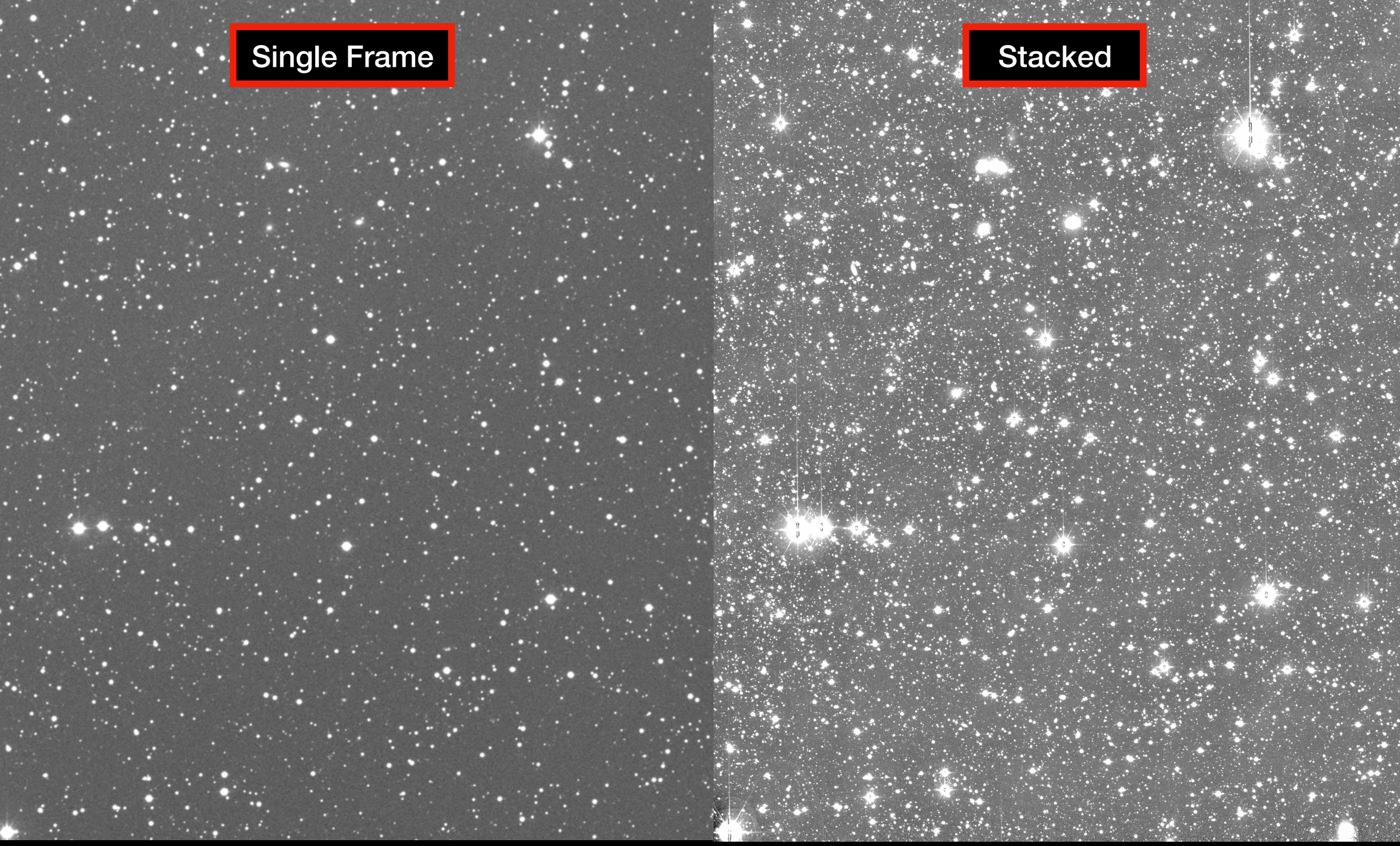


The ZTF Coadd Facility

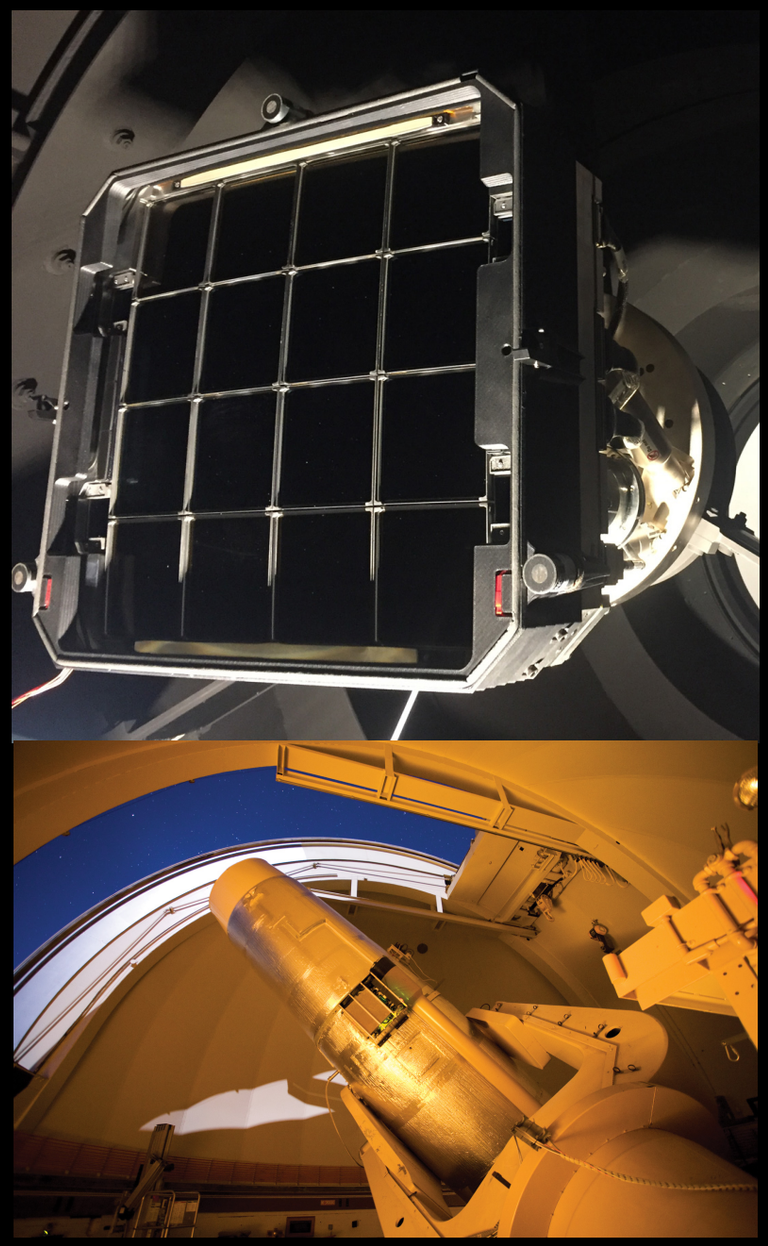
with P. E. Nugent, Y. Yao, A. Goobar, S. R. Kulkarni

Danny Goldstein

Hubble Fellow (Caltech)

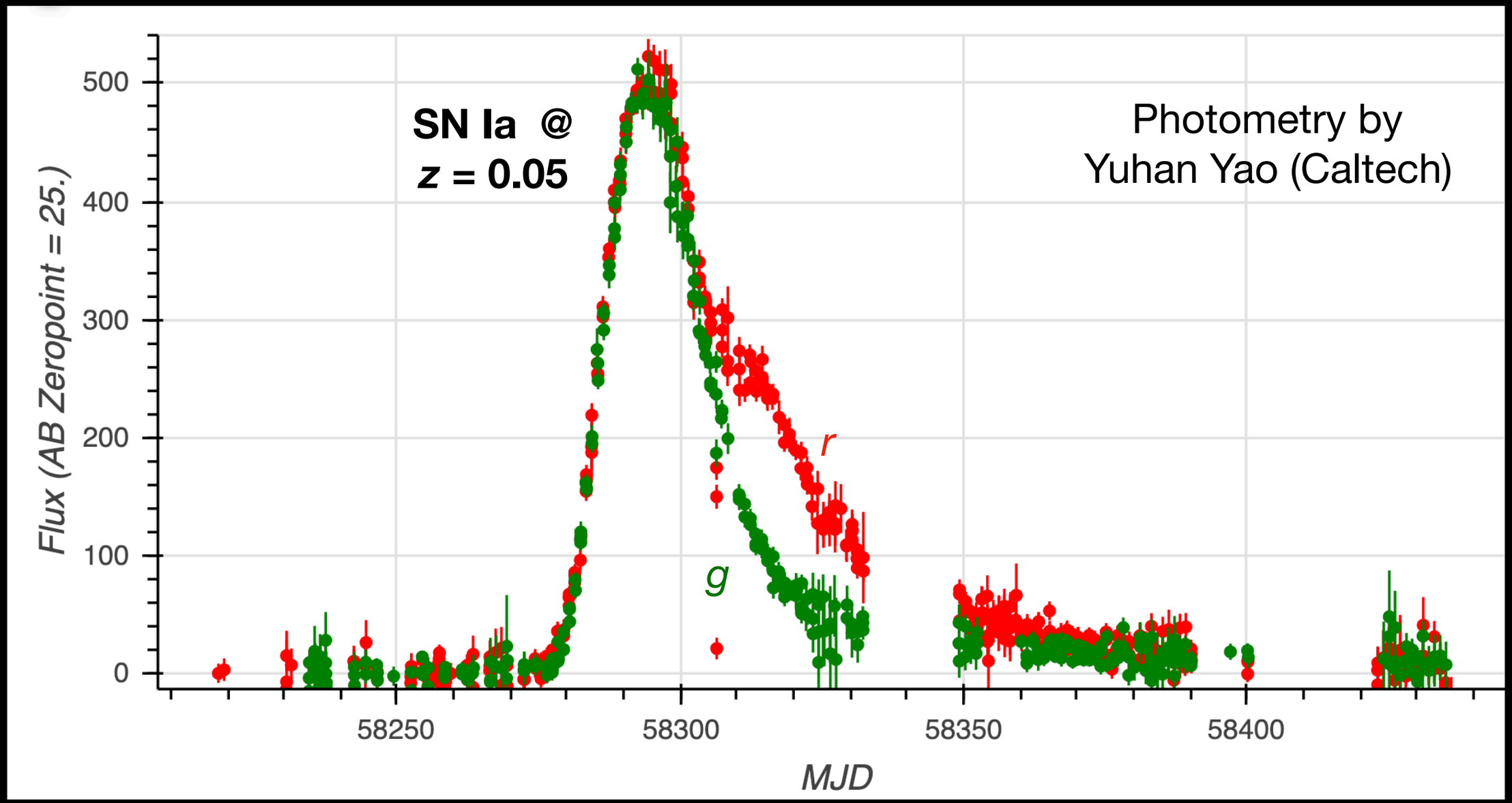
The Zwicky Transient Facility and Partnership Survey

