Cosmology with Gravitational Lens Time Delays

Sherry Suyu
Max Planck Institute for Astrophysics
Technical University of Munich
Academia Sinica Institute of Astronomy and Astrophysics

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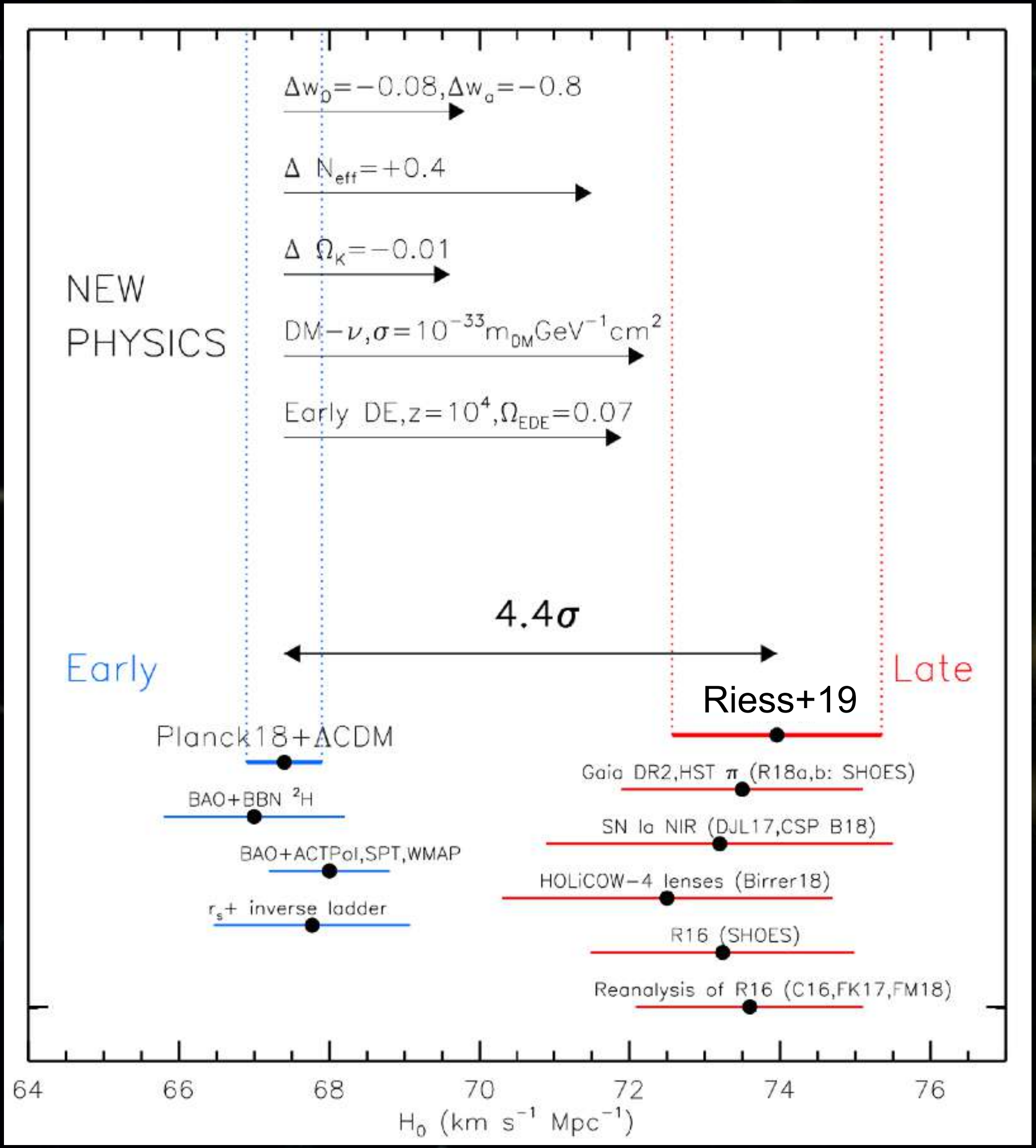
Hubble tension



[Riess et al. 2019]

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

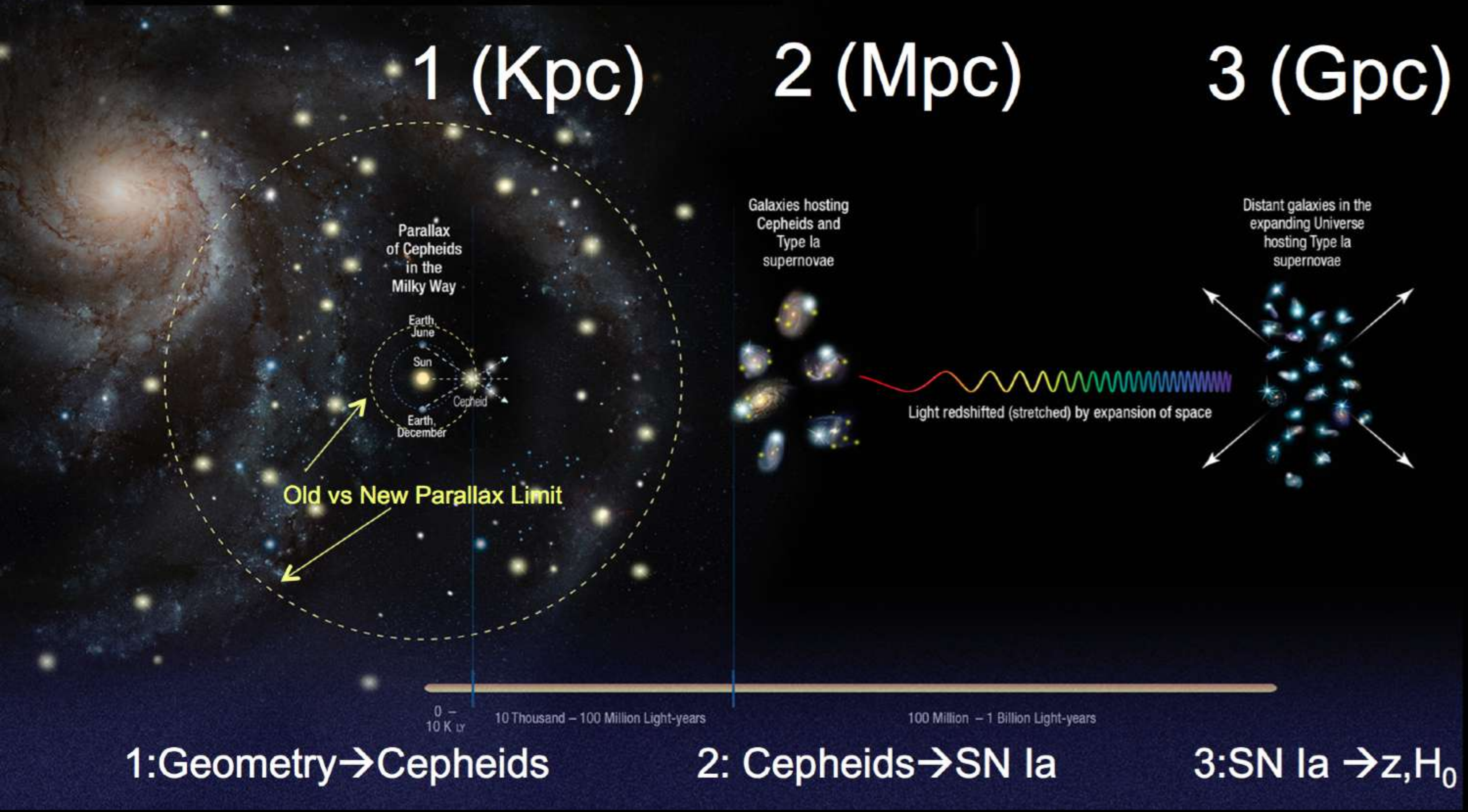
Tension? New physics?

➡ 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]

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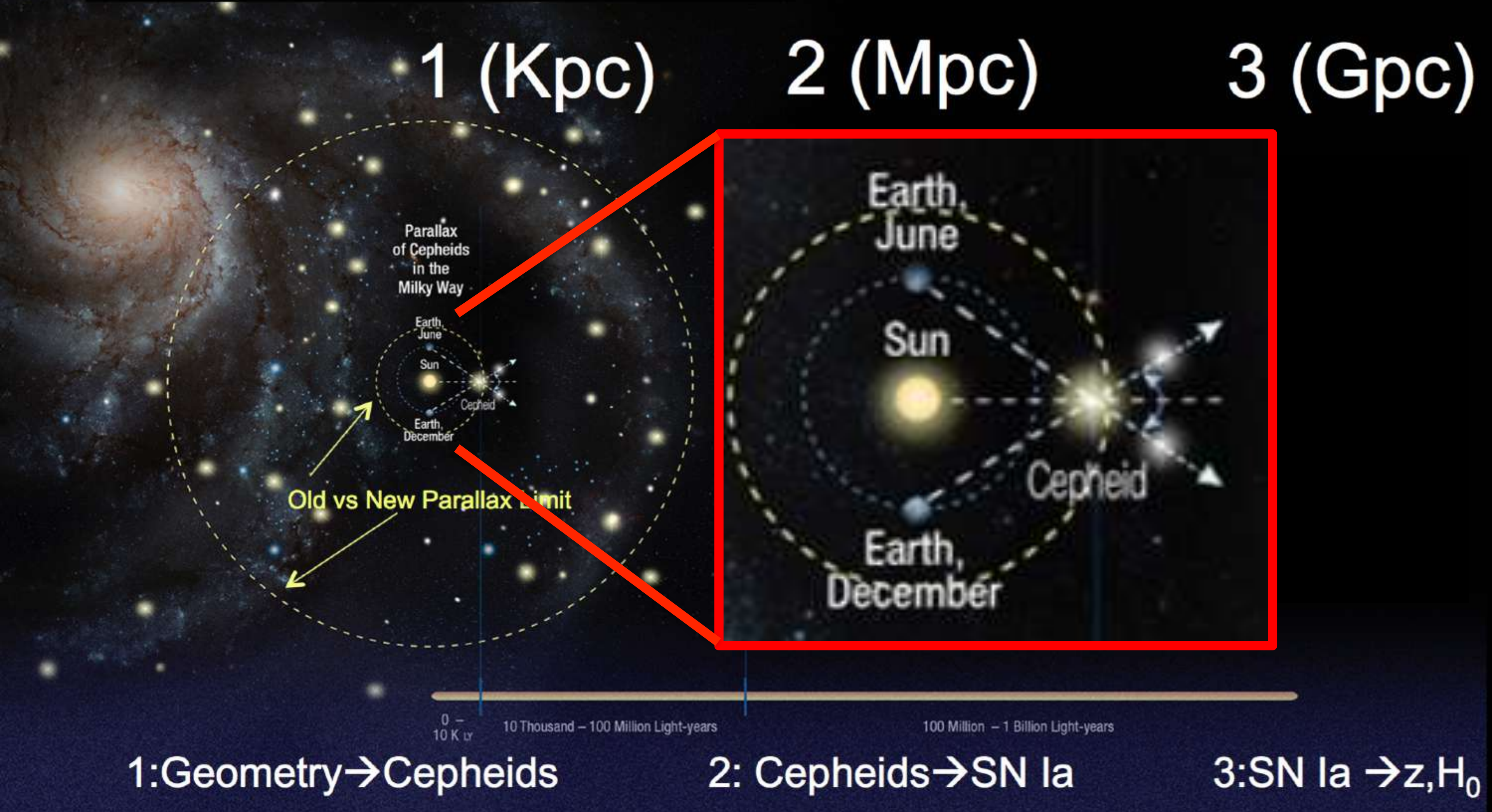

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Distance Ladder

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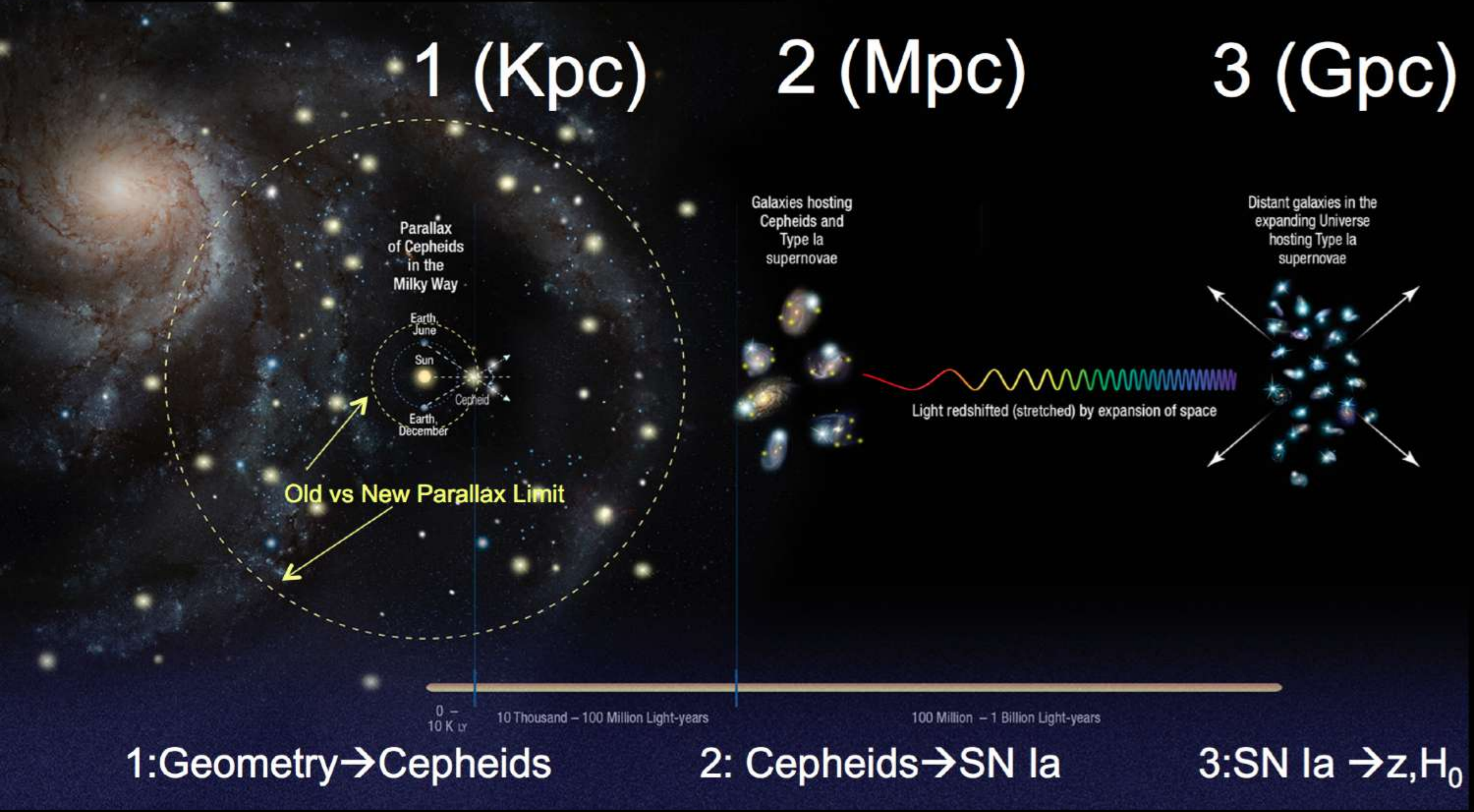


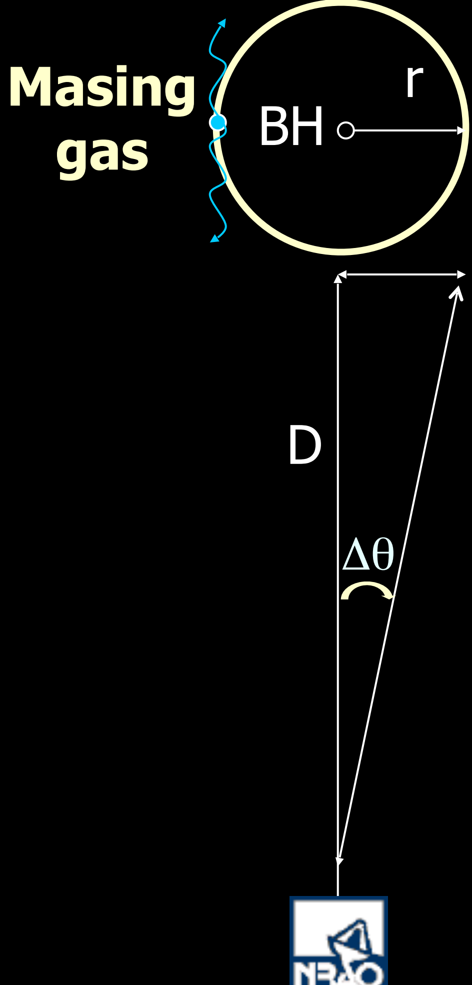
[slide material courtesy of Adam Riess]

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 = 69.6 ± 0.8 (stat) ± 1.7 (sys) km s^{-1} Mpc^{-1} [Freedman et al. 2019, 2020]

