Progress toward an accurate Hubble Constant

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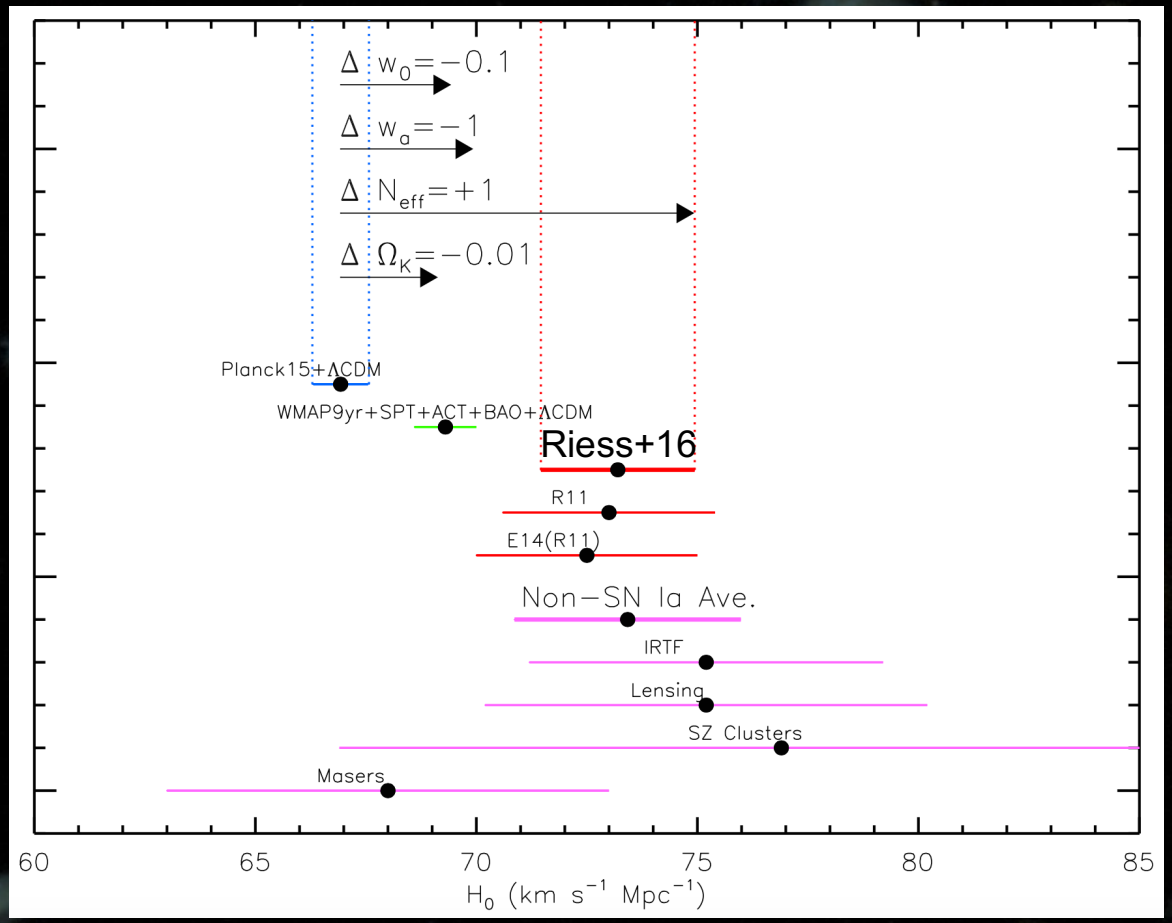
Hubble Constant: key parameter



[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

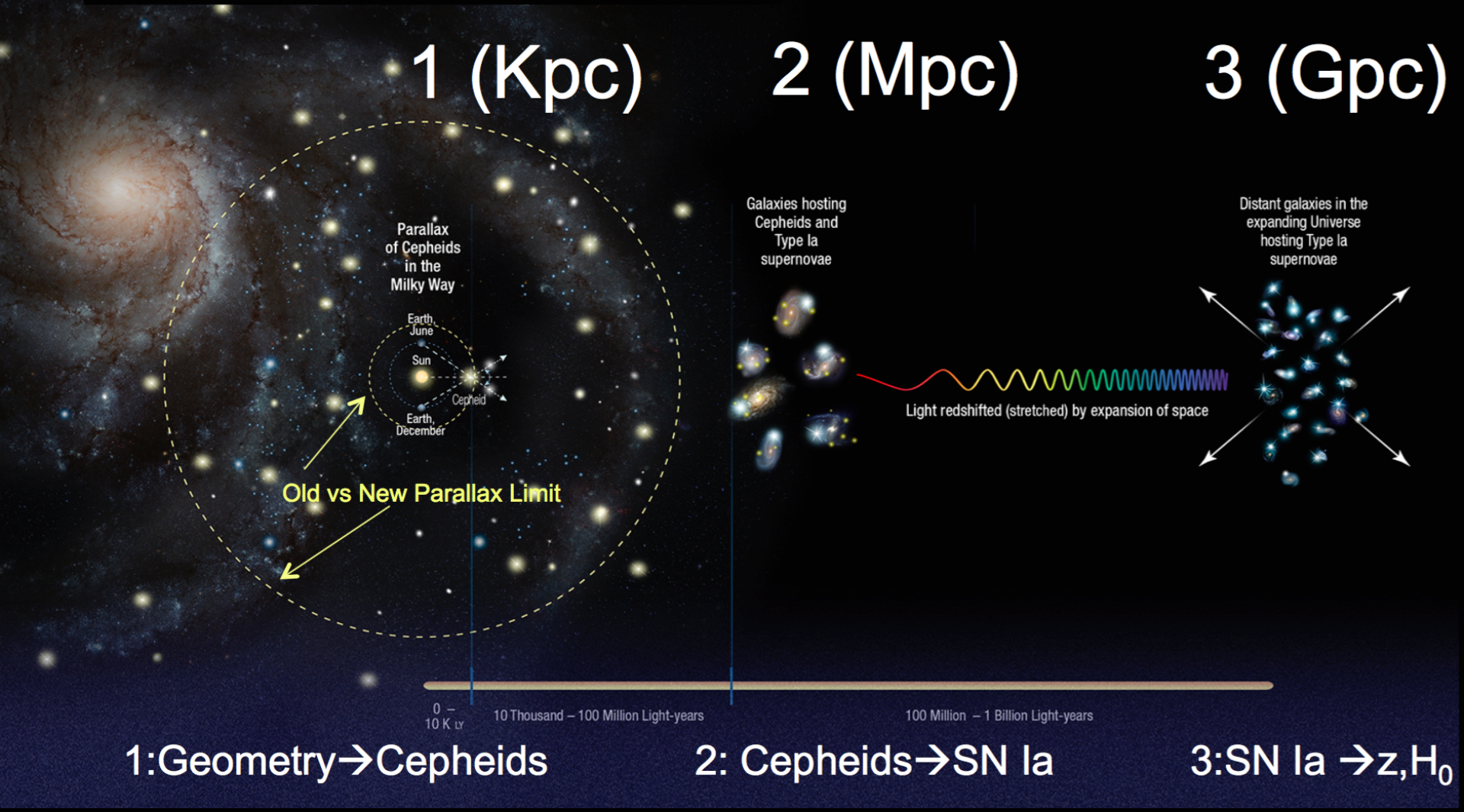
Megamasers

Geometric method to measure D_A to maser galaxies, hence H_0

Next talk by Jim Braatz:
Megamaser Cosmology Project

Distance Ladder

ladder to reach objects in Hubble flow ($v_{peculiar} << v_{Hubble}$)



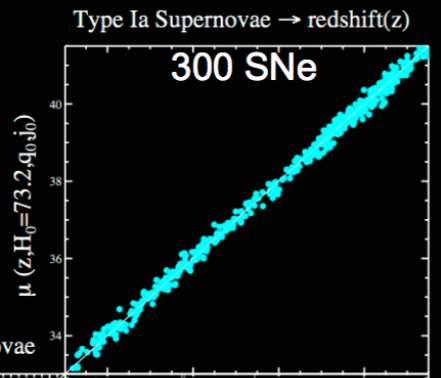
[slide material courtesy of Adam Riess]

