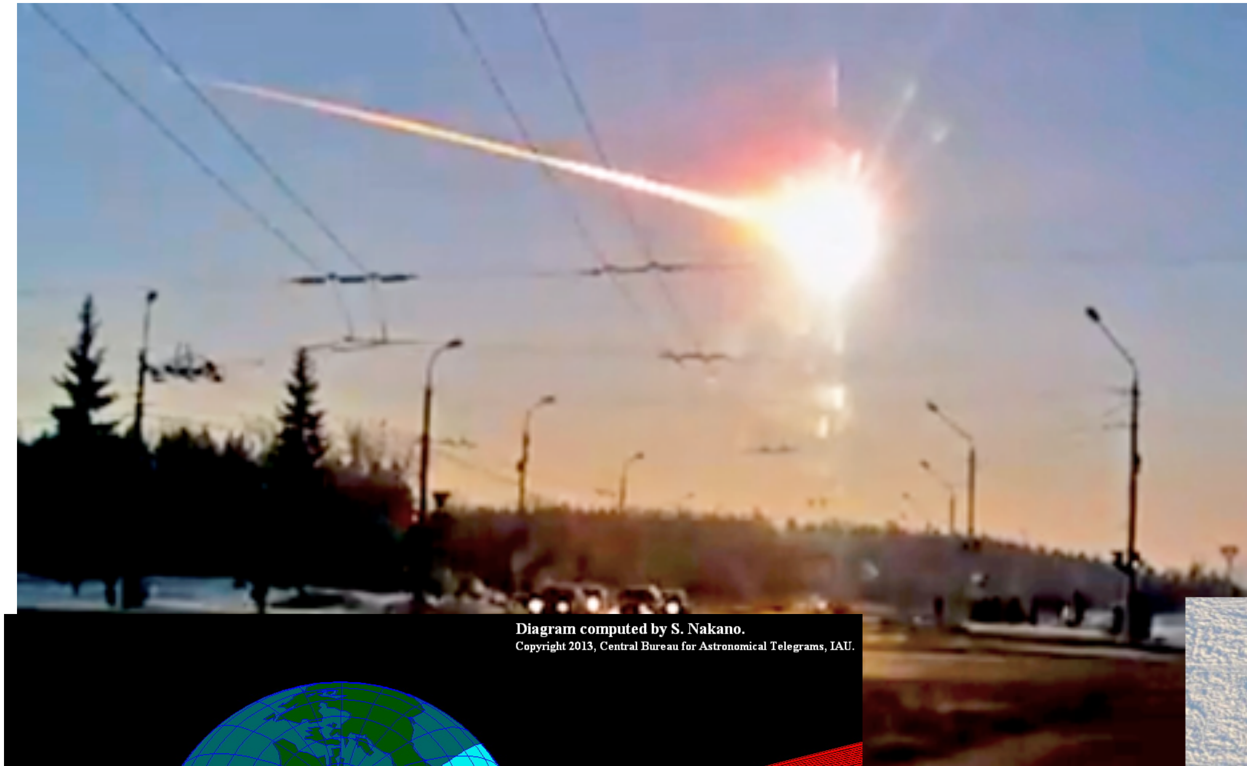
- 30m diameter (2Mton TNT)

- Closest approach 28,000km $= 4.4\ R_E$
- Orbital period changed from 368 to 317 days

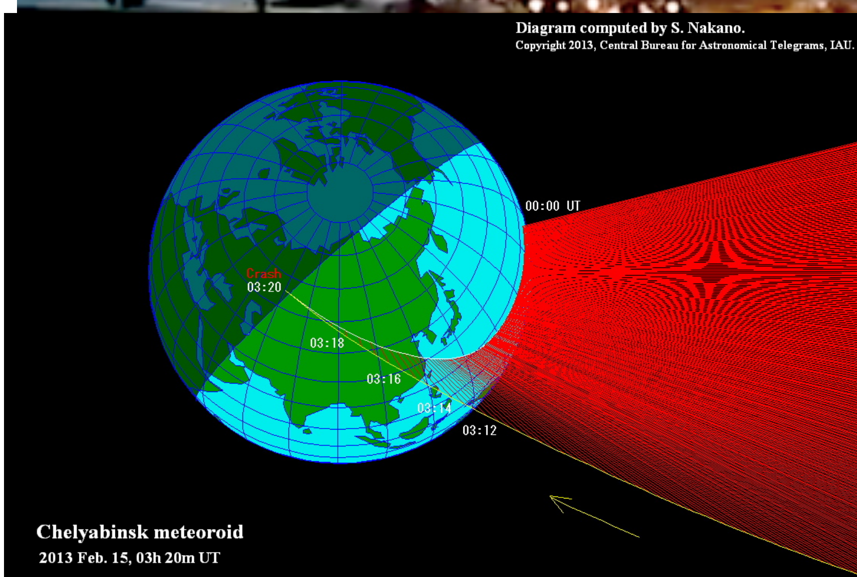




Chelyabinsk: 2013-Feb-15



- 19m diameter,
- 0.5Mton TNT
- 30km altitude

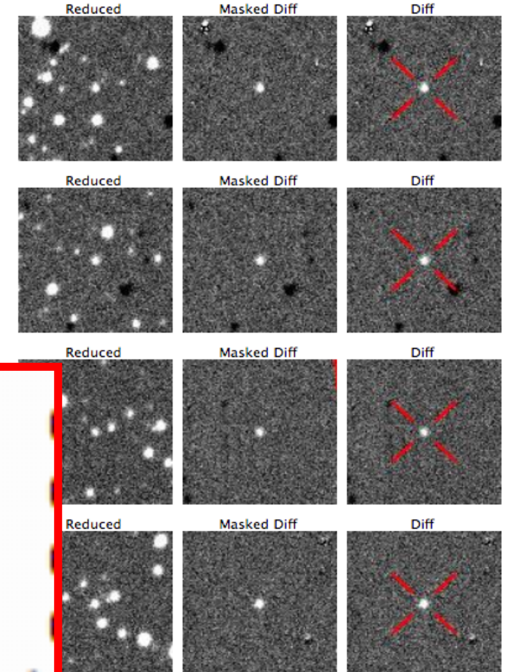


Tracklet ID	Status	Classification	Known As	V_{tot} (deg/day)	Pos Ang (deg)	Score	GCR (arcsec)
725608 Show trail-fitted astrometry | MPCheck Detections MPC | DES | ATLAS IOD Search Submitted as **A106kXM** by **denneau**	UNATTRIBUTED	NONSYNTHETIC	N/A	**1.952** RA −1.947 DEC −0.144 Ecliptic λ −1.802 Ecliptic β −0.751	−94.2	**NEO 100.0** Prob 0.73	0.87

Field ID	Detection ID	Epoch (MJD)	Δt	RA (deg)	Dec (deg)	Orient	S/N	Mag	Filter	V-Mag	Obscode	MOPS Object Name
01a58158o0843o (150548) Map | JPEG TA215S25 PA: 0.6° Decider | IQ Device X, Y: 1249.7 2285.8	127984126	58158.591302 2018-02-09 14:11:28.0 UT	--	219.046840 14h36m11.24s ±0.15" (0.20")	−27.495020 −27d29'42.07" ±0.15" (0.20")	N/A	38.46	16.71 ±0.03	o	16.71 ±0.03	T08	NS
01a58158o0860o (150595) Map | JPEG TA215S25 PA: 0.6° Decider | IQ Device X, Y: 1253.6 2217.2	128029444	58158.599122 2018-02-09 14:22:44.0 UT	+11m	219.029940 14h36m07.19s ±0.17" (0.21")	−27.496580 −27d29'47.69" ±0.17" (0.21")	N/A	21.74	16.79 ±0.05	o	16.79 ±0.05	T08	NS
01a58158o0877o (150601)	128033817	58158.606931	+22m	219.012750	−27.497710	N/A	19.23	17.19	o	17.19	T08	NS

Stamp
Blinkable GIF | Download ZIP

Submit



-0.0117 0.000 0.004
-0.0039 0.003 -0.043
0.0039 -0.002 0.053
0.0117 0.001 -0.007
RAU= 5.7719e-03 VRkms= 3.63e+00
3.52e-02 7.14e-01 -0.380

Analy
Full resul

MPC Di
Desig.
T72560

MOPS D
Desig.
MT0000

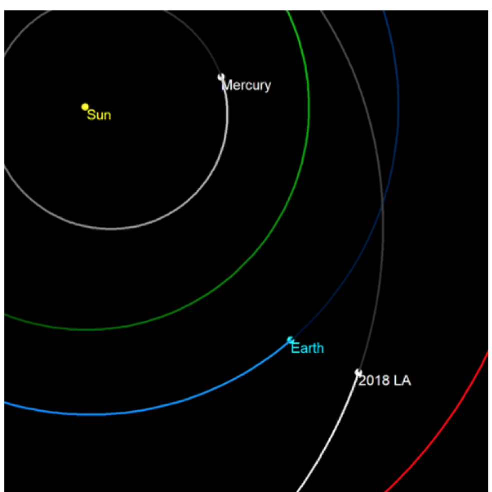
72
Obj

```
SSORB

Command: ssorb -trd /tmp/wssorb.725608.WLLBhWn.dat -linear
  -lng -155.5763 -lat 19.5362 -alt 3397 -r 0 -verbose 1
/tmp/wssorb.725608.WLLBhWn.dat:
58158.591302  219.04684  -27.49502 0.026
58158.599122  219.02994  -27.49658 0.046
58158.606931  219.01275  -27.49771 0.052
58158.614737  218.99540  -27.49840 0.033

Output:
Rock loc: -0.765768  0.623071 -0.001173   vel: -21.979266 -25.770751 -0.695858
   dti[day]    xresid     tresid     chi^2    RAobs    Decobs    RAfit    Decfit
  -0.0117      0.000      0.004      0.001   219.0468  -27.4950  219.0468  -27.4950
  -0.0039      0.003     -0.043      0.020   219.0299  -27.4966  219.0299  -27.4966
   0.0039     -0.002      0.053      0.025   219.0128  -27.4977  219.0128  -27.4977
   0.0117      0.001     -0.007      0.001   218.9954  -27.4984  218.9954  -27.4984
RAU= 5.7719e-03 VRkms= 3.63e+00  Chi= 0.012  RMSx,t= 0.002 0.034  CRVx,t= 2.923 -3.324 4.426  dlnR,dV,cov=
3.52e-02 7.14e-01 -0.380
```

2018 LA

- Discovered by Rich Kowalski (Catalina Sky Survey: G96)
  - 02 JUN 2018 08:22 UTC
  - Observed by ATLAS 12:00 UTC
  - Impact over Namibia 16:44 UTC
  - 2 m diameter (H=30.6), 0.4 kT

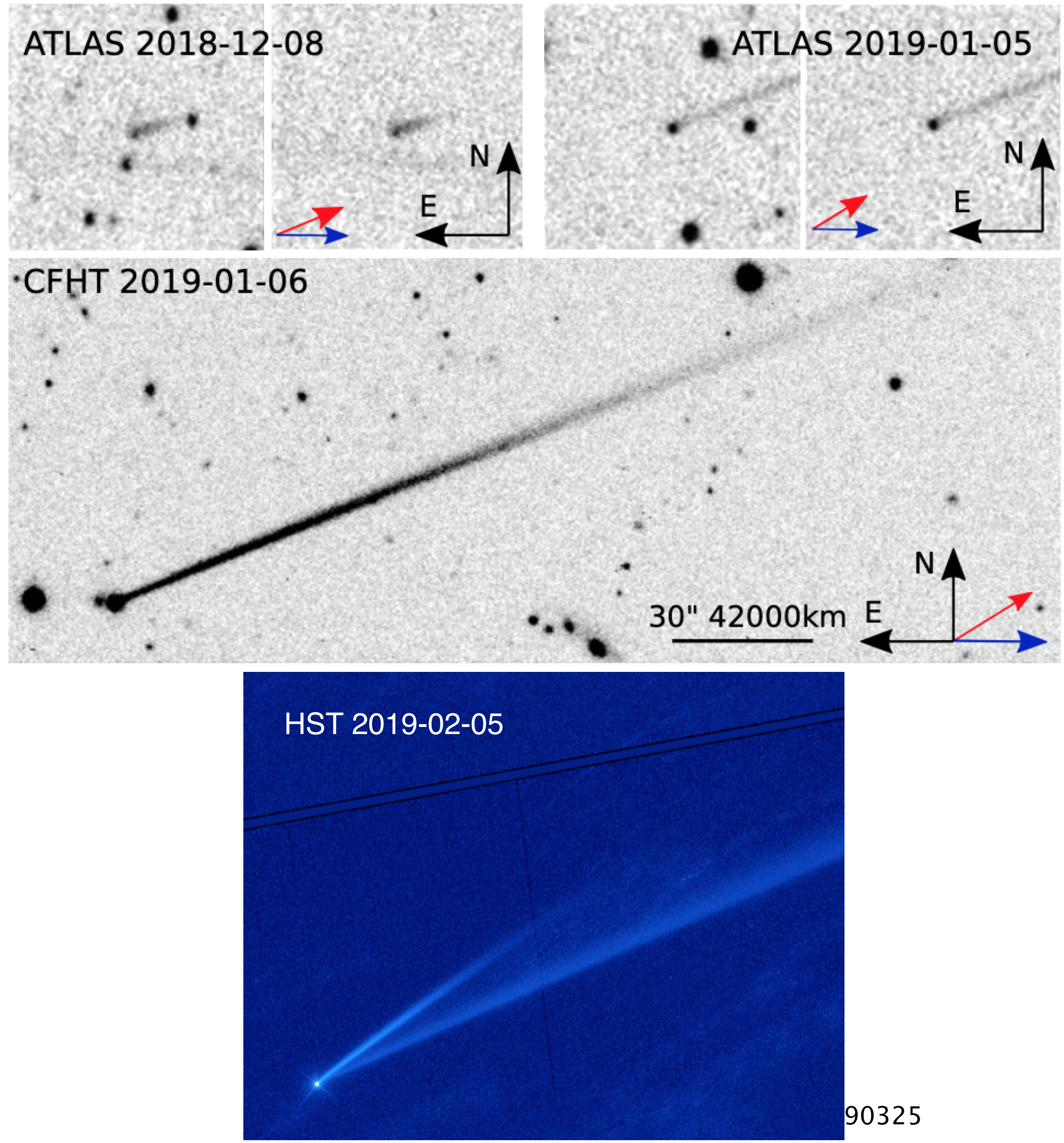
2018 LA seen before impact in NE South Africa
UTC 16:44 (Courtesy Barend Swanepoel)
https://www.youtube.com/watch?v=rnBvSNYy-EY



Orbital configuration 02 May 2018

Asteroid Gault (6478)

- Discovered by ATLAS collaborator Ken Smith while inspecting images for supernova transients (would have been spotted by the asteroid team 6 hours later)
- 6–10km size, 2.3 AU, inner MB
- Previously inactive, episodic outbursts suggest ongoing rotational disruption.

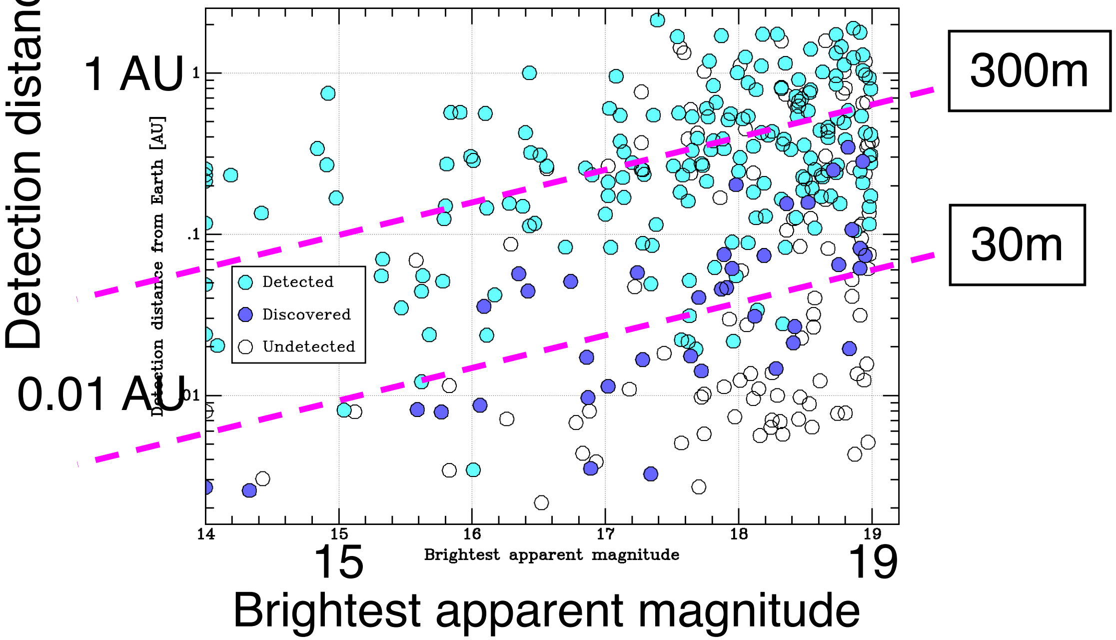


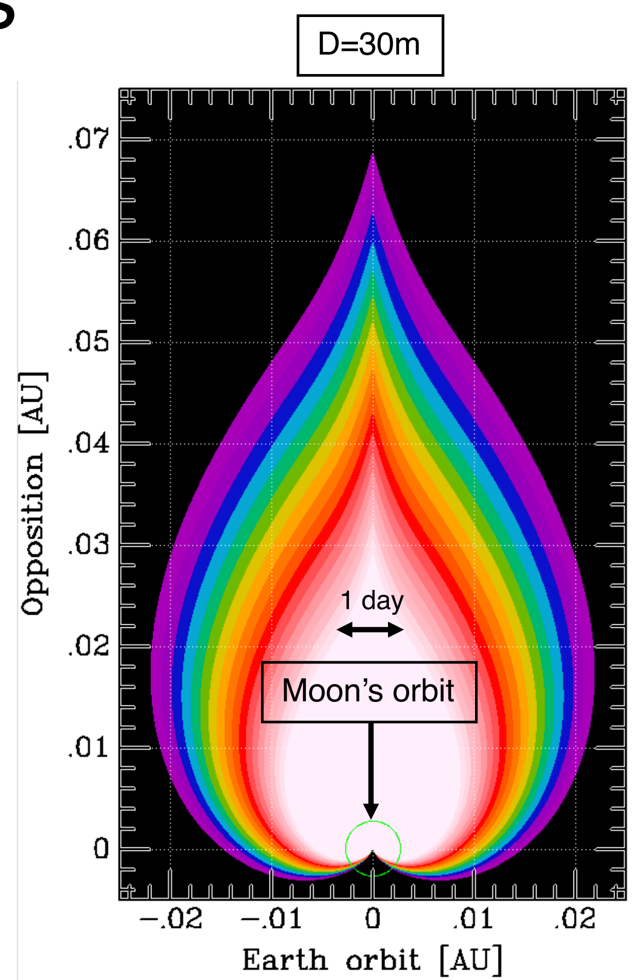
90325

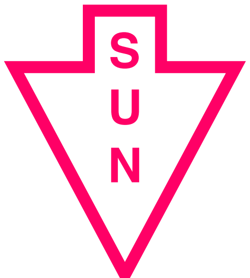
ATLAS and NEOs

- ATLAS should have 2—9 NEOs of D~30m in view at any given time, depending on poorly known number.
- Most 30m asteroids that come within 1 lunar distance should be detected by ATLAS

Jun-Sep 2017 (122 days)

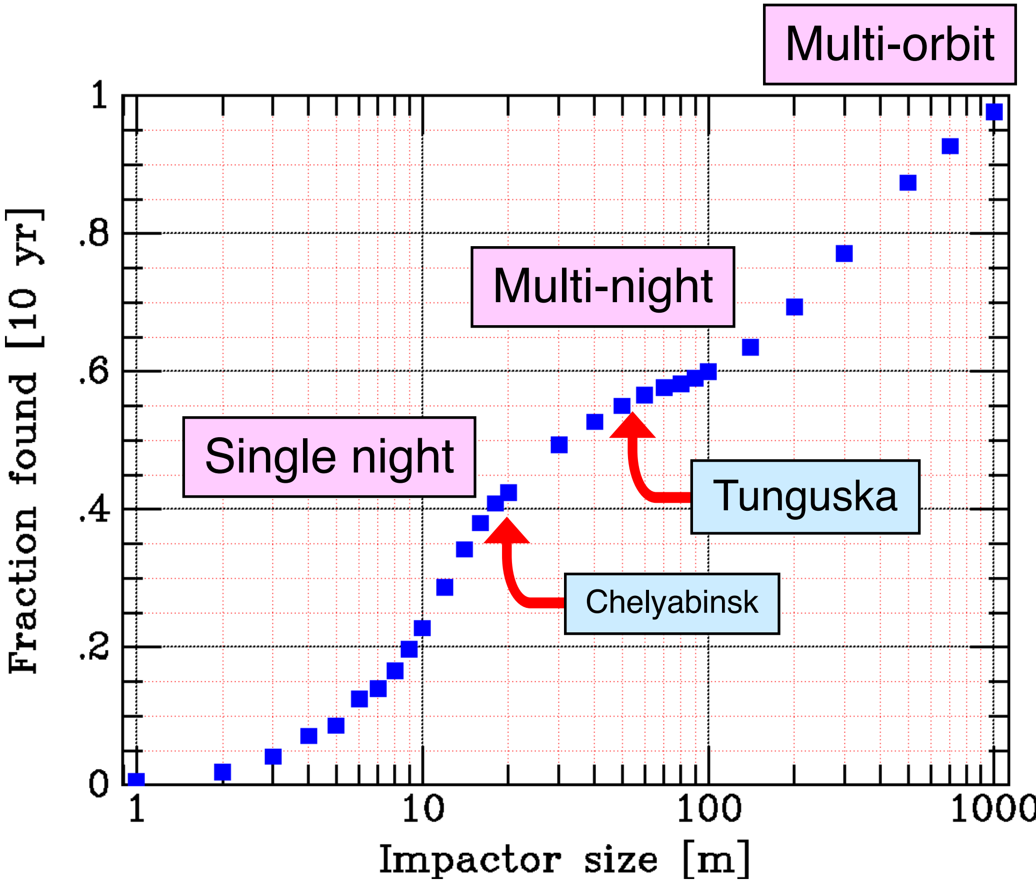






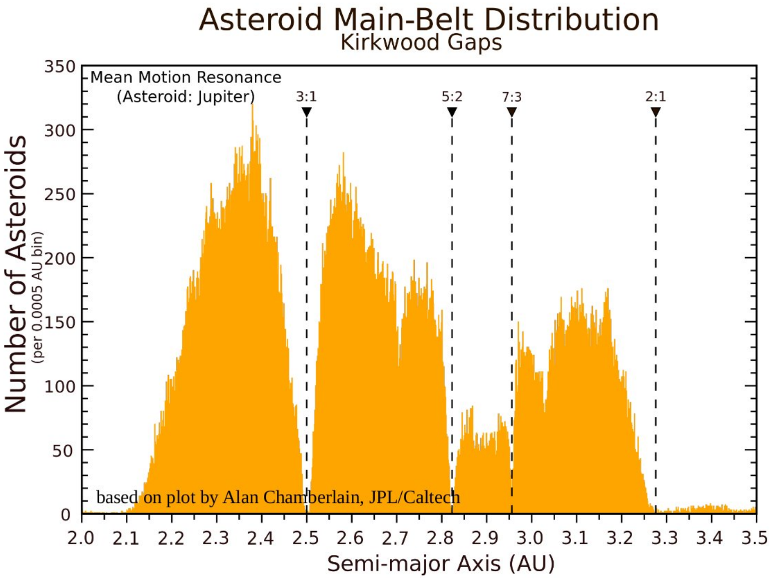
ATLAS Impactor Discovery Probability

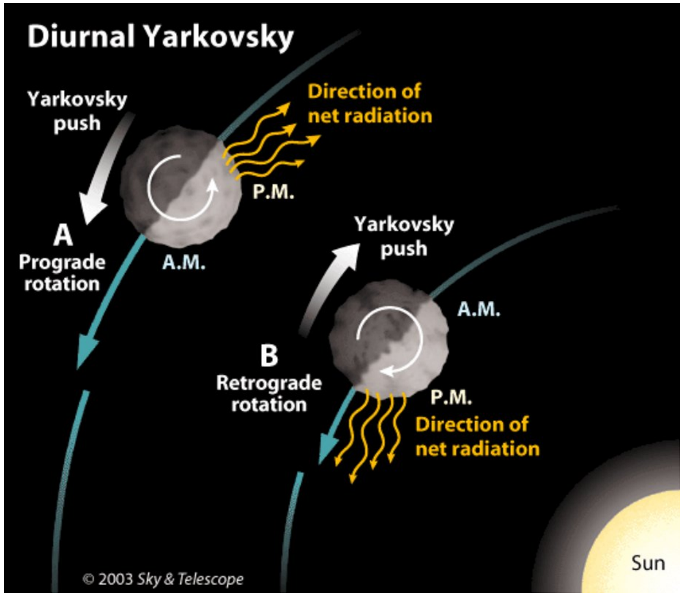
- ATLAS discovery probability depends on size and survey duration
  - Small (<10m) only seen on last day or two.
  - Medium (10–140m) seen for days to weeks before impact.
  - Large (>140m) are often seen on orbits prior to impact.

