H0LiCOW

H_0 from lensed quasars

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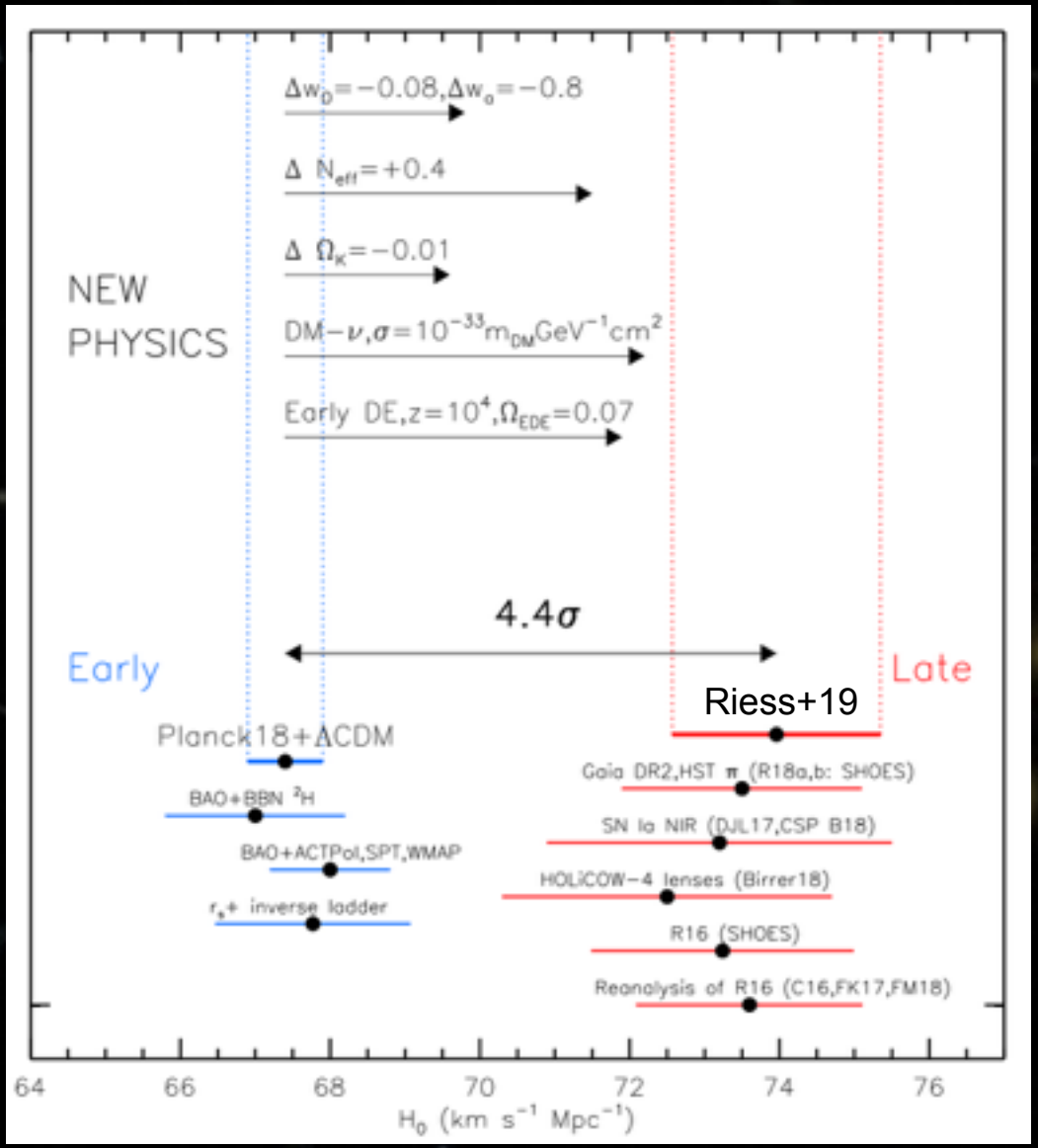
Hubble constant: key parameter



[Riess et al. 2019]

Hubble constant H_0

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

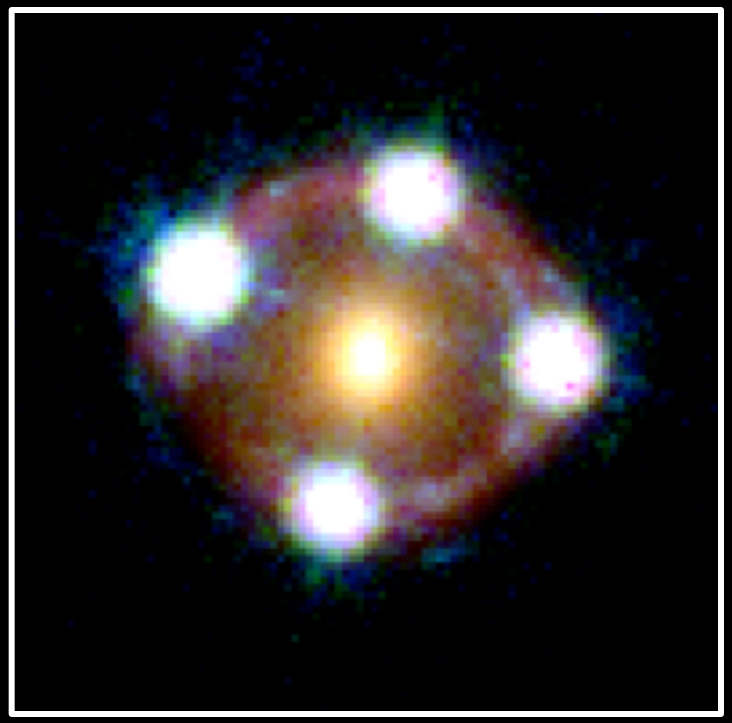
Tension? New physics?

➡ Need more precise & accurate H_0

Need Independent methods to overcome systematics, especially the unknown unknowns

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:

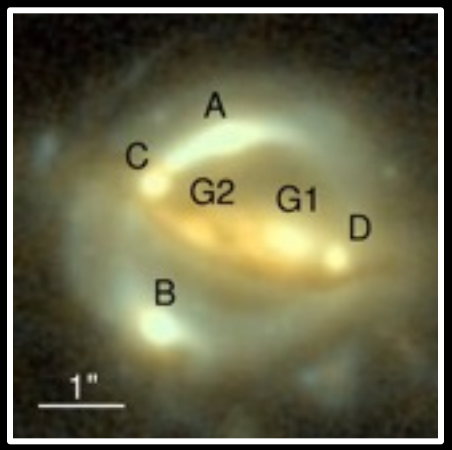
- simple geometry & well-tested physics

- one-step physical measurement of a cosmological distance

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring

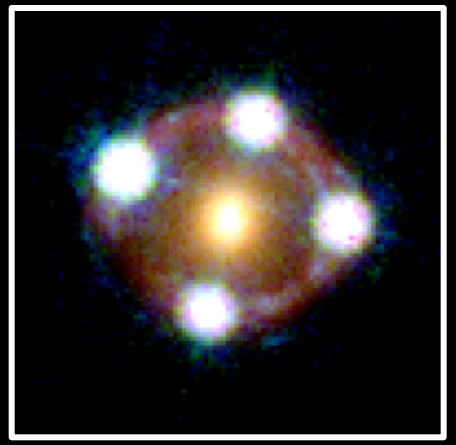
B1608+656



RXJ1131-1231

H_0 to <3.5% precision

HE0435-1223



WFI2033-4723

HE1104-1805

[Suyu et al. 2017]

