# Cosmology with Gravitational Lens Time Delays

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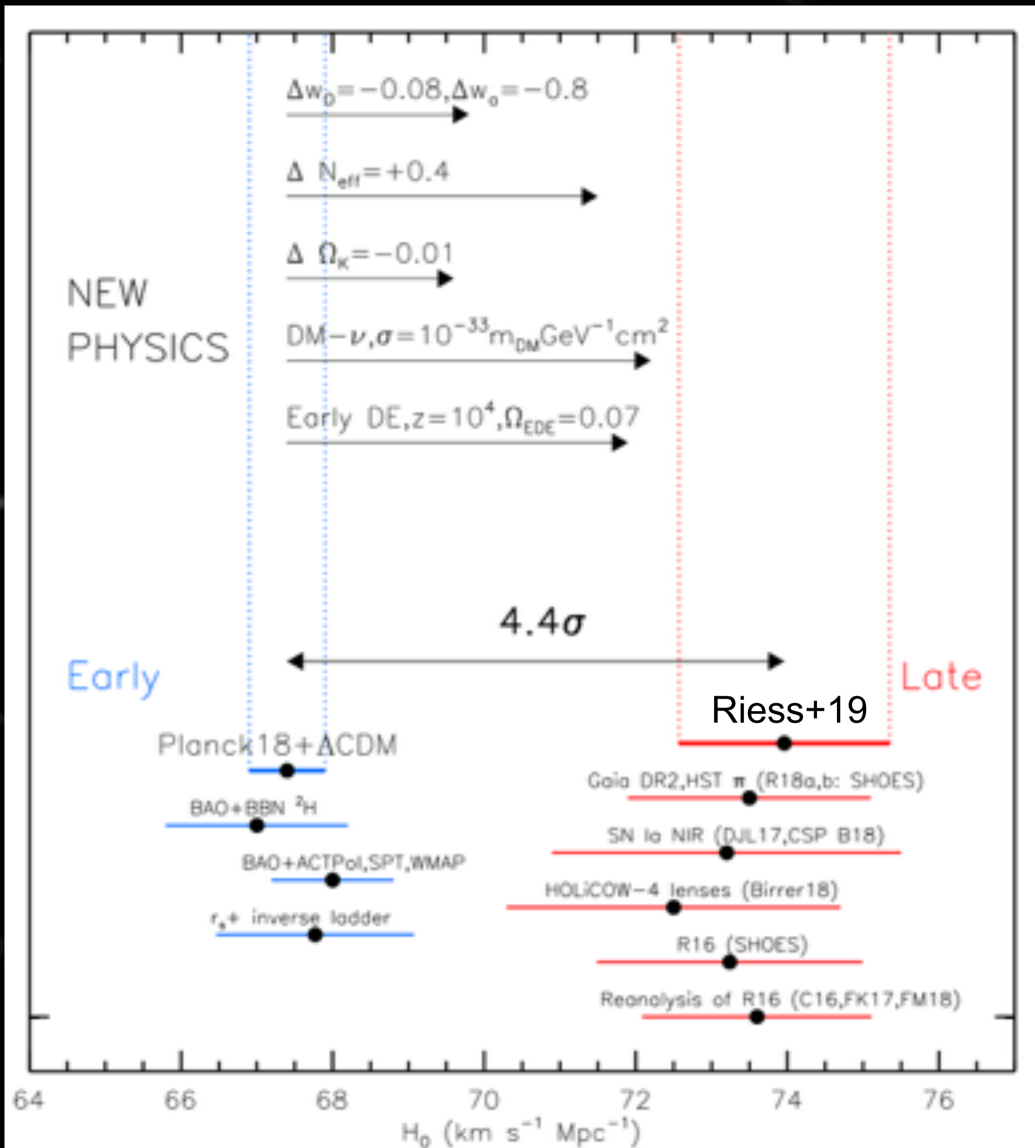
Understanding cosmological observations @ Benasque

# Hubble constant: key parameter




[Riess et al. 2019]

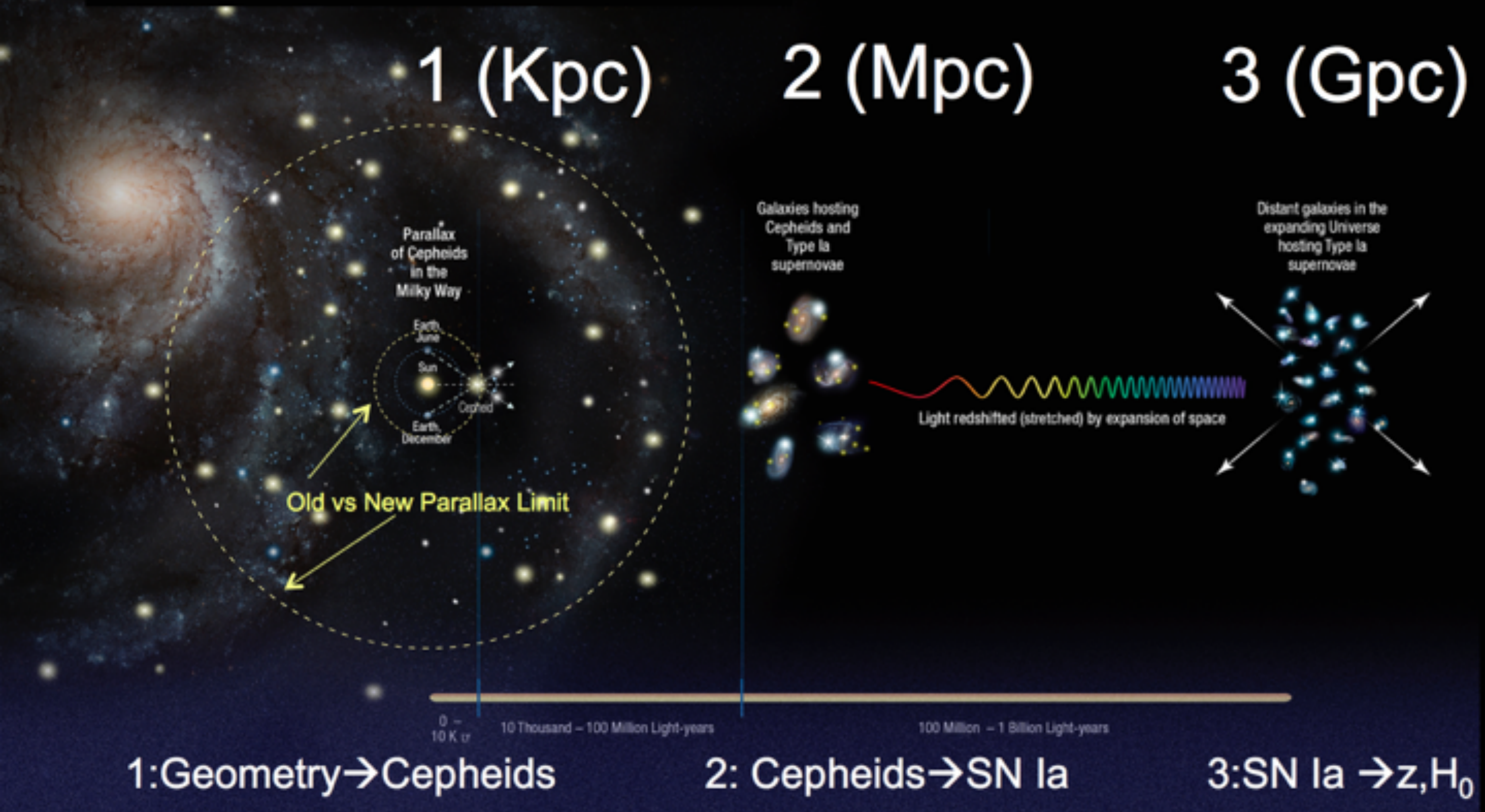
Hubble constant $H_0$
- age, size of the Universe
- expansion rate: $v = H_0 d$

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

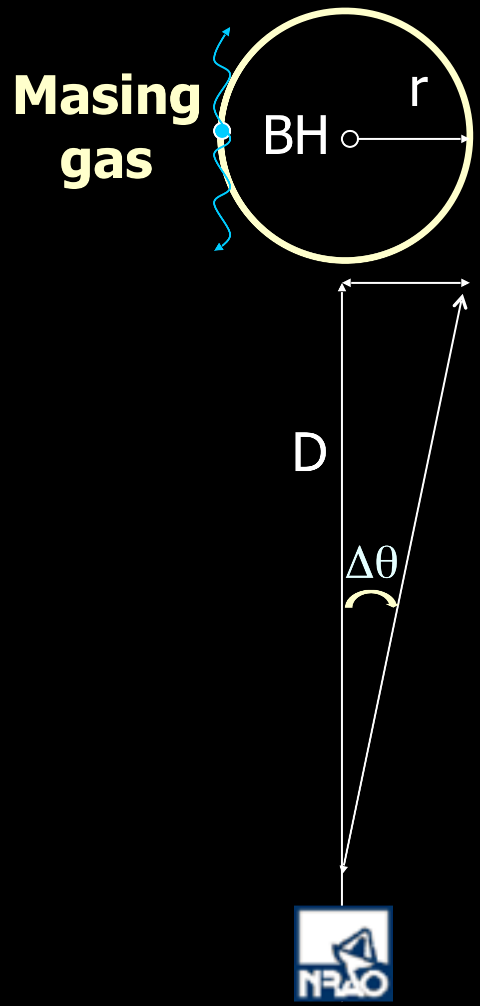
- Carnegie Hubble Program [Freedman et al. 2012]
  - $H_0$ = 74.3 ± 2.1 km s$^{-1}$ Mpc$^{-1}$ (2.8% uncertainty)

- 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 :

$a = V_0^2 / r$ ➡ $r = V_0^2 / a$

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

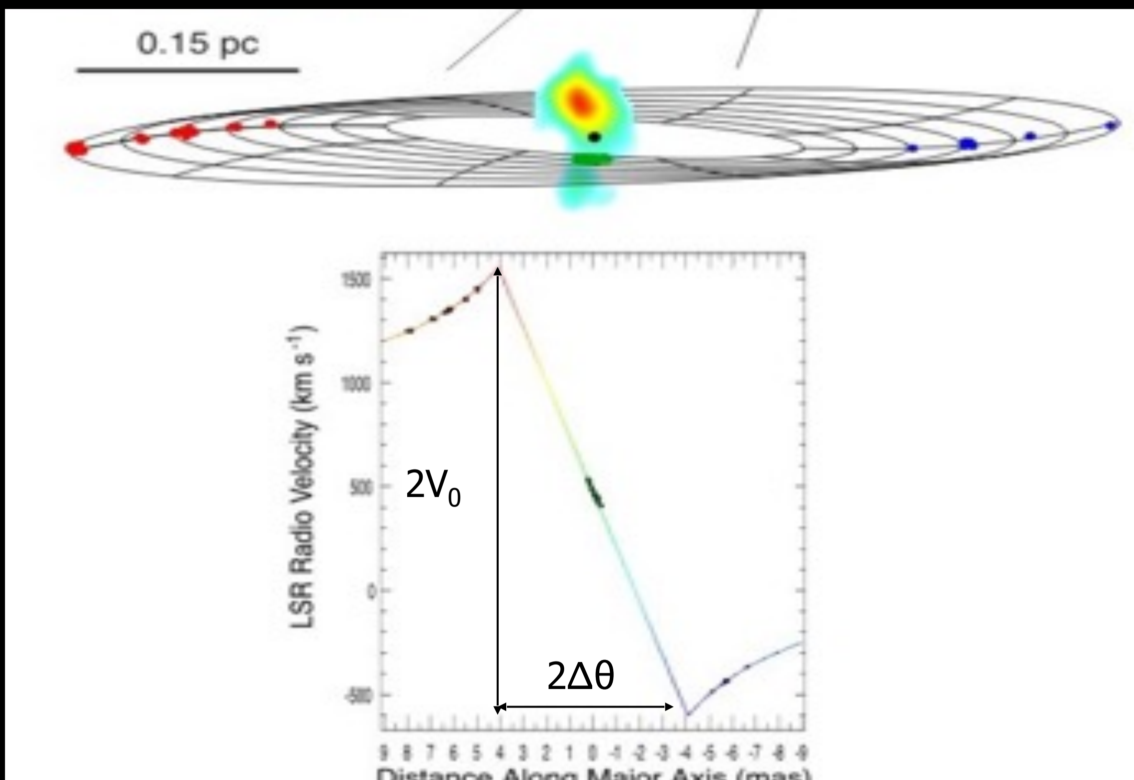
$$D = V_0^2 \sin i / a\, \Delta\theta$$

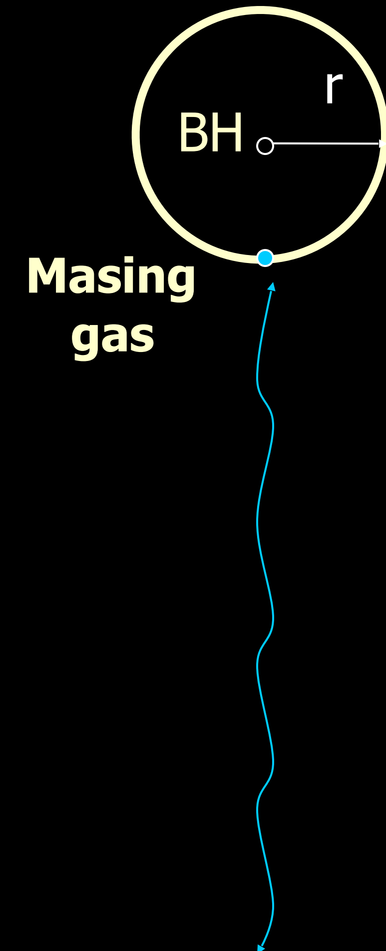
[slide material courtesy of C.-Y. Kuo]

# 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

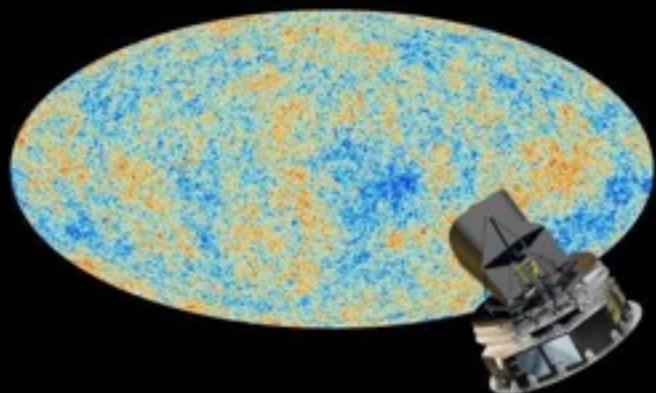
$$H_0 = 69.3 \pm 4.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

| | | | |
|---|---|---|---|
| UGC 3789 | 45.0 ± 4.7 Mpc | $H_0 =$ 76 ± 8 | (updated from Reid et al. 2013) |
| NGC 6264 | 137 ± 19 Mpc | $H_0 =$ 68 ± 9 | (Kuo et al. 2013) |
| NGC 6323 | 107 ± 42 Mpc | $H_0 =$ 73 ± 26 | (Kuo et al. 2015) |
| NGC 5765b | 126 ± 11 Mpc | $H_0 =$ 66 ± 6 | (Gao et al. 2016) |

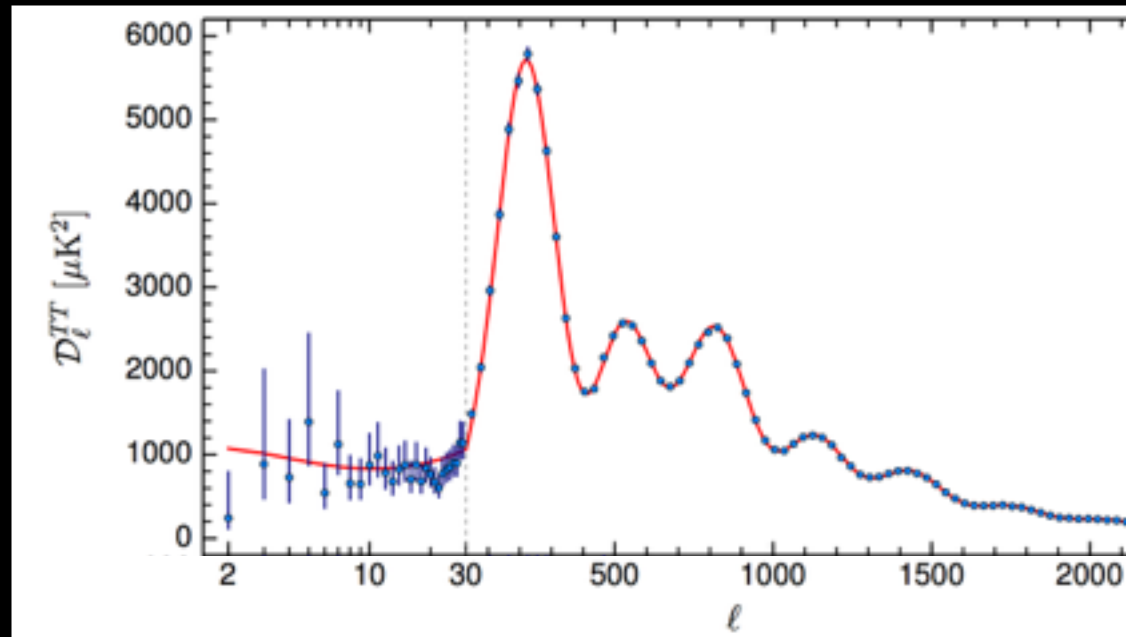
[slide material courtesy of Cheng-Yu Kuo]

