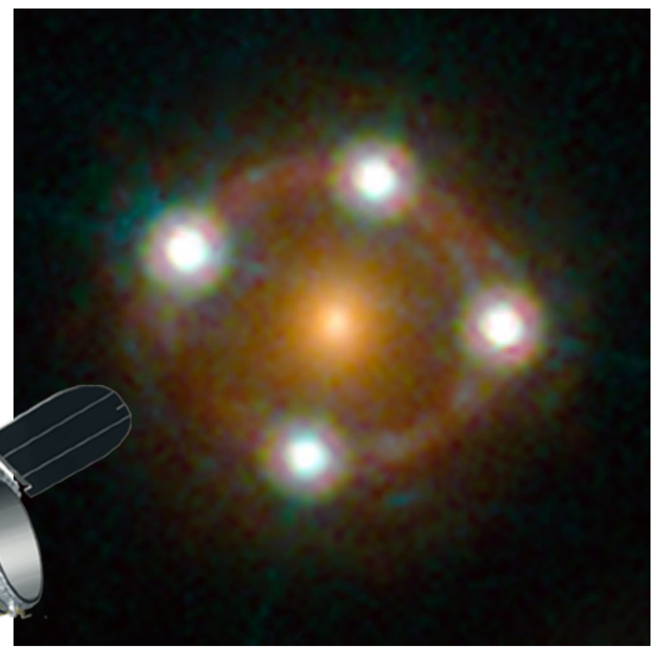
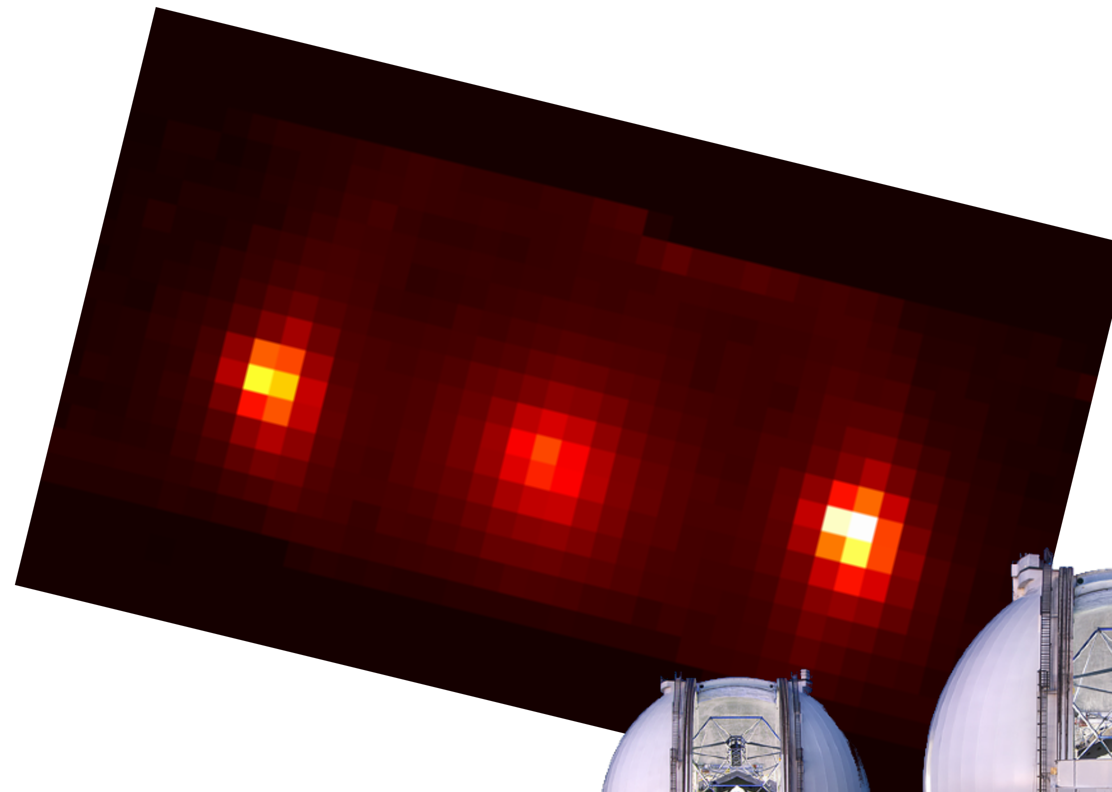
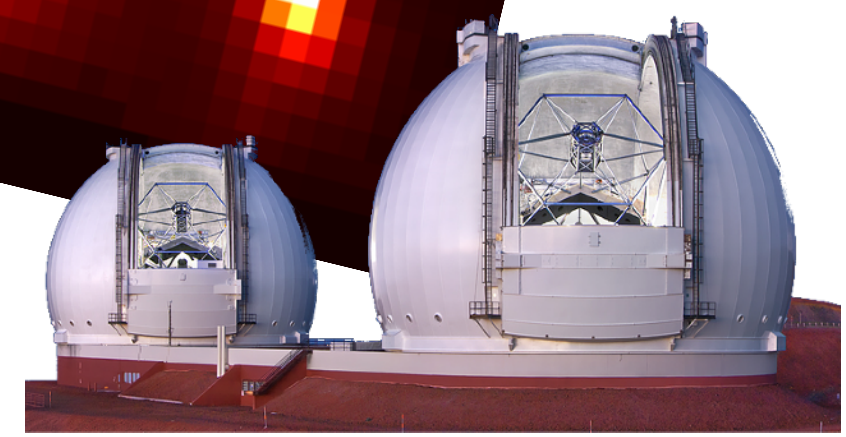
The Hubble tension and strong-lensing time-delays: Hint of new physics?



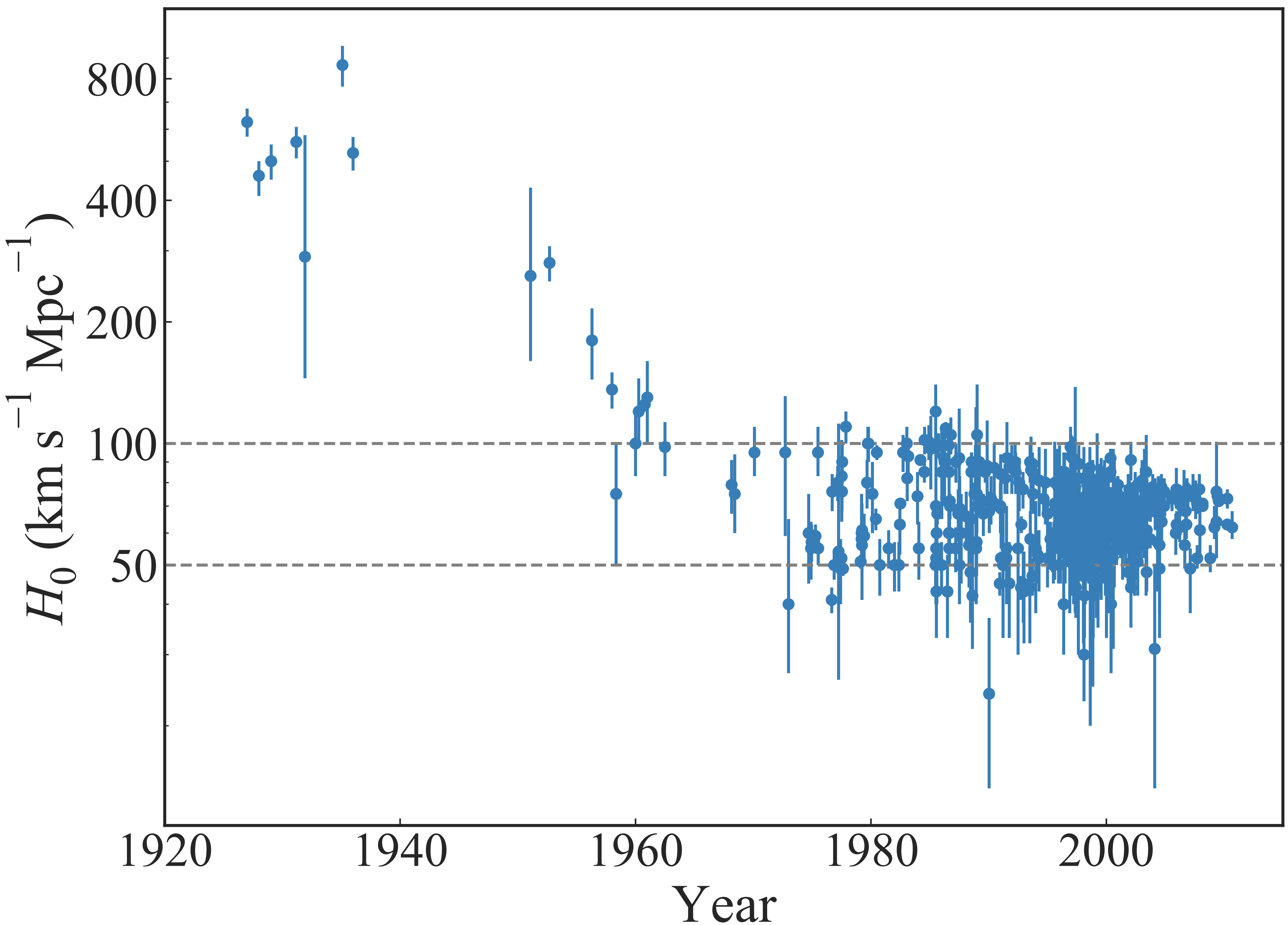




Anowar J. Shajib
Dissertation Year Fellow
University of California, Los Angeles

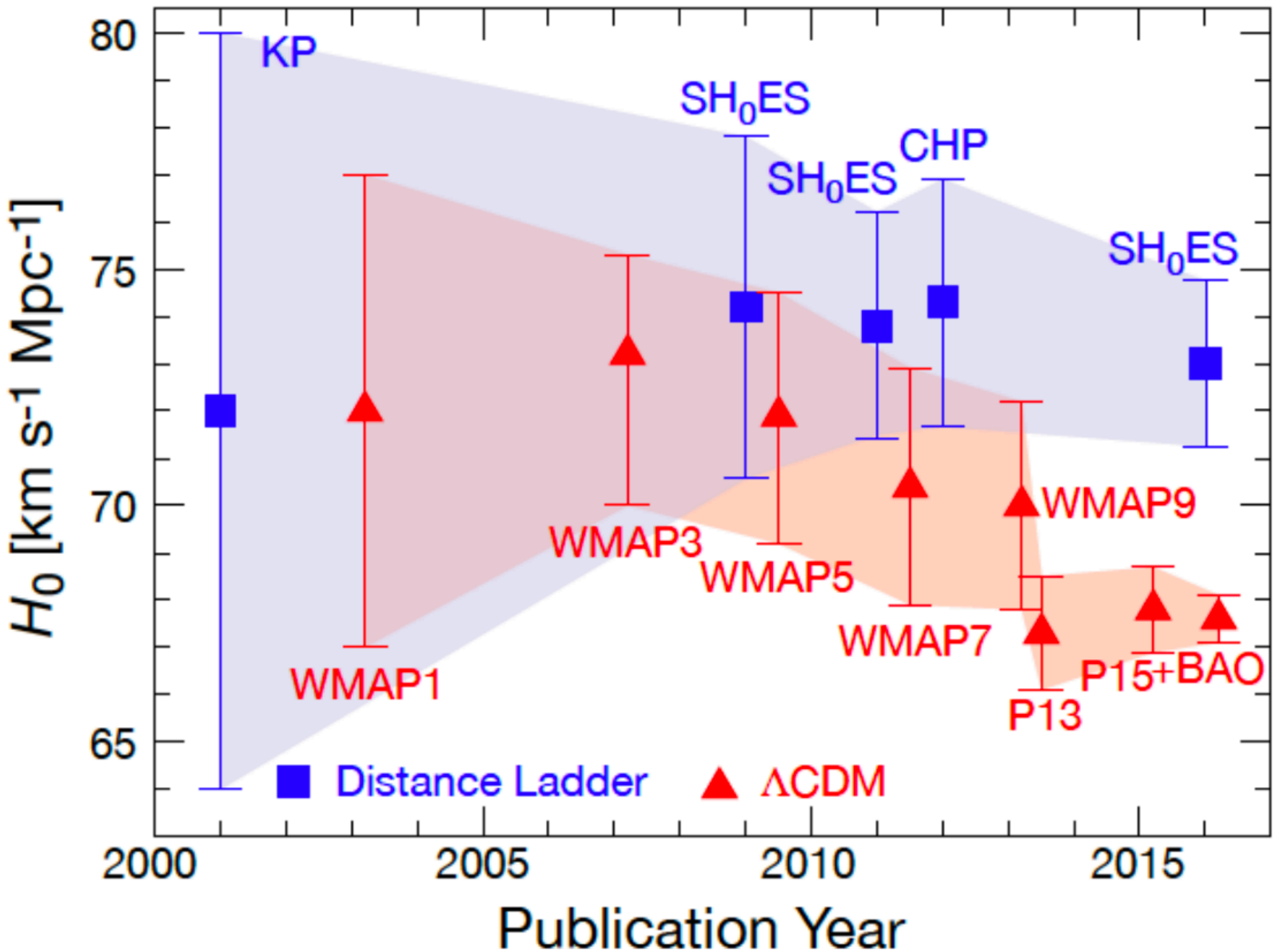
Advisor: Tommaso Treu
Collaborations: STRIDES and H0LiCOW

