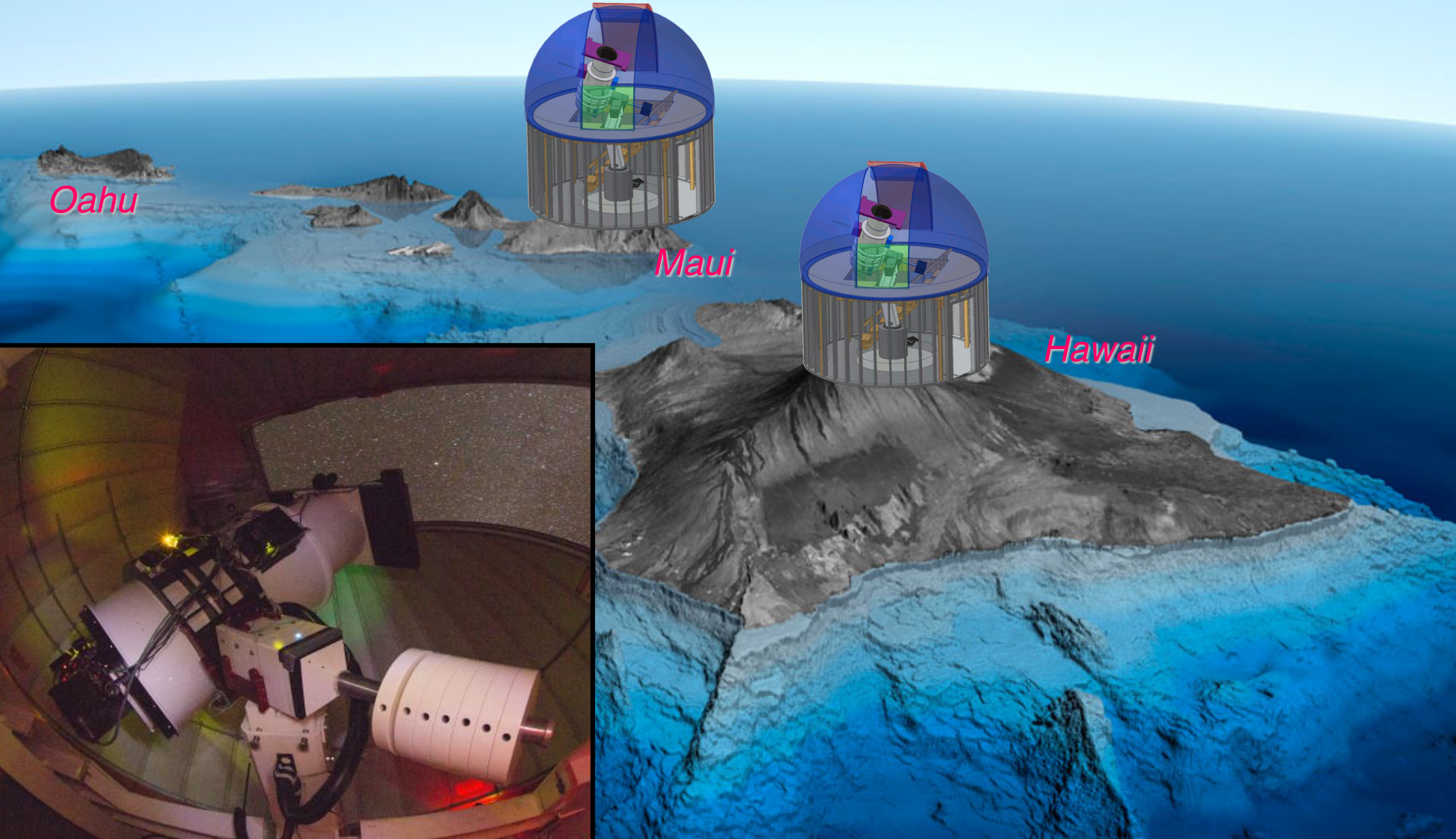
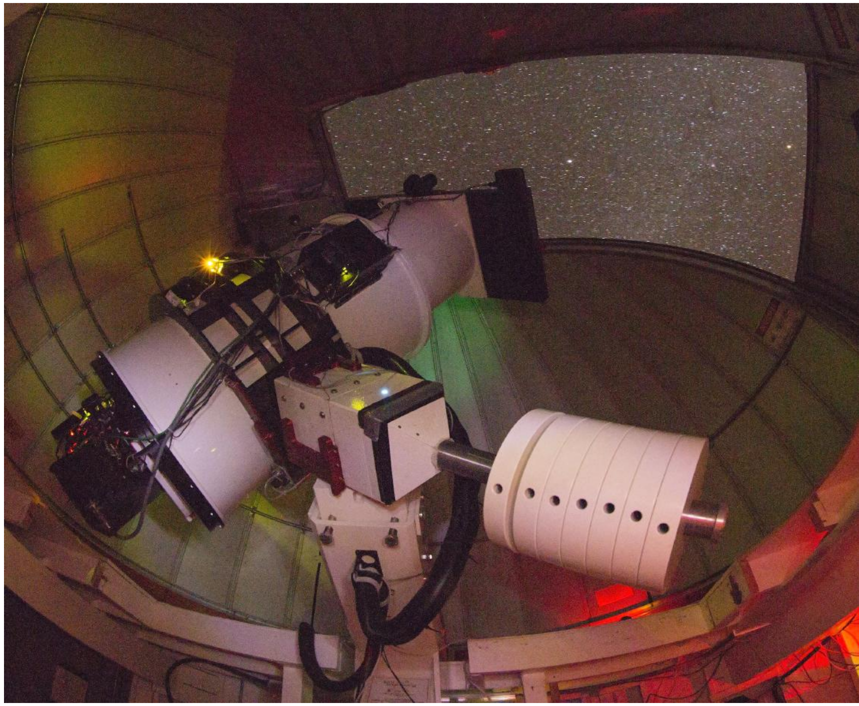
ATLAS



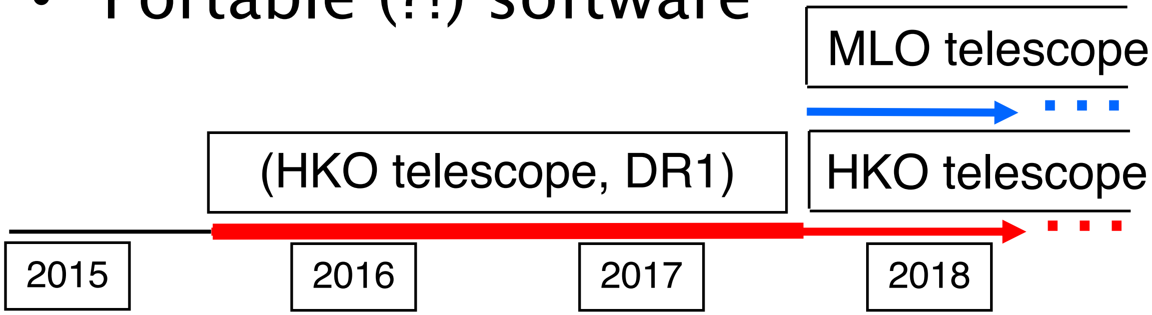
Why Survey the Sky?

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

ATLAS in a Nutshell

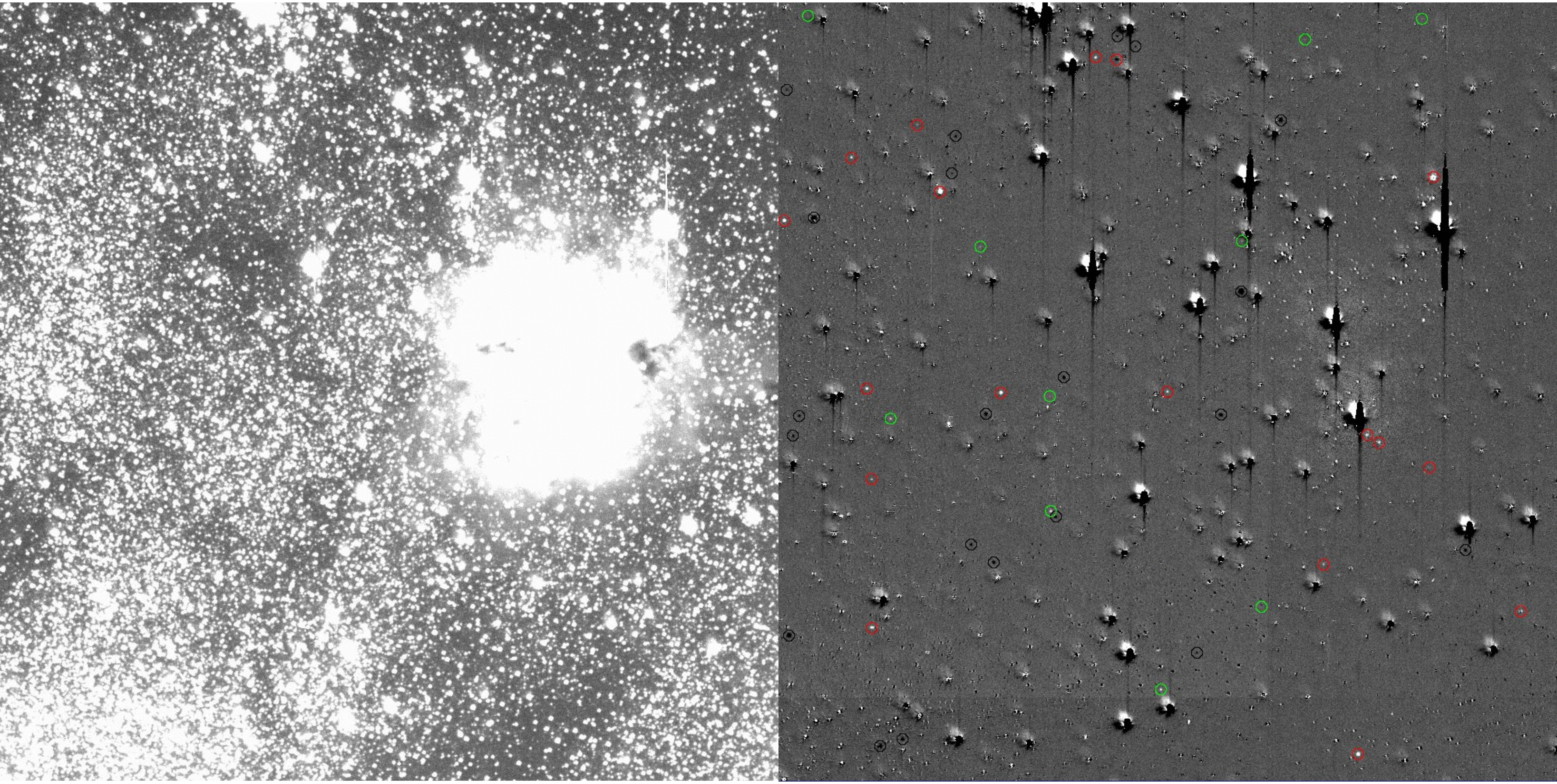


- Domes (Ash) on HKO, MLO
- German mounts (APM)
- 0.5m telescopes (DFM)
  - f/2 Schmidt
  - 8 filters (co, uvgri, BVRI, Hα,[OIII])
- 10k cameras (IFA/STA)
  - 1.86” pixels, 5.4°x5.4° field of view
- 50Mb/s ethernet
- 50,000 deg^2/nt (4xsky/2) to m~19.5 in c (g+r) or o (r+i)
- Computers totaling >1PB,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



Tonry et al. 2018, PASP.
arXiv:1802.00879

Autonomous operation, reduction, and analysis



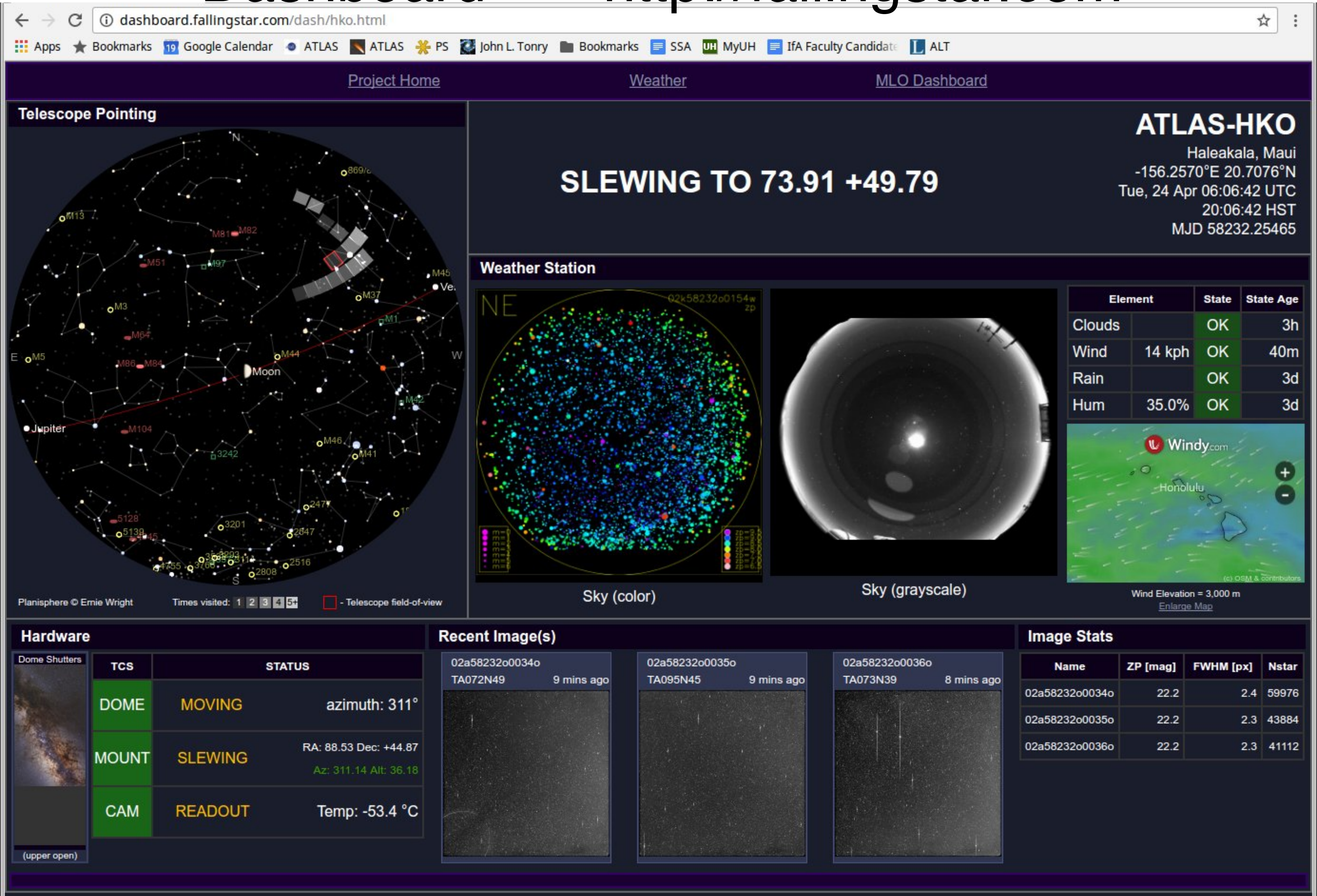
- 2 x 1,000 image = 0.5 TB per night
- 700,000 images to date
- Fully robotic system
- Gaia astrometry, Pan-STARRS photometry

○ Known asteroid

○ Variable (pos)

○ Variable (neg)

Dashboard - http://fallingstar.com



Telescope Pointing

Planisphere © Ernie Wright

Times visited: 1 2 3 4 5+

☐ - Telescope field-of-view

SLEWING TO 73.91 +49.79

ATLAS-HKO

Haleakala, Maui
-156.2570°E 20.7076°N
Tue, 24 Apr 06:06:42 UTC
20:06:42 HST
MJD 58232.25465

Weather Station

Sky (color)

Sky (grayscale)

Element		State	State Age
Clouds		OK	3h
Wind	14 kph	OK	40m
Rain		OK	3d
Hum	35.0%	OK	3d

Wind Elevation = 3,000 m
Enlarge Map

Hardware

Dome Shutters
(upper open)

TCS	STATUS	
DOME	MOVING	azimuth: 311°
MOUNT	SLEWING	RA: 88.53 Dec: +44.87 Az: 311.14 Alt: 36.18
CAM	READOUT	Temp: -53.4 °C

Recent Image(s)

02a58232o0034o
TA072N49 9 mins ago

02a58232o0035o
TA095N45 9 mins ago

02a58232o0036o
TA073N39 8 mins ago

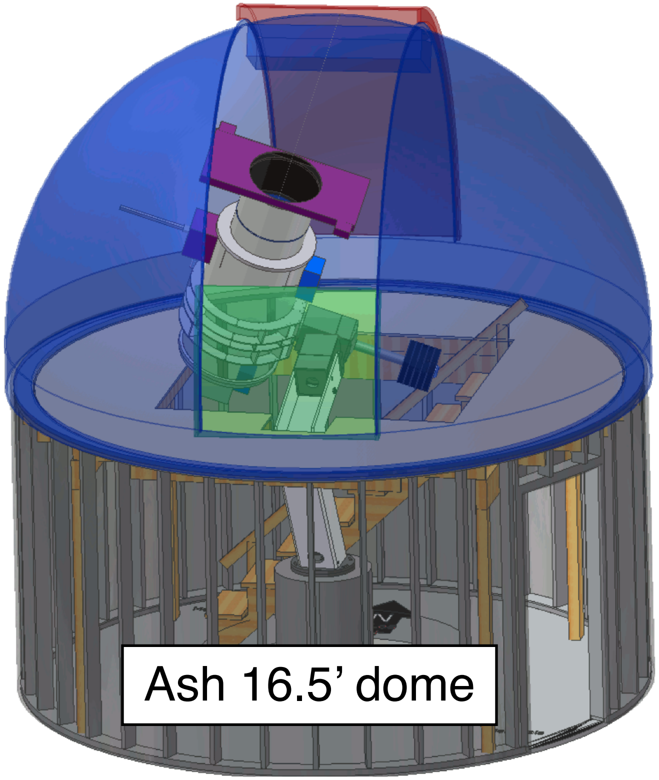
Image Stats

Name	ZP [mag]	FWHM [px]	Nstar
02a58232o0034o	22.2	2.4	59976
02a58232o0035o	22.2	2.3	43884
02a58232o0036o	22.2	2.3	41112

ATLAS DETAILS

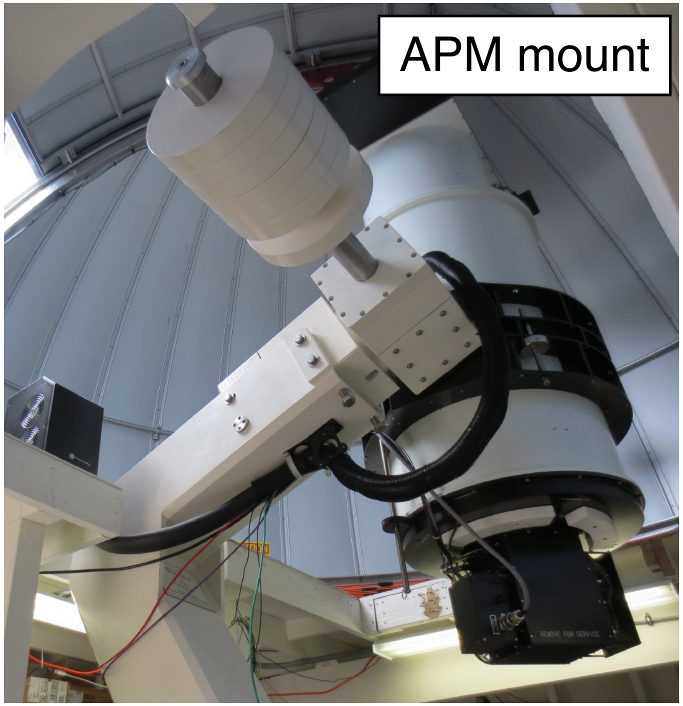
Lots of details about hardware and software

Enclosures and Mounts



Ash 16.5' dome

Haleakala

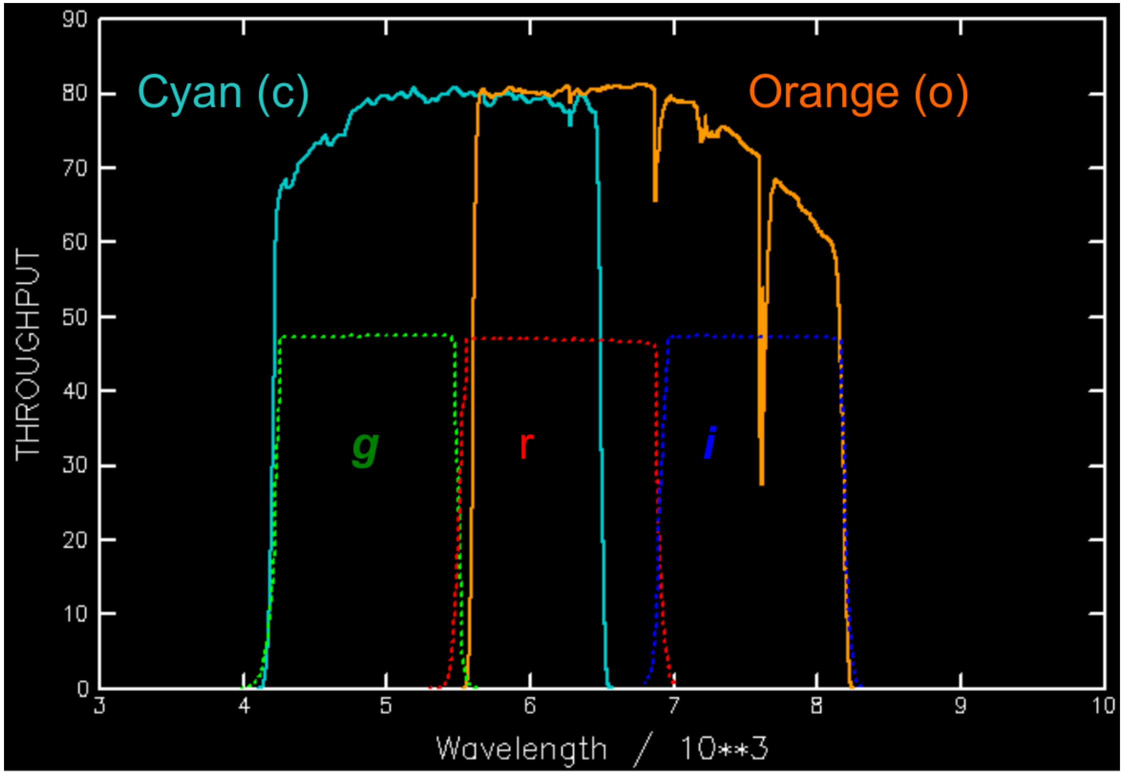


APM mount

Mauna Loa

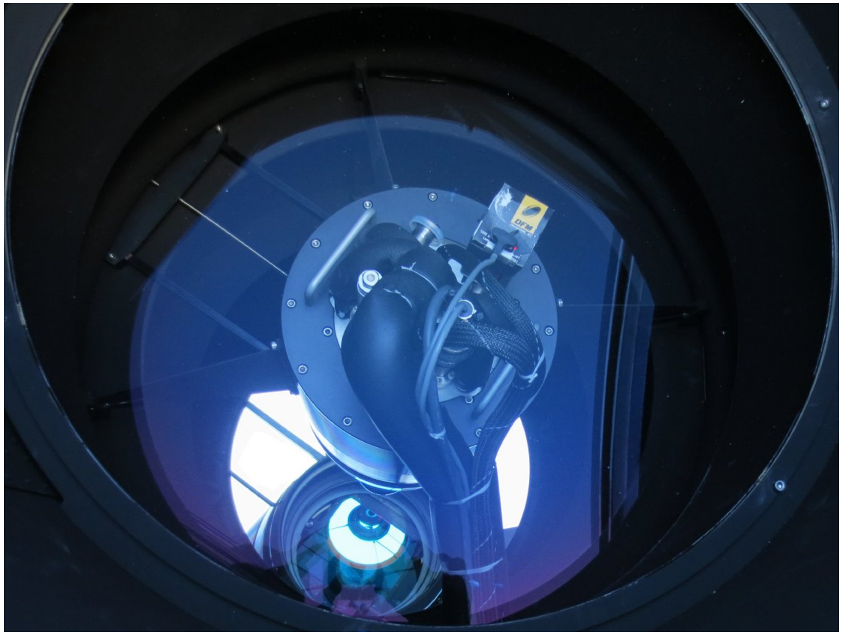
Filters

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



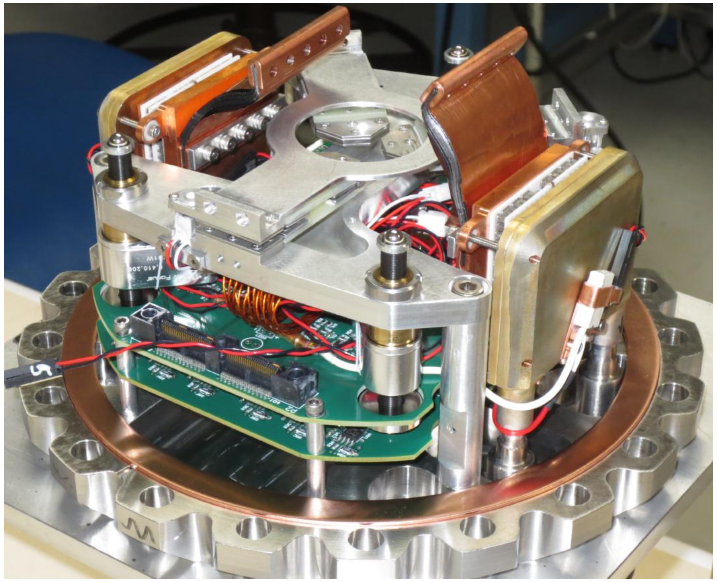
Telescopes and Cameras

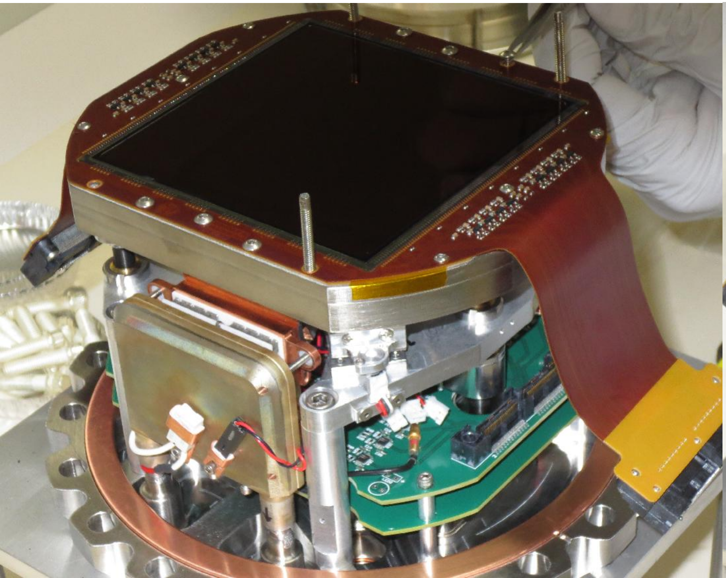
- DFM telescopes
  - 0.5m f/2 Schmidt telescope gives 1.86” per pixel over 8° field without vignetting
  - PSF is ~2 pixels; m_{lim}~19.5 in 30 sec exposure
- Acam
  - STA-1600: 110 Mpixel, 10e- read noise, ~8 sec readout, good QE, good cosmetics
  - TEC cooling to <-50°C, negligible dark current
  -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