# 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, $w$, $N_{eff}$)

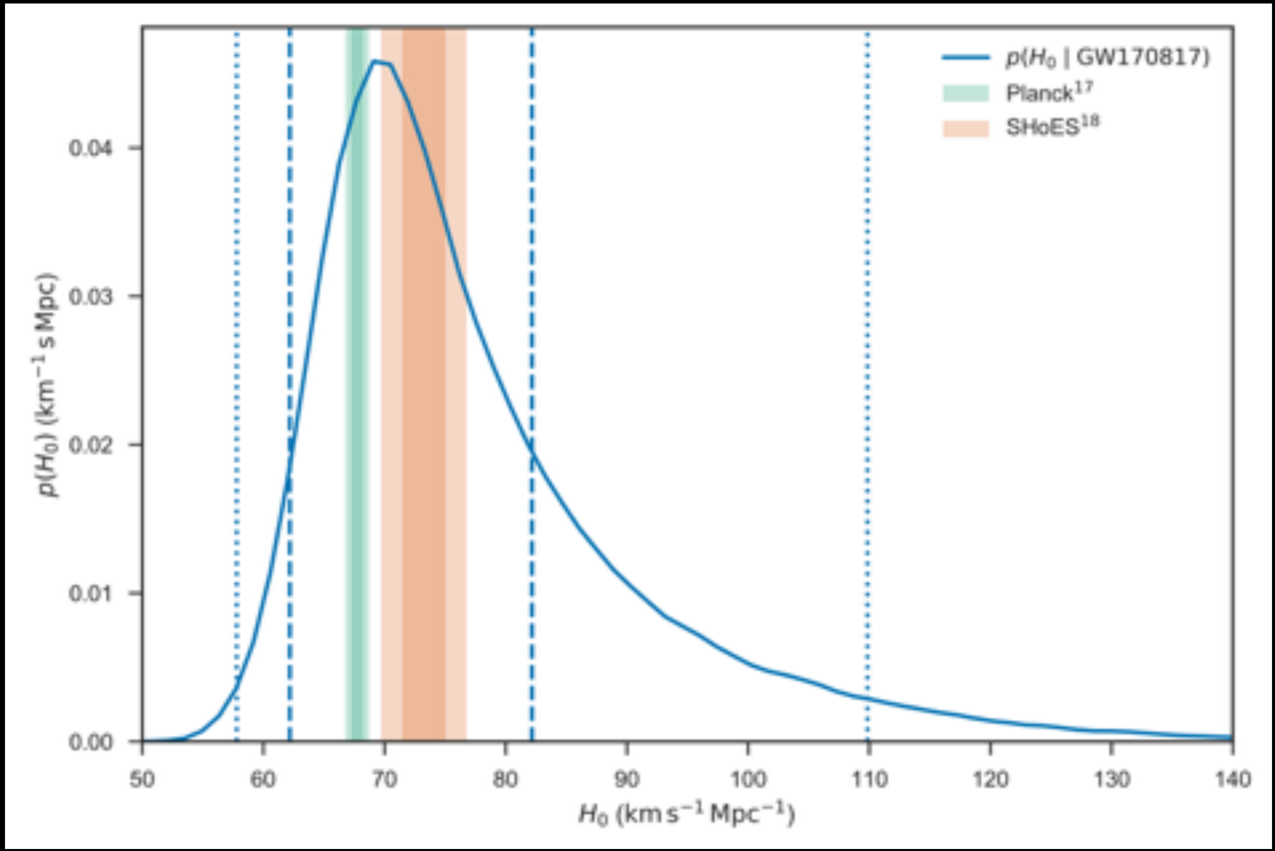
# Standard Siren

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

$H_0 = v / D$

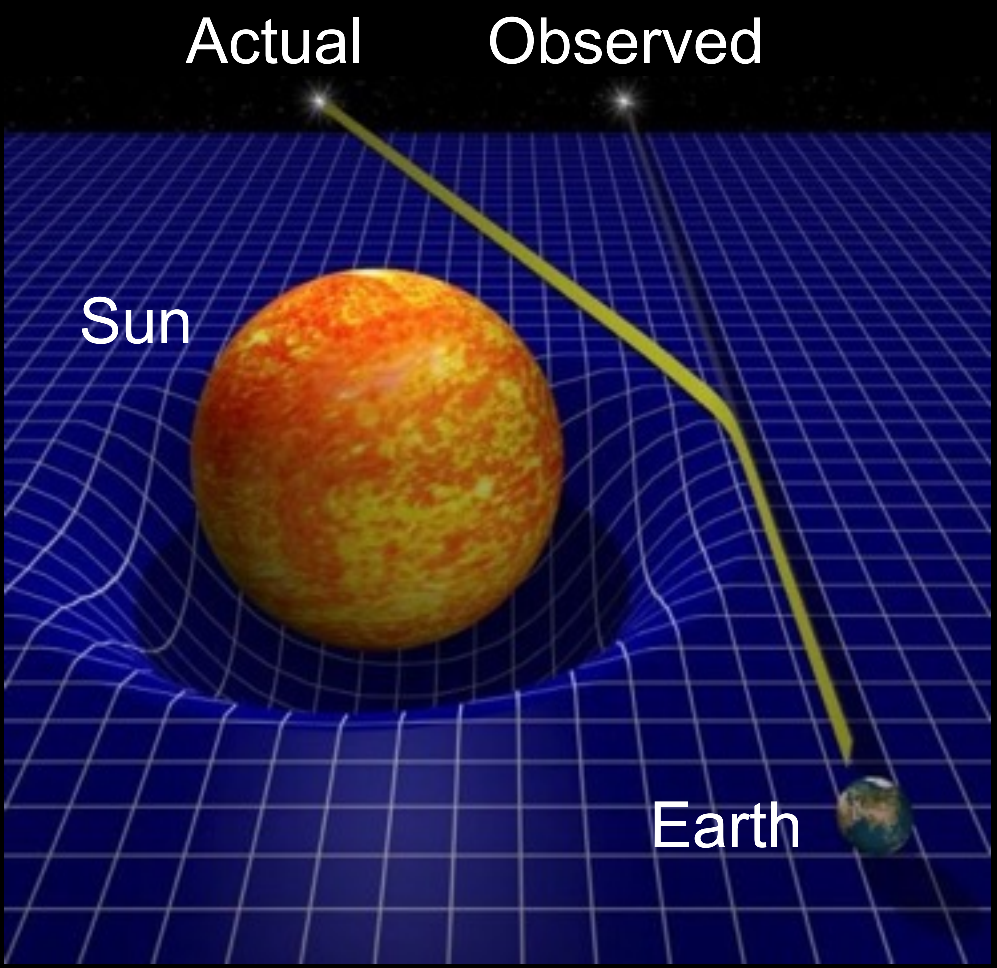
[Image credit: M. Garlick]

GW170817: First measurement of $H_0$

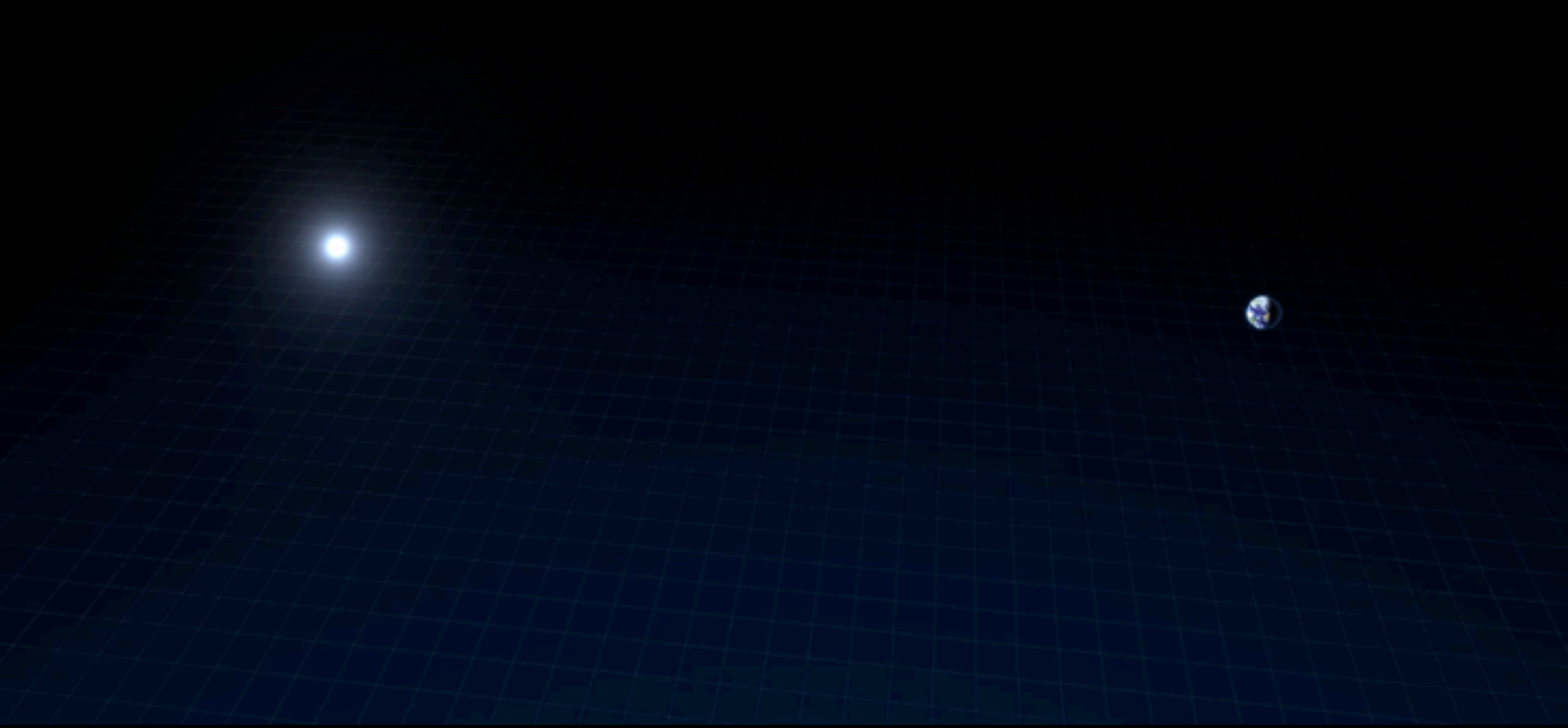



[LIGO, VIRGO, 1M2H, DES, DLT40, LCO, VINROUGE, MASTER collaborations, 2017]

# Gravitational Lensing



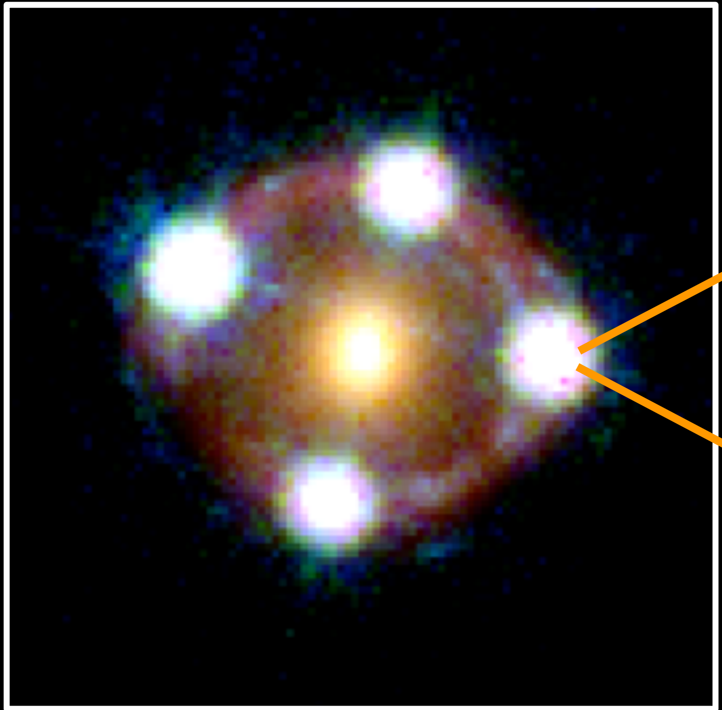
# Strong gravitationally lensed quasar



[Credit: ESA/Hubble, NASA]

# Variability of quasar emission

HE0435-1223



[Suyu et al. 2017]

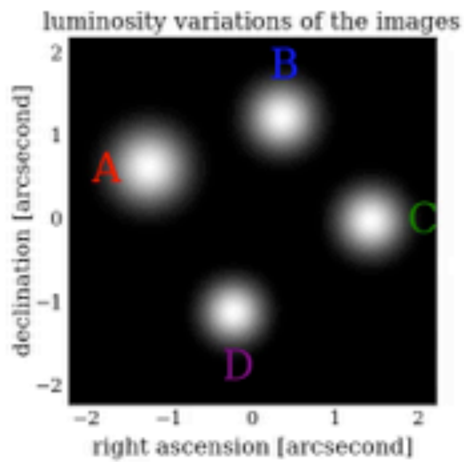
quasar powered by accretion of material onto supermassive black hole:

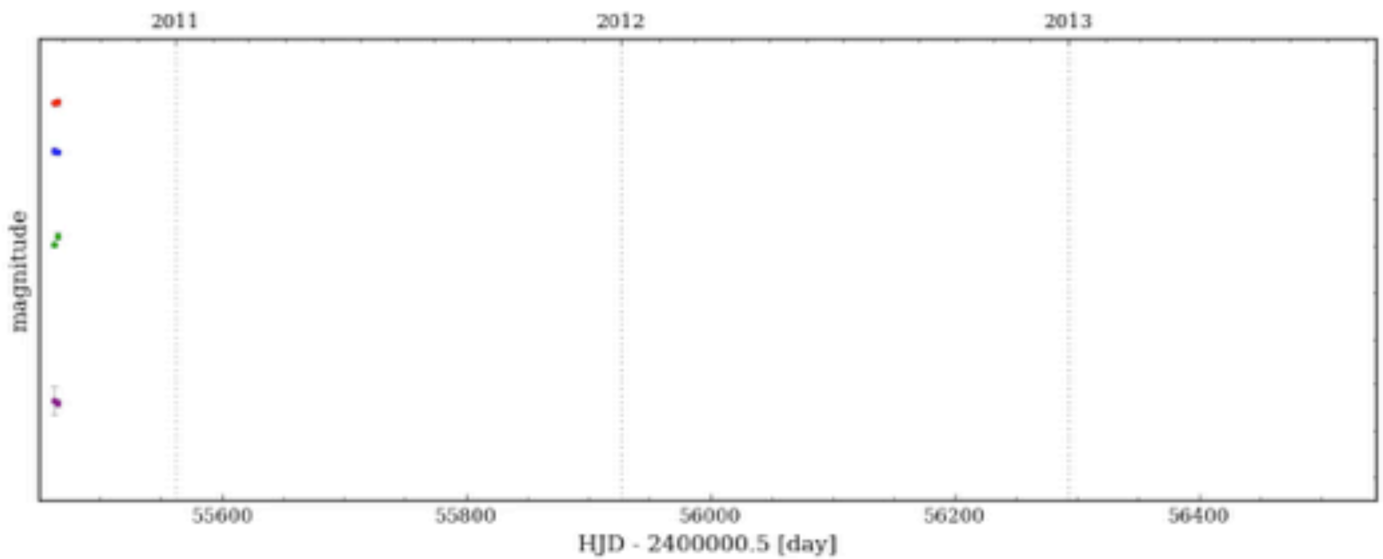
light emitted from quasar changes in time ("flickers")

# Cosmology with time delays

COSMOGrail

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

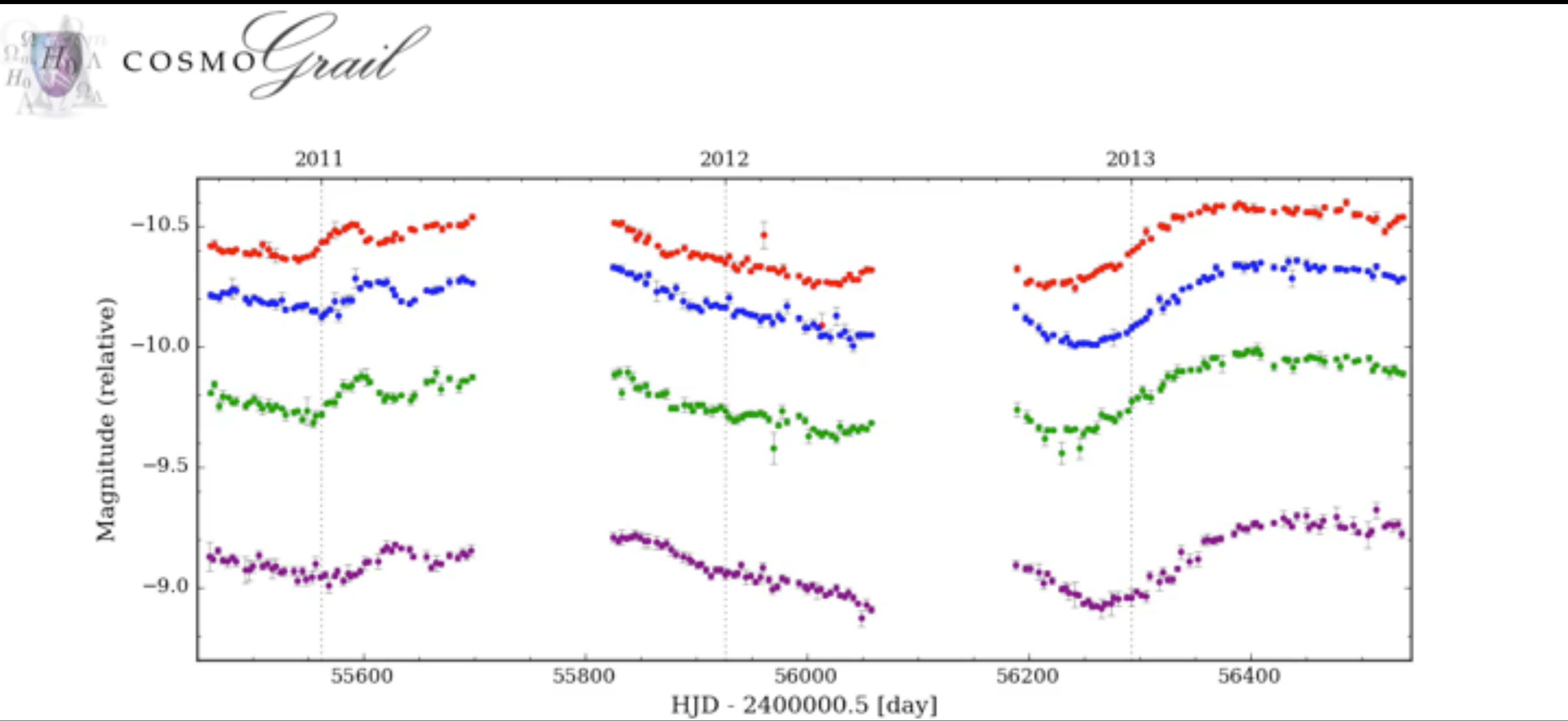





[Credit: V. Bonvin]

# Cosmology with time delays

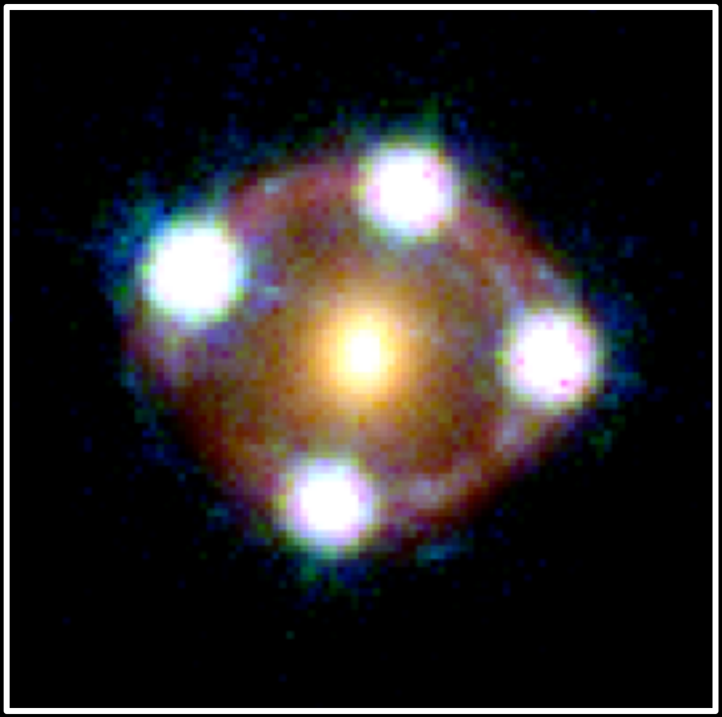





[Credit: V. Bonvin]

# 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

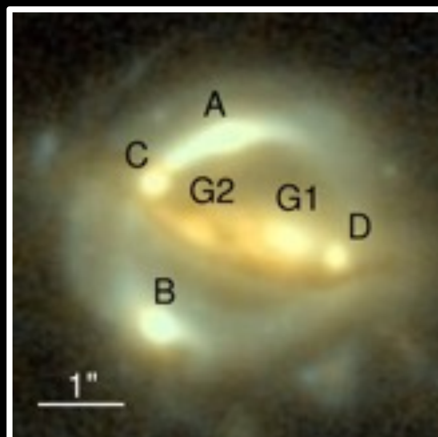
For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

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

# H0LiCOW

## $H_0$ Lenses in COSMOGRAIL's Wellspring

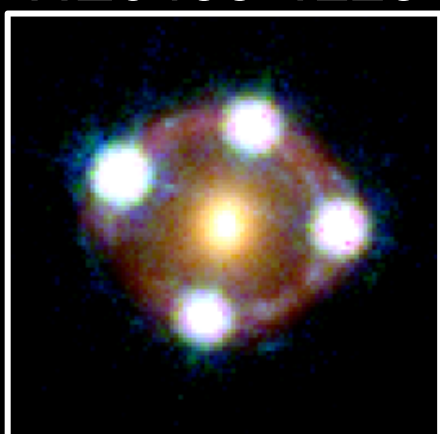
B1608+656



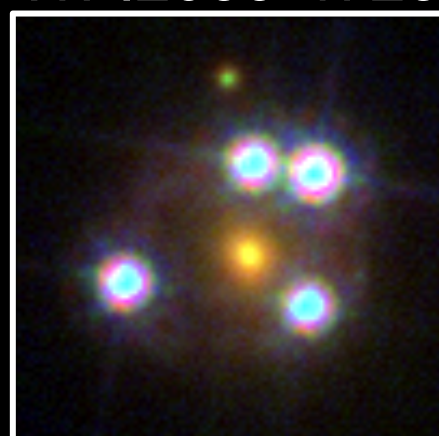

RXJ1131-1231

$H_0$ to <3.5% precision

HE0435-1223



WFI2033-4723



HE1104-1805

[Suyu et al. 2017]

