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An Updated Measurement of the Hubble Constant from the H_0 Lenses in COSMOGRAIL's Wellspring (H0LiCOW)

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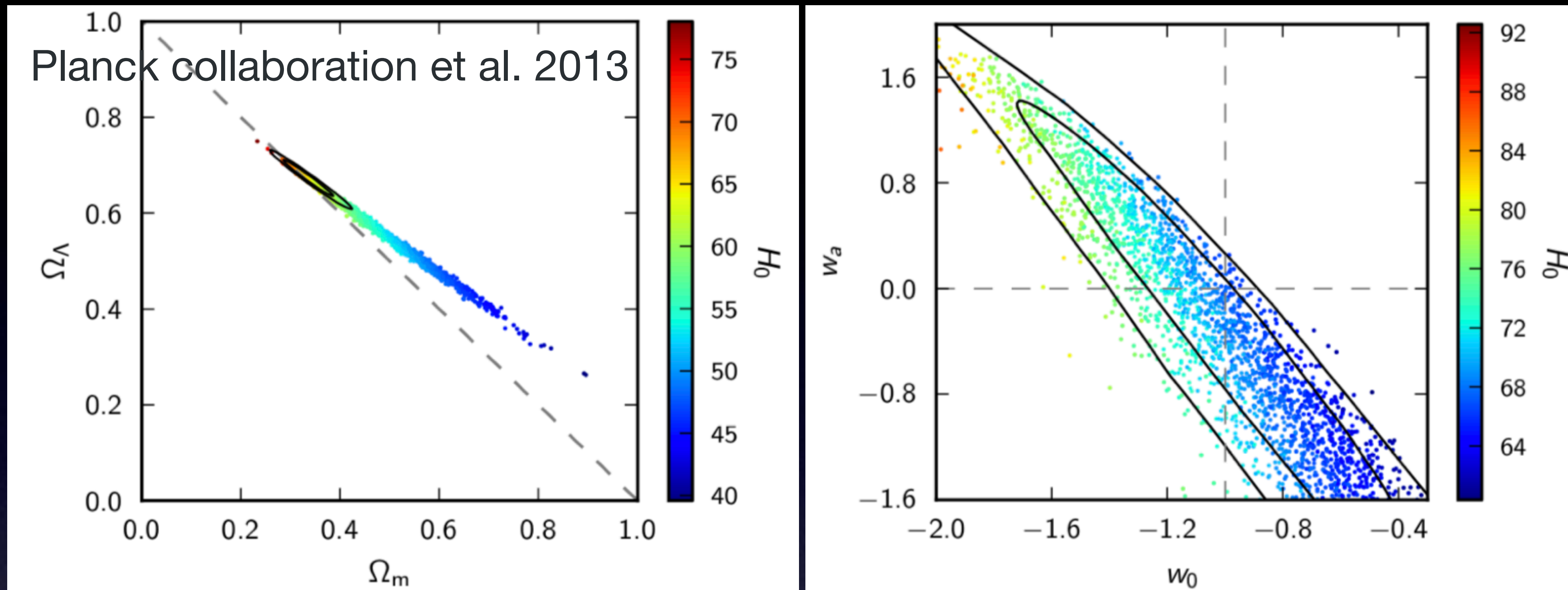
Outline

- Motivation: the Hubble Constant
- Constraining cosmological parameters with gravitational lens time delays
- H0LiCOW and our newest results
- Towards the future

Motivation: The Hubble Constant H_0

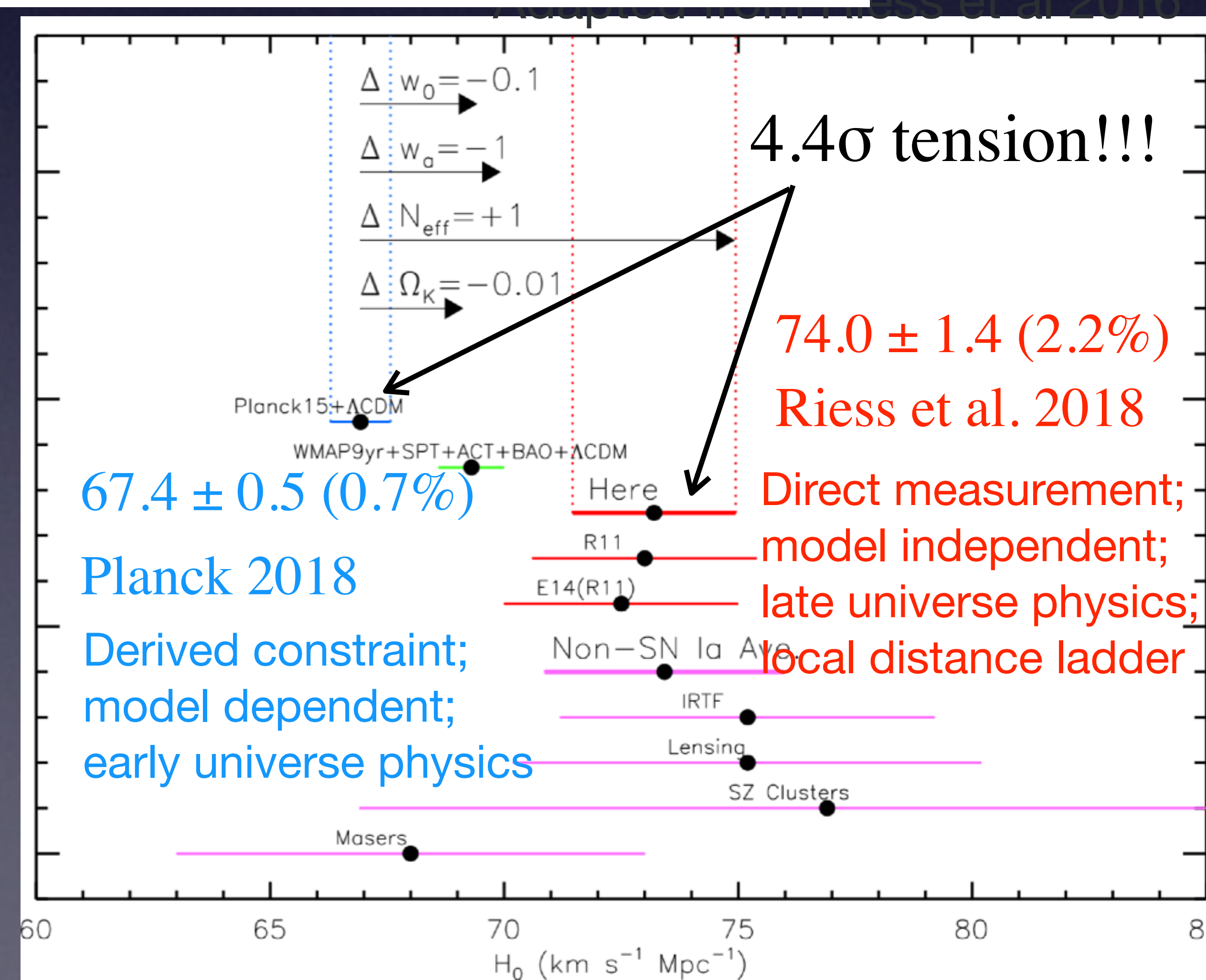
- H_0 is tightly constrained by Planck, but only under in the 6-parameter flatΛCDM



Currently, there is tension between H_0 measurements from different probes...

