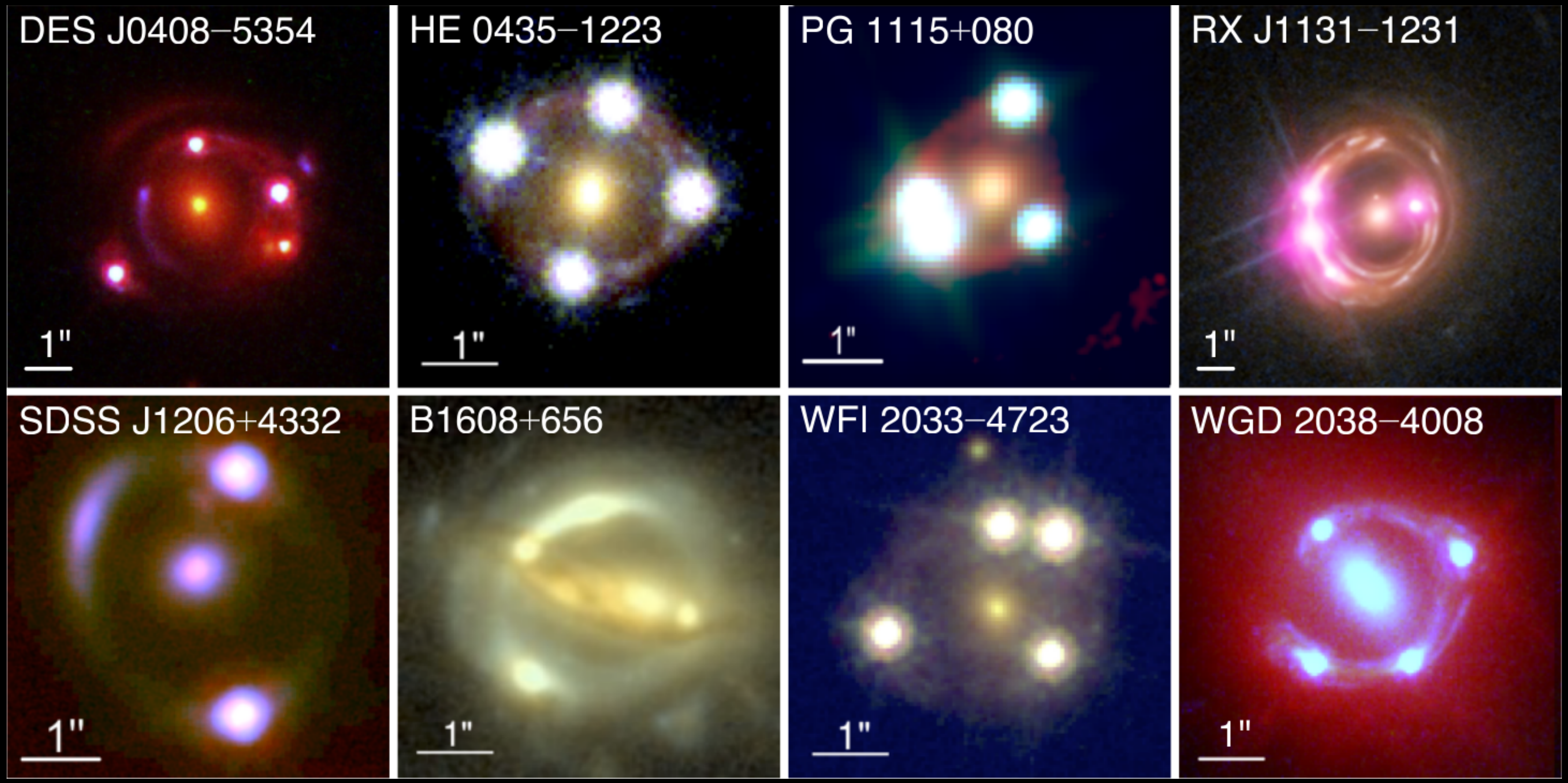
TDCOSMO: Cosmological constraints from strong lensing time delays



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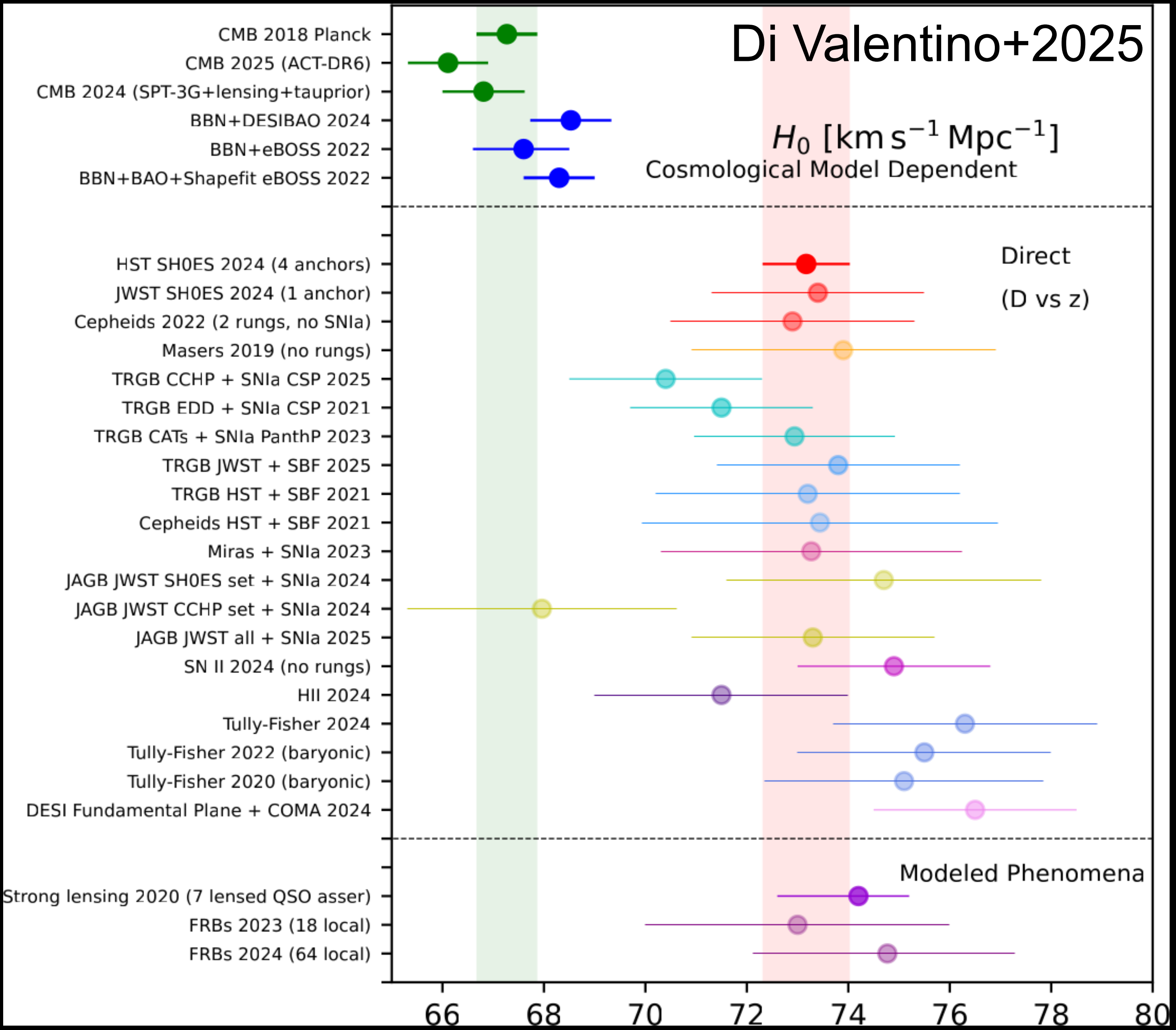
Precision Cosmology with Strong Lensing Time Delays
August 3, 2026

科研費 KAKENHI

東京大学 THE UNIVERSITY OF TOKYO

The Hubble Tension

- Tension in early-Universe and late-Universe measurements of H_0
  - *Planck* CMB: 67.4 ± 0.5 km/s/Mpc (assuming flat ΛCDM)
  - SH0ES (Cepheid distance ladder): 73.2 ± 0.9 km/s/Mpc (Riess+2024)
  - CCHP (TRGB + JAGB + Cepheid distance ladder): 70.0 ± 1.5 km/s/Mpc (Freedman+2025)
- Reason for discrepancy currently unknown
  - systematic errors?
  - rejection of flat ΛCDM (i.e., new physics)?
- *Independent measurements of H_0 are key to test for systematics*



