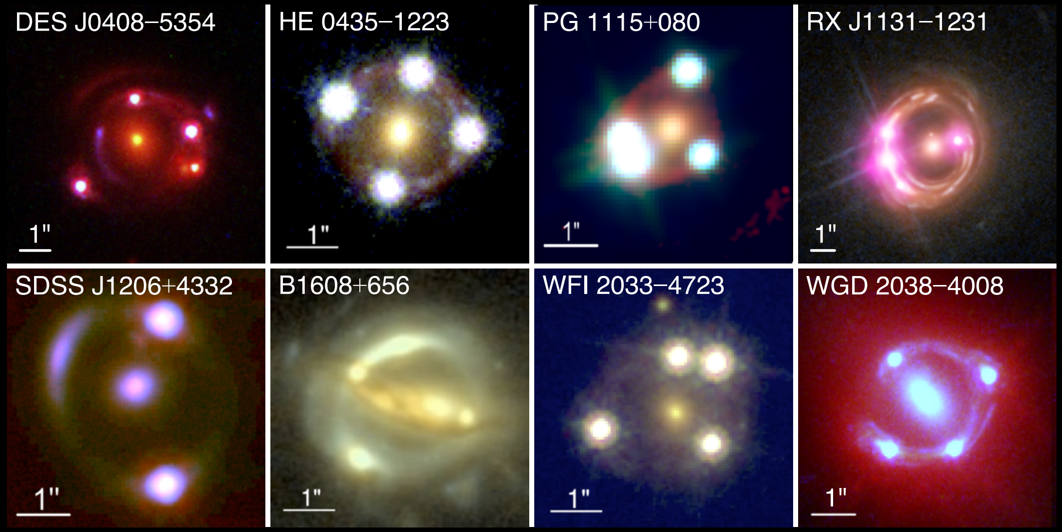
TDCOSMO 2025: Cosmological constraints from strong lensing time delays



Martin Millon

(ETH Zurich)

On behalf of the TDCOSMO collaboration

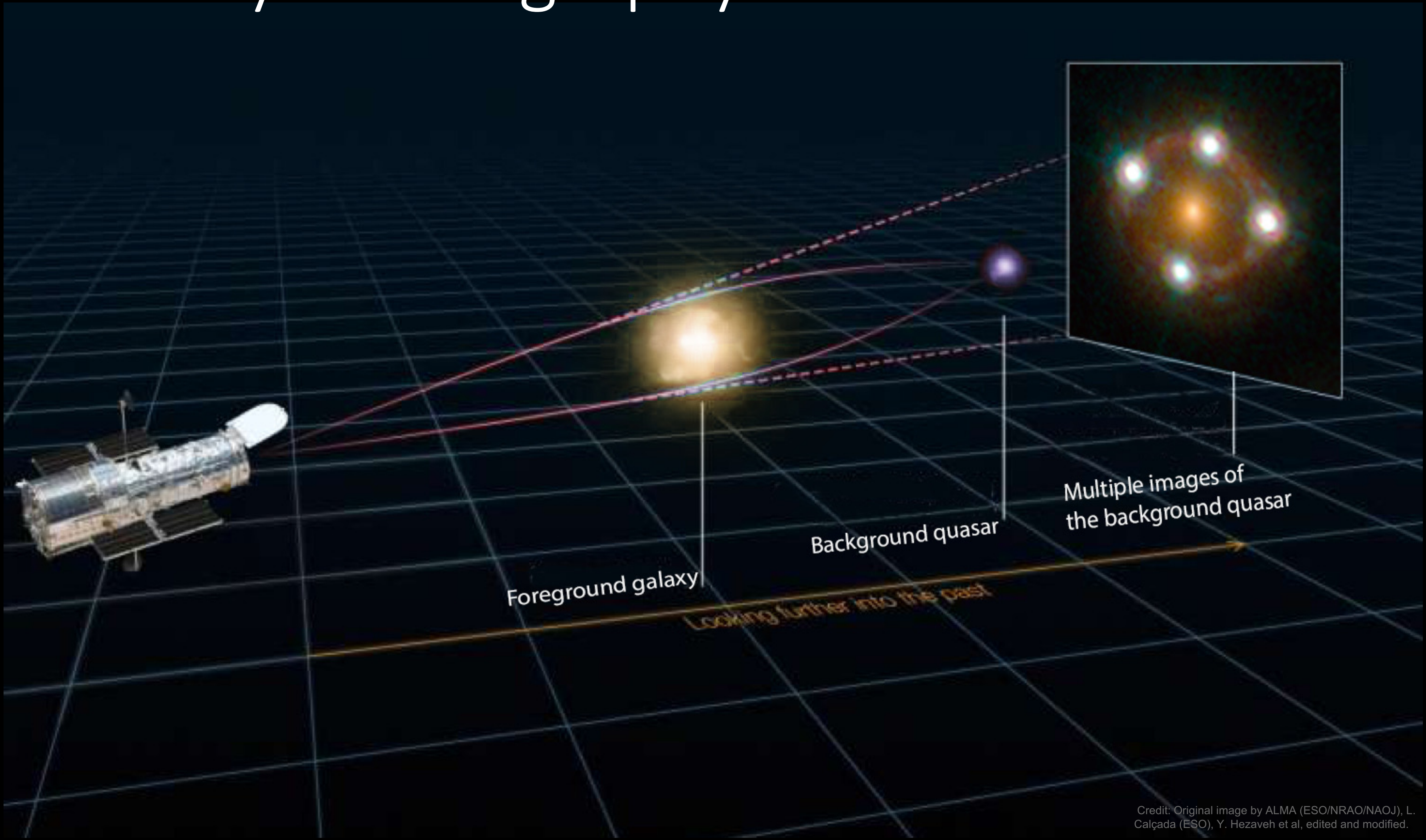
ETH zürich

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

Swiss Cosmo Days, June 5th 2025

https://arxiv.org/abs/2506.03023v1

Time-delay cosmography :



Credit: Original image by ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al, edited and modified.

Time-delay cosmography :

