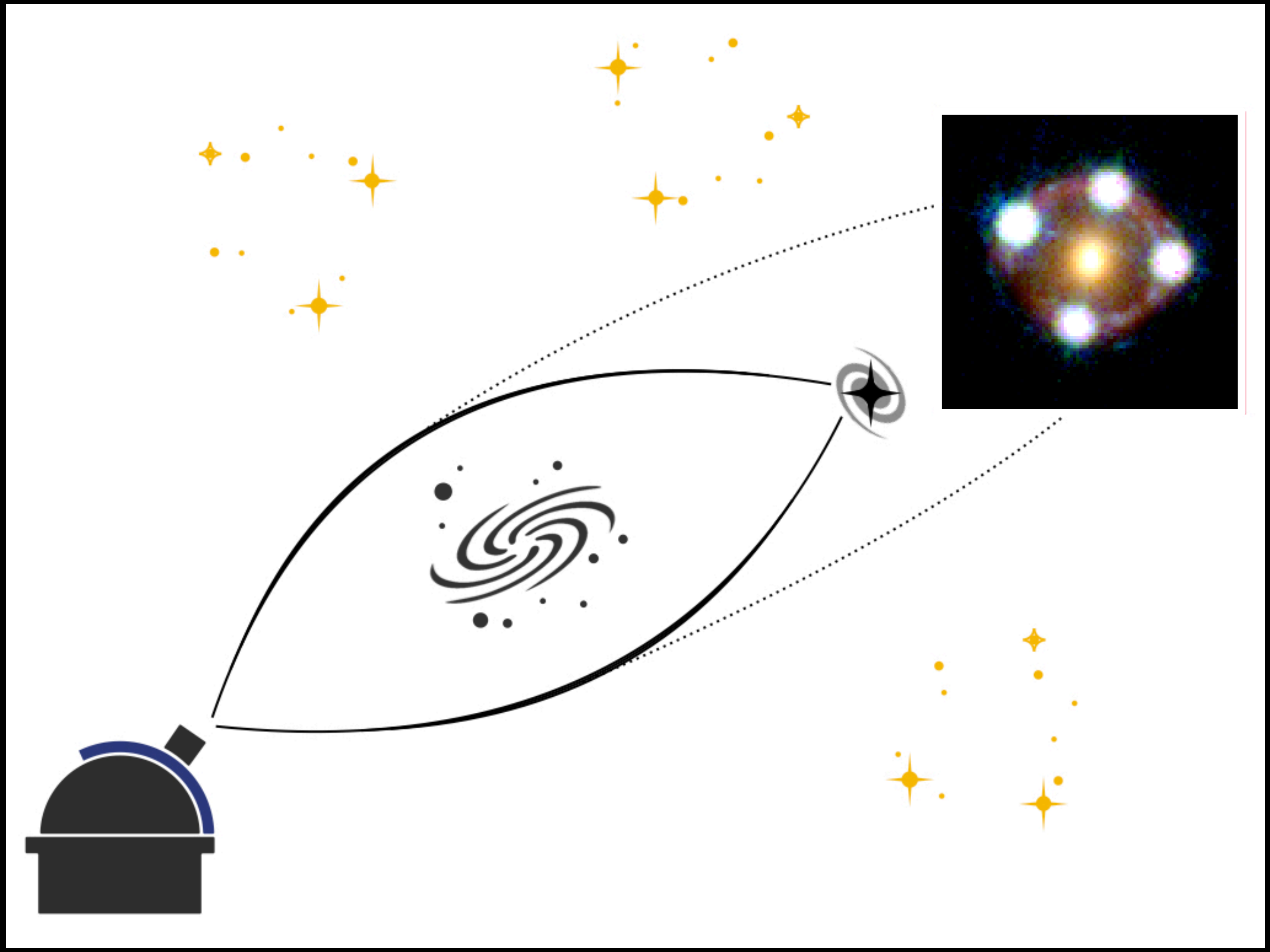
An Independent Measurement of H_0 from Lensed Quasars



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Rencontres de Blois
Exploring the Dark Universe
May 24, 2022

科研費 KAKENHI

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The Hubble Tension

- Flat ΛCDM cosmology is an excellent fit to a variety of observations, including CMB
- Recent tension in early-time and late-time measurements of Hubble constant (H_0)
  - H_0 sets the present-day expansion rate of the Universe
  - *Planck* CMB finds H_0 = 67.4 ± 0.5 km/s/Mpc (assuming flat ΛCDM)
  - SH0ES distance ladder finds H_0 = 73.0 ± 1.0 km/s/Mpc (Riess+2021)
  - a challenge for flat ΛCDM cosmology
- Independent measurements of H_0 are key to test for systematics

