H0LiCOW: Measurement of H_0 from lensing

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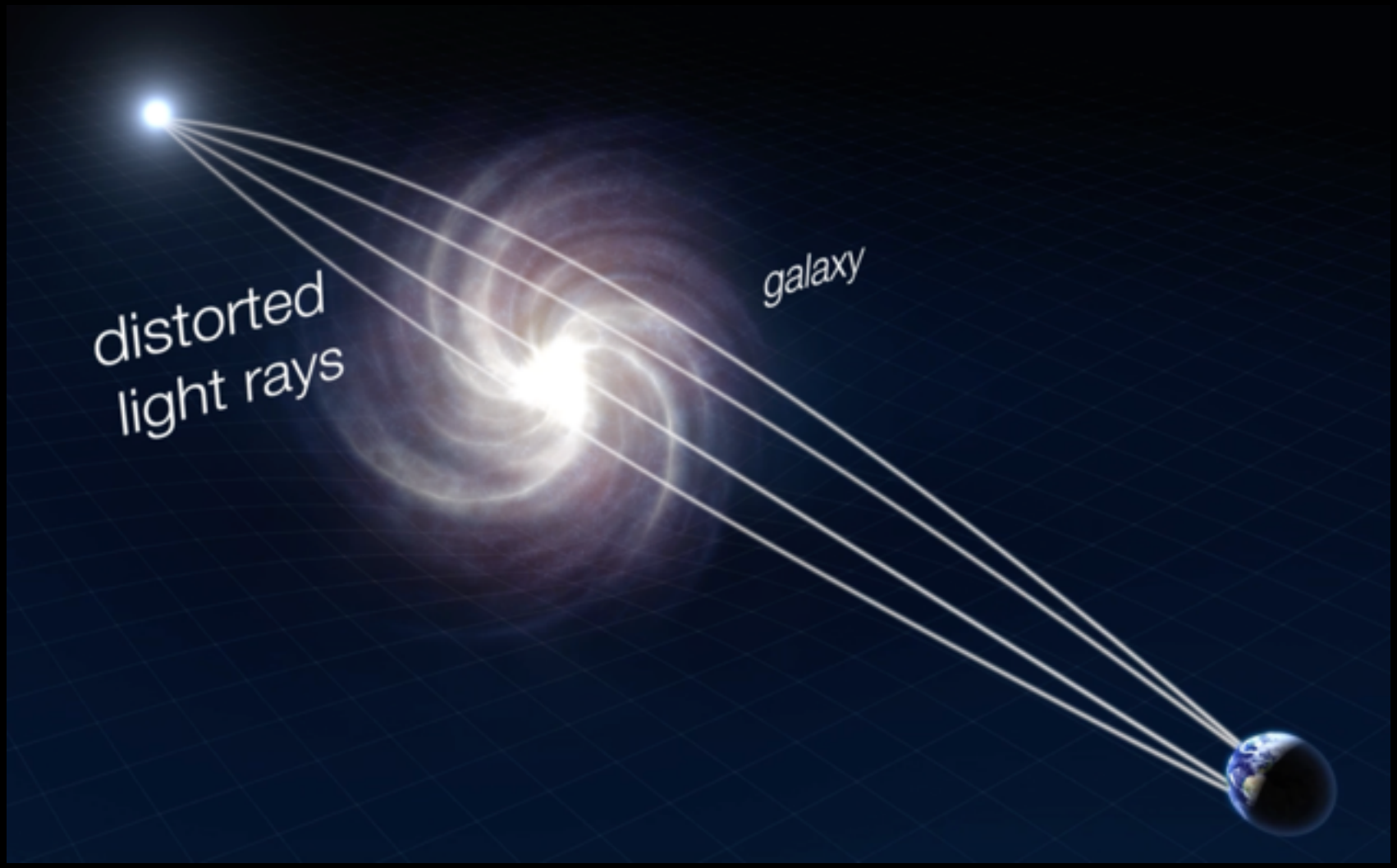
Strong gravitationally lensed quasar

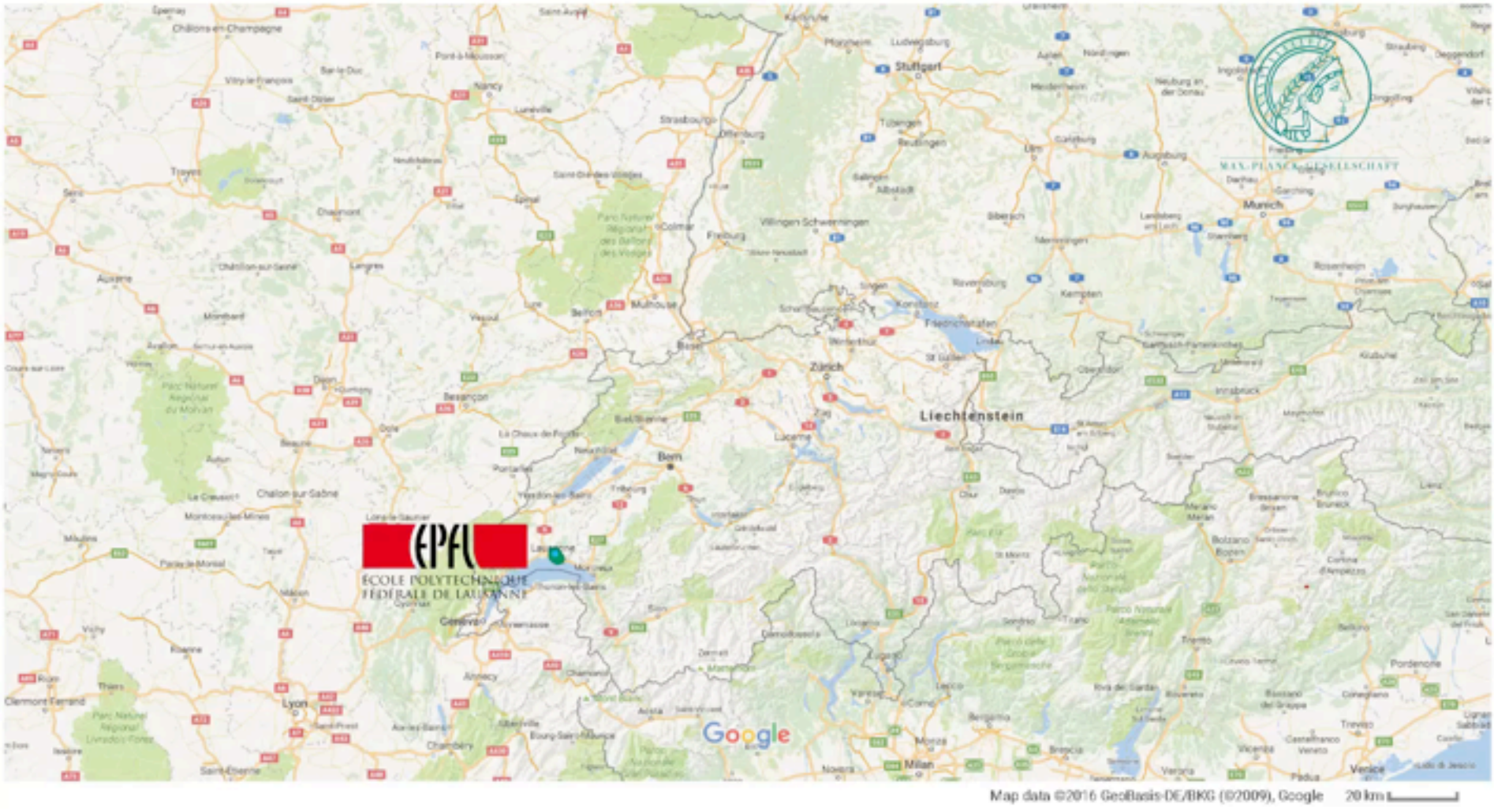
[Credit: ESA/Hubble, NASA]

Time delays



[Credit: ESA/Hubble, NASA]

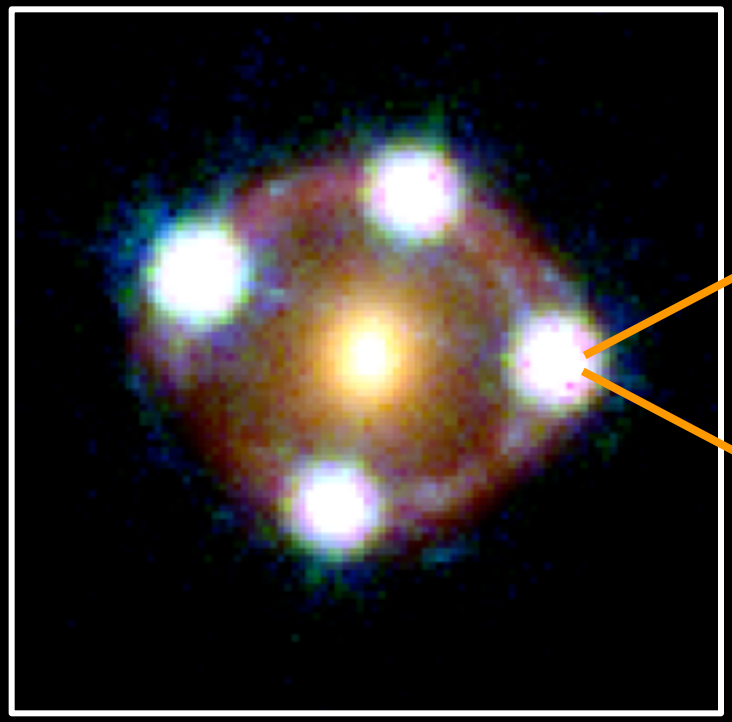
Time delays



[Credit: L. Huang, ASIAA]

