H_0 from Lensed Quasars

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DOI:
10.5281/zenodo.4062127

Publication date:
2020

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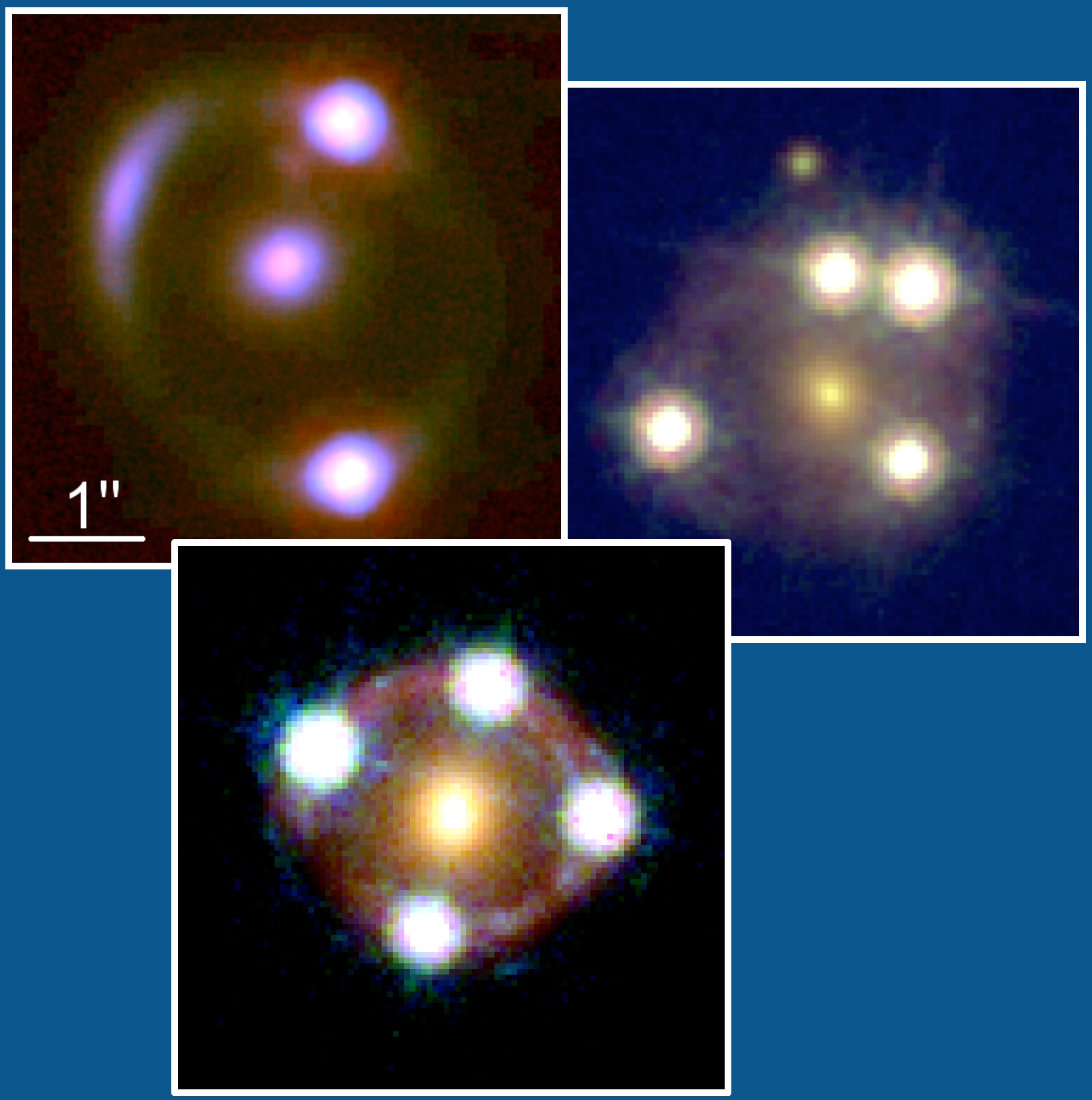

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on behalf of the H0LiCOW/TDCOSMO collaboration

H_0 2020
June 24, 2020

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
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Recent Tension in H_0 Measurements

- *Planck* finds H_0 = 67.4±0.5 km/s/Mpc in flat ΛCDM
- Independent type Ia SNe results calibrated by the distance ladder find H_0 = 74.0±1.4 km/s/Mpc (SH0ES; Riess+2019)
- 4.4σ discrepancy
  - systematic errors?
  - new physics?
- Need more independent measurements of H_0