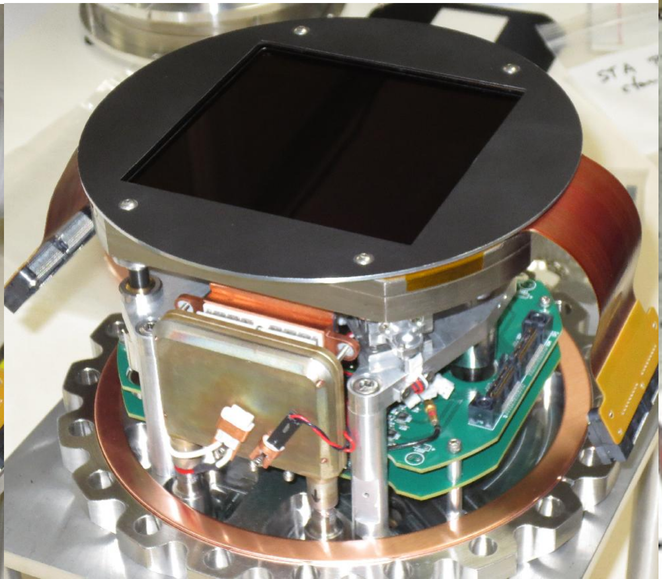


Acam

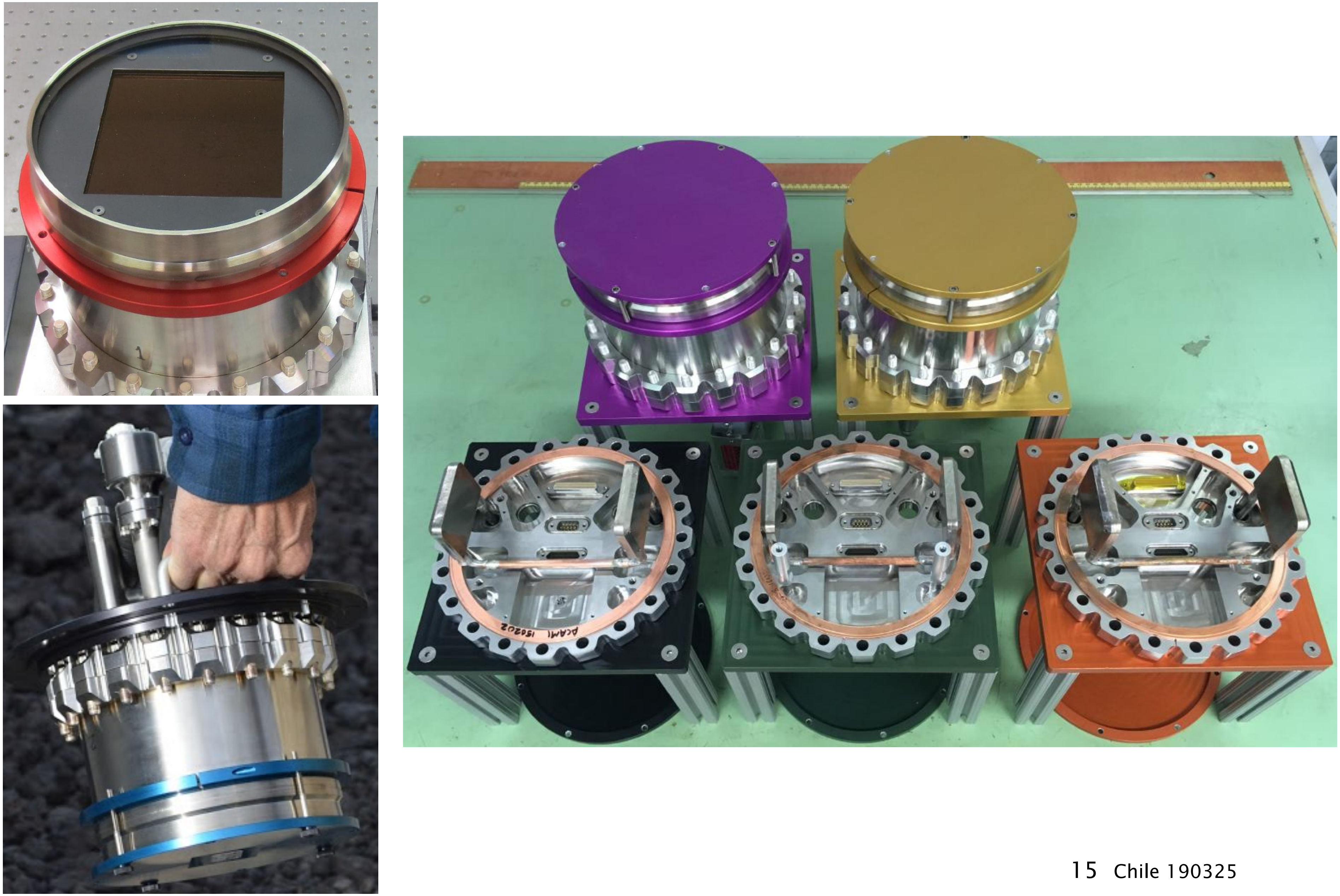
- All metal: no pumping required
- Buffer PCBs: no interference
- TEC cooling
- Picomotors
- Large area to volume ratio



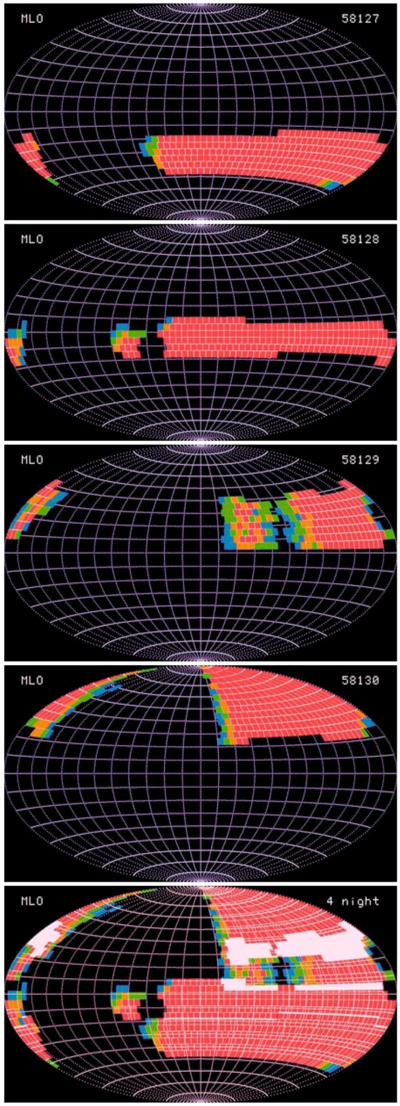




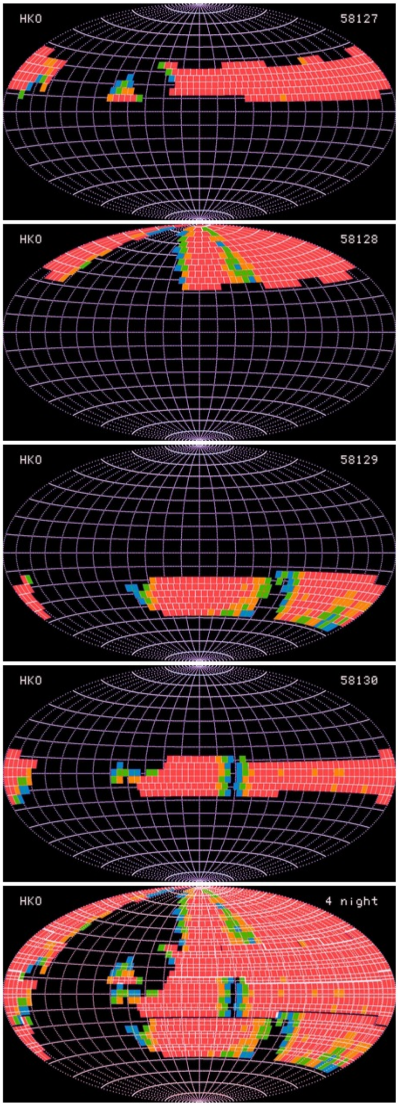
Five More Cryostats Ready for a Home…



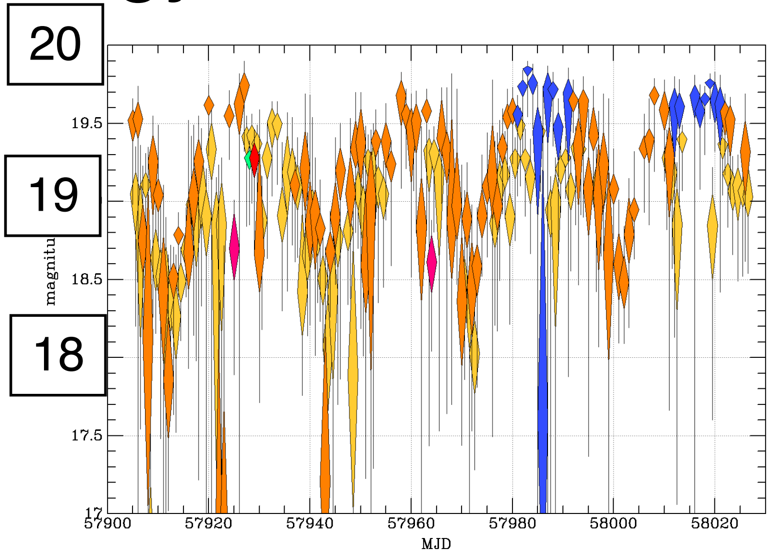
Survey Strategy



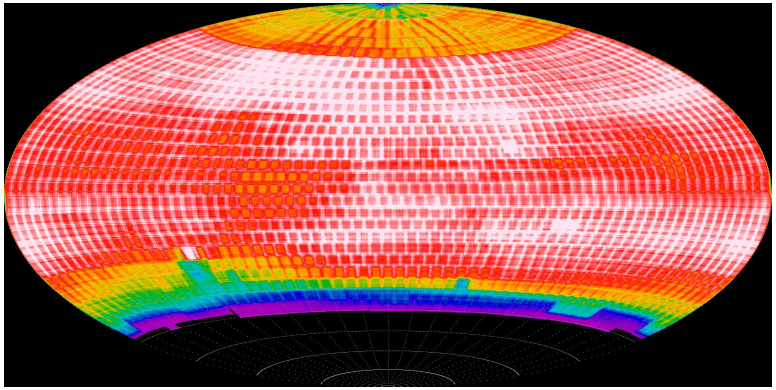
4 Nights MLO
(red=4 visits)



4 Nights HKO
(red=4 visits)



Limiting Magnitude (4 months)



Sky coverage to date
(red=500 visits)

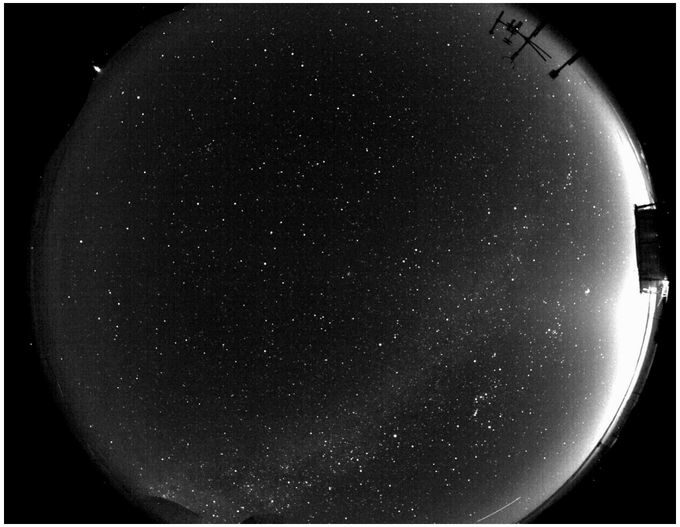
Auxiliary Camera #1

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

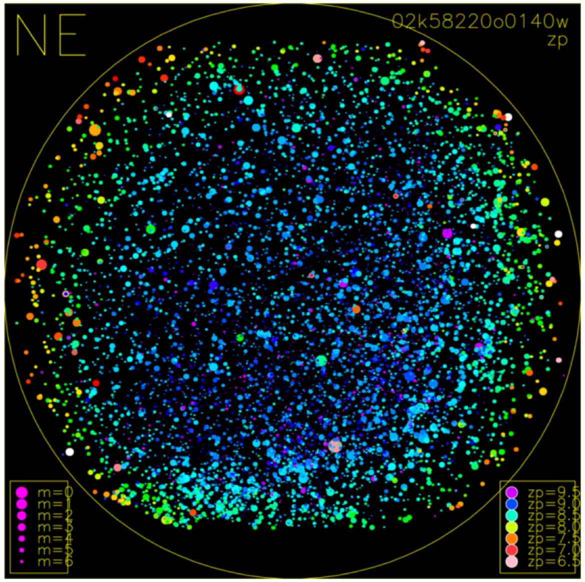
Auxiliary Camera #2

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

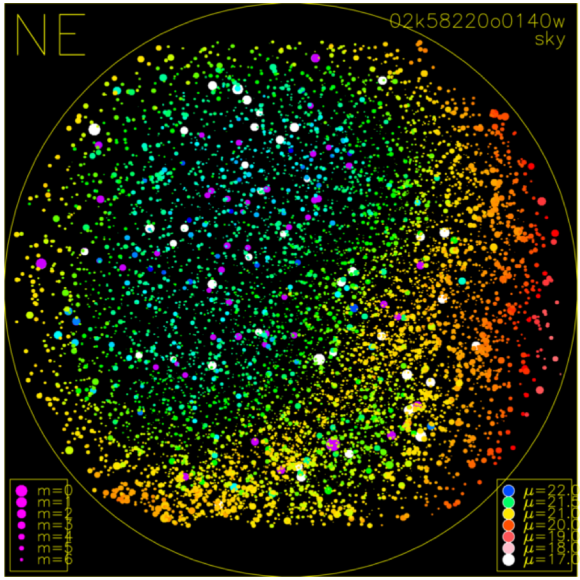
Image



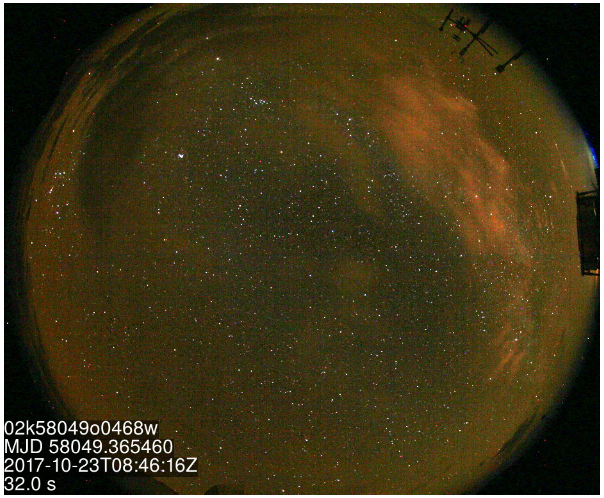
Zeropoint

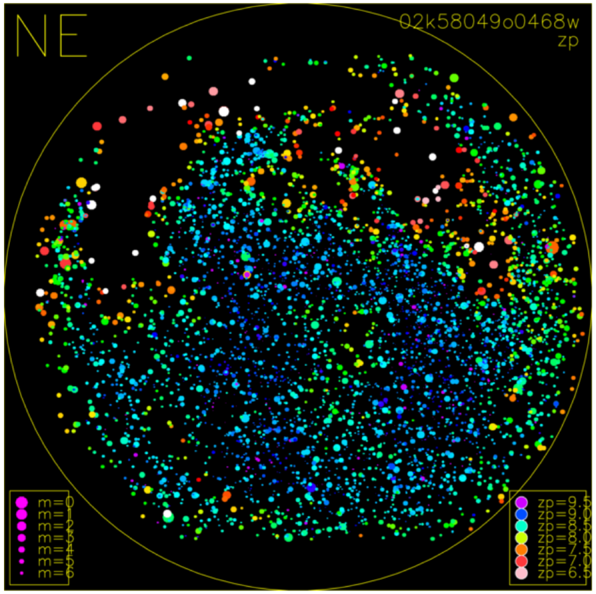


Sky Brightness

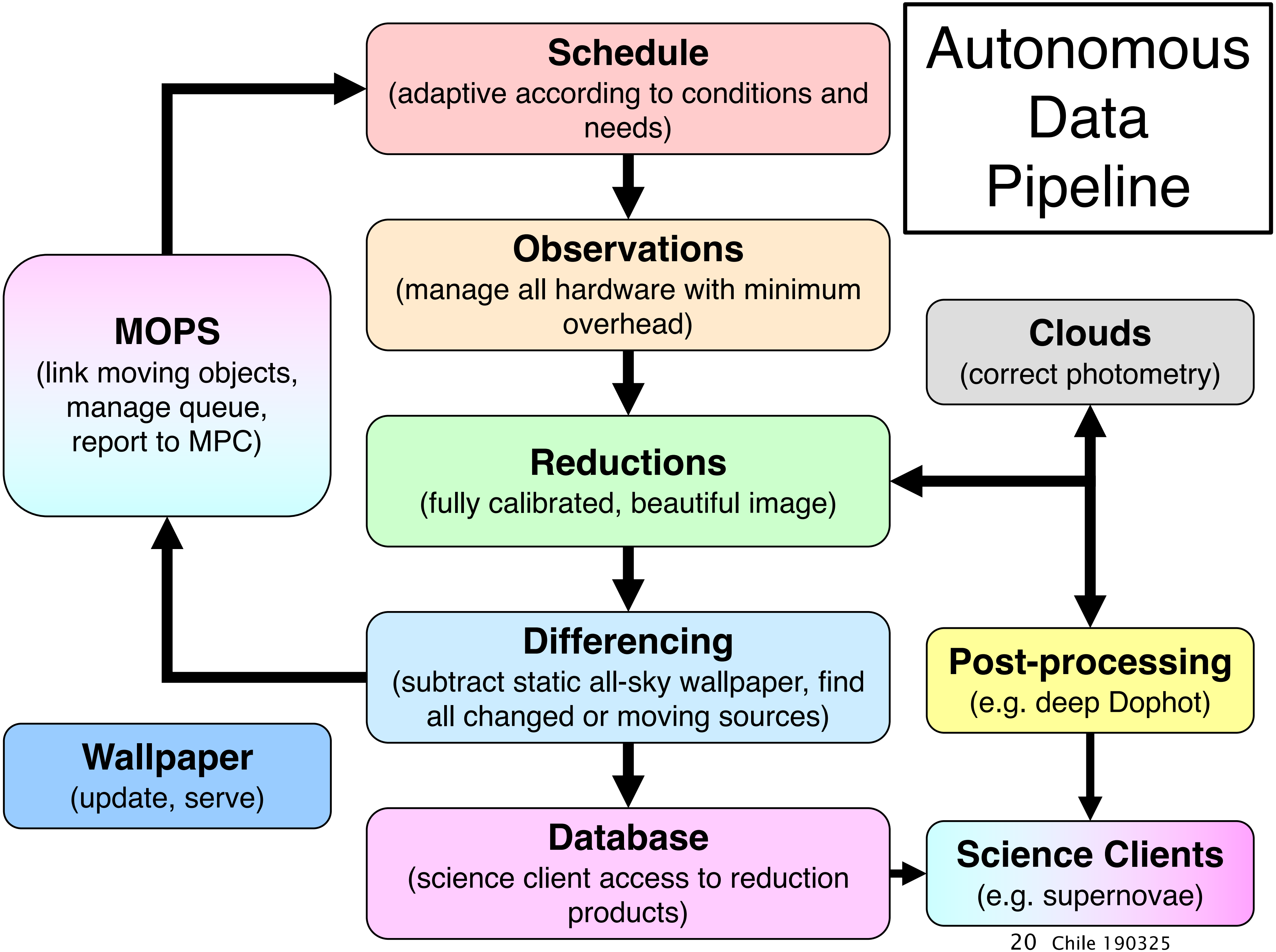


Photometric all-sky measurement





Autonomous Data Pipeline



Schedule
(adaptive according to conditions and needs)

Observations
(manage all hardware with minimum overhead)

Reductions
(fully calibrated, beautiful image)

Differencing
(subtract static all-sky wallpaper, find all changed or moving sources)

Database
(science client access to reduction products)

MOPS
(link moving objects, manage queue, report to MPC)

Wallpaper
(update, serve)