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 :

$a = V_0^2 / r$ ⟹ $r = V_0^2 / a$

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

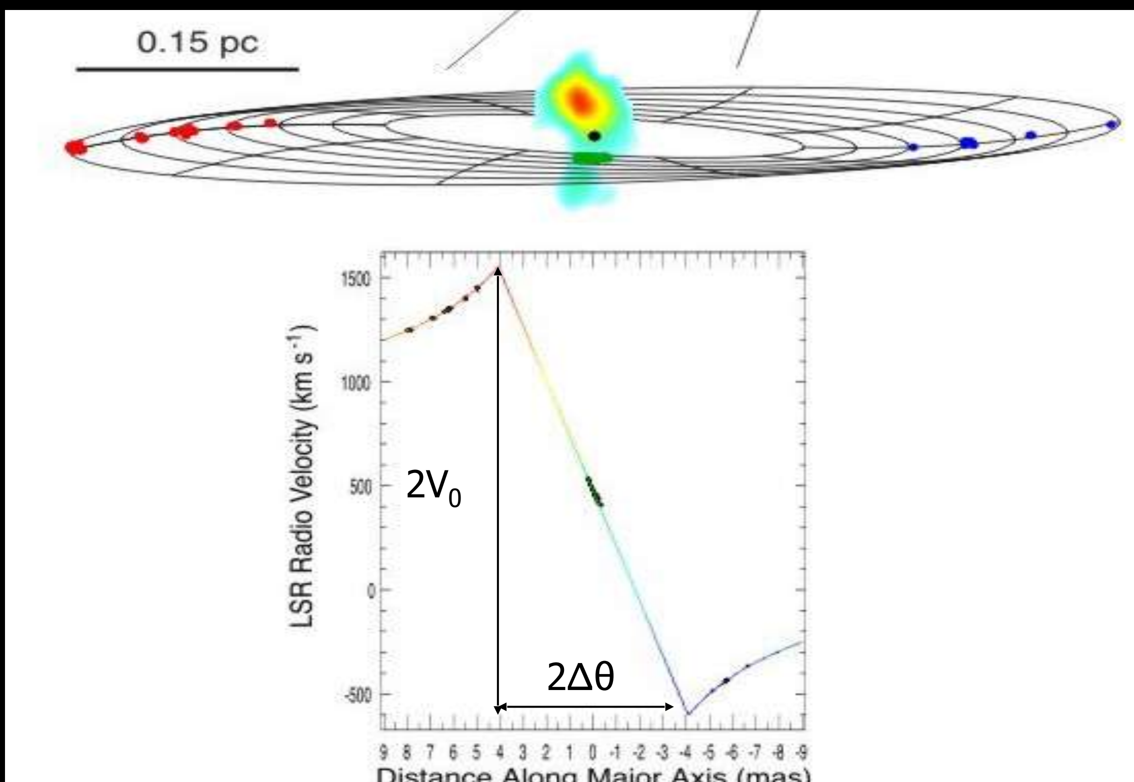
$$D = V_0^2 \sin i / a \, \Delta\theta$$

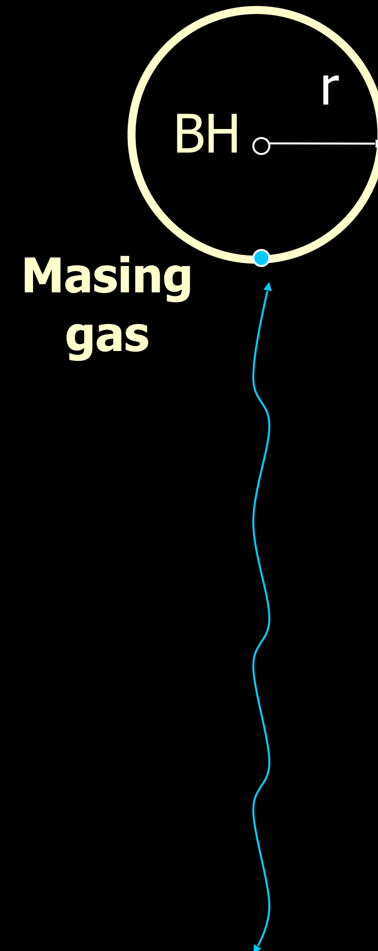
[slide material courtesy of C.-Y. Kuo]

Megamasers

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

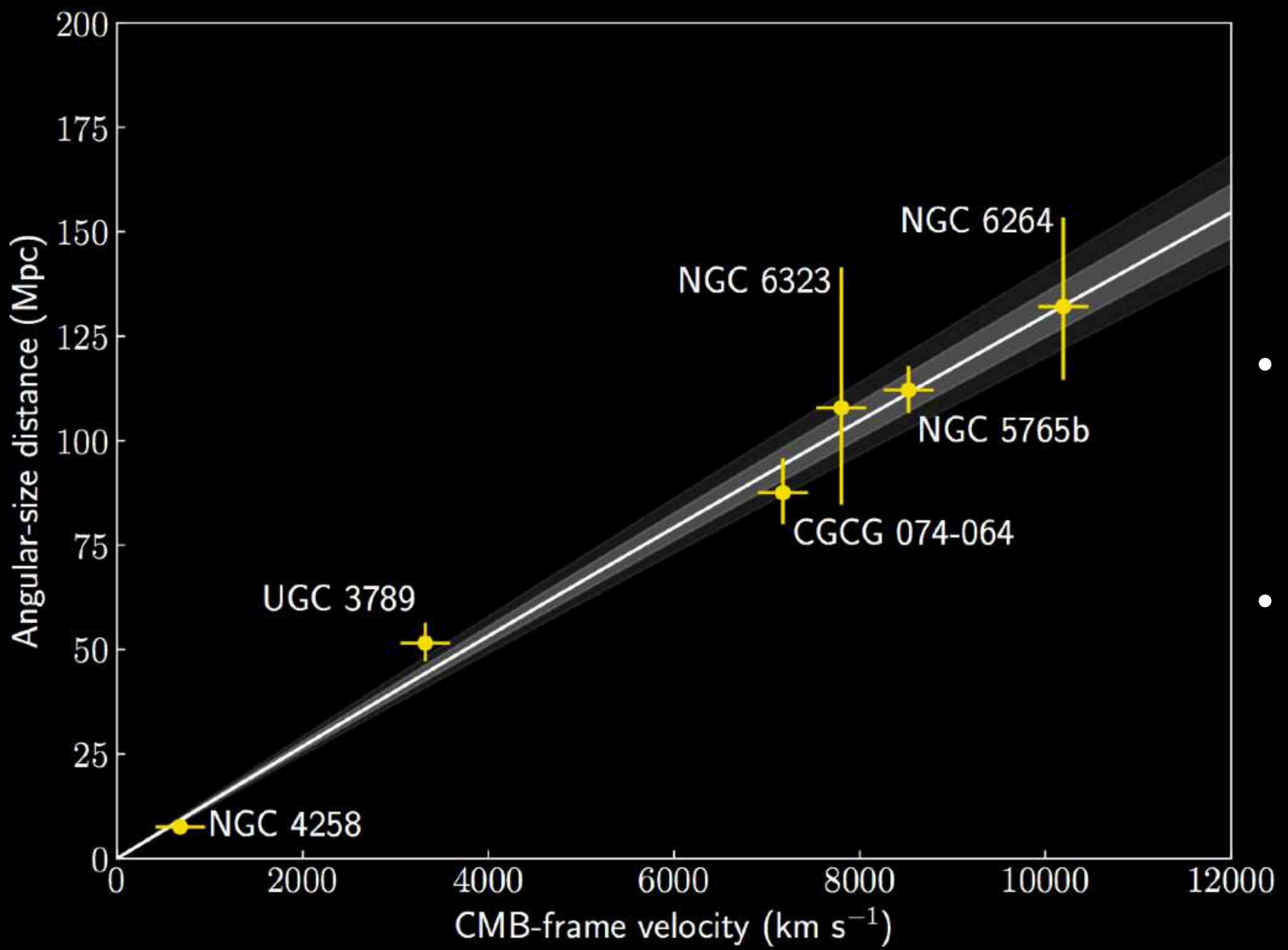
How to measure V_0, $\Delta\theta$, a and i?





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

Megamaser Cosmology Project



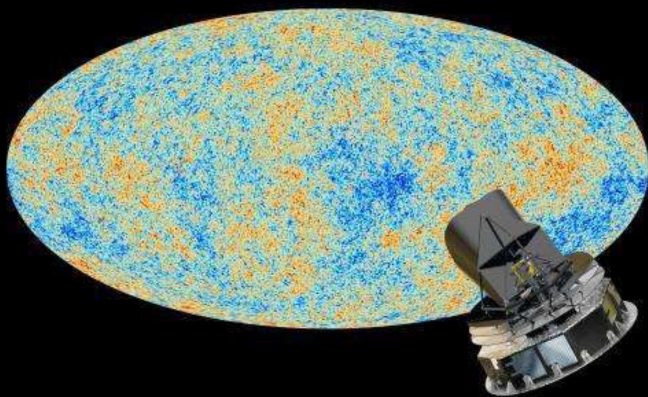
$H_0 = 73.9 \pm 3.0$ km s^{-1} Mpc^{-1}

- assuming uncertainty of 250 km/s for peculiar motions
- peculiar motion is currently the dominant source of uncertainty

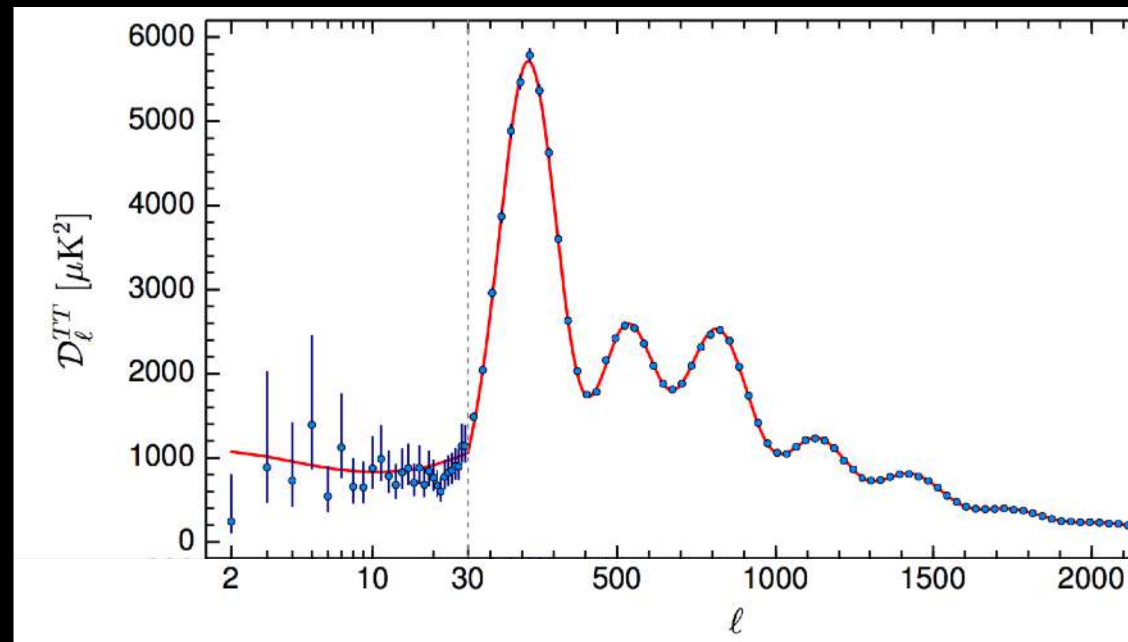
[Pesce et al. 2020]

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, $N_{\rm eff}$)

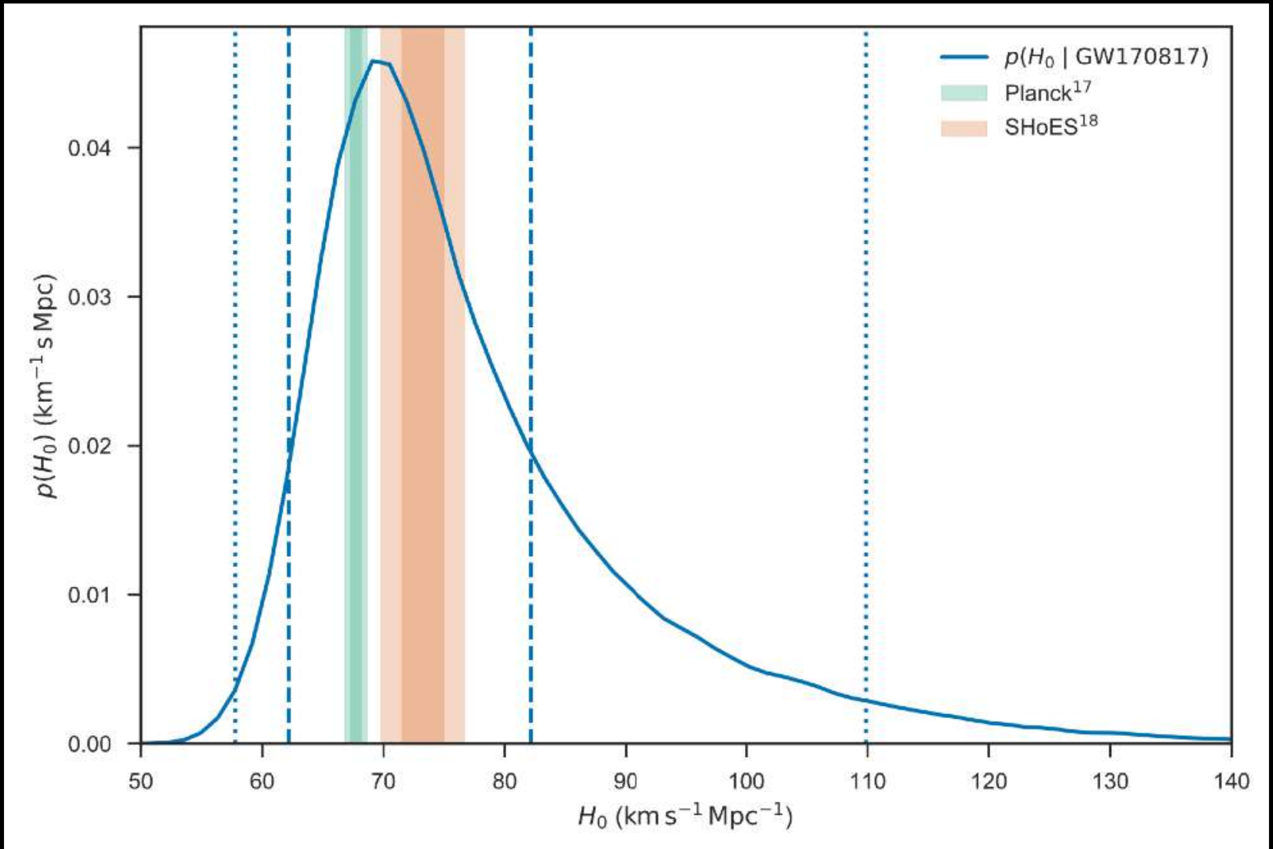
Standard Siren

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

$H_0 = v / D$

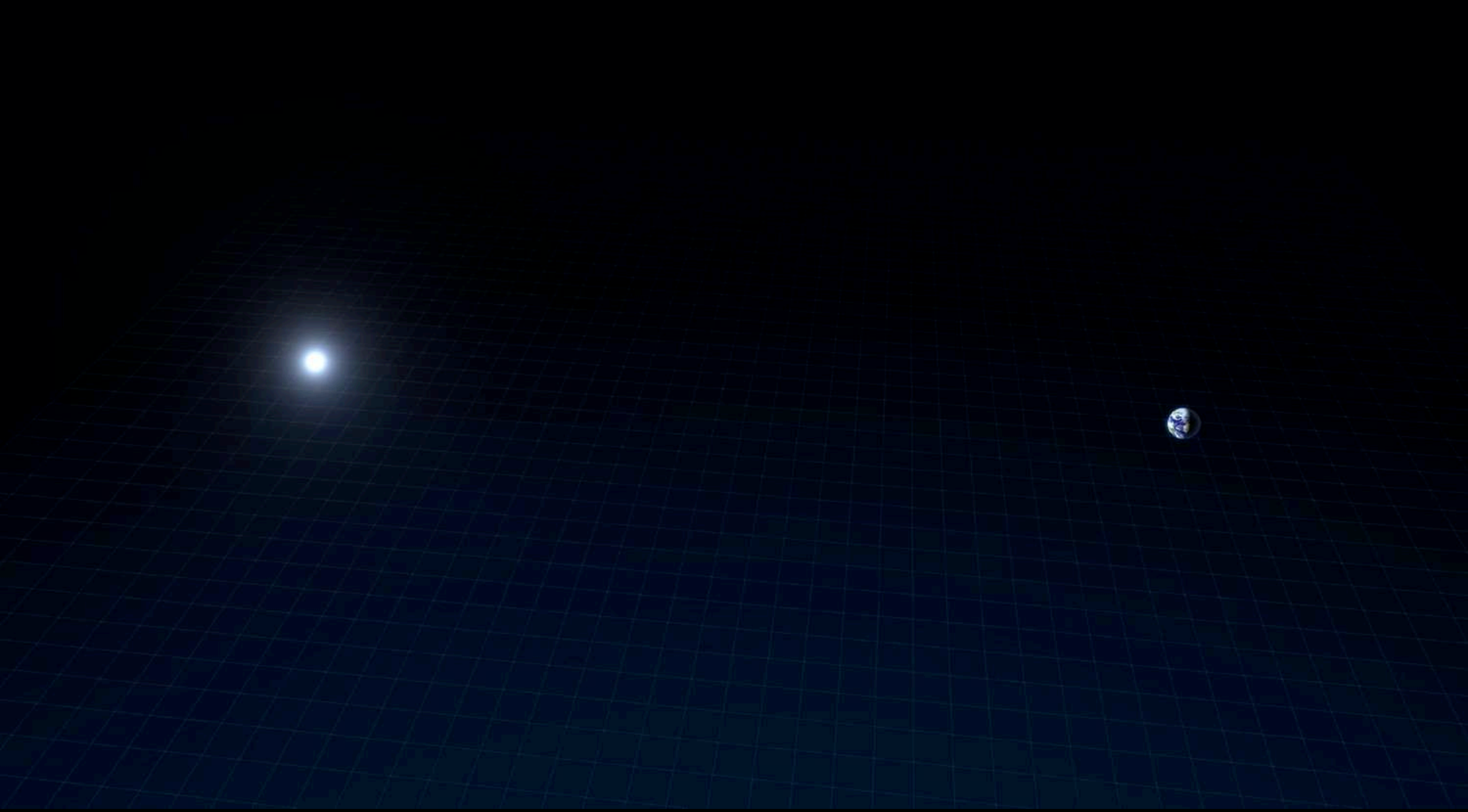
[Image credit: M. Garlick]

