Cosmology with Gravitational Lens Time Delays

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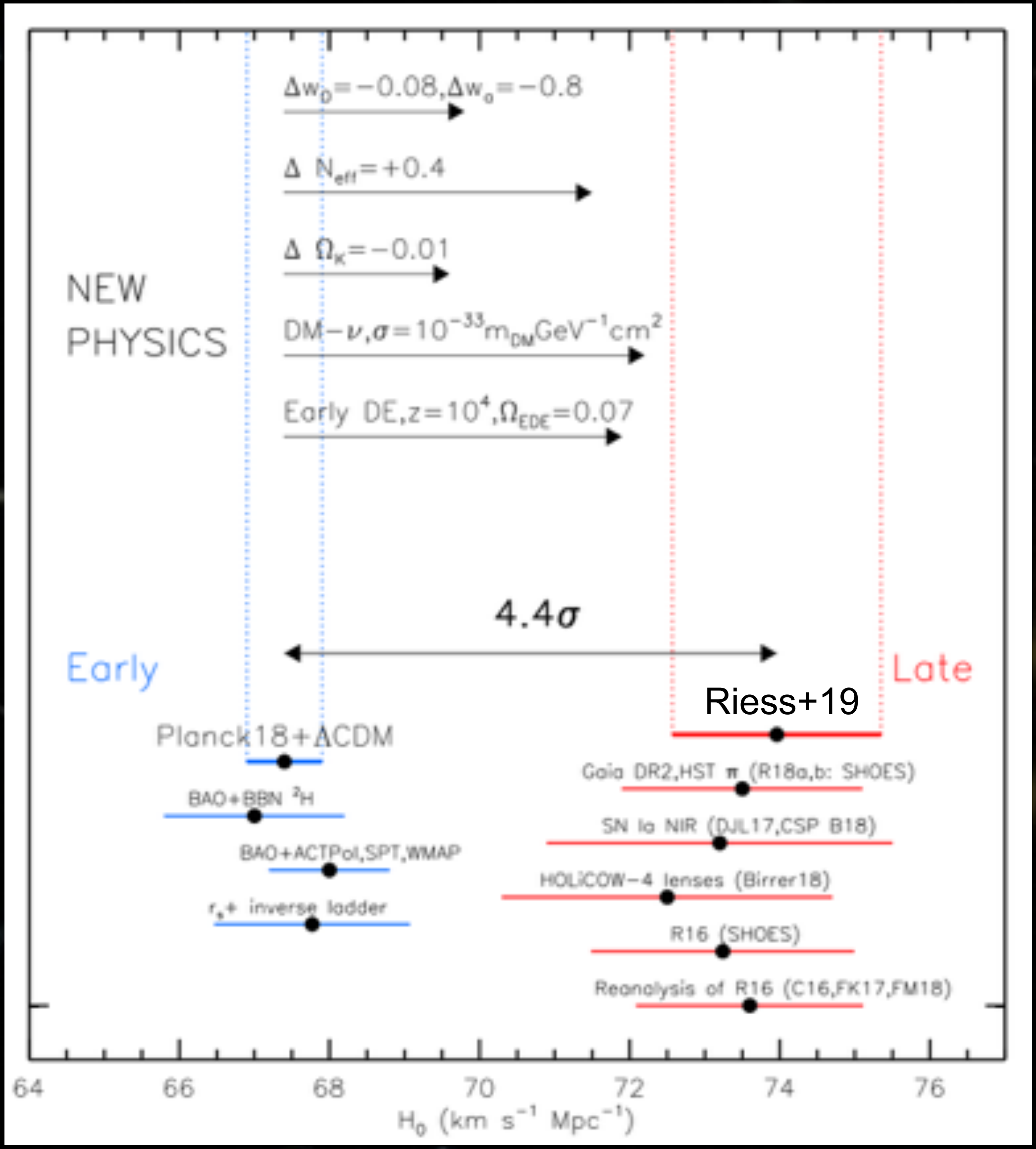
November 18, 2019
Seminar @ Max-Planck-Institut für Kernphysik

Hubble tension



[Riess et al. 2019]

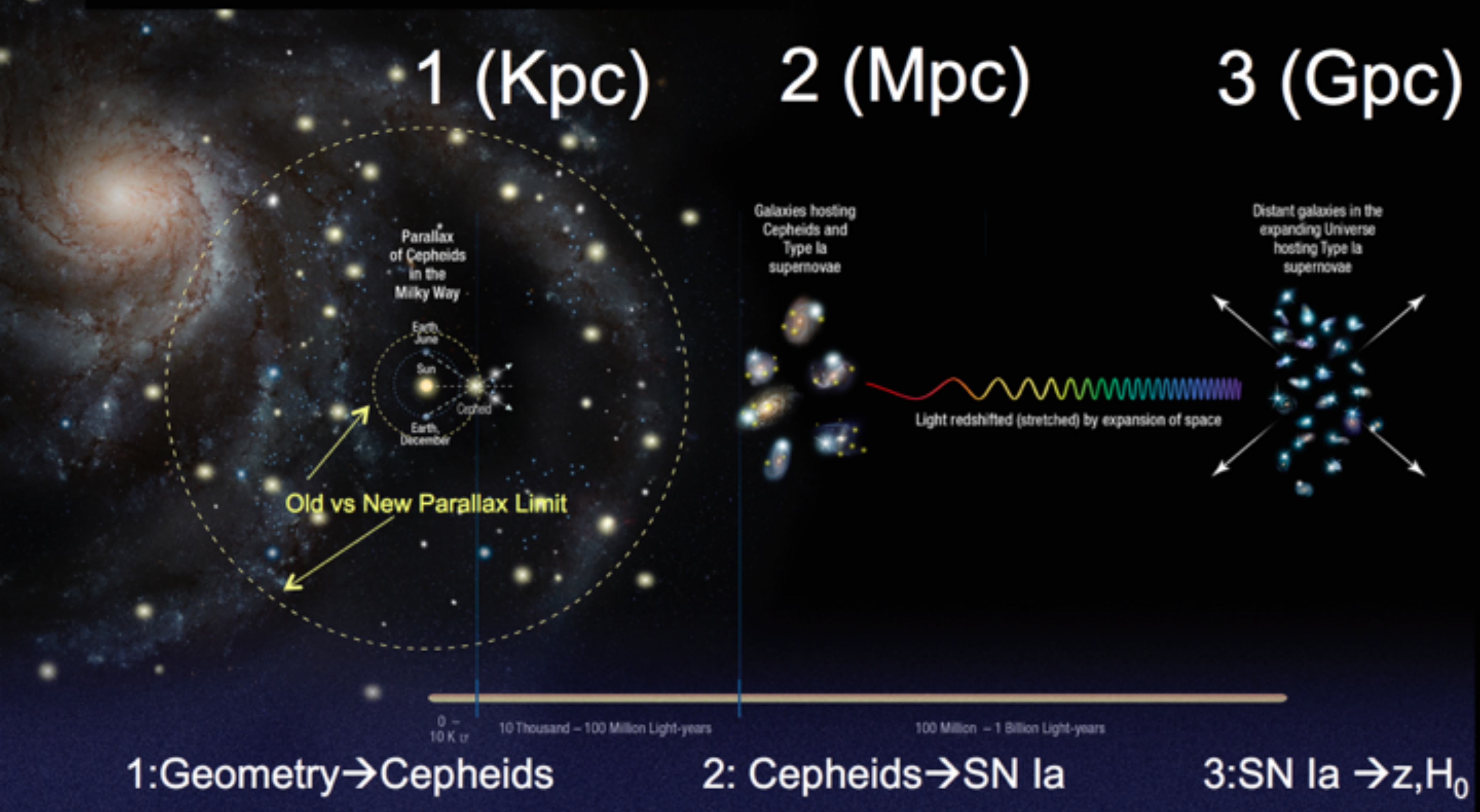
Hubble constant H_0
- age, size of the Universe
- expansion rate: $v = H_0 d$

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

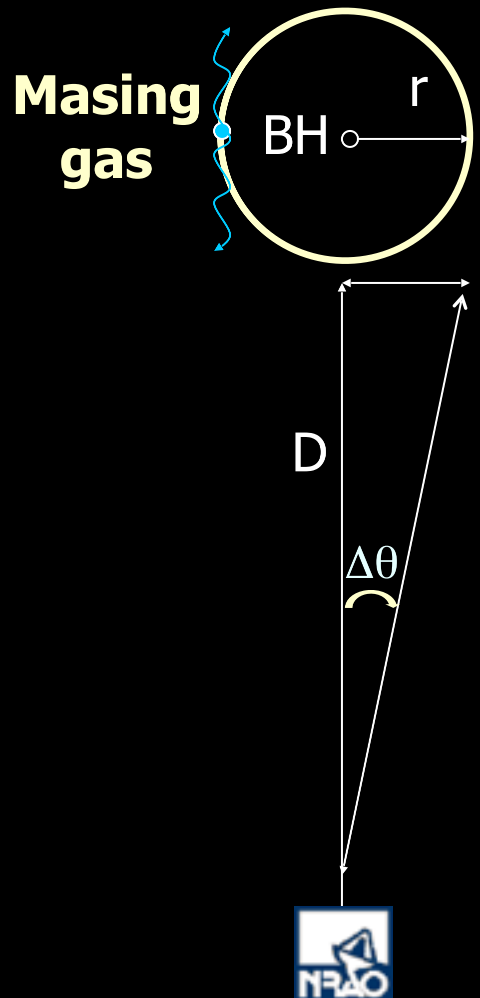
- Carnegie Hubble Program [Freedman et al. 2012]
  - H_0 = 74.3 ± 2.1 km s^{-1} Mpc^{-1} (2.8% uncertainty)

- 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)

- 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
  - H_0 = 69.8 ± 0.8 (stat) ± 1.7 (sys) km s^{-1} Mpc^{-1} [Freedman et al. 2019]

Megamasers

Direct distance measurement without any calibration on distance ladder



1. Distance : $D = r / \Delta\theta$ (for $D >> r$)

2. Gravitational acceleration in a circular orbit :

$a = V_0^2 / r \Rightarrow r = V_0^2 / a$

$$D = V_0^2 / a\, \Delta\theta$$

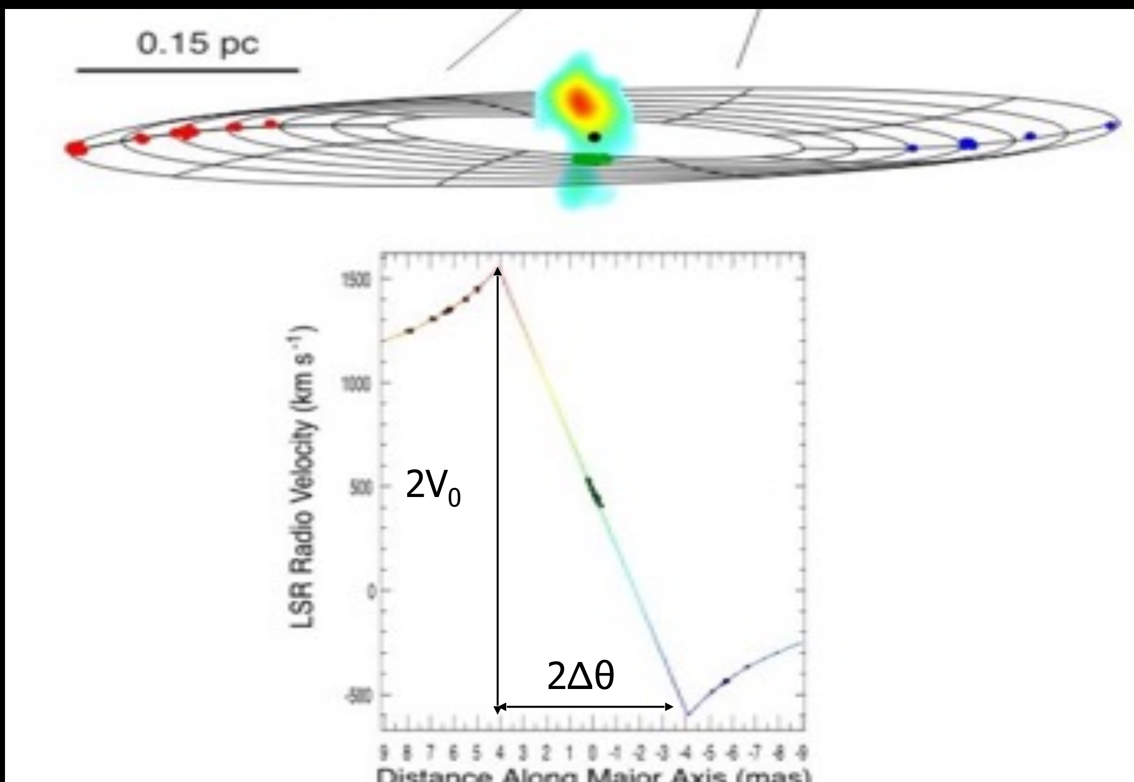
$$D = V_0^2 \sin i / a\, \Delta\theta$$

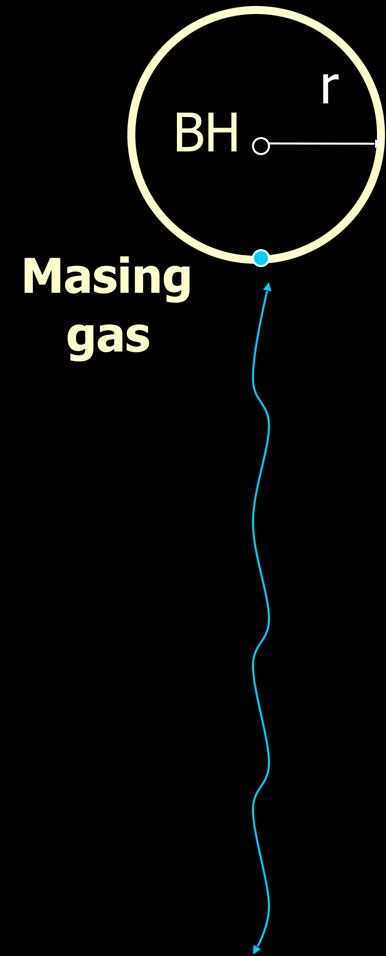
[slide material courtesy of C.-Y. Kuo]

Megamasers

$$D = V_0^2 \sin i \,/\, a\,\Delta\theta$$

How to measure V_0, $\Delta\theta$, a and i?





[slide material courtesy of C.-Y. Kuo]

Megamaser Cosmology Project

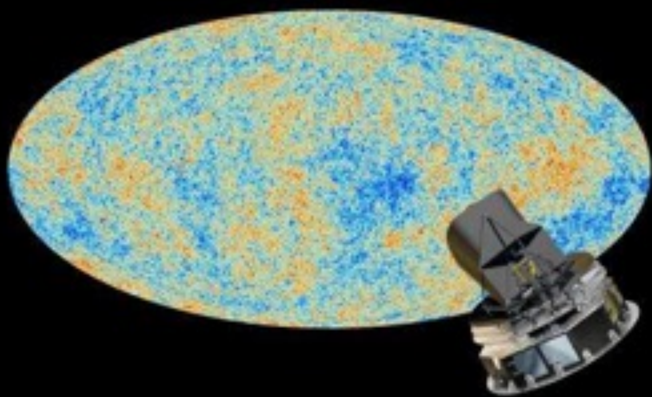
$$H_0 = 74.8 \pm 3.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

	Distance (Mpc)	H_0 (km s^{-1} Mpc^{-1})
UGC 3789	53	66.2 ± 6.3
CGCG 074-064	85	83.2 ± 6.7
NGC 5765b	110	75.5 ± 4.5
NGC 6264	141	74.9 ± 10.8

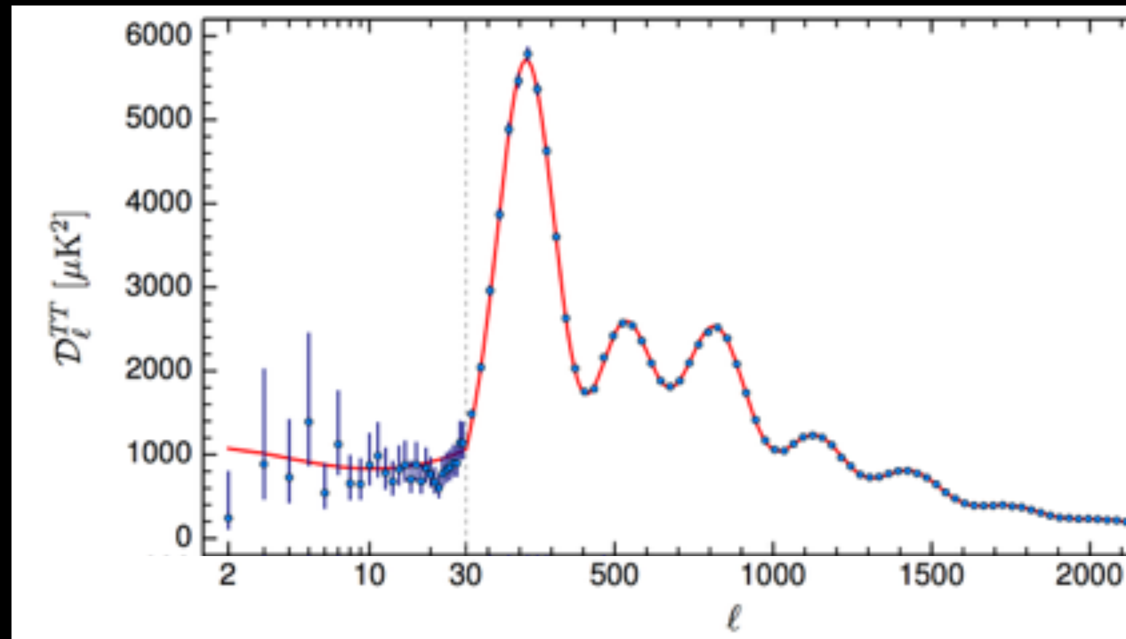
[slide material from Mark Reid's talk at KITP conference in July 2019]

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})