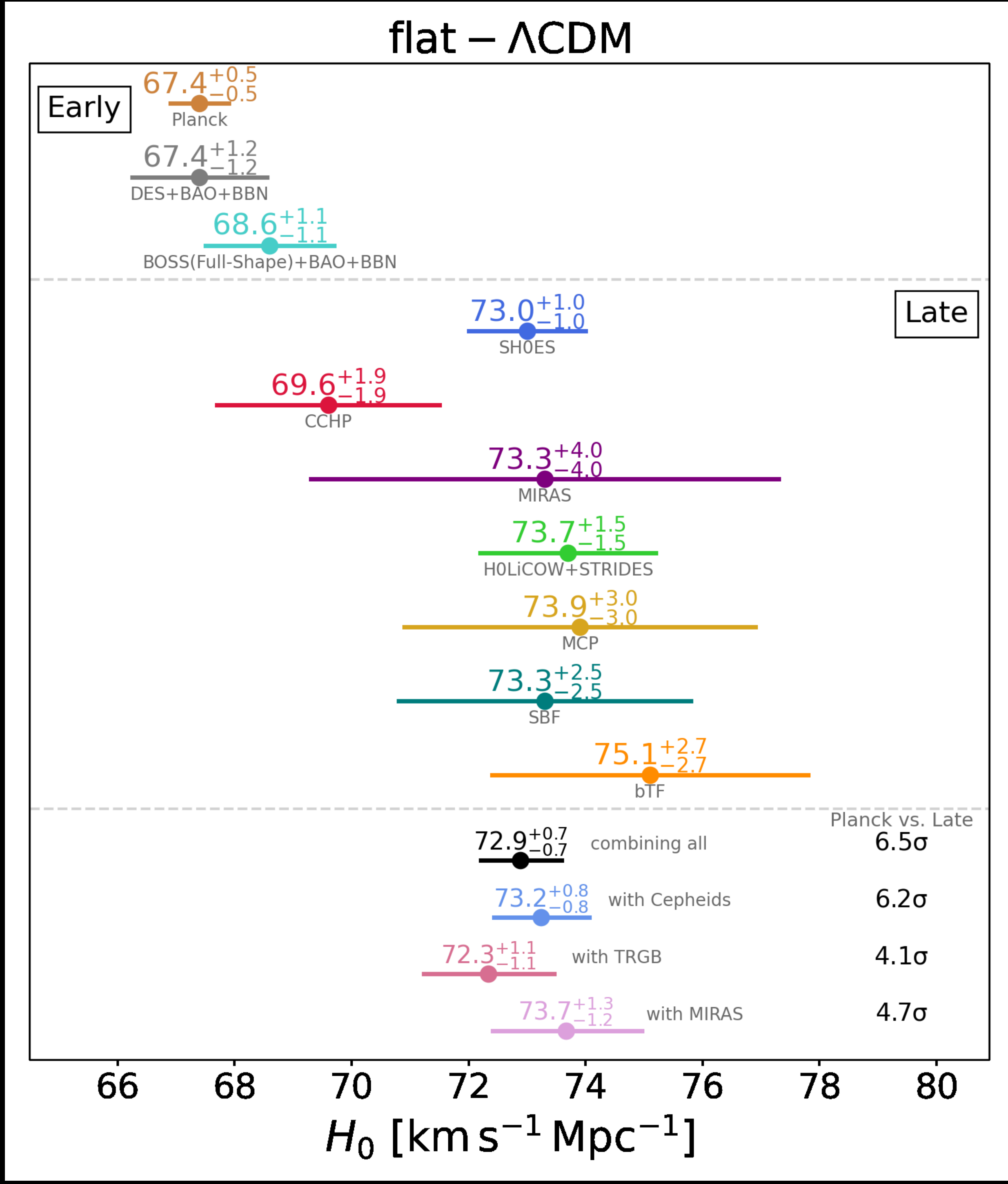
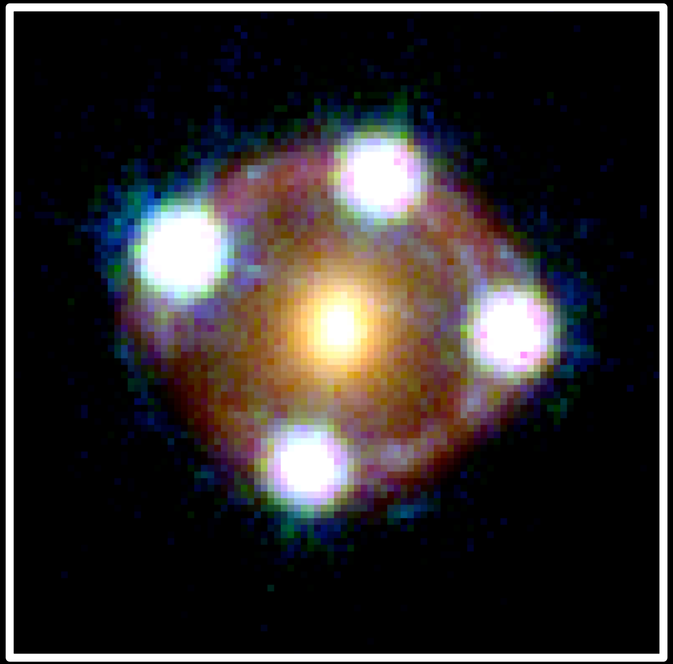


figure adapted from Verde, Treu, & Riess (2019)

Strong Gravitational Lensing & Time-Delay Cosmography

- Background object (source) magnified by foreground object (lens)
- Multiple images → create lens model
- "Time-delay cosmography" - lensed quasars can be used to constrain H_0, *independent of other methods*
- Need:
  - measured time delay between multiple images
  - accurate lens mass model from high-resolution imaging + kinematics
  - estimate of mass along line of sight



Time delay (observed)

Time-delay distance

Fermat potential (from lens model)

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

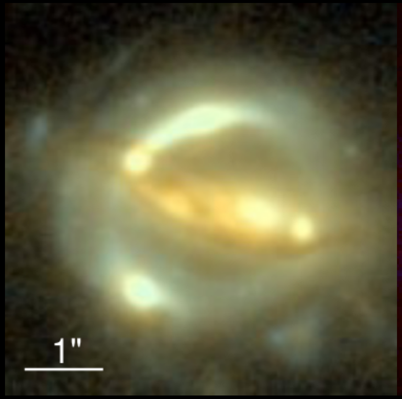
$$D_{\Delta t} \propto \frac{1}{H_0} \qquad \Phi_{\rm lens}$$

Animation credit: M. Mori

TDCOSMO / H0LiCOW

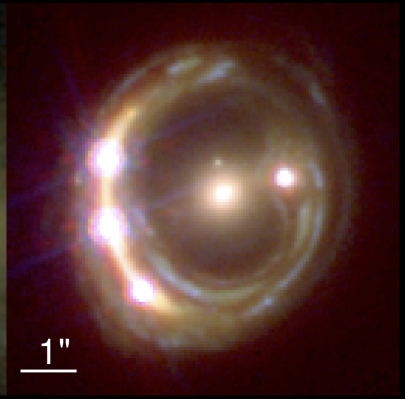
- TDCOSMO (formerly H0LiCOW; Suyu+2017) project has performed detailed analysis of several time-delay lenses
  - long term monitoring from COSMOGRAIL (Courbin+2005), VLA (Fassnacht+2002) for accurate time delays
  - high-resolution imaging for detailed lens modeling
  - wide-field imaging/spectroscopy to characterize mass along LOS
  - spectroscopy to measure lens velocity dispersion
- Seven lenses analyzed to date (see Wong+2020, Shajib+2020, Birrer+2020 for latest results)