# H0LiCOWers

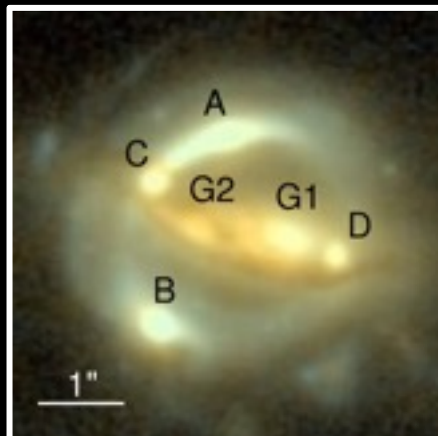

**H0LiCOW: $H_0$ Lenses in COSMOGRAIL's Wellspring**

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

# H0LiCOW

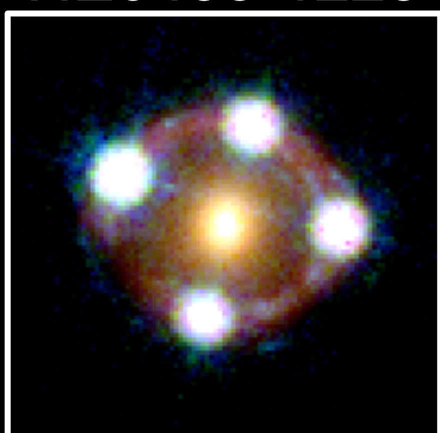
## $H_0$ Lenses in COSMOGRAIL's Wellspring

B1608+656

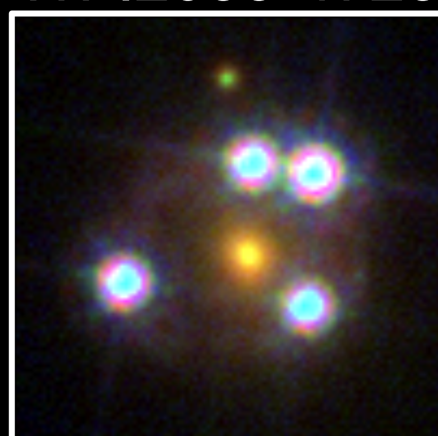



RXJ1131-1231

HE0435-1223



WFI2033-4723



HE1104-1805

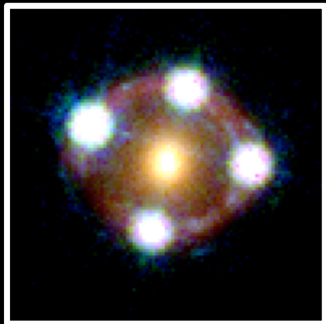
[Suyu et al. 2017]

# Time Delays

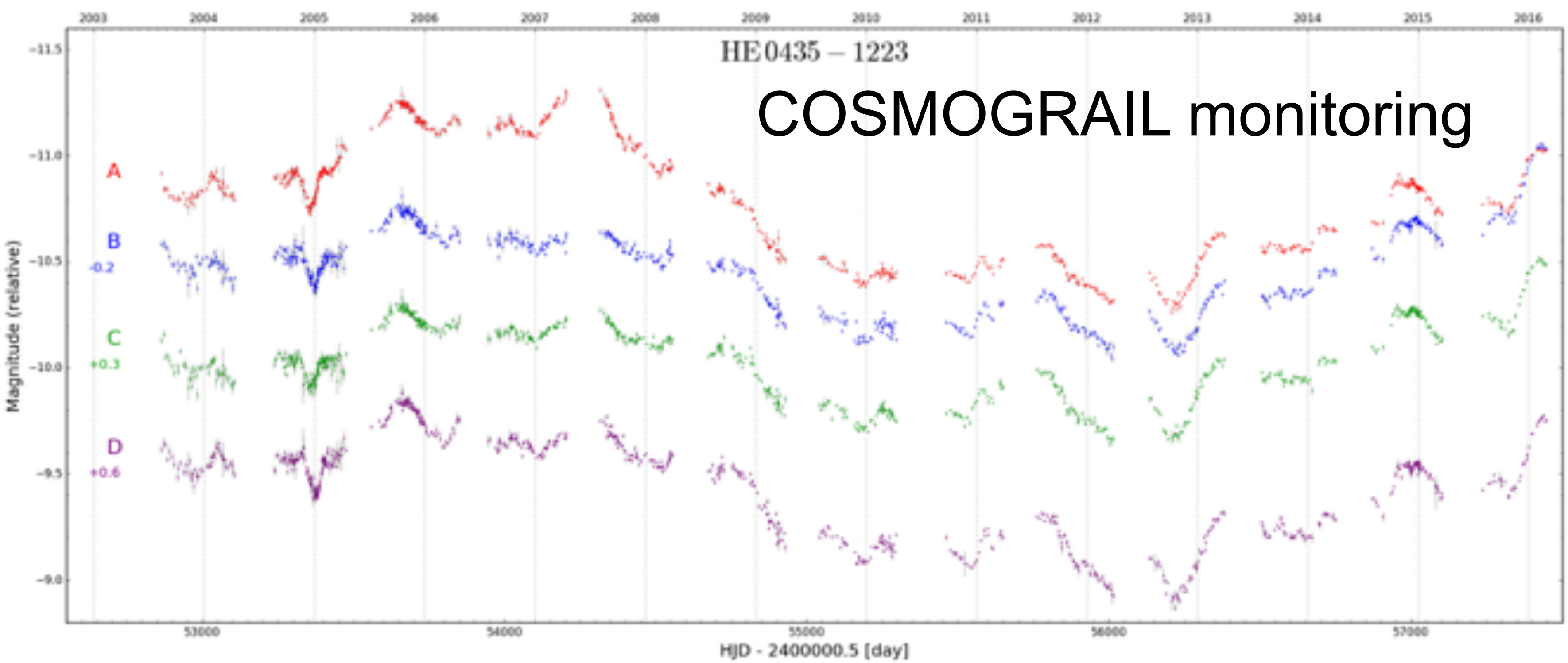
[Cosmological Monitoring of Gravitational Lenses]

- monitoring lensed quasars since 2004 in the optical

**EPFL**: **F. Courbin**, **G. Meylan**, V. Bonvin, M. Millon, J. Chan, M. Tewes,
Y. Revaz, N. Cantale, C. Faure, A. Eigenbrod, C. Vuissoz
**IIA Bangalore**: T. Prabhu, C.S. Stalin, R. Kumar, D. Sahu
**Univ. Liège**: D. Sluse, P. Magain, E. Eulaers, V. Chantry
**UzAS Tashkent**: I. Asfandiyarov
**Univ. Zürich**: P. Saha, J. Coles
**Univ. Nottingham**: S. Dye
**Now also in close collaboration (monitoring, microlensing) with**:
C. Kochanek, A. Mosquera (Ohio), C. Morgan, C. MacLeod, L. Hainline (USNA)



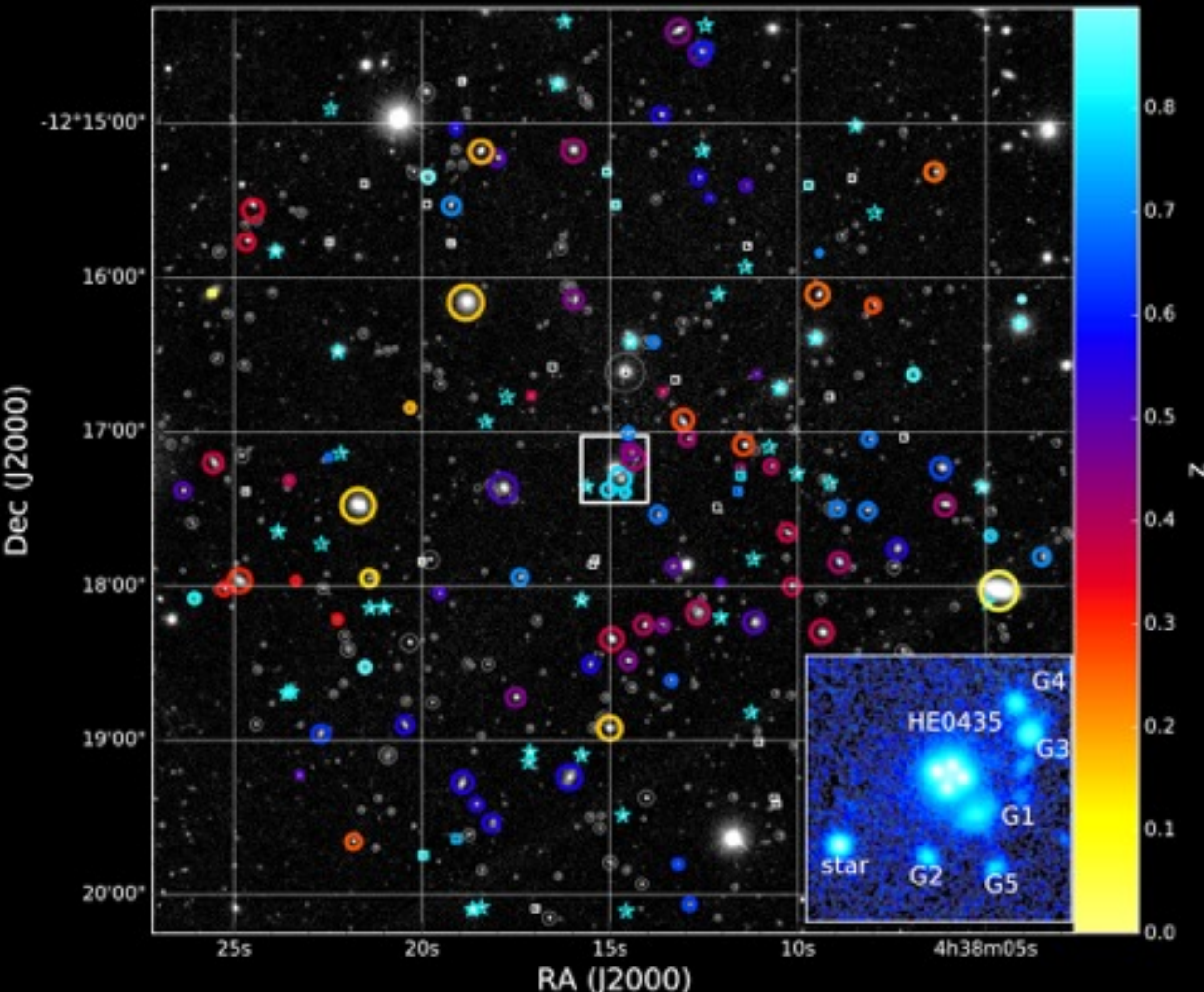
# Time Delays




13-year light curve of HE0435-1223
Time delay with 6.5% uncertainty
[Bonvin, Courbin, Suyu et al. 2017]

# Lens environment

HE0435 has nearby mass structures at different redshifts [e.g., Morgan et al. 2005, Momcheva et al. 2015]

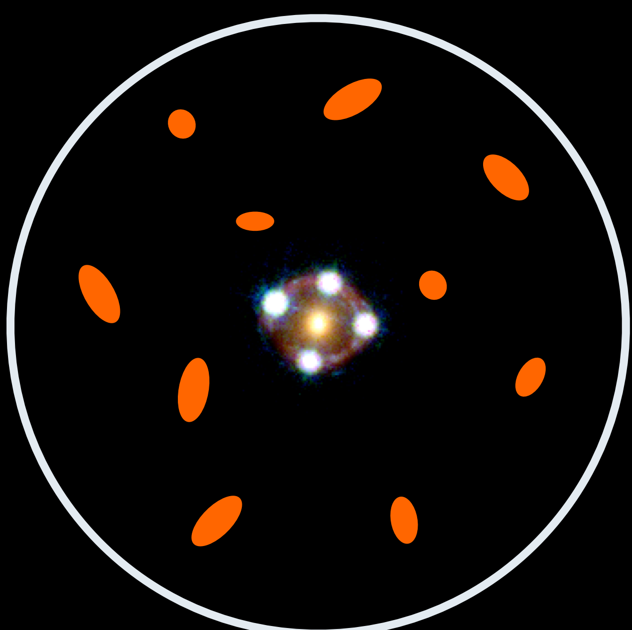


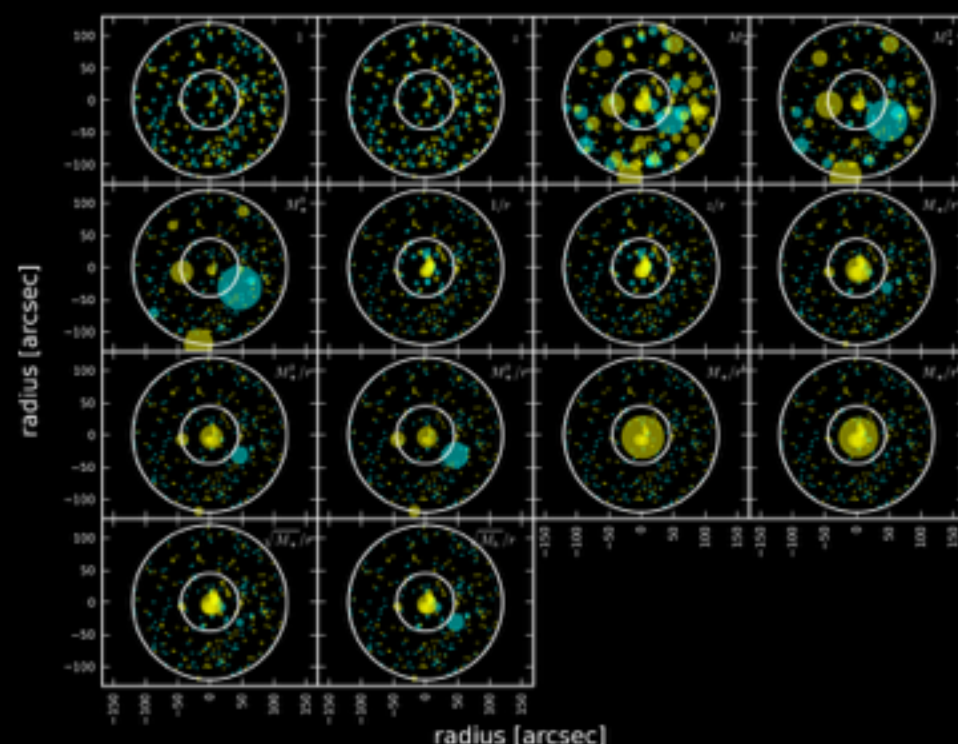

Wide-field spectroscopy for group identification [Sluse, Sonnenfeld, Rumbaugh et al. 2017]

Wide-field imaging to get external mass distribution [Rusu, Fassnacht, Sluse et al. 2017]

# Lens environment

- weighted number counts + Millennium Simulation to quantify $\kappa_{ext}$ [Fassnacht et al. 2011; Hilbert et al. 2007, 2009; Suyu et al. 2010, 2013, Greene et al. 2013]
- thorough investigation of weighting schemes with CFHTLenS [Heymans et al. 2012] as control field
- get $\kappa_{ext}$ distribution with uncertainty $\sigma_\kappa$=0.025 [Rusu et al. 2017]





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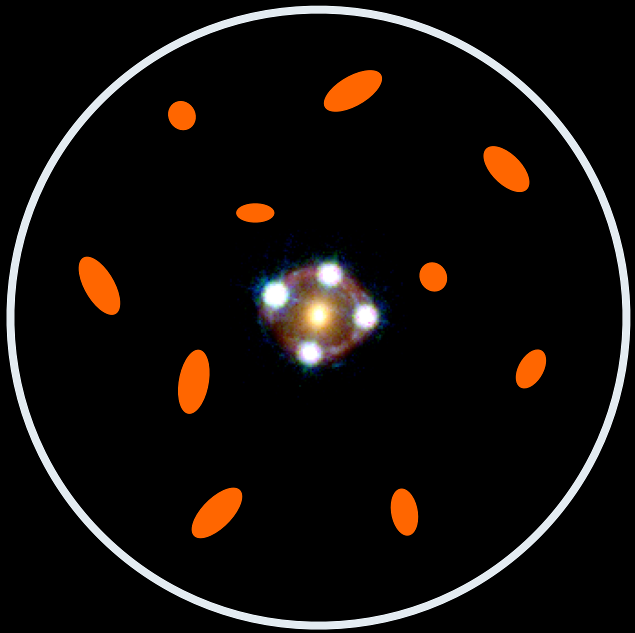

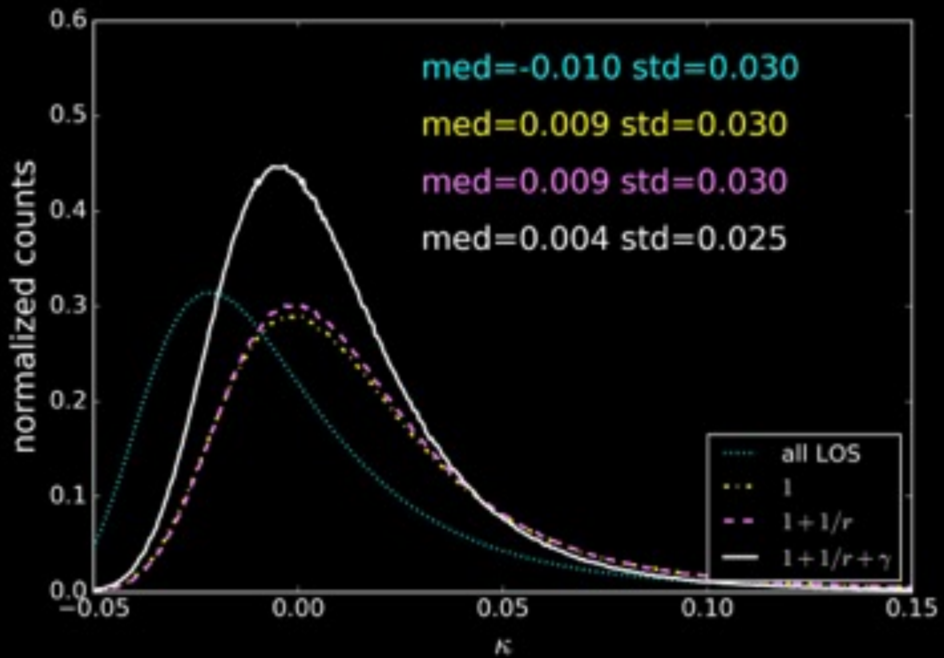

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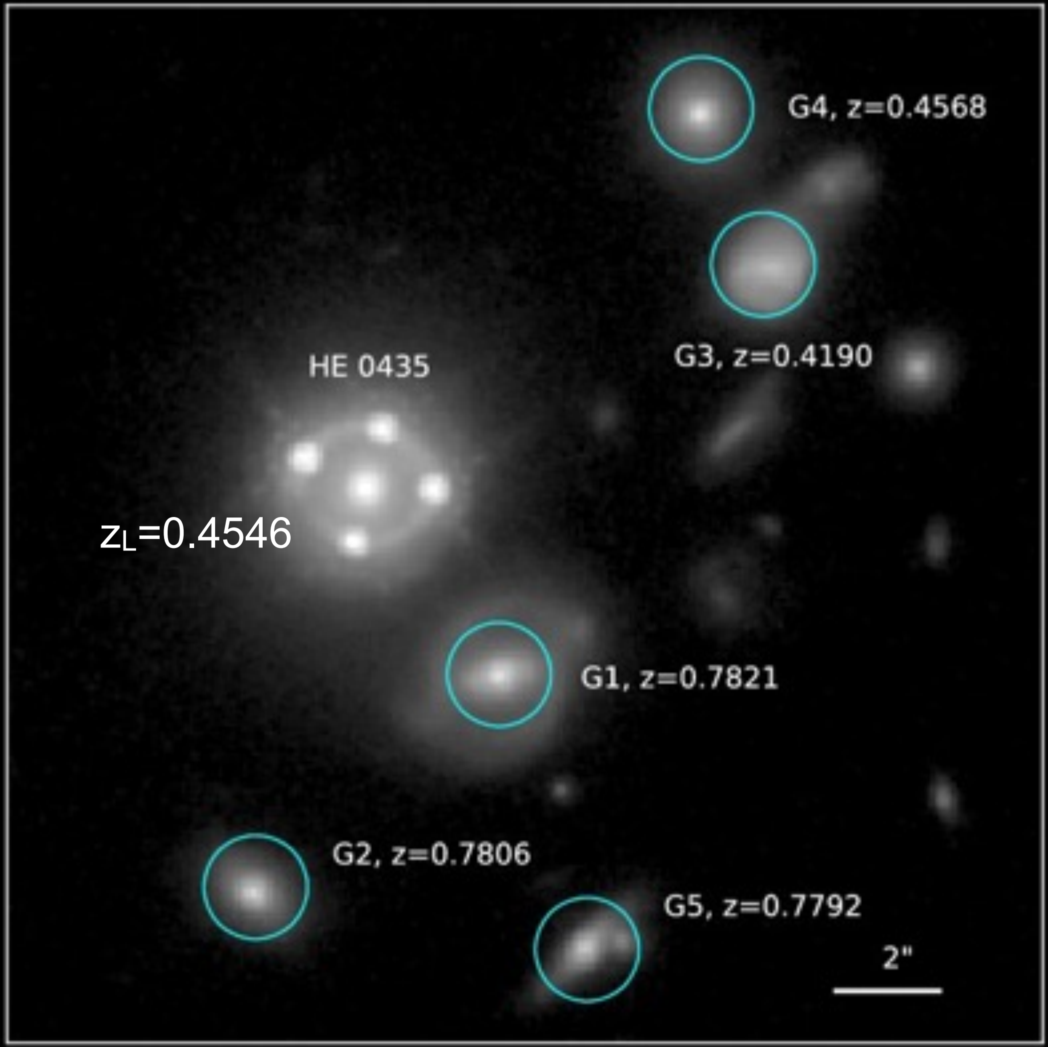



