Observational Cosmology and Hubble Constant

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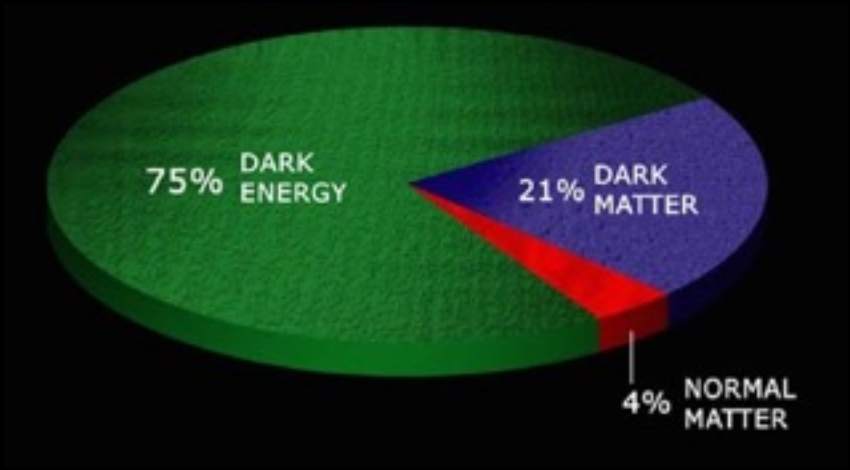
Puzzles in cosmology



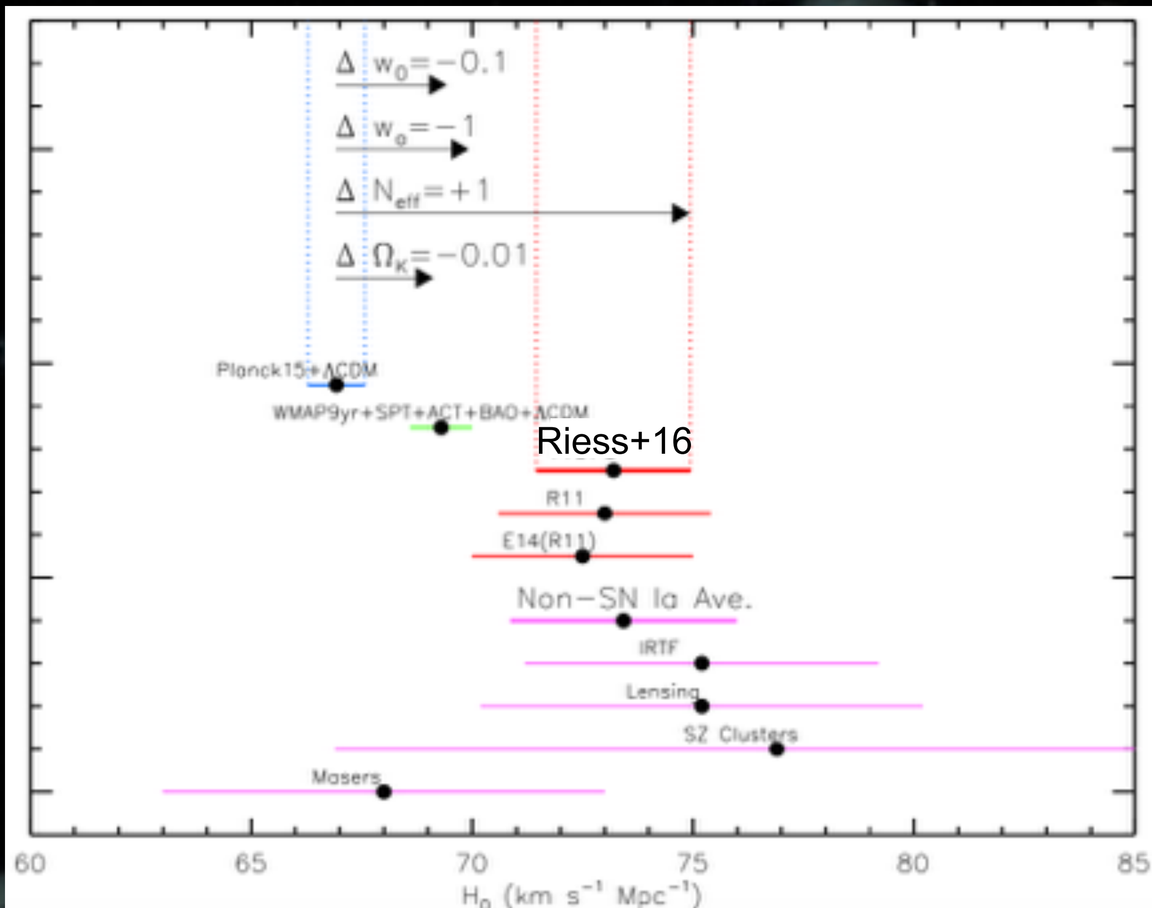
What is the nature of dark energy and dark matter?

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: $v = H_0 d$

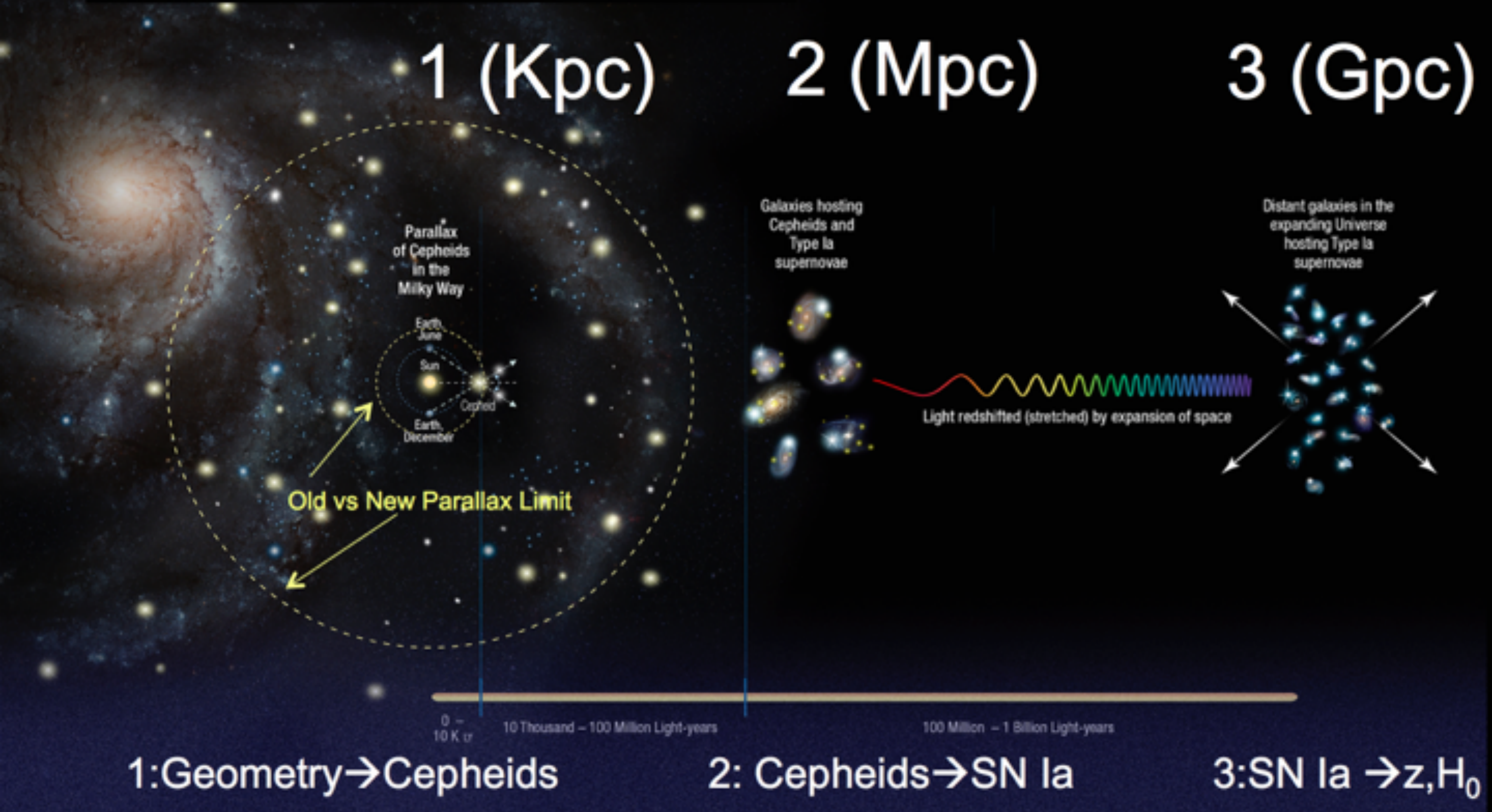
Tension? New physics?

➡ 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 ($v_{peculiar} << v_{Hubble}$)



[slide material courtesy of Adam Riess]

Distance Ladder

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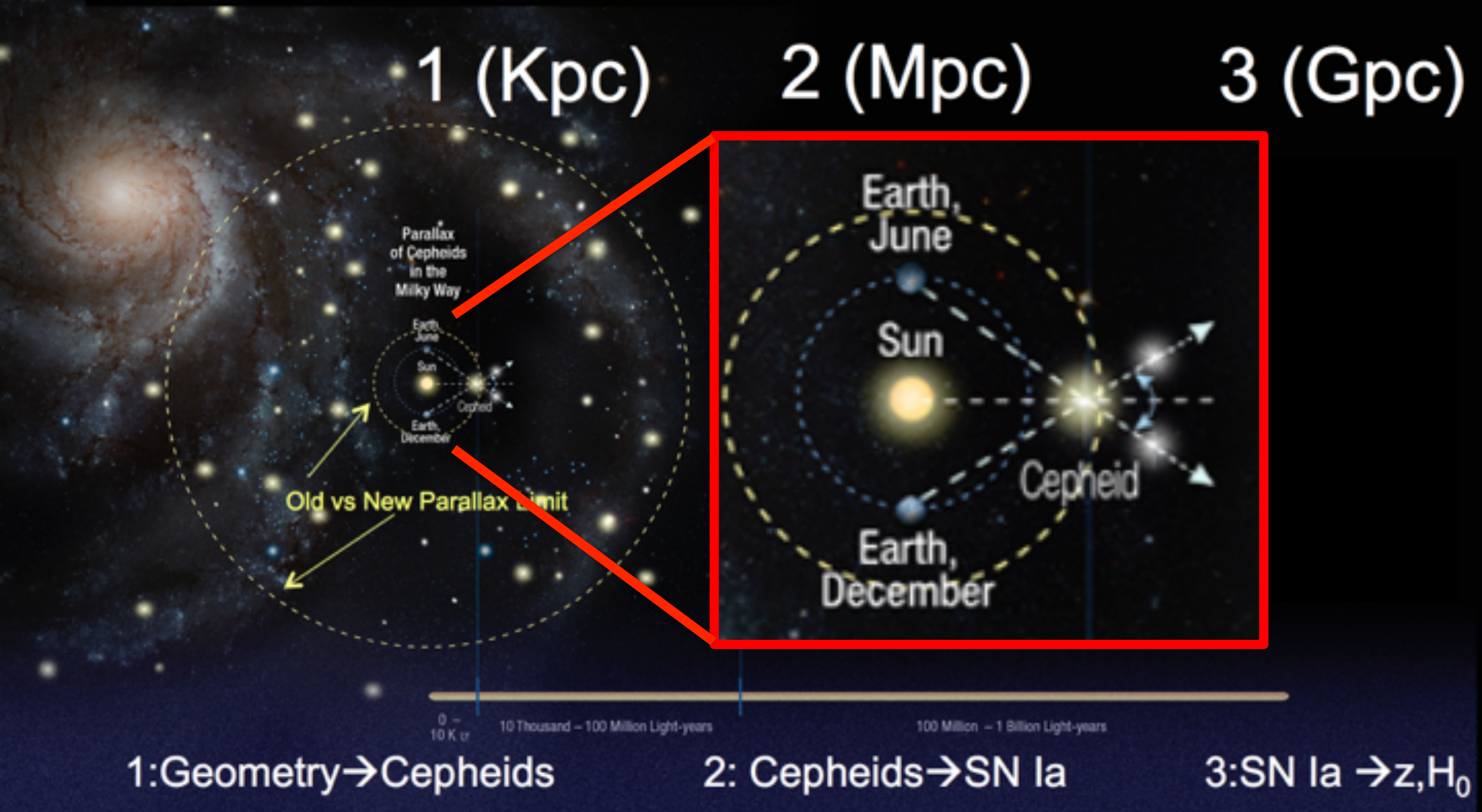