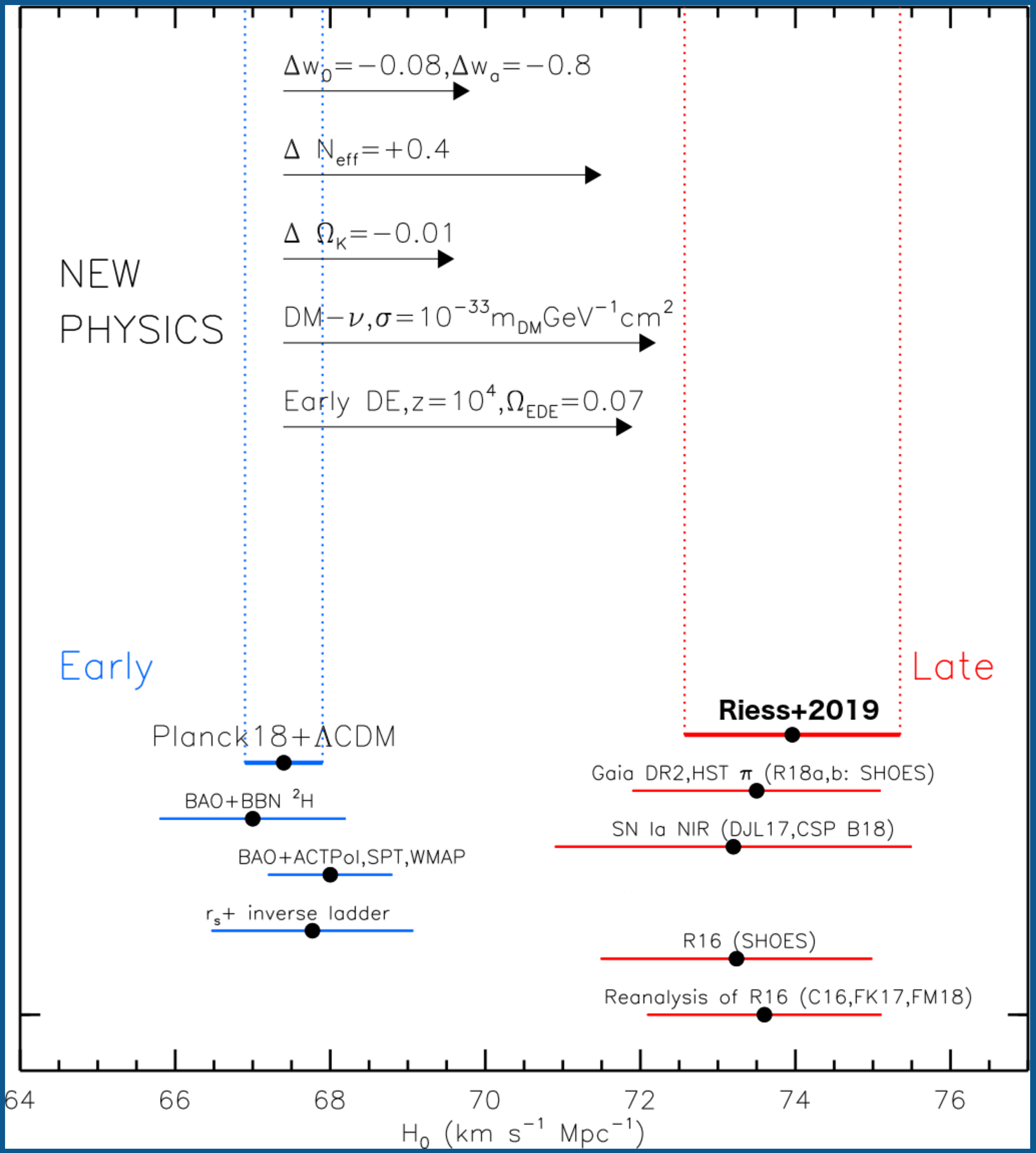


figure adapted from Riess+2019

Gravitational Lensing

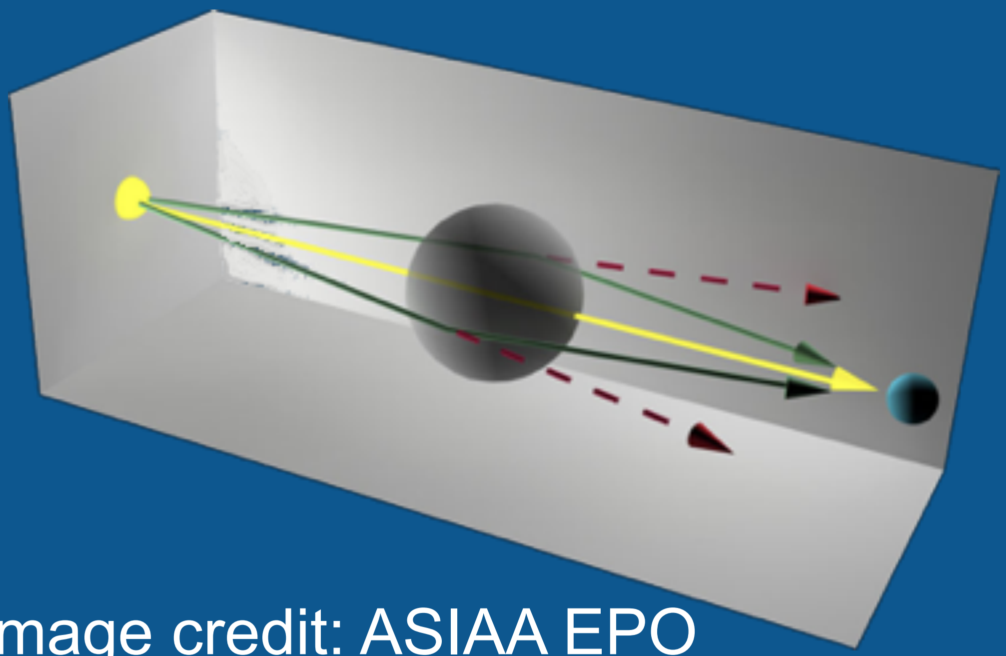
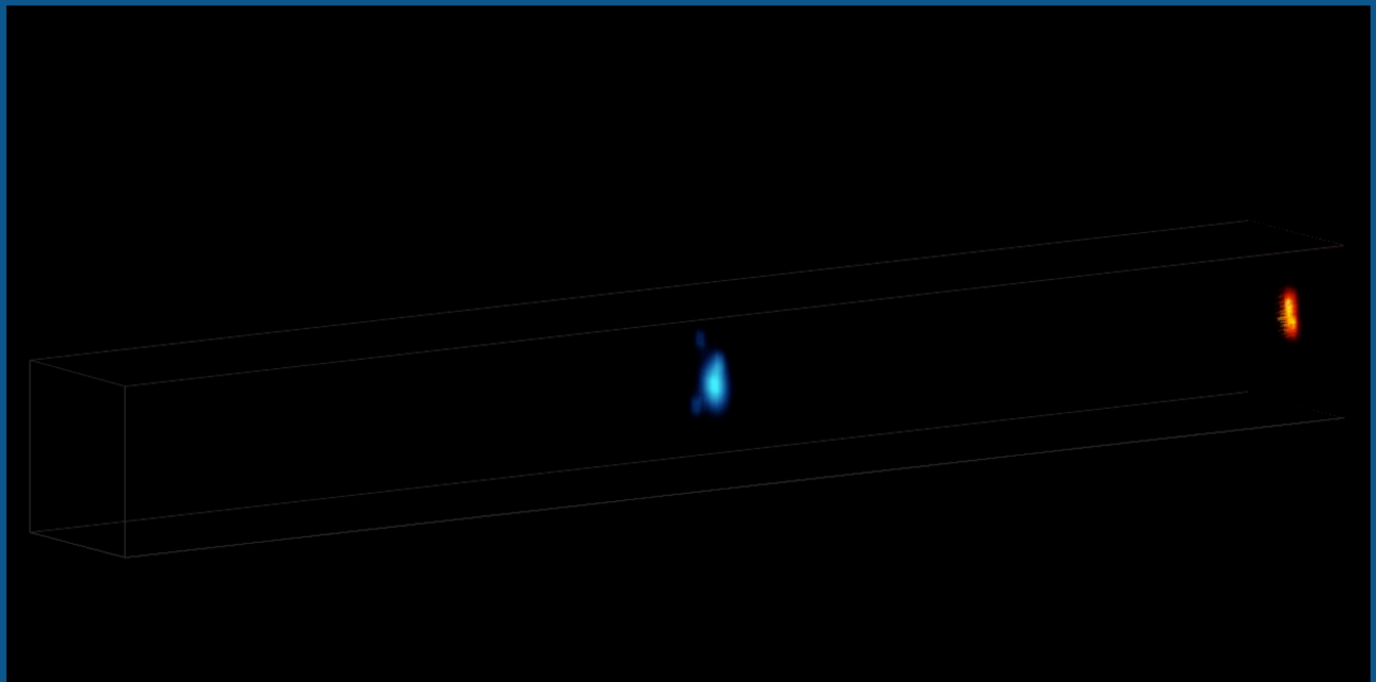


Image credit: ASIAA EPO

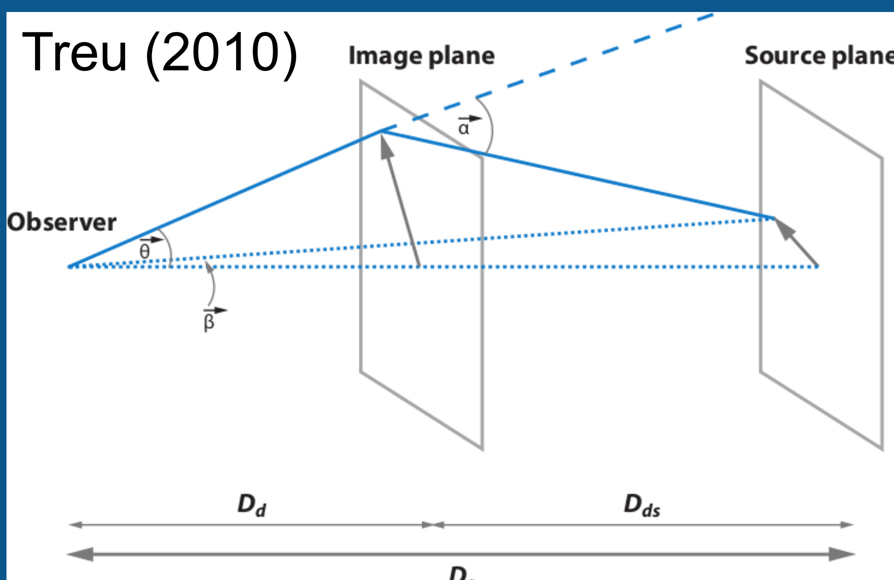
- Background object (source) magnified by foreground object (lens)
- Multiple images → create lens model
- Lensing effect depends on:
  - mass distribution of lens
  - line of sight structure
  - **cosmology**

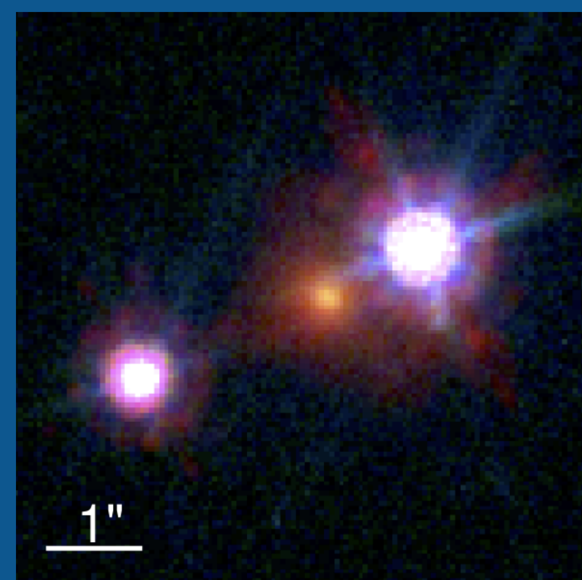


Animation credit: Y. Hezaveh

Time-Delay Cosmography

- There is a "time delay" between the multiple variable lensed images
  - due to different path length, gravitational potential at different images
- Can determine "time-delay distance" $D_{\Delta t}$, inversely proportional to H_0
- One-step method to infer H_0, *independent of CMB and distance ladder*