Wide-field spectroscopy for group identification [Sluse, Sonnenfeld, Rumbaugh et al. 2017]

Wide-field imaging to get external mass distribution [Rusu, Fassnacht, Sluse et al. 2017]

# Lens mass modeling

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

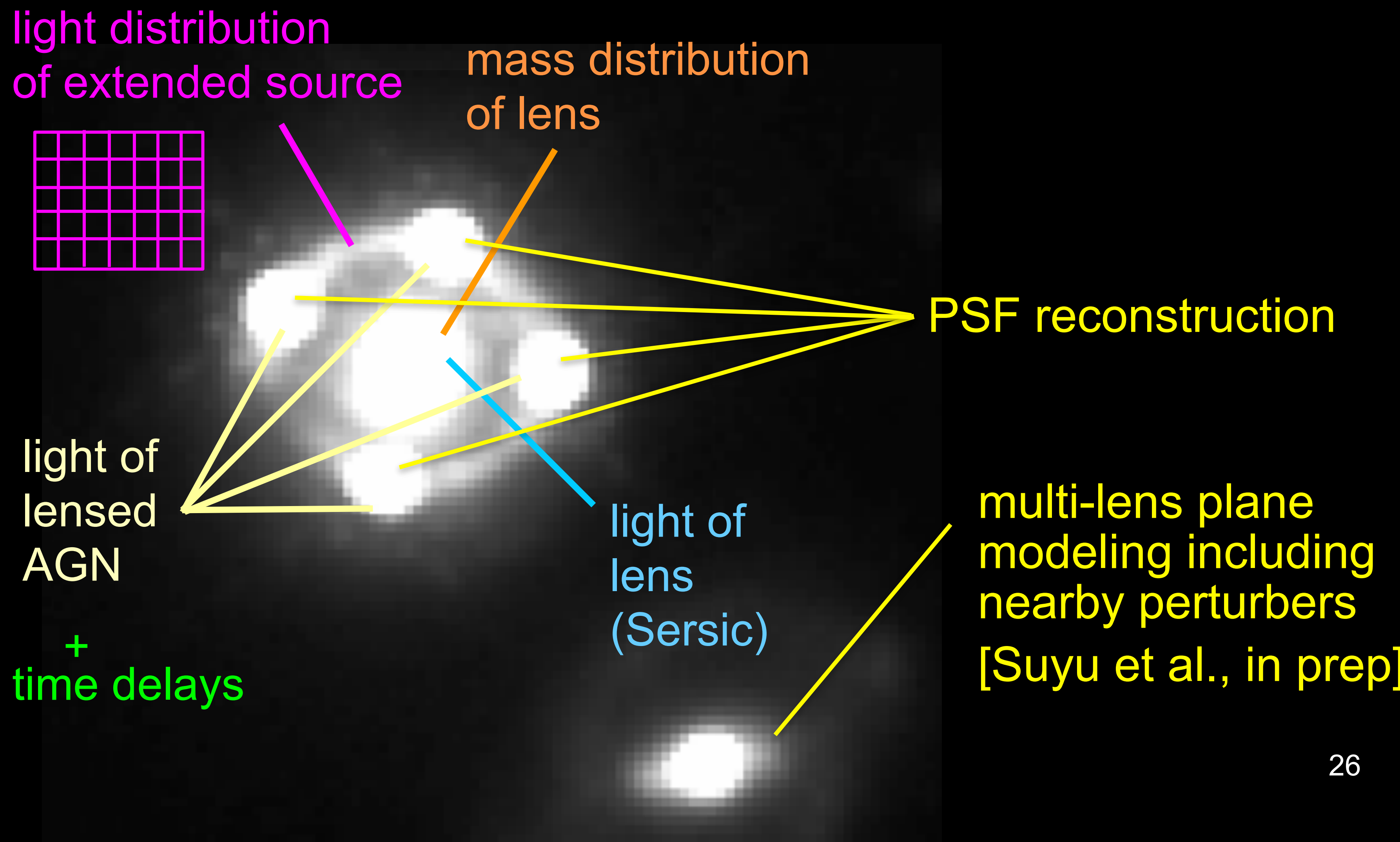
**Modeling with GLEE :)**

**G**ravitational
**L**ens
**E**fficient
**E**xplorer

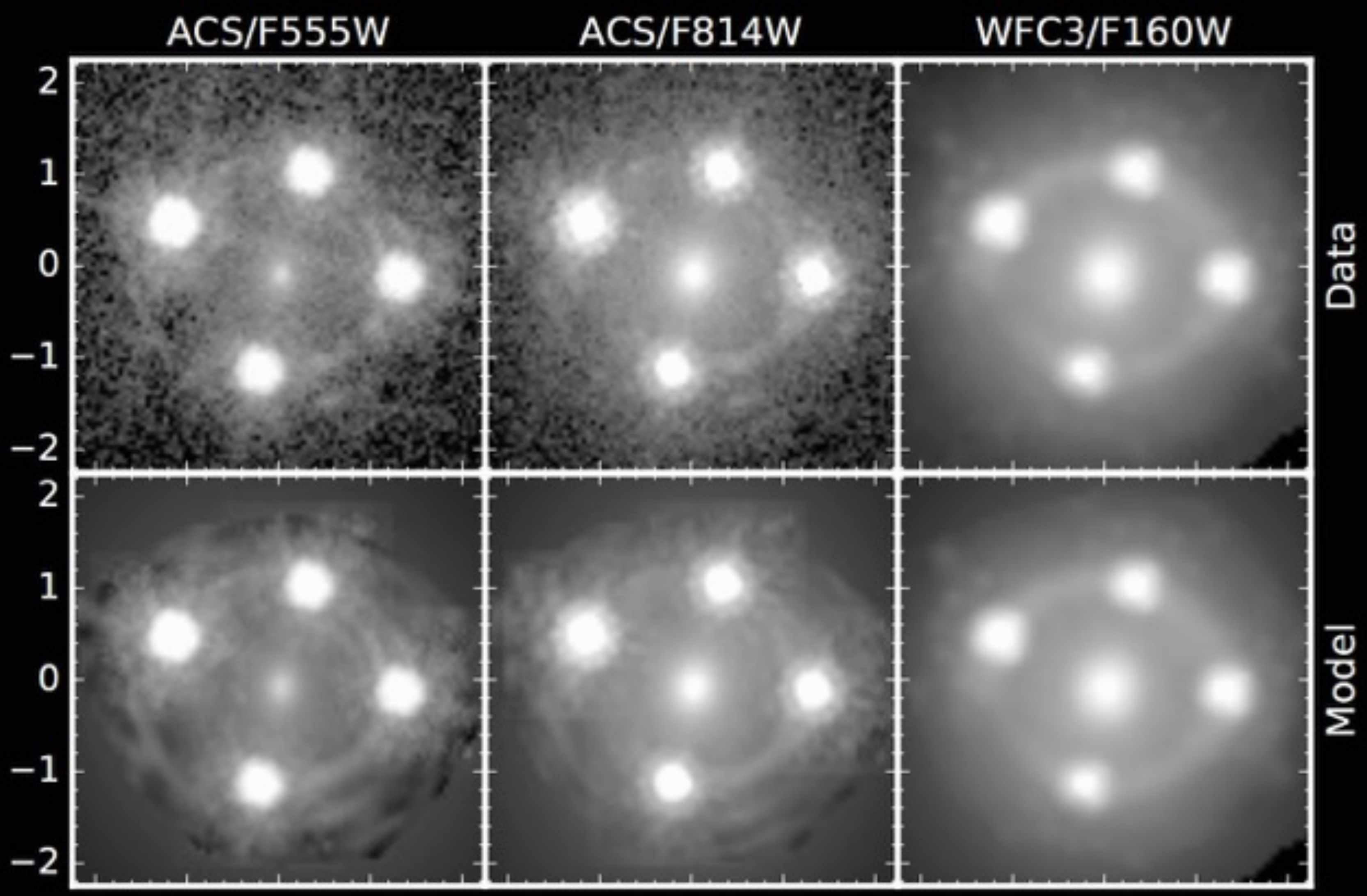
[Suyu & Halkola 2010]

# Lens mass modeling

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



# Lens reconstruction

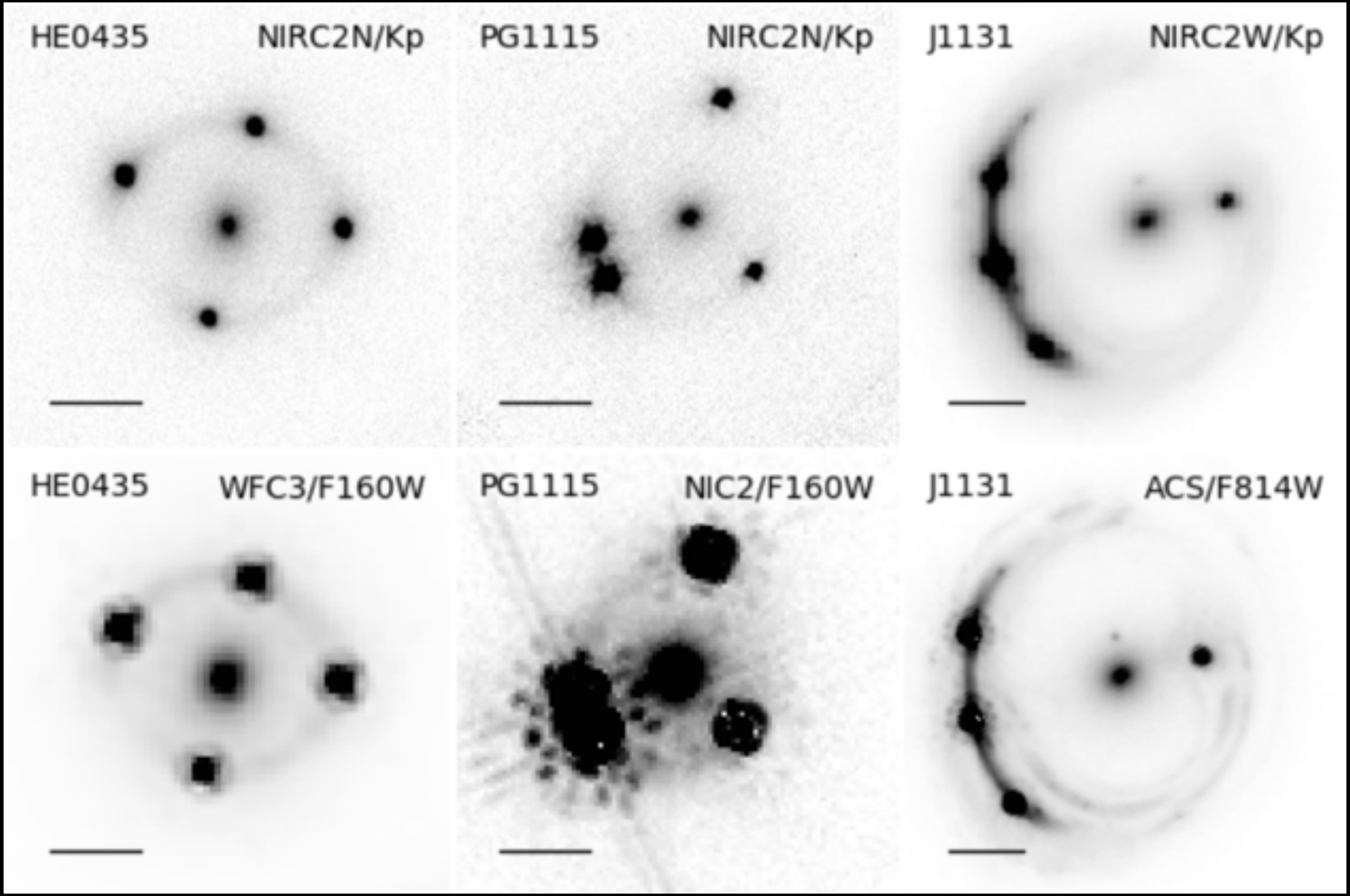



[Wong, Suyu, Auger et al. 2017]

# Cosmology with Adaptive Optics

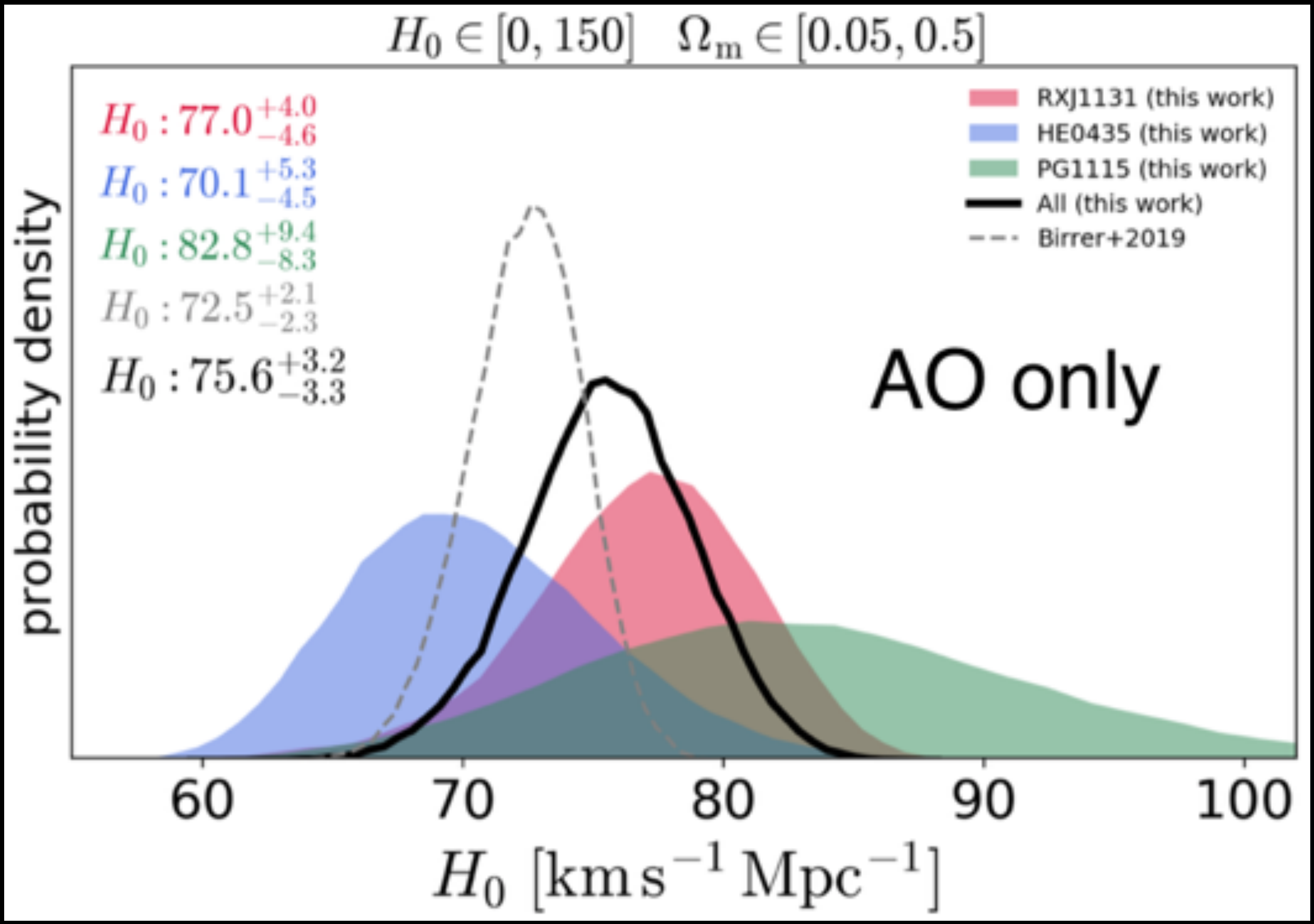
Keck AO

HST




[Chen, Fassnacht, Suyu et al. submitted (arXiv:1907.02533)]

# Cosmology with Adaptive Optics

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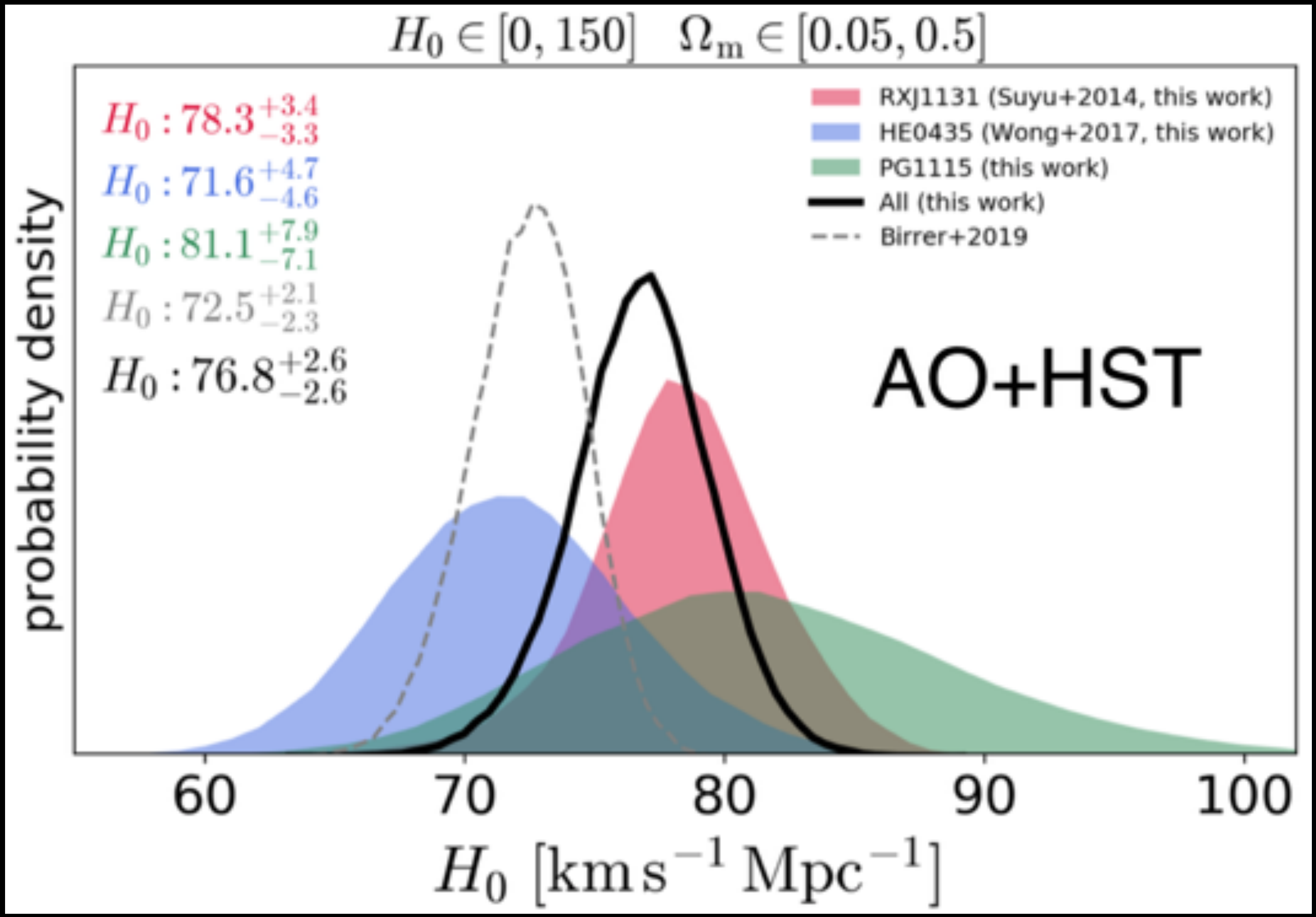
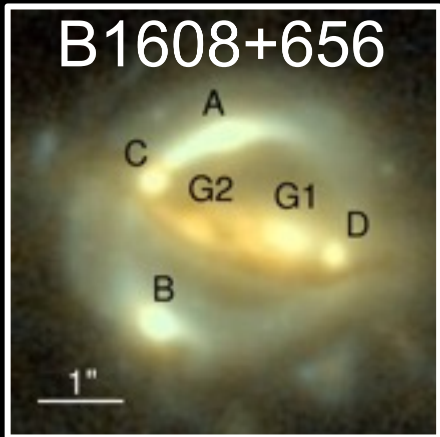
# Cosmology with Adaptive Optics