Hubble constant through the years



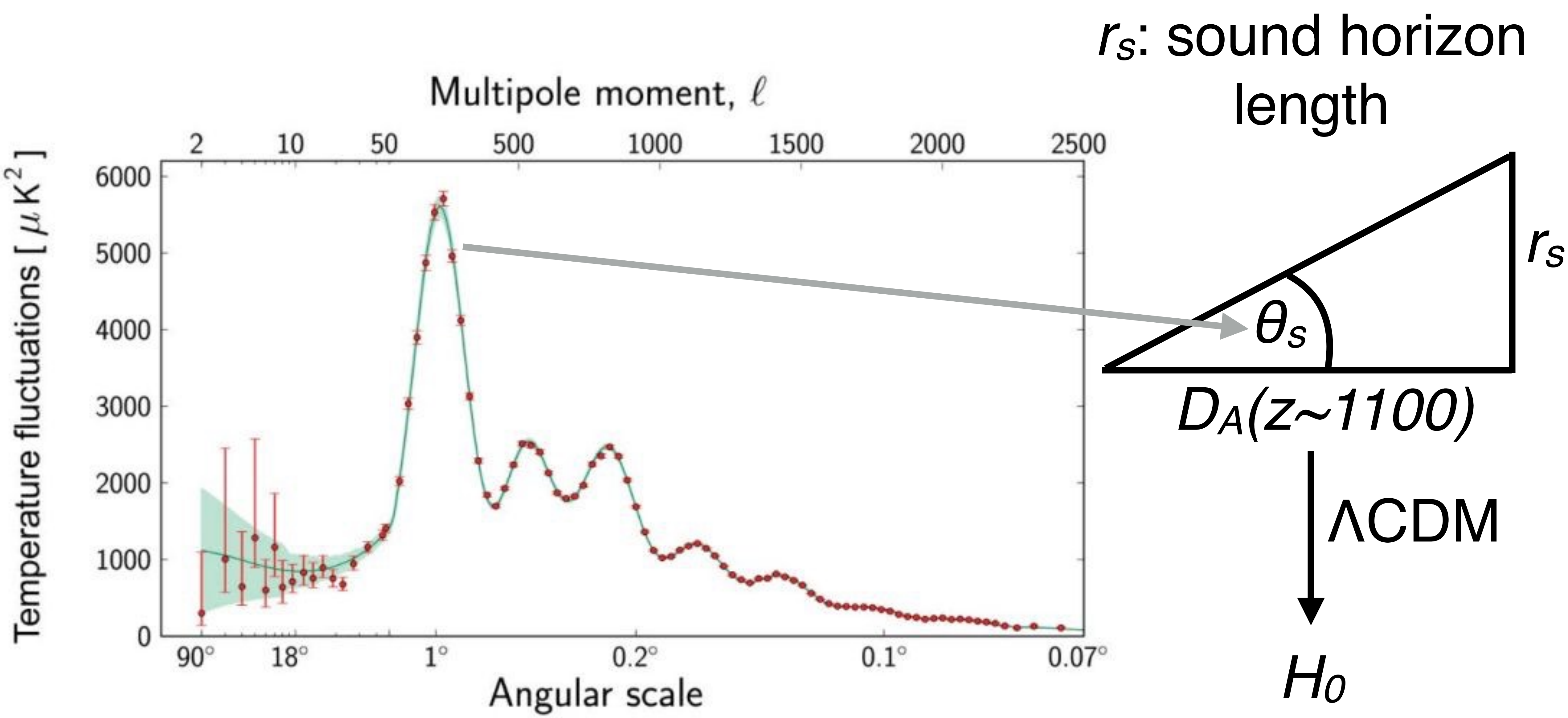
Collected by John Huchra

Recent debate over Hubble constant



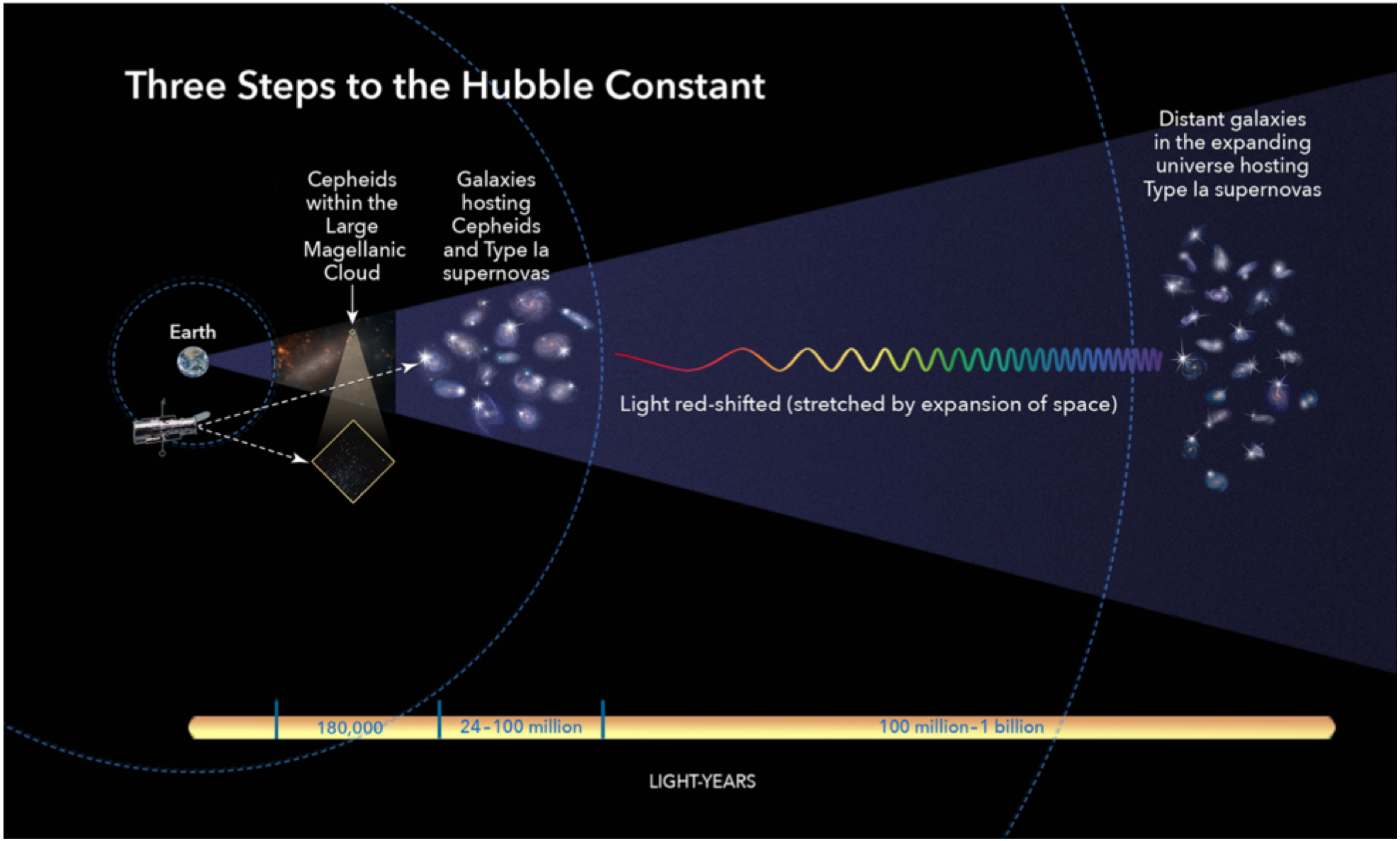
Freedman (2017)

Early-Universe H_0 measurement: CMB



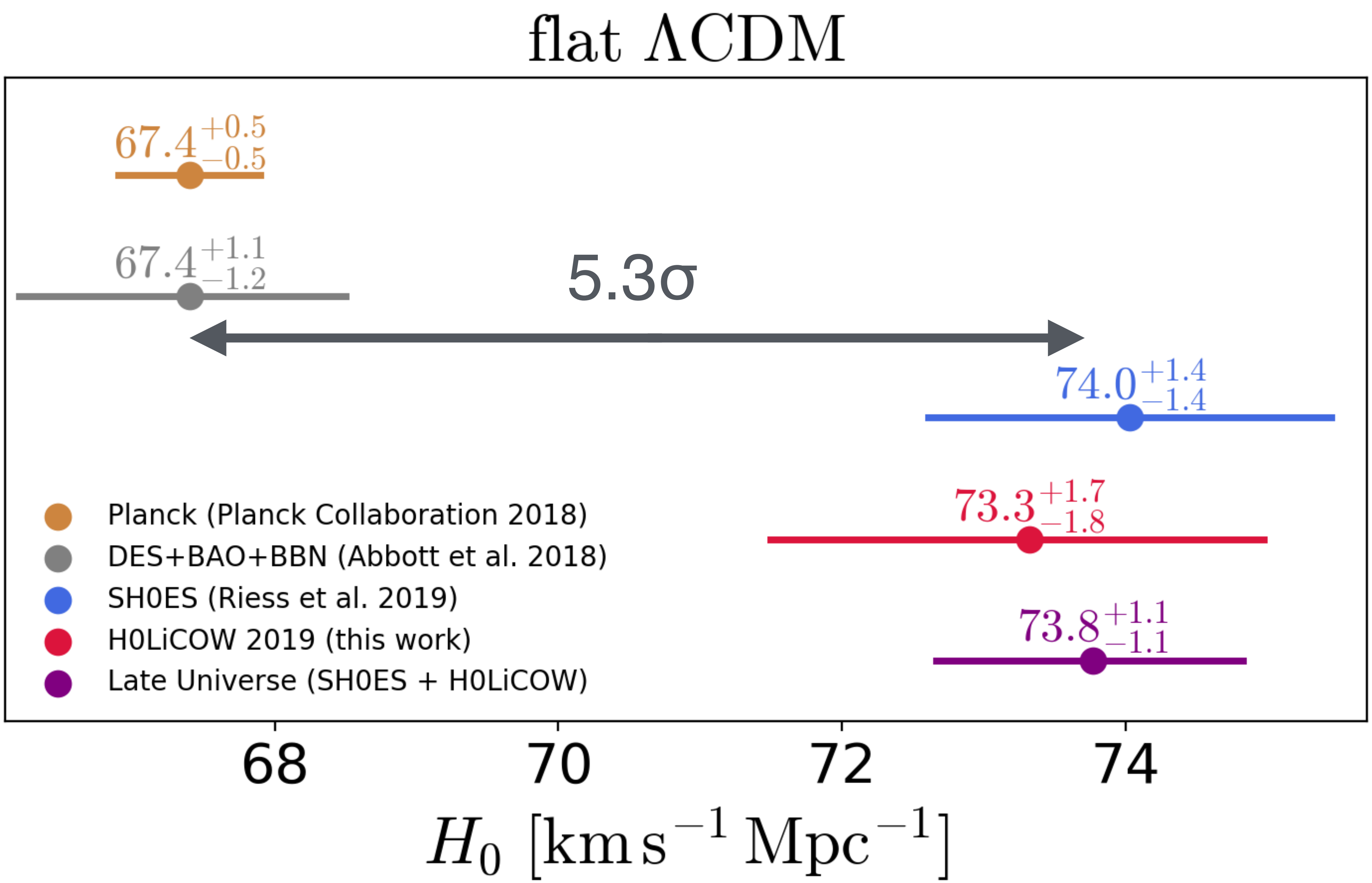
Planck Collaboration (2013)

Late-Universe H_0 measurement: cosmic distance ladder

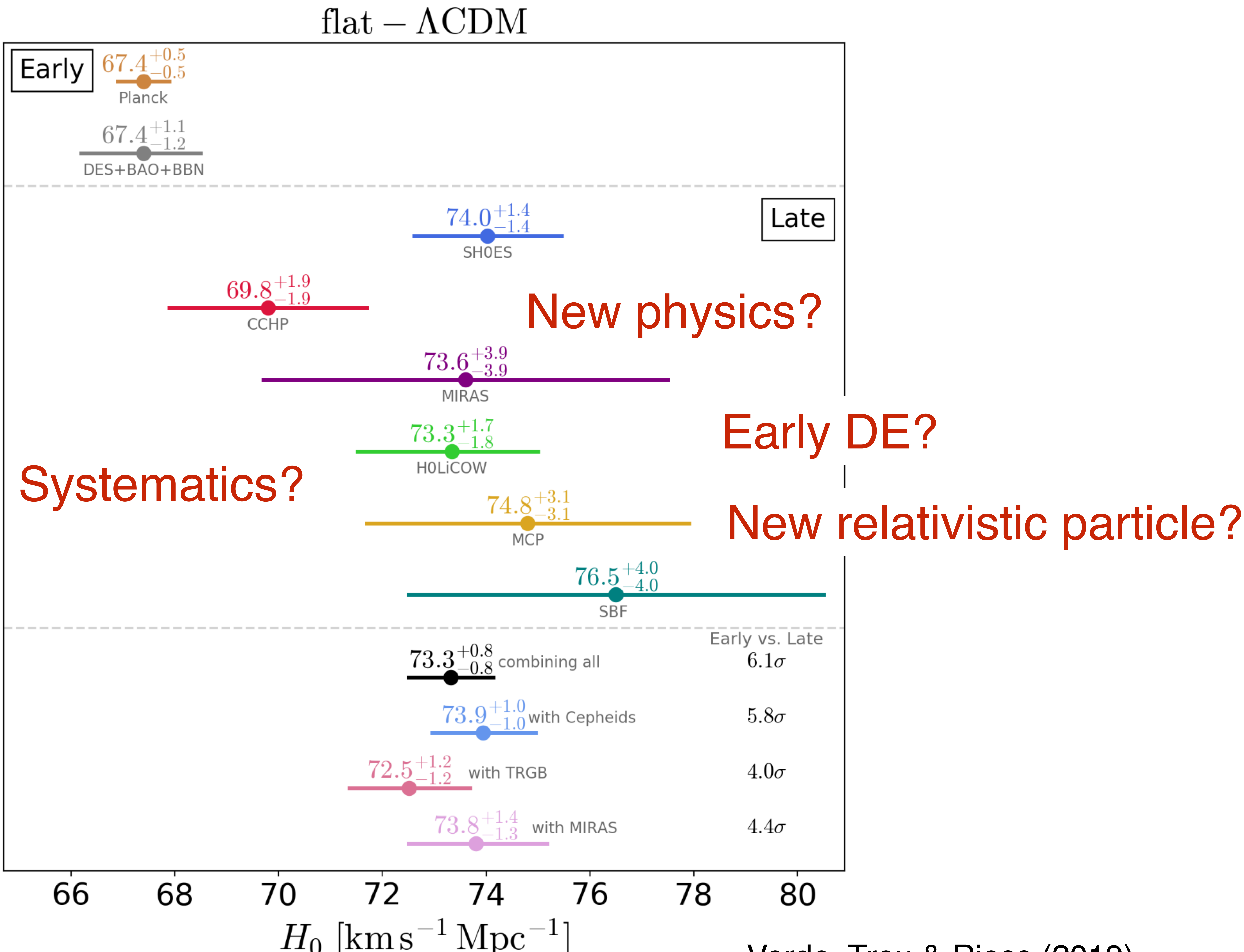


Riess et al. (2019), Image: https://www.photonicsspectra-digital.com

The “tension” becomes 5.3σ!