Variability of quasar emission

HE0435-1223

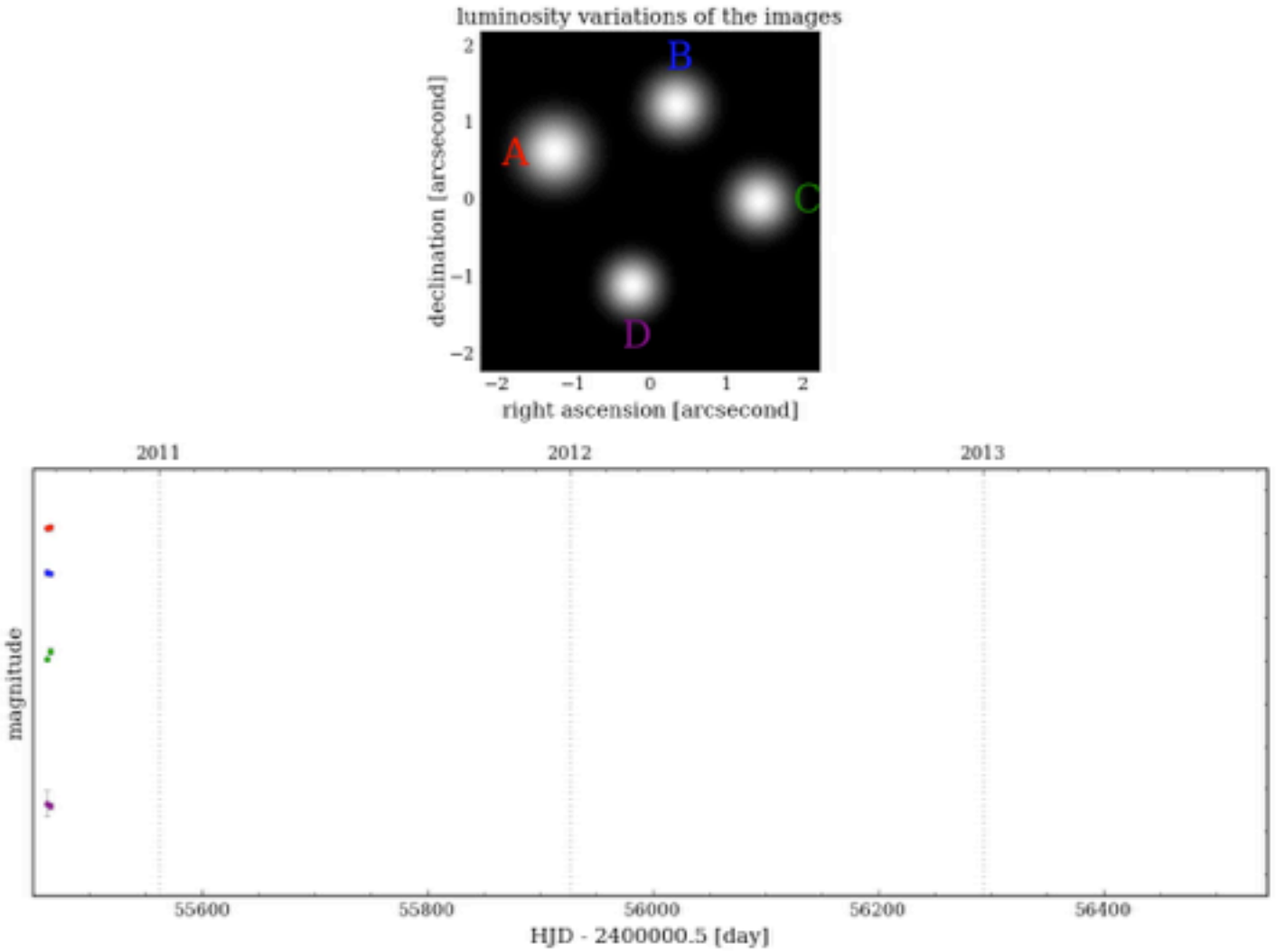


[Suyu et al. 2017]

quasar powered by accretion of material onto supermassive black hole:

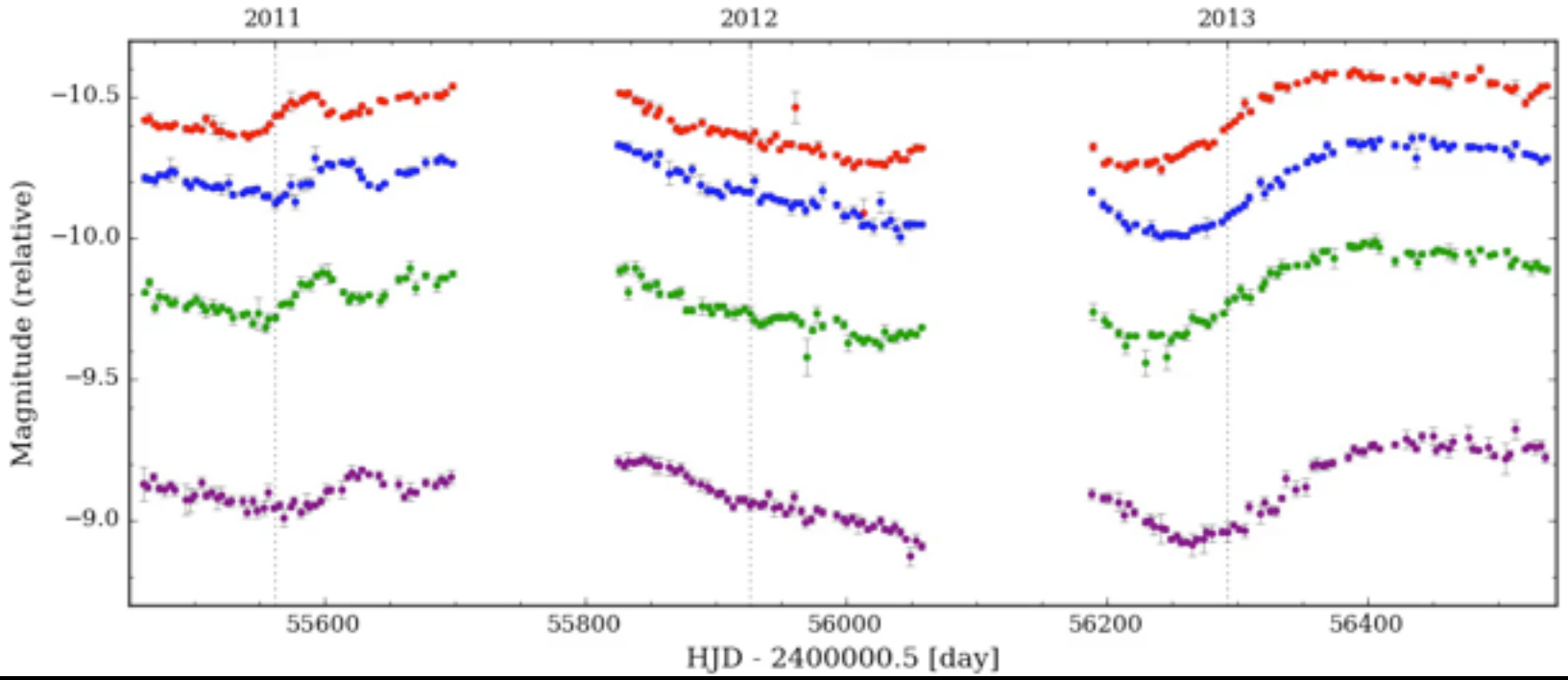
light emitted from quasar changes in time (“flickers”)

Time delays



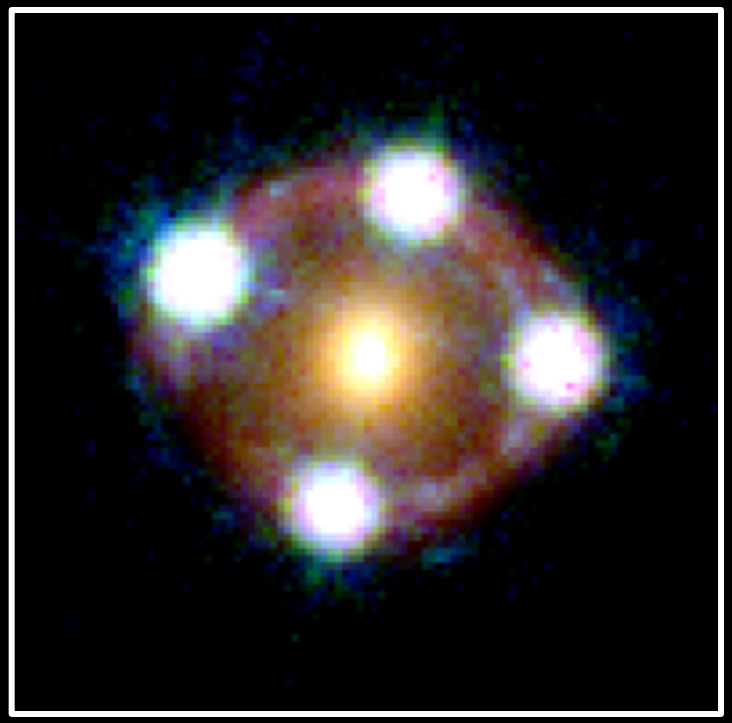
[Credit: V. Bonvin]

Time delays


2011
2012
2013
−10.5
−10.0
−9.5
−9.0
Magnitude (relative)
55600
55800
56000
56200
56400
HJD - 2400000.5 [day]

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

For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

Advantages:

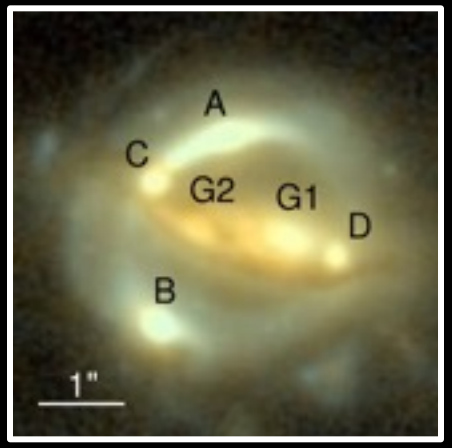
- simple geometry & well-tested physics

- one-step physical measurement of a cosmological distance

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

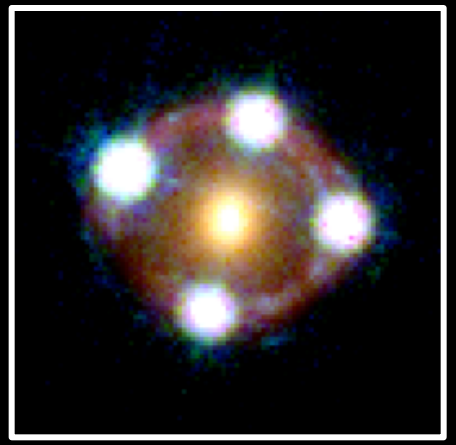
B1608+656



RXJ1131-1231

H_0 to <3.5% precision

HE0435-1223

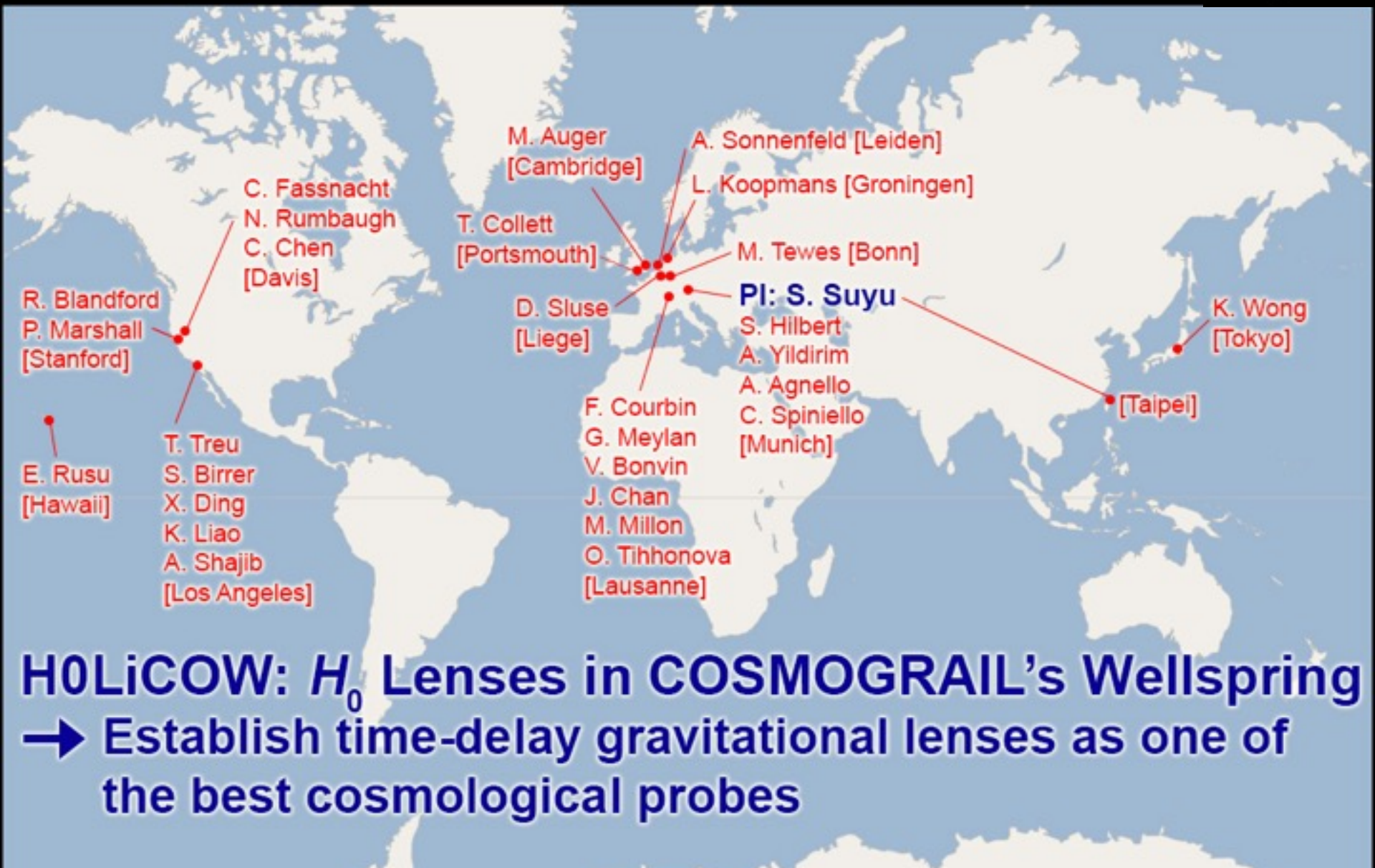


WFI2033-4723

HE1104-1805

[Suyu et al. 2017]

H0LiCOWers



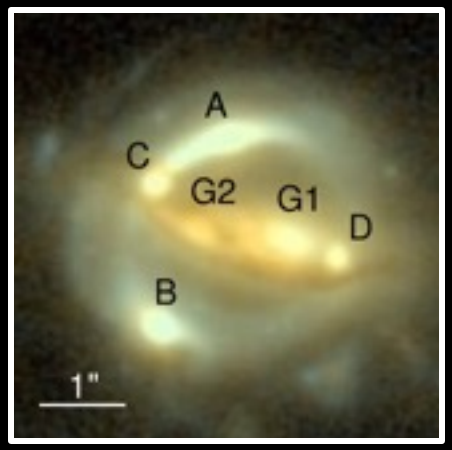
H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

→ **Establish time-delay gravitational lenses as one of the best cosmological probes**

H0LiCOW: latest results

B1608+656

[Suyu et al. 2010]

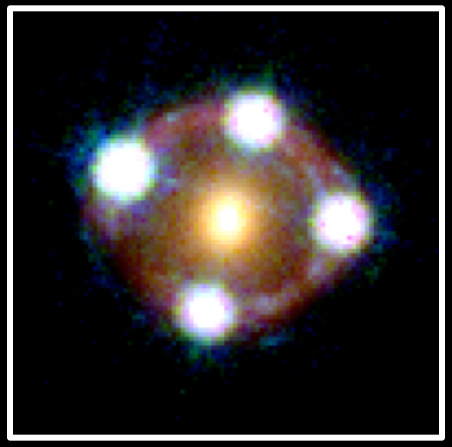


RXJ1131-1231

[Suyu et al. 2013, 2014; Tewes et al. 2013]

HE0435-1223

[Wong, Suyu et al. 2017; Rusu et al. 2017; Sluse et al. 2017; Bonvin et al. 2017]



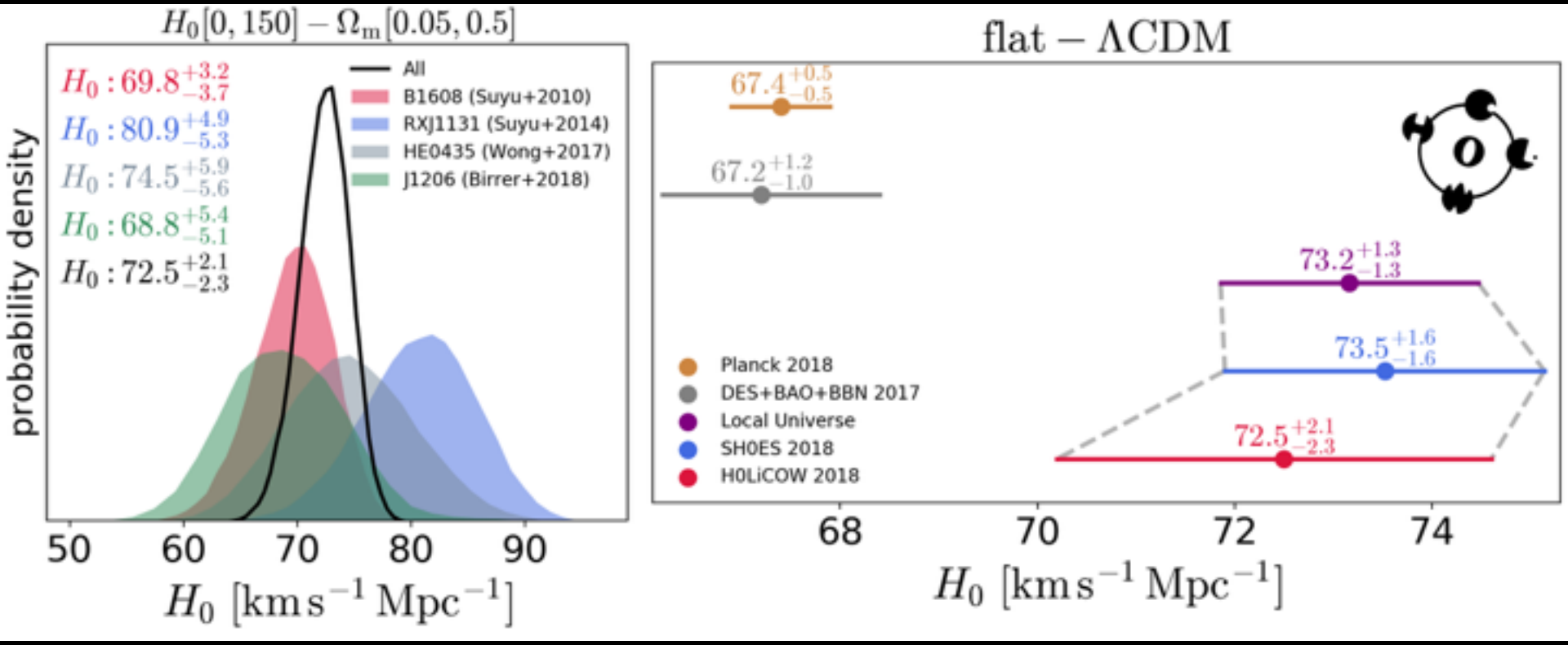
SDSS1206+4332

part of extended sample

[Birrer et al. 2018]

H_0 from 4 strong lenses

Blind analysis to avoid confirmation bias



H_0 with 3% precision in flat ΛCDM

Looking forward

WFI2033-4723

HE1104-1805

PG1115+080

WFI2033-4723:
blind analysis ongoing
[Rusu et al., Sluse et al., Wong et al., in prep.]

PG1115+080 :
blind analysis of adaptive-optics and HST images ongoing
[Chen et al., in prep.]

Towards hundreds of lenses

Hyper Suprime-Cam Survey


8m Subaru Telescope
Mauna Kea, Hawaii

- 1400 deg^2 with i_{limit}~26
- 2014-2019
- expect ~600 lenses
  [Oguri & Marshall 2010]

Dark Energy Survey


STRong-lensing Insights into Dark Energy Survey (PI: Treu)
4m Blanco Telescope, CTIO, Chile

- 5000 deg^2 with i_{limit}~24
- 2012-2017
- expect ~1100 lenses
  [Oguri & Marshall 2010]