[slide material courtesy of Adam Riess]

Distance Ladder

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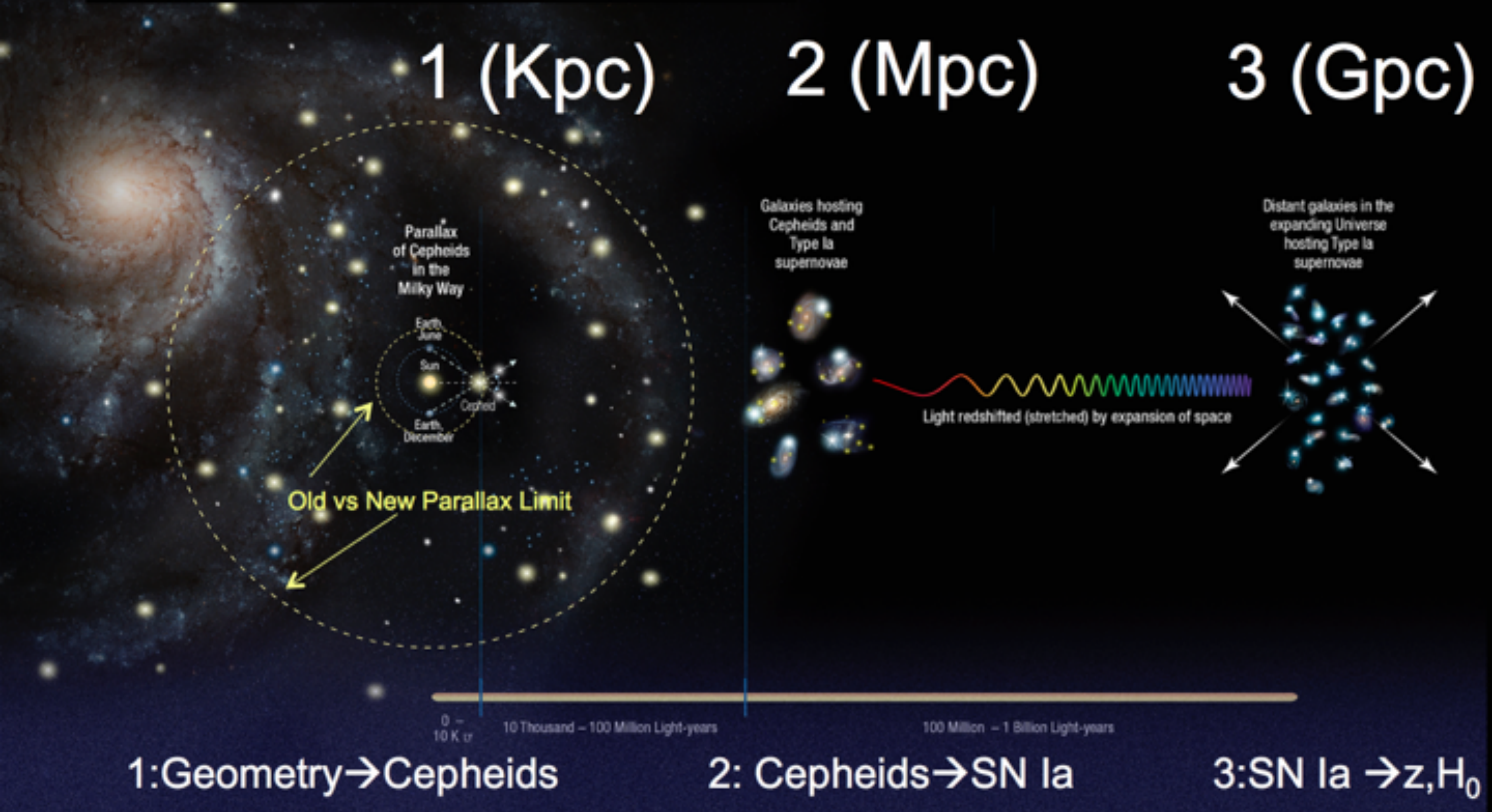


[slide material courtesy of Adam Riess]

Distance Ladder Measurements

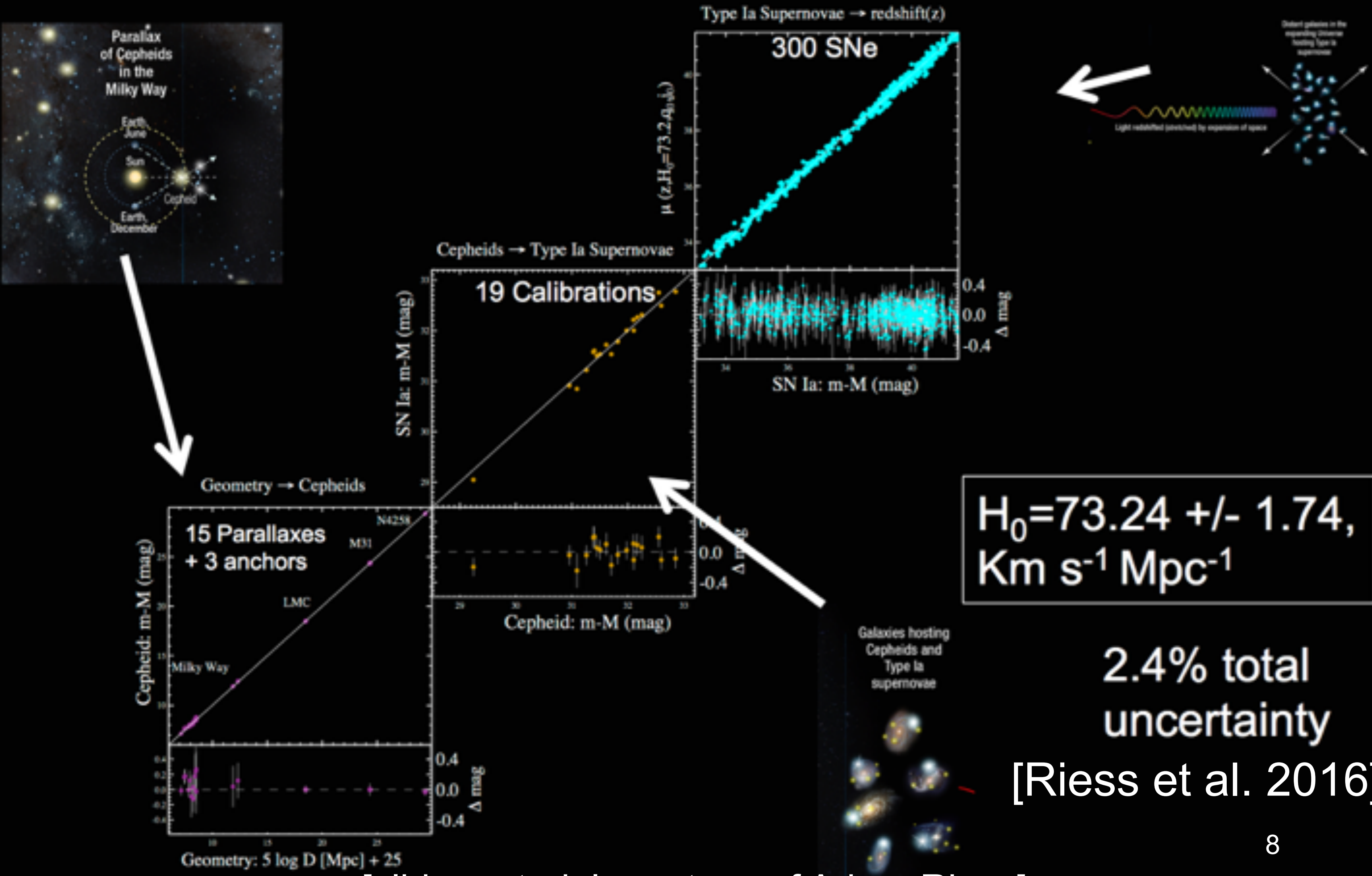
- *Hubble Space Telescope* Key Project [Freedman et al. 2001]
  - H_0 = 72 ± 8 km s^{-1} Mpc^{-1} (10% uncertainty)
  - resolving multi-decade "factor-of-two" controversy

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

- 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}

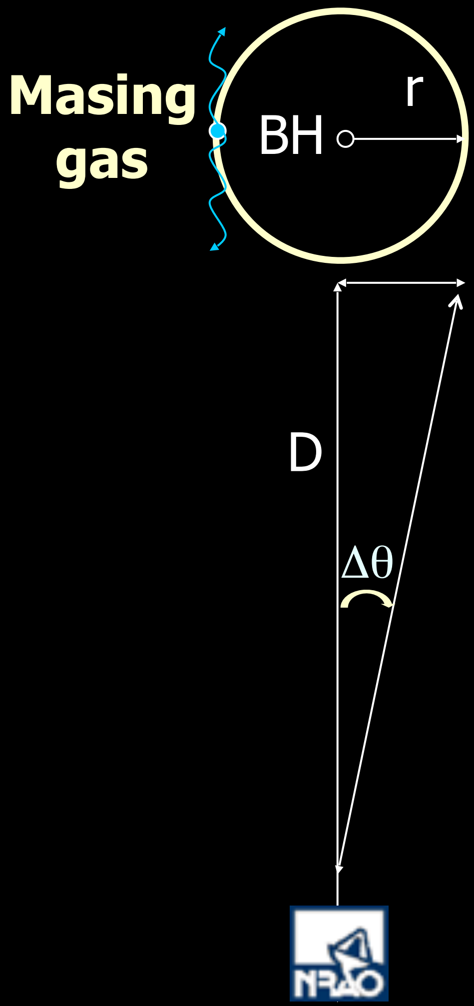
2.4% total uncertainty

[Riess et al. 2016]