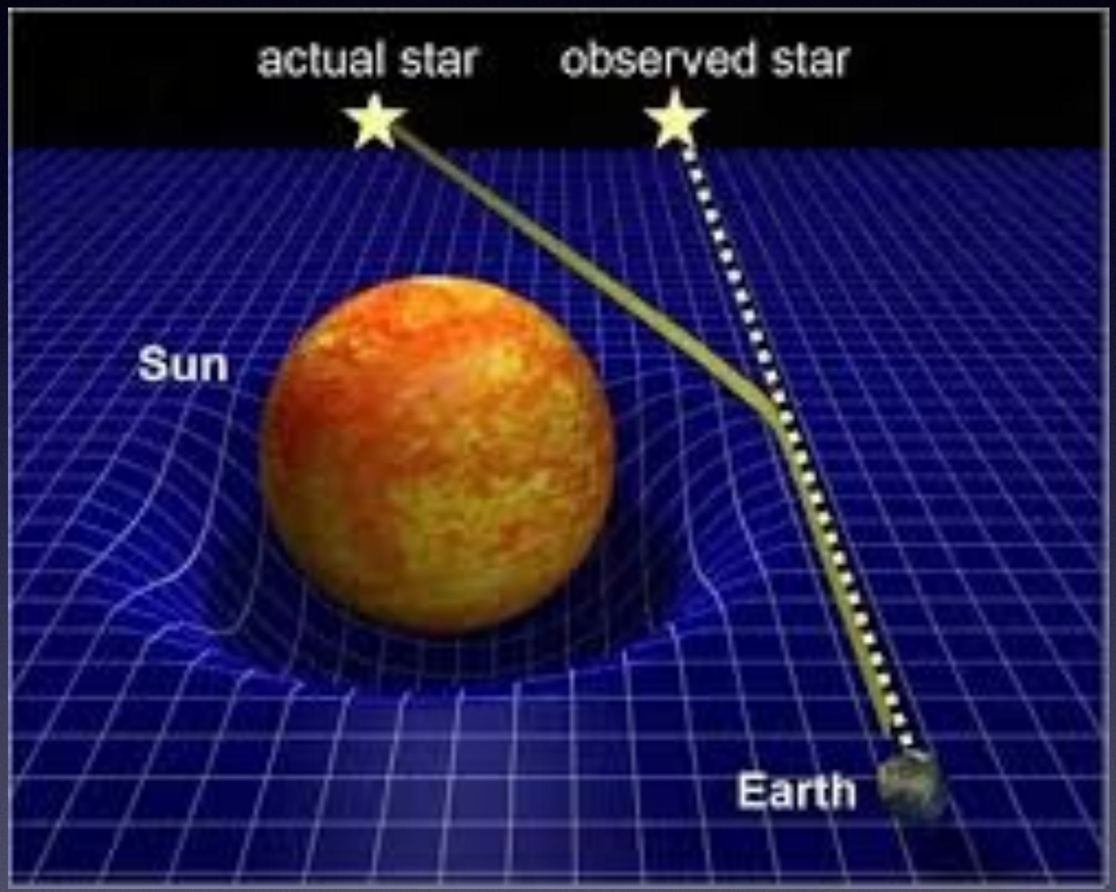
1) systematic measurement errors?
2) New physics?

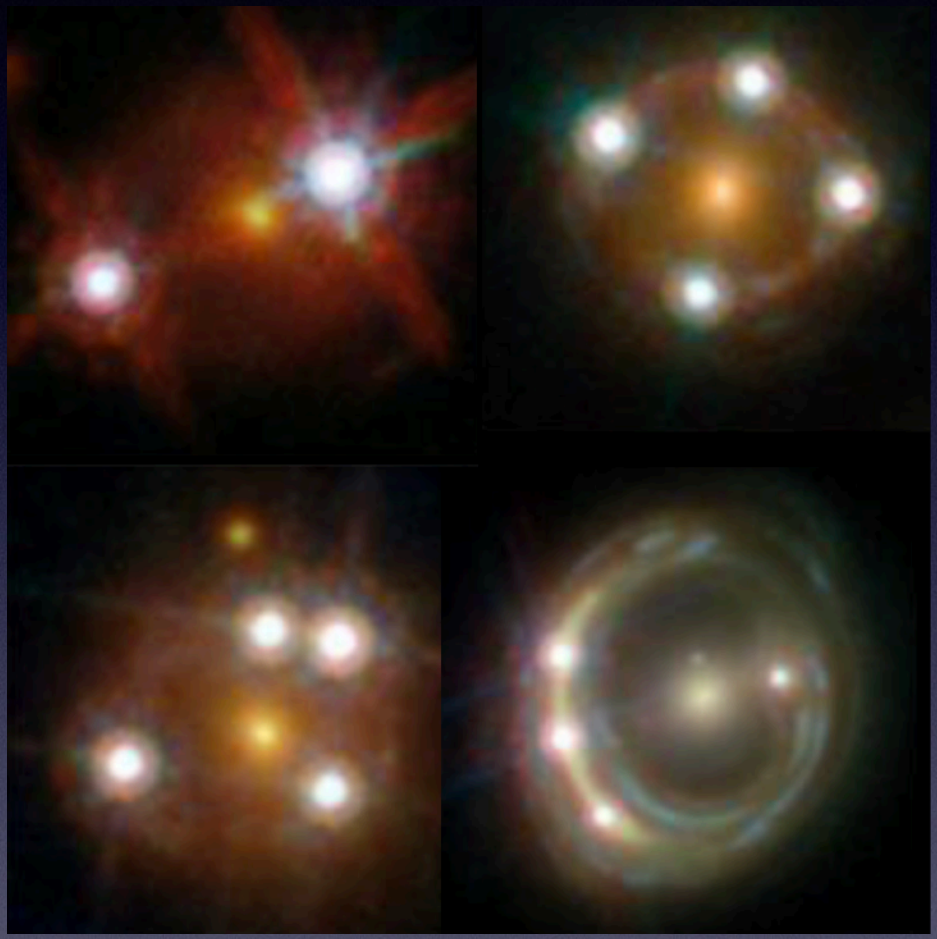
An independent method of comparable precision is needed to test for hidden systematics and check for consistency



