Schedule

Each discussion is allocated 45 minutes. Leaders are expected to wrap up their discussion by 25 minutes and leave 20 minutes for discussion. Recall that the purpose of the meeting is to explore synergies between TDA (photometric surveys) and SDSS Phase V. Start by outlining the key problems in the field (the science motivation) and then suggest a plausible path to solving this using TDA+SDSS-V. Explore if the TDA survey should be slaved to SDSS-V (or less likely the other way around). A desirable outcome of the workshop is to identify unique science that results from combining TDA and dynamic spectroscopy, especially in stellar and AGN astronomy.

Friday, May 3, 2019

08:00-08:55 Light Breakfast

08:55-12:30 Session I

0855: Welcome by Juna KOLLMEIER
09:00-09:45 Why are binaries (especially large samples) interesting? Maxwell MOE
09:45-10:30 The brighter the better E. Sterl PHINNEY

10:30-10:45 Short Break

10:45-11:30 Light Curves of AGN Matthew GRAHAM & Scott ANDERSON
11:30-12:15 Advances in Short Period Binaries Kevin BURDGE

12:30-13:30 LUNCH

13:30-15:00 Session II

13:30-14:15 Interesting Pulsators JJ HERMES
14:15-15:00 Asteroids & Interstellar Interlopers Eran OFEK

15:00-15:30 BREAK

15:30-17:15 Session III

15:30-16:15 Compact Object Binaries Carles BADENES
16:15 -17:00 Rare Objects (Binaries & Otherwise) Melissa NESS
17:00-17:15 Deep Learning & TDA Dmitry DUEV

1715-1800: Open Discussion
1800: Depart for Dinner
18:30 Dinner at Green Street Tavern, 69 West Green Street, Pasadena, 91105

Saturday, May 4, 2019

08:00-09:00 Light Breakfast

09:00-12:30 Session IV

09:00-09:45 Massive stars & Stellar Outbursts James FULLER
09:45-10:30 Maximizing Asteroseismology w/ Spectroscopy Dan HUBER

10:30-10:45 Break

10:45 -11:30 Young Stars (including gyrochronology) Lynne HILLENBRAND
11:30 -12:15 Galaxies & Galactic Structure Joshua SIMON

12:15-13:15 LUNCH

1315-1600 Exciting New Stuff

13:15 -14:00 Limits of ground-based photometry & astrometry Eran OFEK
14:00-14:30 Initial results from Tomo-e Gozen (a wide-field CMOS imager) N. ARIMA & Makoto ICHIKI
14:30 -15:00 Introduction to TESS light curves Ryan OELKERS

15:00 -16:00 OPEN DISCUSSION

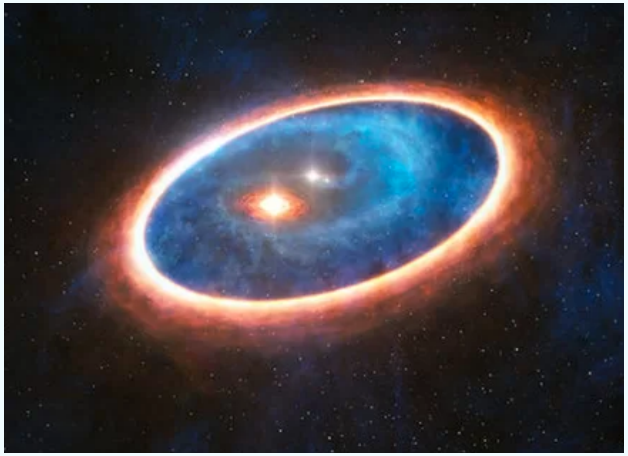
```
# For Unix aficionados:
# Problem: how to automatically "build a book" from a website?
# (you can have any ordering by using sort but here it is by alpha)

# change directory where the pdf files are located

$ wkhtmltopdf ../PM_Presentations.html A0Table.pdf
$ pdfunite $(ls -1 *.pdf | xargs) ../Program.pdf
```

Large Samples of Binary Stars - Tools for Understanding:

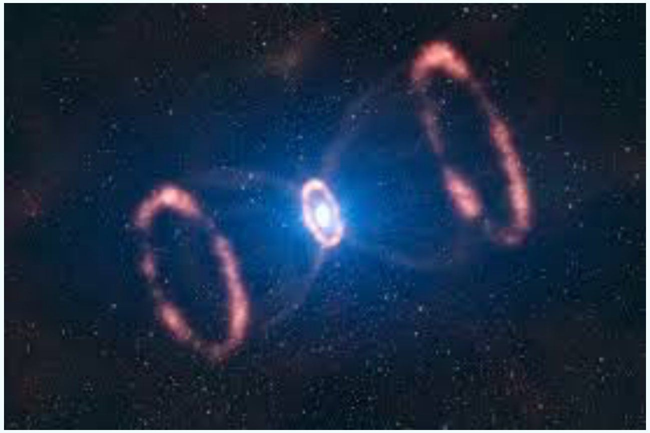
Star & Planet Formation



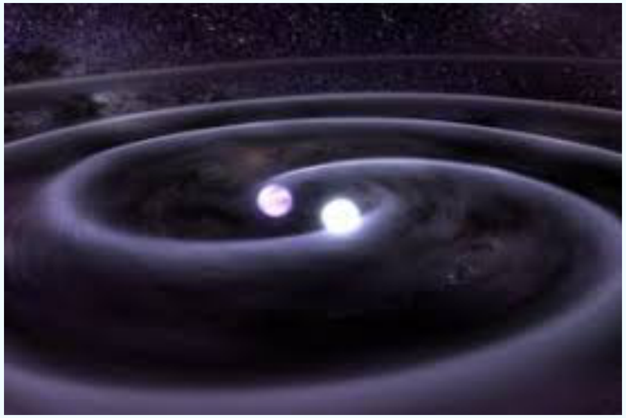
Stellar Astrophysics & Binary Evolution

Galaxies & Stellar Populations

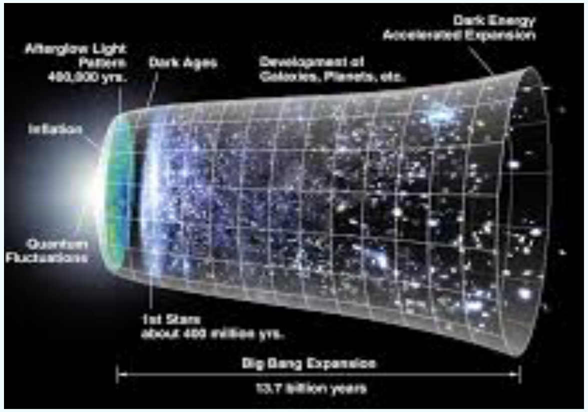
Supernovae & Transients



Gravitational Waves



Cosmology



Maxwell Moe (University of Arizona)

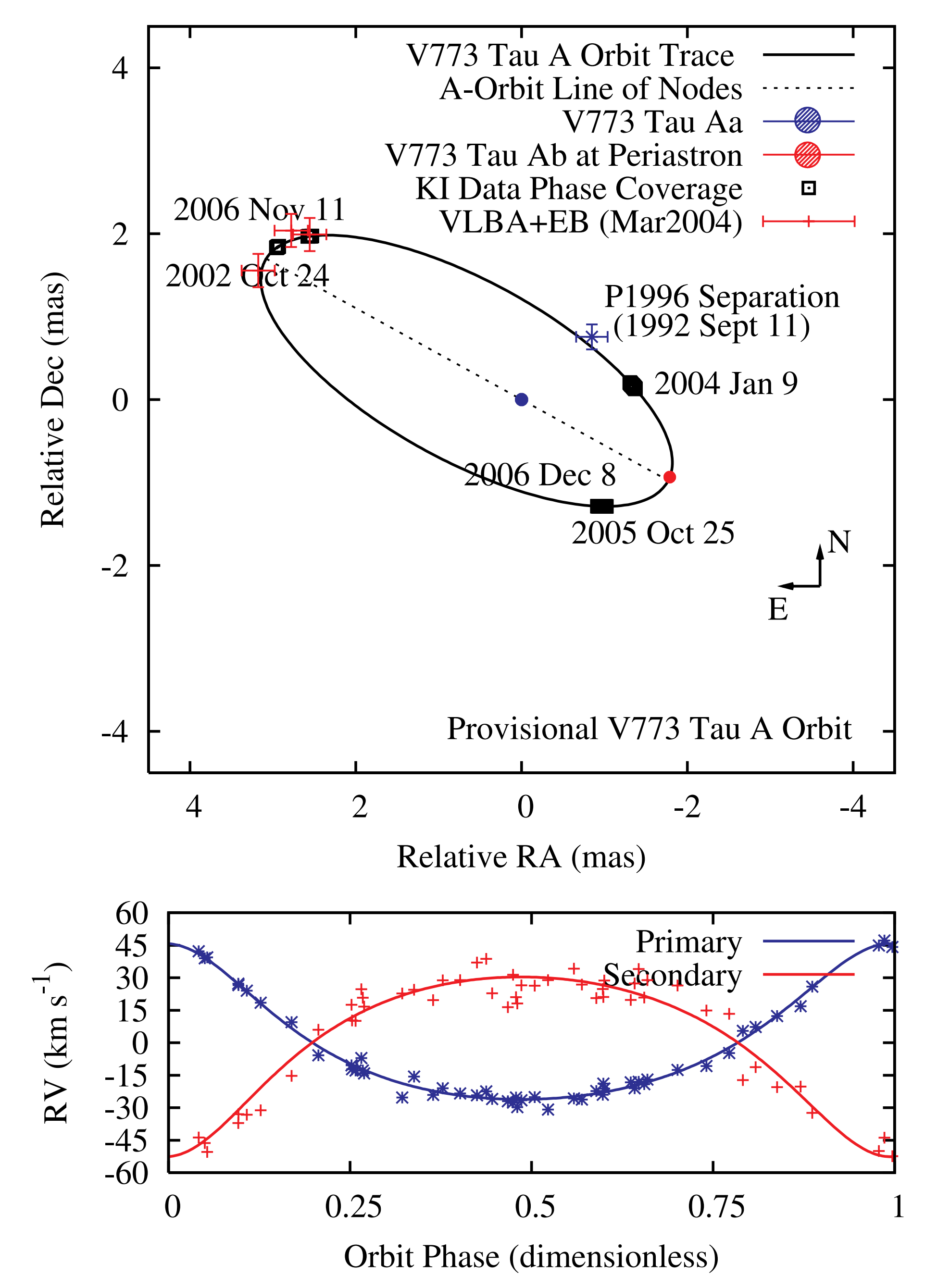
Binaries constrain stellar tracks and serve as standard candles

M-R-L relations historically measured from EBs / SB2s.

Theoretical MS relations and pre-MS tracks of solar-type stars agree with observations.

But tracks of low-mass stars are currently discrepant with the measurements (Torres 2013).

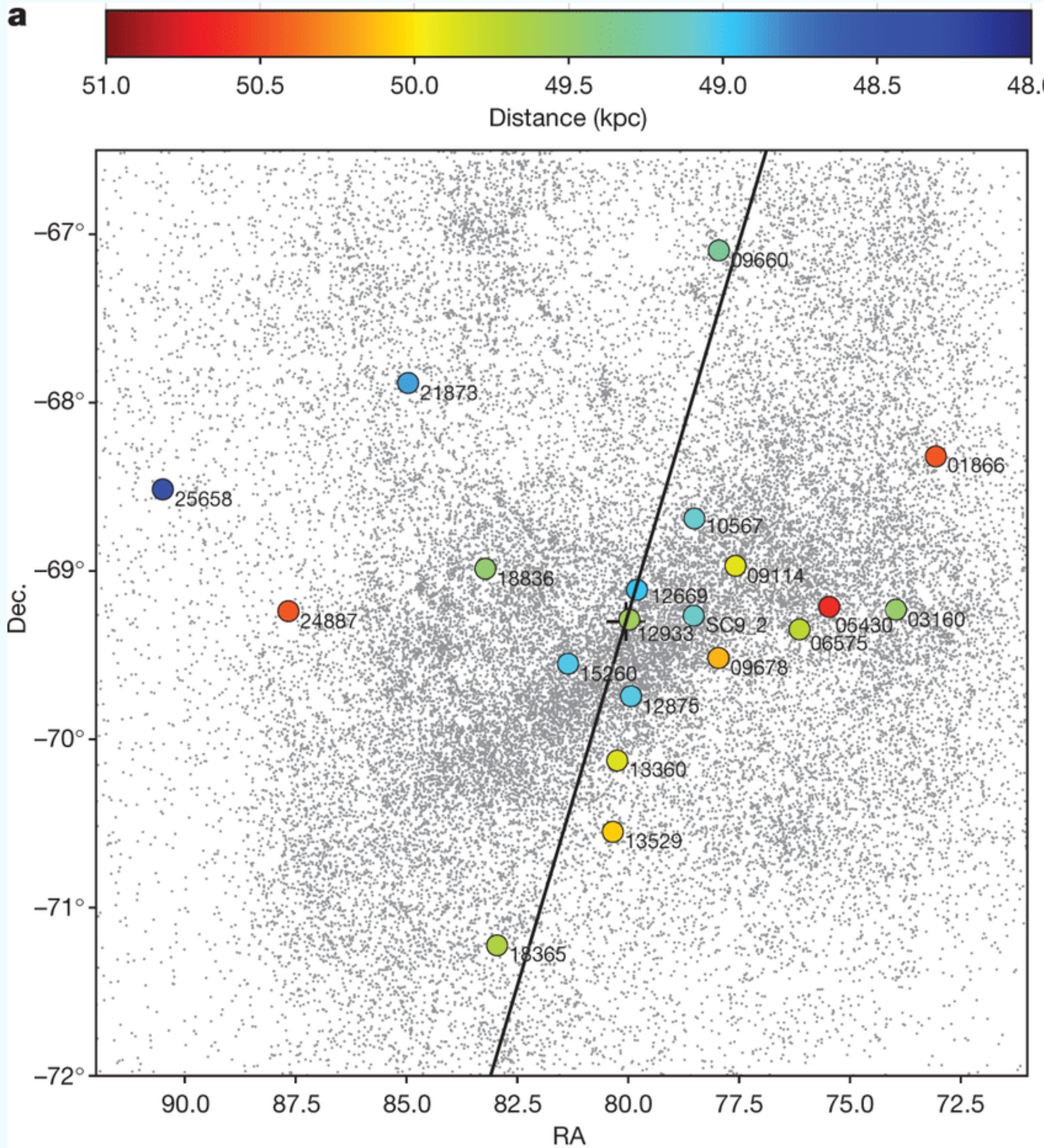
RV observations of astrometric pre-MS binaries also yield dynamical masses (Boden et al. 2007).



OGLE discovered ~40,000 EBs in the LMC (Pawlak et al. 2016).

20 were giant + giant EBs used to measure distance to 1.2% precision (Pietrzynski et al. 2019).

The ~4.4σ discrepancy in H_o between Planck / ΛCDM and local Cepheids / SN Ia hinge on EB distance to LMC Cepheids (Riess et al. 2019).



Dependence on Primary Mass M_1

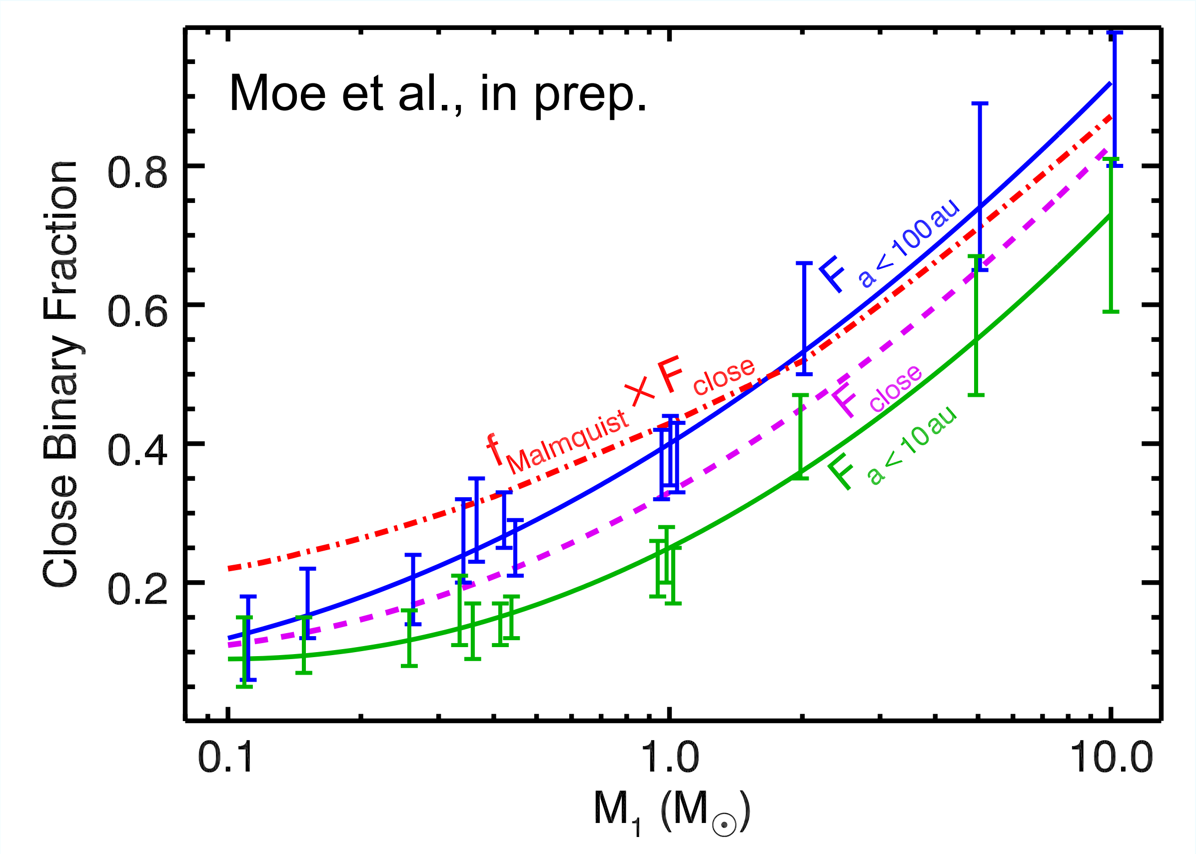
Binary fraction increases with primary mass, **especially** at close separations a < 10 AU

Photometric Surveys:

~1% of G dwarfs and ~10% of OB stars are EBs.

Spectroscopic Surveys:

~10% of G dwarfs and ~50% of OB stars are SBs, depending on RV sensitivity and cadence.



Characterizing RV variables / SBs (Carles Badenes):

2-3 epochs: ΔRV_{max}

4-7 epochs: Bayesian MCMC (The Joker; Price-Whelan 2016)

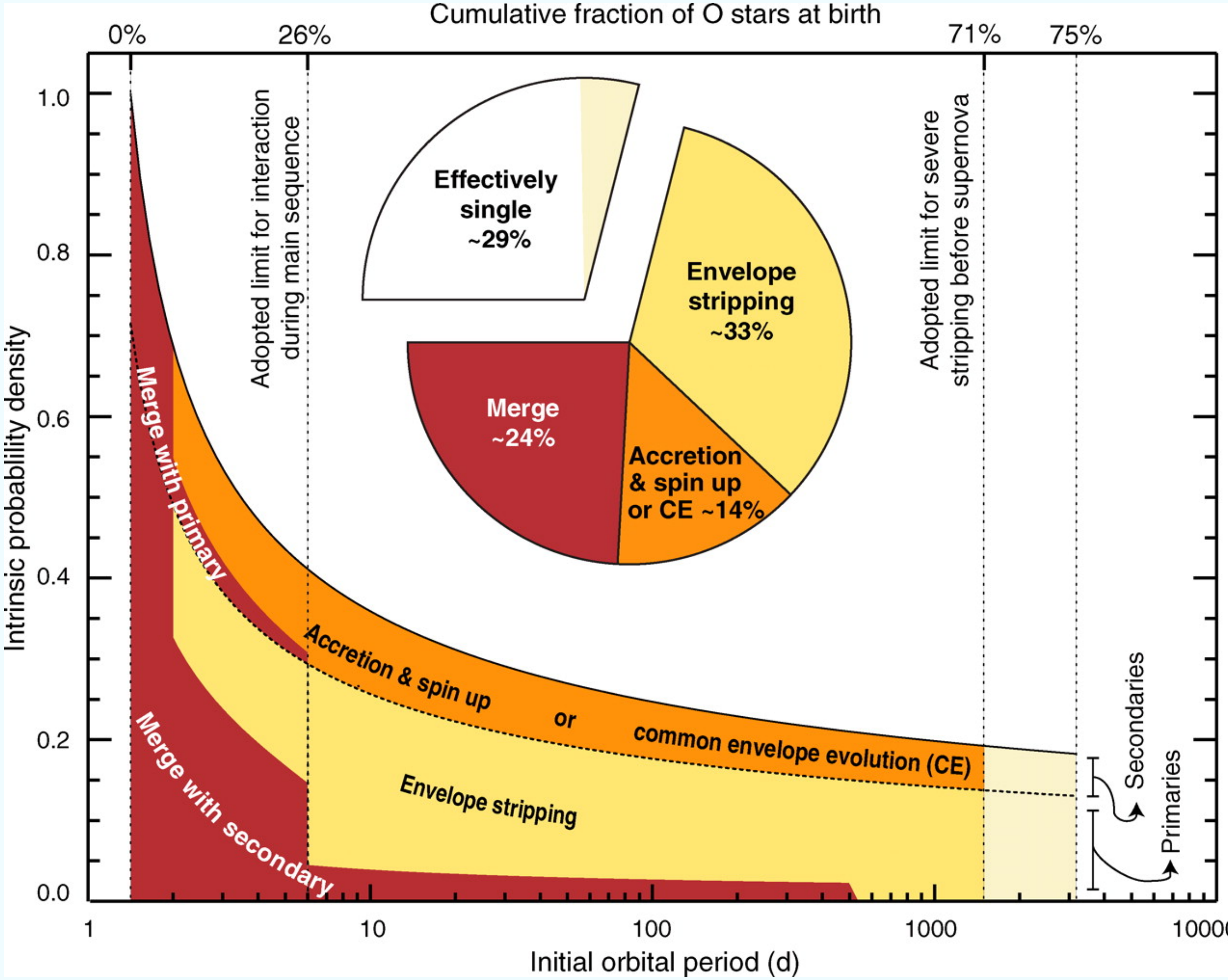
>8 epochs: fit orbits

Always need measurement **and systematic uncertainties** in RVs

Binary interactions dominate the lives of massive stars (Sana et al. 2012).

~70% of O stars have companions within a < 10 AU.

About half of these close companions will strip hydrogen envelope, revealing a hot He core.

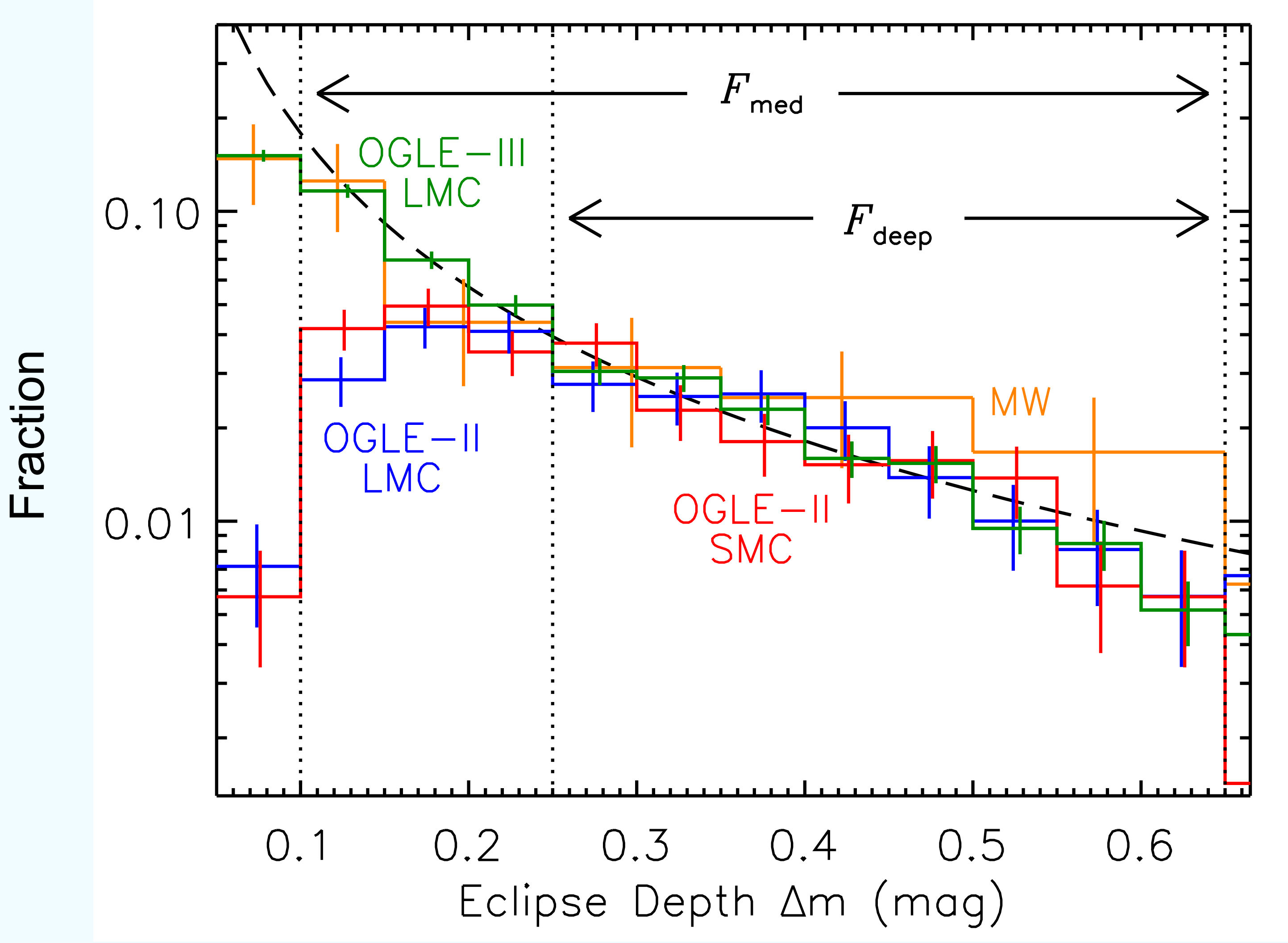


Majority of SN Ib/c and long GRBs likely derive from binary interactions (Izzard et al. 2004; Yoon et al. 2015).

Hot He cores may also contribute to re-ionization (Gotberg et al. 2018).

Dependence on Metallicity [Fe/H]

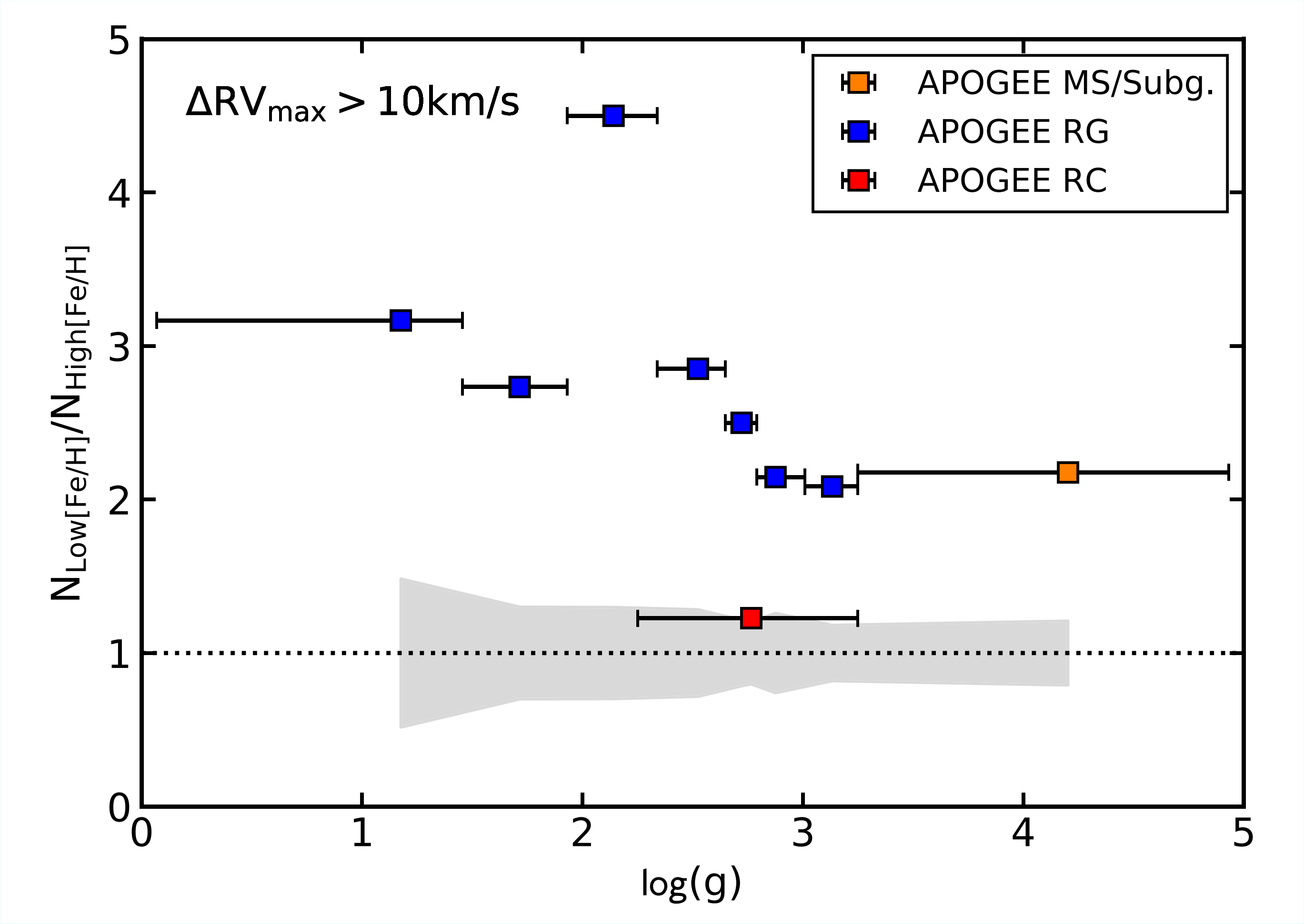
B-type EBs in the SMC, LMC, and MW (Moe & Di Stefano 2013)



Properties of close massive binaries are invariant across –0.8 < [Fe/H] < 0.2.

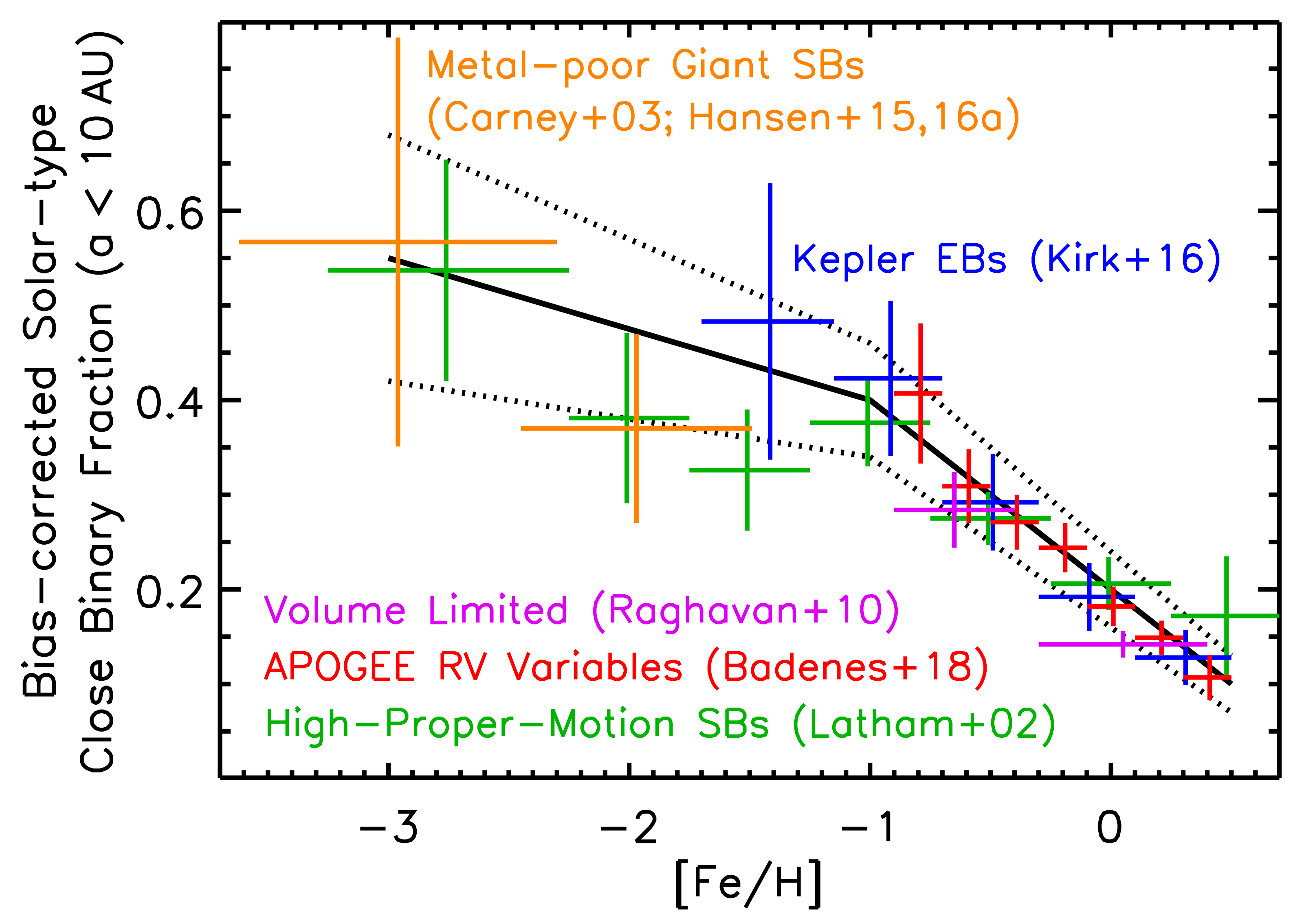
APOGEE RV Variability Fraction of GK stars (Badenes et al. 2018)

~90,000 GK stars; mostly giants; N_{RV} = 2 - 5; ΔRV_{max} > 10 km s^{-1}



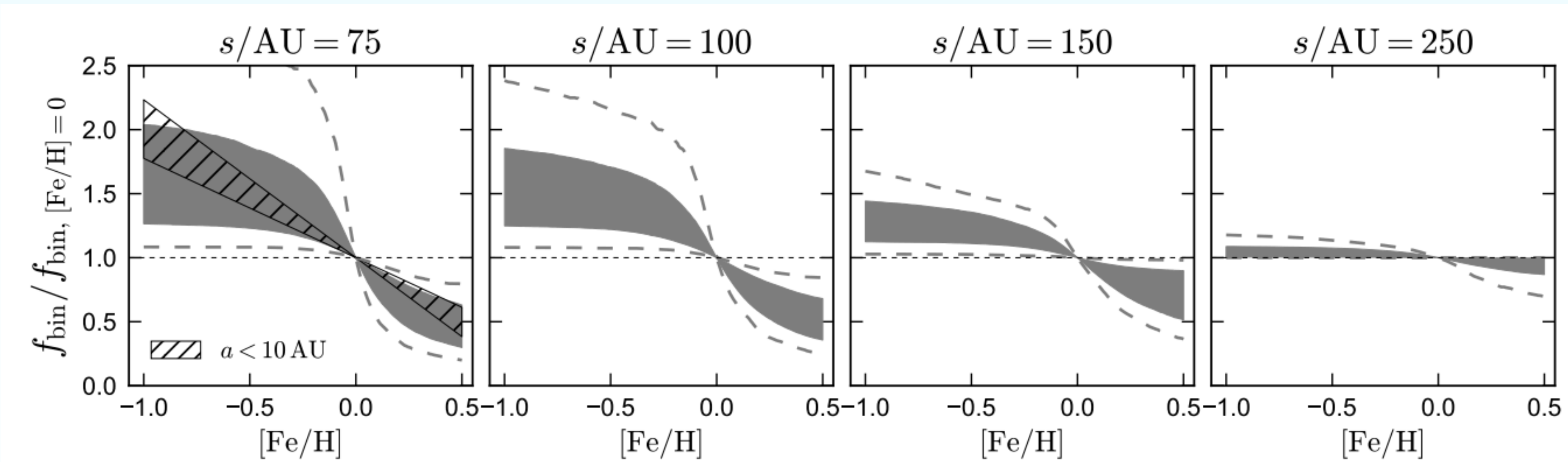
Metal-poor tercile exhibits ~2-3 times the RV variability fraction than the metal-rich tercile across all surface gravities.

Close binary fraction of solar-type stars decreases significantly with metallicity (Moe et al. 2019).



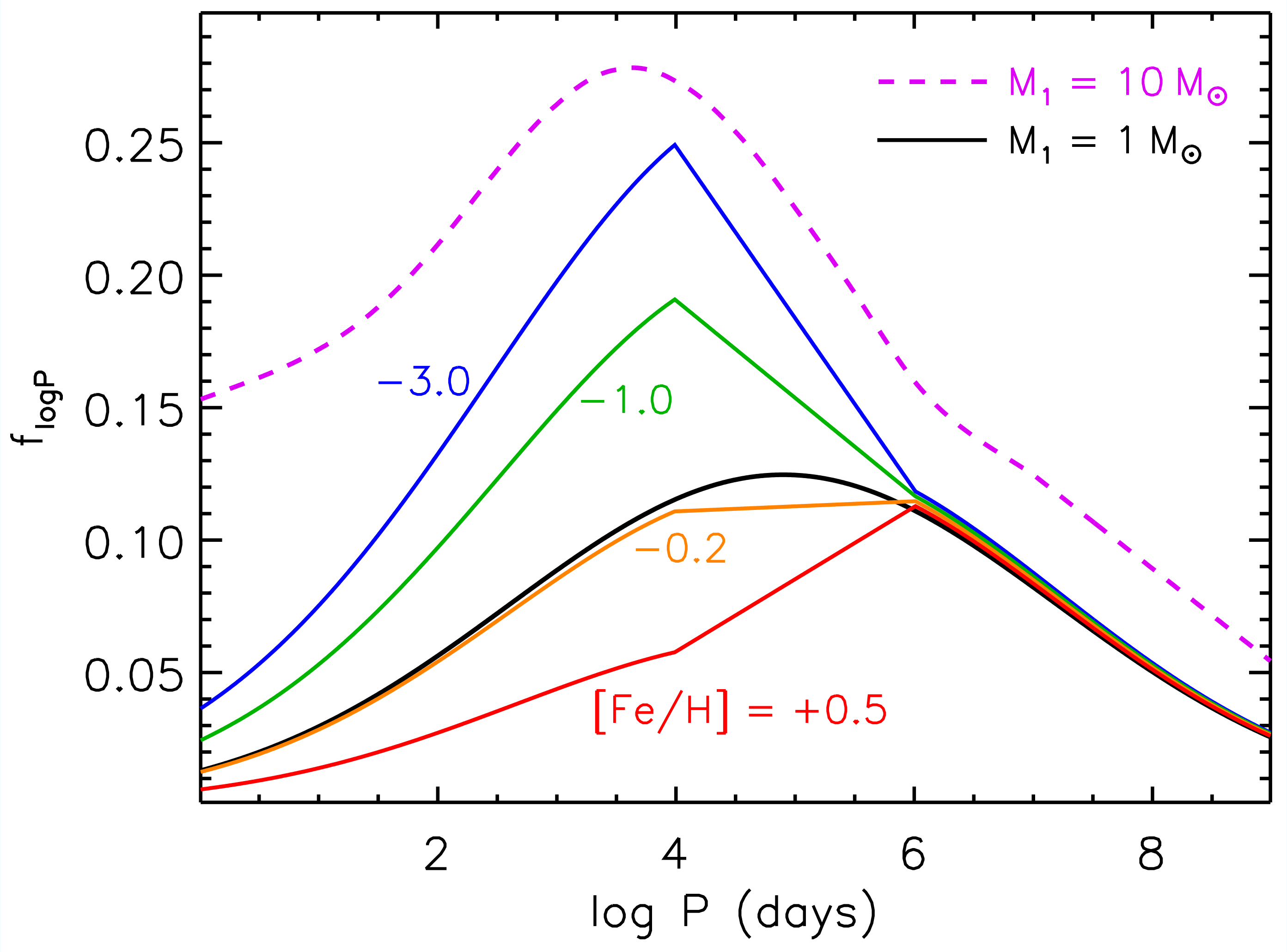
All five samples/methods provide consistent trend!

But imaging reveals the wide (a > 200 AU) binary fraction of solar-type stars is metallicity invariant (Moe et al. 2019).



Utilizing Gaia common-proper-motion binaries with [Fe/H] measurements from wide-field spectroscopic surveys, El-Badry & Rix (2019) confirmed the metallicity dependence emerges below a < 200 AU.

Binary period distribution as a function of M_1 and [Fe/H] (Moe et al. 2019)



The close binary fraction of solar-type stars decrease with metallicity, but the close binary fraction of OB stars, wide binary fraction, and IMF are invariant across -1.0 < [Fe/H] < 0.5.

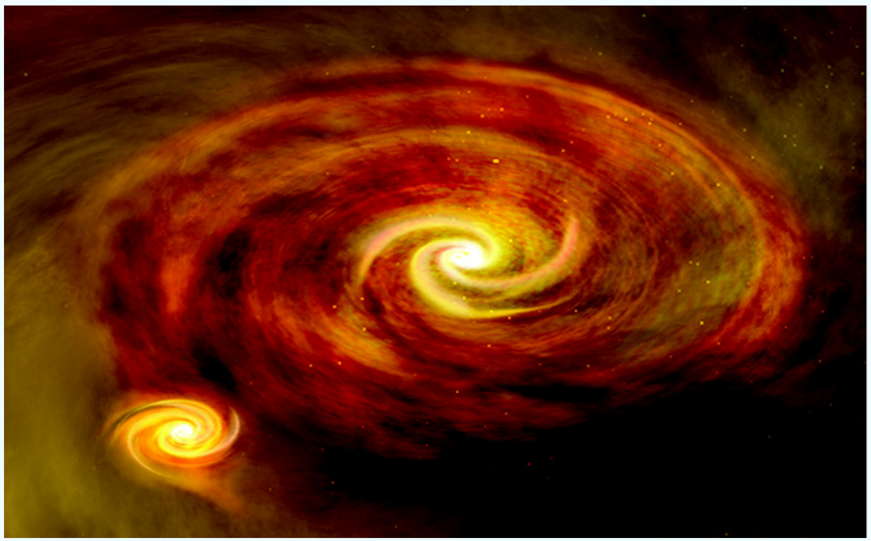
Two Modes of Binary Star Formation

(Kroupa et al. 1995; Bate et al. 1995, 2002; Tohline 2002; Kratter et al. 2002, 2006; Offner et al. 2010; Tobin et al. 2016; Lee et al. 2017; Moe et al. 2017, 2019)

Gravitational Instability and Fragmentation of **Optically Thick Disks**:

$Q_{Toomre} = c_s^2\Omega/\pi G\Sigma = 3\alpha c_s^3/G\dot{M} < 1$;

$a < 200$ AU

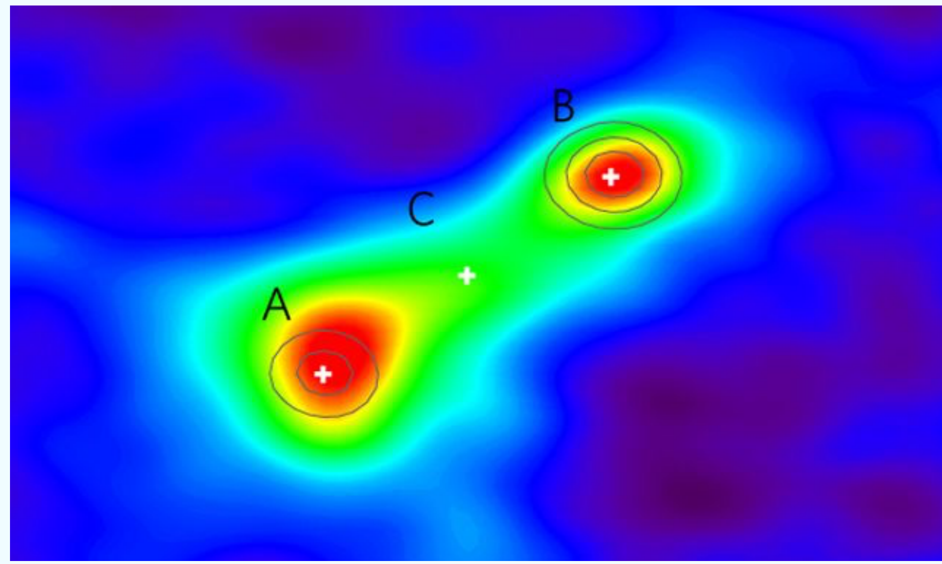


With decreasing [Fe/H], disks become less optically thick, become cooler, and fragment;

massive disks of OB protostars always fragment, even at [Fe/H] = 0

Turbulent Fragmentation of **Optically Thin Molecular Cores**:

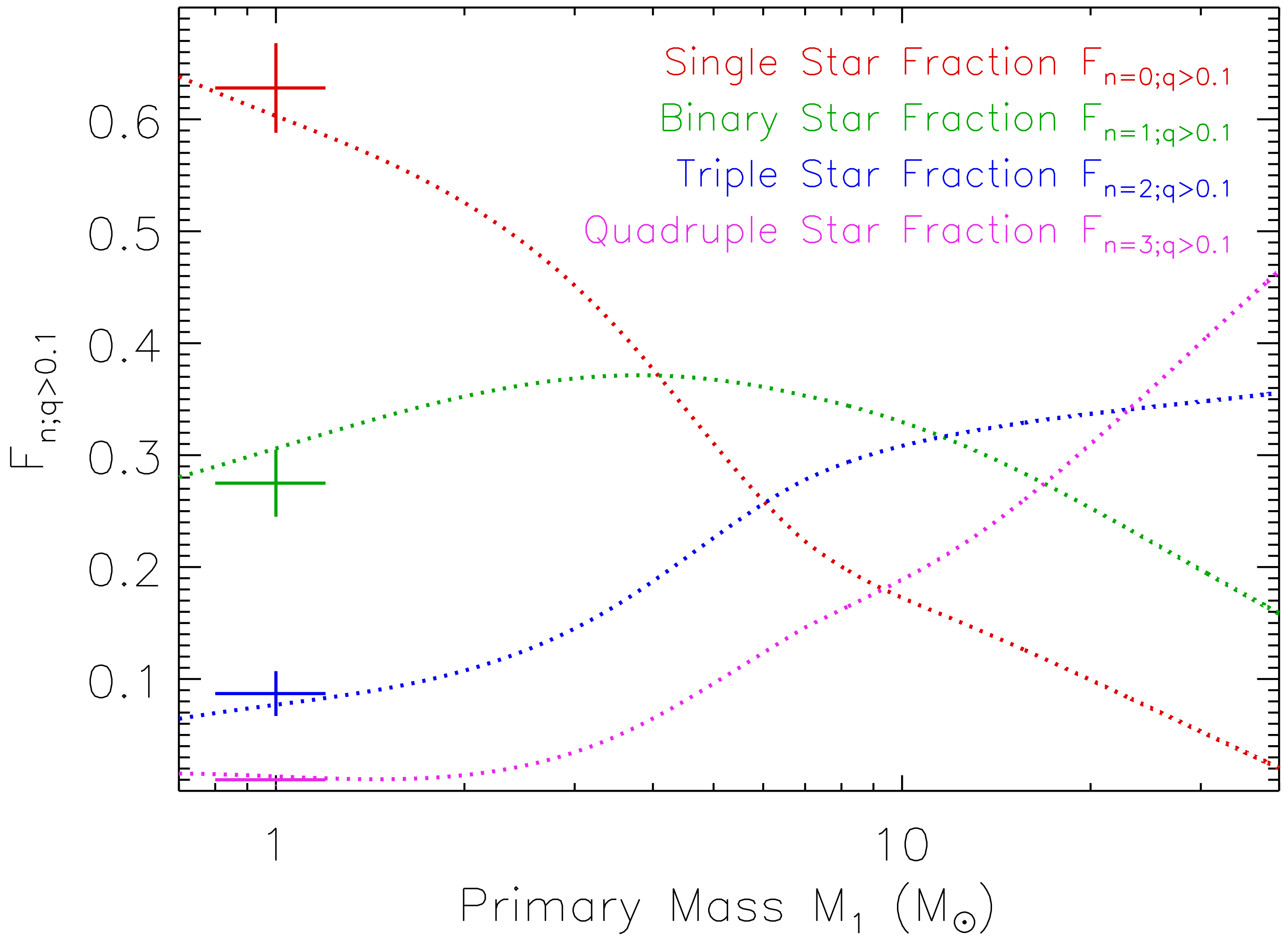
Mach $= \sigma_v/c_s > 1$; $a > 200$ AU



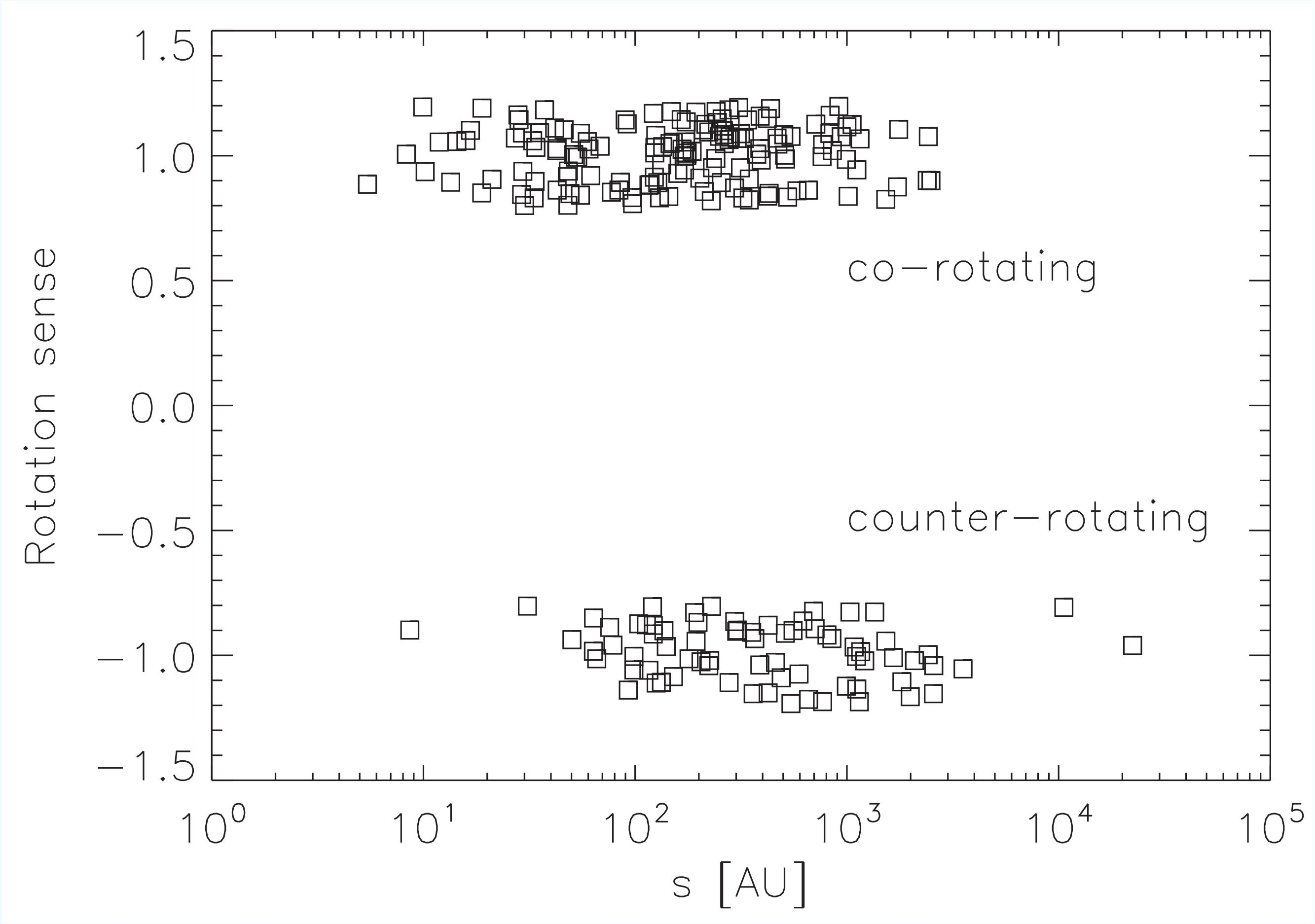
Independent of opacity (wide binary fraction and IMF are metallicity invariant)

Triples

Like the binary fraction, the triple and quadruple star fractions increase with primary mass (Moe & Di Stefano 2017).



Most compact solar-type triples with a_{out} < 50 AU are coplanar (i < 40°)
(Borkovits et al. 2016; Tokovinin 2017)



Majority of very close solar-type binaries could NOT have dynamically hardened via Kozai-Lidov oscillations and tidal friction (Moe & Kratter 2018)

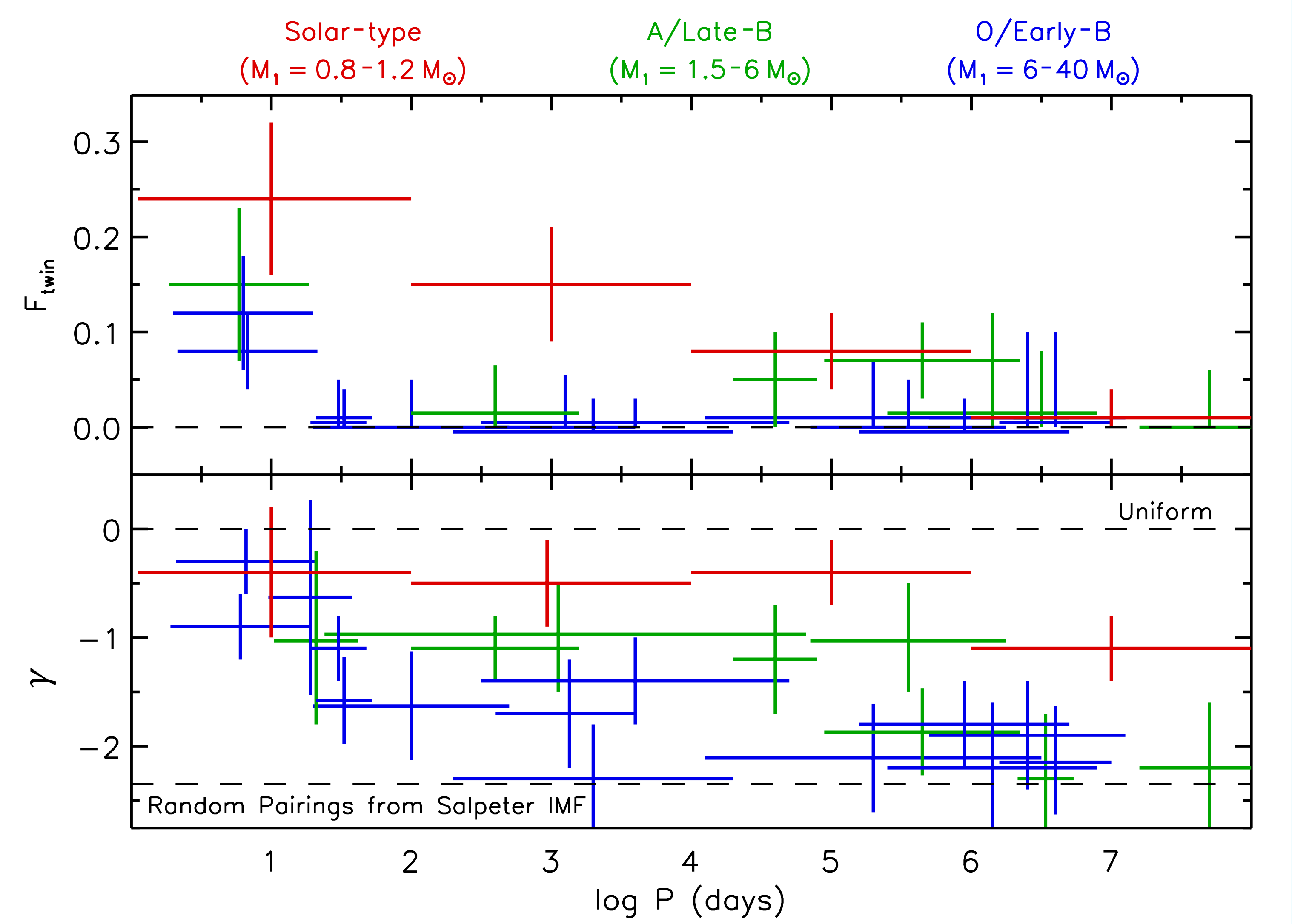
Orientations of massive triples not yet measured! → RV & astrometry

Mass Ratios $q = M_2/M_1$

Mind your Ps and Qs: $f(P,q) \neq f(P)f(q)$ (Moe & Di Stefano 2017)

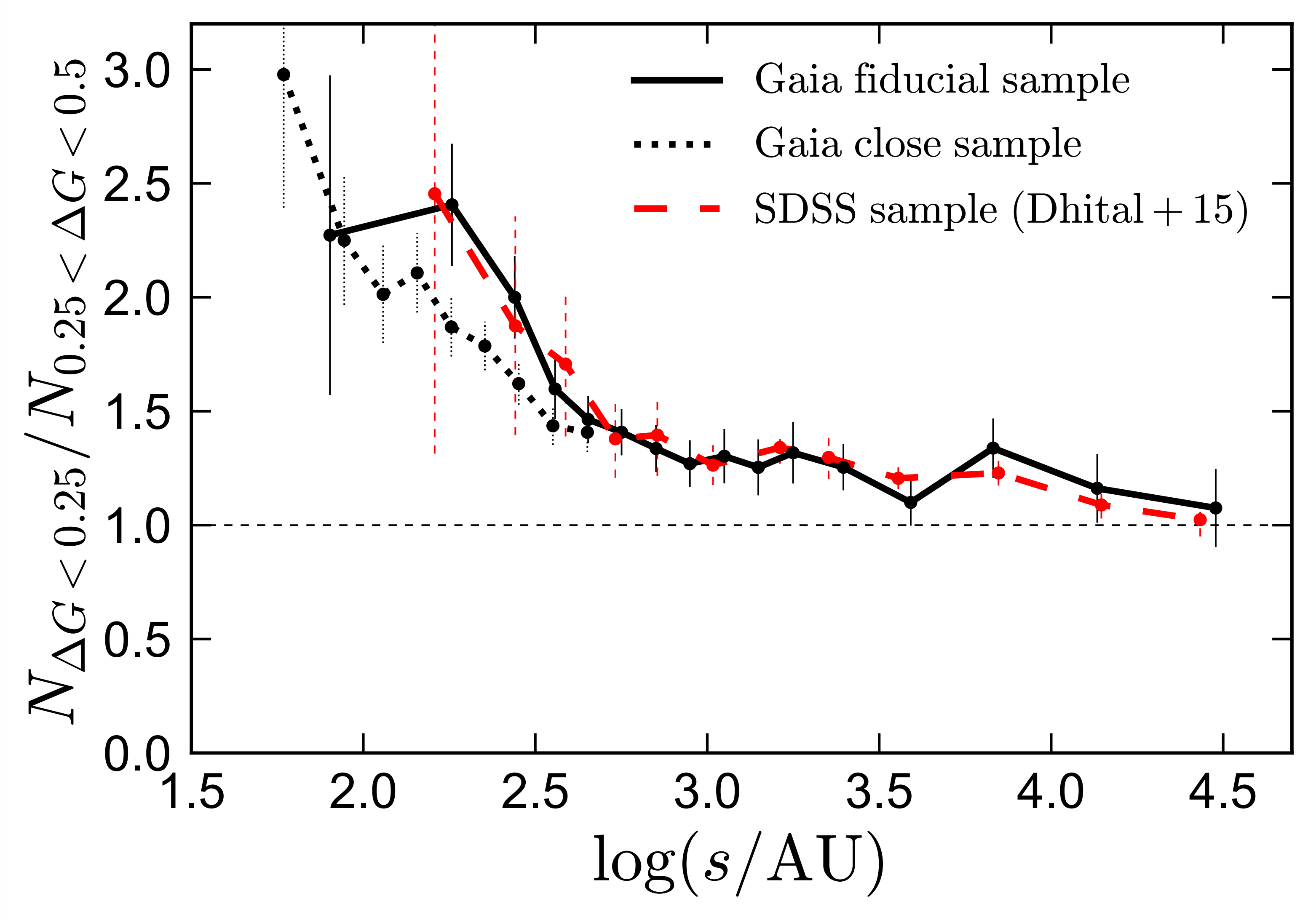
Excess fraction of twins with $q > 0.95$

Power-law slope $f \propto q^{\gamma}$



Close binaries have a uniform mass-ratio distribution and excess twin fraction due to shared accretion in the disk.
Wide binaries from core fragmentation are weighted toward smaller q.

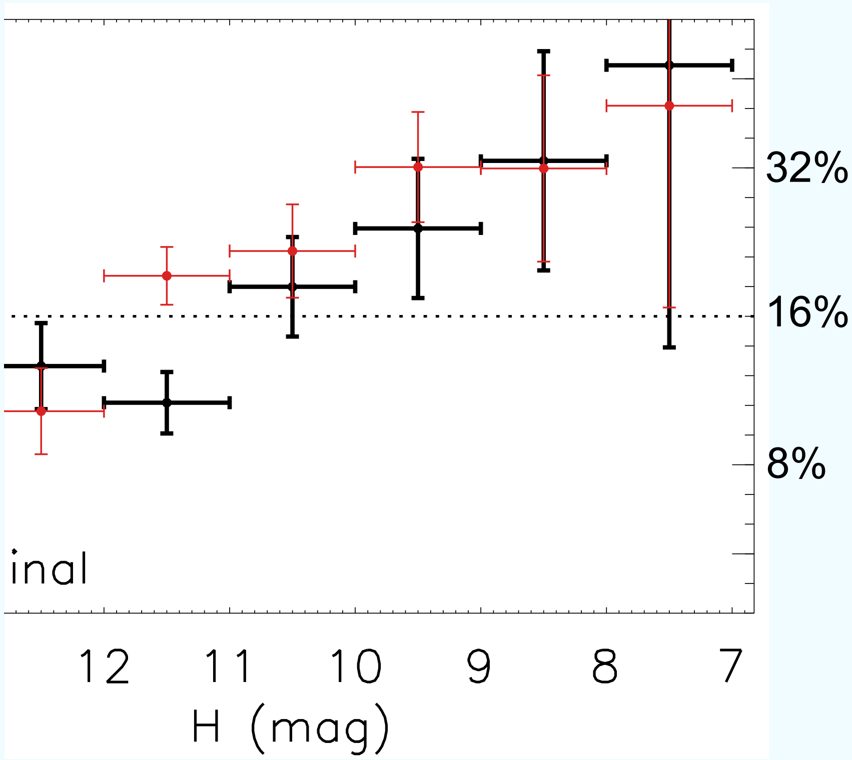
El-Badry et al. (in prep) is confirming a large excess twin fraction inside a < 200 AU, but is also finding a smaller but statistically significant twin excess extending to a ~ 10,000 AU (larger disks?; dynamical softening?)



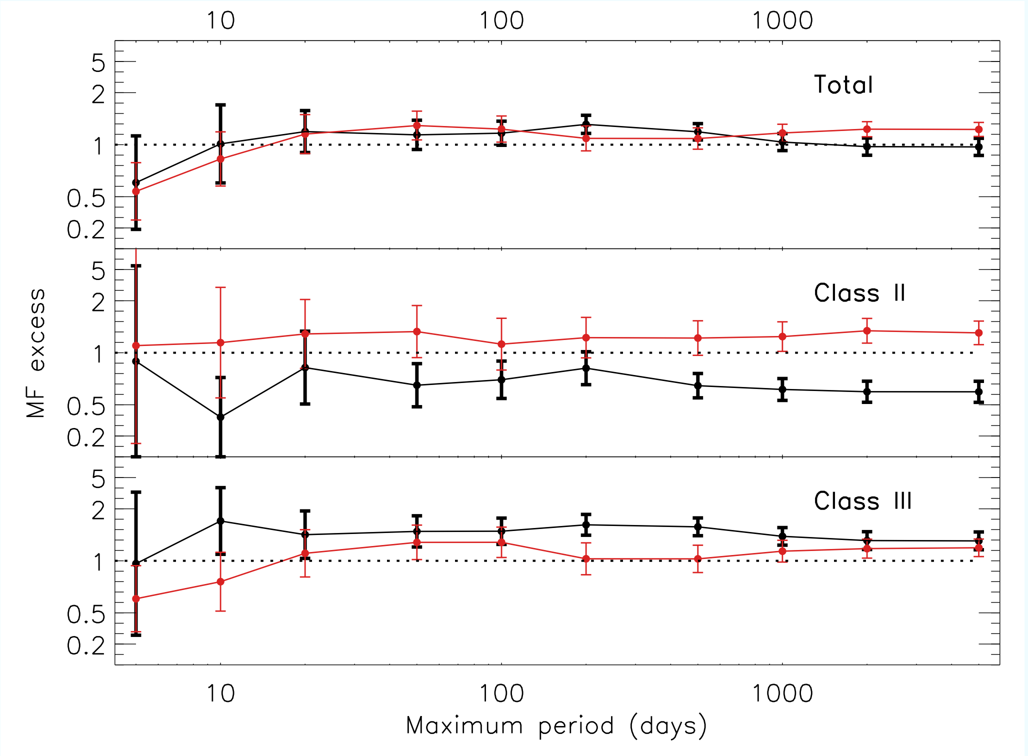
Pre-MS Binaries

Kounkel et al. (2019) analyzed APOGEE spectra of ~5,000 T Tauri stars, and discovered ~400 binaries (SB2s from CCF and SB1s from RV variability).

Close binary fraction (a < 10 AU) increases with luminosity (i.e., M_1), consistent with the field.

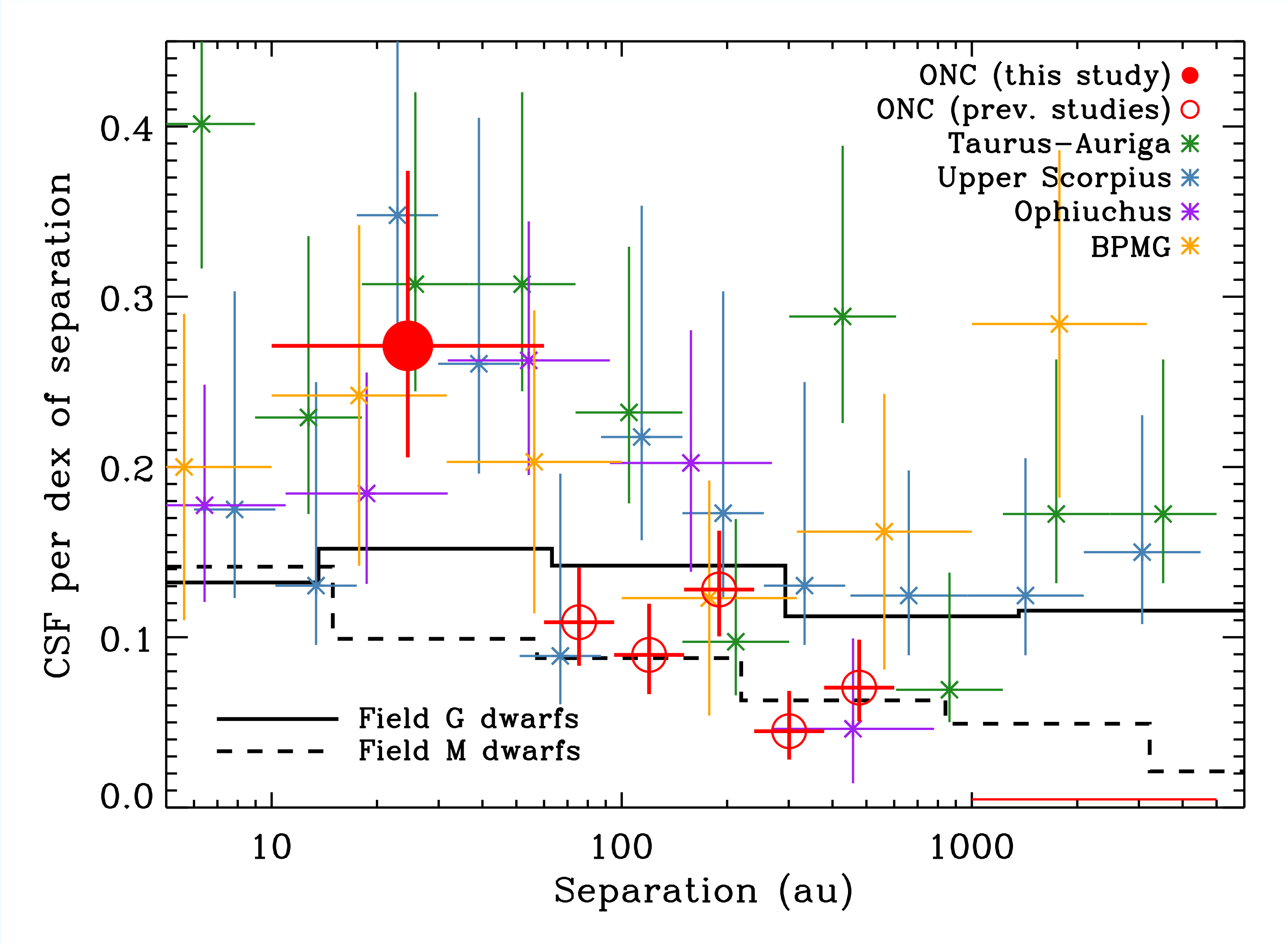


Separation distribution across a = 0.1 - 10 AU matches field distribution.



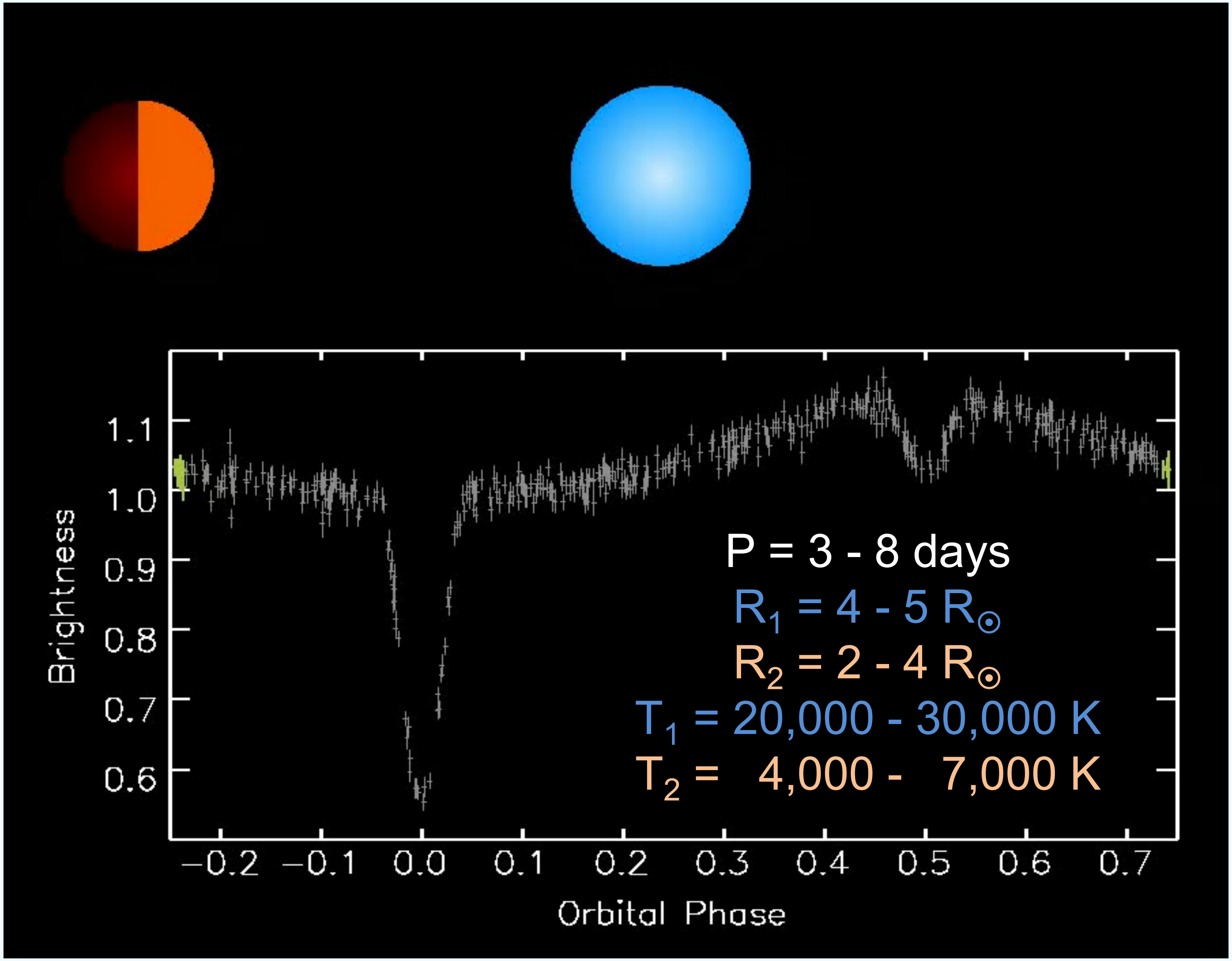
Close binary properties of M_1 = 0.3 – 3 $M_\odot$ primaries set by ~1 Myr!

AO and sparse aperture masking reveal an excess of young T Tauri binaries across a = 10 – 60 AU compared to the field (Duchene et al. 2018).



The consistency below a < 10 AU and excess beyond a > 10 AU is a mystery; perhaps long-term RV and astrometric monitoring can bridge the gap.

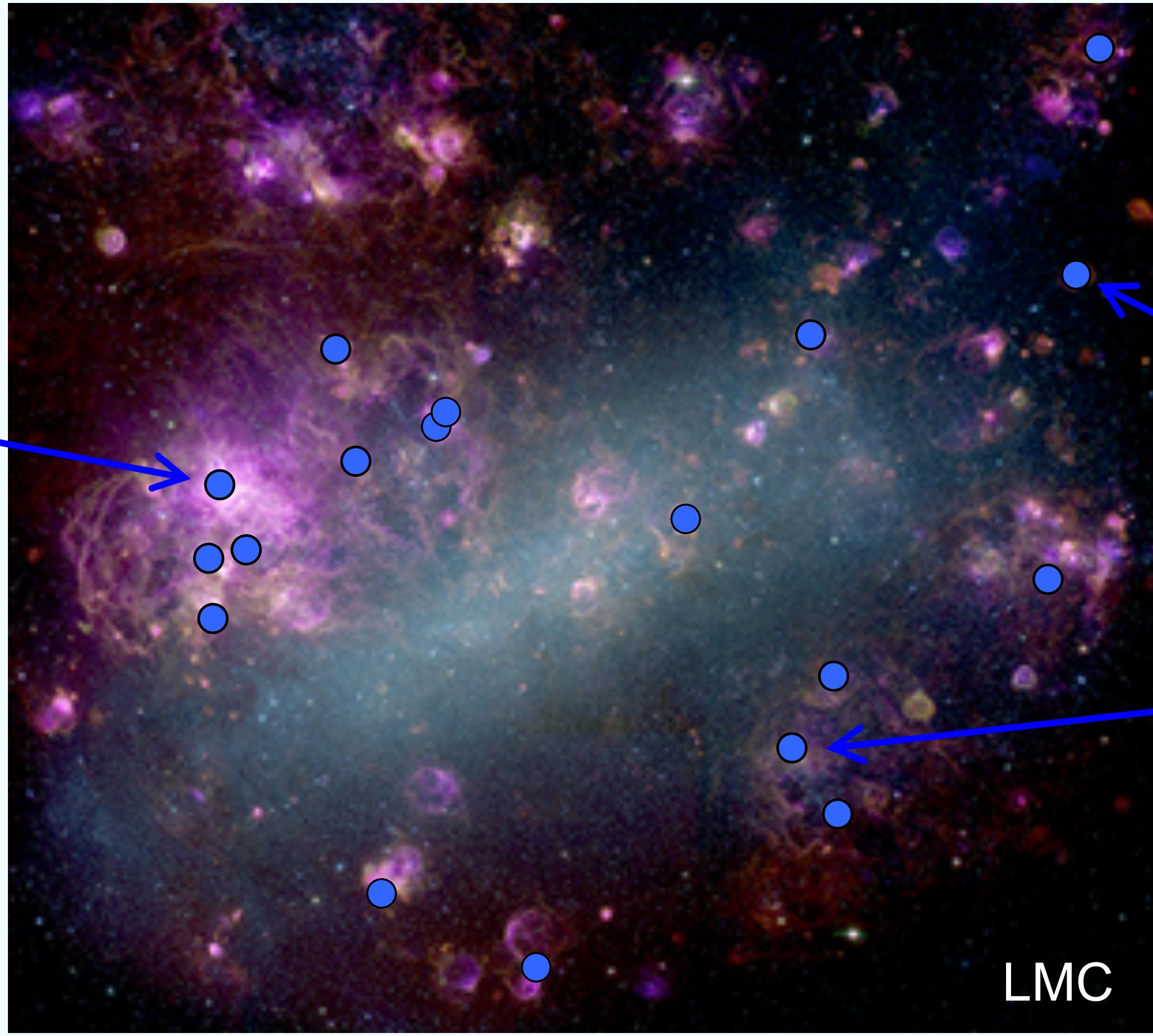
A New Class of Nascent EBs with Extreme Mass Ratios (Moe & Di Stefano 2015a)



Discovered 18 MS + pre-MS EBs exhibiting irradiation effects in the LMC:
M_1 = 7 - 20 $M_\odot$, M_2 = 0.8 - 2.4 $M_\odot$ (q = 0.05 - 0.3), & τ = 0.6 - 8 Myr.

MS + pre-MS OGLE EBs are in H II regions (Moe & Di Stefano 2015a)

ΔI_1 = 2.8 mag,
ΔI_{refl} = 0.12, &
τ = 0.6 Myr
in bright
Tarantula
Nebula



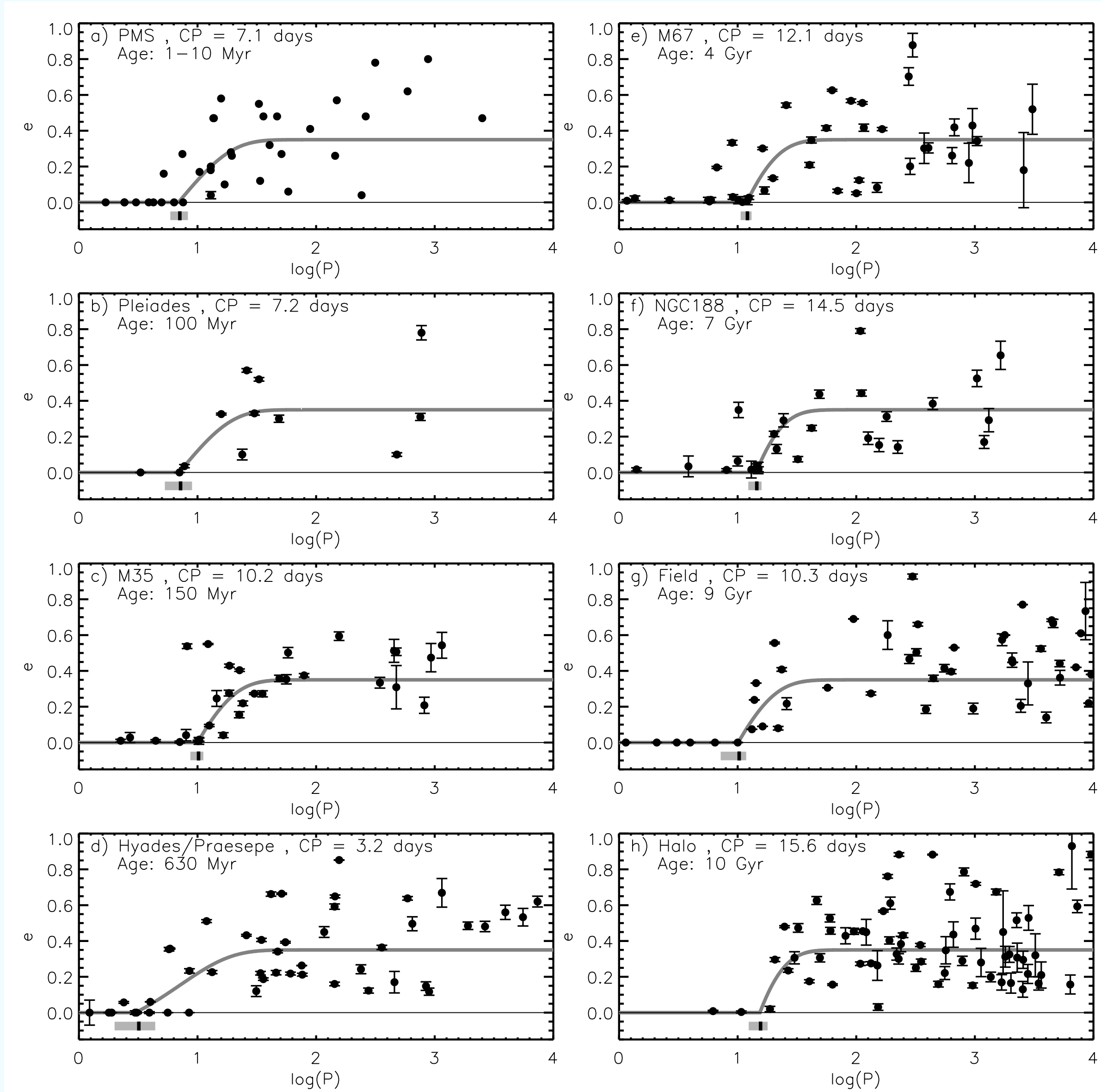
τ = 0.9 Myr
in compact
H II region

ΔI_1 = 0.2 mag,
ΔI_{refl} = 0.02, &
τ = 8 Myr
in large diffuse
H II region

Age dating of EBs provide important diagnostics for star-forming environments: expansion of H II regions, feedback, age dispersion, etc.

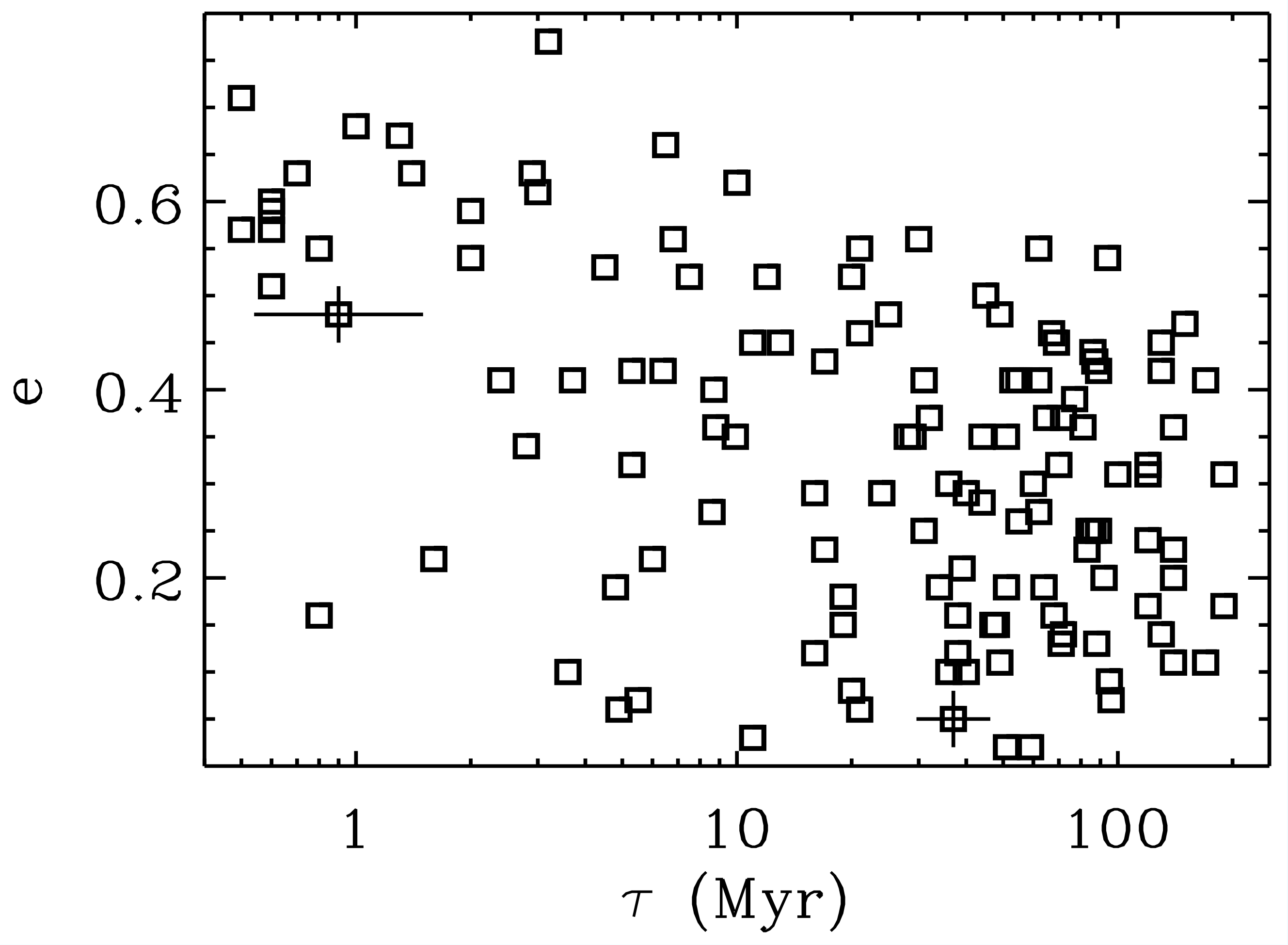
Tidal Evolution

Measured P and e of solar-type binaries with different ages:



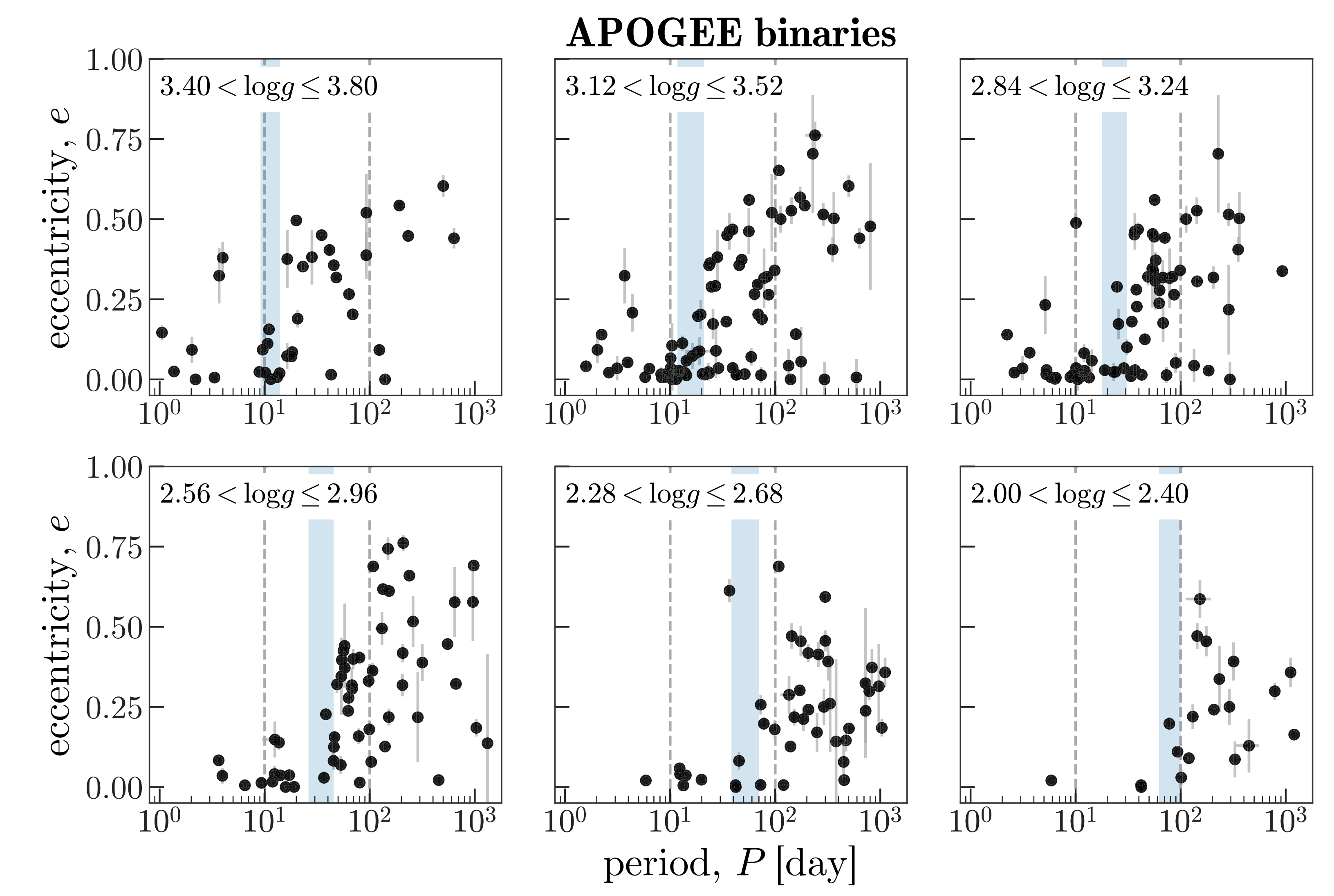
Observed circularization timescales are ~50 times faster than tidal theory predictions (Meibom & Mathieu 2005; Belczynski et al. 2008; Moe & Kratter 2018).

OGLE B-type EBs with P = 20 – 50 days in the LMC (Moe & Di Stefano 2015b)



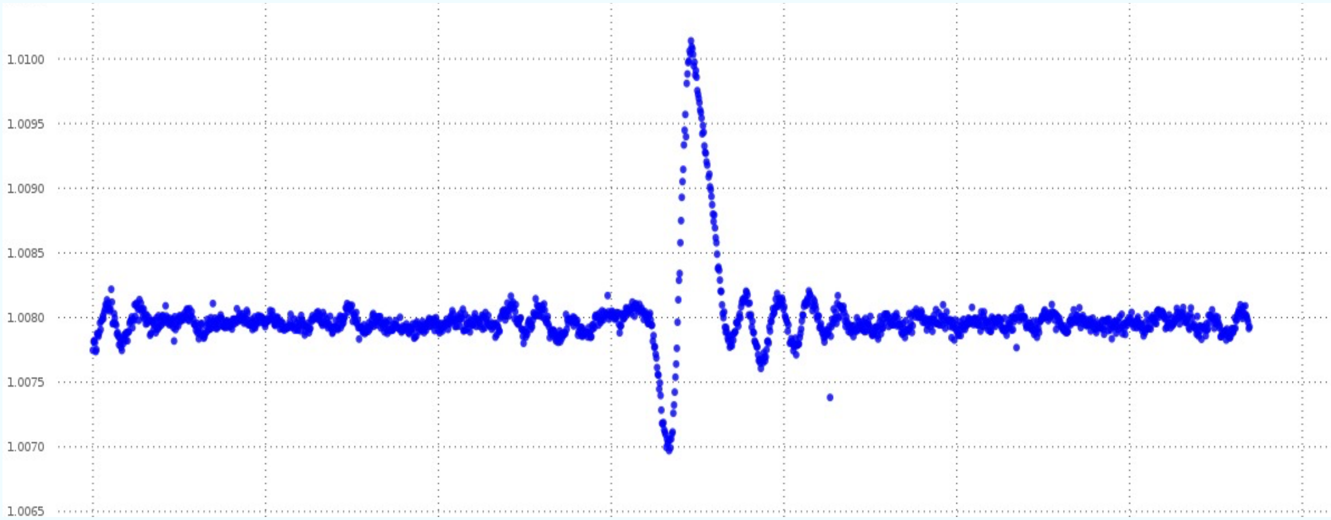
Measured timescale τ ~ 50 Myr to tidally evolve from e = 0.7 to e = 0.4 is ~3 orders of magnitude faster than predicted by weak-friction tides.

APOGEE binaries with giant primaries (Price-Whelan & Goodman 2018)

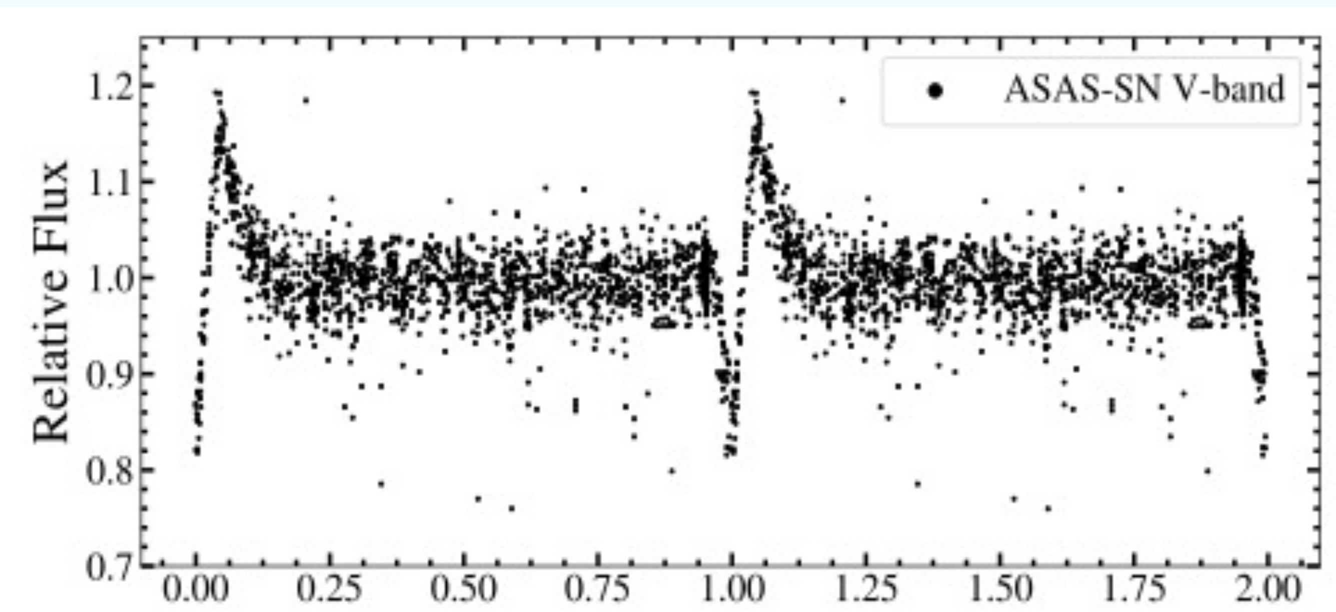


For large convective giants with small cores, observations are consistent with equilibrium-tide theory of Zahn (1977) and Verbunt & Phinney (1995).

Heartbeat stars: eccentric binaries raising a tidal bulge at periastron

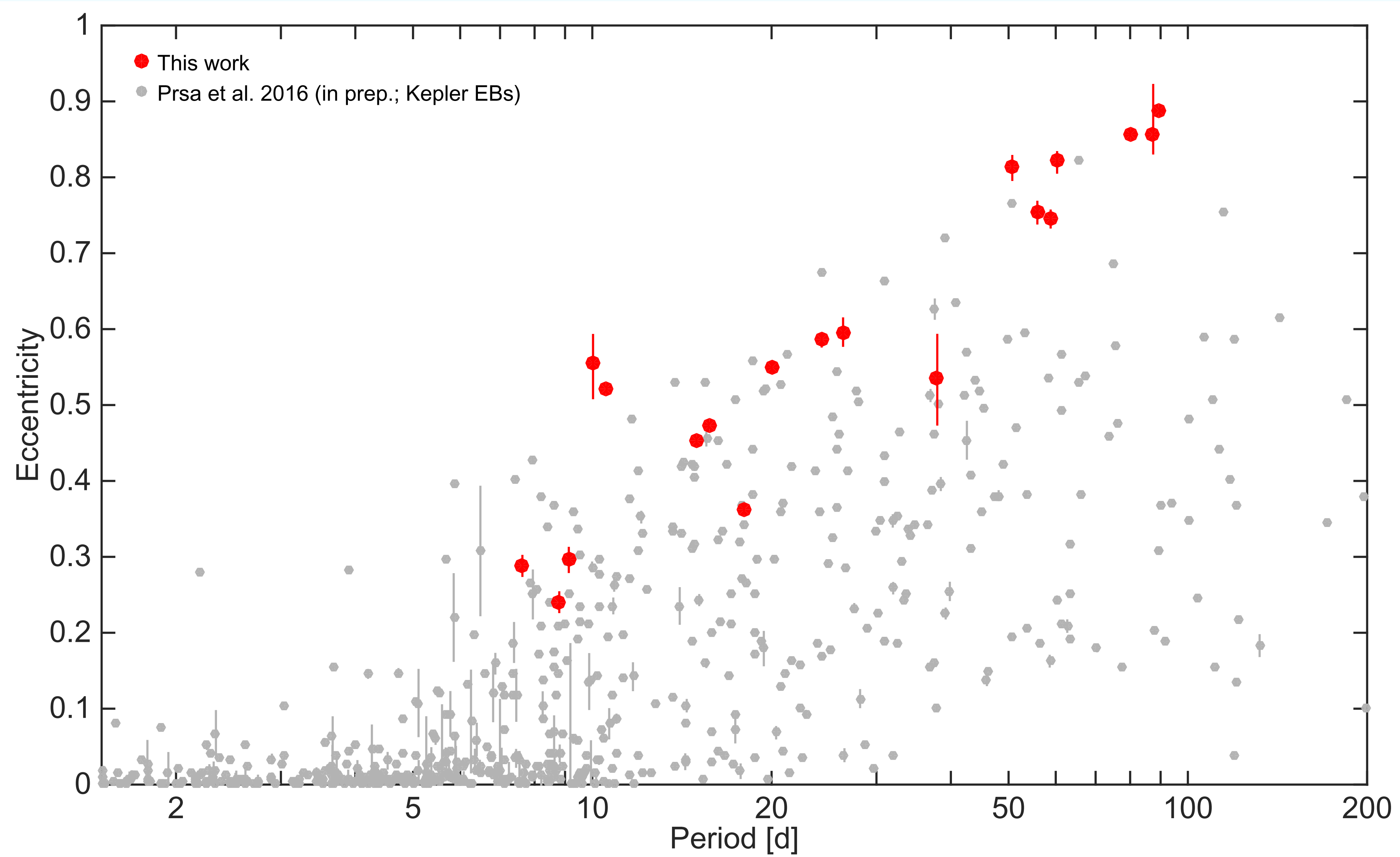


Kepler heartbeat star
(Thompson et al. 2012)



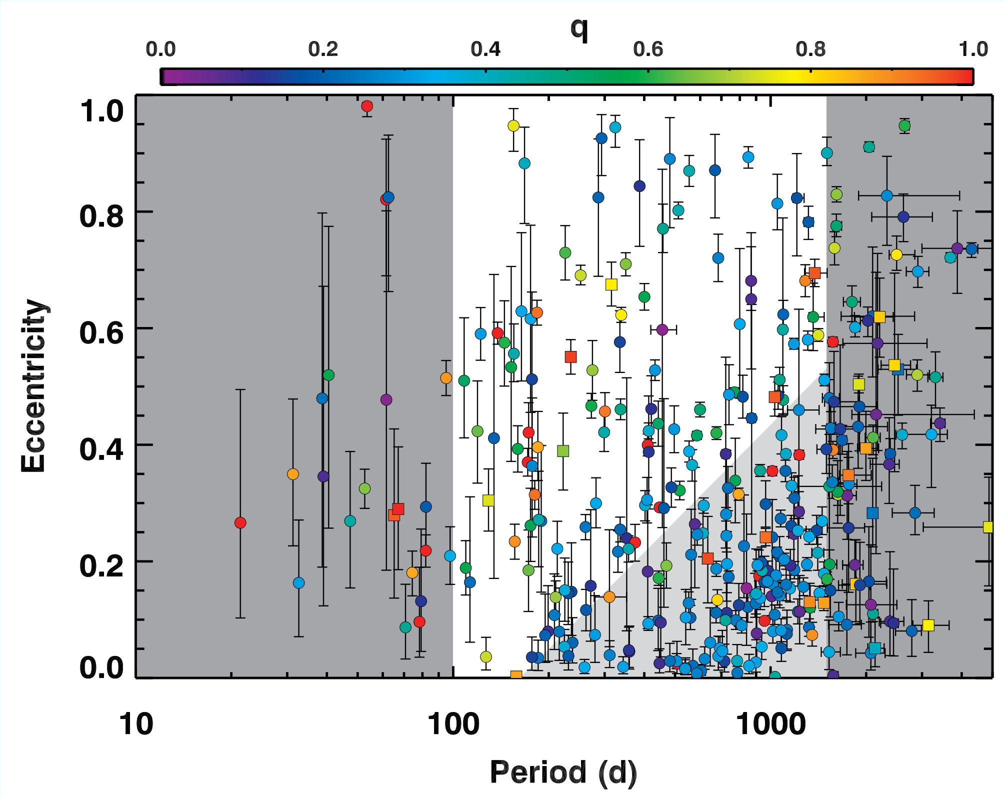
Young massive heartbeat star in the LMC discovered by ground-based ASASSN
(Jayasinghe et al. 2019)

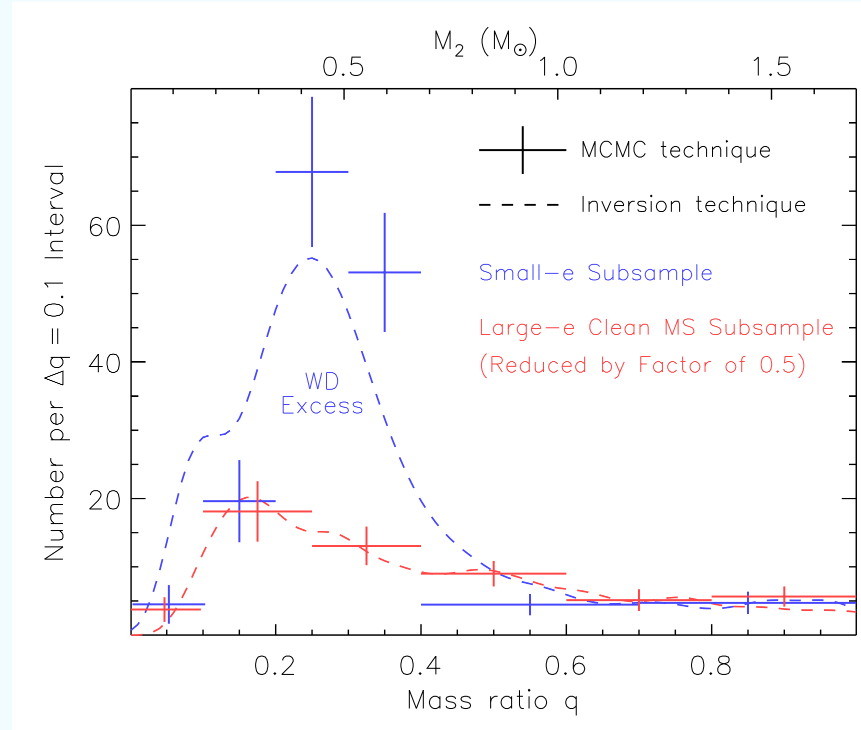
RV monitoring shows heartbeat binaries trace the upper envelope of the eccentricity versus period distribution (Shporer et al. 2016).



WD companions to MS stars

For solar-type primaries, ~30% of SB1s (20% of close binaries) have WD companions (Moe & Di Stefano 2017)

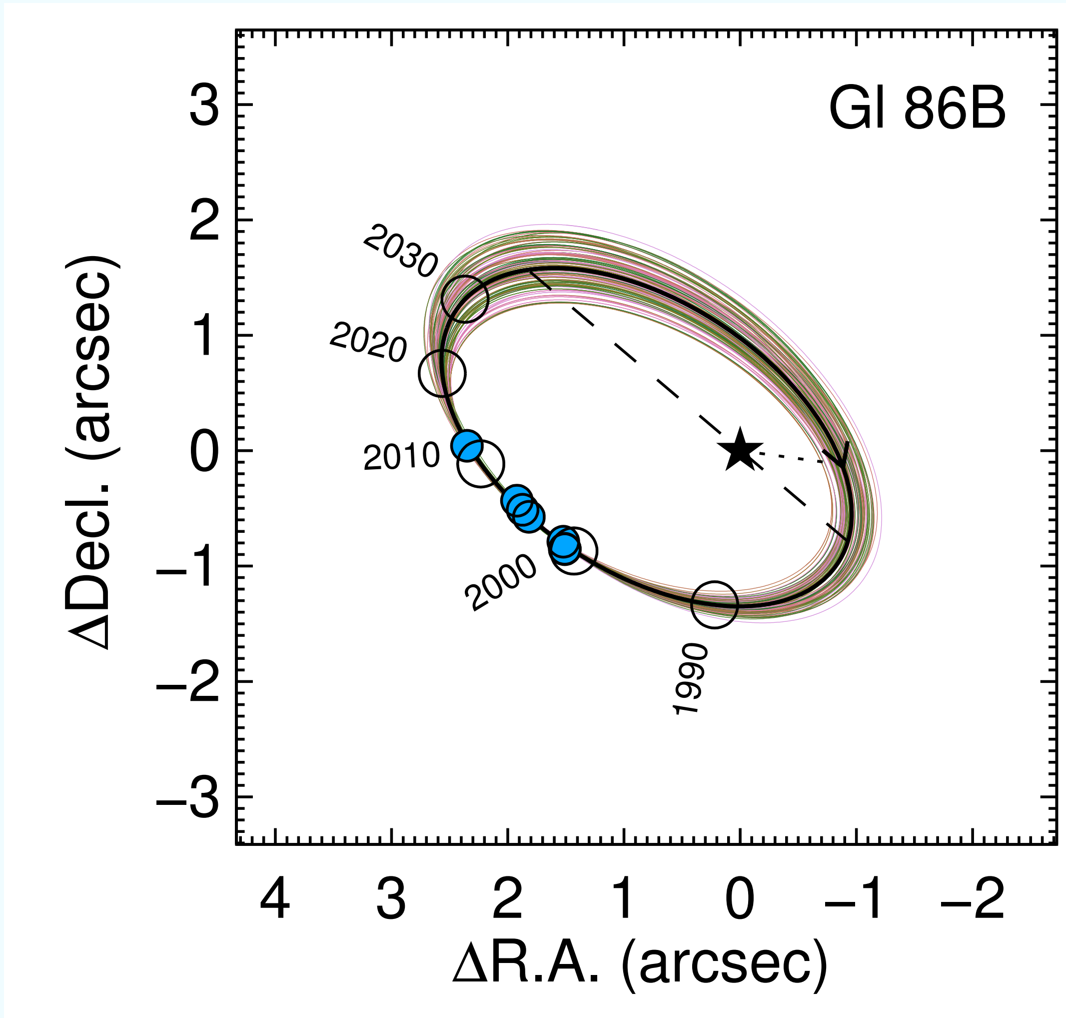




Phase modulation of Kepler pulsating δ Scuti stars (older A/F dwarfs) reveal binary companions across a = 0.5 – 5 AU (Murphy et al. 2018)

22% ± 6% of the companions are WDs with small eccentricities

Combination of RV measurements, Gaia / Hipparcos proper motions, and HST astrometry constrain the WD mass in Gl 86 to 0.60 ± 0.01 $M_\odot$ (Brandt et al. 2018)

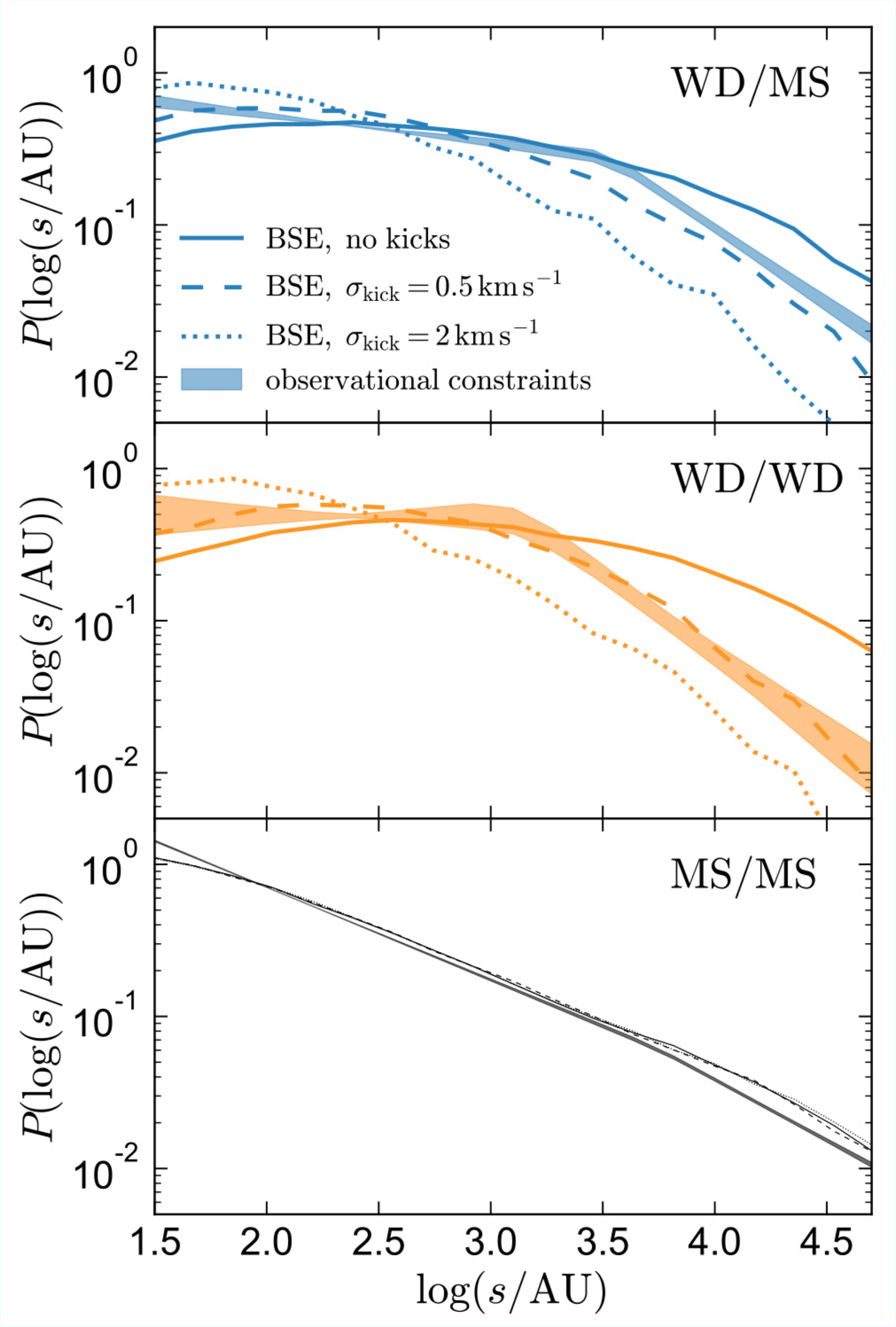


In a volume-limited sample of Gaia common proper motion binaries, wide WD + MS binaries have a different separation distribution than wide MS + MS binaries (El-Badry & Rix 2018).

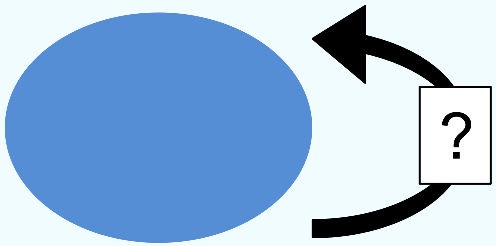
Modeling suggests WDs receive a recoil kick of ~0.7 km/s during AGB mass loss and that a substantial fraction of very wide binaries are disrupted.

Explanations:

1) Asymmetric AGB mass loss
2) $M_{env}/\dot{M}_{AGB} < P_{orb}$



Regulus: a rapidly rotating B8IV star;
P = 40 day SB1, likely a WD companion



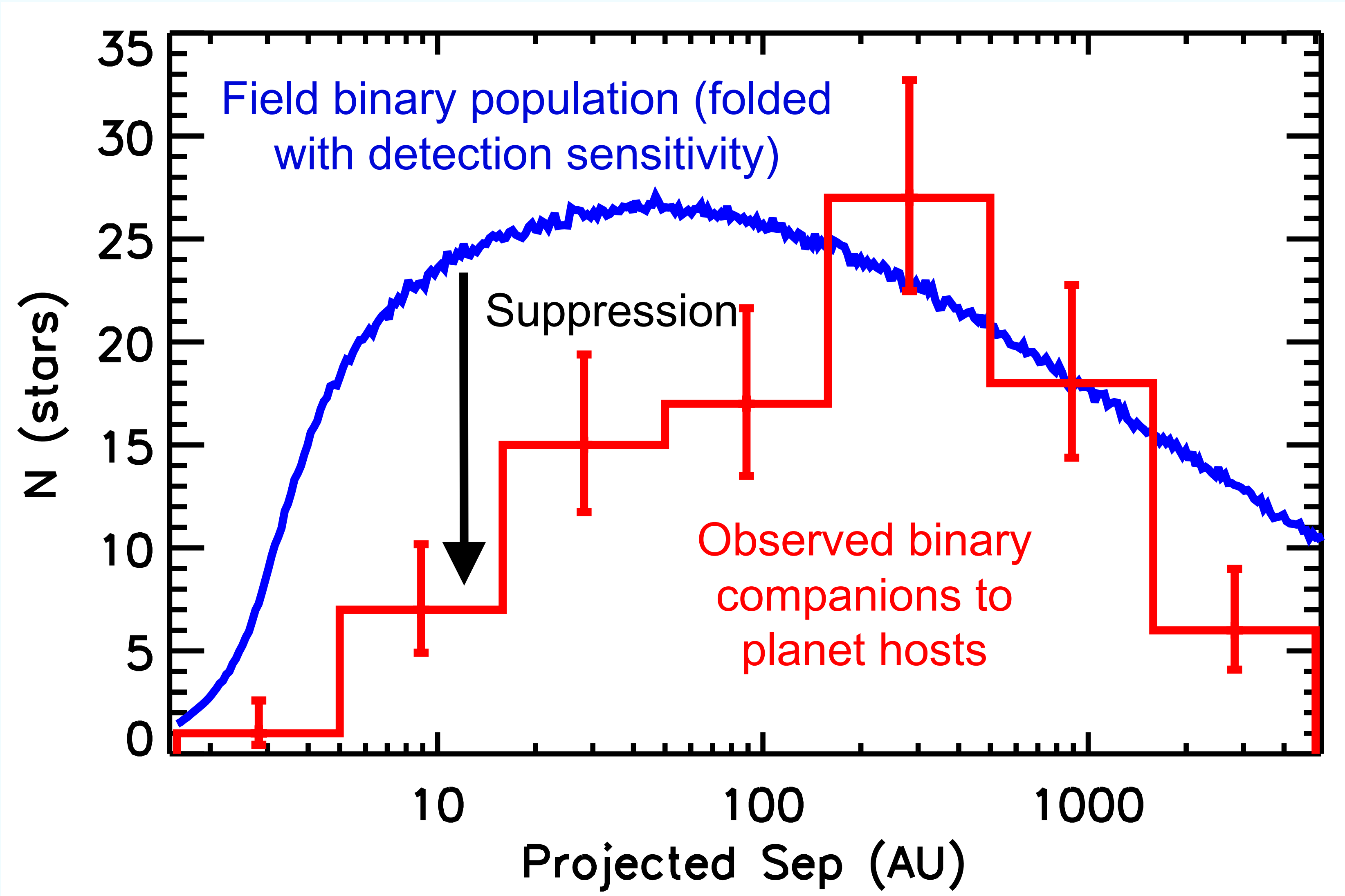
Malachi Regulus Moe

We do not yet know the frequency or properties of close WD companions to A/late-B MS stars, even though they are the progenitors of SN Ia (in both SD & DD scenarios)

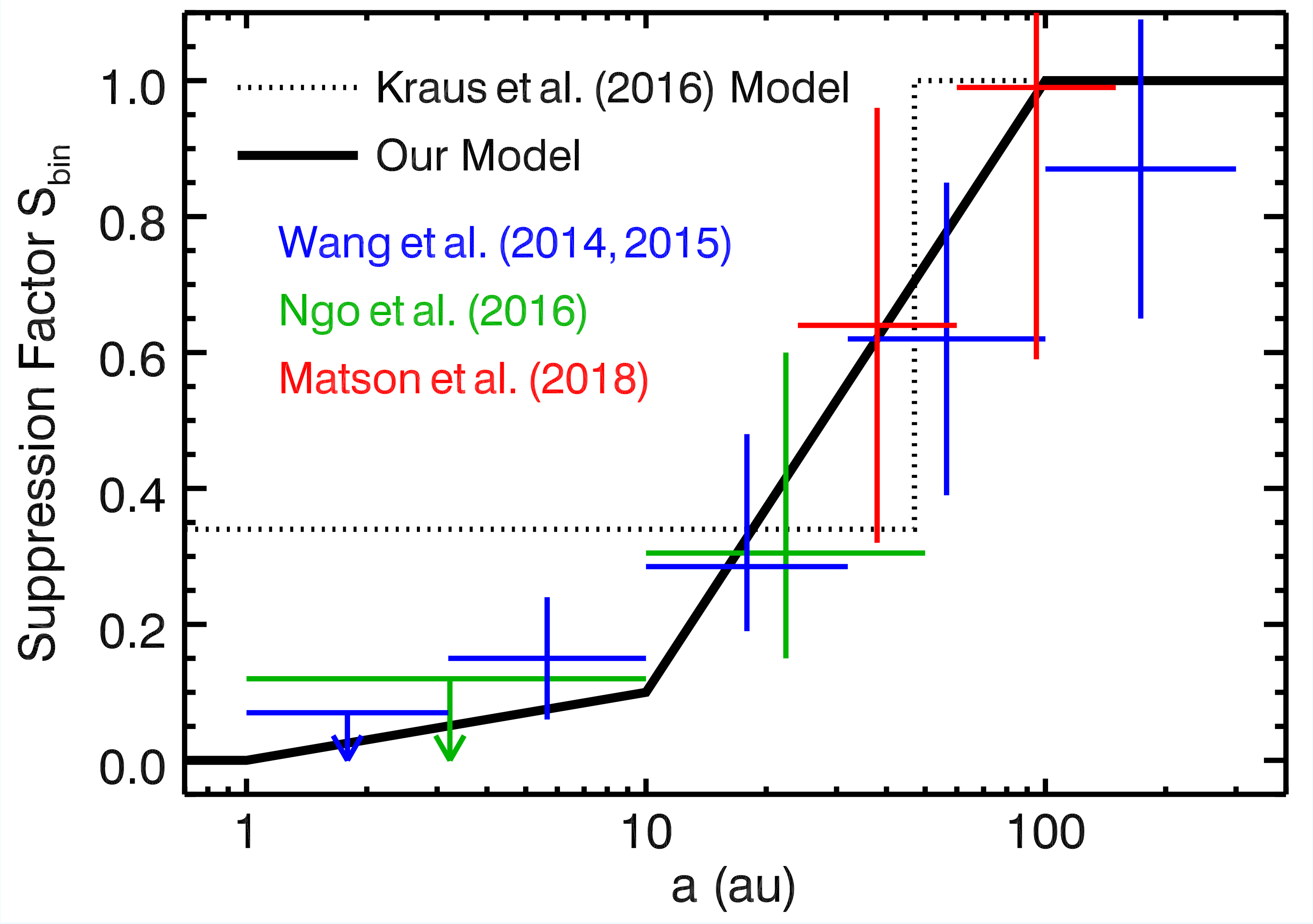
Currently creating a volume-limited sample of Regulus-like candidates: A/late-B SB1s that are rapid rotators, have large binary mass functions, and/or lack X-ray emission (Moe et al., in prep.)

Planets in Binaries

Although very close binaries can harbor circumbinary (P-type) planets, binaries with a < 50 AU suppress formation of circumstellar (S-type) planets (Wang et al. 2014; Kraus et al. 2016)

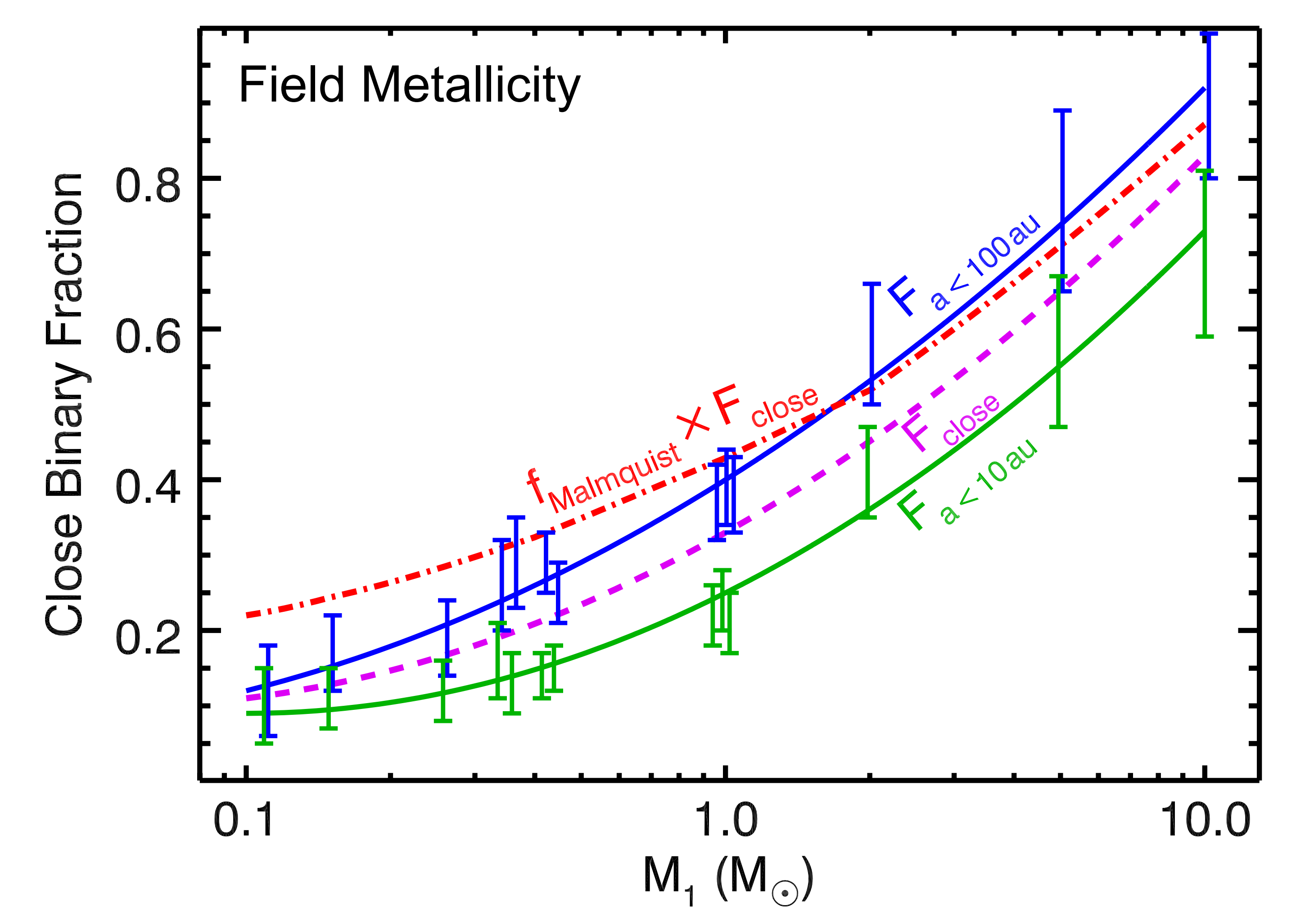


Suppression factor is a function of binary separation (Moe et al., in prep)



Planet suppression by close binaries is **NOT** just due to dynamical stability.

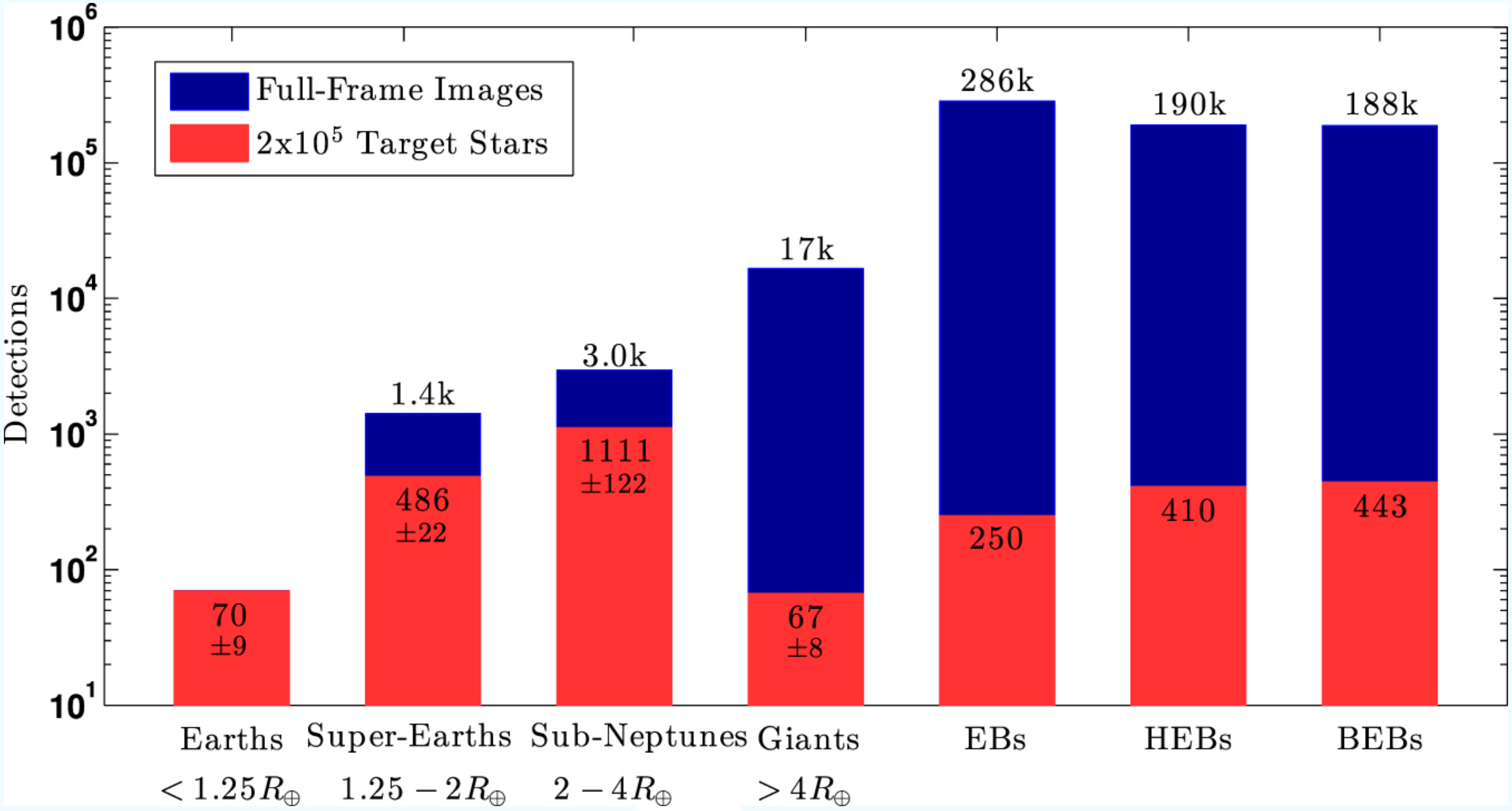
Impact of Close Binaries on Planet Statistics (Moe et al., in prep.)



In magnitude-limited samples, 43% of solar-type stars cannot host close planets because they are already in close binaries.

Binaries in Current Surveys

In full-frame images, TESS will discover ~300,000 EBs and ~400,000 planet false-positives, i.e., background EBs and EBs in hierarchical triples.

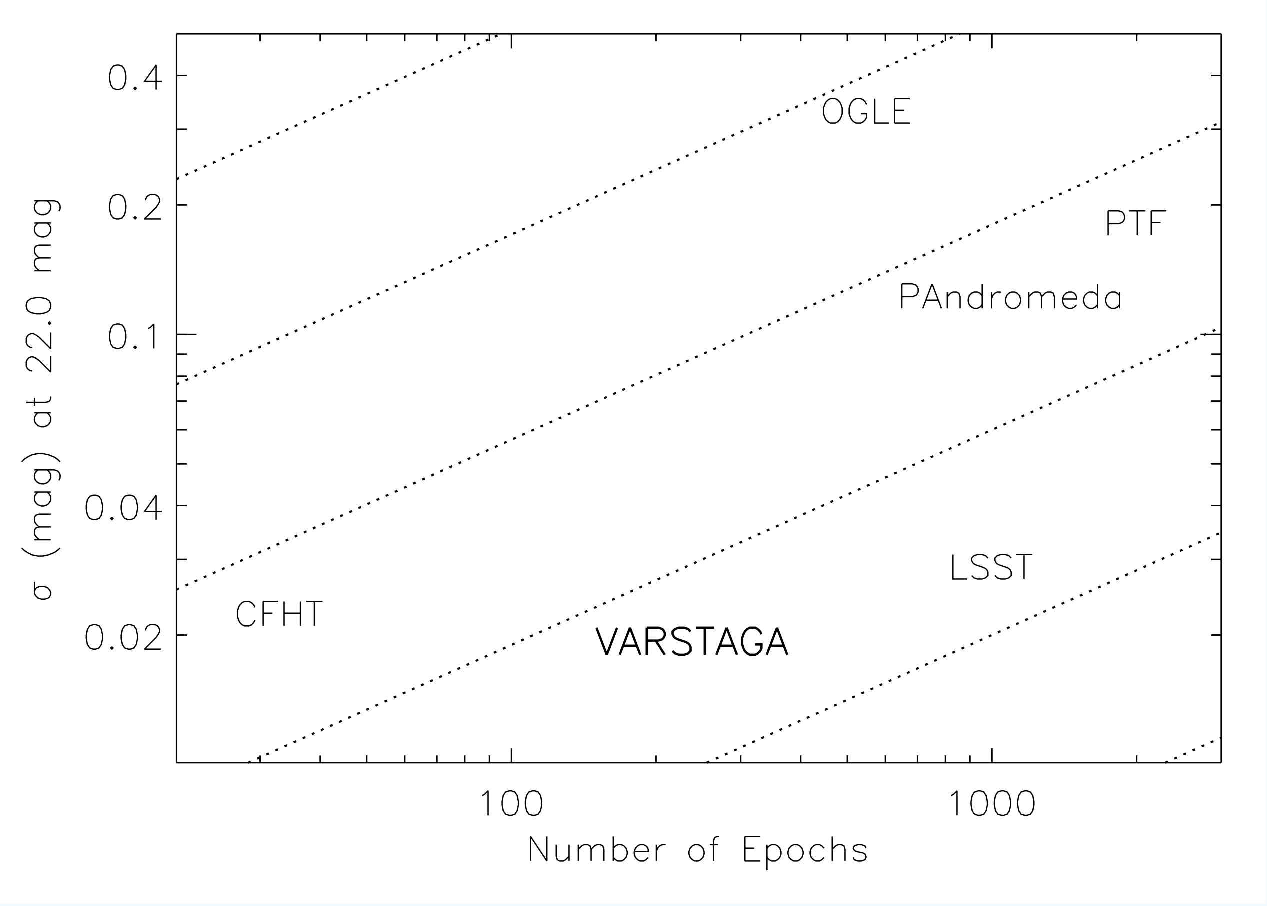


Gaia DR3: millions of EBs, SBs and astrometric binaries; dynamical mass measurements; triple star orientations, etc.

ZTF: millions of EBs; investigate EB fraction, e and P as a function of T_{eff}, proper motion, galactic scale height, etc.

VARSTAGA: VARiability Survey of the TriAngulum GAlaxy

First deep and high-cadence survey of a local group galaxy. One epoch is ~45 minutes with 2.3m Bok Telescope and 1.0 deg^2 90Prime imager.



Science Goals:

~10,000 EBs

~10 giant EBs: measure distance to 2% accuracy

~20 helium star EBs: progenitors of SN Ib/c & contributor to reionization

Measure occurrence rate of FU Orionis outbursts

The Value of Studying Bright Stars, AGN, etc

E. Sterl Phinney

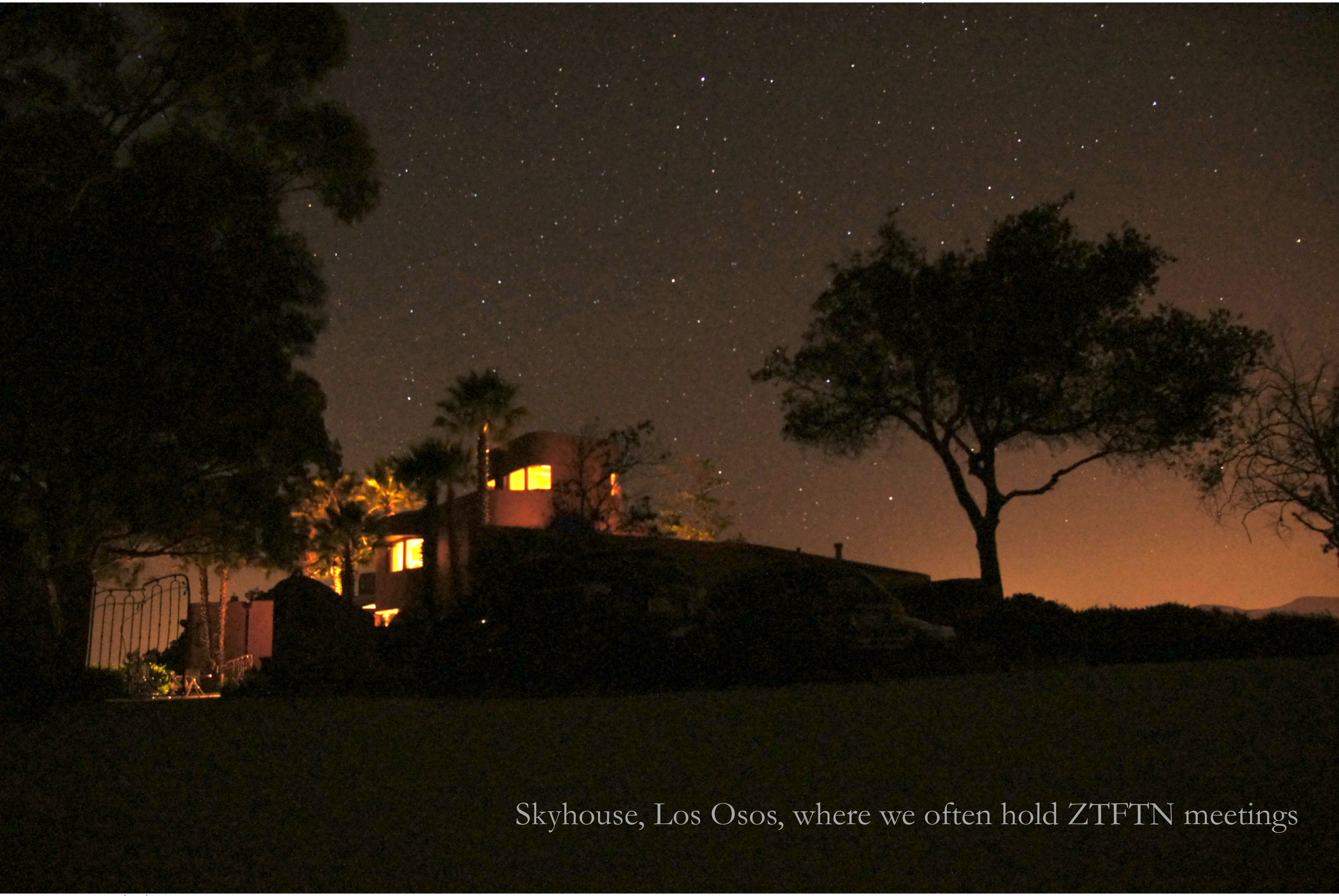
Caltech

“A tree is a tree. How many more do you have to look at?”

---California Governor Ronald Reagan, 1966, opposing the proposal to create Redwood National Park (est. 1968)

But are all trees really uninterestingly similar?

Where I grew up. House built 1782.
The sugar maple tree likely pre-dates
the house (is huge in 1905 photos!).

