Discovering sources of millihertz gravitational radiation using photons from synoptic surveys

Michael W. Coughlin

June 14, 2023

Discovering sources of millihertz gravitational radiation using photons from synoptic surveys

With Special Thanks to Kevin Burdge (MIT) and Yashvi Sharma (CIT)

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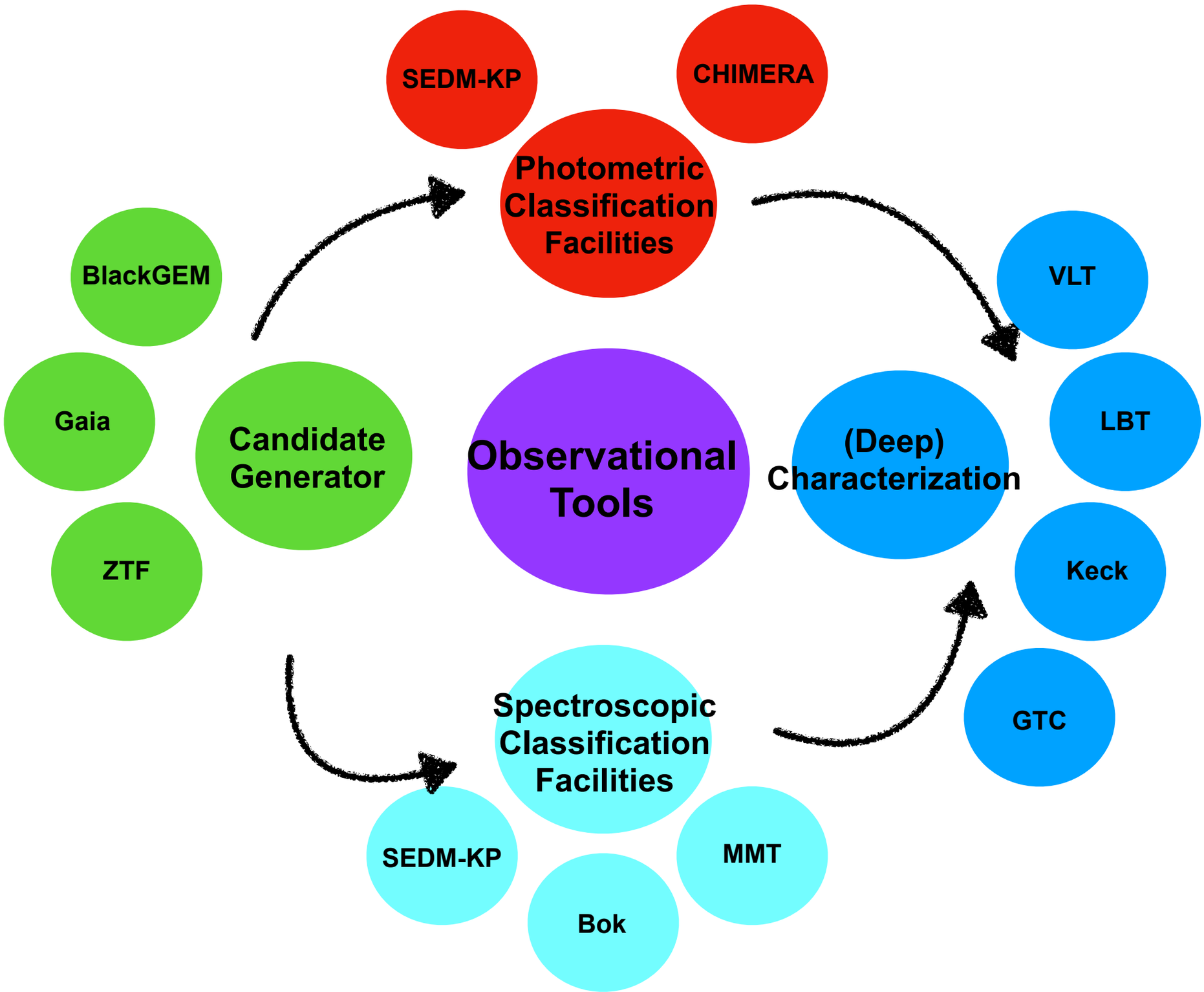
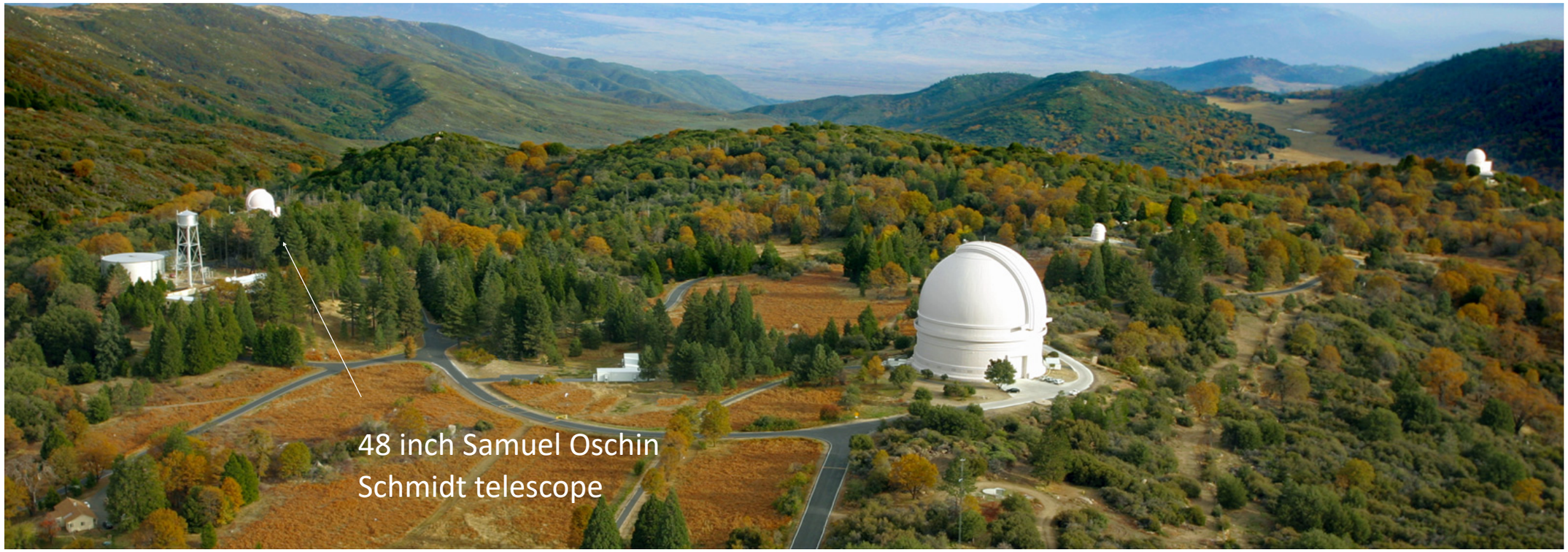
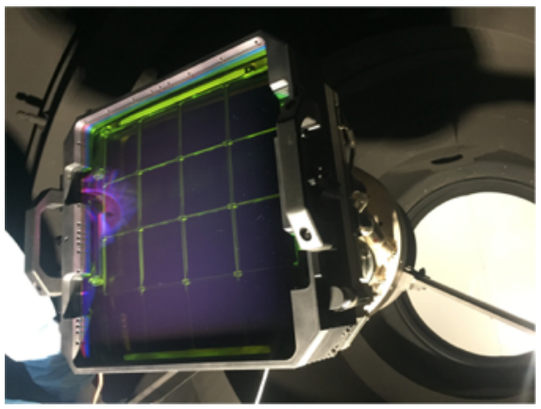
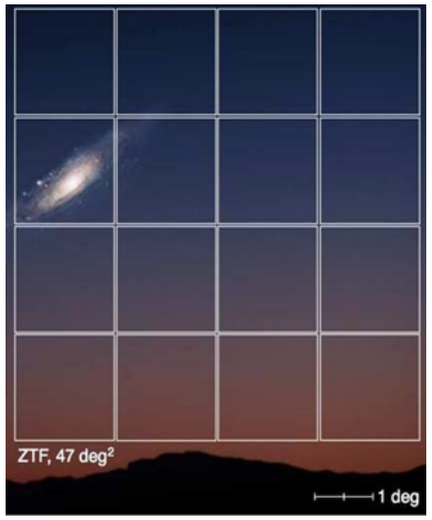
The Observational Landscape



From gravitational waves to photons

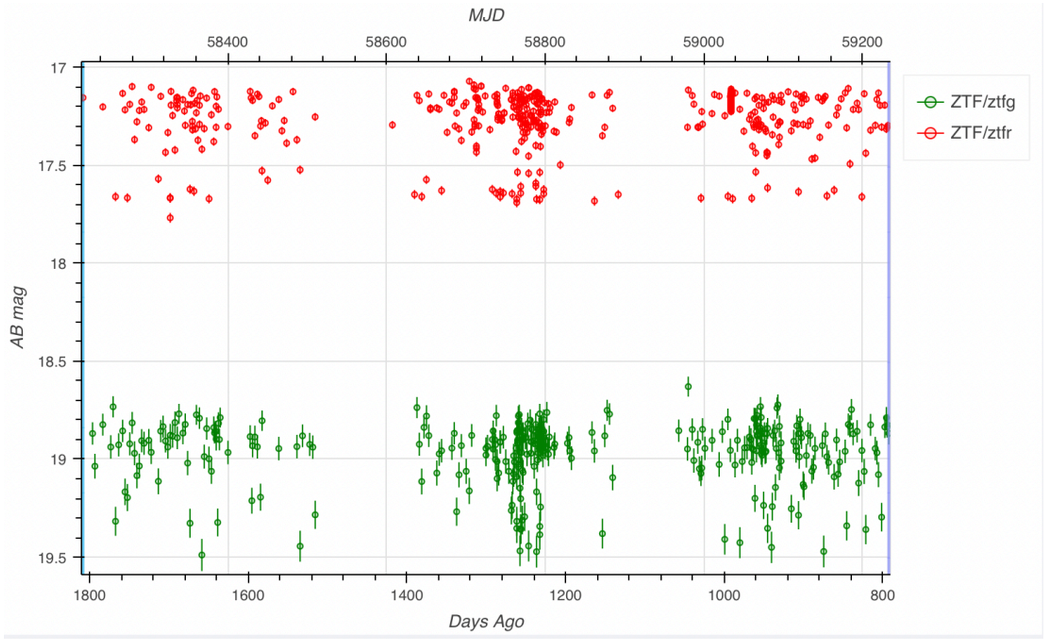




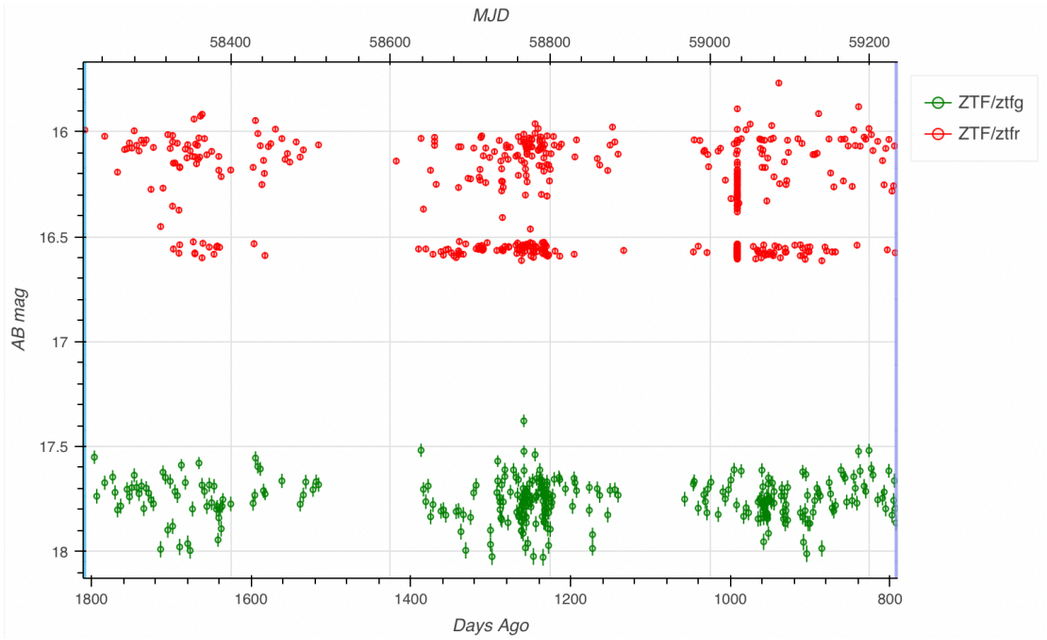


The crucial element: ZTF has a large field of view, and accumulates many images quickly