H_0 (km/s/Mpc)

Time-Delay Cosmography

- Strong lensing causes a "time delay" among the multiple lensed images
  - different path length & gravitational potential
  - can be determined from time-series observations if variable source (e.g., quasar)
- 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*

Animation credit: M. Mori

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

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

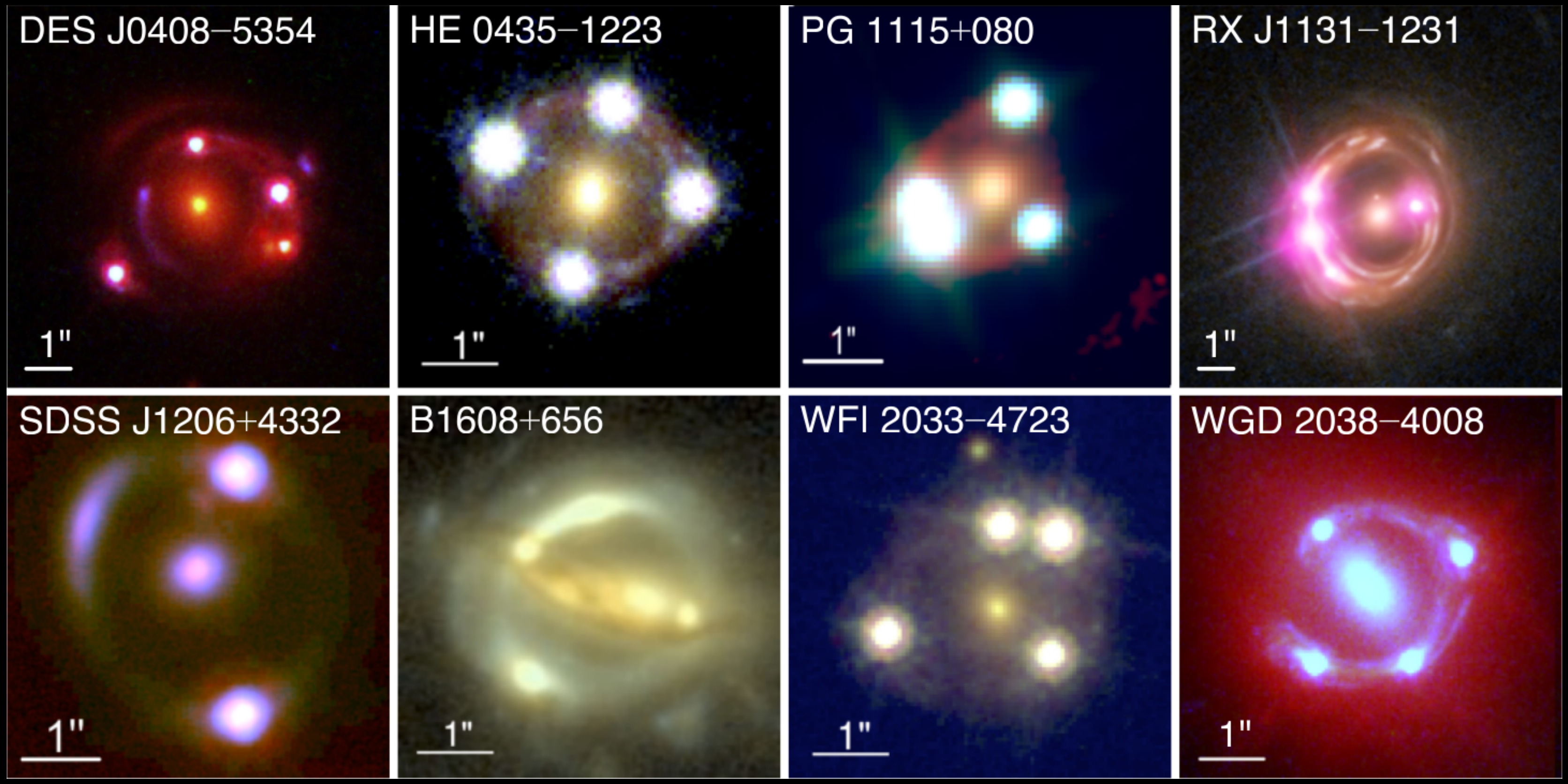
Time delay (observed)

Time-delay distance ($\propto H_0^{-1}$)

Fermat potential (from lens model)

TDCOSMO

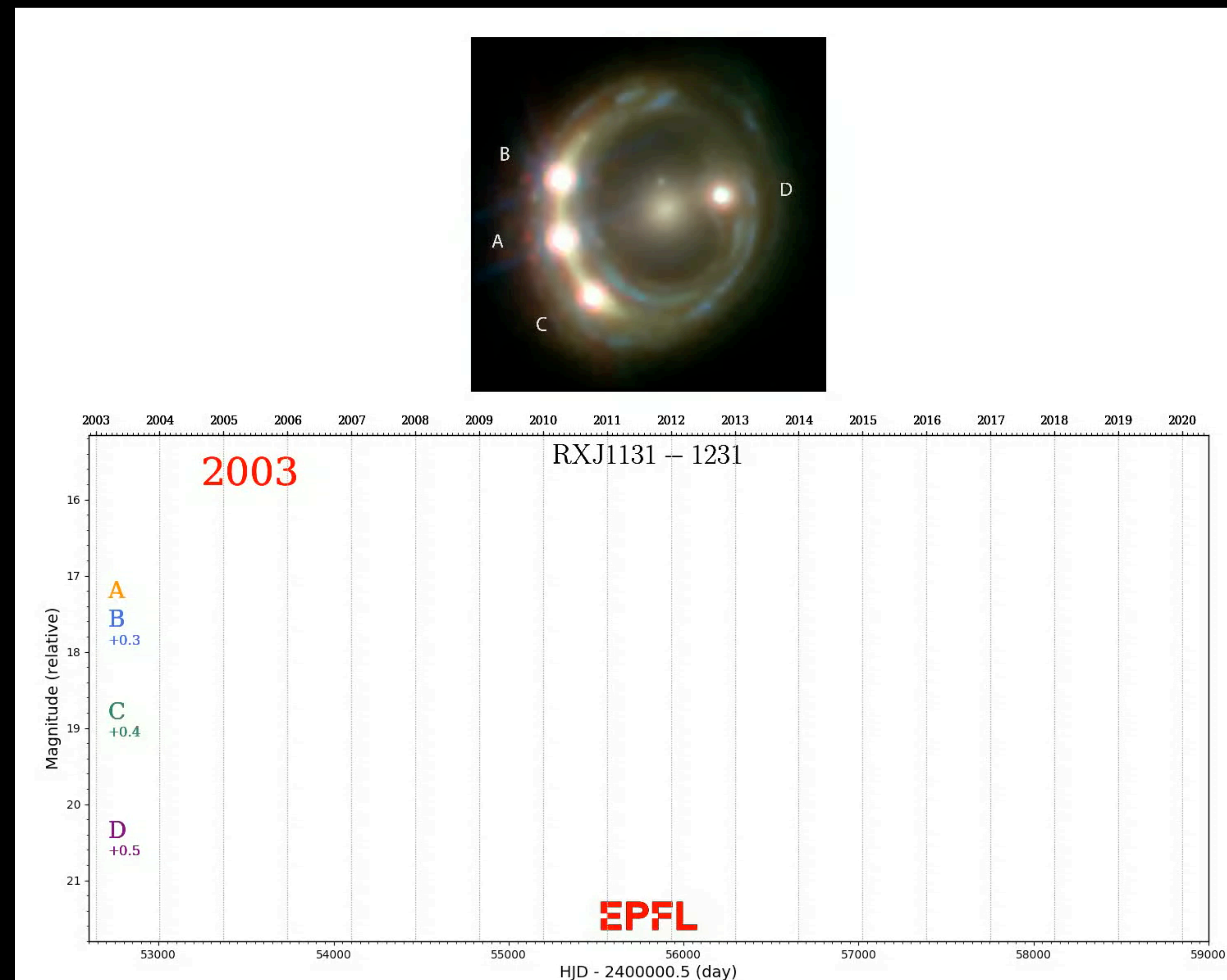
- TDCOSMO (formerly “H0LiCOW”; Suyu+2017) project is performing a detailed analysis of time-delay lensed quasars
  - long term monitoring for accurate time delays
  - high-resolution imaging for detailed lens modeling
  - wide-field imaging/spectroscopy to characterize mass along LOS
  - spectroscopy to measure stellar kinematics
- Eight lenses analyzed in latest milestone result (TDCOSMO Collaboration 2025)
- Lenses analyzed blindly with respect to key parameters (e.g., H_0) until publication