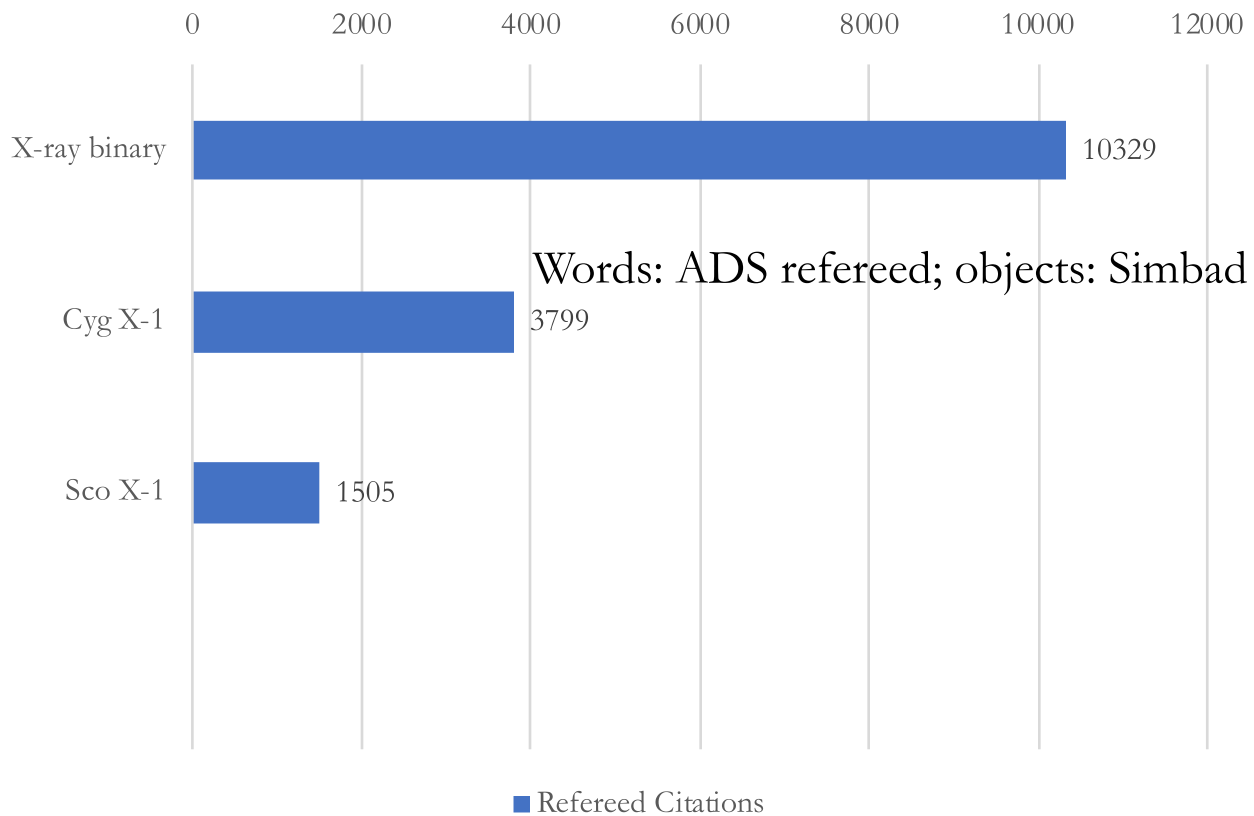

Skyhouse, Los Osos, where we often hold ZTFTN meetings

Phinney's Propositions:

1. For broadly similar objects:
   Information content $\propto$ $1+\log_{10}$(sample size)
   - Measure information content by # refereed papers written
   - The brightest or first found object of a given type is forever studied *far* more than the 10^5-10^6'th ever are.
   - The village phenomenon: the 100 people you know best are individuals; everyone else is statistics and stereotypes.
     - The most influential astronomical catalogs all have ~ 100 objects (Messier, Palomar-Green BQS, 3C, 4U, …)

Empirical evidence for prop 1:

X-ray source citations



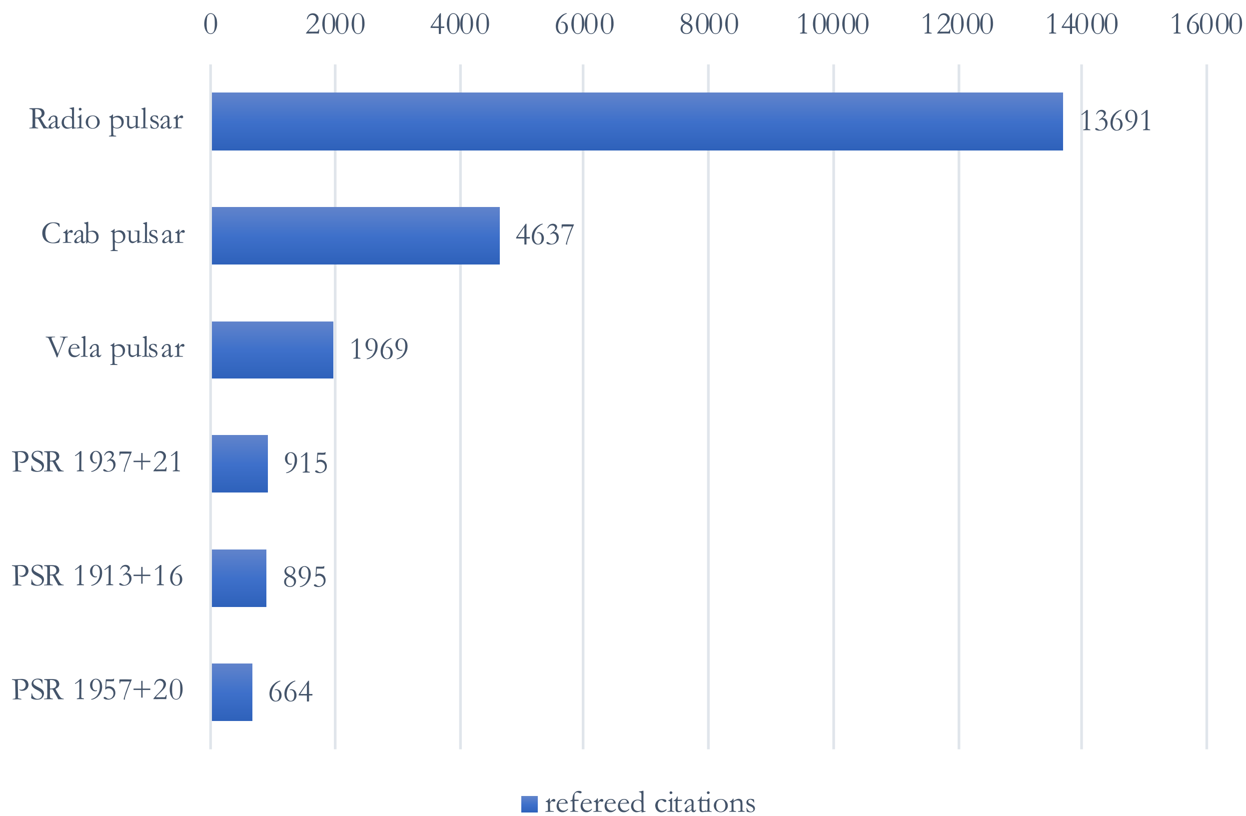
4th Uhuru (4U) catalog: 339 sources, 3484 citations

2nd Rosat (2RXS) catalog: 135,000 sources (x400), 11390 citations (x3)

Pulsar citations

ADS

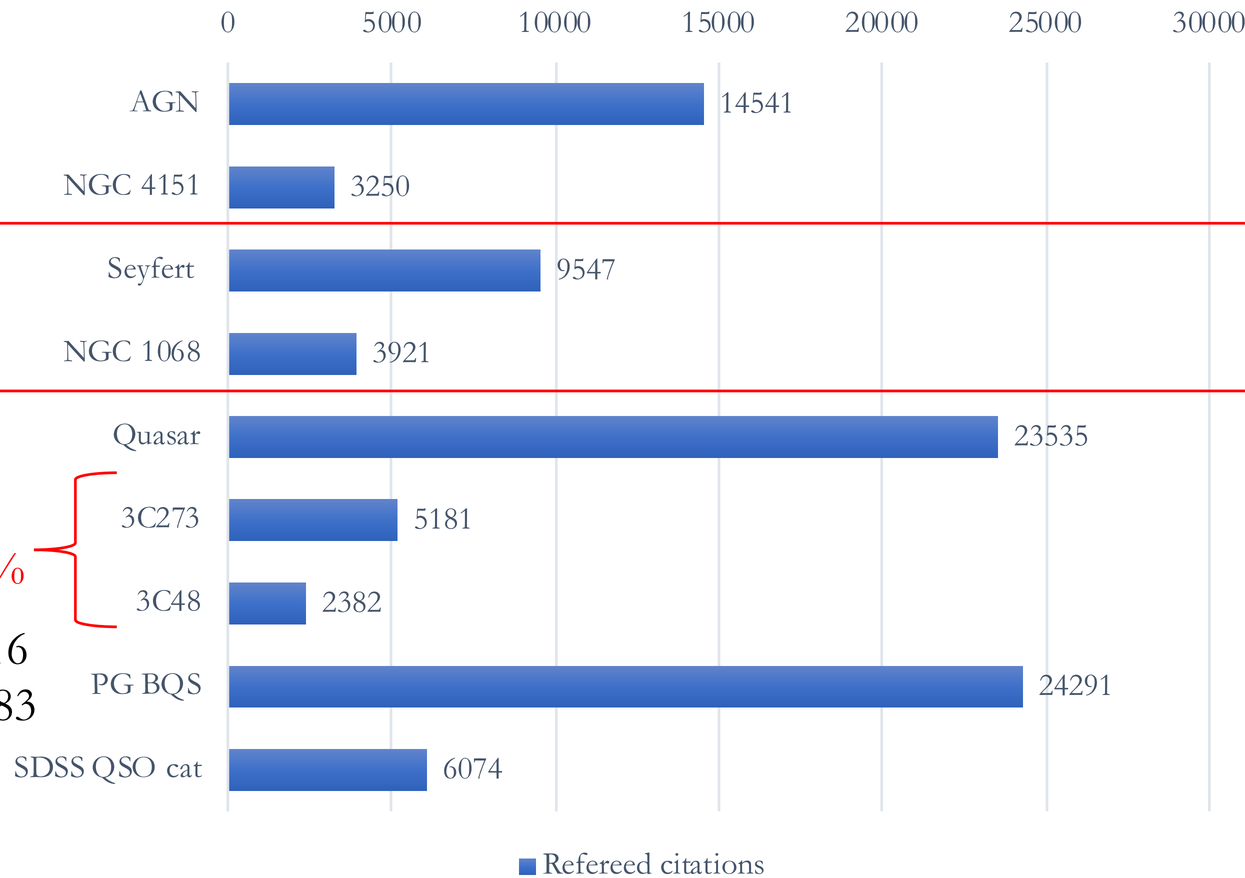
66% of all refereed citations of radio pulsars (Simbad)



Quasar and AGN citations

22%

41%



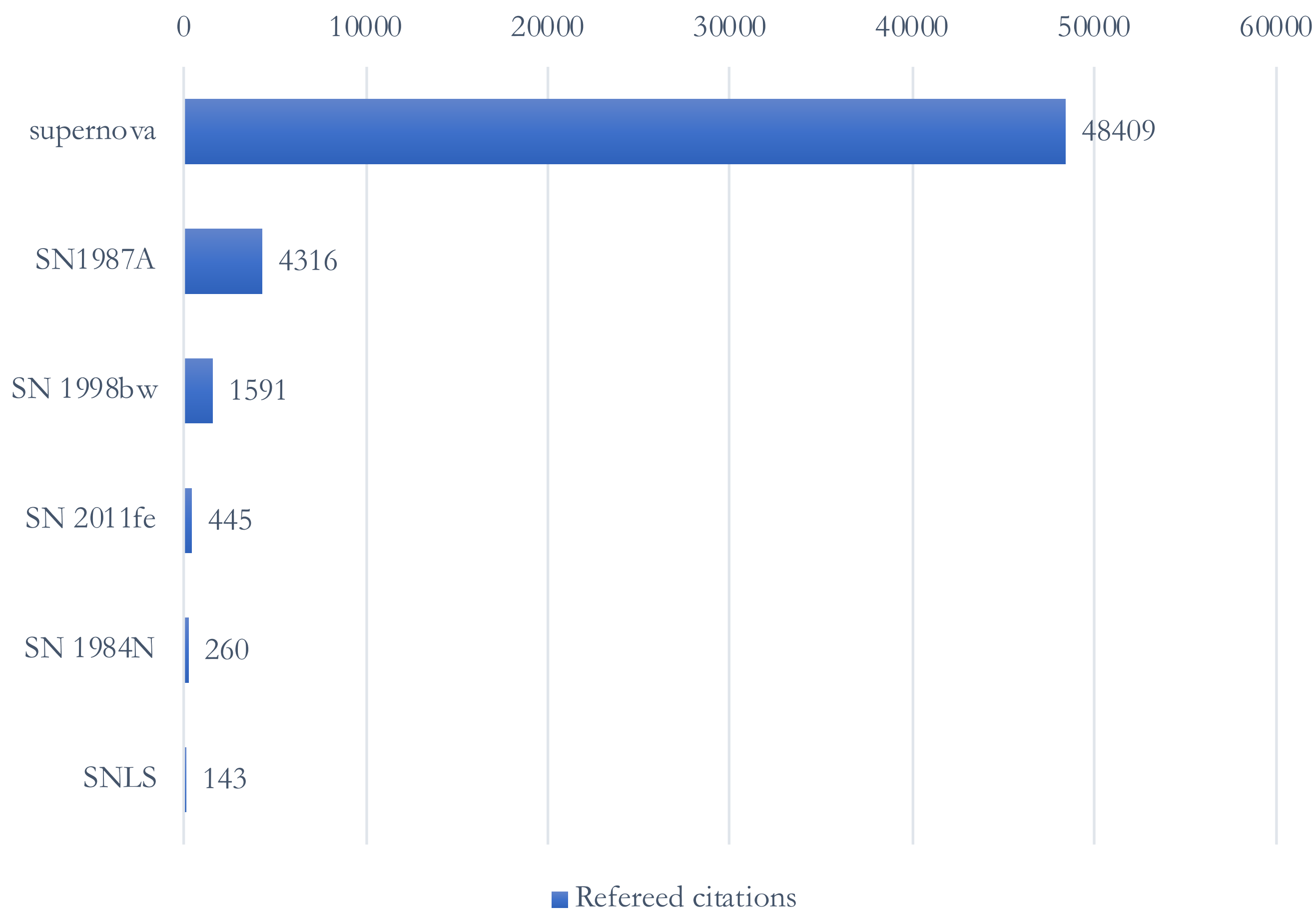
The first two, and brightest quasars: 32%

PG: 114 quasars B<16
Schmidt & Green 1983

SDSS DR14Q:
526,356 quasars

Words: ADS refereed; objects: Simbad

Supernova citations



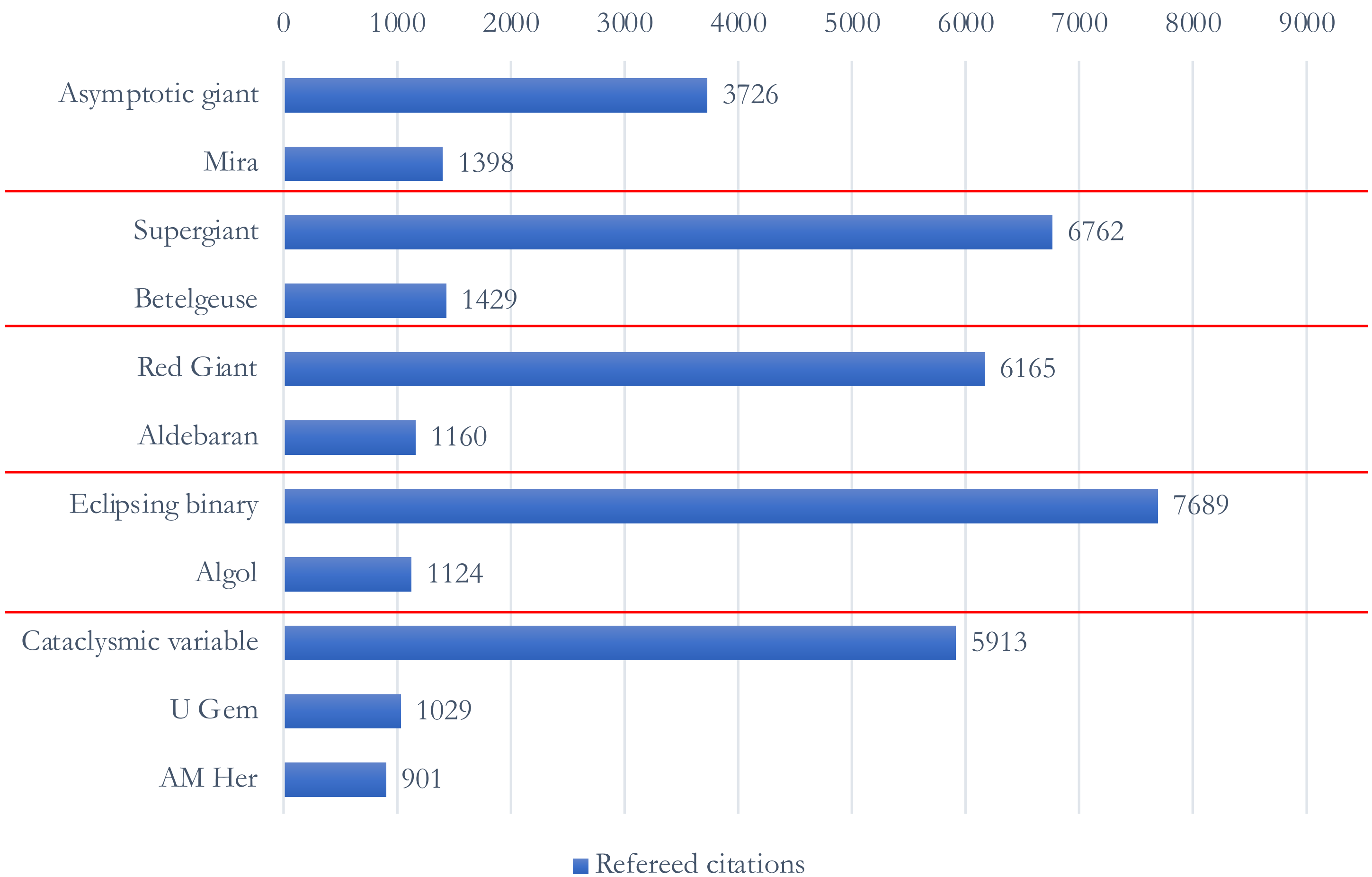
First GRB/BL Ic

Ia in M101, 7Mpc

First Ib

2000 supernovae
to z=1
(2003-2008)

Star citations



Astronomers & others on Twitter

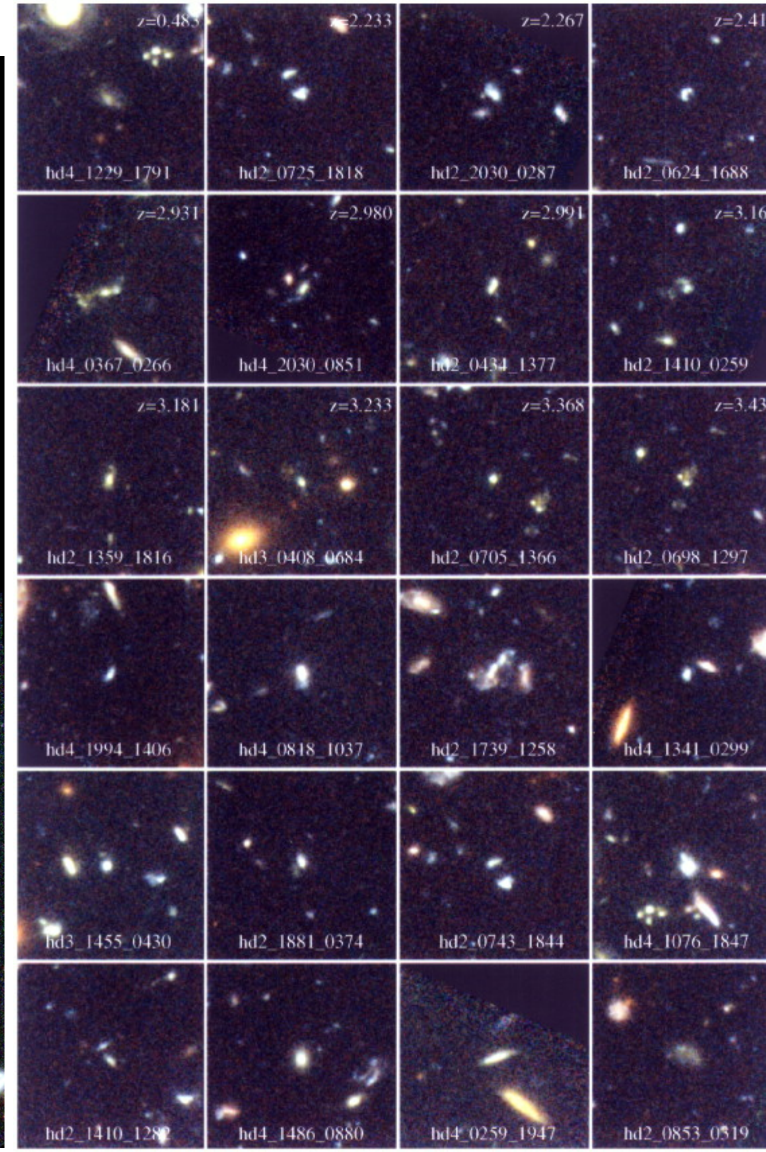
	followers	tweets
Avi Loeb/Harvard ITC	866	503
Caltech Ay faculty except:	0	0
Phil Hopkins	359	99
Evan Kirby	374	290
Andrew Howard	569	624
My top former students	on twitter	
Steinn Sigurdsson	1,600	10,000
Mike Hartl	33,000	9,400
Katie Mack	308,000	100,000
Non-astronomers famous	for being famous	
Kim Kardashian	60,500,000 (20% of all twitter users!)	29,200
Donald Trump	60,000,000	41,600

I often heard it said that “the plural of ‘anecdote’ is not data.”
--- but actually, it pretty much is.
-Michael Hartl 2019 (@RailsTutorial, @mhartl)

Phinney's Propositions, continued

2. Big samples are more useful for finding correlations than causation.
   - "The only normal people are the ones you don't know very well." –Joe Ancis
   - "One rarely falls in love without being as much attracted to what is interestingly wrong with someone as what is objectively healthy." –Alain de Botton
3. Detailed study of a few individuals is most useful for elucidating the physics of how things work.
   - cf. SN 1987A neutrinos; solar neutrinos, helioseismology…

Hubble Deep Field

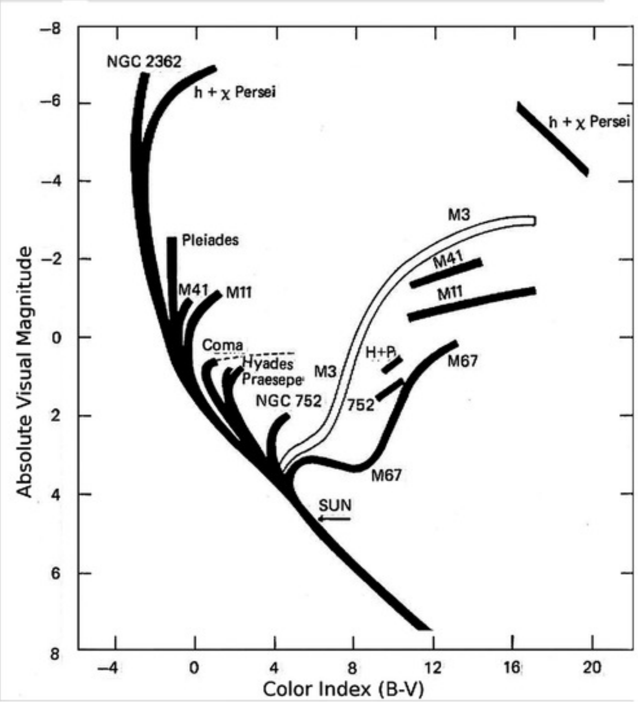


z~3 galaxies of HDF (Steidel+ 1996, Lowenthal+ 1997…).

LMC,
16cm telescope
1060 h exposures
6 filters,
r,g,B,
Hα 656,
SII 672,
OIII 500.7

So when are large samples important?

1. When objects distributed in a multi-dimensional distribution have properties or outcomes that vary a lot with position in parameter space:
   - -Classic Carnegie/Caltech example (Arp, Sandage, Fowler, Hoyle): photometry of cluster stars



$$N(L, T, t) \text{ in clusters}$$

$$\rightarrow L(M, t), T(M, t)$$

Theory of stellar evolution: Hertzsprung gap, Red giant, AGB, mass loss, WD formation

Current frontier $N(L,T,t,Z,\Omega)$

So when are large samples important?

1. When objects distributed in a multi-dimensional distribution have properties or outcomes that vary a lot with position in parameter space:
   - -cf. main sequence binary stars:

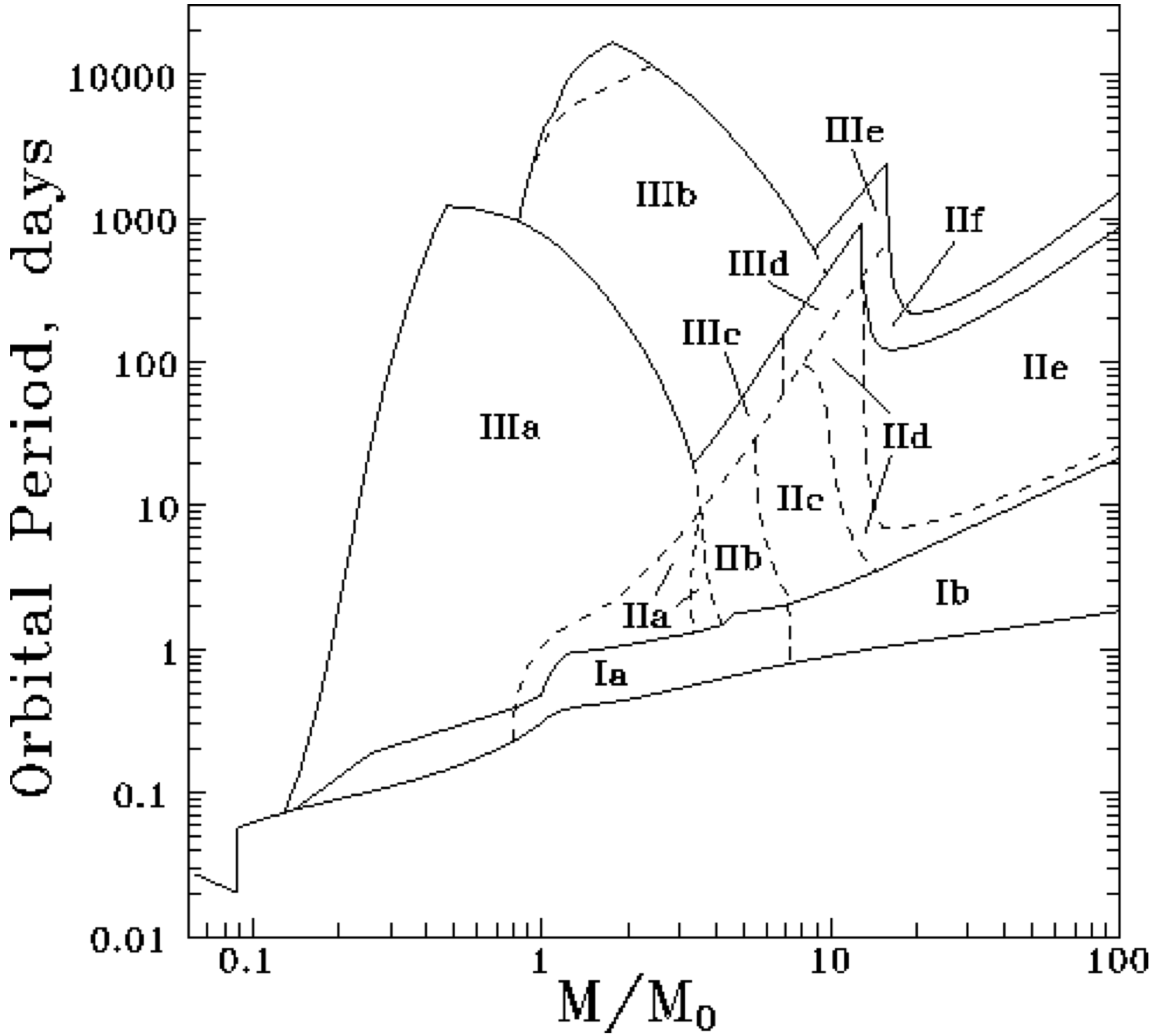
$$f_2(M_1, q = M_2/M_1, a, e)$$

Future evolution, remnant type

Stability of Mass xfer

Future evolution, type of mass transfer

Tides, synchronization, circularization, mass xfer



Webbink 1979
IAU Colloq 53, 426
Modes of
first mass
transfer in binaries

Case A: MS xfer
Case B: RG xfer
Case C: AGB xfer

How many binary stars needed?

$$f_2(M_1, q = M_2/M_1, a, e) dM_1 \; dq \; da \; de$$

$$M_1 : (0.1 - 100 M_\odot) \text{ in factors of } 1.5 : 17$$
$$M_2 : (0.01 - M_1) \text{ in factors of } 1.5 : 8.5$$
$$a : (R_1 - 10^3 R_\odot) \text{ in factors of } 1.5 : 20$$
$$e : (0.01 - 1) \text{ in factors of } 1.5 : 11$$
$$17 \times 8.5 \times 20 \times 11 = 32,000 \text{ bins!}$$

if want 20% statistics, need 30 per bin, so minimum 10^6 binaries with well-determined orbits!

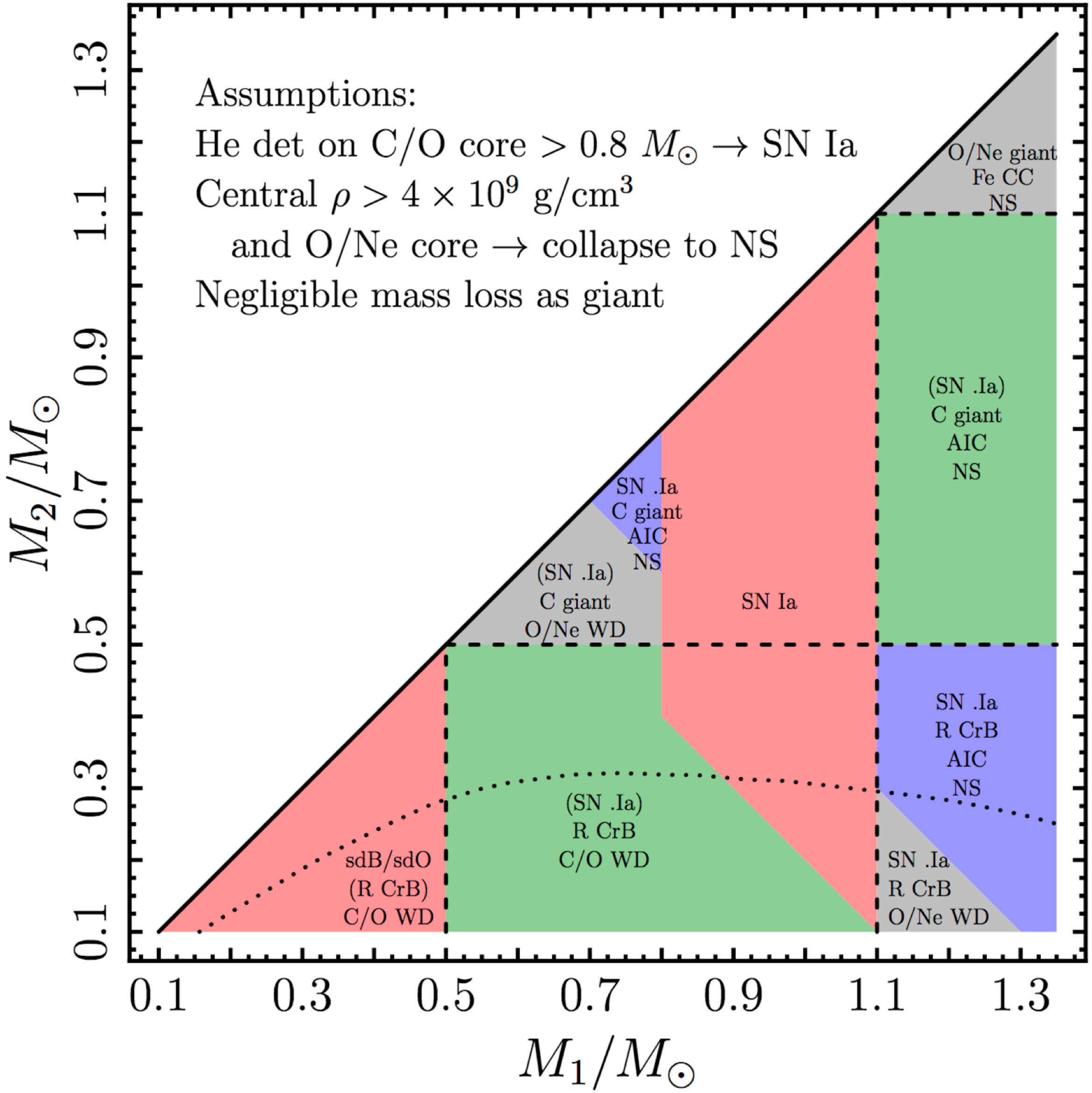


Figure 3. Schematic of interacting double WD binary outcomes. See Section 5 for details.

Shen 2015
1502.05052

Outcomes of White dwarf Mergers.

If we finish binaries: triples, quadruples await!

- Most massive stars are in higher multiplicities than binary. Consider just triples, M_1>2 Msun

$$f_3(M_1, q_1 = M_2/M_1, q_3 = M_3/M_1, a_1, a_2, e_1, e_2)$$

$$\sim 4 \times 10^6 \text{ bins!}$$

$$\text{At 30 stars/bin for 20\% stats, need} \sim 10^8 \text{well measured triples!}$$

Current data – e.g. Tokovinin 2018 Multiple Star Catalog: just ~2000 hierarchies in stars <70pc, O stars at kpc [all mostly brighter than 13th mag!]
cf Moe…

Even the Galaxy may not be enough…

Multiple stars in clusters

- (Open clusters good for multiplex spectroscopy – globulars too crowded?):
  - Population of known age can be used to quantify evolutionary effects that can't be quantified in the field
    - e.g. *single best constraint* on common envelope evolution is still V471 Tau in Hyades (Pacsynski 1976! 0.8Msun hot WD+ K dwarf, P=12h)!
    - Best calibration of (convective star) tidal circularization is still Verbunt & Phinney 1995, used just 31 binary orbits in 12 clusters painstakingly observed by Mermilliod & Mayor, Mathieu, Latham.
    - Initial mass –final mass relations; white dwarf cooling, stellar rotation
    - But also 3-body exchanges, dynamical evolution…

Binary, triple… -star evolution outcomes

- Huge array of branch points and diverse outcomes, and intermediate evolutionary stages to study:
  - E.g. accretion rate determines He nova vs deflagration vs detonation (Ia) vs AIC to neutron star.
  - Accretion rate in turn depends on M_2, *a*, age, reflection effect/heating, magnetic fields
  - Which in turn depend on angular momentum loss, common envelope behavior (M_1, age)…

$$N(M_1, q, a, e, t, Z)$$

Clusters will be less useful/more interesting because of 3-body interactions, exchanges, hardening, etc; cf. Sigurdsson & Phinney 1993, N. Leigh+ 2017, 2018

Binary pulsars

- NS formation vs AIC, electron capture SN (low kick?) – most binaries survive, core collapse (high kick?) –most binaries don't survive.
- NS companions: planets, brown dwarf, M stars, B stars, He WD, CO WD, ONeMg WD, NS, black hole
- Orbital periods 1.5 h to 1200d and 10^4 years!
- $e=2\text{x}10^{-7}$ to 0.98
- $B_d=10^8$ G to $10^{11.5}$ G, P=0.0015s-1.8s, age…
- magnetic braking, GW braking, accretion cycles, companion heating, driven winds…
- And triples!

Huge parameter space, with totally different physics in each bin, and great tests of fundamental physics in many! ~200 binaries known hasn't even touched many interesting parts of parameter space (e.g. a detached red giant+NS, where pulsar timing measured eccentricity evolution due to convection, while asteroseismology of the RG measured the excited tides…)

Evolved binary, triple… stars

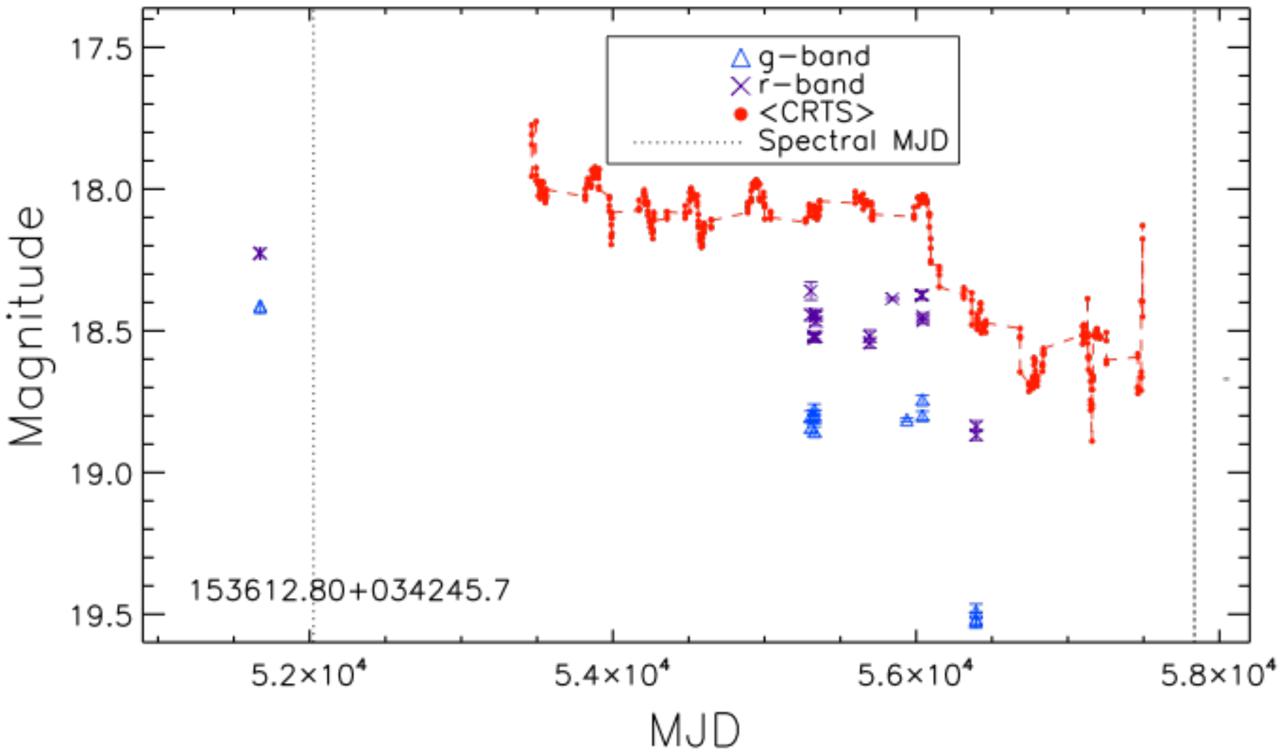
- Similarly, formation and evolution of binaries, triples with other outcomes will be similarly rich (magnetic, nonmagnetic white dwarfs of all surface compositions), sdB, sdO stars, synchronized or not, Kozai, reflection effects, L2 mass loss. Connections to variety of transients in different locations in different galaxy types…
- Still TBID:
  - WD-NS mergers
  - WD-BH mergers
  - BH-NS mergers
  - Thorne-Zytkow objects

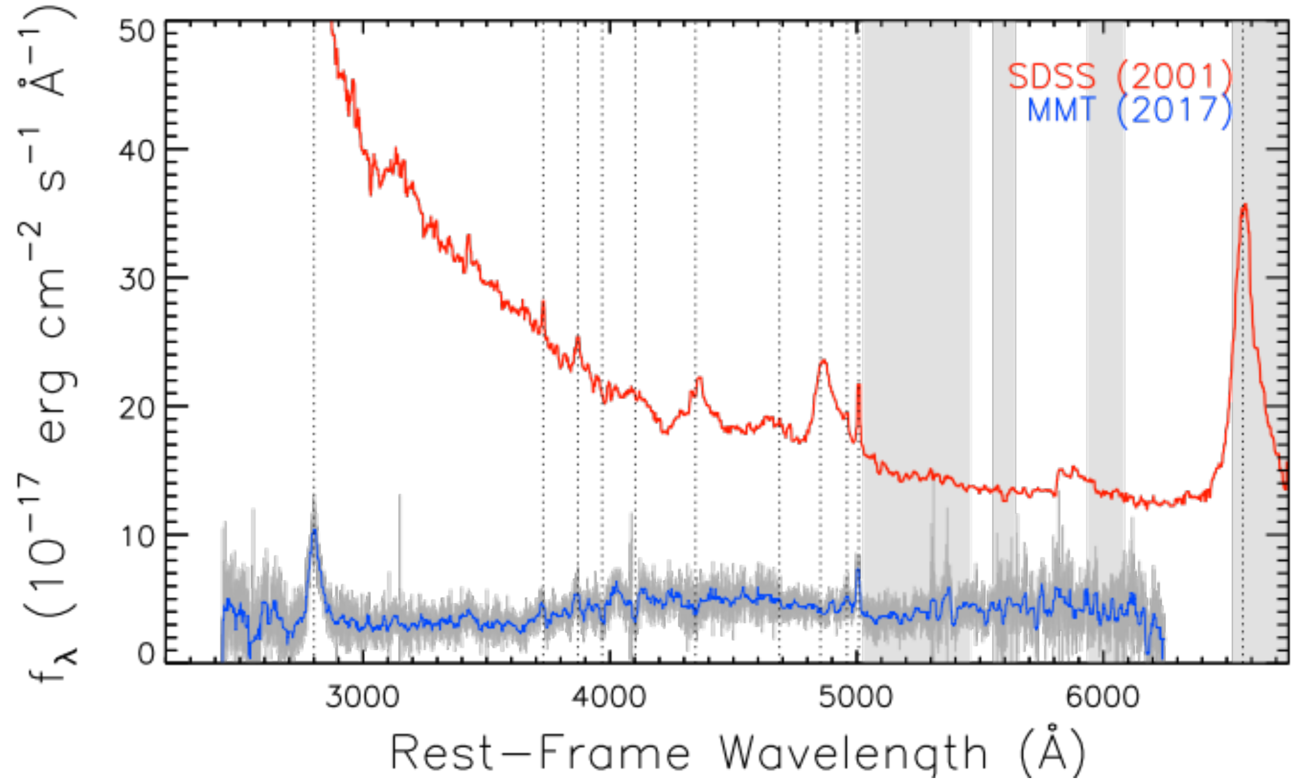
When else are large samples important?

2. When you are looking for rare objects (diagnostic of especially interesting or uncertain physics)
   - Short-lived phases
     - Stars just years before or after merger
     - AGB stars undergoing a thermal pulse (via asteroseismology)
     - AGN binaries with orbital periods of months (10^4 y to merger for 10^7 Msun, q=0.2)
     - Interacting supernovae (binary, where both components SN within a year of each other: must be >1 in 10^5 CC SNae –more if convergent evolution in mass xfer).
     - Triple star system in its first e=0.99999 Lidov-Kozai plunge or undergoing angular momentum flip.
     - Thorne Zytkow objects
   - Improbable series of events needed to make them
     - A tidal disruption event's accretion disk gravitationally micro lensed by a 100Msun black hole in a foreground galaxy.
     - Supernova whose kick sent proto-NS into companion star and tidally disrupted it.
     - Detached black hole binaries (cf Thompson et al arXiv:1806.02751?). If LIGO stories correct, must be common in clusters.

Based on Phinney's Proposition 1:

- The brightest (nearest) one to ten examples of the rare or short-lived events will be the ones that provide the most information about the physics.
  - One or two of each at 19-20th mag will be at least as valuable as 10^4 of them at 27th mag…





Changing Look Quasars, via wide-field time-domain light curves & spectroscopy

Collated/adapted by Scott Anderson, Matthew Graham, Robert Antonucci

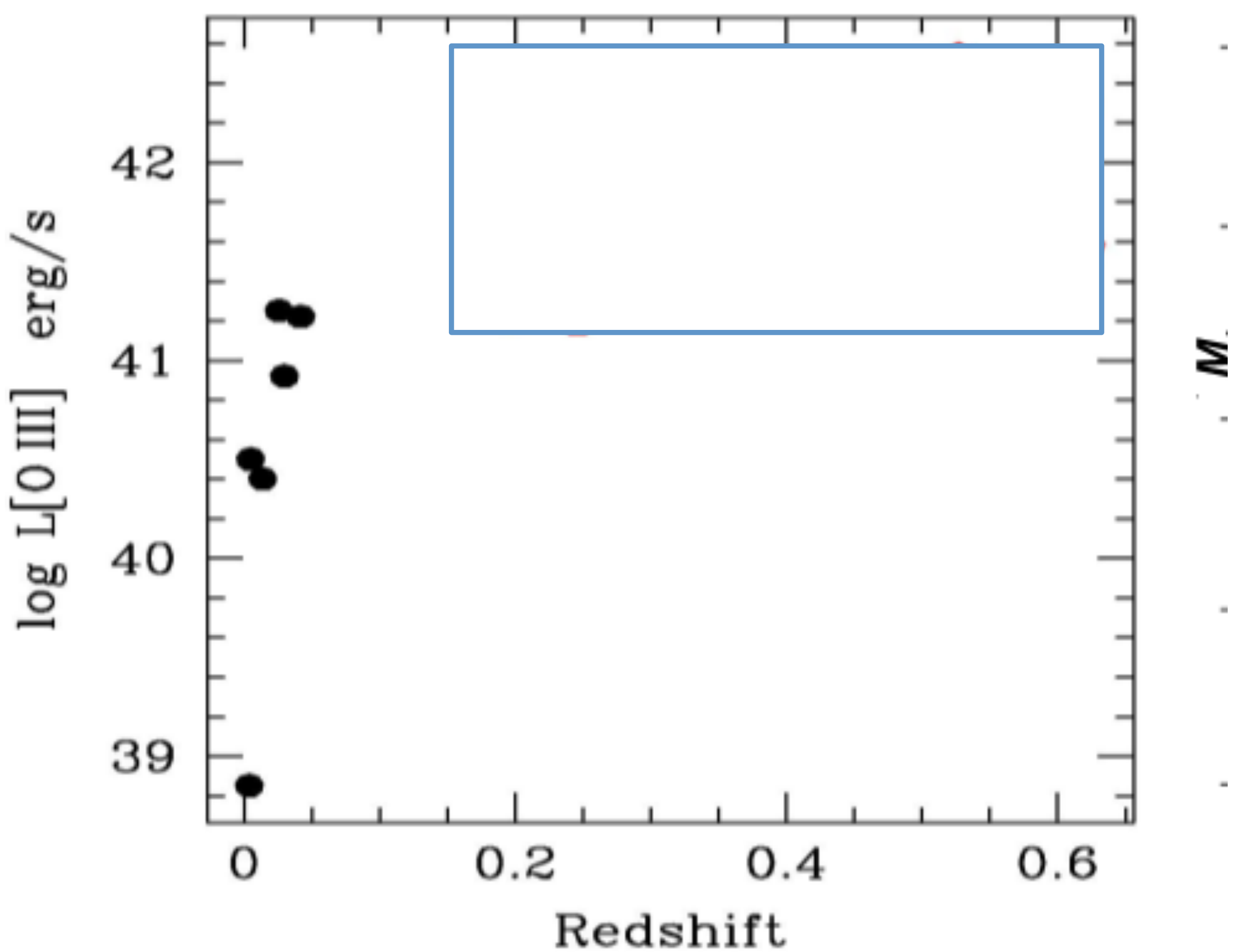
and including additional slide contributions from
Mike Eracleous, Sara Frederick, Suvi Gezari, Paul Green, Kate Grier, Chelsea MacLeod, Andrea Merloni, John Ruan, Jessie Runnoe, Yue Shen

SDSS

ZTF

Occasional "Changing Look" AGN known for several decades, mainly low-luminosity cases

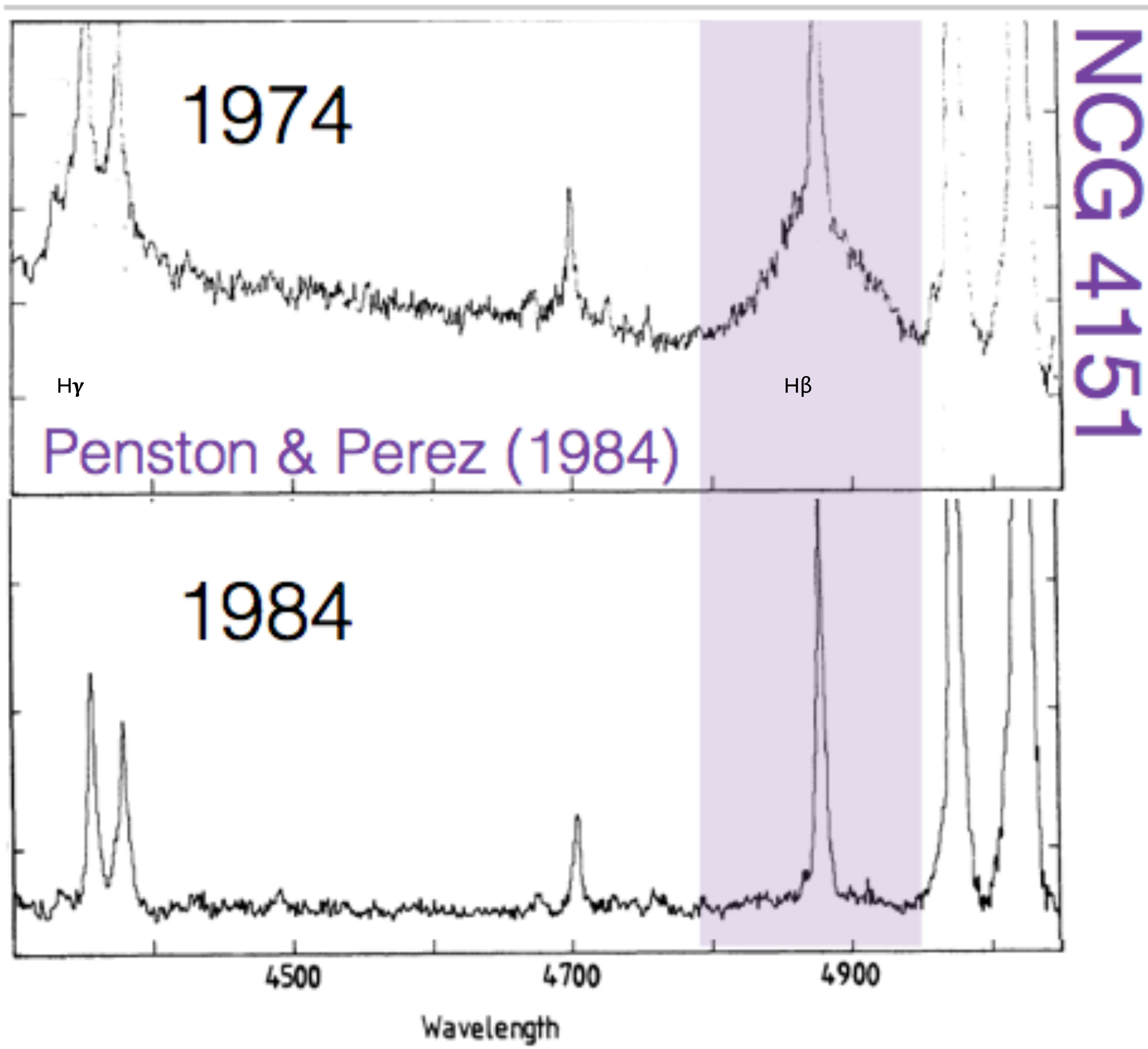
Some varied in X-rays, some changed in optical spectra often from Type 1 toward Type 2 (but also other direction, and also more modest changes such as Sy 1.5 to Sy 1.9 etc.), on short timescales, years to decades.



Adapted from C. Macleod

Changing Look AGN

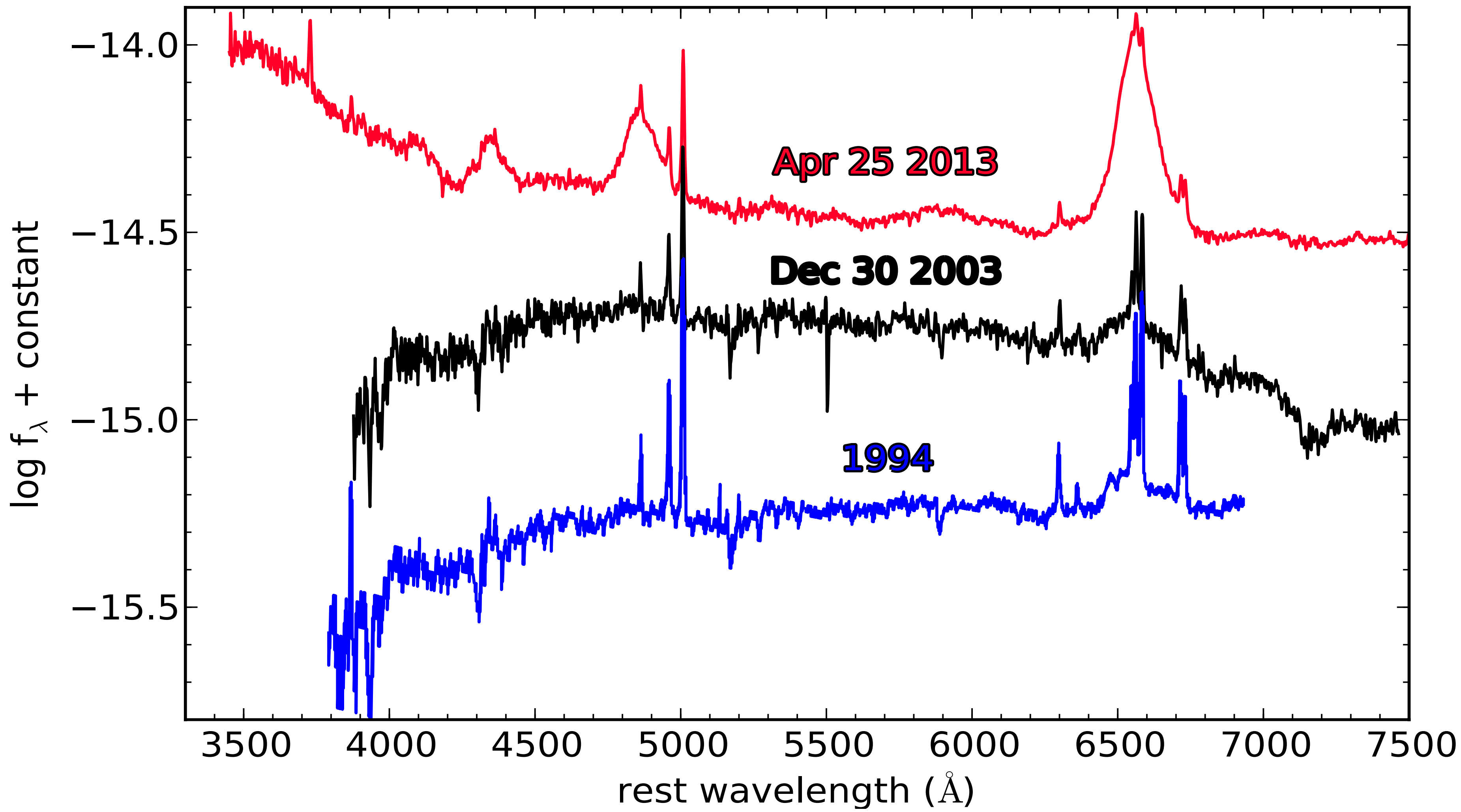
- Often (Balmer) broad line disappearance with change in continuum flux



Adapted from C. Macleod

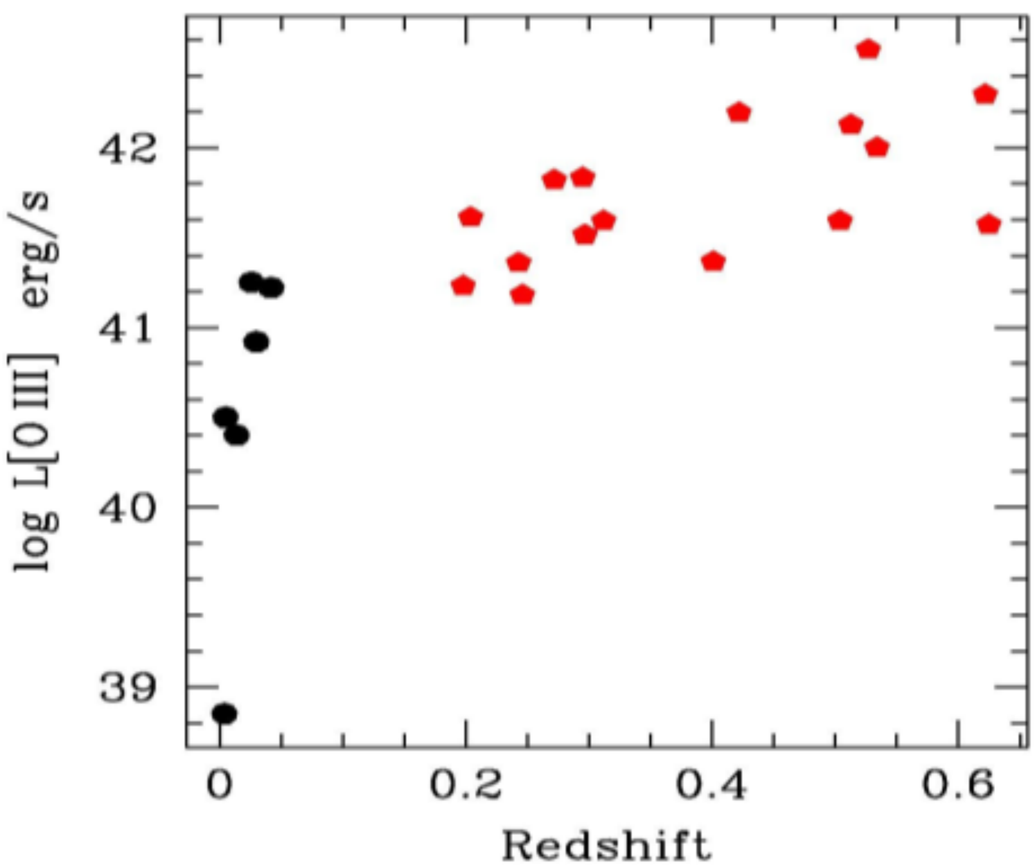
Changing Look AGN

- Sometimes (Balmer) broad line appearance with change in continuum flux



NGC 2617 (Shappee et al. 2014; ASAS-SN, etc.)

Since 2015, renewed interest in Changing Look *Quasars (CLQs)* at $L_{bol} \gtrsim 10^{44}$ erg s^{-1}

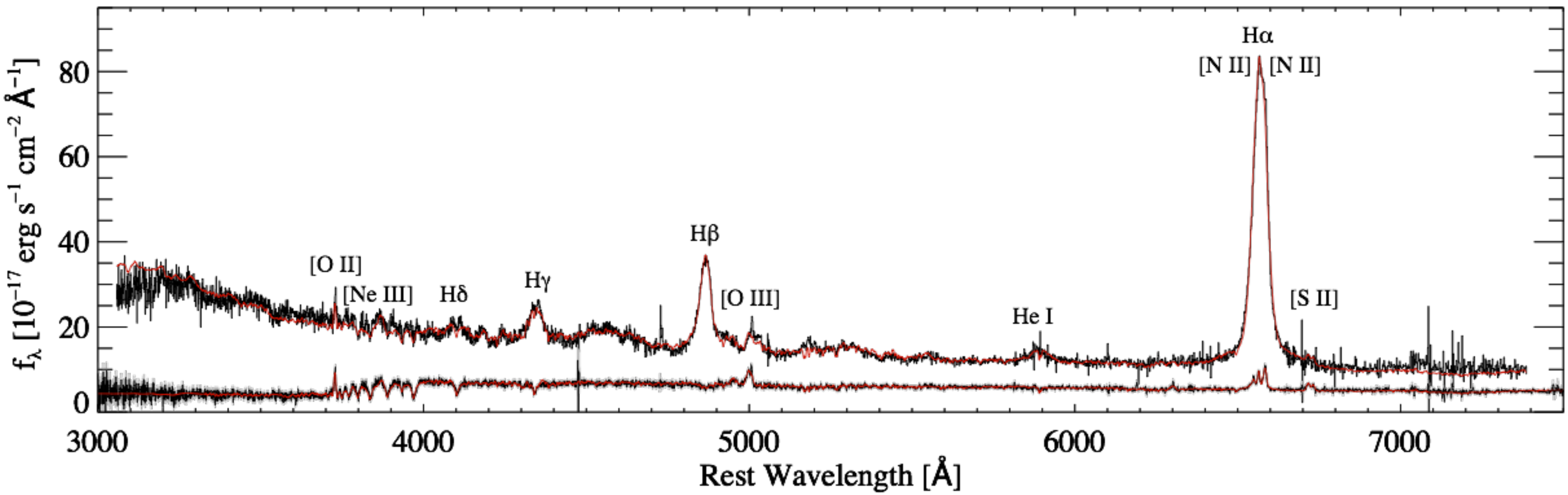


LaMassa+ 2015 (SDSS archive)
Merloni+ 2015
Ruan+ 2016 (4; SDSS archive)
Runnoe+ 2016 (1; SDSS/TDSS)
MacLeod+ 2016 (10; PS1 SDSS)
Gezari+ 2017 (1*; iPTF, SDSS, etc.)
Yang+ 2018 (21; multiple but includes LAMOST, SDSS, CRTS, PTF,…)
Stern+2018 (1*; WISE)

- 2015 renewed interest via higher luminosity cases, the 1st from LaMassa et al: serendipitous discovery from multi-epoch SDSS QSO spectra (also X-rays).
- Nearly simultaneously with early SDSS (and later LAMOST) multi-epoch spectral cream-skimming, photometric imaging/LC searches invoked too with PS1, PTF, iPTF, CRTS, ZTF, etc.
- In most recent studies, rapid advances especially enabled from large area sky coverage in time domain spectroscopic or imaging surveys, and commonly now/ future with both….

Adapted from C. Macleod

Spectral Change of the SDSS/TDSS CLQ J101152 (Runnoe et al. 2016)



Upper spectrum during earlier (2003) bright state; lower spectrum during more recent (2015) dim state; same flux scaling.

Adapted from M. Eracleous

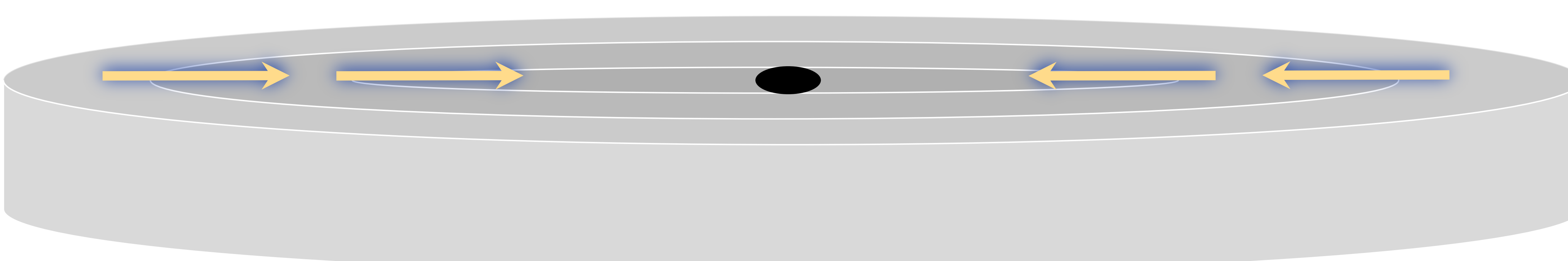
Renewed interest: timescale observed << anticipated for major accretion changes, if…

- …**Viscous** (“radial drift”) timescale in disk

For AGN in *optical*:
$\sim 10^4$ yrs vs. 1-10 yrs CLQs
(& time scales with M_{BH})

For stellar-mass BHs
(X-ray binaries),
days to months

$$t_{\rm infl} = 5\times 10^4 \left[\frac{\alpha}{0.1}\right]^{-1} \left[\frac{\lambda_{\rm Edd}}{0.05}\right]^{-2} \left[\frac{\eta}{0.1}\right]^{2} \left[\frac{r}{50R_S}\right]^{7/2} \left[\frac{M_8}{2.1}\right] \mathrm{yr}.$$



Adapted from C. Macleod

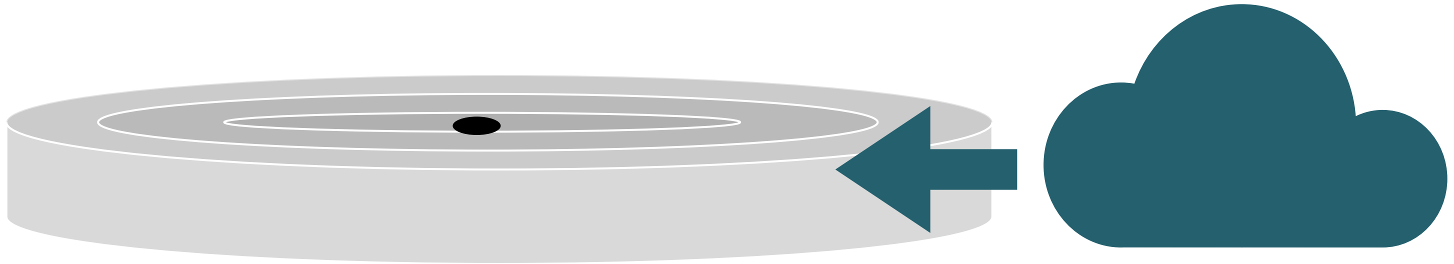
Renewed interest: timescale observed << anticipated for major accretion changes, if viscous "radial drift"… but

- …observed variability vs. viscous timescale mismatch has a lengthy history (e.g., see review by Antonucci 2015)

- …and of course there are other physical timescales in quasars (often also scaling with M_{BH})….

But … there are other physical timescales in quasars (often also scaling with M_{BH})

	Accretion Disk	Broad Line Region
Viscous ("radial drift")	10,000 yr	-
Light travel	Hours	Days
Dynamical	Days	Years
Thermal	Days-years	-
Dust Crossing time	-	$24\ M_8^{-1/2}\ L_{44}^{3/4}$ yr



Adapted from C. Macleod

Selected Possible CLQ Interpretations

- **Nuclear transient: tidal disruption or SN…less favored as:**

Duration too long for some TDEs (but note some slow TDEs); too luminous to be standard SN.

- **Obscuration by transiting, dusty thing…less favored as:**

Transition time often shorter than crossing time. E(B-V) for continuum inconsistent with broad lines. Also some early polarization studies (e.g., Hutsemekers et al. 2019).

- **Marked change in accretion rate or instability at some critical state… currently more favored:**

e.g., Inflow time is short enough in some cases (and/or from inner disk), also some ideas about critical Eddington ratio

- **Disk thermal fluctuations; multiple further emerging ideas.**

Adapted from M. Eracleous

So CL Quasars at higher luminosity may add yet more to CLAGN puzzle

- How do these fit with unification? Most not well explained by obscuration changes (spectral modeling inconsistent with variable dust extinction as cause of BEL changes).

- Are they (some?) merely extremes in a distribution of quasar variability, or (some?) caused by some major event in or around the central engine?

- If fast changes are accretion state or instabilities, are there new ideas, or (other?) analogies to stellar BH binaries, etc.?

Adapted from C. MacLeod

Selected Very Recent (esp. wide-field) CLQ Studies

- Individual unusual/related cases are still emerging (e.g., Trakhtenbrot et al. 2019)…But broadly building toward *large-sample or sub-group studies* (some also less biased, e.g., to find turn-on cases, thanks esp. to LCs/diff imaging).

- MacLeod et al. 2019 (SDSS, PS1, CTRS, Magellan, MMT, Palomar … followup): 17 higher-confidence, 12 lower confidence, 200 unconfirmed *candidates* from LCs (but only single epoch spectrum, when in quasar state).

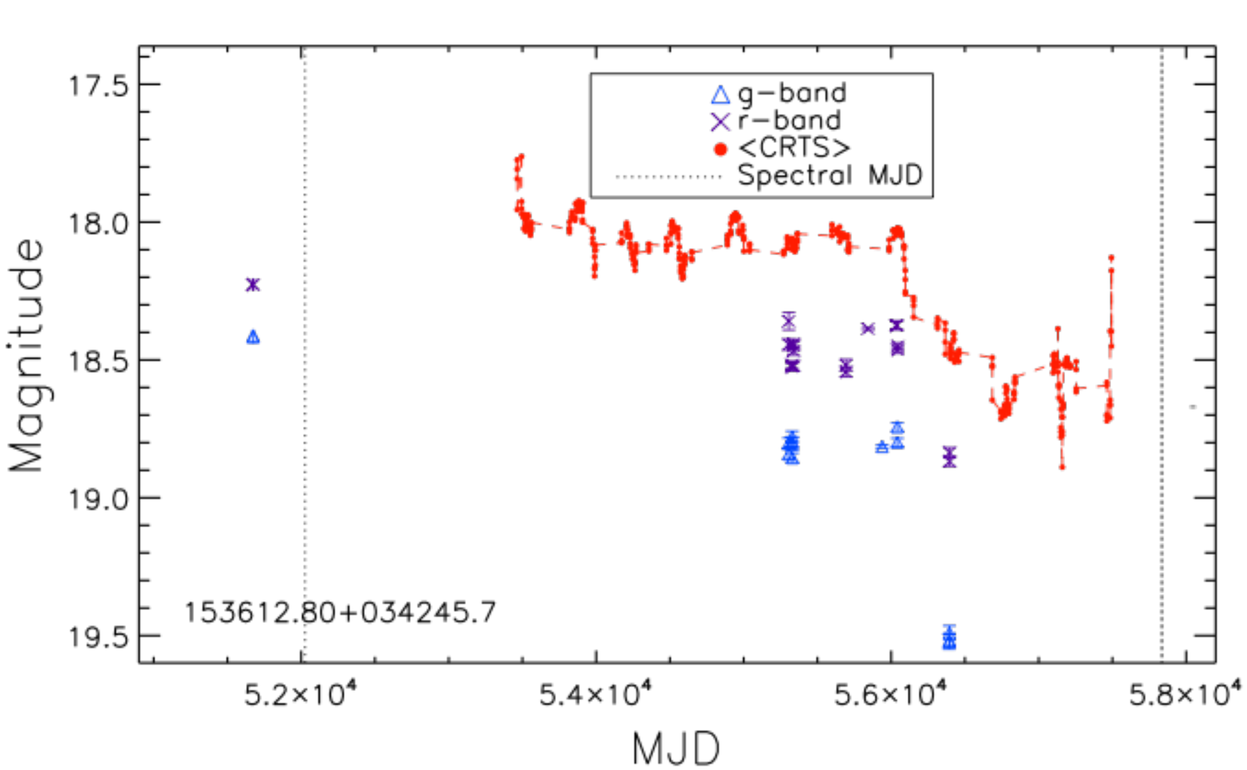
- Graham et al. 2019 (CRTS based): ~73 cases, with 36 declining, 37 increasing; 5000 more candidates from LCs. A higher luminosity counterpart to existing sample.

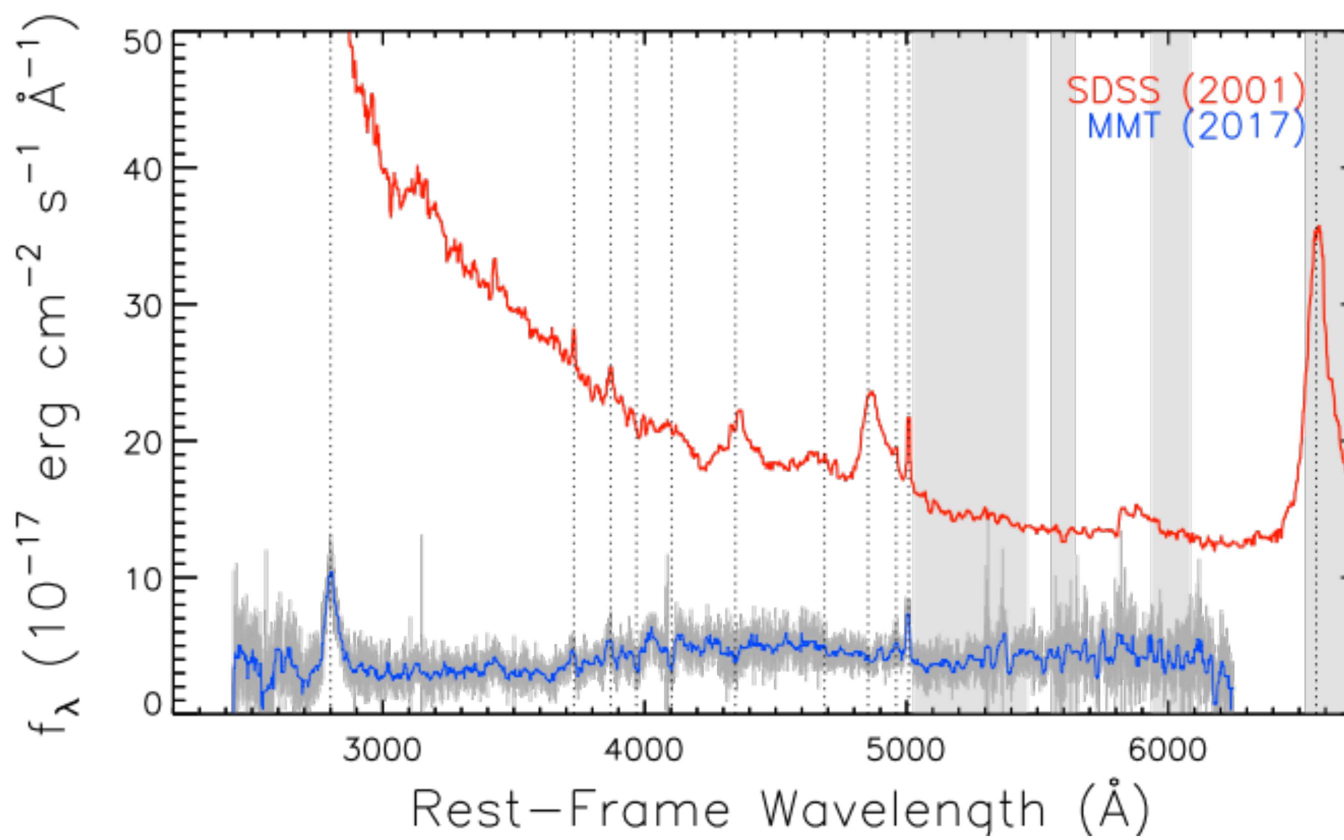
- Frederick et al. 2019 (ZTF, CRTS, DCT, Palomar, SDSS etc.): ~6 more dramatic *turn-on* cases, Liners to Type 1's!

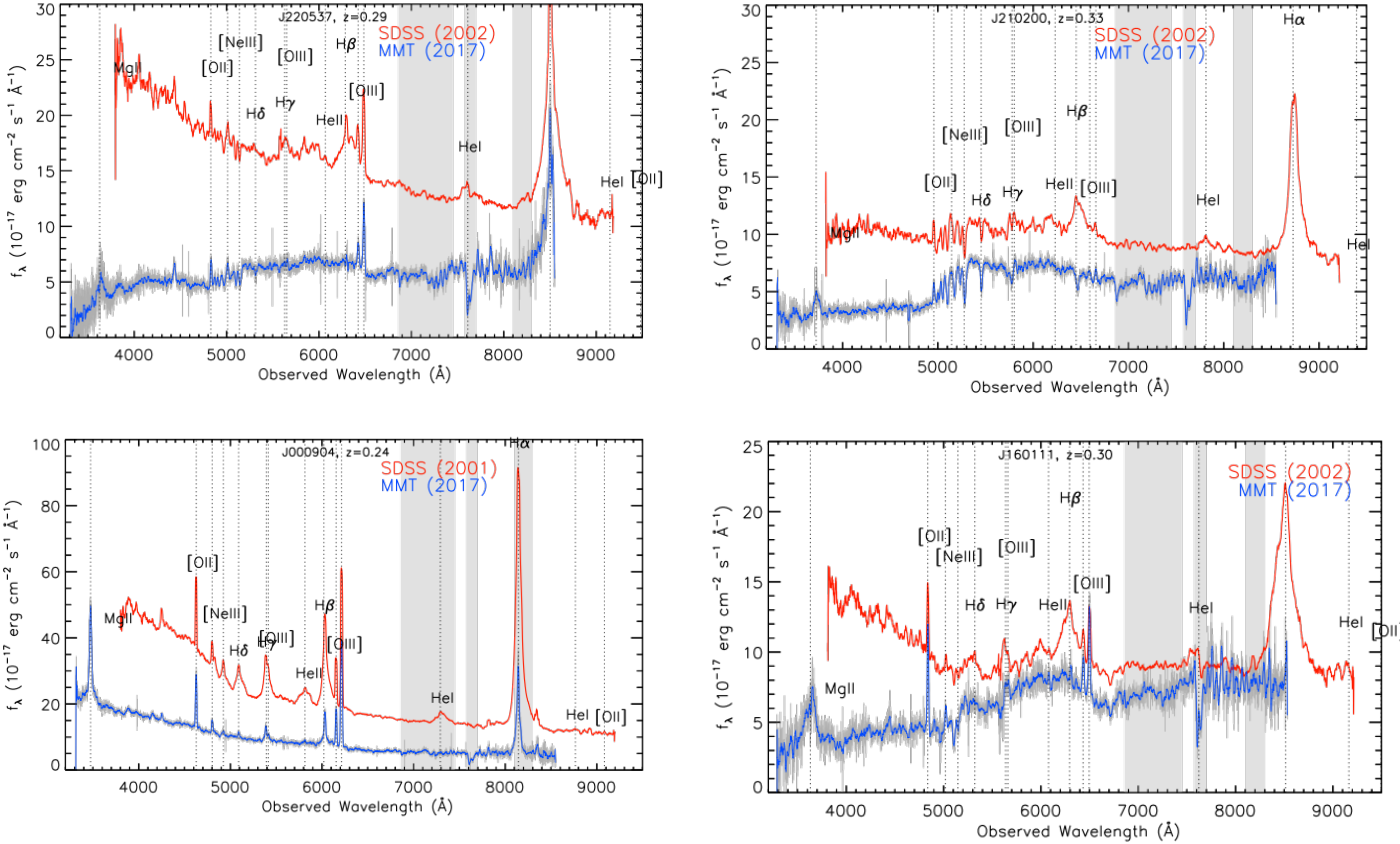
Changing Look Quasars via: SDSS 1st-epoch spectra; SDSS, PS1, CRTS Variables; MMT etc. later-epoch spectra (Macleod+ 2019)

Selection	Total #
SDSS Quasars in DR7Q	105783
Lacking BOSS spectra	80299
EVQs*: $\lvert\Delta g\rvert > 1$ mag, $\lvert\Delta r\rvert > 0.5$ mag ($\sigma < 0.15$ mag), $z < 0.83$	1727
Observed spectroscopically *(MMT: 64%, Mag.: 15%, WHT: 15%, Pal.: 6%)*	130
CLQs: Hβ (dis)appearance at $N_\sigma(\mathrm{H}\beta) > 3$	16

* EVQ = Extremely Variable Quasar



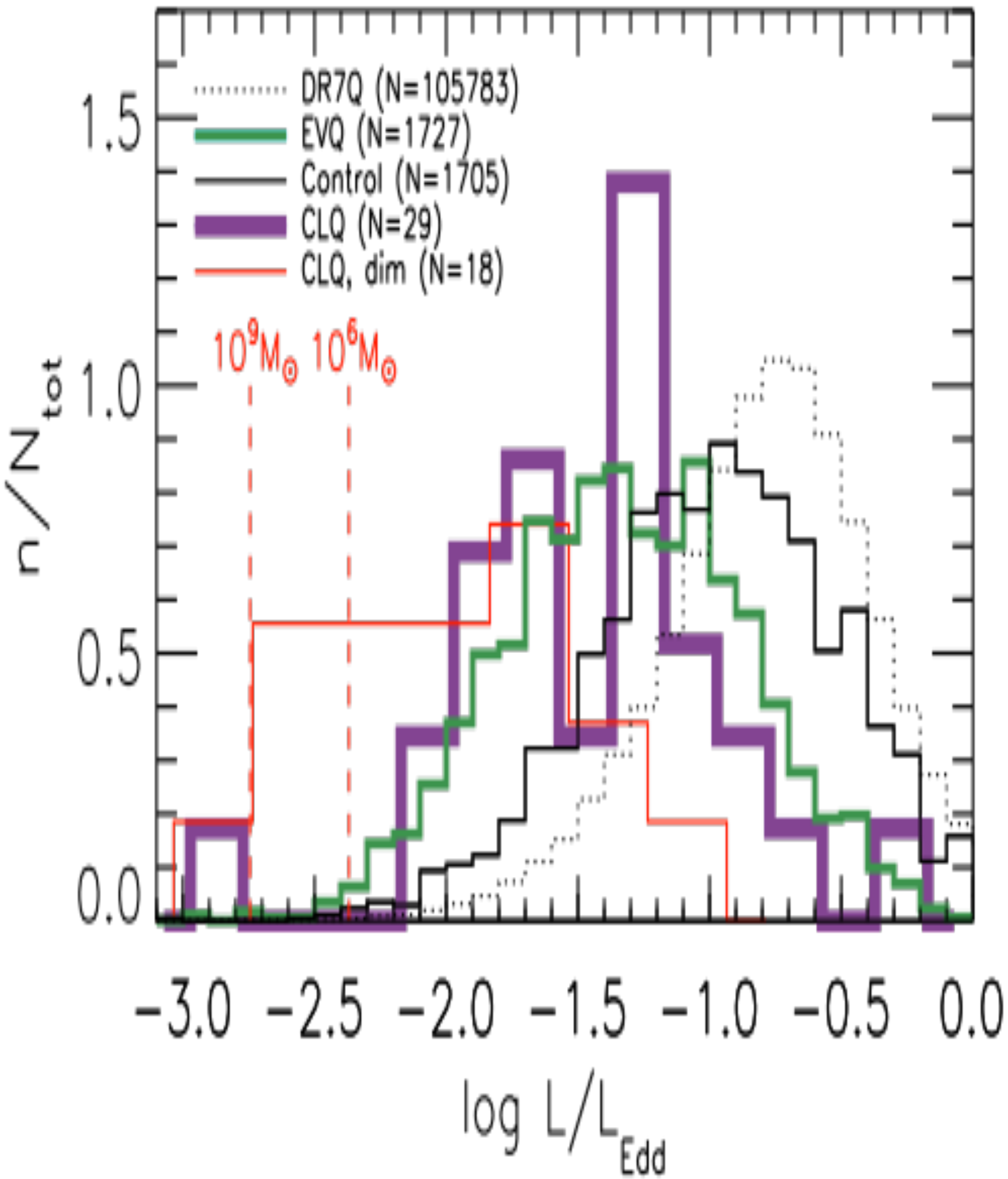


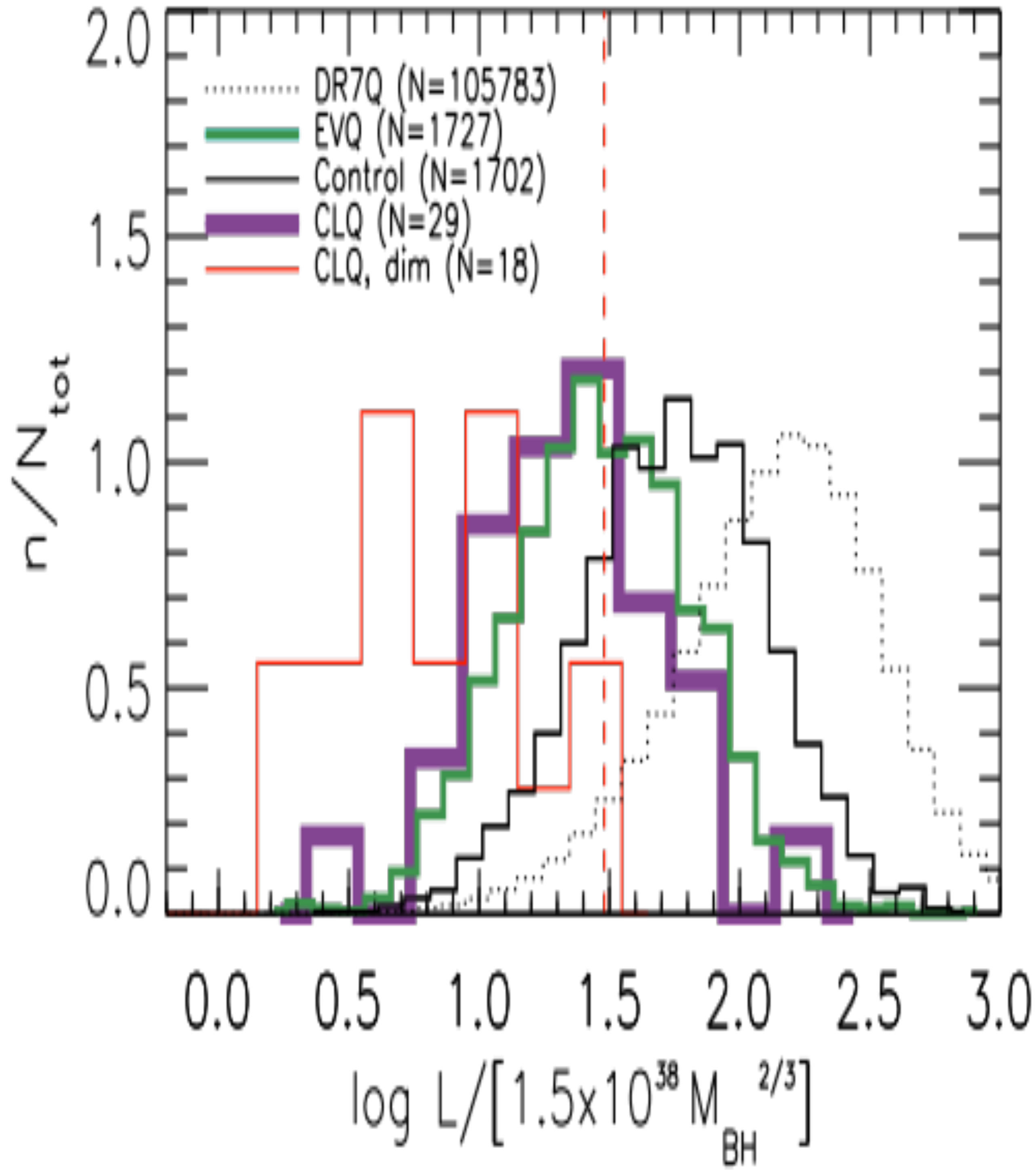


- CLQ fraction is ~20% of |Δg| >1 mag targets (17 high-confidence, 12 lower-confidence, 200 candidates)

Macleod et al. 2019

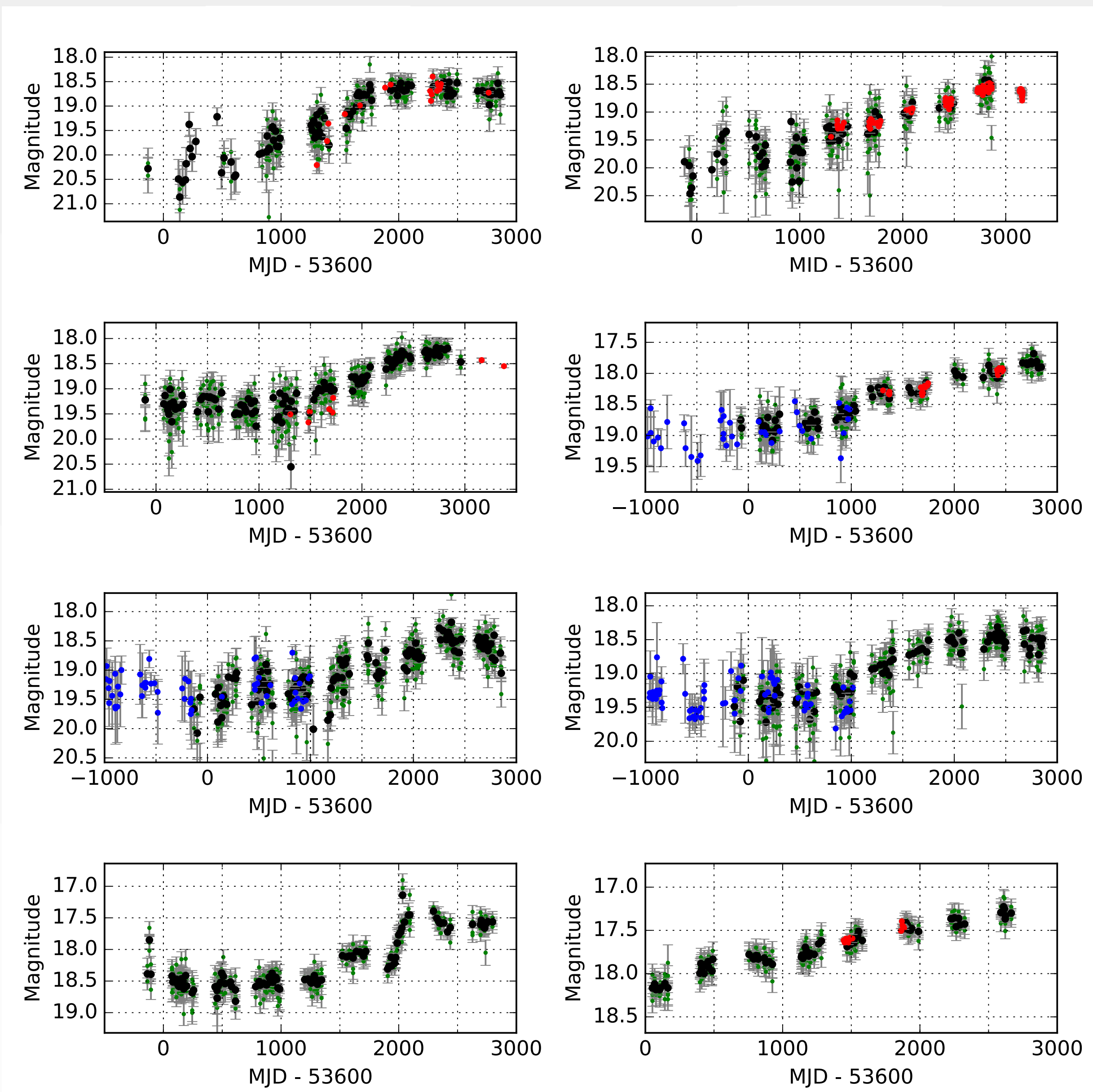
CLQ Trend with Eddington Ratio, or with Accretion Rate in a Disk-Wind Scenario (MacLeod et al. 2019)

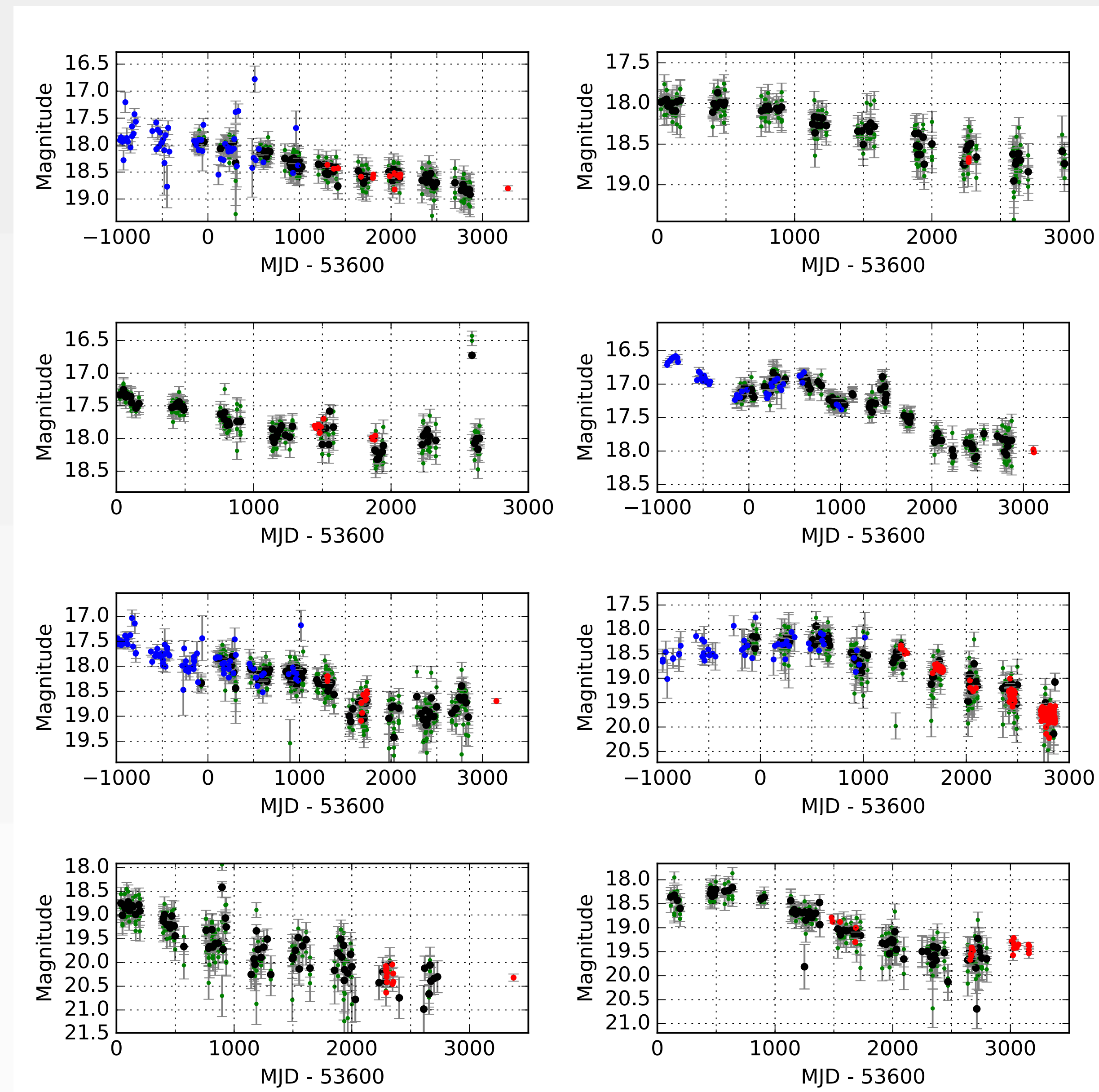




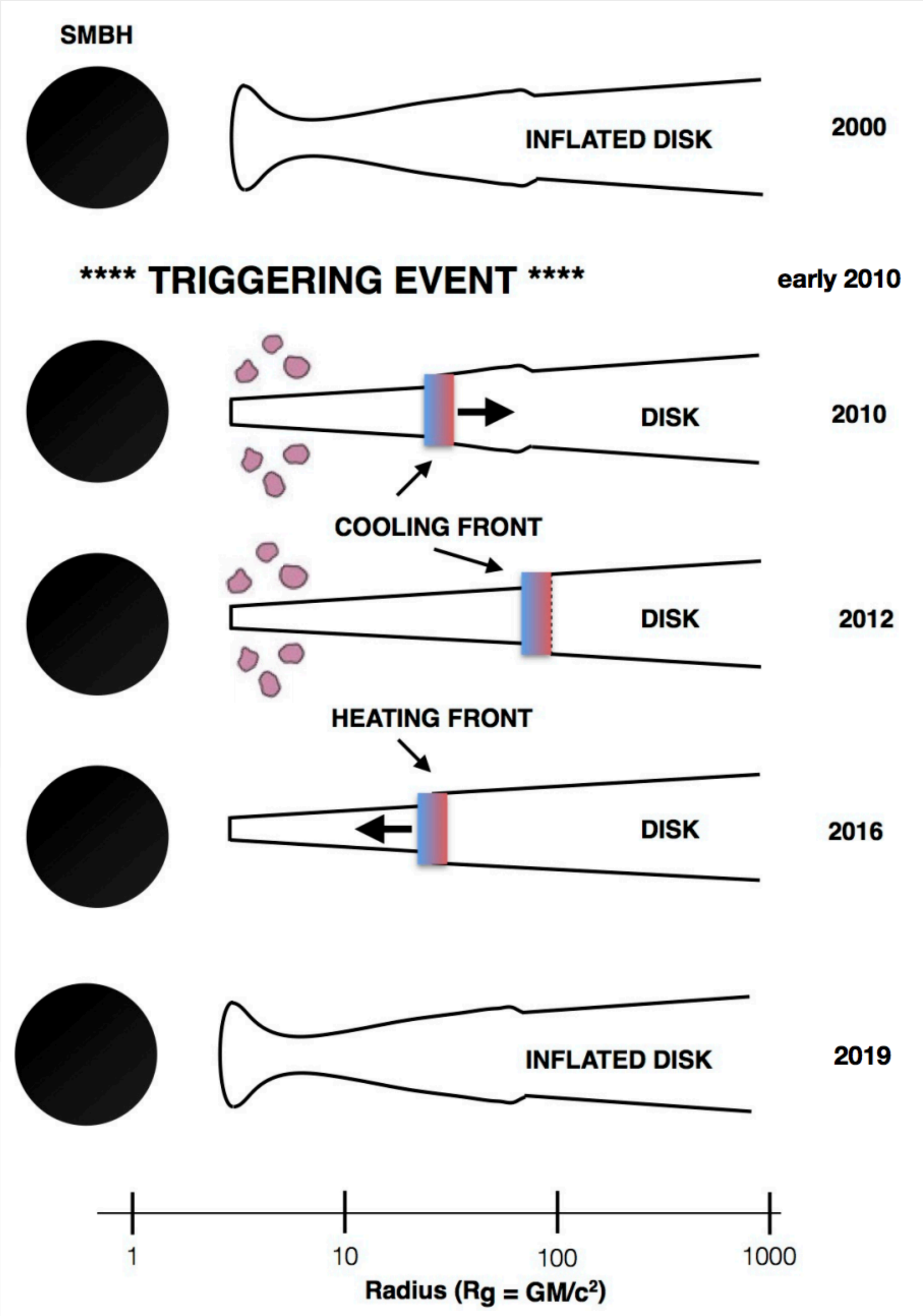
Changing look/state quasars

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

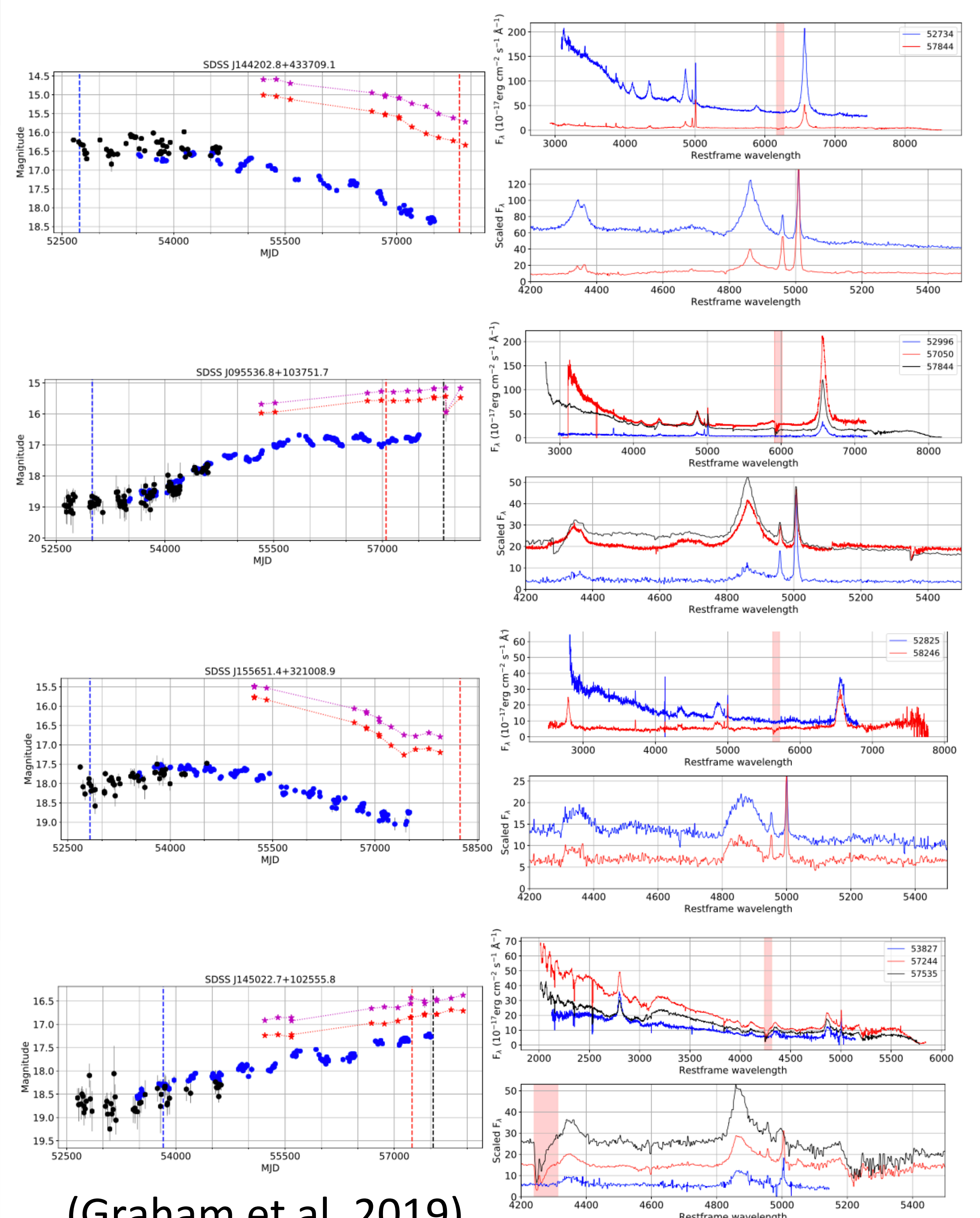




Propagating fronts as an explanation



(Ross et al. 2018)

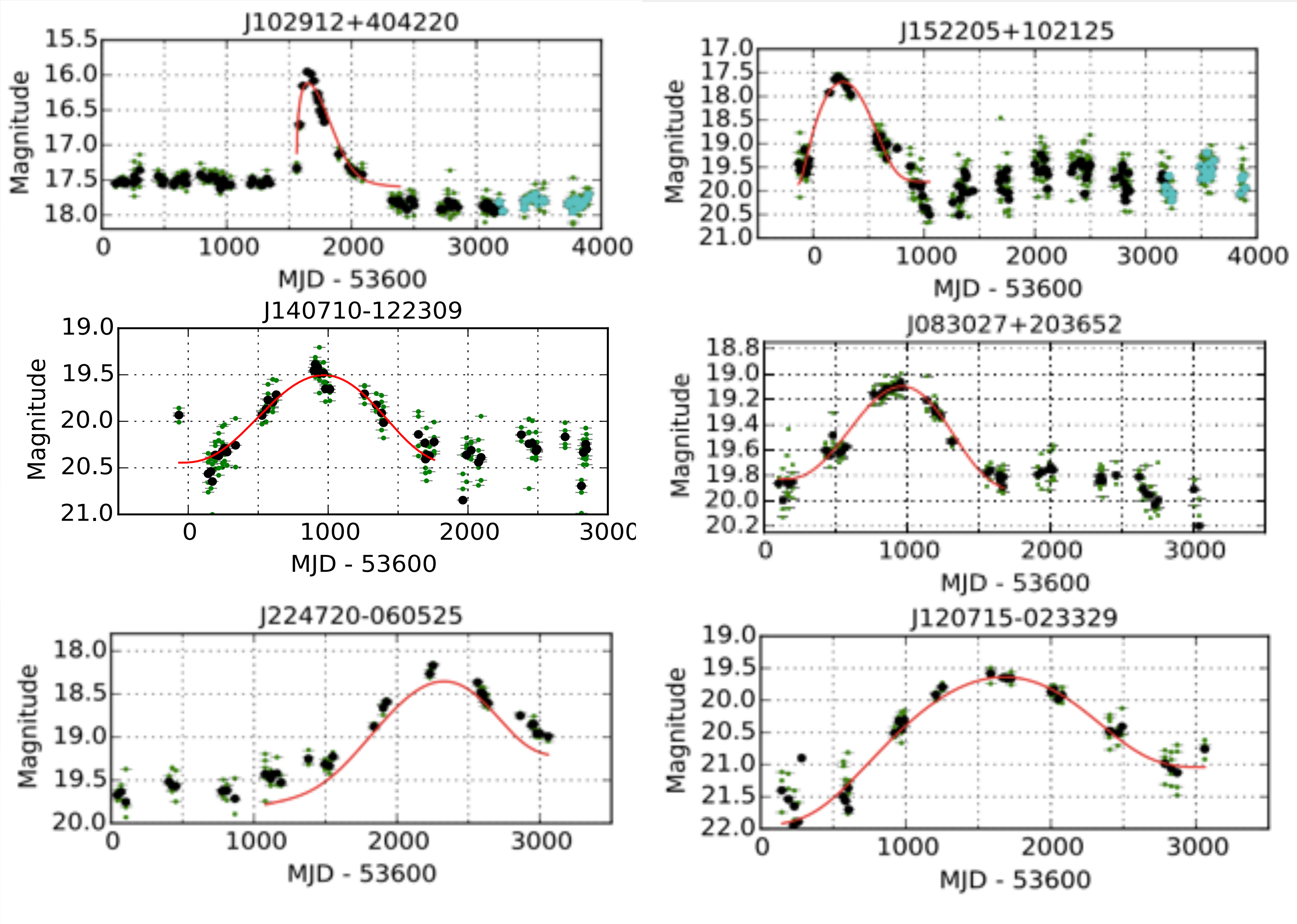


(Graham et al. 2019)

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



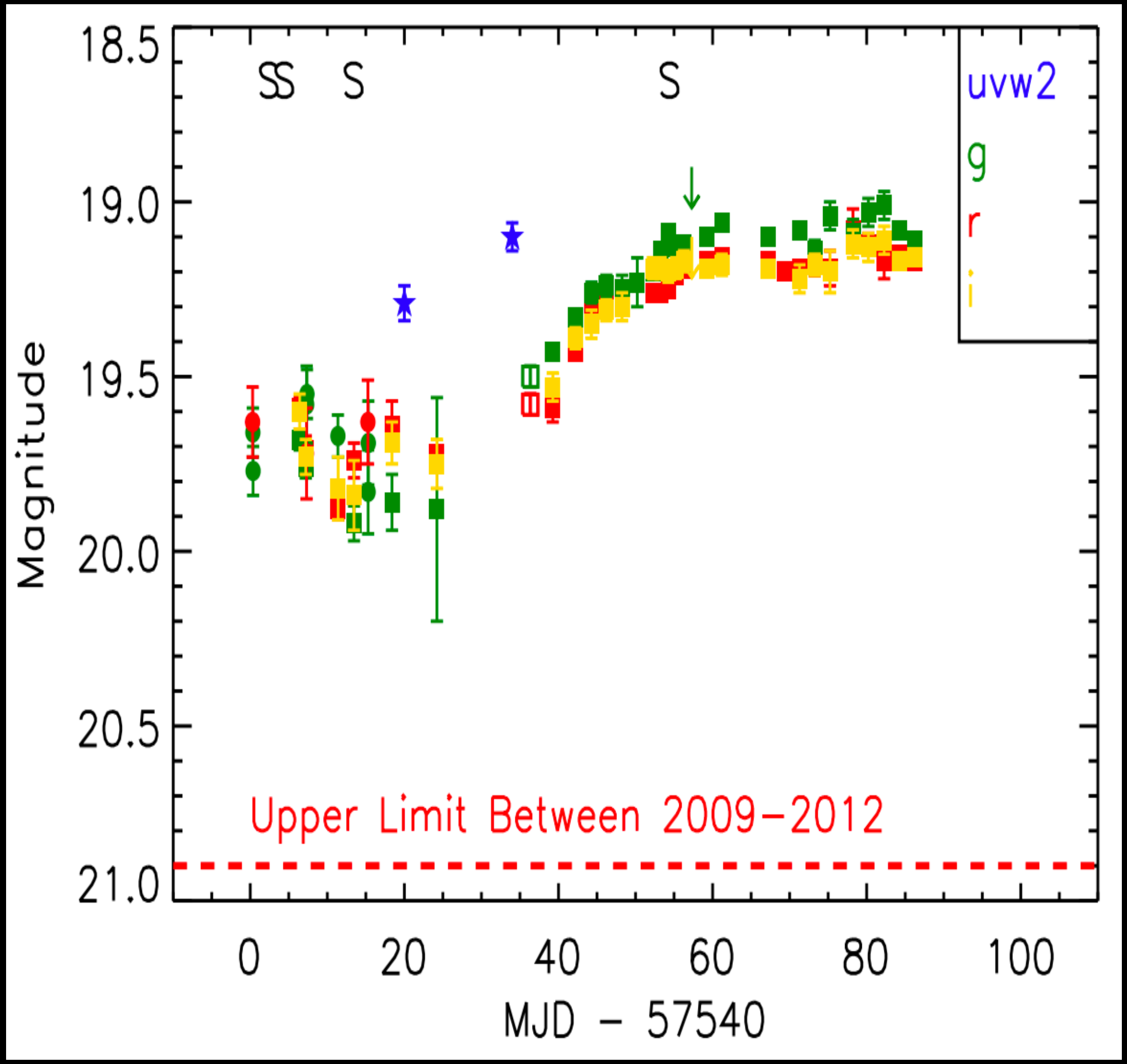
(Graham et al. 2017)

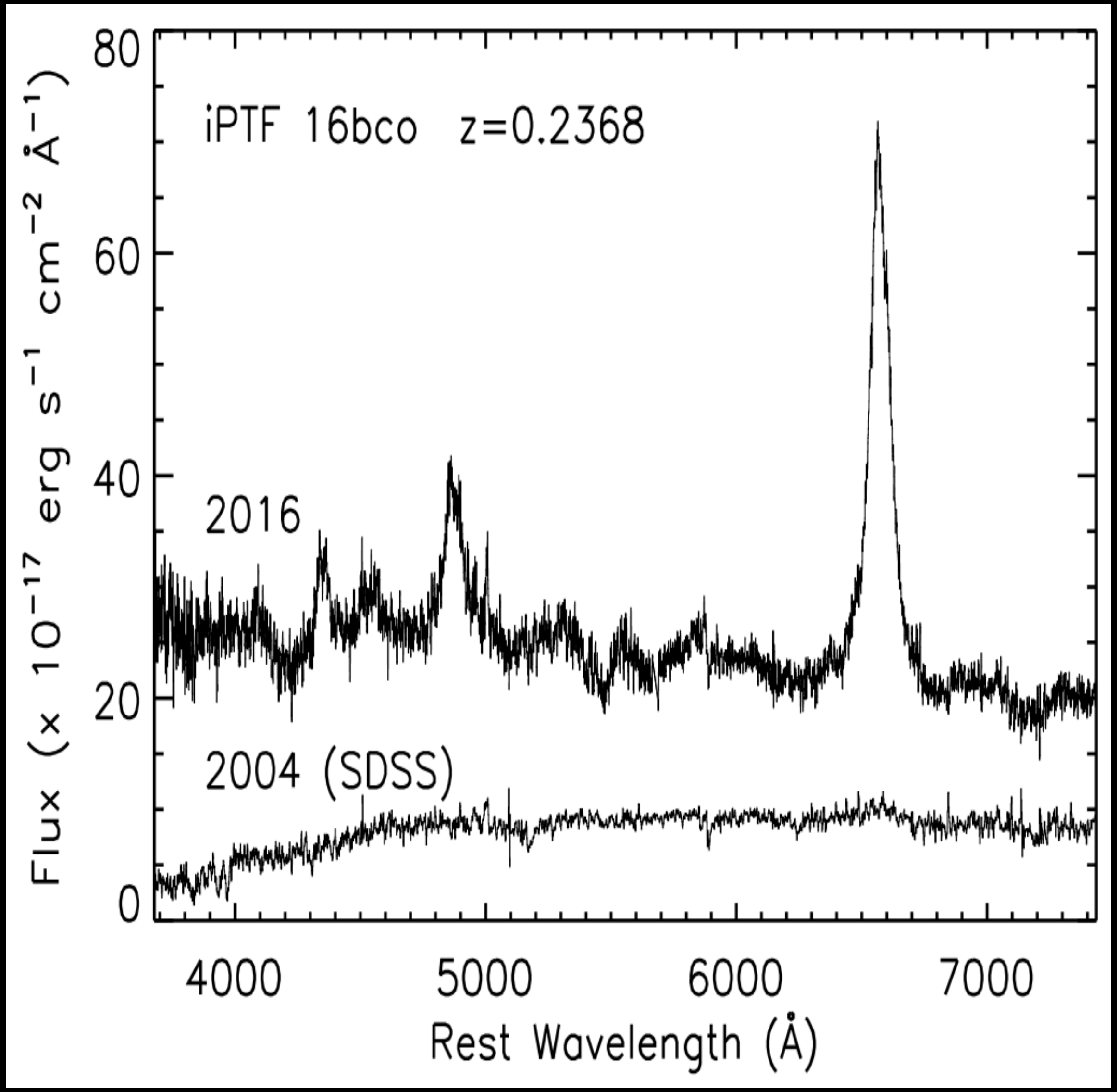
CLQ Large Sample Recap

- Surveys (imaging plus spectroscopic) are uncovering extreme quasar variability on timescales of 1-10 years (even shorter), perhaps especially in low Eddington-ratio objects. Objects make actually be diverse (flaring events vs. smoother CLQ LCs).
- Significant change in accretion rate has been leading notion, but short timescale at odds with standard disk theory. Latest sample results may suggest consistent critically-low Eddington ratio or similar where BEL not observable or BLR doesn't form (or is unstable).
- CLQ fraction from spectra is ~20% among strongly variable photometric quasars; and *contemporaneous photometrc monitoring* can both discover and tie together more sparsely sampled time-domain spectra.
- Future all-sky repeat spectroscopic+imaging surveys (like SDSS-V) plus LCs (strongly preferred to be contemporaneous like ZTF+) will establish CLQs in context of general quasar variability, probe accretion physics, and can catch objects in transition (not just before/after).

Adapted from C. Macleod

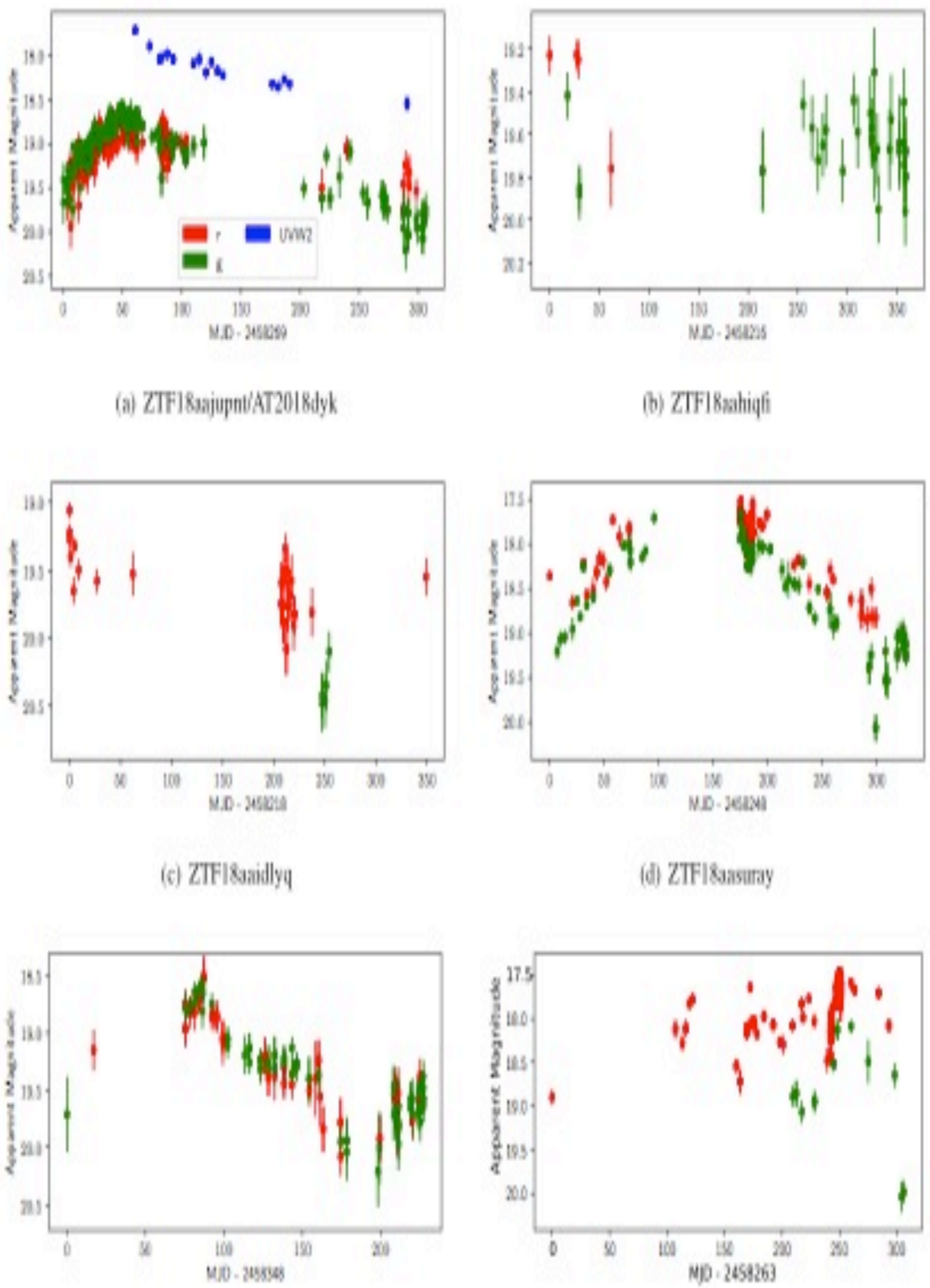
Wide area optical LC surveys also superb resource to trigger new-epoch spectra, e.g., to find *dramatic* turn-on CLQs (Gezari+2017)

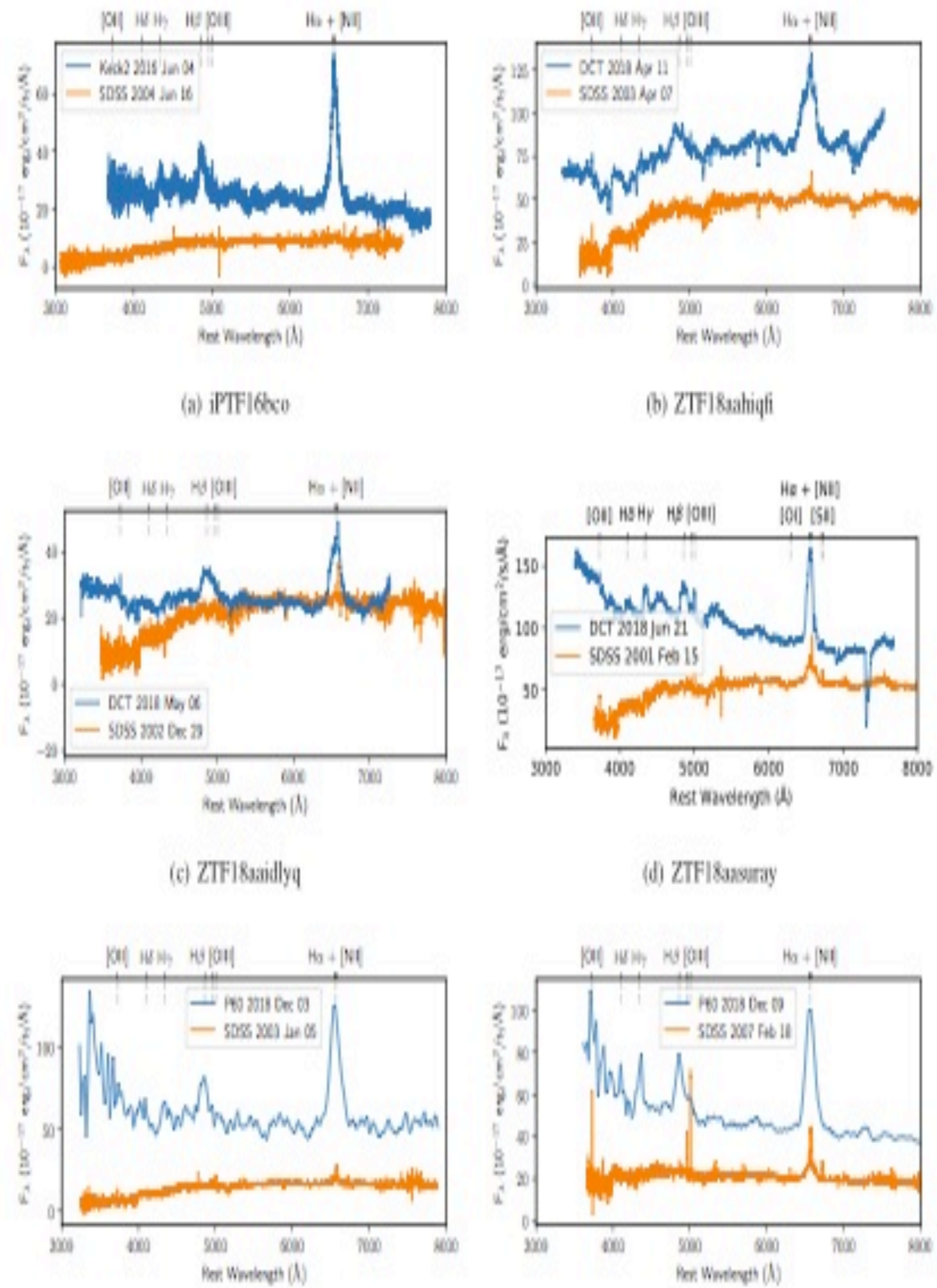




Slide coutesy of J. Ruan

More *Dramatic* Turn-on CL-*Liners* from ZTF: ZTF LCs/ image differencing trigger new spectra (*Quasar*) vs. SDSS archival (*Liner*). Just posted—Frederick+ 2019





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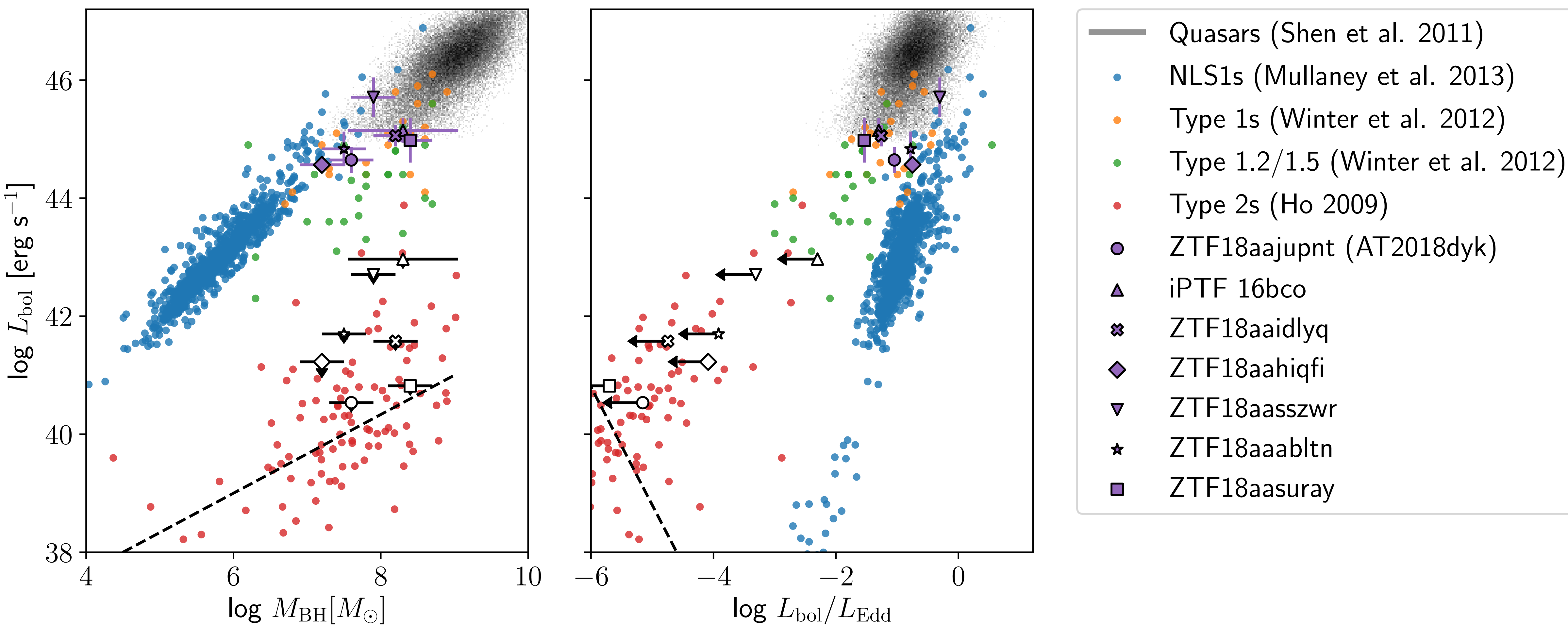


While many past spectroscopic CLQ discovery programs may favor turn-offs (or flickers on/off), wide area optical imaging/LCs such as ZTF provide a superb resource to trigger new confirming and monitoring spectra, of dramatic turn-on CLQs.

Outline of *current* Black Hole Mapper (BHM) spectral plans in SDSS-V

- Quasar/AGN emphasis, as among Universe's most luminous objects, powered by accretion onto SMBHs.
- BHM exploits – with order(s) of magnitude advances -- two hallmark characteristics of quasars: marked variability on a range of timescales, and prodigious luminosity extending to X-rays.
- *Repeat time-domain (TD) optical spectra of ~$10^{4.5}$ known (SDSS) quasars over broad range of timespans from days to decades, sampling changes on light-travel, thermal, dynamical, etc. timescales, to measure BH masses, BLR dynamics, astrophysics of quasar accretion & outflows – including CLQs (i.e., spatially unresolved size scales, probed via TD).*
- Optical follow-up spectra of *eROSITA* X-ray sources: IDs & redshifts, demographics, evolution, & astrophysical/variability studies of ~$10^{5.5}$ X-ray source counterparts—esp. quasars, but also gal clusters, XRBs, CVs, flaring stars—from first 1.5 years of *eROSITA* repeat scans.

BHM Spectral Time-Domain Survey Outline

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

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

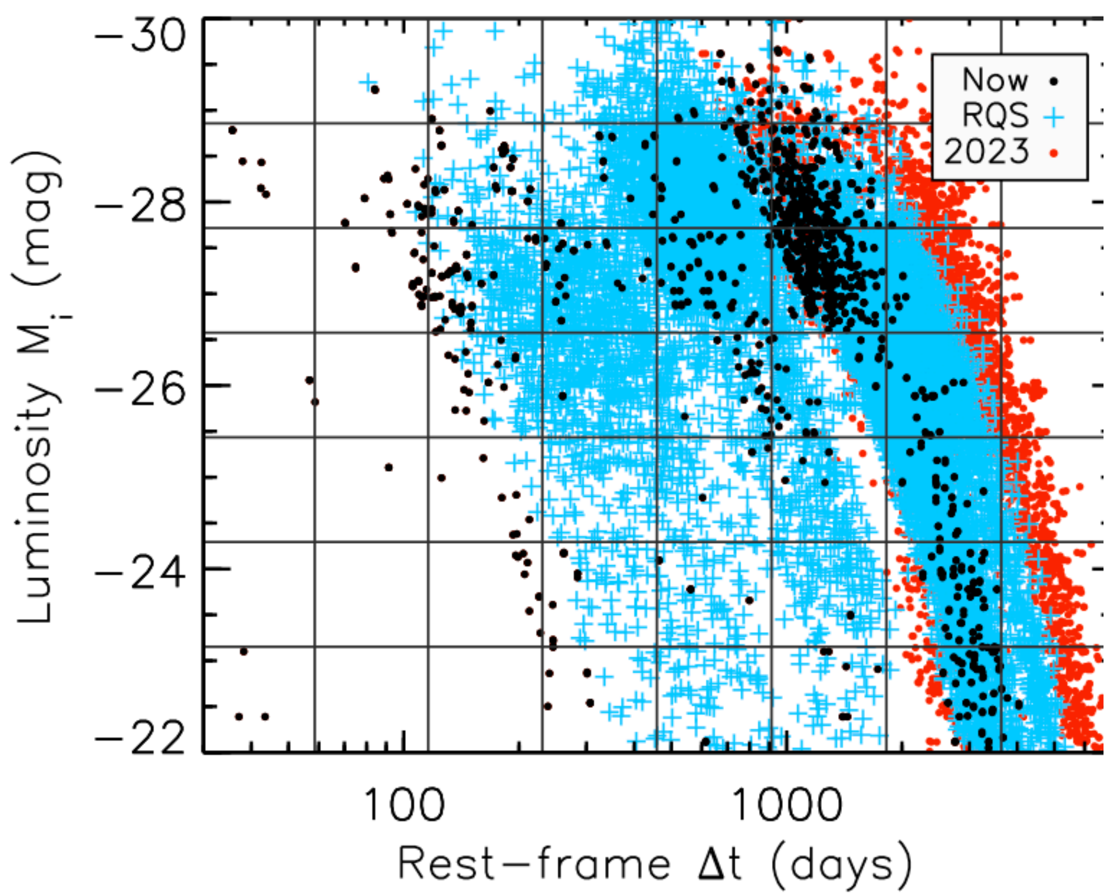
- For >2000 quasars, ~12 epochs (maybe in concentrated ~2 yrs), probing down to ~1-month to 1-year timescales, adding unfolding BLR structural and dynamical changes *(medium tier; >~300 deg^2)*.

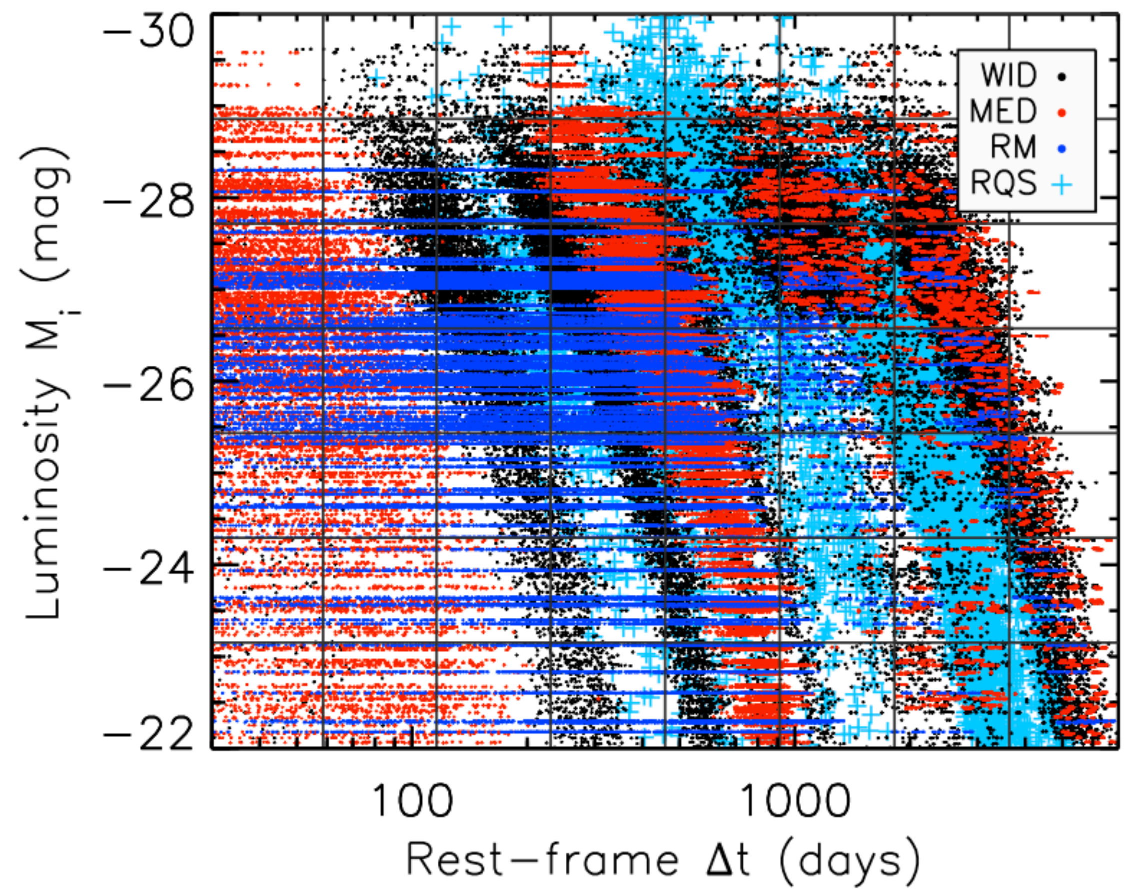
- Reverberation mapping (RM) for >1000 quasars in 5-6 fields, >170 epochs, sampling down to days to weeks; lags between continuum and BLR emission yield BH masses; premier RM sample at high L, z. (small area, but high-cadence spectral tier; >~30 deg^2).

- High desirability and science yield of contemporaneous LCs evident

BHM TD Samples Quasars Across M_i - Δt Plane

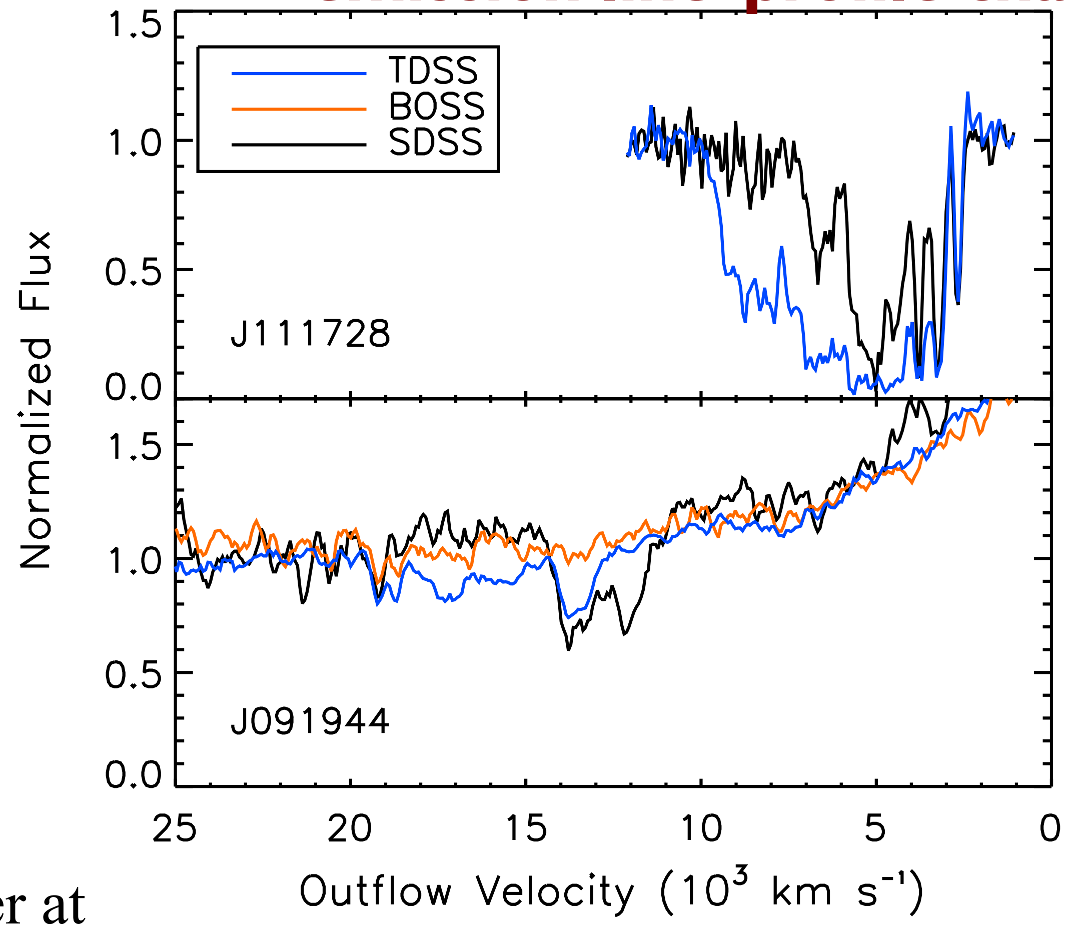
(med/low cadence tiers yield~60K fiber-epochs, w/ good sampling across plane; C. MacLeod and P. Green et al.)



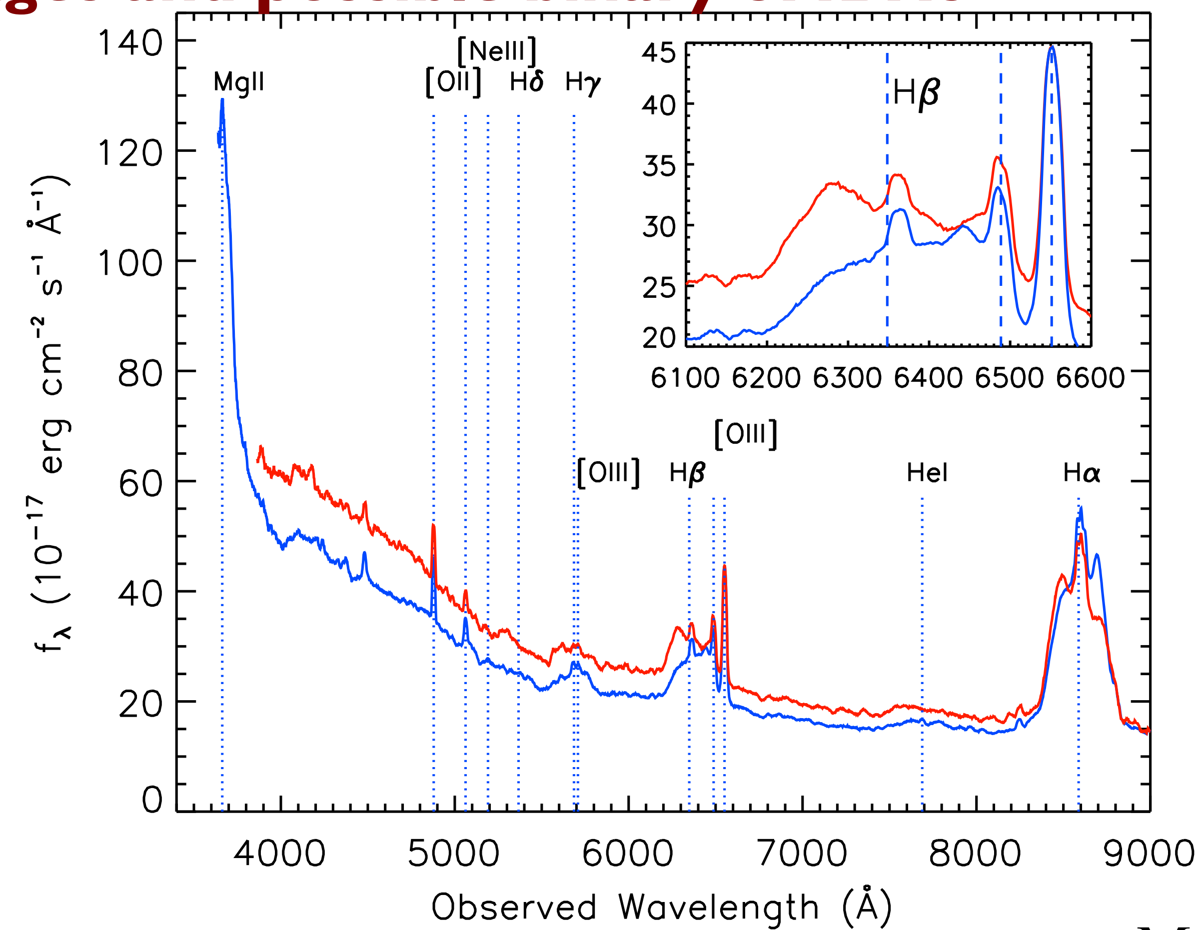


For i<19, TD current (left) vs. future (right) expectations in example 200deg^2 region. *Left:* black points show earlier coverage of M_i-Δt plane in random repeat SDSS quasar spectra; cyan adds RQS (MacLeod et al. 2018) forthcoming in SDSS-IV. *Right:* shows SDSS-V expectation, with BHM wide/low-cadence tier (>20,000 quasars w/several added spectral epochs; black), BHM medium tier with ~12 epochs (>2500 quasars; red), plus RM with >170 epochs which fills shorter timescales too populating the plane.

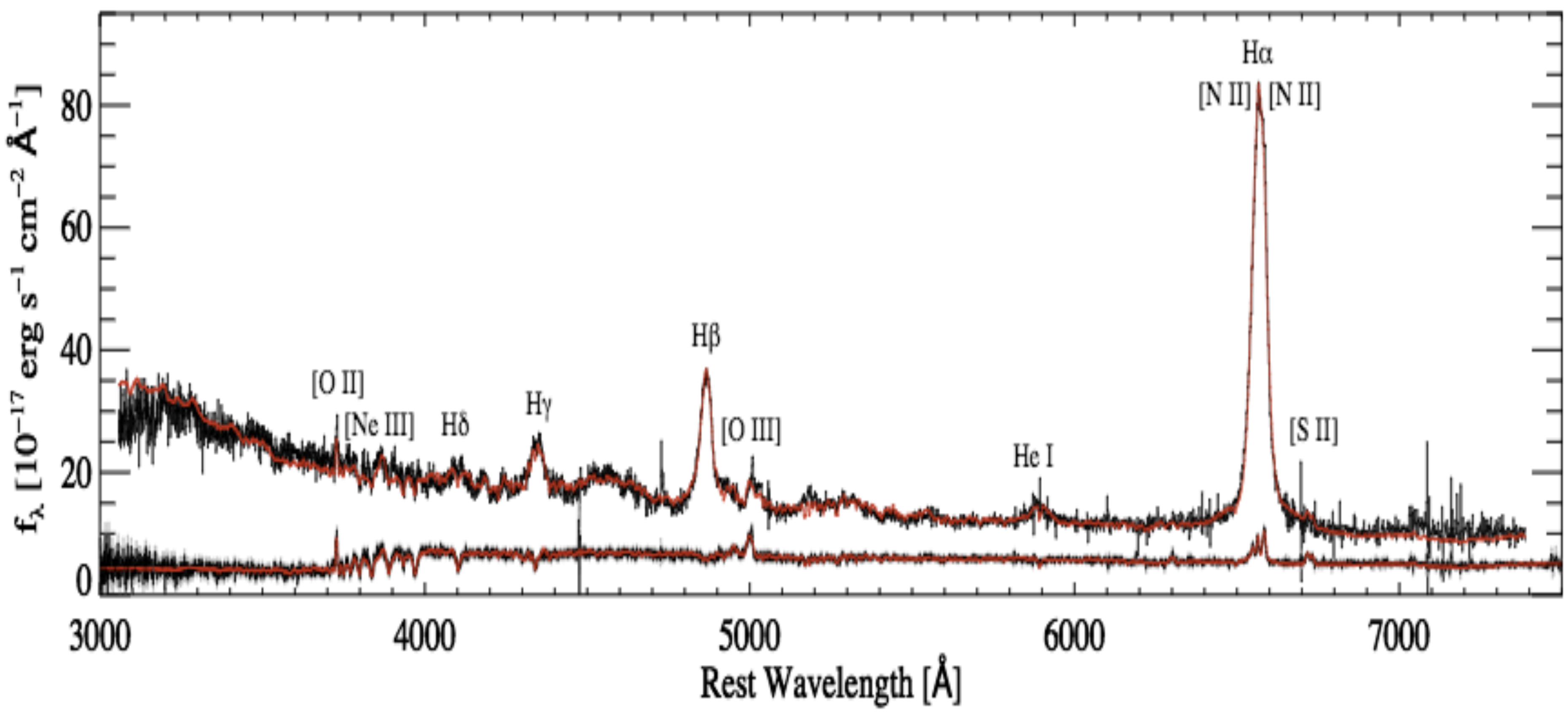
BHM/TD encompasses range of science (examples here from TDSS) . BHM low- and medium-cadence tiers e.g., CLQs, but also variable BALs, and emission line-profile changes and possible binary SMBHs



Grier at al. 2016; McGraw et al. 2017



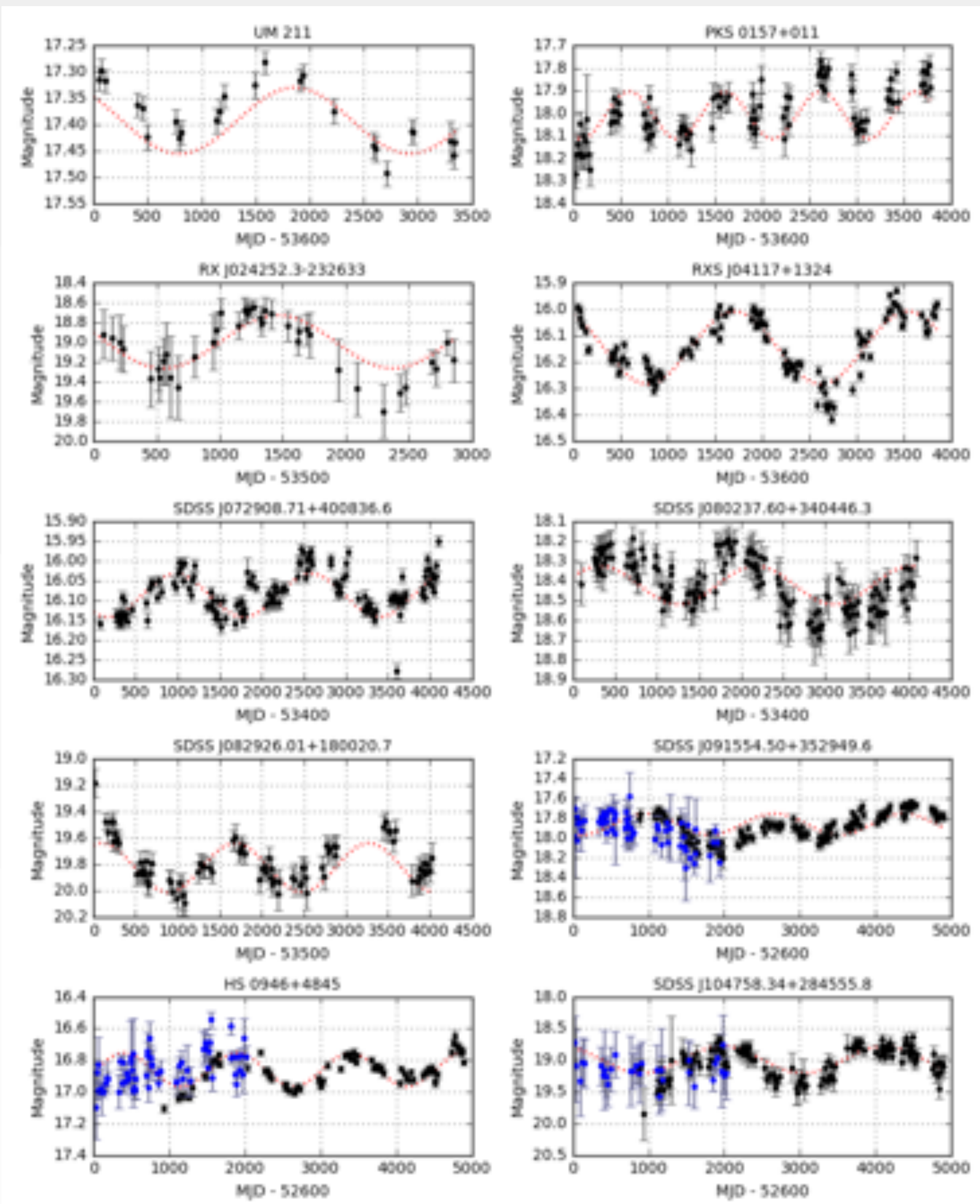
Macleod et al. 2018

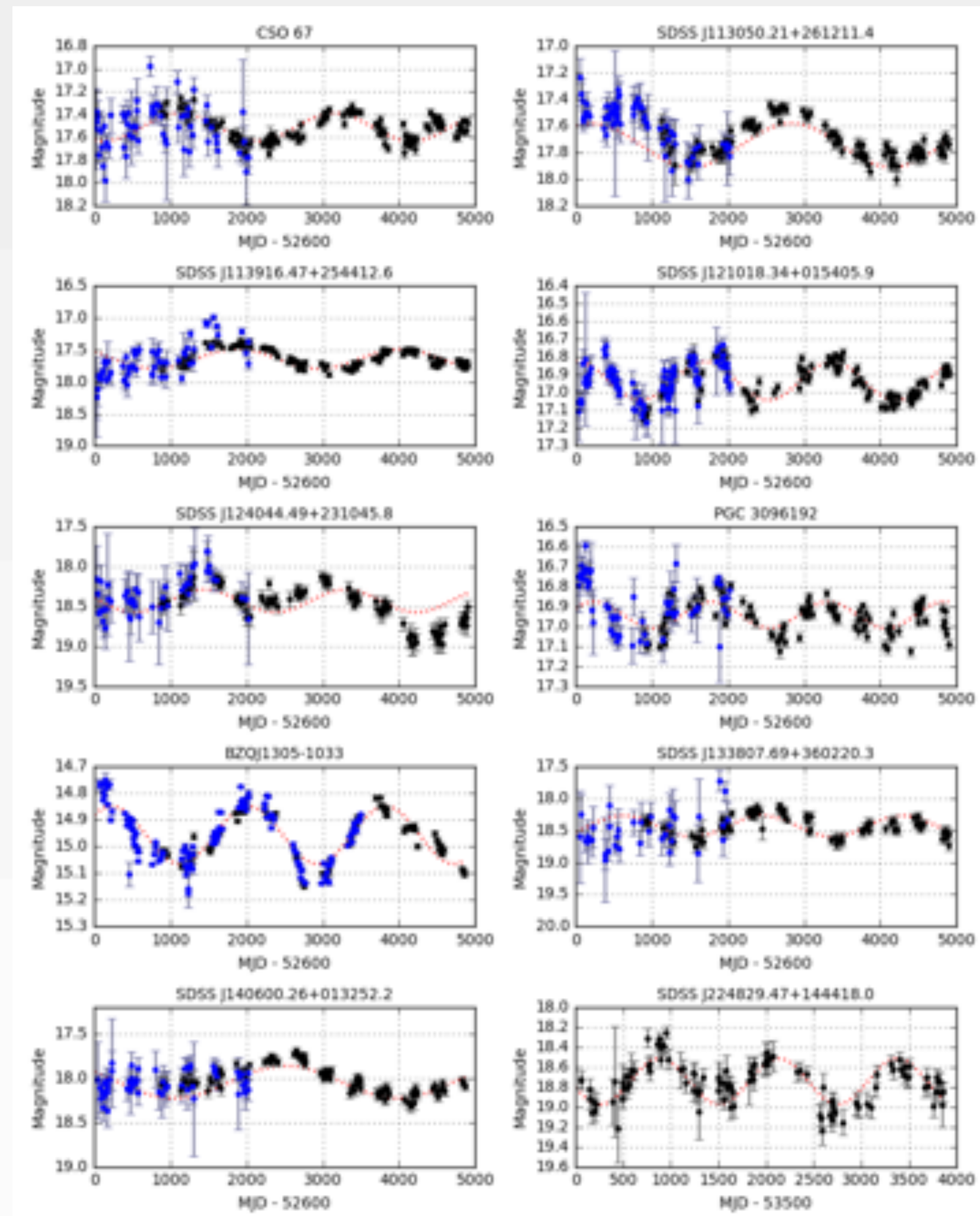


Runnoe et al. 2016

Periodic quasars

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





(Updated data Graham et al., in prep)

Consider also Limitations of the Historical RM AGN Sample (slide courtesy of Y. Shen)

~60 AGN with RM lag measurements

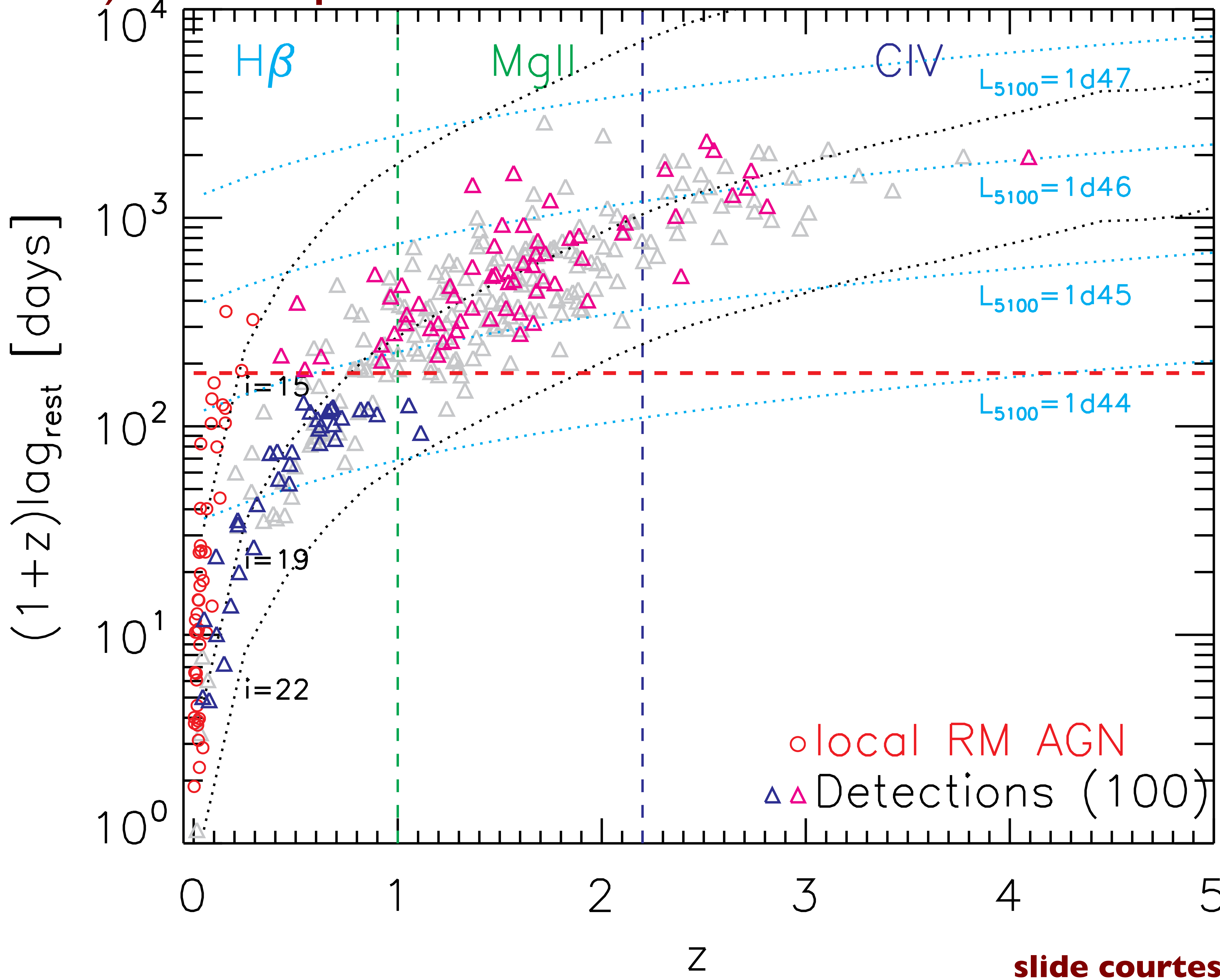
- almost exclusively at z<0.3
- Most are Hbeta lags with sparse CIV lags
- Sample heterogeneous, and does not uniformly sample AGN parameter space (luminosity, Eddington ratios, emission line properties)

→ Two decades of effort !

The limitations of the current RM sample severely impact the reliability of the single-epoch BH mass estimators at high-redshift.

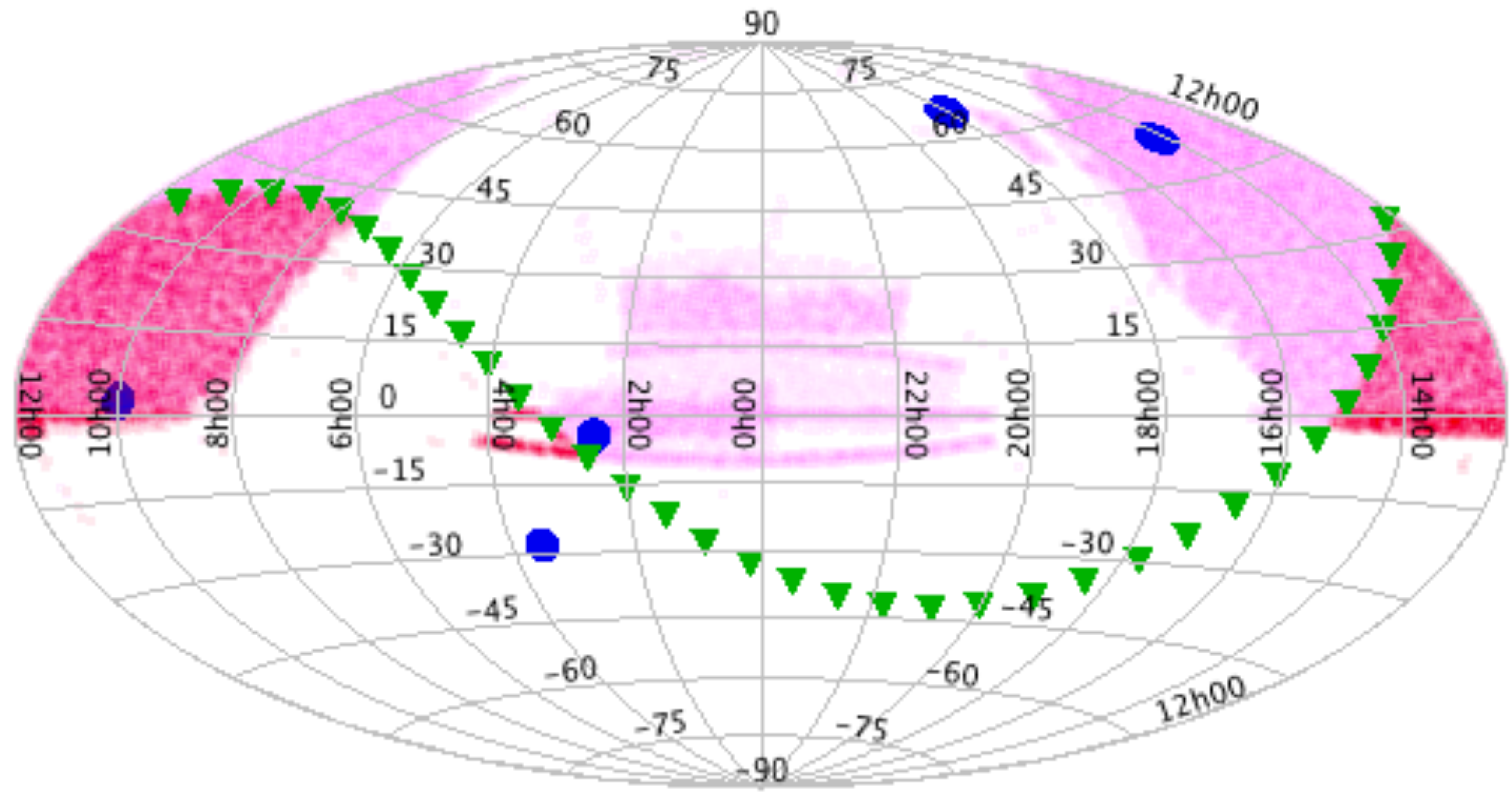
Need to substantially improve the RM sample, in a more efficient way.

