Strongly lensed AGNs and SNe with LSST

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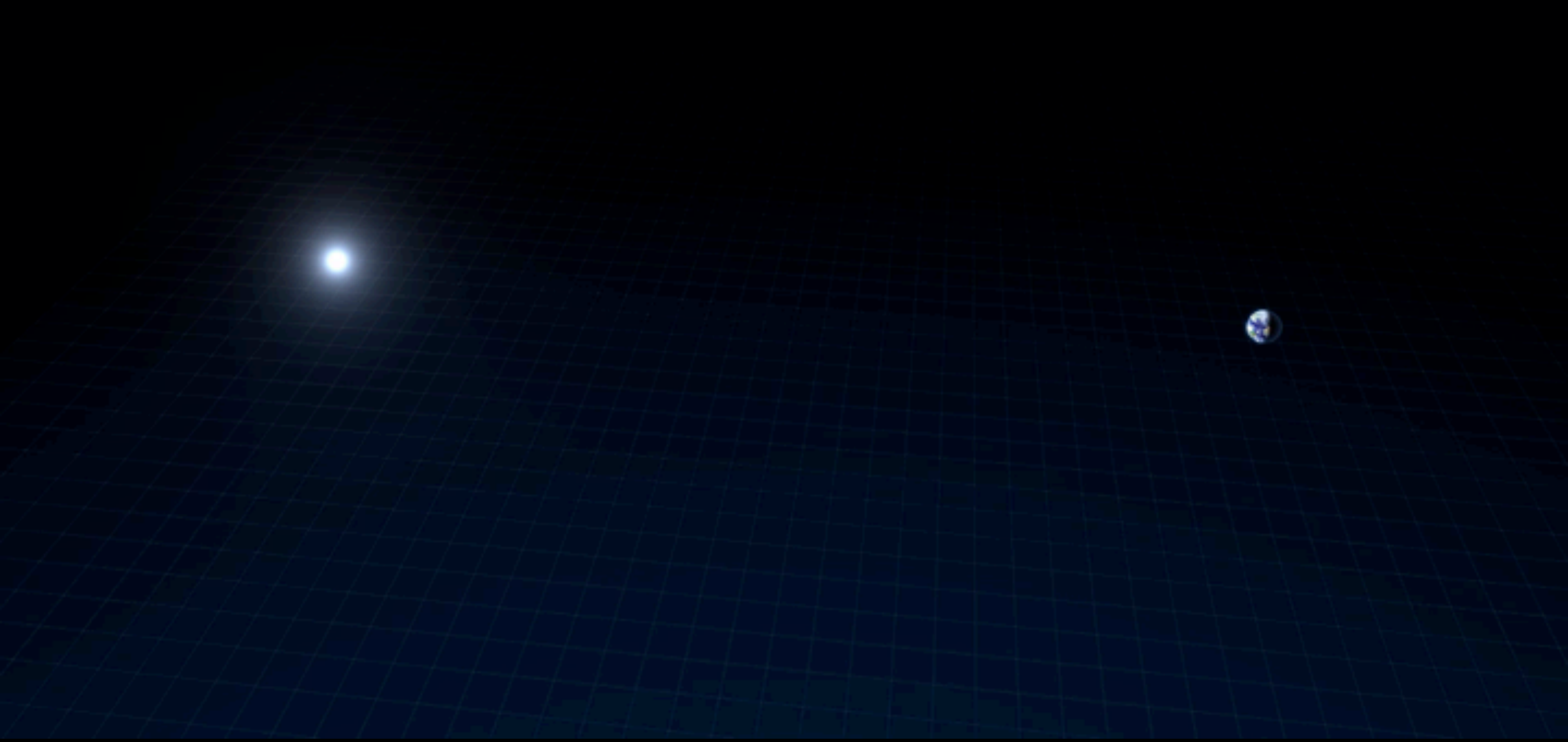
Strong lensed quasar

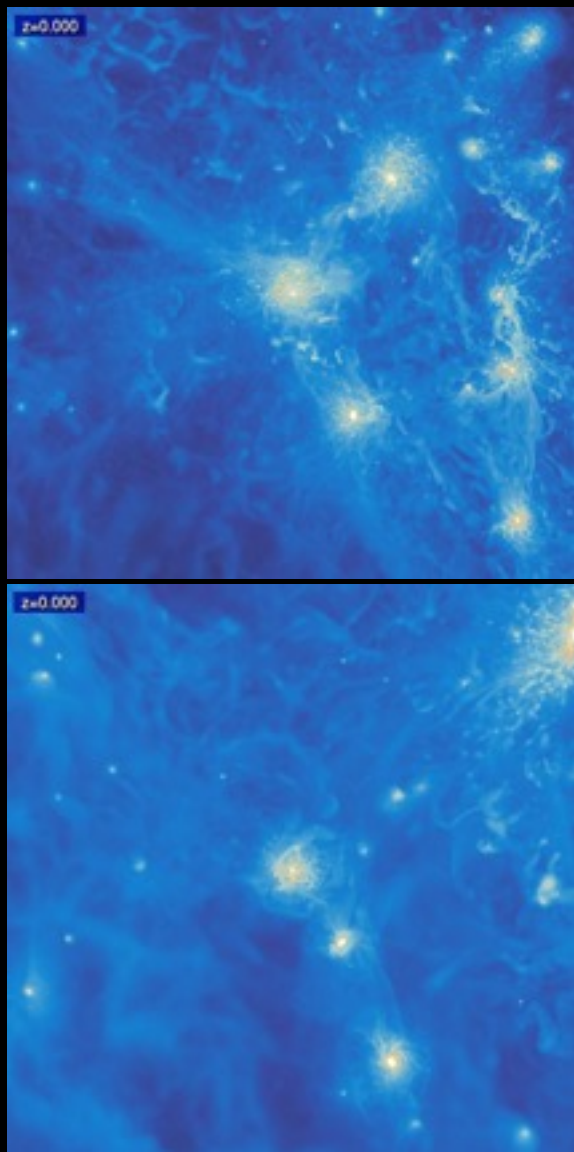


[Credit: ESA/Hubble, NASA]

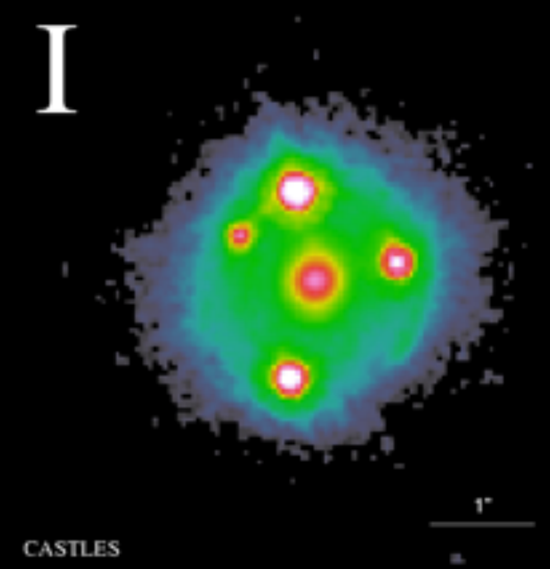
Galaxy substructure
nature of dark matter

CDM

WDM



[credit: K. Riebe, CLUES]

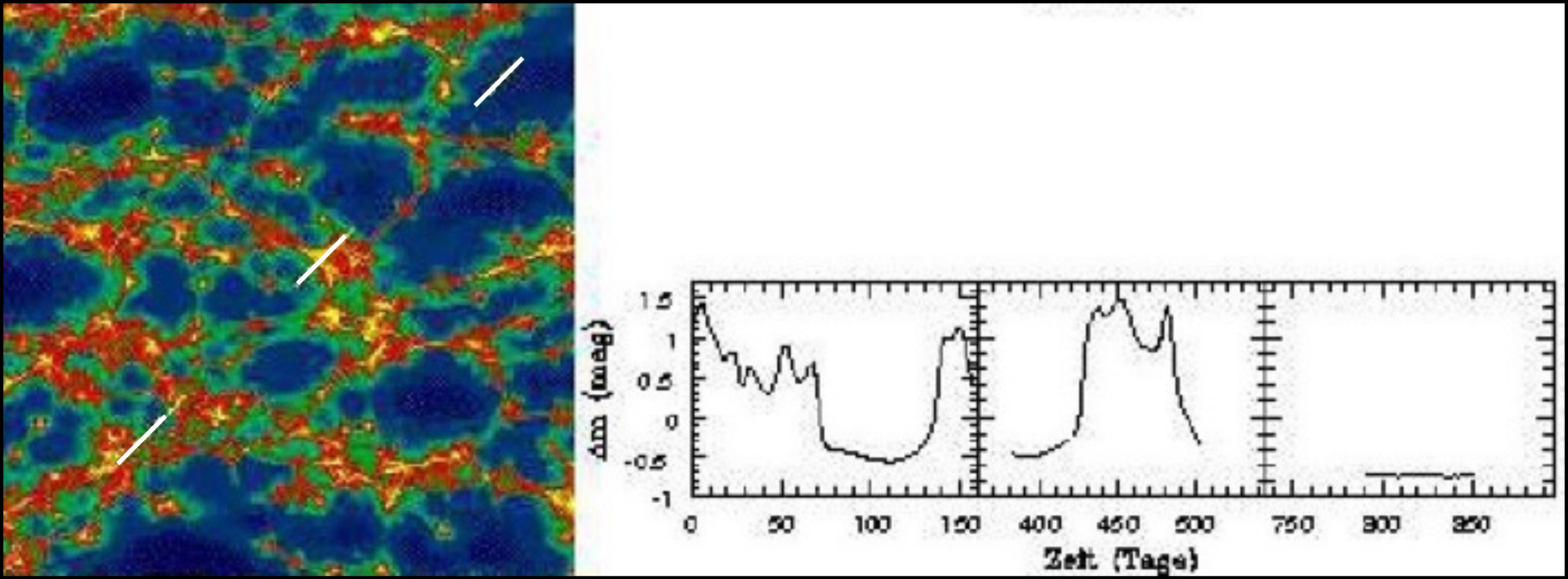


[CASTLES]

Flux ratios between multiple images sensitive to substructures
➜ lensing is a unique probe of dark satellites

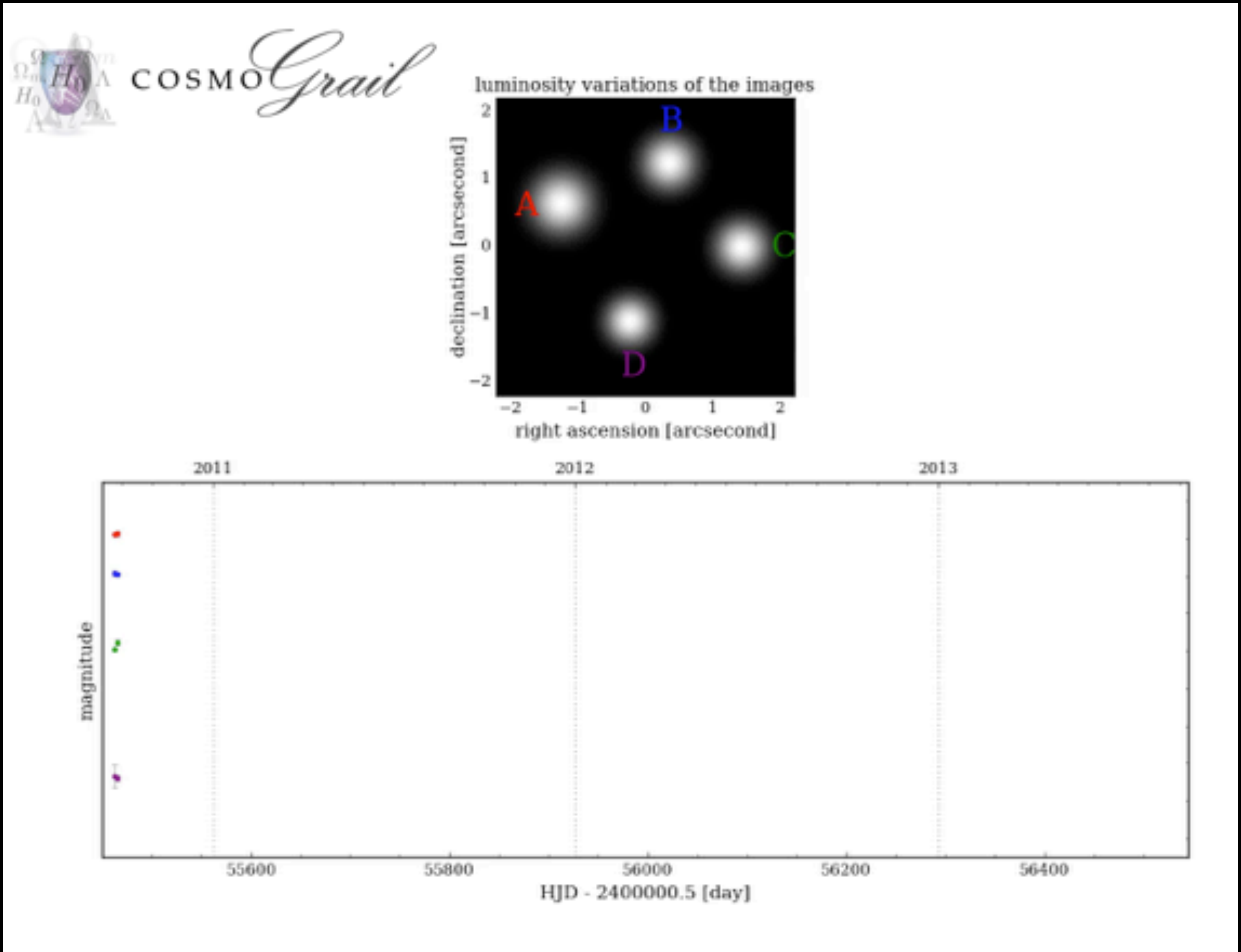
Inner structures of AGNs

- measure accretion disk size through microlensing: variability depends on
  - source size (accretion disk)
  - mass of microlenses (stars)