Wong,..,Shajib et al. (2019)

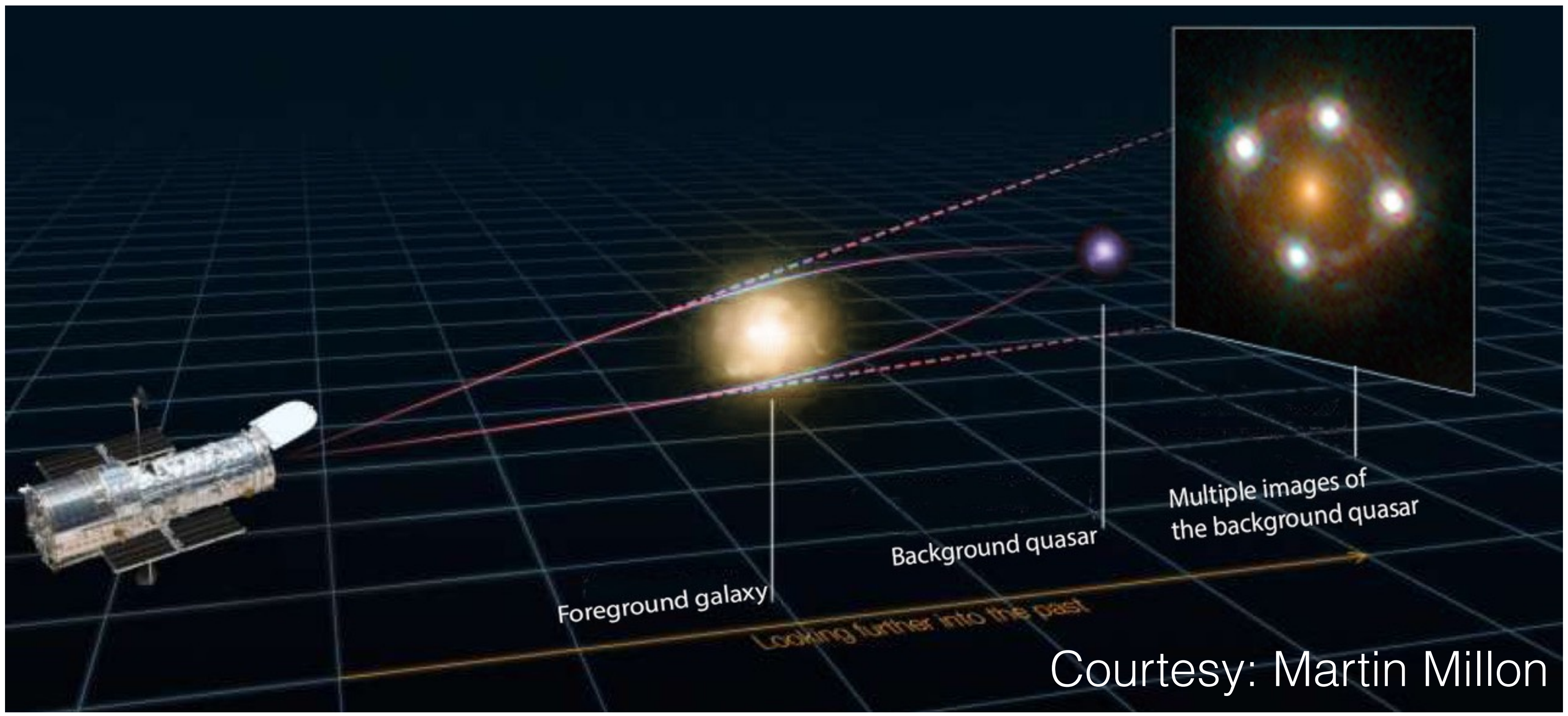


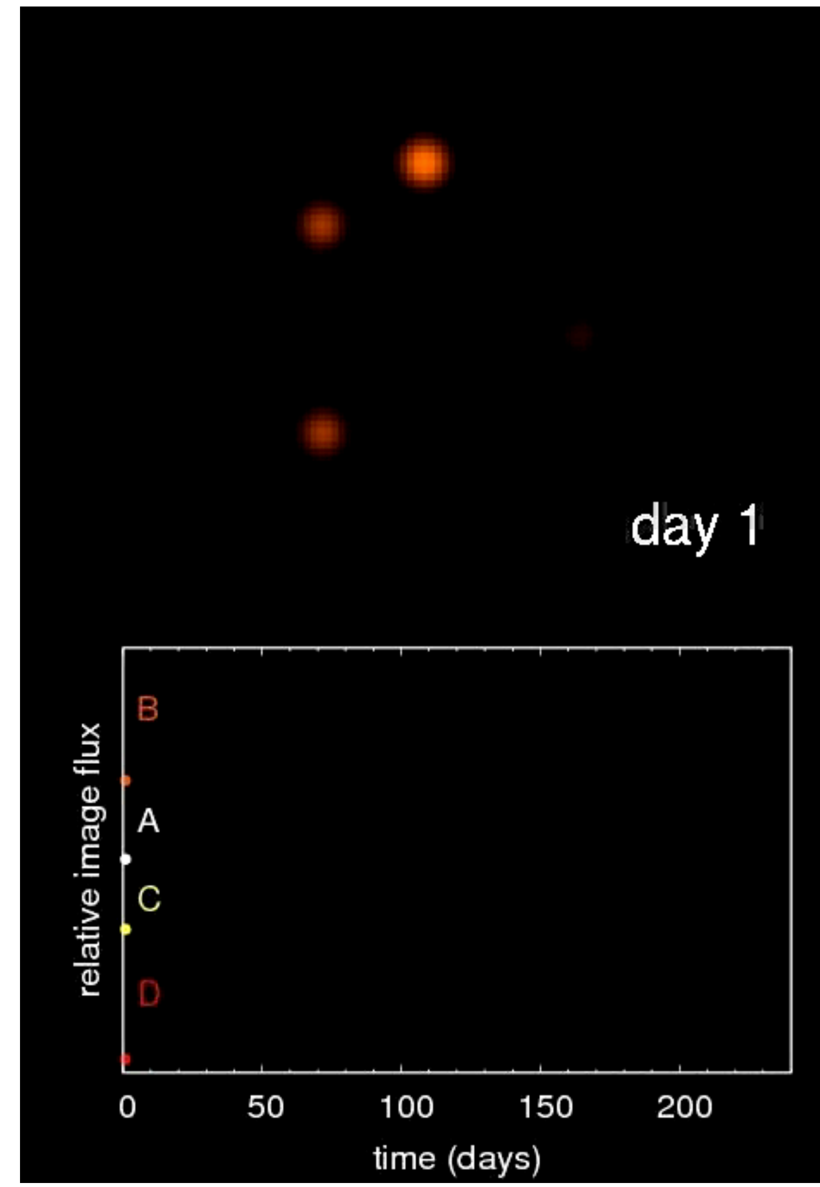
Verde, Treu & Riess (2019)

Time delay cosmography

- **Past:** Introduction and recent results
- **Present:** Current works in progress
- **Future:** Further improvements and forecasts

Time-delay Cosmography





Courtesy: Fred Courbin

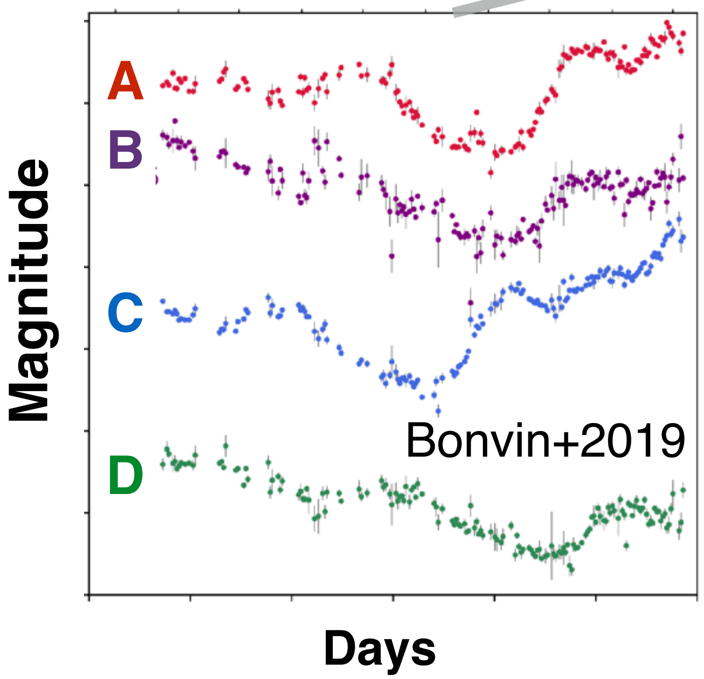
- Time-delay distance

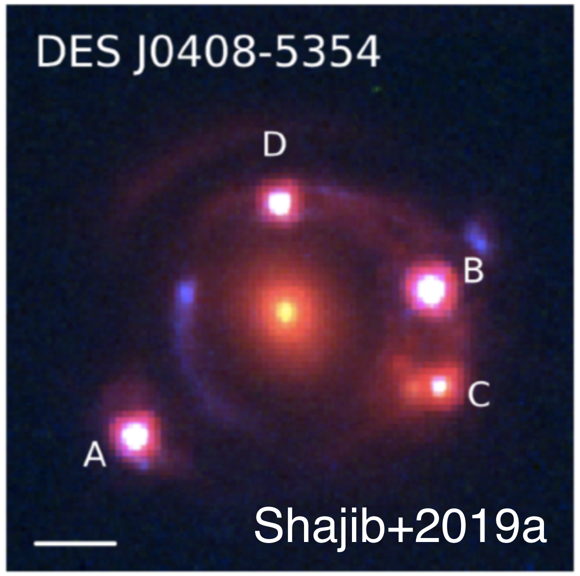
$$D_{\Delta t} \propto \frac{\Delta t}{\Delta \Psi} \propto \frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}} \propto \frac{1}{H_0}$$

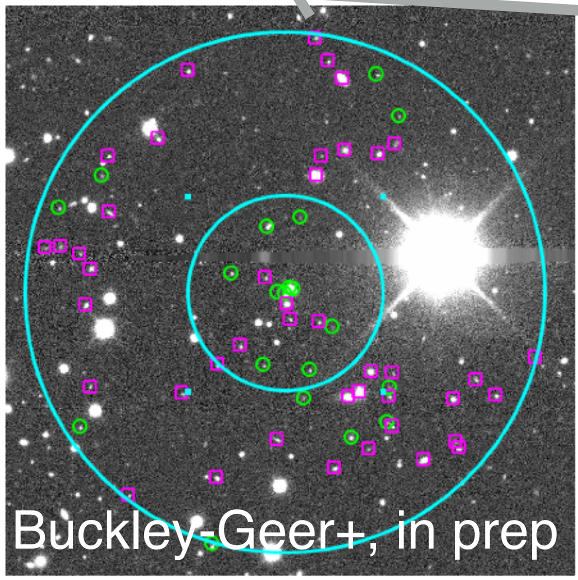
Necessary data for time-delay distance measurement

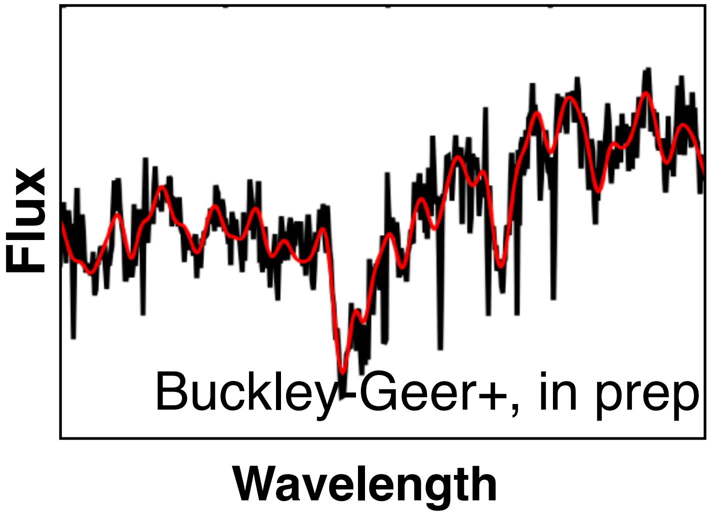
Time delay distance:

$$D_{\Delta t} = \frac{c\Delta t}{\Delta\Psi}\frac{1}{1-\kappa_{\rm ext}}$$







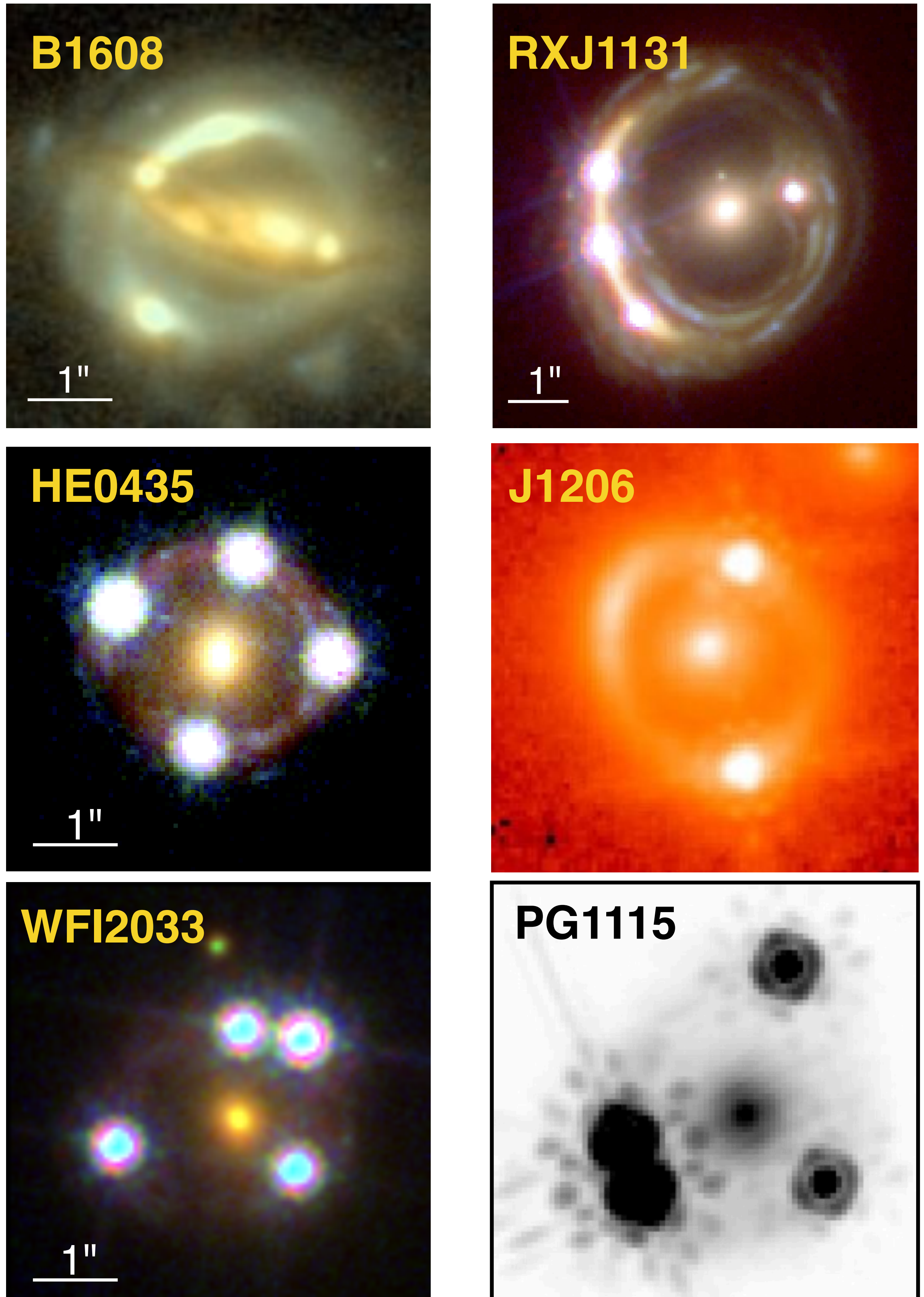


- Time delay measurement
- High resolution imaging of the lens
- Estimate of line-of-sight effects
- Kinematics

H0LiCOW sample of 6 time-delay lenses

Suyu et al. (2010)

Suyu et al. (2014)