GW170817: First measurement of H_0



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

Strong gravitational lensing

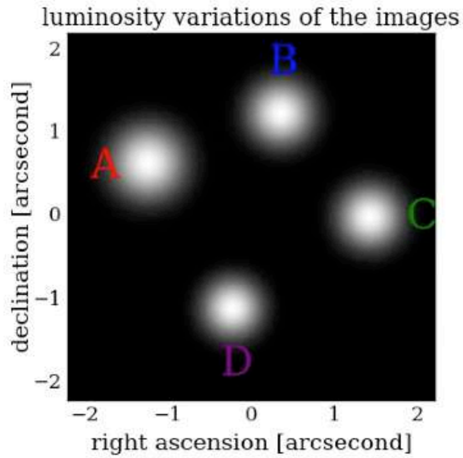


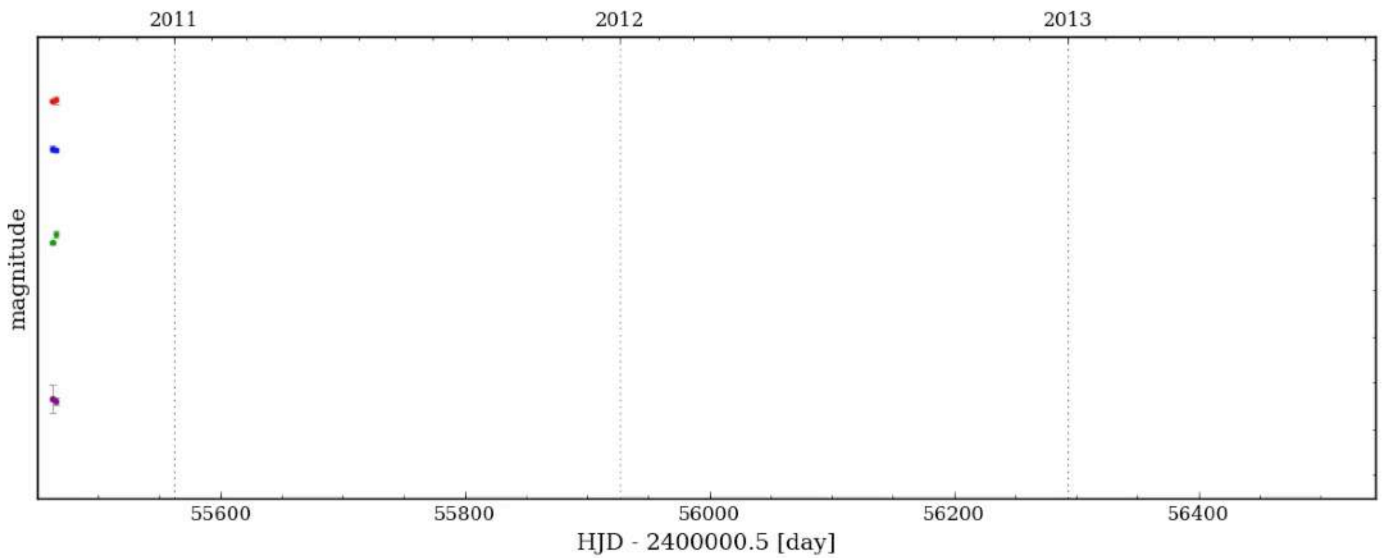
[Credit: ESA/Hubble, NASA]

Cosmology with time delays

COSMOGrail

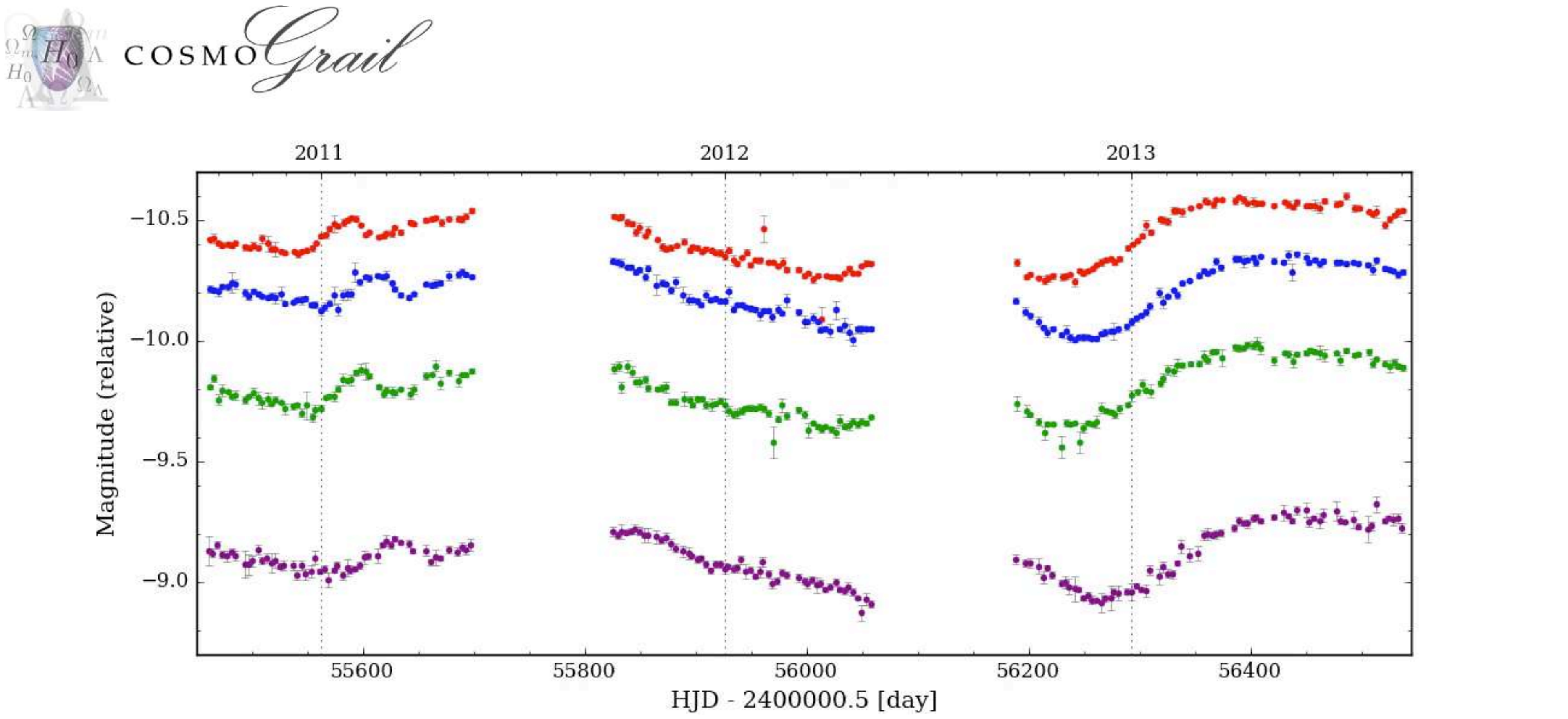
[**COS**mological
MOnitoring of
GRAv**I**tational
Lenses;
PI: F. Courbin,
G. Meylan]





[Credit: V. Bonvin]

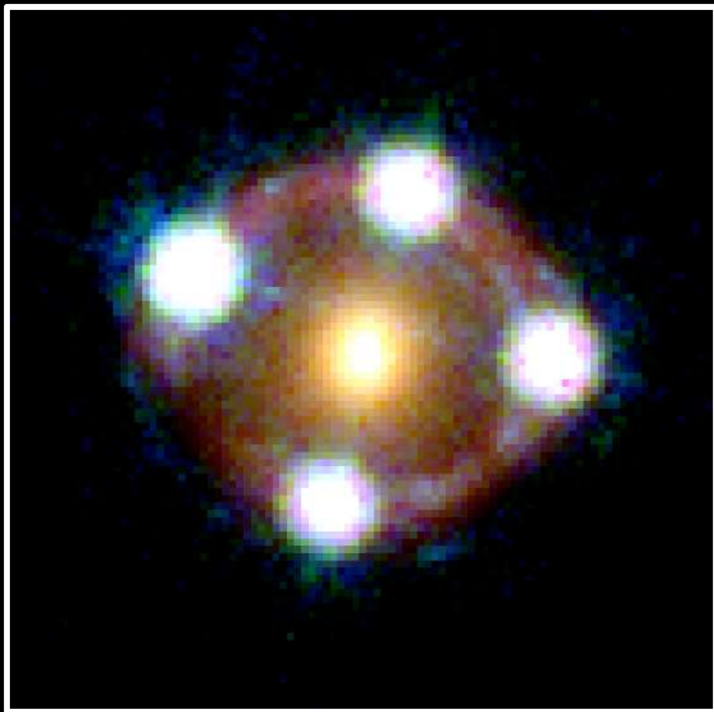
Cosmology with time delays



[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:

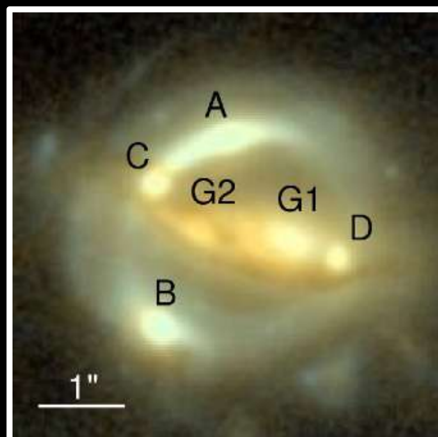
- simple geometry & well-tested physics

- one-step physical measurement of a cosmological distance

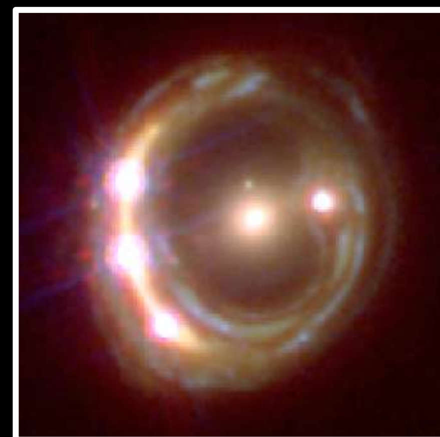
H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

B1608+656

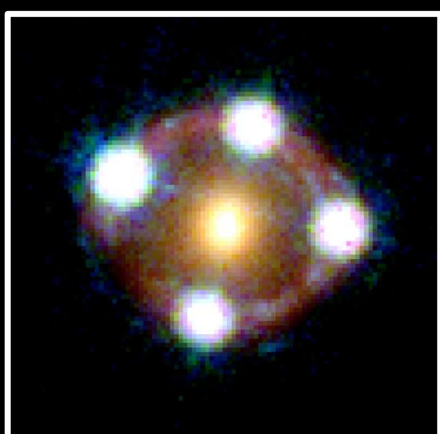


RXJ1131-1231



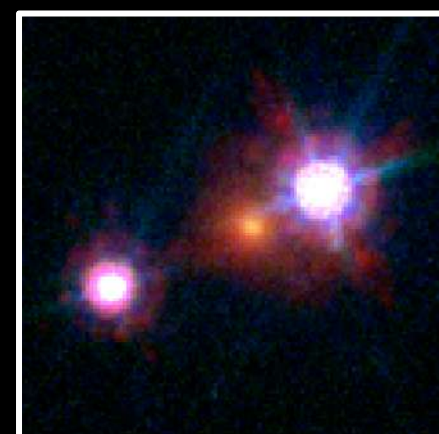
H_0 to <3.5% precision

HE0435-1223



WFI2033-4723

HE1104-1805



[Suyu et al. 2017]