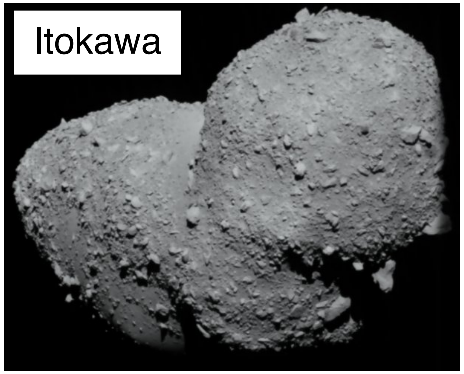


Non-gravitational Forces Create Fresh Hazard

- Yarkovsky
  - Slowly changes orbits
  - At resonance orbits change chaotically
- YORP (tangential Yarkovsky) and "Spin-barrier"
  - YORP can spin up asteroids and cause them to fission, changing orbit







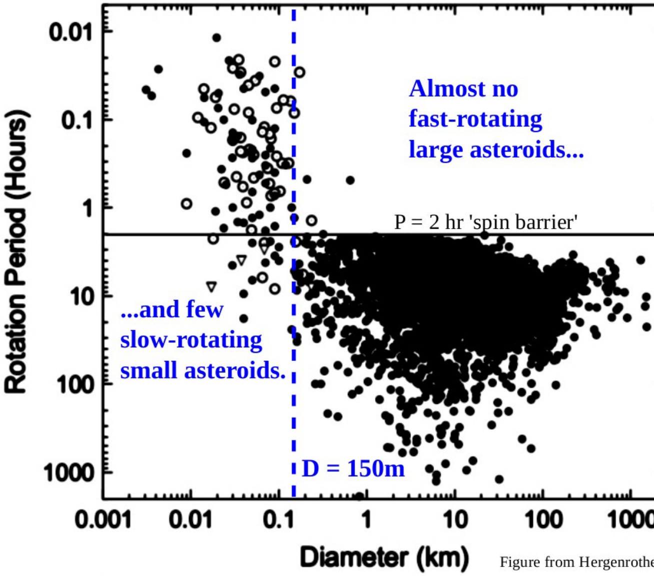
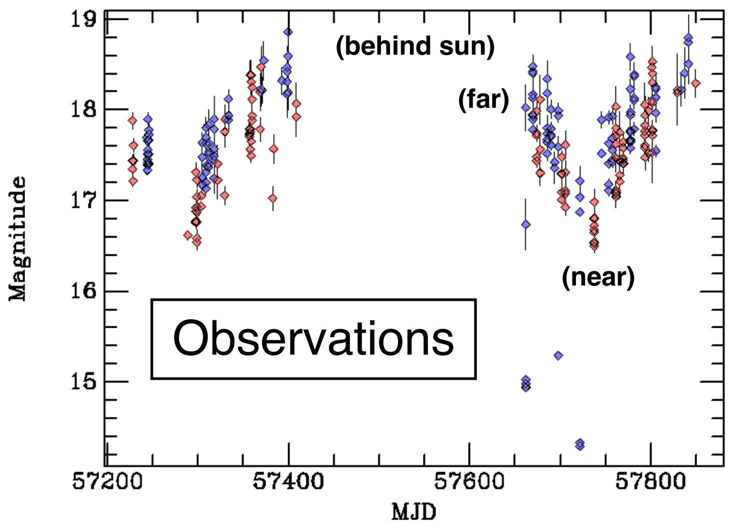


Figure from Hergenrother et al. (2011)

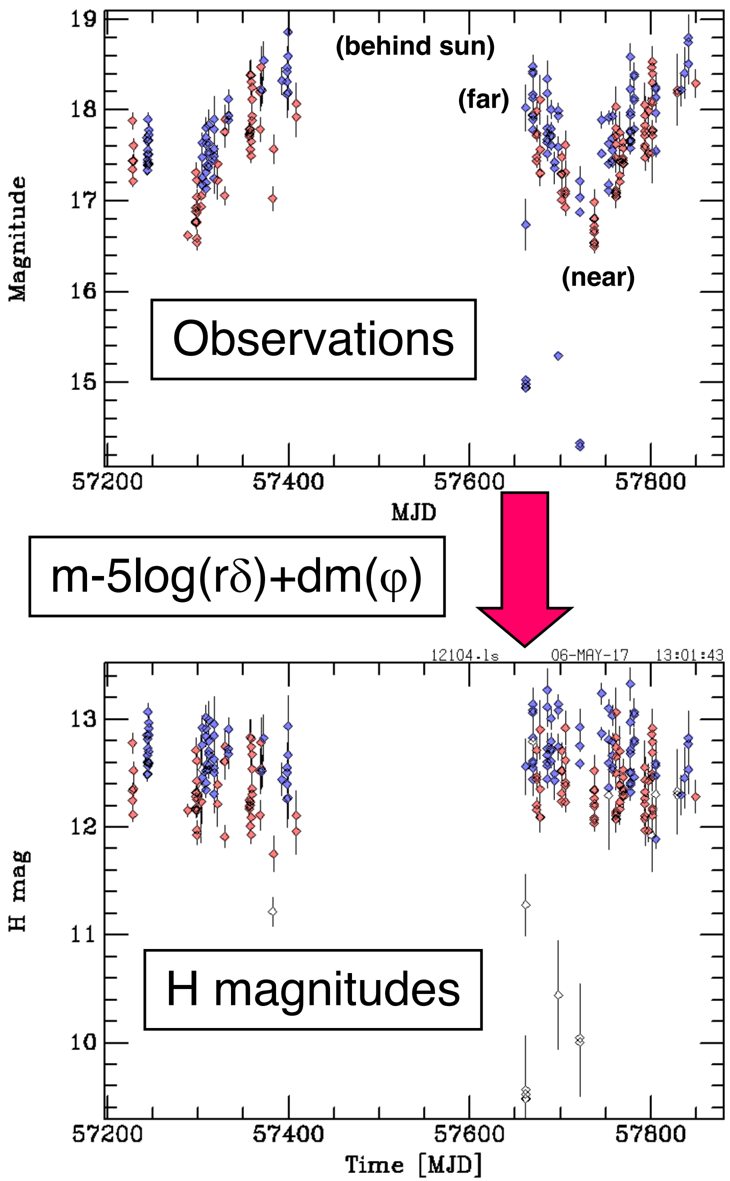
Asteroid light curves

- Asteroid observed magnitudes
  - Images and difference images



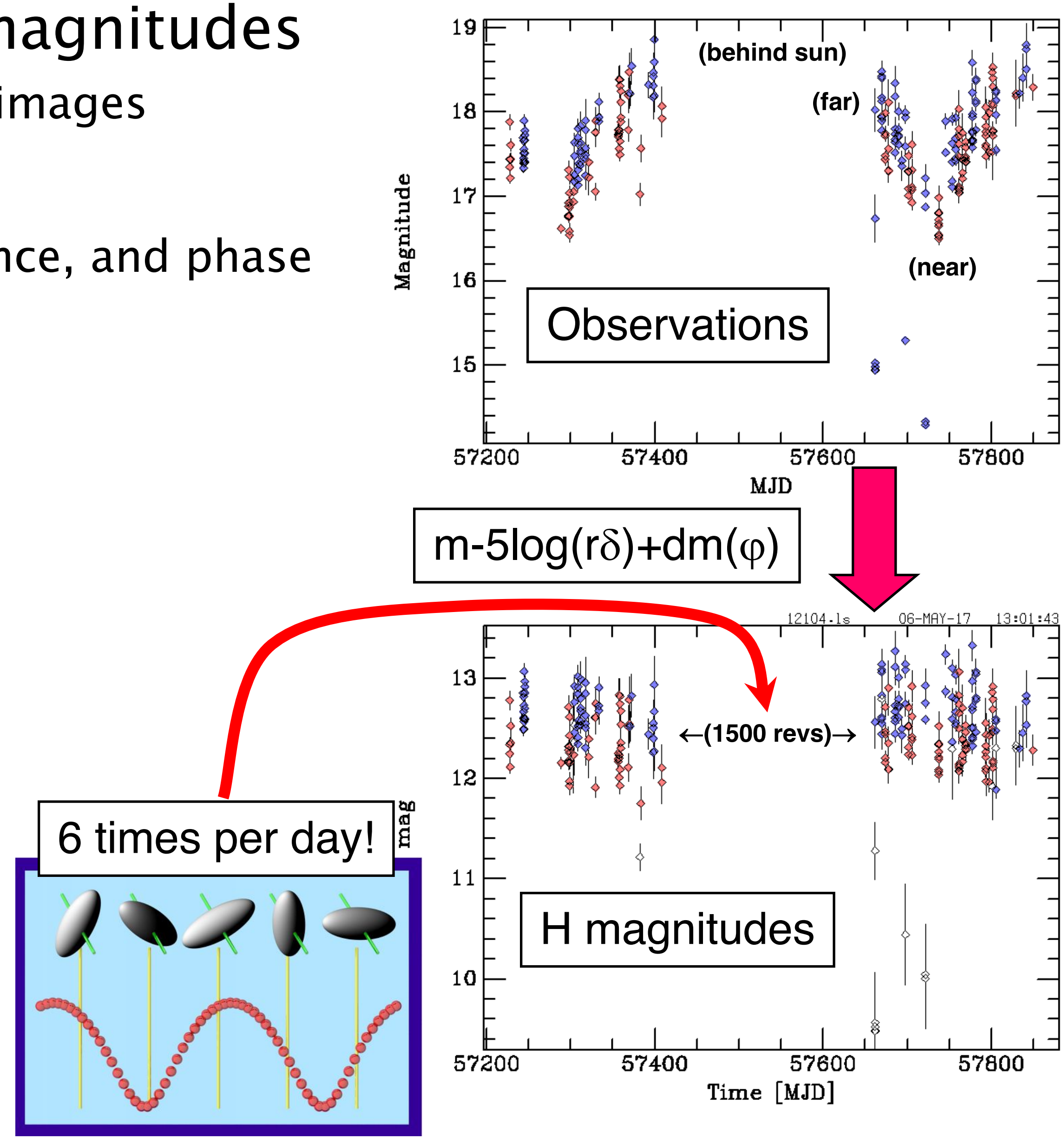
Phasing light curves

- Asteroid observed magnitudes
  - Images and difference images
- Correct to “H”
  - Light travel time, distance, and phase function



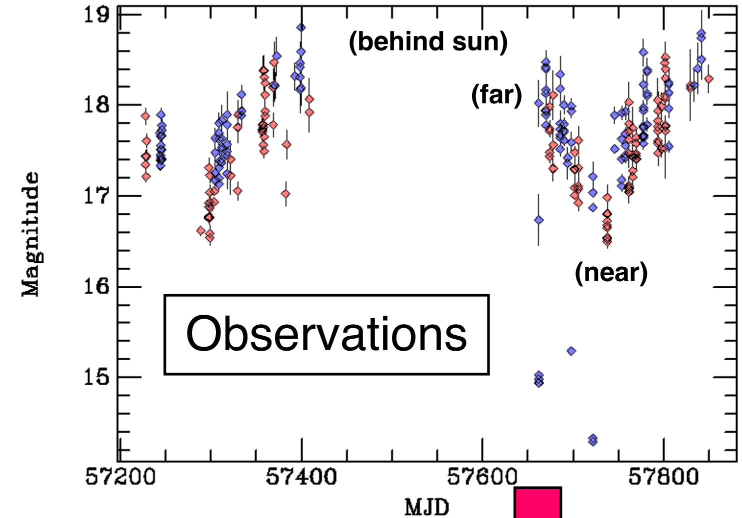
Phasing light curves

- Asteroid observed magnitudes
  - Images and difference images
- Correct to "H"
  - Light travel time, distance, and phase function

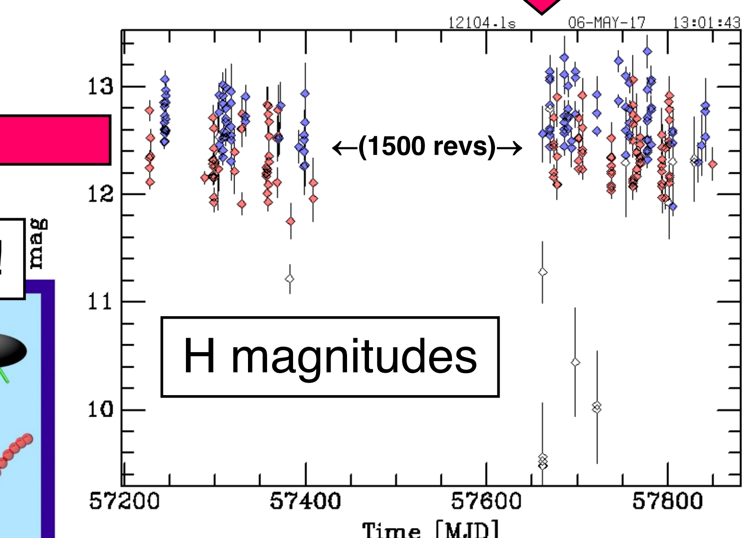


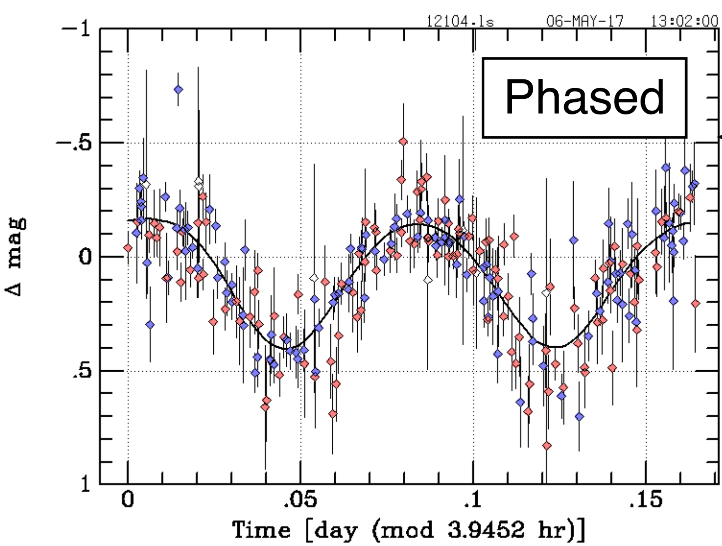
Phasing light curves

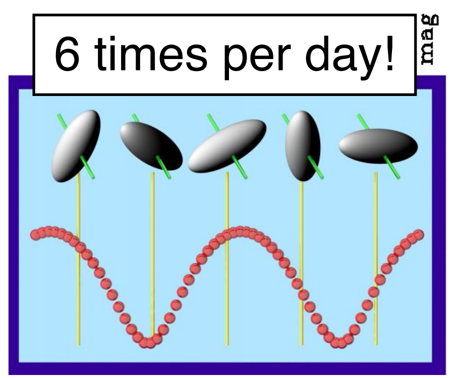
- Asteroid observed magnitudes
  - Images and difference images
- Correct to “H”
  - Light travel time, distance, and phase function
- Search for periodicity
  - Lomb-Scargle, color fits, outlier rejection, Fourier fits, choose best



m-5log(rδ)+dm(φ)

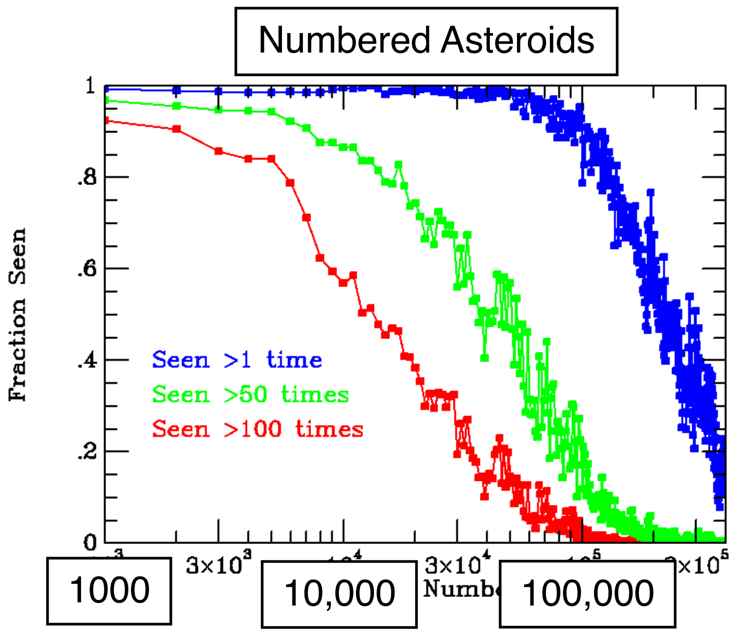


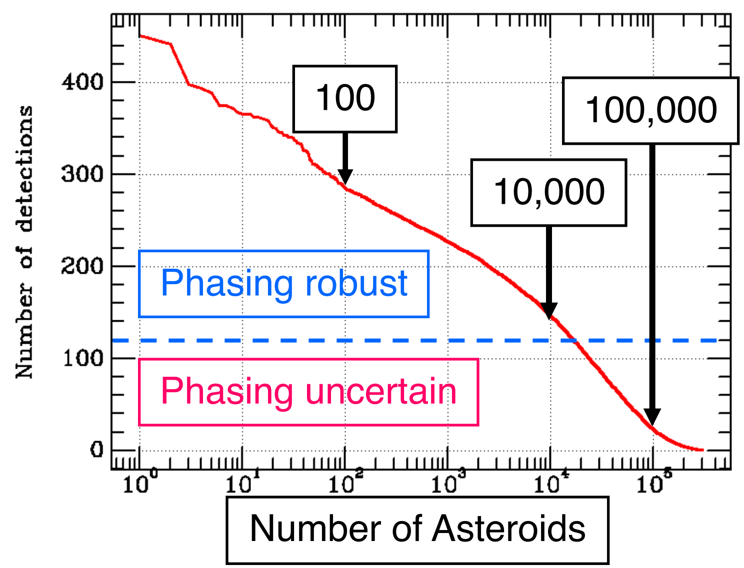




Asteroid Properties from ATLAS

- ATLAS provides more than astrometry and orbits
  - 8.7 million detections of 271,919 numbered asteroids as of May 2017 (numbers have doubled since)
  - Photometry: size, color, taxonomy, phase function…
  - Light curves: rotation, shape, spin axis
- >100,000 asteroids will be measured as observations accumulate; change in properties may emerge…



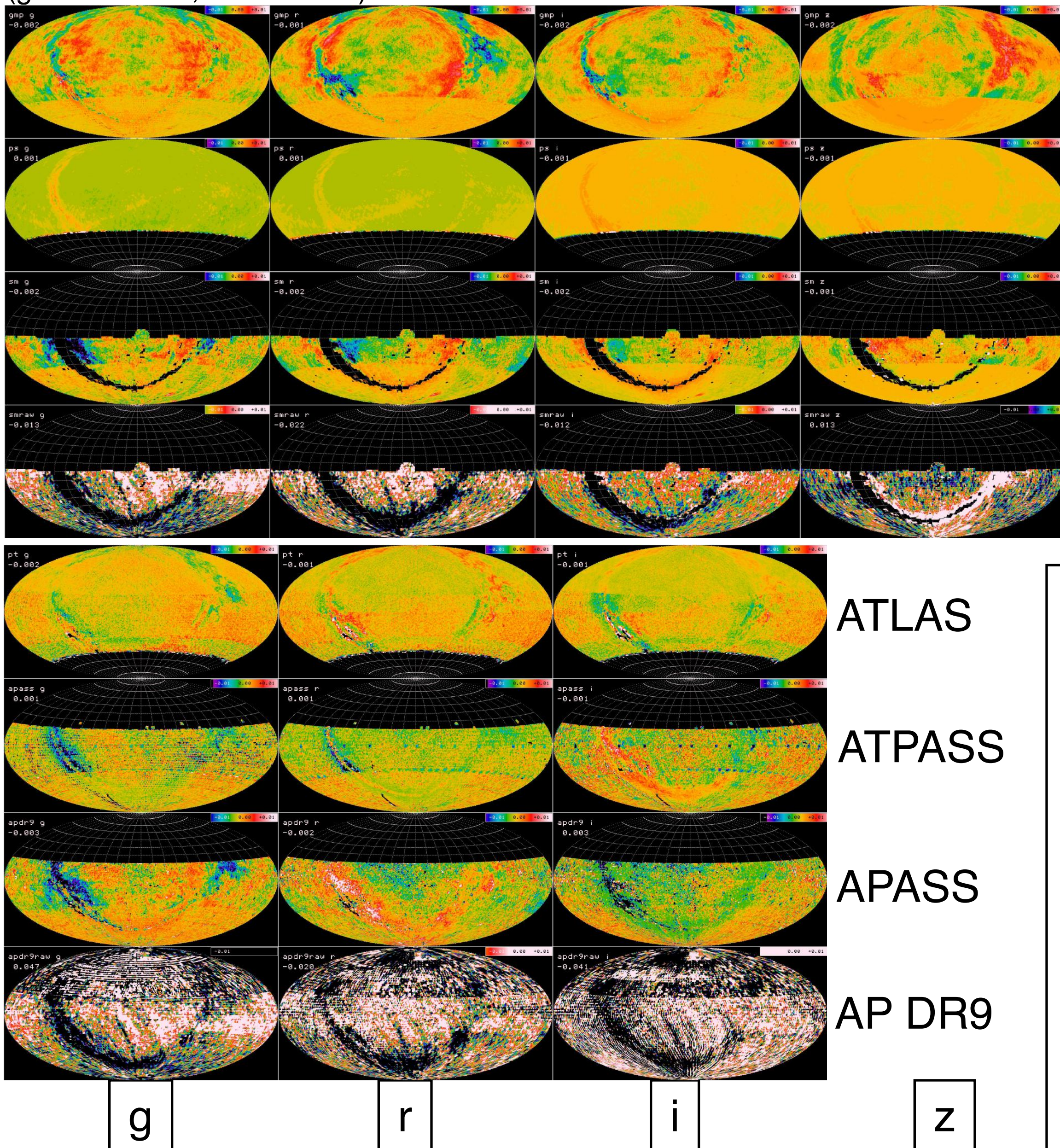


Useful Byproducts

- ATLAS is putting in the extra work to make things that can be useful to others.
- Software (with man pages!)
  - Fisheye pipeline
  - Sort library
  - colmerge = merge two files by matching column entries
  - xclist = pattern match two files of x,y and x',y'
  - puma = get a 3D location for points on an asteroid or satellite tracklet
- Refcat2
  - All sky griz to m~19 with Gaia DR2, available from STScI and arXiv
- Data products (in addition to asteroids to MPC, maybe)
  - ATLAS has better time sampling than any other survey (4x per night)
  - Ongoing updates for all variables with m<19
  - Light curves of everything with m<19
  - Outburst alerts for AGN, unhappy stars, etc.

Refcat2 – arXiv 1809.09157

(green=-0.005, red=+0.005)

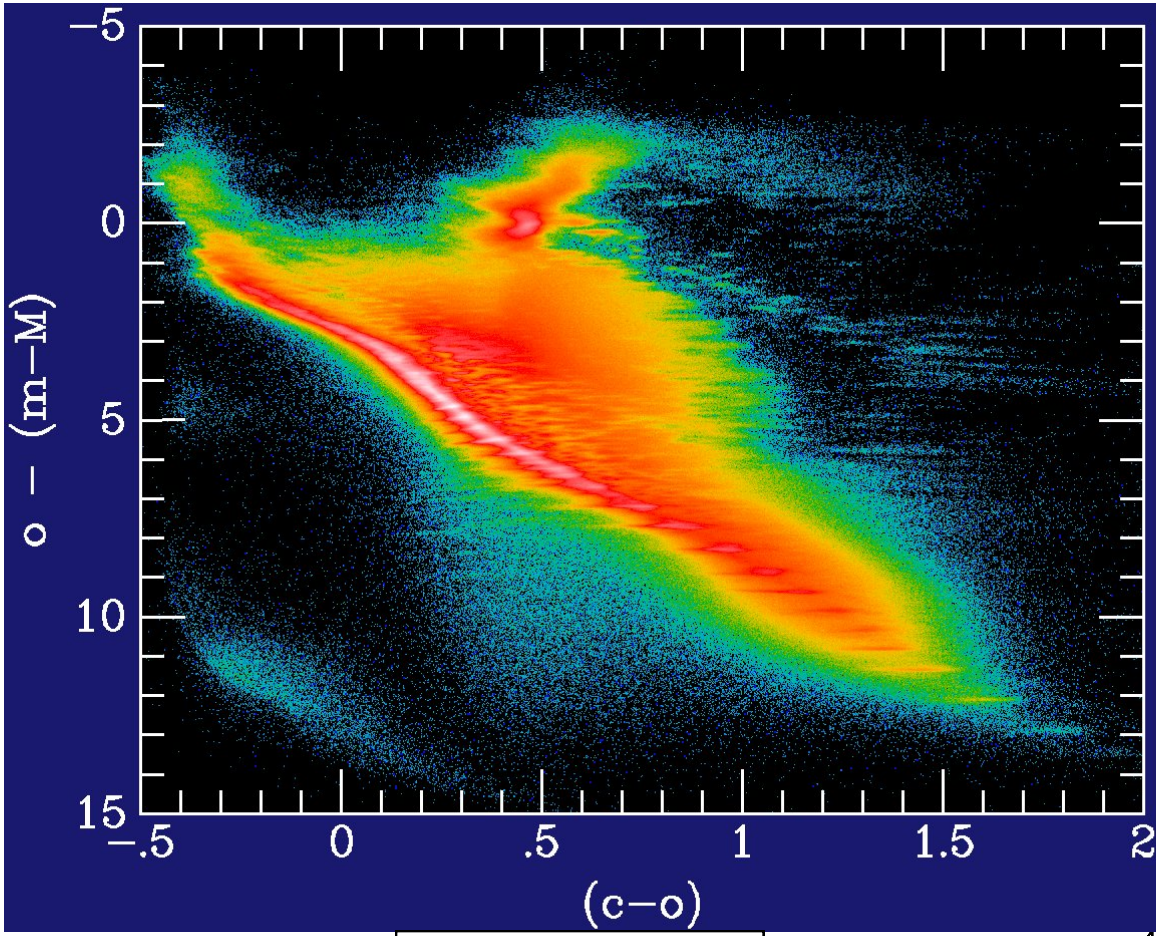


All-sky g,r,i,z from:

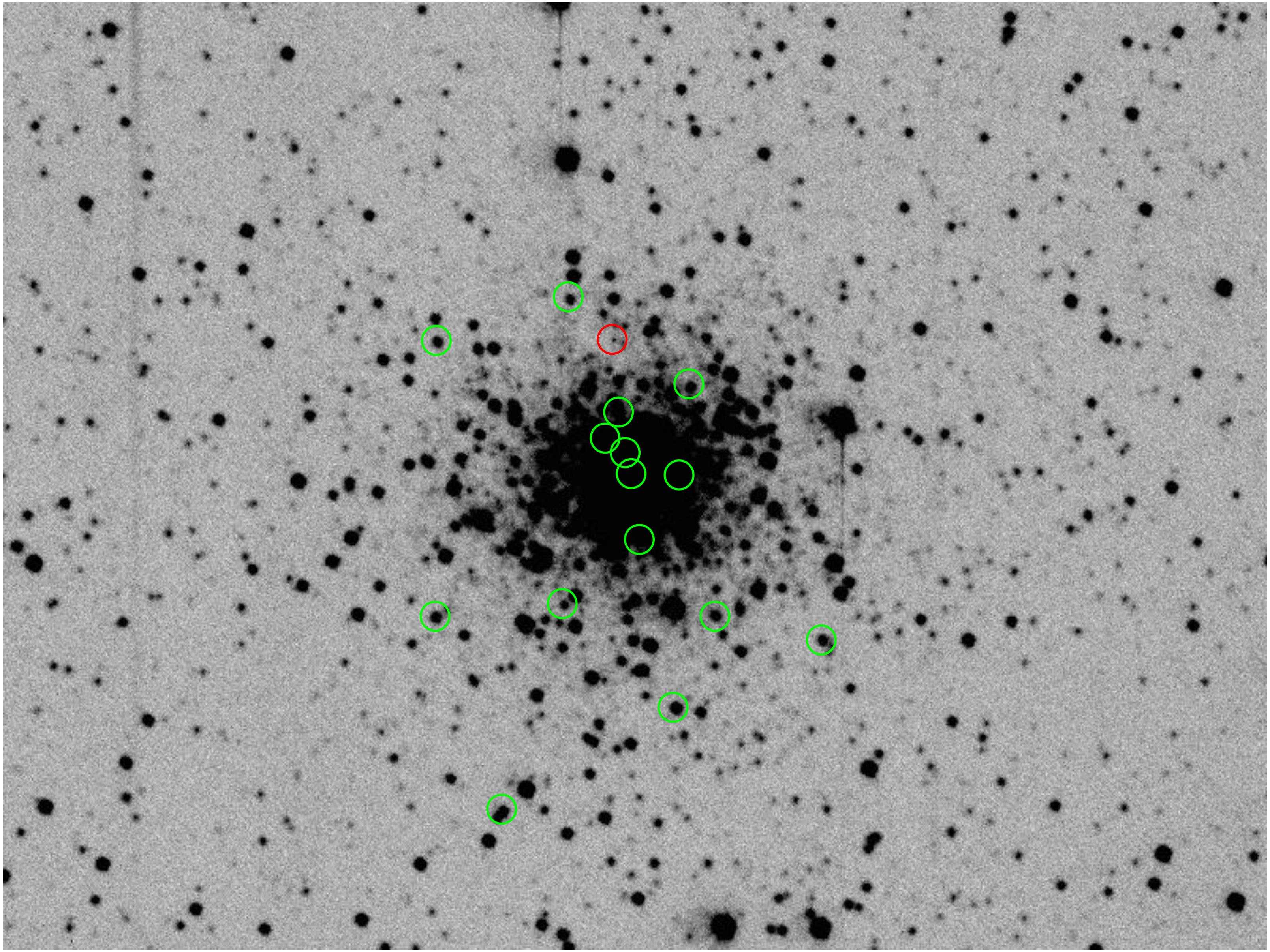
- Gaia DR2 and 2MASS
- Pan-STARRS , Dec>-30°
- ATLAS gri, Dec>-50°
- APASS/ATLAS gri, Dec<+20°
- SkyMapper griz, Dec<+0°
- 991M stars, G|B|R<19
- 210M stars g|r|i<17

