Hubble Constant at the Late Universe

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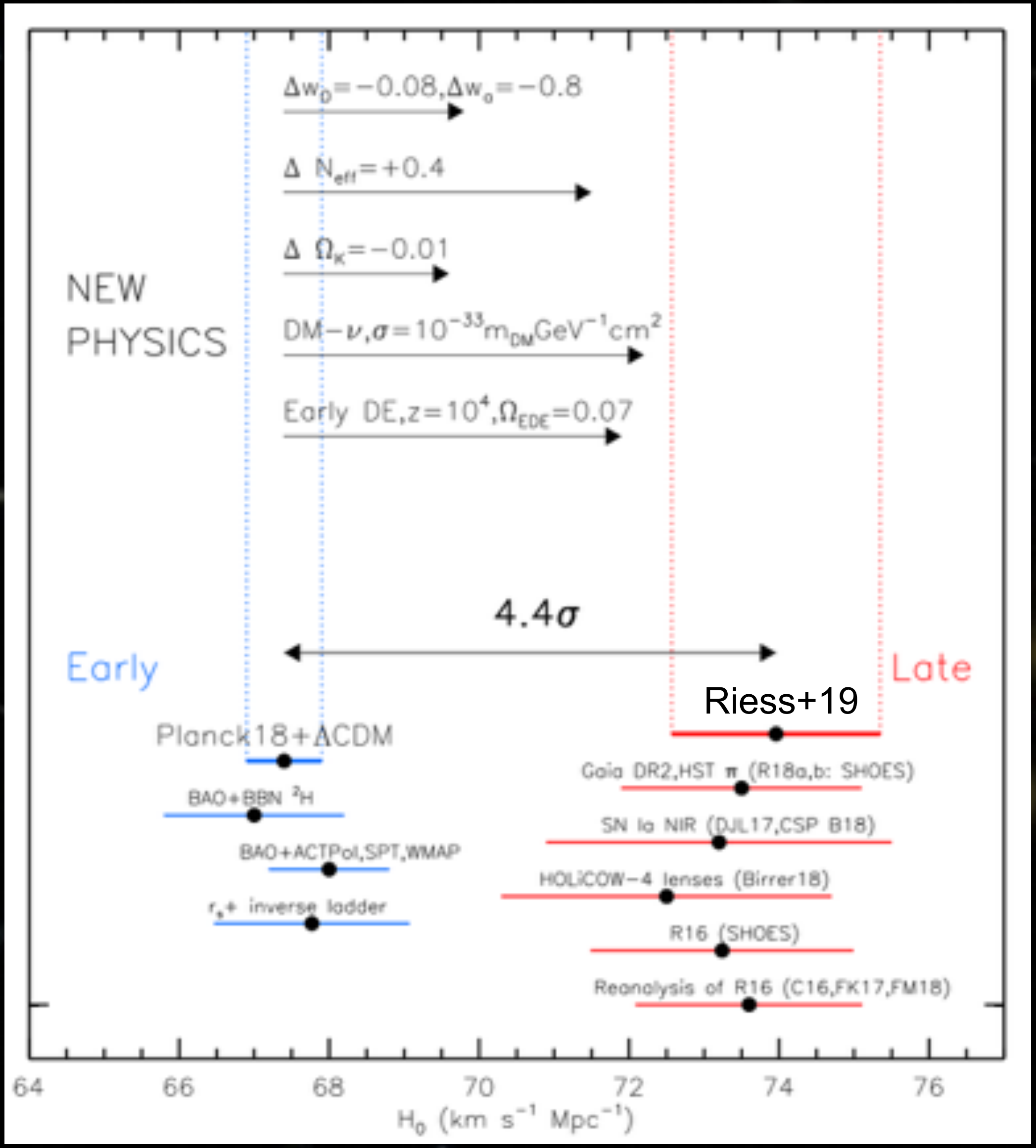
European Research Council

Hubble tension



[Riess et al. 2019]

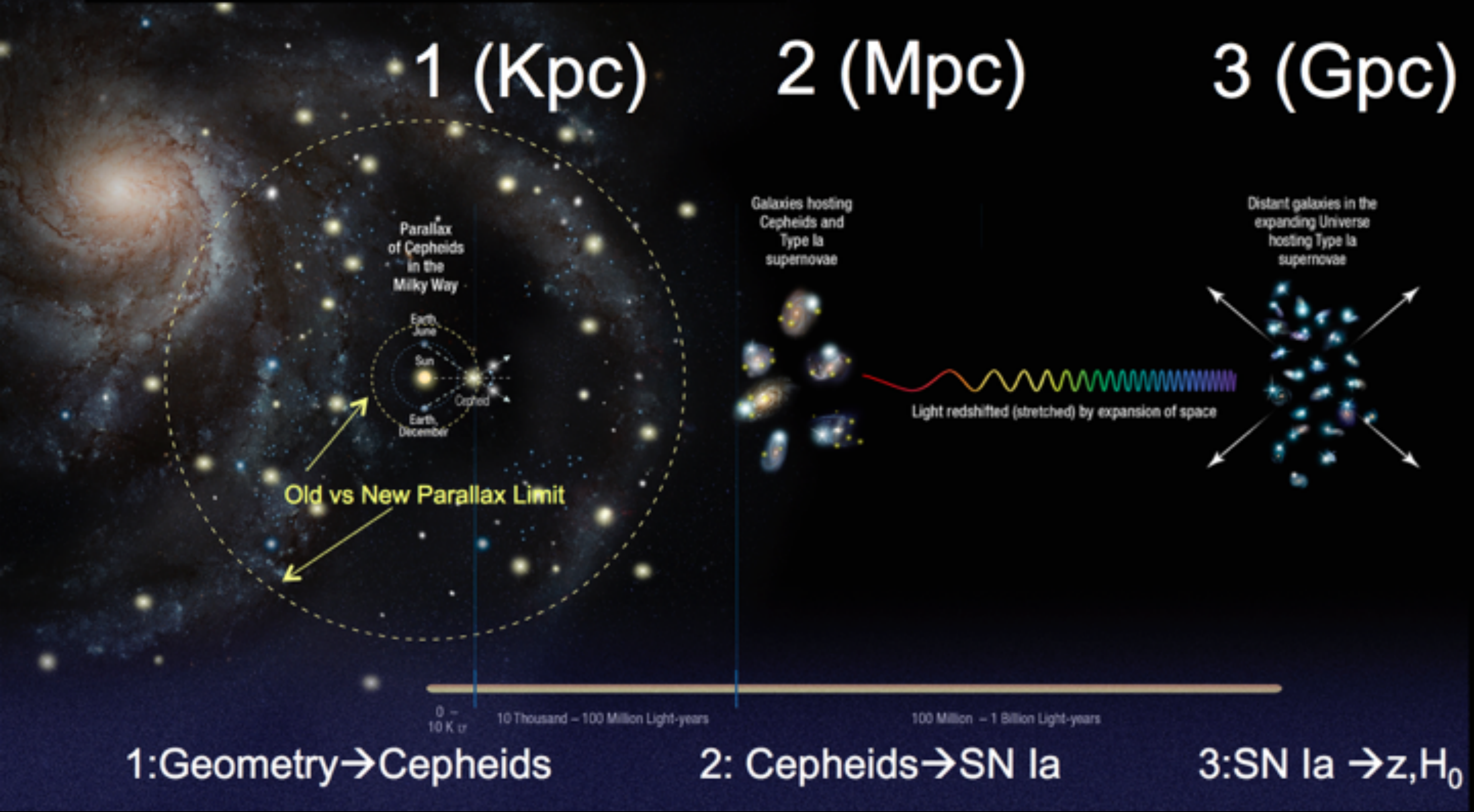
Hubble constant H_0
- age, size of the Universe
- expansion rate: $v = H_0 d$