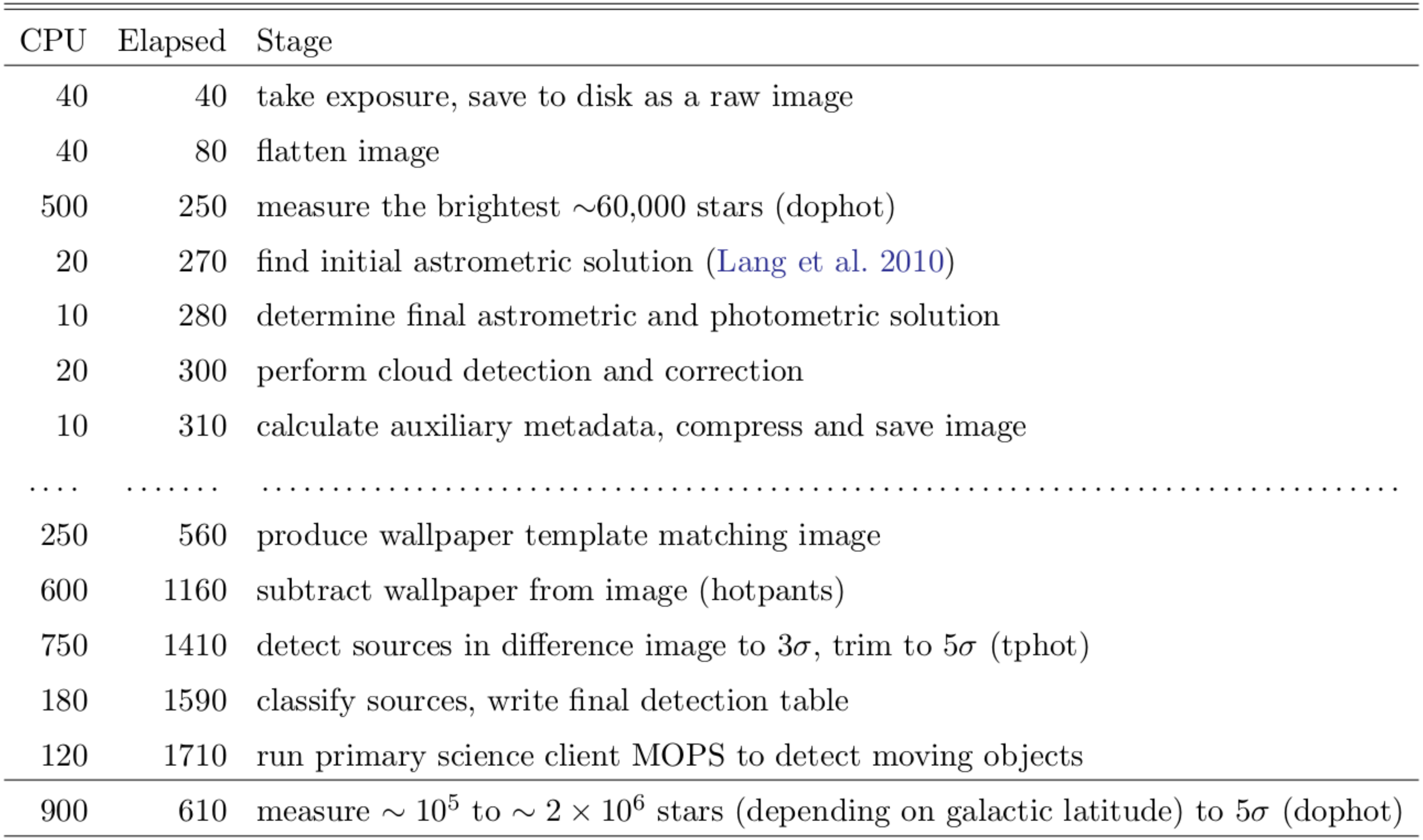
Clouds
(correct photometry)

Post-processing
(e.g. deep Dophot)

Science Clients
(e.g. supernovae)

Processing Time and Latency

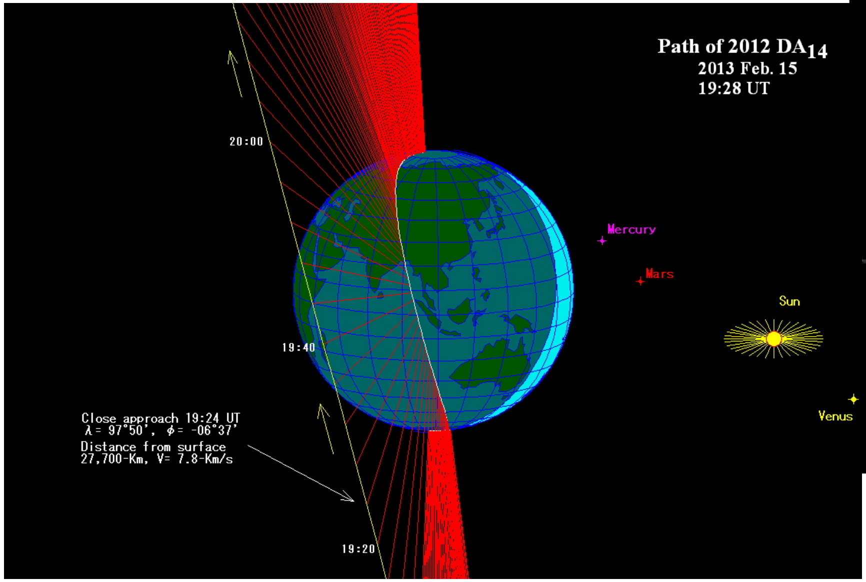
- Latency from shutter open to final results ~30 minutes
- Latency from start of quad exposure to asteroid warning ~90 minutes

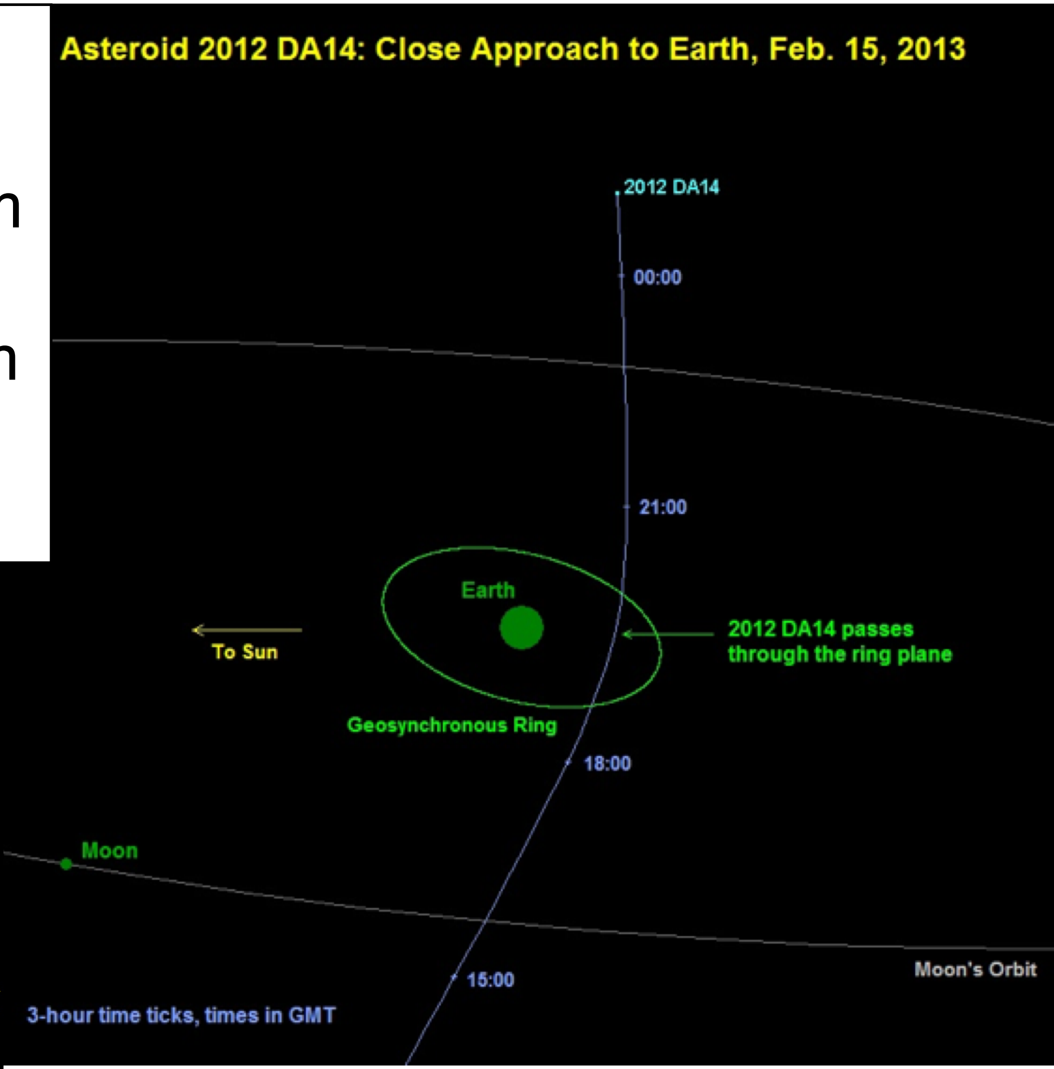


CPU	Elapsed	Stage
40	40	take exposure, save to disk as a raw image
40	80	flatten image
500	250	measure the brightest ~60,000 stars (dophot)
20	270	find initial astrometric solution (Lang et al. 2010)
10	280	determine final astrometric and photometric solution
20	300	perform cloud detection and correction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

2012 DA 14: 2013-Feb-15

- 30m diameter (2Mton TNT)
- Closest approach 28,000km = 4.4 R_E
- Orbital period changed from 368 to 317 days





Chelyabinsk: 2013-Feb-15

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

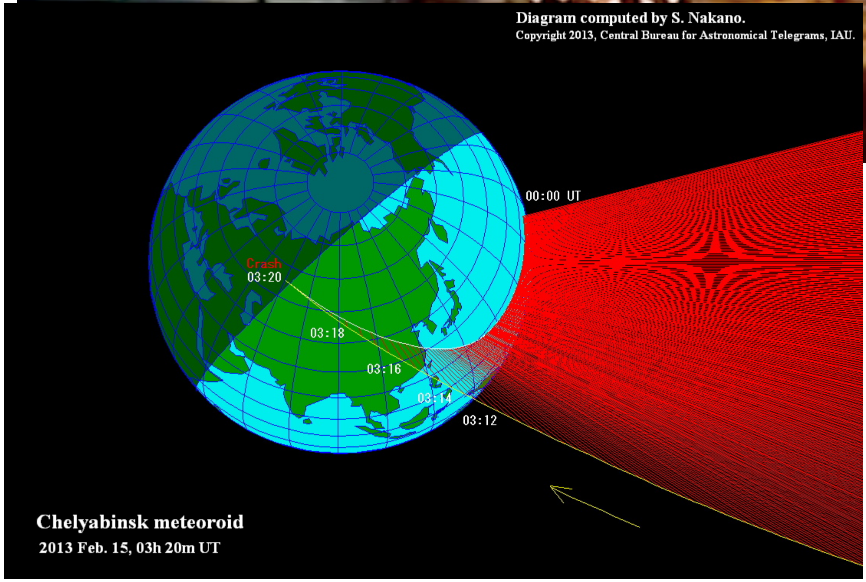
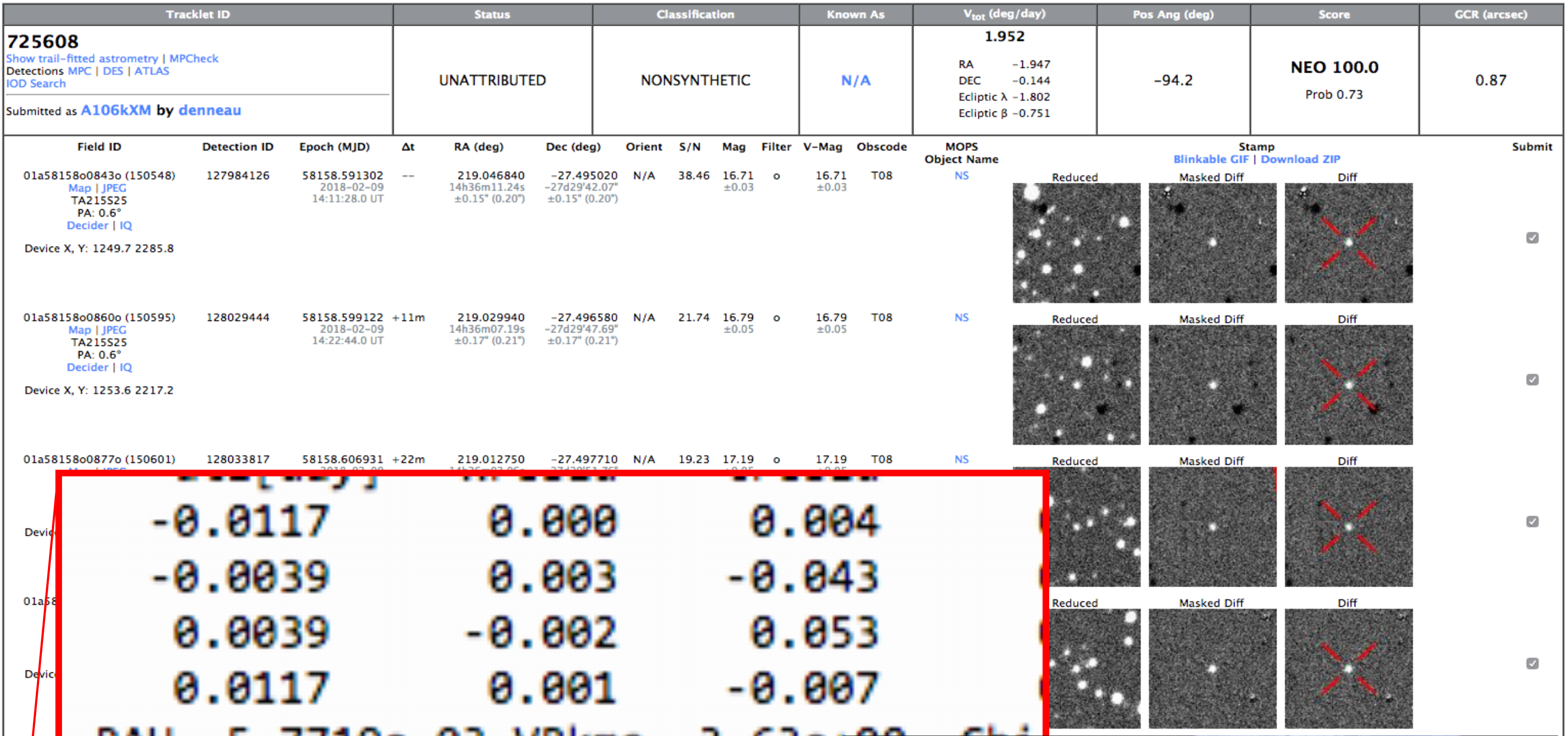


Diagram computed by S. Nakano.
Copyright 2013, Central Bureau for Astronomical Telegrams, IAU.



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

Field ID	Detection ID	Epoch (MJD)	Δt	RA (deg)	Dec (deg)	Orient	S/N	Mag	Filter	V-Mag	Obscode	MOPS Object Name	Stamp Blinkable GIF | Download ZIP	Submit
01a58158o0843o (150548) Map | JPEG TA215S25 PA: 0.6° Decider | IQ Device X, Y: 1249.7 2285.8	127984126	58158.591302 2018-02-09 14:11:28.0 UT	--	219.046840 14h36m11.24s ±0.15" (0.20")	-27.495020 -27d29'42.07" ±0.15" (0.20")	N/A	38.46	16.71 ±0.03	o	16.71 ±0.03	T08	NS	Reduced | Masked Diff | Diff	☑
01a58158o0860o (150595) Map | JPEG TA215S25 PA: 0.6° Decider | IQ Device X, Y: 1253.6 2217.2	128029444	58158.599122 2018-02-09 14:22:44.0 UT	+11m	219.029940 14h36m07.19s ±0.17" (0.21")	-27.496580 -27d29'47.69" ±0.17" (0.21")	N/A	21.74	16.79 ±0.05	o	16.79 ±0.05	T08	NS	Reduced | Masked Diff | Diff	☑
01a58158o0877o (150601) Devi	128033817	58158.606931	+22m	219.012750	-27.497710	N/A	19.23	17.19	o	17.19	T08	NS	Reduced | Masked Diff | Diff	☑
01a58 Devic													Reduced | Masked Diff | Diff	☑