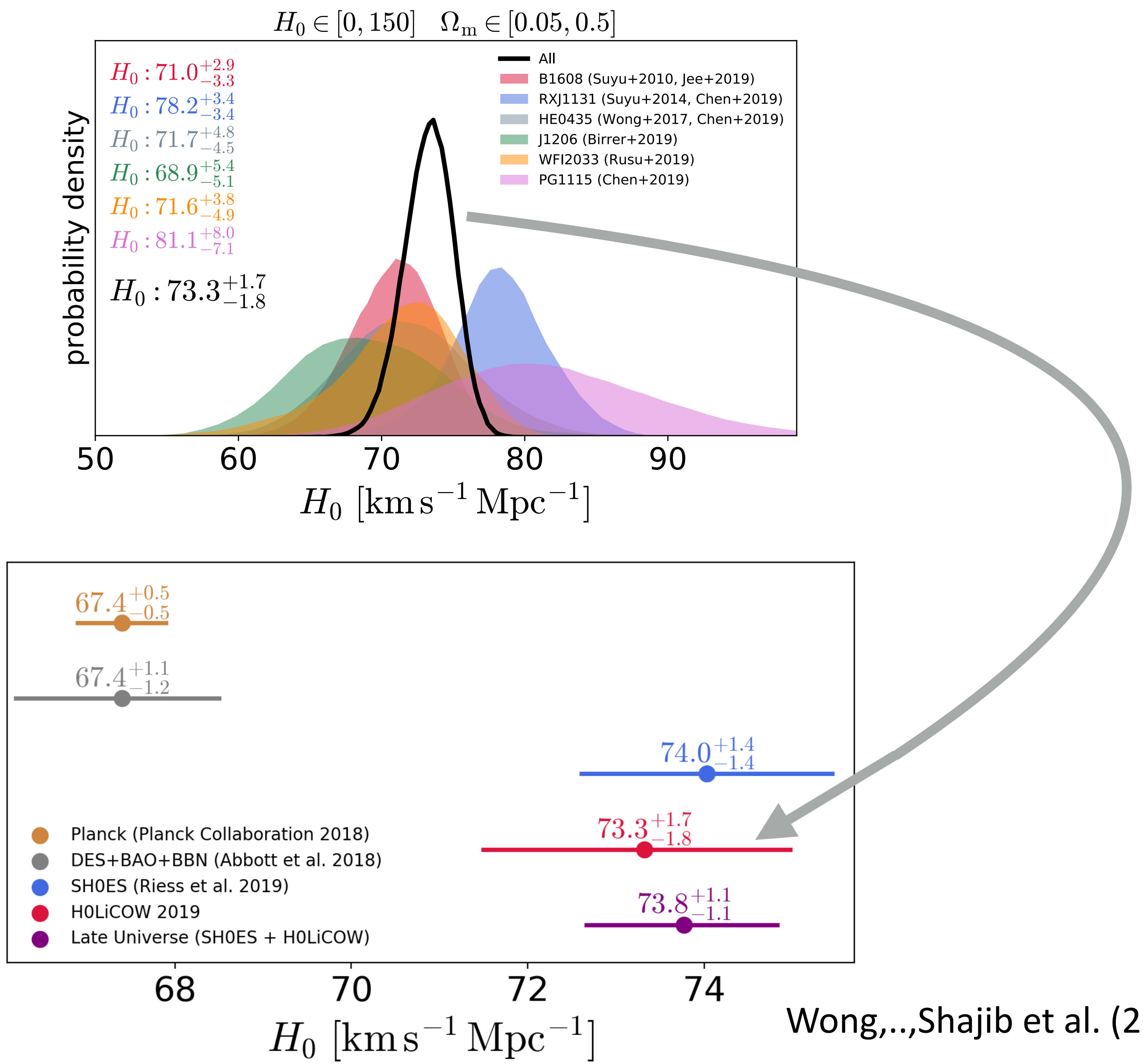
Wong et al. (2017)

Birrer,..,Shajib et al. (2019)

Rusu,..,Shajib et al. (2019)

Chen,..,Shajib et al. (2019)

Combining “blind” measurements from H0LiCOW: 2.4% precision in H_0

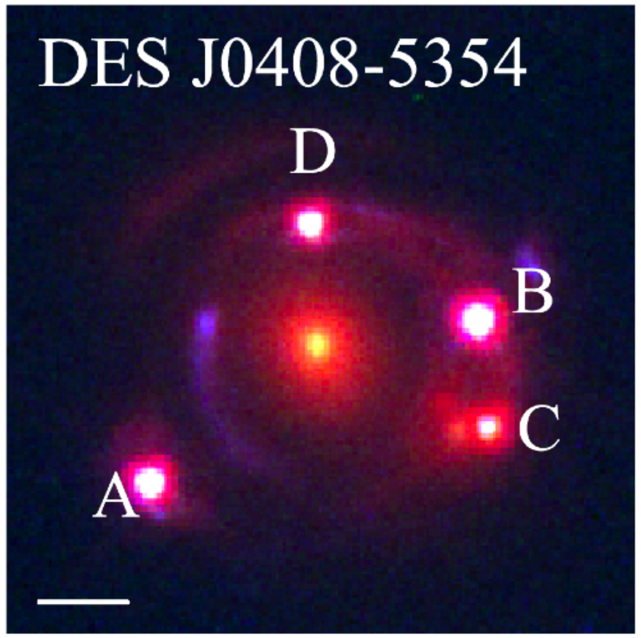


Wong,..,Shajib et al. (2019)

Time delay cosmography

- **Past:** Introduction and recent results
- **Present:** Current works in progress
- **Future:** Further improvements and forecasts

One new time-delay lens from the STRIDES collaboration



Independent analysis by **2** teams to check for systematics:

- Shajib et al. (UCLA) using “Lenstronomy”
- Yildirim et al. (MPA) using “GLEE”

Each lens requires coordinated effort by a large team.

- Lenstronomy lead developer: **S. Birrer**, KIPAC, Stanford

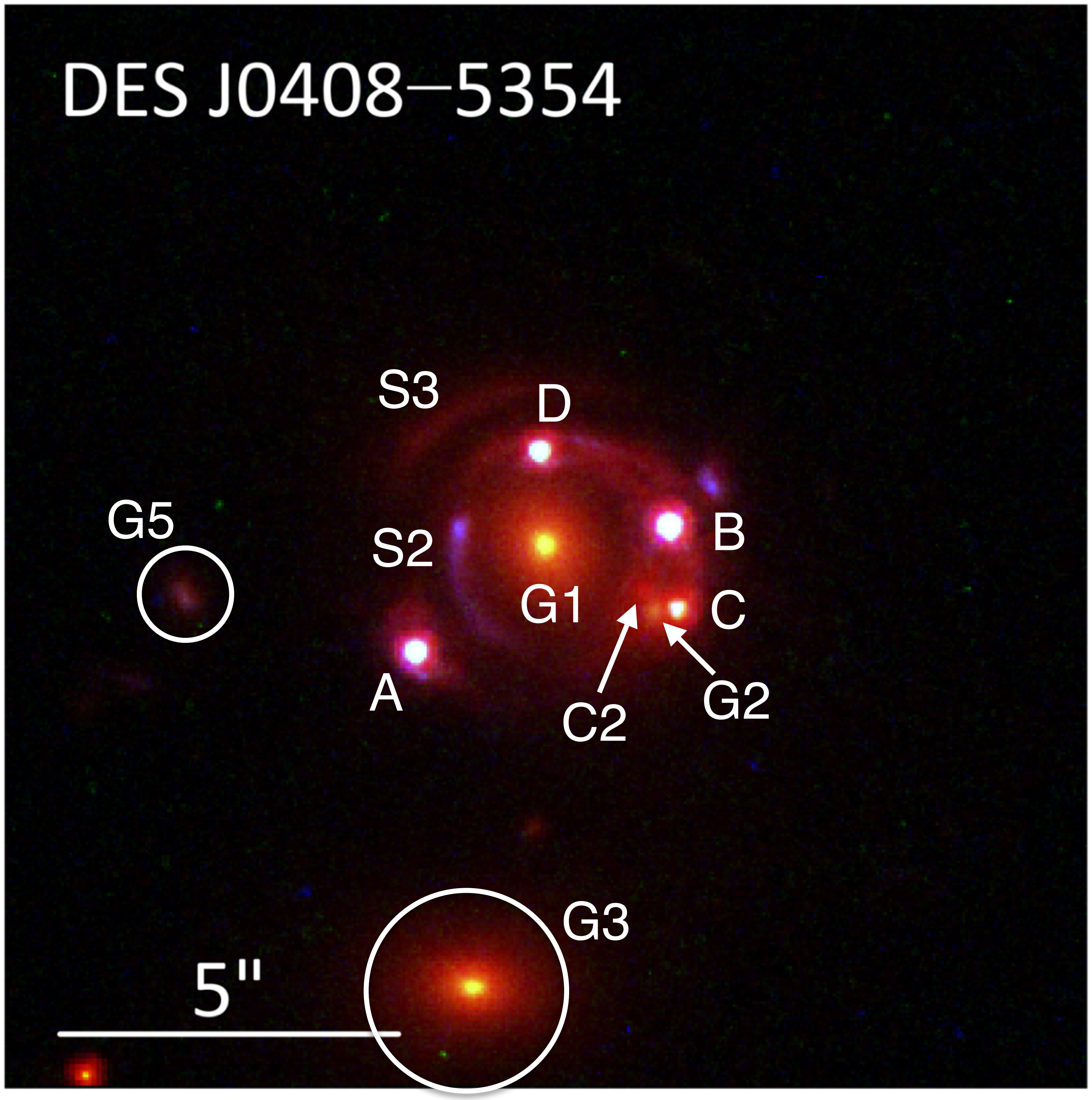
- Time-delays from COSMOGRAIL: **Courbin** et al. (2018)

- External convergence estimate: **E. Buckley-Geer** (Fermilab) and **C. E. Rusu** (NAOJ)

- Kinematics of the deflector: **H. Lin** (Fermilab)

- Nearby galaxy group detection: **J. Poh**, PhD student, (UChicago), **H. Lin** (Fermilab)

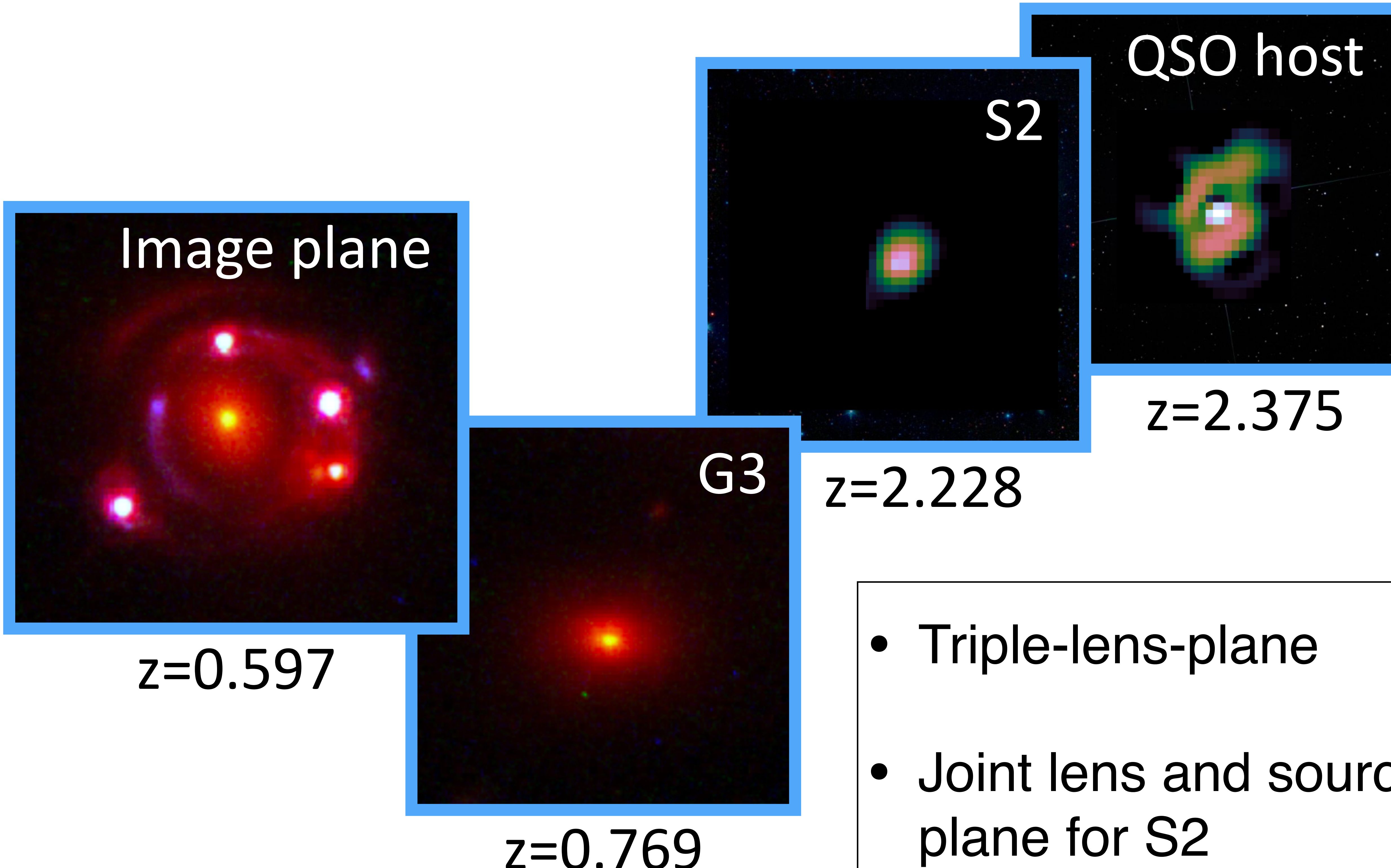
The most complex lensed quasar to-date



- Nearby satellite (G2)
- Additional image (C2)
- Multiple sources (S2, S3)
- Line-of-sight perturbers (G3, G5)

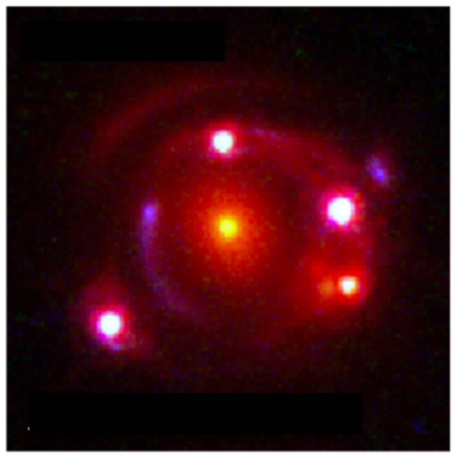
Shajib et al. (2019c)

