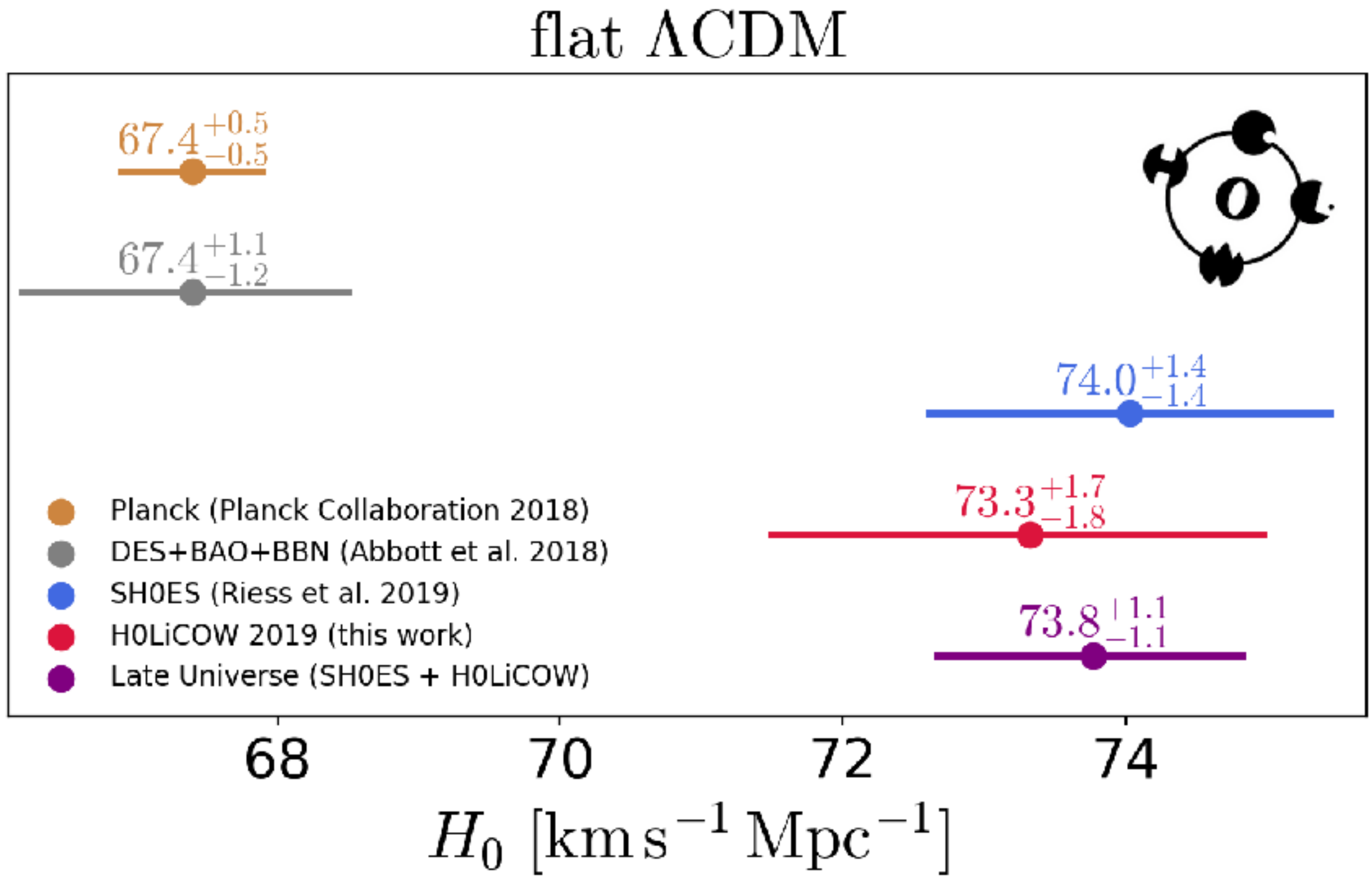
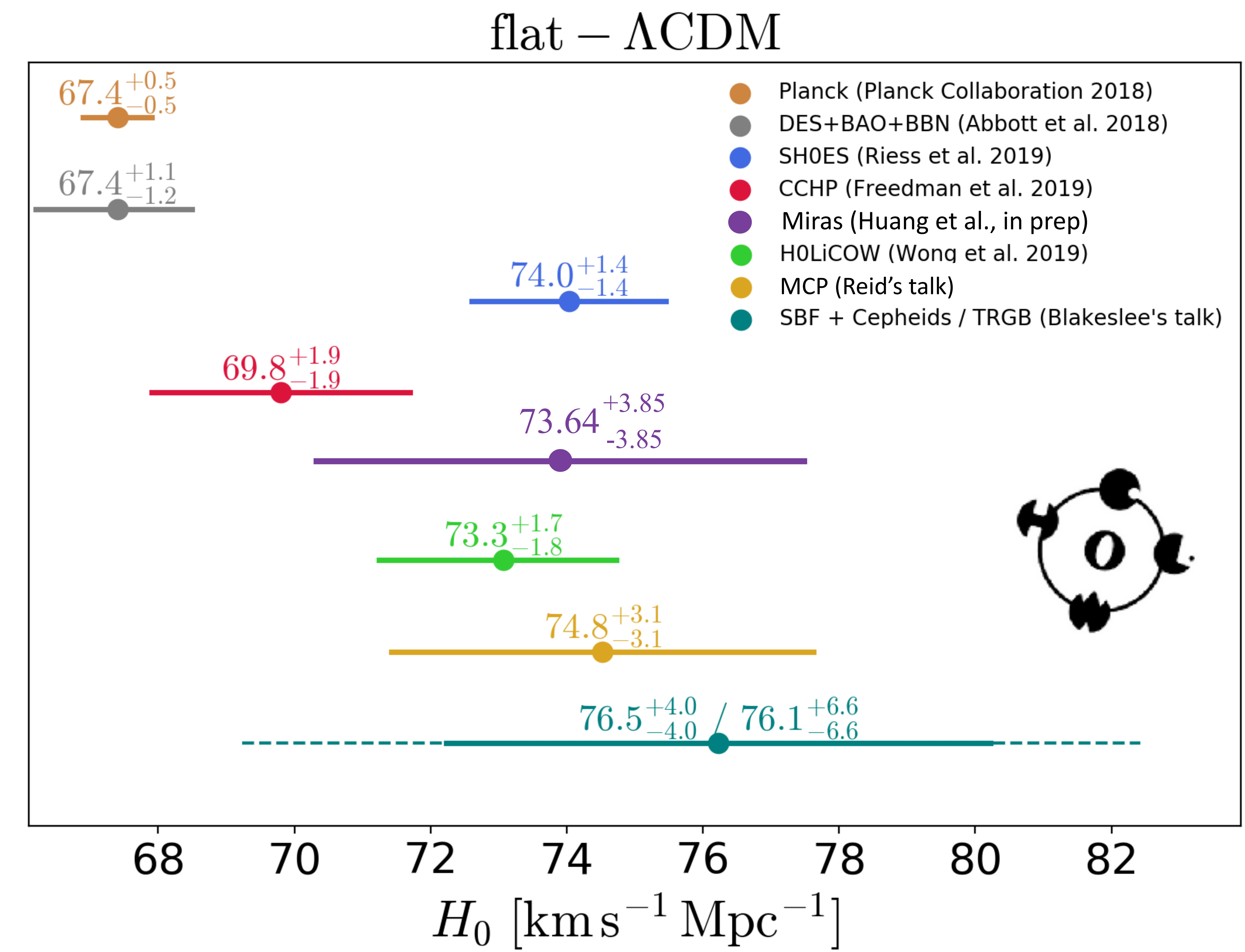
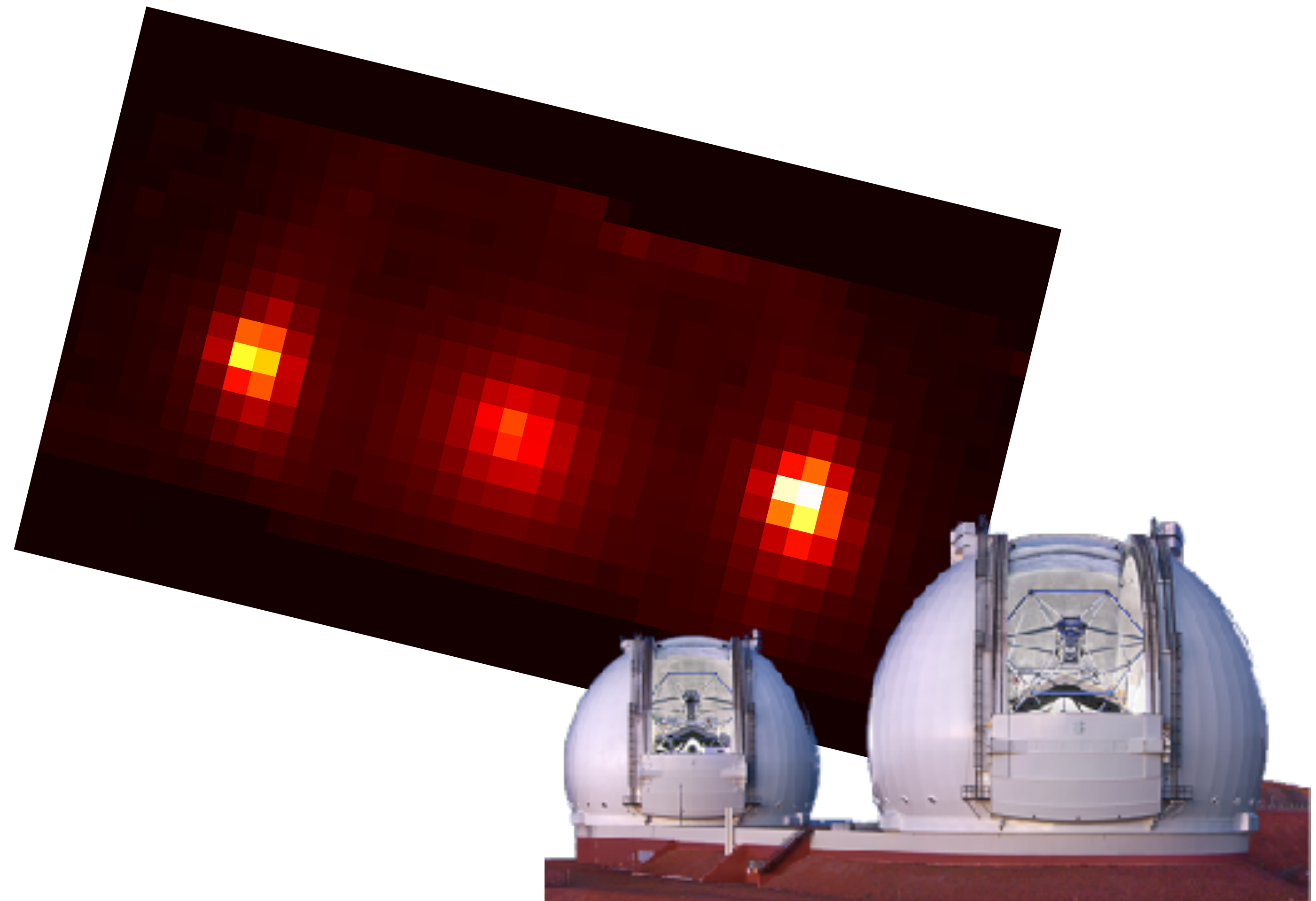


flat ΛCDM
$67.4^{+0.5}_{-0.5}$
$67.4^{+1.1}_{-1.2}$
$74.0^{+1.4}_{-1.4}$
$73.3^{+1.7}_{-1.8}$
$73.8^{+1.1}_{-1.1}$
Planck (Planck Collaboration 2018)
DES+BAO+BBN (Abbott et al. 2018)
SH0ES (Riess et al. 2019)
H0LiCOW 2019 (this work)
Late Universe (SH0ES + H0LiCOW)
68
70
72
74
H_0 [km s^{-1} Mpc^{-1}]



flat − ΛCDM
Planck (Planck Collaboration 2018)
DES+BAO+BBN (Abbott et al. 2018)
SH0ES (Riess et al. 2019)
CCHP (Freedman et al. 2019)
Miras (Huang et al., in prep)
H0LiCOW (Wong et al. 2019)
MCP (Reid's talk)
SBF + Cepheids / TRGB (Blakeslee's talk)
$67.4^{+0.5}_{-0.5}$
$67.4^{+1.1}_{-1.2}$
$74.0^{+1.4}_{-1.4}$
$69.8^{+1.9}_{-1.9}$
$73.64^{+3.85}_{-3.85}$
$73.3^{+1.7}_{-1.8}$
$74.8^{+3.1}_{-3.1}$
$76.5^{+4.0}_{-4.0}$ / $76.1^{+6.6}_{-6.6}$
68 70 72 74 76 78 80 82
H_0 [km s^{-1} Mpc^{-1}]

Towards 1% H_0 measurement with time-delay cosmography



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

Advisor: Tommaso Treu
Collaborators: Simon Birrer (UCLA), Adriano Agnello (ESO), STRIDES and H0LiCOW collaborations.