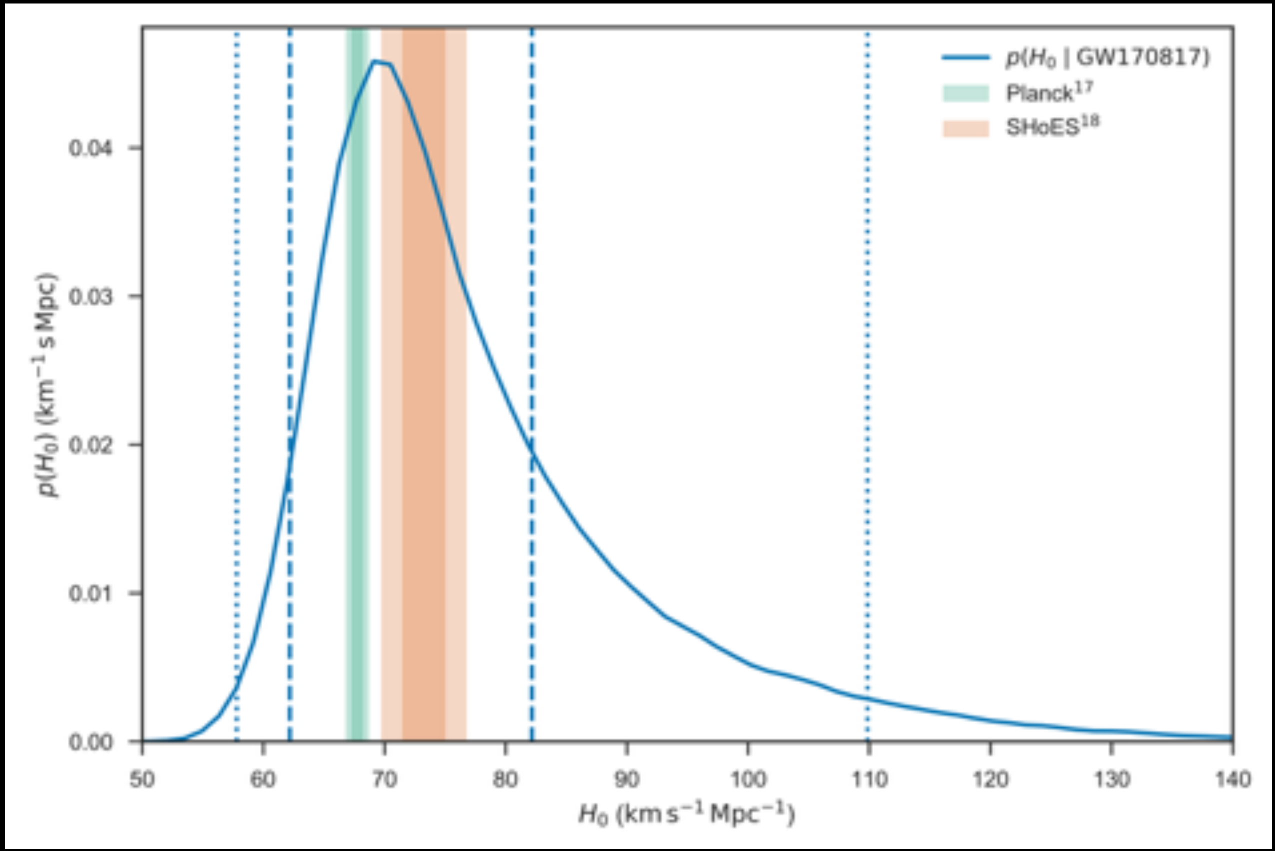
Standard Siren

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

$H_0 = v / D$

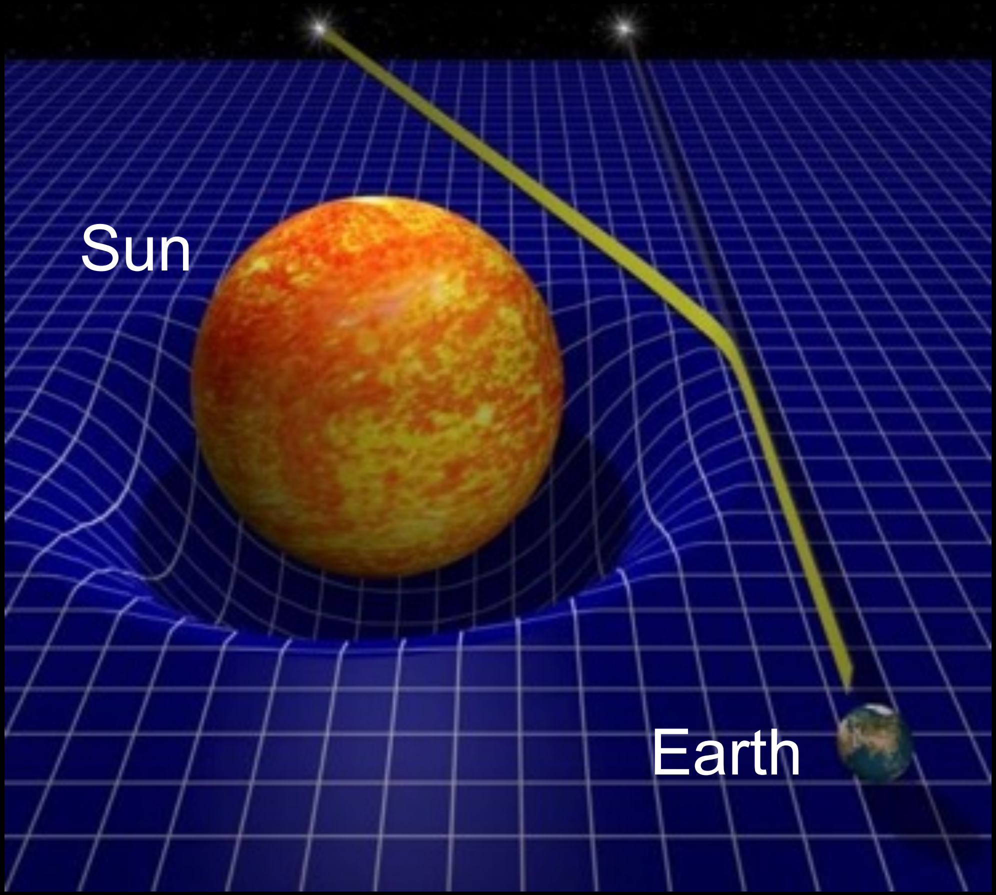
[Image credit: M. Garlick]

GW170817: First measurement of H_0

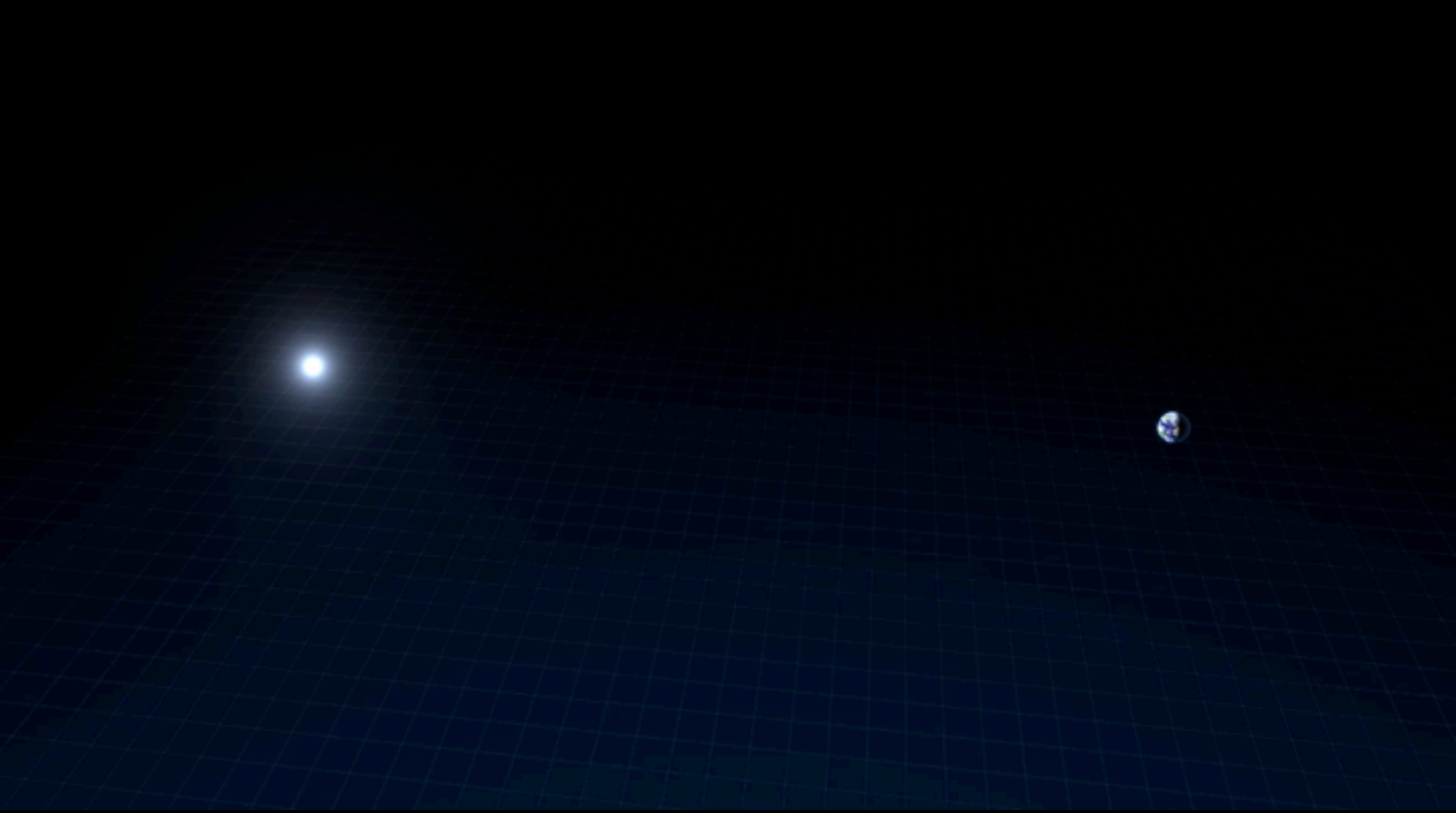


[LIGO, VIRGO, 1M2H, DES, DLT40, LCO, VINROUGE, MASTER collaborations, 2017]

Gravitational Lensing



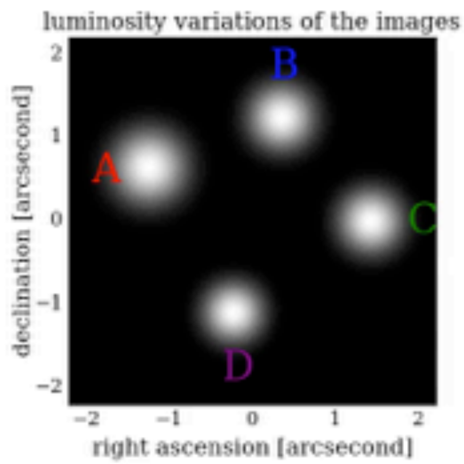
Strong gravitationally lensed quasar

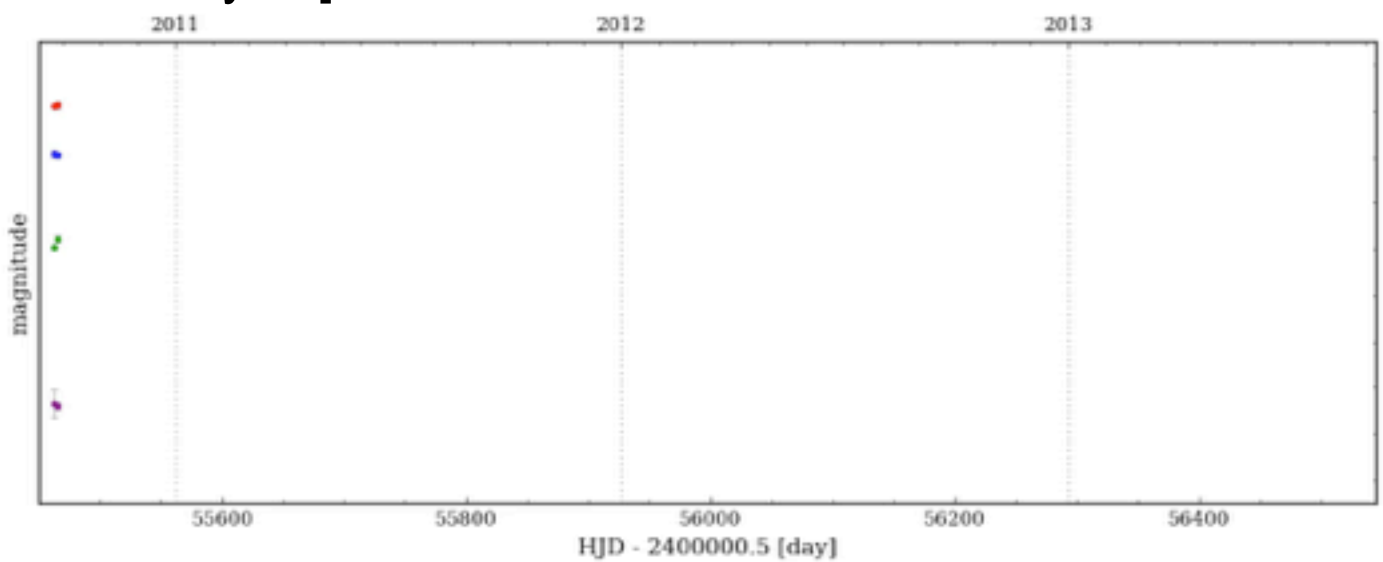


[Credit: ESA/Hubble, NASA]

Cosmology with time delays

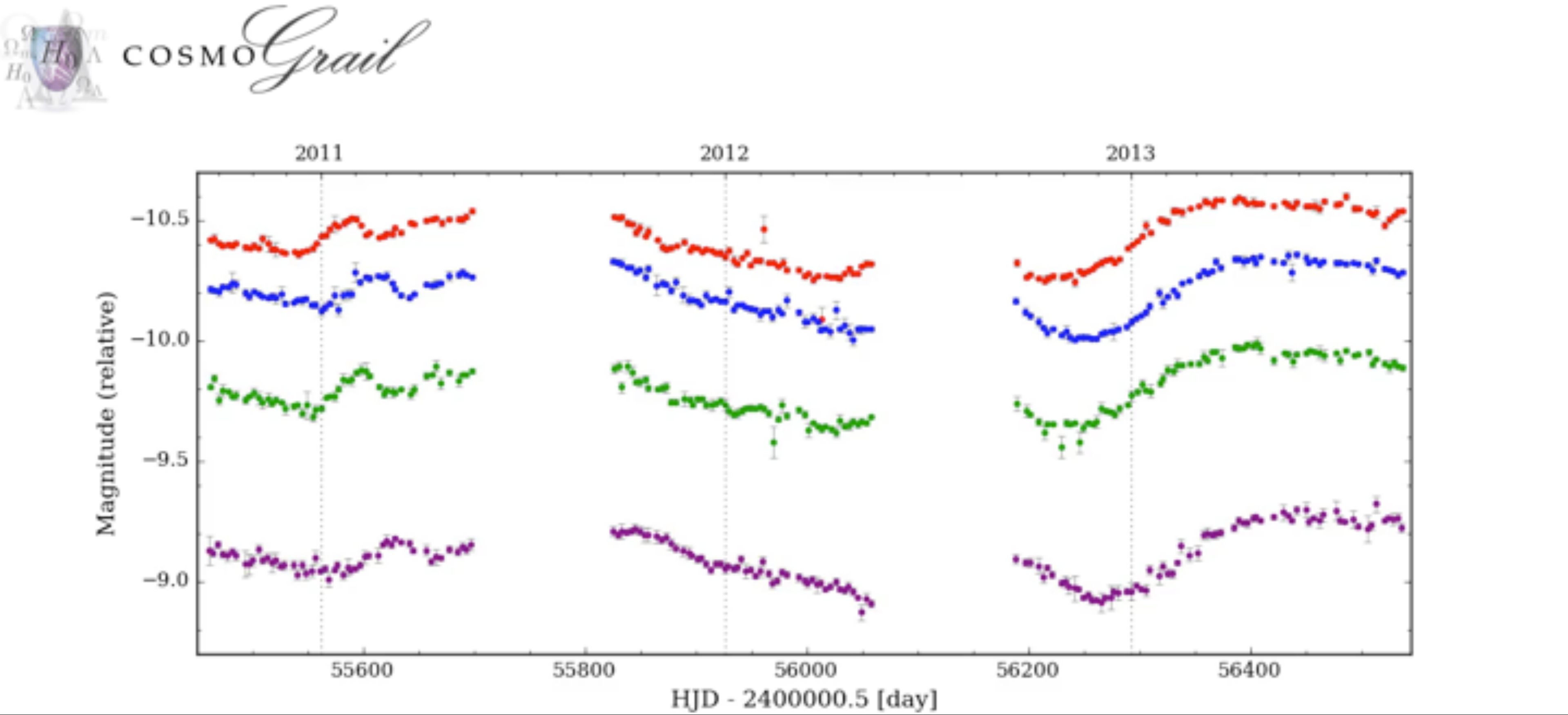
[**COS**mological **MO**nitoring of **GRA**v**I**tational **L**enses;
PI: F. Courbin, G. Meylan]





[Credit: V. Bonvin]

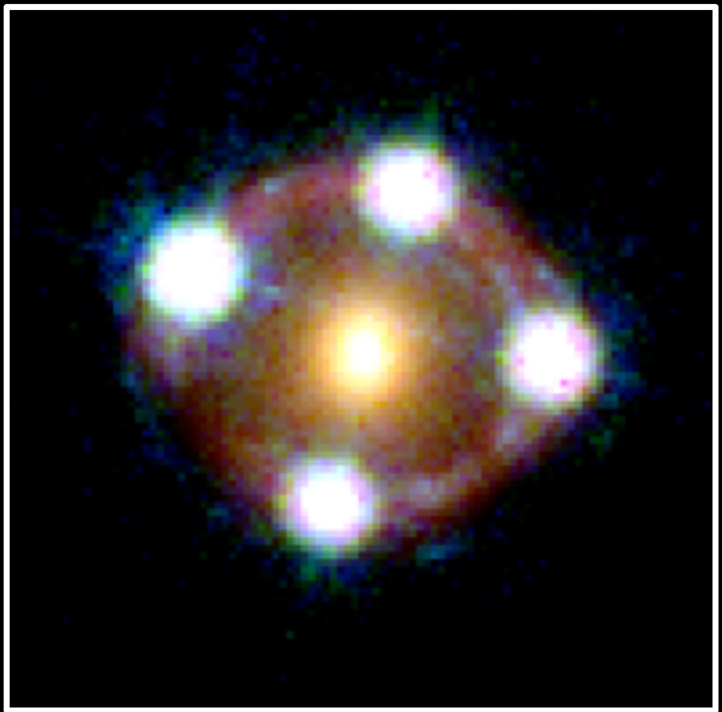
Cosmology with time delays



[Credit: V. Bonvin]

Cosmology with time delays

HE0435-1223



[Suyu et al. 2017]

Time delay:

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

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:

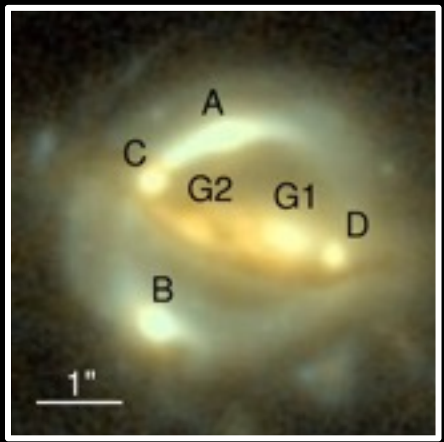
- simple geometry & well-tested physics

- one-step physical measurement of a cosmological distance

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

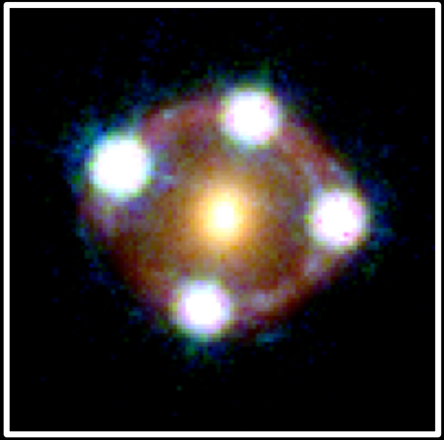
B1608+656



RXJ1131-1231

H_0 to <3.5% precision

HE0435-1223



WFI2033-4723

HE1104-1805

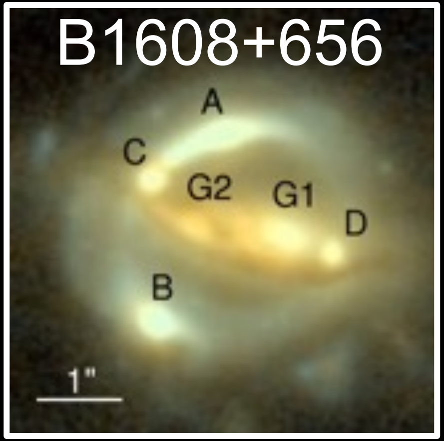
[Suyu et al. 2017]

H0LiCOWers

H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

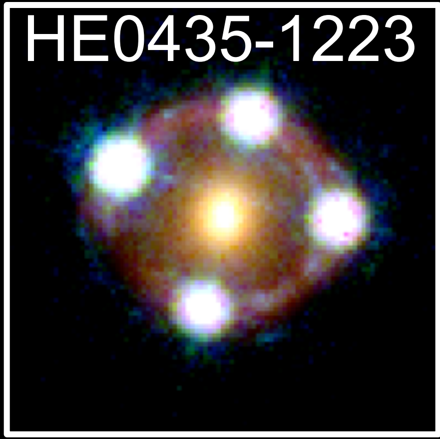
→ Establish time-delay gravitational lenses as one of the best cosmological probes

H0LiCOW latest results



[Suyu et al. 2010]

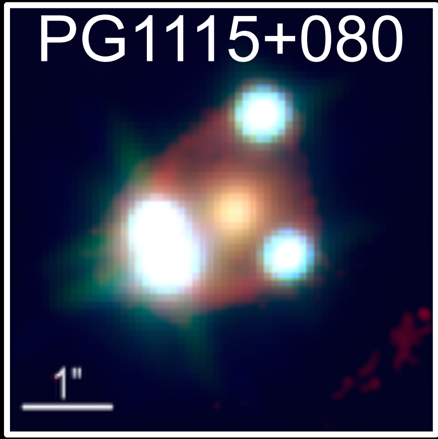
[Suyu et al. 2013, 2014; Tewes et al. 2013]



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

part of extended sample [Birrer et al. 2019]

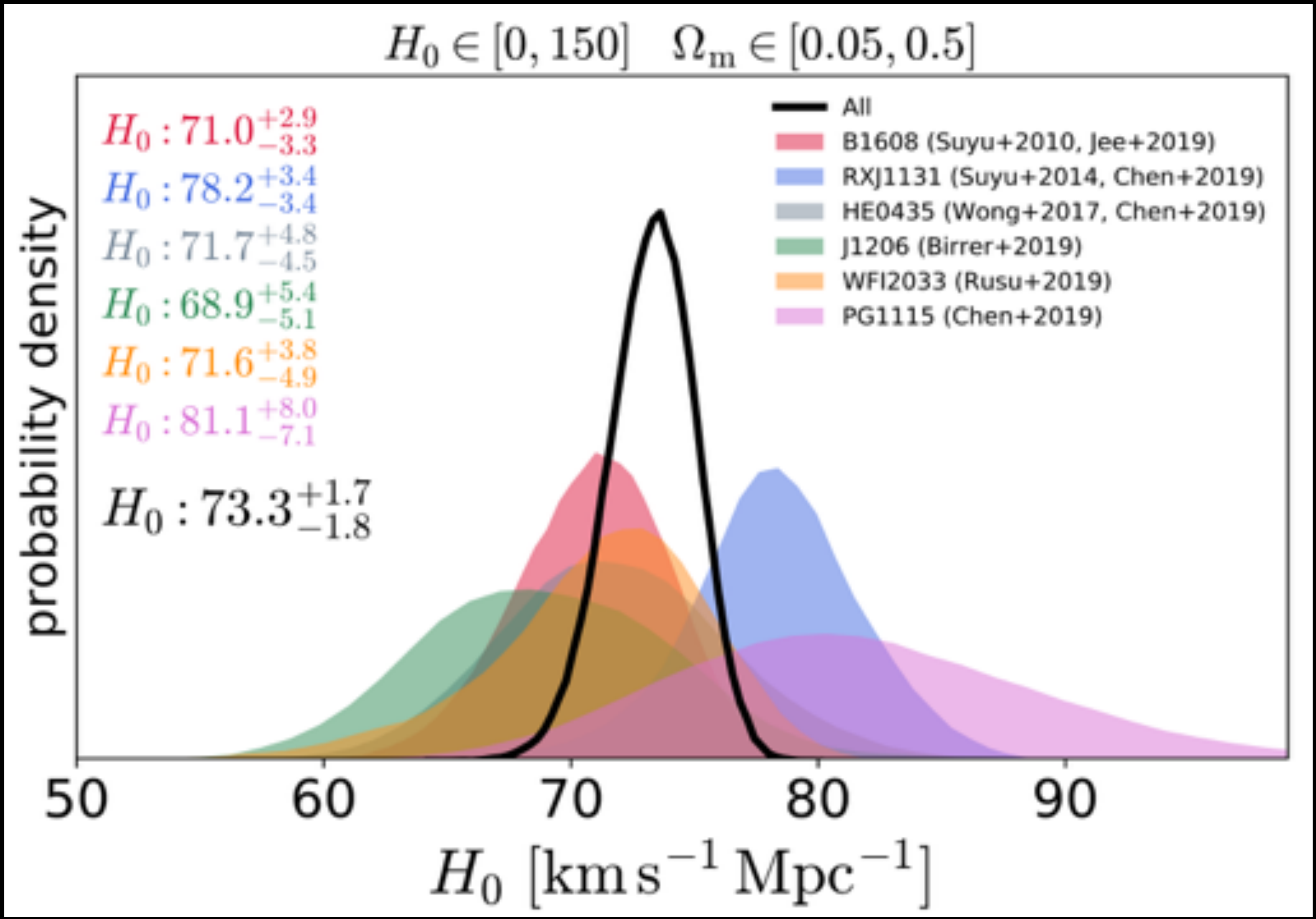
[Bonvin et al. 2019; Sluse et al. 2019; Rusu et al. 2019]



part of Keck AO sample of SHARP program [Chen et al. 2019]

H_0 from 6 strong lenses

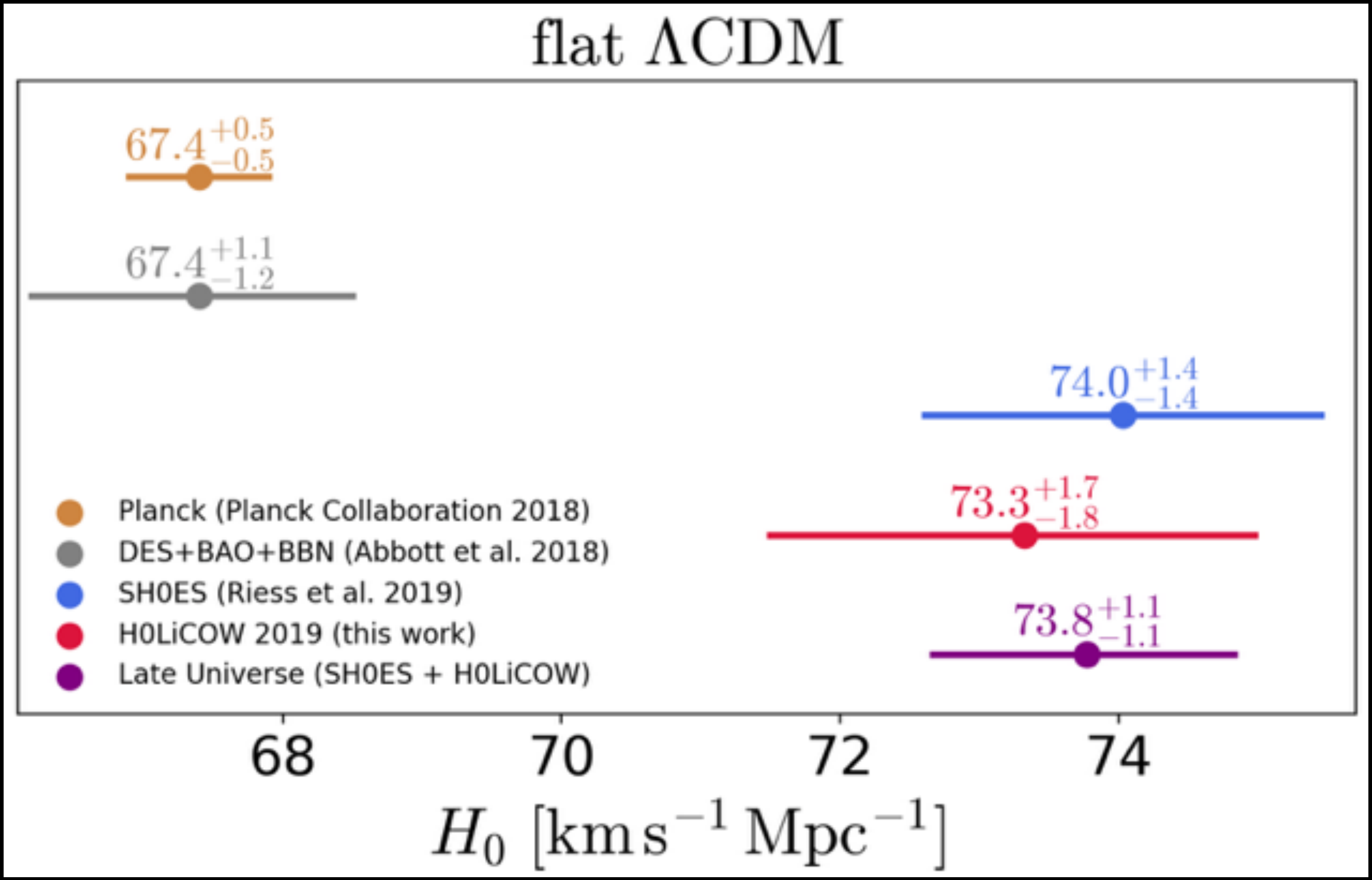
Blind analysis to avoid confirmation bias



H_0 with 2.4% precision in flat ΛCDM

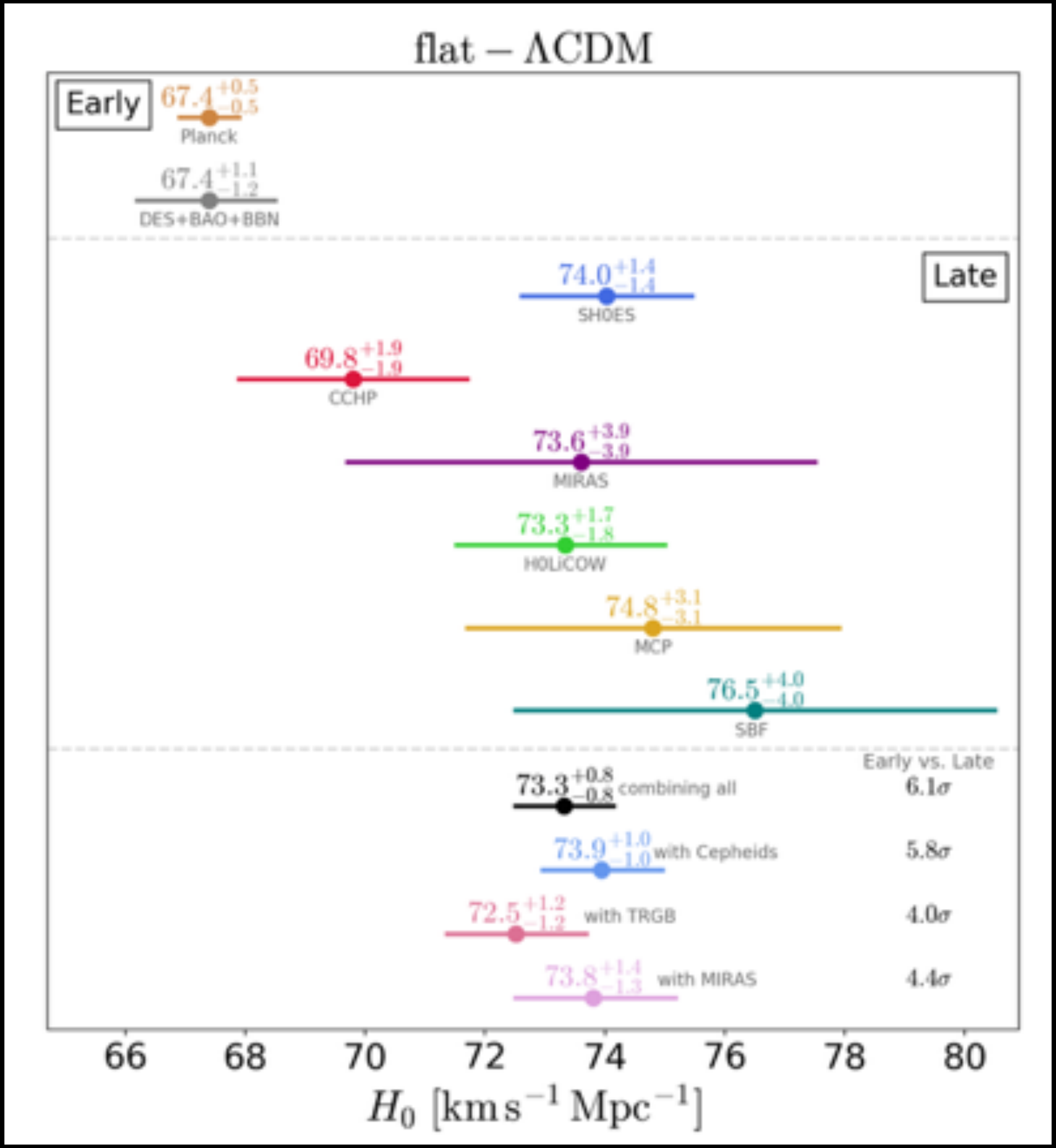
[Wong, Suyu, Chen et al. 2019]

H_0 comparison



[Wong, Suyu, Chen et al. 2019]

Tensions between Early and Late Universe



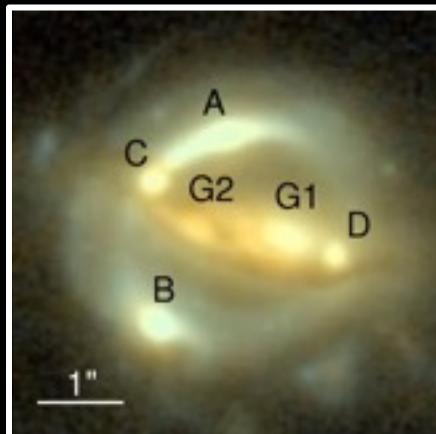
[credit: V. Bonvin]

[Verde, Treu, Riess 2019]

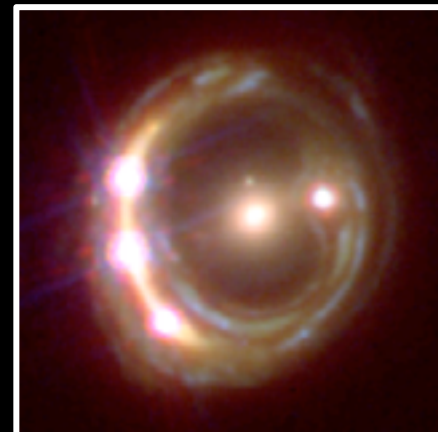
Calibrating SNe distances with $D_{\Delta t}$

[Suyu et al. 2010]

B1608+656



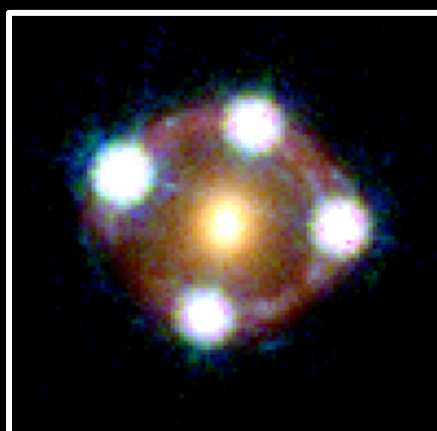
RXJ1131-1231



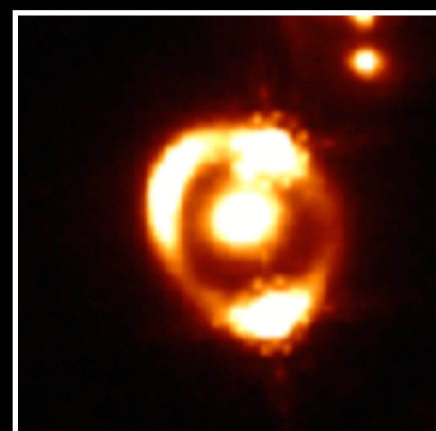
[Suyu et al. 2013, 2014; Tewes et al. 2013]

