H0LiCOW! Cosmology with Gravitational Lens Time Delays

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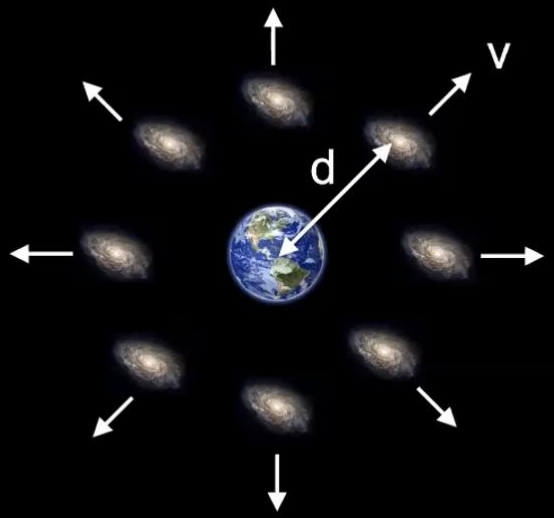
Expanding Universe

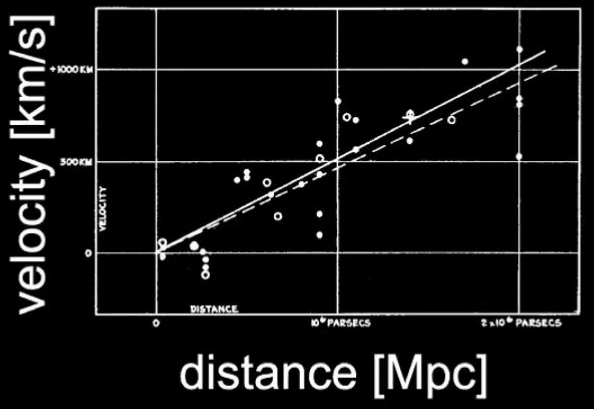
1920s Discovery



Lemaître & Hubble independently measured the expansion rate

$v = H_0 \times d$

Hubble Constant



distance [Mpc]

H_0 sets age and size of Universe! [Hubble 1929]

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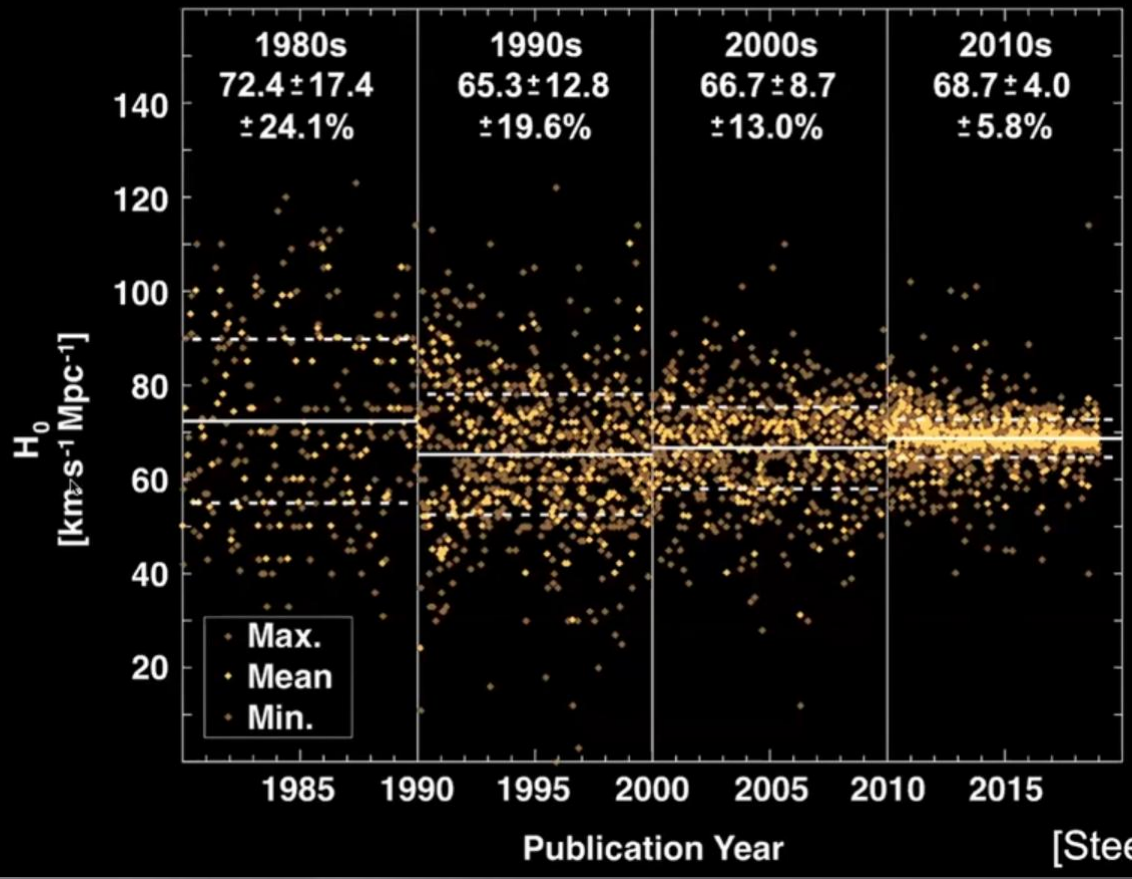
Measurements in the last decades



[Steer 2020]

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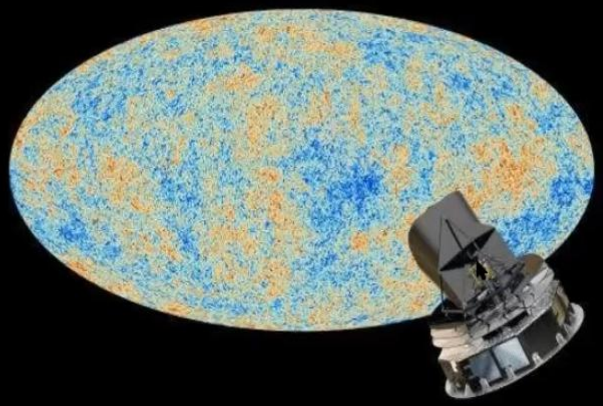
Tension in H_0

Measurement from early universe:
Cosmic Microwave Background



[Planck collaboration 2020]

67.4 ± 0.5
assuming ΛCDM

Measurement from local universe:
supernova distance ladder

[credit: NASA/JPL-Caltech]

SH0ES [Riess et al. 2020]

73.2 ± 1.3

H_0
[$km^{-1}s^{-1}Mpc^{-1}$]

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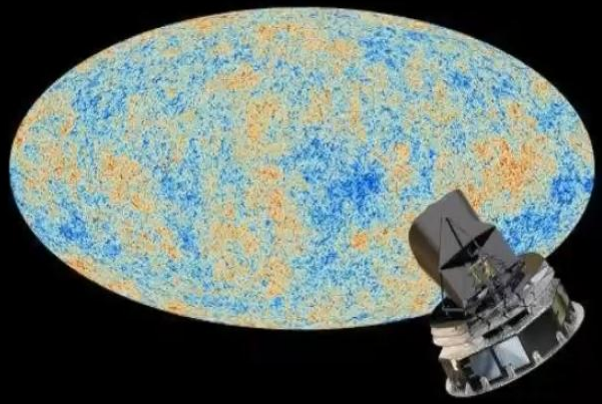
Tension in H_0

Measurement from early universe:
Cosmic Microwave Background



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Measurement from local universe:
supernova distance ladder

[credit: NASA/JPL-Caltech]

SH0ES [Riess et al. 2020]

73.2 ± 1.3

4.2σ tension

New physics beyond standard cosmological model ΛCDM?

H_0 [$km^{-1}s^{-1}Mpc^{-1}$]