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

Analy
Full resul

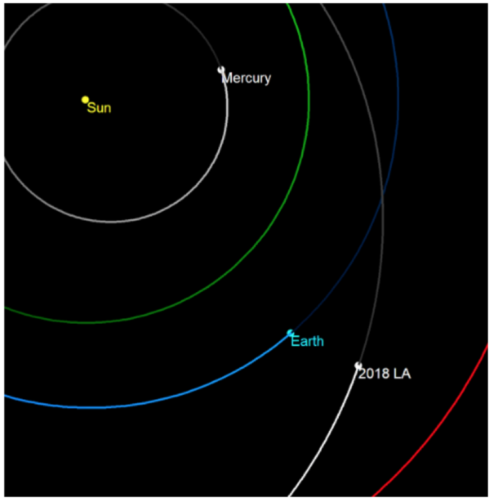
```
MPC Di
Desig.
T72560


MOPS D
Desig.
MT0000

SSORB

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

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

72
Obj

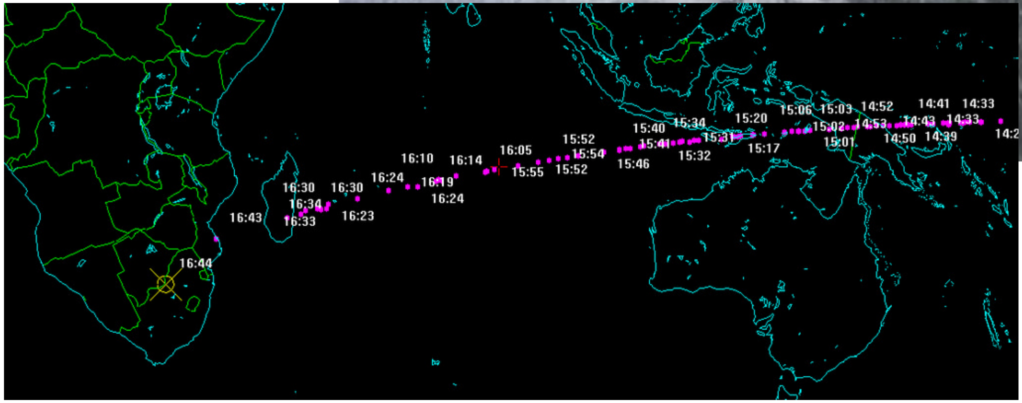
2018 LA

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

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

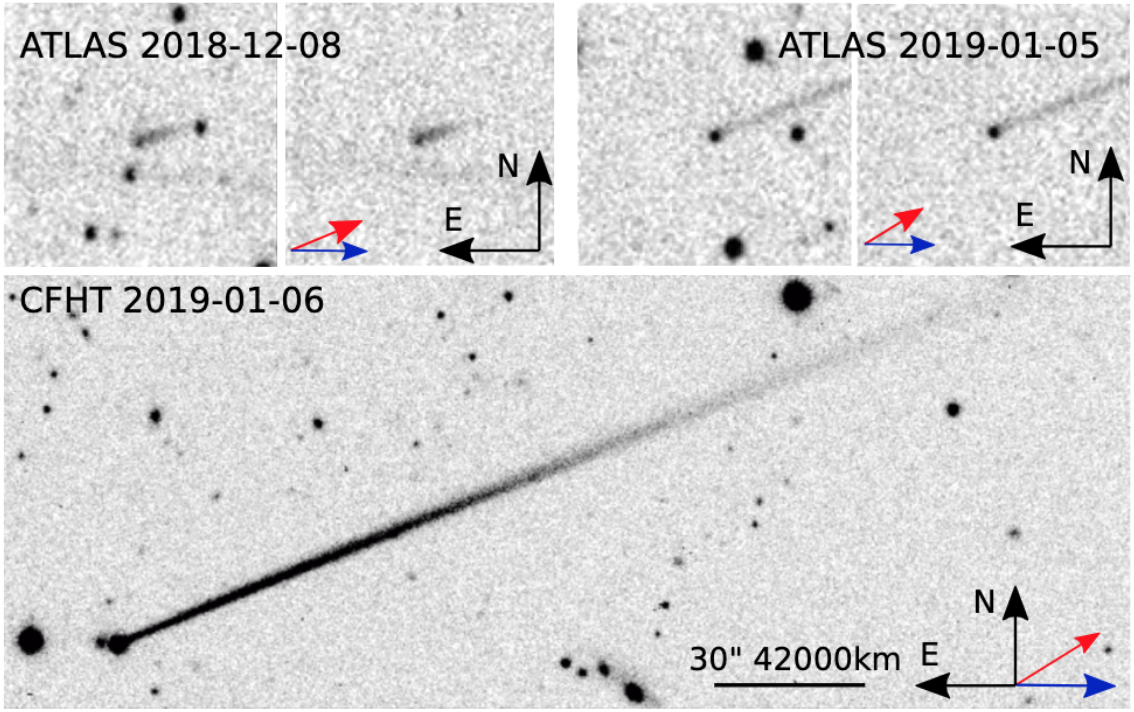


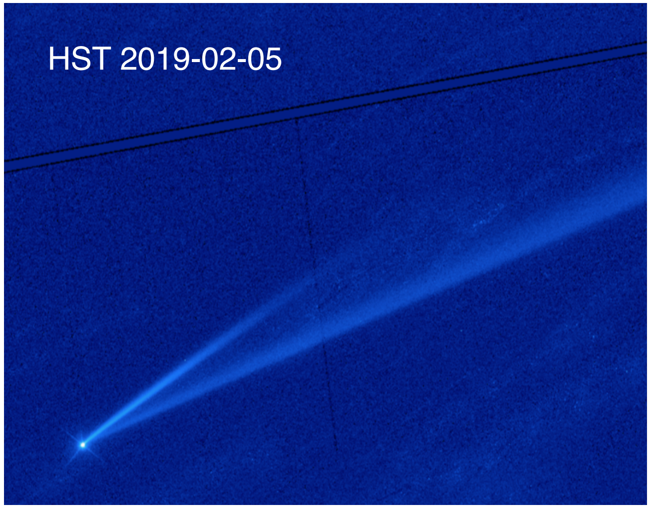
Orbital configuration 02 May 2018



Asteroid Gault (6478)

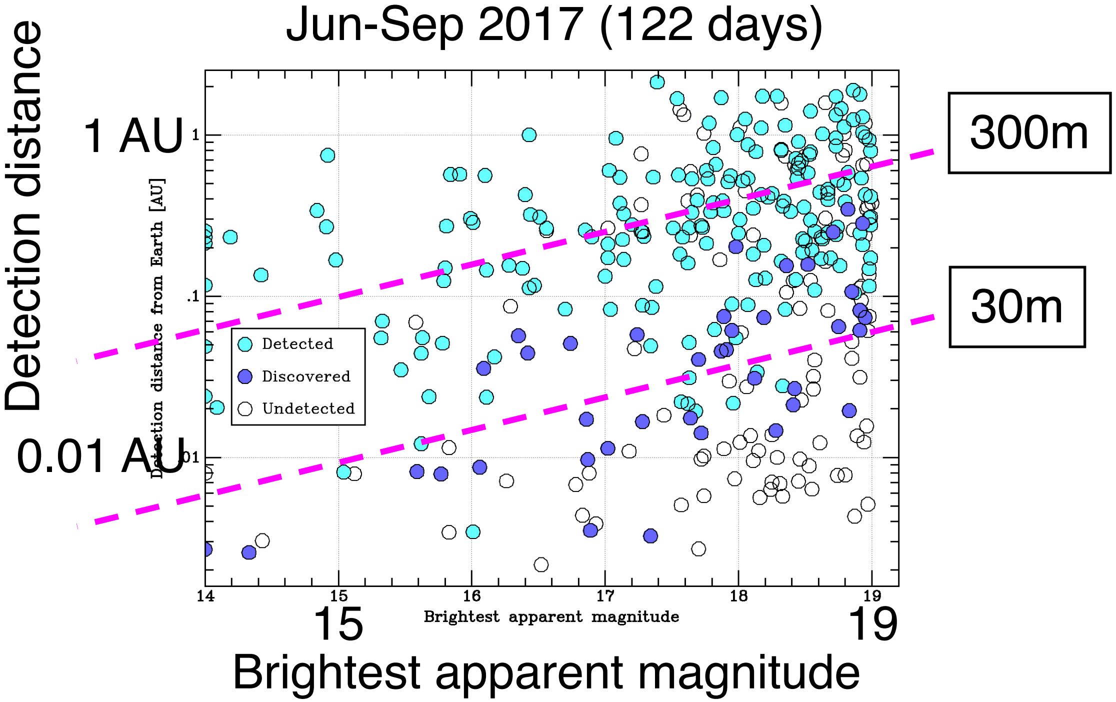
- Discovered by ATLAS collaborator Ken Smith while inspecting images for supernova transients (would have been spotted by the asteroid team 6 hours later)
- 6–10km size, 2.3 AU, inner MB
- Previously inactive, episodic outbursts suggest ongoing rotational disruption.

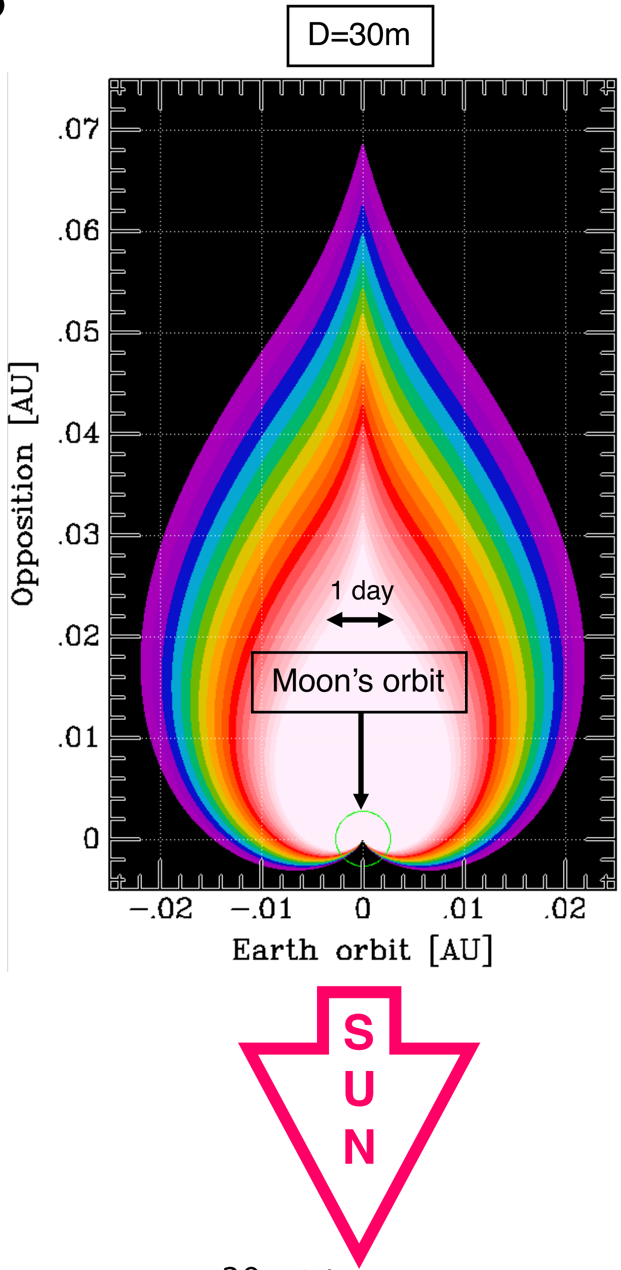




ATLAS and NEOs

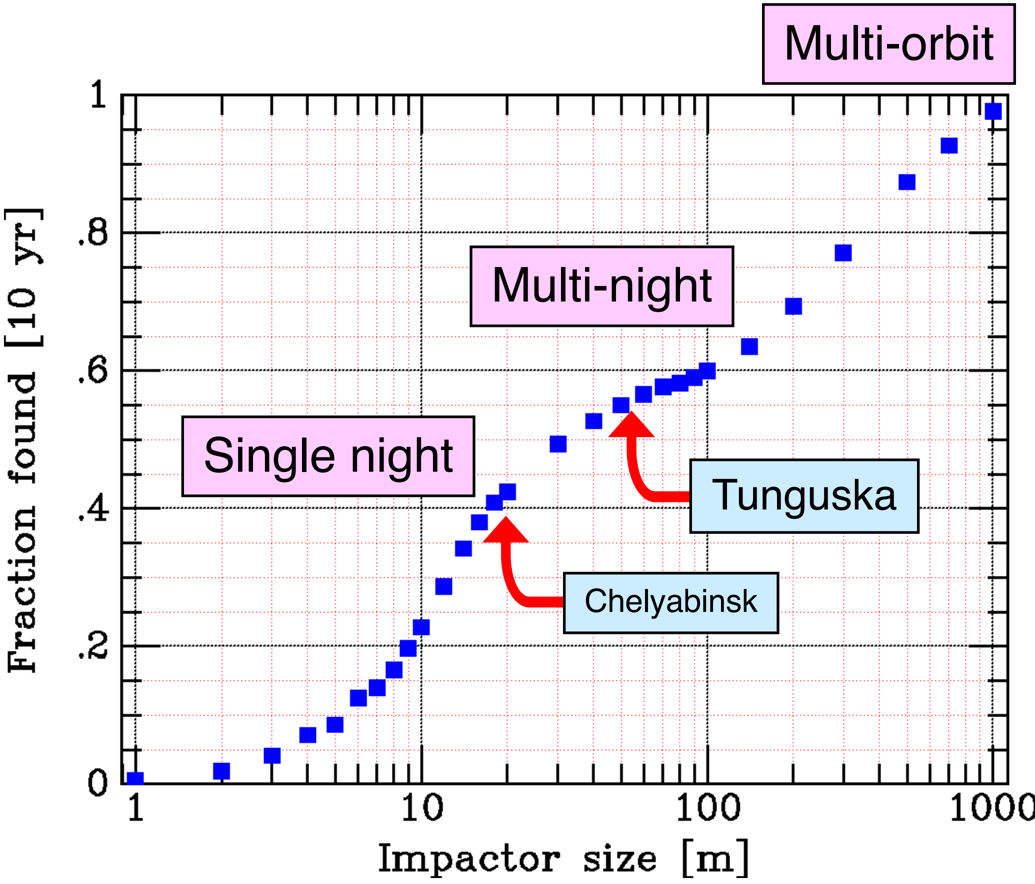
- ATLAS should have 2—9 NEOs of D~30m in view at any given time, depending on poorly known number.
- Most 30m asteroids that come within 1 lunar distance should be detected by ATLAS


Jun-Sep 2017 (122 days)



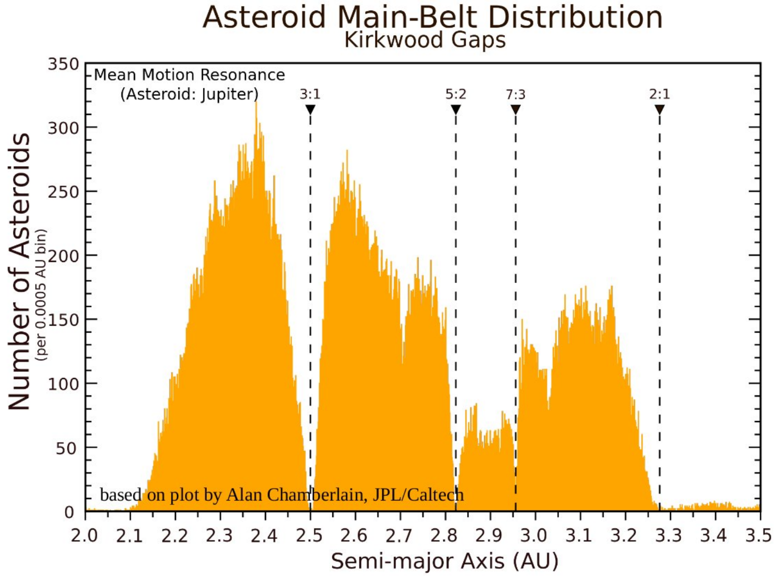
ATLAS Impactor Discovery Probability

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

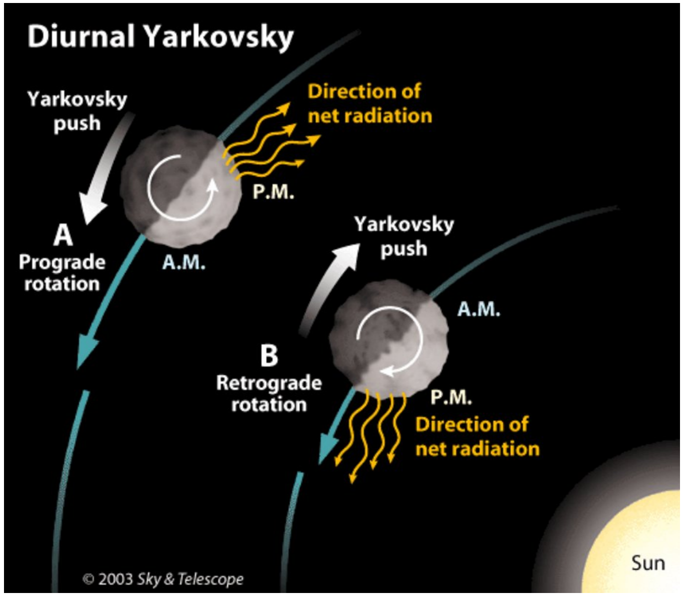


Non-gravitational Forces Create Fresh Hazard

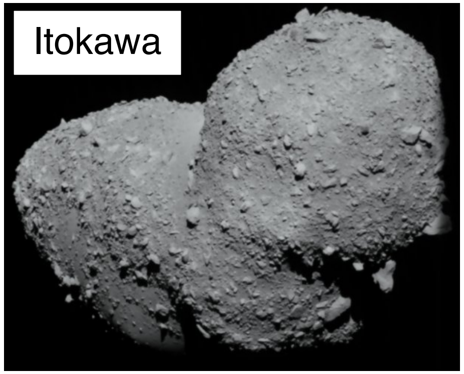
- Yarkovsky
  - Slowly changes orbits
  - At resonance orbits change chaotically
- YORP (tangential Yarkovsky) and “Spin-barrier”
  - YORP can spin up asteroids and cause them to fission, changing orbit


Asteroid Main-Belt Distribution
Kirkwood Gaps

based on plot by Alan Chamberlain, JPL/Caltech



© 2003 Sky & Telescope



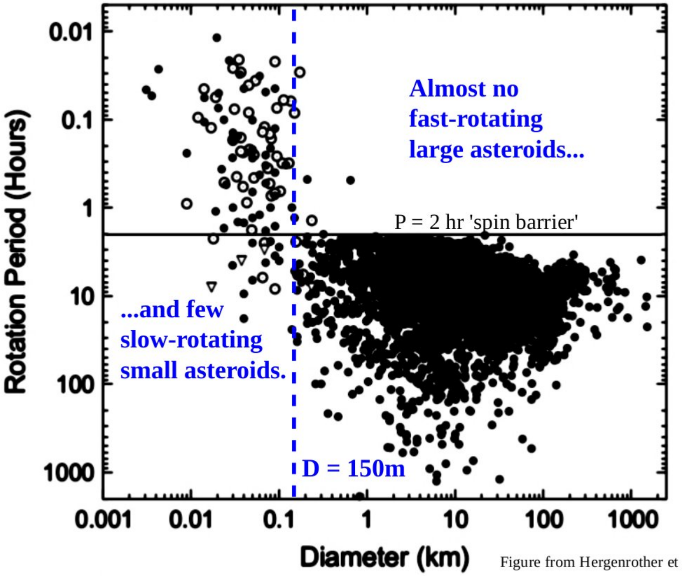
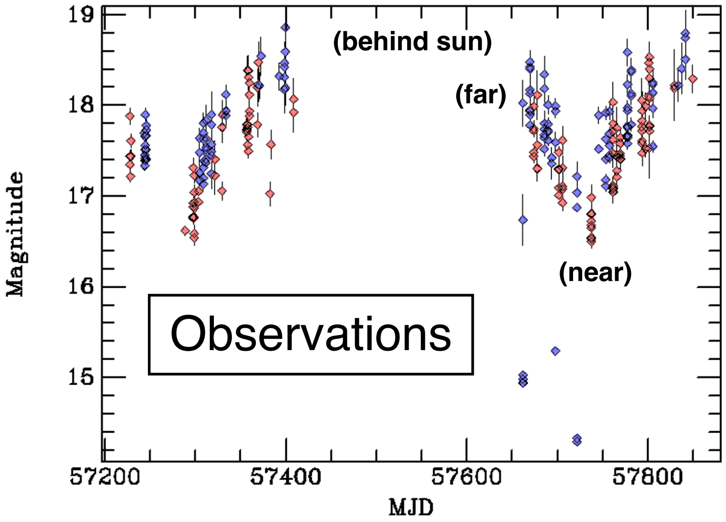


Figure from Hergenrother et al. (2011)

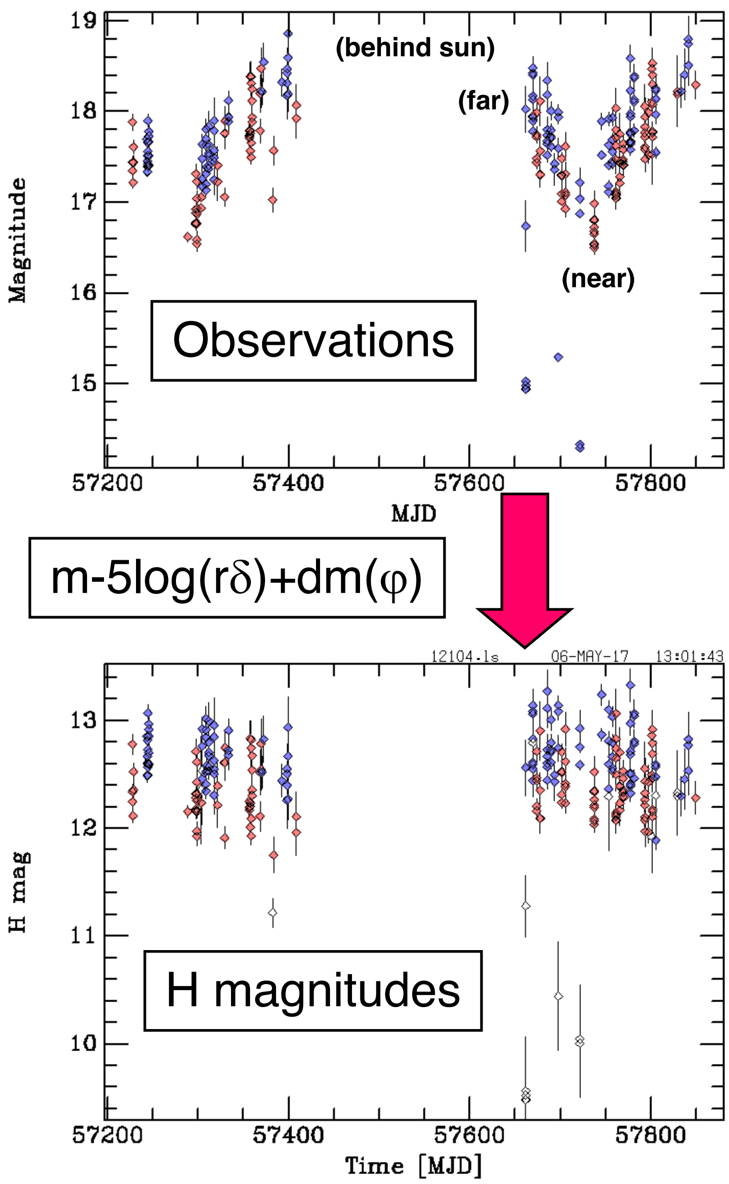
Asteroid light curves

- Asteroid observed magnitudes
  - Images and difference images



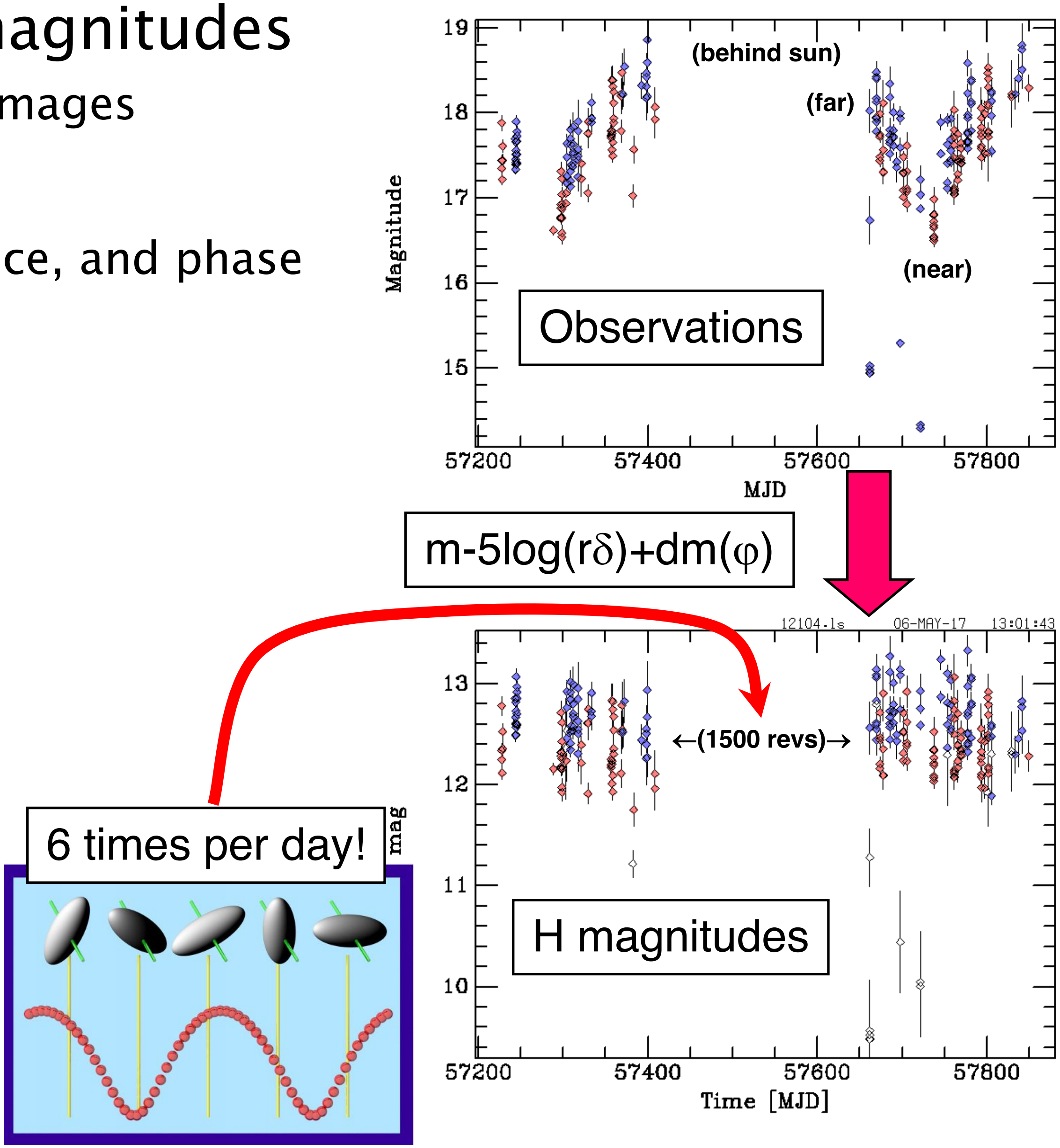
Phasing light curves

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



Phasing light curves

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



Observations

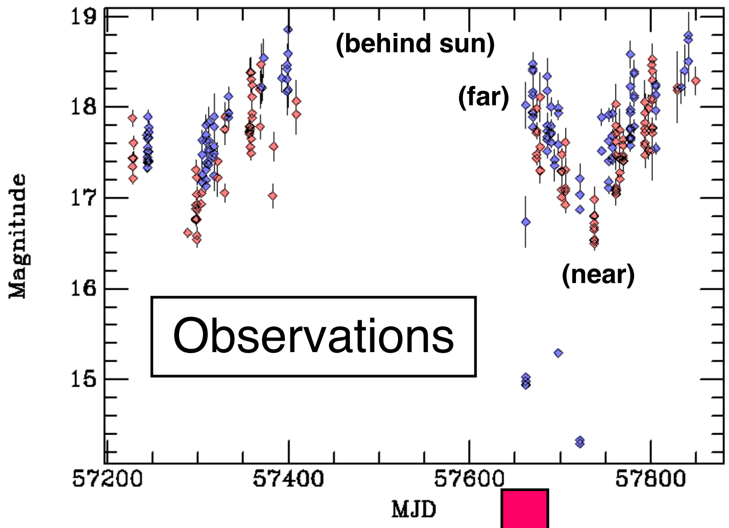
m-5log(rδ)+dm(φ)

6 times per day!

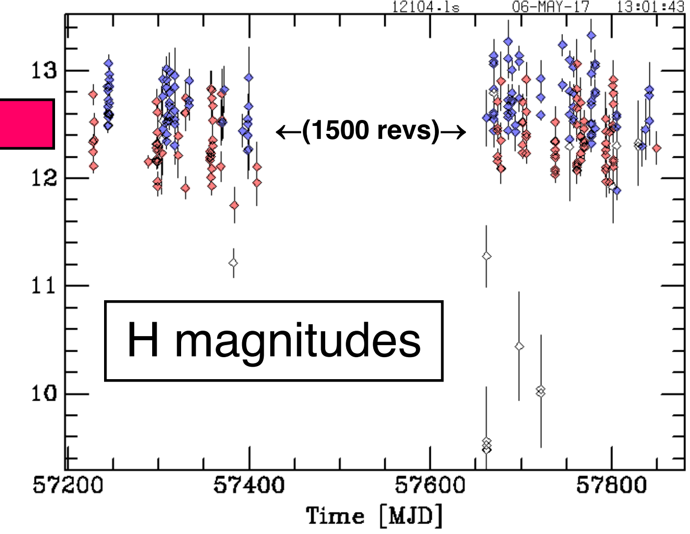
H magnitudes

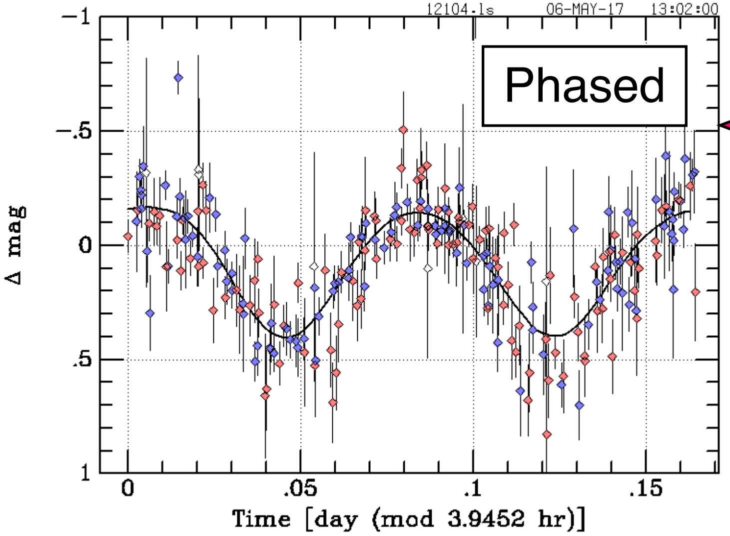
Phasing light curves

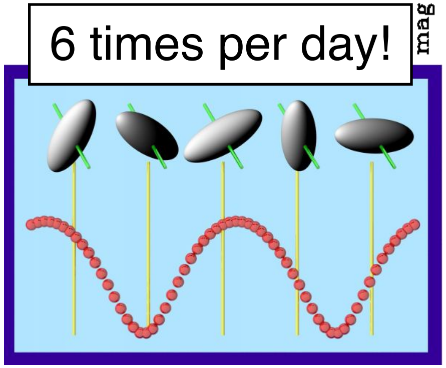
- Asteroid observed magnitudes
  - Images and difference images
- Correct to “H”
  - Light travel time, distance, and phase function
- Search for periodicity
  - Lomb-Scargle, color fits, outlier rejection, Fourier fits, choose best