TDCOSMO Collaboration+2025

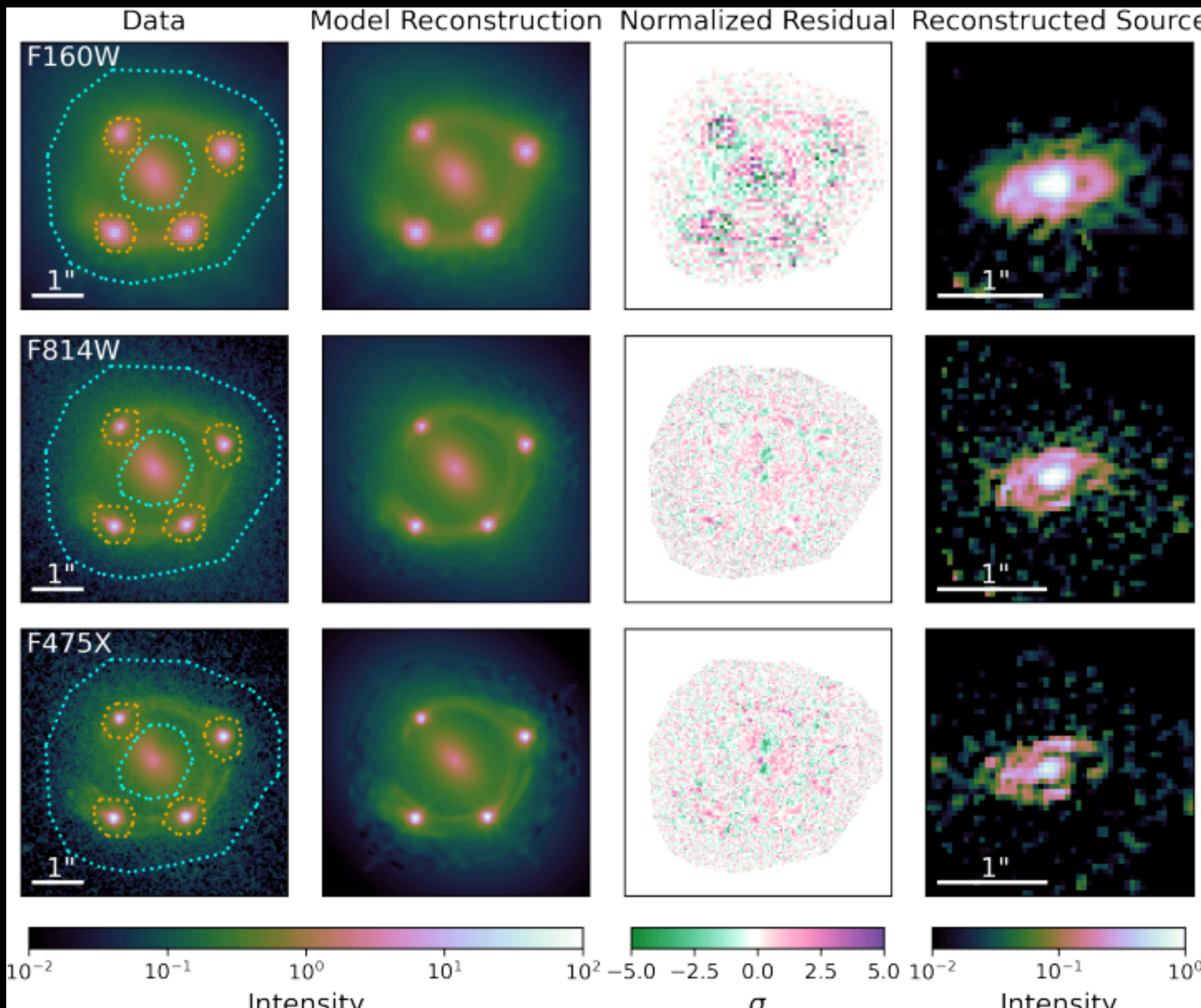
Time Delay Measurements

- 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, Bonvin+2016)
- High-cadence monitoring can get time delays in ~1 year (Courbin+2018, Millon+2020c; Dux+2025)