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

HE0435-1223



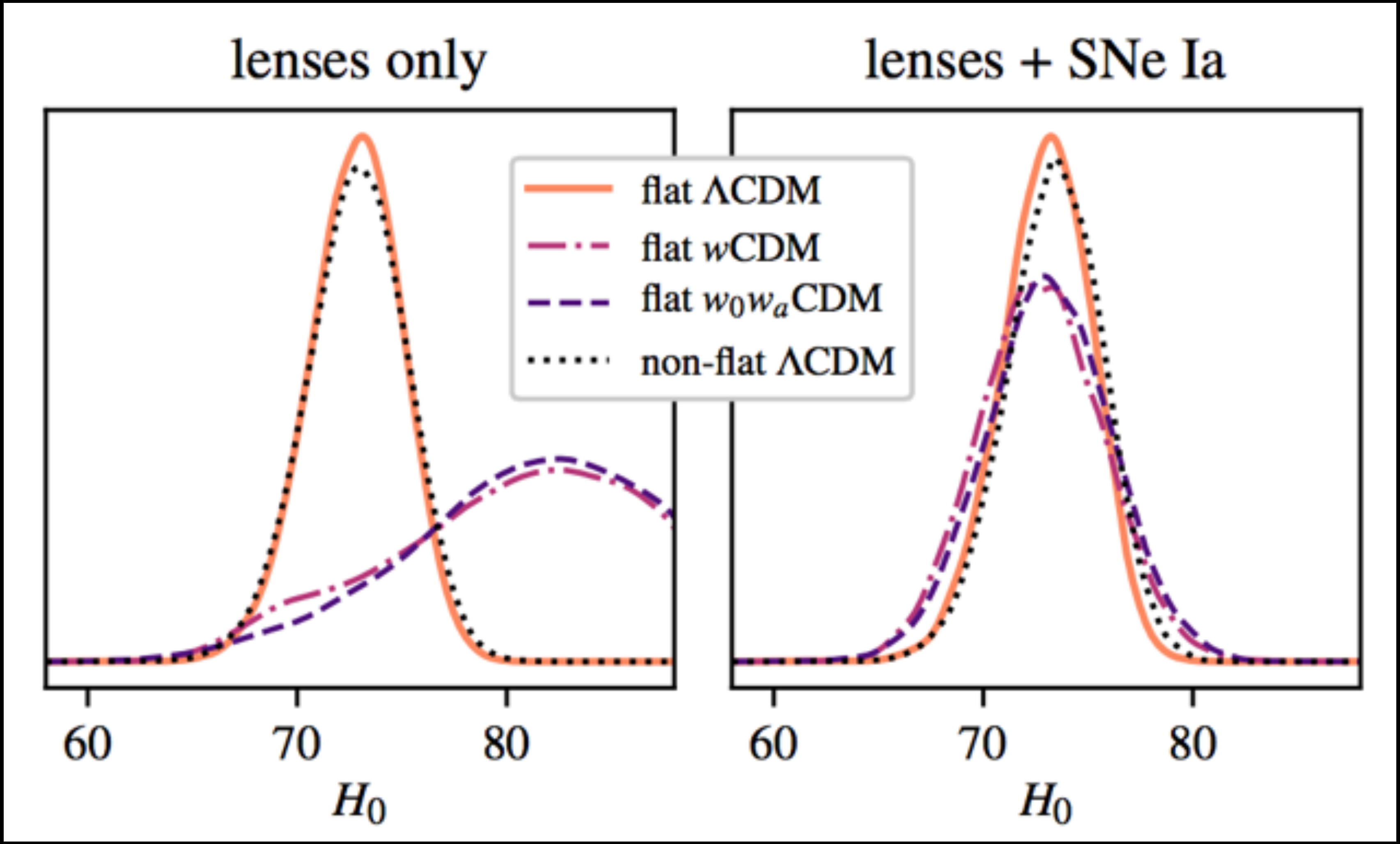
SDSS1206+4332



part of extended sample

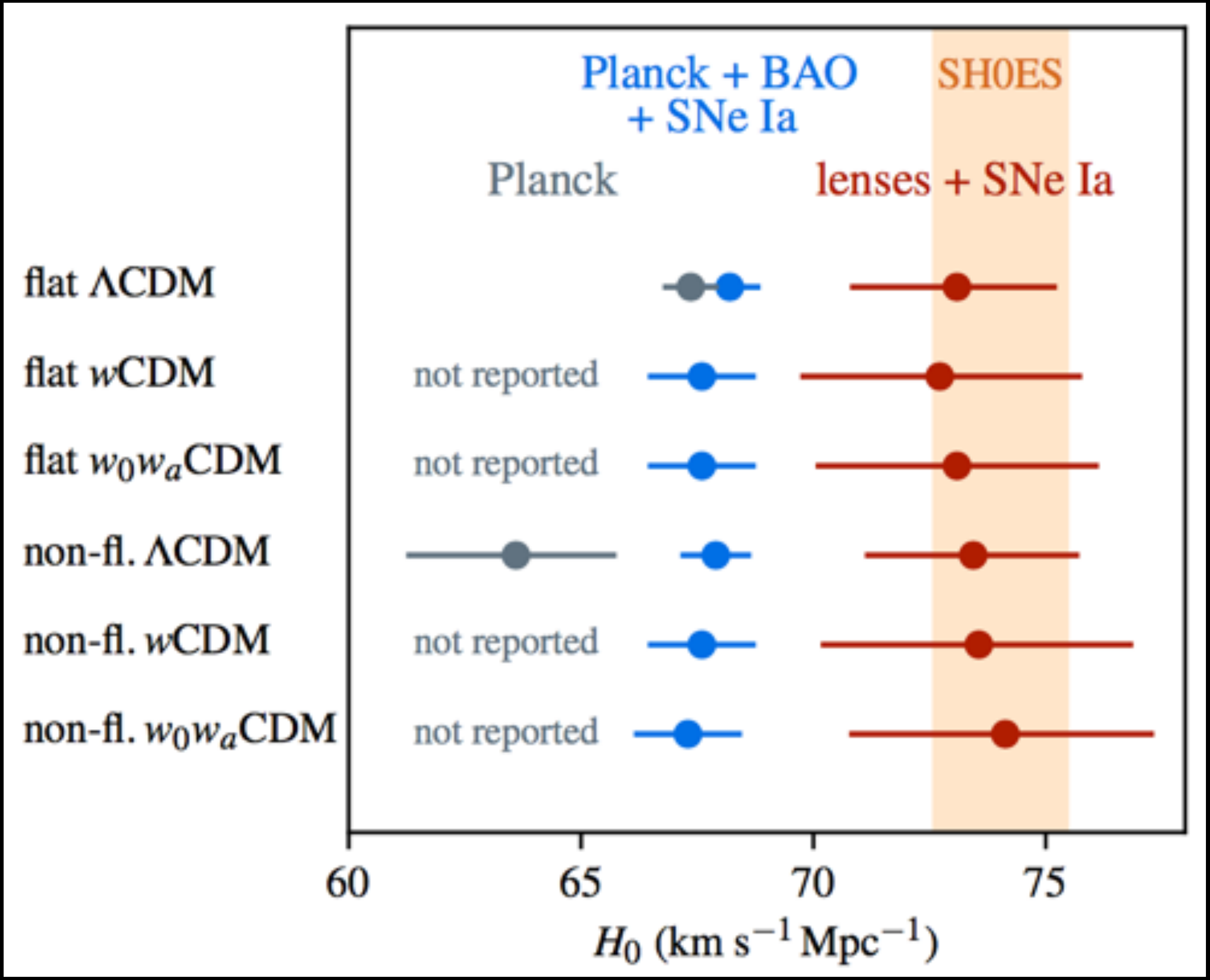
[Birrer, Treu Rusu et al. 2018]

Reduced cosmological dependence



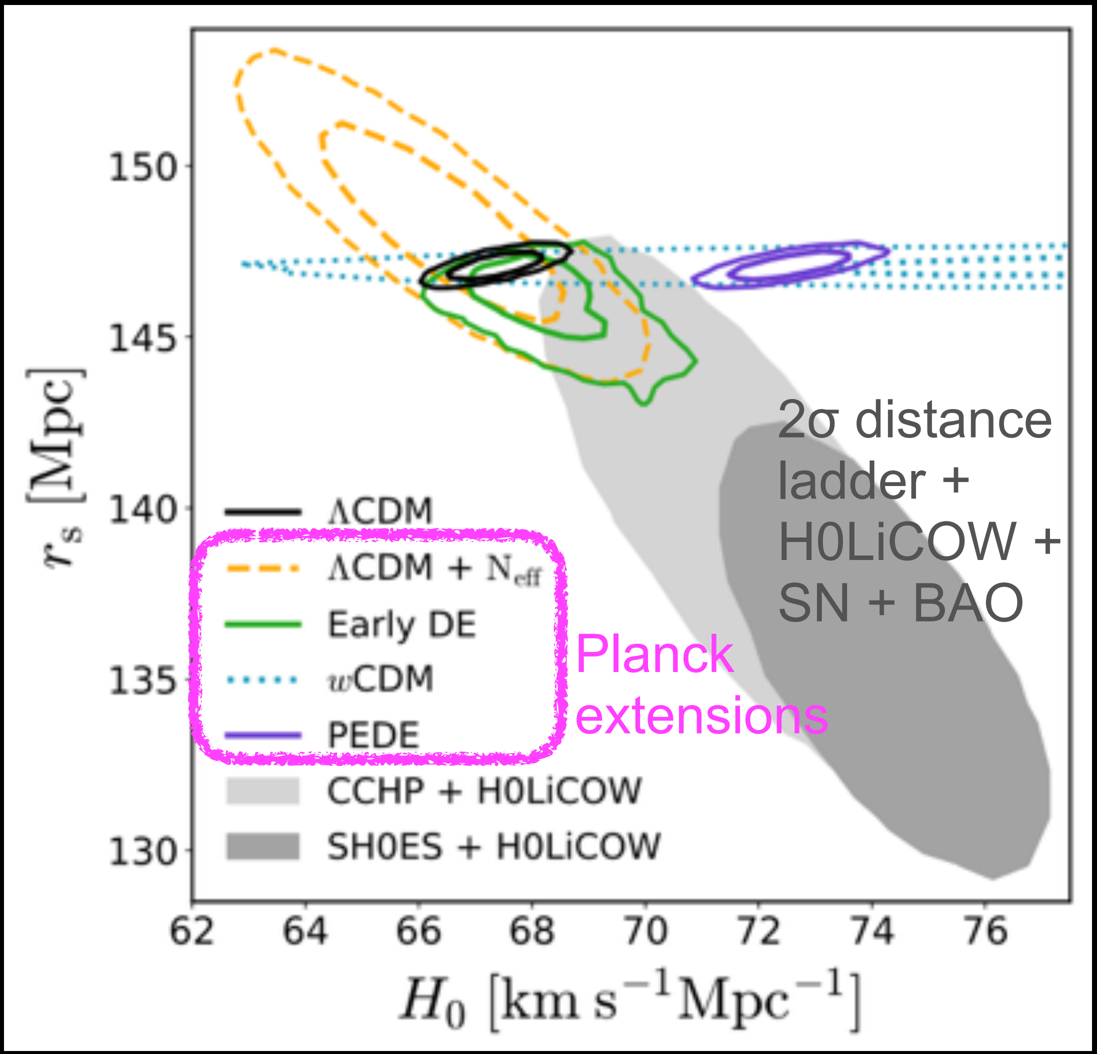
[Taubenberger, Suyu, Komatsu et al. 2019]

Reduced cosmological dependence



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

Solution: shorter sound horizon

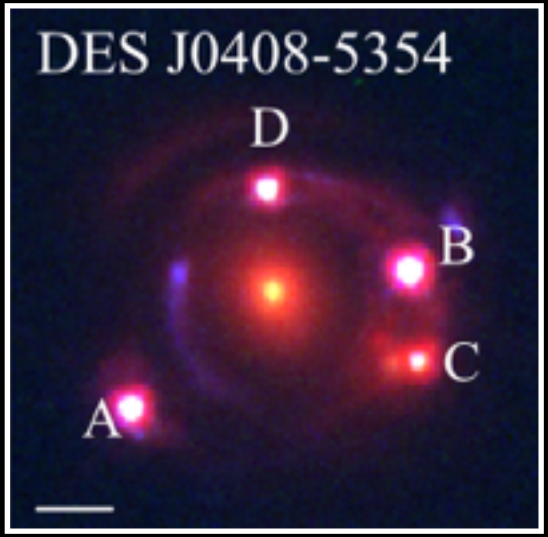


[Arendse, Wojtak, Agnello et al. 2019]

Make sound horizon shorter

- new relativistic particle?
- early dark energy?

Looking forward

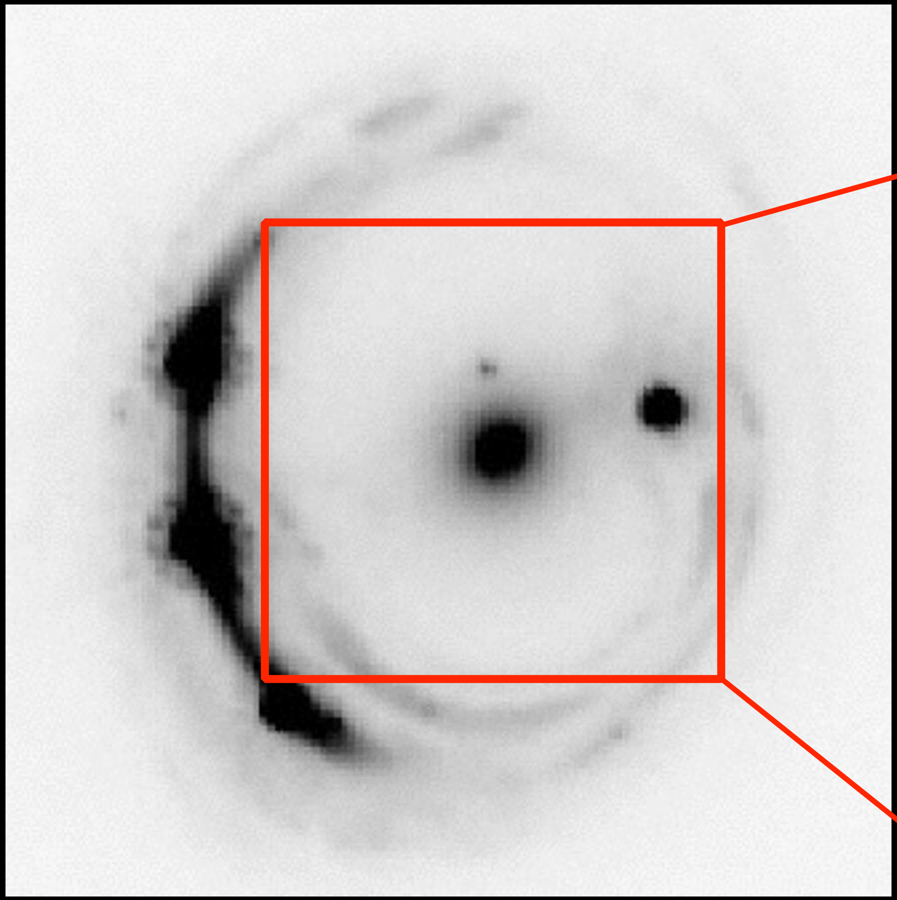


- Part of STRIDES collaboration
  [Treu et al. 2018]
- Blind analysis with two independent lens modeling softwares
  [Shajib et al. 2019ab; Shajib et al. in prep; Yıldırım et al. in prep; Wong et al. in prep]

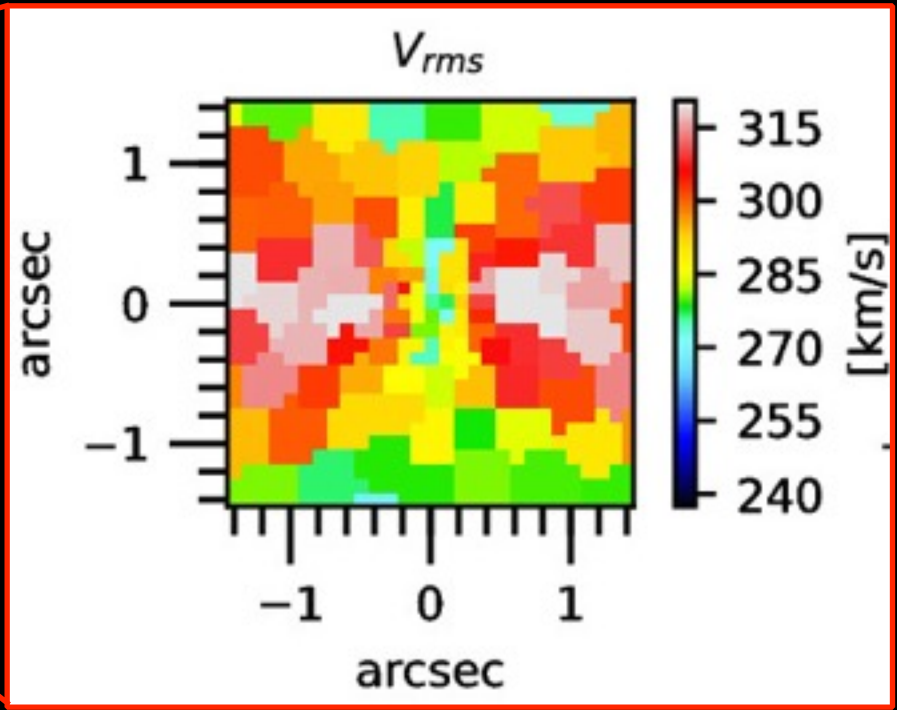
Looking forward

Latest result
➜ Shajib et al. 2019b

Stellar kinematics really helps

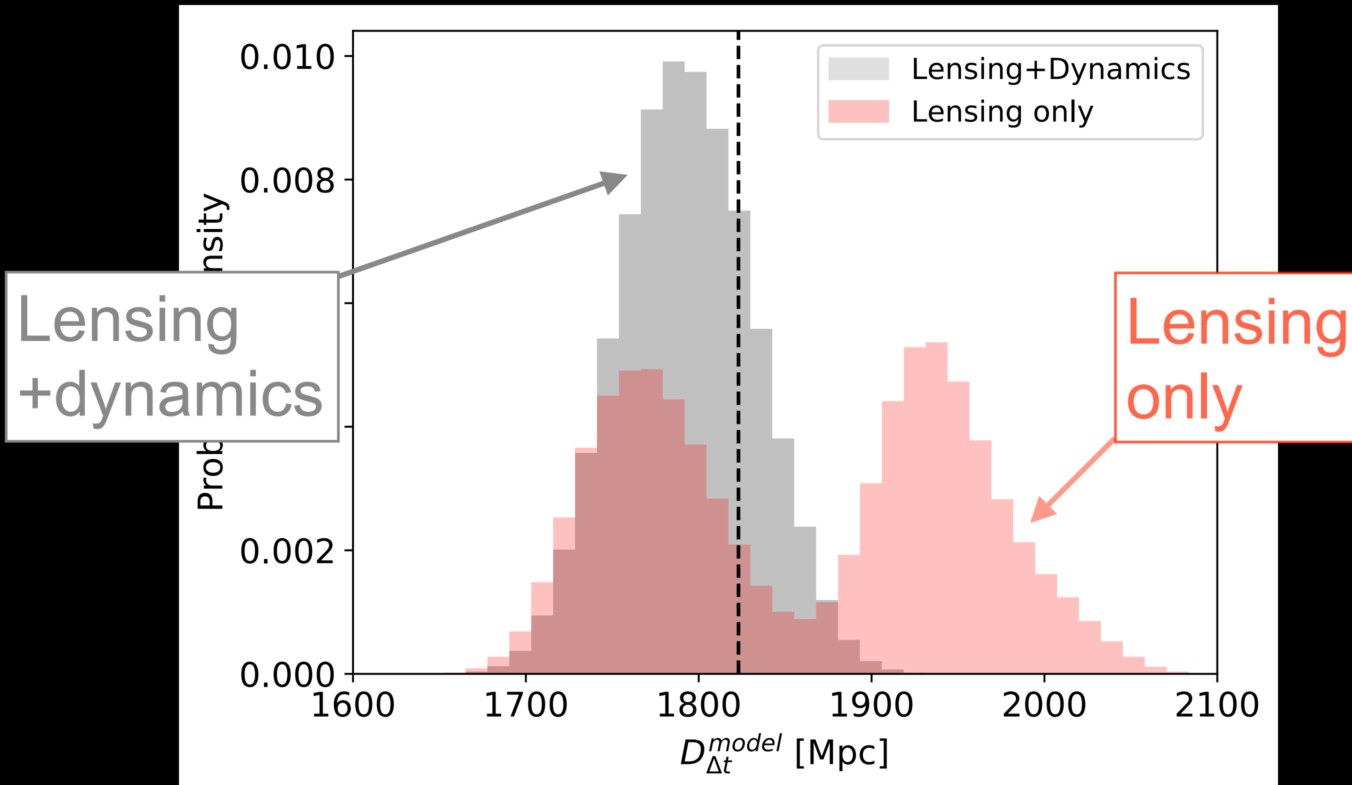


simulated James Webb Space Telescope NIRSpec observations of stellar kinematic map of lens