Time delay cosmography

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

Time delay cosmography

- **Past:** Introduction and recent results
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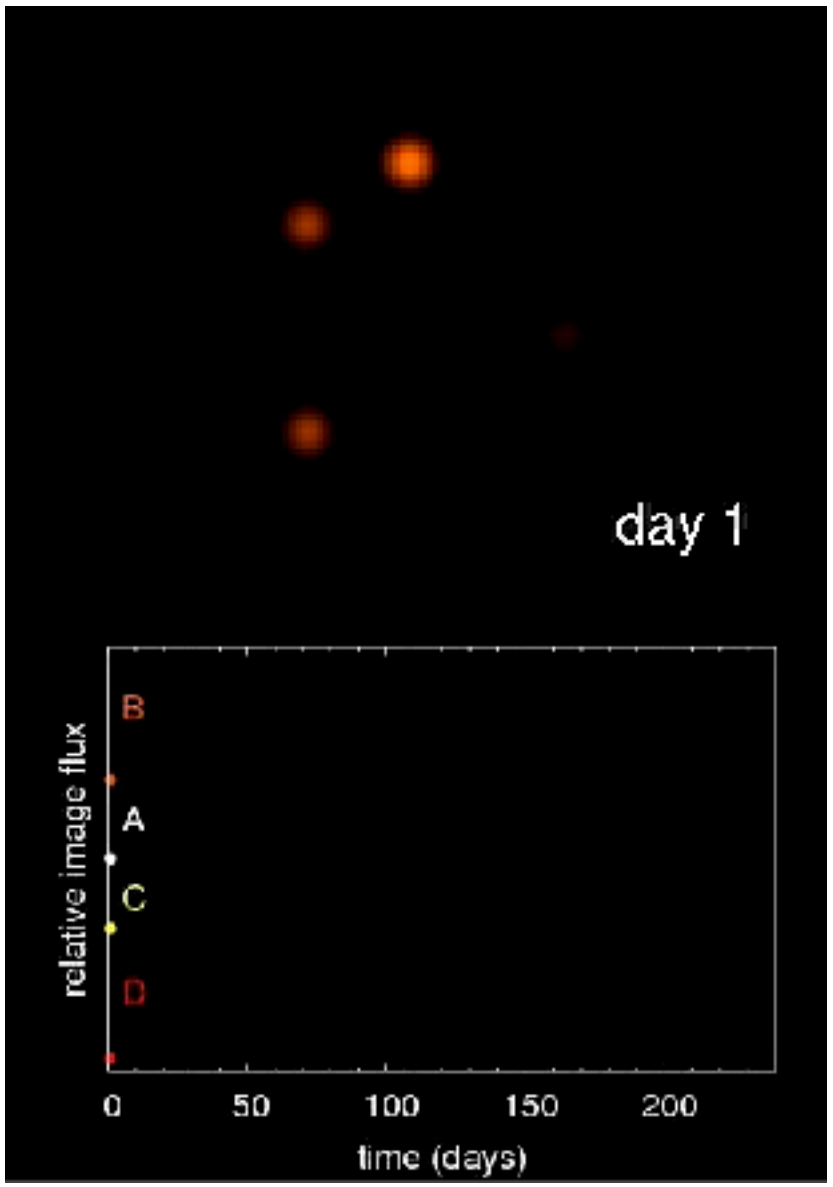
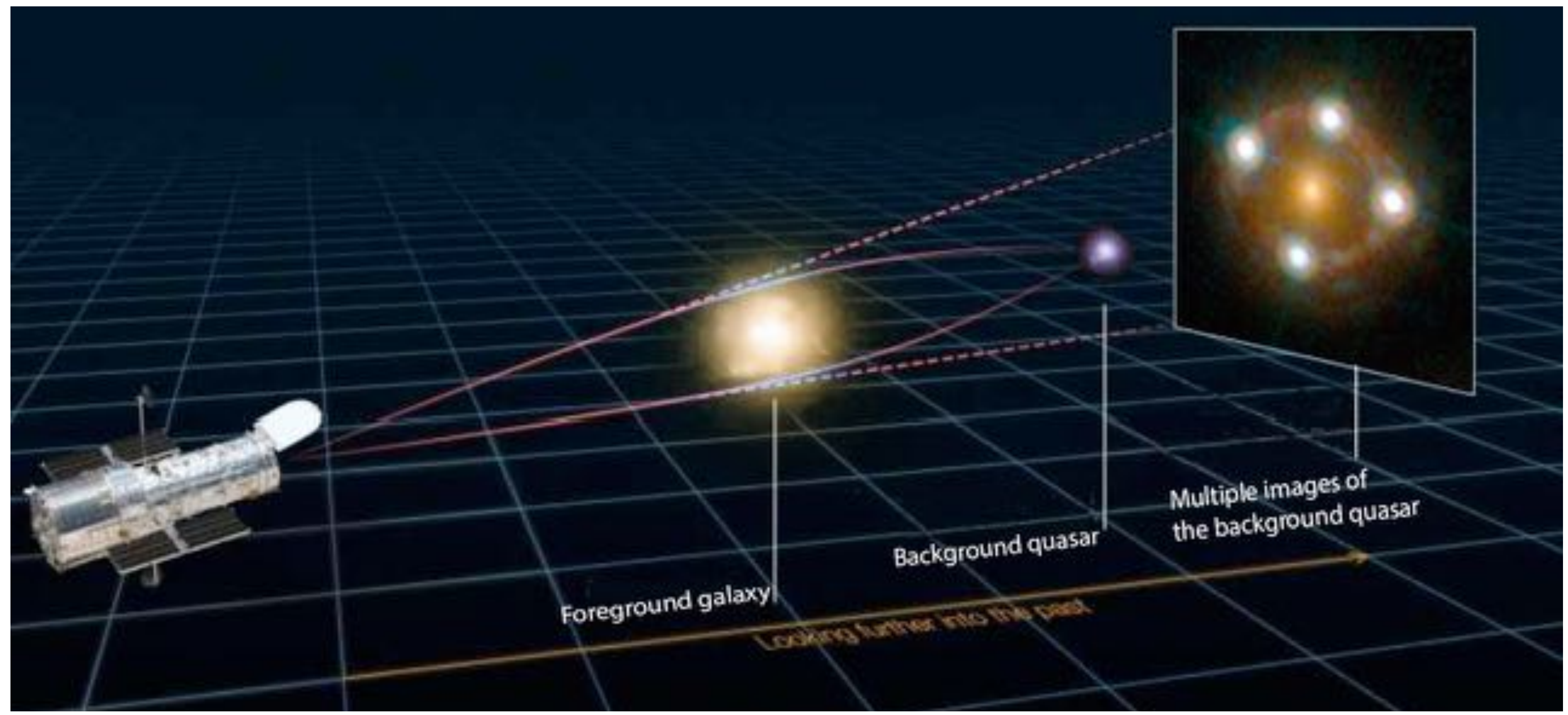
Time-delay Cosmography





Courtesy: Martin Millon

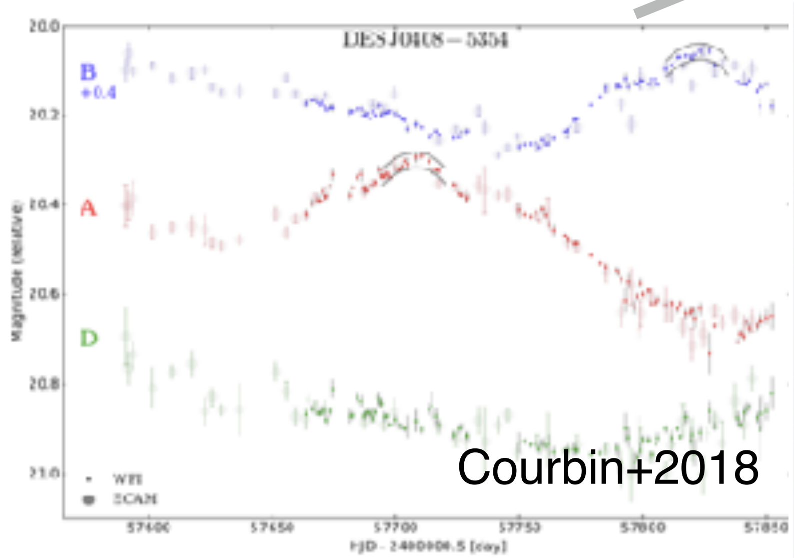
- Time-delay distance

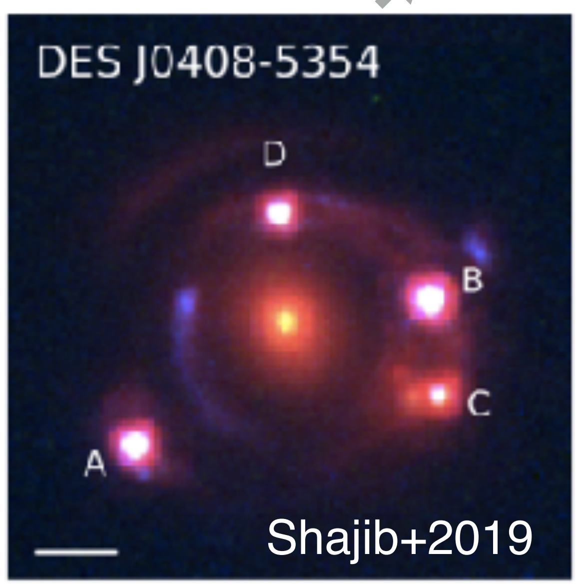
$$D_{\Delta t} = (1 + z_{\rm d}) \frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}} \propto \frac{\Delta t}{\delta \Psi} \propto \frac{1}{H_0}$$

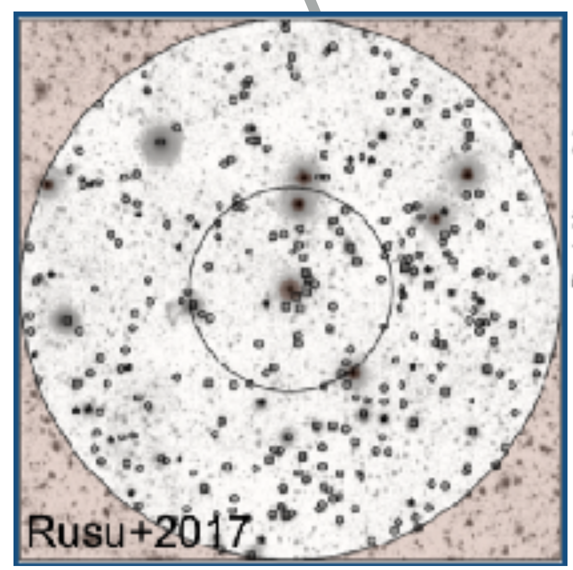
Necessary data for time-delay distance measurement