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

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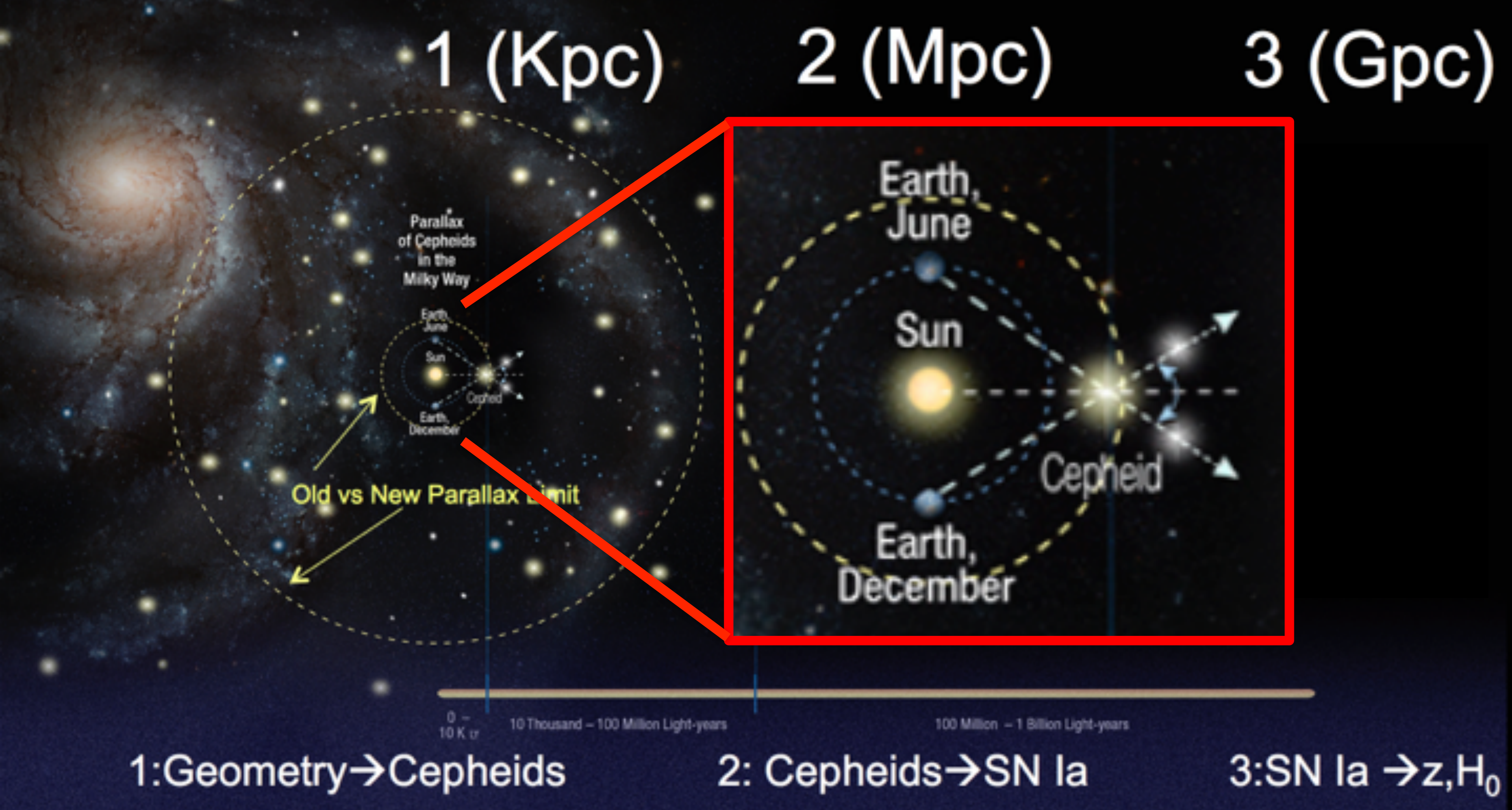

[slide material courtesy of Adam Riess]

Distance Ladder

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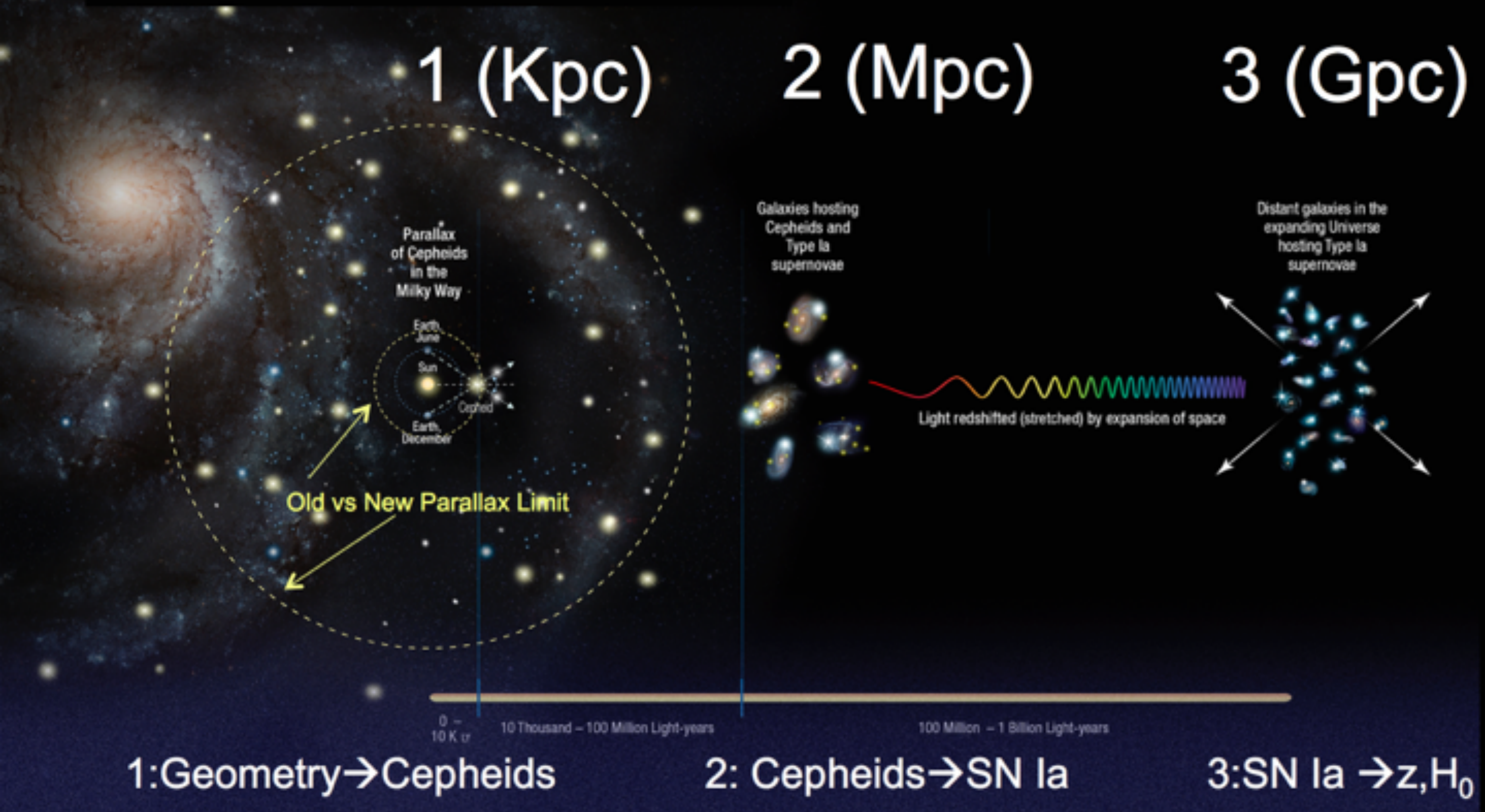


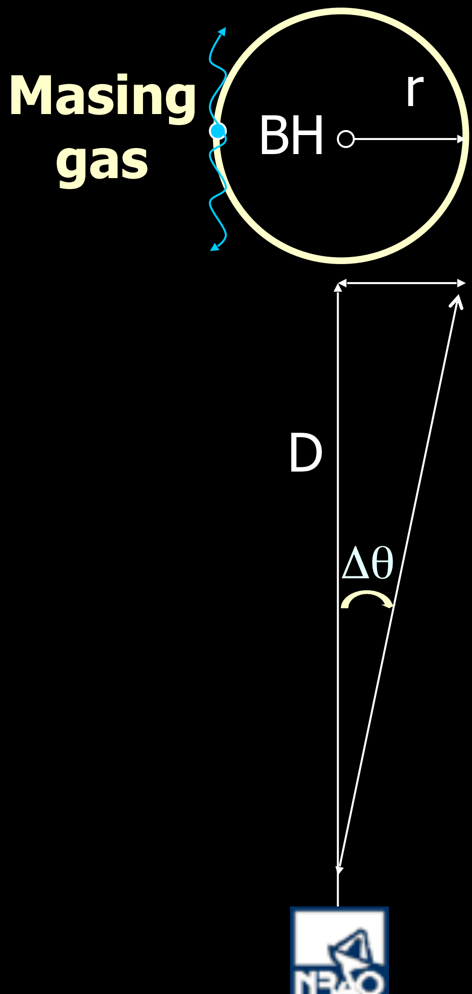
[slide material courtesy of Adam Riess]

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)
- 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 = 69.6 ± 0.8 (stat) ± 1.7 (sys) km s^{-1} Mpc^{-1} [Freedman et al. 2019, 2020]

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 :

$a = V_0^2 / r \Rightarrow r = V_0^2 / a$

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

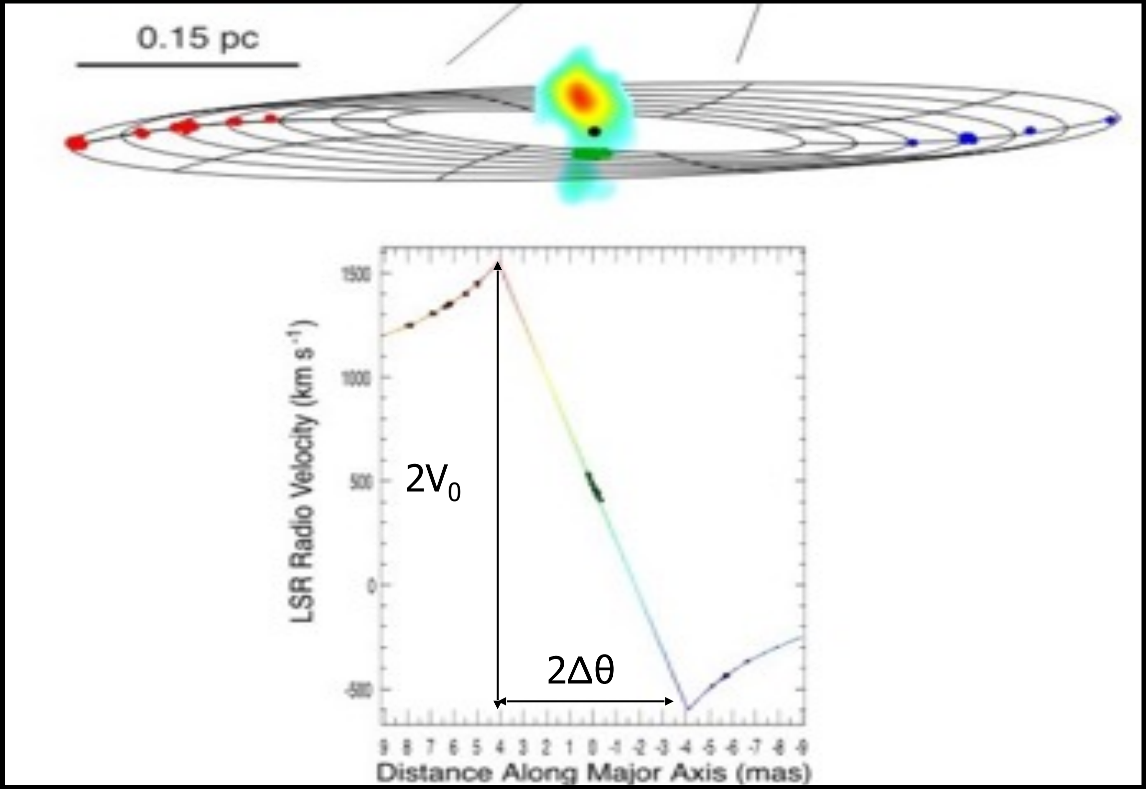
$$D = V_0^2 \sin i / a \, \Delta\theta$$