Optical Data



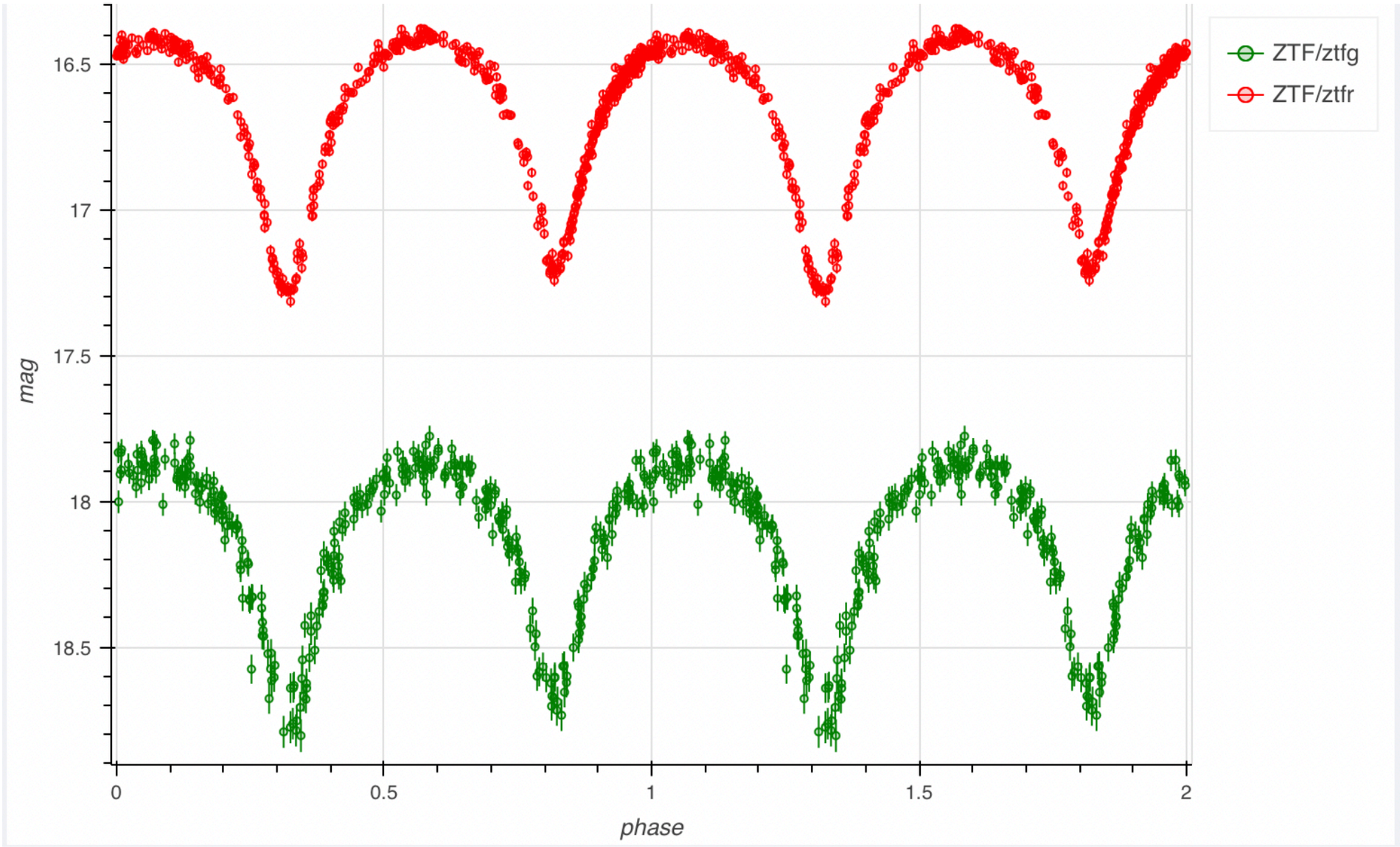
Beta Lyrae



Blend

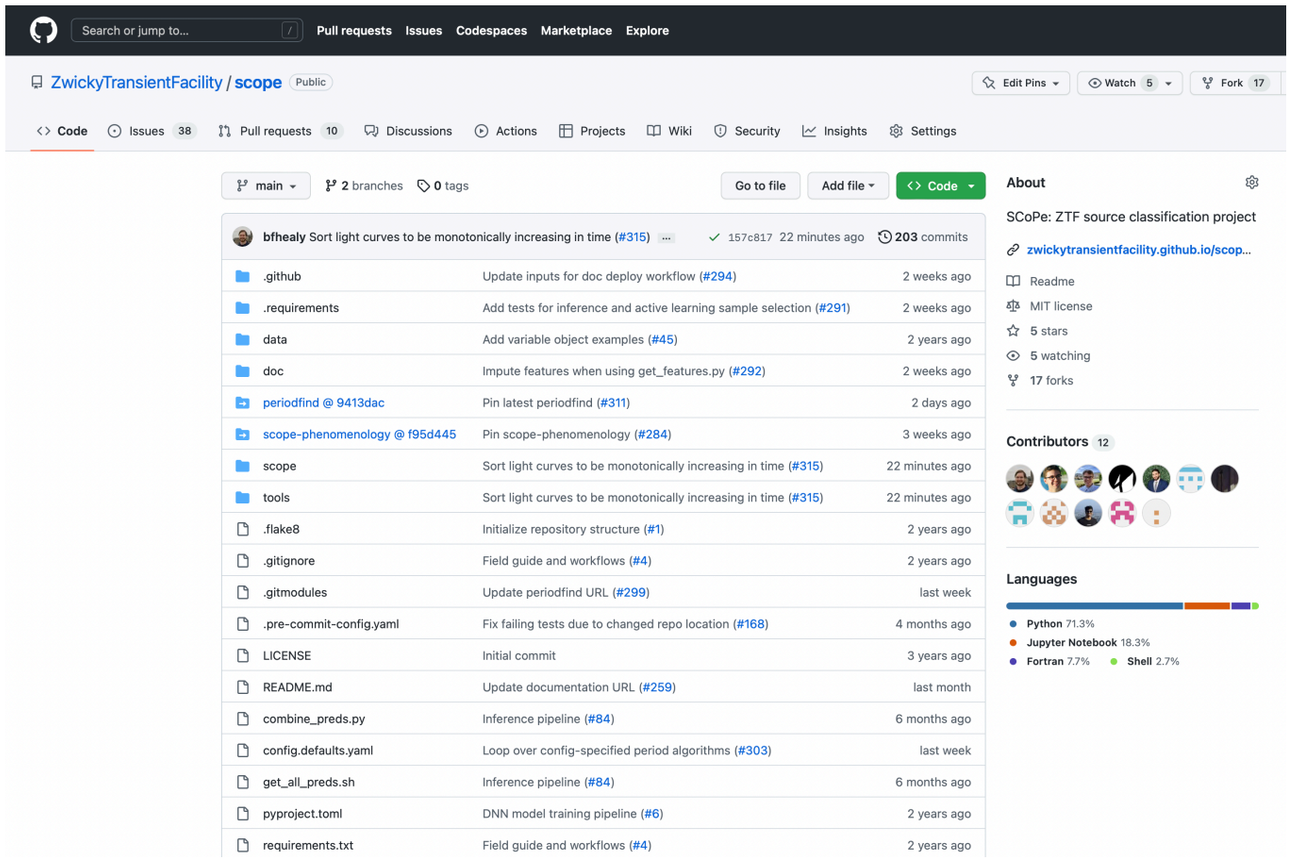
And with the help of some other kinds of hardware…

Optical Data



W Ursae Maj
(contact binary)
P = 0.35017 d

ZTF Source Classification Project



- Open-source
- Python-based
- CI/CD pipeline
- Regularly updated docs

- **Supervised, active learning:** training set built up over time (w/human input)
- **Two taxonomies:** ontological (intrinsic), phenomenological (light curve shape)
  - Provides useful information for anomalous sources
  - Avoids complications of overlapping classes

(van Roestel et al. 2021, Coughlin et al. 2021)

Many identified… many yet to be discovered.

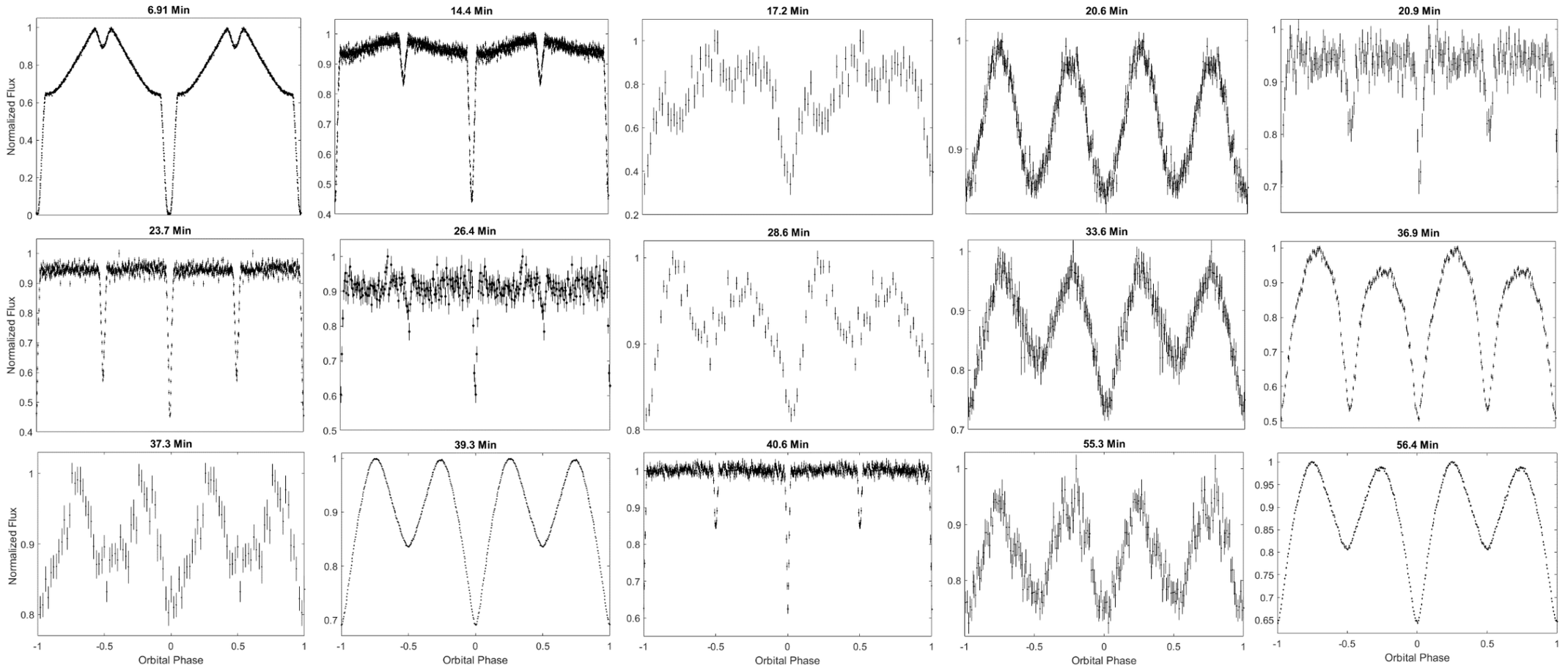
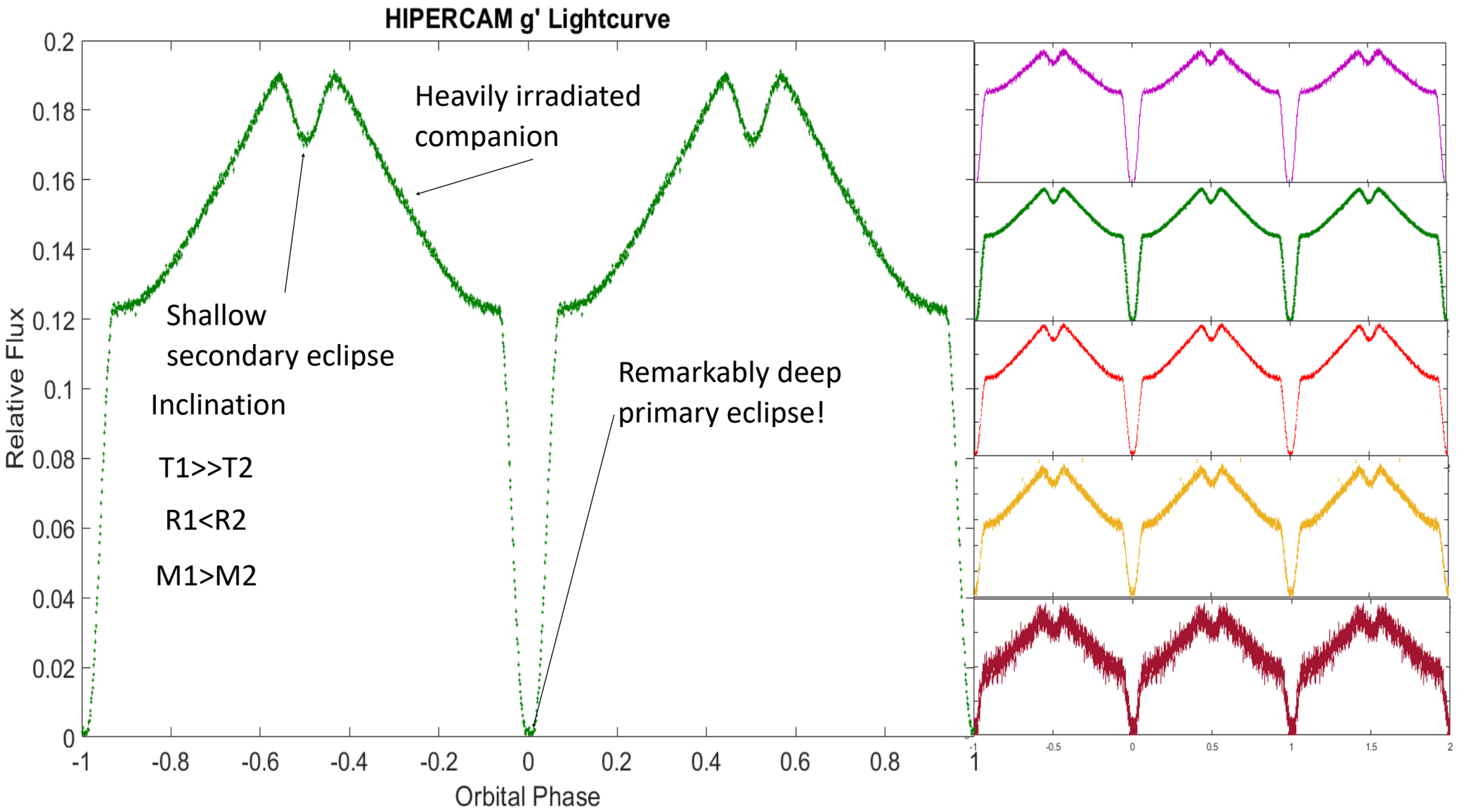


Figure from Burdge et al. 2020

- ZTF contains more than 20,000 objects exhibiting periodic flux variations at timescales shorter than half an hour
- This includes many new detached and accreting double degenerates
- Many other classes of sources, including intermediate polars, ZZ Cetis, DB WD pulsators, sdB pulsators, rapidly rotating isolated magnetic WDs, etc

