Shedding Light on the Dark Cosmos through Gravitational Lensing

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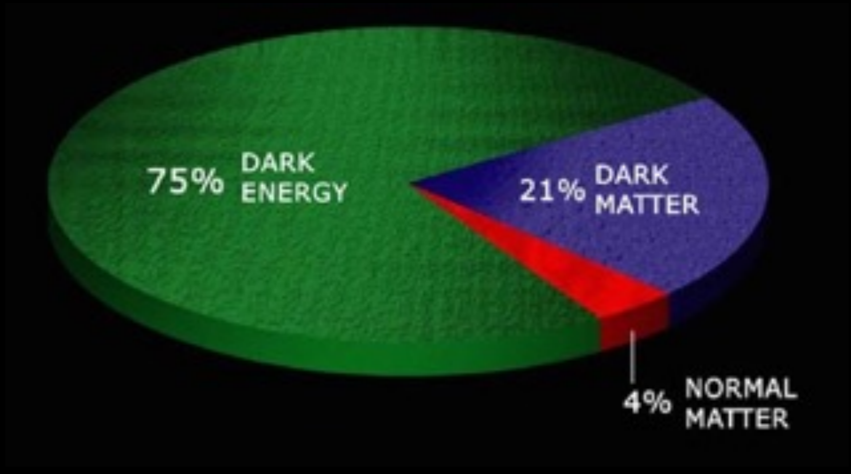
seminar @ ESAC

Puzzles in cosmology



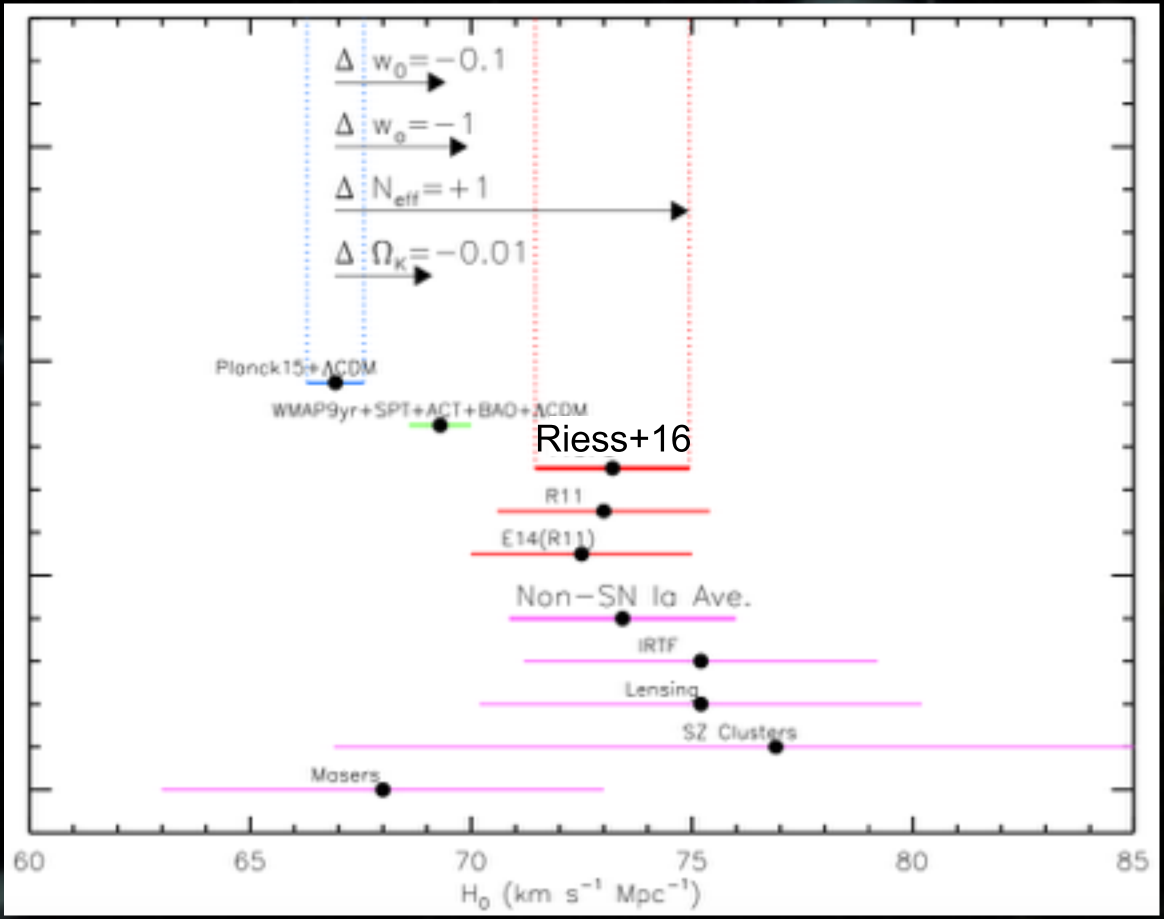
What is the nature of dark energy and dark matter?

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. 2016]

Hubble constant H_0

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

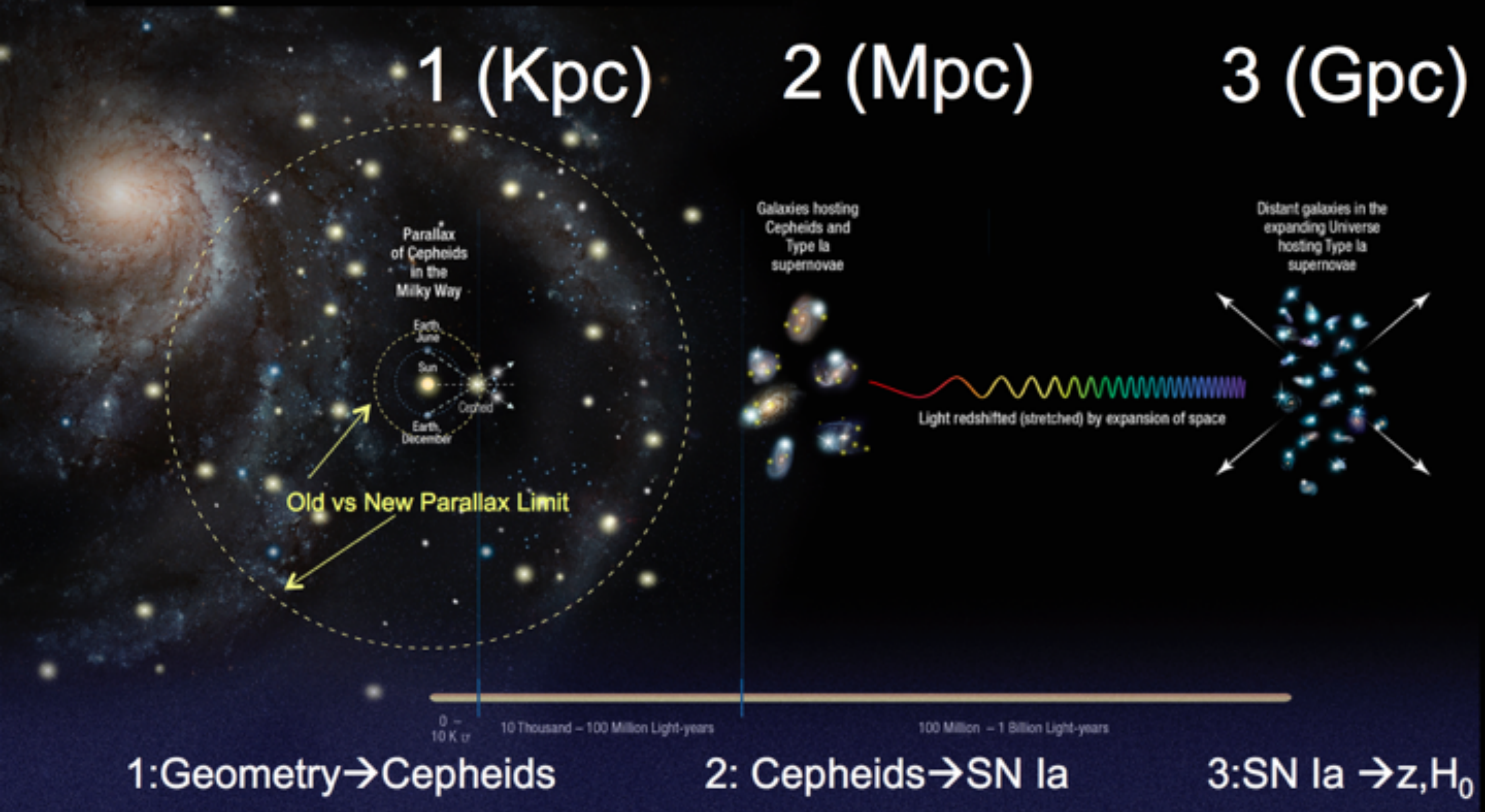
Tension? New physics?

➡ 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

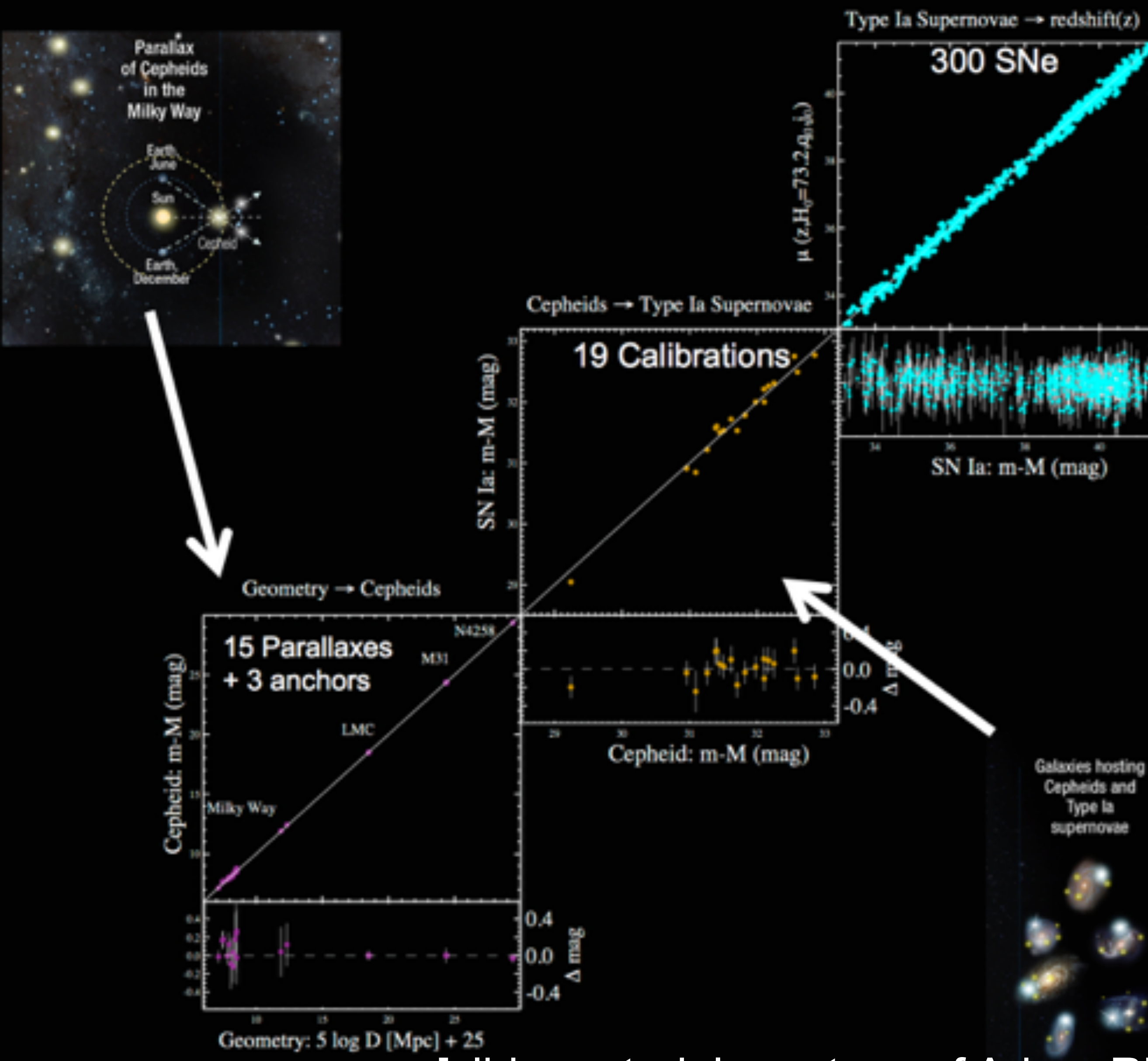
- *Hubble Space Telescope* Key Project [Freedman et al. 2001]
  - H_0 = 72 ± 8 km s^{-1} Mpc^{-1} (10% uncertainty)
  - resolving multi-decade "factor-of-two" controversy

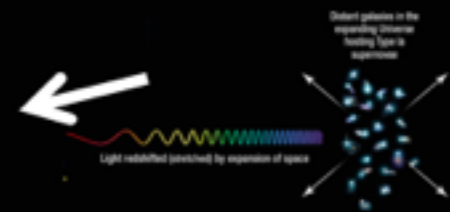
- Carnegie Hubble Program [Freedman et al. 2012]
  - H_0 = 74.3 ± 2.1 km s^{-1} Mpc^{-1} (2.8% uncertainty)

- 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. 2016]

H_0 from SH0ES





H_0=73.24 +/- 1.74, Km s^{-1} Mpc^{-1}

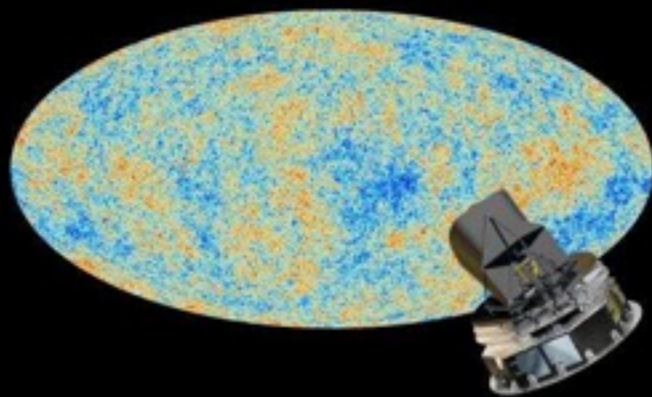
2.4% total uncertainty

[Riess et al. 2016]

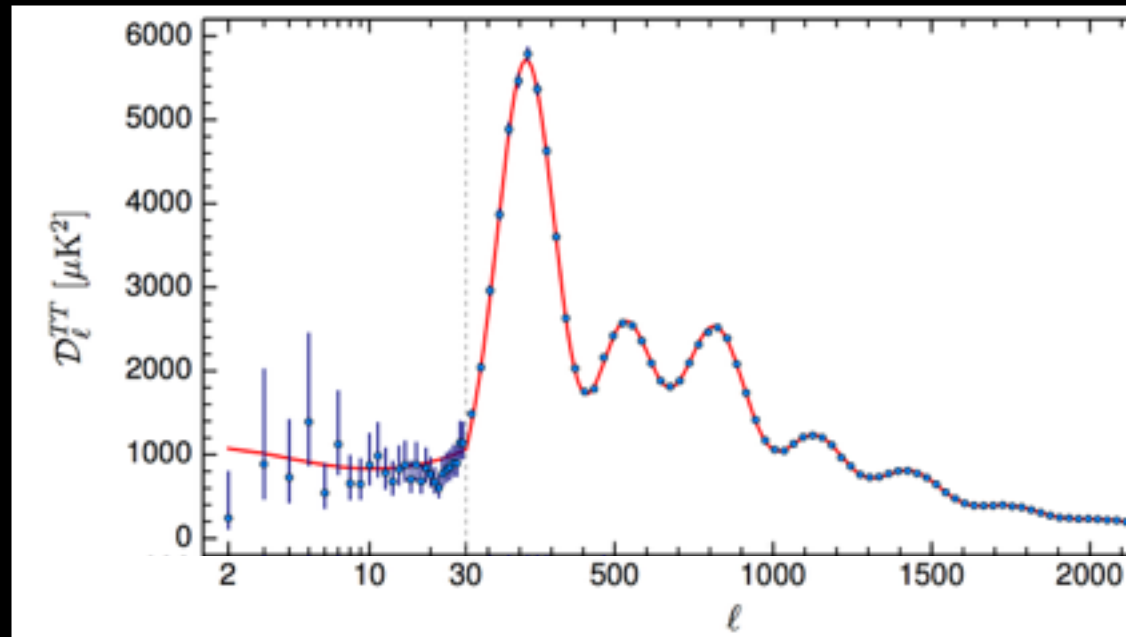
[slide material courtesy of Adam Riess]

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 = 0.678±0.009 [Planck collaboration 2016]
- Without **flat ΛCDM** assumption, h highly degenerate with other cosmological parameters (e.g., curvature, w, N_{eff})

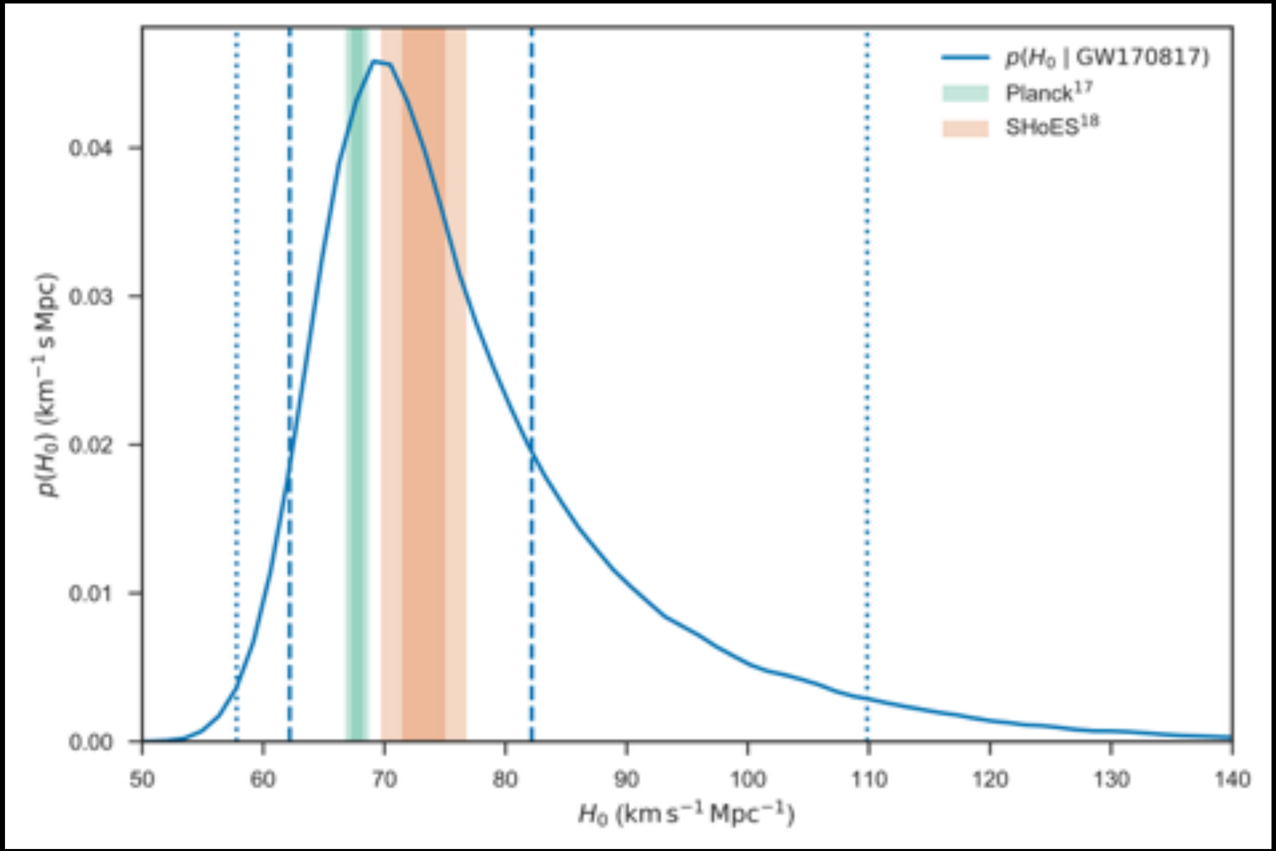
Standard Siren

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

$H_0 = v / D$

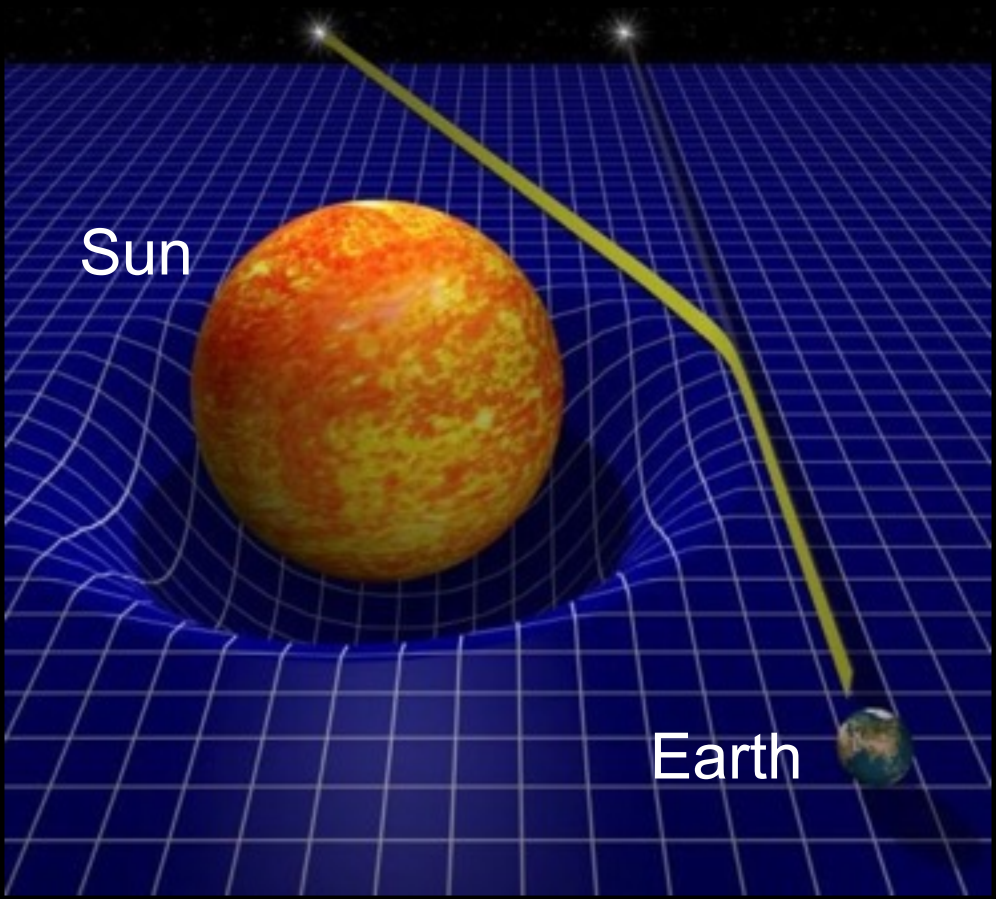
[Image credit:
M. Garlick]