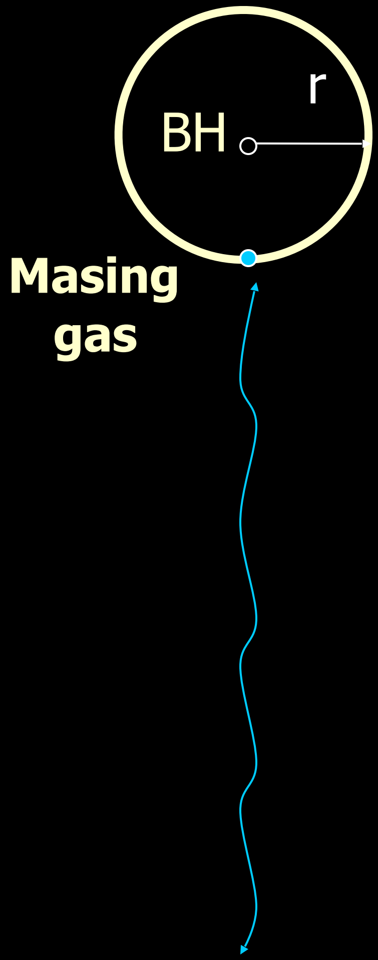
[slide material courtesy of C.-Y. Kuo]

Megamasers

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

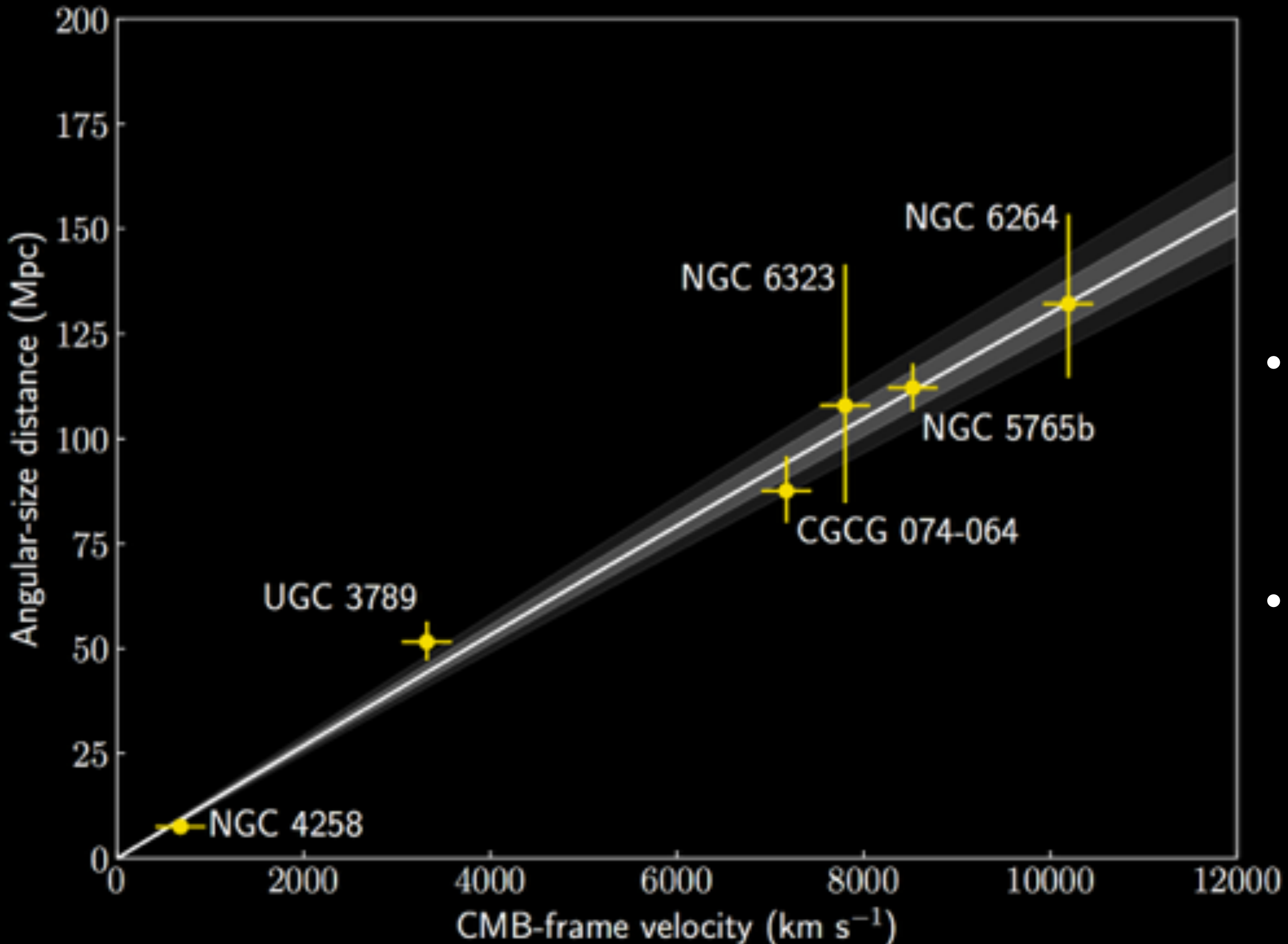
How to measure V_0, $\Delta\theta$, a and i?





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

Megamaser Cosmology Project



$H_0 = 73.9 \pm 3.0$ km s^{-1} Mpc^{-1}

- assuming uncertainty of 250 km/s for peculiar motions
- peculiar motion is currently the dominant source of uncertainty

[Pesce et al. 2020]