[slide material courtesy of Adam Riess]

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 :

$a = V_0^2 / r$ ⟹ $r = V_0^2 / a$

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

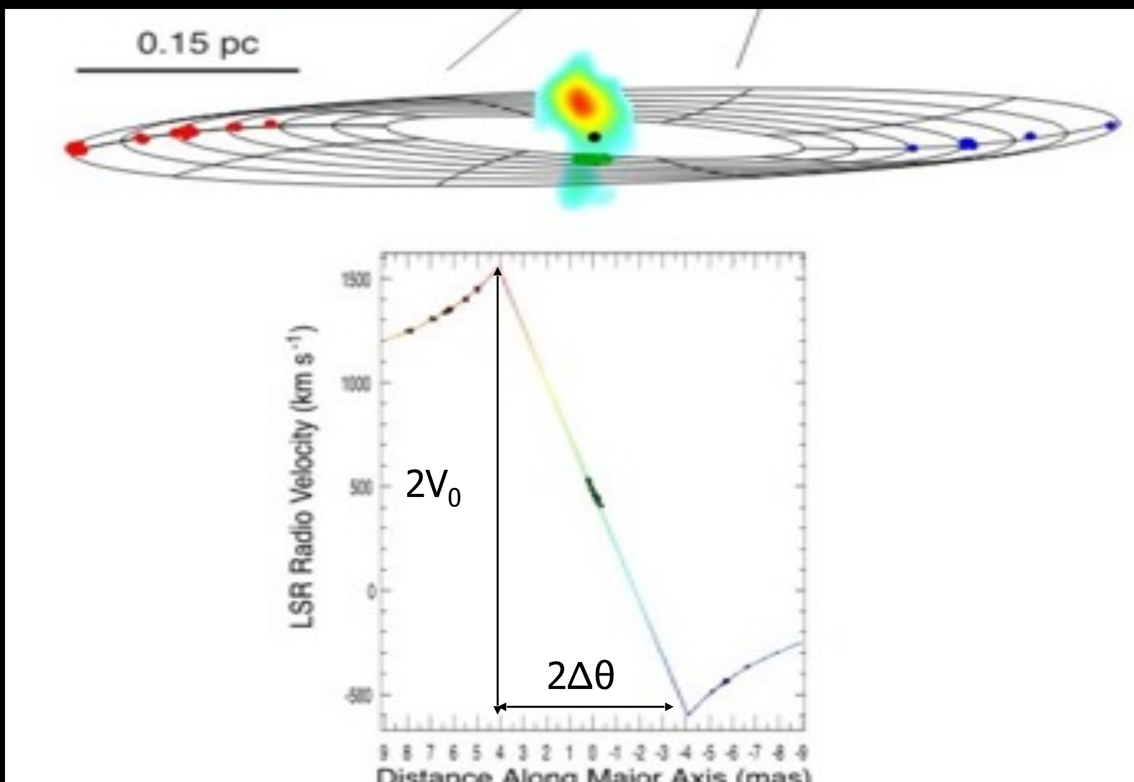
$$D = V_0^2 \sin i / a \, \Delta\theta$$

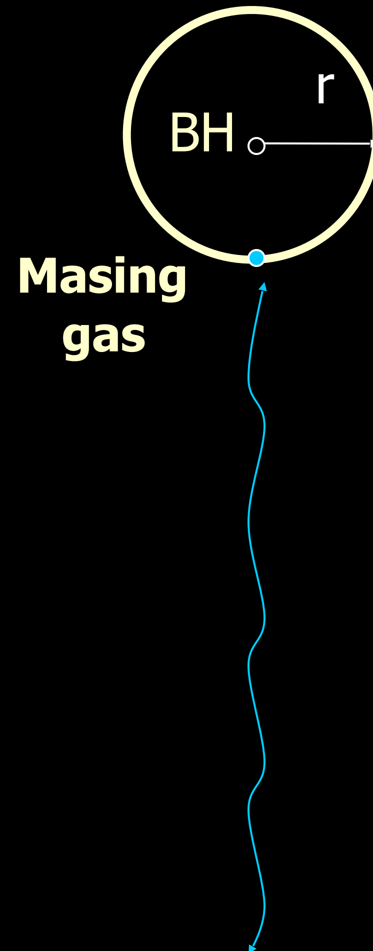
[slide material courtesy of C.-Y. Kuo]

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]

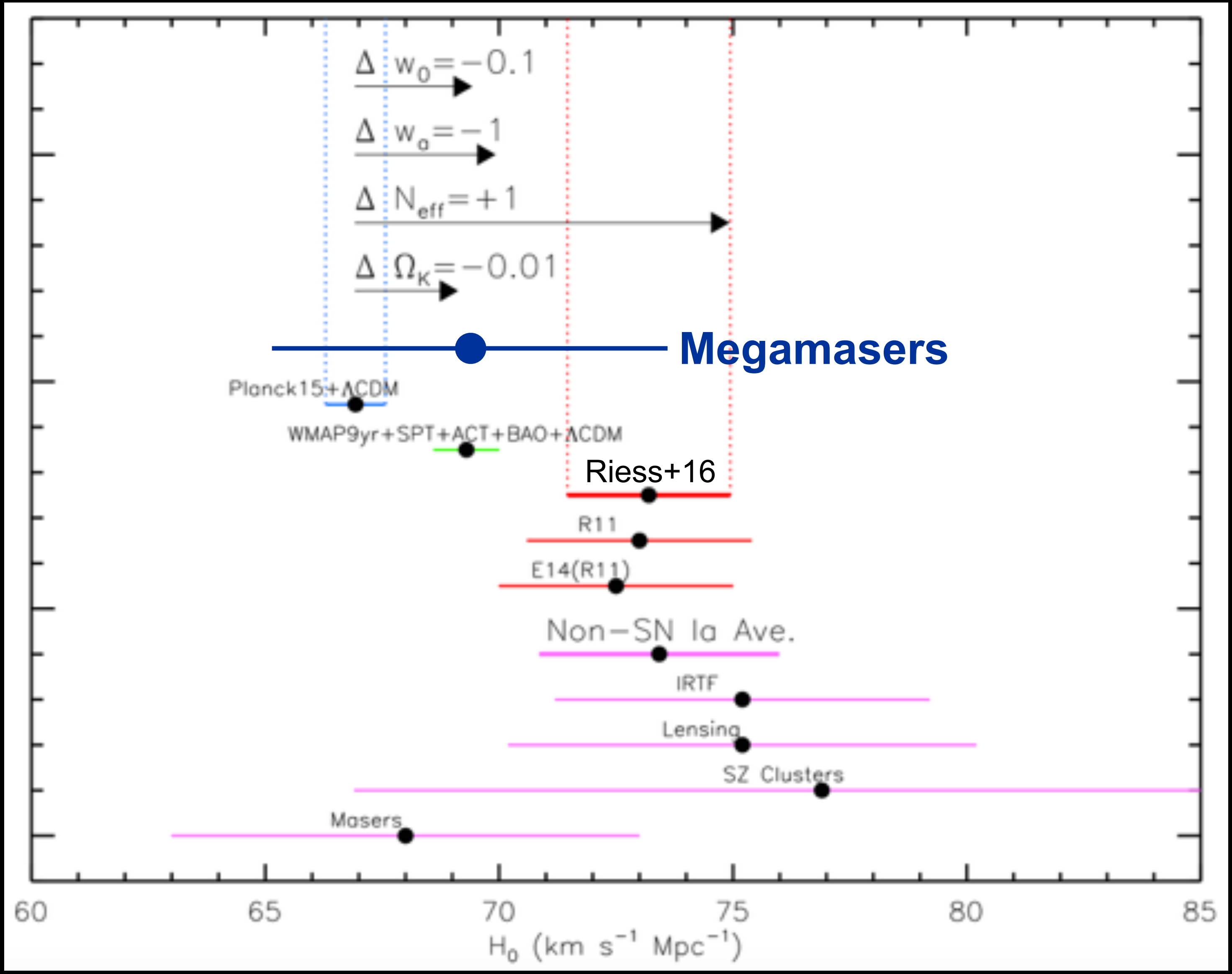
Megamaser Cosmology Project

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

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]

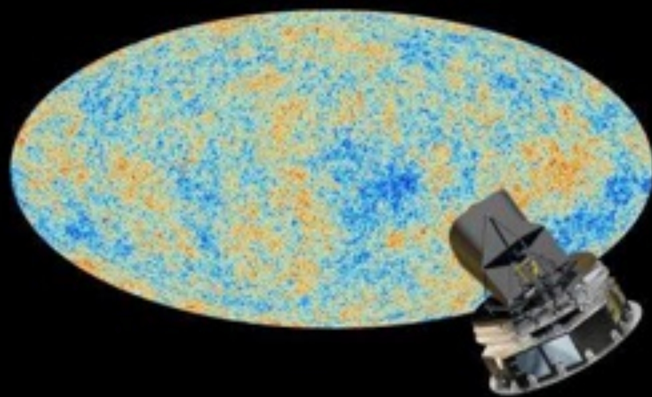
H_0 with Megamasers



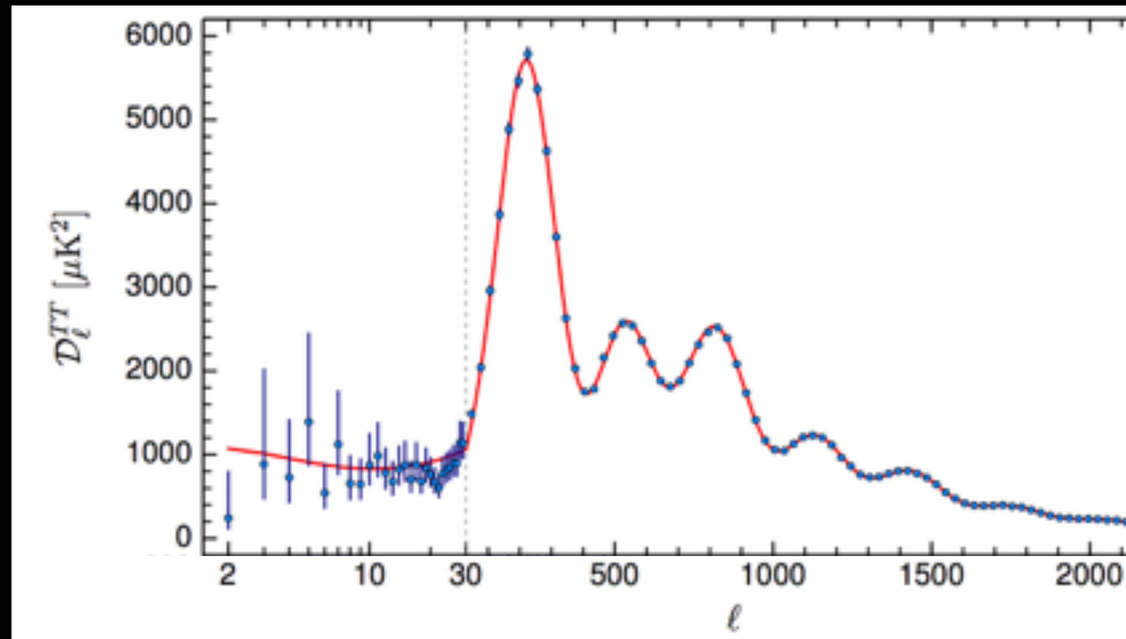
[Riess et al. 2016]

