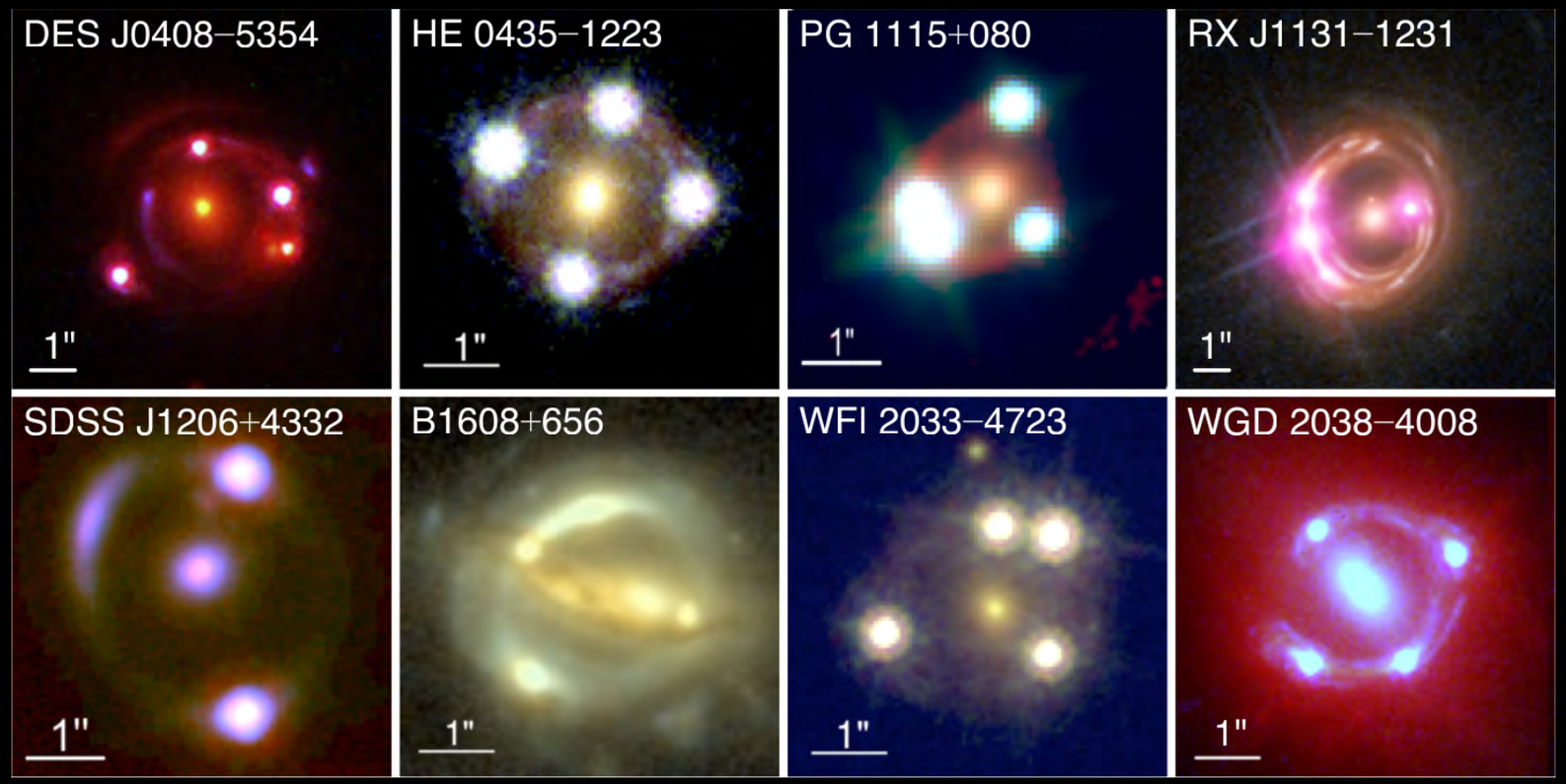
TDCOSMO 2025: Cosmological constraints from strong lensing time delays