ATLAS-Gaia HR diagram

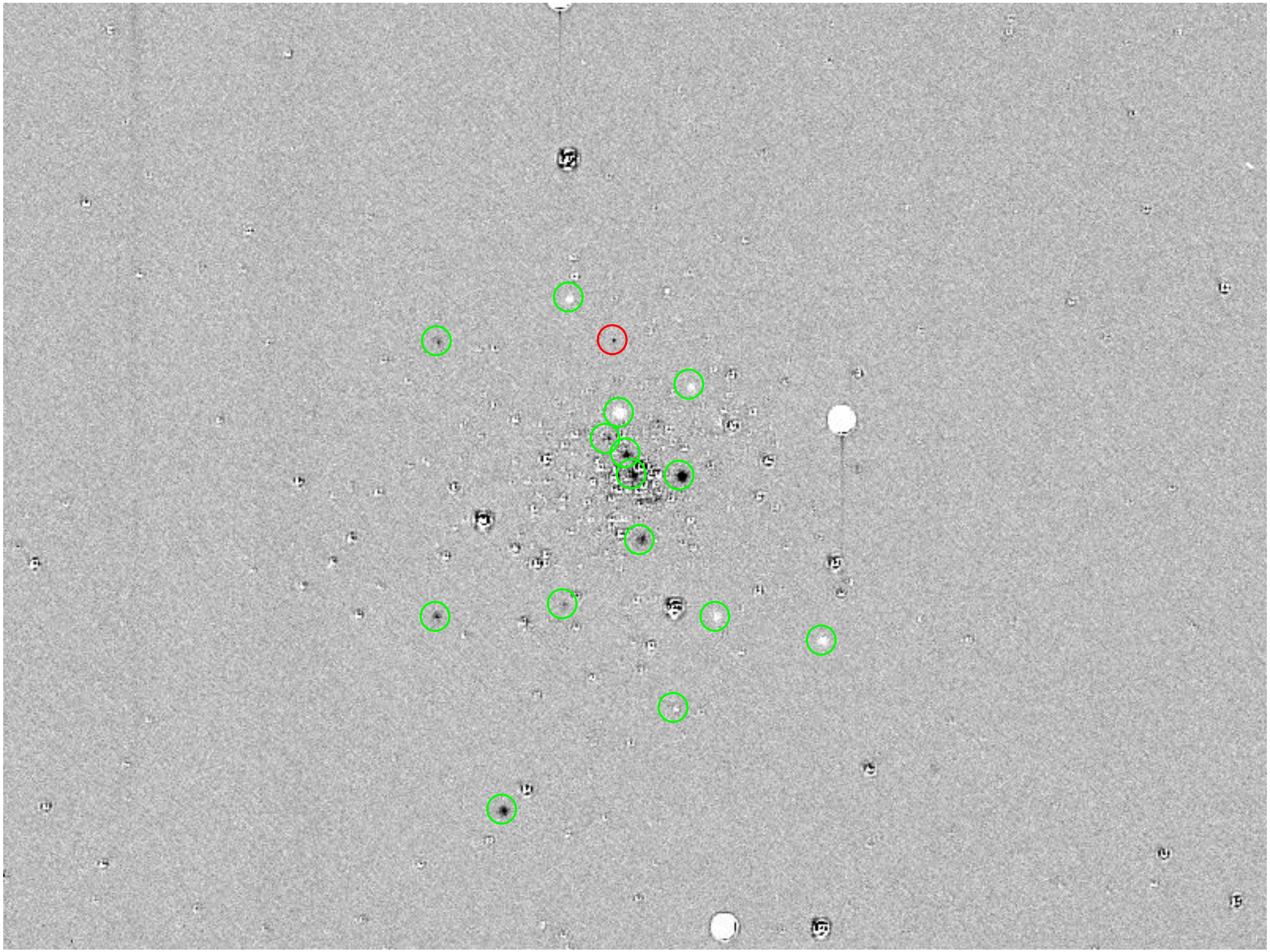
- 40M stars have ATLAS light curves and Gaia parallax with error smaller than 10%.
- Every star has a ~1000 epoch light curve behind it



(count: 1—1000 log stretch)



M107 globular cluster   RA 248.132   Dec -13.054

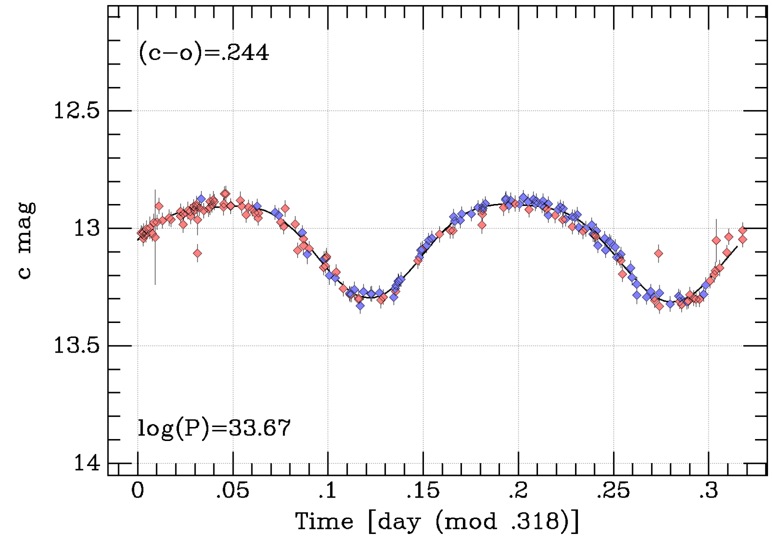


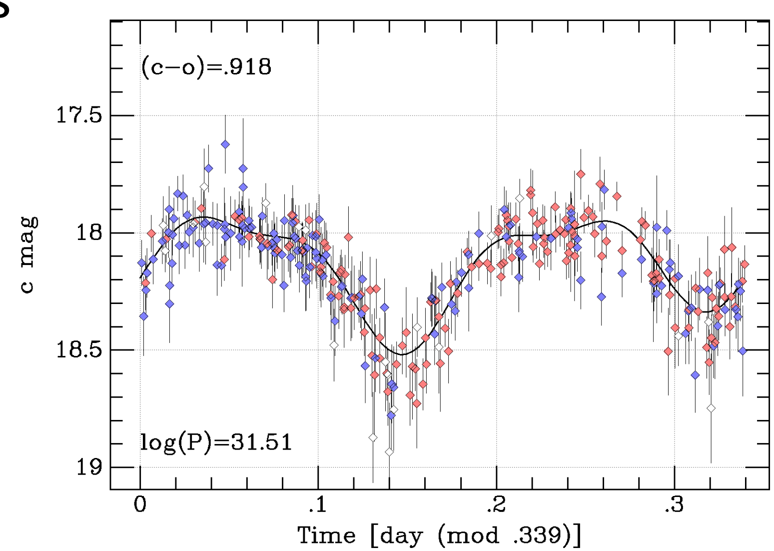
M107 globular cluster RA 248.132 Dec -13.054

 Chile 190325

Variable Stars

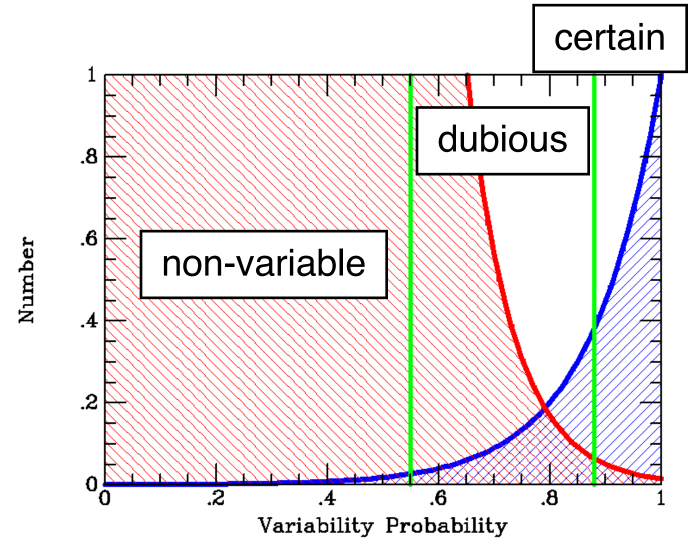
- ATLAS has ~500 point light curves for ~250M stars.
  - All (nearly) stars with −45<Dec<+90 and 11<m<19 examined
  - SNR ~10 at m~18, per detection
  - Sampling ~4/night over ~1 hour, revisit every ~2 days
  - c~(g+r) and o~(r+i) colors
  - Lomb-Scargle and variability statistics computed for all light curves
- ~5M light curves with ~1M variables from DR1 140M stars are now available from STScI (Heinze et al. arXiv:1804.02132)





Classifying Stars

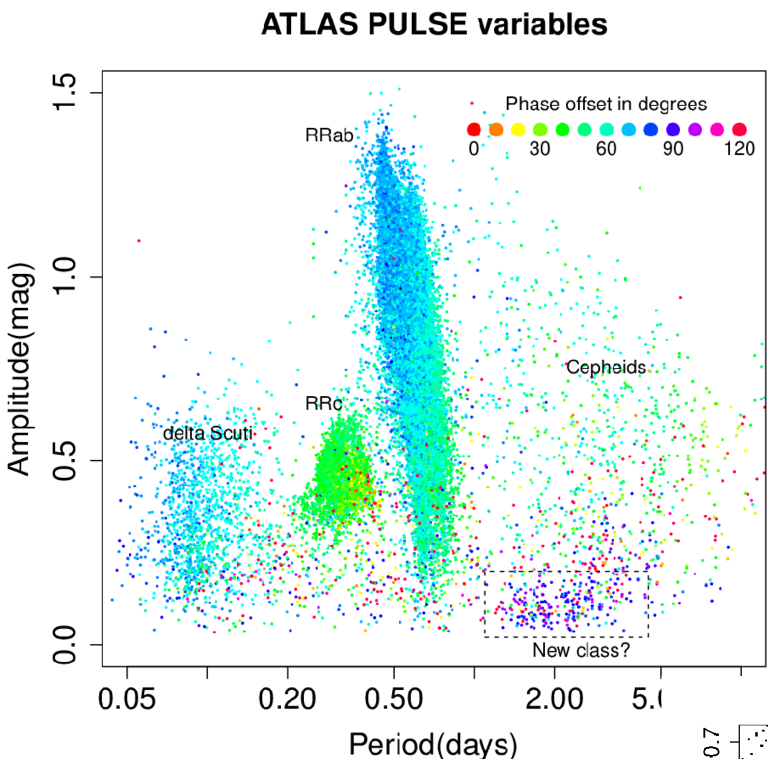
- Machine learning classification of 140 million light curves
  - Morphological classes such as "sinusoidal", "pulsating" (sawtooth), "close binary", "distant binary", "mira", etc.
  - Good but not perfect correspondence with physical classes: work to be done
  - ~0.5M are "certain" (low false alarm rate)
  - ~5M are "dubious" (10:1 false alarm rate)
- Counts ("certain" only)
  - Eclipsing 100,000 (70% new)
  - Pulsating 50,000 (40% new)
  - Long period variable 50,000 (60% new)
  - Sine 100,000 (90% new)

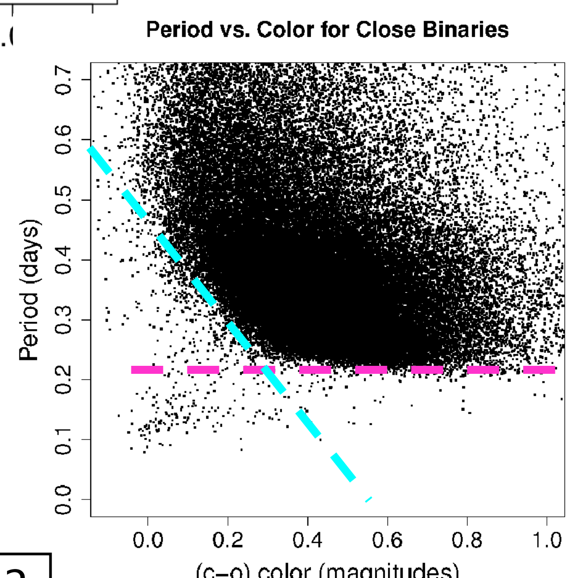


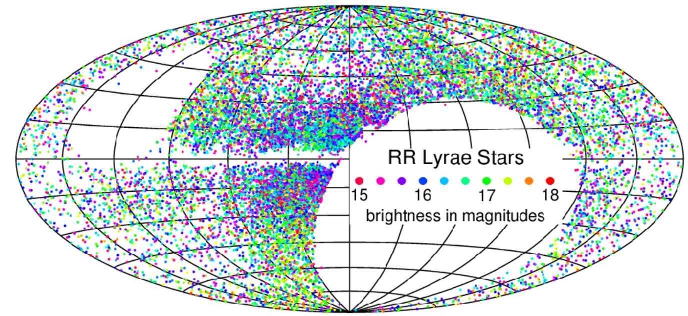
Red = non-variable stars
Blue = variable stars

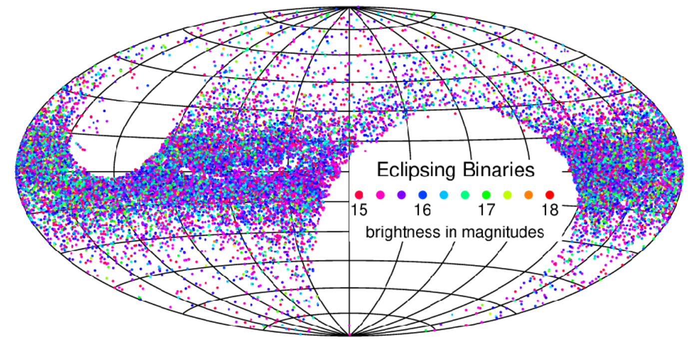
Heinze et al. arXiv:1804.02132

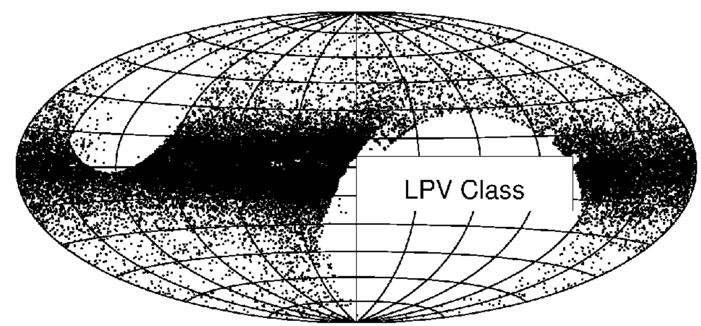
Distributions

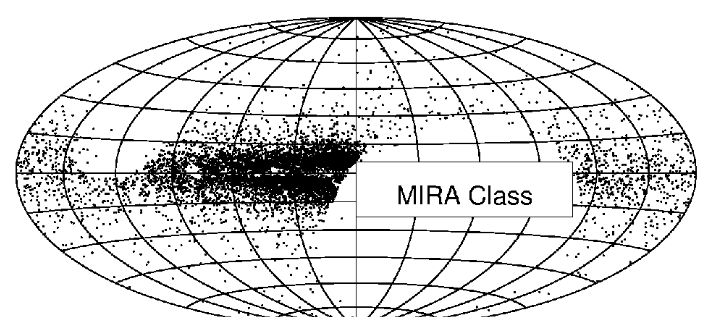










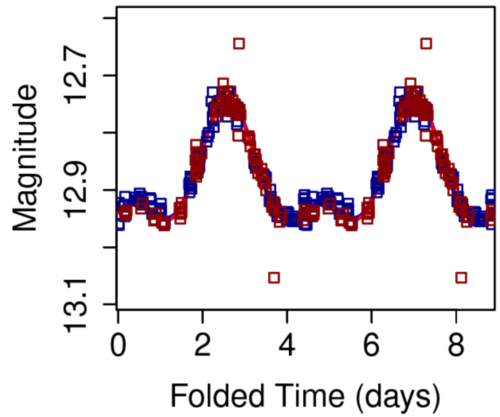


Heinze et al. arXiv:1804.02132

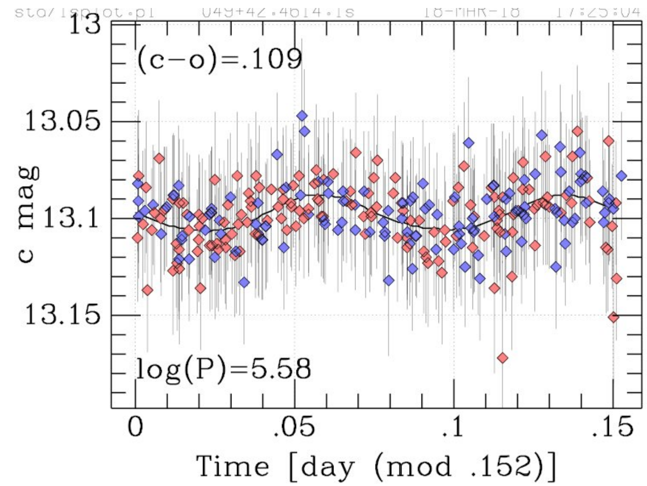
Interesting Light Curves

Ap star

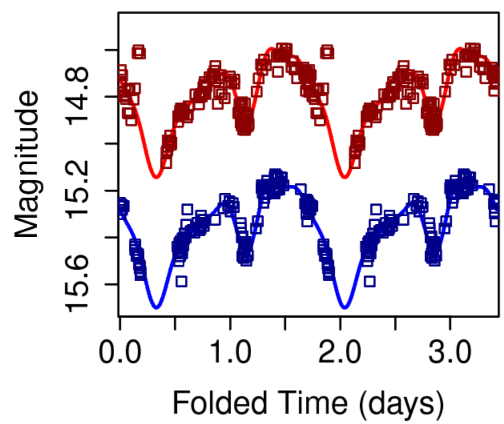
ATO J010.7230+57.8087



0.01 mag amplitude

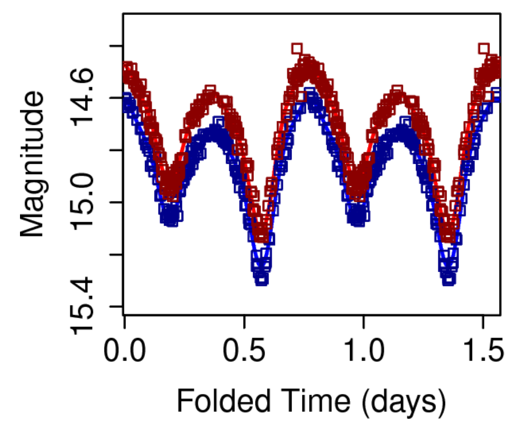


ATO J267.4192+48.8914



Eclipsing pulsator?

ATO J054.8250+42.1556



O'Connell effect

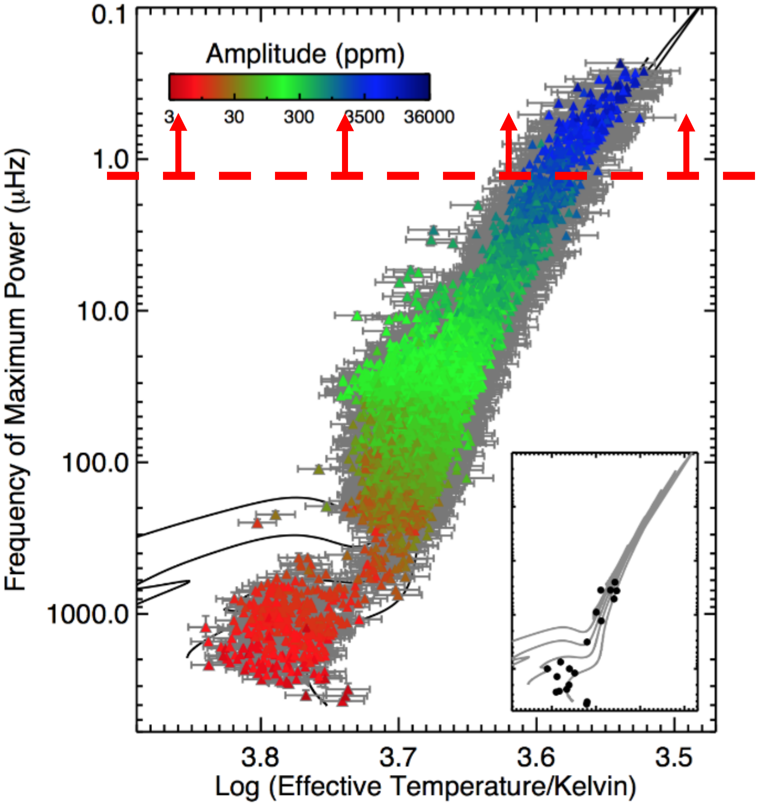
Heinze et al. arXiv:1804.02132

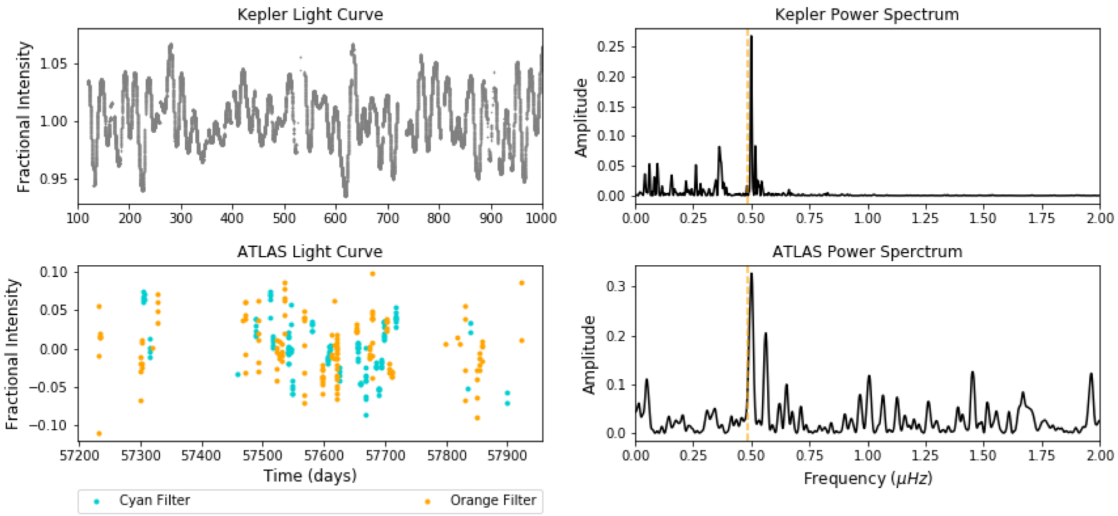
Asteroseismology

- ATLAS light curves reveal giant star oscillation frequency, providing luminosity for a given temperature and mass.

$$\frac{\nu_{max}}{\nu_{max,\odot}} \approx \frac{M}{M_\odot}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{3.5}\left(\frac{L}{L_\odot}\right)^{-1}$$

- 60,000 stars in Milky Way available (more than Kepler or TESS) for studies of dust extinction and stellar properties (Huber & Auge).