Forecast for a *single* BHM RM field in SDSS-V (5-6 fields planned), & comparison to the current/local AGN sample



slide courtesy of Y. Shen

Main Current BHM Spectral Targeting Area (TD, mainly N.)



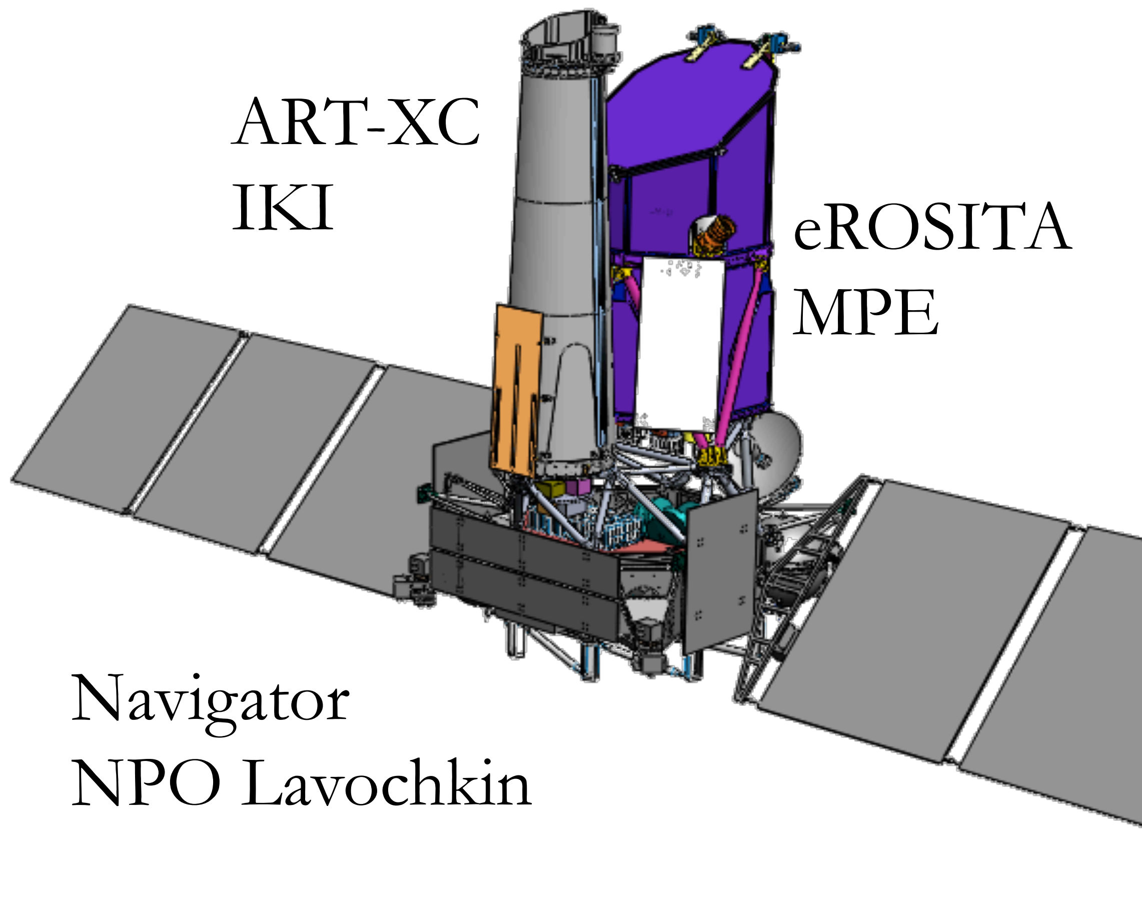
BHM /TD quasar targets mainly in North. Red and dark blue show, respectively, likely target areas for wide-area/low-cadence spectral TD, and high-cadence RM fields. Specific areas for medium tier TBD, but magenta+red depicts DR14 area coverage from which many known Sloan quasars might receive repeat spectra. The red region is one prime for low-cadence TD tier, as it also overlaps the *eROSITA*-DE North area; in this ~3000 deg^2 area both BHM TD quasars, and *eROSITA* X-ray sources get SDSS-V optical spectra. But (nearly) entire region in color of DR14 quasars also boosted to high interest with LCs, especially if contemporaneous (also including ~4 RM fields accessible from North).

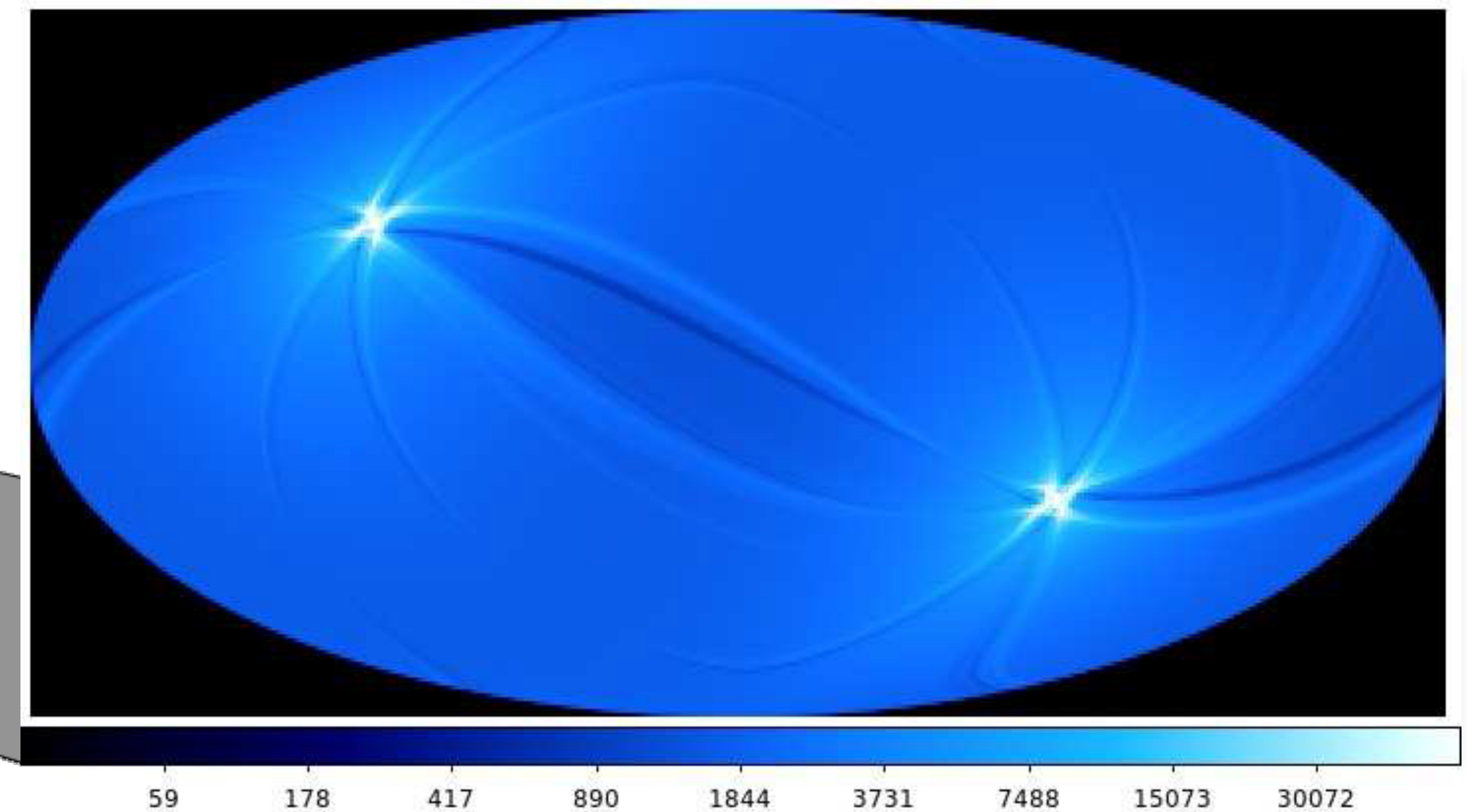
BHM eROSITA Survey Outline

Optical spectra of *eROSITA* X-ray sources in DE half of sky, mainly first ~1.5 years of *eROSITA*. Largest X-ray/optical survey yet.

- BHM optical spectroscopic IDs/redshifts, evolution, & astrophysics of >300,000 X-ray source counterparts, especially AGN/quasars.
- X-rays escape relatively unaltered from inner regions near SMBHs, enabling obscuration-unbiased AGN samples vs. optical-only. Repeat eROSITA scans provide sparse (frequent at ecliptic poles) X-ray LCs of obscured and unobscured AGN (e.g., including X-ray CLQs)
- Plus optical spectra of ~10^4 X-ray emitting clusters of galaxies, for cluster physics and cosmology. Also X-ray emitting CVs & other compact binaries, flaring stars, transients in MW & nearby galaxies.
-
- LCO provides spectral access to S. hemisphere, accessing bulk of *eROSITA*-DE area. But ~4500 deg^2 at high latitude of eROSITA-DE is North of dec>-15 deg, with spectra from North at APO, and accessible to *contemporaneous* ZTF LCs.

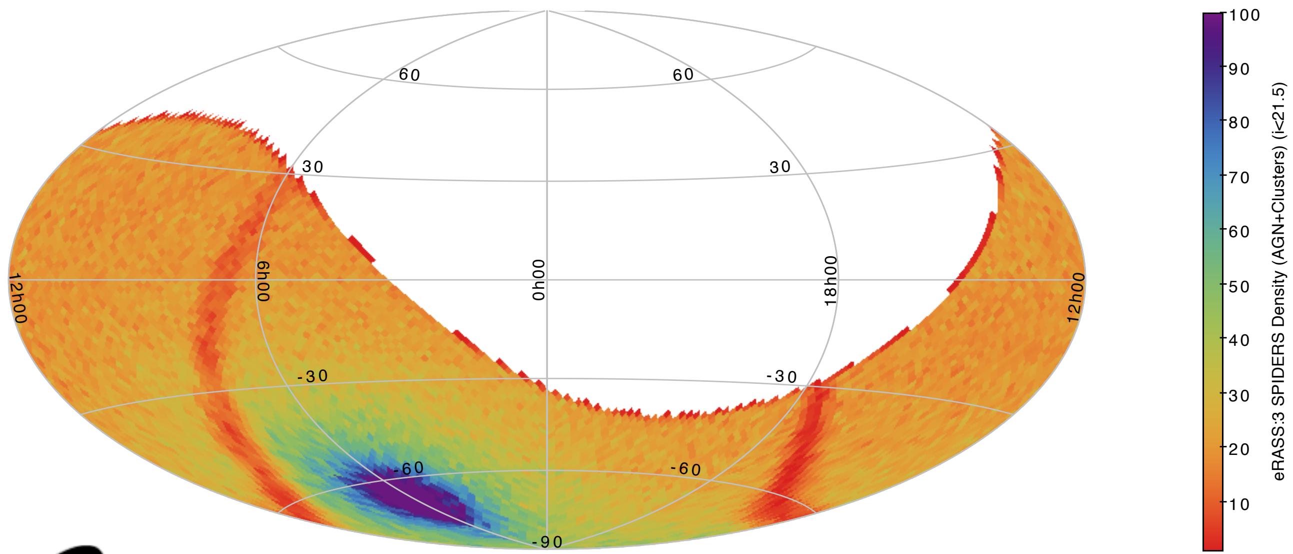
eROSITA/SRG Ready! Mission timeline

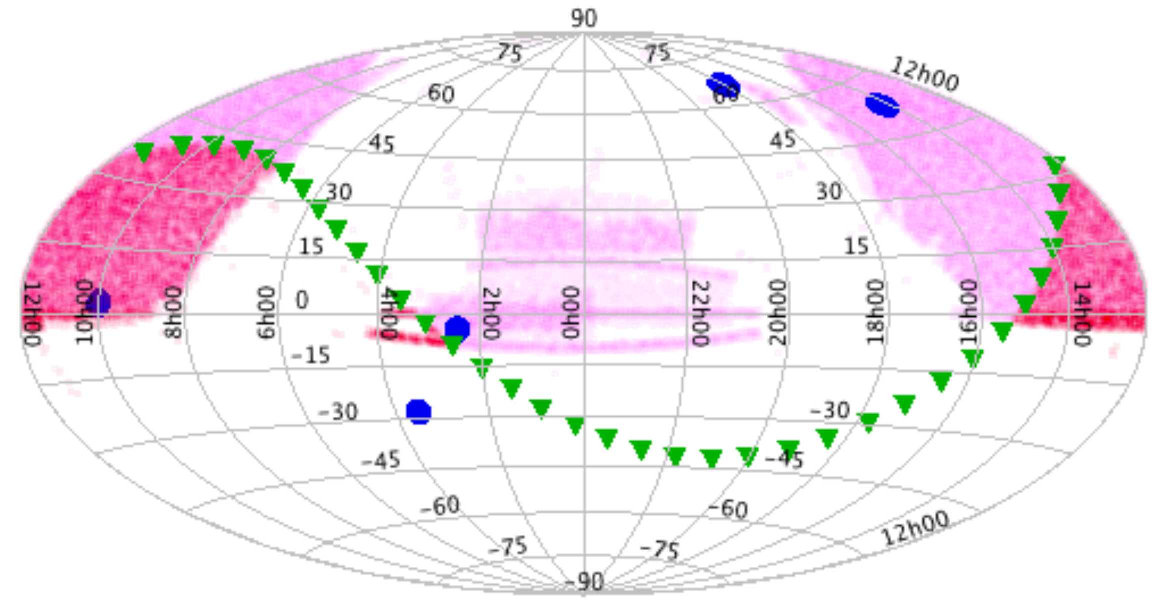




- **eROSITA delivered to Russia**: January 20, 2017 *(now at Baykonour!)*
- **T0= Launch estimate*:** Summer'19 from Baykonour
- **3 Months:** flight to L2, PV and calibration phase (mini-survey, possible targets for SDSS-IV)
- **4 years**: 8 all sky surveys eRASS:1-8 (scanning mode: 6 rotations/day)
  - eRASS:1 catalog ready as early as T0+10 months
  - eRASS:3 catalog ready as early as T0+22 months
- **Data releases (TBC):** [2021, eRASS:1]; [2022, eRASS:3]?

BHM Areas: *eROSITA*-DE mainly S., Time-Domain mainly N., but…





Estimated eRASS:3 source density in DE half of sky, after 3 *eROSITA* all-sky scans completed about 1.5 years into mission. *About 4500 deg^2 is North of dec>-15deg (& accessible to ZTF LCs)* .

Total BHM program takes about ½ of the dark fiber-hours, North and South, approx evenly split between *eROSITA* and TD.

Although BHM/*eROSITA*-DE targets are South of green triangles, note 3000 deg^2 of *eROSITA*-DE coverage North of dec>0 degs overlaps with one prime area for BHM time-domain wide/low-cadence tier. In this ~3000 deg^2 North area, both TD quasars & *eROSITA* X-ray sources will be spectroscopic targets in SDSS-V/BHM, and ~all would be mutually accessible to ZTF LCs as well.

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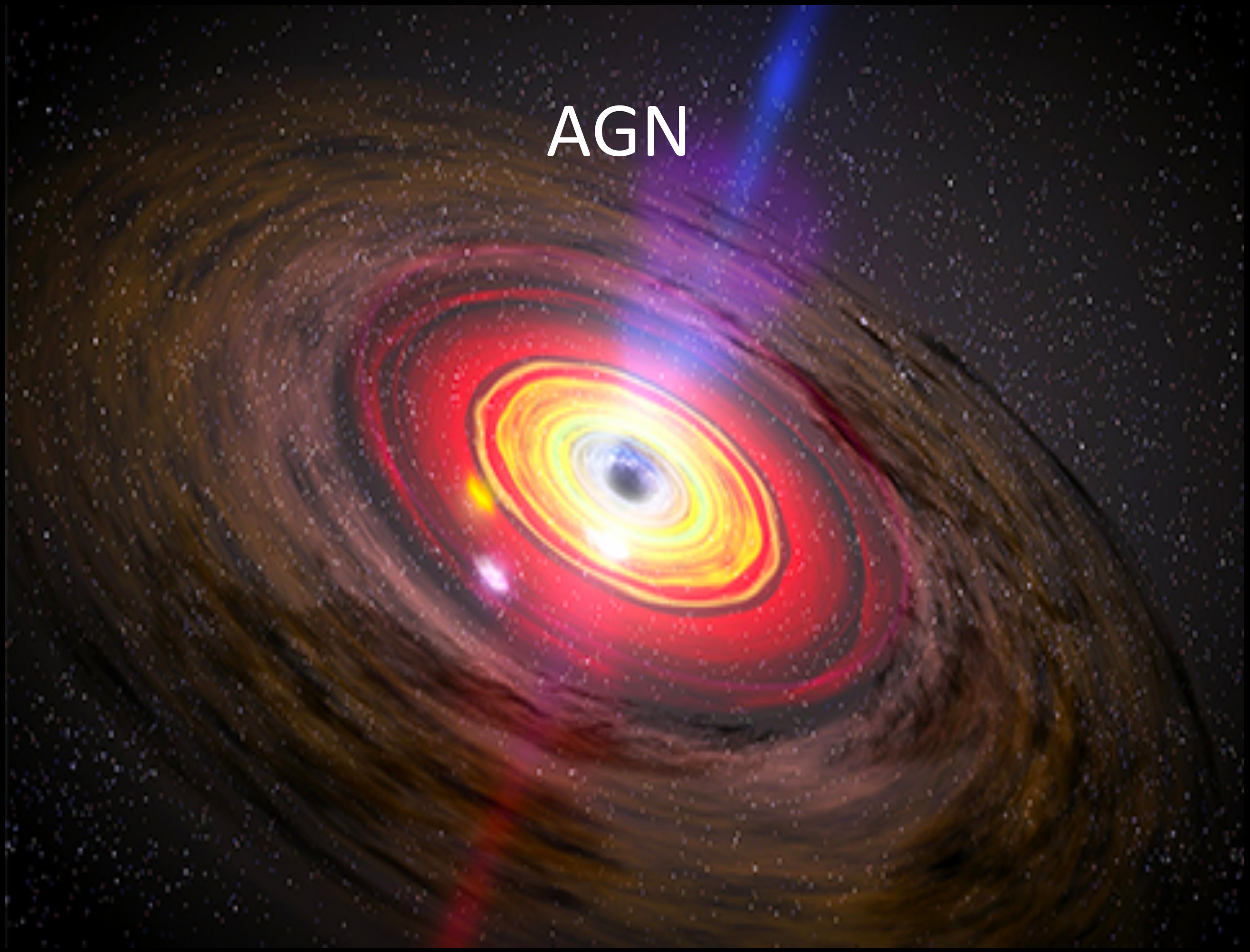
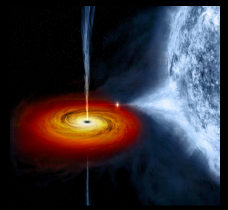
CLQs as scaled, distant relatives of X-ray binaries?

(Ruan et al. 2019)

- Is structure of the disk-corona system self-similar?
- Does this analogy hold in different accretion states?
- Do accretion state transitions display similar phenomenology?

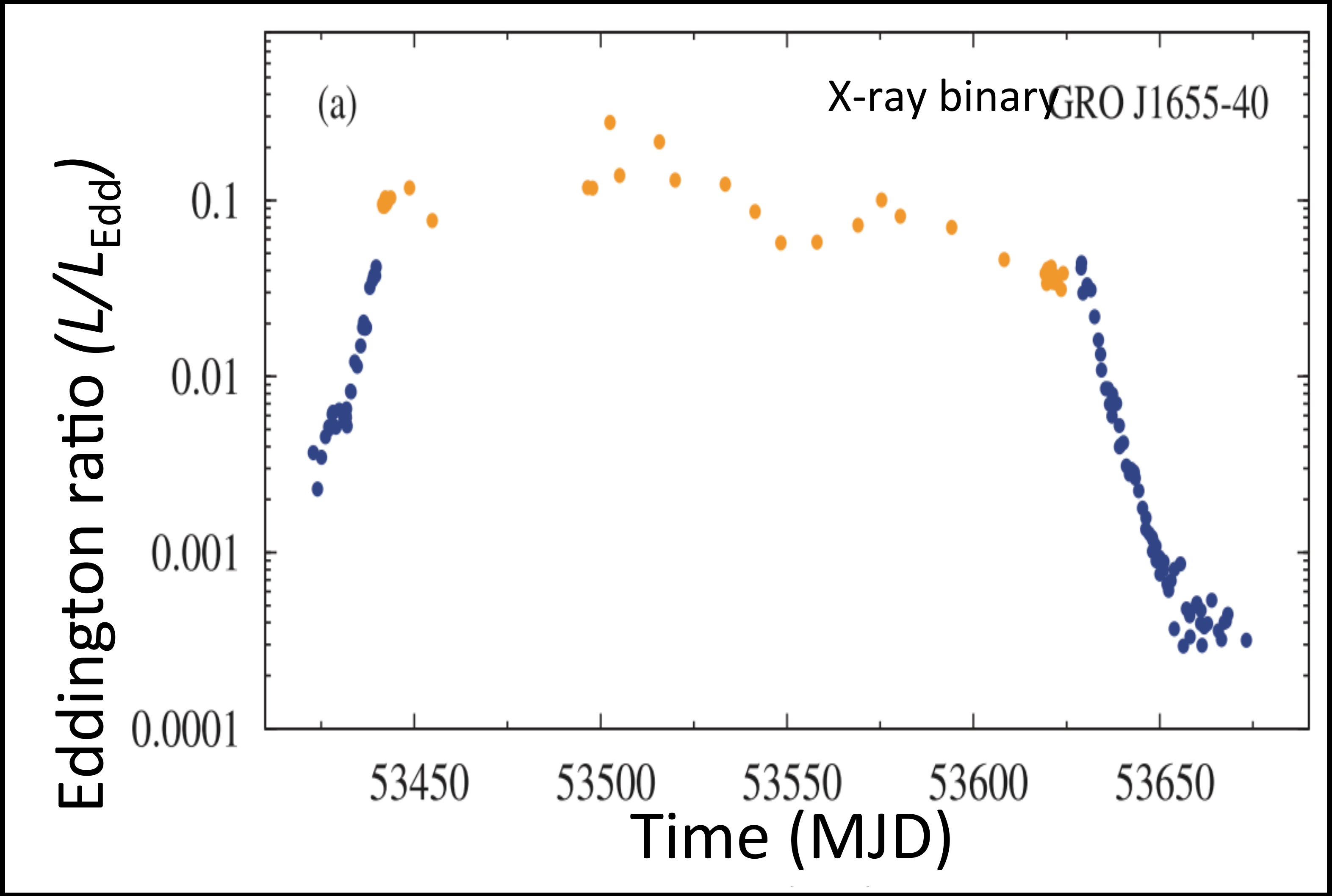


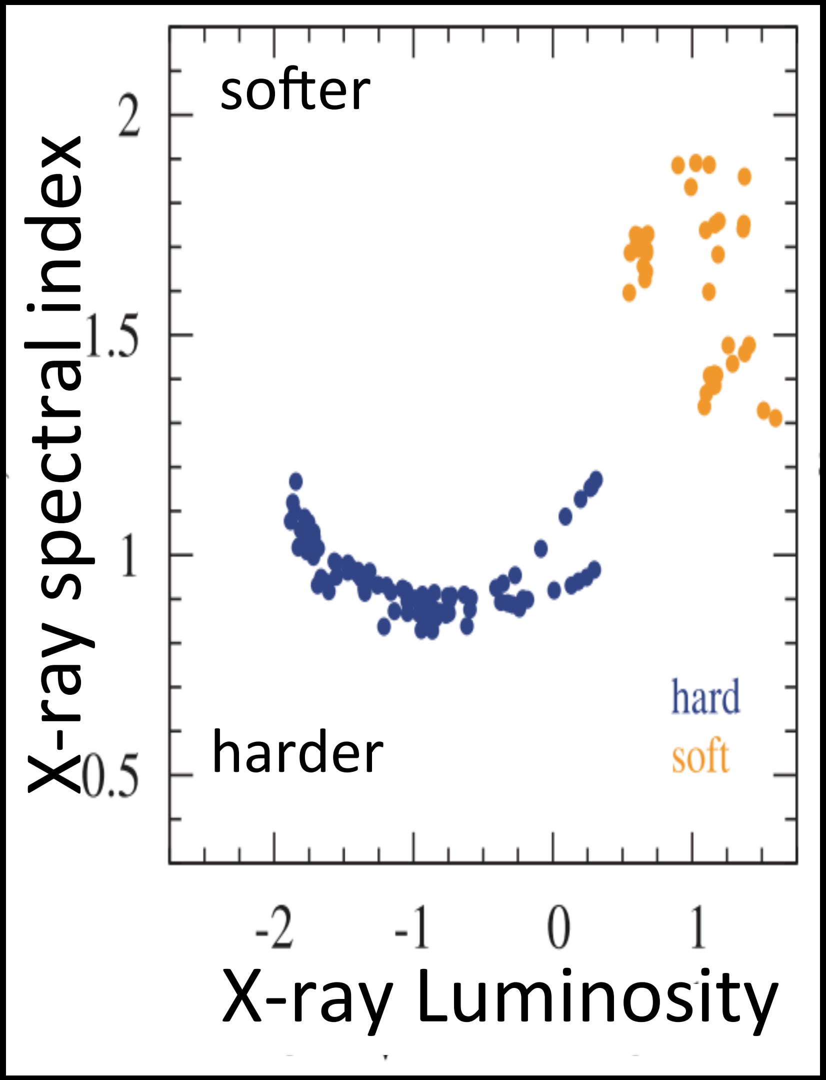
XRB



Scaled up by 10^7?

For X-ray binaries in outburst, X-ray spectral index probes the evolution of the disk-corona system

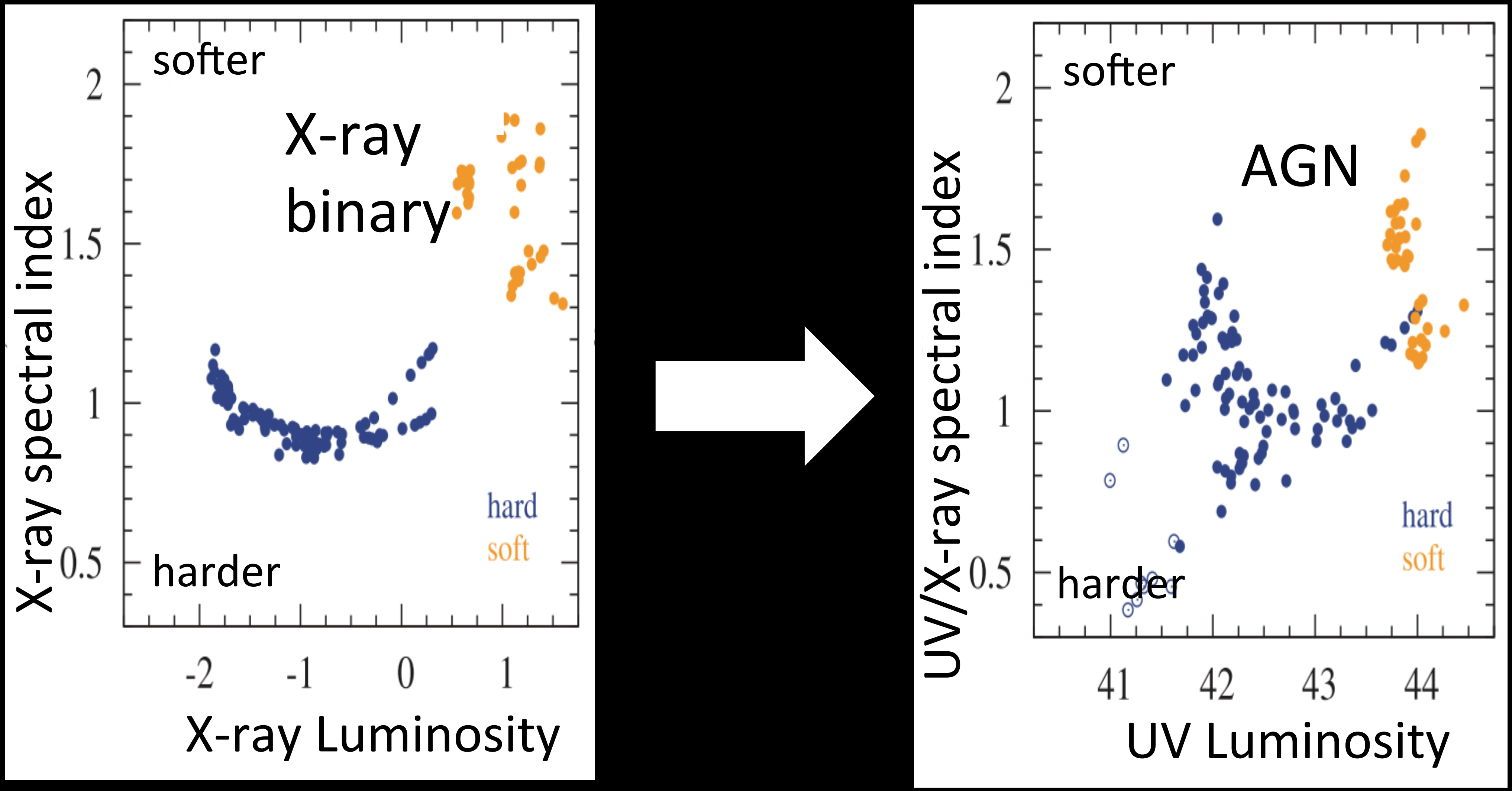




Sobolewska+11

Adapted from J. Ruan

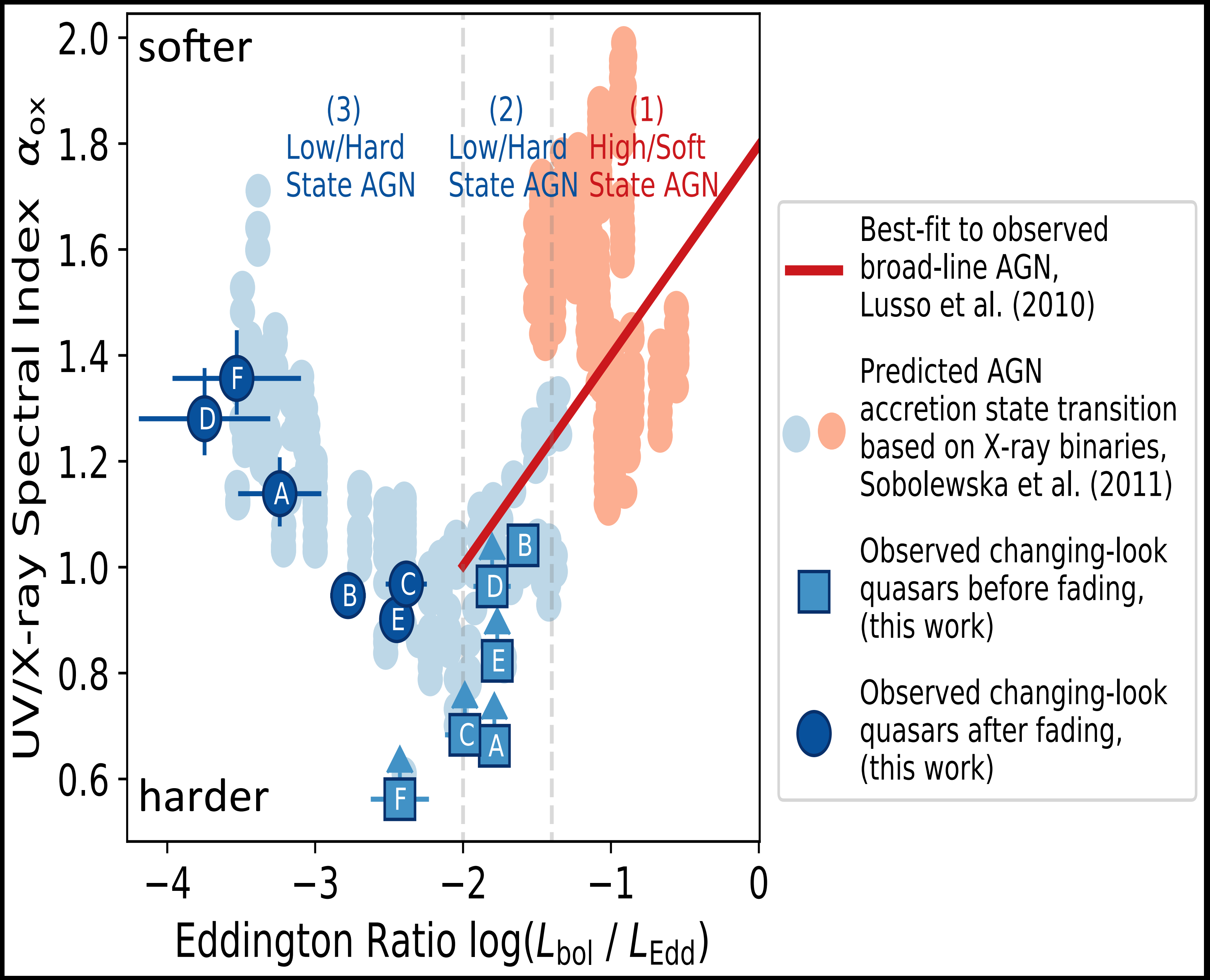
Scale SEDs of X-ray binaries undergoing state transitions to AGN, to predict what AGN state transitions look like: AGN predicted to first harden as they transition from high/soft to low/hard state, then soften again at lower luminosities at $L/L_{\rm Edd} \sim 0.01$



Adapted from J. Ruan

Sobolewska+11

The potentially similar X-ray/optical spectral evolution of AGN and X-ray binaries suggests structure of their disk-corona systems may be analogous (but note timescales still don't scale).



J. Ruan+19

BHM/SDSS-V Spectra +ZTF LCs Summary

Combining optical variability and X-ray surveys across the sky, could jointly in ~2020-2025 provide order(s) of magnitude advances in quasar/SMBH and related studies, such as:

- Repeat spectra and contemporaneous LCs of >20,000 quasars sampling timescales from months to decades that reveal the astrophysics of SMBH accretion disk properties and CLQs/accretion state transitions, dynamical changes in broad line regions, binary black hole signatures, and variability constraints on quasar outflows.

- RM black hole mass measures using higher cadence SDSS-V spectra and contemporaneous LCs (extending down to weeks or days) for about a thousand quasars of diverse redshift and luminosity (vs. the current/historical RM sample that relies on only ~60 nearby & lower-luminosity AGN).

- Redshifts and spectral identifications for >300,000 obscured & unobscured *eROSITA* X-ray emitting AGN, providing highly unbiased measures/mappings of quasar clustering, demographics, and growth and evolution of SMBHs over cosmic time…plus a closely related spectral survey of >10,000 X-ray emitting clusters from the *eROSITA* survey.. Plus ~10^4 X-ray stars in Milky Way and nearby galaxies….all with sparse X-ray LCs, and potentially >one-third with well sampled contemporaneous optical LCs.

Exploring Ultracompact Binaries using SDSS-V+ZTF

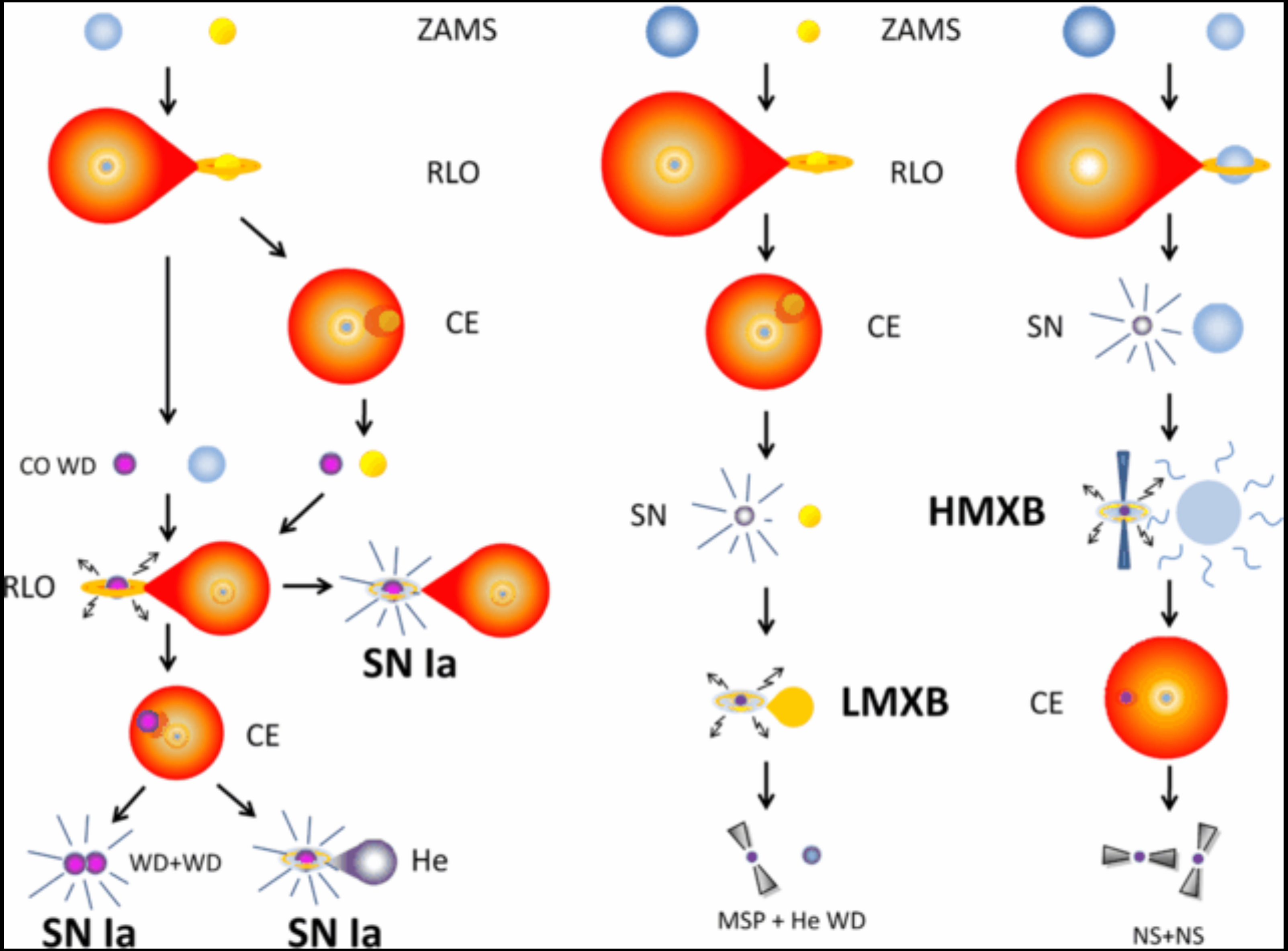
Kevin Burdge

California Institute of Technology

Ultracompact Binaries: What do they tell us?

- Probes of common envelope evolution

Common envelope evolution crucial for explaining how double NS and WD systems form



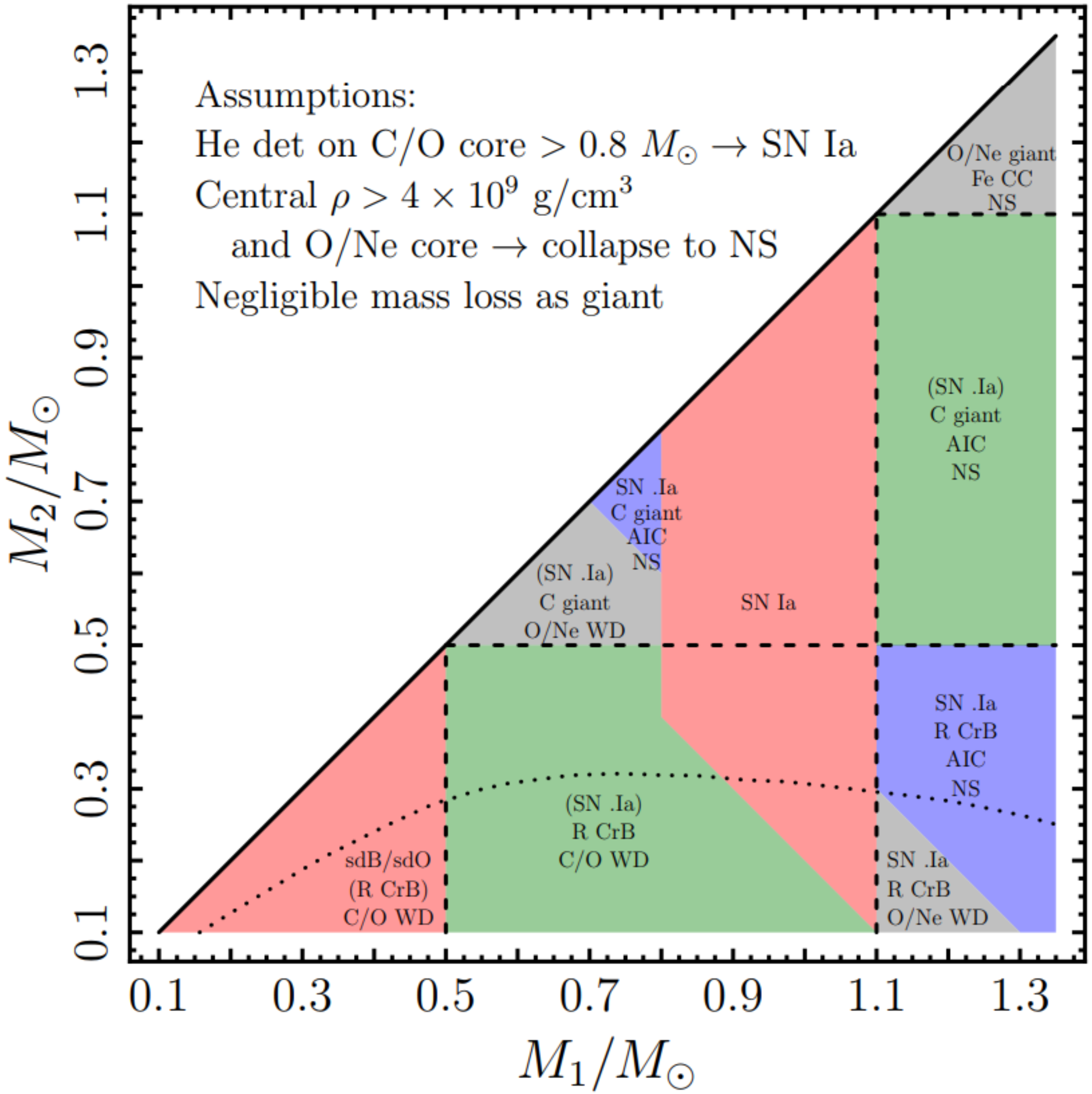
Ivanova et al. 2013

Ultracompact Binaries: What do they tell us?

- Probes of common envelope evolution

- Tests of the products of binary evolution

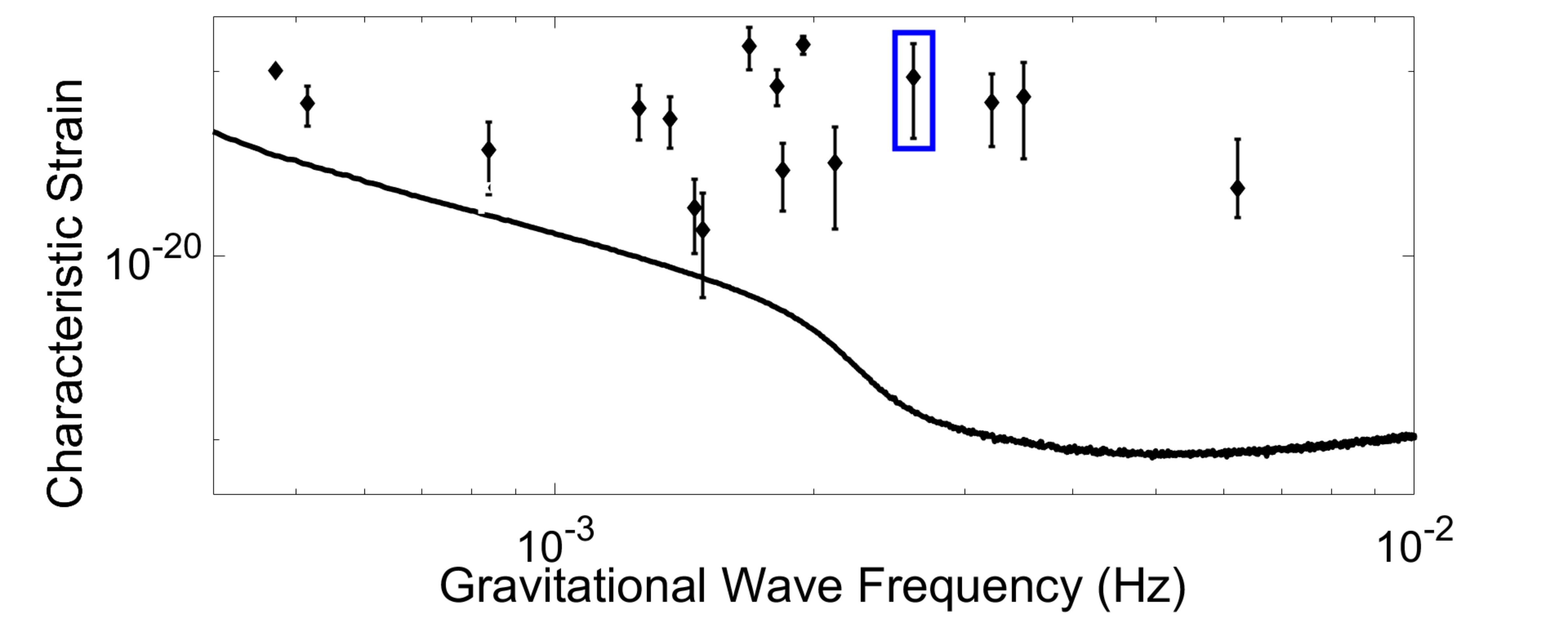
Rich phase space of outcomes of DWD mergers



Shen 2015

Ultracompact Binaries: What do they tell us?

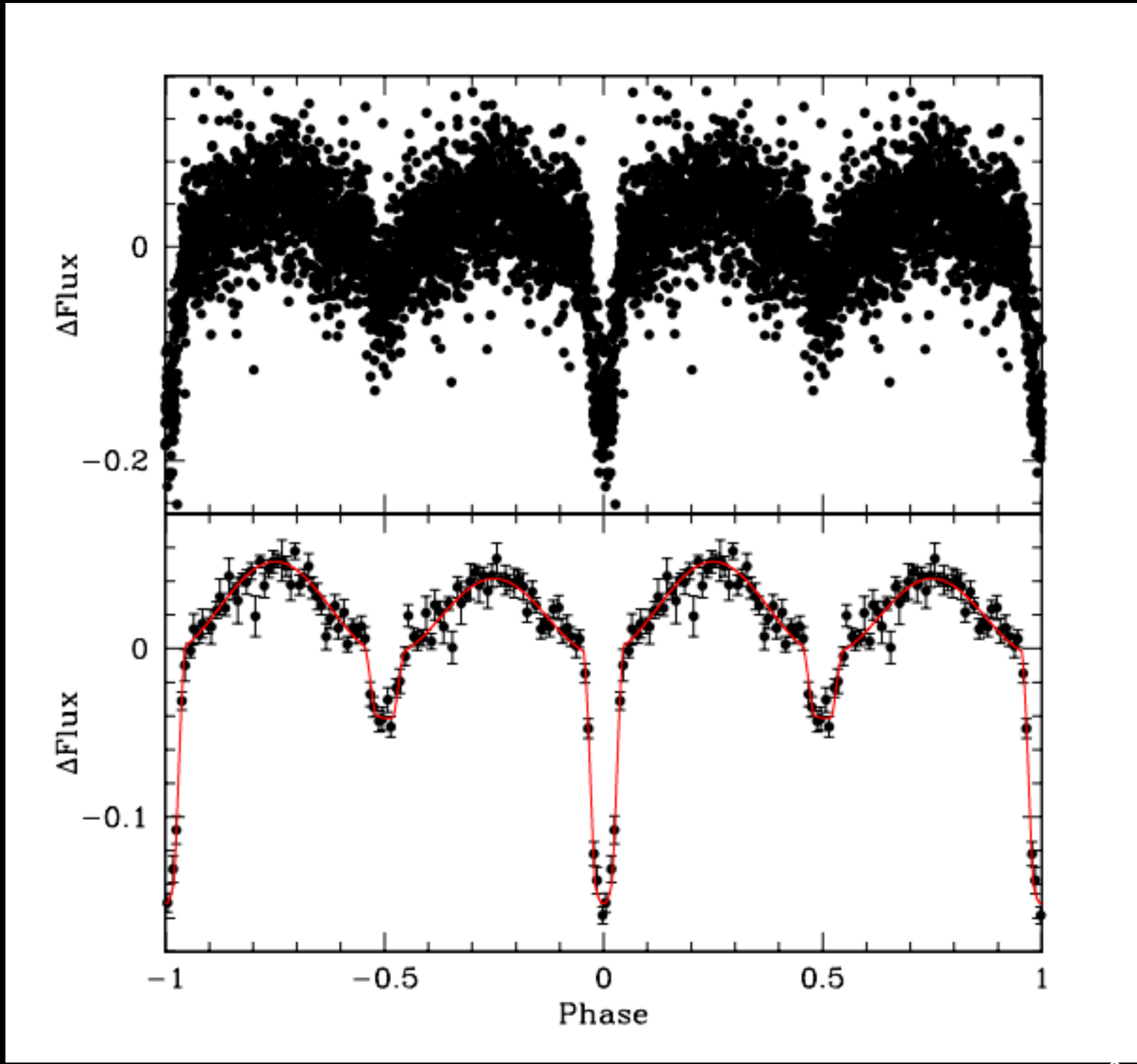
- Probes of common envelope evolution
- Tests of the products of binary evolution
- Sources of gravitational radiation in the LISA band



There are very few LISA detectable DWDs known

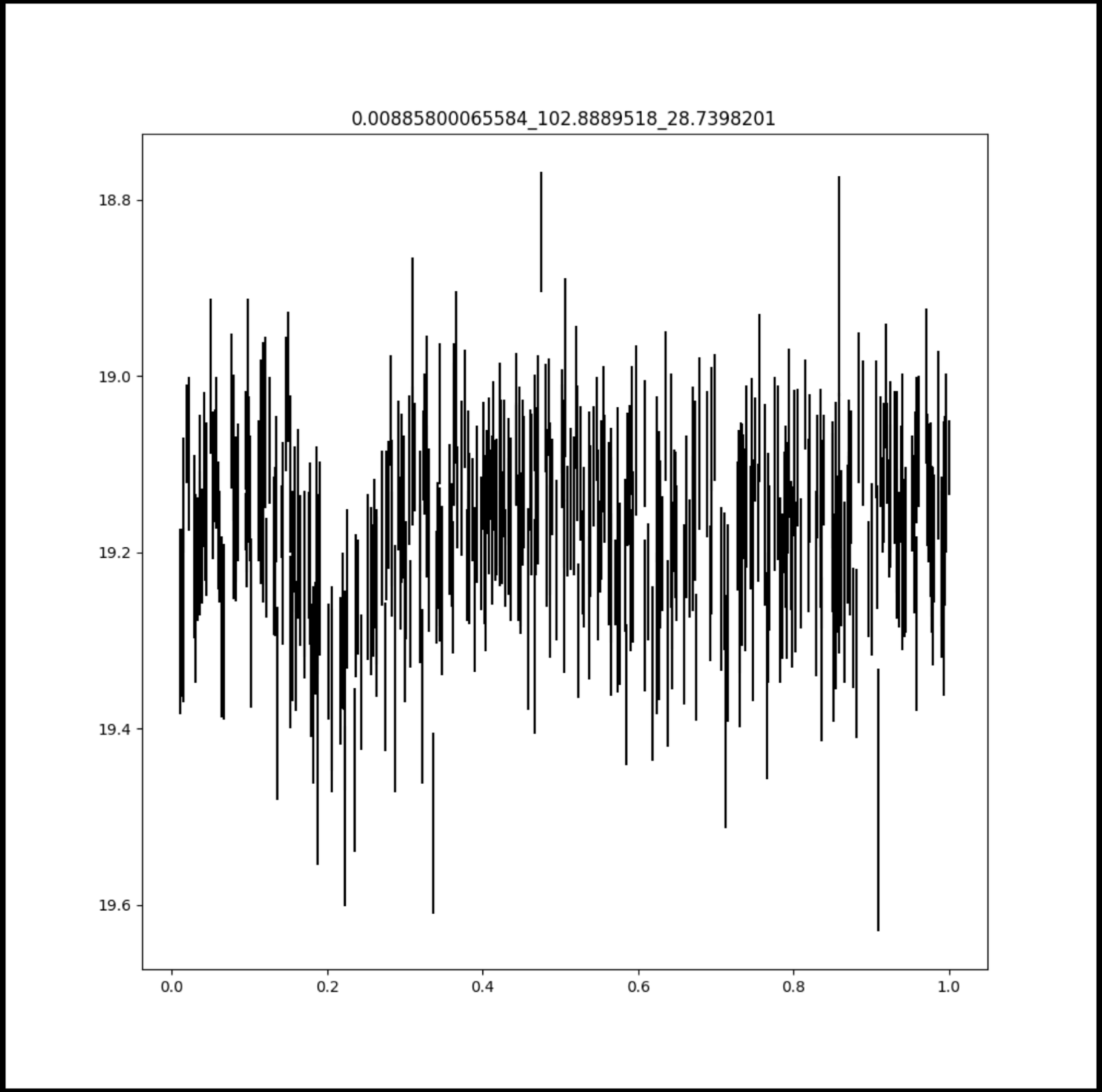
How do we find White Dwarf Binaries in the time domain

- Eclipses
- Ellipsoidal modulation
- Irradiation of companion



J0651, a 12.75 minute binary (Brown et al. 2011, Hermes et all 2012)

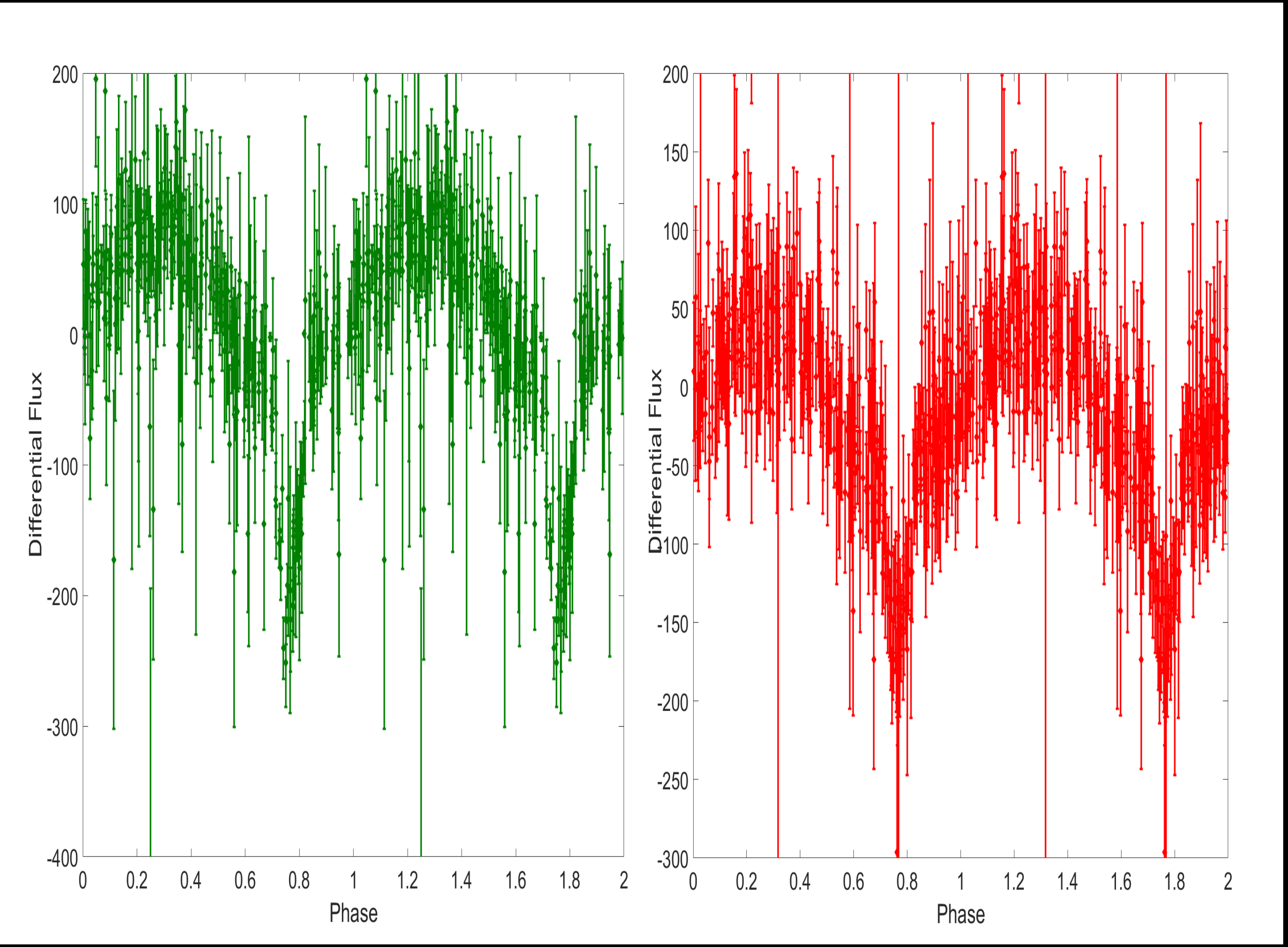
A demonstration that we can find these rare binaries with ZTF



Photometry

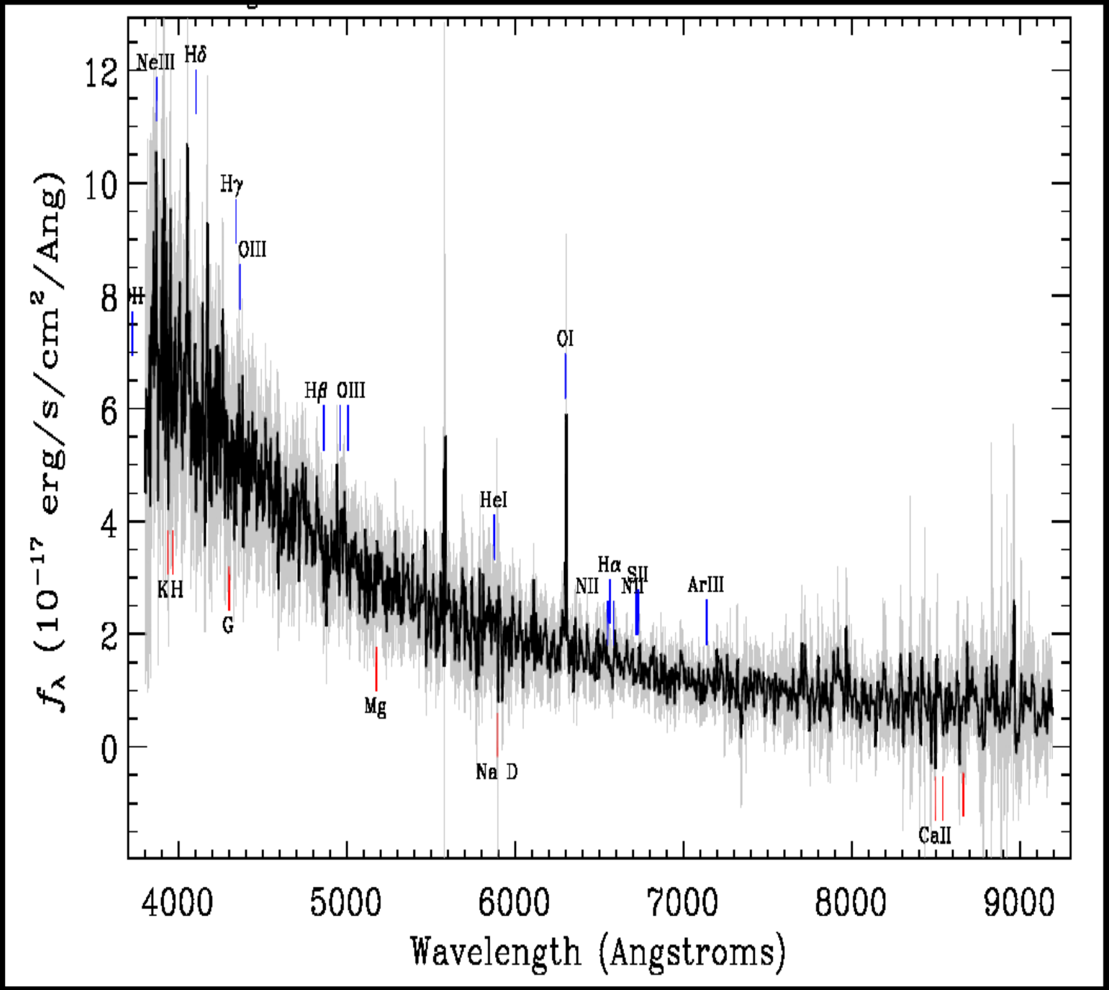
- Can be used to probe SED, and therefore temperature

- Can be used a geometric constraint via eclipses



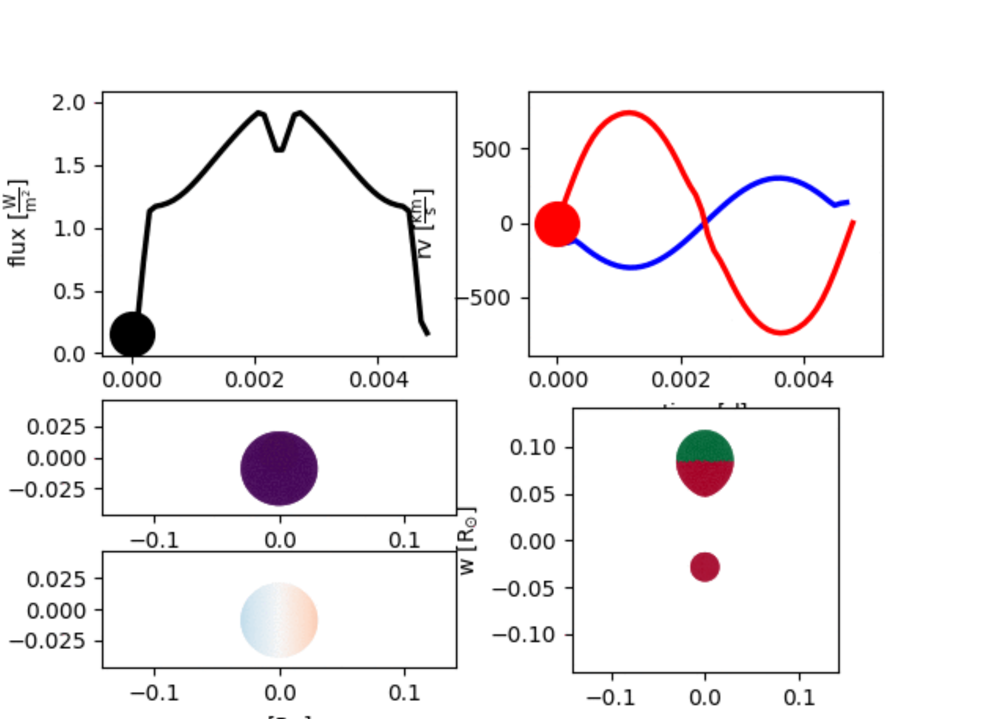
Spectroscopy of a binary

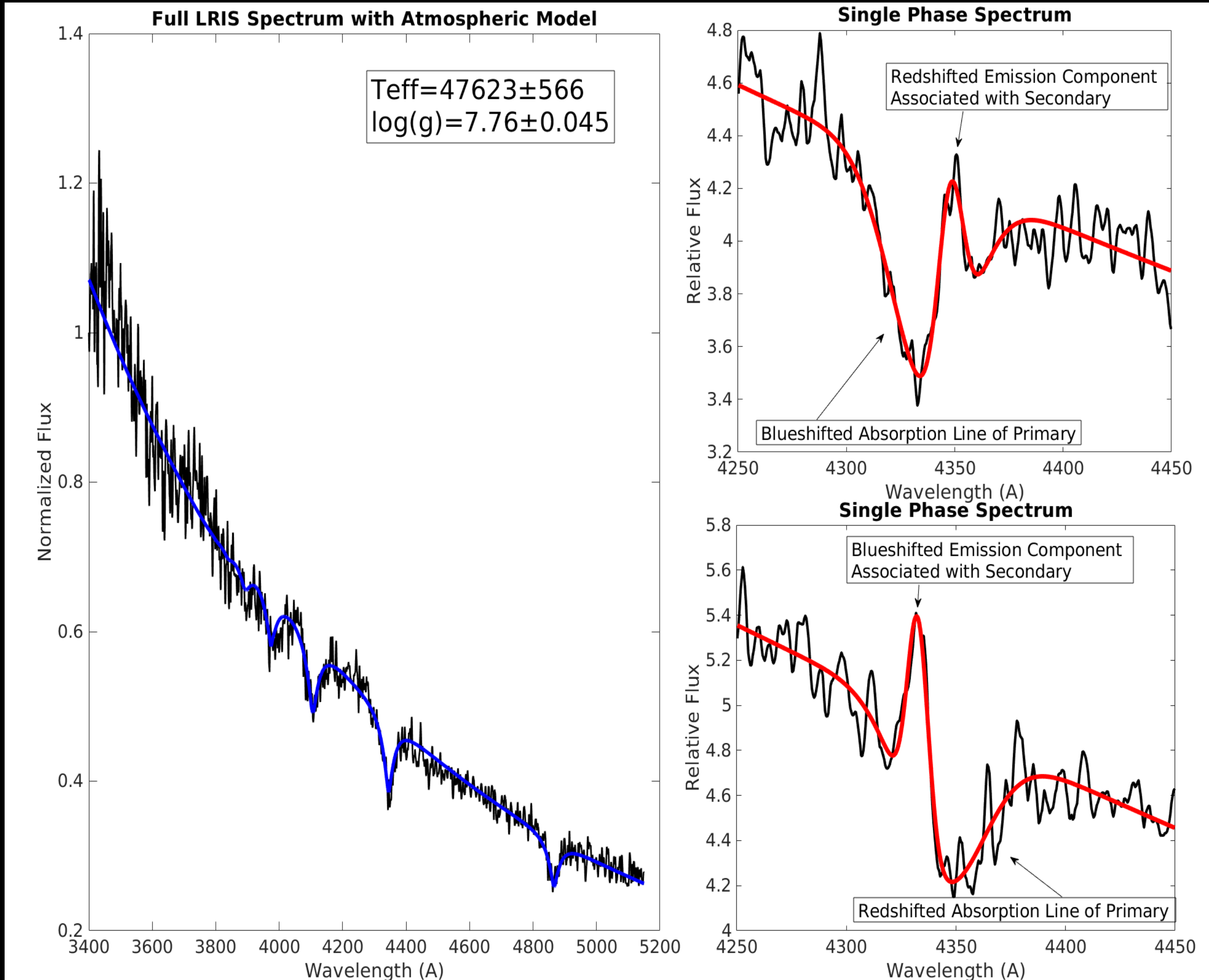
- Directly probes radial velocities
- Can measure atmospheric properties such as surface gravity, effective temperature, etc



Spectroscopy+Photometry

By combining temporal information in spectra and photometry, we can completely constrain some binary systems.



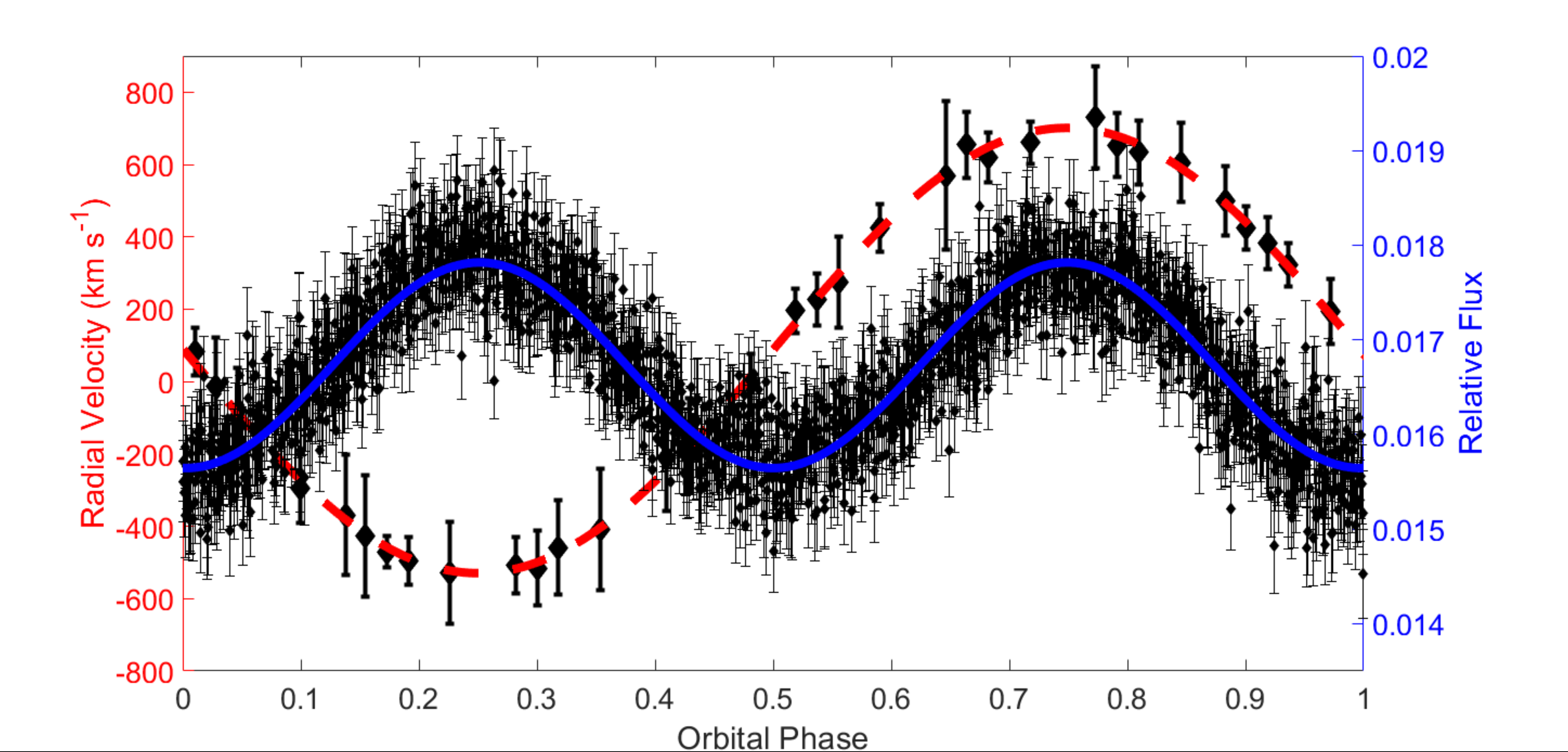


Question: How can we use SDSS-V and ZTF to characterize/confirm/identify short period binaries?

- If period is short, RVs are large (>several 100 km/s)

- Temporal resolution required

An Example of the Synergy Between Spectroscopy and Photometry



Spectroscopy: Pros and Cons

- Radial velocity measurements high fidelity way to confirm binarity (not many false positives)
- In some cases, provide measurements of log(g), Teff, abundances, magnetic fields, etc
- Can directly probe for accretion signatures in the form of emission lines

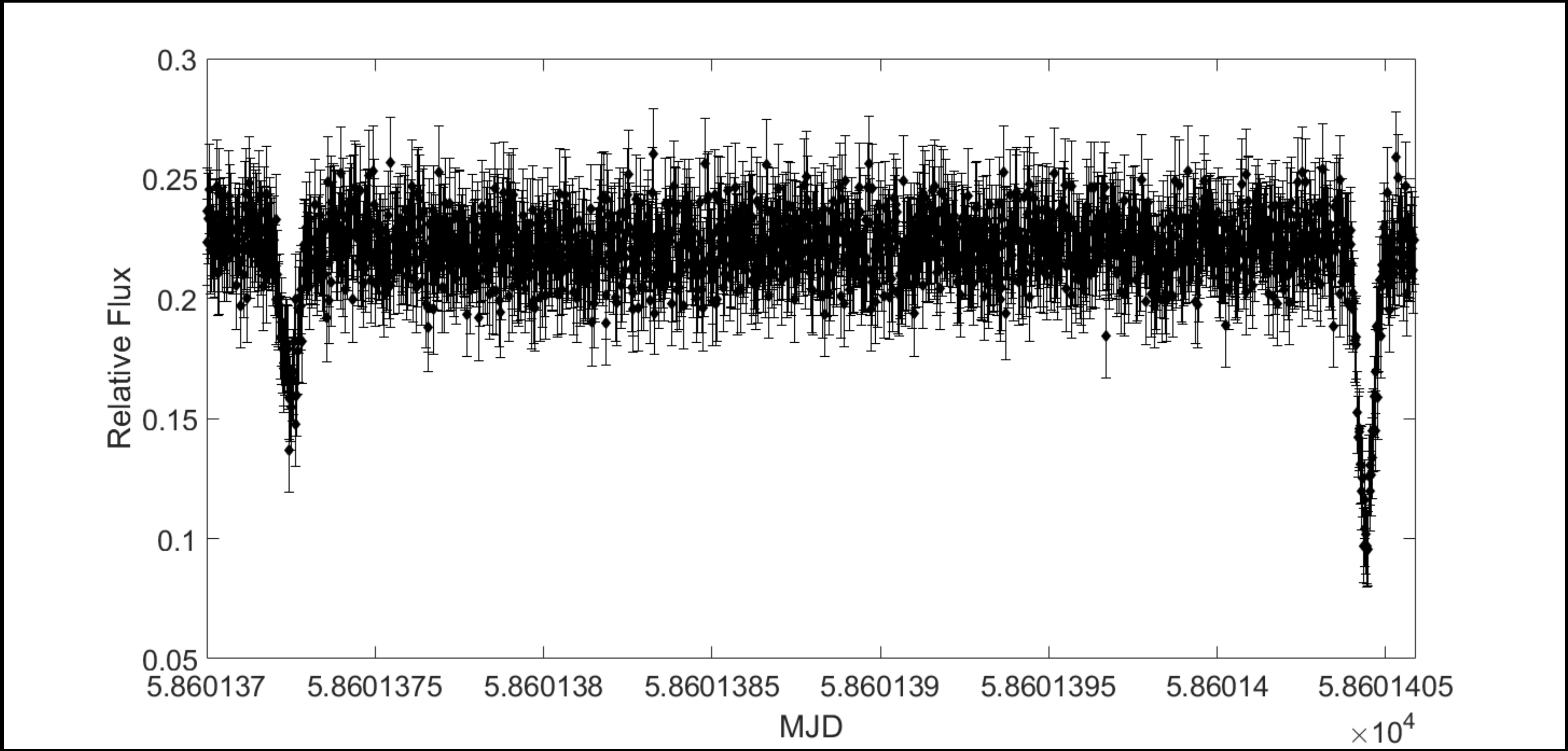
- Expensive to get—photons are spread thin, so challenging for faint objects, especially with short exposures
- More challenging to find periods, etc, especially in low SNR cases

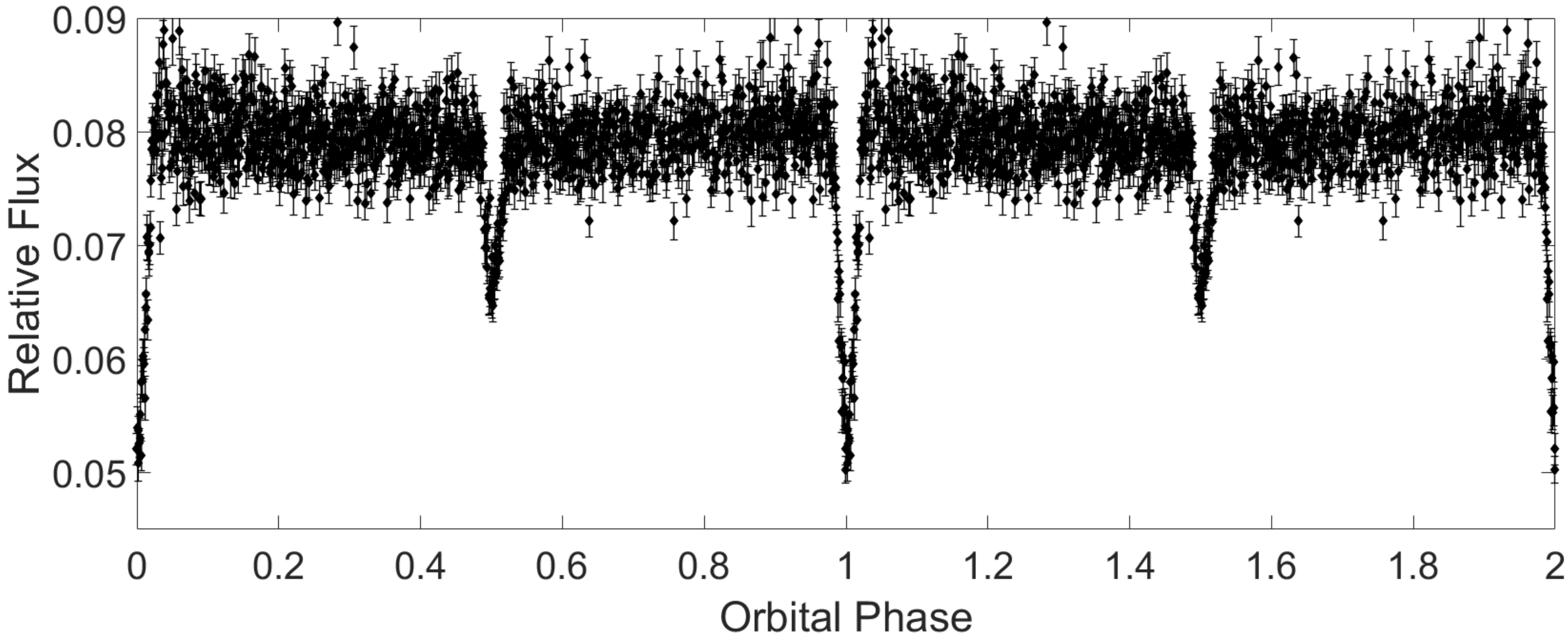
Photometry: Pros and Cons

- Easy to get—many photons consolidated into a single piece of information with a brightness+timestamp
- Great for quickly identifying periodic behavior, and easy to systematically search

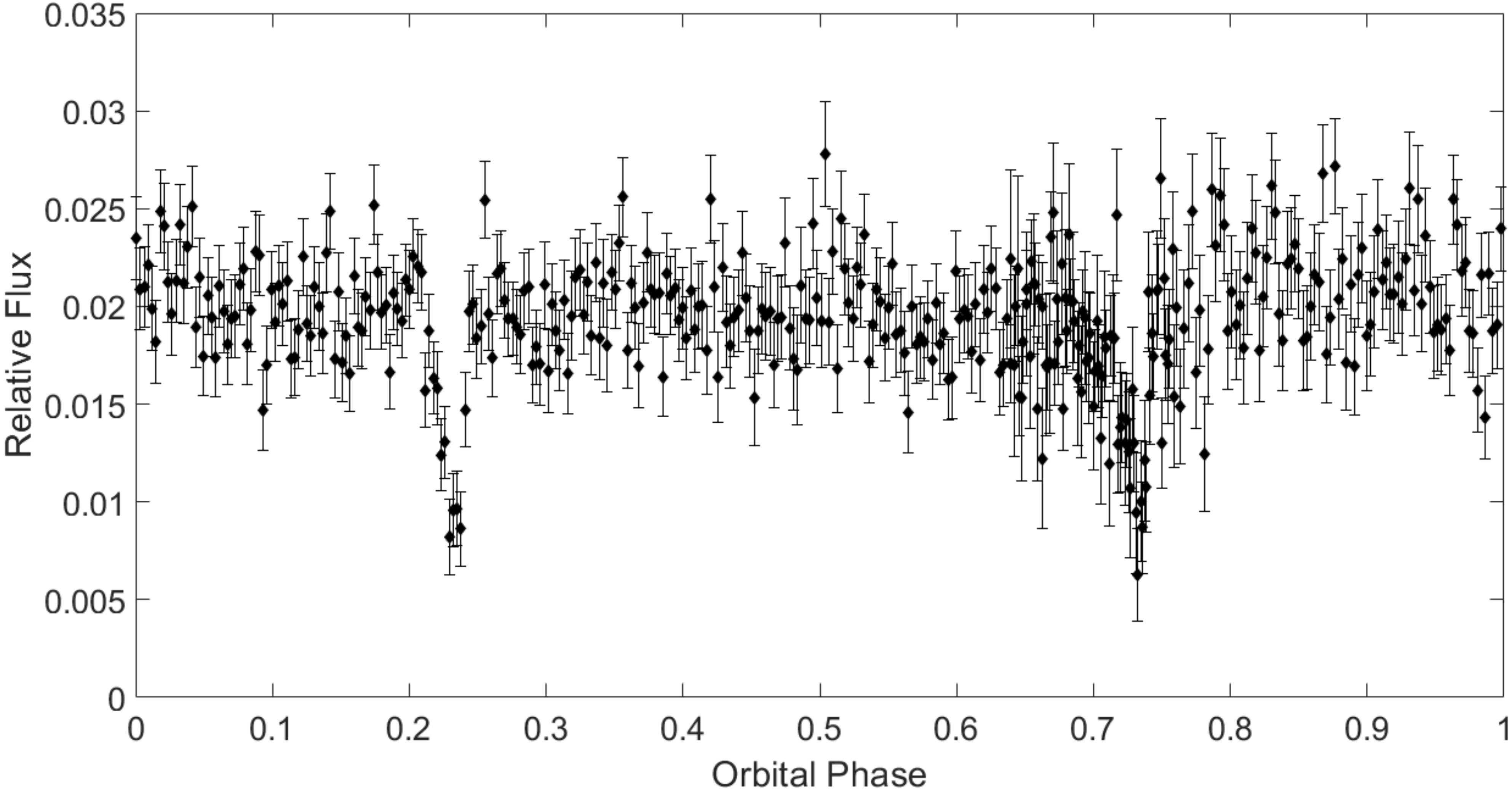
- Frequently can tells very little about the nature of objects, resulting in many false positives when looking for binaries
- Can be quite challenging to model in order to extract physical parameters (especially ellipsoidal modulation)
- Accreting systems, although frequently periodic, can change states, making searching for periodicity challenging

Examples from ZTF (how could we use SDSS-V for these systems?)

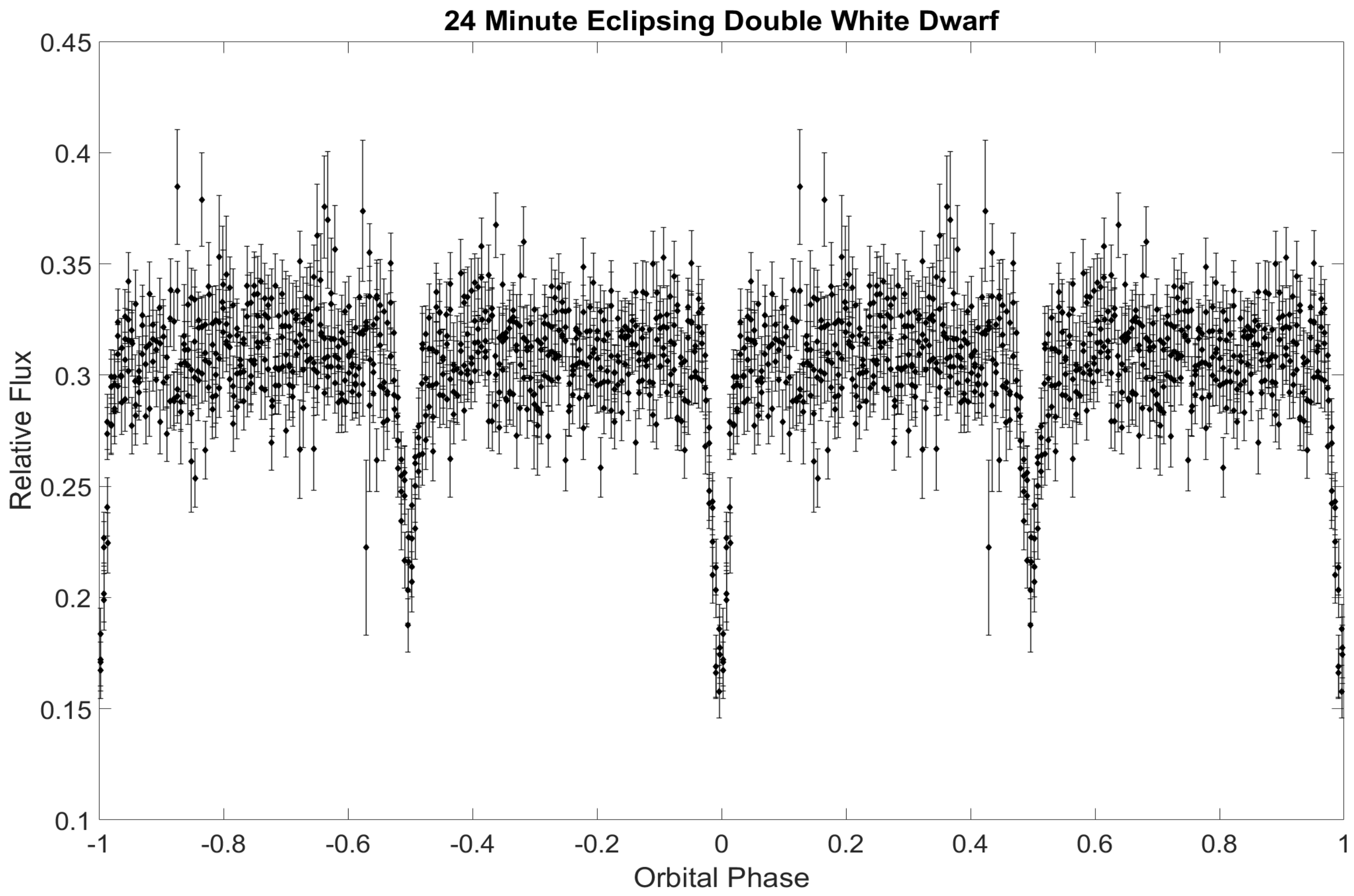




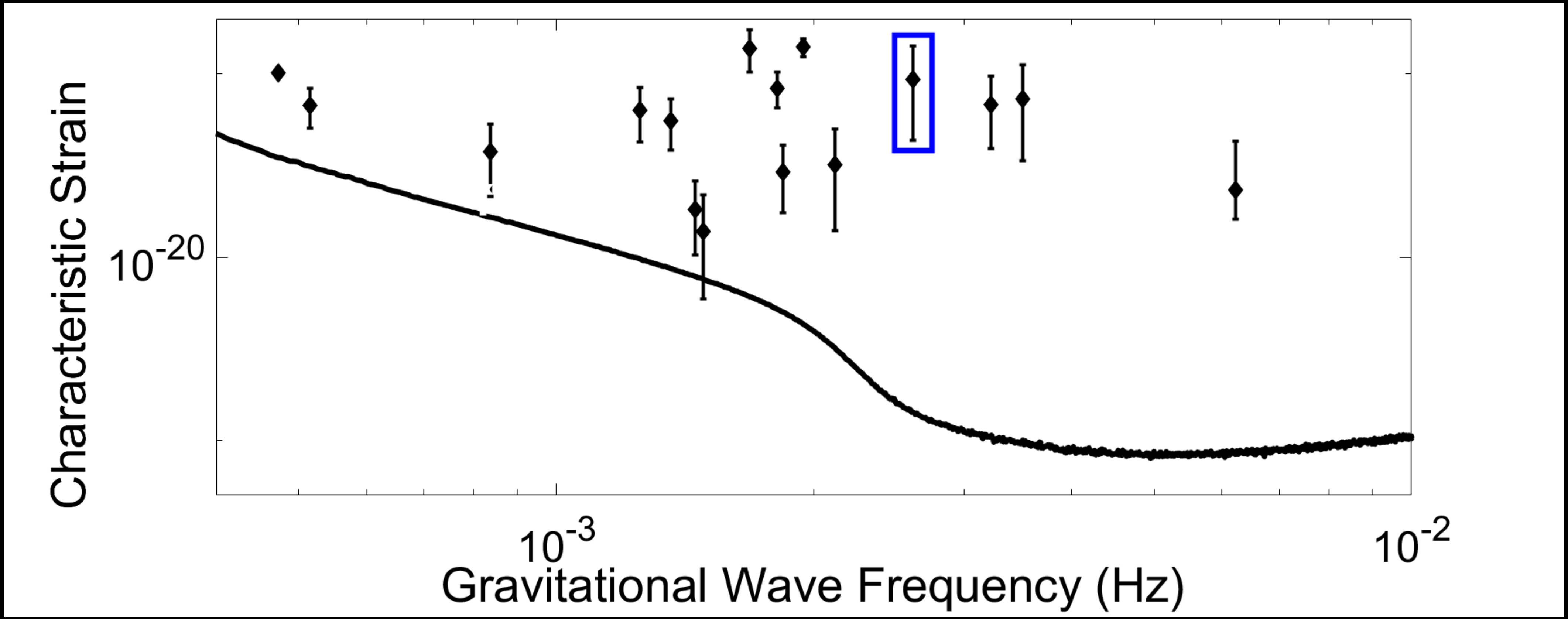
0.09
0.08
0.07
0.06
0.05
Relative Flux
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Orbital Phase



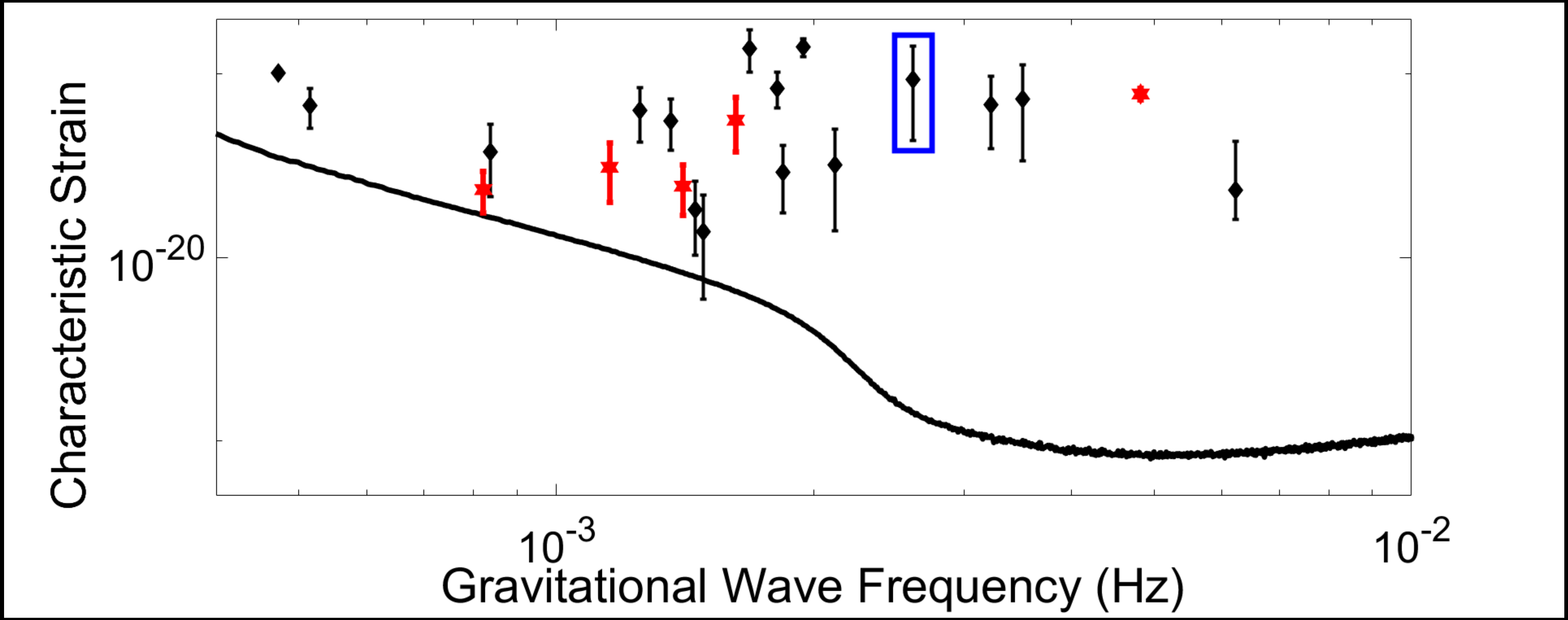
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Relative Flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Orbital Phase

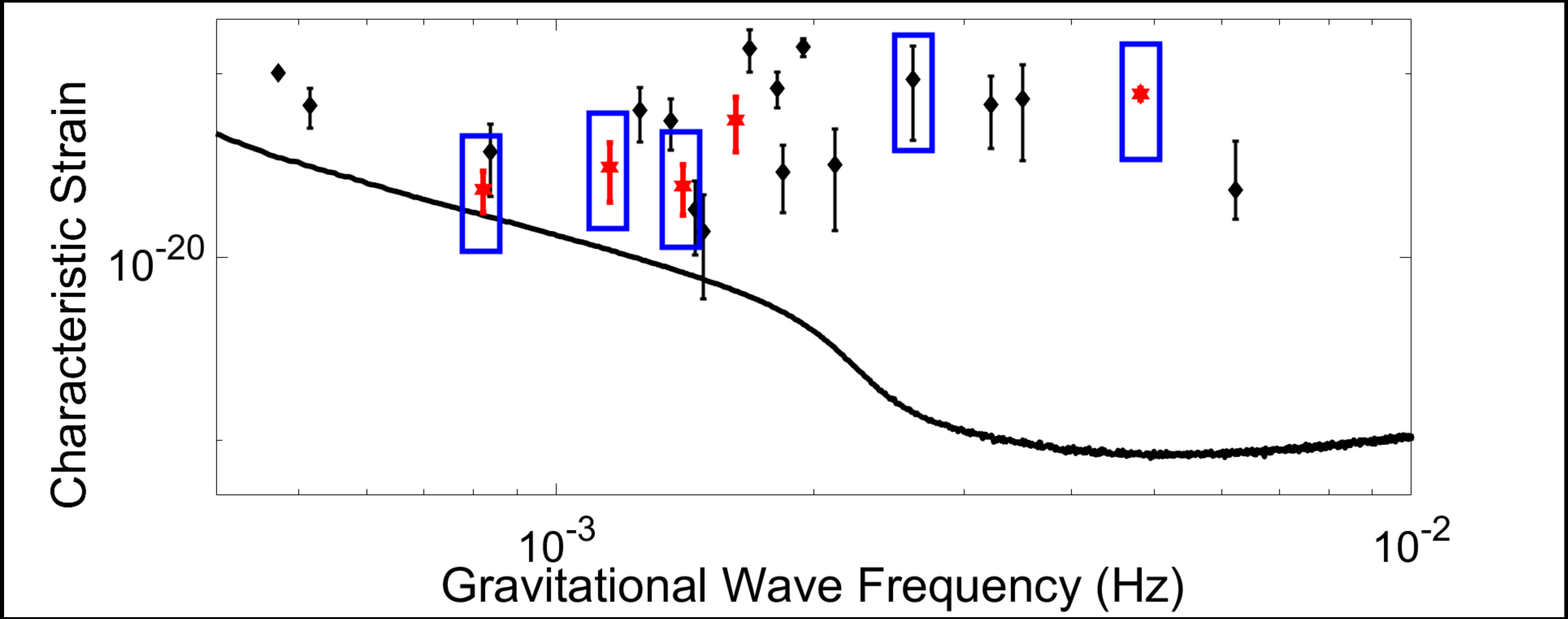


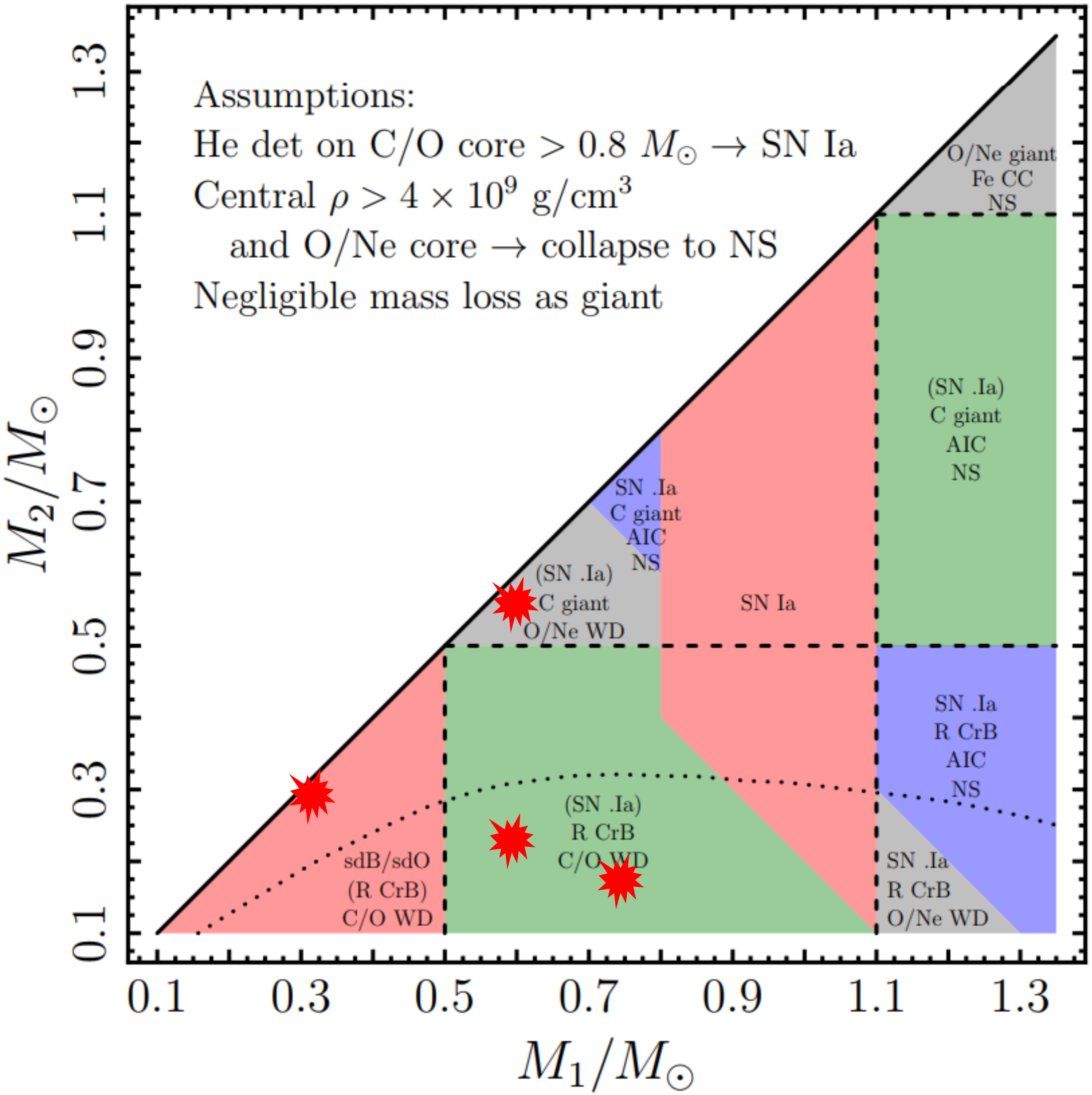
24 Minute Eclipsing Double White Dwarf
Relative Flux
Orbital Phase
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1



Characteristic Strain
10^{-20}
10^{-3}
10^{-2}
Gravitational Wave Frequency (Hz)


Characteristic Strain
10^{-20}
10^{-3}
10^{-2}
Gravitational Wave Frequency (Hz)


Characteristic Strain
10^{-20}
10^{-3}
10^{-2}
Gravitational Wave Frequency (Hz)

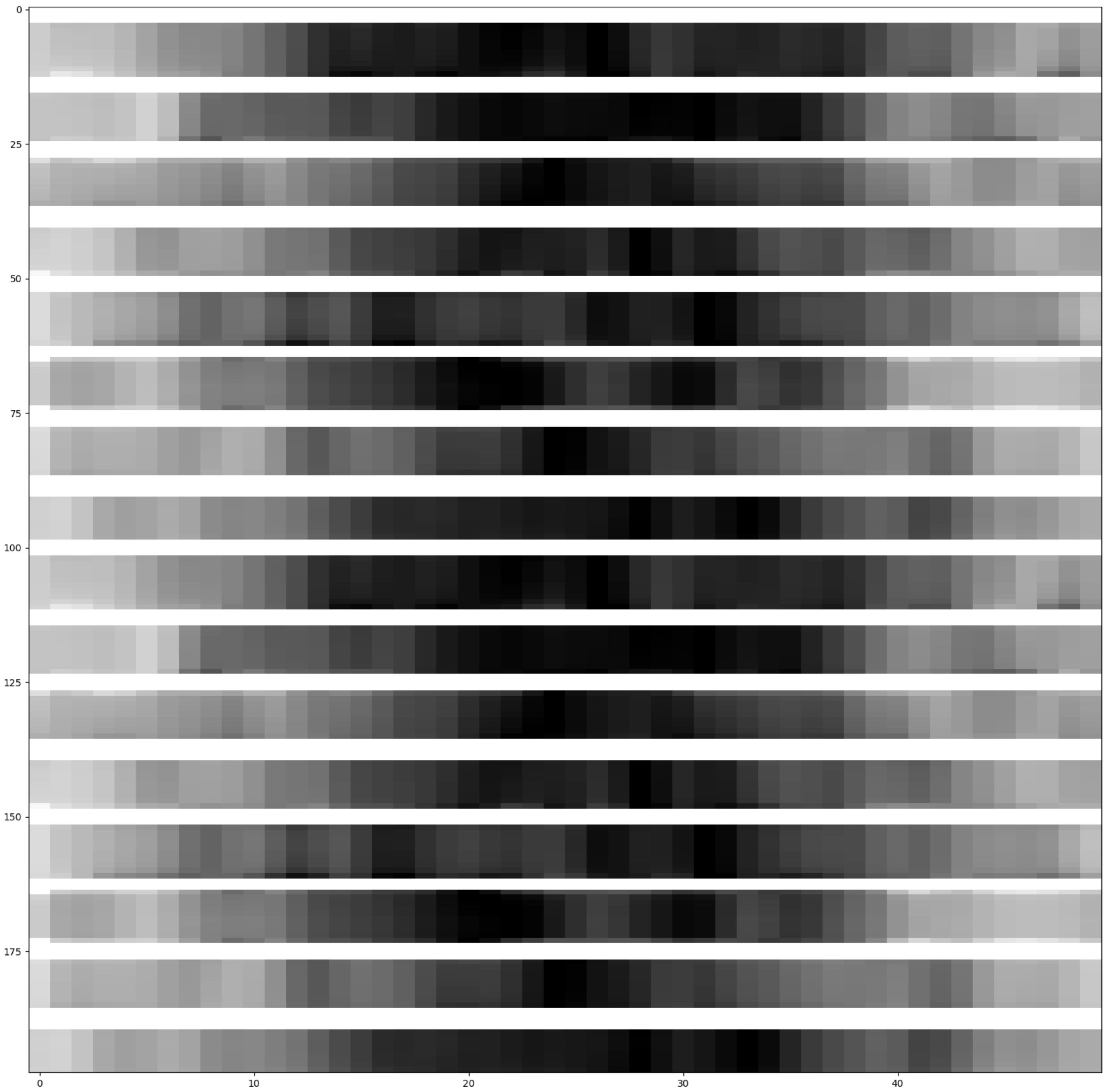


Assumptions:
He det on C/O core > 0.8 $M_\odot$ → SN Ia
Central $\rho > 4 \times 10^9$ g/cm^3
and O/Ne core → collapse to NS
Negligible mass loss as giant
O/Ne giant
Fe CC
NS
(SN .Ia)
C giant
AIC
NS
SN .Ia
C giant
AIC
NS
(SN .Ia)
C giant
O/Ne WD
SN Ia
SN .Ia
R CrB
AIC
NS
(SN .Ia)
R CrB
C/O WD
sdB/sdO
(R CrB)
C/O WD
SN .Ia
R CrB
O/Ne WD
$M_2/M_\odot$
$M_1/M_\odot$

Shen 2015

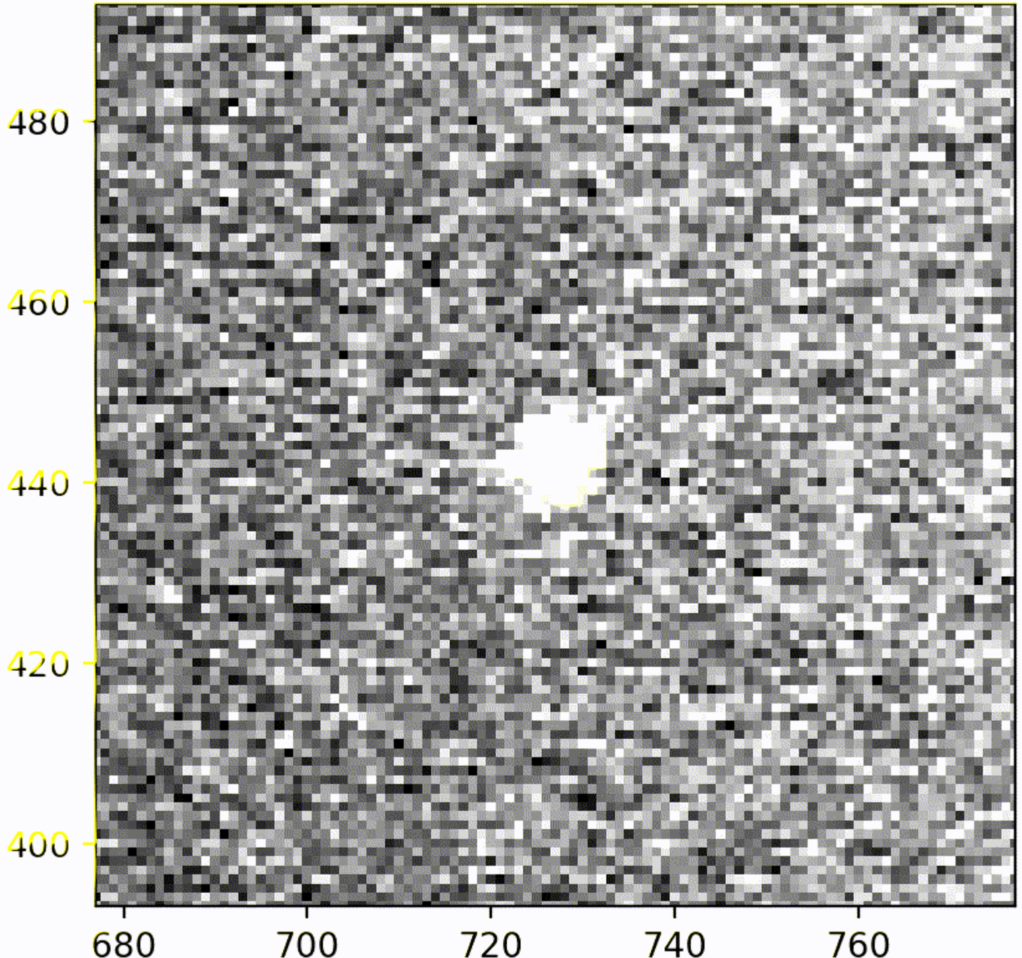
Some things to think about for SDSS-V

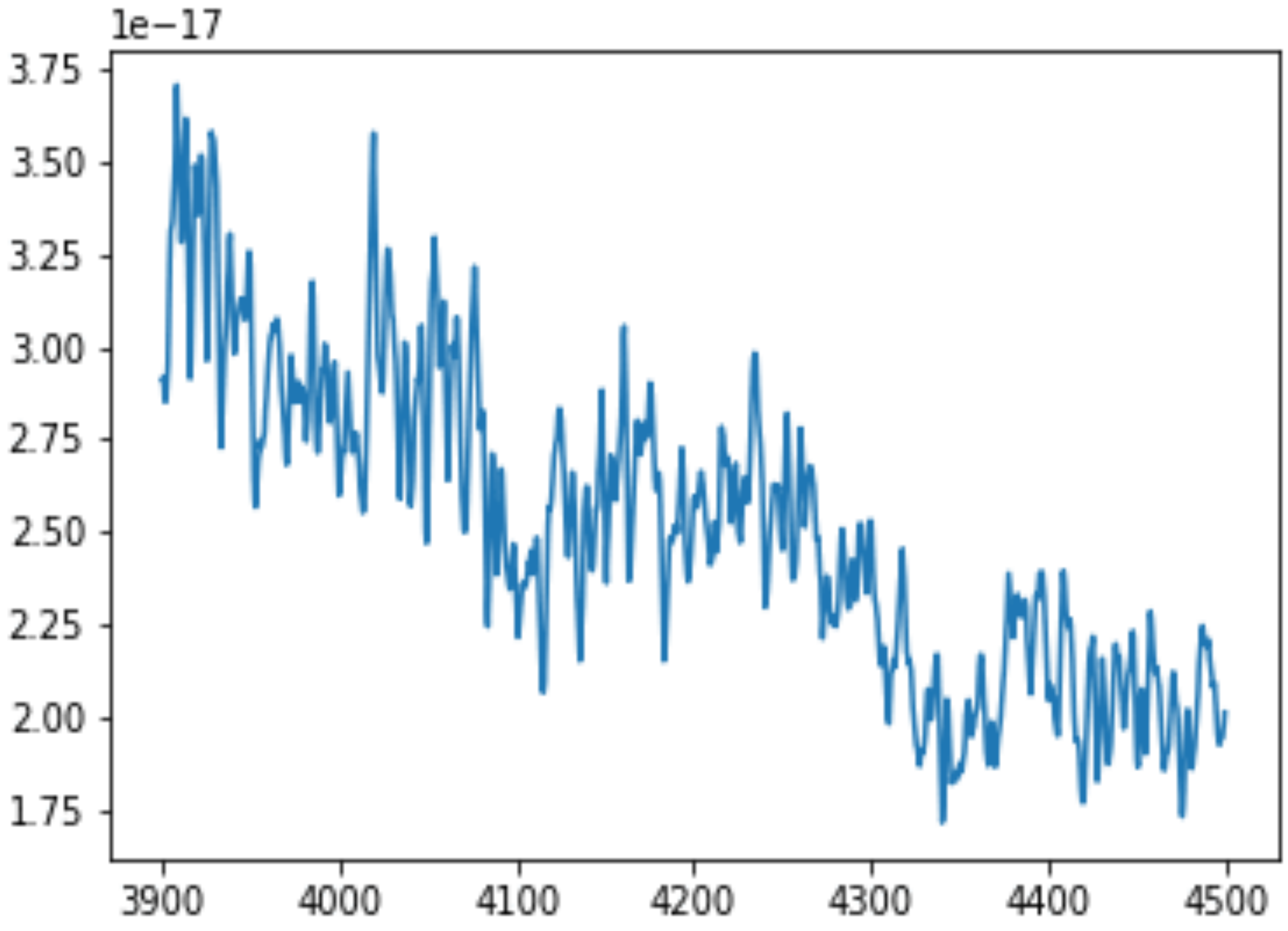
- What temporal resolution will exposure times let us get to?
- How easy will it be to search the time resolved spectra for signatures of Doppler shits (and what is the best method for quickly determining RVs for millions of spectra)?
- Could changing measured Teff/log(g) be used as an alternative to an RV search for double lined systems?
- For eclipsing systems in ZTF, phase is well determined, so RVs could be strategically acquired at max blueshift/redshift?

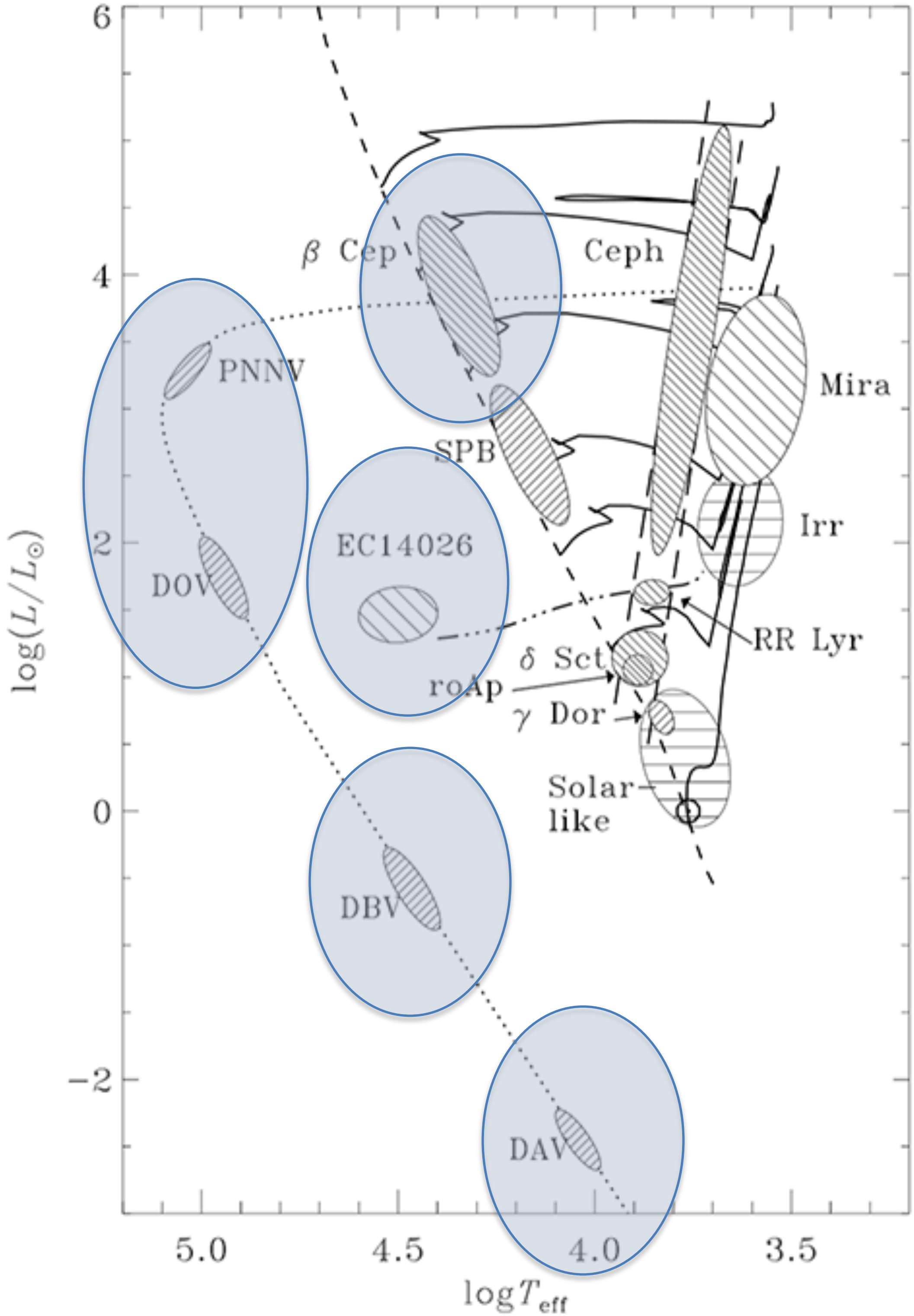

0
25
50
75
100
125
150
175
0
10
20
30
40

Photometry

Spectroscopy

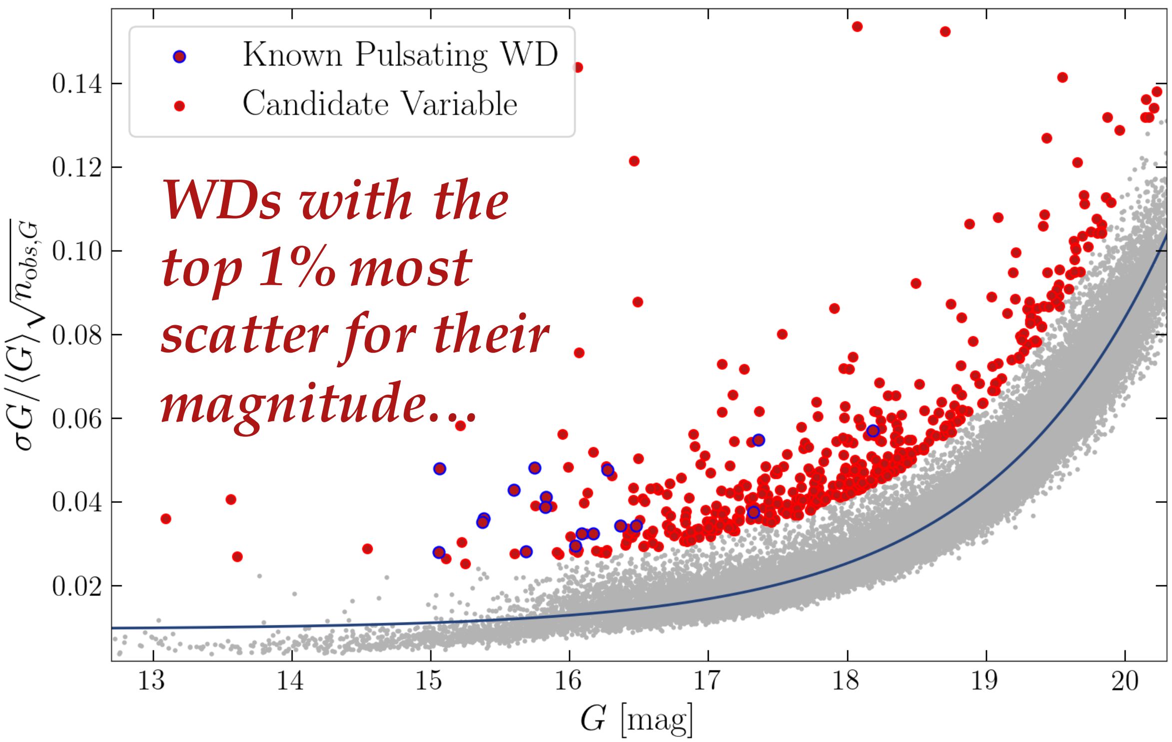






All Other (**Hot**) Pulsators:

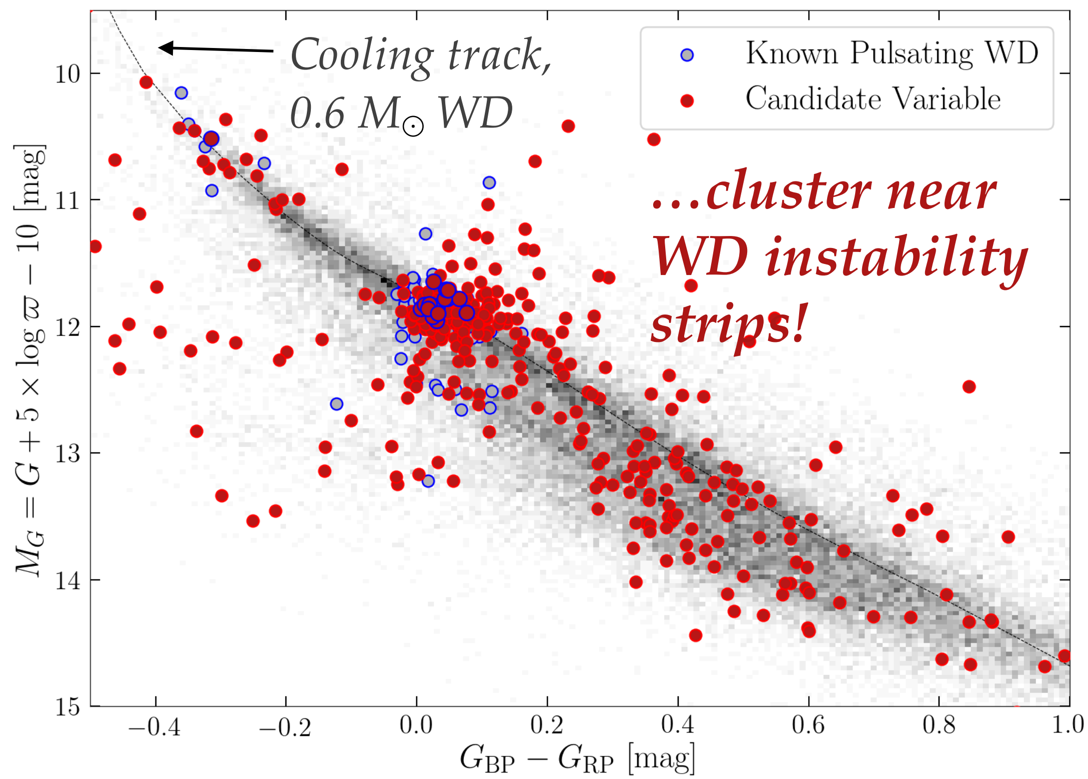
ZTF + SDSS



Let's Start with the Isolated White Dwarfs

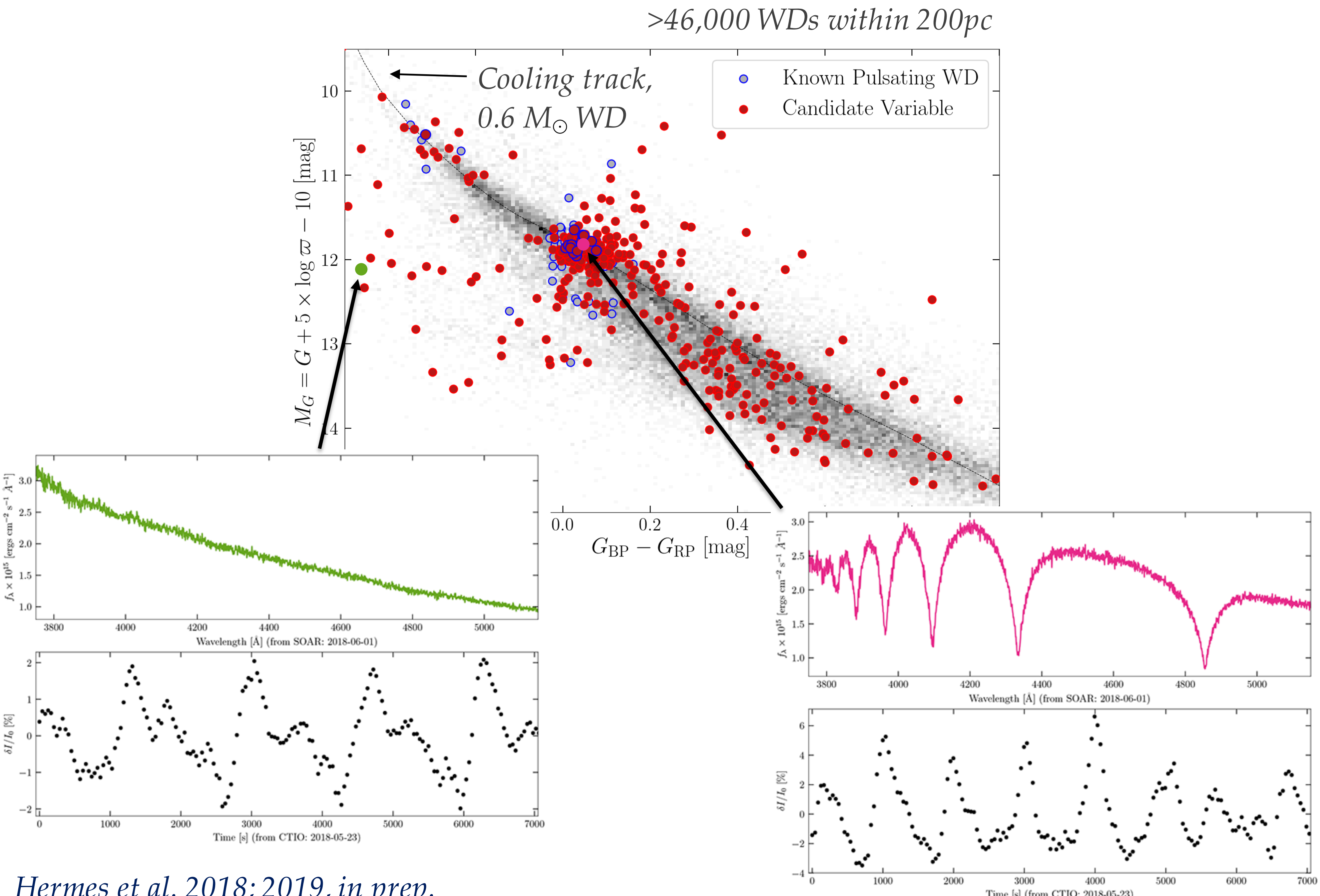
>46,000 WDs within 200pc

Gaia Empirical Uncertainties as a Proxy for Variability



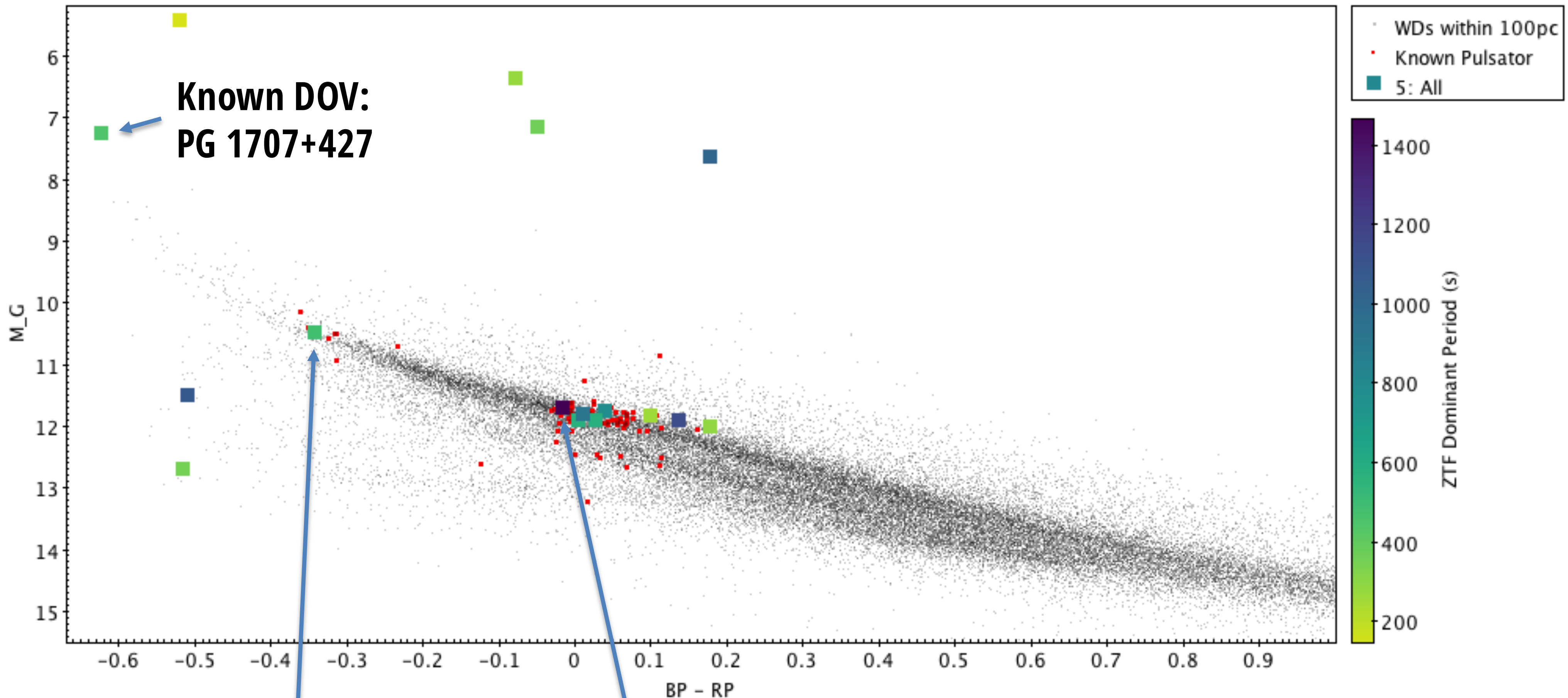
Hermes et al. 2018; 2019, in prep.

Spectra Reveal Whether WD is Pulsating or a Spot Rotator



Hermes et al. 2018; 2019, in prep.

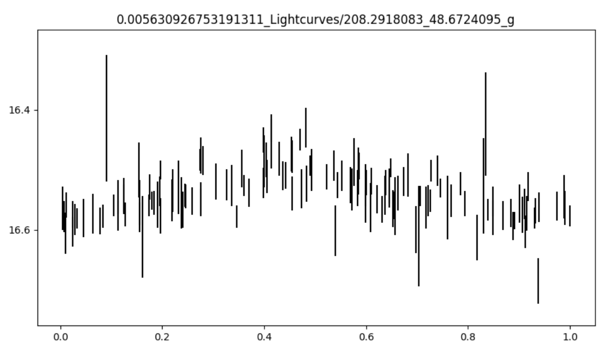
New 3-20 min, blue candidate variables in ZTF

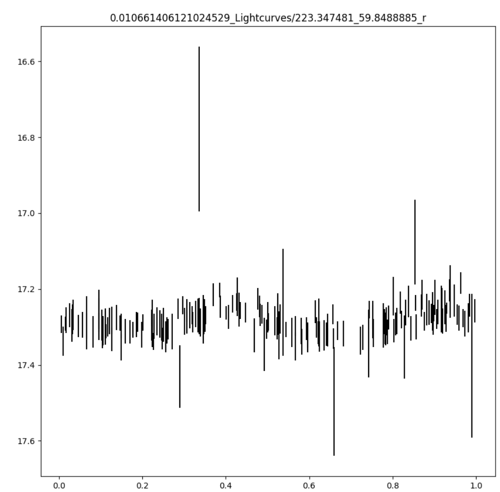


Known DOV:
PG 1707+427

Known DBV:
WD 1351+489

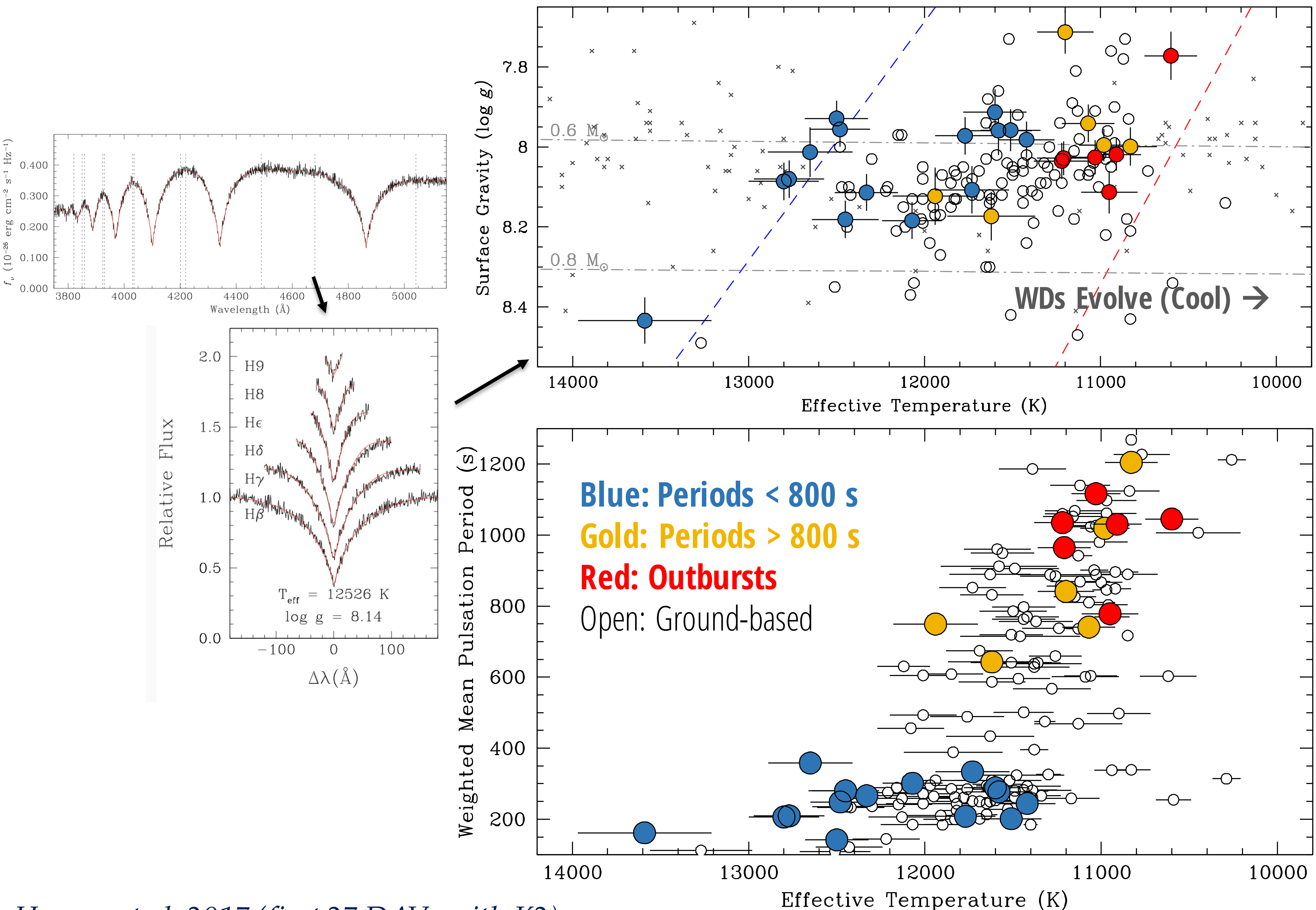
Known DAV:
WD 1452+600





Candidates from
Kevin Burdge

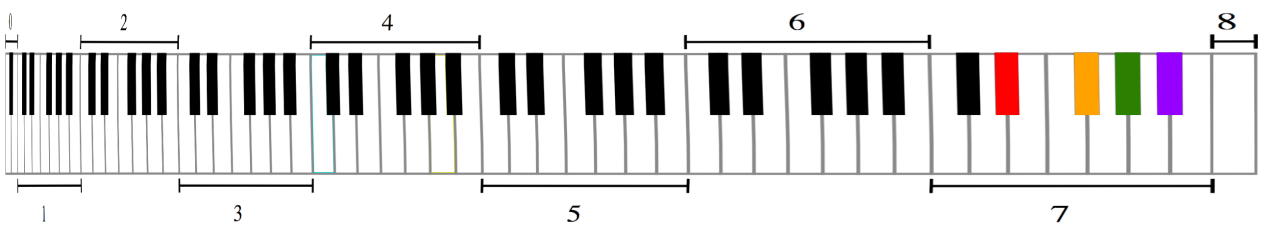
Spectroscopy of DAs (H atm.) Yield Atmospheric Params.

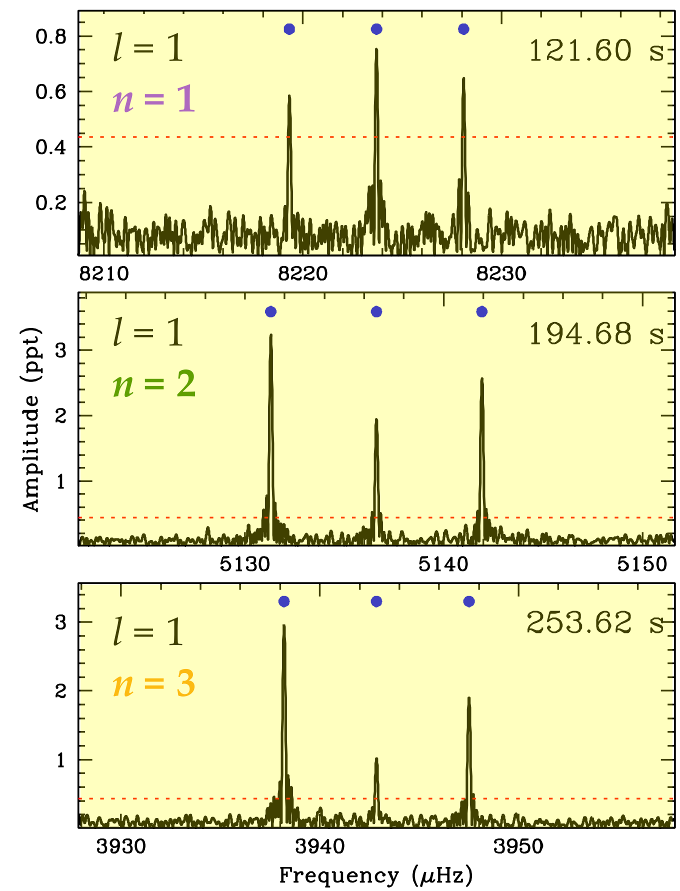


Hermes et al. 2017 (first 27 DAVs with K2)

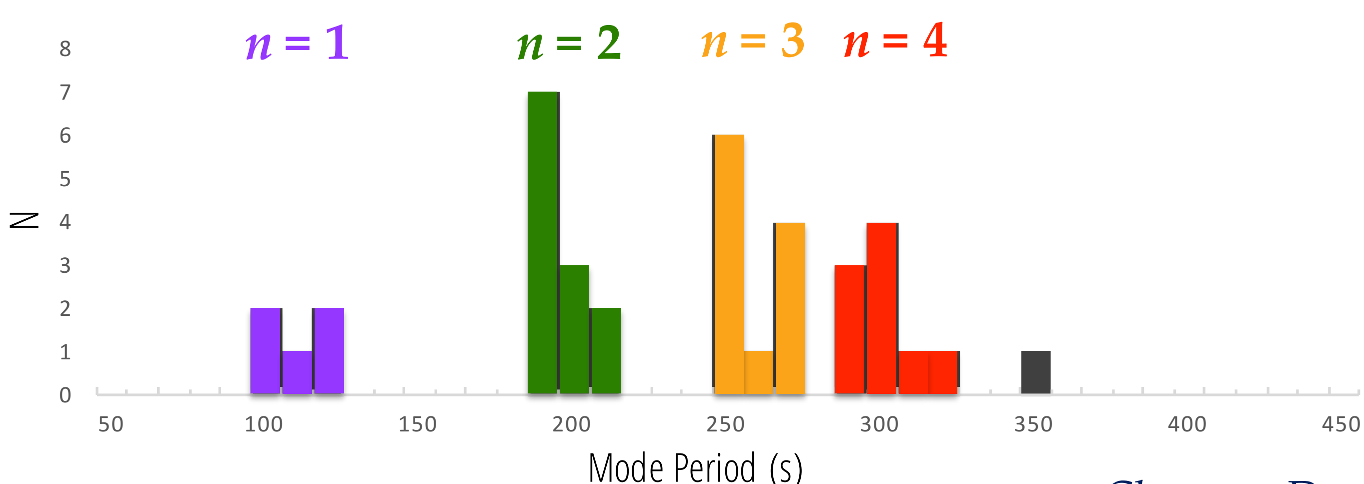
An experiment in ensemble asteroseismology with ZTF

Kepler made mode identification relatively trivial





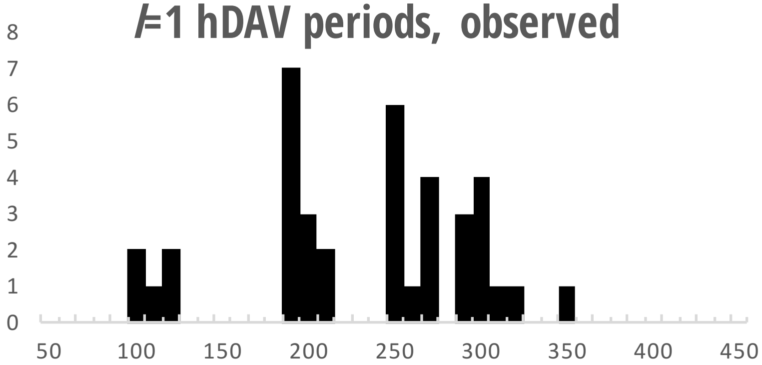
If we only plot identified l=1 (m=0) modes:



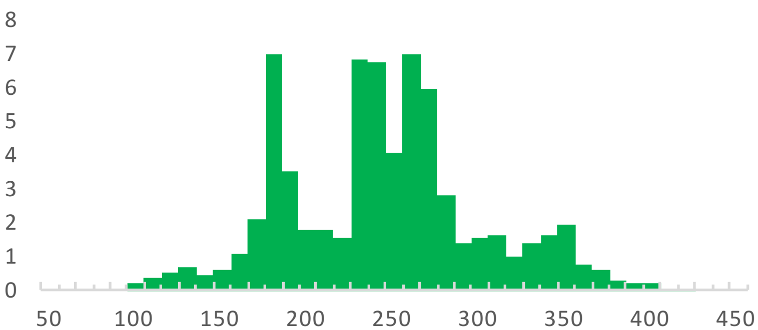
Clemens, Dunlap, Hermes et al. 2019, in prep.

An experiment in ensemble asteroseismology with ZTF

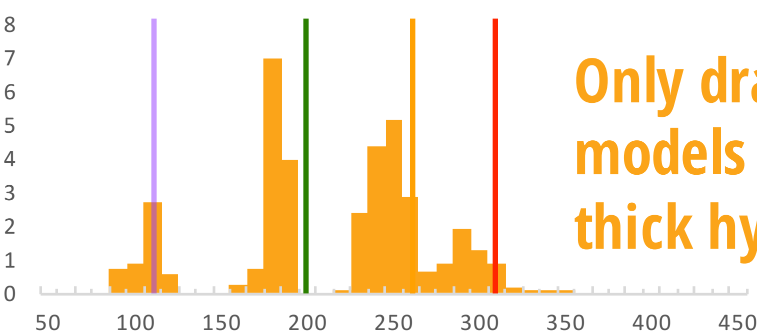
ℓ=1 hDAV periods, observed

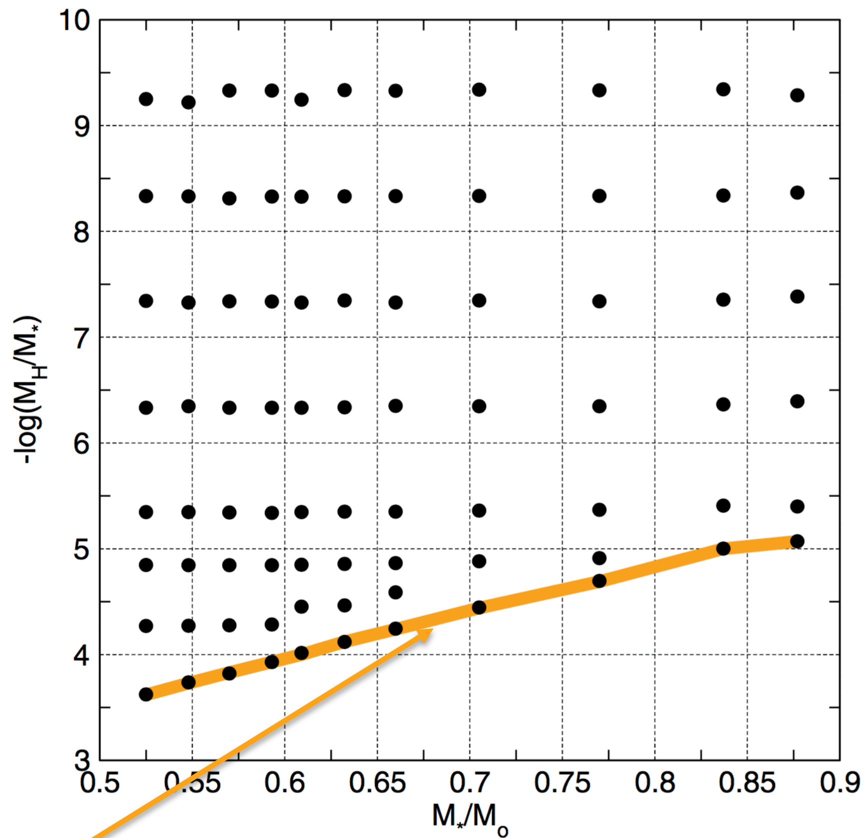


ℓ=1 random M_H simulation



ℓ=1 canonical M_H simulation



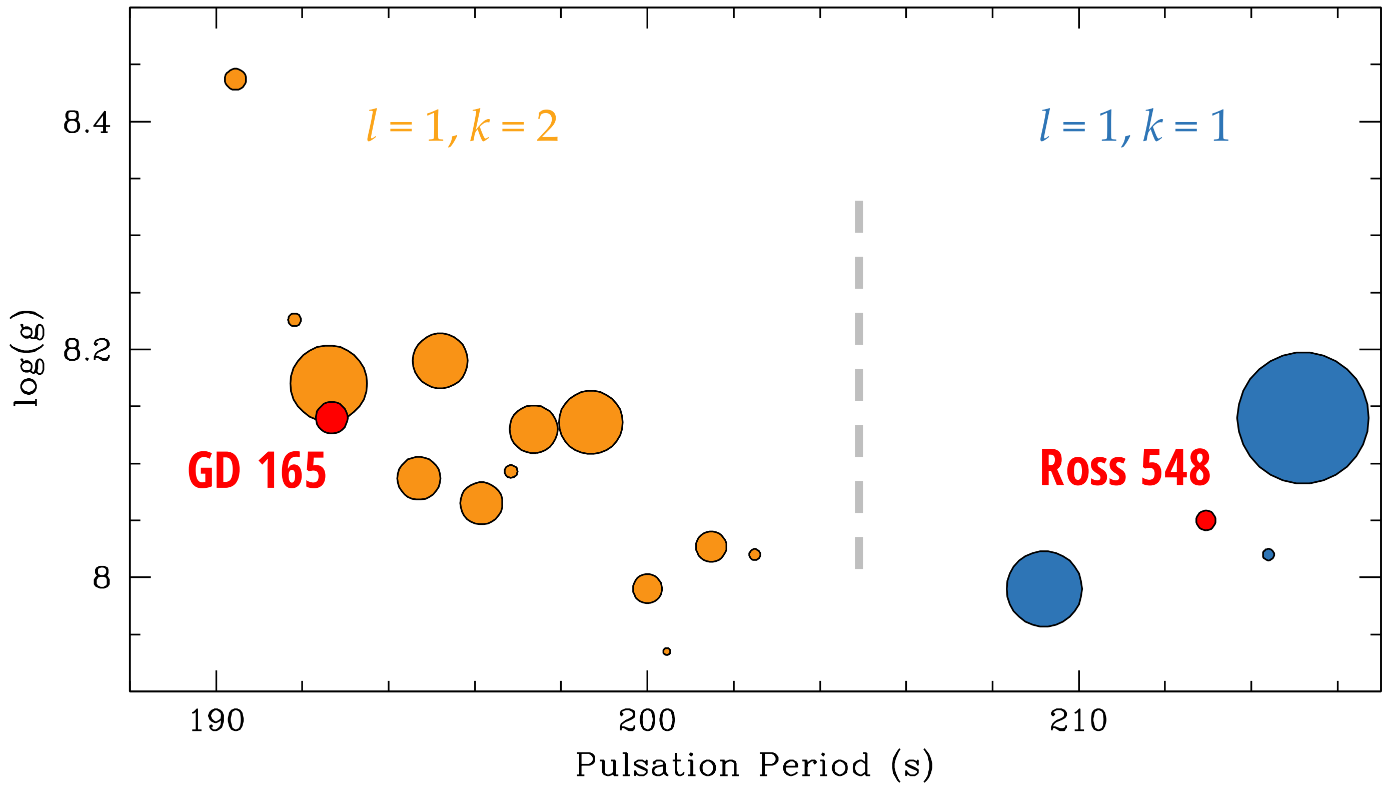


Full evolutionary models computed by ***Romero et al. 2012***

Only drawing from the models with canonically thick hydrogen layers

Clemens, Dunlap, Hermes et al. 2019, in prep.