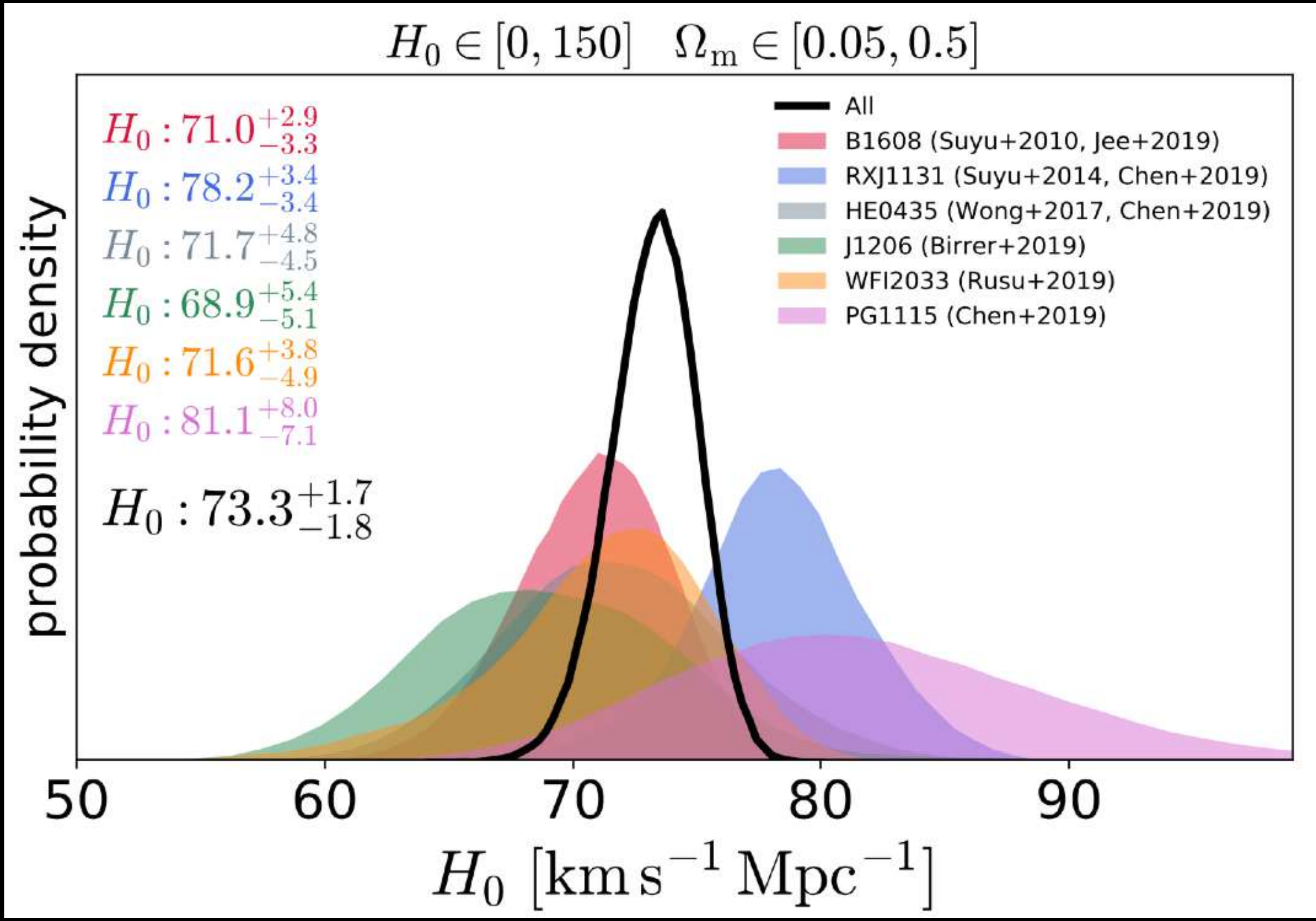
H0LiCOWers

H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

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

H_0 from 6 strong lenses

Blind analysis to avoid confirmation bias

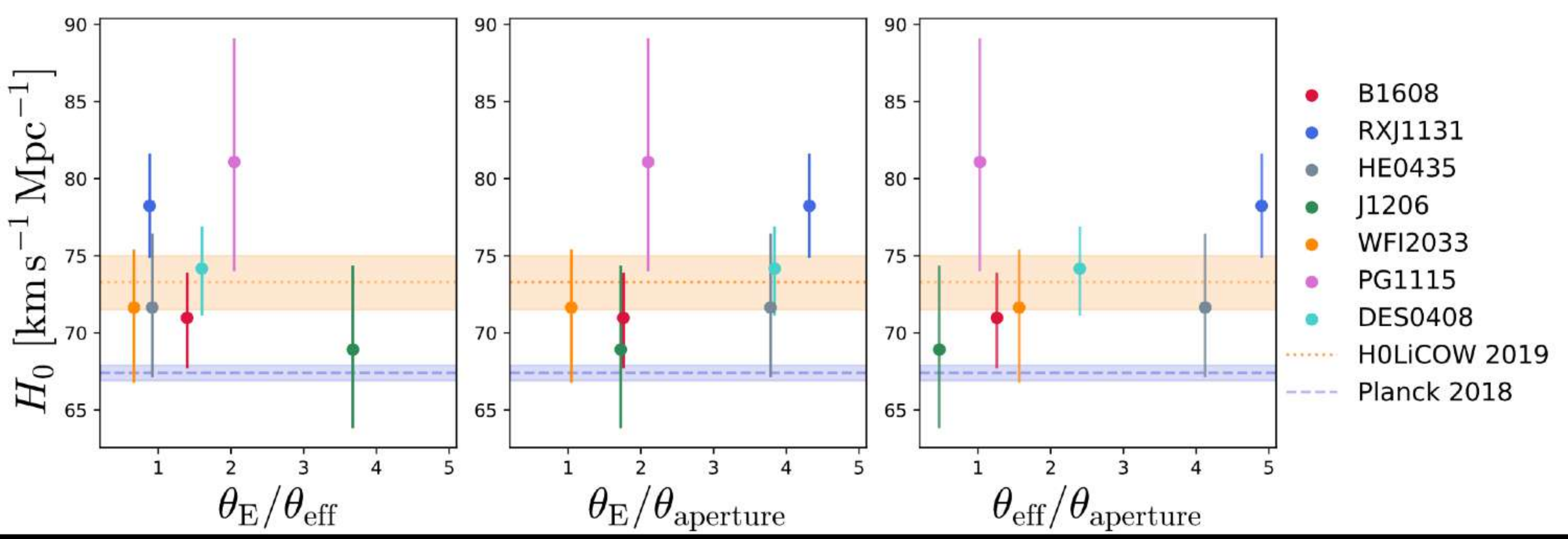


H_0 with 2.4% precision in flat ΛCDM

[Wong, Suyu, Chen et al. 2020]

Residual systematics?

No significant residual systematics detected wrt Einstein radii, effective radii, kinematic apertures

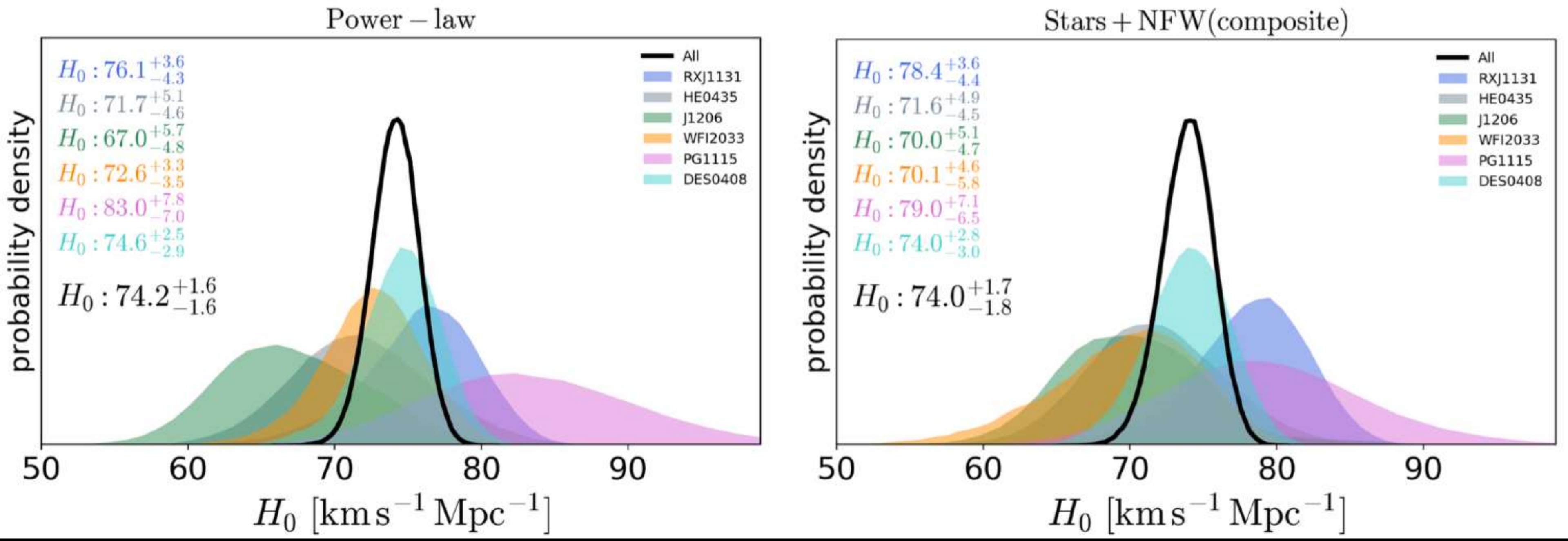


[Millon, Galan, Courbin et al. 2020; TDCOSMO I]

TDCOSMO = COSMOGRAIL + H0LiCOW + STRIDES + SHARP

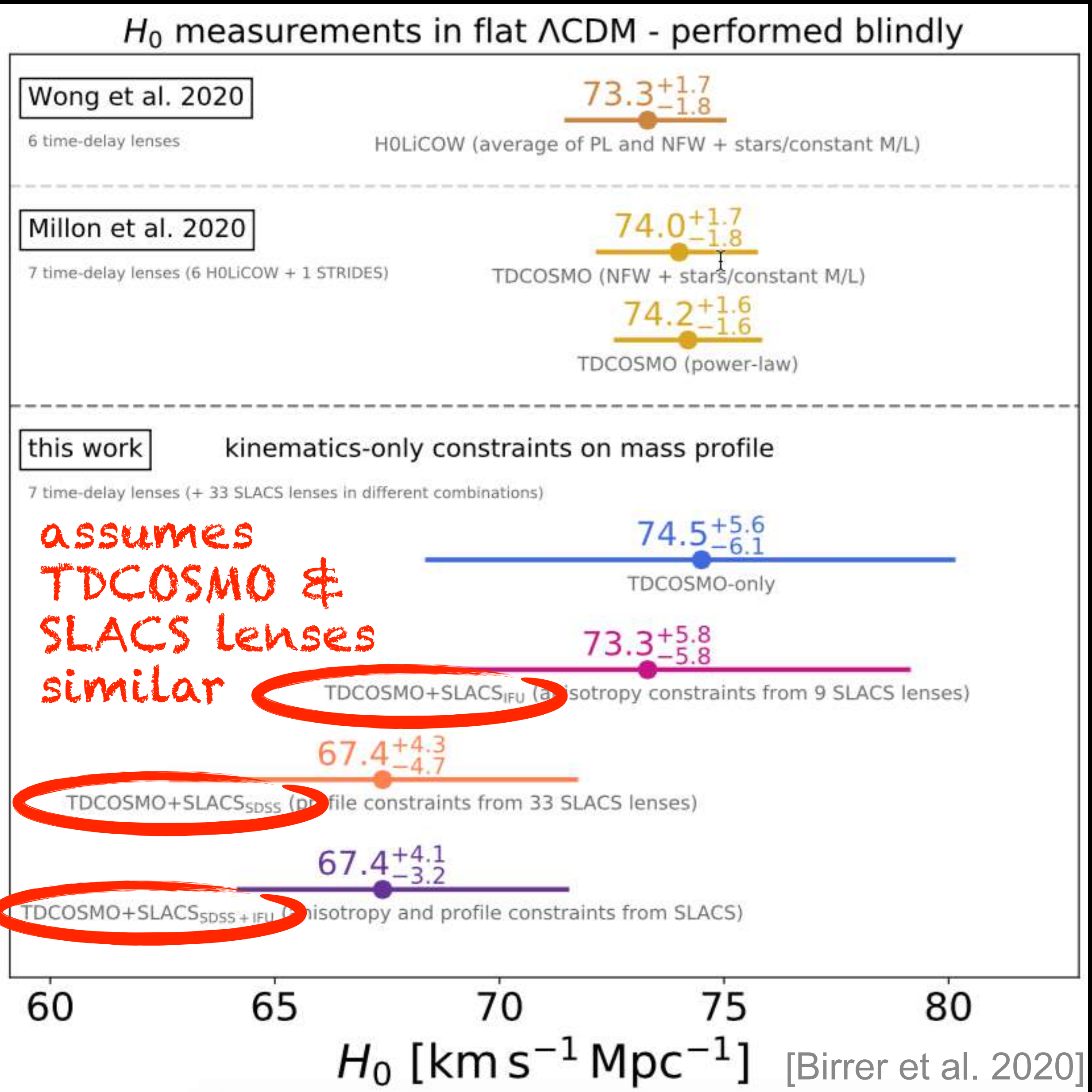
Residual systematics?

No significant residual systematics detected wrt mass model assumptions



[Millon, Galan, Courbin et al. 2020]

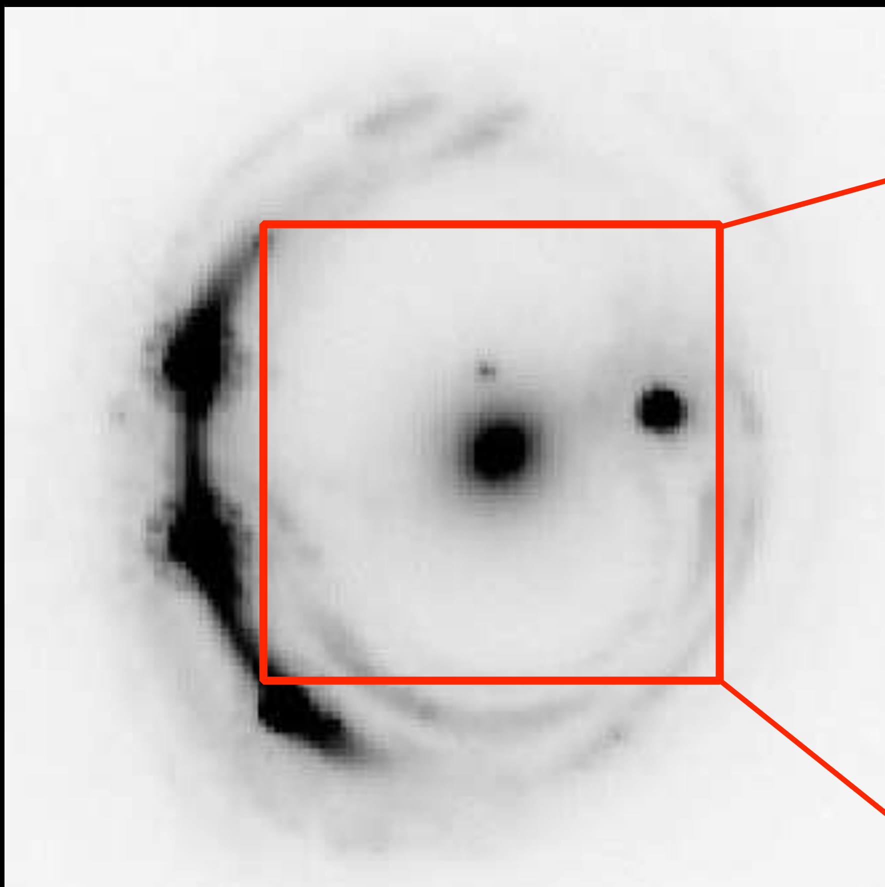
TDCOSMO



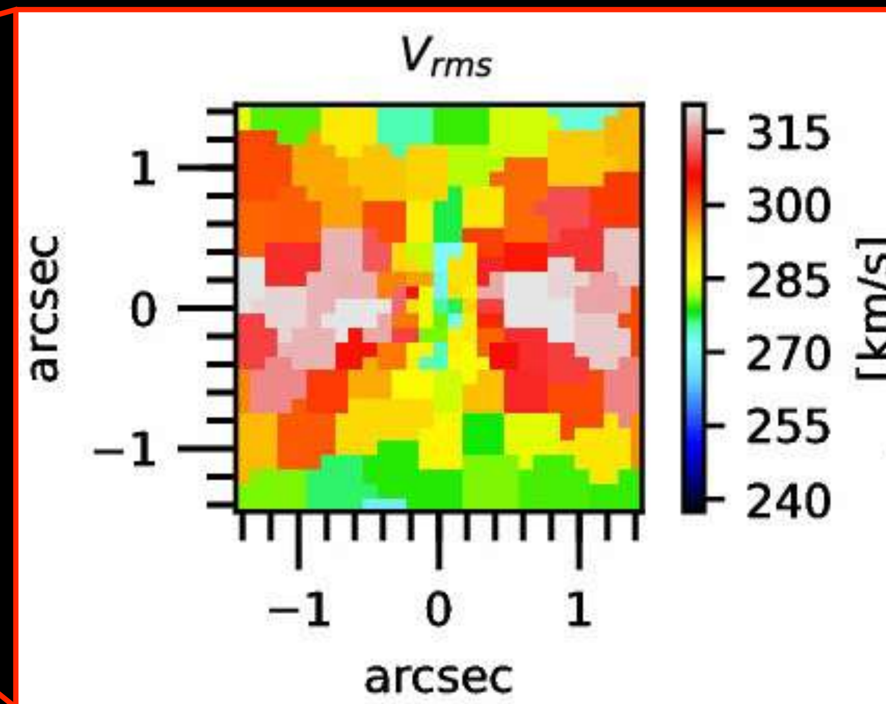
H0LiCOW used physical and well-motivated lens mass profiles

TDCOSMO Paper IV [Birrer et al. 2020]
➜ relax assumptions on lens mass profile
➜ use lens kinematic measurements
➜ use info of galaxy properties from SLACS lens systems

Stellar kinematics really helps

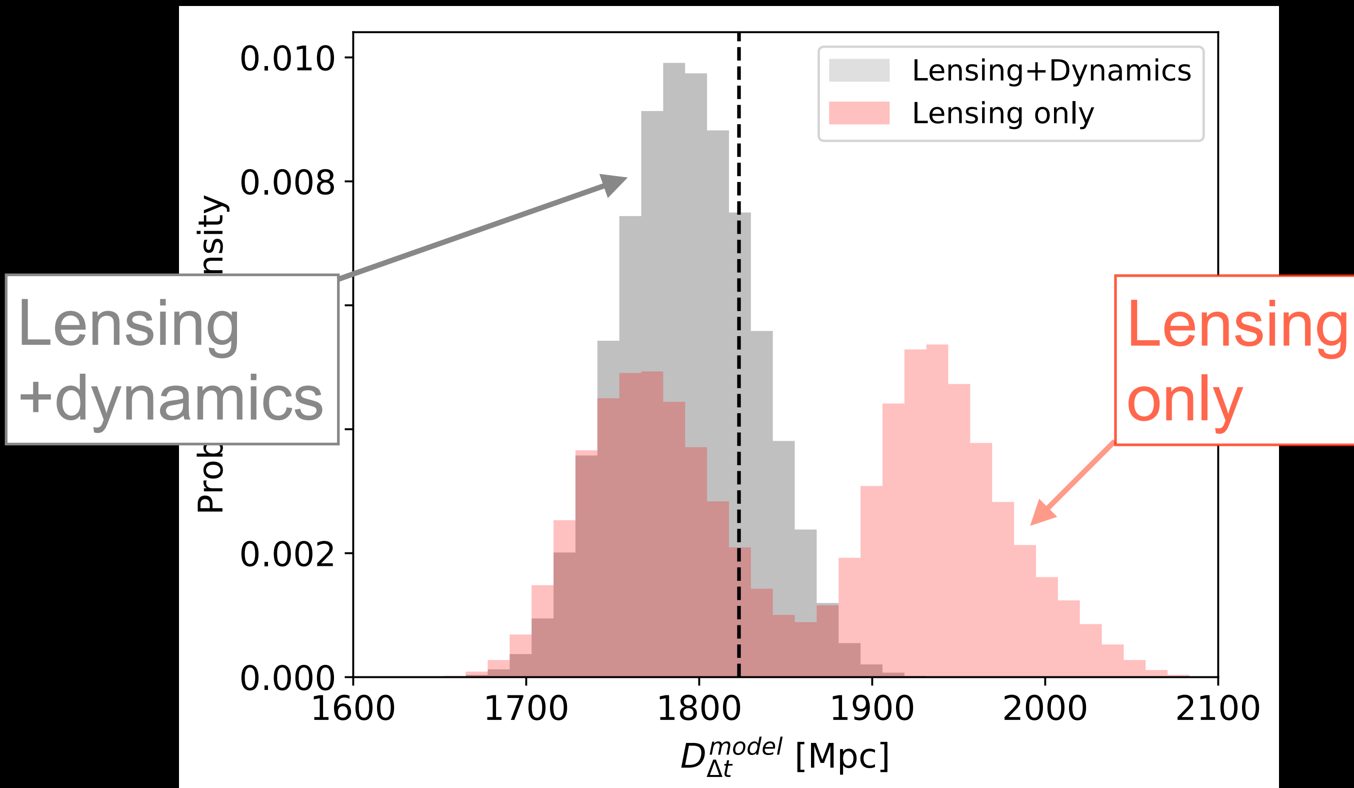


simulated James Webb Space Telescope NIRSpec observations of stellar kinematic map of lens