TDCOSMO Collaboration et al. 2025, A&A, 704, 63



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EAMA 11

Niigata, Japan

December 11, 2025

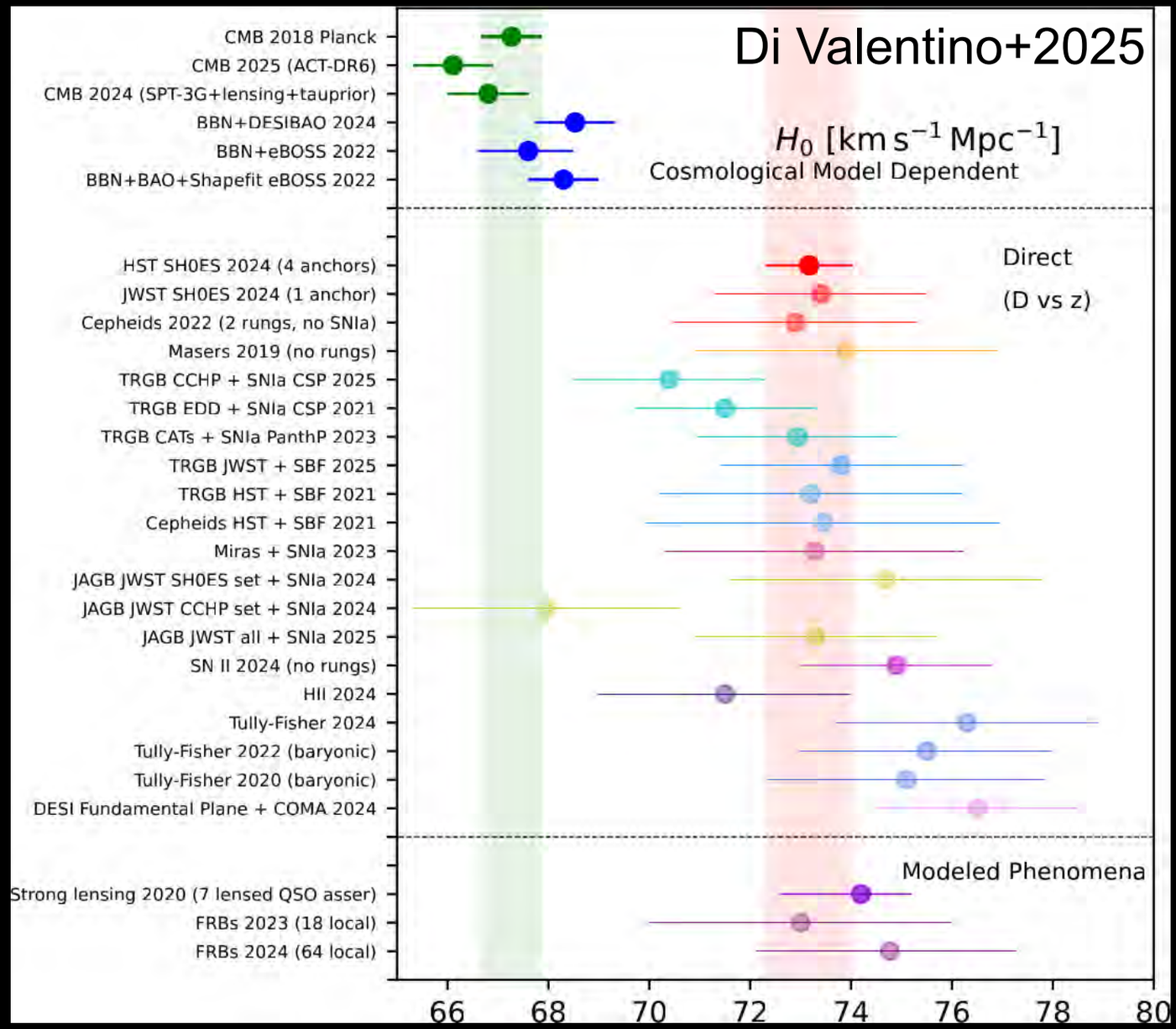
科研費 KAKENHI

東京大学 THE UNIVERSITY OF TOKYO

RESCEU

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*



Time-Delay Cosmography

- Strong gravitational lensing
  - background object (source) magnified by foreground object (lens)
  - can determine mass distribution of lens by fitting a model to reproduce observed image configuration
- "time delay" between the multiple lensed images
  - due to 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
  - need time delay, lens mass model, stellar kinematics of lens galaxy, estimate of LOS perturbations
  - one-step method to infer H_0, *independent of CMB and distance ladder*

Animation credit: M. Mori

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

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

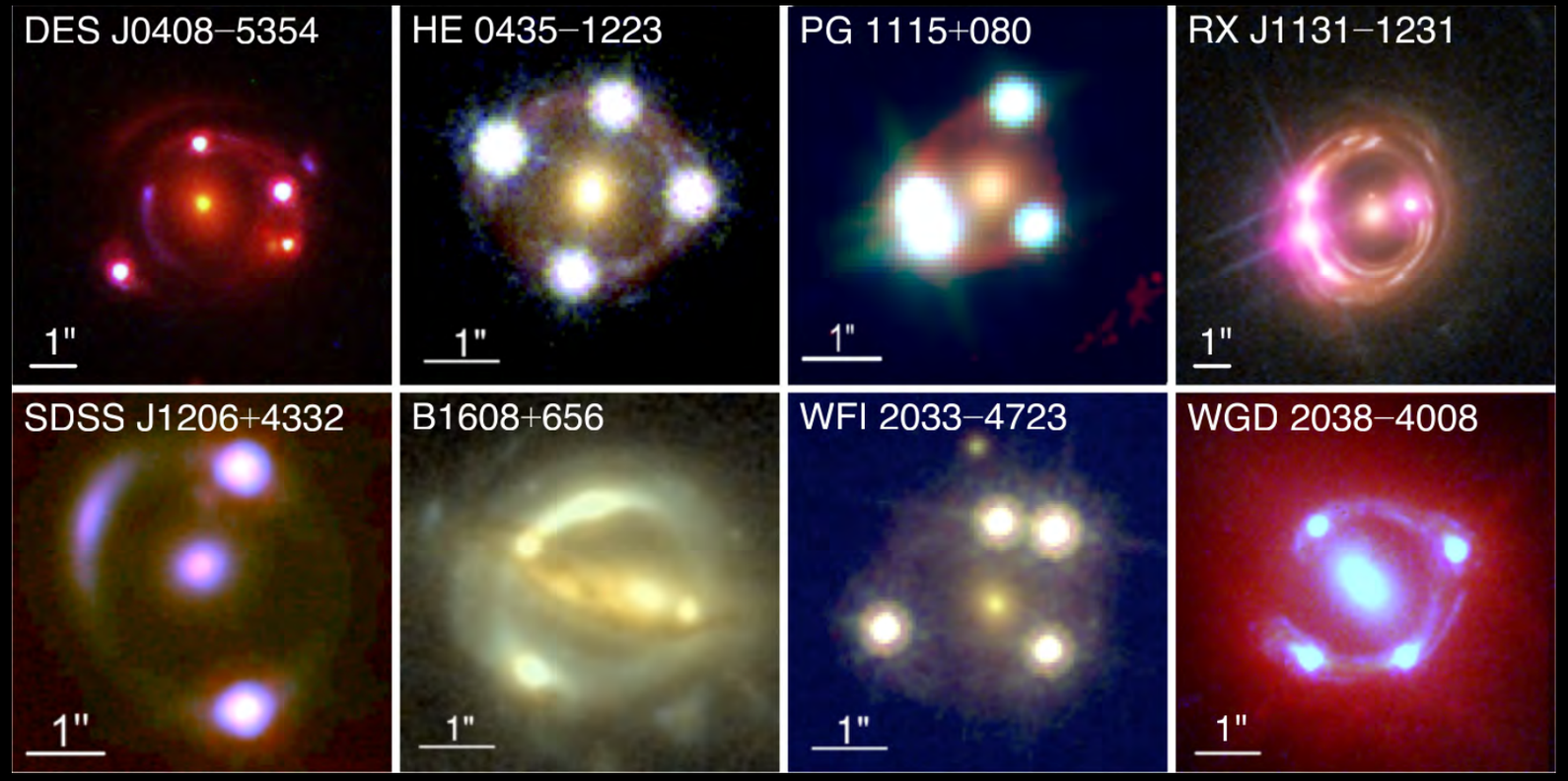
Δt: Time delay (observed)

$D_{\Delta t}$: Time-delay distance

$\Phi_{\rm lens}$: Fermat potential (from lens model)