- Optical imager with 47 square degree field of view
- Mounted on 48-inch (1.2m) telescope at Palomar observatory
- 30 second exposures - limiting mag of 20.5 in *g*, *r*
- Partnership (“high-cadence”) survey covers 2,000 square degrees of northern sky ***six times per night*** in g, r to 20.5 per visit



See Bellm et al. (2019), Graham et al. (2019)

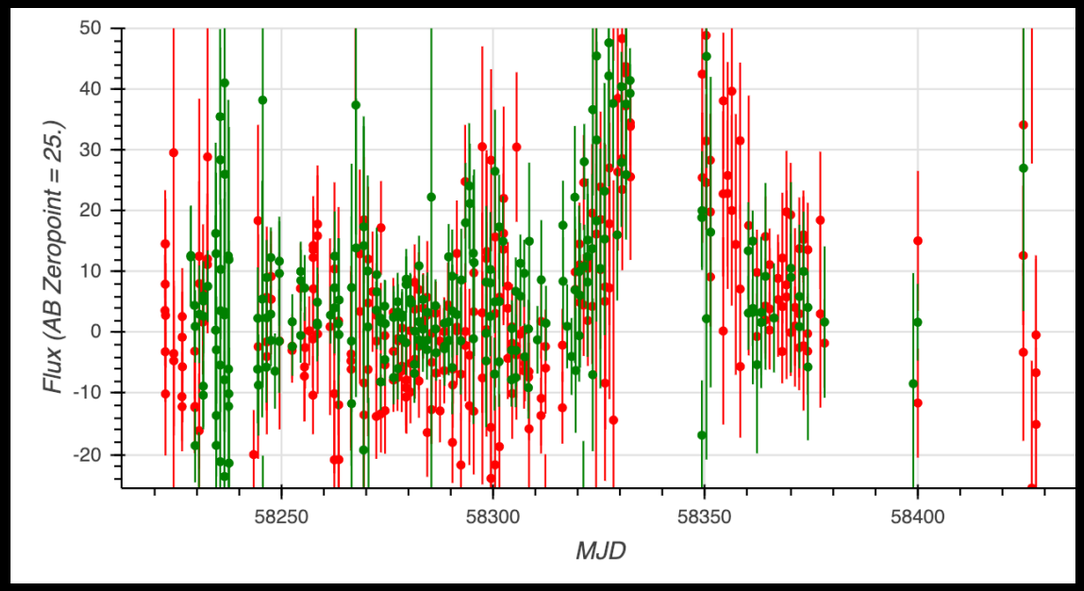
Typical Light Curve from the Partnership Data



Yao et al. (2019, in prep)

The Cost of High Cadence

- ZTF is producing fantastic data, but 6 visits / night is overkill for most science cases.
- Since only objects detected at at least 5 sigma on single-epoch difference images can trigger alerts, fainter transients, which are still present in the data, but not at 5 sigma in single-epoch subtractions, are missed.



This object was not detected by the single-epoch pipeline as none of its individual detections have SNR > 5.

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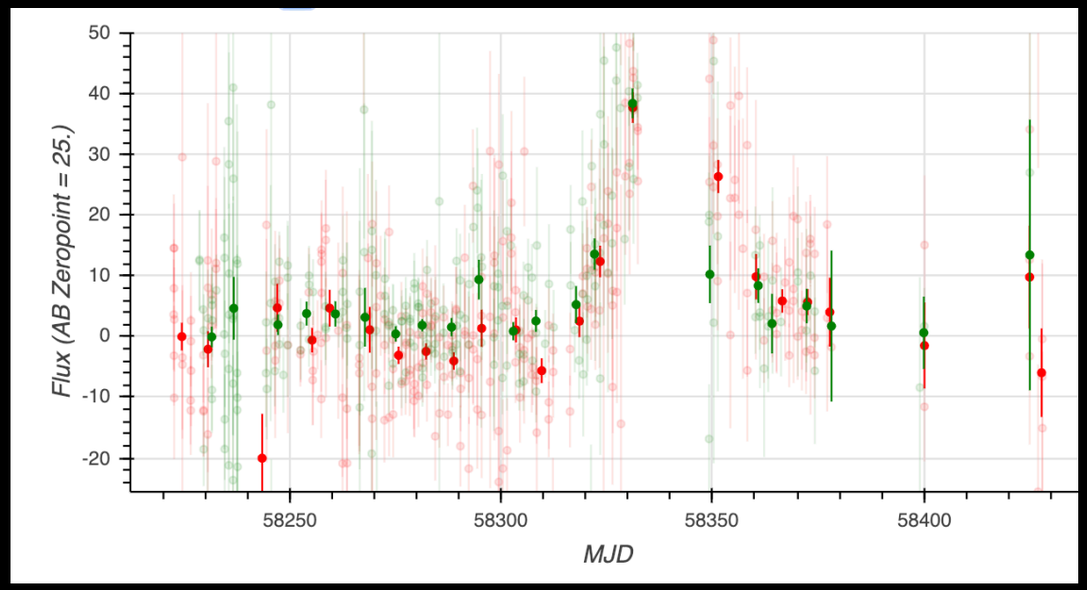
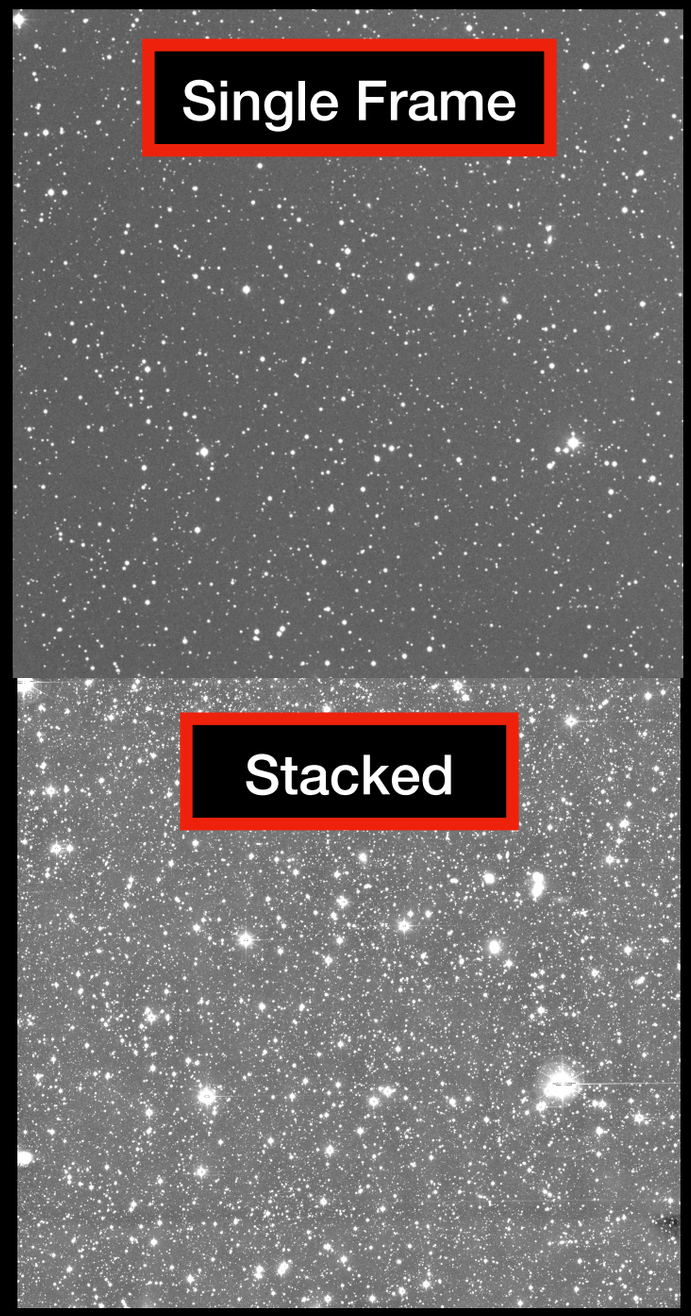


This object was not detected by the single-epoch pipeline as none of its individual detections have SNR > 5.

Solution: The ZTF Coadd Facility

- The ZTF Coadd Facility is an automated software tool that produces deep subtractions from coadded ZTF science images, increasing the sensitivity of the survey to faint transients.
- The idea is to trade the survey's cadence for depth. The coadded light curves are deeper, but sparser in time.
- Ideally suited to many different science cases where light curves evolve over days or weeks, not hours: supernovae, nuclear transients, stellar variability, microlensing, etc…



Key Takeaway: Increasing the Depth of ZTF

- Using the ZTF coadd facility, the partnership survey is *not* limited to finding transients brighter than *g, r* ~ 20.5 — it can go deeper. When considering what science is possible with ZTF, it is important to keep this key point in mind.