Multi-lens-plane lens modelling

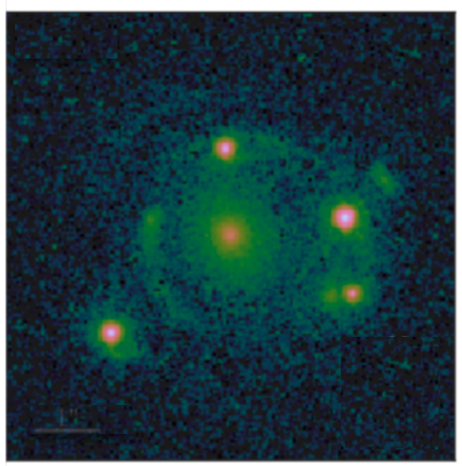


- Triple-lens-plane
- Joint lens and source plane for S2

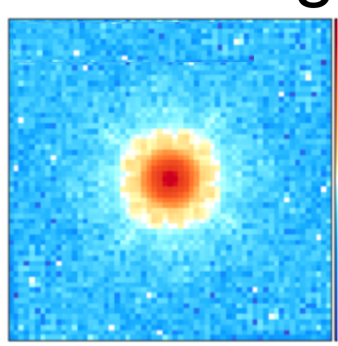
Behind the scene of lens modeling



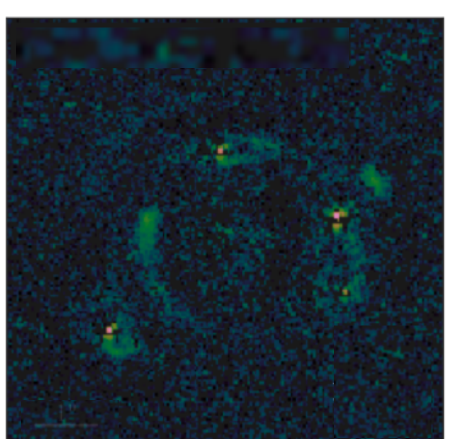
Data: 3-band



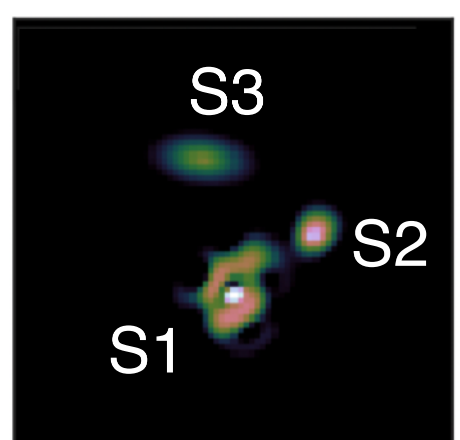
Data: single band



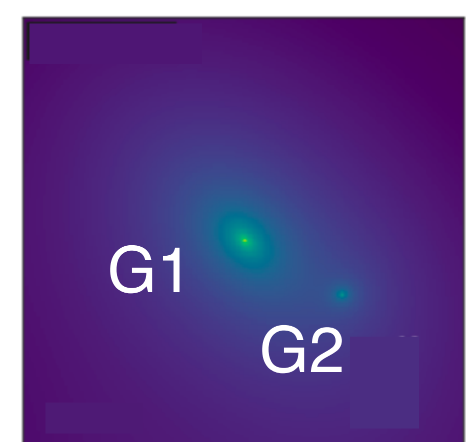
PSF



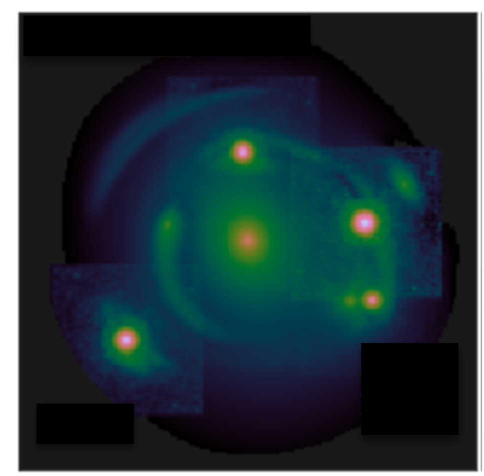
Lensed host galaxy



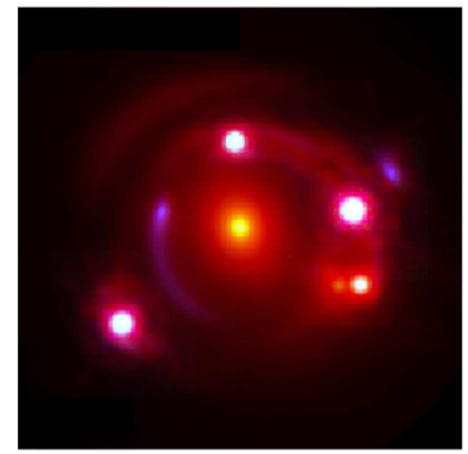
Recons-tructed source



Mass

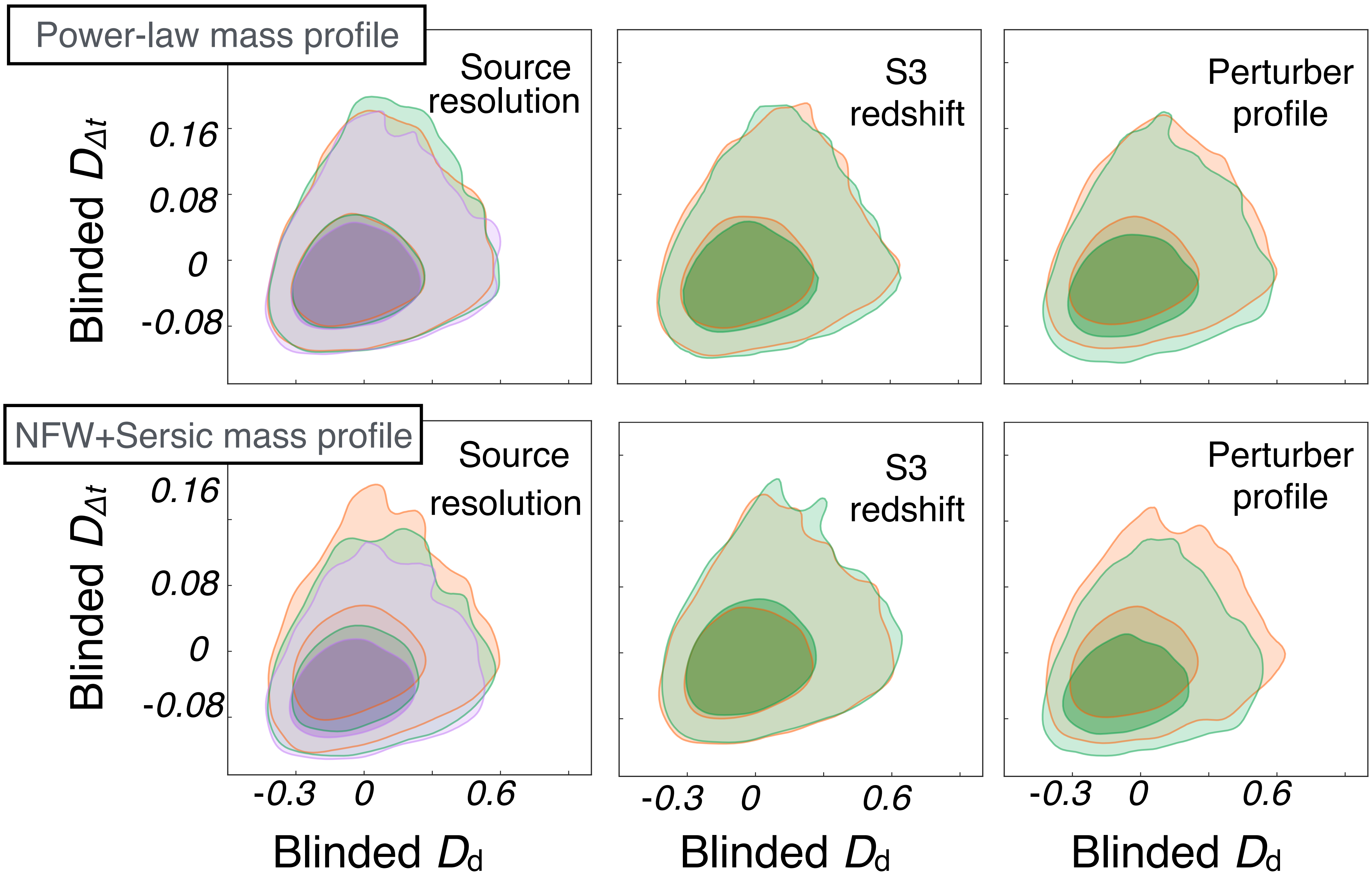


Reconstructed: single band



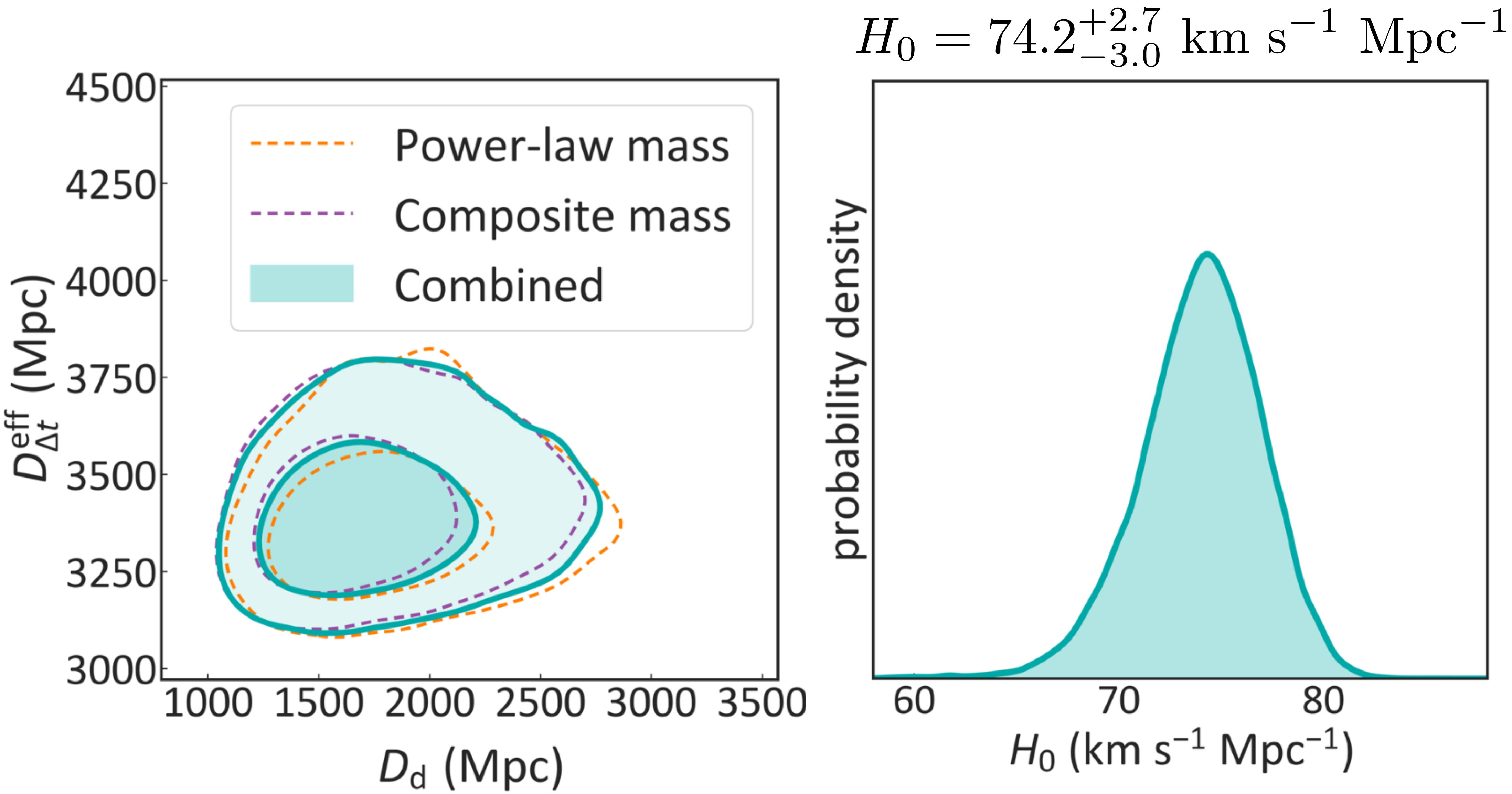
Reconstructed: multi-band

Marginalizing systematics in lens modelling



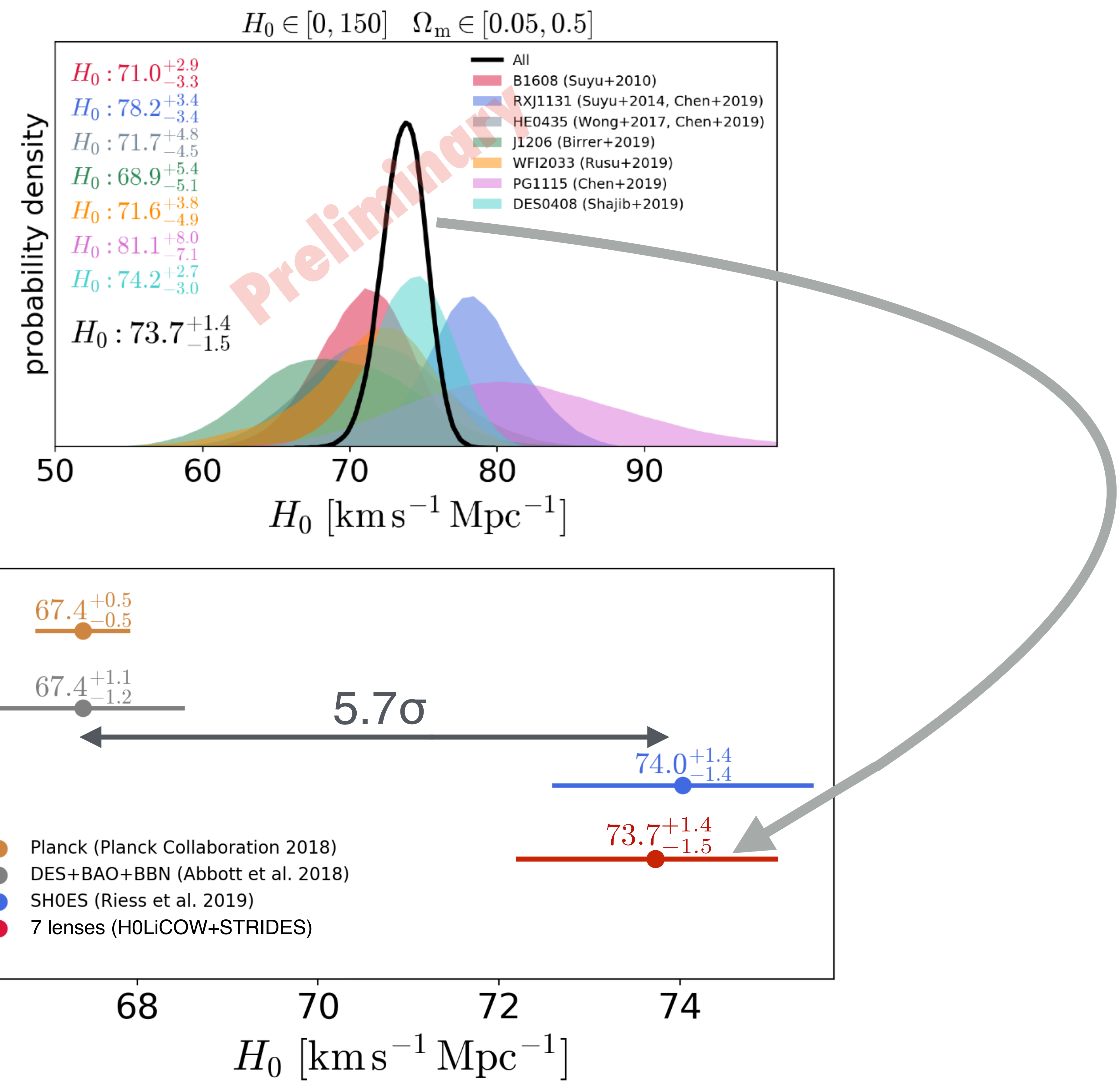
Shajib et al. (2019c)

H_0 from DES J0408-5354



- 3.9% precision from a single lens, highest to-date
- Consistent with the previous sample of 6-lenses