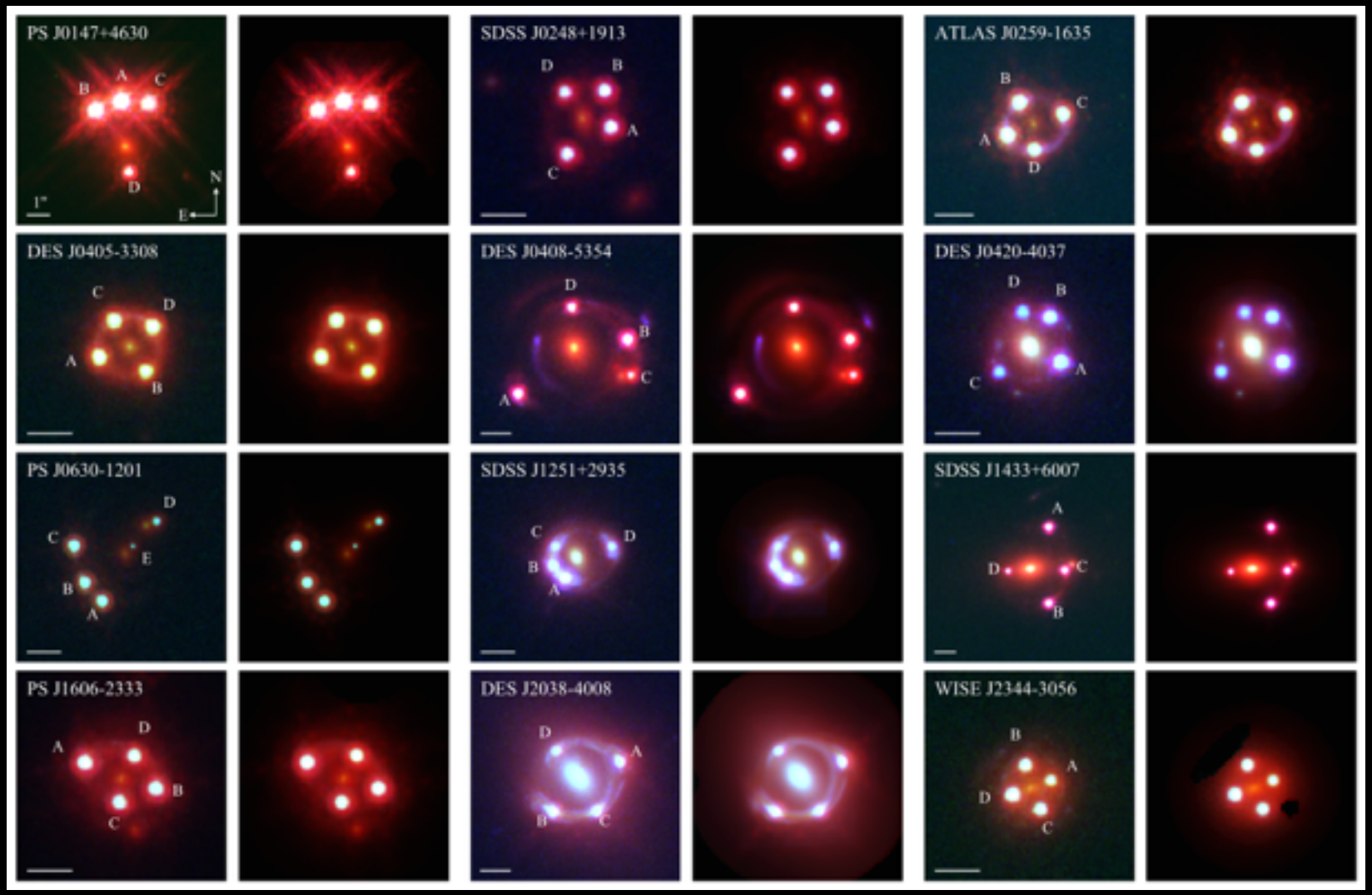
Kilo Degree Survey

2.6m VLT Survey Telescope, Paranal, Chile

- 1500 deg^2 with r_{limit}~25
- 2011-~2018

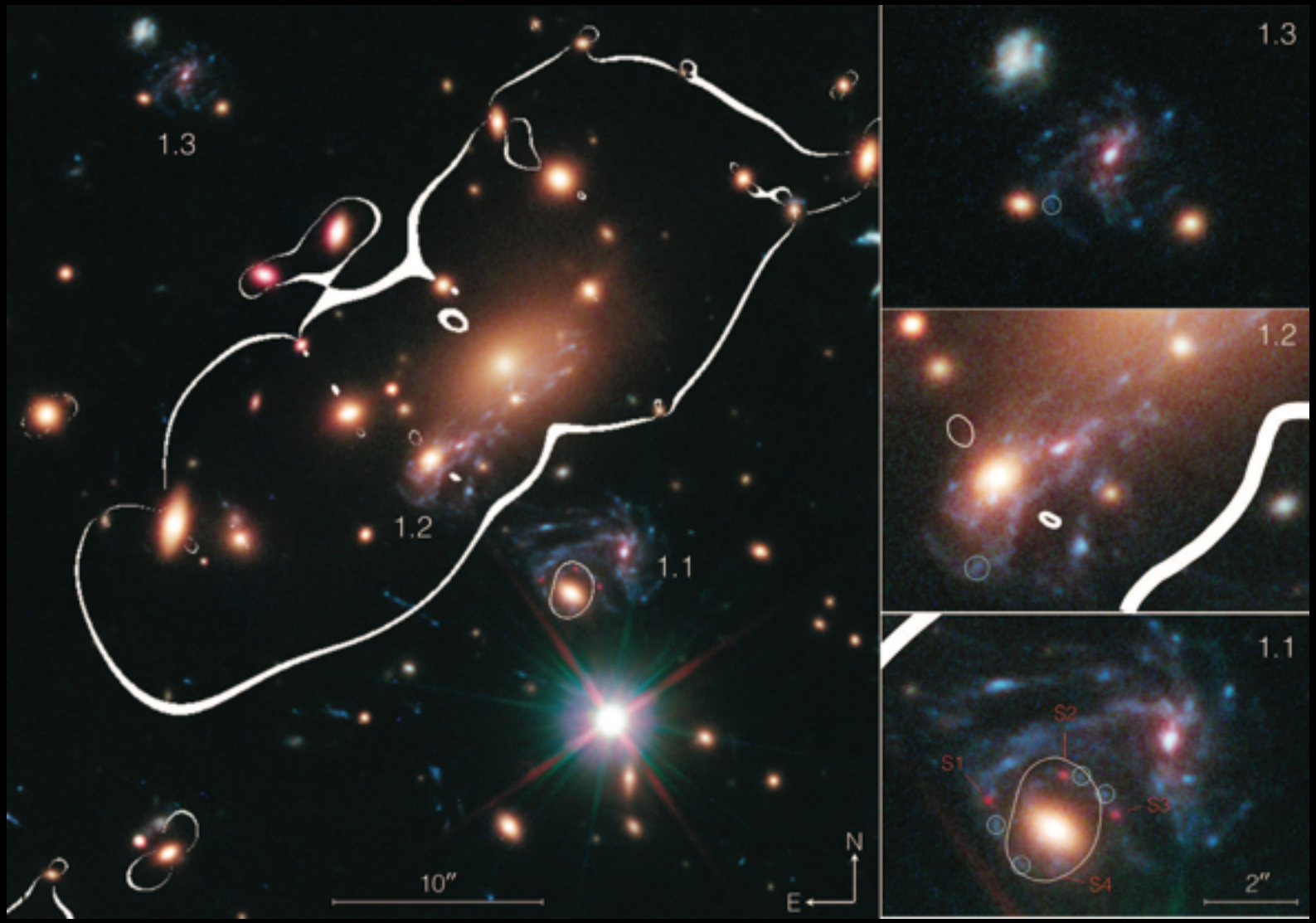
New quads imaged with HST

New lens systems discovered in DES, Pan-STARRS, SDSS, ATLAS:



[Shajib et al. 2018]

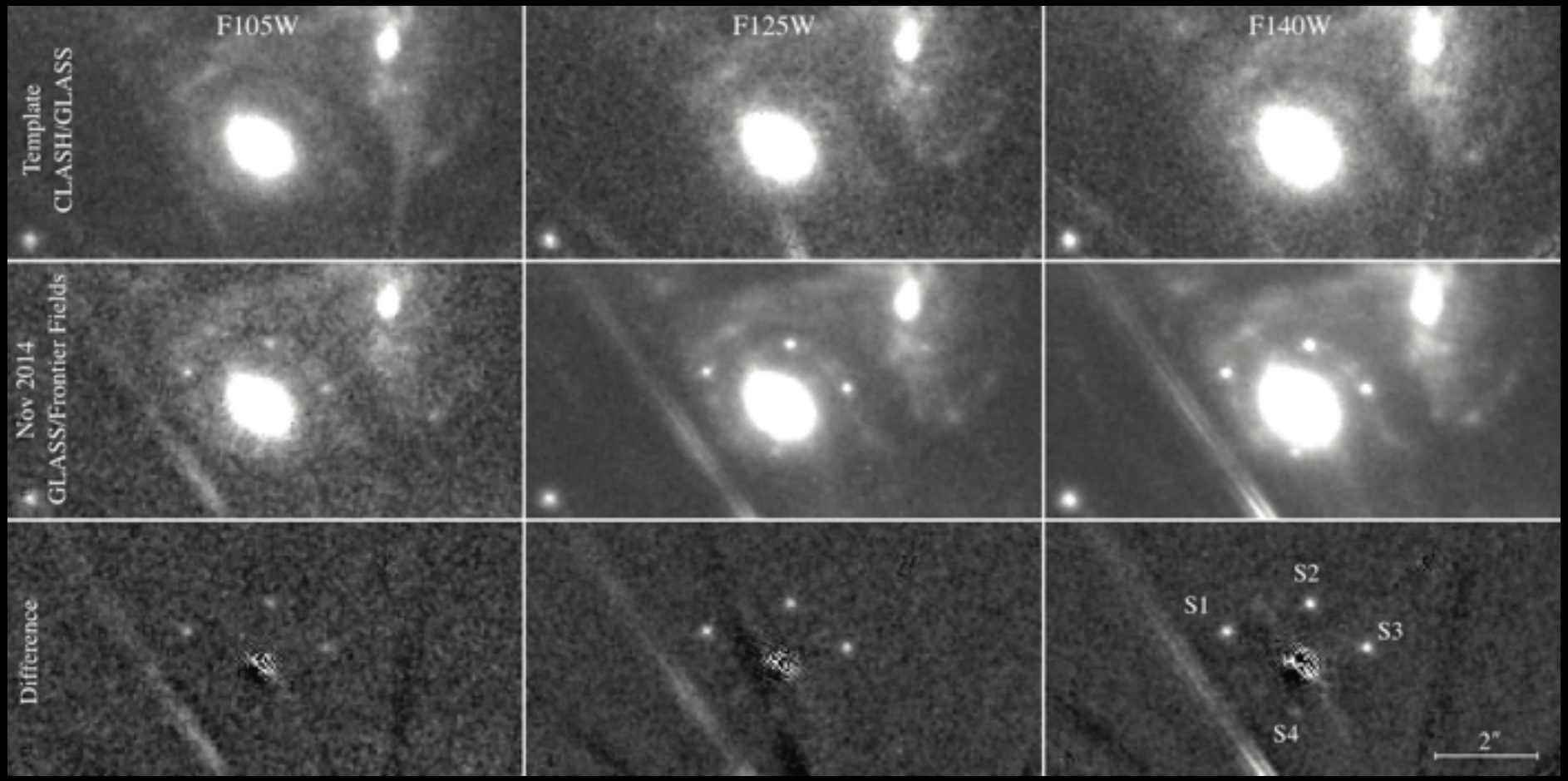
Strongly lensed supernova



MACS 1149.6+2223 [Kelly et al. 2015]