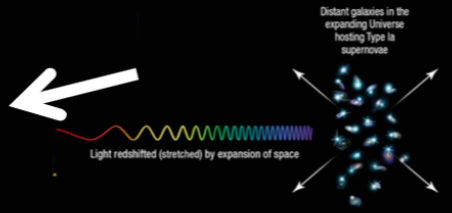
Distance Ladder Measurements

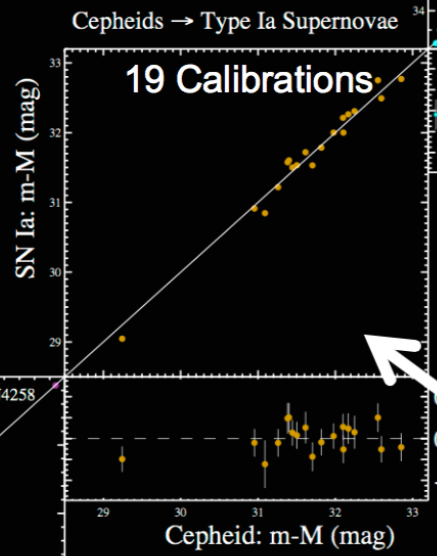
- *Hubble Space Telescope* Key Project [Freedman et al. 2001]
  - $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1} (10% uncertainty)
  - resolving multi-decade "factor-of-two" controversy
- Carnegie Hubble Program [Freedman et al. 2012]
  - $H_0 = 74.3 \pm 2.1$ km s^{-1} Mpc^{-1} (2.8% uncertainty)
- Carnegie-Chicago 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]

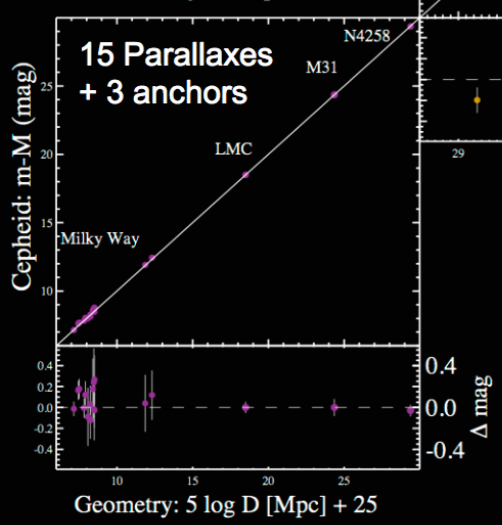
H_0 from SH0ES

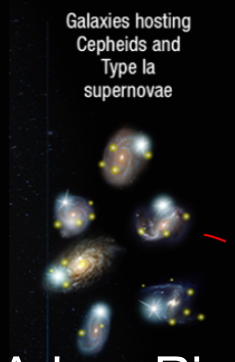












H_0=73.24 +/- 1.74,
Km s^{-1} Mpc^{-1}

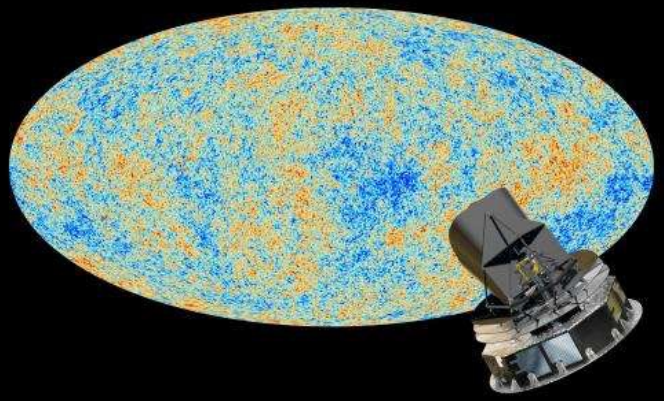
2.4% total uncertainty

[Riess et al. 2016]

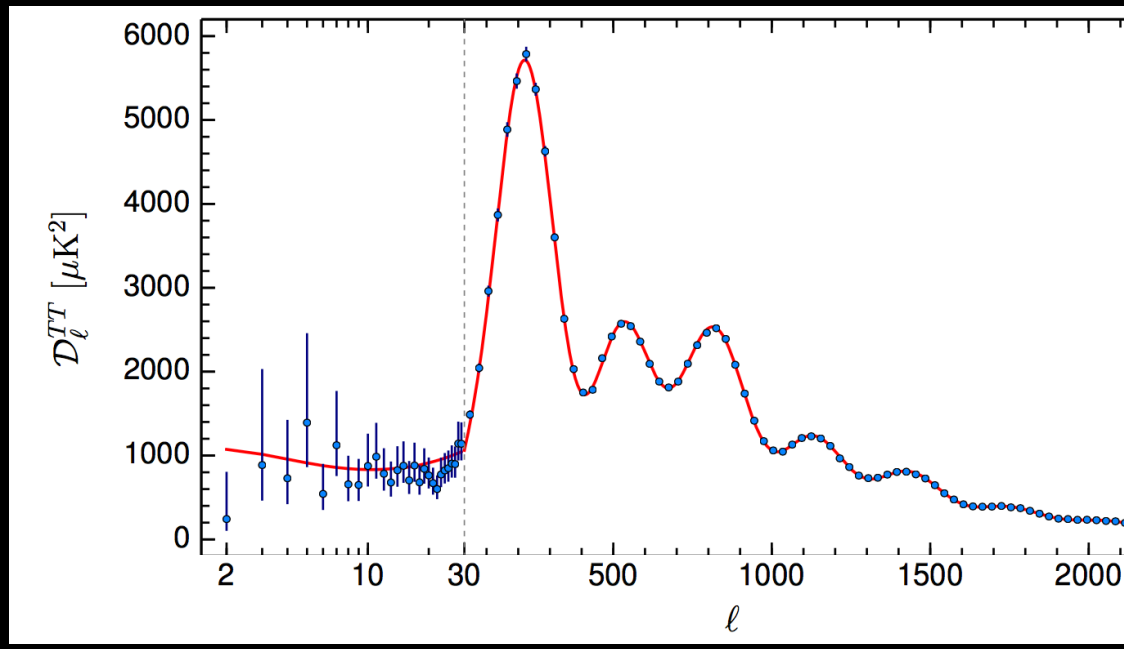
[slide material courtesy of Adam Riess]

Cosmic Microwave Background

CMB Temperature fluctuations



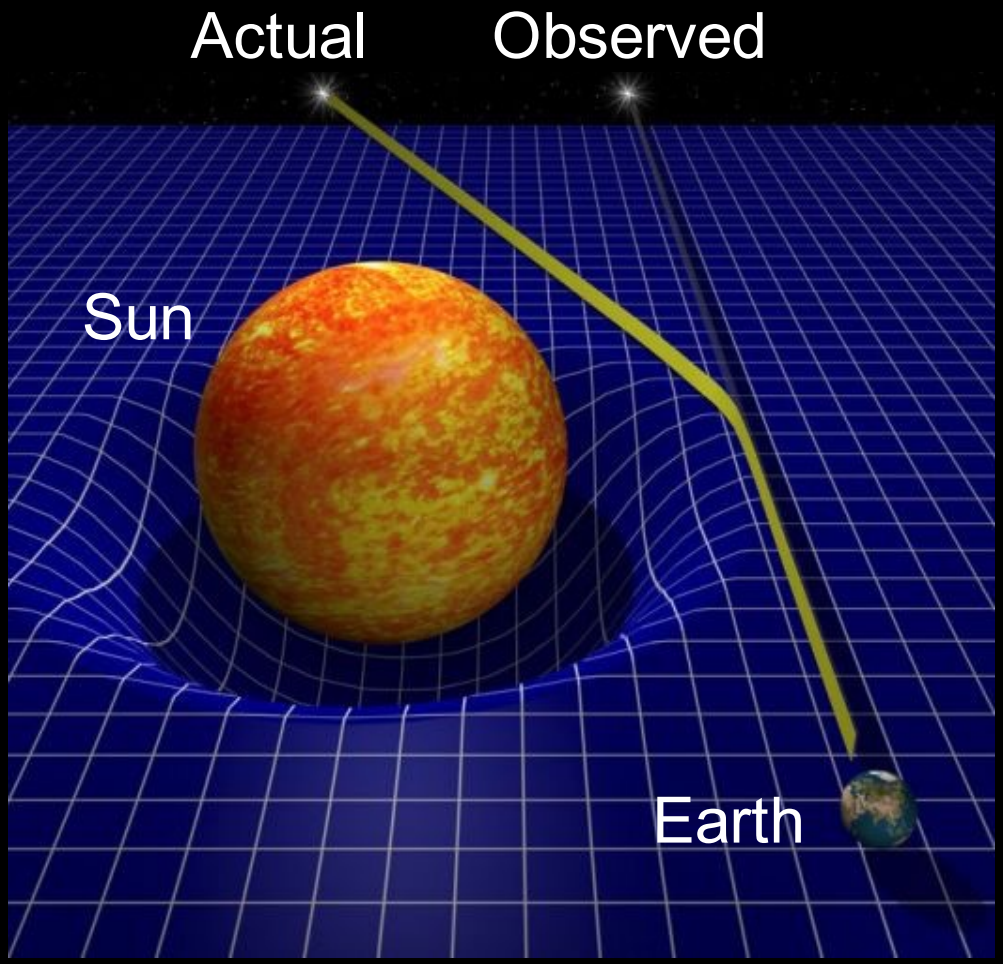
[Planck Collaboration 2016]