An experiment in ensemble asteroseismology with ZTF



size = amplitude of mode

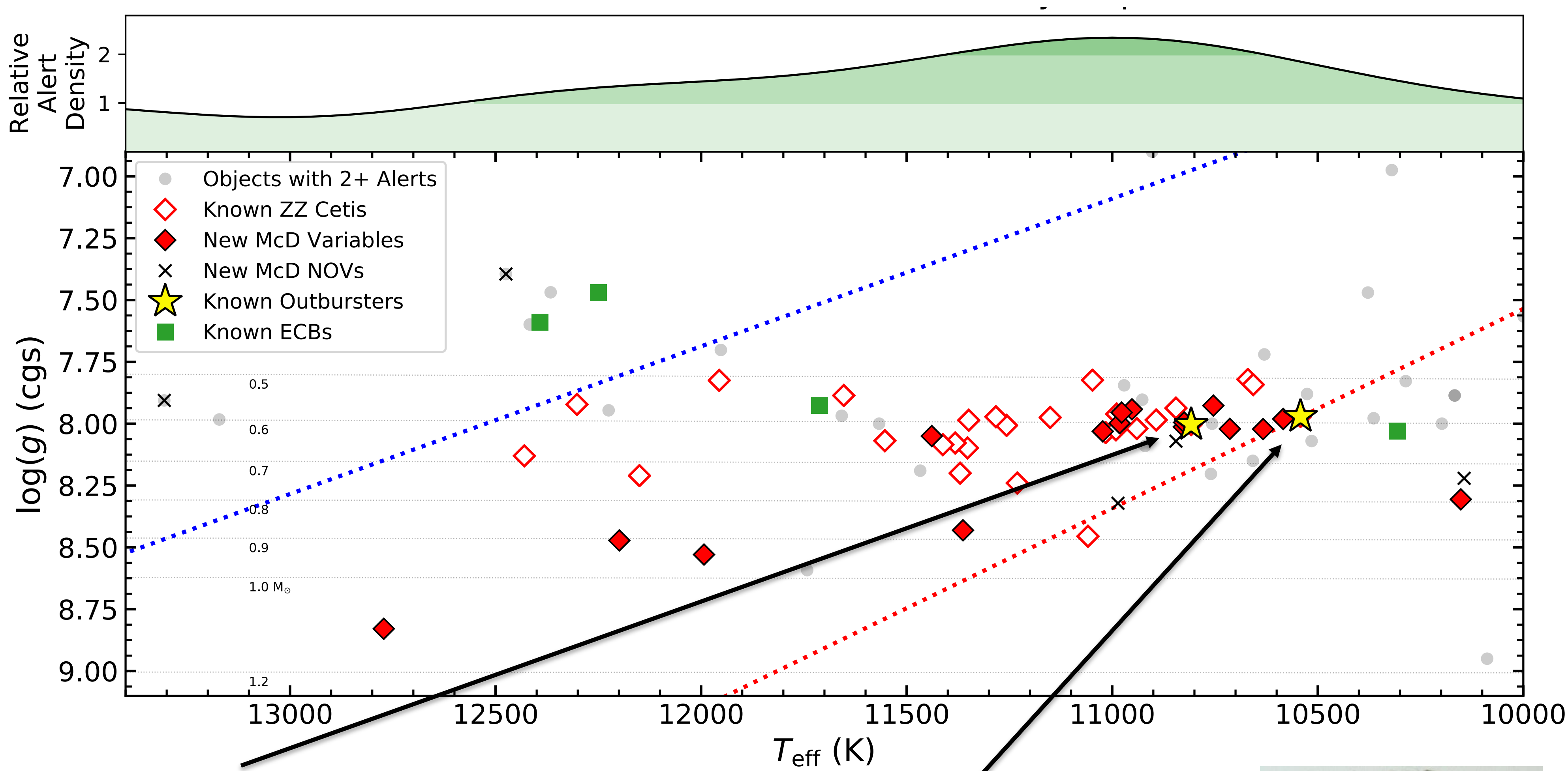
Thick H Layer: ~10^{-4} $M_H/M_\star$
He Layer: ~$10^{-1.7}$ $M_{He}/M_\star$
"Canonical" nuclear burning sets envelope masses

Thin H Layer: <10^{-7} $M_H/M_\star$
~He Layer: $10^{-2.9}$ $M_{He}/M_\star$
Very late thermal pulses?

GD 165 & R548 from Giammichele et al. 2016

Clemens, Dunlap, Hermes et al. 2019, in prep.

Overdensity of ZTF Alerts Near Outbursting White Dwarfs

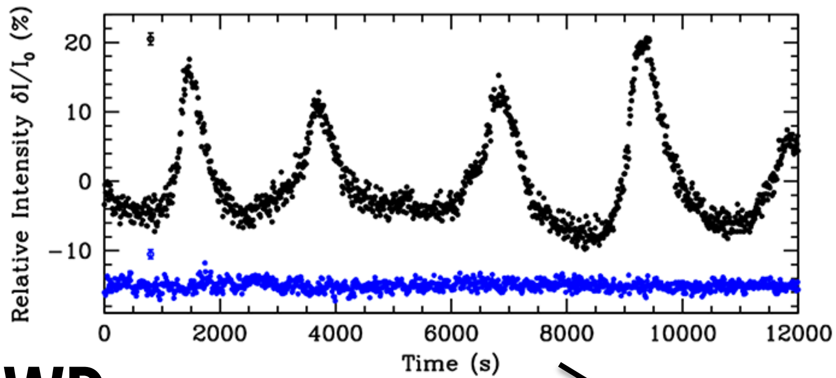


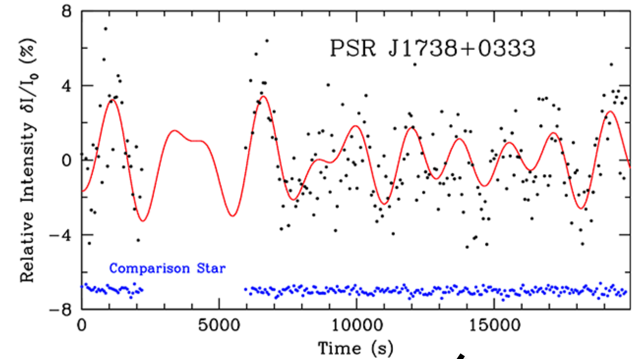
GD1212 (g=13.2 mag):
2 low-RB ZTF alerts

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

courtesy Zachary Vanderbosch (UT-Austin)

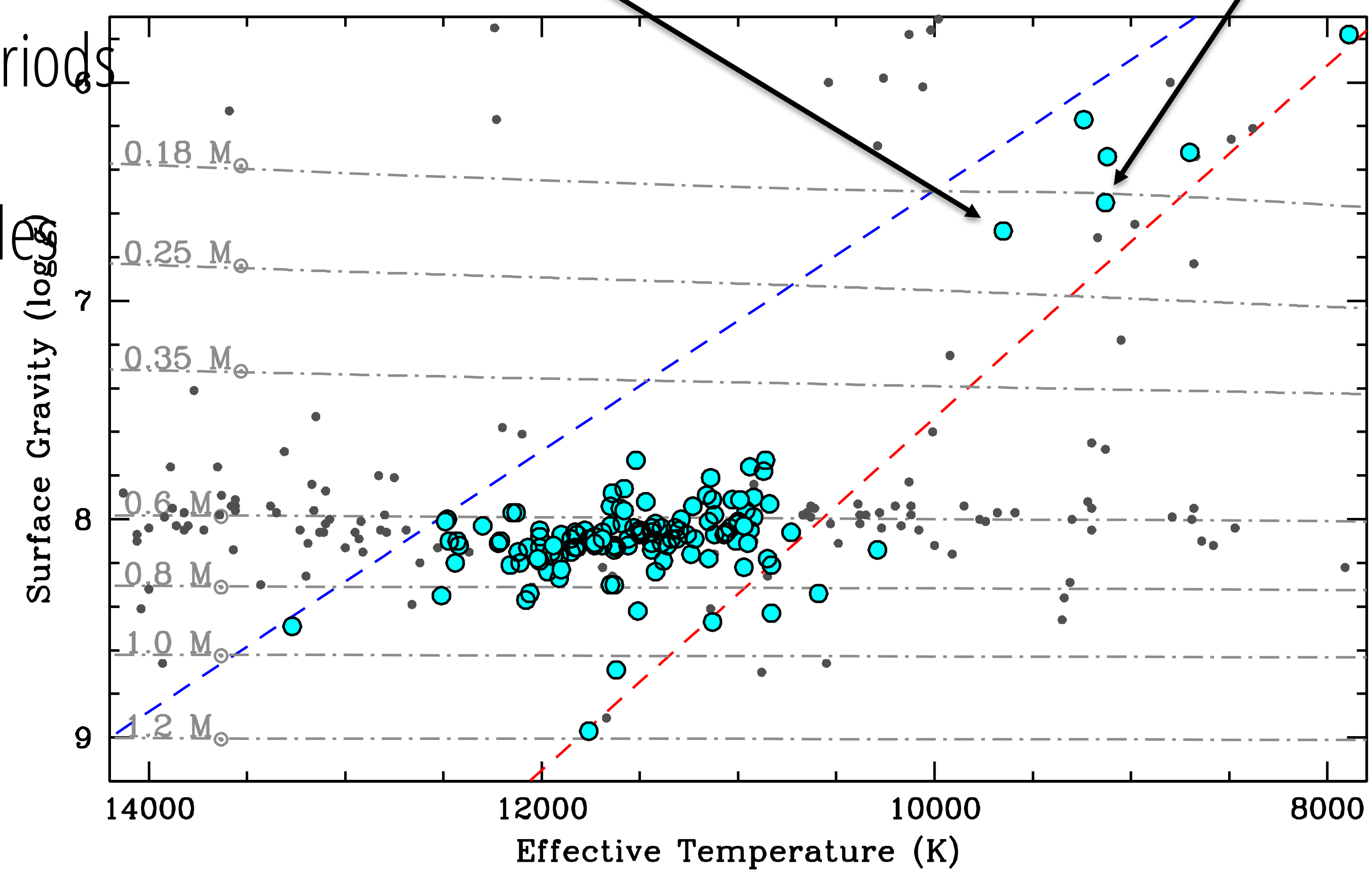
Pulsations in He-Core, ELM WDs: Binary White Dwarfs





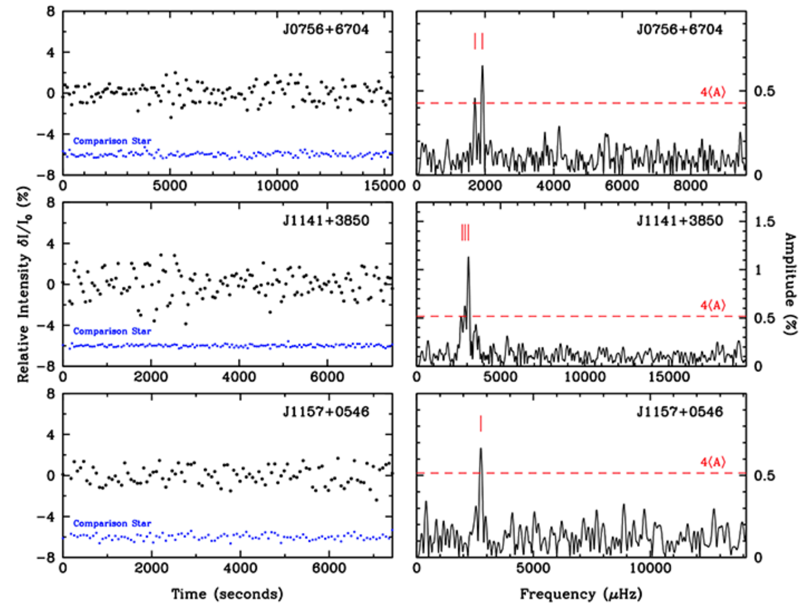
He-core ELM WDs:

1000-4000 s periods
(g-modes)
1-20% amplitudes
9-10.5 kK
log(g) ~ 6.5



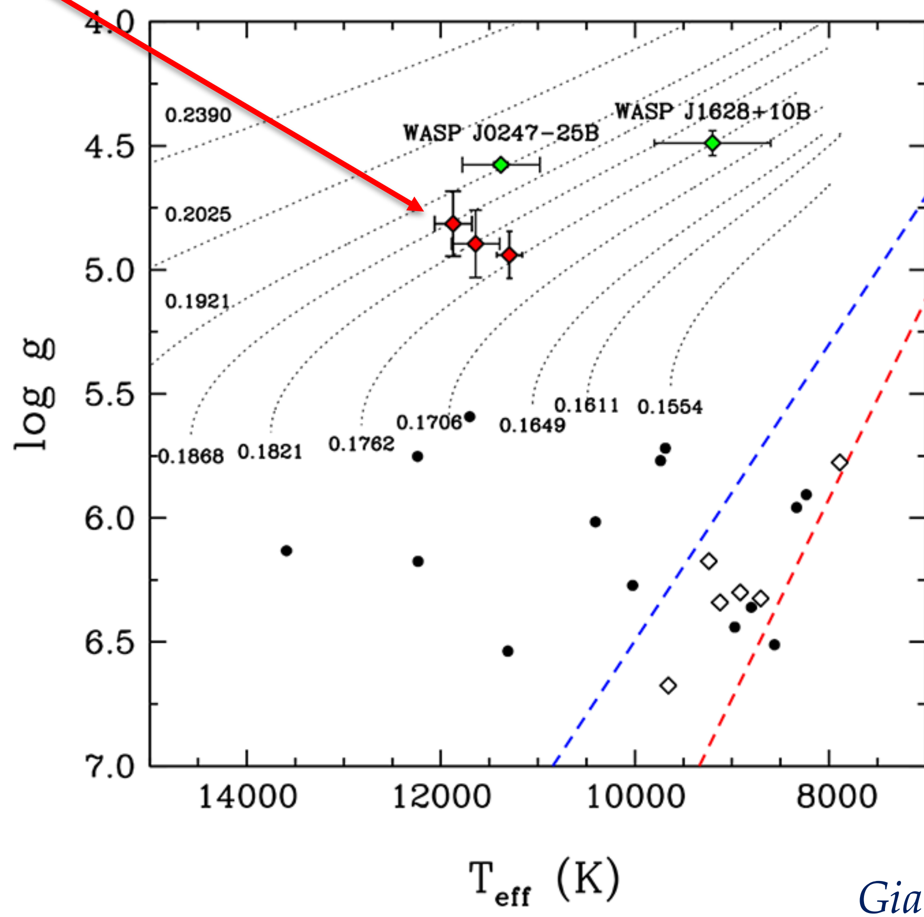
Hermes et al. 2013; Kilic et al. 2015

Pulsations in Pre-He-core WDs



Pre-He-core ELM WDs:

320-600 s periods
(p-modes)
0.5-1.2% amplitudes
11-12 kK
log(g) ~ 5.0

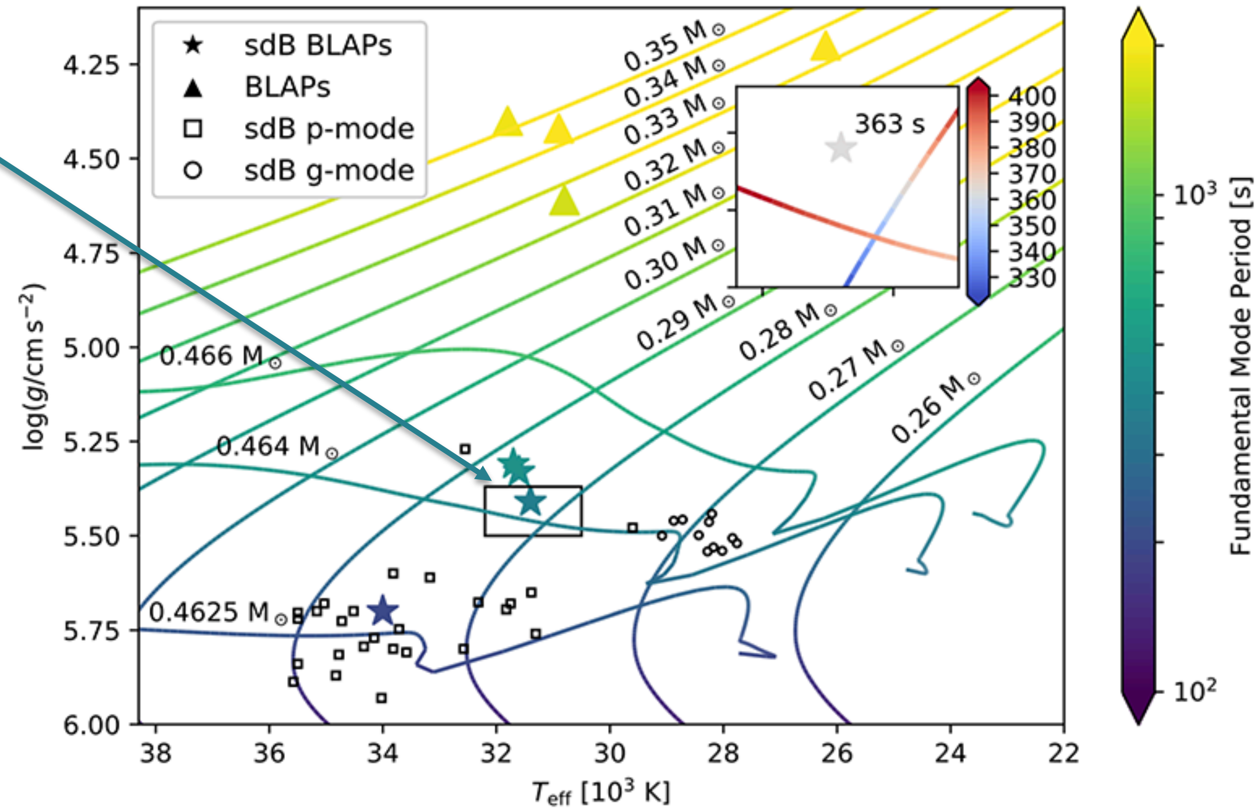


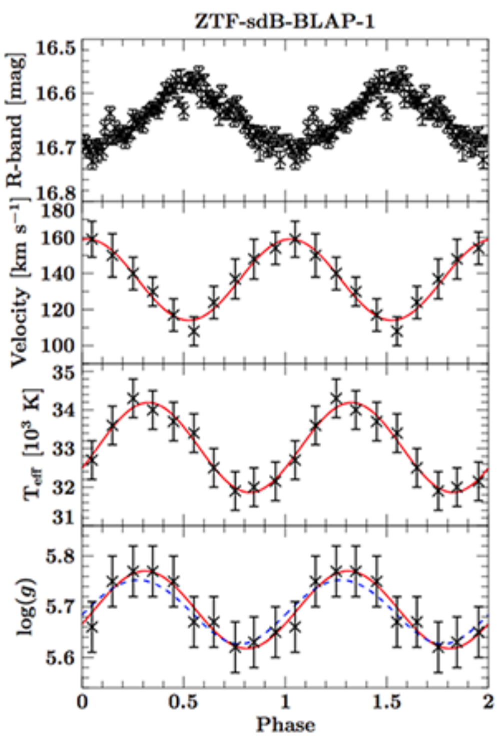
Gianninas et al. 2016

Pulsations in Pre-Pre-He-core(?) WDs

Pre-Pre-He-core ELM WDs (high-gravity BLAPs):

200-500 s periods
(radial modes)
5-15% amplitudes
30-34 kK
log(g) ~ 5.5





Kupfer et al. 2019, in prep.

Pulsations in Pre-Pre-Pre-He-core(?!) WDs

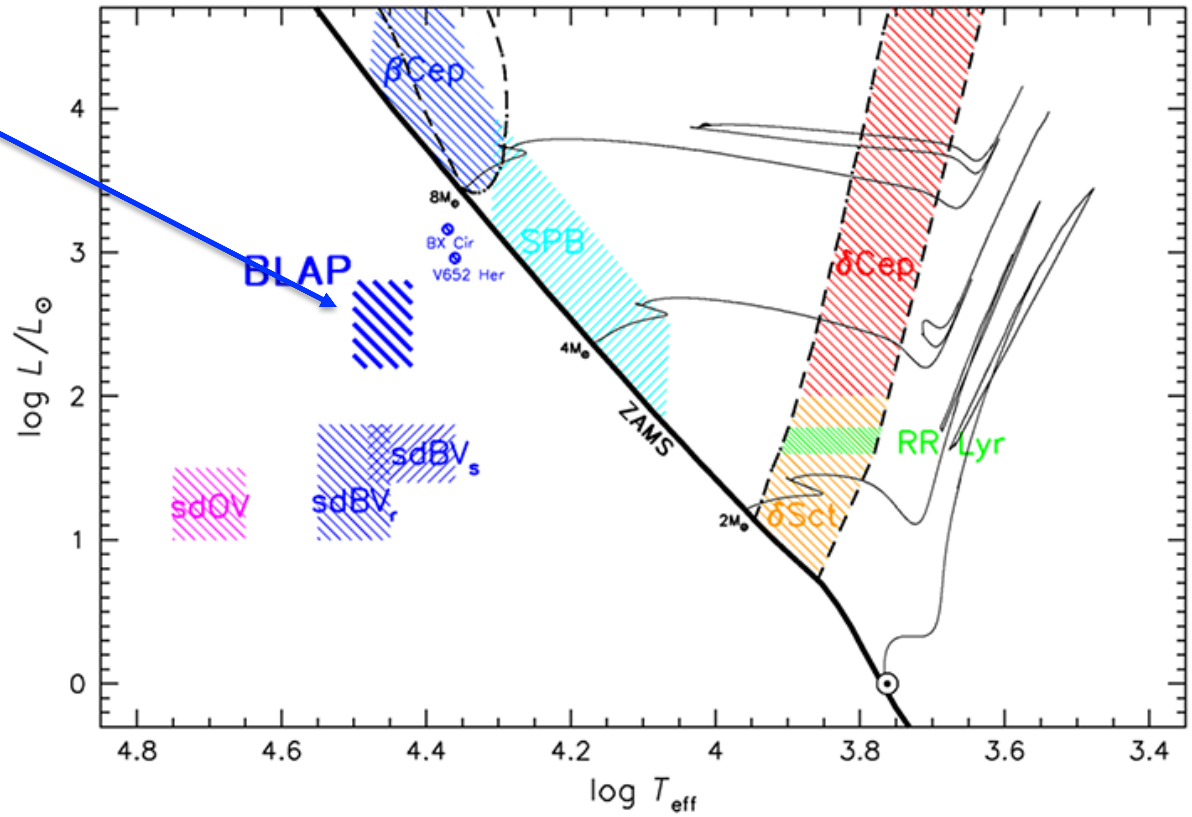
BLAPs (Blue Large-Amplitude Pulsators):

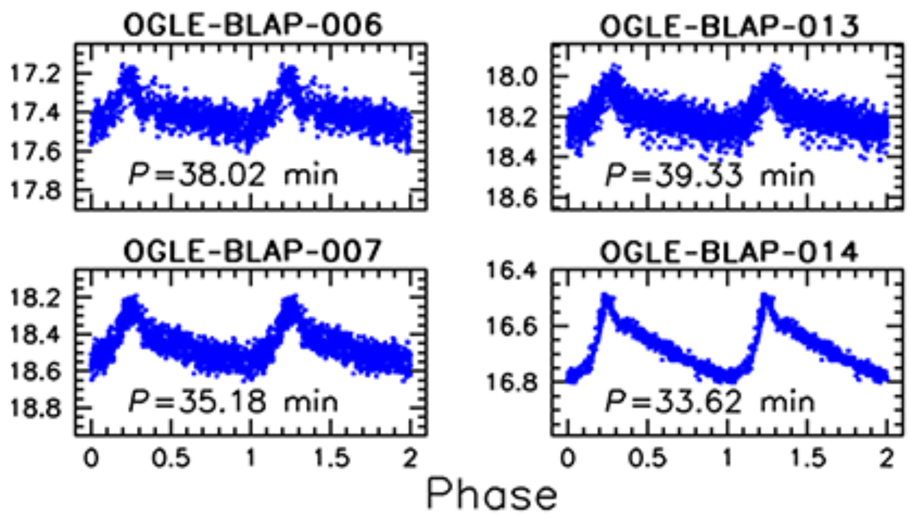
20-40 min periods (radial modes)

20-40% amplitudes

26-32 kK

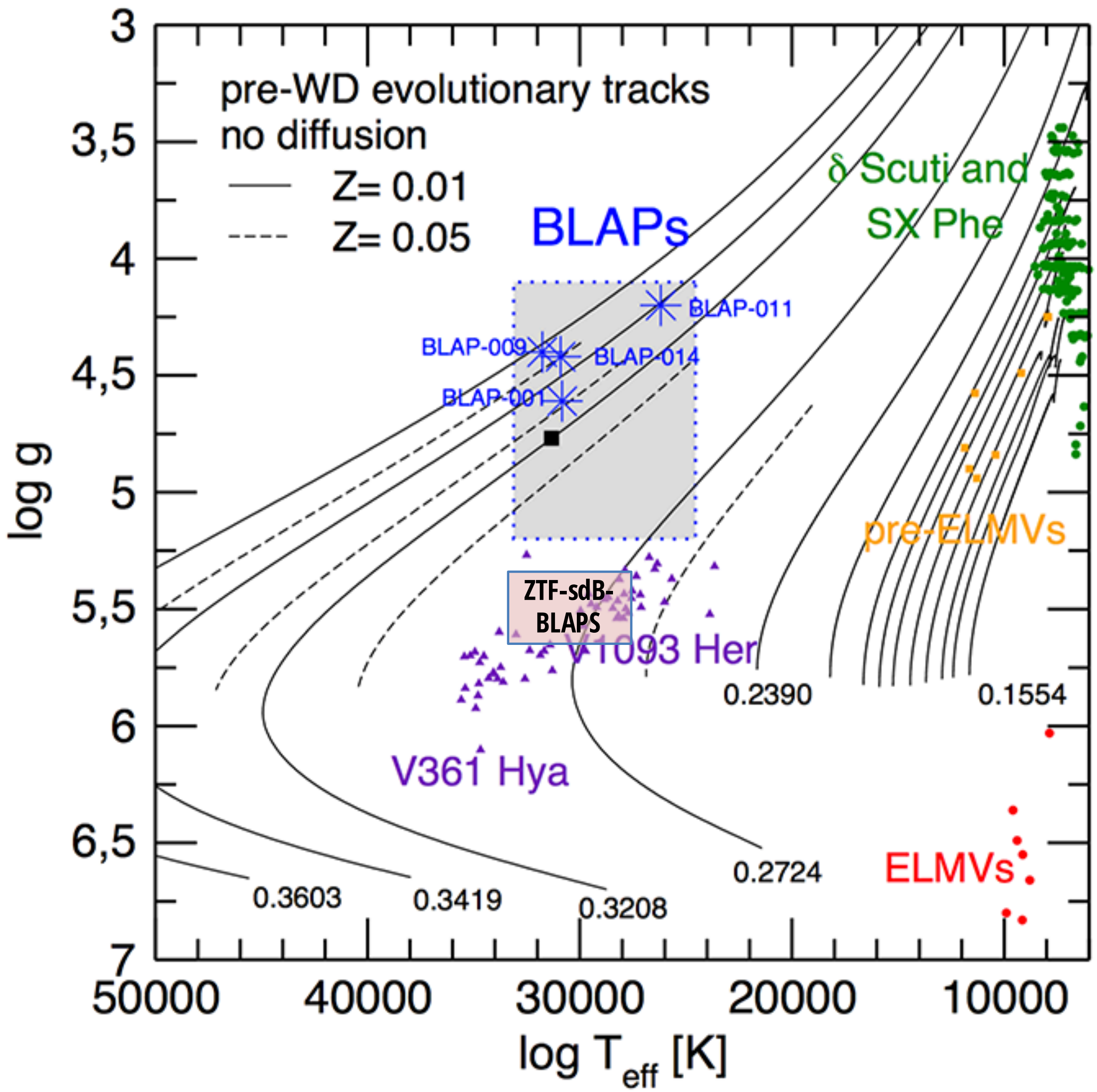
log(g) ~ 4.5



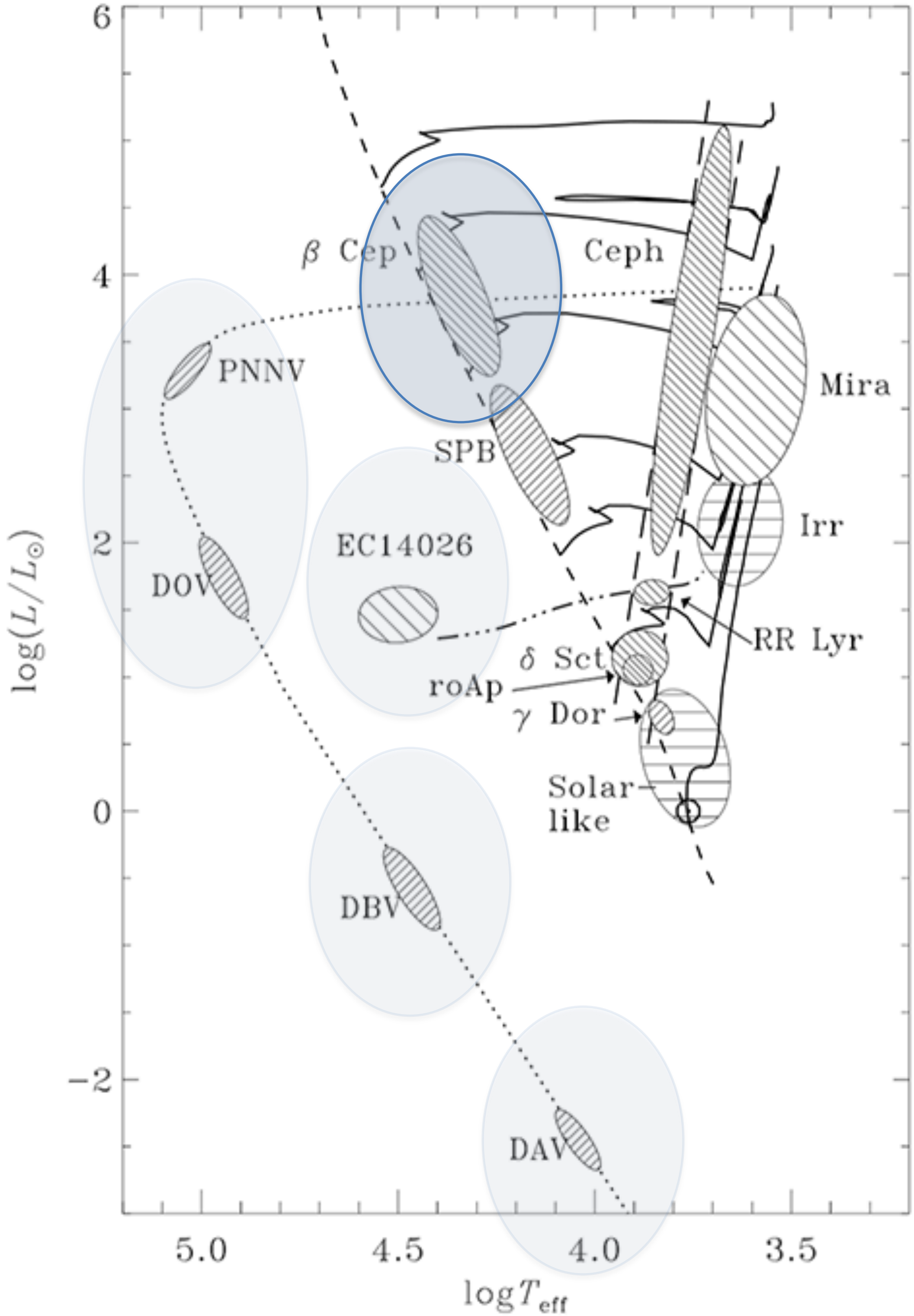


Pietrukowicz et al. 2017

ZTF + SDSS-V can help clean up our picture of exotic binary evolution!



Romero et al. 2018



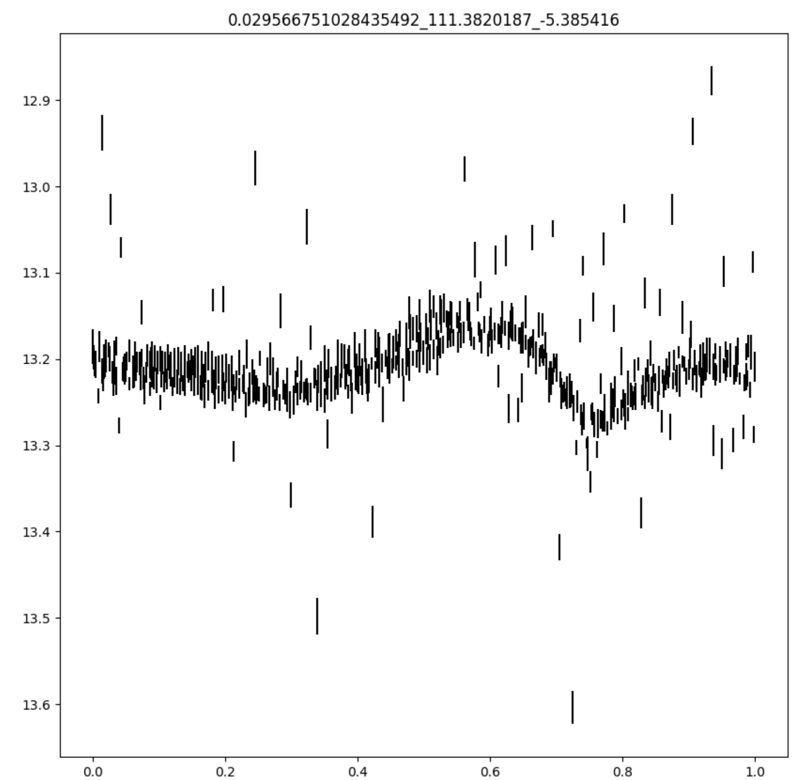
Beta Cep pulsators:

0.5-8 hr periods

(p-modes)

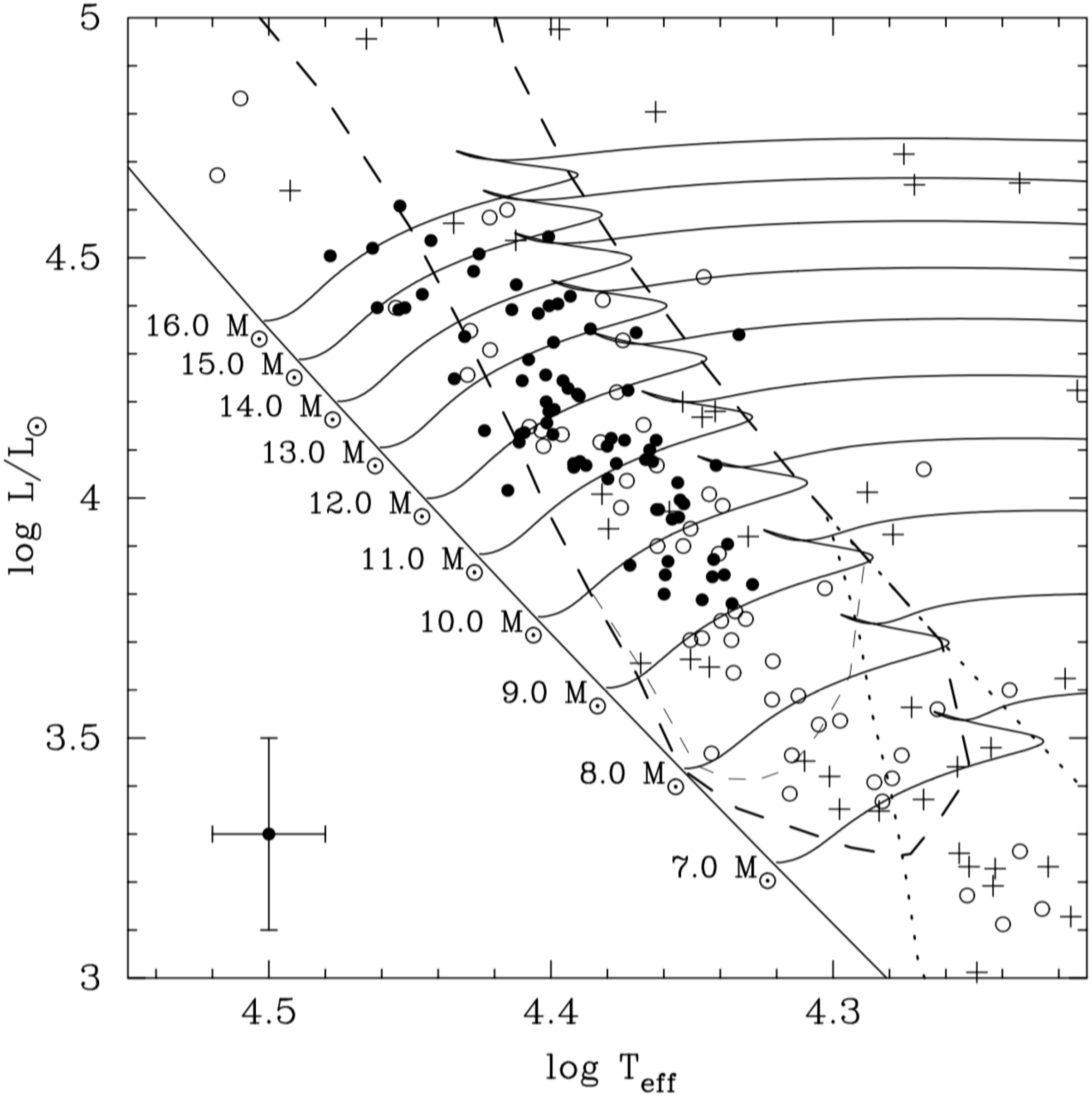
0.01-0.3 mag amplitudes

B0-B2 (8-18 Msun)



(0.7 hr)

Beta Cep instability strip (Fe bump driving)



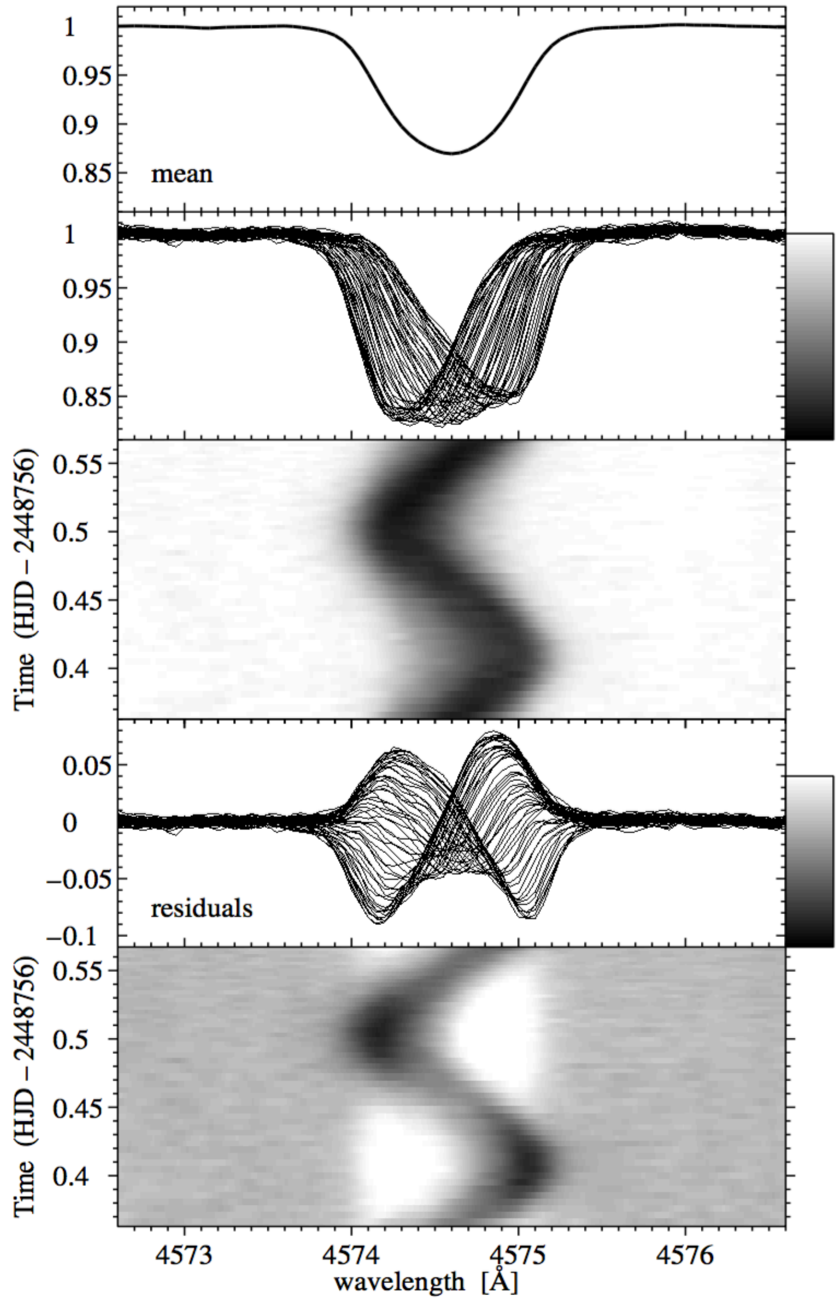
Filled Circle: Confirmed

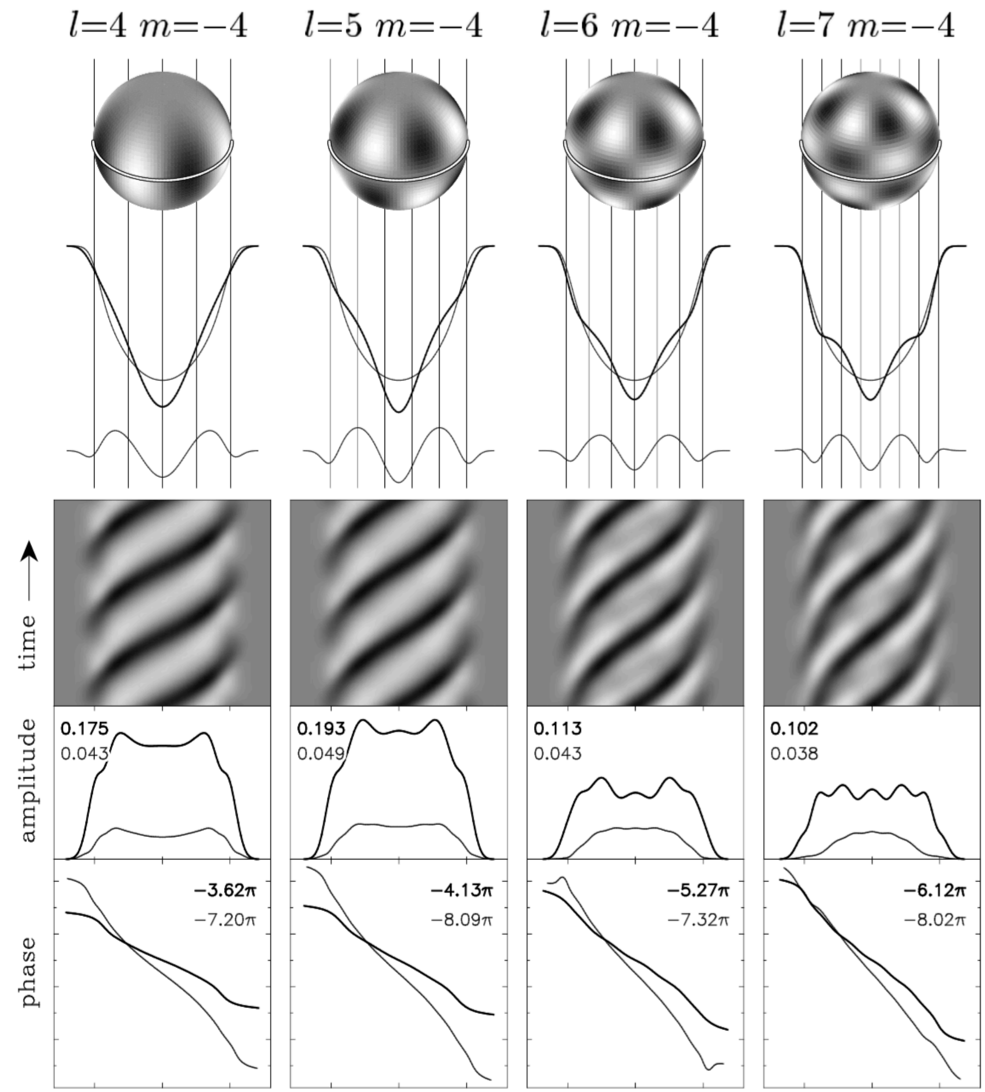
Open Circle: Candidate

Plus Sign: Rejected

Stankov & Handler 2005

Beta Cep line-profile variations: mode identification





Telting, Aerts & Mathias 1997

Telting & Schrijvers 1997

Interlopers

Eran Ofek
Weizmann Institute of Science

Based on the work of **Boaz Katz**

With: Boaz Katz, Subo Dong, Doron Kushnir

Outline

- The rate of interlopers
- Comets & meteors with hyperbolic orbits
- A/2017U1 (‘Oumuamua)
- “unique” properties
- Origin: interstellar or Solar System?
  - C/1857A1 and other beasts
- Conclusions

The rate of interlopers

- Many orders of magnitude Uncertainty
  - stellar density $n^{*}\sim 0.1\ pc^{-3}$
  - Assuming $n_{oort}=10^{12}$ objects >1 km in Oort cloud
  - Assuming size distribution with PL index of $\alpha=-4$
  - Assuming $\varepsilon=0.03$ efficiency
  - Assuming can detect 100m comets a=0.3 AU from sun:
  - V=6.28 AU/yr
  - Uncertain detection efficiency (e.g., comet activity)
- $n^{*} \times n_{oort}/\varepsilon \times (0.1/1)^{-a} \times \pi a^{2} \times V \sim 10^{-3}$–1/yr

Where are they

- There are comets with $e>1$
- There are reports on meteors with $e>1$

Comets with e>1

- There are 4 comets with e>1.01 (1.016, 1.028, 1.058, 1.201) - however 1838 with e=1 (many with poorly estimated e)
- Most notably A/2017U1 (‘Oumuamua)

A/2017U1 (‘Oumuamua)

- Some claim rate too high
- Velocity near LSR (but 10s km/s)
- Variability amplitude larger than any asteroid or comet
- High Albedo?
- Non-grav. Forces?, but no activity

Meteros

- There are many meteors with e>1
- Weigert (2014) estimate that 10^{-4} meteors will have apparent e>1, but due to scattering (mainly be Mercury).
- Observed rate of e>1 meteors is $<10^{-3}$ of bound meteors
- Many examples in the literature: e.g., Kolomiyets 2014 + Guliyev 2014 + …
- See recent example in Siraj & Loeb (2019)
- Estimated density 10^{21} pc-3
- Extrapolating from Oort cloud α~3

Meteros

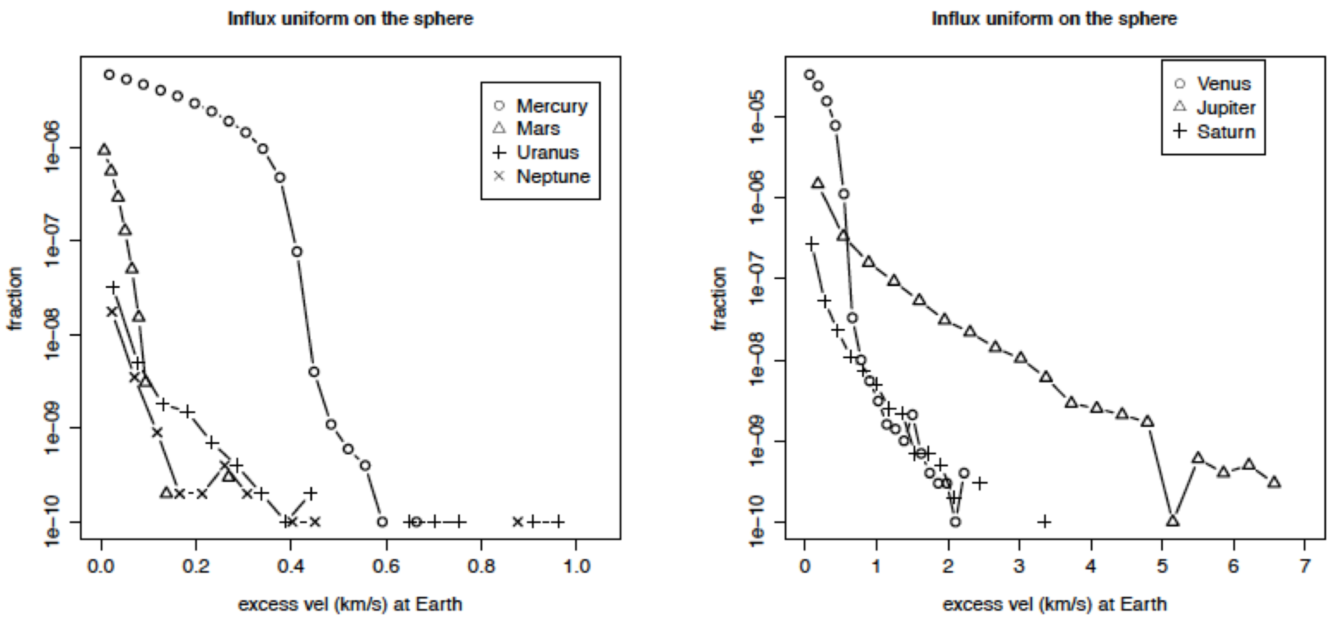
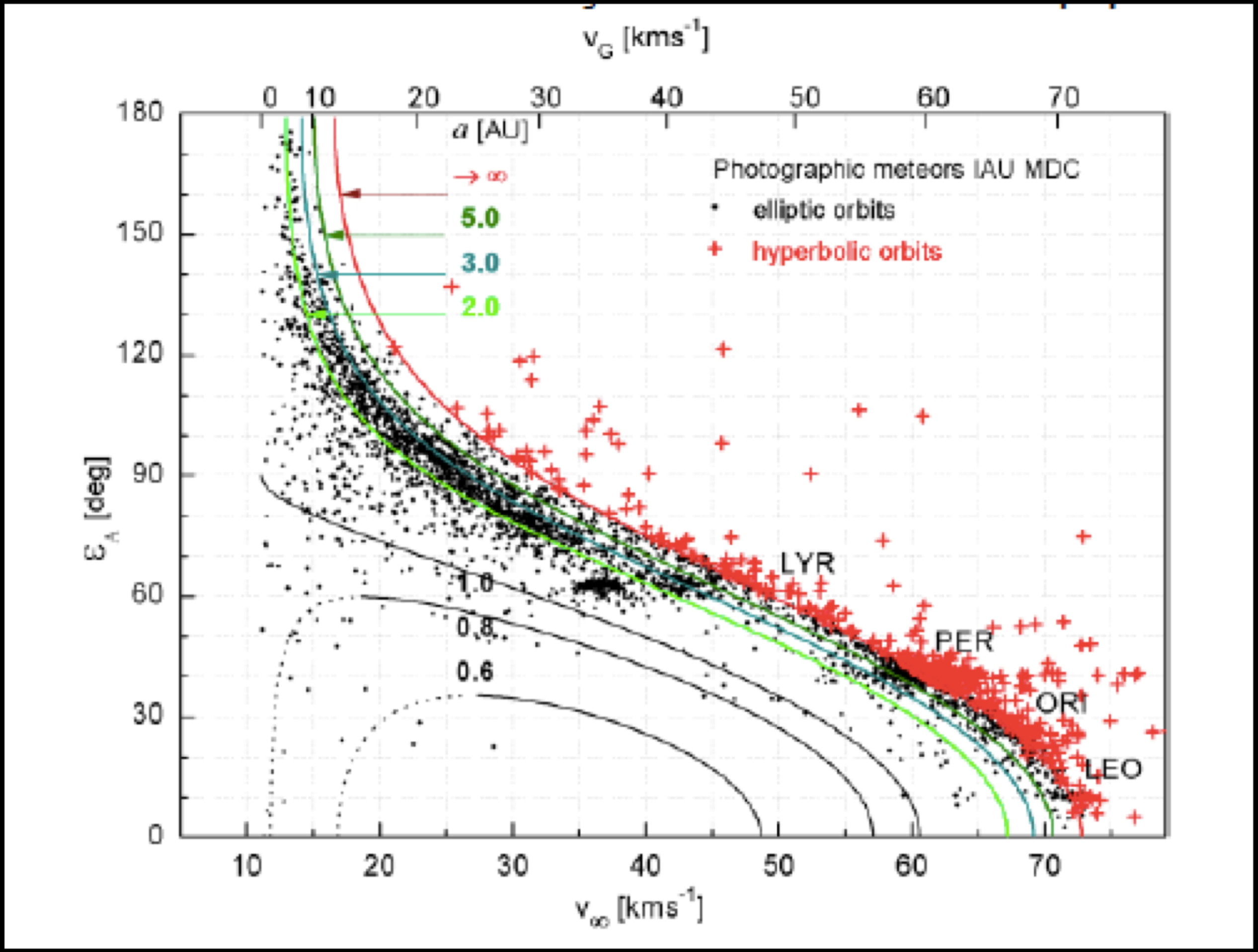
- There are many meteors with e>1
- 

Fig. 2.— The excess velocity with which a meteoroid reaches the Earth's orbit in the case of the planet being uniformly bombarded by particles from all directions.

Weigert 2014

Meteros

- There are many meteors with e>1
-



Hujdukova+2018

Meteros

- Guliyev 2014 (conf. abstract) - analyzed 238 hyperbolic meteors. Claims that their perihelia concentrated near the anto Apex of the Sun.

Meteros - conclusion

- Most reports are likely due to inaccurate orbit determination.
- Requires new surveys and data

The case of A2017U1

- $e=1.26$, $v_{inf}=26$ km/s
- weird properties:
-
- The community assumes it is interstellar

Is A2017U1 interstellar?

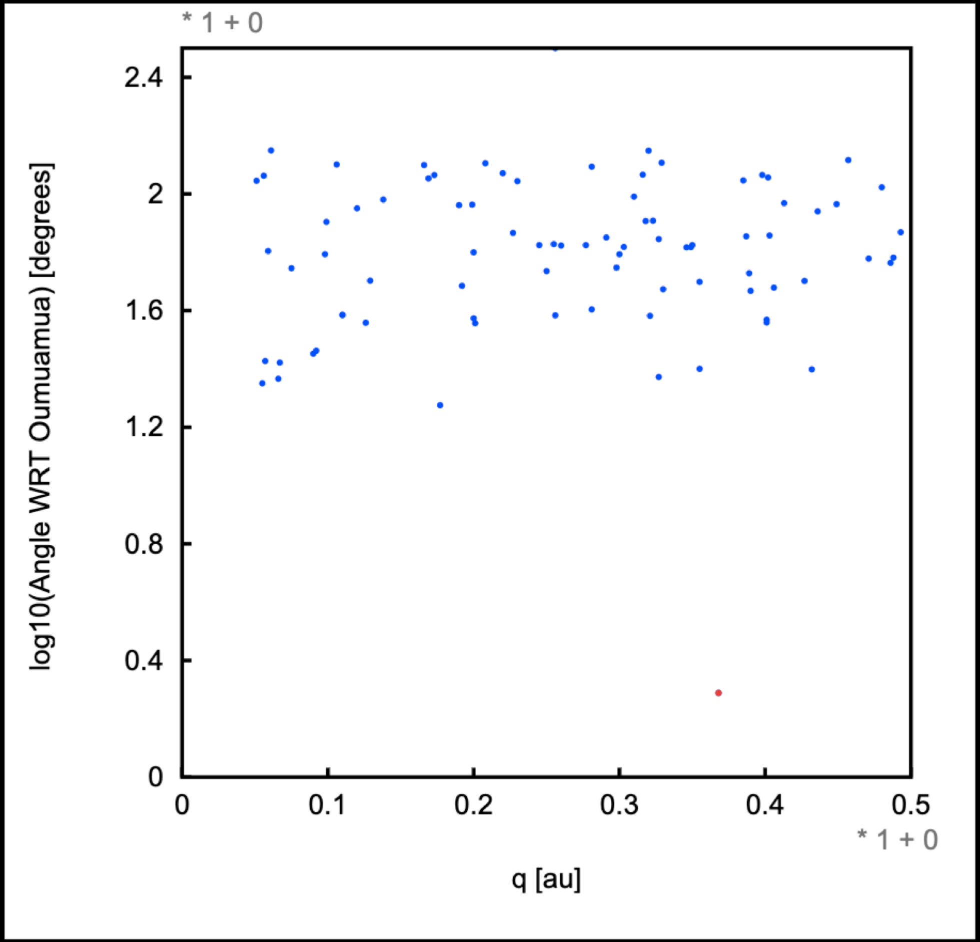
- v_{inf}=26 km/s BUT near perihelion only 5 km/s!
- If meteorites arrived from Mars than 5km/s kick is possible
- Comets passing <0.3 AU from the Sun tend to explode!
- A2017U1 can be result of asteroid collision (less likely)
- or debris from exploding comet

Exploding/evaporating comets

- C1882 R1 (q=0.003); C1999 S4 (q=0.76); C1975V1 (q=0.20); ...
- Its common to comets passing q<0.3 AU from the Sun to breakup/evaporate/explode
- Can such a fragment explain A2017U1?
  - explosion can explain velocity
  - high albedo
  - shape and hence variability amplitude

Looking for candidates

- Change in orbit of C/2017 S3



Looking for candidates

- The case of 1857A1 (B. Katz)

Name	q	i	Ω	H
C/1857A1	0.368	121.03	134.07	
A/2017U1	0.256	122.74	241.81	22.1

- but requires kick velocity of 60 km/s – likely too high

Conclusions

- A2017U1 is a good interstellar comet candidate, but it could be originated from our own Solar System
- Interstellar comets should have specific v_{inf} distribution, and specific distribution of their V,U,W velocities
- The completeness of comets/asteroid searches is not well characterized
- Best strategy: maybe meteors?

End

Compact Binaries: a Discussion

Carles Badenes
University of Pittsburgh / PITT PACC

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

Framework

- **Compact Binaries**: binaries with at least one compact object (CO: WD, NS, or BH. Google doc [link], contributions from many of you.

- Finding Strategies:

  - Detached: light from stars. Photometric variability can help, but in general must see CO or infer its presence from RV variations ⇒ spectra. Search volume depends on luminosity of photometric primary: RGB (~10 kpc), MS (~1 kpc), WD (~100 pc).

  - Accreting: light from mass transfer. This is messy (really!). X-ray flux or rapid optical variability. Spectra necessary to constrain properties.

Some General Considerations

- Mass functions of COs in binaries are a key constraint on *binary* stellar evolution scenarios ⇒ mass transfer, CE physics, SN explosion physics.

    - WDs: Claims that WDs in CVs are more massive than in the field [Zorotovic+ 11], mass transfer and SN Ia physics.

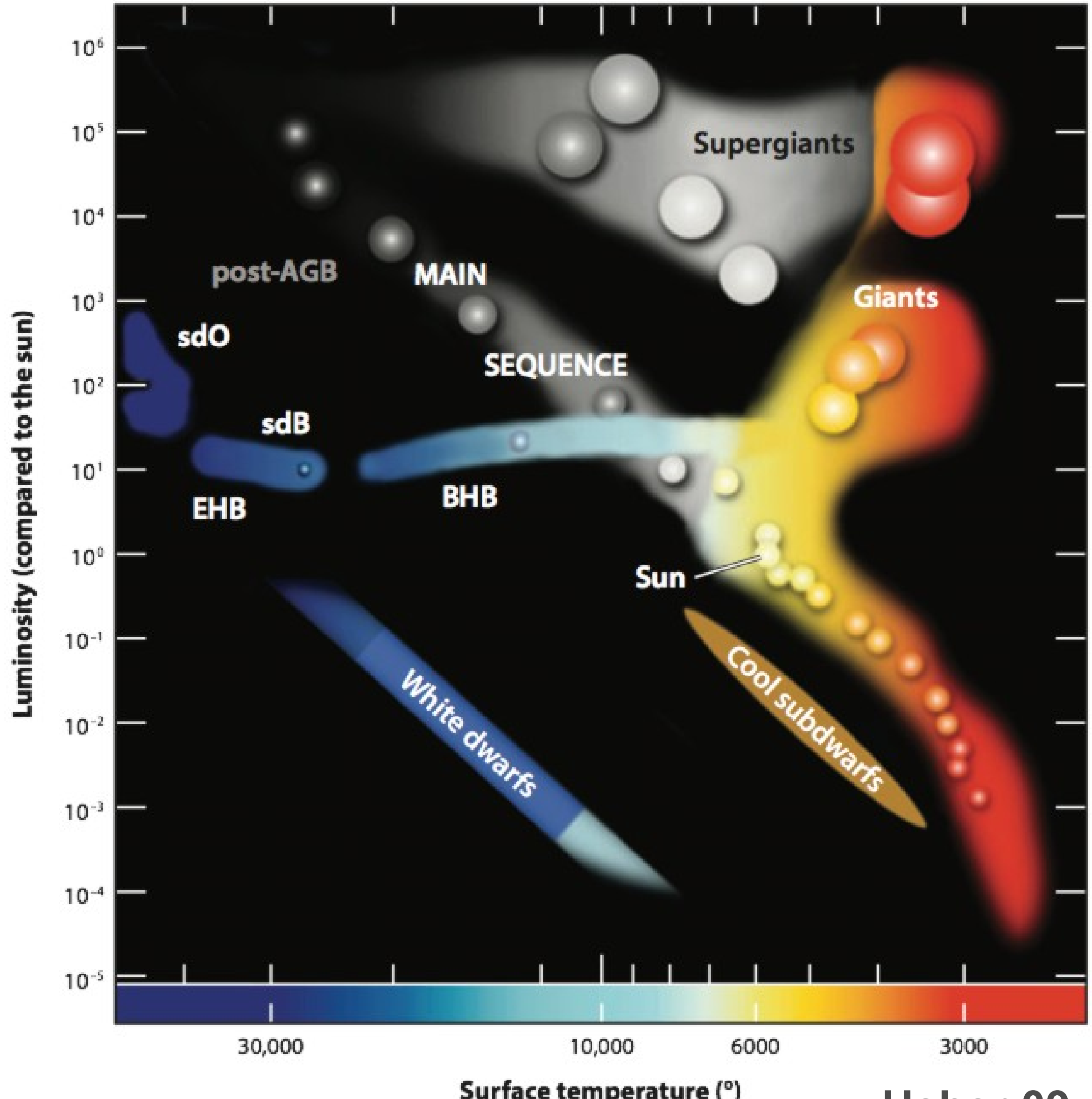
    - NSs: CC SN physics. Compare MS/RGB+NS w/ WD+NS and binary pulsar population. Link to GW sources.

    - BHs: CC SN physics. Link to GW sources.

- Many of these projects/ideas require substantial telescope time for RV follow-up of log N ~2 to 3 objects. Key to identify the best telescopes (capability AND willingness/availability)!!!

Subdwarfs

- Like ELMWDs, subdwarfs are always interesting (need binary interactions).
- Largest RV follow-up program: MUCHFUSS [Geier+15]. Found low mass WD companions at high latitudes - some claims of NS/BH [Geier+ 08].
- Photometric variability in PTF/ZTF found high mass WD companions at low latitudes [Kupfer slides].
- Same region of HR diagram where D6 stars live [Shen+ 18].



Heber 09

Subdwarfs

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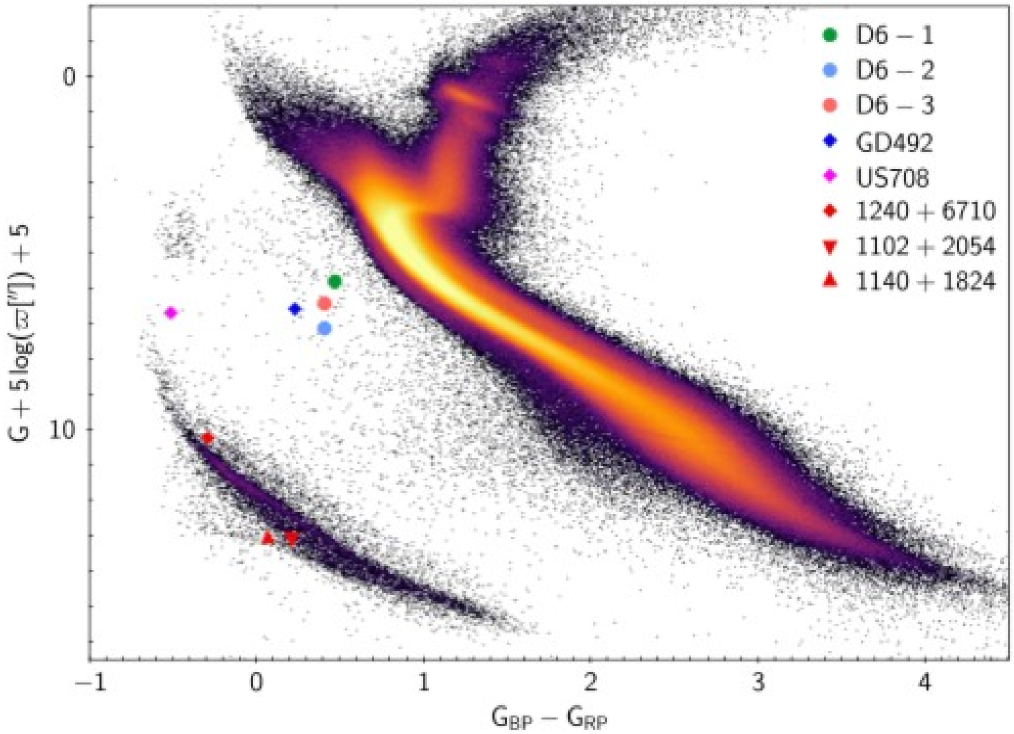


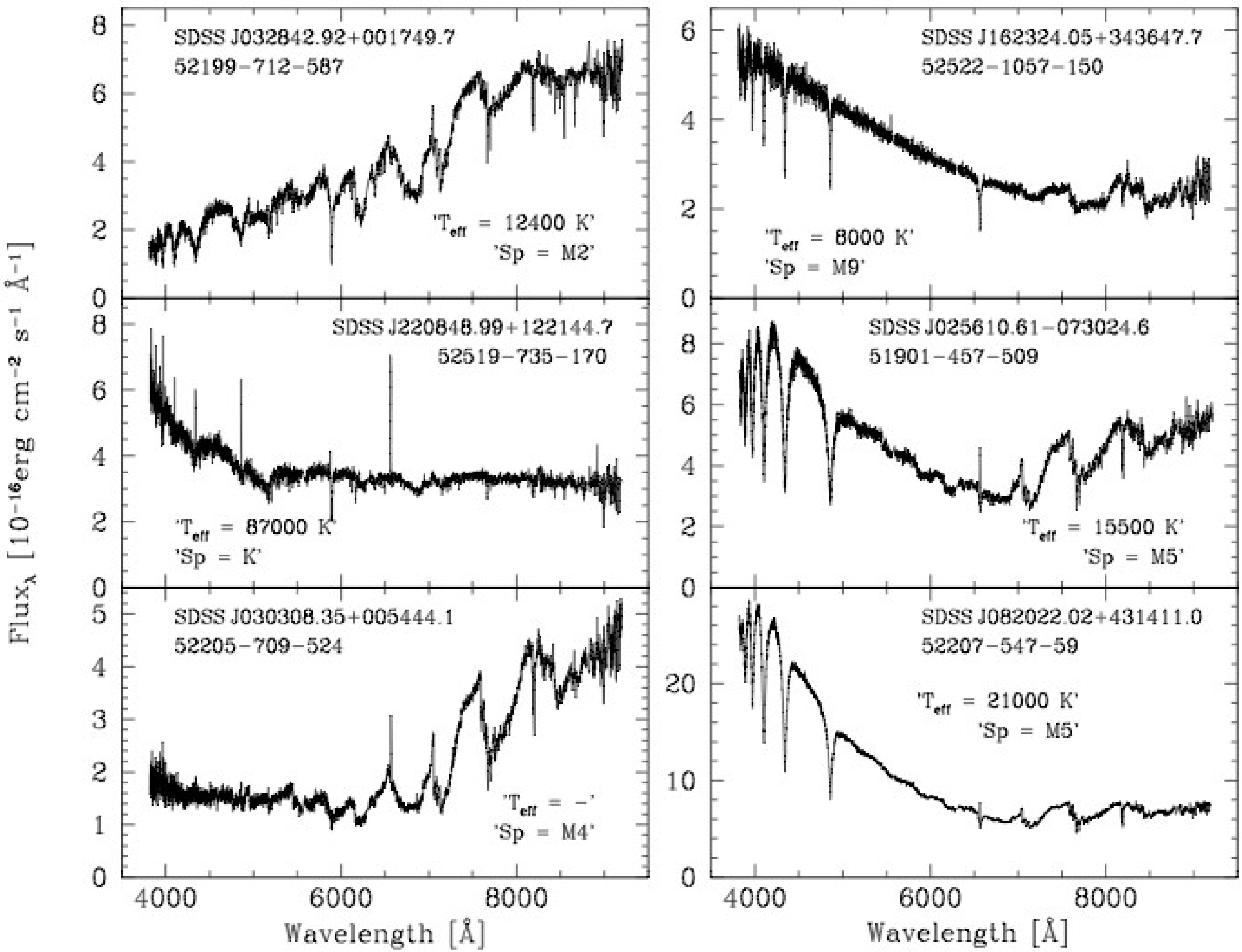
Figure 10. Color–magnitude diagram of the three hypervelocity candidates, GD 492, US 708, and three chemically peculiar WDs (colored symbols). The black circles and colored regions show reliably measured stars from *Gaia*.

Shen+ 18

WD+M dwarf binaries

Carles Badenes
SDSSV+ZTF

- See both components ⇒ catalogs (2000+ objects) [R-M+ 07, 10, 11].
- Largest collection PCEB periods [Nebot+ 11] (requires follow-up).
- Can we do the same with SEDs & Gaia parallaxes?



Rebassa-Mansergas+ 10

WD+M dwarf binaries

Carles Badenes
SDSSV+ZTF

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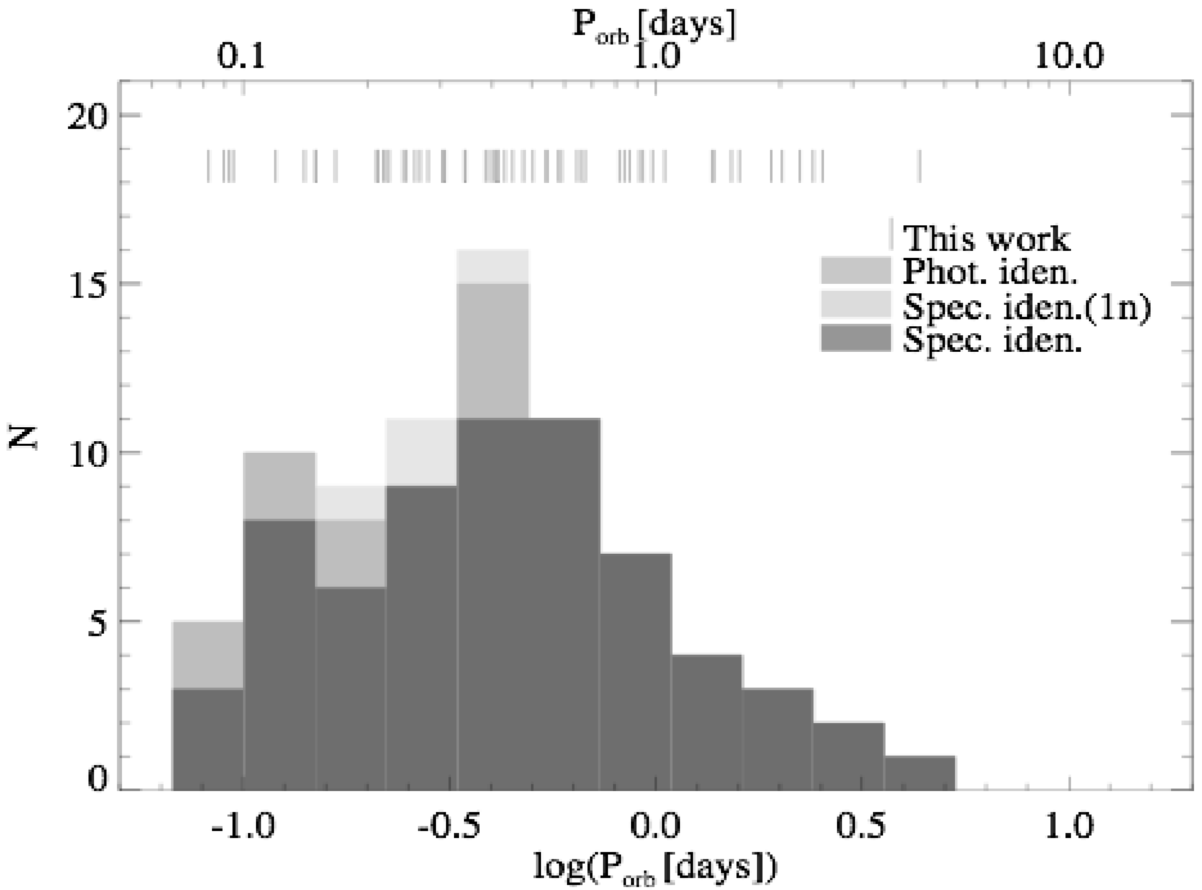


Fig. 7. Orbital period distribution of the 79 SDSS PCEBs characterised to date. Systems identified as PCEBs based on spectroscopic observations are shown in light grey if the spectra were taken during the same night and dark grey otherwise. In medium grey we show those systems that were identified as PCEBs based on photometry. The 58 systems added by this paper to the orbital period distribution are indicated with vertical lines.

Nebot G-M+ 11

WD + nondegenerate stars

Carles Badenes
SDSSV+ZTF

- SEDs that extend to the UV + Gaia parallaxes could be promising.

- WD eclipses detectable in LCs from exoplanet missions (Kepler, TESS) [Zhang+ 17]. RV follow-up required to identify them as WDs [Hermes].

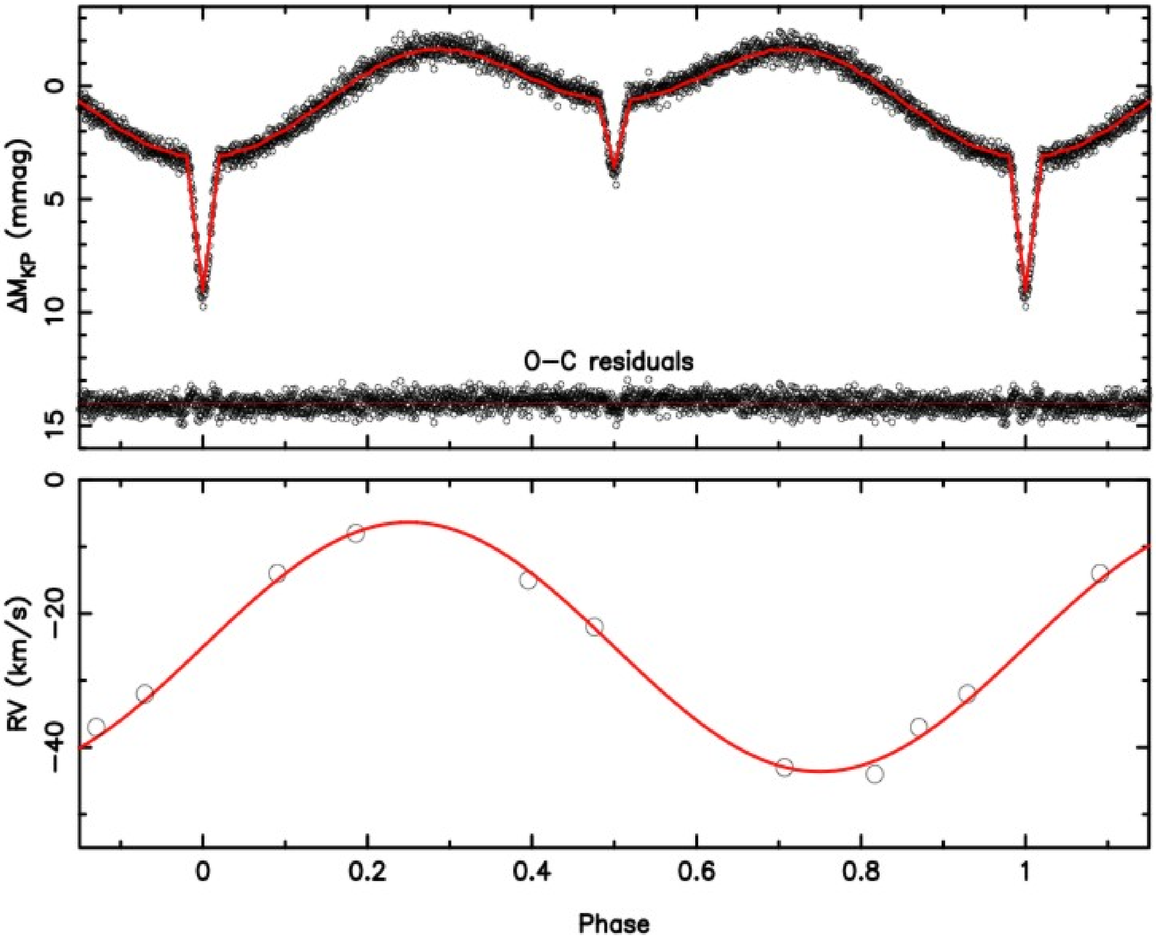
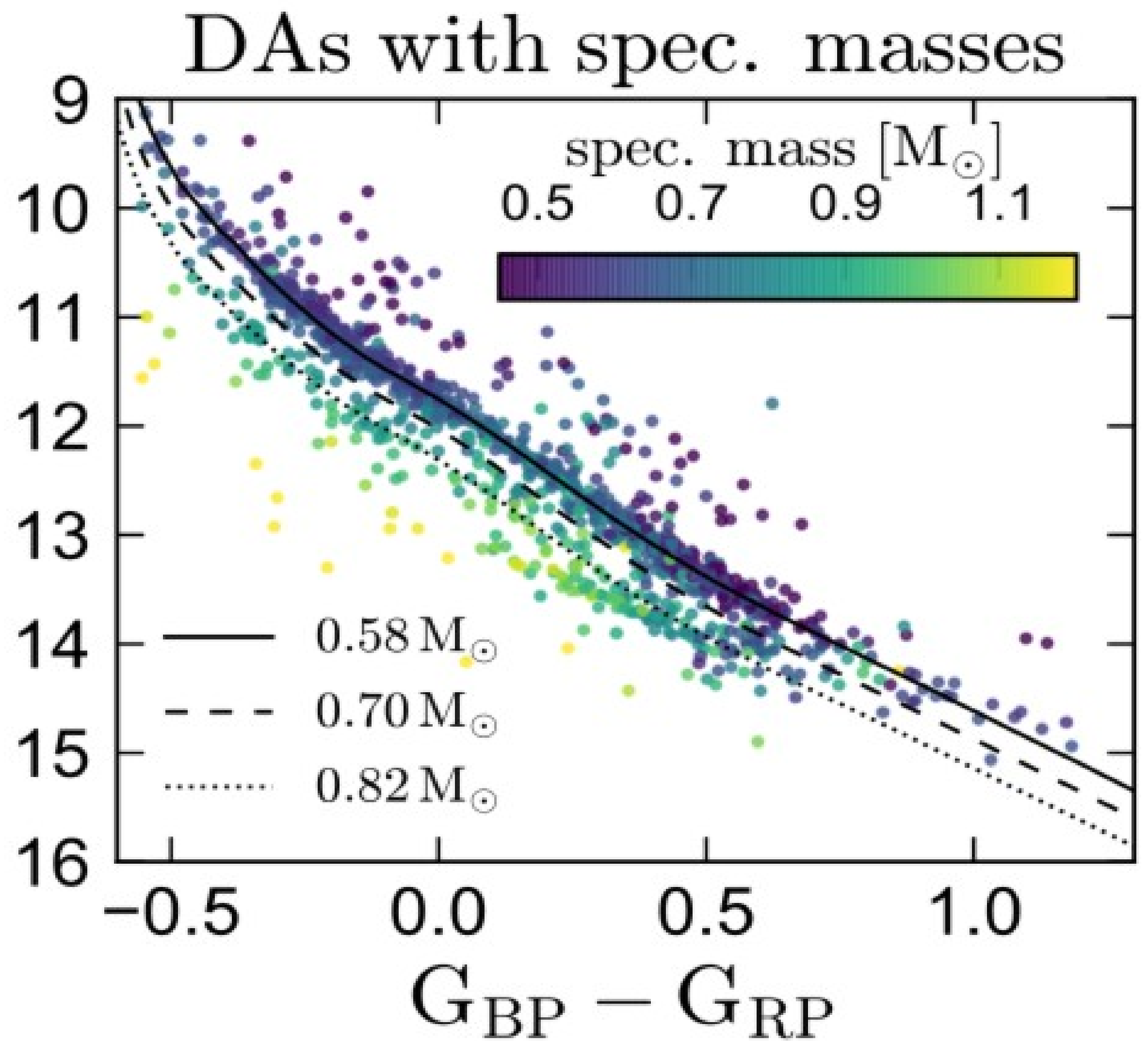


Figure 1. Light and radial velocity curves of KIC 10989032 and the theoretical synthesis.

Zhang+ 17

Binary WDs in the Gaia era

- The Gaia HR diagram contains hundreds of thousands of potential WDs [Gentile Fusillo+ 18].
- Photometric discoveries with ZTF [Burdge].
- An ambitious time-domain spectroscopy follow-up program of Gaia-identified WDs would be very interesting (BOSS spectra?).
- DESI would be even better.

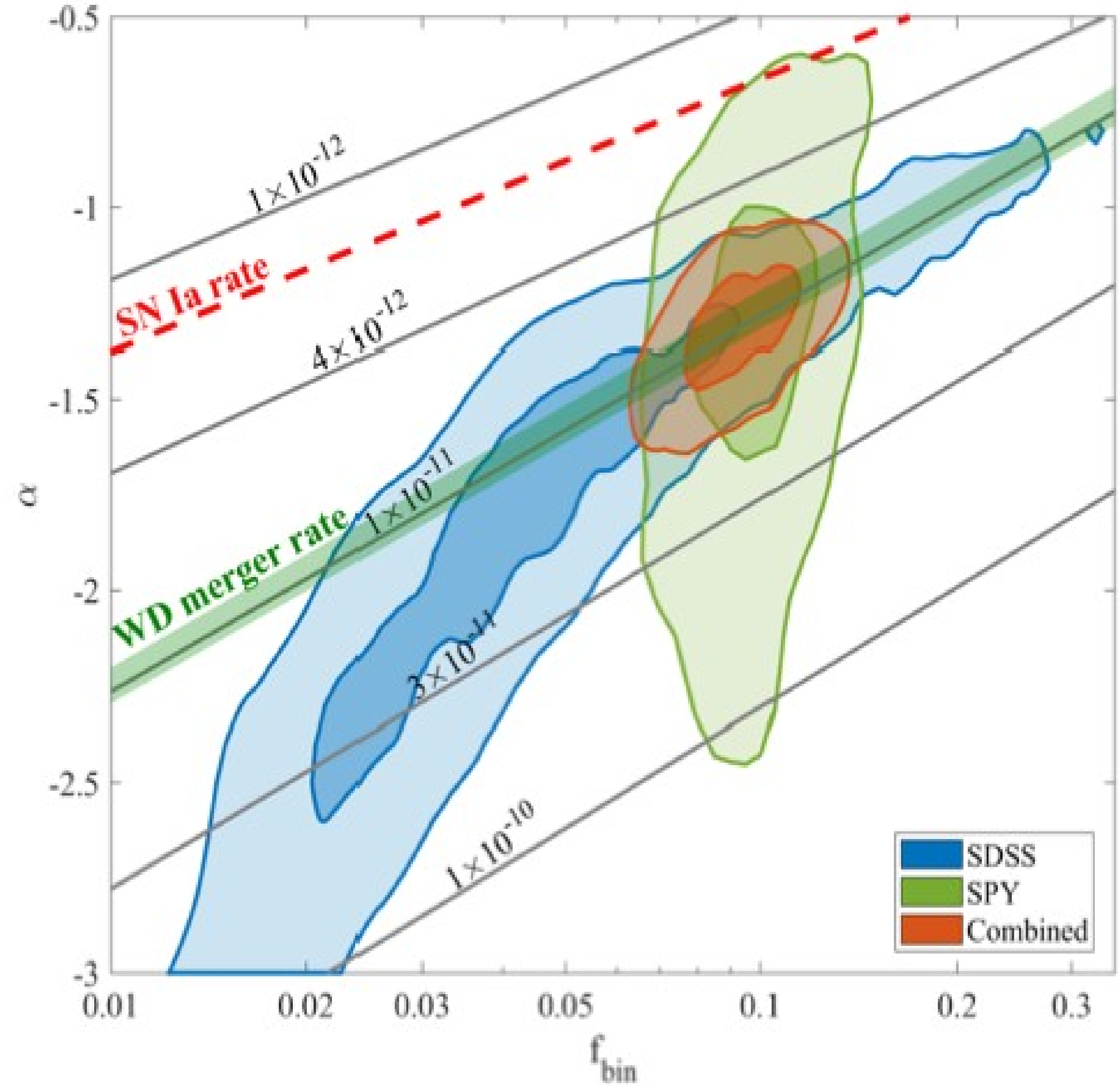


El-Badry+ 18

Binary WDs in the Gaia era

Carles Badenes
SDSSV+ZTF

- The Gaia HR diagram contains hundreds of thousands of potential WDs [Gentile Fusillo+ 18].
- Photometric discoveries with ZTF [Burdge].
- An ambitious time-domain spectroscopy follow-up program of Gaia-identified WDs would be very interesting (BOSS spectra?).
- DESI would be even better.



Maoz+ 18

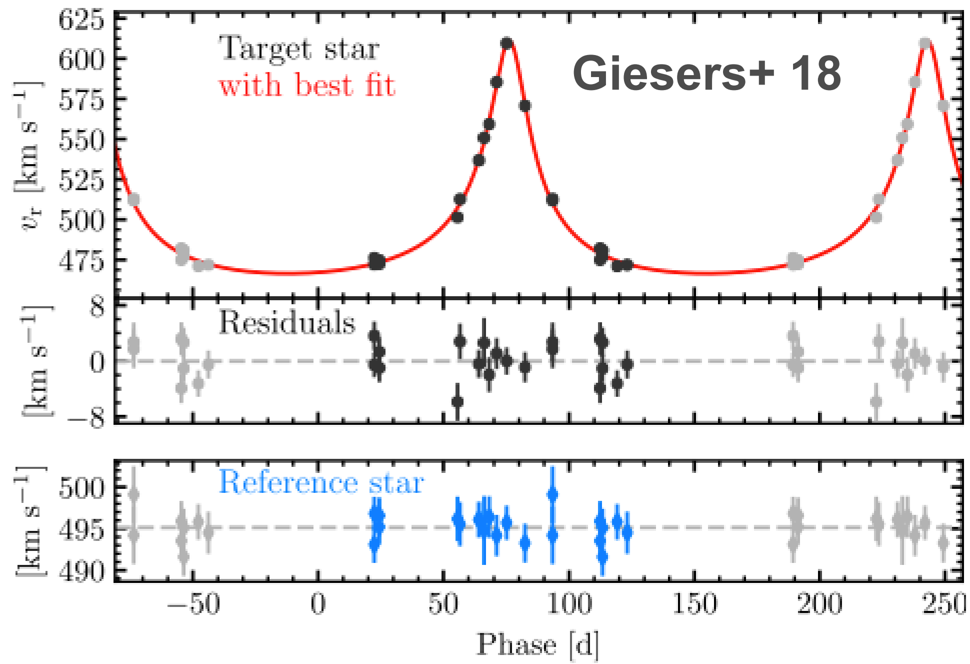
Finding COs with RV Shifts

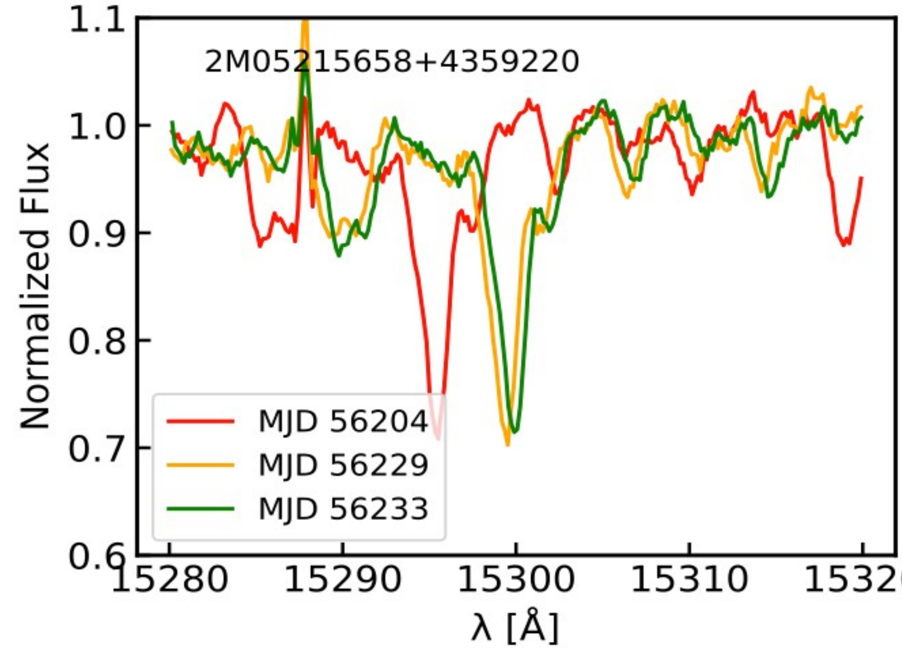
Carles Badenes
SDSSV+ZTF

- Discovery of detached BH binaries in the field [Thompson+ 19] and in a globular cluster [Giesers+ 18].

- Very different discovery methods (multiple RVs vs. only 3) and objects (likely captured vs. coeval).

- For TAT-1, having a photometric period was key ⇒ break inherent degeneracies in sparsely sampled RV curves. APOGEE ΔRV_{max} = 88 km/s (2K=89.2 km/s)





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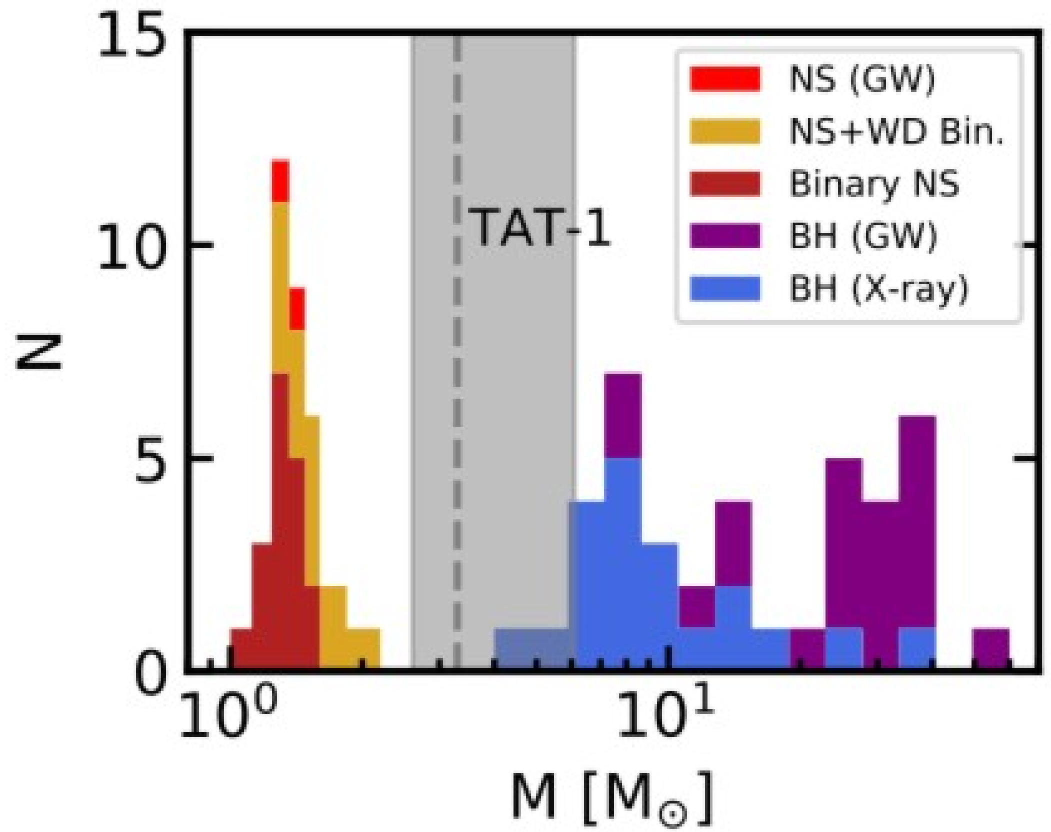
$$f = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{P_{\rm orb}\, K^3}{2\pi G}.$$



Finding COs with Gaia

Carles Badenes
SDSSV+ZTF

- Gaia will find thousands of CO binaries (DR 3 in 2021) [Breivik+ 17].
- It is possible to find a few (dozens?) of these systems with existing capabilities and characterize them fully.
- Bayesian fits to sparsely sampled RV curves can help if there are enough systems with 4+ RVs [Price-Whelan+ 18].

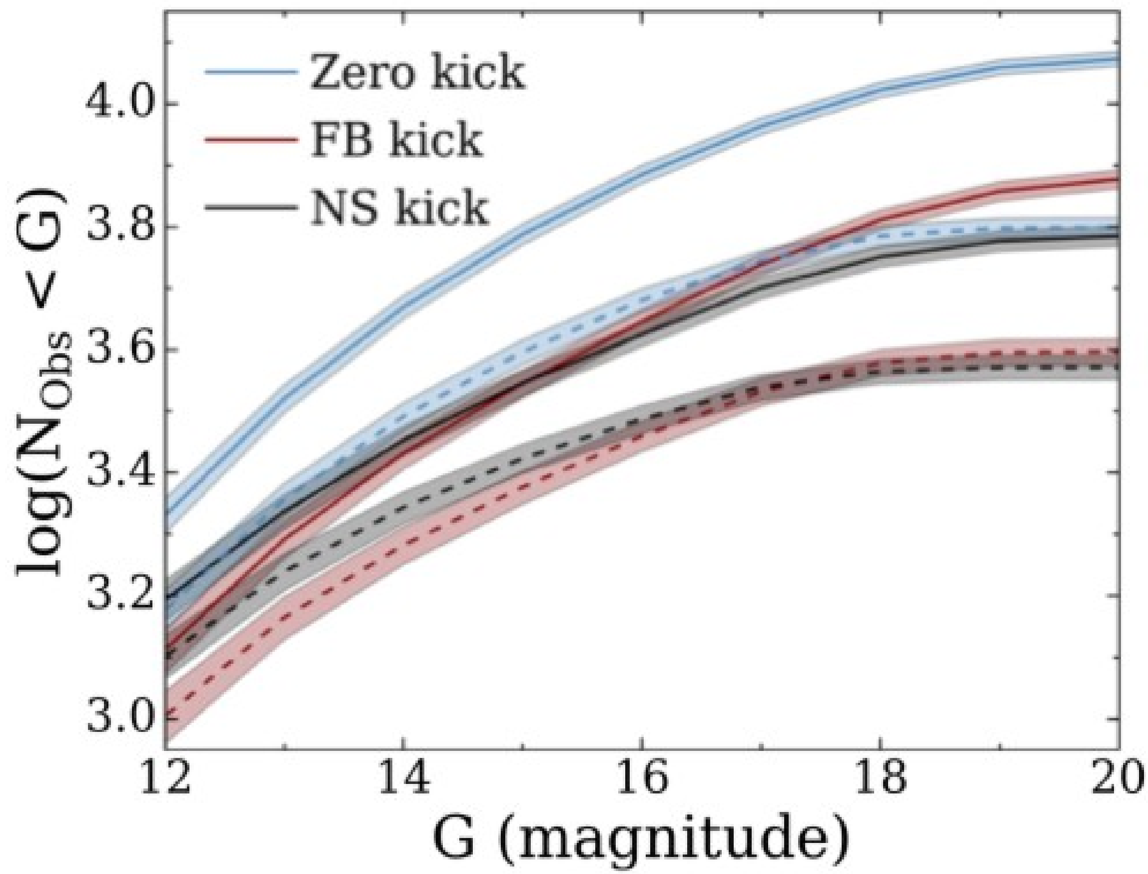


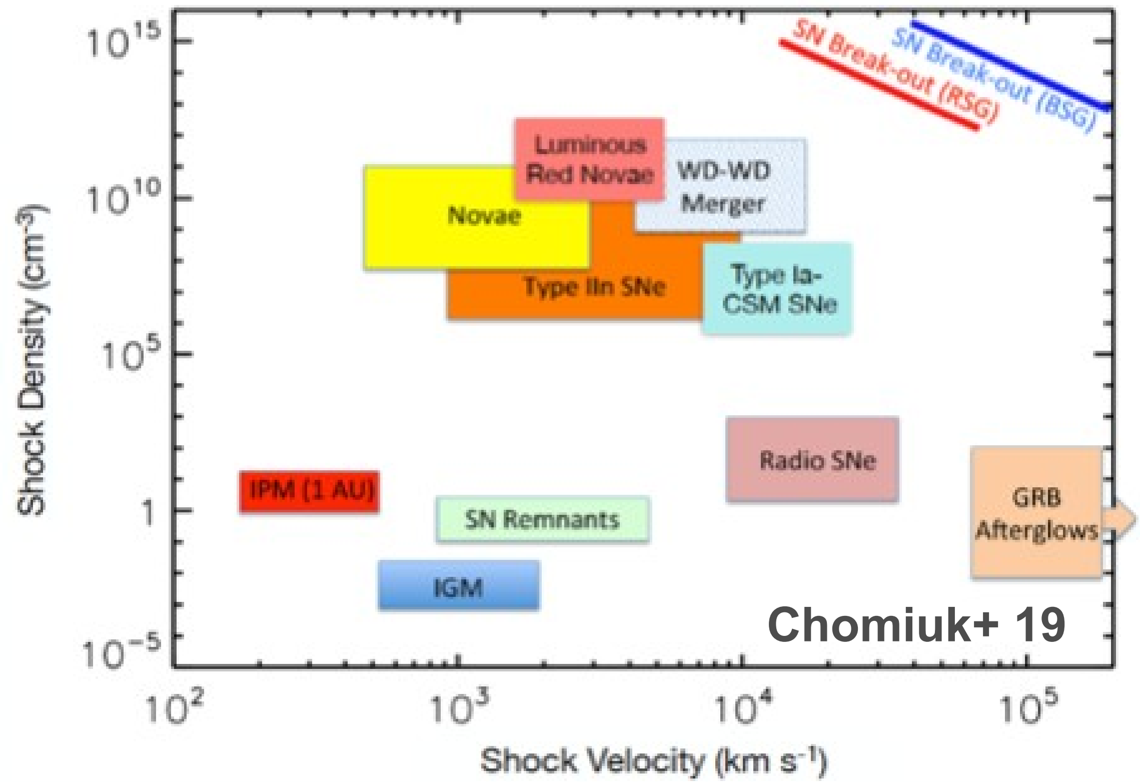
Figure 3. Mean number of observable BH-LCs as a function of limiting G magnitude computed from 500 Galactic realizations. Shades show 3σ regions above and below the mean denoted by the lines. Dashed (solid) lines denote our estimates using pessimistic (optimistic) astrometric cuts (Section 2.4). Blue, red, and black shading denote Zero-kick, FB-kick, and NS-kick models, respectively.

Breivik+ 17

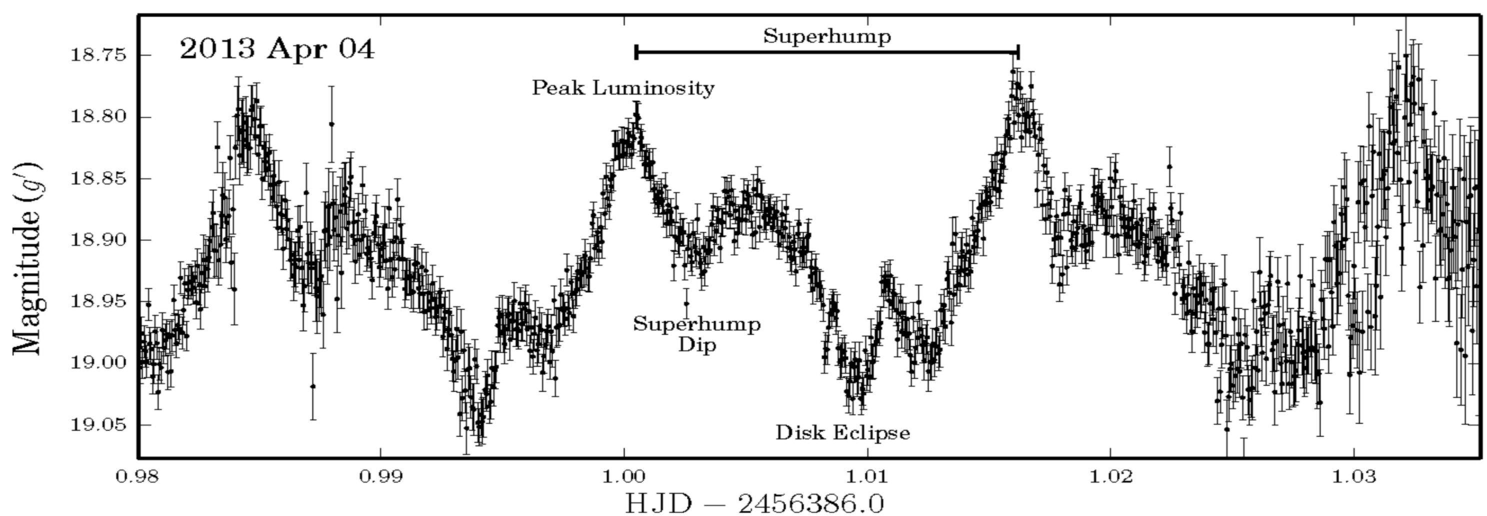
CO Binaries with Accretion

Carles Badenes
SDSSV+ZTF

- CVs and novae are plentiful, ideally suited for time domain surveys. Exciting physics (shocks, TeV) [Chomiuk+ 19]. MSPs masquerading as CVs? [Hermes]
- AM CVn stars through photometric variability in high state [Kupfer]



Chomiuk+ 19



Levitan+ 14

CO Binaries with Accretion

Carles Badenes
SDSSV+ZTF

- LMXBs and HMXBs - several low-purity signatures: [Bellm]
  - State changes in the optical (/X-ray)
  - Optical “flickering” variability
  - Cross-correlation with X-ray/gamma-ray catalogs
  - Identification of H-alpha excesses in narrowband imaging
  - Identification of broadened H-alpha in spectra
  - Identification of high-excitation emission components (e.g., the Bowen blend) in spectra

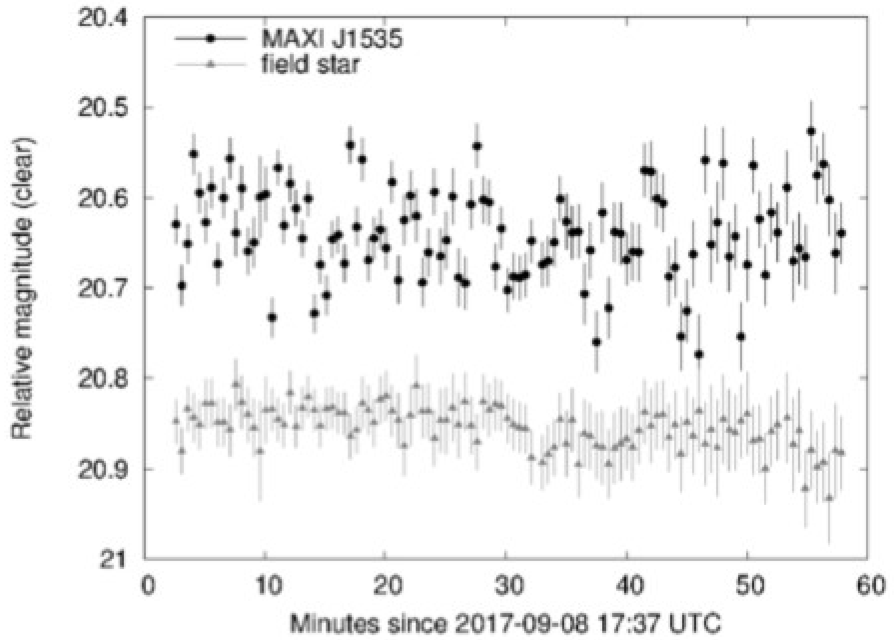


Figure 5. Optical (white light) light curve of J1535 obtained with SALT–SALTICAM on Sept. 8th (MJD 58004.734).

Baglio+ 14

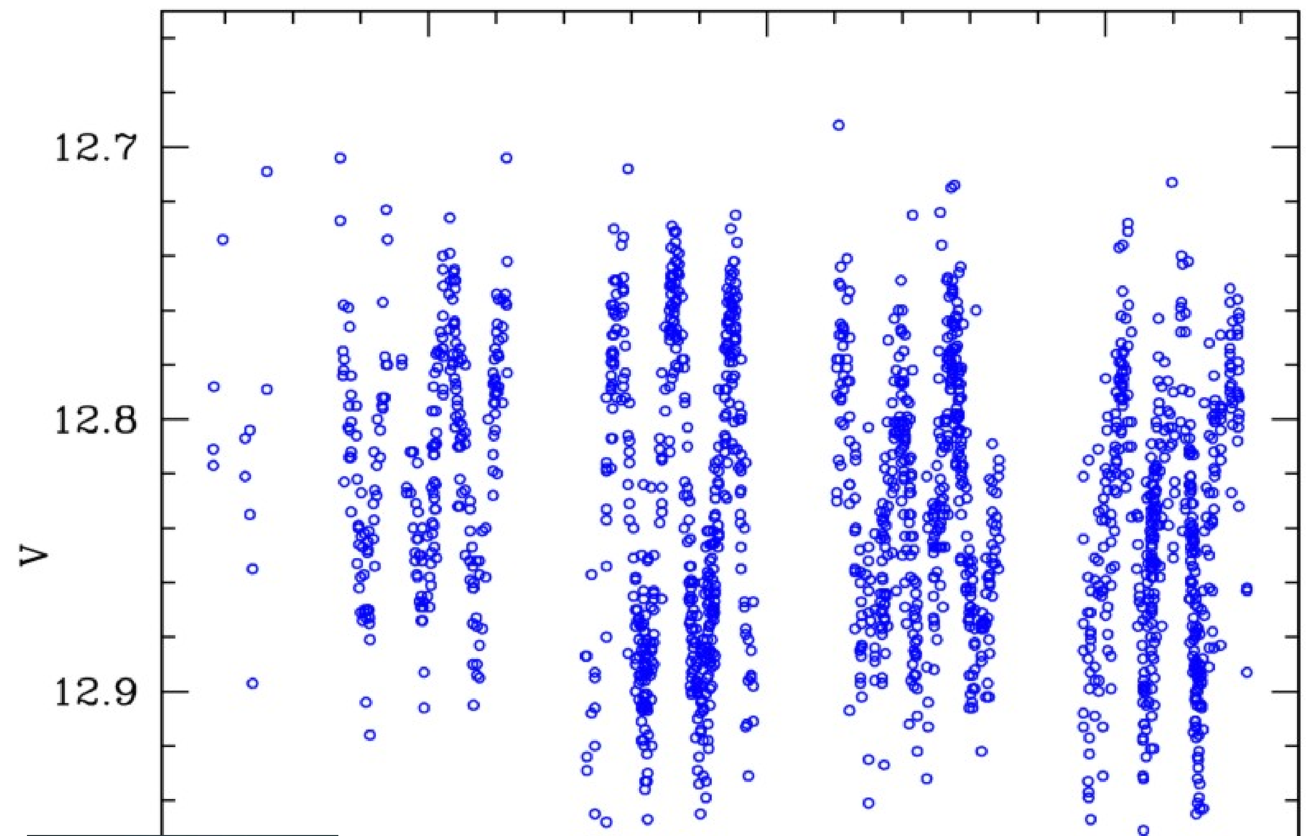
Discussion

- Present and future facilities (SDSS, ZTF, Gaia) can and will produce a large number of confirmed and candidate CO binaries.
- Many interesting projects require a large number ($\sim 10^2 - 10^3$) of follow-up spectra, mainly for RVs to constrain dynamics.
- Telescope capabilities vs. availability/willingness – you all heard our esteemed SDSS-V director!
- We should have an open discussion on facilities, projects, and teams.

Discovery of TAT-1

Carles Badenes
SDSSV+ZTF

- 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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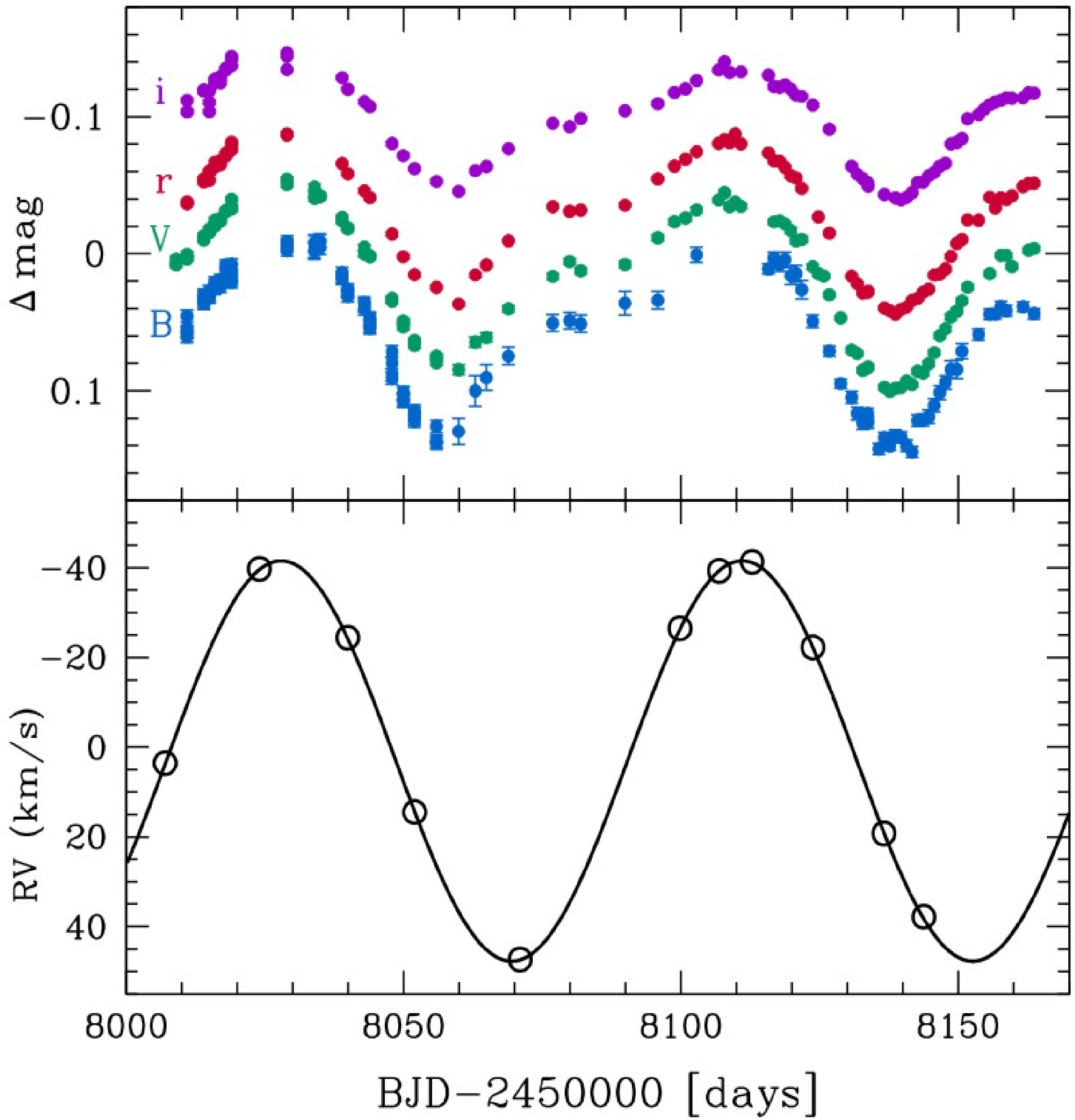

Thompson+ 19

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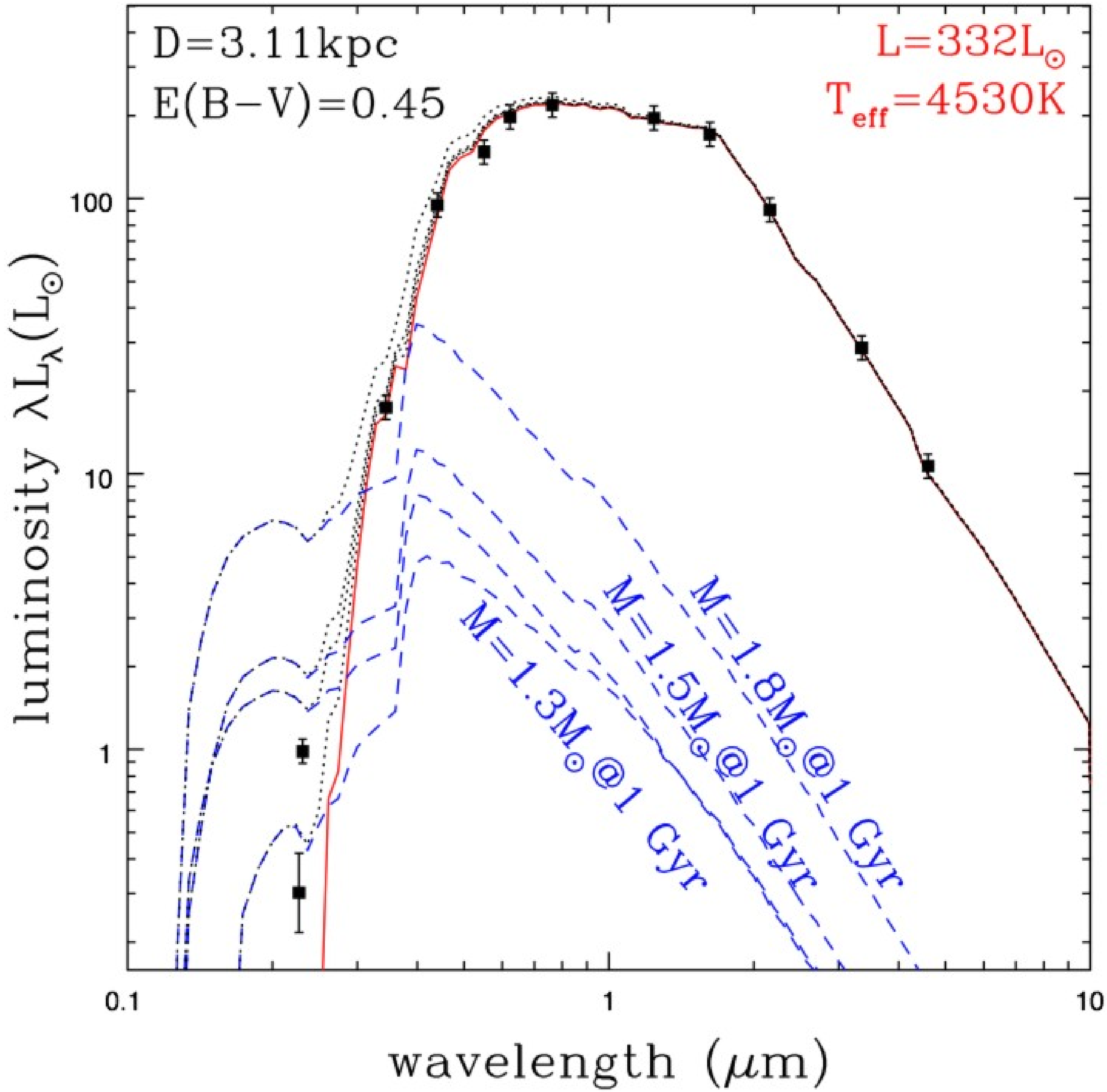

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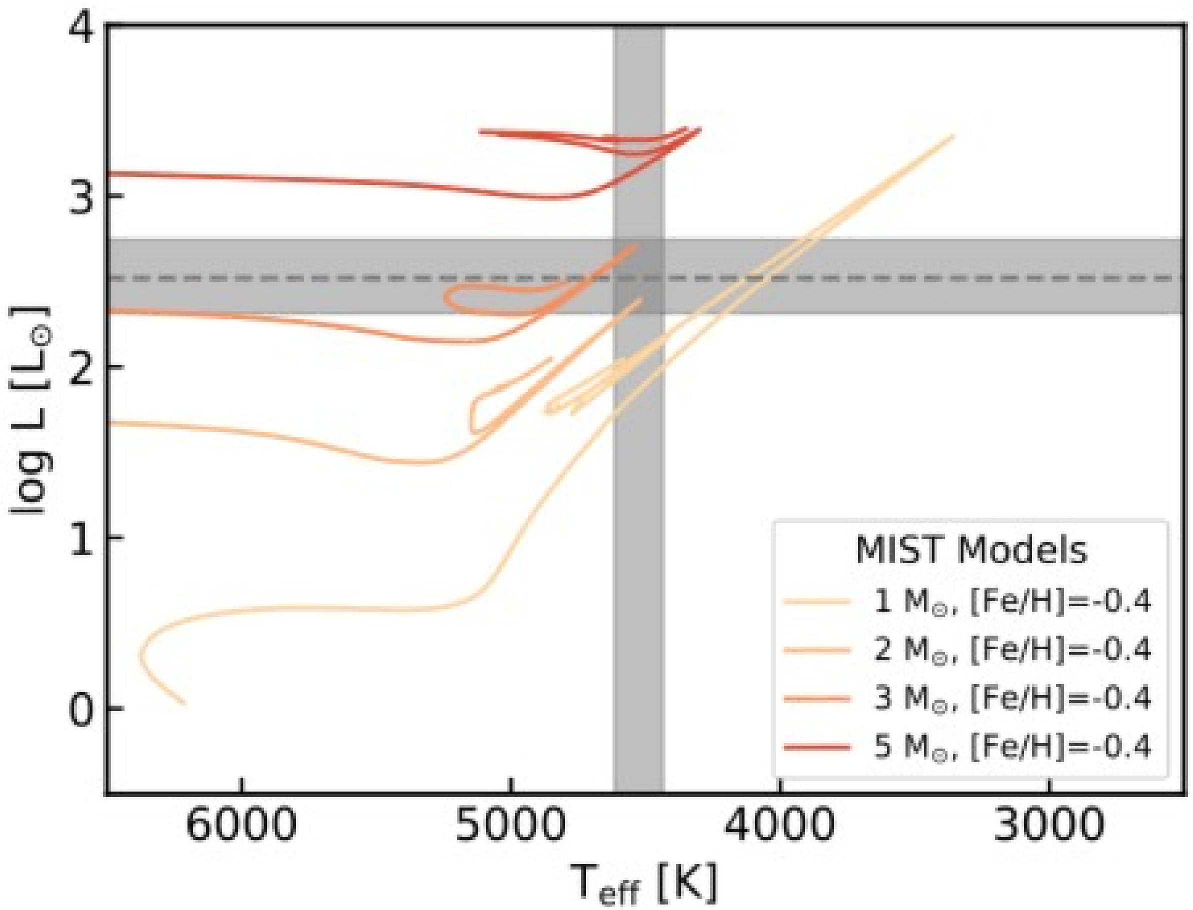

Thompson+ 19

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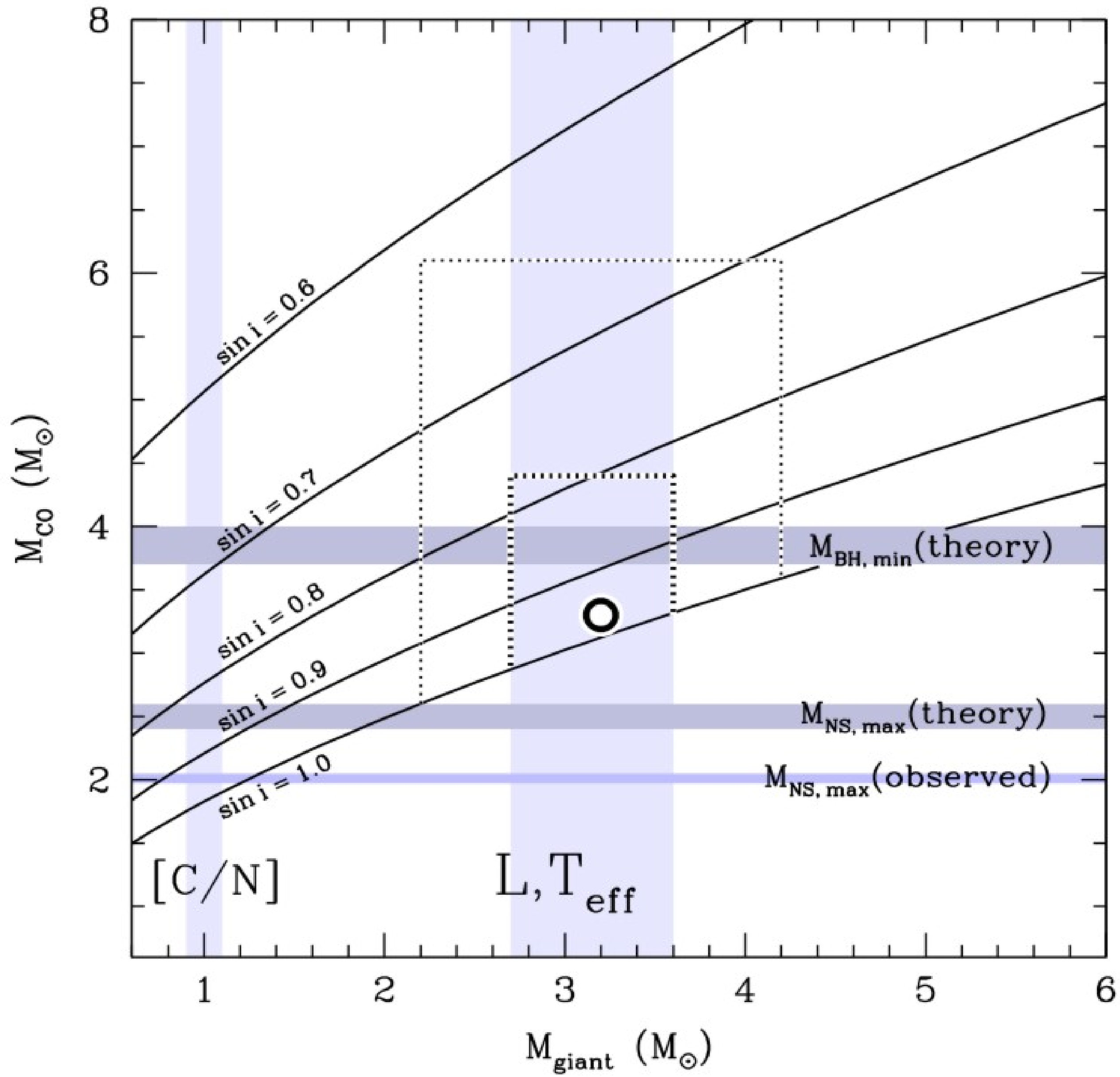

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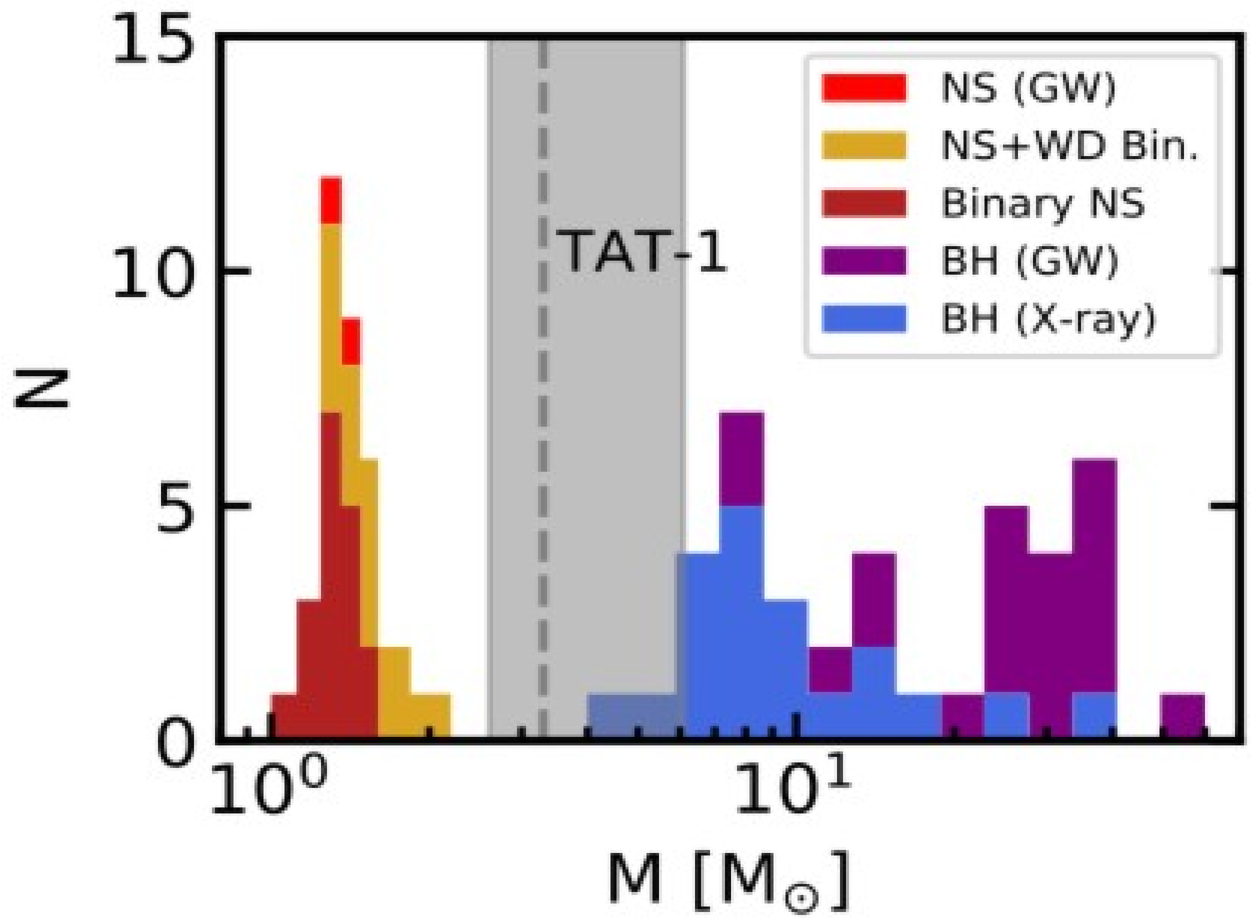


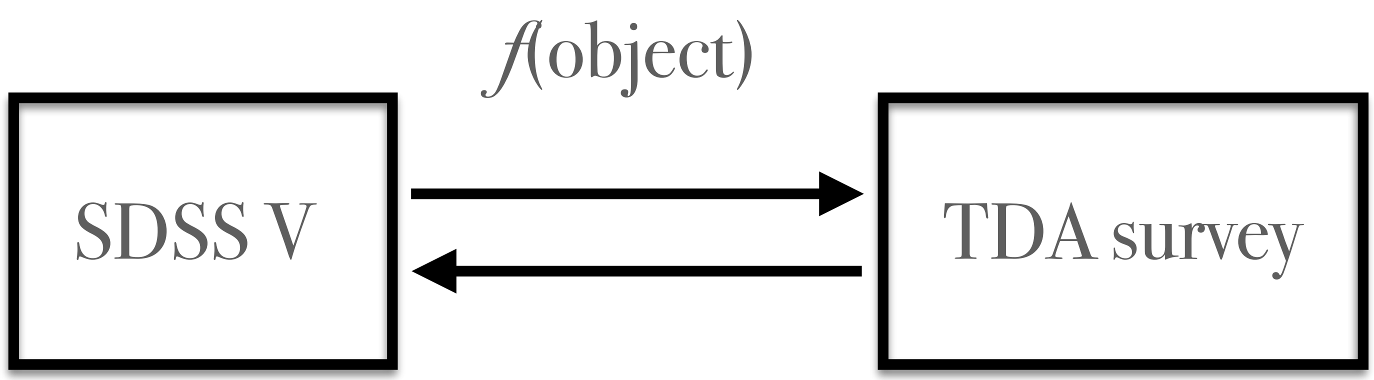
Thompson+ 19

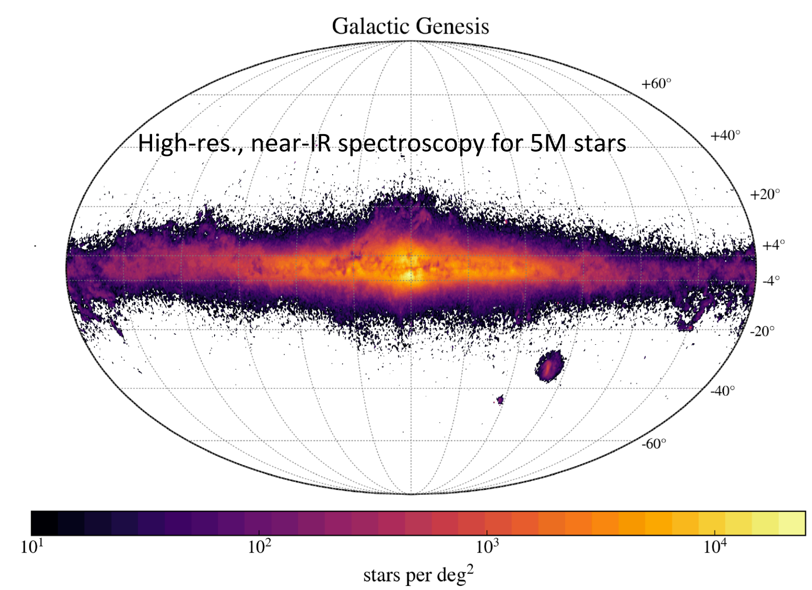
Rare Objects Discussion
(Binaries & Otherwise)

Melissa Ness
Columbia University/Flatiron Institute, New York City

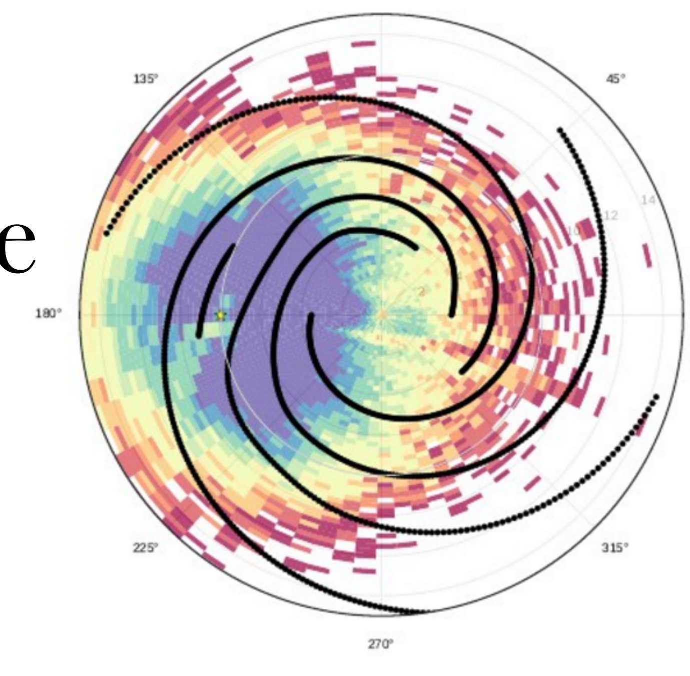
Science Opportunity

- In the SDSS V, TDA era - orders of magnitude less restricted in terms of **sampling**
  - sampling in both sheer numbers and galactic coverage



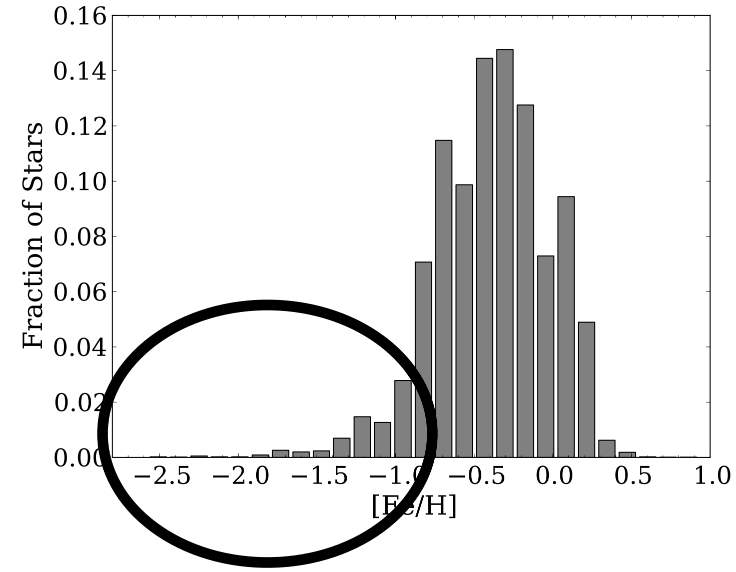


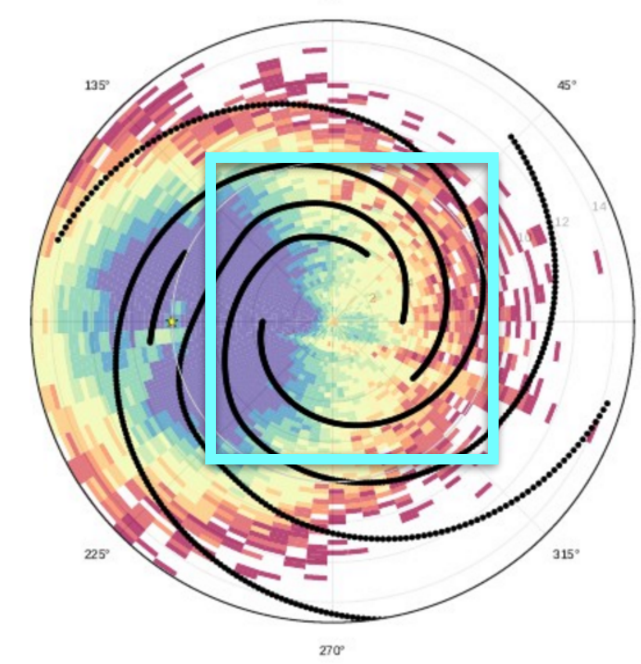
Science Motivation – Rare Objects Perspective



- disk and bulge assembly,
- stellar physics;
- stellar death and interaction (gravitational wave sources) ,
- stars as families

Disk & **Bulge** Assembly





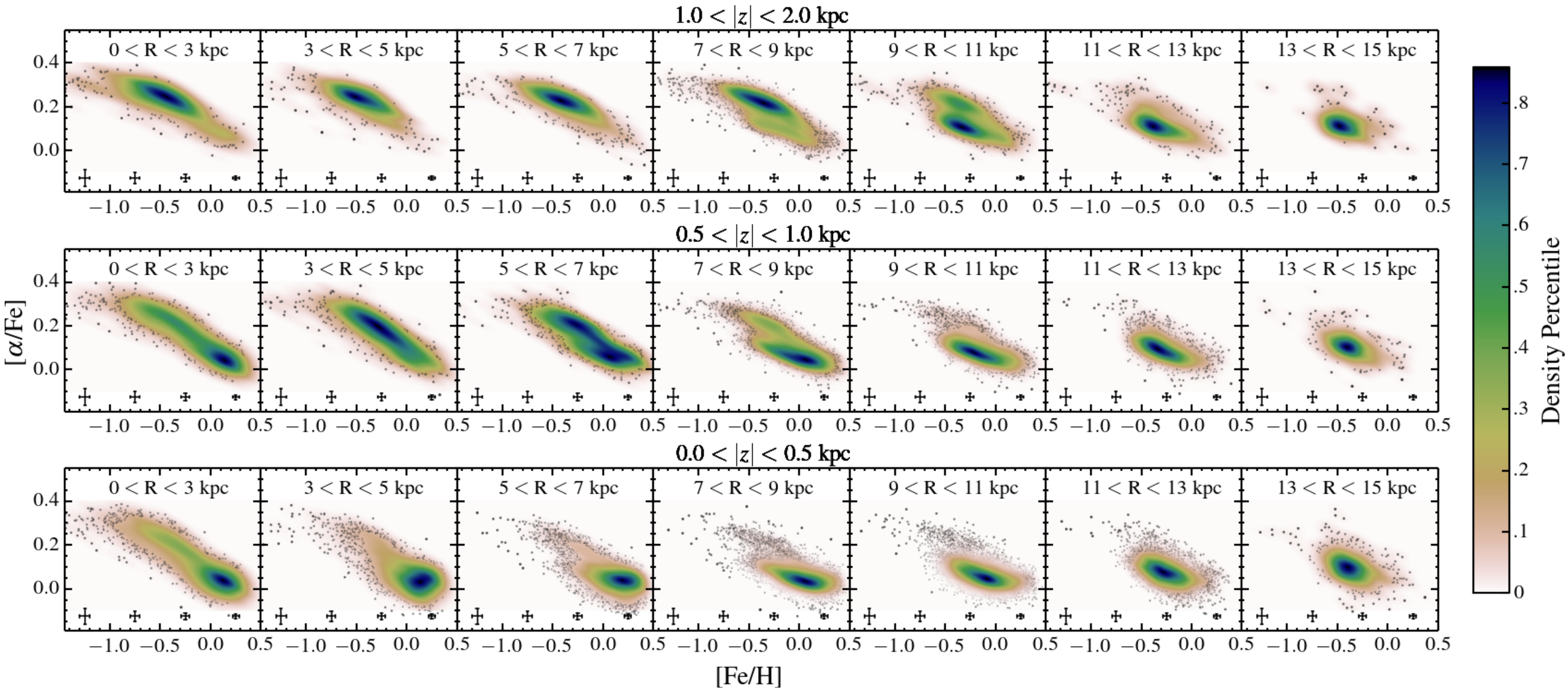
- bulge formation mechanisms - debate e.g. **metal-poor stars**
  - unique bulge population / halo in inner region / globulars ?
  - chemically resemble globular clusters, halo or unique? orbits?
  - argued that oldest stars will be in the bulge..until recently,

El Badry et al., 2018, Where are the most ancient stars in the Milky Way? https://arxiv.org/pdf/1804.00659.pdf
Schiavon, R et al., Chemical tagging with APOGEE: discovery of a large population of N-rich stars in the inner Galaxy http://adsabs.harvard.edu/abs/2017MNRAS.465..501S
Lucey, M et al., The COMBS survey I: Chemical Origins of Metal-Poor Stars in the Galactic Bulge http://adsabs.harvard.edu/abs/2019arXiv190311615L

Disk & Bulge Assembly

- The disk is “boring” (from a rare objects perspective)

70,000 giants from Hayden, M from **APOGEE**

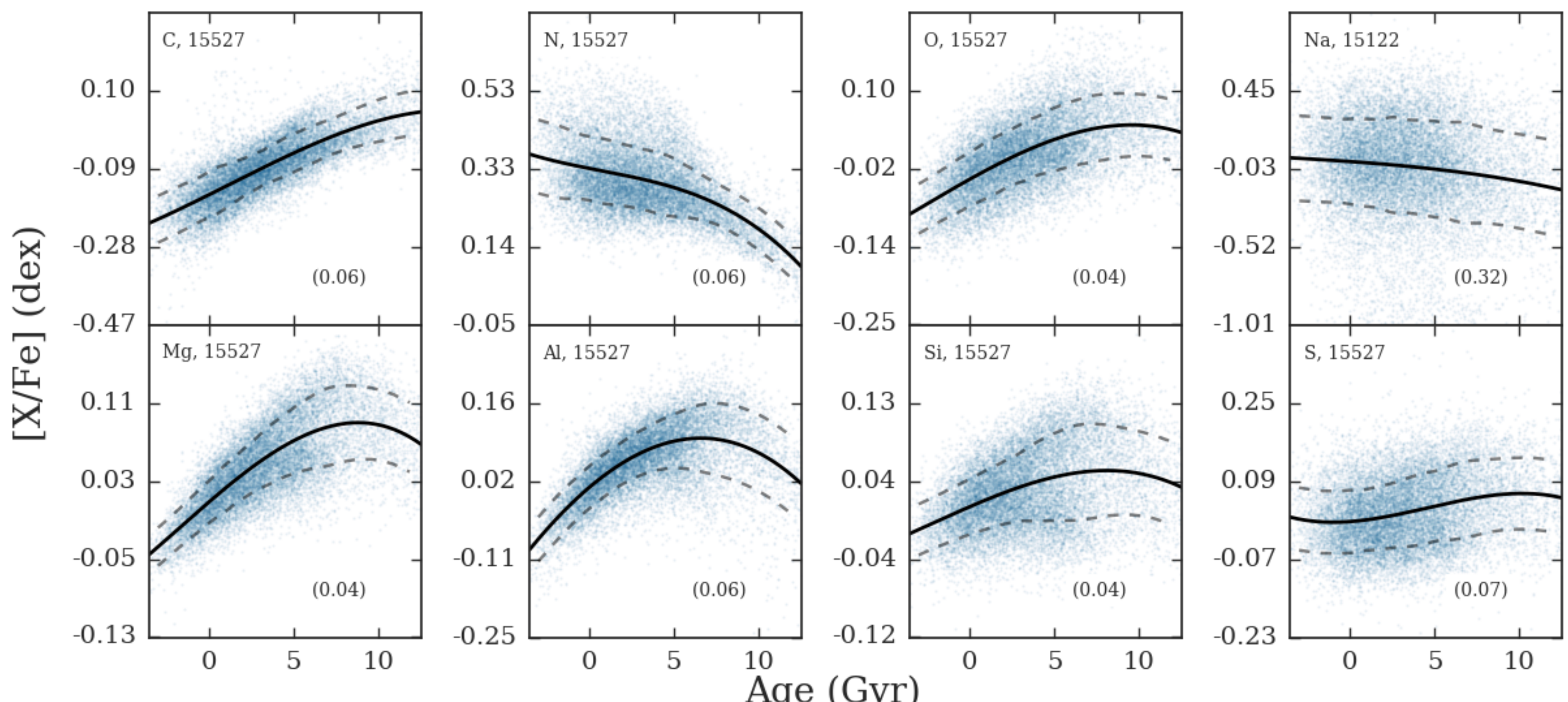


- inside-out, upside-down formation (e.g. Bird+ 2013, Freudenburg+ 2017, Ness 2018)

Disk & Bulge Assembly

- Three stellar characteristics **([Fe/H], [α/Fe], age)**
  - describe the distribution of stars across the disk

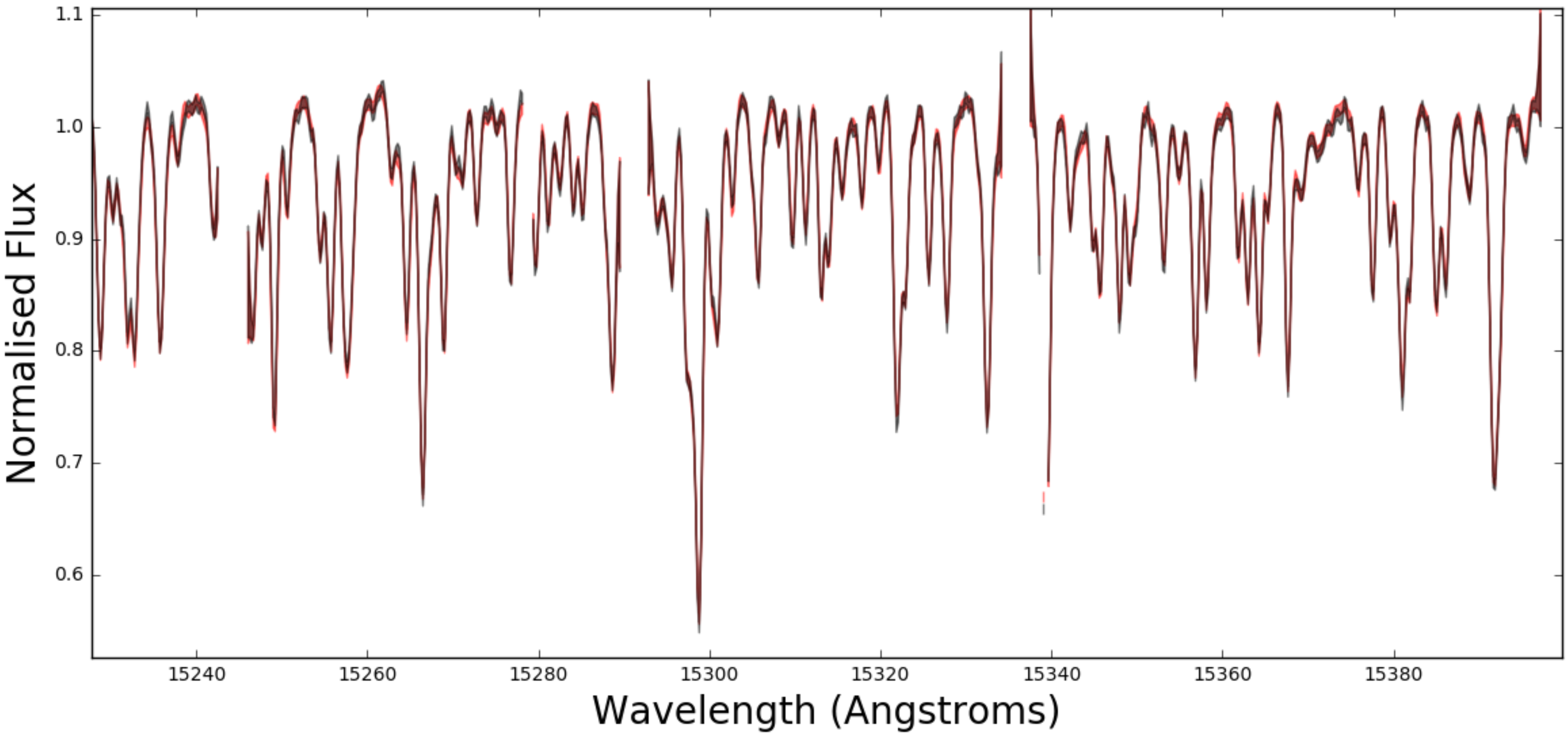
- multi-dimensional chemical abundances = ages (mostly)



Ness in prep 2019

Disk & Bulge Assembly

- A lot of disk doppelgangers: in APOGEE, 1 in 100 stars are chemically identical (20 elements) –



Ness et al., 2018 Galactic Doppelgängers: The Chemical Similarity Among Field Stars and Among Stars with a Common Birth Origin http://adsabs.harvard.edu/abs/2018ApJ...853..198N

Disk & Bulge Assembly

- **very few outliers** in abundances in the disk - strong constraints on past & accretion

- by sheer luck know of odd disk stars - *link to galactic evolution (archeology)*

Schlaufman, K, et al., 2018, An Ultra Metal-poor Star Near the Hydrogen-burning Limit
http://adsabs.harvard.edu/abs/2018ApJ...867...98S

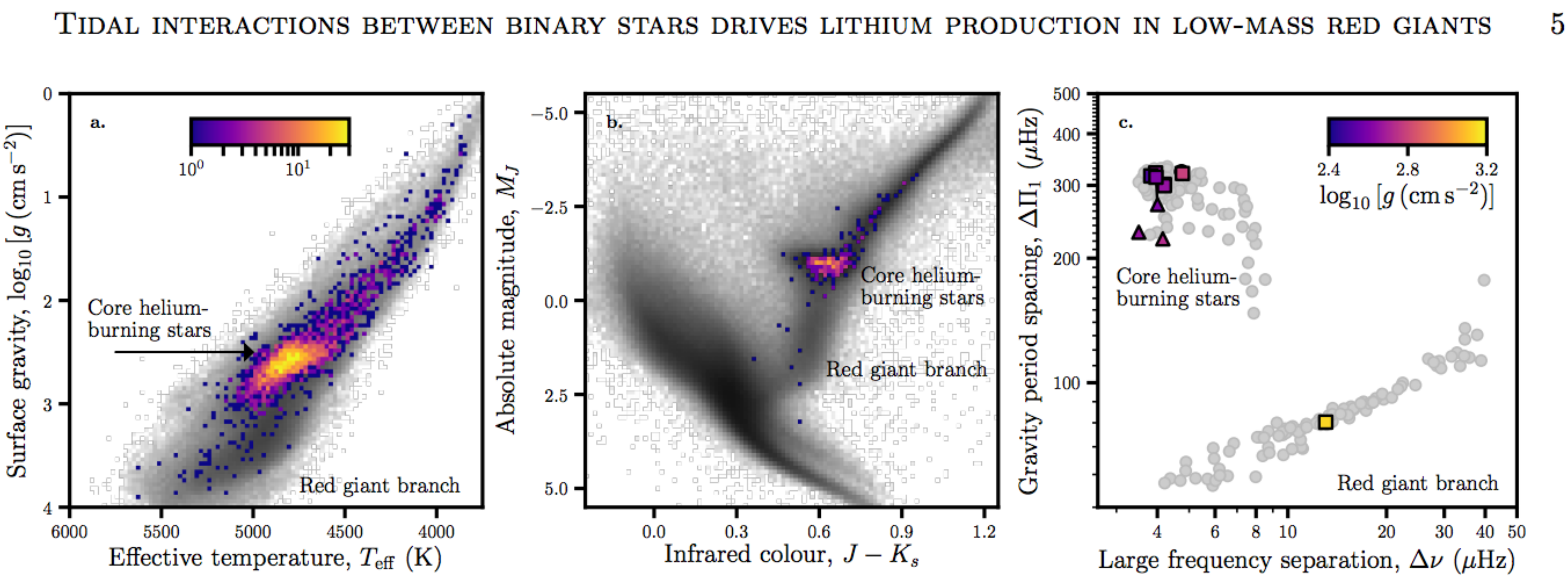
- such (exciting) oddities offer constraints on total abundance distribution, scale of disk at early times, or migration or accretion

- by sheer numbers and new data-driven abundance derivations have identified (2000) Lithium rich stars - link to stellar physics (I'll come back to this)

Casey, A. et al., 2018 Tidal interactions between binary stars drives lithium production in low-mass red giants http://adsabs.harvard.edu/abs/2019arXiv190204102C

Stellar physics & stars as families

- Lithium rich stars (Casey et al., 2019) - 2000 Li rich stars in the disk



- Need: Multiple epoch RV′s or photometric brightness variations to test for binarity

Stellar physics & stars as families

- Stars behaving strangely - e.g. KIC_8462852 - anomalously large variation in brightness over short timescales

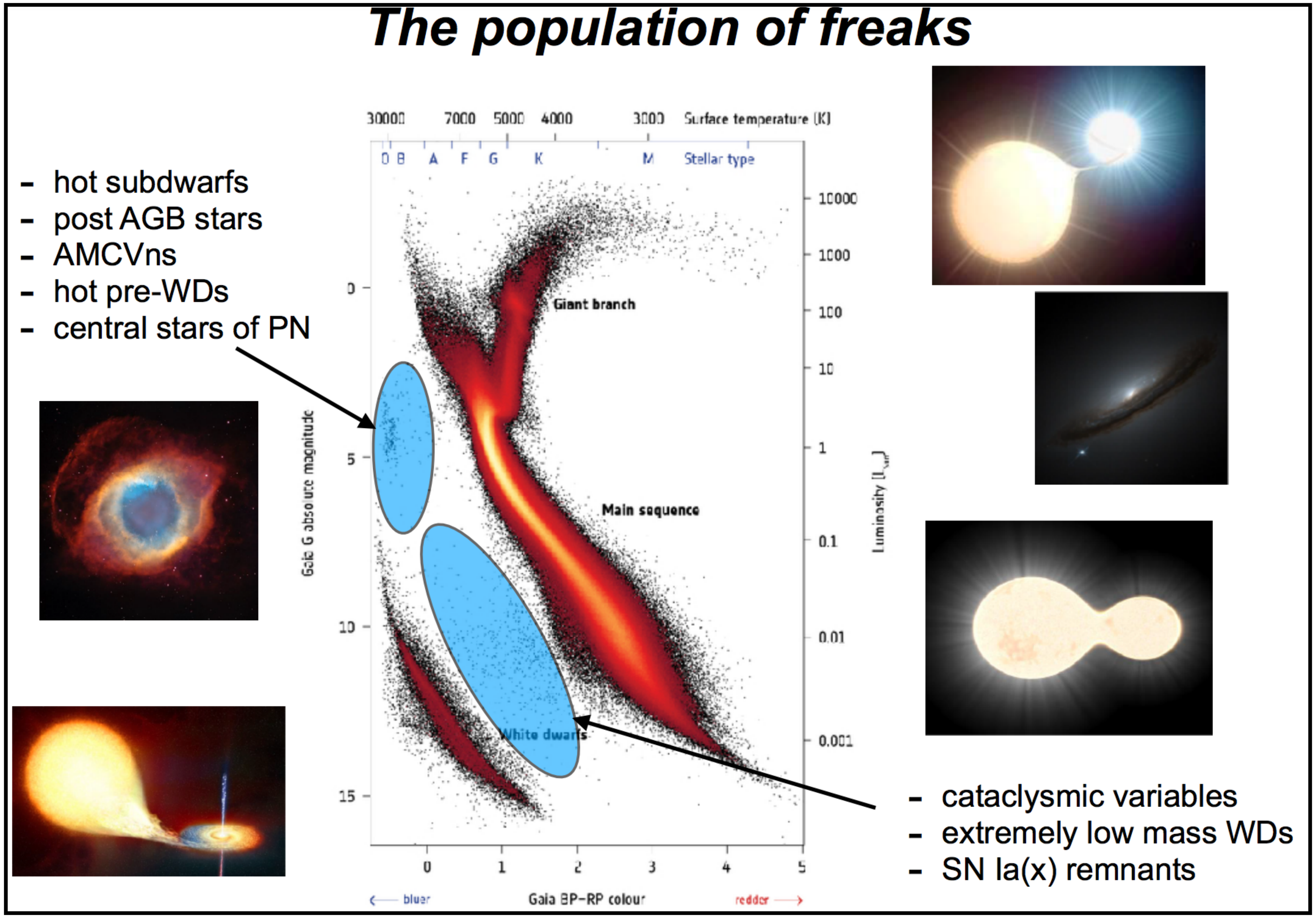
- what about the unknown?
- flexibility in surveying (target of opportunity)
- flexibility in **data-processing** to **identify** these odd things
  - unsupervised classification

From Jan van Roestel's talk
Remaining challenges for machine learning in astronomy
Outlier and novelty detection
(e.g. how to identify new types of objects/events?)