[Yıldırım, Suyu, Halkola 2020]

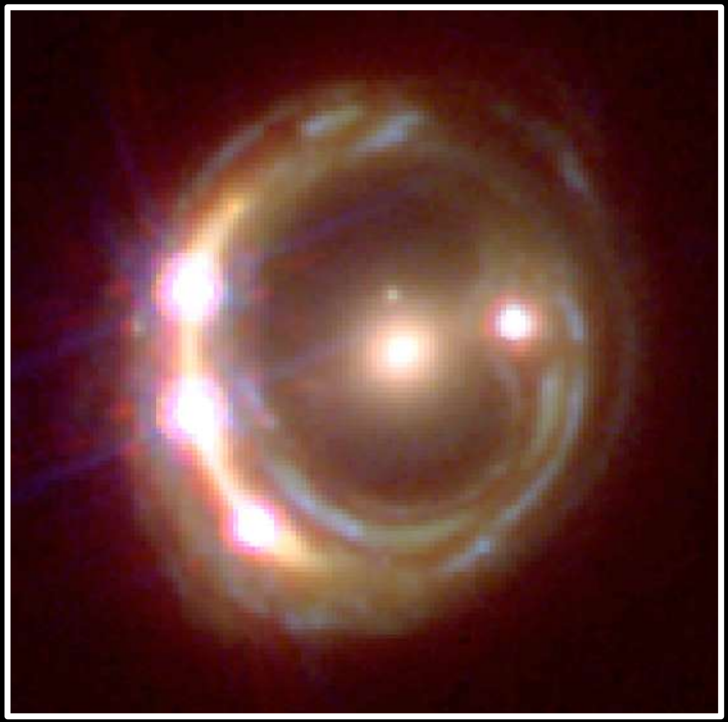
Stellar kinematics really helps



- 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 2020]

D_A to the lens



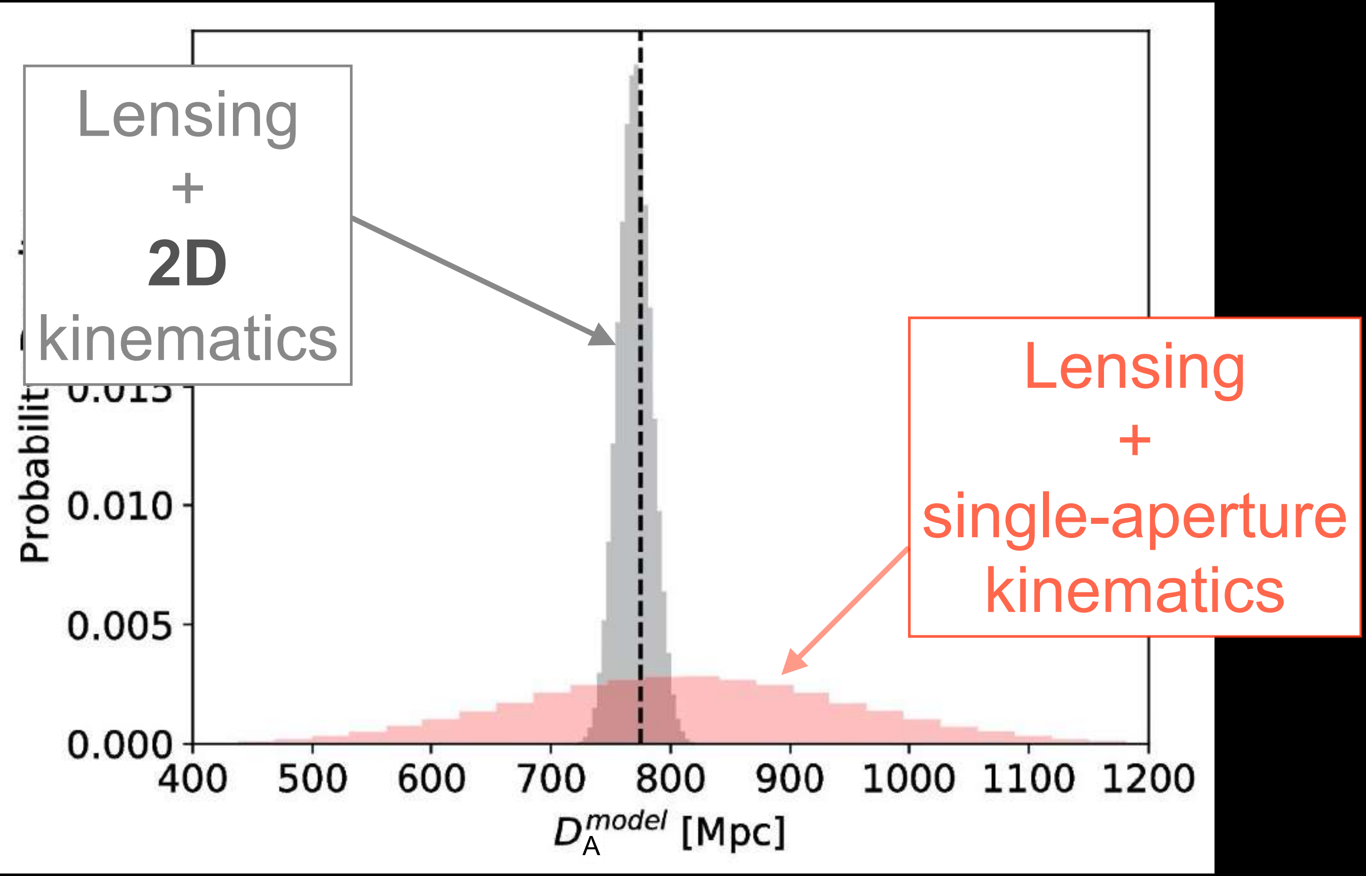
Angular diameter distance to the lens:

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

- D_A more sensitive to dark energy than $D_{\Delta t}$
- 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



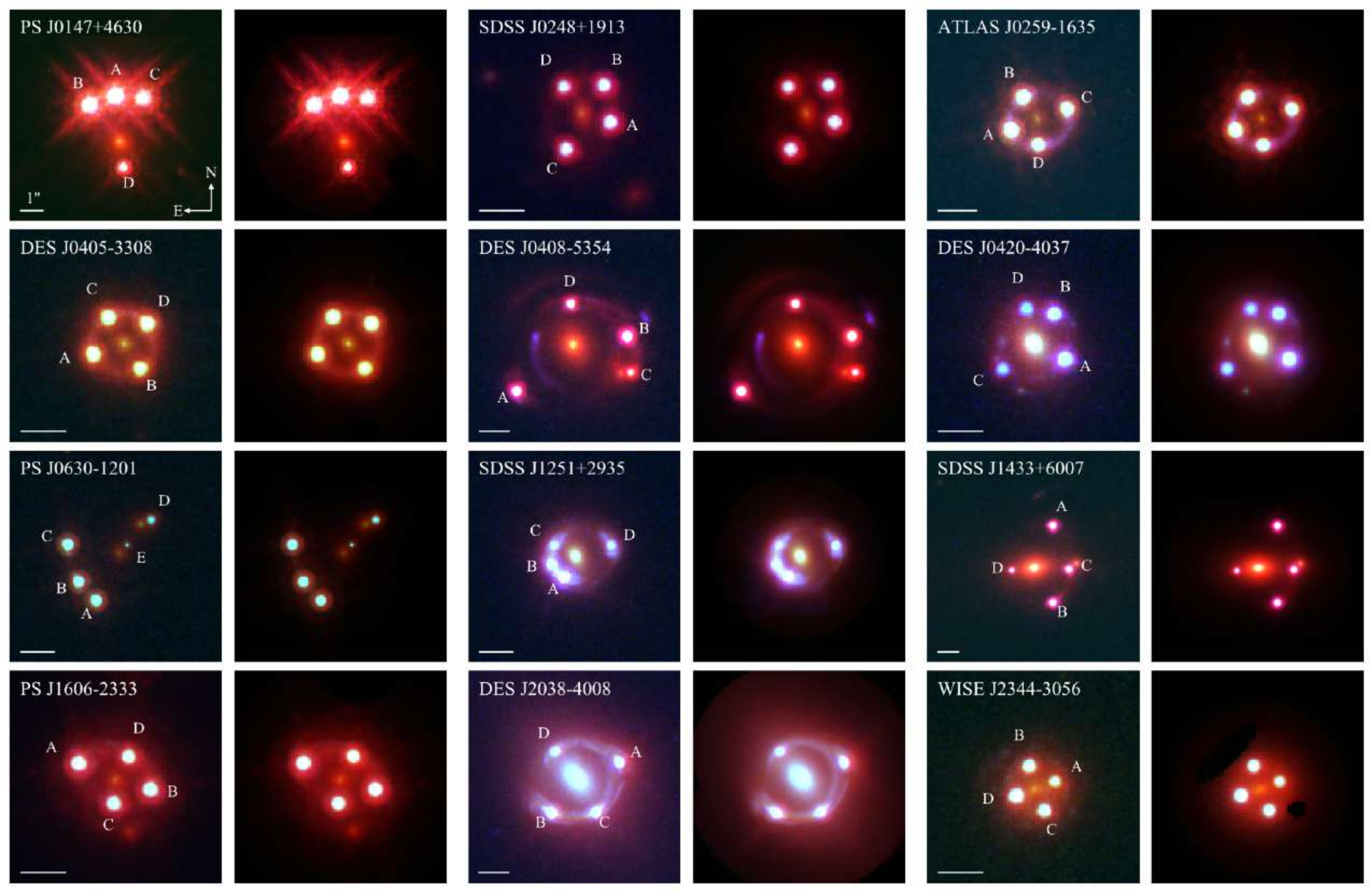
Including spatially-resolved (2D) kinematic data:

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

[Yıldırım, Suyu, Halkola 2020]

New quads imaged with HST

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



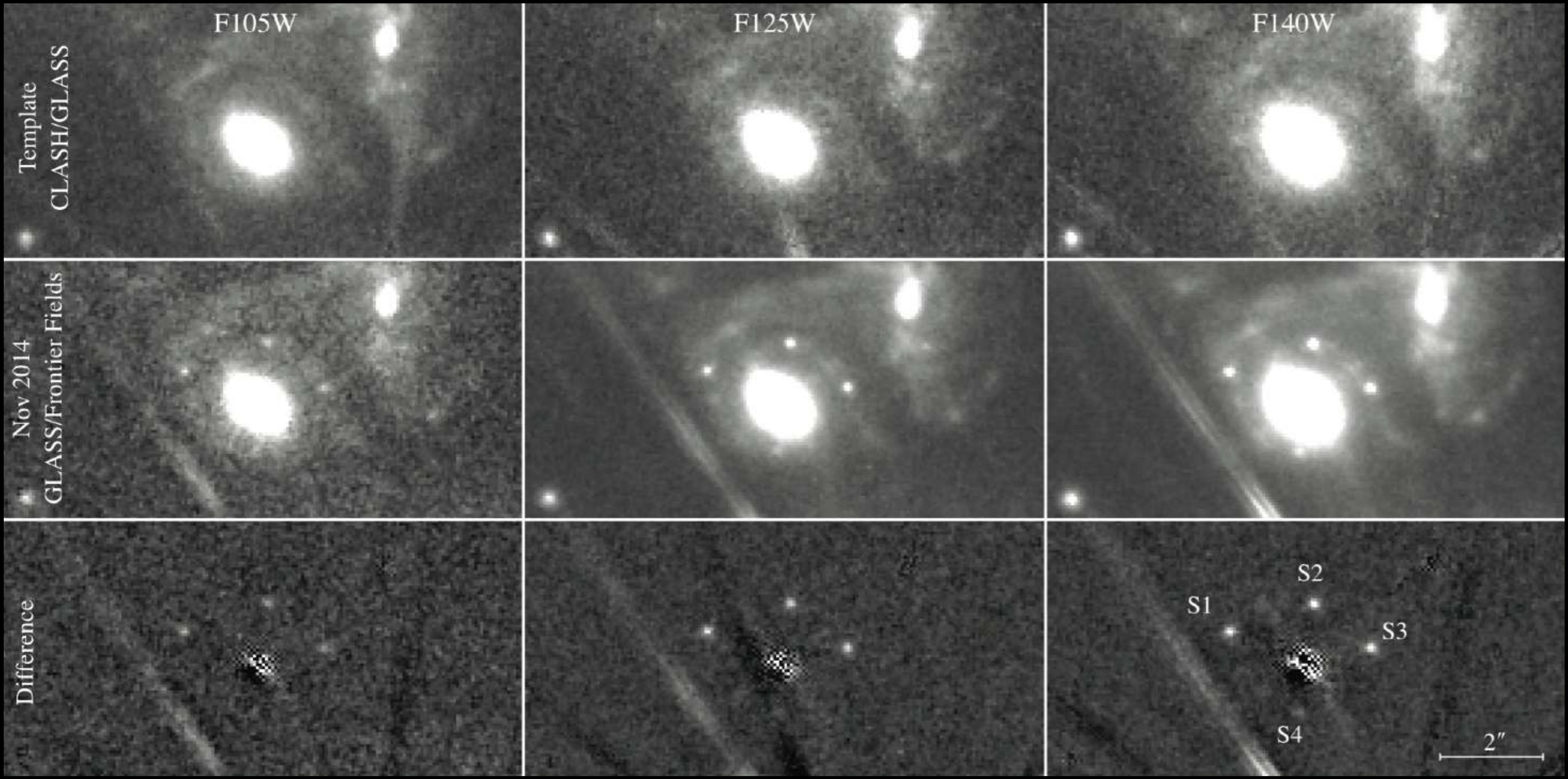
[Shajib et al. 2018]

Strongly lensed supernova

MACS 1149.6+2223 [Kelly et al. 2015]

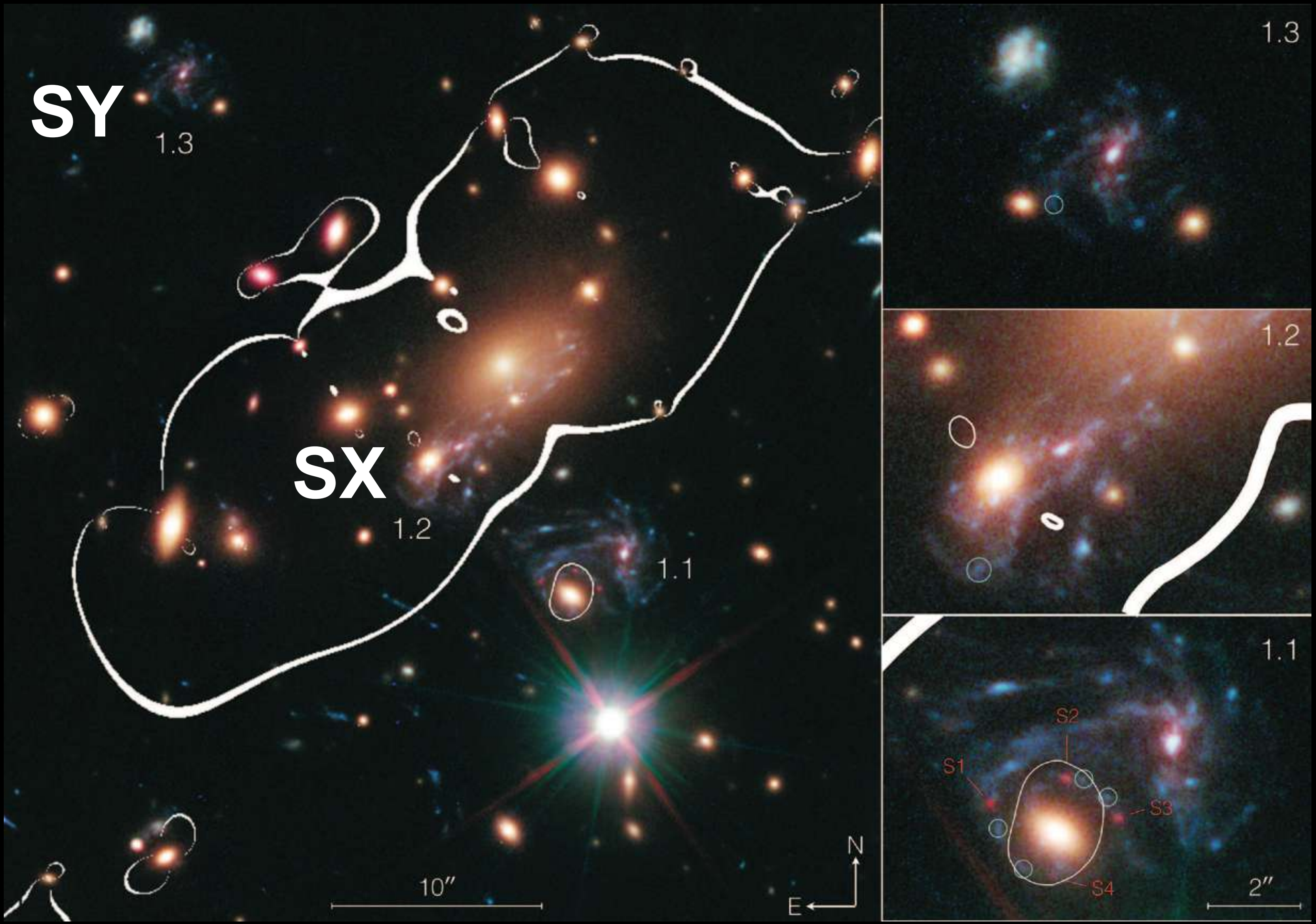
Supernova “Refsdal”

discovered serendipitously in November 2014



[Kelly et al. 2015]