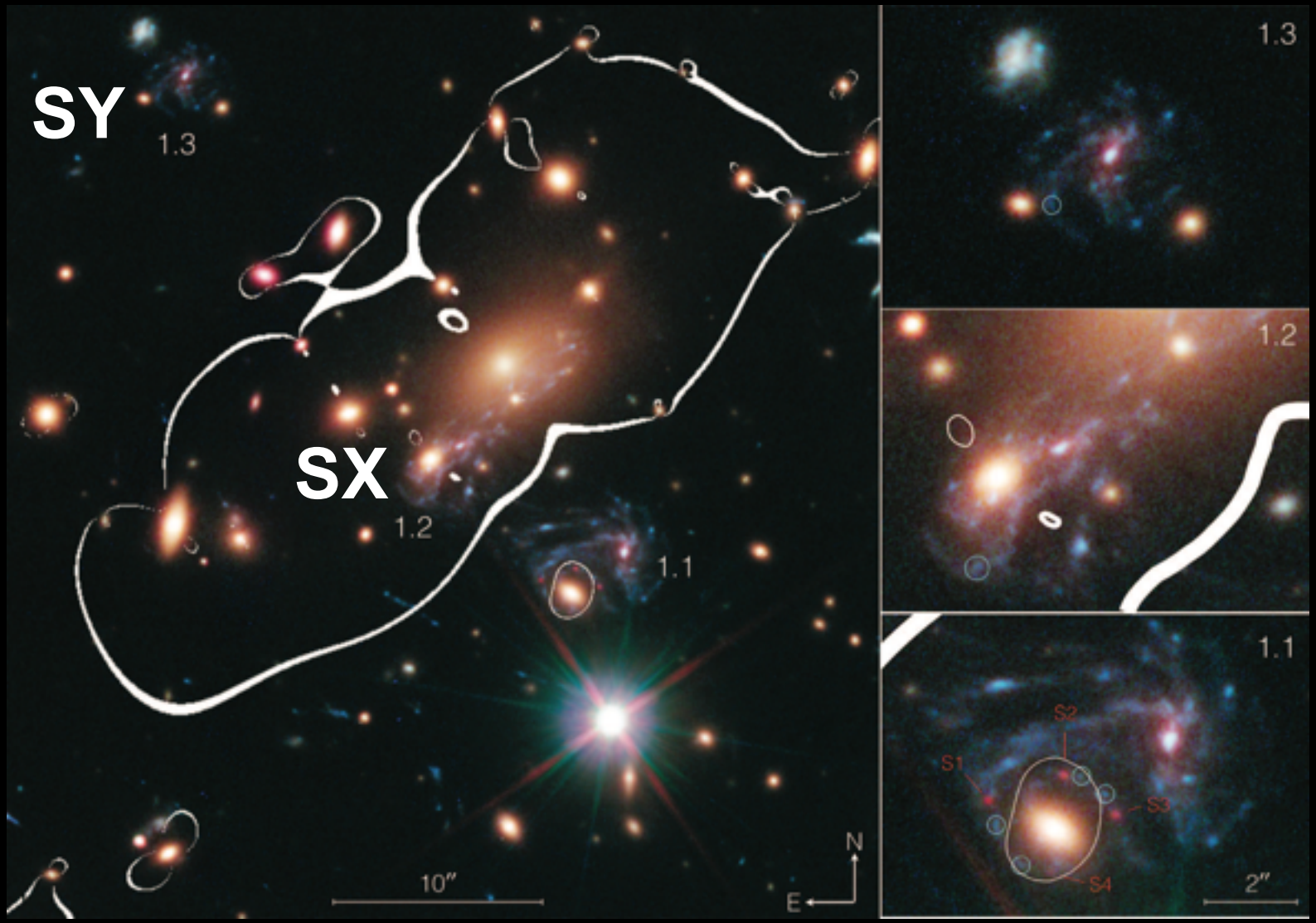
Supernova “Refsdal”

discovered serendipitously in November 2014



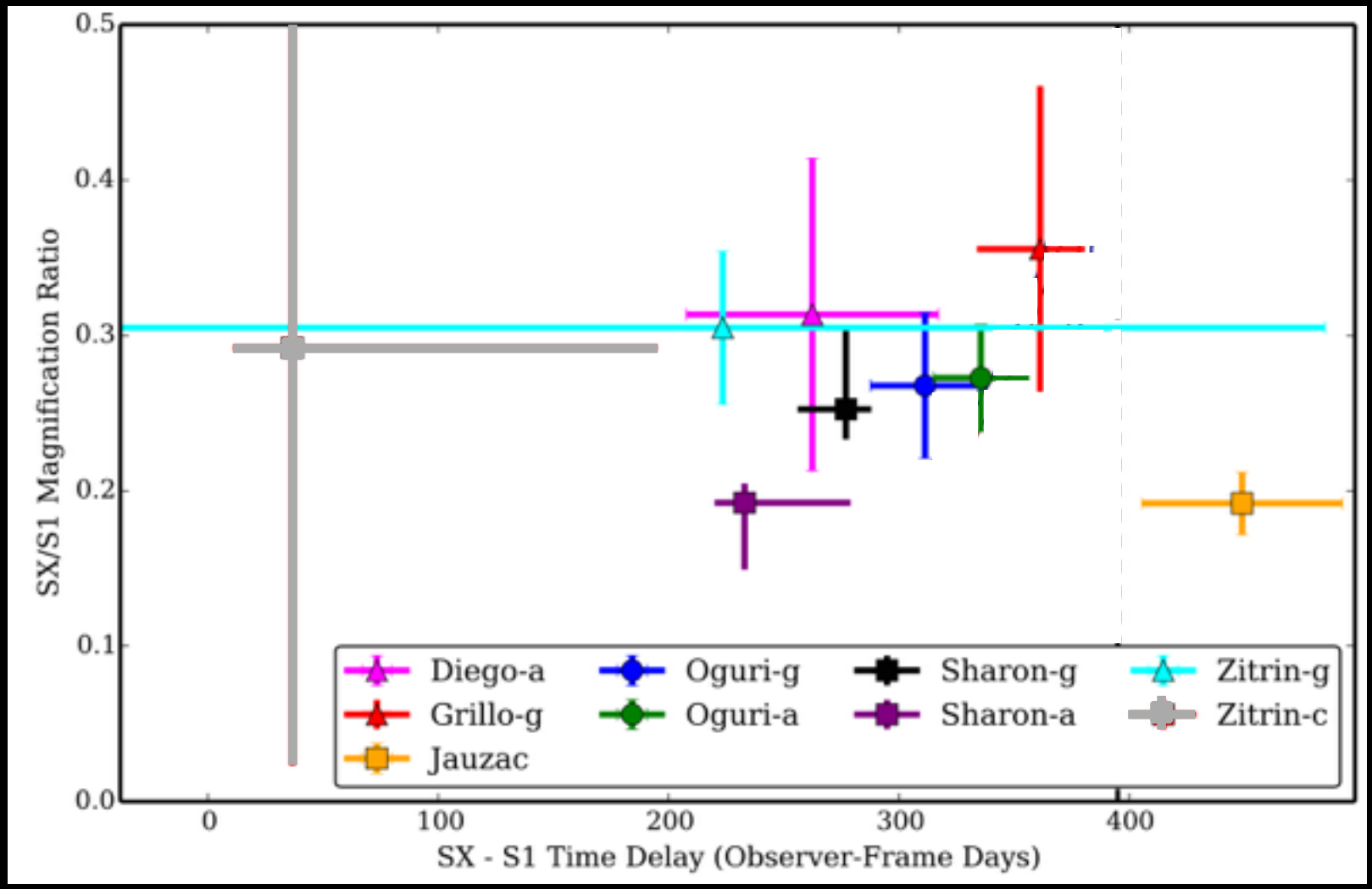
[Kelly et al. 2015]

When will the other SN images appear?



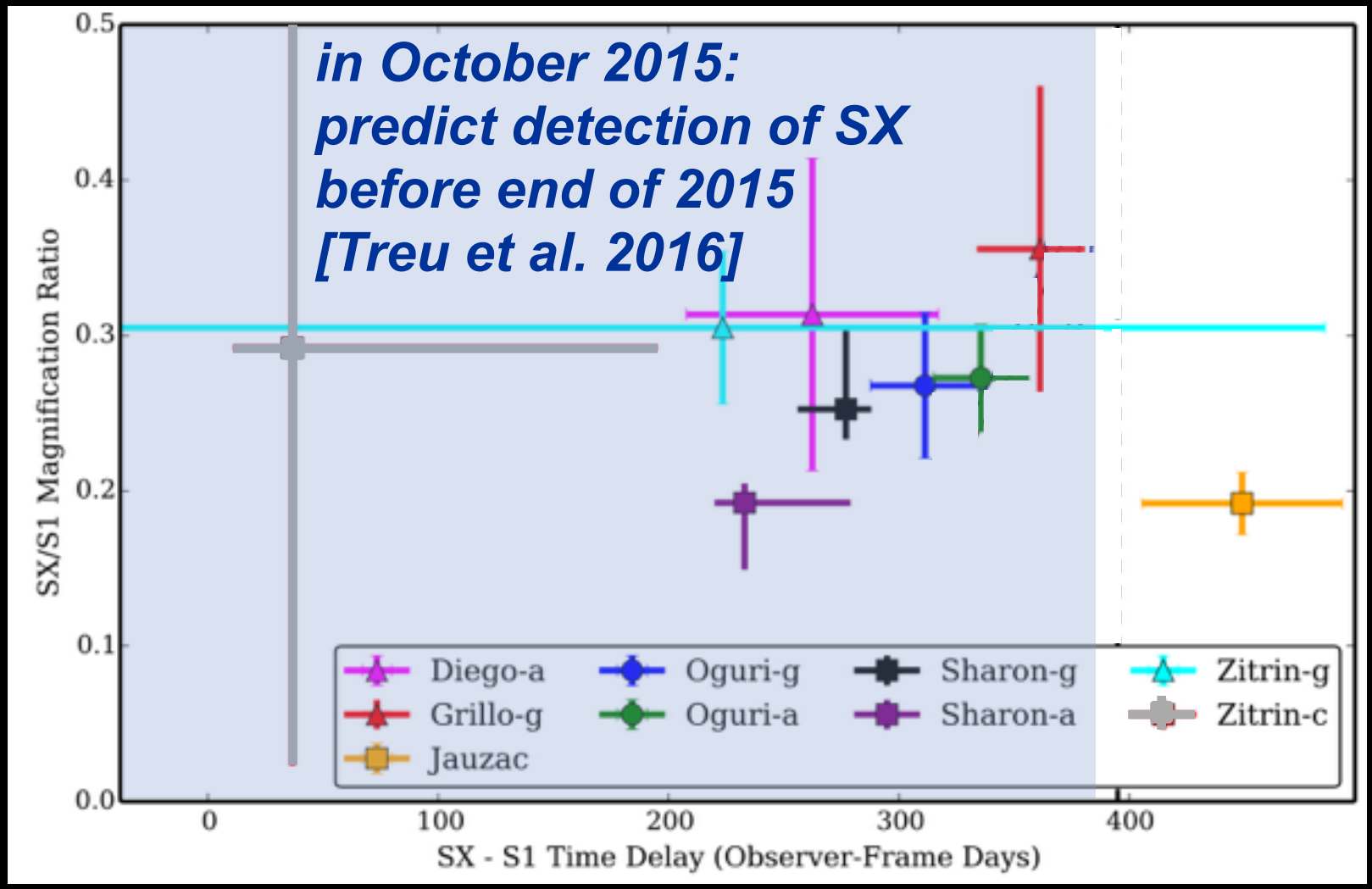
MACS 1149.6+2223 [Kelly et al. 2015]