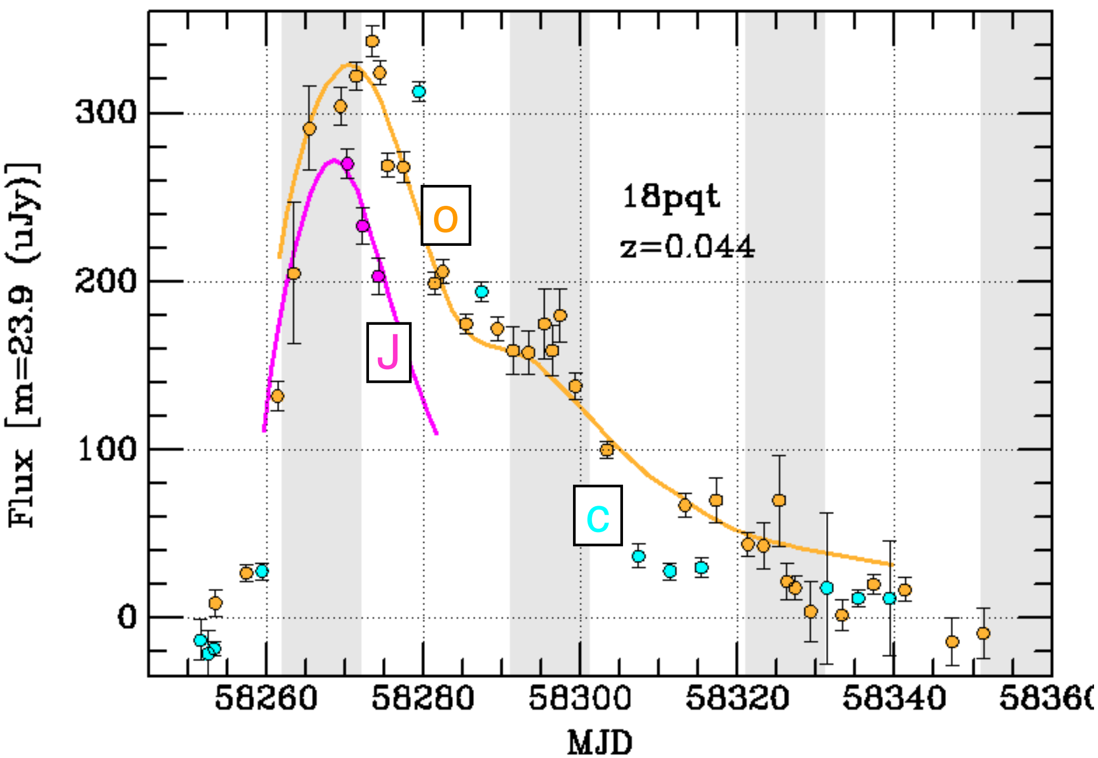


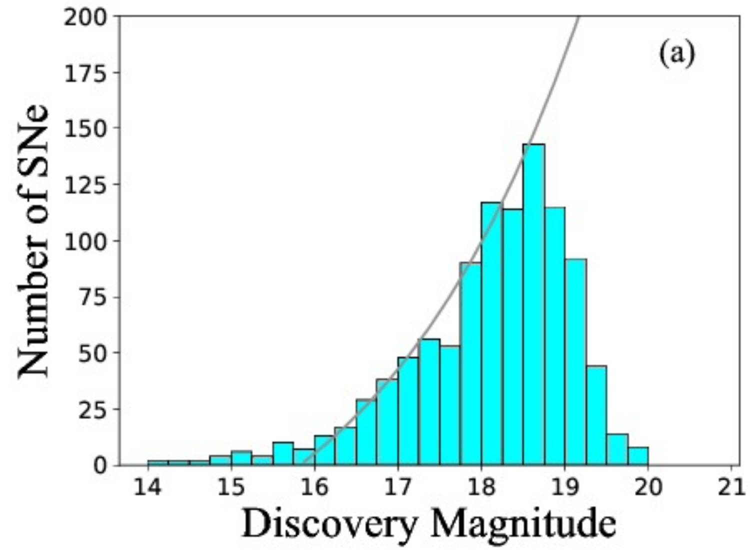
Transients and Cosmic Variables

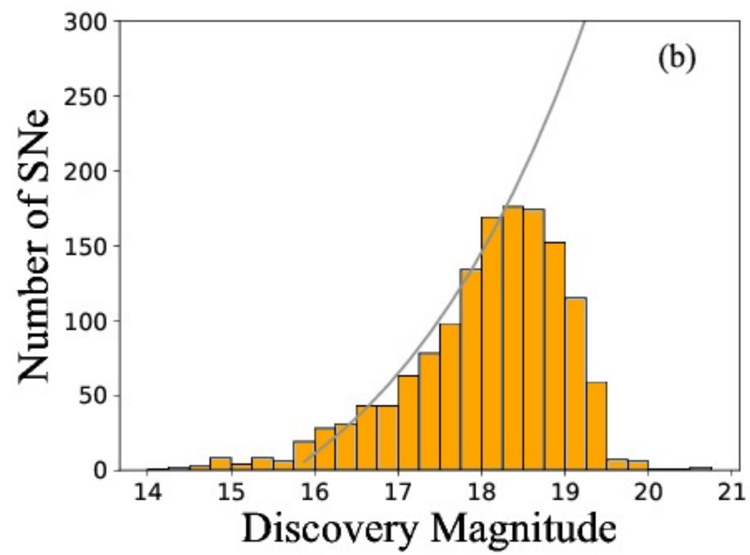
- ATLAS sees ~5,000 supernovae per year to V~19
- There are ~200,000 AGN brighter than V~19 that ATLAS monitors daily.
- ATLAS depth and SNR at m~19 depends on averaging time:
  - ~1 hour (1 exposure), m_{lim}~19.5, SNR > 7 at m~19
  - ~1 day (4 exposures), m_{lim}~20.2, SNR > 14 at m~19
  - ~1 week (20 exposures), m_{lim}~21, SNR > 30 at m~19
  - ~1 month (50 exposures), m_{lim}~21.5, SNR > 50 at m~19

ATLAS SNIa Discoveries

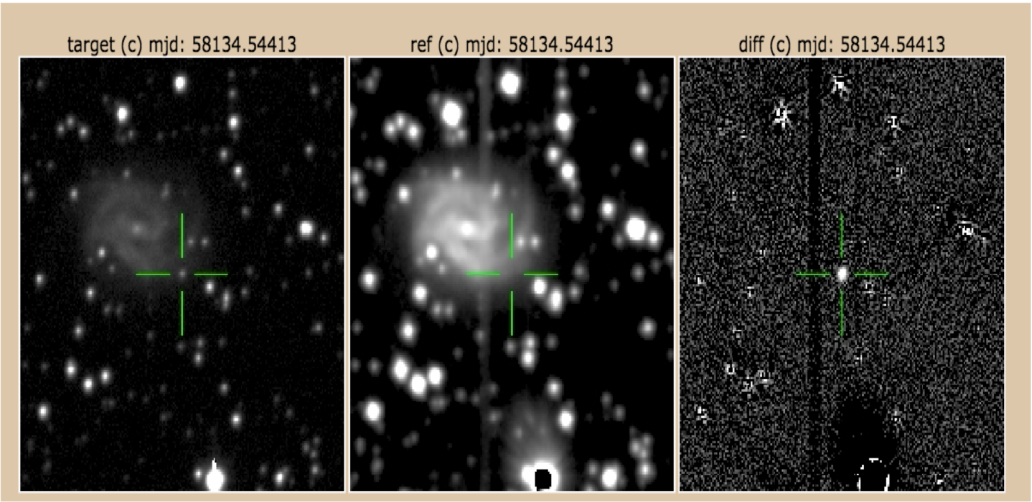
- ATLAS can find (nearly) all SNIa that explode within z<0.1
  - ~5000 per year
  - SNR sufficient to establish decline rate
  - Follow-up IR photometry at peak and spectrum can get ~7-10% distance.

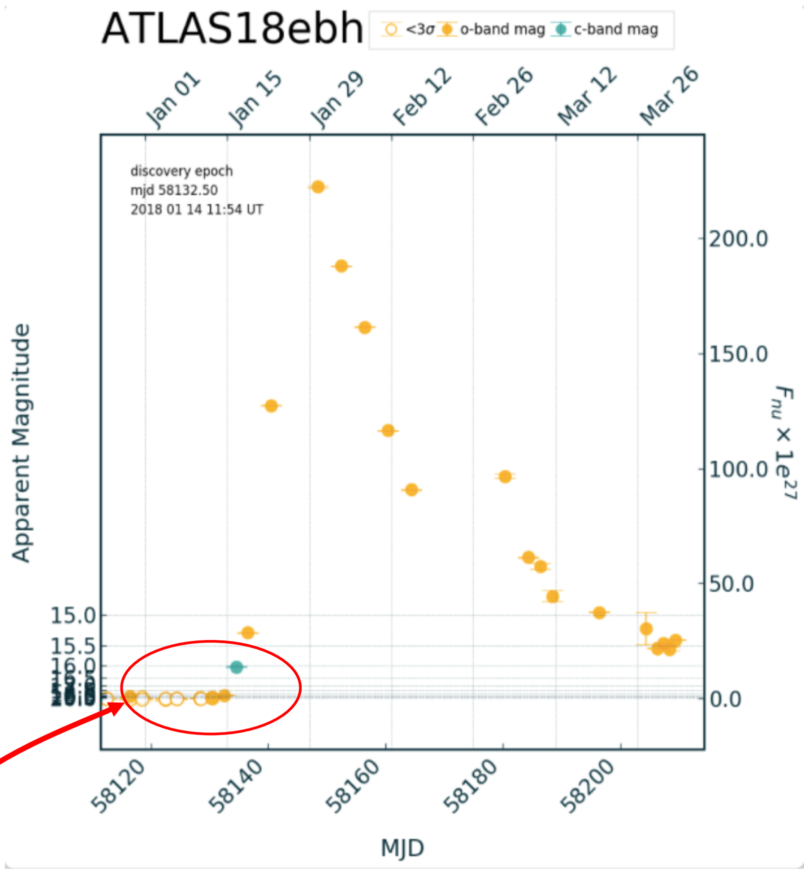






Most nearby SN detected within first ~24hrs





Example :

ATLAS18ebh = SN2018gv

NGC2525, 20 Mpc

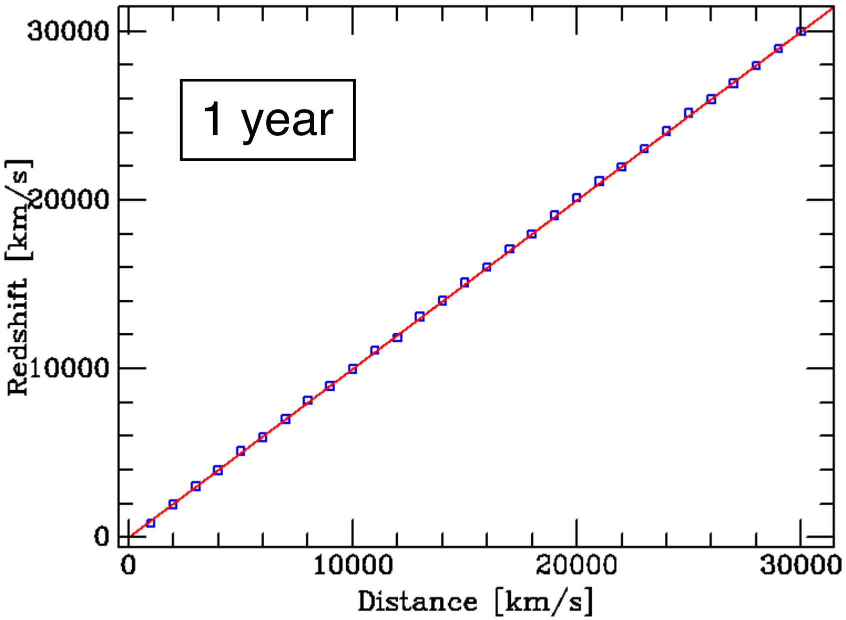
Normal Type Ia

ATLAS early detections and limits constrain explosion to ~12hrs

Automated forced photometry run on all ATLAS transients, reliable photometry and limits instantly (*forced using tphot)*

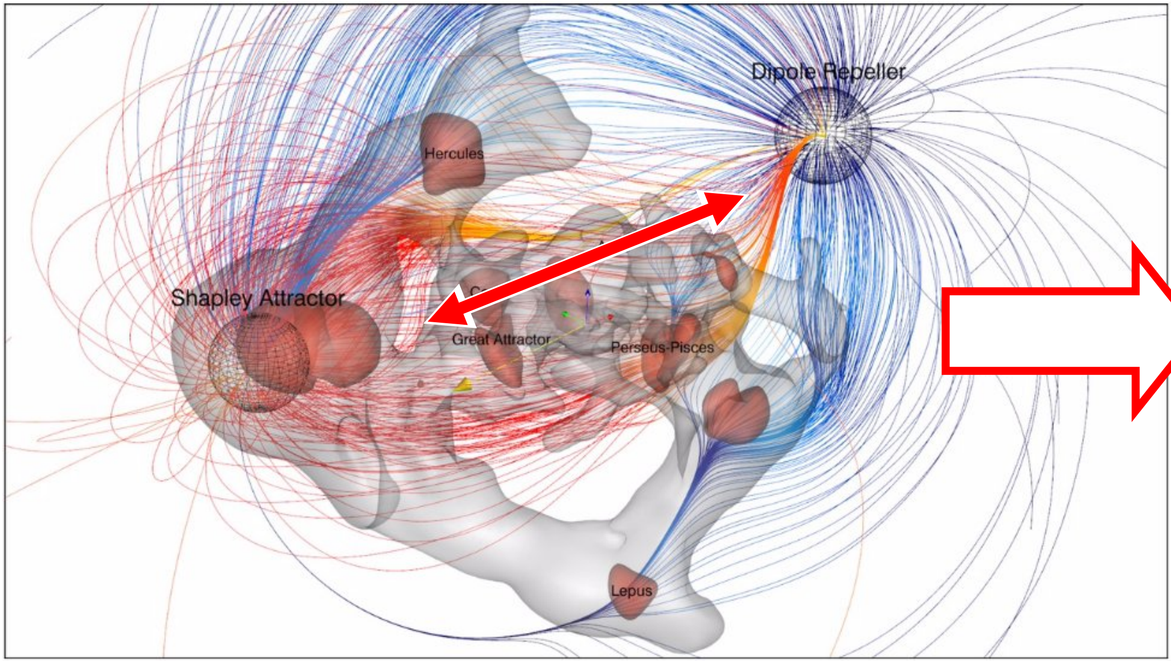
Hubble Flow, Large Scale Flows

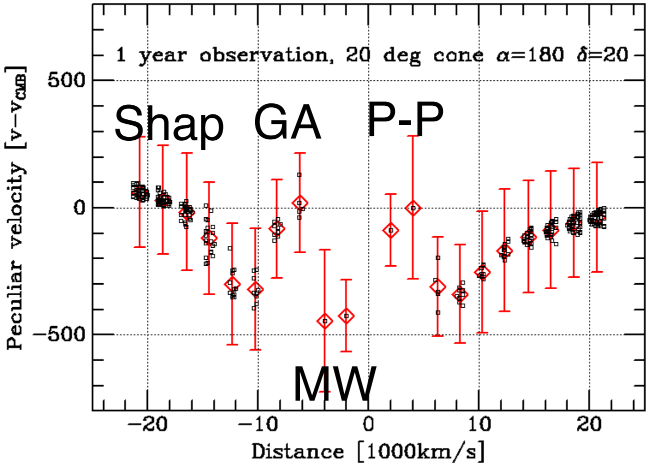
- Use SNIa as standardizable candles:
  - ~10% distance accuracy per SNIa
  - ~1 SNIa each year per $(30\text{Mpc})^3$.
  - Therefore measure the distance of a shell of thickness 1,000 km/s with an accuracy of 100 km/s per year *<u>independent of distance</u>*, limited when systematics dominate (z~0.1?)
  - Measure Dark Matter distribution:
    - Monopole (Hubble bubble)
    - Multipole (large scale flows)
  - Also require follow-up of each SN
    - 2-3 epochs IR photometry
    - spectrum for typing and z
  - Pilot project now underway with Shappee and Tully…



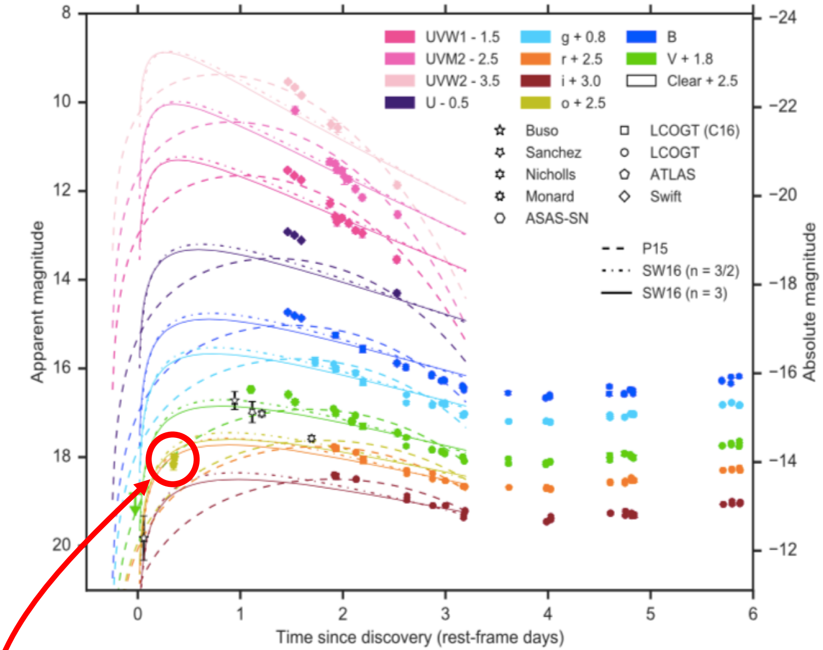
Large Scale Flows and Dark Matter

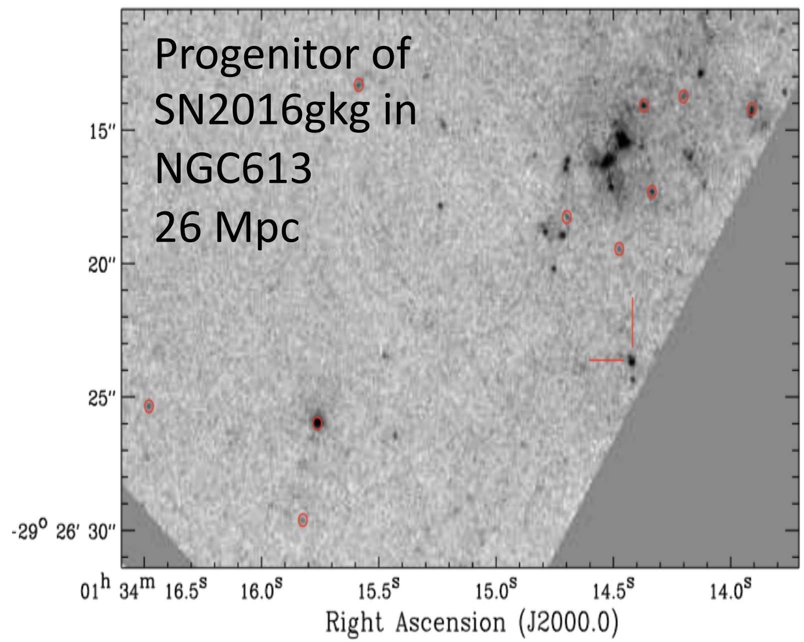
- Constrained N-body simulations can predict dark matter distribution from observations of large scale flows (e.g. Tully et al. Cosmic Flows).
- These can be directly tested (and improved) in 1 year of ATLAS SNIa observations.





Detections of very young supernova : shock breakout

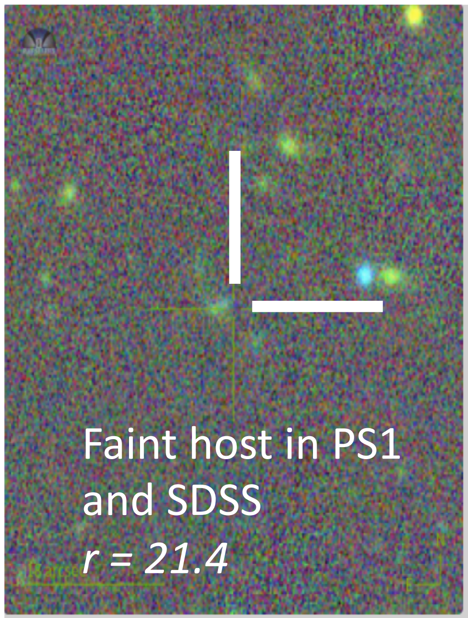


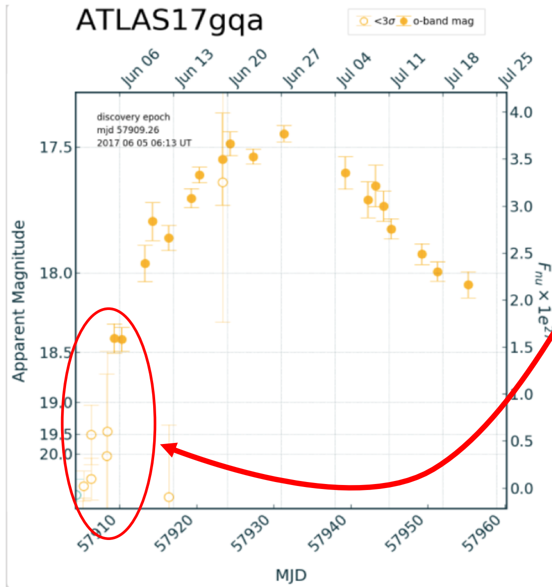


- SN2016gkg : type IIb with progenitor detection AND very early lightcurve (shock breakout)
- Progenitor in HST pre-explosion image – gives luminosity and mass
- ATLAS constrained explosion epoch (about 8hrs after explosion)
- Can use both to test progenitor mass, luminosity and radius and shock physics

Arcavi et al. 2017,
Tartaglia et al. 2017,
Kilpatrick et al. 2017

ATLAS17gqa : very unusual super-luminous SN

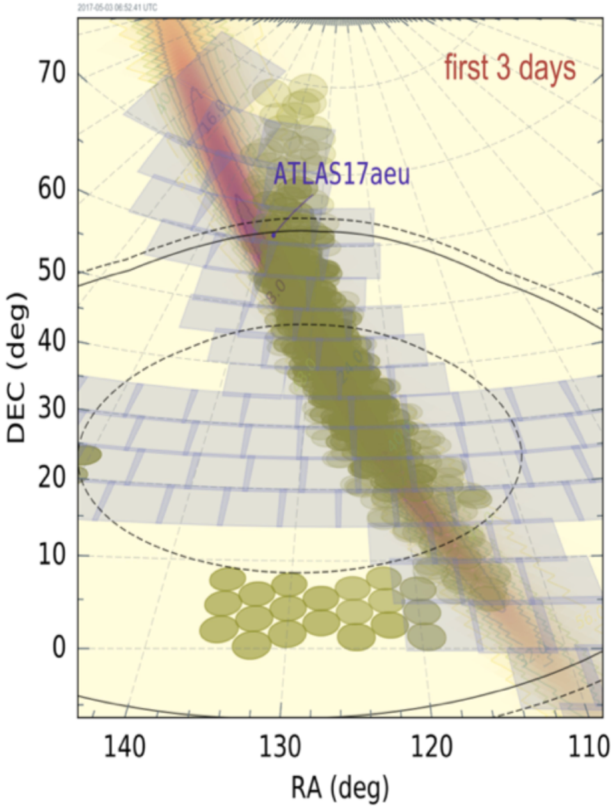




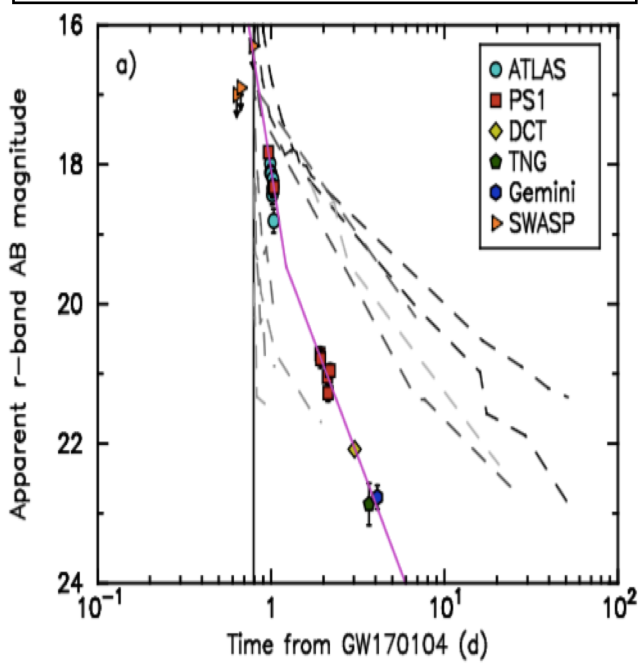
- Explosion epoch constrained to 24hrs
- $z = 0.1086$
- Peak mag : $M_o = -21$
- Full multi-band lightcurve and ESO spectra

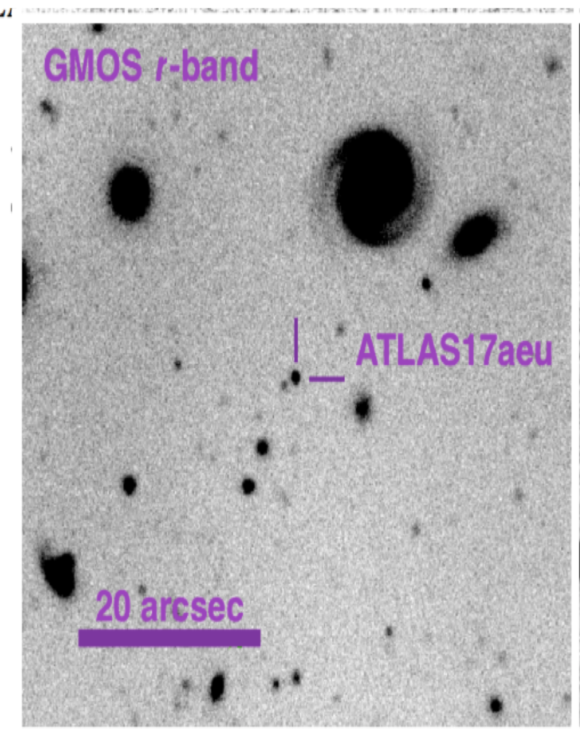
- ATLAS + PESSTO paper in prep (Chen et al.)
- Stunning x-shooter spectra, showing host of narrow <u>absorption</u> !
- Spectra + bolometric lightcurve : suggest pulsational pair instability supernova

Follow-up of LIGO-Virgo GW sources



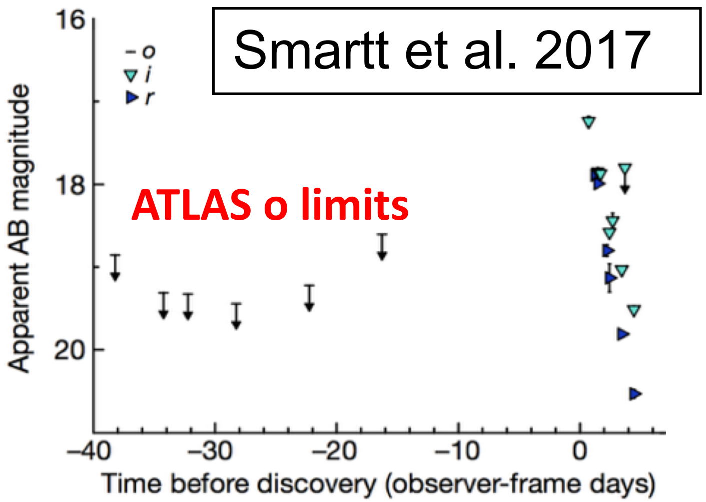
Stalder, Tonry et al 2017.