Preliminary combination of 7 lenses: 2% precision in H_0



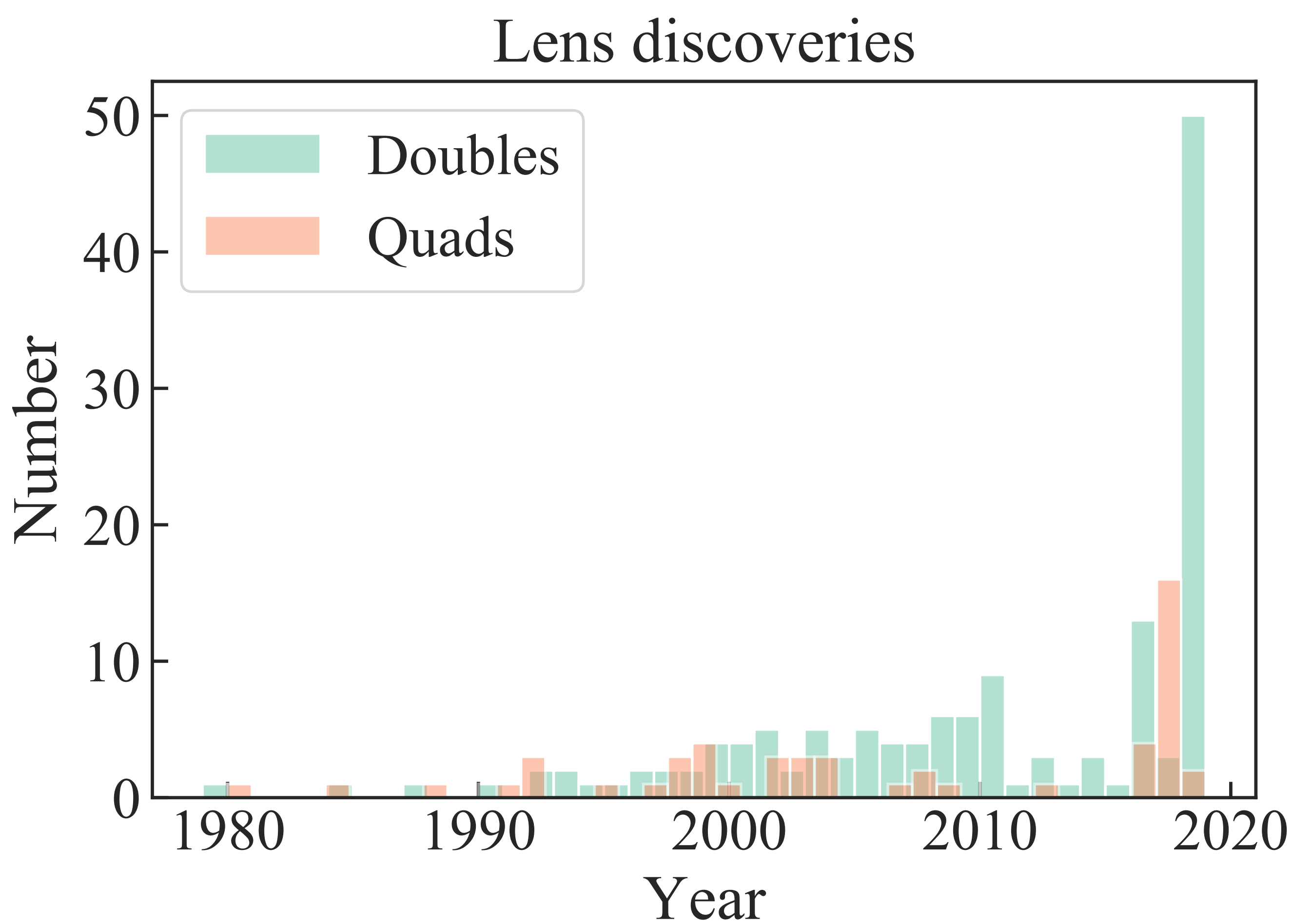
Time delay cosmography

- **Past:** Introduction and recent results
- **Present:** Current works in progress
- **Future:** Further improvements and forecasts

Future goal is 1% H_0 measurement.

- Two Ways to improve precision
    - Increase sample size
    - Improve precision per system
- Thoroughly investigate to find unknown systematics

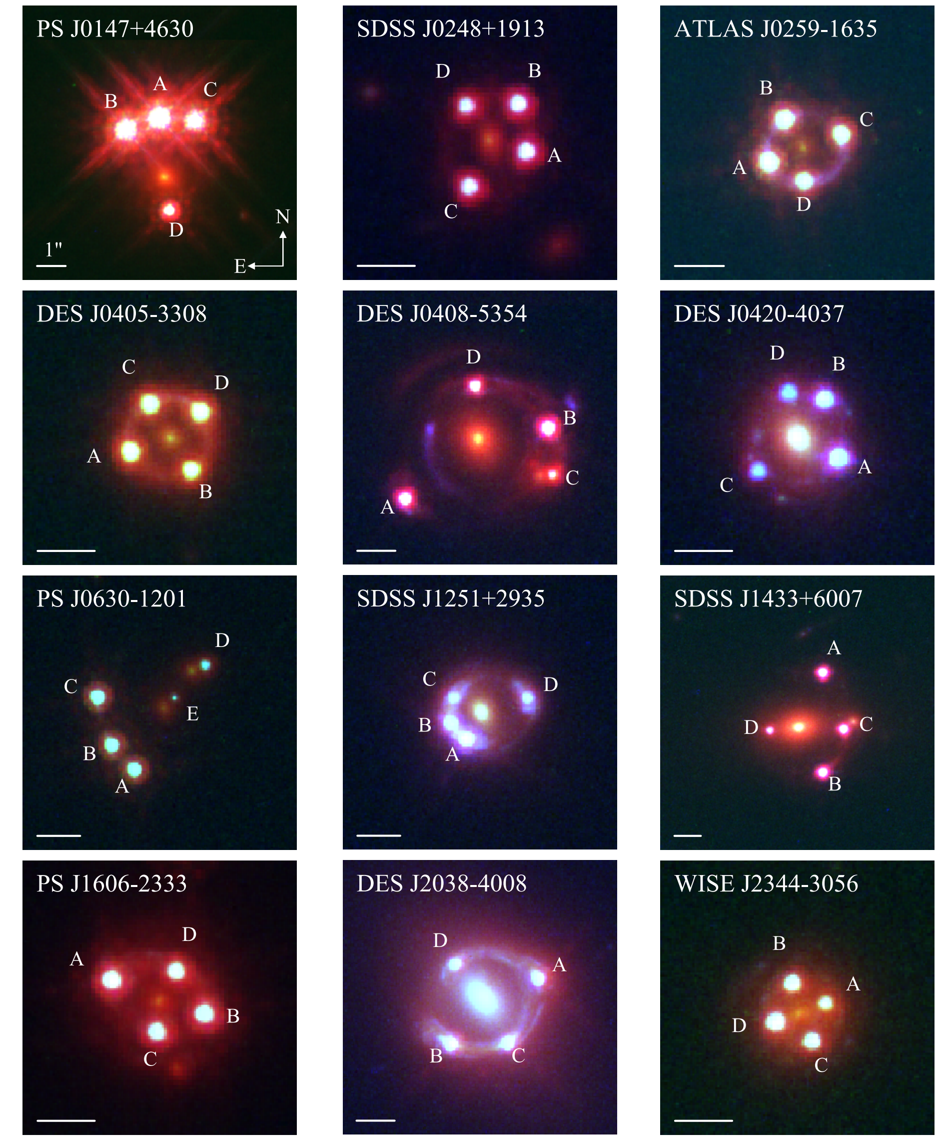
Approach 1: Increasing sample size



Data courtesy: Lens DB by Cameron Lemon

We have already discovered enough quasars to reach 1% in H_0.

From HST Cycle 25

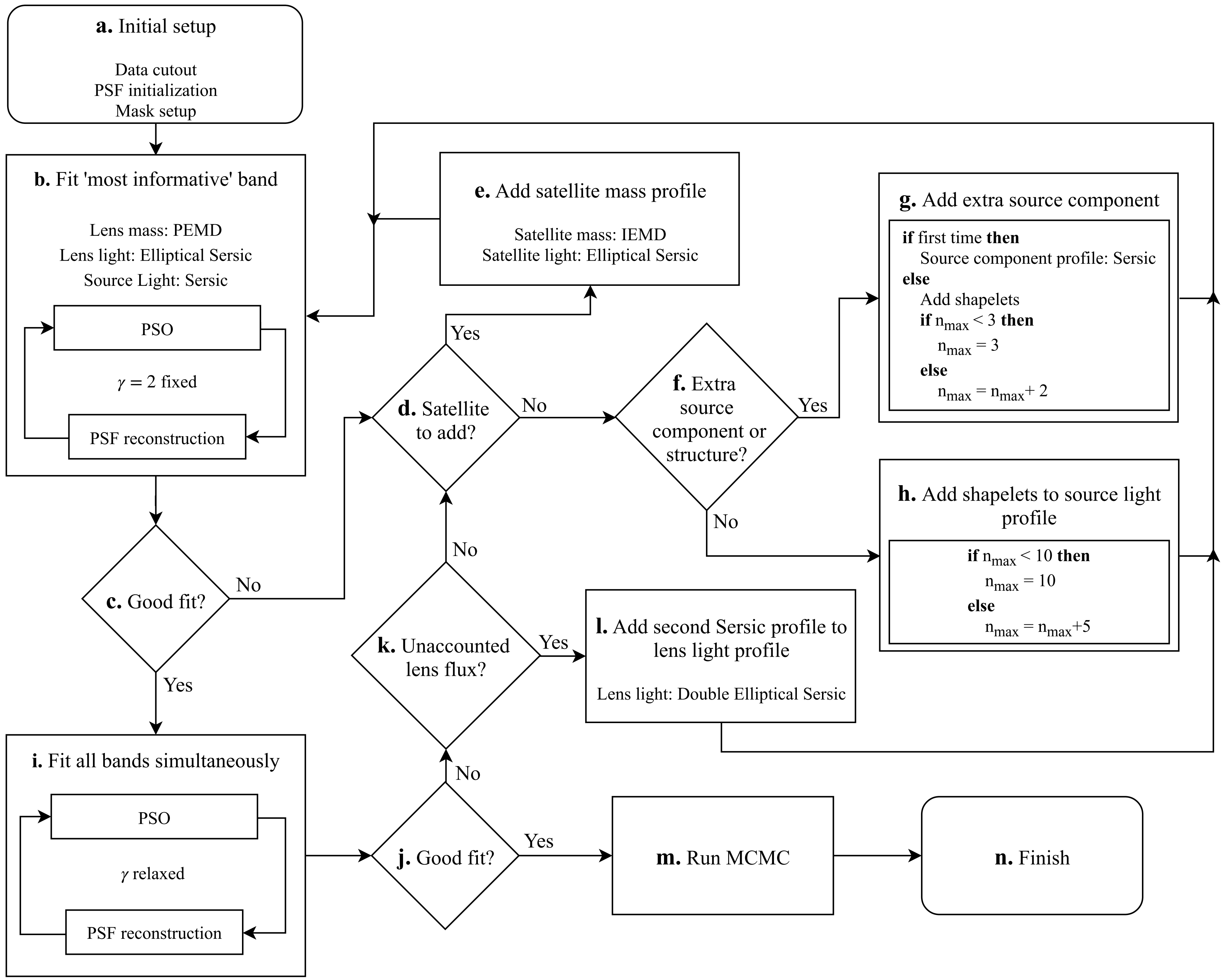


Shajib et al. 2019a

From HST Cycle 26

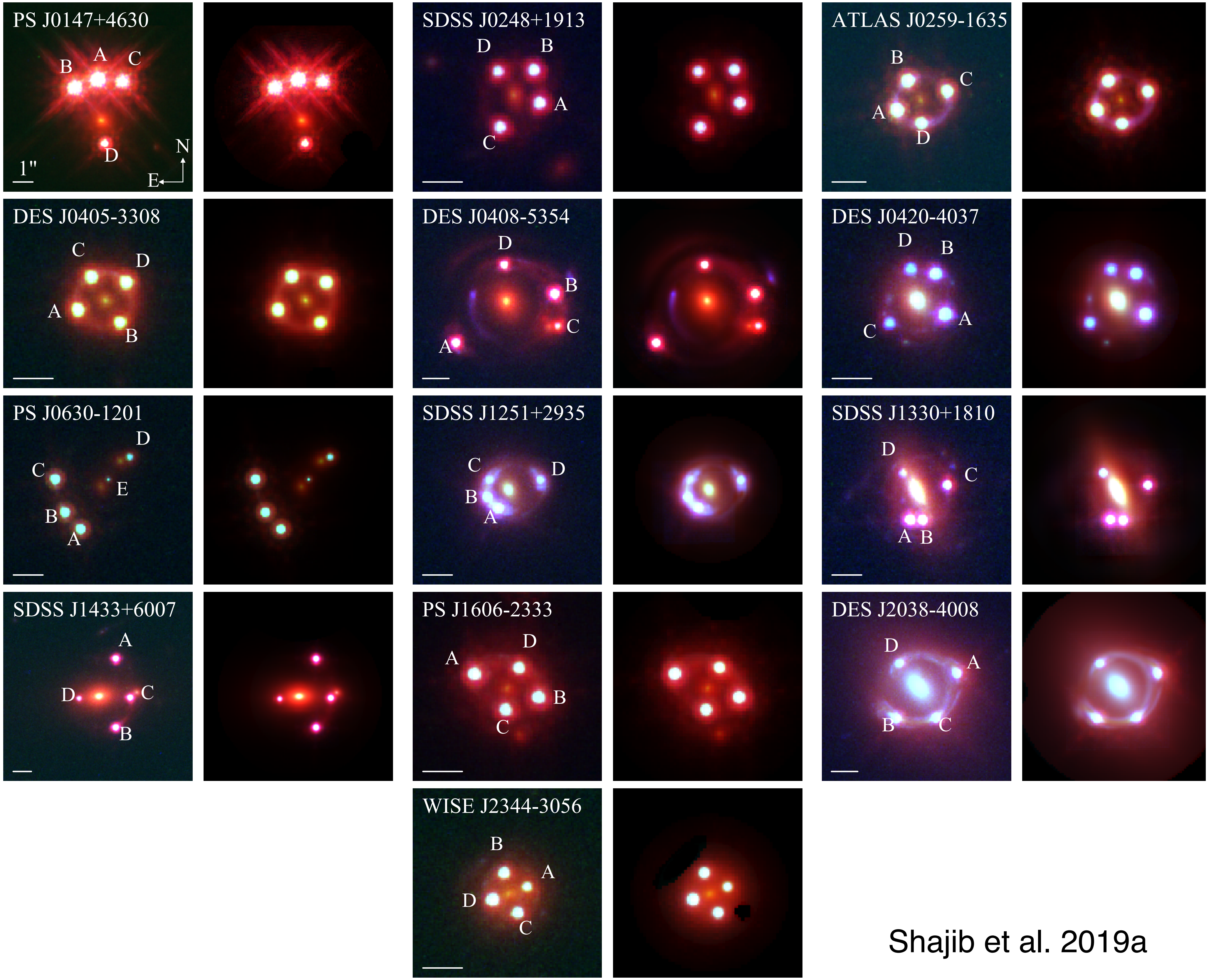
… and 15 more to be observed.