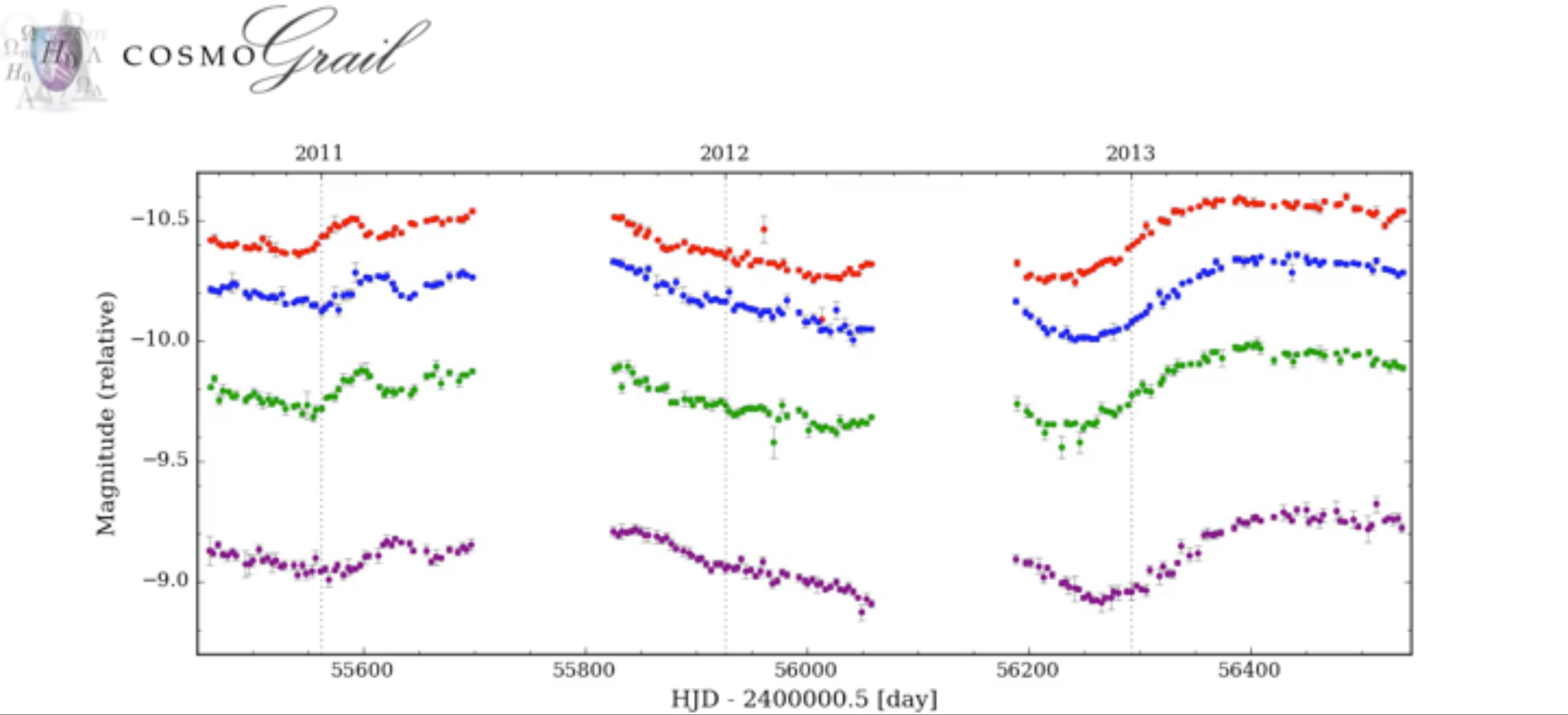
[Wambsganss 2006]

Cosmology with time delays



[Credit: V. Bonvin]

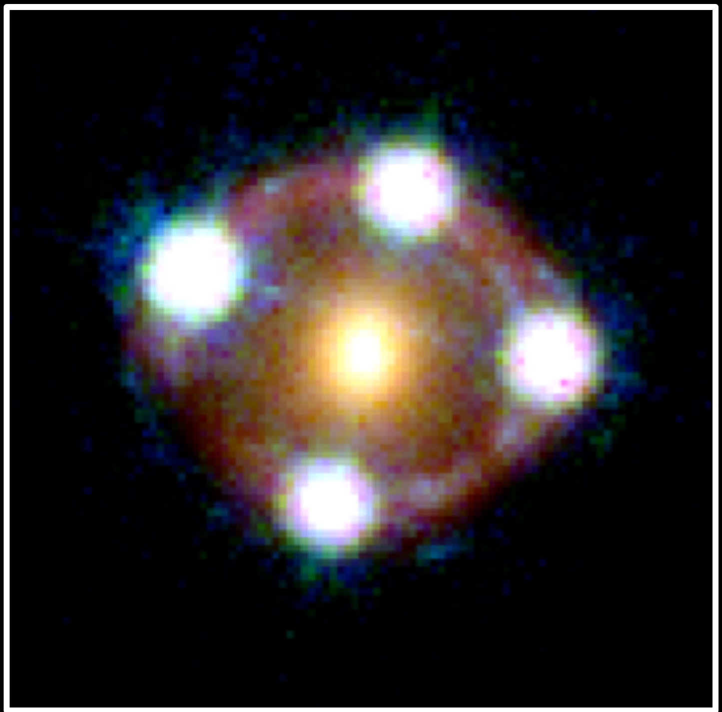
Cosmology with time delays



[Credit: V. Bonvin]

Cosmology with time delays

HE0435-1223



[Suyu et al. 2017]

Time delay:

$$t = \frac{1}{c} D_{\Delta t} \, \phi_{\text{lens}}$$

Time-delay distance:

$$D_{\Delta t} \propto \frac{1}{H_0}$$

Obtain from lens mass model

distance-redshift relation

➜ constrain H_0

➜ important to address tension in H_0

Advantages:

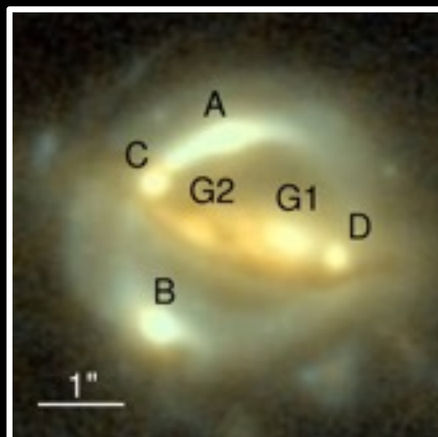
- simple geometry & well-tested physics

- one-step physical measurement of a cosmological distance

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

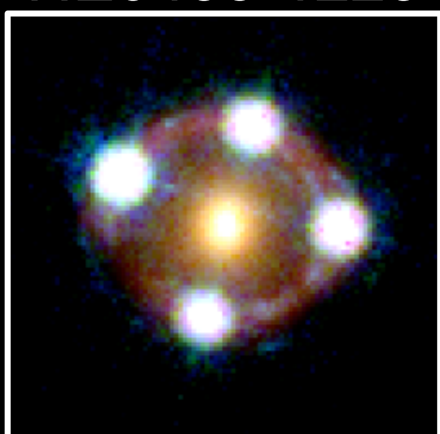
B1608+656



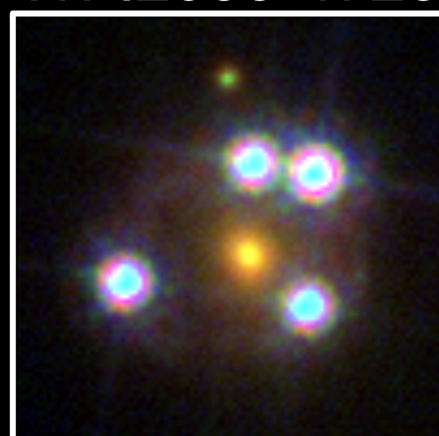
RXJ1131-1231

H_0 to <3.5% precision

HE0435-1223



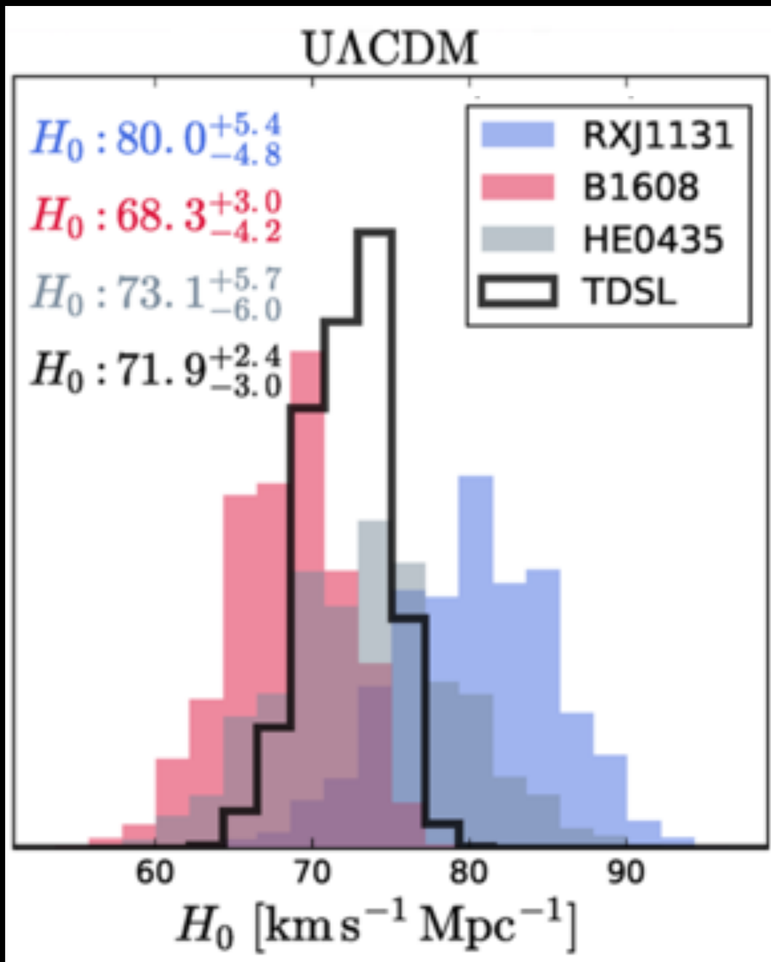
WFI2033-4723



HE1104-1805

[Suyu et al. 2017]