GW170817: First measurement of H_0



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

Gravitational Lensing



Strong Optical Lensing

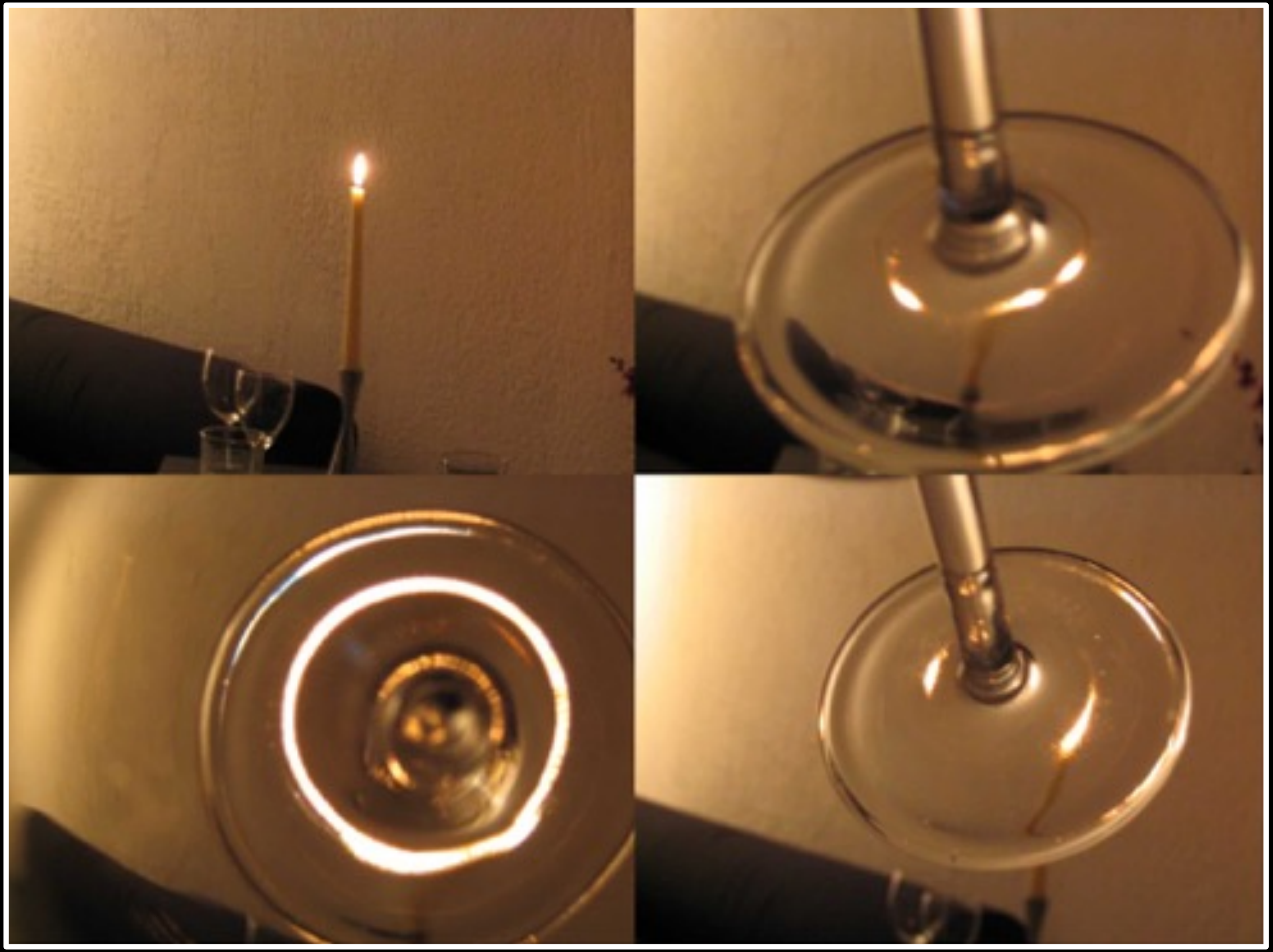
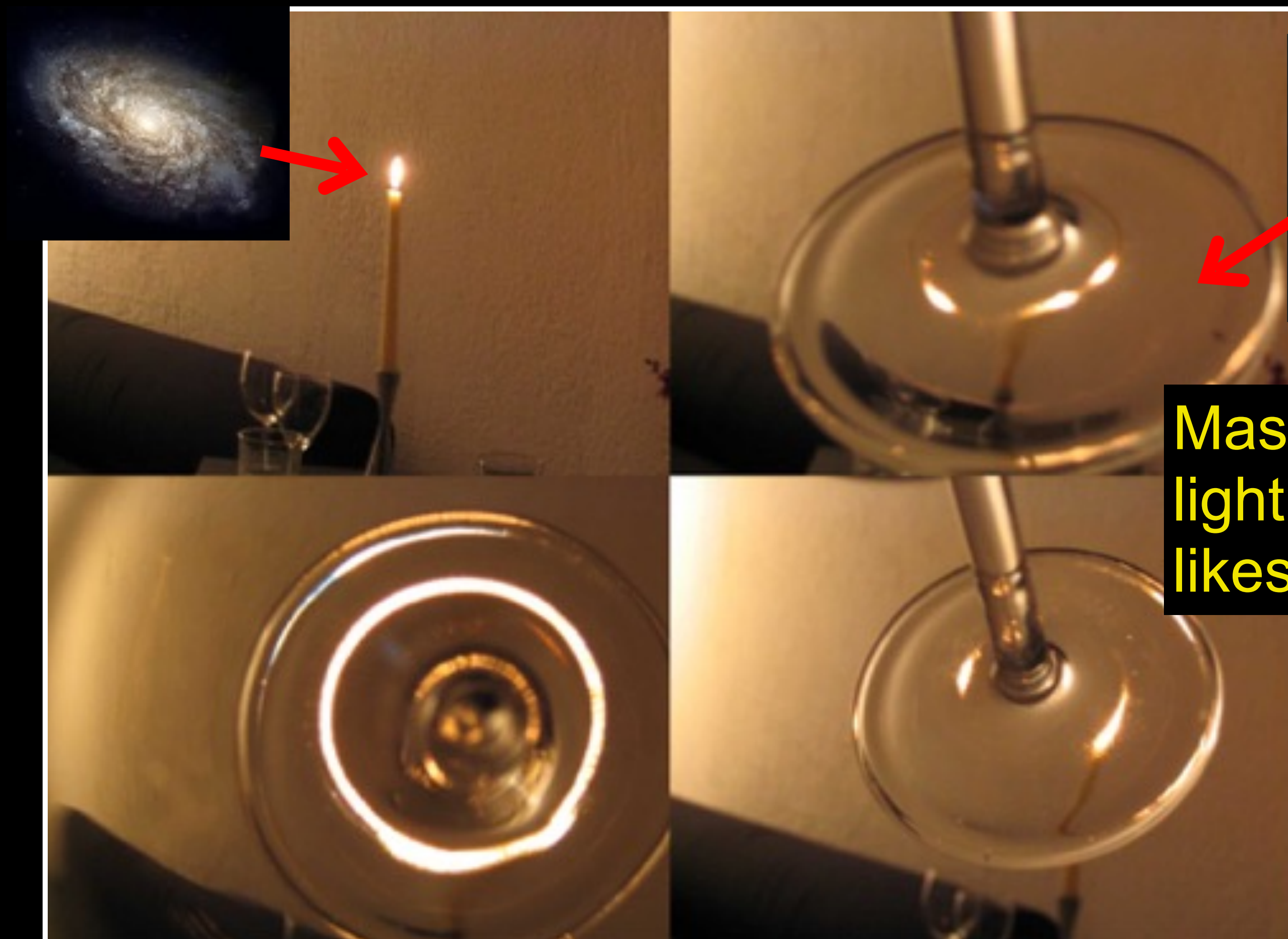


Image Credit: P. J. Marshall

Gravitational
Strong ~~Optical~~ Lensing



Mass "bends" light and acts likes a lens

Image Credit: P. J. Marshall

Gravitational Lens

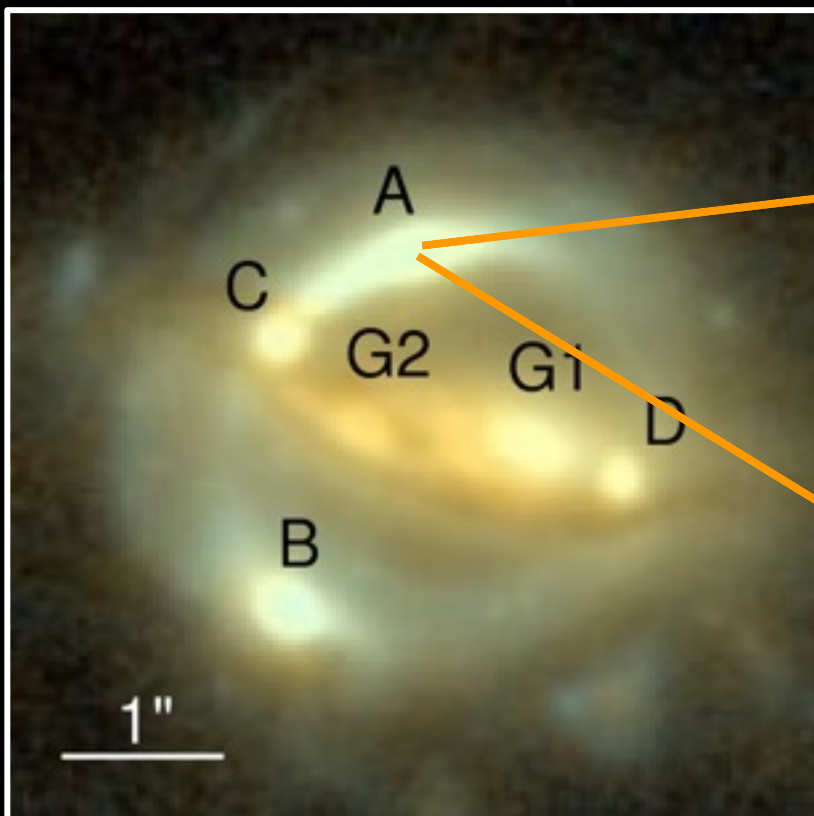
HST image: SLACSJ0737+3216

Image Credit: P. J. Marshall

Marshall et al. (2007)

Strong Gravitational Lensing

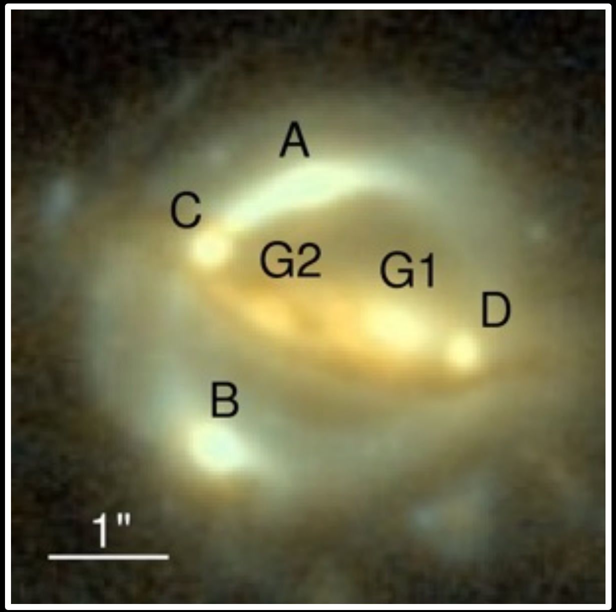
B1608+656

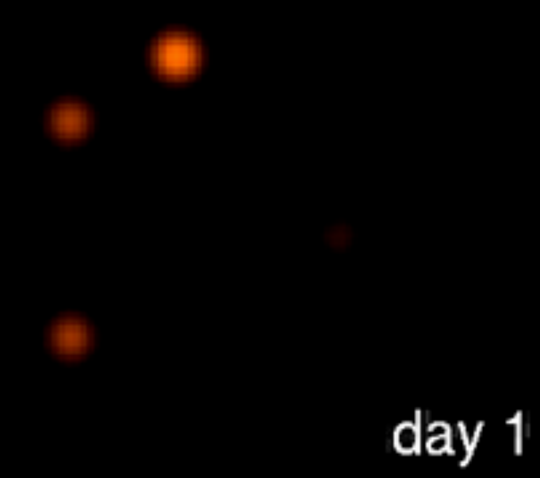


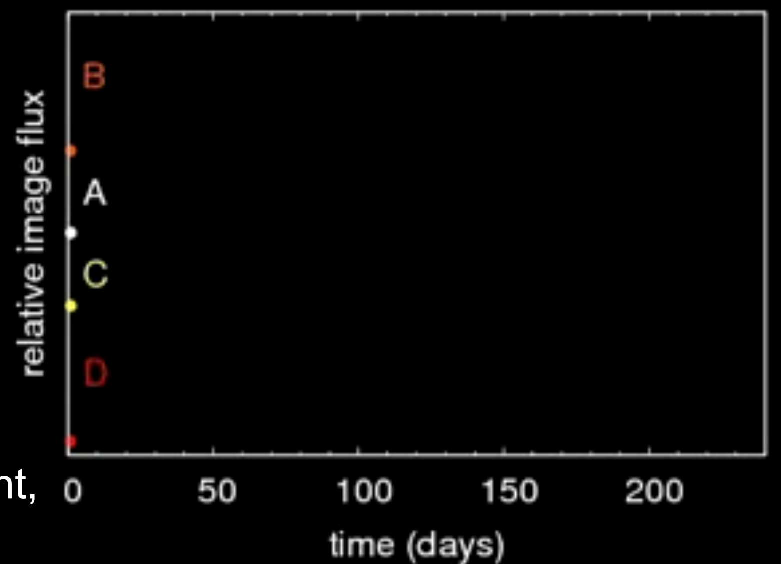
Active galactic nucleus (AGN) in the source from accretion of material onto supermassive black hole:

Light emitted from AGN changes in time ("flickers")

Gravitational Lens Time Delays

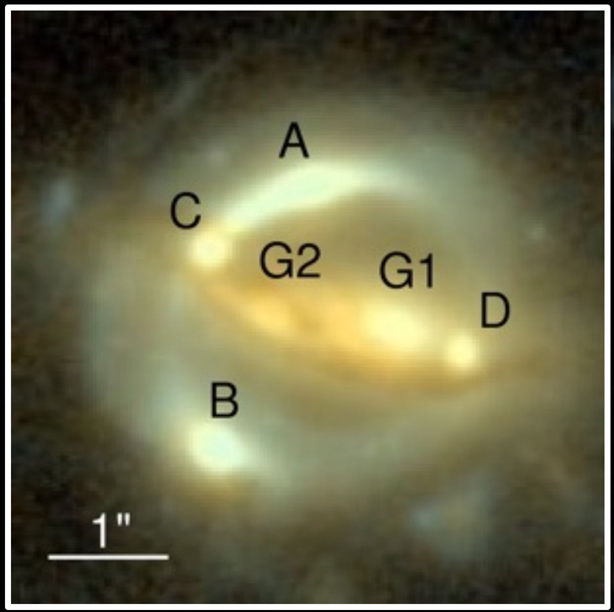






[Fassnacht et al. 1999, 2002]
Movie Credits: S. H. Suyu, C. D. Fassnacht,
NRAO/AUI/NSF

Gravitational Lens Time Delays



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

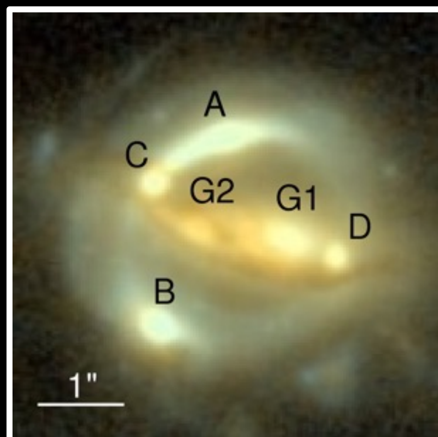
For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

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

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

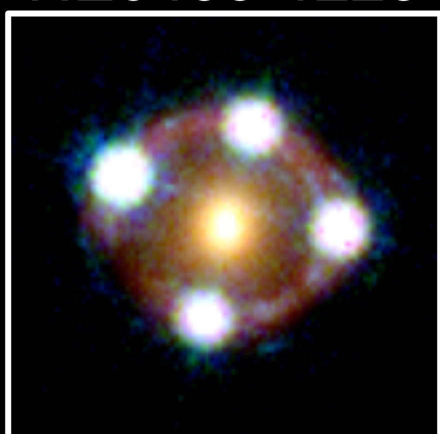
B1608+656



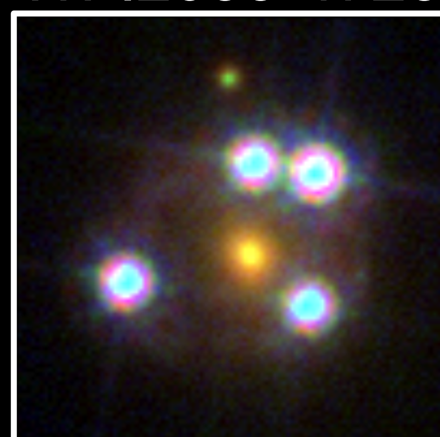
RXJ1131-1231

H_0 to <3.5% precision

HE0435-1223



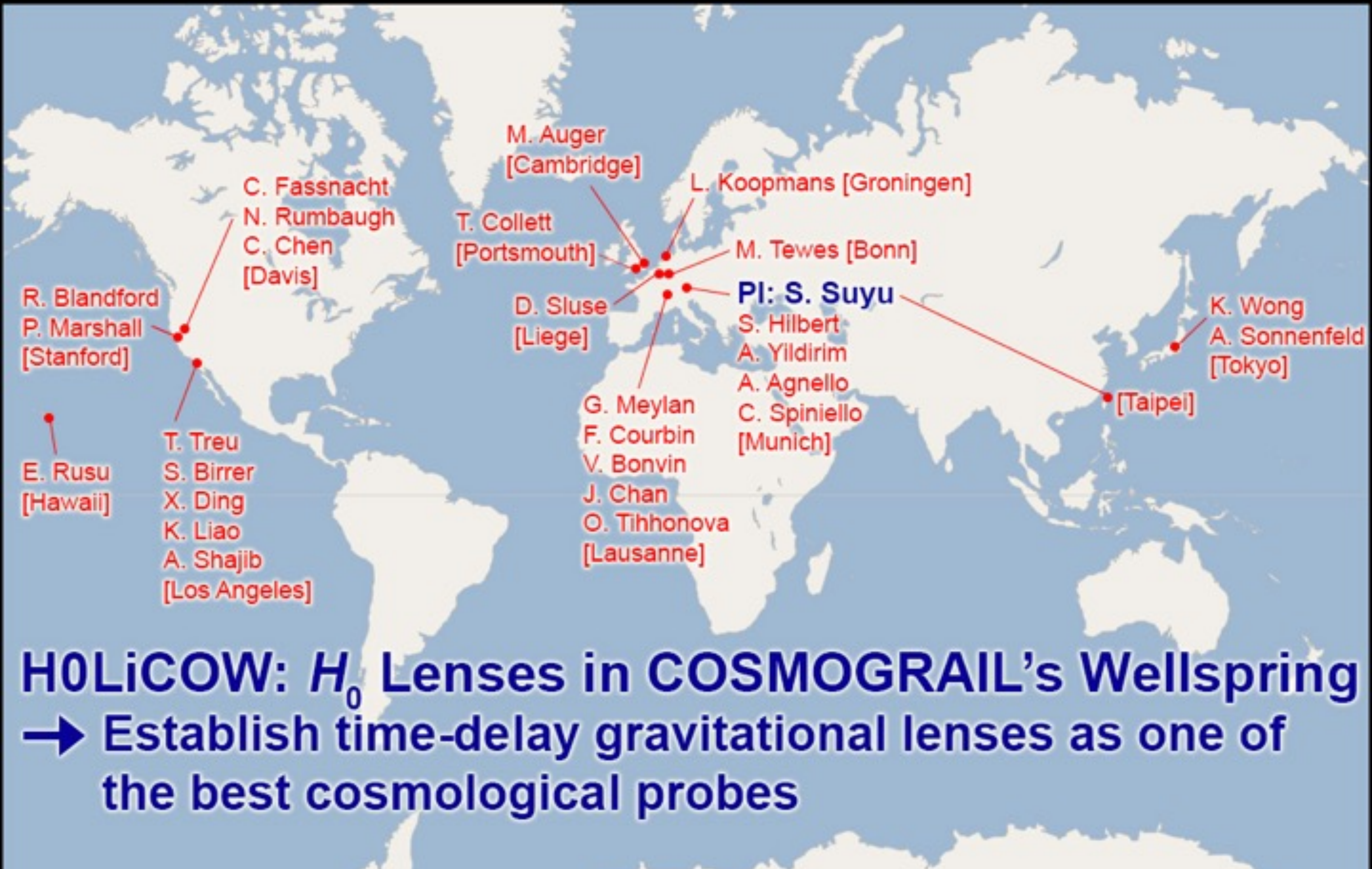
WFI2033-4723



HE1104-1805

[Suyu et al. 2017]