Constraining cosmology with GL time delays: I

- General Relativity: mass curves spacetime -> deflection of light rays



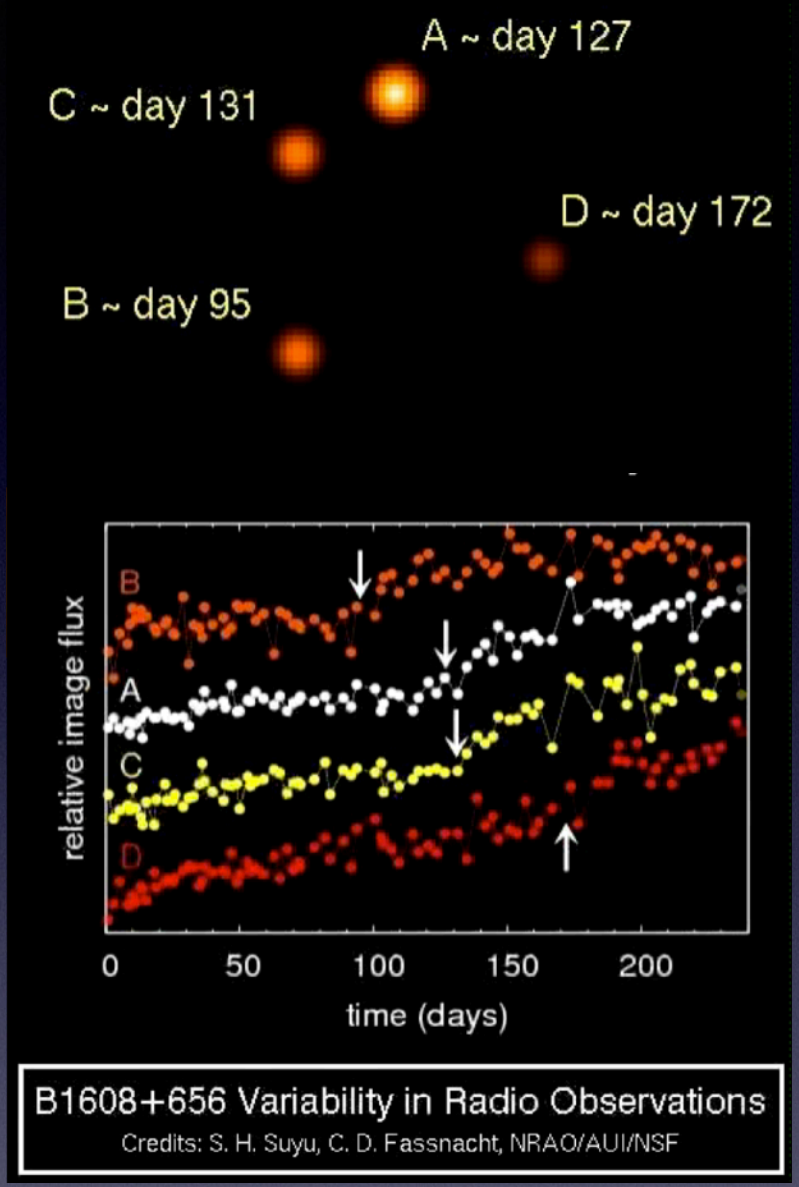


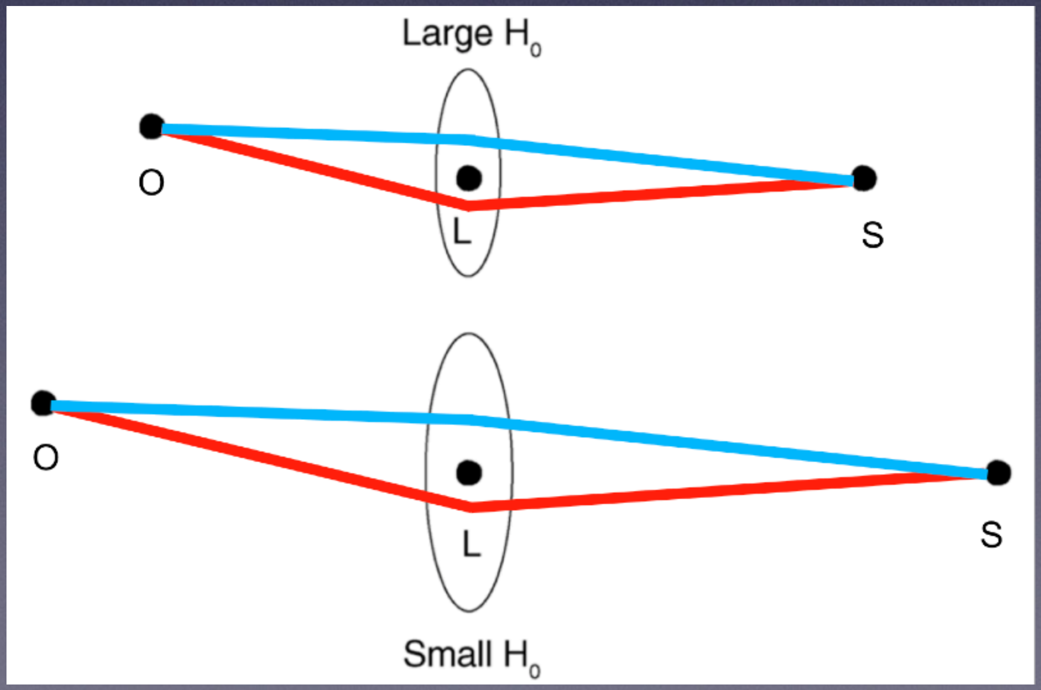
Hubble Telescope images of GLs

- With the right alignment, massive galaxies acting as GLs produce multiple images of background sources

Constraining cosmology with GL time delays: II

- Quasars are powered by accretion into SMBH
- Quasars "flicker" in time



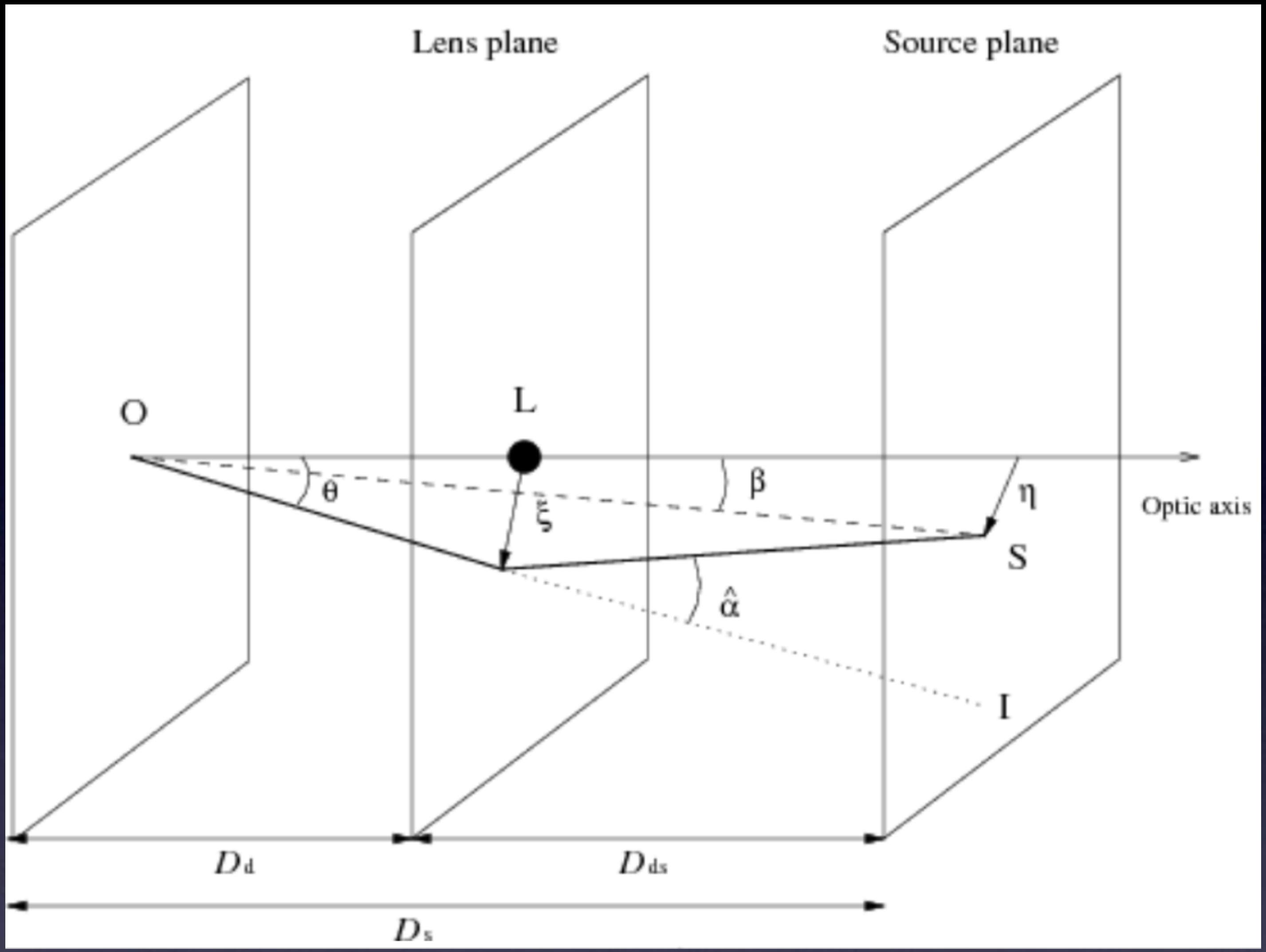


$$v = H_0 d$$

$$\frac{\text{length - length}}{c} = \Delta t$$

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

Constraining cosmology with GL time delays: III



Angular diameter distances:

$$D(z) = \frac{c}{H_0}\frac{1}{1+z}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

$$t(\theta,\beta) = \frac{1}{c}\boxed{\frac{D_d D_s}{D_{ds}}(1+z_d)}\phi\left[\frac{(\theta-\beta)^2}{2} - \psi(\theta)\right]$$

$$D_{\Delta t} \propto \frac{1}{H_0}$$ time delay distance

We measure relative time delays between pairs of images:

$$\Delta t = \frac{1}{c} D_{\Delta t}\Delta\phi$$

monitoring (→ Δt) lens modeling (→ $\Delta\phi$)