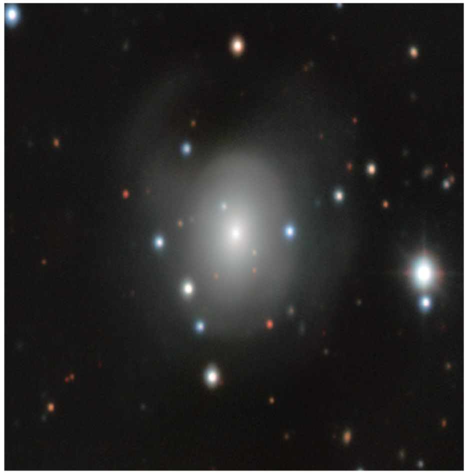




- We showed in O1 and O2 : Powerful facility for finding bright, fast sources in LIGO-Virgo maps
- Discovered ATLAS17aeu (GW170104) – fast transient within 24hrs of GW source
- Turned out to be the afterglow of a GRB – but only 3rd time a GRB afterglow was detected without a high energy trigger

GW170817 : ATLAS limits pre-discovery, closest deep limits on the kilonova AT2017gfo

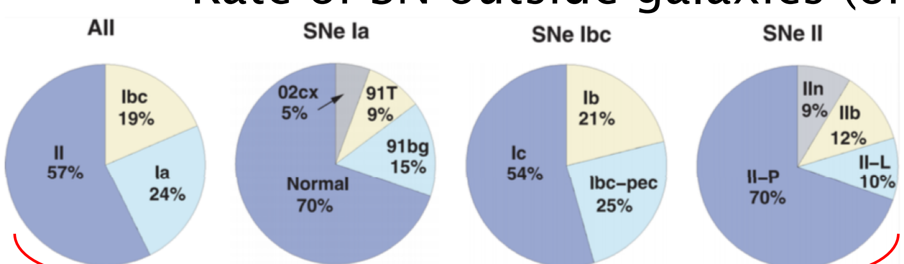




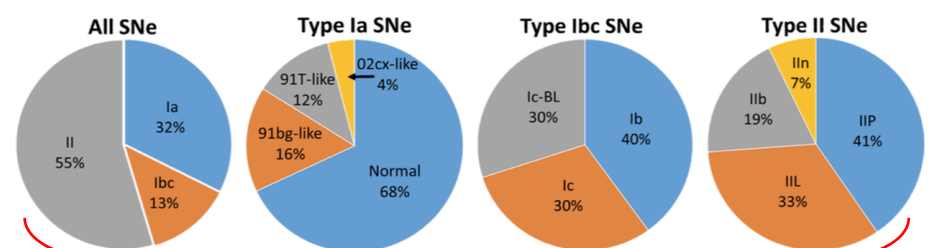
- ATLAS would easily have detected AT2017gfo, except our survey schedule had shifted away from the sun
- Kilonovae are detectable on ATLAS within ~100 Mpc
- Scolnic et al (2018): LIGO-Virgo rates of NS-NS mergers imply ATLAS should find 2 – 10 kilonovae per year, irrespective of GW trigger. ATLAS is the best survey for detecting kilonovae with no GW trigger
- McBrien et al. (in prep) : several candidates from 18 months survey, all foreground CVs, reliable volumetric rate estimate coming. Will provide independent constraint on NS-NS merger rates.

ATLAS Local Universe SN rates

- Lick Observatory SN Search (LOSS)
  - 10 year results (Leaman et al 2011, Li et al 2011)
  - 180 SNe within ~80 Mpc, volume limited sample
  - But – targeted galaxy survey creates bias
- ATLAS initial results
  - 1.7 year period (mostly 1 telescope). No galaxy (metallicity) bias – full volume: all SNe regardless of dwarf host (or no host evident)
  - 77 SNe within ~60 Mpc, volume limited sample
  - Each year we will equal LOSS statistics within ~80 Mpc (but no bias), good light curves and spectra for all
- Preliminary results
  - Agreement with LOSS rates, e.g. Rcc = $0.48 \pm 0.07 \times 10^{-4}$ Mpc^{-3} yr^{-1}
  - Rate of SN outside galaxies (or in dwarfs Mr > −12) is < 5% total rate



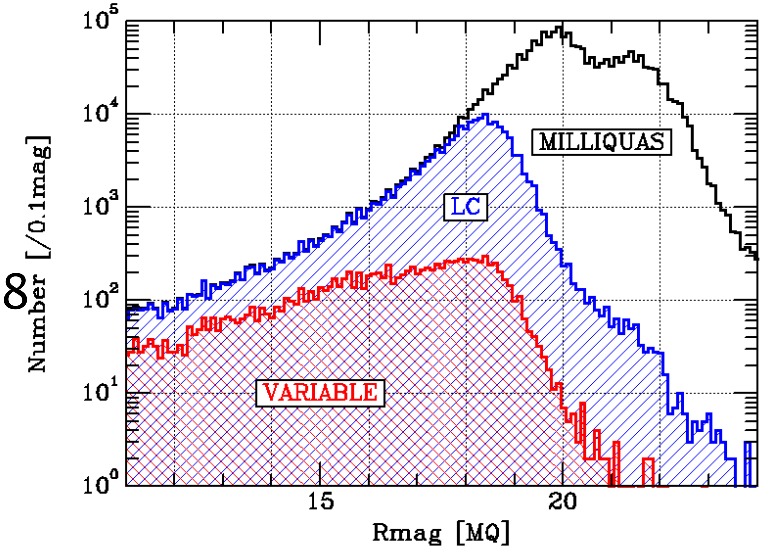
LOSS

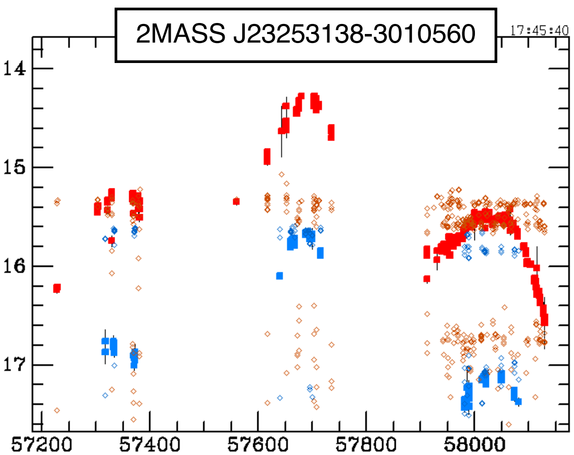


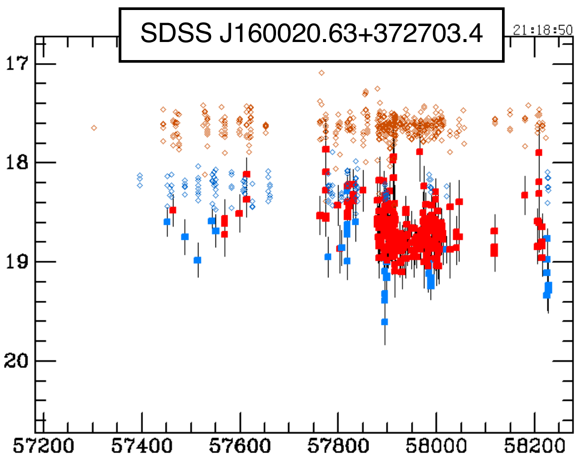
ATLAS

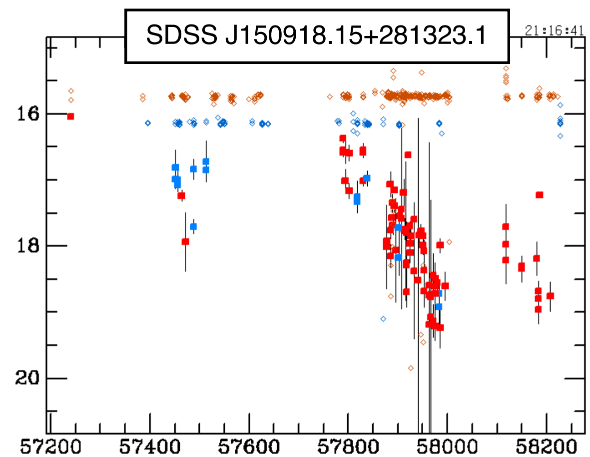
Quasars and ATLAS

- The “Milliquas 5.2” sample
  - ~0.6 million confirmed QSOs
  - ~1.3 million suspected QSOs
- ATLAS DR1 (Dec>-30)
  - Light curves for ~10^5 brighter than R~18
  - ~1/3 at m<15.5 are clearly variable
- ATLAS DR2 (Dec>-45)
  - Light curves for ~2×10^5, better SNR, better time sampling, longer duration









More Opportunities

The data from ATLAS carries lots and lots of other science…

Gravitational Lensing

- Microlensing
  - Lots of generic microlensing events
  - Near-field events: lensing star close enough to see lens and source separate (after a while)
    - m=18 expect ~40 mas/yr proper motion
    - Total expected is ~23 events per year at m<18, 58 events per year at m<19
  - ATLAS will see ~30/yr total, and ~10/yr at high SNR and time coverage

- Strong lensing
  - Expect ~40 AGN lensed at x3 or more, and ~7 AGN lensed at x10 or more.
  - These are likely to have multiple images and accessible time delay

Results

Nobody has yet looked in our 500,000,000 detections…

Galaxies

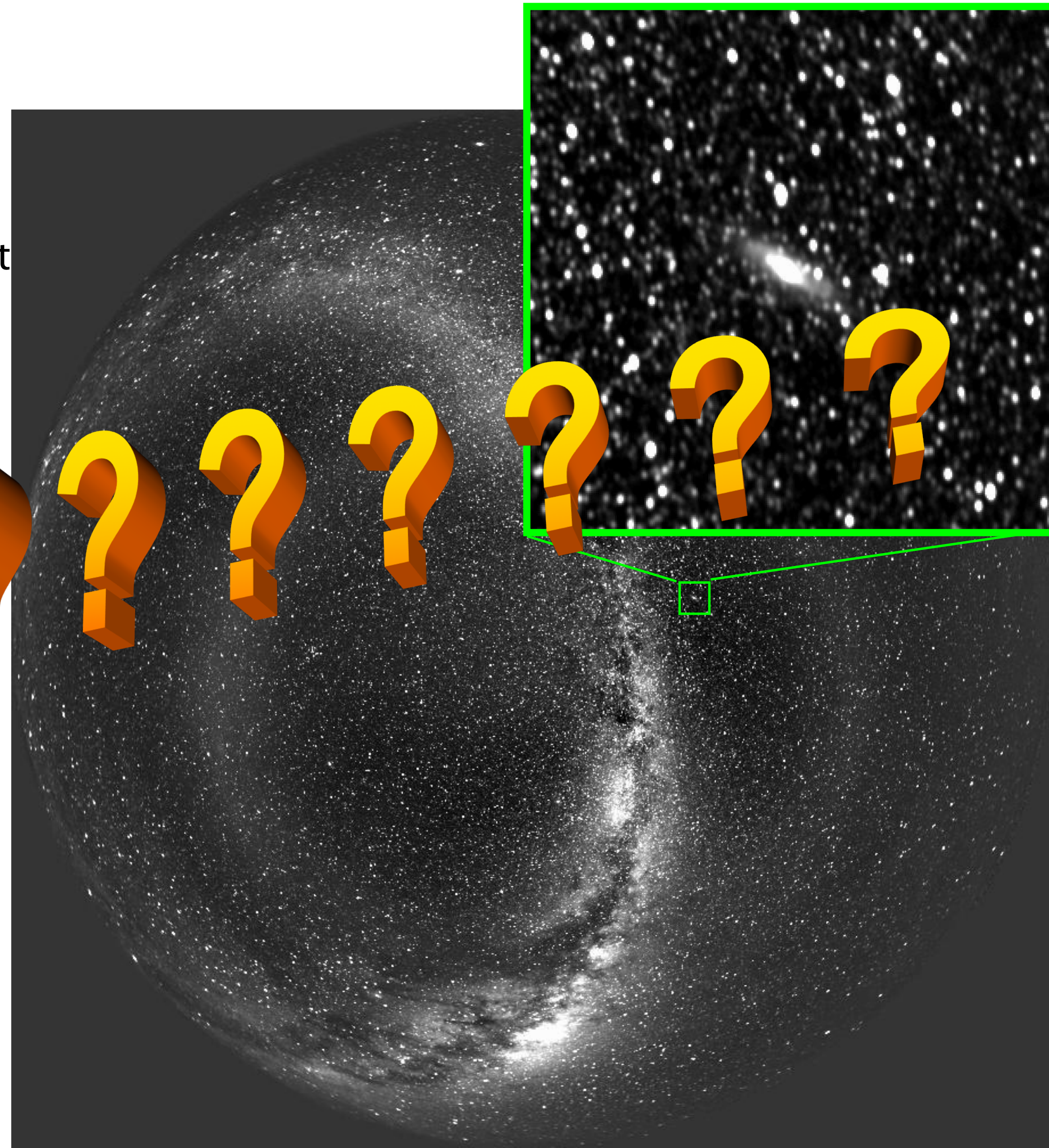
- Low surface brightness
  - ATLAS does very well for building up SNR at low surface brightness.
  - Ongoing project to determine all-sky surface brightness to high accuracy in order to remove atmospheric glow and scattered light…
- Low metallicity
  - ATLAS can search for $H\alpha$ and [OIII] at $z<0.004$
    - all-sky survey to m_{AB}~17 (point source) in one night
    - $f \sim 2 \times 10^{-14}$ erg/s/cm^2 or $L \sim 10^5 L_\odot$/s at 17 Mpc.
- Outbursts comparable to galaxy luminosity will be seen in substantial numbers
  - ~20 BH stellar accretion events (MV ~ −18) per year at 0.1mag photometric accuracy

Results

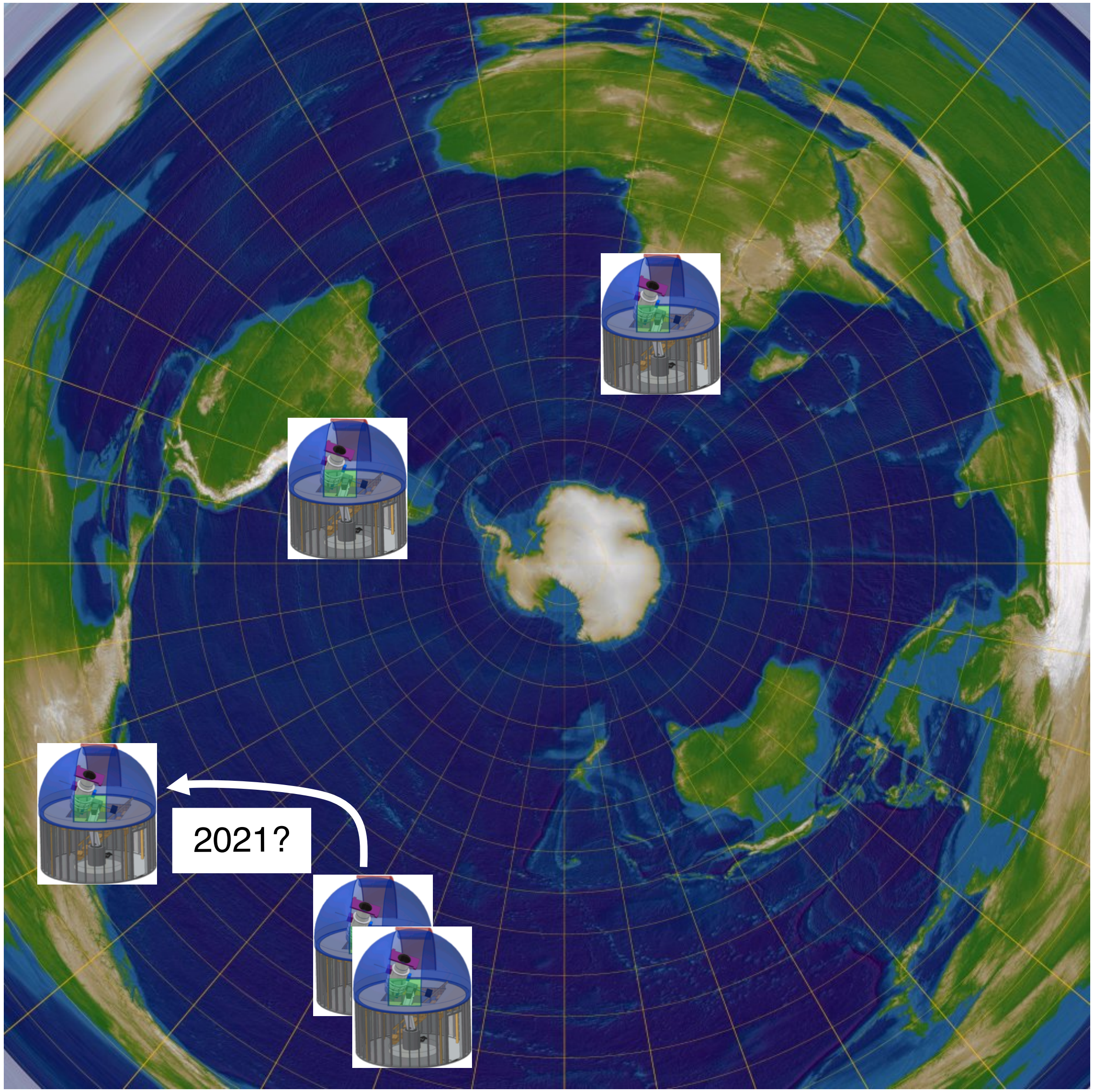
Nobody has yet made a case for the observations…

Unknown Unknowns from Fisheyes

- Fisheyes monitor all sky continuously
  - 100mi separation disambiguates flashes that occur in the atmosphere
  - m_{lim}~7 for $\Delta t<1$ min
  - m_{lim}~9 for $\Delta t<1$ hour
  - m_{lim}~10 for $\Delta t<1$ day
  - m_{lim}~12 f … < … nth



ATLAS expansion (late 2020)



Heather Flewelling,
Planetary Defense Researcher

John Tonry, ATLAS PI

Brian Stalder, Postdoc
(now with LSST)

Stephen Smartt

Larry Denneau, Co-PI

Ken Smith

Henry Weiland,
Observatory Tech

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Ari Heinze, Postdoc

The ATLAS Team

- IFA Manoa
  - John Tonry
  - Larry Denneau
  - Andrei Sherstyuk RIP
  - Brian Stalder
  - Ari Heinze
  - Henry Weiland
  - Jessica Young
  - Karl Uyehara
  - Amy Miyashiro
  - Richard Wainscoat
- IFA Maui
  - Mike Maberry
  - Joey Perreira
  - Tom McCall
  - Garry Nitta
- IFA Hilo
  - Klaus Hodapp
- External
  - Armin Rest
  - Stephen Smartt
  - Ken Smith
  - Alan Fitzsimmons
  - Chris Stubbs
- Friends
  - Phil Whitney
  - Gareth Wynn-Williams
  - Chris Oliver
  - The STAC

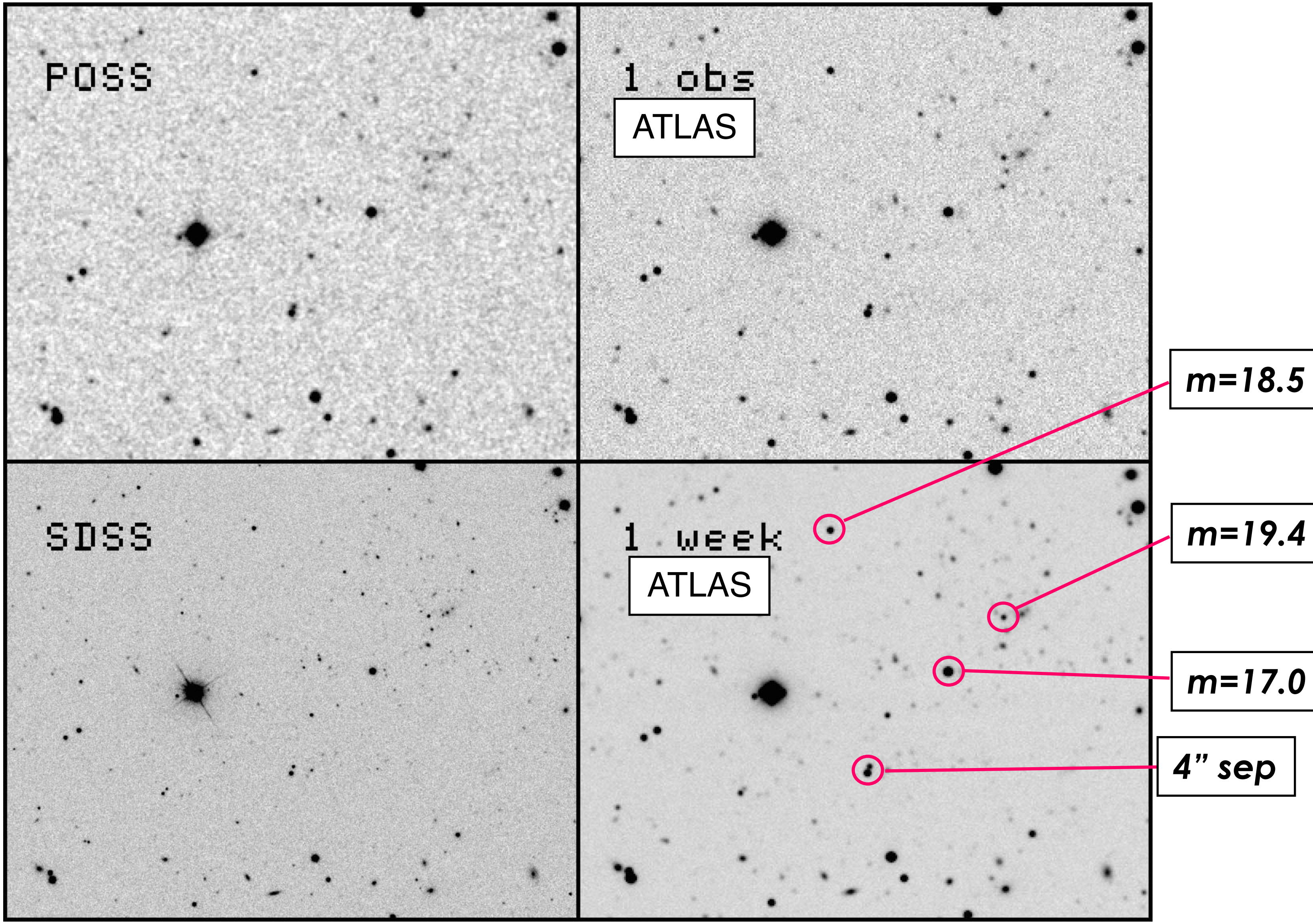
Static Sky

- ATLAS observes most of the sky ~500 times per year
  - m~23.4 from one year stacked sensitivity at 5σ
    - ~3 mag fainter than POSS
    - ~1 mag fainter than SDSS
    - similar to PS1 3pi 3 year (but only 2 bandpasses)

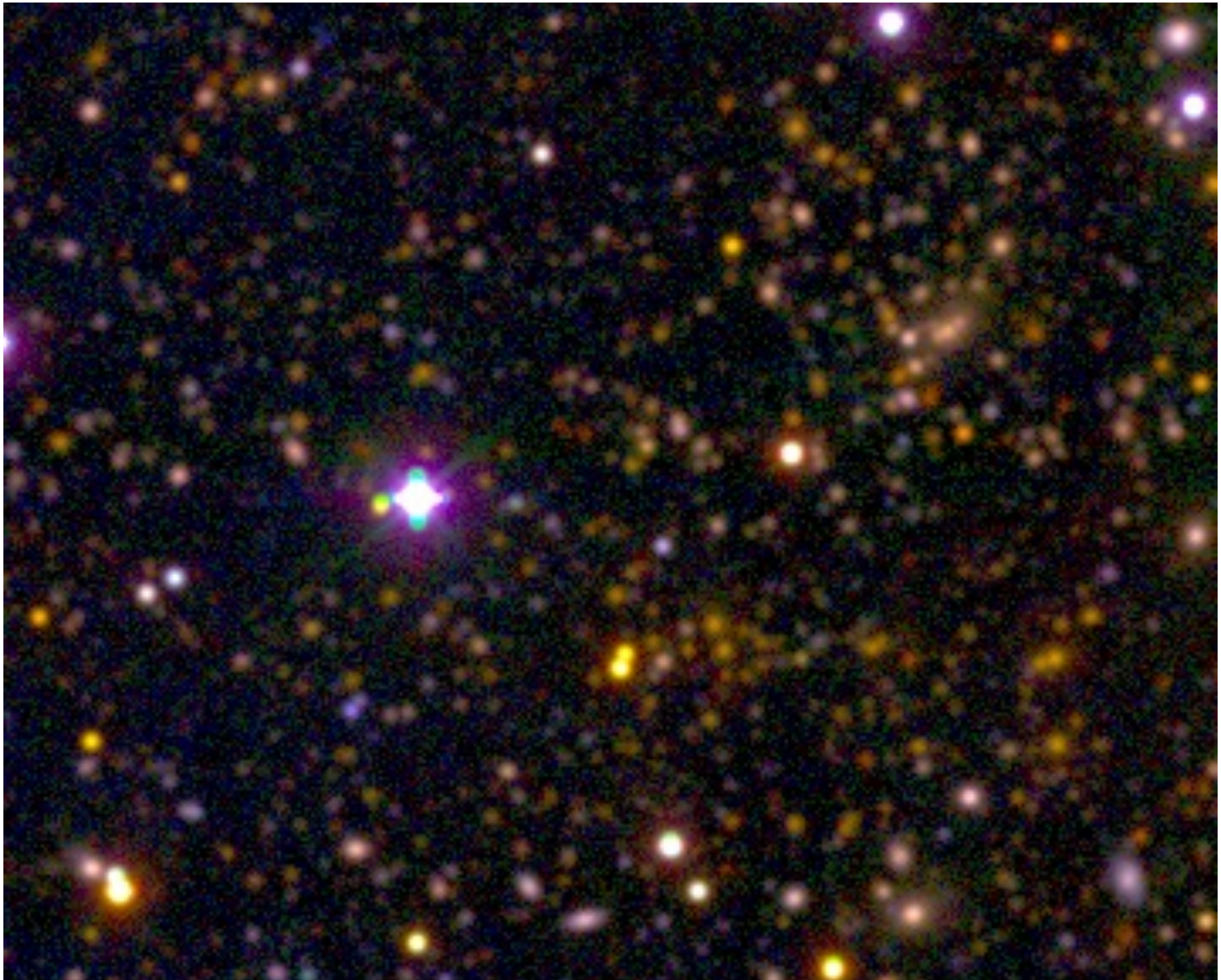
- *But note* highly confused for static sources, although excellent for differencing

- *Unconfused* for variable sources: ATLAS has a sliding sensitivity into variability structure function:
    - m~20.6 at 1 day,
    - m~21.7 at 10 day,
    - m~22.9 at 100 day.