H_0 from 3 lensed quasars

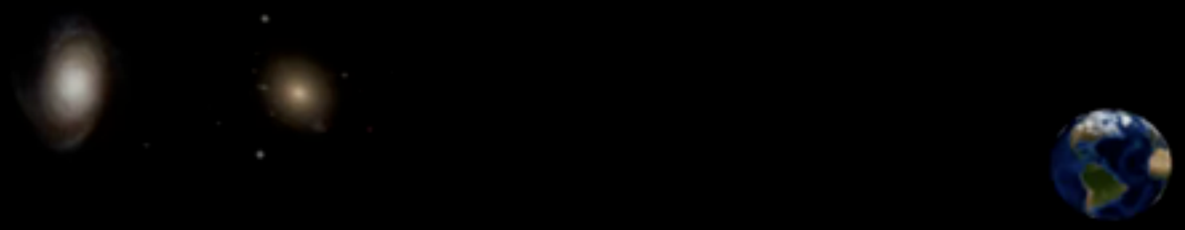


$H_0 \in [0,150]$ km/s/Mpc
$\Omega_m = 1 - \Omega_\Lambda \in [0,1]$
w = -1

H_0 with 3.8% precision for flat ΛCDM

[Bonvin, Courbin, Suyu et al. 2017]

Strongly lensed supernova event

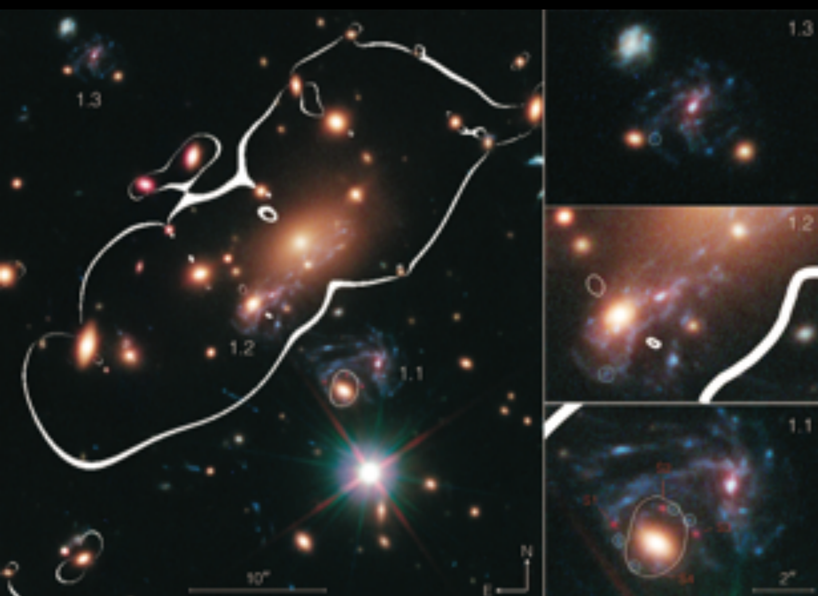


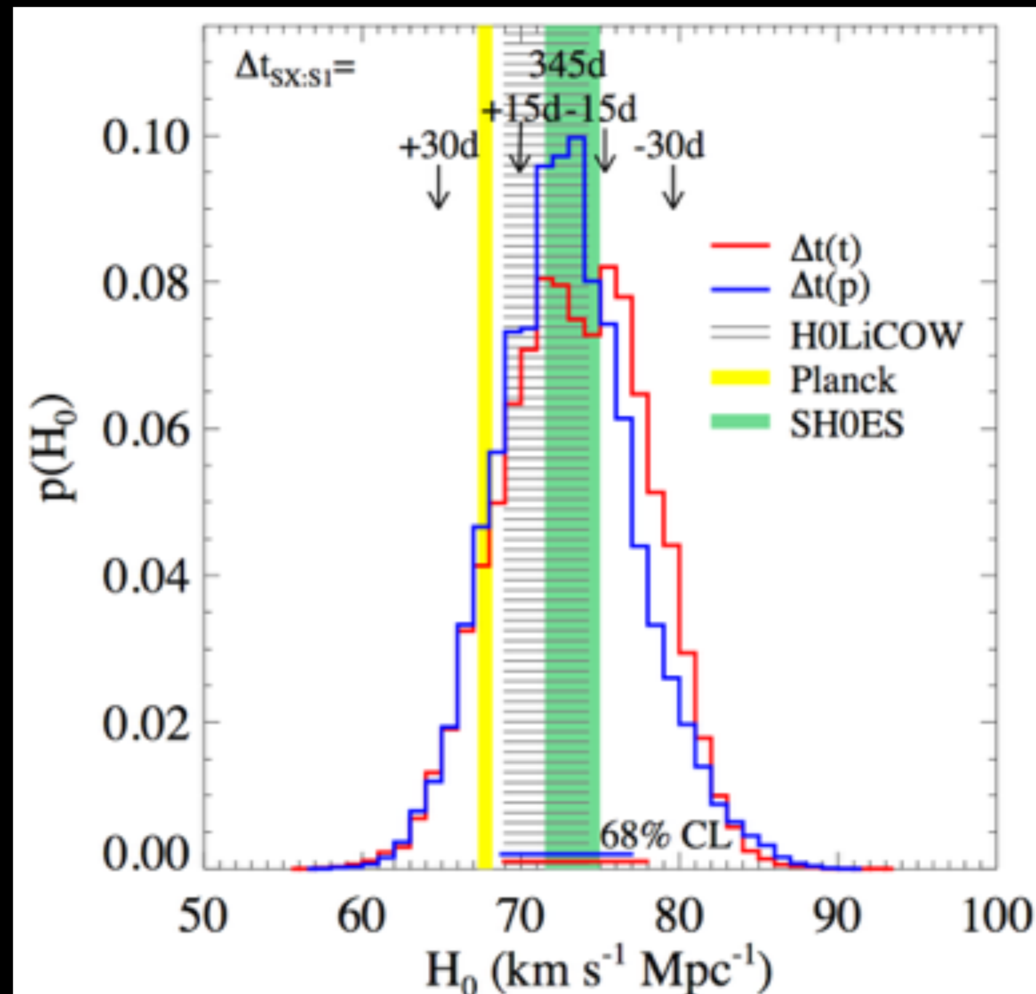
[Credit: S. More]

multiple images of the SN event appear around the foreground lens galaxy, at ***different*** times

H_0 à la Supernova Resfdal

feasibility study of using SN Refsdal for H_0 measurement



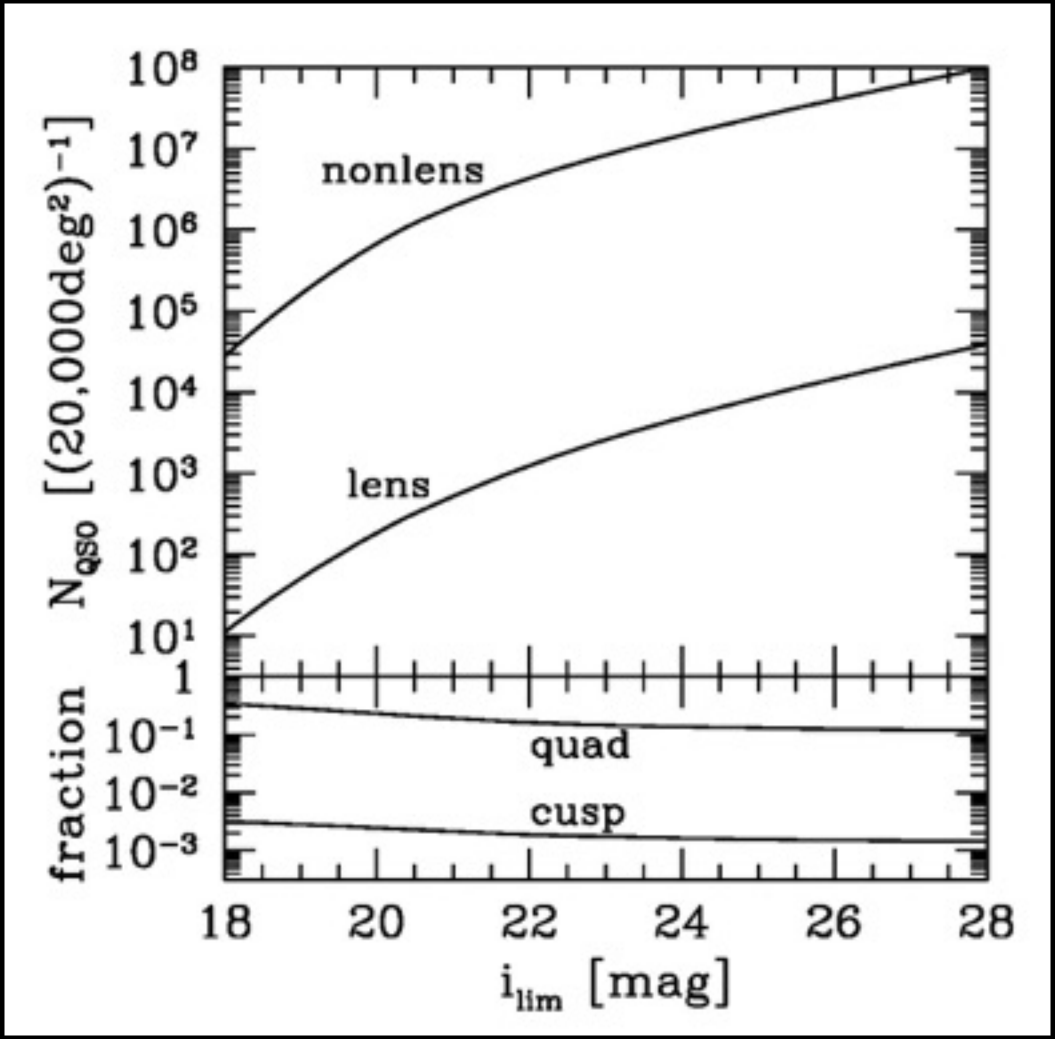


- S1-S2-S3-S4 delays from Rodney et al. (2016)
- SX-S1 delay estimated based on detection in Kelly et al. (2016)

[Grillo, Rosati, Suyu et al. 2018]

How many lenses in LSST?

Expected number of lensed quasars

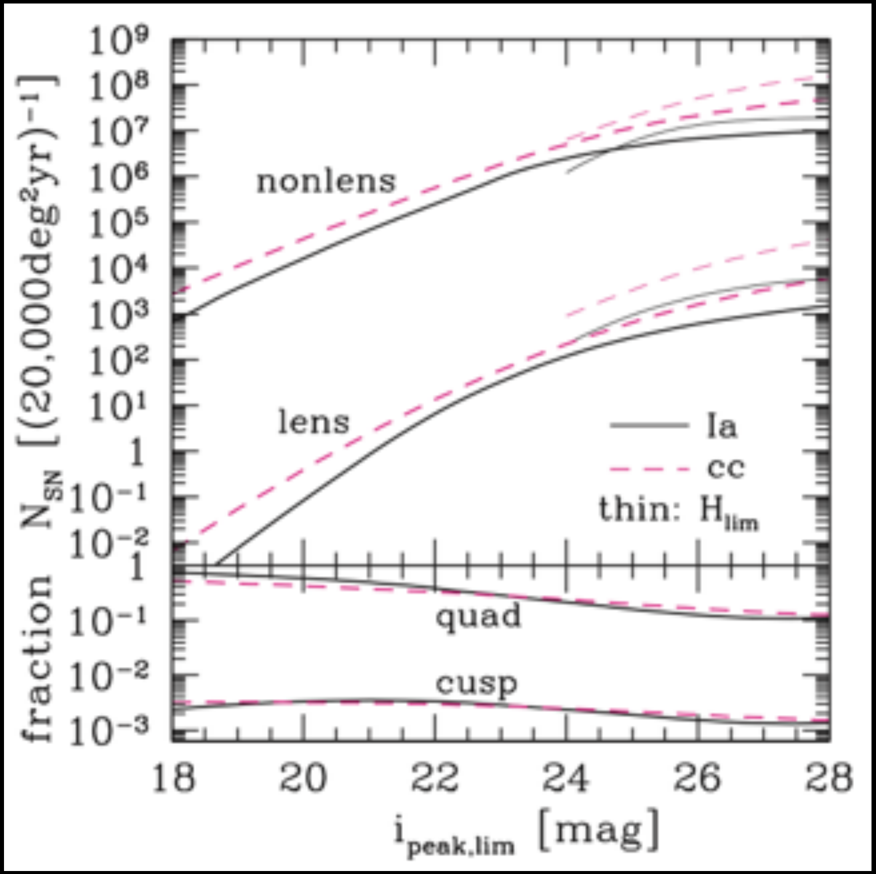


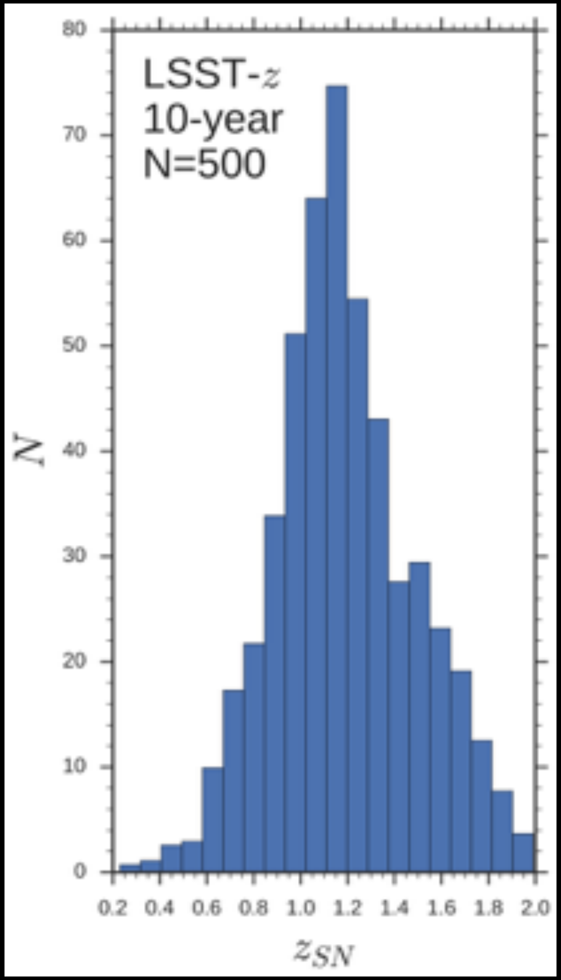
[Oguri & Marshall 2010]