$D_{\Delta t}$ encloses the cosmological information, and is primarily sensitive to H_0

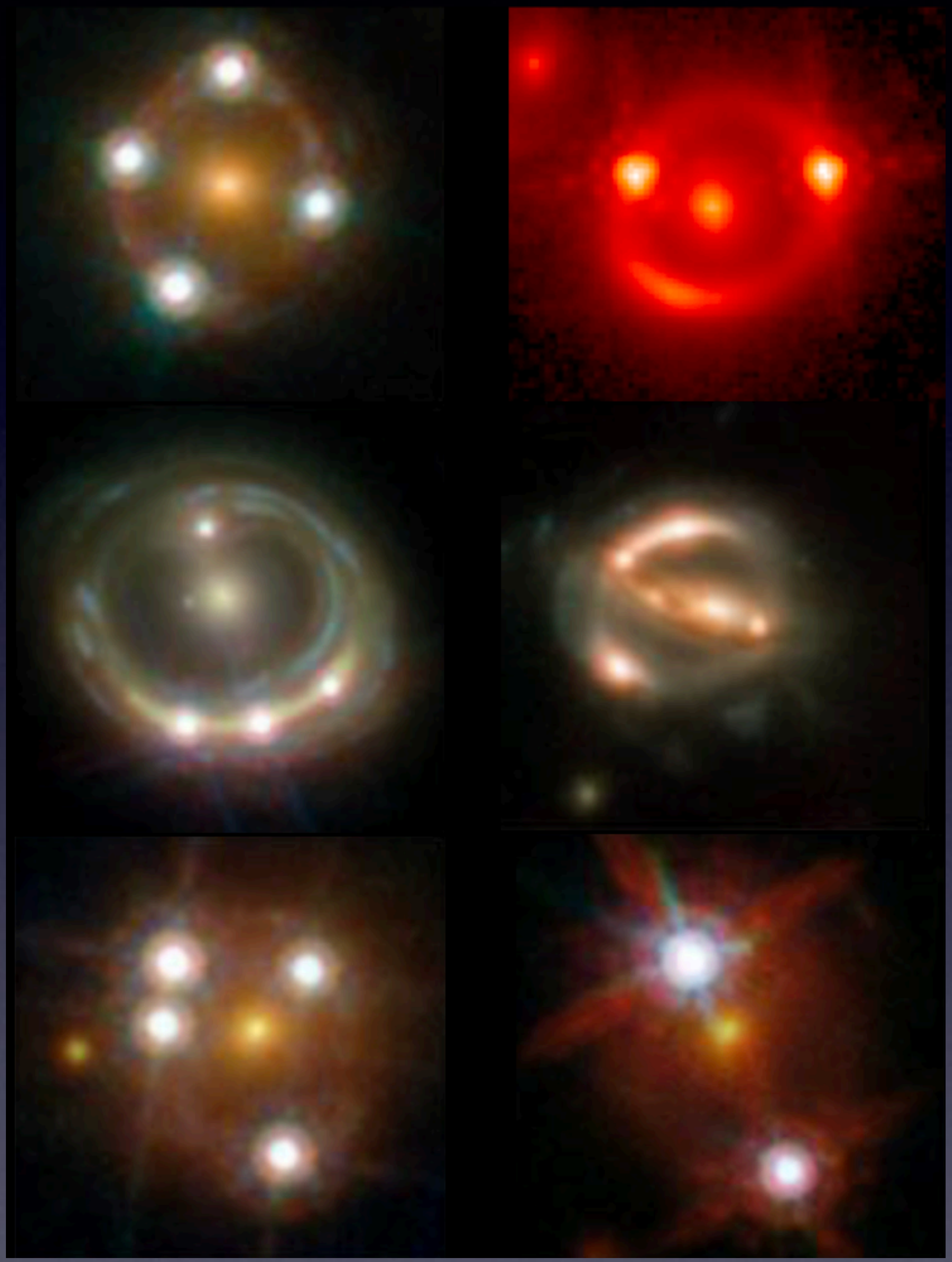
- based on angular diameter distances → immune to dust, no calibration issues
- an absolute distance; provides a distance-redshift relation
- Based on well-understood physics (GR)

HOLiCOW: our mission

• We focus on GL systems for which we can gather an exhaustive set of data, and account in detail for all known systematics

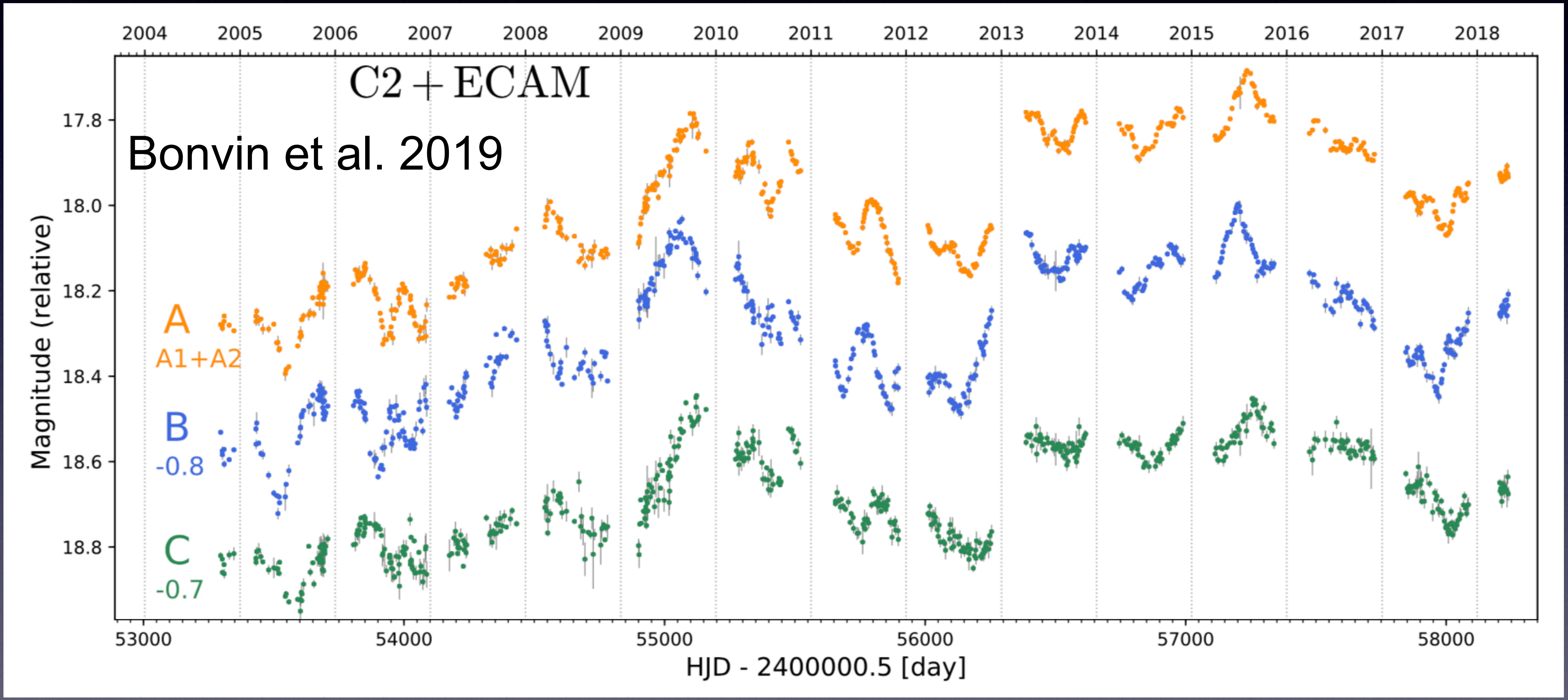
• a single lens with well-measured time delays can be used to measure time delay distances to 6-7% uncertainty (random and systematic; Suyu et al. 2010, 2013)

• Thus, when doing joint inference we insure both precision and accuracy



H0LiCOW: what do we need?