m-5log(rδ)+dm(φ)

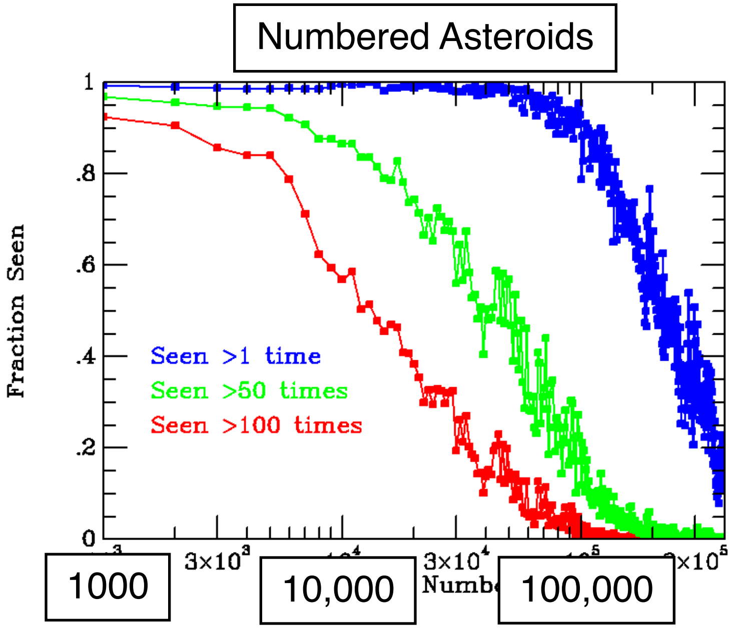


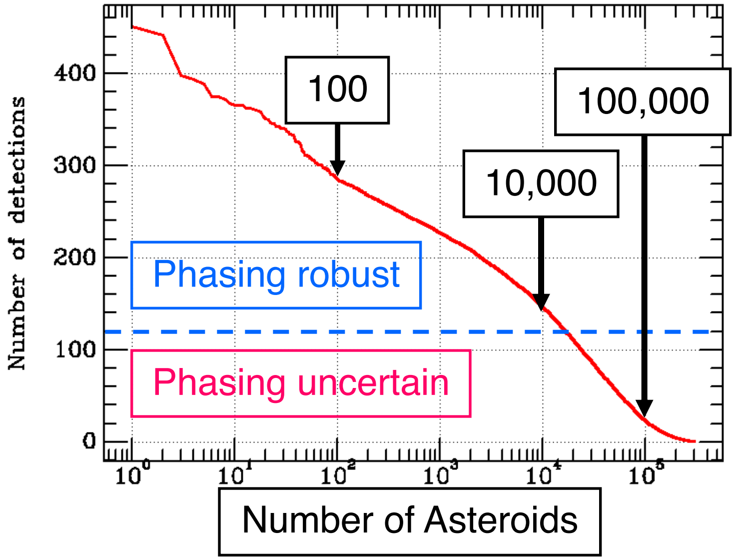




Asteroid Properties from ATLAS

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



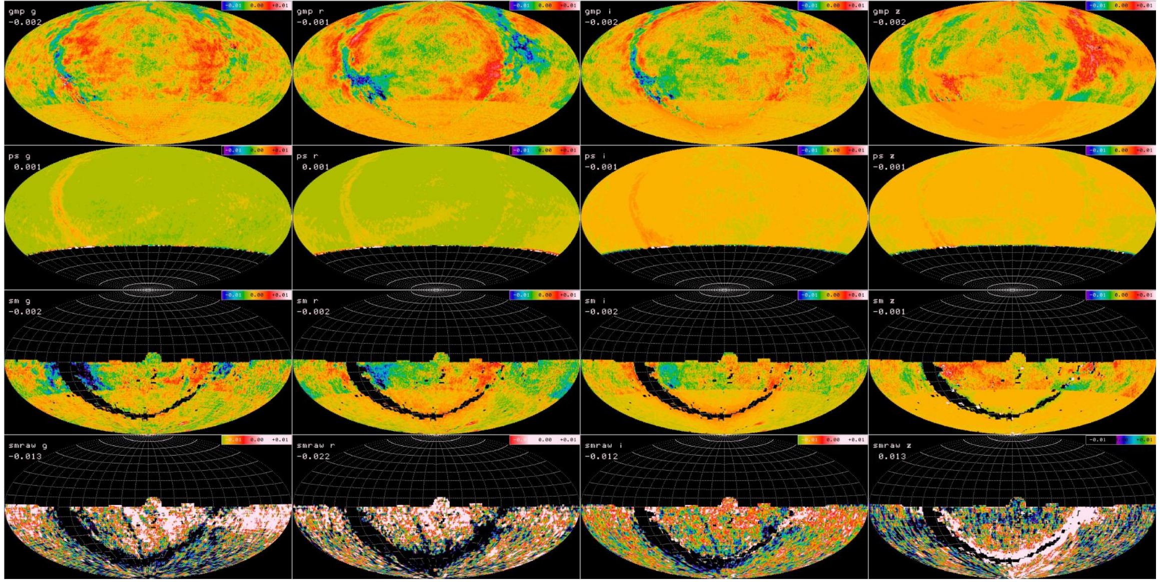


Useful Byproducts

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

Refcat2 – arXiv 1809.09157

(green=-0.005, red=+0.005)

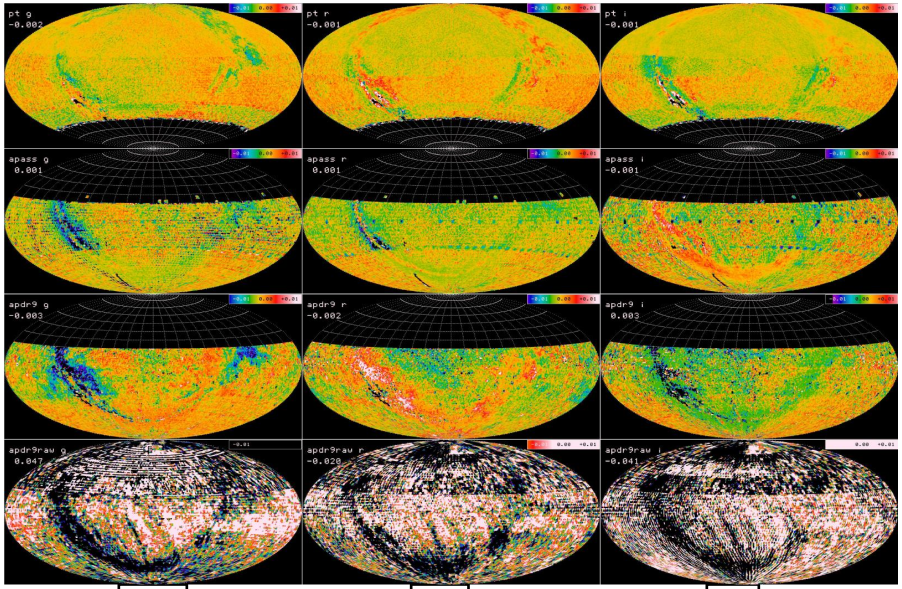


Gaia+2MASS subset

Pan-STARRS

SkyMapper

SkyMapper DR1.1



ATLAS

ATPASS

APASS

AP DR9

g r i z

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

Gaia DR2 and 2MASS

Pan-STARRS , Dec>-30°

ATLAS gri, Dec>-50°

APASS/ATLAS gri, Dec<+20°

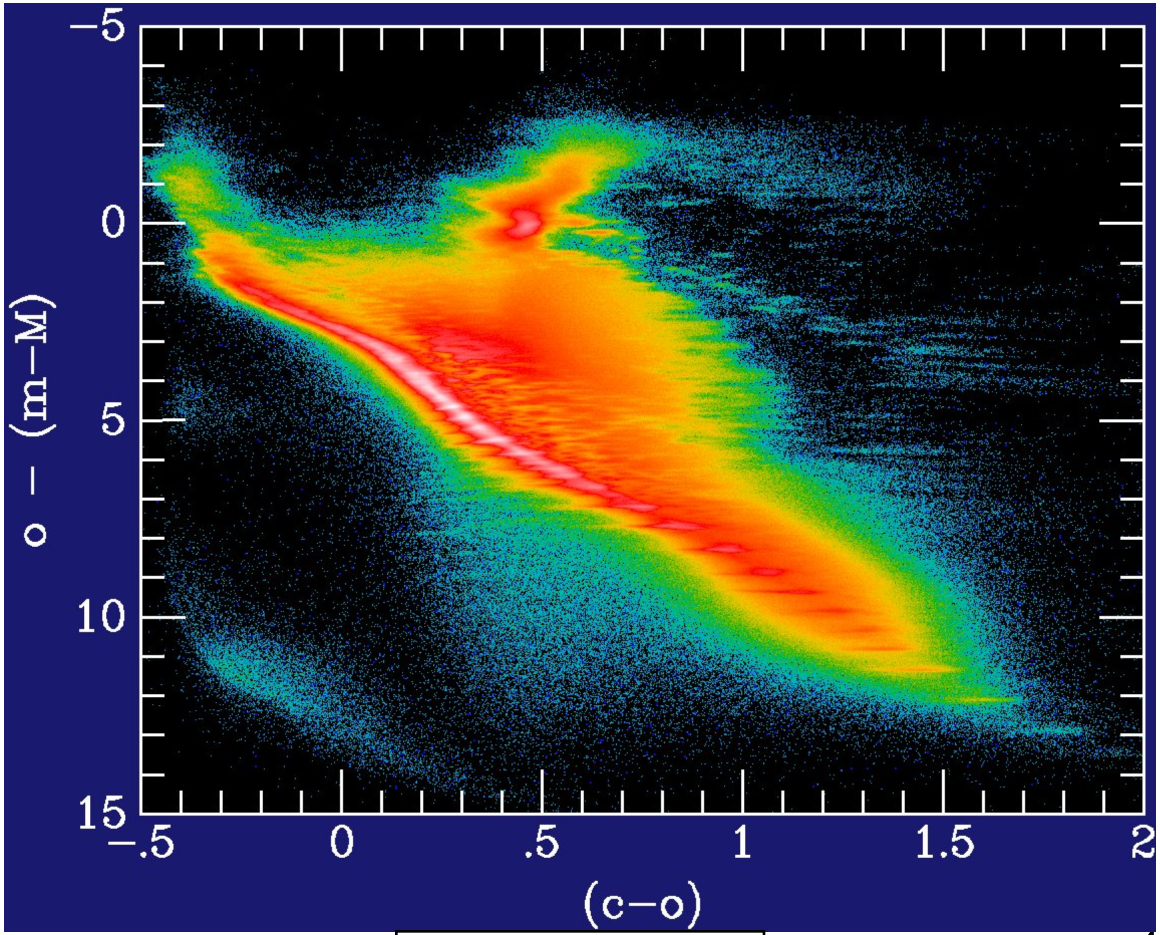
SkyMapper griz, Dec<+0°

991M stars, G|B|R<19

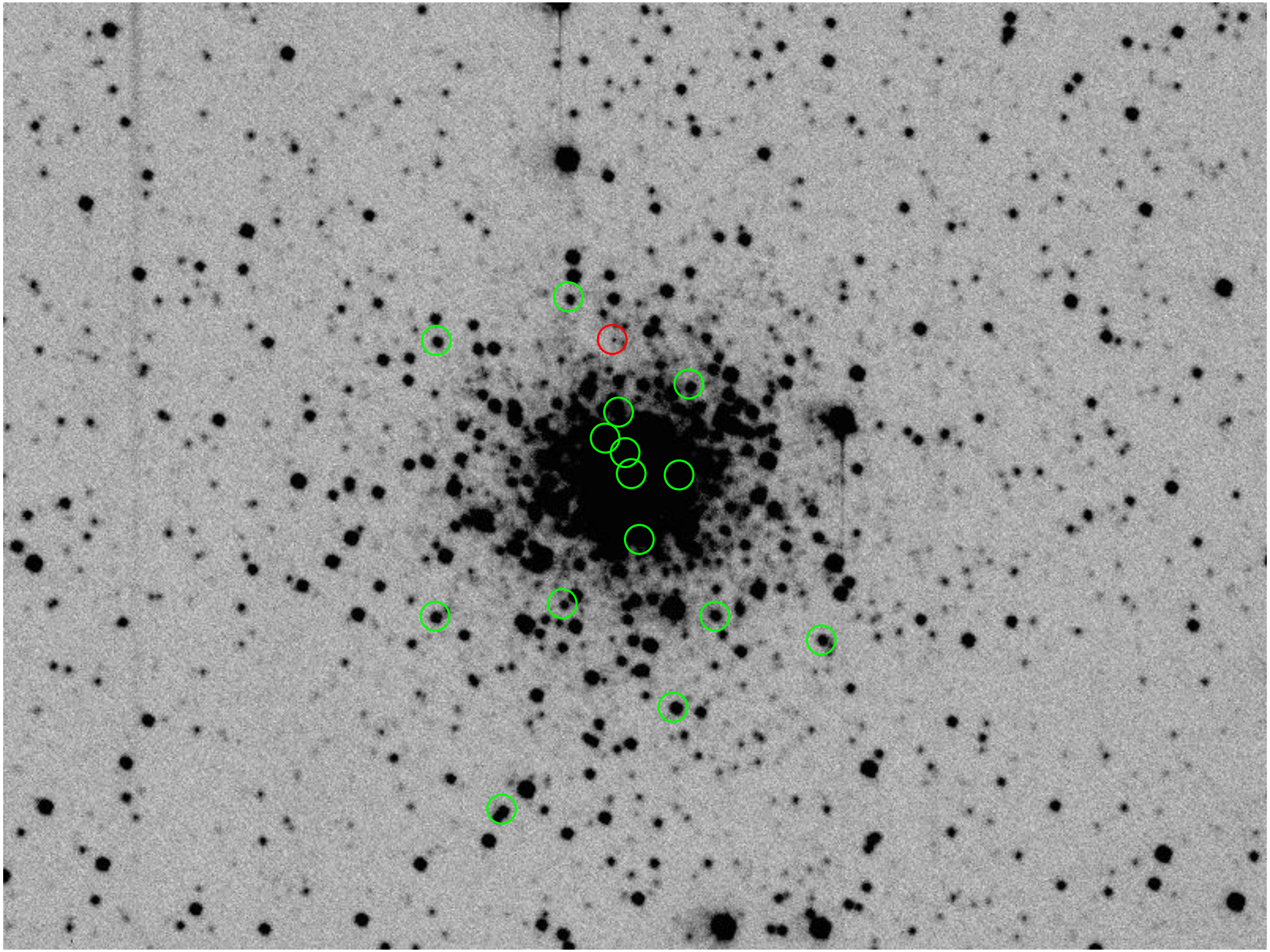
210M stars g|r|i<17

ATLAS-Gaia HR diagram

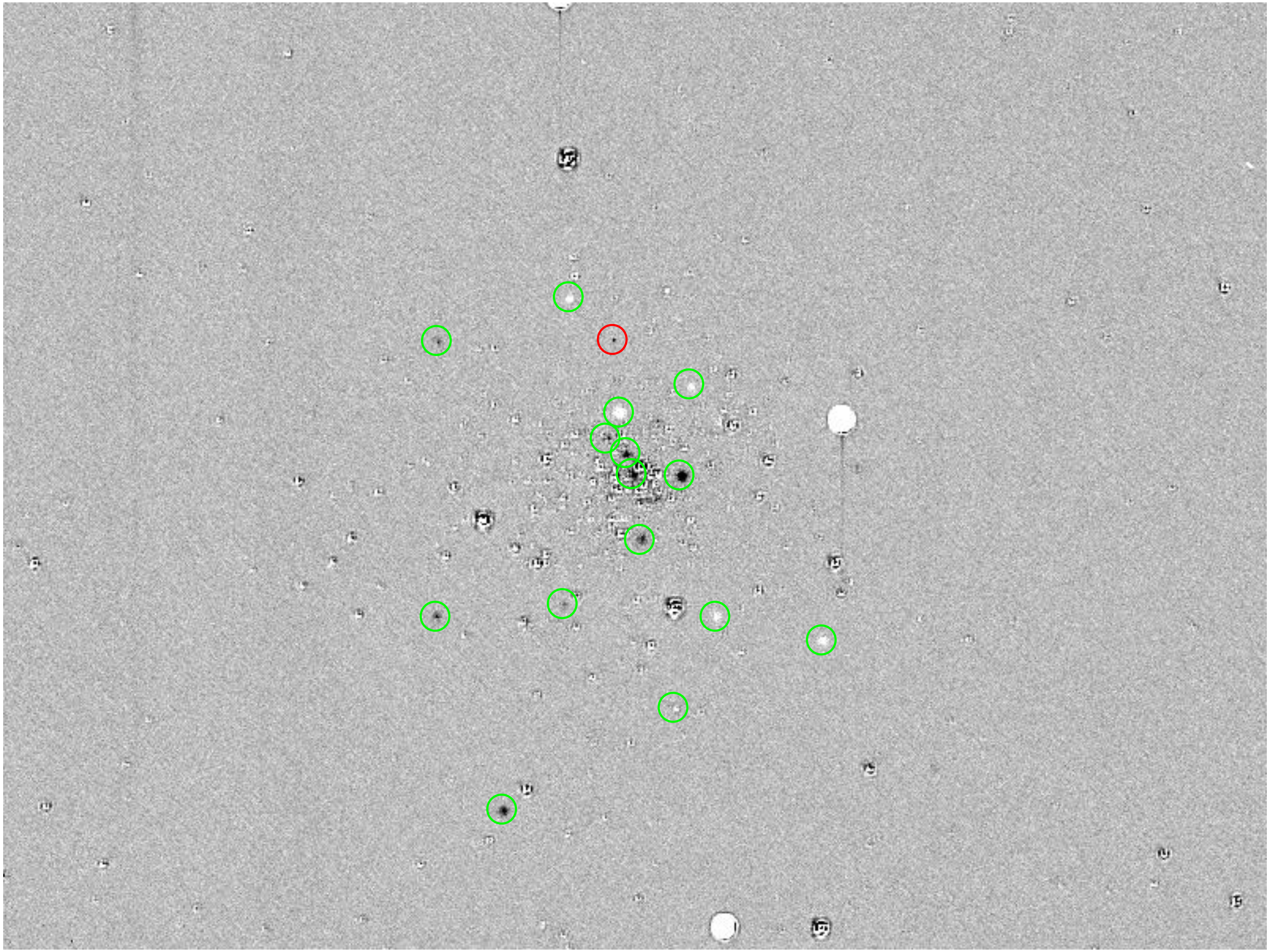
- 40M stars have ATLAS light curves and Gaia parallax with error smaller than 10%.
- Every star has a ~1000 epoch light curve behind it



(count: 1—1000 log stretch)



M107 globular cluster RA 248.132 Dec -13.054

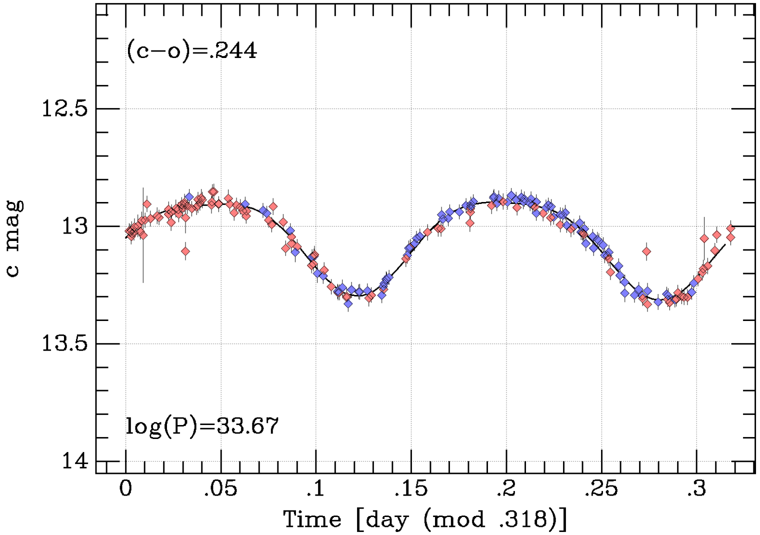


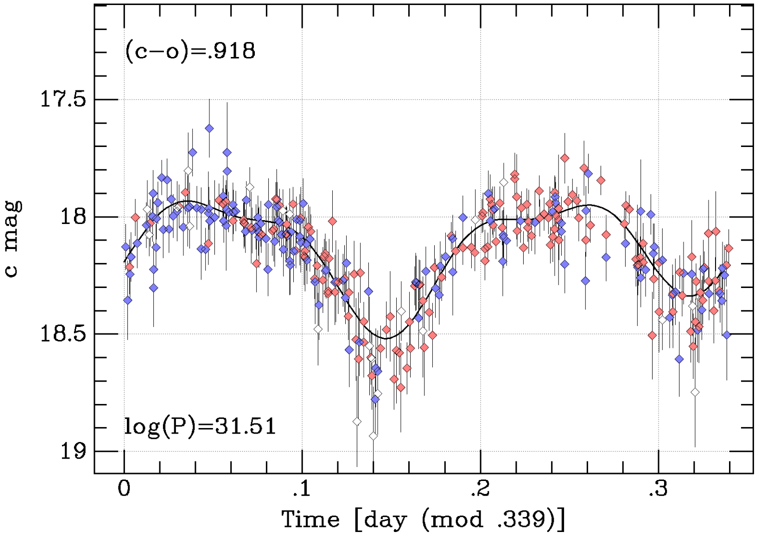
M107 globular cluster   RA 248.132   Dec -13.054

Chile 190325

Variable Stars

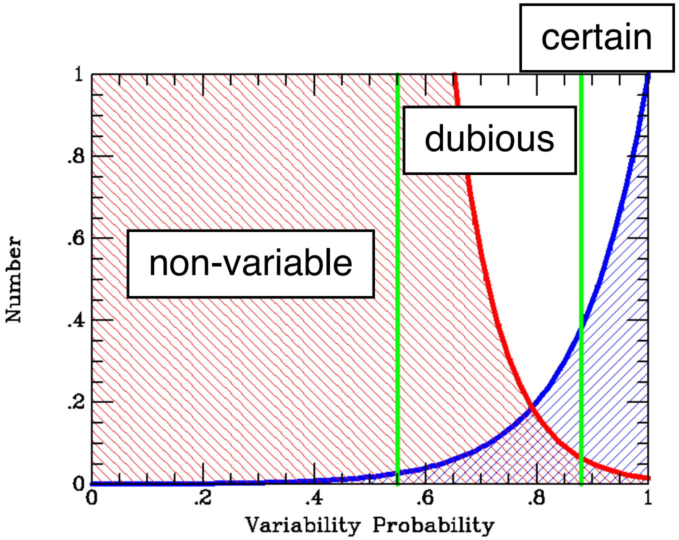
- ATLAS has ~500 point light curves for ~250M stars.
  - All (nearly) stars with −45<Dec<+90 and 11<m<19 examined
  - SNR ~10 at m~18, per detection
  - Sampling ~4/night over ~1 hour, revisit every ~2 days
  - c~(g+r) and o~(r+i) colors
  - Lomb-Scargle and variability statistics computed for all light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





Classifying Stars

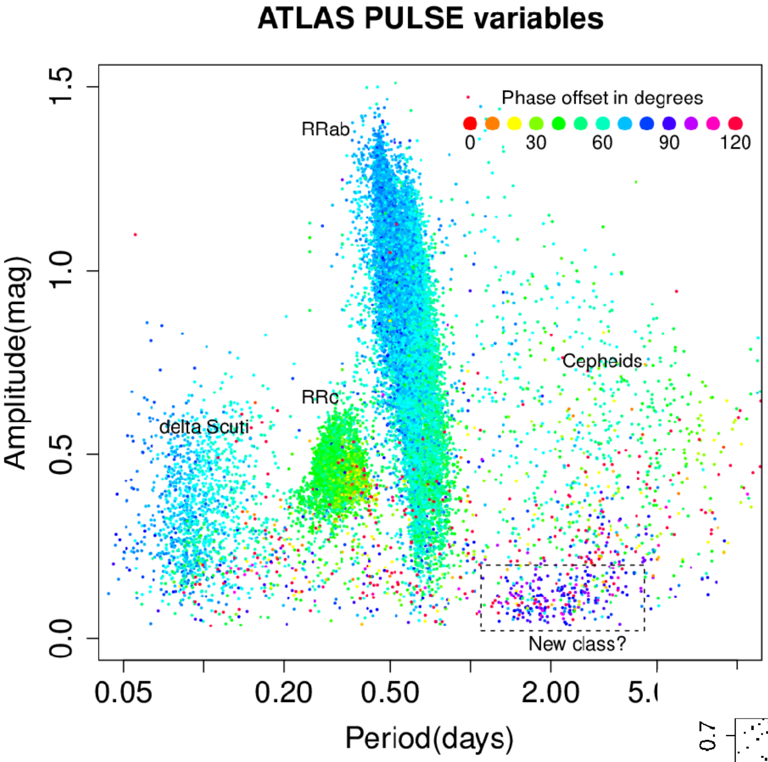
- Machine learning classification of 140 million light curves
  - Morphological classes such as “sinusoidal”, “pulsating” (sawtooth), “close binary”, “distant binary”, “mira”, etc.
  - Good but not perfect correspondence with physical classes: work to be done
  - ~0.5M are “certain” (low false alarm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

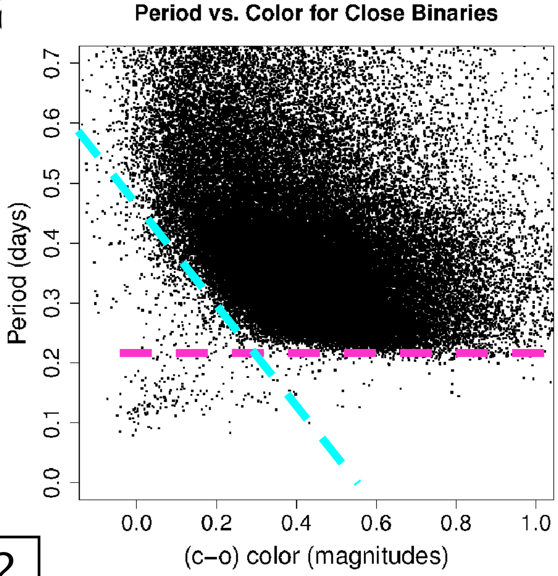


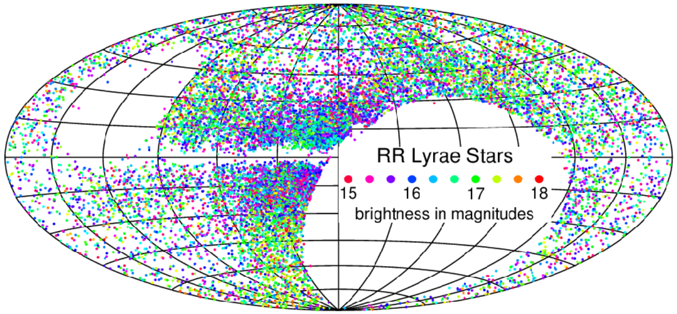
Red = non-variable stars
Blue = variable stars

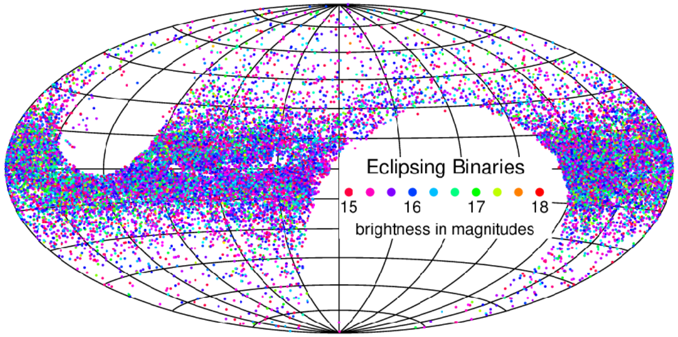
Heinze et al. arXiv:1804.02132

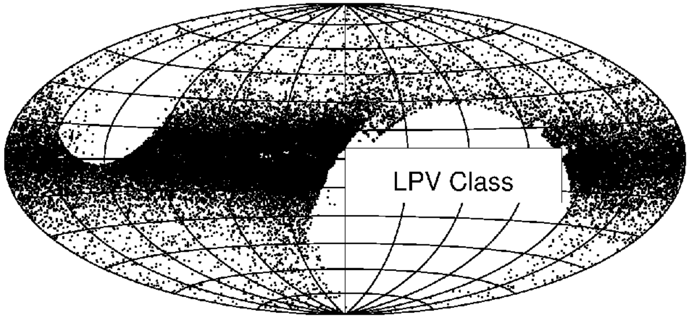
Distributions

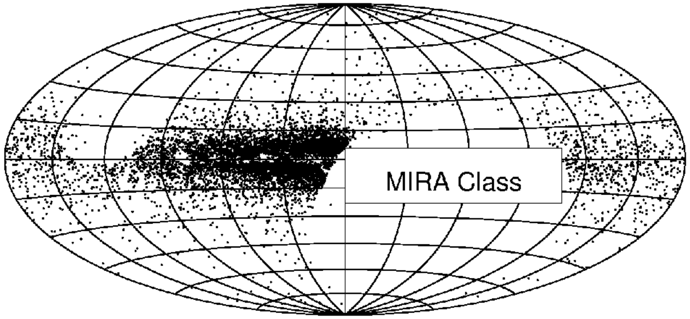










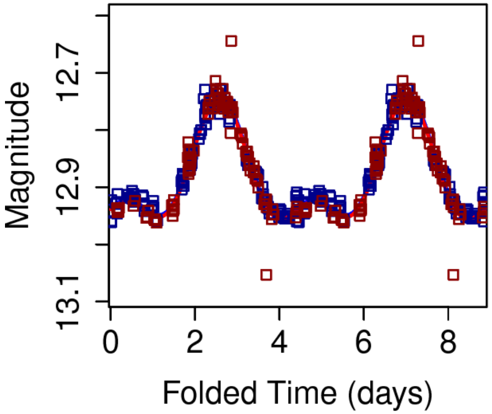


Heinze et al. arXiv:1804.02132

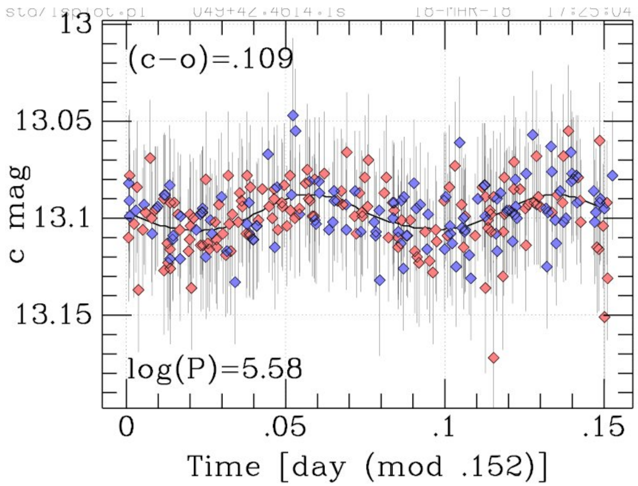
Interesting Light Curves

Ap star

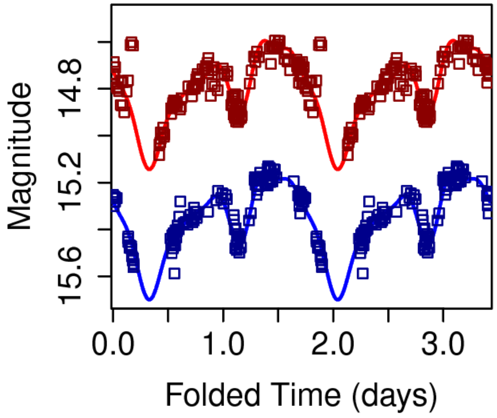
ATO J010.7230+57.8087



0.01 mag amplitude

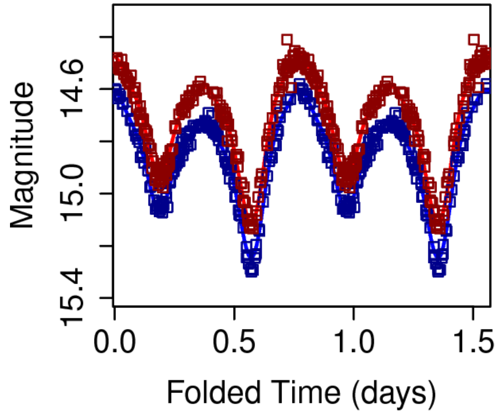


ATO J267.4192+48.8914