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

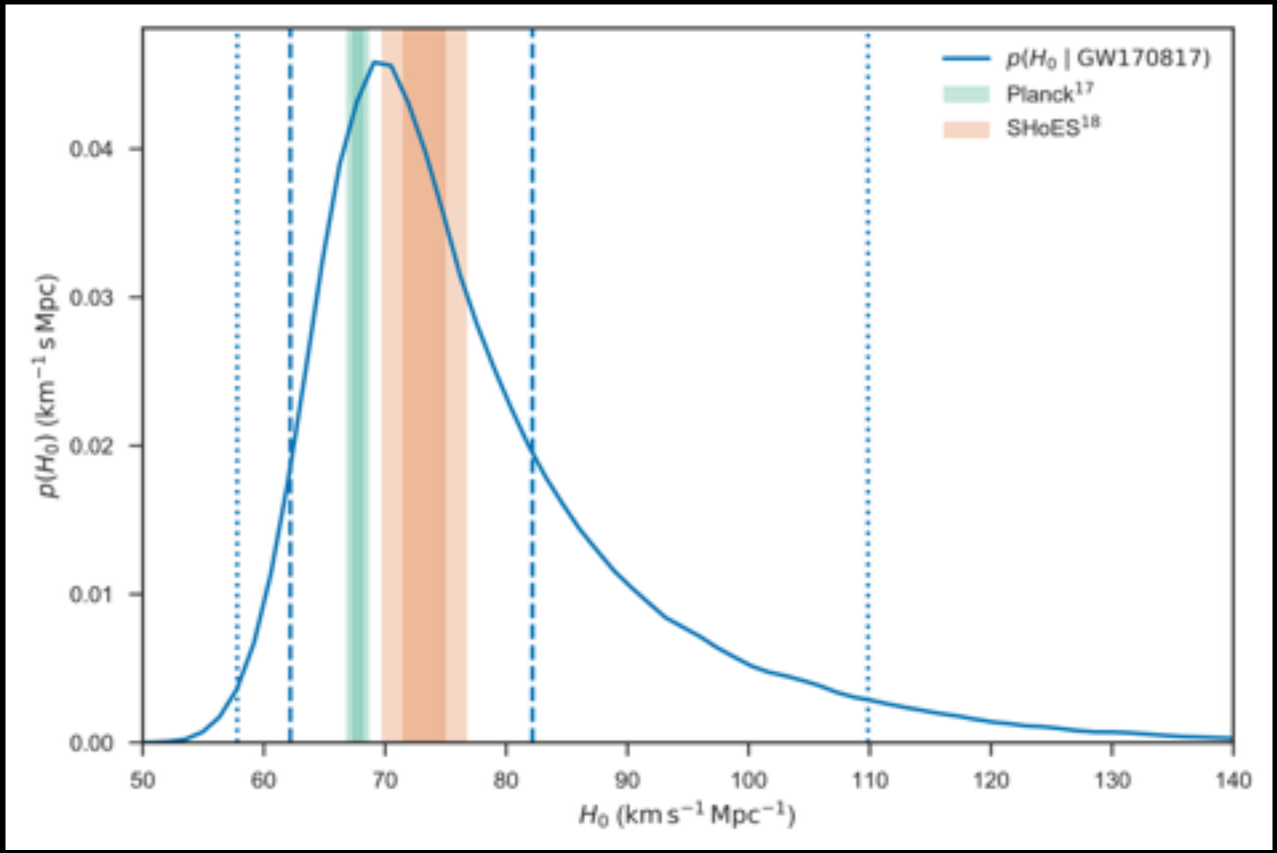
Standard Siren

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

$H_0 = v / D$

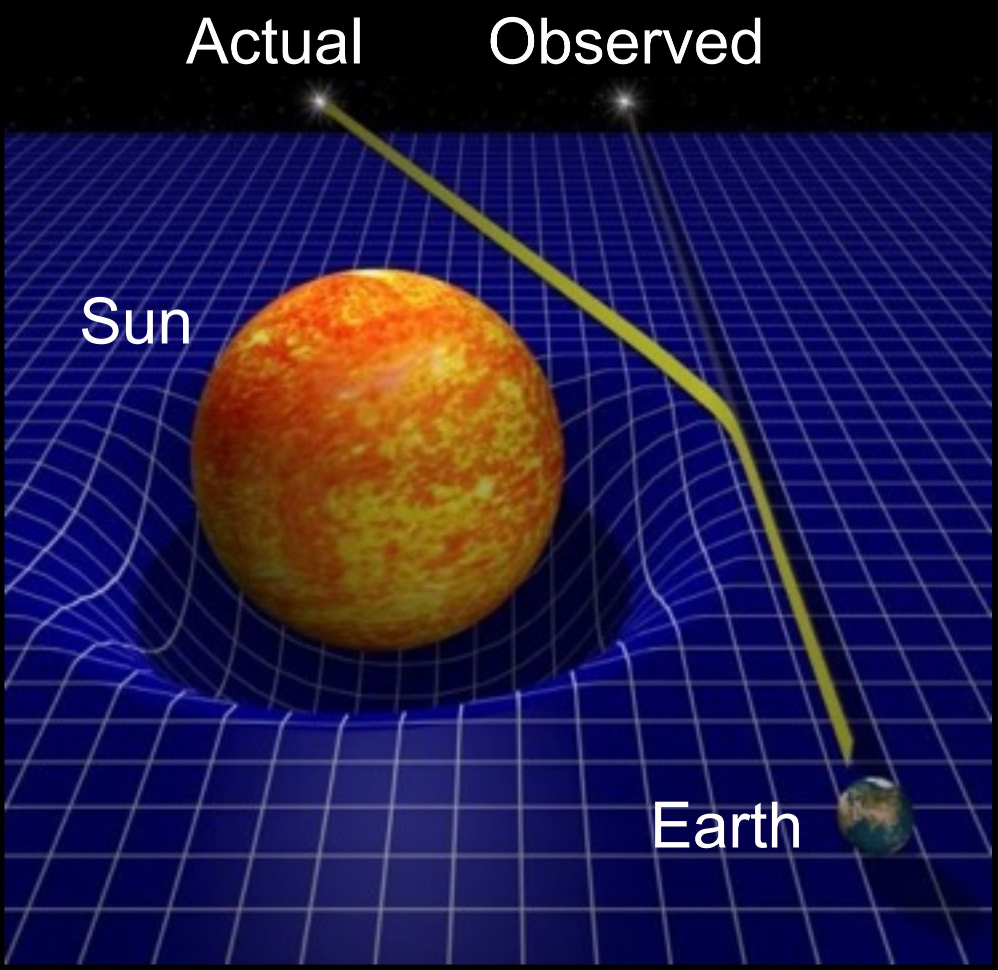
[Image credit: M. Garlick]