B1608+656



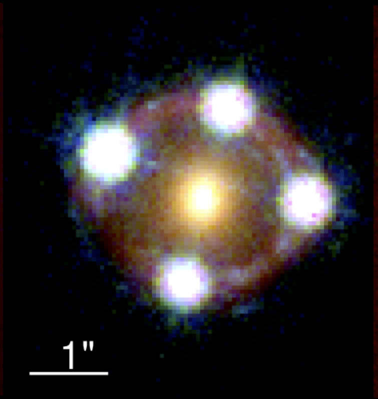
Suyu+2010
Jee+2019

RXJ1131-1231



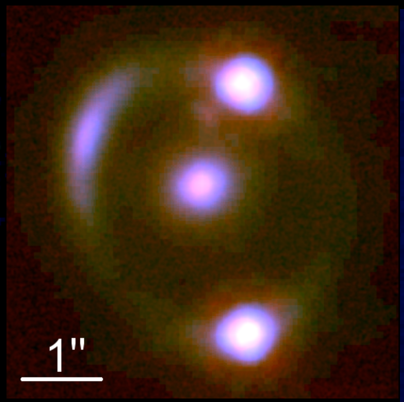
Suyu+2013,2014
Chen+2019

HE 0435-1223



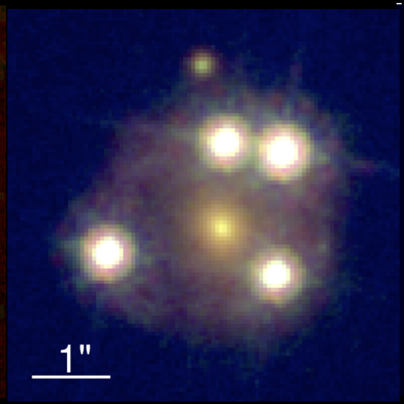
Wong+2017
Chen+2019

SDSSJ1206+4432



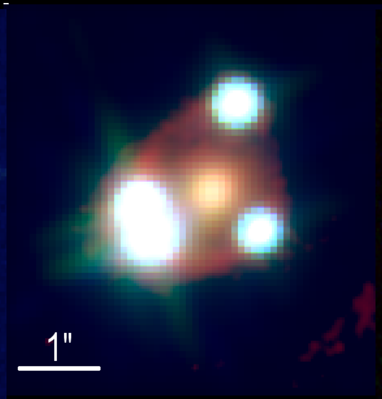
Birrer+2019

WFI2033-4723



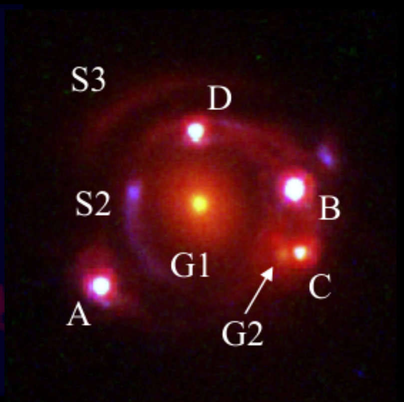
Rusu+2020

PG 1115+080



Chen+2019

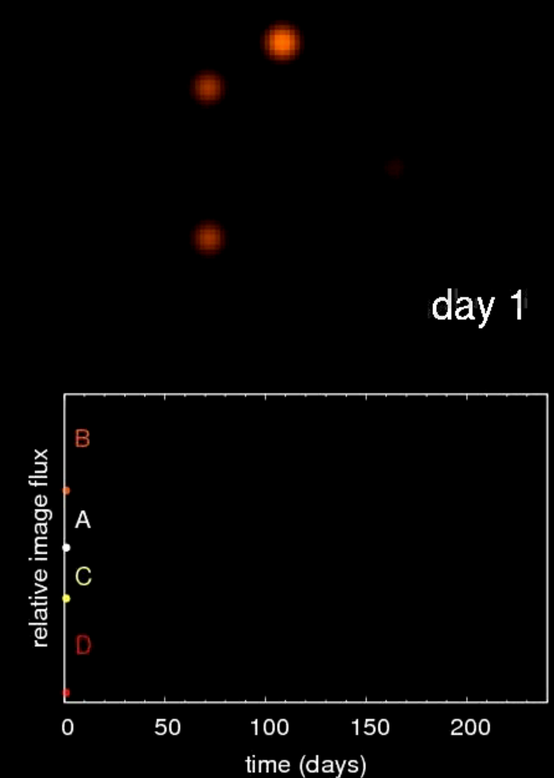