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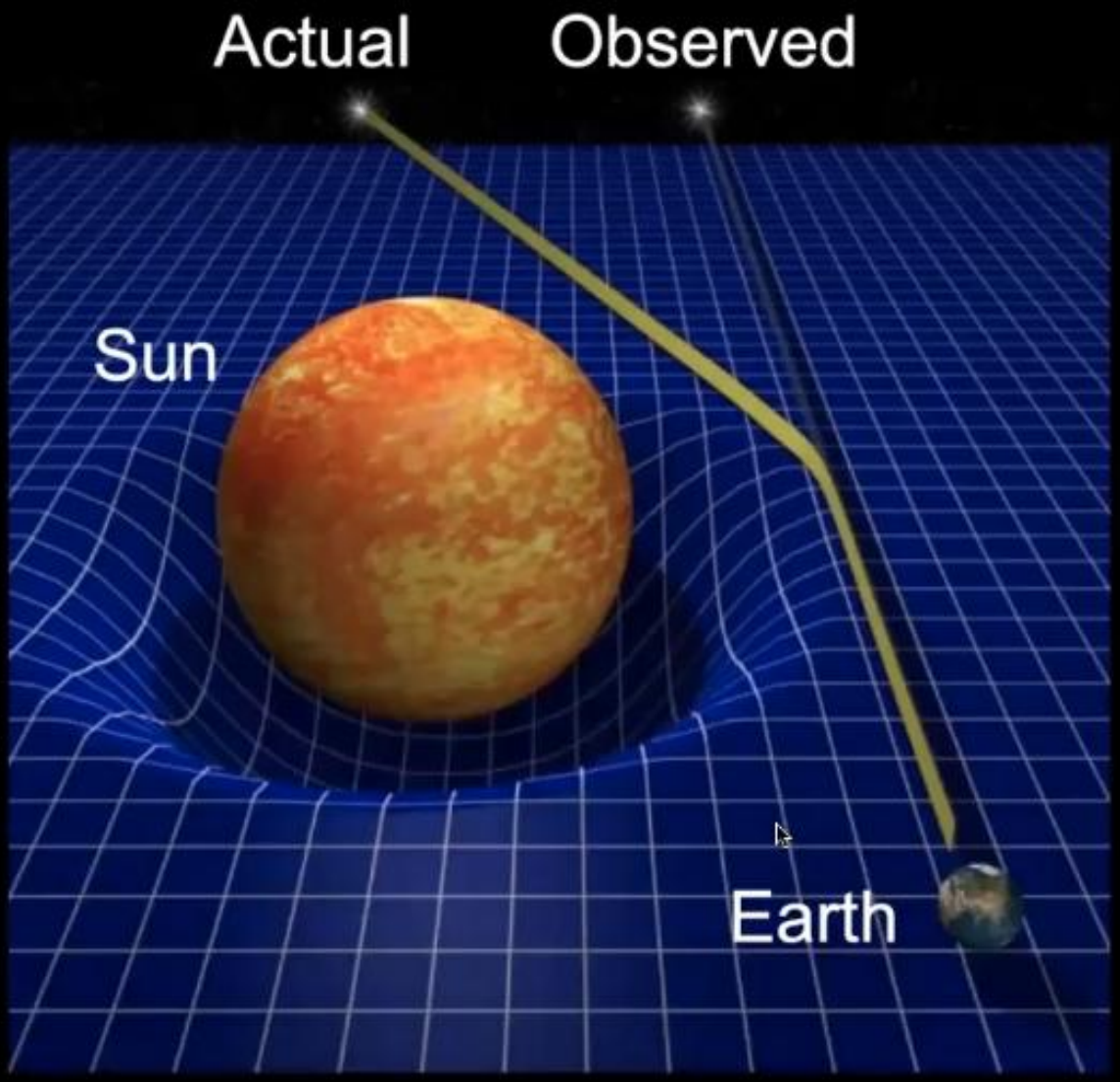
Gravitational Lensing



Strong Optical Lensing

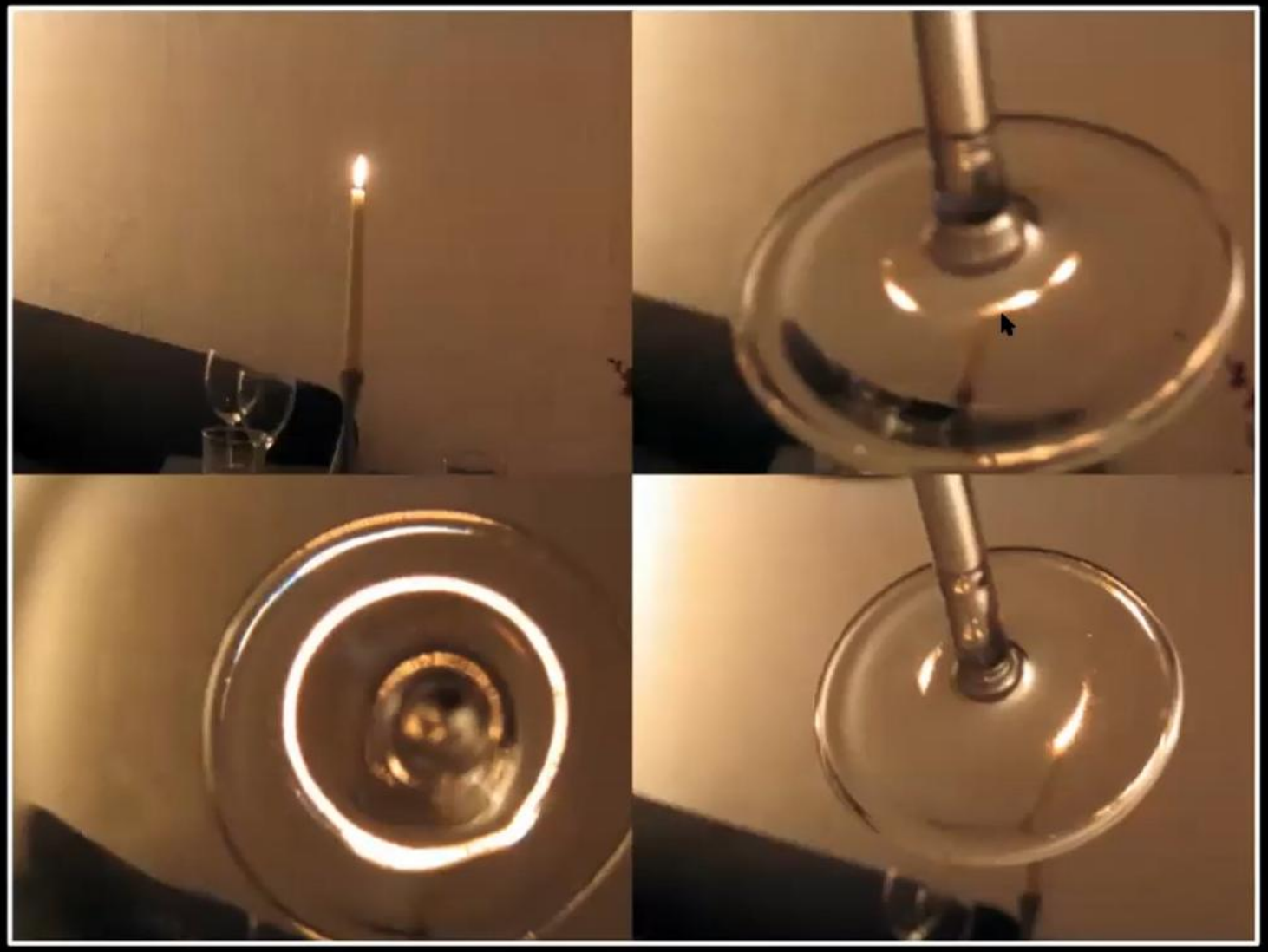
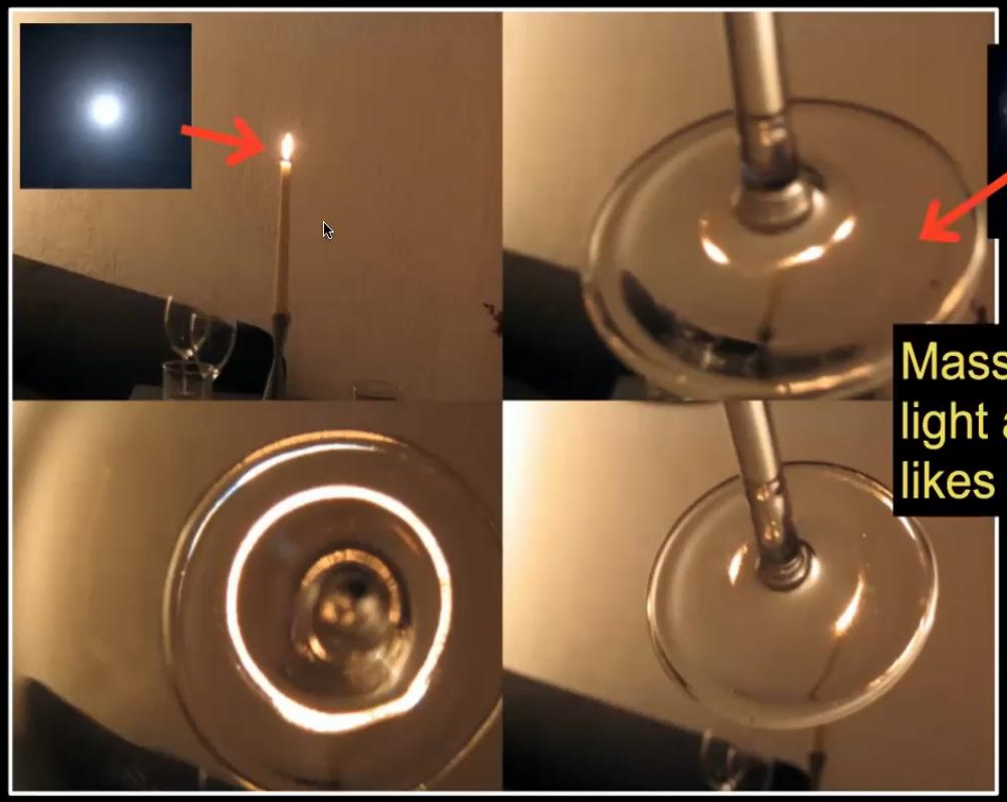