H0LiCOWers



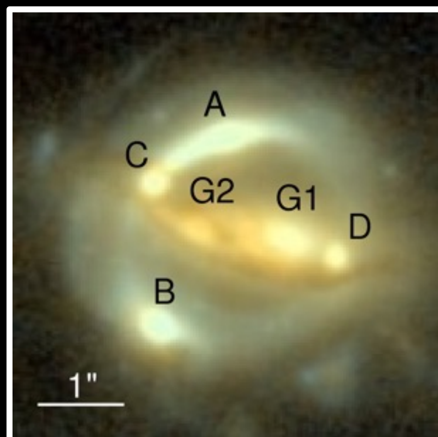
H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

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

H0LiCOW

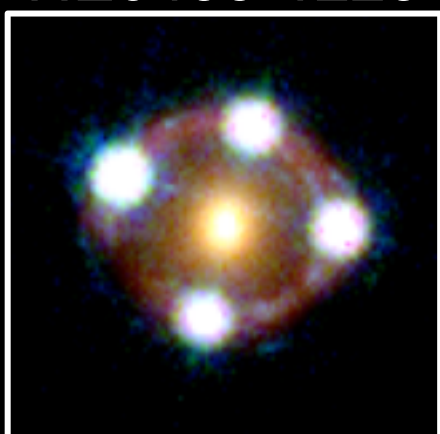
H_0 Lenses in COSMOGRAIL's Wellspring

B1608+656



RXJ1131-1231

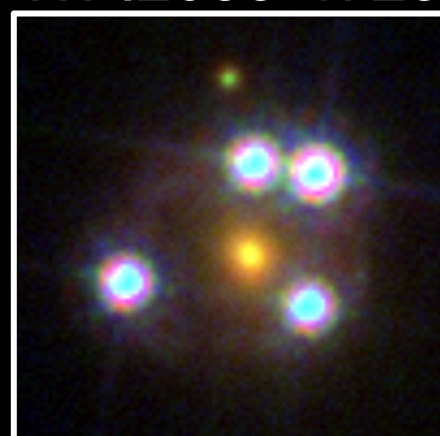
HE0435-1223



completed

[Suyu et al. 2010, 2013, 2014, 2017, Rusu et al. 2017, Sluse et al. 2017, Wong et al. 2017, Bonvin et al. 2017]

WFI2033-4723



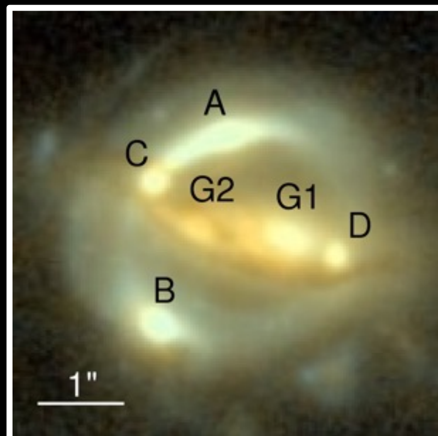
HE1104-1805

ongoing

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

B1608+656



RXJ1131-1231

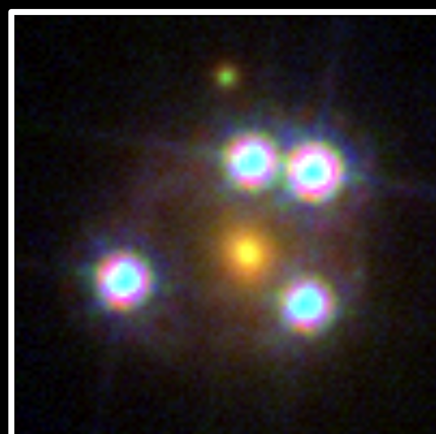
completed

[Suyu et al. 2010, 2013, 2014, 2017, Rusu et al. 2017, Sluse et al. 2017, Wong et al. 2017, Bonvin et al. 2017]

focus

HE0435-1223

WFI2033-4723



HE1104-1805

ongoing

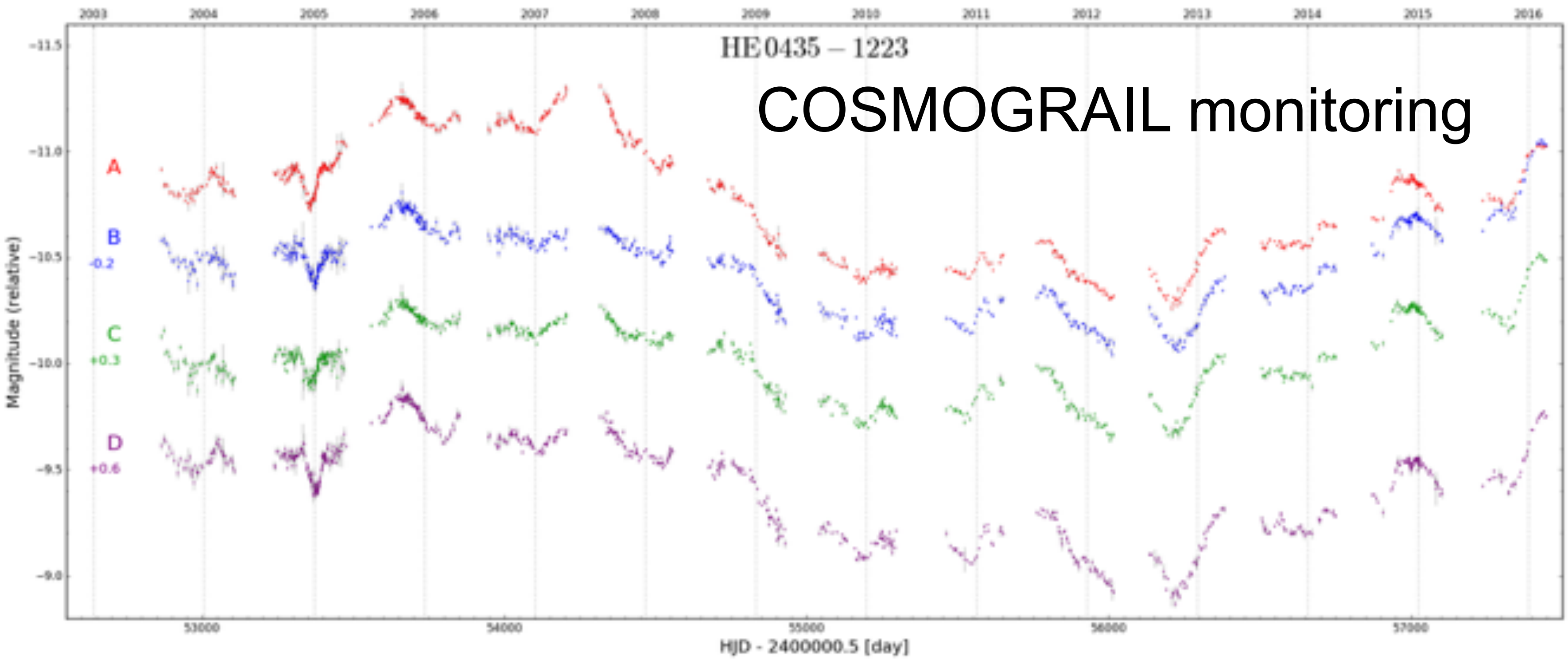
Time Delays

[Cosmological Monitoring of Gravitational Lenses]

- monitoring lensed quasars since 2004 in the optical
- expect to have delays with a few percent error for ~10 lenses

EPFL: **G. Meylan, F. Courbin**, V. Bonvin, 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)

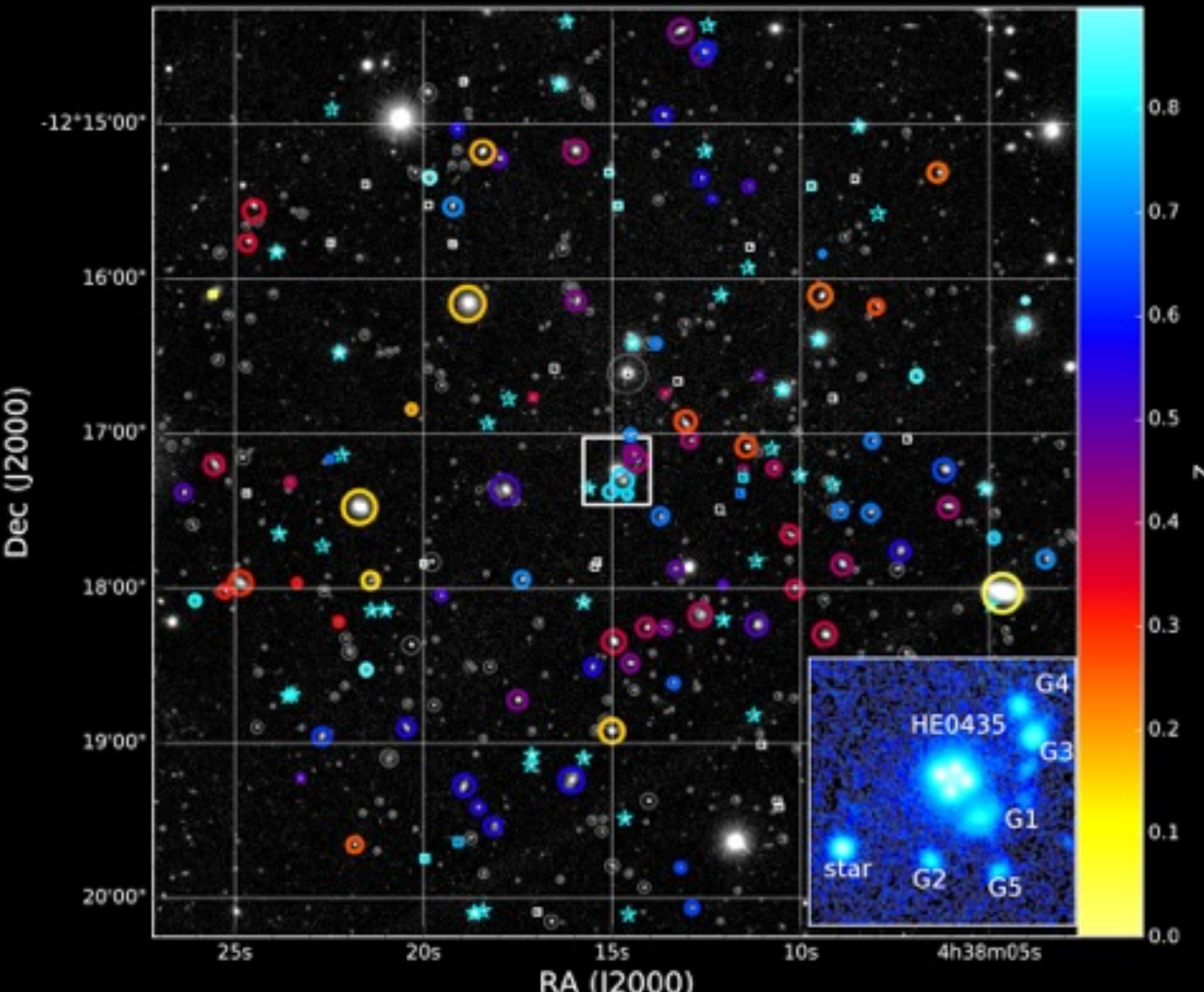
Time Delays



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

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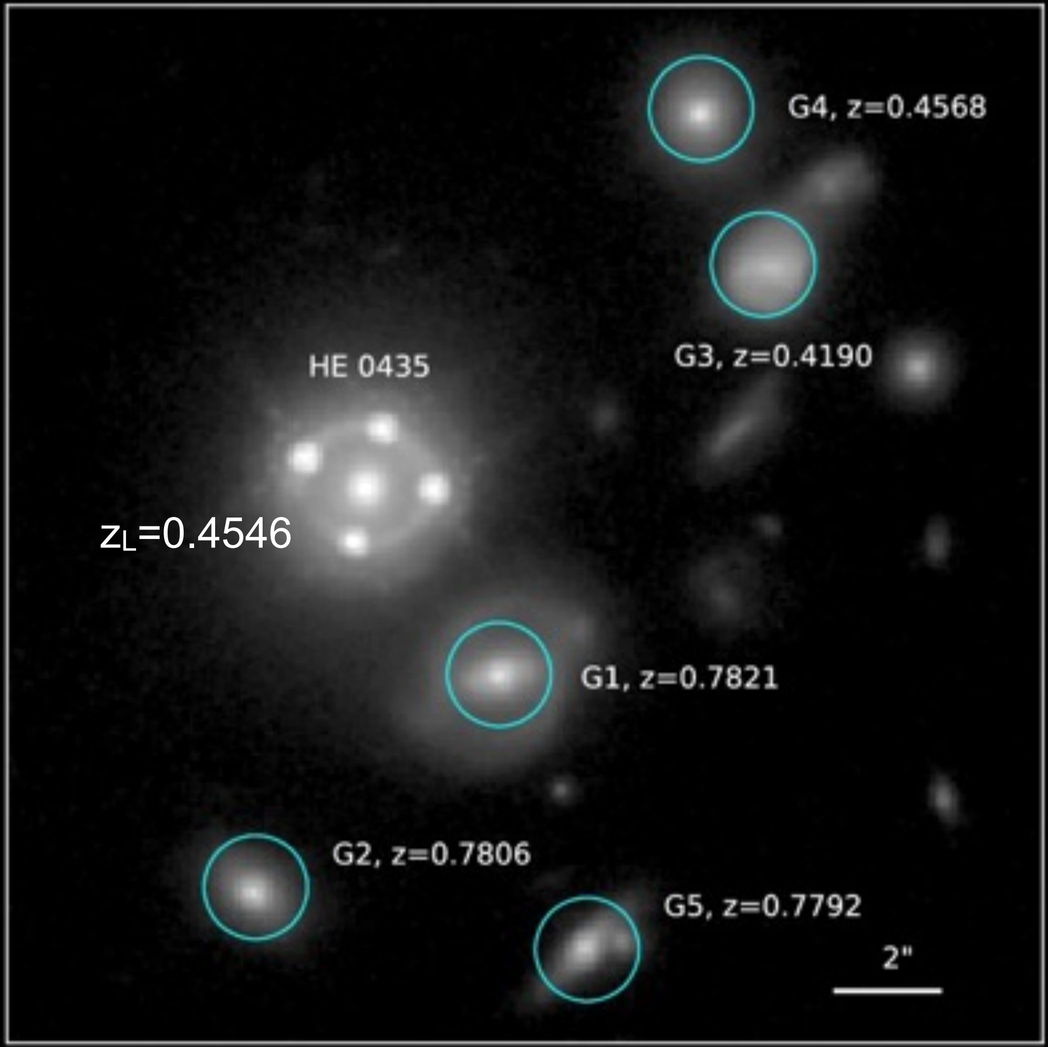


Wide-field spectroscopy for group identification [Sluse, Sonnenfeld, Rumbaugh et al. 2017]

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

Lens mass modeling

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

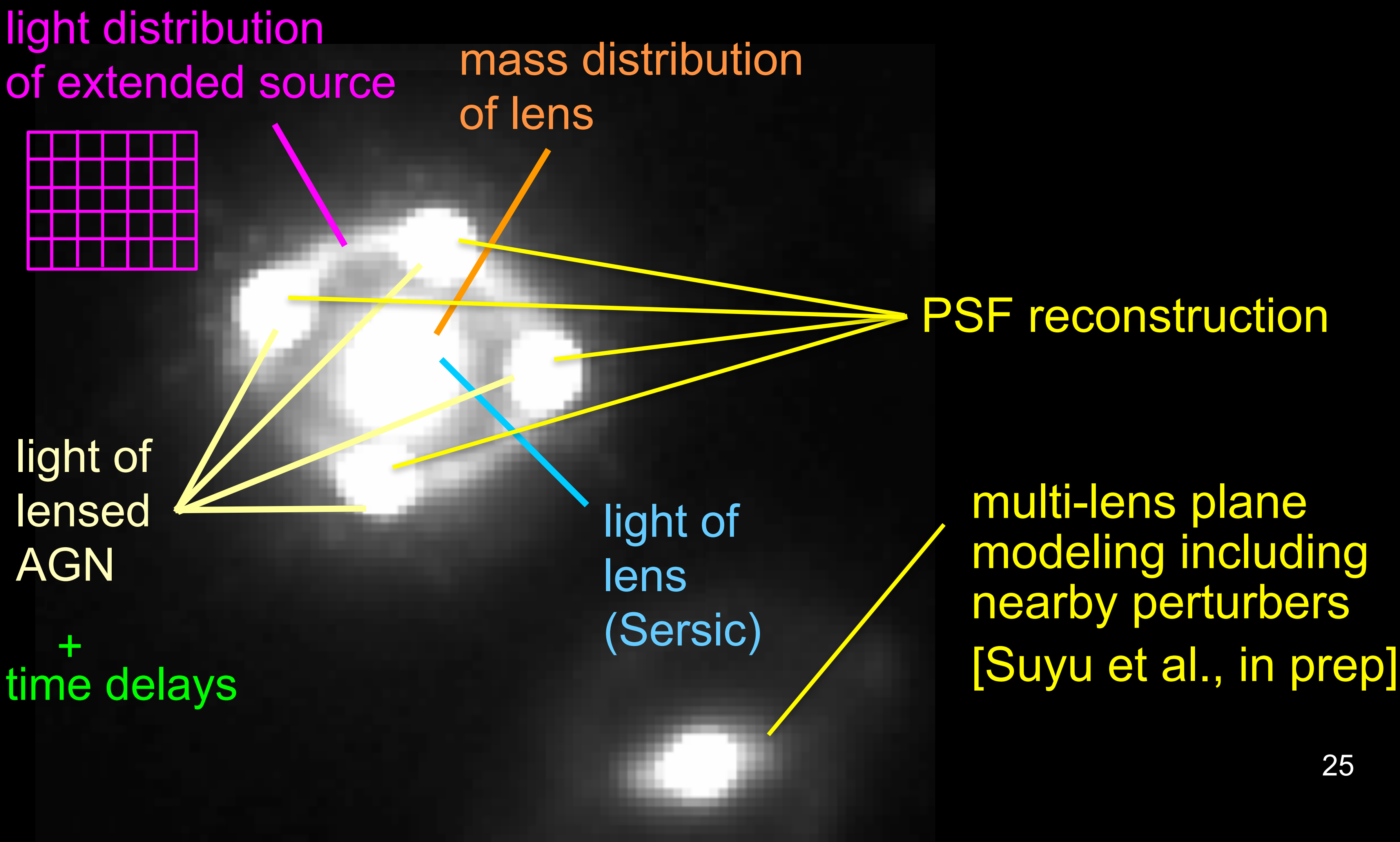
Modeling with GLEE :)