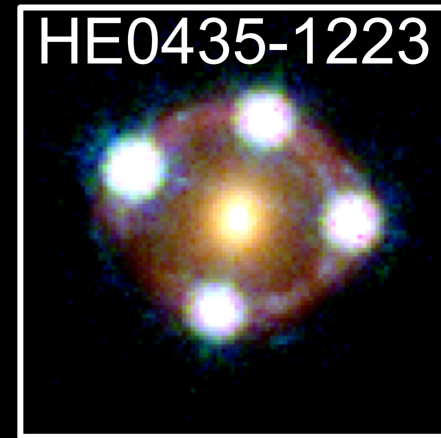

[Chen, Fassnacht, Suyu et al. submitted (arXiv:1907.02533)]

# H0LiCOW latest results




[Suyu et al. 2010]

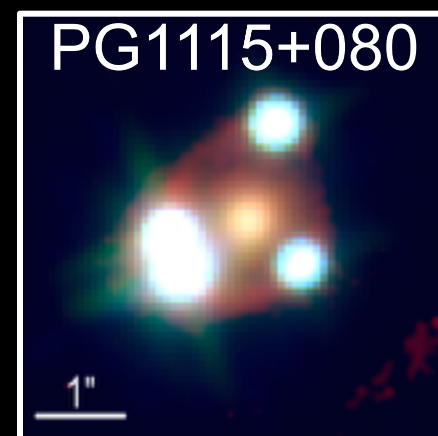

[Suyu et al. 2013, 2014; Tewes et al. 2013]




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


part of extended sample [Birrer et al. 2019]

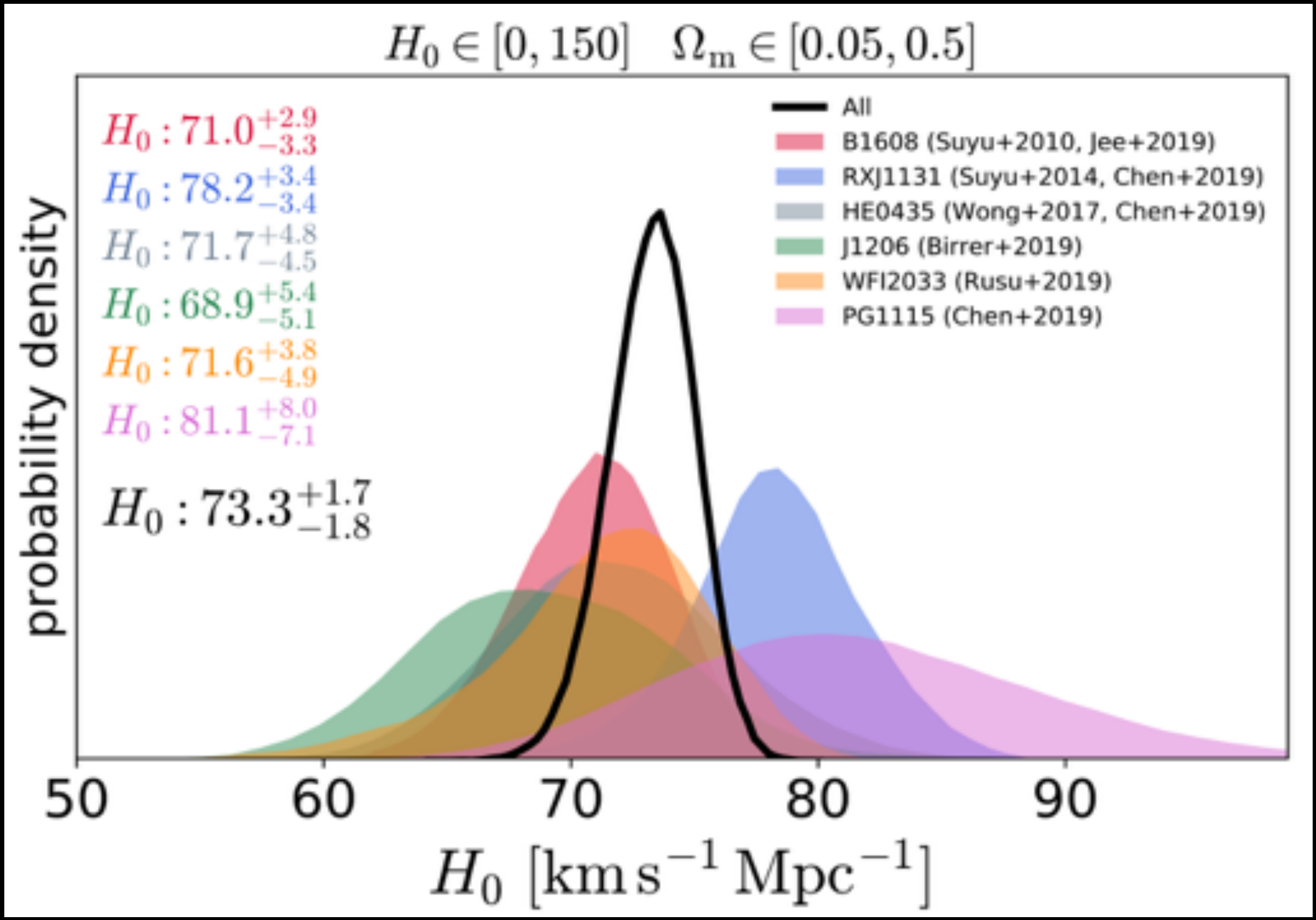

[Bonvin et al. 2019; Sluse et al. 2019; Rusu et al. 2019]




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

# $H_0$ from 6 strong lenses

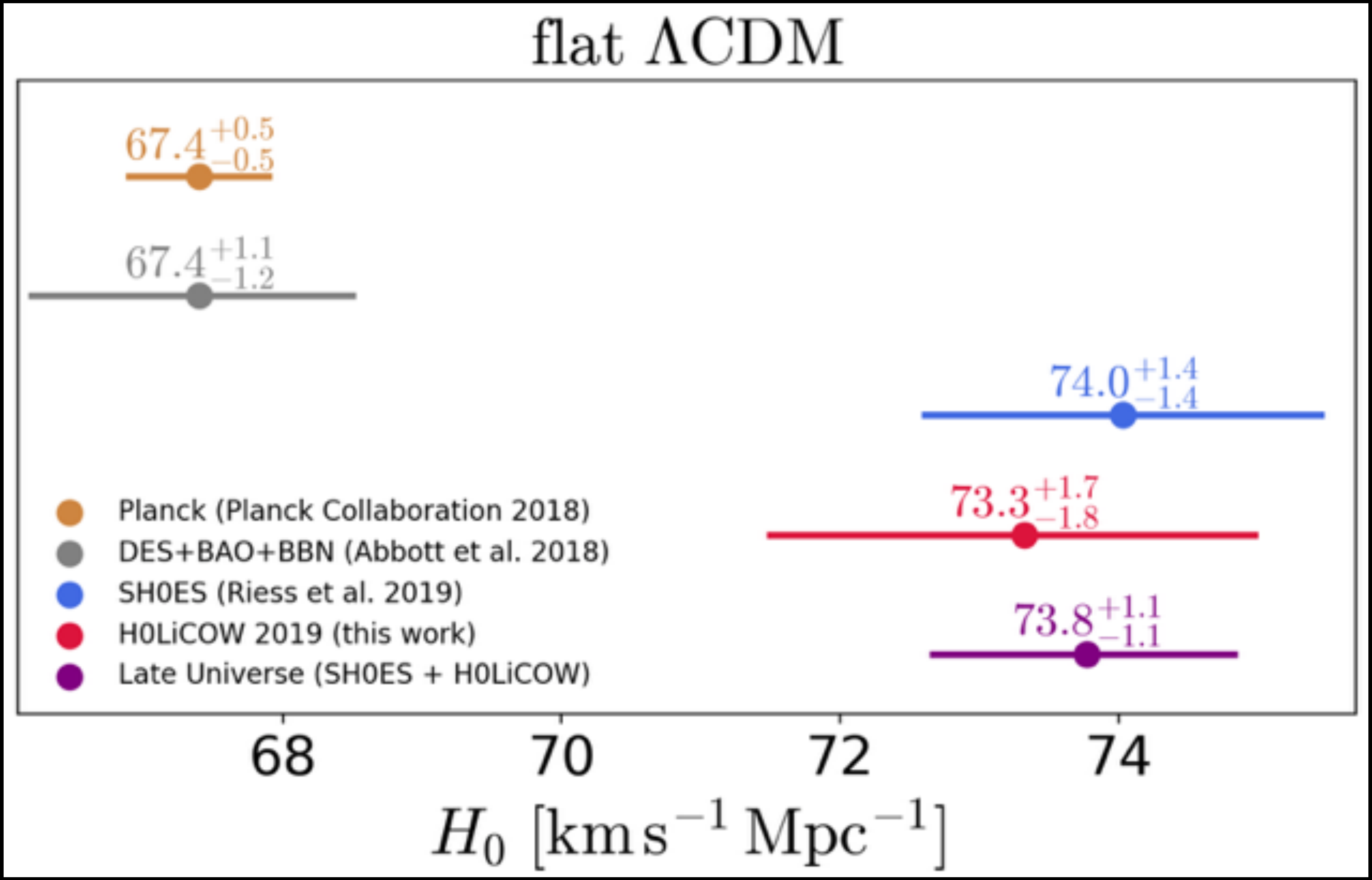
Blind analysis to avoid confirmation bias




***$H_0$* with 2.4% precision in flat ΛCDM**

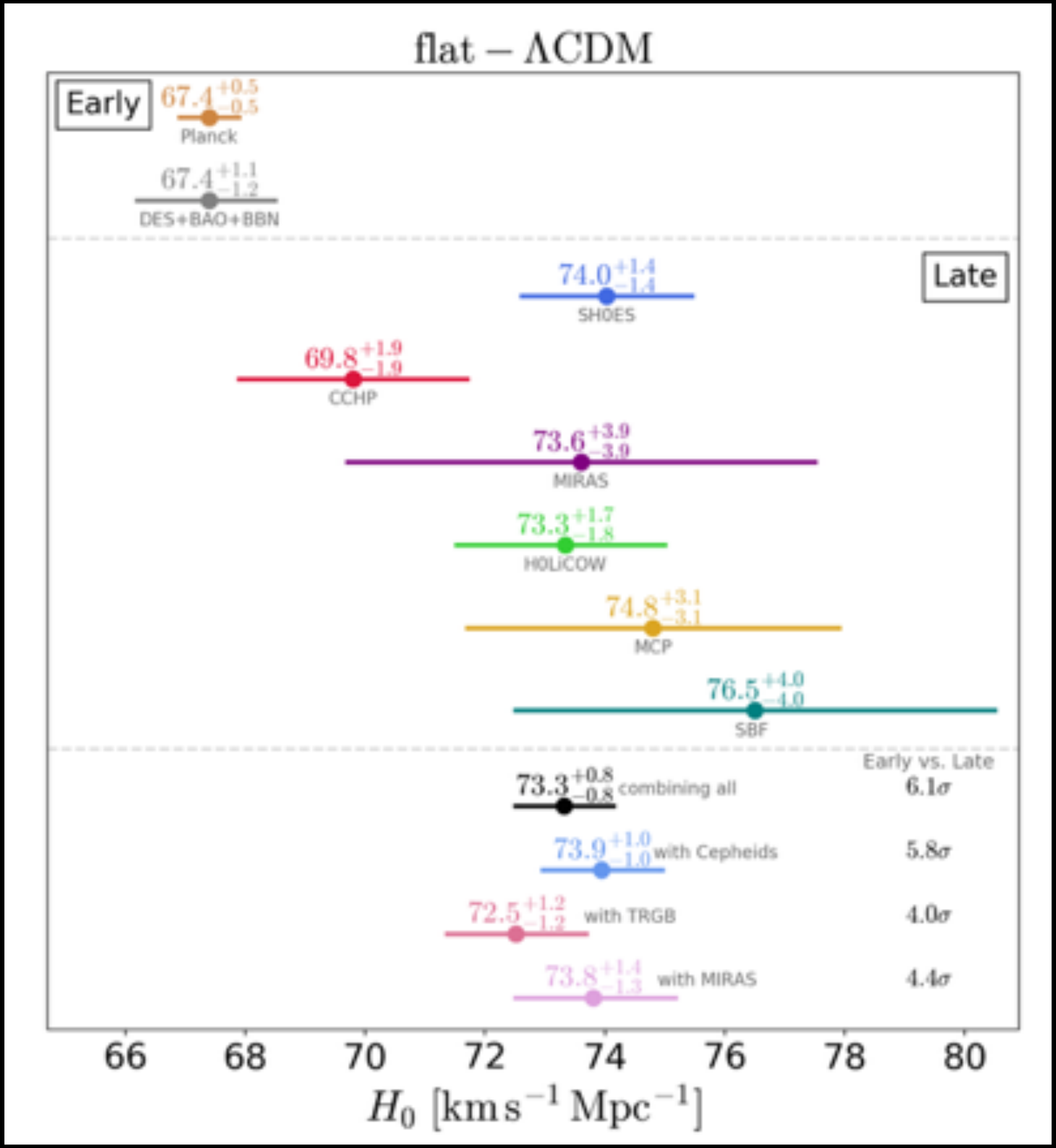
[Wong, Suyu, Chen et al. submitted (arXiv:1907.04869)]

# $H_0$ comparison




[Wong, Suyu, Chen et al. submitted (arXiv:1907.04869)]

# Tensions between Early and Late Universe

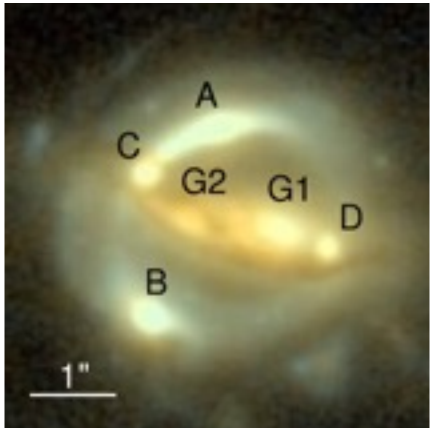



[Verde, Treu, Riess (arXiv:1907.10625)]

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

B1608+656

[Suyu et al. 2010]

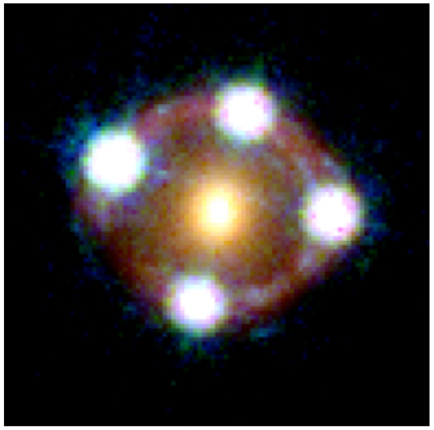



RXJ1131-1231

[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]