(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})

Gravitational Lensing



Strong Optical Lensing

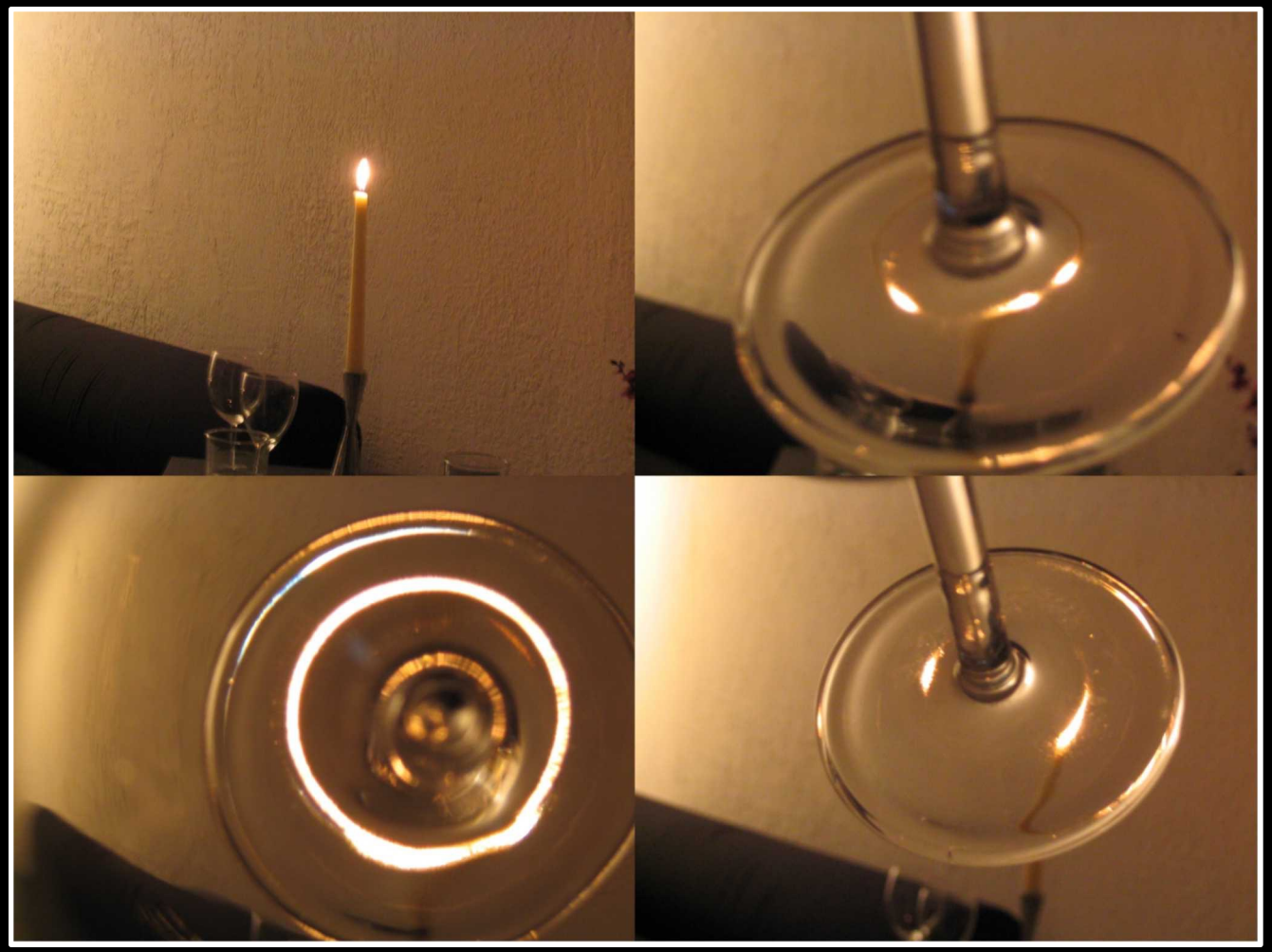
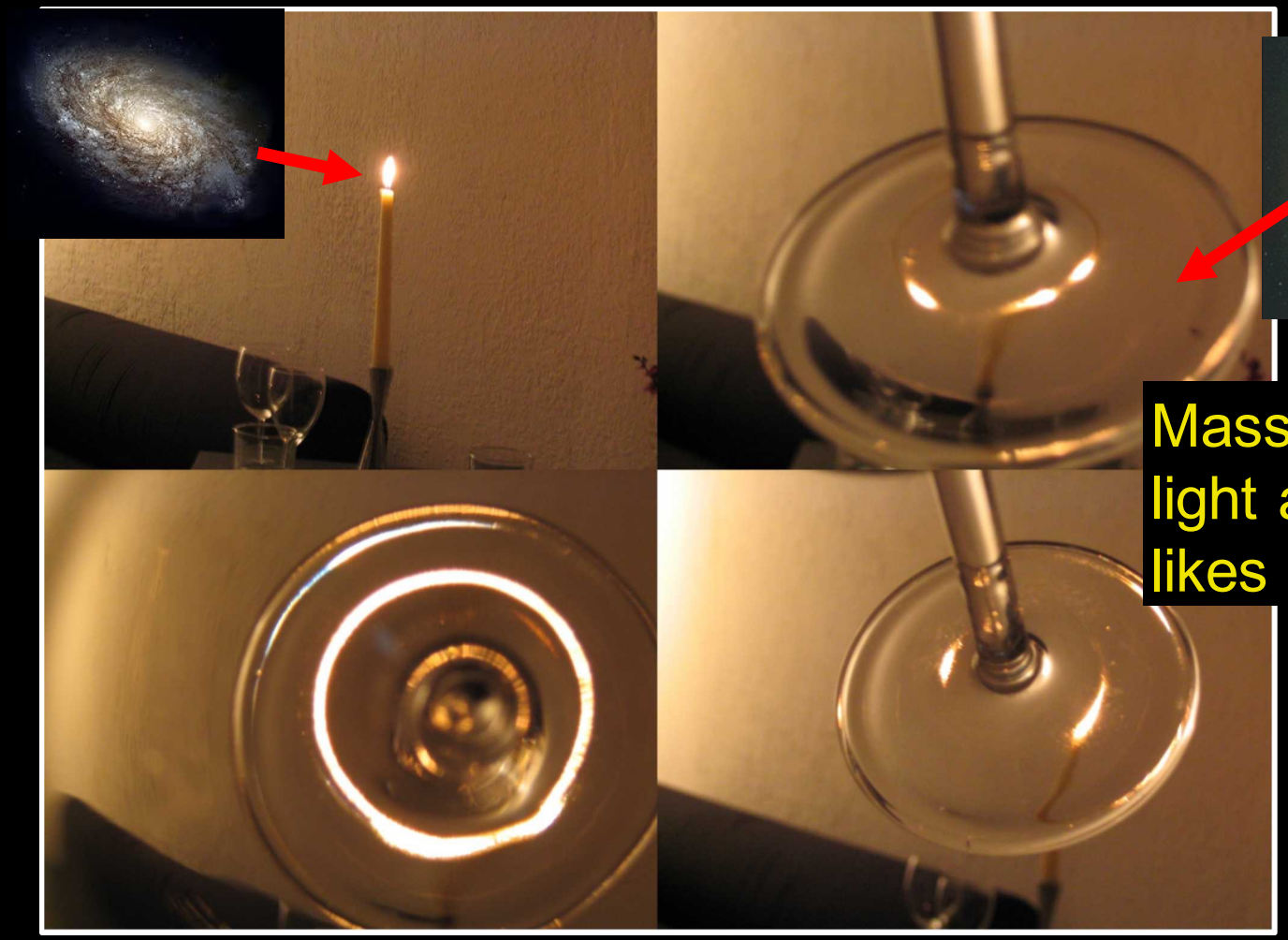