H0LiCOWers

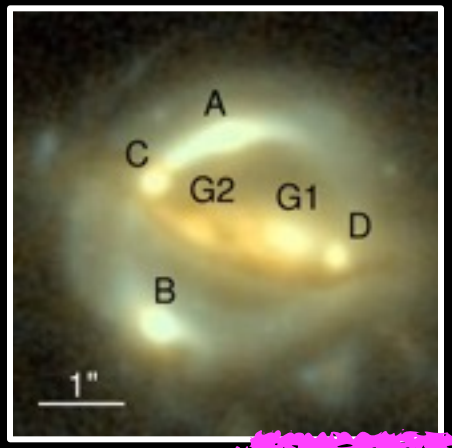
H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

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

H0LiCOW

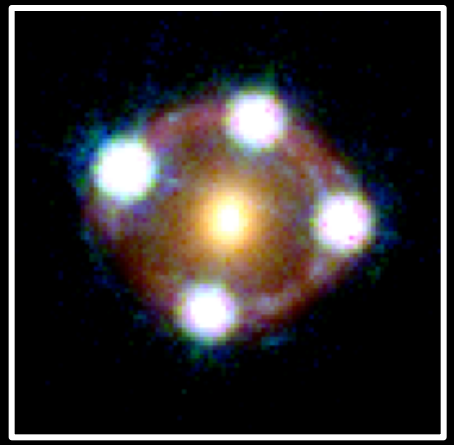
H_0 Lenses in COSMOGRAIL's Wellspring

B1608+656



RXJ1131-1231

HE0435-1223



WFI2033-4723

HE1104-1805

[Suyu et al. 2017]