Image Credit: P. J. Marshall

Gravitational Strong ~~Optical~~ Lensing



Mass “bends” light and acts likes a lens

Image Credit: P. J. Marshall

Strong gravitationally lensed quasa

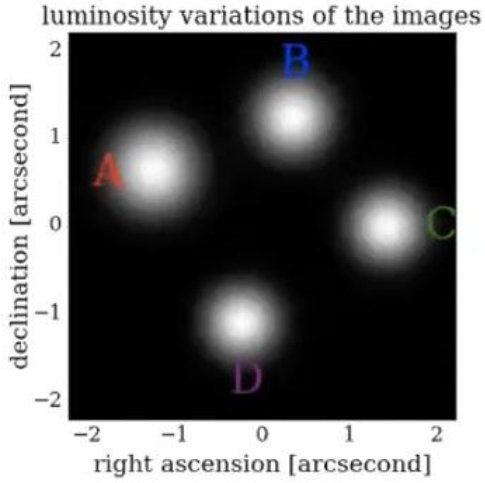
Strong gravitationally lensed quasa

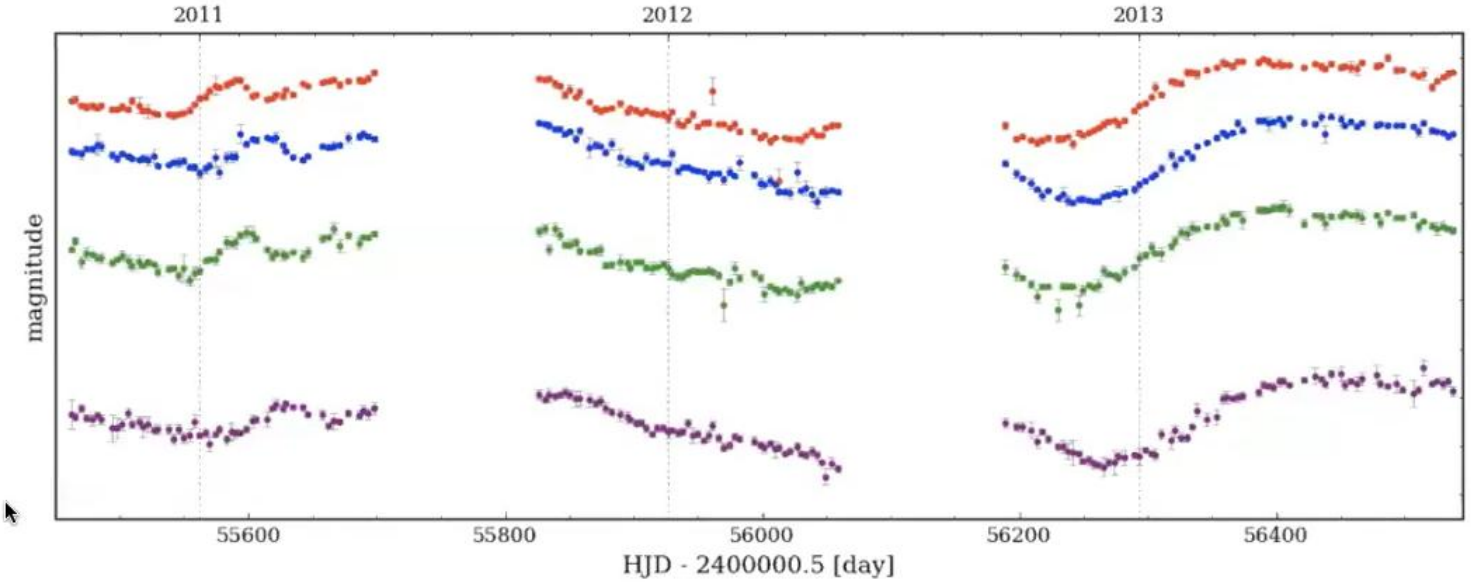
lensed quasar
images

Gravitational Lens Time Delays

COSMOGrail

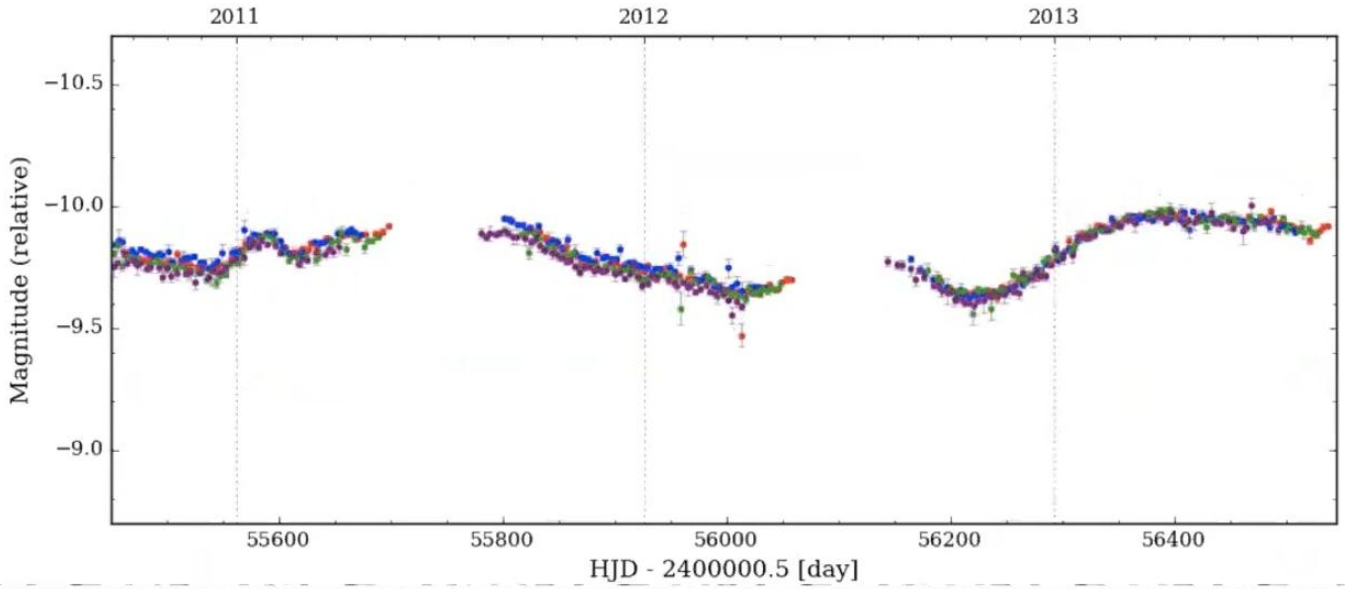
[**COS**mological **MO**nitoring of **GRA**v**I**tational **L**enses; PI: F. Courbin, G. Meylan]





Measuring time delays

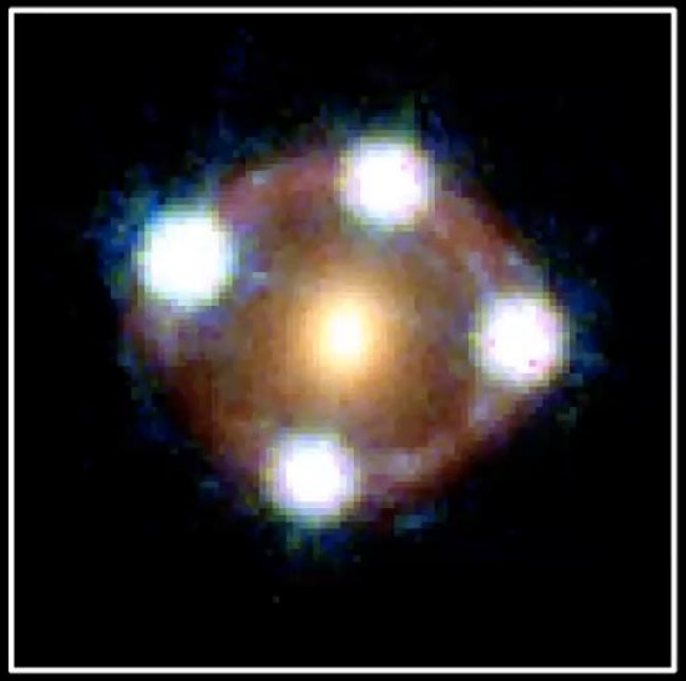
COSMOGrail



[Credit: V. Bonvin]

Cosmology with time delays

HE0435-1223



[Suyu et al. 2017]

Time delay:

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

Time-delay distance:

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

Obtain from lens mass model

[Refsdal 1964]