Image Credit: P. J. Marshall

Gravitational Strong ~~Optical~~ Lensing

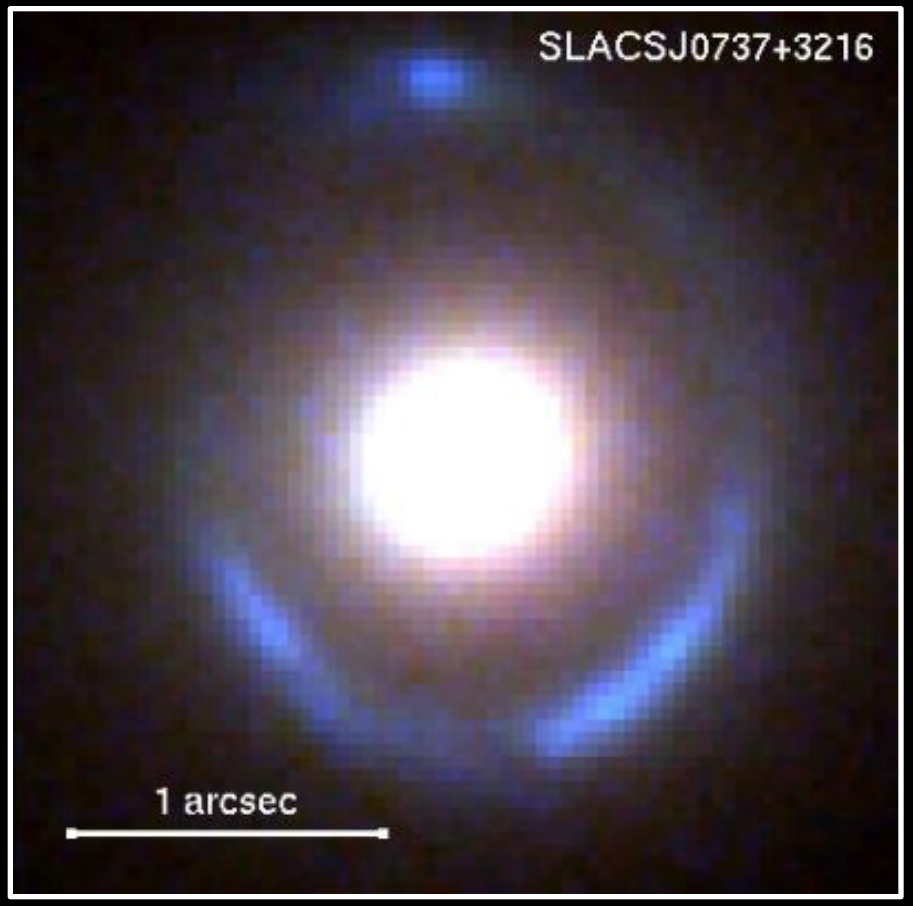


Mass “bends” light and acts likes a lens

Image Credit: P. J. Marshall

Gravitational Lens

HST image: SLACSJ0737+3216

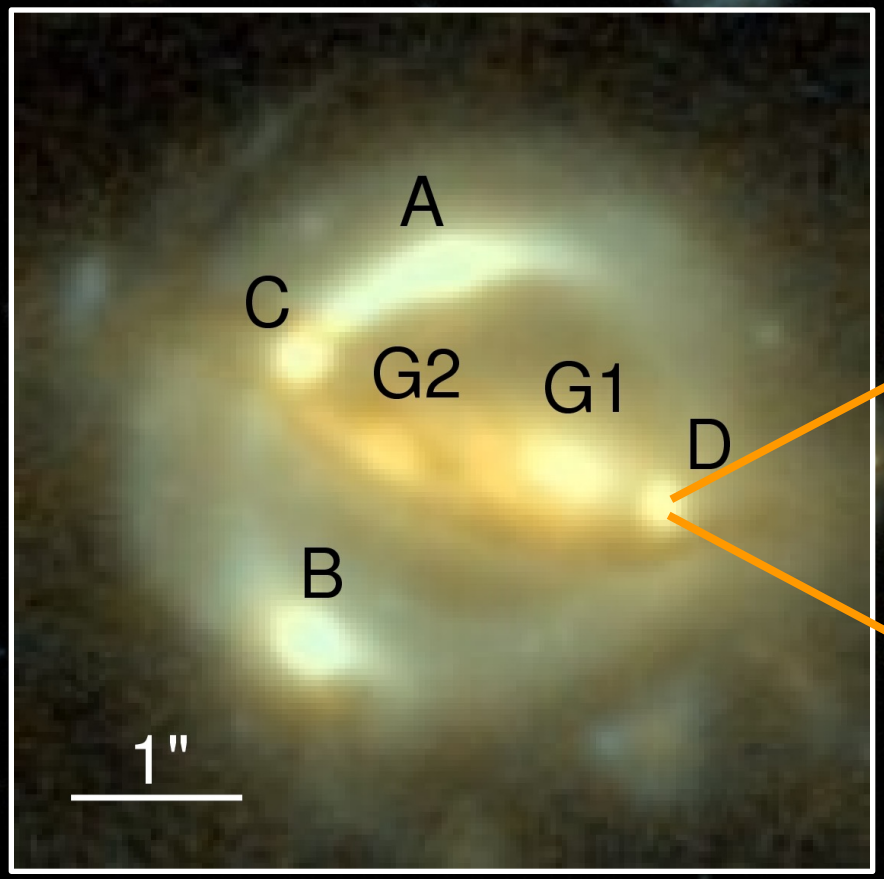


Marshall et al. (2007)



Image Credit: P. J. Marshall

Strong Gravitational Lens with Active Galactic Nucleus

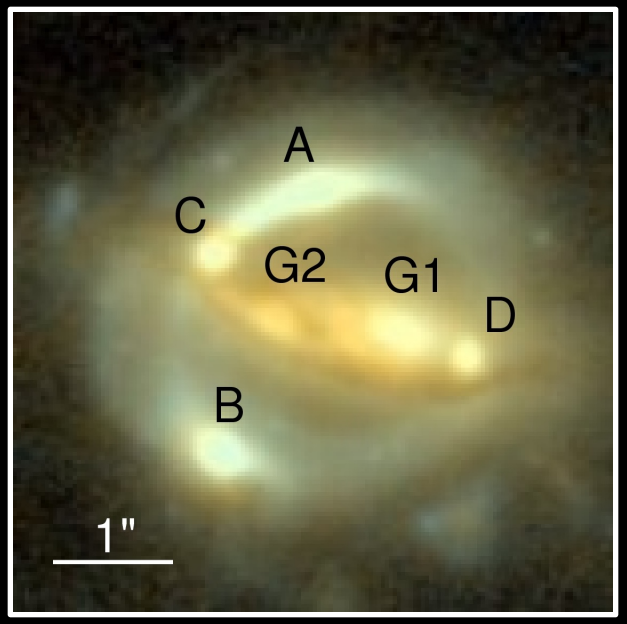


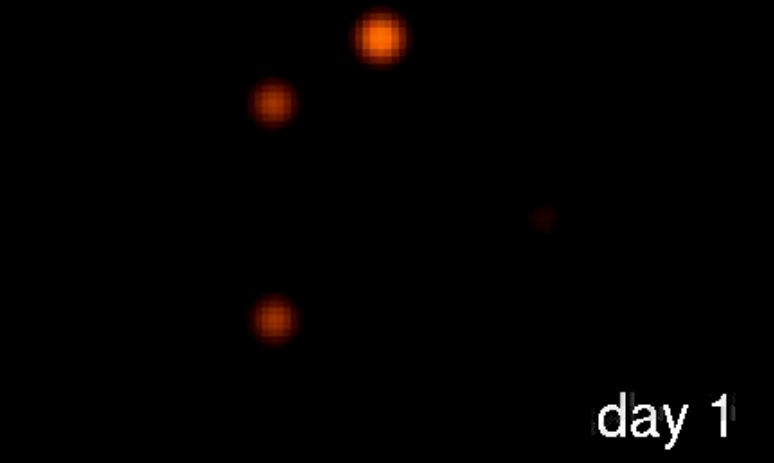
Active galactic nucleus (AGN) in the source from accretion of material onto supermassive black hole:

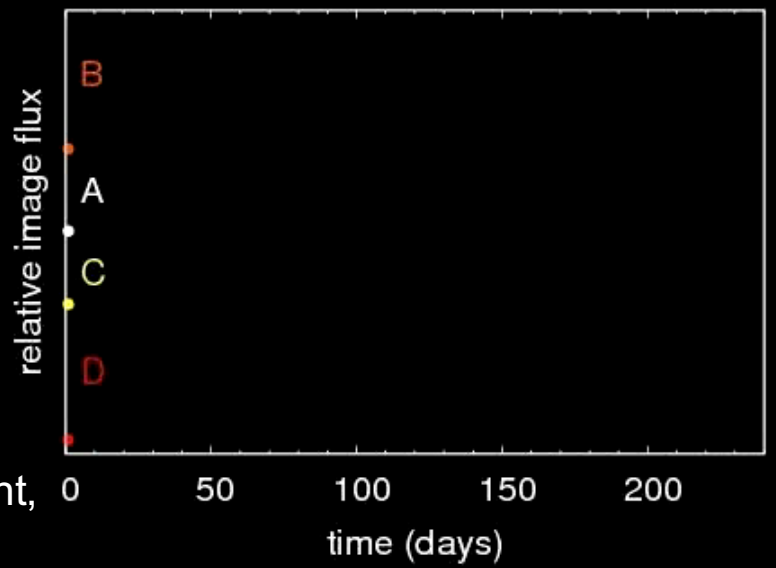


Light emitted from AGN changes in time (“flickers”)