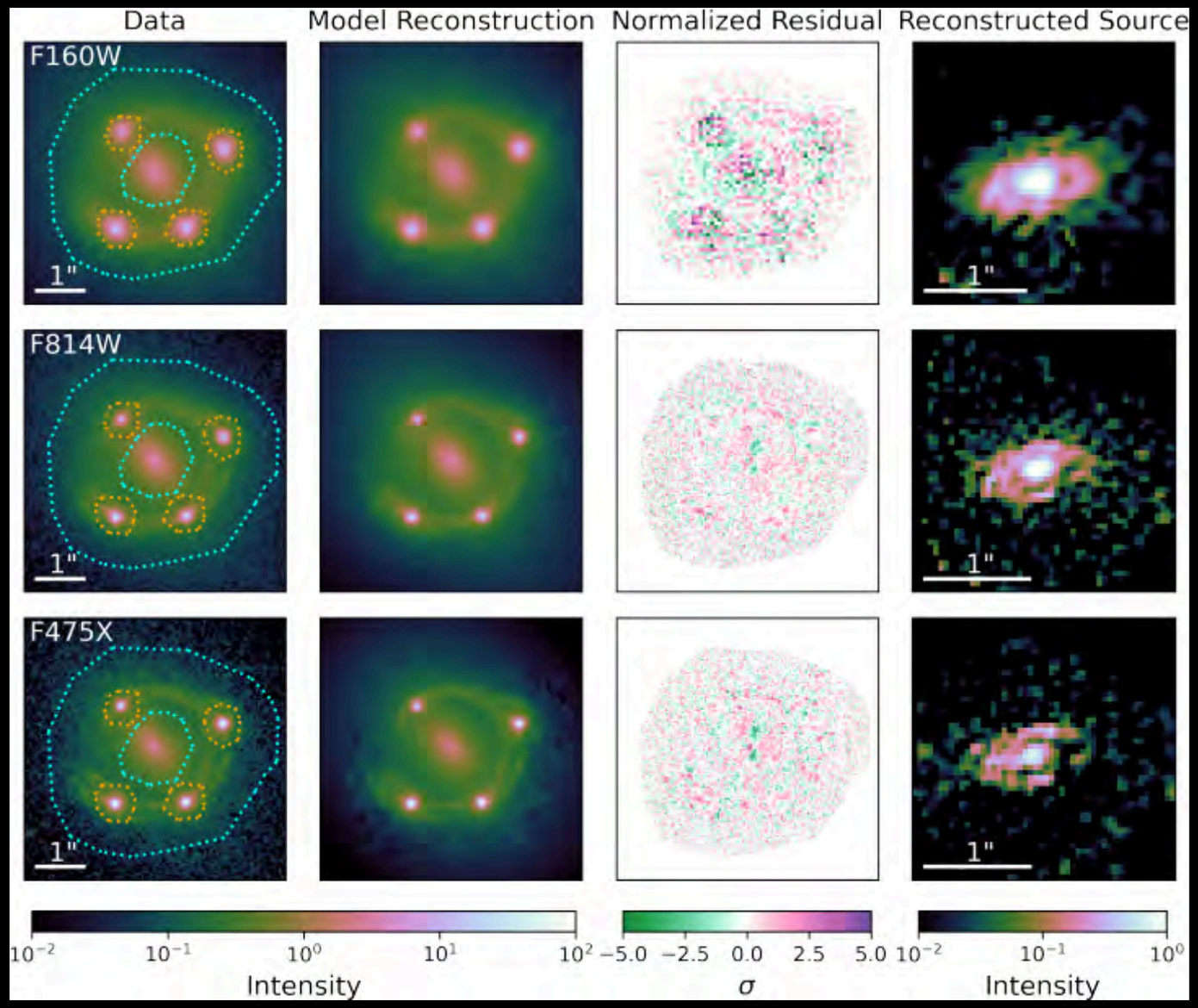
TDCOSMO

- 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 to date (TDCOSMO Collaboration 2025)
- Lenses analyzed blindly with respect to key parameters (e.g., H_0) until publication



