Cosmology with Gravitational Lens Time Delays

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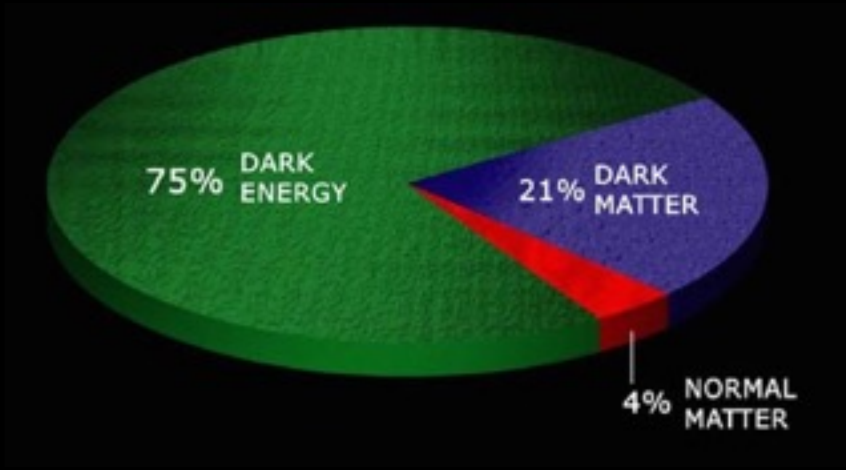
Puzzles in cosmology



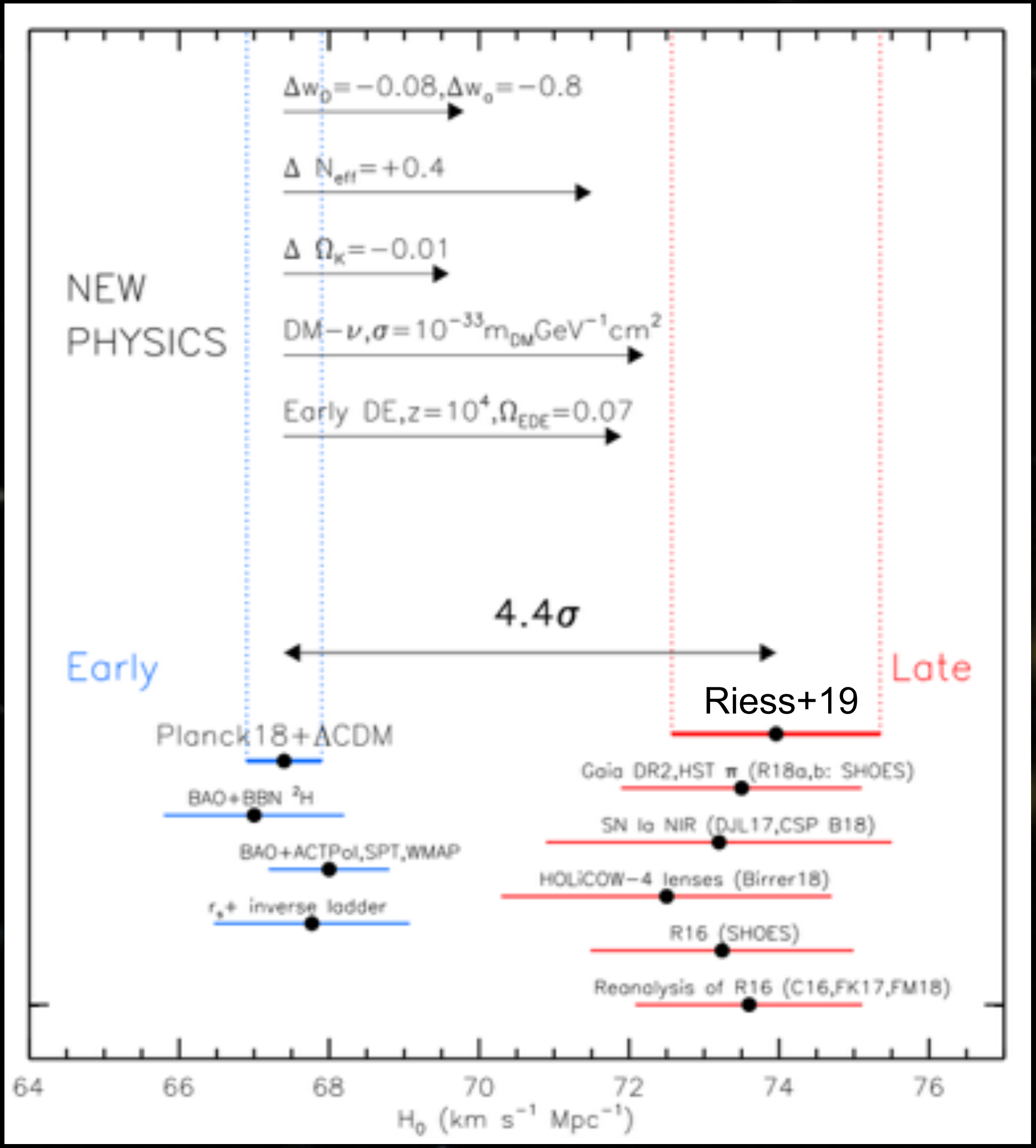
What is the nature of dark energy and dark matter?

Is our Universe spatially flat?

How many relativistic species are present in the early Universe?

Measuring the Hubble constant (H_0) provides a way to address these questions

Hubble constant: key parameter



[Riess et al. 2019]

Hubble constant H_0

- age, size of the Universe
- expansion rate: $v = H_0\, d$

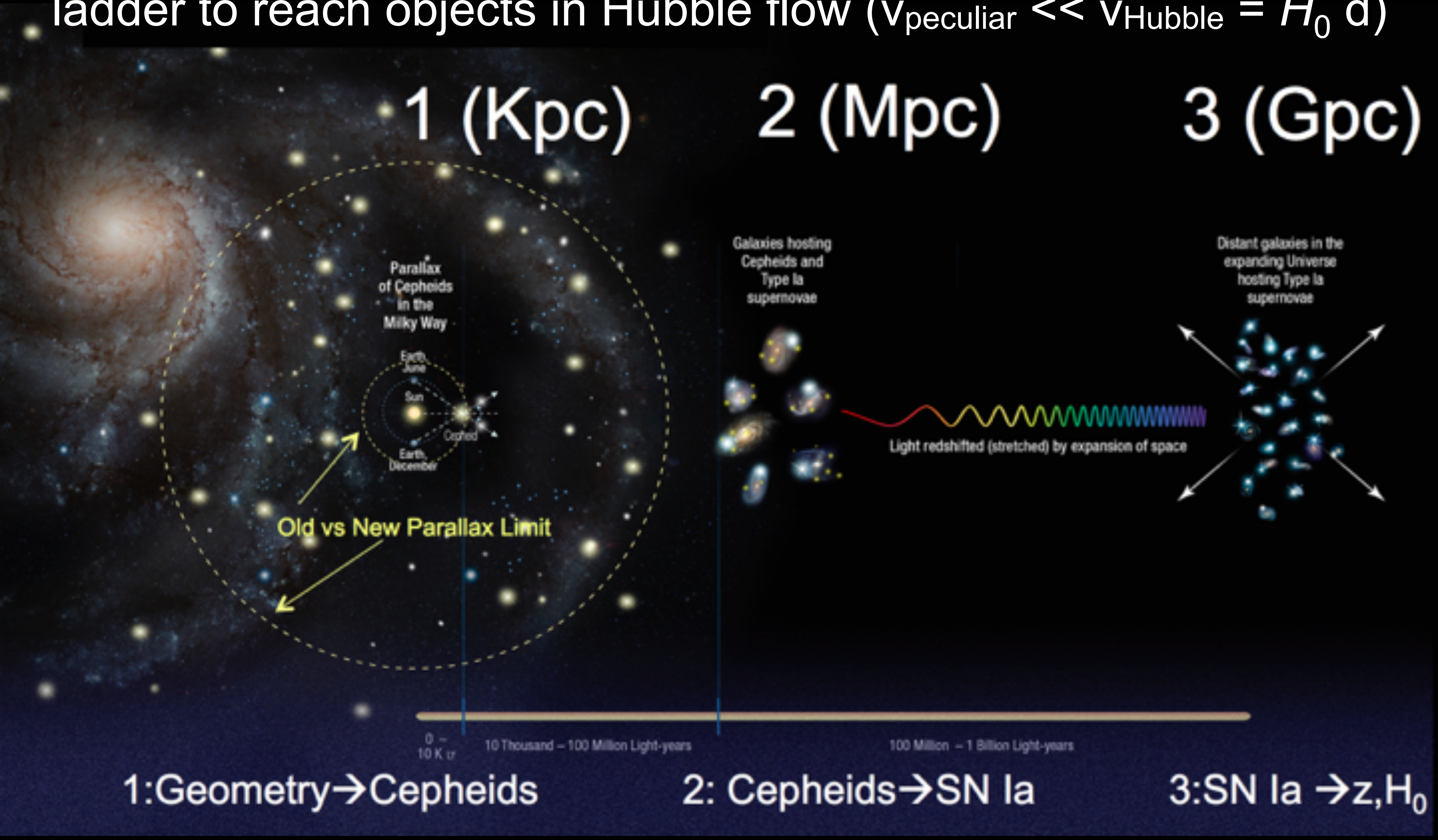
Tension? New physics?

➡ Need more precise & accurate H_0

Need Independent methods to overcome systematics, especially the unknown unknowns

Distance Ladder

ladder to reach objects in Hubble flow ($v_{peculiar} << v_{Hubble} = H_0$ d)



[slide material courtesy of Adam Riess]

Distance Ladder Measurements

- *Hubble Space Telescope* Key Project [Freedman et al. 2001]
  - H_0 = 72 ± 8 km s^{-1} Mpc^{-1} (10% uncertainty)
  - resolving multi-decade "factor-of-two" controversy

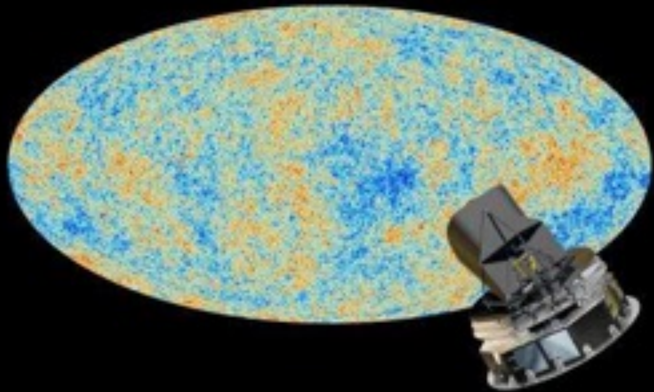
- Carnegie Hubble Program [Freedman et al. 2012]
  - H_0 = 74.3 ± 2.1 km s^{-1} Mpc^{-1} (2.8% uncertainty)

- Carnegie-Chicago Hubble Program [Beaton et al. 2016]
  - aim 3% precision in H_0 via independent route with RR Lyrae, the tip of red giant branch, SN Ia

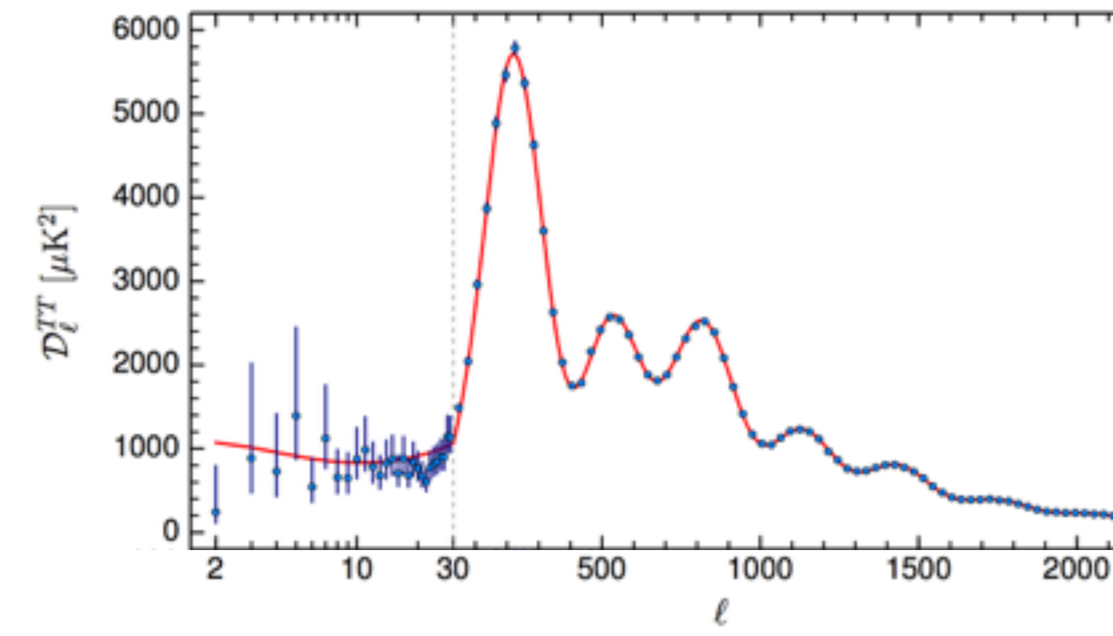
- Supernovae, H_0 for the dark energy Equation of State "SH0ES" project [Riess et al. 2019]
  - H_0 = 74.03 ± 1.42 km s^{-1} Mpc^{-1} (1.9% uncertainty)

Cosmic Microwave Background

CMB Temperature fluctuations



[Planck Collaboration 2016]



(1) Ratio of peak heights ➜ $\Omega_m h^2$, $\Omega_b h^2$ [h = H_0 / 100 km/s/Mpc]
(2) Location of the first peak in **flat ΛCDM** ➜ $\Omega_m h^{3.2}$

- Under **flat ΛCDM** assumption, (1) and (2) yield
  h = 0.674±0.005 [Planck collaboration 2018]
- Without **flat ΛCDM** assumption, h highly degenerate with other cosmological parameters (e.g., curvature, w, N_{eff})

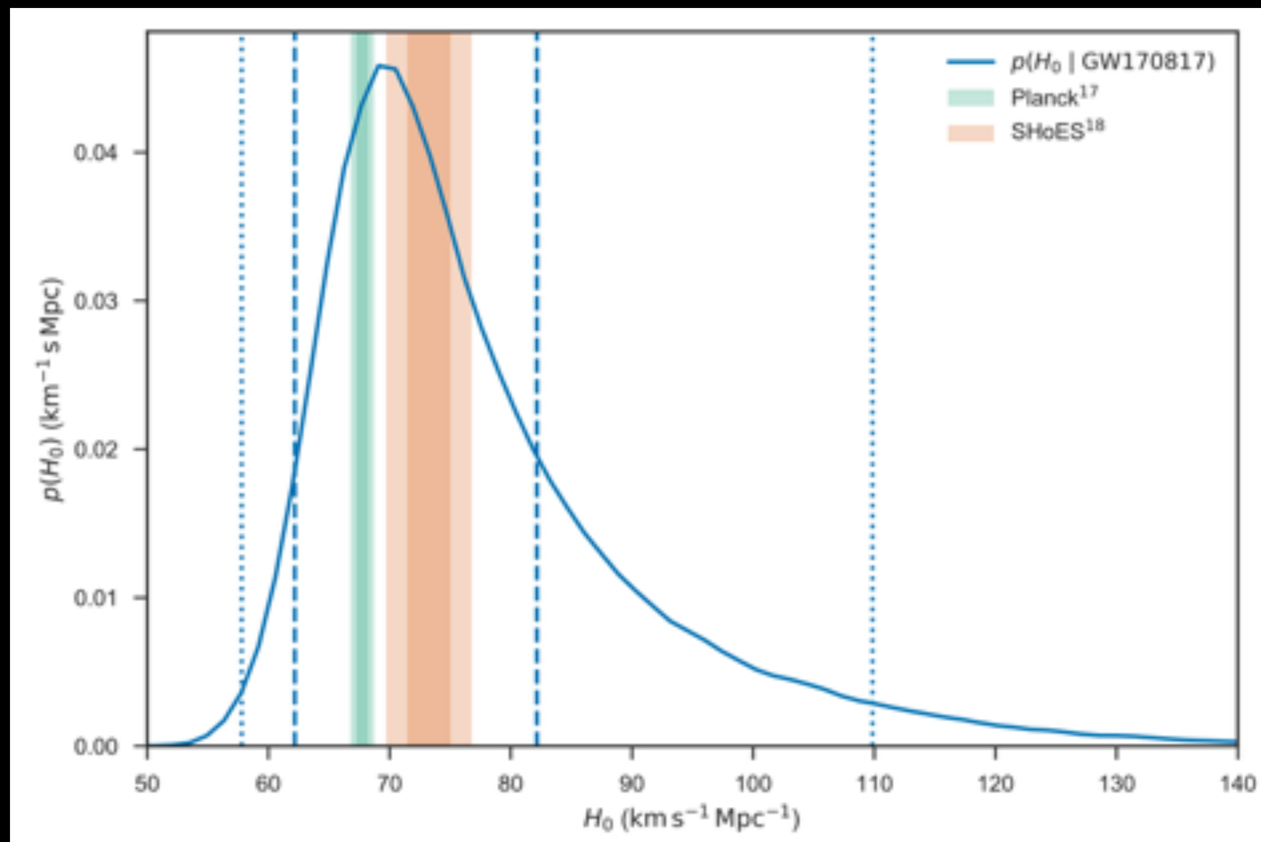
Standard Siren

Gravitational wave form ➜ luminosity distance D
Measure recessional velocity of EM counterpart v