And high-cadence follow-up allows for precision measurement



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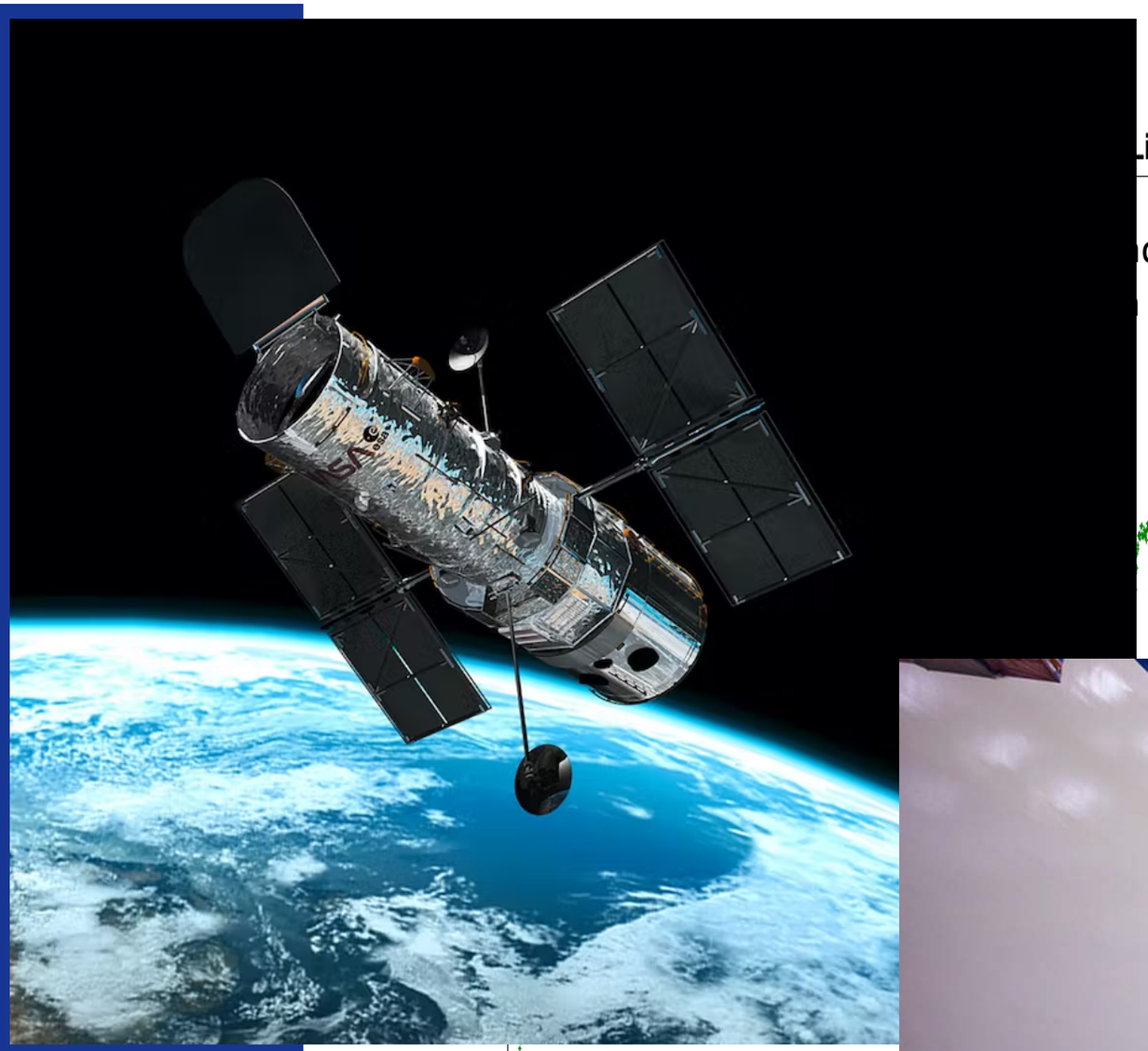

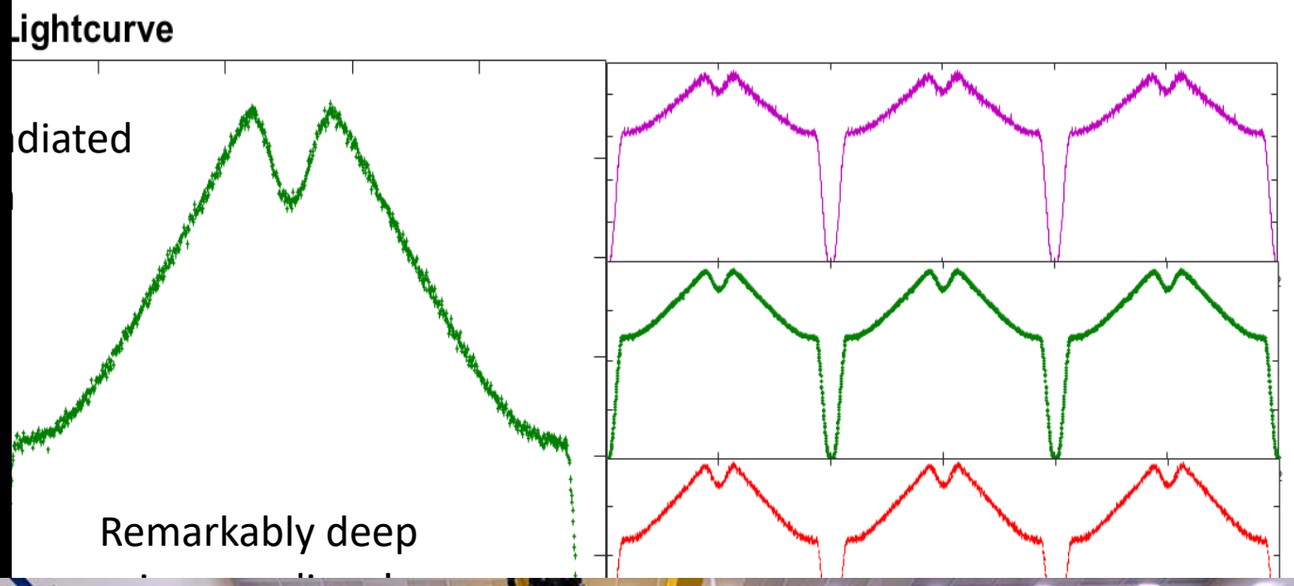

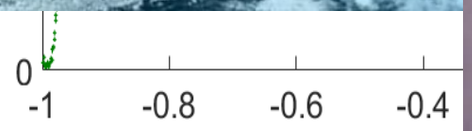

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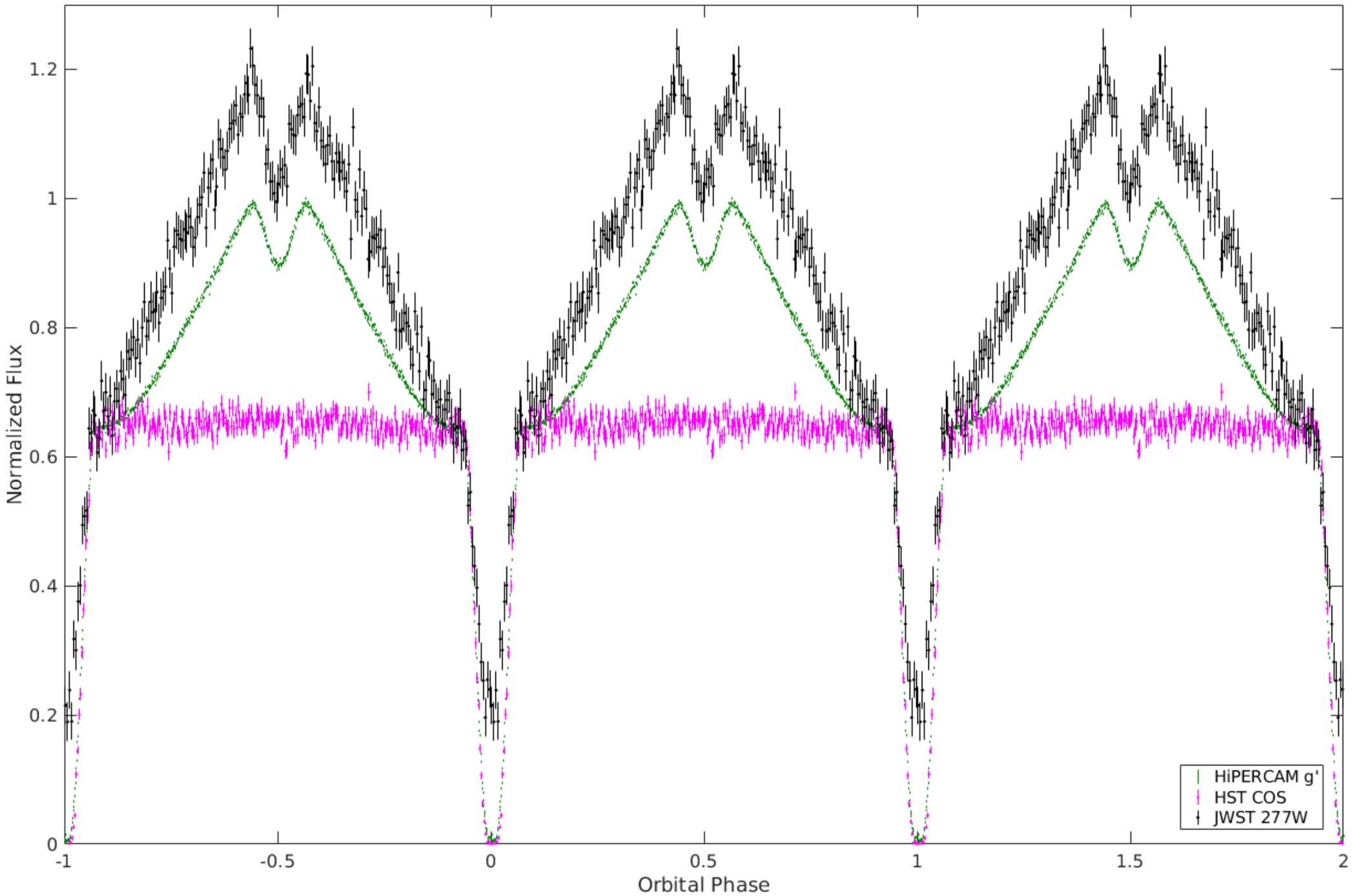
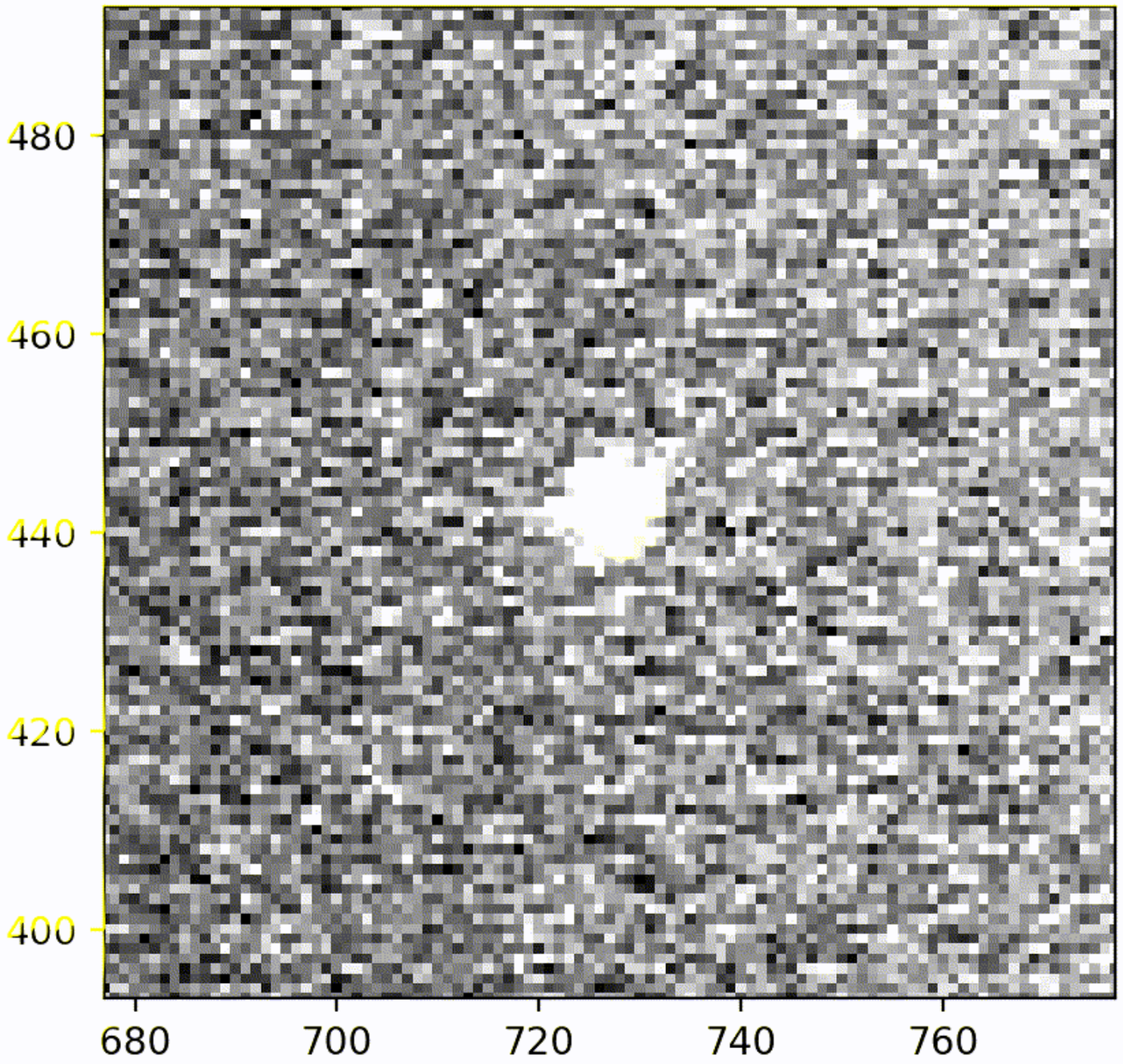
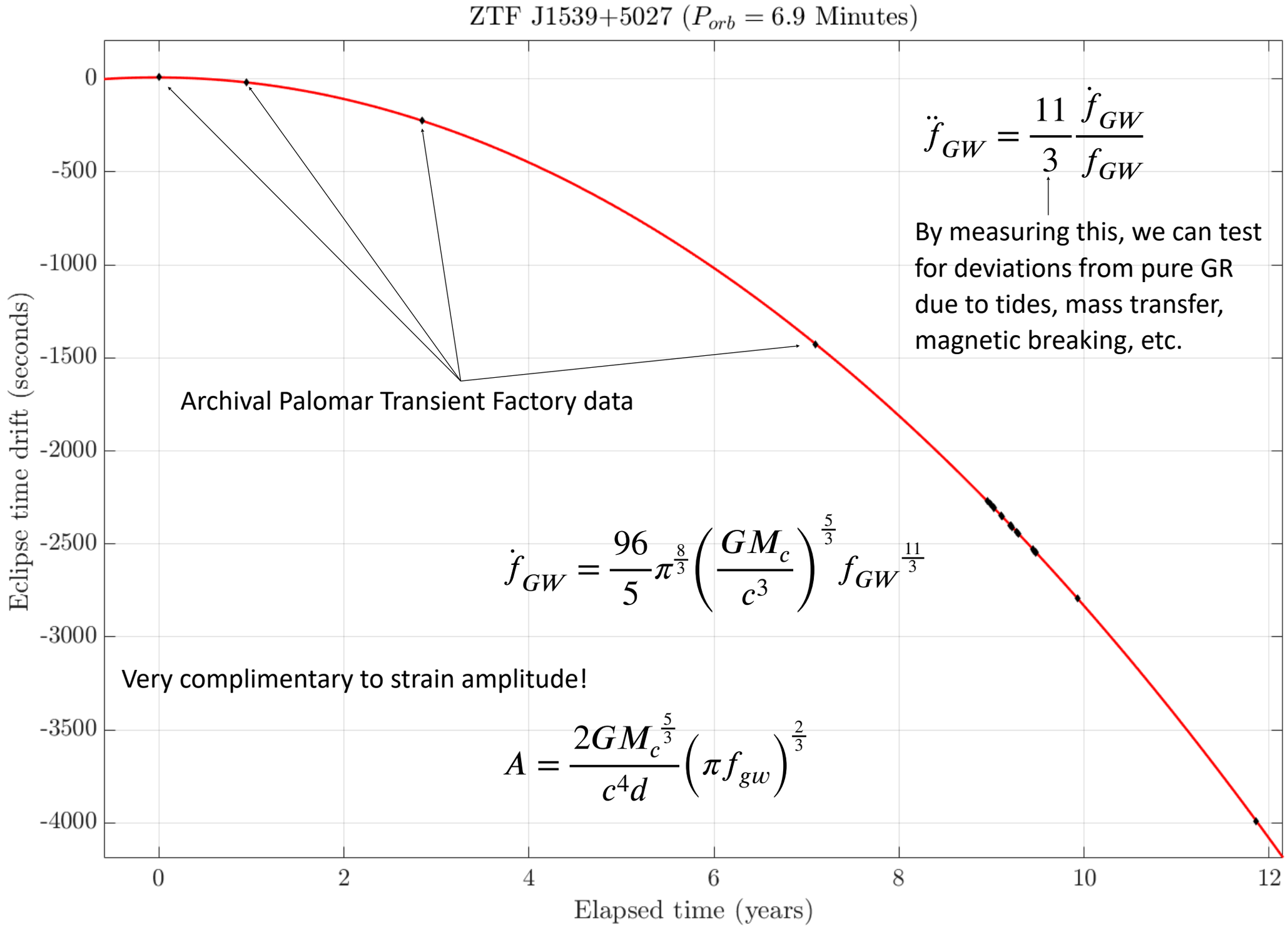


NB: The UV flux off the 50000K WD gets reprocessed at the temperature of the photosphere of the cooler WD, and it is so cool that basically nothing gets reprocessed in the UV.