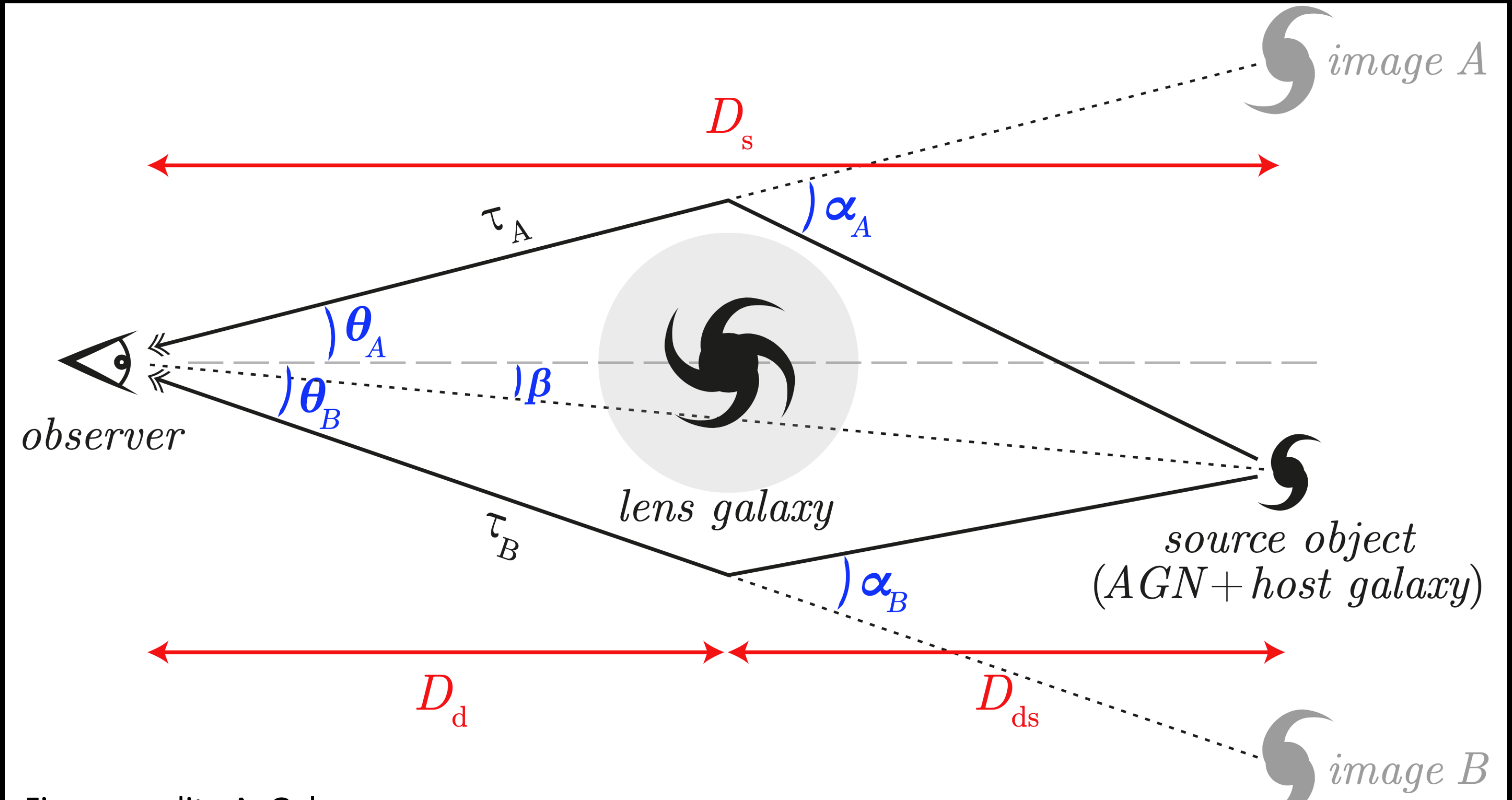


Figure credit : A. Galan

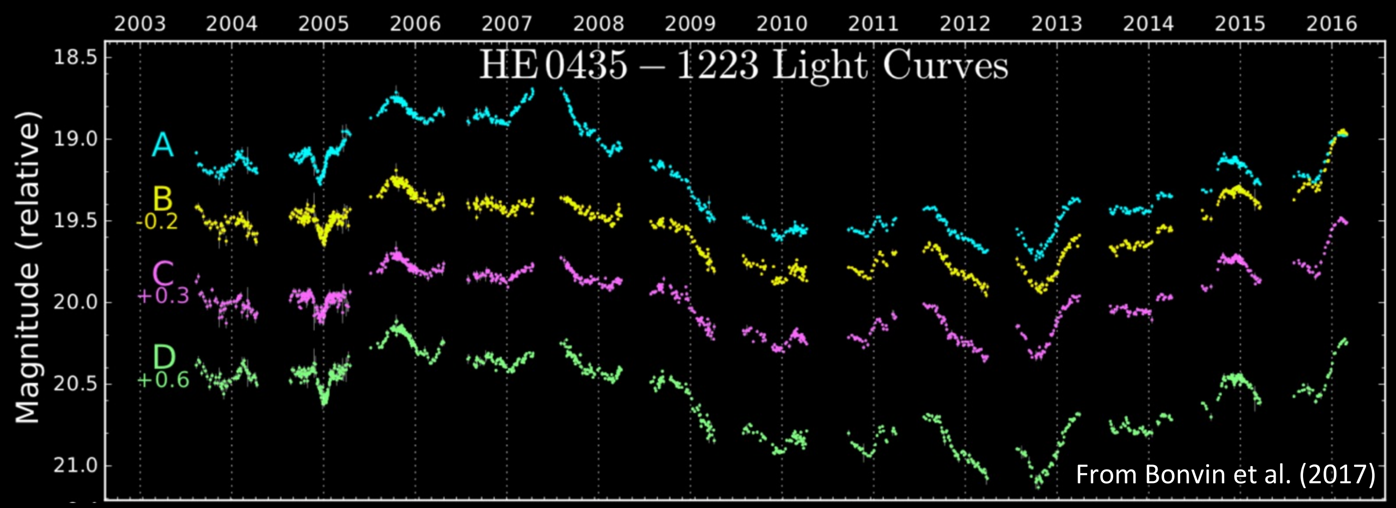
Arrival time :

$$\tau(\vec{\theta},\vec{\beta}) = \frac{D_{\Delta t}}{c}\left[\frac{(\vec{\theta}-\vec{\beta})^2}{2} - \psi(\vec{\theta})\right]$$

$$D_{\Delta t} = (1+z_d)\frac{D_d D_s}{D_{ds}}$$

We need 3 ingredients to infer H_0 :

- Time Delays Measurement
- Lens Modelling
- External Convergence



From long-term monitoring

$$D_{\Delta t} = \frac{c\tau_{AB}}{(1-\kappa_{ext})[\Phi(\theta_A) - \Phi(\theta_B)]}$$

From wide field observation of the lens environment

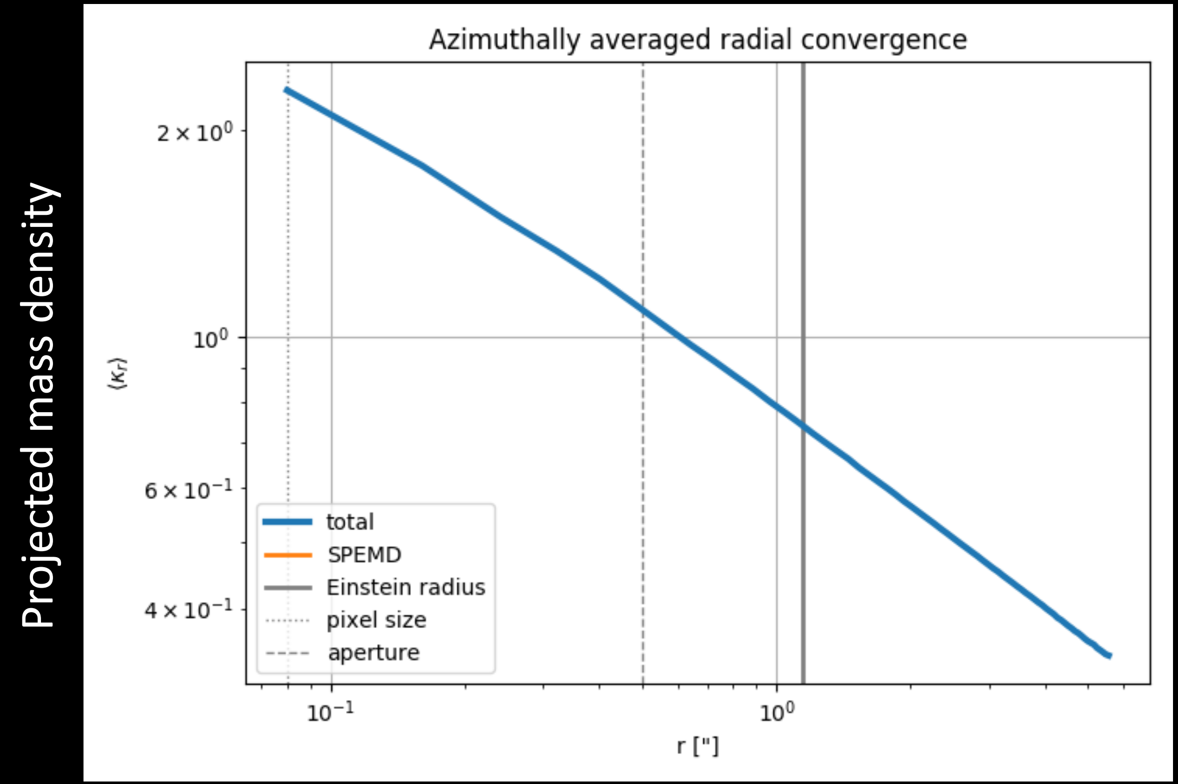
$$H_0^{-1} \propto D_{\Delta t}$$

From high-resolution images and stellar kinematics

H0LiCOW results:

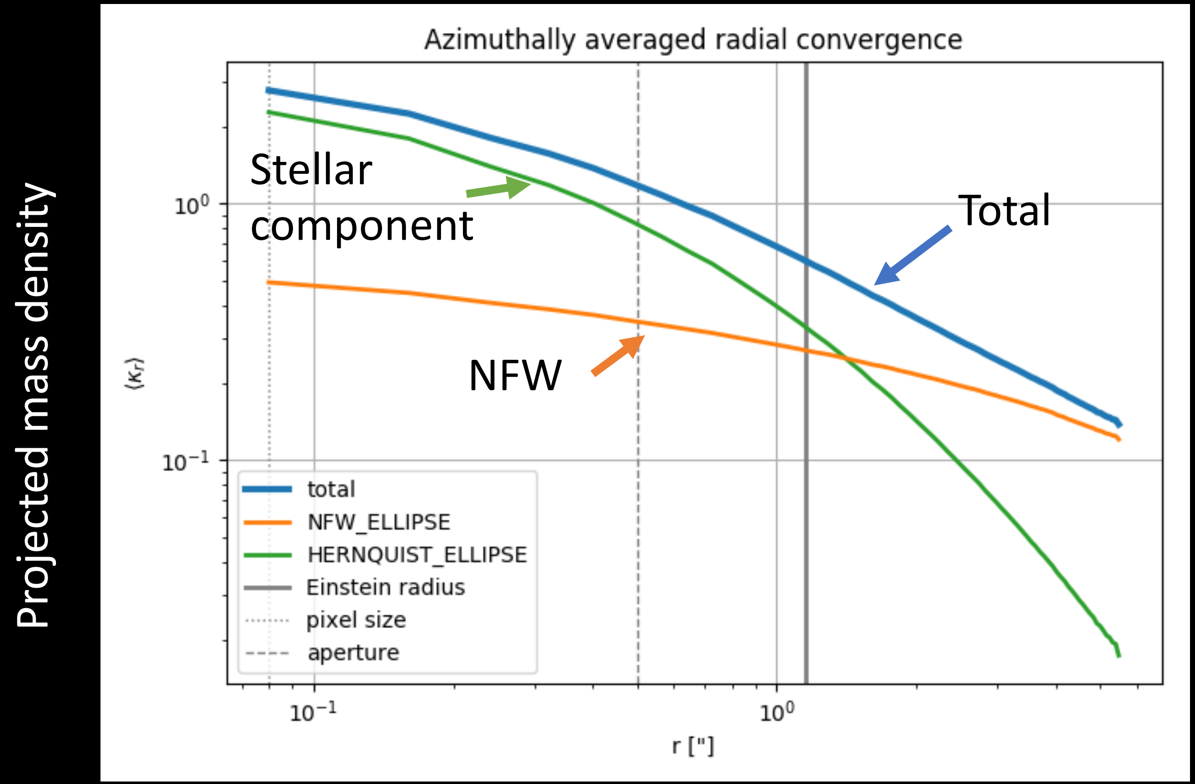
Modeling the lens mass distribution:

Power-law mass model



Radius from the center of the galaxy

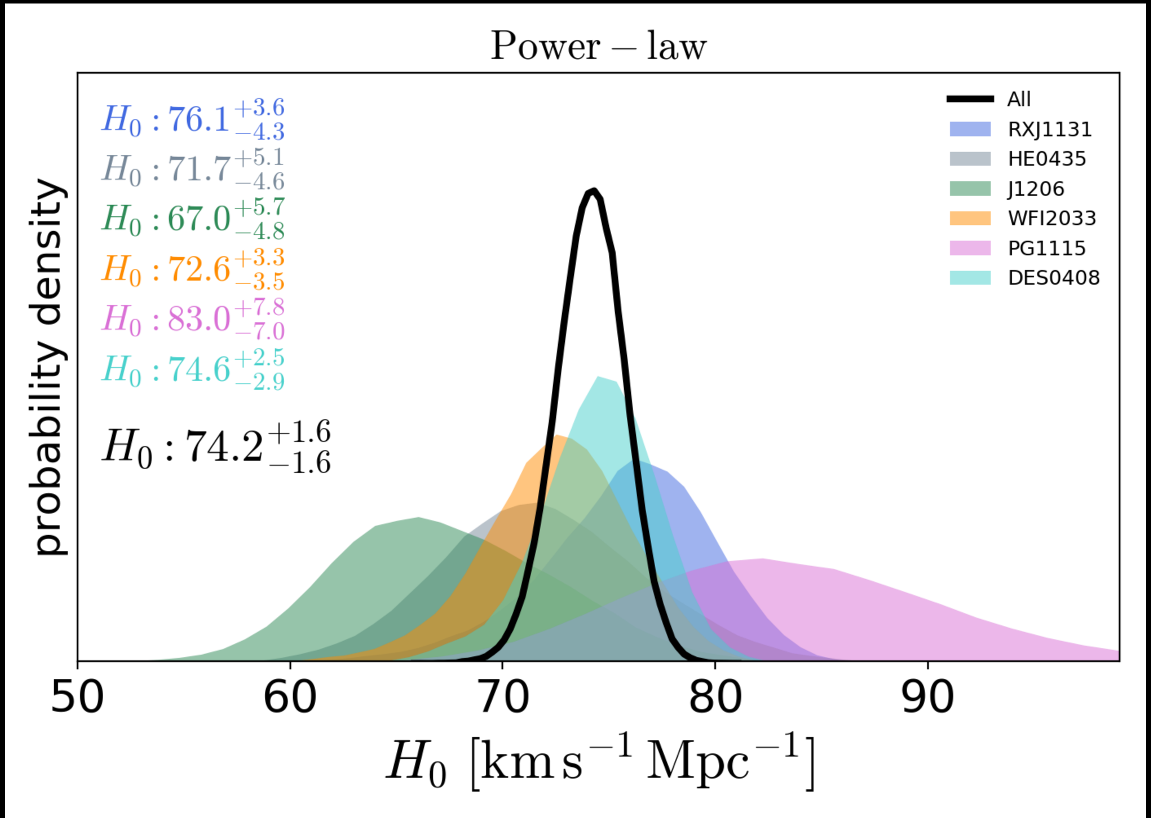
NFW + Stars (Composite) mass model

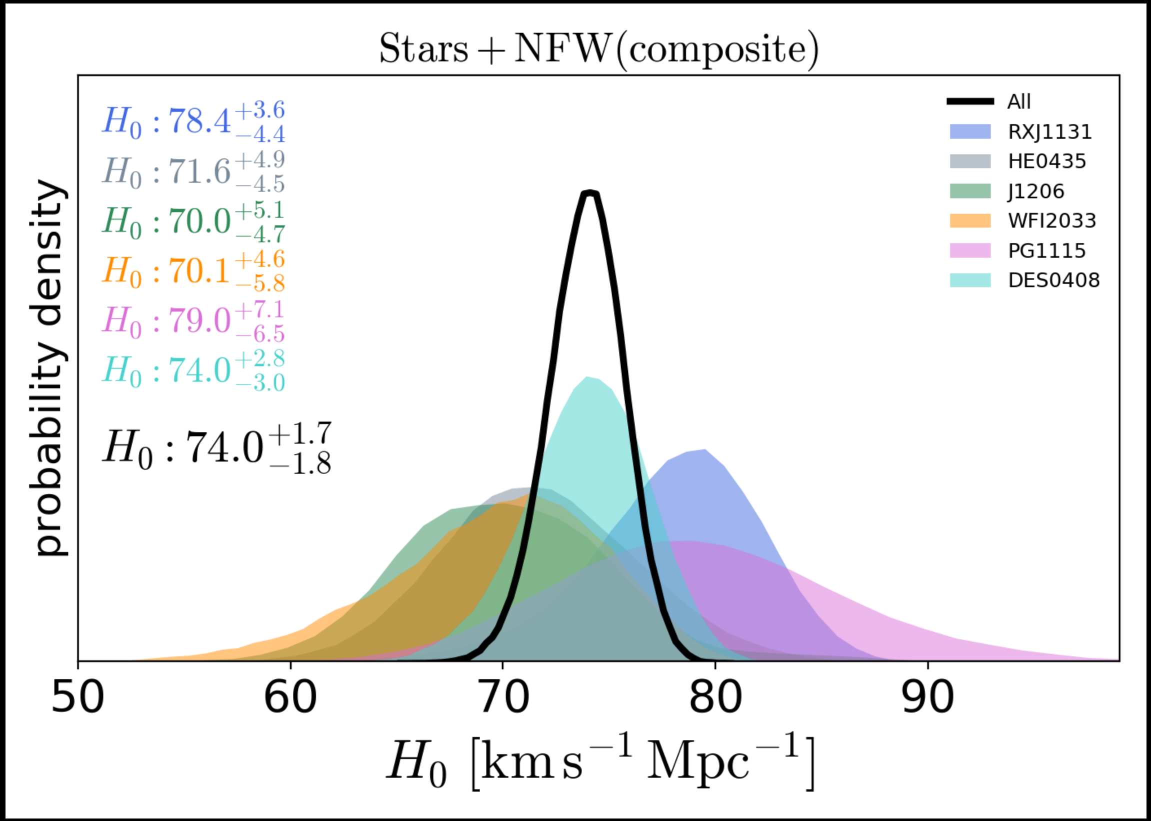


Radius from the center of the galaxy

Constrained with lensing + stellar kinematics

Do the two model families give the same H_0 ?