$H_0 = v / D$

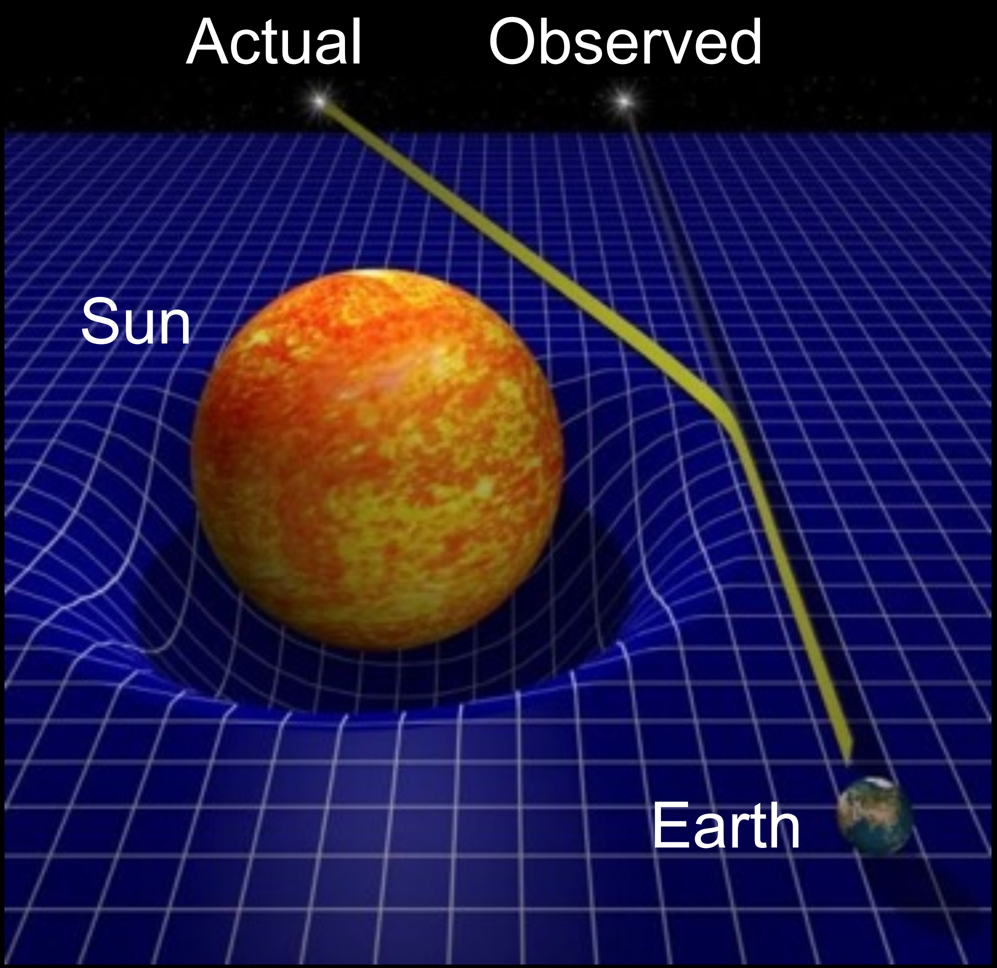
[Image credit: M. Garlick]

GW170817: First measurement of H_0

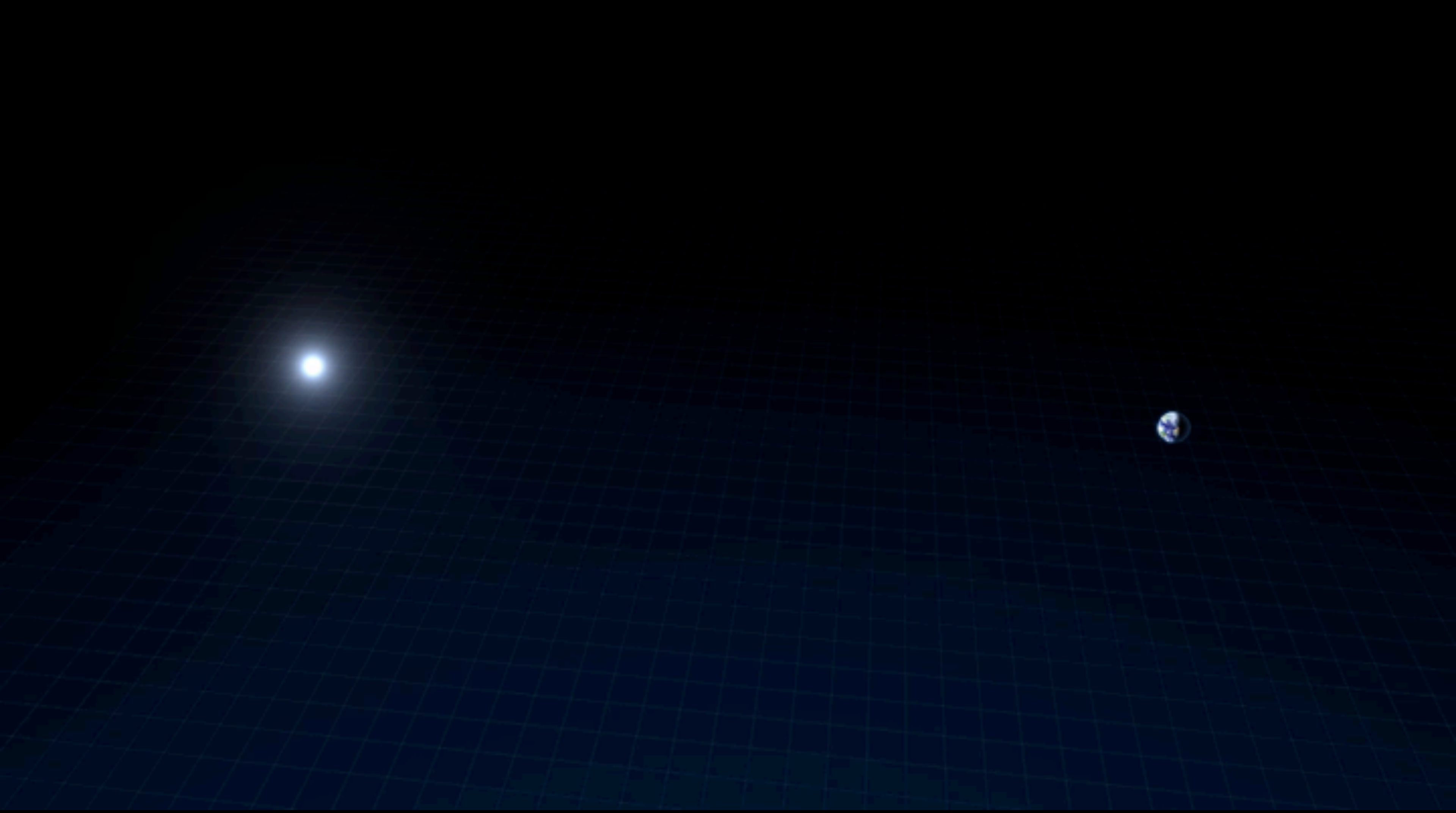


[LIGO, VIRGO, 1M2H, DES, DLT40, LCO, VINROUGE, MASTER collaborations, 2017]

Gravitational Lensing



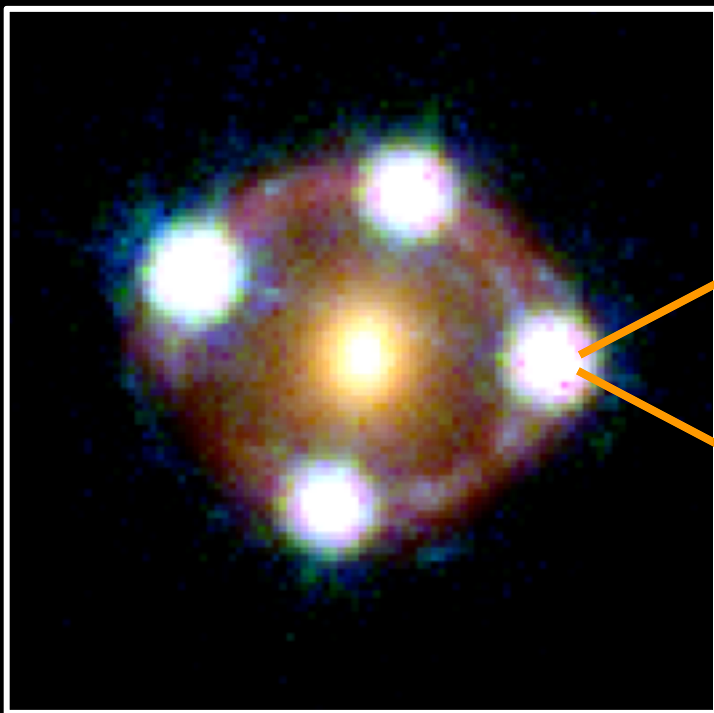
Strong gravitationally lensed quasar



[Credit: ESA/Hubble, NASA]

Variability of quasar emission

HE0435-1223



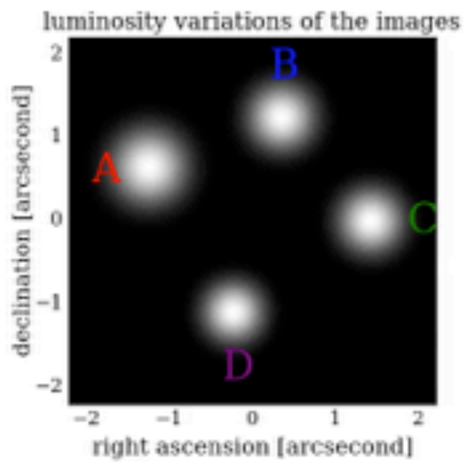
[Suyu et al. 2017]

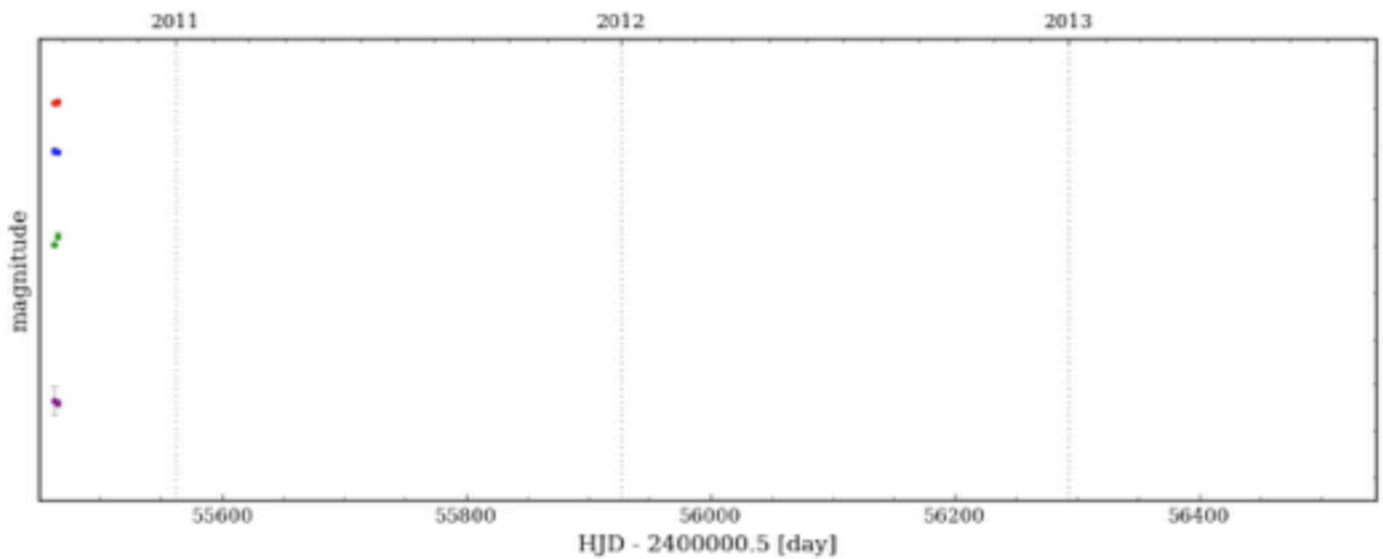
quasar powered by accretion of material onto supermassive black hole:

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

Cosmology with time delays

[COSmological MOnitoring of Gravitational lenses;
PI: F. Courbin]

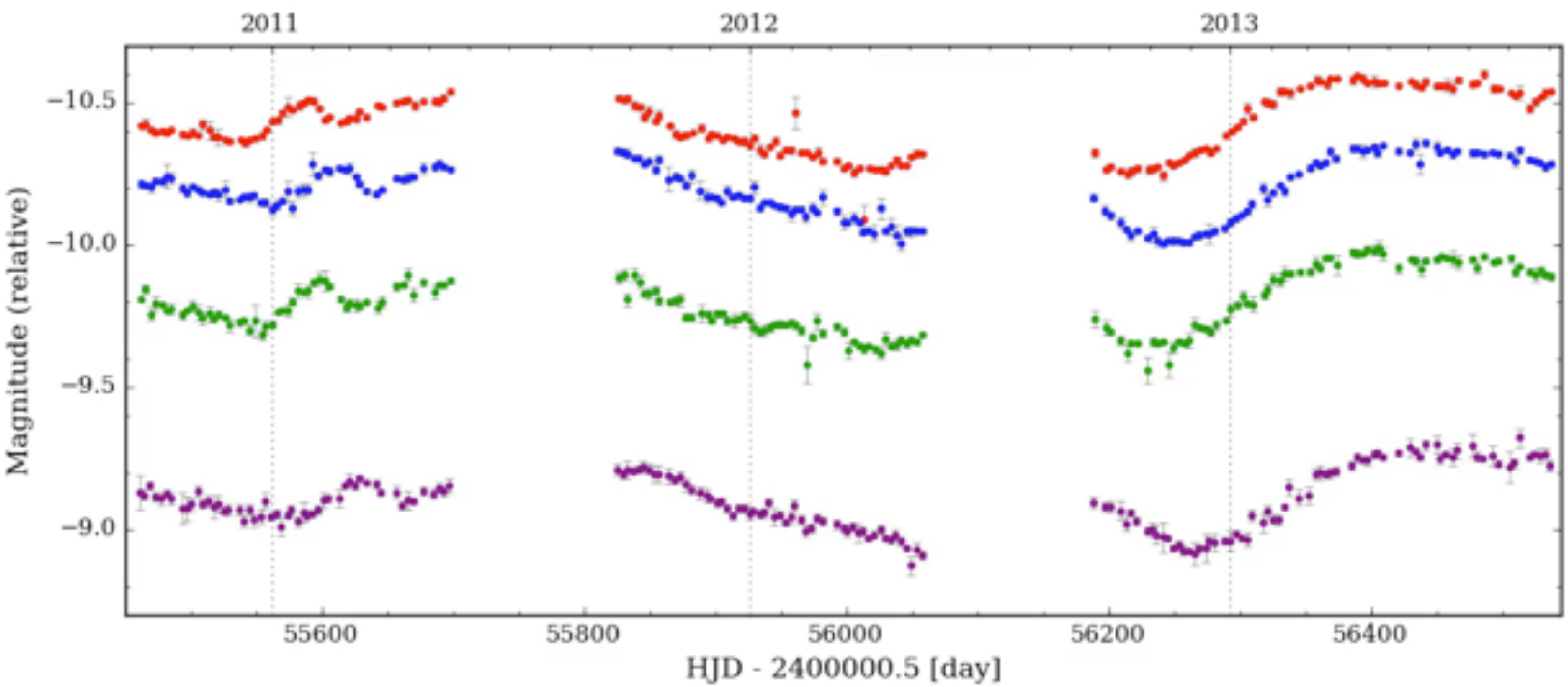




[Credit: V. Bonvin]

Cosmology with time delays

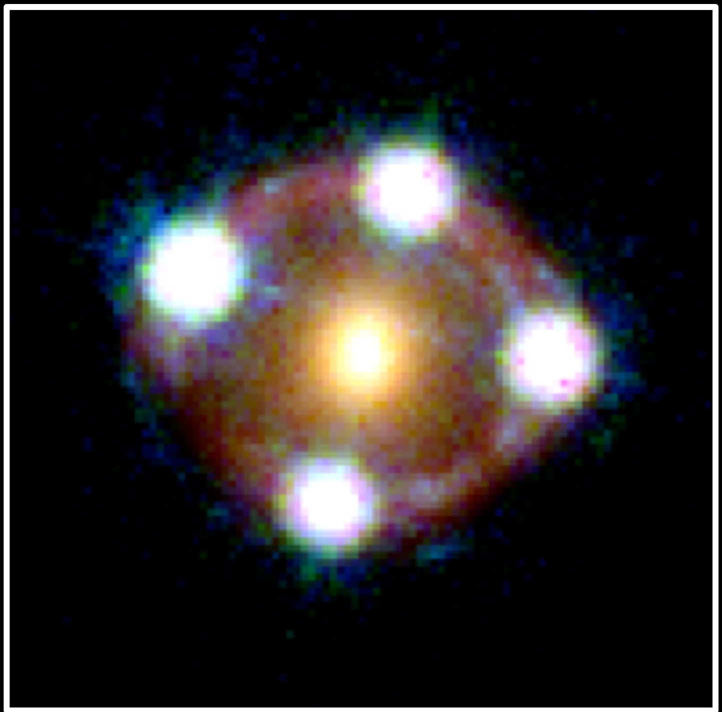
COSMOGrail



[Credit: V. Bonvin]

Cosmology with time delays

HE0435-1223



[Suyu et al. 2017]

Time delay:

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

Time-delay distance:

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

Obtain from lens mass model

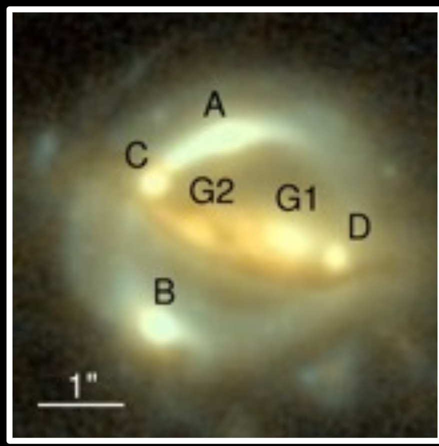
For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

Advantages:
- simple geometry & well-tested physics
- one-step physical measurement of a cosmological distance

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

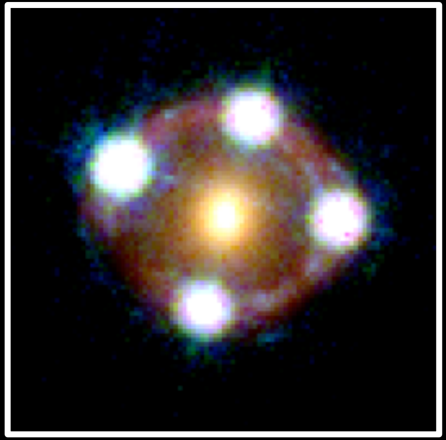
B1608+656



RXJ1131-1231

H_0 to <3.5% precision

HE0435-1223



WFI2033-4723

HE1104-1805

[Suyu et al. 2017]

H0LiCOWers

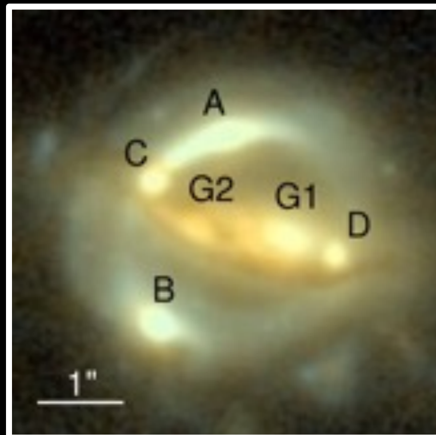
H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

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

H0LiCOW: latest results

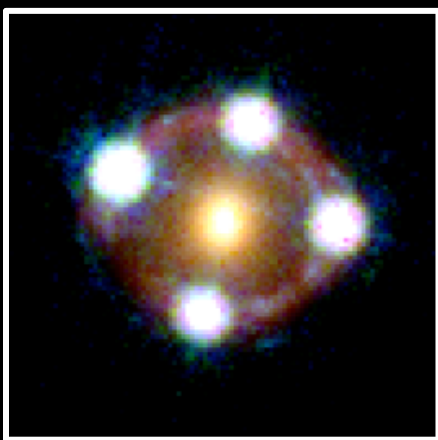
B1608+656

[Suyu et al. 2010]



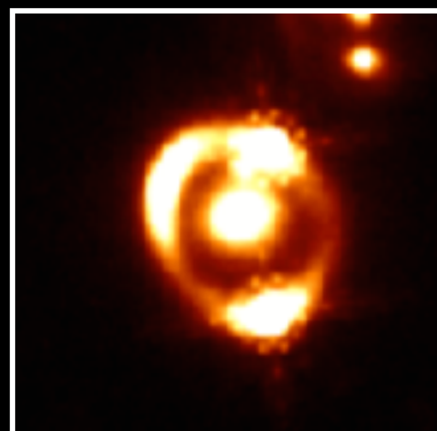
RXJ1131-1231

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



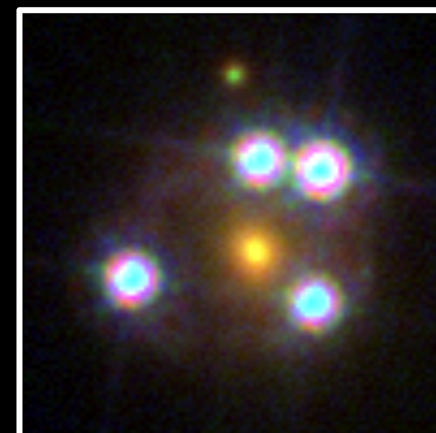
HE0435-1223

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



SDSS1206+4332

part of extended sample [Birrer et al. 2019]



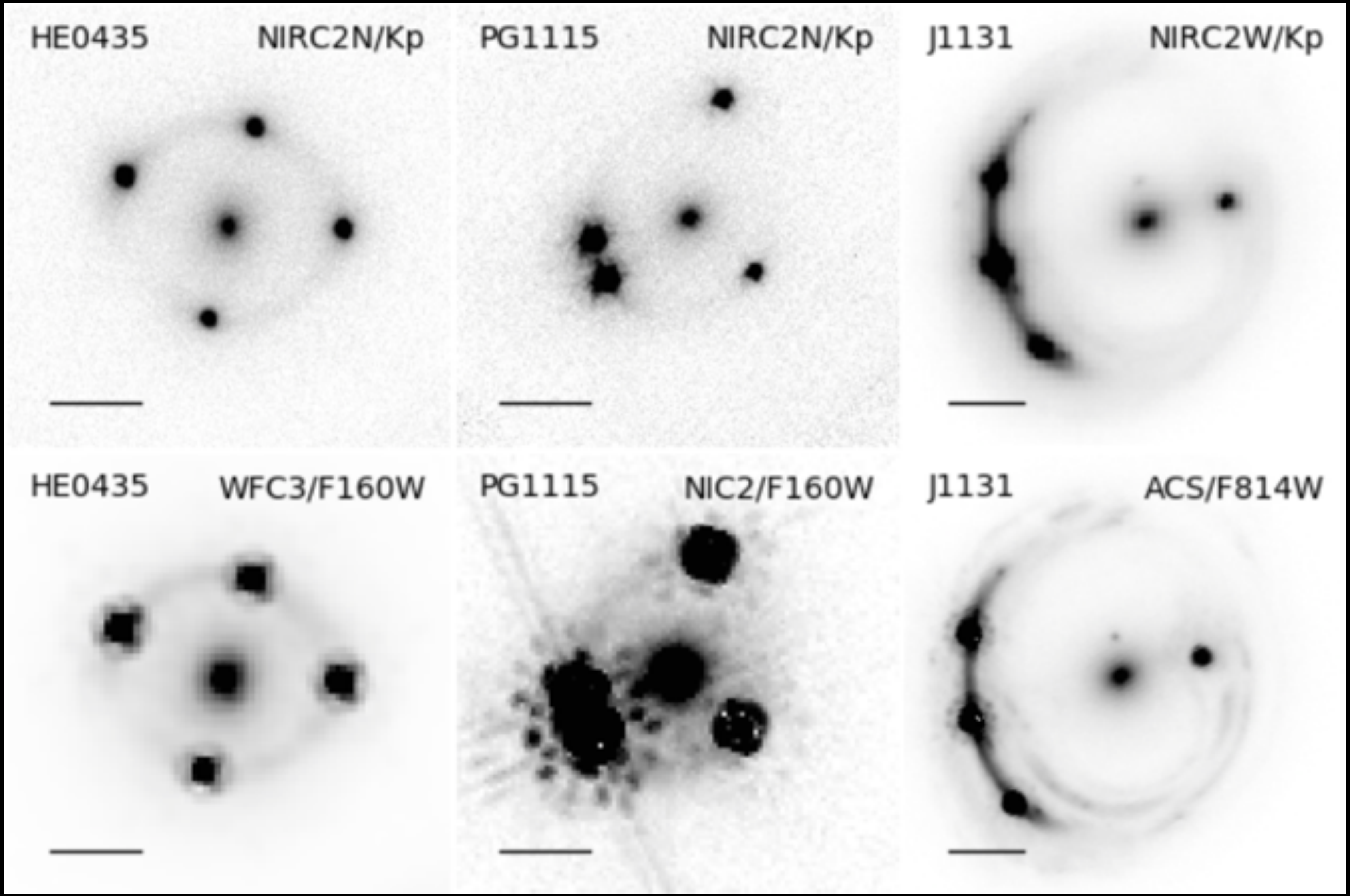
WFI2033-4723

[Bonvin et al. 2019; Sluse et al. 2019; Rusu et al. 2019]

Cosmology with Adaptive Optics

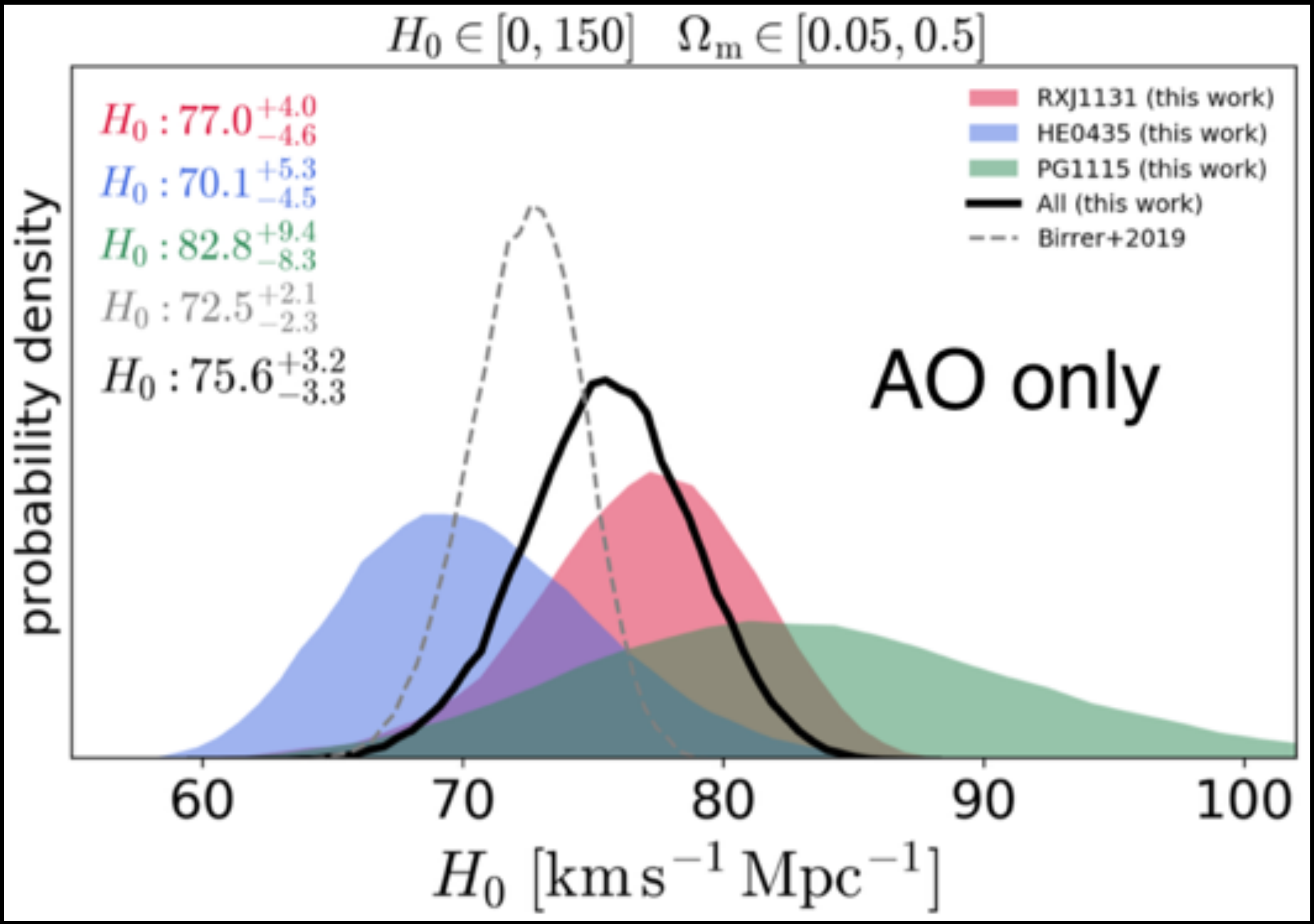
Keck AO

HST



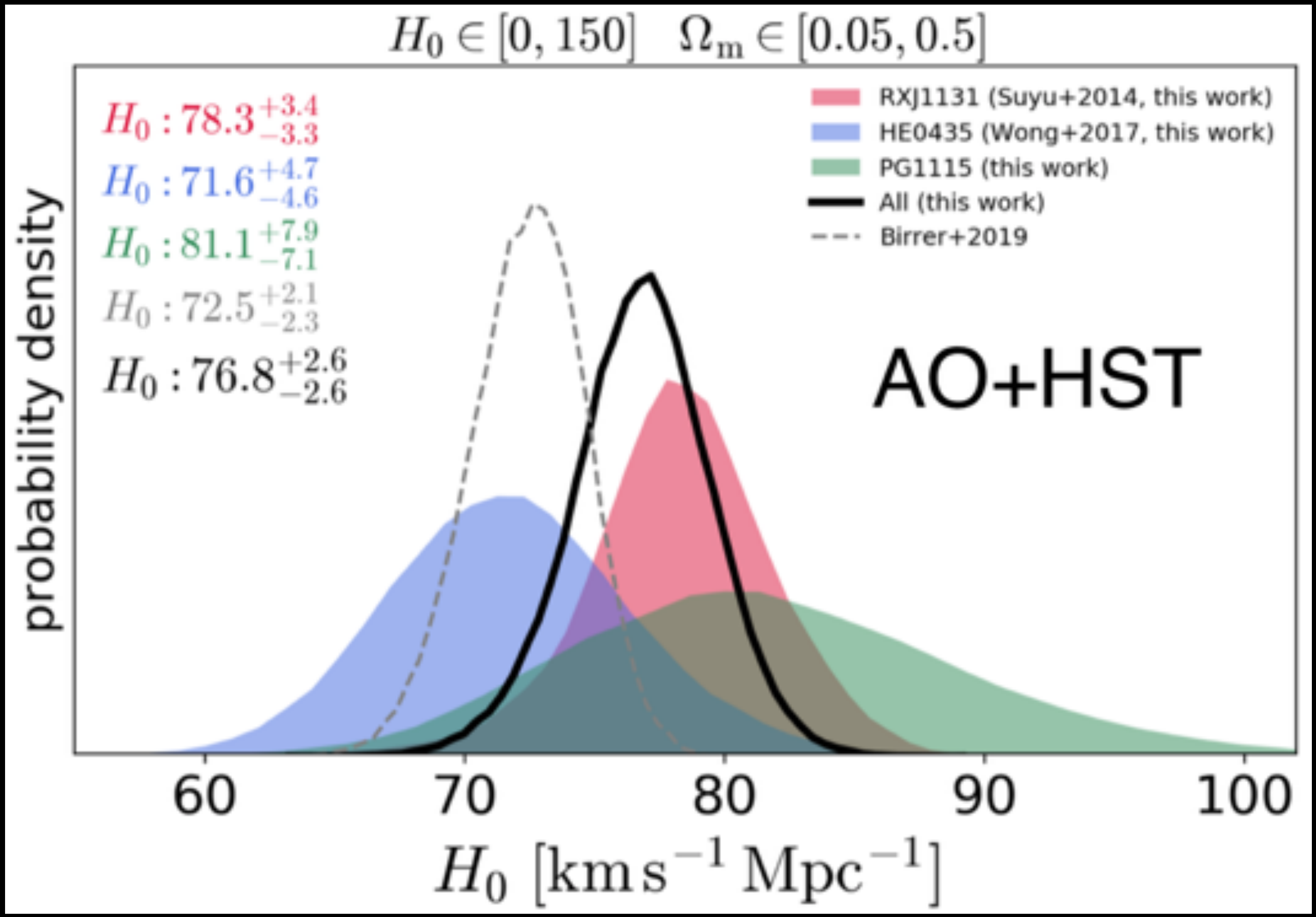
[Chen, Fassnacht, Suyu et al. 2019]

Cosmology with Adaptive Optics



[Chen, Fassnacht, Suyu et al. 2019]

Cosmology with Adaptive Optics

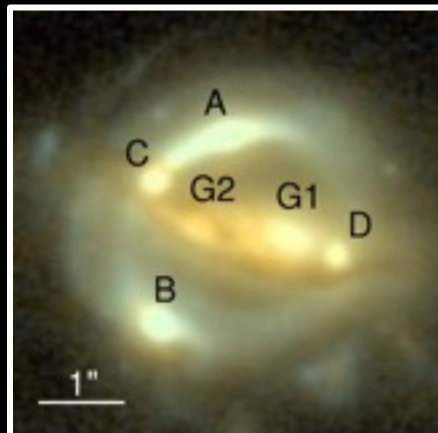


[Chen, Fassnacht, Suyu et al. 2019]

Calibrating SNe distances with $D_{\Delta t}$

[Suyu et al. 2010]

B1608+656

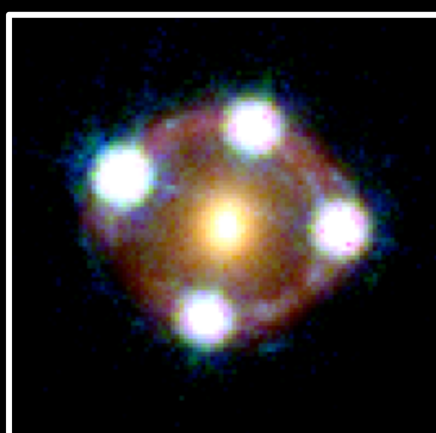


RXJ1131-1231

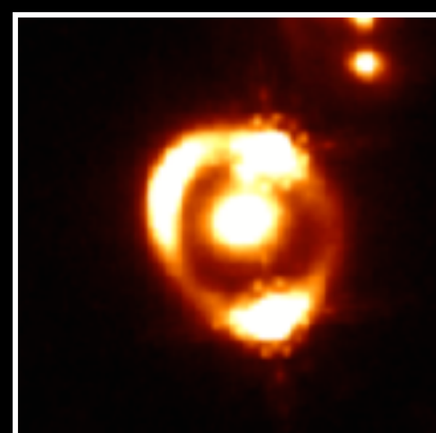
[Suyu et al. 2013, 2014; Tewes et al. 2013]