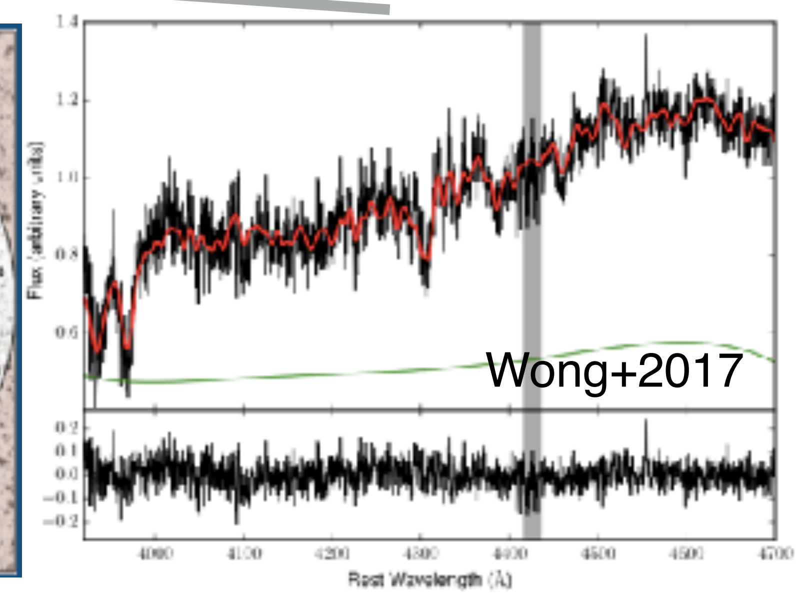
Time delay distance:

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





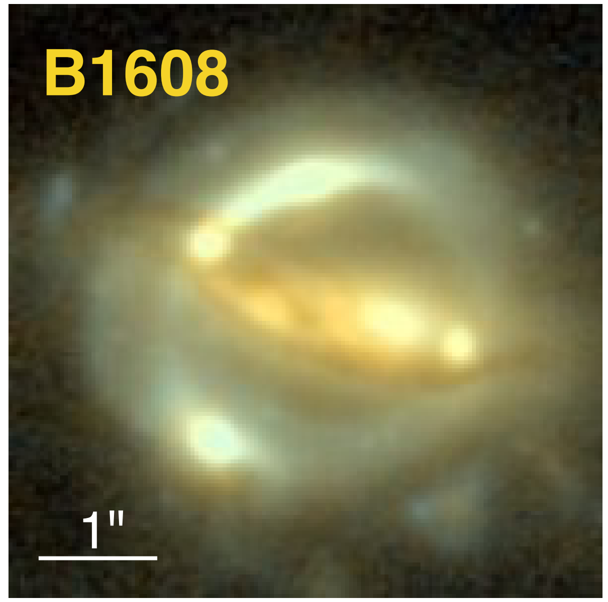


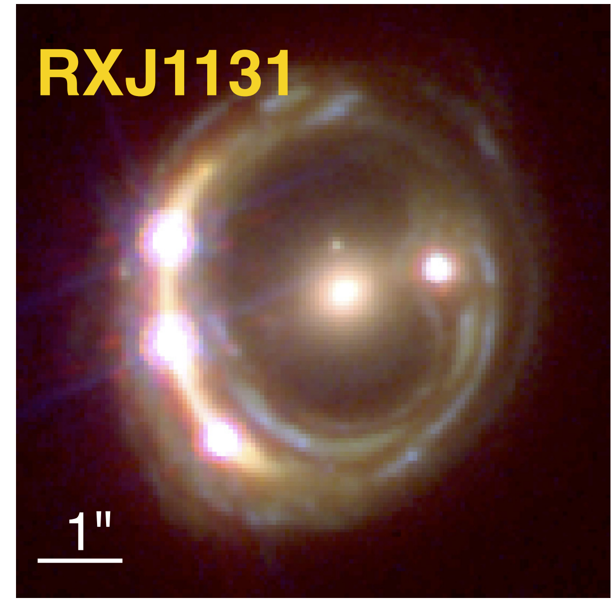


- Time delay measurement
- High resolution imaging of the lens
- Estimate of line-of-sight effects
- Kinematics