ATLAS-POSS-SDSS Comparison



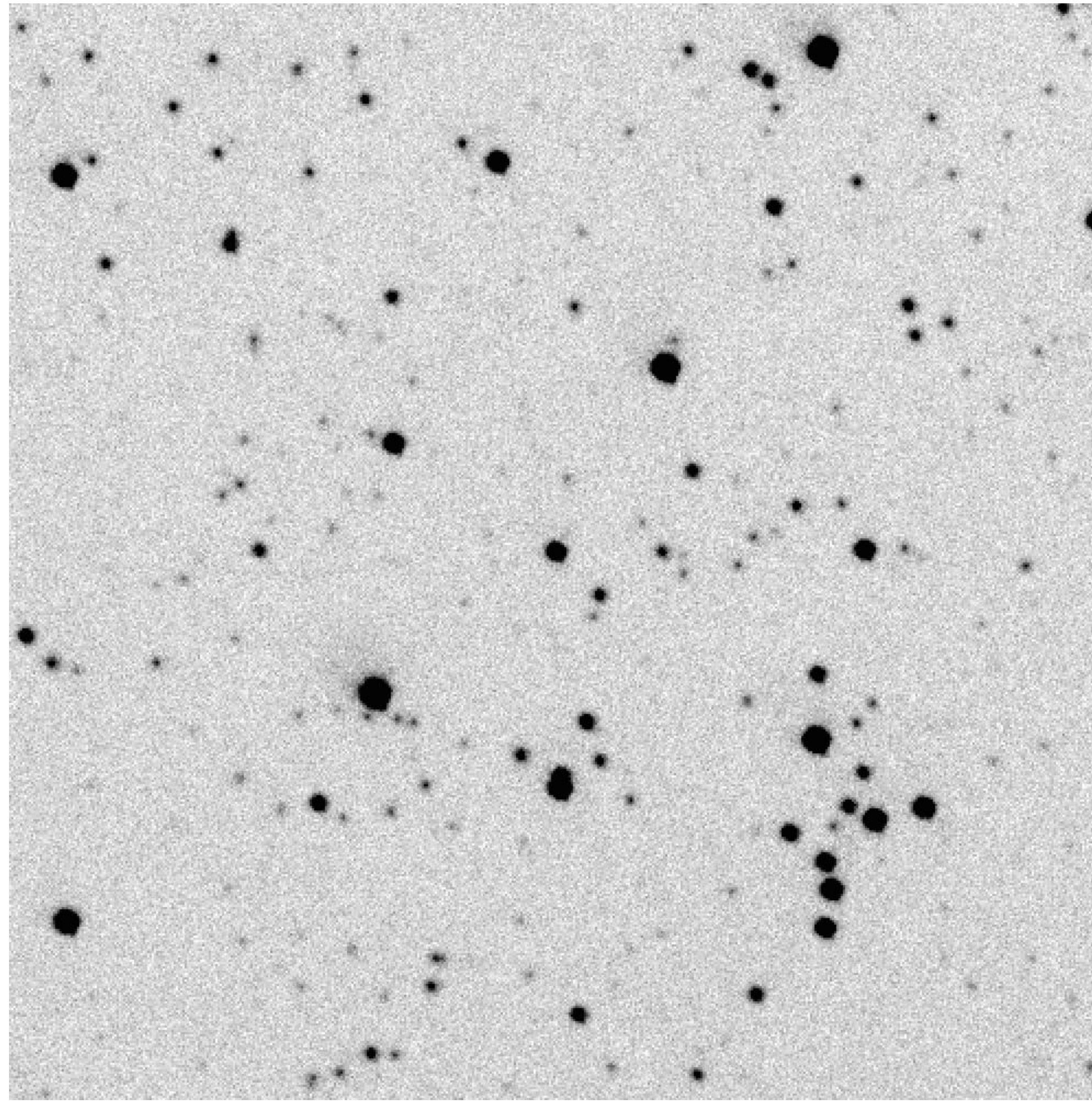
ATLAS: one year observation



SDSS

Schmidt corrector saga: 150601 — 170419

- PSF ~ 3.7 pixels
  ~ 7.0 arcsec
- m_{lim} ~ 19

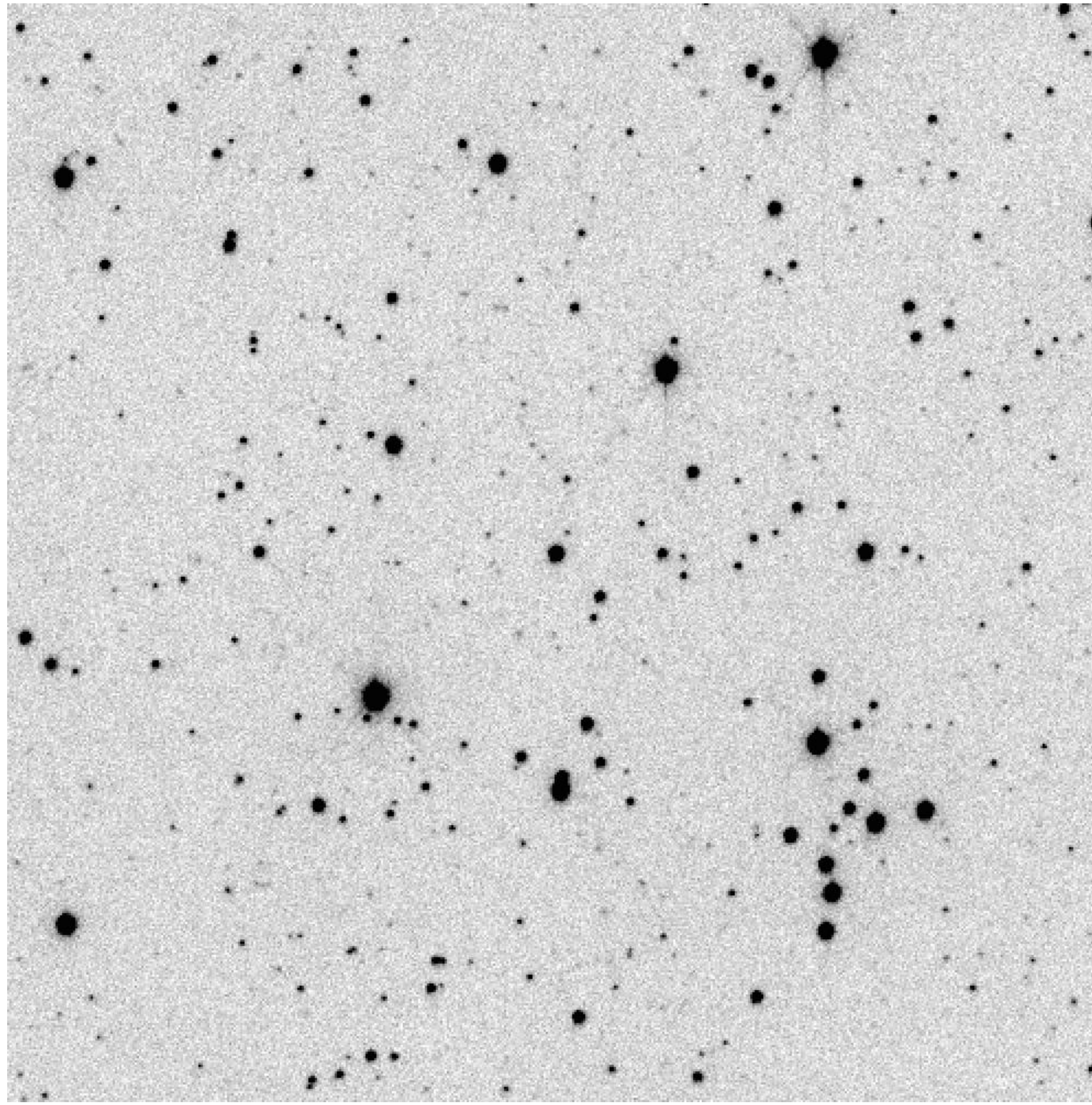


(All results in this talk are from the first telescope on HKO with blurry images. From now on we gain ~1 mag at fixed uncertainty or 2.5x smaller uncertainty at fixed mag.)

Schmidt corrector saga: 170420 —

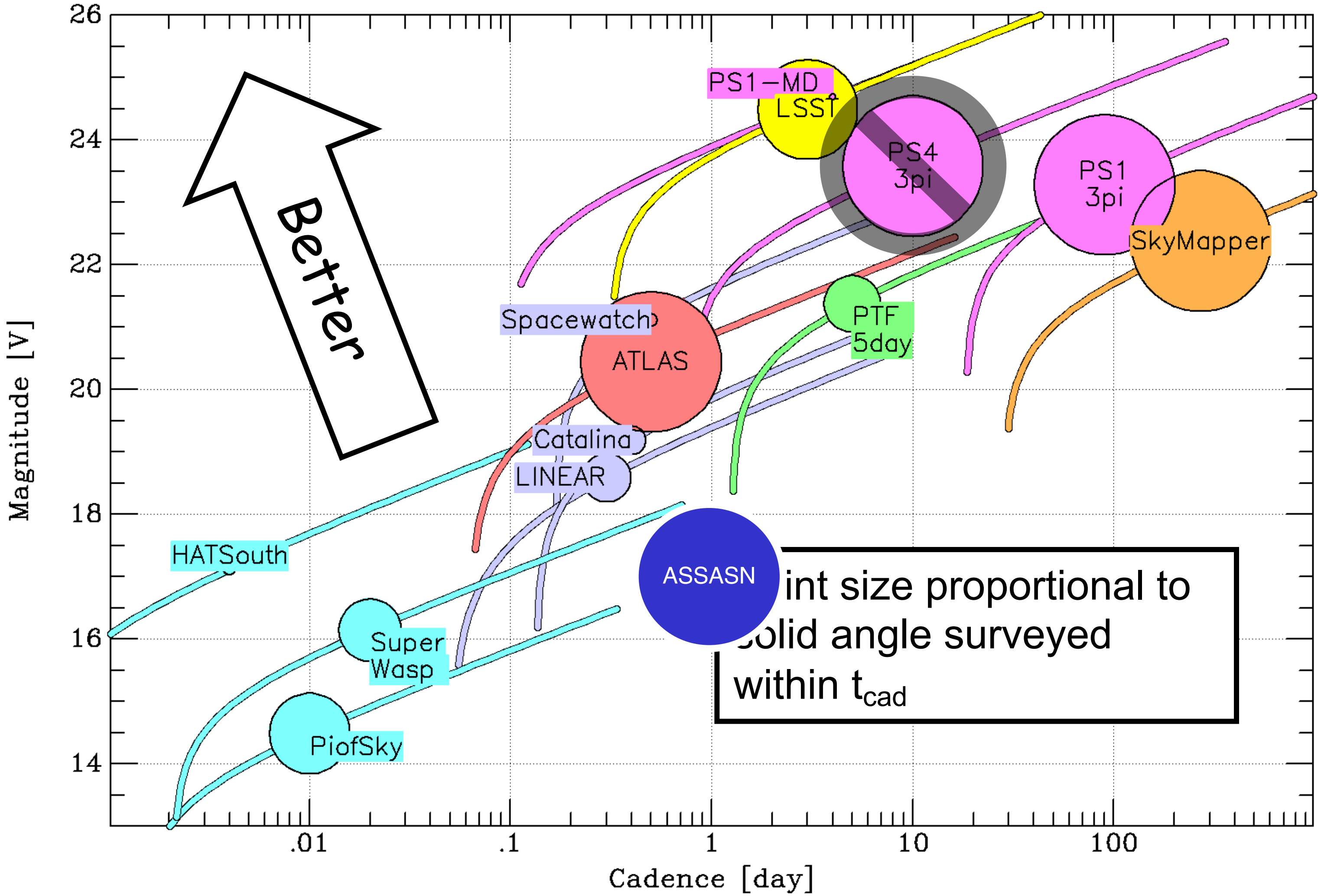
- PSF ~ 2.0 pixels
  ~ 3.7 arcsec
- m_{lim} ~ 20

- PSF < 2 pixels?
  - Collimation
  - Detector tilt
  - Focus
  - Tracking
  - Dome seeing



(All results in this talk are from the first telescope on HKO with blurry images. From now on we gain ~1 mag at fixed uncertainty or 2.5x smaller uncertainty at fixed mag.)

Survey Speed



Tonry 2011, PASP 123, 58

Survey Speed

$$M = \underbrace{\frac{A\Omega_0\epsilon\delta}{\omega}10^{+0.4(\mu+m_0)}}_{\boxed{\text{Design}}} = \underbrace{\frac{S_1^2\Omega}{t_{\mathrm{cad}}}10^{+0.8\,\mathrm{m}}}_{\boxed{\text{Operation}}}. \qquad (9)$$

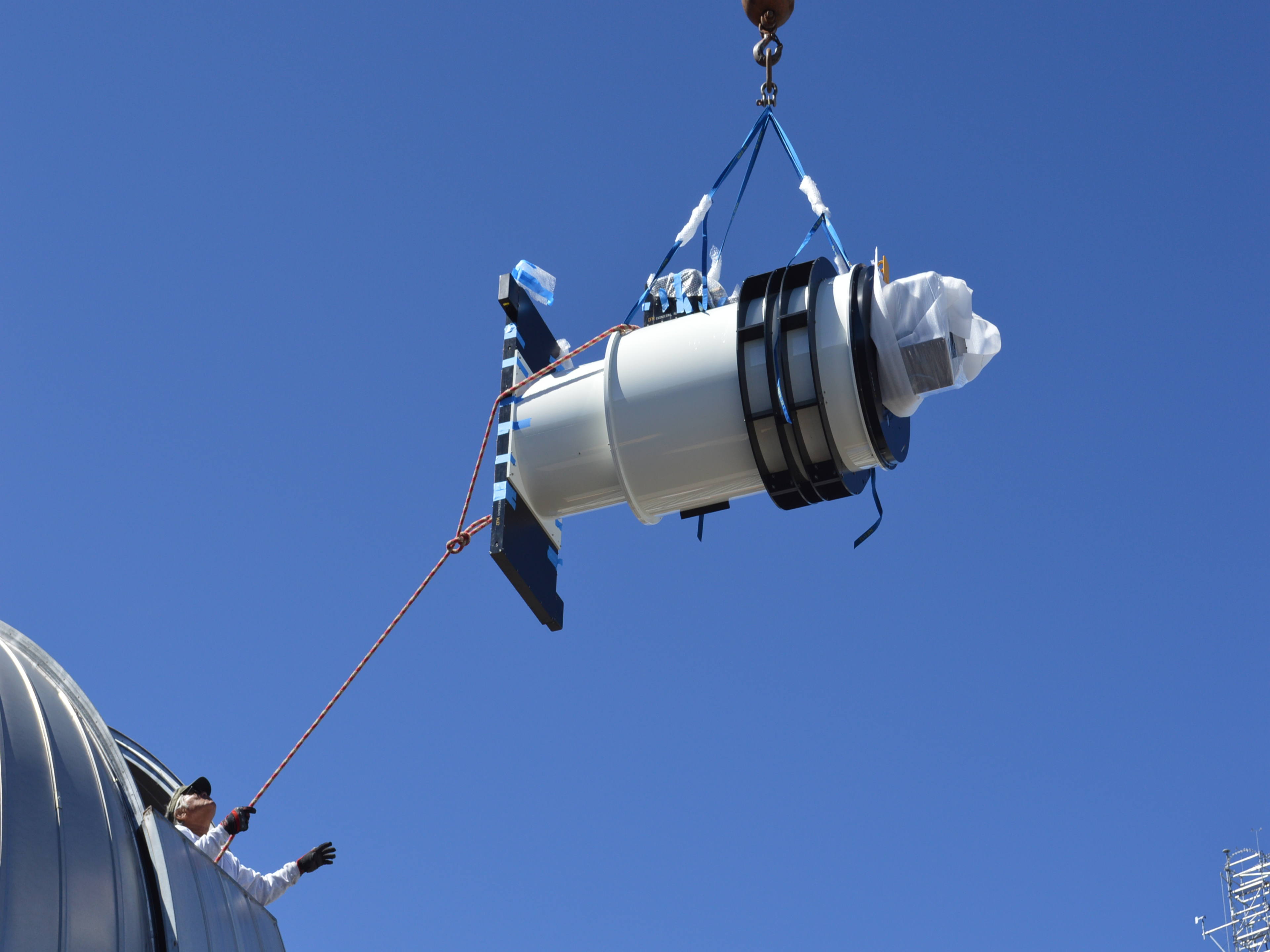
Tonry 2011 PASP 123, 58

- M = "survey speed"
- A = aperture area
- Ω_0 = solid angle per exposure

- ω = PSF area = "effective noise" footprint
- ε = throughput efficiency
- δ = duty cycle

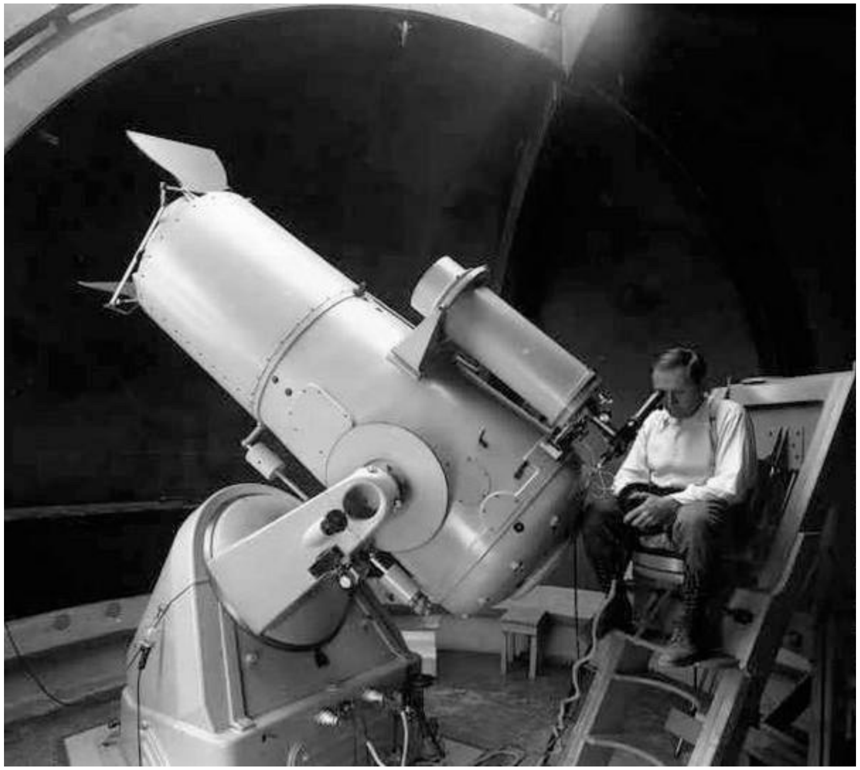
- μ = sky brightness

- S_1 = SNR per exposure
- Ω = total solid angle covered in t_{cad}
- m = detection magnitude
- t_{cad} = cadence for covering Ω



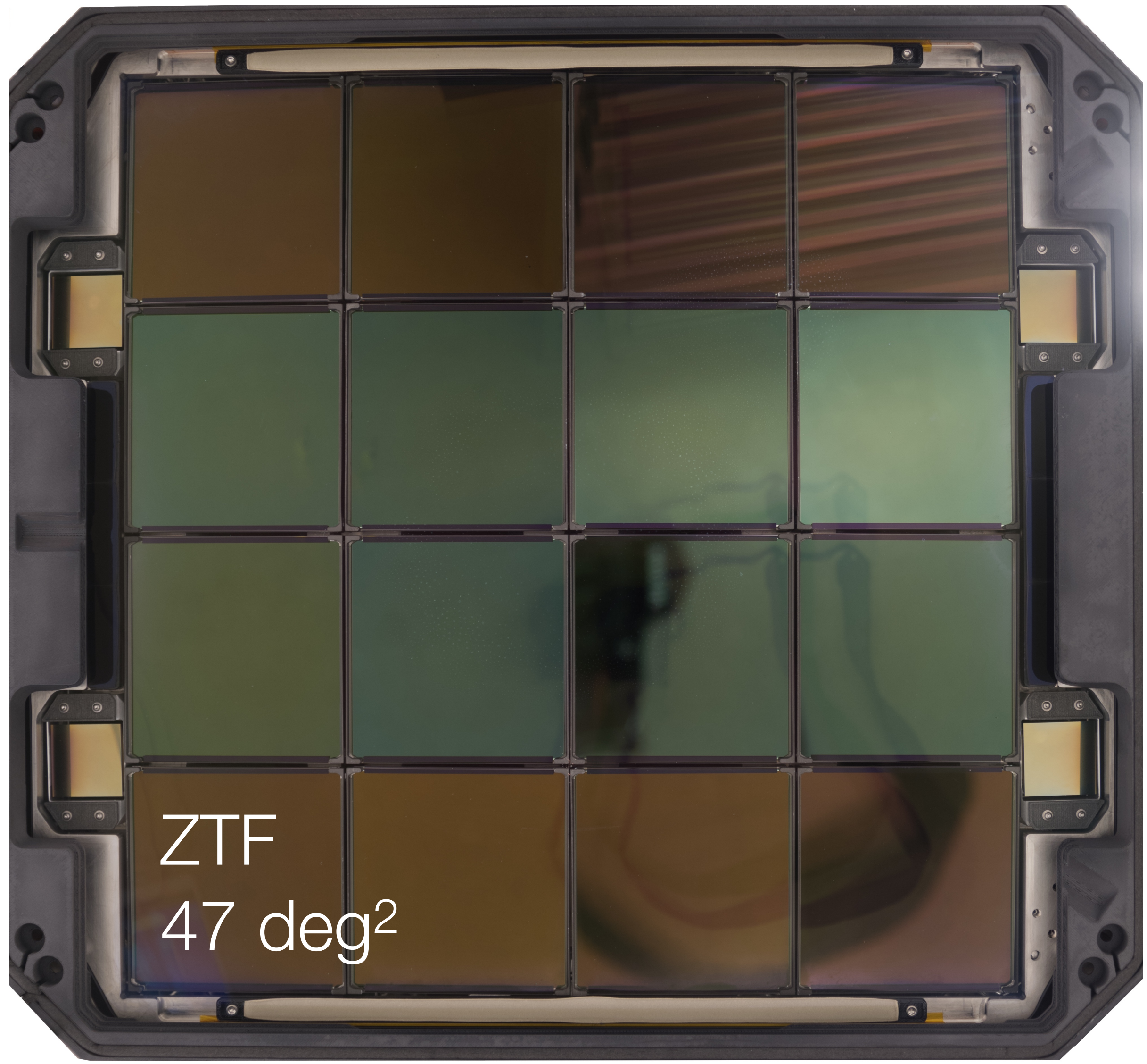
ZTF Surveys & Performance

Eric Bellm
Survey Scientist
University of Washington



ZTF surveys with a powerful new wide-field camera.

	ZTF
Active Area	47.7 deg^2
Exposure Time	30 sec
Readout time	8.2 sec
Filters	g / r / i
Image Quality (FWHM)	2.1” / 2.0” / 2.1”
Limiting magnitude	20.8 / 20.6 / 19.9
CCDs	16x 6k x 6k 1.0”/pixel
Filter change time	~ 110 sec with slew to slow
Areal survey rate	4300 deg^2/hr



Bellm+ 2019a

A PASP Focus Issue provides key references for ZTF.

Publications of the Astronomical Society of the Pacific

https://zwicky.tf/3w9

The Zwicky Transient Facility

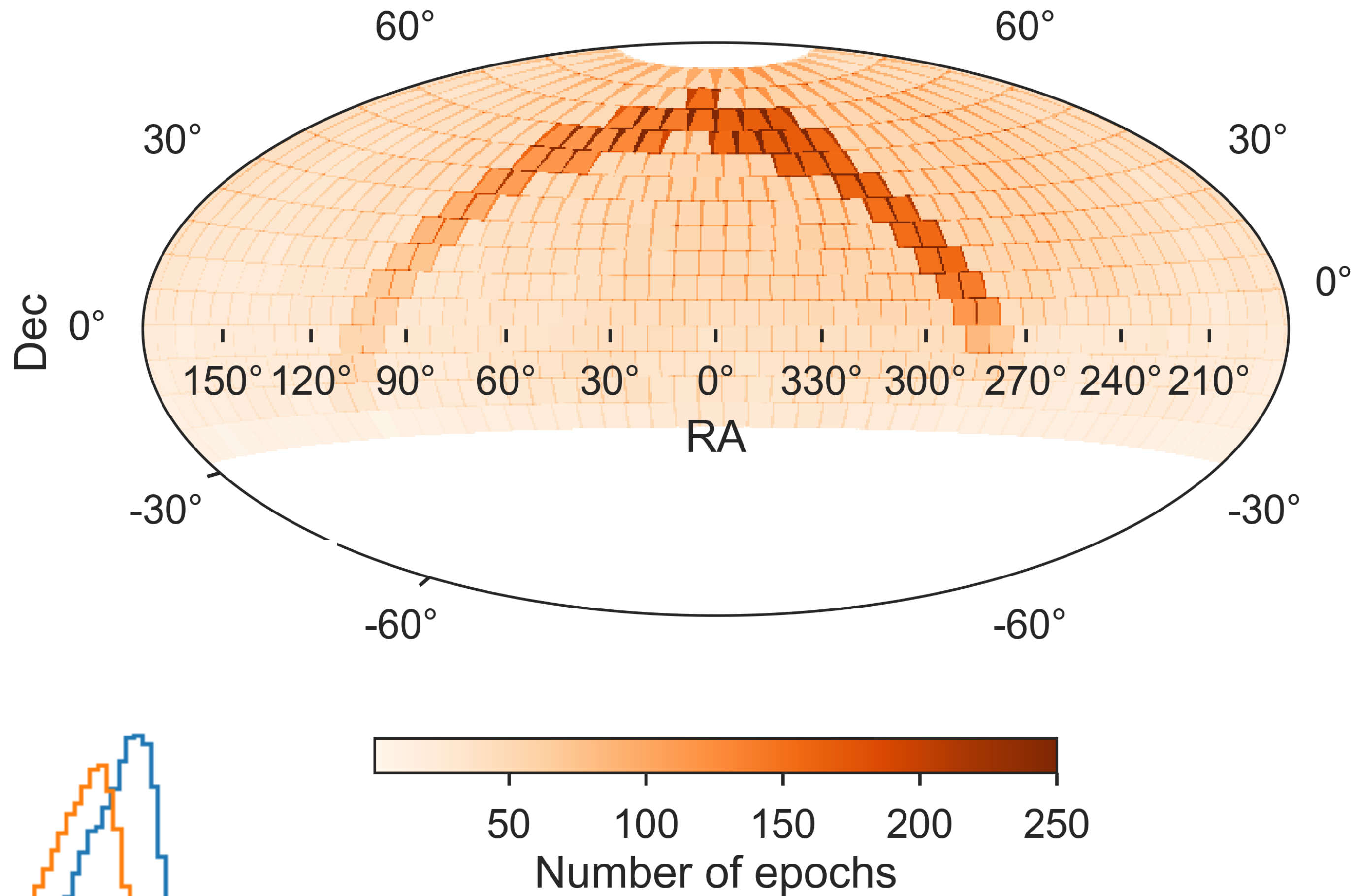
Eric C. Bellm, *University of Washington, USA*

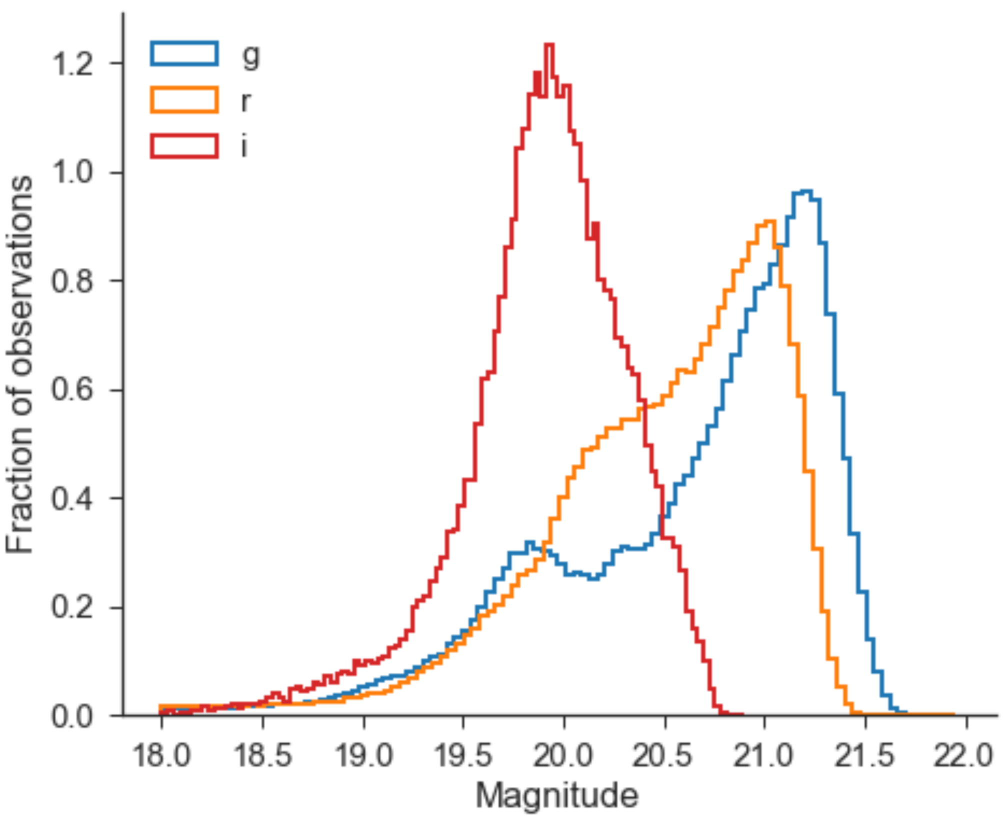
The Zwicky Transient Facility (ZTF) is a new optical time-domain survey using the 48 inch Schmidt Telescope at Palomar Observatory. An innovative new wide-field CCD mosaic camera provides a 47 square degree instantaneous field of view and fast readout time. This capability enables ZTF to conduct wide-area, high-cadence surveys designed to discover rare astrophysical transients, variables, and moving objects. A dedicated data system provides rapid reduction and near-real-time dissemination of public alerts that anticipate those of the Large Synoptic Survey Telescope. Articles in this focus issue present a broad overview of the ZTF project, including:

Credit: Caltech Optical Observatories

- Origins of and scientific motivations for the ZTF project
- Detailed system specifications
- Design of the camera and observing system
- Implementation of the data reduction pipelines and data archive
- Software tools developed to enable ZTF science, including the alert distribution system, machine learning classifiers, and web portals
- An overview of the planned ZTF surveys
- On-sky performance
- Expected scientific returns
- First scientific results

ZTF sources are well-matched for SDSS followup.