Angular diameter distances $D \propto \frac{1}{H_0}$

$$t(\theta, \beta) = \underbrace{\frac{1}{c} \frac{D_d D_s}{D_{ds}} (1 + z_d)}_{D_{\Delta t}} \underbrace{\left[\frac{(\theta - \beta)^2}{2} - \psi(\theta) \right]}_{\Phi_{\rm lens}}$$

Time delay

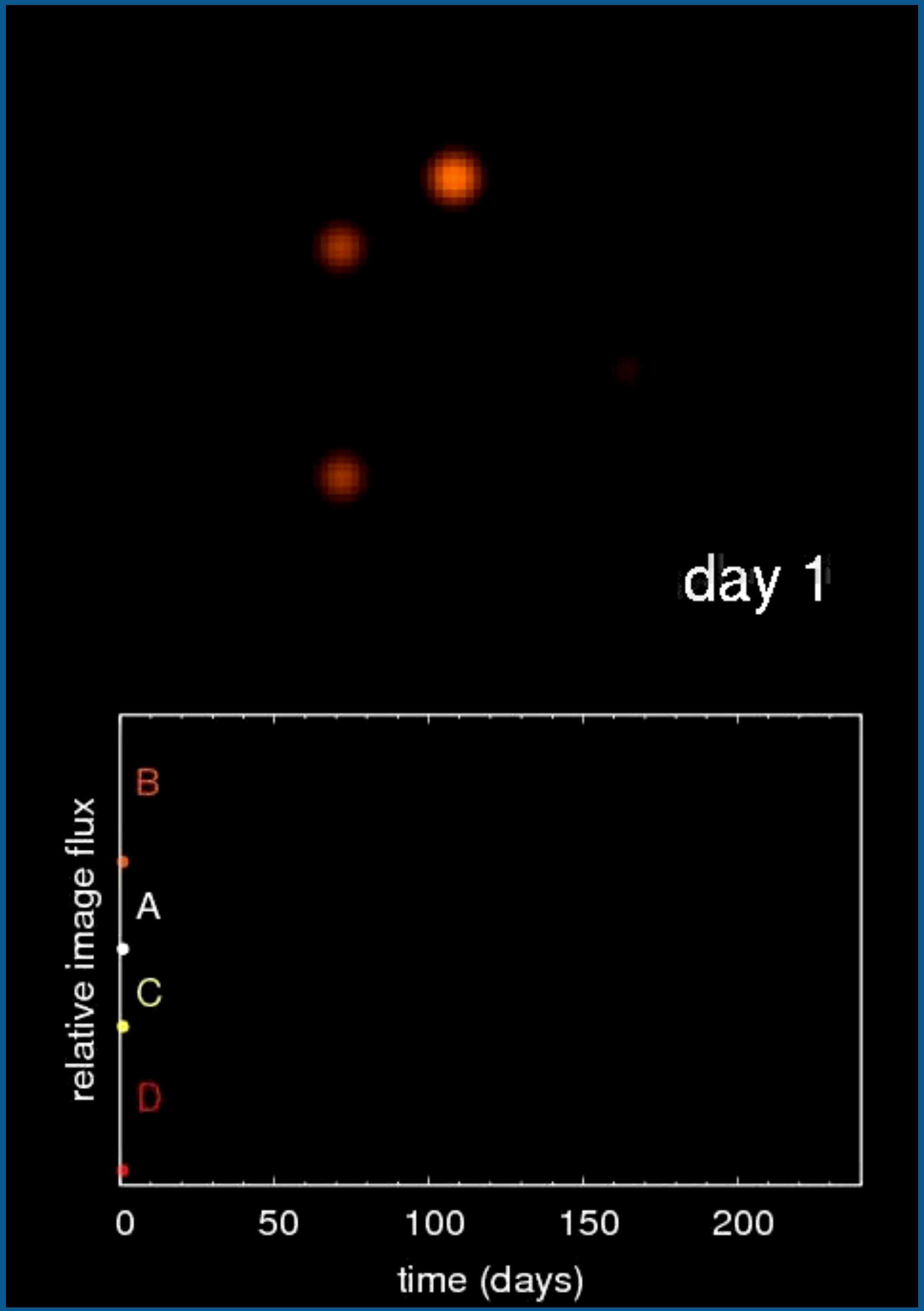
Time-delay distance

Fermat potential (from lens model)

$$\Delta t = \frac{D_{\Delta t}}{c} \times \Delta \Phi_{\rm lens} \Rightarrow D_{\Delta t} \propto \frac{1}{\mathbf{H_0}}$$

Cosmology with Lensed Quasars

- Lensed quasars
  - variable on short timescales (~days)
  - bright and easy to detect
- Measure time delay by monitoring lensed quasars over time
  - identical features in light curve correspond to same source event, but shifted in time



Animation credit: C. Fassnacht, S. Suyu

Cosmology with Lensed Quasars

- To constrain $D_{\Delta t}$, need:
  - Measured time delay (Δt)
  - Accurate lens model (to determine Φ_{lens})
  - Estimate of mass along line of sight (κ_{ext}; can bias $D_{\Delta t}$)
  - Lens galaxy velocity dispersion (complementary constraints on lens model and cosmological parameters; e.g., Jee+2015, 2016)

Time delay — Time-delay distance — Fermat potential (from lens model)

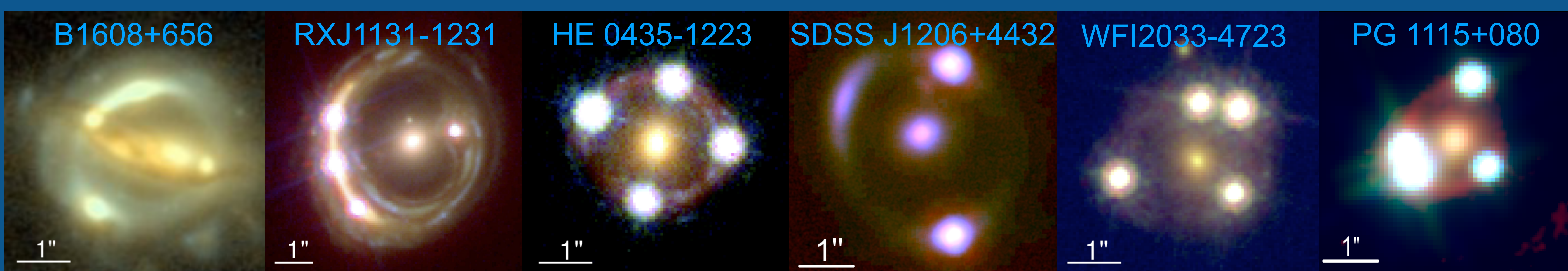
$$\Delta t = \frac{D_{\Delta t}}{c} \times \Delta\Phi_{\rm lens} \;\Rightarrow\; D_{\Delta t} \propto \frac{1}{\mathbf{H_0}}$$

Improvements in Time-Delay Cosmography

- Theory behind time-delay cosmography is old (Refsdal 1964)
  - predates first observed gravitational lens (Walsh+1979)
- Past attempts to use lensed quasars to determine H_0 were problematic
  - poorly-sampled light curves
  - not enough lens model constraints
  - simplistic / invalid assumptions about lens mass profile
  - ignored effects of mass along the line of sight
- Data and analysis methods have greatly improved since early days, time-delay cosmography now a competitive cosmological probe