- Time delays measured of ~ 10 years from COSmological MOnitoring of GRAvItational Lenses (COSMOGRAIL)

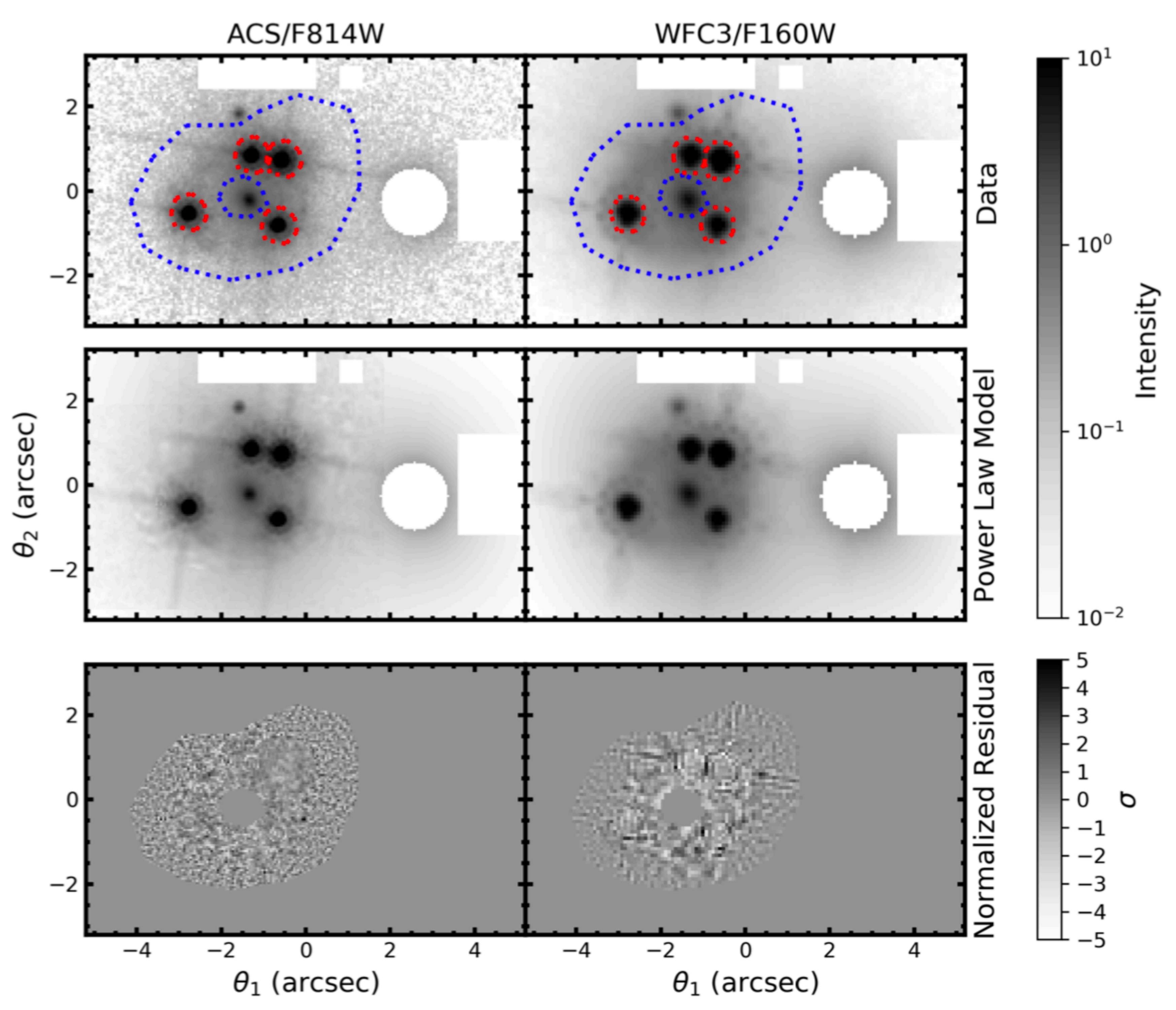


$$\boxed{\Delta t} = \frac{1}{c} D_{\Delta t} \Delta \phi$$

HOLiCOW: what do we need?

- High-resolution Hubble Telescope images of the lenses, using the constraints from 1000s of pixels in the arcs to constrain the mass potential

Bonvin et al. 20



Rusu et al. 2019

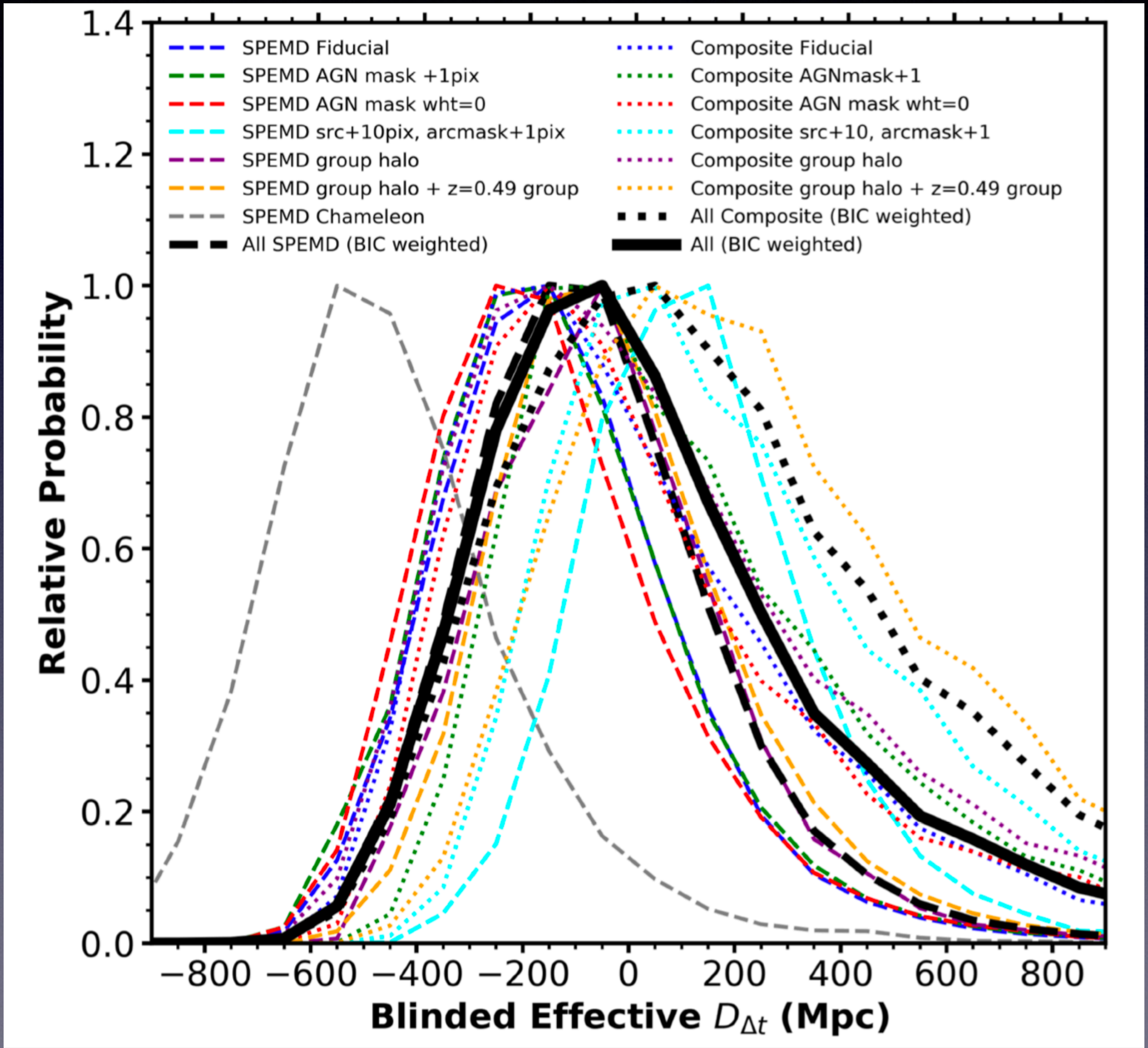
$$\Delta t = \frac{1}{c} D_{\Delta t} \Delta\phi$$