[Yıldırım, Suyu, Halkola 2019]

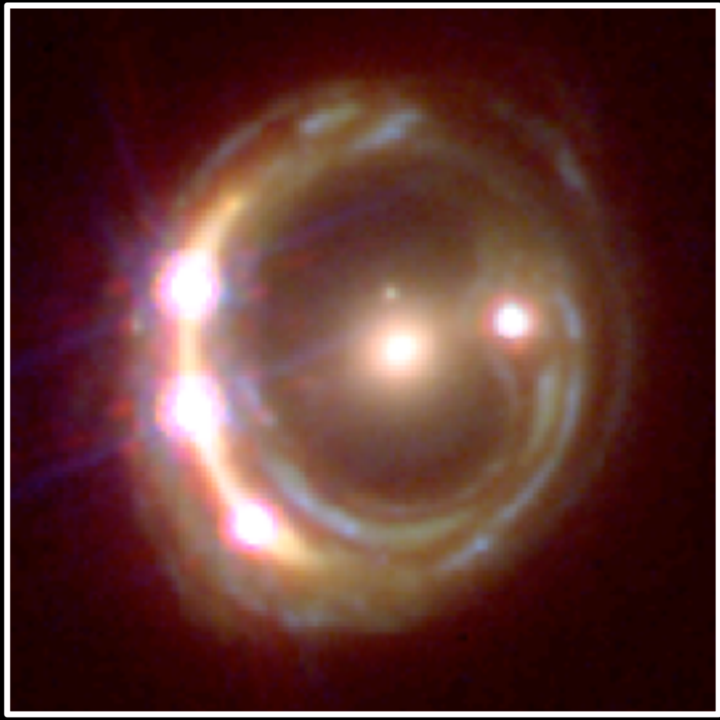
Stellar kinematics really helps



- 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:

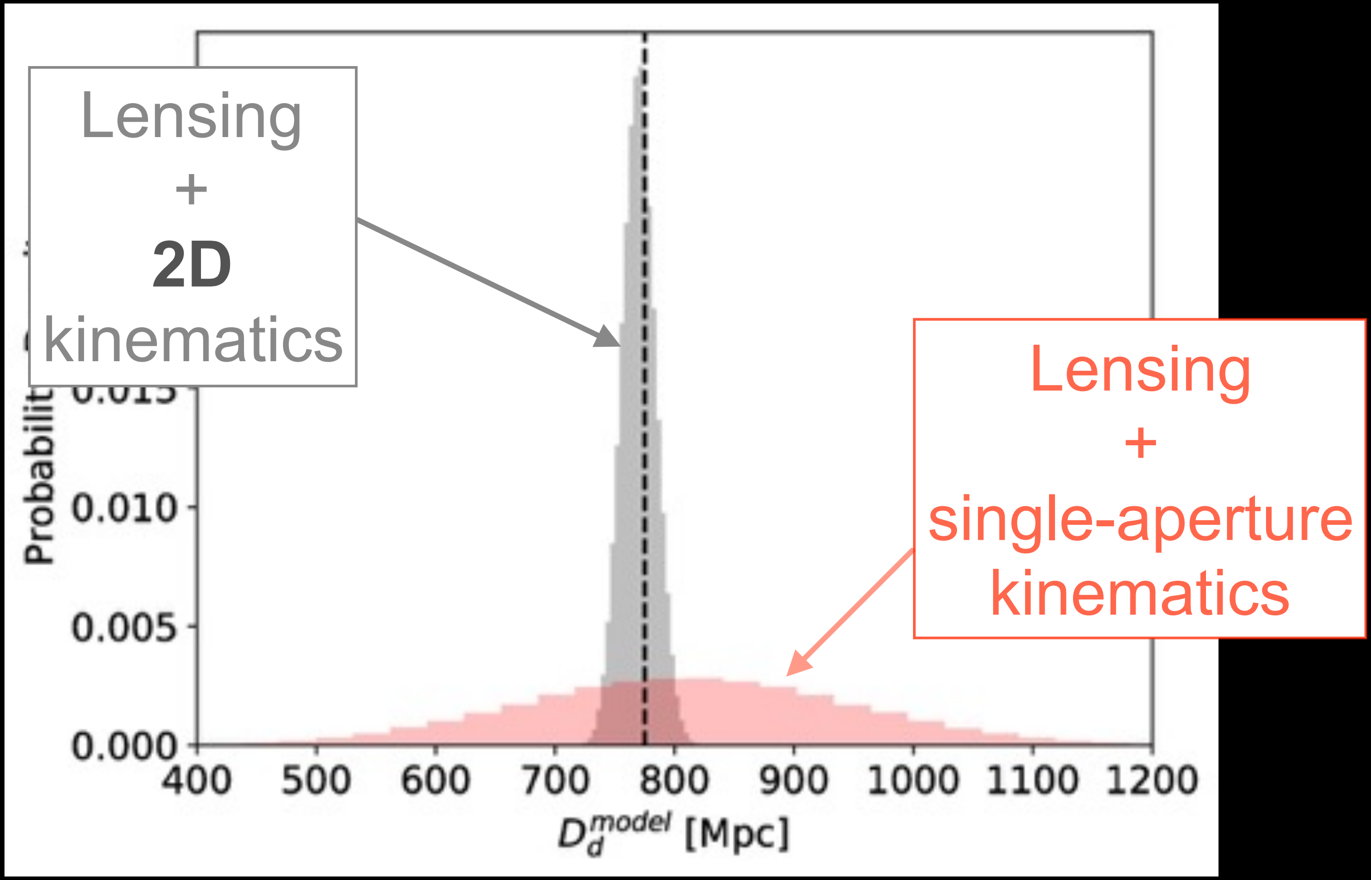
$$D_A \sim r/\Delta\theta$$

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

- 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., 2019]

Stellar kinematics really helps



Including spatially-resolved (2D) kinematic data:

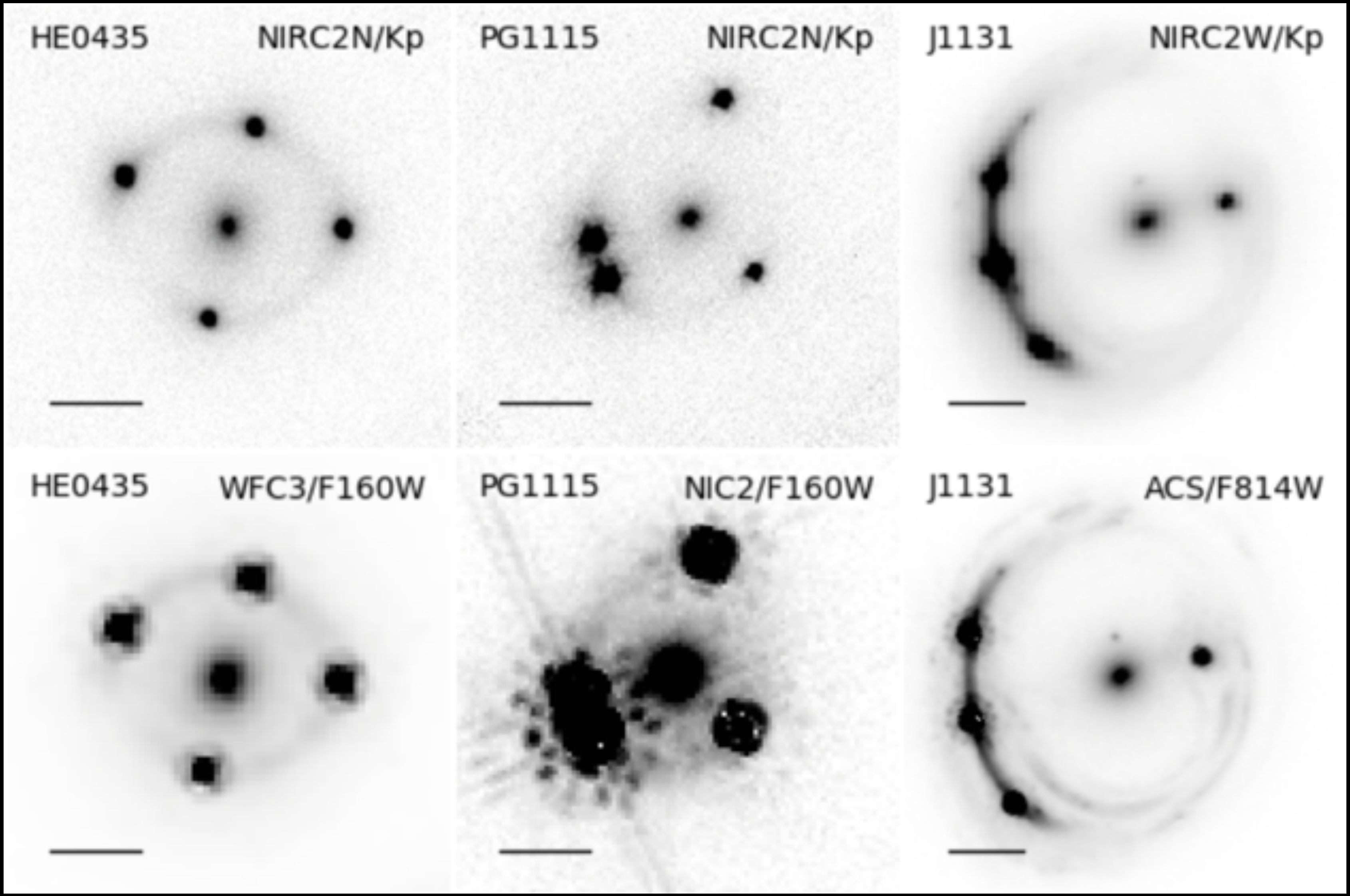
- drastically reduces the uncertainty of D_A from ~15% to ~3%
- sensitive to systematic errors in kinematic measurements

[Yıldırım, Suyu, Halkola 2019]

Cosmology with Adaptive Optics

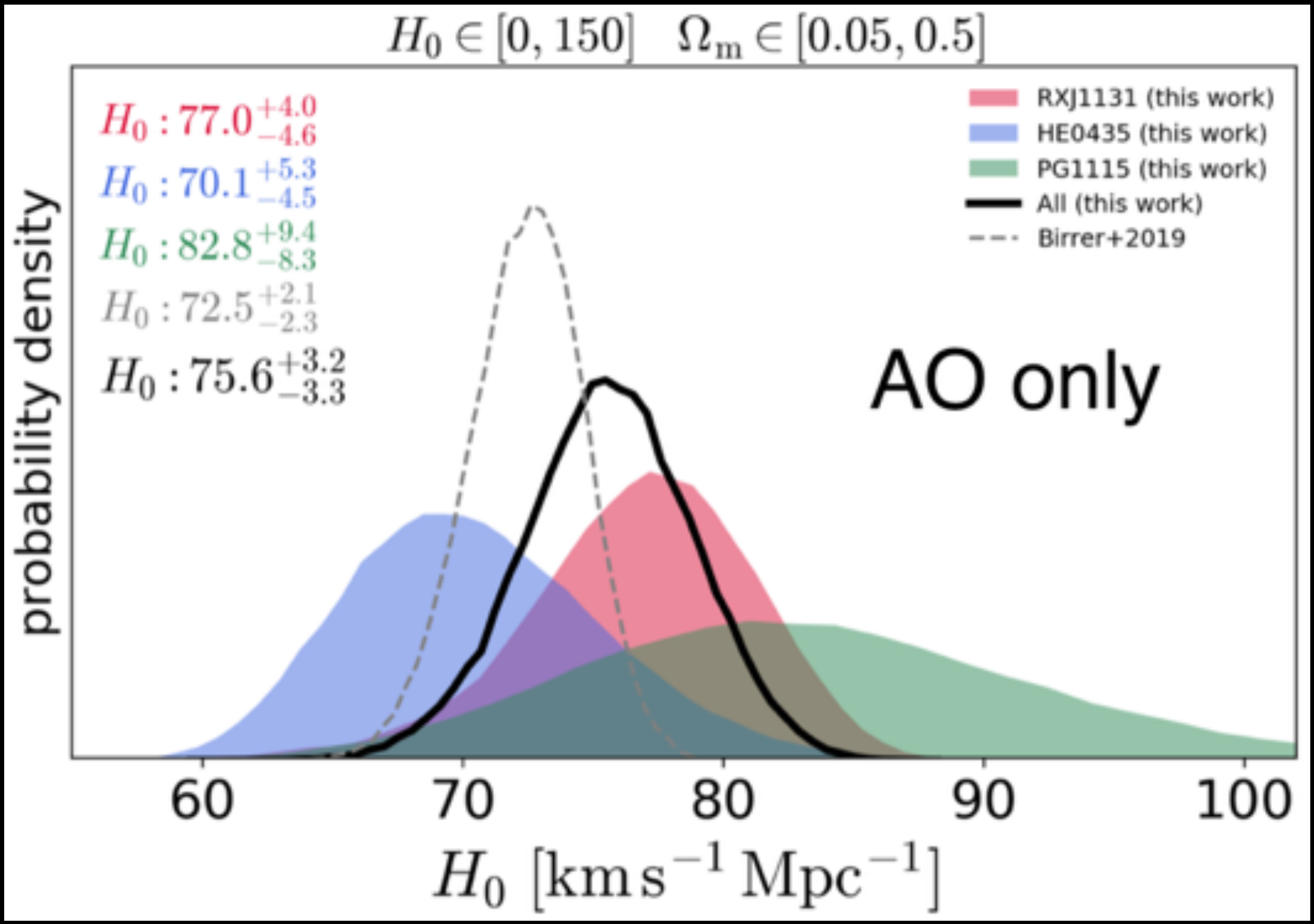
Keck AO

HST



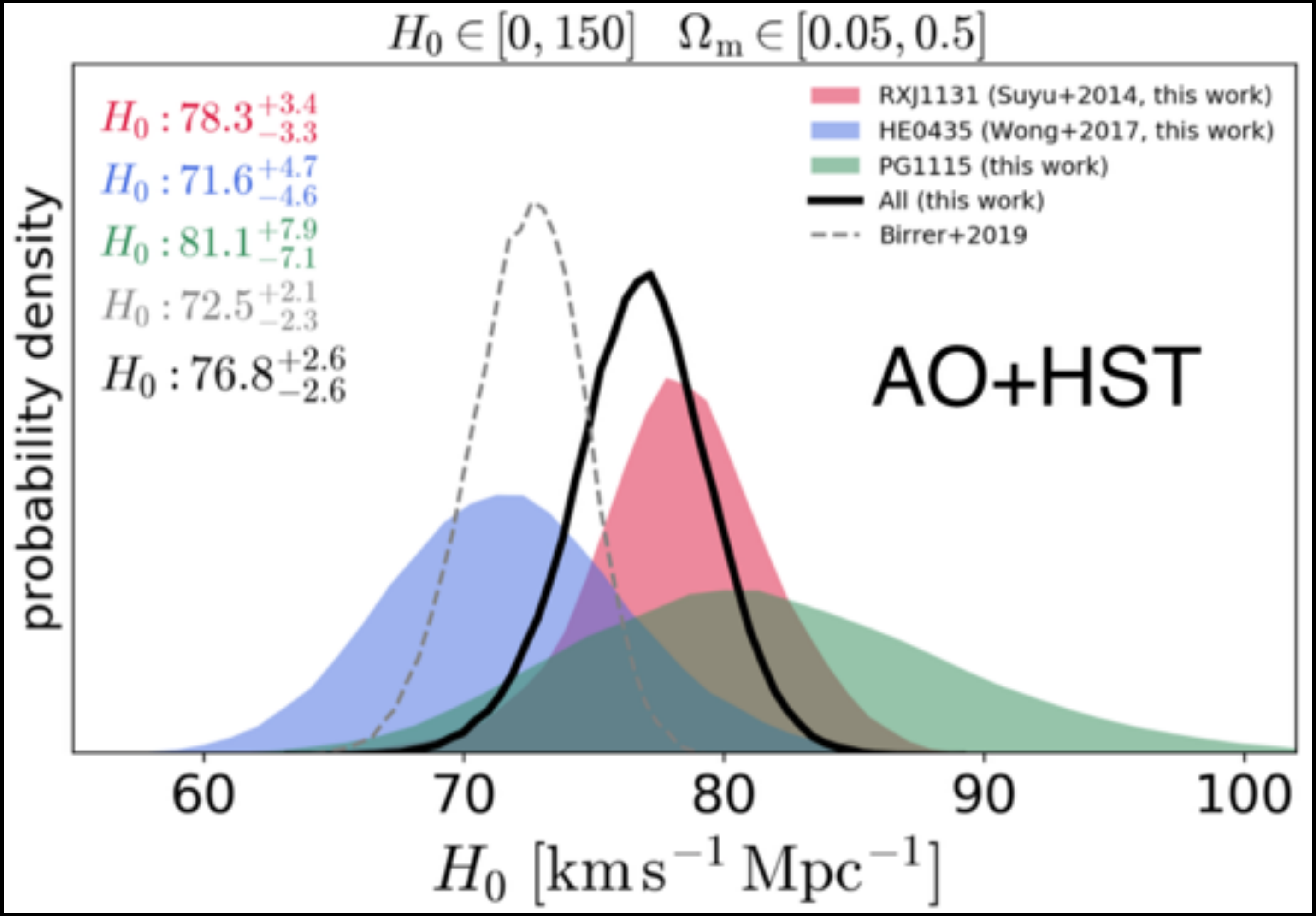
[Chen, Fassnacht, Suyu et al. 2019]

Cosmology with Adaptive Optics



[Chen, Fassnacht, Suyu et al. 2019]

Cosmology with Adaptive Optics



[Chen, Fassnacht, Suyu et al. 2019]

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]