The 6.9 minute binary on the Kitt Peak 2.1 meter



Measuring period derivatives



$$\ddot{f}_{GW} = \frac{11}{3}\frac{\dot{f}_{GW}}{f_{GW}}$$

By measuring this, we can test for deviations from pure GR due to tides, mass transfer, magnetic breaking, etc.

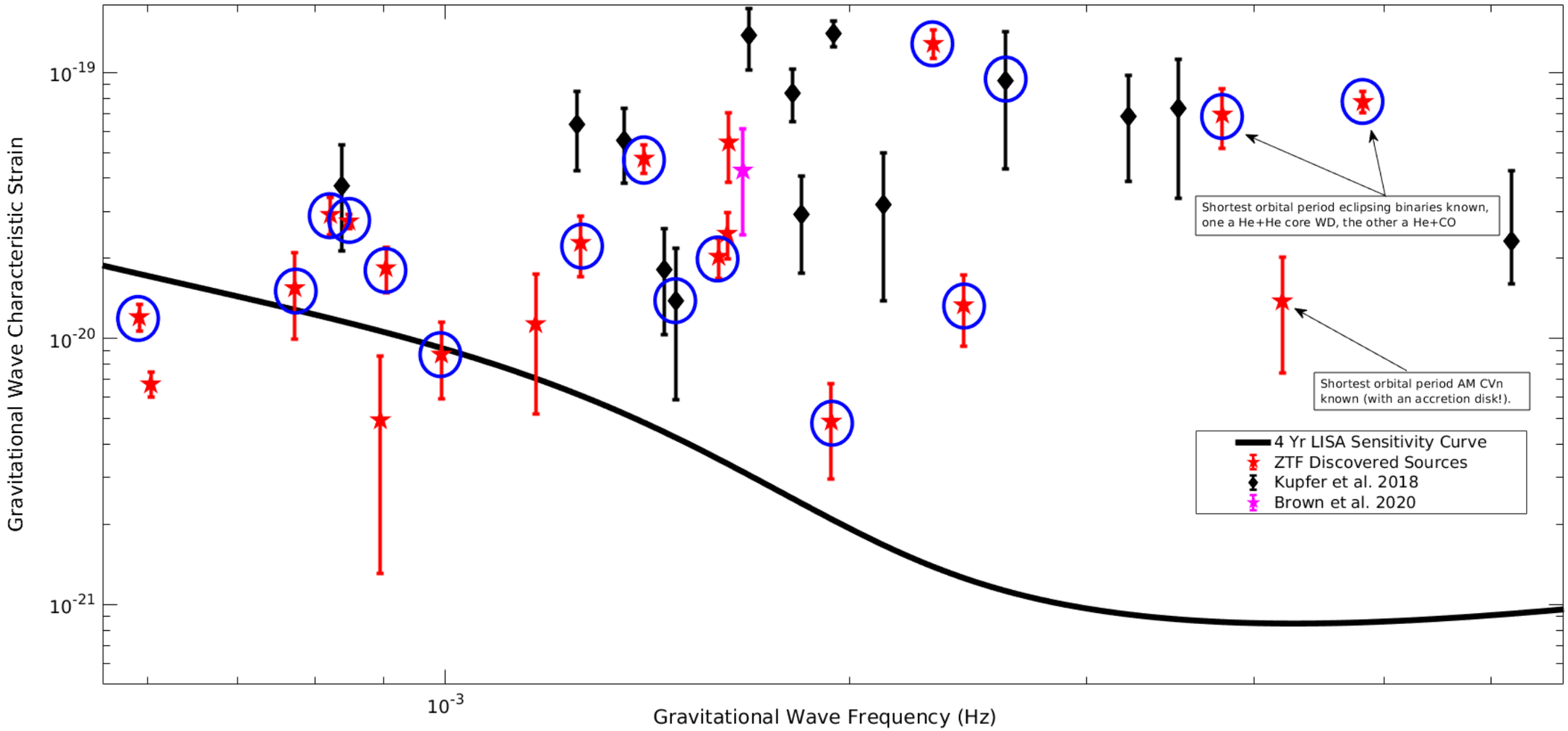
Archival Palomar Transient Factory data

$$\dot{f}_{GW} = \frac{96}{5}\pi^{\frac{8}{3}}\left(\frac{GM_c}{c^3}\right)^{\frac{5}{3}} f_{GW}{}^{\frac{11}{3}}$$

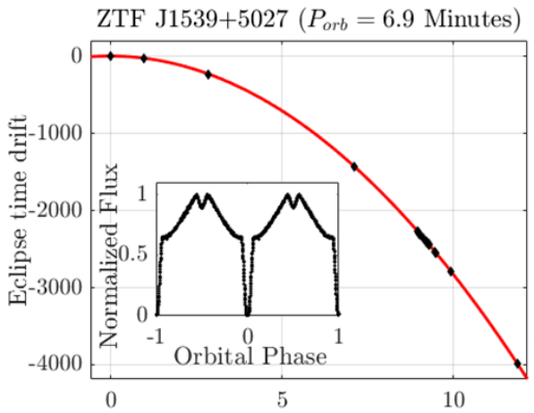
Very complimentary to strain amplitude!

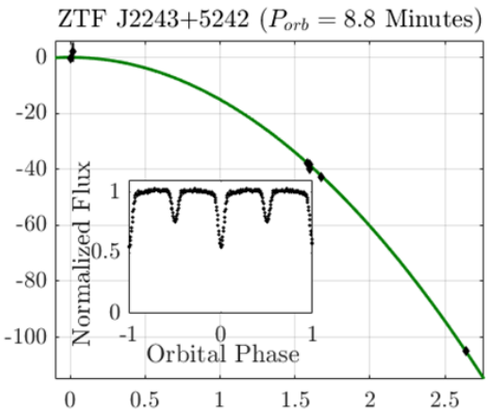
$$A = \frac{2GM_c{}^{\frac{5}{3}}}{c^4 d}\left(\pi f_{gw}\right)^{\frac{2}{3}}$$