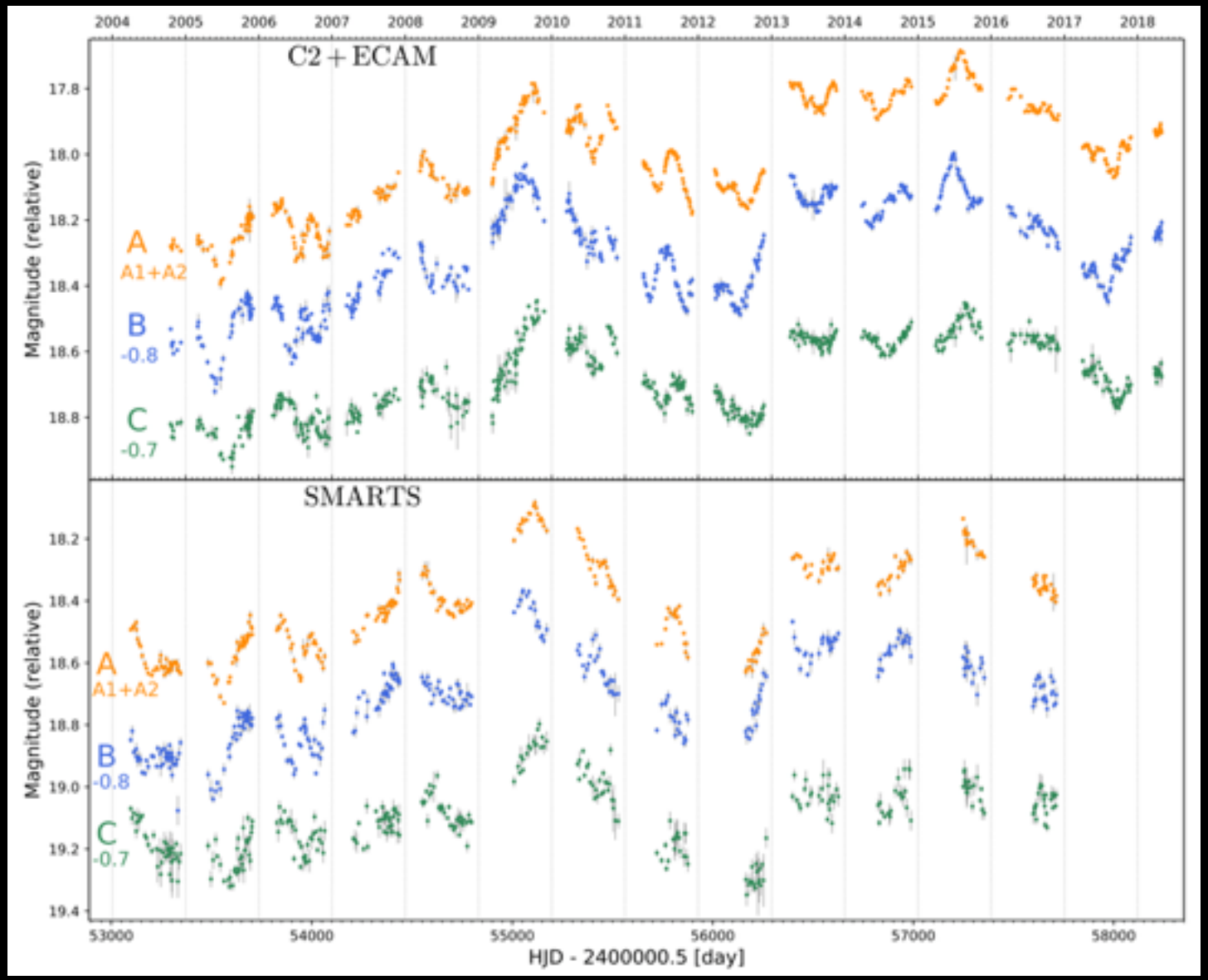
Time Delays

[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

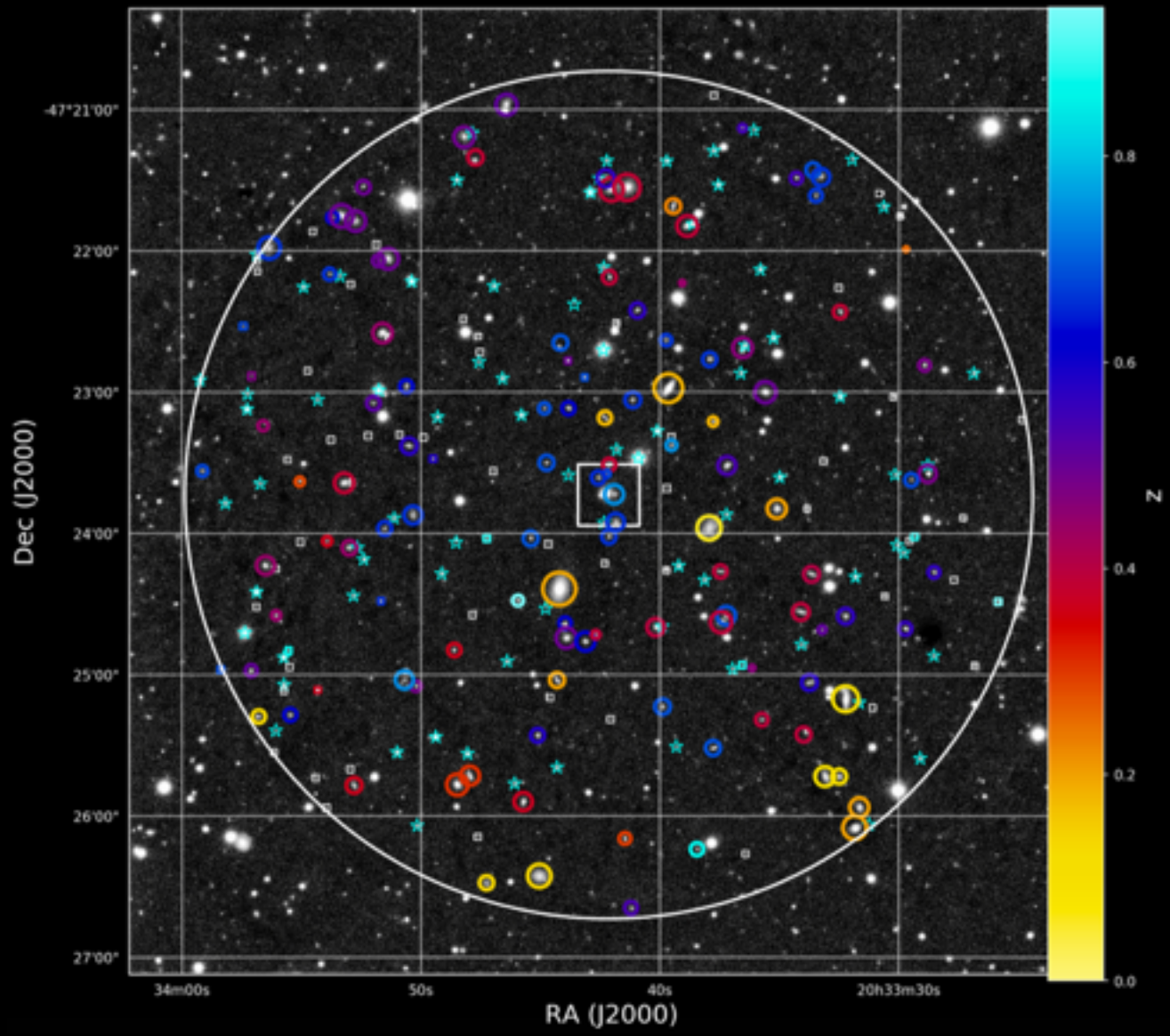


[Bonvin et al. 2019]

Time Delays

Delay (AB) with 2.1% precision [Bonvin et al. 2019]

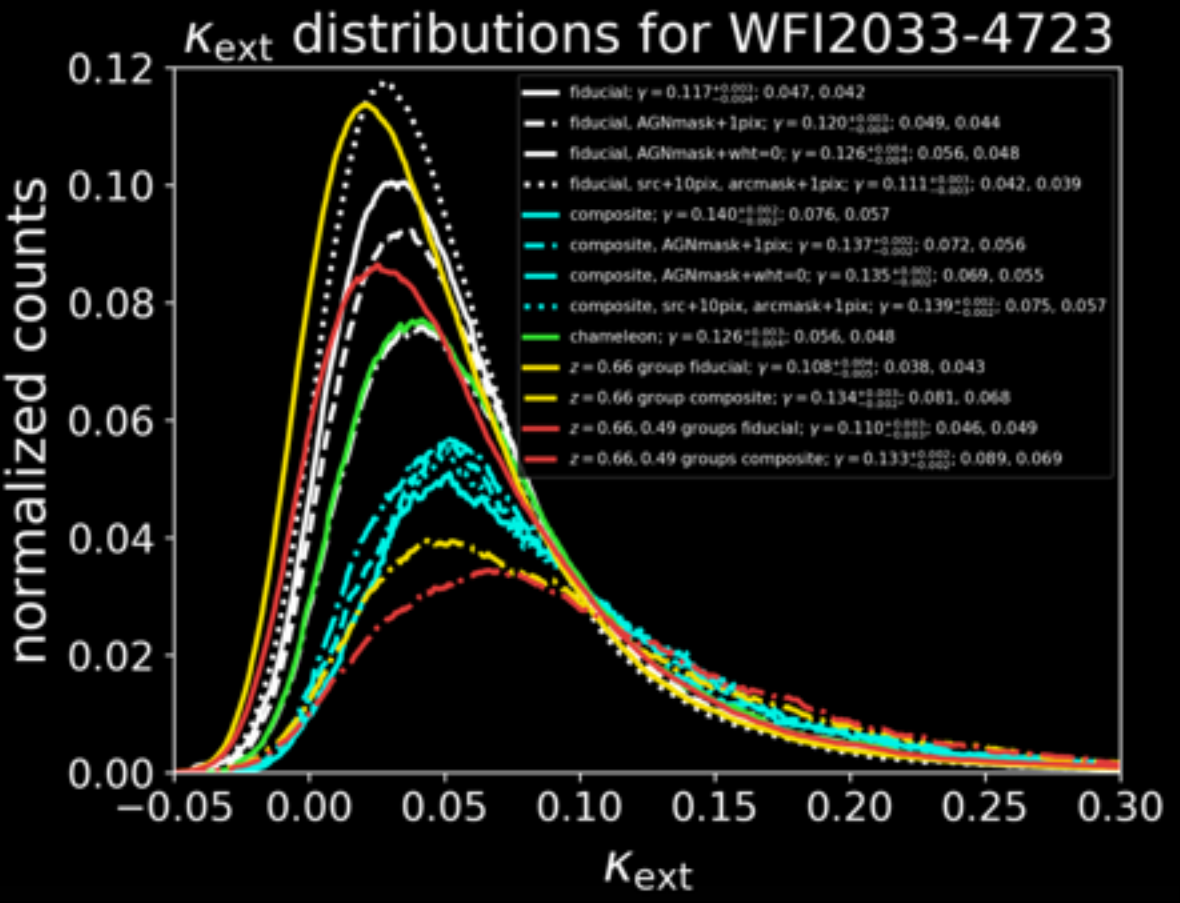
Lens environment



Wide-field spectroscopy and imaging for redshift measurements and group identification [Sluse et al. 2019 (H0LiCOW X)]