Predicted magnification and delay



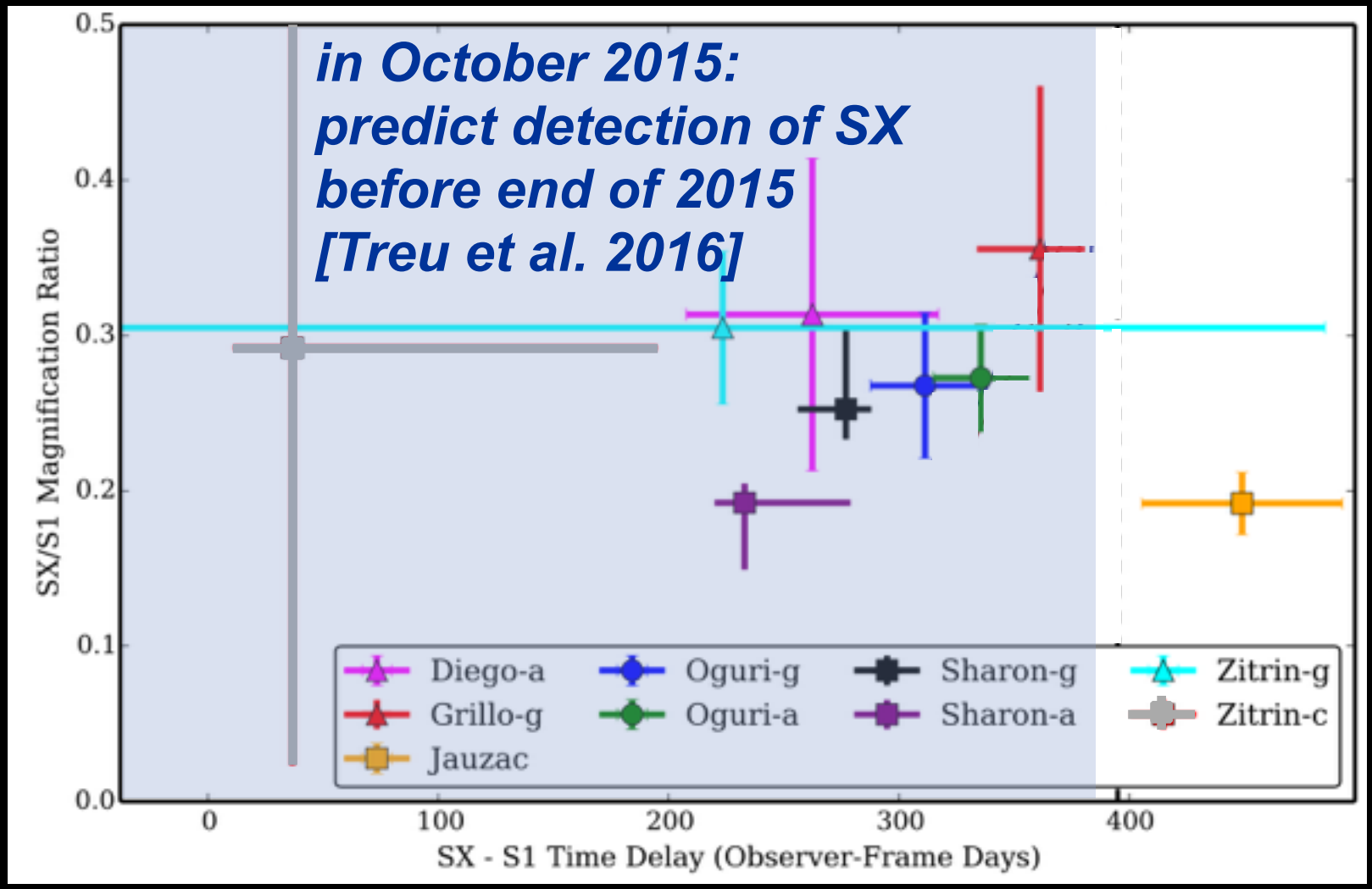
[Kelly et al. 2016]

Predicted magnification and delay



[Kelly et al. 2016]

Predicted magnification and delay

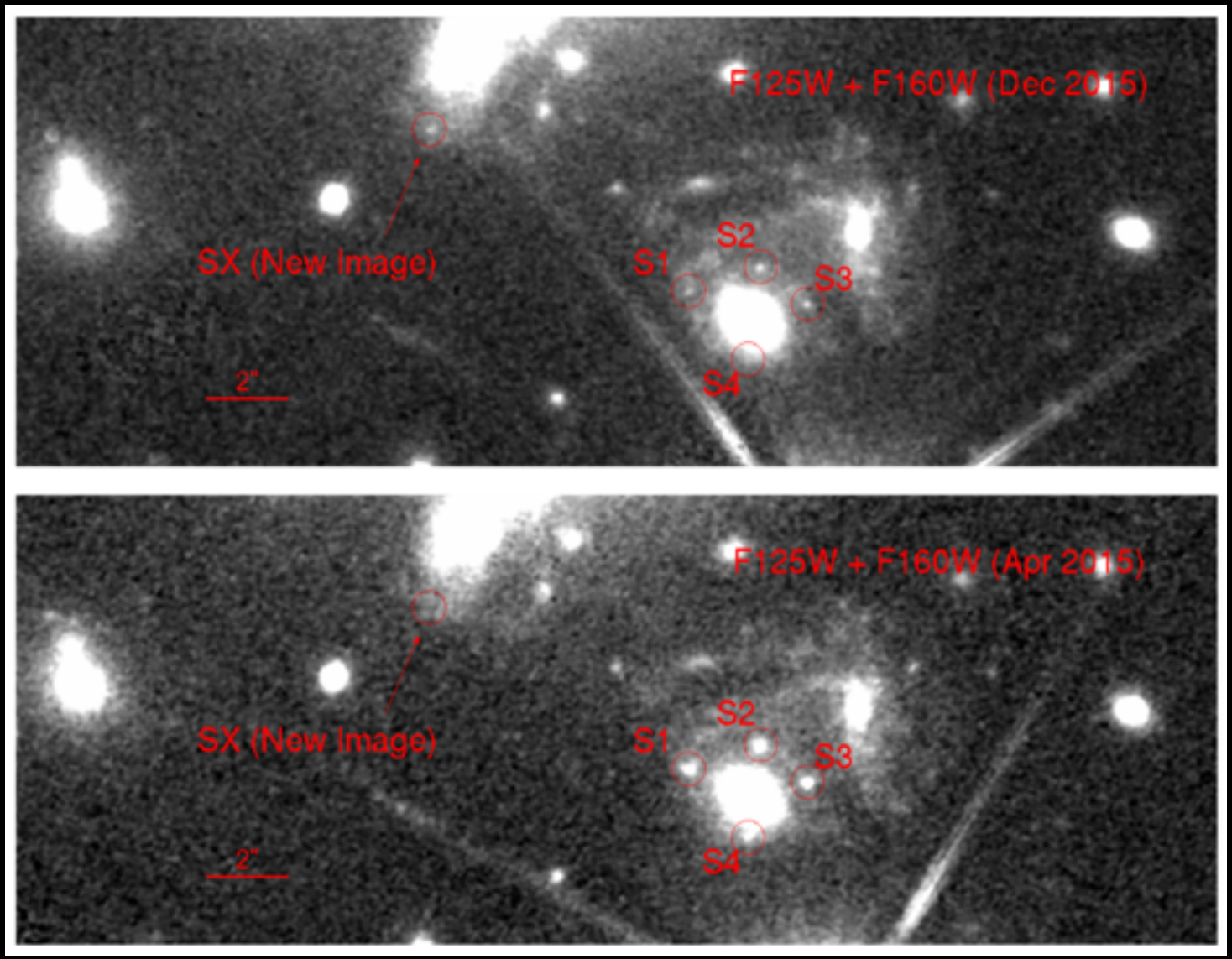


[Kelly et al. 2016]