GW170817: First measurement of H_0



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

Gravitational Lensing



Strong Optical Lensing

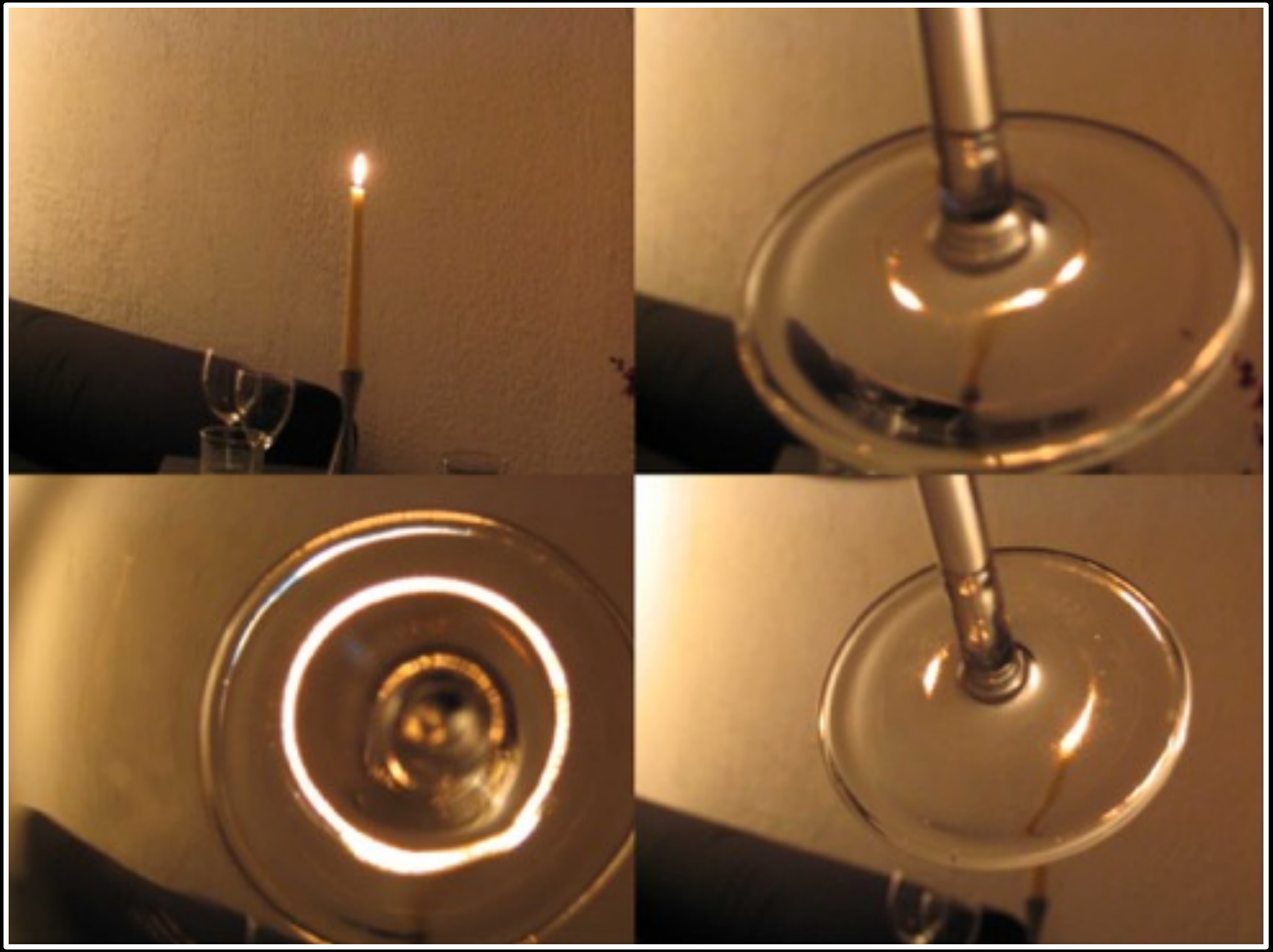
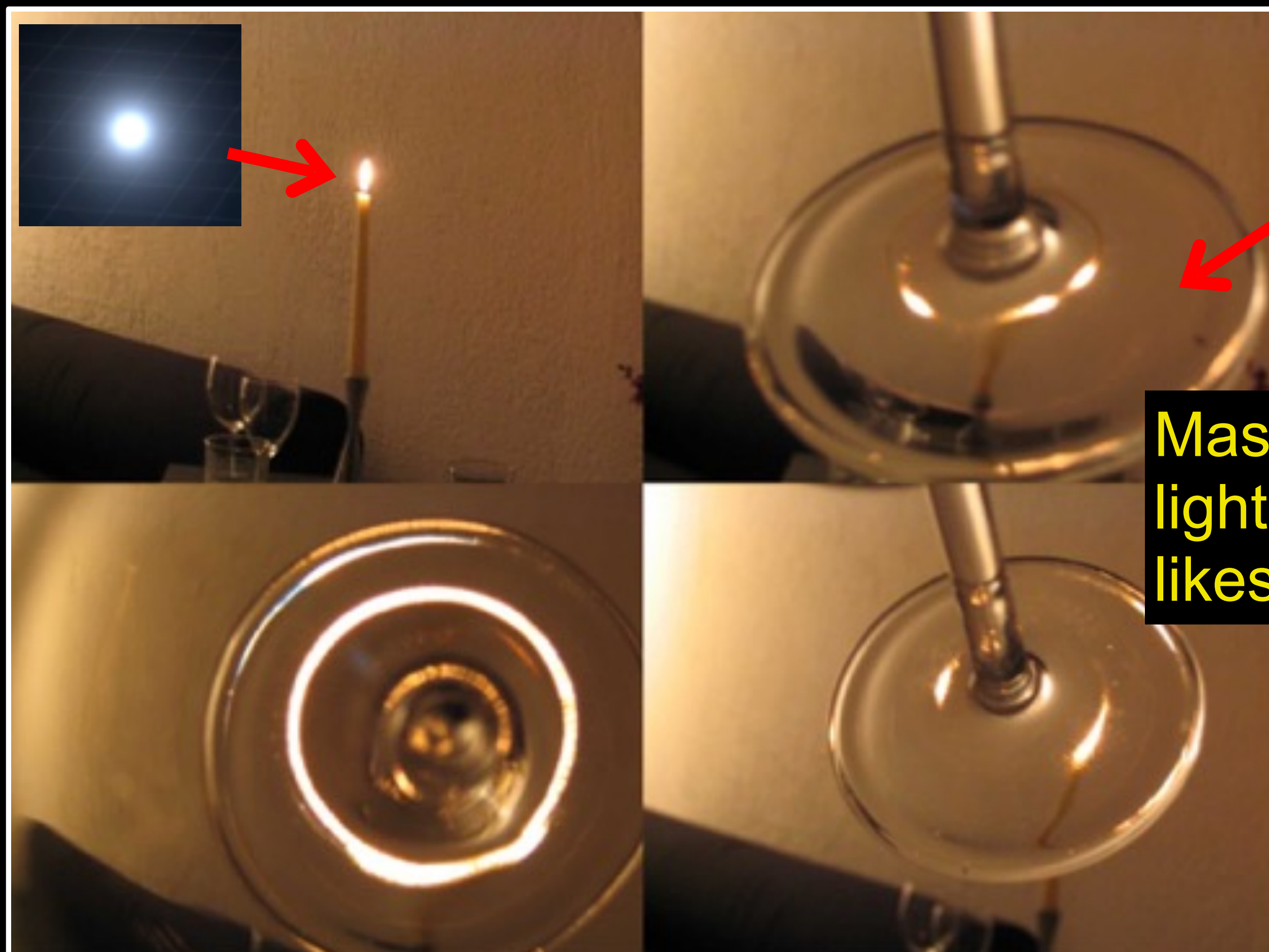


Image Credit: P. J. Marshall

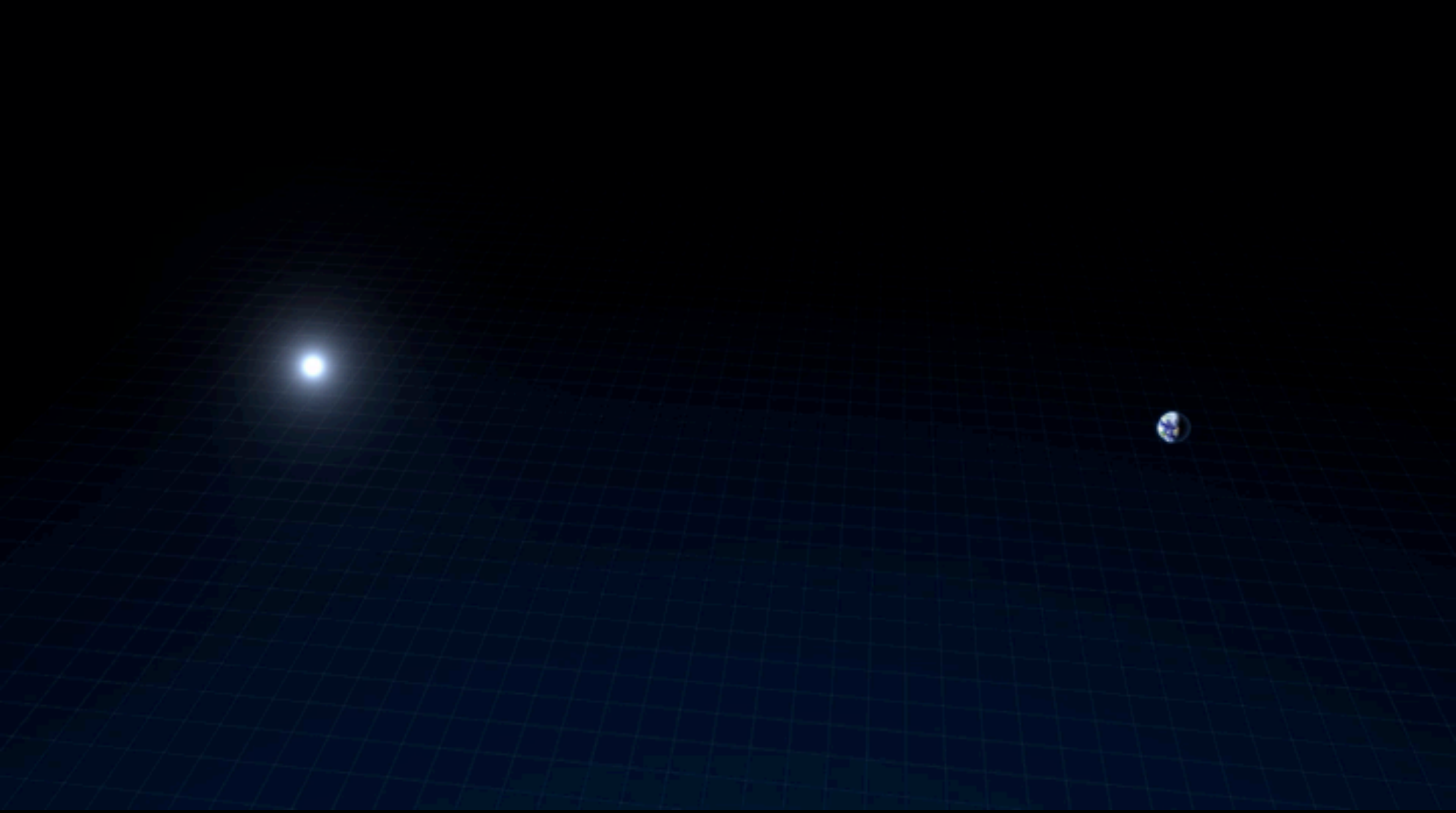
Gravitational
Strong ~~Optical~~ Lensing



Mass “bends” light and acts likes a lens

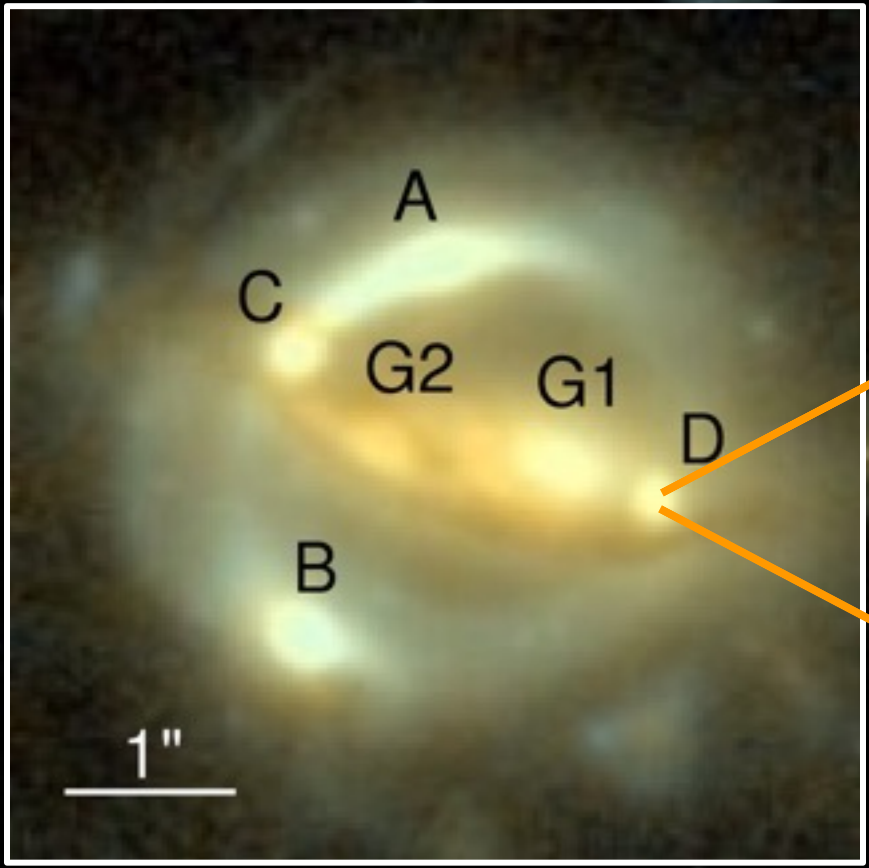
Image Credit: P. J. Marshall

Strong gravitationally lensed quasar



[Credit: ESA/Hubble, NASA]