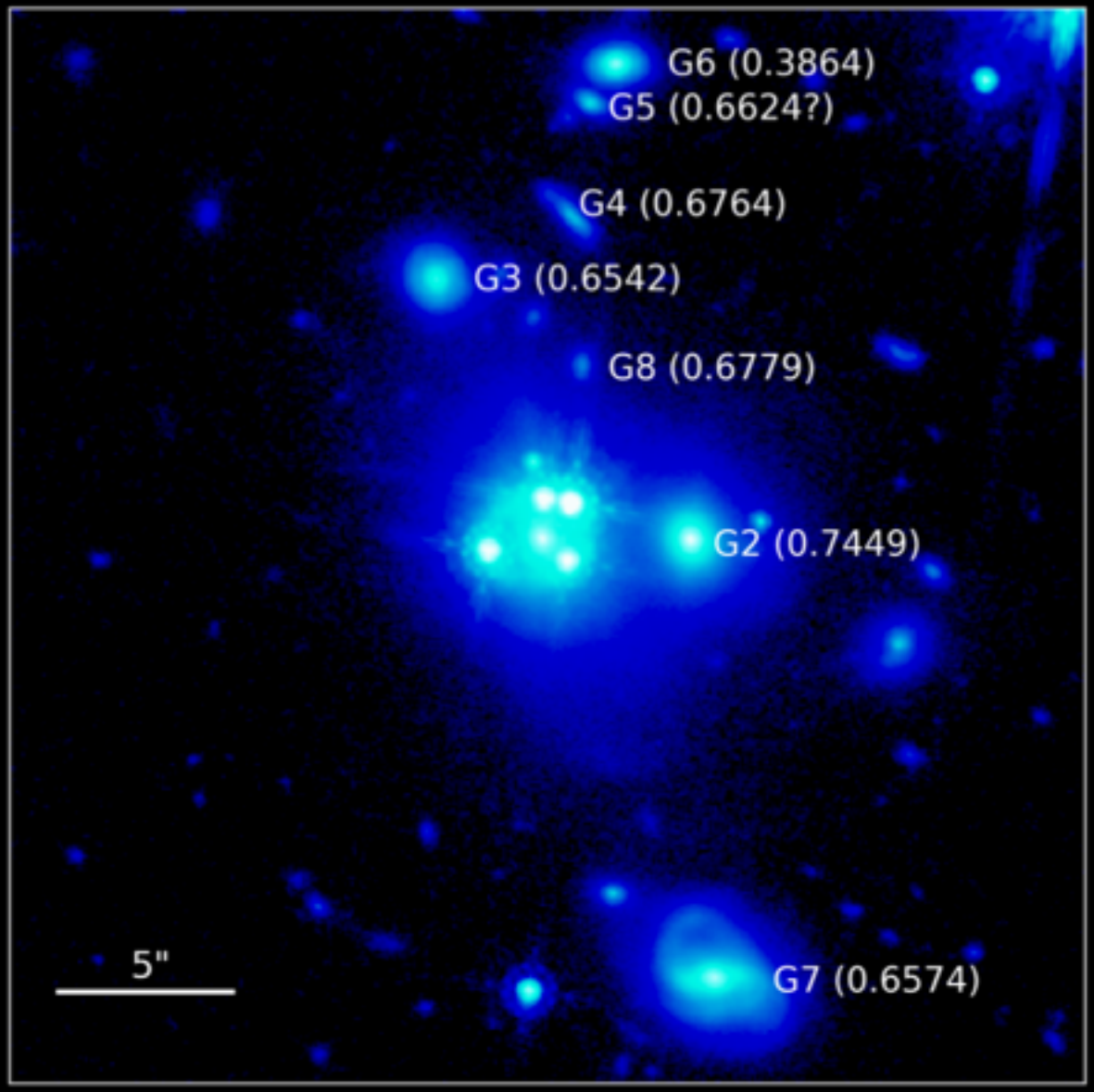
Lens environment

- weighted number counts + Millennium Simulation to quantify κ_{ext} [Fassnacht et al. 2011; Hilbert et al. 2007, 2009; Suyu et al. 2010, 2013, Greene et al. 2013]



[Rusu, Wong et al 2019 (H0LiCOW XII)]

Lens environment



Wide-field spectroscopy and imaging for redshift measurements and group identification [Sluse et al. 2019 (H0LiCOW X)]

Lens mass modeling

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

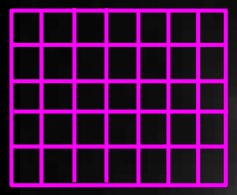
Modeling with GLEE :)

Gravitational
Lens
Efficient
Explorer

[Suyu & Halkola 2010]

Lens mass modeling

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



light distribution of extended source

mass distribution of lens

PSF reconstruction

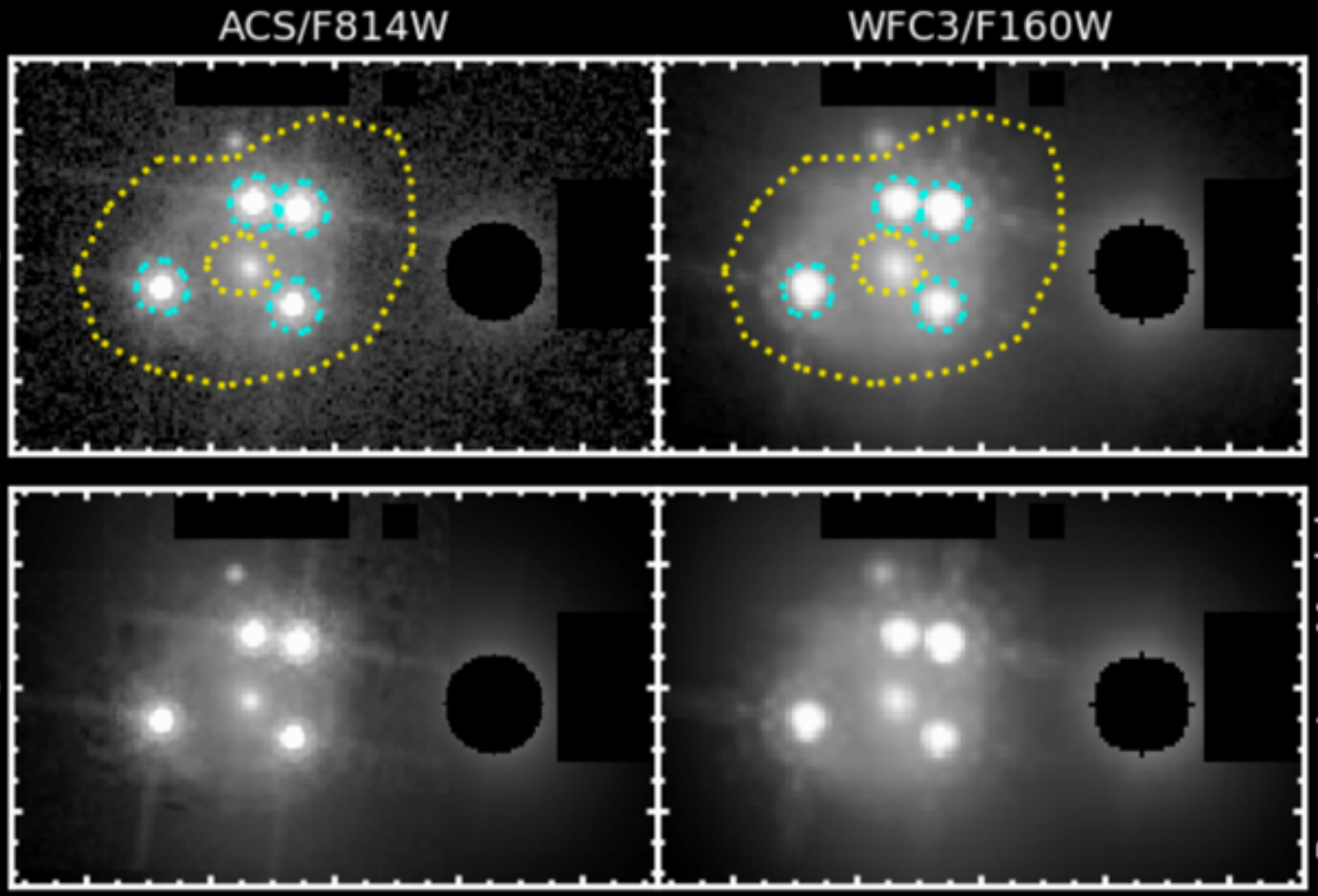
light of lensed AGN

+ time delays

light of lens (Sersic)

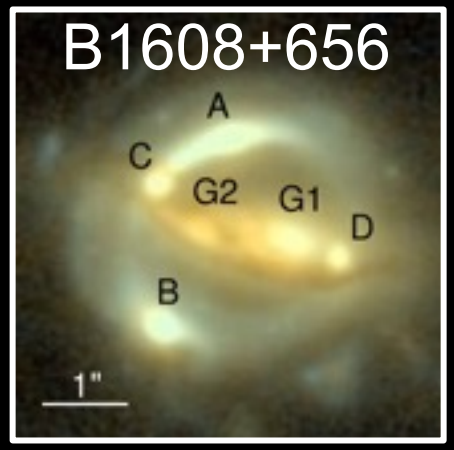
multi-lens plane modeling including nearby perturbers [Suyu et al., in prep]

Lens reconstruction



[Rusu, Wong et al 2019 (H0LiCOW XII)]

H0LiCOW latest results



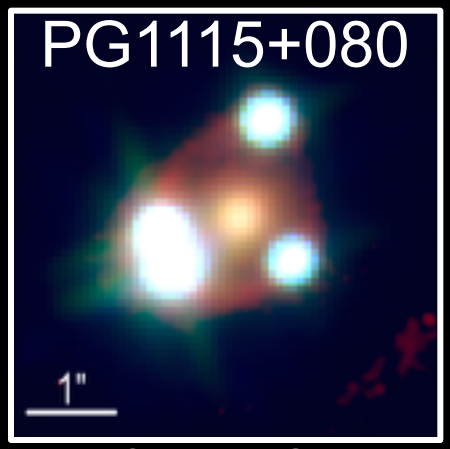
[Suyu et al. 2010]