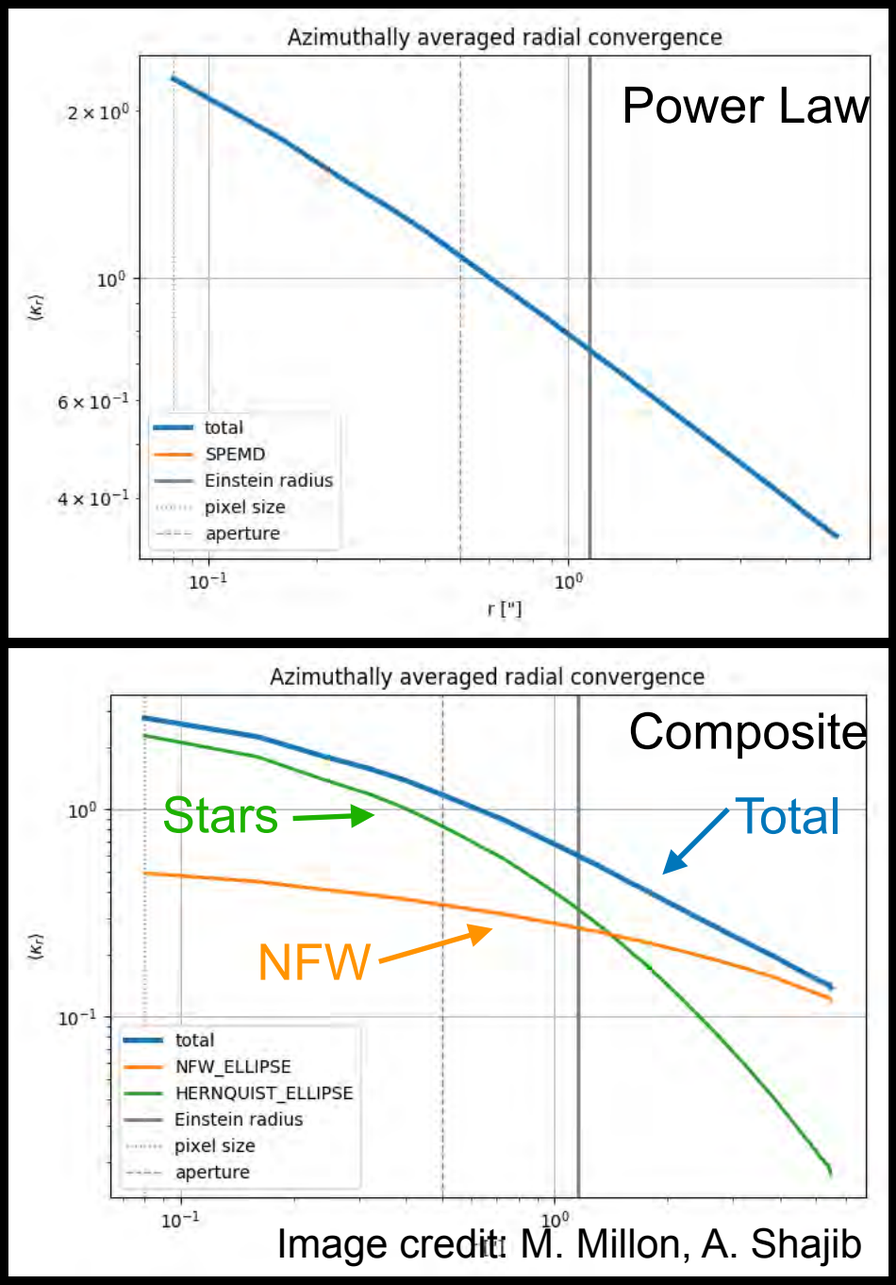
TDCOSMO Collaboration+2025

Lens Modeling



Shajib, Wong et al. 2022

Projected mass density

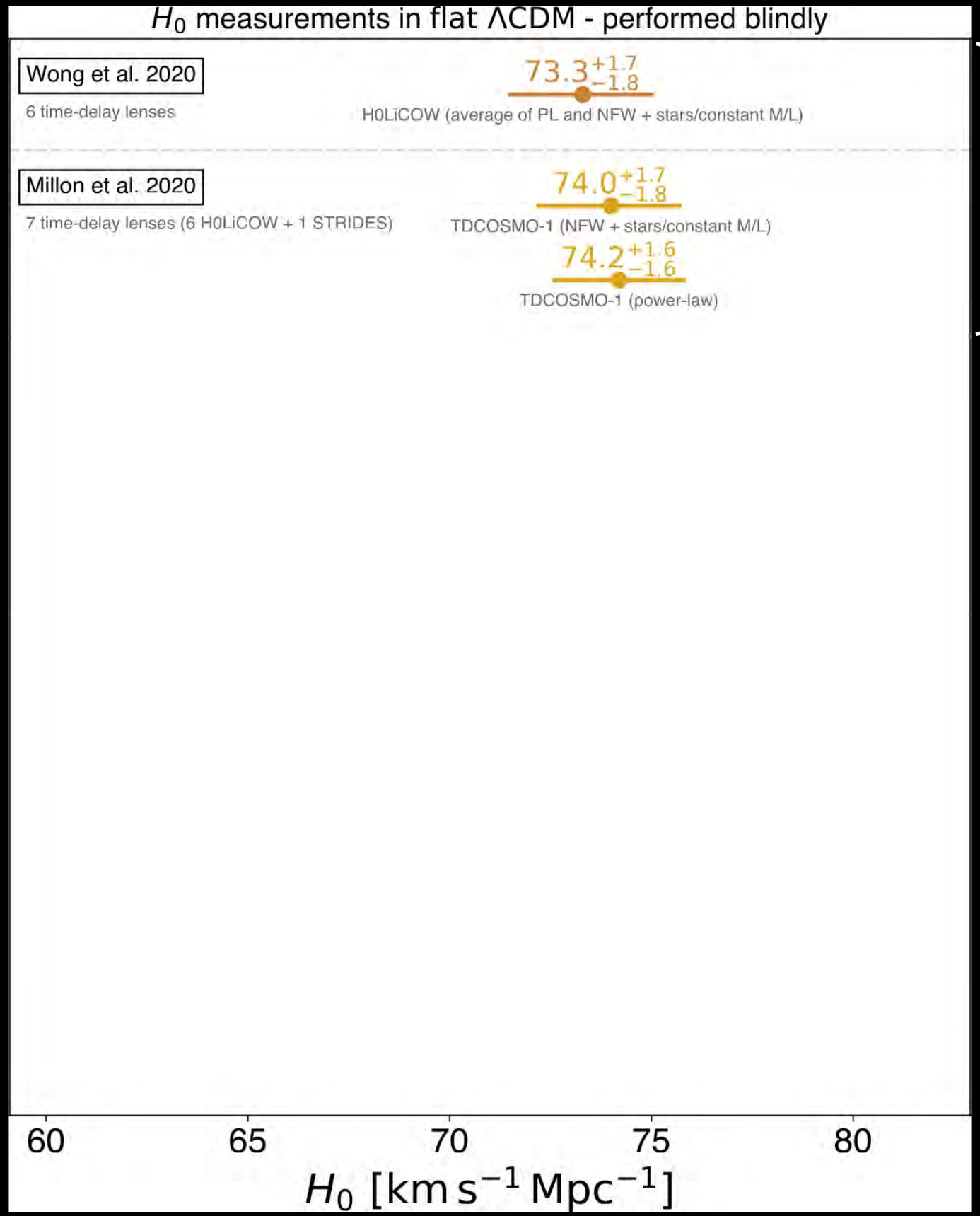


Radius

Assume either a power law or stars+NFW (composite) model, combine results

H0LiCOW

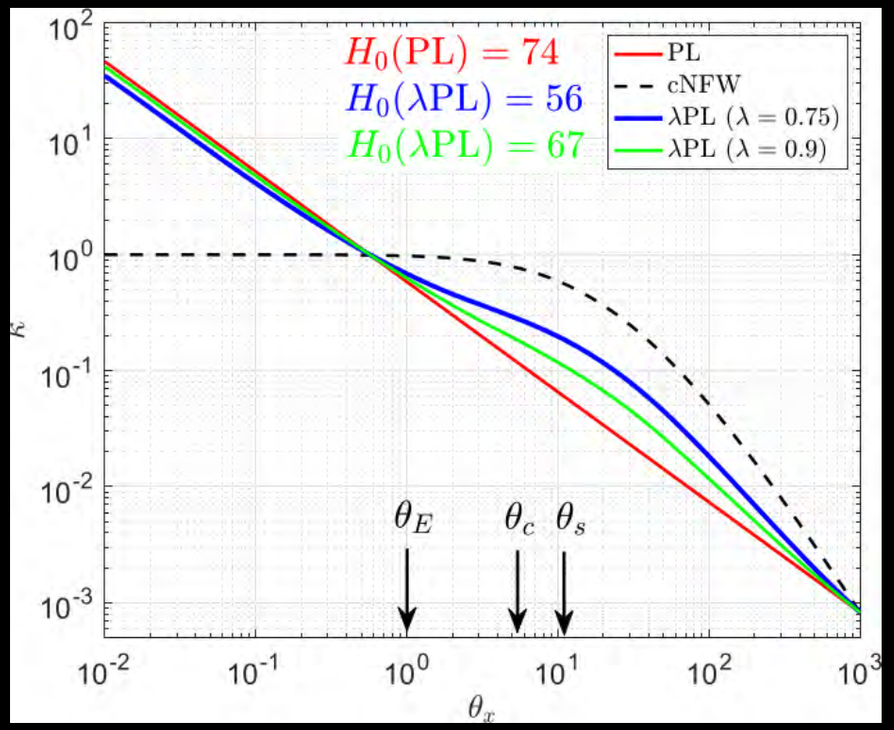
TDCOSMO-I



Assumes explicit form of lens galaxy mass profile

Stellar Kinematics: Addressing the 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 either/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