- The actual limiting magnitude of the partnership survey (2000 deg sq) is:

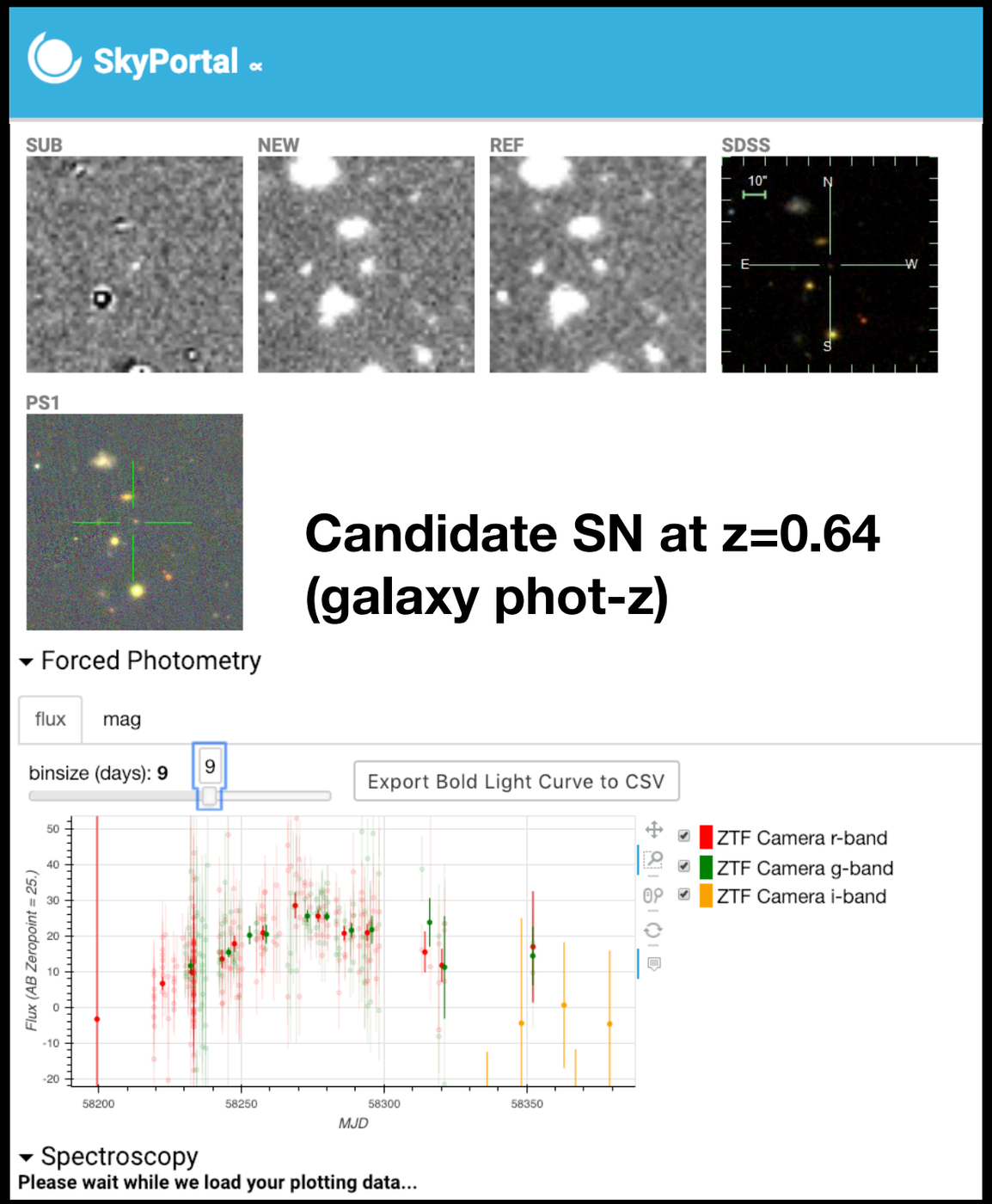
$$m_{\rm lim}(\Delta t) \approx 20.5 + 2.5 \log\left(\sqrt{6\Delta t}\right)$$

where Δt is the effective cadence after coaddition.

$m_{\rm lim}(1\,{\rm day}) \approx 21.5$ $\quad$ $m_{\rm lim}(5\,{\rm days}) \approx 22.4$

$m_{\rm lim}(2\,{\rm days}) \approx 21.9$ $\quad$ $m_{\rm lim}(10\,{\rm days}) \approx 22.7$

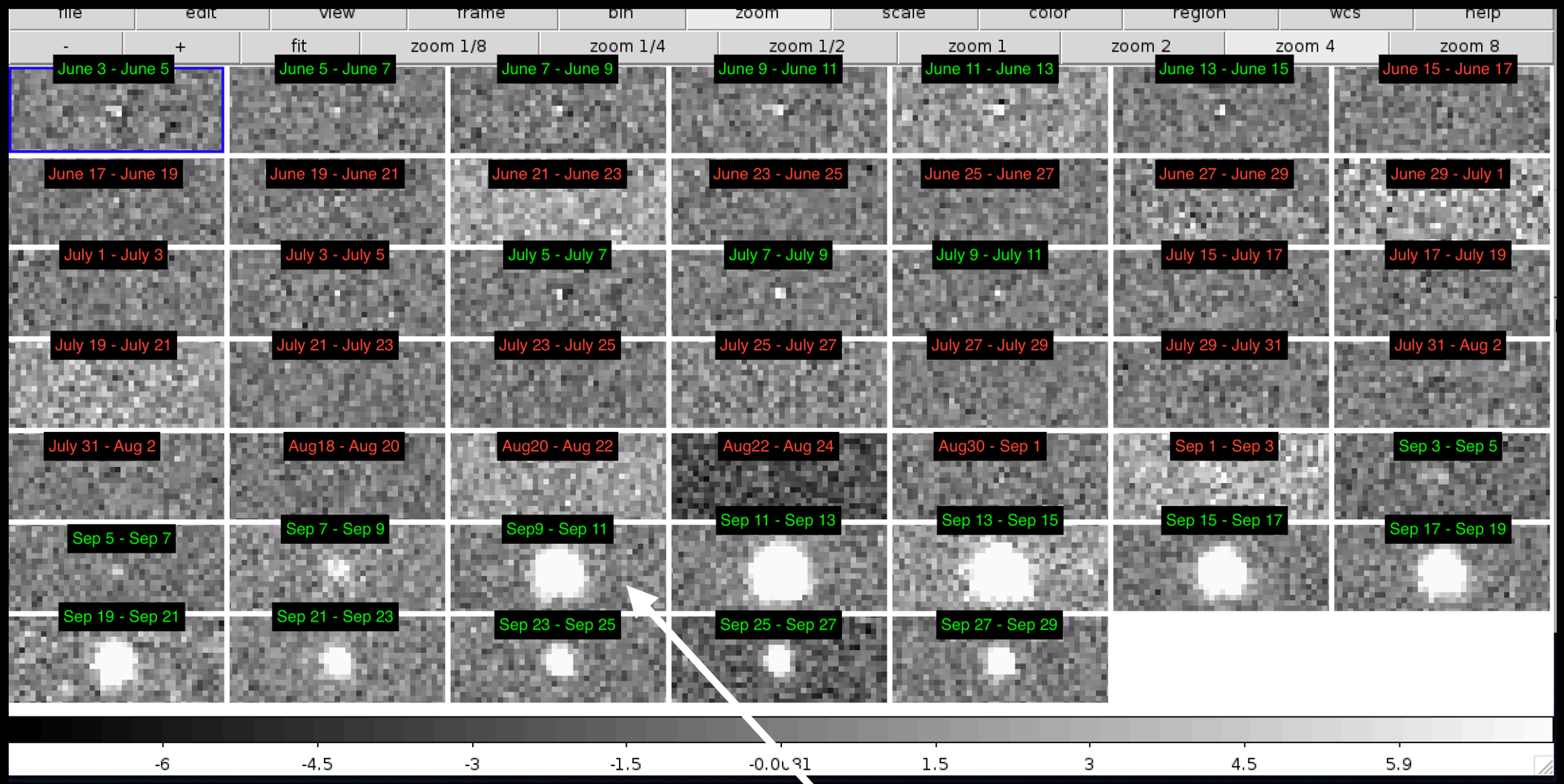
Interface to the Coadd Facility: Skyportal Marshal



- Beautiful interface to coadded data written by expert developers: Stefan van der Walt, Arien Crellin-Quick, and Josh Bloom (Berkeley)
- Enables custom filtering of events based on light curves and contextual information
- Interactive stacking of photometry
- Open source software: http://github.com/skyportal/skyportal

Early Science with the Coadds

Detection of pre-supernova outbursts (*M* ~ -13) from a broad-lined SN Ic progenitor (Ho et al. in prep).