Gravitational Lens Time Delays



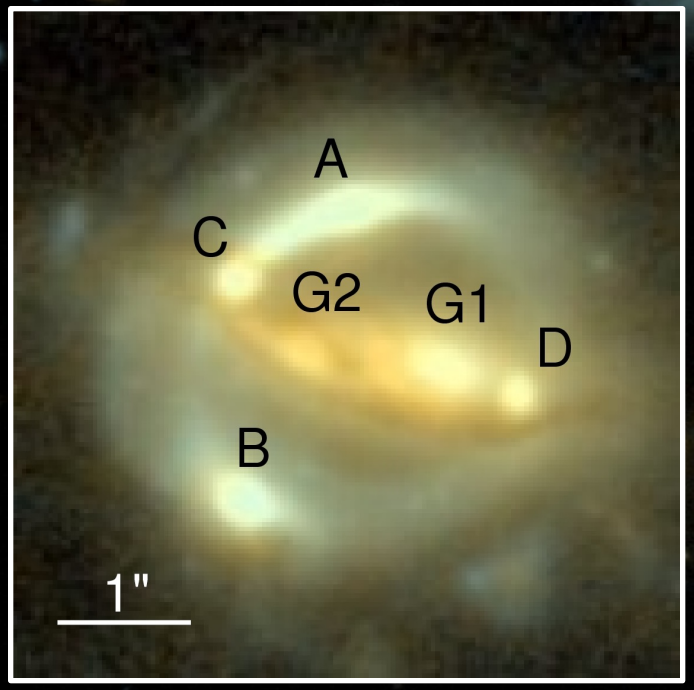




[Fassnacht et al. 1999, 2002]

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

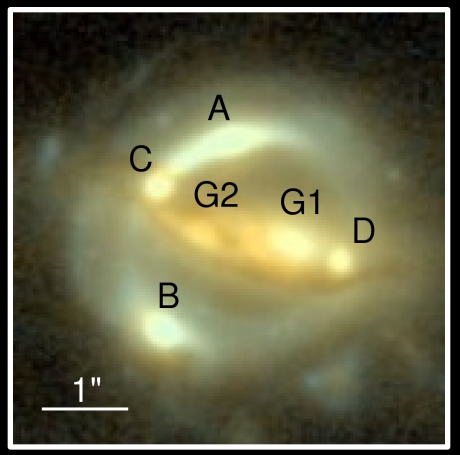
For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

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

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

B1608+656



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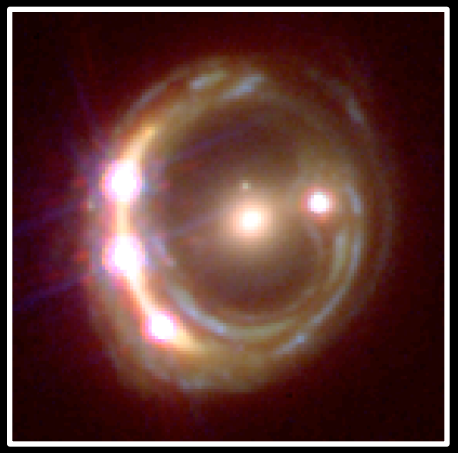
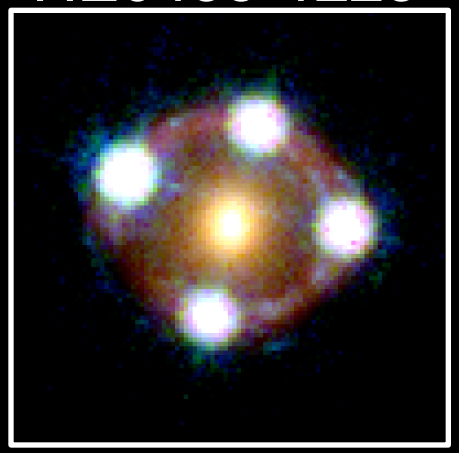


H_0 to <3.5% precision

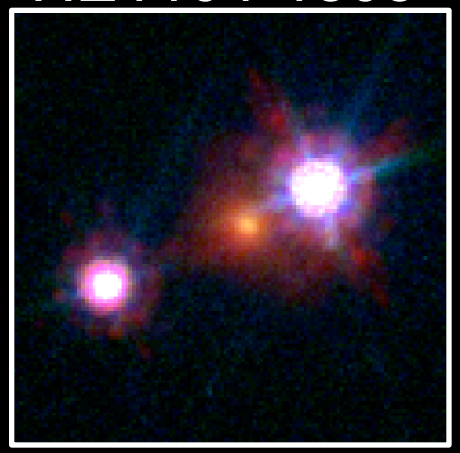
HE0435-1223



WFI2033-4723

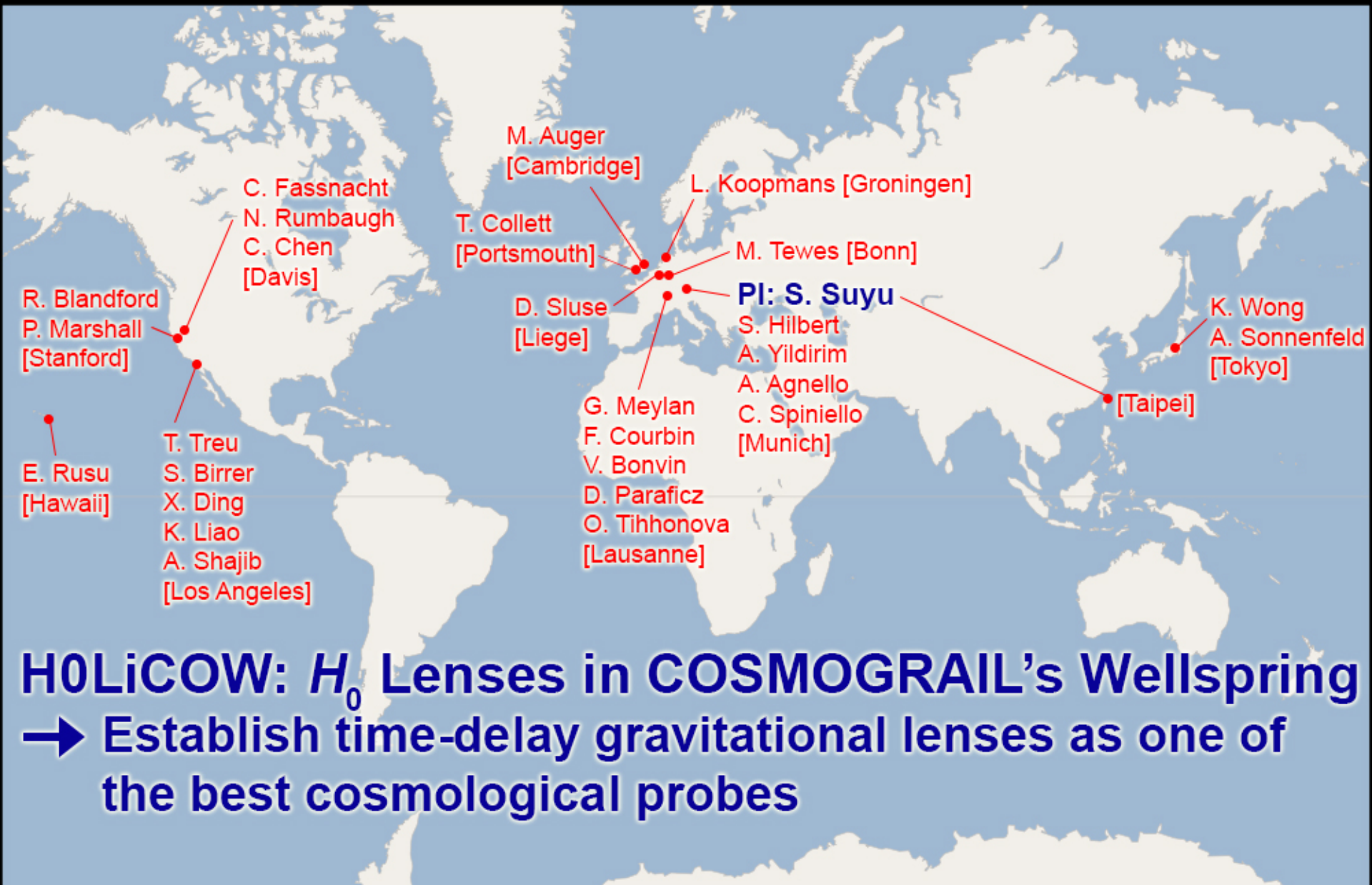


HE1104-1805



[Suyu et al. 2017]