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

HE0435-1223



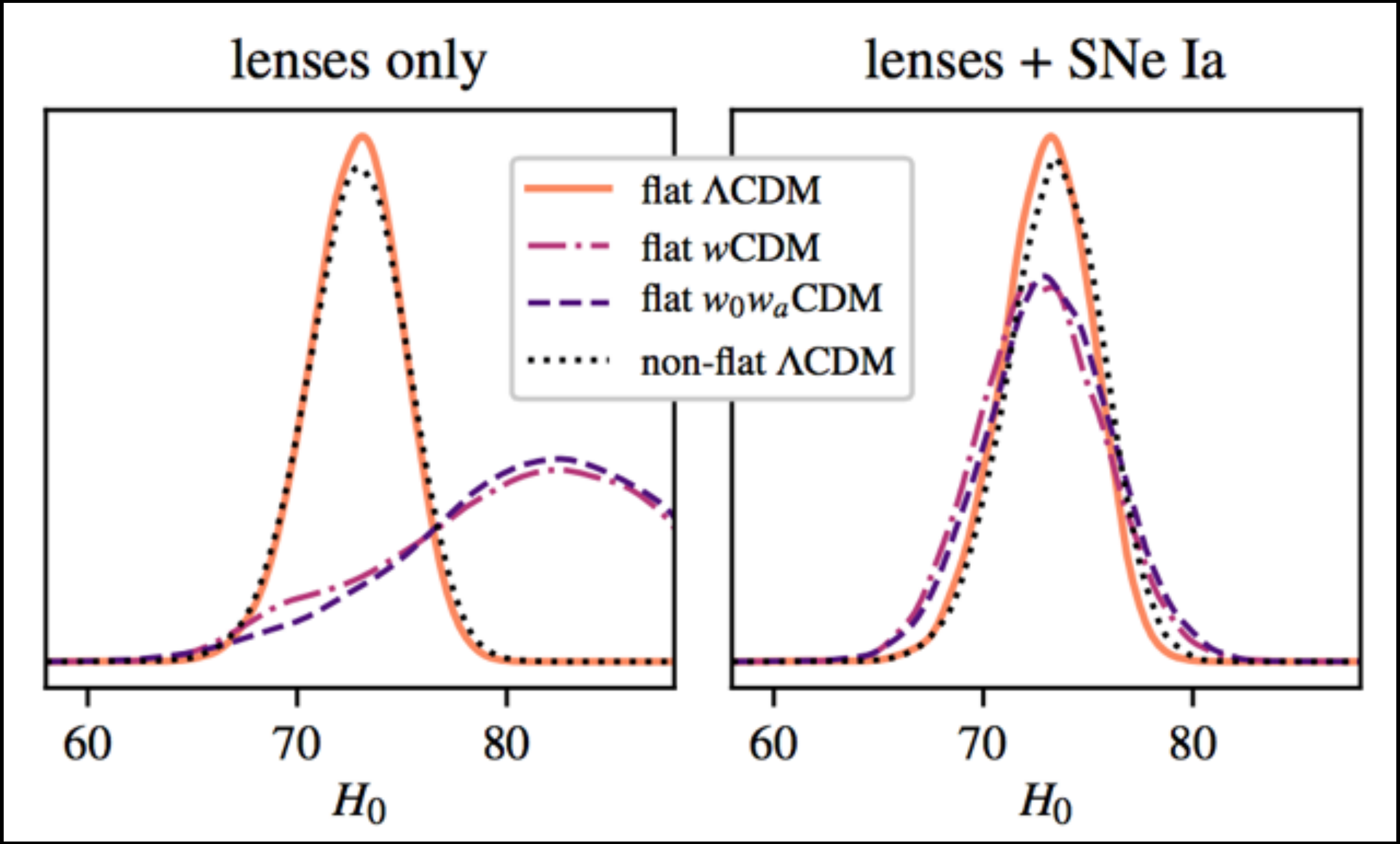
SDSS1206+4332



part of extended sample

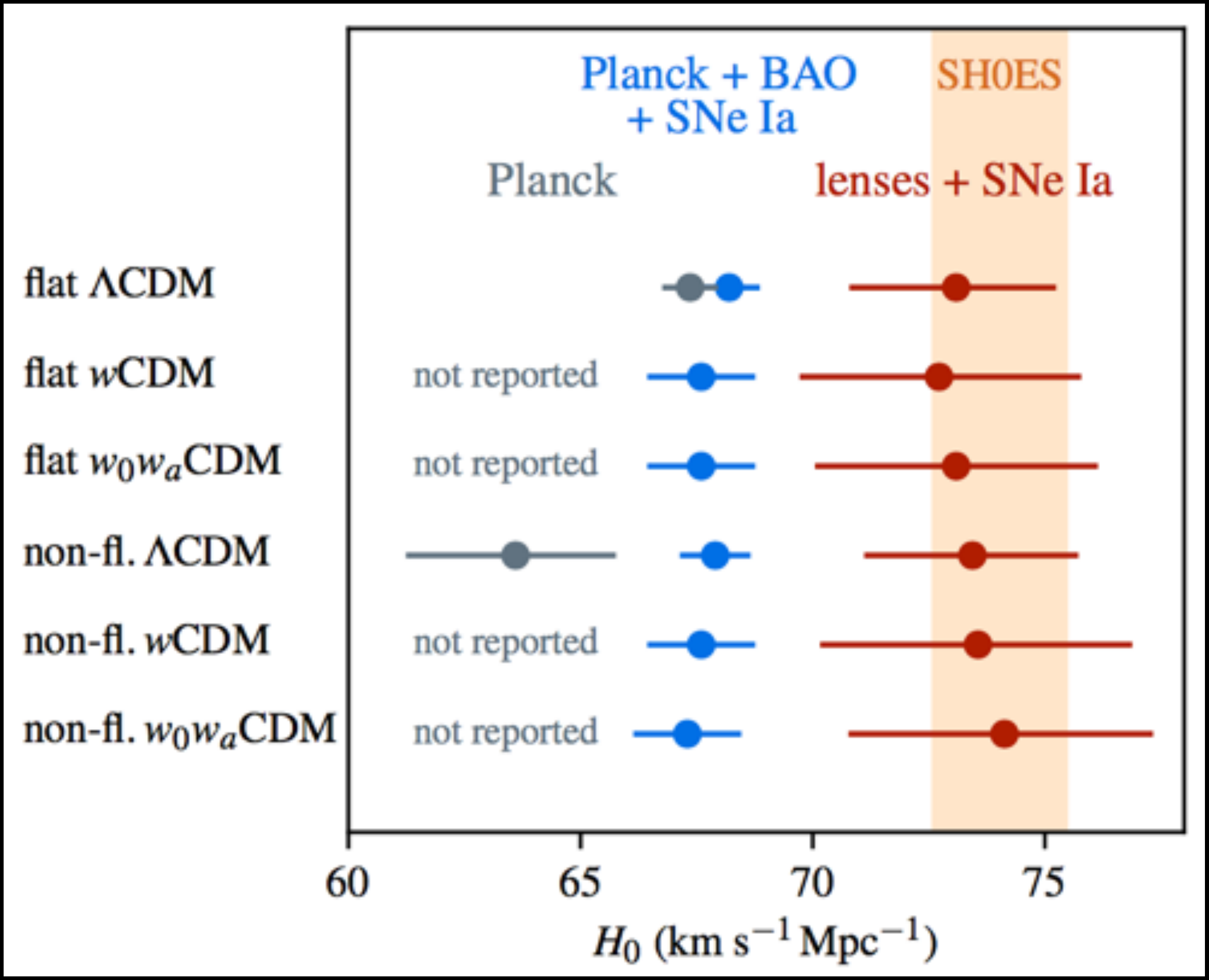
[Birrer, Treu Rusu et al. 2018]

Reduced cosmological dependence



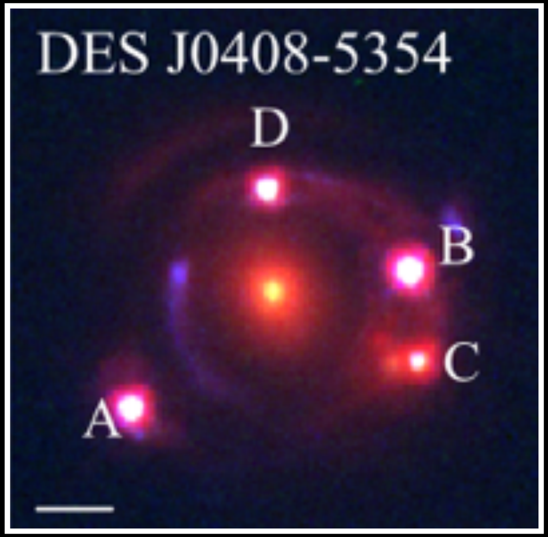
[Taubenberger, Suyu, Komatsu et al. 2019]

Reduced cosmological dependence



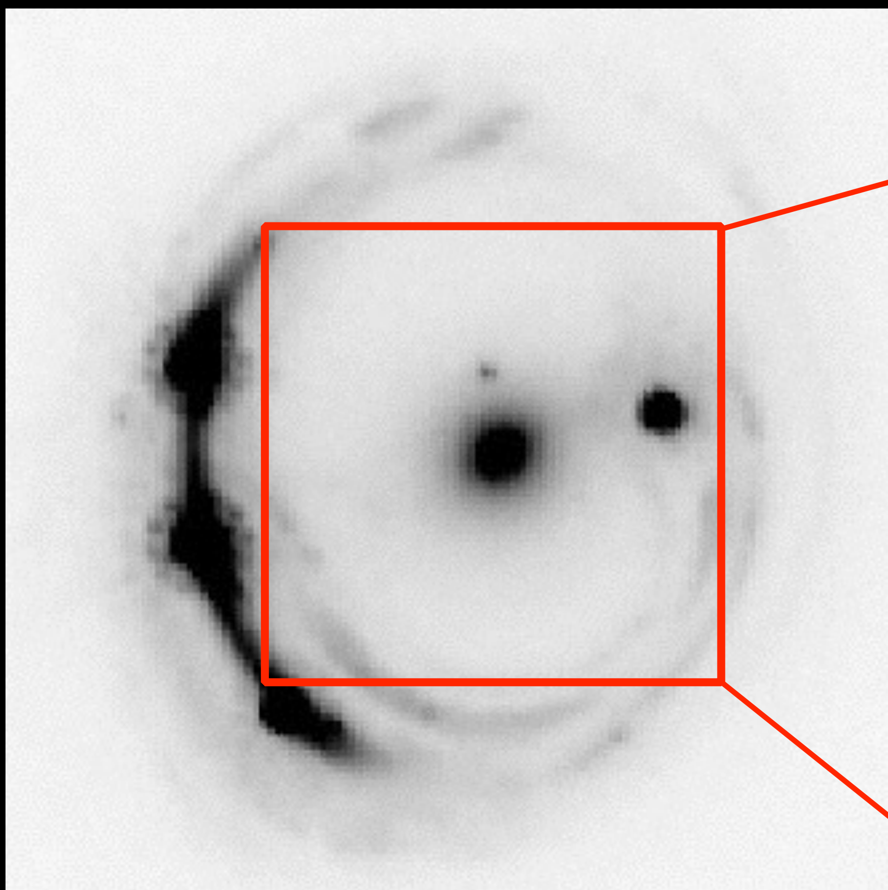
[Taubenberger, Suyu, Komatsu et al. 2019;
see also Arendse, Agnello & Wojtak 2019]

Looking forward

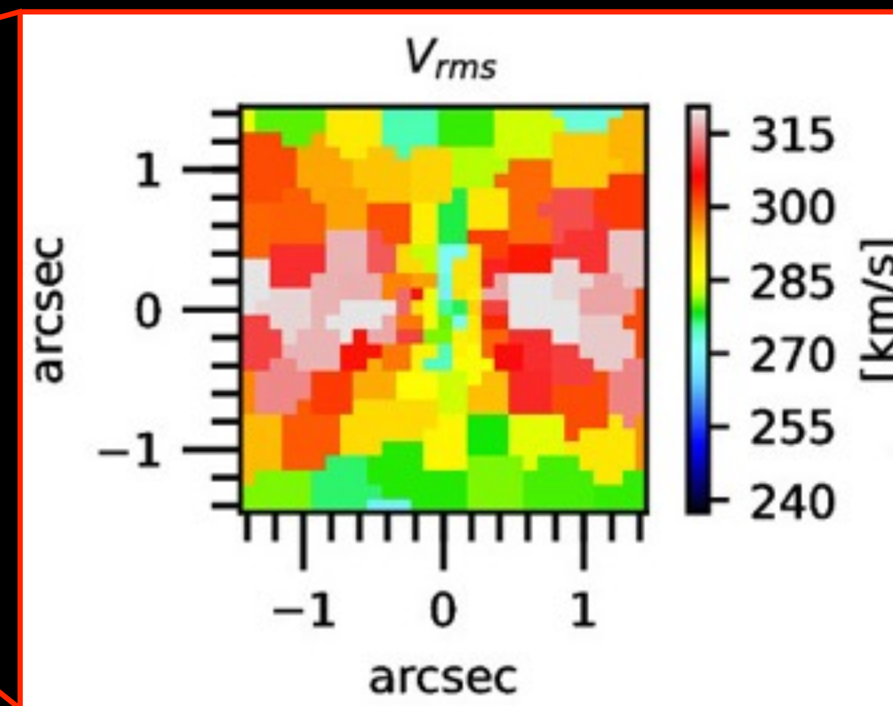


- Part of STRIDES collaboration [Treu et al. 2018]
- Blind analysis with two independent lens modeling softwares [Shajib et al. 2019; Shajib et al. in prep; Yıldırım et al. in prep; Wong et al. in prep]

Stellar kinematics really helps

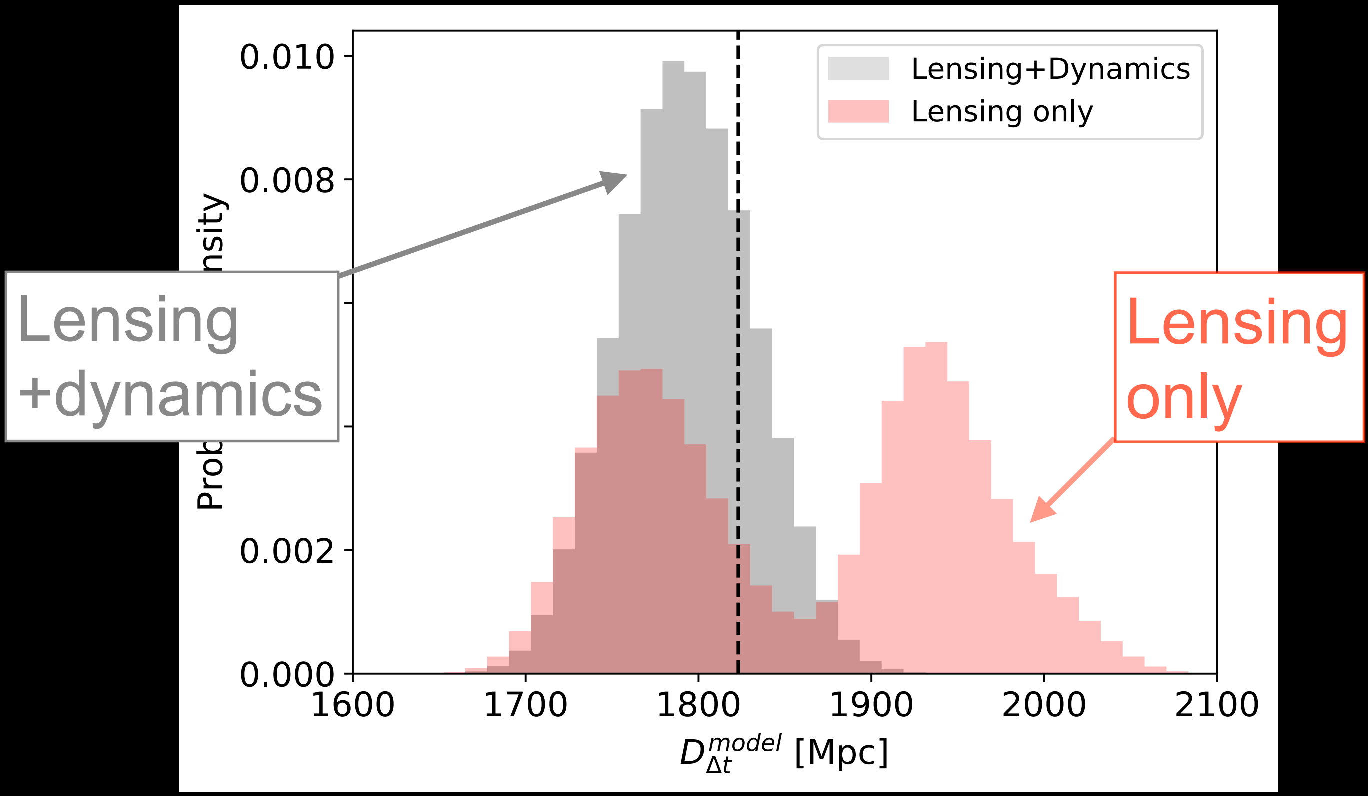


simulated James Webb Space Telescope NIRSpec observations of stellar kinematic map of lens



[Yıldırım, Suyu, Halkola 2019]