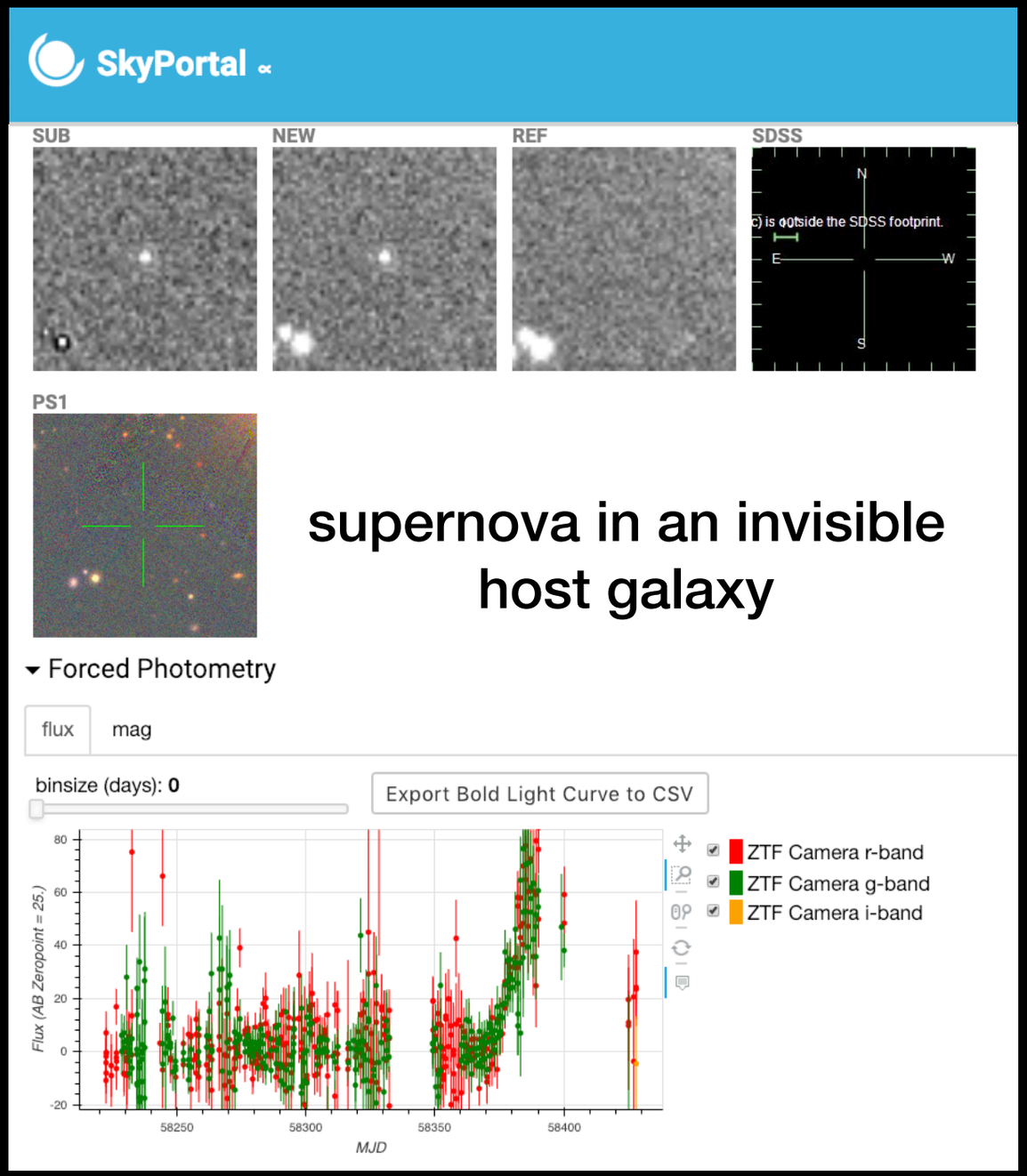


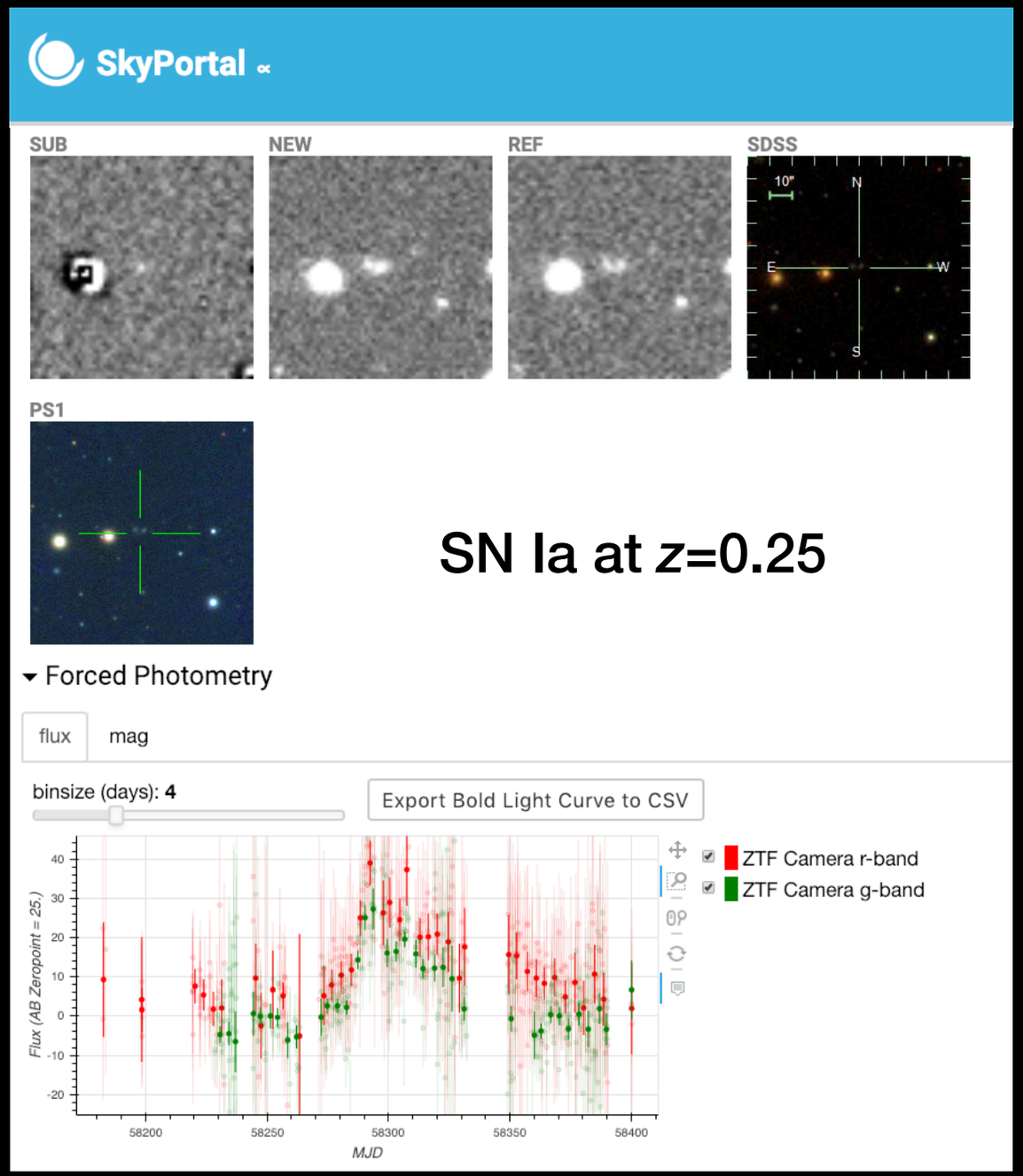
All images show coadd facility subtractions.