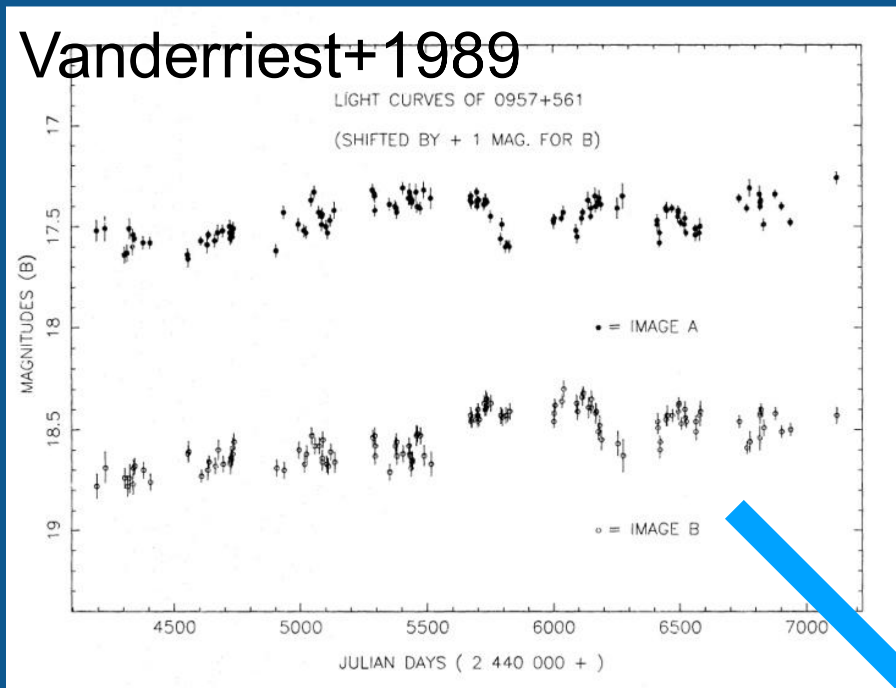
H_0 Lenses in COSMOGRAIL's Wellspring (H0LiCOW)

- Detailed analysis of several time-delay lenses (Suyu+2017)
  - long term monitoring from COSMOGRAIL (Courbin+2005), VLA (Fassnacht+2002) for accurate time delays
  - high-resolution imaging for detailed lens modeling
  - wide-field imaging/spectroscopy to characterize mass along LOS
  - spectroscopy to measure lens velocity dispersion
- ***Six*** lenses in latest milestone paper (Wong+2020)
  - 7th lens has been analyzed (Shajib+2020)

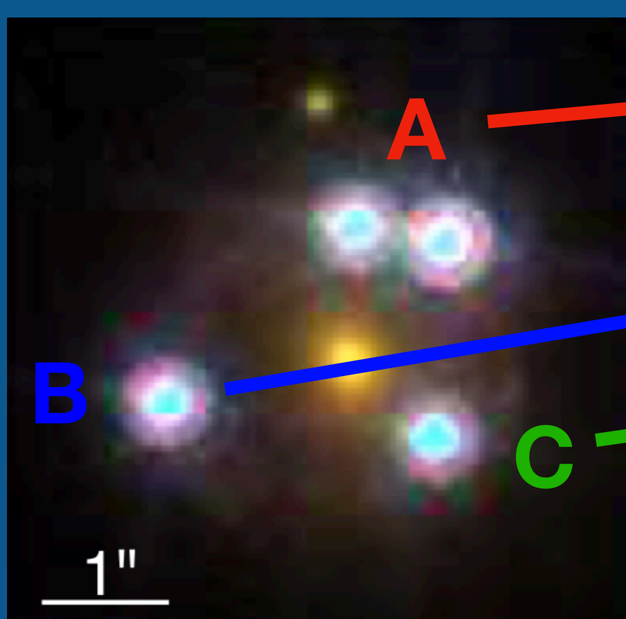


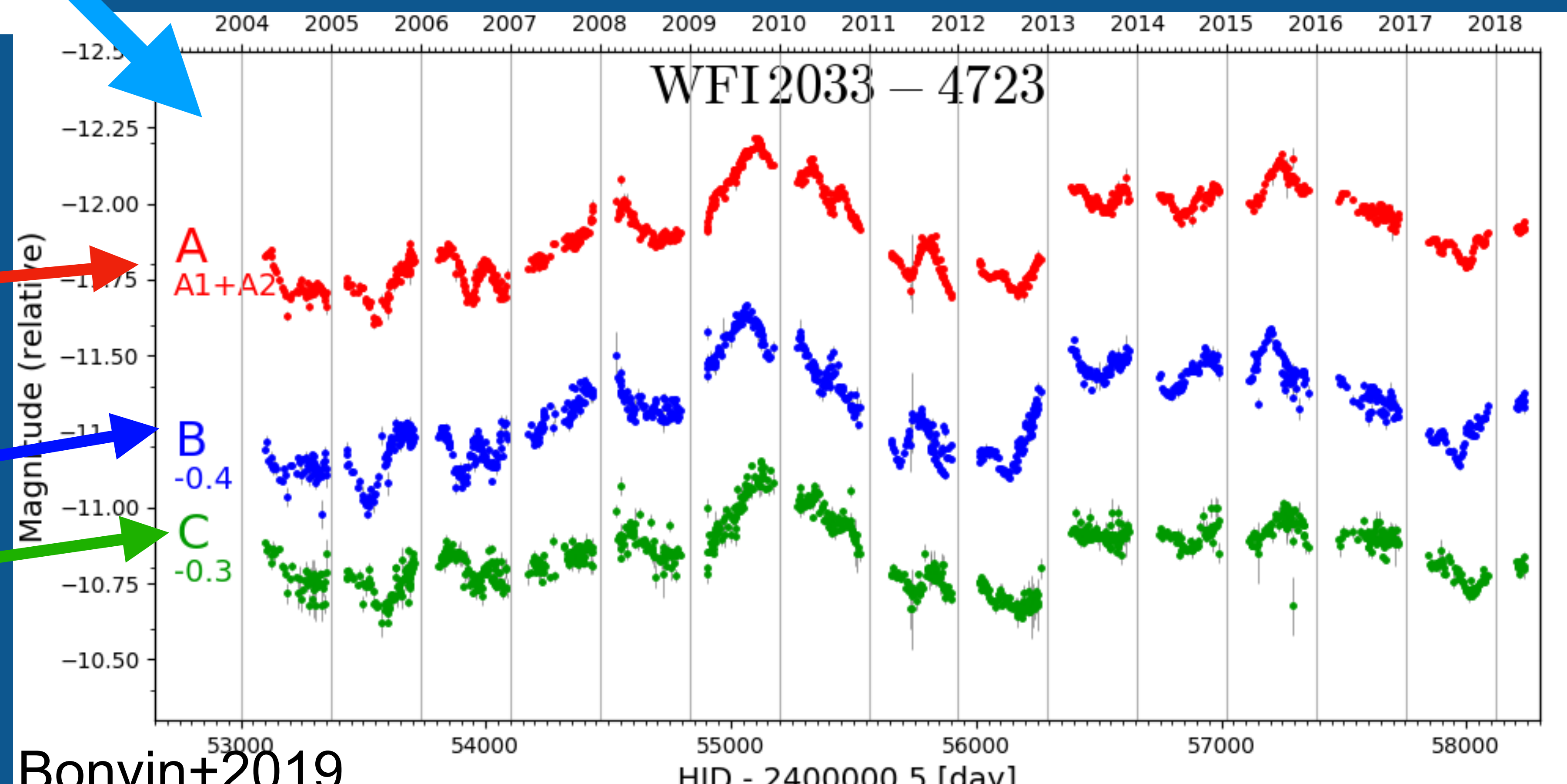
Suyu+2010 Jee+2019	Suyu+2013,2014 Chen+2019	Wong+2017 Chen+2019	Birrer+2019	Rusu+2020	Chen+2019