Data Processing as a Priority

- All the data that is resting….
  - e.g. APOGEE
    - fast rotators
    - RR Lyrae
    - Binaries, e.g. El Badry et al., 2018, discovery and characterization of 3000+ main-sequence binaries from APOGEE spectra - http://adsabs.harvard.edu/abs/2018MNRAS.476..528E
  - **Need automated methodologies enabling classification, discovery, characterization**

Stellar physics & stars as families



[from Kupfer presentation online]

targeting programs in Sloan V (for some), how else can combine TDA/SDSS?

Stellar Death & Interaction (& families)

- Candidate neutron stars and black holes in binary systems

T. Thompson et al., 2019 -- Discovery of a Candidate Black Hole−Giant Star Binary System in the Galactic Field https://arxiv.org/pdf/1806.02751.pdf

The neutron star and stellar black hole mass functions directly constrain the **mechanism of core-collapse supernovae**, its success and failure rate as a function of metallicity, and the physics of **binary star evolution**.

To date our **knowledge of neutron star and black hole demography is limited** -- mass measurements come from pulsar and accreting binary systems selected from radio, X-ray, and gamma-ray surveys.

The recent discovery of merging black hole and neutron star binaries by **LIGO** provides a new window on compact object masses, but these systems are an **intrinsically biased subset of the parent population.**

Price Whelan et al., 2018: Binary Companions of Evolved Stars in APOGEE DR14: Search Method and Catalog of ~5000 Companions https://arxiv.org/abs/1804.04662

Stellar Death & Interaction

- Candidate neutron stars and black holes in binary systems

[Discussion with T.Brandt - & see talk online]

- Candidates being identified using Hipparcos+Gaia DR2-> accelerations -> mass
- Need RV follow up to get orbit to isolate the neutron star black holes from the 10^5 objects being run through infrastructure to get accelerations
- Sloan V will enable radial velocities of <300m/s precision
  - enable identification of the rare neutron star & black hole objects -
  - and we will get the chemical compositions of these objects for free, to test e.g. **mass transfer**
- Gaia DR3 accelerations will enable new regime for object discovery
- Planetary systems - can characterise chemical composition [new discoveries relevant from GAIA astrometry - of order of 1000's + TESS, Kepler follow up with Sloan V]

Do we ensure we target or will we take what we get for free?

Stellar Death & Interaction

Do we ensure we target or will we take what we get for free?

- Hypervelocity stars from supernovae and the galactic center

Stellar Death & Interaction

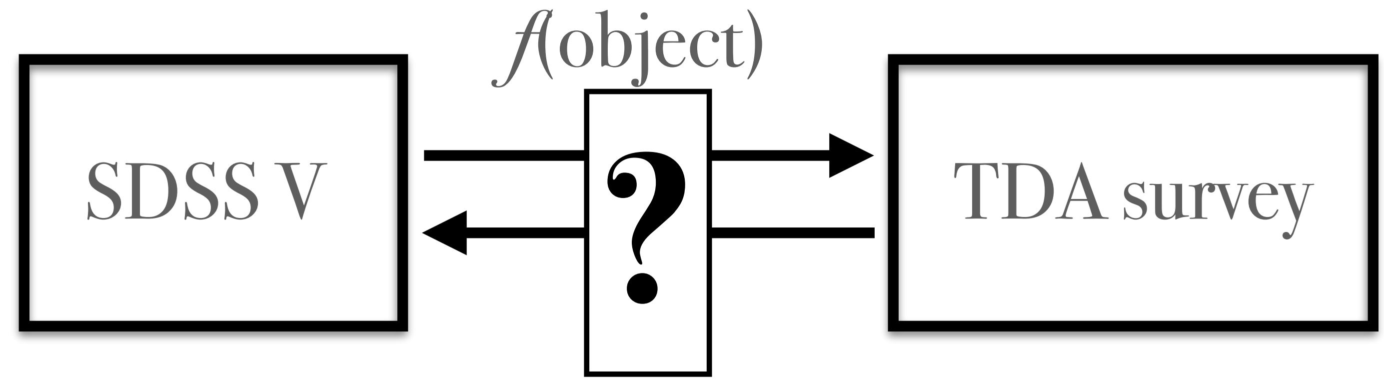
- Rare supernovae – progenitor of Supernovae Ia ? Kishalay et al., 2019 A Massive Helium-shell Double Detonation on a Sub-Chandrasekhar-mass White Dwarf http://adsabs.harvard.edu/abs/2019ApJ...873L..18D

- Powerful superluminous supernovae (SLSNe) - rare class of transients with peak luminosities 10–100 times higher than ordinary core-collapse and Type Ia SNe. e.g. AT2018cow/ATLAS18qqn - p

Graham, Matthew J et al., 2019 The Zwicky Transient Facility: Science Objectives http://adsabs.harvard.edu/abs/2019arXiv190201945G

Does Sloan V contribute here or are other facilities more suitable?

Opportunities & discussion



- Abundance anomalies linked to stellar physics and/or galactic formation by combining TD observations with SDSS abundance measurements/RV variability
- How much of this do we get for free? How much decision based targeting now?
  - Target of opportunity scope?
    - Repeat visits in SDSS to objects for RV variability/target objects in TDA?

- Sloan V can optimise multi-epoch targeting to take advantage of time-domain discovery space (neutron stars, black holes, other binary systems) to characterise parameters of system and deliver abundances for free

- Challenges in data processing to identify the unexpected and classify rare objects

- Beyond the Milky Way?

Deep Learning meets Time-Domain Astronomy

Dmitry A. (Dima) Duev

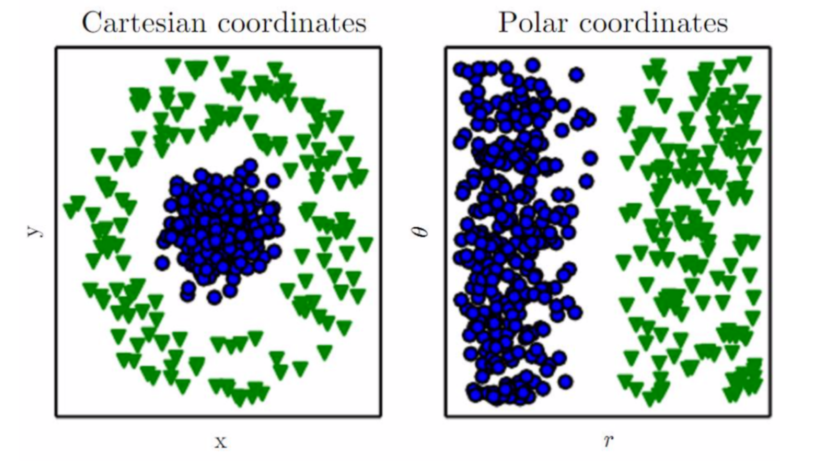
Research Scientist | Astro Dept | Caltech

duev@caltech.edu

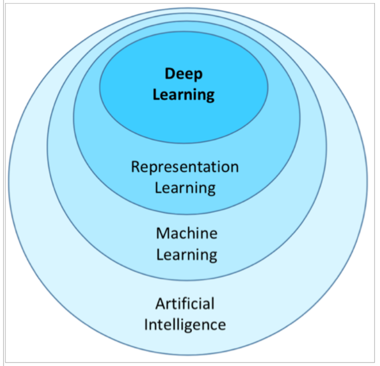
Deep Learning in one slide

- What is DL?
  - Automatically extracting useful patterns from data
- How?
  - Neural networks + optimization
- How (in practice)?
  - Python + TensorFlow and friends
- Hard part?
  - Good Questions + Good Data (lots of it!)
- Why now?
  - Data, hardware, tools, community, investment
- Where do we stand?
  - Most big questions of intelligence have not been answered nor properly formulated
- Exciting progress:
  - Image classification, semantic segmentation, object recognition, sequence-to-stuff (text-to-speech generation, machine translation), ads, search, digital assistance, GANs: generating new data, reinforcement learning…

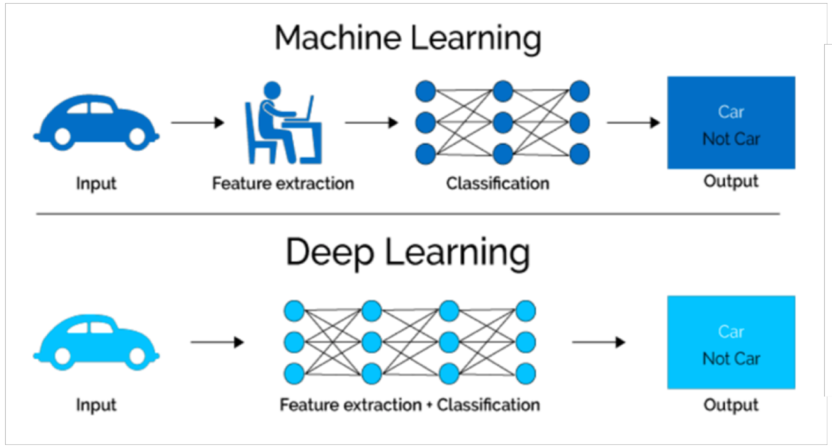
- Representation matters:

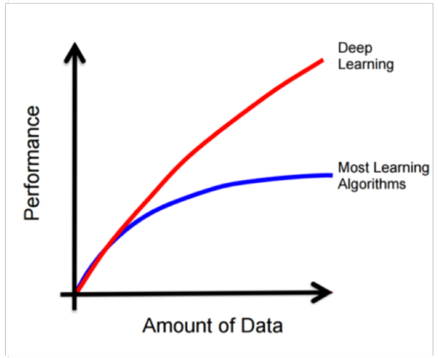


Task: Draw a line to separate the **green triangles** and **blue circles**.



- Why Deep?

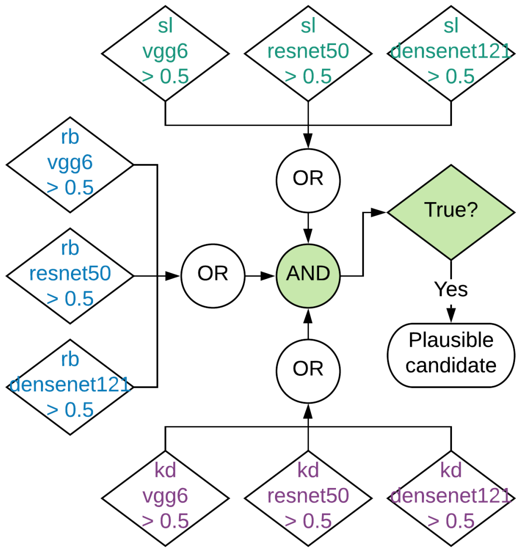


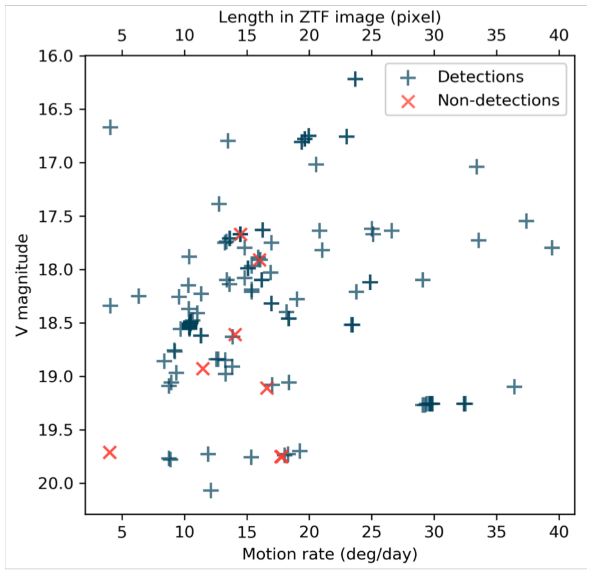


DeepStreaks: finding real streaks in ZTF data

- Convolutional-neural-network, deep-learning system designed to efficiently identify streaking FMOs (e.g. near-Earth asteroids) in ZTF data
  - "rb": bogus or real streak? Identify all streak-like objects, including actual streaks from FMOs, long streaks from satellites, and cosmic rays
  - "sl": long or short streak?
  - "kd": ditch or keep? Is this a real streak, or a cosmic ray/some other artifacts?
- Three different CNN architectures within each family: VGG6, ResNet50, and DenseNet121
- ~30k training examples; used Zwickyverse for labeling; trained on GPU

Duev+ 2019, MNRAS

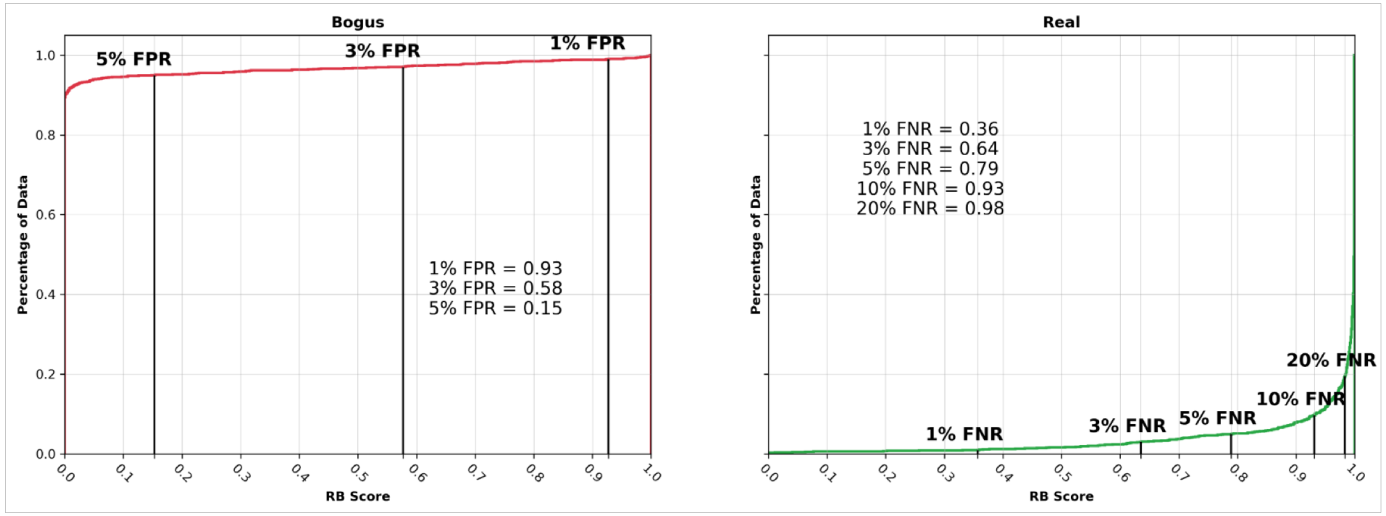


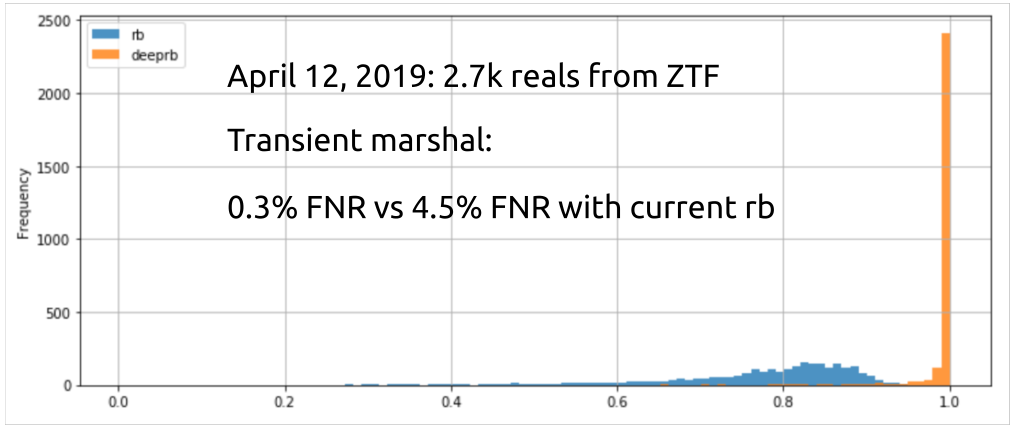


- 96-98% true positive rate, depending on the night
  - Quantified by performance on test data sets and using known NEOs observed by ZTF
- Below 1% false positive rate, **50x-100x improvement over original RF classifier**
- Near-real-time operations; below 10 min per day spent by human scanners vs ~hours with original RF classifier
- 25 confirmed new NEAs
  - Another 30+ "lost" due to insufficient follow-up

braai: deep real-bogus classifier for ZTF

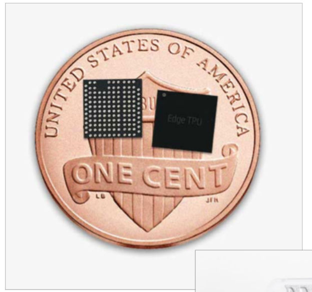
- braai: bogus/real adversarial artificial intelligence
- CNN-based architecture ("VGG6")
- Input: stacked triplets [science, reference, ZOGY]
- ~30k training examples; used Zwickyverse for labeling; trained on GPU
- ~2% FPR and FNR at rb=0.5





Google's Edge TPUs:

- Compiled (uint8) model -> same performance
- 7 minutes to process 200k alerts, ~20-40x beefy multi-core desktop
- ~$100 ($75 TPU + $35 Raspberry Pi)



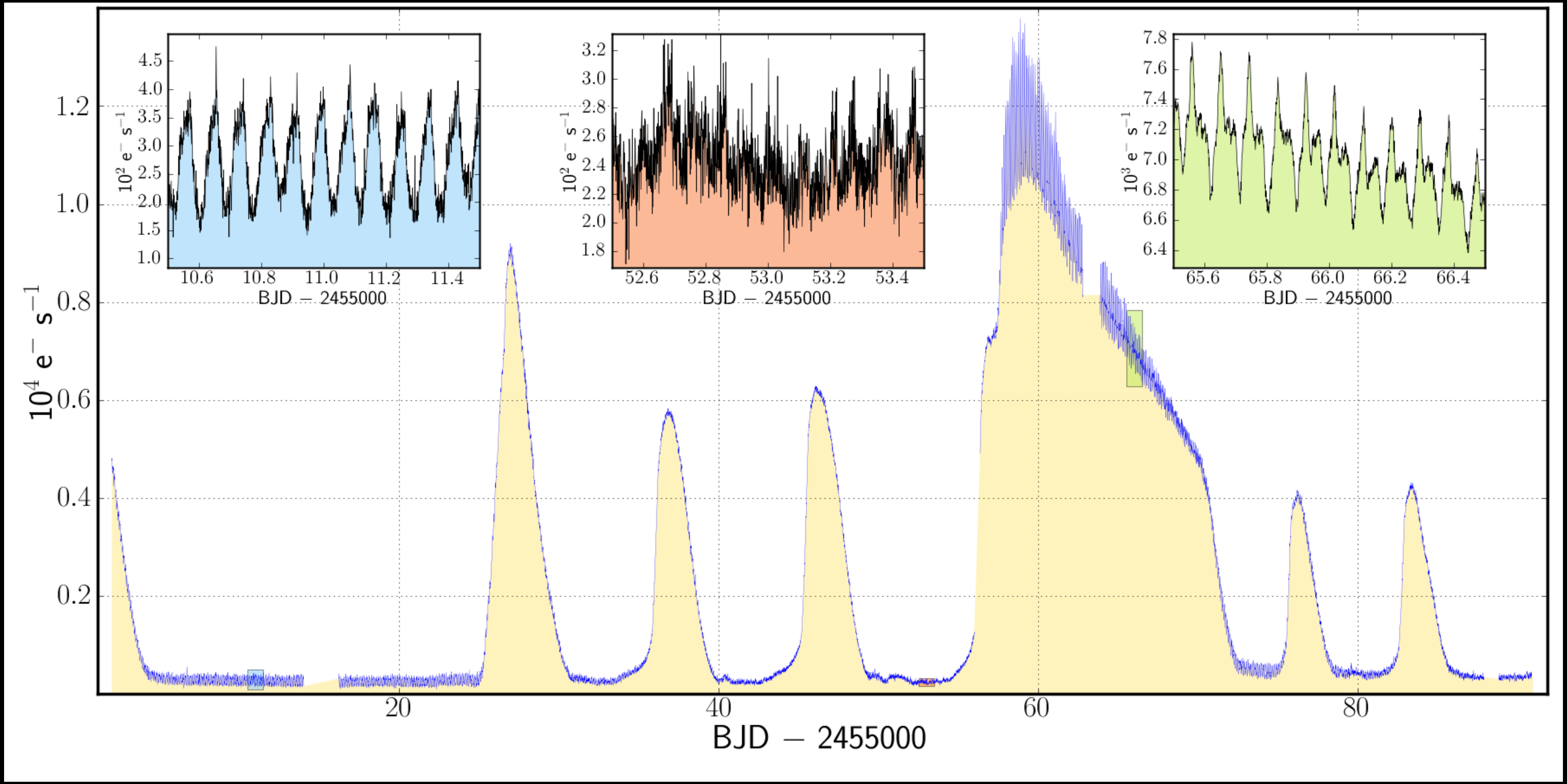
Duev+ 2019, in prep.

Why should I care?

- Got a classification/regression problem? DL is here to help
  - Images + light curve + spectrum
  - Training data sets are critically important
- Variable sources
  - Hierarchical classification -> taxonomy
  - Anomaly detection
  - population studies, small populations of anomalous variables
- Aperiodic sources
  - discovering new AGN, color variability

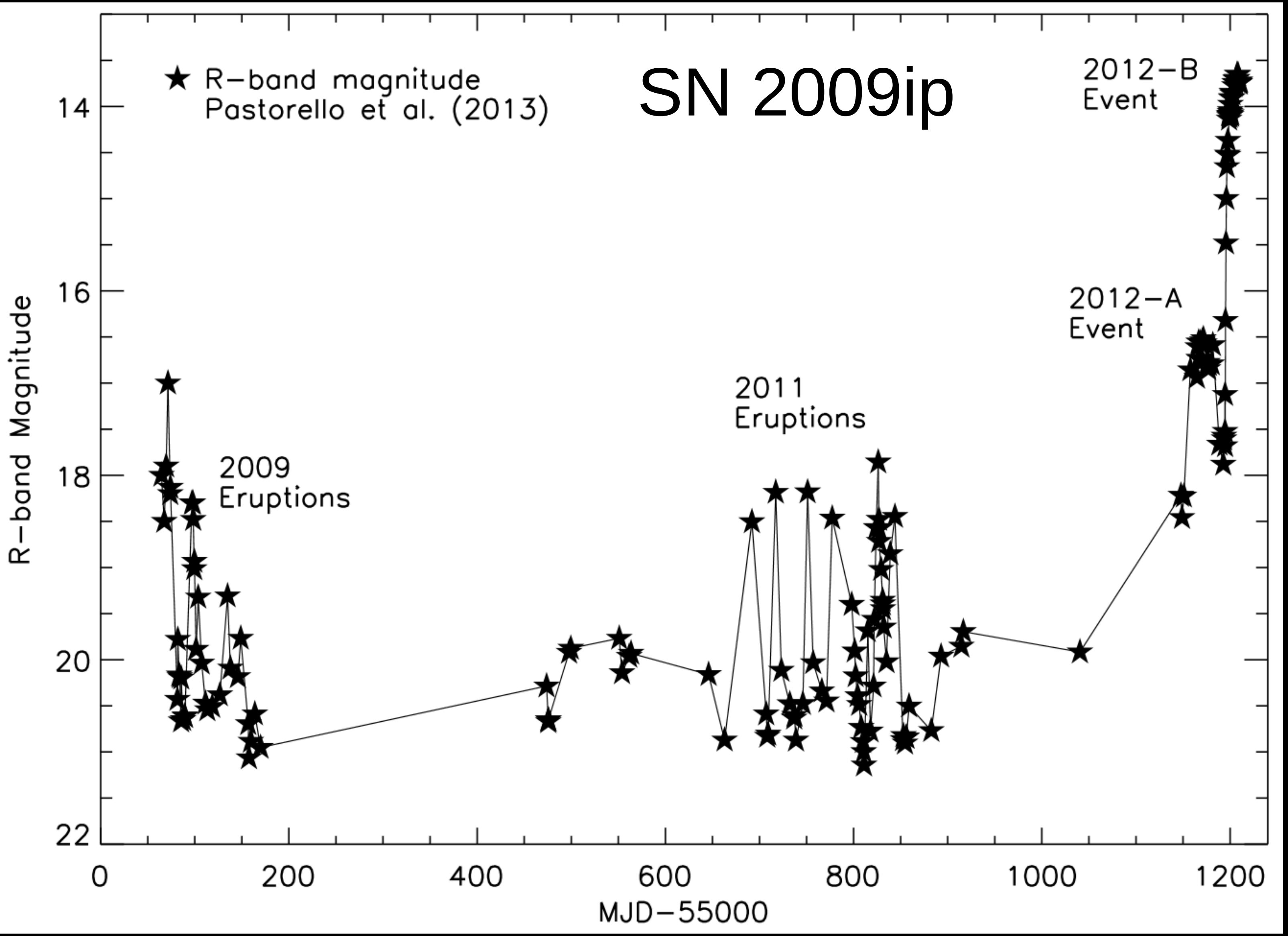
Stellar Outbursts

Jim Fuller



Pre-Supernova Outbursts

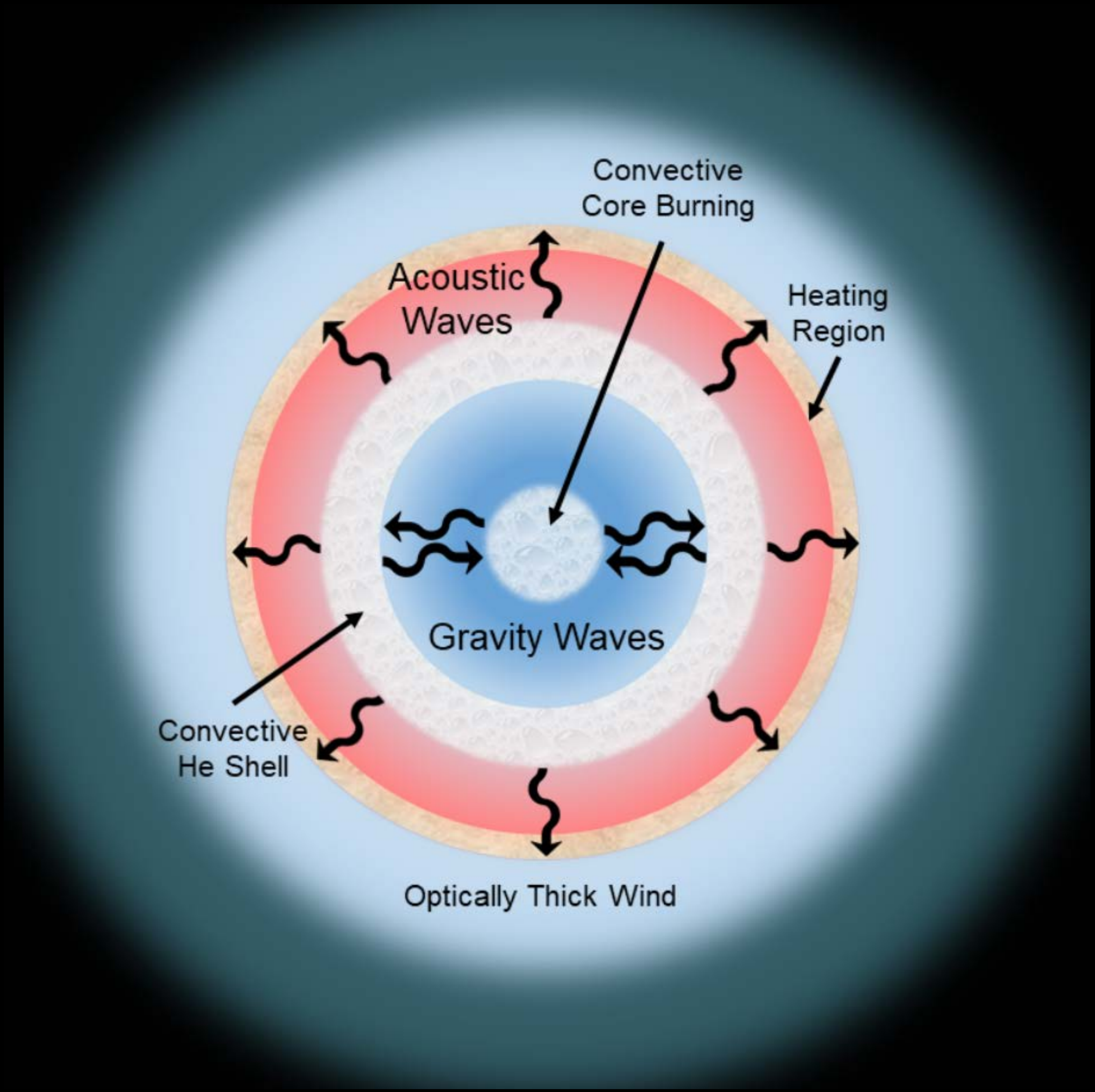
- Pre-SN outbursts observed or inferred for many types of SNe



Graham et al. 2014

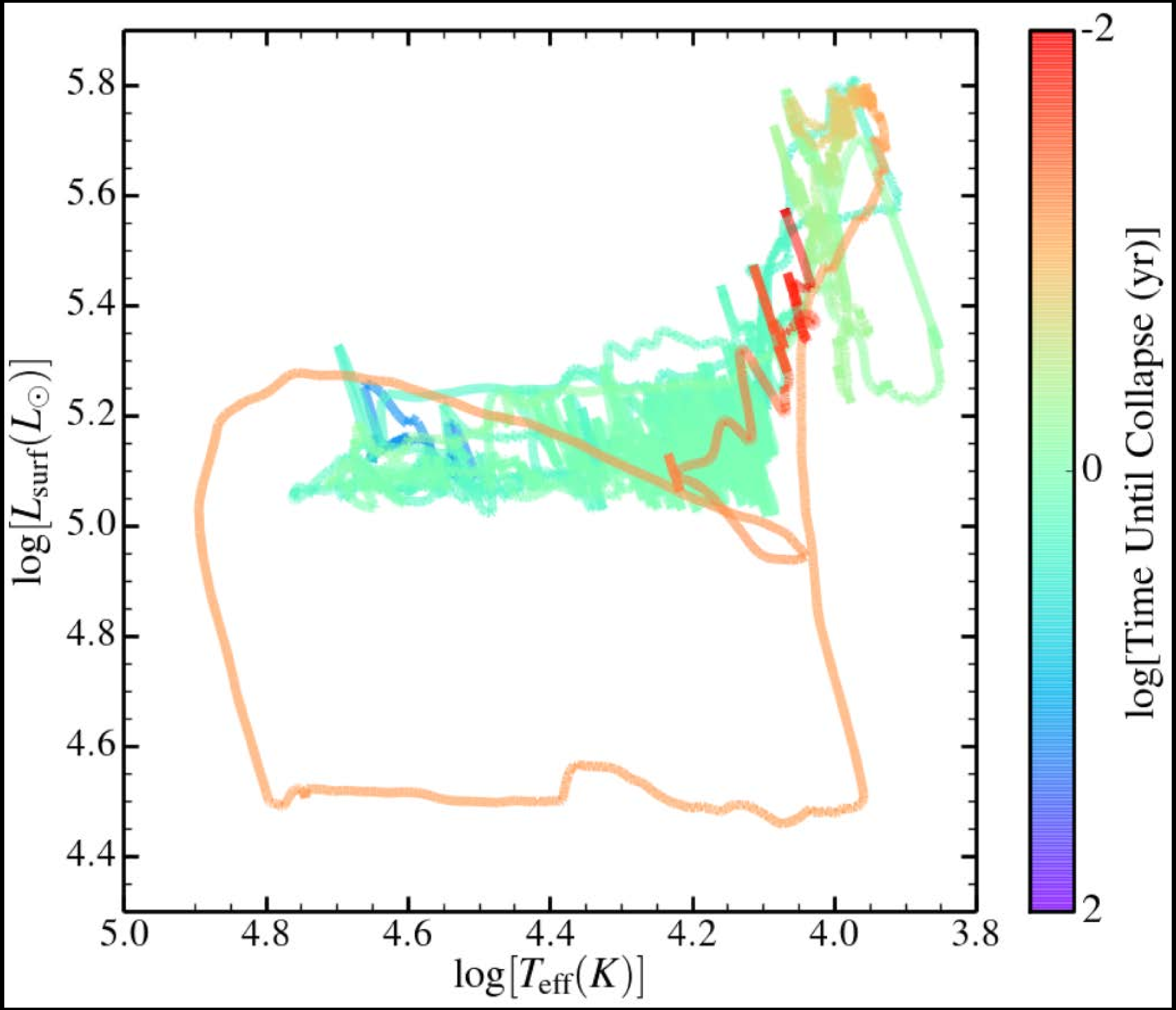
Wave-driven pre-SN outbursts

- Waves generated by convection in core
- Waves damp near stellar surface
- Wave heat unbinds launches super-Eddington wind



Wave energy transport may cause pre-SN outbursts

Quataert & Shiode (2012)
Shiode & Quataert (2014)

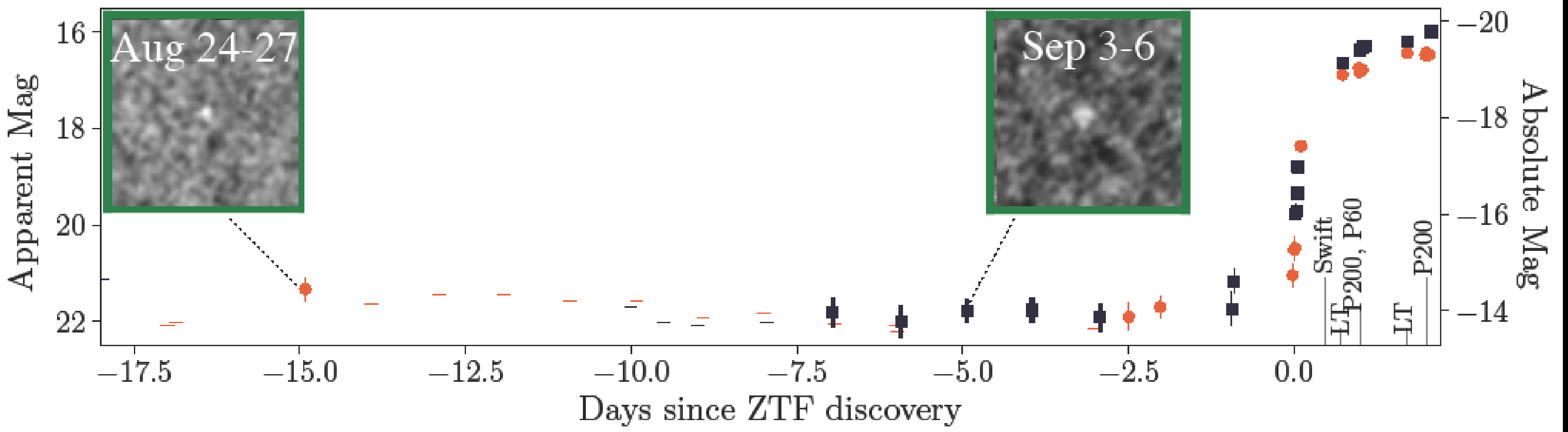


Fuller & Ro 2018

ZTF can detect progenitors

Search for pre-explosion emission

ZTF coaddition pipeline: Danny Goldstein (Hubble Fellow, Caltech)



First definitive pre-explosion detection of a Ic-BL
(but see also PTF11qcj; Corsi et al. 2014)

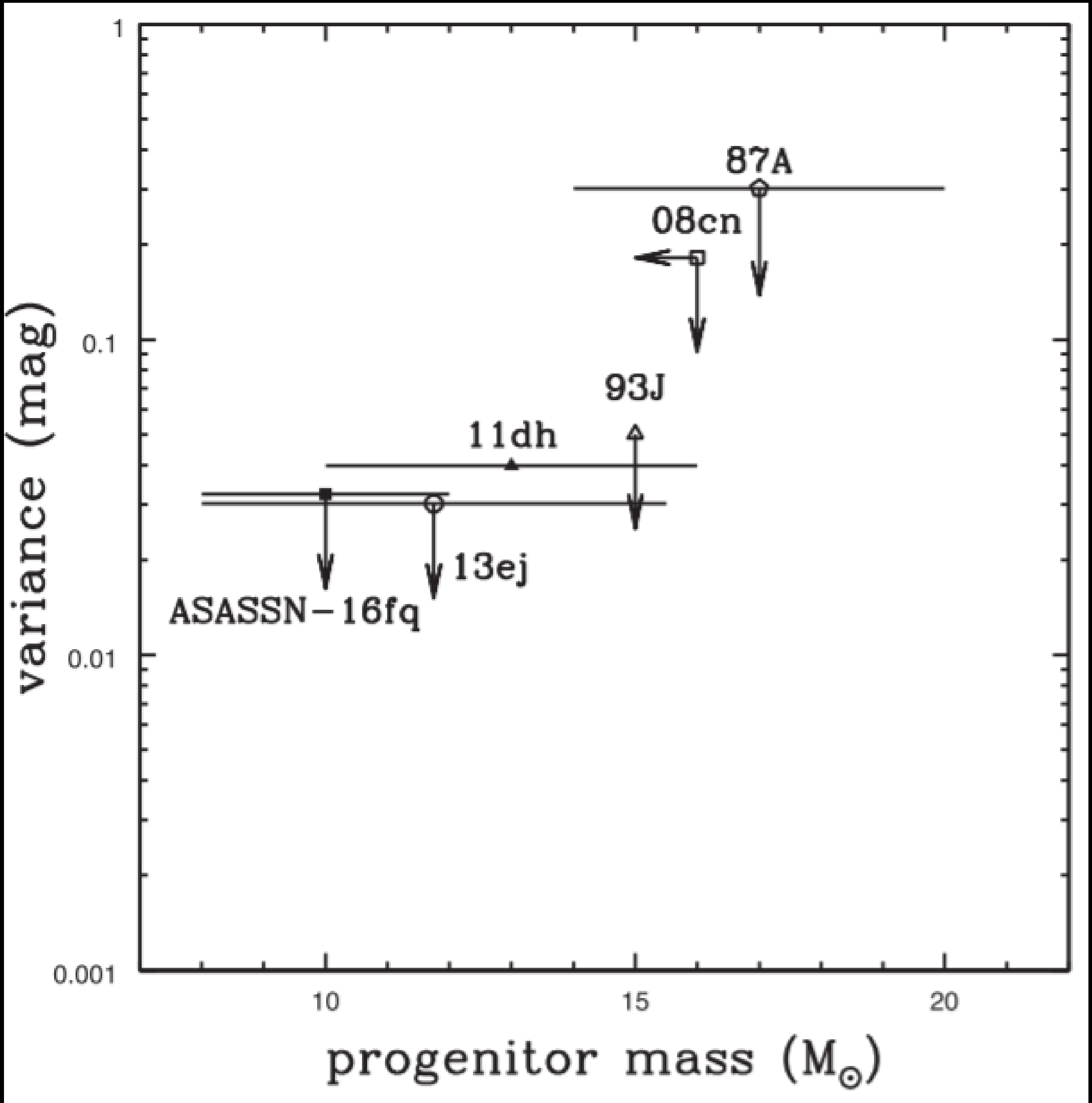
$$R_{\rm sh} = R_* + v_{\rm w} t \approx (8.64 \times 10^{12}\,{\rm cm}) \left(\frac{v_w}{1000\,{\rm km\,s^{-1}}}\right) \left(\frac{t}{\rm day}\right)$$

$\sim 10^{14}$ cm at 10 days

Ho et al. 2019

Variability of Progenitors

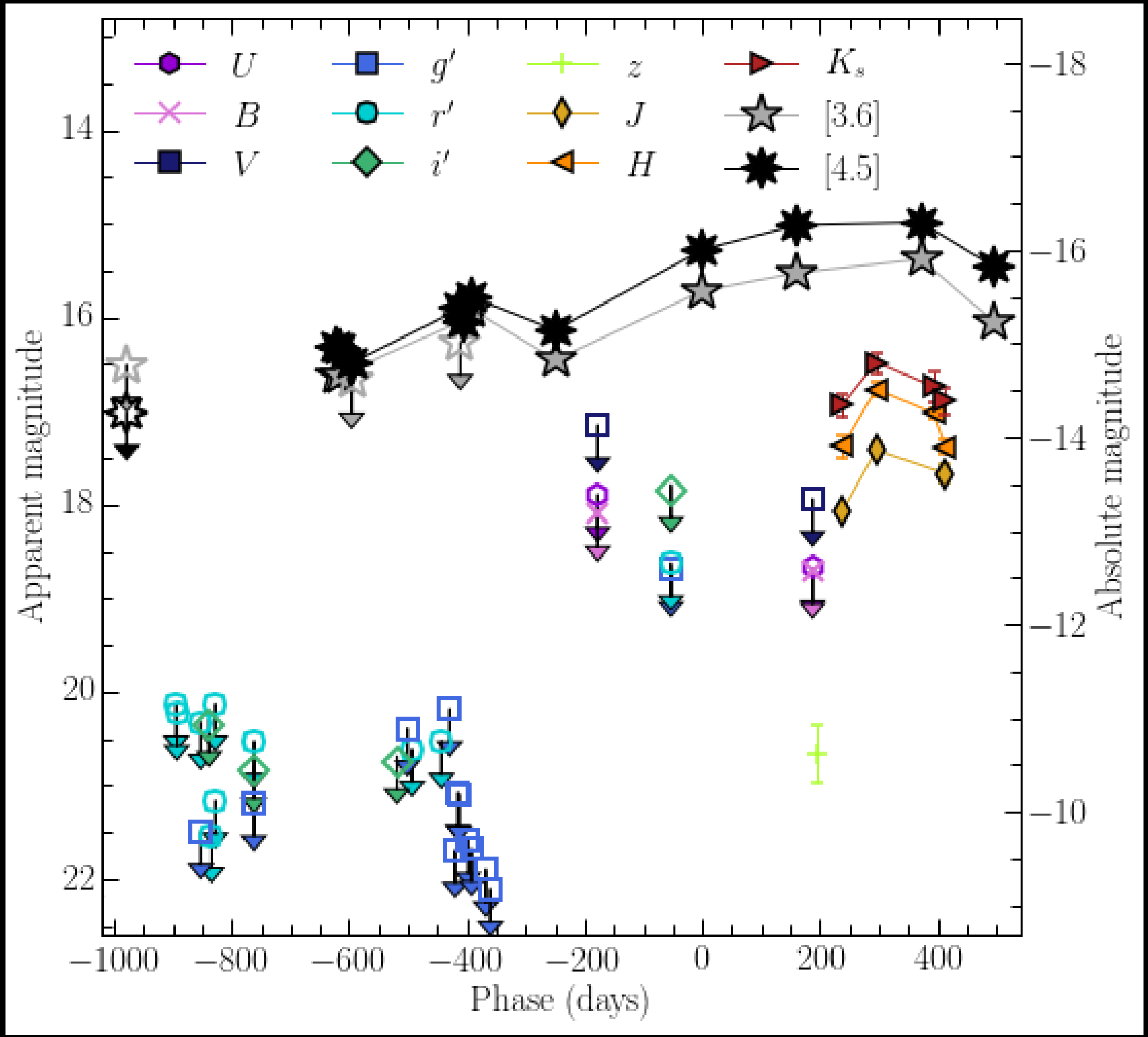
- Outbursts may be uncommon

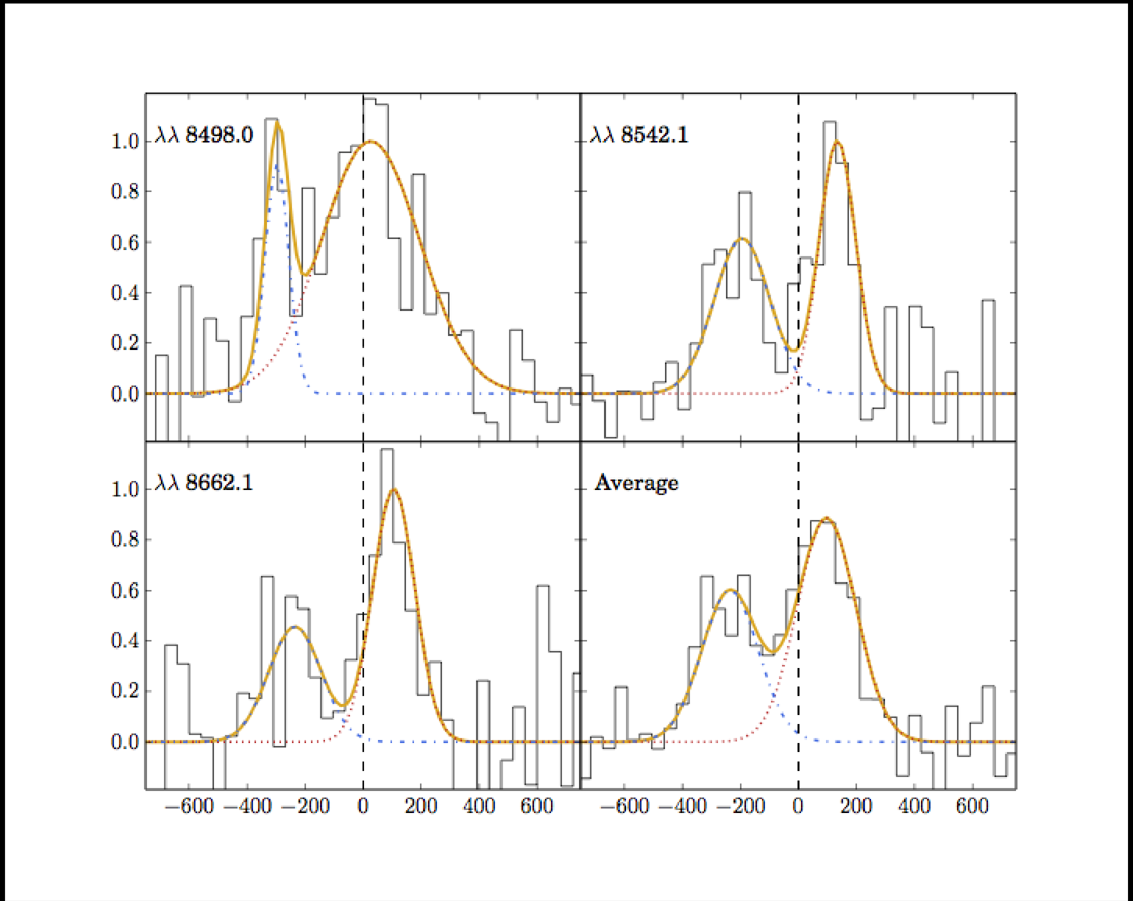


Kochanek et al. 2017

Multiple, luminous IR outbursts before terminal explosion

Jacob Jencson





Jenson et al. 2019a

SPIRITS is discovering a wide range of IR transient sources

Jacob Jencson

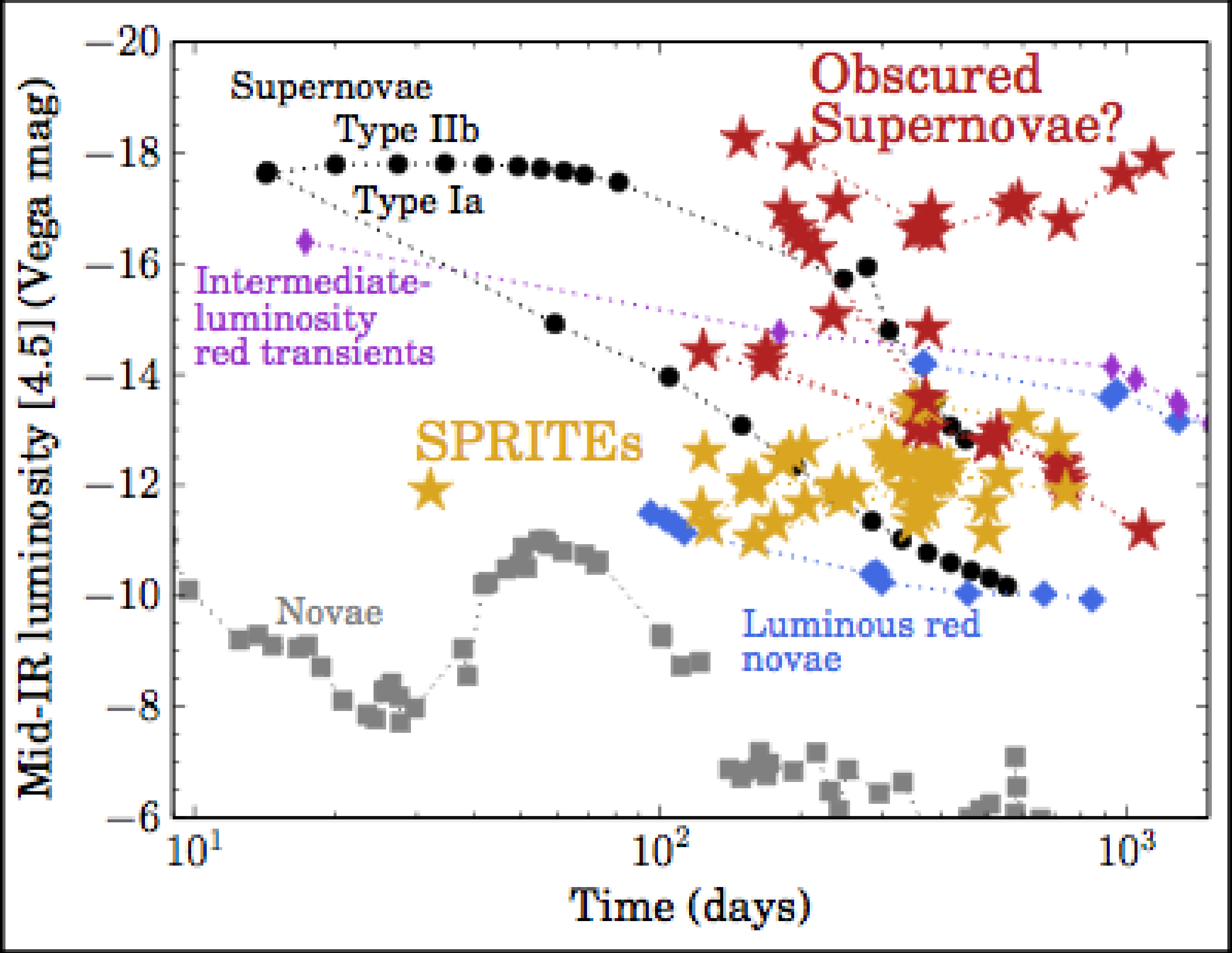
Identified 131+ transients

-49 known supernovae

-10 candidate obscured supernovae

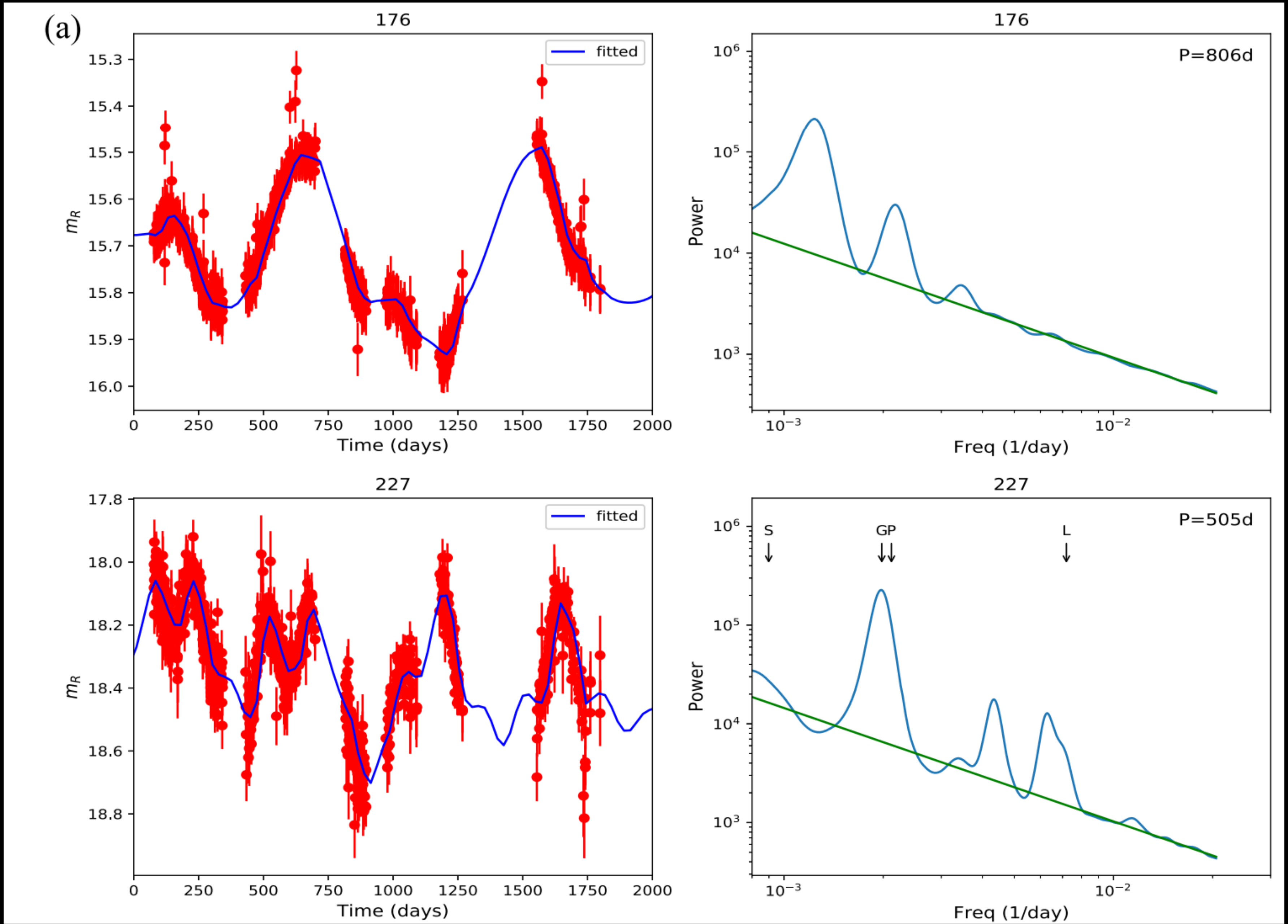
-8 likely classical novae

-64 eSPecially Red Intermediate-luminosity Transient Events (SPRITEs)

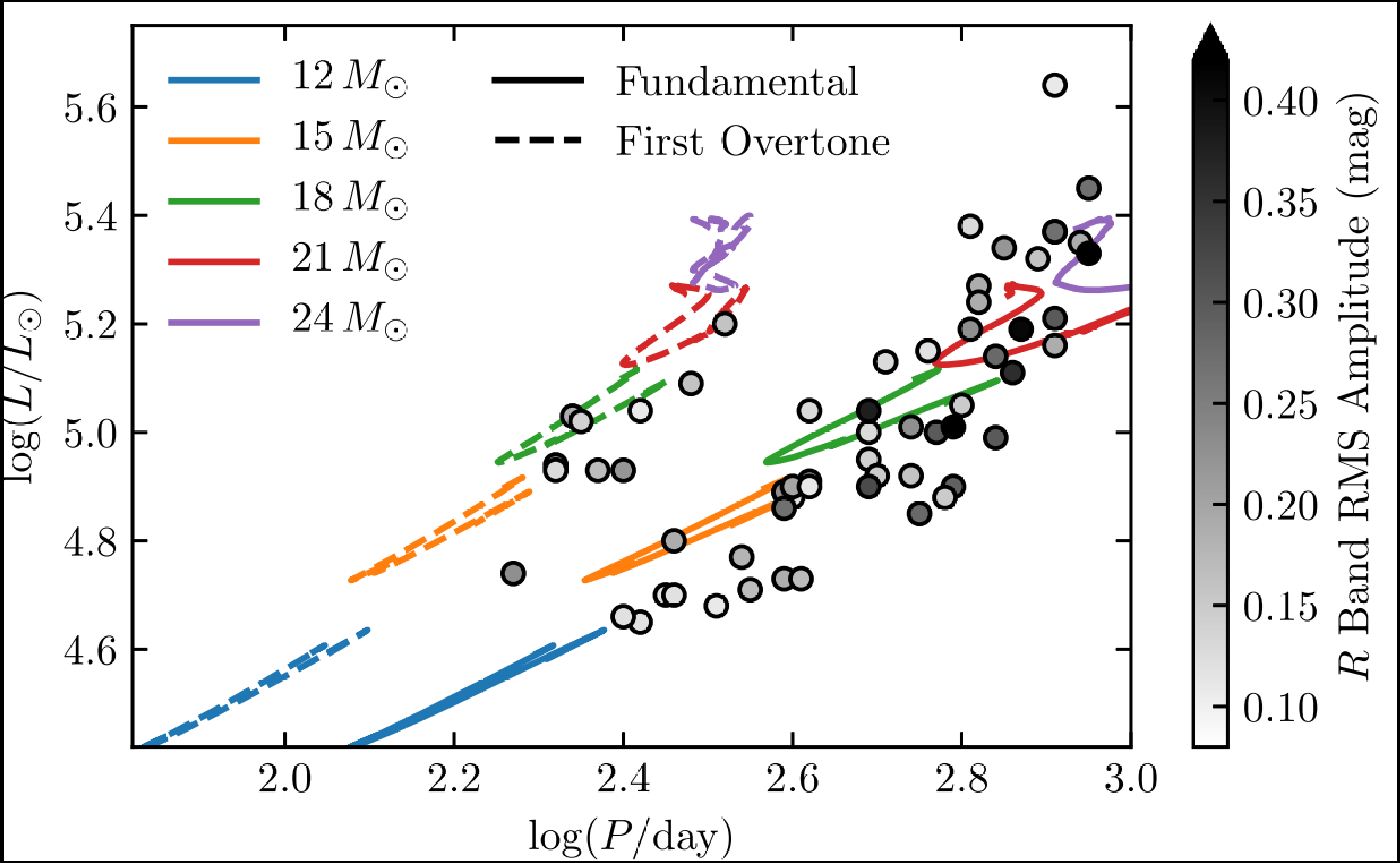


Red Supergiant Variability

- Variable RSGs in M31 with PTF



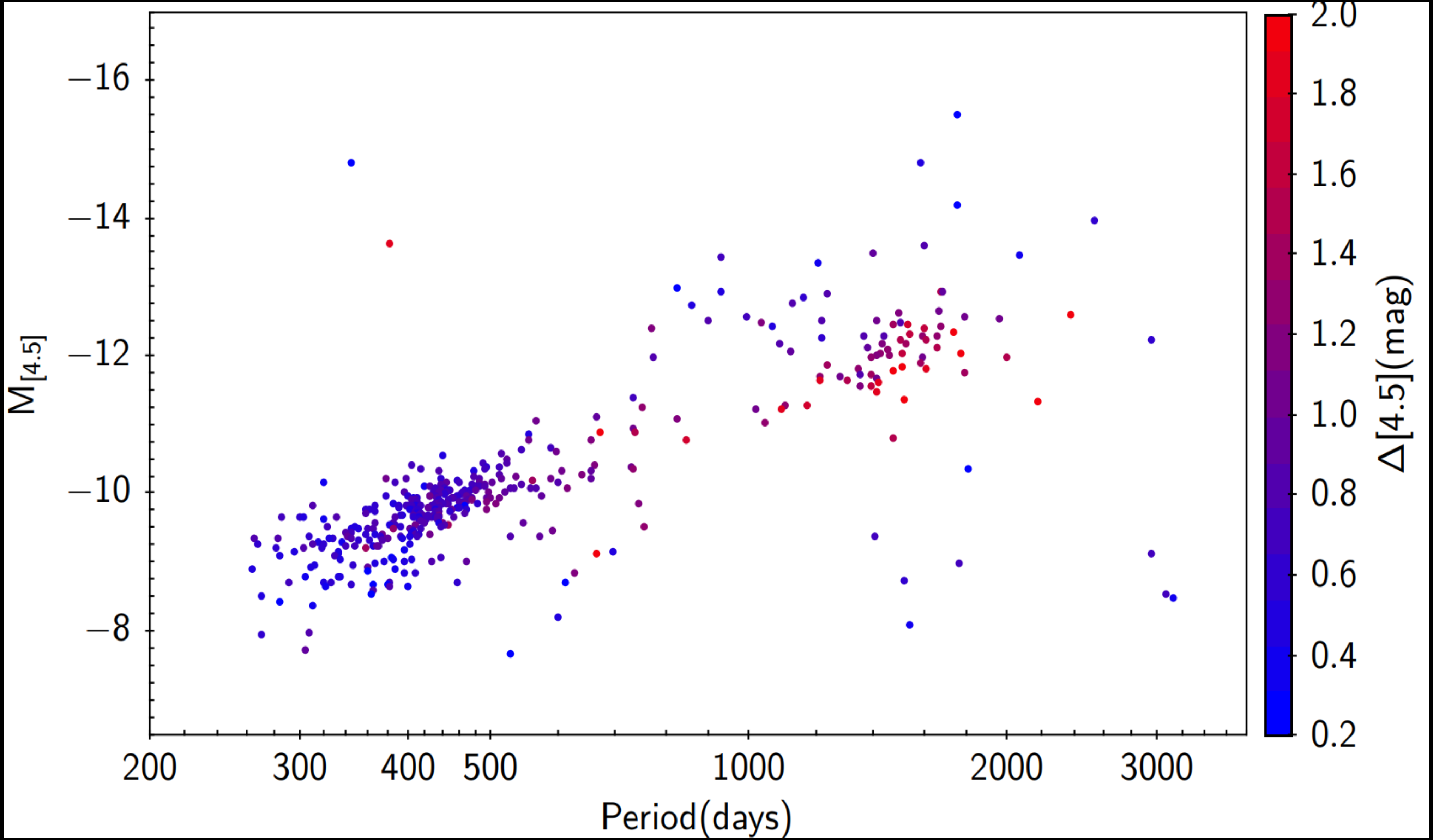
Soraisam et al. 2018



Soraisam et al. 2018

Very Long Period Variables

Huge variability!

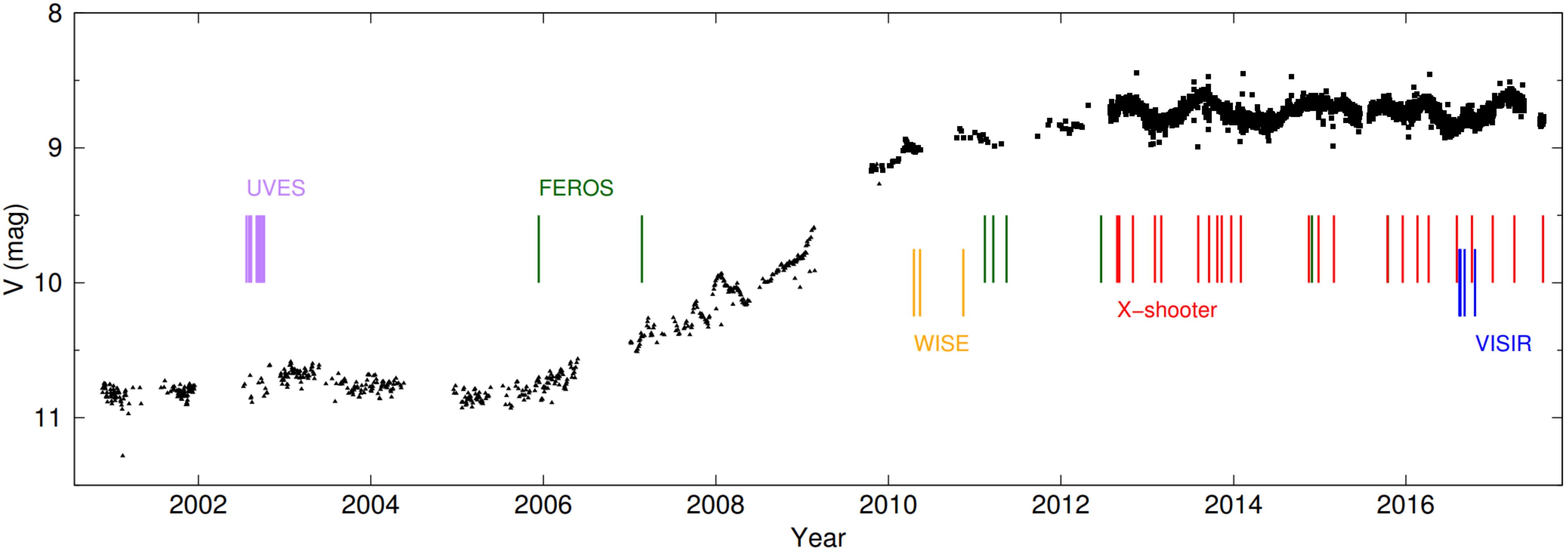


Karambelkar et al. 2019

SN Progenitor Masses

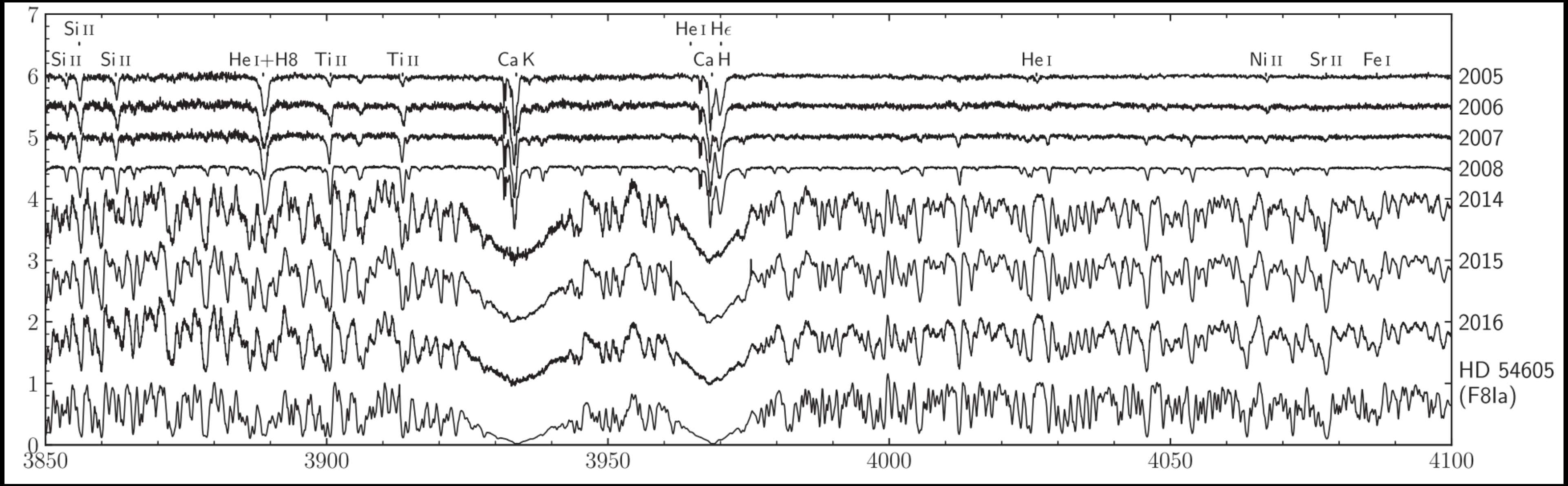
- Evidence for lack of high-mass (M > 20 Msun) RSG SN progenitors
- Masses estimated from color and magnitude, stellar model tracks
- Can we measure RSG masses in local group to calibrate this relation?

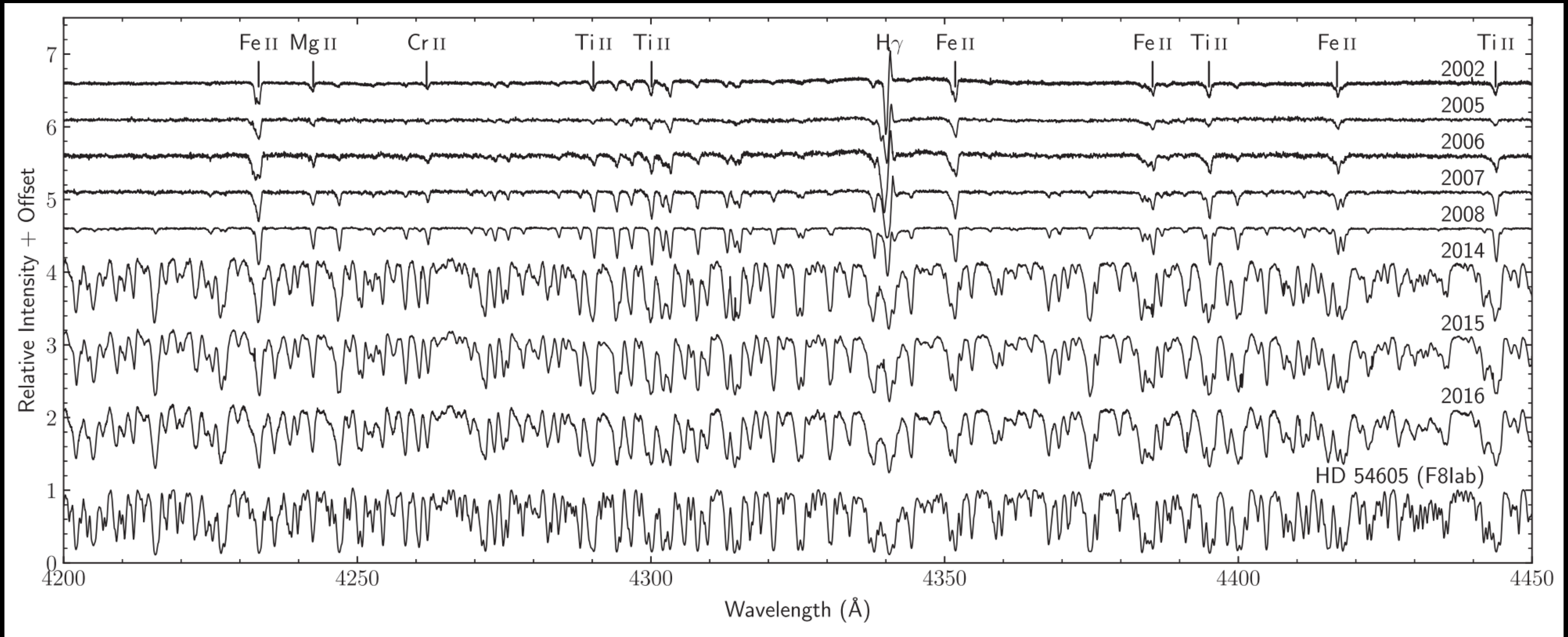
Luminous Blue Variables



Mehner et al. 2017

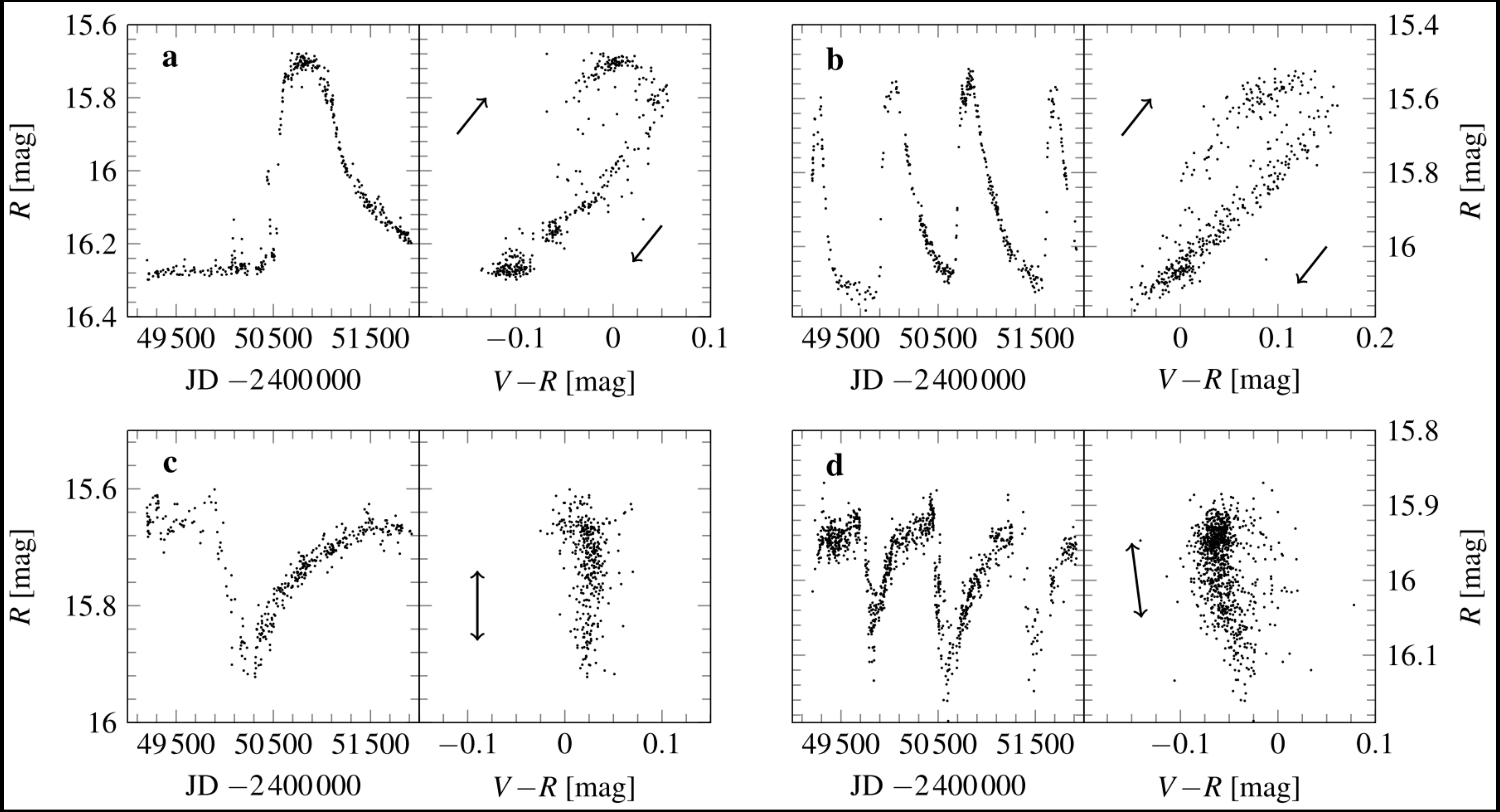
Spectral Variability





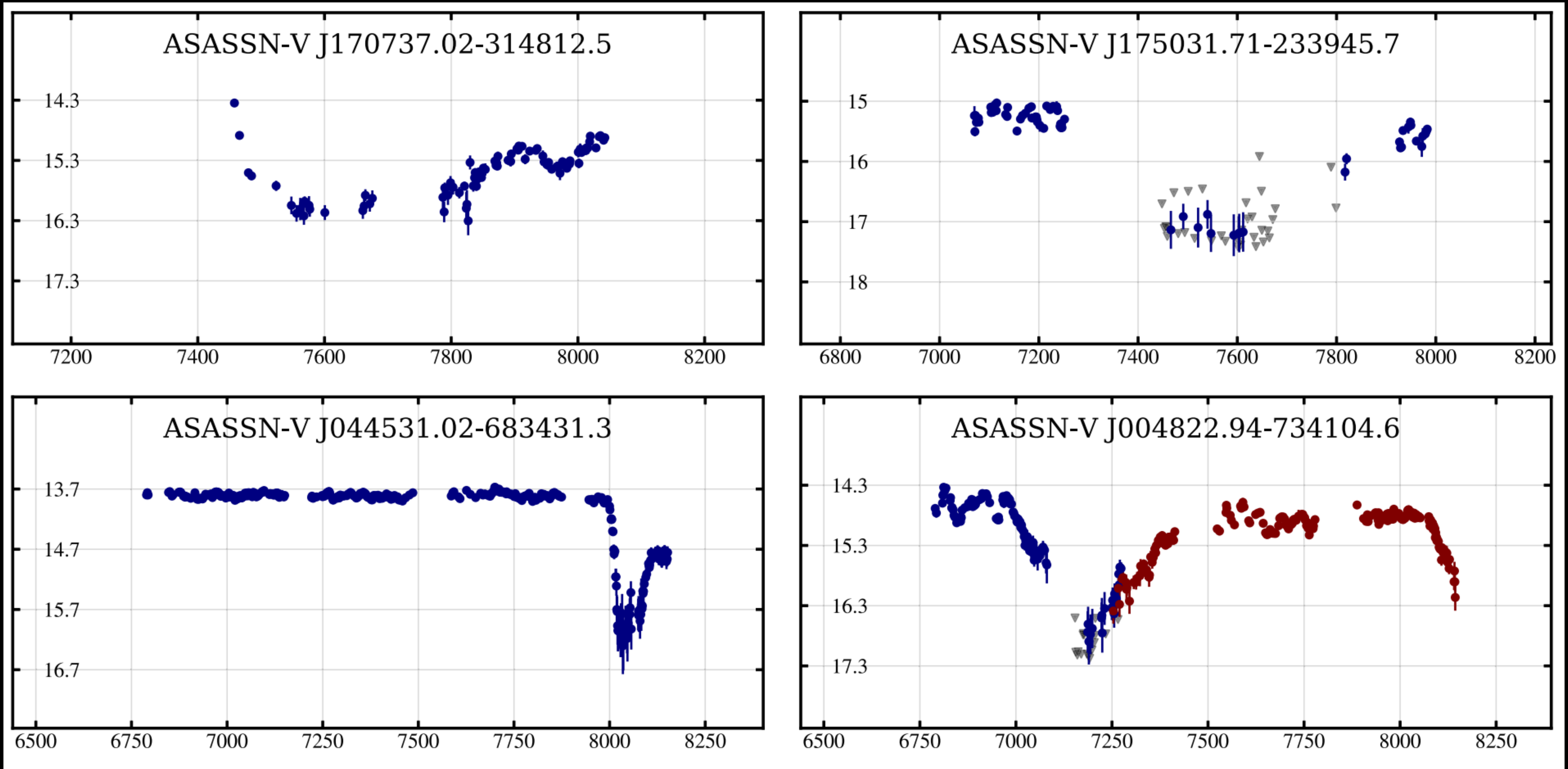
Campagnolo et al. 2018

Be Star Outbursts



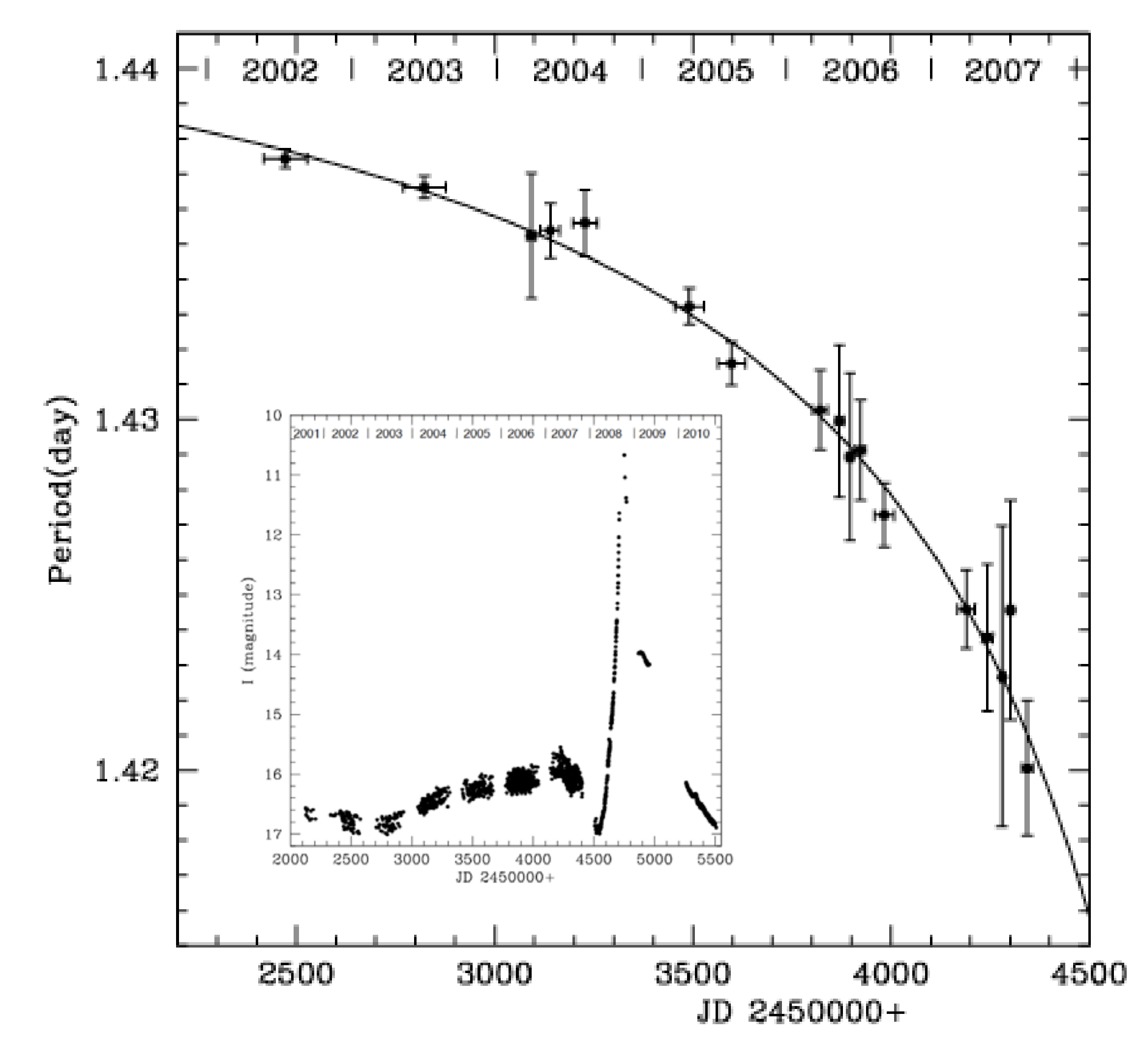
Rivinius 2013

R Coronae Borealis Stars

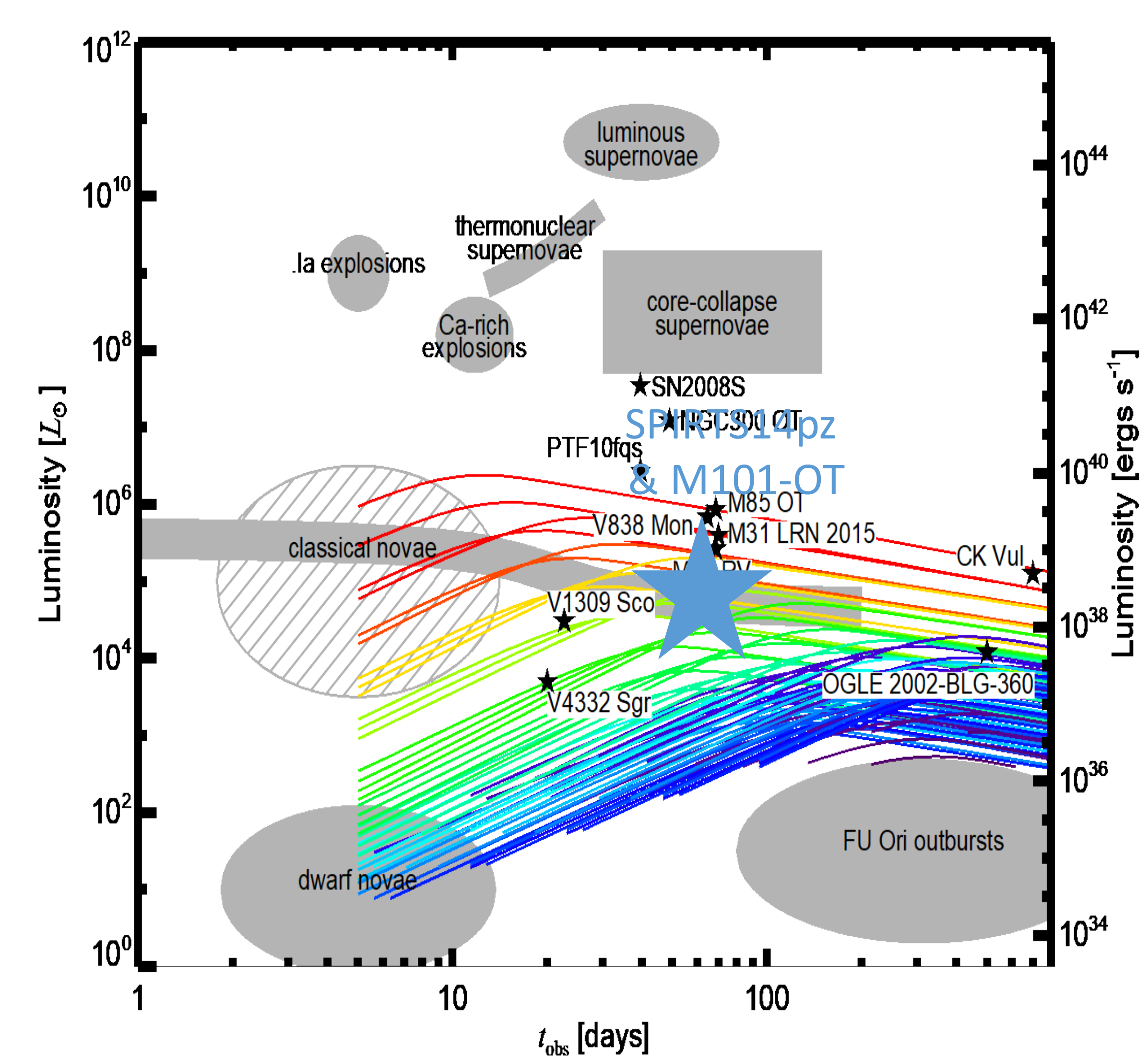


Shields et al. 2019

Stellar mergers



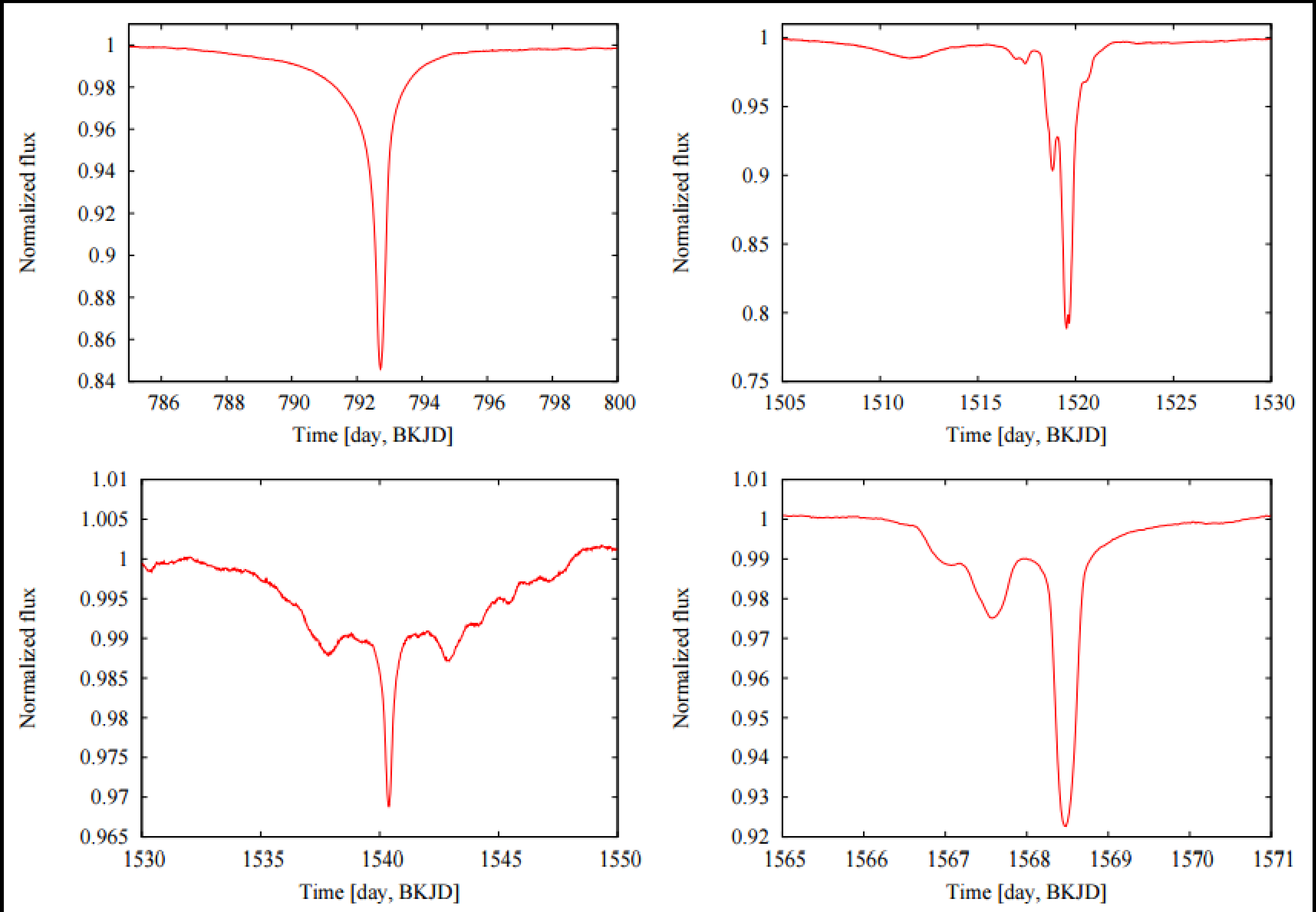
Tylenda et al. 2011



Ivanova et al. 2013, Pejcha et al. 2015

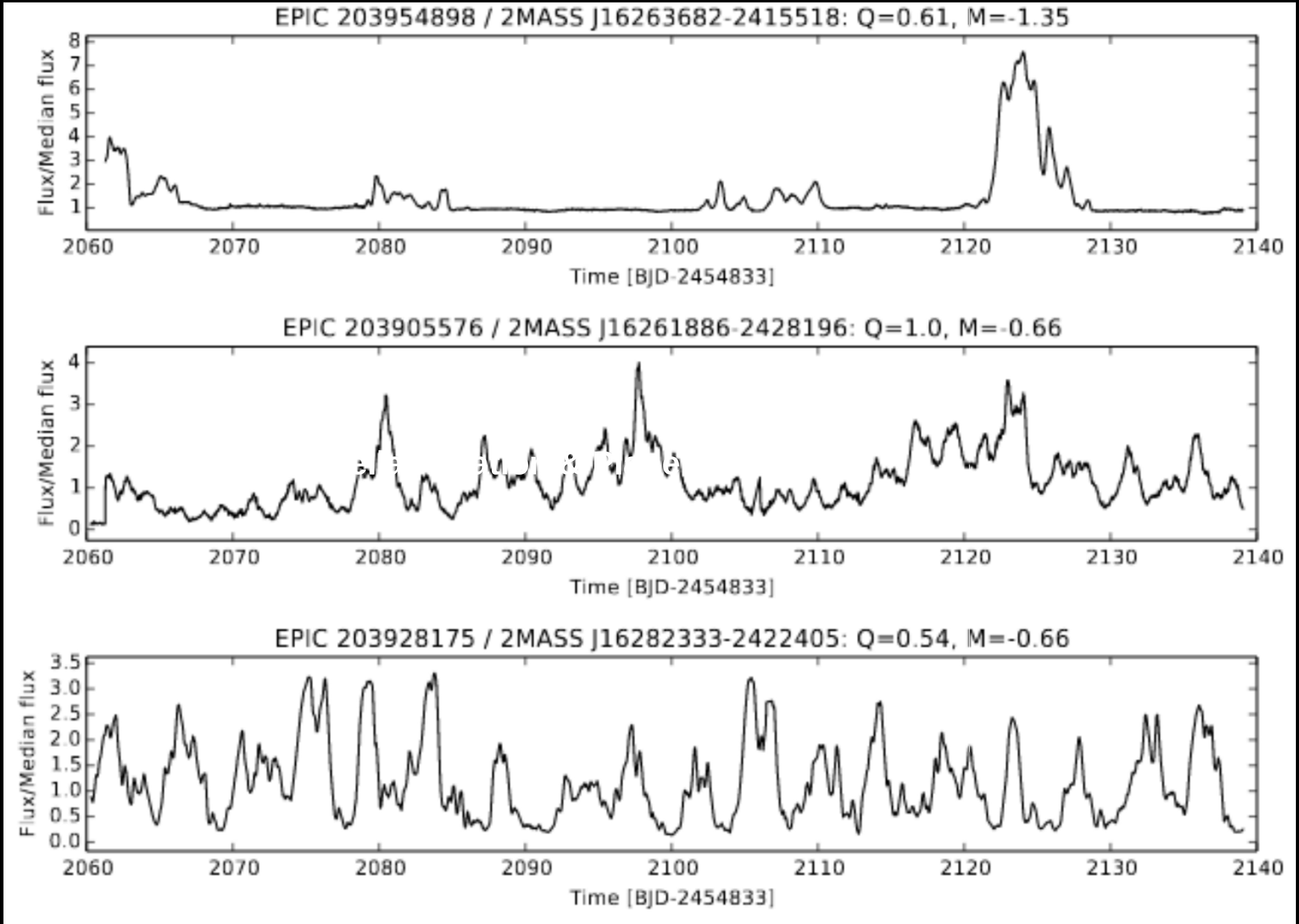
Peculiar stars

e.g., Tabby's star



Boyajian et al. 2016

Variable Pre-MS Stars

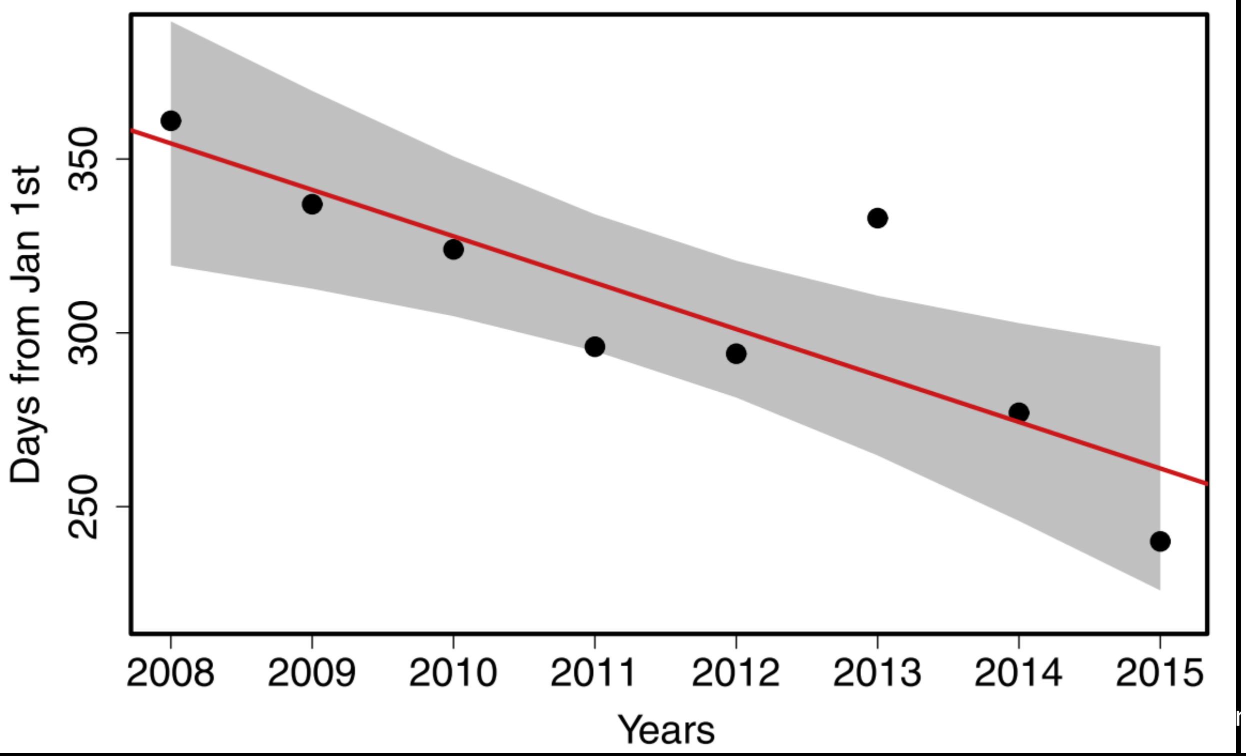


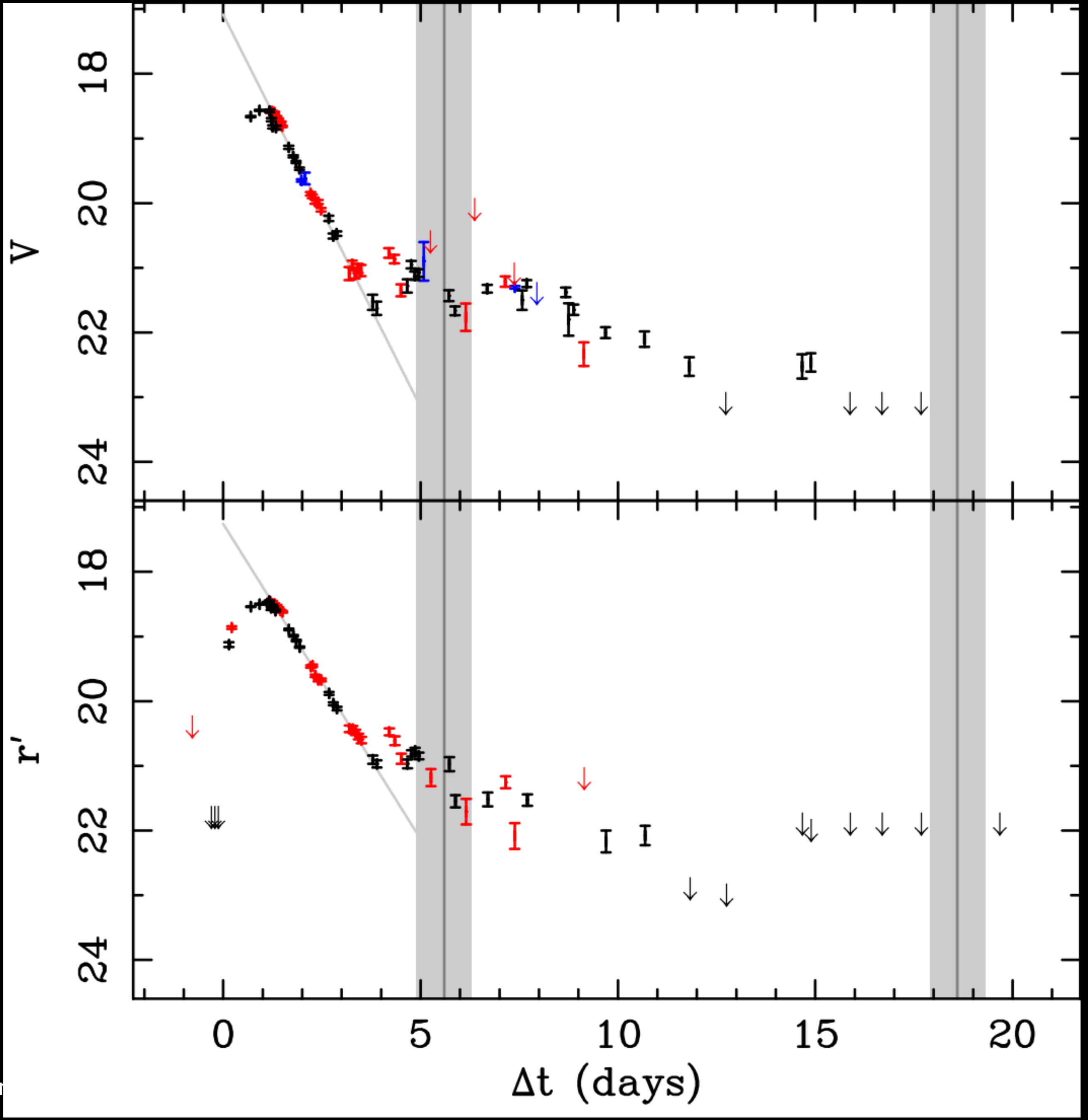
Cody et al. 2017

Novae

Fastest recurrent nova: M31N 2008-12a

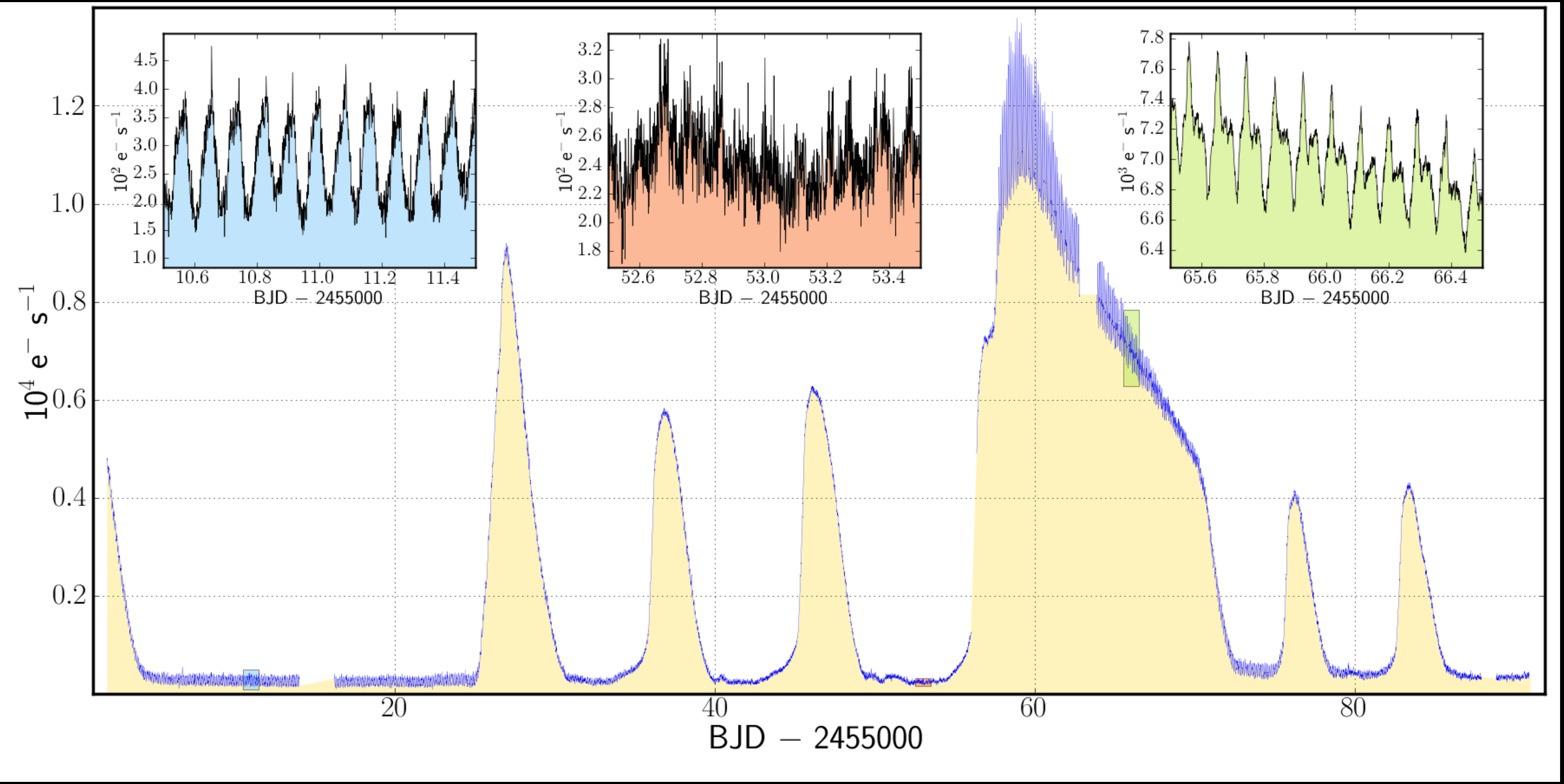
Darnley et al. 2016



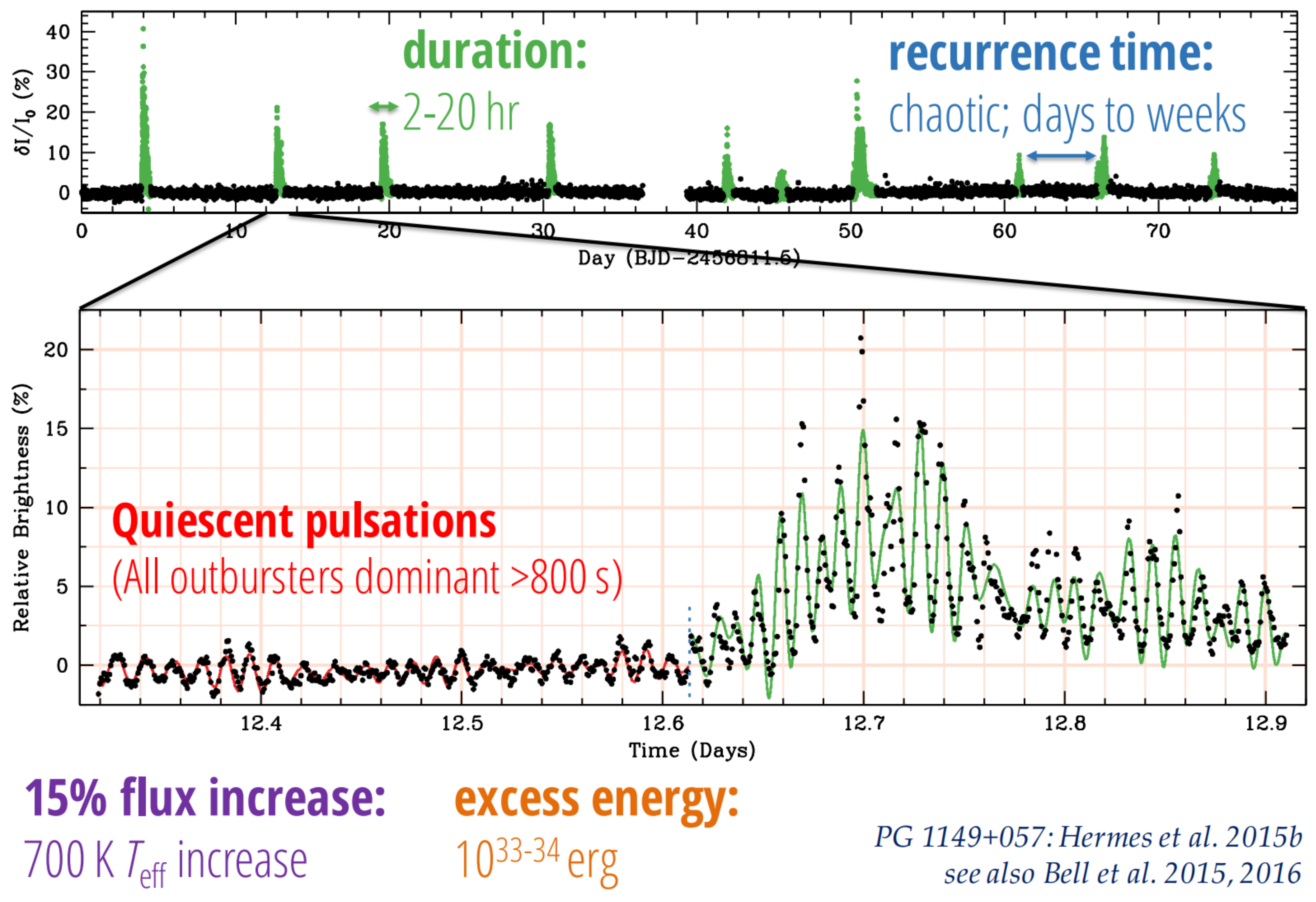


Dwarf Novae

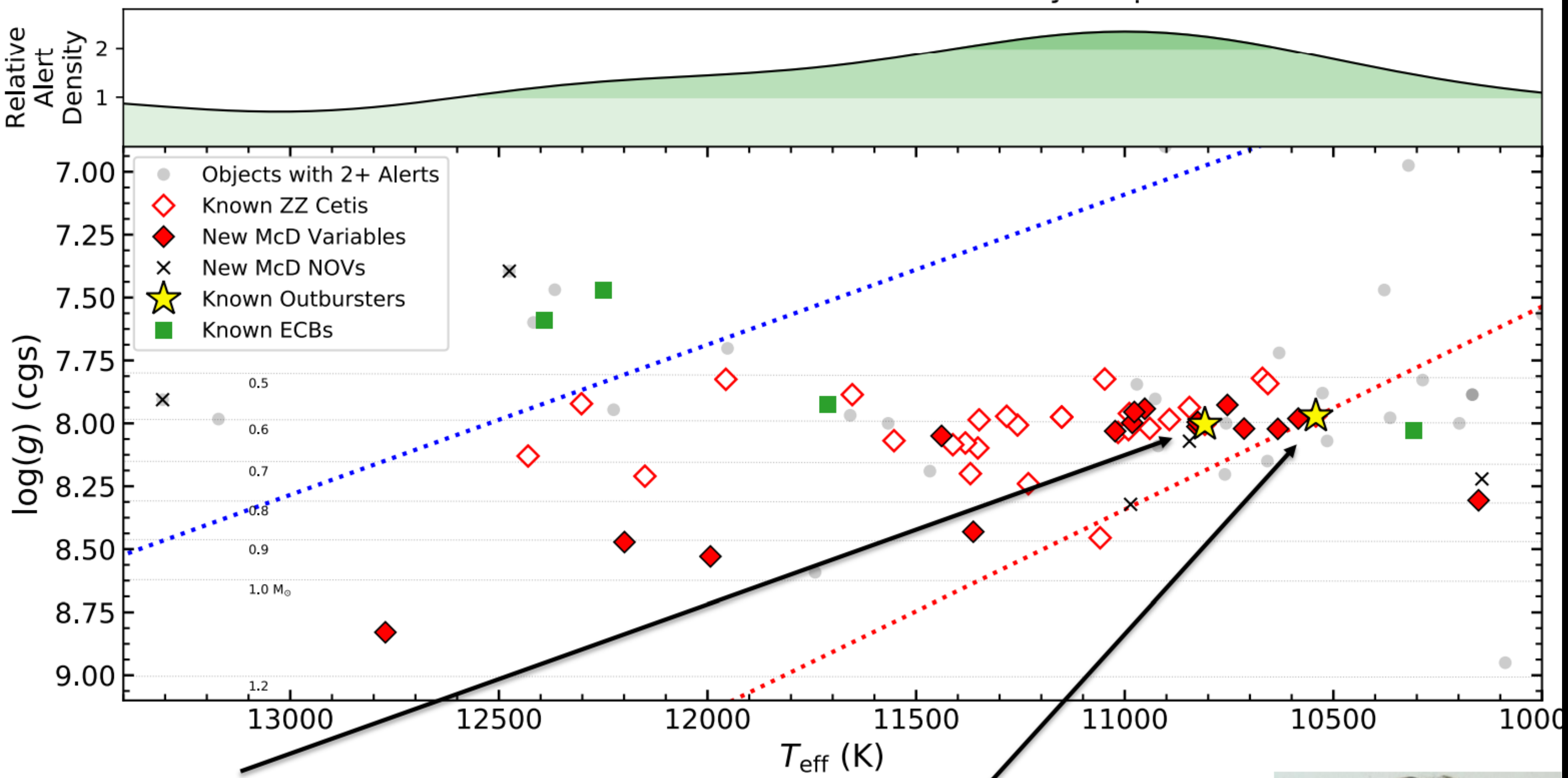
-Accretion disk instabilities of CVs



White Dwarf Outbursts



Overdensity of ZTF Alerts Near Outbursting White Dwarfs



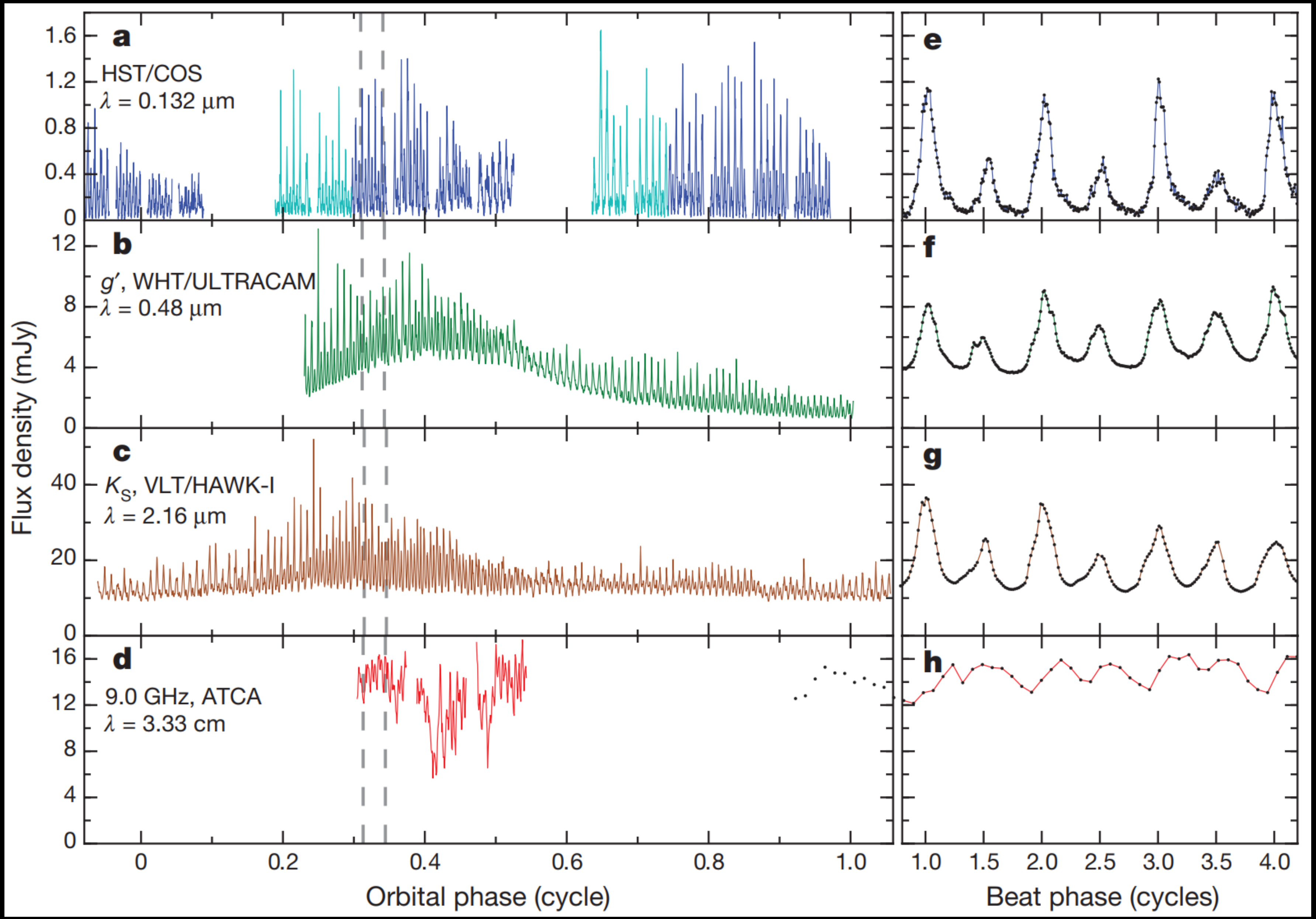
GD1212 (g=13.2 mag):
2 low-RB ZTF alerts

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

courtesy Zachary Vanderbosch (UT-Austi

AR Scorpii

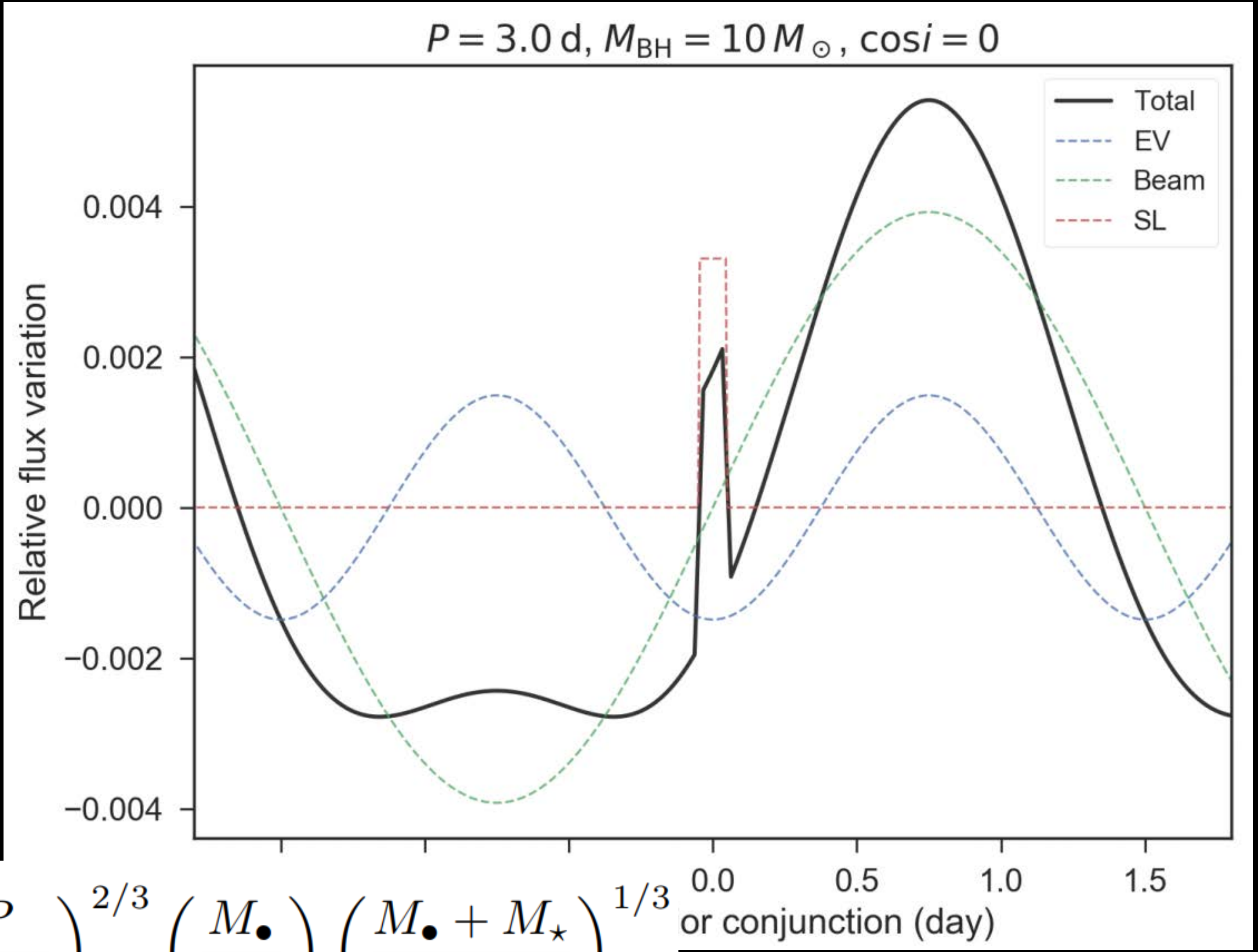
- WD-M dwarf binary
- P_{orb} ~ 4 hours
- P_{spin} ~ 2 minutes



Marsh et al. 2016

Self-lensing binaries

- 4 WD-main sequence binaries detected with Kepler

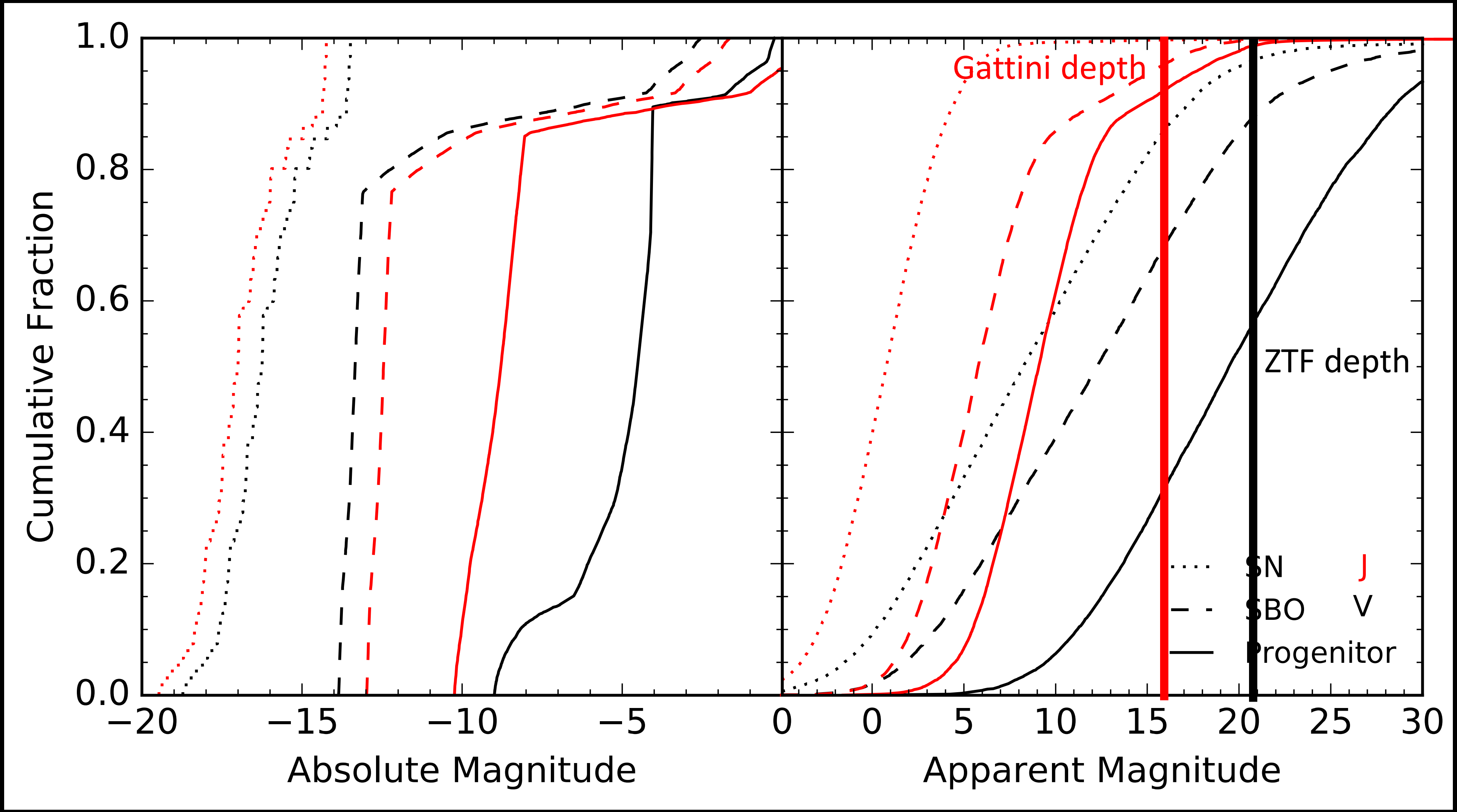


$$s_{\rm sl} = 2\left(\frac{R_{\rm E}}{R_\star}\right)^2 = 7.15\times10^{-5}\left(\frac{R_\star}{R_\odot}\right)^{-2}\left(\frac{P}{1\,\mathrm{day}}\right)^{2/3}\left(\frac{M_\bullet}{M_\odot}\right)\left(\frac{M_\bullet+M_\star}{M_\odot}\right)^{1/3}$$

$$R_{\rm E} = \sqrt{\frac{4GM_\bullet a}{c^2}} = 4.27\times10^{-2}R_\odot\left(\frac{P}{1\,\mathrm{yr}}\right)^{1/3}\left(\frac{M_\bullet}{M_\odot}\right)^{1/2}\left(\frac{M_\bullet+M_\star}{M_\odot}\right)^{1/6}$$

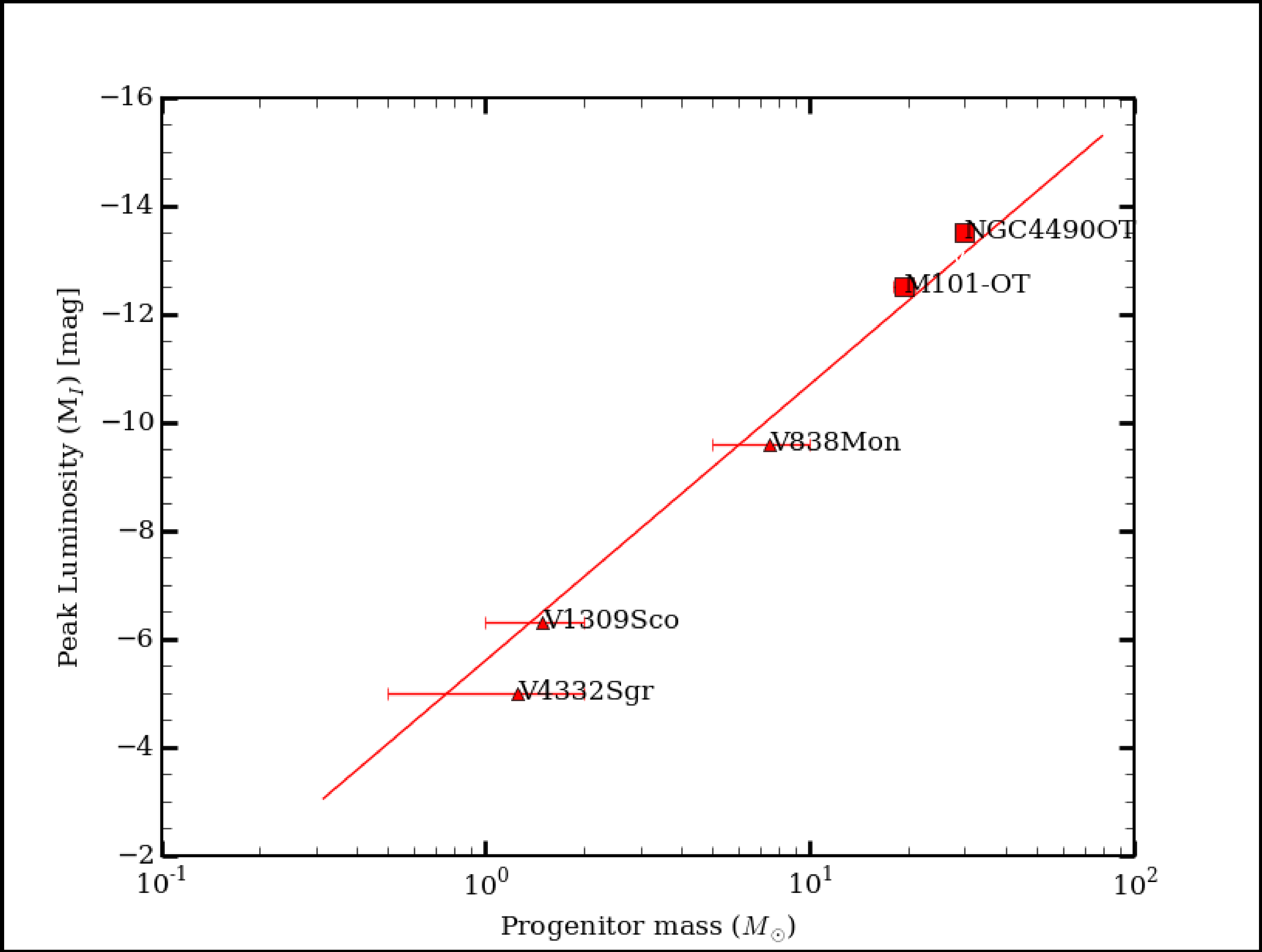
Bonus Material!