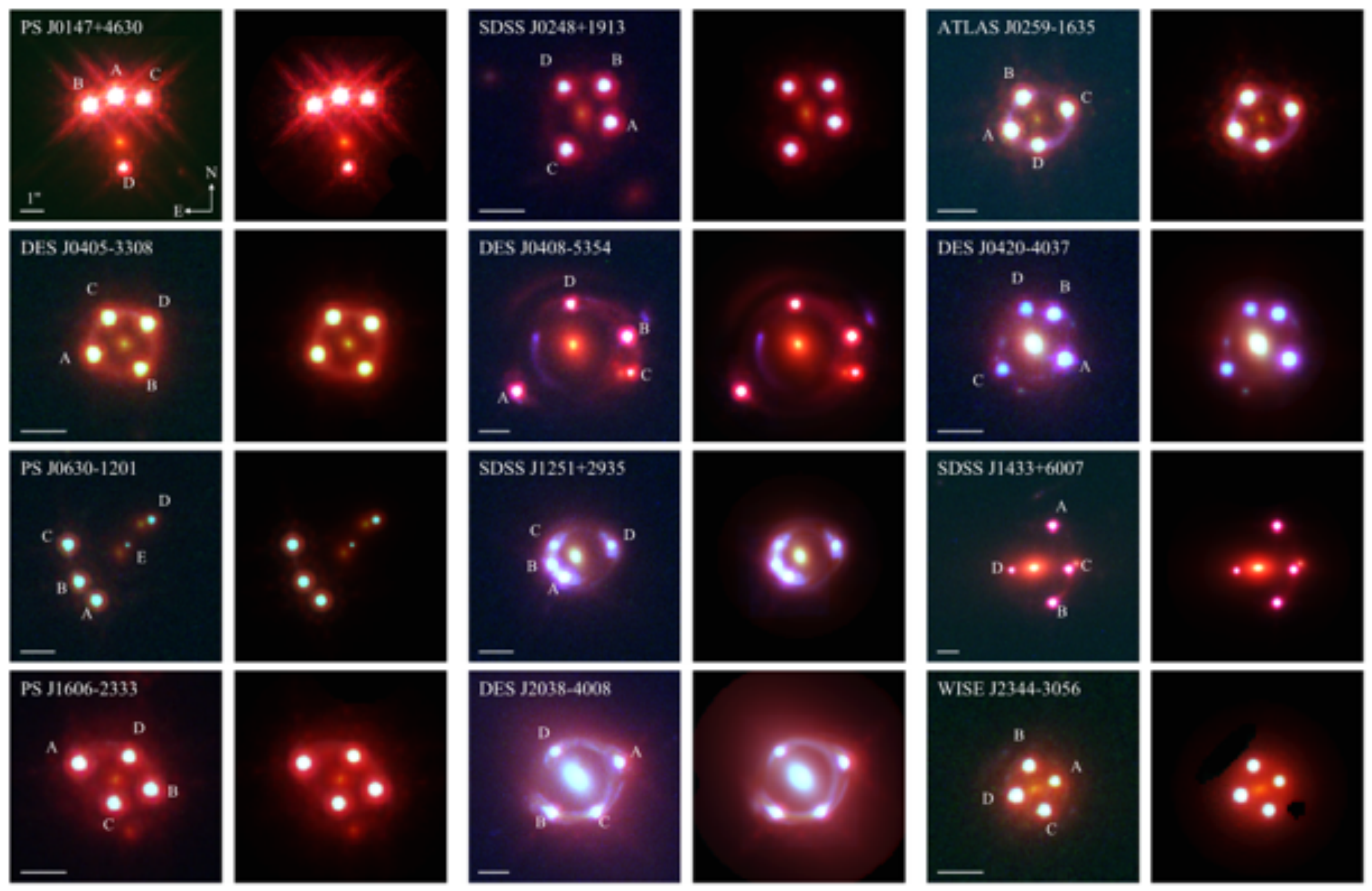
Kilo Degree Survey

2.6m VLT Survey Telescope, Paranal, Chile

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

New quads imaged with HST

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



[Shajib et al. 2018]

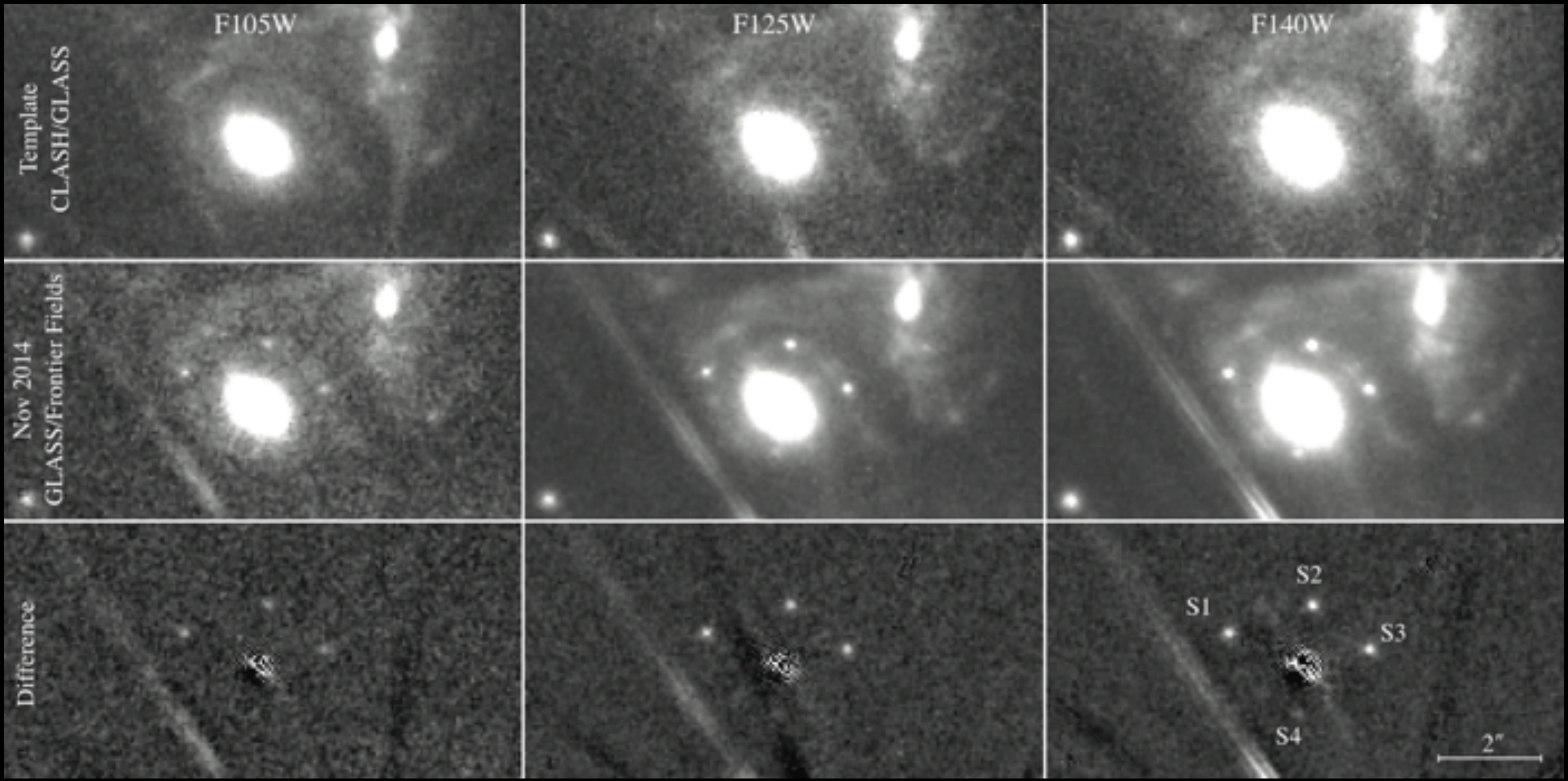
Strongly lensed supernova

MACS 1149.6+2223

[Kelly et al. 2015]

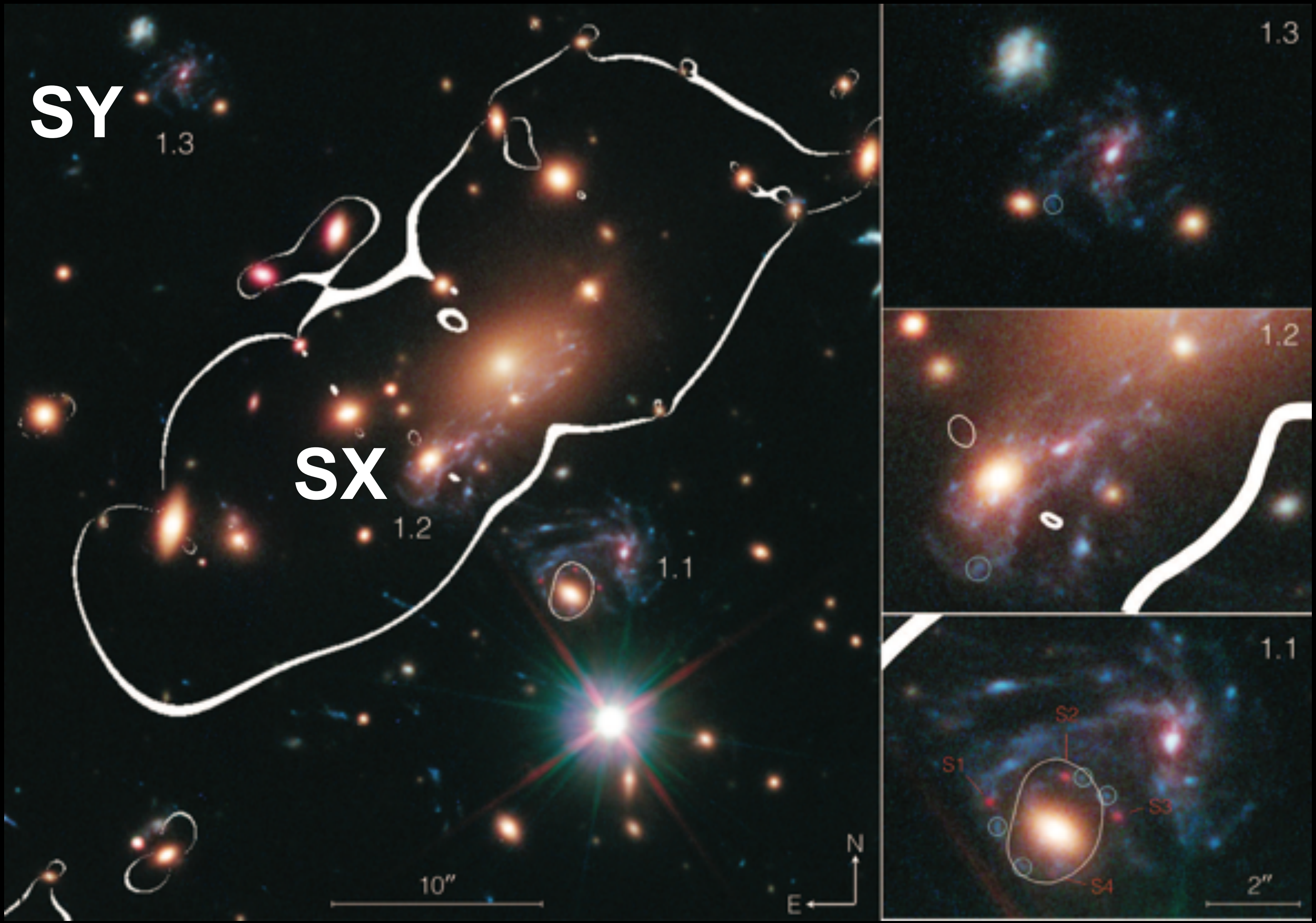
Supernova “Refsdal”

discovered serendipitously in November 2014



[Kelly et al. 2015]

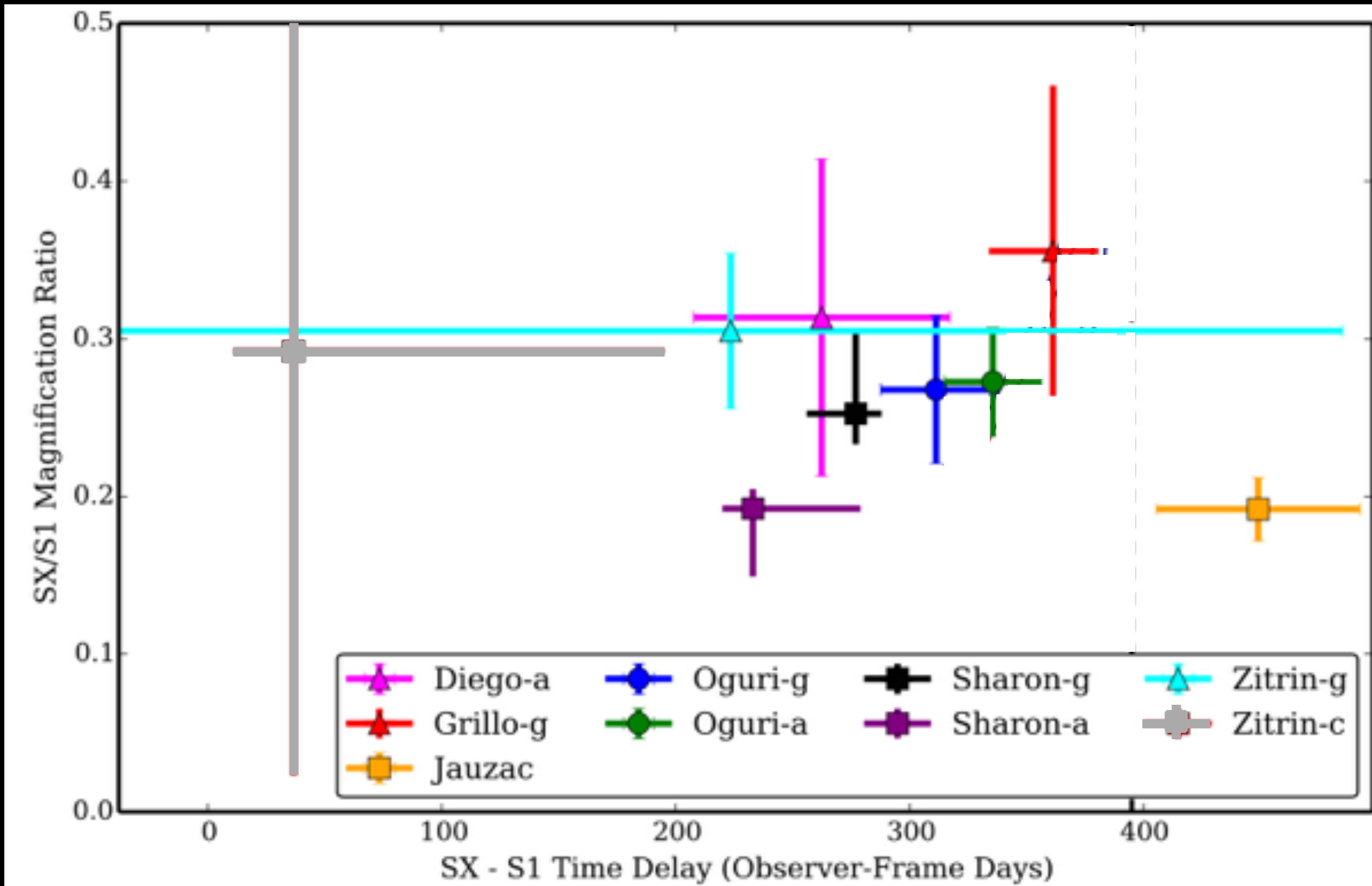
When will the other SN images appear?



MACS 1149.6+2223

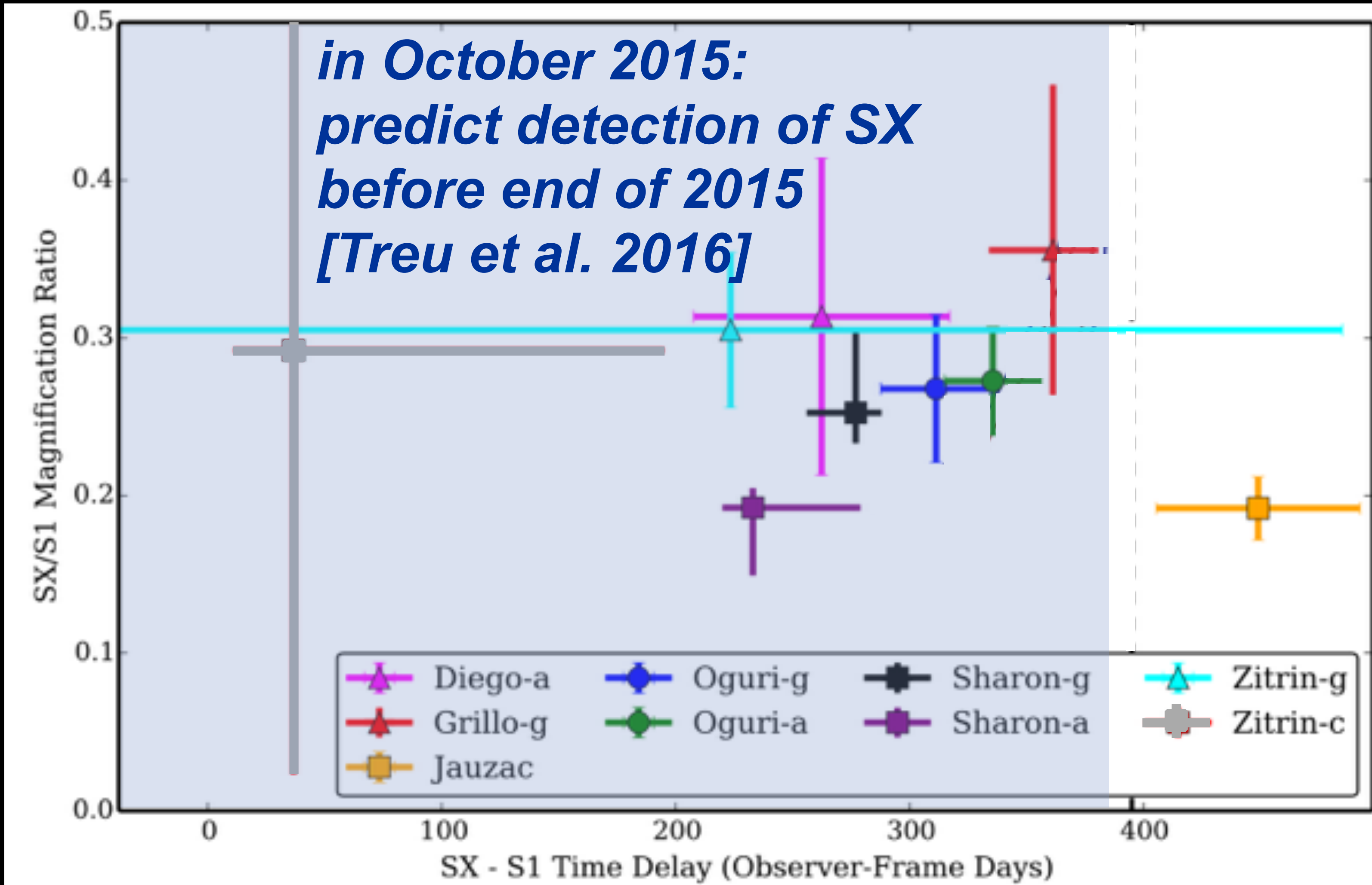
[Kelly et al. 2015]