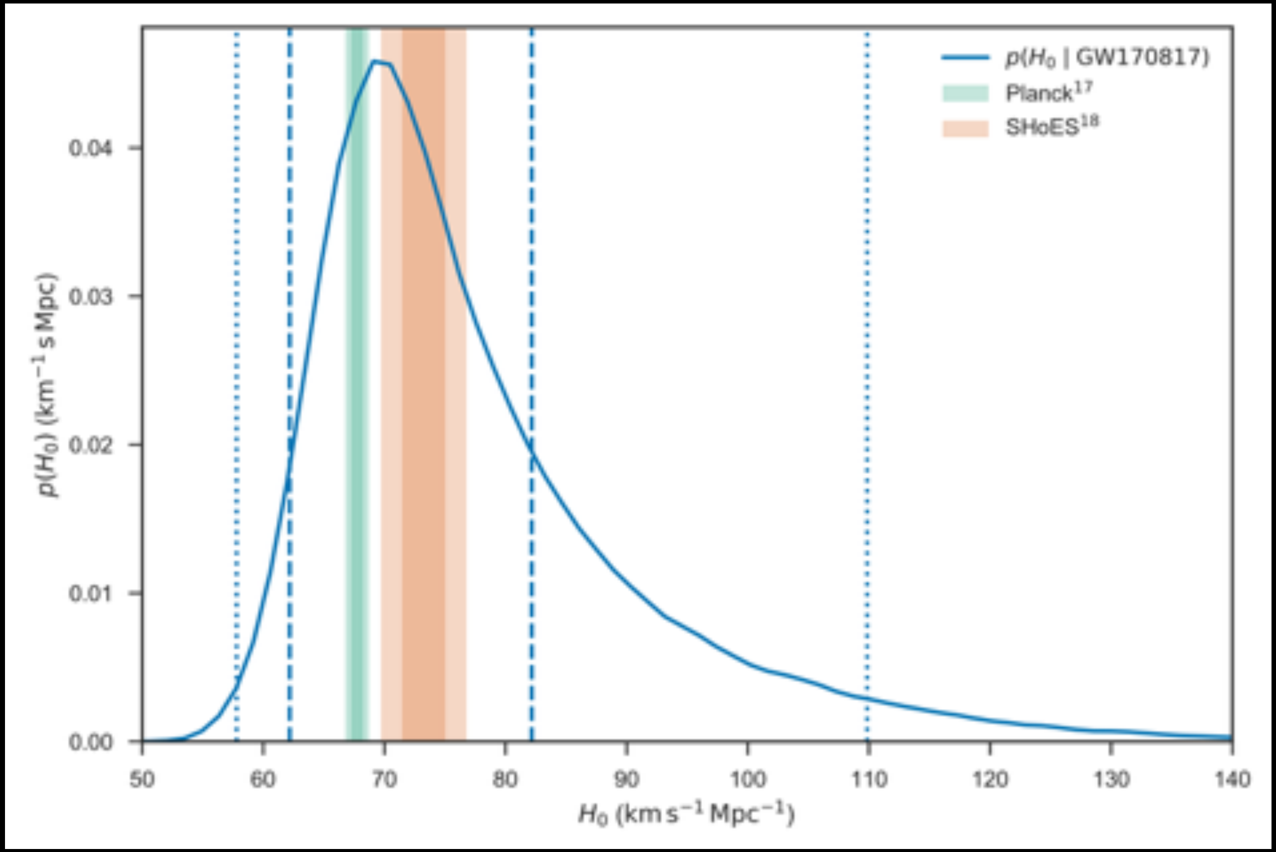
Standard Siren

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

$$H_0 = v / D$$

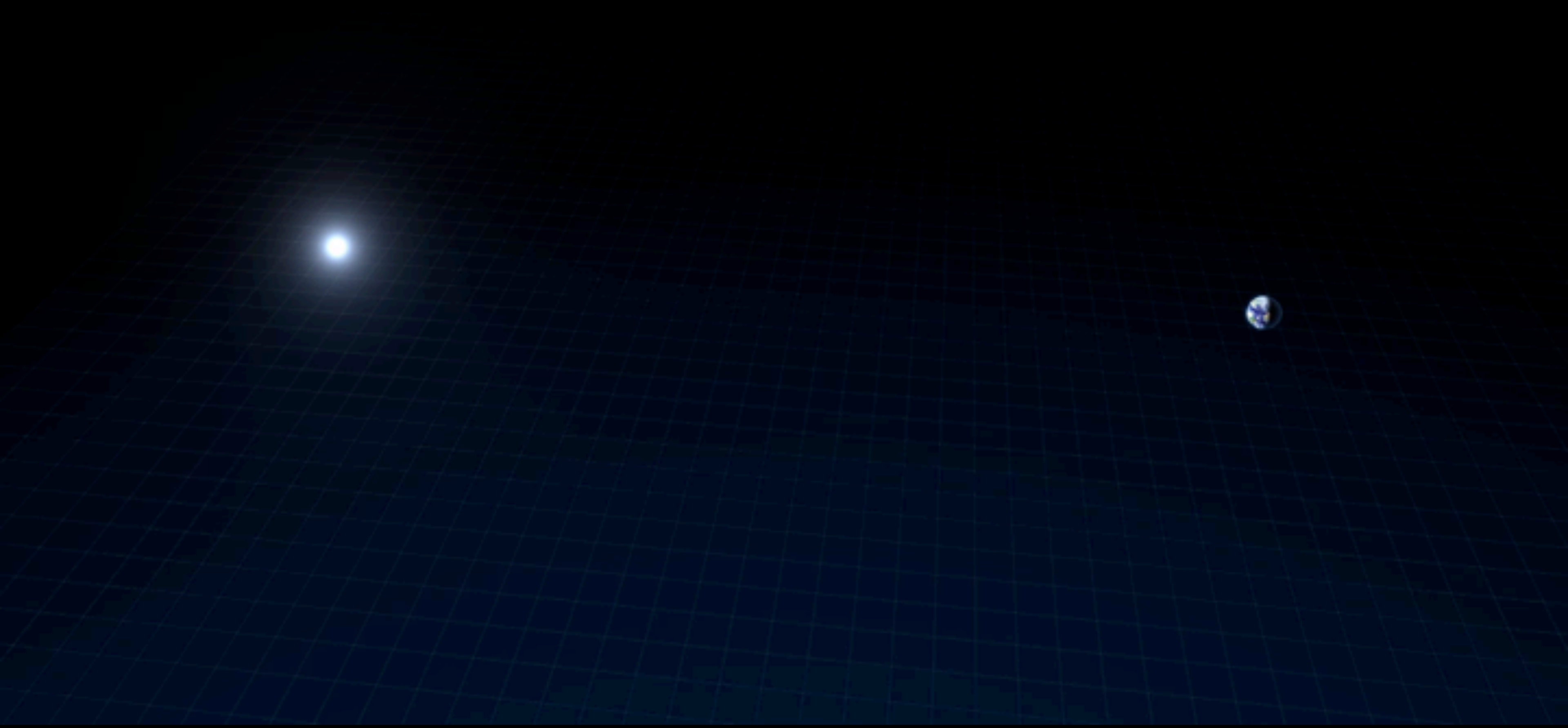
[Image credit: M. Garlick]

GW170817: First measurement of H_0



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

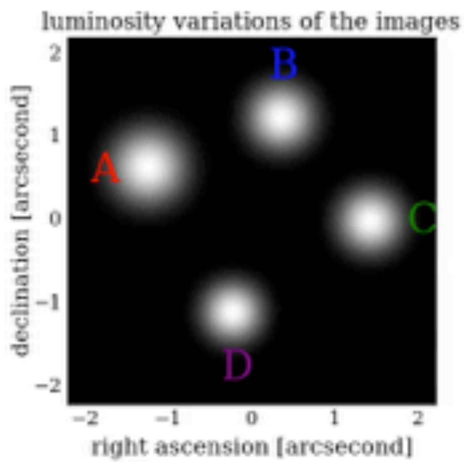
Strong gravitational lensing

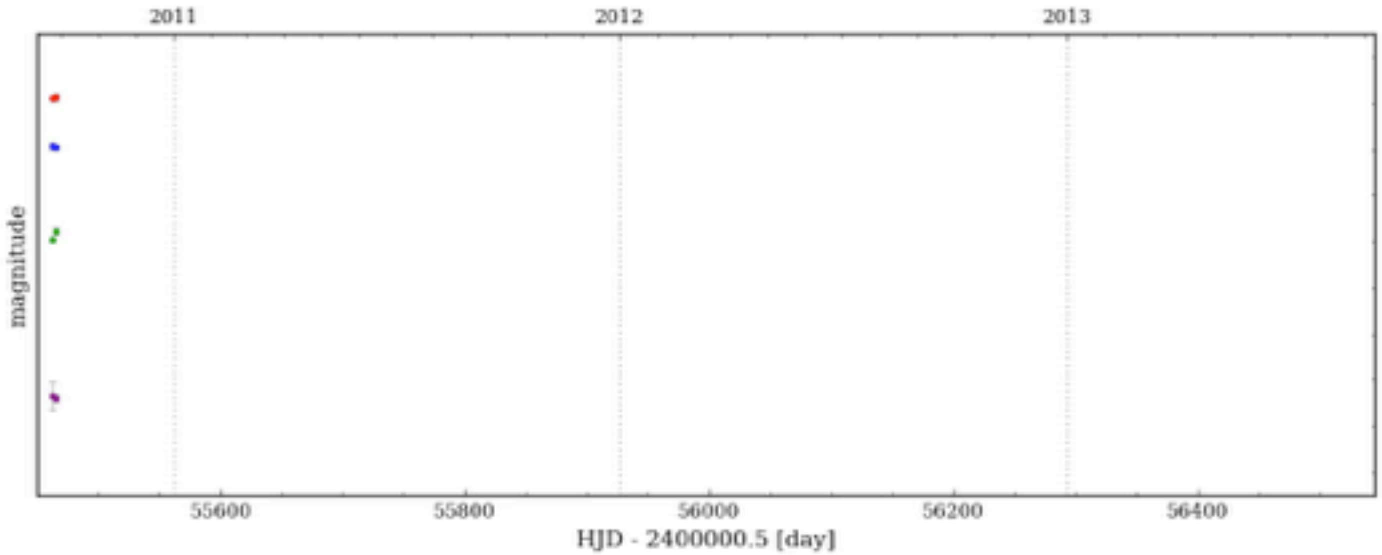


[Credit: ESA/Hubble, NASA]