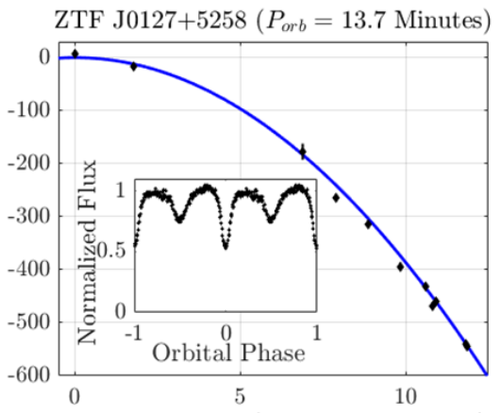
LISA strain sensitivity

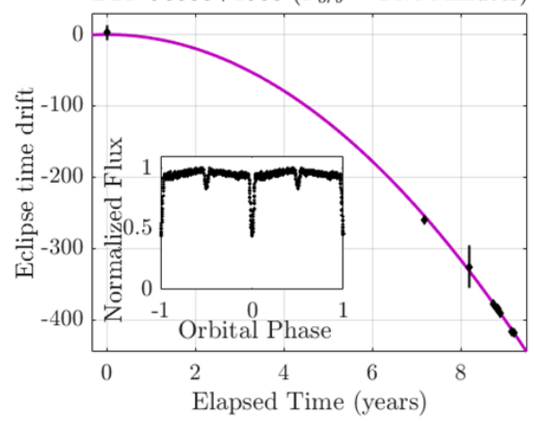


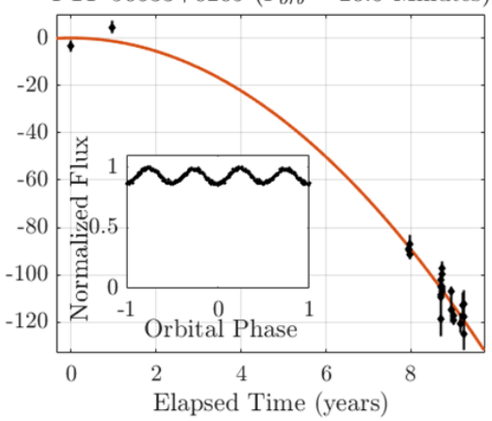
A growing sample for tracking

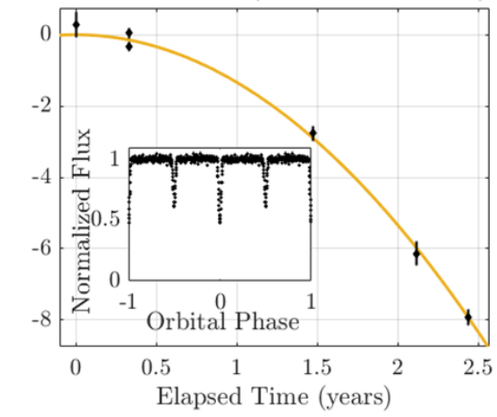


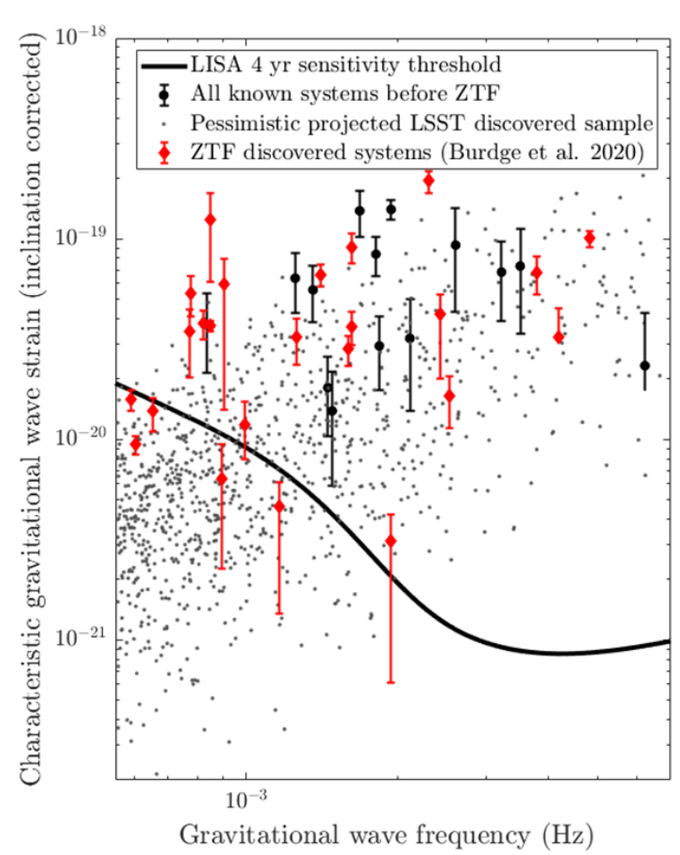












LISA EM-GW pipelines

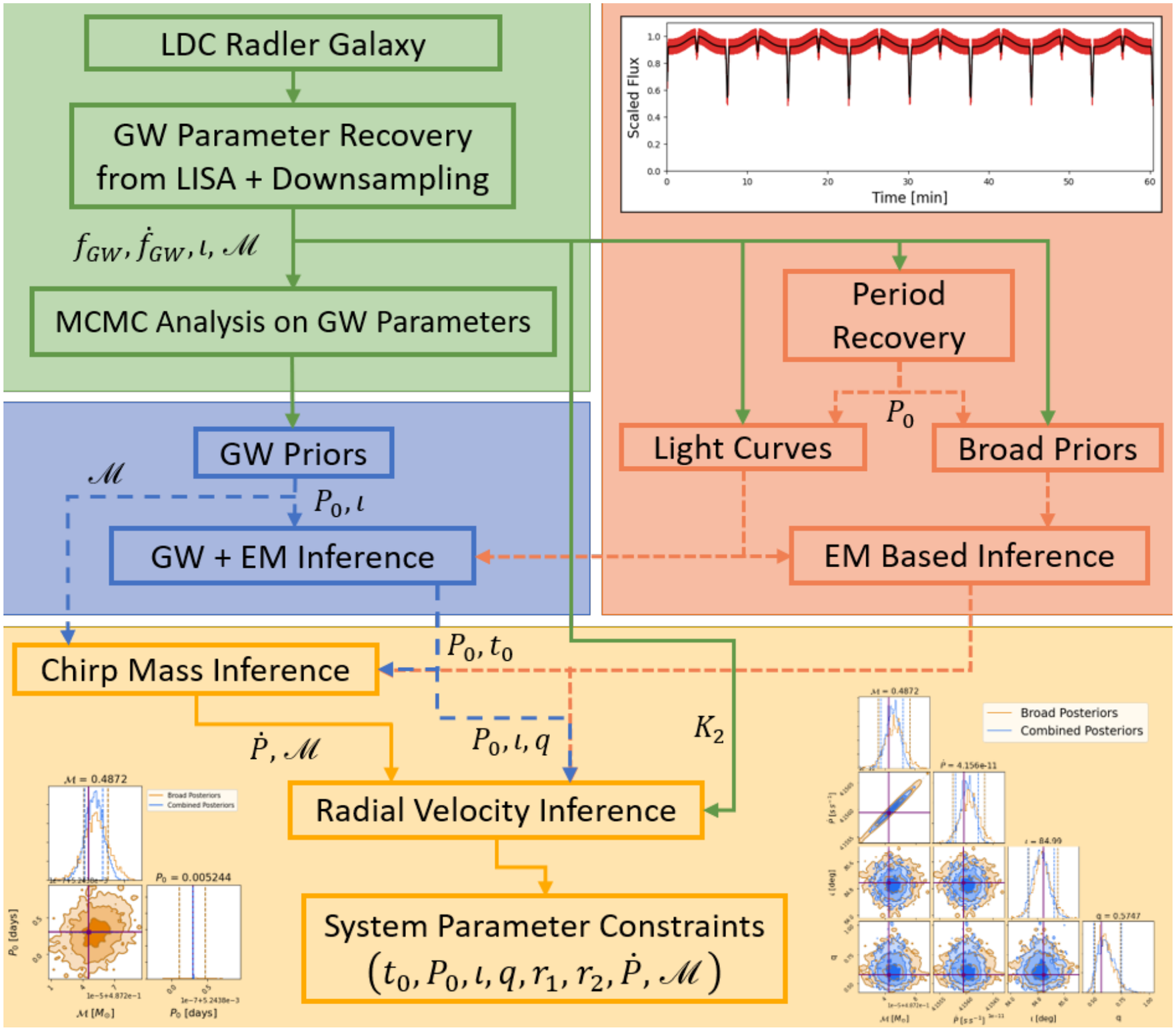
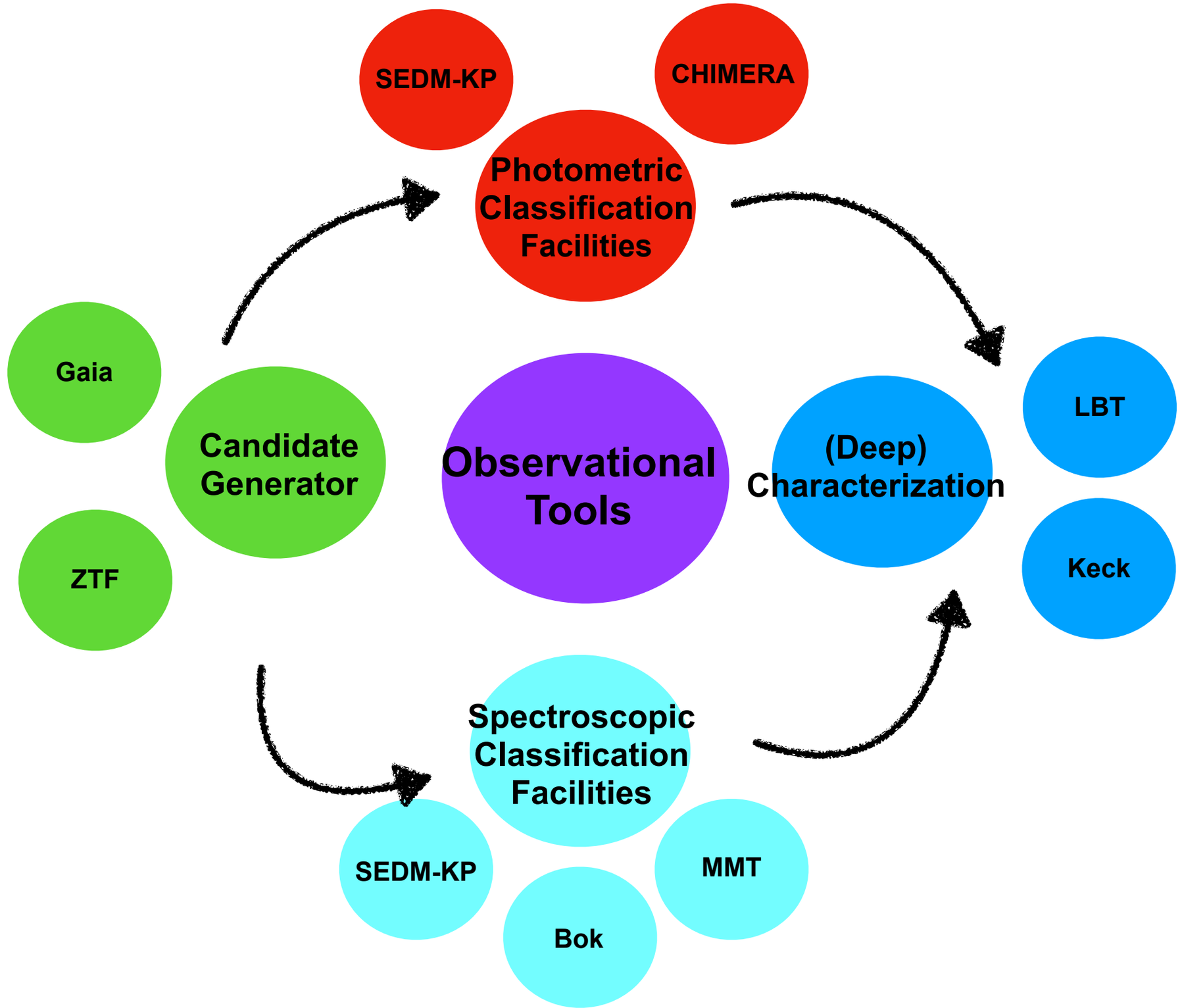