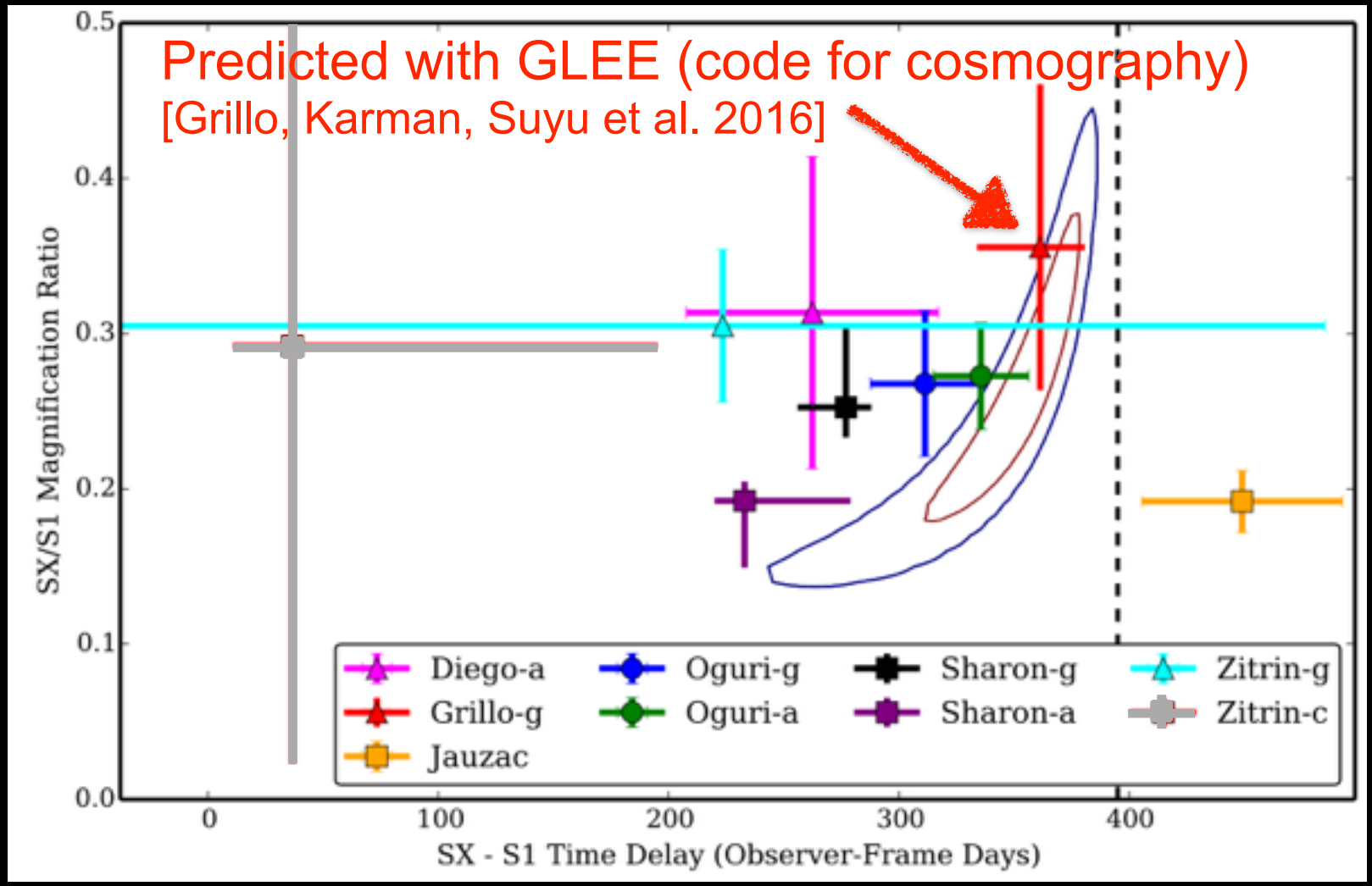
HST observations in Oct 2015: no sign of SX
in Nov 2015: no sign of SX…

Appearance of image SX

December 2015 [Kelly et al. 2016]

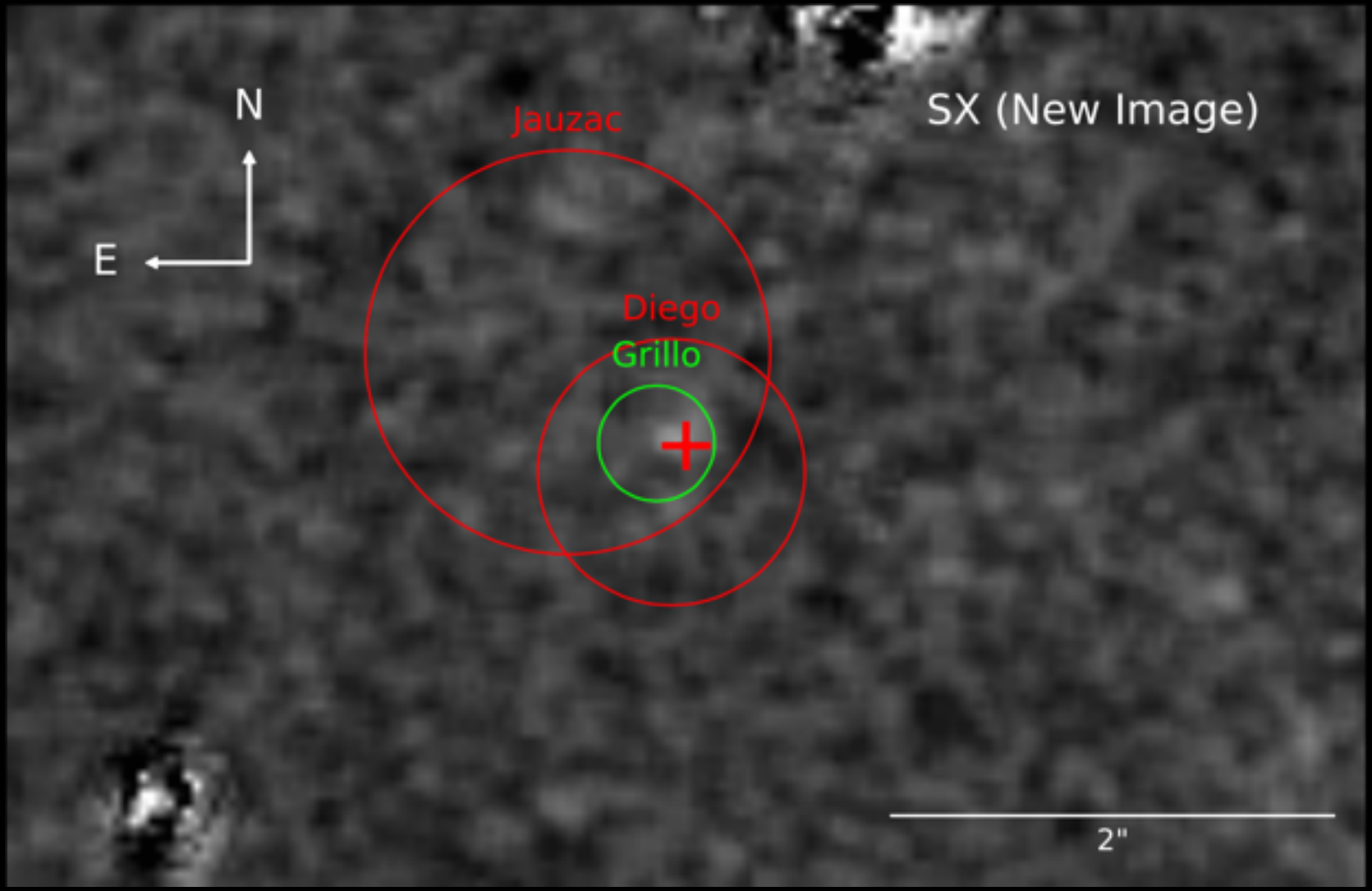


Magnification and delay



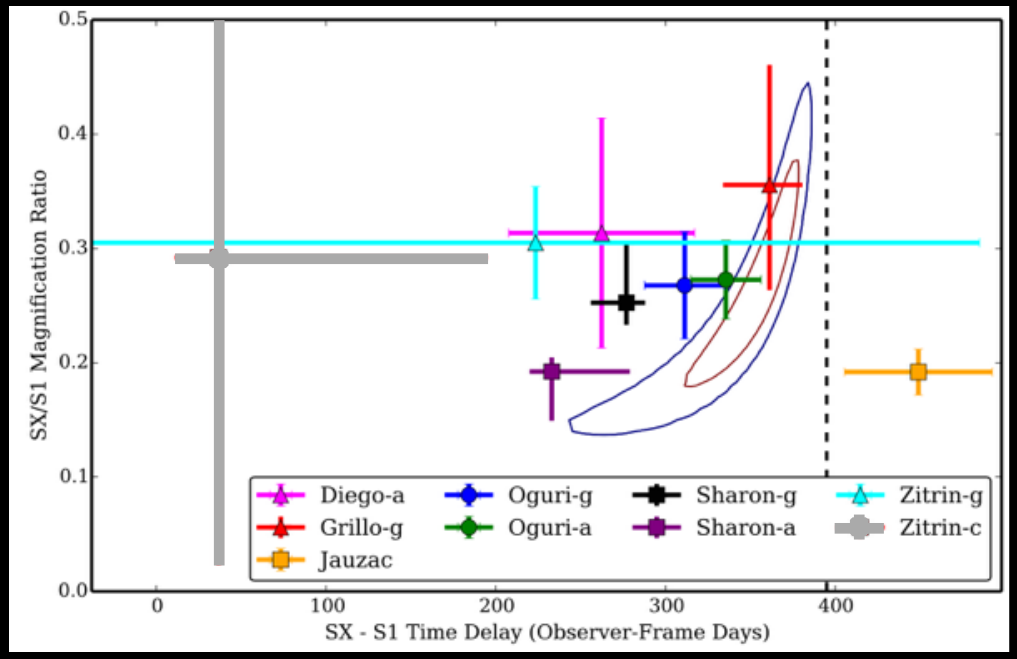
[Kelly et al. 2016]

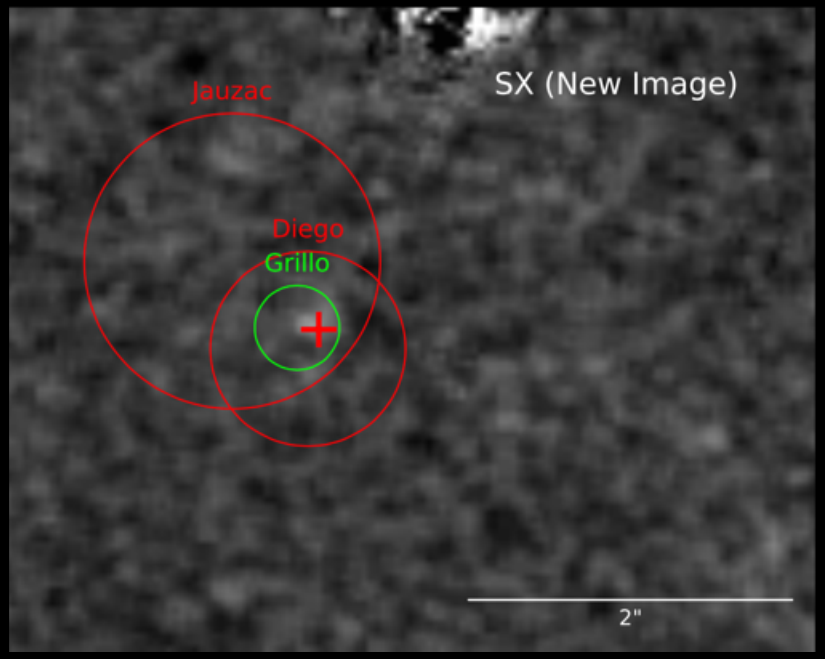
Spot on!