Cosmology with time delays

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

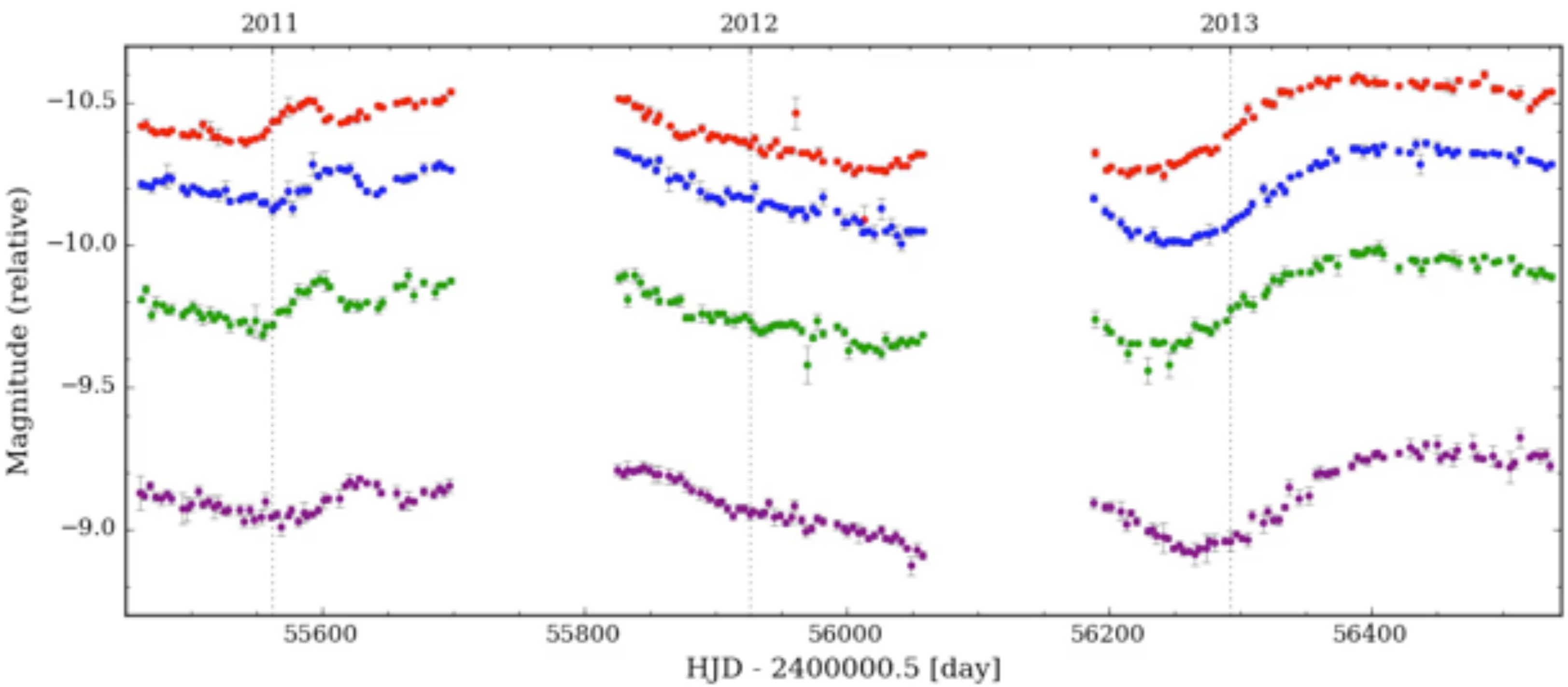




[Credit: V. Bonvin]

Cosmology with time delays

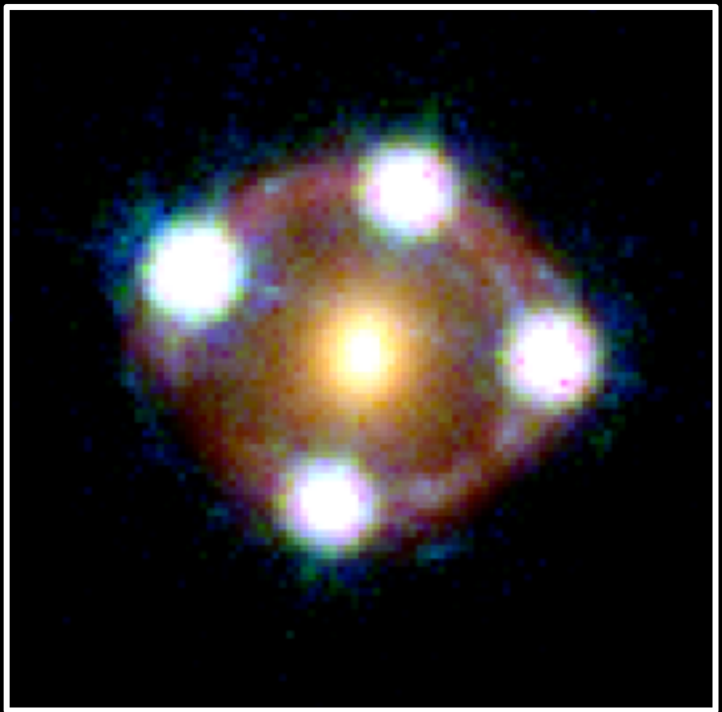
COSMOGrail



[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

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

Advantages:

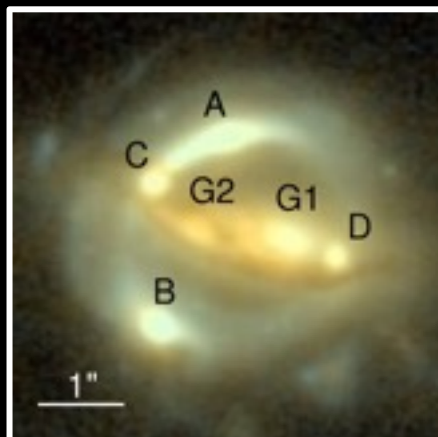
- simple geometry & well-tested physics

- one-step physical measurement of a cosmological distance

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

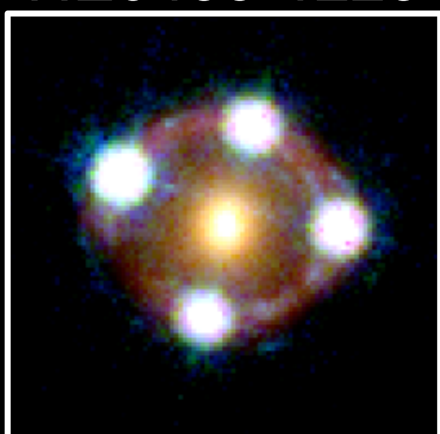
B1608+656



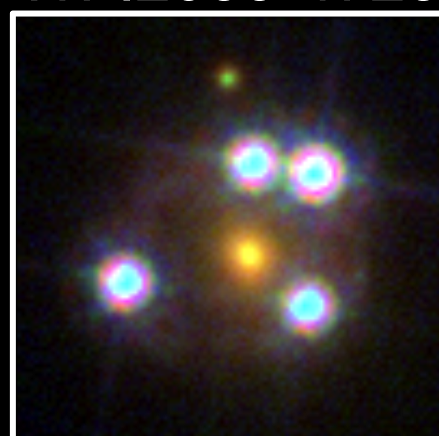
RXJ1131-1231

H_0 to <3.5% precision

HE0435-1223



WFI2033-4723



HE1104-1805

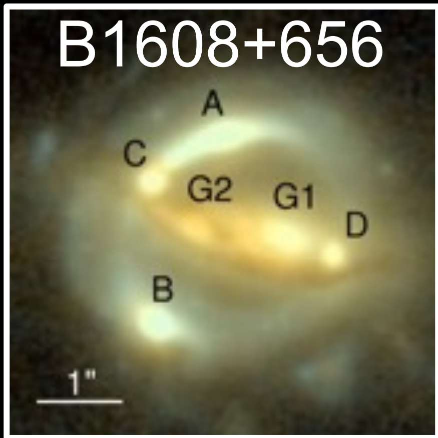
[Suyu et al. 2017]

H0LiCOWers

H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

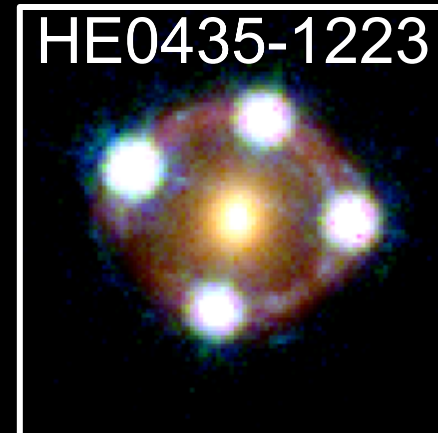
→ Establish time-delay gravitational lenses as one of the best cosmological probes

H0LiCOW latest results



[Suyu et al. 2010]

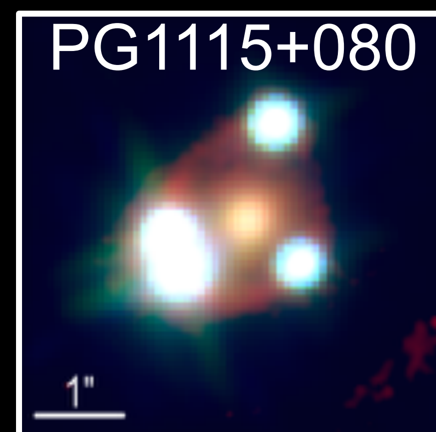
[Suyu et al. 2013, 2014; Tewes et al. 2013]



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

part of extended sample [Birrer et al. 2019]

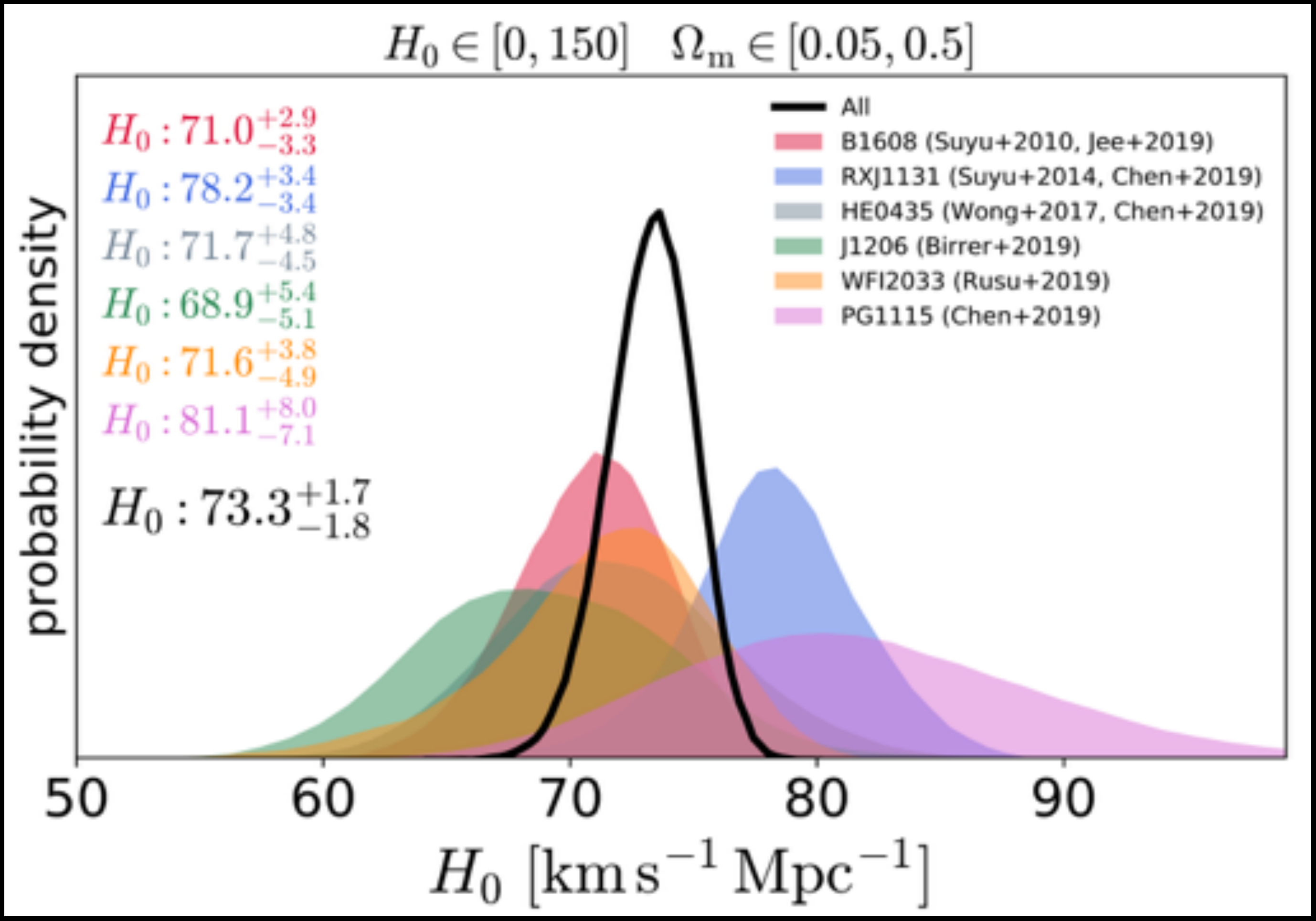
[Bonvin et al. 2019; Sluse et al. 2019; Rusu et al. 2019]