[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]

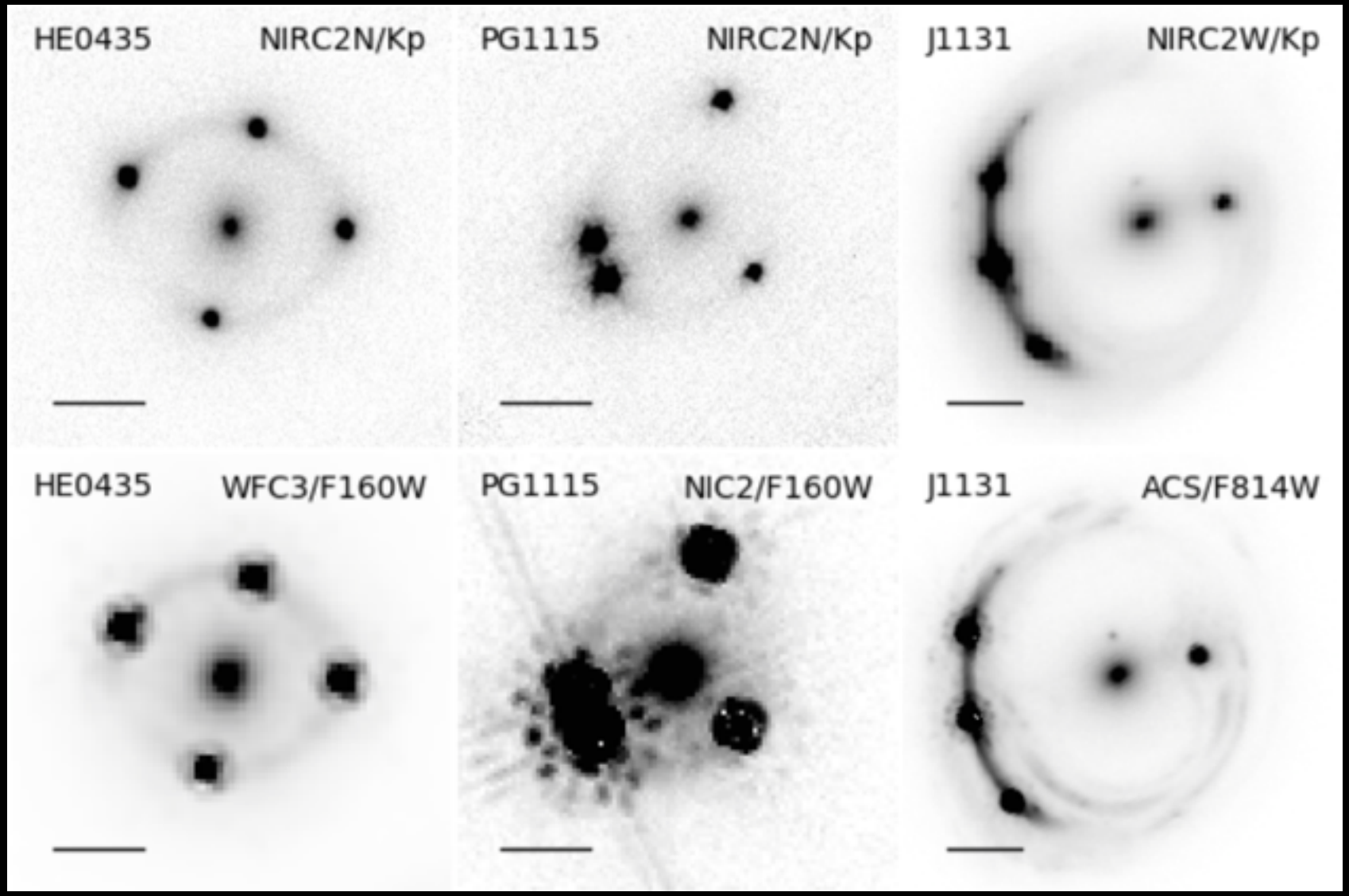
part of extended sample [Birrer et al. 2019]

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



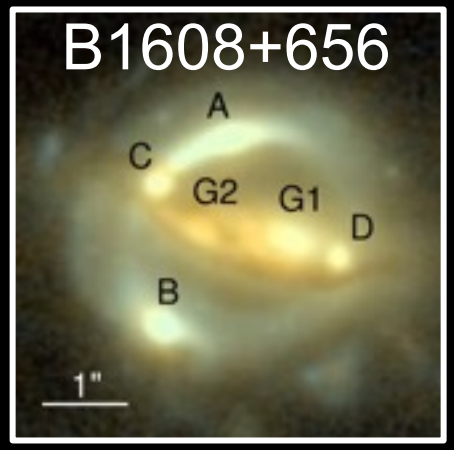
part of Keck AO sample of SHARP program [Chen et al. 2019]

Cosmology with Adaptive Optics



[Chen, Fassnacht, Suyu et al. 2019]

H0LiCOW latest results



[Suyu et al. 2010]

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

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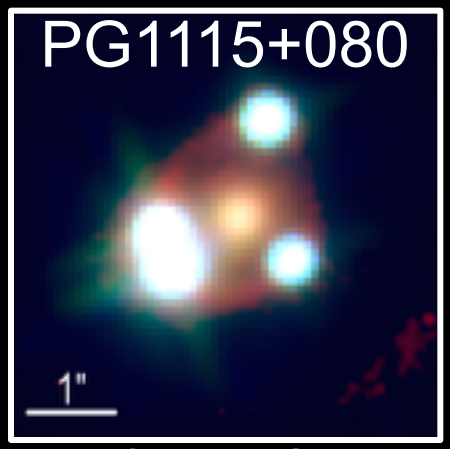
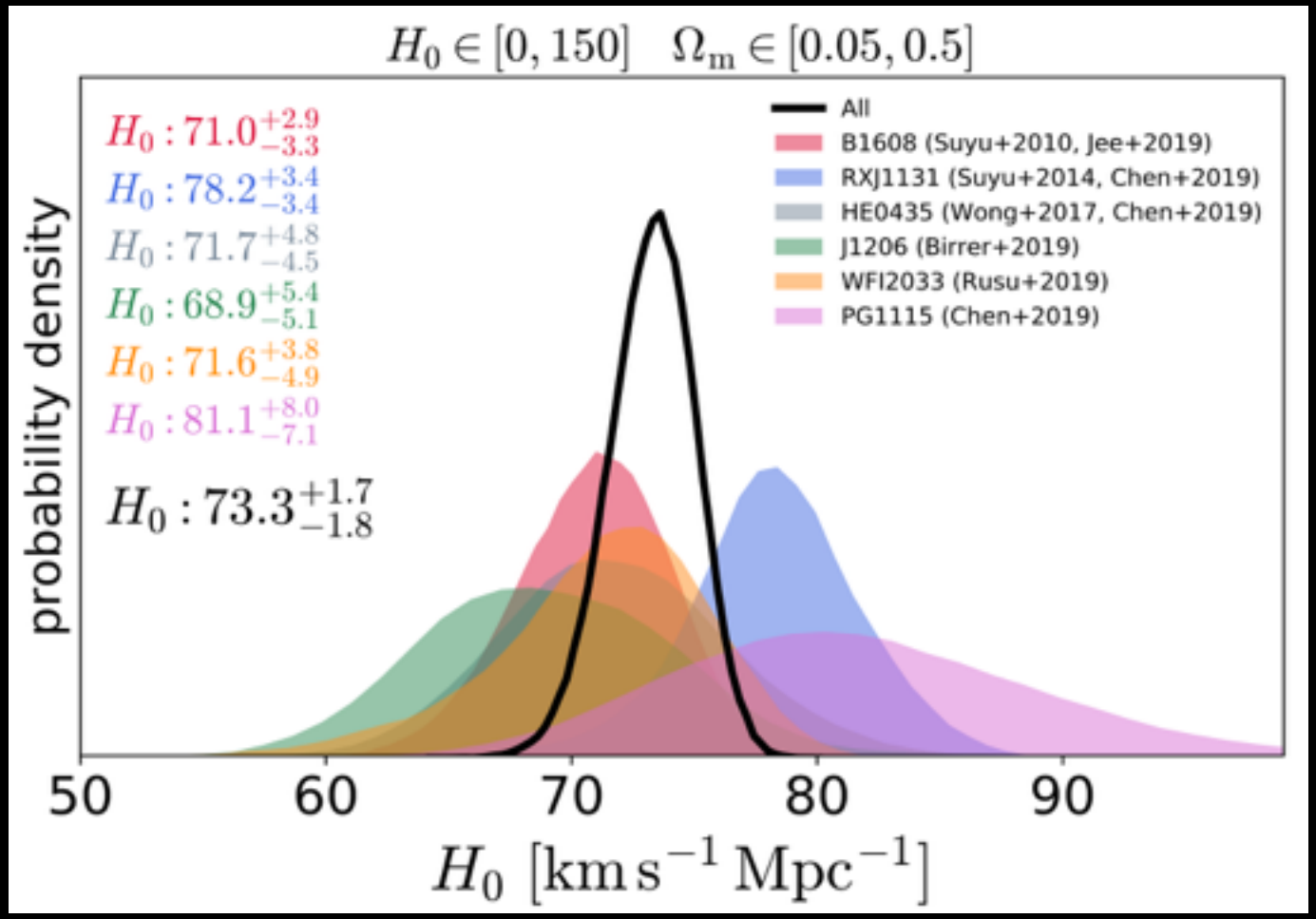