Time Delay Measurements



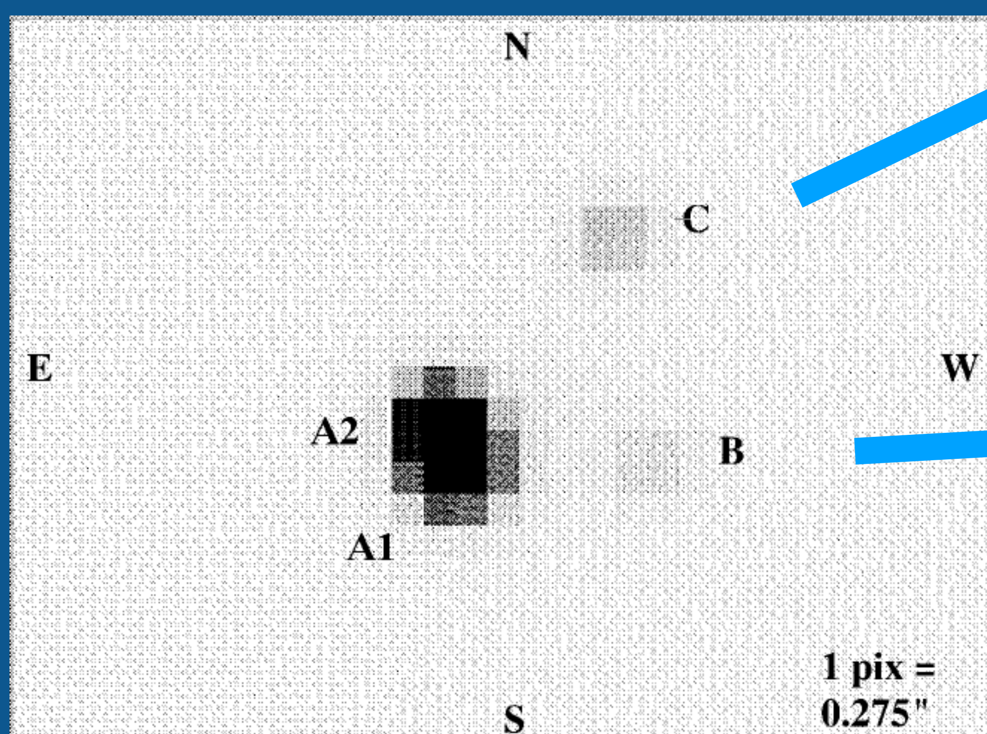
- COSMOGRAIL: long-term monitoring of time-delay lenses using small (1-m and 2-m) telescopes (Courbin+2011; Bonvin+2017)
- Well-tested algorithms for time-delay measurements (Tewes+2013)
- Long time baselines needed to minimize effects of microlensing (but working on high-cadence monitoring)



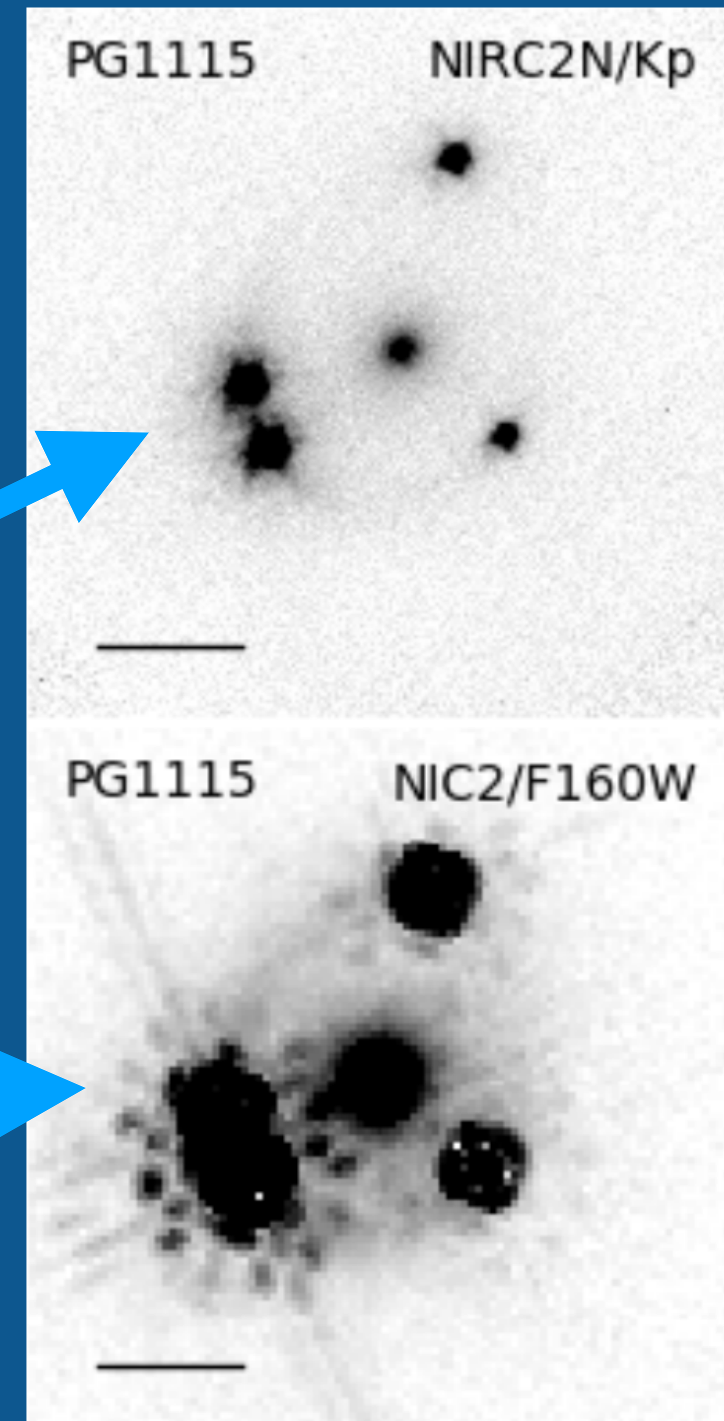


Lens Modeling

- Accurate lens model using deep *HST* and AO imaging
- High resolution needed to model quasar host galaxy
- Adaptive PSF correction using quasar images (e.g. Chen+2016)
- Incorporate velocity dispersion of lens galaxy to reduce model degeneracies