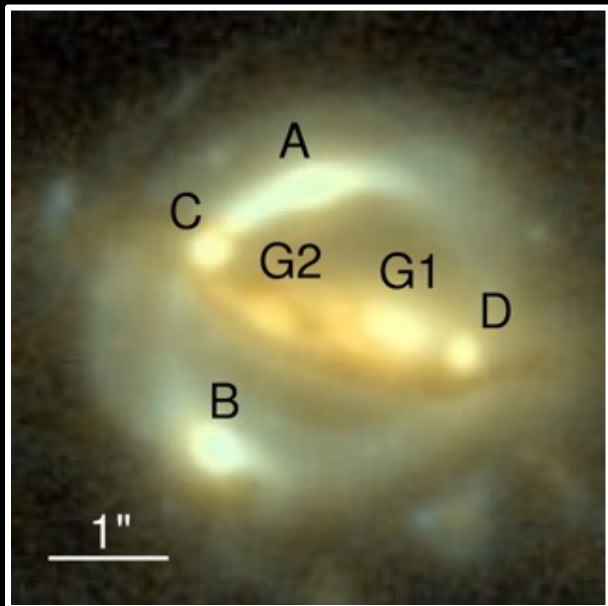
Strong Gravitational Lens with Active Galactic Nucleus

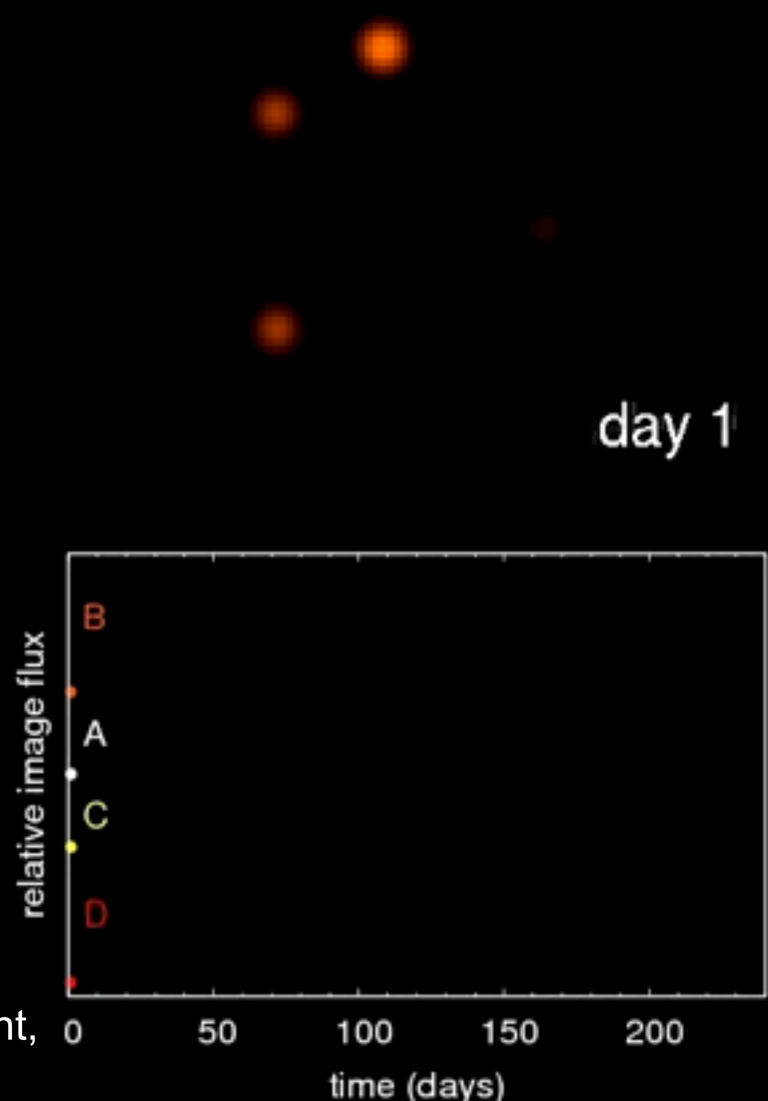


Active galactic nucleus (AGN) in the source from accretion of material onto supermassive black hole:

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

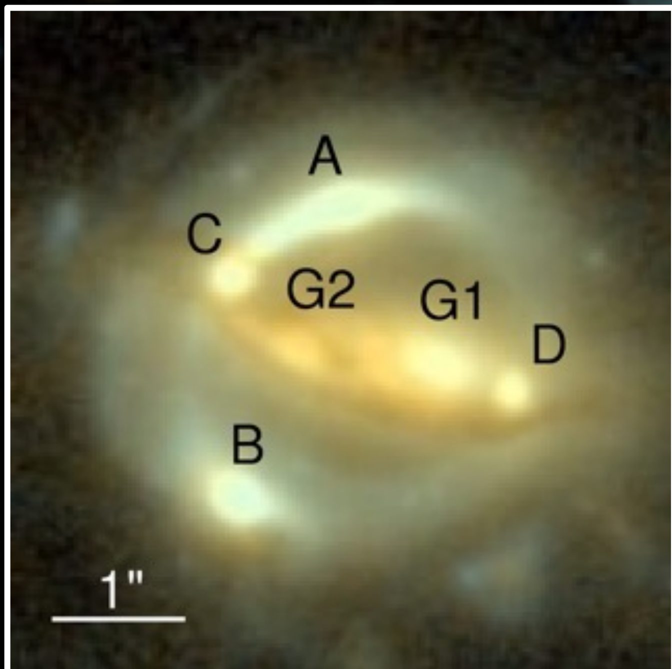
Gravitational Lens Time Delays





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

Gravitational Lens Time Delays



Time delay:

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

Time-delay distance:

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

Obtain from lens mass model

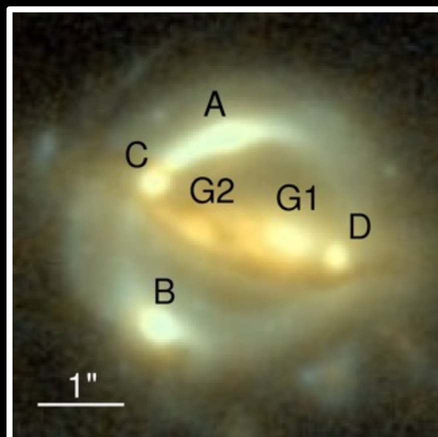
For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

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

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

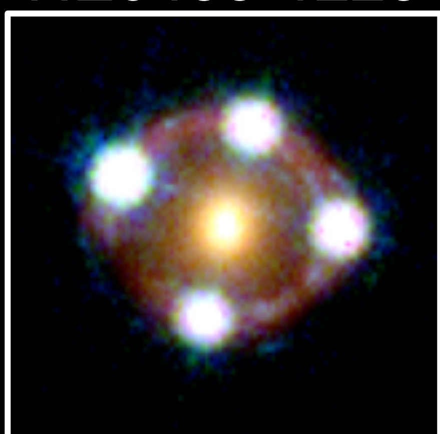
B1608+656



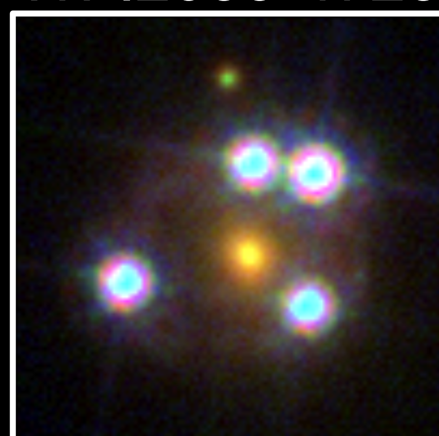
RXJ1131-1231

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

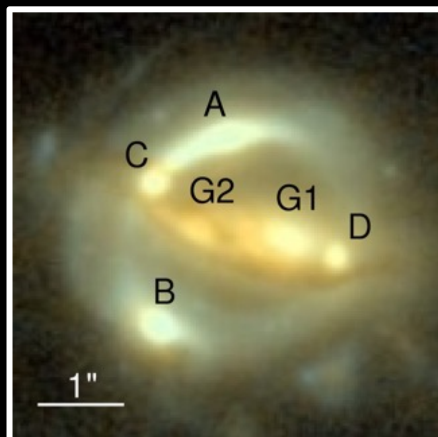
H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

completed

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

B1608+656



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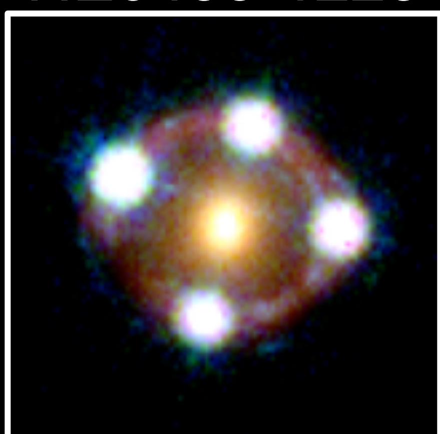

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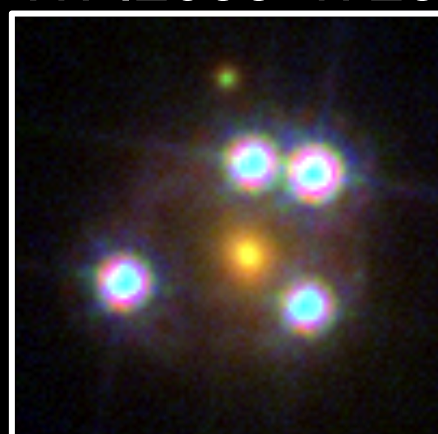
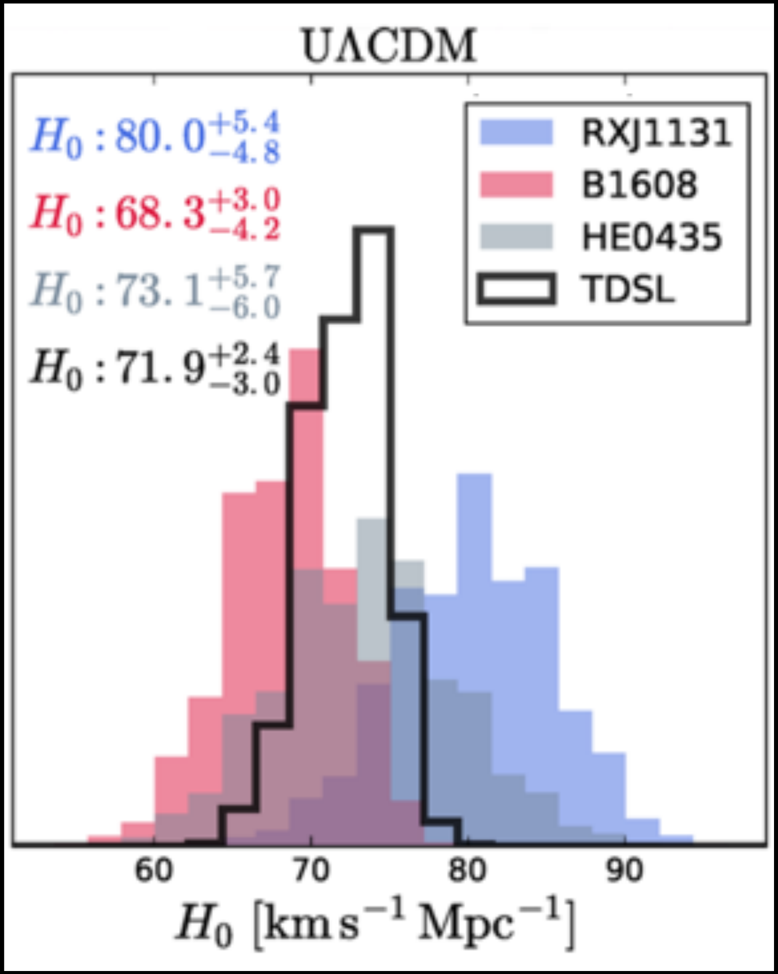