Gravitational
Lens
Efficient
Explorer

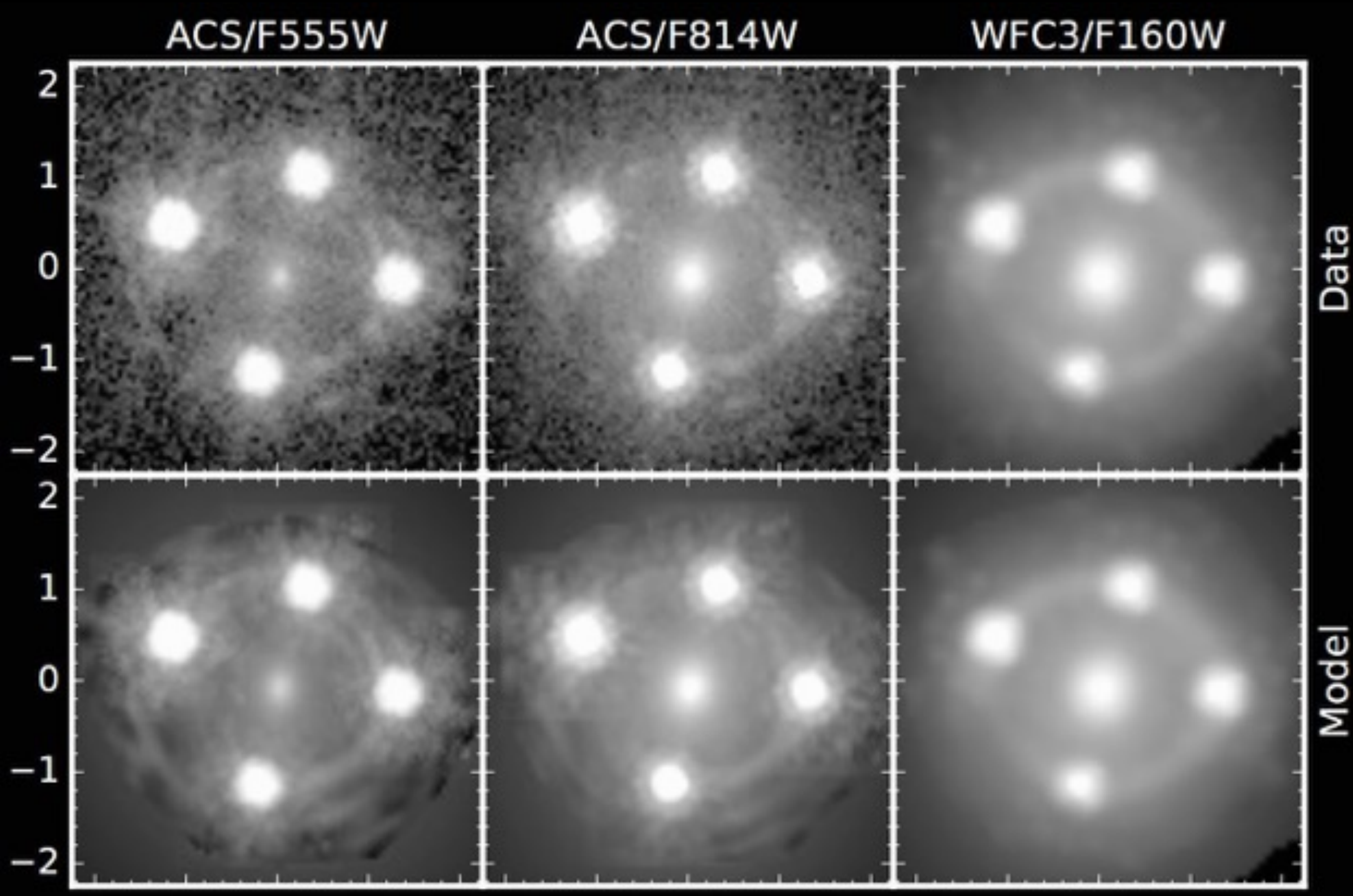
[Suyu & Halkola 2010]

Lens mass modeling

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

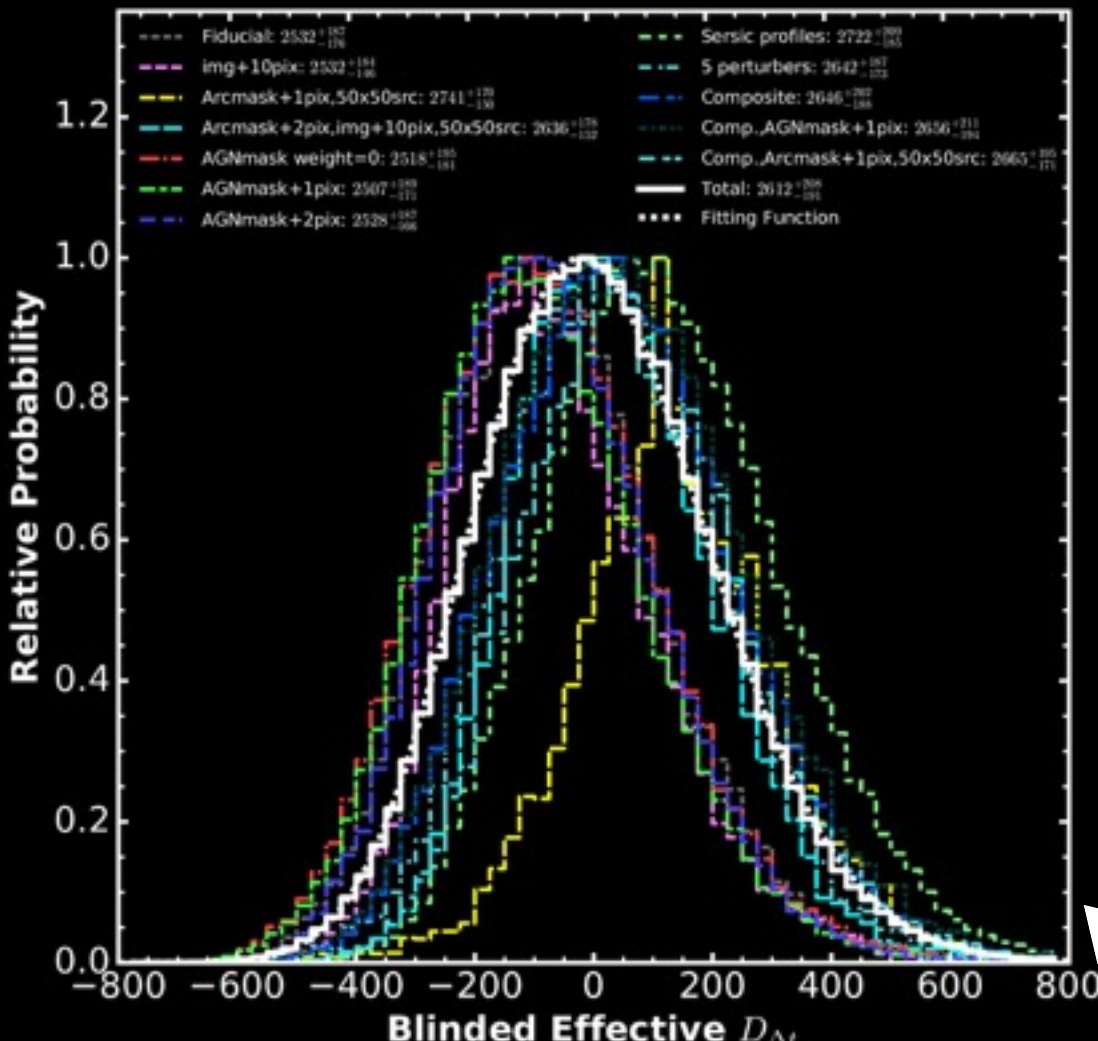


Lens reconstruction



[Wong, Suyu, Auger et al. 2017]

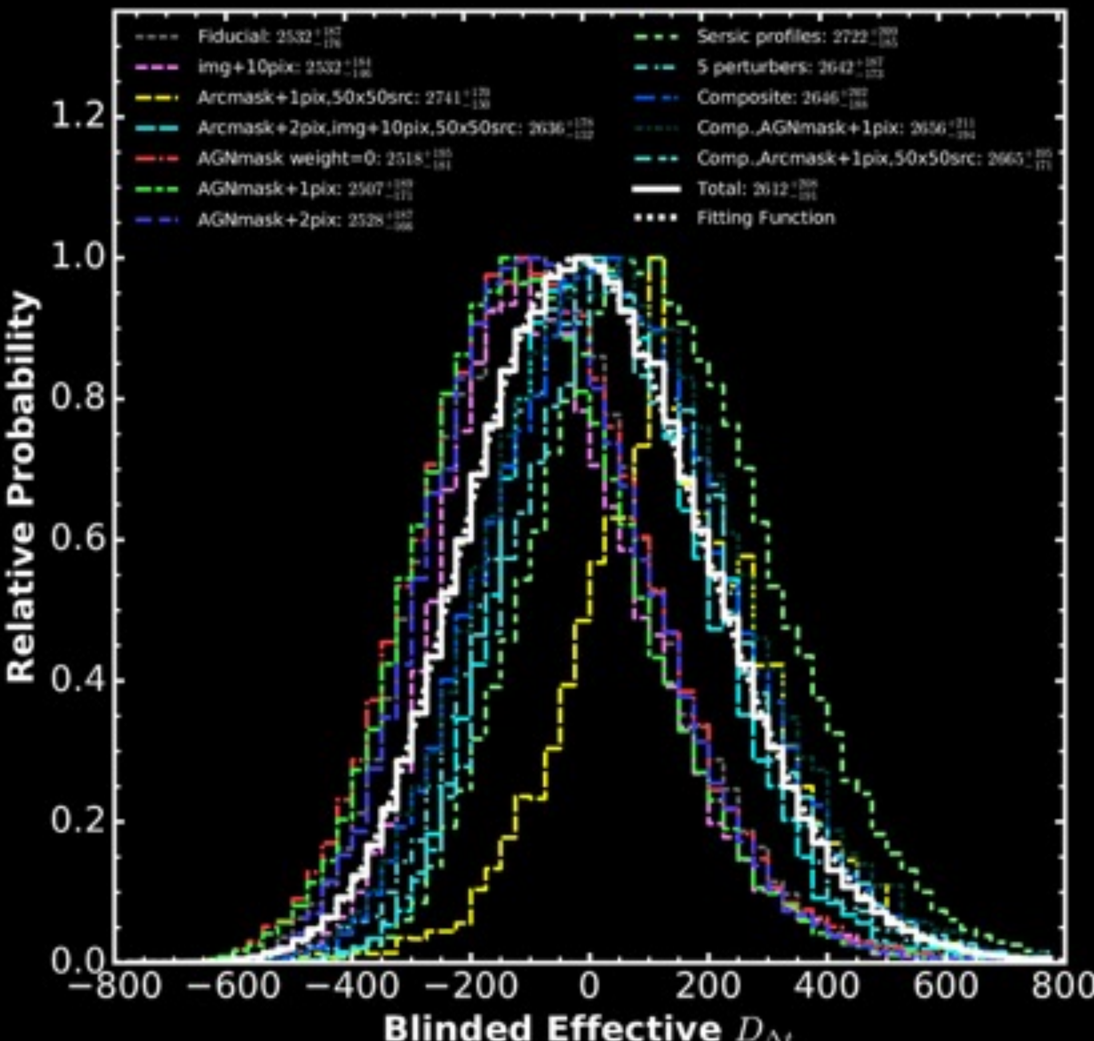
Blind analysis in action



- Blind analysis to avoid confirmation bias
- throughout analysis, cosmological distances and parameters are offset from median, i.e., blinded

[Wong, Suyu, Auger et al. 2017]

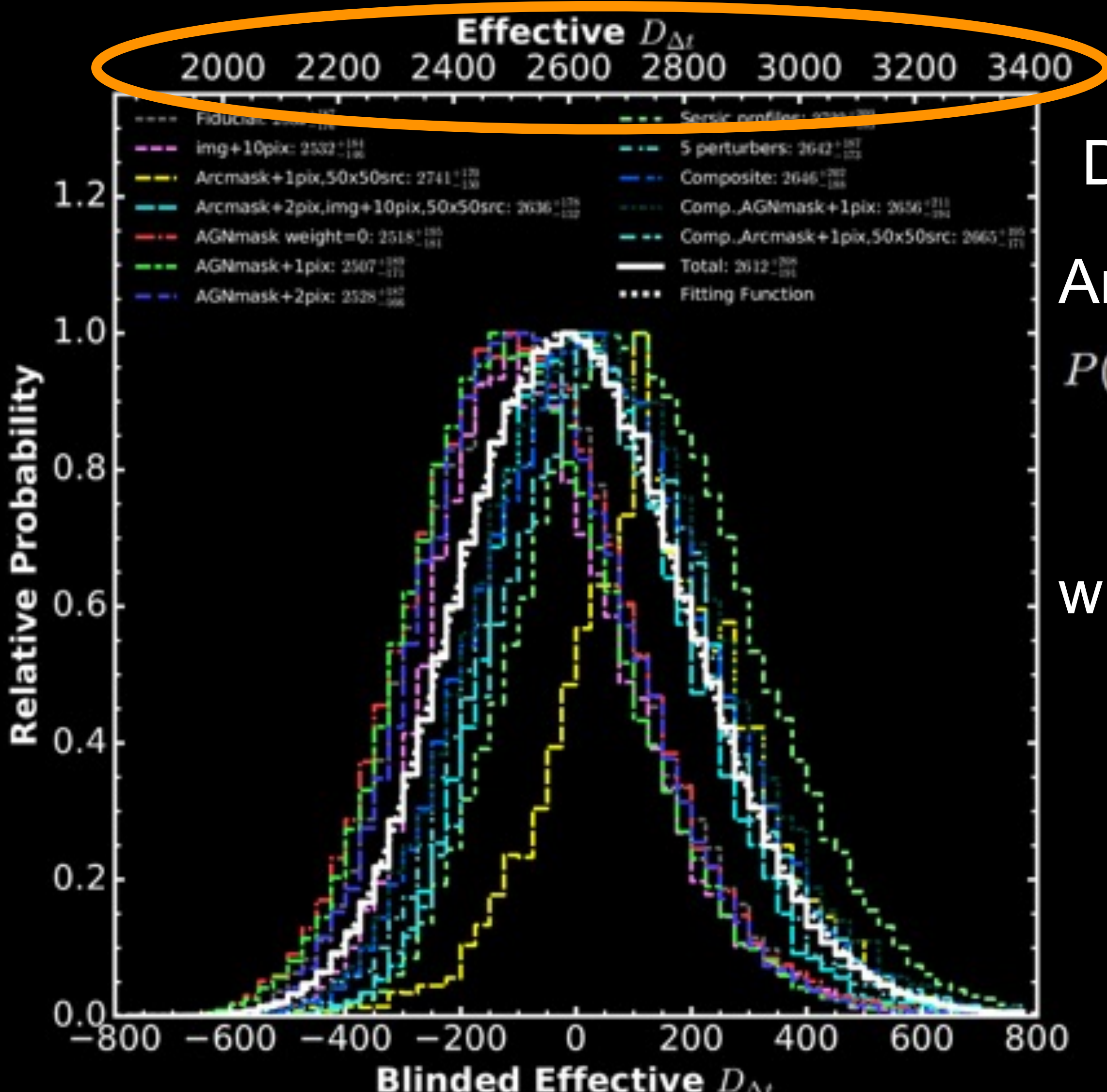
Blind analysis in action



[Wong, Suyu, Auger et al. 2017]

- Blind analysis to avoid confirmation bias
- throughout analysis, cosmological distances and parameters are offset from median, i.e., blinded
- collaboration agreed: when unblind, publish $D_{\Delta t}$ without modification
- scheduled unblinding telecon on June 2
- scheduled again for June 16

Time-delay distance of HE0435



$D_{\Delta t} = 2612^{+208}_{-191}$ Mpc

Analytic fit for $D_{\Delta t}$

$$P(D_{\Delta t}) = \frac{1}{\sqrt{2\pi}(x-\lambda_D)\sigma_D} \exp\left[-\frac{(\ln(x-\lambda_D)-\mu_D)^2}{2\sigma_D^2}\right]$$

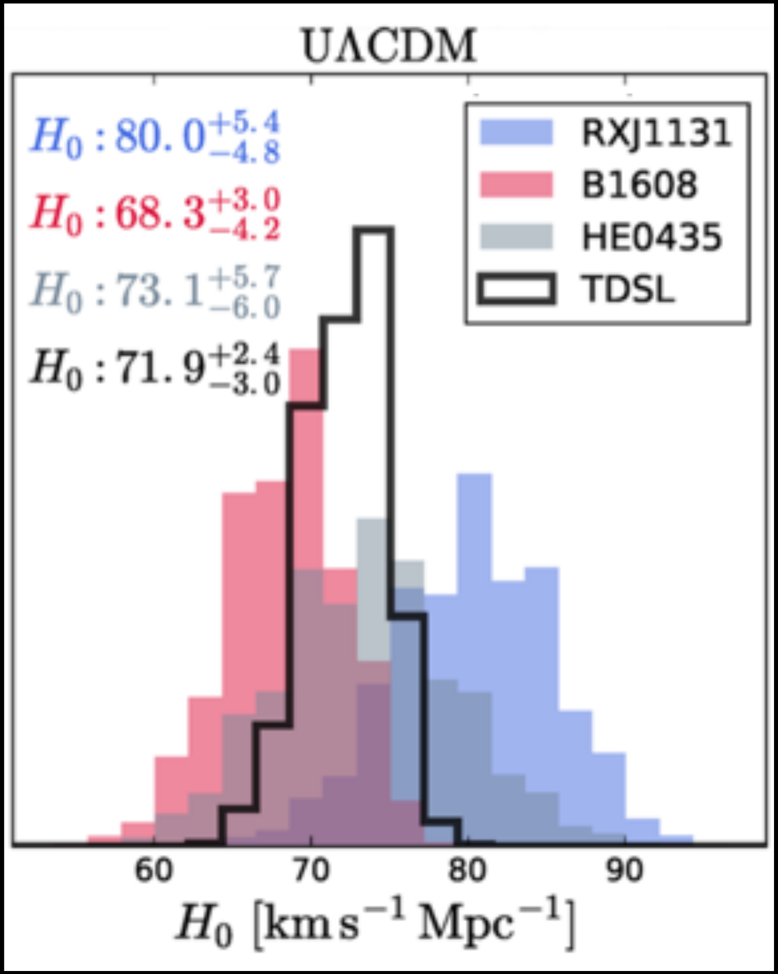
where

$$x = D_{\Delta t}/(1\,\mathrm{Mpc})$$
$$\lambda_\mathrm{D} = 653.9$$
$$\mu_\mathrm{D} = 7.5793$$
$$\sigma_\mathrm{D} = 0.10312$$

Can be combined with any other probe

[Wong, Suyu, Auger et al. 2017]