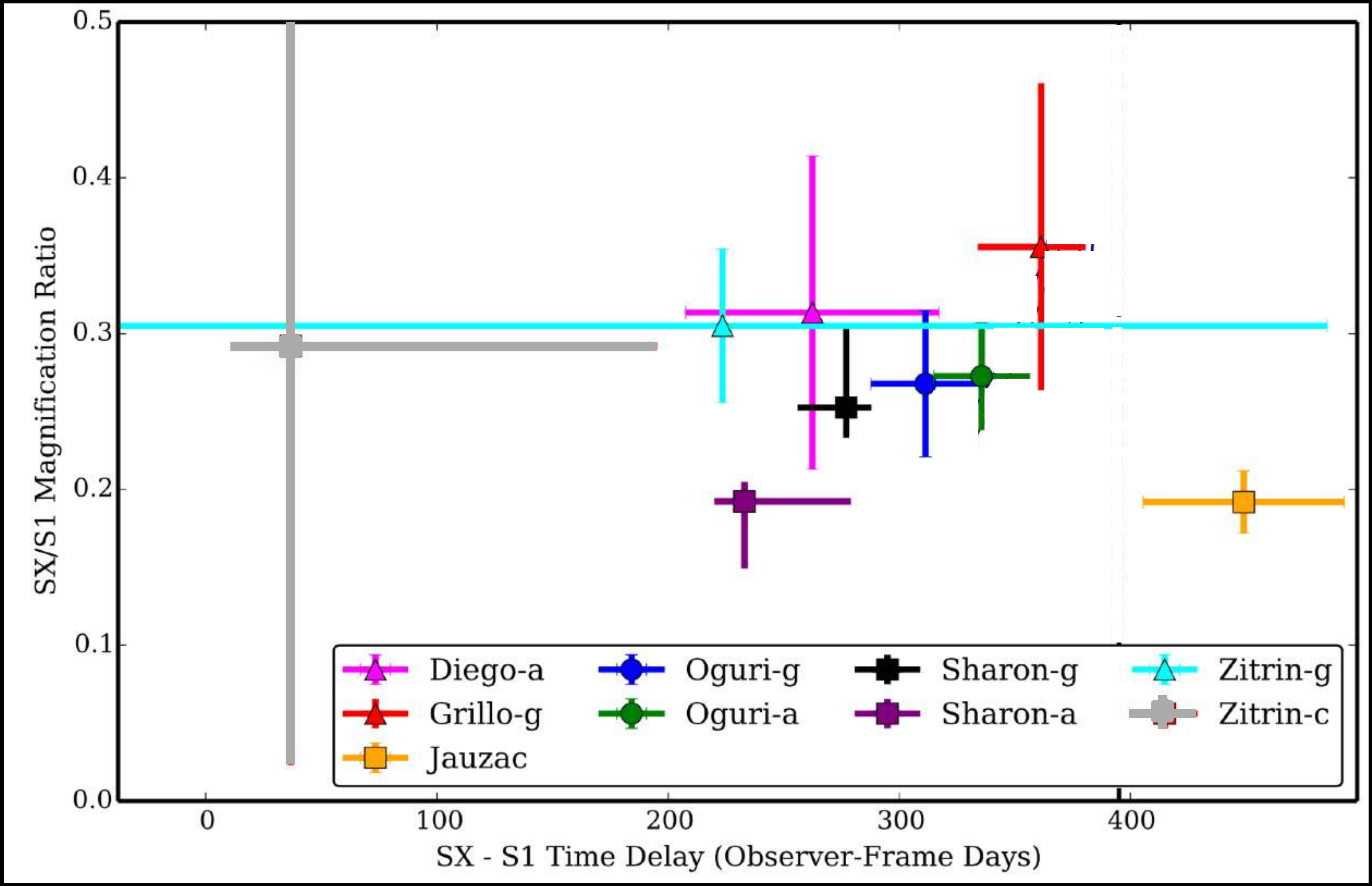
When will the other SN images appear?



MACS 1149.6+2223

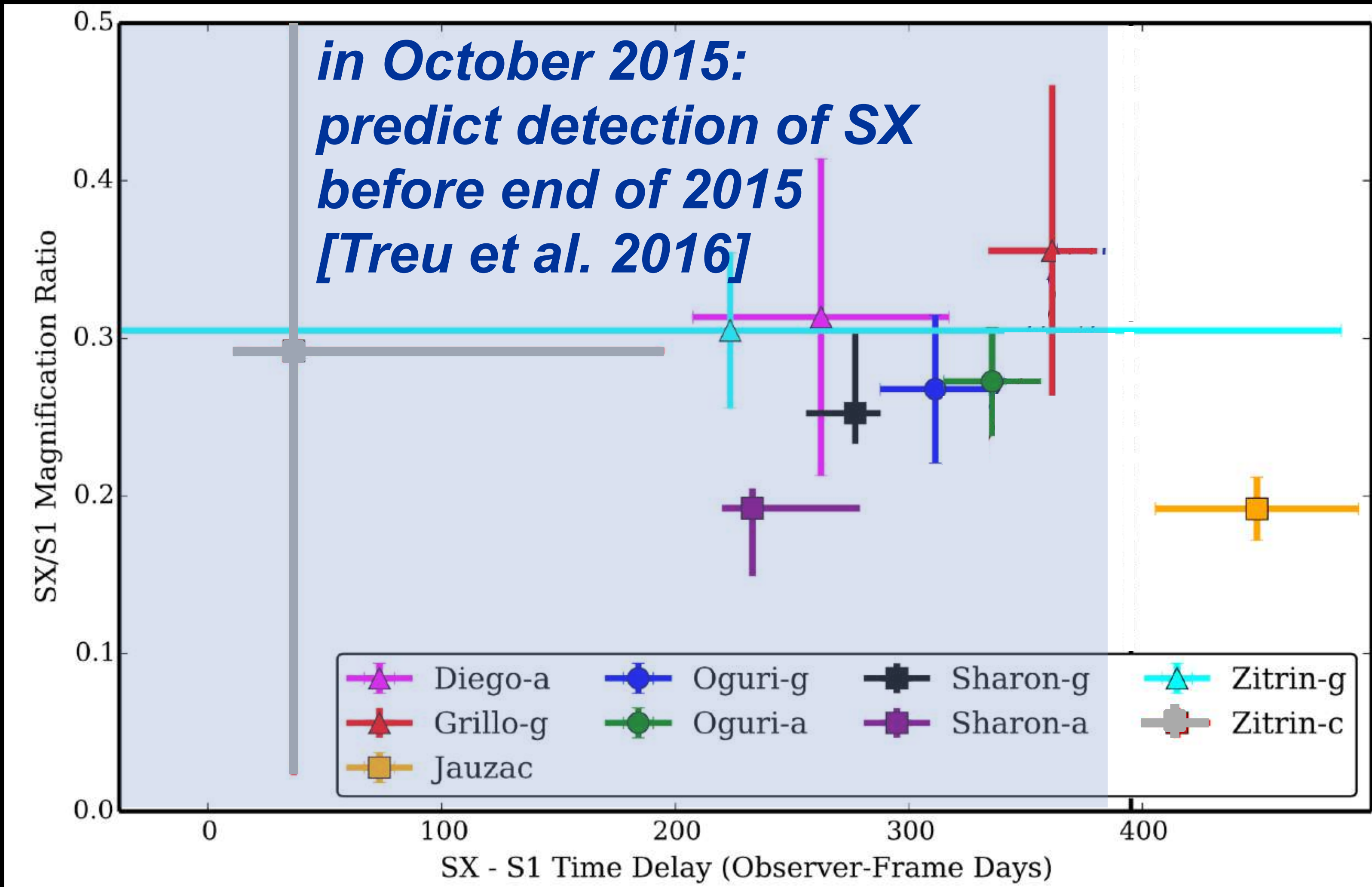
[Kelly et al. 2015]

Predicted magnification and delay



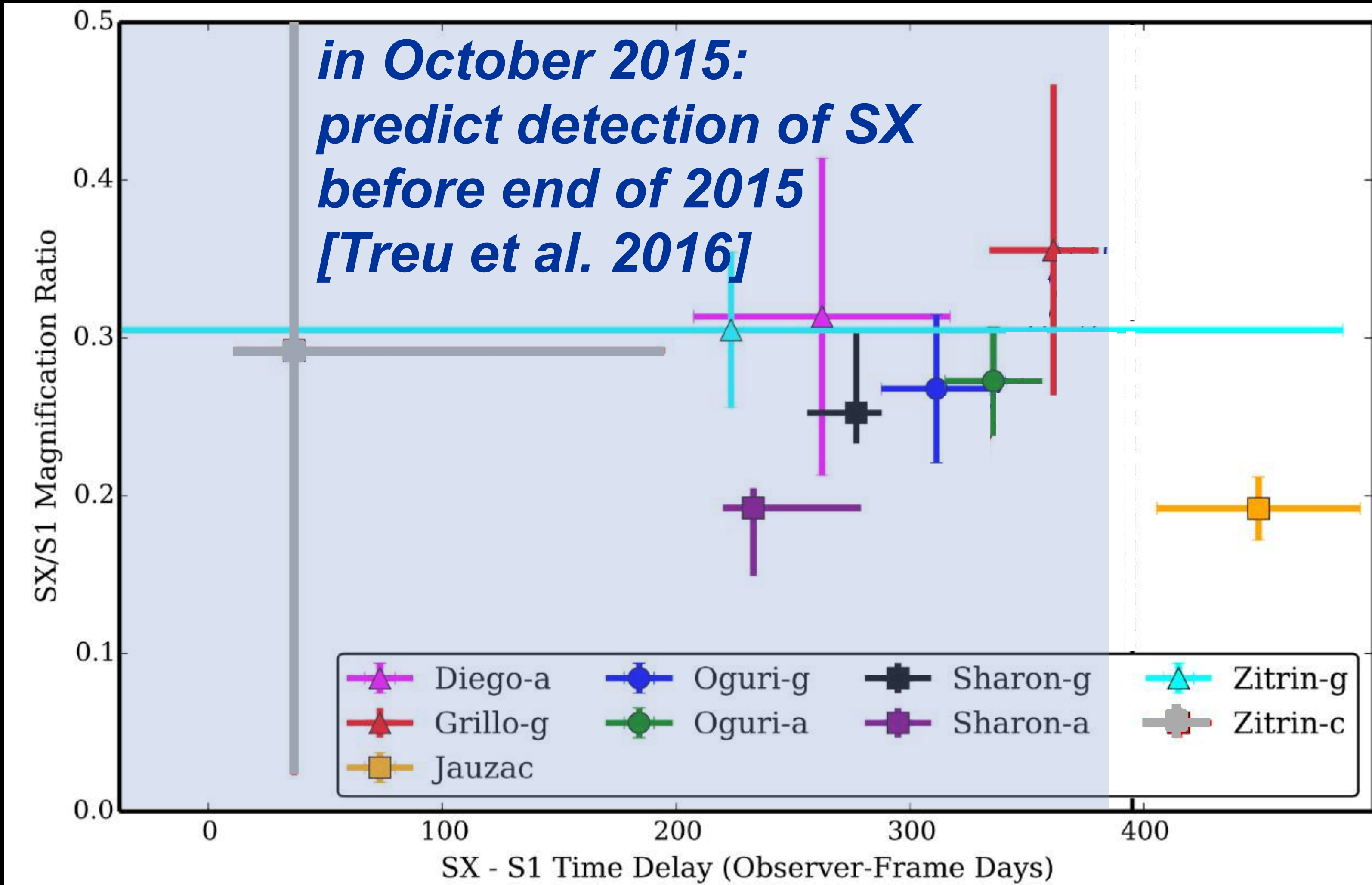
[Kelly et al. 2016]

Predicted magnification and delay



[Kelly et al. 2016]

Predicted magnification and delay



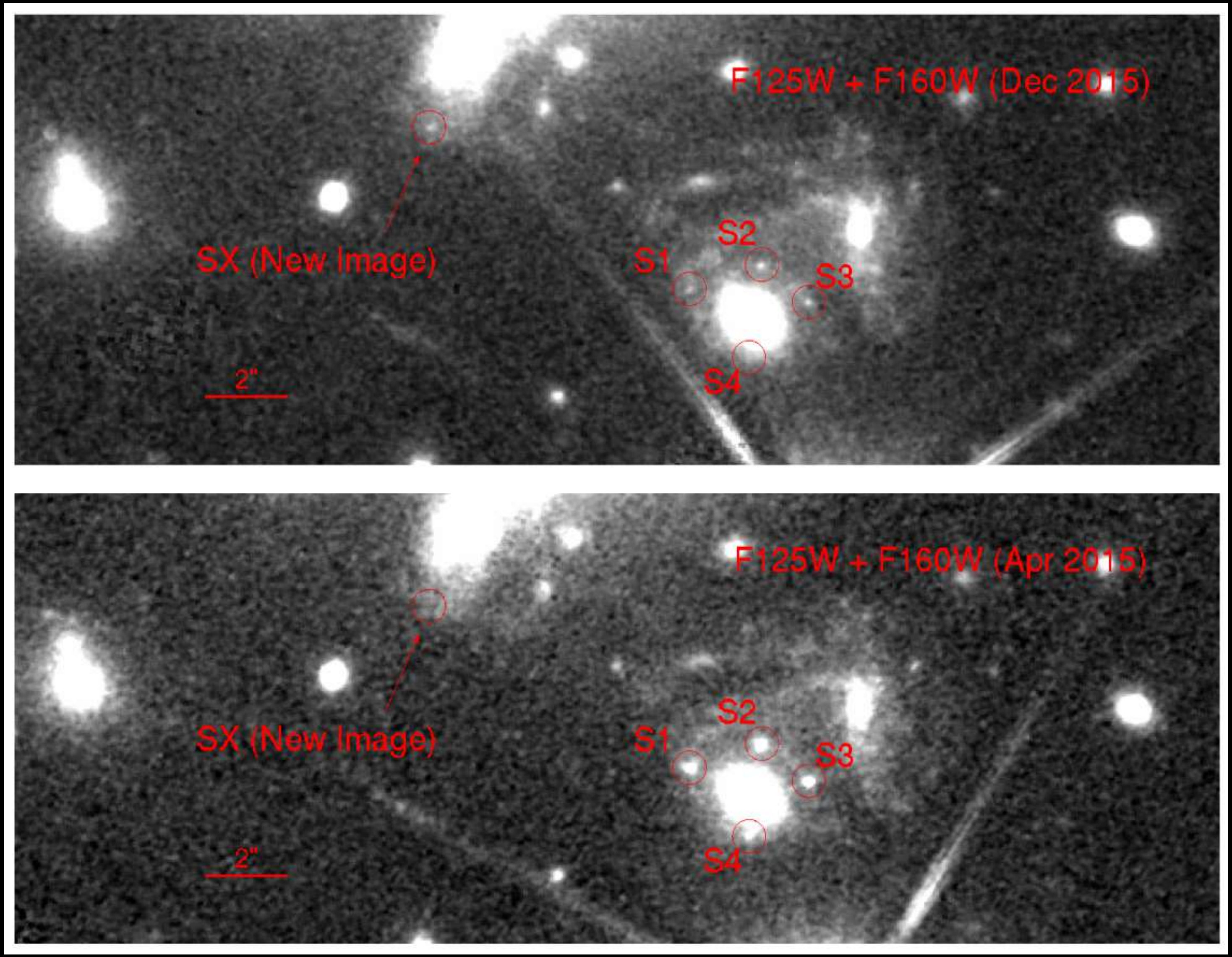
[Kelly et al. 2016]