HE1104-1805

ongoing

H_0 from 3 strong lenses



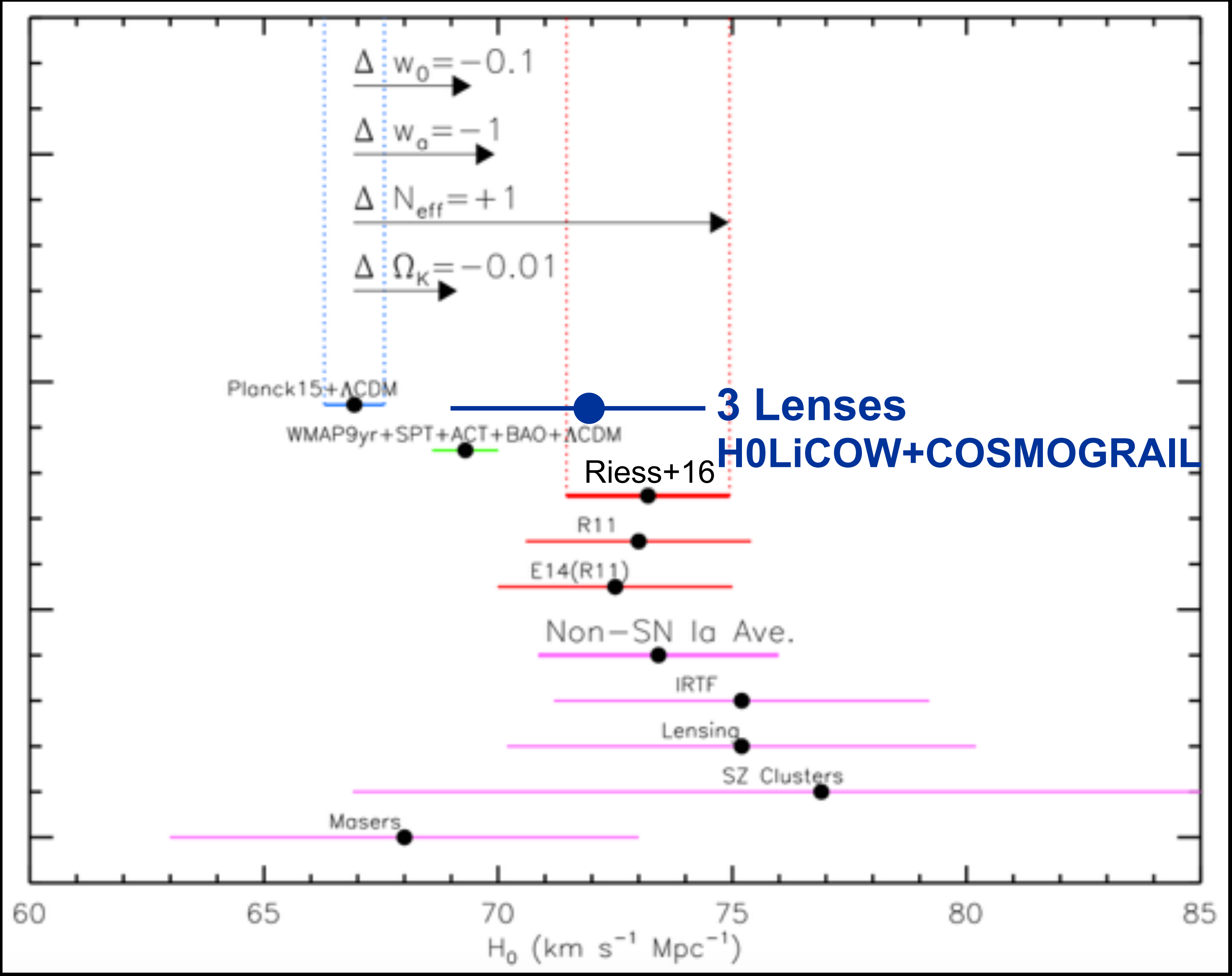
Blind analysis to avoid confirmation bias

$H_0 \in [0,150]$ 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]

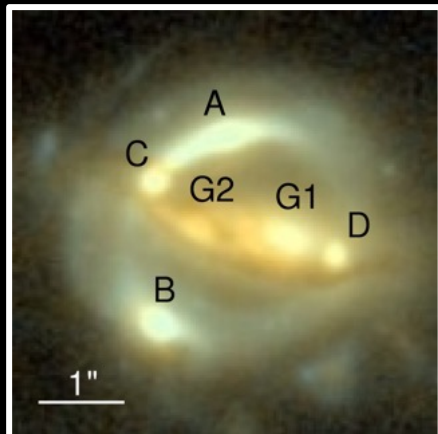
H_0 with 3 Lenses



[Riess et al. 2016]

Looking forward

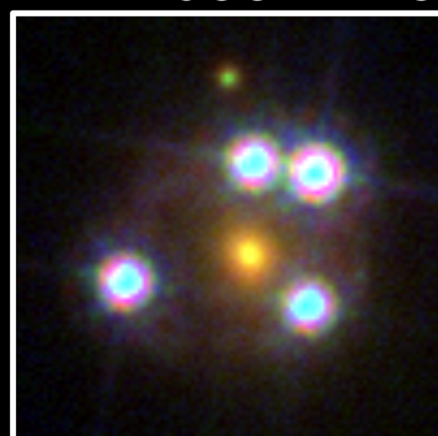
B1608+656



RXJ1131-1231

HE0435-1223

WFI2033-4723



HE1104-1805

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]