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

H_0 from 6 strong lenses

Blind analysis to avoid confirmation bias

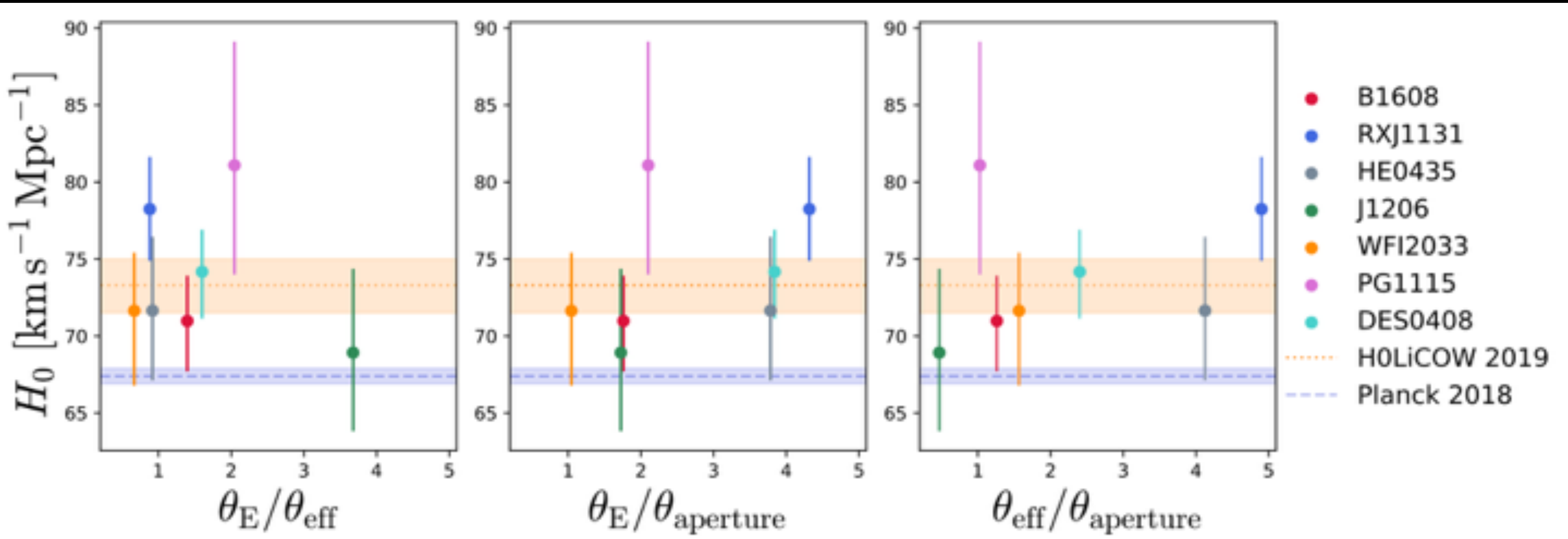


***H_0* with 2.4% precision in flat ΛCDM**

[Wong, Suyu, Chen et al. 2019]

Residual systematics?

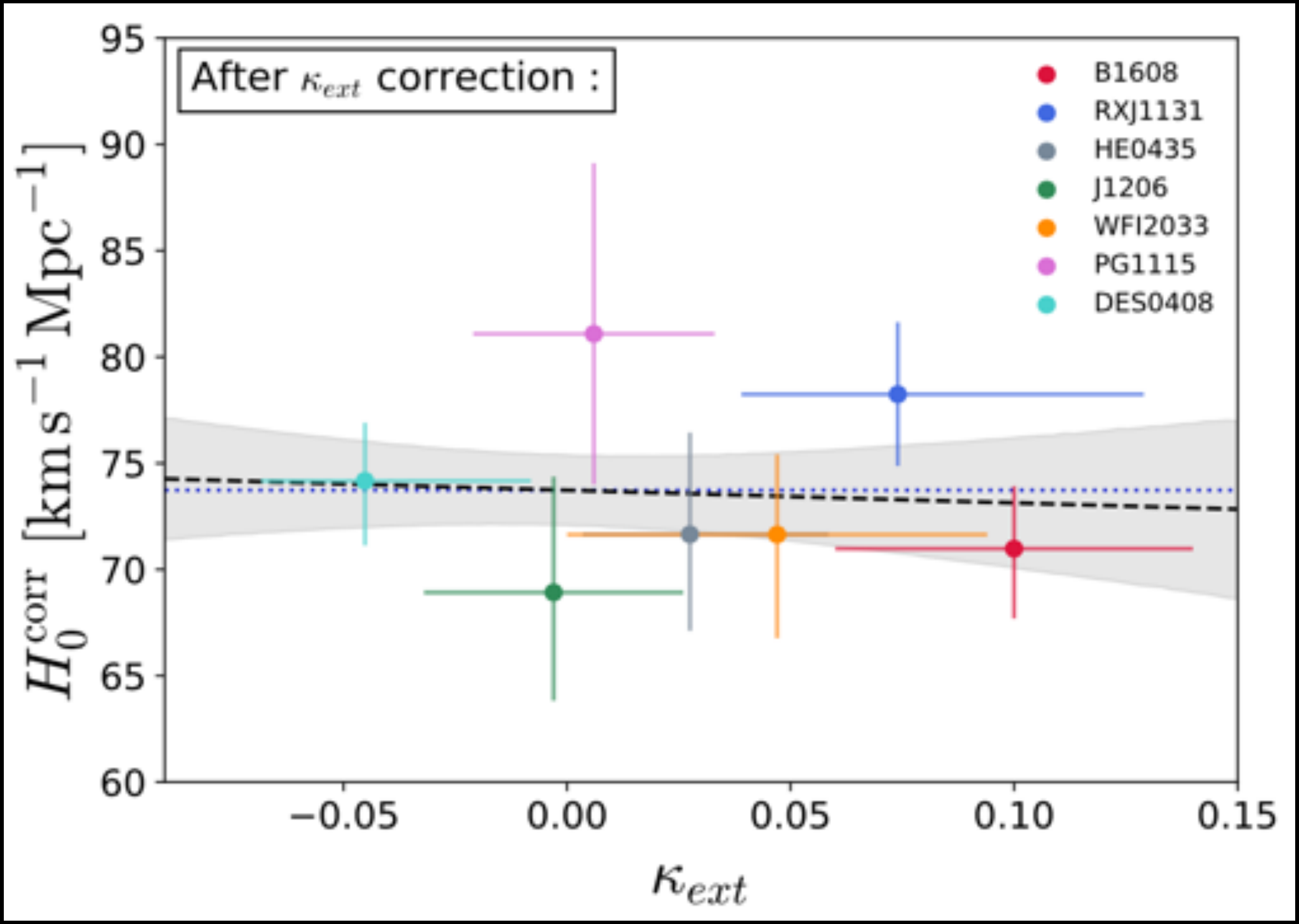
No significant residual systematics detected wrt Einstein radii, effective radii, kinematic apertures



[Millon, Galan, Courbin et al. 2019; TDCOSMO I]

Residual systematics?