Date of first ZTF *single-epoch* detection of the supernova

Early Science with the Coadds

Discovery of faint or high-redshift SNe missed by nominal survey

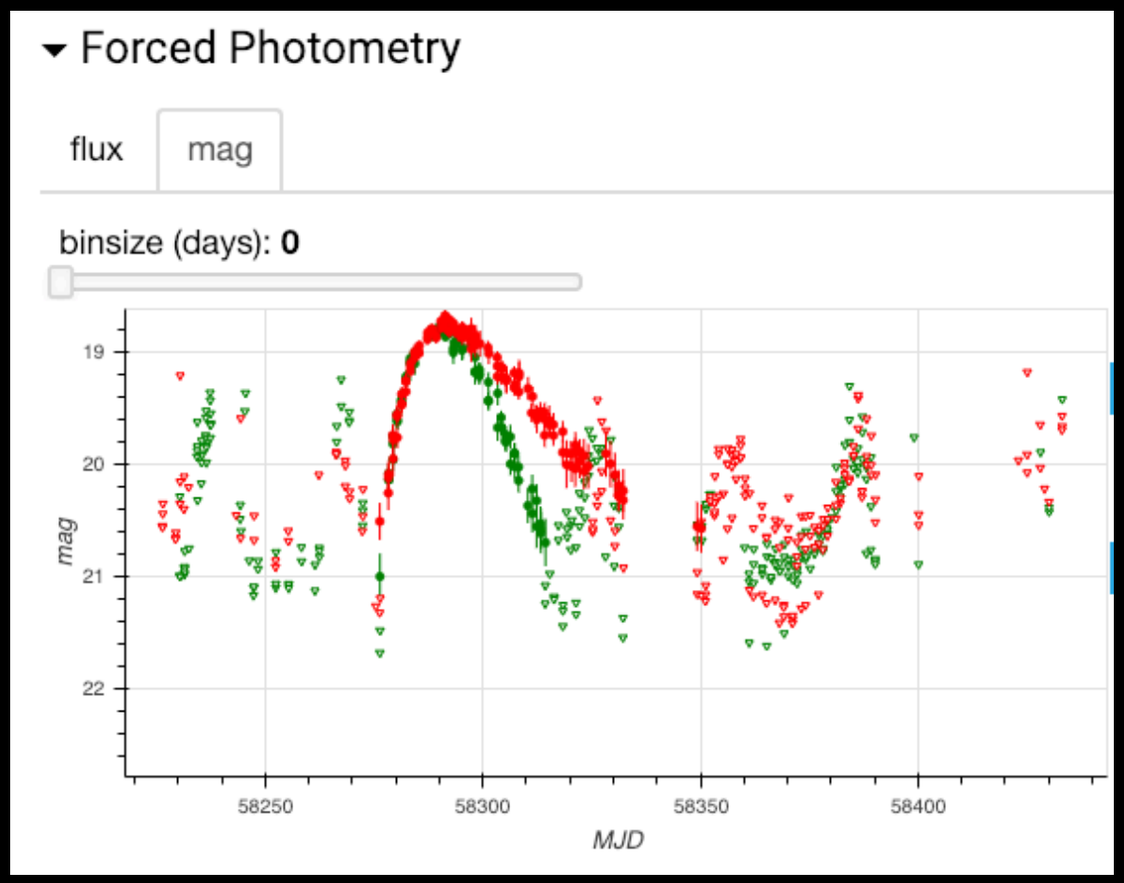




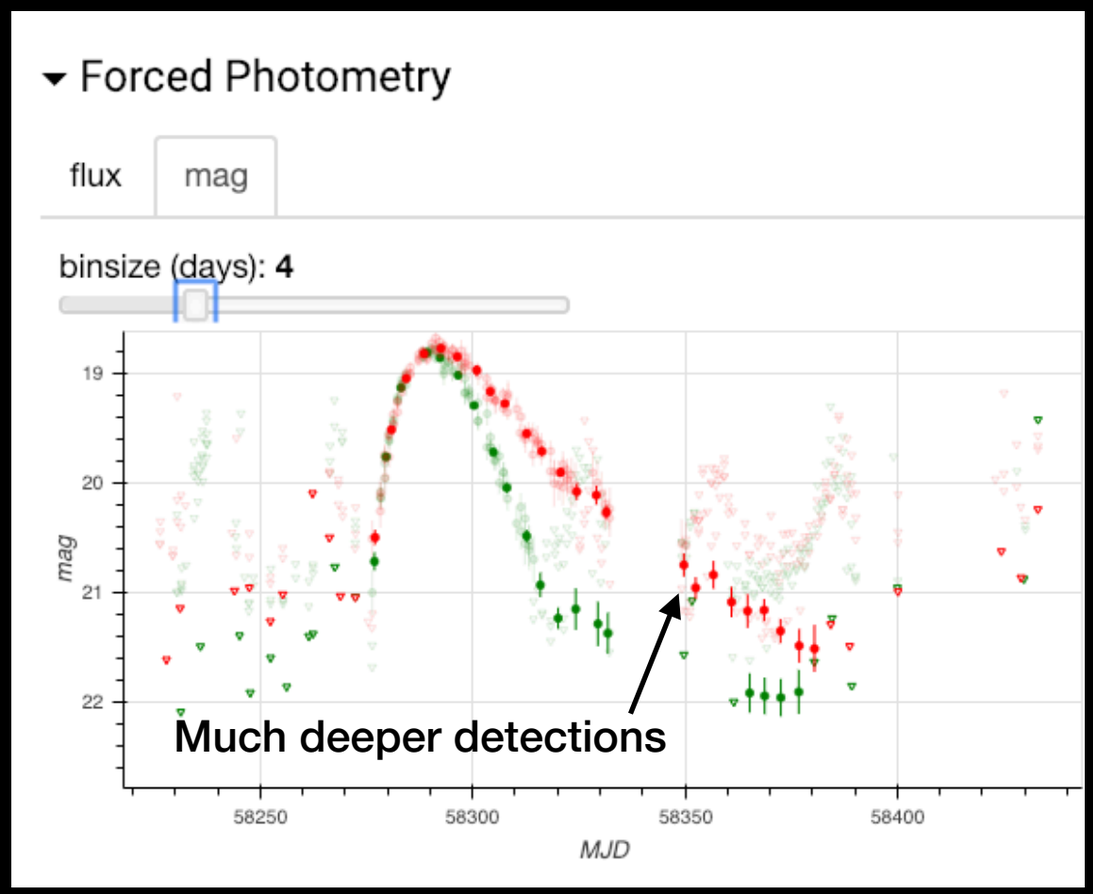
Early Science with the Coadds

Extension of supernova light curves into nebular phase

SN Ia at z=0.07



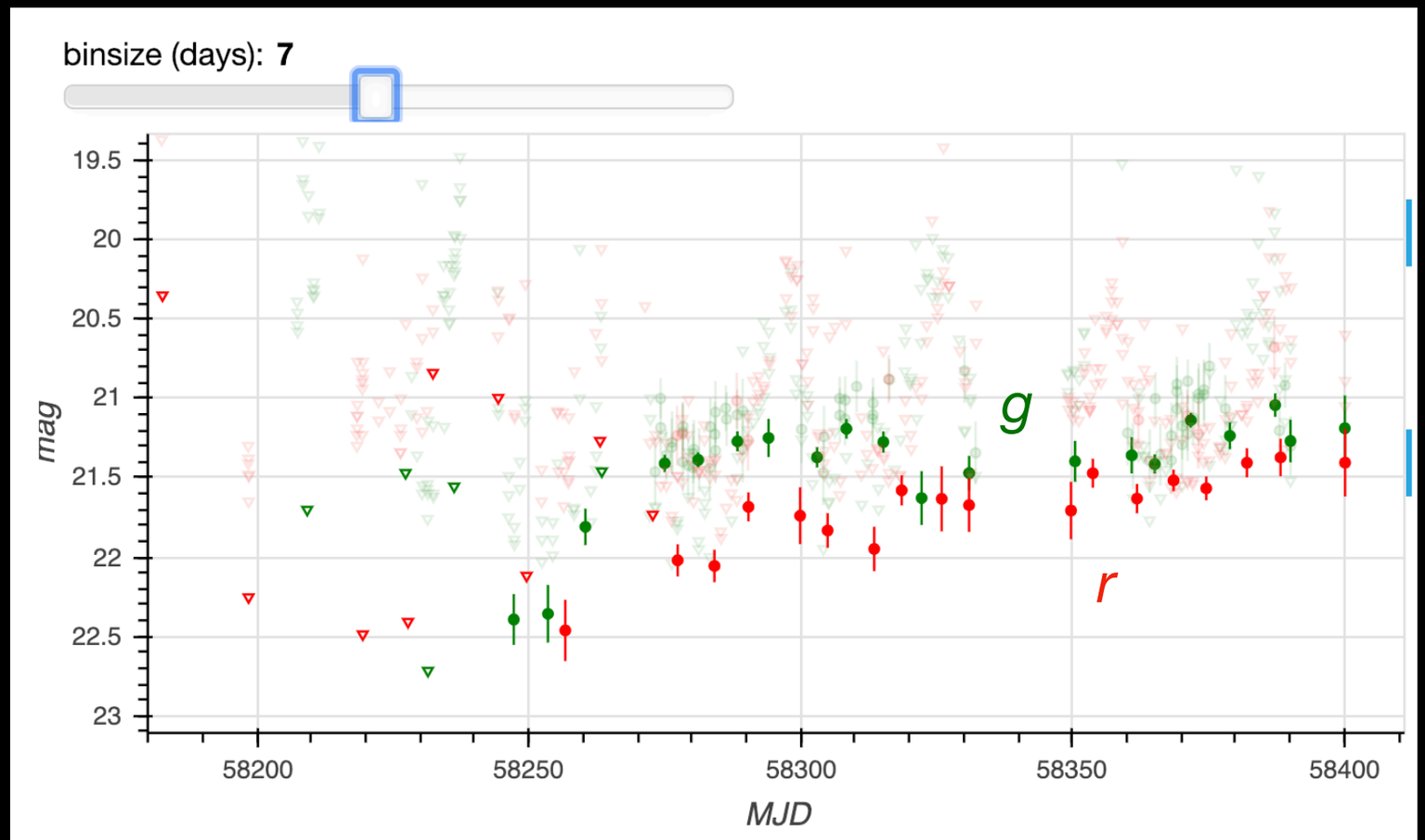
Without Stacking



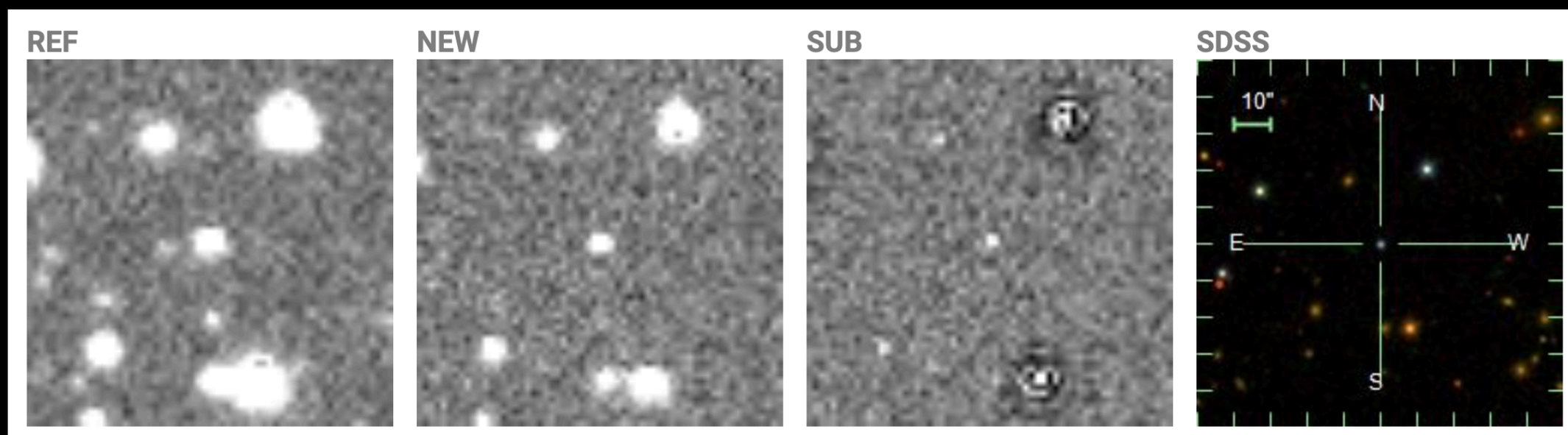
With Stacking

Early Science with the Coadds

Monitoring of faint stellar / AGN variability