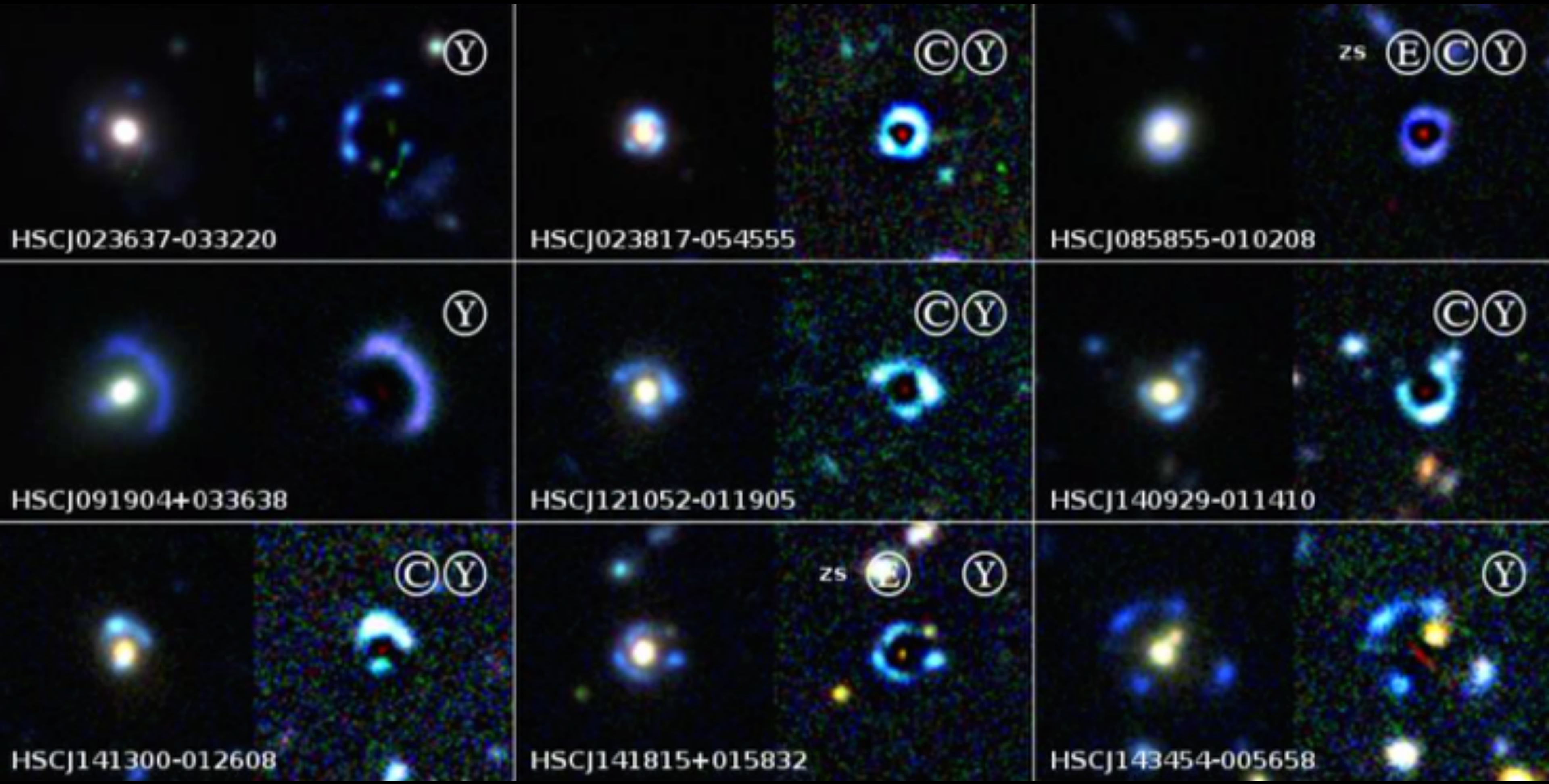
Kilo Degree Survey

2.6m VLT Survey Telescope, Paranal, Chile

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

SuGOHI: new lenses from HSC

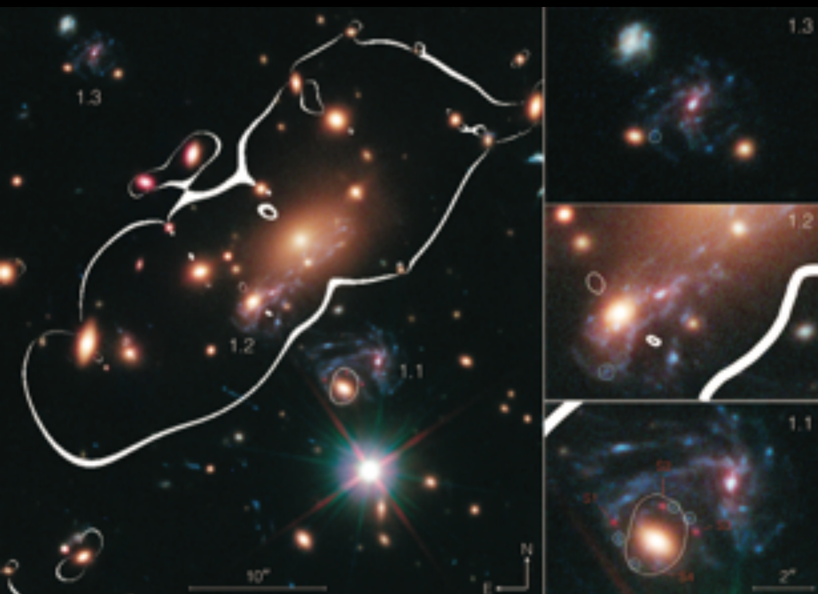
[Survey of Gravitationally-lensed Objects in HSC Imaging]

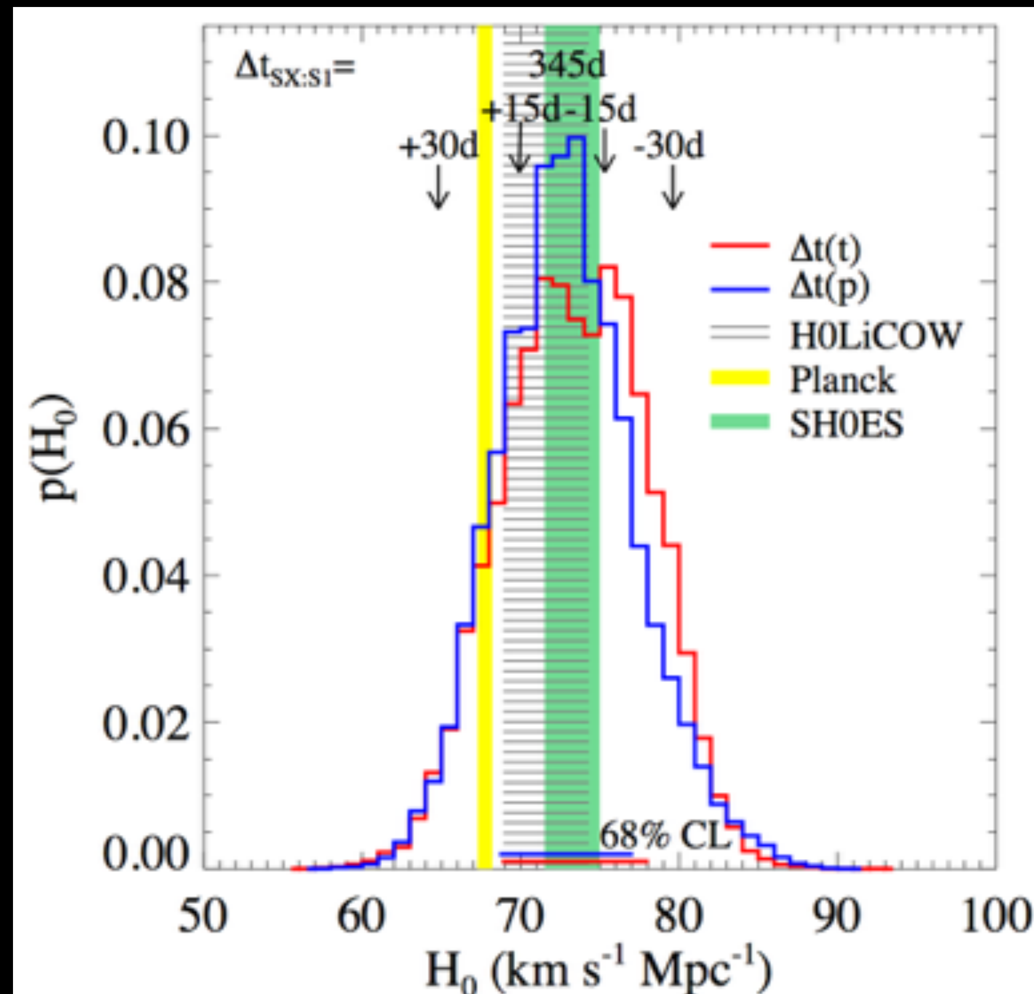


[Sonnenfeld, Chan, Shu et al. 2017]

First strongly lensed supernova!

feasibility study of using Supernova Refsdal for H_0 measurement





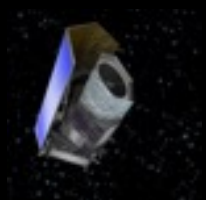
- S1-S2-S3-S4 delays from Rodney et al. (2016)
- SX-S1 delay estimated based on detection in Kelly et al. (2016)

[Grillo, Rosati, Suyu et al. 2018]

Future Prospects

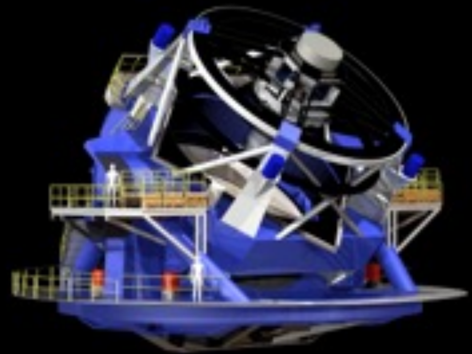
Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid



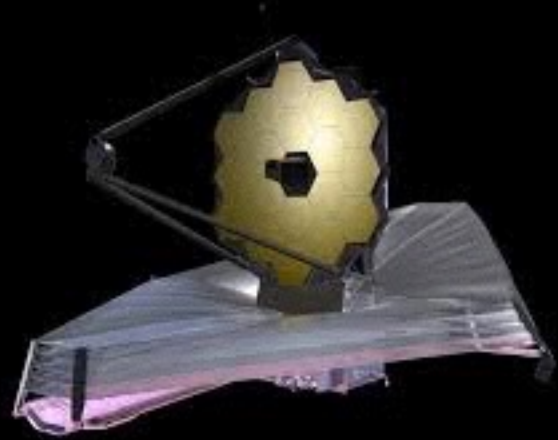
Discovery
Imaging
Spectroscopy

LSST



Discovery
Time delays
Imaging

JWST

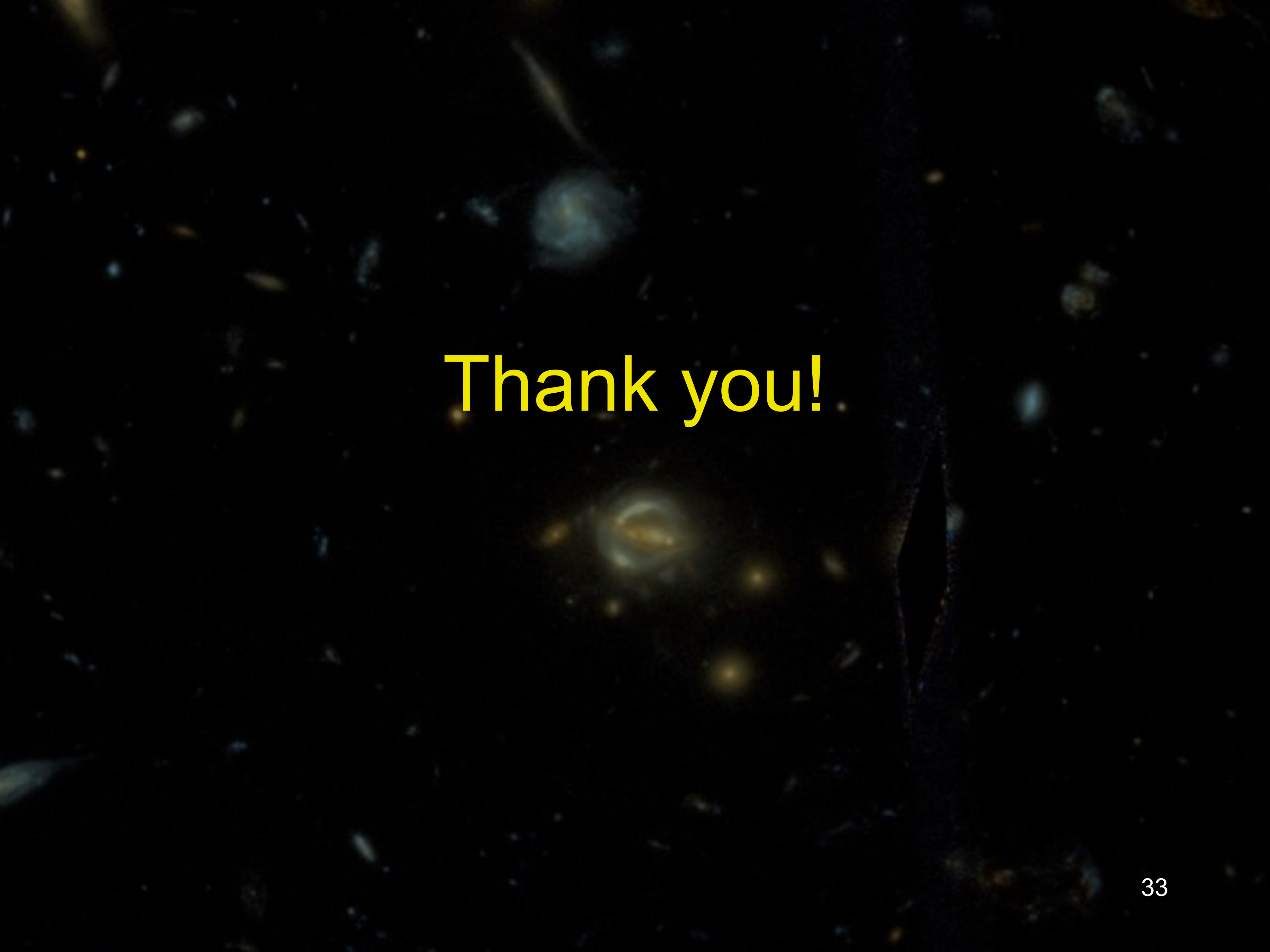


High-resolution imaging
& spectroscopy

Summary

- 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!