Approach 1: Automating the lens modeling



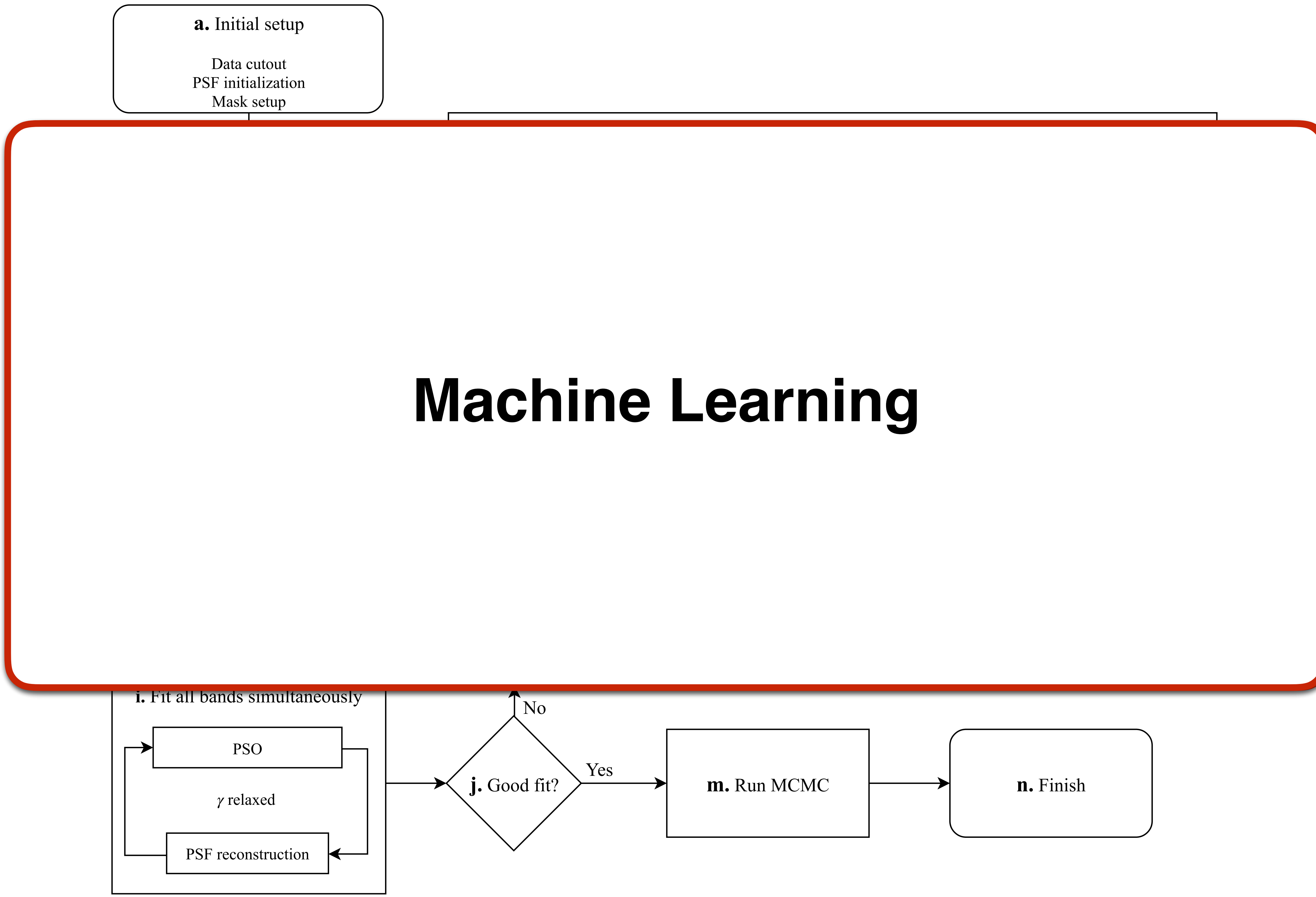
Shajib et al. 2019a

Approach 1: Automated lens models of 13 lenses



Shajib et al. 2019a

Approach 1: Automating the lens modelling

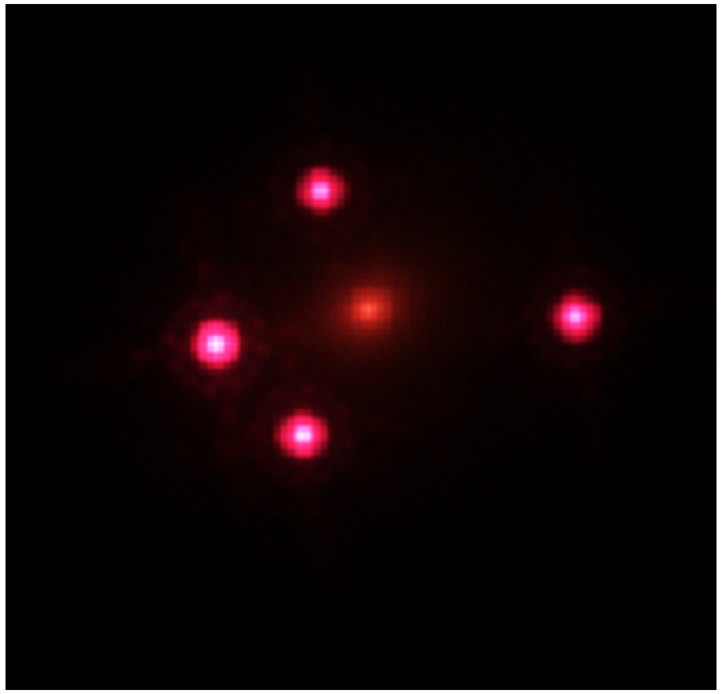


Shajib et al. 2019a

Approach 1: Future direction in automated lens modelling

- **Machine learning** for initializing lens models
    - Work of Vedant Sahu, UCLA undergraduate

Image from validation set

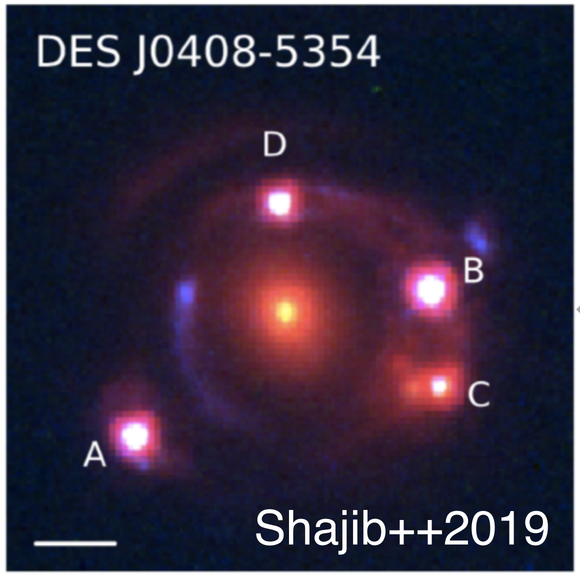


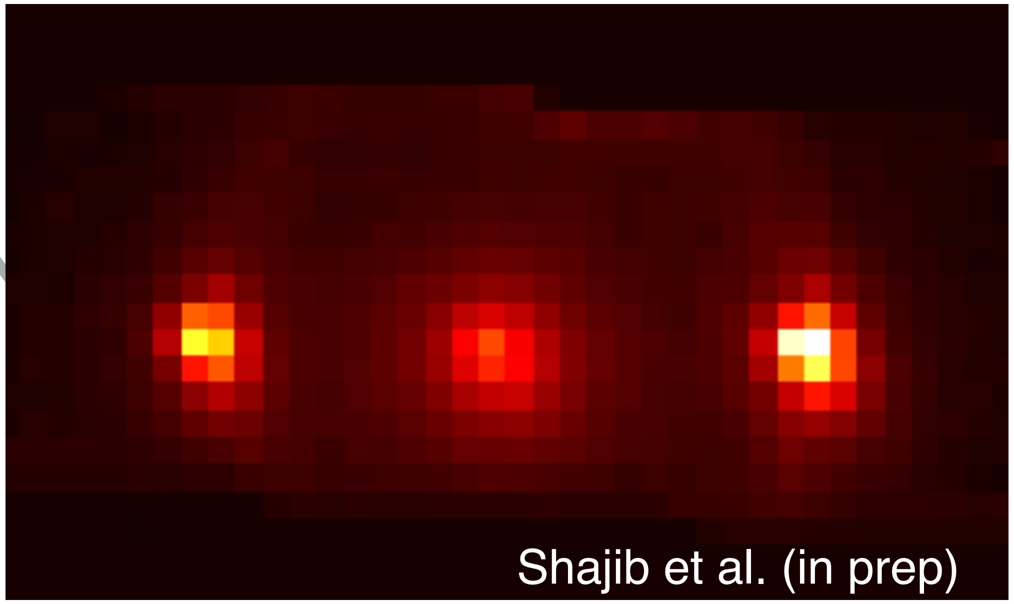
Detected quasar images and lensing galaxy

Approach 2: Improving Precision Per System

Time delay distance:

$$D_{\Delta t} = \frac{c\Delta t}{\Delta\Psi}\frac{1}{1-\kappa_{\rm ext}}$$

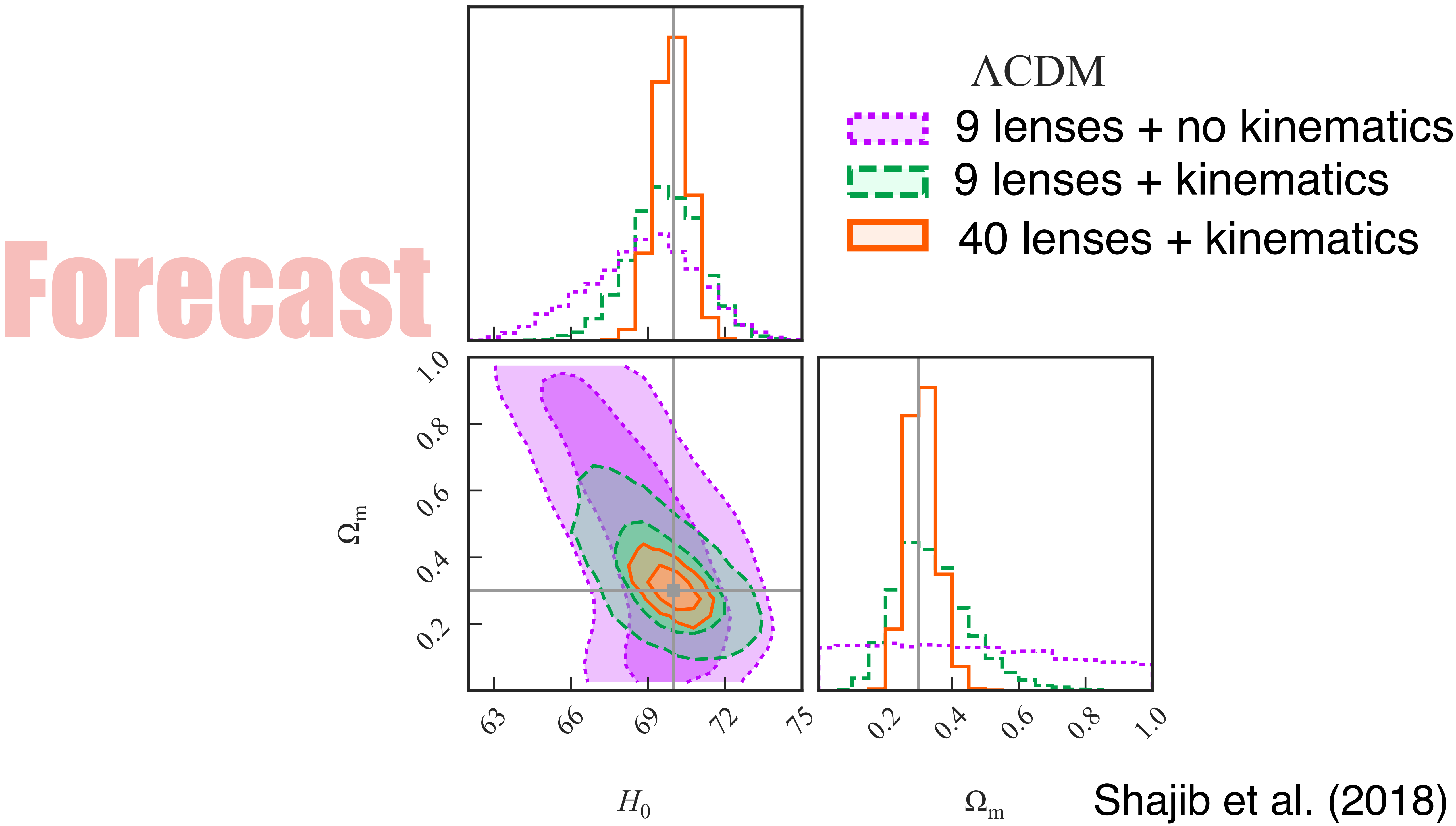




Spatially resolved kinematics

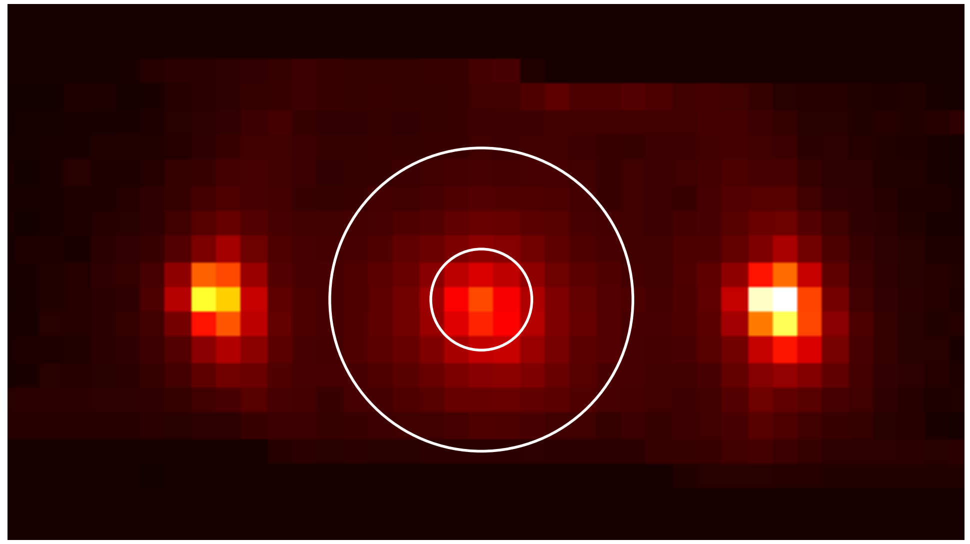
Spatially resolved kinematics improves precision on the mass profile slope.

Approach 2: Spatially resolved kinematics helps determine H_0 1% from a sample of 40 lenses.