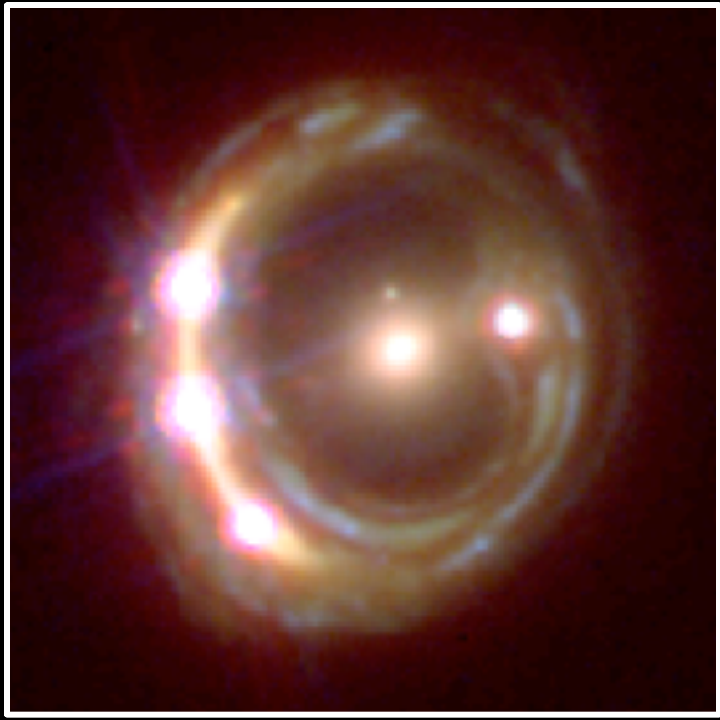
Stellar kinematics really helps



- Inferred $D_{\Delta t}$ depends on assumptions of mass model
- Including kinematic data:
  - reduces dependence of $D_{\Delta t}$ on mass model assumption
  - tightens constraints on $D_{\Delta t}$

[Yıldırım, Suyu, Halkola 2019]

D_A to the lens



Time delay:

$$\Delta t \sim GM$$

Lens velocity dispersion:

$$\sigma^2 \sim GM/r$$

Angular diameter distance:

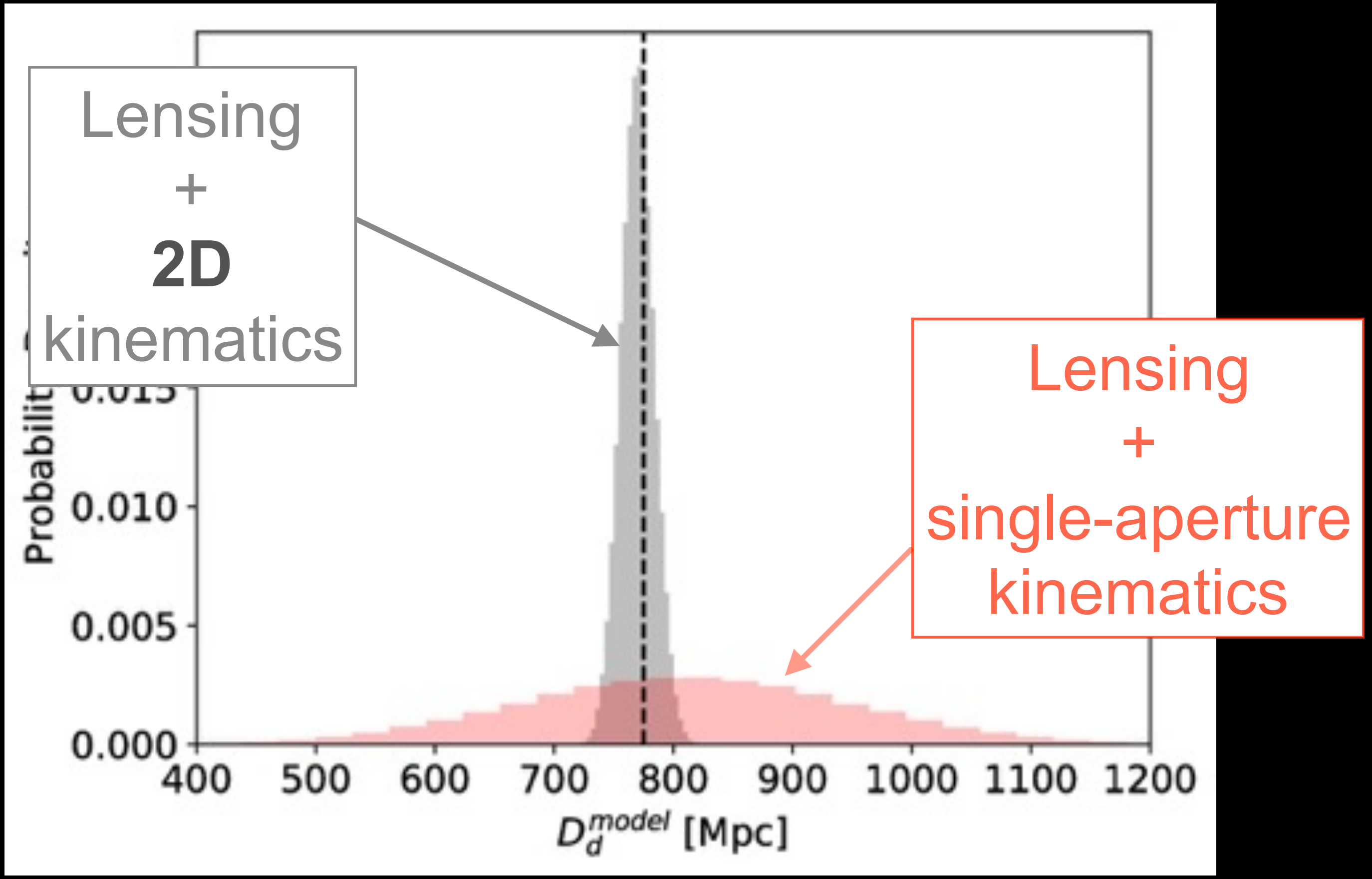
$$D_A \sim r/\Delta\theta$$

$$\boxed{D_A \sim \frac{\Delta t}{\sigma^2 \Delta\theta}}$$

- D_A more sensitive to dark energy than $D_{\Delta t}$
- D_A insensitive to mass along LOS, but depend on anisotropy in stellar velocity dispersion
- Can measure D_A to ~15% per lens with current data

[Paraficz & Hjorth 2009; Jee, Komatsu & Suyu 2015; Jee, Suyu, Komatsu et al., accepted]

Stellar kinematics really helps



Including spatially-resolved (2D) kinematic data:

- drastically reduces the uncertainty of D_A from ~15% to ~3%
- sensitive to systematic errors in kinematic measurements

[Yıldırım, Suyu, Halkola 2019]

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

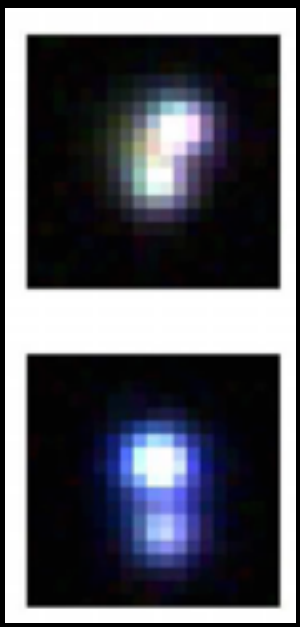
- 5000 deg^2 with i_{limit}~24
- 2012-2017
- expect ~1100 lenses
  [Oguri & Marshall 2010]

Kilo Degree Survey

2.6m VLT Survey Telescope, Paranal, Chile

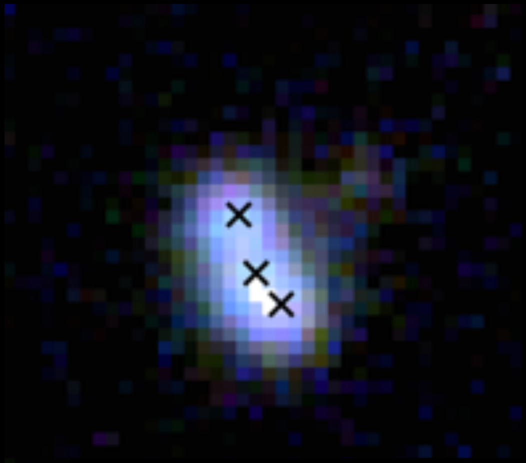
- 1500 deg^2 with r_{limit}~24
- 2011-2019

New lensed quasars systems

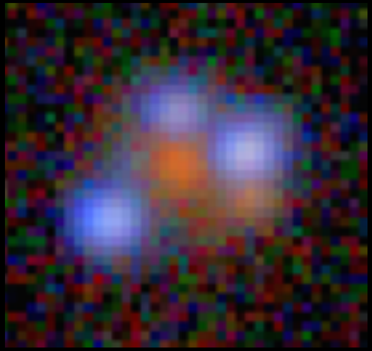


[Agnello et al. 2015]

[More et al. 2017]



[Ostrovski et al. 2017]

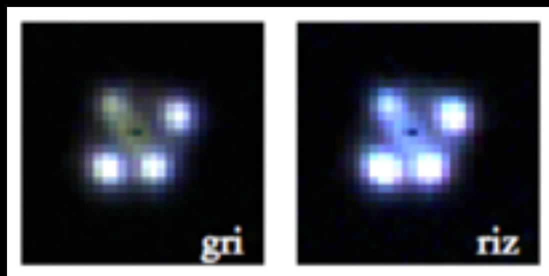


[Lin et al. 2017]

[Berghea et al. 2017]

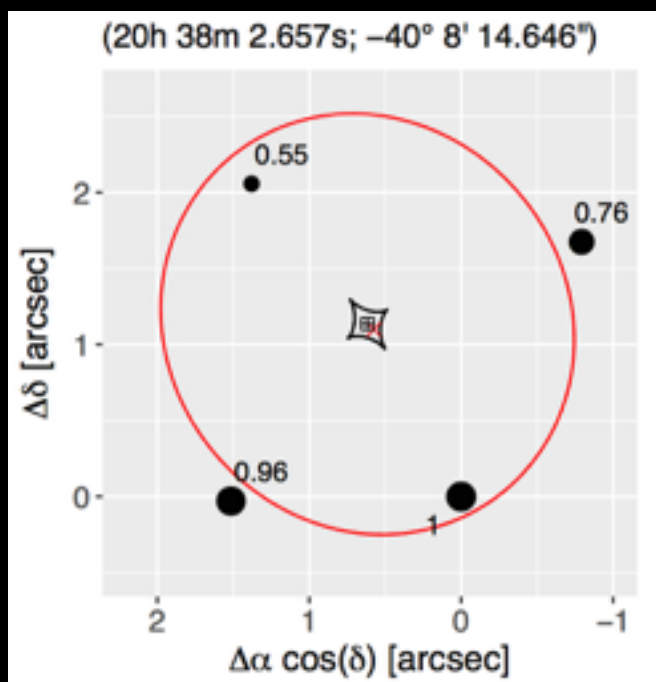
Gaia reveals lensed quasars

Gaia
+ DES
+ WISE



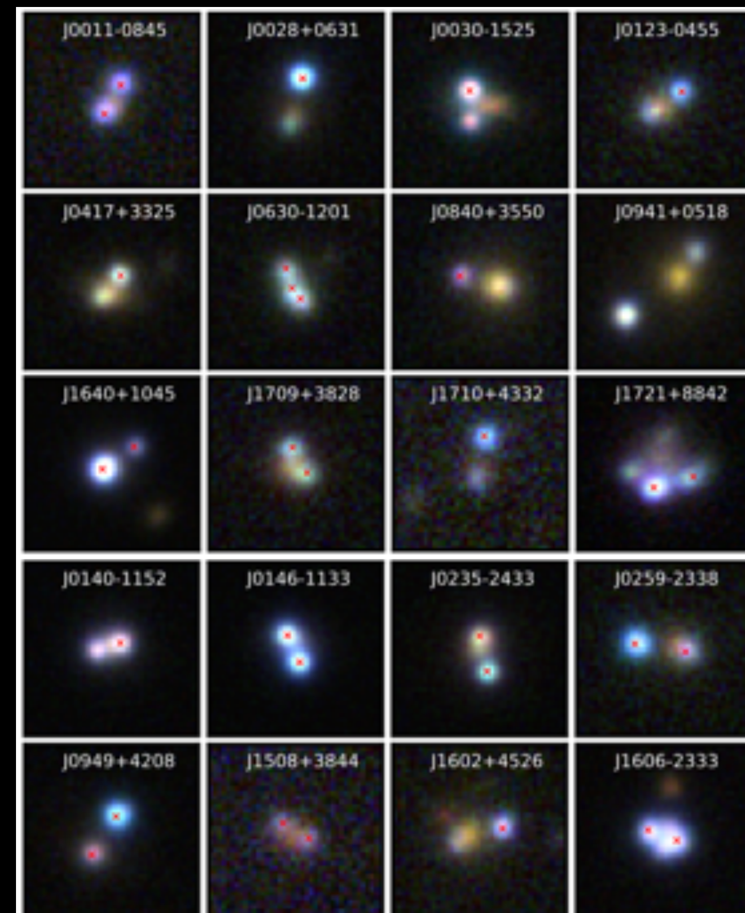
[Agnello et al. 2018]

Gaia
only



[Krone-Martins et al. 2018]

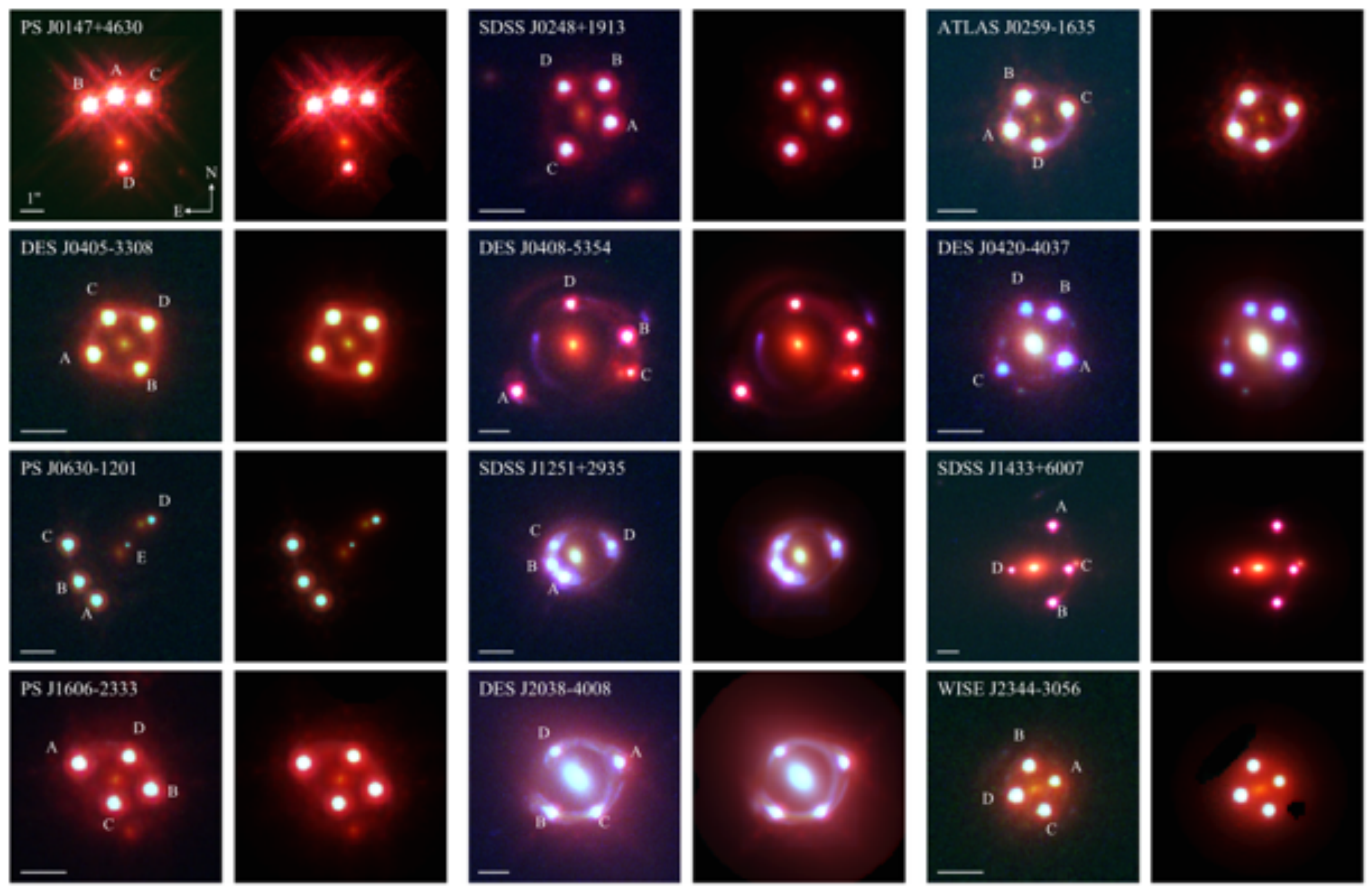
Gaia + WISE/SDSS
+ Pan-STARRS



[Lemon et al. 2018]

New quads imaged with HST

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



[Shajib et al. 2018]