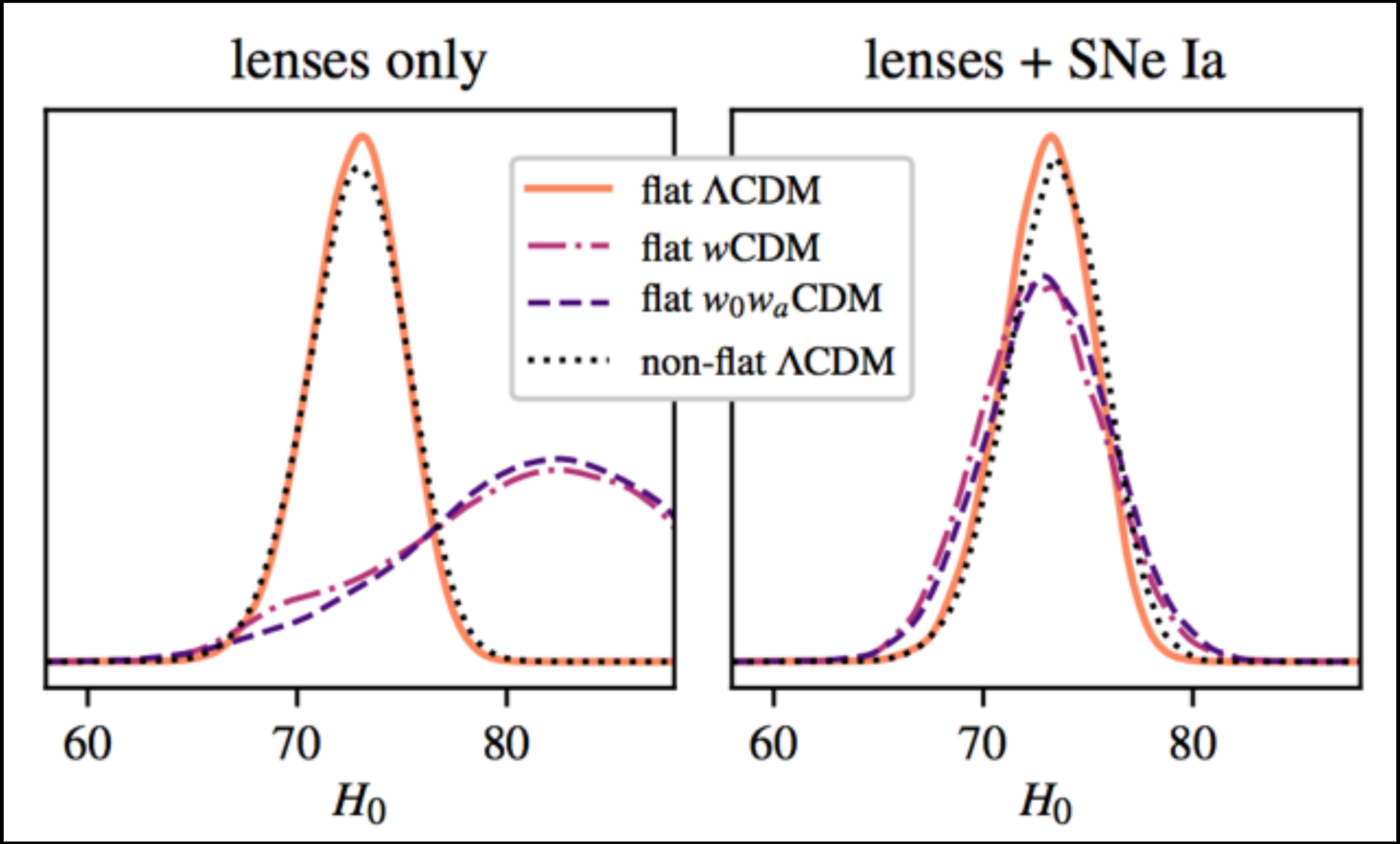


SDSS1206+4332

part of extended sample

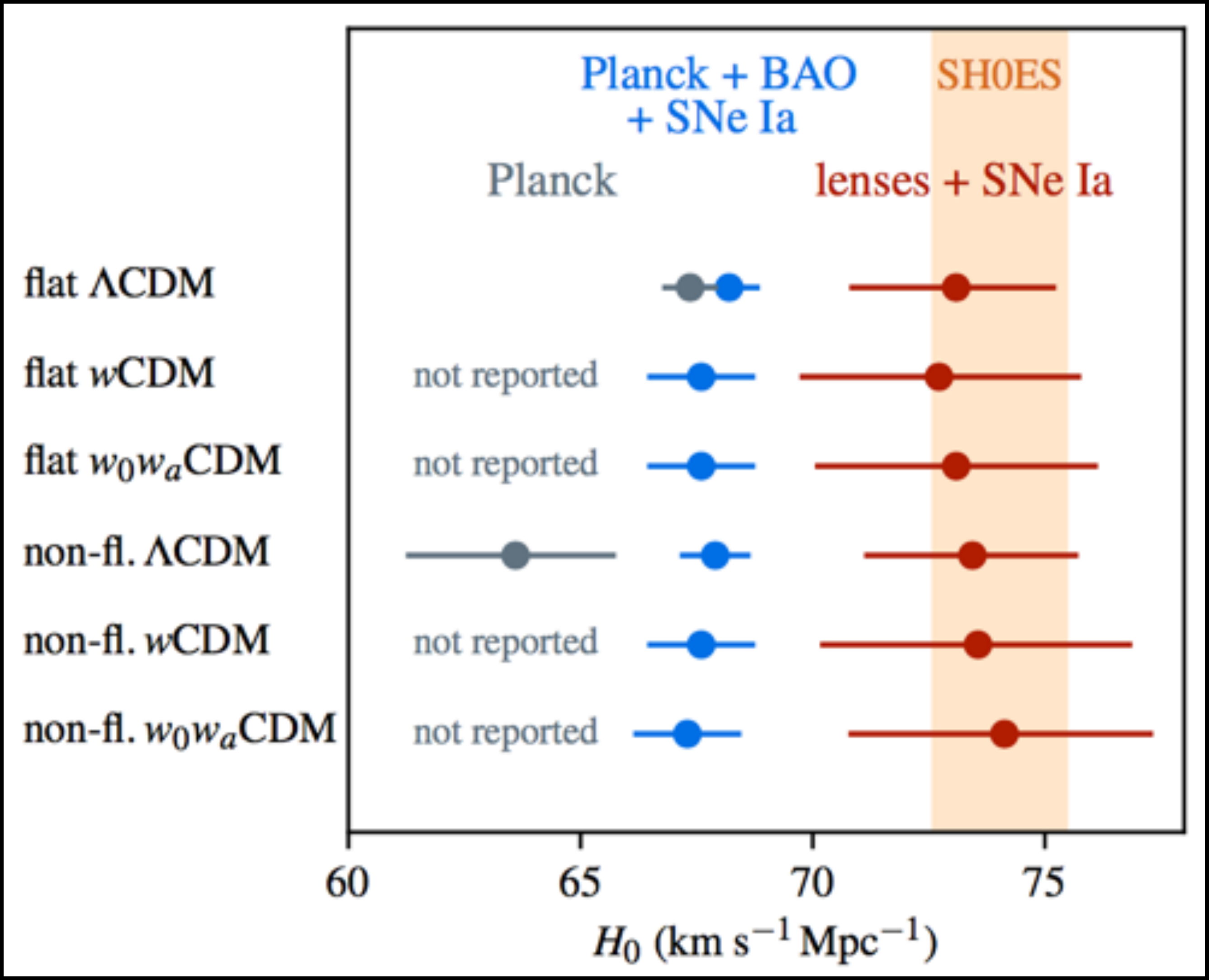
[Birrer, Treu Rusu et al. 2018]

# Reduced cosmological dependence



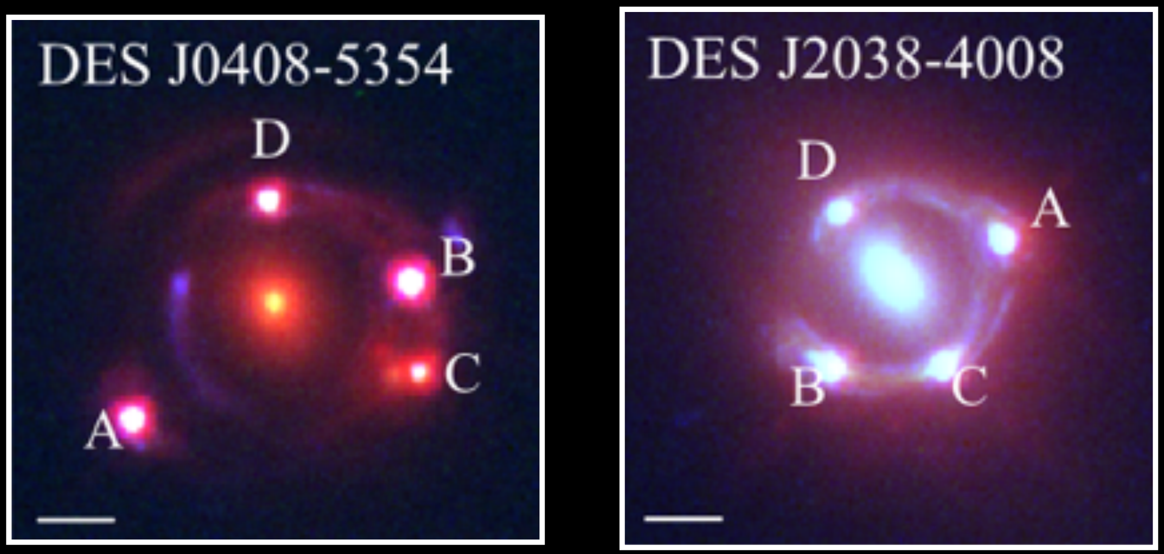

[Taubenberger, Suyu, Komatsu et al. 2019]

# Reduced cosmological dependence



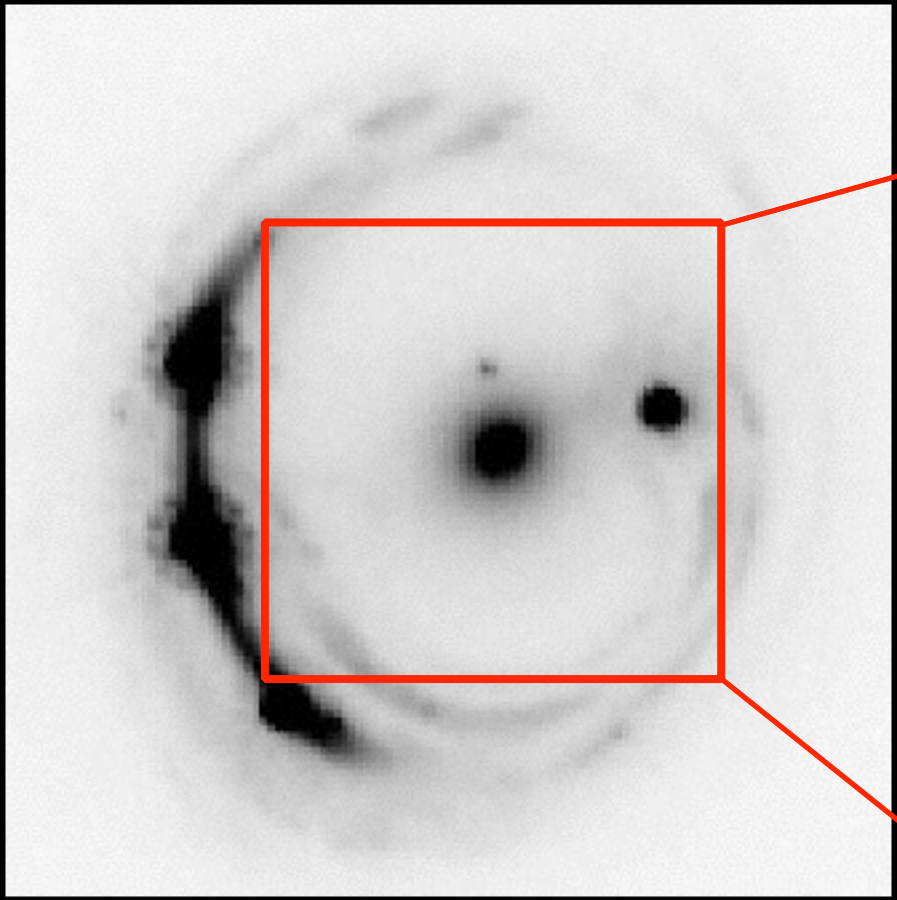

[Taubenberger, Suyu, Komatsu et al. 2019;
see also Arendse, Agnello & Wojtak 2019]

# Looking forward

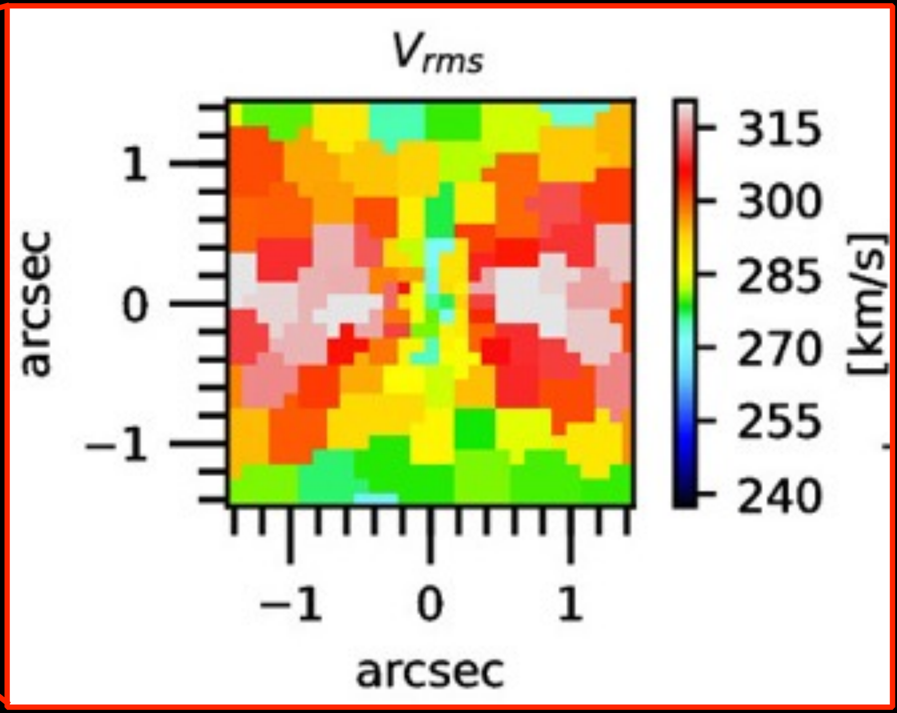



- Part of STRIDES collaboration [Treu et al. 2018]
- Blind analysis with two independent lens modeling softwares [Shajib et al. 2019; Shajib et al. in prep; Yıldırım et al. in prep; Wong et al. in prep]

# Stellar kinematics really helps

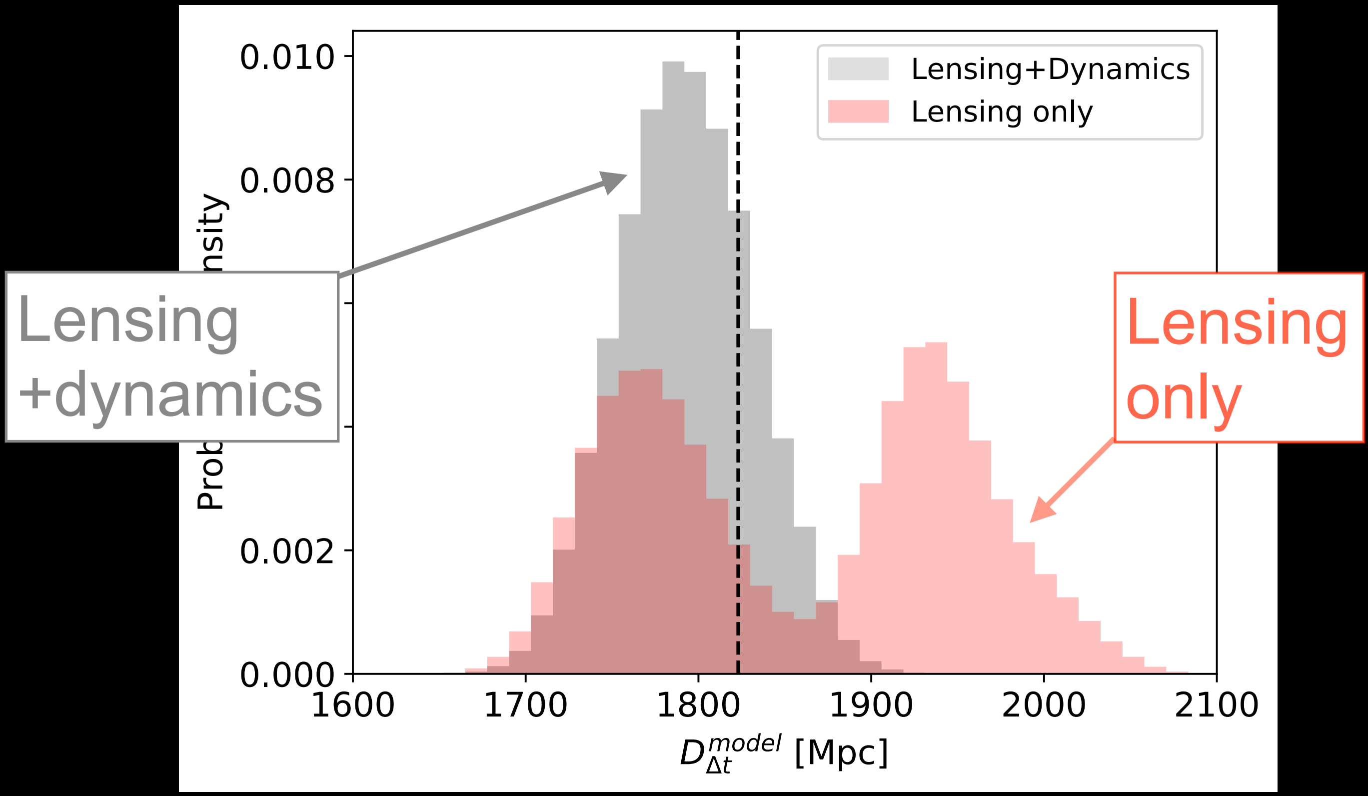


simulated James Webb Space Telescope NIRSpec observations of stellar kinematic map of lens




[Yıldırım, Suyu, Halkola 2019]

# Stellar kinematics really helps

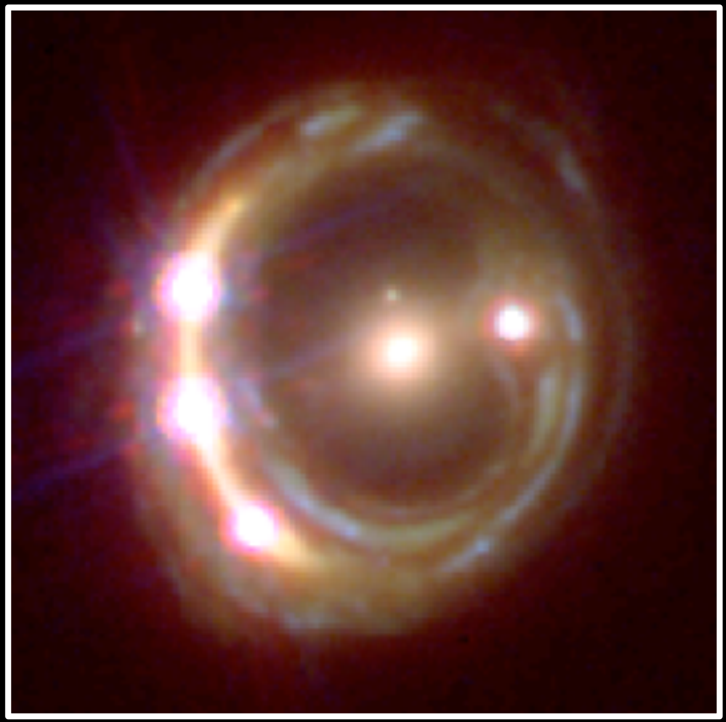



- Inferred $D_{\Delta t}$ depends on assumptions of mass model
- Including kinematic data:
  - reduces dependence of $D_{\Delta t}$ on mass model assumption
  - tightens constraints on $D_{\Delta t}$



[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:

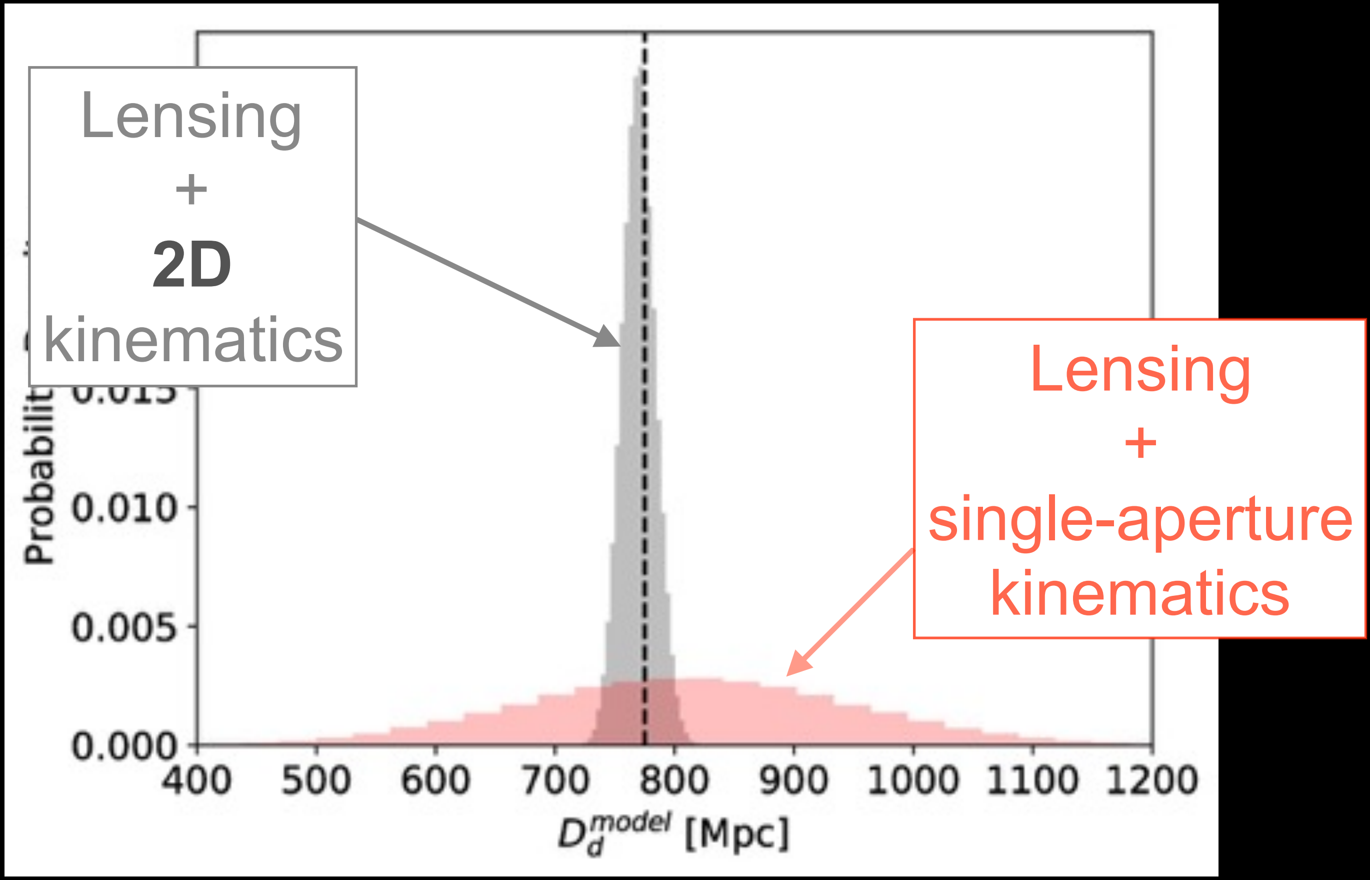
$$D_A \sim r/\Delta\theta$$

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

- $D_A$ 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

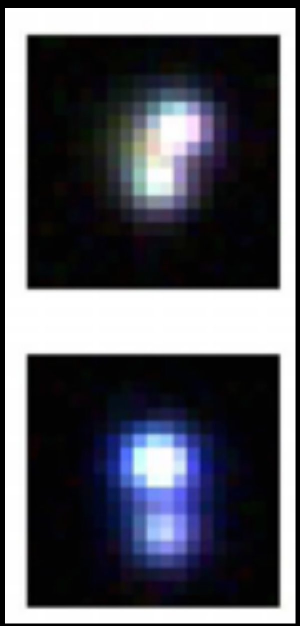
- 5000 deg$^2$ with $i_{limit}$~24
- 2012-2017
- expect ~1100 lenses
  [Oguri & Marshall 2010]