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

Refsdal 1964

S1 et S2 →2 images de S

Time delay distance =

fonction complexe de

a_S , a_B et SO

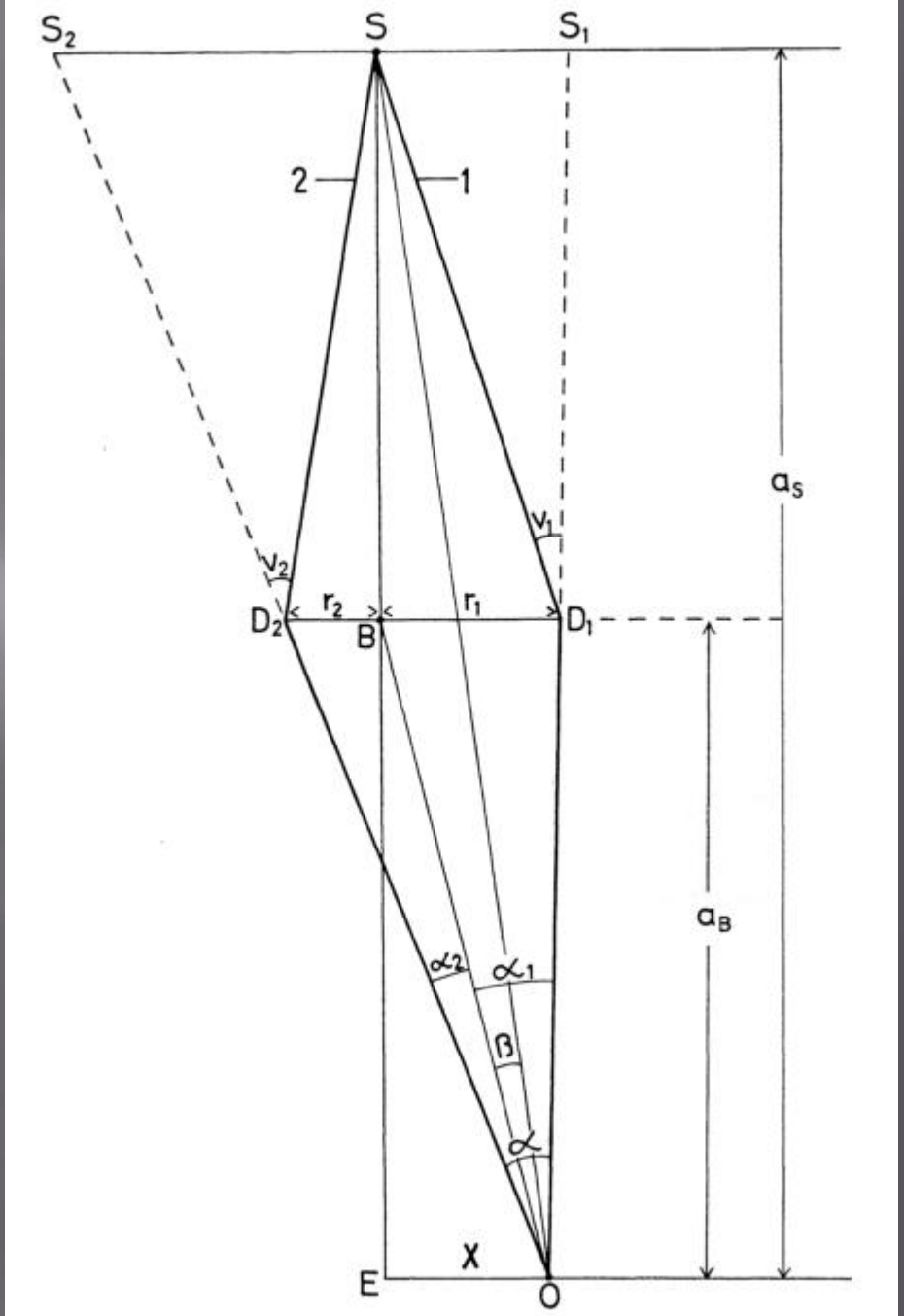
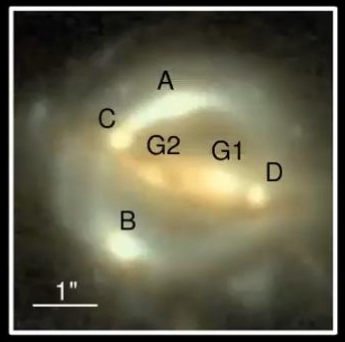


FIG. 1.—*The two light rays from S to O.*

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

B1608+656



RXJ1131-1231

HE0435-1223

WFI2033-4723

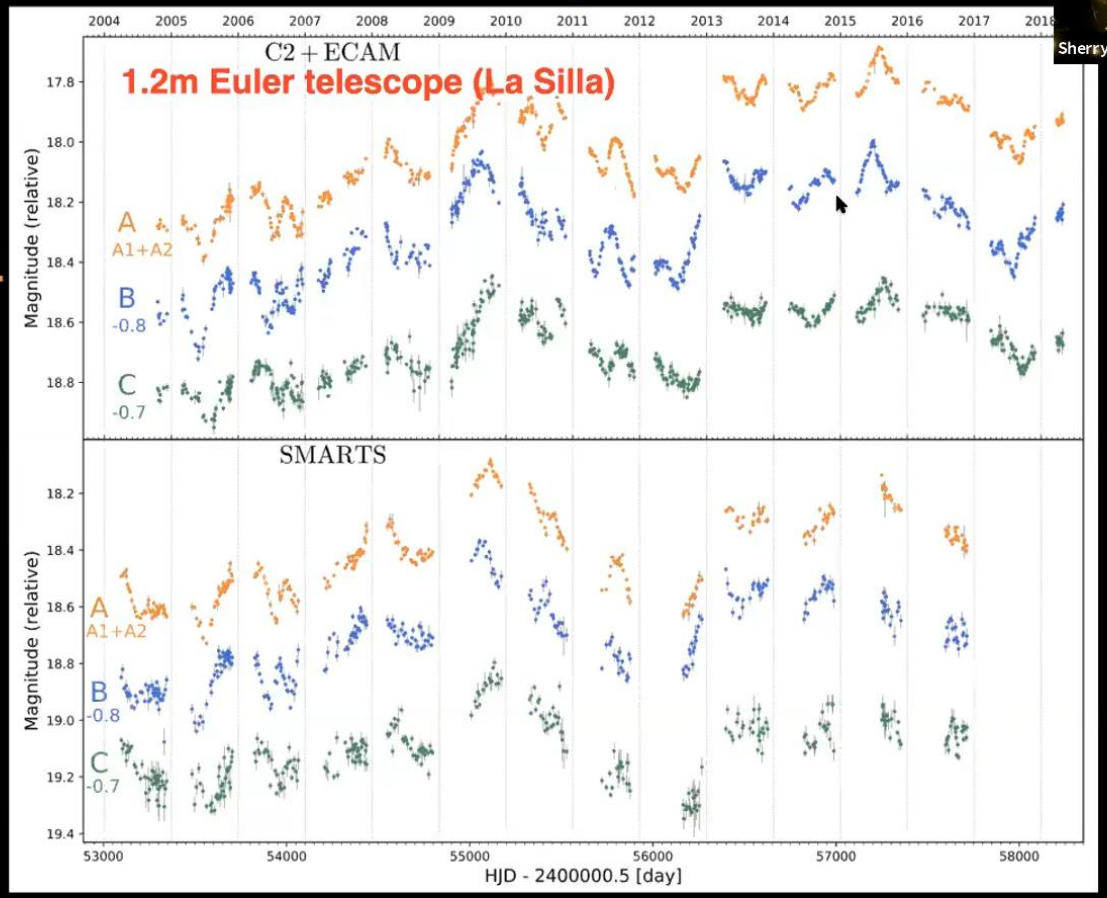
HE1104-1805

[Suyu et al. 2017]

Time Delays

COSMOGRAIL
[Cosmological Monitoring of Gravitational Lenses]

PI: F. Courbin
G. Meylan



[Bonvin et al. 2019]

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Time Delays

Delay (AB) with 2.1% precision [Bonvin et al. 2019]

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Lens mass modeling

$$t = \frac{1}{c} D_{\Delta t} \phi_1$$

Modeling with GLEE :)

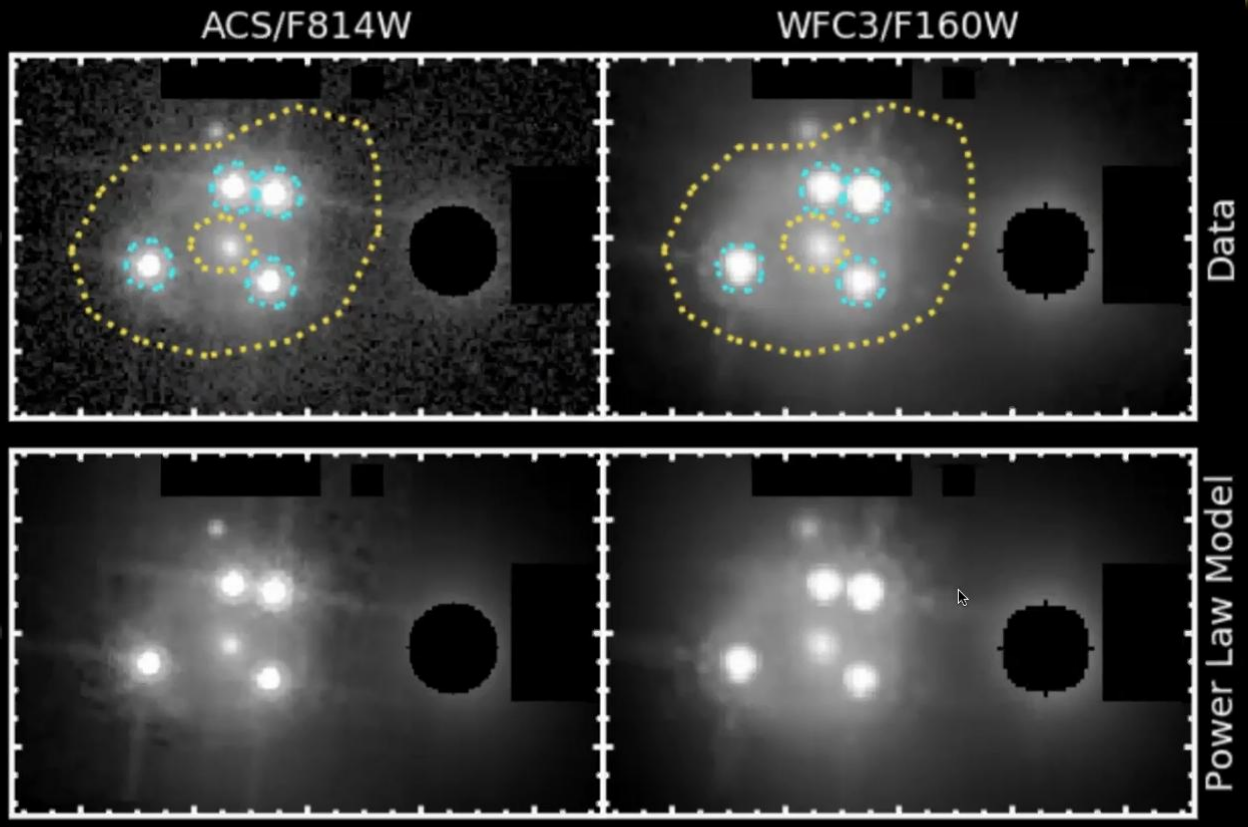
Gravitational
Lens
Efficient
Explorer

[Suyu & Halkola 2010]