part of Keck AO sample of SHARP program [Chen et al. 2019]

H_0 from 6 strong lenses

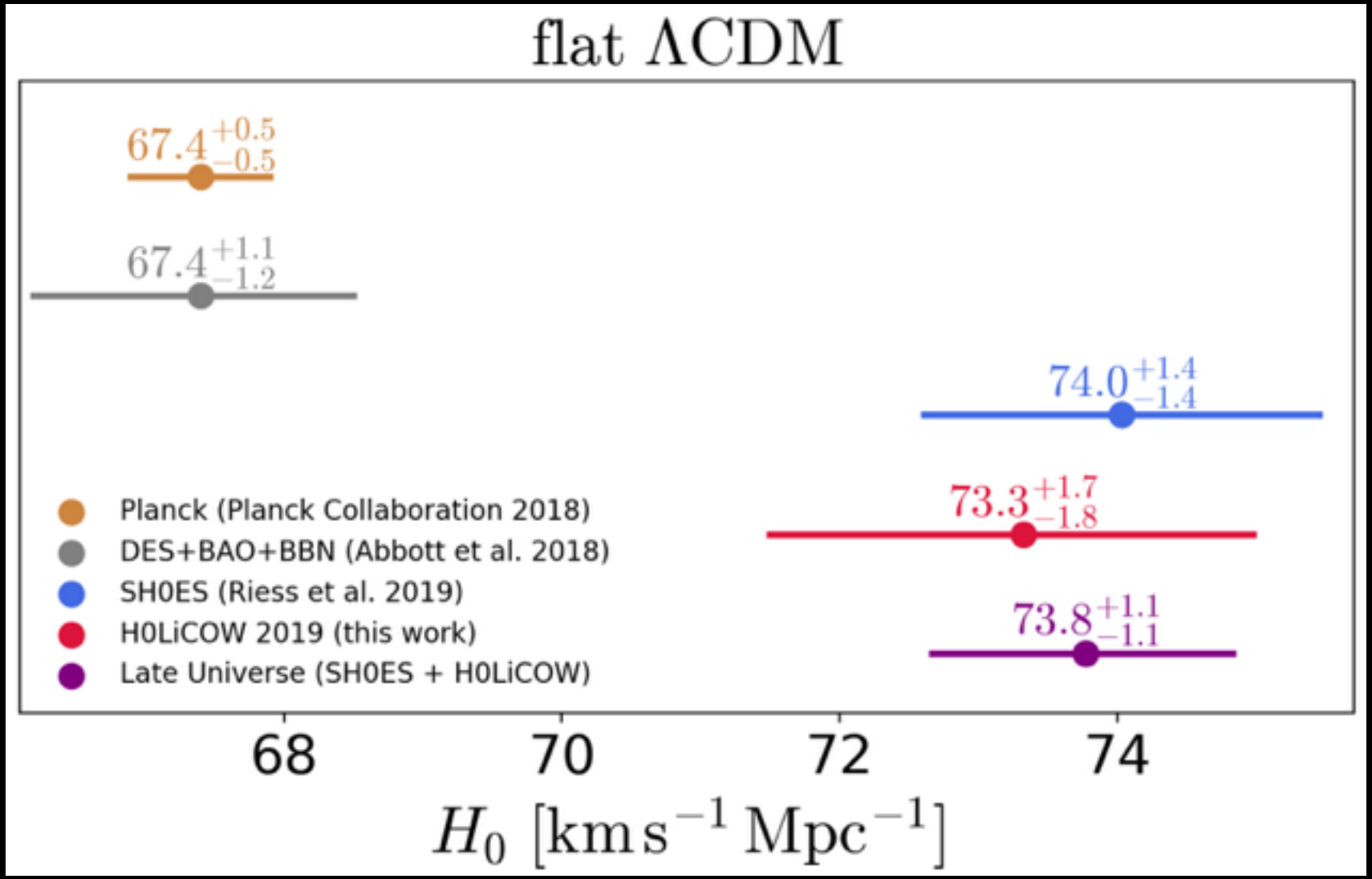
Blind analysis to avoid confirmation bias