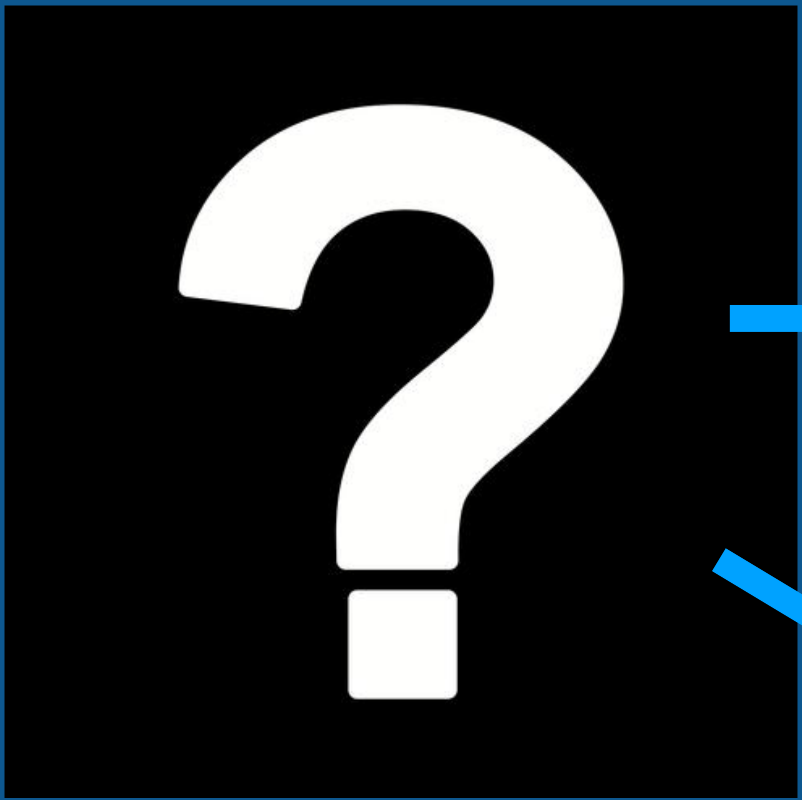


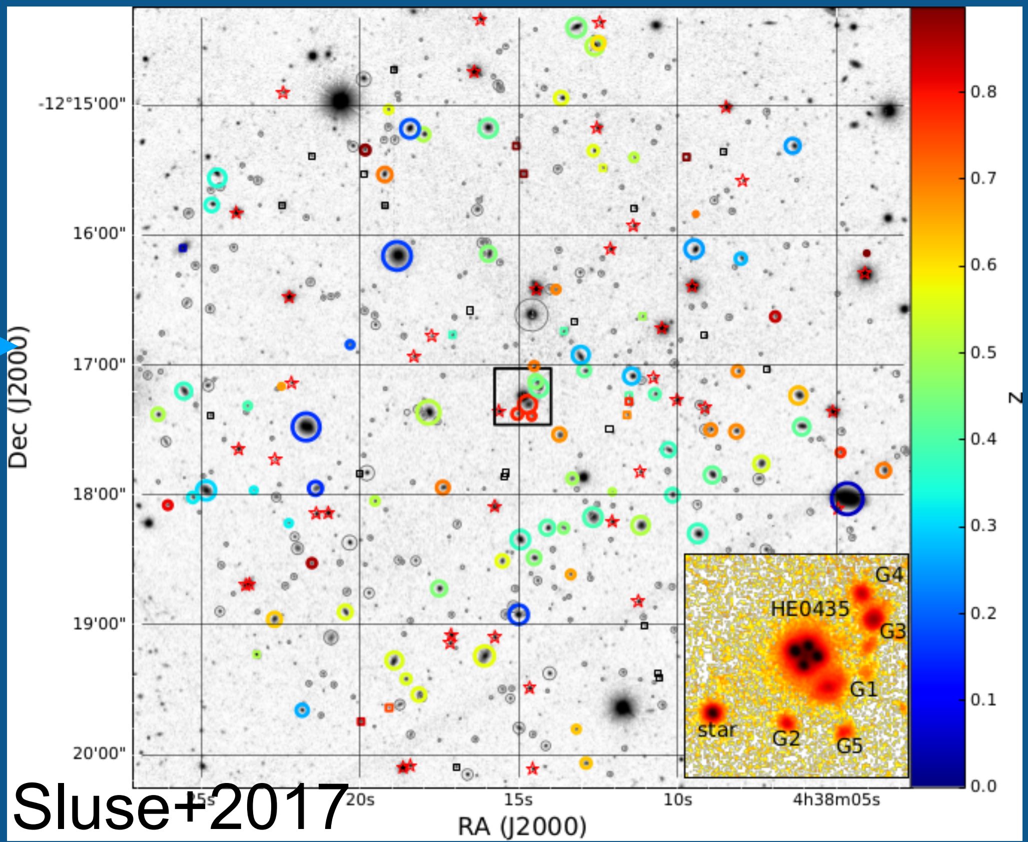
Schechter+1997

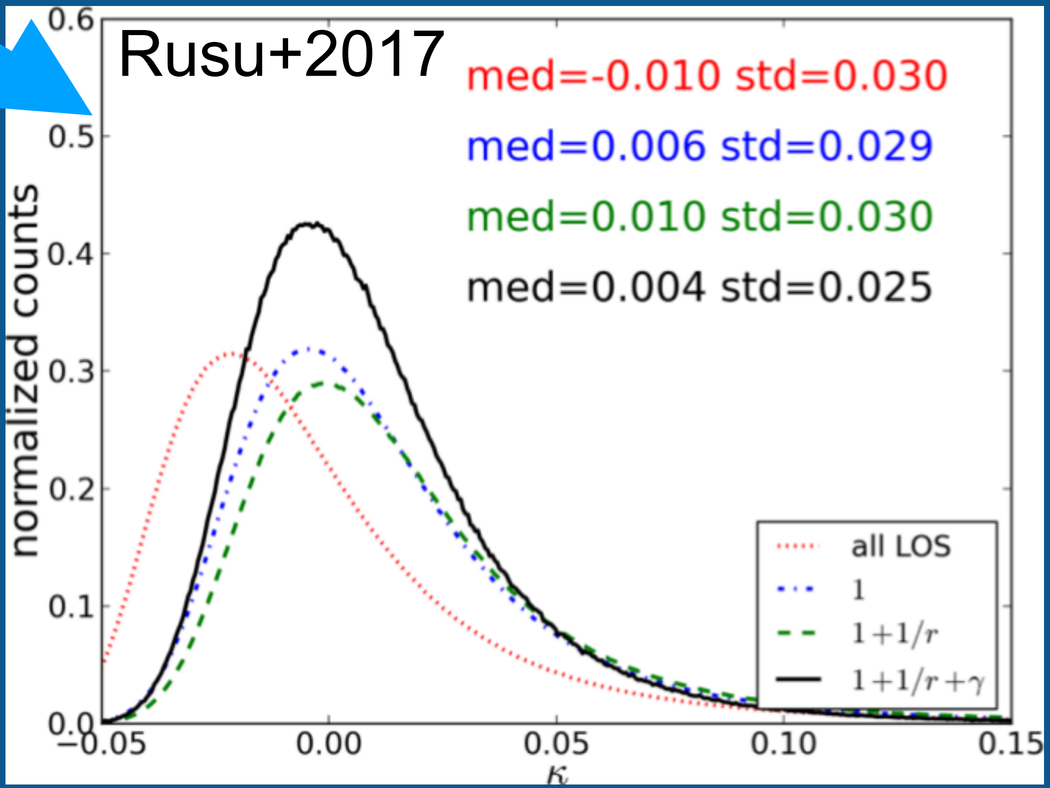


Chen+2019

Mass Along the Line of Sight



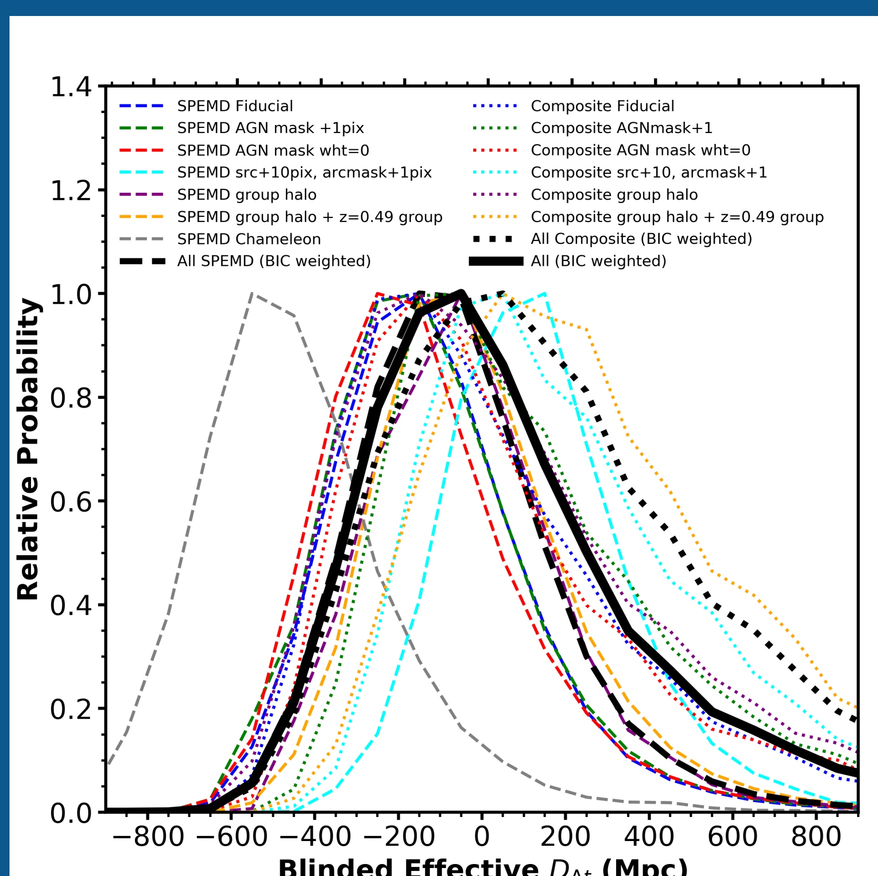


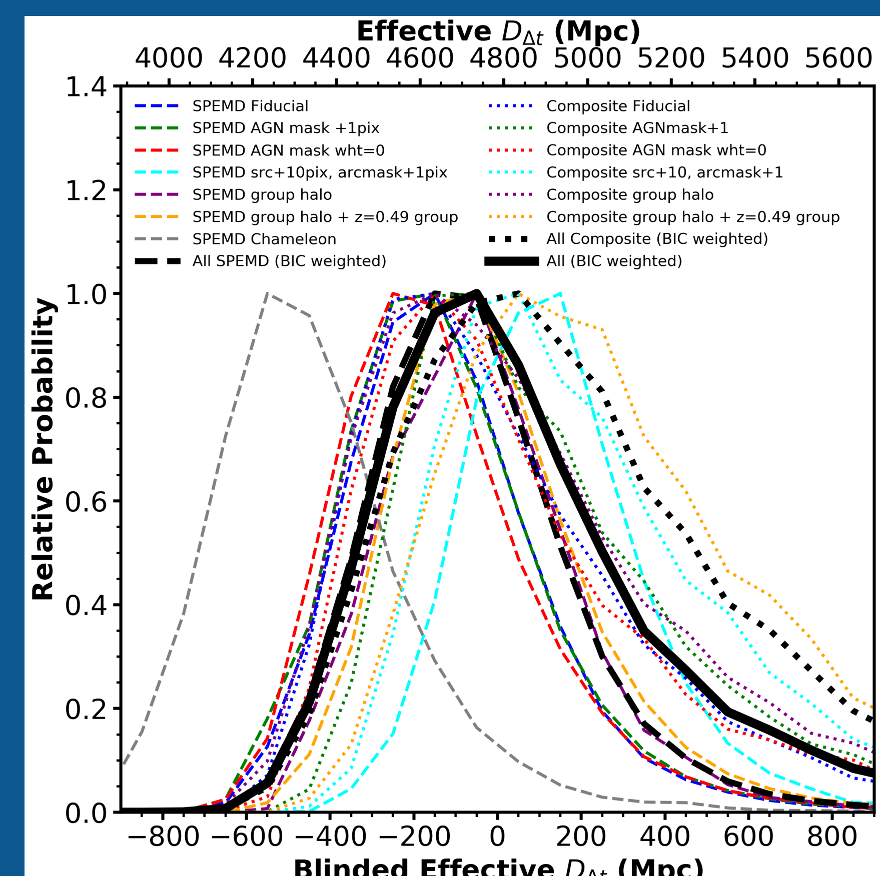


- Lenses lie in overdense LOS due to local lens environment (e.g., Fassnacht+2011; Wong+2018)
- Some strong perturbers need to be included explicitly in lens model (e.g., Wilson+2016; McCully+2017; Sluse+2017)
- Estimate effect of weaker perturbers using weighted galaxy number counts calibrated by simulations (e.g., Greene+2013; Rusu+2017,2020)