H_0 from 3 strong lenses

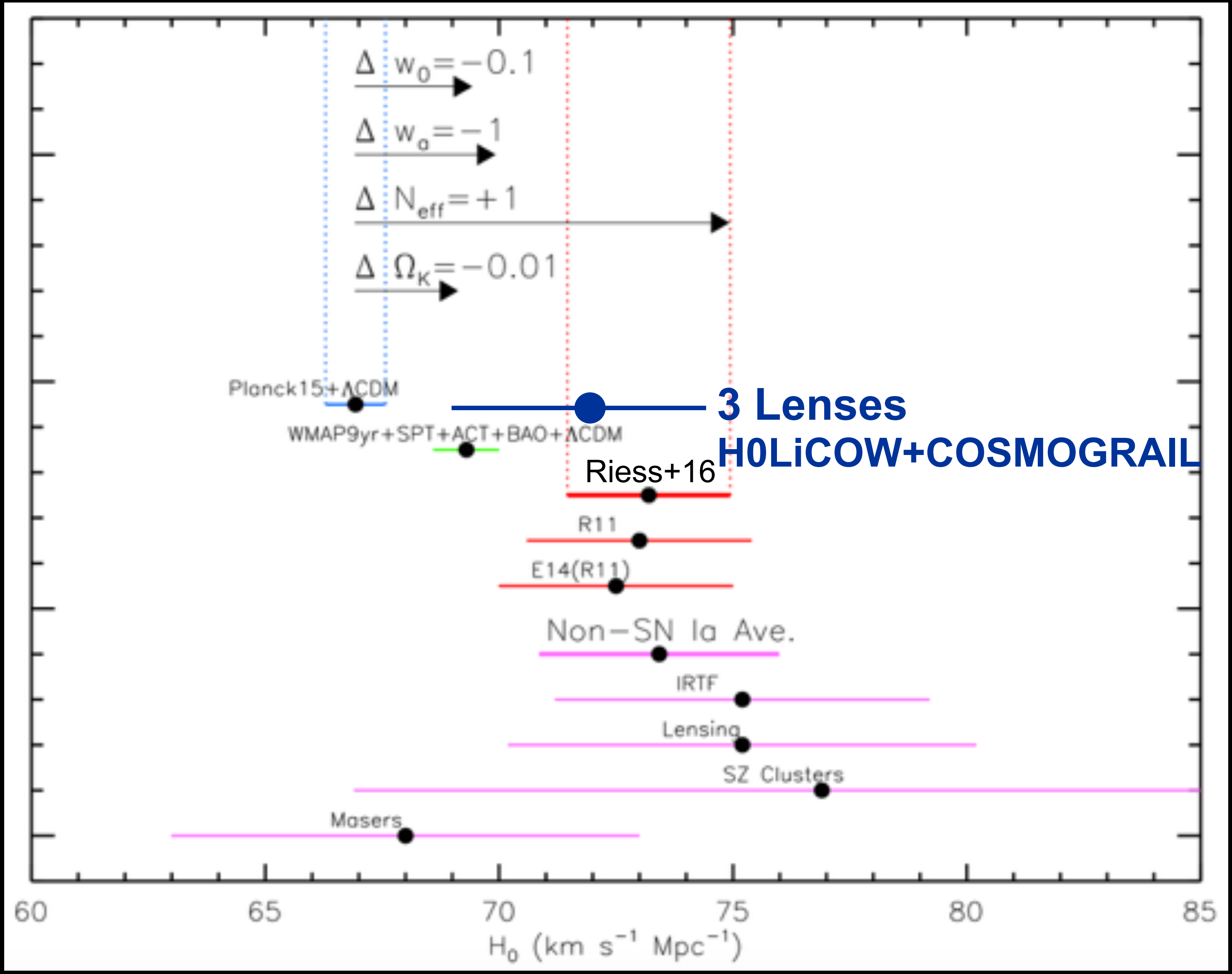


$H_0 \in [0,150]$ km/s/Mpc
$\Omega_m = 1 - \Omega_\Lambda \in [0,1]$
w = -1

H_0 with 3.8% precision for flat ΛCDM

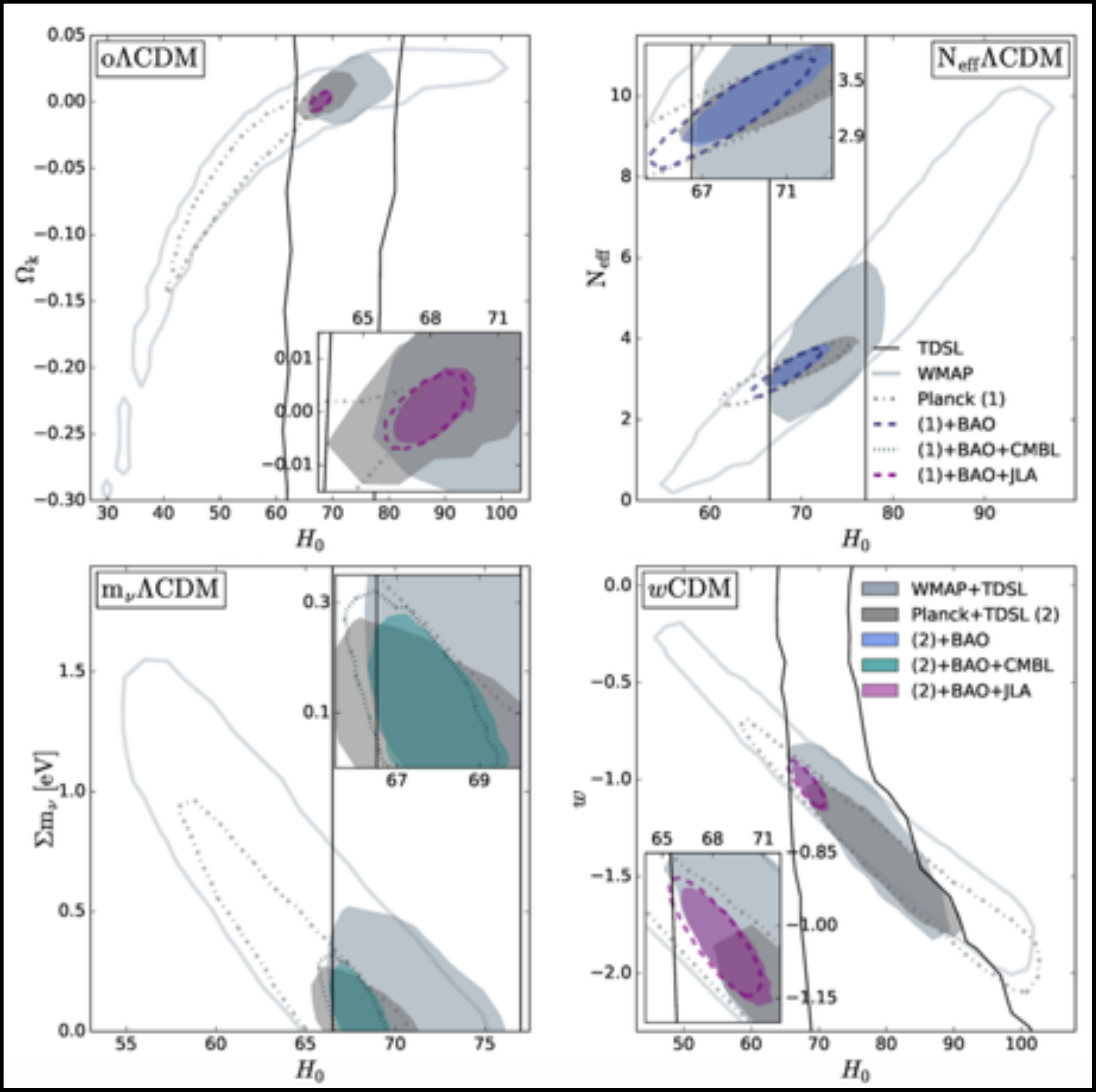
[Bonvin, Courbin, Suyu et al. 2017]

H_0 with 3 Lenses



[Riess et al. 2016]

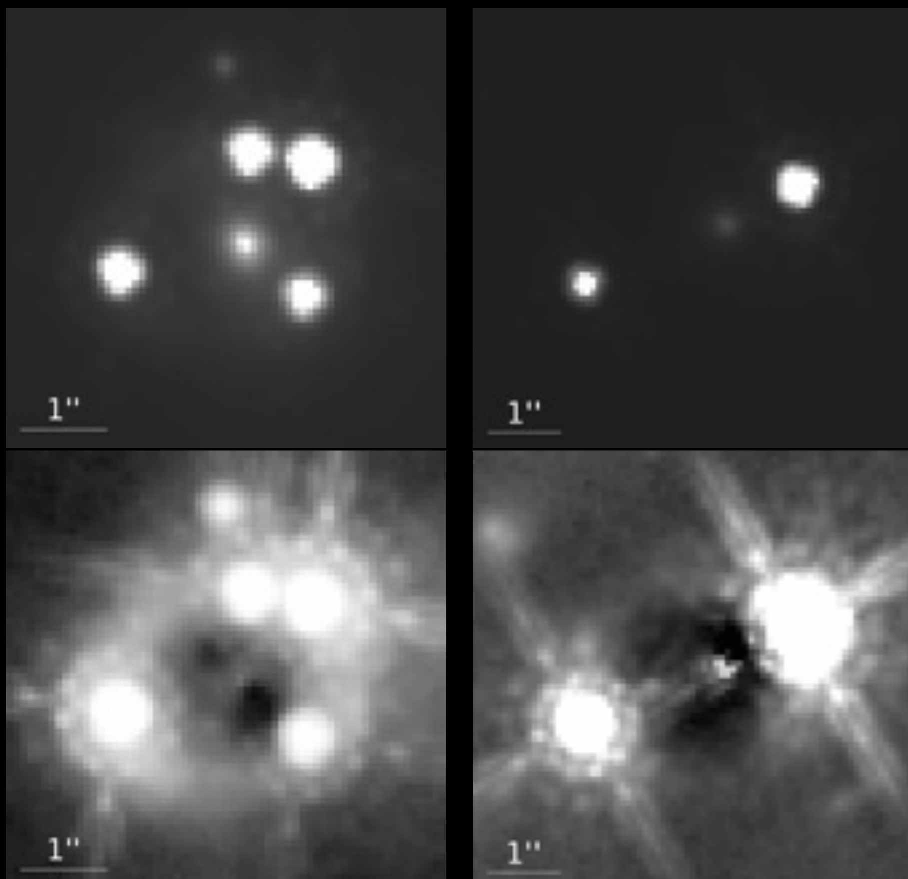
Lensing REALLY helps



[Bonvin, Courbin, Suyu et al. 2017]

Looking forward

WFI2033-4723 HE1104-1805



- 2 more H0LiCOW lenses
- 4 more doubles with HST imaging in c23 (PI: Treu)
- follow-up data partly in-hand and partly pending
- HST image show Einstein ring

Expectation from H0LiCOW:
<3.5% uncertainty on H_0
for most cosmologies with w=-1
(HST proposal aim of 3.8% achieved with 3/5 lenses thanks to the improved time delays from COSMOGRAIL)

[Suyu, Bonvin, Courbin et al. 2017]

How to get more lenses?

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]

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]

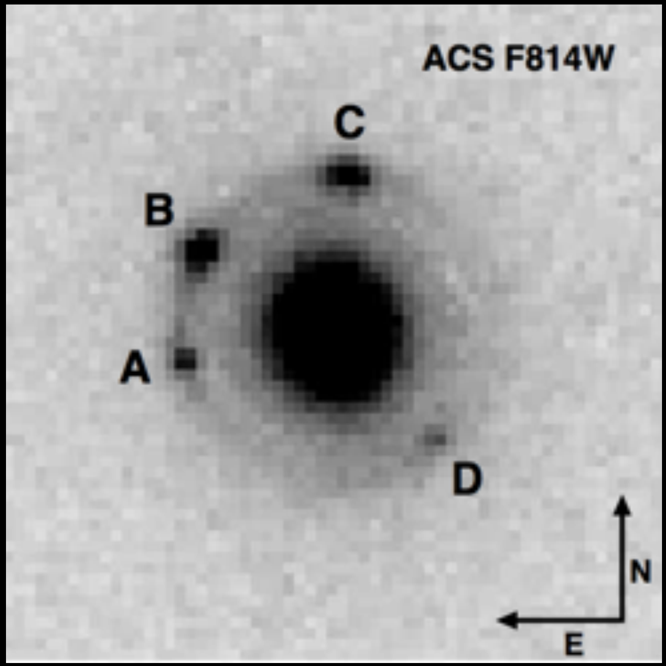
Kilo Degree Survey

2.6m VLT Survey Telescope, Paranal, Chile

- 1500 deg^2 with r_{limit}~25
- 2011-~2018

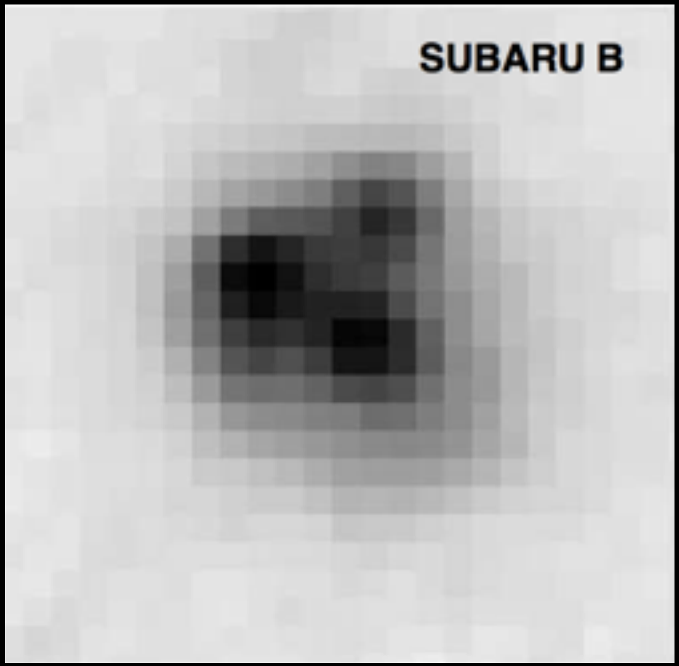
Lensed quasars from the ground

Space (HST)



[Anguita et al. 2009]

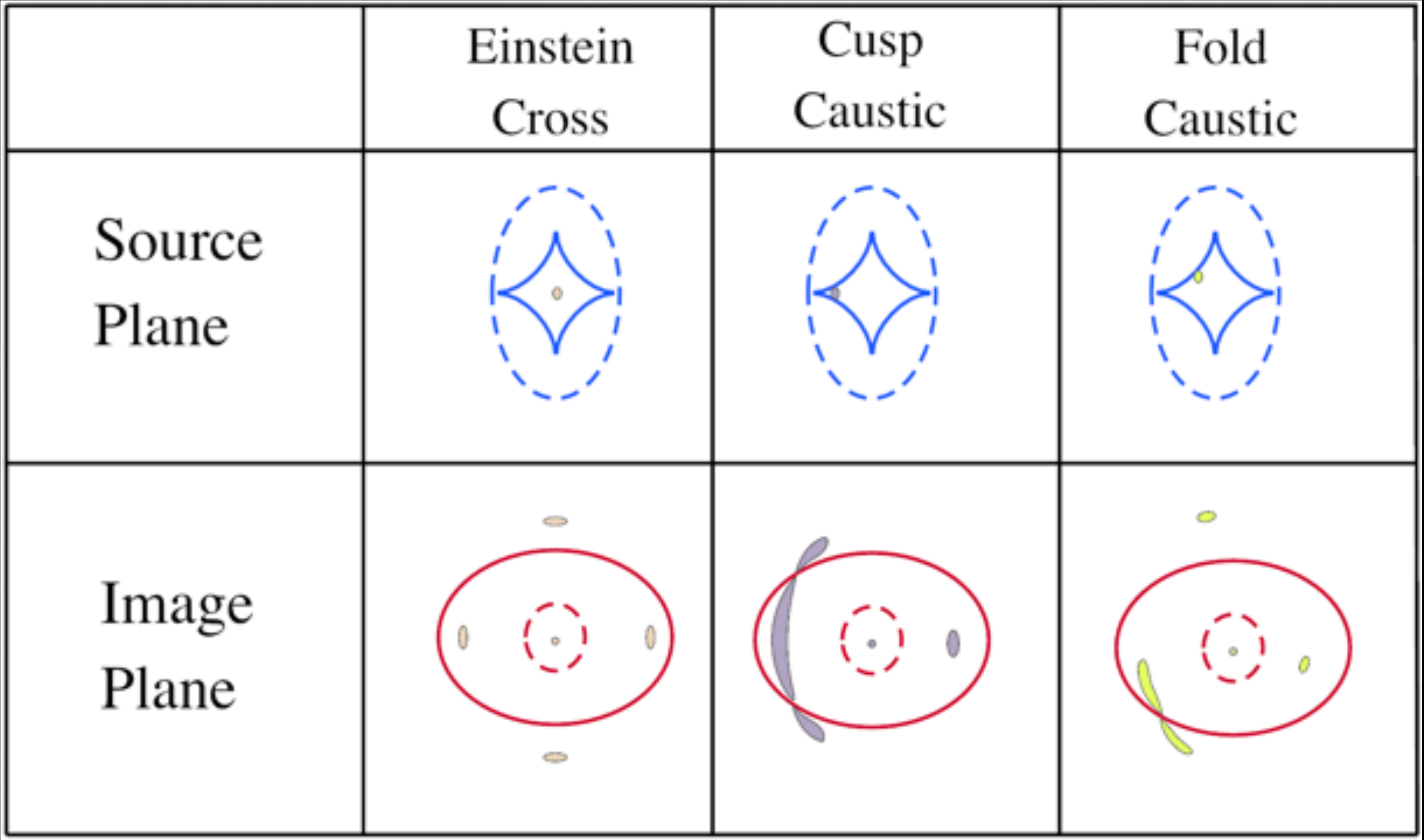
Ground (Subaru)



How to tell if this is a lens?

➡ Use configuration of blended images and lens modeling

Image configurations of lenses



[Image credit: A. Amara]

Ways to find lensed quasars

For a system to qualify as a lens candidate, it must be explained by a plausible lens model

Direct Modeling

- **LensTractor**
  [Marshall et al., in prep.]
  classification based on explicit model comparison
- **CHITAH**
  [Chan et al., 2015]
  classification based on simple lens model fitting

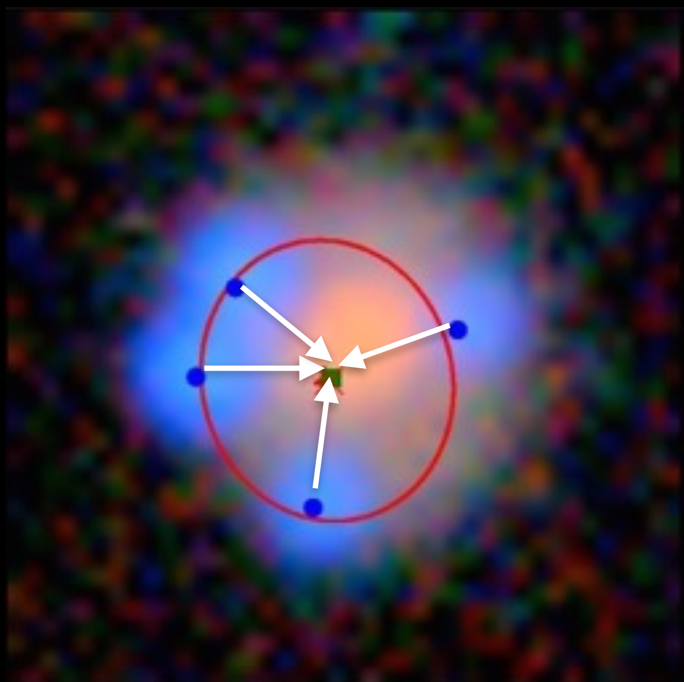
Machine Learning

implicit lens model (prior) enters via the training set [e.g., Agnello et al. 2014]

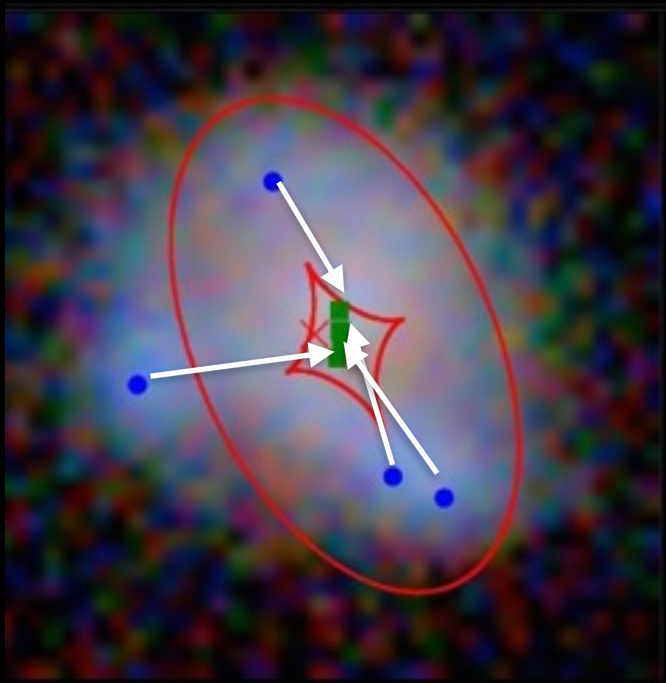
Citizen Science

[Marshall et al. 2015; More et al. 2015]
citizens visually identify lenses after familiarizing with lens configurations

New hunter for lensed quasars



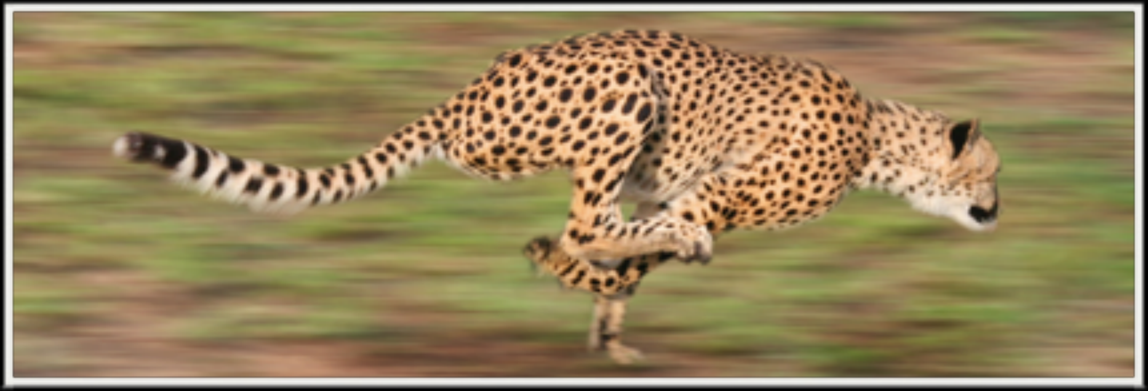
Probably a lens



Probably NOT a lens

James Chan has developed an automated and fast algorithm to use multiband imaging for lens classification [Chan, Suyu et al. 2015]