LSST Deep-Wide-Fast
- 18,000 deg^2
- $\theta_{min\_sep} = (2/3)\ \theta_{PSF}$

Detectable/resolvable:
- 8,000 lensed quasars
- ~15% quads (4-images)

Expected number of lensed SNe





Spatially resolvable:

- ~130 lensed SNe (Ia & cc)
- ~30% quads (4-images)

[Oguri & Marshall 2010]

All (resolved/unresolved):

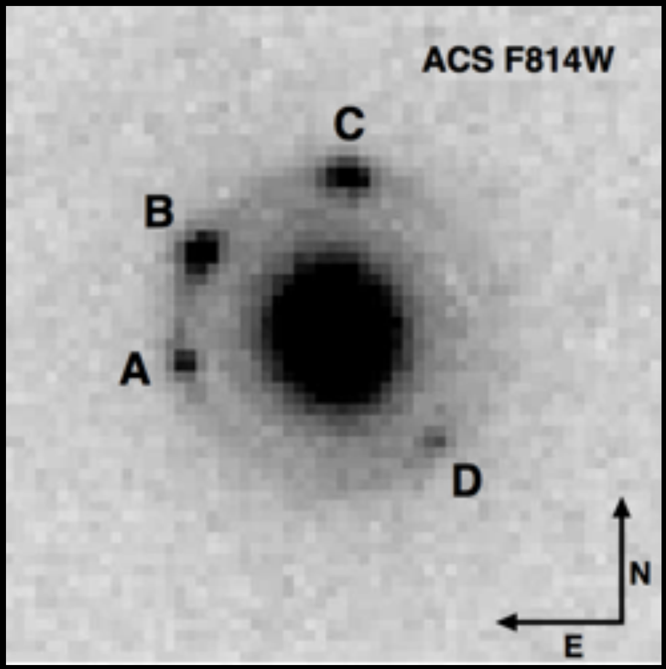
- ~900 lensed SNe Ia

[Goldstein & Nugent 2017, Goldstein et al 2018]

How to find the lenses in LSST?

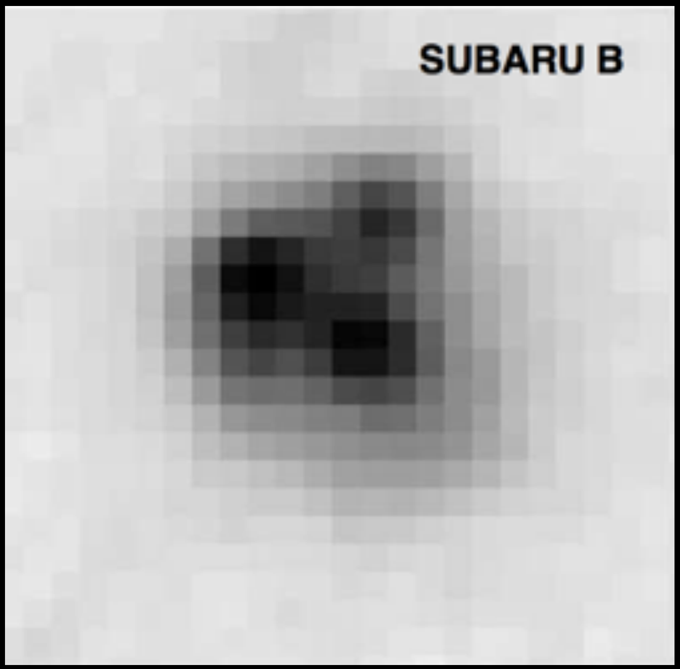
Challenges from the ground

Space (HST)



[Anguita et al. 2009]

Ground (Subaru)



How to tell if this is a lens?

Ways to find lensed quasars

For a system to qualify as a lens candidate, it must be explained by a plausible lens model

Direct Modeling

- **LensTractor**
  [Marshall et al.]
  classification based on explicit model comparison
- **CHITAH**
  [Chan et al., 2015]
  classification based on simple lens model fitting

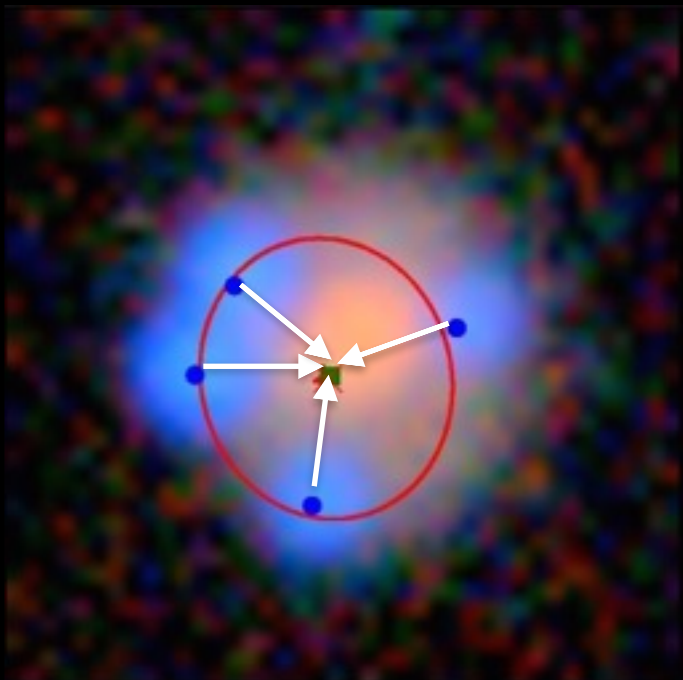
Machine Learning

implicit lens model (prior) enters via the training set [e.g., Agnello et al. 2014, Ostrovski et al. 2017]

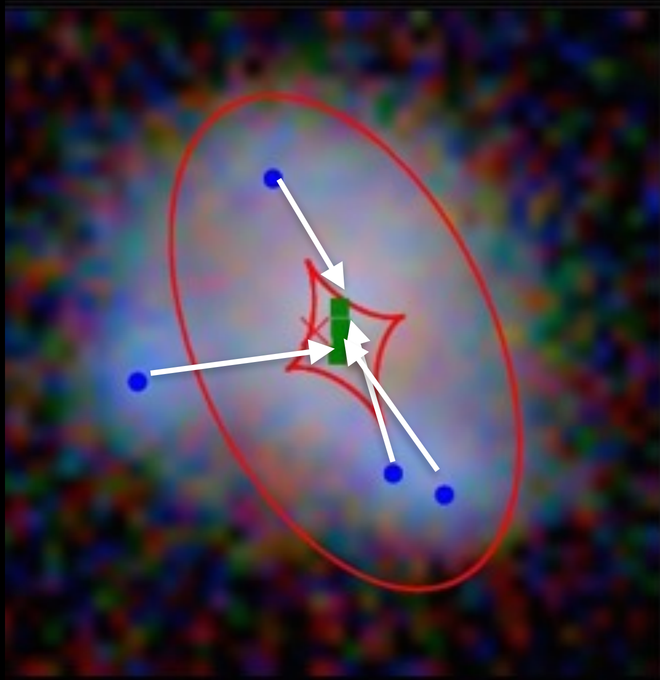
Citizen Science

[Marshall et al. 2015; More et al. 2015]
citizens visually identify lenses after familiarizing with lens configurations

CHITAH: hunter for lensed quasars



Probably a lens



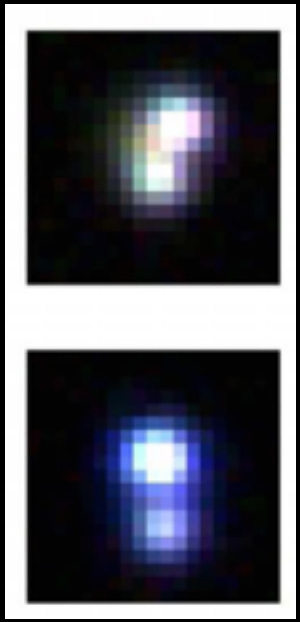
Probably NOT a lens

James Chan has developed CHITAH, an automated and fast algorithm using multiband imaging for lens classification [Chan, Suyu et al. 2015]

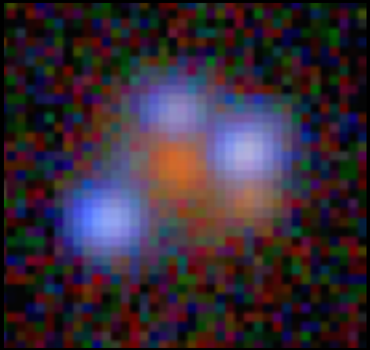
New lensed quasars systems

[More et al. 2017]

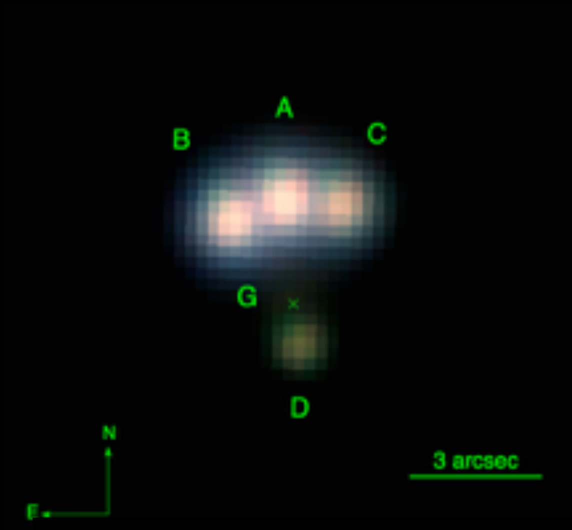
[Ostrovski et al. 2017]



[Agnello et al. 2015]



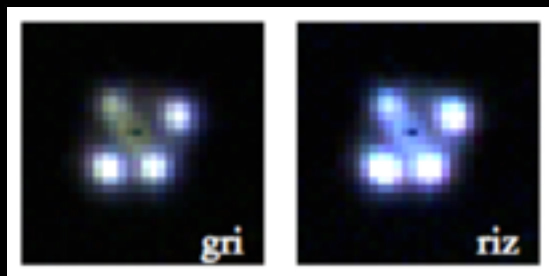
[Lin et al. 2017]



[Berghea et al. 2017]