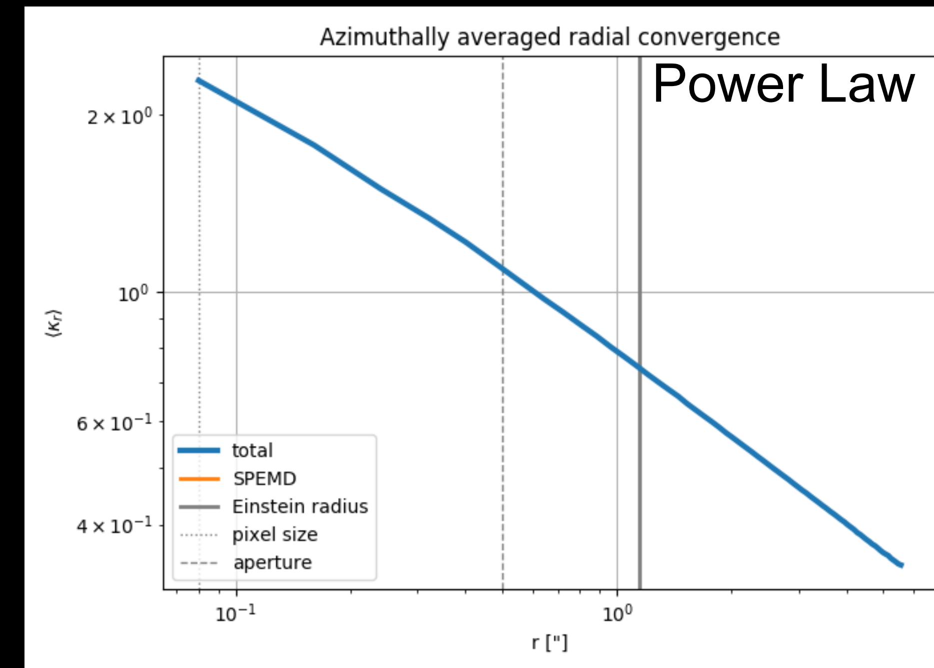
Animation credit: M. Millon

Lens Modeling



Shajib, Wong et al. 2022

Projected mass density



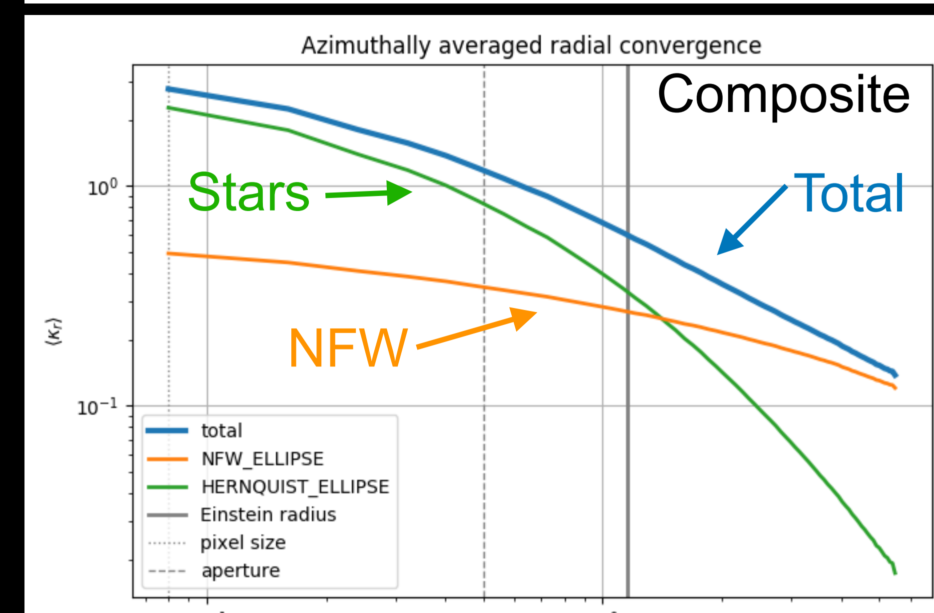


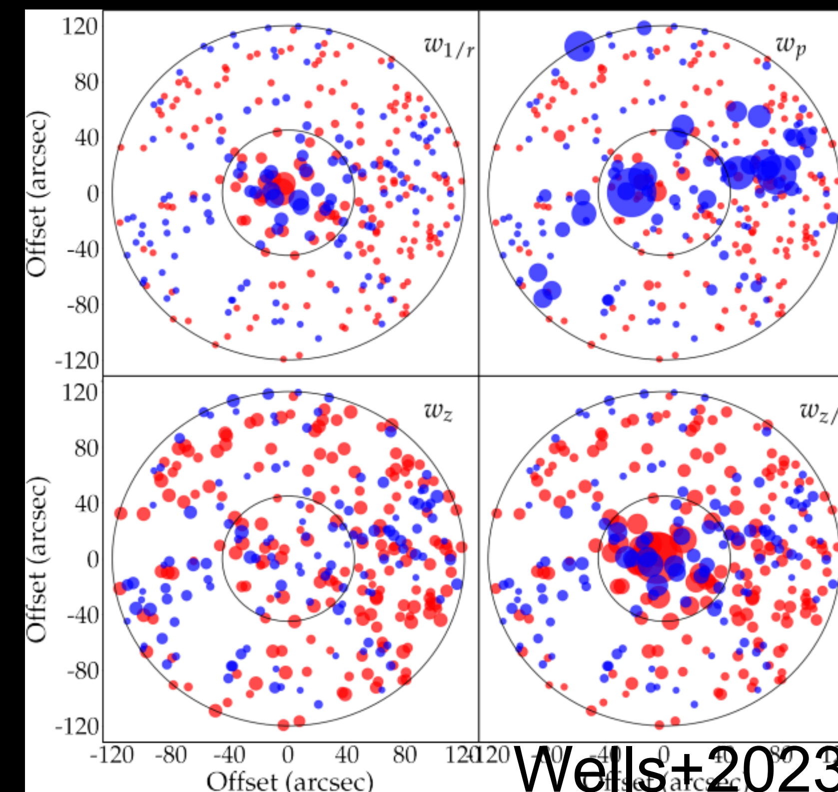
Image credit: M. Millon, A. Shajib

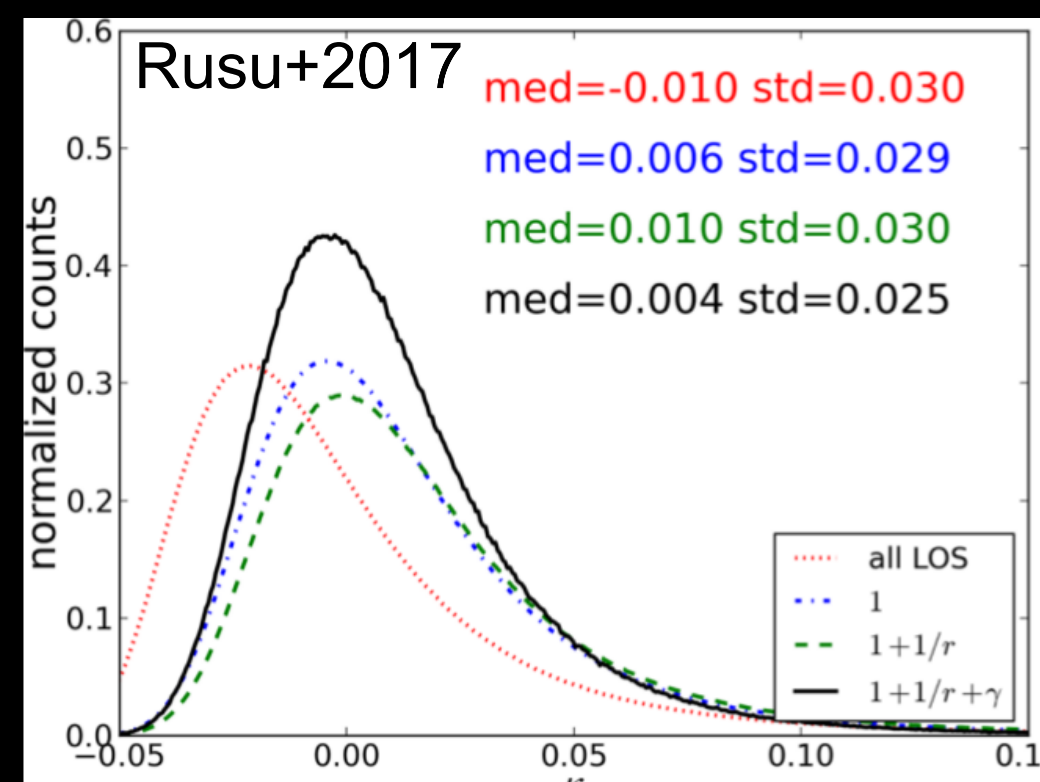
Radius

For more details about modeling, see following talk by Devon Williams

Mass Along the Line of Sight

Animation credit: M. Mori

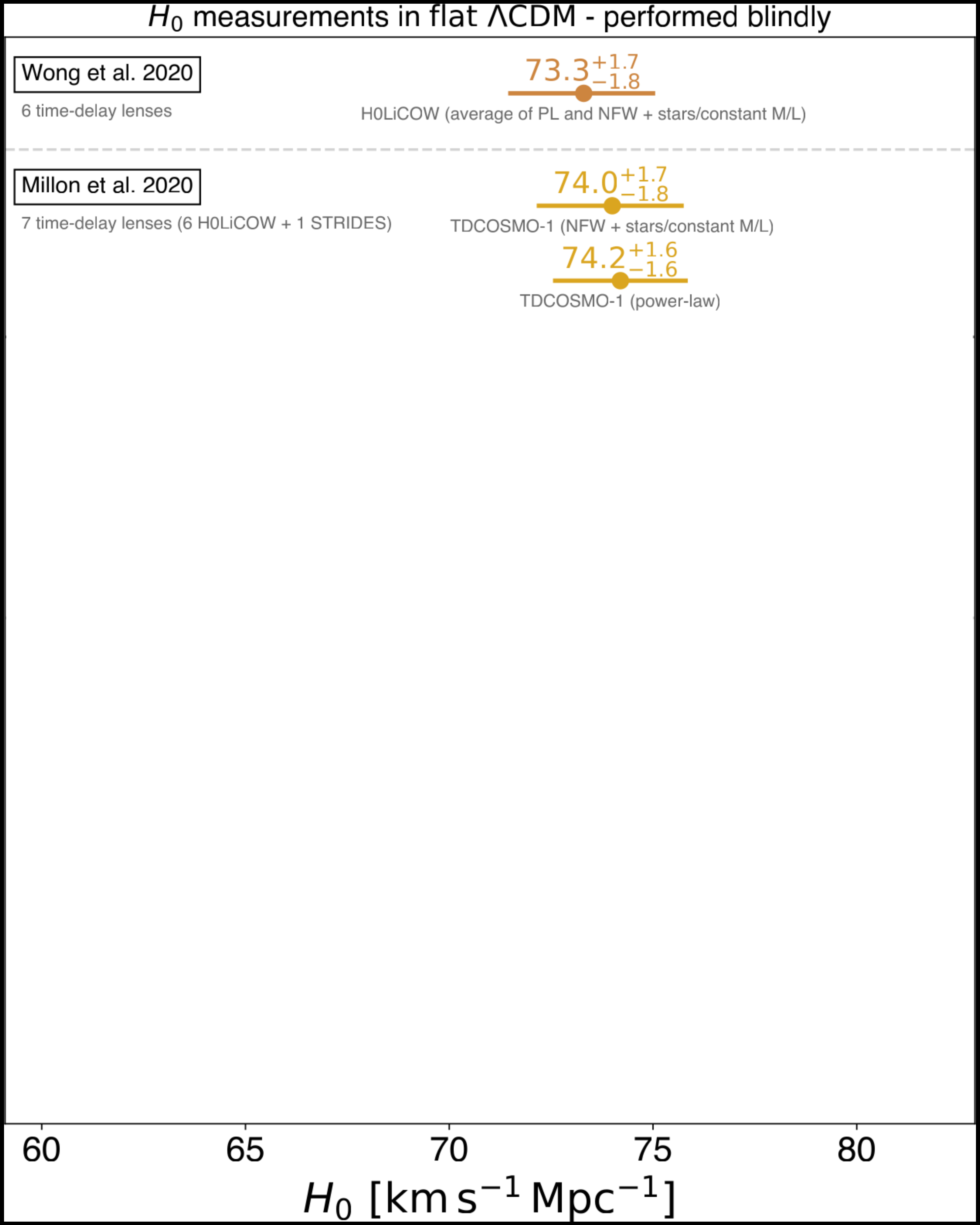




- Lenses lie in overdense LOS due to local lens environment (e.g., Fassnacht+2011; Wong+2018)
- Some strong perturbers need to be included explicitly in lens model (e.g., Wilson+2016; McCully+2017; Sluse+2017)
- Estimate effect of weaker perturbers using weighted galaxy number counts calibrated by simulations (e.g., Greene+2013; Rusu+2017,2020; Wells+2023)
- Independent weak lensing analysis agrees with weighted number counts method (Tihhonova+2018,2020)