HST observations in Oct 2015: no sign of SX

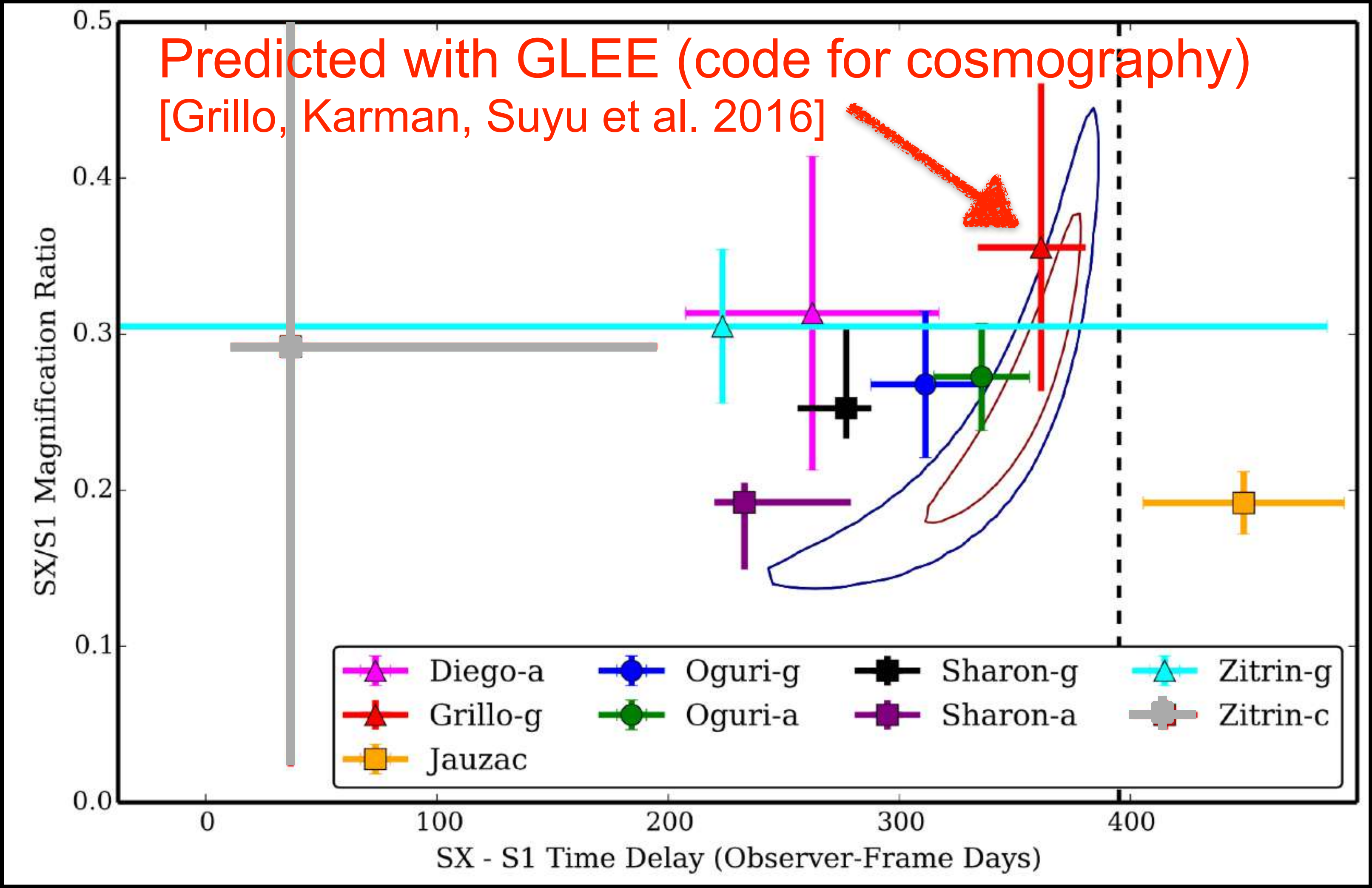
in Nov 2015: no sign of SX…

Appearance of image SX

December 2015 [Kelly et al. 2016]

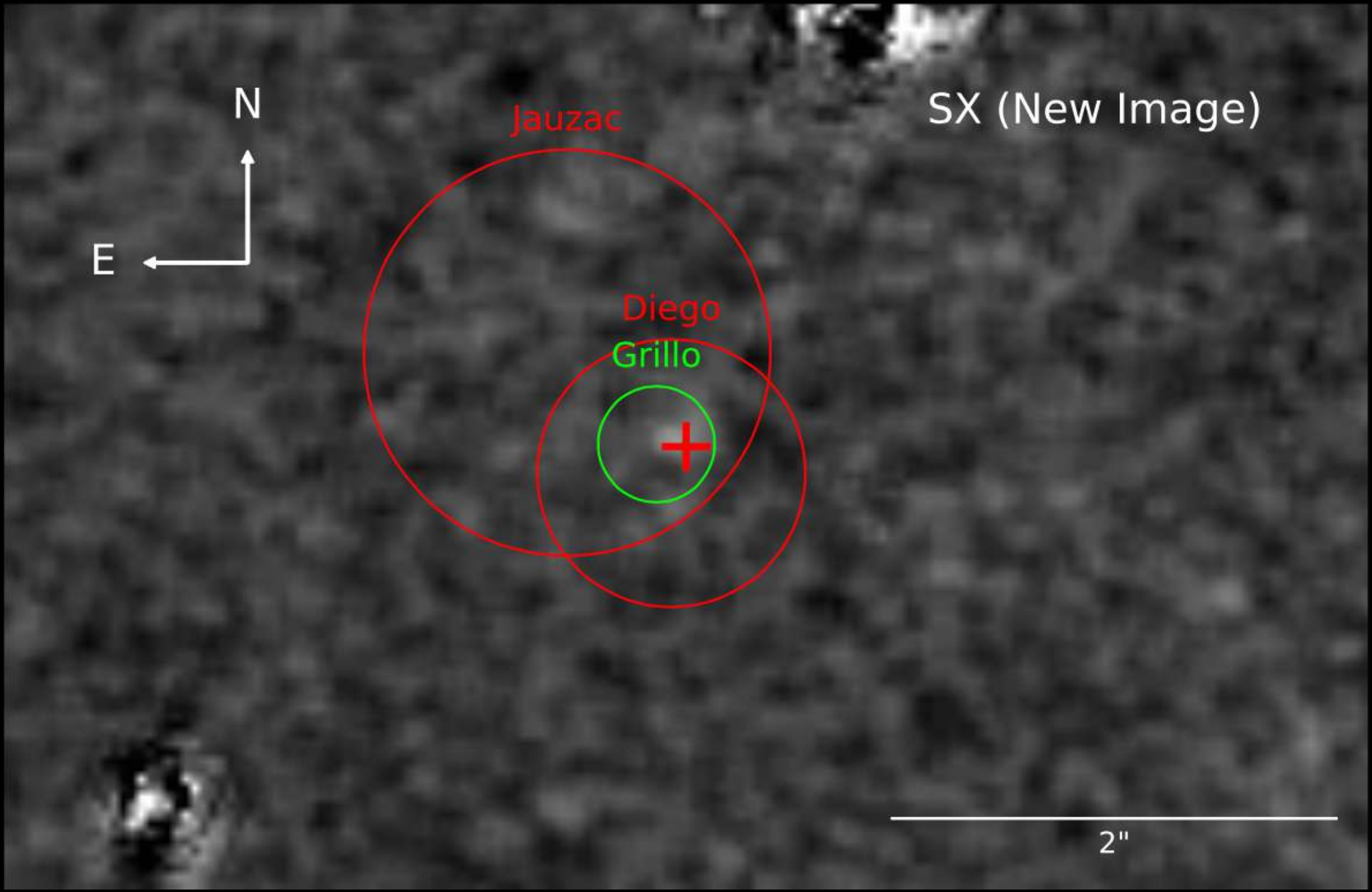


Magnification and delay



[Kelly et al. 2016]

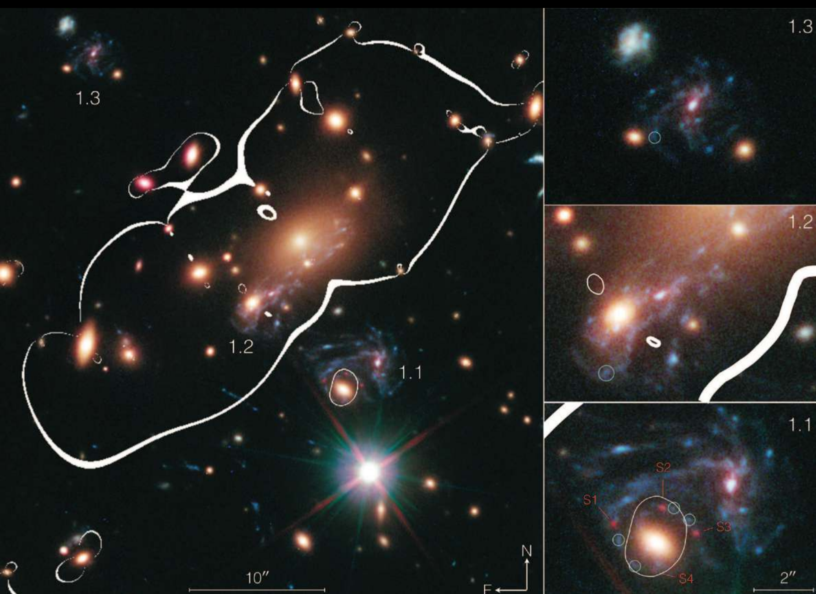
Spot on!

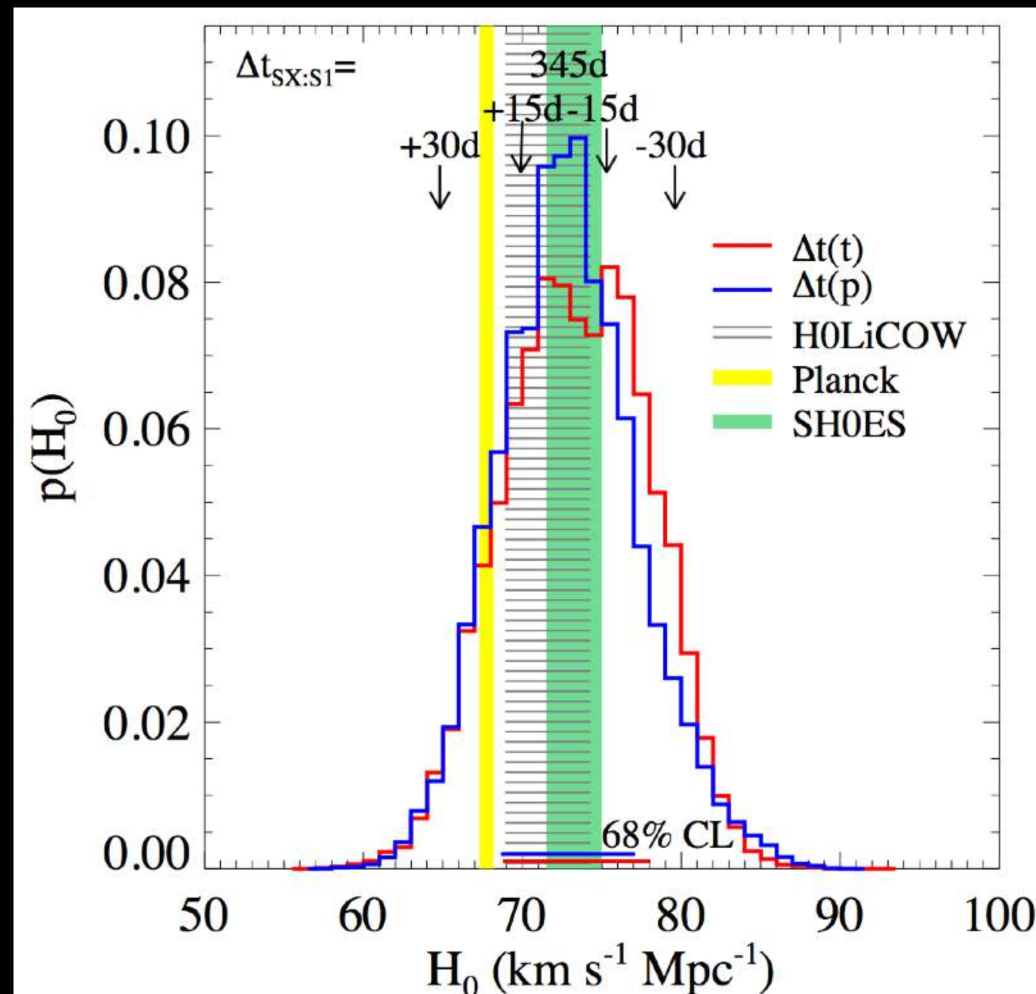


[Kelly et al. 2016]

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, 2020]

HOLISMOKES

Highly **O**ptimised **L**ensing **I**nvestigations of **S**upernovae, **M**icrolensing **O**bjects, and **K**inematics of **E**llipticals and **S**pirals

PI: S. H. Suyu

Lensed supernovae provide great opportunities for

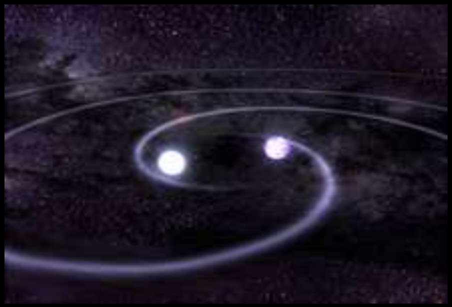
1) Constraining the progenitor of Type Ia supernova

single degenerate

White dwarf (WD) accreting from non-degenerate companion

or

double degenerate



WDs merging

2) Measuring the expansion rate of our Universe

[Suyu, Huber, Cañameras et al. 2020]

Search for lensed SNe

Zwicky Transient Facility (ZTF):

Combine ZTF + Pan-STARRS to search for lensed SNe

New lenses in Pan-STARRS

- Find lensed galaxies in Pan-STARRS as potential hosts of SN
- Used Deep Learning to cope with huge data volume
- $3x10^9$ sources in Pan-STARRS 3π survey

➜ $2.3x10^7$ after simple photometric cuts, star removal

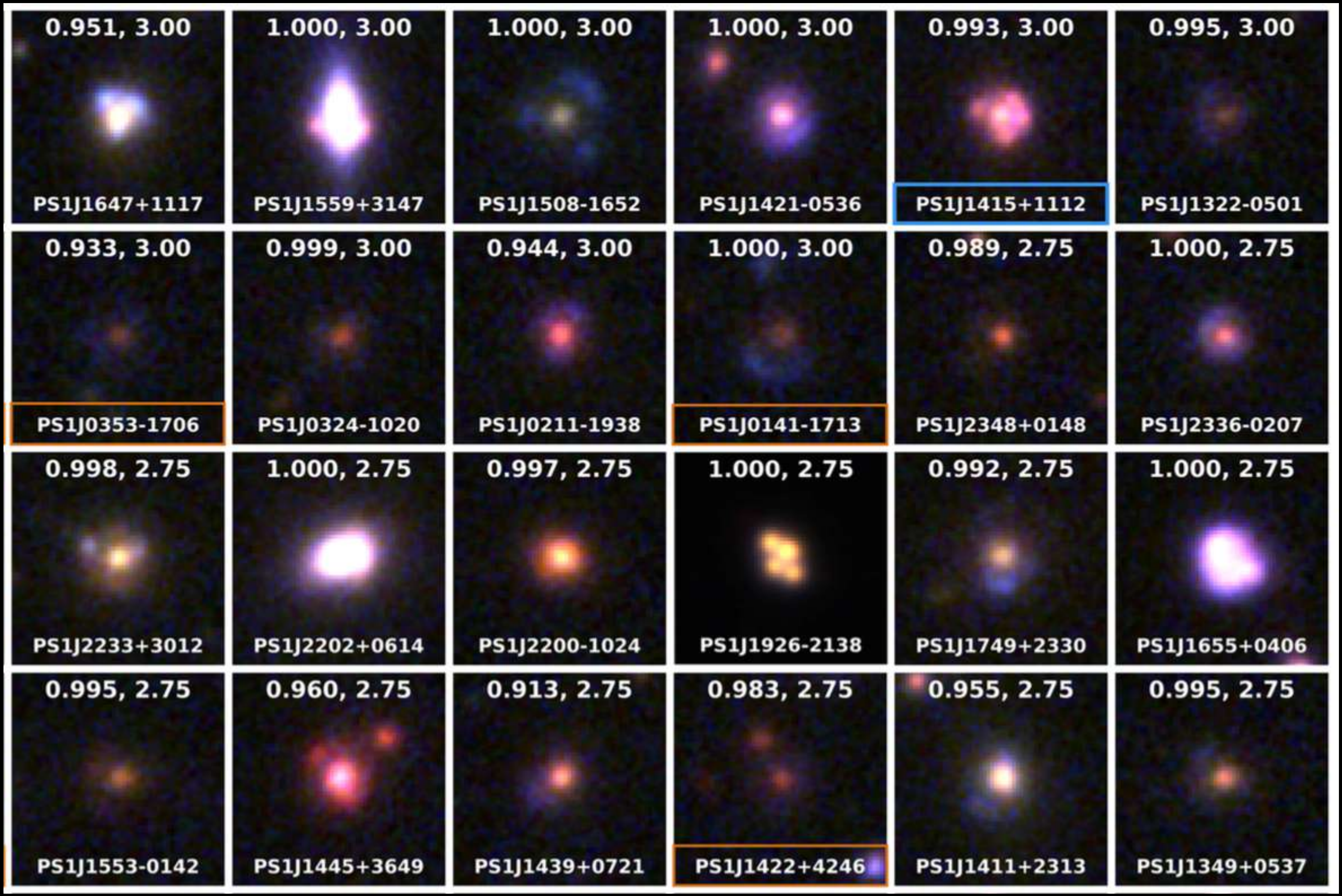
➜ $1.0x10^6$ after apply neural network on photometric measurements