## Kilo Degree Survey

2.6m VLT Survey Telescope, Paranal, Chile

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

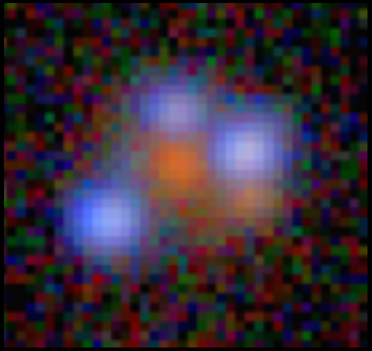
# New lensed quasars systems



[Agnello et al. 2015]

[More et al. 2017]

[Ostrovski et al. 2017]

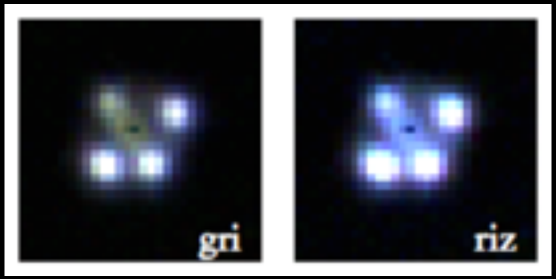


[Lin et al. 2017]


[Berghea et al. 2017]

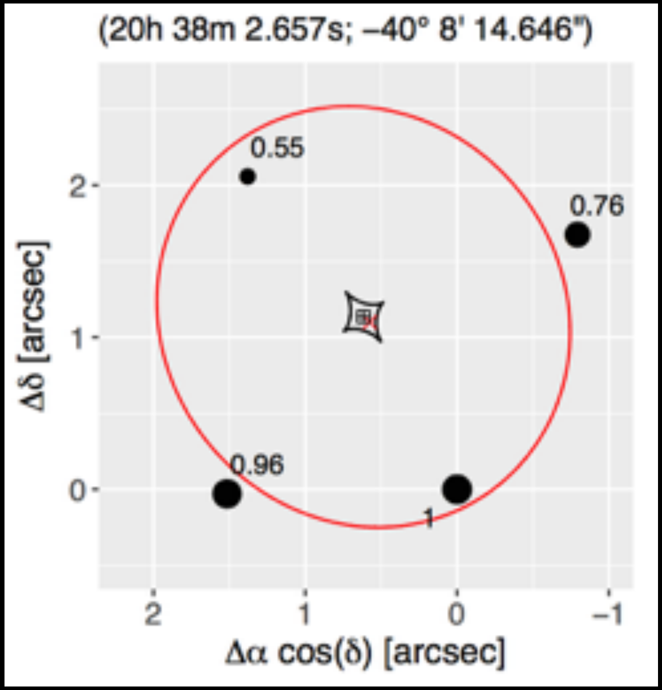
# Gaia reveals lensed quasars

Gaia
+ DES
+ WISE



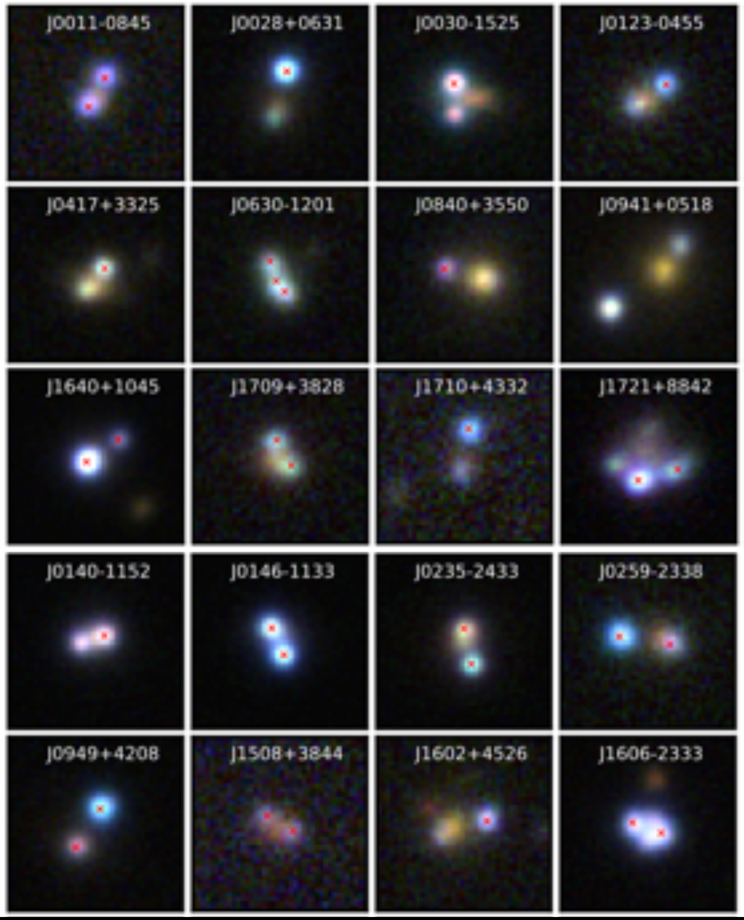

[Agnello et al. 2018]

Gaia
only




[Krone-Martins et al. 2018]

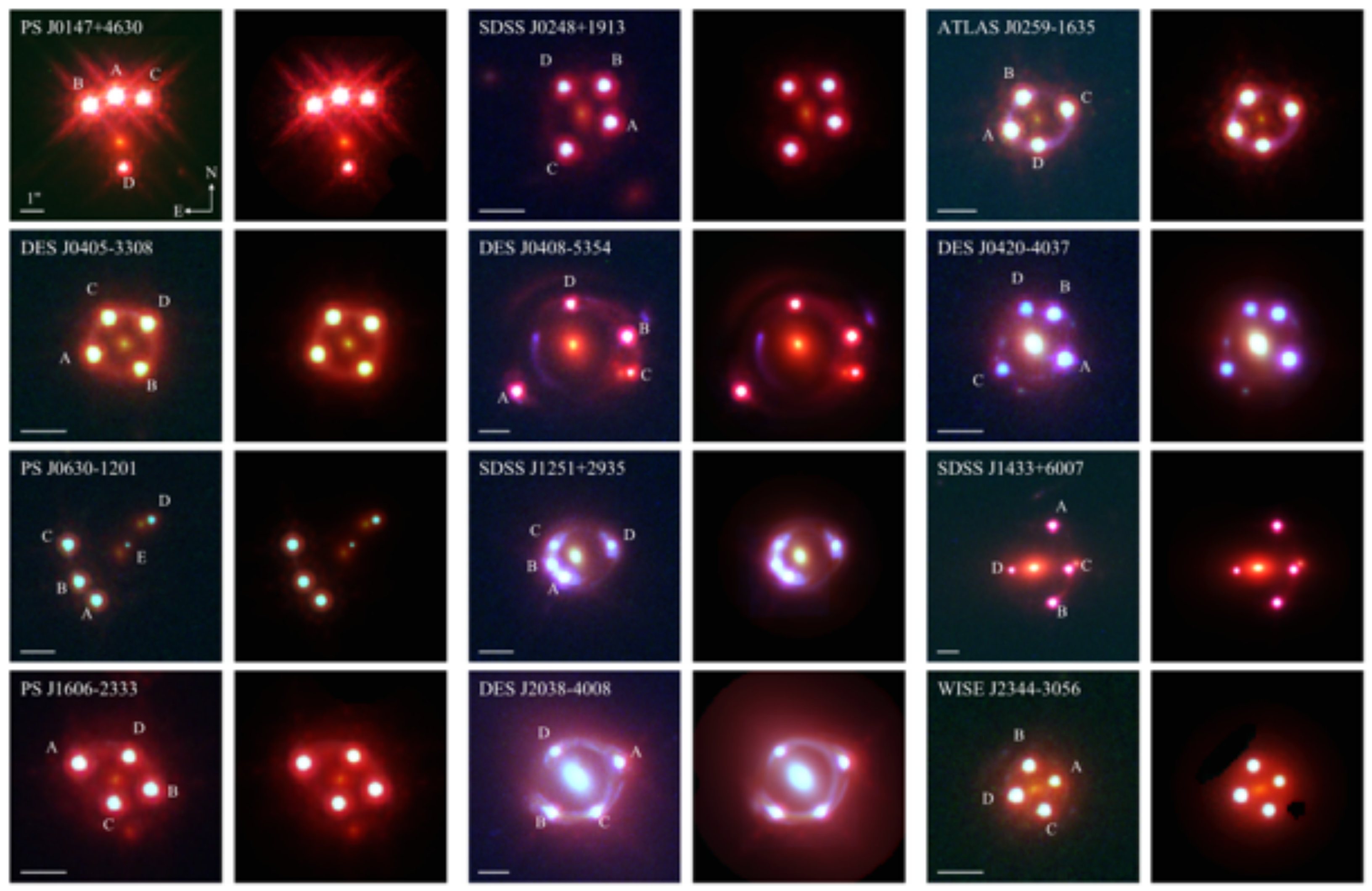
Gaia + WISE/SDSS
+ Pan-STARRS




[Lemon et al. 2018]

# New quads imaged with HST

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




[Shajib et al. 2018]

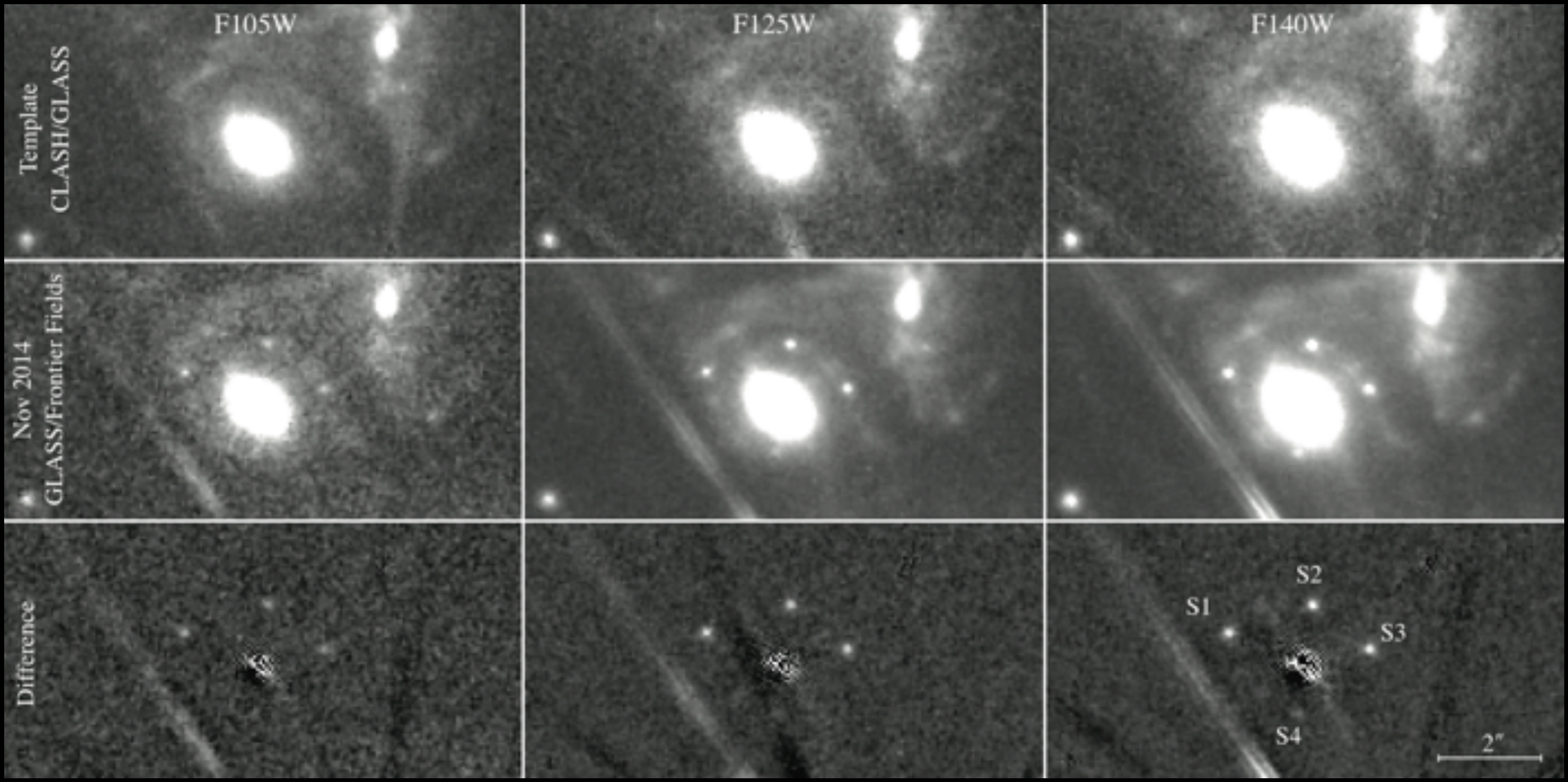
# Strongly lensed supernova


MACS 1149.6+2223

[Kelly et al. 2015]

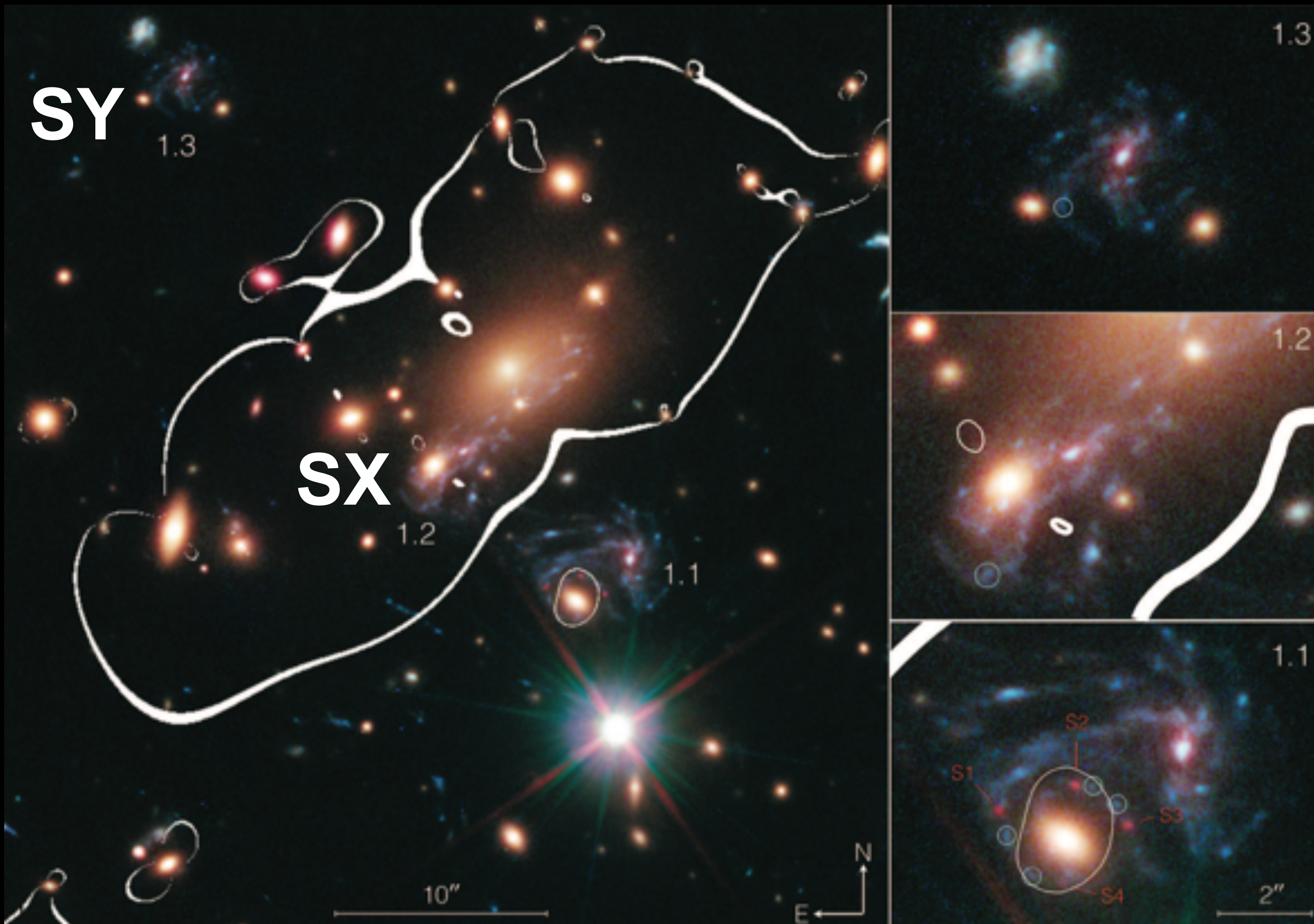
# Supernova "Refsdal"

discovered serendipitously in November 2014




[Kelly et al. 2015]

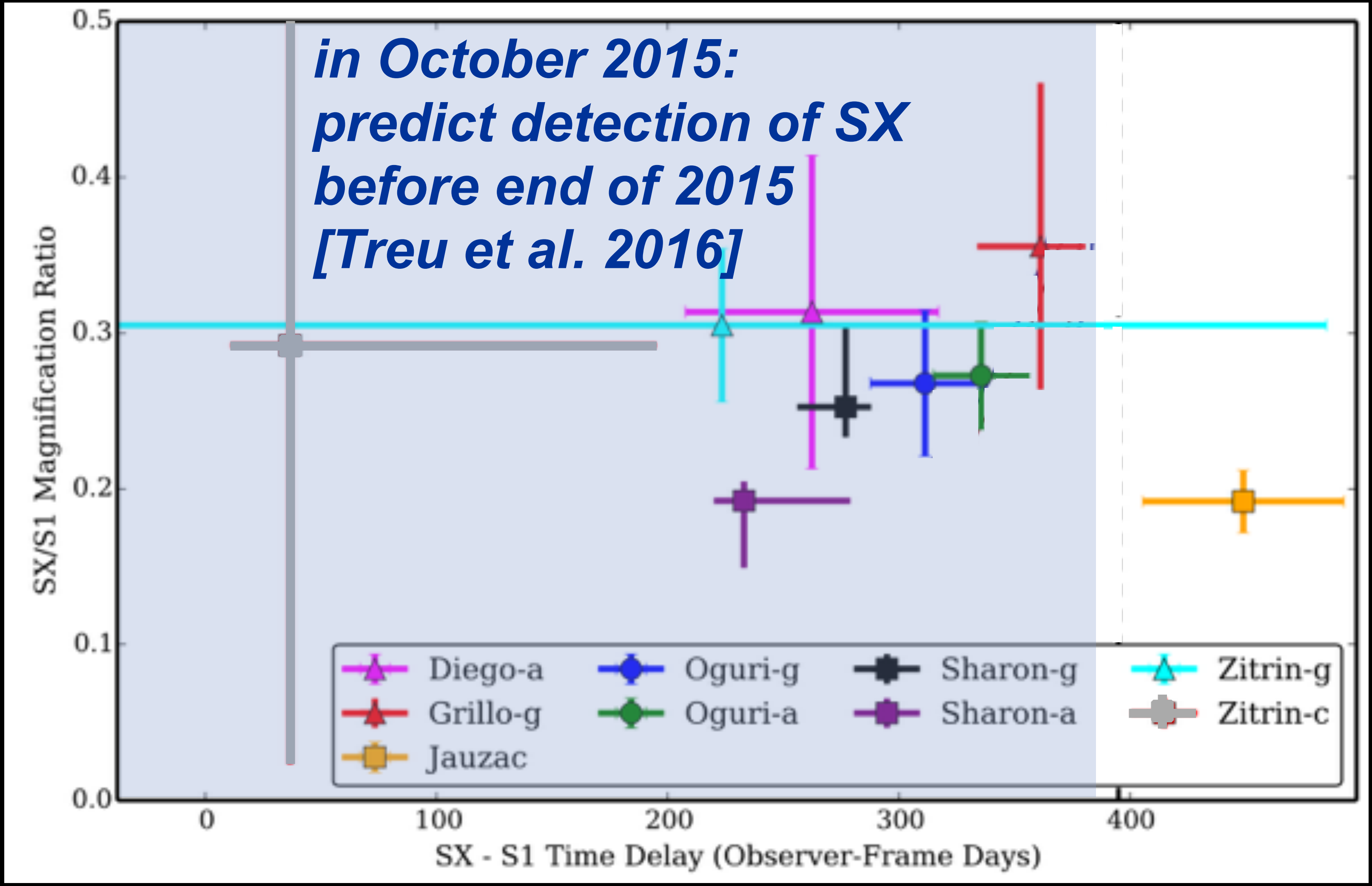
# When will the other SN images appear?