Eclipsing pulsator?

ATO J054.8250+42.1556



O’Connell effect

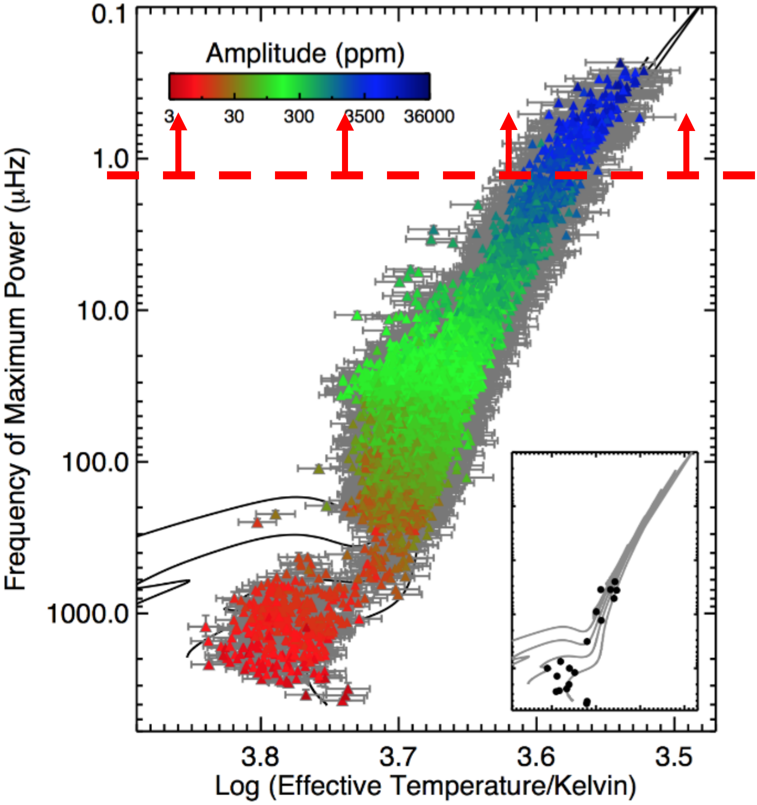
Heinze et al. arXiv:1804.02132

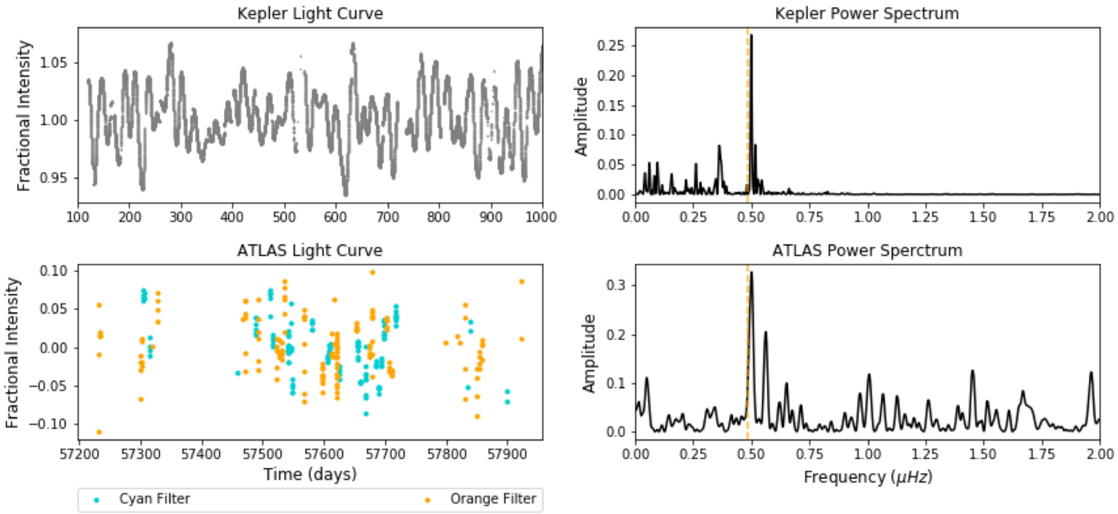
Asteroseismology

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

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

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





Transients and Cosmic Variables

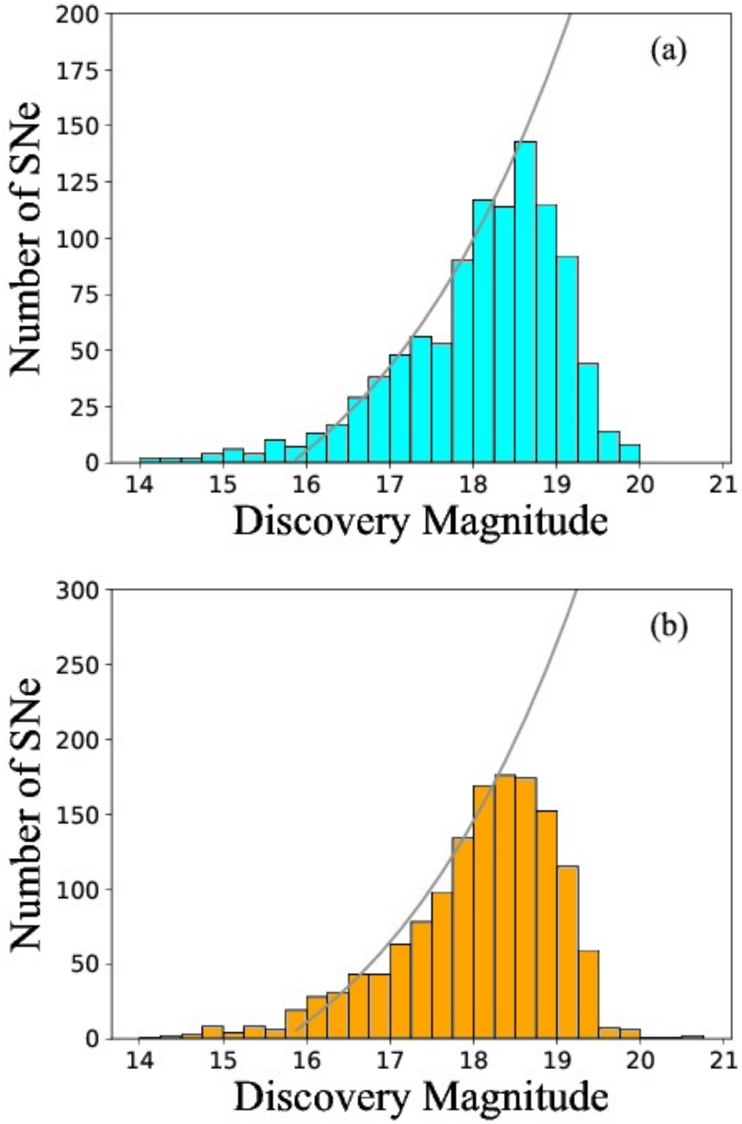
- ATLAS sees ~5,000 supernovae per year to V~19

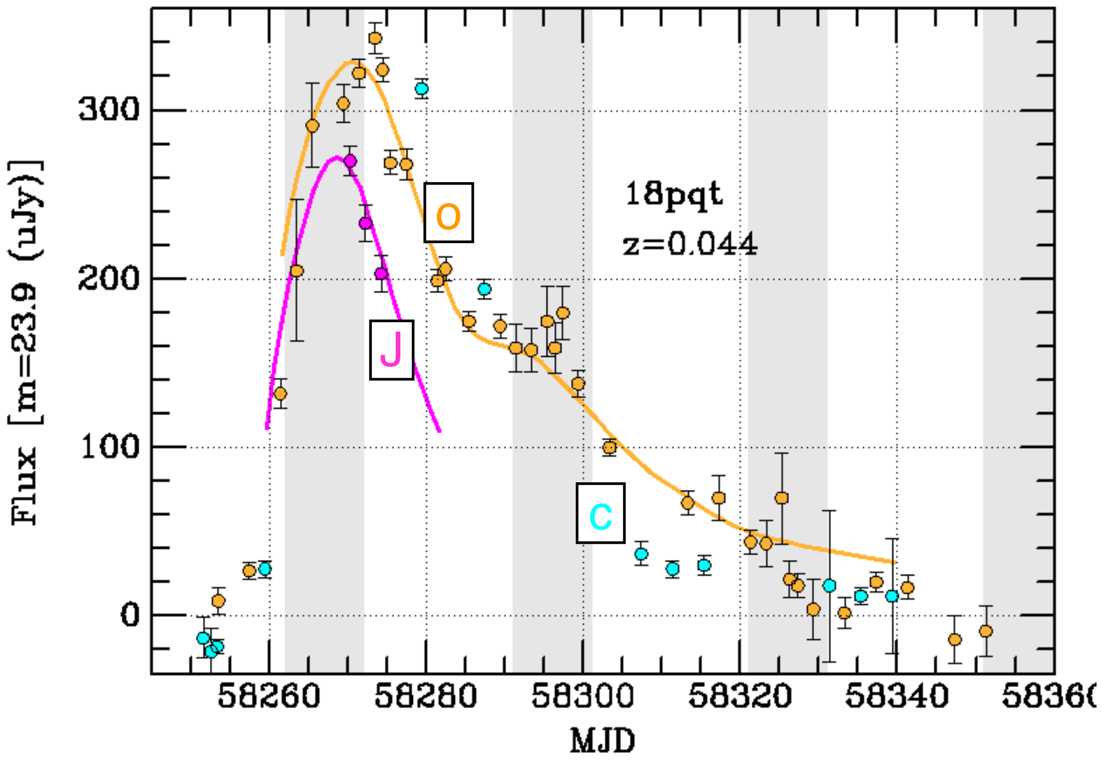
- There are ~200,000 AGN brighter than V~19 that ATLAS monitors daily.

- ATLAS depth and SNR at m~19 depends on averaging time:
  - ~1 hour (1 exposure), m_{lim}~19.5, SNR > 7 at m~19
  - ~1 day (4 exposures), m_{lim}~20.2, SNR > 14 at m~19
  - ~1 week (20 exposures), m_{lim}~21, SNR > 30 at m~19
  - ~1 month (50 exposures), m_{lim}~21.5, SNR > 50 at m~19

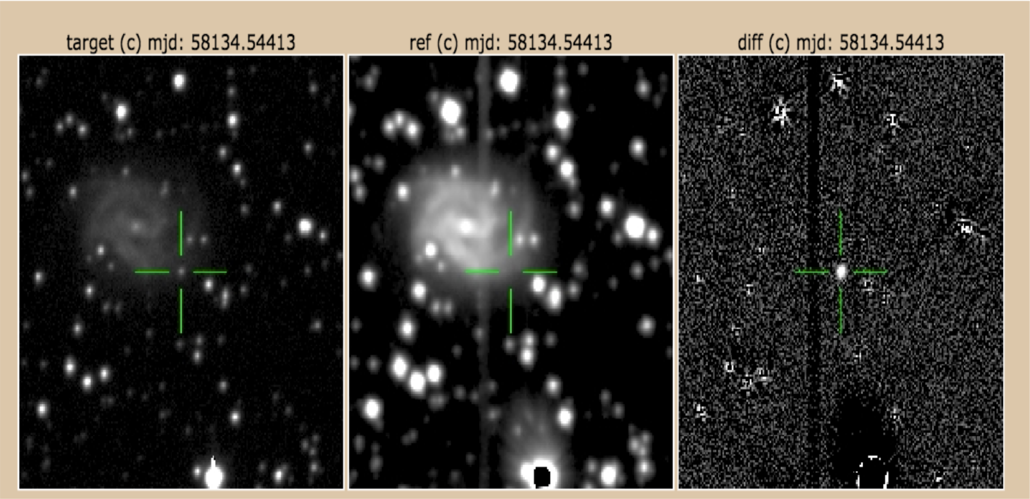
ATLAS SNIa Discoveries

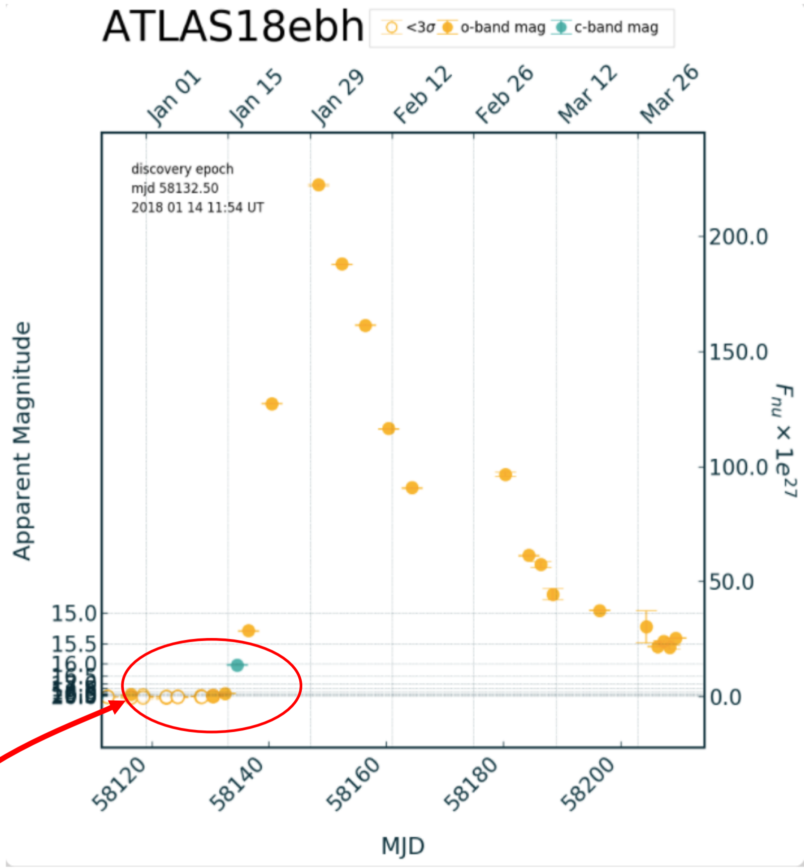
- ATLAS can find (nearly) all SNIa that explode within z<0.1
    - ~5000 per year
    - SNR sufficient to establish decline rate
    - Follow-up IR photometry at peak and spectrum can get ~7-10% distance.





Most nearby SN detected within first ~24hrs





Example :

ATLAS18ebh = SN2018gv

NGC2525, 20 Mpc

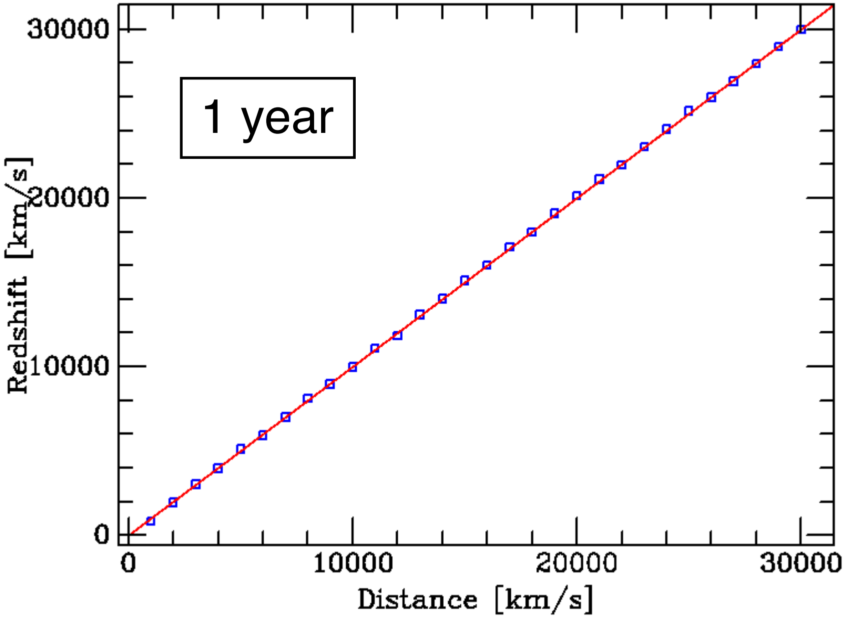
Normal Type Ia

ATLAS early detections and limits constrain explosion to ~12hrs

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

Hubble Flow, Large Scale Flows

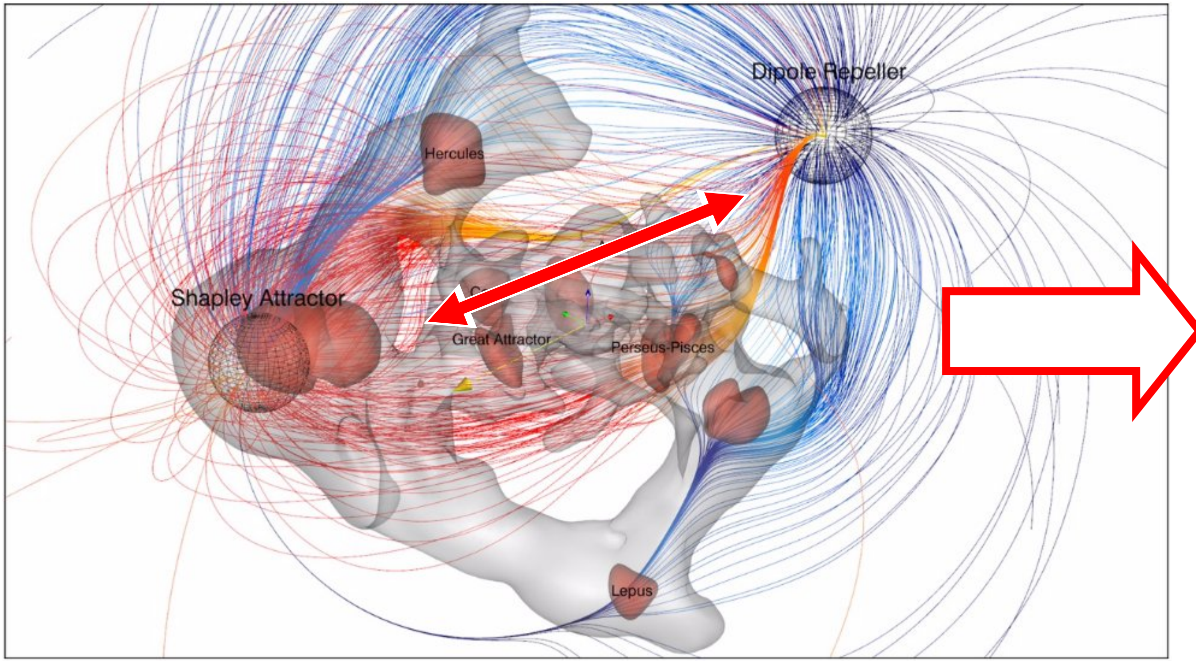
- Use SNIa as standardizable candles:
  - ~10% distance accuracy per SNIa
  - ~1 SNIa each year per $(30\text{Mpc})^3$.
  - Therefore measure the distance of a shell of thickness 1,000 km/s with an accuracy of 100 km/s per year *independent of distance*, limited when systematics dominate (z~0.1?)
  -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

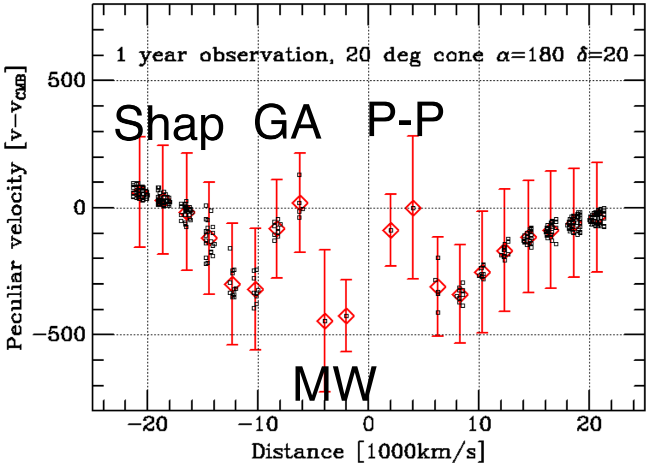


  - Pilot project now underway with Shappee and Tully…

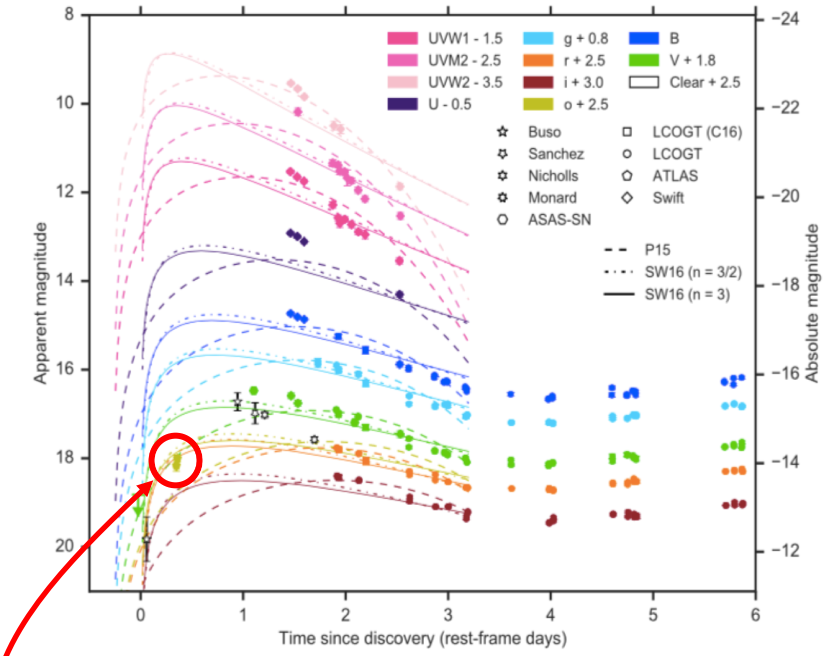
Large Scale Flows and Dark Matter

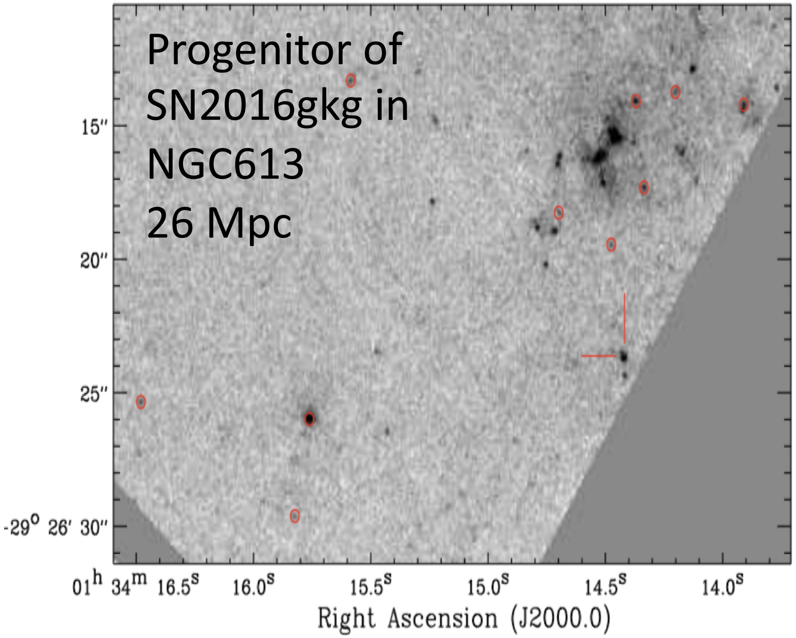
- Constrained N-body simulations can predict dark matter distribution from observations of large scale flows (e.g. Tully et al. Cosmic Flows).
- These can be directly tested (and improved) in 1 year of ATLAS SNIa observations.





Detections of very young supernova : shock breakout



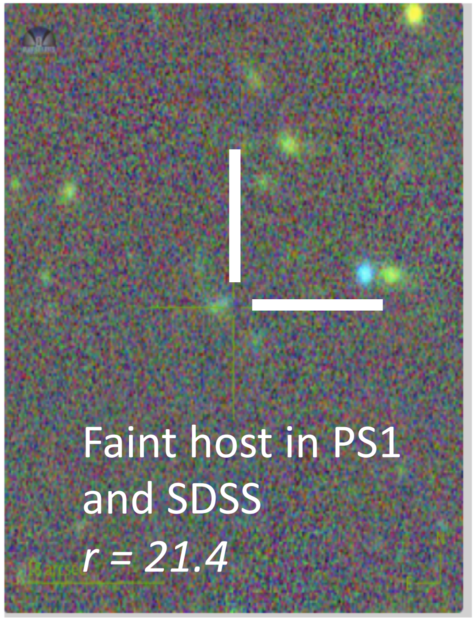


Progenitor of
SN2016gkg in
NGC613
26 Mpc

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

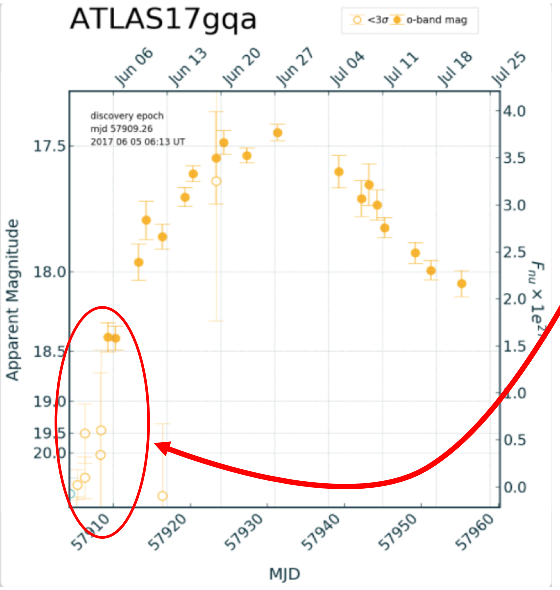
Arcavi et al. 2017,
Tartaglia et al. 2017,
Kilpatrick et al. 2017

ATLAS17gqa : very unusual super-luminous SN