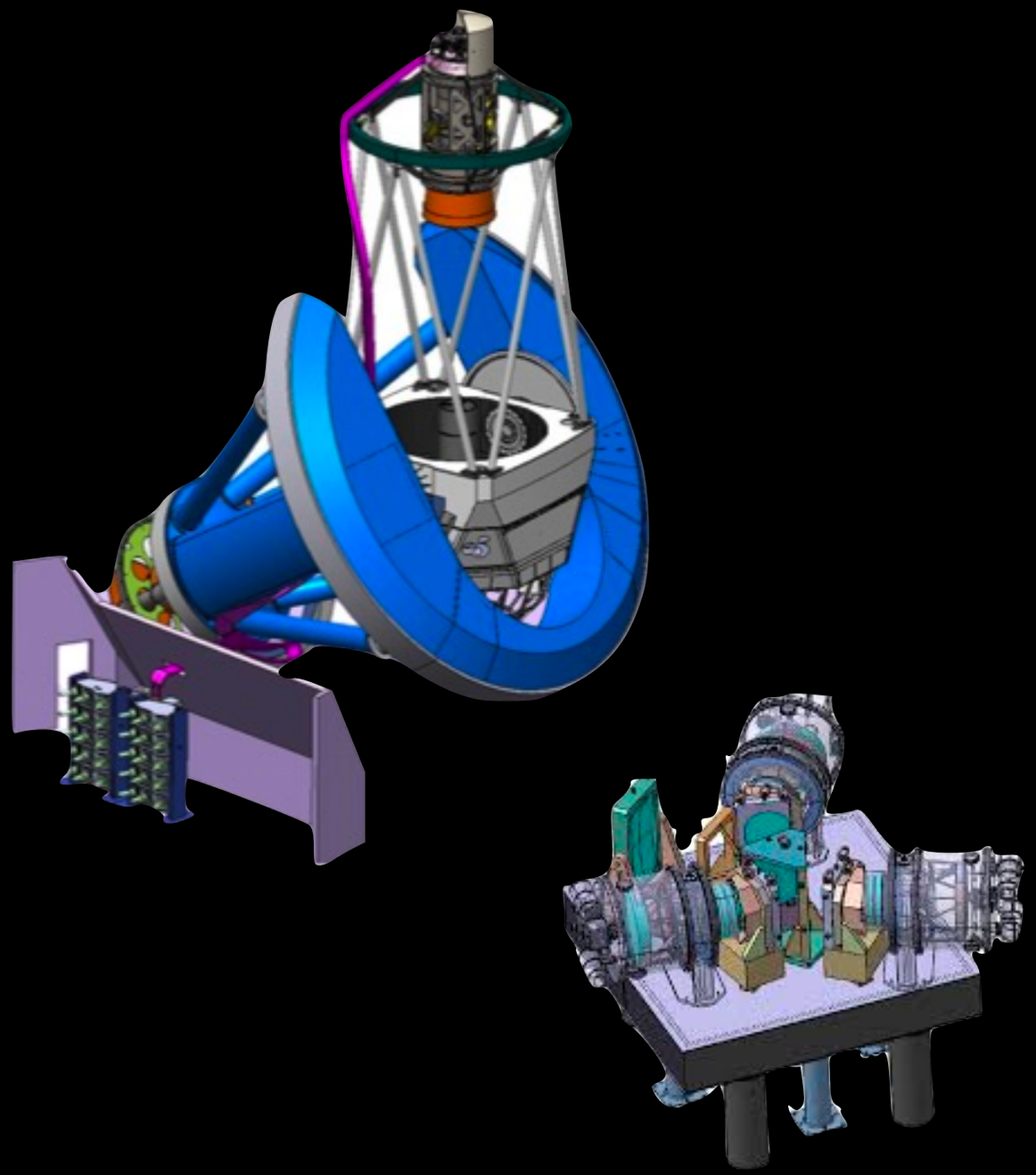


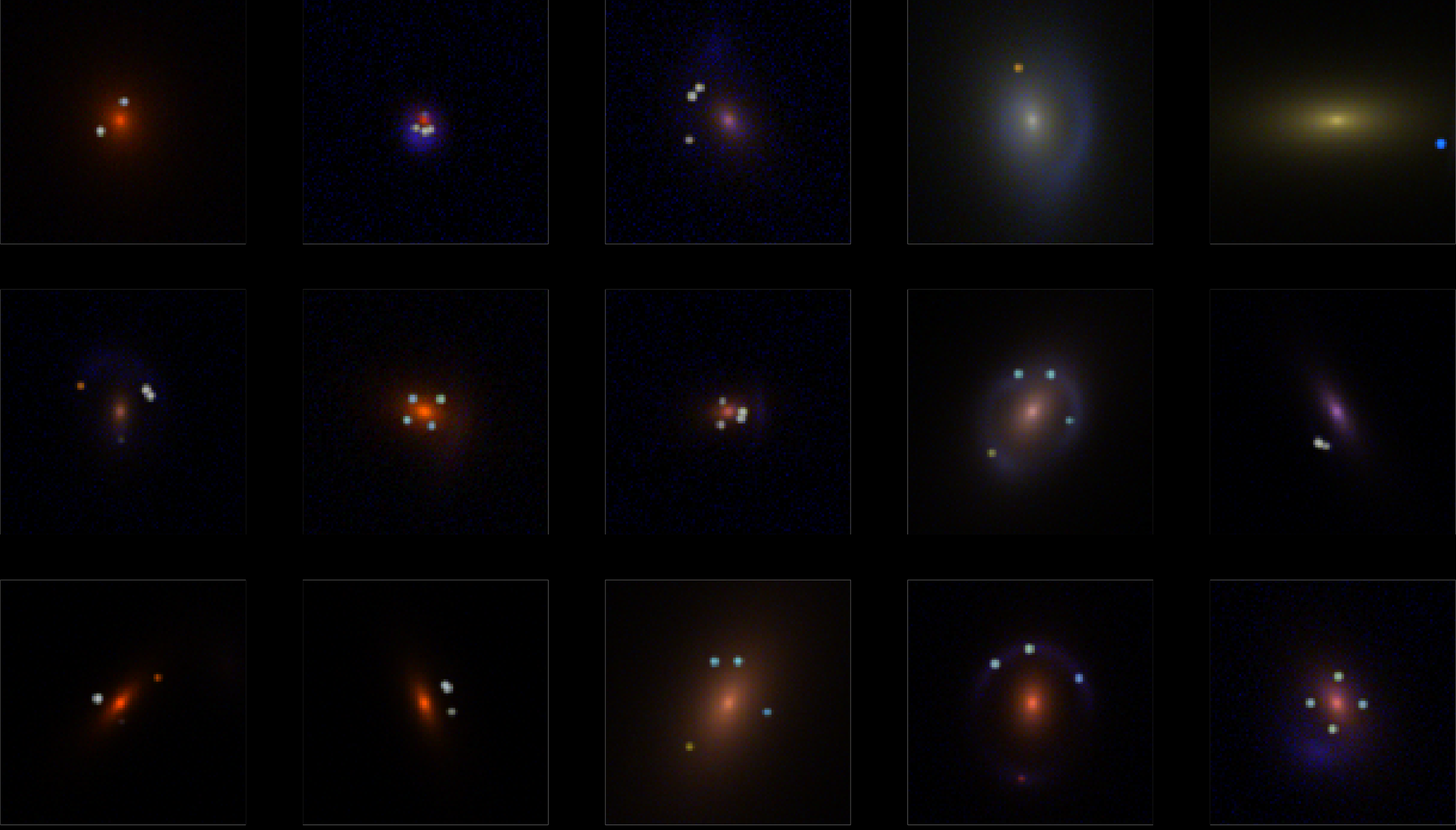
Variability at 21-22 mag



Connection to TDAMMS

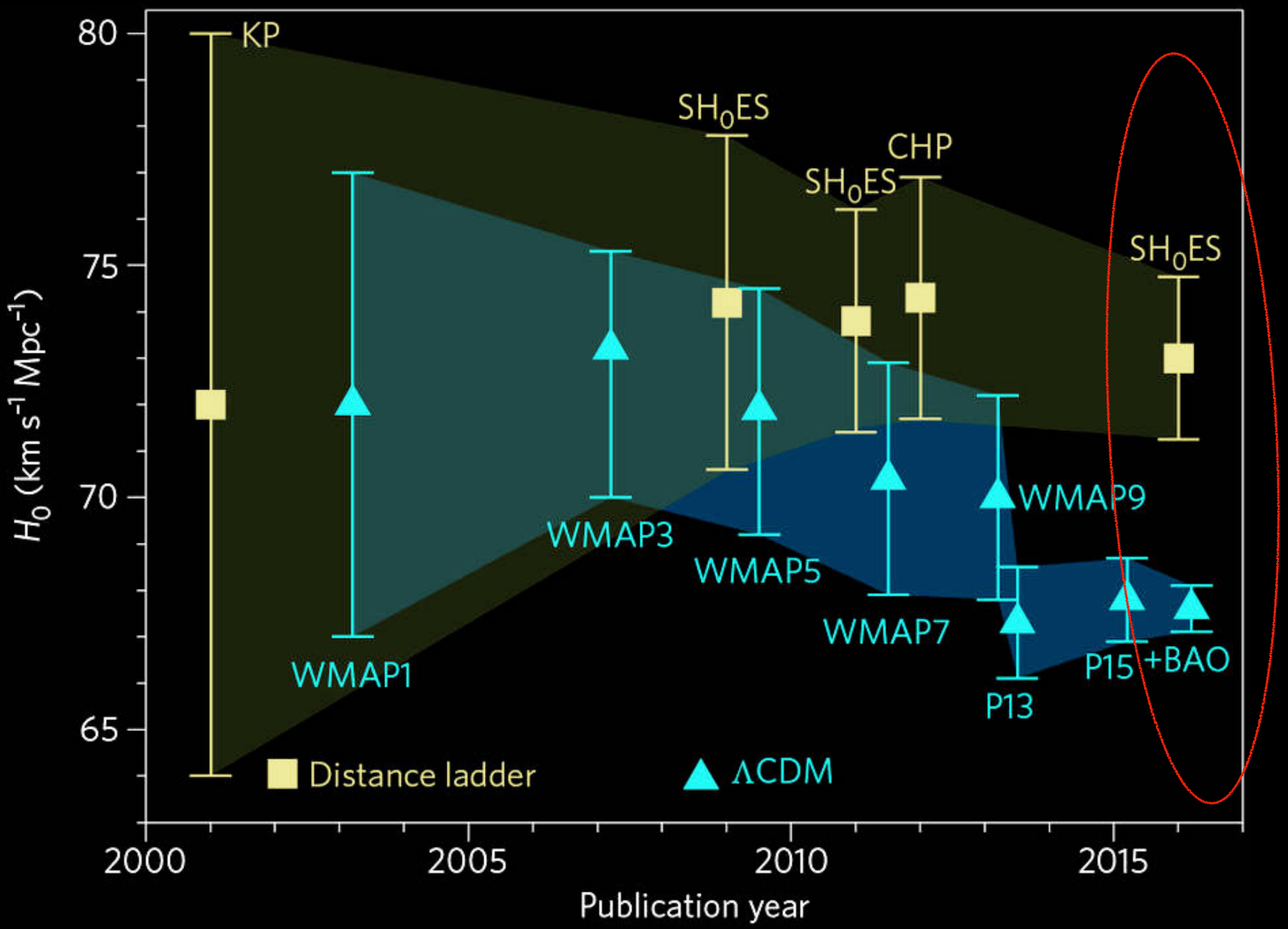
- The ZTF Coadd Facility will roughly double the size of the ZTF partnership transient stream
- Most of these new transients are too faint for the facilities performing rapid follow-up of ZTF targets, e.g. SEDM.
- However, some of them will be well-suited for larger MMS facilities, such as DESI, 4MOST, and PFS.
- Need to start thinking now about coordinating with these facilities.