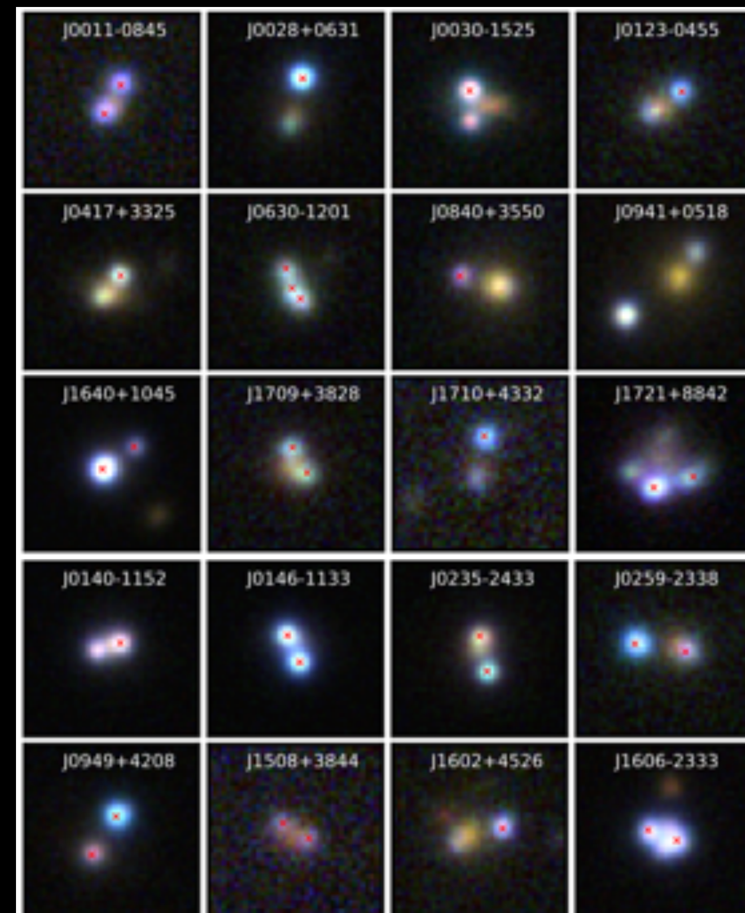
Gaia reveals lensed quasars

Gaia
+ DES
+ WISE



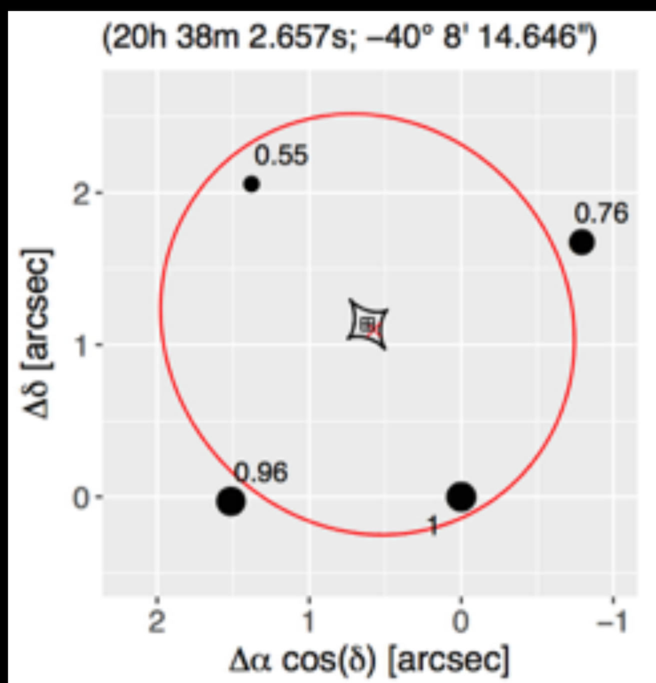
[Agnello et al. 2018]

Gaia + WISE/SDSS
+ Pan-STARRS



[Lemon et al. 2018]

Gaia
only

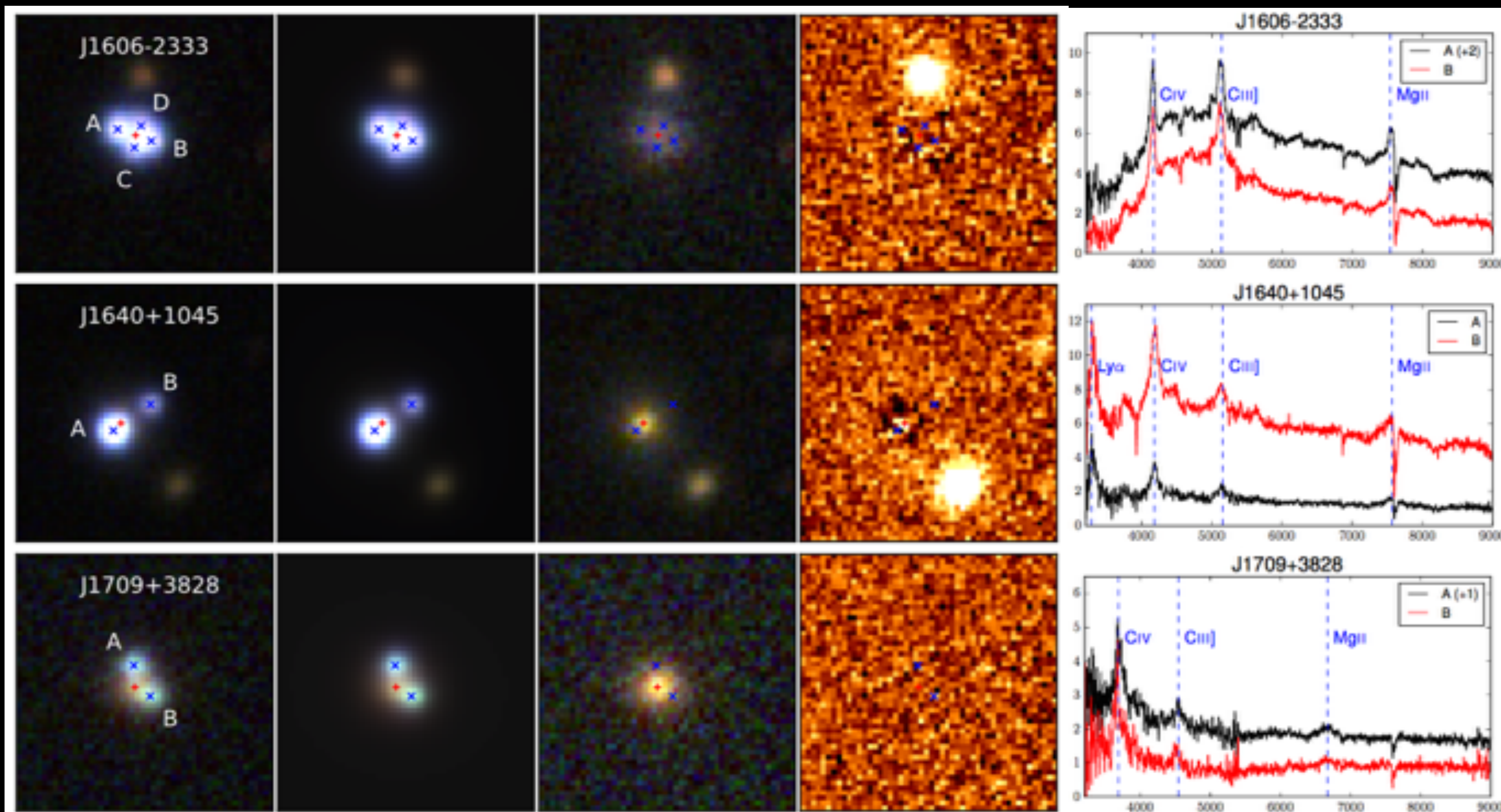


[Krone-Martins et al. 2018]

Gaia reveals lensed quasars

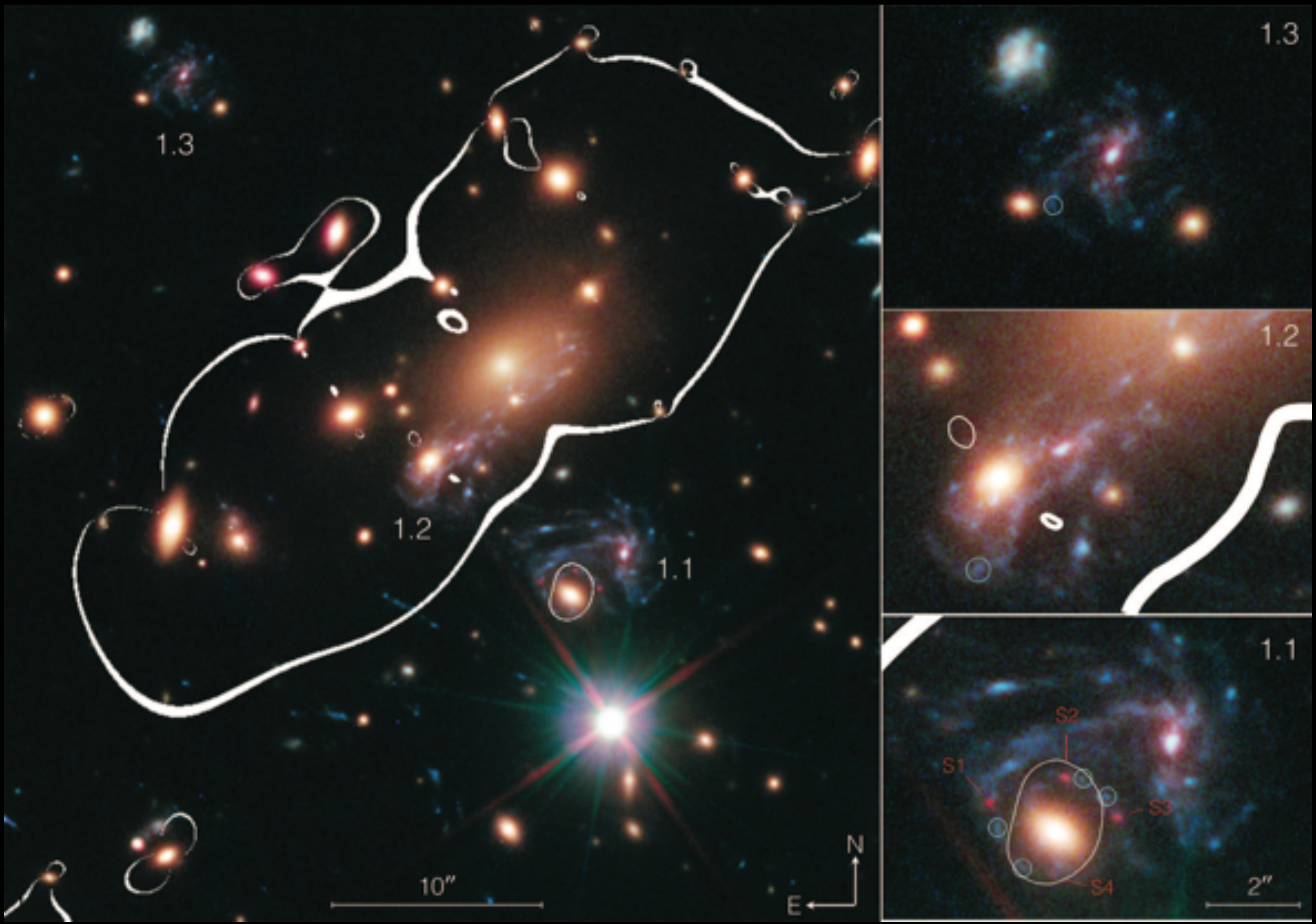
pixel-based modeling and spectroscopic confirmation

data model quasar sub. residuals spectra



[Lemon et al. 2018]