DESJ0408-5354



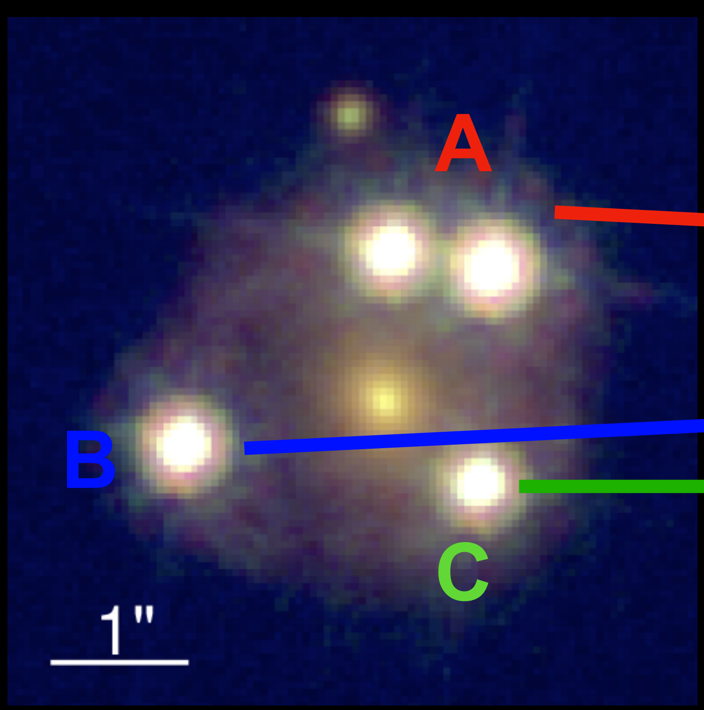
Shajib+2020

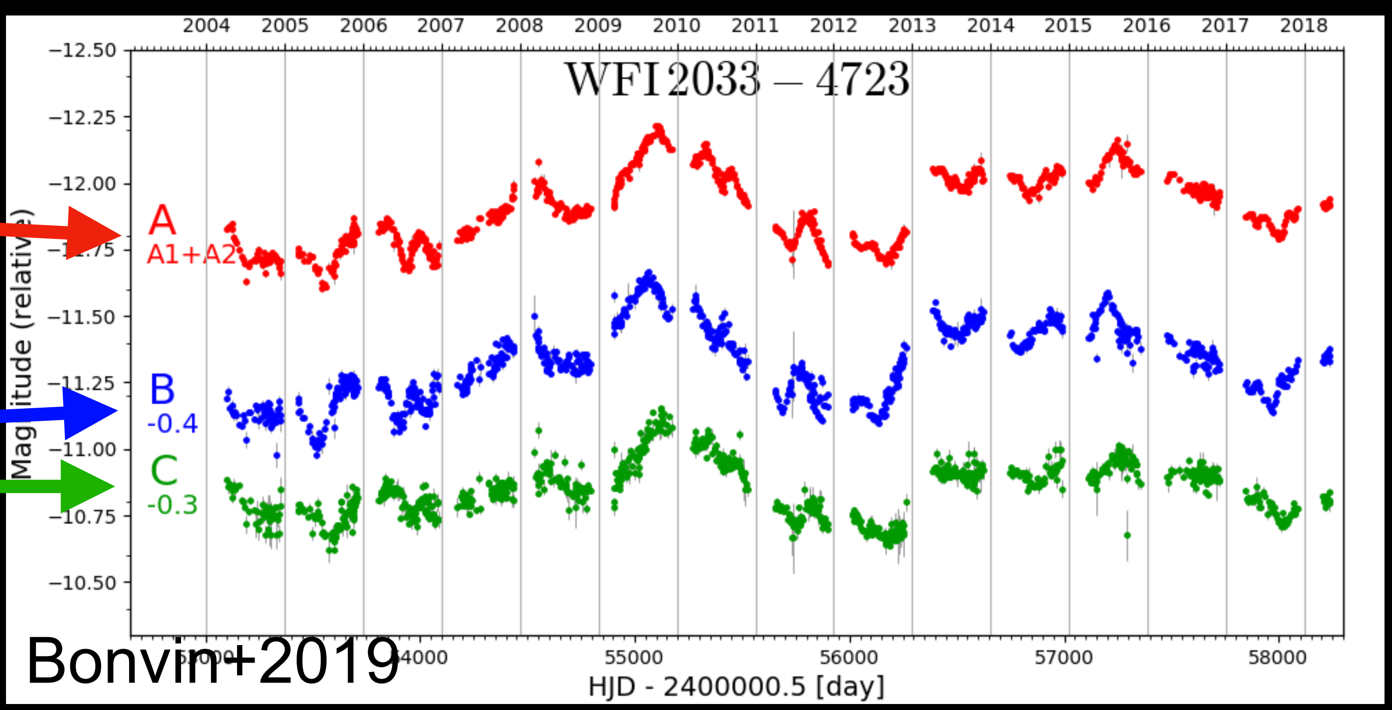
Time Delay Measurement

- Long-term monitoring of time-delay lenses using small (1-m and 2-m) telescopes (COSMOGRAIL collaboration; Courbin+2011; Bonvin+2017)
- Well-tested algorithms for time-delay measurements (Tewes+2013)
- Recent development: high-cadence monitoring to get time delays in ~1 year (Courbin+2018, Millon+2020b)