Faint host in PS1 and SDSS

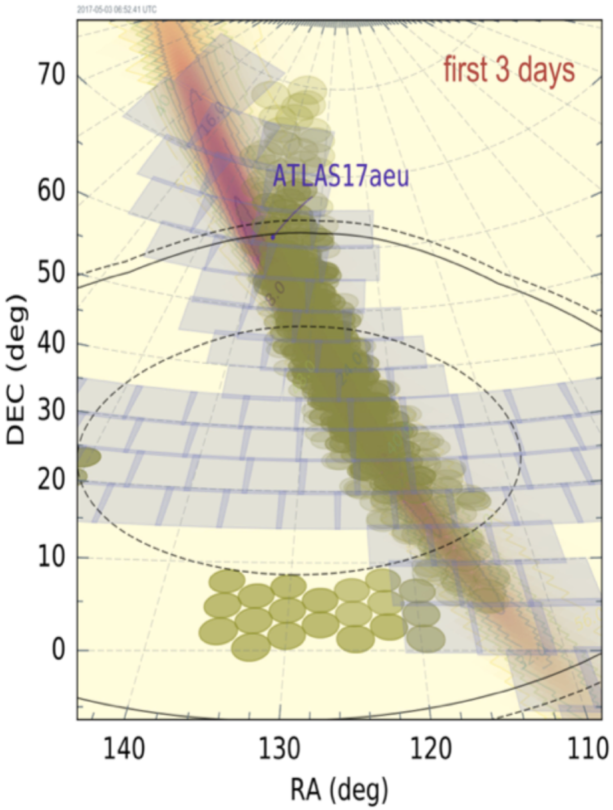
r = 21.4



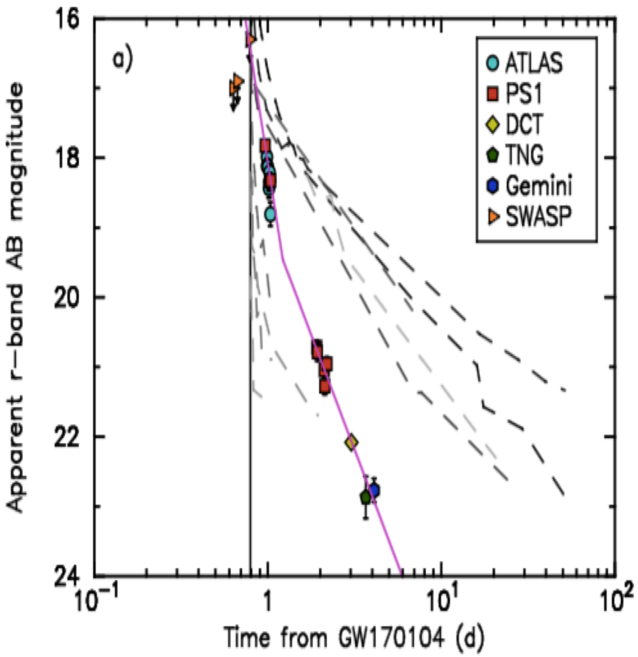
- Explosion epoch constrained to 24hrs
- $z = 0.1086$
- Peak mag : $M_o = -21$
- Full multi-band lightcurve and ESO spectra

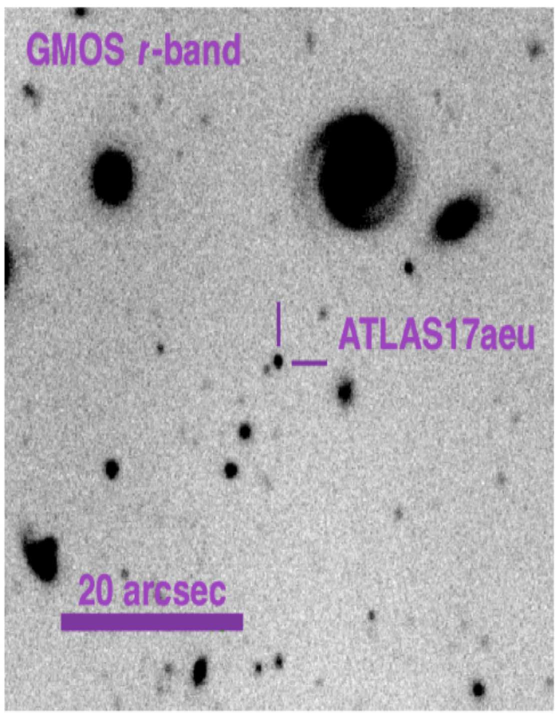
- ATLAS + PESSTO paper in prep (Chen et al.)
- Stunning x-shooter spectra, showing host of narrow absorption !
- Spectra + bolometric lightcurve : suggest pulsational pair instability supernova

Follow-up of LIGO-Virgo GW sources



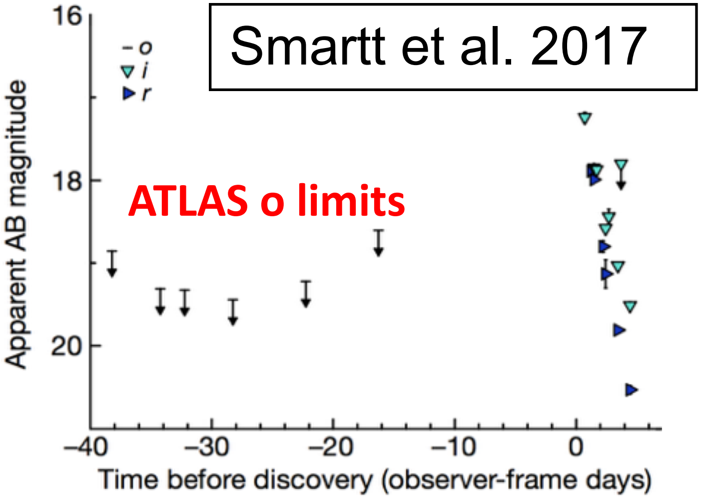
Stalder, Tonry et al 2017.

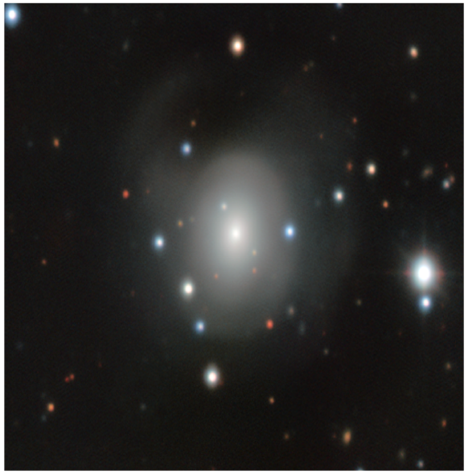




- We showed in O1 and O2 : Powerful facility for finding bright, fast sources in LIGO-Virgo maps
- Discovered ATLAS17aeu (GW170104) – fast transient within 24hrs of GW source
- Turned out to be the afterglow of a GRB – but only 3rd time a GRB afterglow was detected without a high energy trigger

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

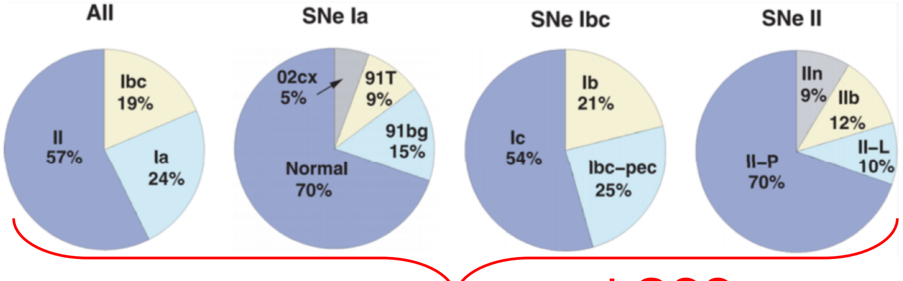




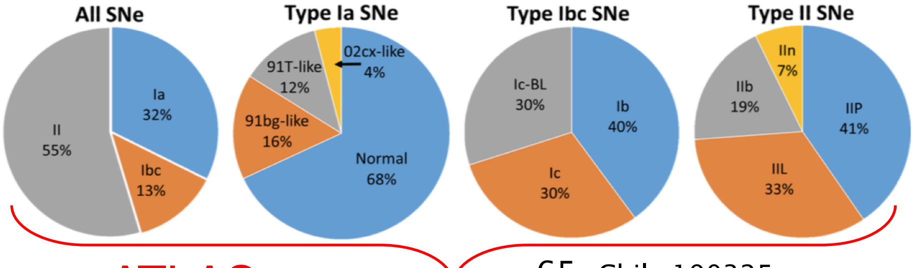
- ATLAS would easily have detected AT2017gfo, except our survey schedule had shifted away from the sun
- Kilonovae are detectable on ATLAS within ~100 Mpc
- Scolnic et al (2018): LIGO-Virgo rates of NS-NS mergers imply ATLAS should find 2 – 10 kilonovae per year, irrespective of GW trigger. ATLAS is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

ATLAS Local Universe SN rates

- Lick Observatory SN Search (LOSS)
  - 10 year results (Leaman et al 2011, Li et al 2011)
  - 180 SNe within ~80 Mpc, volume limited sample
  - But – targeted galaxy survey creates bias
- ATLAS initial results
  - 1.7 year period (mostly 1 telescope). No galaxy (metallicity) bias – full volume: all SNe regardless of dwarf host (or no host evident)
  - 77 SNe within ~60 Mpc, volume limited sample
  - Each year we will equal LOSS statistics within ~80 Mpc (but no bias), good light curves and spectra for all
- Preliminary results
  - Agreement with LOSS rates, e.g. Rcc = $0.48\pm0.07\times10^{-4}$ Mpc^{-3} yr^{-1}
  - Rate of SN outside galaxies (or in dwarfs Mr > -12) is $<$ 5% total rate



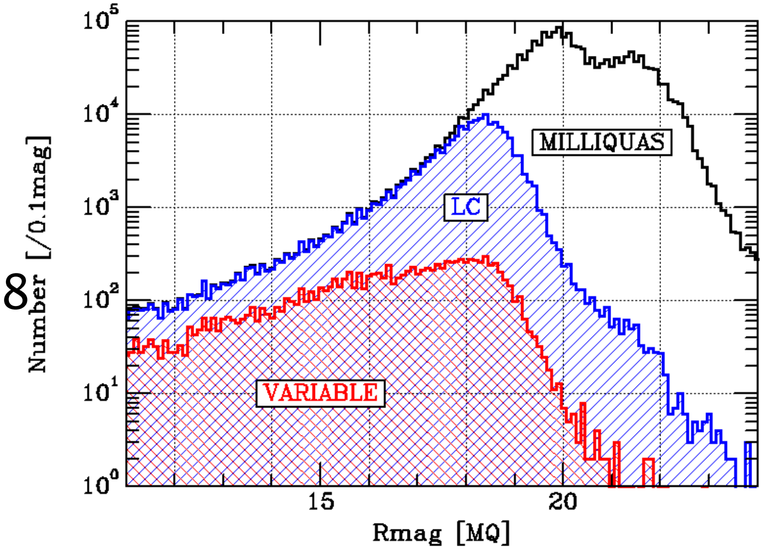
LOSS

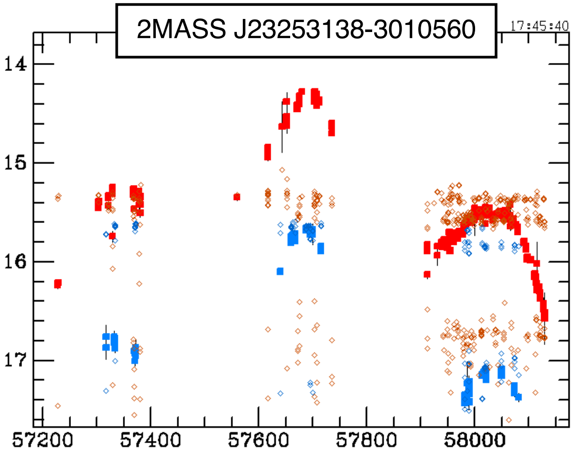


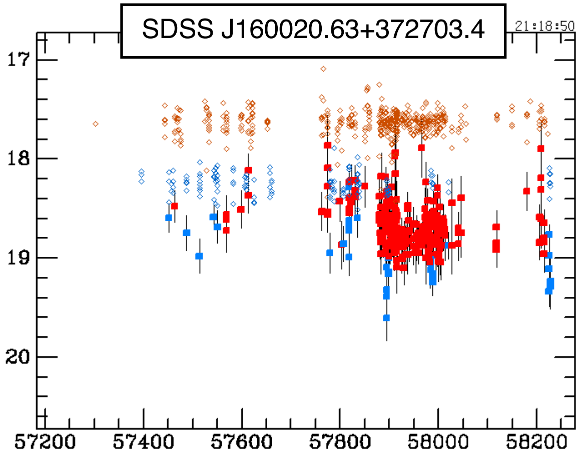
ATLAS

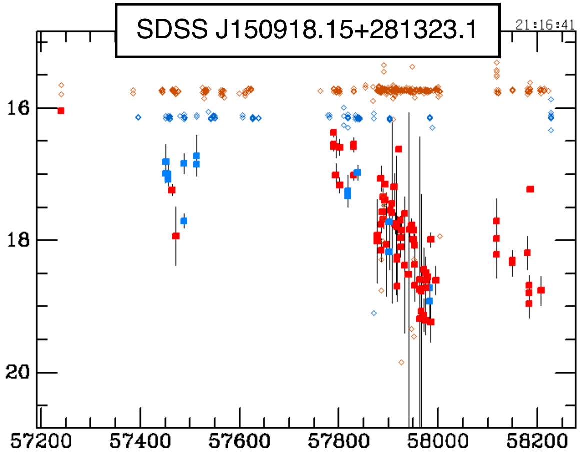
Quasars and ATLAS

- The “Milliquas 5.2” sample
  - ~0.6 million confirmed QSOs
  - ~1.3 million suspected QSOs
- ATLAS DR1 (Dec>-30)
  - Light curves for ~10^5 brighter than R~18
  - ~1/3 at m<15.5 are clearly variable
- ATLAS DR2 (Dec>-45)
  - Light curves for ~$2x10^5$, better SNR, better time sampling, longer duration




2MASS J23253138-3010560


SDSS J160020.63+372703.4