H_0 with 2.4% precision in flat ΛCDM

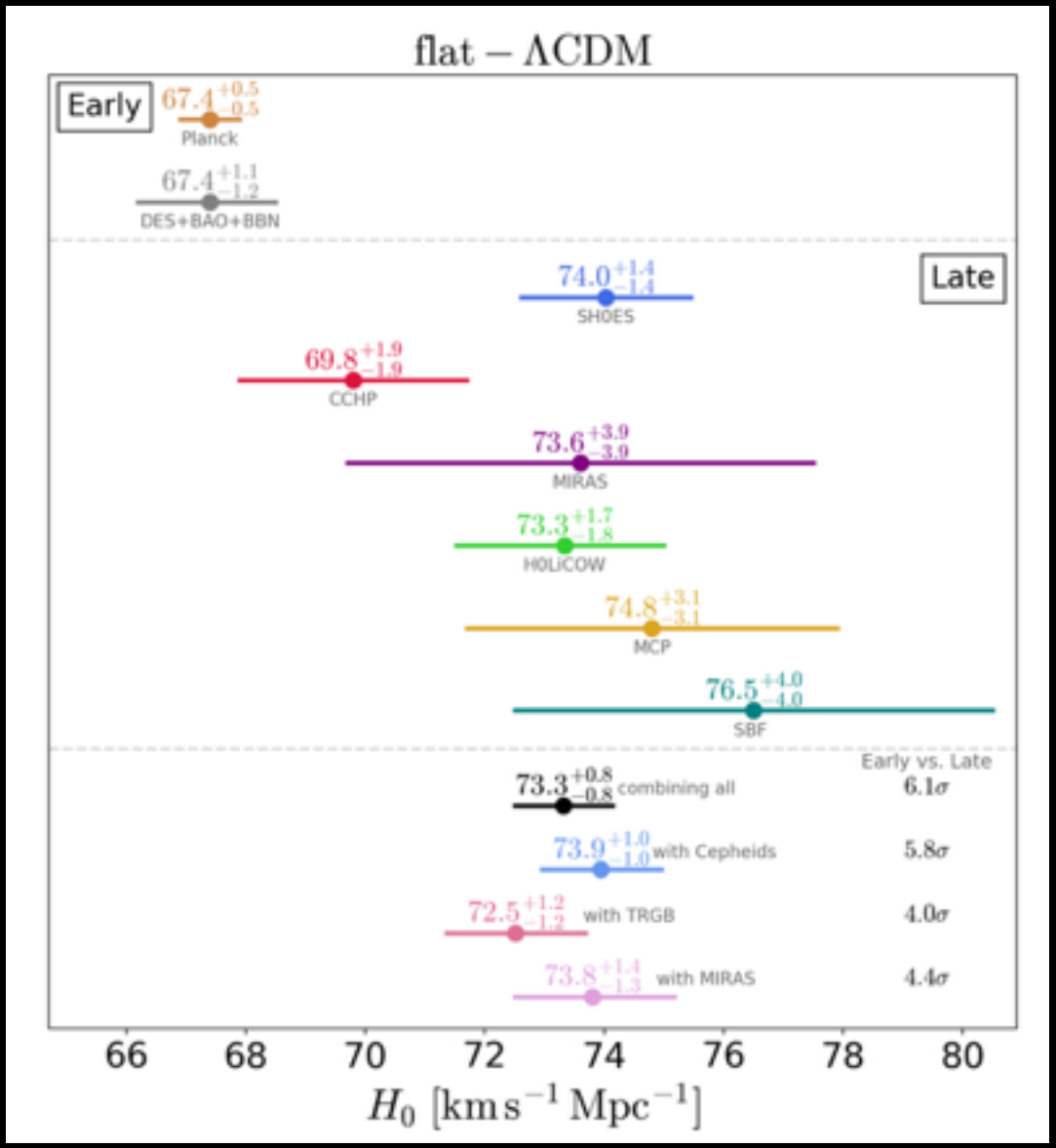
[Wong, Suyu, Chen et al. 2019 (H0LiCOW XIII)]

H_0 comparison



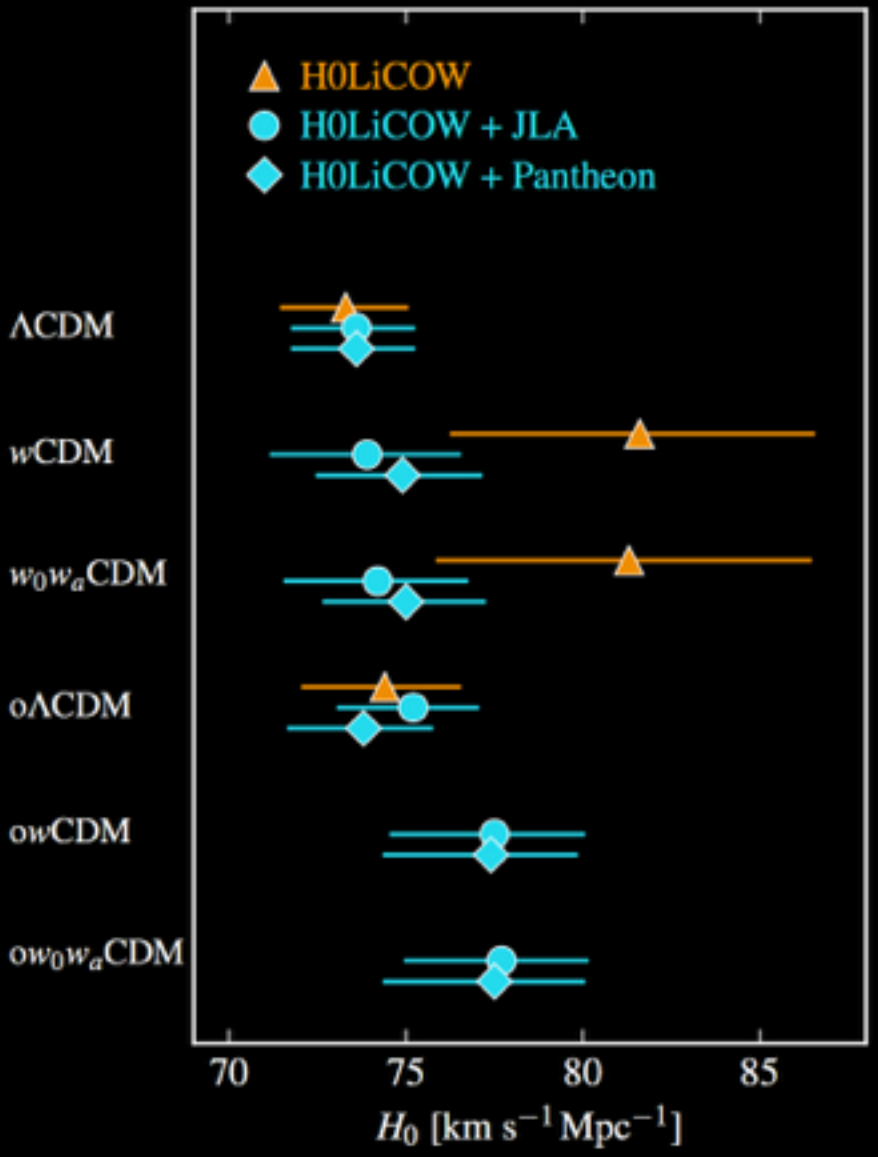
[Wong, Suyu, Chen et al. 2019 (H0LiCOW XIII)]

Tensions between Early and Late Universe



[Verde, Treu, Riess 2019]