and

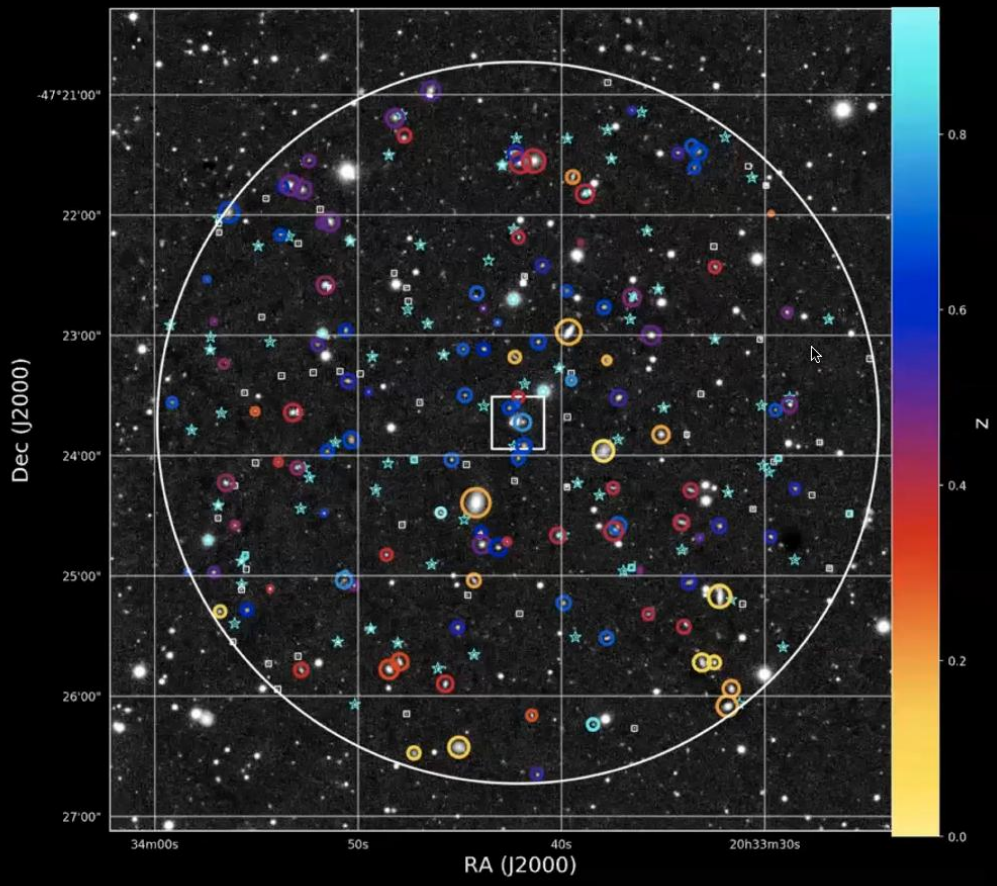
Lenstronomy
[Birrer & Amara 2018]

Lens reconstruction



[Rusu, Wong, Bonvin et al 2020 (H0LiCOW XII)]

Lens environment



Wide-field spectroscopy and imaging for:

- redshift measurements and galaxy group identification [Sluse et al. 2019 (H0LiCOW X)]
- quantifying the amount of external mass along the line of sight through galaxy counts [Rusu et al 2020 (H0LiCOW XII)]

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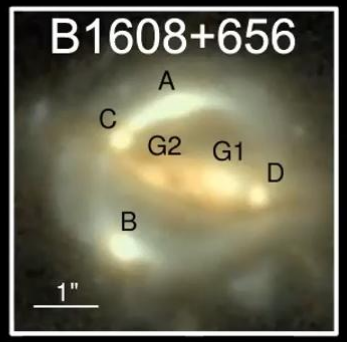
H0LiCOW latest results



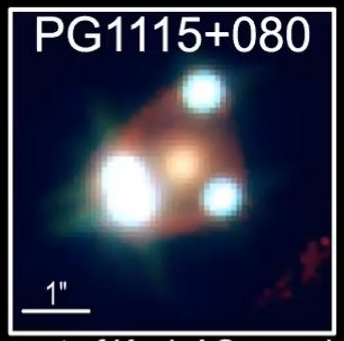
[Suyu et al. 2010]

[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. 2020]



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

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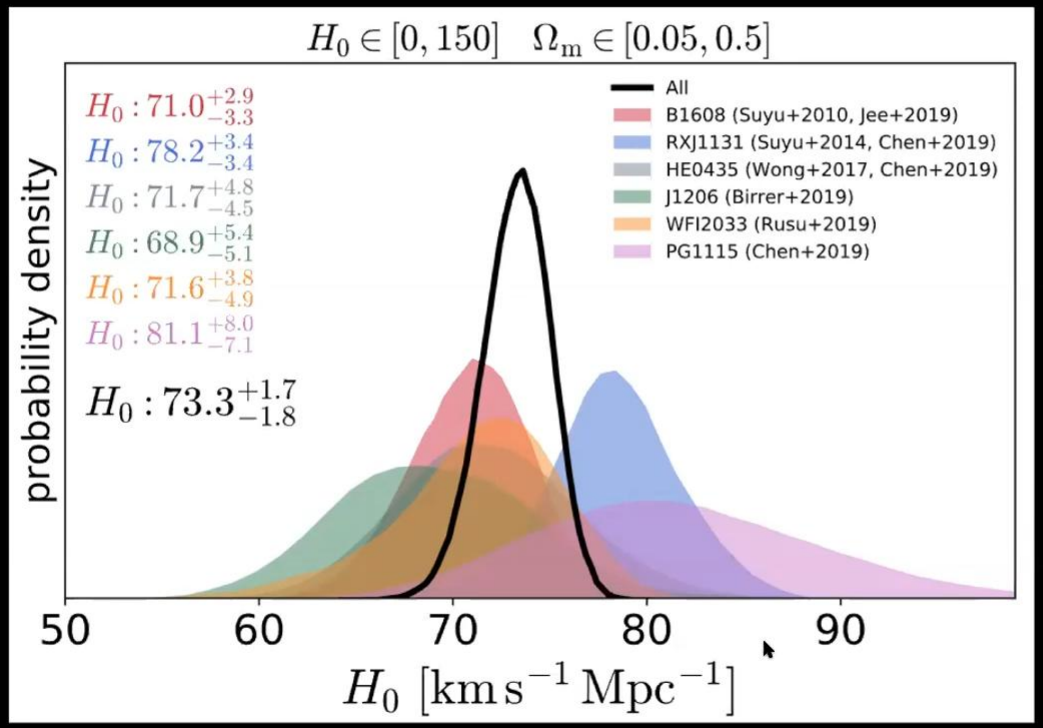
H0LiCOW: H_0 from 6 strong lenses

Blind analysis to avoid confirmation bias

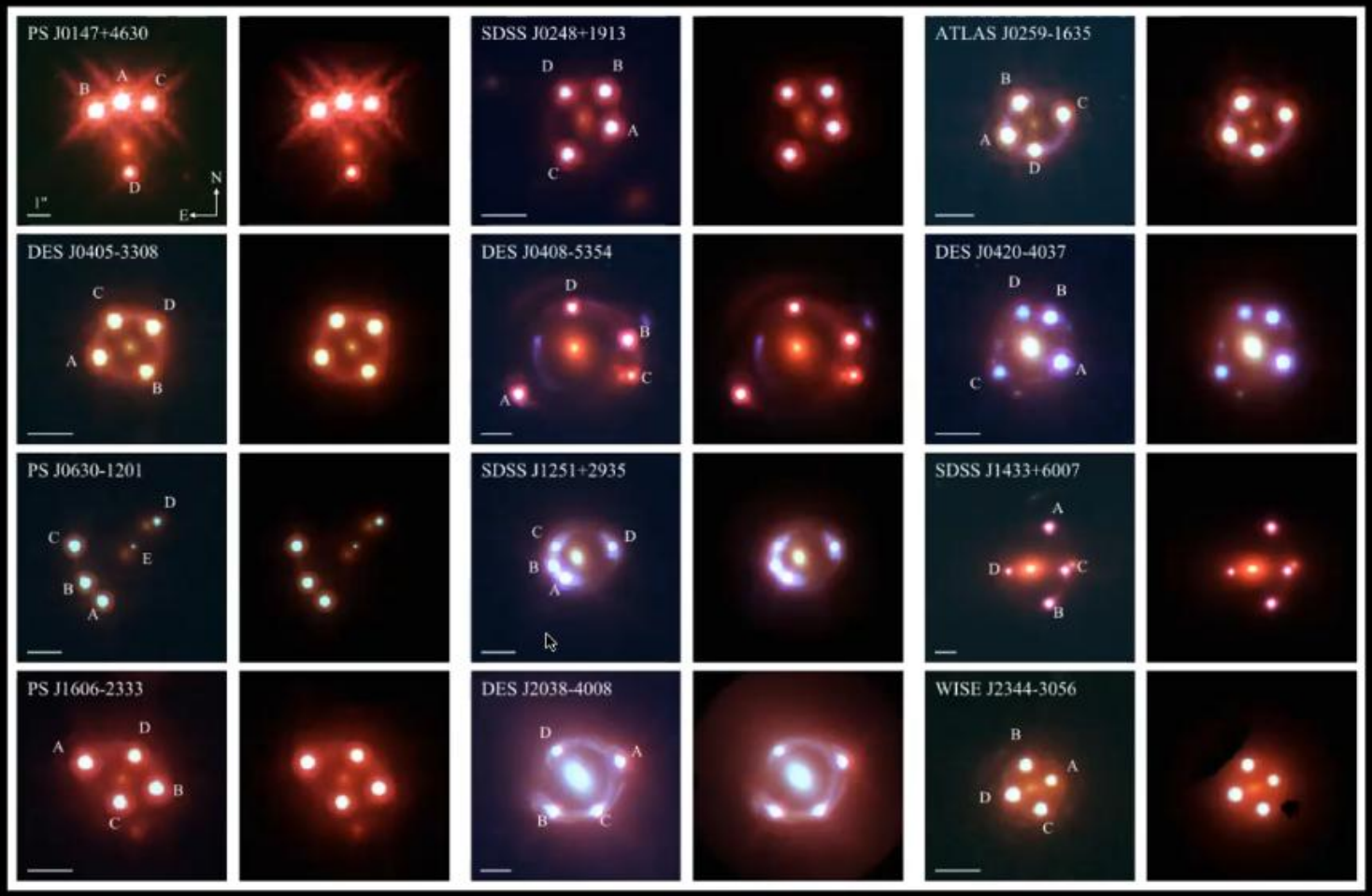


H_0 with 2.4% precision in flat ΛCDM

[Wong, Suyu, Chen et al. 2020; H0LiCOW XIII]