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

$$H_0\,\lambda = \lambda H_0.$$

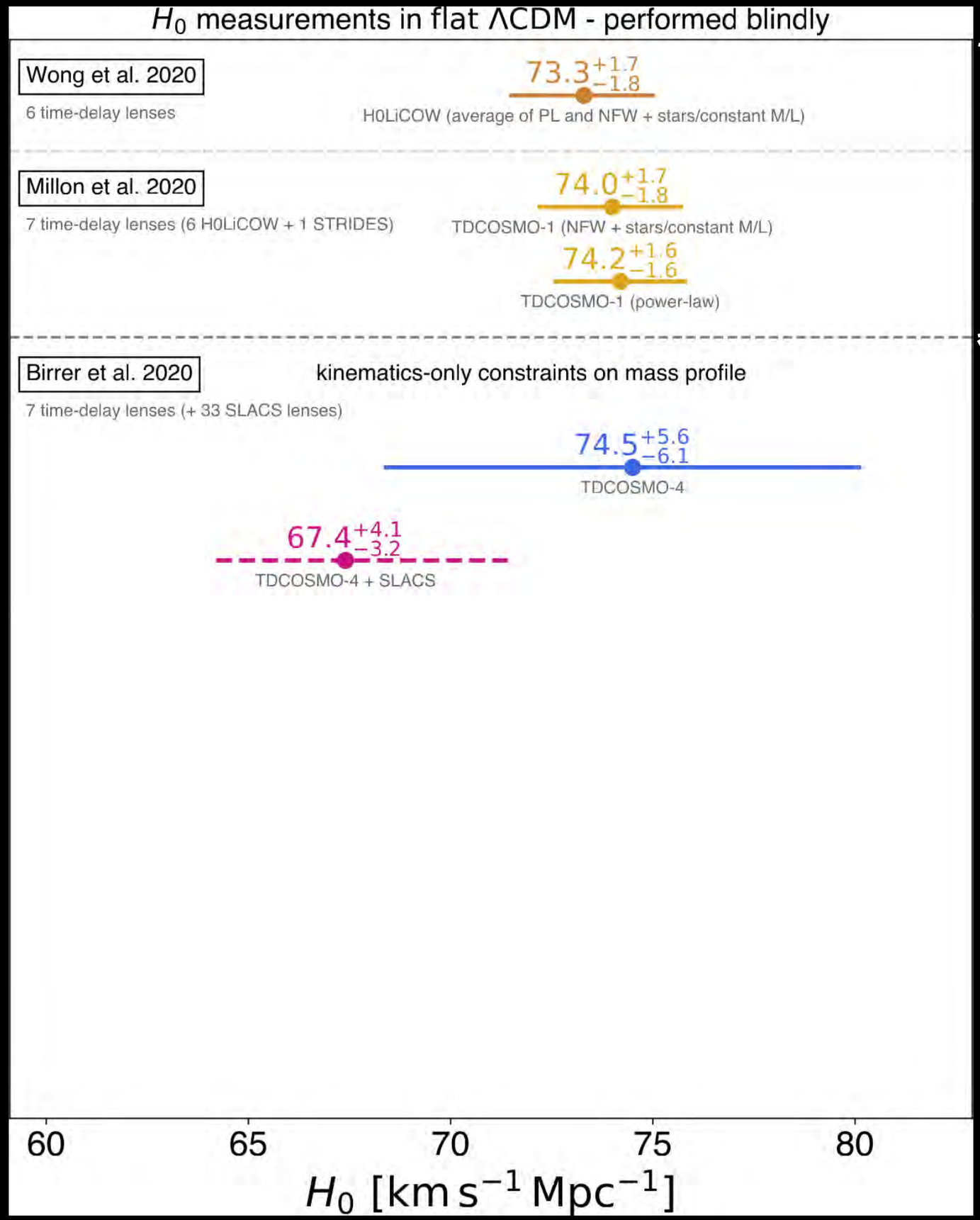
Hierarchical Analysis with free $\lambda_{\rm int}$

- Reanalysis of TDCOSMO lenses using Bayesian hierarchical model allowing $\lambda_{\rm int}$ to vary
  - maximally degenerate with H_0; $\lambda_{\rm int}$ 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, $\lambda_{\rm int}$, 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



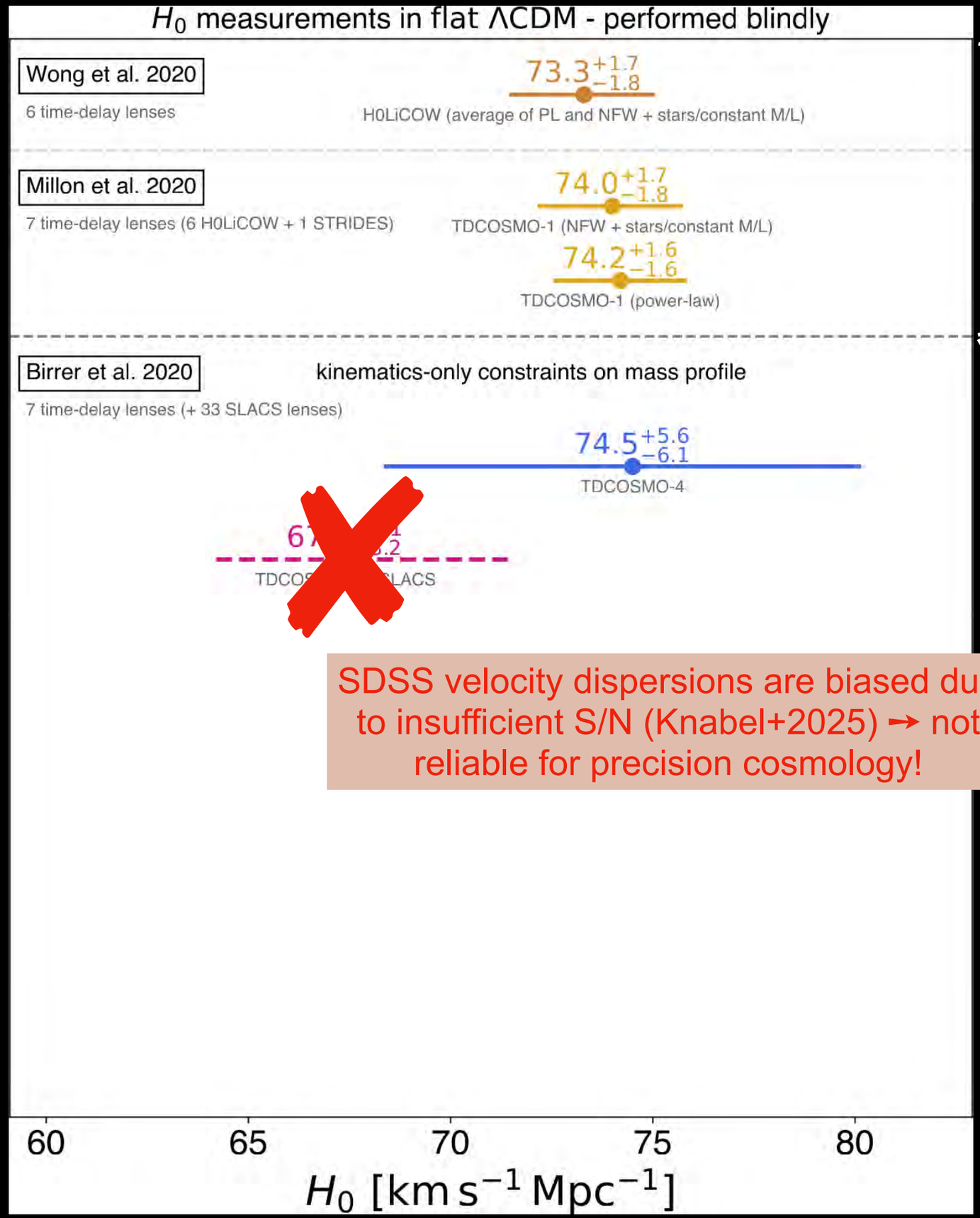
Assumes explicit form of lens galaxy mass profile ($\lambda_{\rm int}$ = 1)