- Independent weak lensing analysis agrees with weighted number counts method (Tihhonova+2018,2020)

Blind Analysis

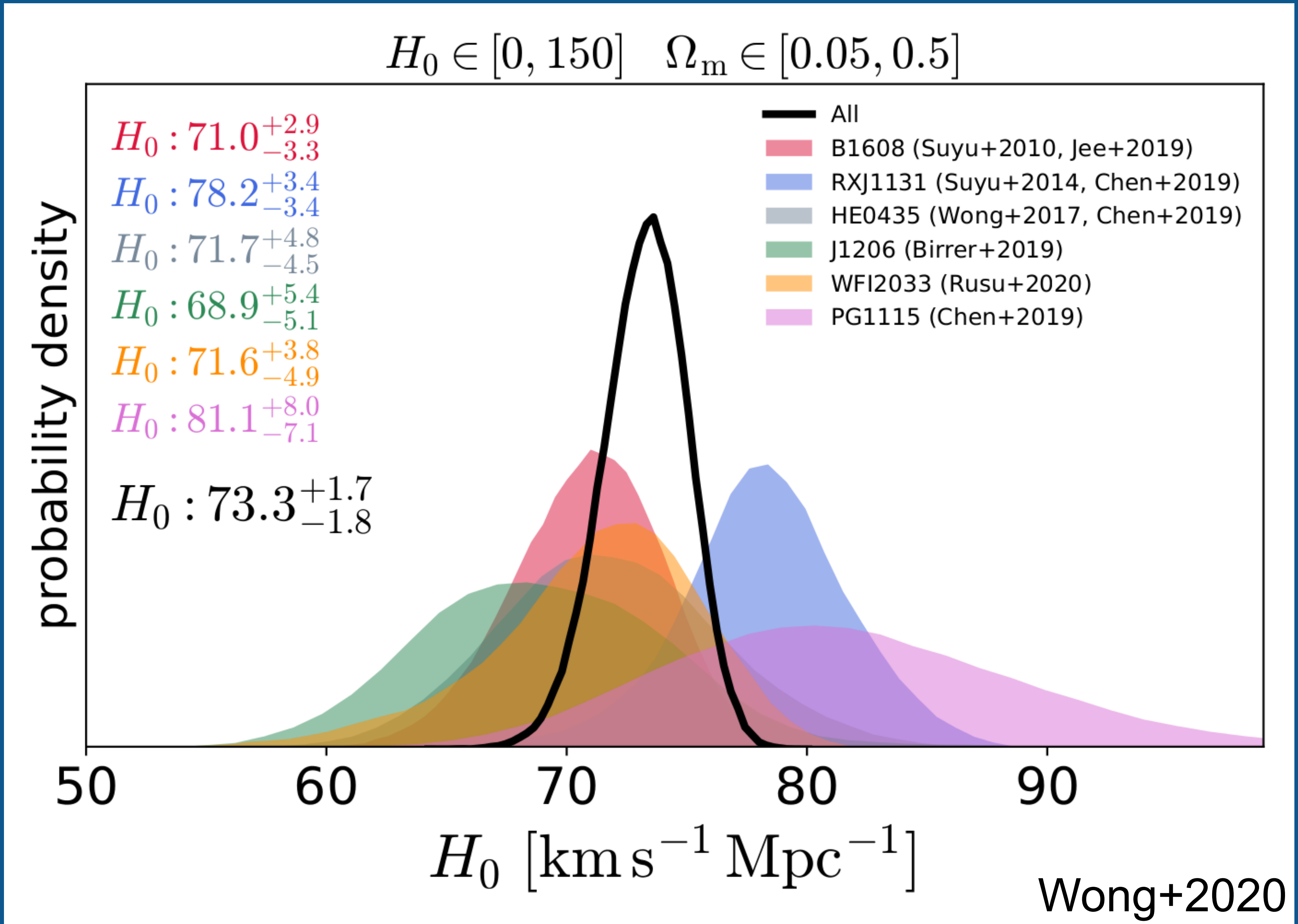
- H_0 and related quantities blinded throughout analysis
  - avoid confirmation bias
  - discover unknown systematics
- Blindness can be implemented by subtracting median of posterior PDF during analysis
- Unblind only after analysis completed, agreement by all coauthors
- Unblinded results published without any further modification