ZTF is conducting an unusually large number of surveys simultaneously.

Program	Survey	Total Area	Cadence
Public Surveys (MSIP; 40%)	Northern Sky Survey	23,675 deg^2	3 day cadence 1 g, 1 r
	Galactic Plane Survey	2800 deg^2	1 day cadence 1 g, 1 r
ZTF Collaboration Surveys (40%)	Extragalactic High Cadence Survey	3000 deg^2	4 day cadence 1 i
	i-band Survey	10,725 deg^2	1 day cadence 3 g, 3 r
	Target of Opportunity	Varies	Varies
	High-Cadence Plane Survey	~2100 deg^2	> 2.5 hours continuous, r
	Twilight Survey	N/A	4 r
	Asteroid Rotation Survey	N/A	> 25 r
Caltech TAC Surveys (20%)	Varies	Varies	Varies

We optimize ZTF for discovery.

Maximize volume surveyed per image:

$$V = \frac{4\pi}{3} d^3$$

$$\propto 10^{0.6 m_{\mathrm{lim}}}$$

(to maximize SNR, use $10^{0.8 m_{\mathrm{lim}}}$)

Limiting magnitude depends on:

filter, sky brightness, airmass, seeing

So: **maximize the *volume-weighted* number of images observed in acceptable cadence windows.**

Bellm 2016, Bellm+ 2019b

We optimize ZTF for discovery.

Maximize volume surveyed per image:

$$V = \frac{4\pi}{3} d^3$$
$$\propto 10^{0.6 m_{\rm lim}}$$

(to maximize SNR, use $10^{0.8 m_{\rm lim}}$)

Limiting magnitude depends on:

filter, sky brightness, airmass, seeing

optimization algorithm

objective function

So: maximize the ***volume-weighted*** number of images observed in acceptable cadence windows.

observing strategy

Bellm 2016, Bellm+ 2019b

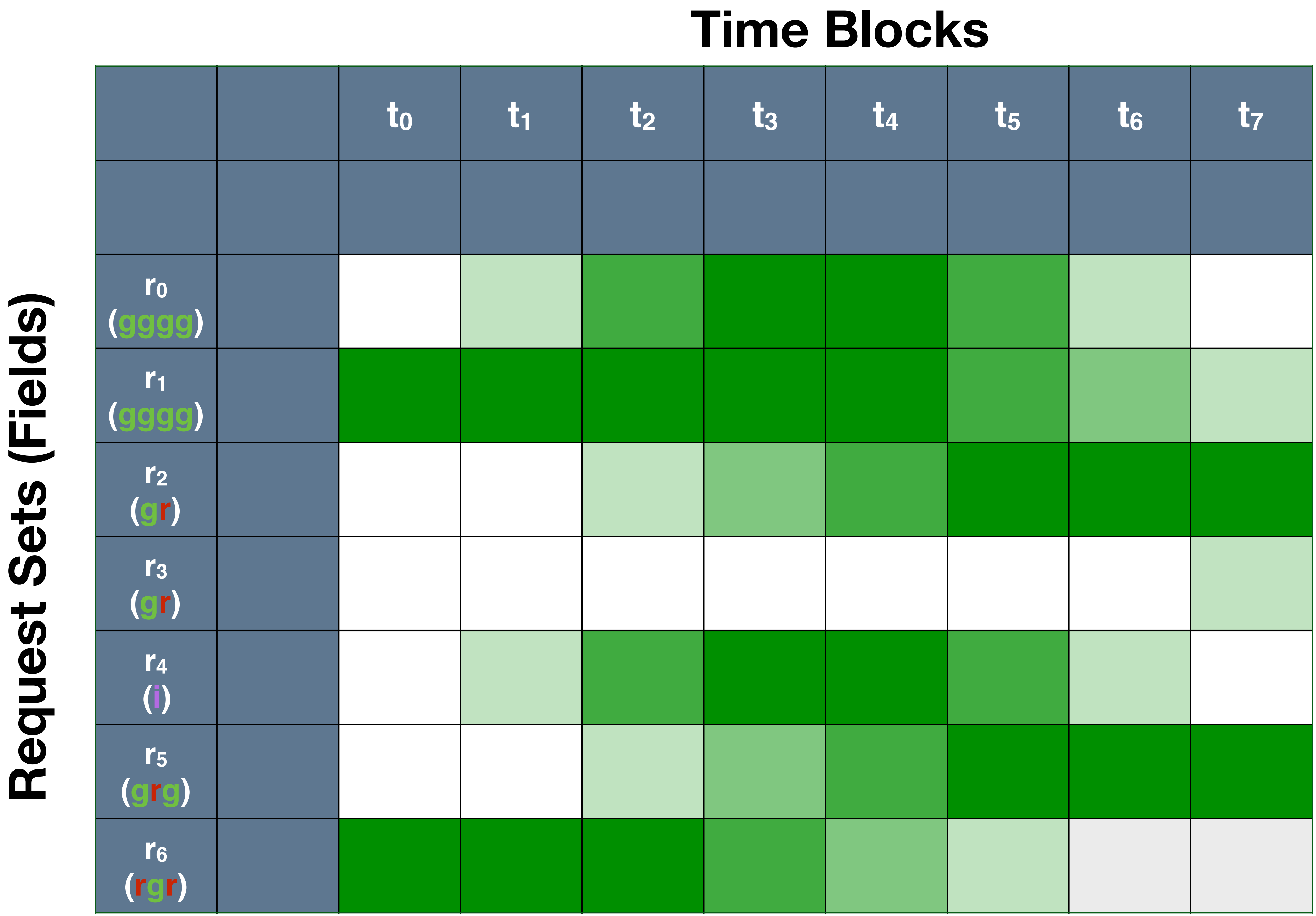
A grid approach enables a nightly solution.

Time Blocks

Request Sets (Fields)

		t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7
r_0 (gggg)									
r_1 (gggg)									
r_2 (gr)									
r_3 (gr)									
r_4 (i)									
r_5 (grg)									
r_6 (rgr)									

A grid approach enables a nightly solution.



We use Integer Programming techniques to perform nightly optimization.

V_{rtf} Volume factor for request field r at time t in filter f

Y_{rtf} ("yes") =1 if we observe r at t in f, 0 otherwise

maximize $$\sum_{r\in R}\sum_{t\in T}\sum_{f\in F} V_{rtf} Y_{rtf}$$

GUROBI OPTIMIZATION

subject to

$$\sum_{t\in T} Y_{rtf} \leq n_{rf} \; \forall \; r \in R, f \in F$$

number of requests in this set

$$\sum_{r\in R} Y_{rtf} \leq n_{\max} \; \forall \; t \in T$$

number of observations in this slot

Bellm+ 2019b

And enforce one filter per slot + program balance

A grid approach enables a nightly solution.

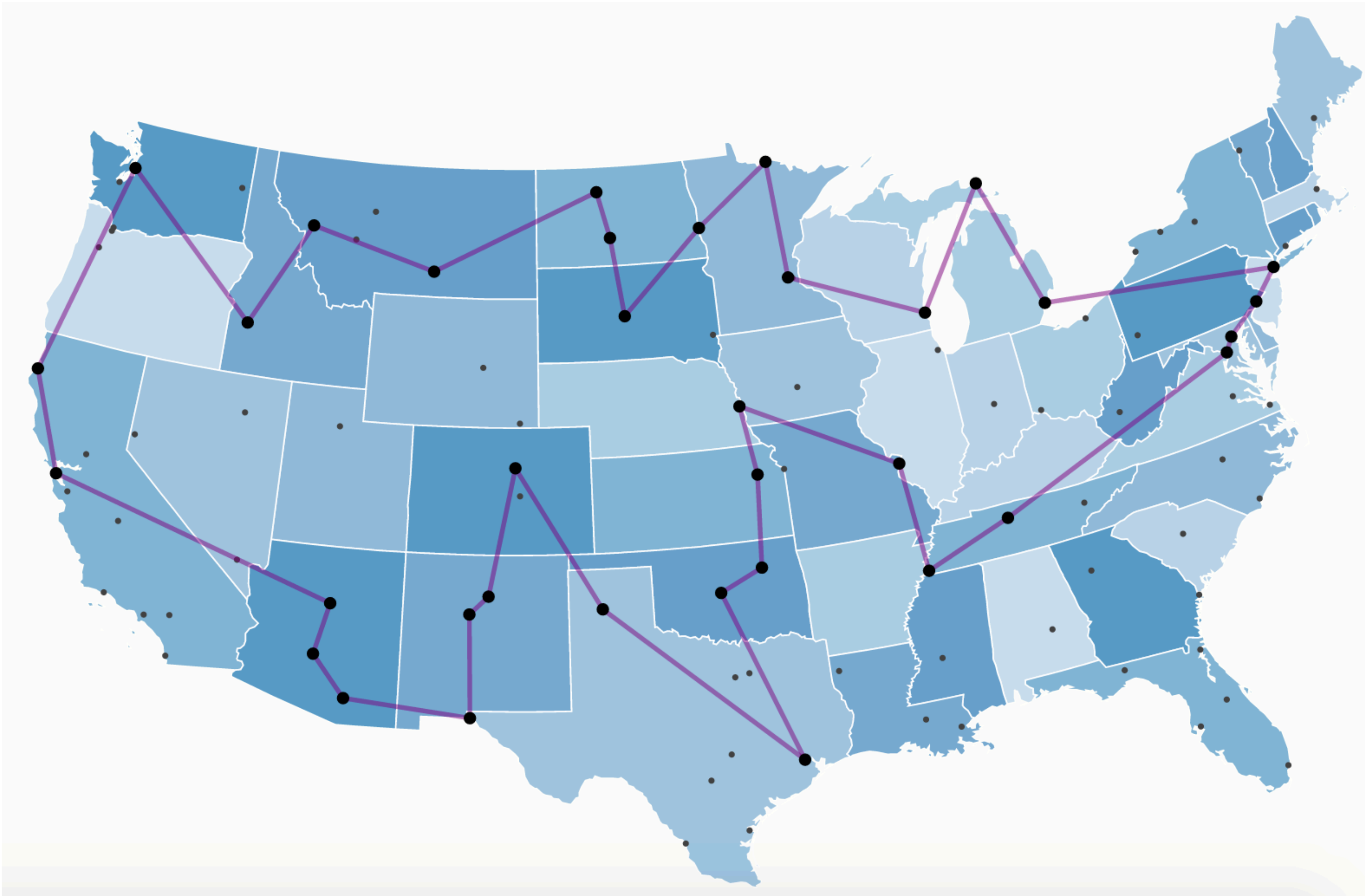
Time Blocks

Request Sets (Fields)

		t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7
		g	r	g	g	i	g	g	r
r_0 (gggg)	$Y_0=1$			X	X		X	X	
r_1 (gggg)	$Y_1=1$	X		X	X		X		
r_2 (gr)	$Y_2=1$							X	
r_3 (gr)	$Y_3=0$								
r_4 (i)	$Y_4=1$					X			
r_5 (grg)	$Y_5=1$						X	X	X
r_6 (rgr)	$Y_6=0$								

Then we sequence each block by solving the TSP.

Distances defined by slew time between requests in this block.



HA and Declination slews don't change with slot, but dome slews do.

Optimization requires tradeoffs!

Strengths:

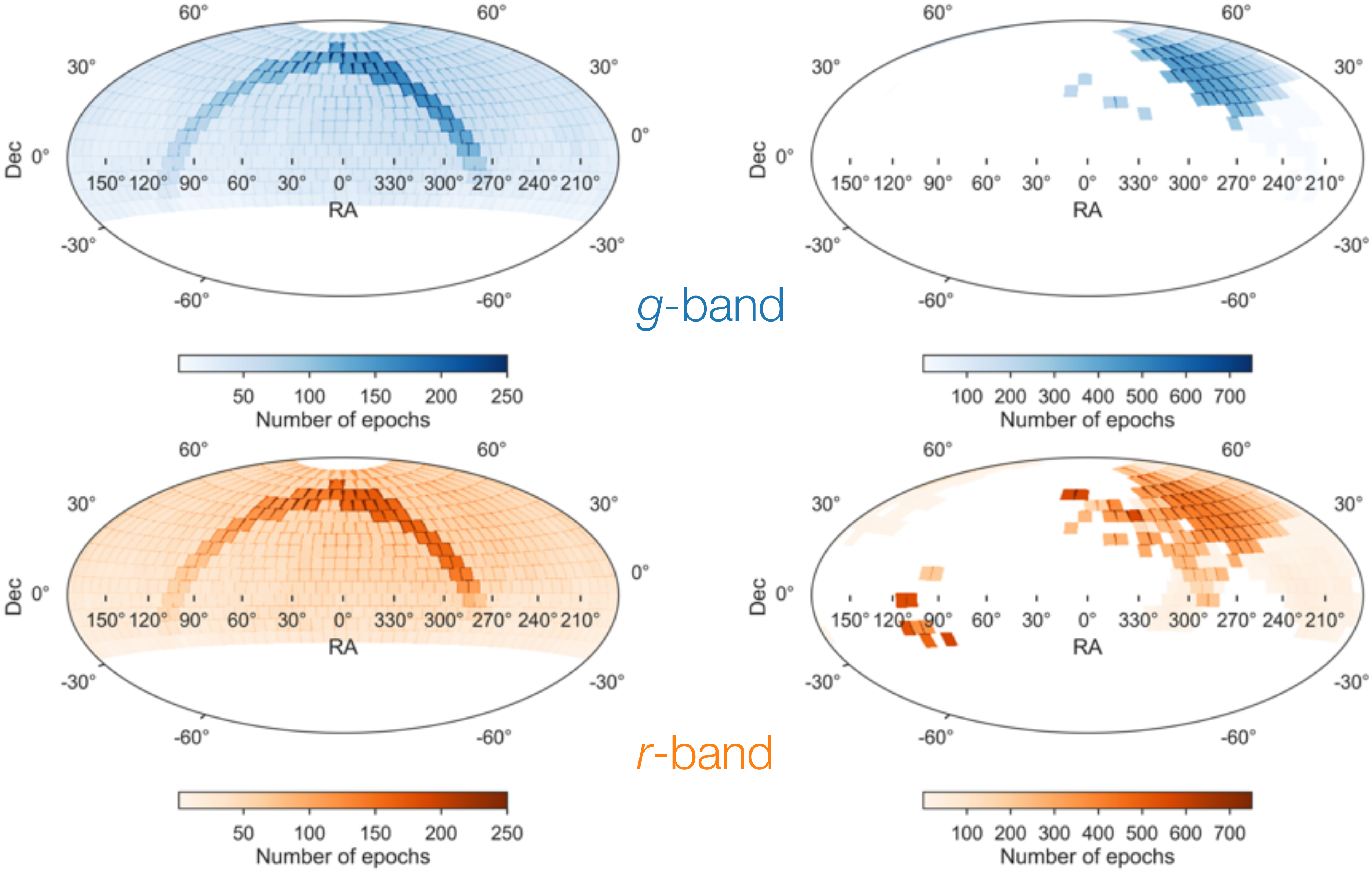
obtains requested observations exactly
maintains cadences
uses lookahead to schedule observations for best conditions
treats surveys uniformly
maintains balance between programs
minimizes slew time*

Weaknesses

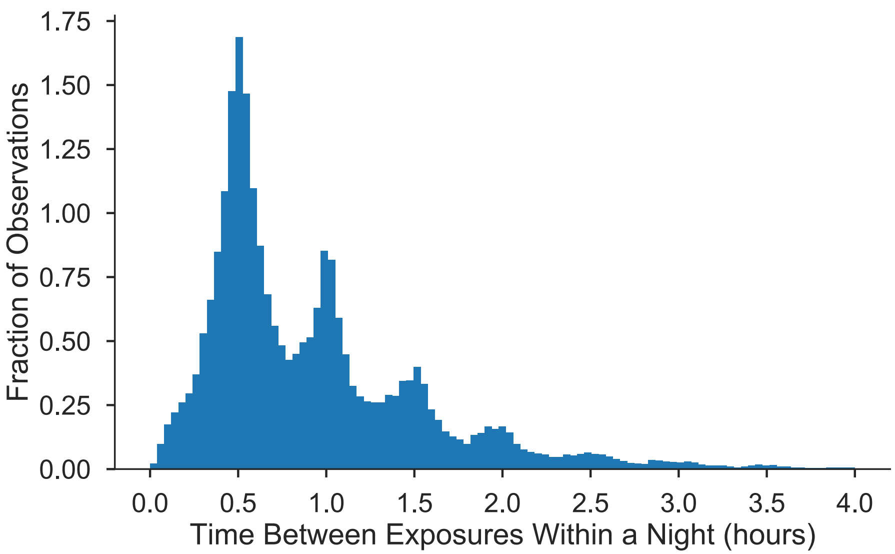
cannot guarantee filter order within the night
cannot enable specifying exact times between observations*
does not always fill all observing time
does not (yet) dynamically adapt to clouds, seeing, etc.

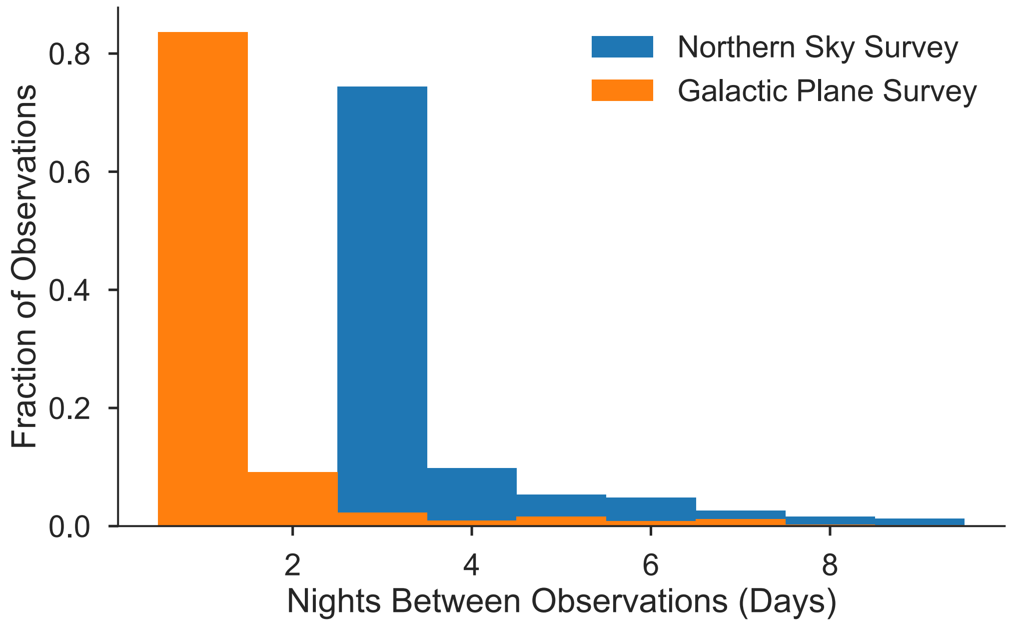
ZTF provides extensive coverage of the Northern sky.

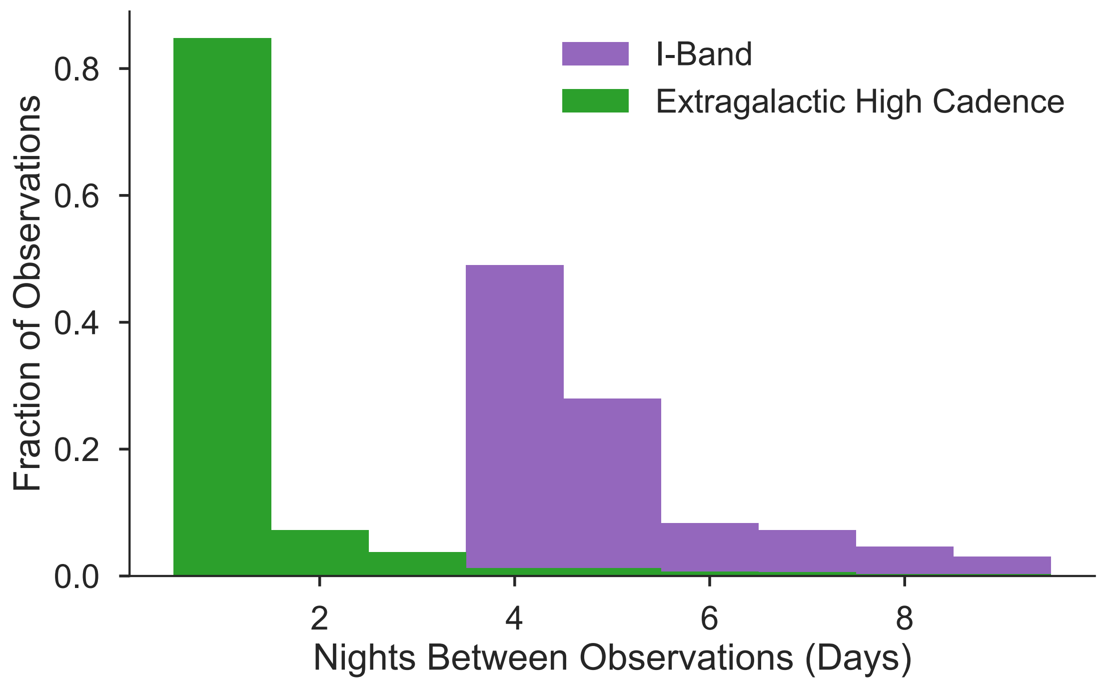
MSIP | Collaboration



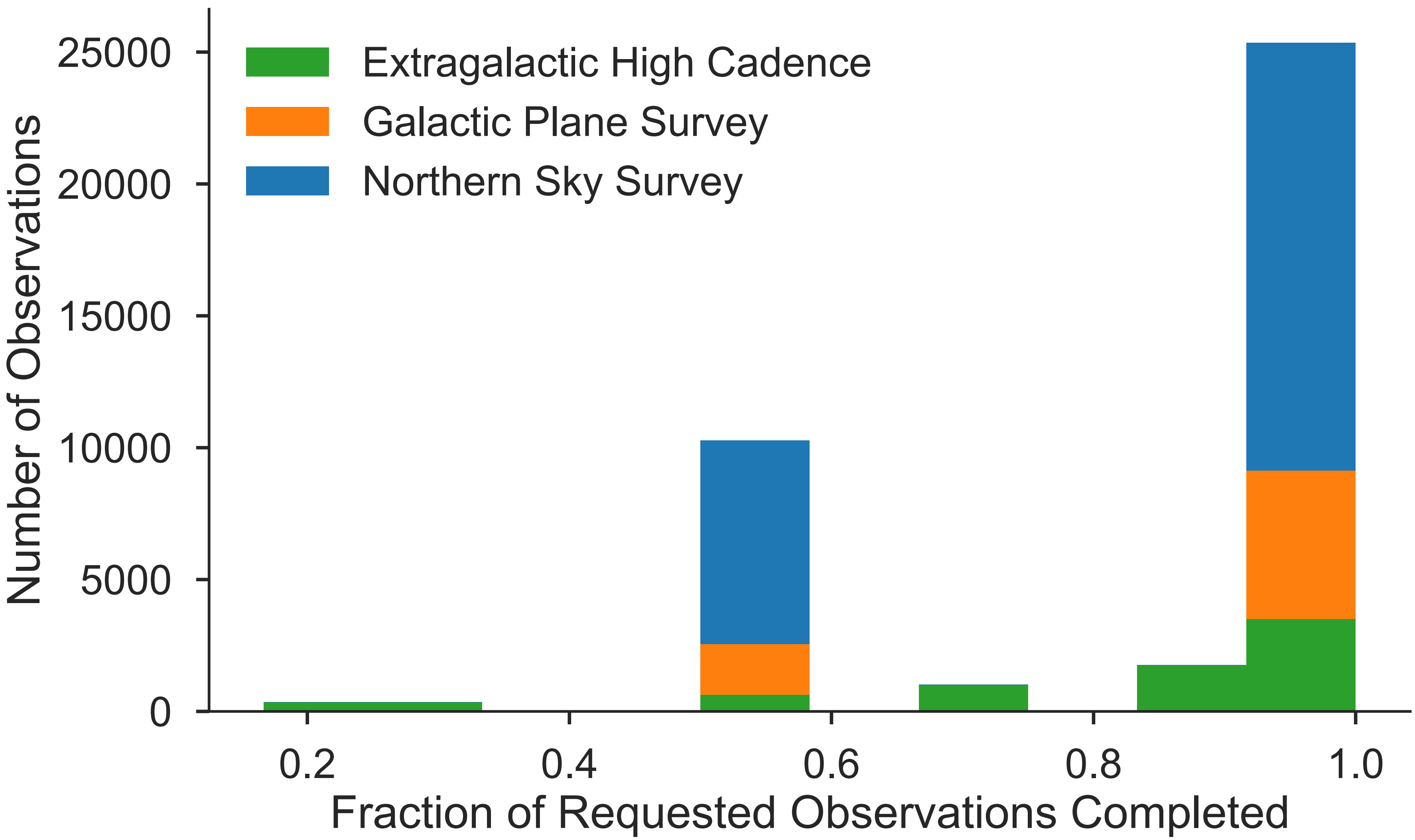
A variety of simultaneous observing programs can be conducted.