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

H0LiCOW

TDCOSMO-I

TDCOSMO-IV



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

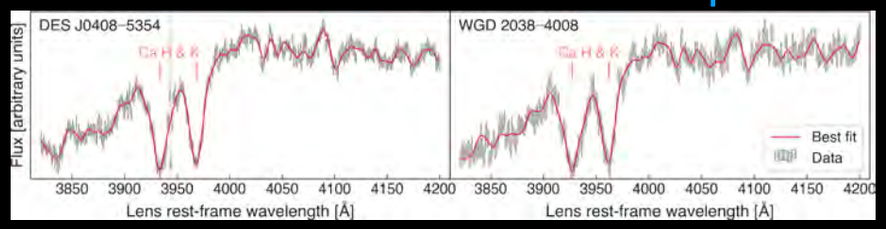
Conservative mass model assumption constrained by kinematics (free $\lambda_{\rm int}$)

TDCOSMO 2025

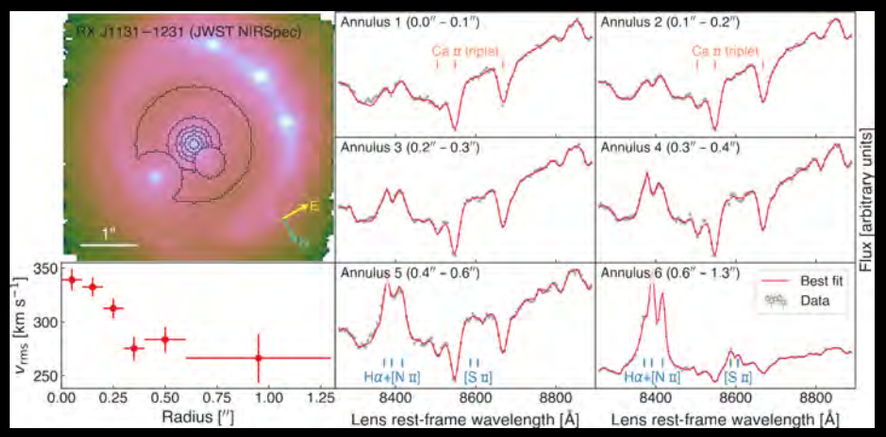
Addition of 8th lens to sample



New kinematics data,
fixed biases due to stellar templates



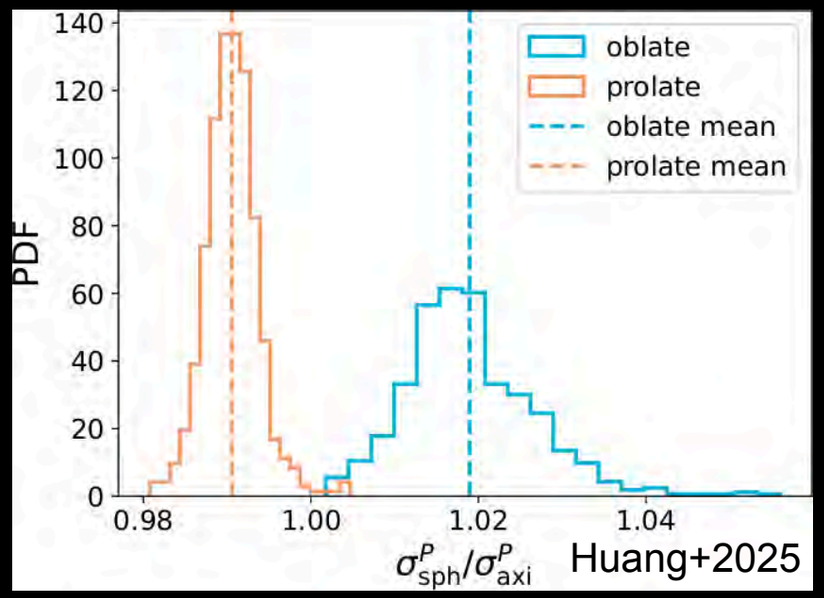
VLT
MUSE



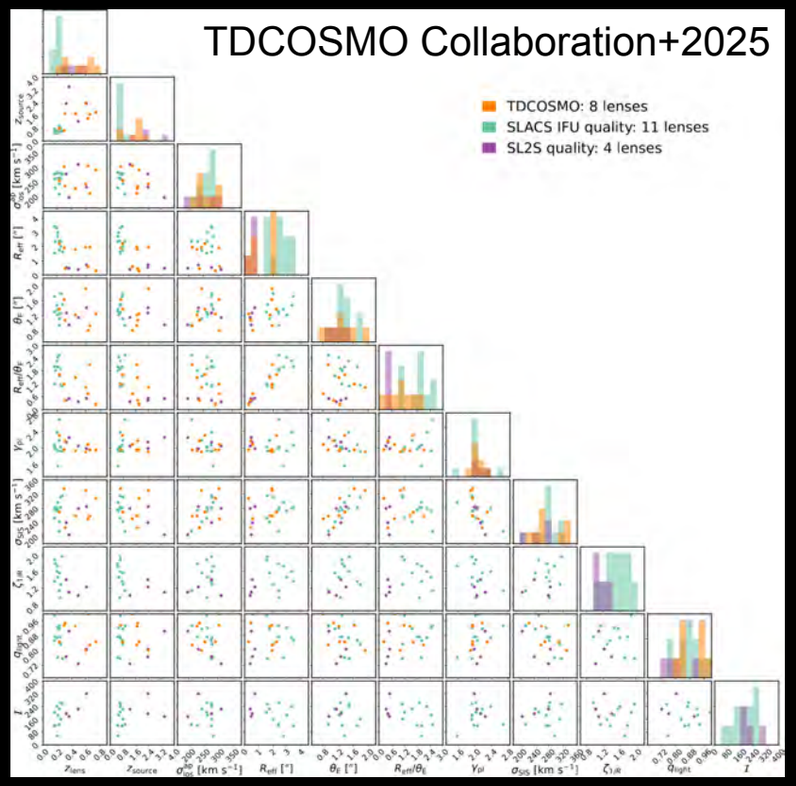
JWST
NIRSpec IFU

TDCOSMO Collaboration+2025

Triaxiality and projection effects
to model stellar kinematics



Better selection and improved data
for external lens datasets

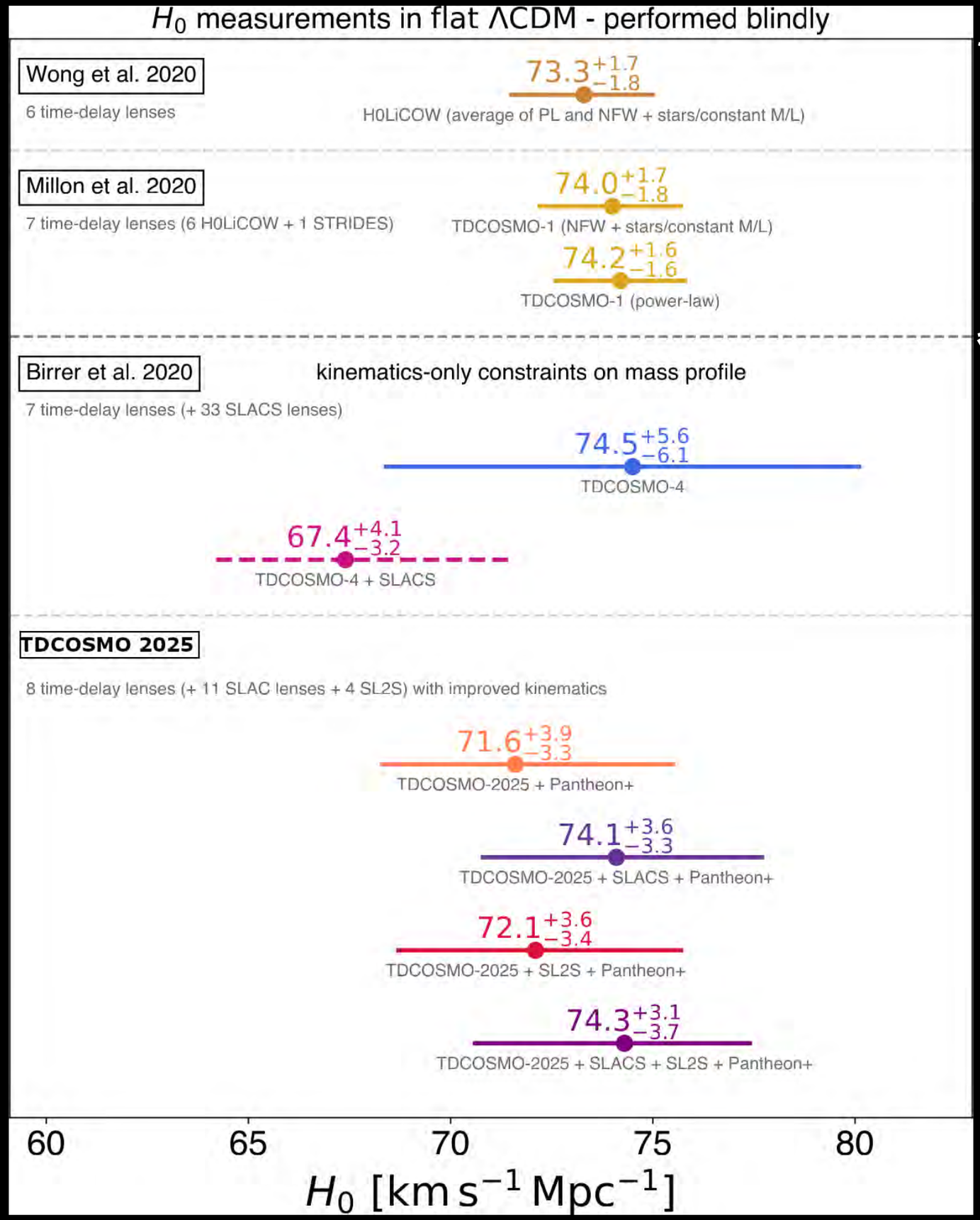


H0LiCOW

TDCOSMO-I