SDSS J150918.15+281323.1

More Opportunities

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

Gravitational Lensing

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

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

Results

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

Galaxies

- Low surface brightness
  - ATLAS does very well for building up SNR at low surface brightness.
  - Ongoing project to determine all-sky surface brightness to high accuracy in order to remove atmospheric glow and scattered light…

- Low metallicity
  - ATLAS can search for Hα and [OIII] at $z<0.004$
    - all-sky survey to m_{AB}~17 (point source) in one night
    - f~$2x10^{-14}$ erg/s/cm^2 or L~10^5 $L_{\odot}$/s at 17 Mpc.

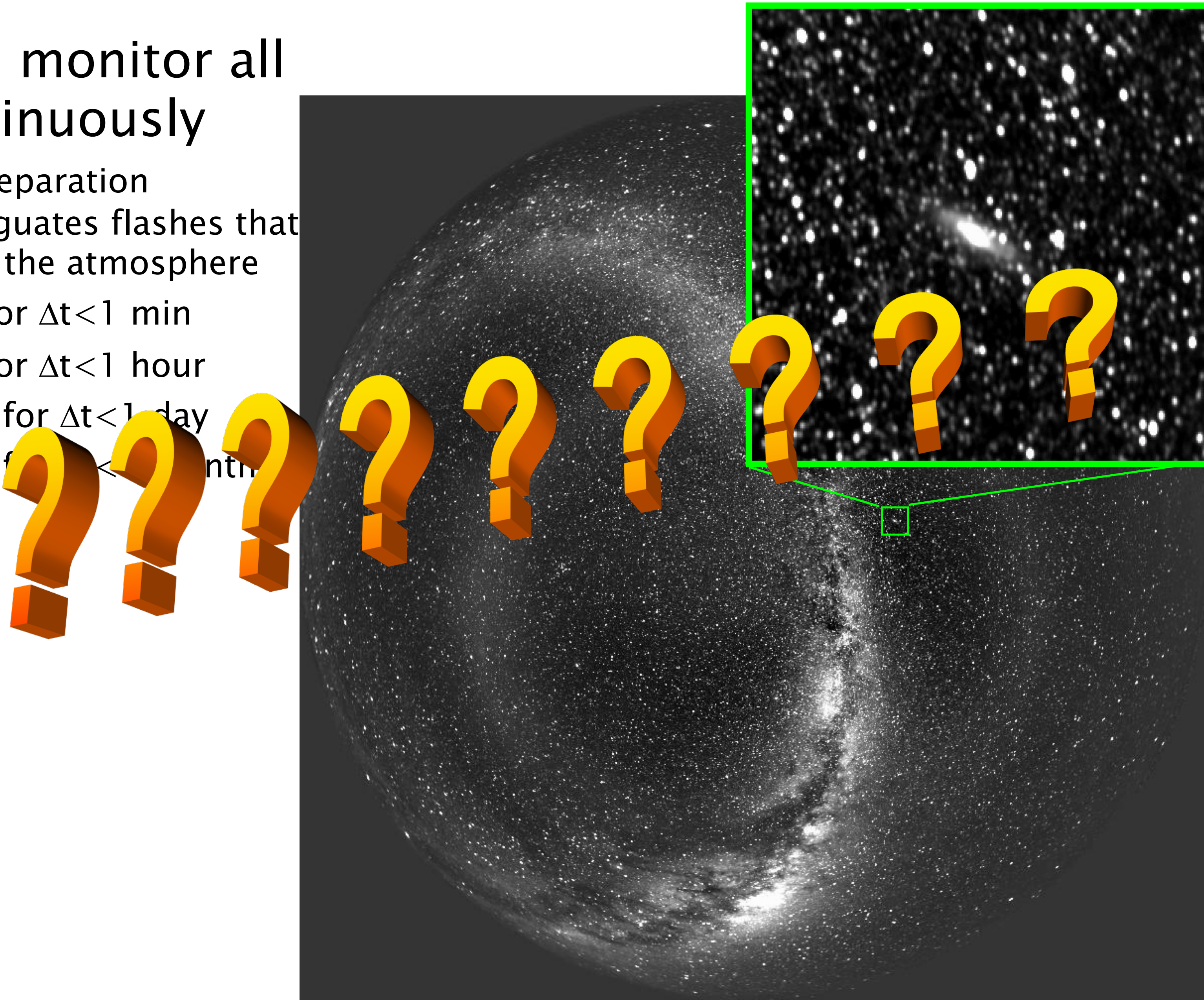
- Outbursts comparable to galaxy luminosity will be seen in substantial numbers
  - ~20 BH stellar accretion events (MV ~ -18) per year at 0.1mag photometric accuracy

Results

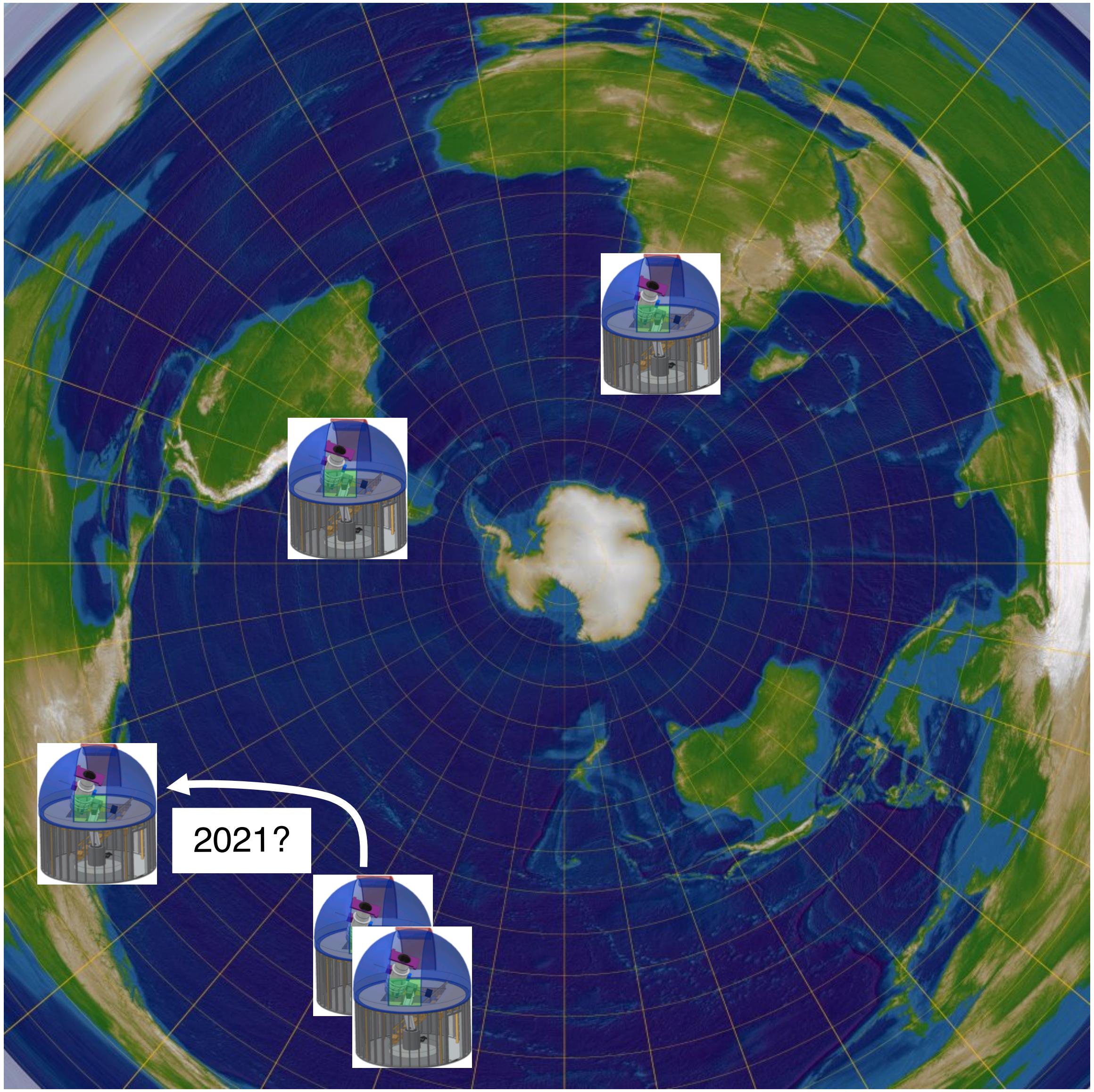
Nobody has yet made a case for the observations…

Unknown Unknowns from Fisheyes

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



ATLAS expansion (late 2020)

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  - Armin Rest
  - Stephen Smartt
  - Ken Smith
  - Alan Fitzsimmons
  - Chris Stubbs
- Friends
  - Phil Whitney
  - Gareth Wynn-Williams
  - Chris Oliver
  - The STAC

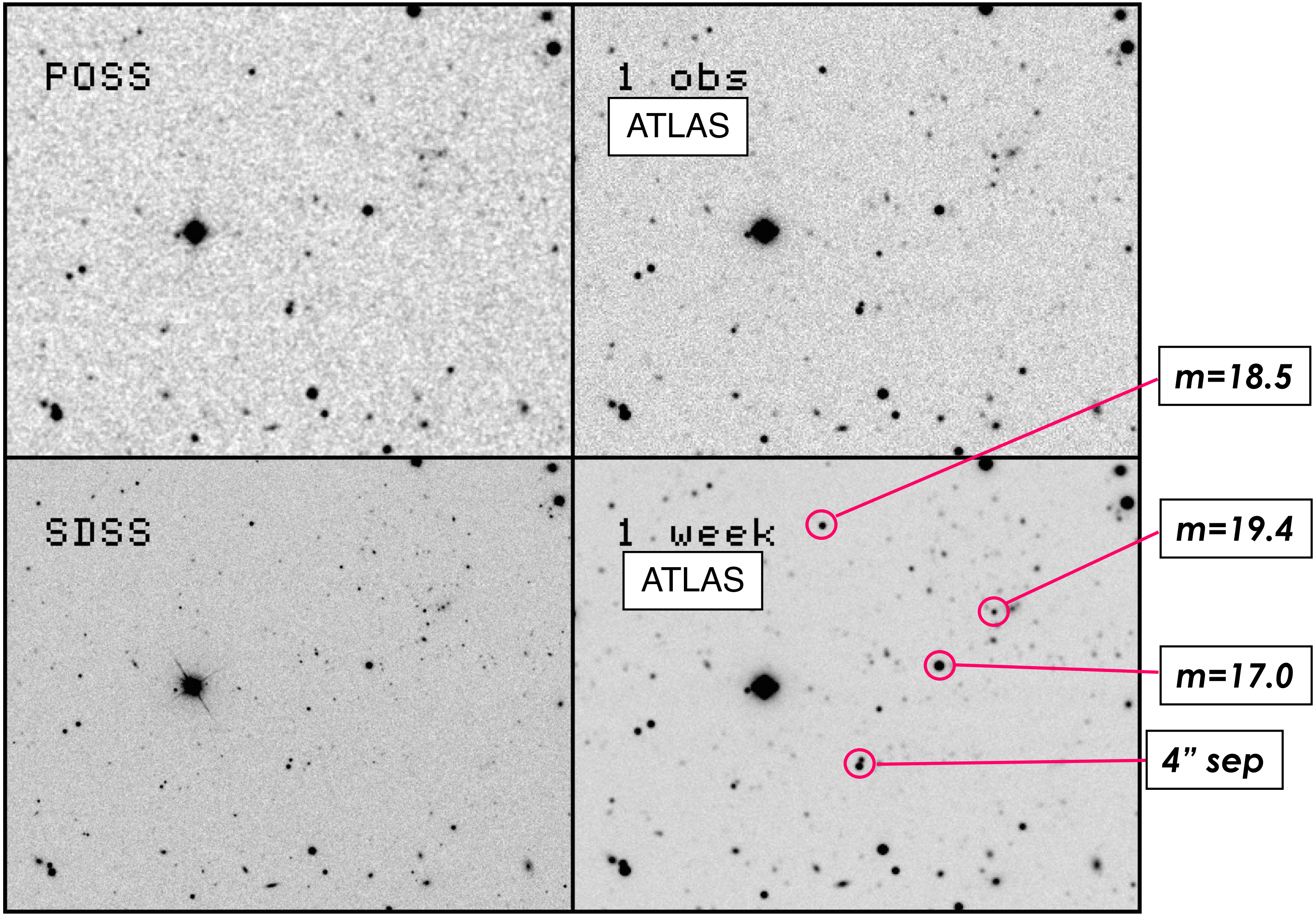
Static Sky

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

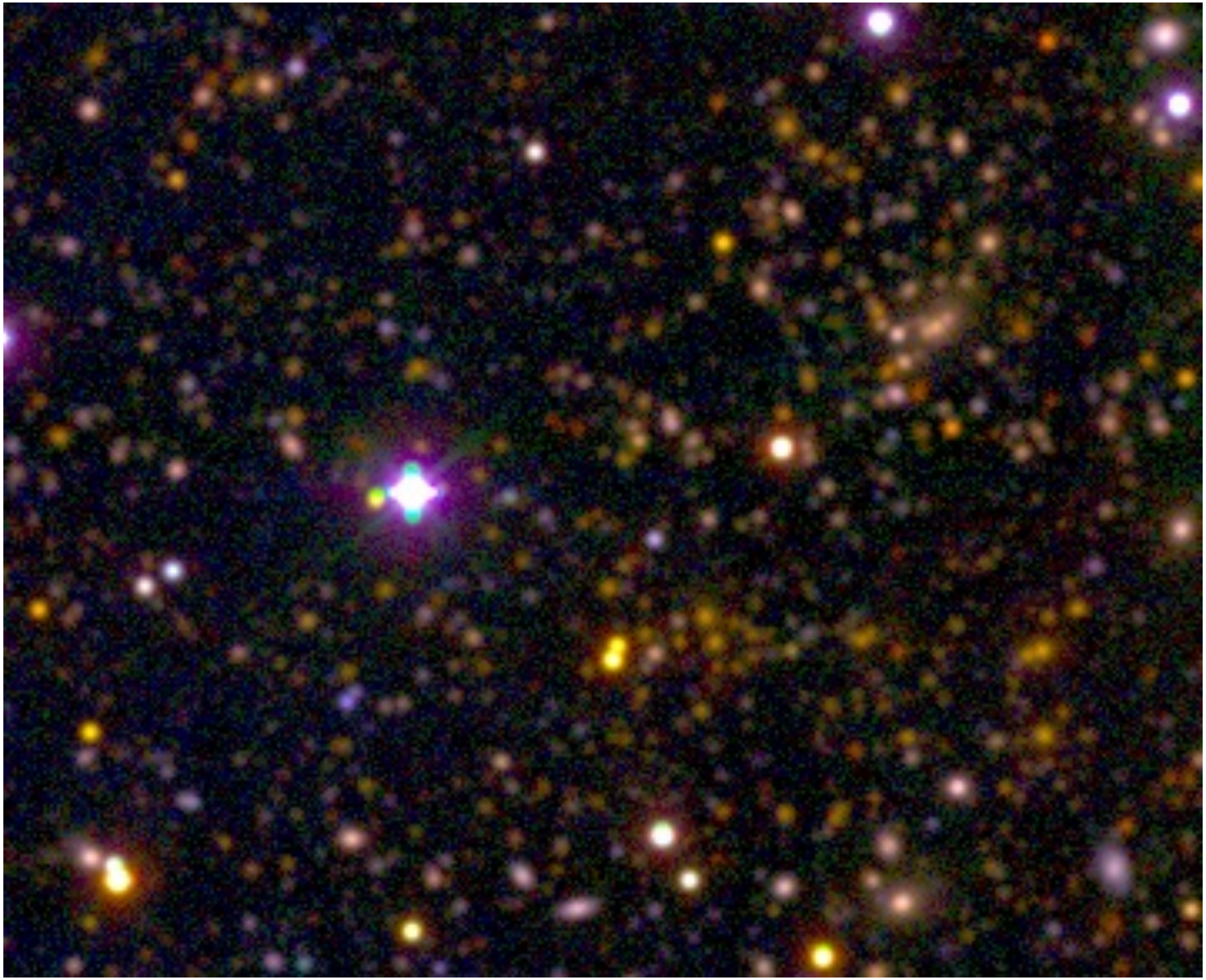
- *But note* highly confused for static sources, although excellent for differencing

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

ATLAS-POSS-SDSS Comparison



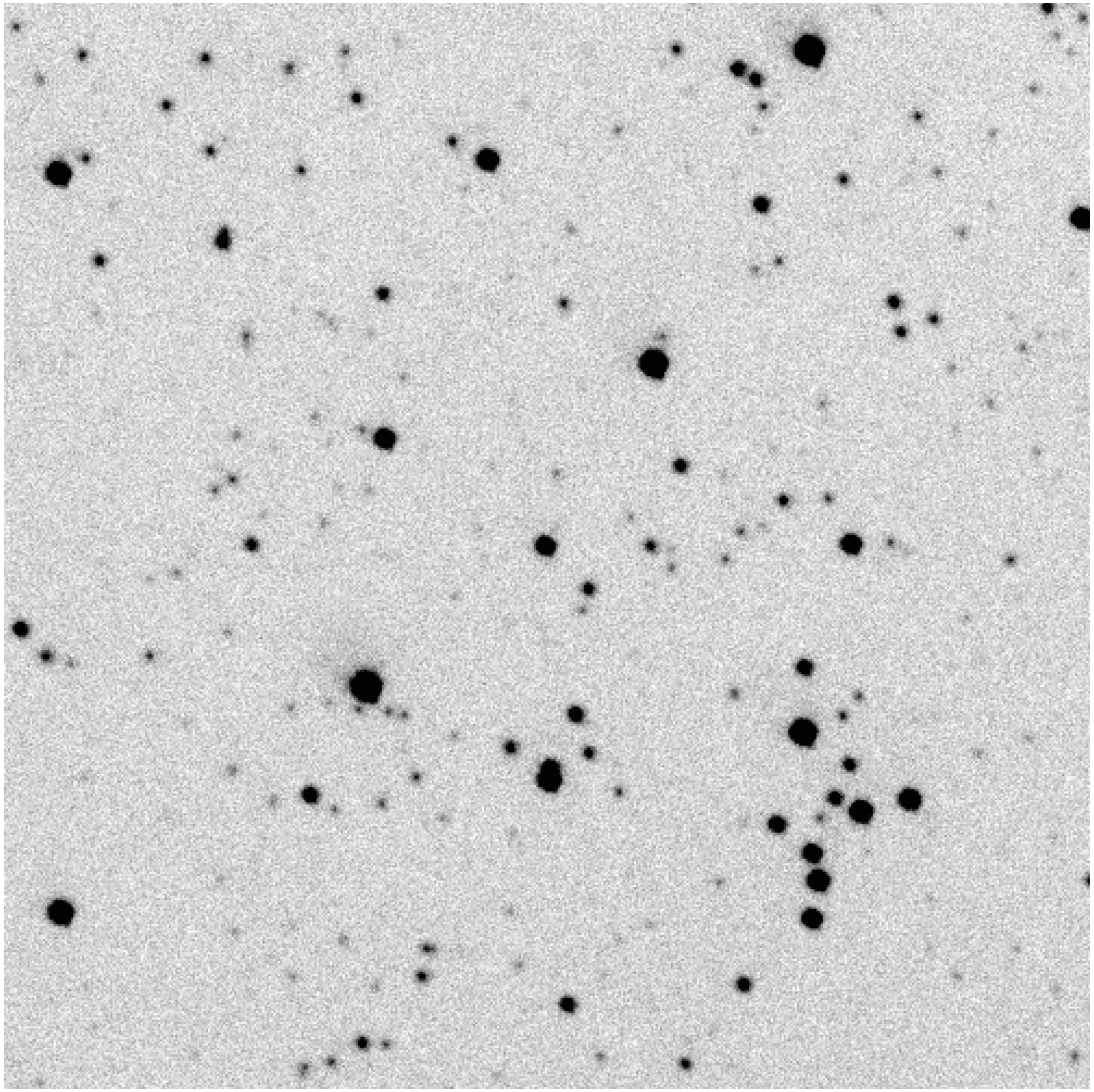
ATLAS: one year observation



SDSS

Schmidt corrector saga: 150601 — 170419

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



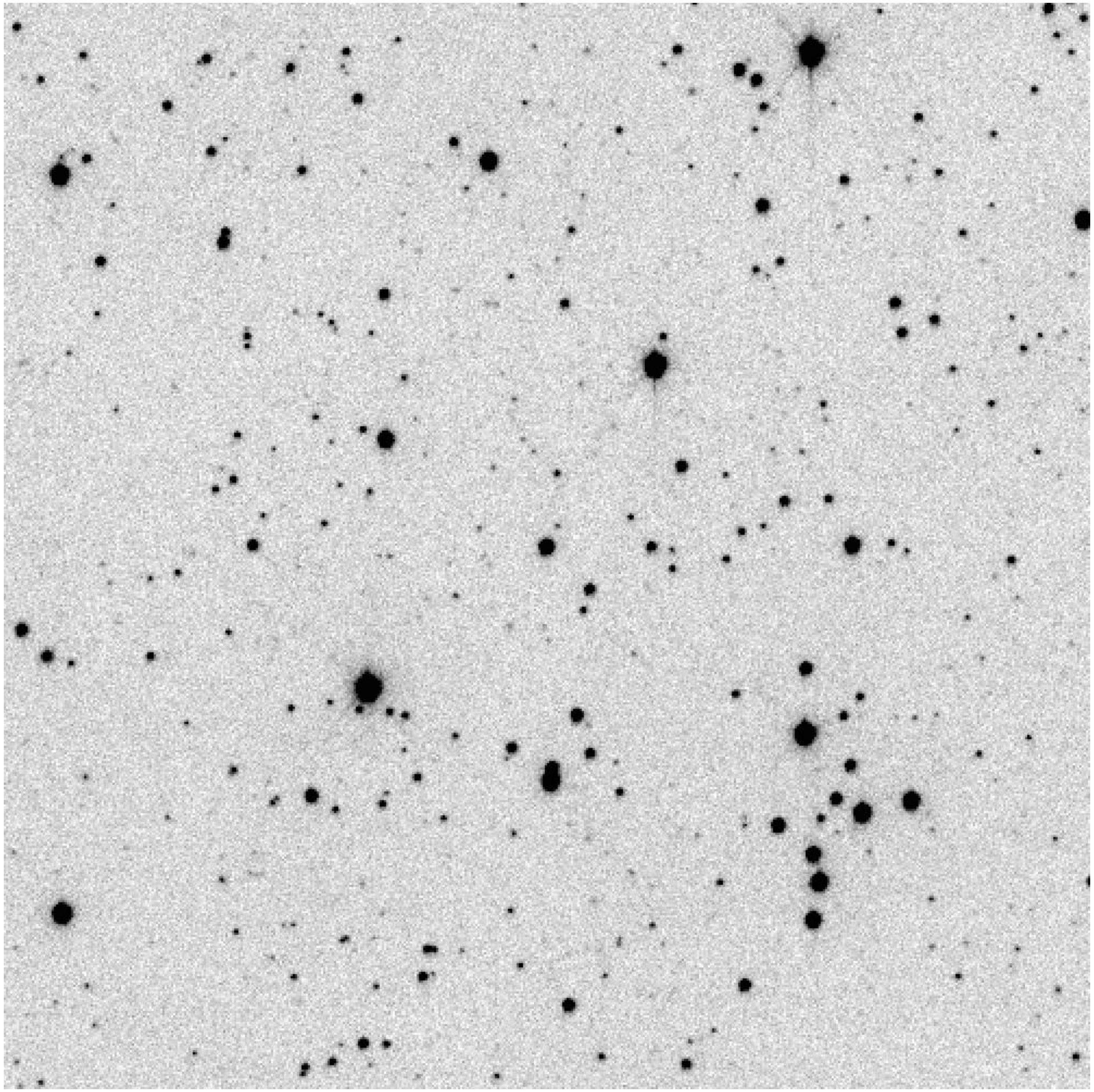
(All results in this talk are from the first telescope on HKO with blurry images. From now on we gain ~1 mag at fixed uncertainty or 2.5x smaller uncertainty at fixed mag.)

Schmidt corrector saga: 170420 —

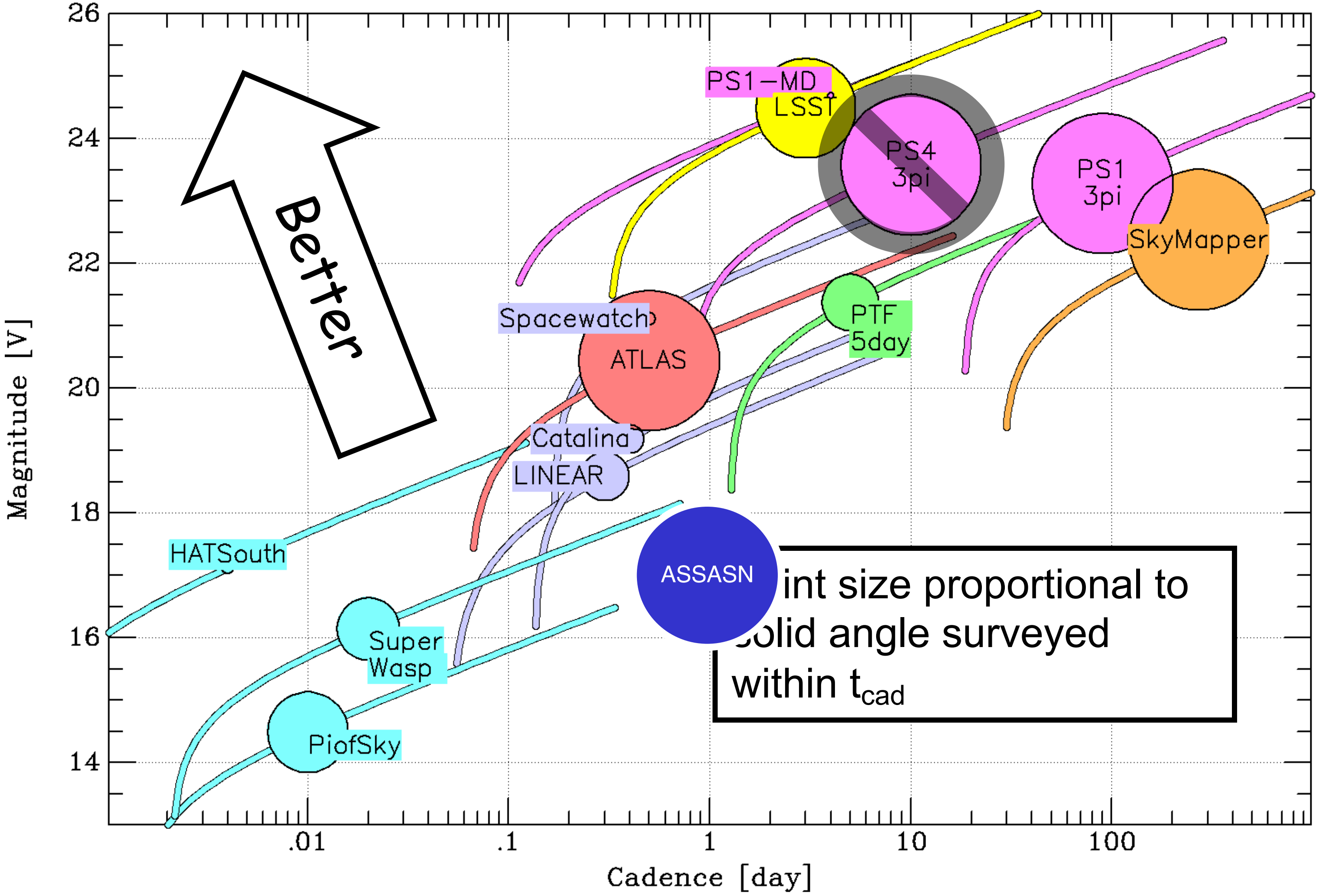
- PSF ~ 2.0 pixels
  ~ 3.7 arcsec
- m_{lim} ~ 20

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

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



Survey Speed



int size proportional to
olid angle surveyed
within t_{cad}

Tonry 2011, PASP 123, 58

Survey Speed

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

Tonry 2011 PASP 123, 58

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

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

- μ = sky brightness

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