➜ $1.2x10^4$ after apply convolutional neural network on g, r, i-band image cutouts of systems

➜ 330 high-quality candidates after visual inspection

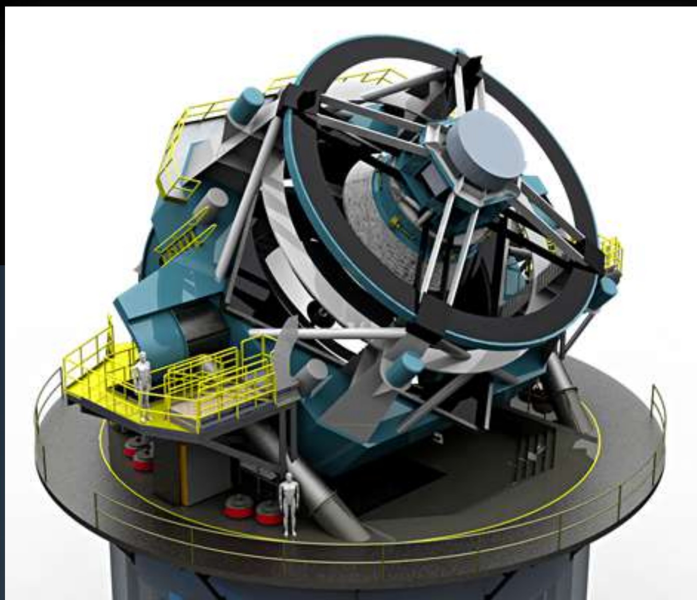
[Cañameras, Schuldt, Suyu, Taubenberger et al., arXiv:2004.13048]

New lenses in Pan-STARRS



[Cañameras, Schuldt, Suyu, Taubenberger et al., arXiv:2004.13048]

Rubin Observatory
Legacy Survey of Space and Time (LSST)



High etendue survey telescope:

Visible sky mapped **every few nights**
Cerro Pachon, Chile: **0.7" seeing**

Ten year movie of the entire Southern sky

Survey starts ~2023

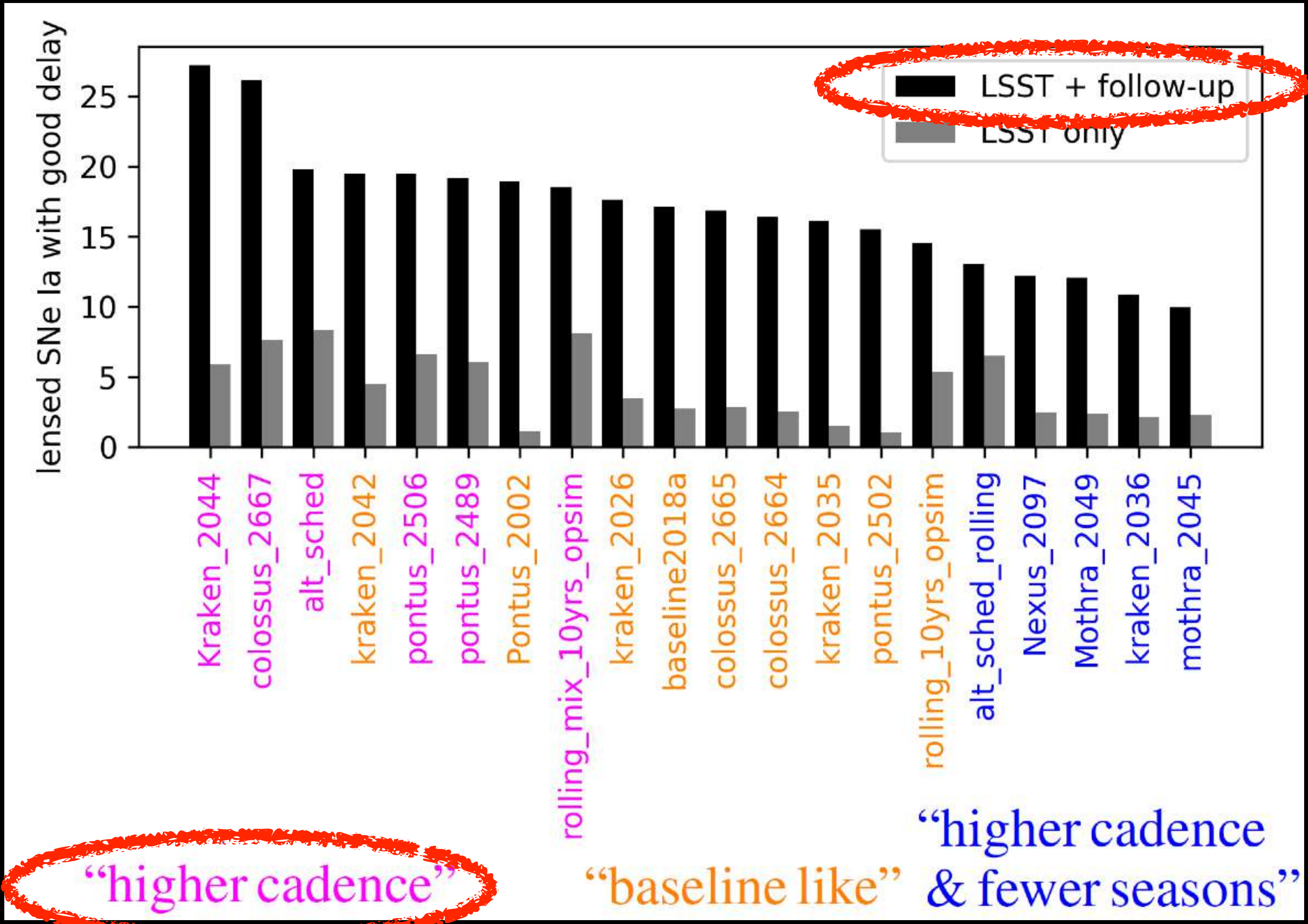
Expect hundreds of lensed SNe in the 10-year LSST survey
[Oguri & Marshall 2010; Goldstein et al. 2017; Wojtak et al. 2019]

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

[Part of slide material courtesy of Phil Marshall]

Cadence Strategy for Lensed SNe

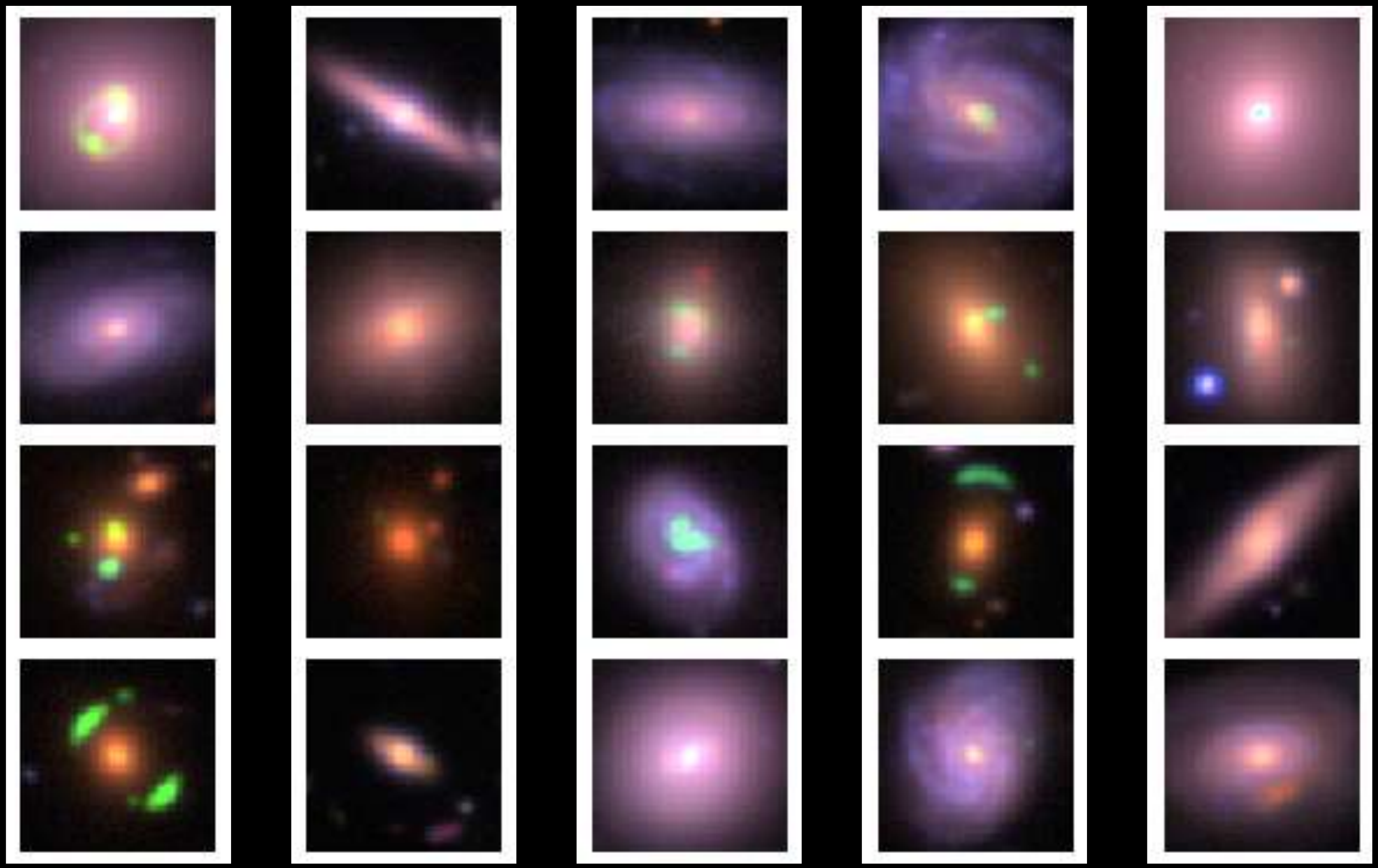
quantitatively compare LSST observing strategies



[Huber, Suyu, Noebauer et al. 2019]

Lens modeling with machine learning

- simulate realistic lenses
- train neural network to infer lens mass parameters
  [Hezaveh et al. 2017; Levasseur et al. 2017]



[Schuldt, Suyu, Meinhardt et al., 2020]

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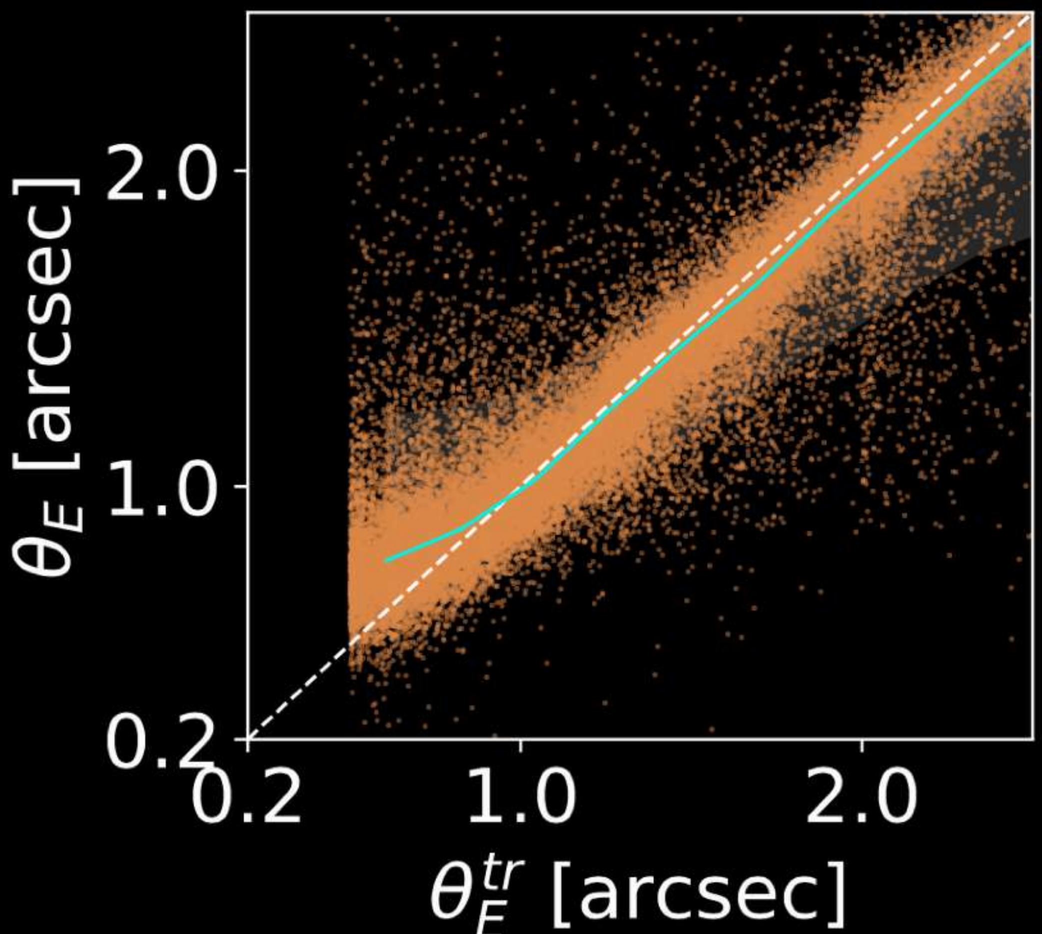


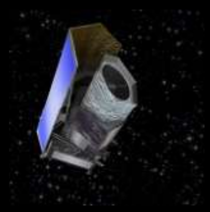
neural network recovers lens mass parameters

[Schuldt, Suyu, Meinhardt et al., 2020]

Future Prospects

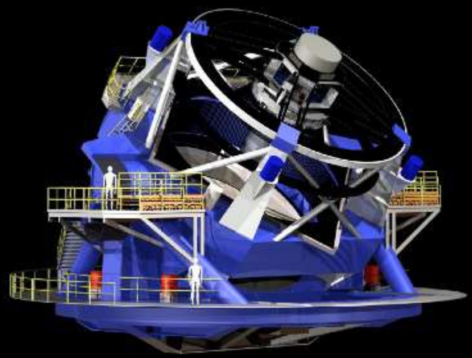
Experiments and surveys in the 2020s including Euclid, Rubin, and Roman observatories will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid



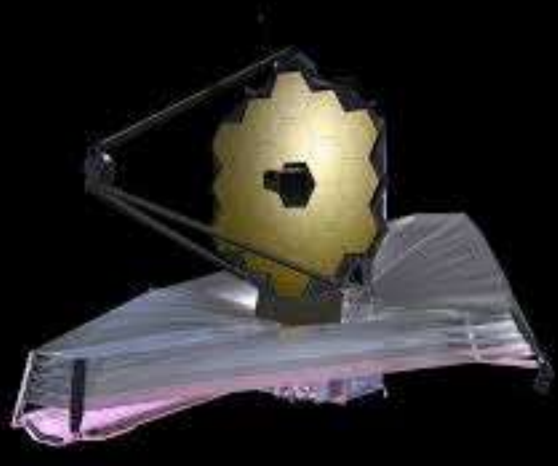
Discovery
Imaging
Spectroscopy

LSST



Discovery
Time delays
Imaging

JWST



High-resolution imaging
& spectroscopy

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Summary

- Time-delay distances $D_{\Delta t}$ of each lensed quasar can be measured with uncertainties of ~5-8% including systematics
- From 6 lensed quasars 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
- New lensed quasar systems being discovered, observed and analysed as part of TDCOSMO
- SN Refsdal blind test demonstrated the robustness of our cluster mass modeling approach and software GLEE
- HOLISMOKES: lensed supernovae to constrain supernova progenitors and cosmology
- Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology and supernova physics