Animation credit: C. Fassnacht, S. Suyu

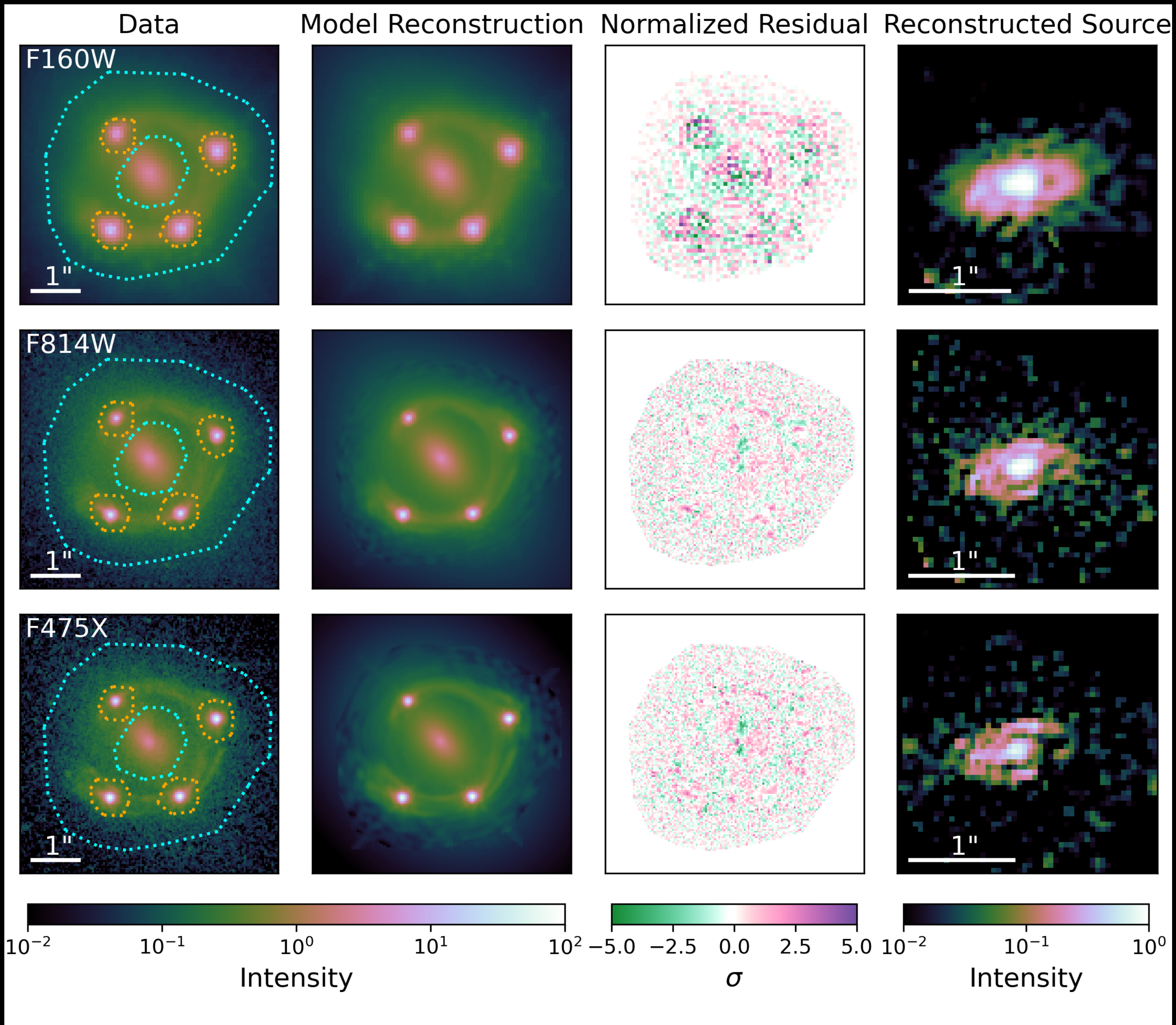




Bonvin+2019

Lens Modeling

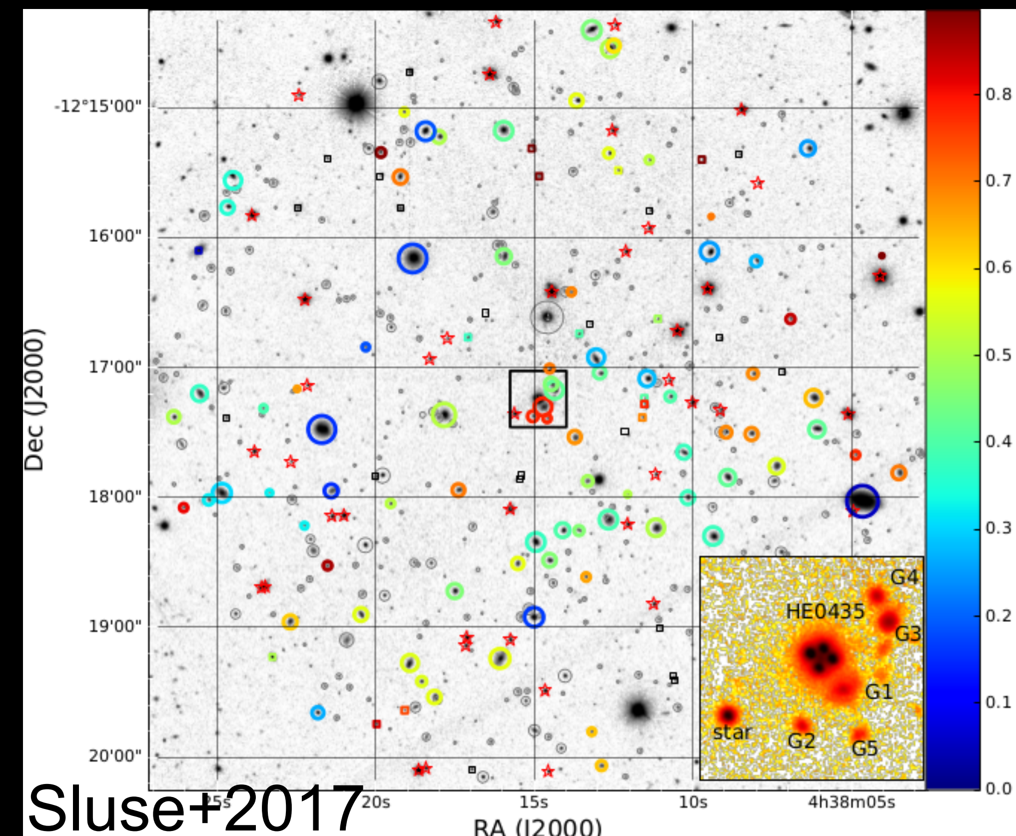
- Accurate lens model using deep *HST* and AO imaging
  - accurate PSF using reconstruction technique to subtract quasar light
  - high resolution needed to model quasar host galaxy
- Velocity dispersion of lens galaxy needed to reduce model degeneracies
- Multiple lens modeling approaches/ softwares (Shajib, Wong, et al. 2022, arXiv:2202.11101)