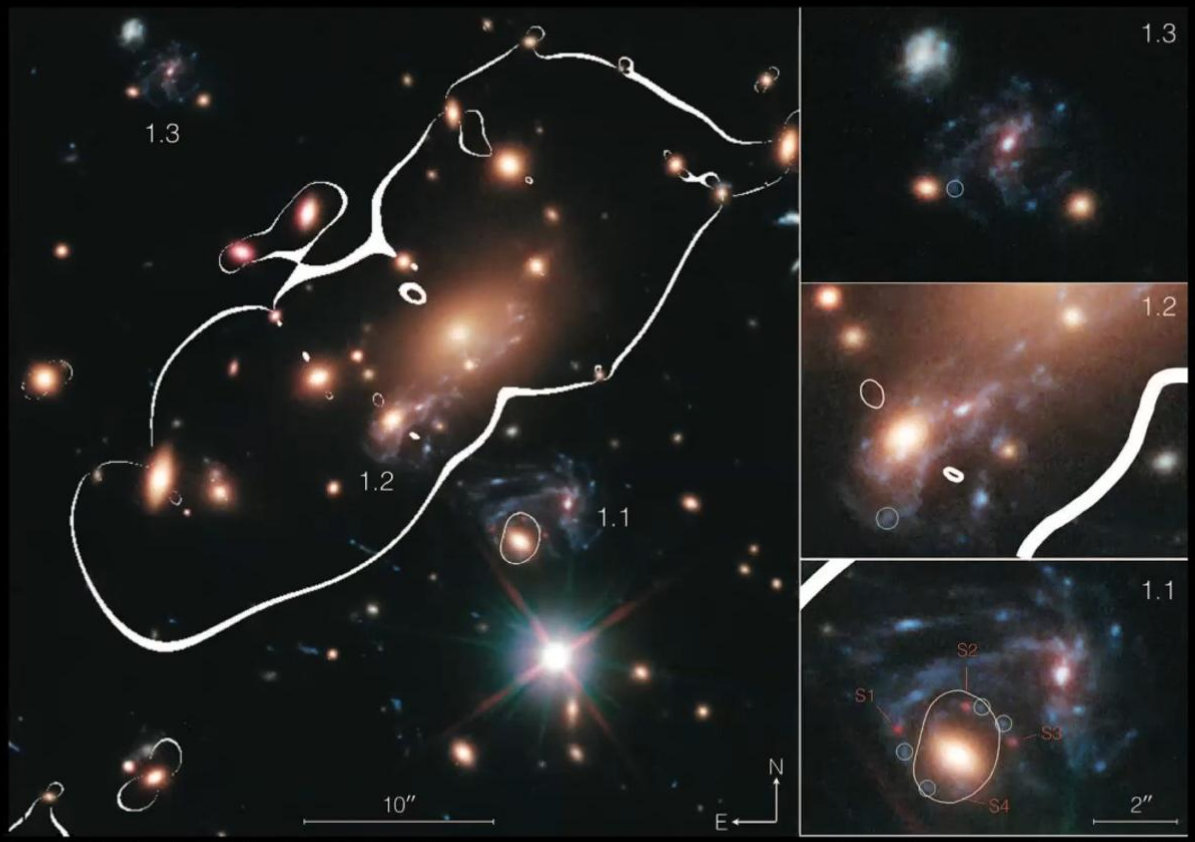
Looking forward: new lens systems

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



[Shajib et al. 2018]

Supernova Refsdal: lensed supernova



MACS 1149.6+2223 [Kelly et al. 2015]

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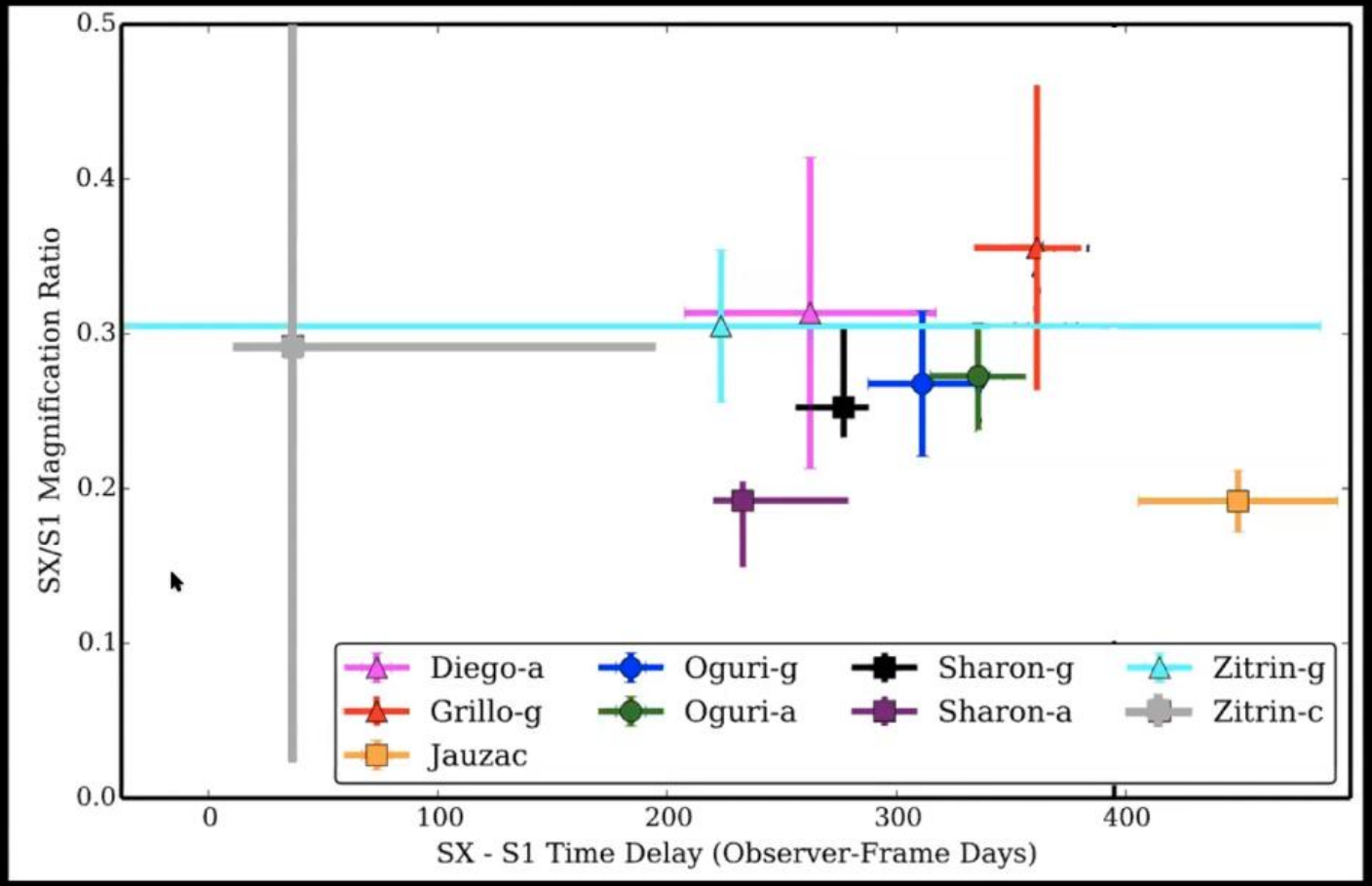
When will the other SN images appear