TDCOSMO-IV

TDCOSMO 2025

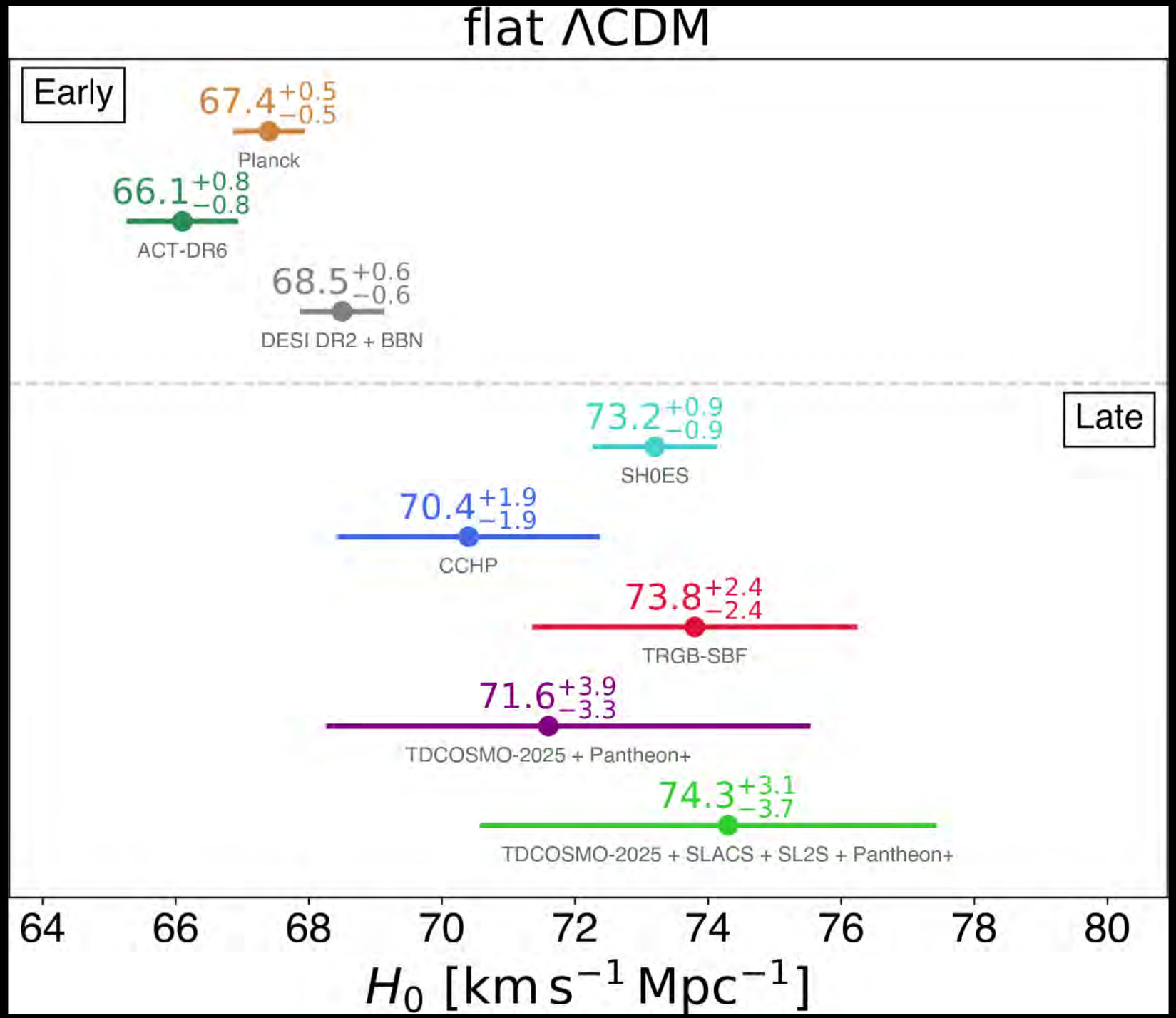


Assumes explicit form of lens galaxy mass profile ($\lambda_{\rm int} = 1$)

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

TDCOSMO Collaboration+2025

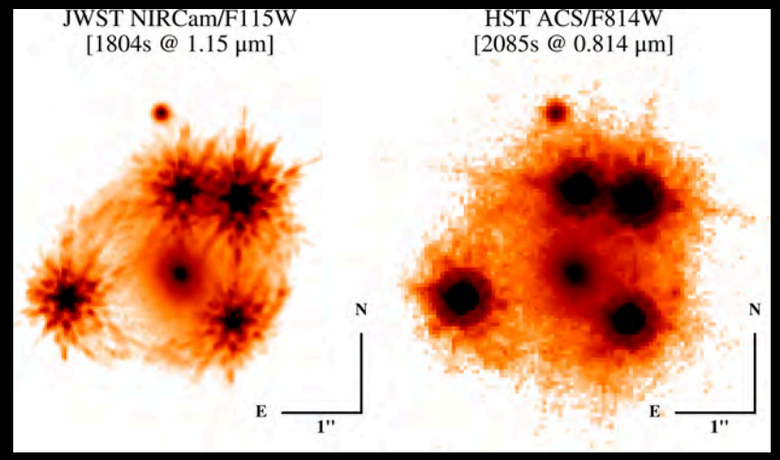
The Hubble Tension



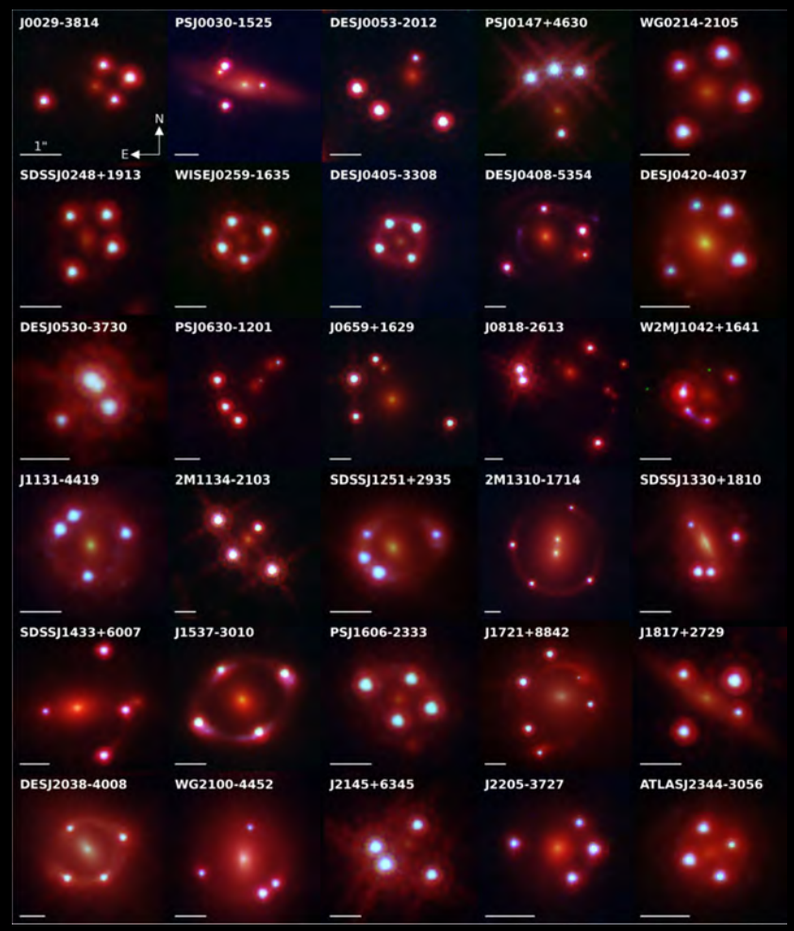
TDCOSMO Collaboration+2025

Future of Time-Delay Cosmography

- Goal: 1-2% precision on H_0
- New data
  - *JWST*/NIRCam imaging for lens modeling (e.g., Williams et al. 2025)
  - *JWST*/NIRSpec IFU data for remaining TDCOSMO sample (Shajib et al. in prep)
- Analysis of large future lens samples
  - LSST/Euclid/Roman will eventually discover ~hundreds or ~thousands of lensed quasars for time-delay cosmography
  - investigate more numerous double-image lenses (e.g., Paic+2025; see talk GF-21C at 12:10 pm today)
  - develop lens search methods on large imaging surveys (e.g., DES, HSC)
  - develop automated modeling techniques (e.g., Schmidt+2023; Ertl+2023)



Williams+2025



Schmidt+2023

Summary

- Time-delay cosmography provides late-Universe measurement of H_0 completely independent of CMB and distance ladder/SNe
- TDCOSMO results from 8 lenses attain ~4.5% precision on H_0 in flat ΛCDM
  - maximally conservative with respect to galaxy mass profiles
  - consistent with SNe Ia + distance ladder
- Future developments will push toward a ~1% constraint
  - larger lens samples, including doubles
  - resolved kinematics for entire sample
  - automated lens modeling