H0LiCOWers



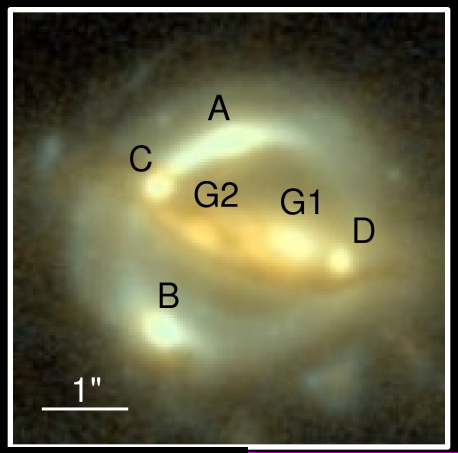
H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

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

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

B1608+656



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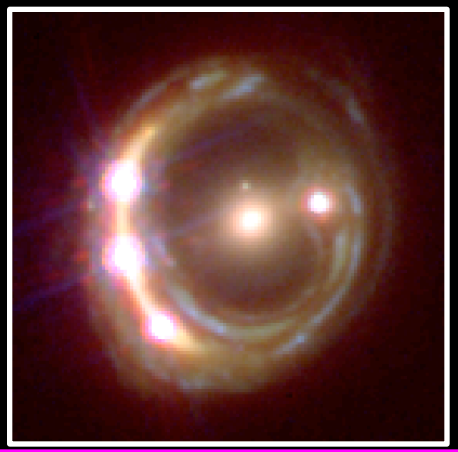
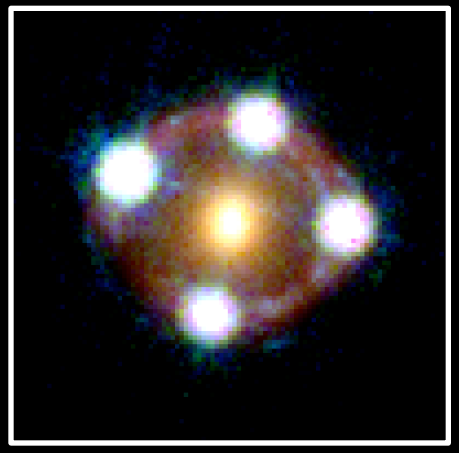


completed

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

HE0435-1223



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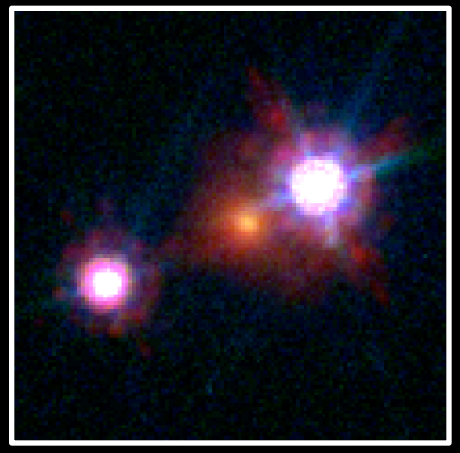
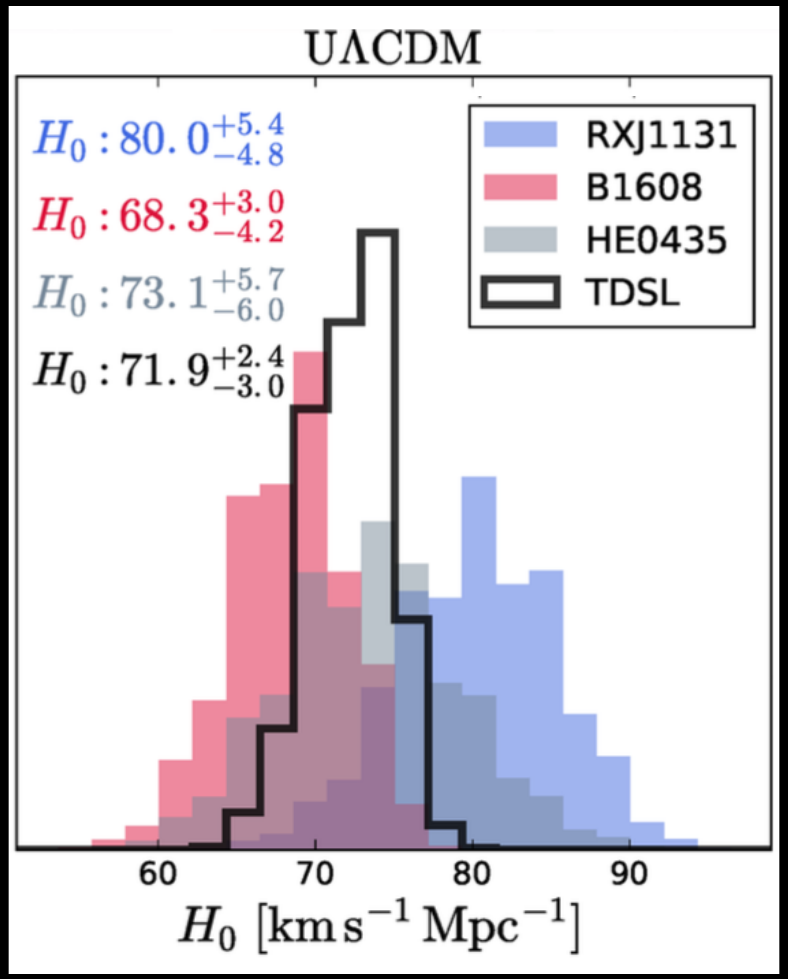


ongoing

H_0 from 3 strong lenses



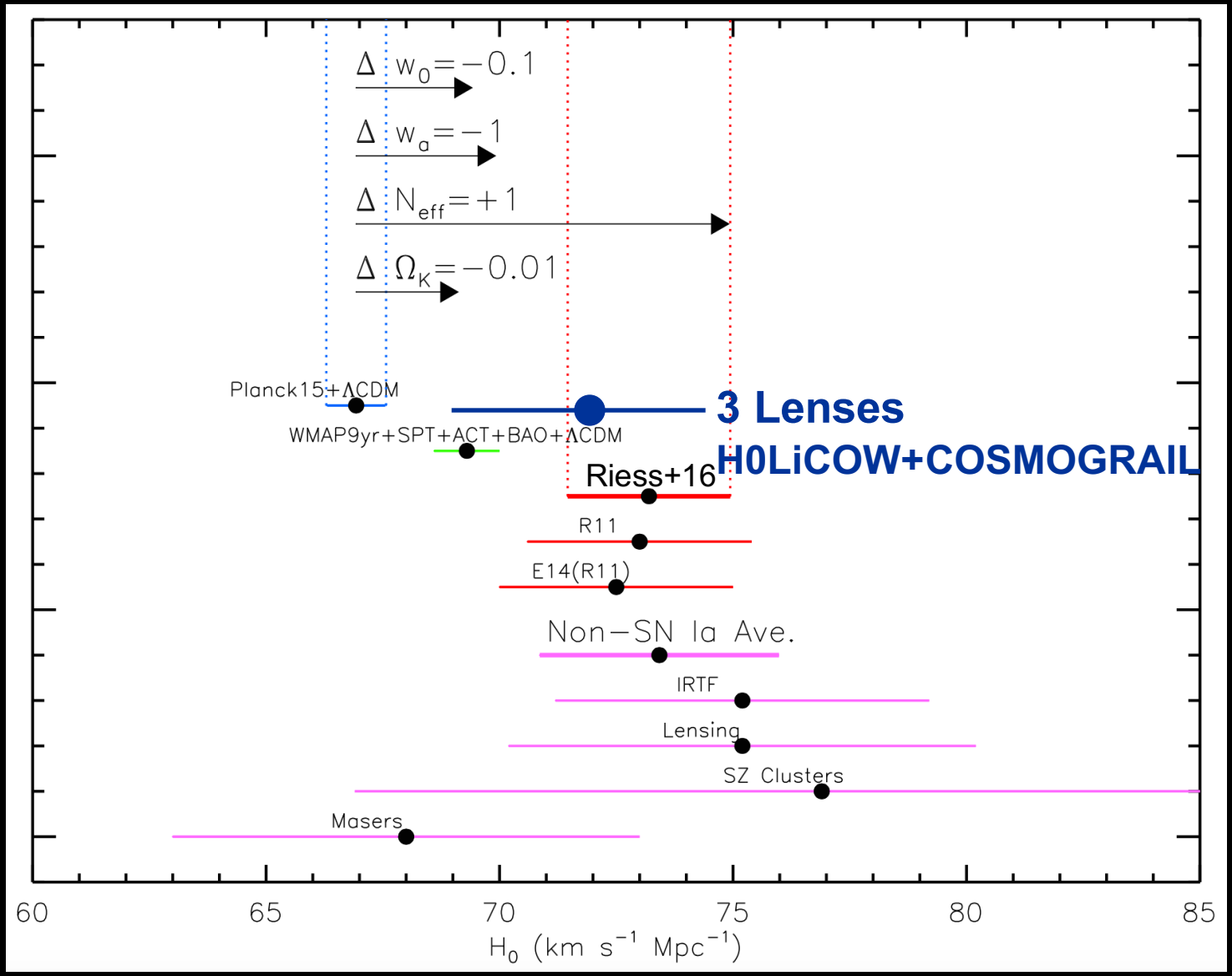
Blind analysis to avoid confirmation bias