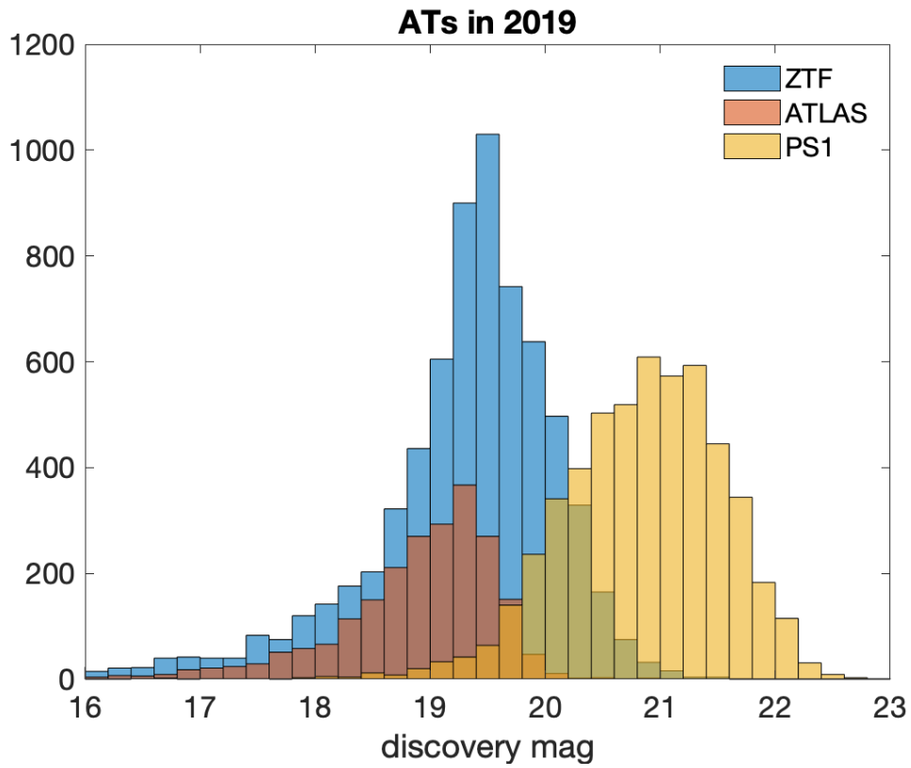
Figure from Johnson et al. 2023

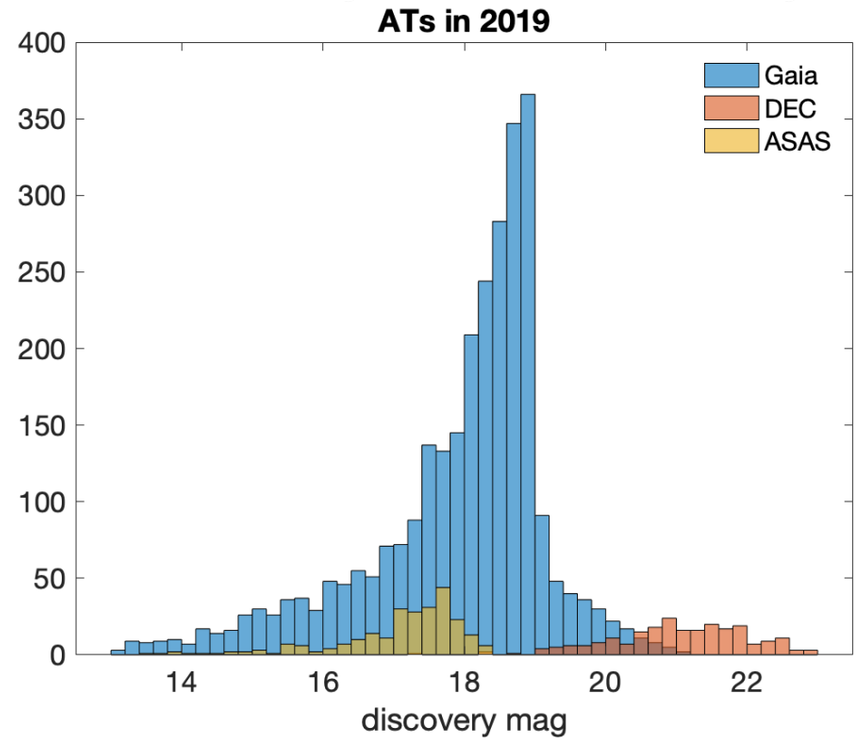
The Observational Landscape

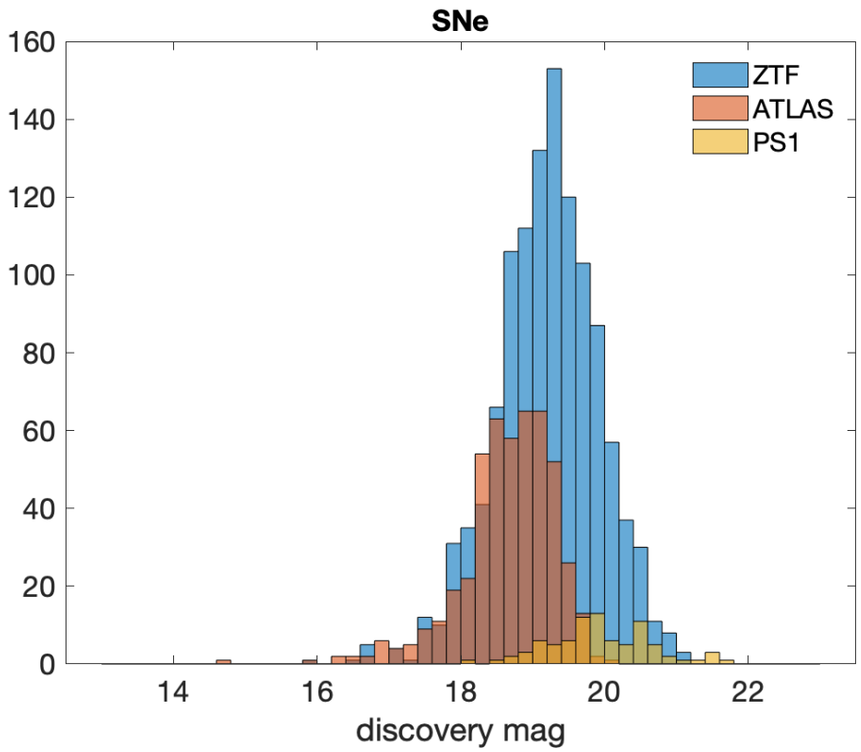


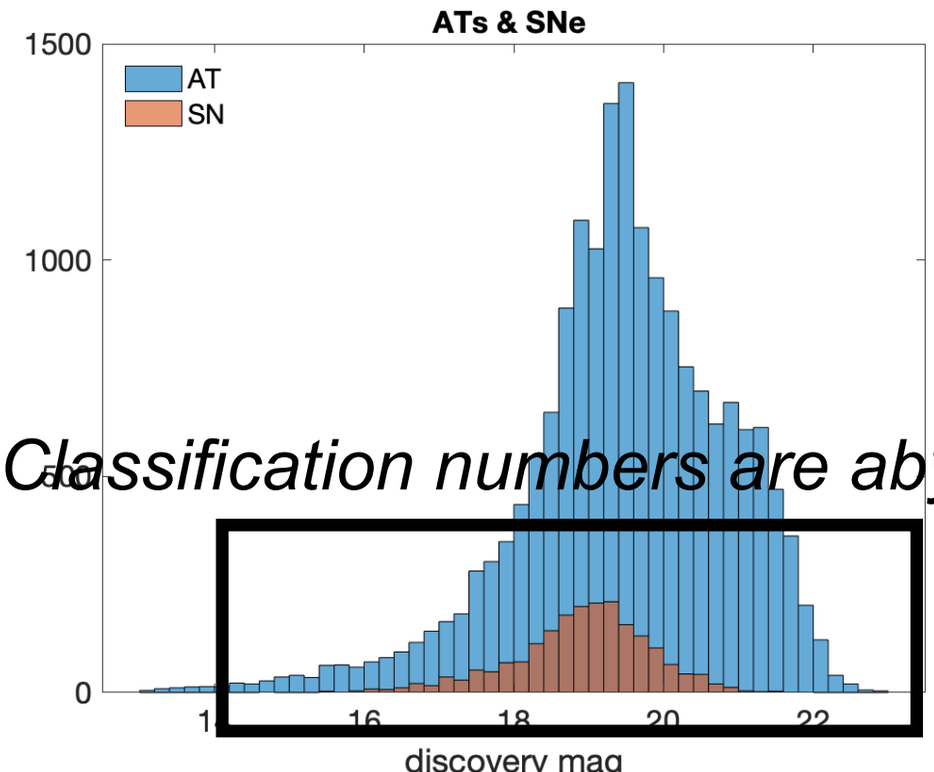
Classifying Astronomical Transients

In 2019 alone, 18,296 ATs were identified by various surveys



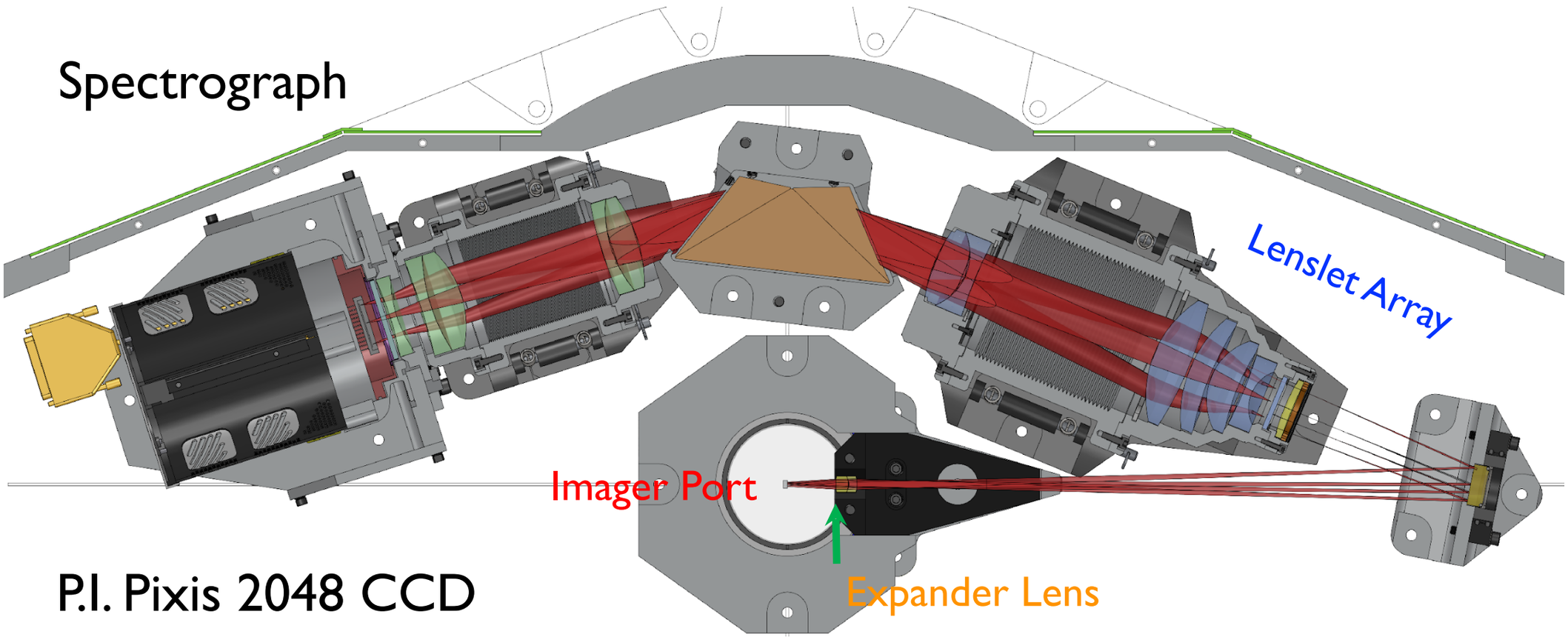






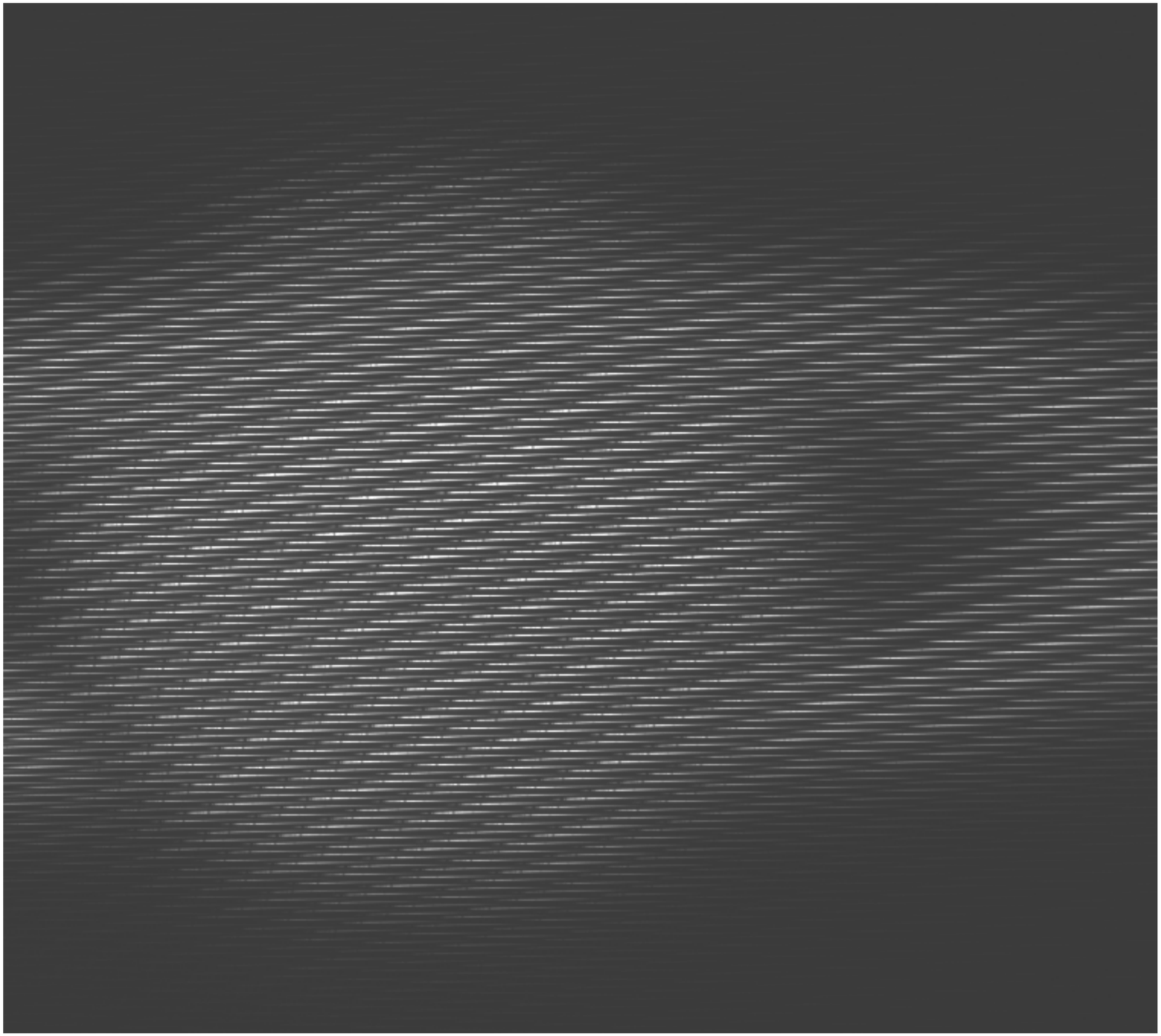
Classification numbers are abysmal

The SED Machine

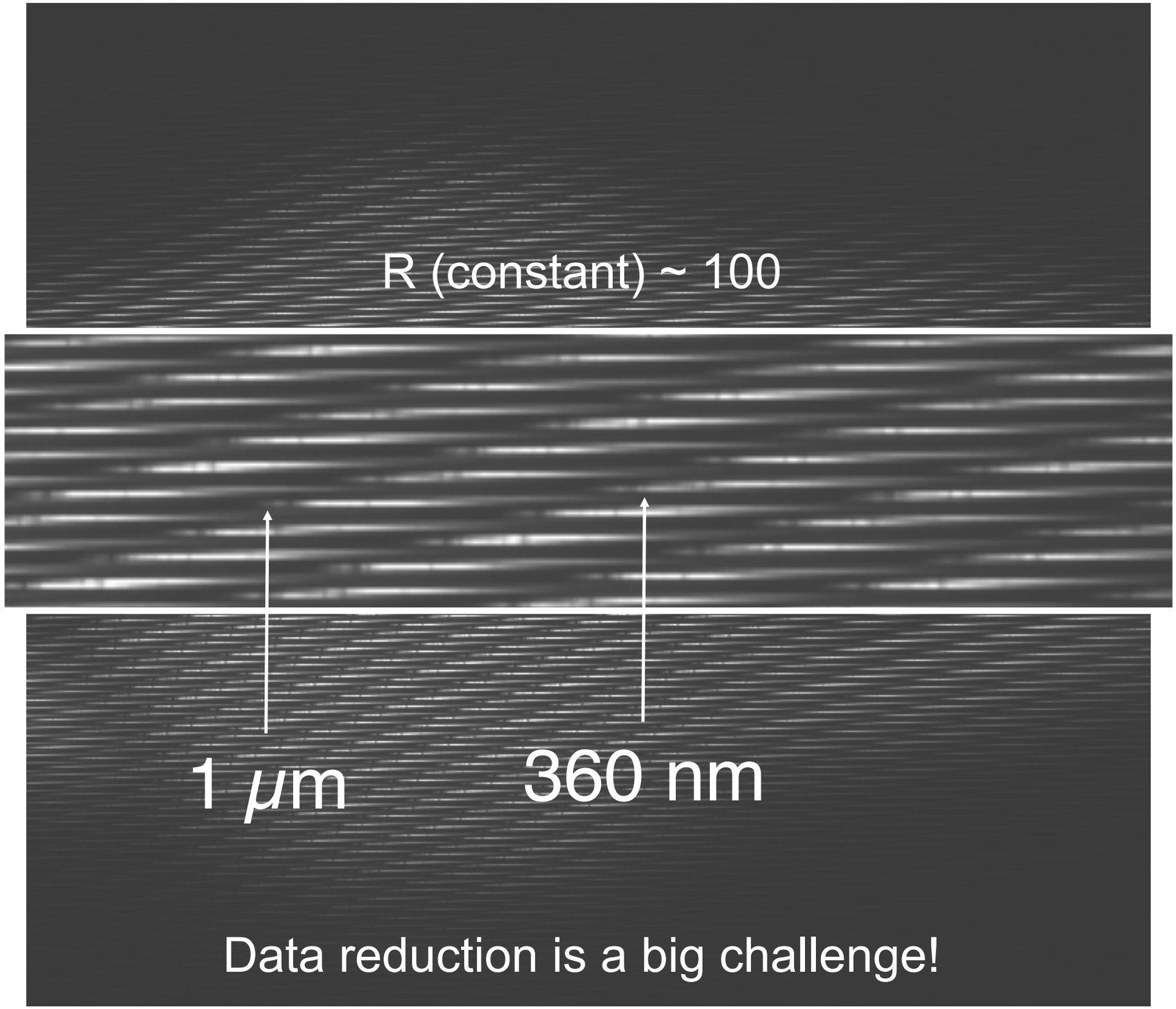


Ultra low resolution (R~100) hyperspectral imaging spectrograph

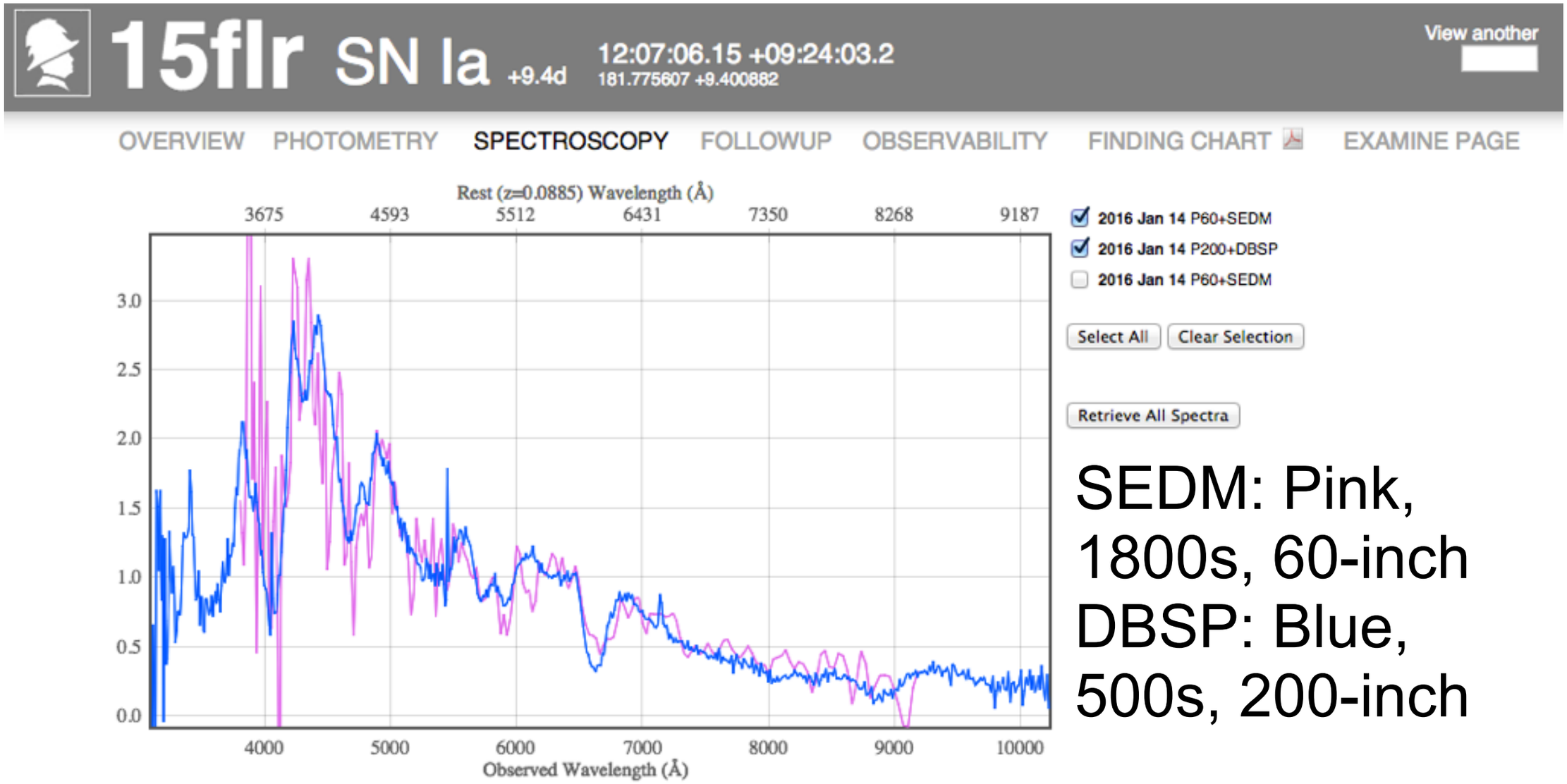
The SED Machine



The SED Machine (zoomed)