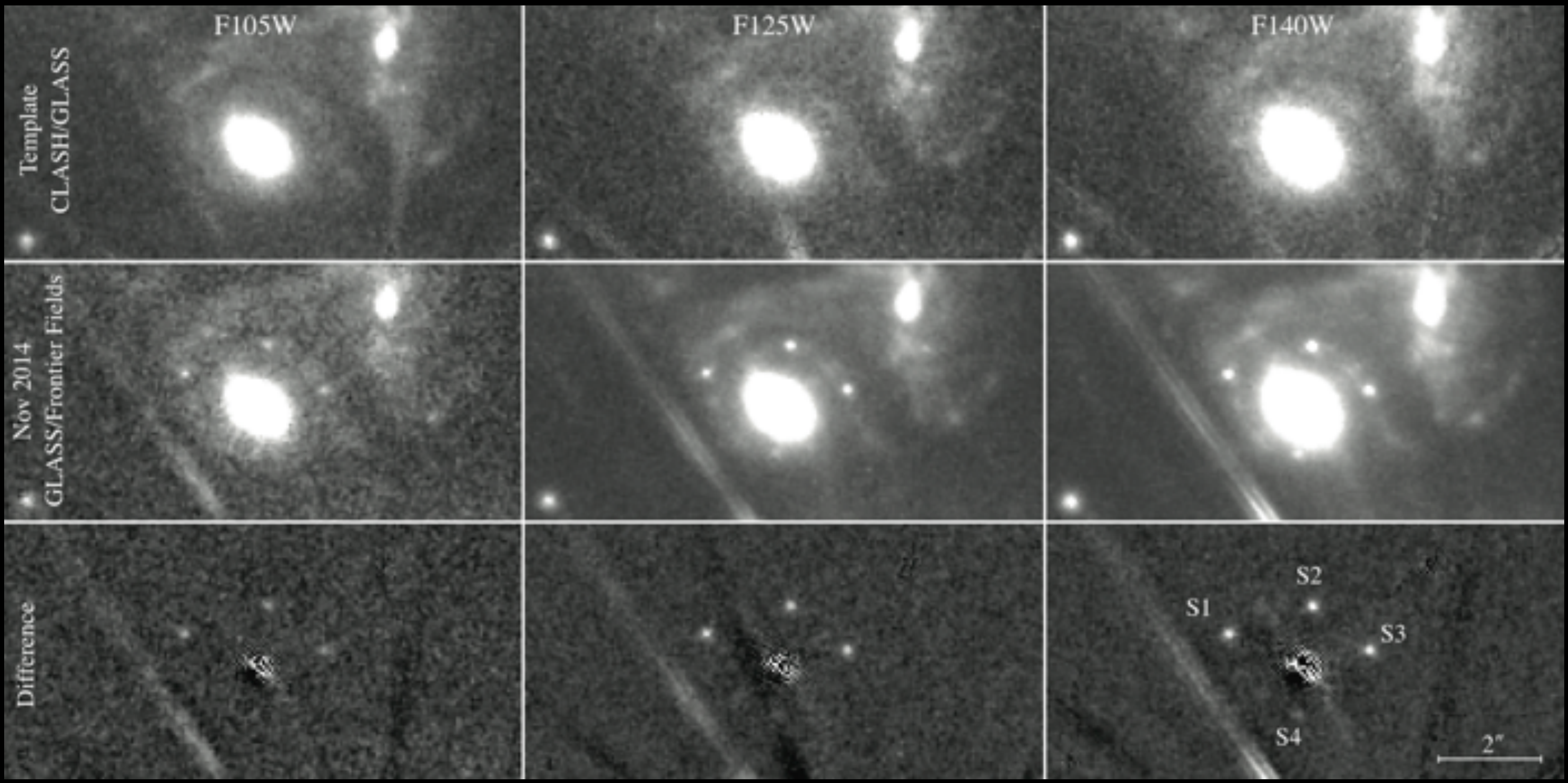
Strongly lensed supernova

MACS 1149.6+2223

[Kelly et al. 2015]

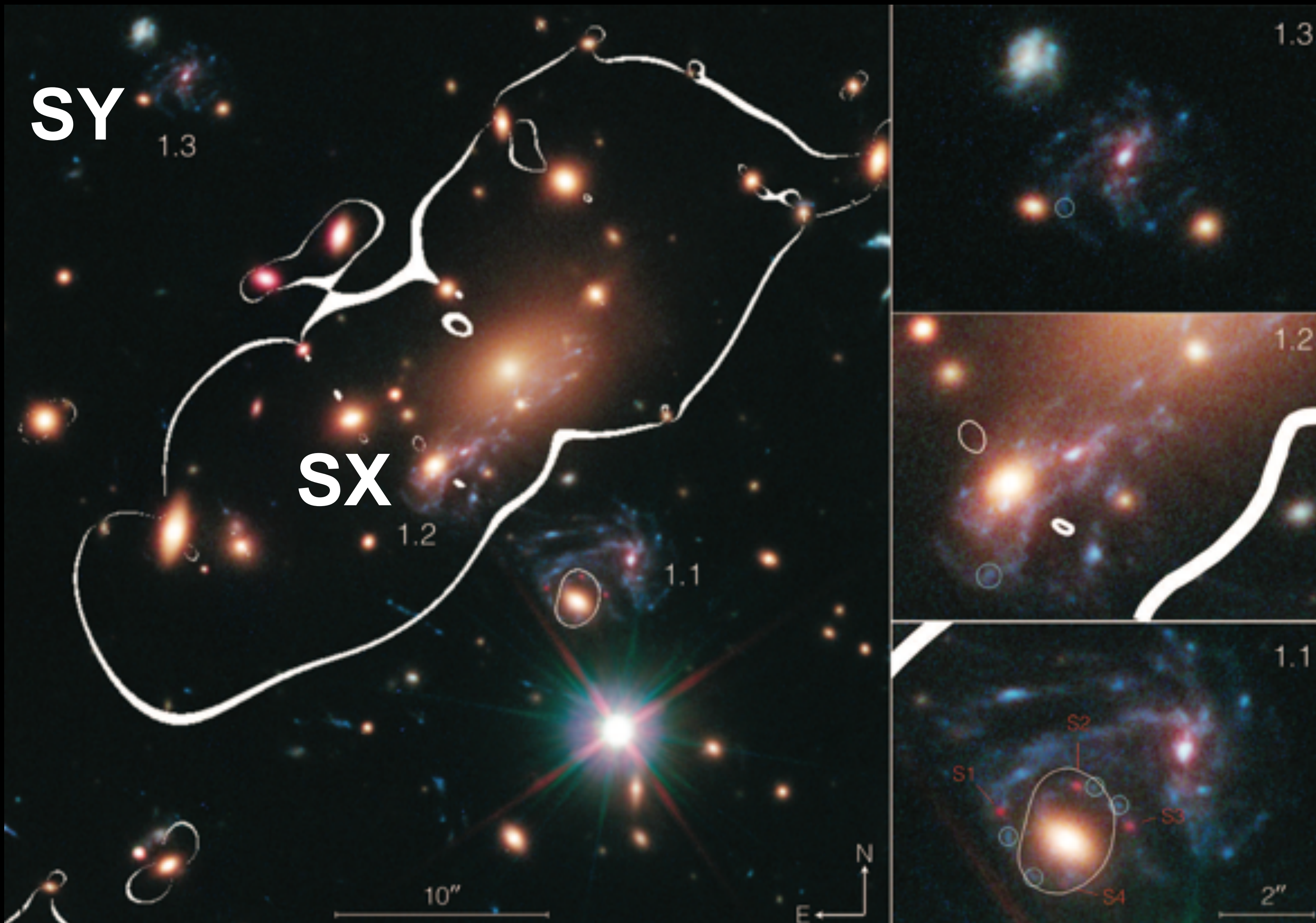
Supernova "Refsdal"

discovered serendipitously in November 2014



[Kelly et al. 2015]

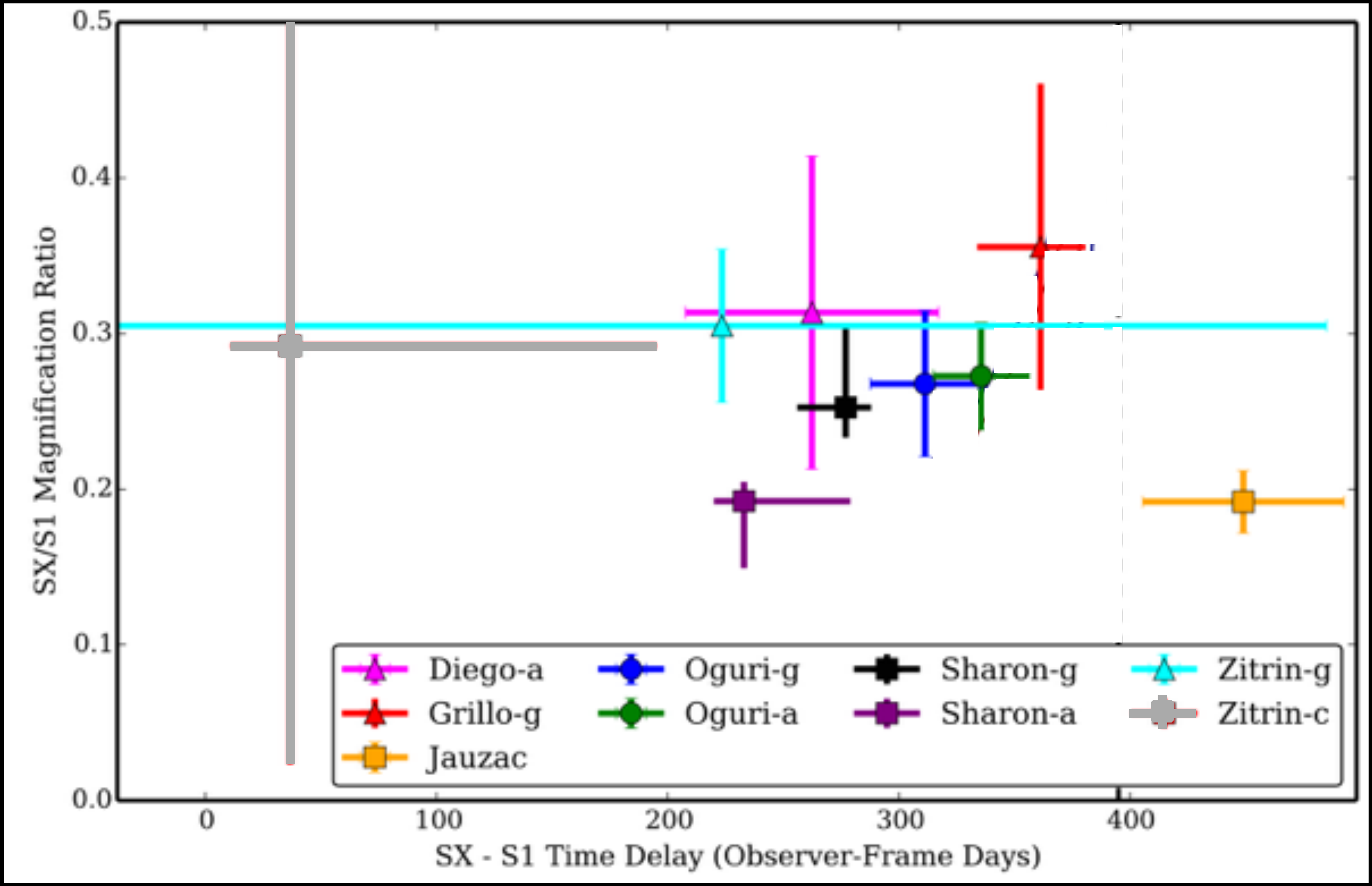
When will the other SN images appear?



MACS 1149.6+2223

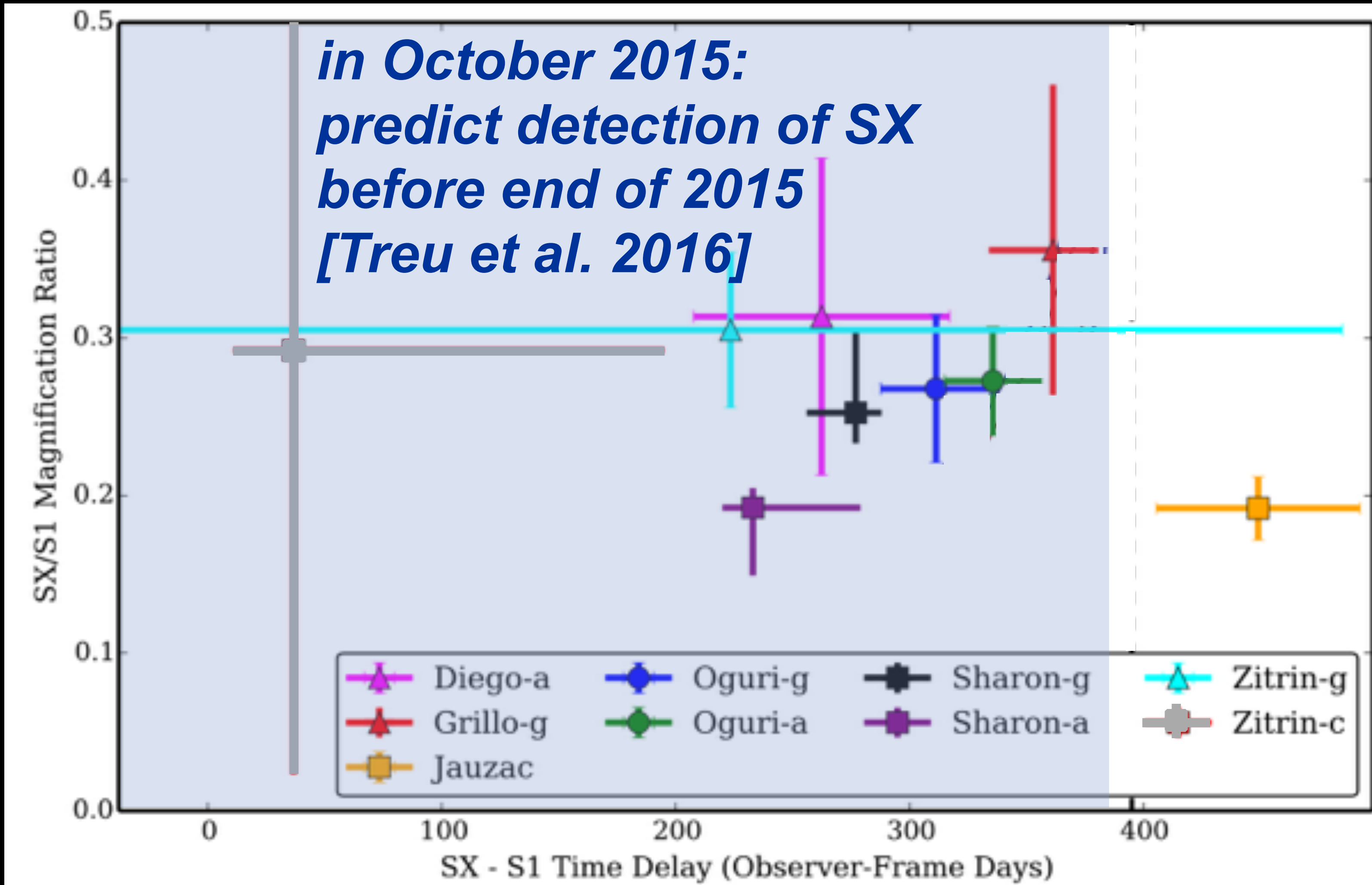
[Kelly et al. 2015]

Predicted magnification and delay



[Kelly et al. 2016]

Predicted magnification and delay

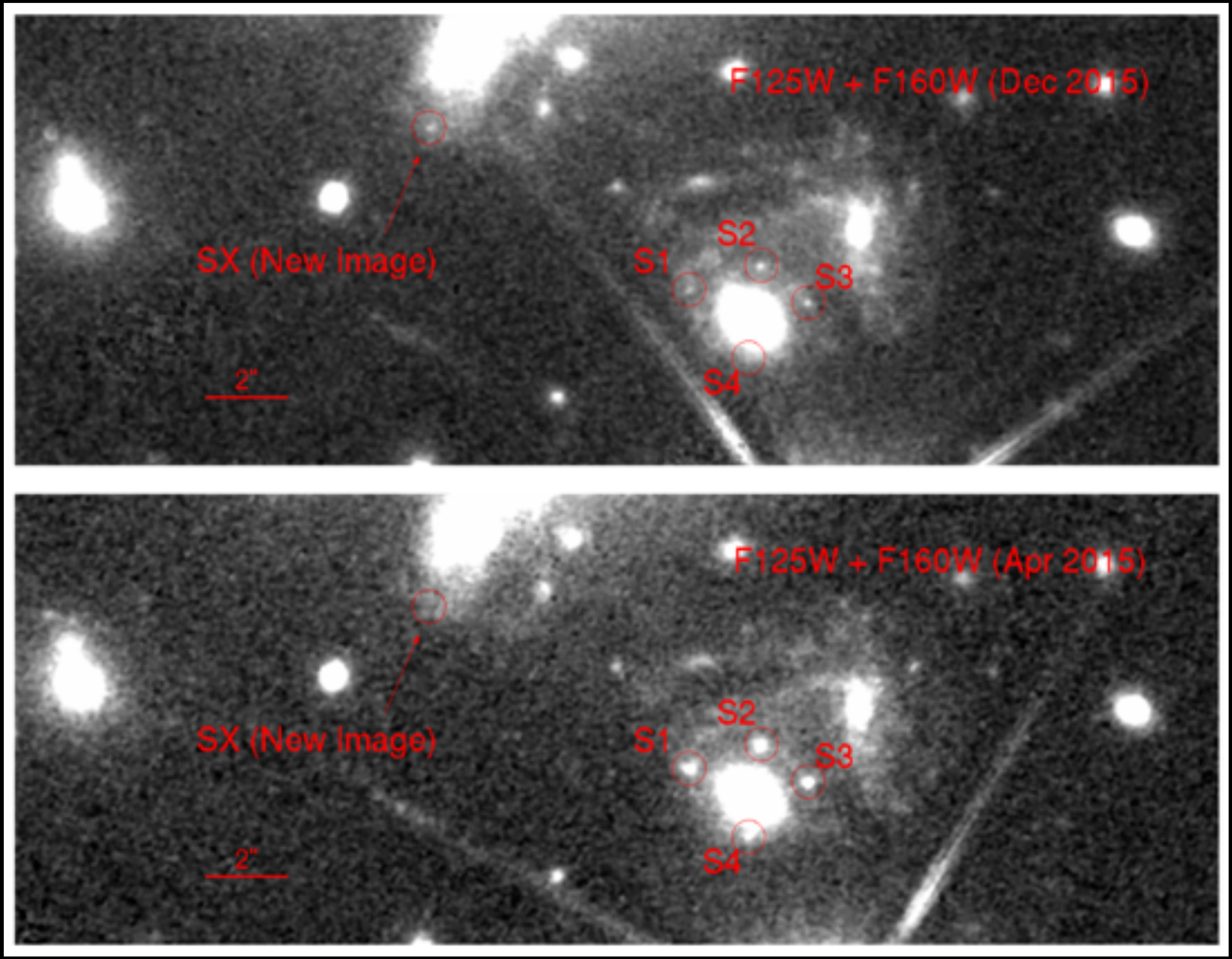


[Kelly et al. 2016]