HOLiCOW: results from the latest GL

- The probability distribution for the time delay distance:

- test for systematics

- blinded determination with centroids offset to origin, following SNe Ia approach in Conley et al. 2006



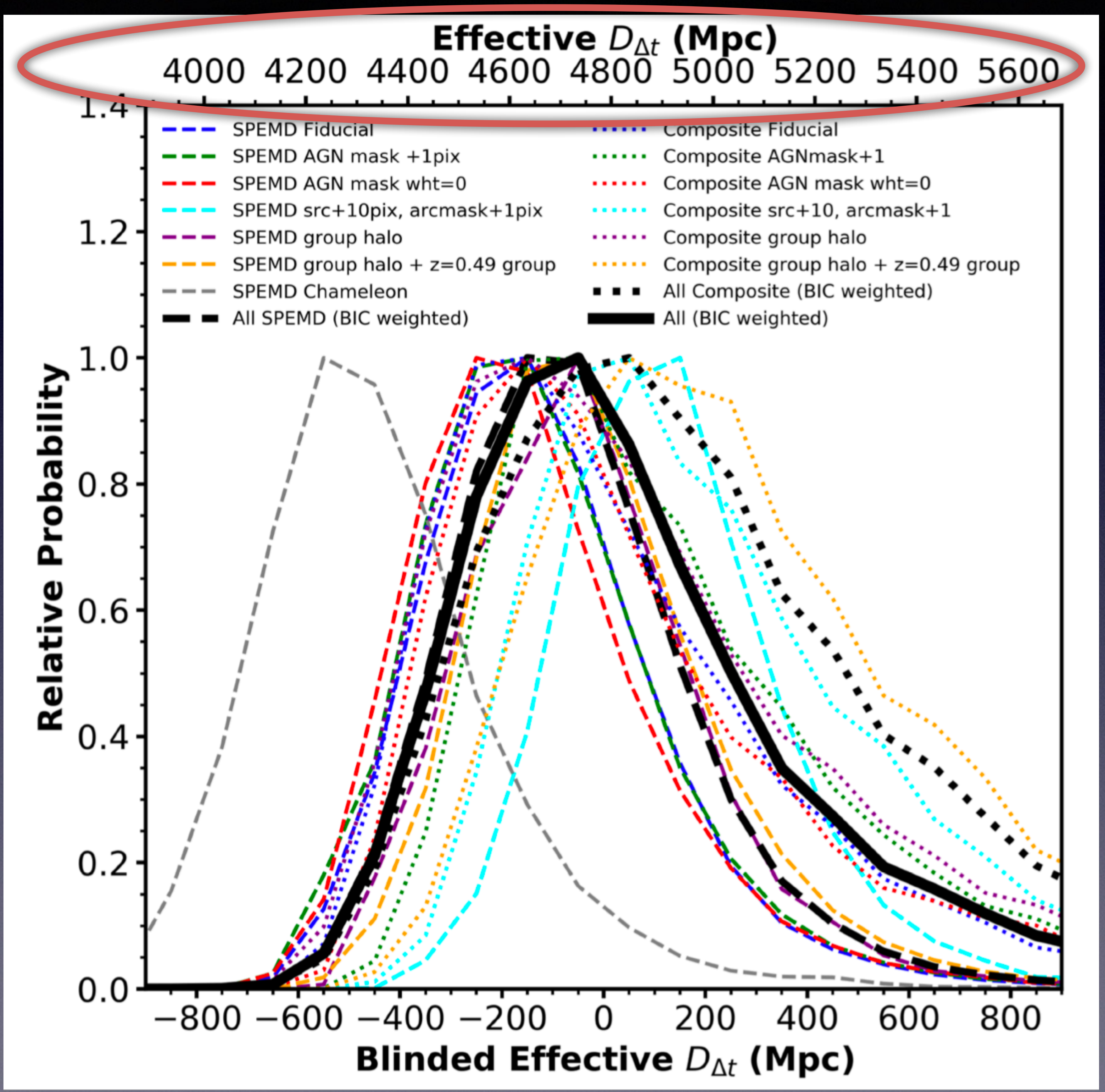
Rusu et al. 2019

HOLiCOW: results from the latest GL

unblinding on 7 May 2019:

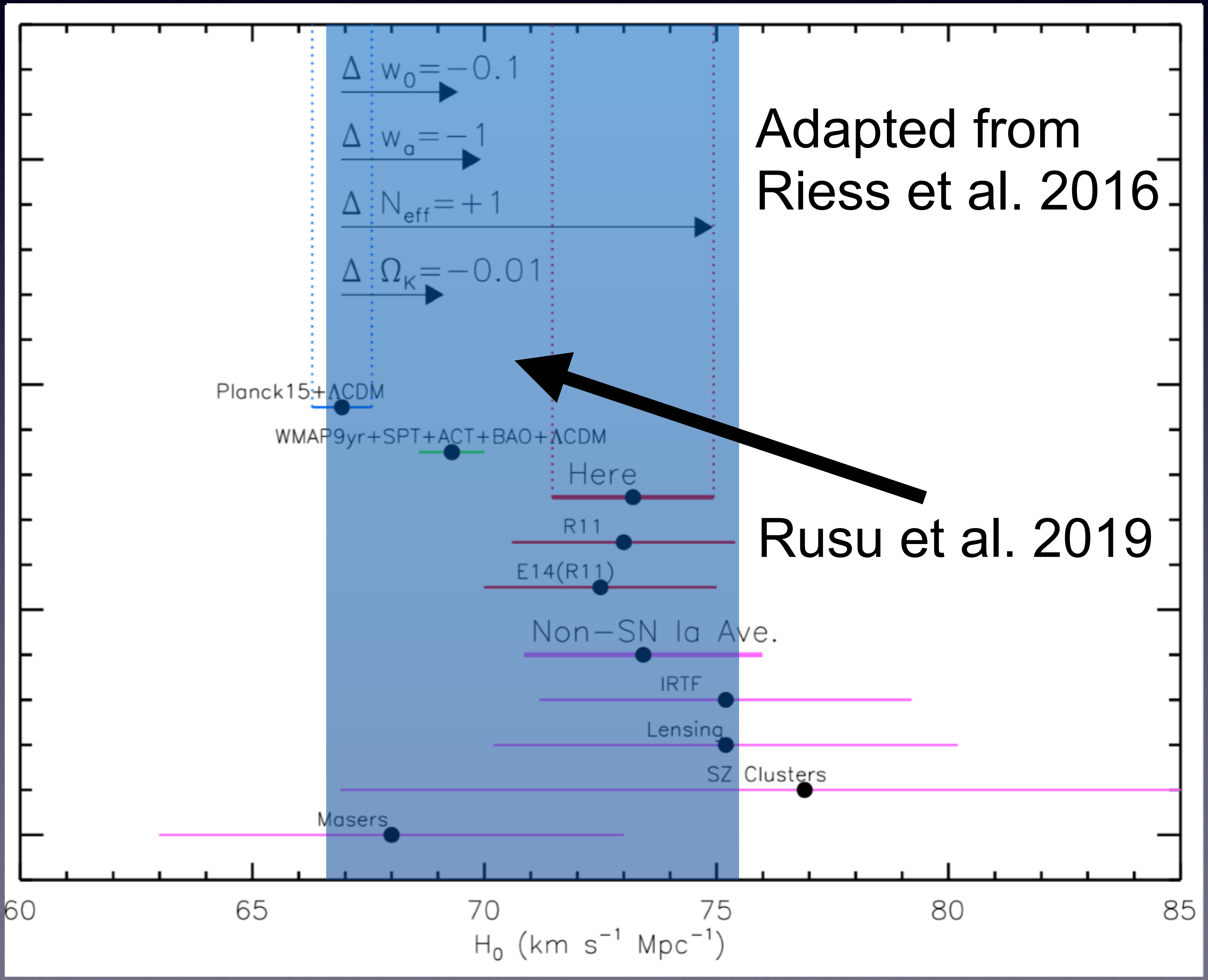
~ 6.6 % uncertainty

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



HOLiCOW: results from the latest GL

- A single lens produces results in agreement with the other probes, but poor precision
- At present, we have independent H0 measurements from 5 lenses
- Compute Bayes factor F to test if the 5 lenses are consistent with same cosmology



$$F = \frac{P(d_1, ..., d_5 | H^{\rm global})}{\prod_{I=1,...,5} P(d_i | H^{{\rm ind},i})} > 1$$

HOLiCOW: results from 5 lenses

Flat-ΛCDM

HOLiCOW: results from 5 lenses

Flat-ΛCDM

HOLiCOW: results from 5 lenses

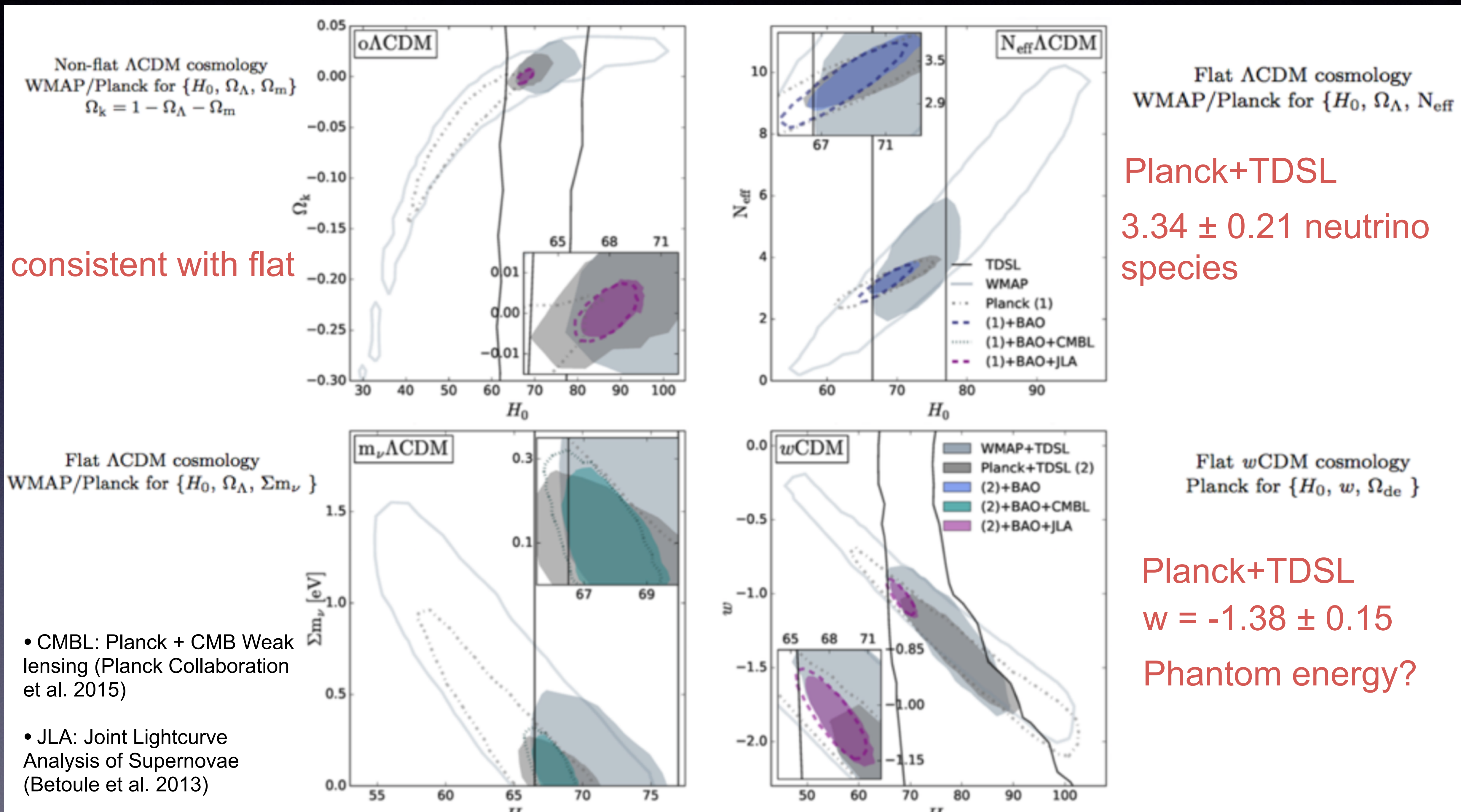
Flat-ΛCDM

HOLiCOW: results from 5 lenses

Flat-ΛCDM

• Tighter constraints are obtained by combining with other probes (complementarity -> break parameter degeneracies)

• Combining 3 H0LiCOW lenses with other probes (Bonvin et al. 2017):



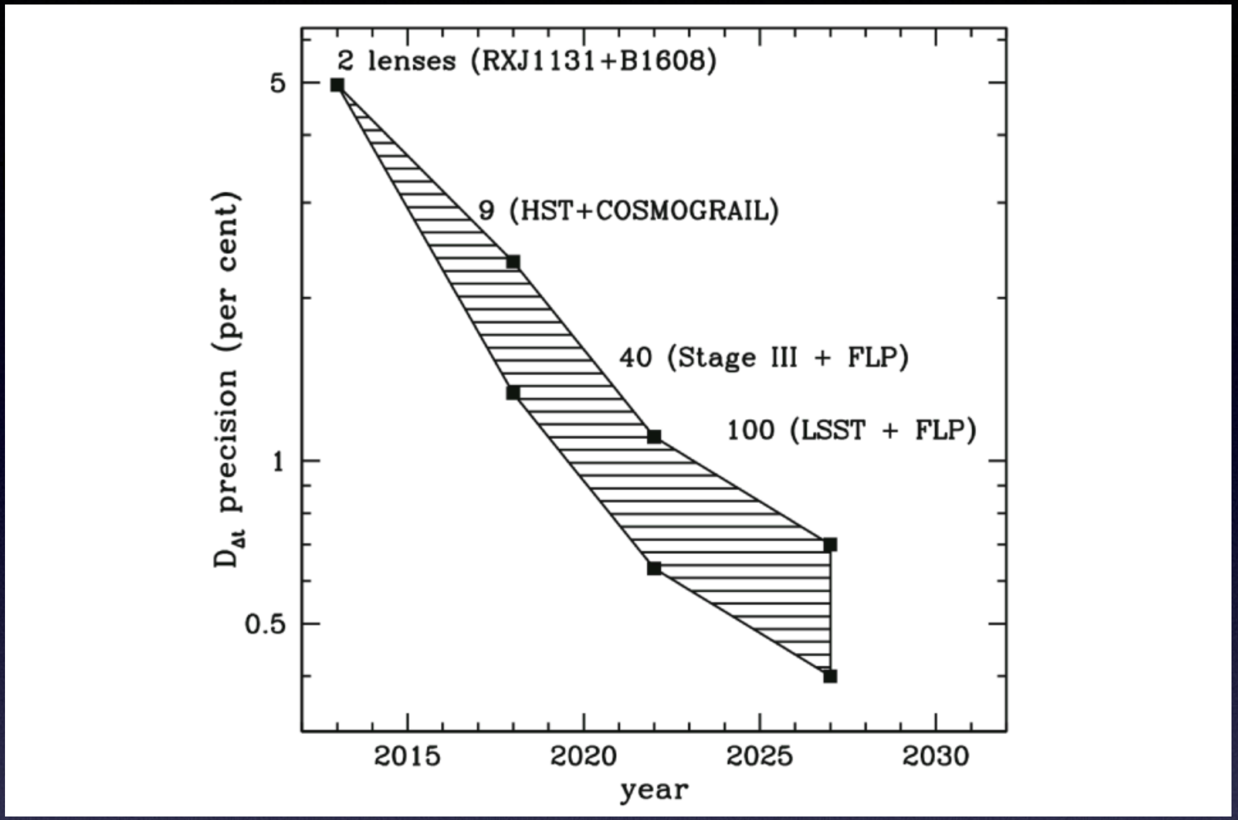
• Wong et al. 2019 will show the combination with 6 lenses