Predicted magnification and delay



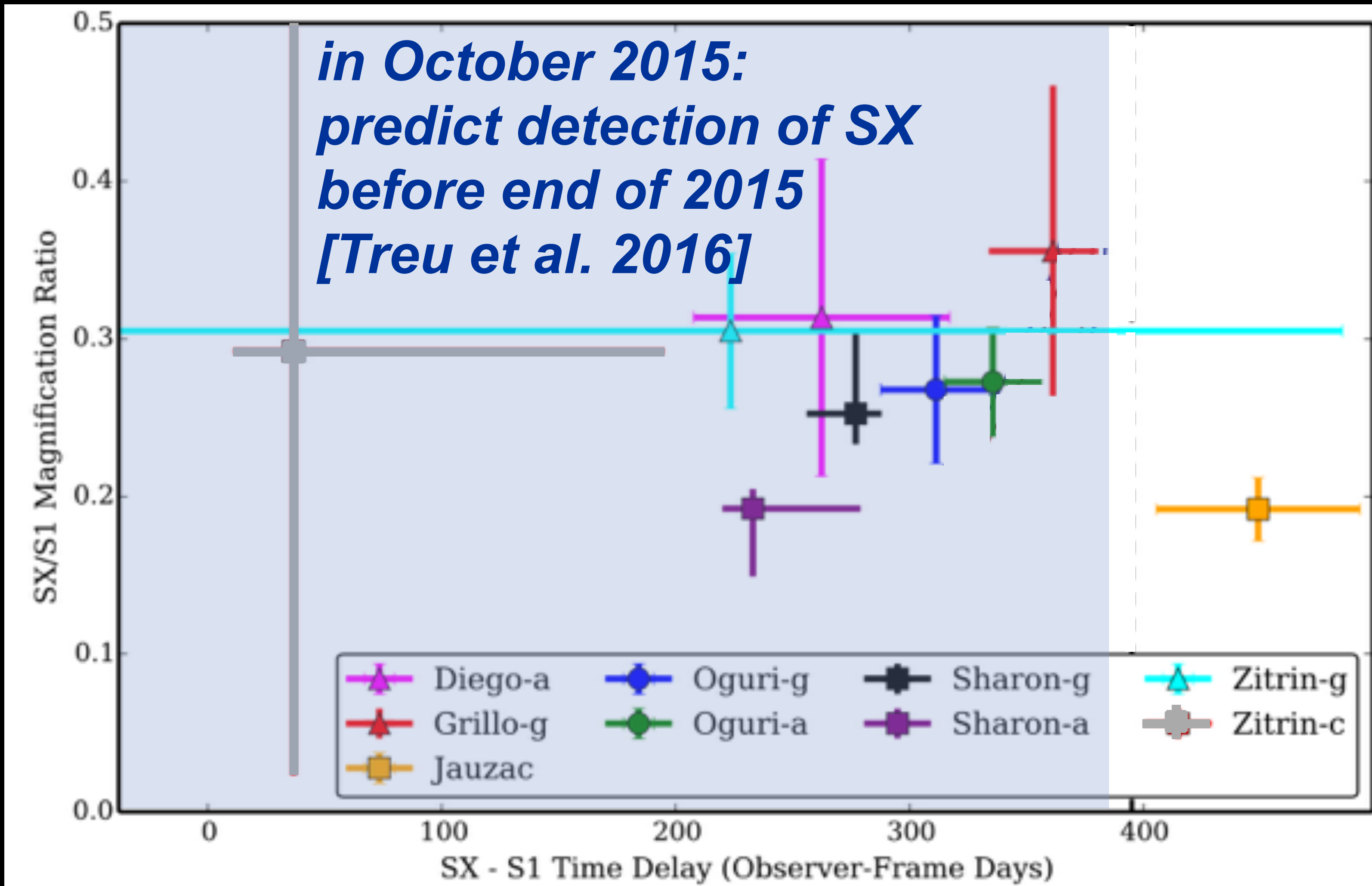
[Kelly et al. 2016]

Predicted magnification and delay



[Kelly et al. 2016]

Predicted magnification and delay

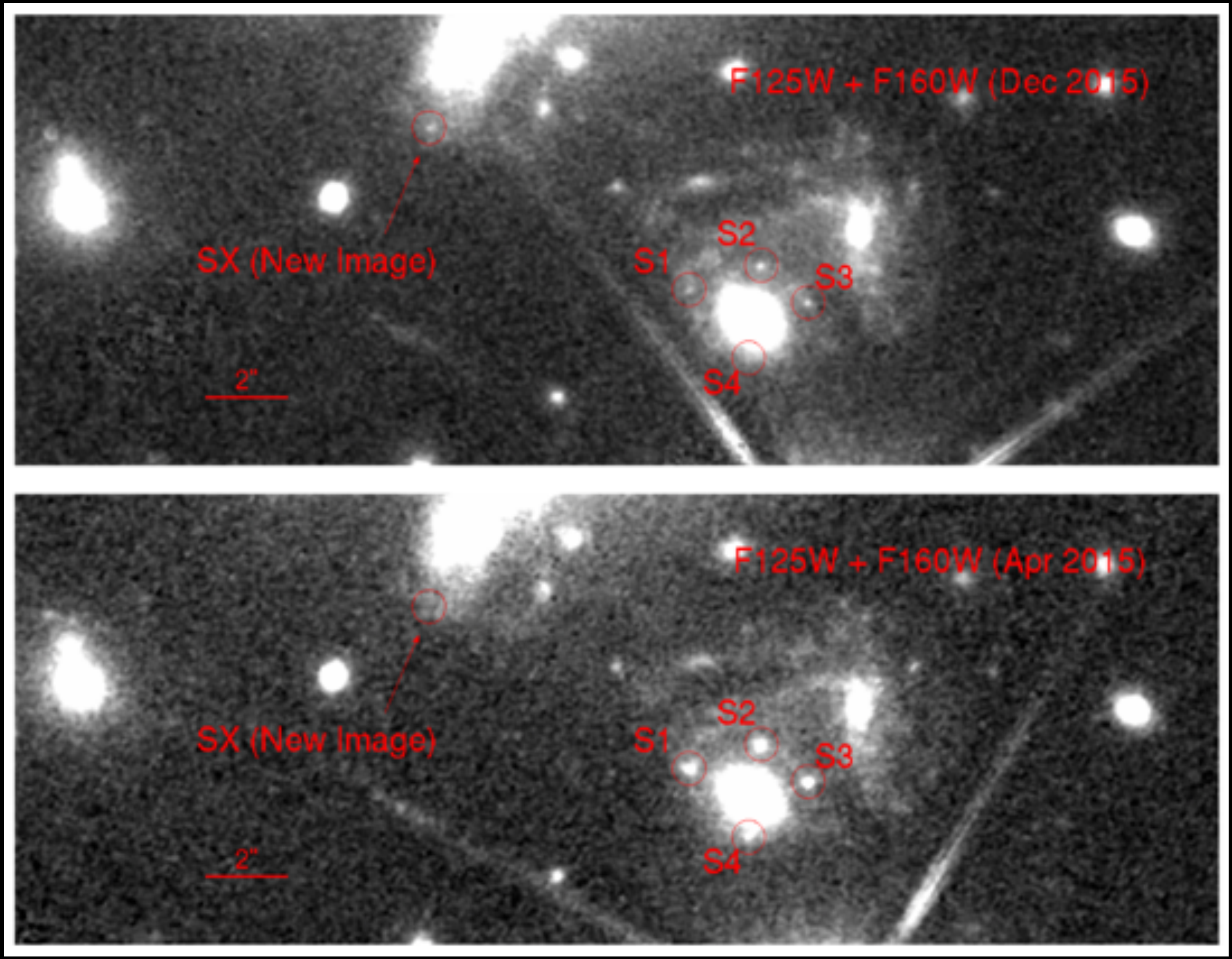


[Kelly et al. 2016]

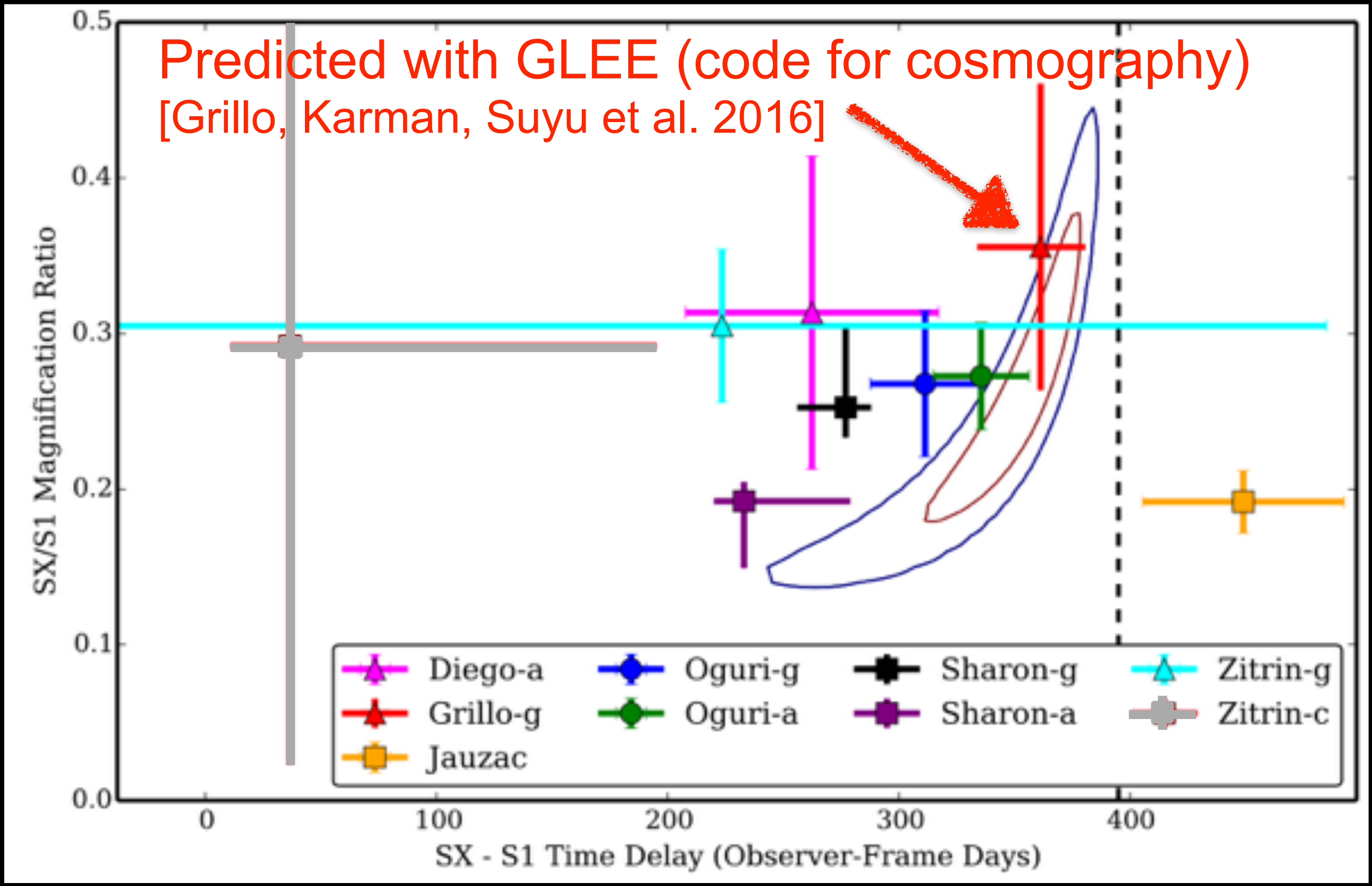
HST observations in Oct 2015: no sign of SX
in Nov 2015: no sign of SX…

Appearance of image SX

December 2015 [Kelly et al. 2016]

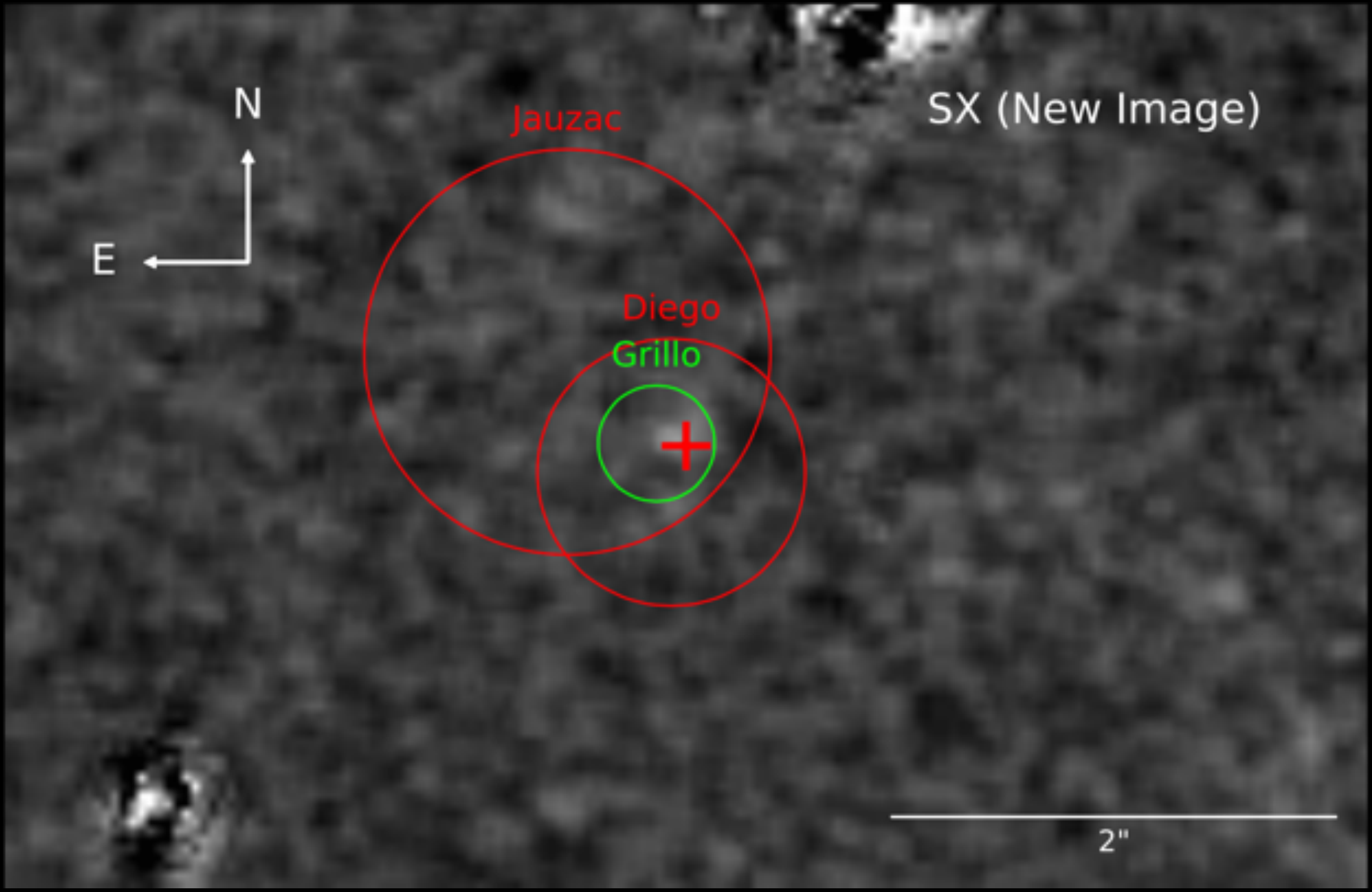


Magnification and delay



[Kelly et al. 2016]

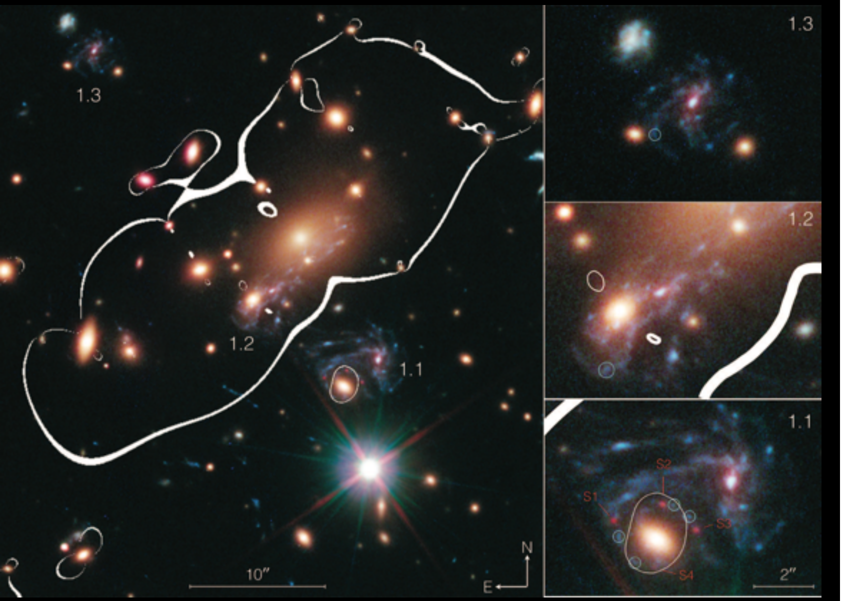
Spot on!