New hunter for lensed quasars

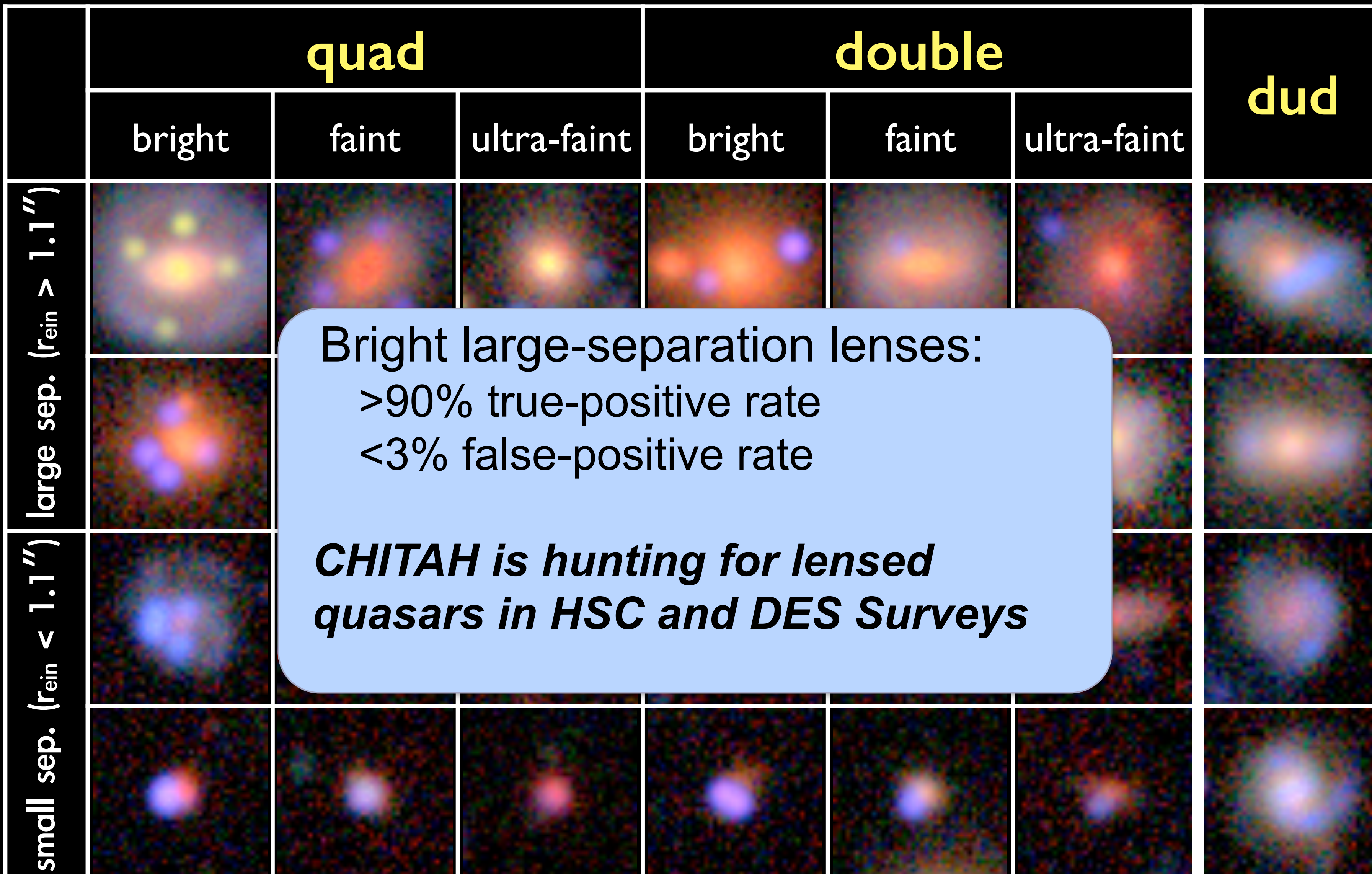


重 力 和 影 像 探 奧 號

Chung-li **H**e **I**n-hsiang **T**an **A**o **H**ao

CHITAH

Testing CHITAH with mock lenses

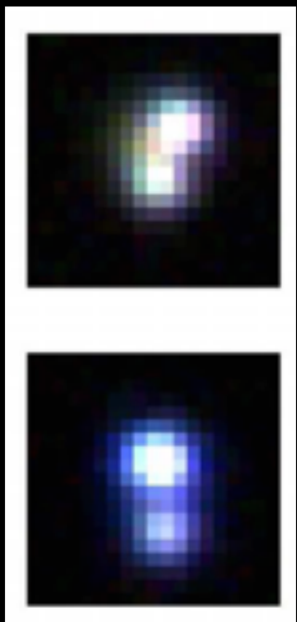


Bright large-separation lenses:
- >90% true-positive rate
- <3% false-positive rate

CHITAH is hunting for lensed quasars in HSC and DES Surveys

[Chan, Suyu et al. 2015]

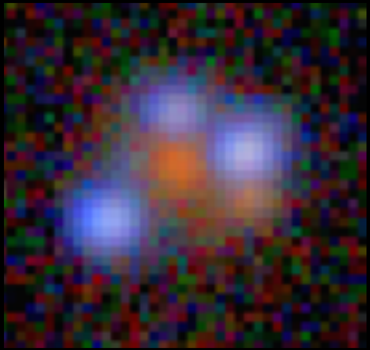
New lensed quasars systems



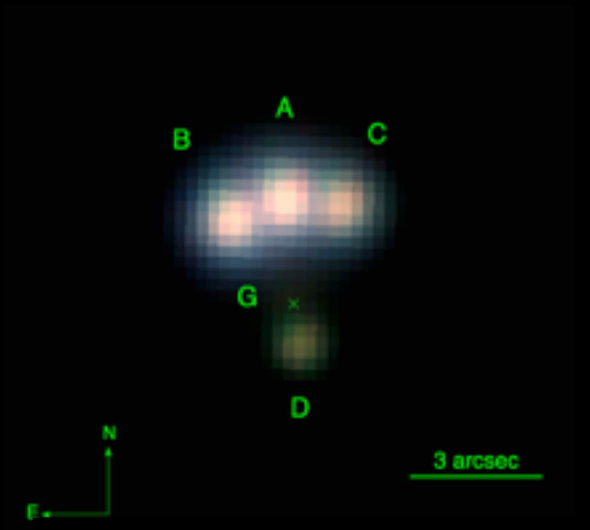
[Agnello et al. 2015]

[More et al. 2017]

[Ostrovski et al. 2017]



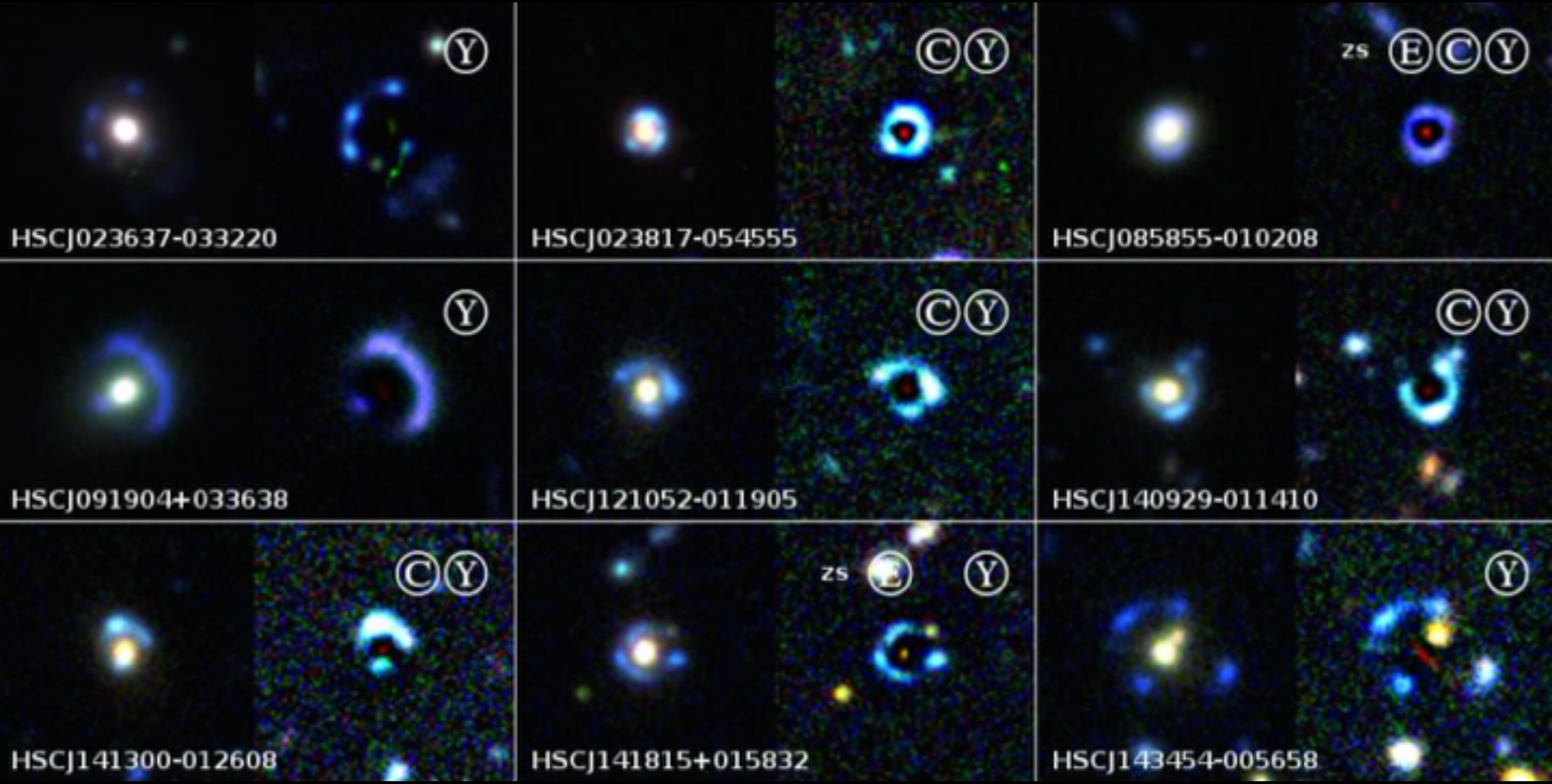
[Lin et al. 2017]



[Berghea et al. 2017]

SuGOHI: new lenses from HSC

[Survey of Gravitationally-lensed Objects in HSC Imaging]



[Sonnenfeld, Chan, Shu et al., 2017]

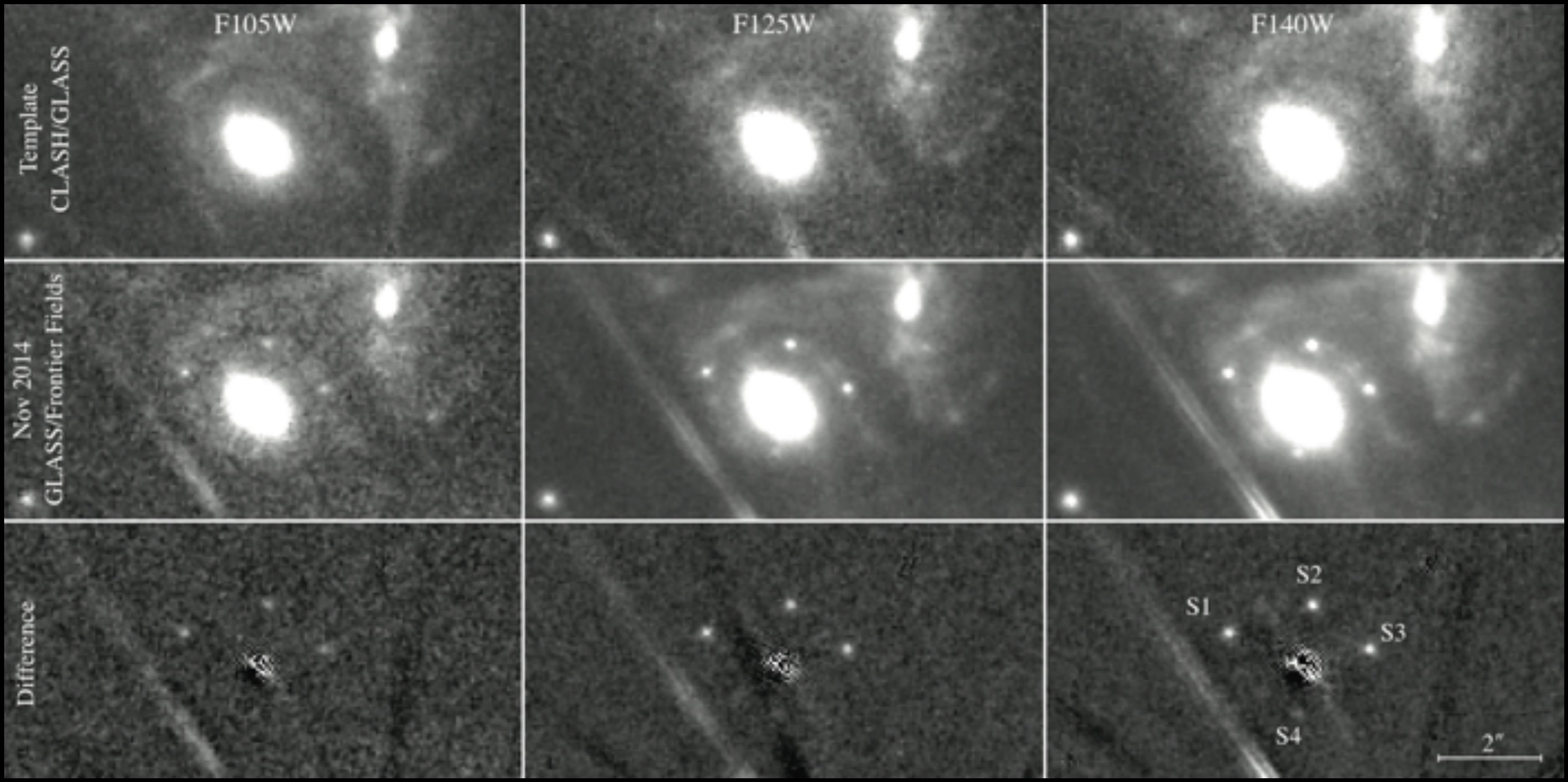
Strongly lensed supernova

MACS 1149.6+2223

[Kelly et al. 2015]

Supernova "Refsdal"

discovered serendipitously in November 2014



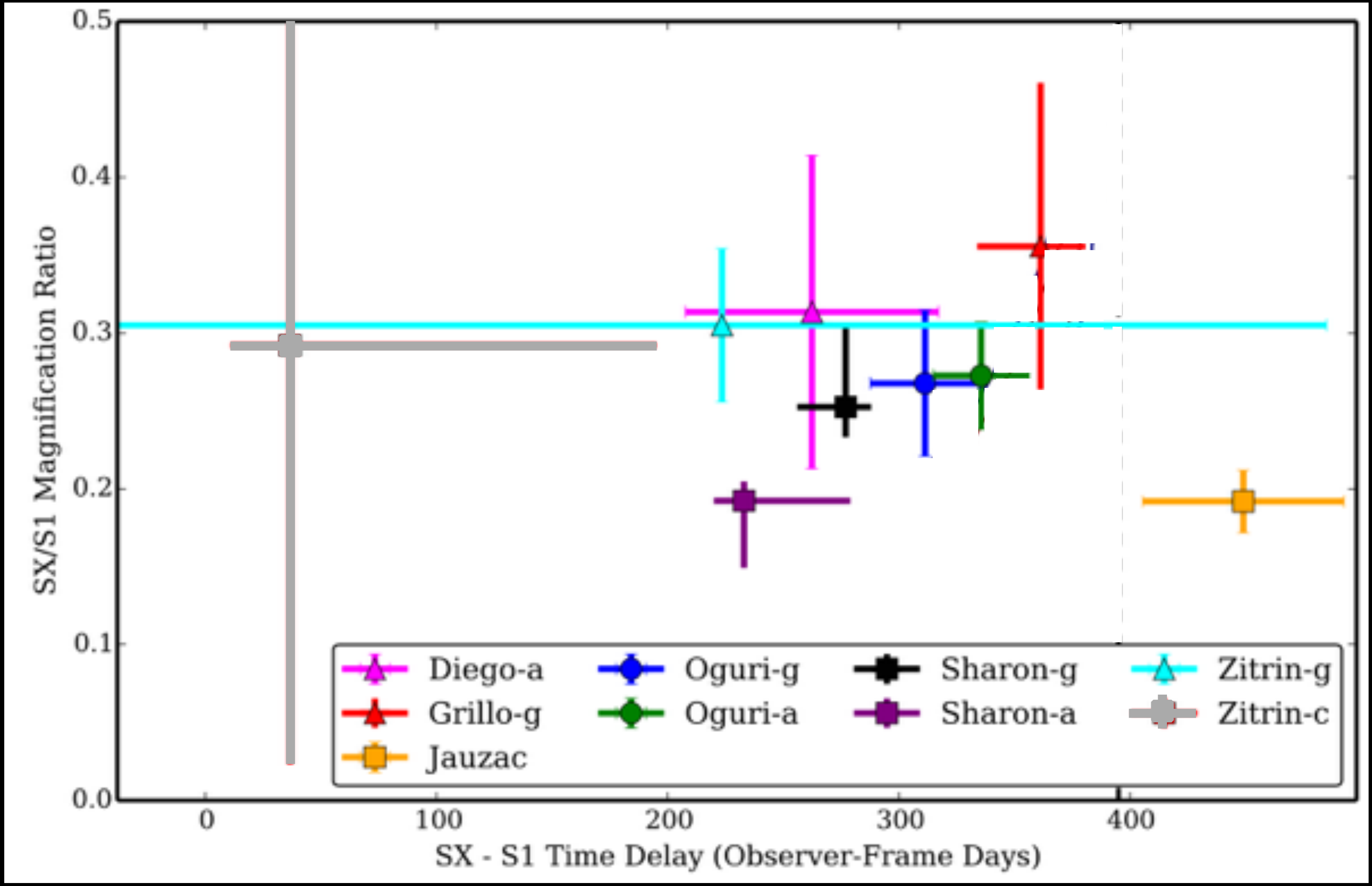
[Kelly et al. 2015]

When will the other SN images appear?

MACS 1149.6+2223

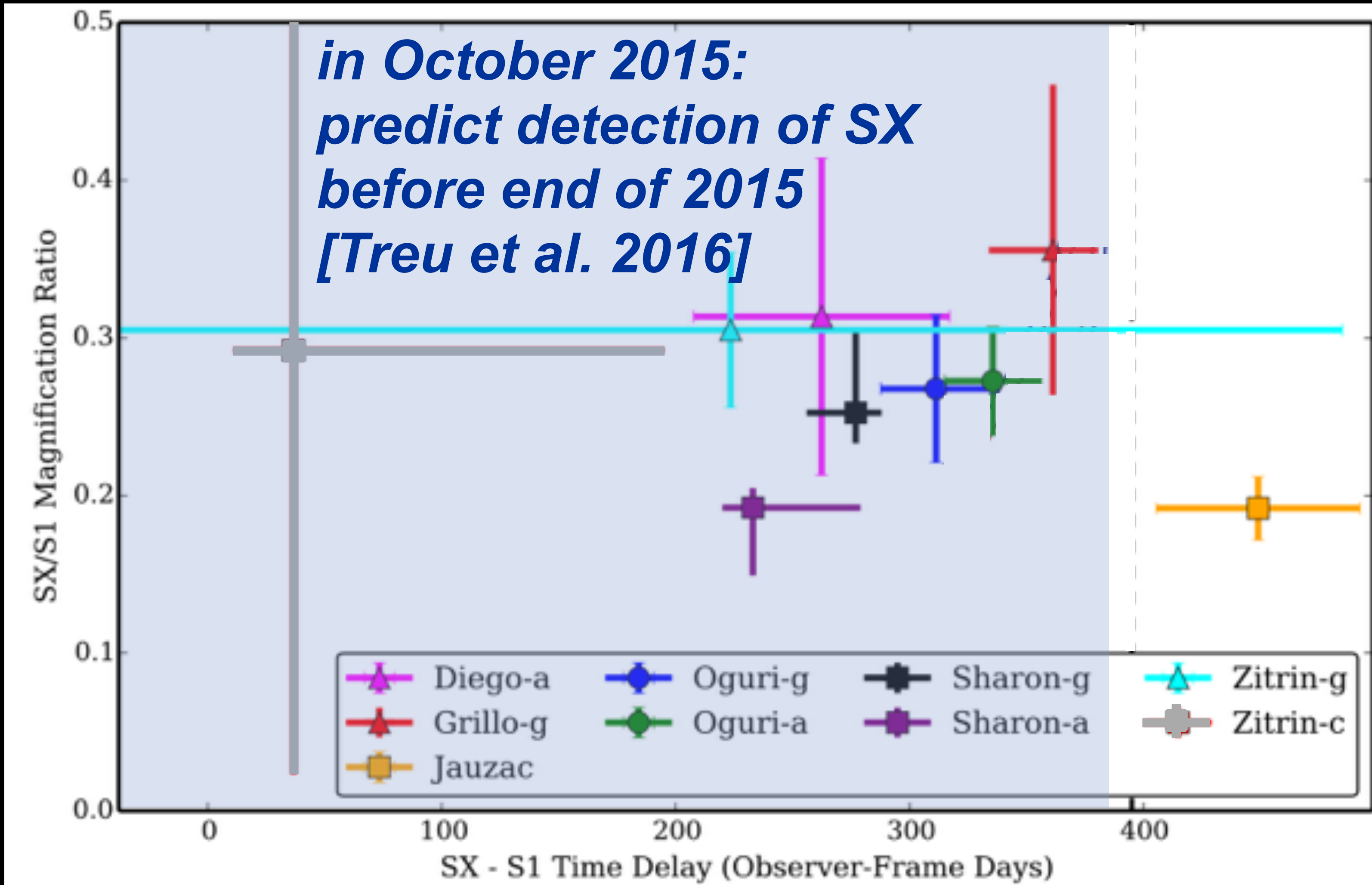
[Kelly et al. 2015]