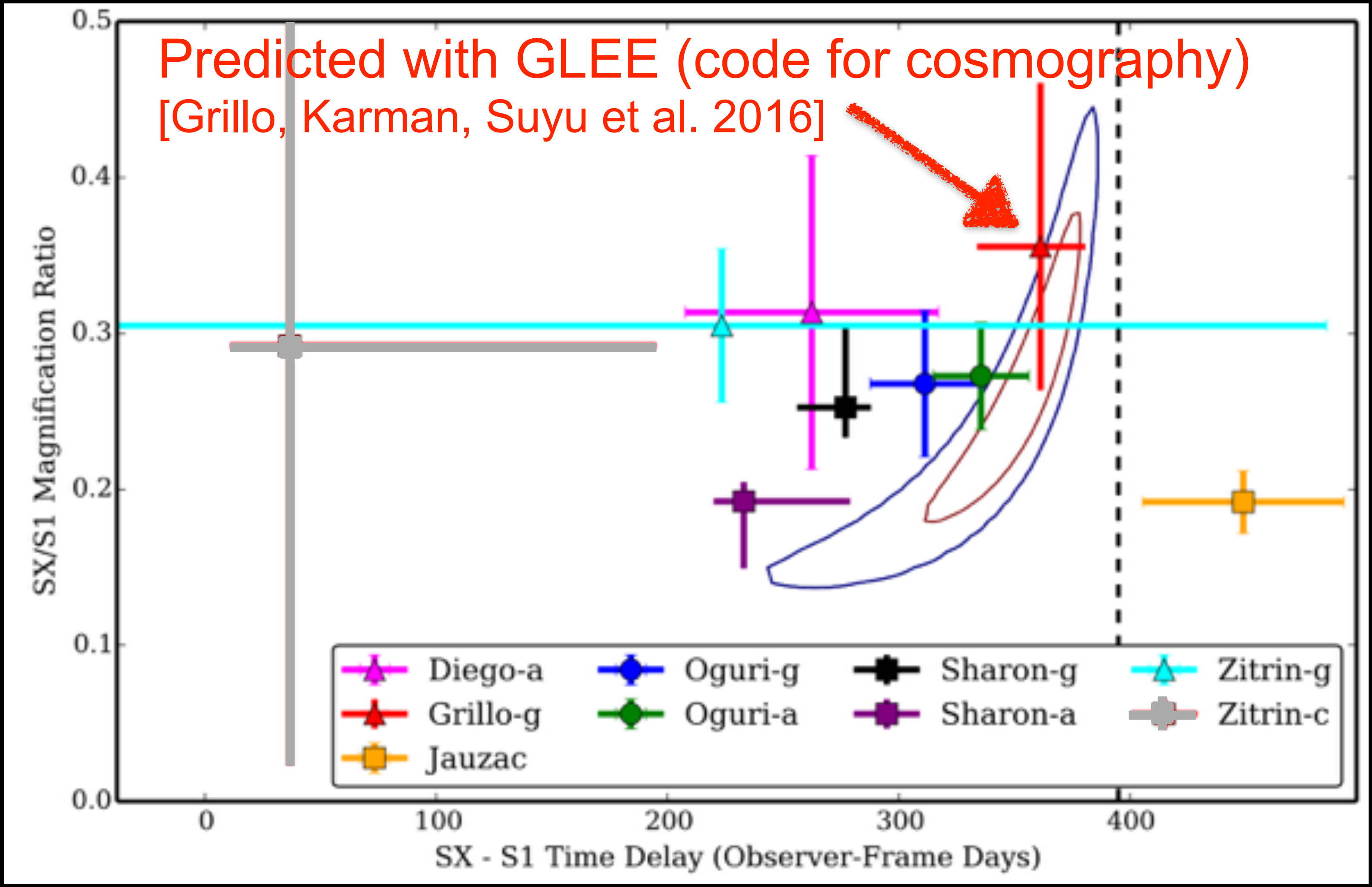
HST observations in Oct 2015: no sign of SX
in Nov 2015: no sign of SX…

Appearance of image SX

December 2015 [Kelly et al. 2016]

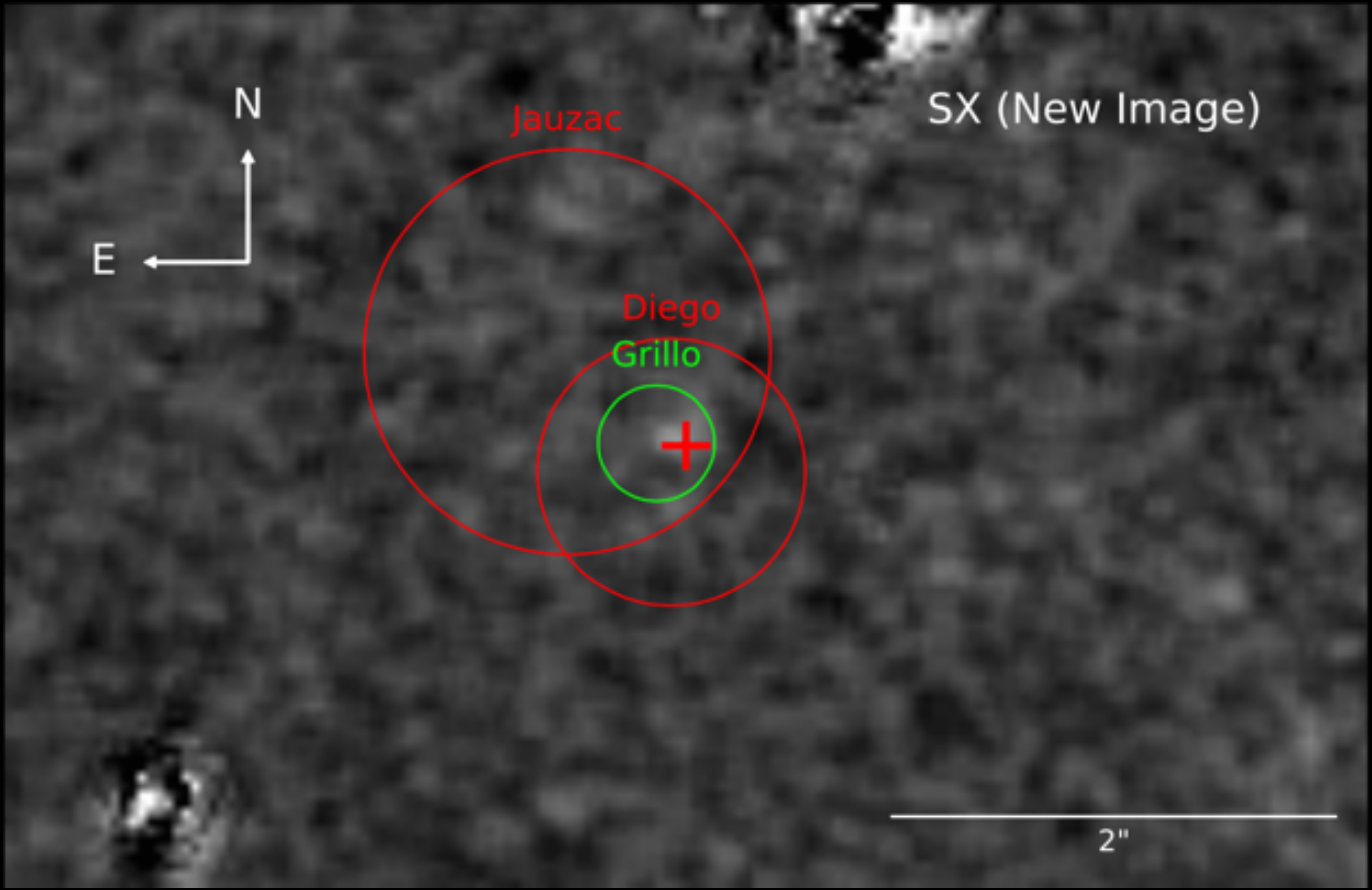


Magnification and delay



[Kelly et al. 2016]

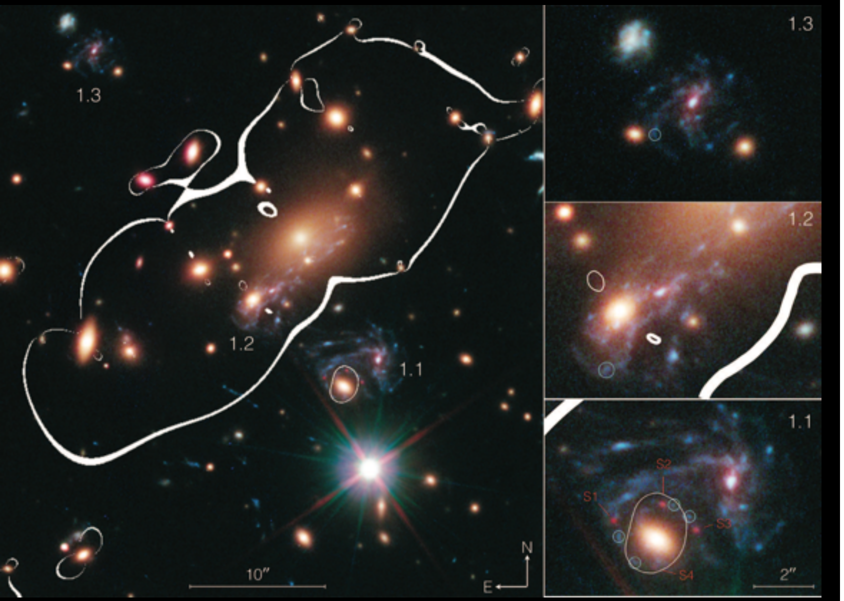
Spot on!

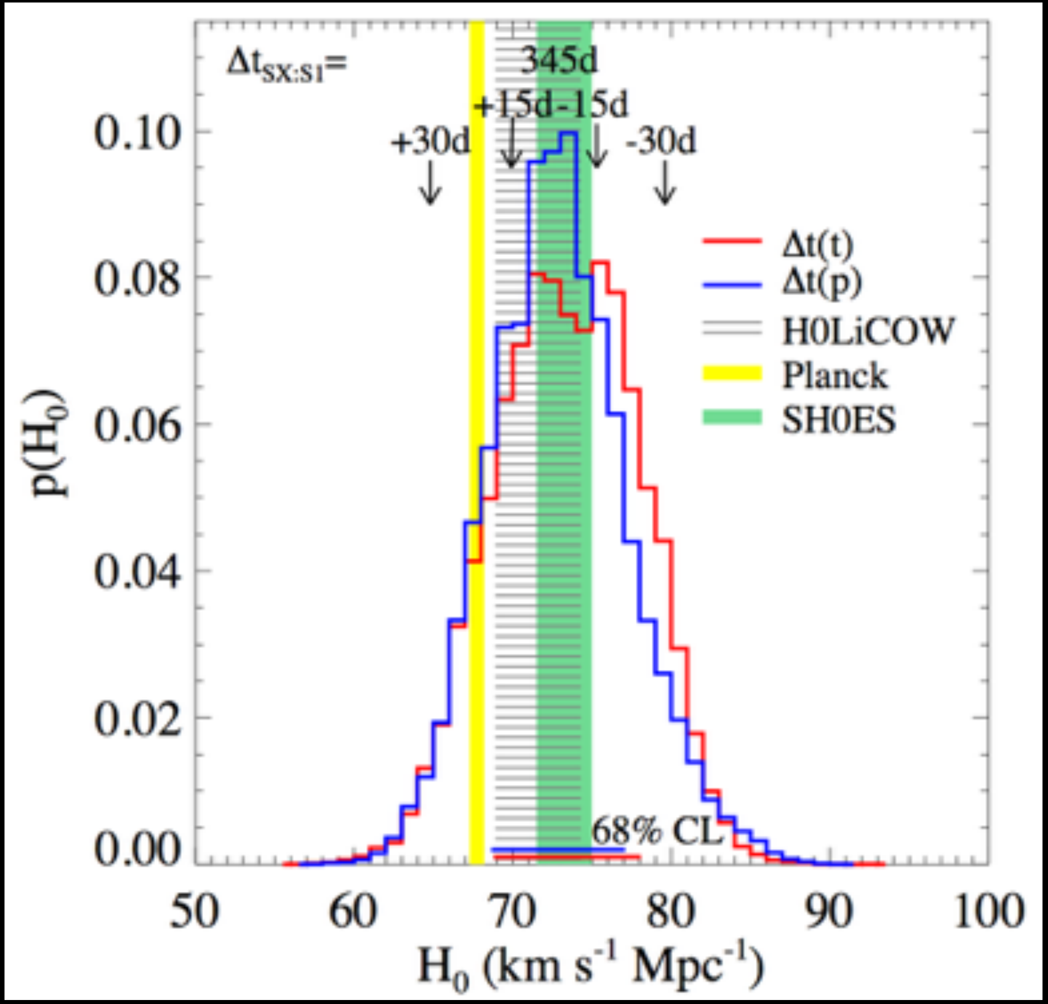


[Kelly et al. 2016]

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]

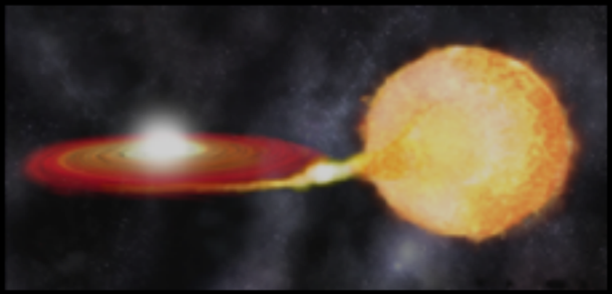
Cosmic Fireworks Première:
Unravelling Enigmas of Type Ia Supernova Progenitor and Cosmology through Strong Lensing

European Research Council
Established by the European Commission

Two longstanding puzzles:

1) What is the progenitor of Type Ia supernova?

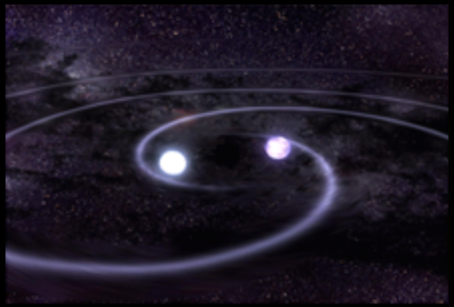
single degenerate



White dwarf (WD) accreting from non-degenerate companion

or

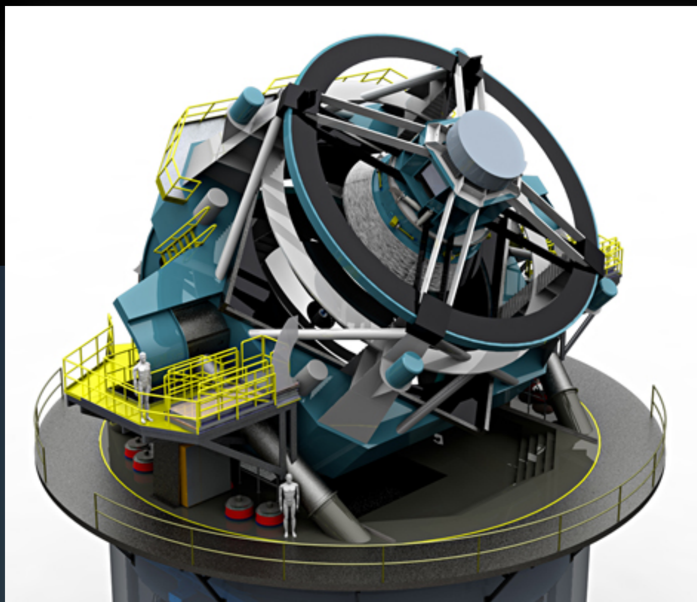
double degenerate



WDs merging

2) What is dark energy?