H0LiCOW sample of 6 time-delay lenses

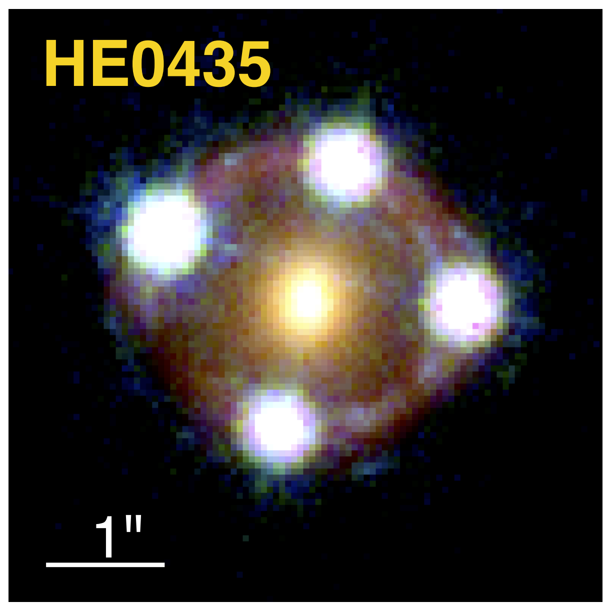
Suyu et al. 2010

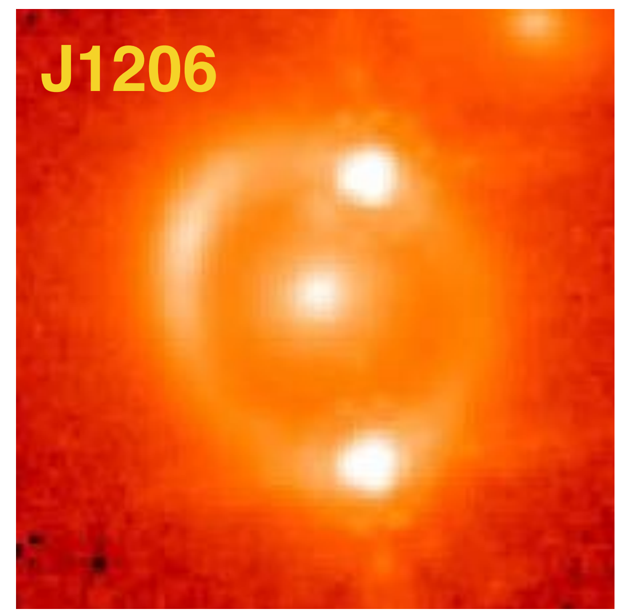




Suyu et al. 2014

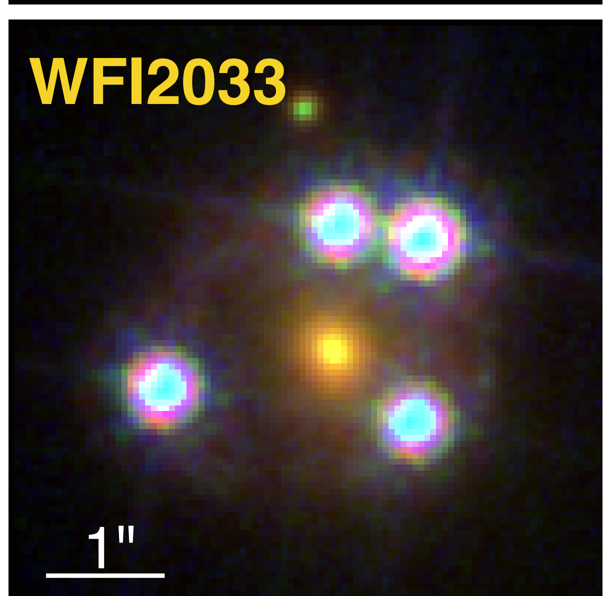
Wong et al. 2017

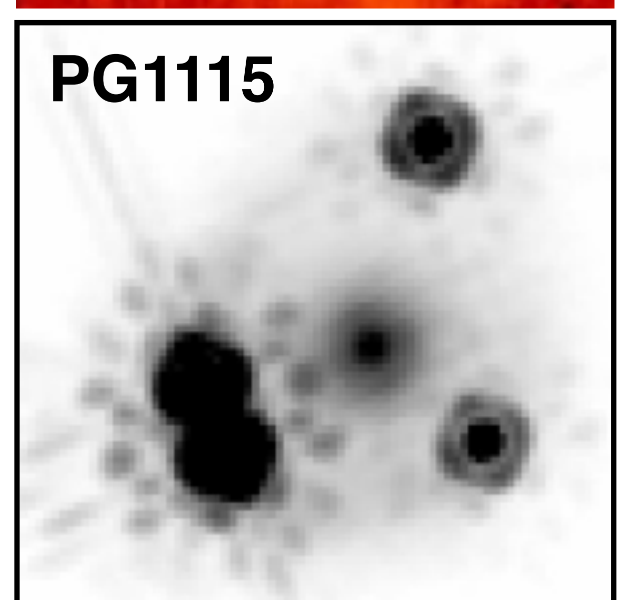




Birrer,..,Shajib et al. 2019

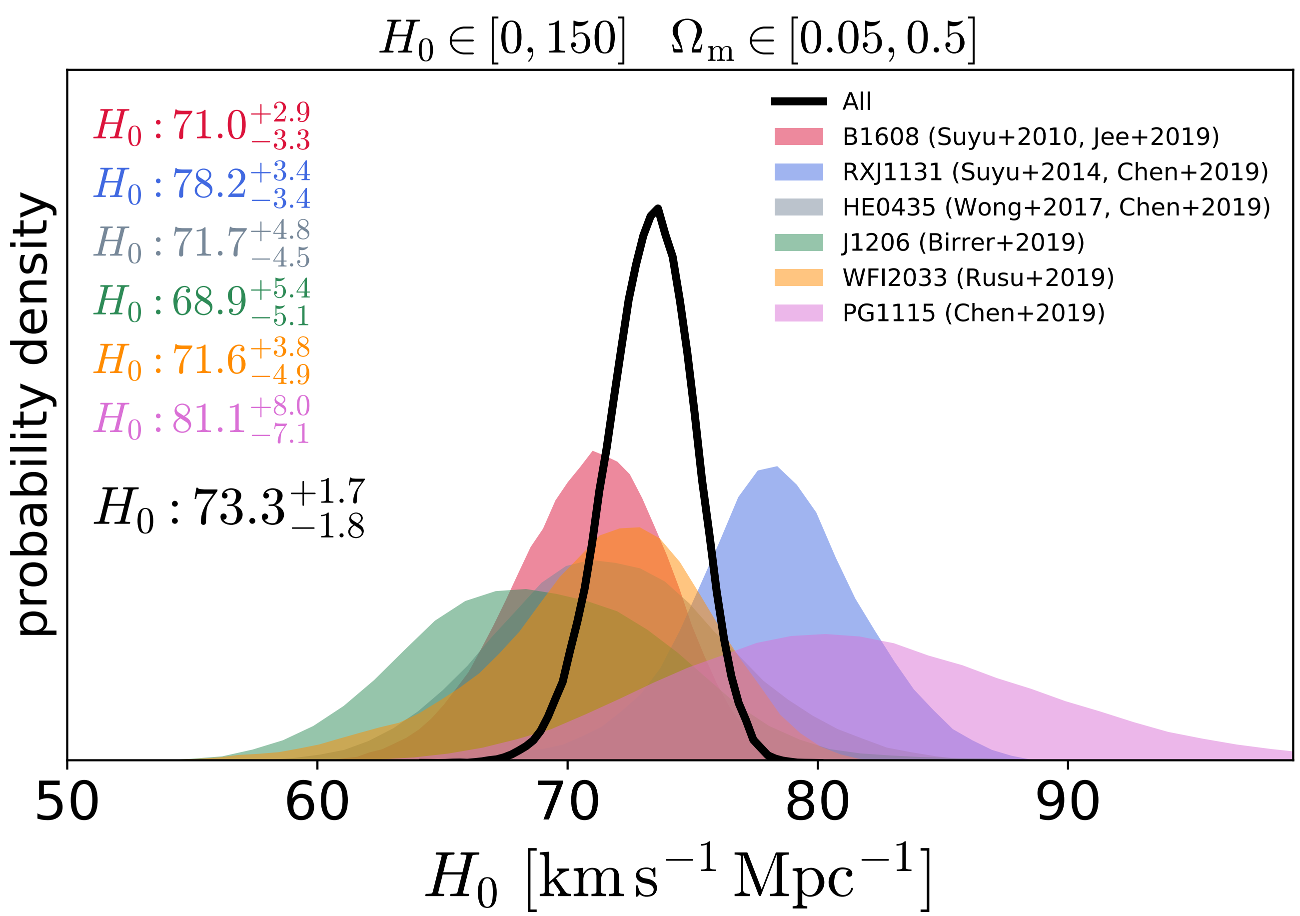
Rusu,..,Shajib et al. 2019

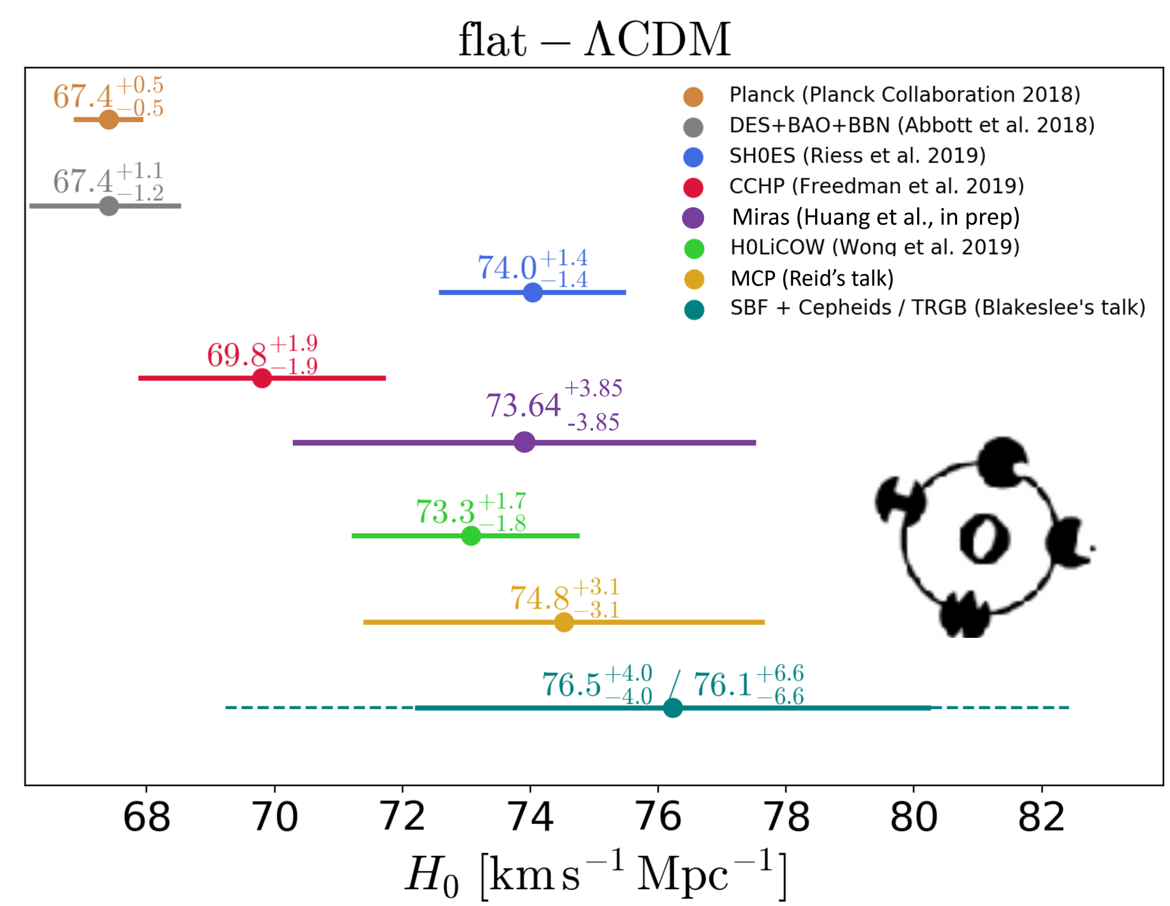




Chen,..,Shajib et al. 2019

Latest "blind" measurement from H0LiCOW: 2.4% measurement of H_0



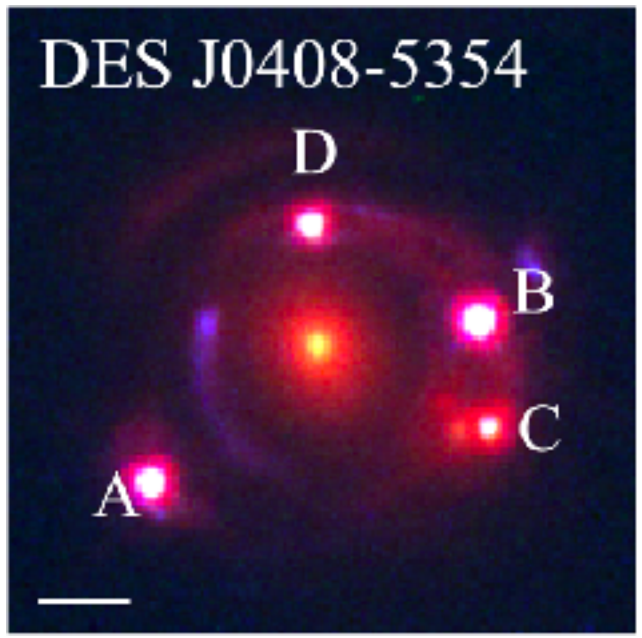


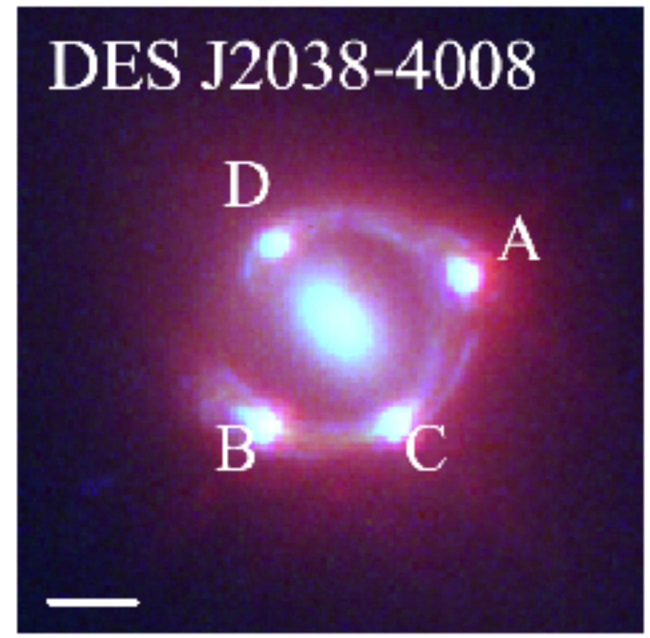
Wong,..,Shajib et al. (2019)

Time delay cosmography

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

Two more time-delay lenses from STRIDES collaboration





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

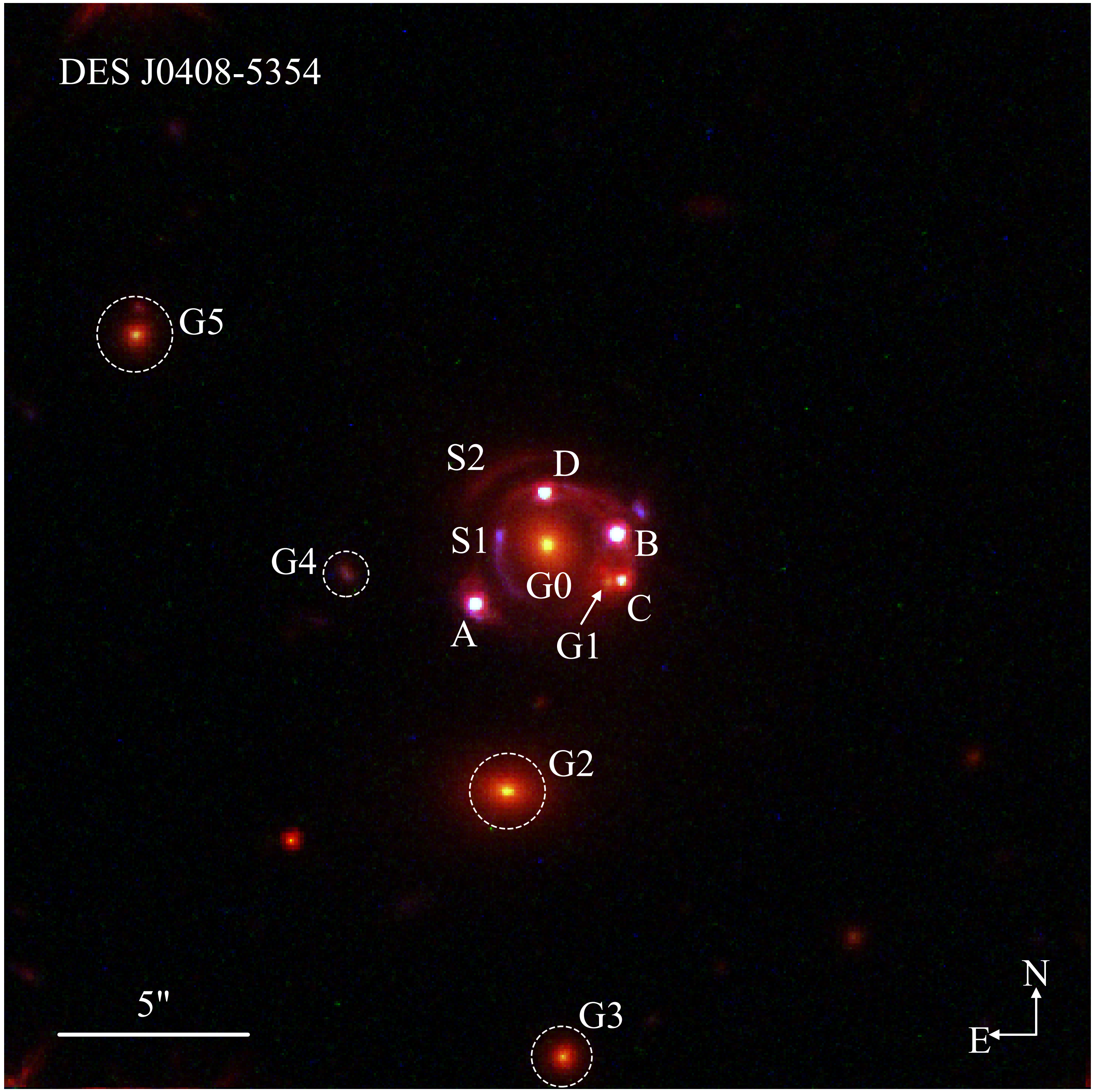
- Shajib et al. (UCLA)
- Yildirim, Wong et al. (MPA Garching, NAOJ)

Stay tuned for new H_0 measurements from these two in Fall 2019.

Projected 2% measurement of H_0 from 8 lenses

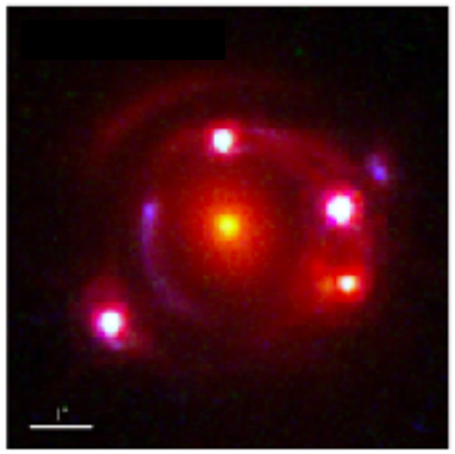
- Would reach comparable precision with the cosmic distance ladder method.
- Confirming or alleviating the tension

Lens systems can be complex.