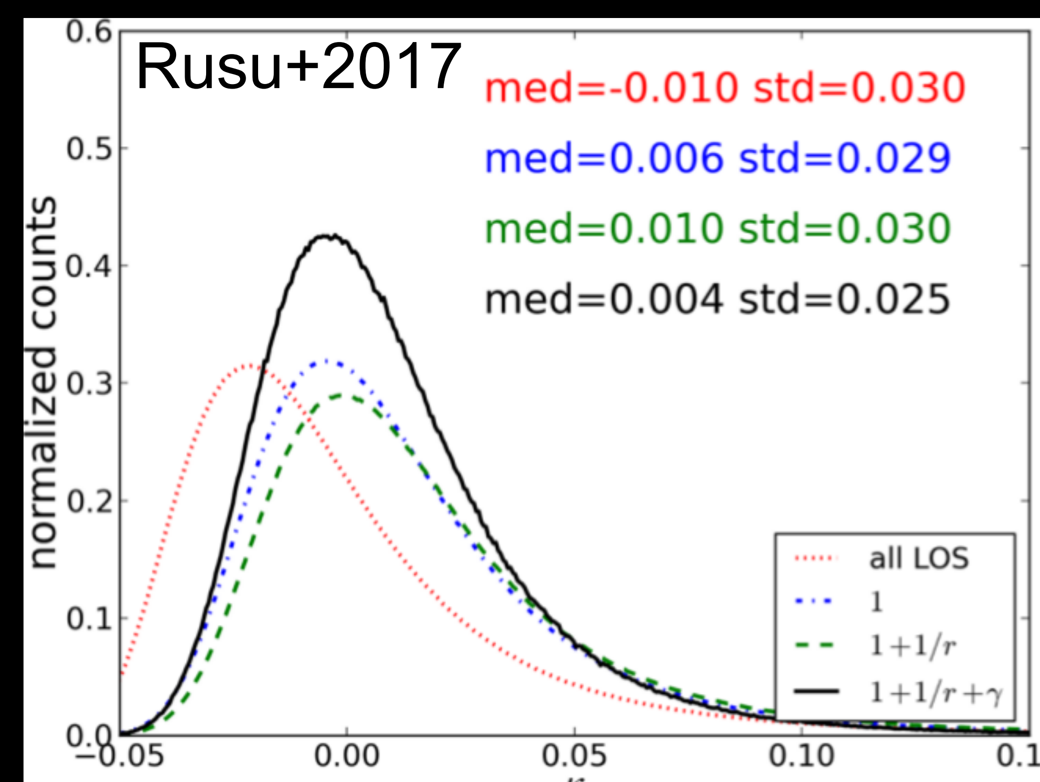


Shajib, Wong, et al. 2022

Mass Along the Line of Sight

Animation credit: M. Mori

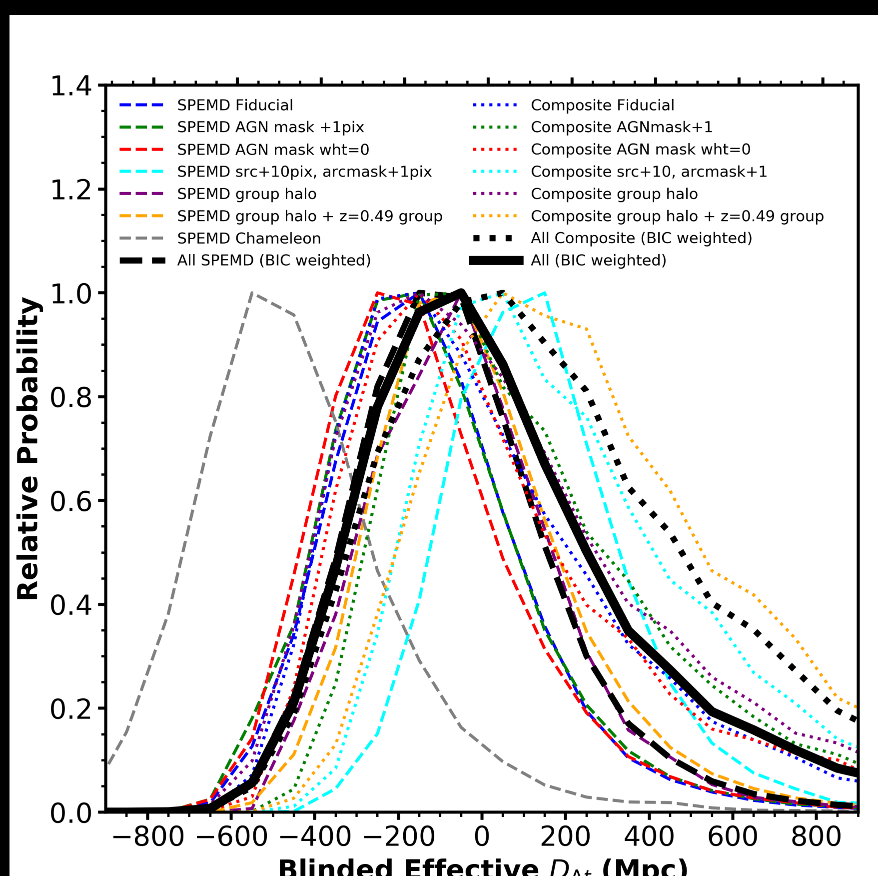


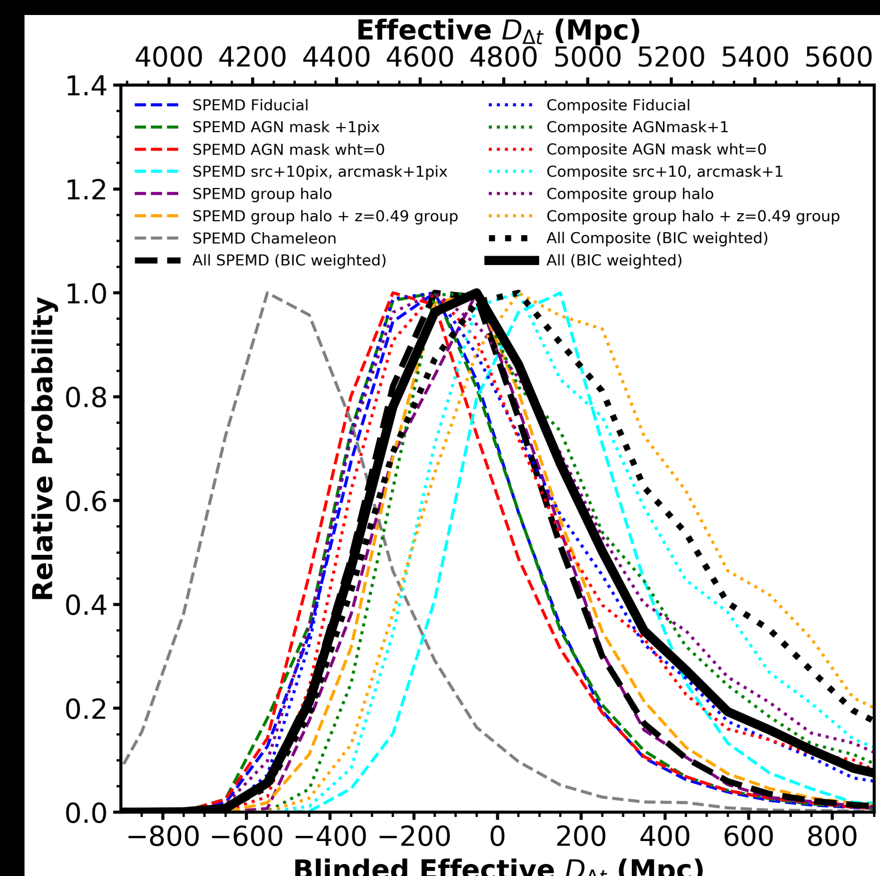


- Lenses lie in overdense LOS due to local lens environment (e.g., Fassnacht+2011; Wong+2018)
- Some strong perturbers need to be included explicitly in lens model (e.g., Wilson+2016; McCully+2017; Sluse+2017)
- Estimate effect of weaker perturbers using weighted galaxy number counts calibrated by simulations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