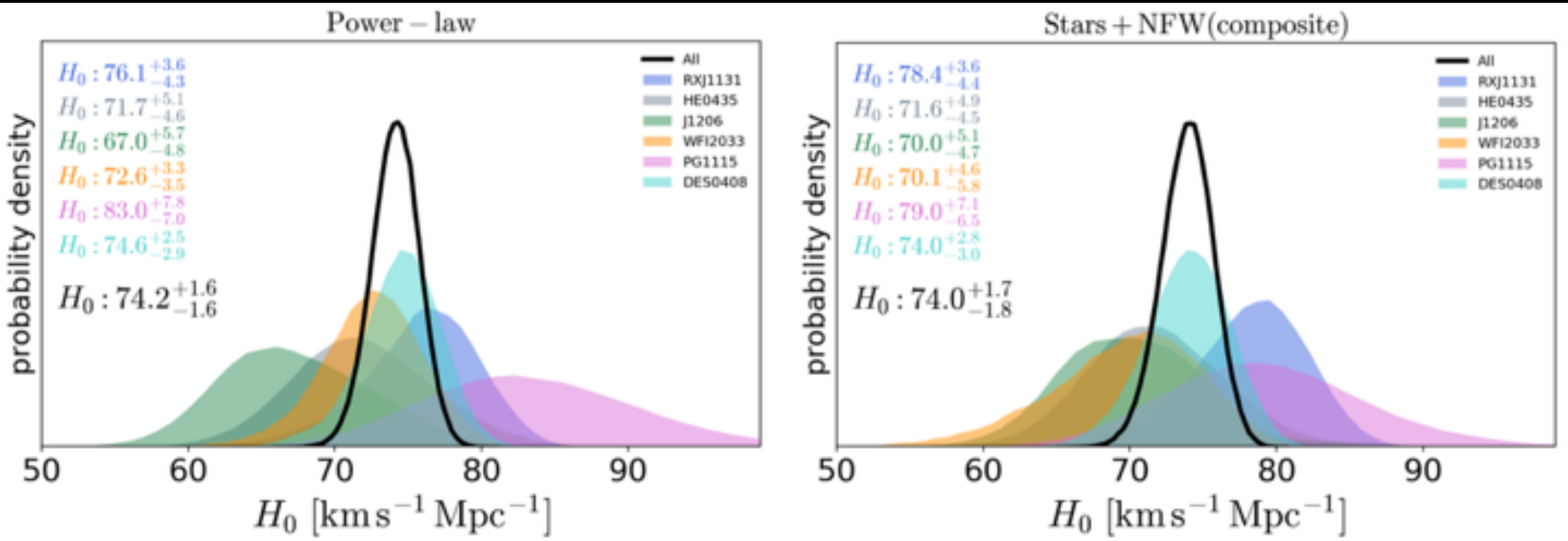
No significant residual systematics detected wrt external convergence



[Millon, Galan, Courbin et al. 2019]

Residual systematics?

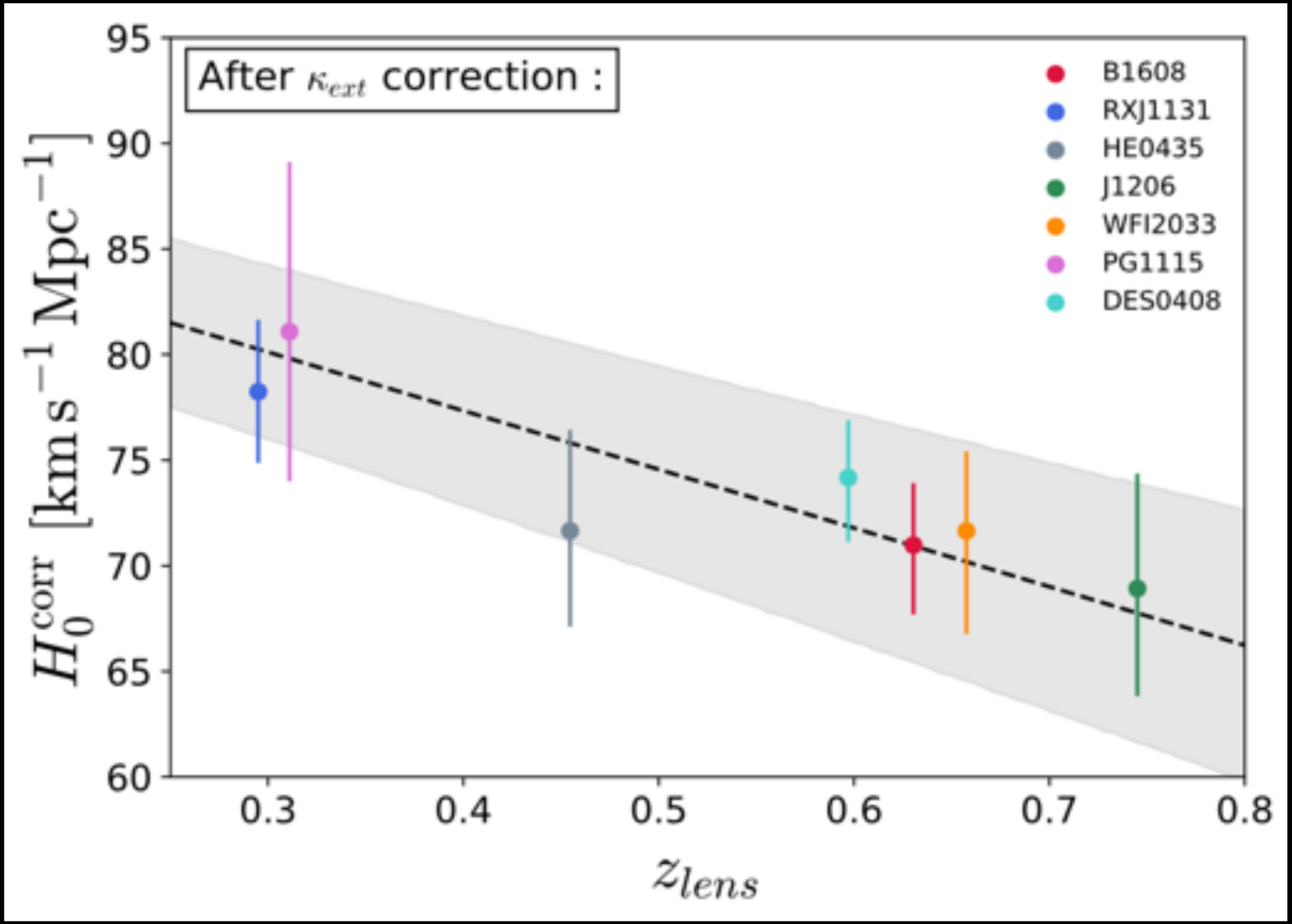
No significant residual systematics detected wrt mass model assumptions



[Millon, Galan, Courbin et al. 2019]

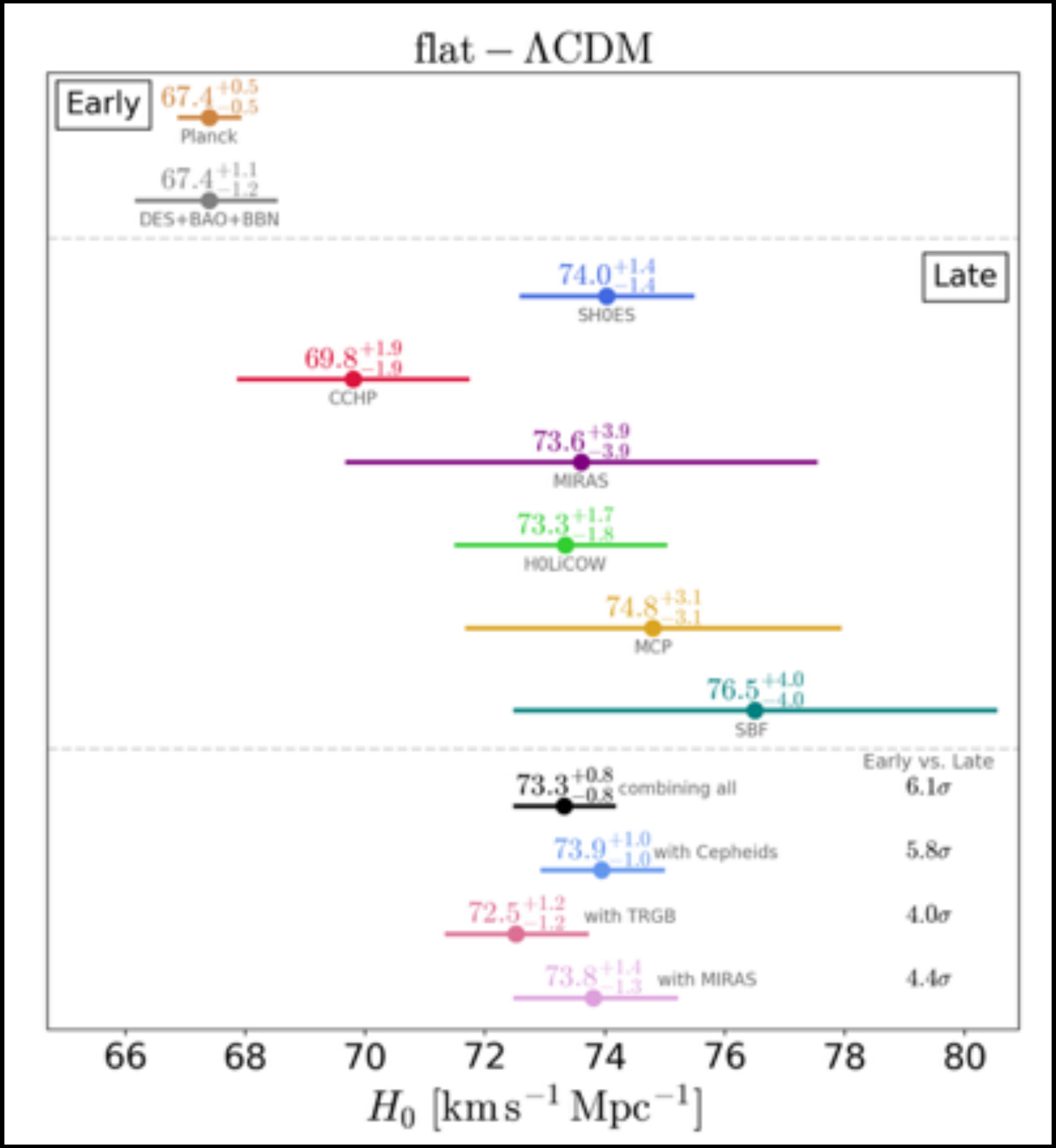
Weak trend with redshift

Weak trend (at 1.7σ) of H_0 wrt redshifts of lens



[Wong, Suyu, Chen et al. 2019;
Millon, Galan, Courbin et al. 2019]