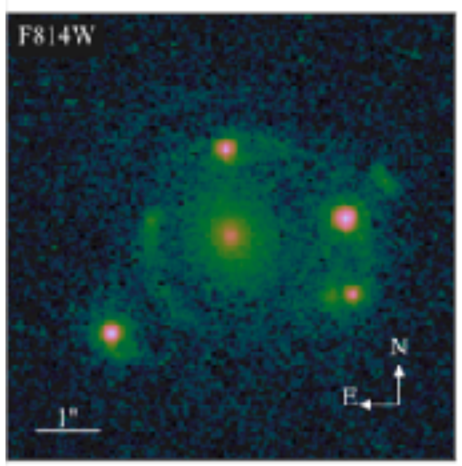


- Nearby satellite
- Multiple sources
- Additional image
- Line-of-sight perturbers

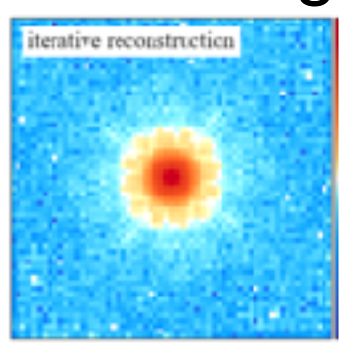
Behind the scene of lens modeling

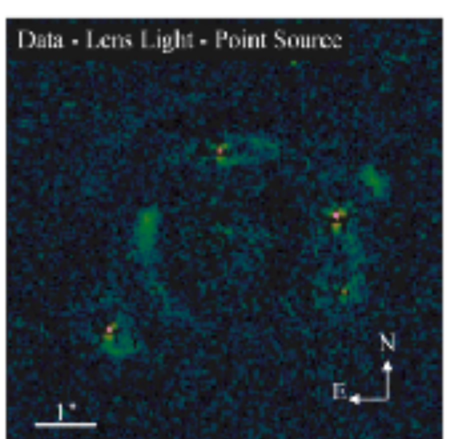


Data: 3-band

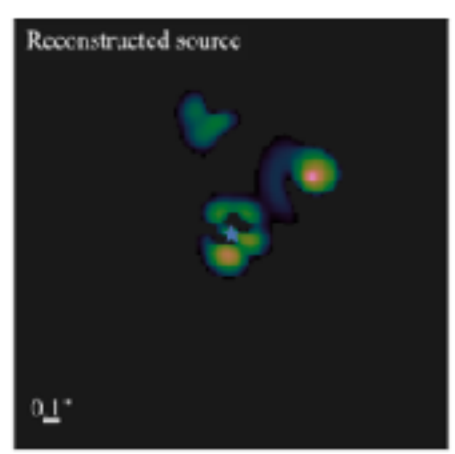


Data: single band

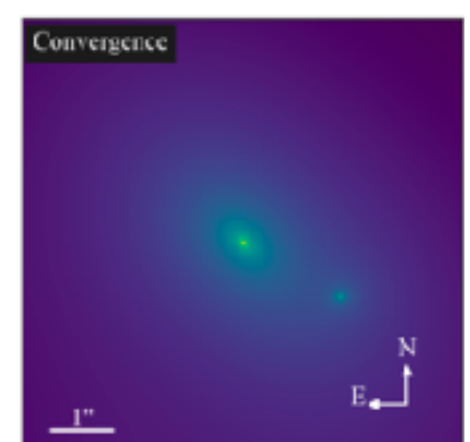




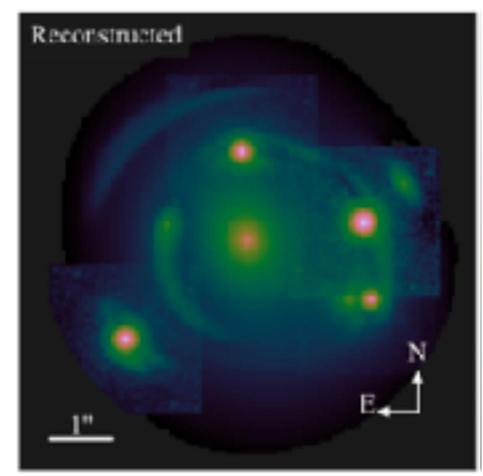
Lensed host galaxy



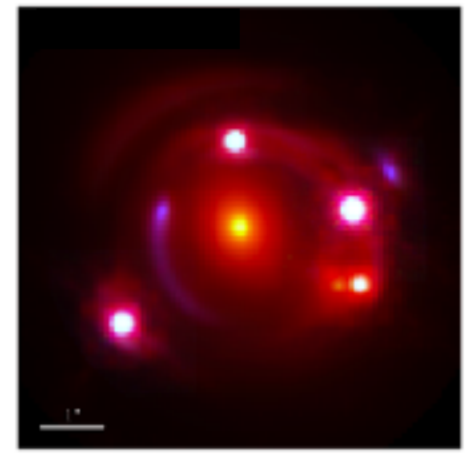
Recons-tructed source



Mass



Reconstructed: single band



Reconstructed: multi-band

Time delay cosmography

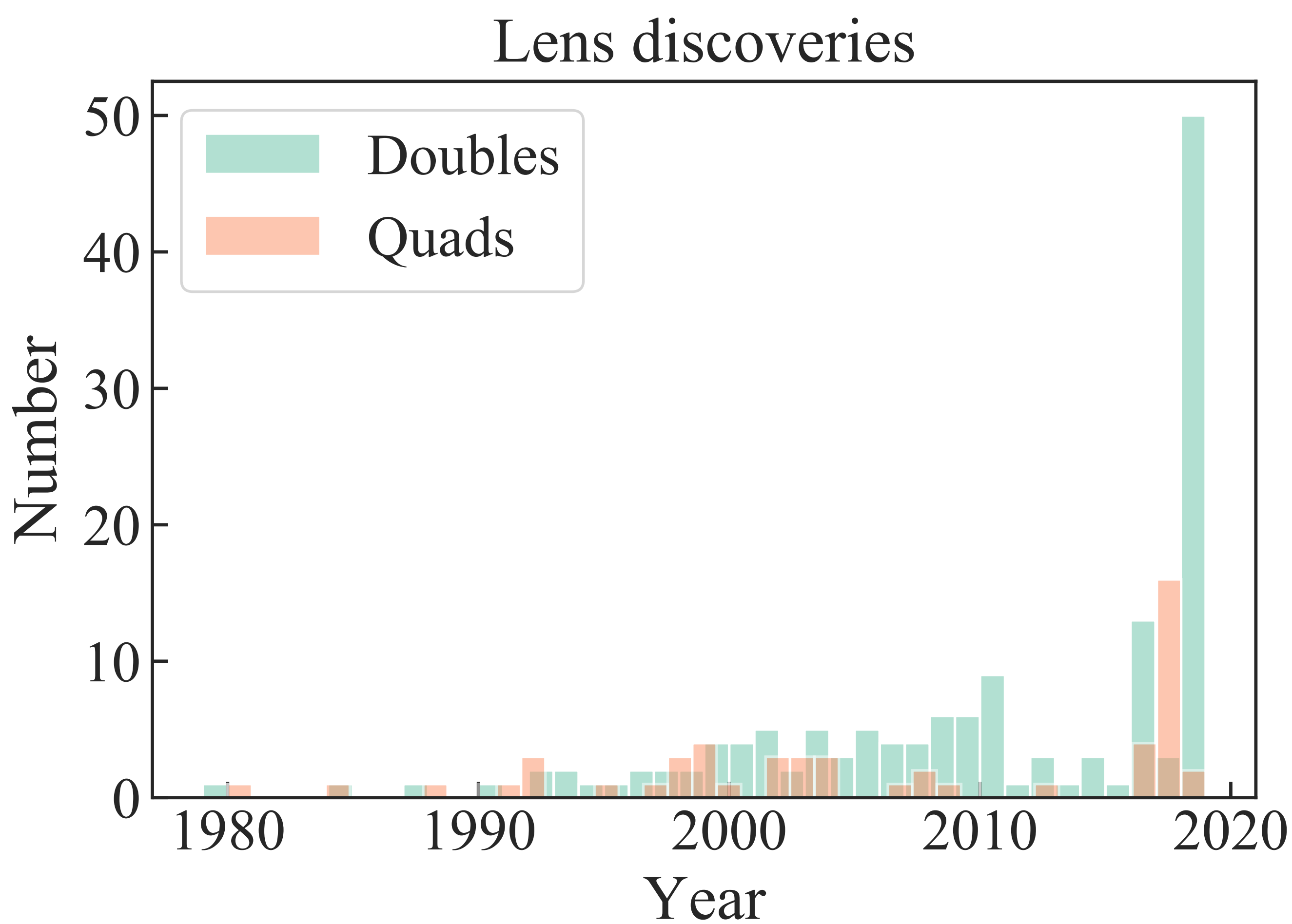
- **Past:** Introduction and recent results
- **Present:** Current works in progress
- **Future:** Further improvements and forecasts

Future goal is 1% H_0 measurement.

Two ways to improve precision:

- Increase sample size
- Improve precision per system

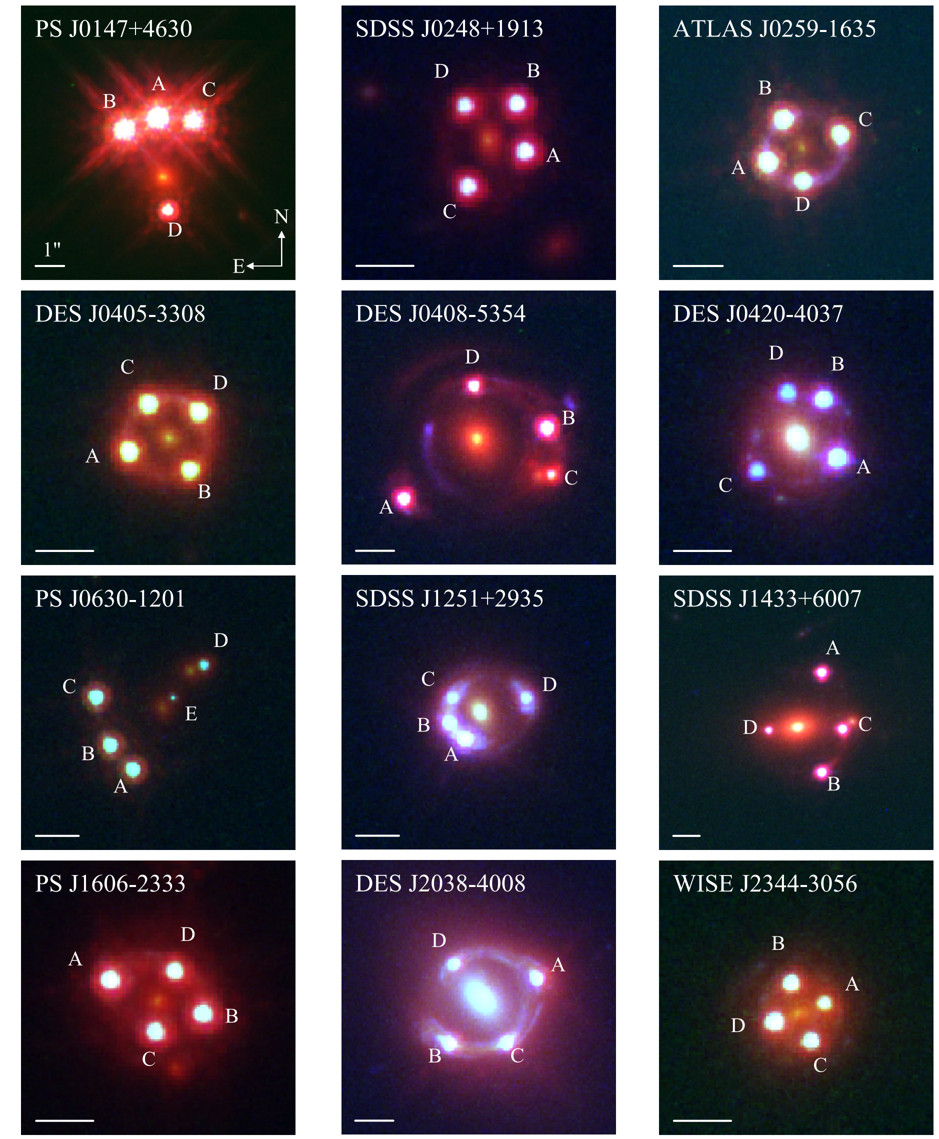
Way 1: Increasing sample size



Data courtesy: Lens DB by Cameron Lemon

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

From HST Cycle 25

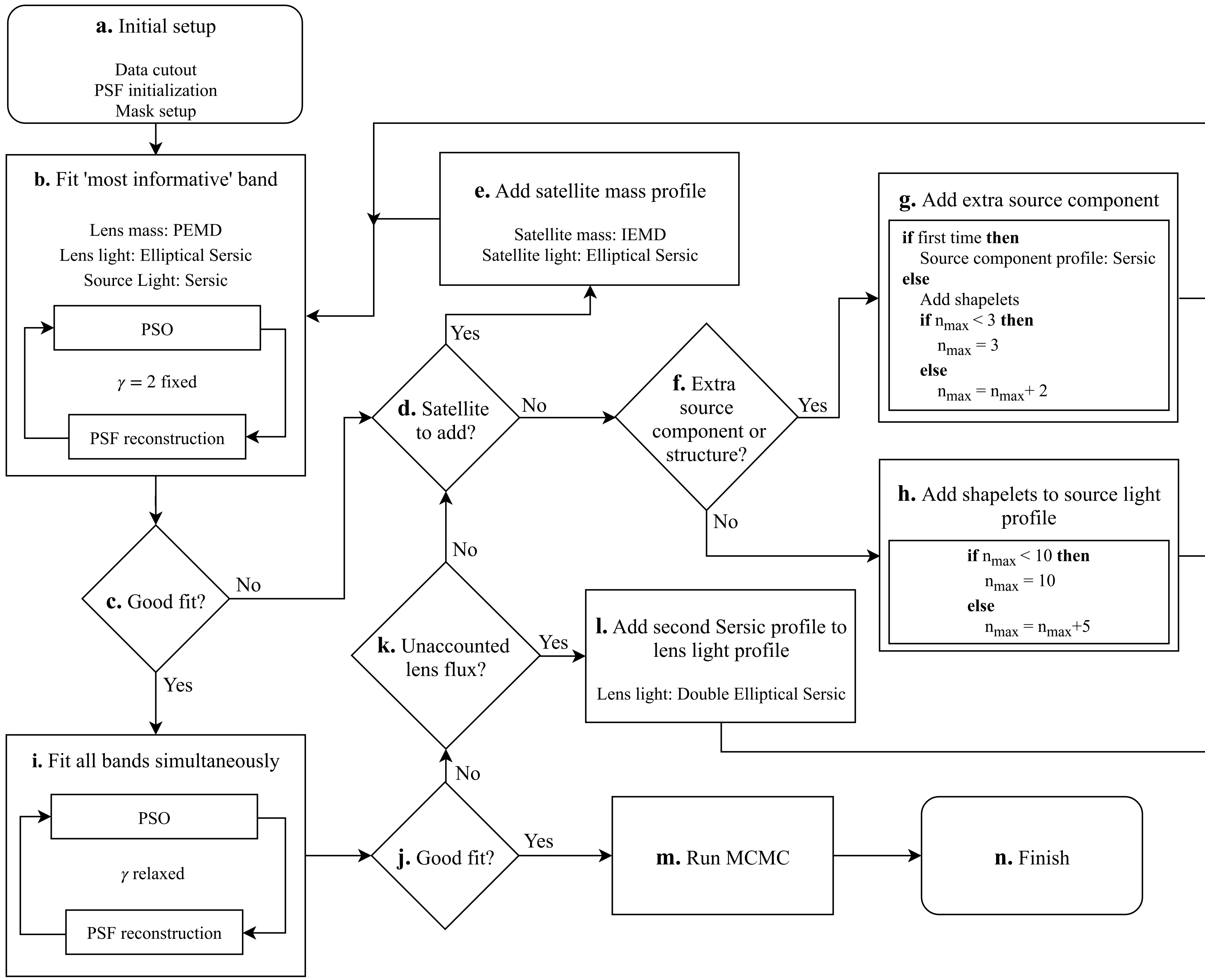


Shajib et al. 2019a

From HST Cycle 26

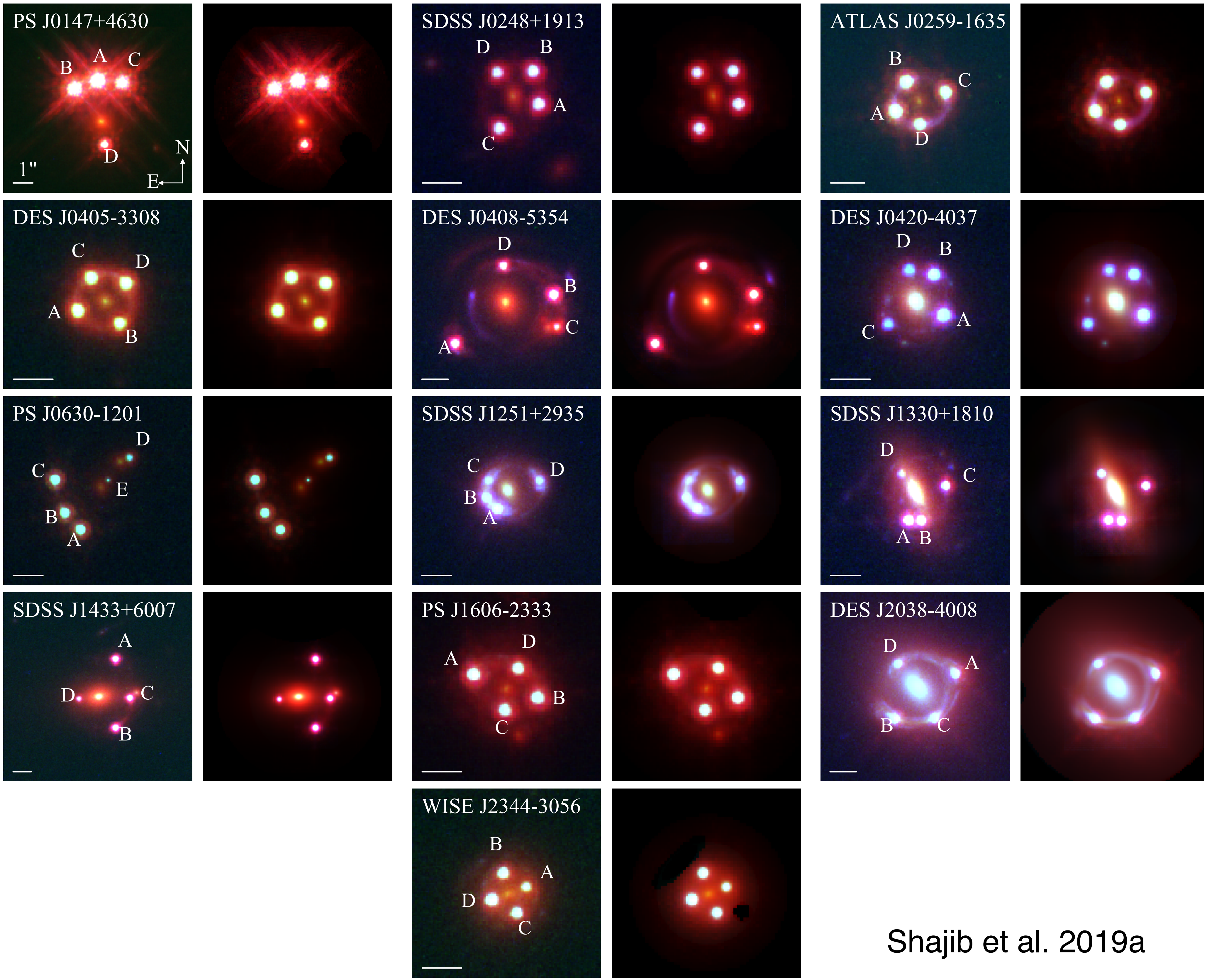
…and 15 more to be observed.

Automating the lens modelling



Shajib et al. 2019a

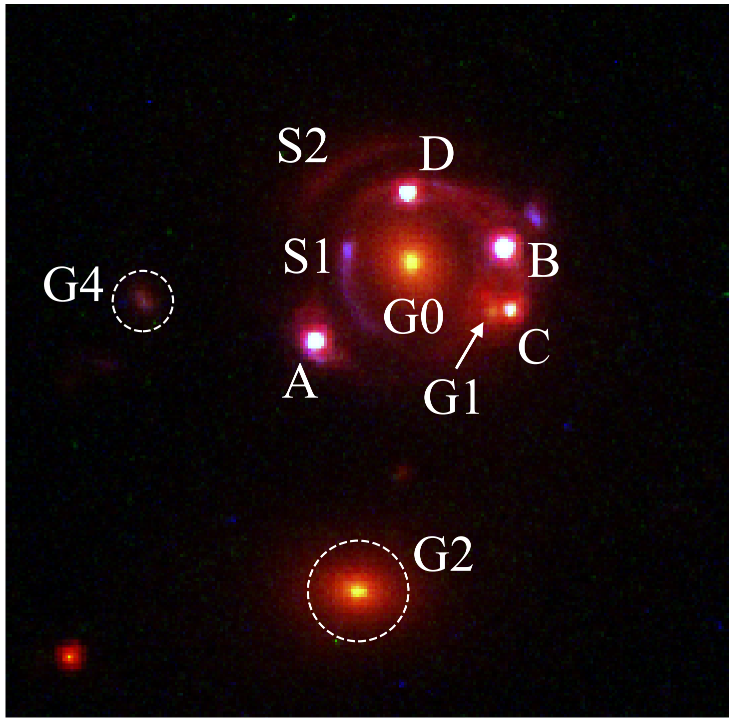
Automated lens models



Shajib et al. 2019a

Future work in automated lens modelling

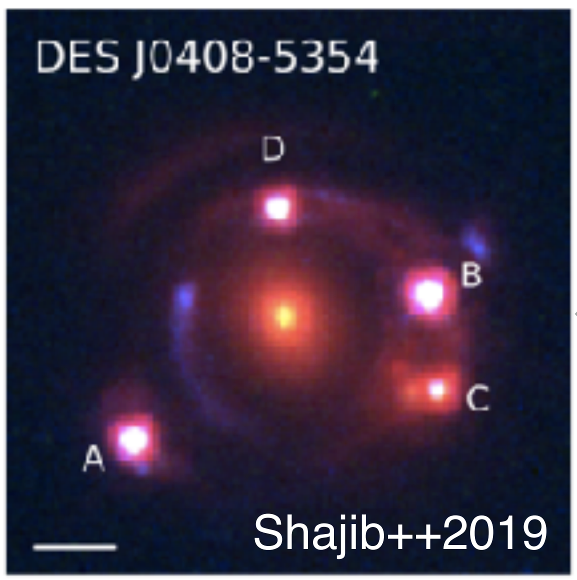
- Machine learning for initializing lens models
    - Work by Vedant Sahu, UCLA undergraduate
- Automating line-of-sight perturber selection