strongly lensed core-collapse supernova



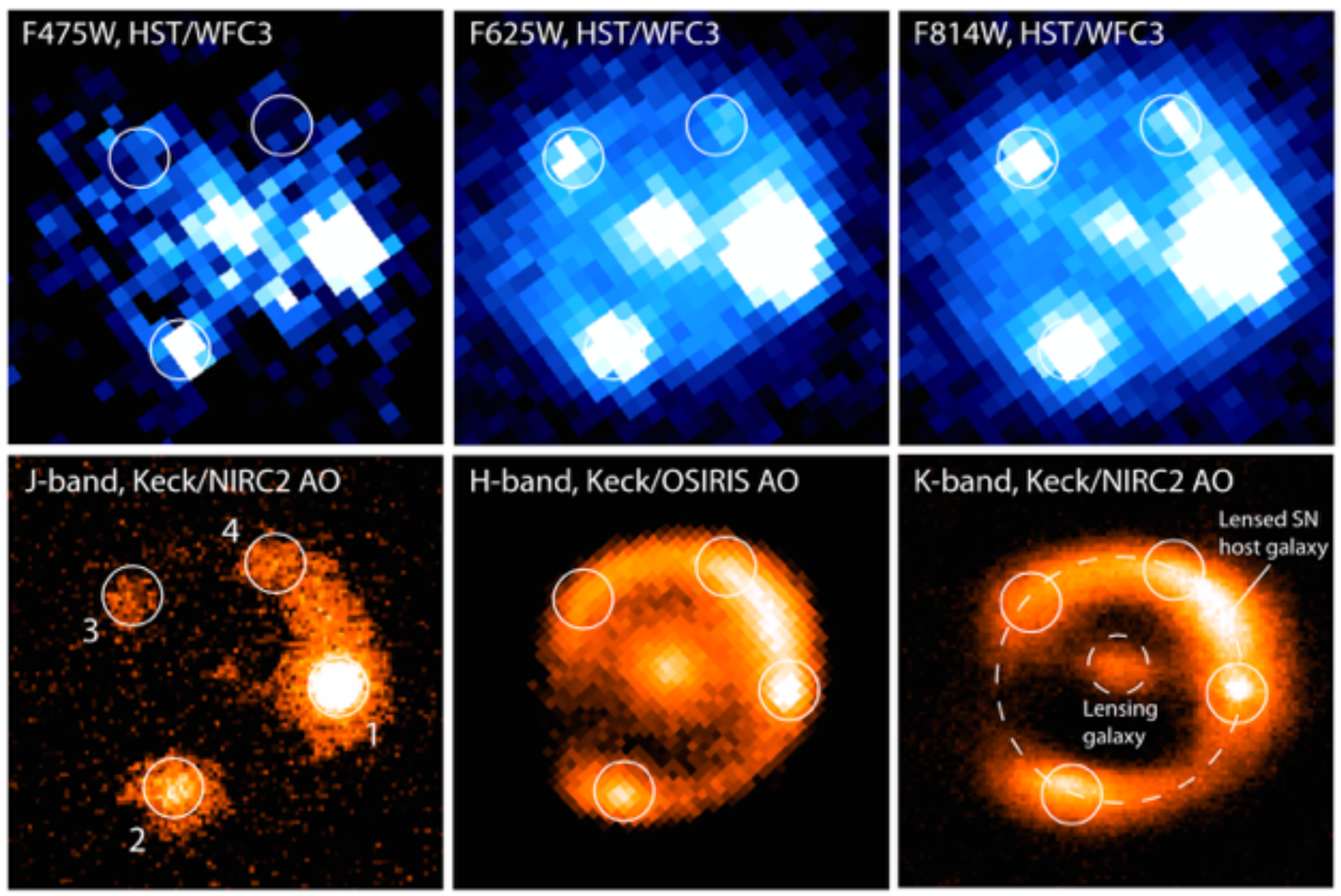
MACS 1149.6+2223

[Kelly et al. 2015]

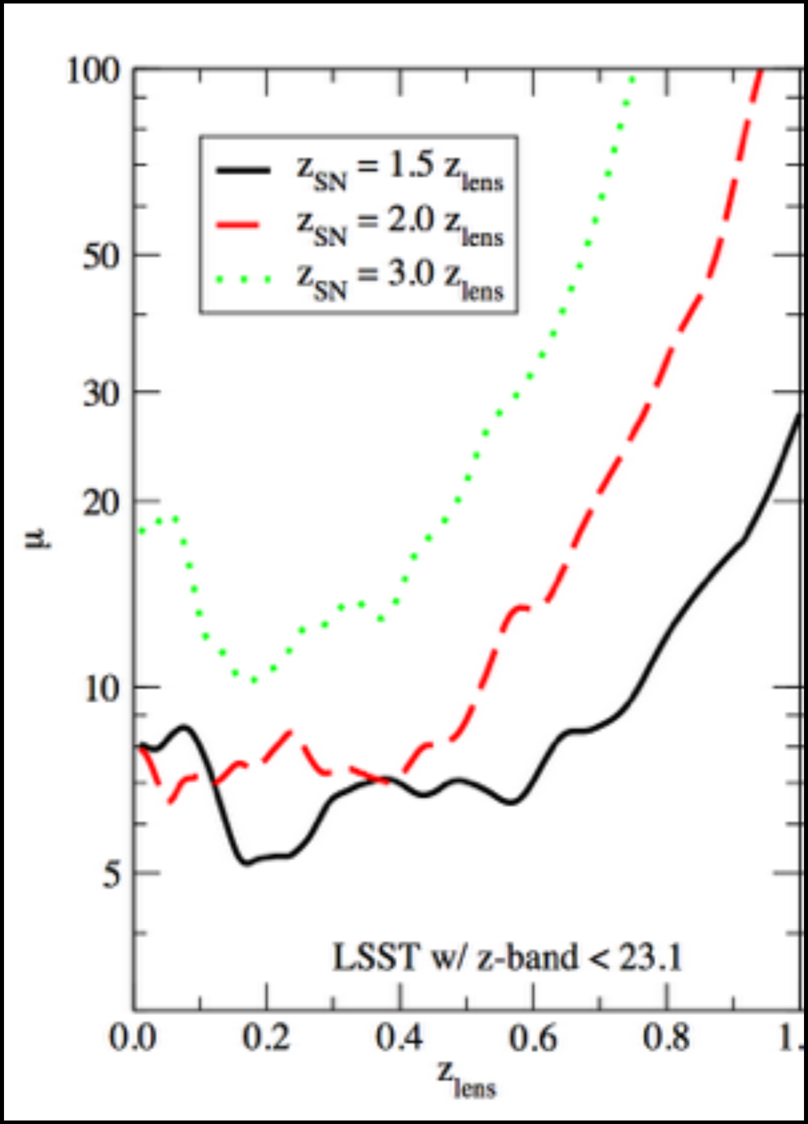
spatially-resolved lensed Type Ia

discovered in iPTF

[Goobar et al. 2017]



Finding lensed SNe



- Lensed SNe are magnified
- Find SNe that are brighter than expected given photo-z of foreground lens galaxy

[Goldstein & Nugent 2017]

Time delays ***for free*** from LSST?

Time-delay challenge: lensed quasars

Time-Delay Challenge 1 (Liao, Treu, Marshall et al. 2015) :

- thousands of simulated LSST-like lensed quasar light curves
- blind test with 7 teams providing measurements
- quantify the following dependence on cadence:
    - accuracy:

$$|A| = \left| \frac{1}{fN} \sum_i \frac{t_i^{\text{meas}} - t_i^{\text{inp}}}{t_i^{\text{inp}}} \right| \approx 0.06\% \left(\frac{\text{cad}}{3\,\text{days}} \right)^{0.0} \left(\frac{\text{sea}}{4\,\text{months}} \right)^{-1.0} \left(\frac{\text{camp}}{5\,\text{years}} \right)^{-1.1}$$

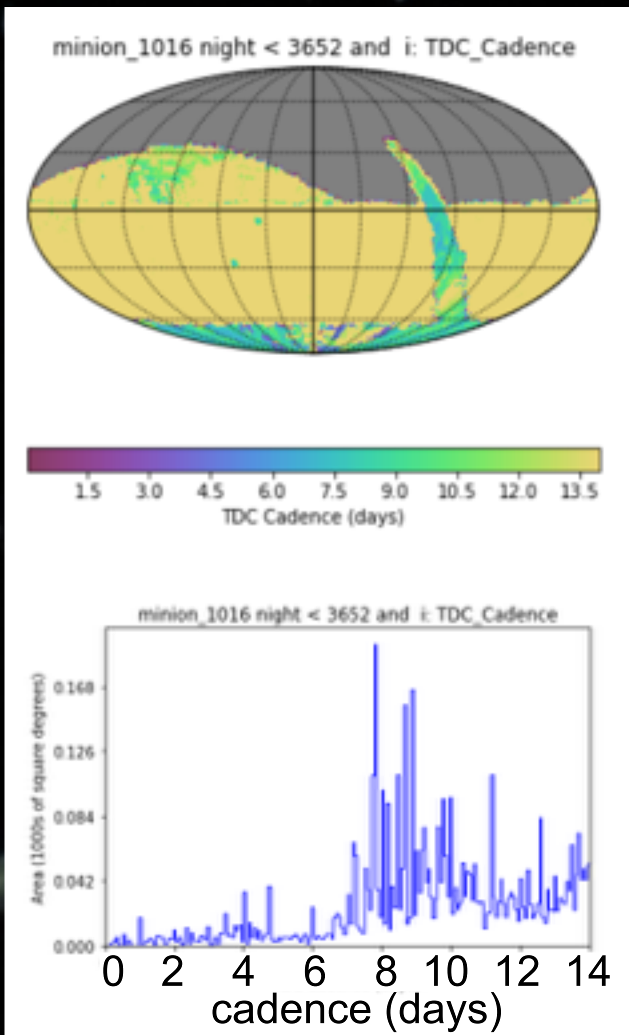
    - precision

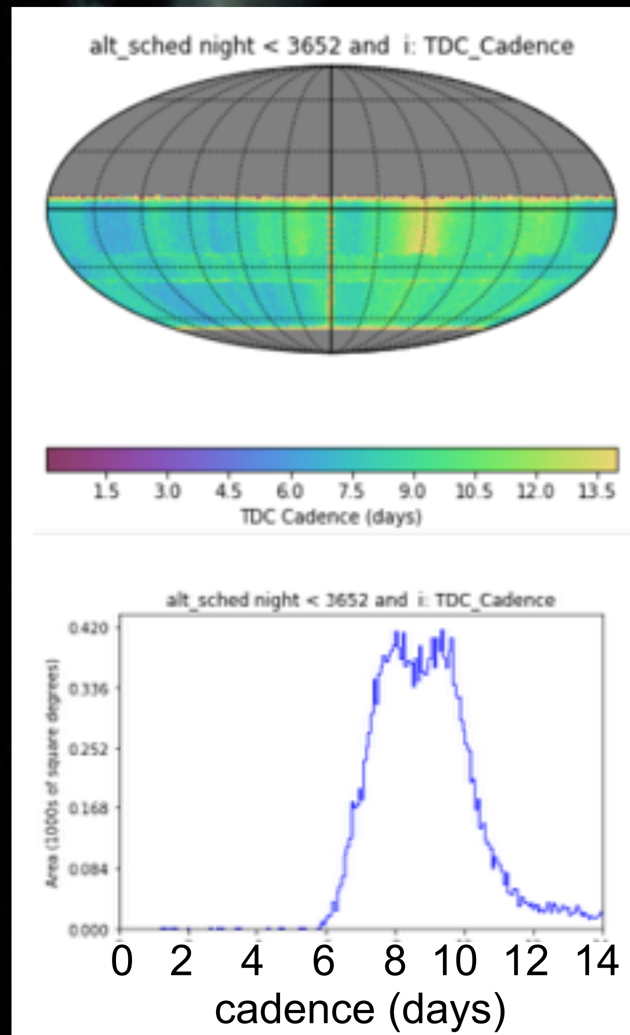
$$P = \frac{1}{fN} \sum_i \frac{\delta_i}{t_i^{\text{inp}}} \approx 4.0\% \left(\frac{\text{cad}}{3\,\text{days}} \right)^{0.7} \left(\frac{\text{sea}}{4\,\text{months}} \right)^{-0.3} \left(\frac{\text{camp}}{5\,\text{years}} \right)^{-0.6}$$

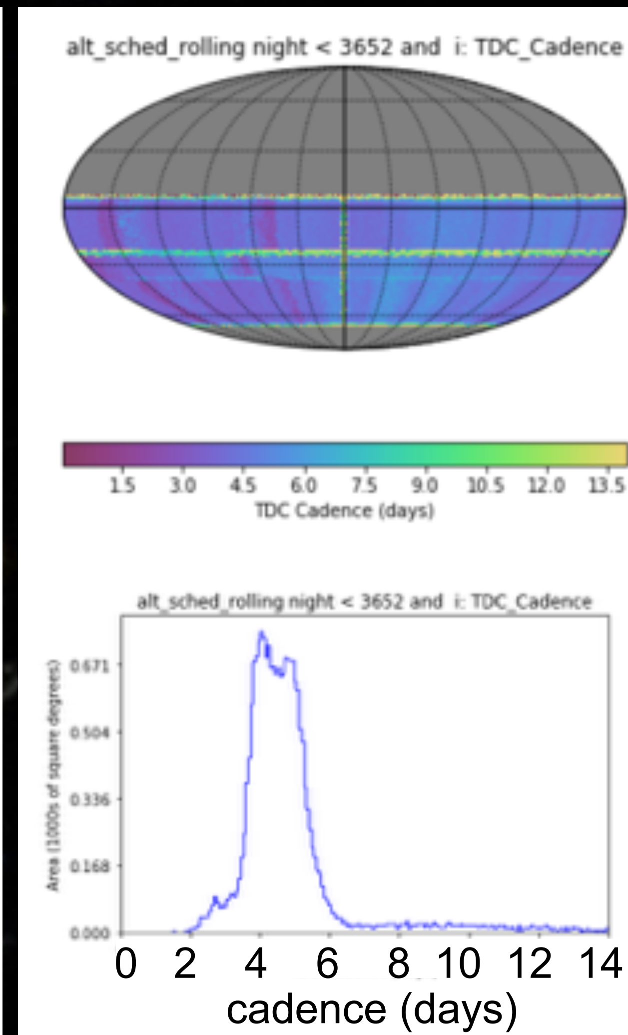
    - success rate f (in measuring a delay)