MACS 1149.6+2223

[Kelly et al. 2015]

# Predicted magnification and delay

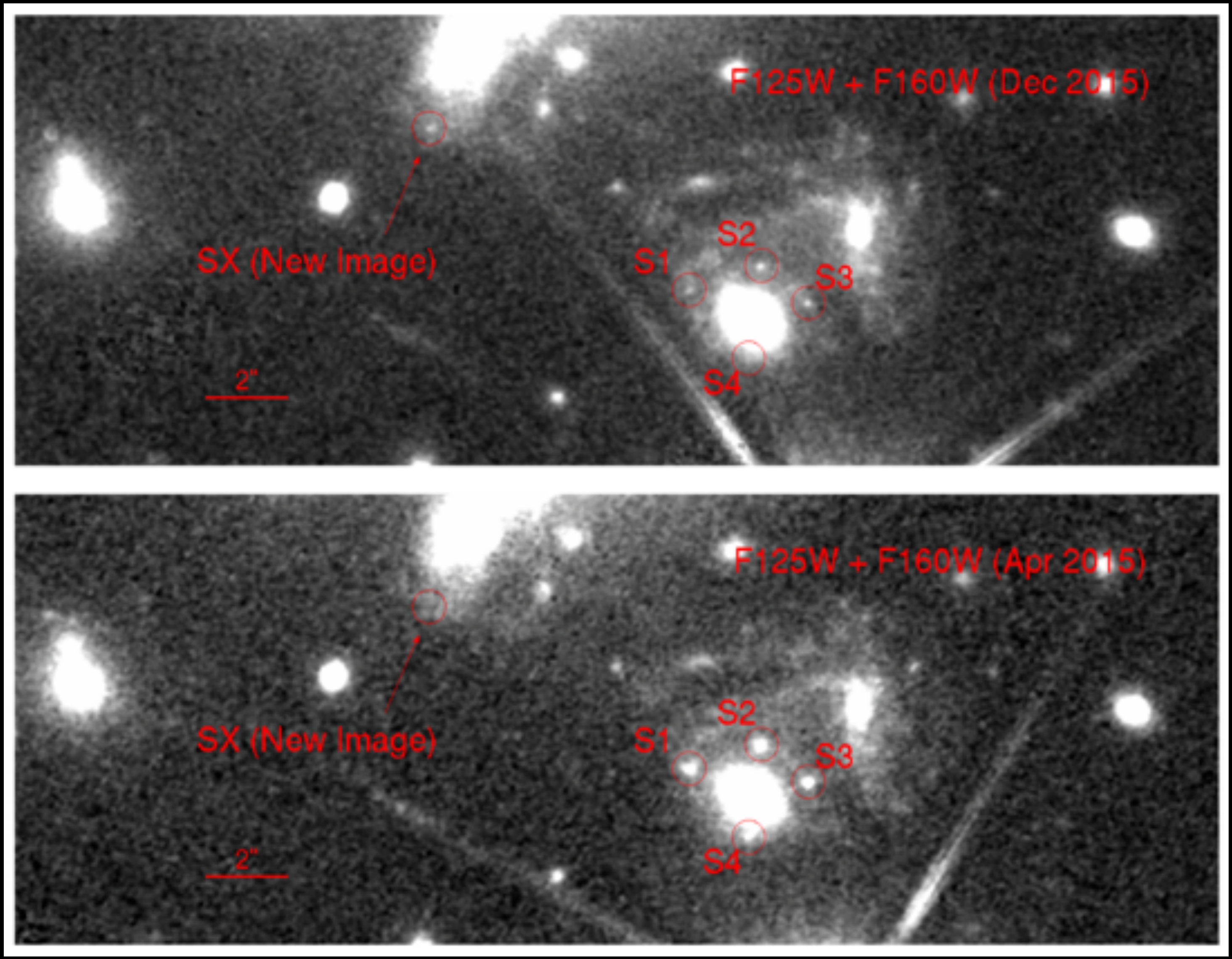



[Kelly et al. 2016]

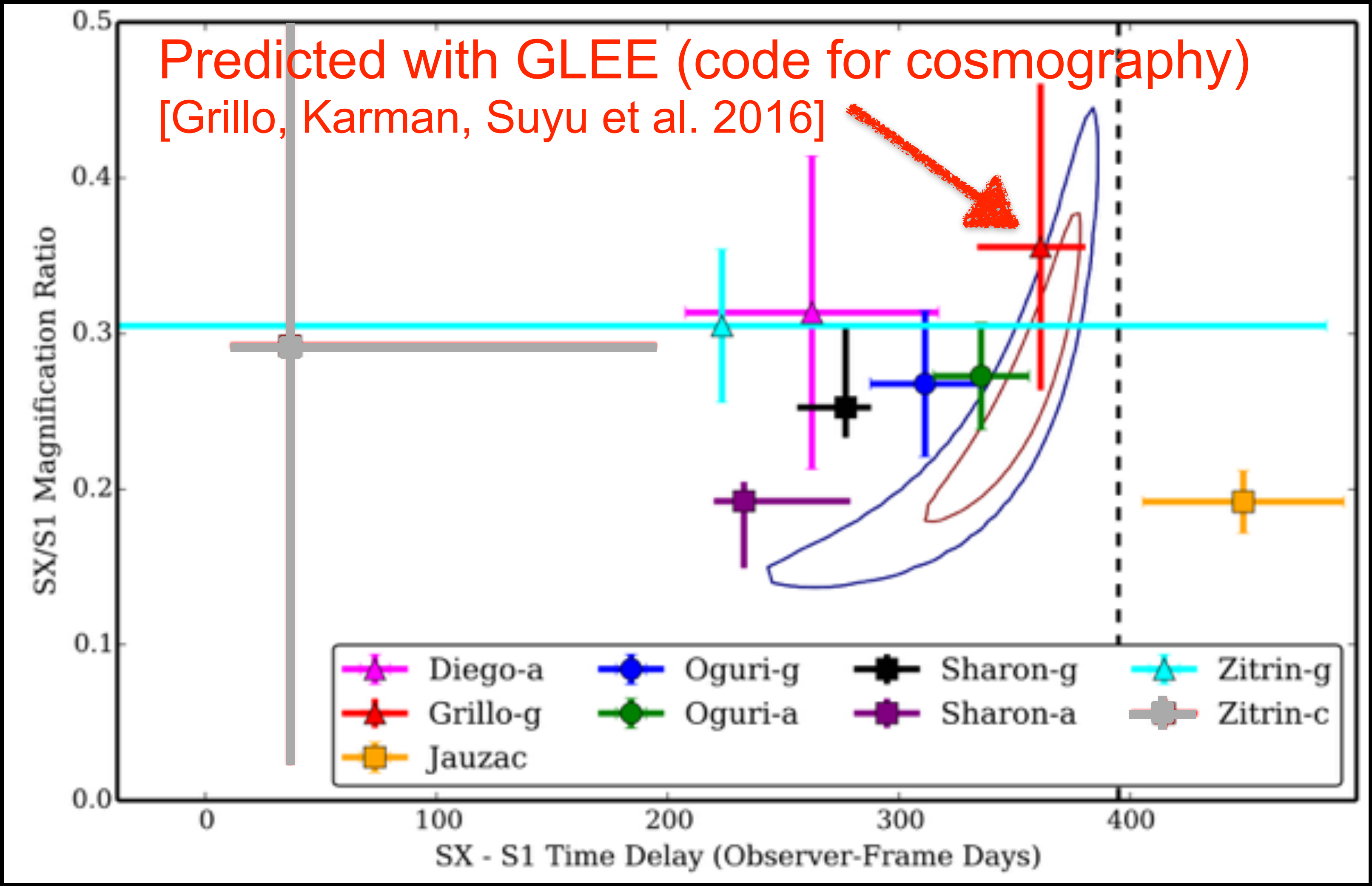
HST observations in Oct 2015: no sign of SX
in Nov 2015: no sign of SX…

# Appearance of image SX

December 2015 [Kelly et al. 2016]

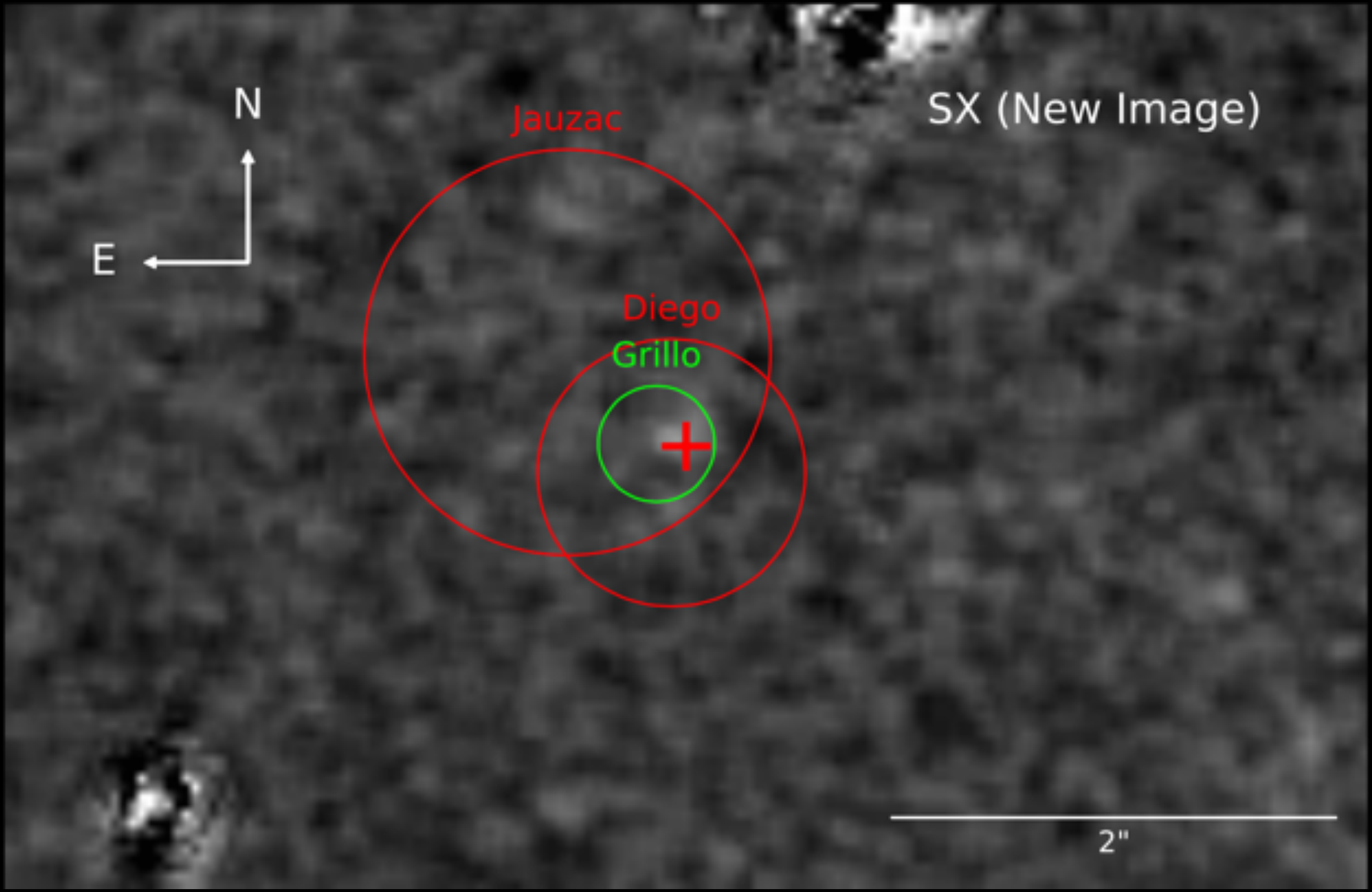


# Magnification and delay




[Kelly et al. 2016]

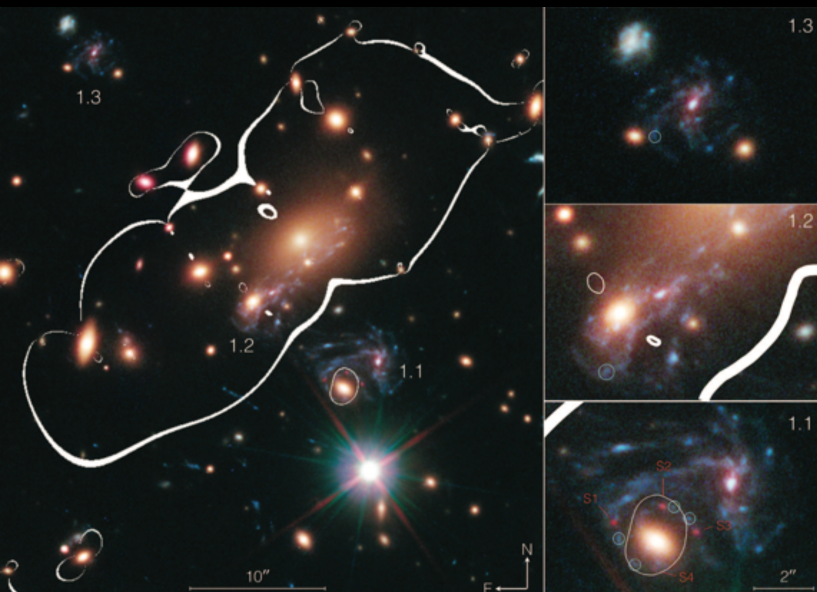
# Spot on!

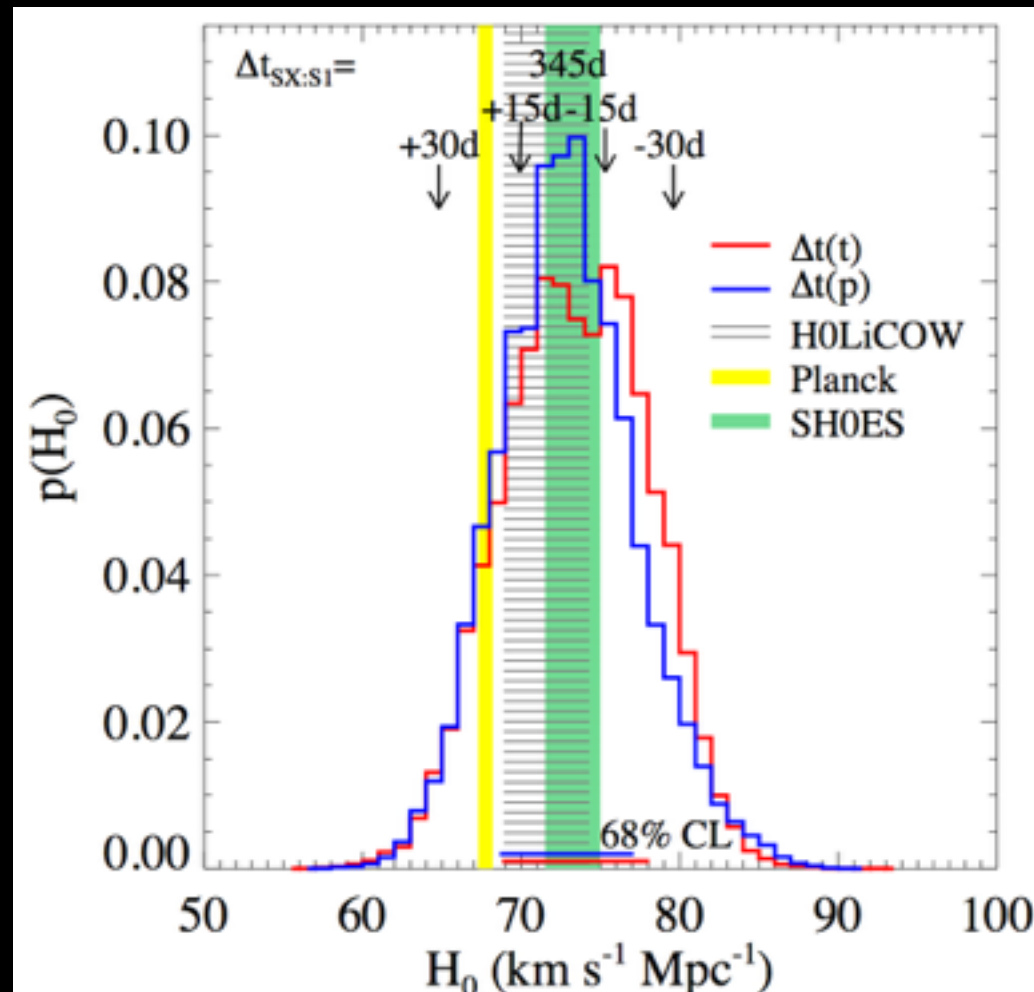



[Kelly et al. 2016]

# $H_0$ à la Supernova Resfdal

feasibility study of using SN Refsdal for $H_0$ measurement



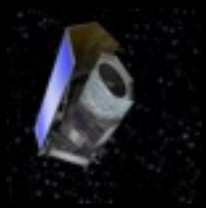

- S1-S2-S3-S4 delays from Rodney et al. (2016)
- SX-S1 delay estimated based on detection in Kelly et al. (2016)

[Grillo, Rosati, Suyu et al. 2018]

# Future Prospects

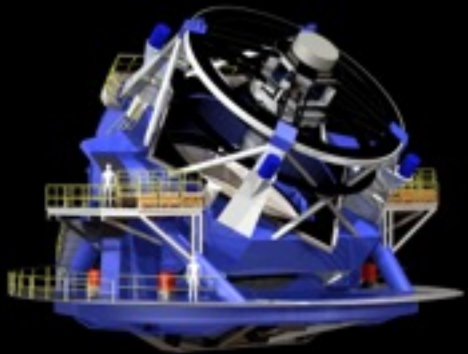
Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid



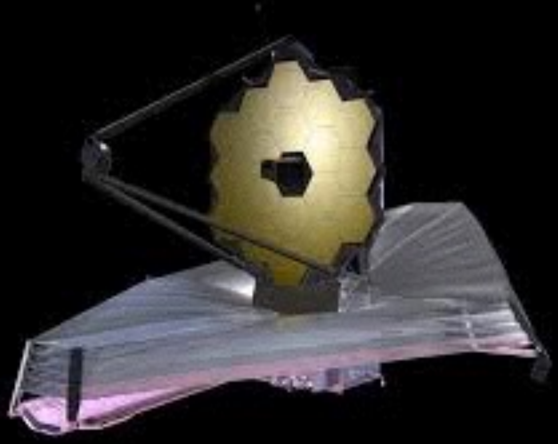
Discovery
Imaging
Spectroscopy

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