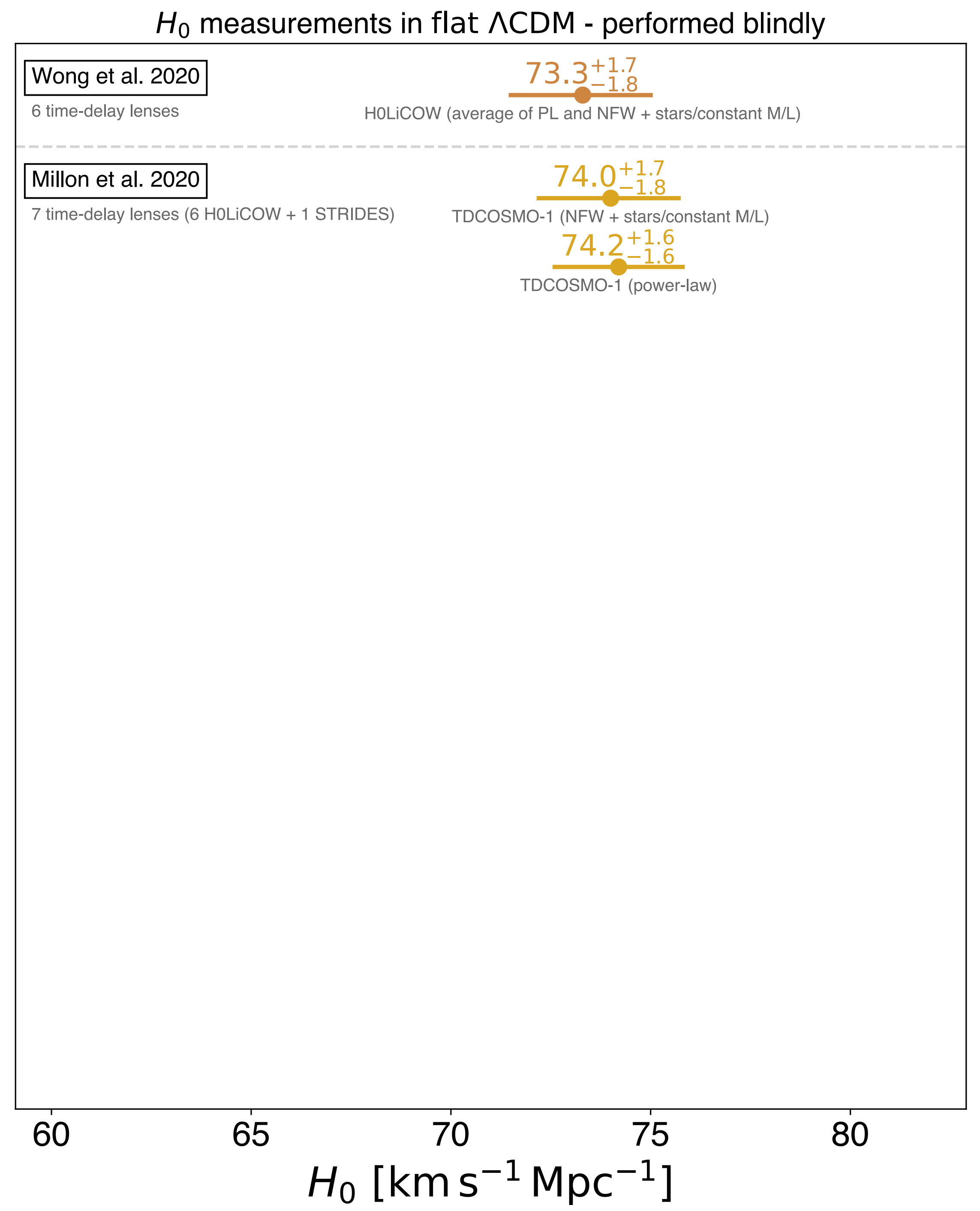


From TDCOSMO I (Millon et al. 2020)

We observe differences for individual lenses
but the combined value does not change.

HOLiCOW results:

TDOCSMO 1 results:



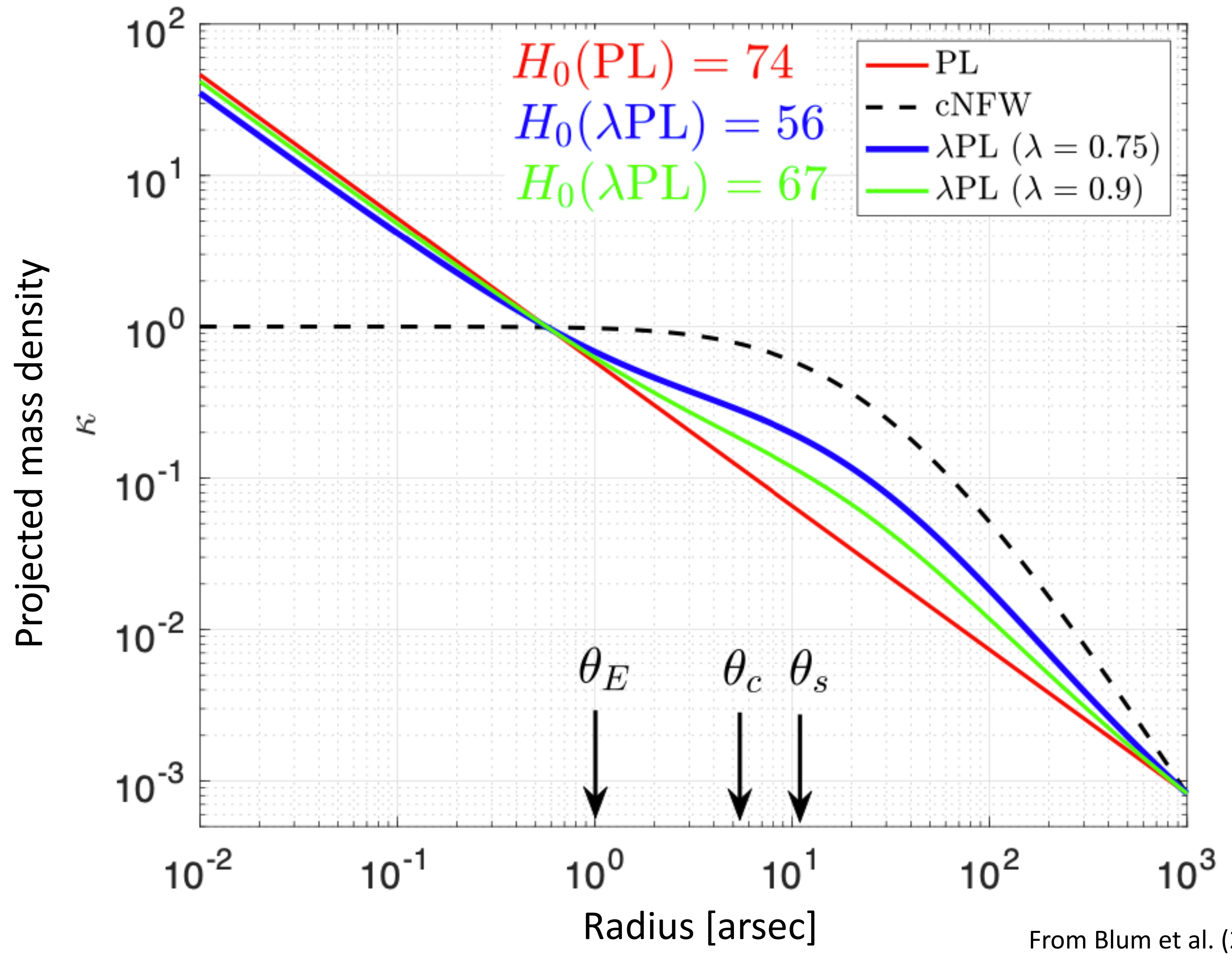
Assertive model assumption

Can we test more general class of model ?

Internal Mass Sheet Degeneracy (MSD) :

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

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



From Blum et al. (2019)

Classical inference (H0LiCOW XIII, Wong et al. 2020)

Classical Bayesian inference:

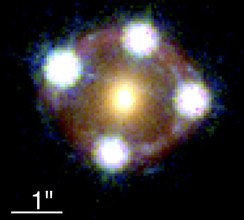
$$P(\boldsymbol{\Omega}|\{\boldsymbol{d}_k\}) \; \alpha \; P(\boldsymbol{\Omega}) \prod_k P(d_k|\boldsymbol{\Omega})$$

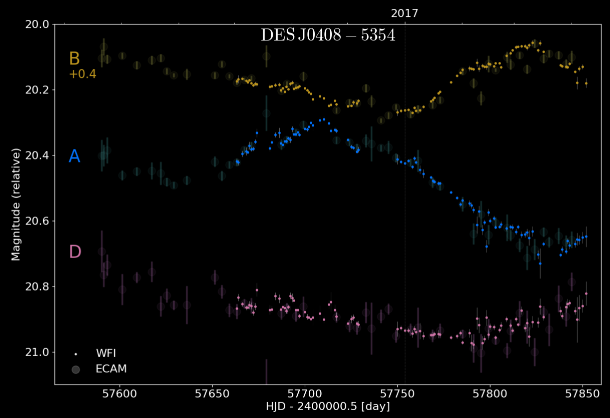
$\boldsymbol{\Omega} = \{H_0$ Ω_m w_0 …$\}$

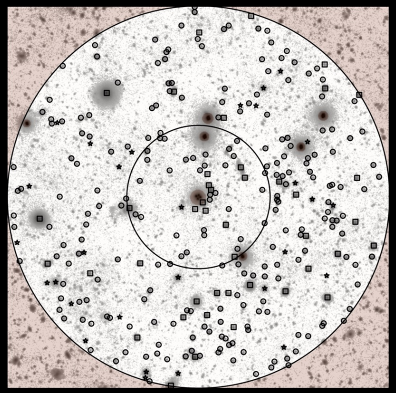
Cosmological parameters

$\{d_k\}$

Data







σ_v

Hierarchical Bayesian inference (TDCOSMO IV, Birrer et al. 2020)

Cosmological parameters

$\boldsymbol{\Omega}$

$\boldsymbol{\nu}$

Hyper-parameters governing the population of lenses

Hierarchical Bayesian inference:

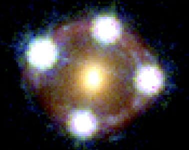
$$P(\boldsymbol{\Omega},\boldsymbol{\nu}\,|\{\boldsymbol{d}_k\}) \propto P(\boldsymbol{\Omega})P(\boldsymbol{\nu}) \prod_k \int P(\boldsymbol{d}_k|\, \xi_k\,)P(\xi_k|\boldsymbol{\Omega},\boldsymbol{\nu}\,)\, d\xi_k$$