Cadence

minion_1016 alt_sched alt_sched_rolling



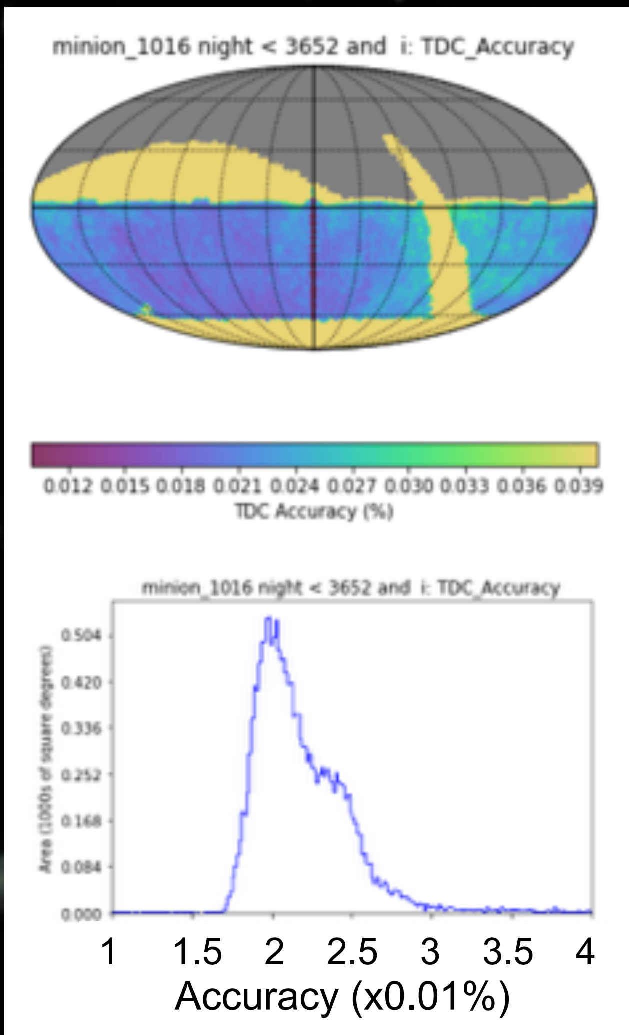




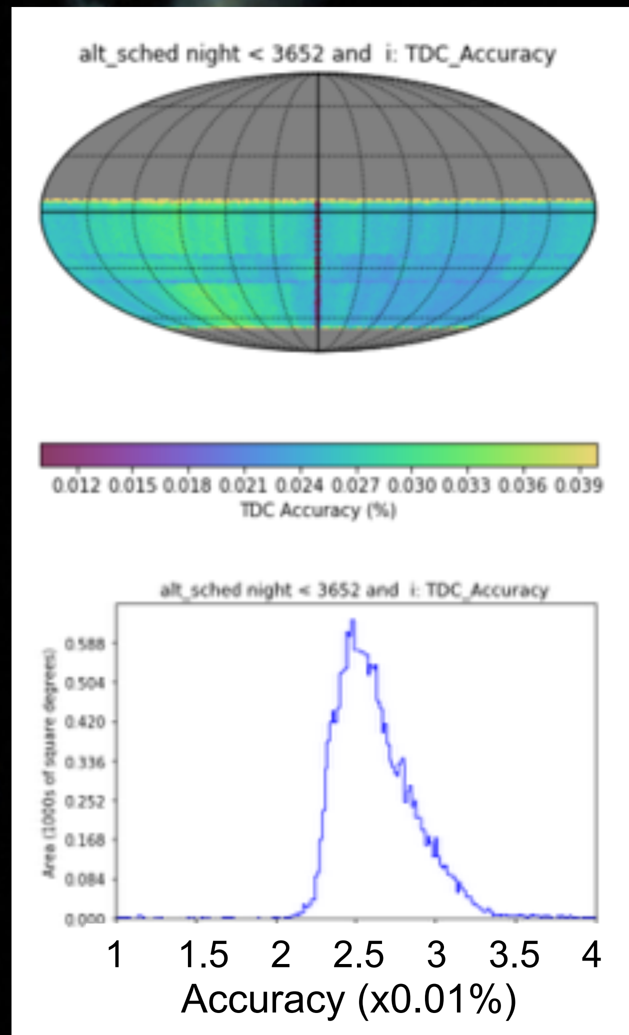
[material courtesy of S. Huber, P. J. Marshall, D. Rothchild]

Accuracy

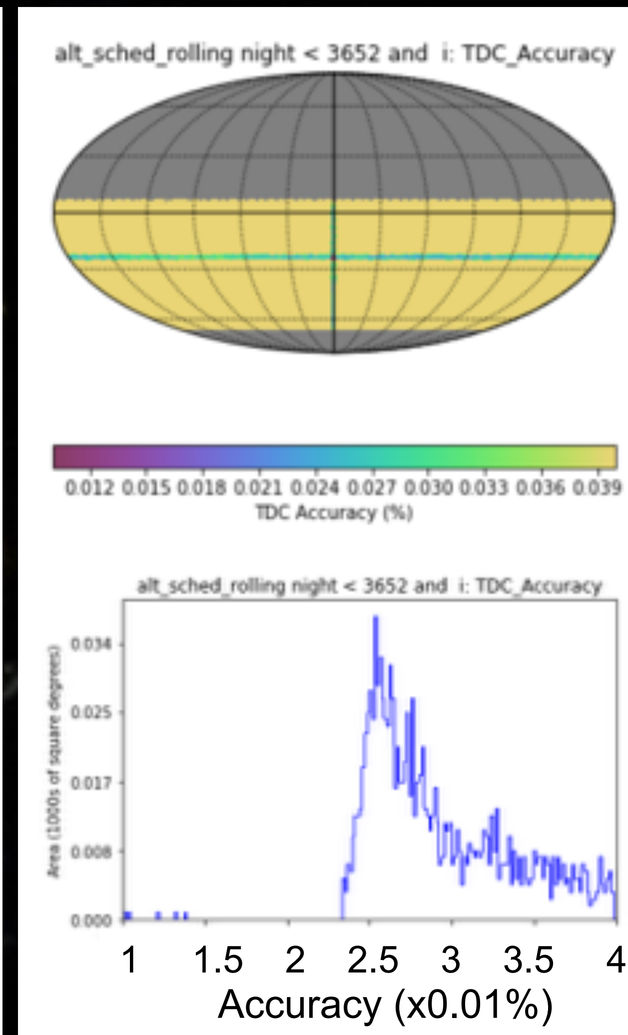
minion_1016



alt_sched



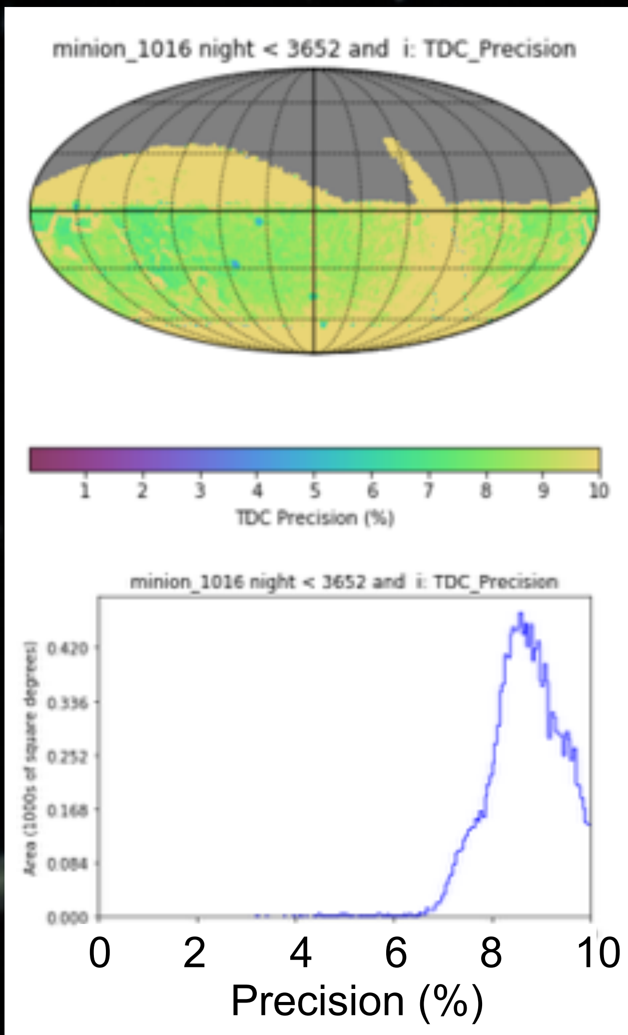
alt_sched_rolling



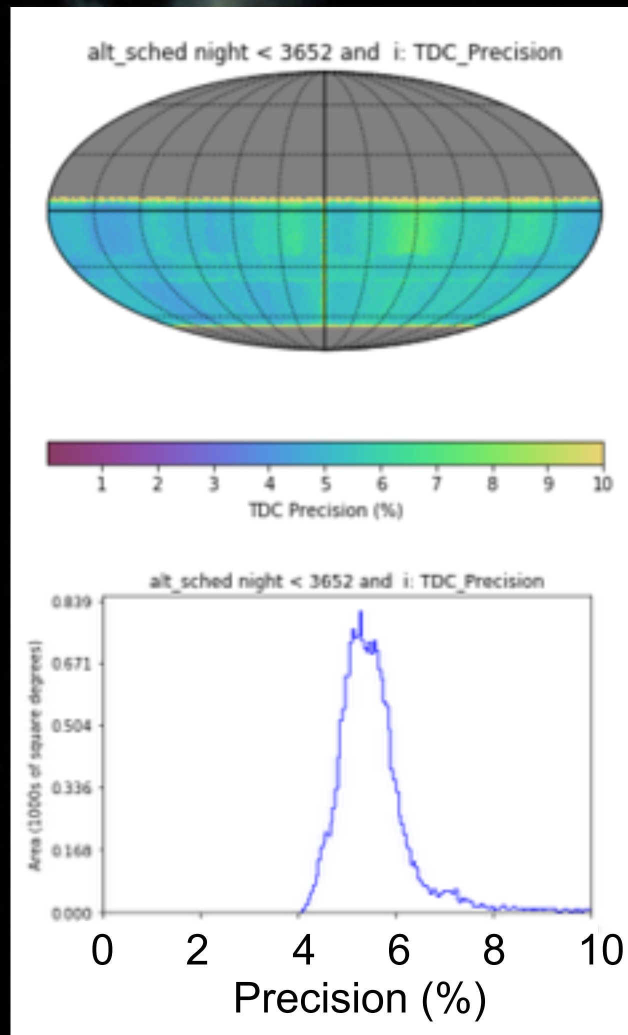
[material courtesy of S. Huber, P. J. Marshall, D. Rothchild]