[Kelly et al. 2016]

Successful prediction



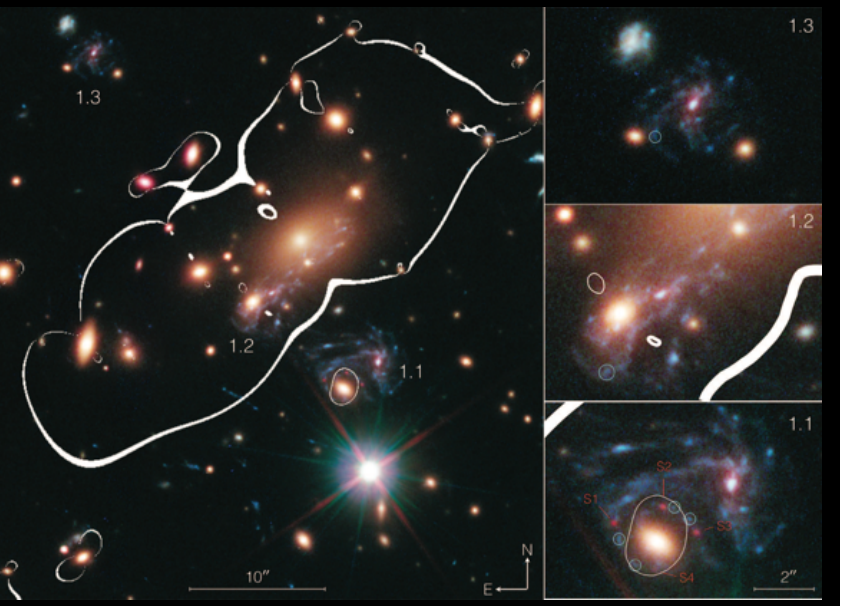


[Kelly et al. 2016]

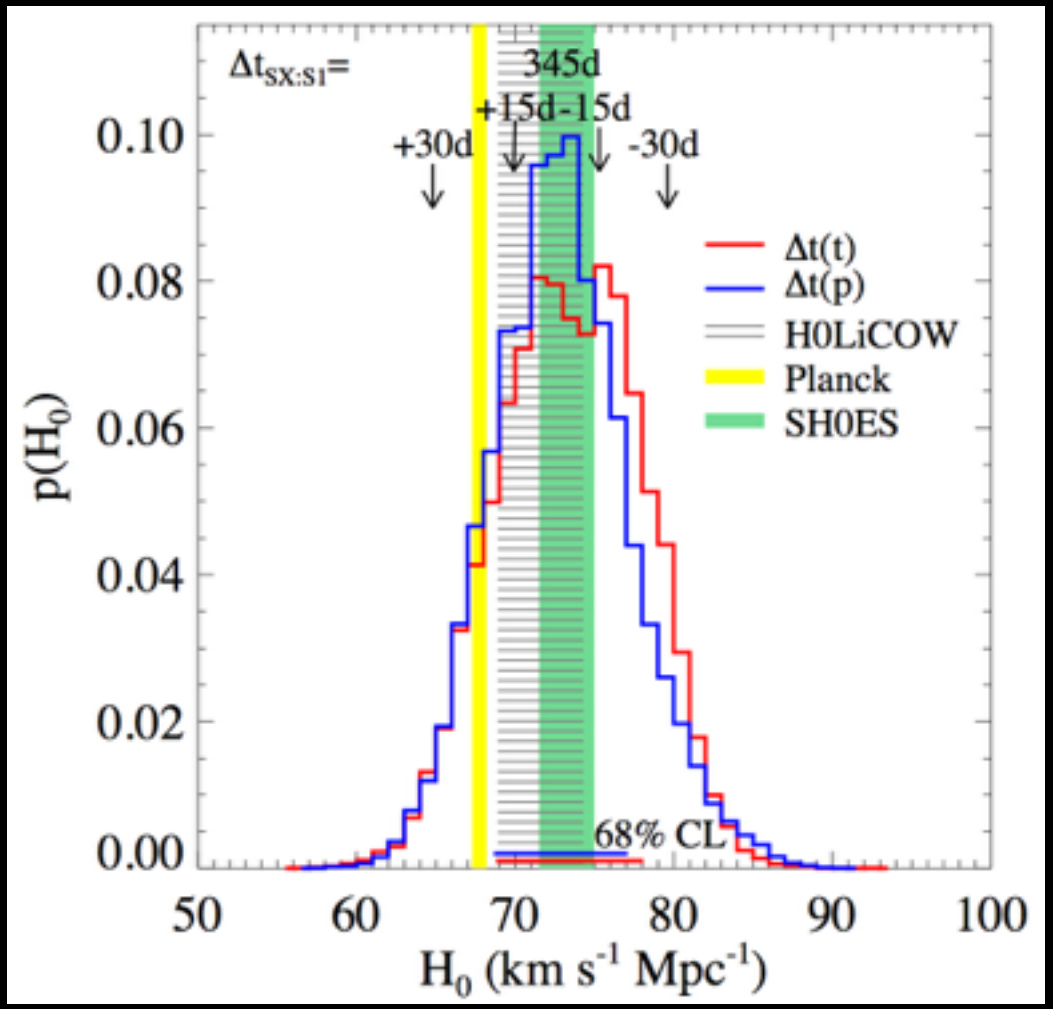
- Grillo et al. predicted successfully and precisely all three observables of image SX: time, magnification and location
- GLEE [Suyu & Halkola 2010] accurately and precisely predicted the appearance of SX as a result of its ability to reconstruct the entire SN host galaxy

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]

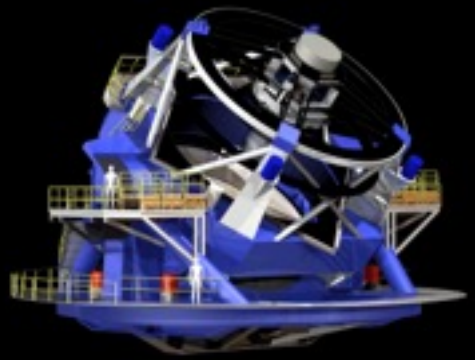
Future Prospects

Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid

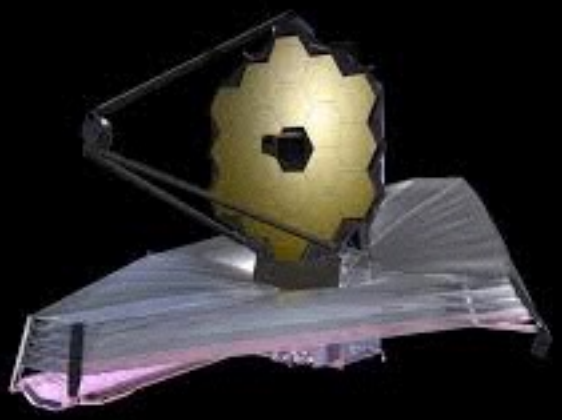
Discovery
Imaging
Spectroscopy

LSST



Discovery
Time delays
Imaging

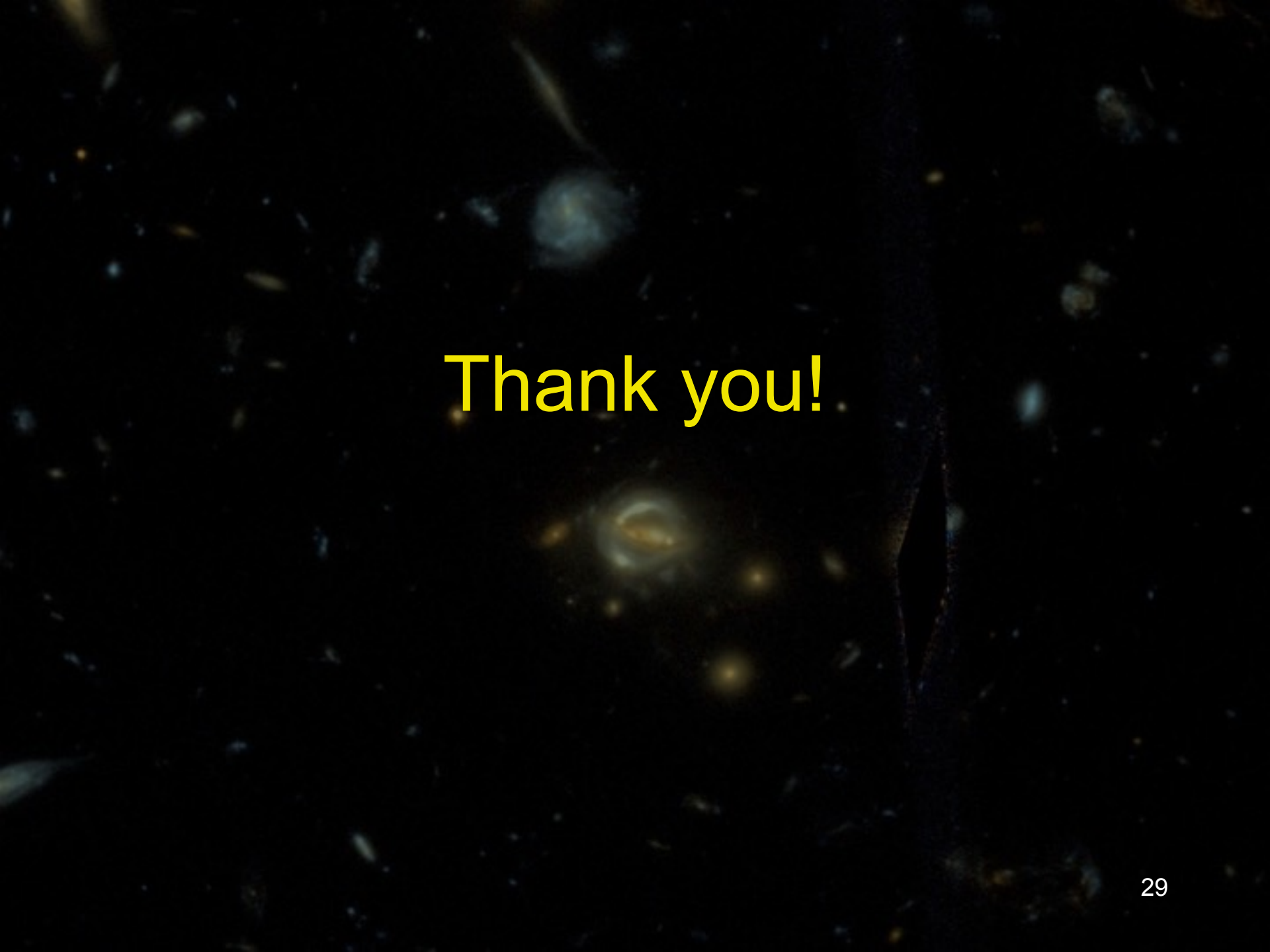
JWST



High-resolution imaging
& spectroscopy

Summary

- Time-delay distances $D_{\Delta t}$ of each lens can be measured with uncertainties of ~5-8% including systematics
- From 4 lenses in H0LiCOW, $H_0 = 72.5^{+2.1}_{-2.3}$ km/s/Mpc in flat ΛCDM, a 3% precision measurement independent of other probes
- Search is underway to find new lenses in DES, HSC, PanSTARRS, and Gaia surveys
- SN Refsdal blind test demonstrated the robustness of our lens mass modeling approach
- Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology


Thank you!