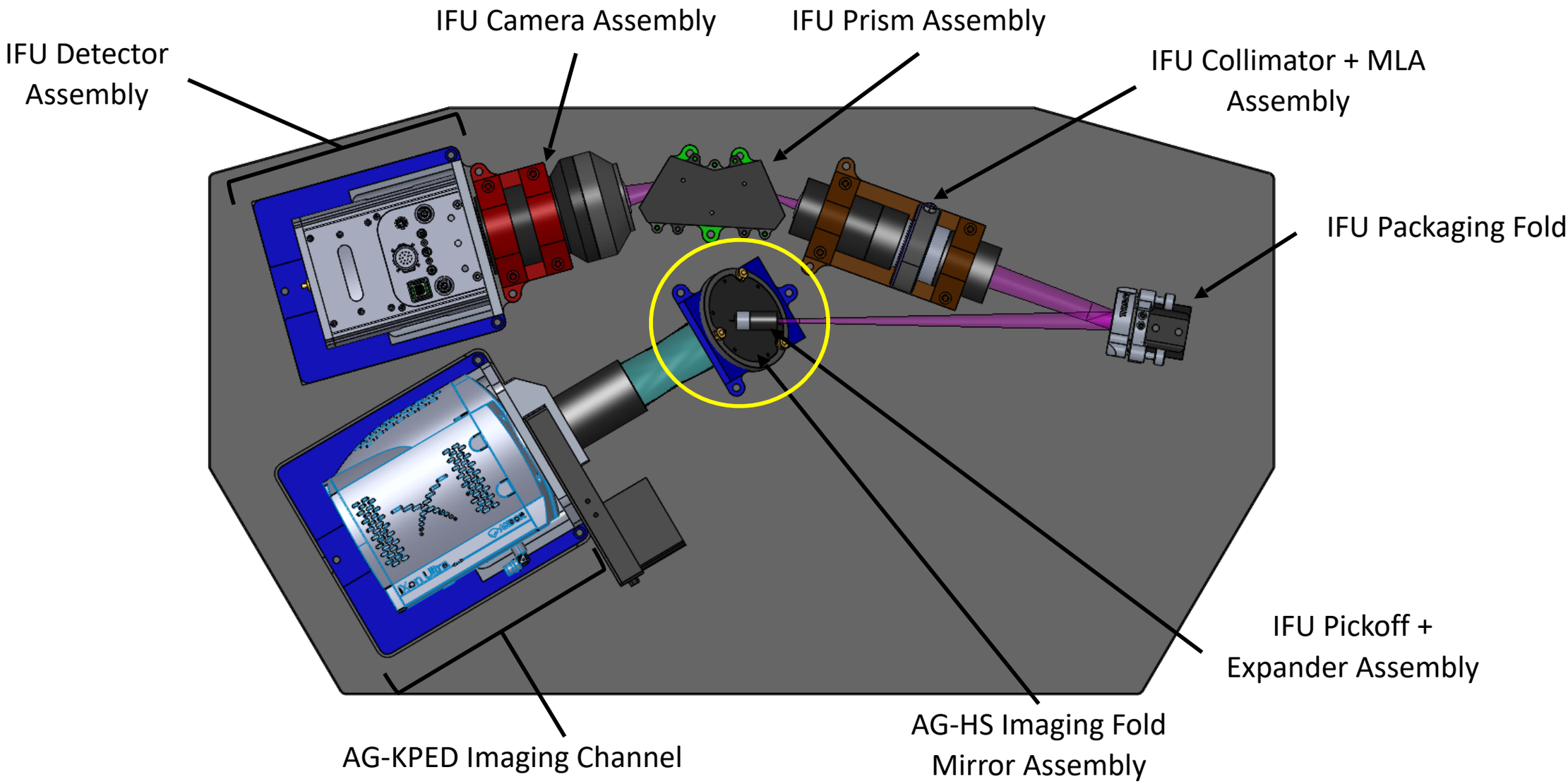
Comparison to higher resolution instruments



SEDM: Pink, 1800s, 60-inch
DBSP: Blue, 500s, 200-inch

- 50% of all SN classifications on TNS website
- Integral part of ZTF impact
- 10-20+ Targets Per Night (Depending on time of year)

SED Machine - Kitt Peak



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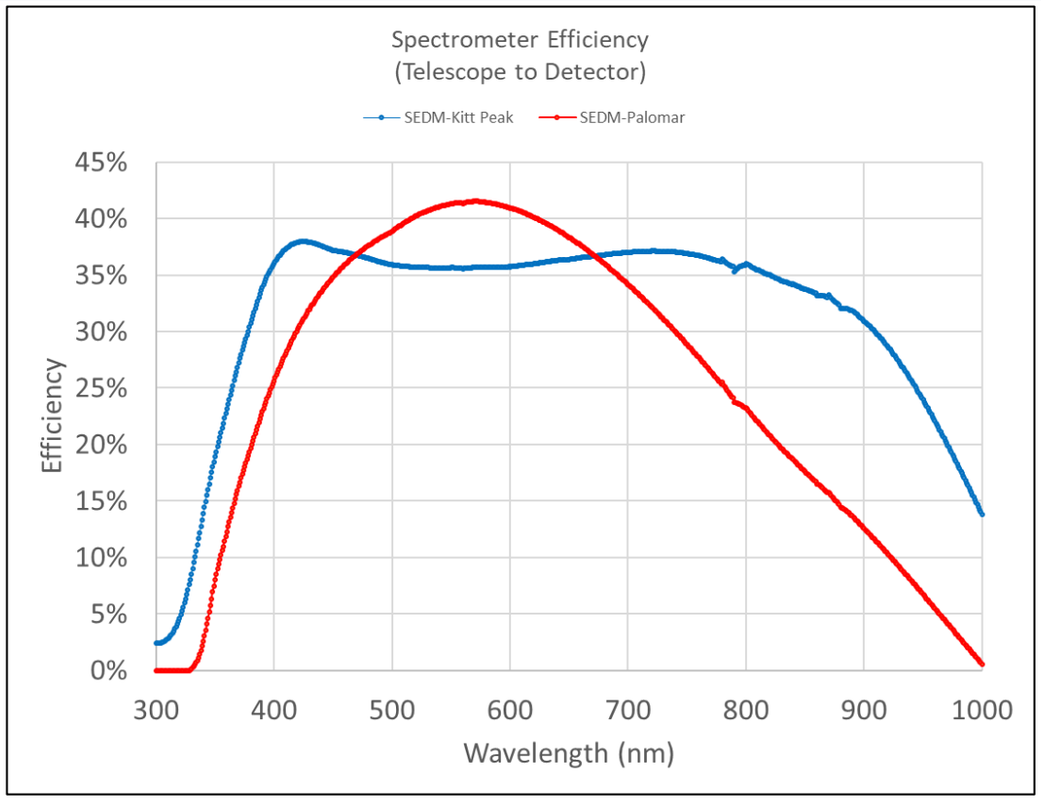


Kitt Peak 2.1m: Facility Specs

- Primary: 2.1m (84in)
- 2x P60 area = +0.75mag
- Secondary: f/7.6
- Automated for KPED

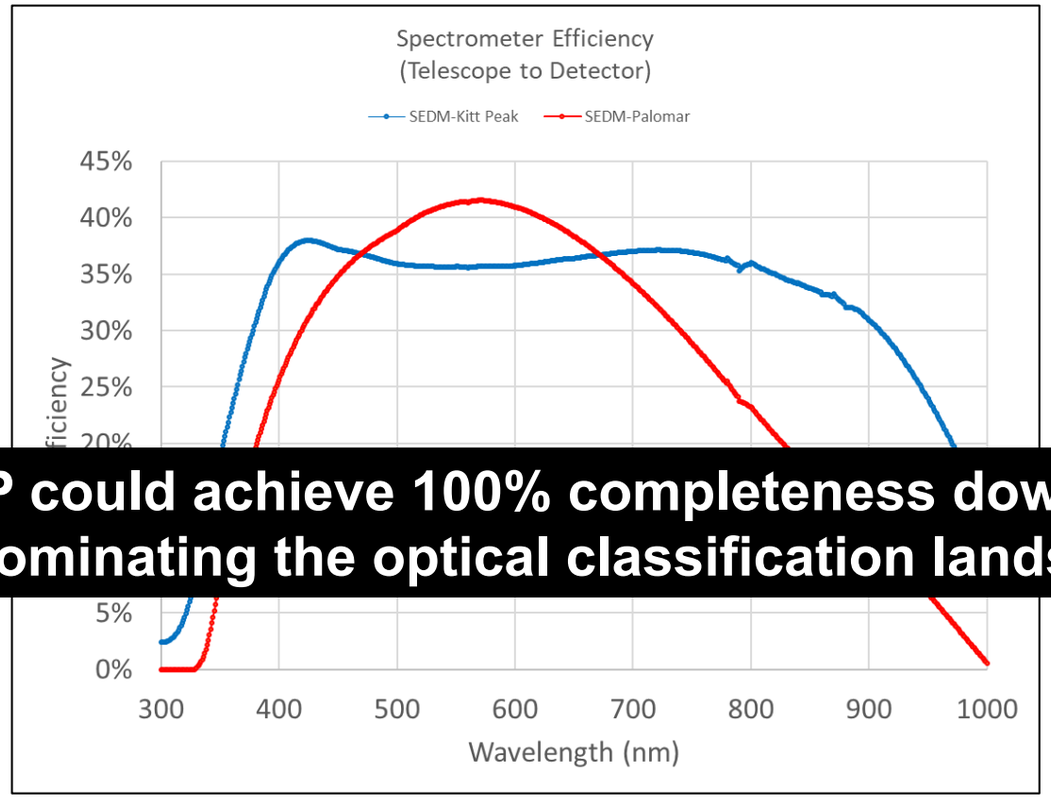
Kitt Peak 2.1m: Facility History

- 3yrs with RoboAO
- 2yr with KPED

Instrument improvements over v1

- Optimize IFU wavelength coverage and throughput
- Optimize imager FOV
- Reduce number of optics
- Improved QE response in imager
- Use filter wheel for imager instead of fixed quadrant design
- Use fold mirror with central hole instead of pickoff mirror

SED Machine - Kitt Peak



SEDM-KP could achieve 100% completeness down to 19+ mag (dominating the optical classification landscape)

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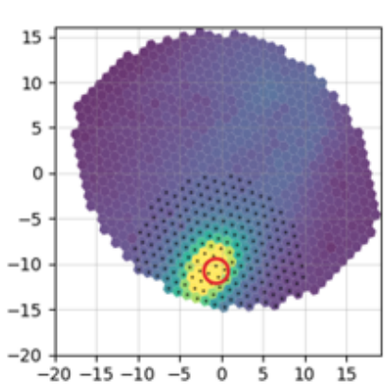
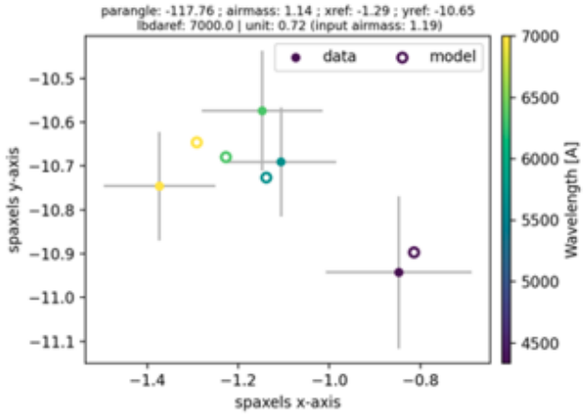
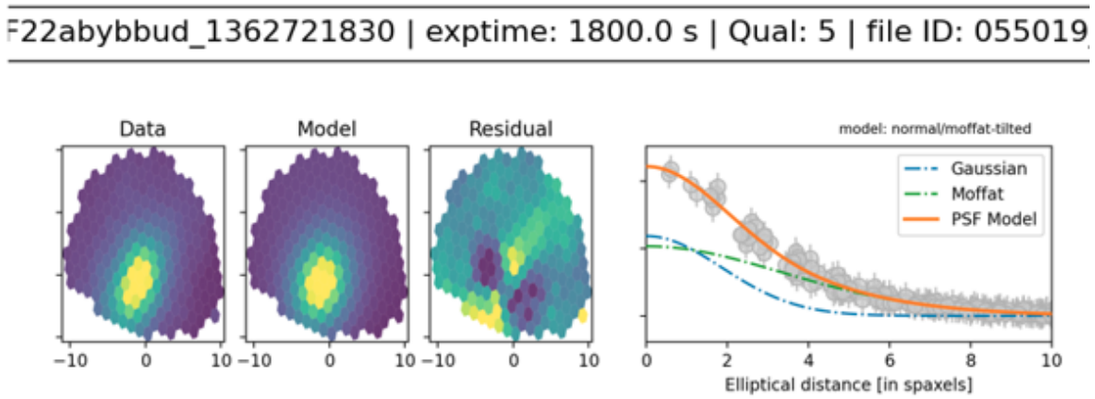
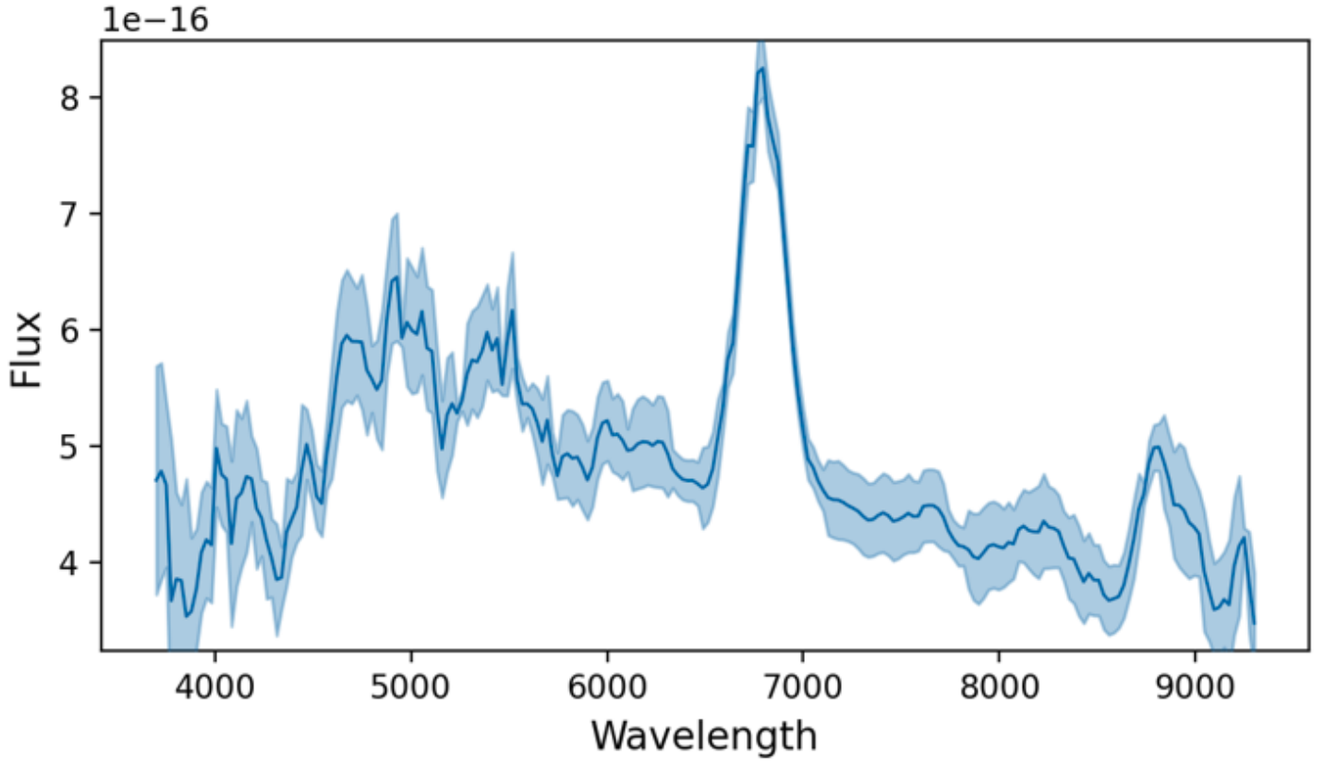
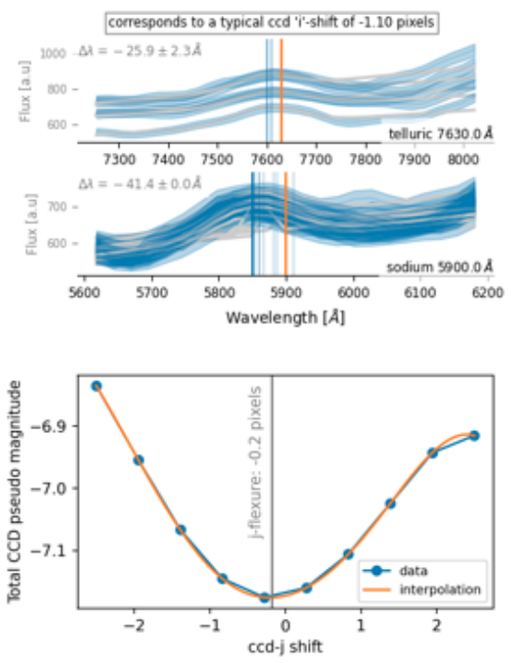
SED Machine - Kitt Peak: First Science Observations











pysedm version 0.30.0 | made the 2023-04-16 at 18:33:00

SED Machine - Kitt Peak: Timeline

June 5 - June 8
First commissioning trip
-Removed KPED
-Put SEDMv2 on with stop-gap prism

June 15
Contreras wildfire - KP evacuated

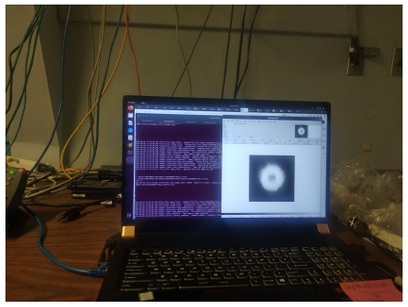
Sep 19 - Sep 30
Second commissioning trip(s)
-No damage to instrument
-Replaced stop-gap prism with tri-prism and realigned
-Put SEDMv2 back
-Operations paused until access to stable power supply

Oct 18
Line power back
Dec 25
Internet restored
BUT
KP84 UPS failure!