Precision

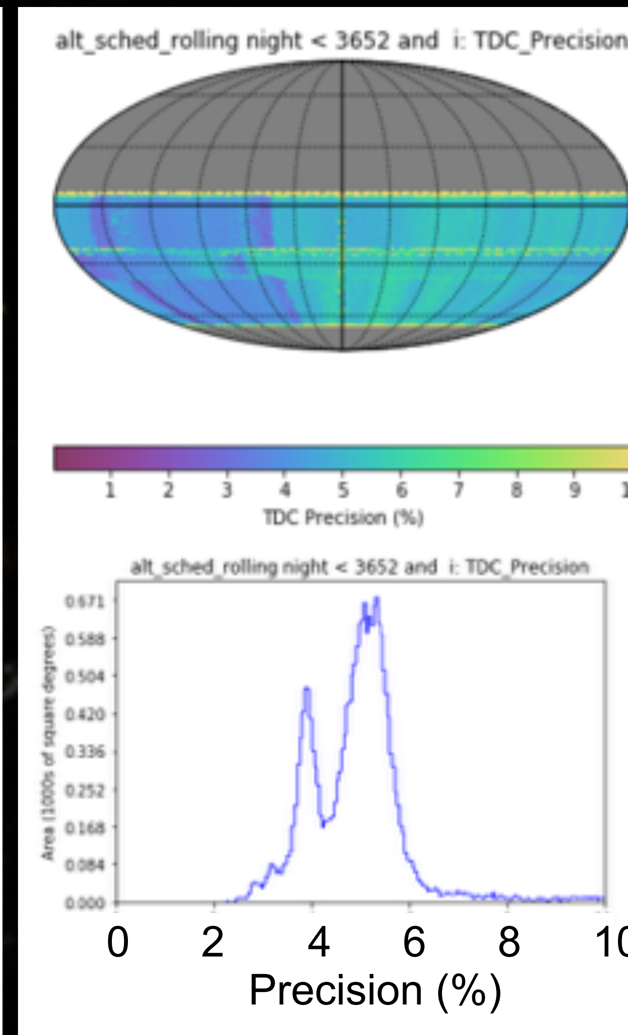
minion_1016



alt_sched



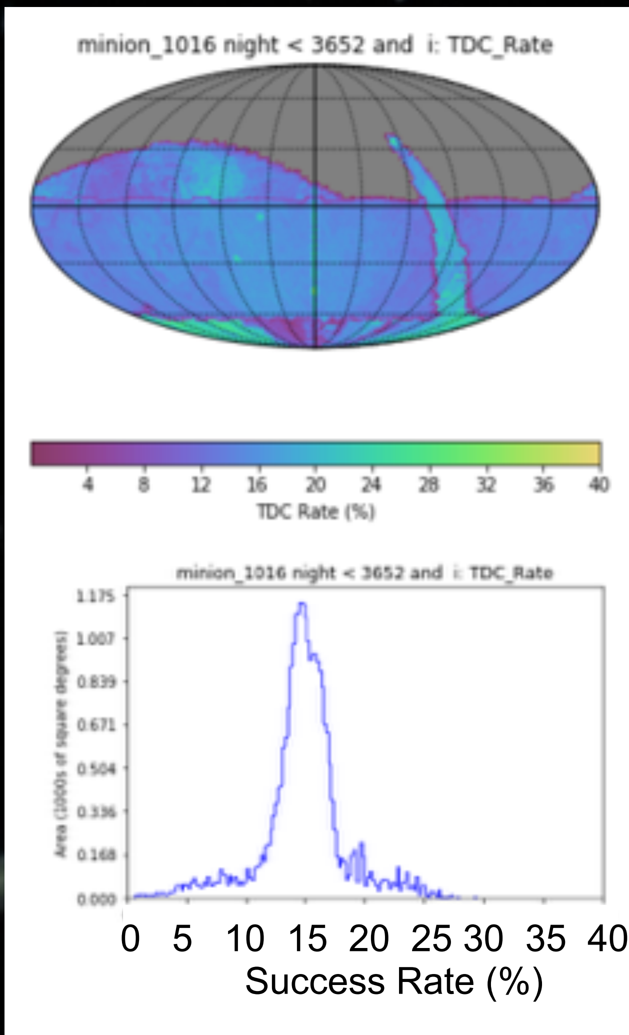
alt_sched_rolling



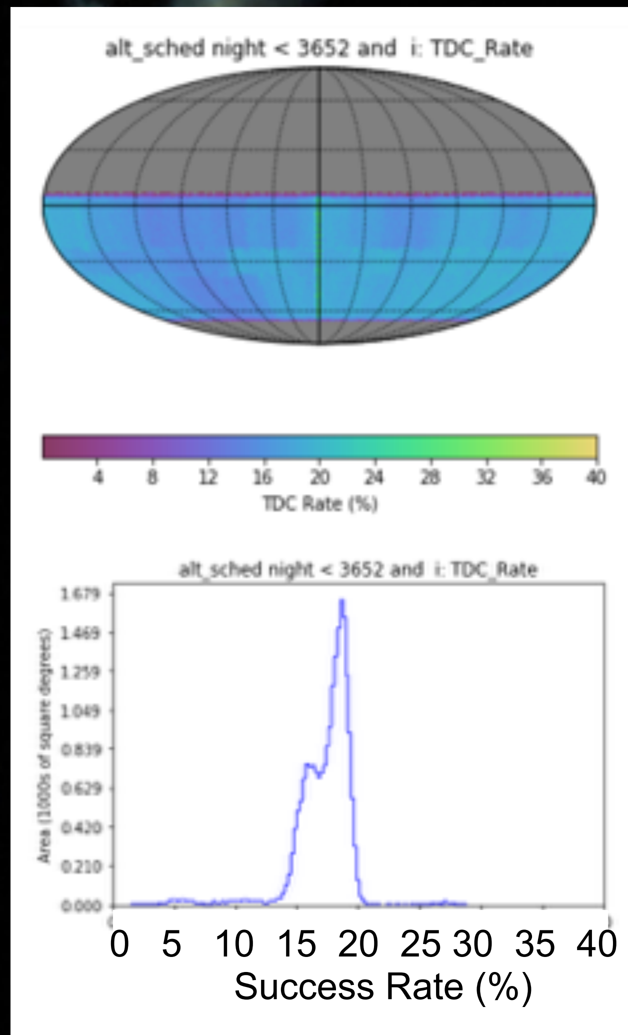
[material courtesy of S. Huber, P. J. Marshall, D. Rothchild]

Success rate

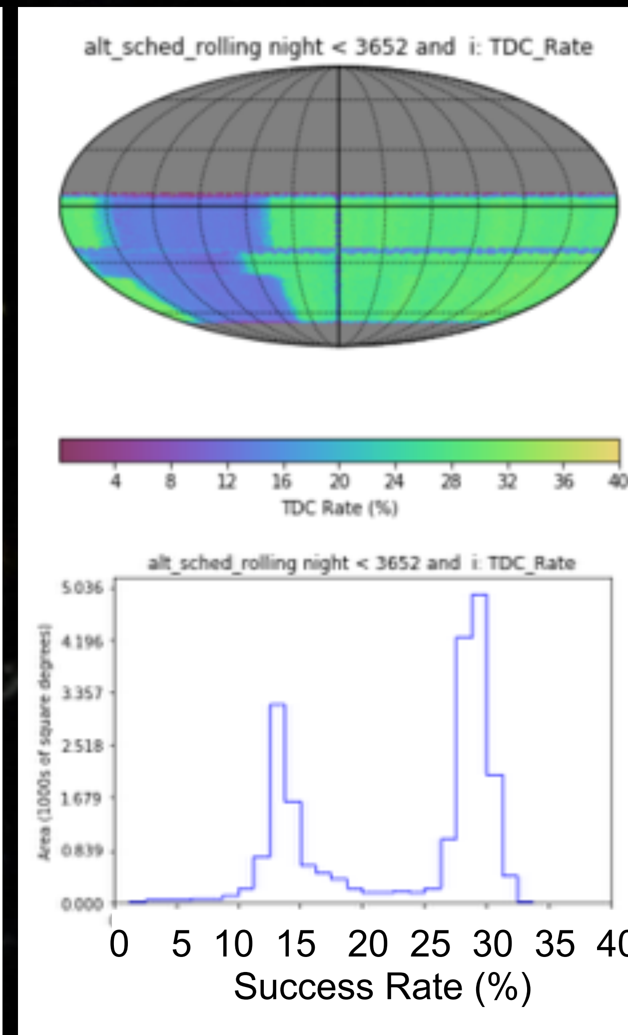
minion_1016



alt_sched



alt_sched_rolling

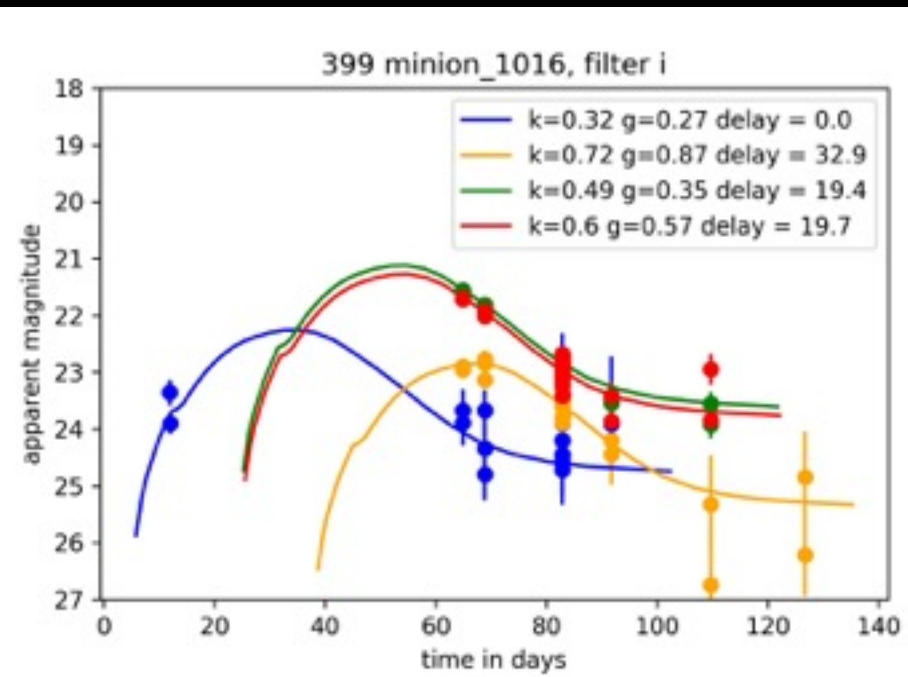


[material courtesy of S. Huber, P. J. Marshall, D. Rothchild]

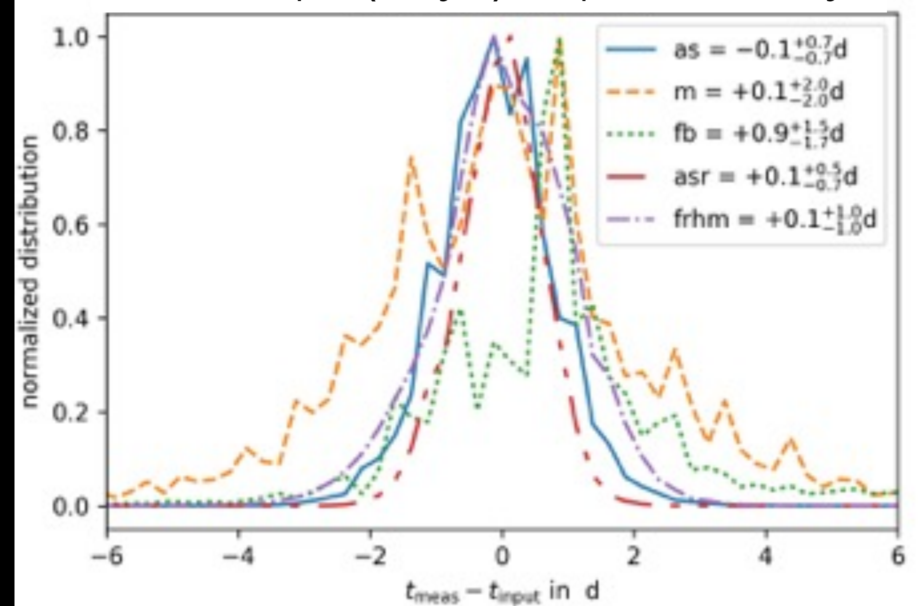
Lensed SNe time delays vs cadence

simulate lensed SNe light curves given LSST cadence strategy

measure time delay PyCS (Tewes++2013, Bonvin++2016)



t_{meas} - t_{input} (days), t_{input} ~ 33 days



(no microlensing included here)

- alt_sched_rolling performs best
- recover t_{input} within ~4%

➜ Simon Huber's talk in session S7B this afternoon

Follow-up observational requirements

<u>High-resolution image</u>

- synergy with Euclid
- HST, JWST or ground-based AO

<u>Spectroscopy</u>

- spec-z of lens and source needed
  - mostly straightforward with wide-separation systems where lens is easily visible under bright quasars

- spectroscopic classification of SNe
  - potentially difficult, since limited window of obs

- spec-z measurements of environment for cosmology
  - mostly straightforward

Summary

- Lensed quasars and SNe are useful for studying cosmology and astrophysics
- LSST: ~8000 lensed quasars and ~100s of lensed SNe
- Various search methods developed for current imaging surveys directly applicable to LSST
- Cadence crucial for cosmology with time delays
  - alt_sched and rolling cadence improves the precision to ~4-6% per system (factor of ~2 improvement) for lensed quasars
  - rolling cadence strategies yield more precise and accurate delay measurements for lensed SNe