Original Motivation for Coadd Facility: Strongly Lensed SNe

H_0: The Biggest Tension in Cosmology



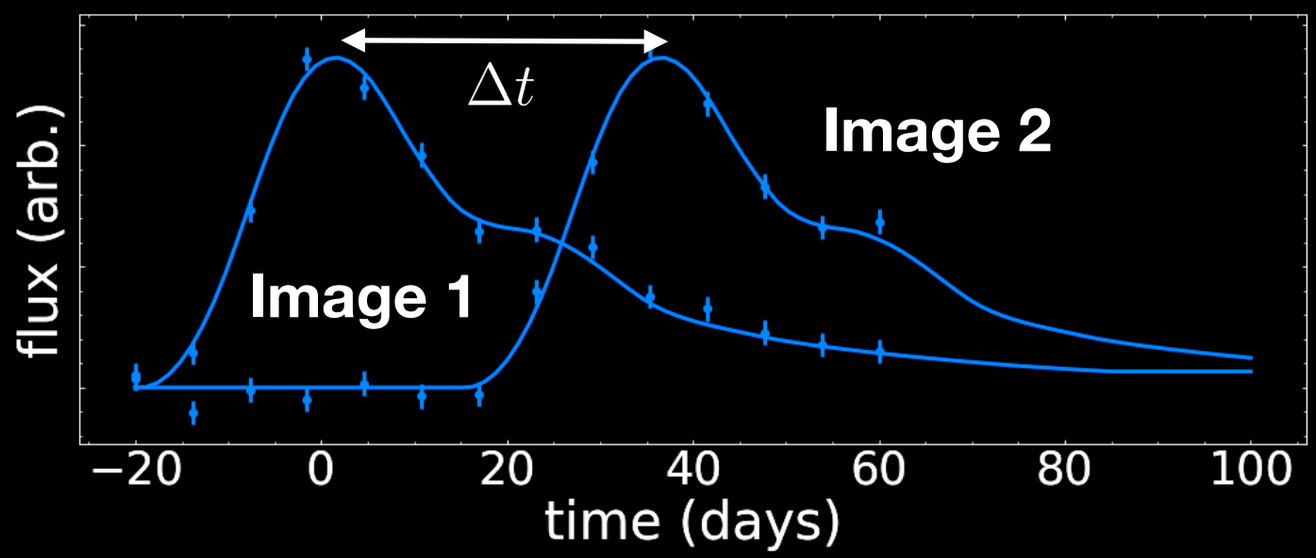
3.4σ

Need H_0 to <1% to resolve tension

Freedman 2017 (Nature Astronomy)

Time Delays: An Independent Route to H_0

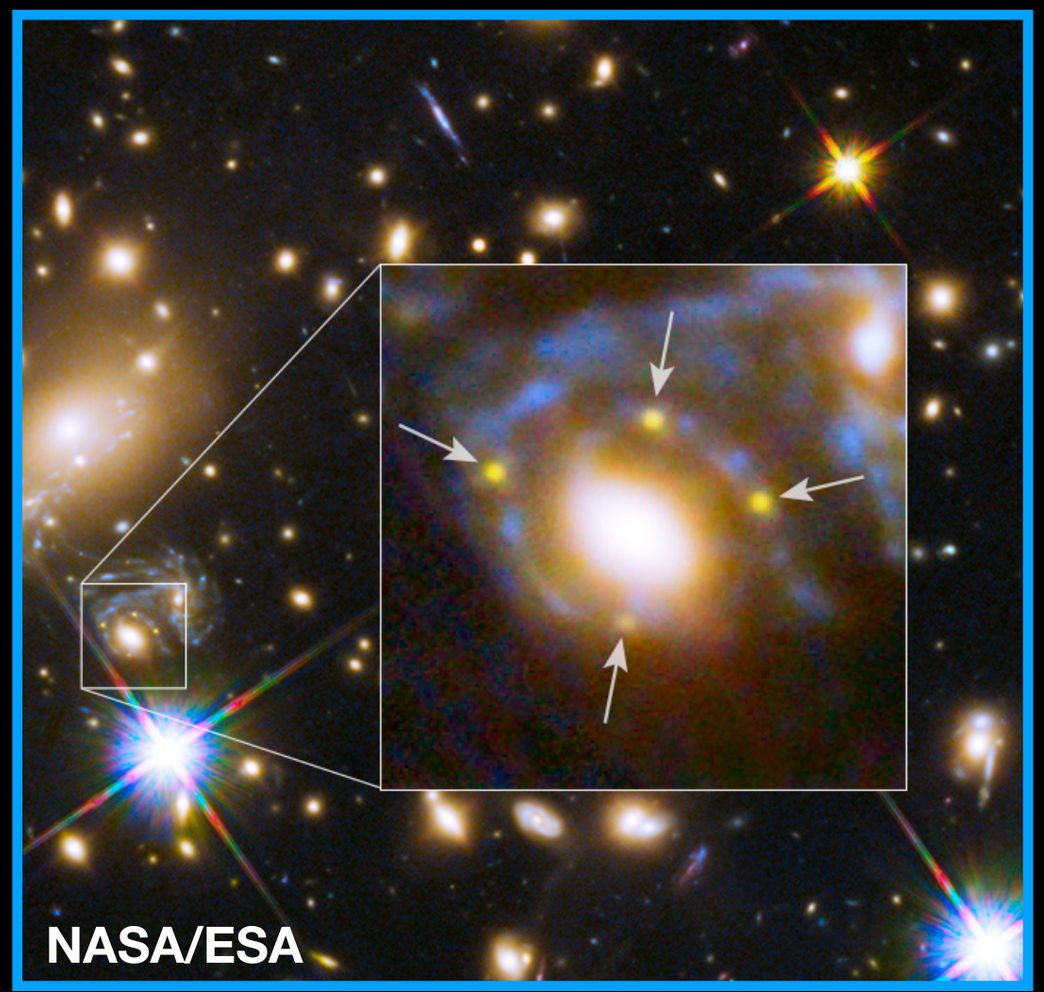
Time delays between multiple images of strongly lensed Type Ia supernovae directly constrain H_0 (Refsdal 1964) and provide leverage on dark energy (Linder 2004, 2011).



$$\Delta t \propto \boxed{\frac{D_l D_s}{D_{ls}}} \propto H_0^{-1} f(w)$$

Triple ratio of distances: a unique cosmology probe

H_0 hasn't been measured well with supernova time delays because only two multiply imaged supernovae have been found.



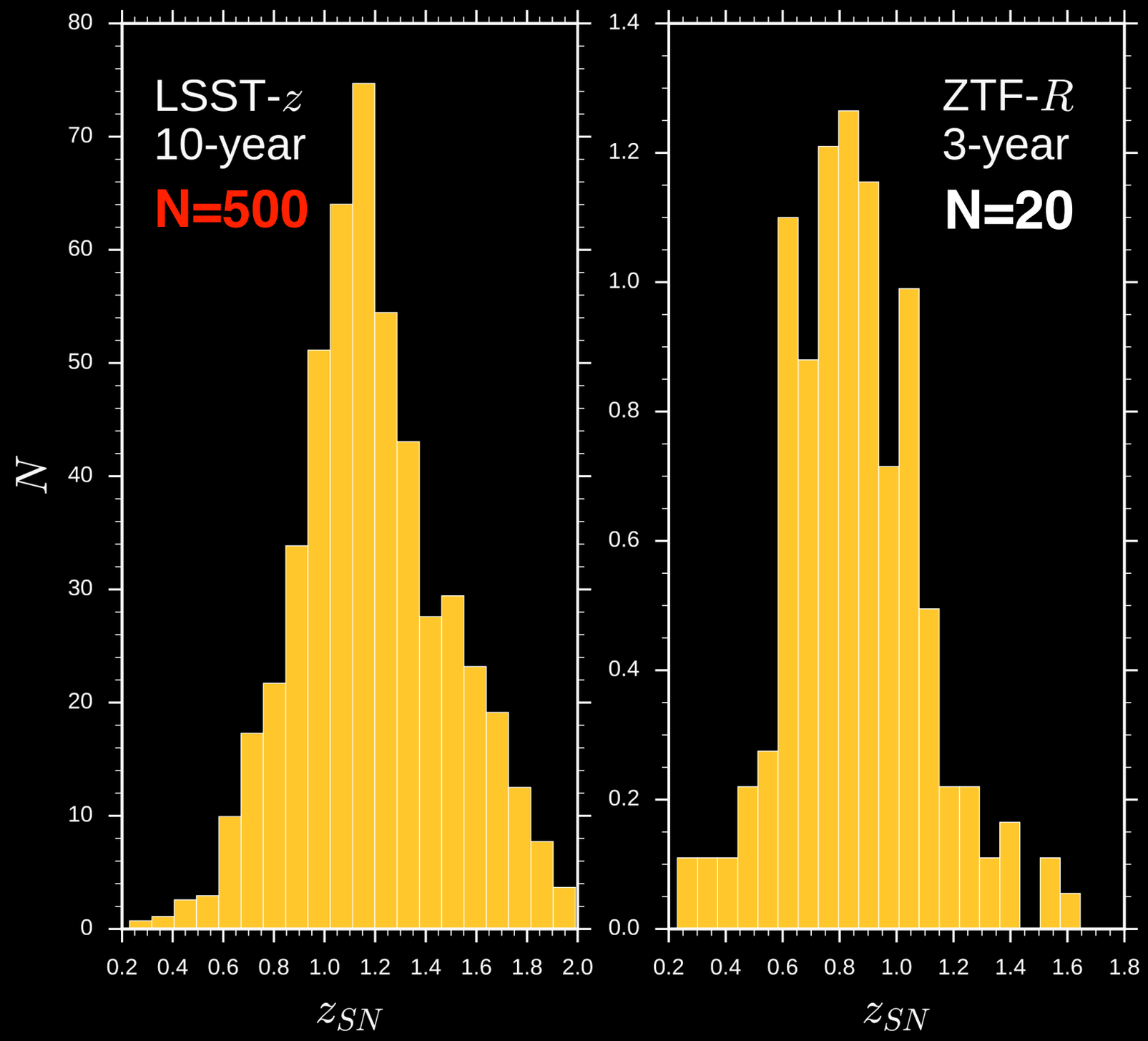
SN "Refsdal" (SN 1987A-like) z=1.49
Kelly et al. 2015 (*Science*)
discovered w/*HST*, μ~ 10,
J~24.2 (AB)

iPTF16geu (SN Ia) z=0.41
Goobar et al. 2017 (*Science*)
discovered w/ P48, μ ~ 52,
i ~ 19 (AB)