MACS 1149.6+2223

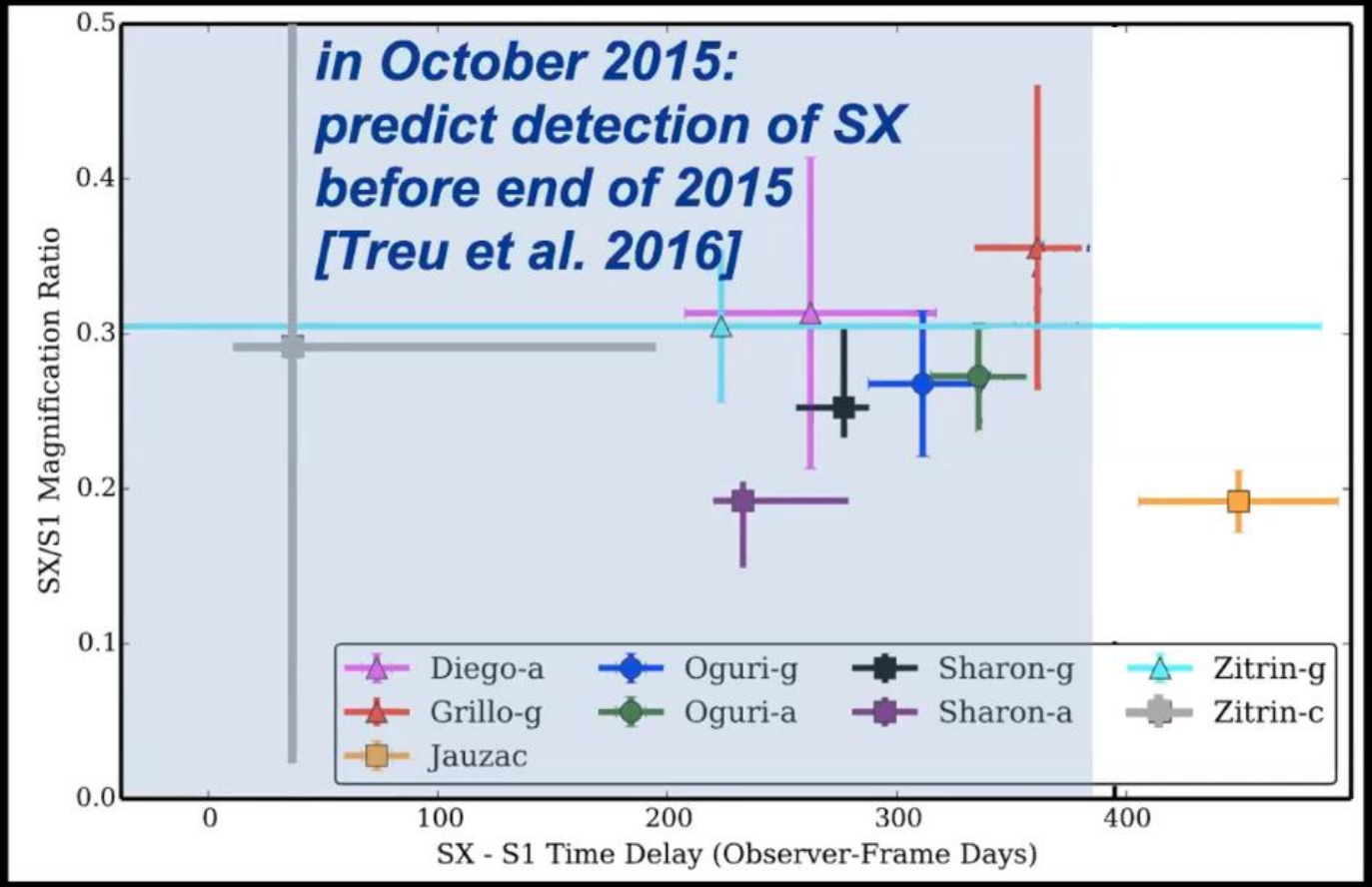
[Kelly et al. 2015] [31]

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…

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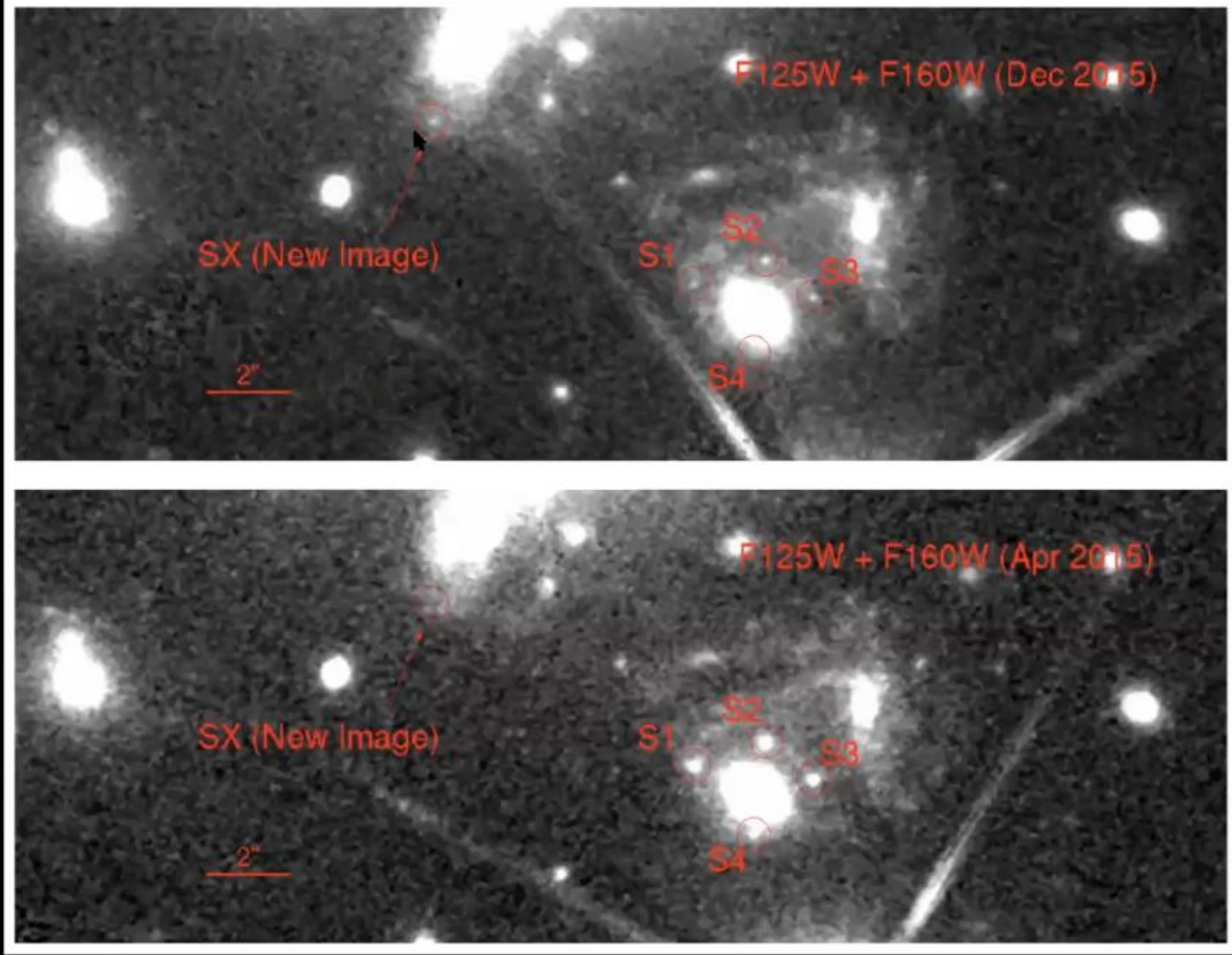
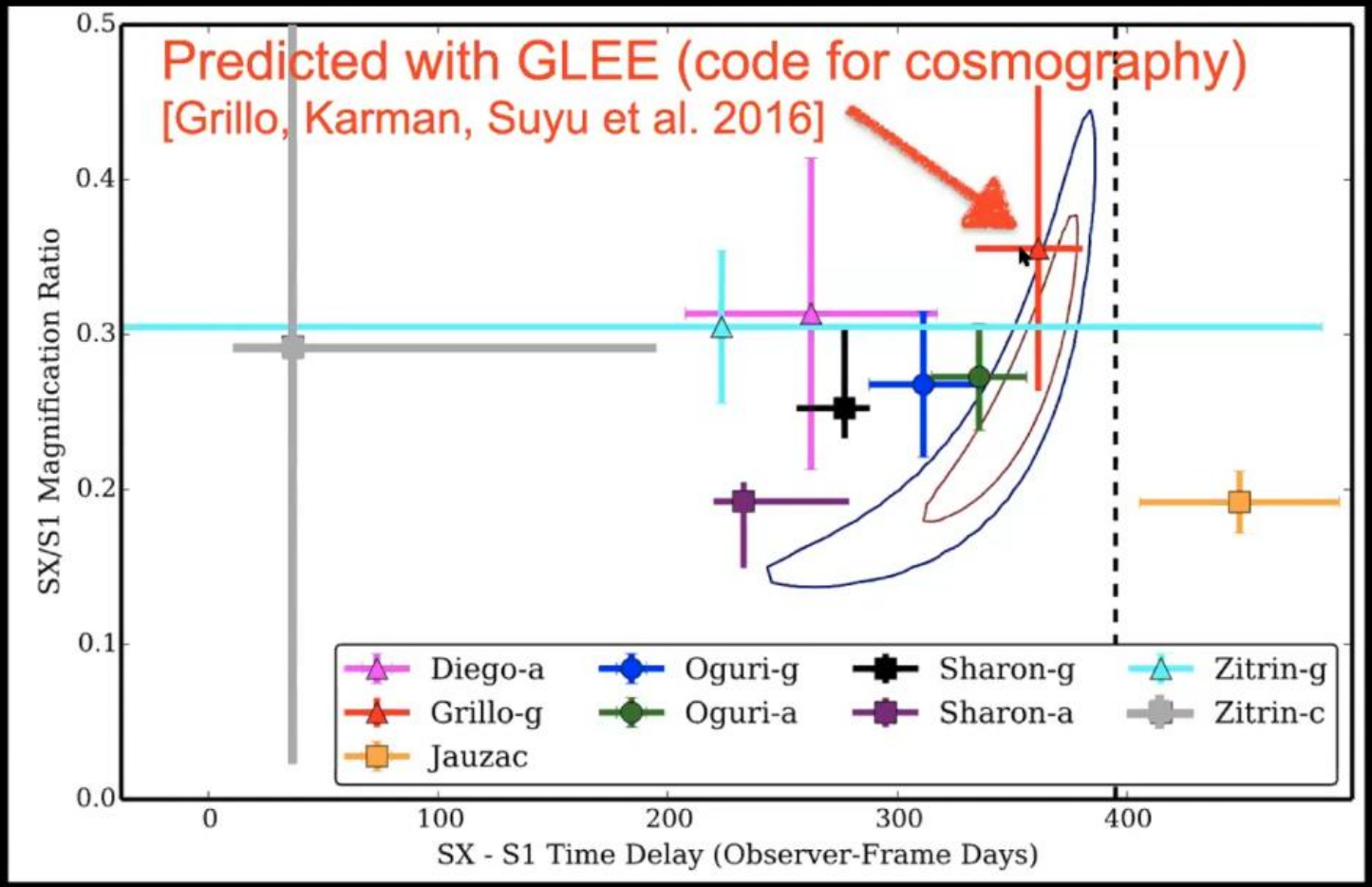
Appearance of image SX