H0LiCOW

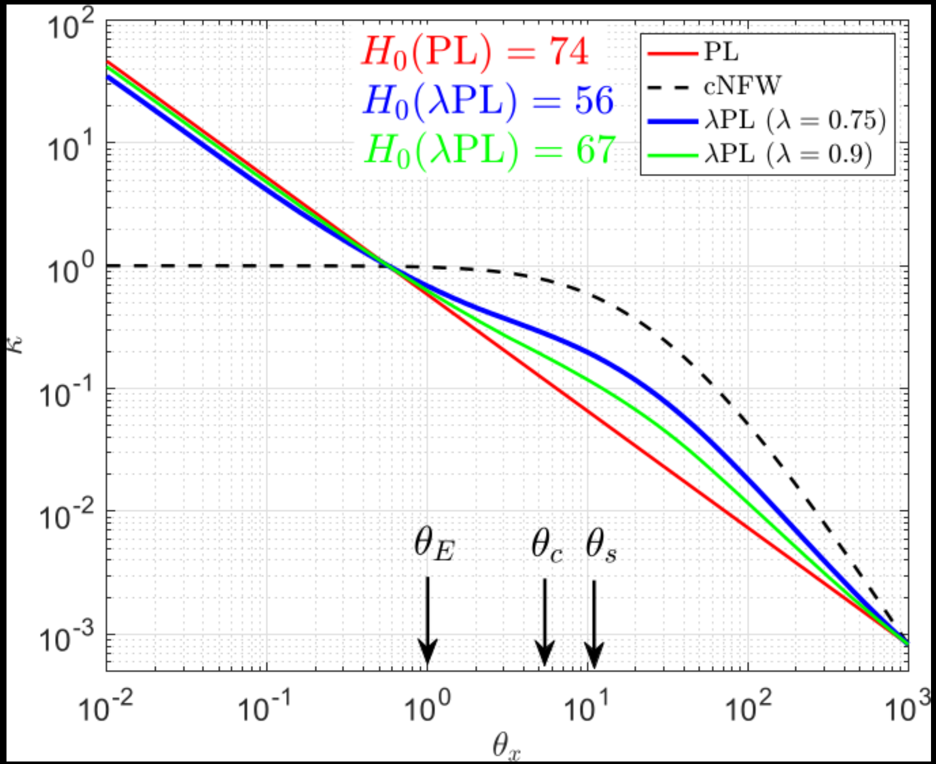
TDCOSMO-I



Assumes explicit form of lens galaxy mass profile

Mass Sheet Degeneracy (MSD)

- Mass sheet degeneracy is a modification of the density profile of the lens by a multiplicative factor λ
  - rescales the time delay and source position, leaving all other observables invariant
  - fundamental degeneracy in lensing (e.g., Falco+1985, Schneider & Sluse 2013,2014)
- Can be due to both an external mass sheet (κ_{ext}) or a modification of the lens mass profile (λ_{int})
- Can be broken with stellar kinematics



Blum+2020

$$\kappa_\lambda(\vec{\theta}) = \lambda\kappa_{\mathrm{PL}}(\vec{\theta}) + (1-\lambda)\kappa_{\mathrm{c}}(\vec{\theta}).$$

$$H_{0\,\lambda} = \lambda H_0.$$

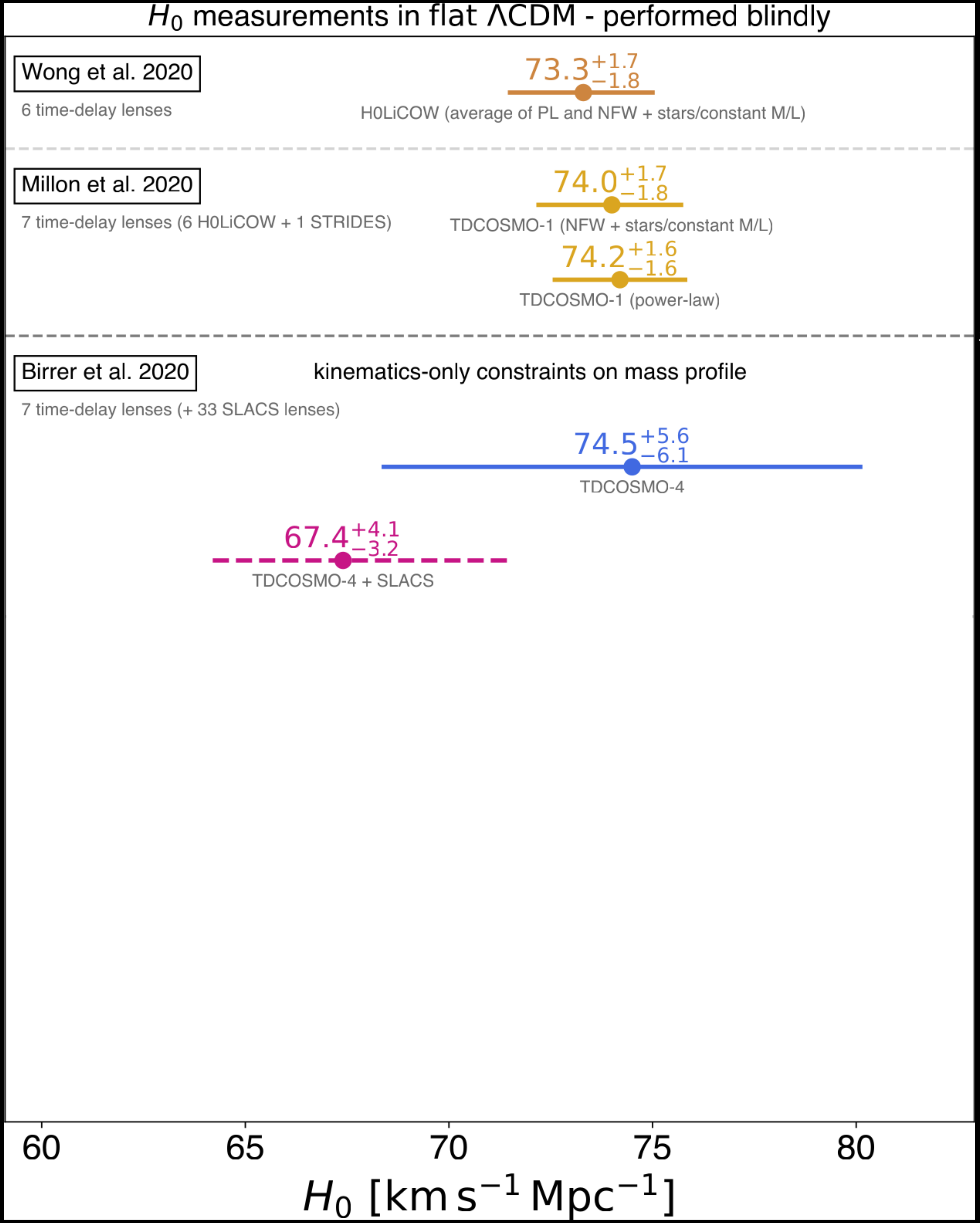
Hierarchical Analysis with free λ_{int}

- Reanalysis of TDCOSMO lenses using Bayesian hierarchical framework allowing λ_{int} to vary
  - maximally degenerate with H_0; λ_{int} constrained **only from kinematics** (most conservative assumption)
  - integrated velocity dispersion of an individual lens galaxy is not sufficient due to the unknown anisotropy of stellar orbits (mass-anisotropy degeneracy)
  - H_0, λ_{int}, and lens galaxy anisotropy parameters are treated as hyperparameters constrained at population level
  - freedom to bring in external datasets (i.e., non-time delay lenses) to constrain hyperparameters