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

H_0 with 3.8% precision for flat ΛCDM

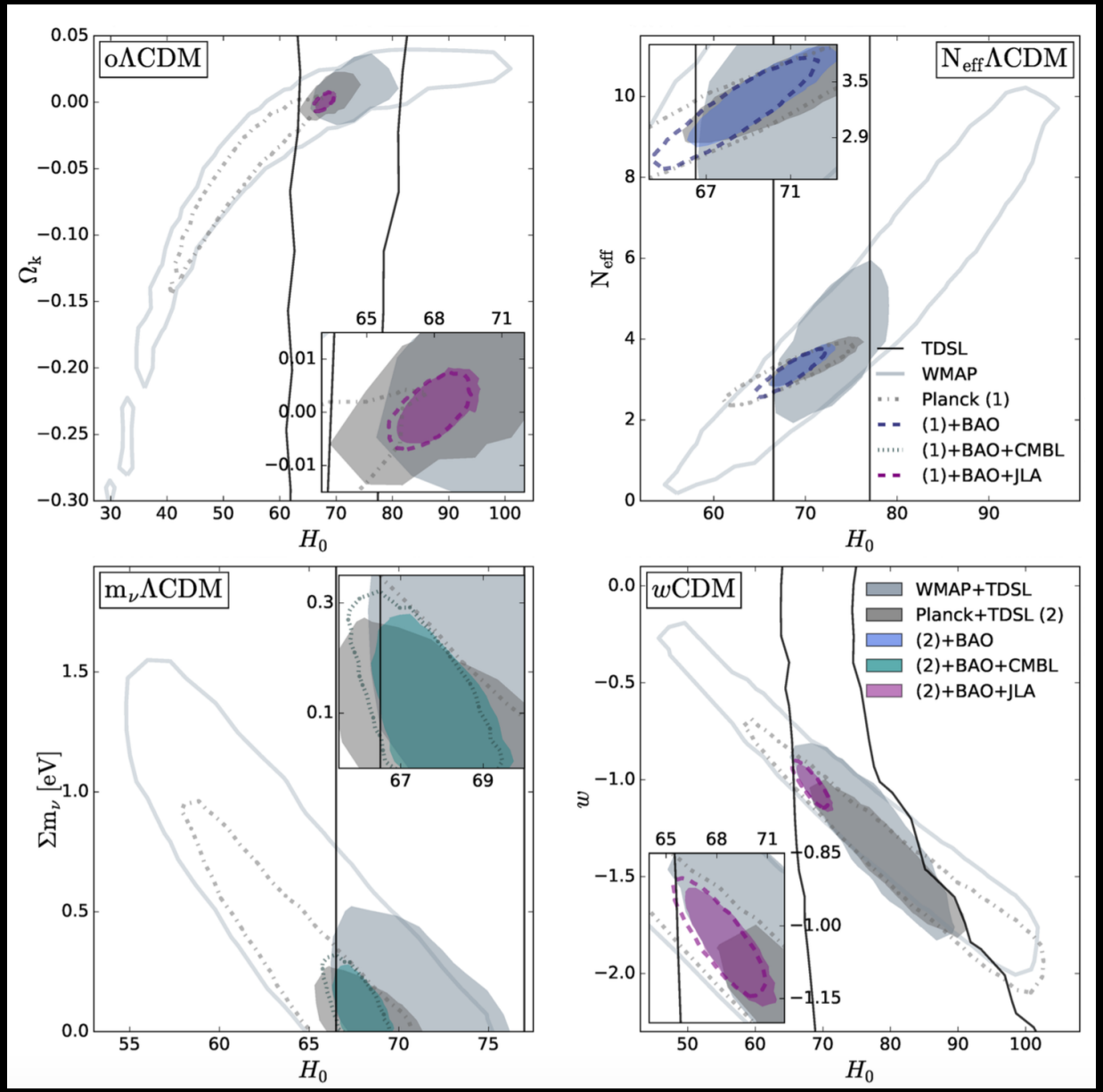
[Bonvin, Courbin, Suyu et al. 2017]

H_0 with 3 Lenses



[Riess et al. 2016]

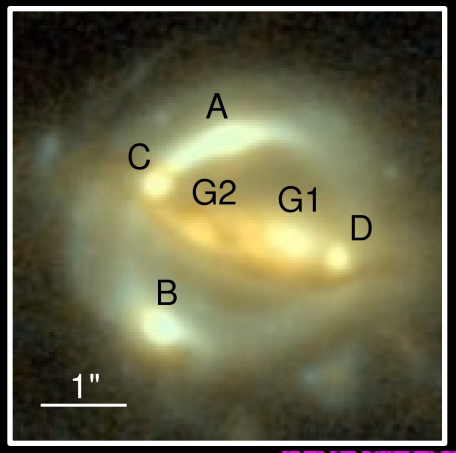
Megamasers and Lensing REALLY help



[Bonvin, Courbin, Suyu et al. 2017]

Looking forward

B1608+656



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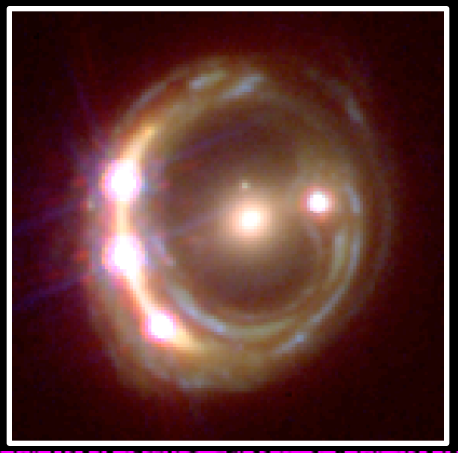

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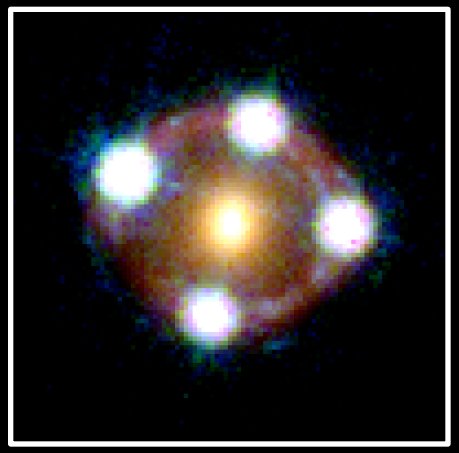

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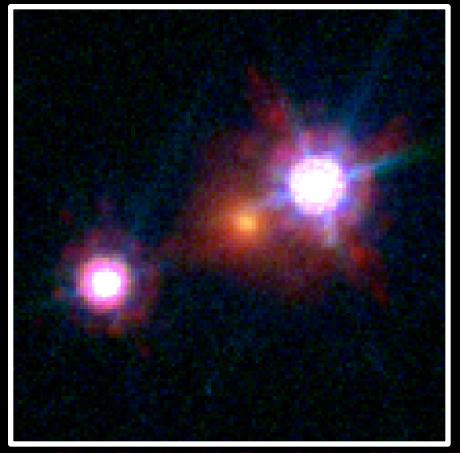