Progenitor Detection



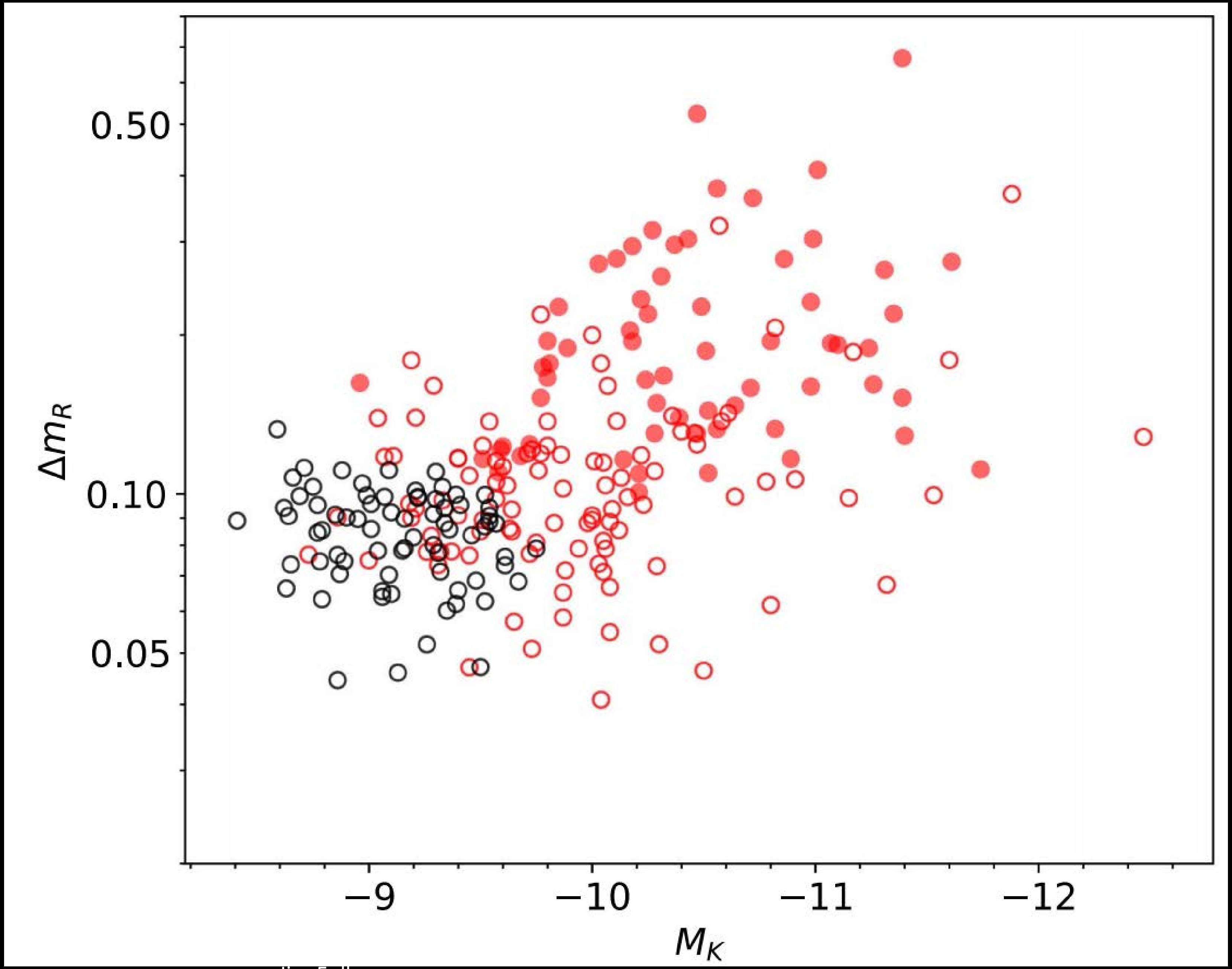
Adapted from Adams et al. 2013

Stellar Mergers:
Luminosity-Mass Correlation

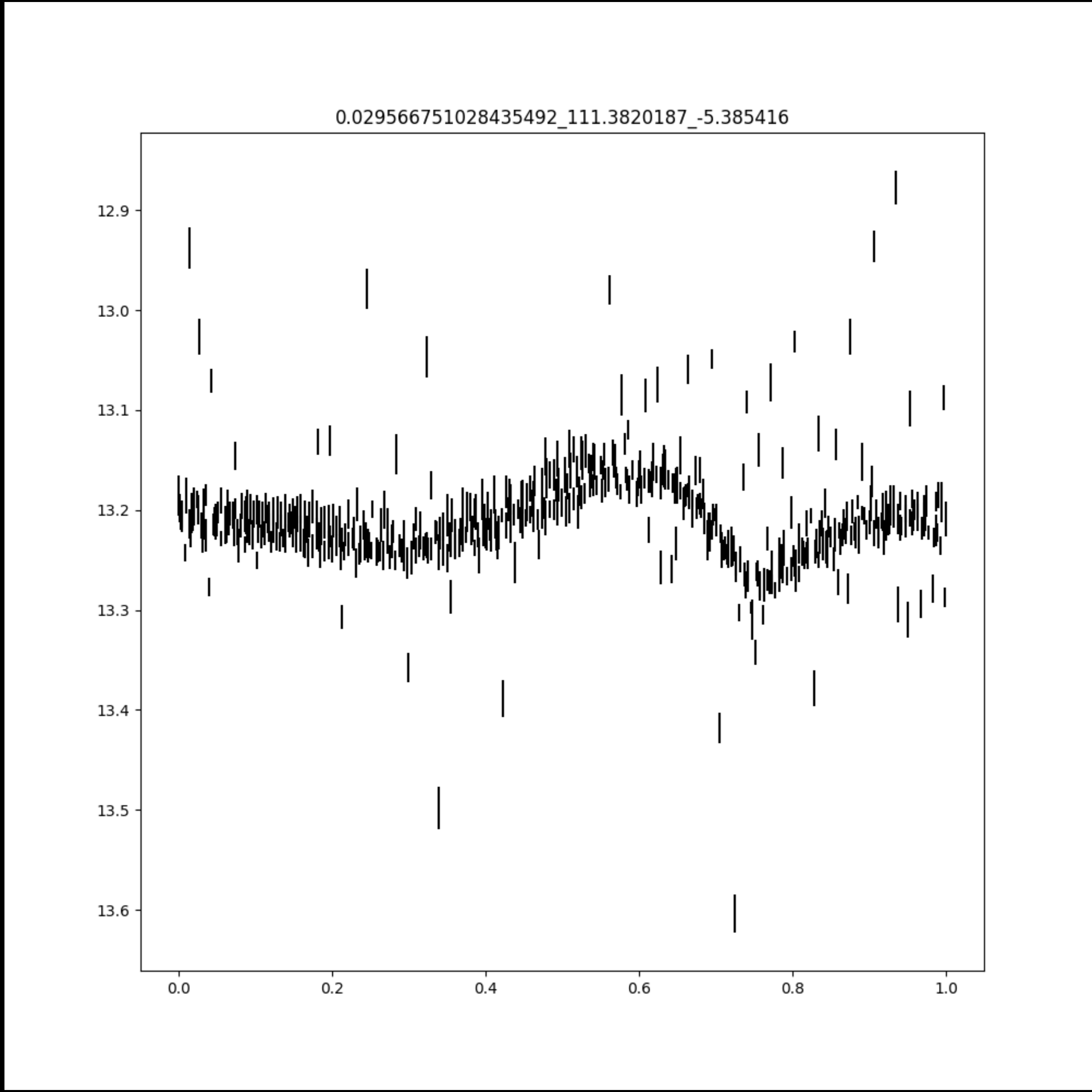


Correlation from
Kochanek et al. 2014

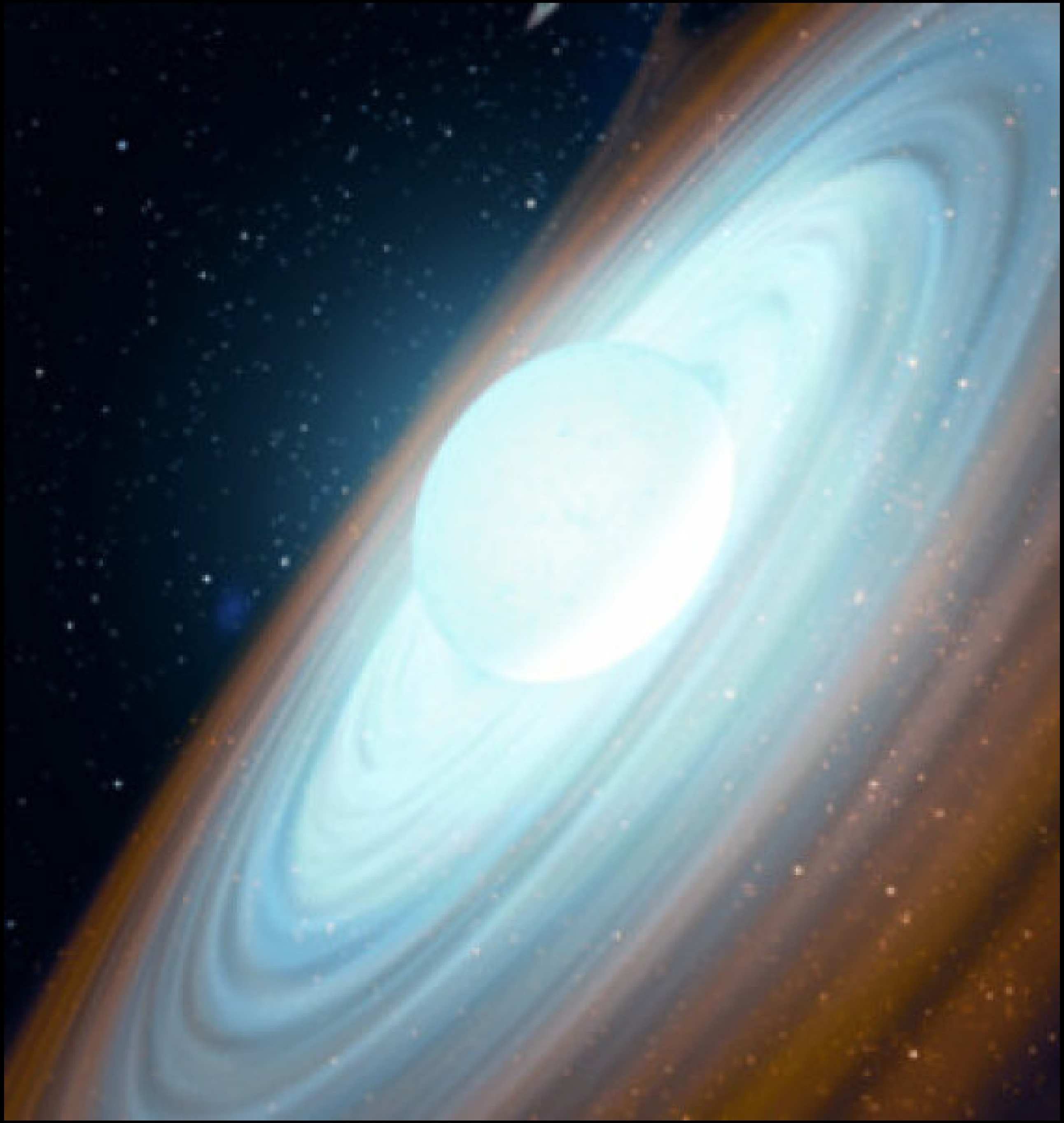
- Luminosity amplitude relation



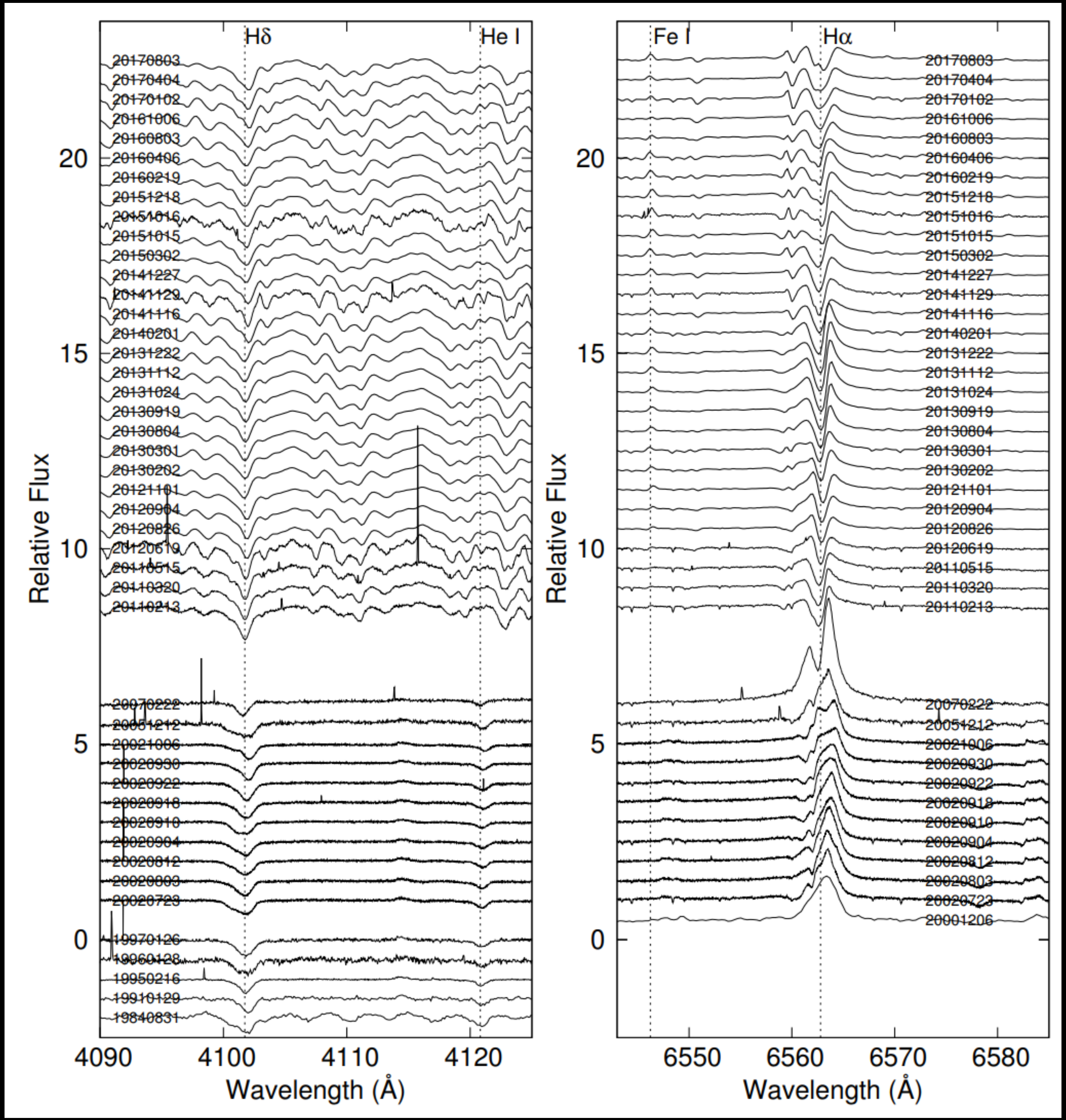
Soraisam et al. 2018


0.029566751028435492_111.3820187_-5.385416
12.9
13.0
13.1
13.2
13.3
13.4
13.5
13.6
0.0
0.2
0.4
0.6
0.8
1.0

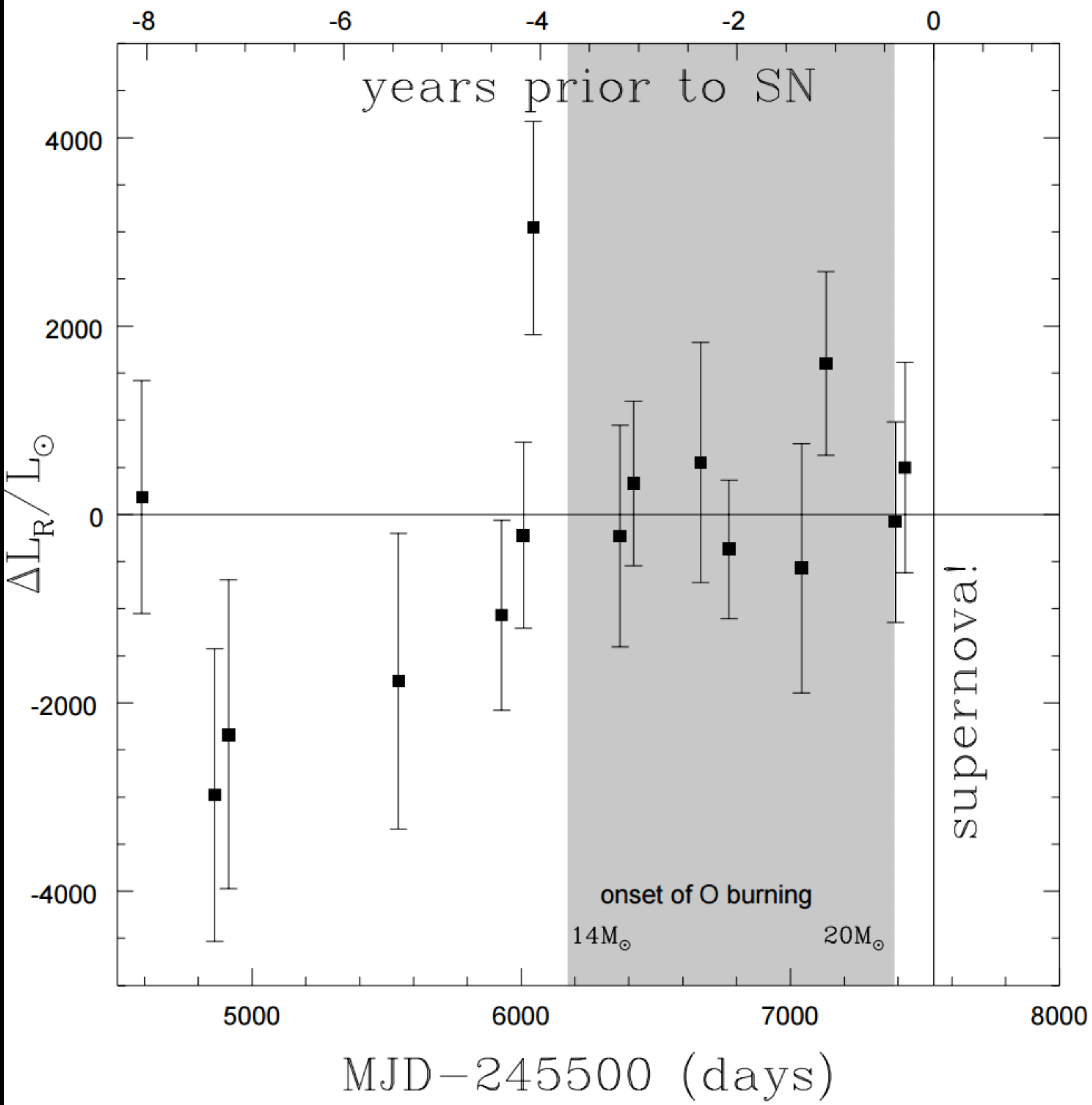
5/4/2019



Mehner et al. 2017

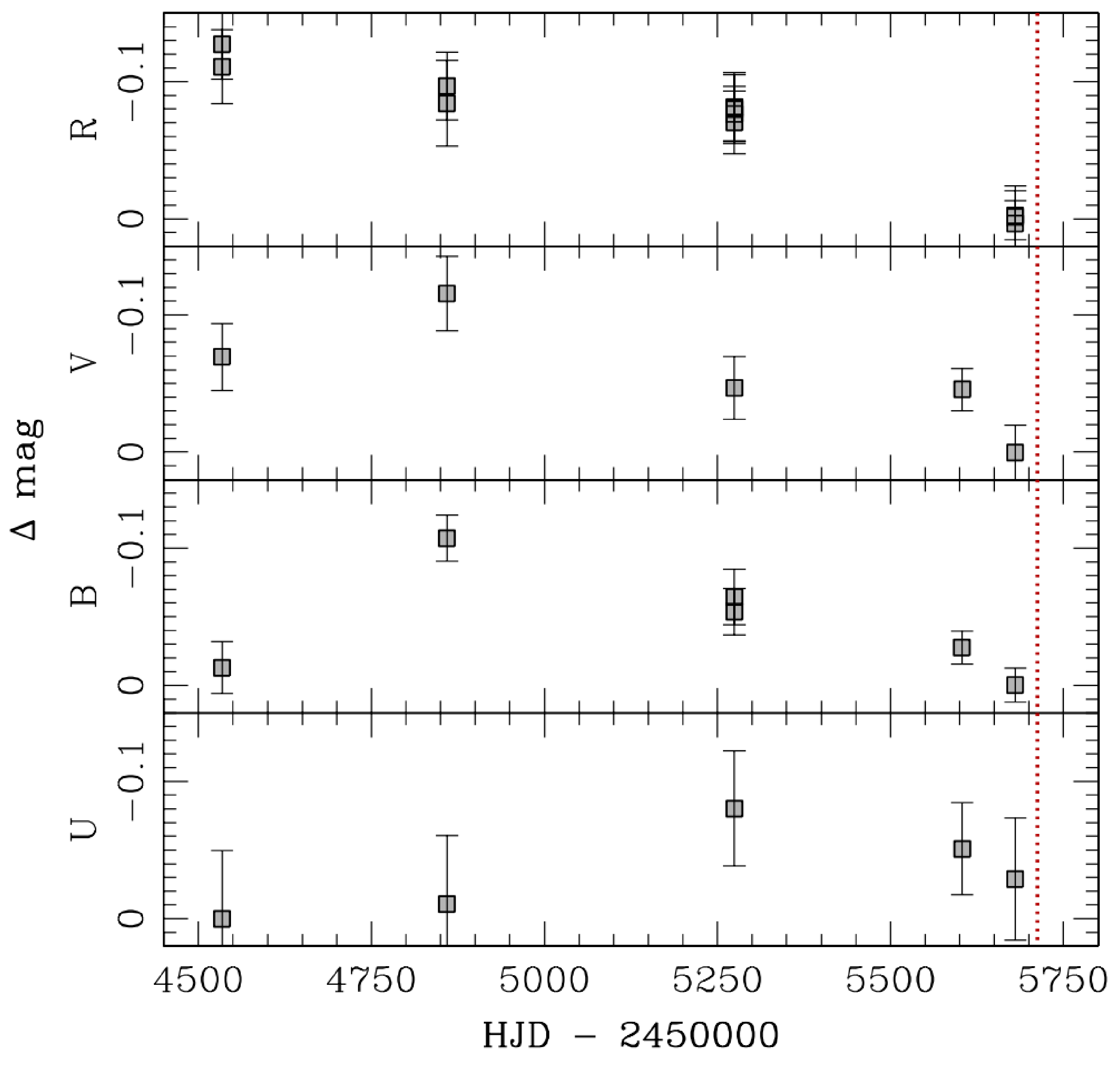


- Type II-P SN ASASSN-16fq did not show large pre-SN variability



Kochanek et al. 2017

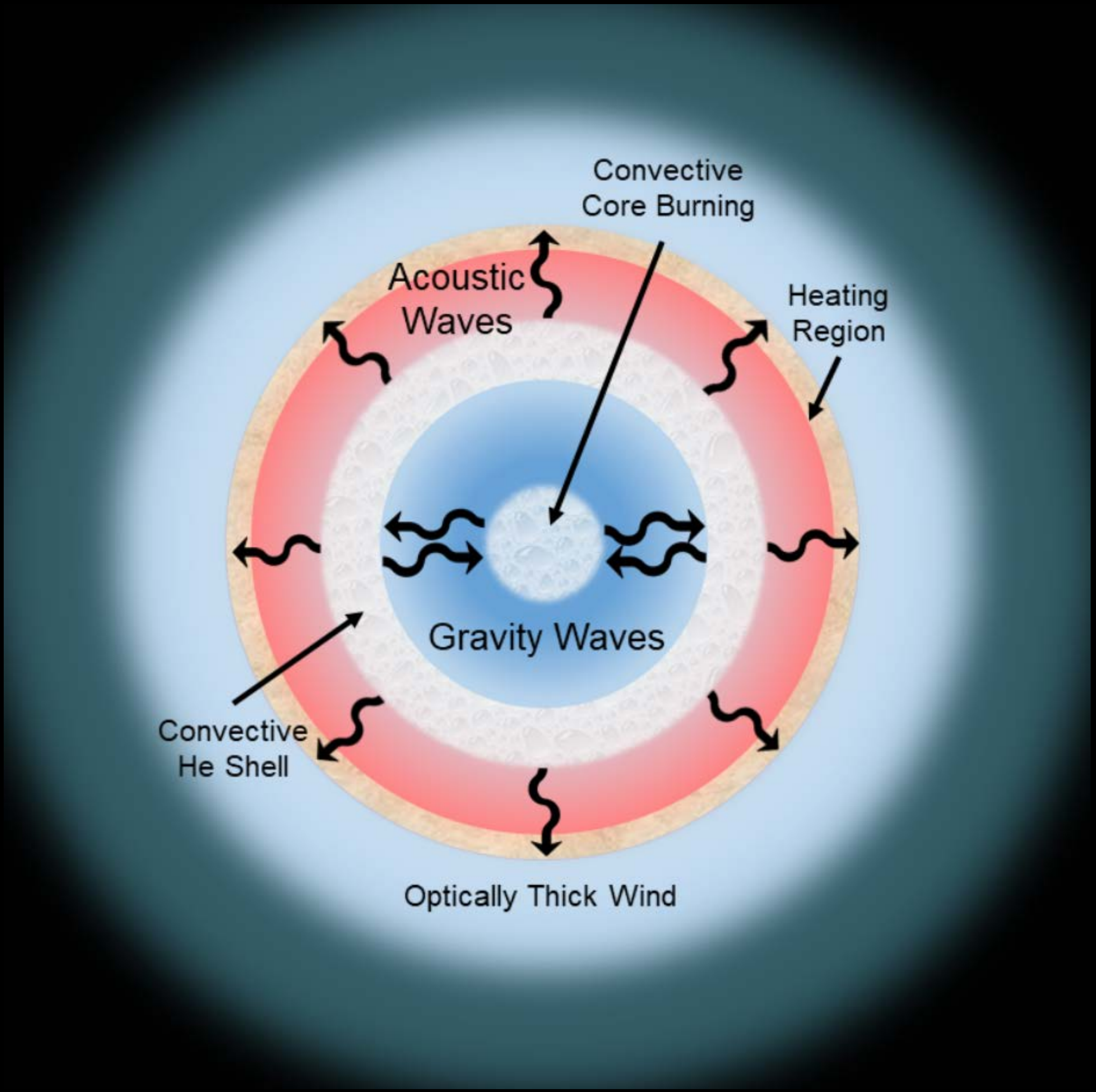
- Type IIb SN 2011dh did not show large pre-SN variability



Sczcygiel et al. 2012

Wave heating in hydrogen-poor stars

- Waves generated by convection in core
- Waves damp near stellar surface
- Wave heat unbinds launches super-Eddington wind



Wave Power in Massive Stars

- Huge energy fluxes during late burning phases

$$L_{\rm wave} \sim \mathcal{M}_{\rm conv}\, L_{\rm conv} \sim 10^8 \left(\frac{L_{\rm conv}}{10^{10}\,{\rm L}_\odot}\right)\left(\frac{\mathcal{M}_{\rm conv}}{0.01}\right) {\rm L}_\odot$$

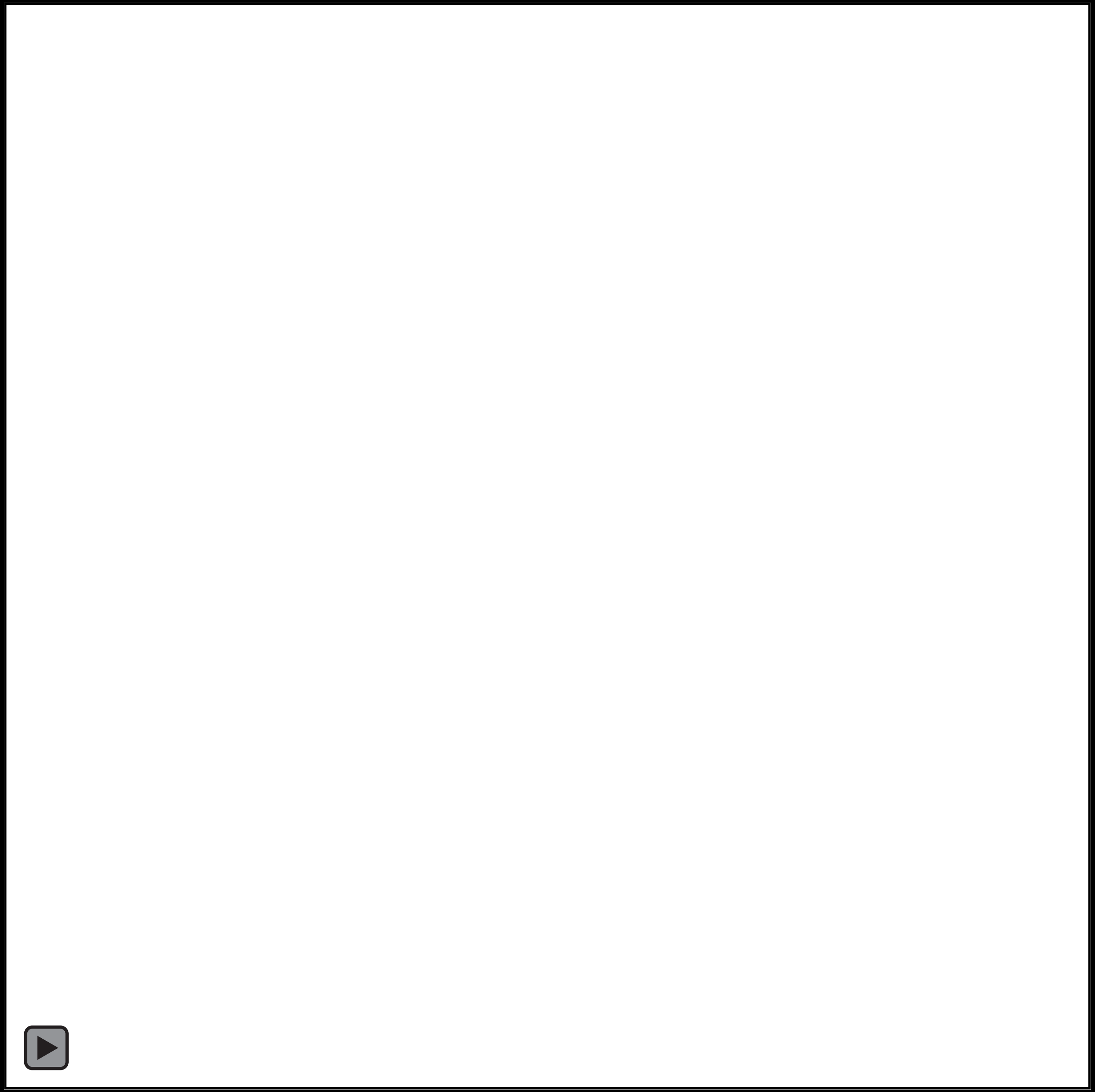
$$E_{\rm waves} \sim 10^{47-48}\,{\rm erg}$$

Table 1. Late stages of massive stellar evolution.

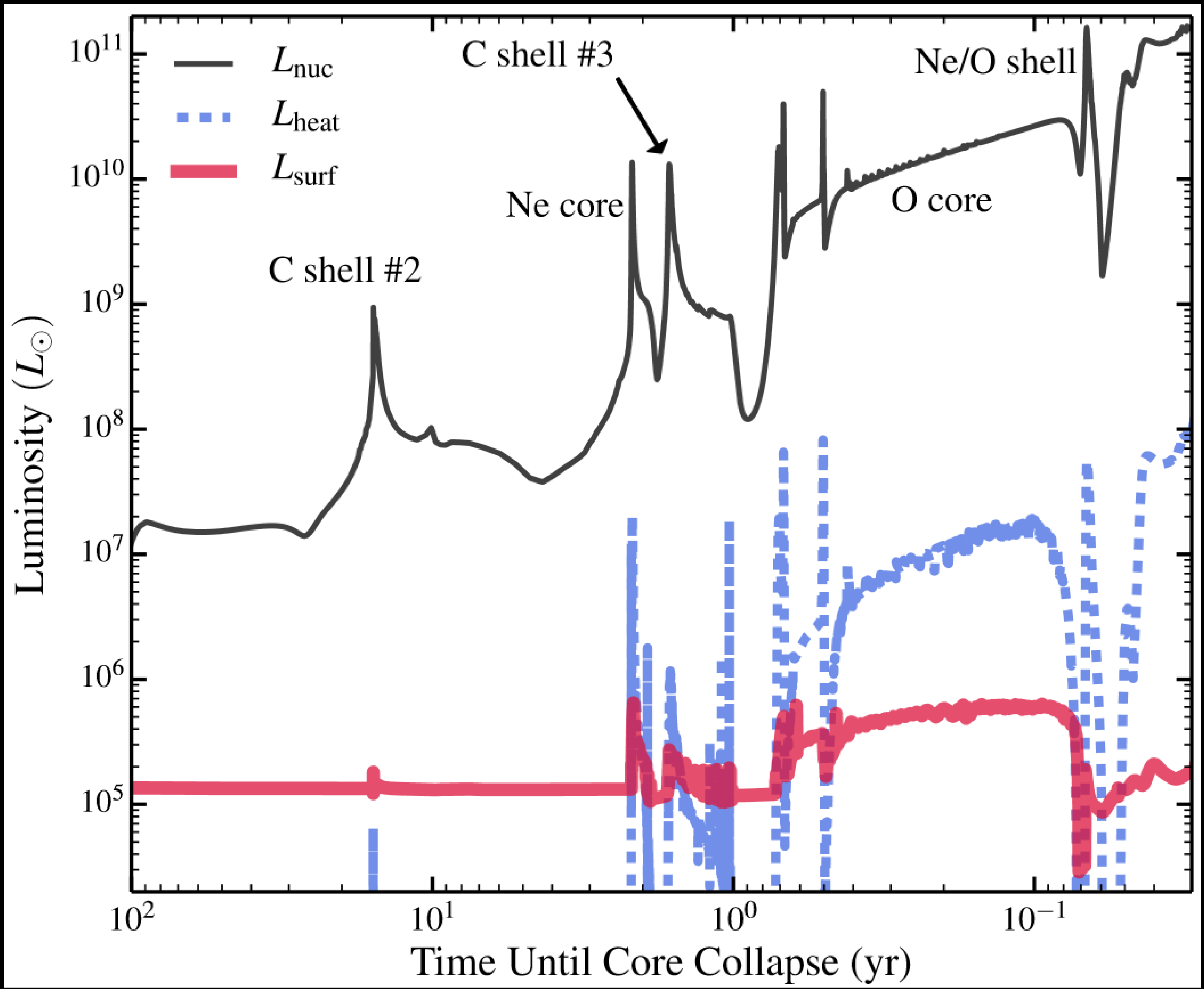
Stage	Duration $(t_{\rm nuc})$	$L_{\rm fusion}$ $({\rm L}_\odot)$	Mach $(\mathcal{M}_{\rm conv})$	$\tau_{\rm c}$ (s)
Carbon	$\sim 10^3$ yr	$\sim 10^6$	~ 0.003	$\sim 10^{4.5}$
Neon	~ 1 yr	$\sim 10^9$	~ 0.01	$\sim 10^3$
Oxygen	~ 1 yr	$\sim 10^{10}$	~ 0.02	$\sim 10^3$
Silicon	~ 1 d	$\sim 10^{12}$	~ 0.05	$\sim 10^2$

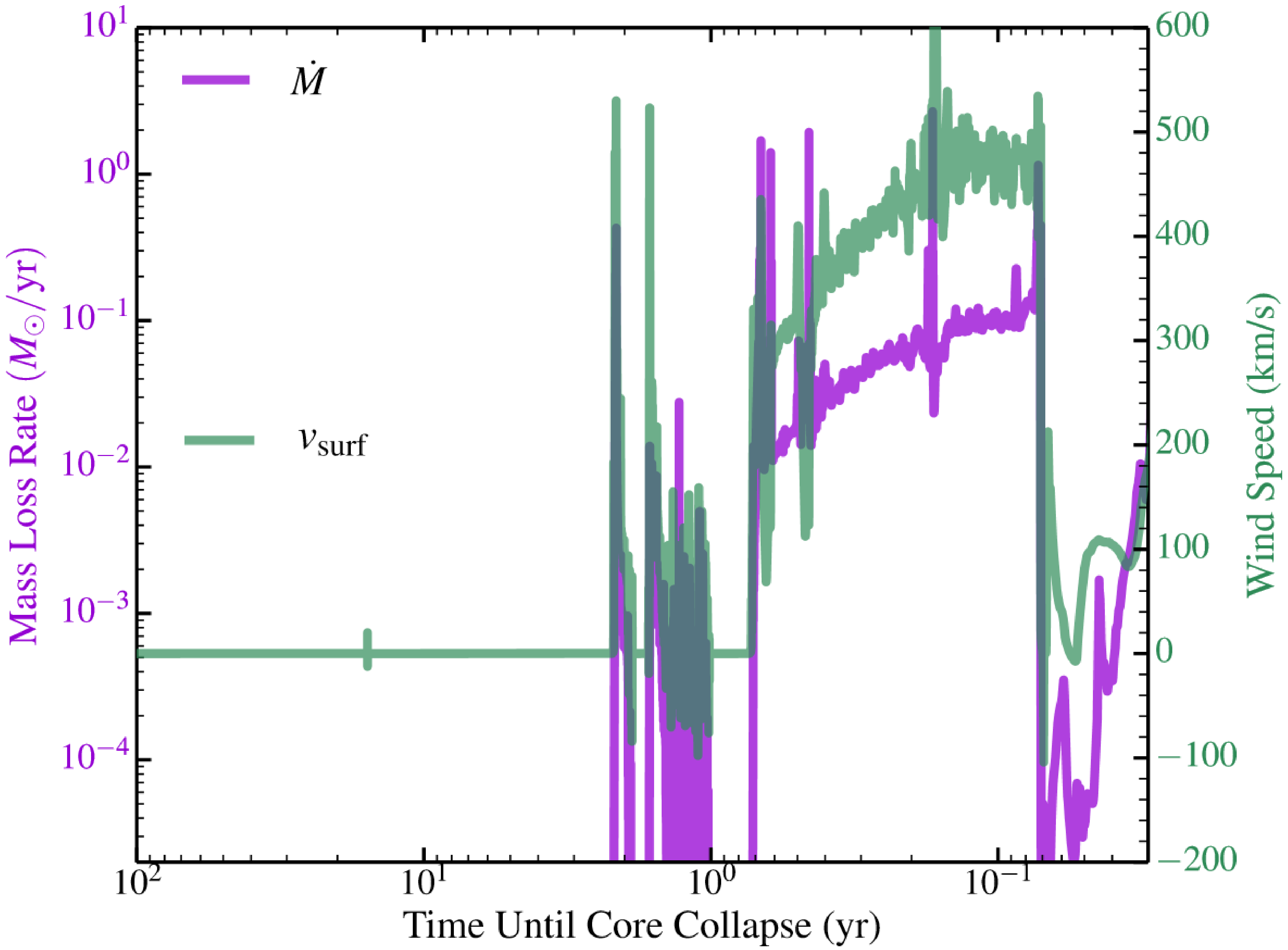
Quataert
& Shiode (2012)

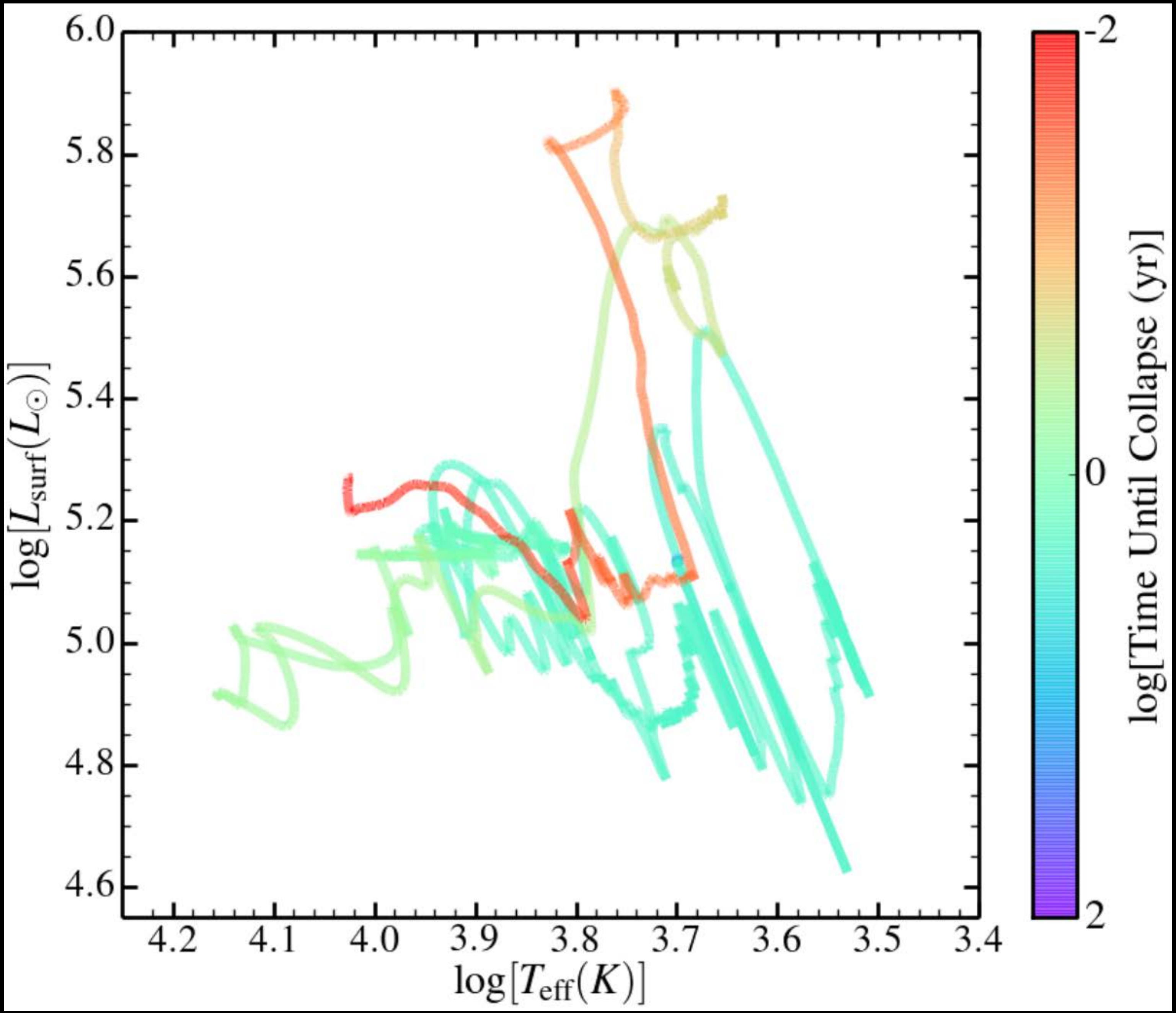
Convection excites gravity waves



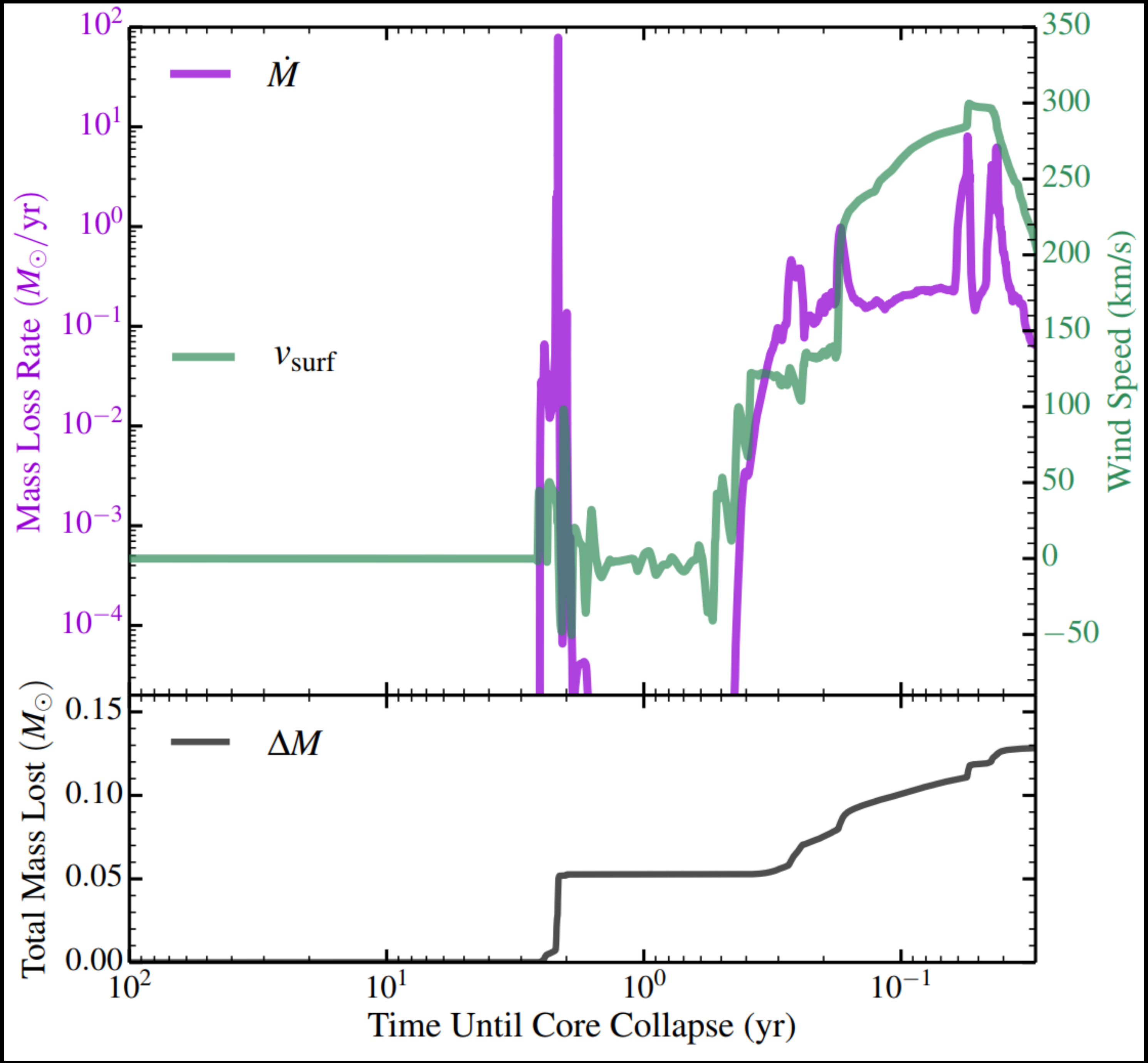
Movie made by
Andrea Cristini


$L_{\rm nuc}$
$L_{\rm heat}$
$L_{\rm surf}$
C shell #3
Ne/O shell
Ne core
O core
C shell #2
Luminosity ($L_\odot$)
Time Until Core Collapse (yr)

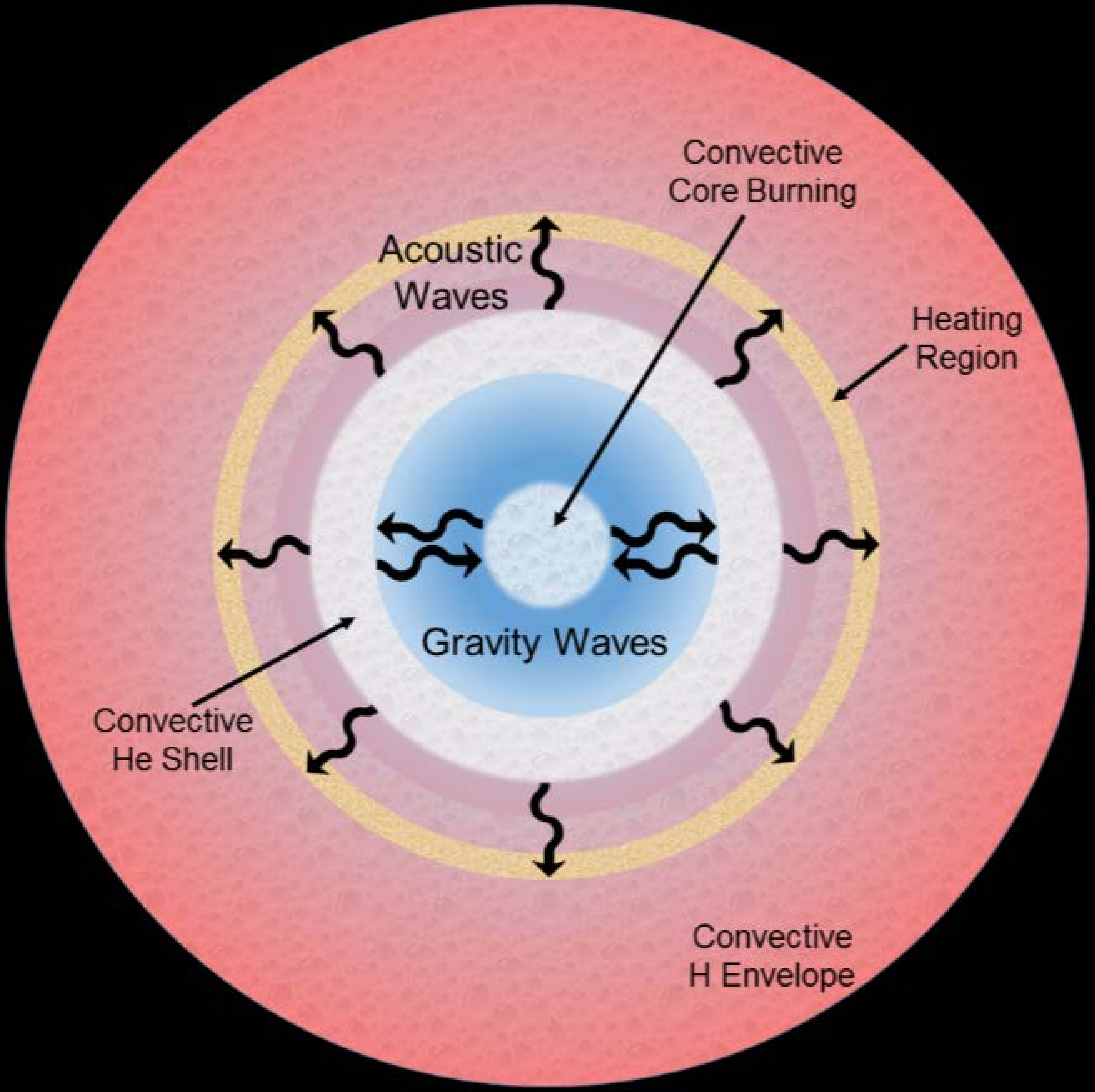

$\dot{M}$
v_{surf}
Mass Loss Rate ($M_\odot$/yr)
Wind Speed (km/s)
Time Until Core Collapse (yr)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
600
500
400
300
200
100
0
−100
−200
10^2
10^1
10^0
10^{-1}



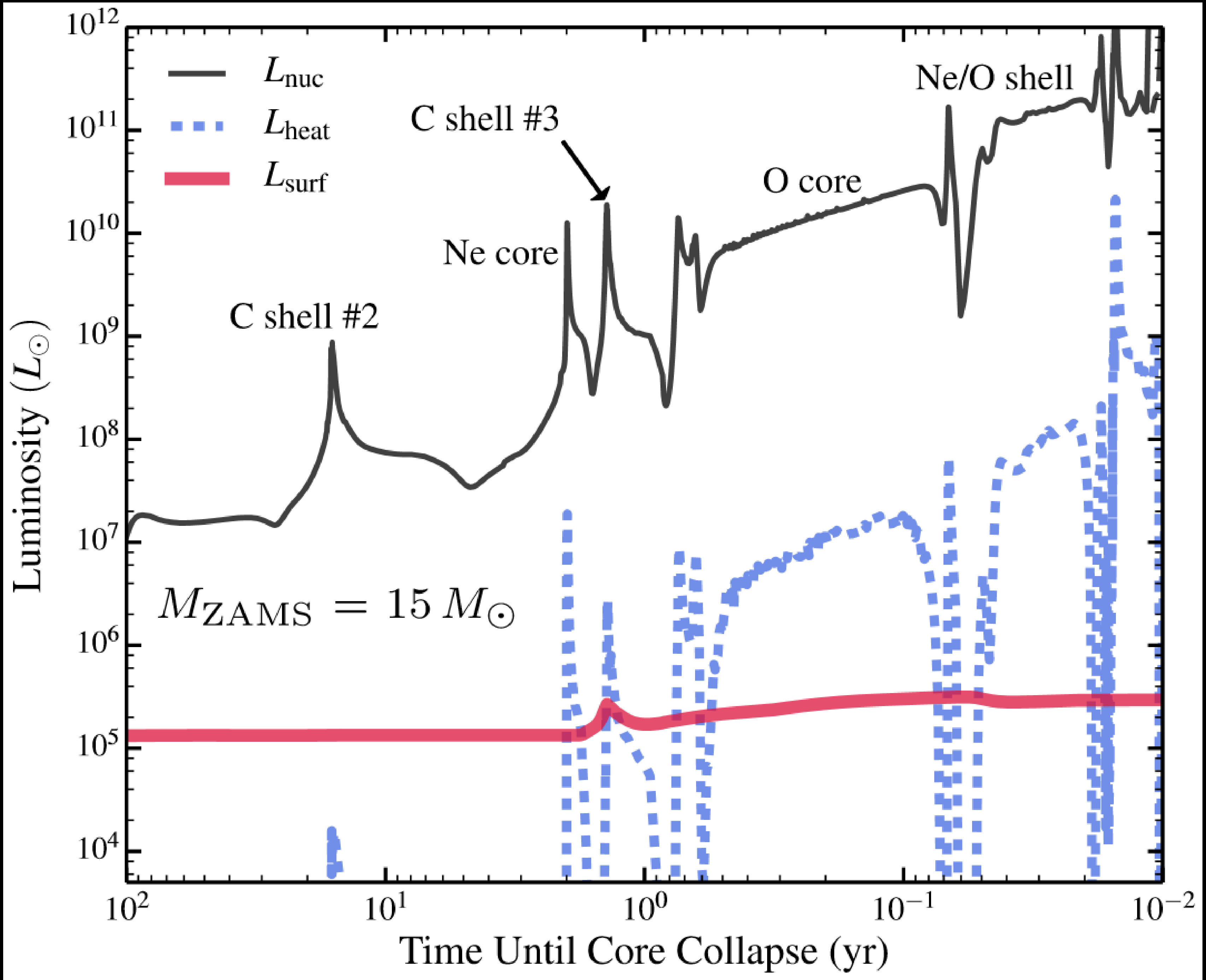
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
$\log[L_{\rm surf}(L_\odot)]$
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
3.4
$\log[T_{\rm eff}(K)]$
-2
0
2
log[Time Until Collapse (yr)]



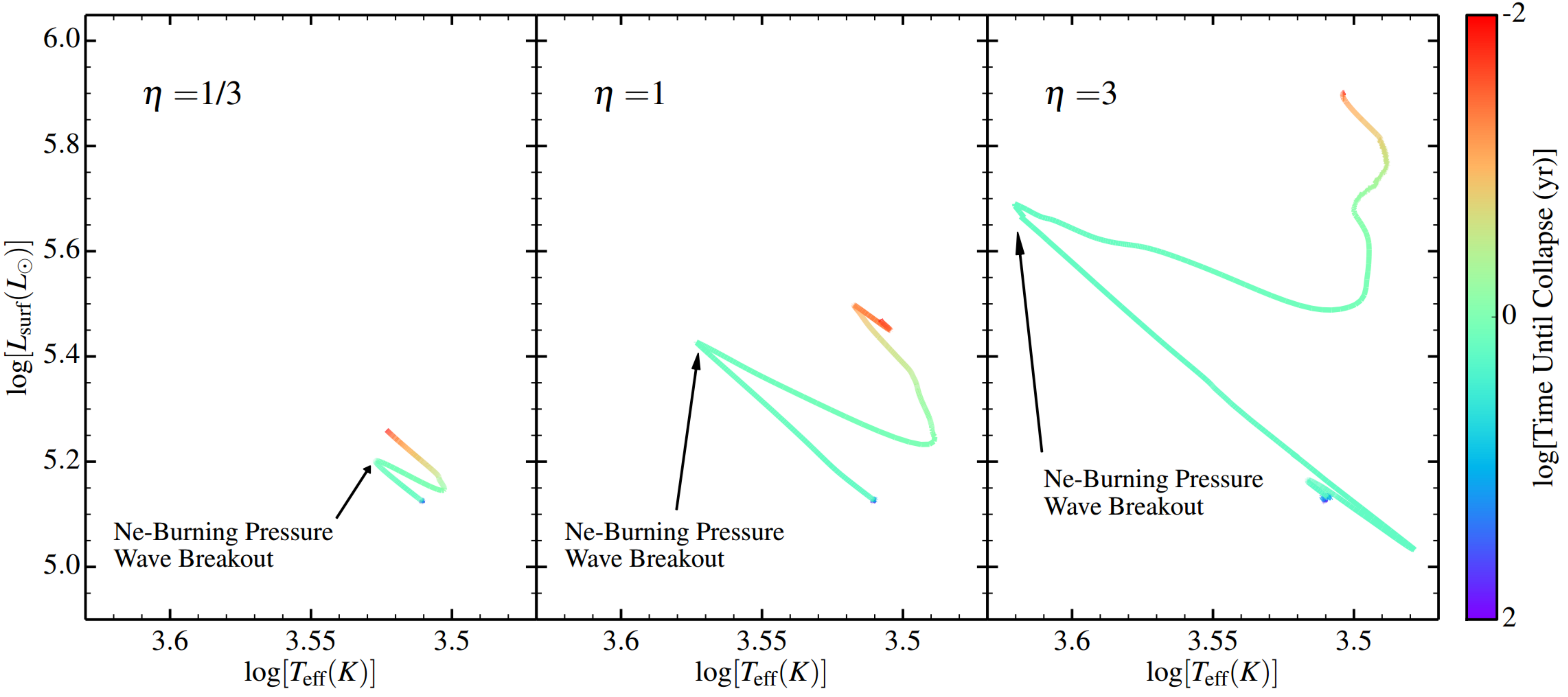
$\dot{M}$
$v_{\rm surf}$
ΔM
Mass Loss Rate ($M_\odot$/yr)
Wind Speed (km/s)
Total Mass Lost ($M_\odot$)
Time Until Core Collapse (yr)


Convective
Core Burning
Acoustic
Waves
Heating
Region
Gravity Waves
Convective
He Shell
Convective
H Envelope

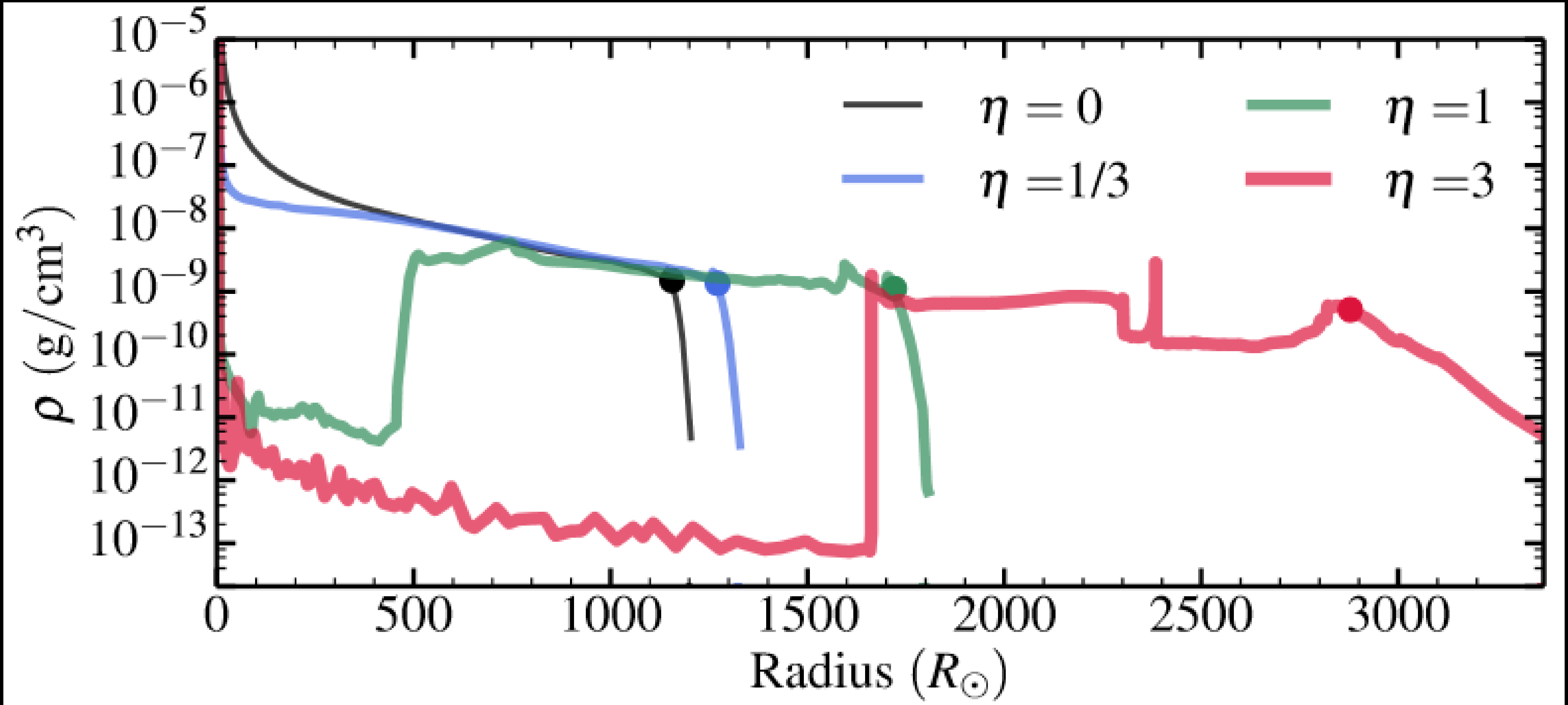
Wave Power



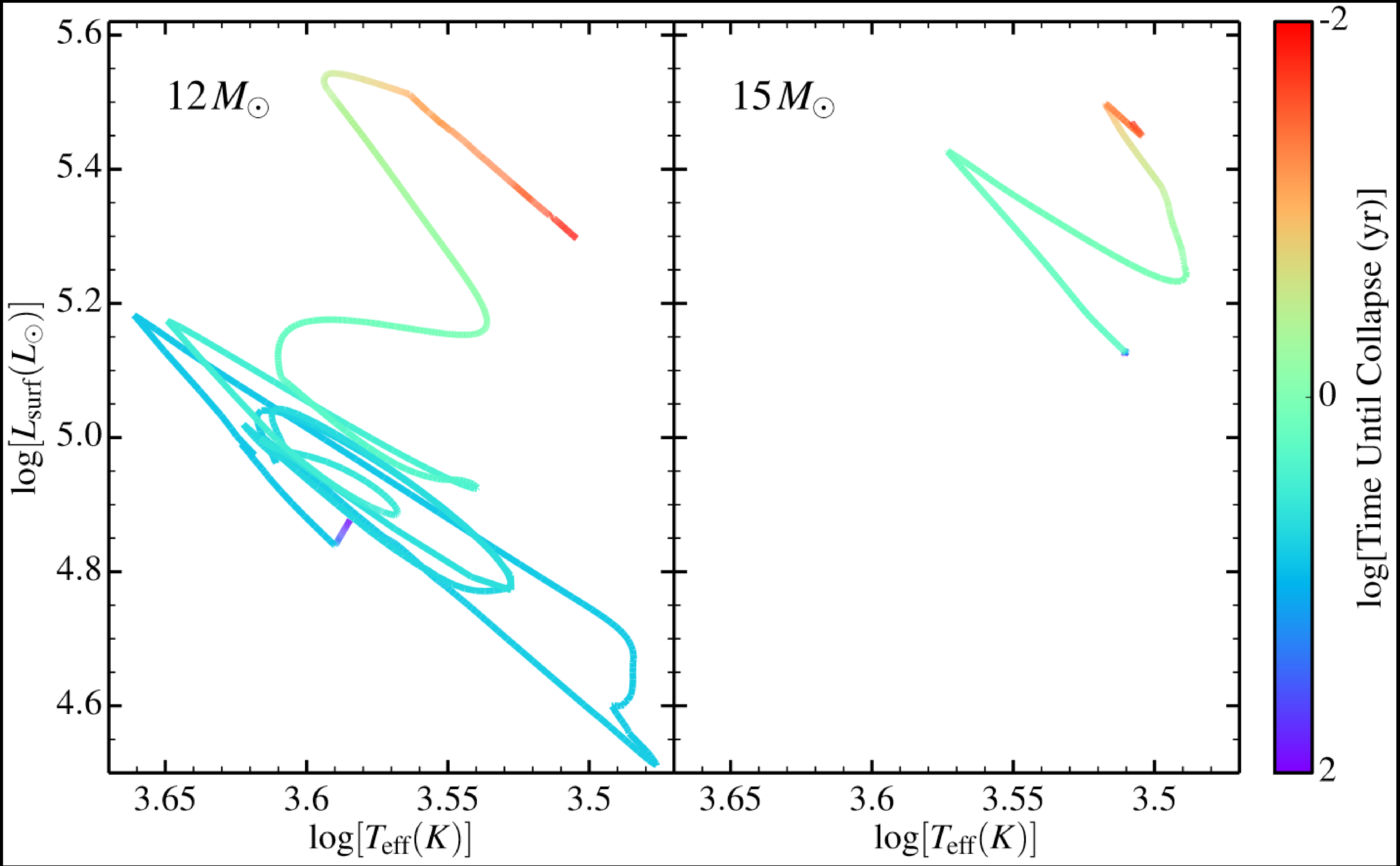
$L_{\rm nuc}$
$L_{\rm heat}$
$L_{\rm surf}$
C shell #3
Ne/O shell
O core
Ne core
C shell #2
$M_{\rm ZAMS} = 15\,M_\odot$
Luminosity ($L_\odot$)
Time Until Core Collapse (yr)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}



η =1/3
η =1
η =3
Ne-Burning Pressure
Wave Breakout
Ne-Burning Pressure
Wave Breakout
Ne-Burning Pressure
Wave Breakout
log[L_surf(L_⊙)]
6.0
5.8
5.6
5.4
5.2
5.0
3.6
3.55
3.5
log[T_eff(K)]
log[Time Until Collapse (yr)]
-2
0
2



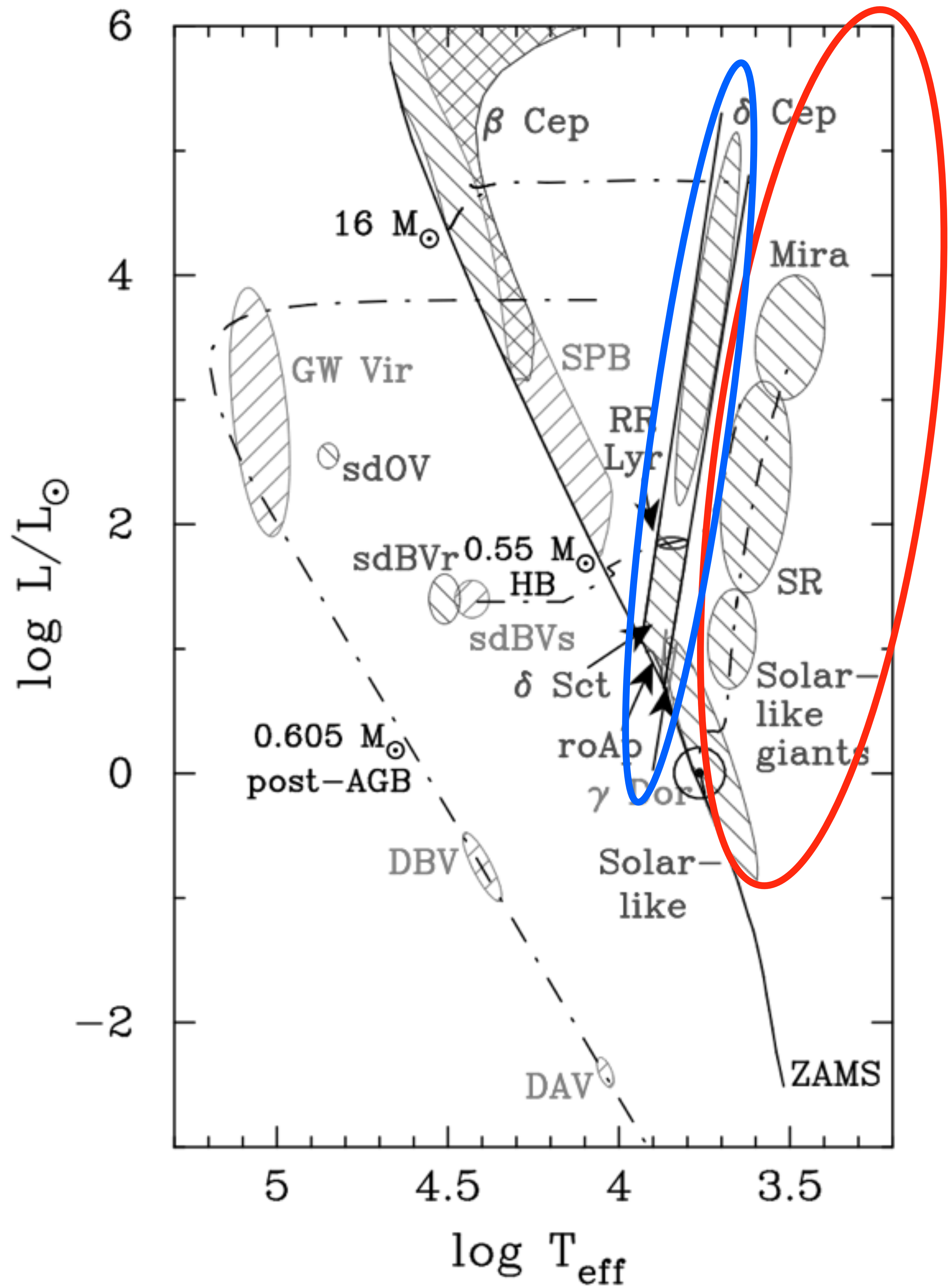
$\eta = 0$
$\eta = 1$
$\eta = 1/3$
$\eta = 3$
ρ (g/cm^3)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0
500
1000
1500
2000
2500
3000
Radius ($R_\odot$)



12 $M_\odot$
15 $M_\odot$
$\log[L_{\rm surf}(L_\odot)]$
$\log[T_{\rm eff}(K)]$
log[Time Until Collapse (yr)]
5.6
5.4
5.2
5.0
4.8
4.6
3.65
3.6
3.55
3.5
-2
0
2

Asteroseismology & Spectroscopy in the SDSS-V Era

Dan Huber (IfA Hawai‘i), Johanna Teske (Carnegie), Melissa Ness (Columbia/CCA)



This discussion:

"cool" pulsators (classical instability strip)

solar-like oscillators (driven by surface convection)

Main Questions:

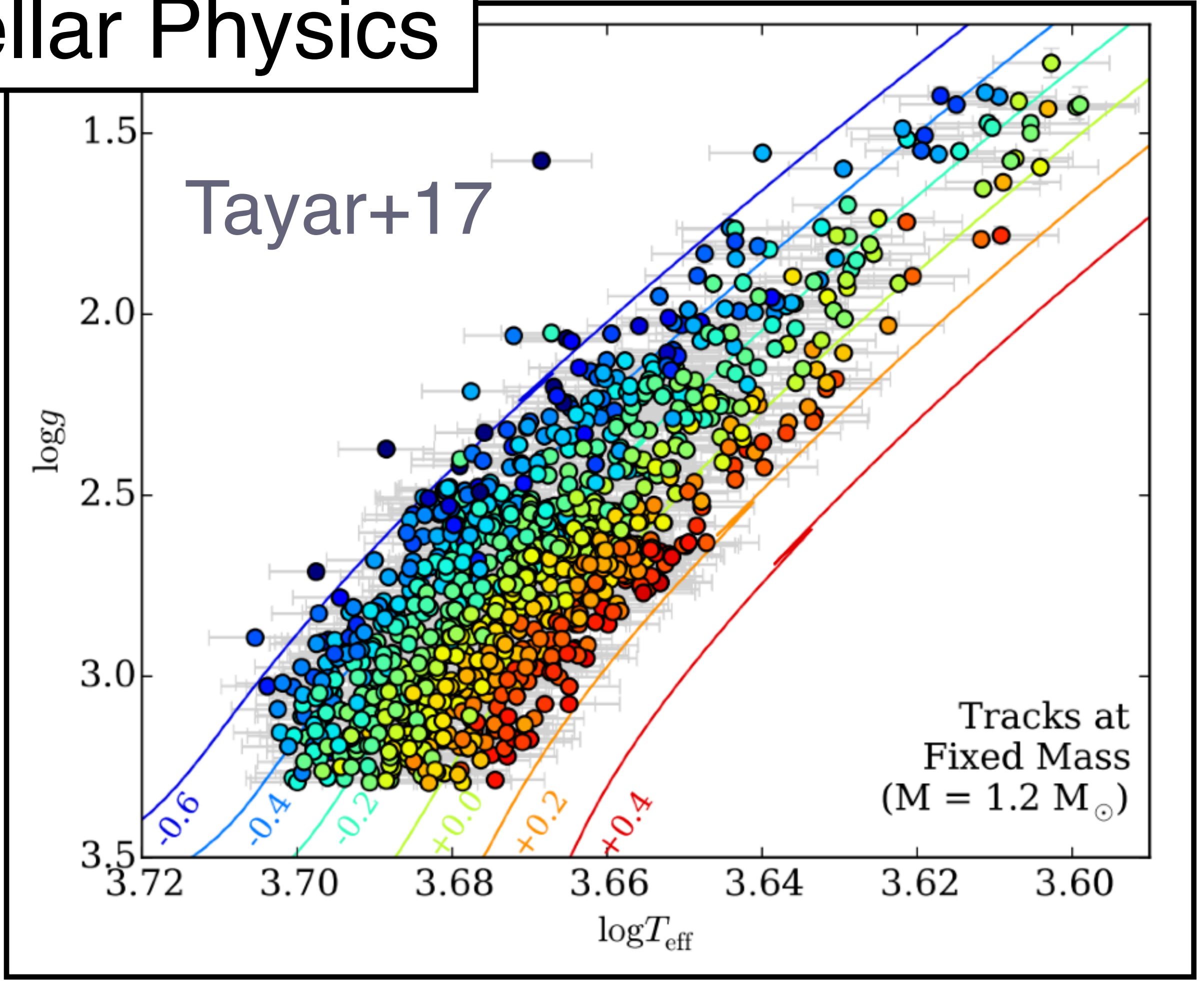
1) How do we optimize spectroscopic follow-up of asteroseismic targets?

2) Can we do asteroseismology with ground-based TDA surveys?

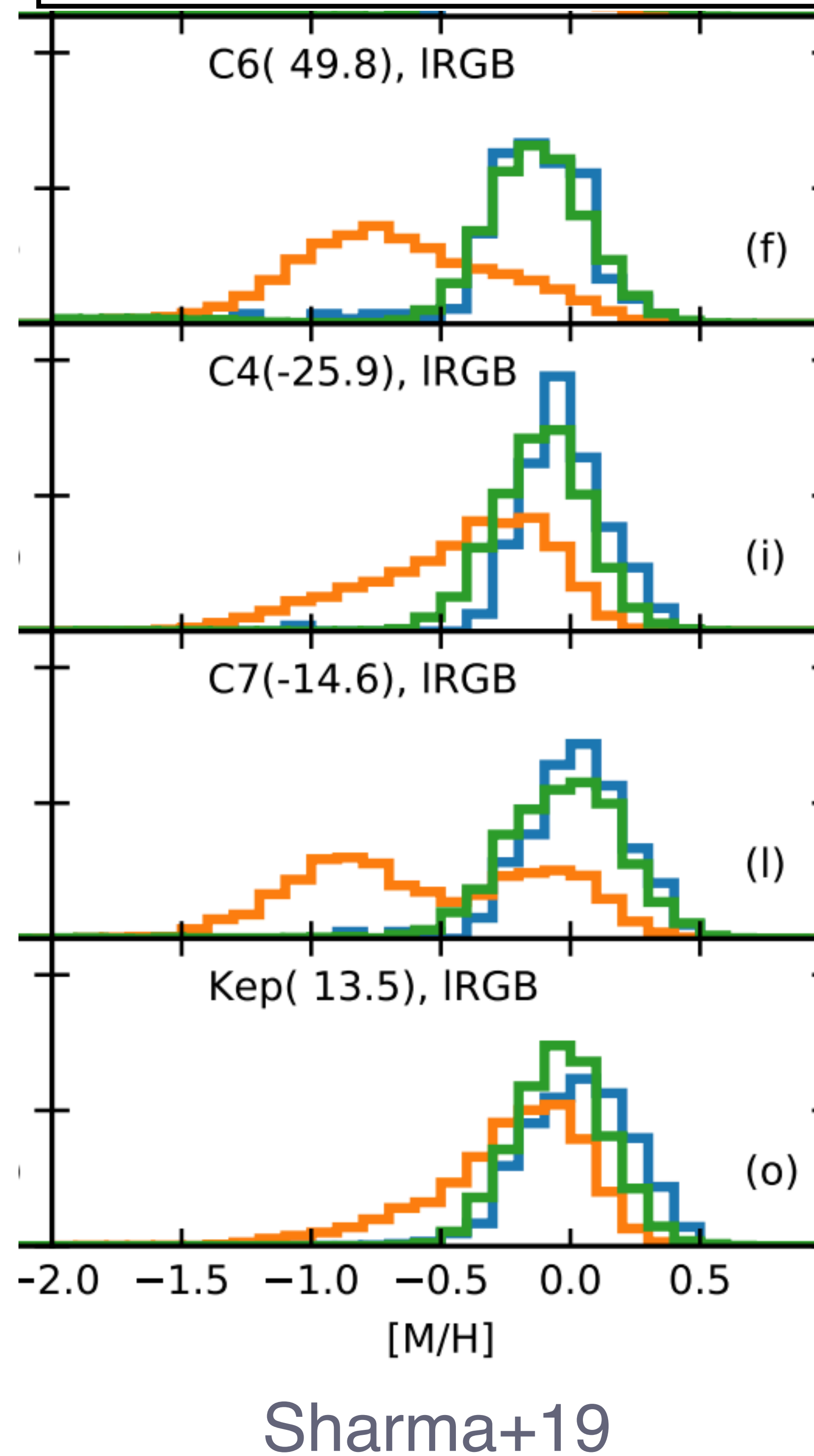
Spectroscopic Follow-Up of Asteroseismic Targets

Why Bother?

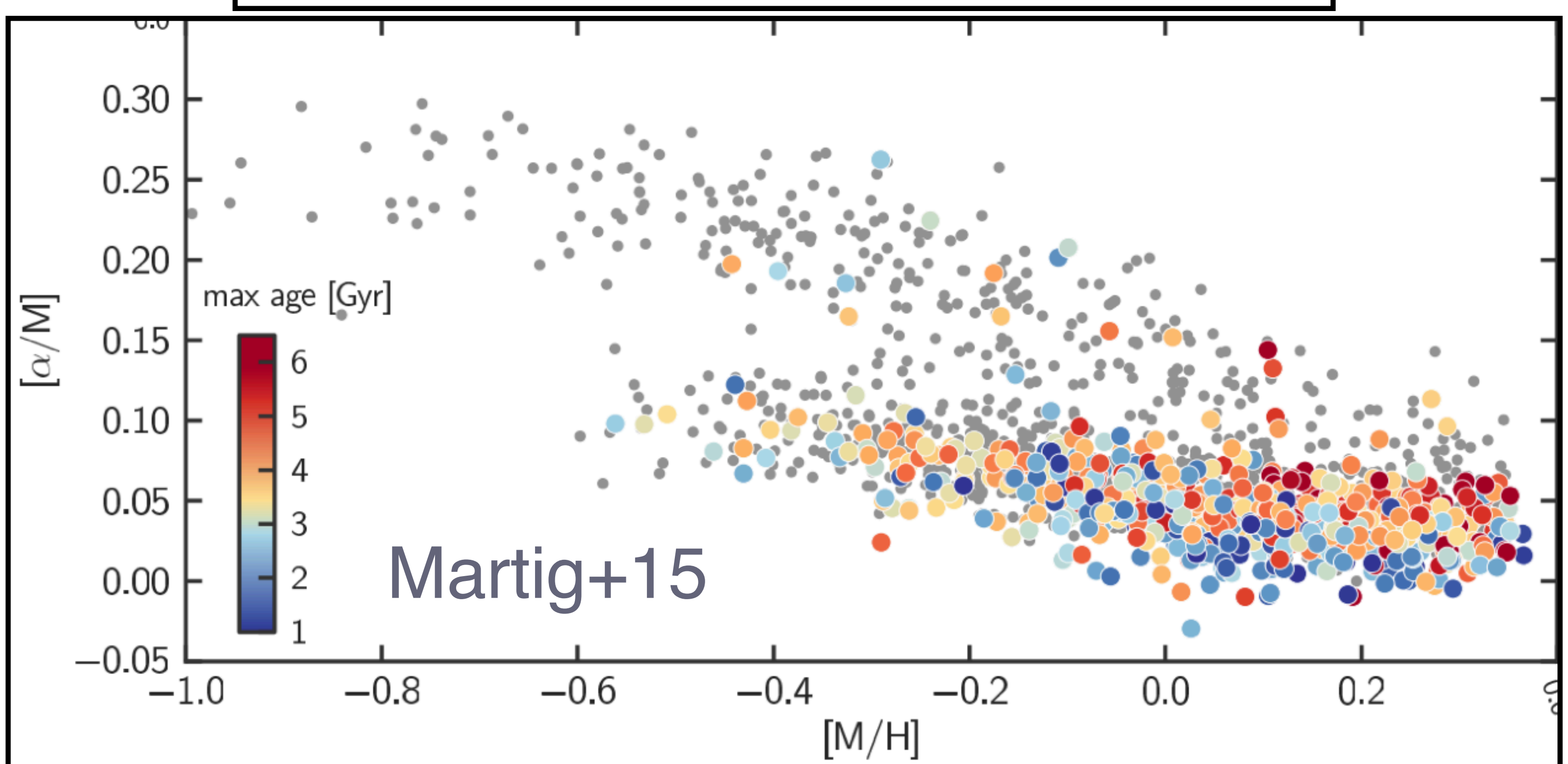
Stellar Physics



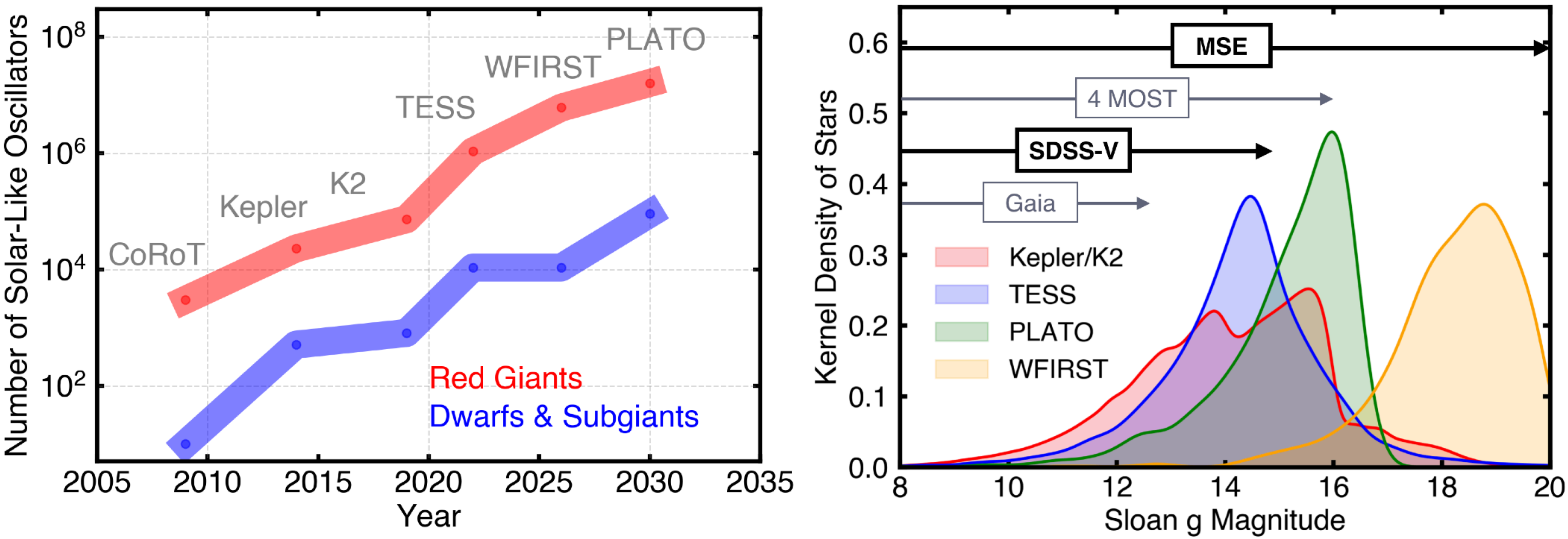
Galactic Archeology



Exotic stellar populations



Asteroseismology in the 2020's



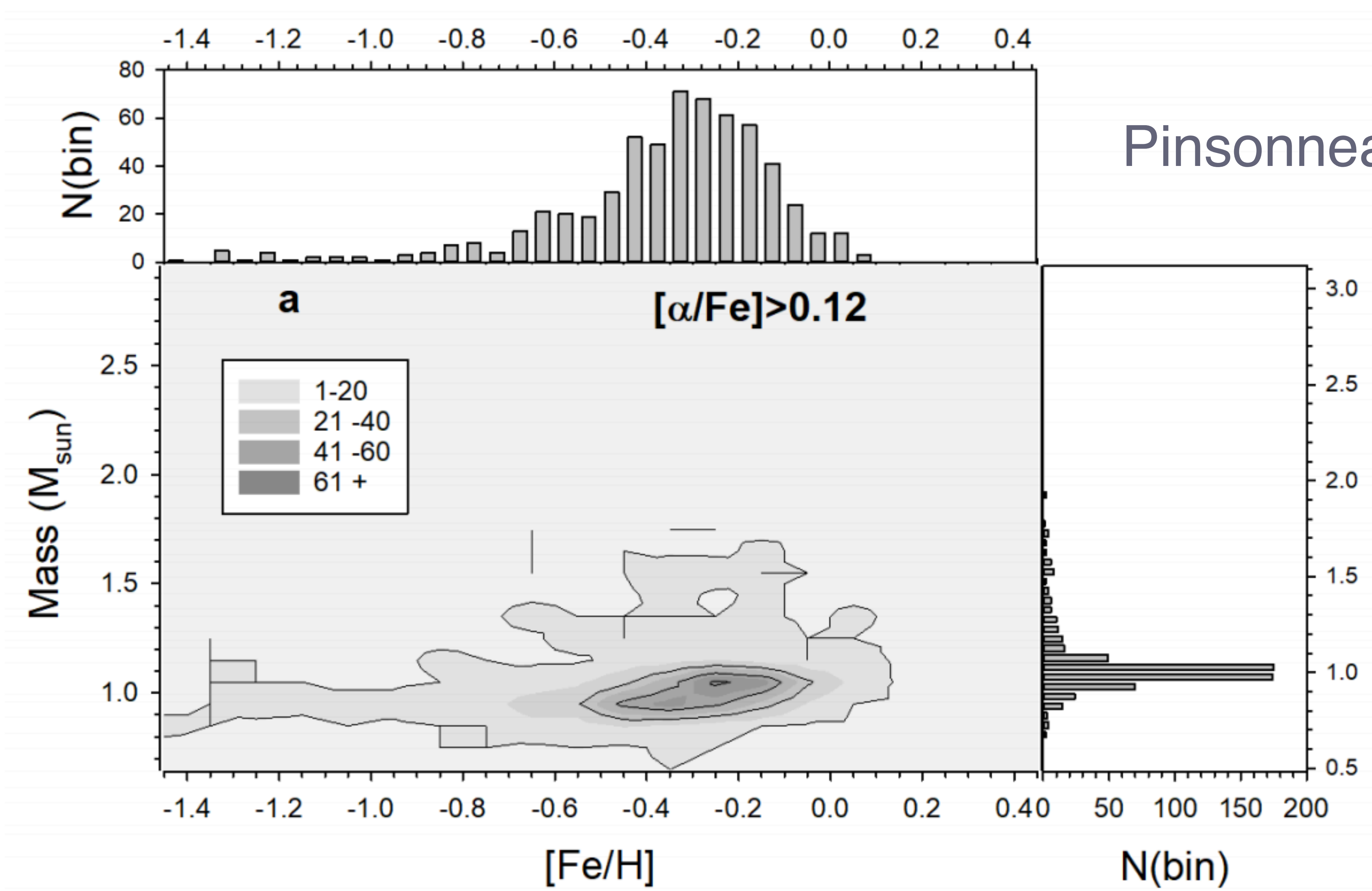
Huber+19 (Astro 2020 White paper)

~ 10^6 - 10^7 oscillating red giants from space-based photometry missions. Impossible to cover them all even with next-gen MOS facilities? Is there significant gain to get all of them?

How do we prioritize follow-up?

Giants in sparsely populated parameter spaces

- metal-poor stars (few stars with [Fe/H] < -1 in Kepler)
- high-luminosity red giants

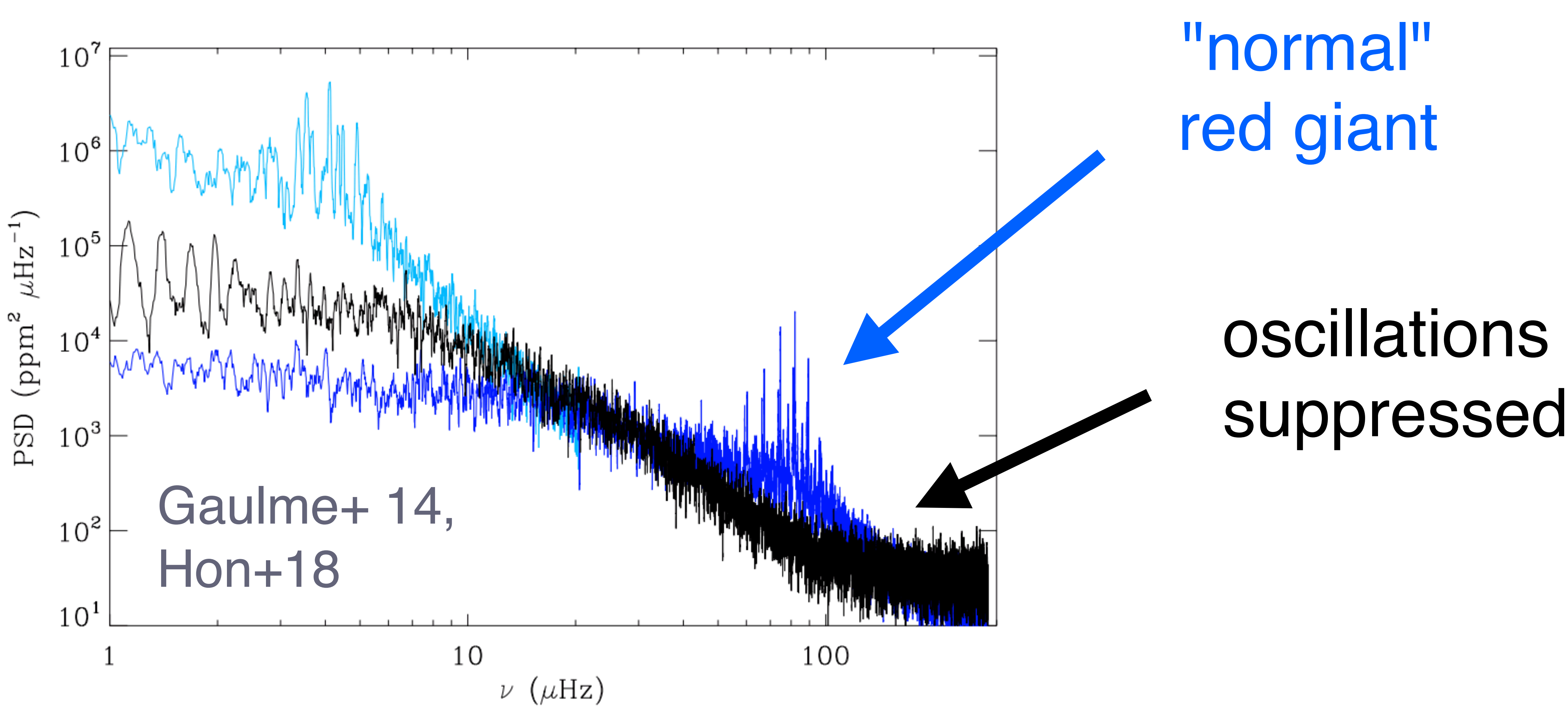


Pinsonneault+ 18

How do we prioritize follow-up?

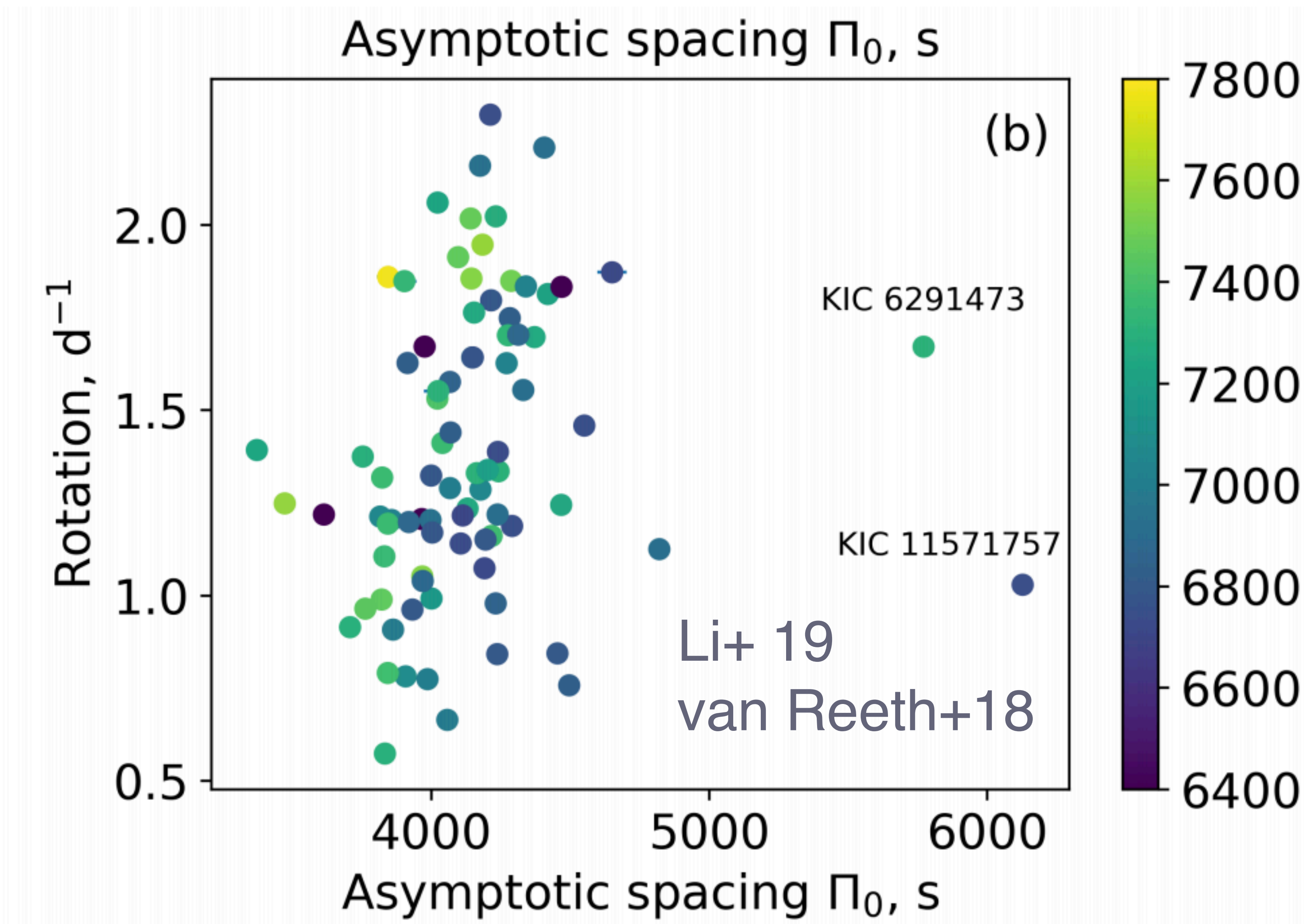
Red giants with strange time-domain behaviour:

- ~10% of Kepler giants do not oscillate; dynamical interactions in close binaries?
- Stars with suppressed dipole modes; link to chemical composition?



How do we prioritize follow-up?

Measure vsin(i) for classical pulsators in the TESS CVZ's. Seismic core rotation often easier to measure than surface rotation from rotational modulation.



Near-core rotation in ~80 γ Dor pulsators. <10% have measured surface rates from rotational modulation

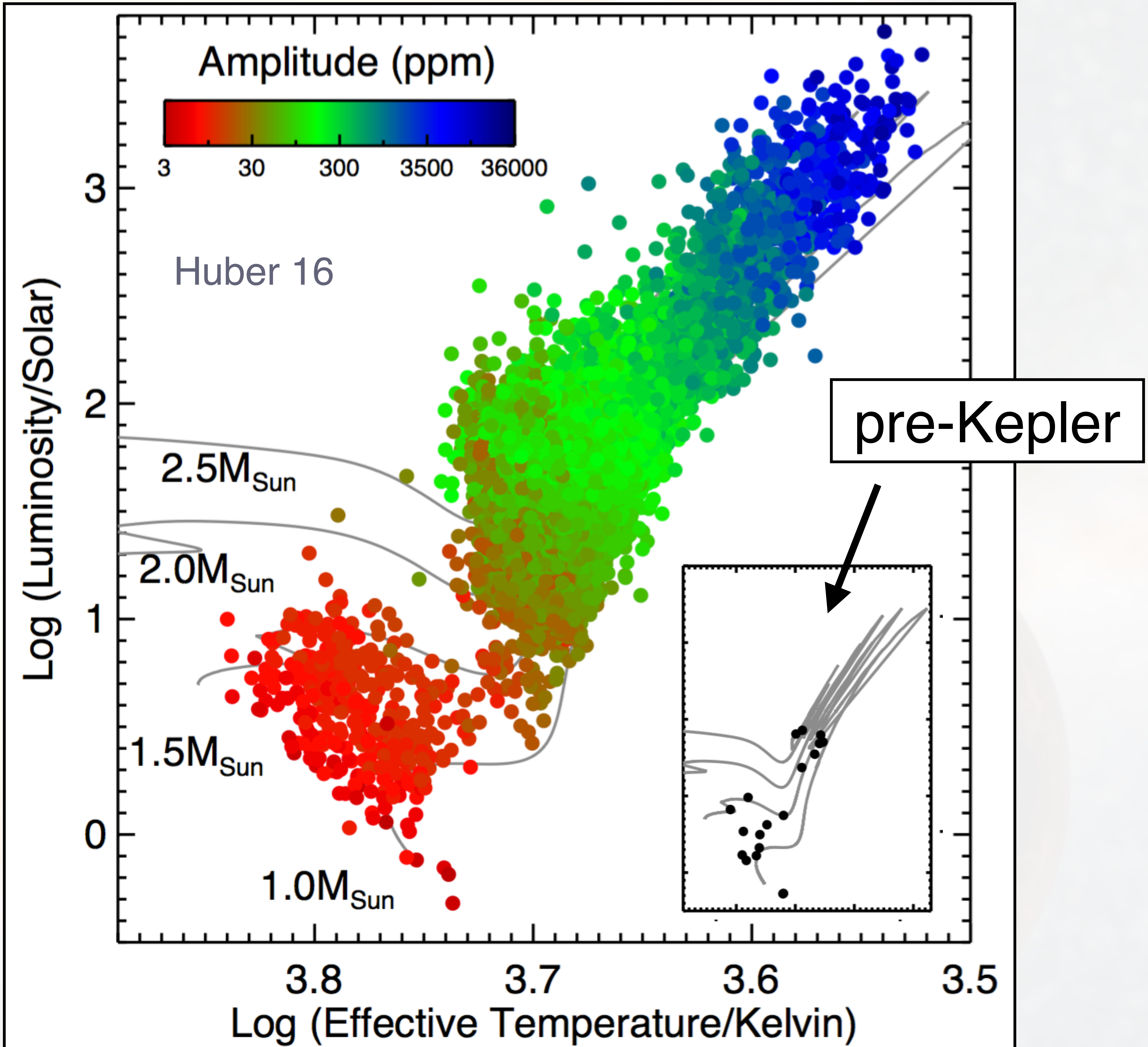
Challenges/Questions

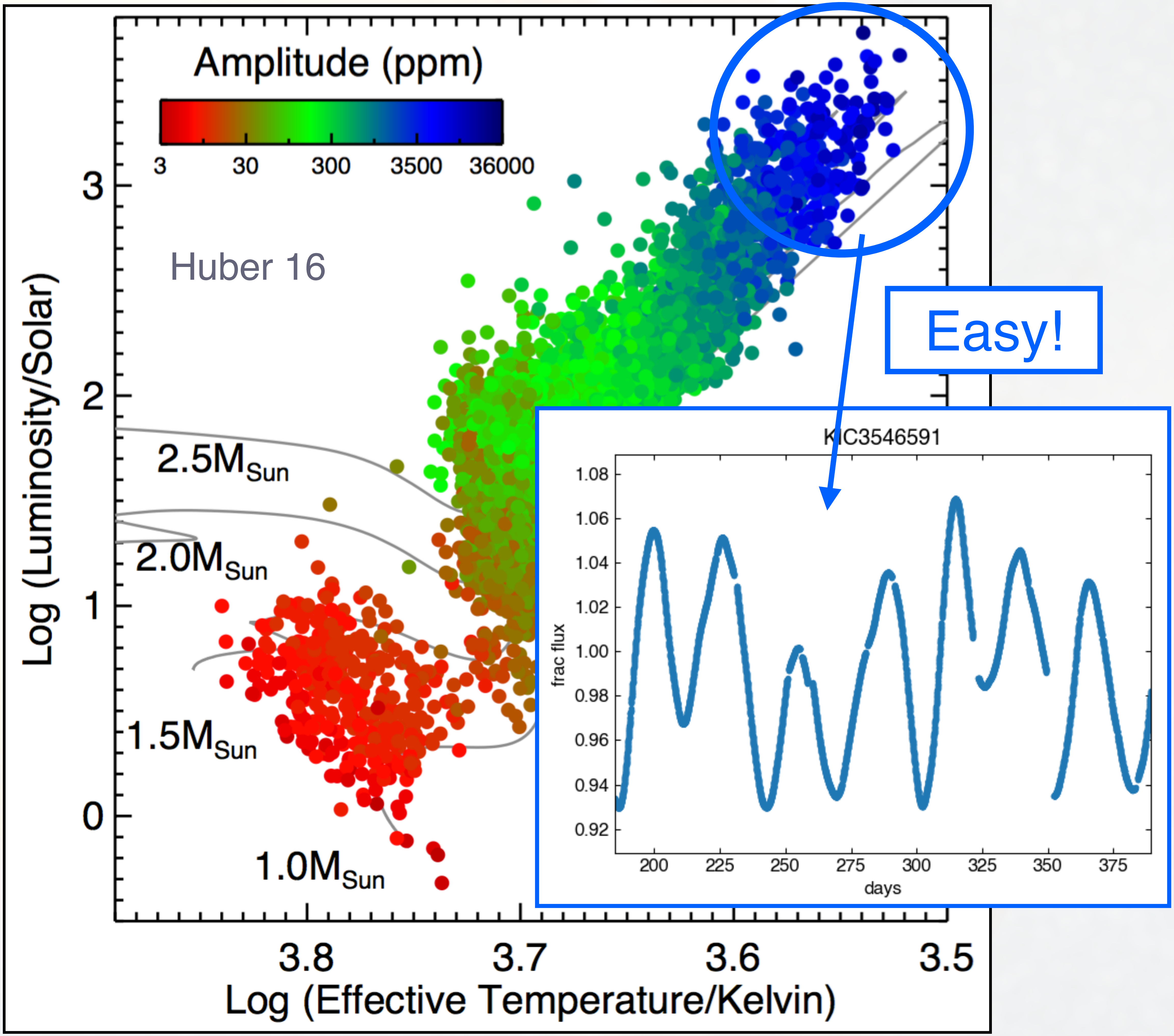
- Can we prioritize spectroscopic follow-up prior to light curves becoming available?

- How can follow-up be tiled efficiently? Use CVZ-S pathfinder to inform this?

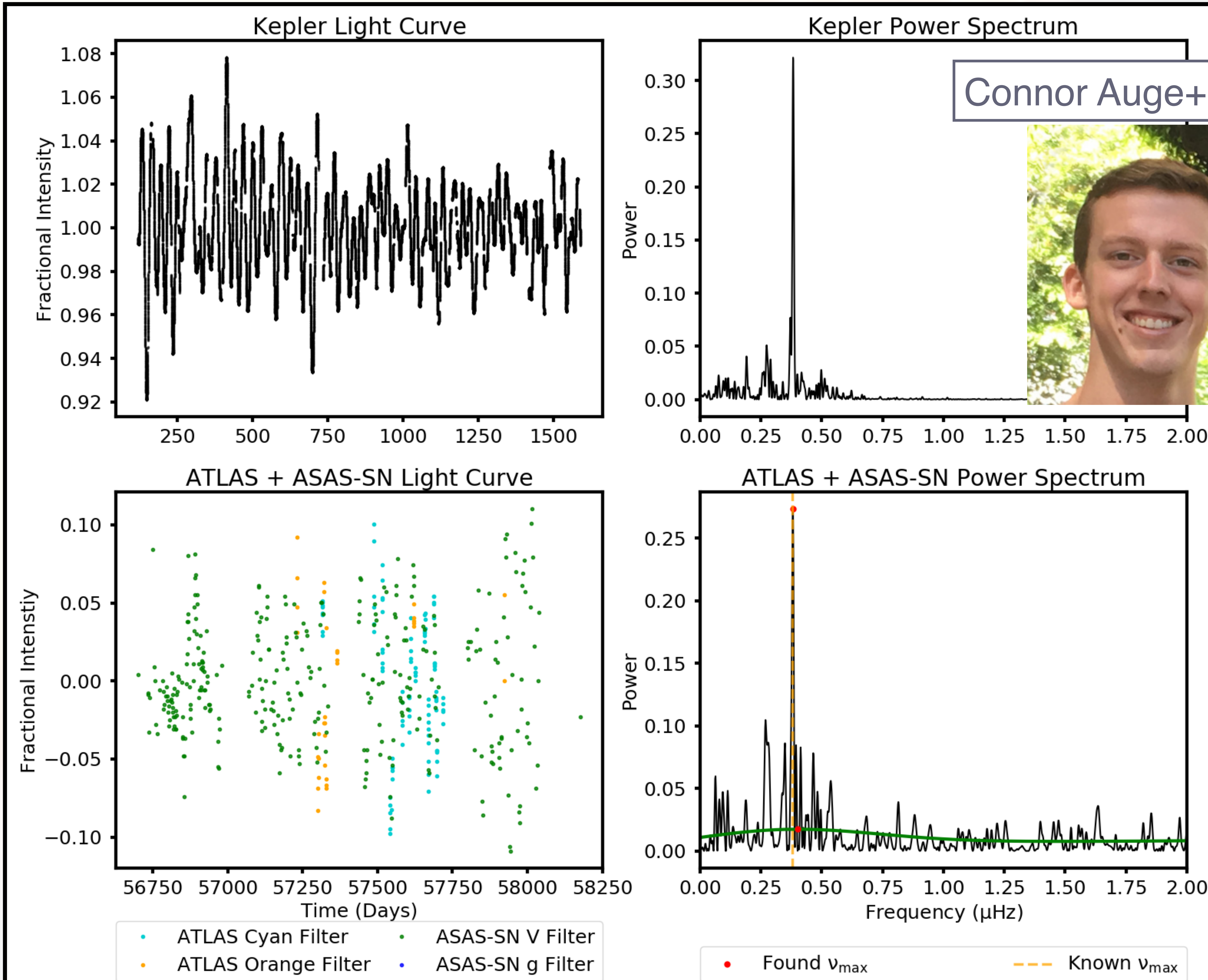
- What are the big galactic archeology questions that can be answered only with seismo+spectra?

Can we do Asteroseismology with ground-based TDA surveys?


Amplitude (ppm)
3
30
300
3500
36000
Huber 16
pre-Kepler
2.5M$_{Sun}$
2.0M$_{Sun}$
1.5M$_{Sun}$
1.0M$_{Sun}$
0
1
2
3
3.8
3.7
3.6
3.5
Log (Luminosity/Solar)
Log (Effective Temperature/Kelvin)

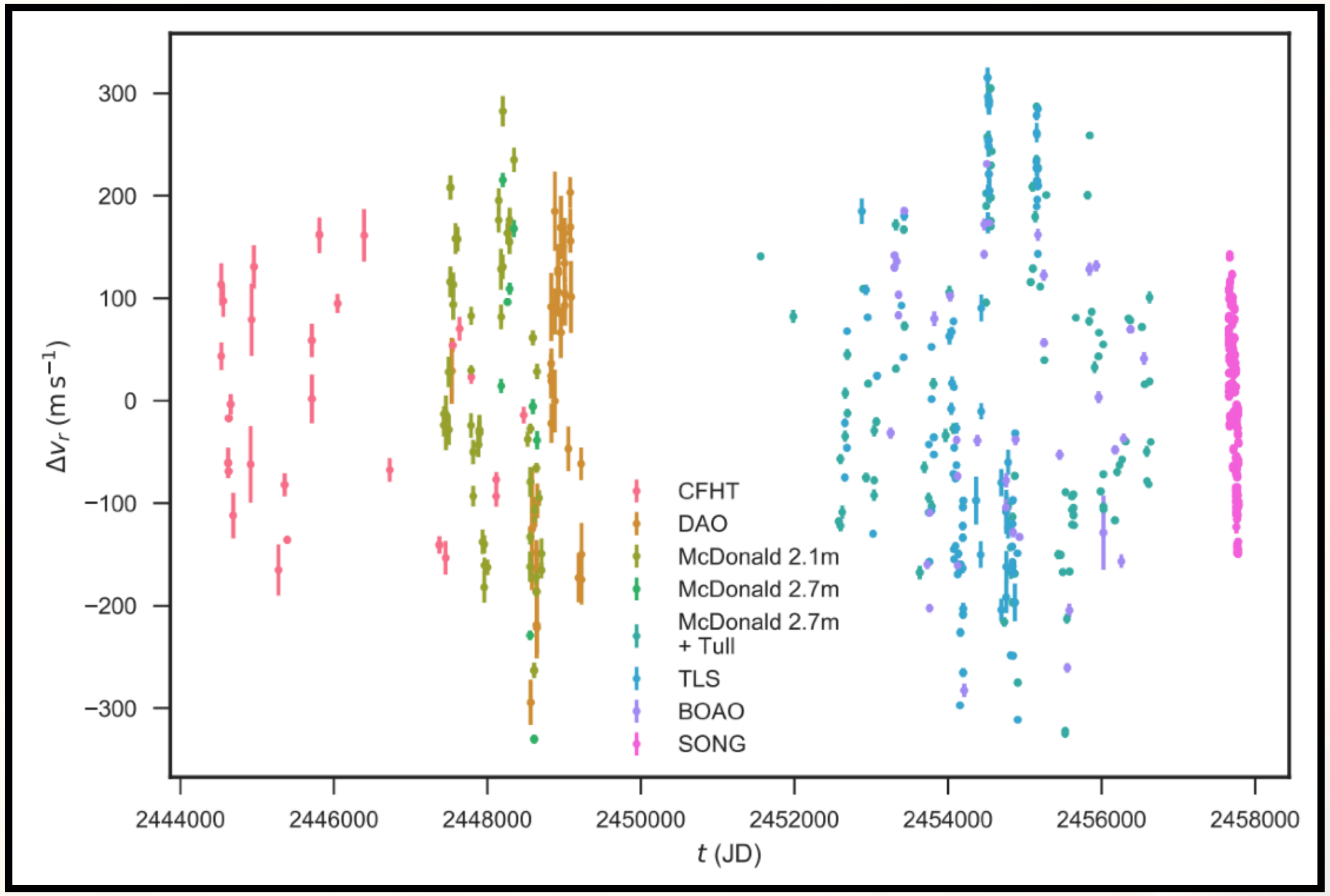


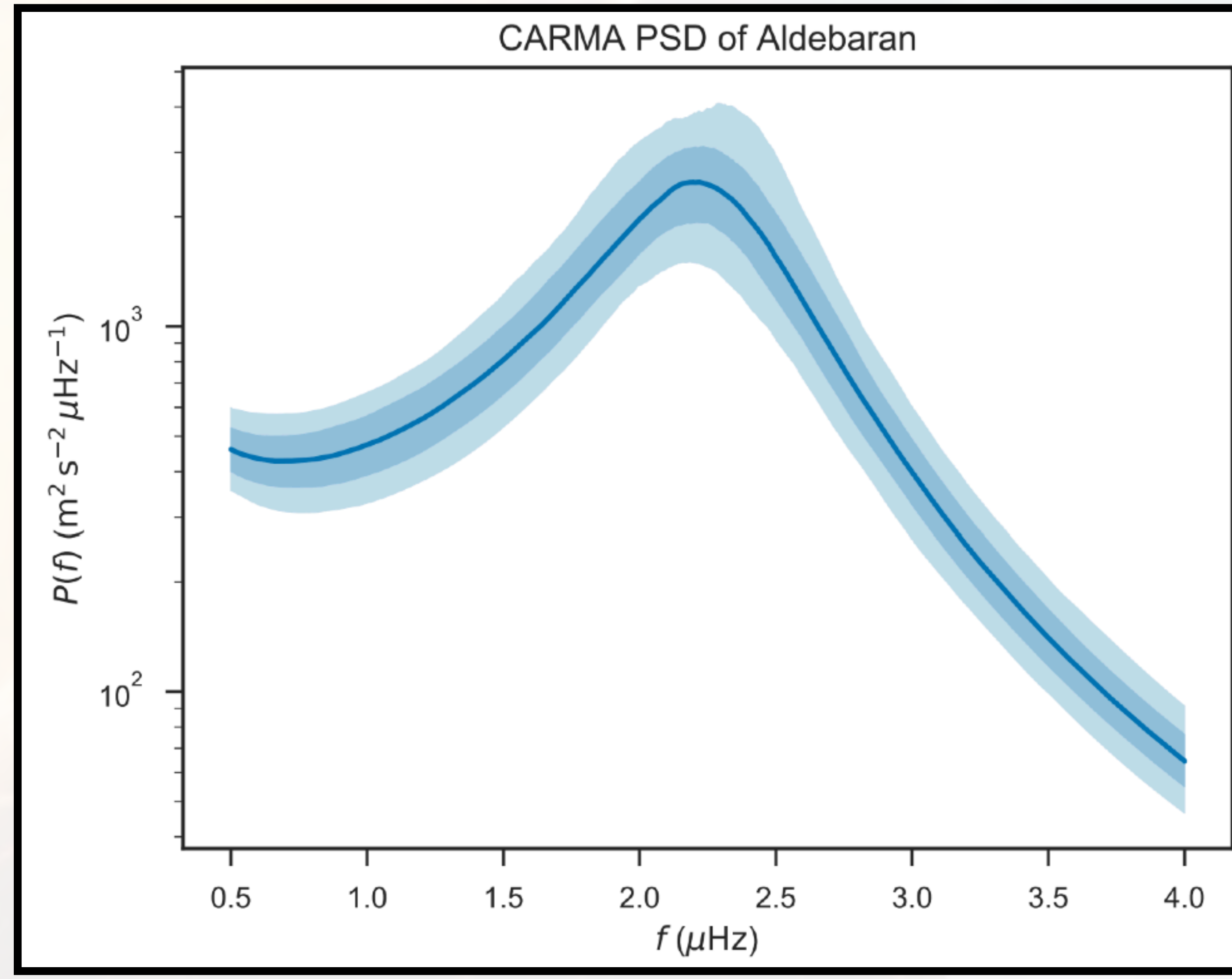
Amplitude (ppm)
3
30
300
3500
36000
Huber 16
2.5MSun
2.0MSun
1.5MSun
1.0MSun
Log (Luminosity/Solar)
3
2
1
0
3.8
3.7
3.6
3.5
Log (Effective Temperature/Kelvin)
Easy!
KIC3546591
frac flux
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.92
200
225
250
275
300
325
350
375
days



Connor Auge+, in prep

"Sparse" RV Asteroseismology

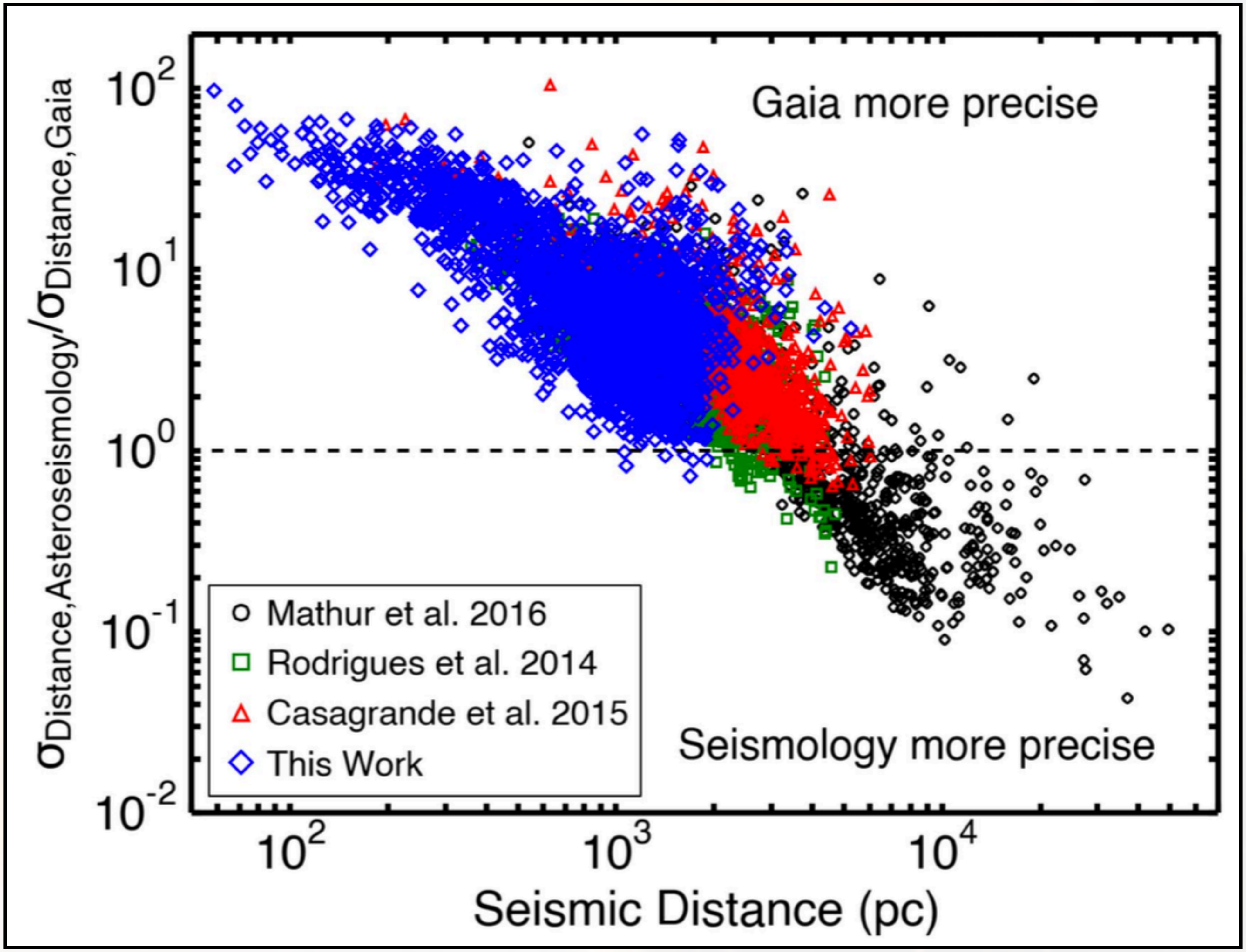




Farr+18

Aldebaran: RVs obtained for planet hunting used to recover asteroseismic oscillations; consistent with K2 photometry, but much better frequency resolution!

Asteroseismology versus Gaia



Huber+ 17

Challenges/Questions

- What is the best sampling strategy? Can we combine ATLAS/ASAS-SN/ZTF in an ideal way?
- Can we push the photometric precision to detect oscillations in lower luminosity giants?
- If not, what questions can be answered just with distances?
- How much can data-driven models help with sparse observations?

Young Star Rotation and Gyrochronology

L. A. Hillenbrand and L. M. Rebull

The Original Variable Catalog of 18 stars by Argelander (1844)

	Name of the star.	1840 AR. °	′	Decl. °	′	Length of the Period d	Magnitude Max.	Min.
1	ο Whale	32	49	− 3	42	332.04	2.	—
2	χ Swan	296	6	+32	31	406.06	5.	—
3	30 Snake	200	15	−22	27	493.86	4.	—
4	Algol	44	26	+40	20	2.8673	2.3	4
5	η Eagle	296	5	+ 0	36	7.1763	4.3	5.4
6	β Harp	281	3	+33	11	12.9119	3.4	4.5
7	In the Lion	144	44	+12	10	311.4	5.6	—
8	δ Cepheus	335	48	+57	35	5.3664	4.3	5.4
9	α Hercules	256	50	+14	35	95	3	4.3
10	In the Crown	235	30	+28	41	335	6	—
11	In Sob. Shield	279	44	− 5	52	60.395	5	7
12	In the Virgin	187	36	+ 7	52	145.43	6	—
13	In the Water carrier	353	53	−16	10	389	7	—
14	In the Serpent	228	33	+14	54	366	8	—
15	Ditto	235	50	+15	38	359	6.7	—
16	α Cassiopeia	7	52	+55	39	79.03	2	3.2
17	α Orion	86	38	+ 7	22	199	1	1.2
18	α Snake	139	56	− 7	58	55 ?	2	2.3

Argelander (1844) as translated by Cannon (1912)

On account of the low state of our knowledge of these stars, nothing in general can at present be offered nor, by any means, can a definite theory be given, which can refer the light changes to any one cause. But happily, hypotheses, even if full of error, fail us not. Omitting those which at first glance are seen to be untenable, cthey resolve themselves into the following three.

1. **Revolution of the stars on their axes, their surfaces being of different luminosity on the different sides**, whereby they would be brighter if they turned towards us the side of greatest illumination, or conversely, darker if the side of less illumination.

2. Revolution on their axes, with **strongly compressed figure, and considerable variation of angle of the axis of rotation towards the line of sight**. If the axis nearly coincides with the line of sight, then the star turns towards us a very extensive surface, sends us much more light, and therefore shines brighter than if they, be- cause of a very large angle, turn their edge, if I may so call it.

3. **Huge planets** revolving around the stars, in the plane of whose orbits the line of sight nearly falls and which, therefore, by inferior conjunction with the star, cut off a large part of the light formerly coming from it to us, so that it seems less bright.

<u>**The first of these hypotheses seems to be the most plausible**</u> and, in general, to explain observed appearances of several of the stars, if we assume that the constitution of these stars is similar to that of our Sun.

	Name of the star.	1840 AR. °	′	Decl. °	′	Length of the Period d	Magnitude Max.	Min.
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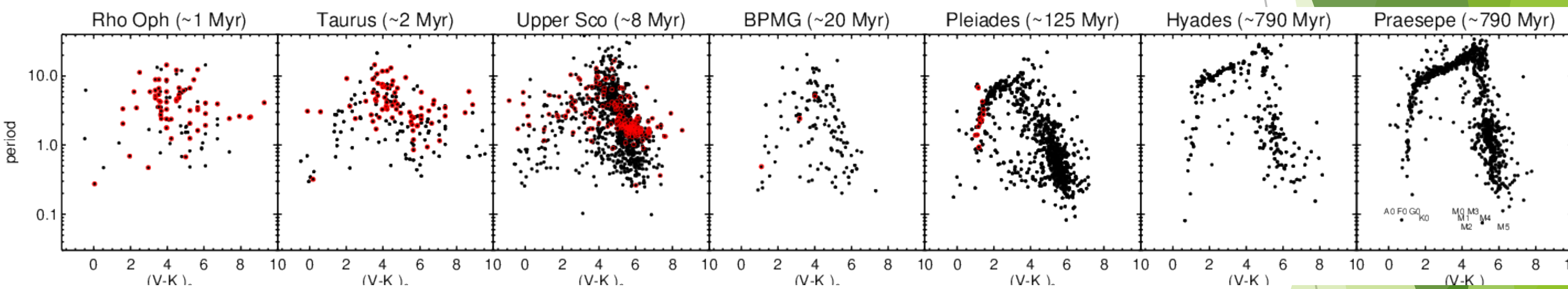
State-of-the-Art K2 Data on Young Clusters

Period vs Color with Age

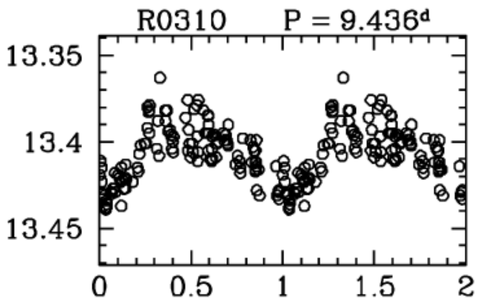


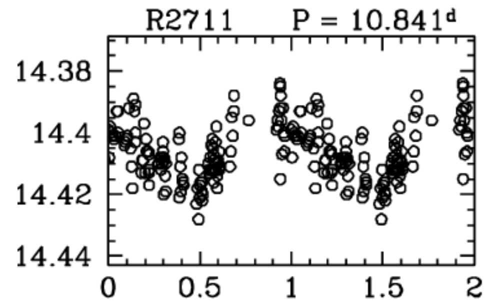
(not from K2)

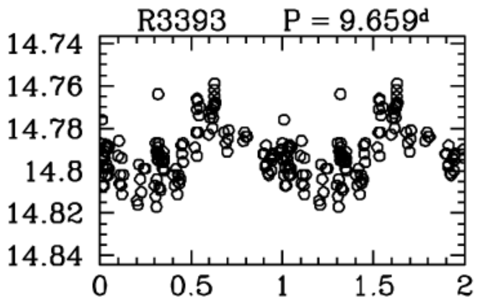
- Red points denote infrared excess (i.e. a circumstellar disk).
- Black points denote disk-free stars.

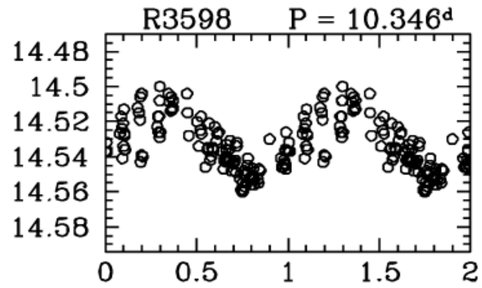
Rebull et al 2016, 2017, 2018, 2019…

Prior best-available from the ground





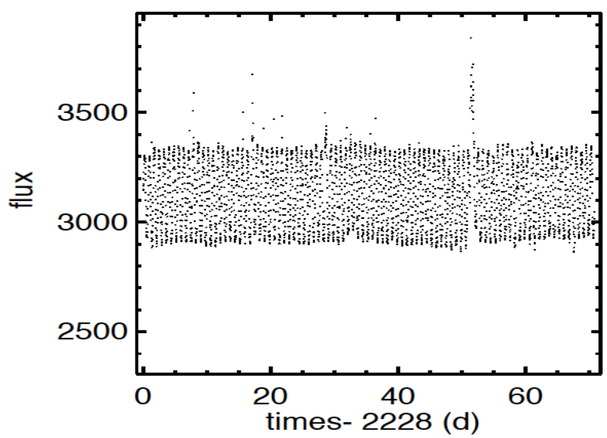




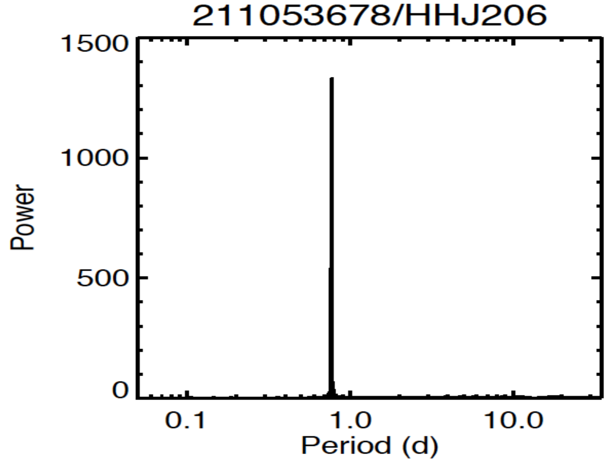
Rebull 2000

With K2, a source is either clearly periodic …

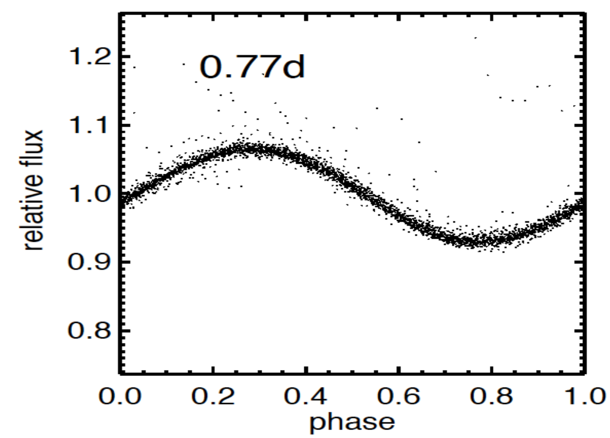
Light curve

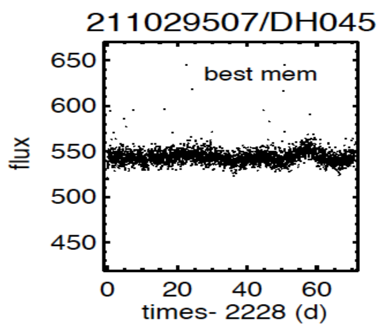


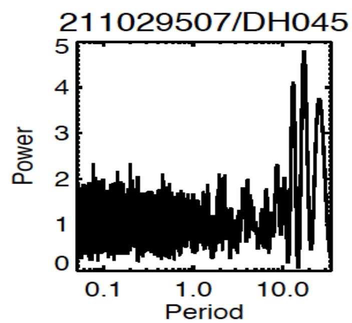
Power Spectrum



Phased to peak





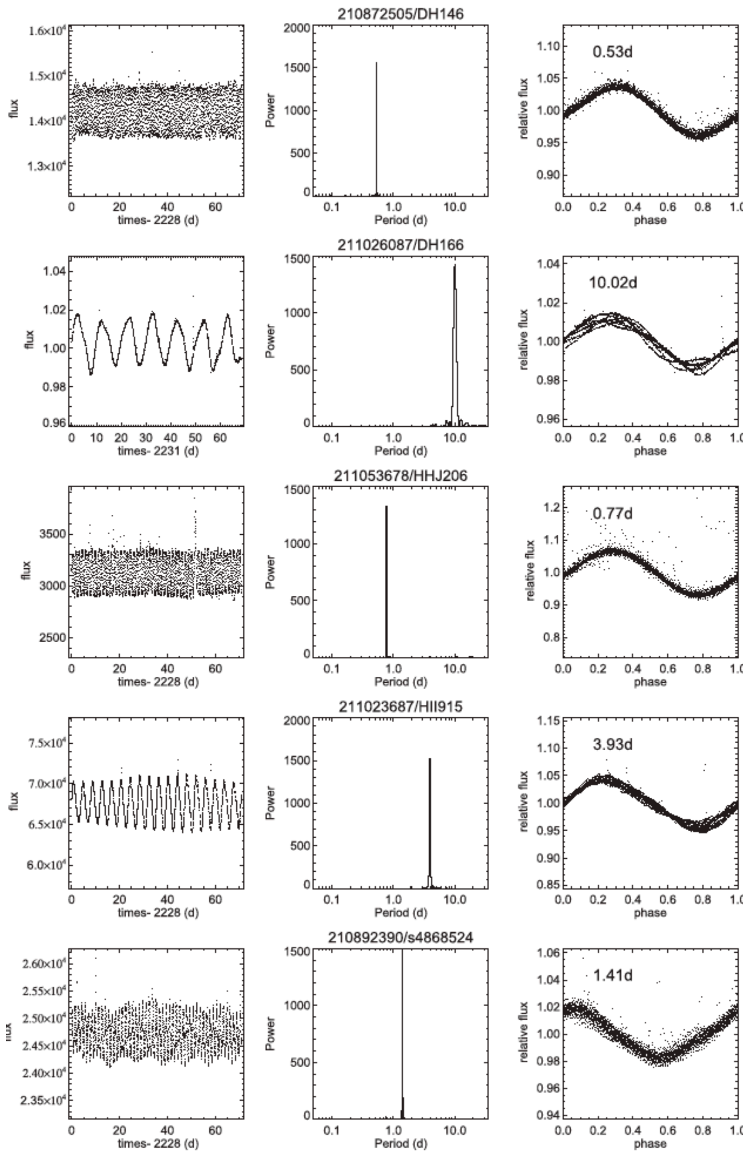


…Or it's obviously not!

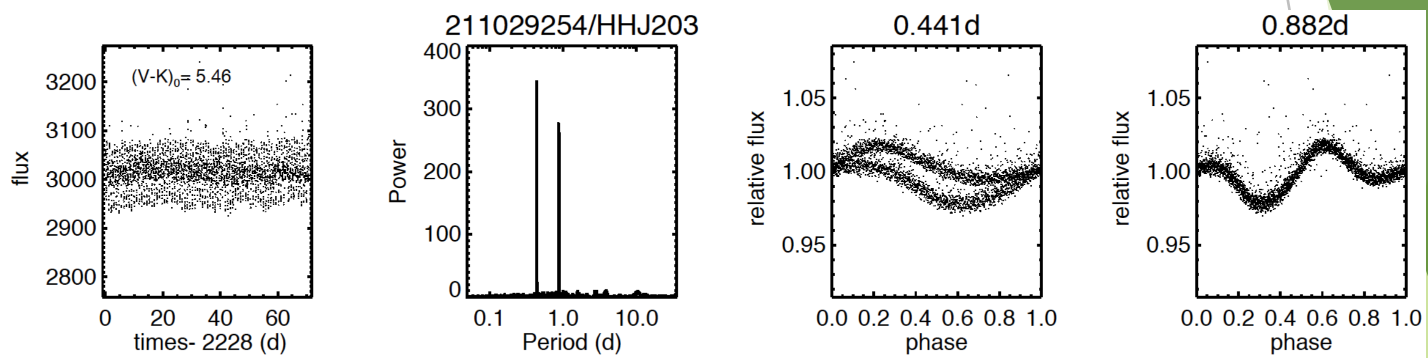
Different Types of Periodicity

Definition: One sinusoidal period.

Interpretation: star spots moving into and out of view as the star rotates.



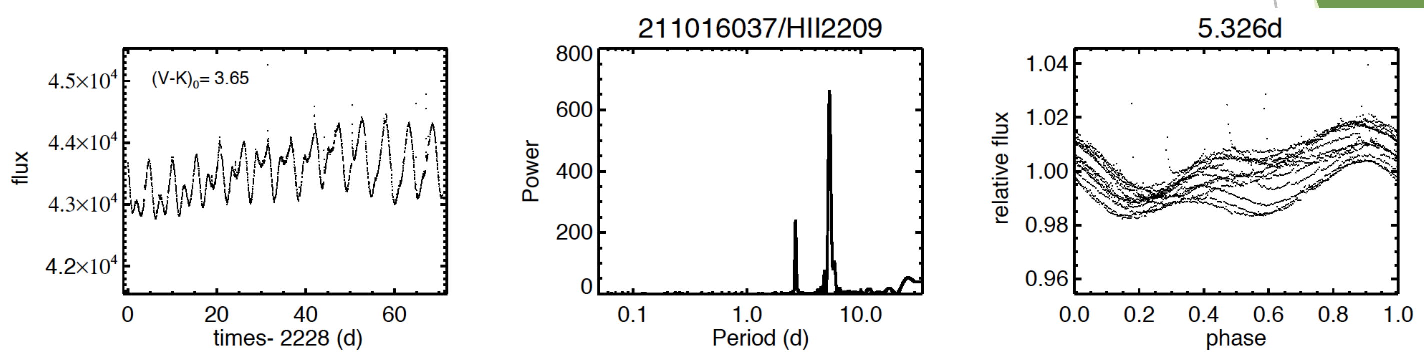
Double Dip



- **Definition:** Two peaks in the periodogram, but only one real period.

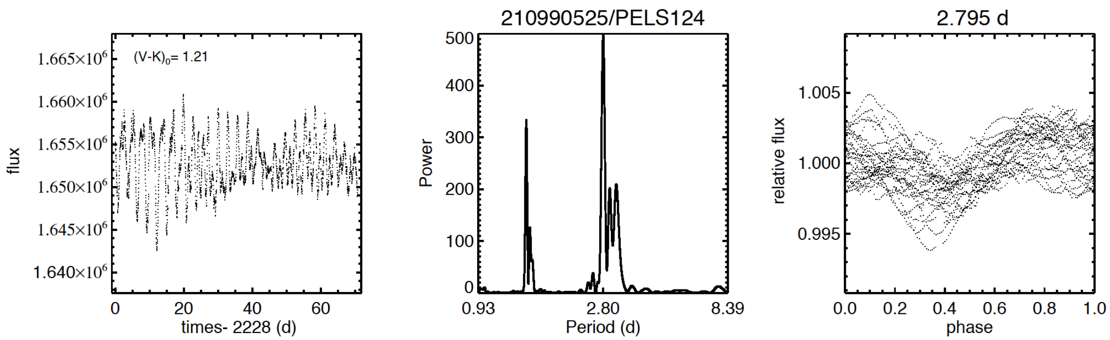
- **Interpretation**: Spots/spot groups that are well-separated in longitude.

Shape Changer



- **Definition:** Structures move during ~70d K2 campaign.
- **Interpretation**: Latitudinal differential rotation and/or spot/spot group evolution.

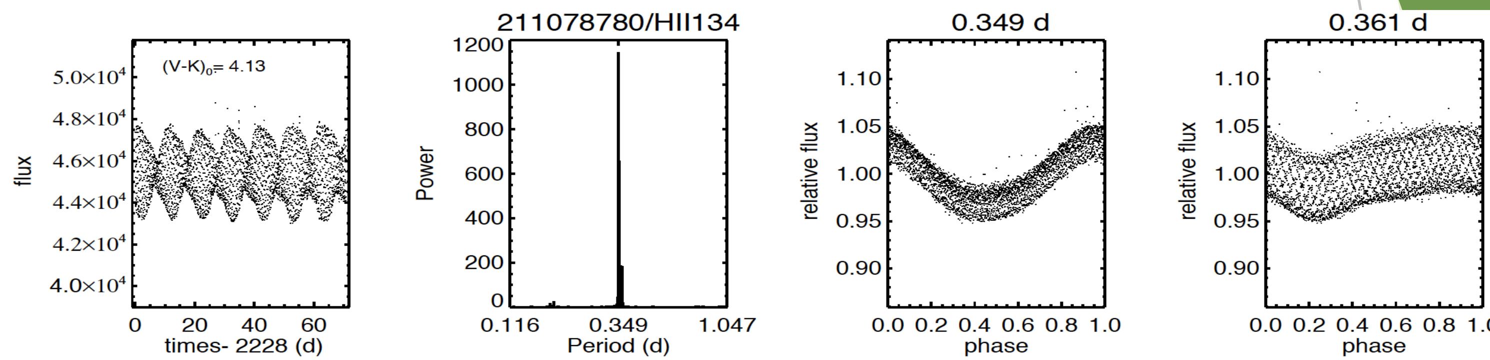
Beater/Complex Peak



- **Definitions:**
  - Beater: Beating signatures seen in light curve.
  - Complex Peak: Periodogram peak is structured or wider than expected.

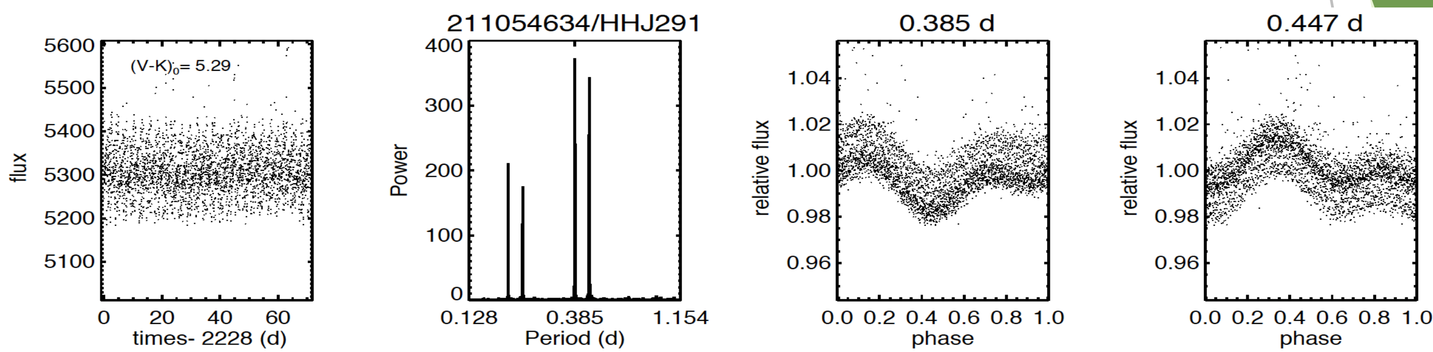
- **Interpretation**: Spot/spot group evolution and/or latitudinal differential rotation.

Resolved Close Peaks



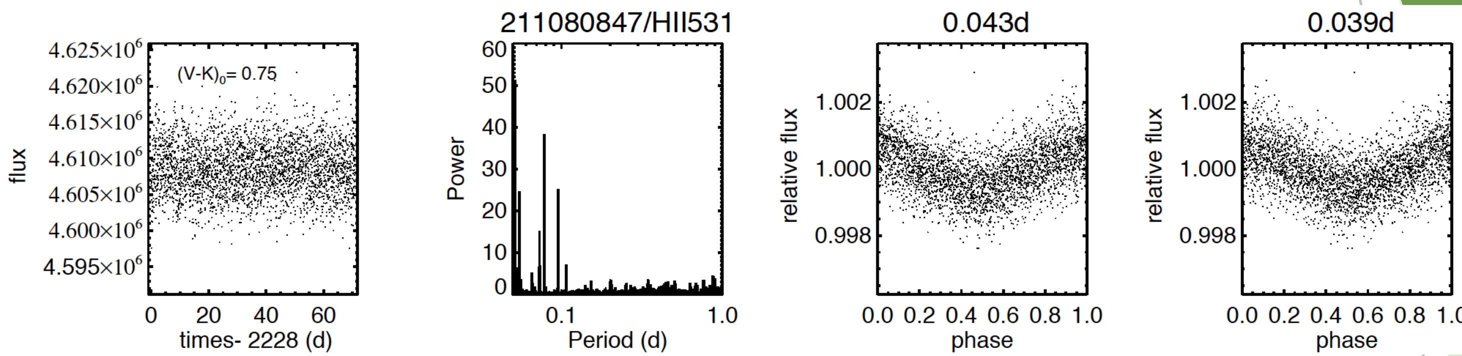
- **Definition:** Two close peaks in the periodogram.
- **Interpretation:** Binarity (later types) and/or latitudinal differential rotation and/or spot/spot group evolution (earlier types).

Resolved Distant Peaks



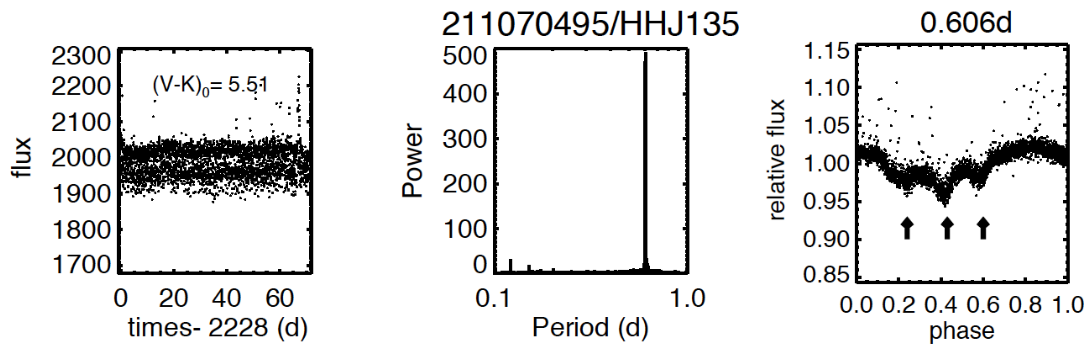
- **Definition:** Two distant peaks in the periodogram.
- **Interpretation:** Binarity.

Pulsator



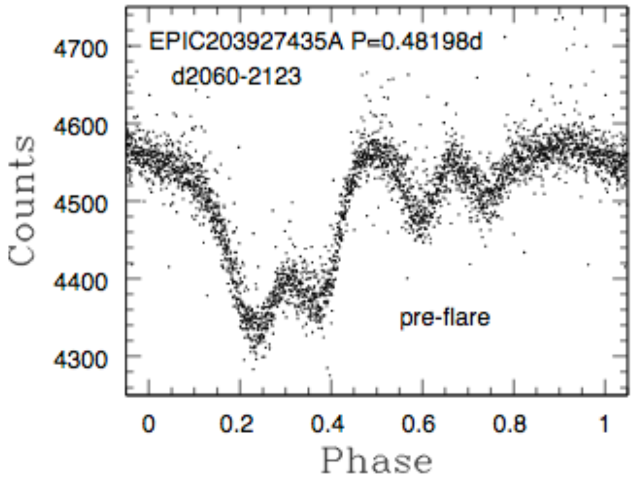
- **Definition**: “Forest” of short-P peaks in periodogram.
- **Interpretation**: Pulsation.

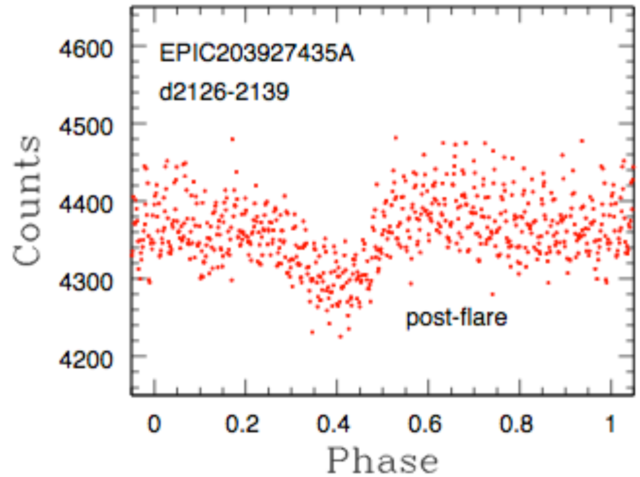
Co-rotating Optically Thin Material



- **Definition:** Distinct narrow features in phased light curve.
- **Interpretation:** Magnetospheric clouds or orbiting debris??
- *Concentrated towards younger sources, e.g. a few in Pleiades and tens in Usco/Tau (Stauffer et al. 2017, 2018).*

Waveform Can Change During the ~80 Day K2 Campaign

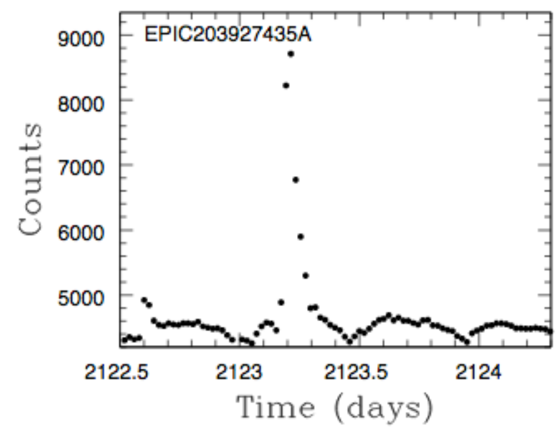




Orbiting Clouds of Material at or near the Keplerian Co-Rotation Radius in Late M Dwarfs WTTs of Upper Sco

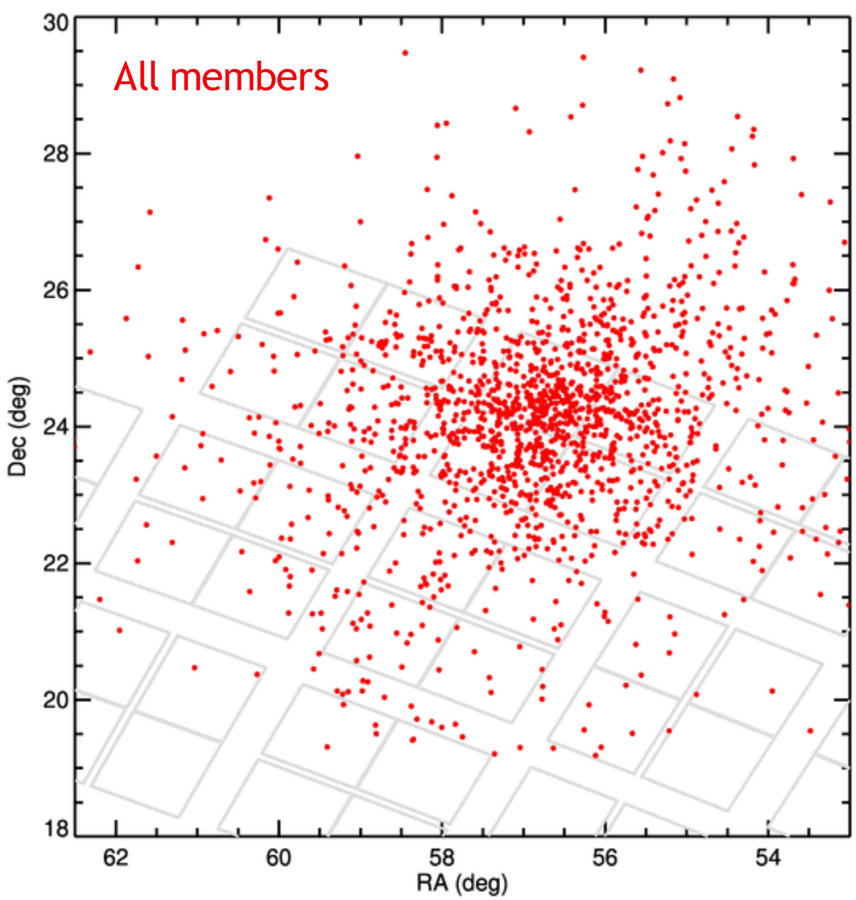
[Stauffer et al. 2017]

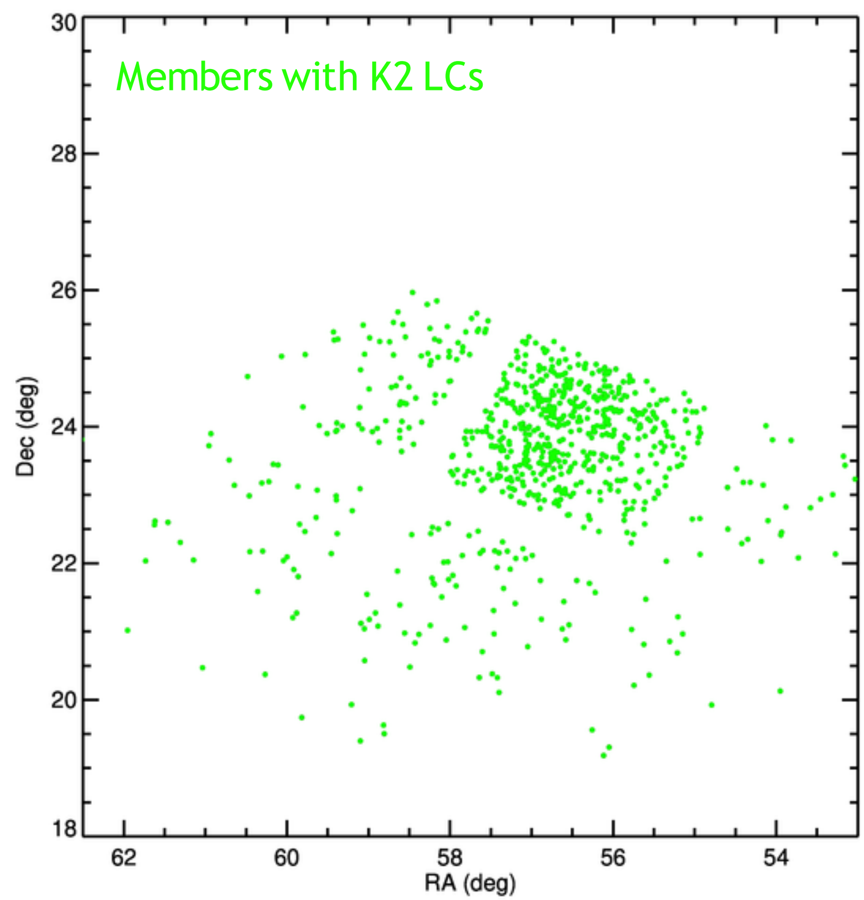
changes seen at restricted phases, sometimes closely following detected flares.



K2 has been a bounty, but did not completely sample benchmark clusters.

Coverage: Pleiades



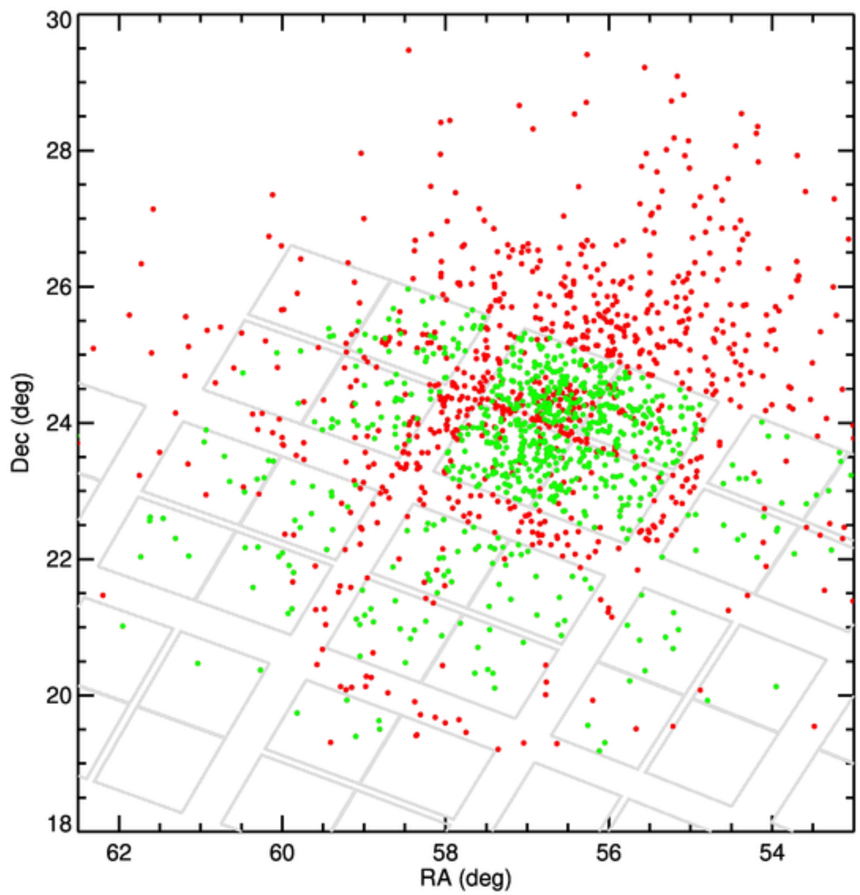


K2 has been a bounty, but did not completely sample benchmark clusters.

Coverage: Pleiades

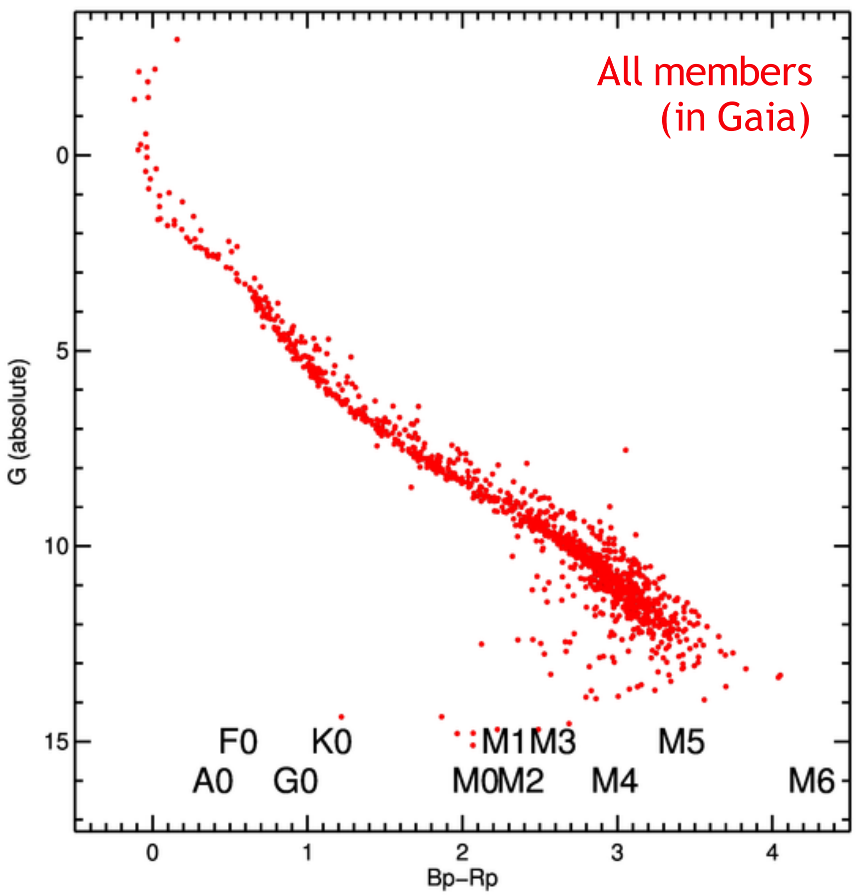
All members

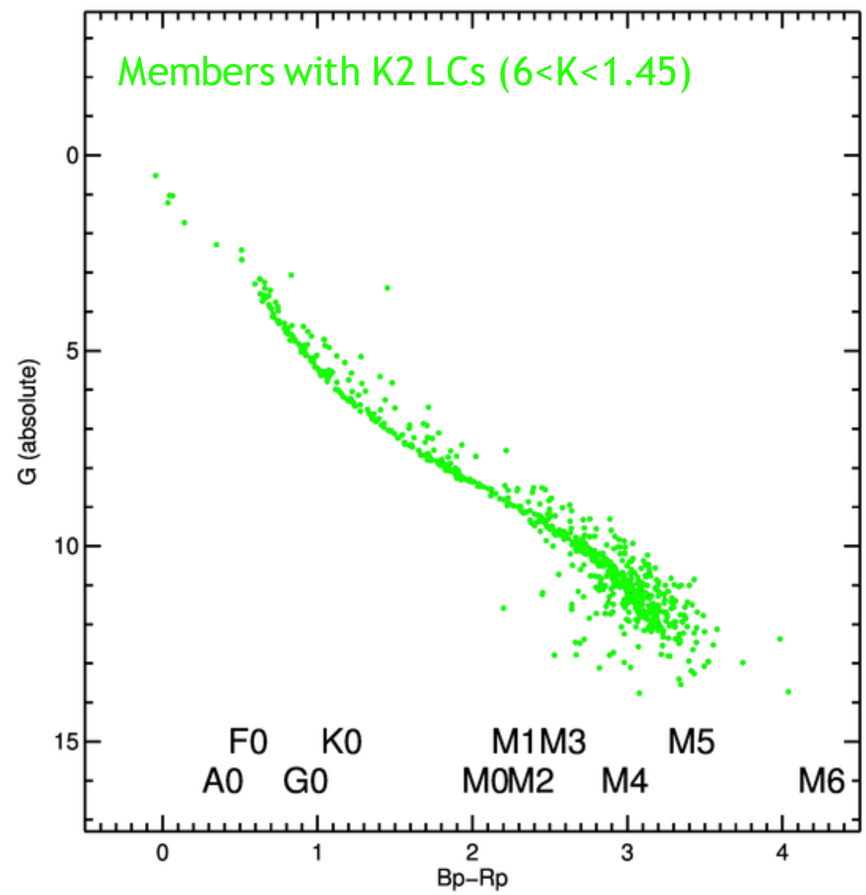
Members with K2 LCs



K2 samples appear representative of the underlying populations though.

Mass (color, SpT) range: Pleiades

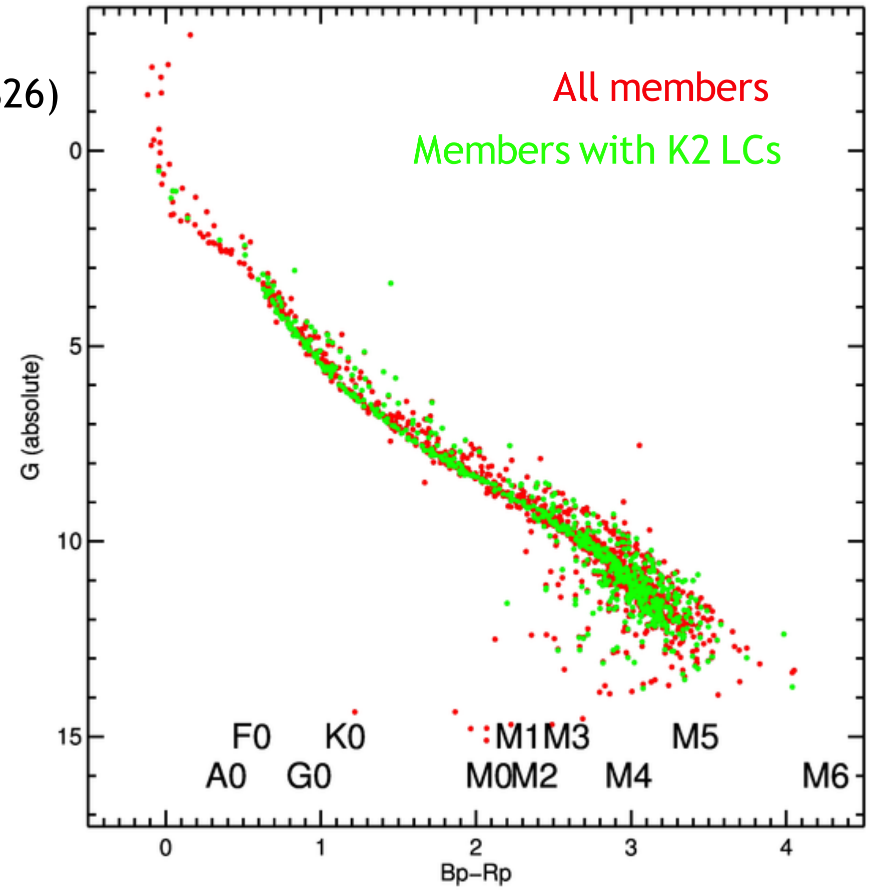




K2 samples appear representative of the underlying populations though.