$\xi_k = \{\lambda, a_{ani}, \ldots\}$

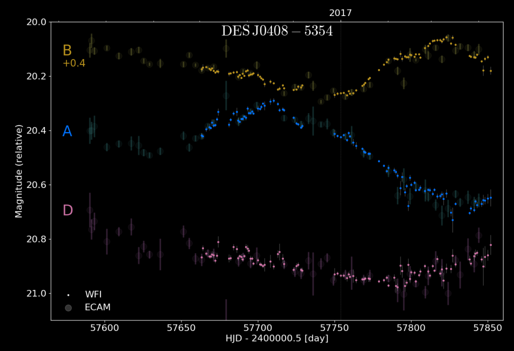
Hierarchically inferred parameters: λ, a_{ani}

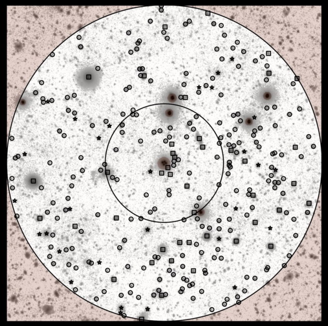
$\{d_k\}$

Data



1"



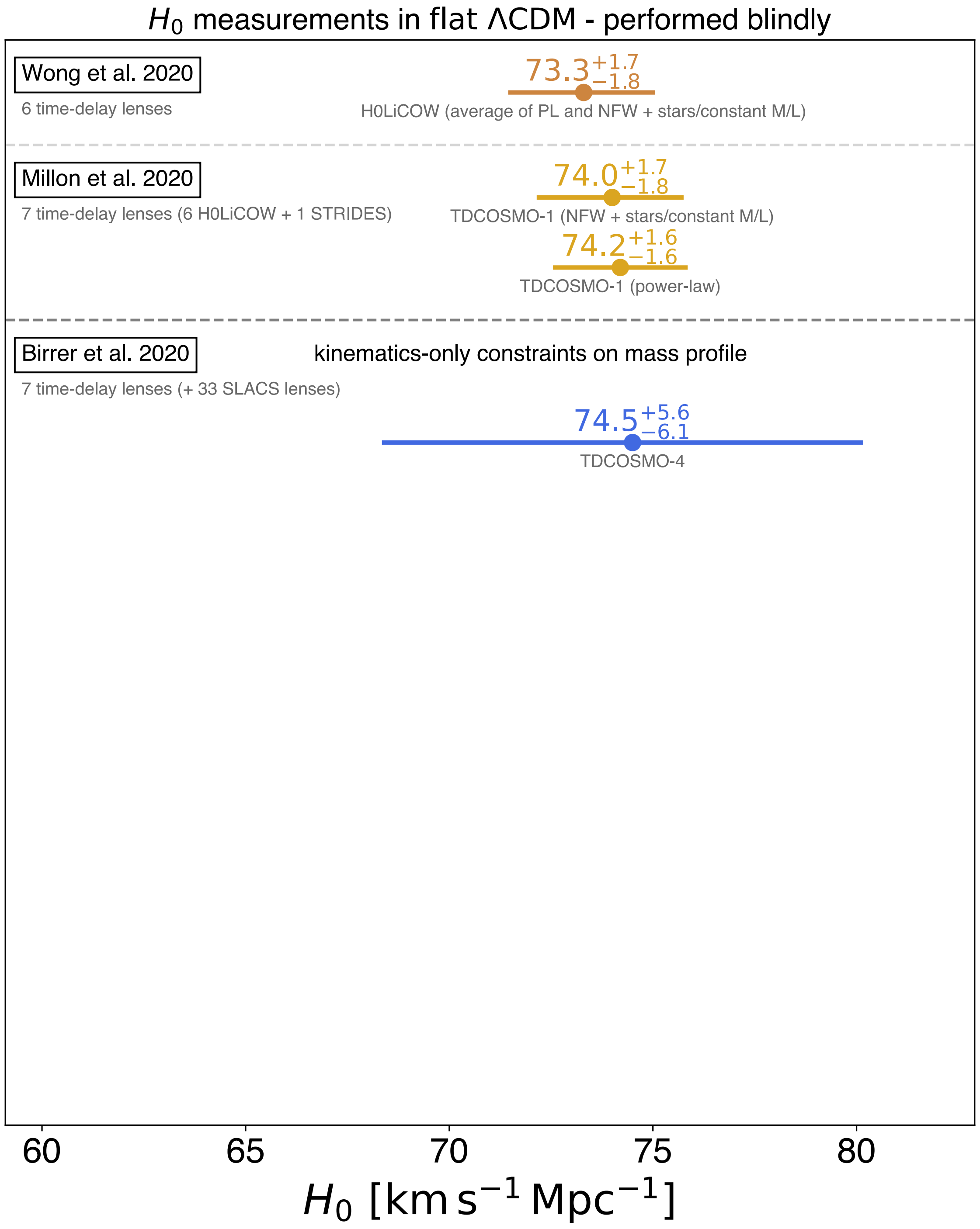


σ_v

HOLiCOW results:

TDOCSMO I results:

TDOCSMO 4 results:



Assertive model assumption

Conservative mass model assumption constrained with kinematic data

Add external SLACS data set :

SLACS: The Sloan Lens ACS Survey www.SLACS.org

A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)

Image credit: A. Bolton, for the SLACS team and NASA/ESA

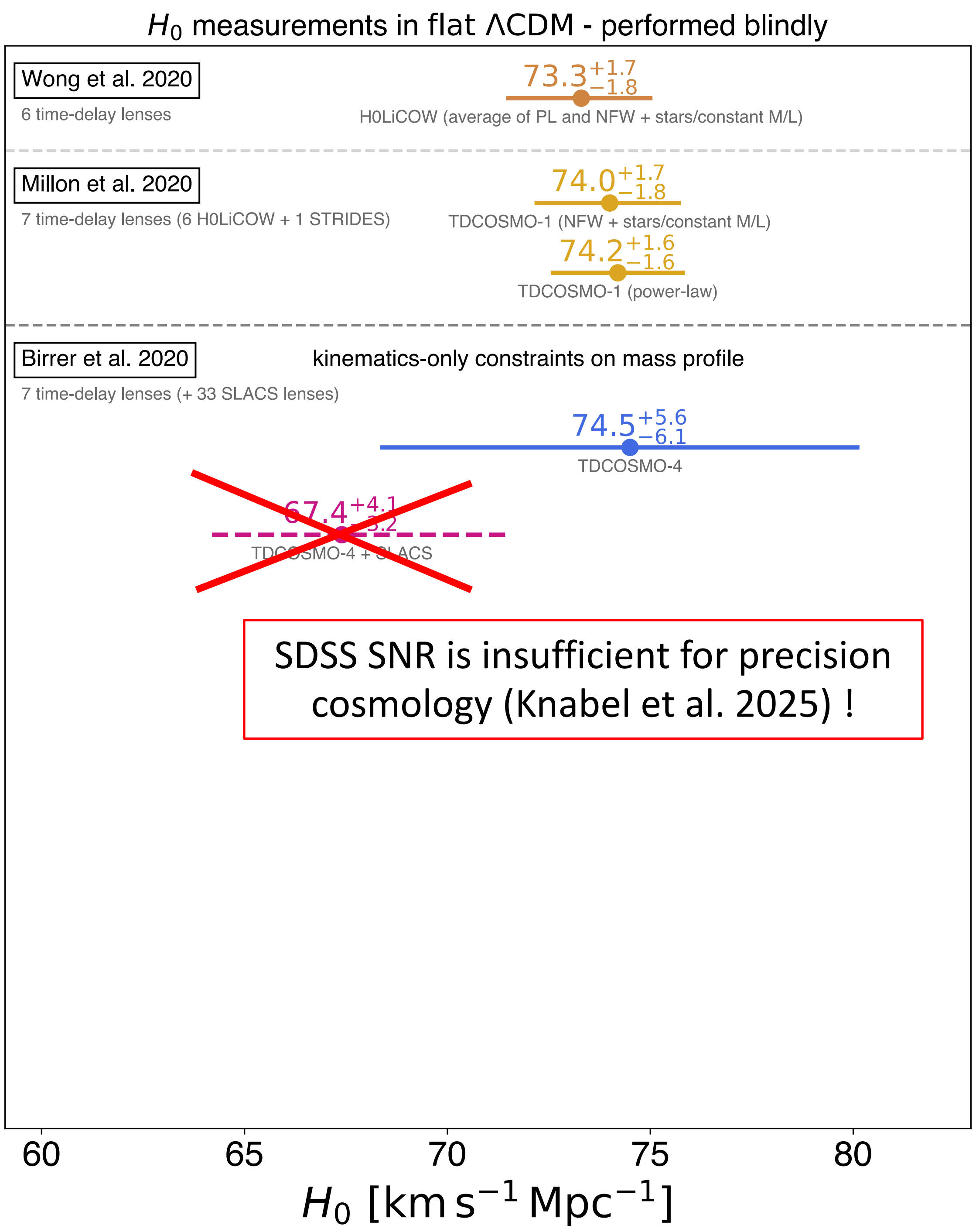
- 33 have aperture velocity dispersion measurement → constraints on the mass density profile

- 9 systems have spatially resolved kinematics → constraints anisotropies properties

H0LiCOW results:

TDOCSMO 1 results:

TDOCSMO 4 results:

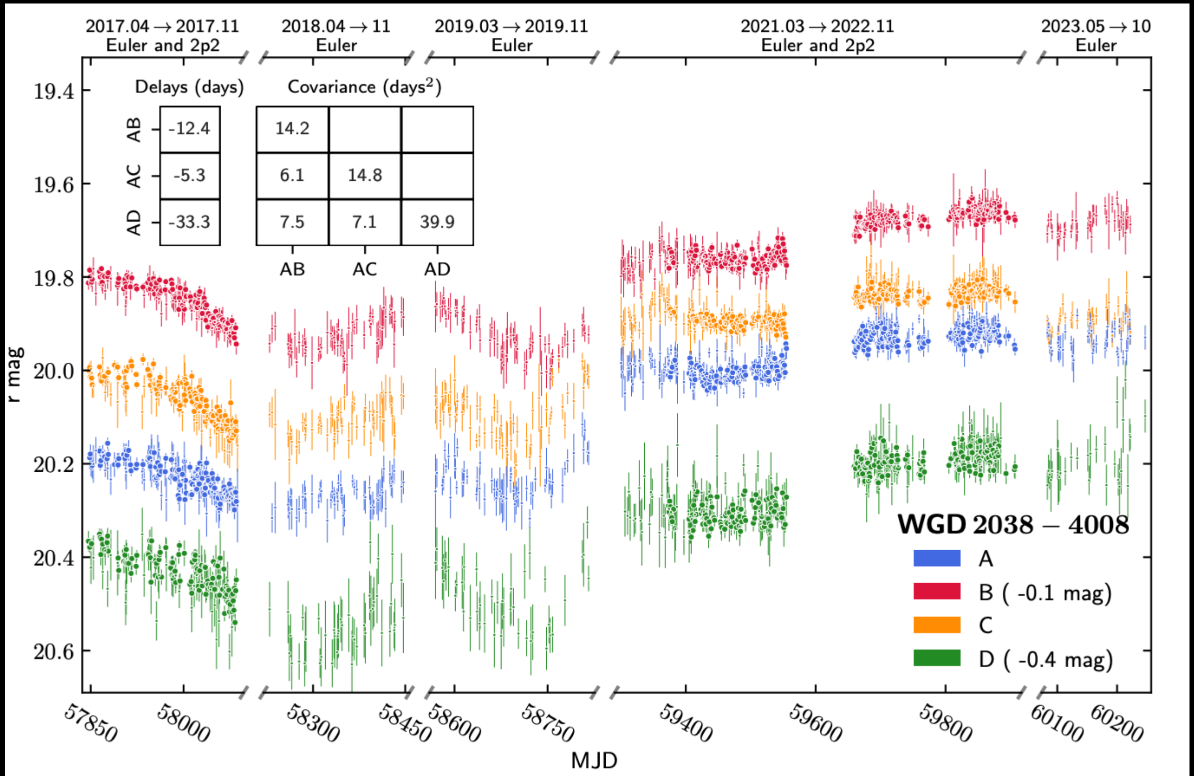


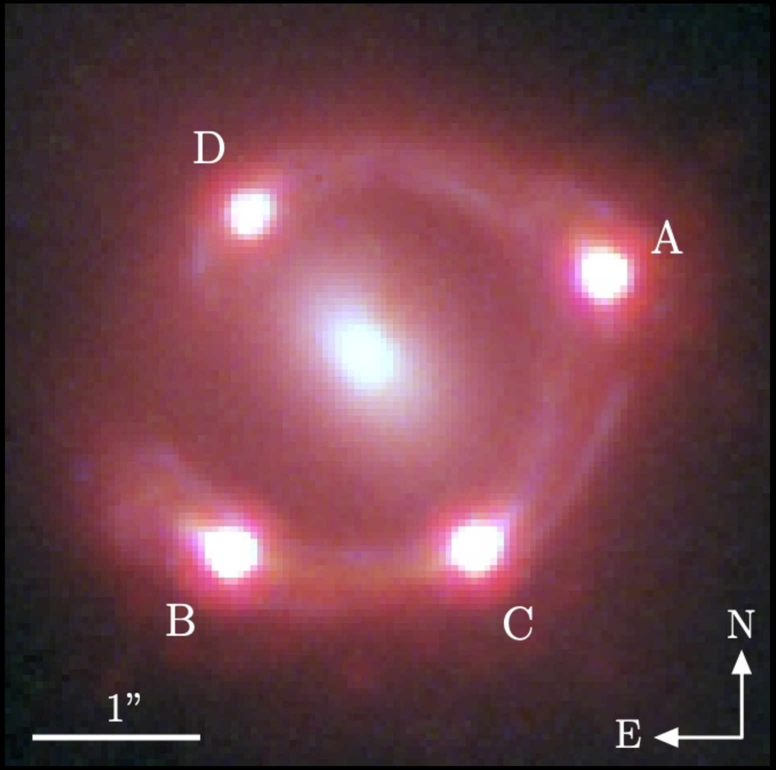
Assertive model assumption

Conservative mass model assumption constrained with kinematic data

What is new in the TDCOSMO-2025 analysis?

- Adding WGD2038-4008

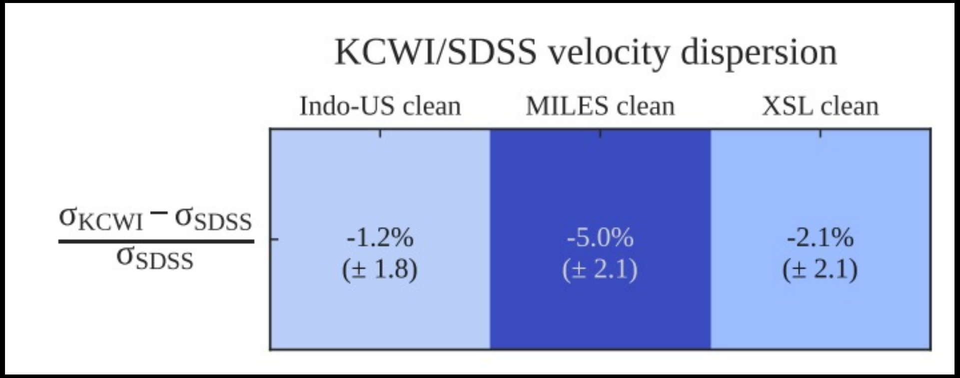




From TDCOSMO XVI, Wong et al. (2024)

What is new in the TDCOSMO-2025 analysis?

- Adding WGD2038-4008
- Improved methods to infer stellar velocity dispersions (Knabel et al. 2025)



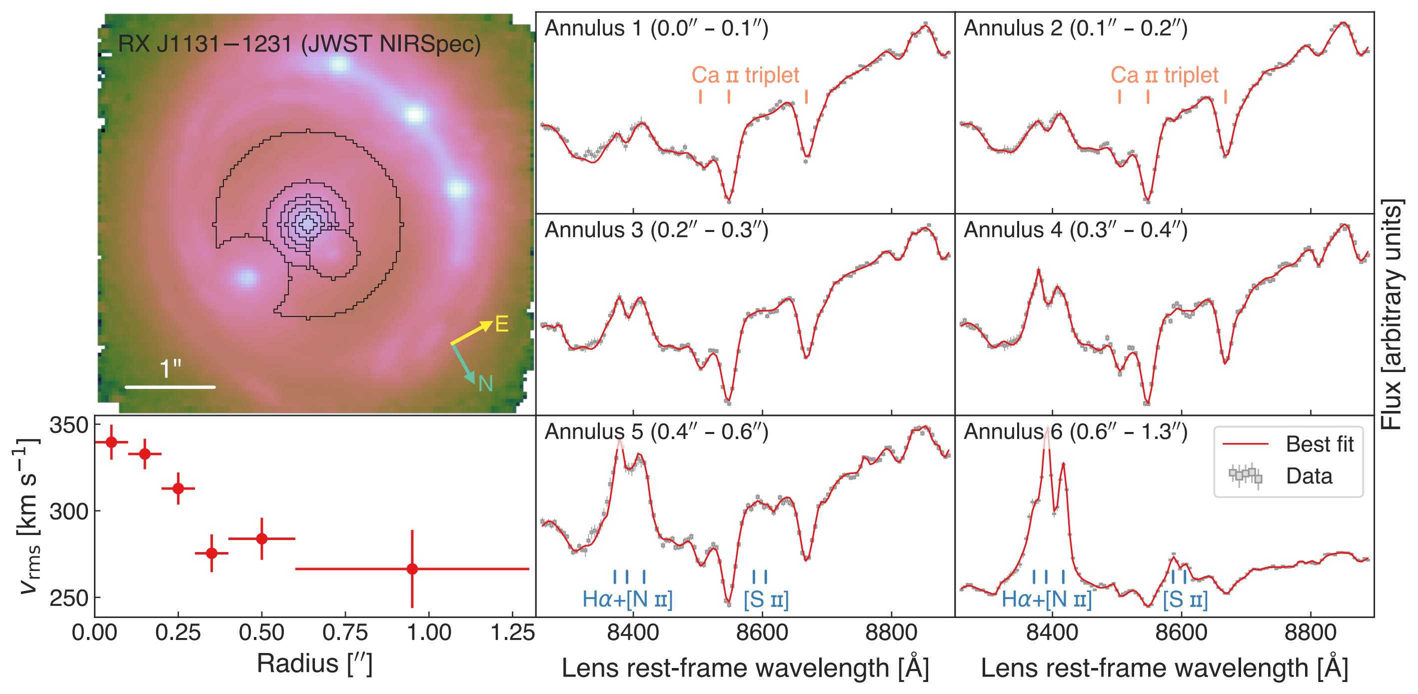
σ_v can be measured at <1% accuracy if:

- SNR > 15 $Å^{-1}$
- "Clean" spectral libraries are used
- Marginalization over different spectral libraries

We have adopted the method from TDCOSMO XIX, Knabel et al (2025) for all our systems !