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

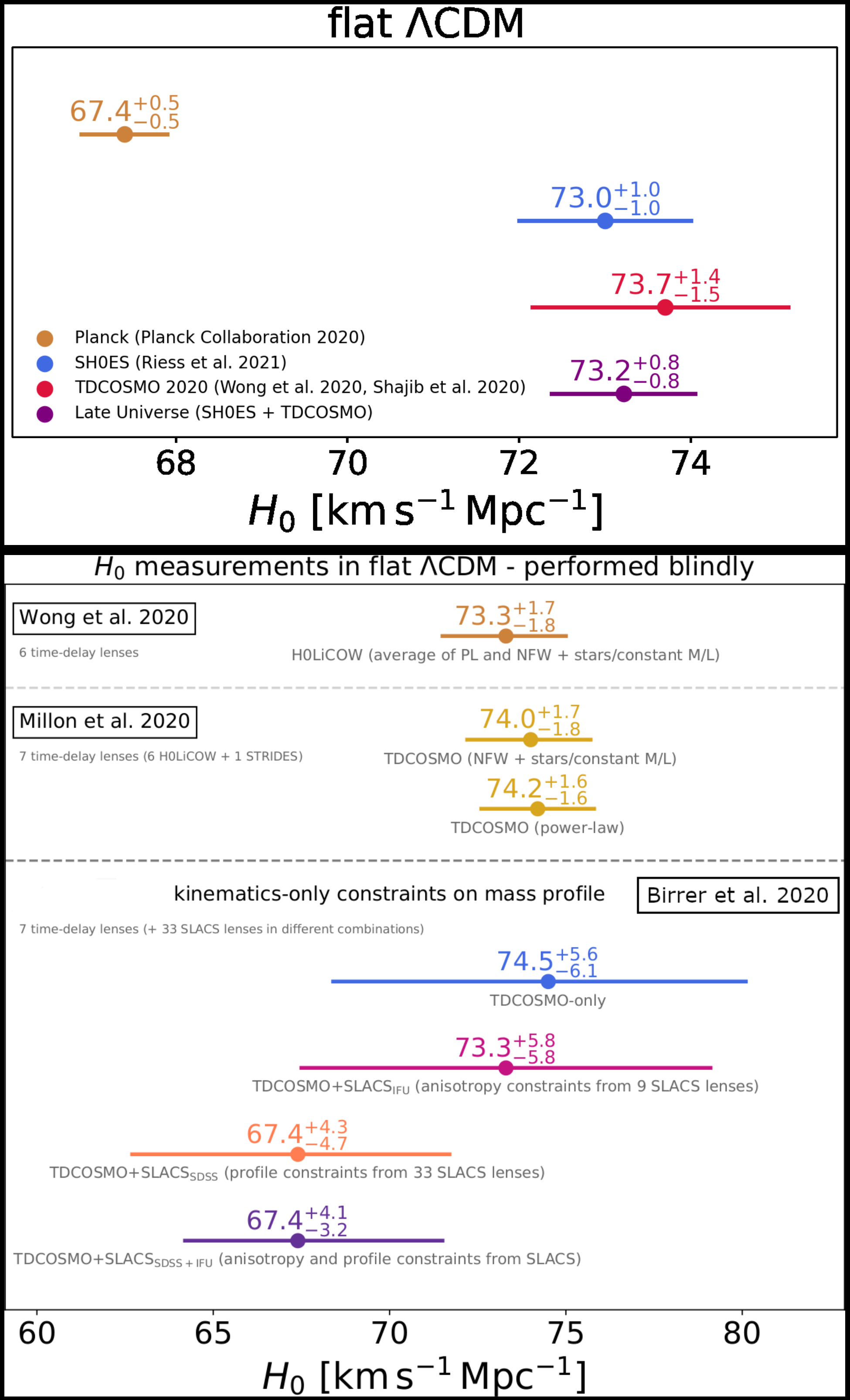




Rusu+2020

TDCOSMO Results

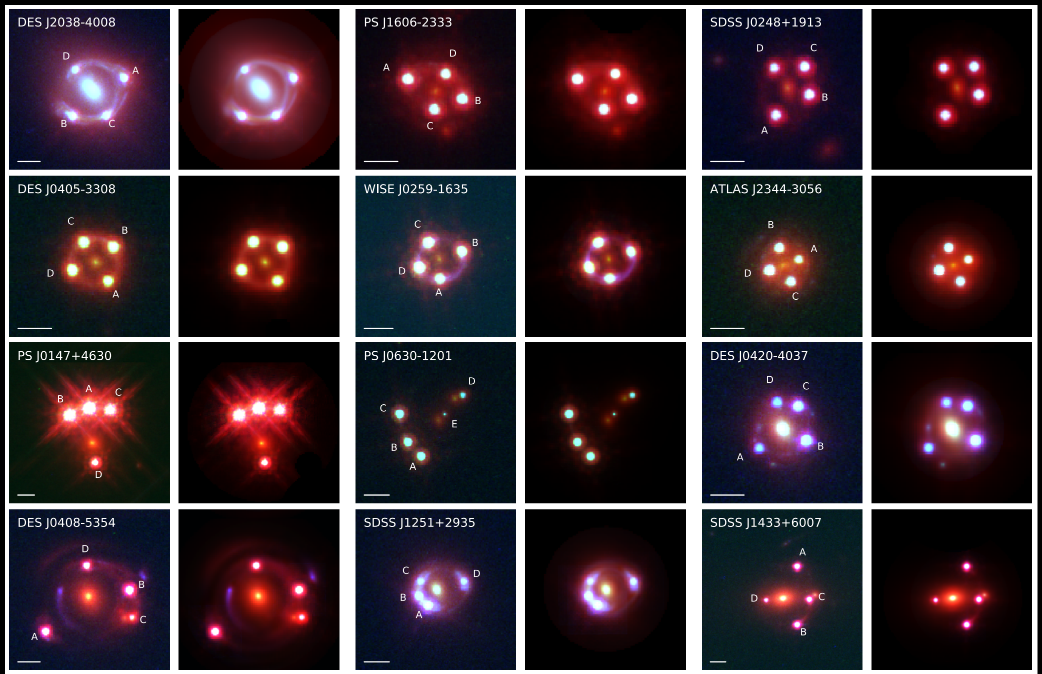
- Combined result: ~2% precision on H_0 for flat ΛCDM from seven lensed quasars
  - consistent with SH0ES SNe Ia + distance ladder (Riess+2021)
  - >4σ tension with *Planck*
  - assumes power-law or composite (stars+dark matter) lens mass profiles
- Updated joint Bayesian hierarchical analysis using kinematics-only constraint: ~5% constrain on H_0
  - maximally conservative, allows for freedom in mass profile
  - external constraints on mass parameters from SLACS lenses (assumes SLACS and TDCOSMO lenses are similar)
  - resolved kinematics from upcoming *JWST/* NIRSpec IFU spectroscopy will break degeneracy



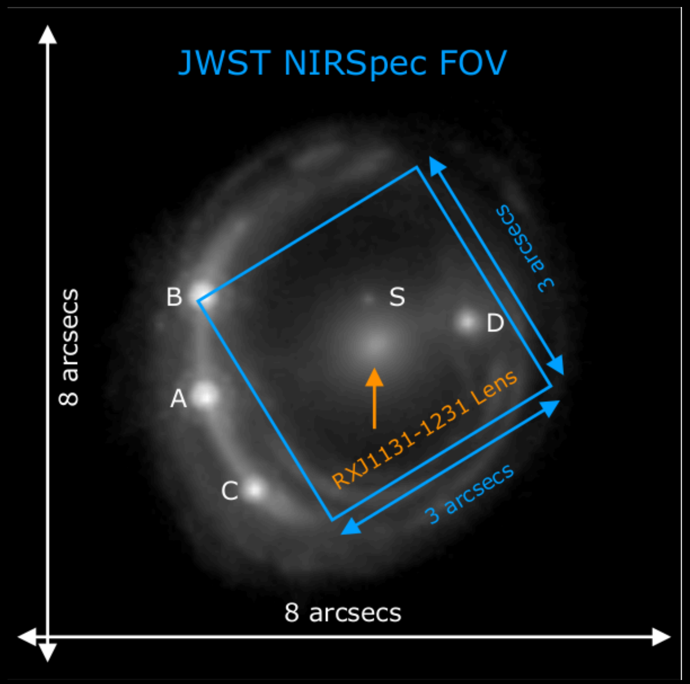
figures adapted from Wong+2020, Birrer+2020

Future of Time-Delay Cosmography

- Goal: 1% precision on H_0
- More data on time-delay lenses
  - spatially-resolved stellar kinematics (e.g., VLT/MUSE, Keck/KCWI, JWST/NIRSpec)
  - improving kinematics measurement and modeling
  - increasing sample size of time-delay lenses (discovery, monitoring, follow-up)
- Testing and controlling for systematic uncertainties
  - more detailed investigation of lens mass profiles
  - multiple modeling approaches (Shajib, Wong et al. 2022)
- Analysis of large future lens samples
  - LSST will eventually discover ~hundreds or ~thousands of lensed quasars for time-delay cosmography
  - develop lens search methods on large imaging surveys (e.g., DES, HSC)
  - develop automated modeling techniques (Schmidt+ in prep.; Ertl+ in prep.)



Shajib+2018



Yildirim+2021

Summary

- Time-delay cosmography measures H_0 completely independent of CMB and distance ladder/SNe
- Latest TDCOSMO results attain ~2% precision on H_0 in flat ΛCDM
  - assumes lenses are accurately described by power-law or stars+DM
  - consistent with SH0ES SNe Ia + distance ladder
  - in >4σ tension with *Planck* CMB value
- Hierarchical analysis using external datasets, relaxed assumptions on mass profile gives ~5% precision on H_0 in flat ΛCDM
  - assumes external lenses from SLACS are similar to TDCOSMO lenses
  - IFU data with upcoming *JWST* observations will break degeneracy
- Future developments will push toward a ~1% constraint
  - larger lens samples
  - further investigation of systematics
  - automated lens modeling

http://www.tdcosmo.org