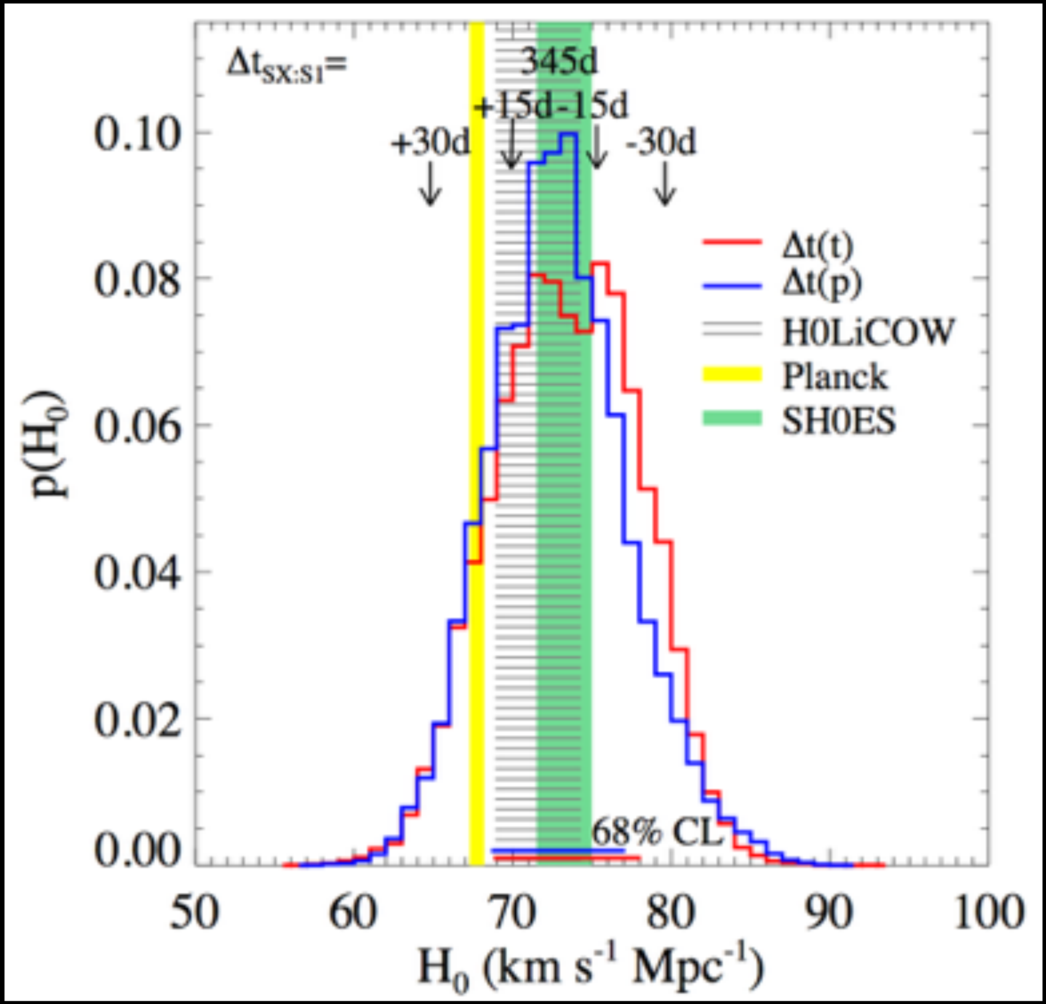


[Kelly et al. 2016]

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

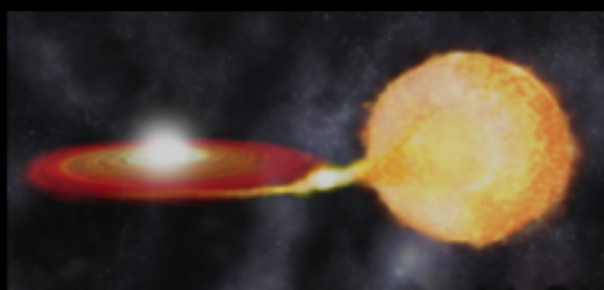
PI: Suyu

European Research Council
Established by the European Commission

Two longstanding puzzles:

1) What is the progenitor of Type Ia supernova?

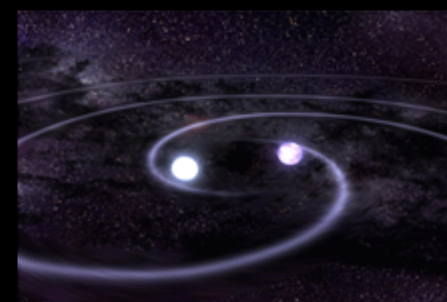
single degenerate



White dwarf (WD) accreting from non-degenerate companion

or

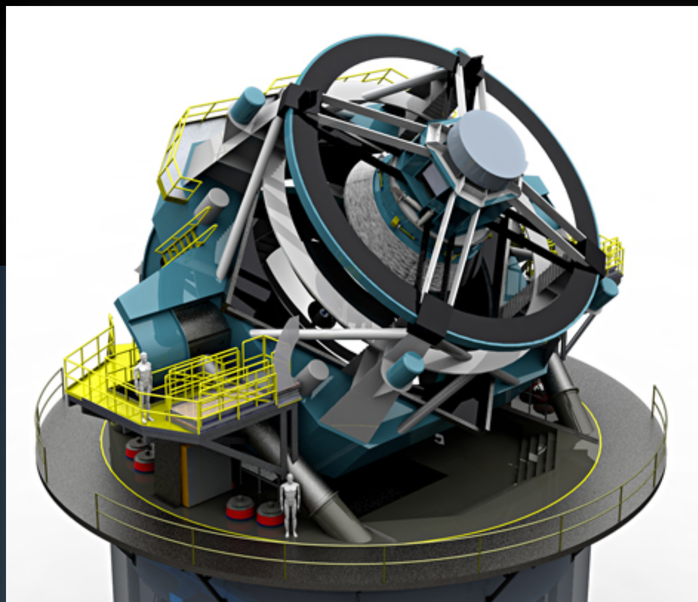
double degenerate



WDs merging

2) What is dark energy?

Large Synoptic Survey Telescope (LSST)



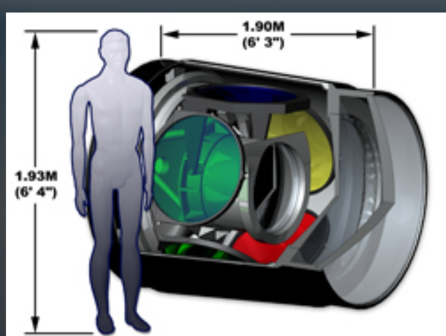
High etendue survey telescope:

- **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

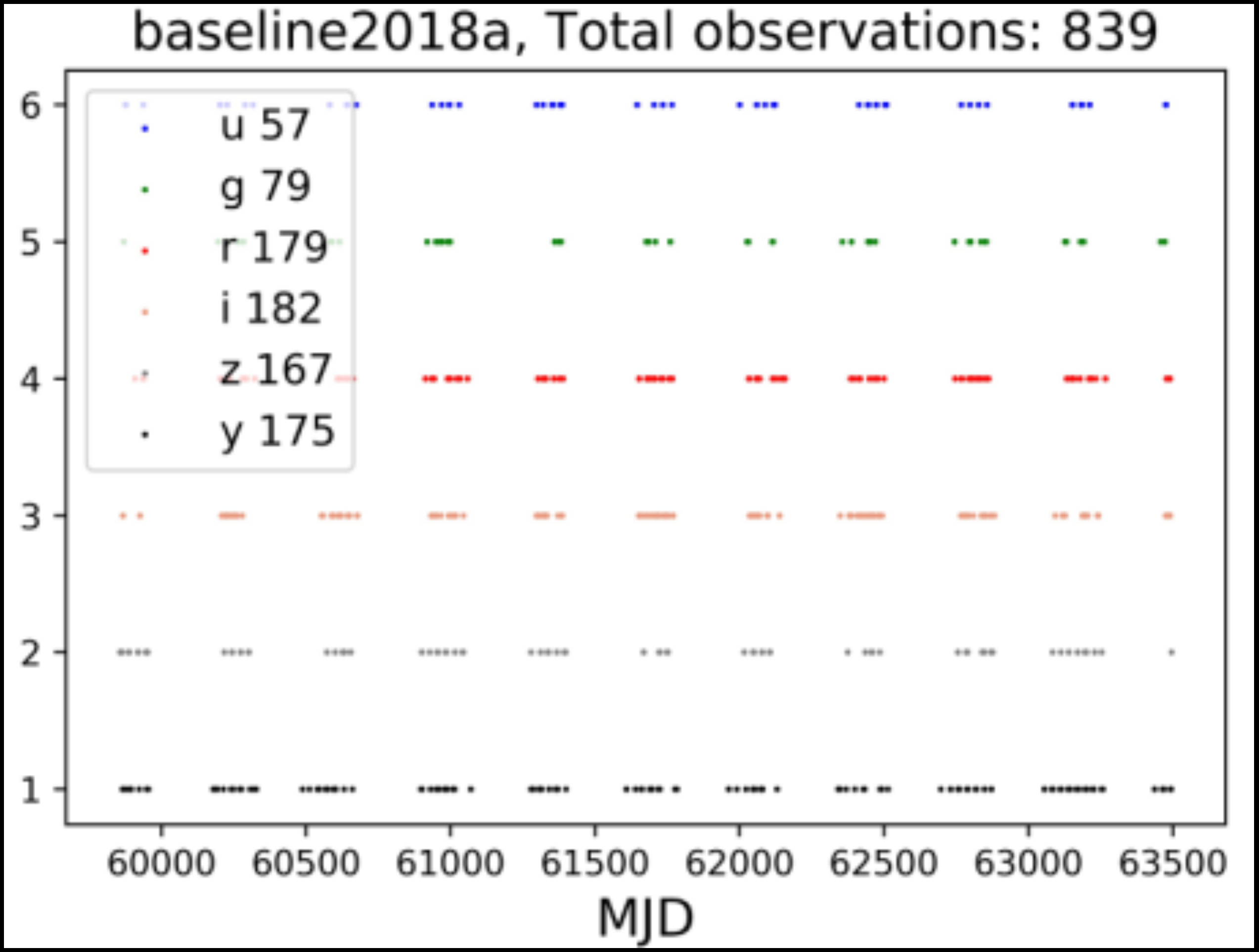
Expect hundreds of lensed SNe in the 10-year LSST survey

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

[Slide material courtesy of Phil Marshall]

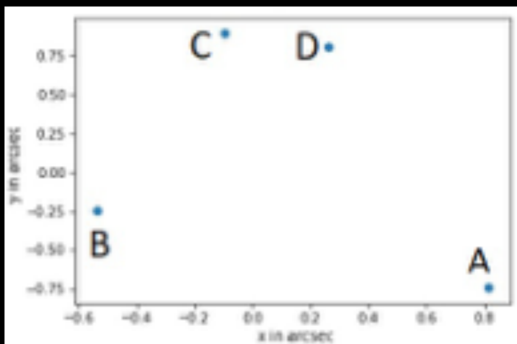
LSST Cadence Strategy for Lensed SNe

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



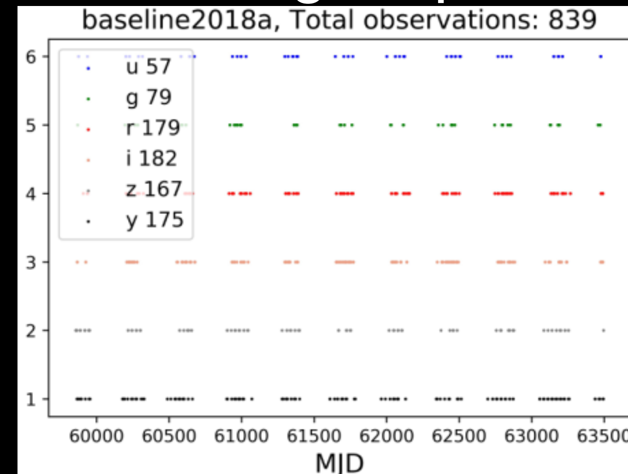
Cadence Strategy for Lensed SNe

mock lens system

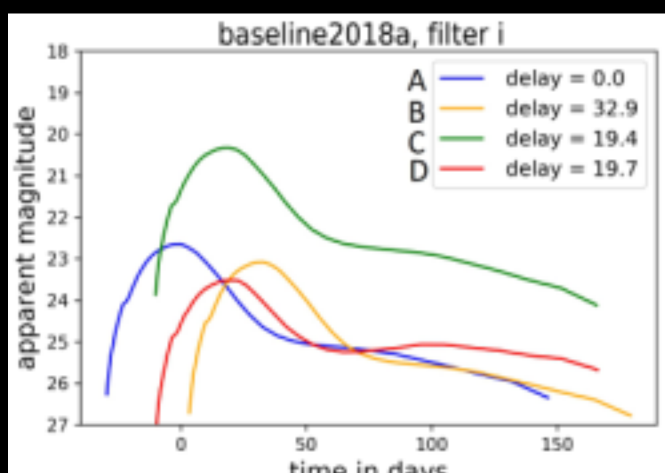


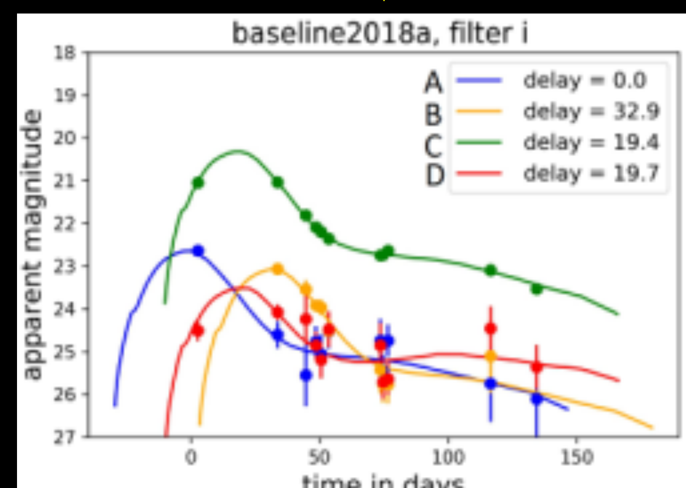
\+ W7 supernova explosion model

observing sequence



theoretical light curves

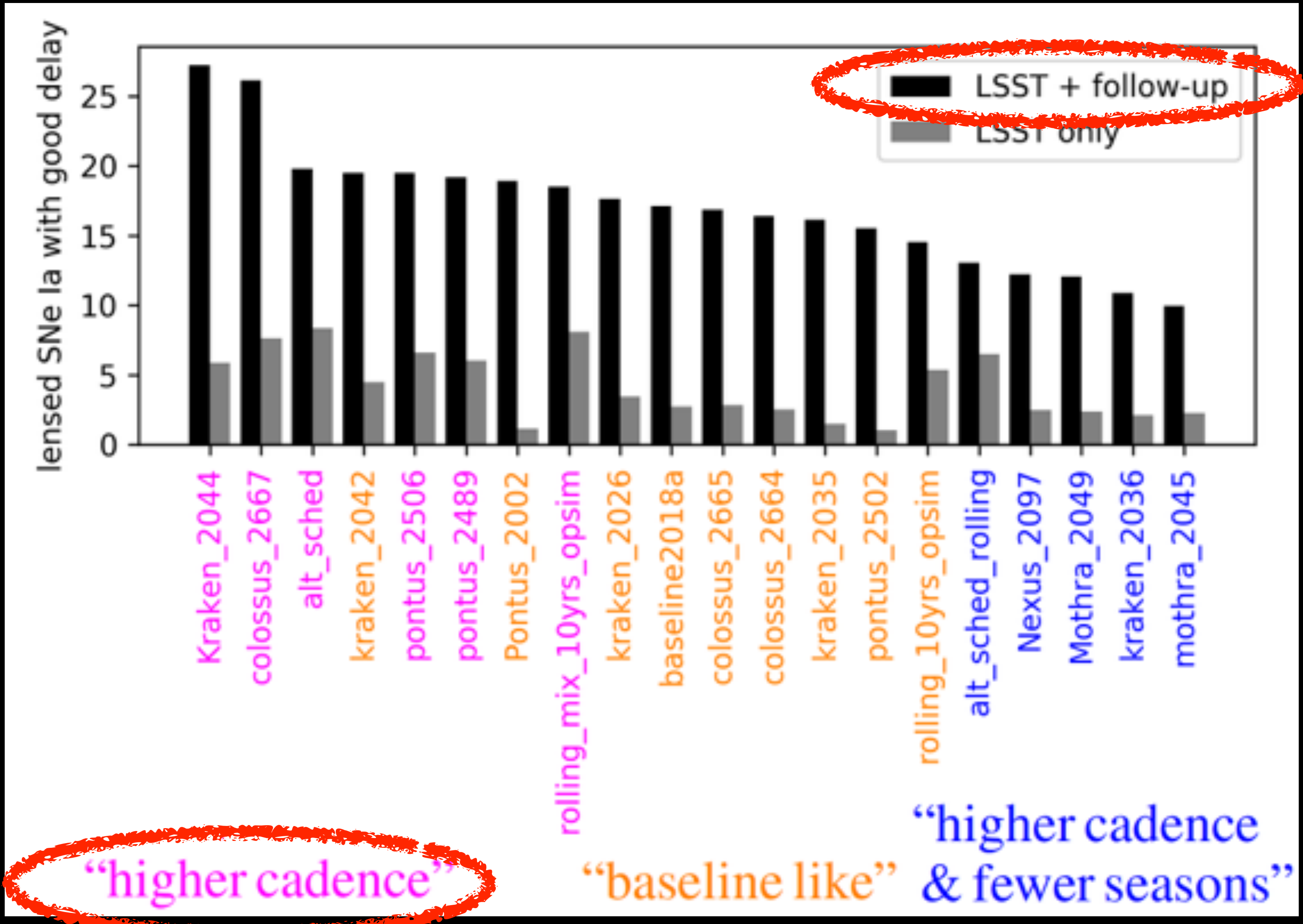




[Huber, Suyu, Noebauer et al. 2019]

Cadence Strategy for Lensed SNe

quantitatively compare LSST observing strategies

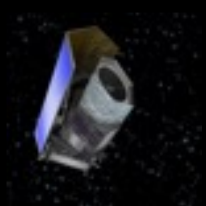


[Huber, Suyu, Noebauer et al. 2019]

Future Prospects

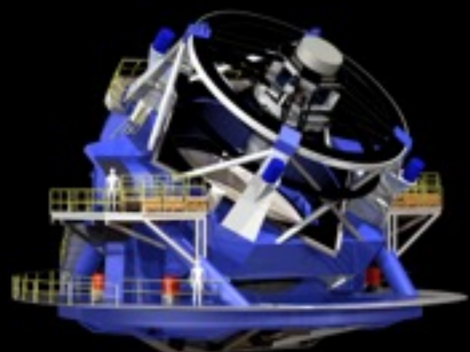
Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid



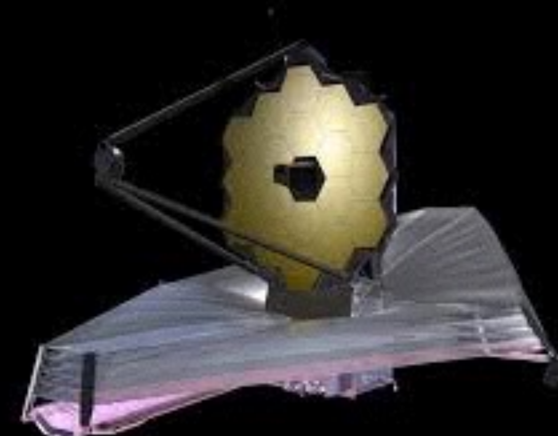
Discovery
Imaging
Spectroscopy

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 6 lenses in H0LiCOW, $H_0 = 73.3^{+1.7}_{-1.8}$ km/s/Mpc in flat ΛCDM, a 2.4% 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