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

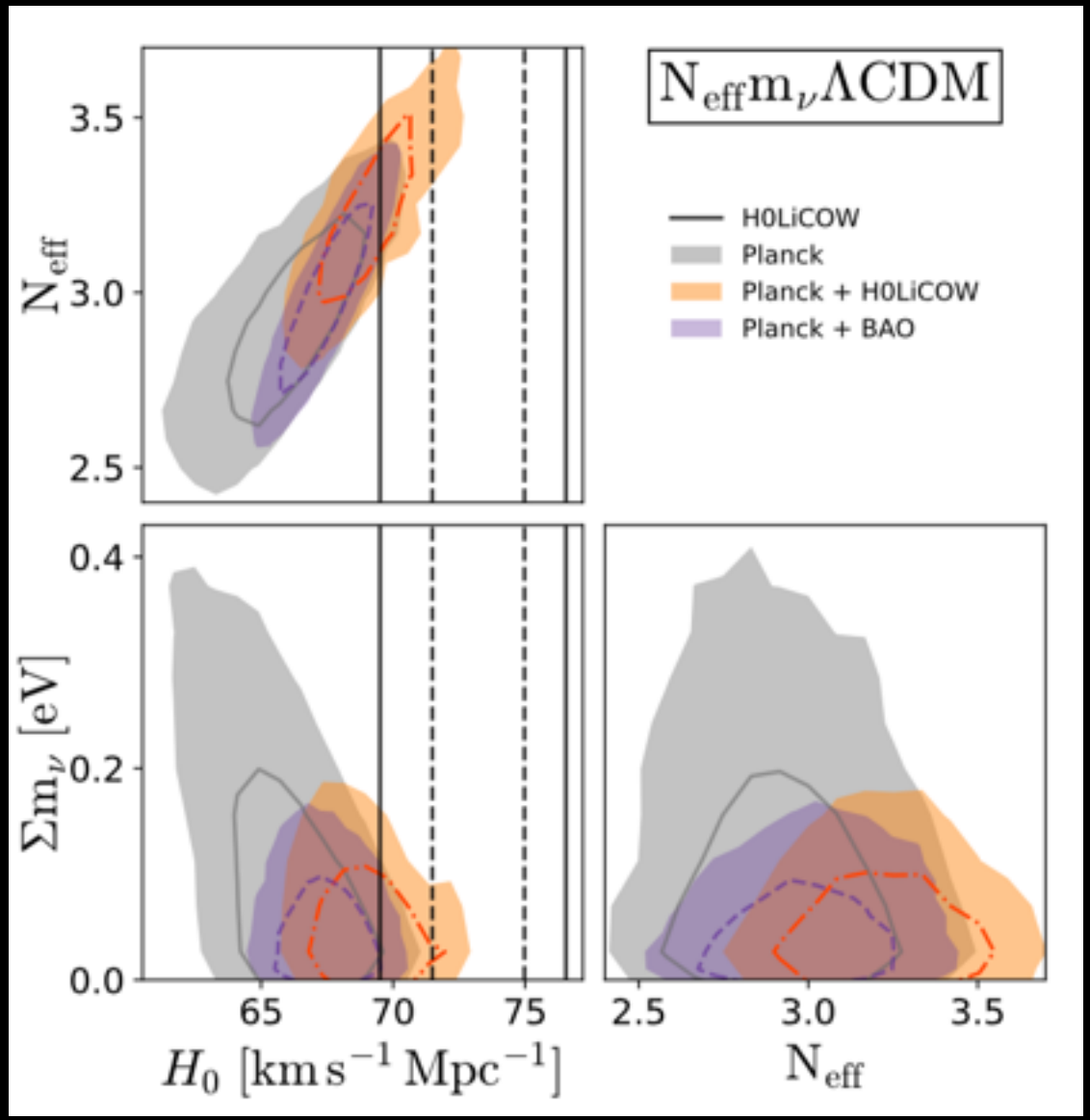


Use H0LiCOW distances to calibrate the SN distance scale

➜ reduces dependence of H0 on cosmology

[Jee, Suyu, Komatsu et al. 2019; Taubenberger, Suyu, Komatsu et al. 2019; Wong, Suyu, Chen et al. 2019 (H0LiCOW XIII)]

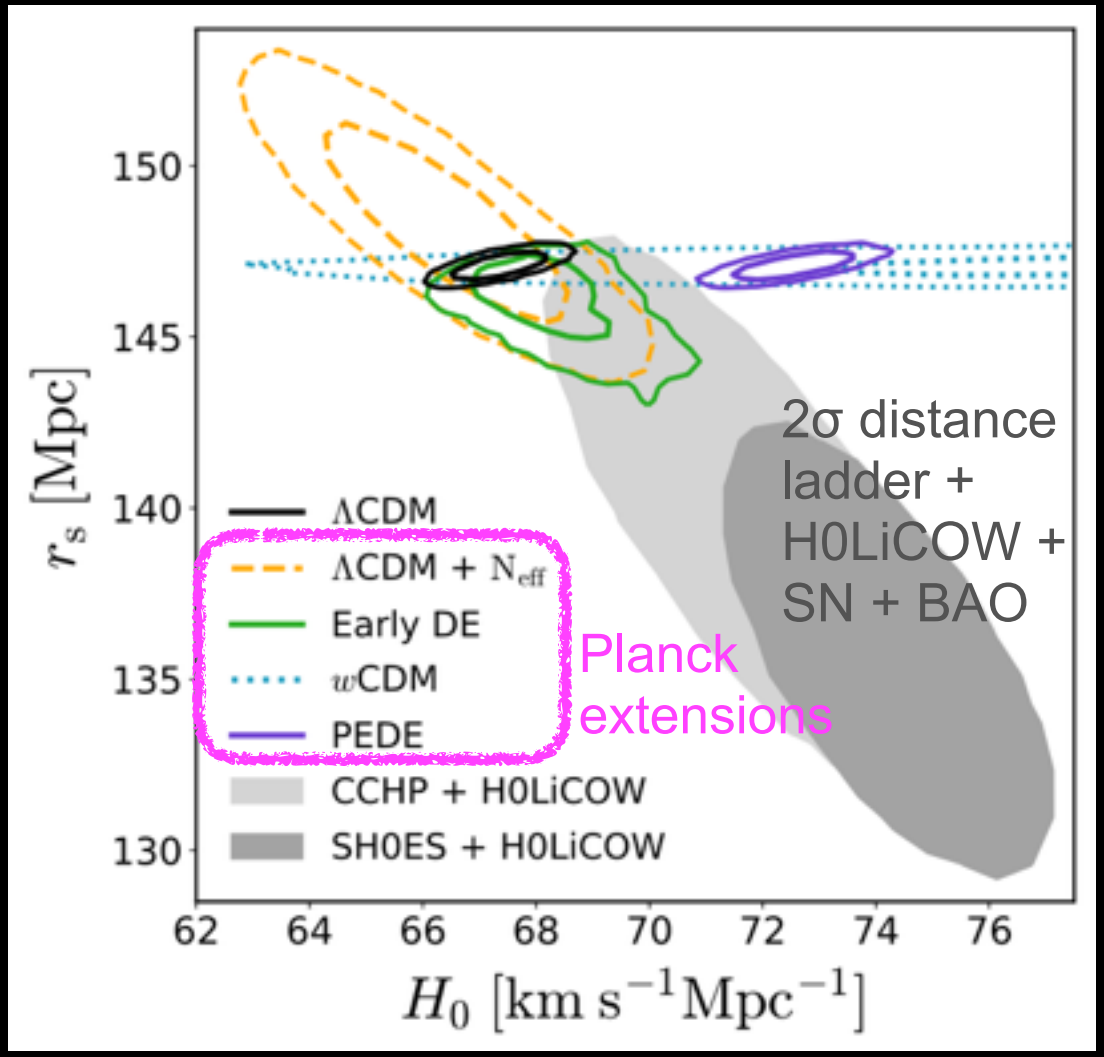
Solution: neutrinos?



Variable N_{eff} and m_ν help alleviate tension

[Wong, Suyu, Chen et al. 2019 (H0LiCOW XIII)]

Solution: shorter sound horizon

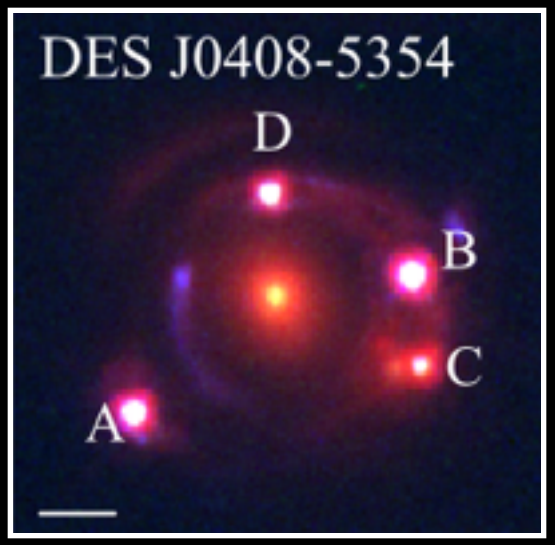


Make sound horizon shorter

- new relativistic particle?
- early dark energy?

[Arendse, Wojtak, Agnello et al. 2019]

Looking forward



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

Looking forward

Latest result
➜ Shajib et al. 2019b