Tensions between Early and Late Universe

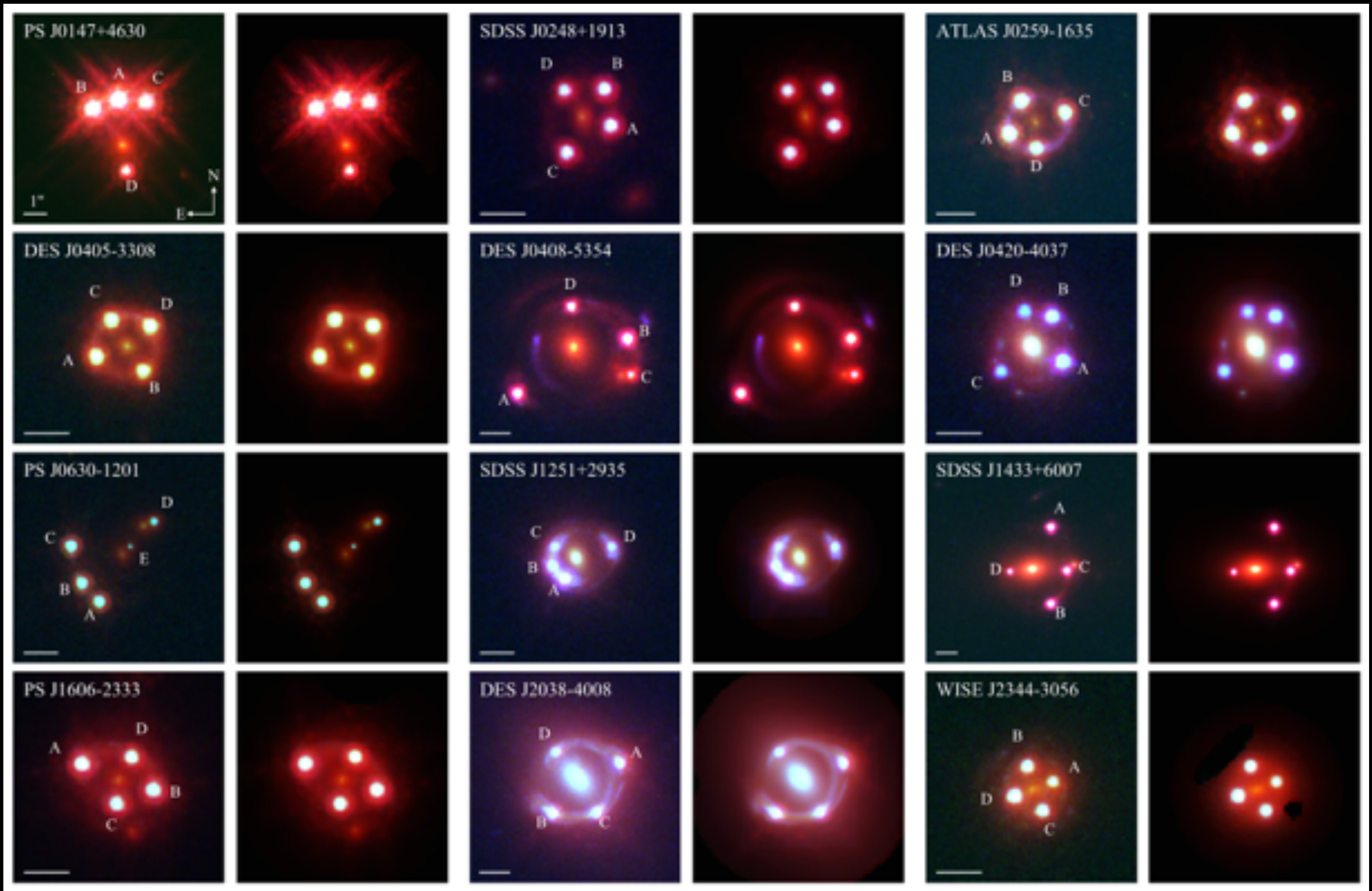


[Verde, Treu, Riess 2019]

[credit: V. Bonvin]

New quads imaged with HST

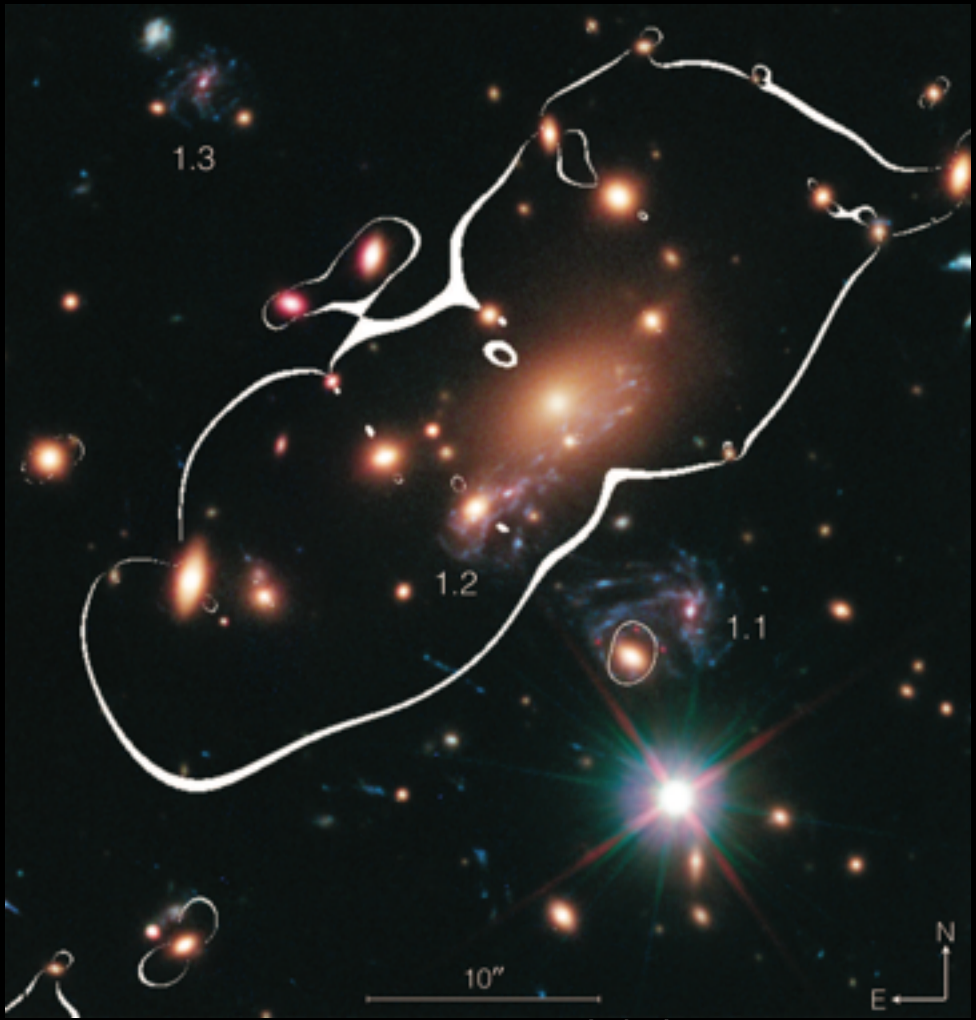
New lens systems discovered in DES, Pan-STARRS, SDSS, ATLAS:



[Shajib et al. 2018]

Strongly lensed supernova

SN Refsdal



[Kelly et al. 2015]

iPTF16geu

[Goobar et al. 2017;
image credit: NASA/ESA]

HOLISMOKES

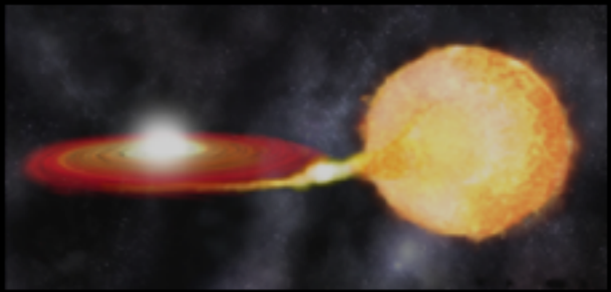
Highly **O**ptimised **L**ensing **I**nvestigations of **S**upernovae, **M**icrolensing **O**bjects, and **K**inematics of **E**llipticals and **S**pirals

PI: S. Suyu

Lensed supernovae provide great opportunities for

1) Constraining the progenitor of Type Ia supernova

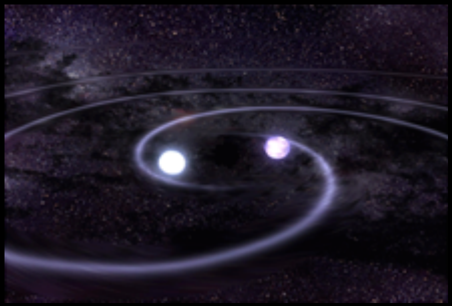
single degenerate



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]

Summary

- Independent techniques for measuring H_0 are necessary for addressing the current H_0 tension
- Time-delay distances $D_{\Delta t}$ of each lensed quasar can be measured with uncertainties of ~5-8% including systematics
- 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
- 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