Rusu+2020

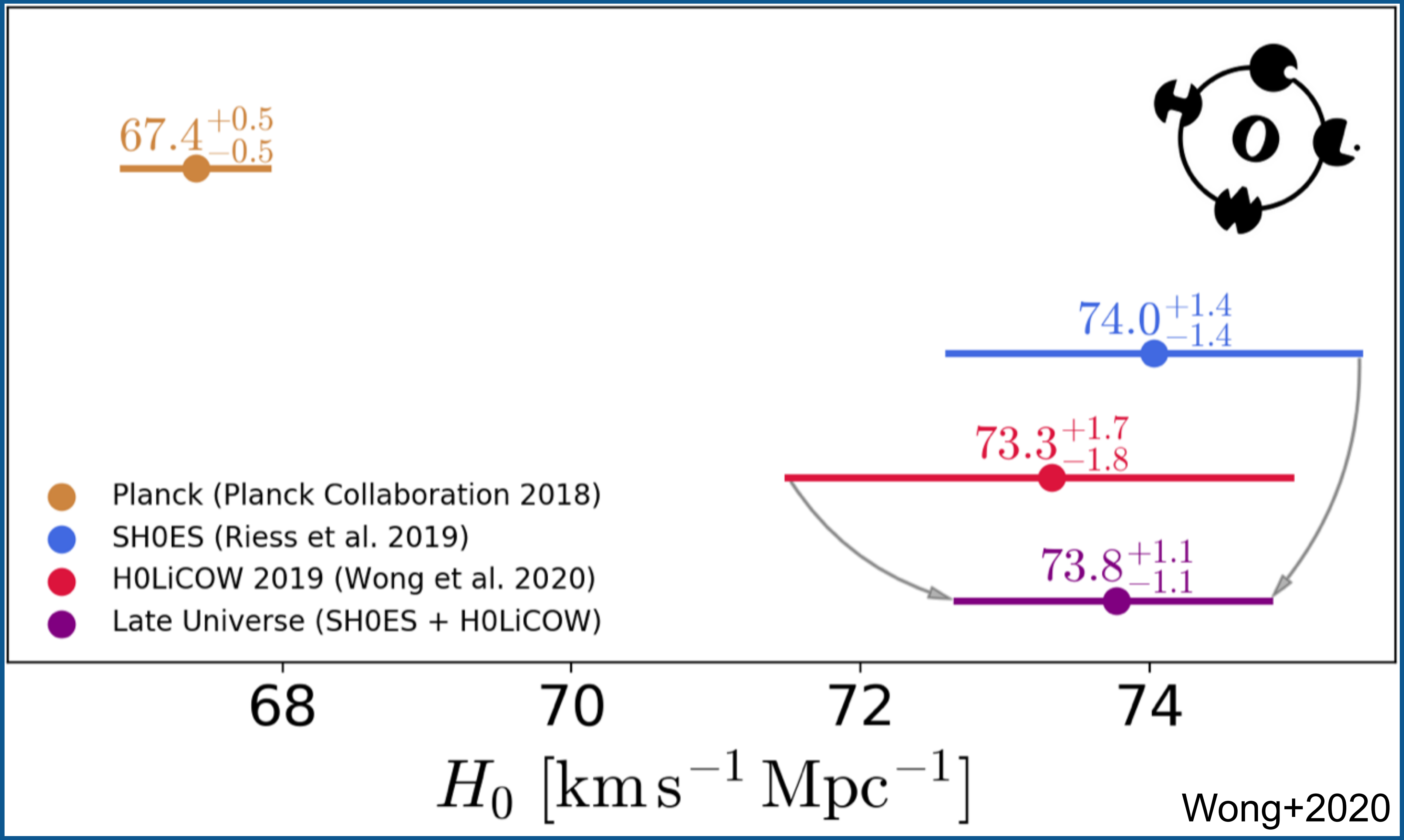
Combined H0LiCOW Results



$H_0 = 73.3^{+1.7}_{-1.8}$ km/s/Mpc for flat ΛCDM cosmology

2.4% precision measurement of H_0 from six H0LiCOW lenses

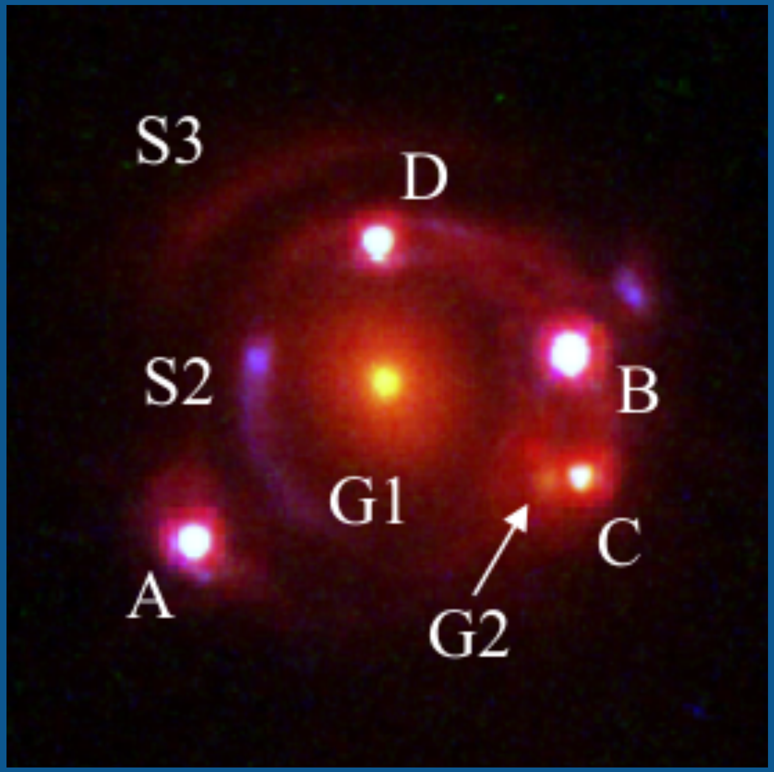
Tension between Early and Late-Universe Probes

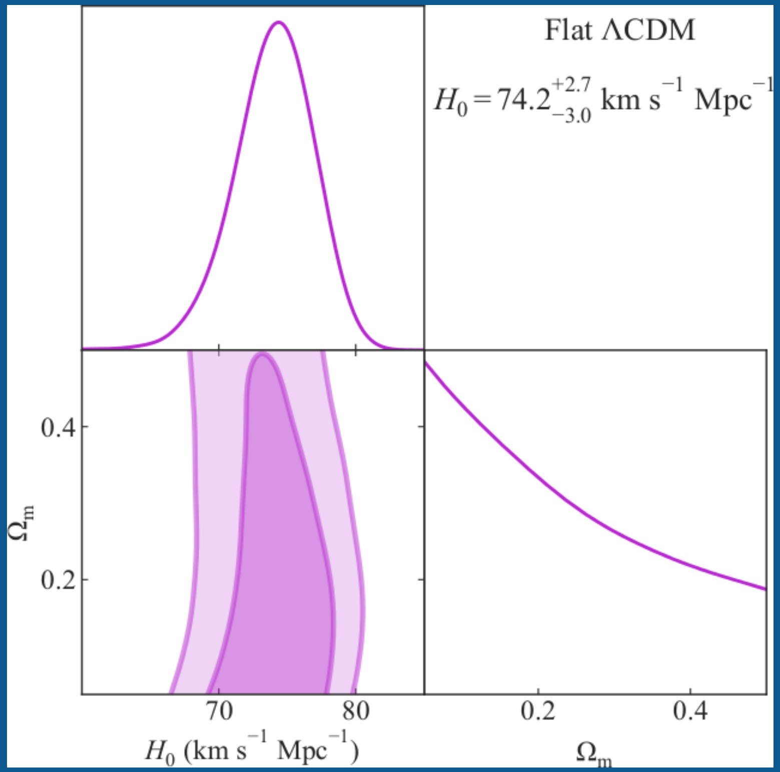


3.1σ tension between H0LiCOW and Planck CMB results
Combined with SH0ES, 5.3σ tension between early and late-Universe probes

Future of Time-Delay Cosmography

- New collaboration: **TDCOSMO**
  - H0LiCOW + COSMOGRAIL + STRIDES (+ others)
- 7th lens has been analyzed (Shajib+2020; Yildirim+ in prep)
  - most precise constraint to date from single lens
- Test of systematics, including model assumptions, line of sight, etc. (Millon+2020)
  - no evidence for unaccounted bias/errors
- Joint hierarchical analysis of entire sample (Birrer+ in prep)
  - relaxed assumptions on mass profile
  - validation on simulated lenses from modeling challenge (Ding+2018,2020)
  - additional lensing+dynamics constraints from SLACS
- Goal: 1% precision on H_0
  - more lenses (~30-40 at current precision; Shajib+2019)
  - better precision per system (e.g., Yildirim+2020)
- Number of known lensed quasars is still small, eventually need to find more to get more precise measurement
  - LSST & Euclid will find thousands of lensed quasars
  - lensed SNe?





Shajib+2020

Summary

- Time-delay cosmography measures H_0 completely independent of CMB and distance ladder/SNe
- From a blind analysis of six lensed quasars, we find $H_0 = 73.3^{+1.7}_{-1.8}$ km/s/Mpc for a flat ΛCDM cosmology
  - consistent with SH0ES SNe Ia + distance ladder
  - in 3.1σ tension with *Planck* CMB value
  - 7th TDCOSMO lens analyzed, more to come
- Combining H0LiCOW + SH0ES (late-Universe probes), there is 5.3σ tension with *Planck* (early-Universe probe)
- Extensive test of modeling assumptions (Millon+2020), future hierarchical analysis of entire sample (Birrer+ in prep)
- Future developments and larger lens samples will push toward a ~1% constraint on H_0

H0LiCOW Collaboration

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Other Collaborators

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H0LiCOW logo credit: O. Tihhonova

http://www.h0licow.org

Recent Publications

Bonvin et al. 2019, A&A, 629, 97
Sluse et al. 2019, MNRAS, 490, 613
Chen et al. 2019, MNRAS, 490, 1743
Jee et al. 2019, Sci, 265, 1134
Rusu et al. 2020, MNRAS, in press (arXiv:1905.09338)
Wong et al. 2020, MNRAS, in press (arXiv:1907.04869)
Shajib et al. 2020, MNRAS, 494, 6072
Millon et al. 2020, A&A, in press (arXiv:1912.08027)