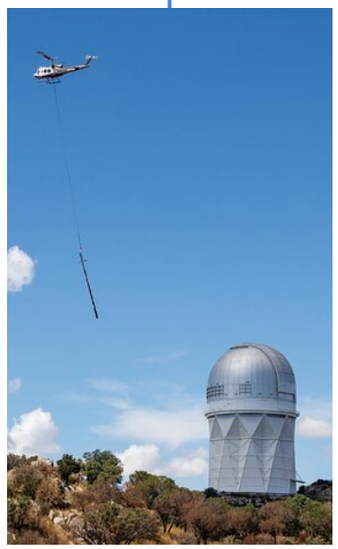
Nov 12 - April 2023
Multiple trips to KP84
-Robotic operations tested
-Taking commissioning data
-Onsite data analysis

To Do
-Fix dome drive
-Mirror recoating
-Fix minor software bugs as we go!

June 8
FIRST LIGHT!
System not yet fully robotic



-Extensive damage to KP power poles, internet cables
-All scientific buildings saved
-Extensive damage to summit road because of landslides during monsoon

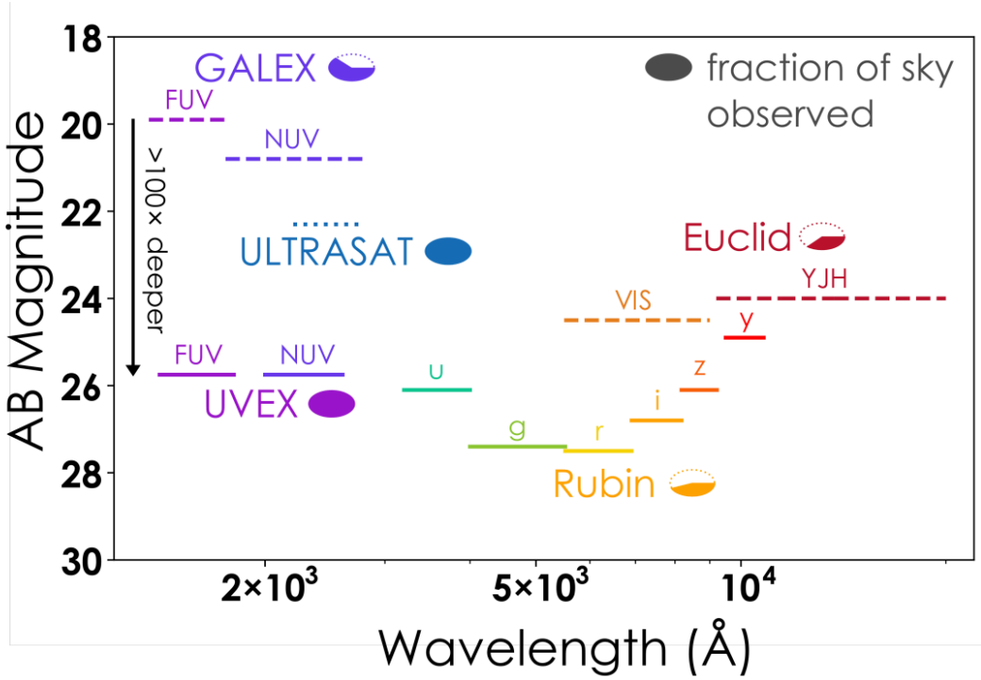


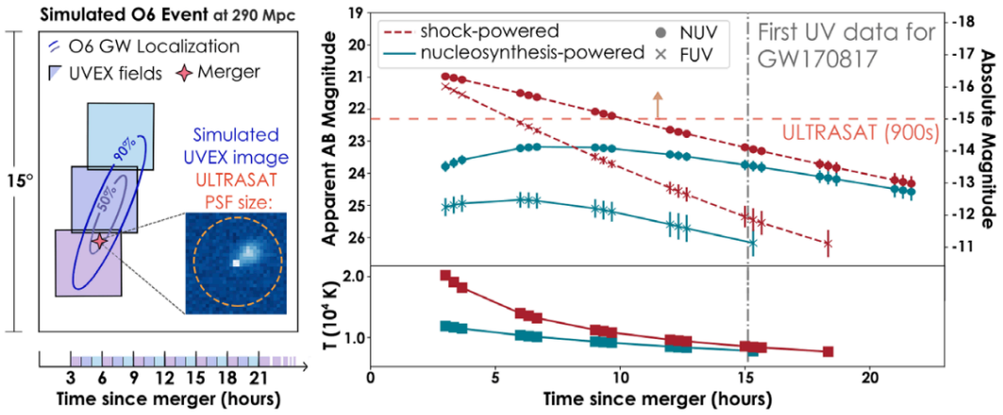
Feb 7
-New UPS installed
-Improved KP84 drive performance
-Guiding implemented

UVEX
Ultraviolet Explorer
All-Sky Imaging
Time Domain
Spectroscopy

ULTRASAT
Ultraviolet Transient Astronomy Satellite

Exploring the Dynamic UV Sky



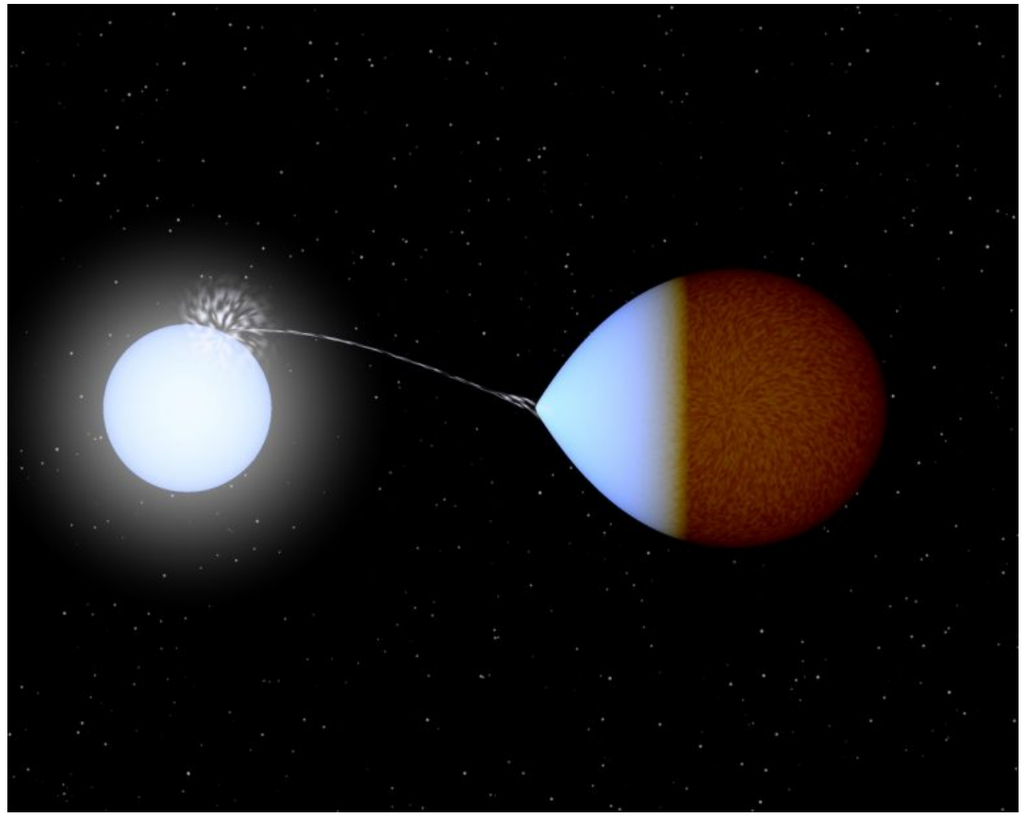


Images: UVEX science team

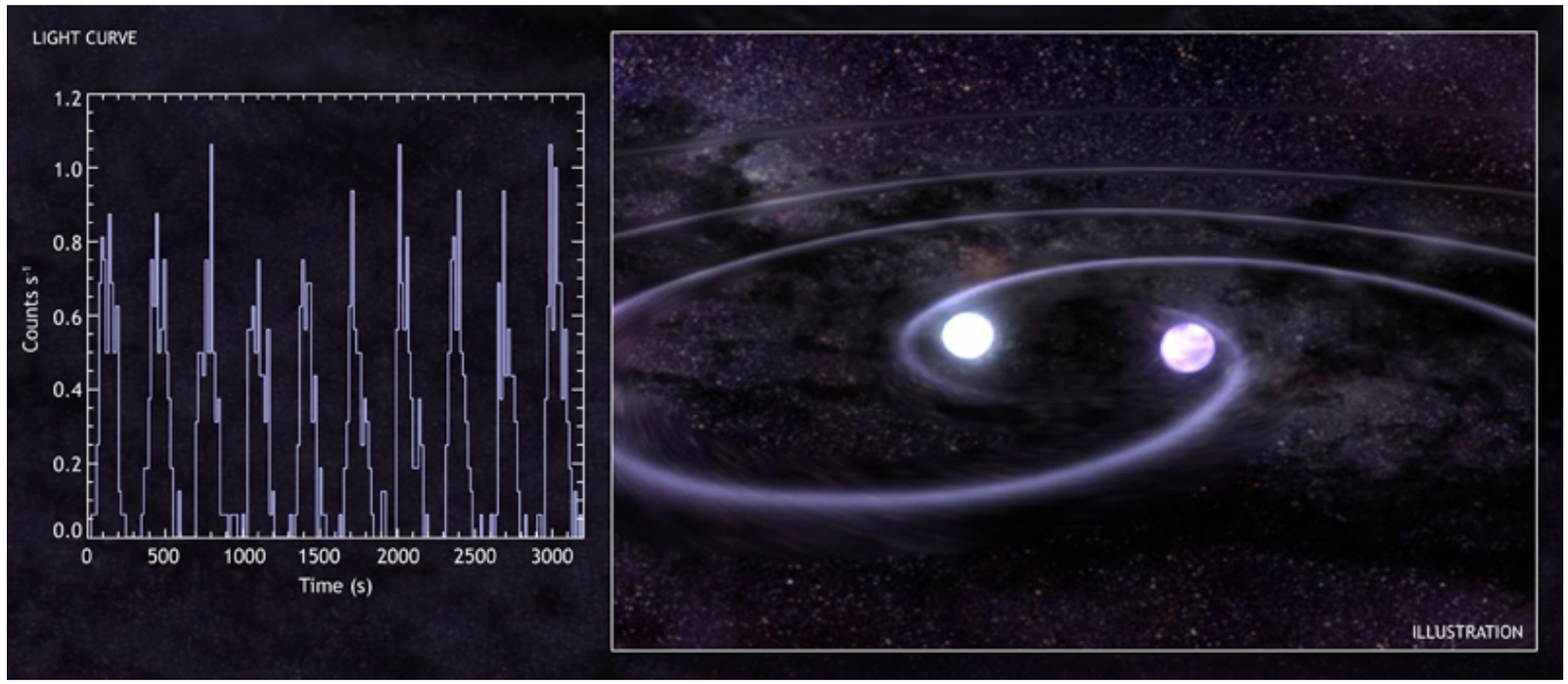
	ULTRASAT	UVEX
Imaging field of view	204 deg²	12 deg²
Imaging bandpass	230-290 nm	FUV: 139–190 nm NUV: 203–270 nm
Imaging depth	22.5 mag in 900 s	25.5 in 900 s
Spectral resolution	(none)	R≥1000
Effective aperture	33 cm	75 cm
PSF	8.3”	2.25”
Orbit	GEO	TESS-like highly elliptical
Launch	2026	2028
Cost	~$100M	~$300M

Rich astrophysical laboratories

- Gravitational waves give constraints on chirp mass, inclination, distance.
- Spectroscopy gives constraints on masses, atmospheric composition, rotation rates, surface gravities, temperatures.
- Multiband lightcurves give constraints on radii, temperatures, inclination, masses, chirp mass (via orbital decay), tidal physics, and other features such as accretion disk geometry, irradiation physics.
- Multiband lightcurves are the most valuable tool here, and that is exactly what Rubin will deliver with its unprecedented dataset
- X-rays, Gamma rays, and radio also extremely interesting.



- The shortest period binary known in the Galaxy, HM Cnc (5.4 min) is a strong periodic x-ray source
- Direct impact accretion



The Future is Bright

- The Vera Rubin Observatory will transform this field with its sensitivity and multi-color lightcurves—right now, we are barely scratching the surface of what is coming.
- High speed imagers on large telescopes would be extremely valuable for following up these sources in the future. Few such instruments exist because few people are exploring such short timescale behavior in the optical.
- Other upcoming facilities/datasets will also make significant contributions to this field, such as Gaia photometry (estimated 2025), Roman (estimated 2027), UVEX (~2028), the Advanced X-ray imaging satellite (early 2030s), and LISA (mid 2030s).
- JWST will be a game changer for this kind of work in globular clusters.

Thank you!