H0LiCOW

TDCOSMO-I

TDCOSMO-IV



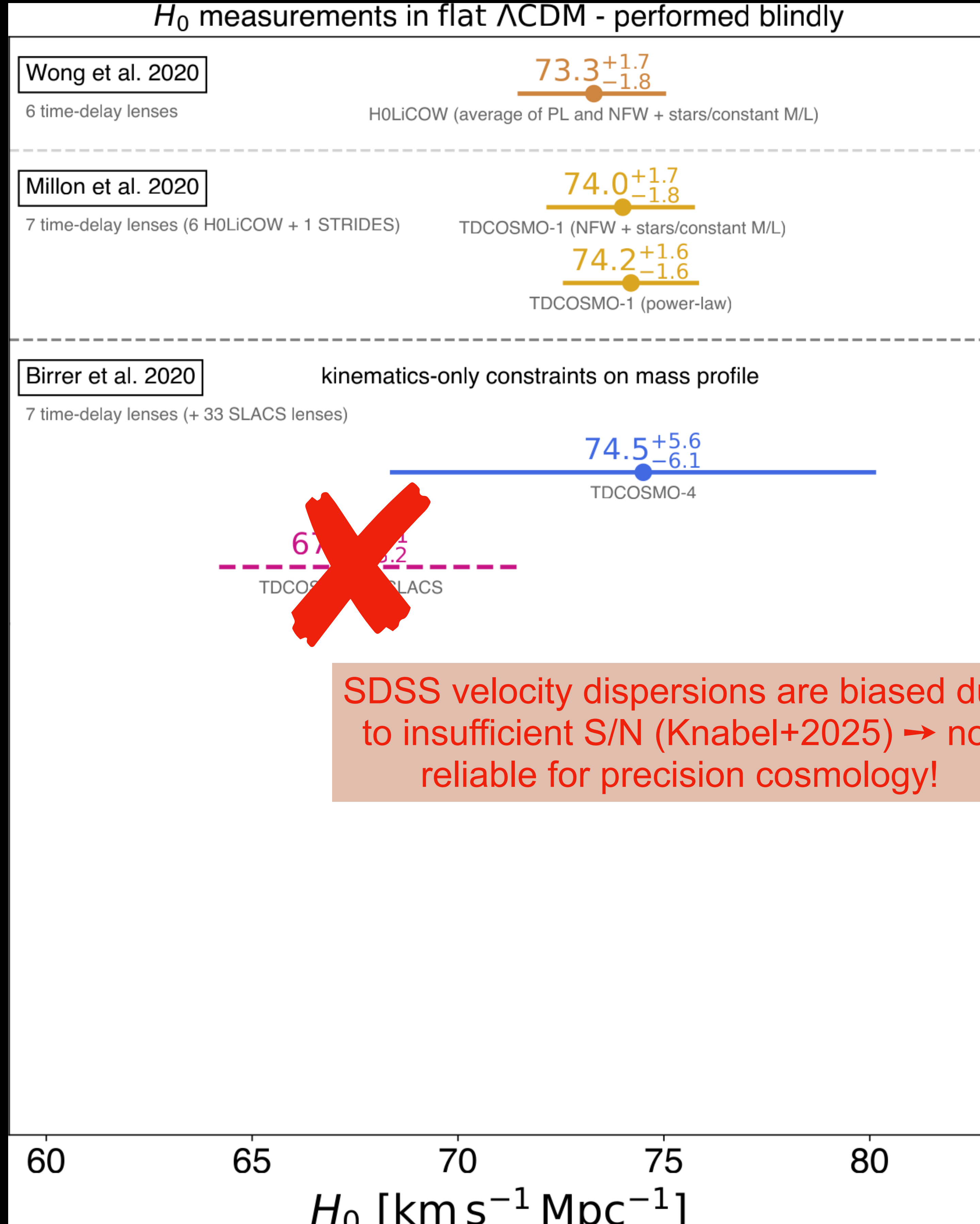
Assumes explicit form of lens galaxy mass profile ($\lambda_{\rm int}$ = 1)

Conservative mass model assumption constrained by kinematics (free $\lambda_{\rm int}$)

HOLiCOW

TDCOSMO-I

TDCOSMO-IV



Assumes explicit form of lens galaxy mass profile ($\lambda_{\rm int}$ = 1)

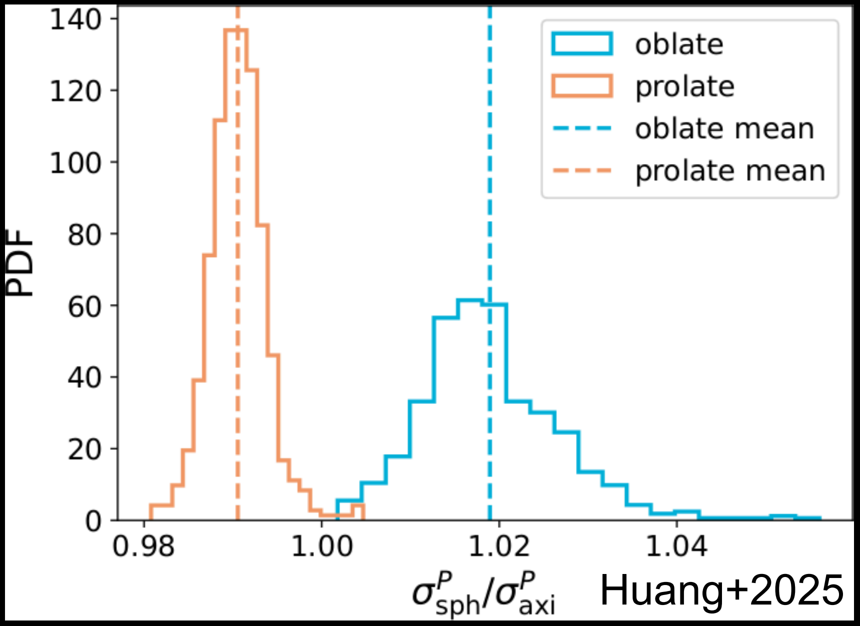
Conservative mass model assumption constrained by kinematics (free $\lambda_{\rm int}$)

TDCOSMO 2025

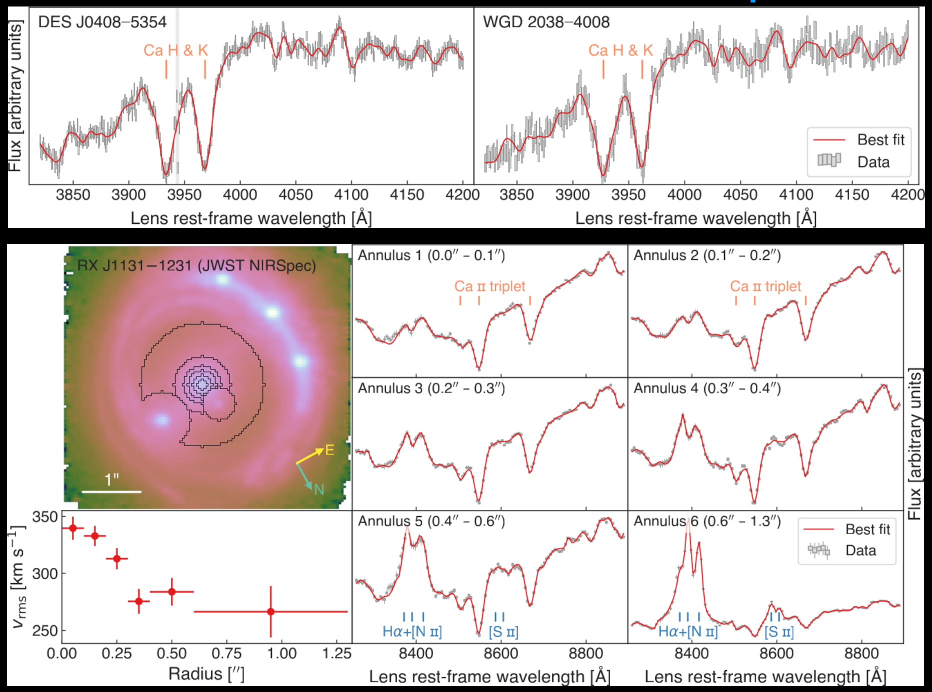
Knowing that the MSD was the largest systematic uncertainty, we focused on obtaining kinematic data (including resolved kinematics) for our latest milestone result

For more details about the kinematics, see Pritom Mozumdar's talk later this morning