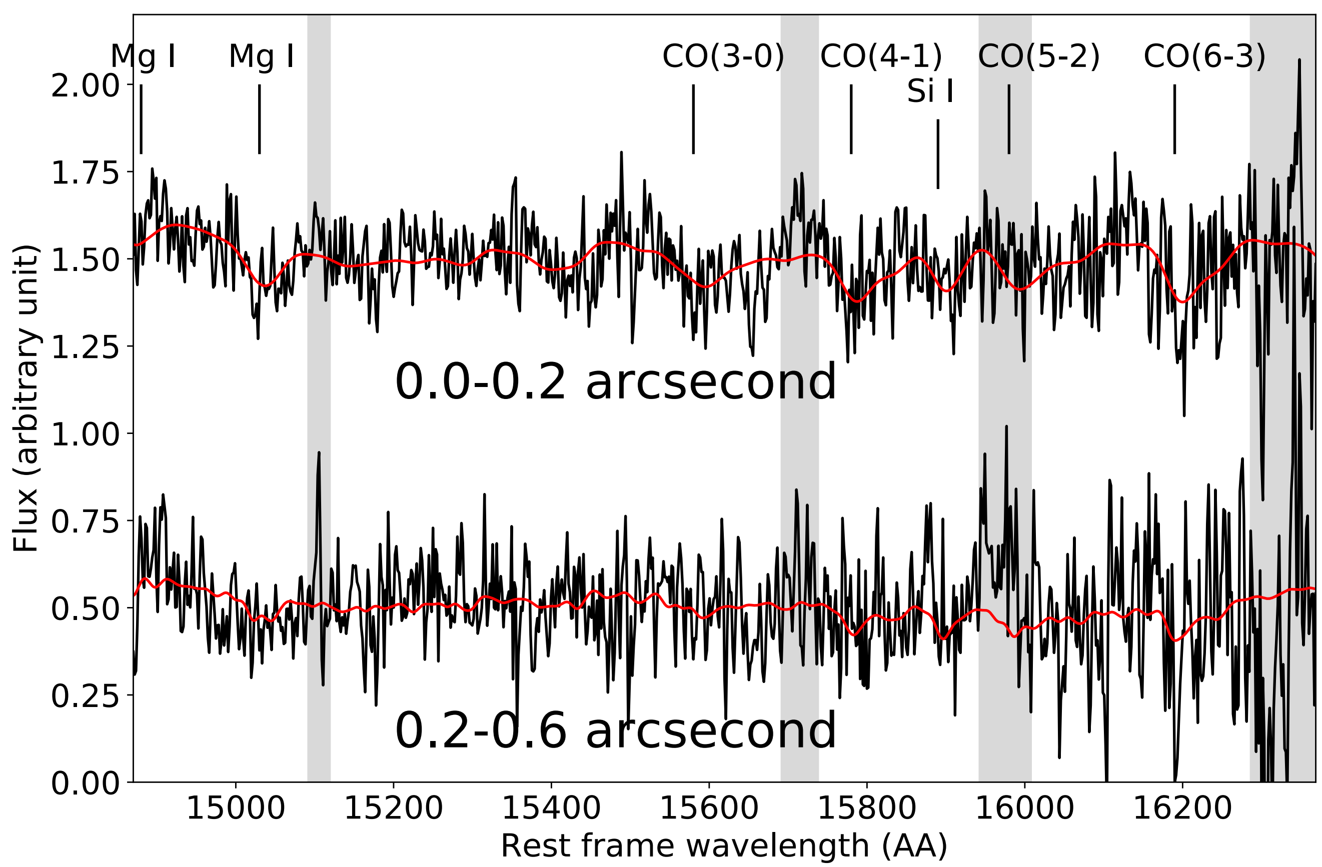
Shajib et al. (2018)

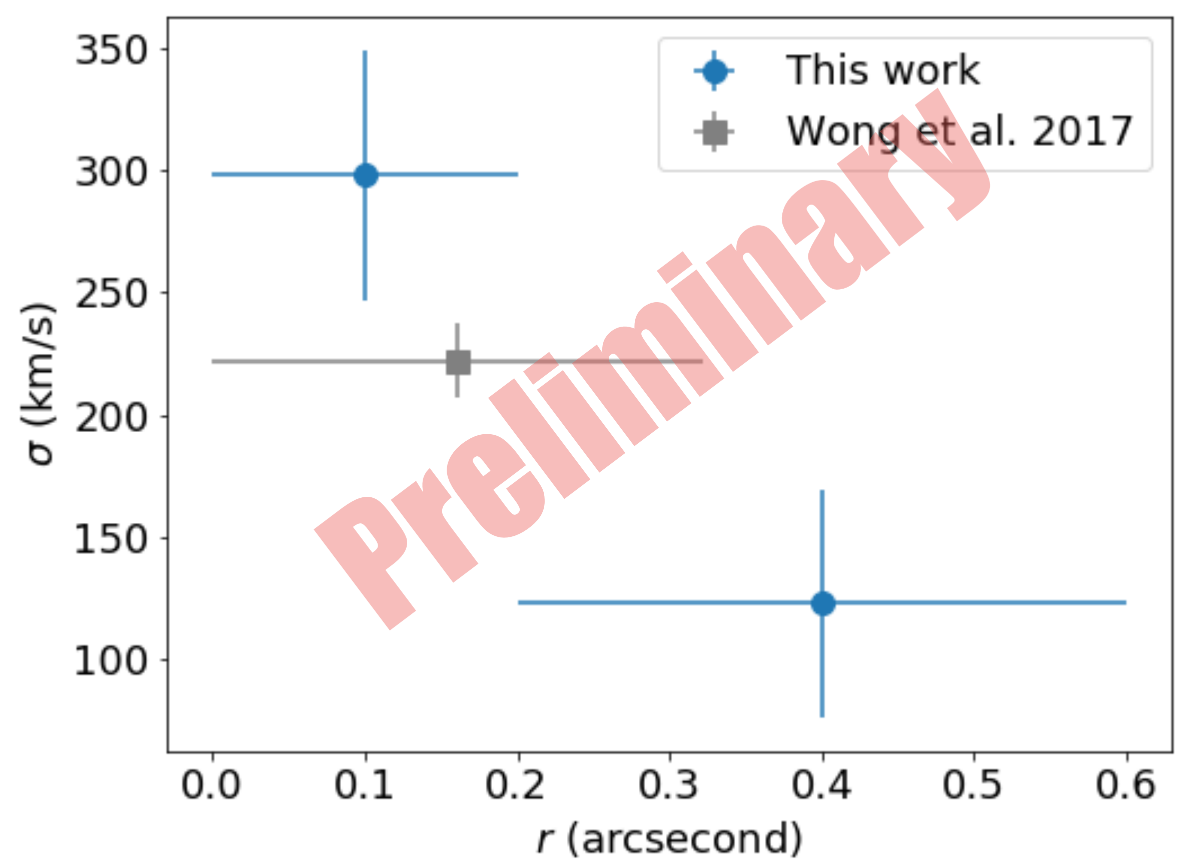
Approach 2: Stellar kinematics from Keck/OSIRIS



Data

Integration time: 4 hours
Target: 8 hours





Shajib et al. (in prep)

Tackling systematic: community data challenge

- To check for **bias** from different codes and modelers
- Simulated data with known, but hidden H_0 (Ding, Treu, Shajib et al.)
- 3 different levels with increasing complexity to understand the source of systematics, if any.
- Challenge finished recently, result to be announced soon

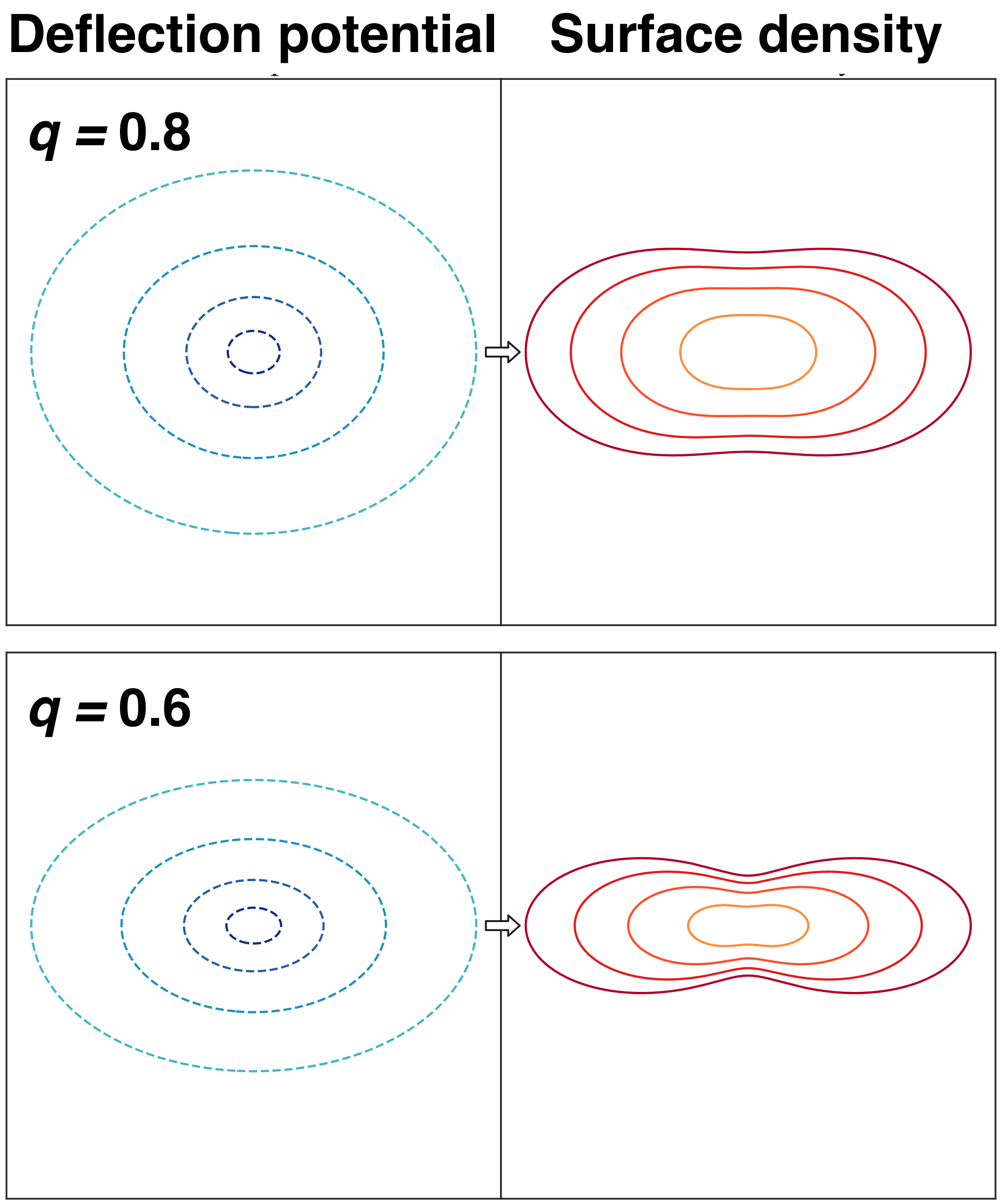
Tackling systematic: exploring more mass models with a novel method

- Elliptical mass profiles are analytically difficult for lensing.

$$\text{deflection angle} = \int \text{surface density}$$

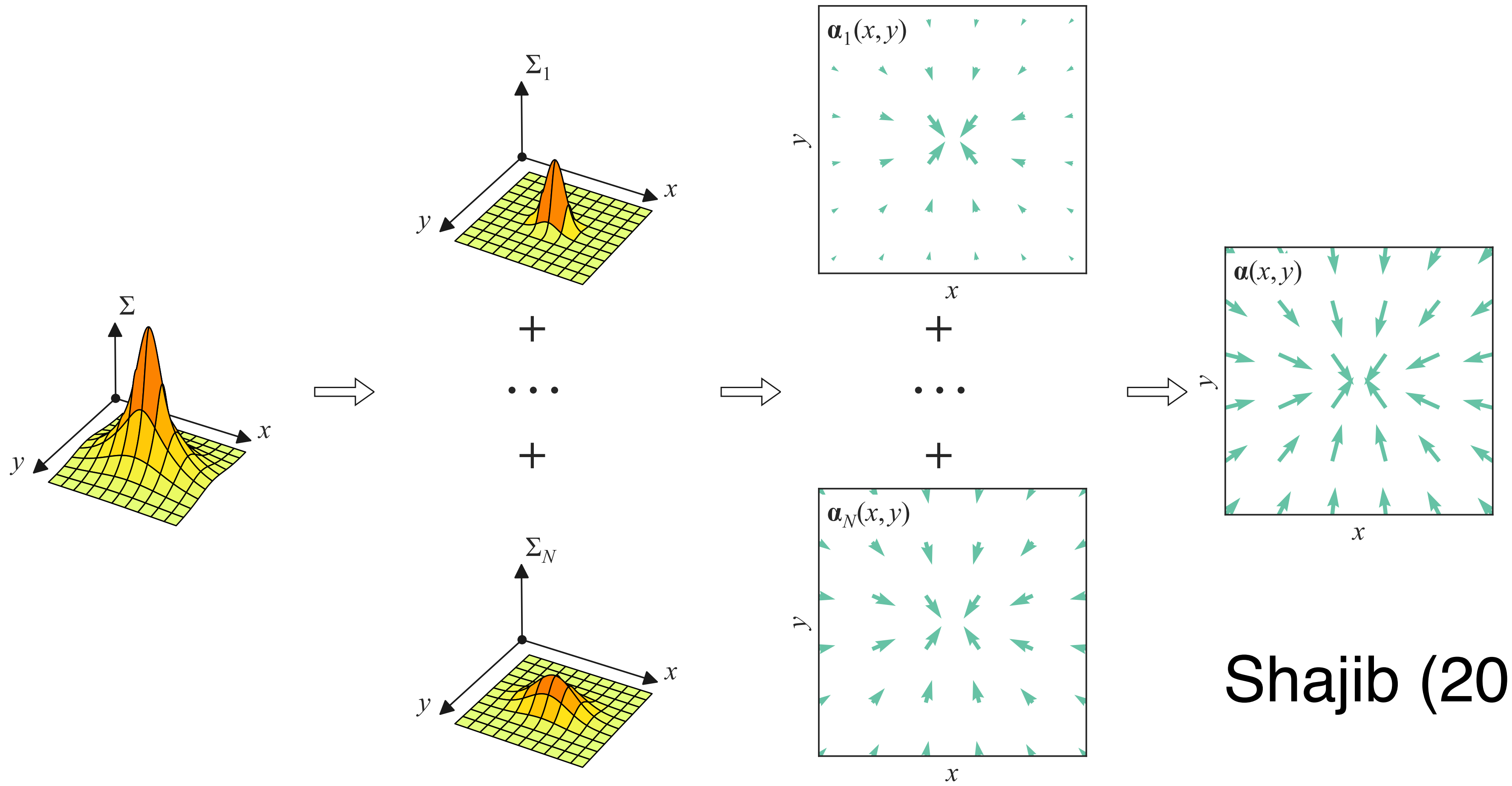
$$\text{potential} = \int \text{deflection angle}$$

- No general solution for three decades.



Shajib (2019b)

Tackling systematic: exploring more mass models with a novel method



Shajib (2019b)

- General and efficient
- Readily pluggable to Jeans anisotropic modeling of kinematics → unified lensing and kinematic analysis

Summary

- 7th time-delay lens gives most precise H_0 measurement at 3.9%
- Preliminary combination increases tension with early-Universe probes to ~5.7σ
- Future directions:
  - Automated lens modelling for large samples
  - Spatially resolved kinematics to improve precision per lens
  - 1% H_0 measurement forecasted from ~40 lenses