HOLiCOW: the future

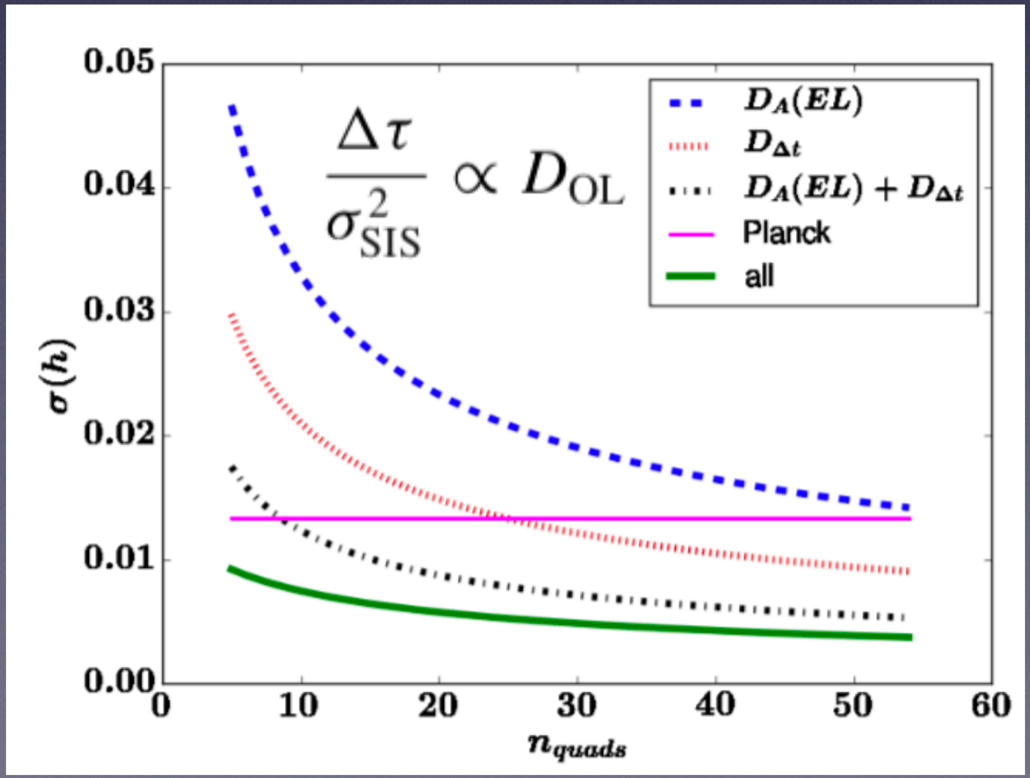
- Things are accelerating:
    - Suyu et al. 2010
    - Suyu et al. 2013
    - Wong et al. 2017
    - Birer et al. 2019
    - Rusu et al 2019
    - Chen et al. 2019, in prep.
- Milestone paper: Wong et al. 2019, in prep. Will combine 6 lenses
- We are making progress at improving our technique:
    - Theoretical progress on breaking the mass-sheet degeneracy
    - We will acquire spatially resolved kinematics to constrain anisotropy
    - We are improving imaging modeling using adaptive optics
- LSST will significantly expand the known sample of lensed quasars

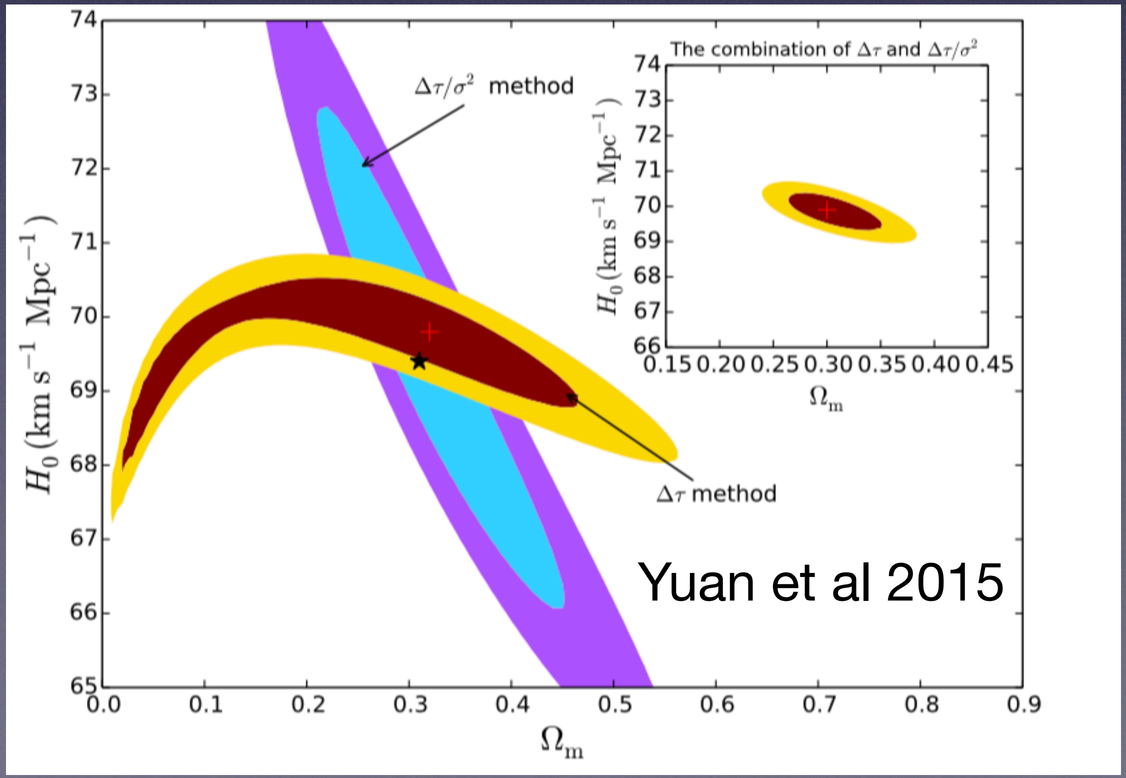
H0LiCOW: the future

- Treu & Marshall 2016 extrapolate 1% precision from H0LiCOW with ~40 lenses



- Jee et al. 2016: We can achieve 1% on H0 in ΛCDM with just ~15 lenses





Summary

- H0 measurements from different lenses give mutually consistent results; 5 lenses constrain H0 to X.X% in flatΛCDM, in good agreement with SH0ES and inconsistent with Planck at X.Xσ

- Milestone paper Wong et al. 2019 in prep. will combine the 6-lens H0LiCOW measurement with different cosmological probes

- H0LiCOW is expected to reach 1% precision on H0 from > ~15 lenses in a few years