December 2015 [Kelly et al. 2016]

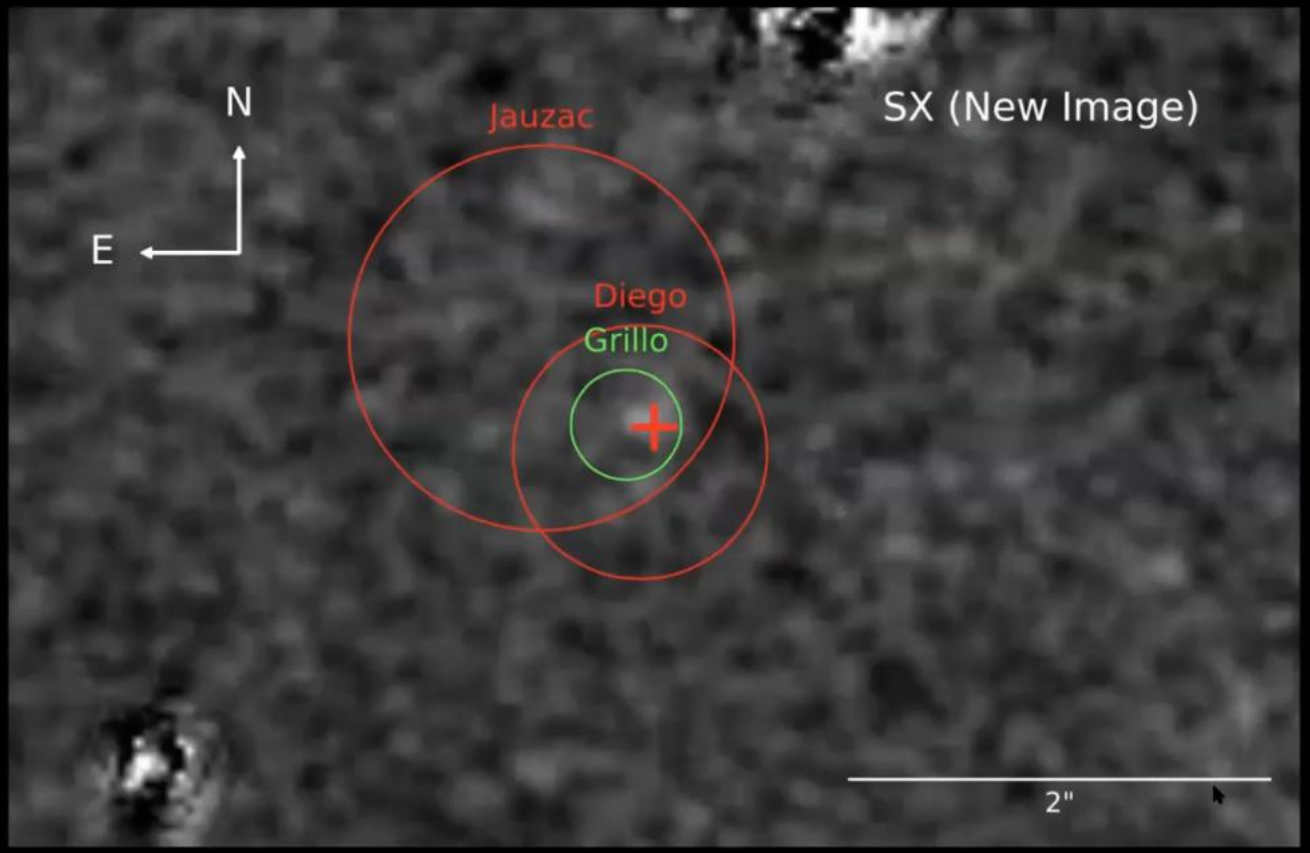


Magnification and delay



[Kelly et al. 2016]

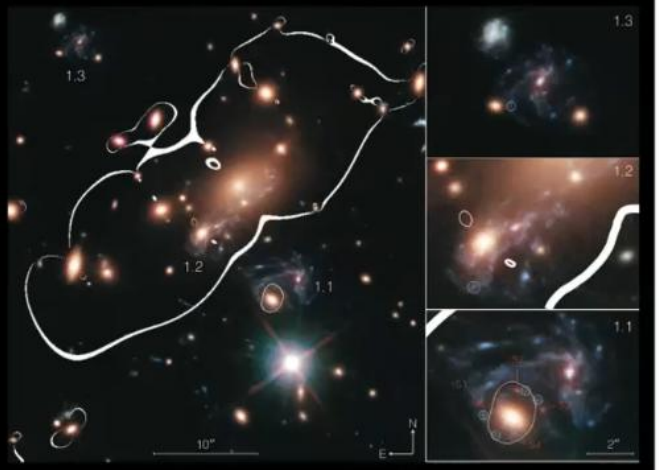
Spot on!



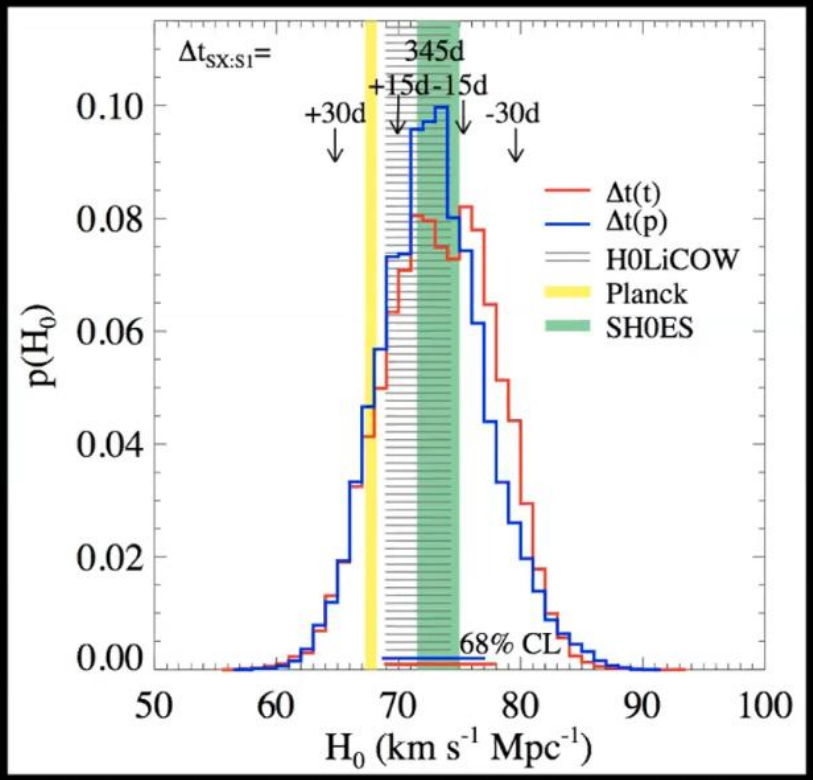
[Kelly et al. 2016]

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**lliptical 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

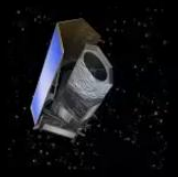
2) Measuring the expansion rate of our Universe

[Suyu, Huber, Cañameras et al. 2020]

Future Prospects

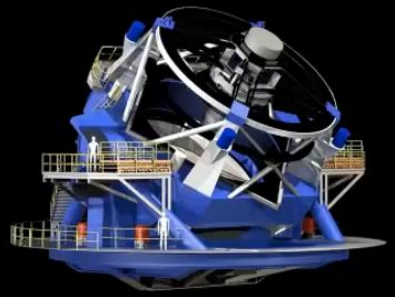
Experiments and surveys in the 2020s including Euclid, Rubin, and Roman observatories will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid



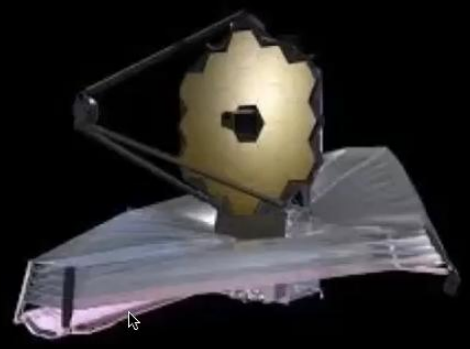
Discovery
Imaging
Spectroscopy

Rubin Observatory



Discovery
Time delays
Imaging

JWST



High-resolution imaging
& spectroscopy

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Summary

- 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

Références « accessibles »

avec Google

Holicow cosmology astrobite.org

https://astrobites.org/2019/07/12/h0ly-cow-a-new-measurement-of-the-hubble-constant/

https://astrobites.org/2021/01/14/meet-the-aas-keynote-speakers-prof-sherry-suyu/