Triaxiality and projection effects to model stellar kinematics



New kinematics data, fixed biases due to stellar templates

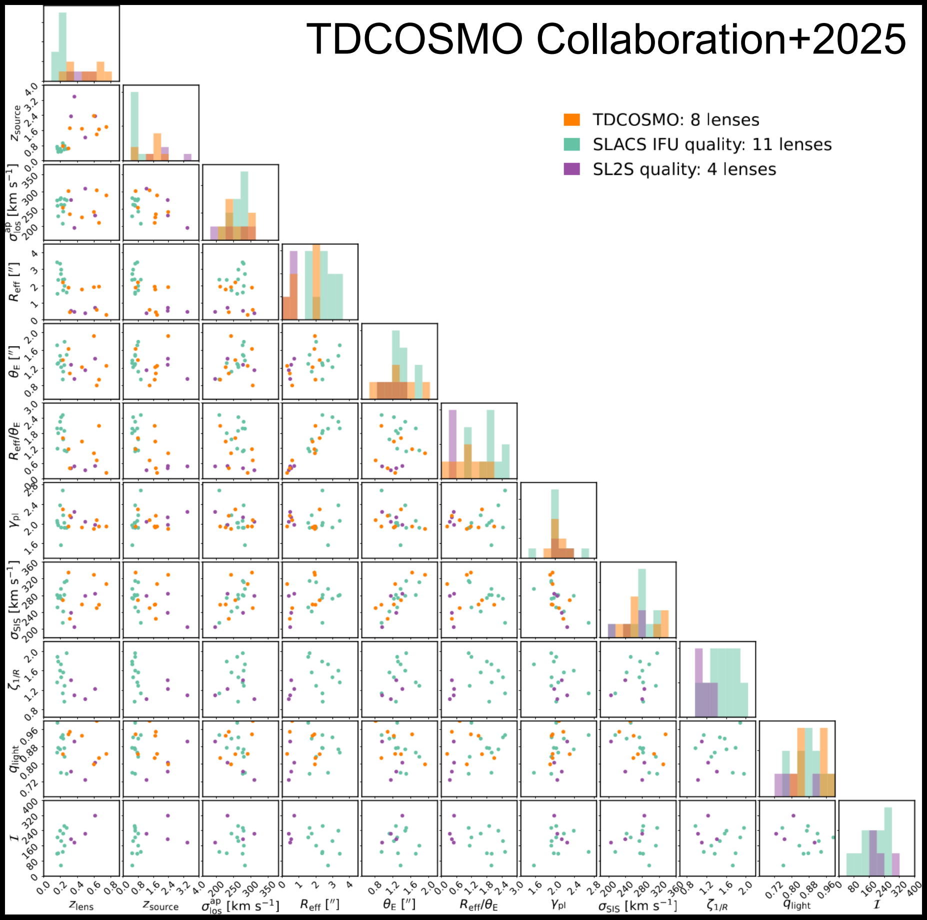


VLT MUSE

JWST NIRSpec IFU

TDCOSMO Collaboration+2025

Better selection and improved data for external lens datasets

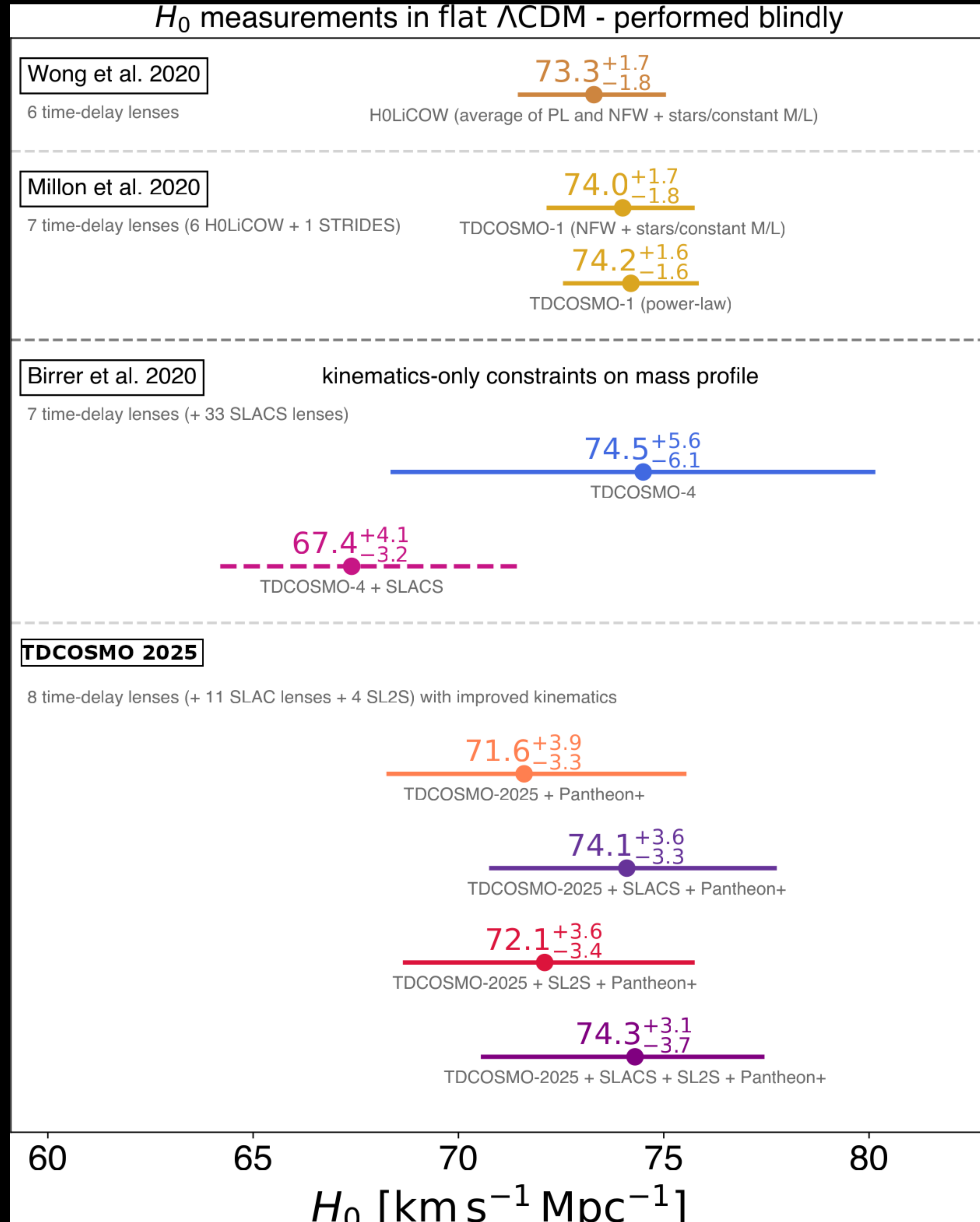


H0LiCOW

TDCOSMO-I

TDCOSMO-IV

TDCOSMO 2025

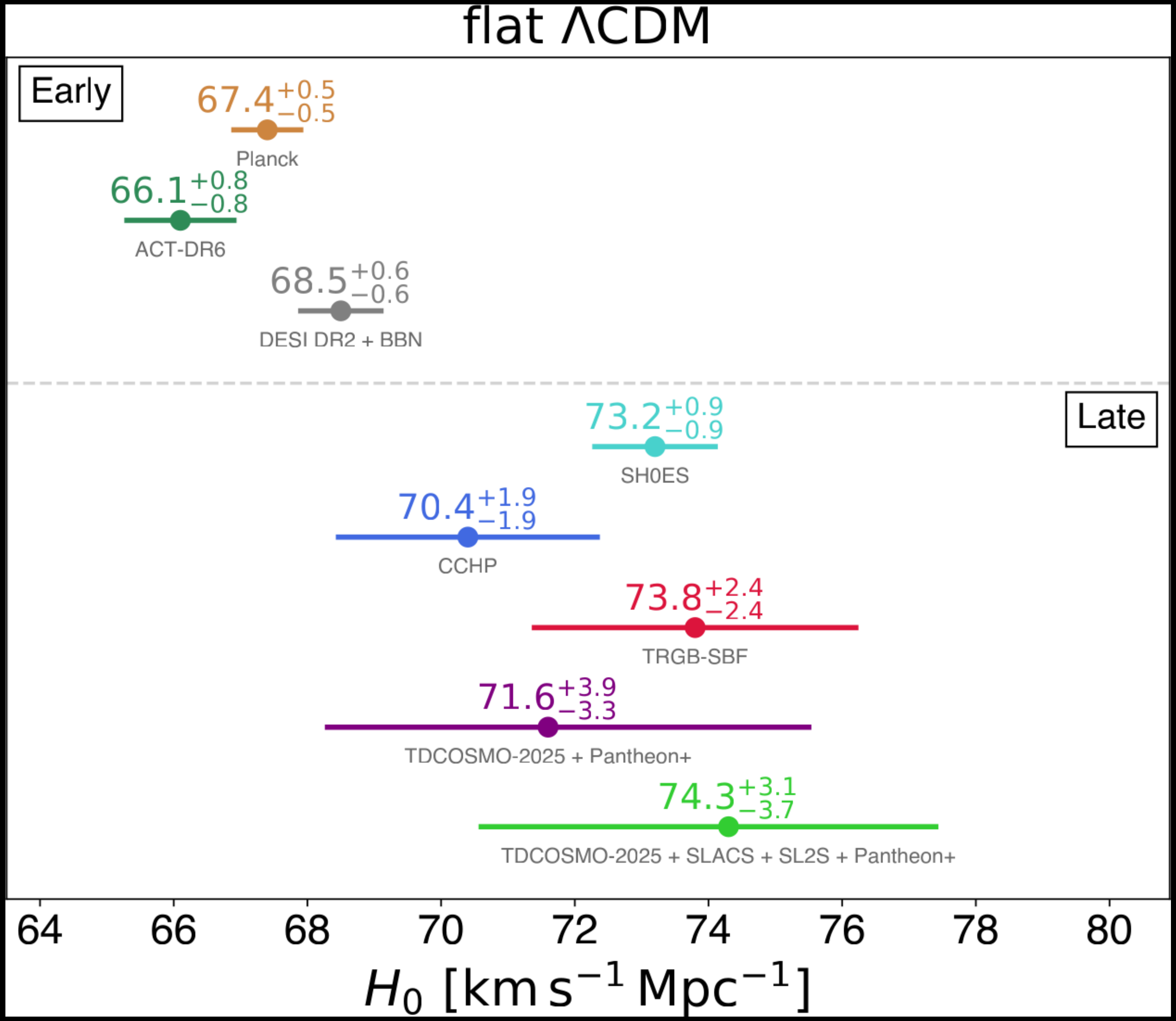


TDCOSMO Collaboration+2025

Assumes explicit form of lens galaxy mass profile ($\lambda_{\rm int}$ = 1)

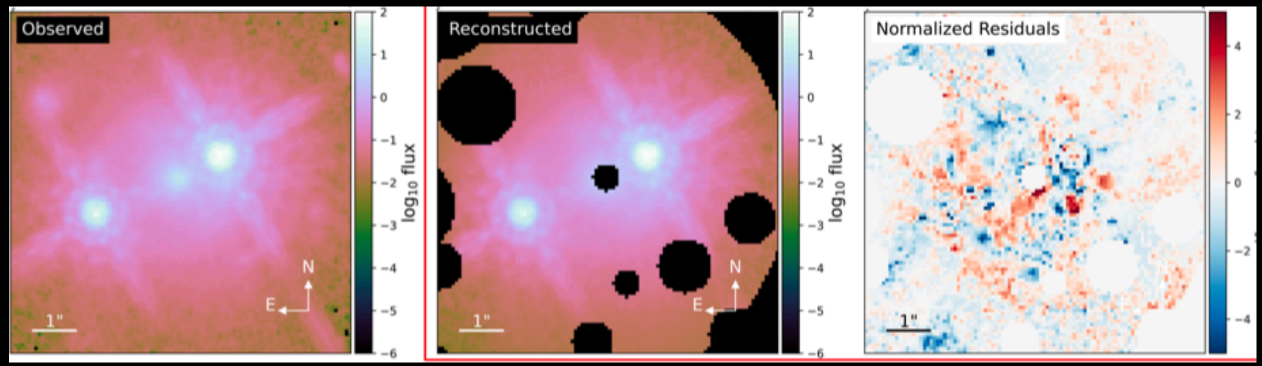
Conservative mass model assumption constrained by kinematics (free $\lambda_{\rm int}$)

The Hubble Tension



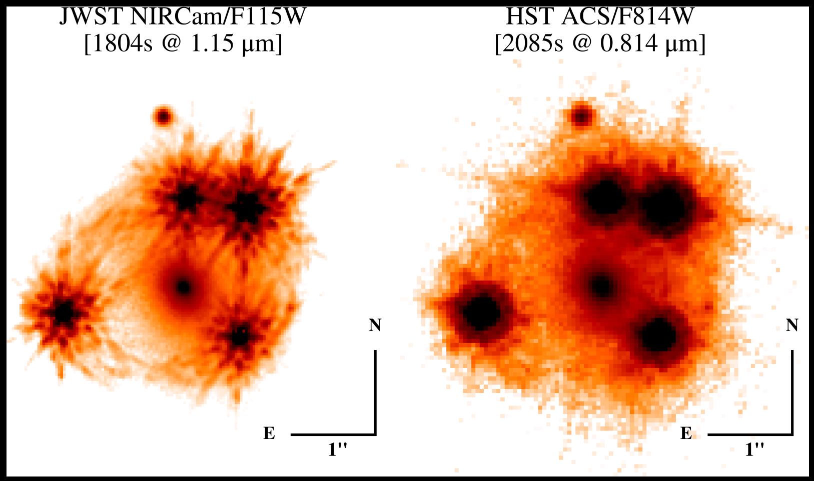
TDCOSMO Collaboration+2025

TDCOSMO 2026 (and beyond)

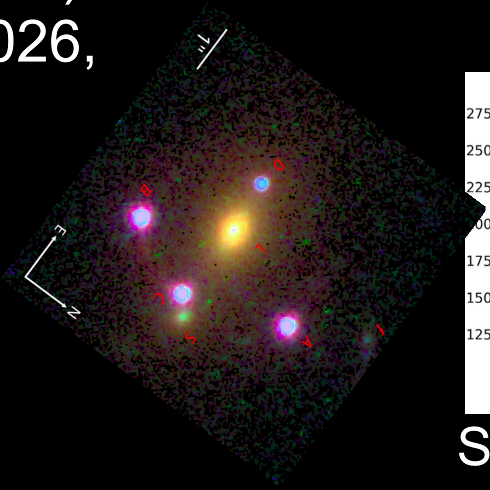


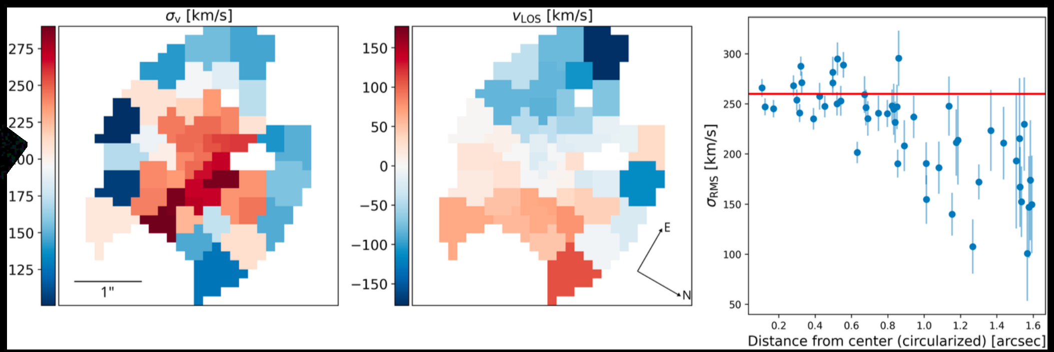
Paic+2026

- Progress has been made, but still need to reduce the uncertainties to the ~1-2% level to be competitive with CMB, distance ladder
  - increase sample size
  - better data → tighter constraints per lens
- **<u>TDCOSMO 2026 milestone result coming later this year</u>**, ~annual milestones to follow
- New data
  - Sample of 11 lensed quasars (including double-image lenses; Paic+2026)
  - *JWST*/NIRCam imaging for lens modeling (e.g., Williams+2025)
  - IFU data (Keck/KCWI; JWST/NIRSpec) for more lenses (e.g., Shajib et al. 2026, Sheu+2026)



Williams+2025





Sheu+2026

Summary

- Time-delay cosmography provides late-Universe measurement of H_0 completely independent of CMB and distance ladder/SNe
- TDCOSMO 2025 results from 8 lenses attain < 5% precision on H_0 in flat ΛCDM
  - maximally conservative with respect to galaxy mass profiles
  - consistent with SNe Ia + distance ladder
- TDCOSMO 2026 and future milestones will push toward a ~1-2% constraint
  - larger lens samples (11 and counting), including doubles
  - more lenses with *JWST*/NIRCam imaging for more detailed lens modeling
  - more lenses with resolved kinematics (including *JWST*/NIRSpec) for breaking MSD