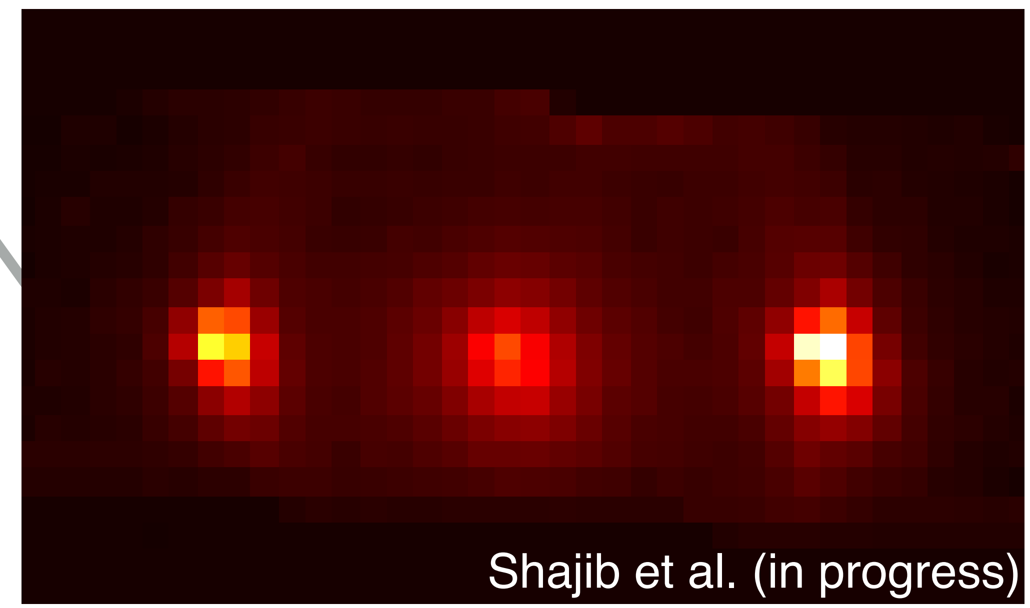


Improving Precision Per System

Time delay distance:

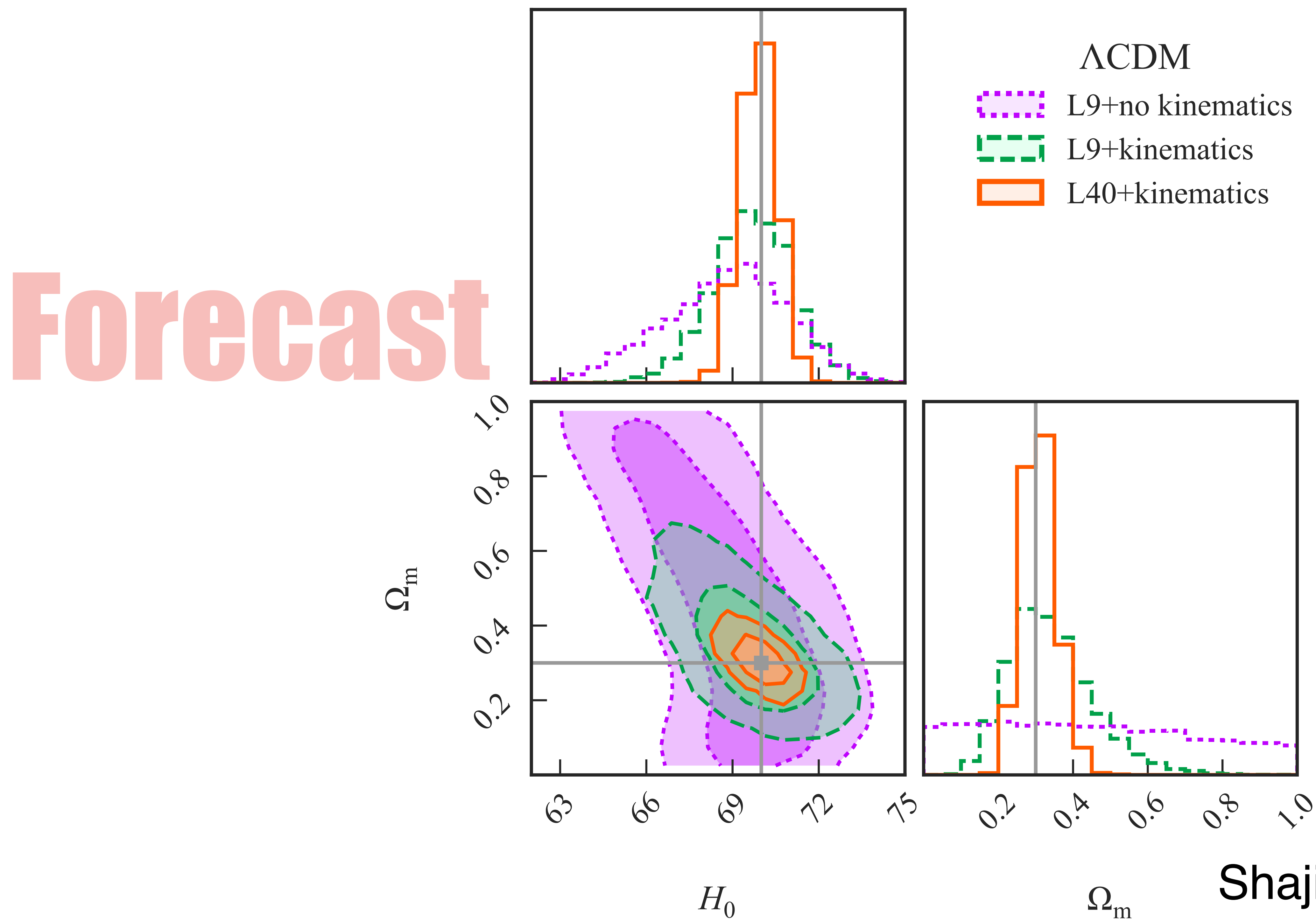
$$D_{\Delta t} = \frac{c\Delta t}{\Delta \Psi}(1 - \kappa_{\rm ext})$$





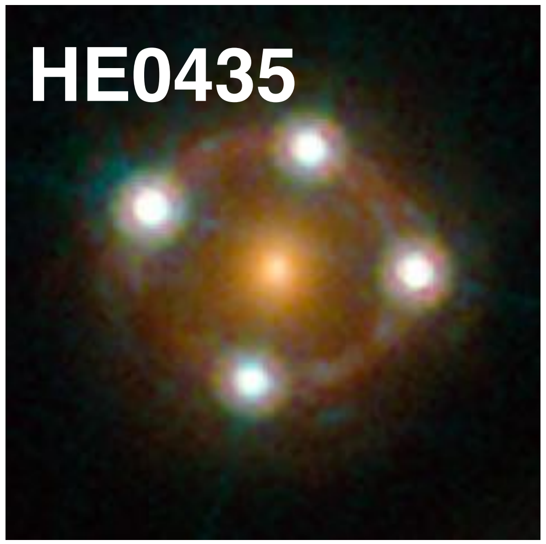
Spatially resolved kinematics improves precision on the mass profile slope.

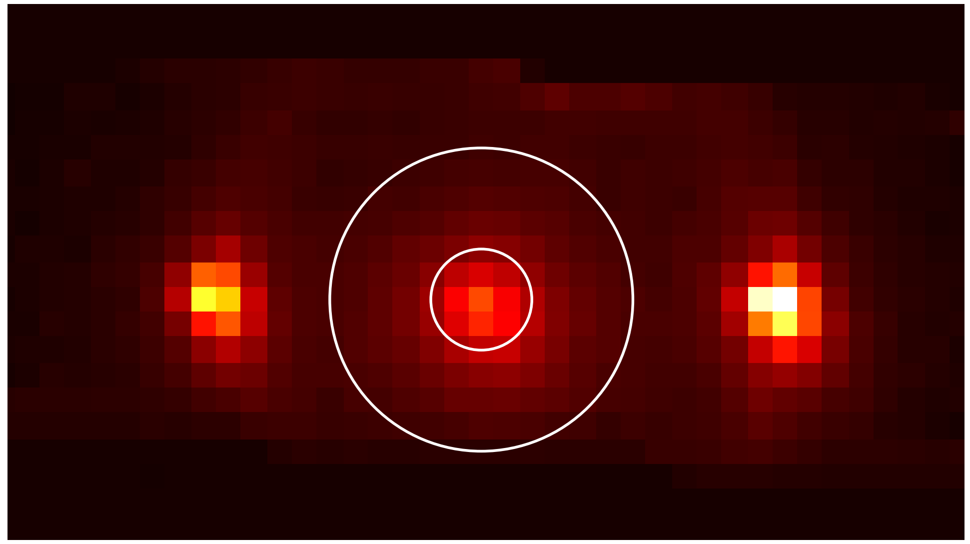
Spatially resolved kinematics helps determine H_0 to 1% from a sample of 40 lenses.