Mass (color, SpT) range: Pleiades

52% of members have LCs.
92% of LCs are periodic (759/826)
20% of periodic have >1 period



Summary on K2 Period Information

- Praesepe: 809 periods (86%)
- Hyades: (>67%)
- Pleiades: 759 periods (92%)
- USco: 969 periods (86%)
- Taurus: 193 periods (86%)
- ρ Oph: 108 periods (60%)

20-25% of the periodic stars are actually multi-periodic

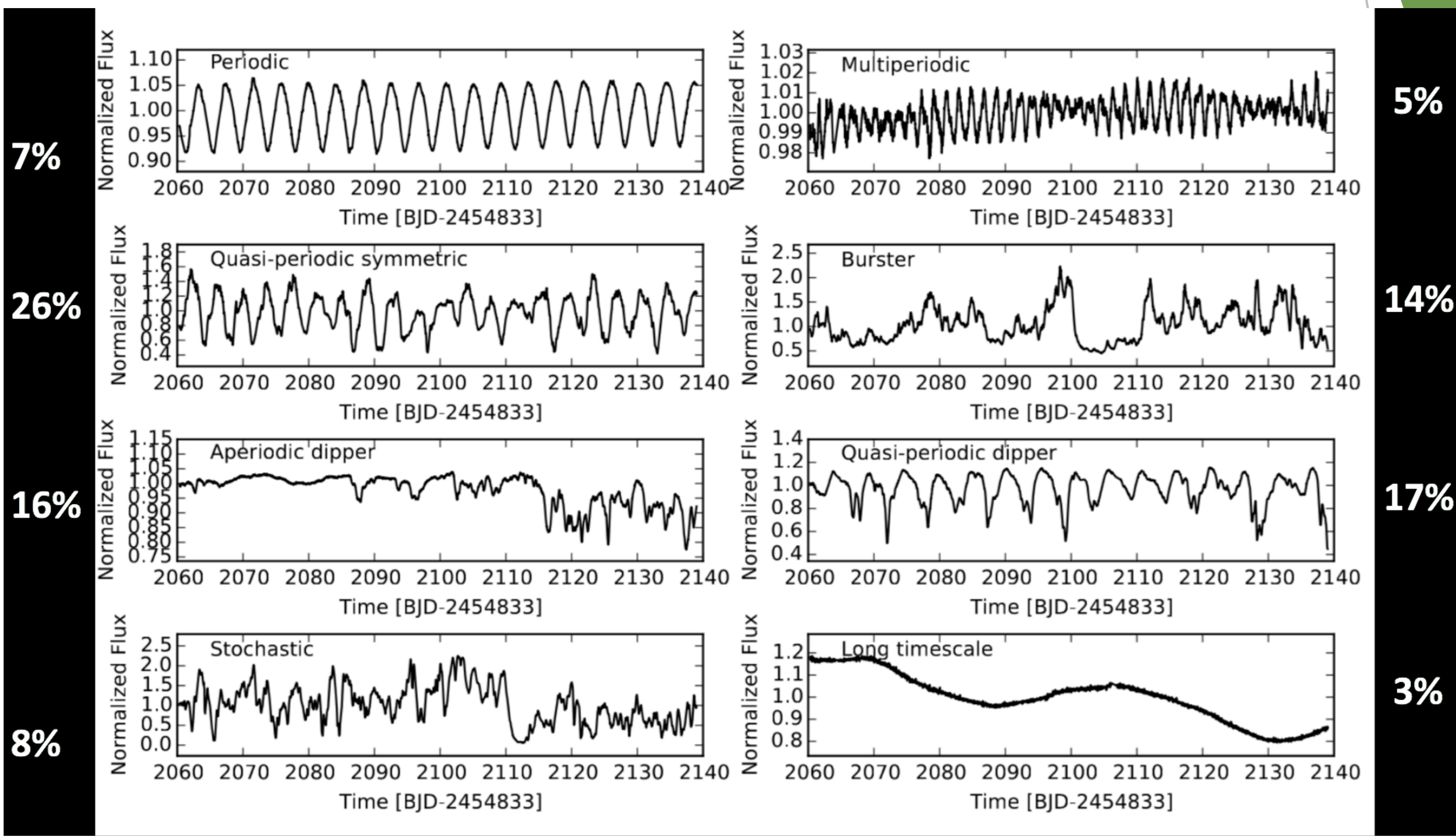
➔ differential rotation with latitude

→ spot evolution during K2 campaign

→ binaries within the K2 point spread function.

Rebull et al. 2016, 2017, 2018, 2019…

Disked stars have additional variability on top of underlying periodicity ==> LC morphology classes

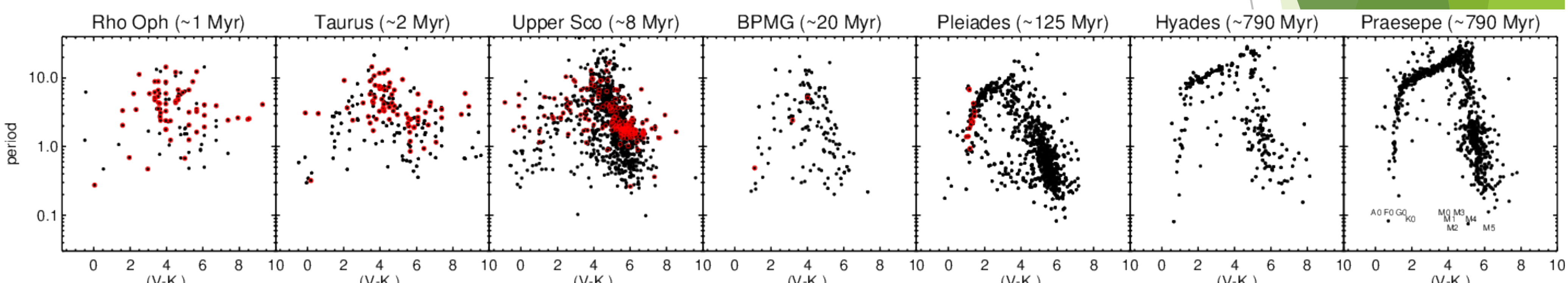


Cody & Hillenbrand 2018

Gyrochronology:

Period-Age Evolution vs Stellar Color (Mass)

Rebull et al. 2016, 2017, 2018, 2019…

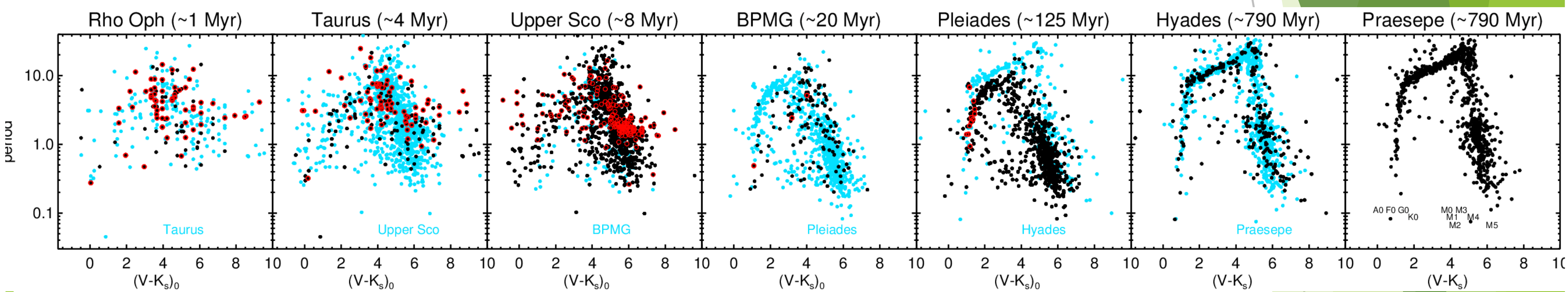


- Youngest stars have rotation regulated by "disk locking" – no period-mass relation.
- Once free of disk, spin-up en route to the main sequence (30 Myr @1 Msun).
- On main sequence, spin-down due to angular momentum loss via winds.
- Mass effects:
  - A,F stars have no dynamo and therefore no spots, so no measured periods.
  - G,K, and early M stars exhibit age-dependent period-mass relationship.
  - late M stars (fully convective) remain rapidly rotating for at least ~1 Gyr.

Gyrochronology:

Period-Age Evolution vs Stellar Color (Mass)

Rebull et al. 2016, 2017, 2018, 2019…



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Gyrochronology Theory

Gallet & Bouvier 2013

- Historically developed for “solar-type” stars without consideration of detailed mass effects.
- Goal was to explain the wide dispersion in rotation in the pre-main sequence up to ~100 Myr Pleiades age, and then the convergence by ~1000 Myr.
- Ingredients:
  - disk locking parameters
  - radial contraction
  - core-envelope (de-)coupling
  - angular momentum transport in to the stellar wind.

A&A 556, A36 (2013)

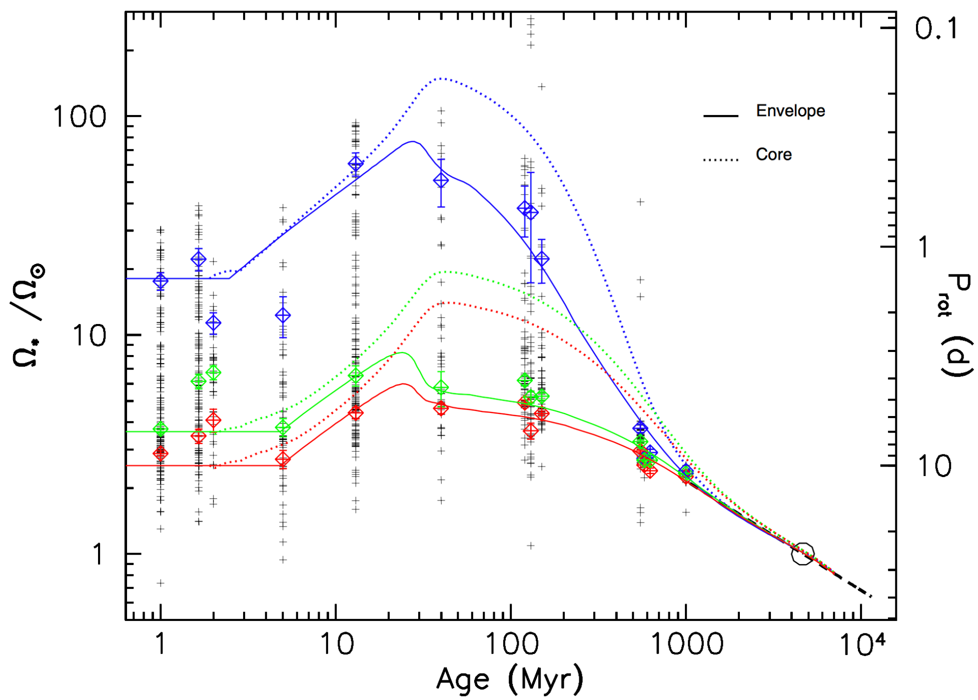
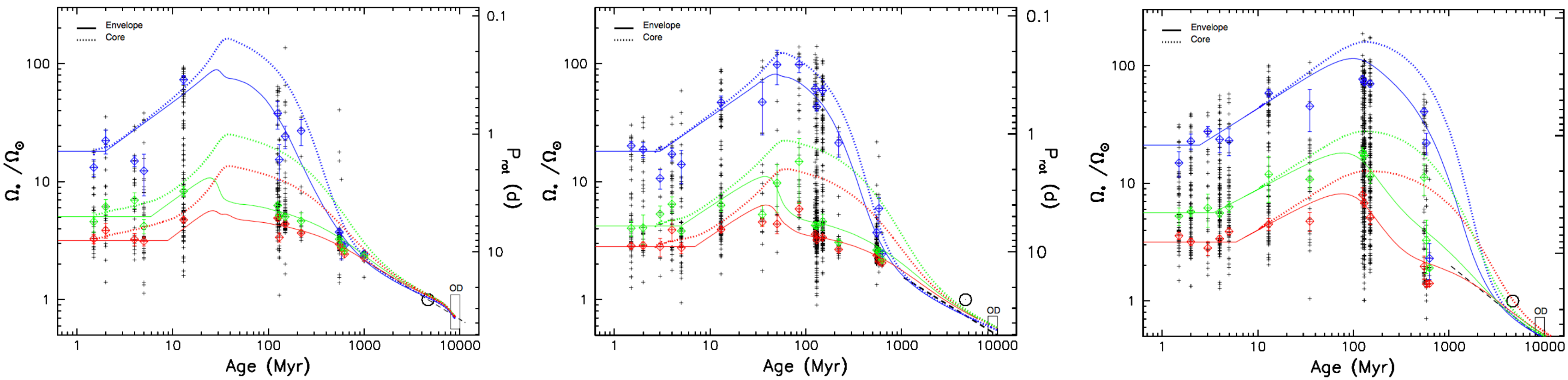


Fig. 3. Angular velocity of the radiative core (dashed lines) and of the convective envelope (solid lines) as a function of time for fast (blue), median (green), and slow (red) rotator models. The angular velocity is scaled to the angular velocity of the present Sun. The blue, red, and green tilted squares and associated error bars represent the 90th percentile, the 25th percentile, and the median, respectively, of the rotational distributions of solar-type stars in star forming regions and young open clusters obtained with the rejection sampling method (see text). The open circle is the angular velocity of the present Sun and the dashed black line illustrates the Skumanich relationship, $\Omega \propto t^{-1/2}$.

Gyrochronology Theory

Now allowing <u>mass-dependence</u> in disk/structure/wind parameters.
Most important for the core-envelope coupling timescale and the wind braking efficiency.



(a) 1 $M_\odot$ (b) 0.8 $M_\odot$ (c) 0.5 $M_\odot$

Gallet & Bouvier 2015

Models can reproduce:

- longer spin-down timescale of lower mass stars
- lower velocities (longer periods) at lower masses by end of spin-down phase

Models predict: lots of angular momentum left in stellar core

Gyrochronology Applied to Field Stars?

- Kepler classic field
- Red = highest flaring frequency, e.g. most active stars.
- "Isochrones" are empirical and were developed for *solar-mass stars* (T=5000-6300 K).

The Astrophysical Journal Supplement Series, 241:29 (19pp), 2019 April

Yang & Liu

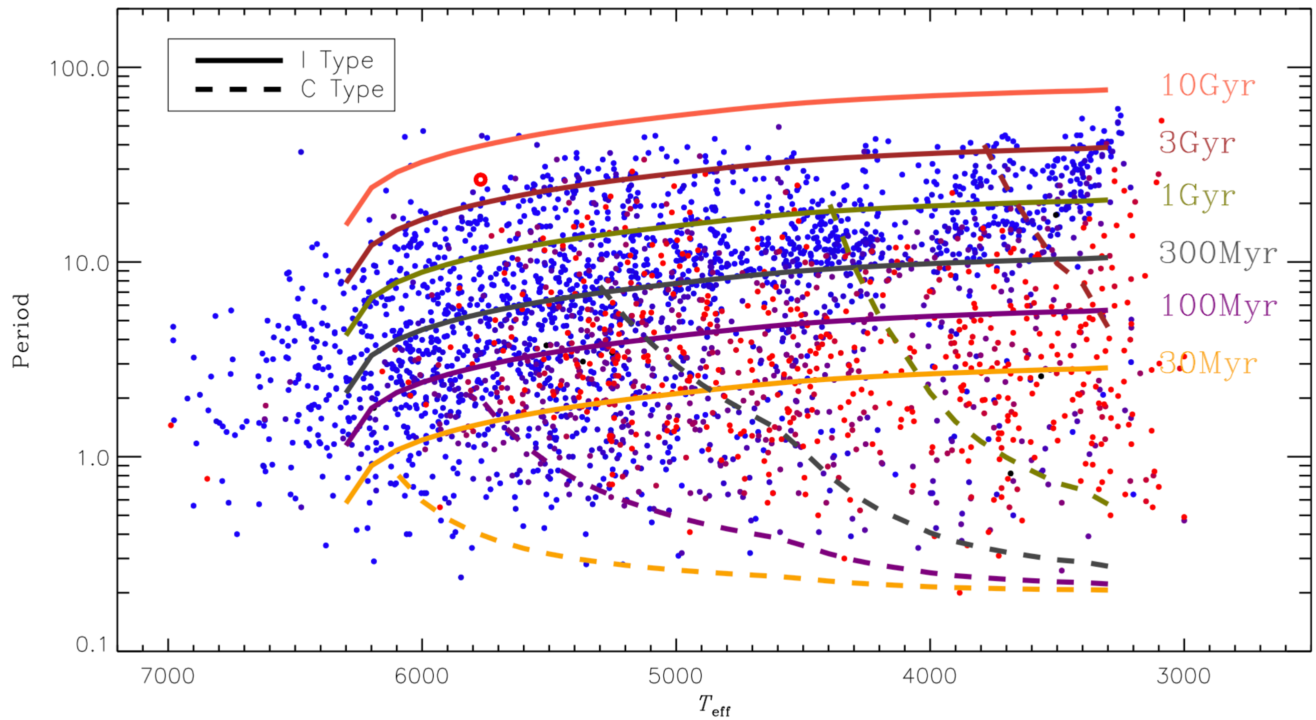
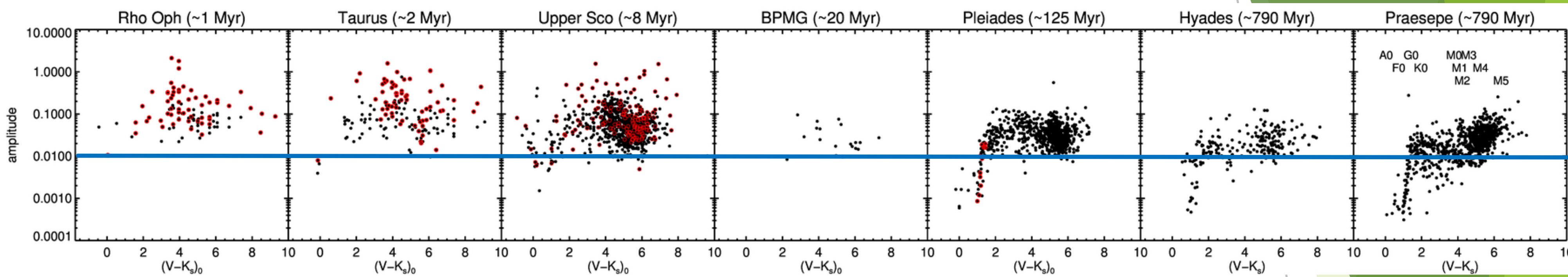
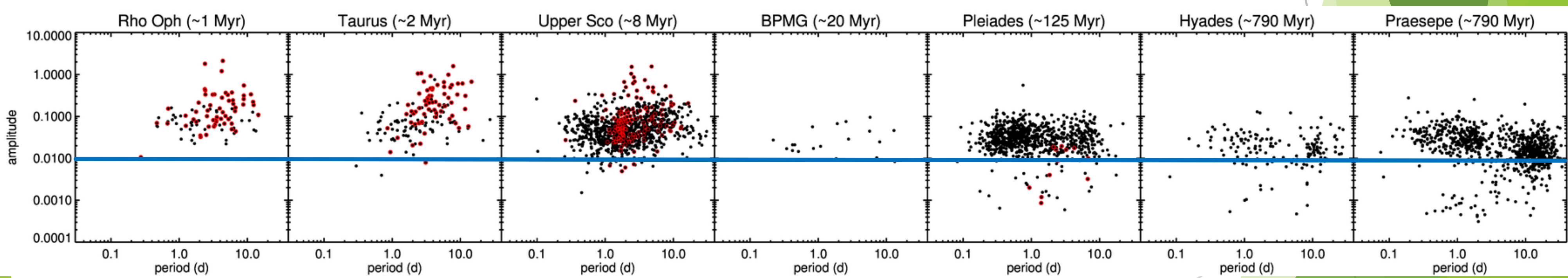


Figure 7. Rotation period vs. temperature. The lines are the empirical ischrones of Gyrochronology, of which the solid line and dashed line represents the I sequence and the C sequence, respectively. The same color of the ischrones denotes the same age. The bifurcations of the lines indicate the transition point when C stars evolve onto I stars. The flare stars are overplotted in the diagram by filled circles. The color of the circle represents the flare activity, which is as the same as Figure 4. The Sun is marked as the open circle. The ischrones of the I sequence are given by Mamajek & Hillenbrand (2008), while the ischrones of the C sequence are according to Barnes (2010). The differences of ischrones of the I sequence among Mamajek & Hillenbrand (2008), Meibom et al. (2009), and Barnes (2010) are too small to affect the analysis and scenario of this study. Transformations from color to temperature are accomplished using Table 1 of Barnes & Kim (2010).

Amplitude vs Color with Age



Amplitude vs Period with Age



- Flat amplitude-period relation at younger ages.
- Lower amplitudes for slower periods at older ages.

What would Spectroscopy Offer?

- Projected rotation (V*sini from SDSS/APOGEE)
  - New information for A,F stars lacking rotation periods
  - Probabilistic inclination for stars with measured rotation periods
- Activity indicators (CaII to Halpha to CaII in SDSS/BOSS)
  - Calibrate activity—age—rotation relations
- Li 6708 (SDSS/BOSS? resolution is not ideal)
  - Better understand lithium depletion dependence on rotation
- Stellar parameters (Teff, log g from SDSS/APOGEE)
  - Better than colors for estimating stellar masses: the real variable of interest
- Multiplicity assessment (SB2 or SB1 identification from SDSS/APOGEE)
  - Characterize multiple-period cases in K2 that are interpreted as binaries.
  - Test activity-age-rotation relationships for binary pairs

What Does Ground-Based Photometry Offer?

Has lower precision but longer baseline, so can:

- Potentially find longer period objects missed due to K2 visibility windows
- Determine flaring statistics
- Characterize activity amplitudes even if periods can not be measured.

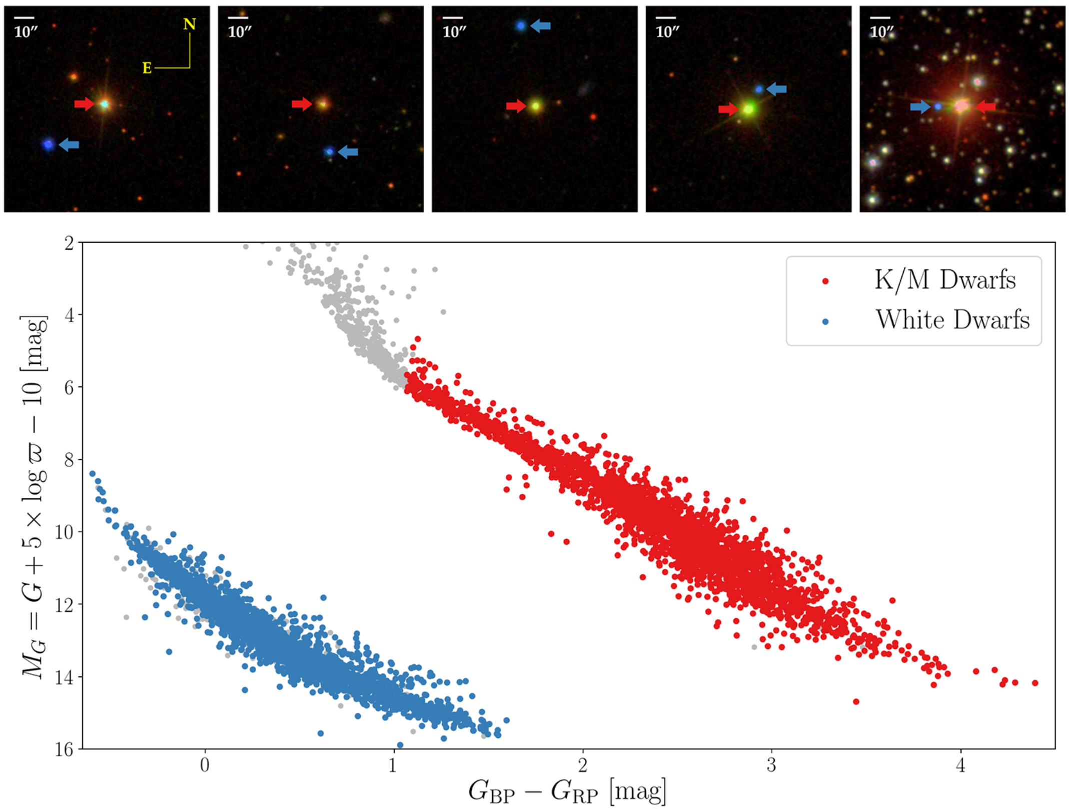
Covers more area, so can:

- Extend work to older clusters (expect lower amplitudes though, <1%)
- Study wide binaries (MS-MS, and also WD-MS where have independent clock)

Elaborating on the Wide-Binary Opportunity

2600+ wide WD+K/M binaries (El-Bardy et al)

Sample should populate the >1 Gyr age range



Elaborating on the Wide-Binary Opportunity

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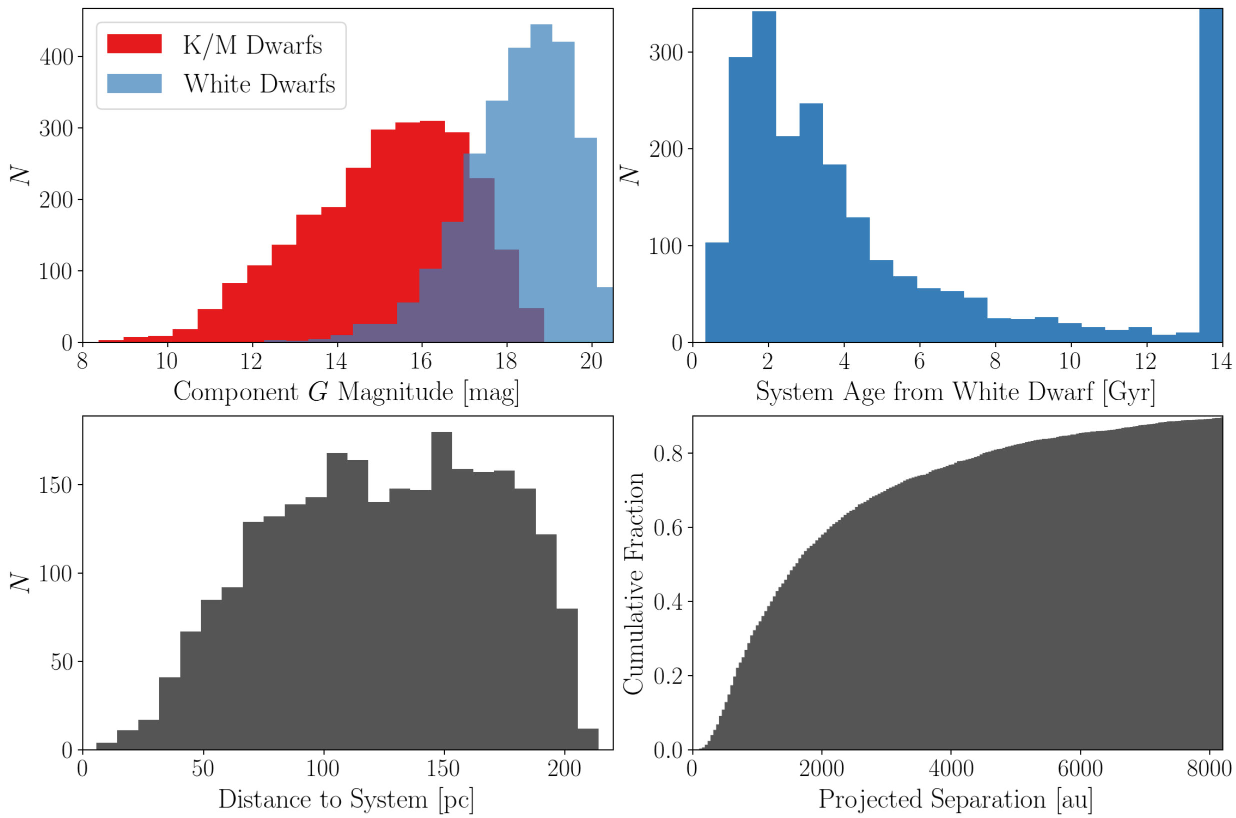
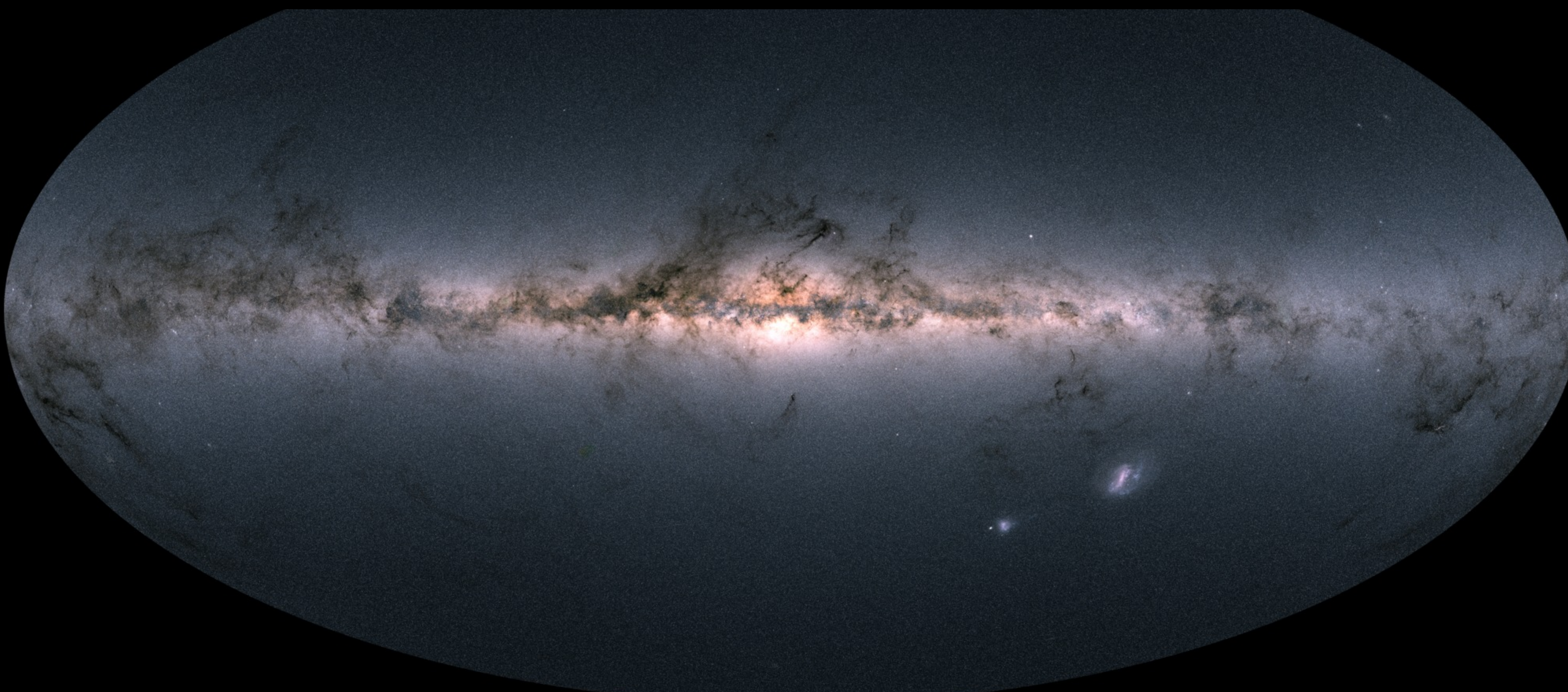


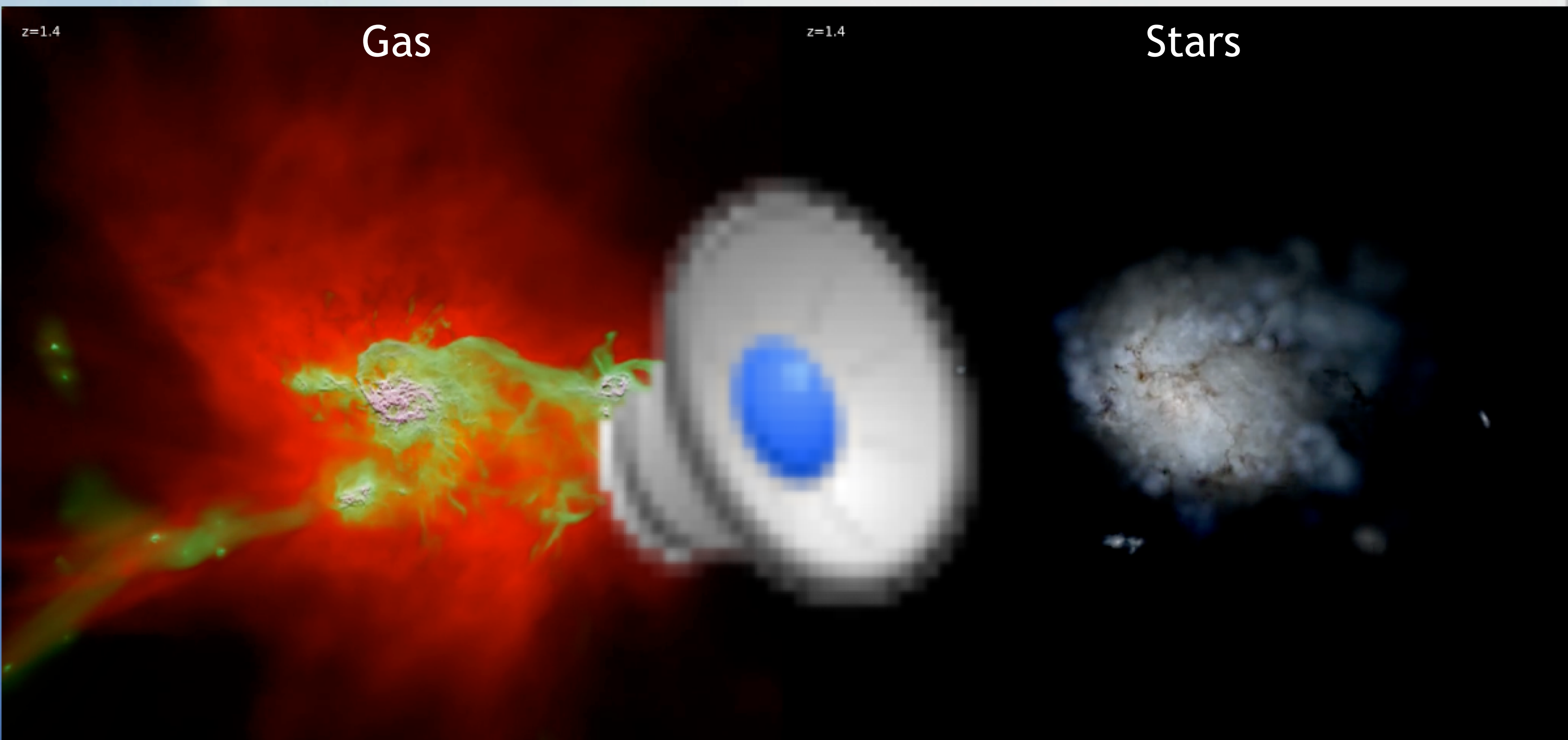
Milky Way and Extragalactic Science with ZTF+SDSS-V

Josh Simon, Nick Konidaris, Juna Kollmeier, George Helou, Mansi Kasliwal



Extragalactic SDSS-V/ZTF Synergies

- Galaxies are shaped by cosmic explosions



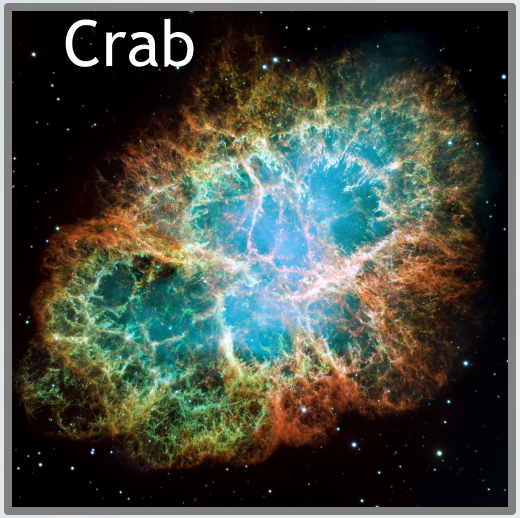
Movie courtesy Shea Garrison-Kimmel

Measuring ISM Energy Injection

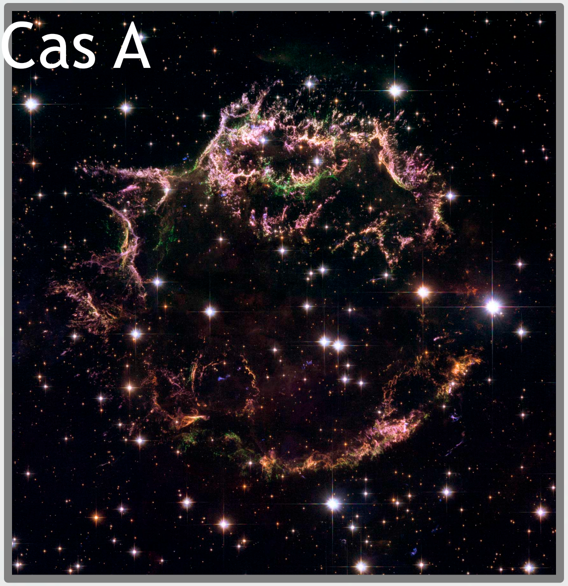
- ZTF identifies supernovae in nearby galaxies
- Multiwavelength follow-up measures electromagnetic energy release
- LVM spectroscopy of Milky Way SN remnants measures kinetic energy

LVM Maps of Supernova Remnants

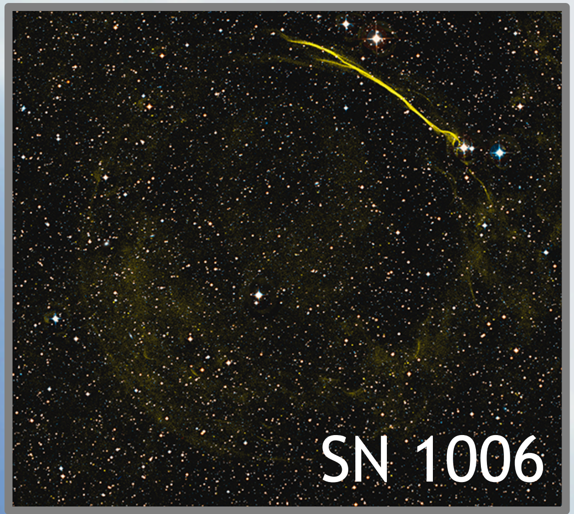
7 arcmin



4 arcmin

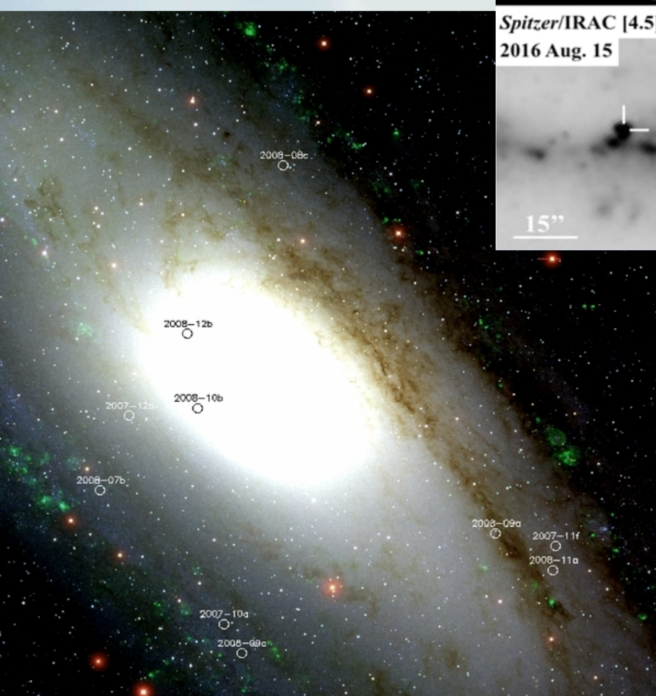


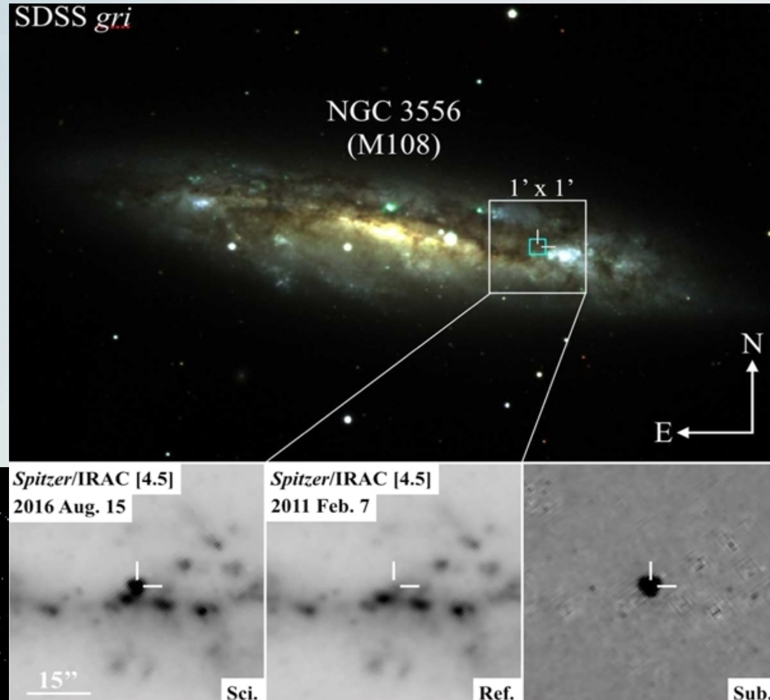
30 arcmin

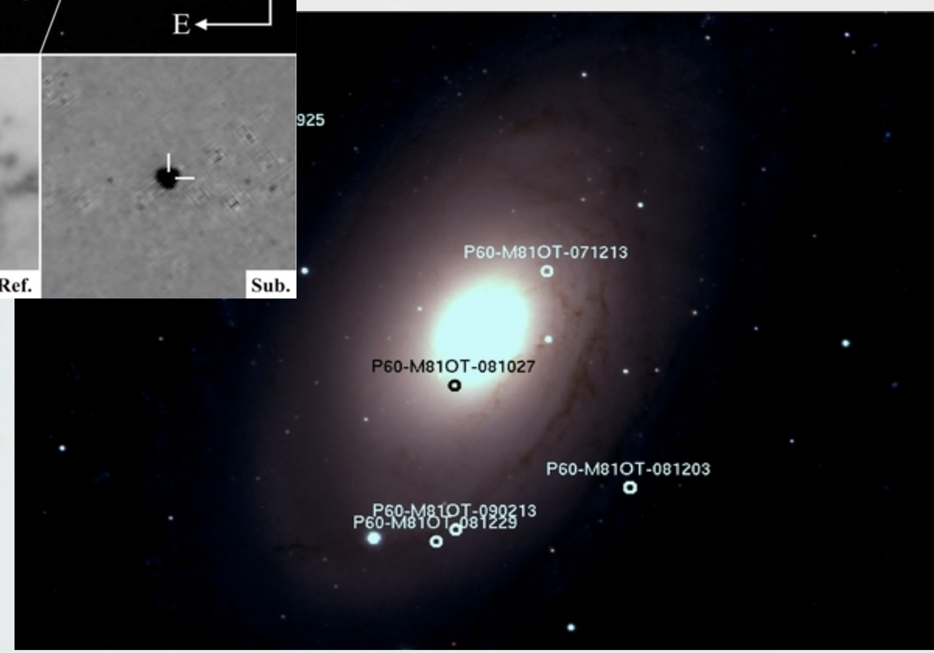


40 arcmin

Transients in Nearby Galaxies



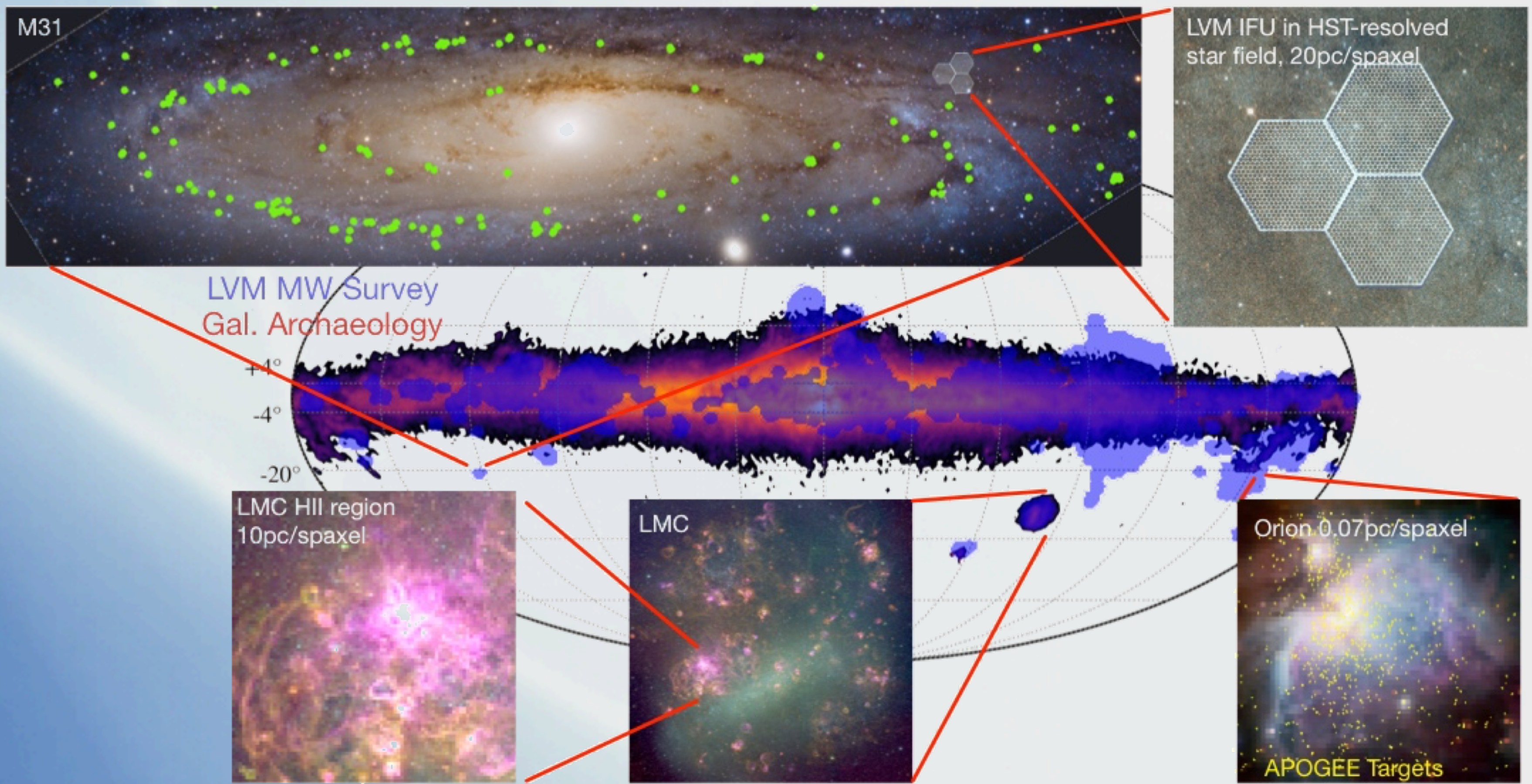




Kasliwal et al. (2011)
Jencson et al. (2018)

Transients in Nearby Galaxies

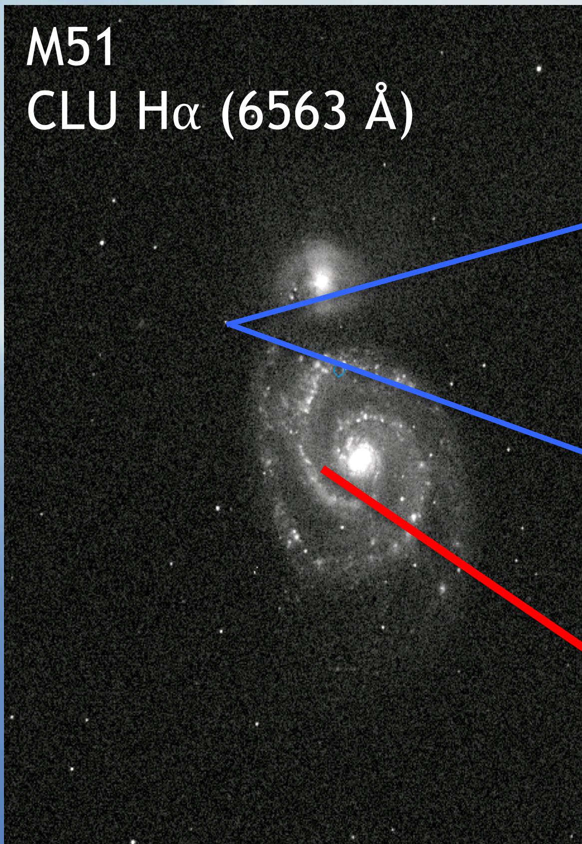
- LVM IFU map for each local environment

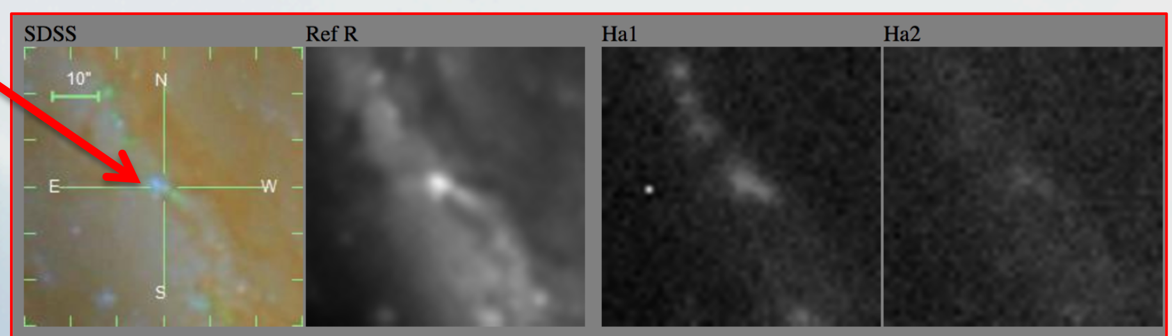


Kollmeier et al. (2017)

Census of the Local Universe (CLU)

[3π Hα Galaxy Survey]

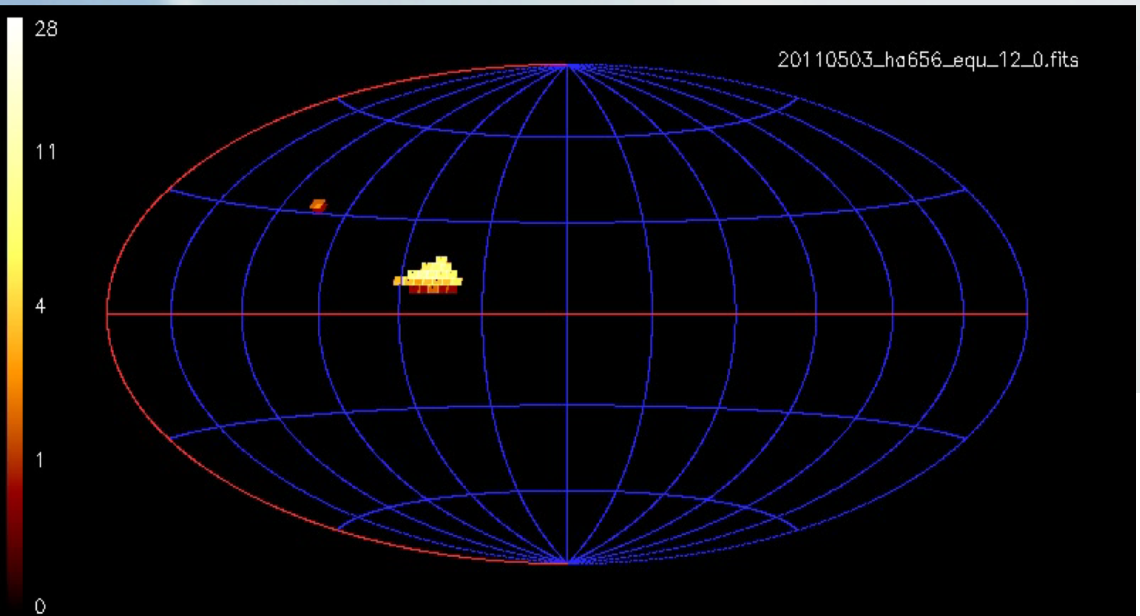


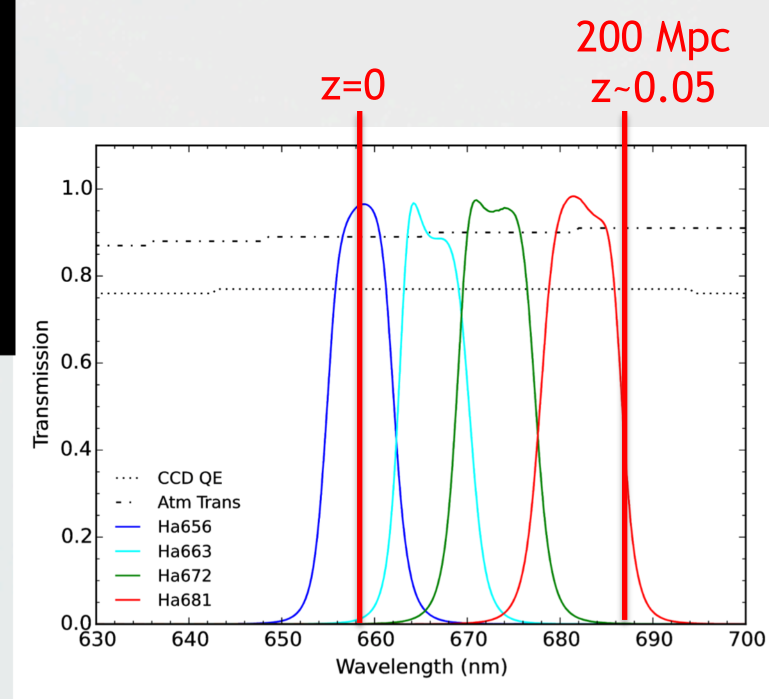


David Cook
(Caltech)

Collaborators:
Mansi Kasliwal (Caltech)
Angie Van Sistine (UW-Milwaukee)
David Kaplan (UW-Milwaukee)
Patrick Brady (UW-Milwaukee)

CLU Hα Imaging



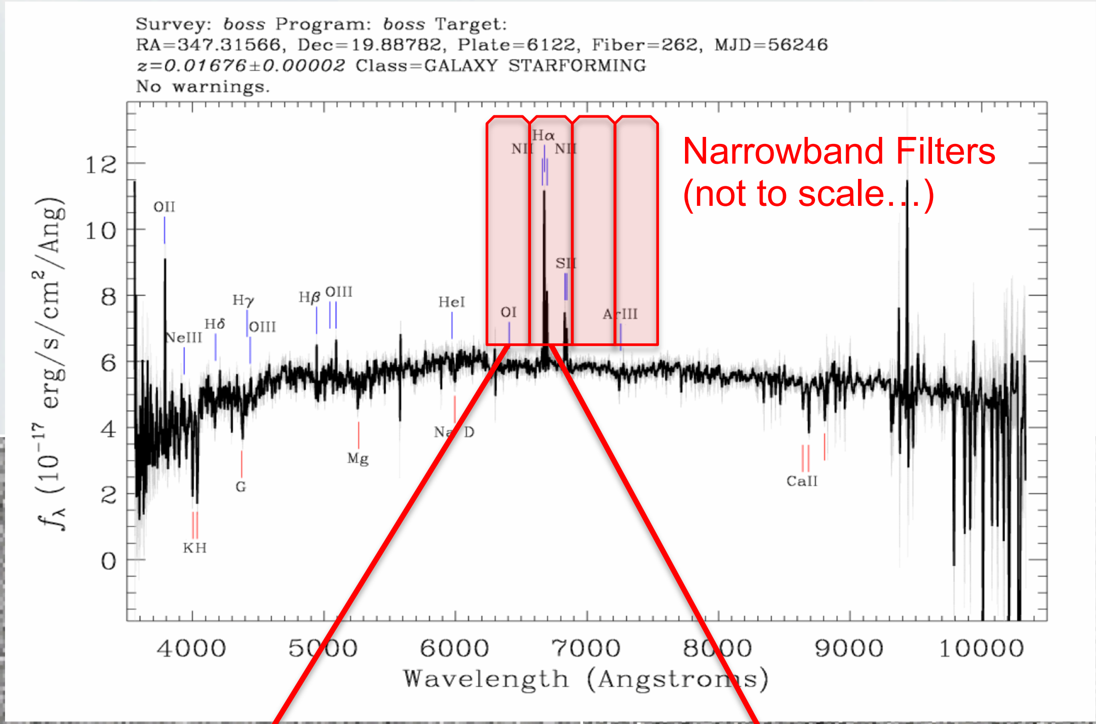


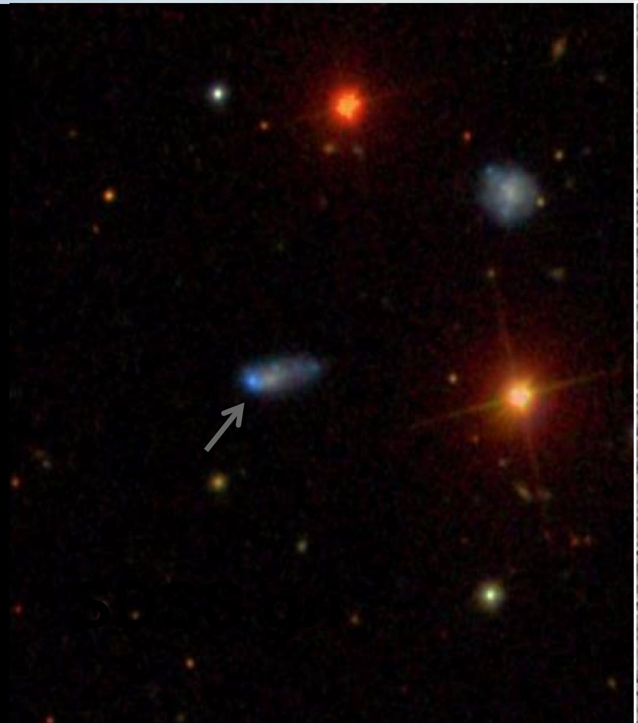
- 3π sr (26,470 deg²) on Palomar 48”
- 1” pixels
- 4 narrow-band filters
- Constrain distance via Hα at different redshifts

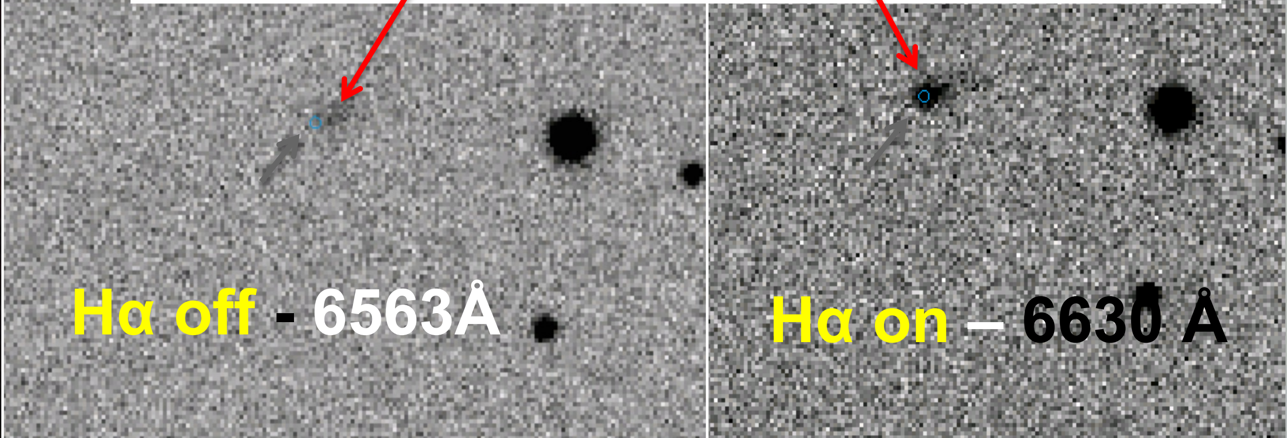
Cook et al. (submitted)

CLU Example

- Uncataloged galaxy
- Hα color (On − Off) = 1.5 mag
- Spec z = 0.0168 (~75 Mpc)







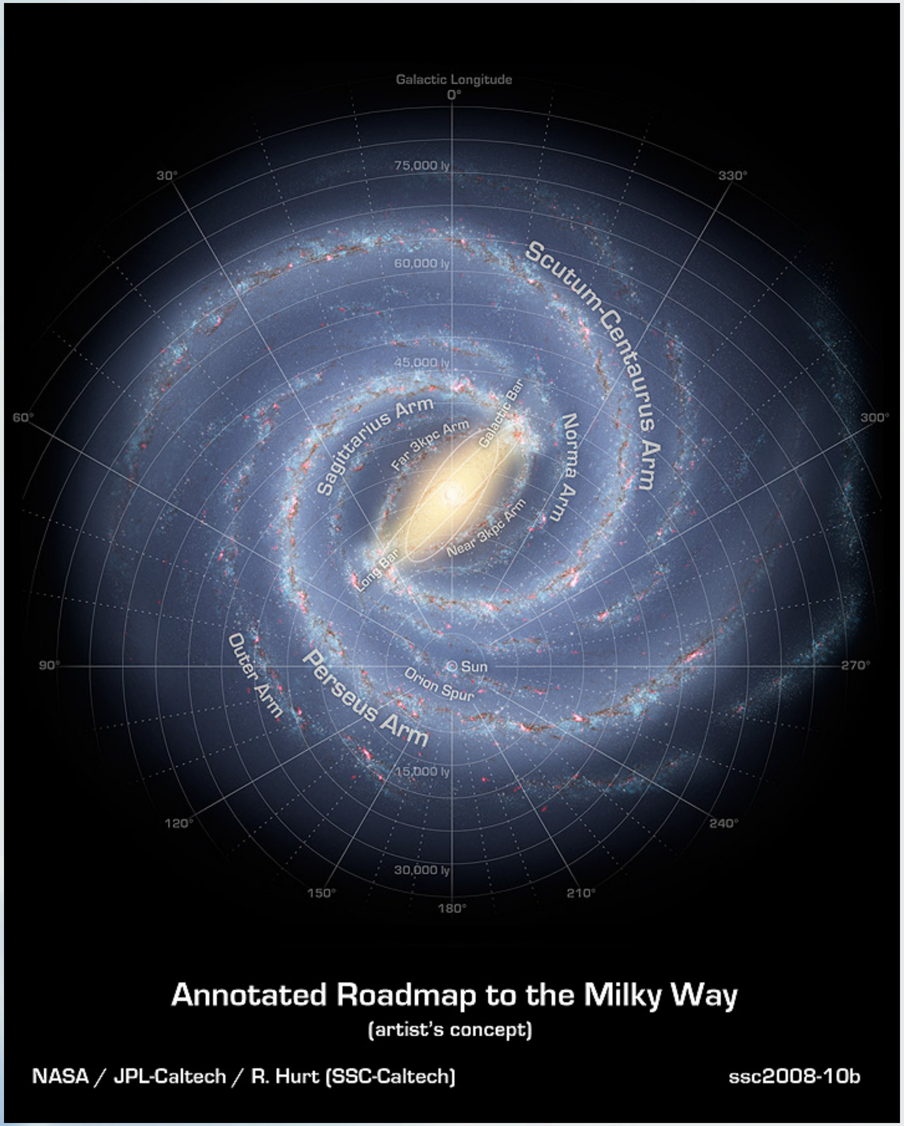
Estimated Spectra Required

- In SDSS footprint (~1/3 of CLU)
  - 90 newly identified galaxies out of 290 total
  - 1200 fields × (90/14 fields) = 8,000 new galaxies
- Outside SDSS (2/3 of CLU)
  - Expect ~20 new galaxies per field
  - 2400 fields x 20 galaxies/field = 50,000 new galaxies
- Lower limit of ~60,000 new galaxies

Galactic Structure: SDSS-V/ZTF Synergies

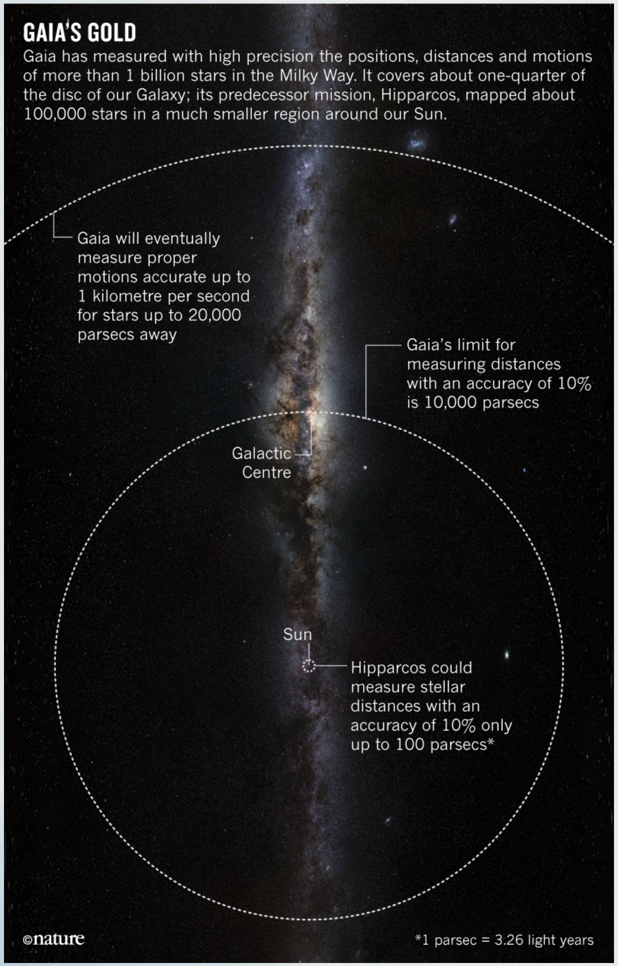
- Key questions regarding Milky Way structure
  - What is the Galaxy's spiral pattern, and what causes it?
  - Is the thick disk a distinct component, and what is its origin?
  - How do stars spread through the Milky Way after they are born?
  - What are the best tidal streams for probing the Milky Way's gravitational potential?

Spiral Structure



Spiral Structure

- Doesn't Gaia already solve this?

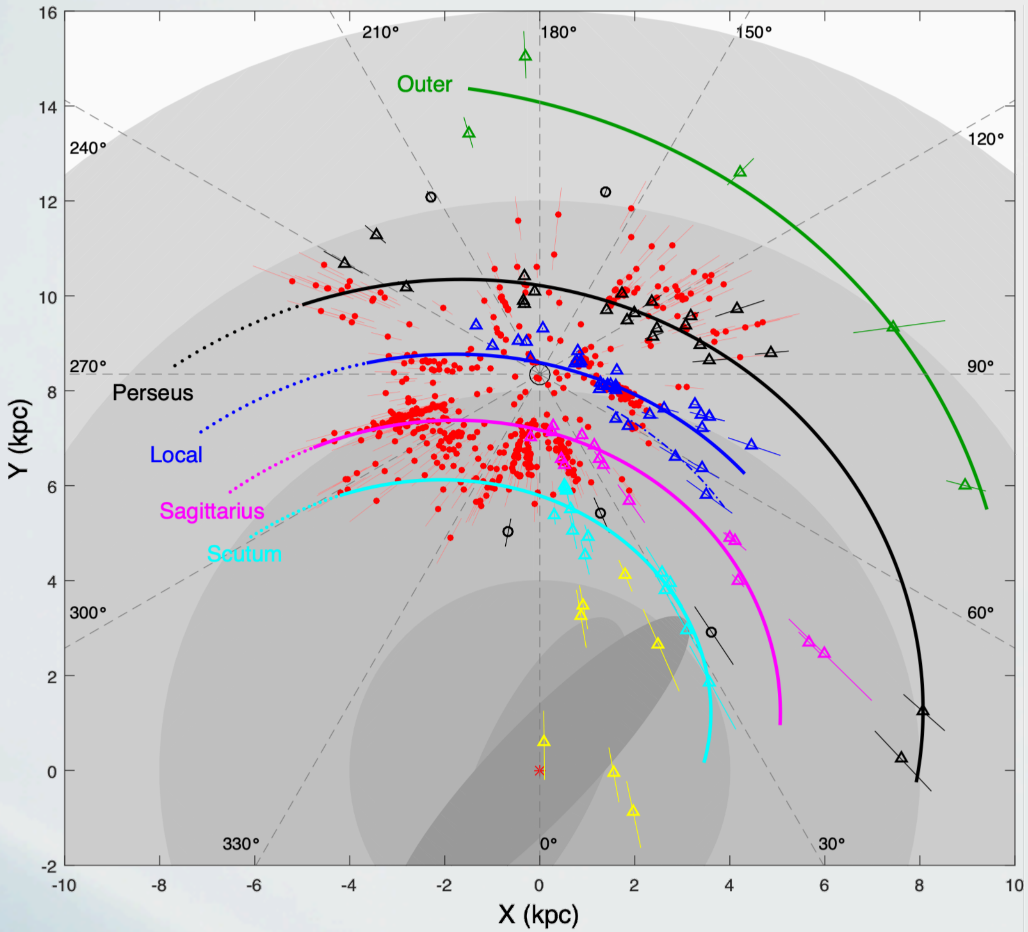


Serge Brunier/ESO/ESA

Spiral Structure

- Not really

▲ 102 Masers (VLBI)
● 635 O stars (Gaia)



Xu et al.

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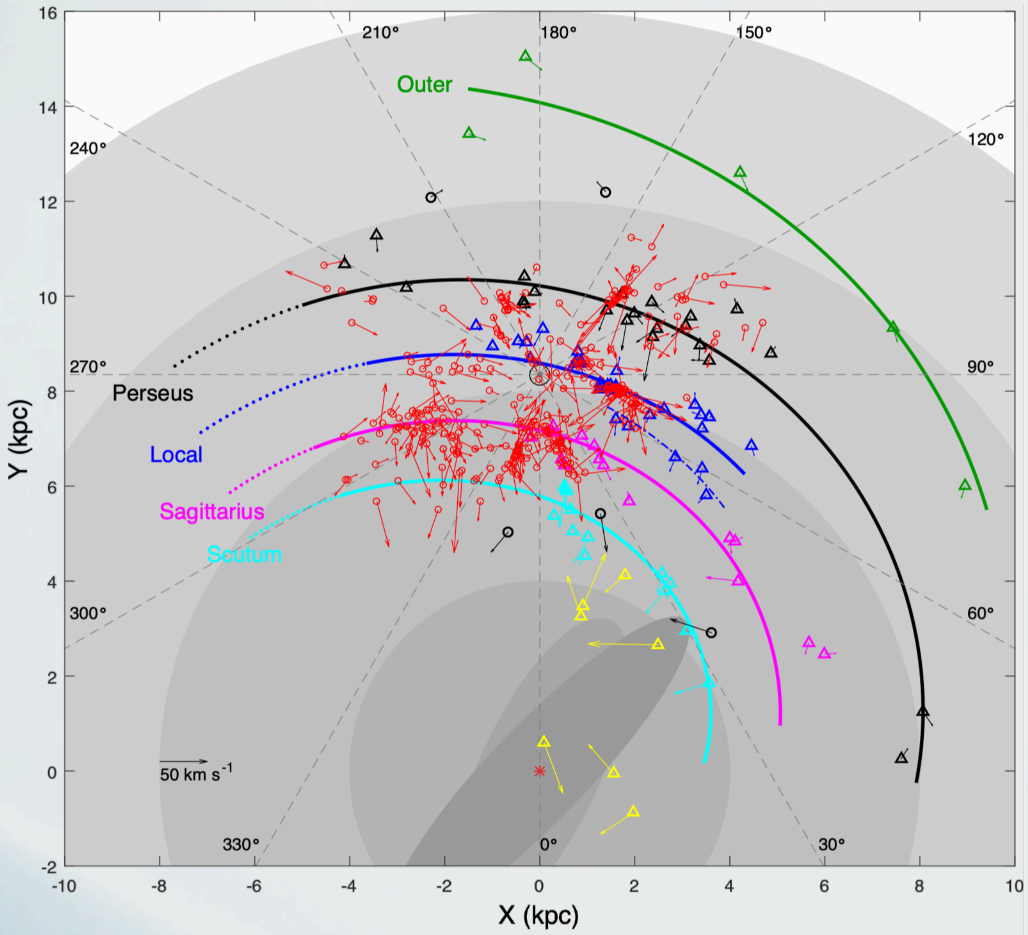
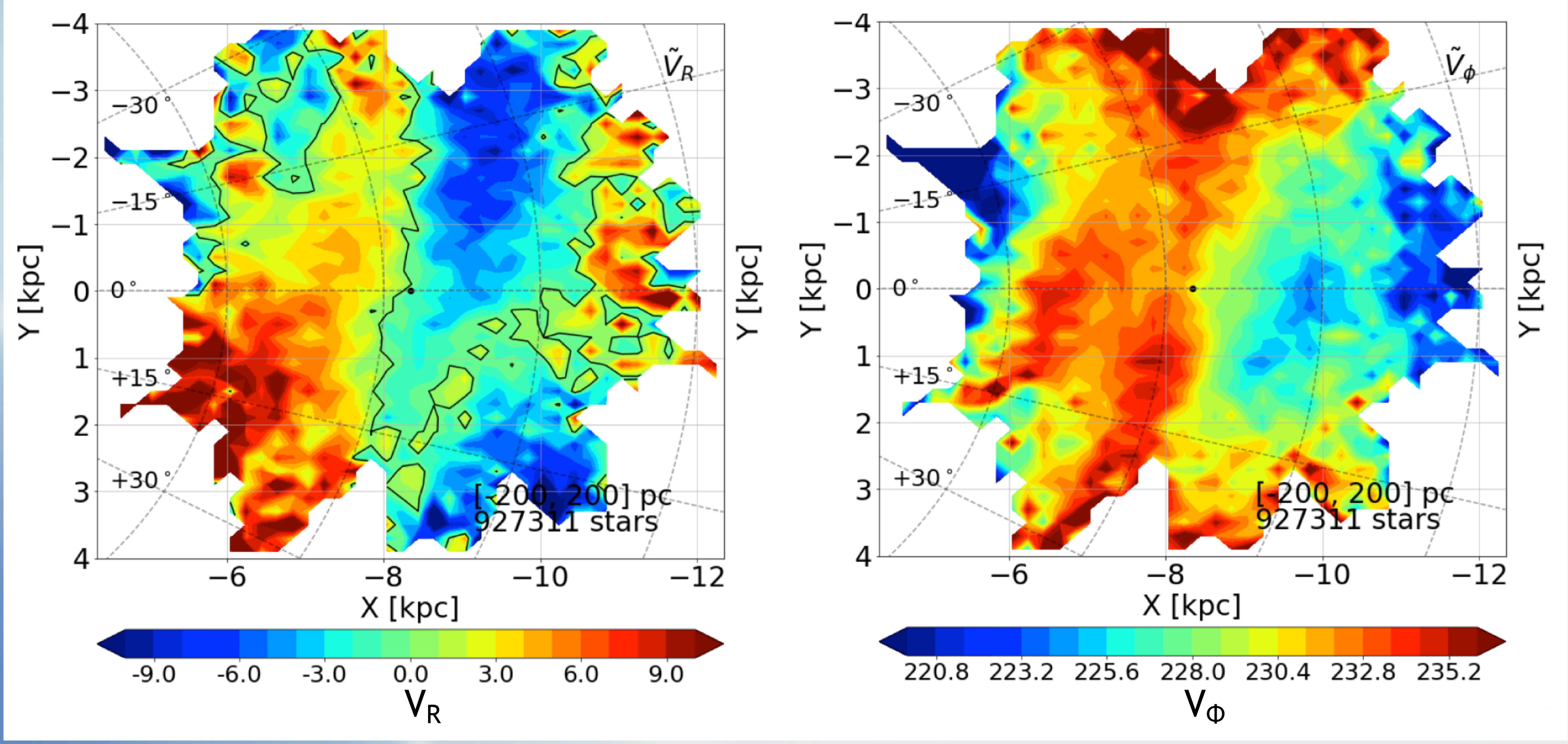


Xu et al.

3D Kinematics from Gaia

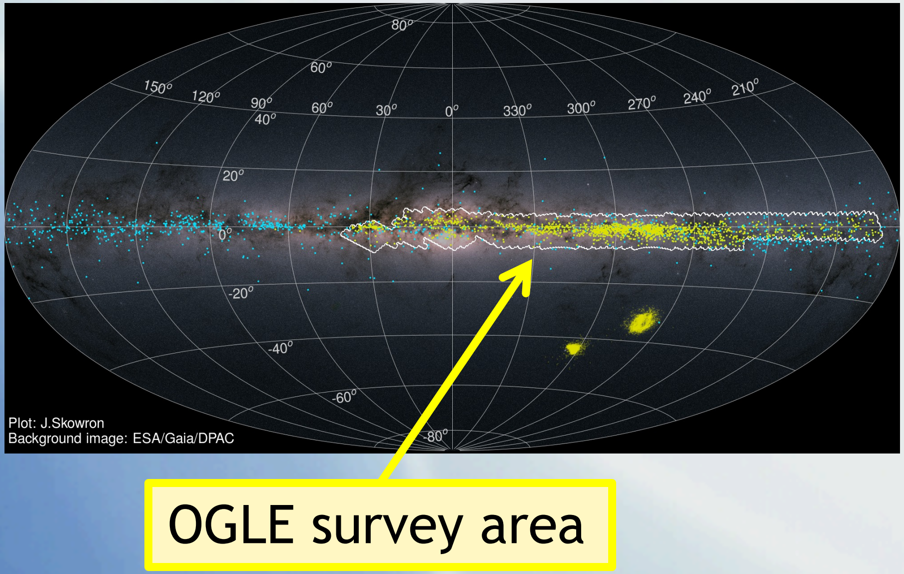
- Currently too limited in distance

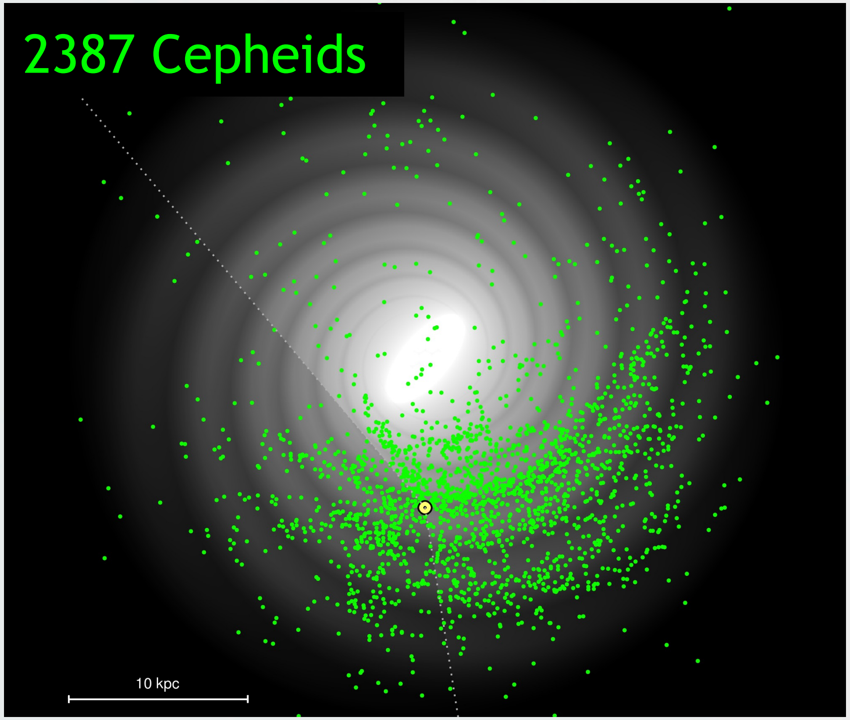


Katz et al. (2018)

ZTF + SDSS-V

- Much larger samples of stars with good distances (Cepheids/Miras with ZTF lightcurves) and velocities (Gaia + SDSS-V) are possible

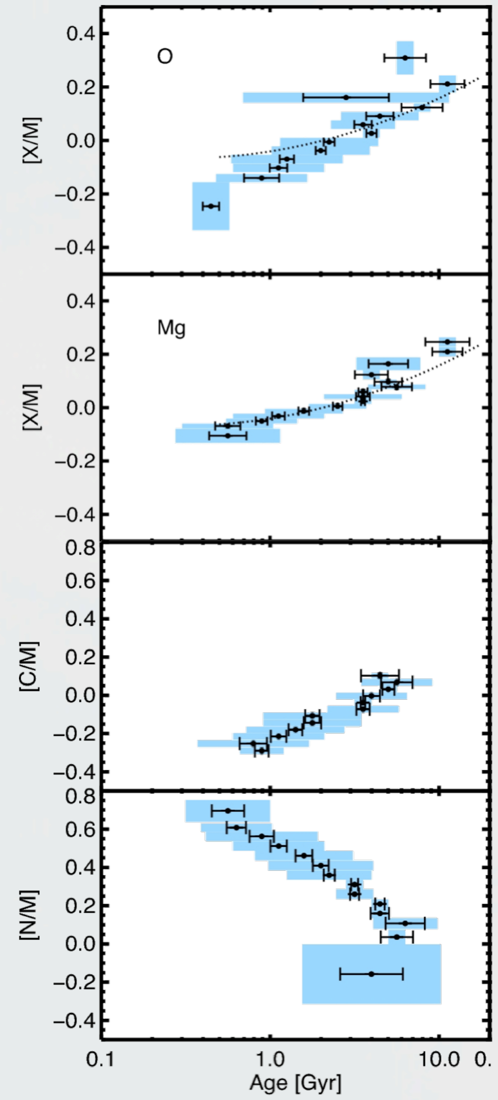




Skowron et al. (2018)

Stellar Ages/Radial Migration

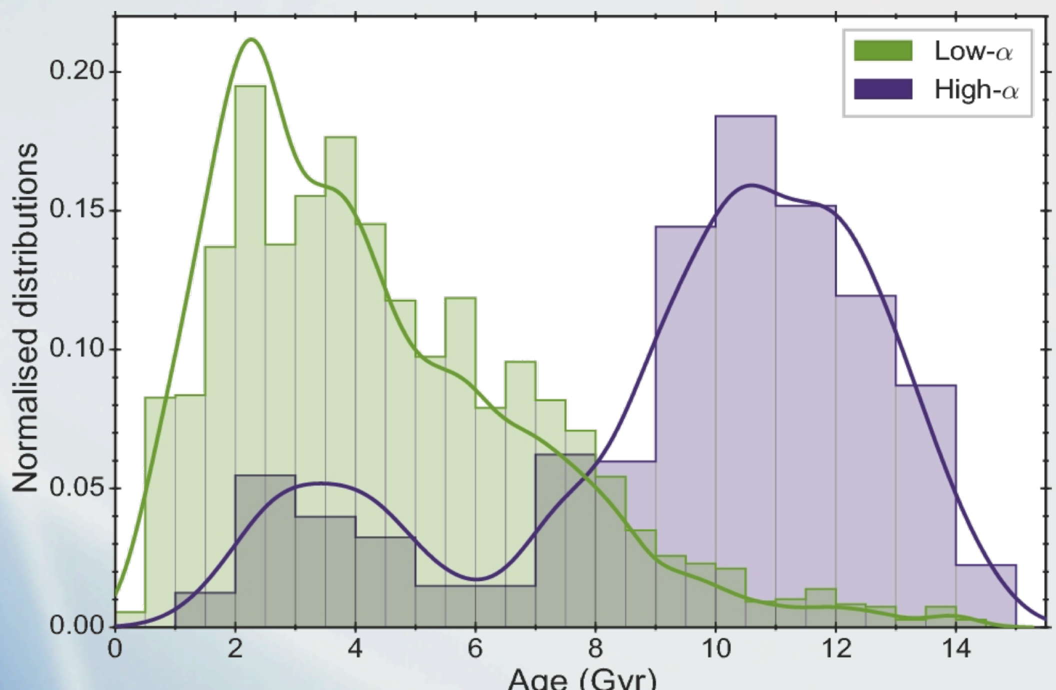
- Disk stars display a tight correlation between abundances and age
- SDSS-V will provide much larger samples of chemical abundances
- These data will strongly constrain models of migration through the disk



Feuillet et al. (2018)

Stellar Ages/Radial Migration

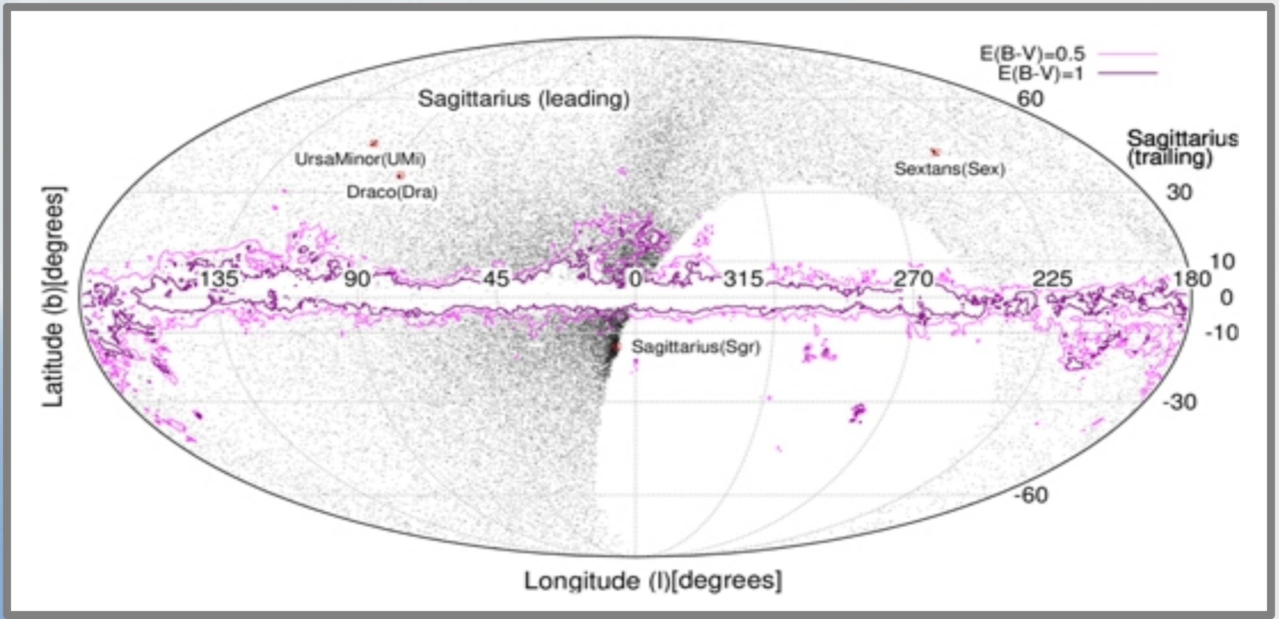
- Ages also reveal thin/thick disk dichotomy
  - Strong synergy with asteroseismology



Silva Aguirre et al. (2018)

Substructure in the Stellar Halo

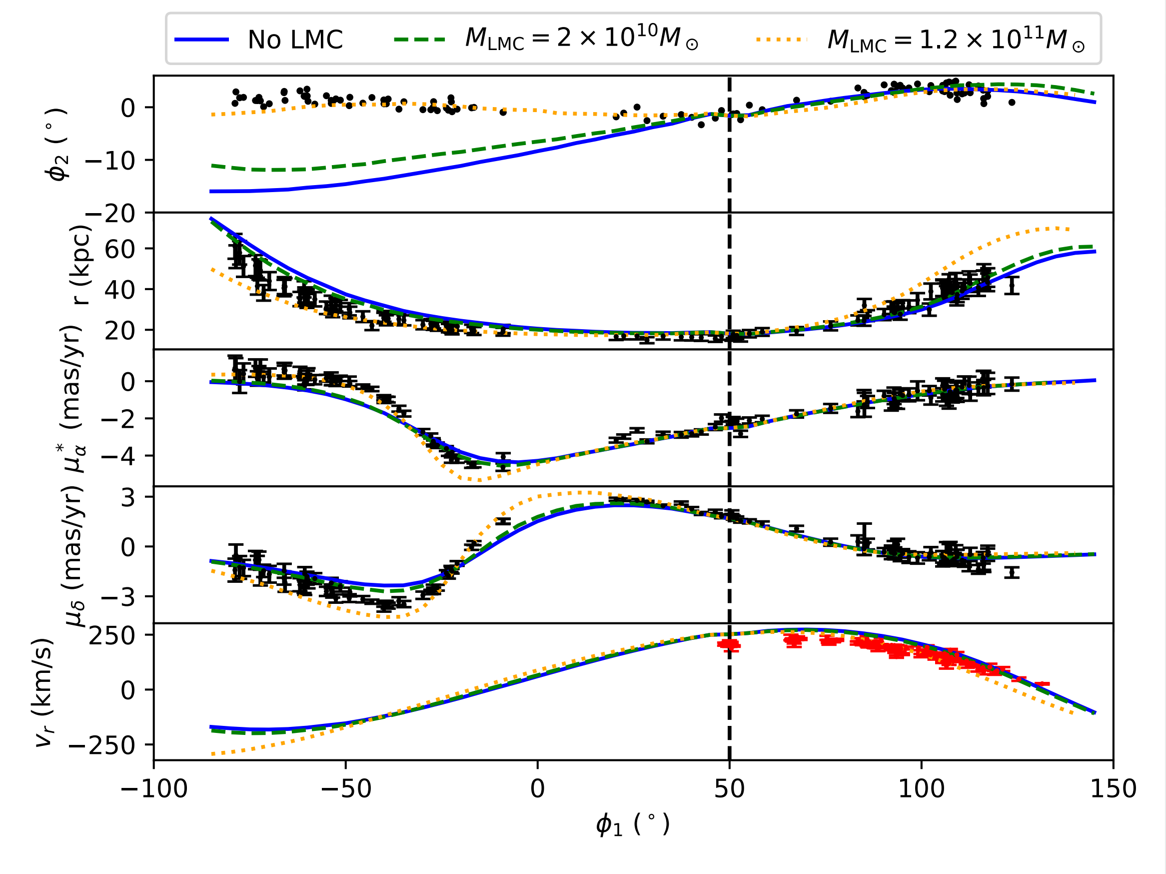
- RR Lyrae variables are the only good distance indicators in the halo
  - Phases essential for spectroscopy, but PS1 phases are now ~7 years out of date



Sesar et al. (2017)

Substructure in the Stellar Halo

- ZTF phases + SDSS-V spectra can provide velocities for halo RR Lyrae



Erkal et al.

Possible ZTF+SDSS-V Projects

- Extragalactic
  - Multiwavelength SN/SNR calorimetry
  - Environmental studies of transients in nearby galaxies
  - Complete CLU survey for future LIGO events
- Galactic structure
  - Trace spiral arms via spectroscopy of Cepheids and Miras
  - Constrain radial migration through stellar age/abundance measurements
  - Probe halo substructure with RR Lyrae

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



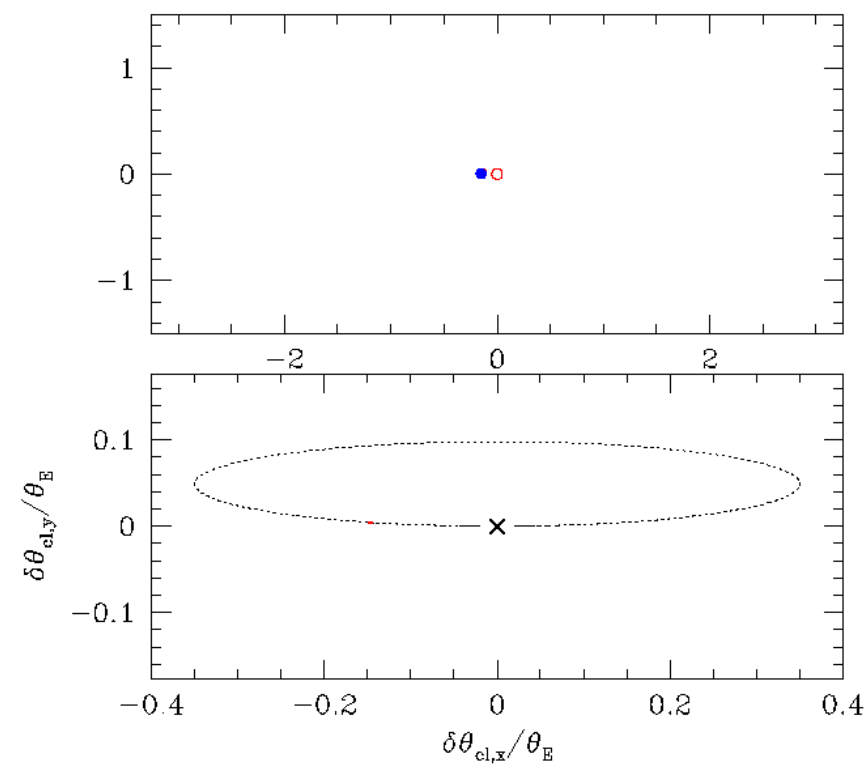





Outline

- 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

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

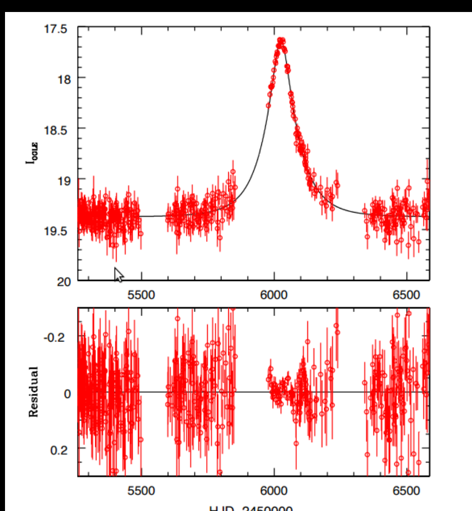
Search for compact objects

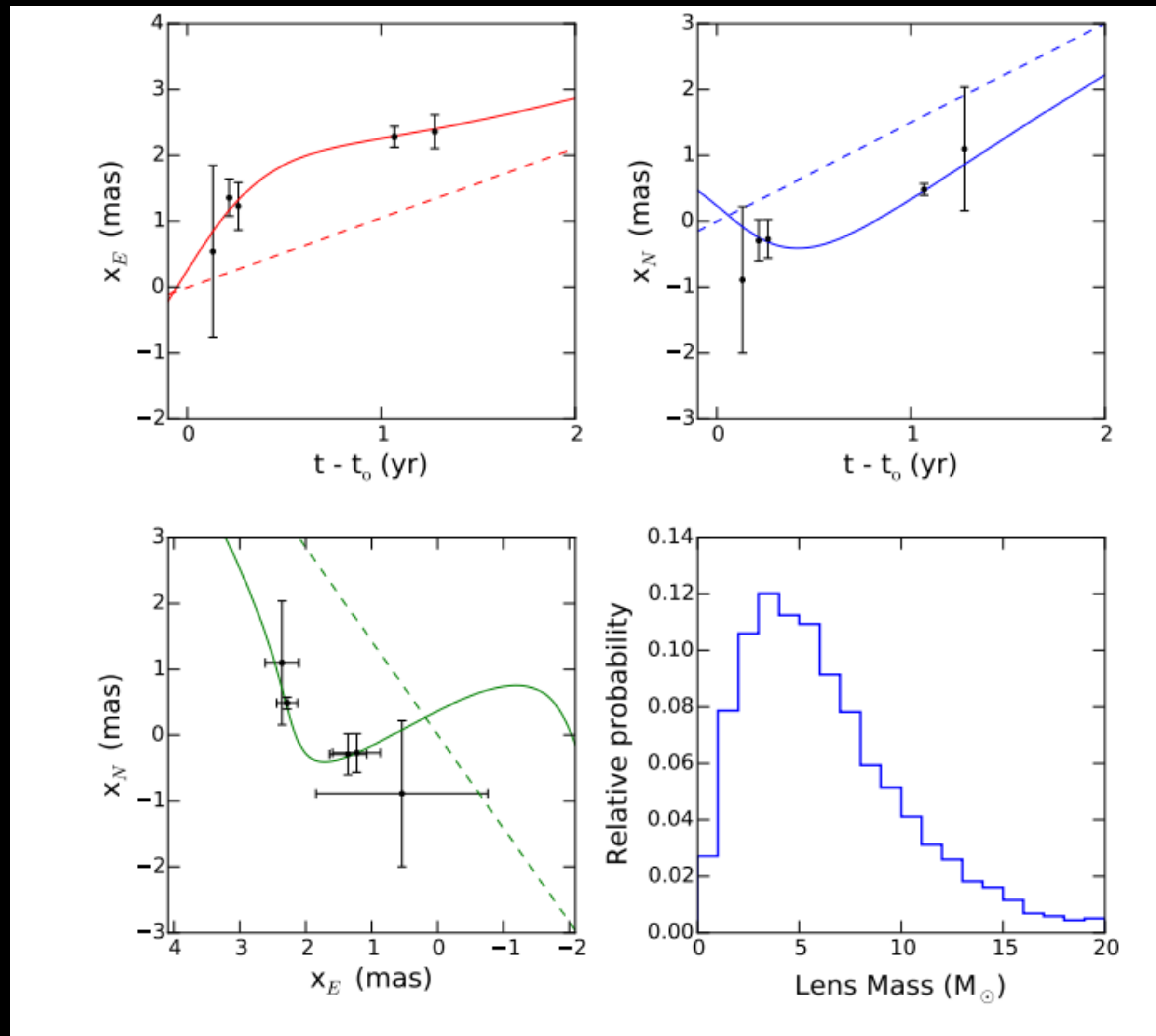
- Stellar-mass isolated BH/NS: product of stellar evolution
- Counting, and mass-function -> stellar death, GW,...

- 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

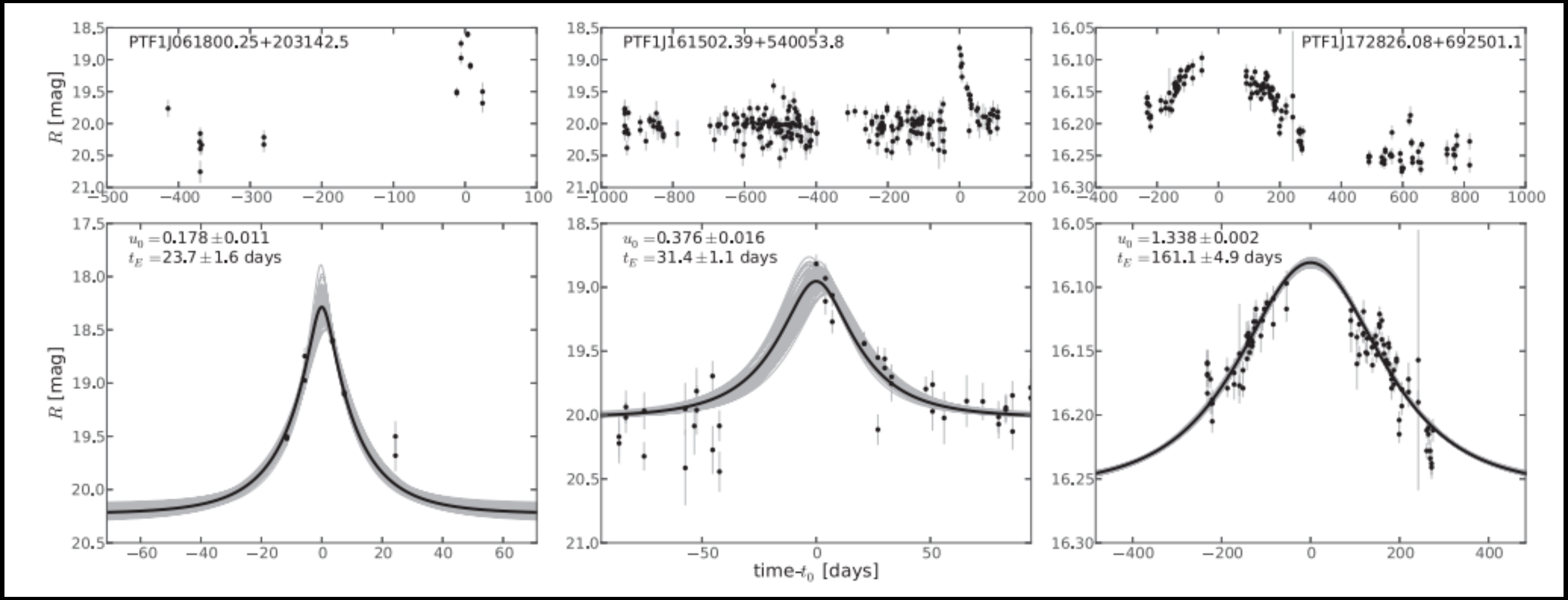




Lu et al. 2016 ApJ 830, 41

Relative Astrometry with ZTF

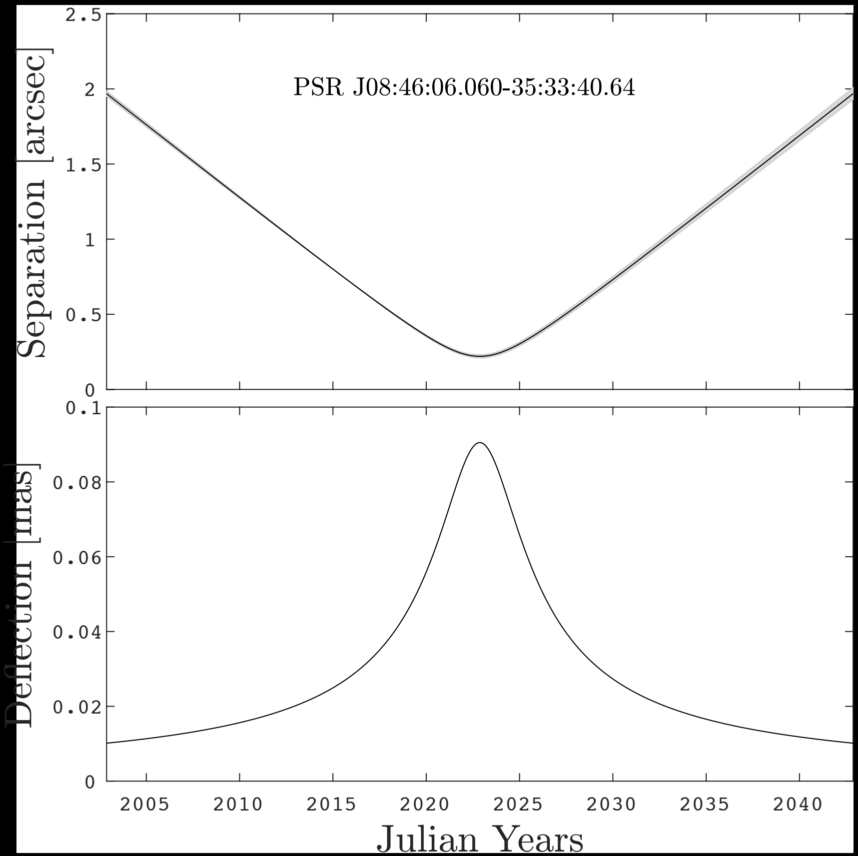
- ZTF can find (very rare) high Galactic latitude ML events (nearby->large θ_E)
- Candidates from PTF:



Price-Whelan et al. 2014

Lensing by pulsars

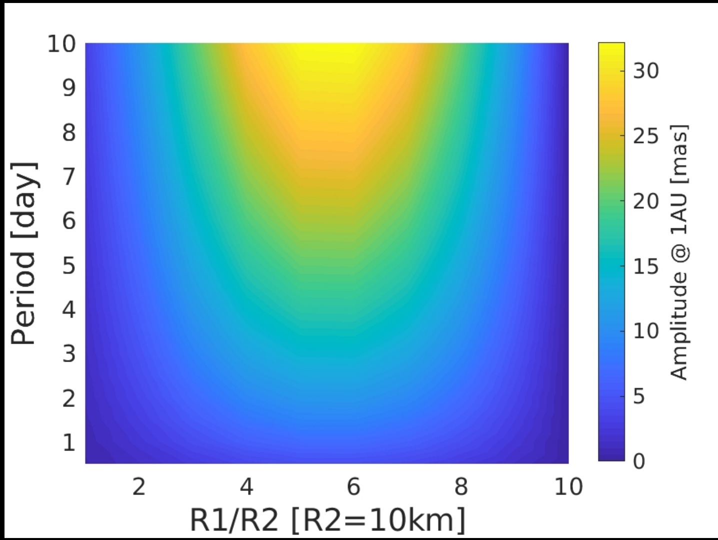
- Another possibility: detecting astrometric lensing of known pulsars on background stars



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?

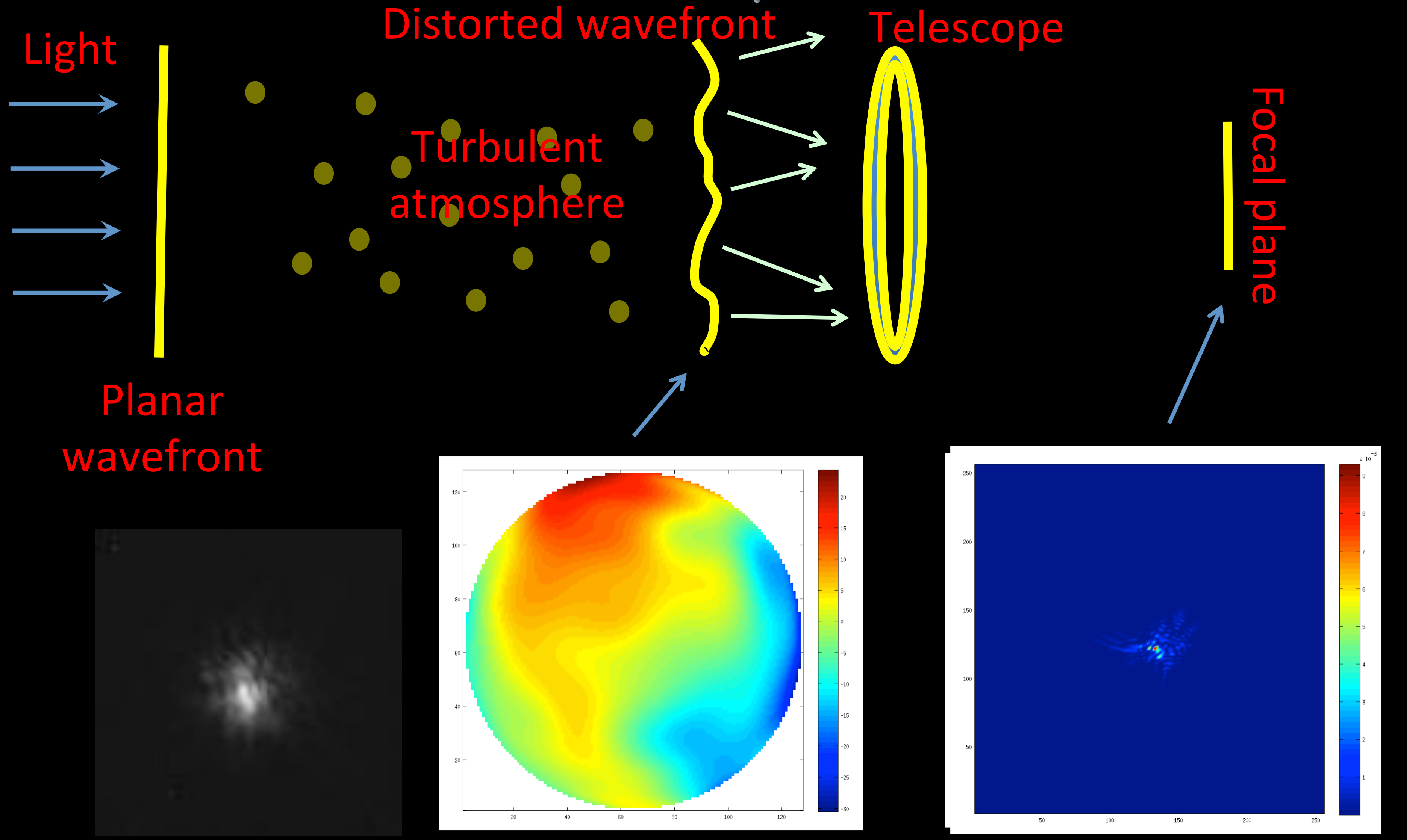
- With AO 100-200 μas is possible
- With GRAVITY ~tens μas is doable
- For seeing limited Monet (1983) claimed 1 mas parallax accuracy, but…
- All methods are likely limited by systematics(!)

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(?)

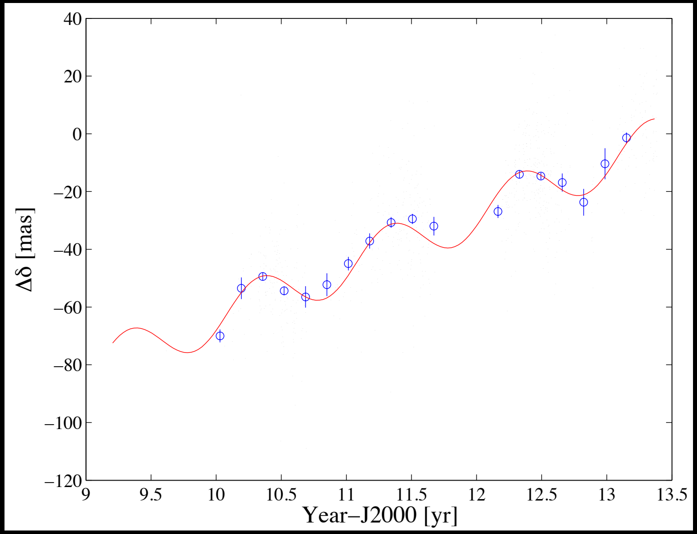
Have model

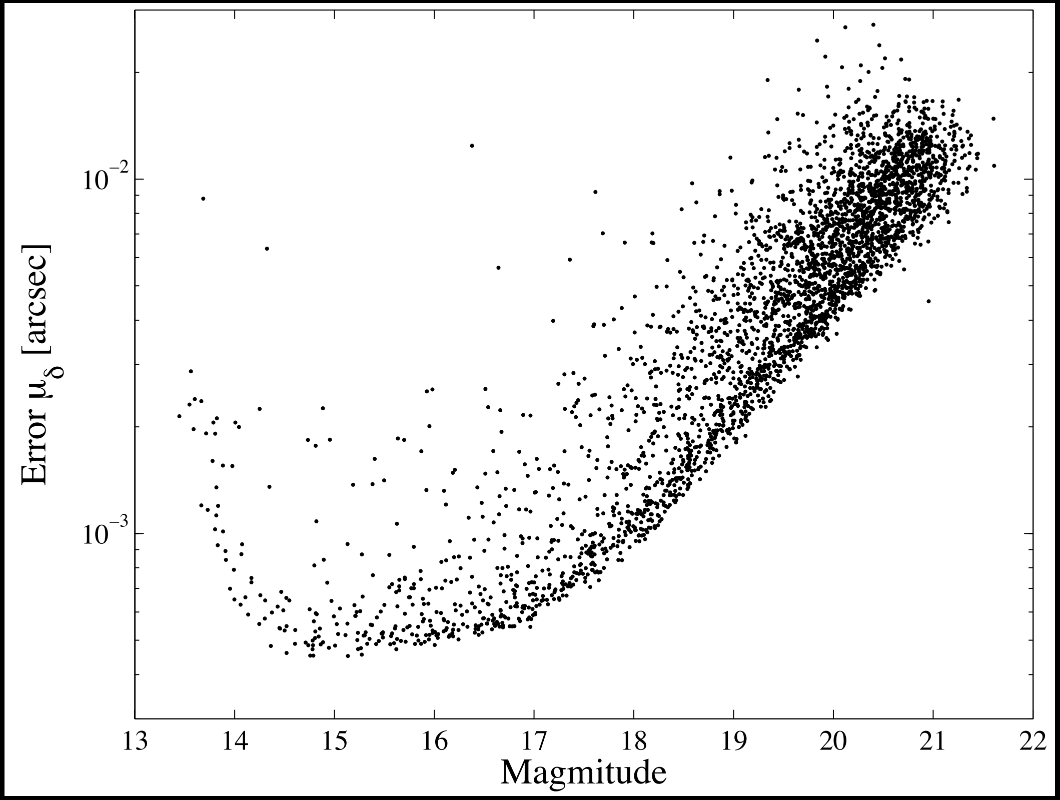
The turbulent atmosphere & the PSF



Before GAIA…

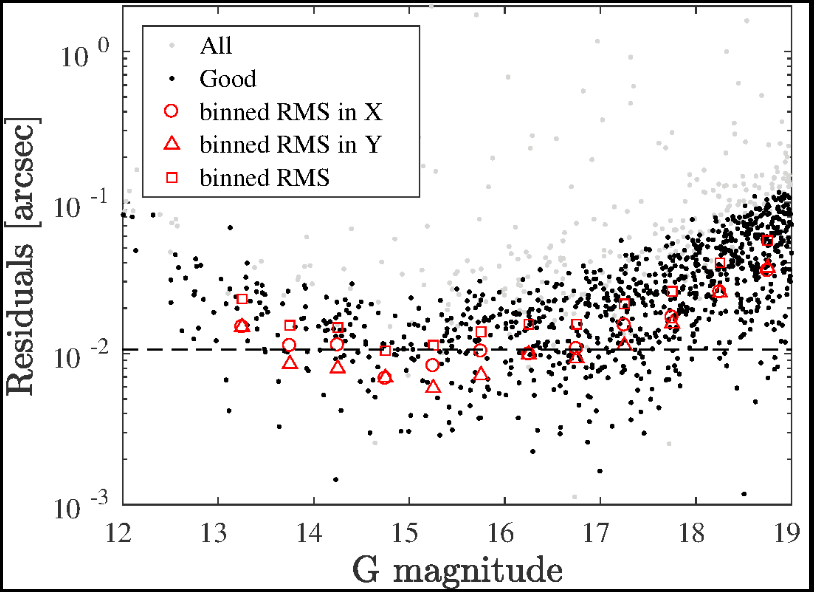
- Relative astrometry w/PTF
- Problem: difficult to estimate if the results are biased





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

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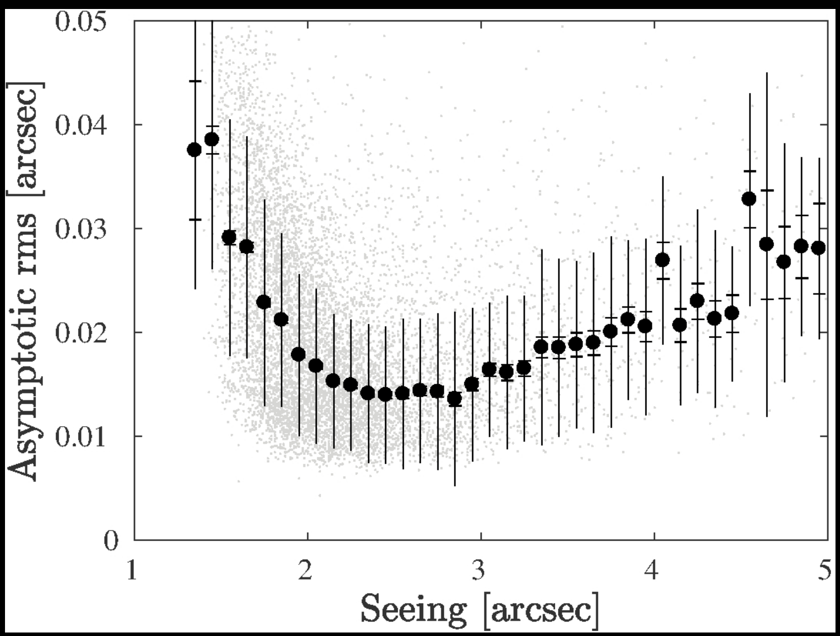
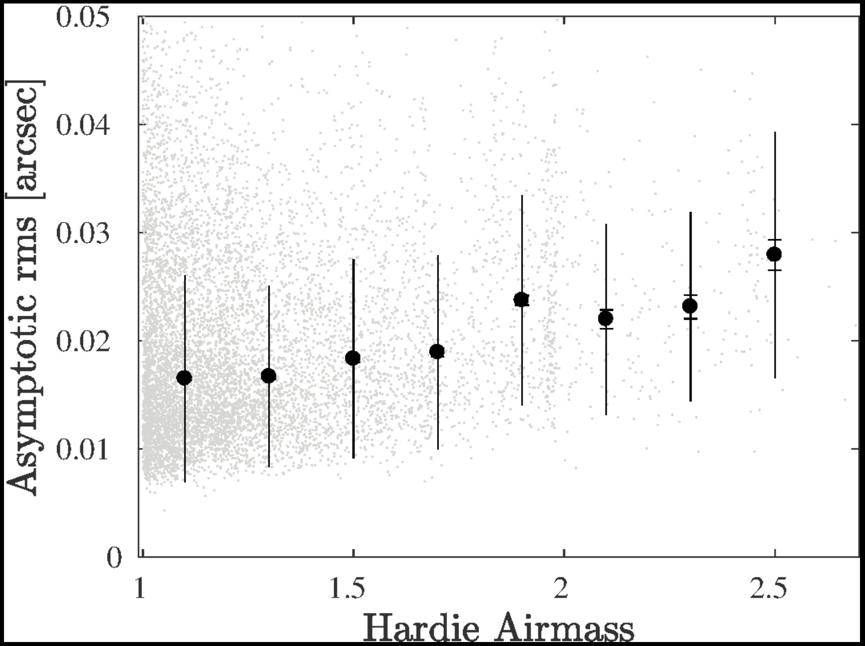
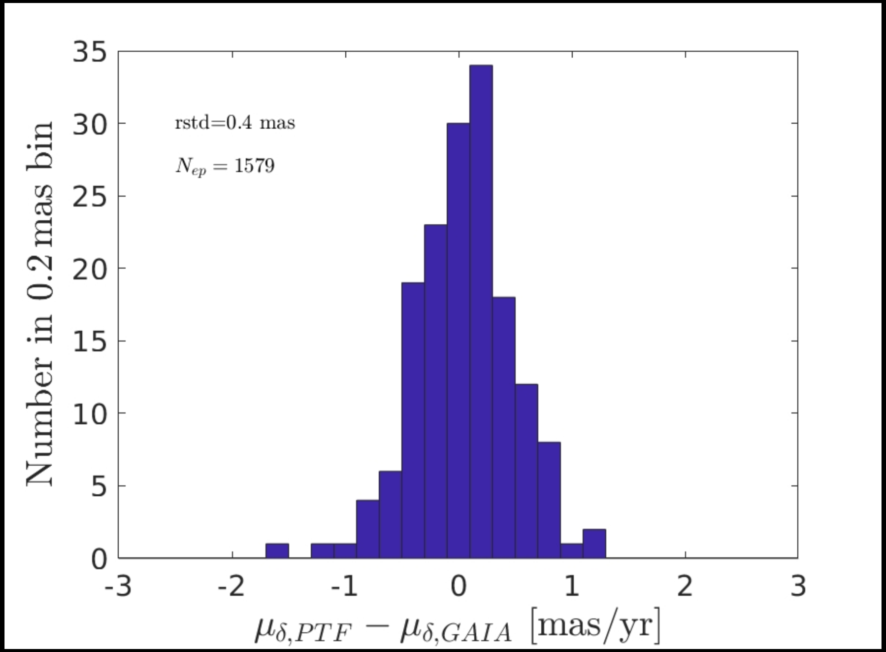
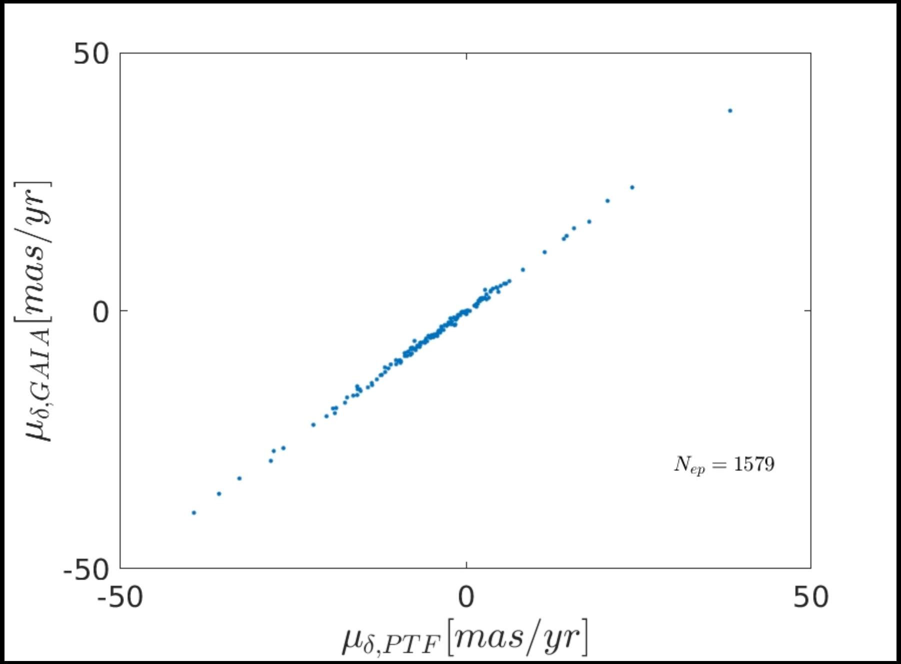




Comparison w/GAIA

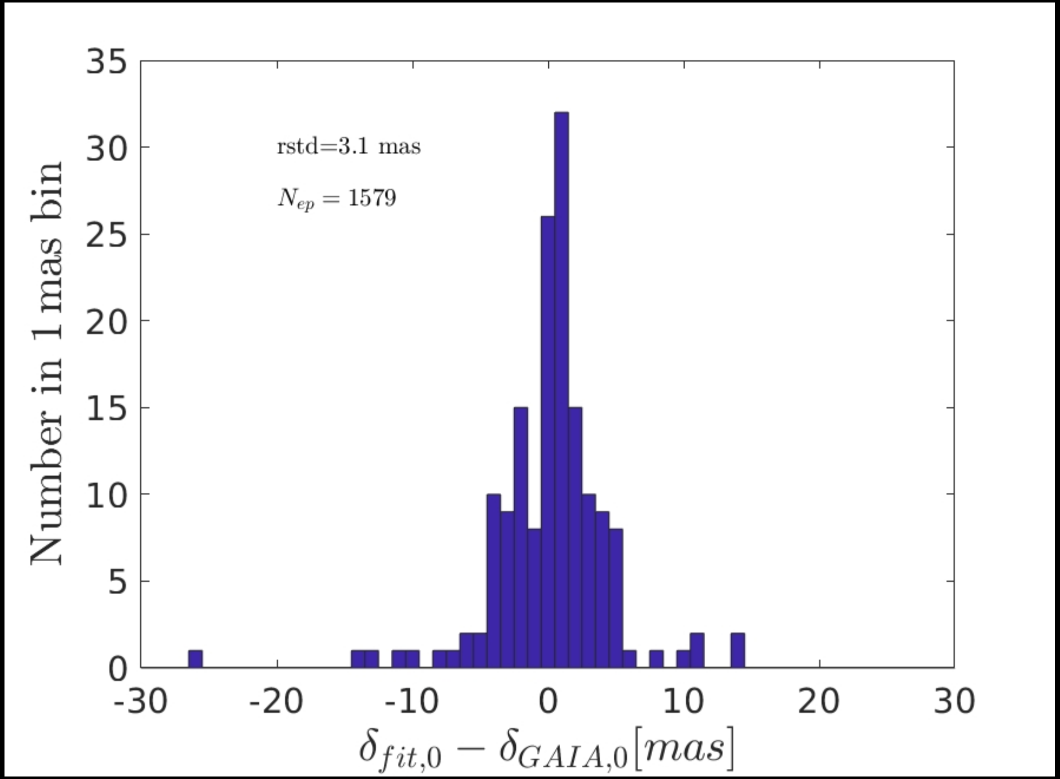
- Use GAIA to verify results
- ~0.4 mas/yr in PM over 7 years





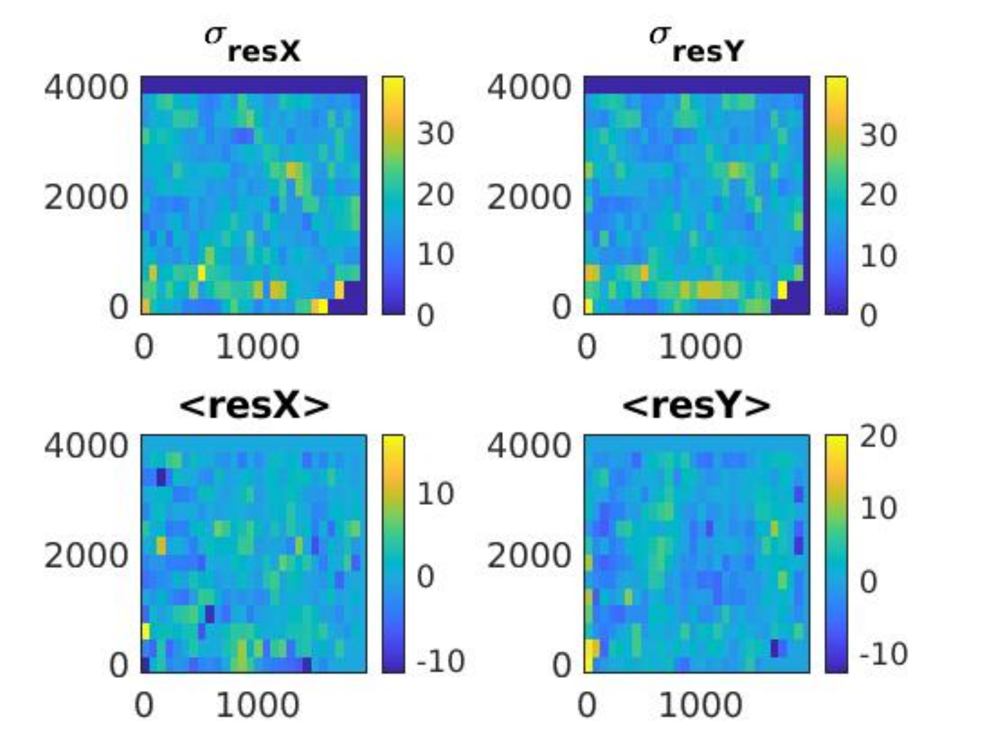
Comparison w/GAIA

- 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

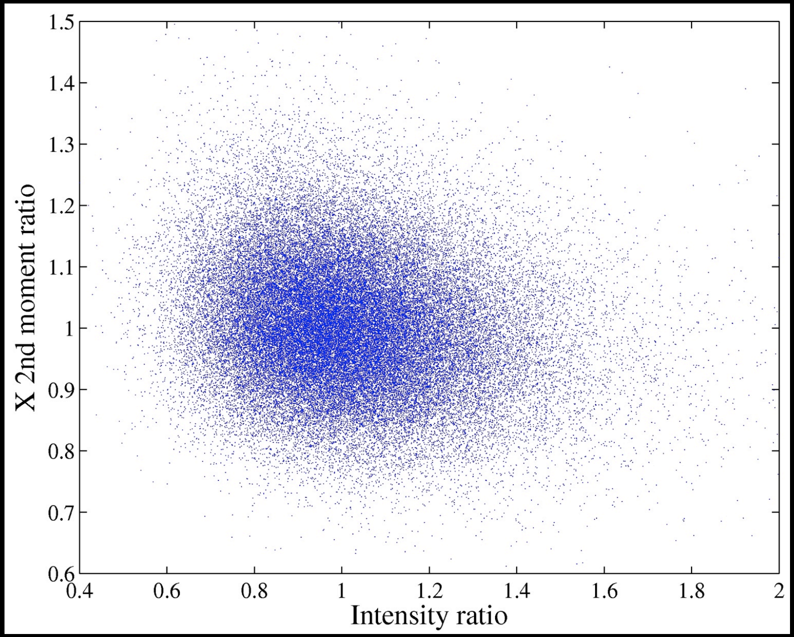
- Ground based seeing limited astrometry is useful
- We currently able to measure stellar positions to accuracy of about 3mas
- We are limited by systematic noise
- Next: trying to beat the systematics

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

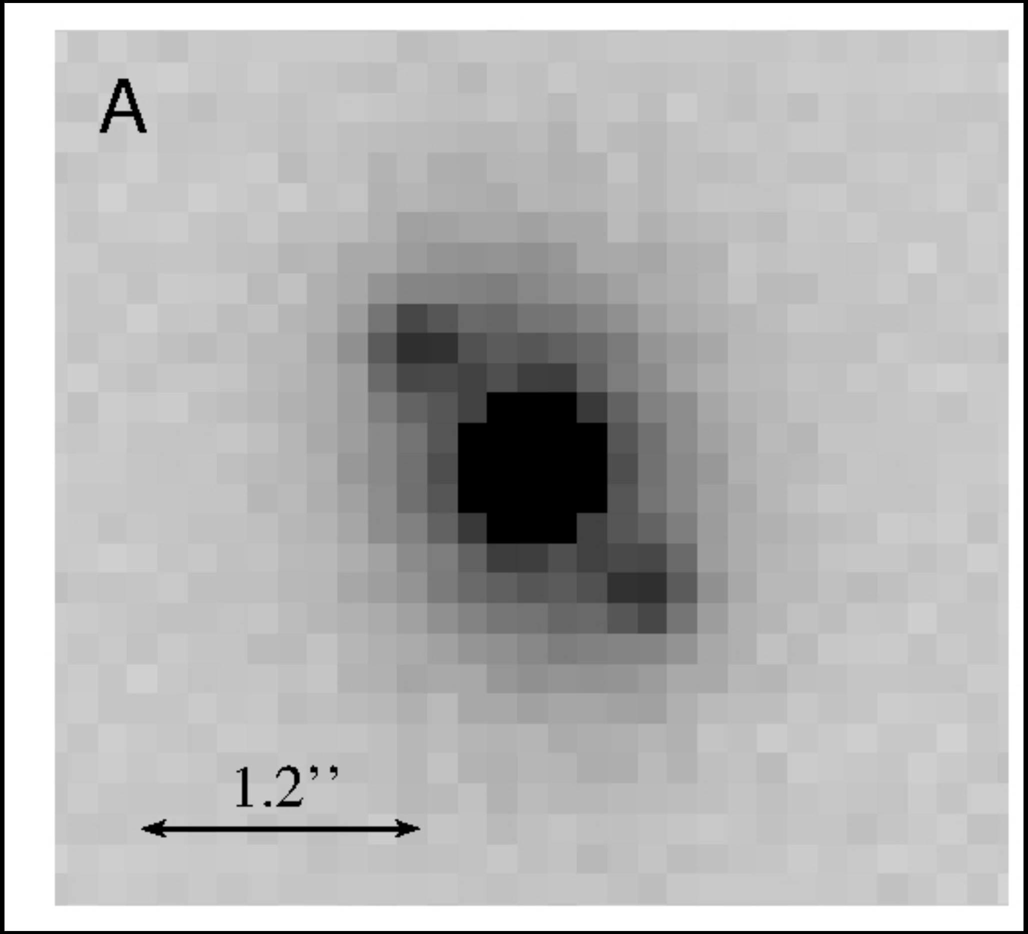
PSF of M_j

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

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

Zackay & EO 15a; 15b

Coaddition: Tests on real images



Zackay & Ofek 2015b

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

Noriaki Arima(D1) & Makoto Ichiki(D2), UTokyo

S. Sako(PI) and the Tomo-e Gozen project team

Stellar/AGN photometric astronomy in the era of SDSS Phase V
@Carnegie Observatories, May 4, 2019

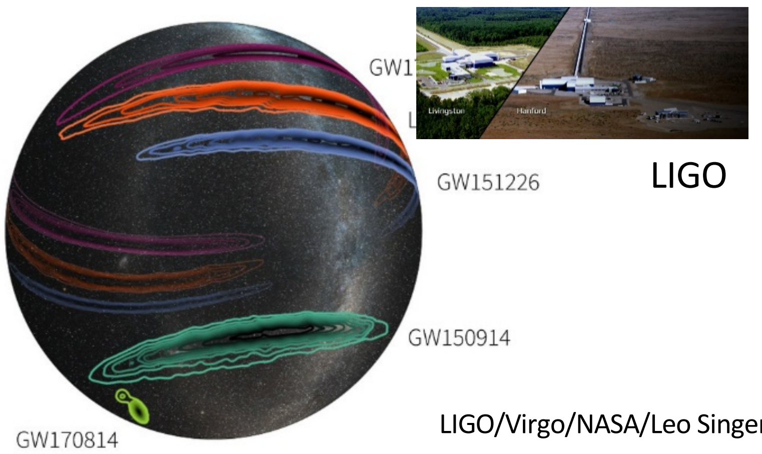
Contents

- Scientific Background
  - Need for quick optical follow-ups
  - Phenomena with short timescale
- The Tomo-e Gozen
- Intensive Science Programs
- Initial Results from the Tomo-e Gozen

Need for quick optical follow-ups

The era of multi-messenger astronomy

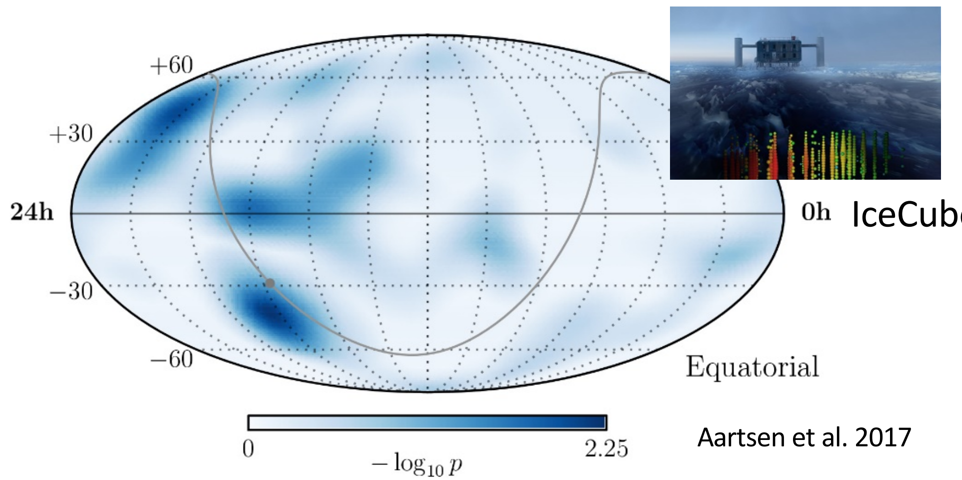
GW events detected by LIGO/Virgo



LIGO/Virgo/NASA/Leo Singer

Typical localization error is 10 – 100 deg^2

Neutrino cascade events detected by IceCube



IceCube

Aartsen et al. 2017

Typical localization error is 10 – 100 deg^2

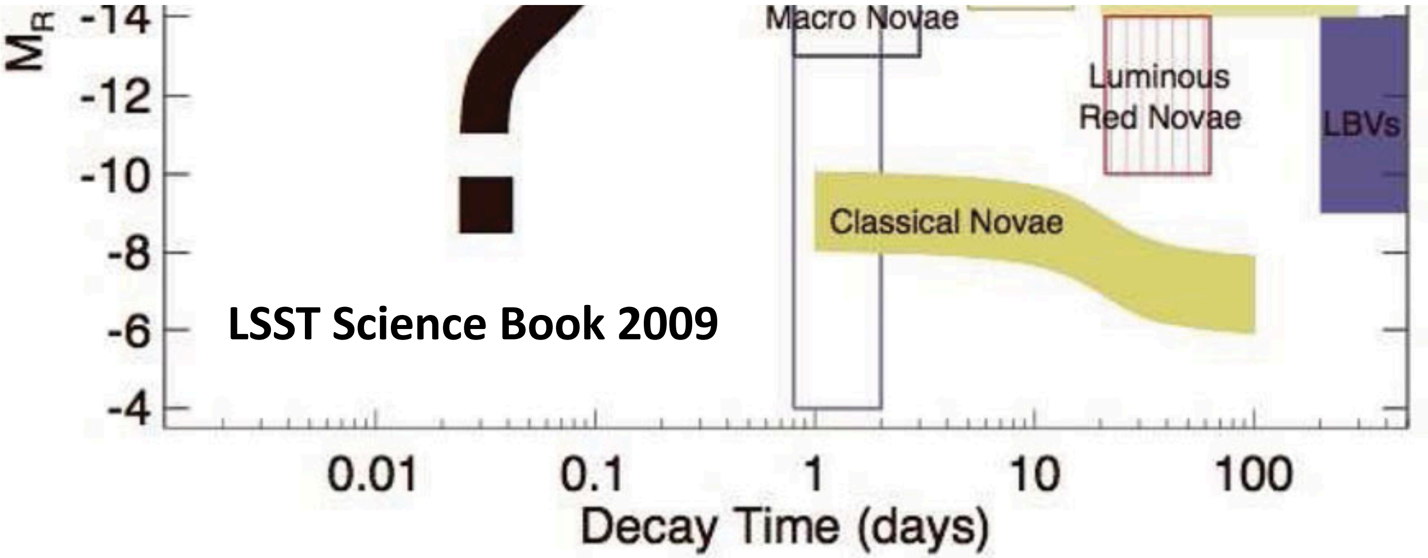
QUICK optical follow-ups with a few 10 DEG^2 are required.

Phenomena w/ short timescale

A phase space of optical transients

Phenomena within a day timescale

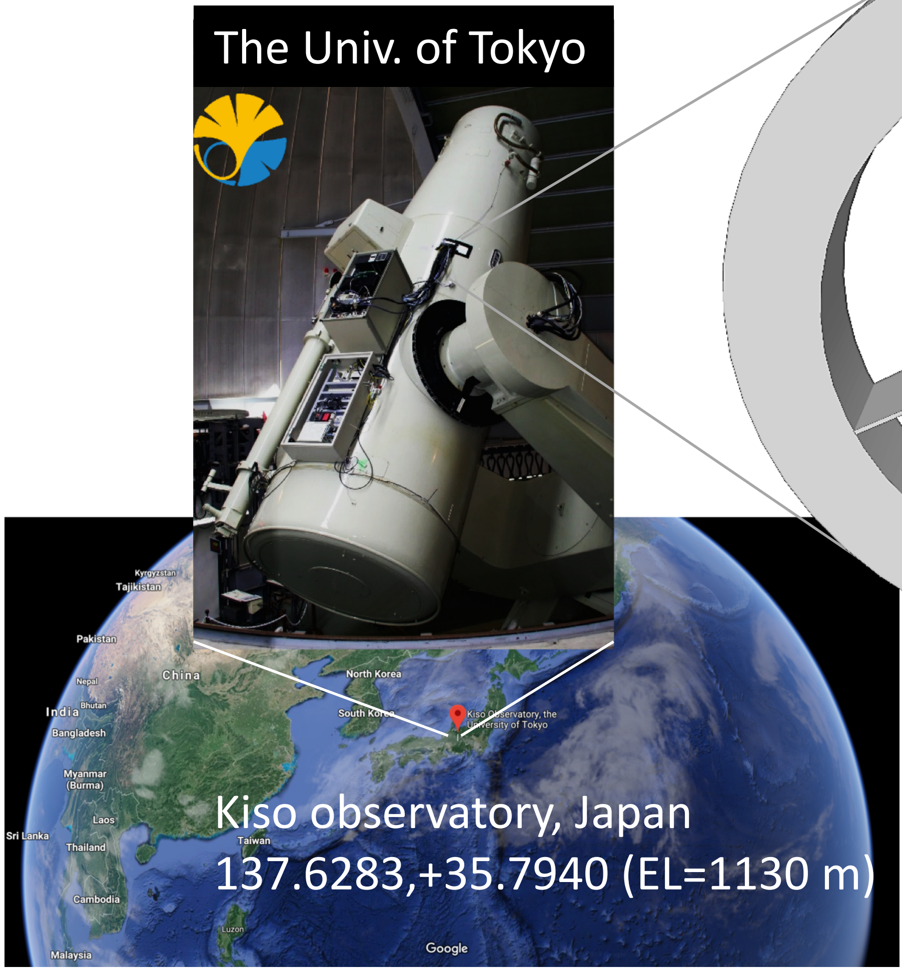
=> desirable high-speed optical instruments

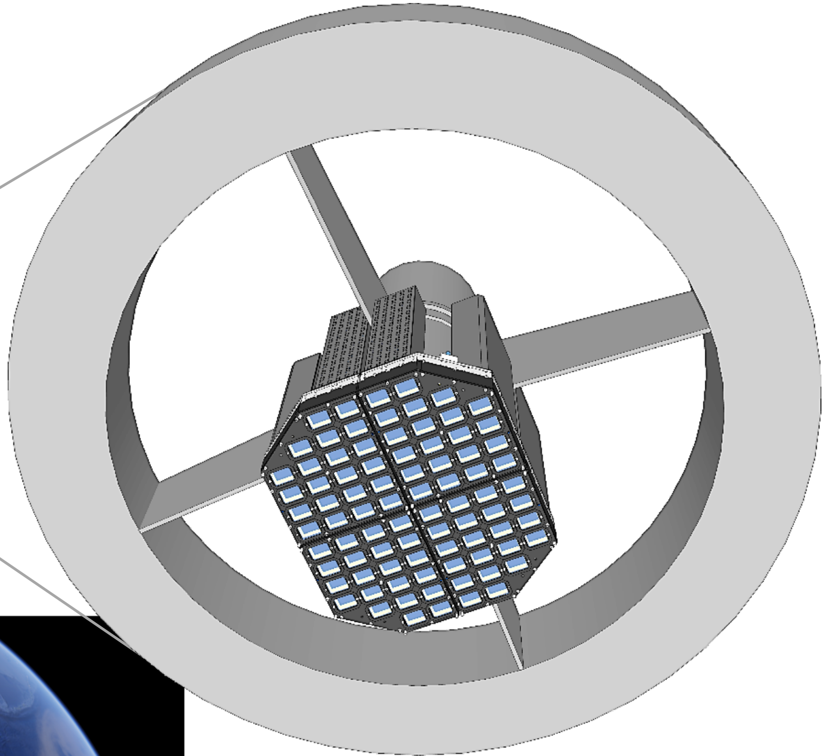


Wide-field high-speed camera

The Tomo-e Gozen

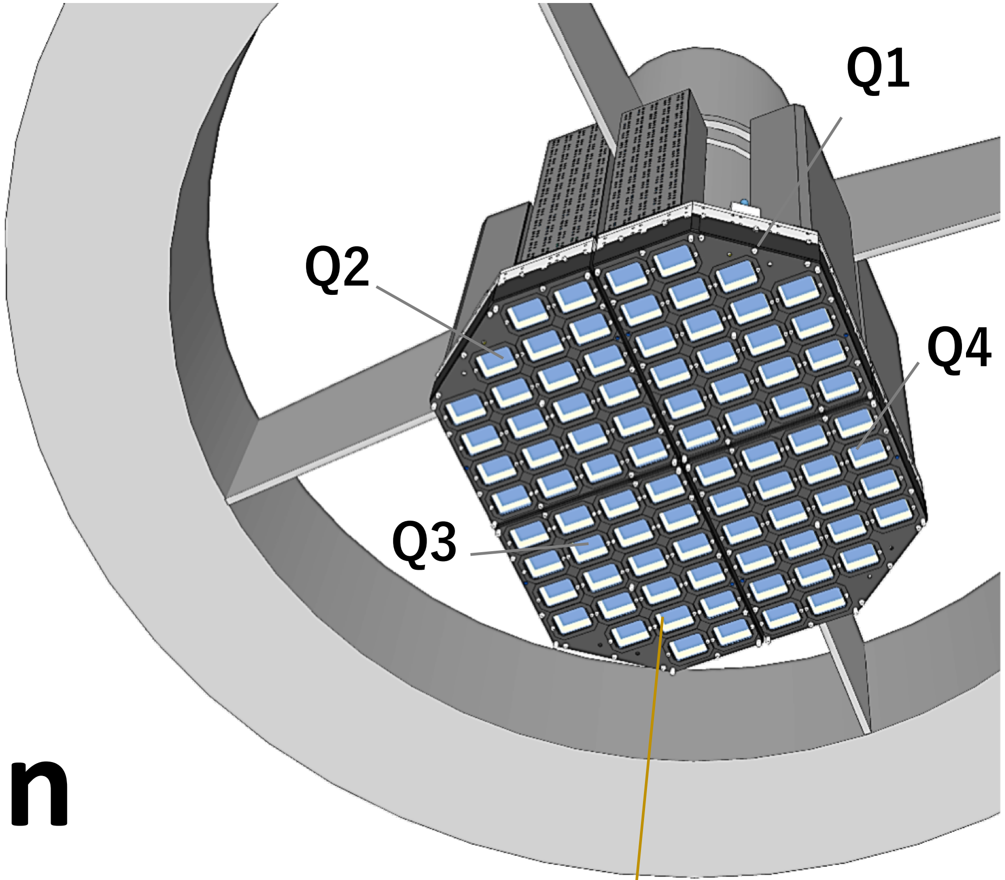
Kiso Schmidt telescope
D=105-cm, f/3.1





the Tomo-e Gozen with
84 CMOS sensors
FoV of 20 deg^2

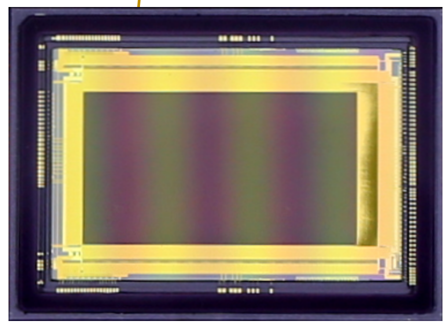
Sako et al. 2018, SPIE, Kojima et al. 2018, SPIE,
Sako et al. 2016, SPIE, Morii et al. 2016, ApJ, Osawa et al. 2016, SPIE



the first wide-field CMOS camera

The Tomo-e Gozen

- **FoV of 20 deg² in ϕ 9 deg**
- **Consecutive frames at 2 fps**
- Big movie data of 30 TB/night (max)
- Room temperature, Non-vacuum



Canon

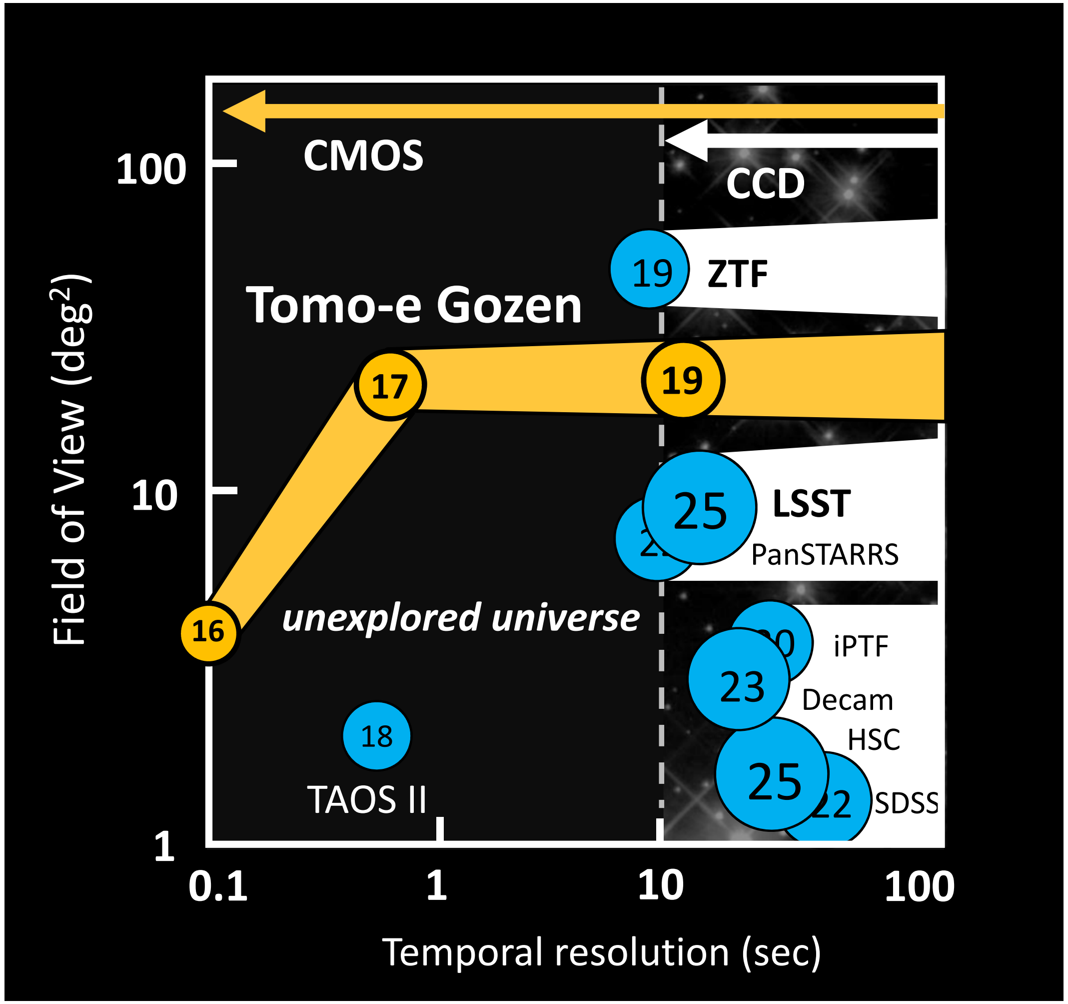
84 chips of CMOS, 1k x 2k pixels

CMOS sensors on the focal plane

Transient sky in second timescale

Default observing mode:
2-fps wide-field movie survey

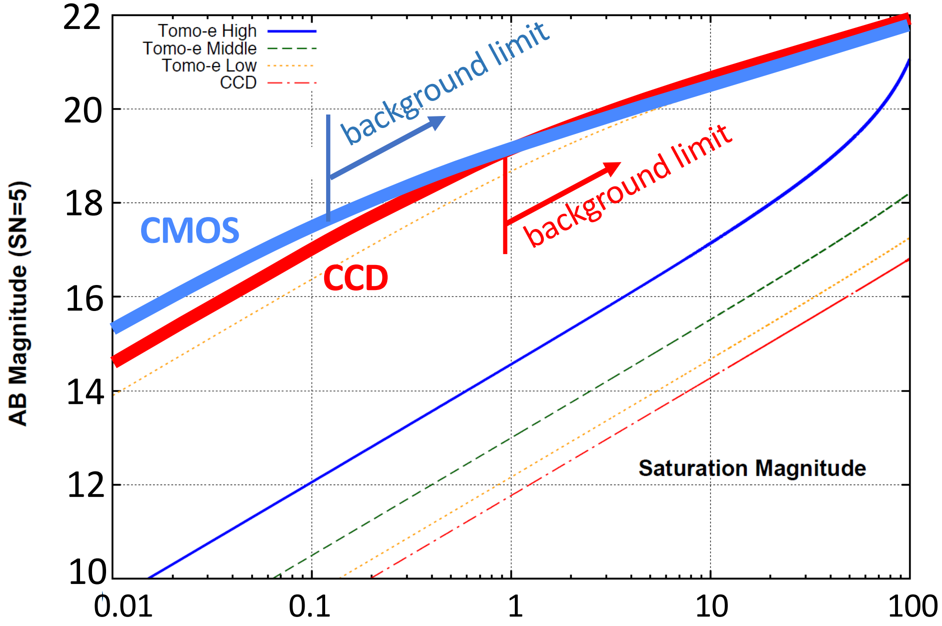
imaging with 2 Hz (2fps)
~17 mag (S/N~20)



The numbers in the circles show target magnitudes.