HOW TO FIND GRAVITATIONALLY LENSED TYPE Ia SUPERNOVAE

DANIEL A. GOLDSTEIN[1,2] AND PETER E. NUGENT[1,2]

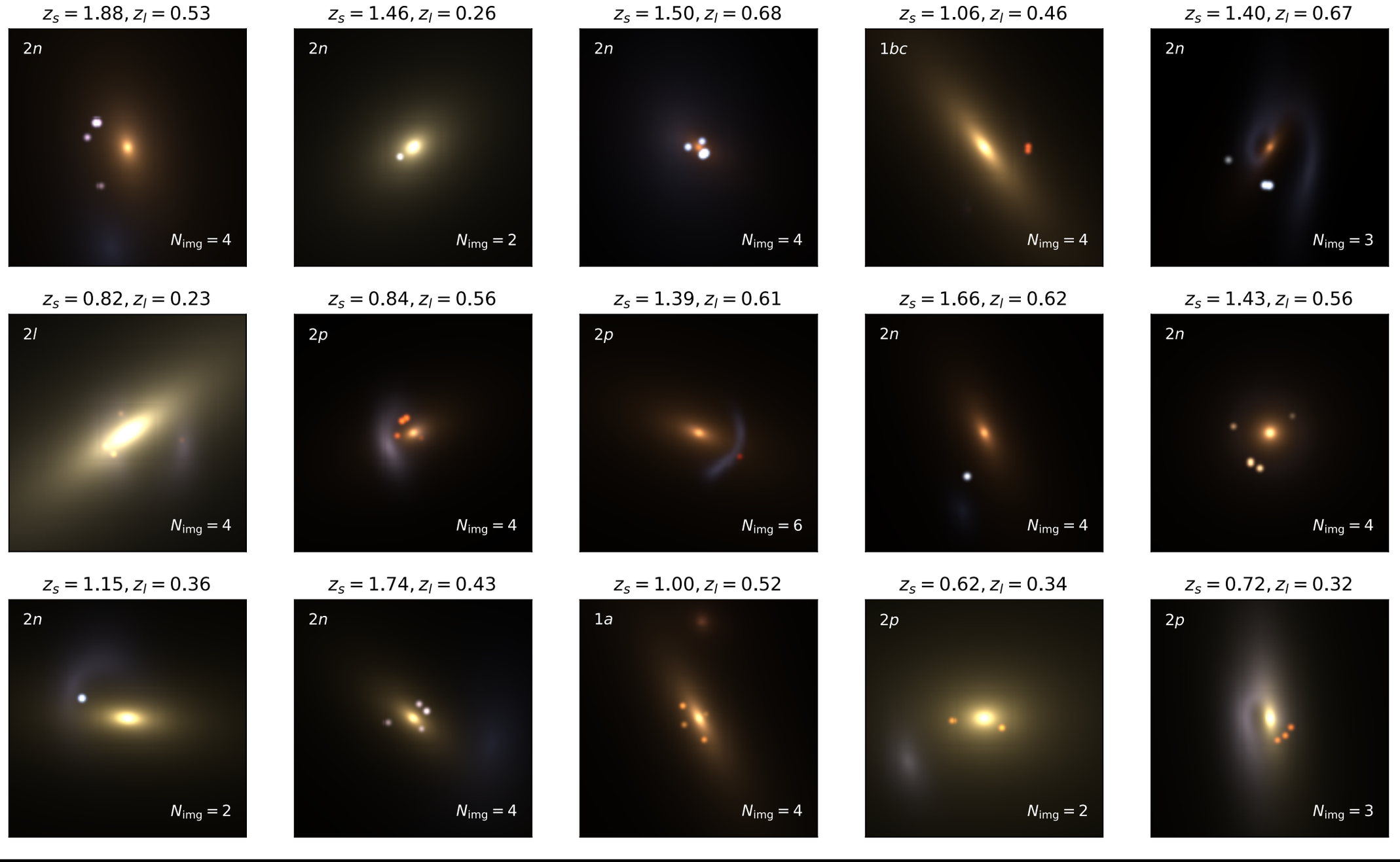
published in ApJL (Jan 2017)



Thanks to new gISN hunting techniques, we are now expecting ~10x as many gISNe from LSST than predictions of Oguri+Marshall (2010), which required resolved images.

Rates and Properties of Strongly Gravitationally Lensed Supernovae and their Host Galaxies in Time-Domain Imaging Surveys

Daniel A. Goldstein,[1,2,3,*] Peter E. Nugent,[2,3] and Ariel Goobar[4]



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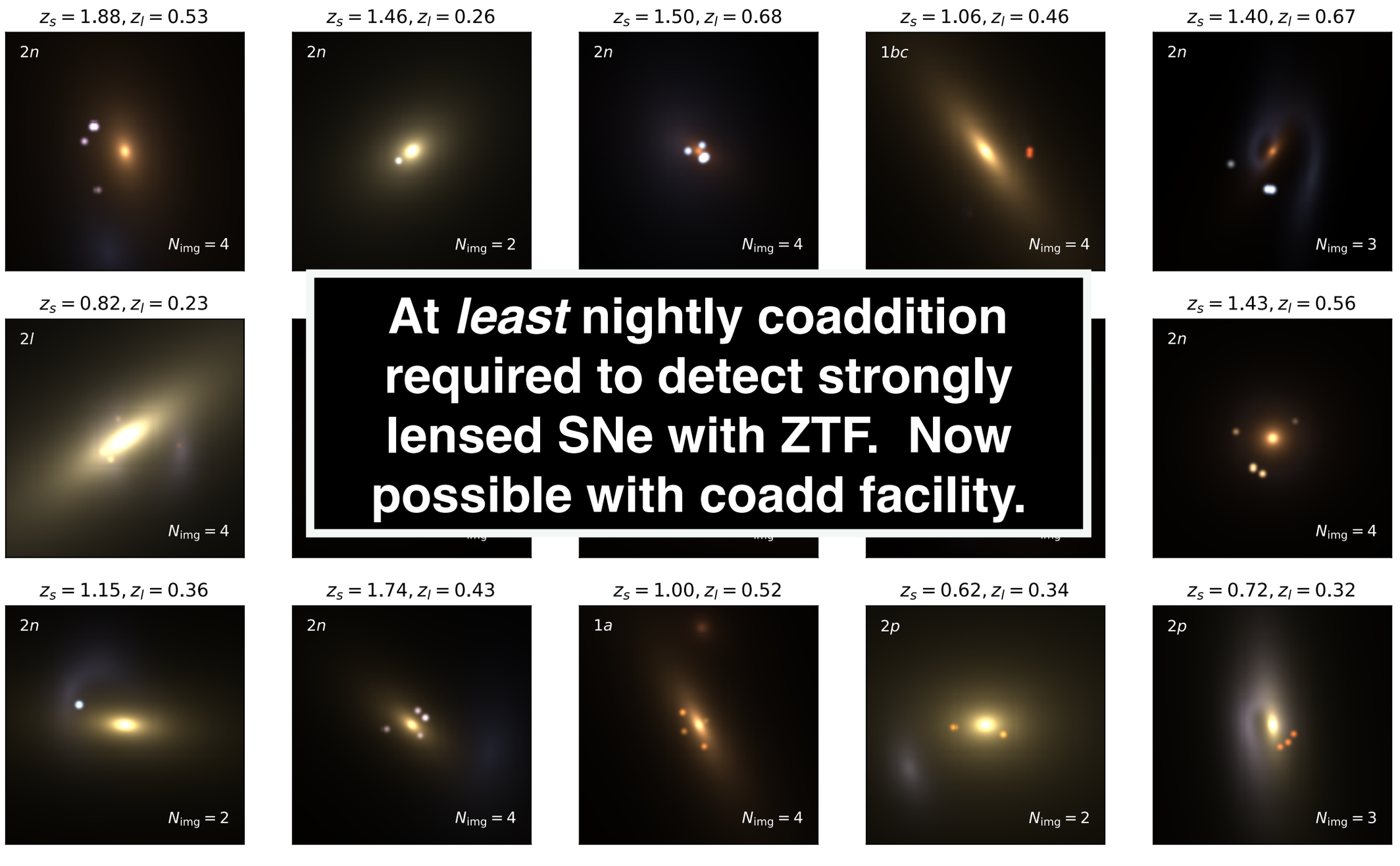

At *least* nightly coaddition required to detect strongly lensed SNe with ZTF. Now possible with coadd facility.

Conclusions and Outlook

- Automated image differencing of coadded wide-field science images is an efficient way to greatly extend the science reach of the current generation of time domain surveys.
- We have implemented a framework for doing this in ZTF, which has been operative for a couple of weeks and produced early science results.
- Using the framework, we can extend the reach of ZTF to ~23rd mag while still maintaining the cadence necessary for many science cases.
- Transients identified by this framework that are too faint for current rapid follow-up resources will be well-suited to future MMS facilities.