Predicted magnification and delay



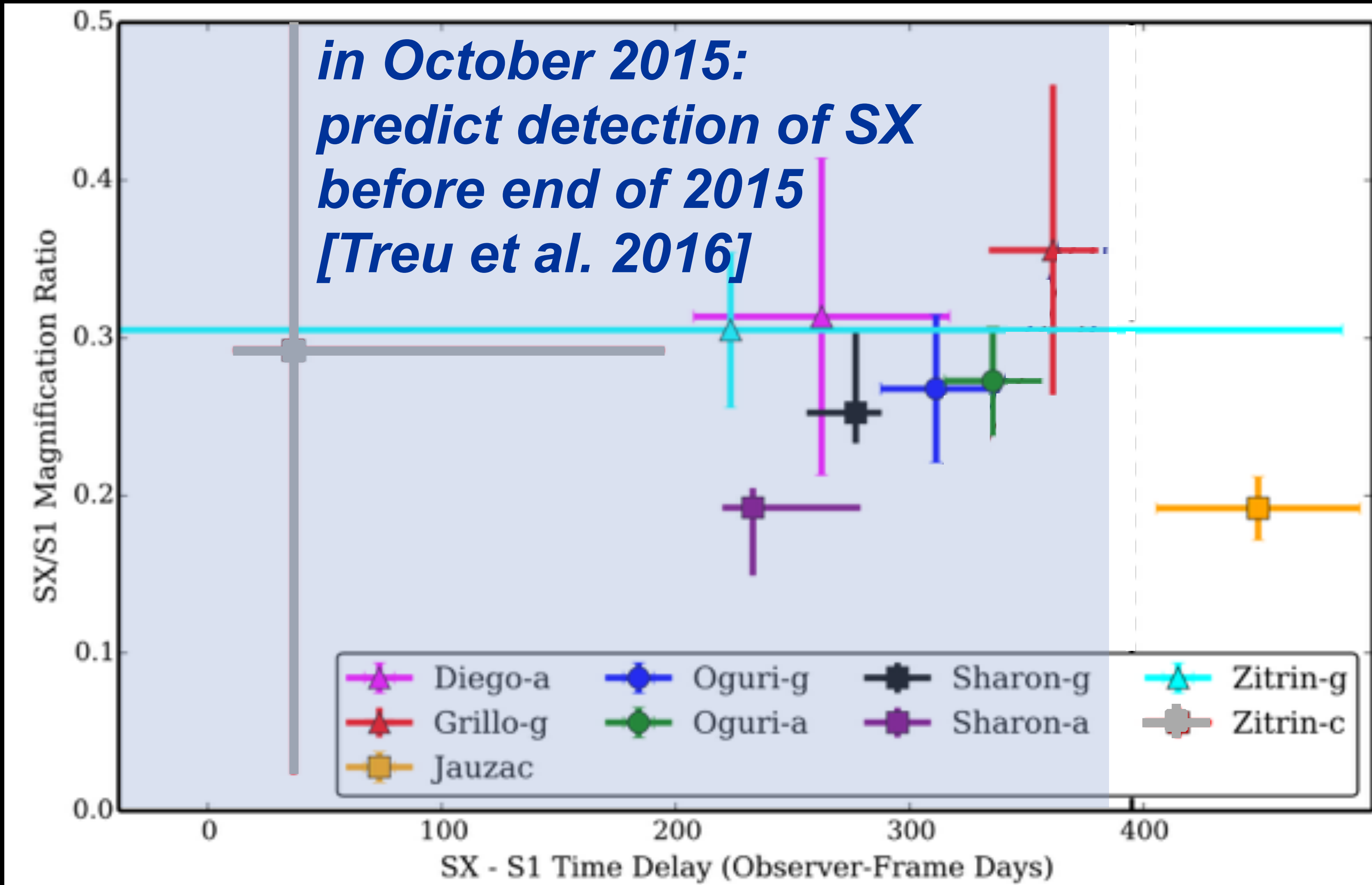
[Kelly et al. 2016]

Predicted magnification and delay



[Kelly et al. 2016]

Predicted magnification and delay

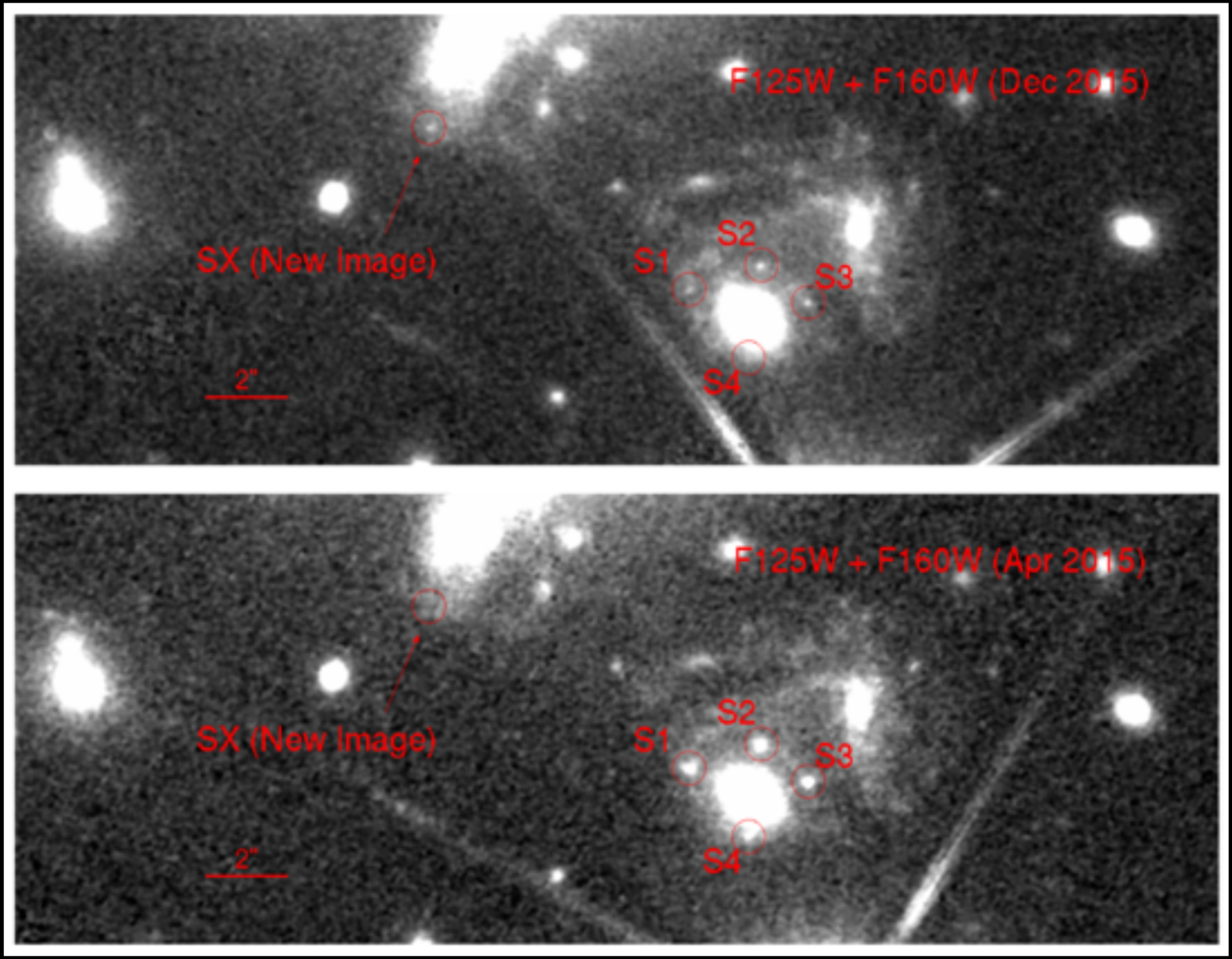


[Kelly et al. 2016]

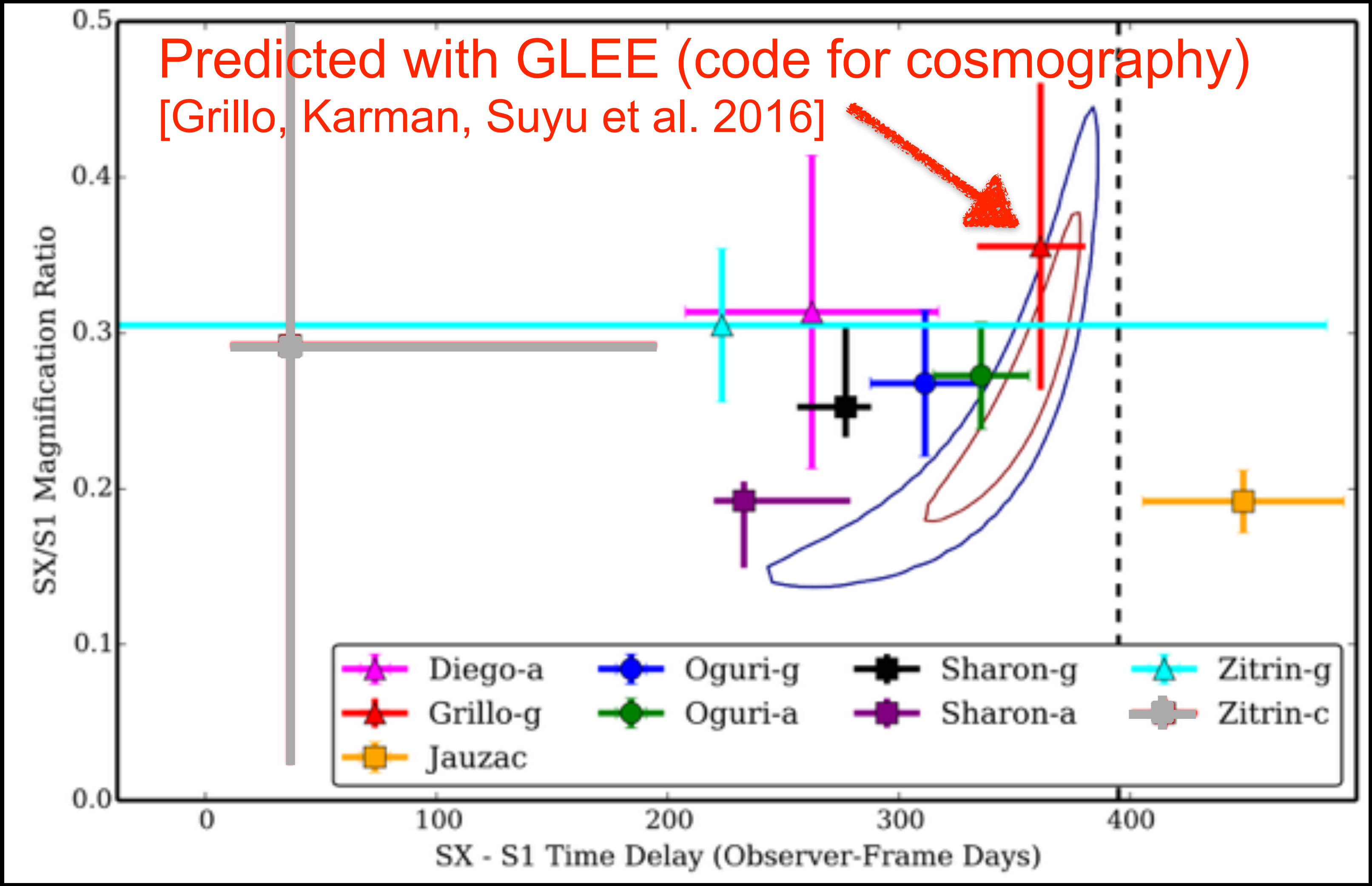
HST observations in Oct 2015: no sign of SX
in Nov 2015: no sign of SX…

Appearance of image SX

December 2015 [Kelly et al. 2016]

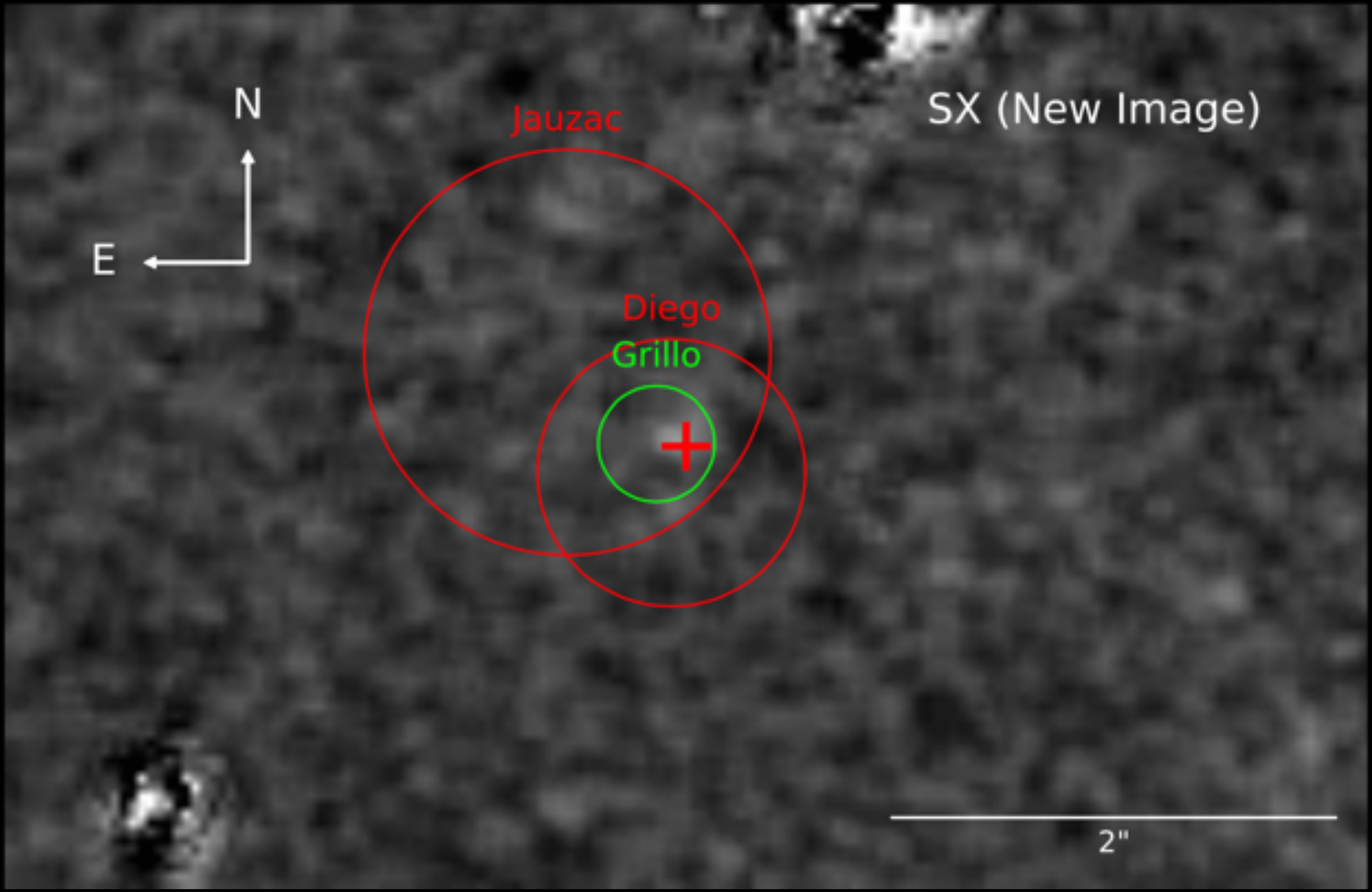


Magnification and delay



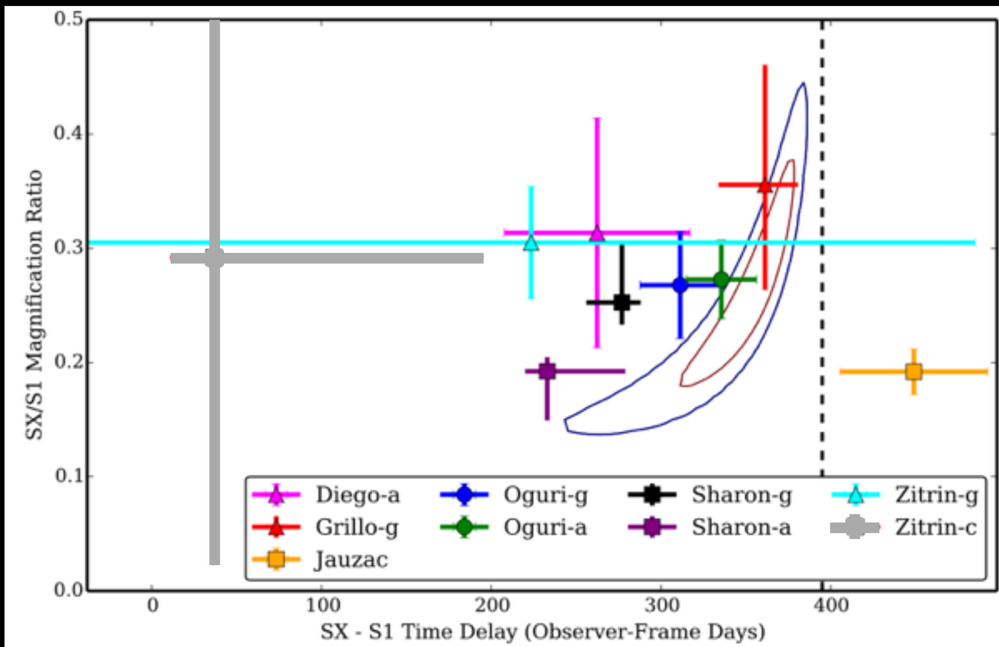
[Kelly et al. 2016]

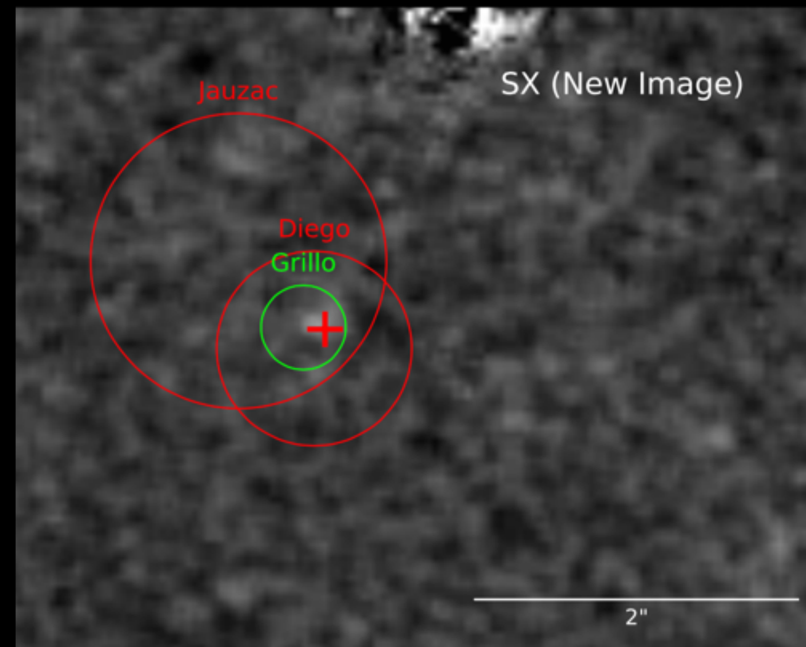
Spot on!