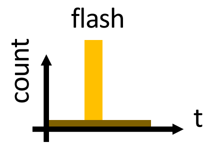
Limiting magnitude

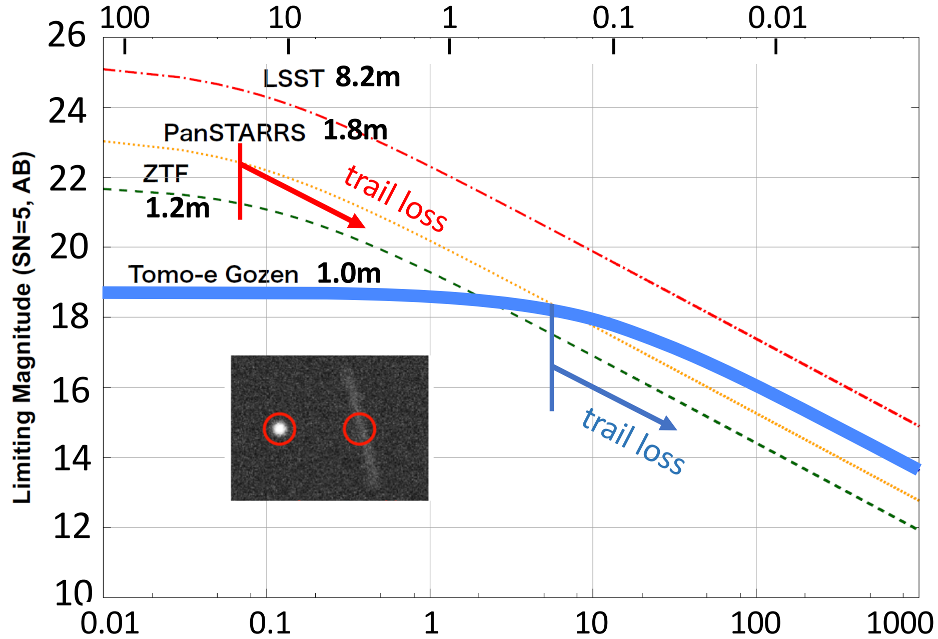
5-σ limiting magnitude (fixed point source)



Exposure time (sec)

Duration time of flash (sec)





Apparent moving speed (arcsec/sec)

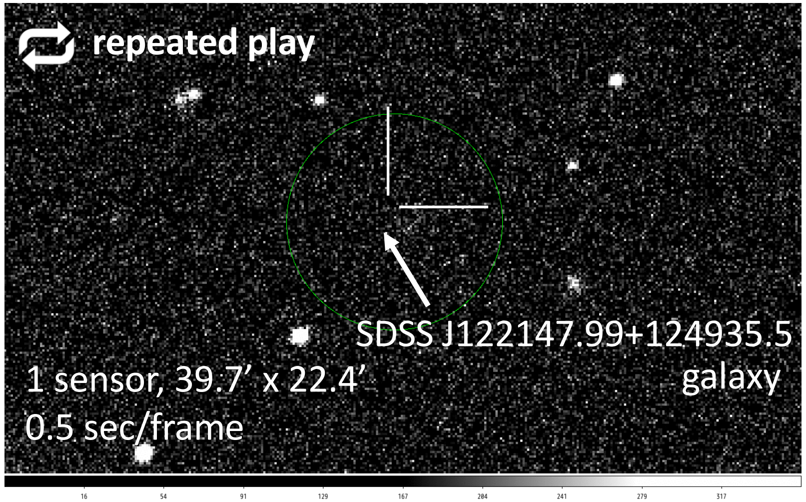
CMOS : efficiency=0.65, N_{read}=2 e-
CCD : efficiency=0.90, N_{read}=5 e-

assuming same filter-bandwidth and pixel size

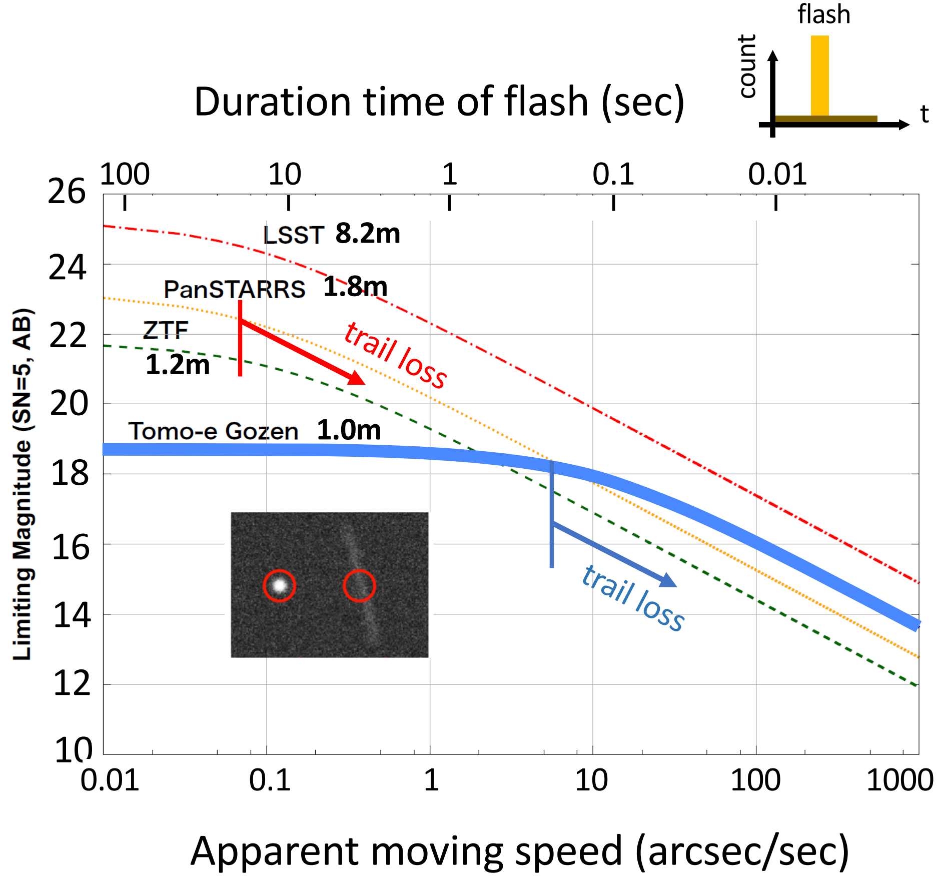
Tomo-e Gozen : 0.5 sec/frame, N_{read}=2 e-
PanSTARRS, ZTF : 30 sec/frame, N_{read}=5 e-
LSST : 60 sec/frame, N_{read}=10 e-

Kojima et al. 2018, SPIE

Limiting magnitude



- Detected in only one frame, < 0.5 sec
- Single event (not repeated), 16-mag
- Same PSF as other sources, ~3"
- No color information obtained



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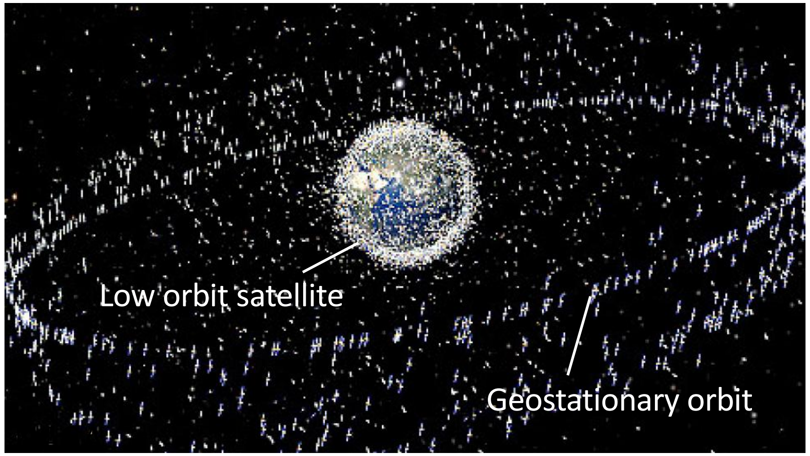
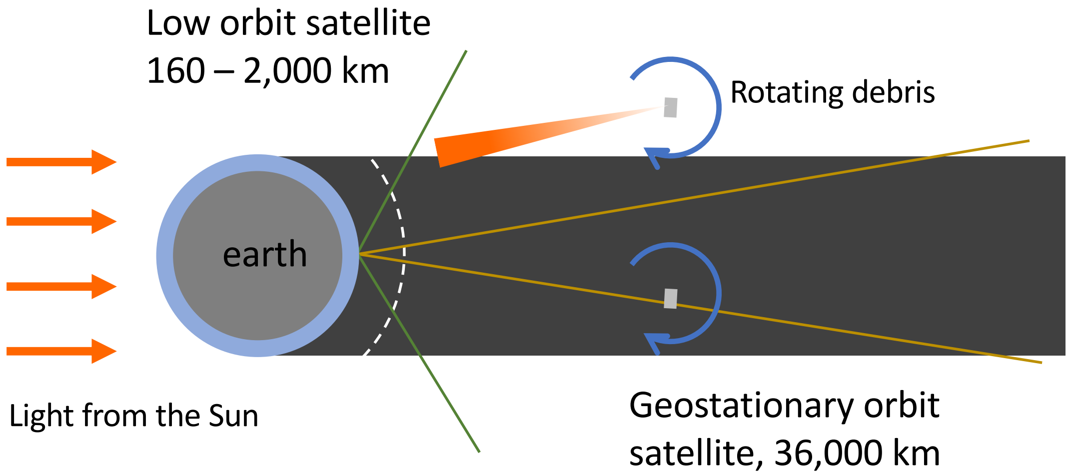
PanSTARRS, ZTF : 30 sec/frame, N_{read}=5 e-
LSST : 60 sec/frame, N_{read}=10 e-

Kojima et al. 2018, SPIE

Single Flash of t < 0.5 sec





- Space debris with ϕ 10-mm on the geostationary orbit can be detected.
- In earth's shadow on the sky => Frontier of such a single flash

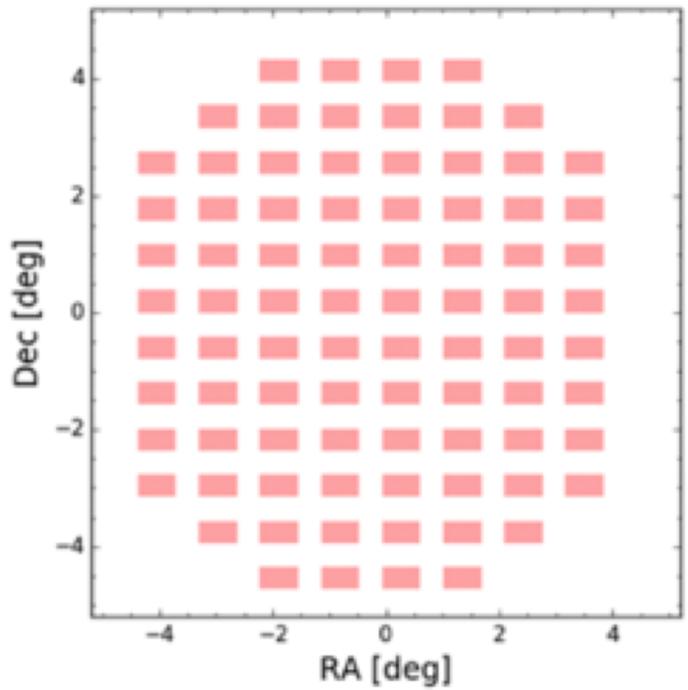
Intensive Science Programs

1. Transient survey

utilize its large FoV

- Elv > 40 deg (7,000 deg^2) every 2 hours
- 3 visits per night
- Record all events < 20 mag (dark clear night)
- SNs, Novae, variables

1 exposure



2. Follow-up / Simultaneous

- GWs, neutrinos
- FRBs, NSs, BBHS, meteors, NEO,

3. Fixed FoV + high-speed

shorter than a second

- 2-fps@ 20 deg^2 -- 200-fps@ 52” x 38” (Ichiki-san’s talk)
- Occultation of TNOs, YSOs, flares, FRBs, NSs, BBHs, meteors, NEOs

Intensive Science Programs

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- Elv > 40 deg (7,000 deg^2) every 2 hours
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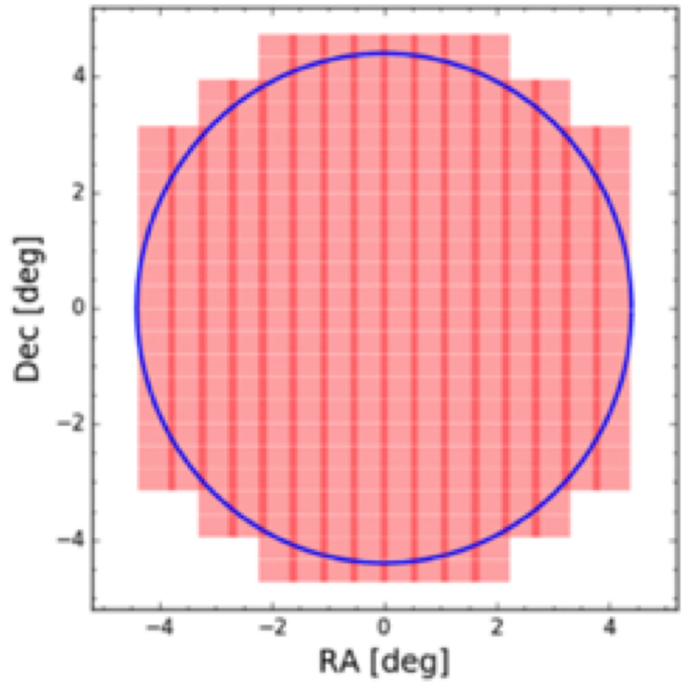
- Record all events < 20 mag (dark clear night)
- SNs, Novae, variables

2 x 2 dithering



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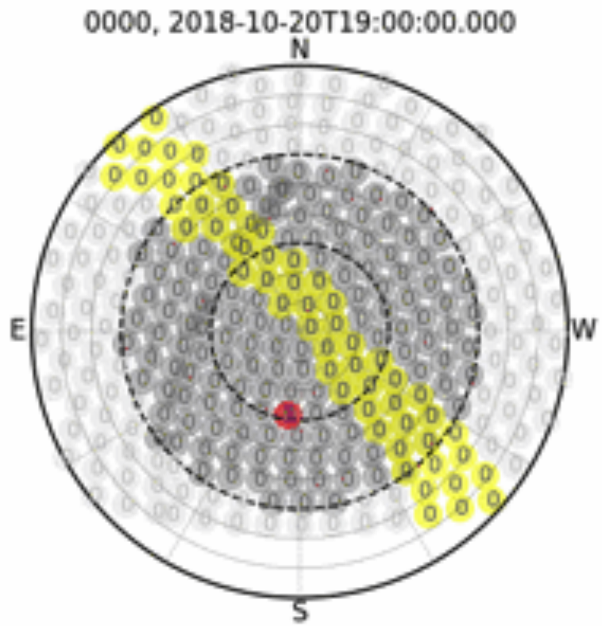


Simulation of transient survey
- Each circle: FoV with Φ9 deg
- Yellow: Milky way

2. Follow-up / Simultaneous

- GWs, neutrinos
- FRBs, NSs, BBHS, meteors, NEO,

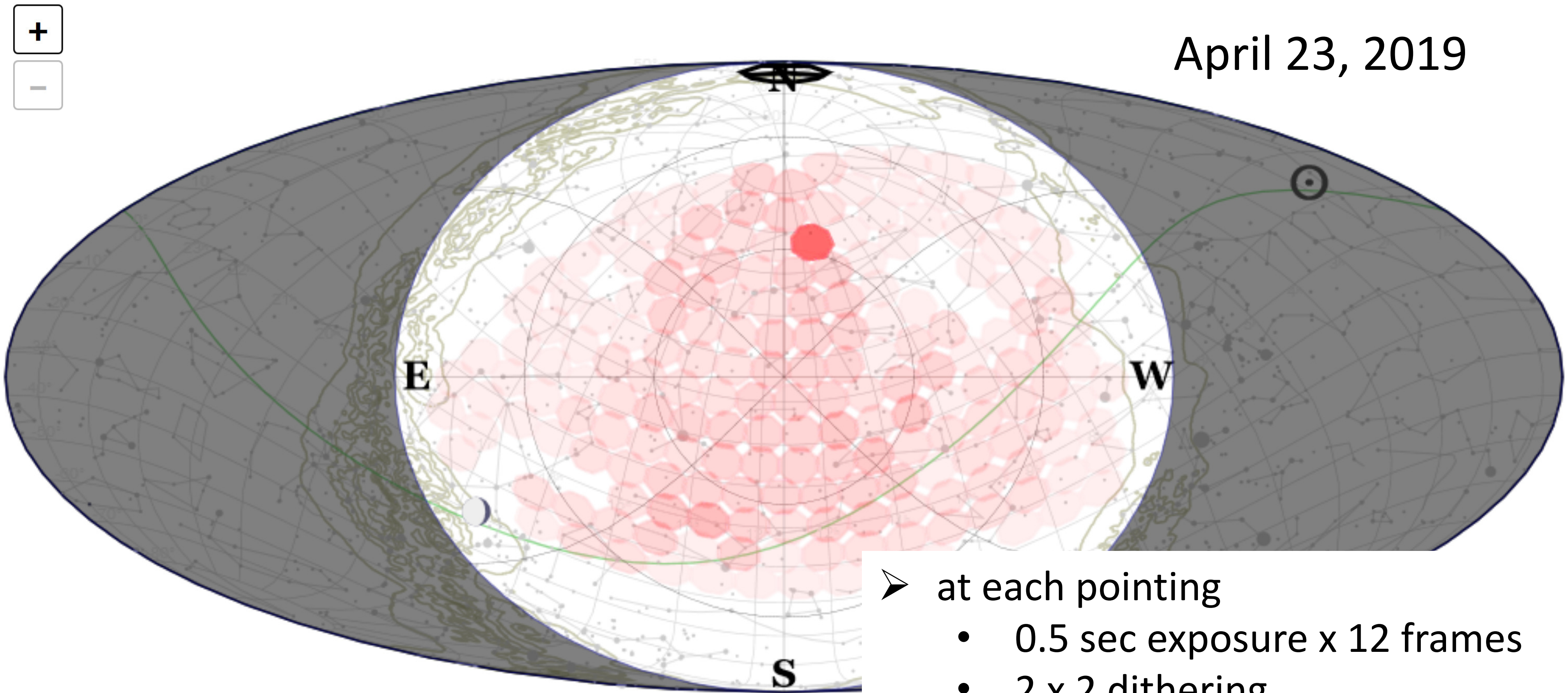
3. Fixed FoV + high-speed

shorter than a second

- 2-fps@ 20 deg^2 -- 200-fps@ 52" x 38"
- Occultation of TNOs, YSOs, flares, FRBs, NSs, BBHs, meteors, NEOs

Tomo-e Gozen sky map

April 23, 2019

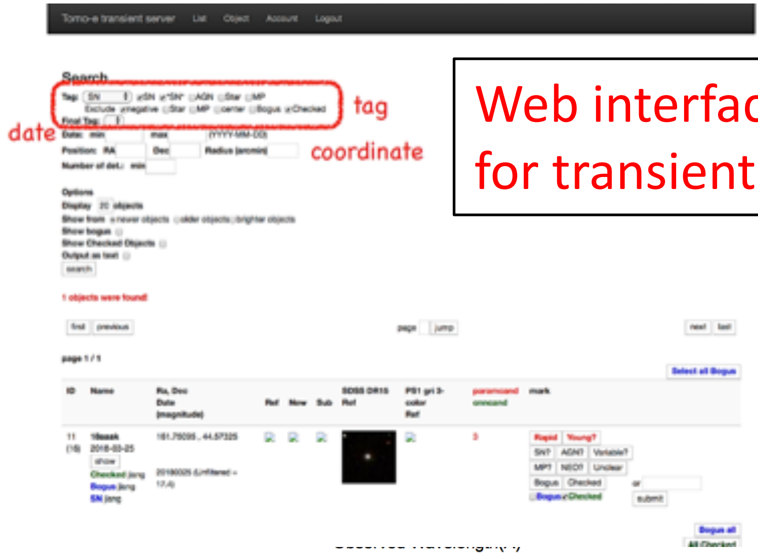


- at each pointing
  - 0.5 sec exposure x 12 frames
  - 2 x 2 dithering
- Limiting magnitude of 5-σ 18 mag is achieved.

Each circle is a FoV of Tomo-e Gozen, ϕ 9 deg

Initial Results from the Tomo-e Gozen

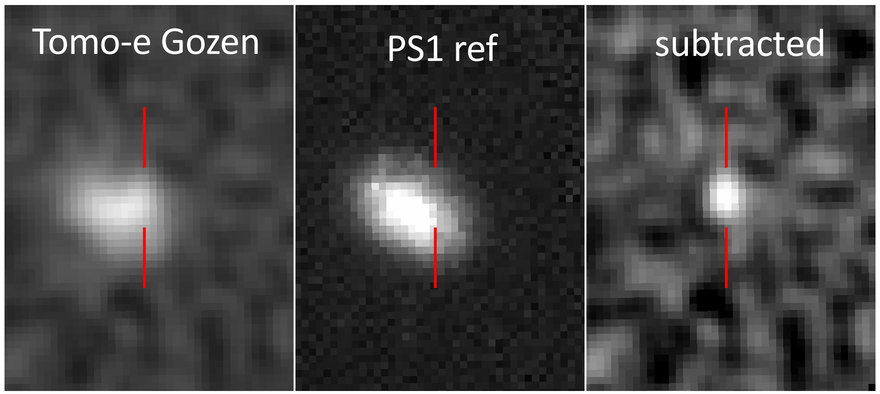
The discovery of SN2019cxx

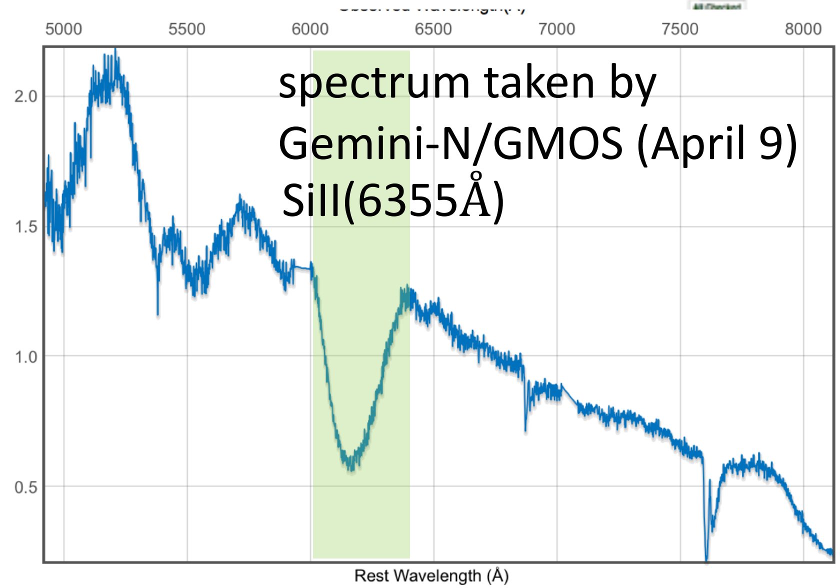


Web interface for transients

The first supernova discovered by Tomo-e Gozen

- discovery: 21:09, April 5, 2019(JST)
- position: 11h17m48.22s +13d43m42.0s
- discv. mag: 18.7(clear)





- SN type: Ia
- host: SDSS J111748.57+134339.5
- redshift: 0.025
- phase: ~5 days before maximum

https://wis-tns.weizmann.ac.il/object/2019cxx

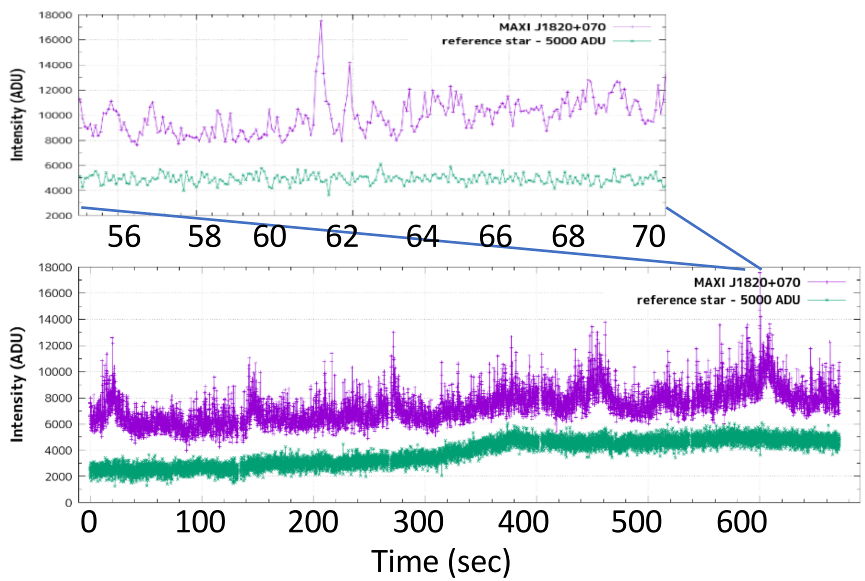
in partial read mode
Tomo-e very high-speed programs

Detection of 10-msec scale flares in the black-hole binary MAXI J1820+070

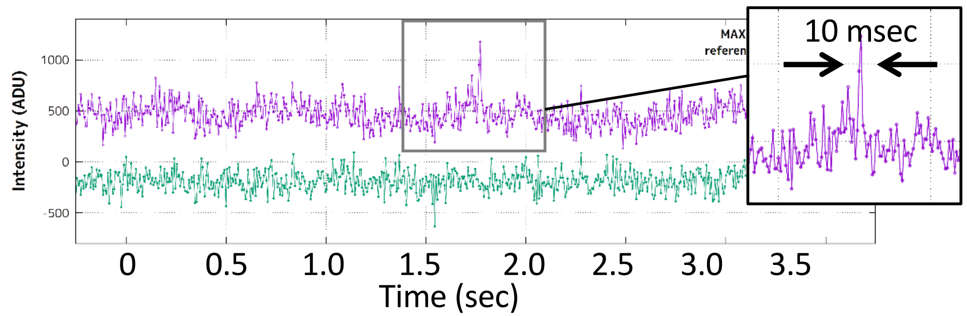
Sako et al. 2018, Atel #11426

Absolute time accuracy: ± 0.2 msec

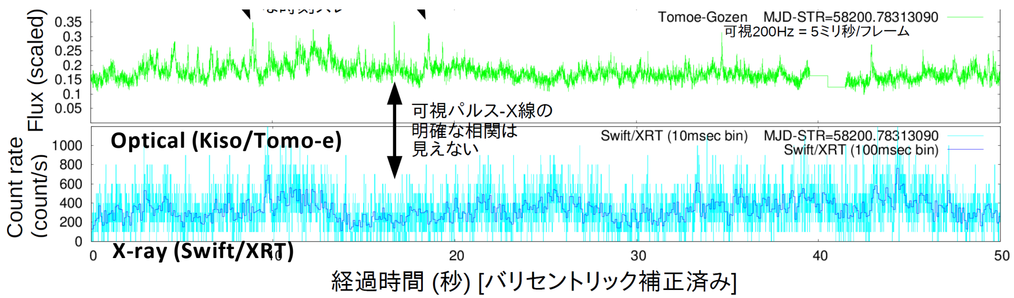
- **66.294 msec/frame,** 9.9' x 7.1‘,
  15 sets of consecutive 2,000 frames



- **6.149 msec/frame,** 1.6' x 0.79‘
  15 sets of consecutive 10,000 frames



Simultaneous observations with Optical and X-ray



Kokubo+ 2018, ASJ spring meeting

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

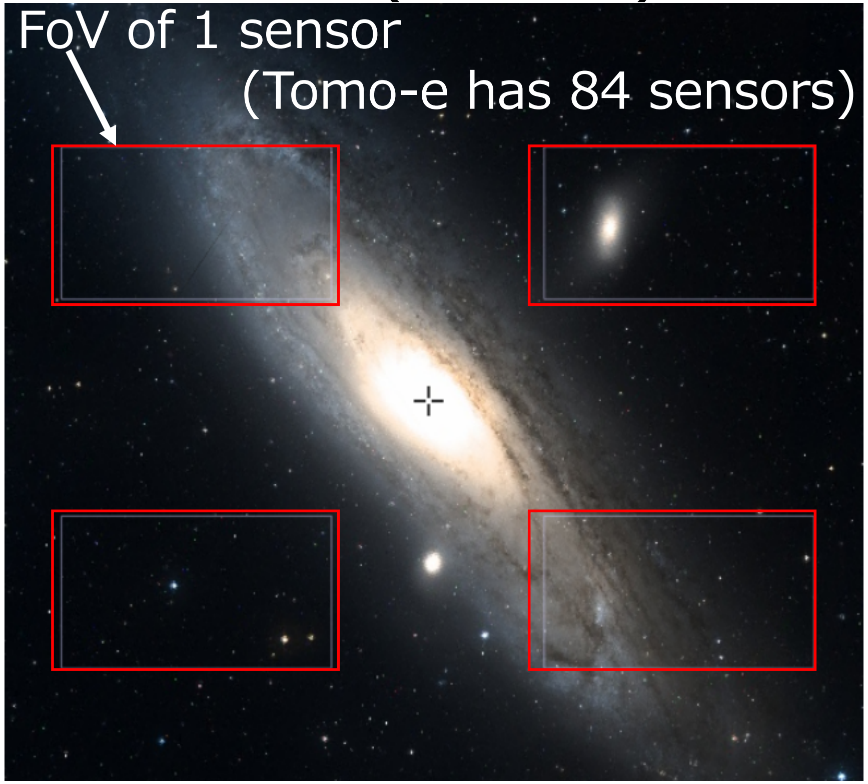
For discussion session

May. 4, A.D.2019 Carnegie Observatories

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

Partial mode (high speed mode) of Tomo-e

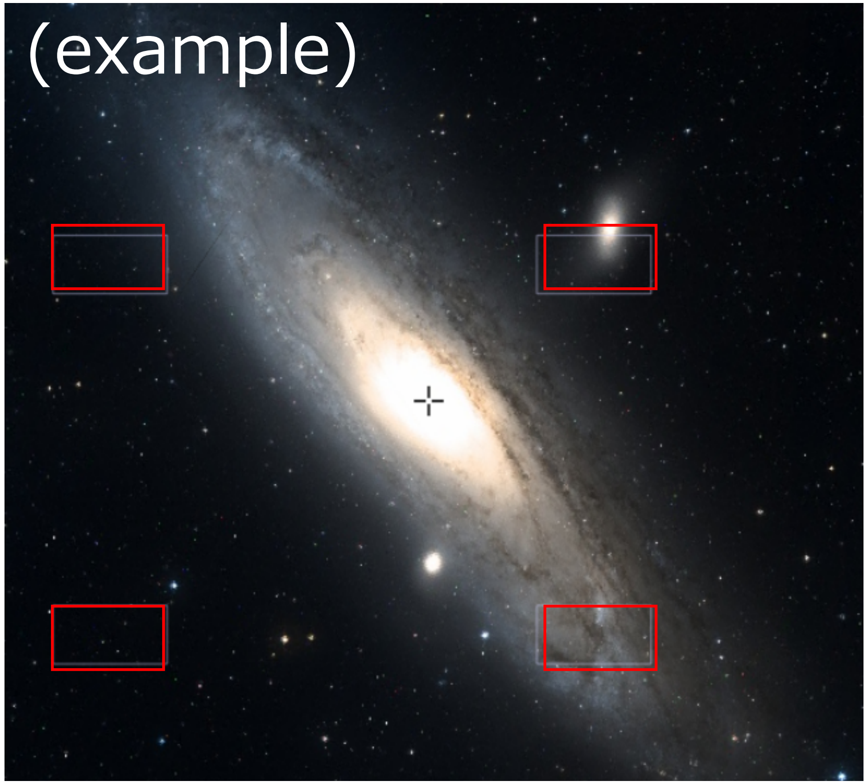
Full frame (normal) mode



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

Total FoV = 22 deg2

Partial frame mode



1000 * 500 pix^2 each
-> <u>0.12 sec cadence</u>

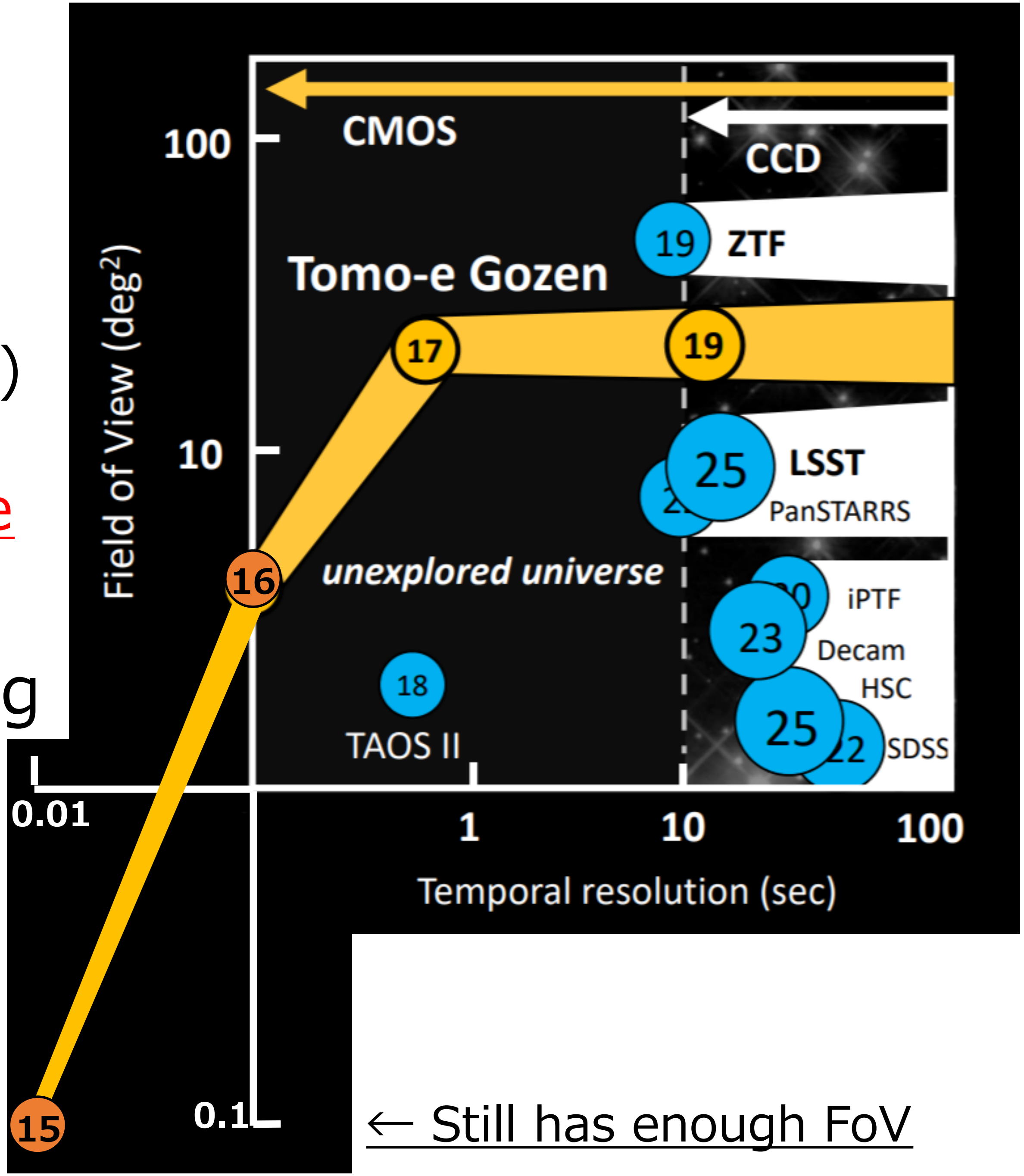
Total FoV = 4.6 deg2

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

Survey power for transients

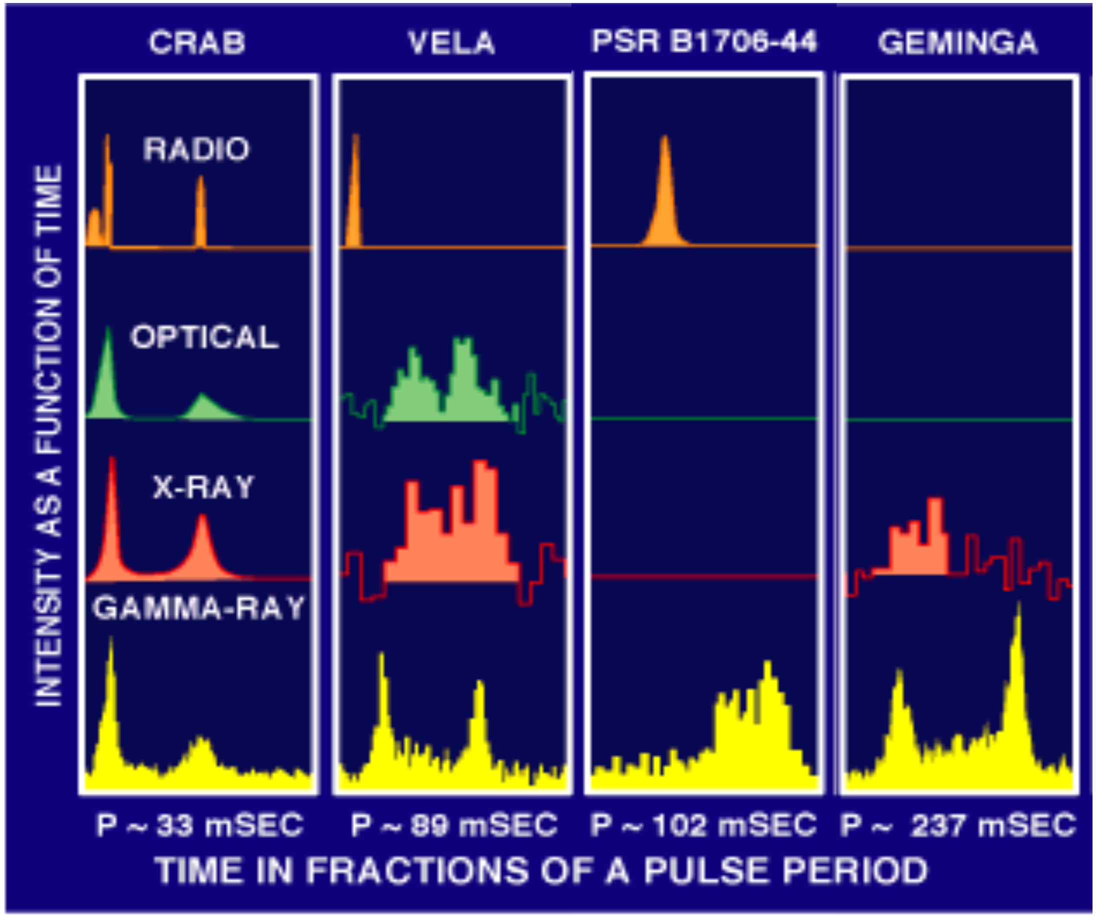
280 * 24 pix^2
(FoV = 0.05 deg^2)
->
5.2 msec cadence

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



← Still has enough FoV

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.

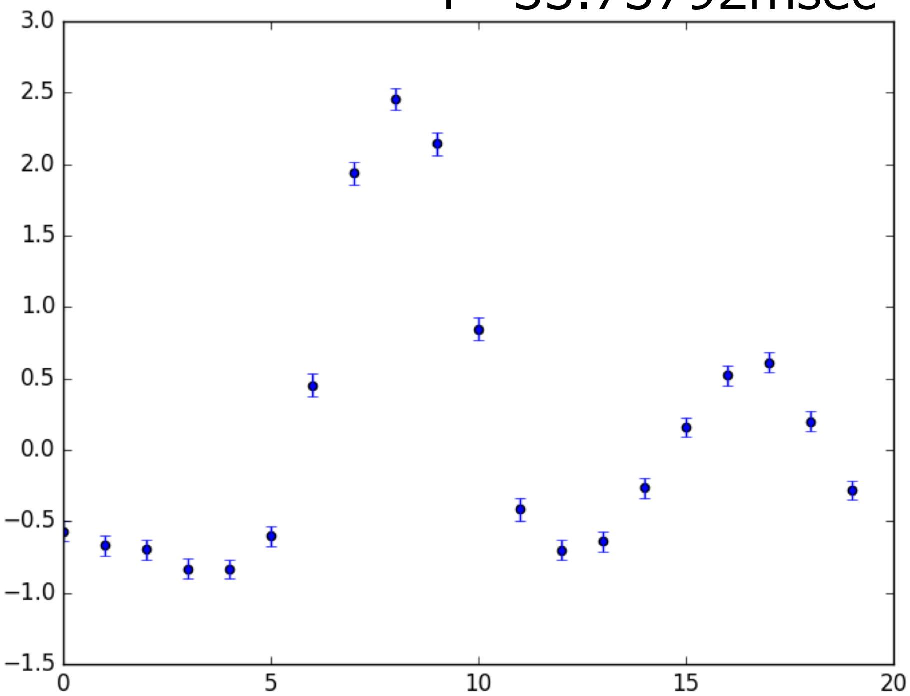
Test observation for Crab pulsar

Oct. 2017 by Tomo-e Q0

↓Mean image for 50000 frames (322 sec)

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

P=33.73792msec



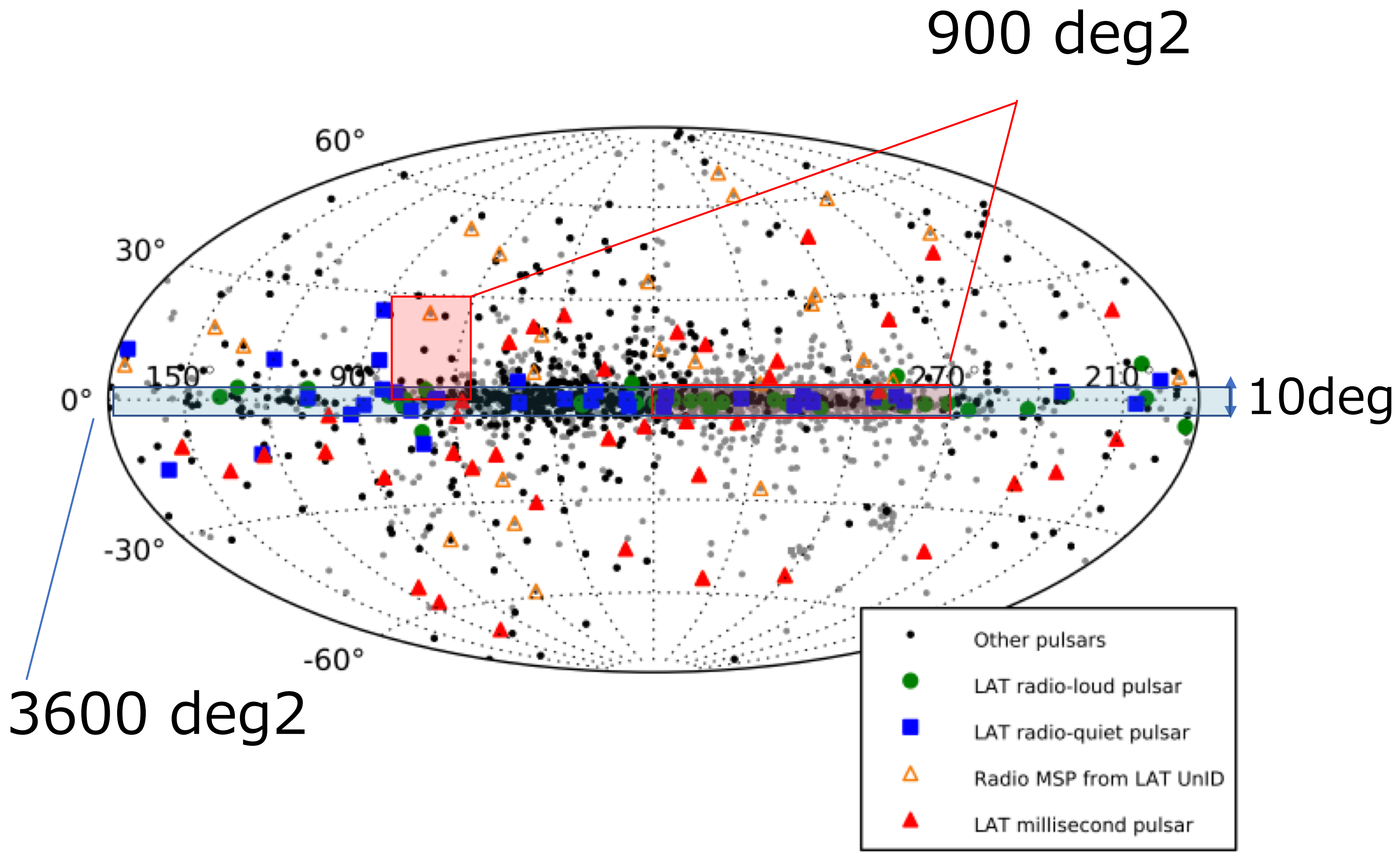
frames	Pulses	SD	S/N
100	∼20	0.73	8
300	∼70	0.46	13
1000	∼200	0.27	22
3000	∼700	0.19	30
10000	∼2000	0.13	50

Relation between number of frames and S/N

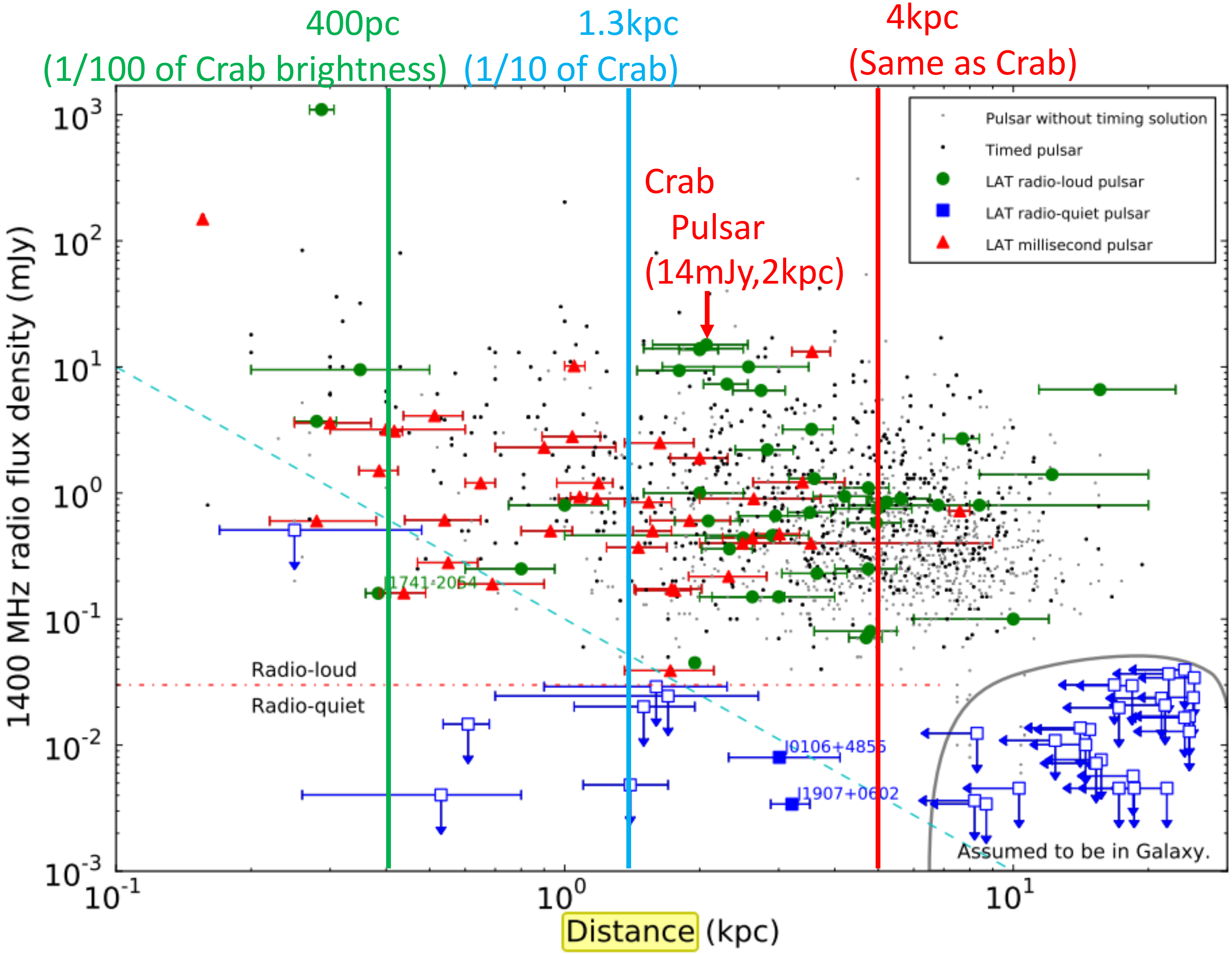
Sufficient S/N for pulsar survey

Survey Area

6 sec/FoV for 10 fine nights -> 900 deg2



Survey depth (for 6 sec /FoV)



Simultaneous observations with radio & 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.

Other Applications (open topic)

Transients

- FRB counterpart survey (<msec)

A flat spectrum gives 23 mag in optical band (too faint for Tomo-e).

Crab-like spectrum (10^5 brighter in optical than flat spectrum) gives 12 mag in 5 msec.

Pulsating Objects

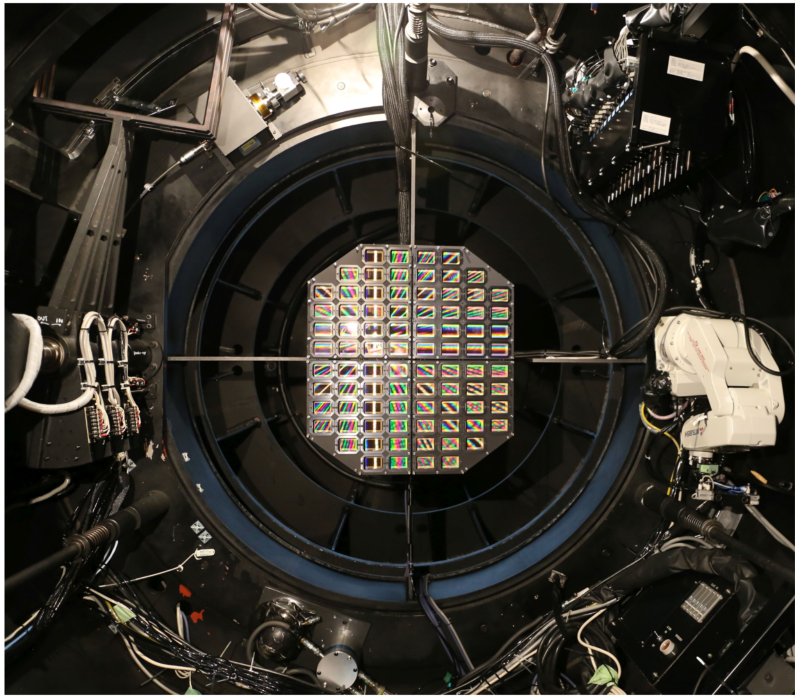
- Magnetar survey (~sec)

Magnetar may have coherent emission (like radio pulsars) in Optical / IR band. (Zane+2010)

SUMMARY of the Tomo-e Gozen

Instrument

- 1-m Kiso Schmidt telescope
- 20 deg^2, 2 fps
- 84 chips of 1k x 2k CMOSs
- 30 TB per night
- 19 mag @t_{exp}=0.5sec
- Optimized for discoveries of transients
- Simple system
- All of raw data is deleted in 7 days



Science targets

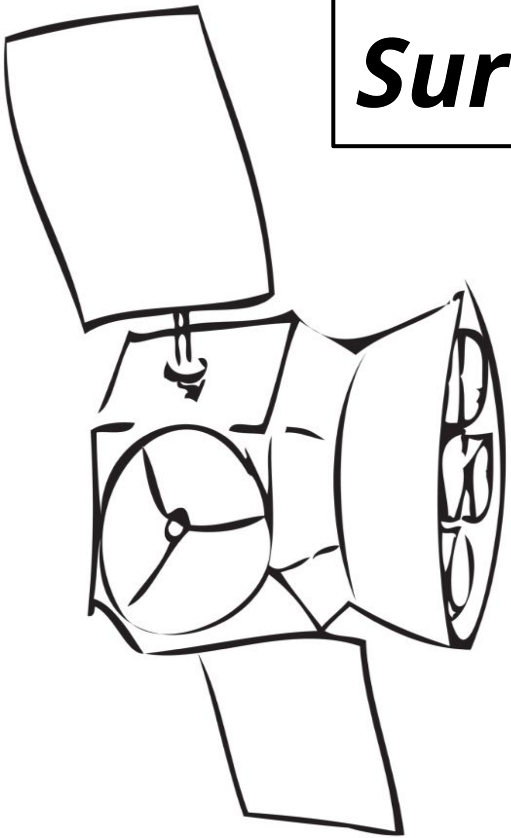
- Tomo-e transient survey, 10,000 deg^2 every 2-3 hours
- GW optical counterparts
- Fast moving objects, high-speed monitoring

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.

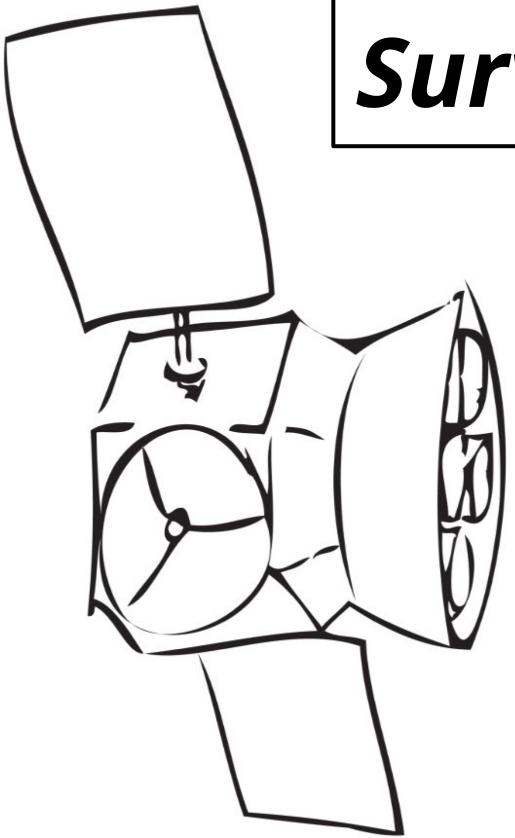
- The survey expects to find ~2000 candidates (300 Earth-sized objects) using the transit method.

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)



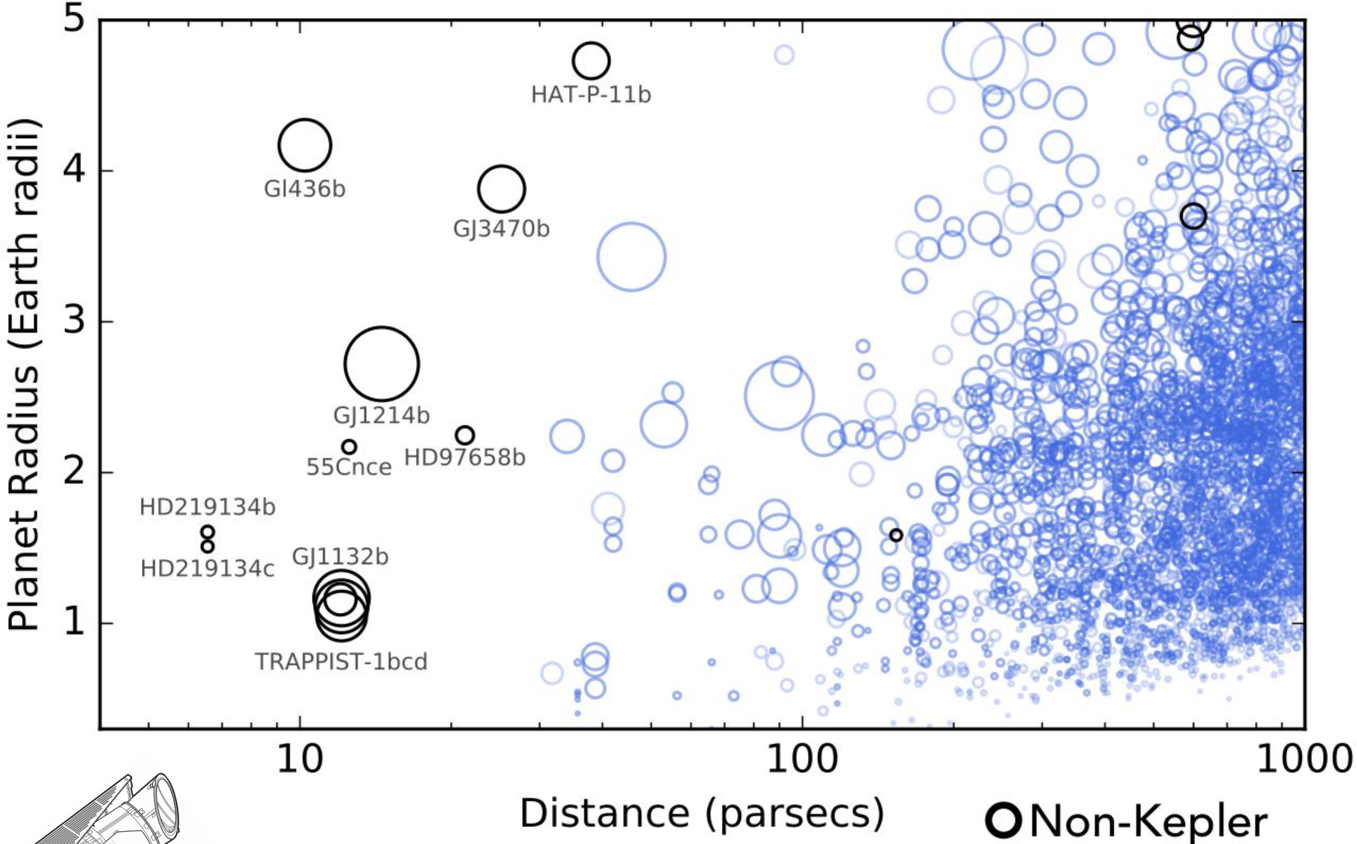
200,000-400,000 stars will be observed every 2 minutes, and nearly 420 million stars will be observed every 30 minutes.

- 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 May, 8 Sectors have been released.

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

The Kepler Detections



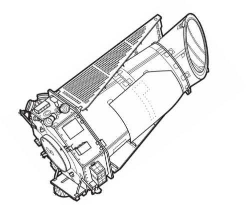
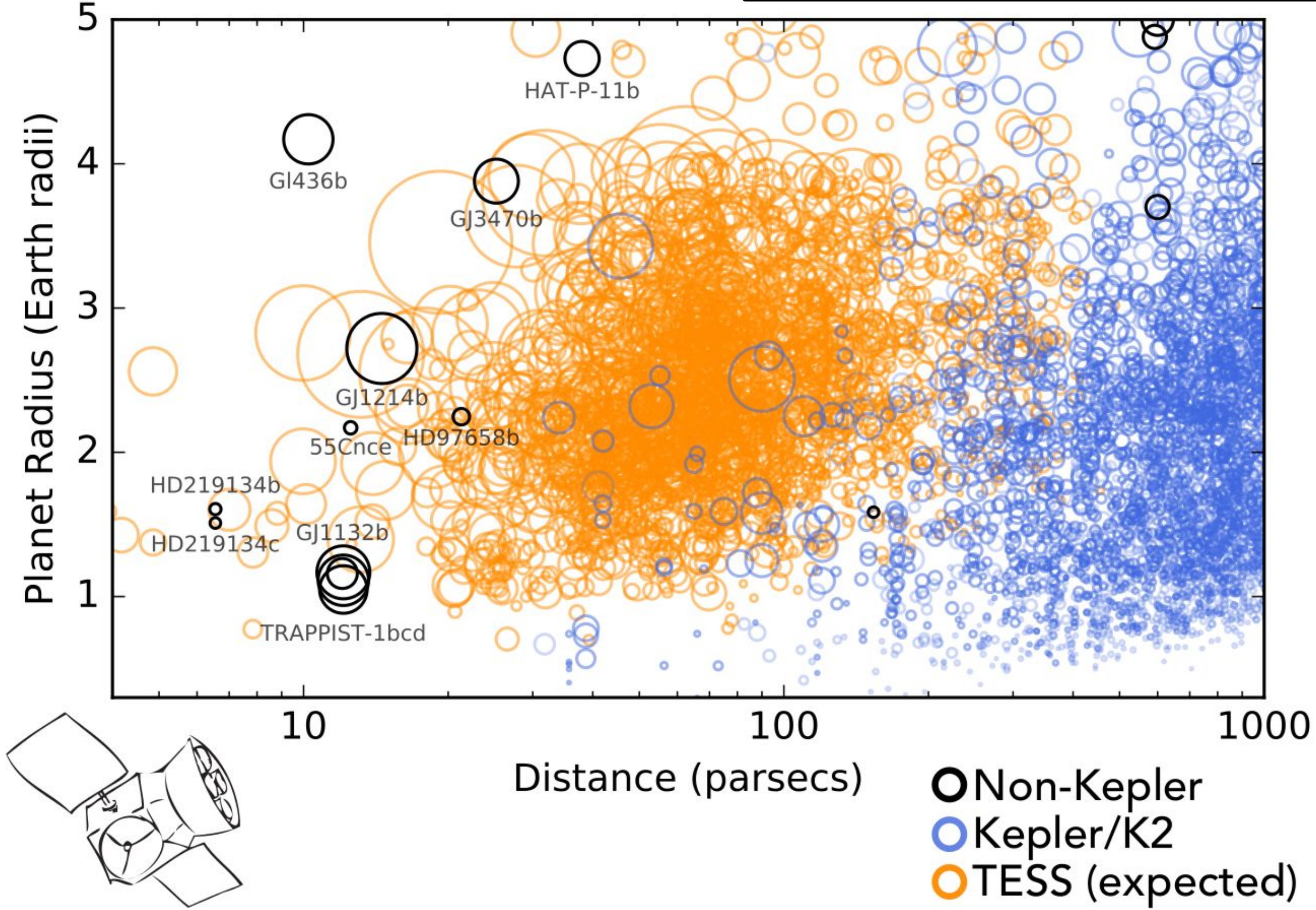


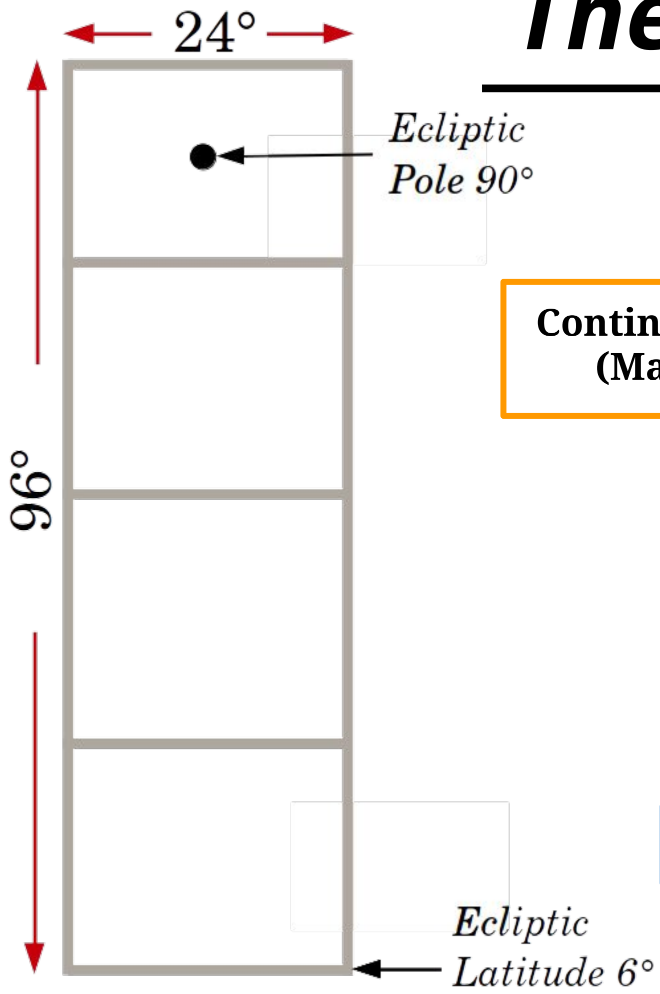
Figure courtesy of Z. B. Thompson

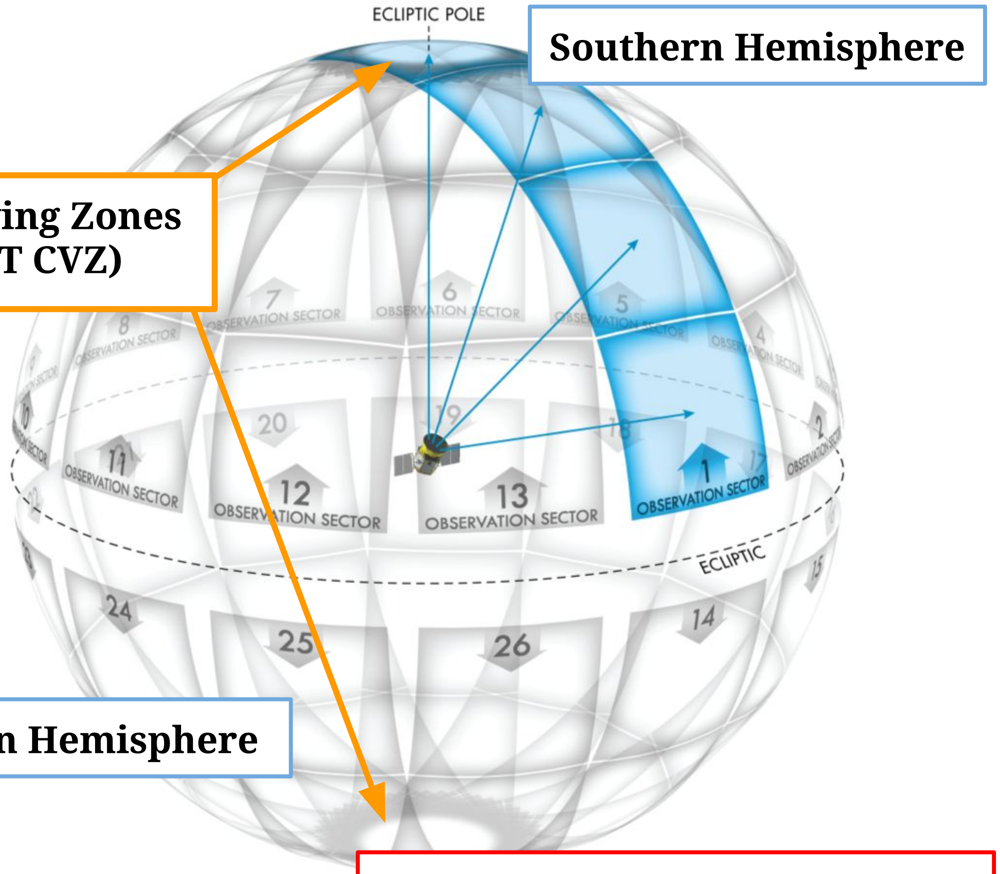
TESS Detections

Figure courtesy of Z. B. Thompson



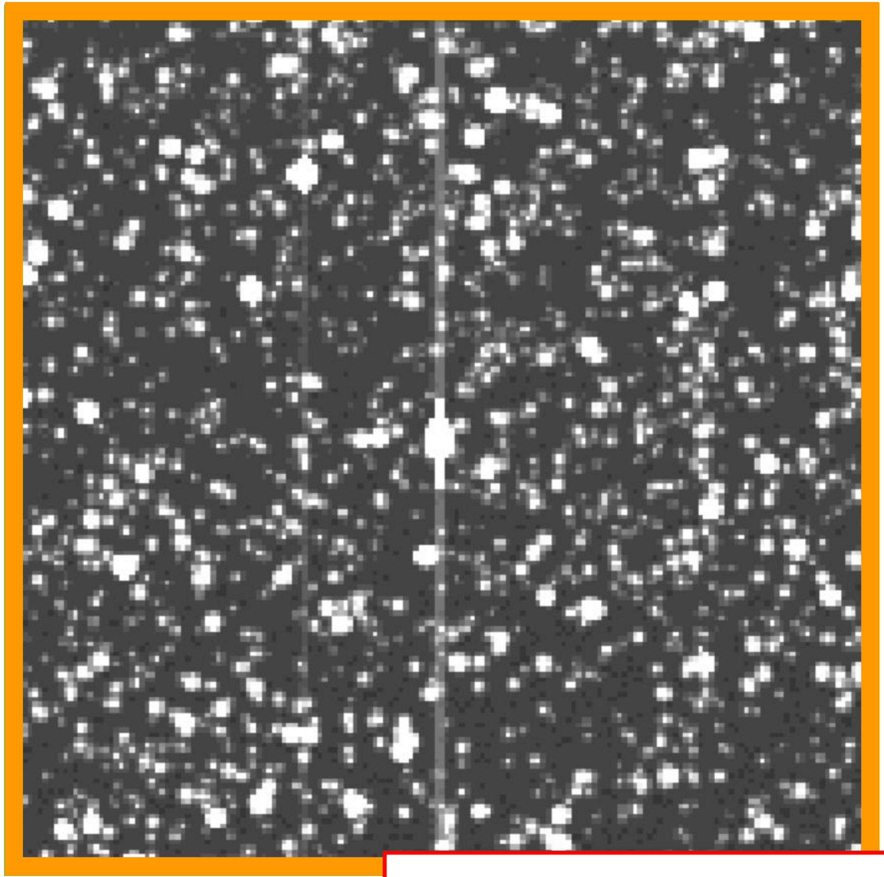
The TESS Observing Strategy





Ricker et al. 2014, Sullivan et al. 2015

The TESS Observing Strategy

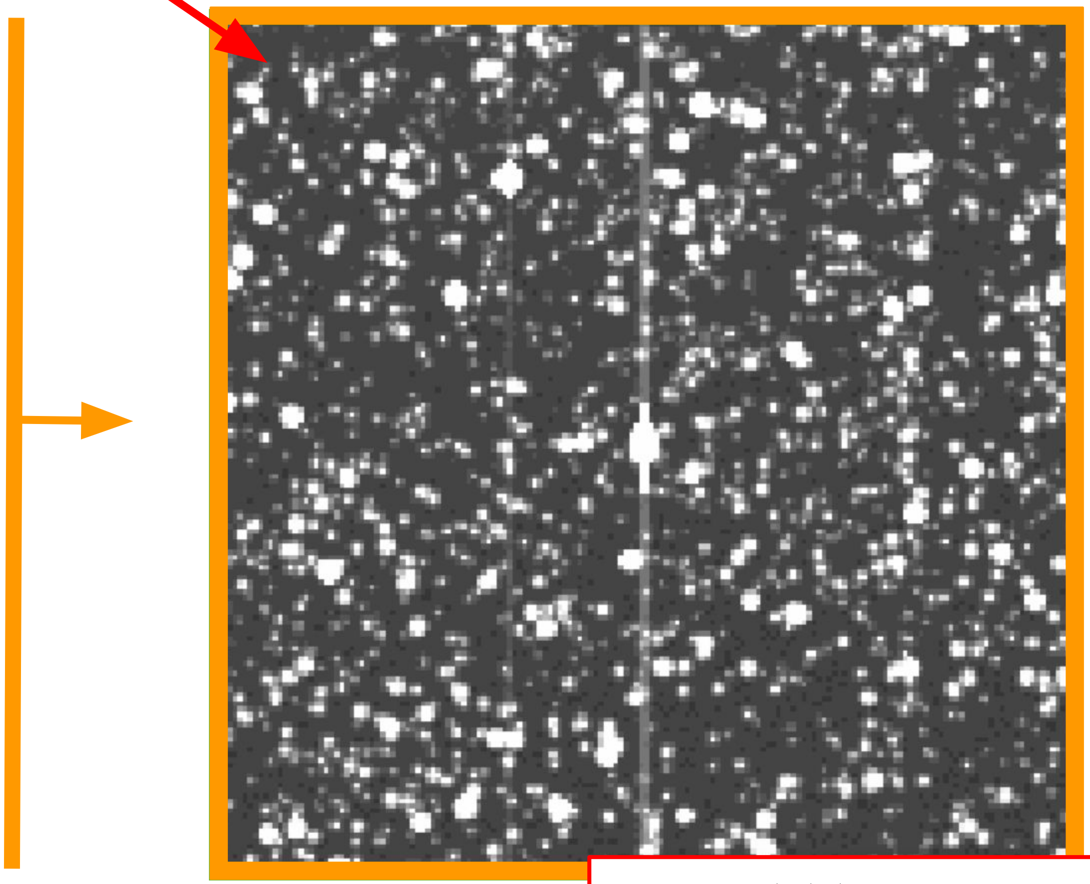


1° on a side

Images and slide sequence courtesy of Zach Berta-Thompson

Each pixel is 21″ on a side!

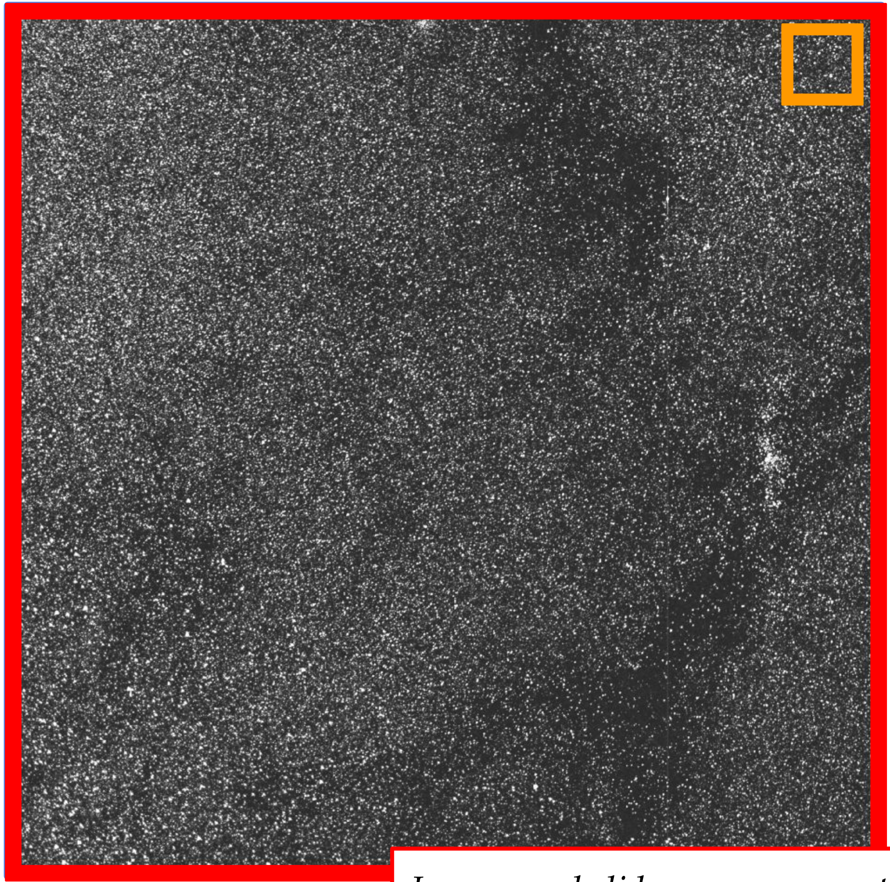
1° on a side



Images and slide sequence courtesy of Zach Berta-Thompson

The TESS Observing Strategy

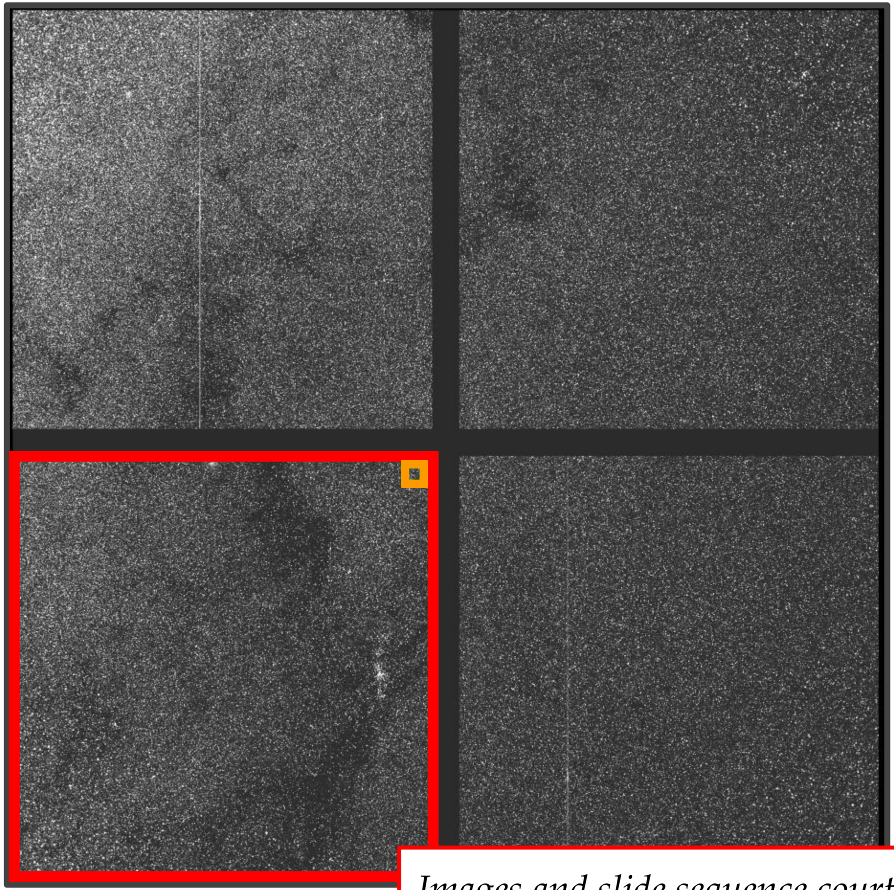
12° on a side -- one CCD



Images and slide sequence courtesy of Zach Berta-Thompson

The TESS Observing Strategy

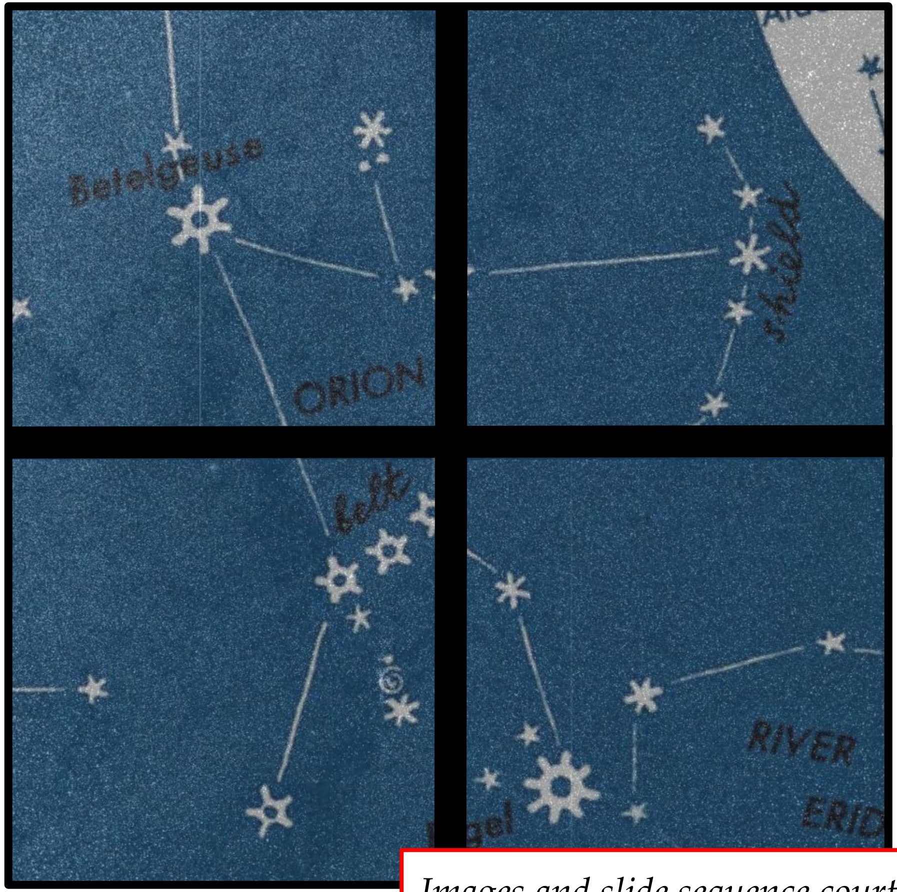
24° on a side -- one camera



Images and slide sequence courtesy of Zach Berta-Thompson

The TESS Observing Strategy

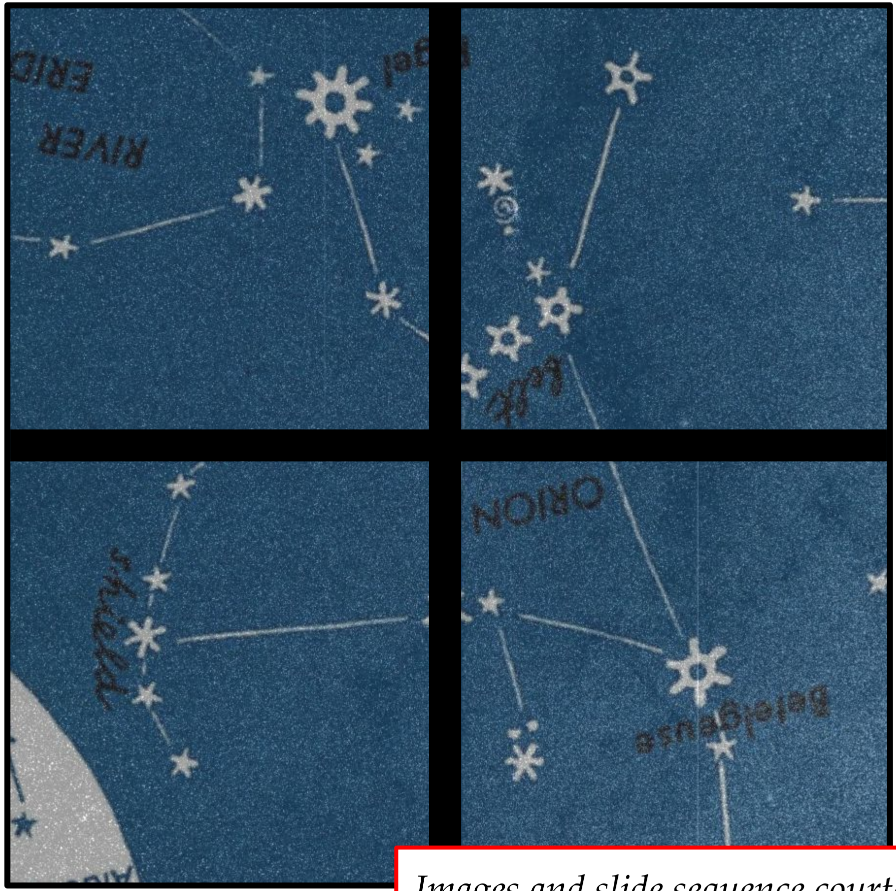
24° on a side -- one camera



Images and slide sequence courtesy of Zach Berta-Thompson

The TESS Observing Strategy

24° on a side -- one camera



Images and slide sequence courtesy of Zach Berta-Thompson

“First-light” Image from TESS

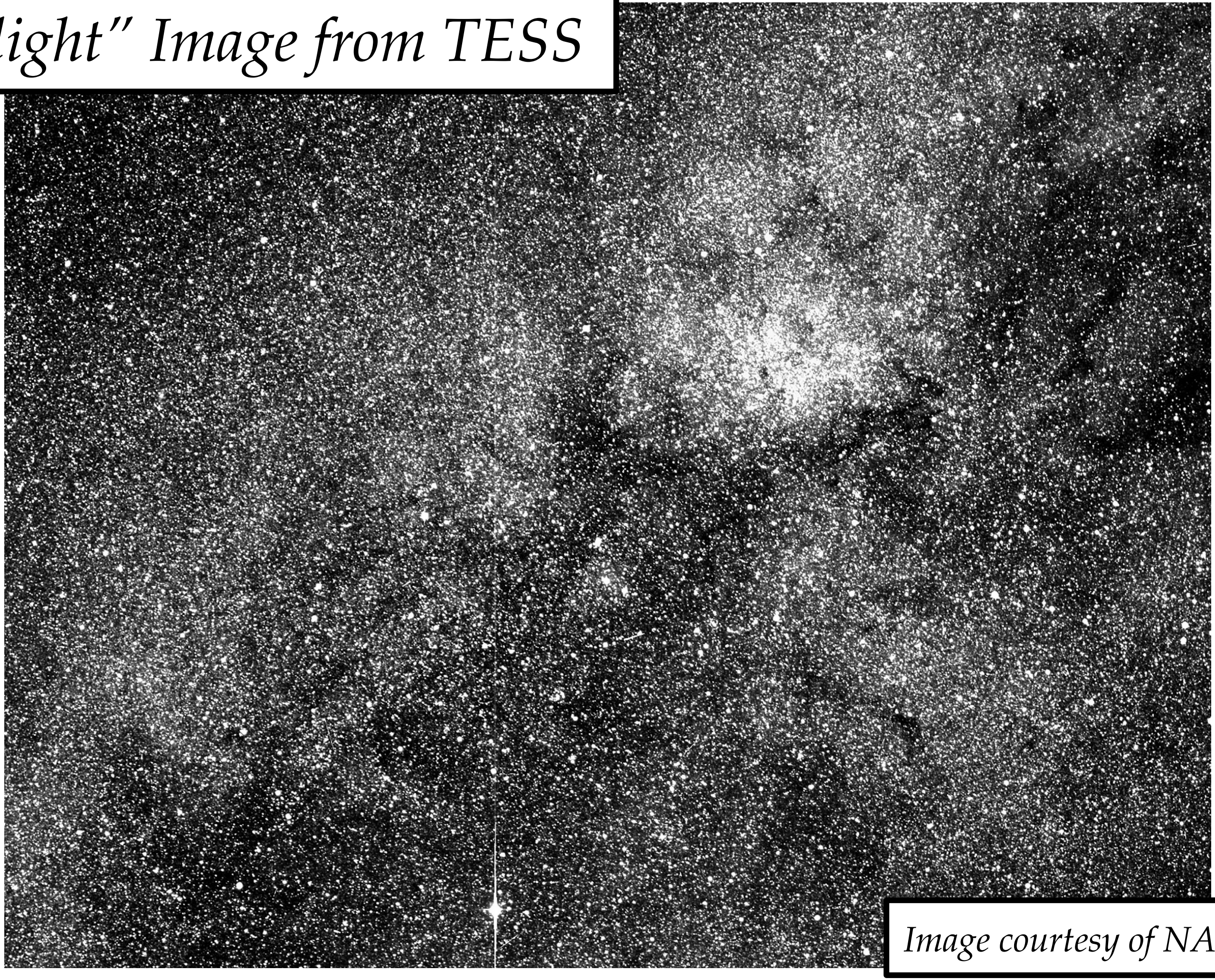


Image courtesy of NASA

Current Observations

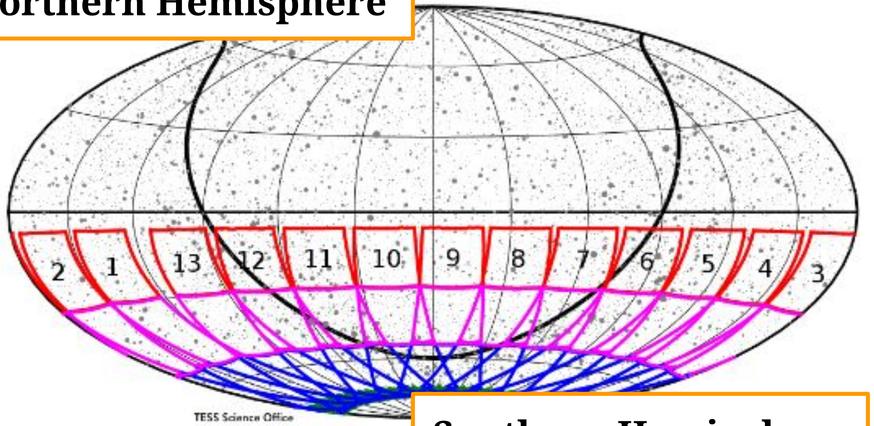
Where is TESS pointed now?

TESS has begun observing Sector 11 in Orbit 29. The pointing direction of the instrument during Sector 11 is:

Ecliptic Longitude (J2000): 226°
Ecliptic Latitude (J2000): -54°

RA (J2000): +189°
Dec (J2000): -66°
Roll (deg): 138°

Northern Hemisphere

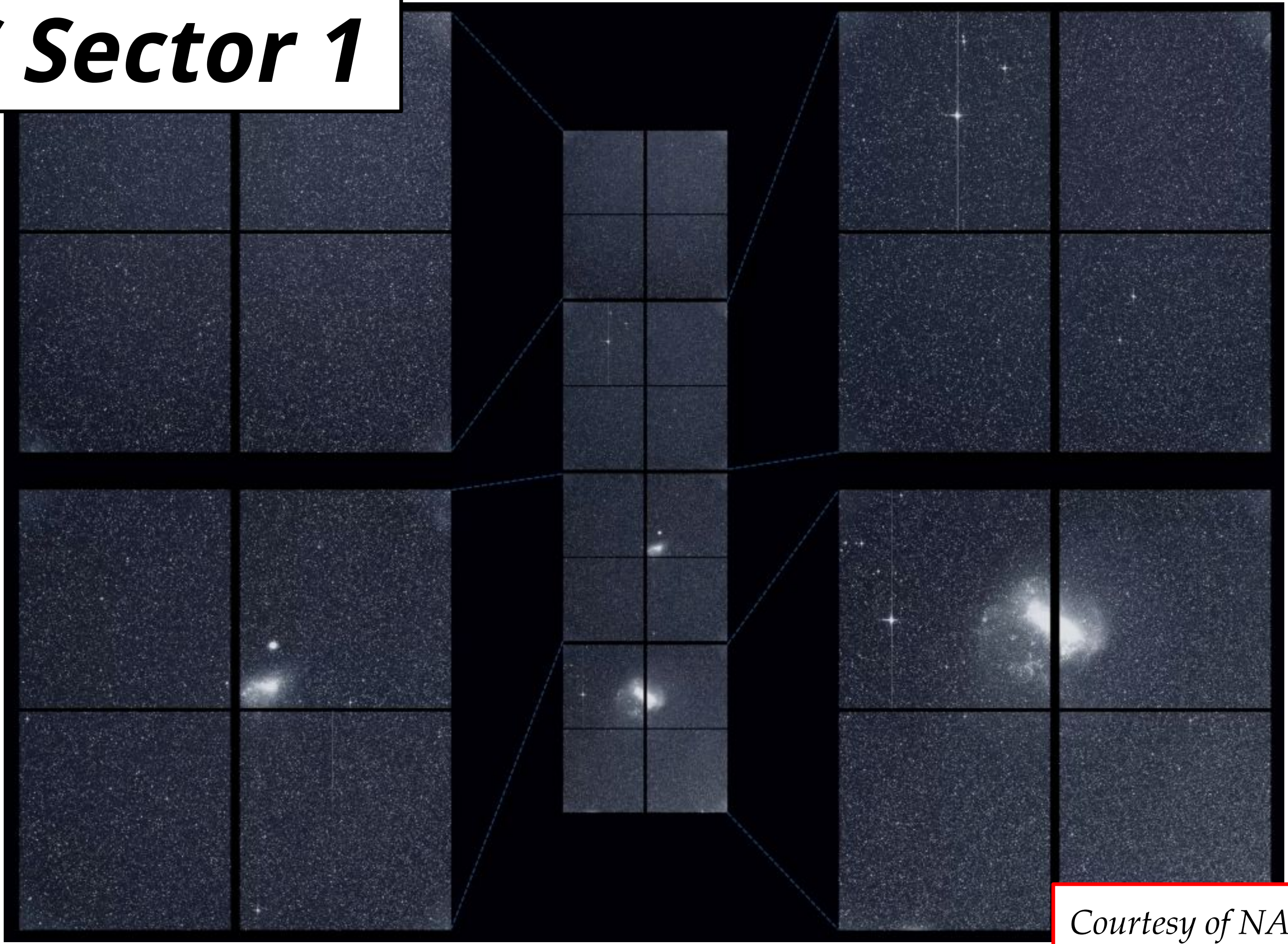


Southern Hemisphere

As of 05/04/2019, TESS has completed 10 sectors, with 8 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

‘Mission’ 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.

‘Mission’ 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.

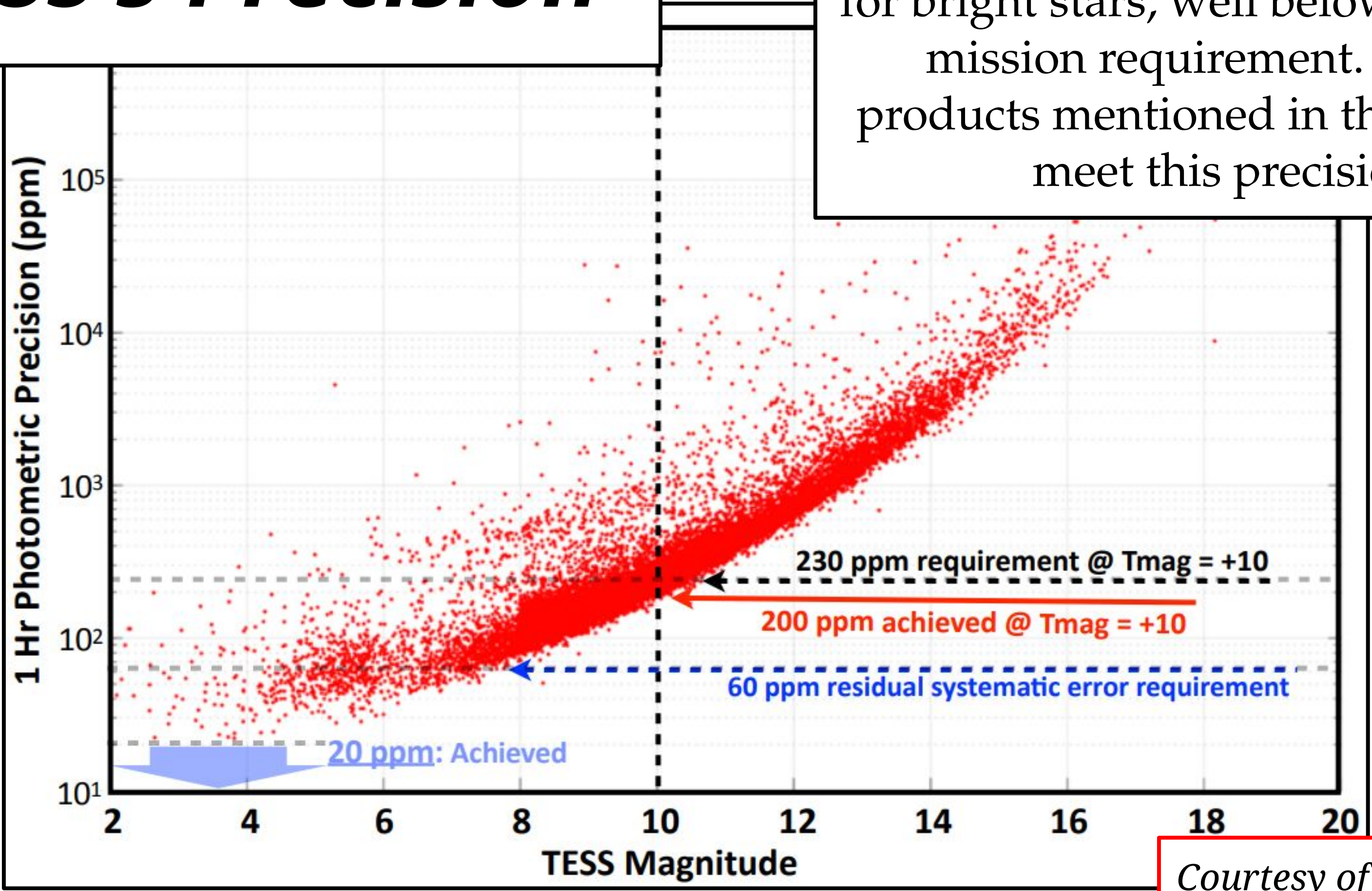
30-minu … 0-minute
cadence … uced to
light cur … n their
own.

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 pipeline 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 phot. pipeline led by MIT (Huang et al. 2018)

TASOC Pipeline: Open access 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: (

Filtergrap versity

LightKur

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

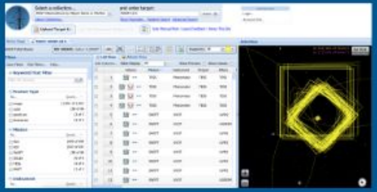
1- Search through data: MAST portal, exo.MAST, Astroquery.MAST
2- Make FFI cut-outs: TESScut

Slides adapted from a presentation by Scott Fleming

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

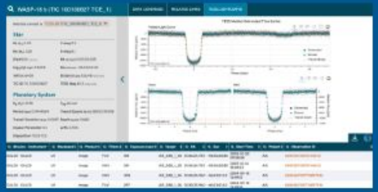
Search Tools

All Search Options TESS Search Tutorials



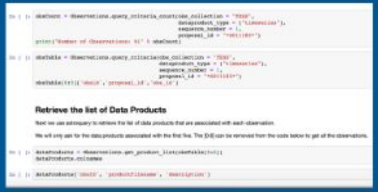
MAST Portal

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.



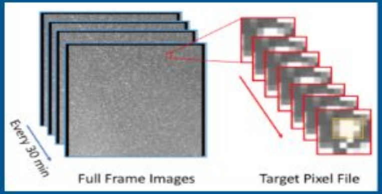
exo.MAST

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.



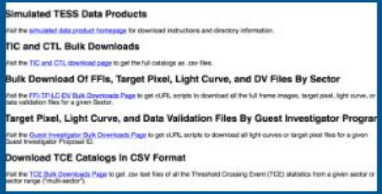
MAST Astroquery

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-8 as of 05/04/19)**

1- 2-minute light curves

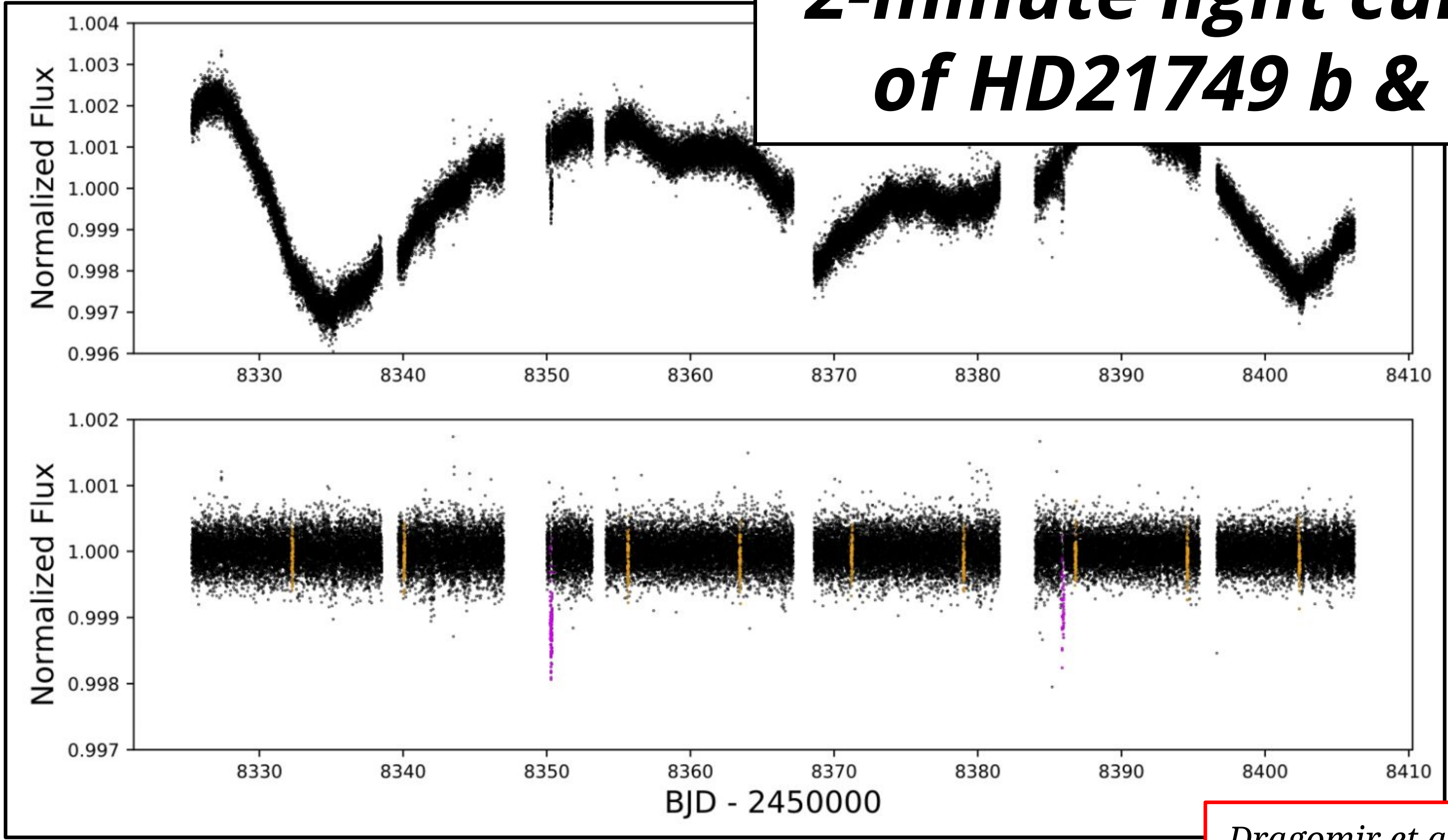
2- Data validation reports and TCE reports

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

4- Co-basis detrending vectors

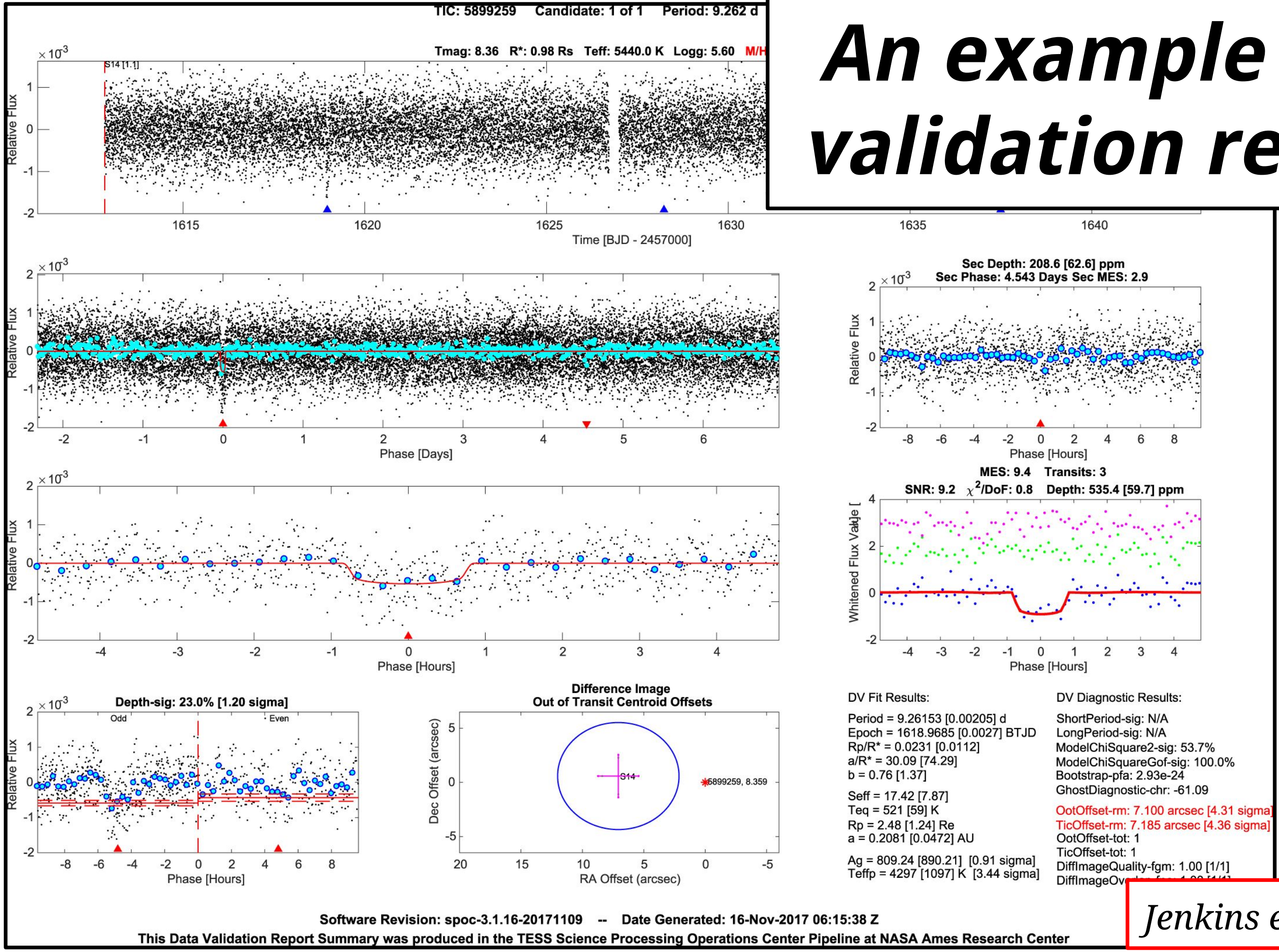
Jenkins et al. 2016 & 2018

2-minute light curve of HD21749 b & c



Dragomir et al. 2019

An example of a validation report



Jenkins et al. 2018

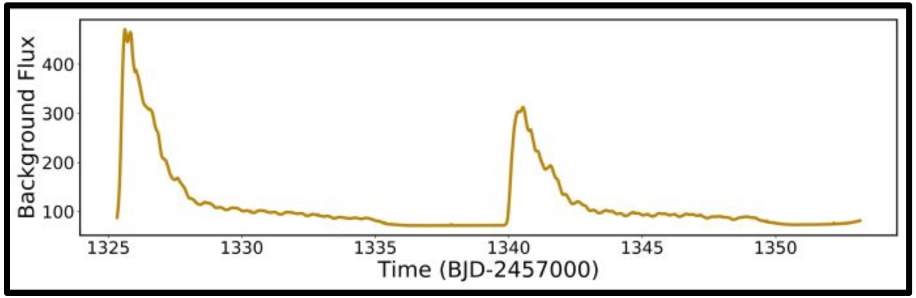
Community Generated Light Curves and Ancillary Data Products

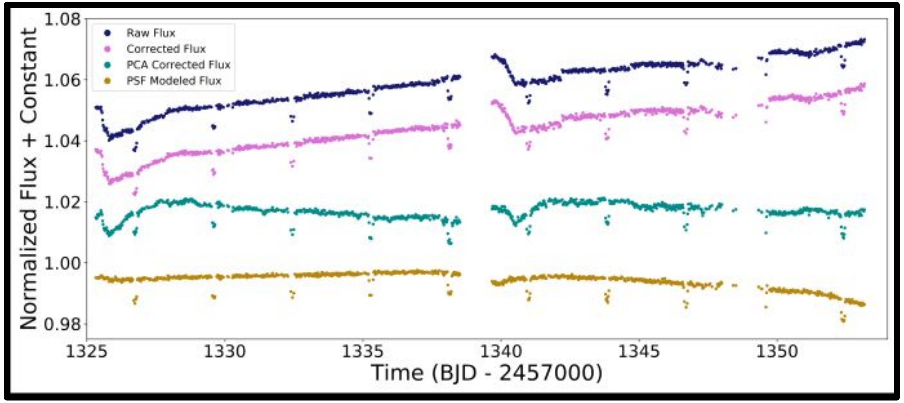
Courtesy of Adina Feinstein

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

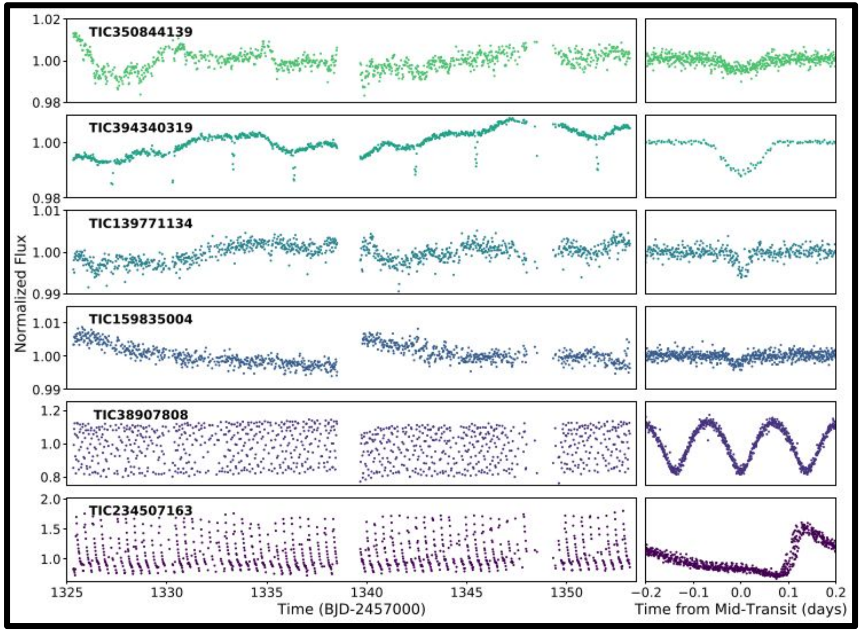




Courtesy of Adina Feinstein

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 (in IDL & Python) and scripts 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

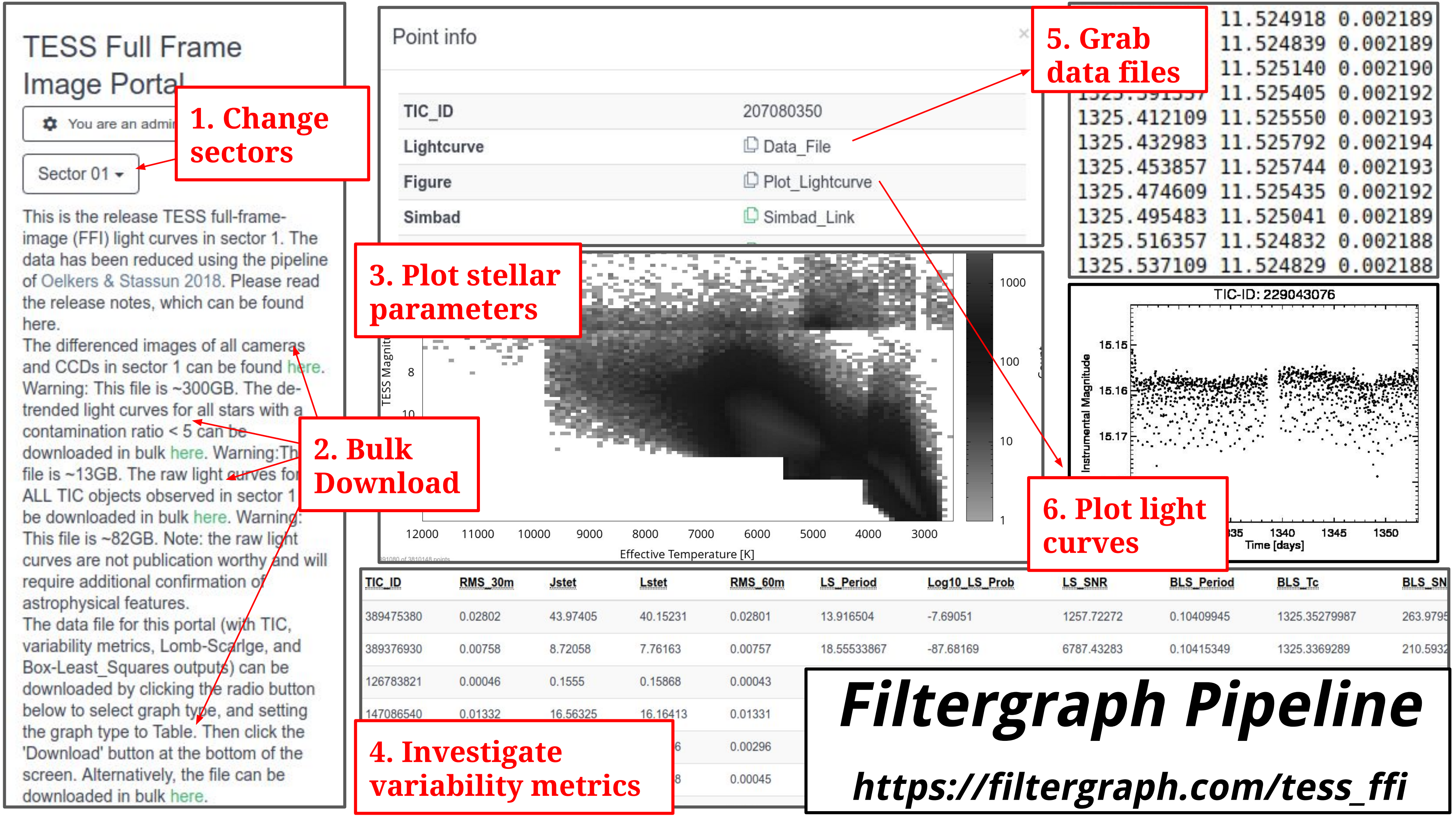
- ➔ Box-Least-Squares output from `VARTOOLS` (Kovacs+2002; Hartman & Bakos 2016)
- ➔ Lomb-Scargle output from `VARTOOLS` (Lomb 1976; Scargle 1982; Hartman & Bakos 2016)
- ➔ Welch-Stetson J & L metrics and rms on 30m and 60m timescales (Stetson 1996; Oelkers+2018)

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
1. Change sectors
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: This 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-Scarlge, 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.
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]
12000 11000 10000 9000 8000 7000 6000 5000 4000 3000
1000 100 10 1
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
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
4. Investigate variability metrics
Filtergraph Pipeline
https://filtergraph.com/tess_ffi

Filtergraph Pipeline

TOI-150b

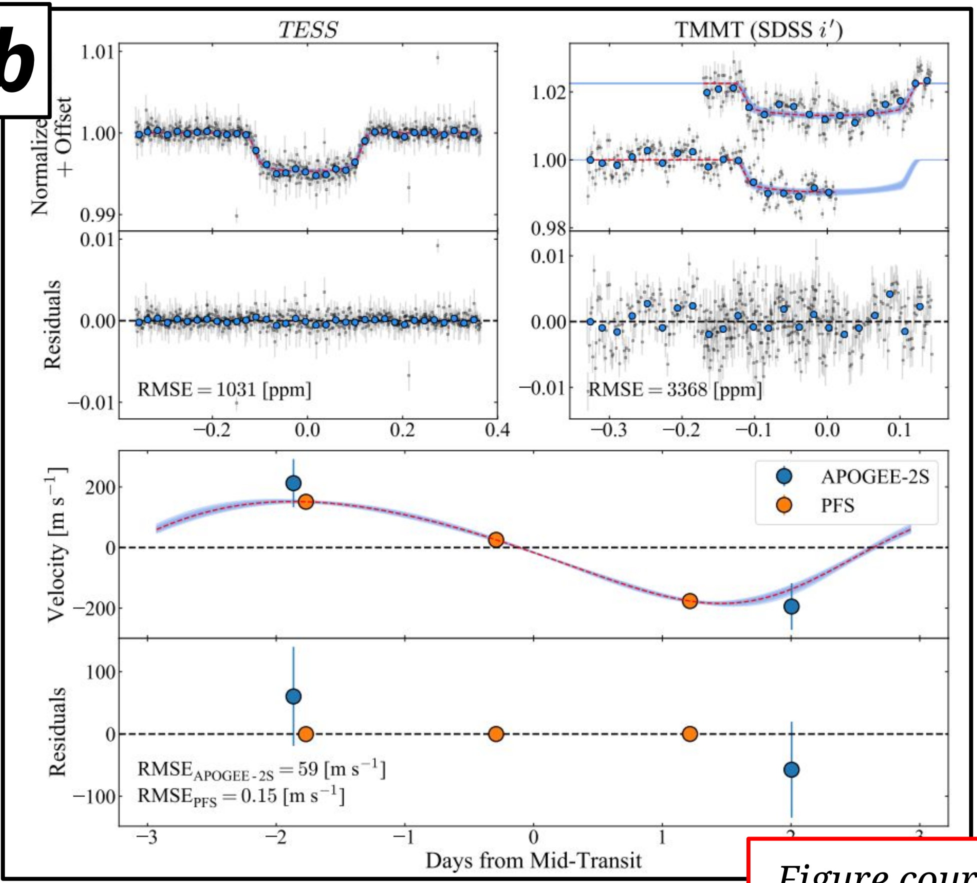


Figure courtesy of Canas et al. 2019

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');
```

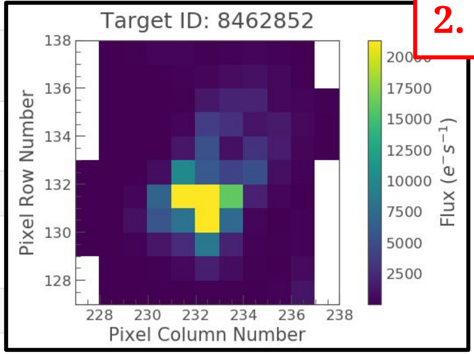
```
[2]: pixelfile.plot(frame=1);
```

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

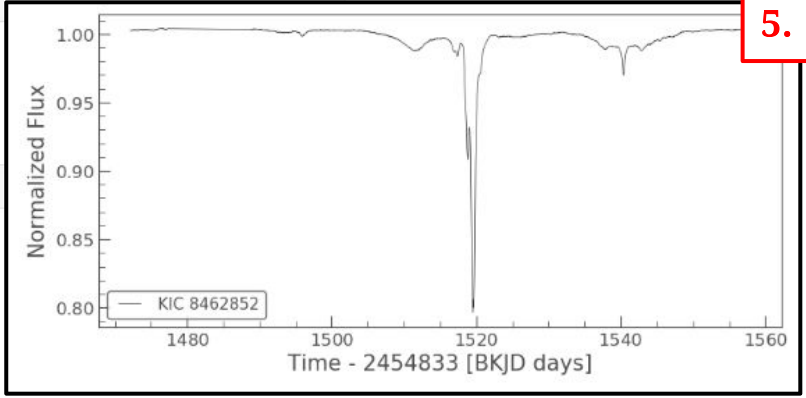
```
[4]: lc.time, lc.flux
[4]: (array([1472.11777934, 1472.13821223, 1472.15864492, ..., 1557.89718798,
             1557.9380561 , 1557.95849016]),
      array([258645.03, 258660.05, 258690.08, ..., 258929.86, 258884.66,
             258865.6 ], dtype=float32))
```

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

2.



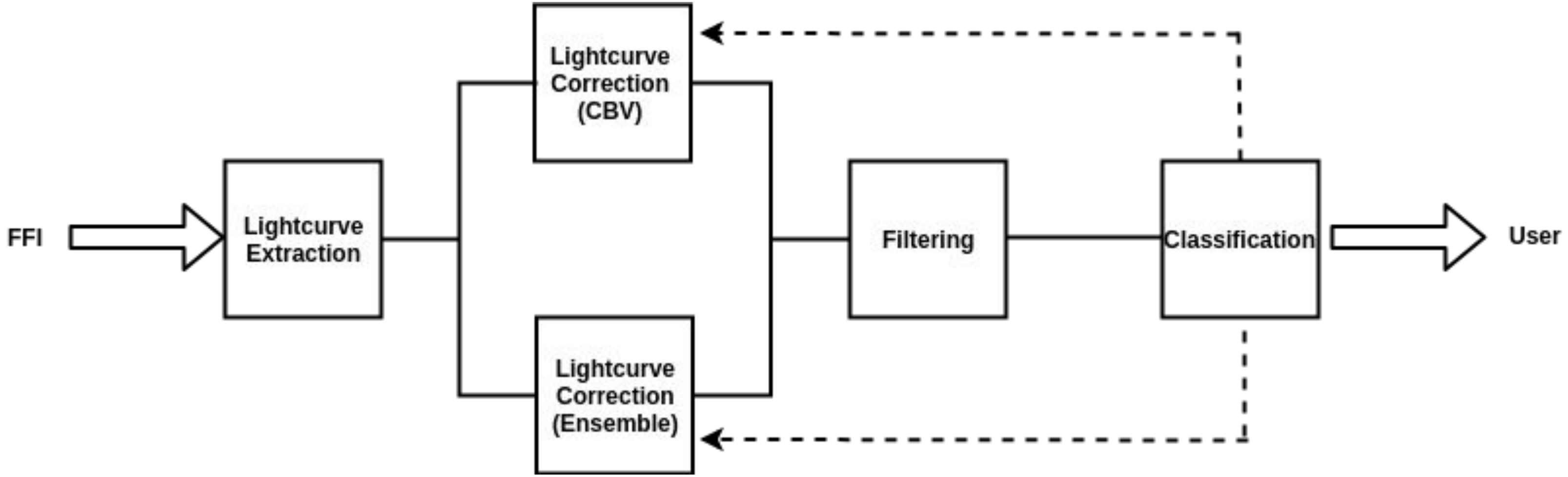
5.



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

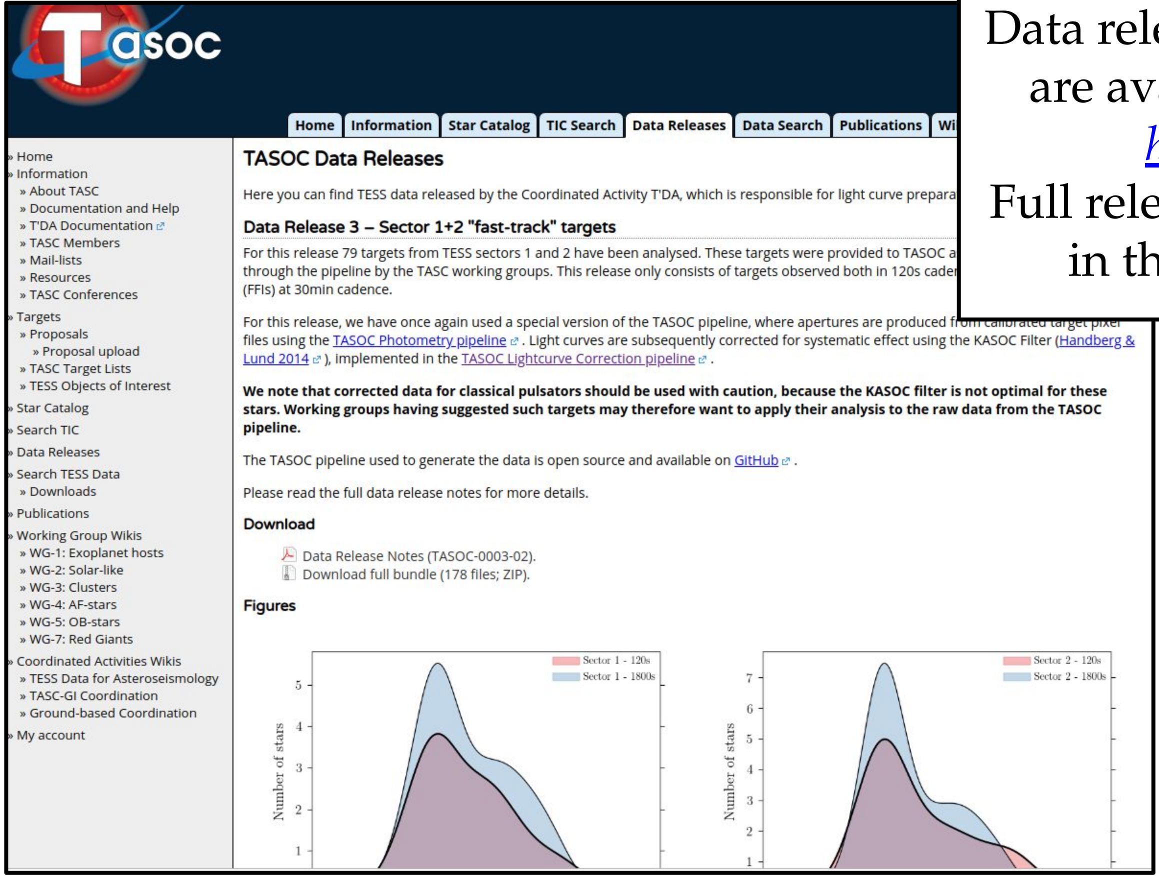
TASOC Pipeline

The pipeline is available on GitHub
https://github.com/tasoc



Slides courtesy of Derek Busazi

TASOC Pipeline

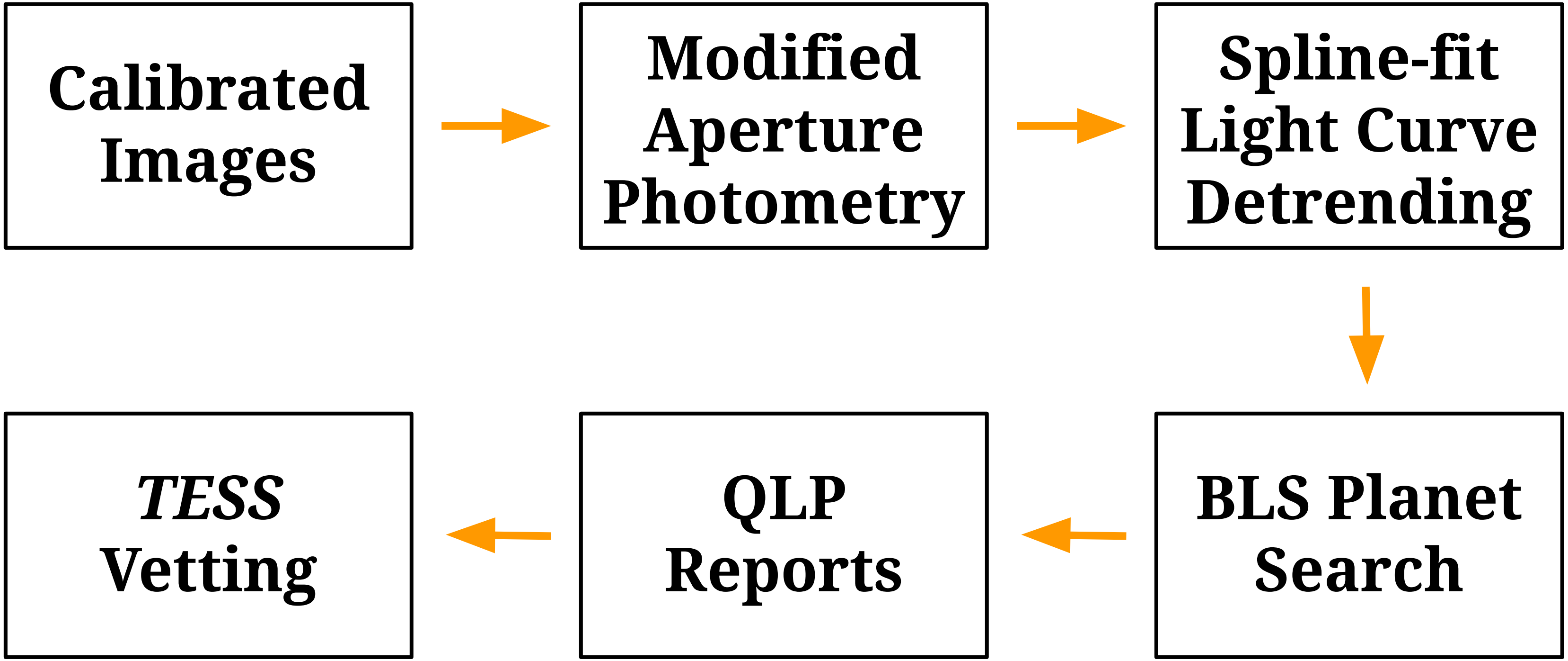


Data release for Sectors 1 & 2 are available currently at https://tasoc.dk
Full release on MAST expect in the coming weeks.

Slides courtesy of Derek Busazi
dbuzasi@fgcu.edu
@astro_derek

MIT Quick-Look Pipeline (QLP)

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

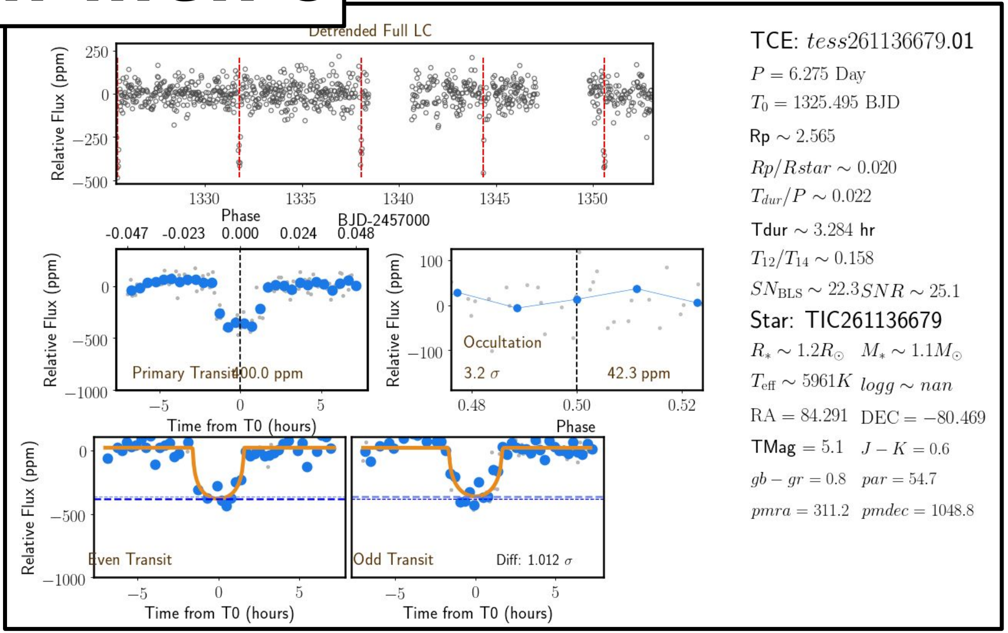


Huang et al. 2018; Slides adapted from a presentation by Lizhou Sha

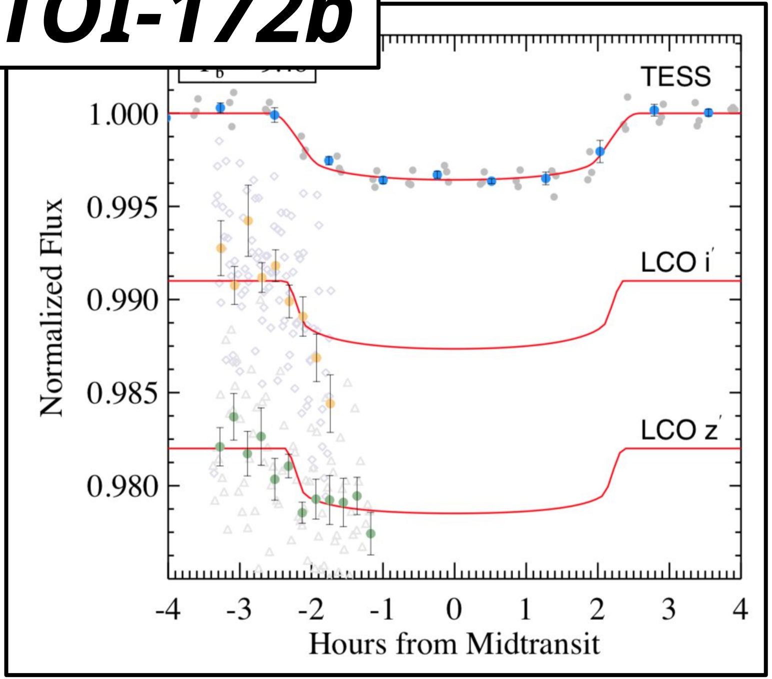
MIT Quick-Look Pipeline (QLP)

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

π Men c



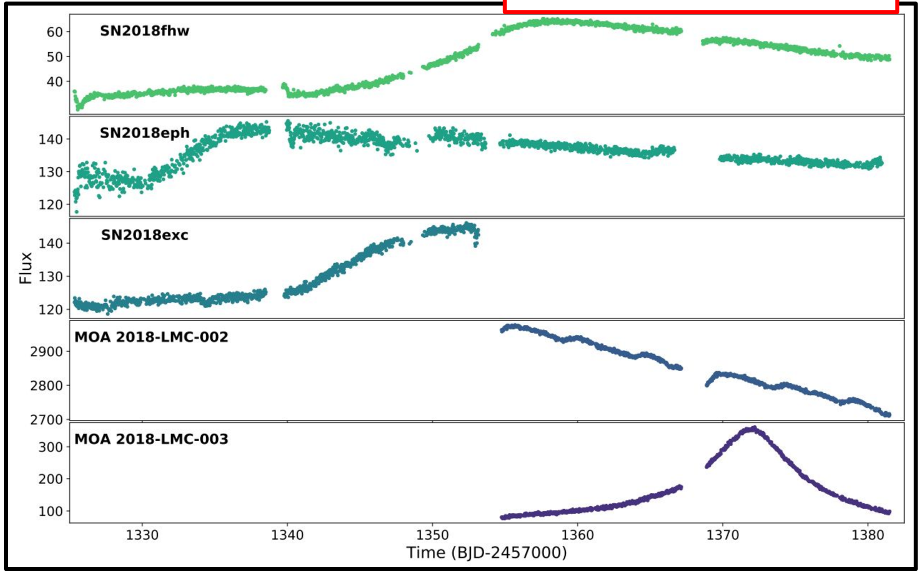
TOI-172b

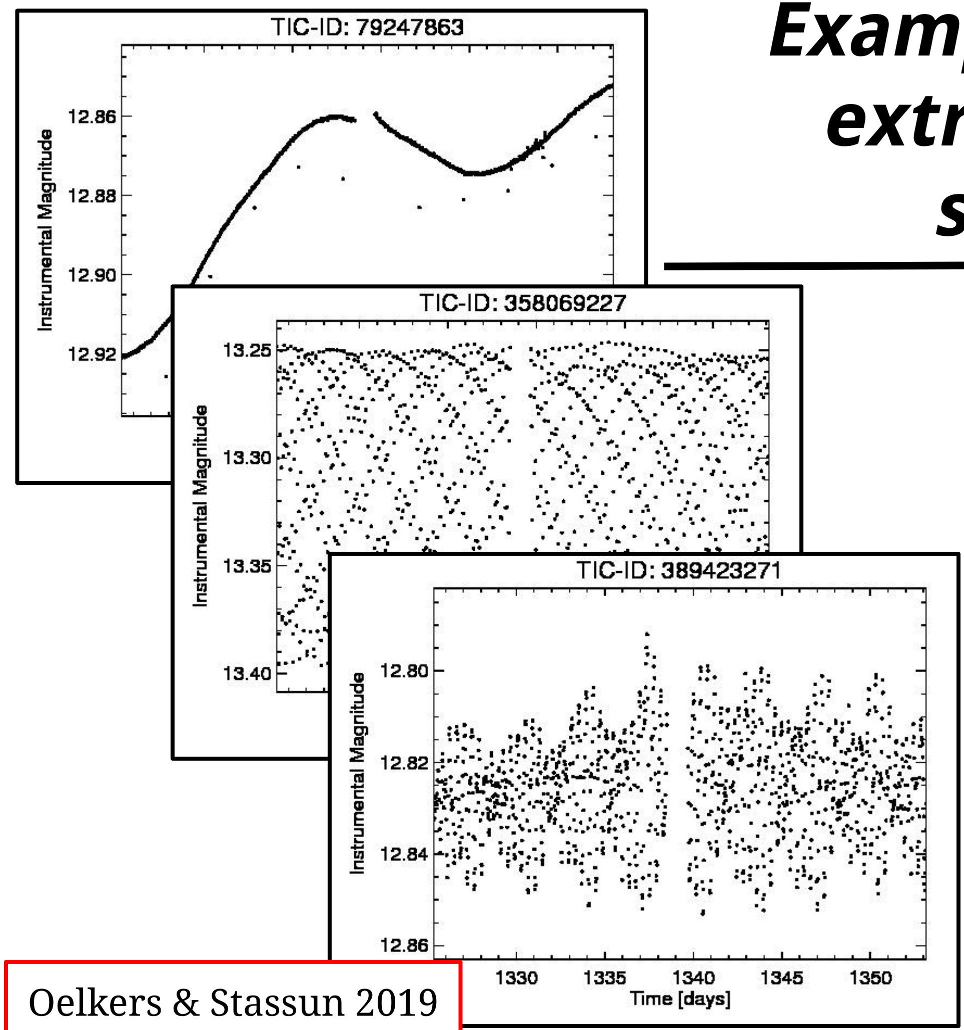


Slides adapted from a presentation by Lizhou Sha

Examples of TESS stellar and extragalactic light curves showing variability

Feinstein et al. 2019

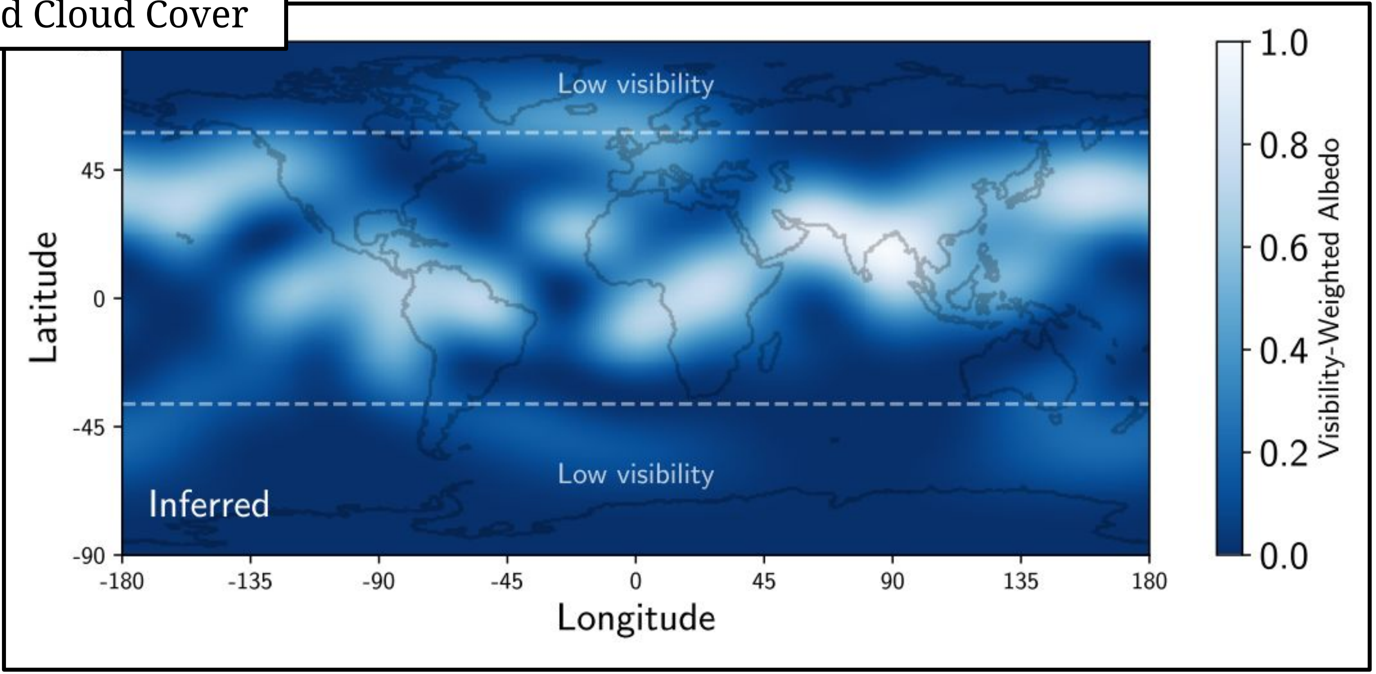




Oelkers & Stassun 2019

Photometric Mapping of a Terrestrial Planet in the Habitable Zone

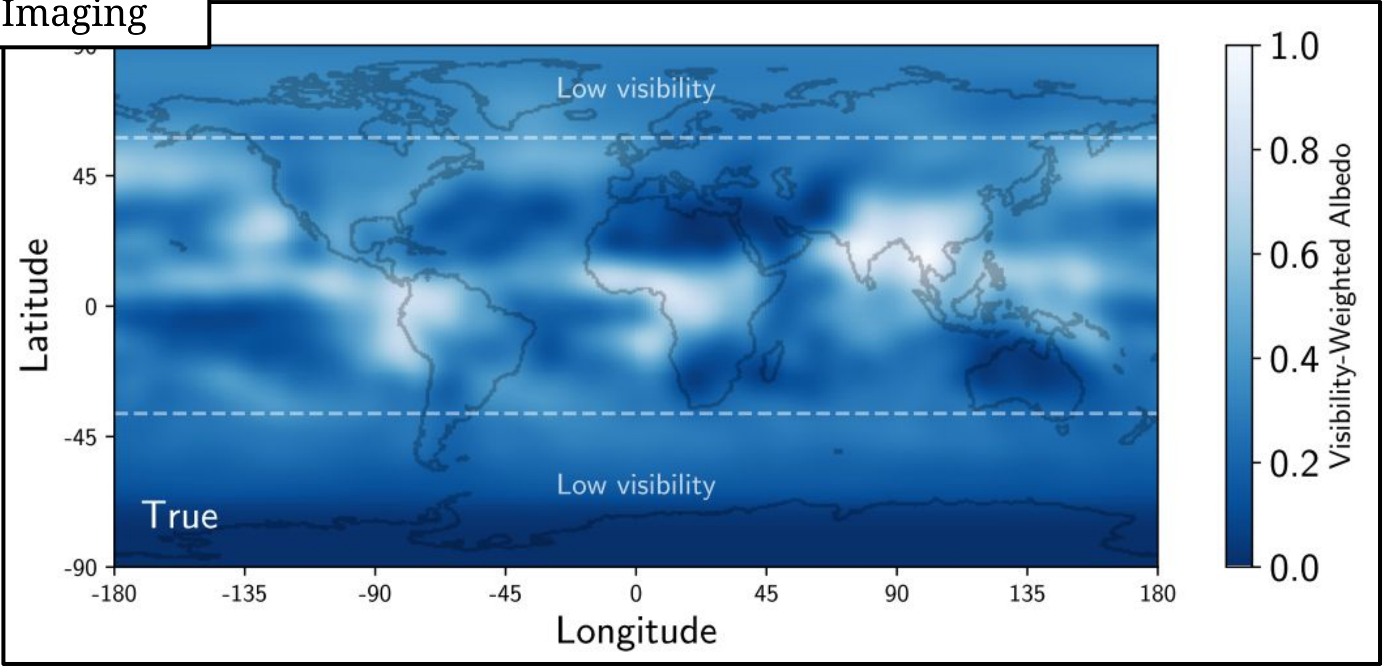
Modeled Cloud Cover



Luger et al. 2019

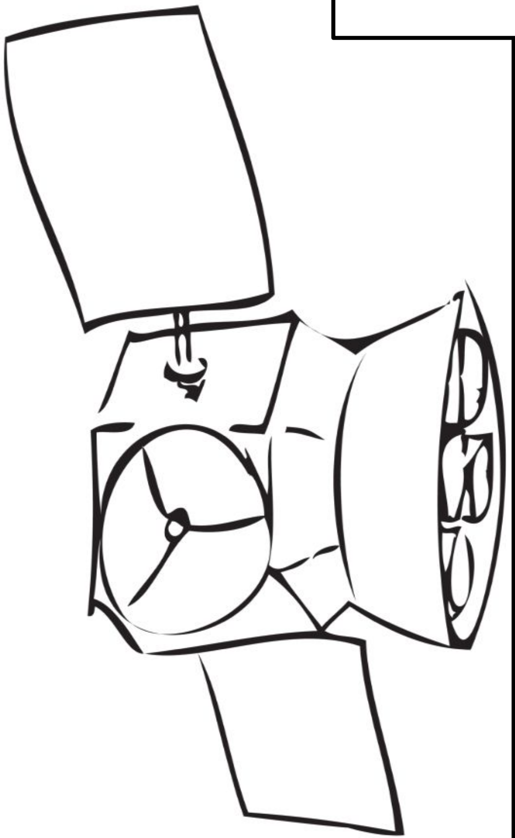
Photometric Mapping of a Terrestrial Planet in the Habitable Zone

VIIRS Imaging



Luger et al. 2019

Summary



TESS is currently observing in Sector 11, with 8 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!