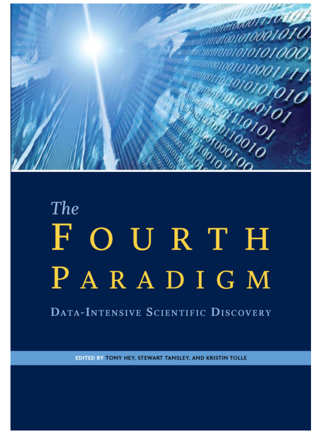


Sequence completion is very high.



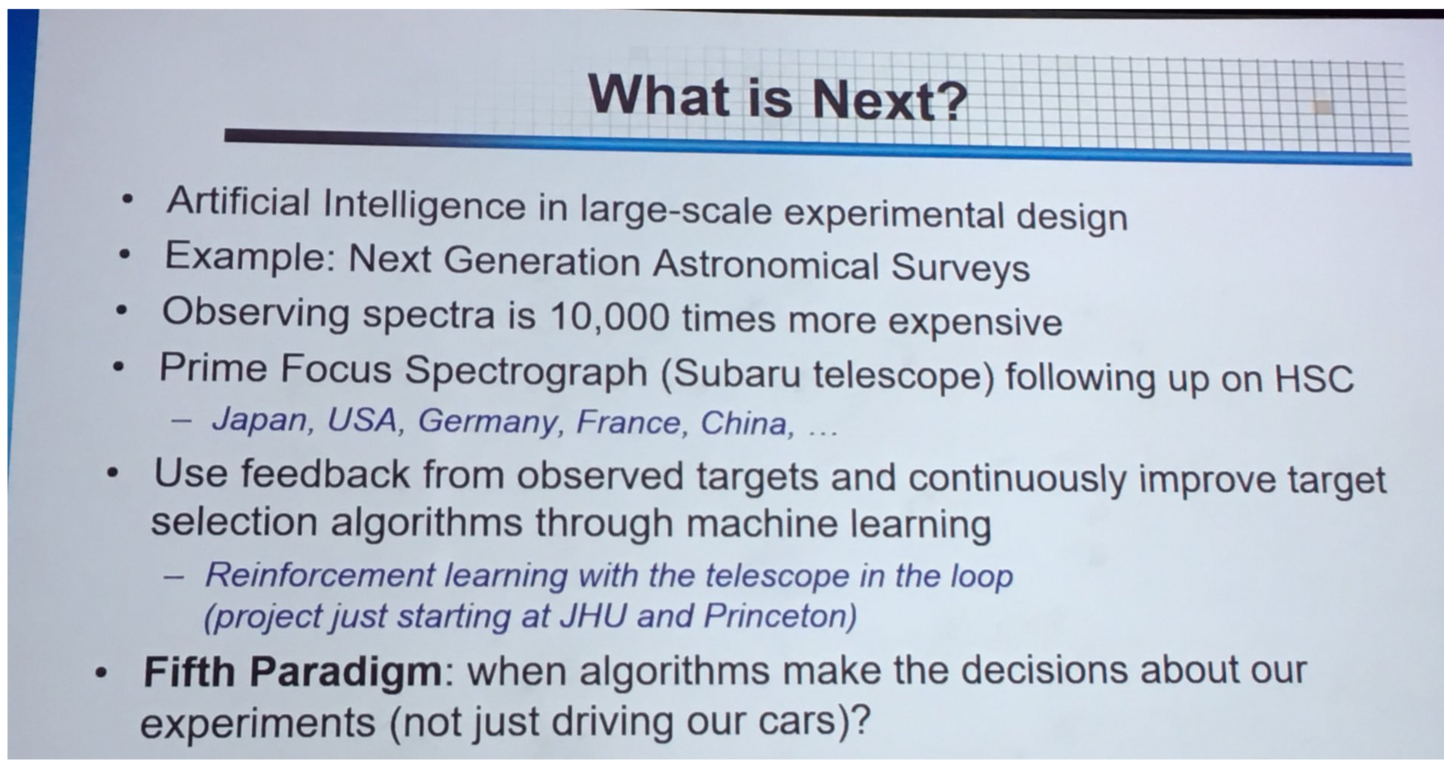
ZTF II x SDSS V: The Fifth Paradigm?

Scientific Paradigms:



1. Observation
2. Analytic Theory
3. Computational Science
4. Data-Intensive Science
5. **Algorithmically-Driven Science (“Self driving surveys”)**

Alex Szalay



Conclusions

ZTF is conducting a powerful time-domain survey across the Northern Hemisphere Sky, with hundreds of epochs yearly in three bands

Image depths make ZTF sources well-matched to SDSS-V followup

The ZTF scheduler can deliver multiple simultaneous time-domain surveys simultaneously

The future of surveys is algorithmic!
Could ZTF-II and SDSS-V scheduling be coupled?

Application of Machine Learning for Stellar Astronomy

By Jan van Roestel

Machine learning

"Machine learning" is a collection of methods (algorithms) that perform a function (classification, regression, clustering, ranking,...), but of instead of being programmed by a human, are optimized using the data itself.

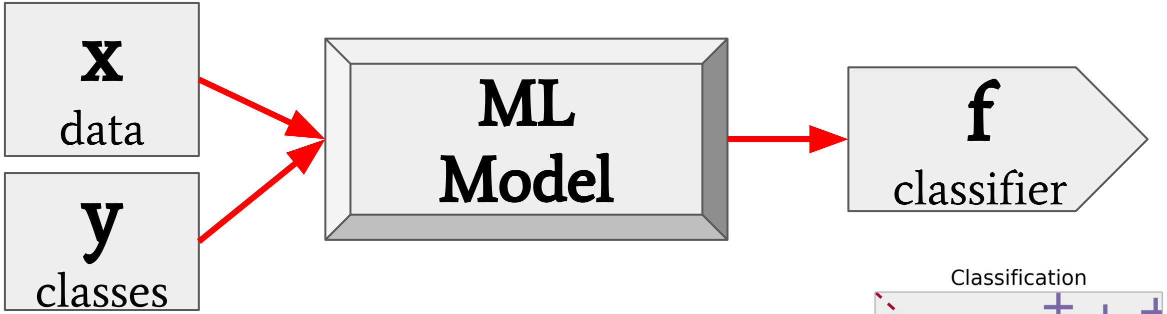
Machine learning can be separated into two types:

1. **Supervised machine learning**
   A subset of the data is known (**'training data'**) and is used to create the ML-model. This is the most common type (in astronomy)
2. **Unsupervised machine learning**
   Nothing is known about the data; the ML-model is created from all data. Examples are principal component analysis (PCA), clustering, data-compression.

Supervised Machine Learning Classification

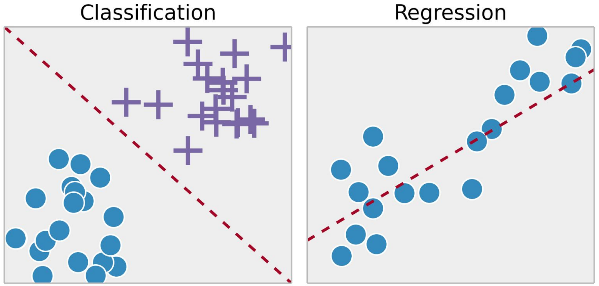
Function ‘f’, which maps input **‘x’** to **‘y’.**

Supervised machine learning: use a known sample (**x**&**y**) to make **‘f’**



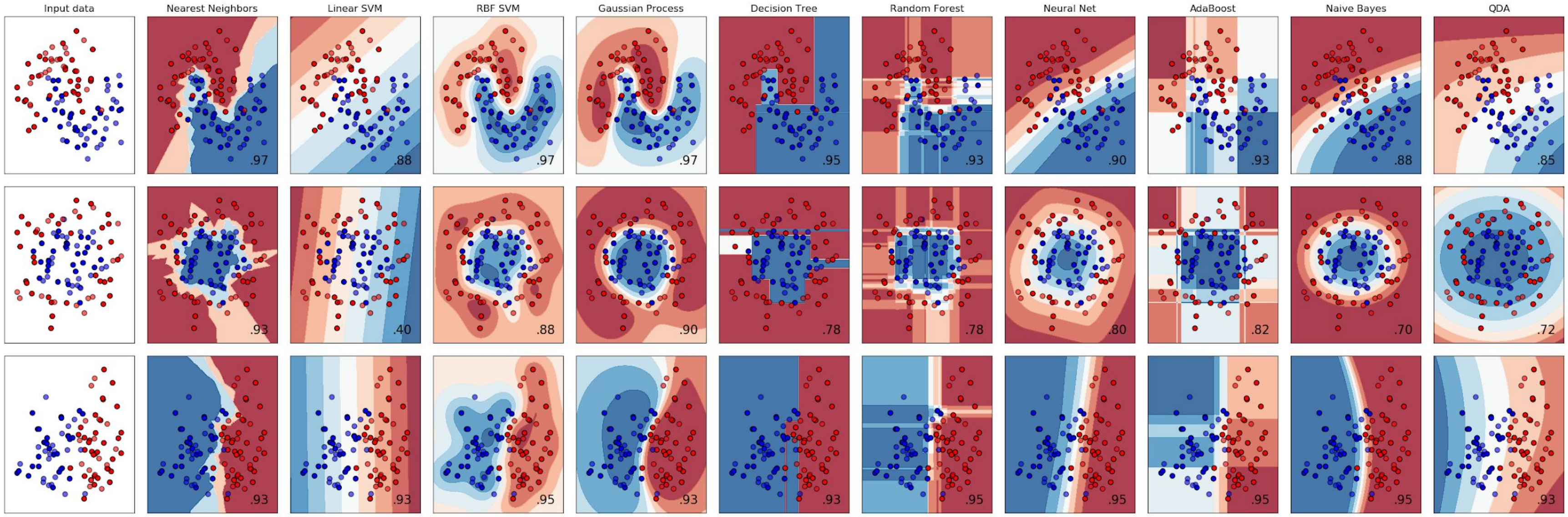
If **y** is discrete; a task is called **‘classification’**

If **y** is continuous; it is called **‘regression’**



A set of very flexible tools

Different types of machine learning methods exists. The choice of algorithm depends on the goal and type of input data, but also on how much it can be used as a black box. Many common algorithms are implemented in the **python package** **Scikit-learn**.



Two most popular algorithms: Random Forest

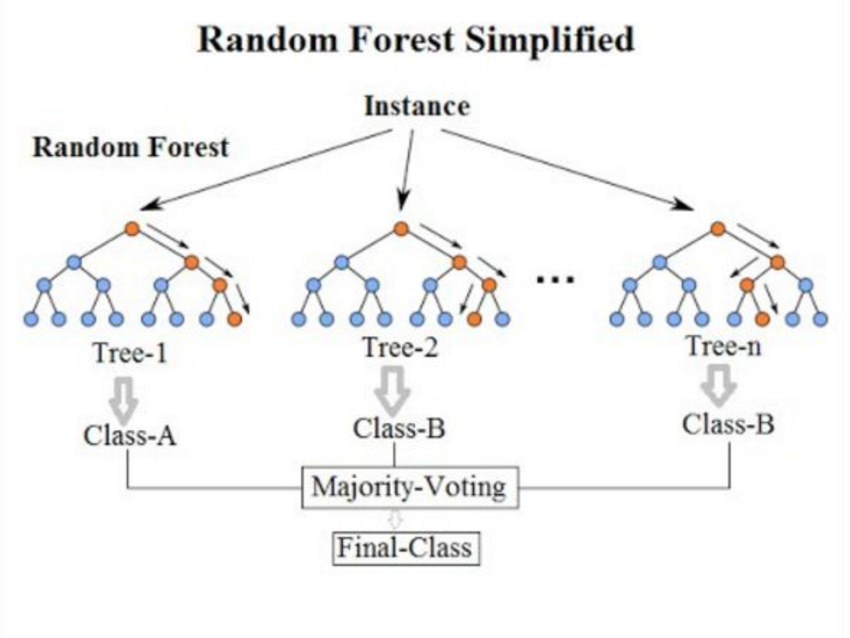
A collection of decision 'trees'

Advantages:

- Fast to train and apply
- Easy to understand
- Works out of the box
- Works with small data samples

Disadvantages

- Not very flexible



Two most popular algorithms: Neural Networks

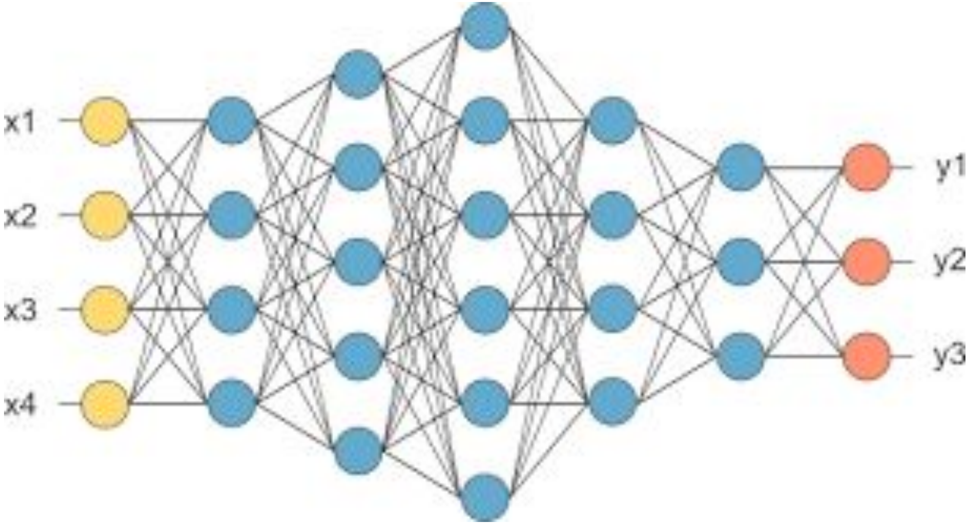
A set of connected ‘neurons’

Advantages:

- Infinitely flexible: `neurons’ can be connected in many different way
- Works with images, timeseries, video, ...

Disadvantages

- Deciding on the the right architecture is difficult
- Needs a lot of data to ‘train’



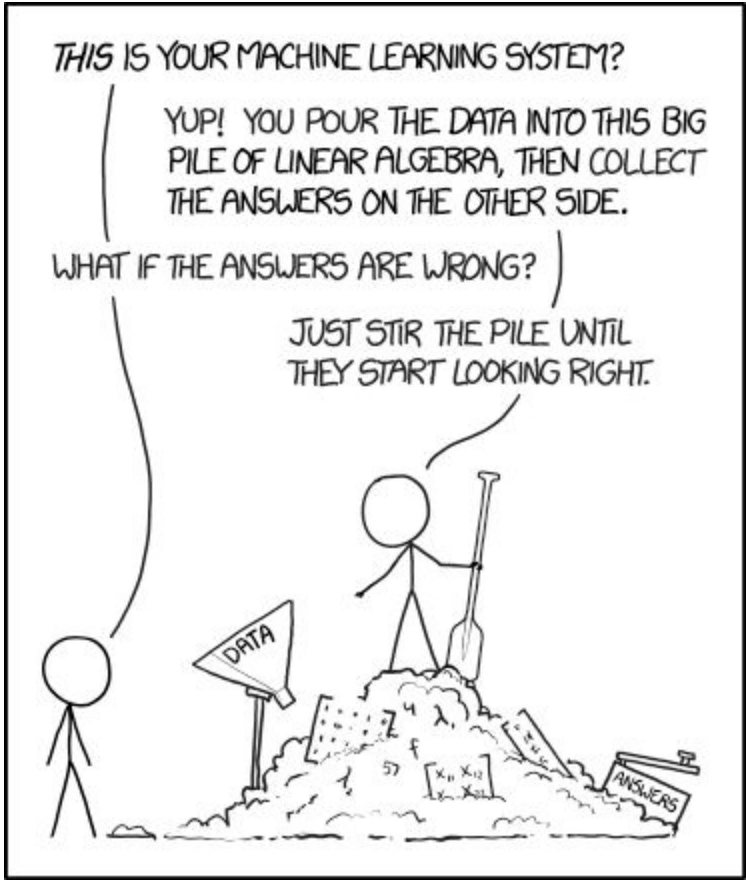
When can machine learning be useful?

Machine learning has been very popular in the last few years. While it can do a lot of things, it is **not a silver bullet**. Typical problems were ML could be useful are:

- Task that a human can do in a split-second, but are hard to program.
- Tasks that take a (very) long time to compute can be approximated using ML methods.
- Any input data that hasn’t been seen yet in the training set, machine learning cannot deal with.

Disadvantages of machine learning: ‘BlackBox’

- **Training data is required** to construct the algorithms, which can be a challenge. In addition, **training data needs to representative** of the overall dataset.
- **Biases** and **completeness** can be difficult to quantify. This can be a problem when the output of machine learning methods are compared to predictions. For example; is the difference between the number of expected RR Lyrae stars versus what a ML-classifier finds an error in the prediction or the classifier?



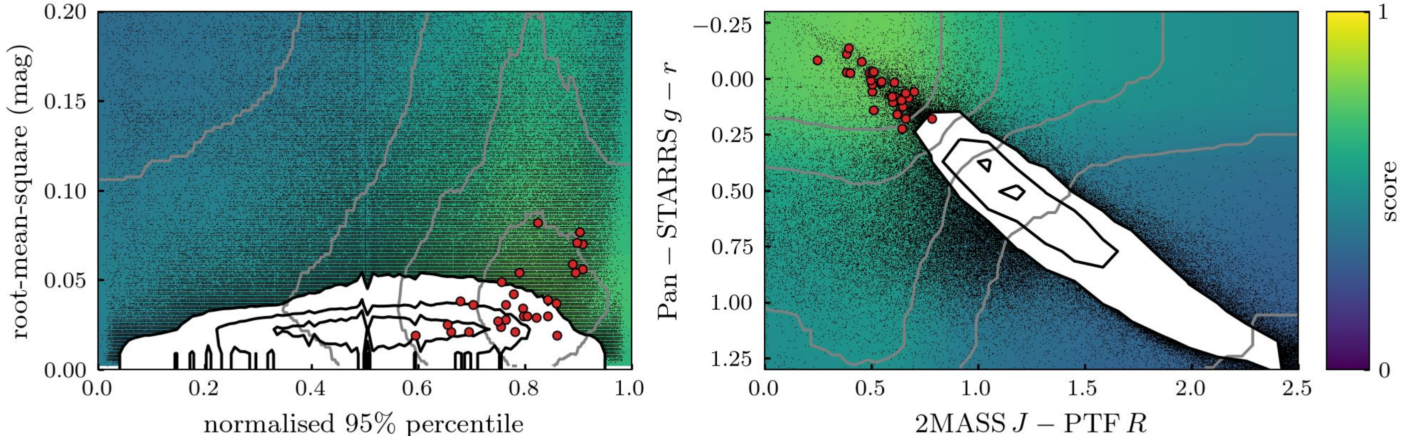
Examples of machine learning in stellar astronomy

Classification of variable stars

To classify variable stars, three types of information are used; variability, colour, and intrinsic luminosity.

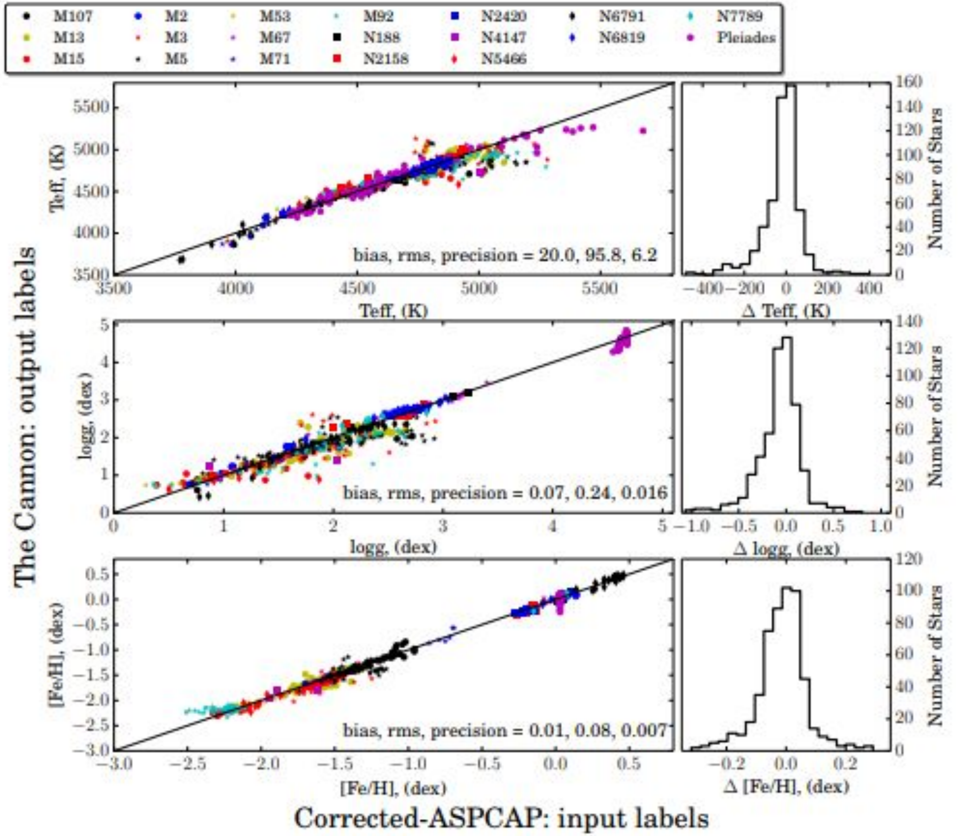
Typically, **lightcurve statistics** (median, RMS, period,...) are calculated, and combined with static colours and a parallax (or proper motion). These are then fed to a ML-classification algorithm (usually RandomForest). More advanced techniques which directly use the ligthtcurves are being investigated.

The figure below shows and example of how the ML-score depends on variability parameters (left) and colours (right). Examples: Richards 2012, Pashchenko 2017



Estimating stellar parameters from spectra

[Ness et al 2017](#) developed a neural network that can quickly estimate stellar parameters (Temperature, surface gravity, [Fe/H]) from a 1D stellar spectrum. It is faster and more accurate than traditional model fitting approaches.



Faster modeling of physics of pulsating stars

Machine learning can also be used to **approximate physics simulations**.

For example, [Hendriks & Aerts] used a neural net to approximate stellar pulsations models (by [MESA] and [GYRE]). The neural net is used to find an approximate solution; **speeding up the 'fitting' process**.

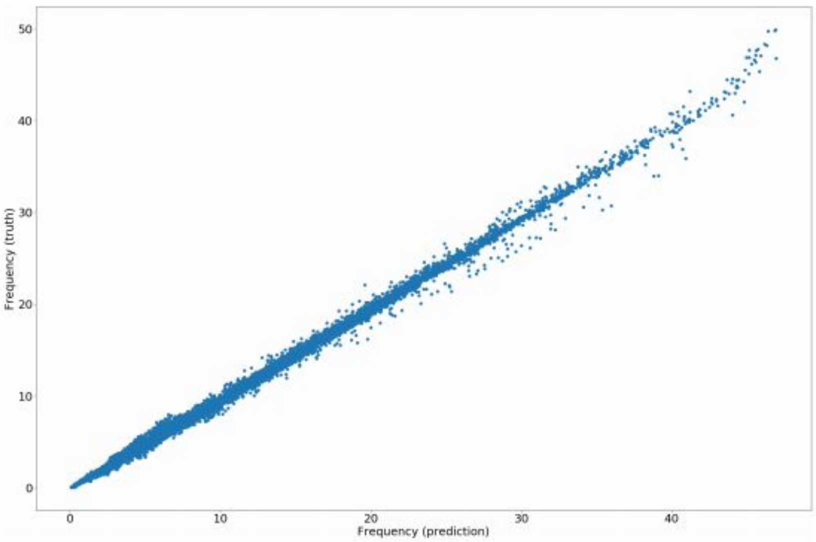
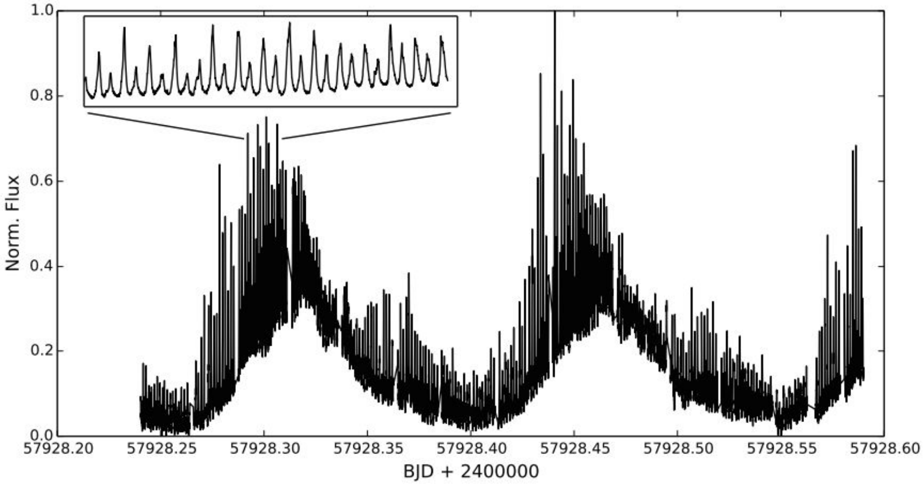


Figure 4. Visualization of the performance of the network. Plotted are the network predictions and the true values (from the dataset), for all stellar parameters and frequency modes. In this plot, 100,000 points from the validation data are shown.

Other examples are: [parameter estimation] of [eclipsing binaries] and determining the [internal structure of Red Giants].

Remaining challenges for machine learning in astronomy

- Outlier and novelty detection (e.g. how to identify new types of objects/events?)
- Uncertainty propagation in data
- How to handle irregular time series directly (e.g. lightcurves)
- How to handle sparse datasets, and how to use informative missing data (limits)



Novelty detection is difficult:
AR Sco (white dwarf ‘pulsar’) has a unique lightcurve but was misclassified as a Delta Scuti variable in the 70s. In 2014, an amature astronomer noticed it’s unique nature.