Shajib et al. 2018

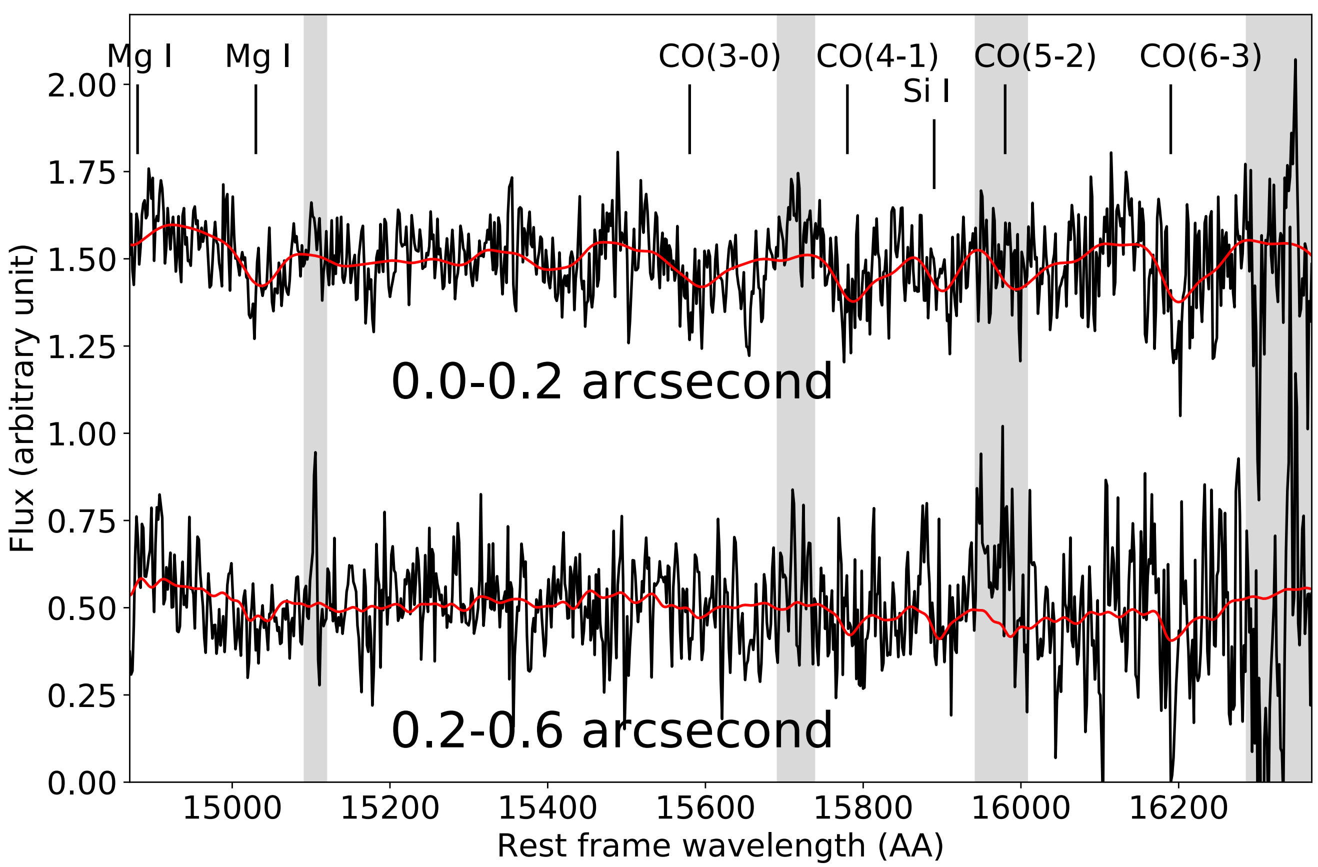
Stellar kinematics from Keck/OSIRIS

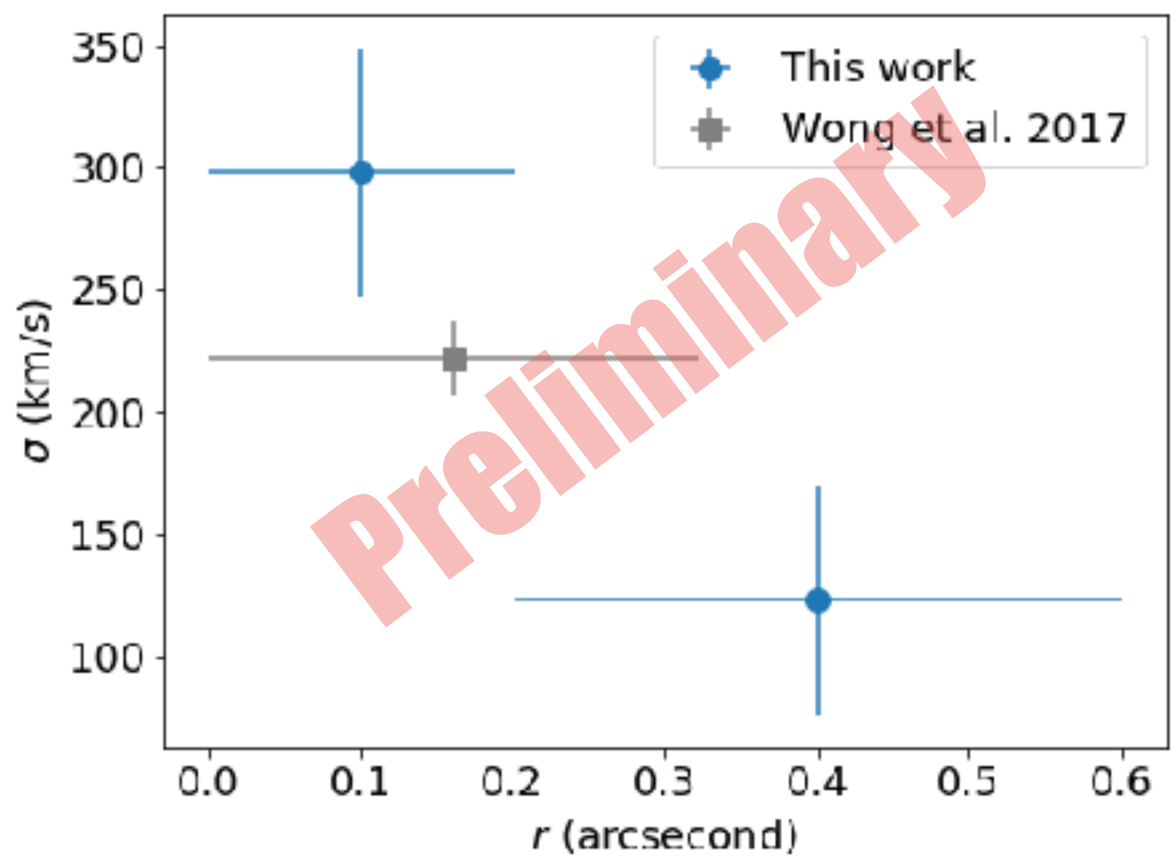




Data

Integration time: 4 hours
Target: 8 hours





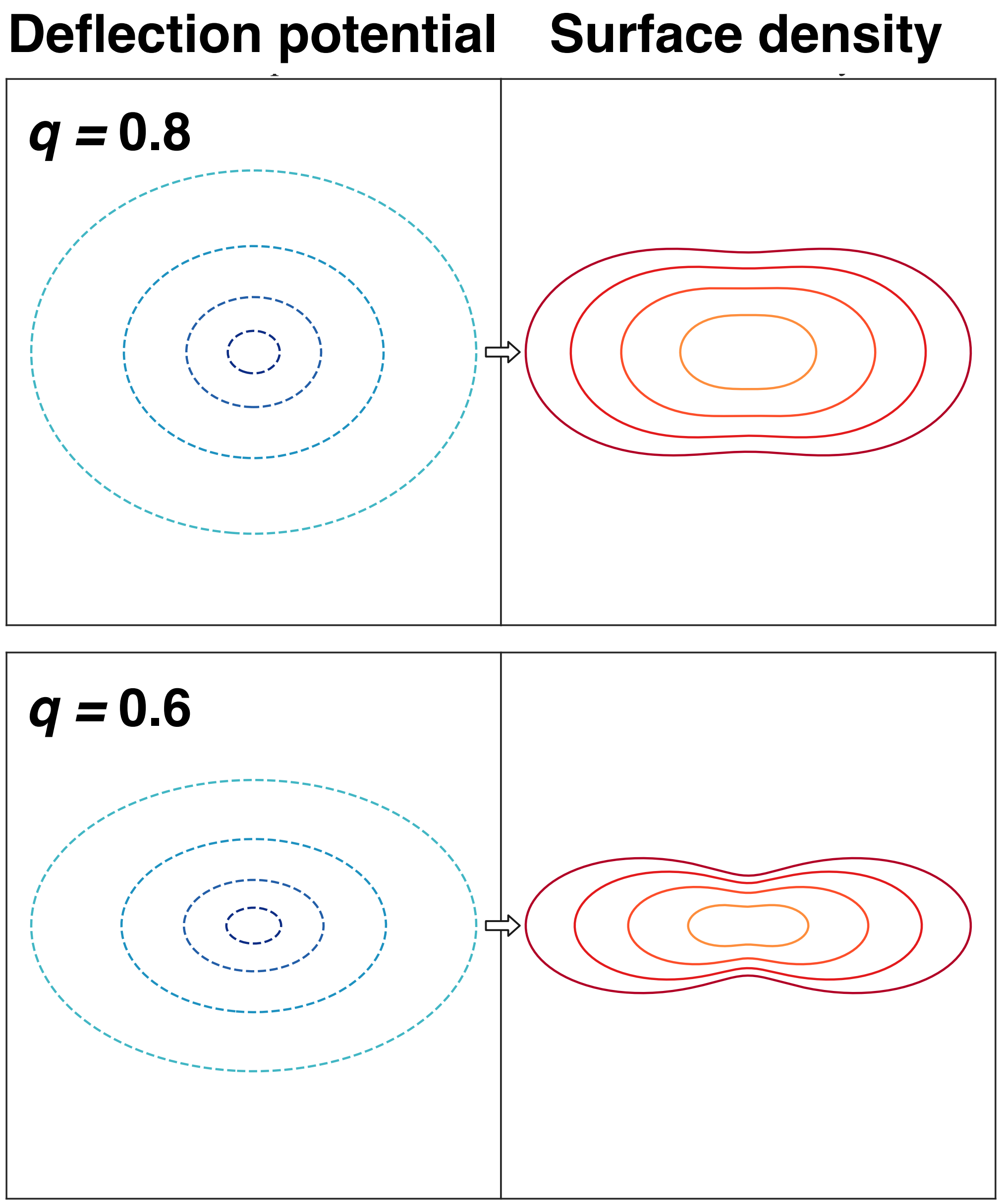
Shajib et al. (in prep)

Novel lensing analysis for general elliptical mass profiles

- Elliptical mass profiles are analytically difficult for lensing.

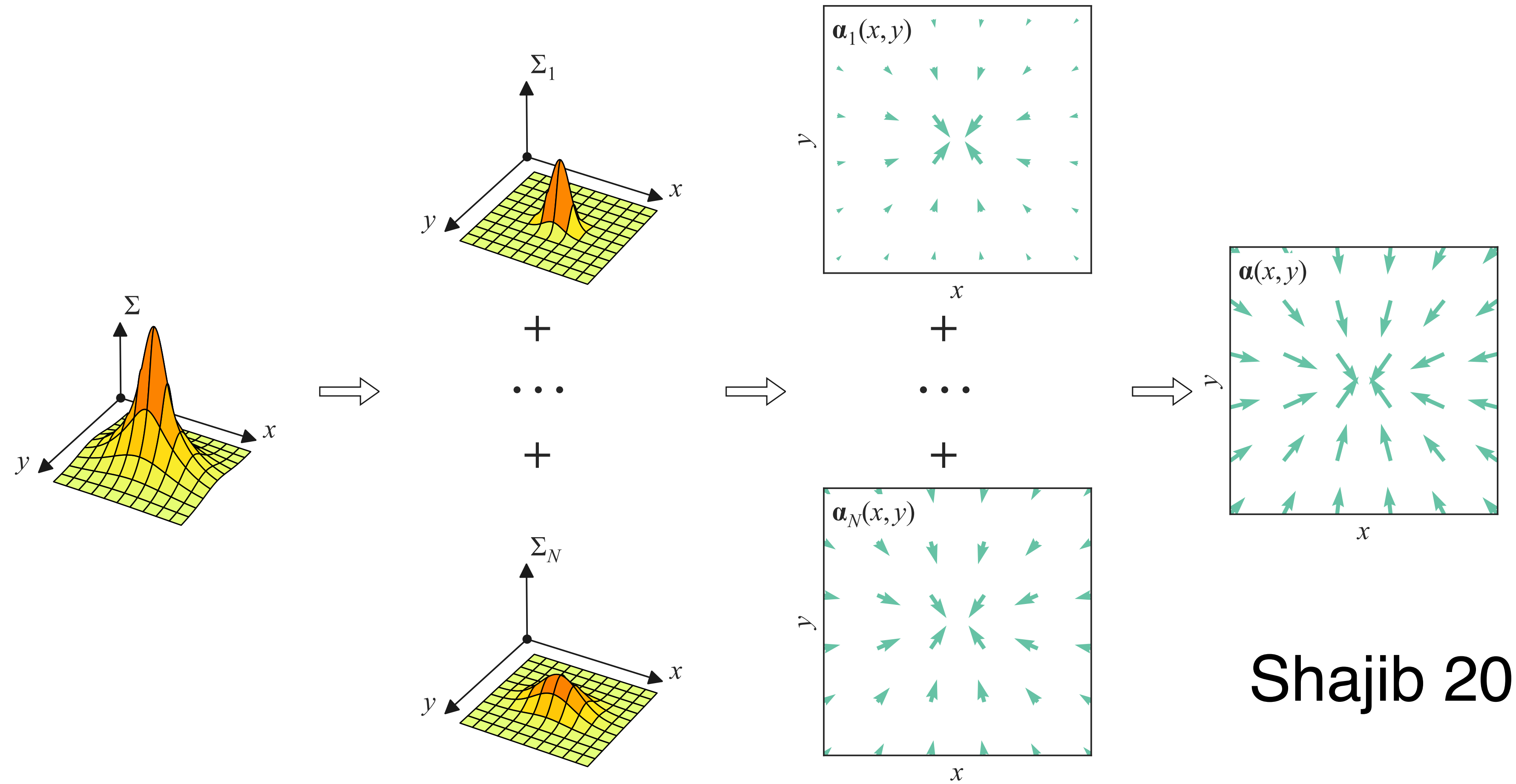
$$\alpha(\theta) = \frac{1}{\pi} \int_{\mathbb{R}^2} \mathrm{d}^2\theta' \, \kappa(\theta') \, \frac{\theta - \theta'}{|\theta - \theta'|^2}$$

- No general solution for three decades…until now.



Shajib 2019b

General analytical framework through concentric Gaussian decomposition



Shajib 2019b

- Works for **any** elliptical mass profile. **Only three times slower** than the simplest profiles in use.
- Allows to pin-down systematics from lens-model choices by exploring more general or empirically-motivated mass profiles.
- Readily pluggable to Jeans anisotropic modeling of kinematics.

Summary

- 2.4% measurement of H_0 from 6 lenses so far, analysis of 2 more lenses are in progress.
- **Future directions:**
  - Automated lens modelling for large samples
  - Spatially resolved kinematics will improve precision per lens
  - 1% H_0 measurement forecasted from ~40 lenses

Thank you!