Large Synoptic Survey Telescope (LSST)



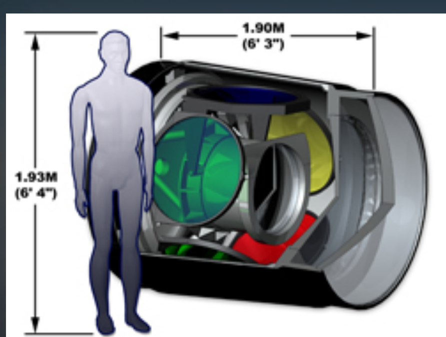
High etendue survey telescope:

- **6.7m effective aperture**
- **10 sq degree field**
- **24 mag in 30 seconds**

Visible sky mapped **every few nights**

Cerro Pachon, Chile: **0.7” seeing**

Ten year movie of the entire Southern sky



120 Petabytes of data

(1Pb = every book ever published)

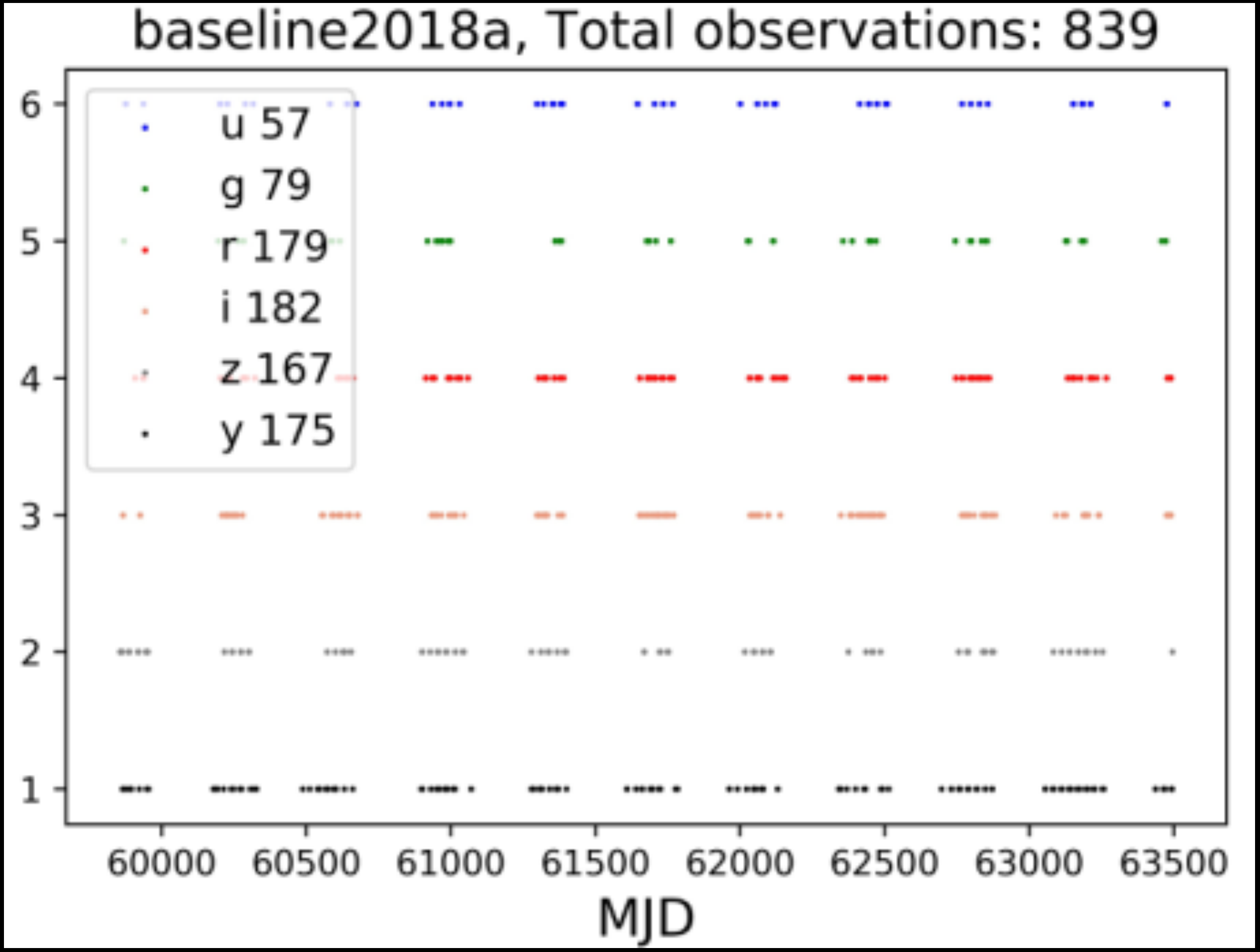
First light ~2020, survey starts ~2022

Expect hundreds of lensed SNe in the 10-year LSST survey

[Oguri & Marshall 2010; Goldstein et al. 2017; Wojtak et al. 2019]

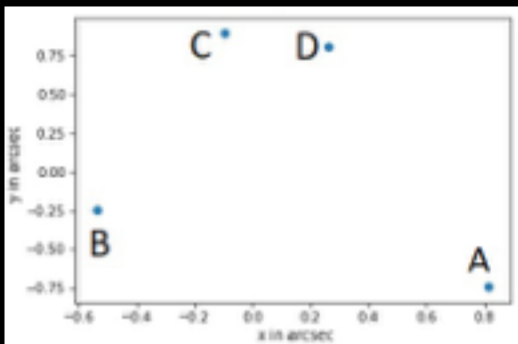
LSST Cadence Strategy for Lensed SNe

- When, where, which filter to observe?
- Affects both number and time delays of SNe



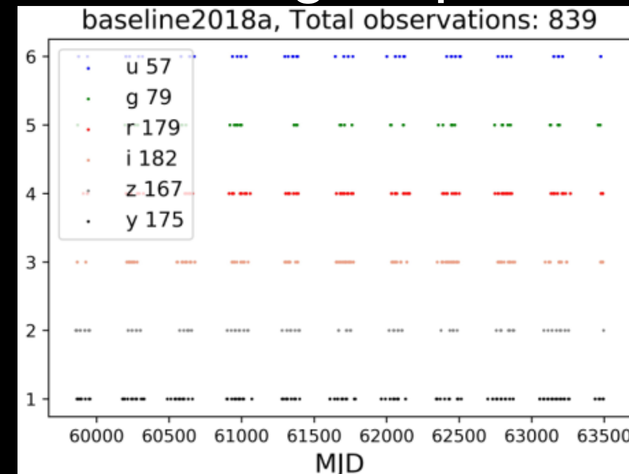
Cadence Strategy for Lensed SNe

mock lens system

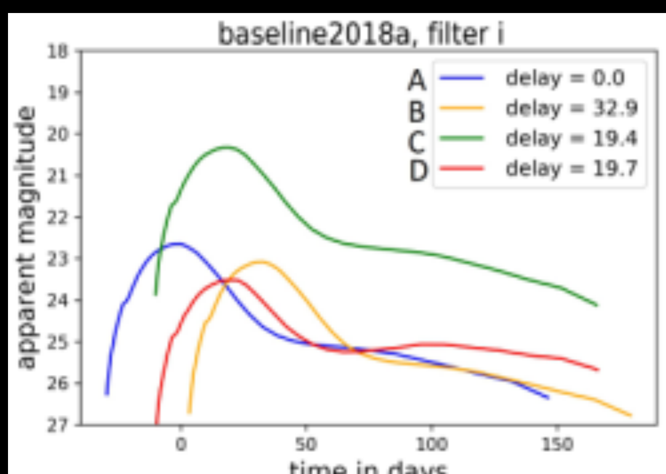


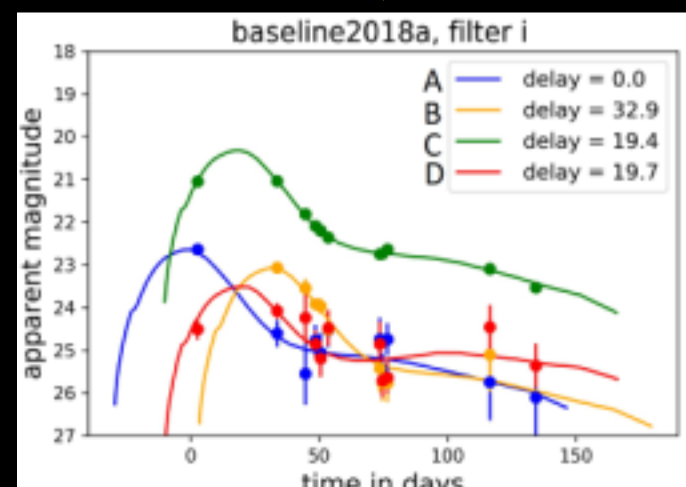
+ W7 supernova explosion model

observing sequence



theoretical light curves

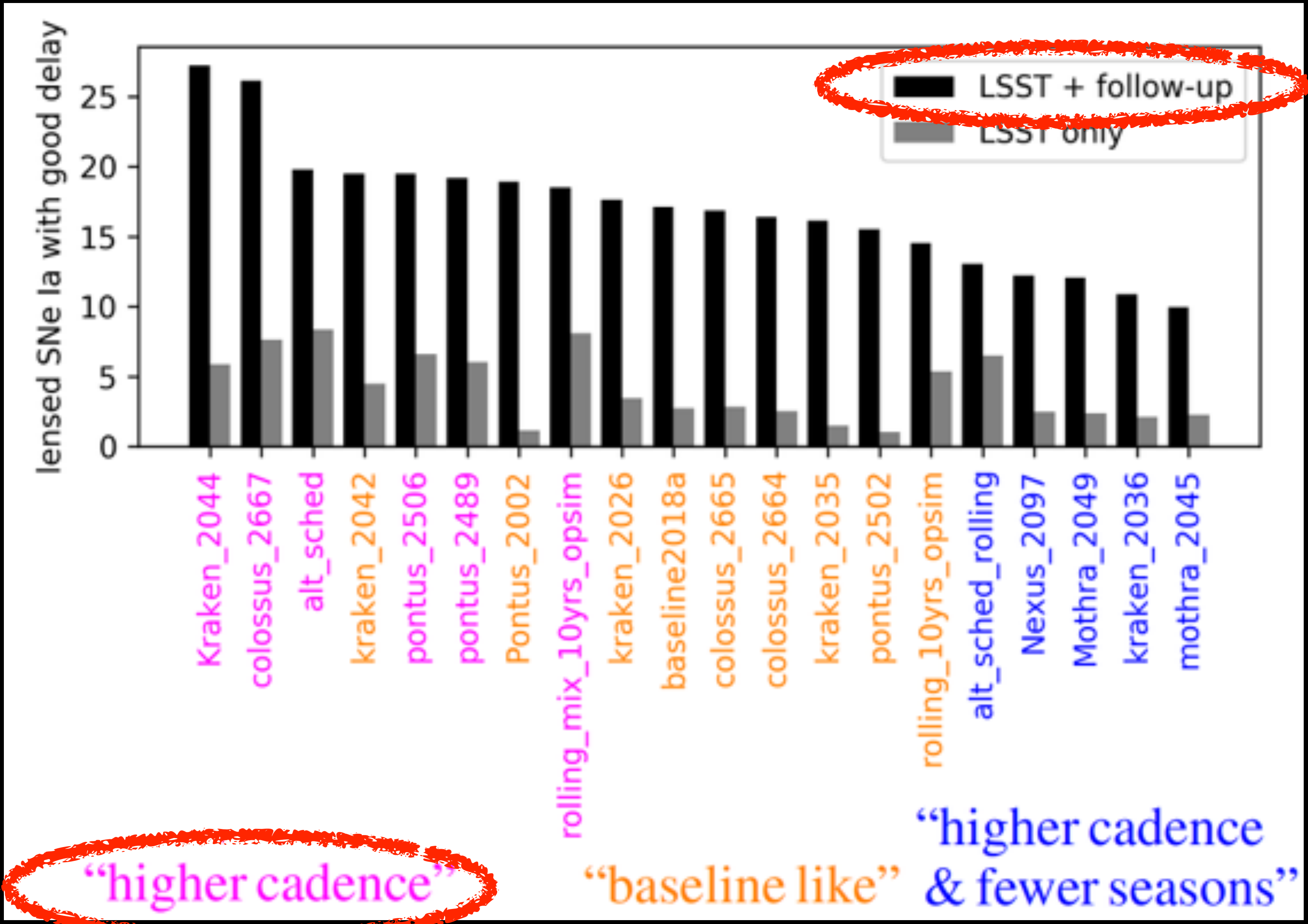




[Huber, Suyu et al. 2019]

Cadence Strategy for Lensed SNe

quantitatively compare LSST observing strategies

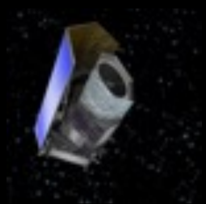


[Huber, Suyu et al. 2019]

Future Prospects

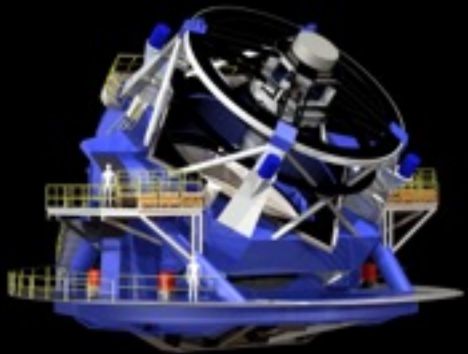
Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid



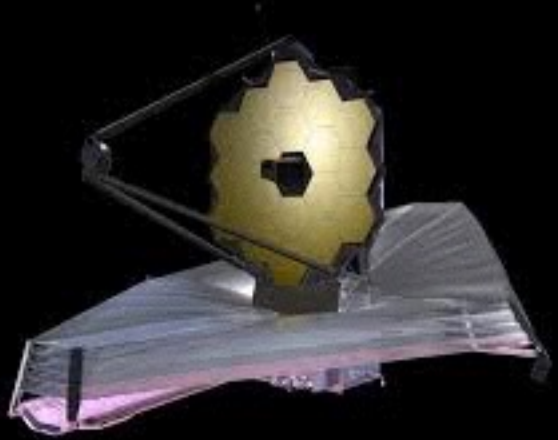
Discovery
Imaging
Spectroscopy

LSST



Discovery
Time delays
Imaging

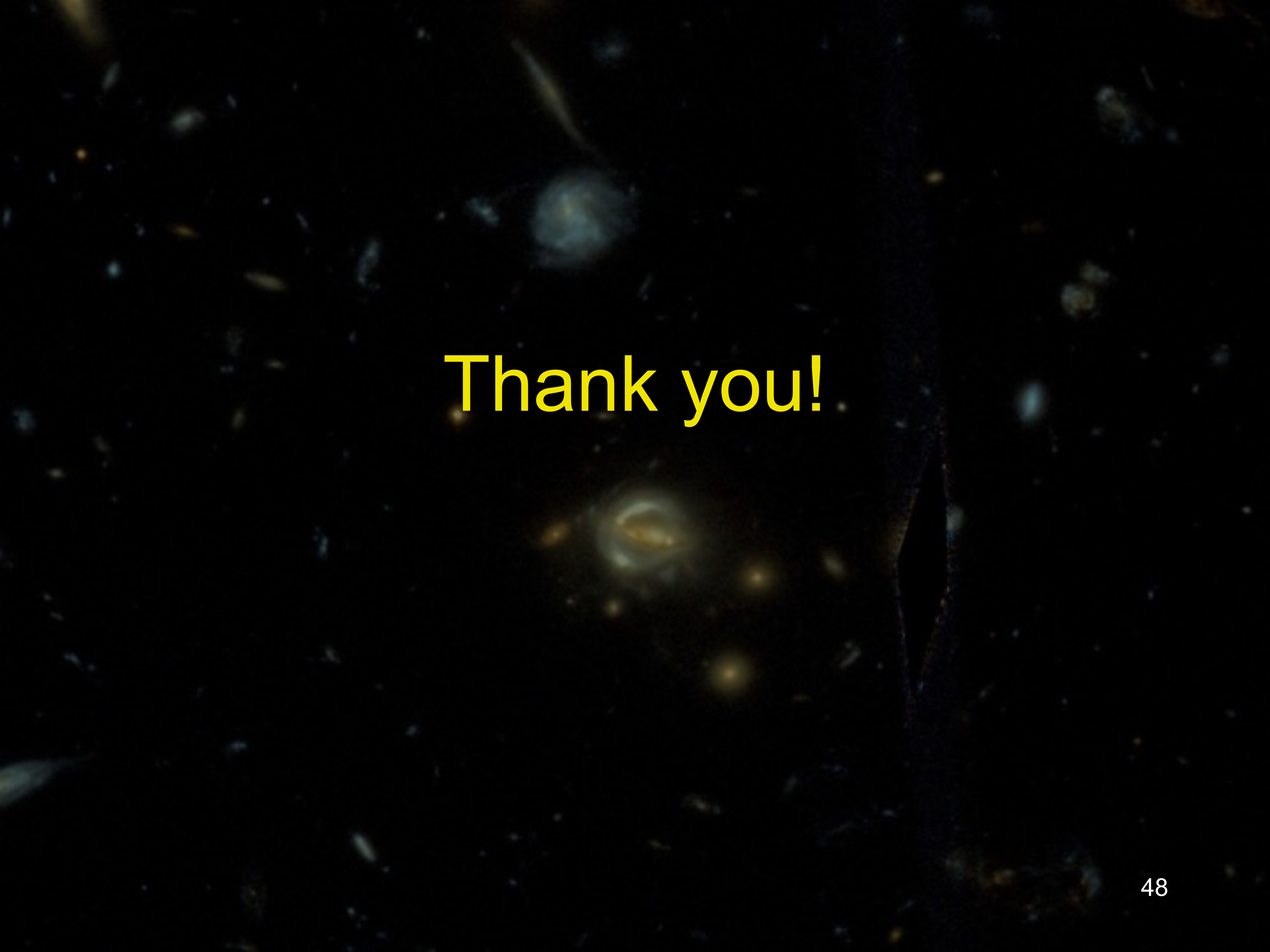
JWST



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 5 lenses in H0LiCOW, $H_0 = 72.5^{+1.8}_{-2.0}$ km/s/Mpc in flat ΛCDM, a 2.6% precision measurement independent of other probes
- Search is underway to find new lenses in imaging surveys including HSC, DES, KiDS, PanSTARRS
- SN Refsdal blind test demonstrated the robustness of our cluster mass modeling approach and software GLEE
- LSST cadence strategies for lensed SNe:
  higher cadence, longer cumulative season length
- Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology


Thank you!