2 more H0LiCOW lenses: analysis ongoing

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

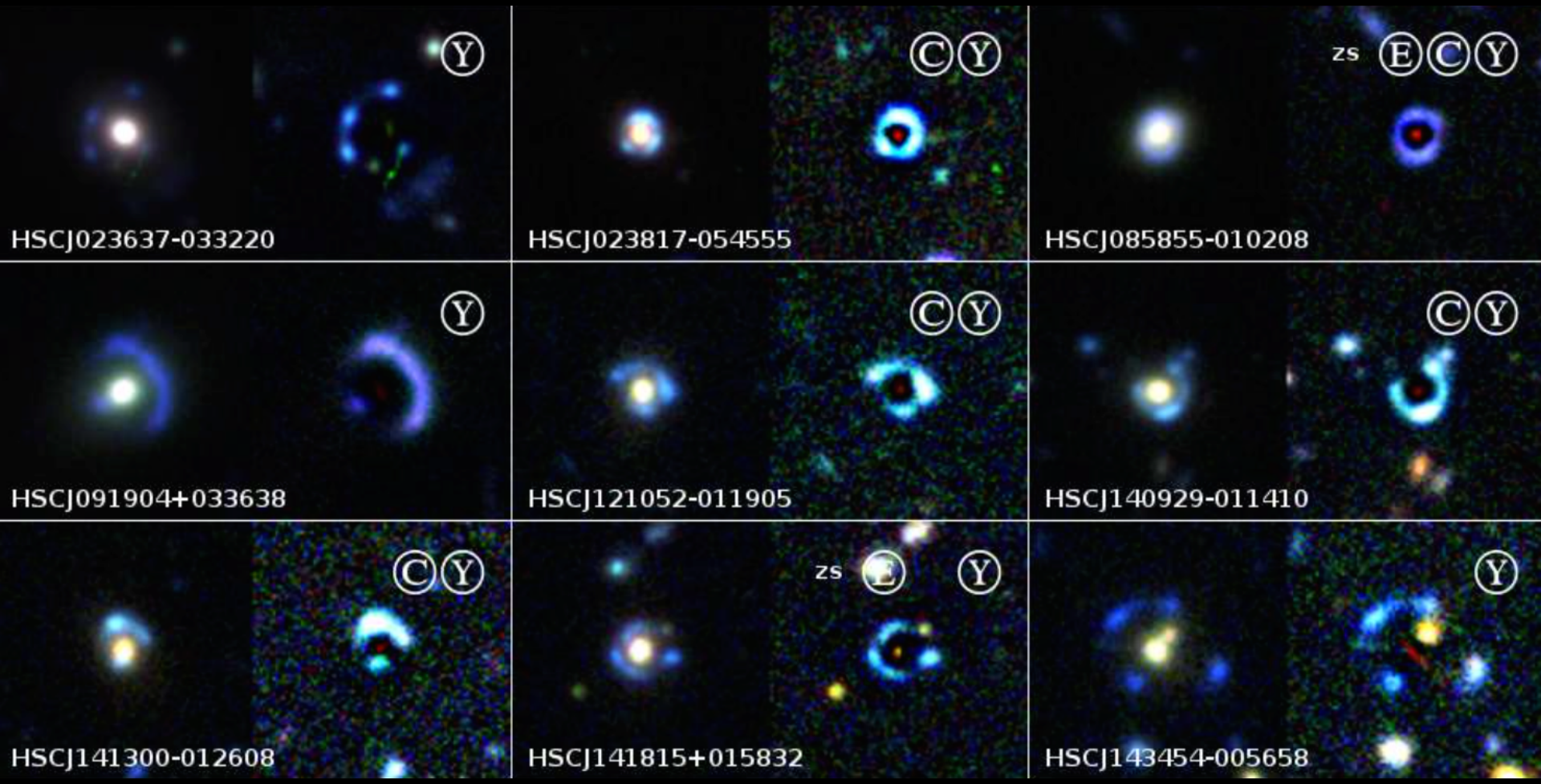


2.6m VLT Survey Telescope, Paranal, Chile

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

SuGOHI: new lenses from HSC

[Survey of Gravitationally-lensed Objects in HSC Imaging]

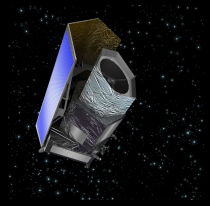


[Sonnenfeld, Chan, Shu et al. 2017]

Future Prospects

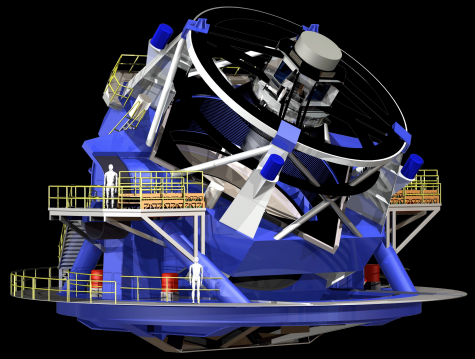
Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid



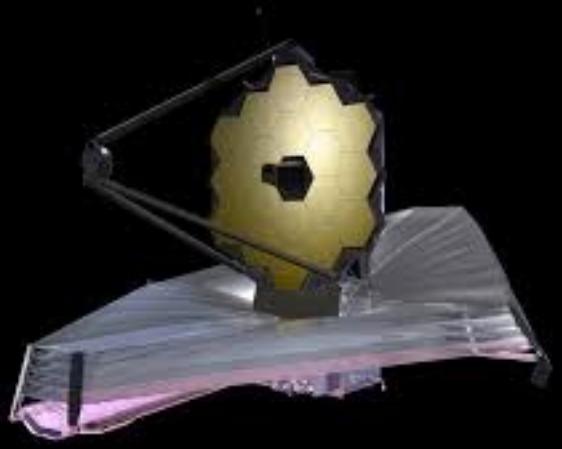
Discovery
Imaging
Spectroscopy

LSST



Discovery
Time delays
Imaging

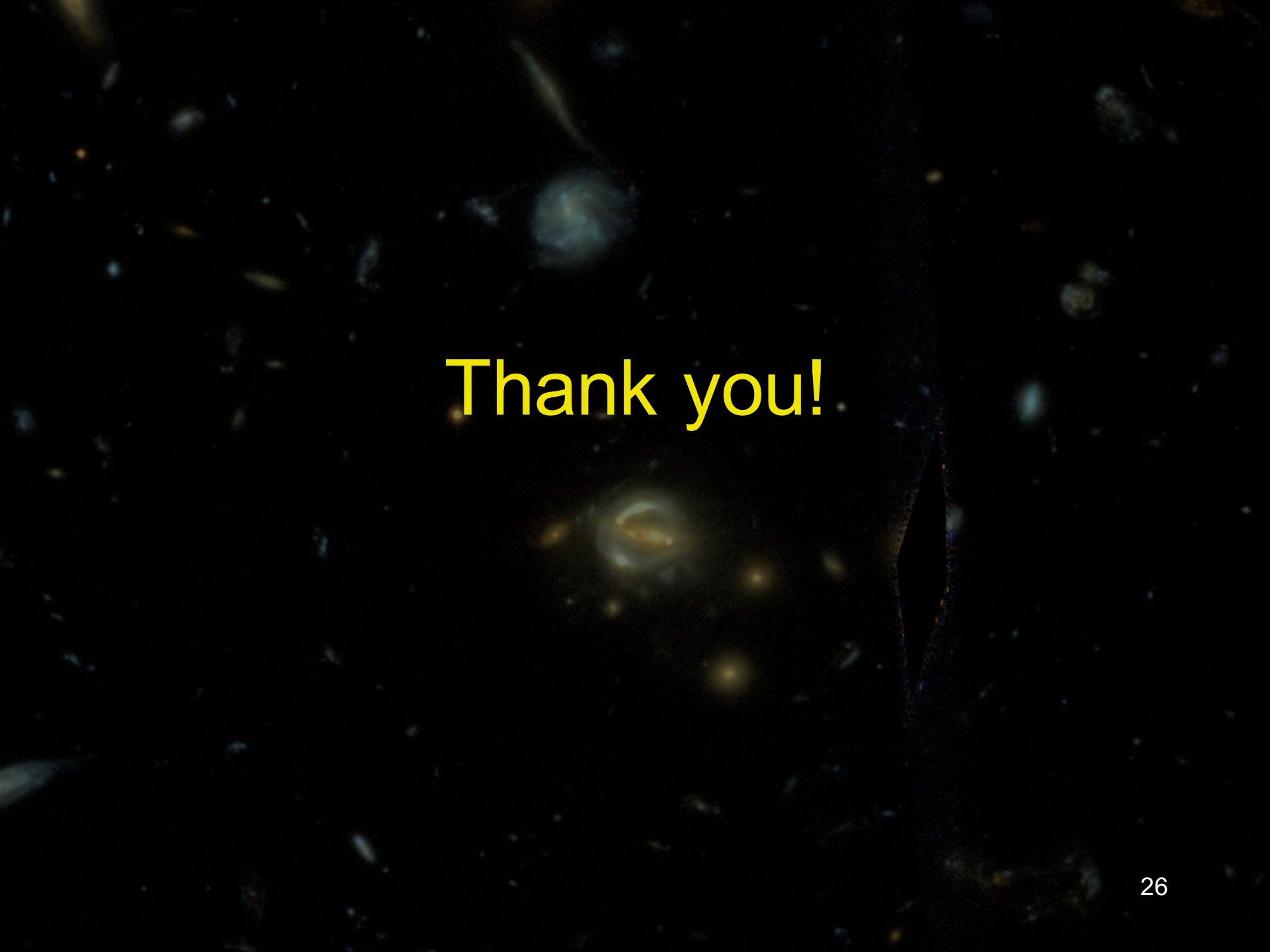
JWST



High-resolution imaging
& spectroscopy

Summary

- Current tension between H_0 from CMB and local distance ladder, indicating possible new physics beyond flat ΛCDM
- With 3 time-delay lenses:
  $H_0 = 71.9^{+2.4}_{-3.0}$ km/s/Mpc in flat ΛCDM
- H0LiCOW: H_0 to <3.5% precision from 5 lenses
- Search is underway to find new lenses in current imaging surveys including HSC, DES, KiDS
- Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology


Thank you!