[Kelly et al. 2016]

Successful prediction



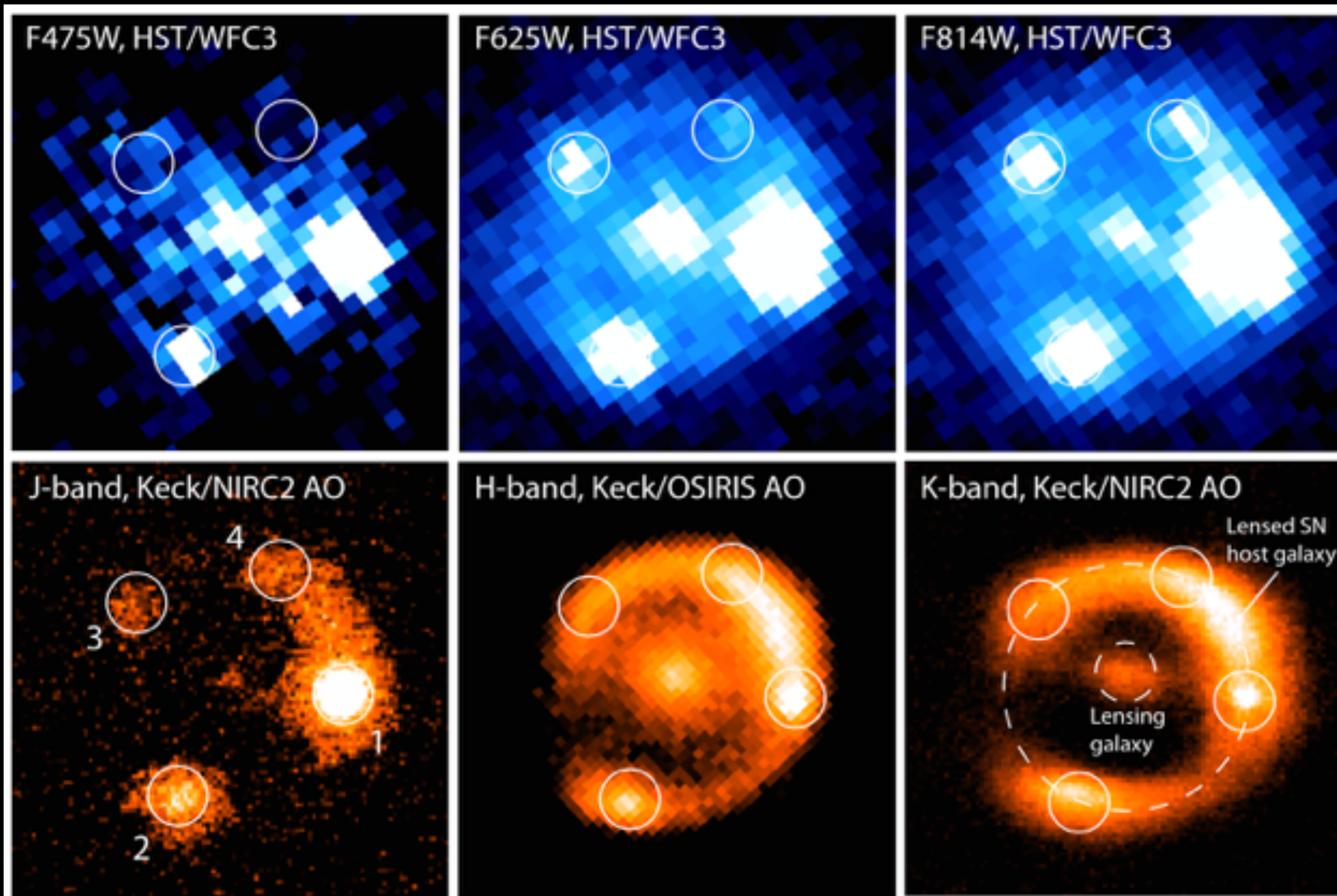


[Kelly et al. 2016]

- Grillo et al. predicted successfully and precisely all three observables of image SX: time, magnification and location
- GLEE [Suyu & Halkola 2010] accurately and precisely predicted the appearance of SX as a result of its ability to reconstruct the entire SN host galaxy

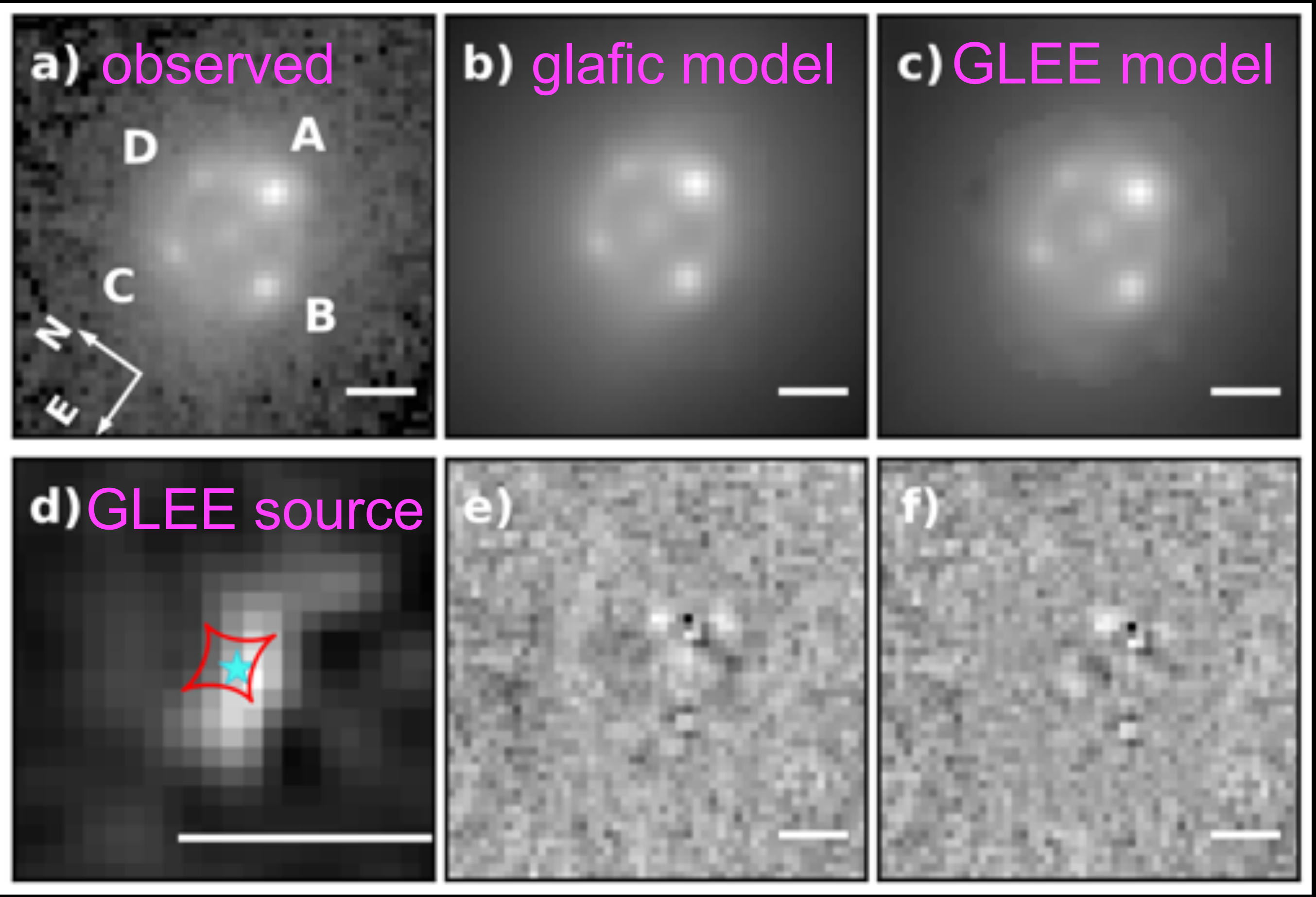
First spatially-resolved lensed Type Ia

discovered in iPTF [Goobar et al. 2017]



Lens model predictions

we modeled the HST image with GLEE [Suyu & Halkola 2010] and glafic [Oguri 2010] to estimate the time delays [More, Suyu, Oguri et al. 2017]

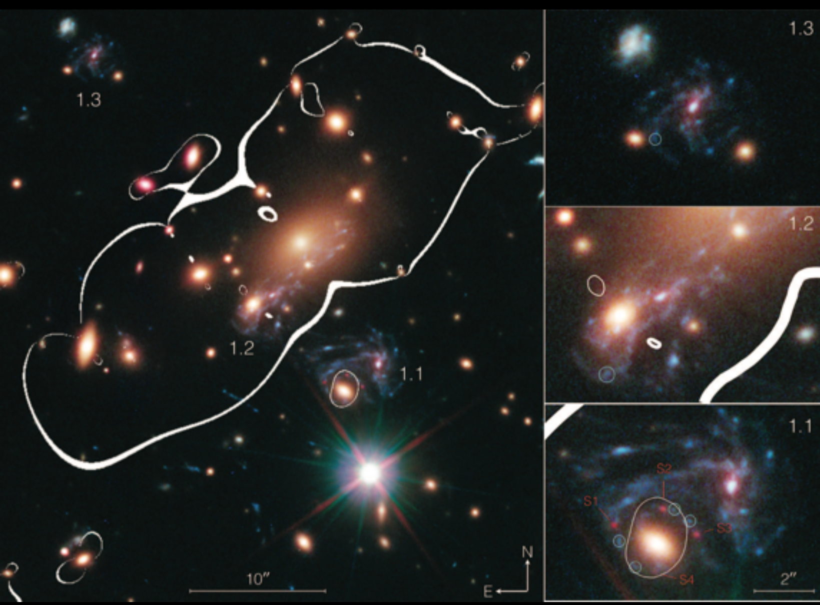


find maximum relative time delay to be <1 day [More, Suyu, Oguri et al. 2017]

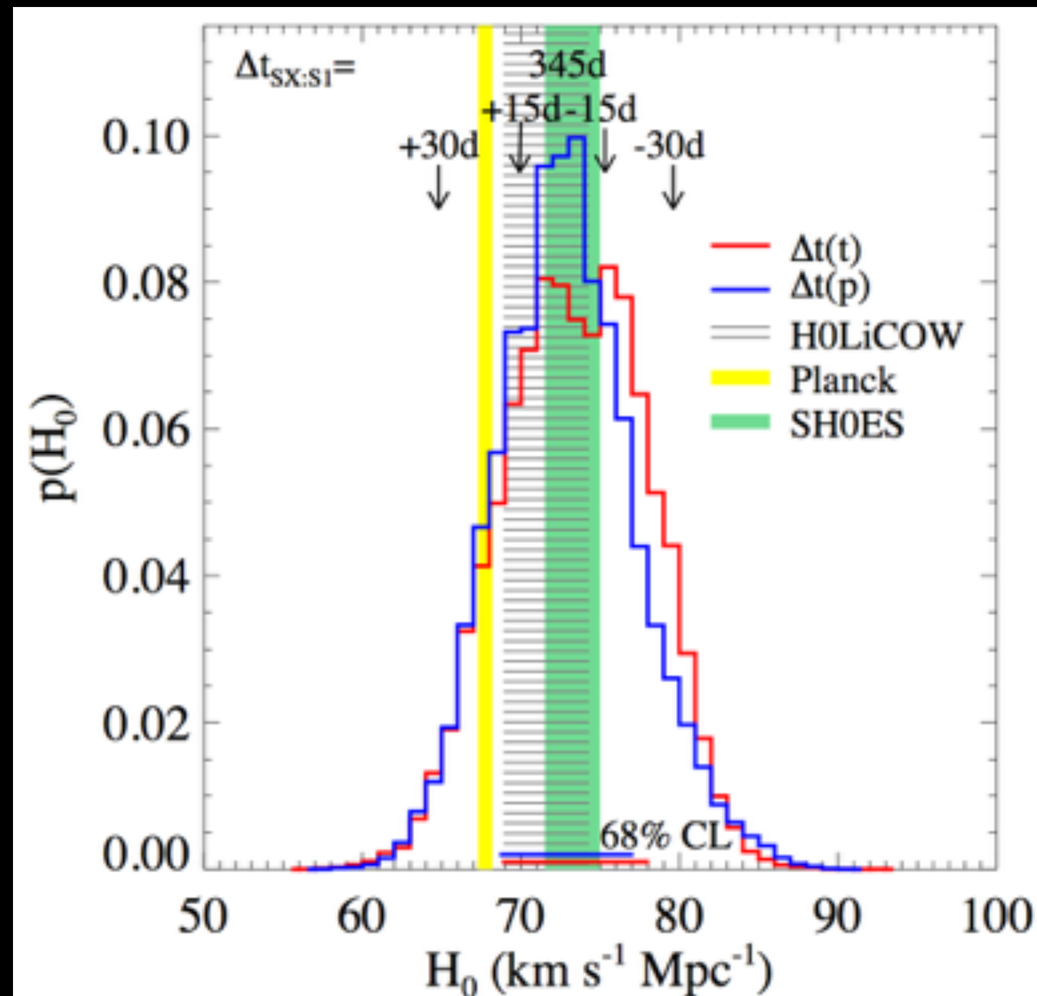
Stay tuned of results of monitoring and follow-up observations from iPTF team

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)

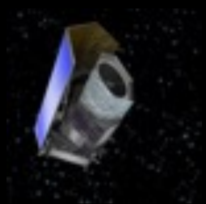


[Grillo, Rosati, Suyu et al. 2018]

Future Prospects

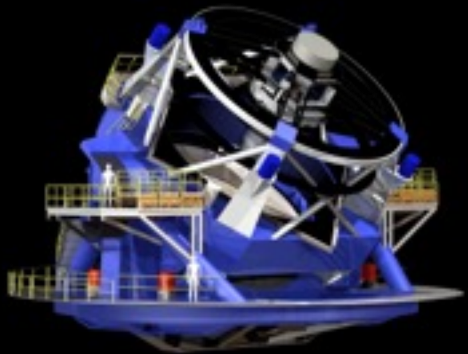
Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid



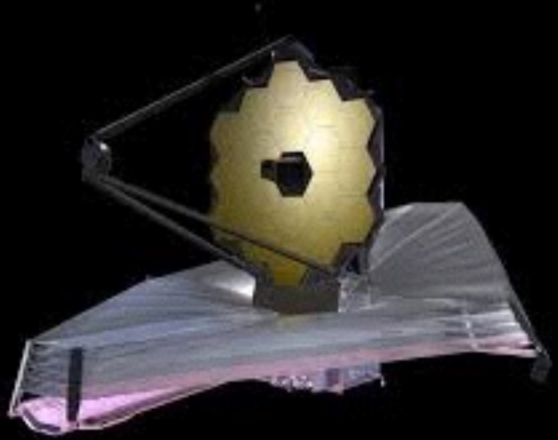
Discovery
Imaging
Spectroscopy

LSST



Discovery
Time delays
Imaging

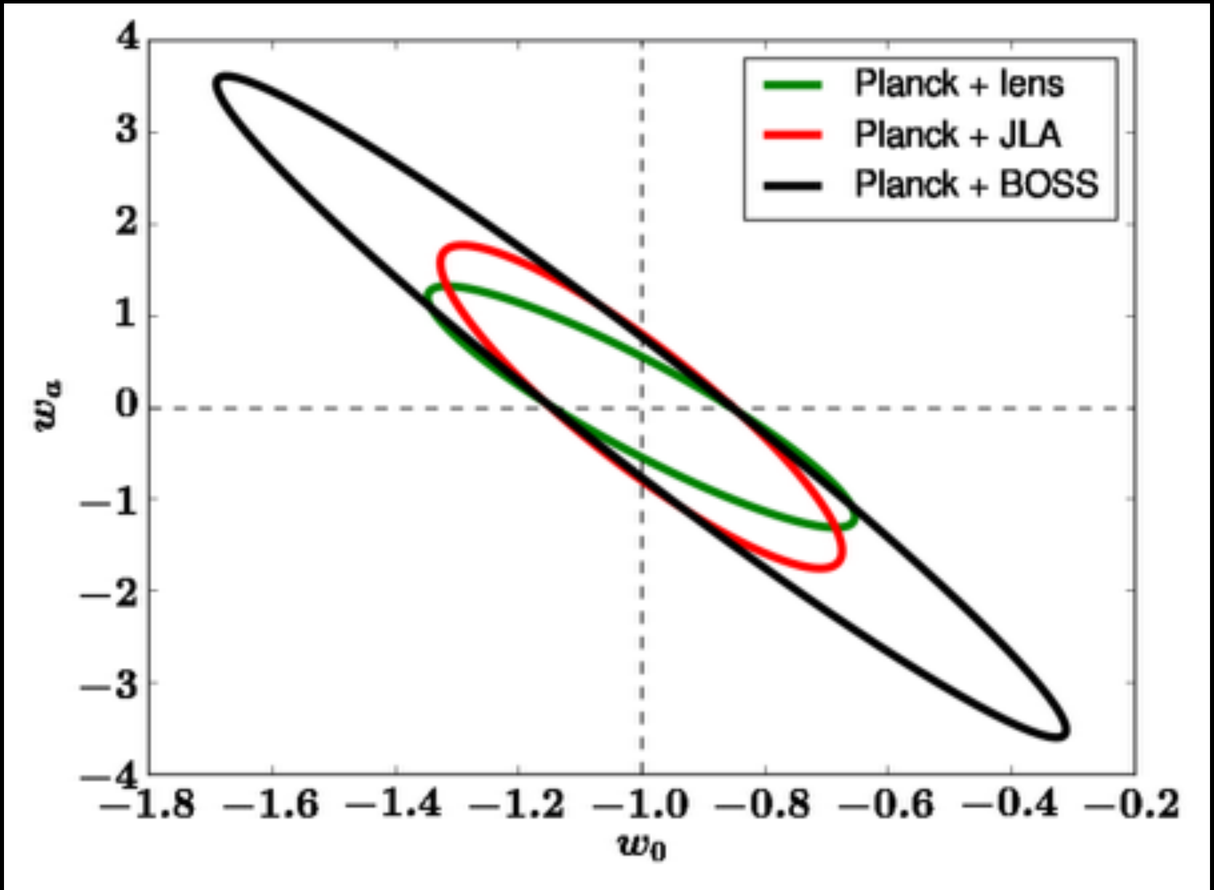
JWST



High-resolution imaging
& spectroscopy

Future Prospects

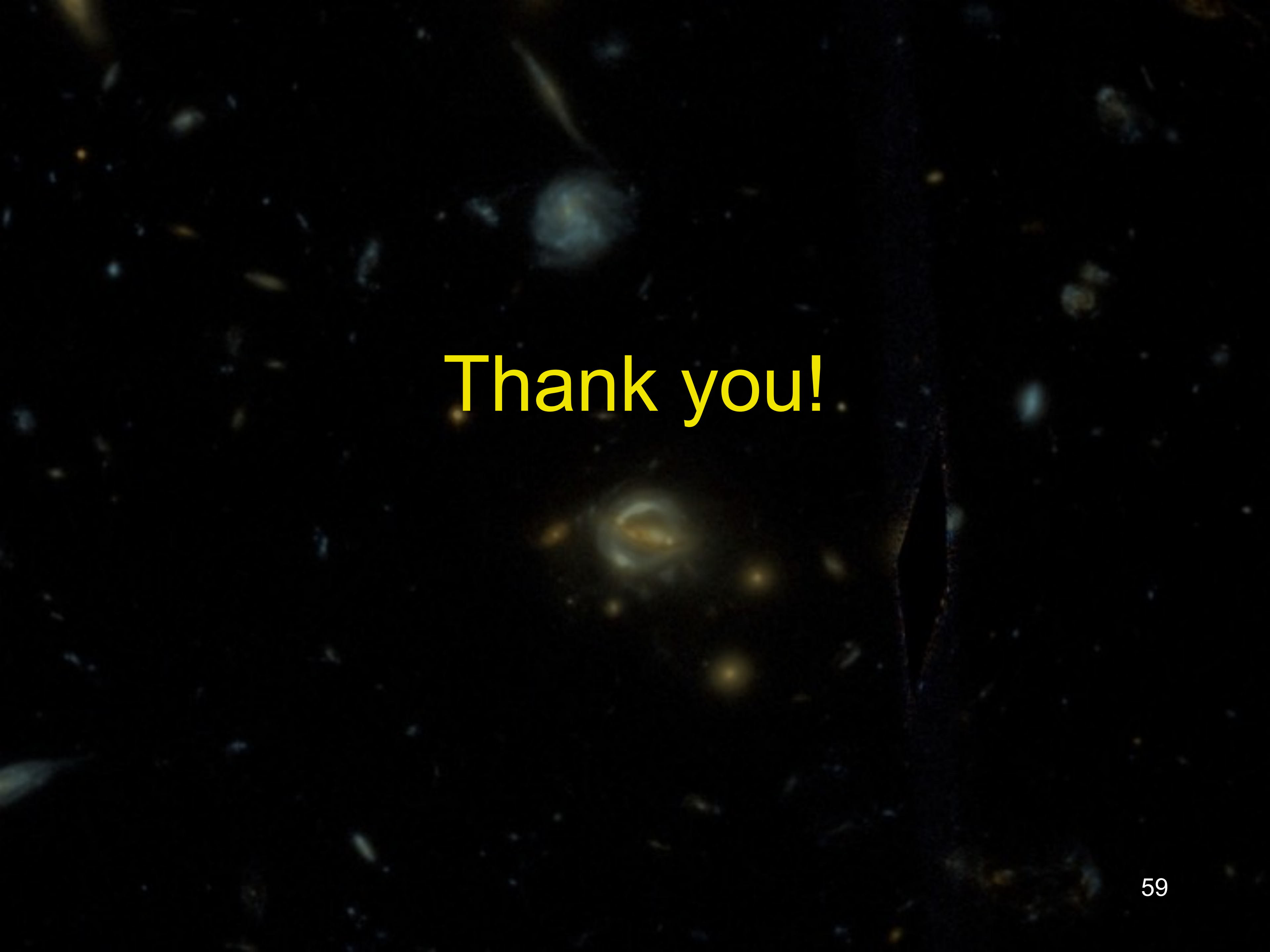
Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae



[Jee, Komatsu, Suyu, Huterer 2016]

Summary

- Time-delay distances $D_{\Delta t}$ of each lens can be measured with uncertainties of ~5-8% including systematics
- From 3 lenses in H0LiCOW, $H_0 = 71.9^{+2.4}_{-3.0}$ km/s/Mpc in flat ΛCDM, a 3.8% precision measurement independent of other probes
- Search is underway to find new lenses in HSC and DES surveys
- SN Refsdal blind test demonstrated the robustness of our cluster mass modeling approach and software GLEE
- First strongly lensed Type Ia discovered by iPTF team, but with small time delays
- Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology


Thank you!