What is new in the TDCOSMO-2025 analysis?

- Adding WGD2038-4008
- Improved methods to infer stellar velocity dispersions (Knabel et al. 2025)
- New spectroscopic data from JWST/Nirspec, KCWI and VLT/MUSE



From TDCOSMO Collaboration et al. (2025)

What is new in the TDCOSMO-2025 analysis?

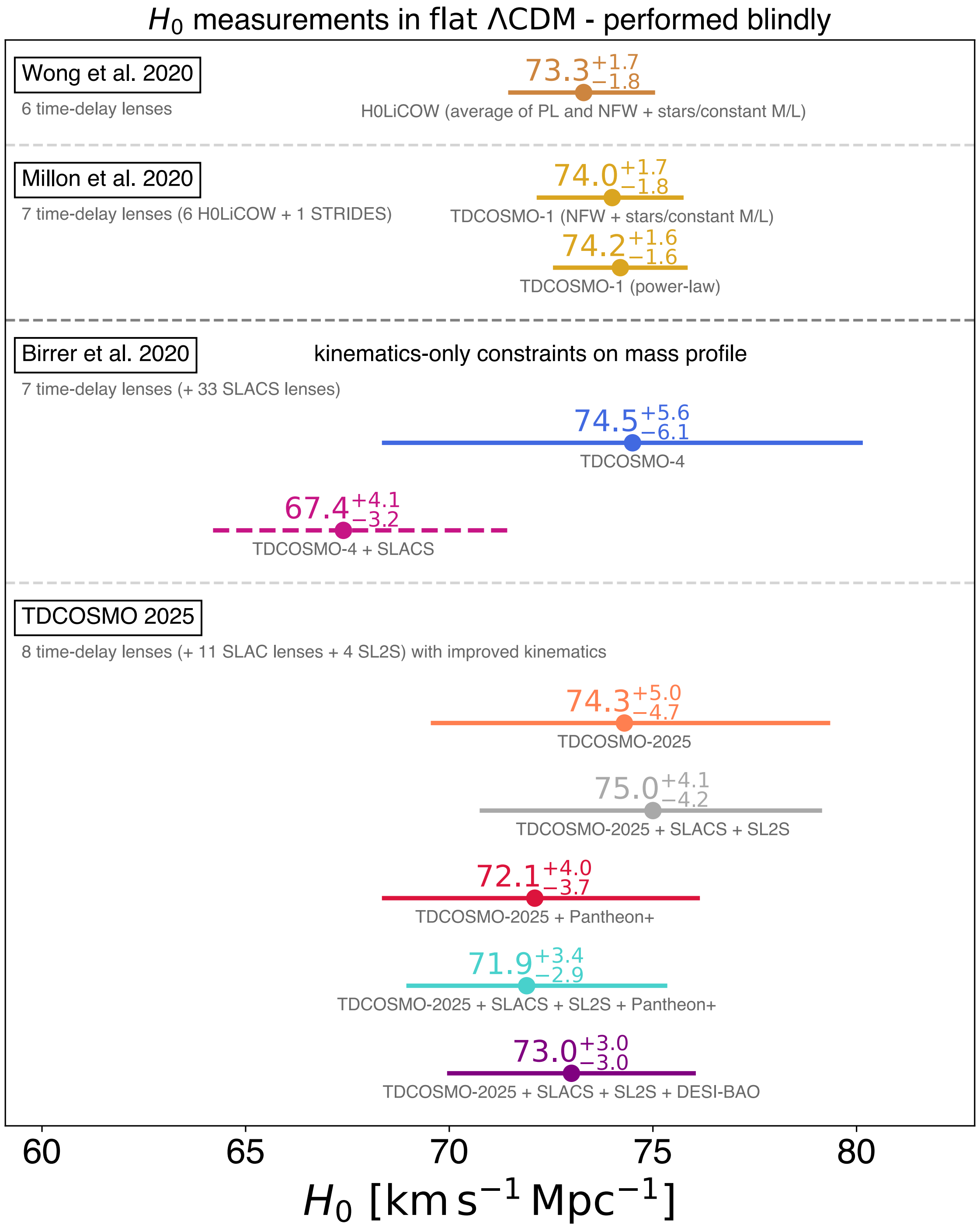
- Adding WGD2038-4008
- Improved methods to infer stellar velocity dispersions (Knabel et al. 2025)
- New spectroscopic data from JWST/Nirspec, KCWI and VLT/MUSE
- Better selection/improved data for the external lenses from SL2S and SLACS
- Correction for a departure from sphericity in the kinematic modelling (Huang et al. 2025)

H0LiCOW results:

TDOCSMO 1 results:

TDOCSMO 4 results:

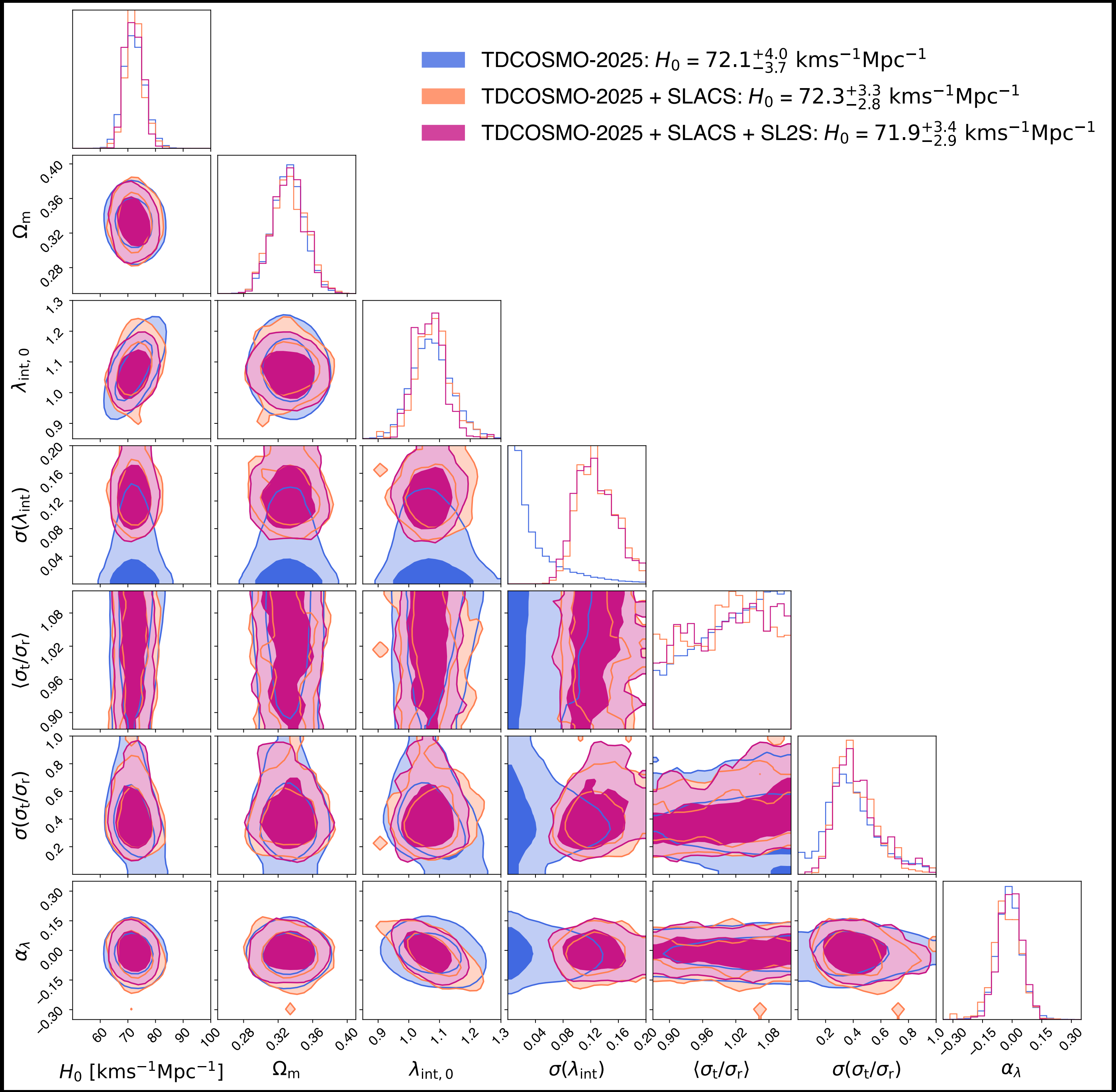
TDOCSMO 2025 results:



Assertive model assumption

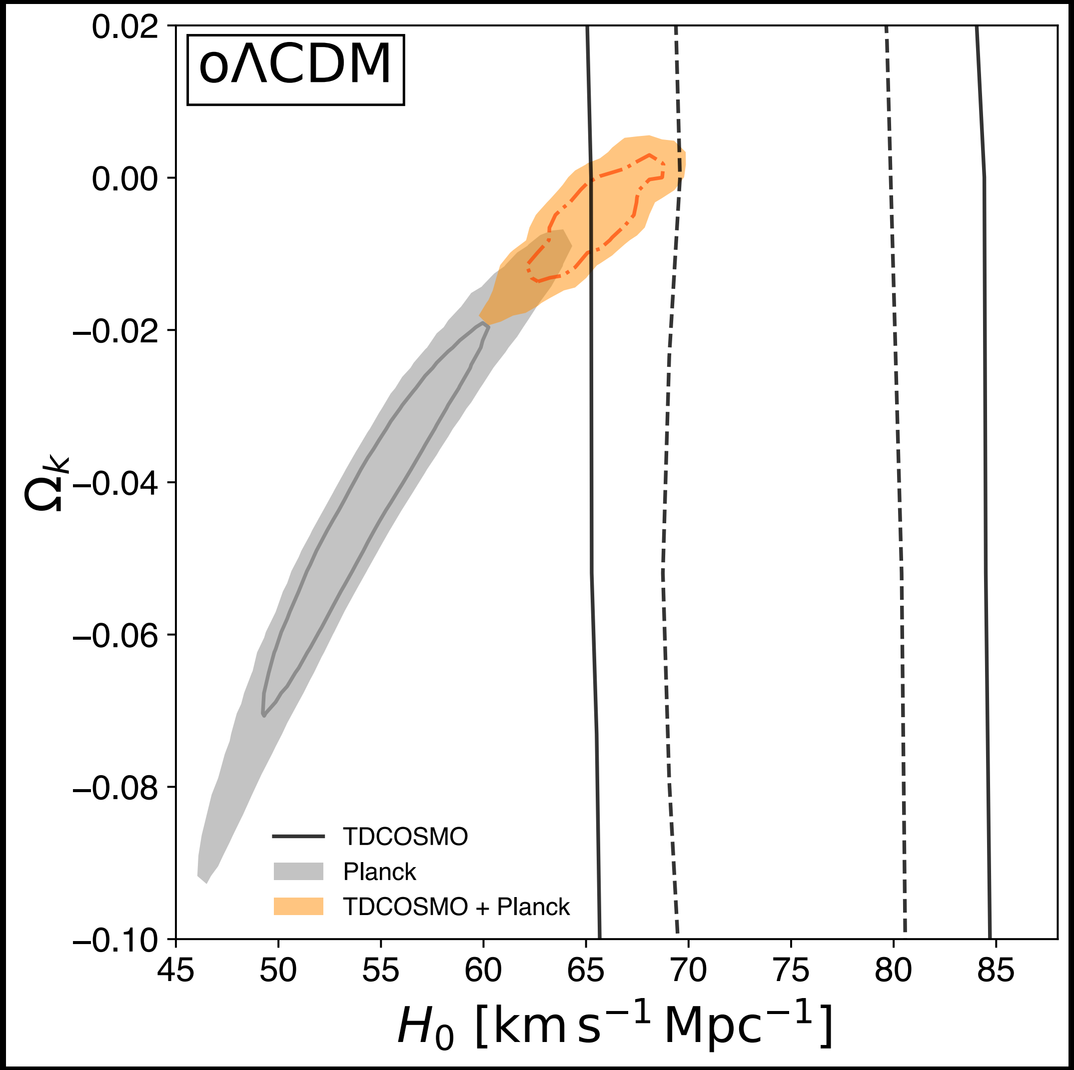
Conservative mass model assumption constrained with kinematic data

TDCOSMO 2025 results in ΛCDM



From TDCOSMO Collaboration et al. (2025)

ΛCDM extensions:



From TDCOSMO Collaboration et al. (2025)

TDCOSMO 2025 only:

$$\Omega_k = -0.021^{+0.328}_{-0.296}$$

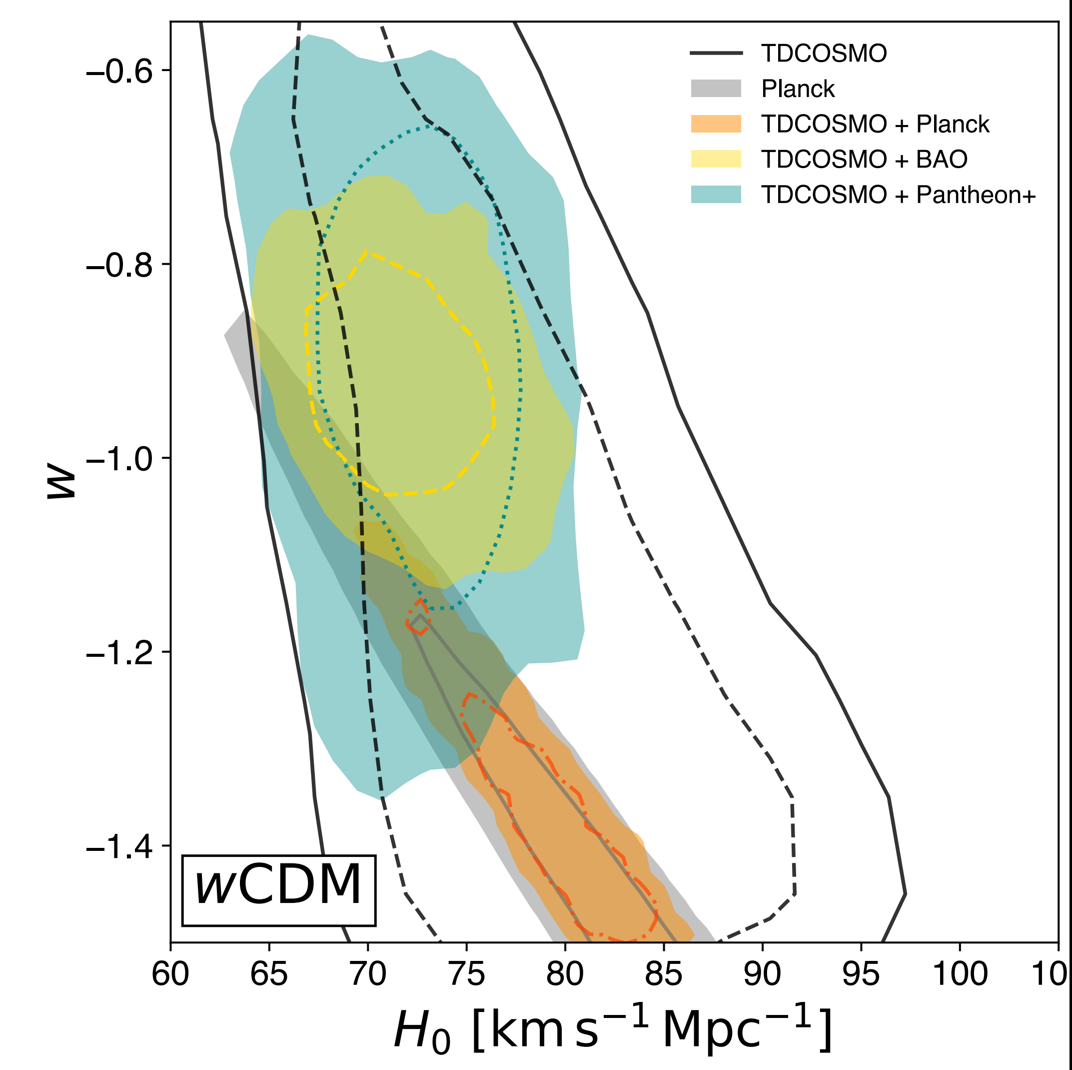
$$H_0 = 74.2^{+4.1}_{-4.6} \text{ km.s}^{-1}\text{.Mpc}^{-1}$$

TDCOSMO 2025 + Planck:

$$\Omega_k = -0.005^{+0.005}_{-0.006}$$

$$H_0 = 65.3^{+1.7}_{-1.9} \text{ km.s}^{-1}\text{.Mpc}^{-1}$$

ΛCDM extensions:



From TDCOSMO Collaboration et al. (2025)

TDCOSMO 2025 only:

$$H_0 = 76.5^{+7.3}_{-7.4}\ \mathrm{km.s^{-1}.Mpc^{-1}}$$
$$w = -1.16^{+0.49}_{-0.25}$$

TDCOSMO 2025 + Planck:

$$H_0 = 79.3^{+3.1}_{-4.1}\ \mathrm{km.s^{-1}.Mpc^{-1}}$$
$$w = -1.37^{+0.13}_{-0.09}$$

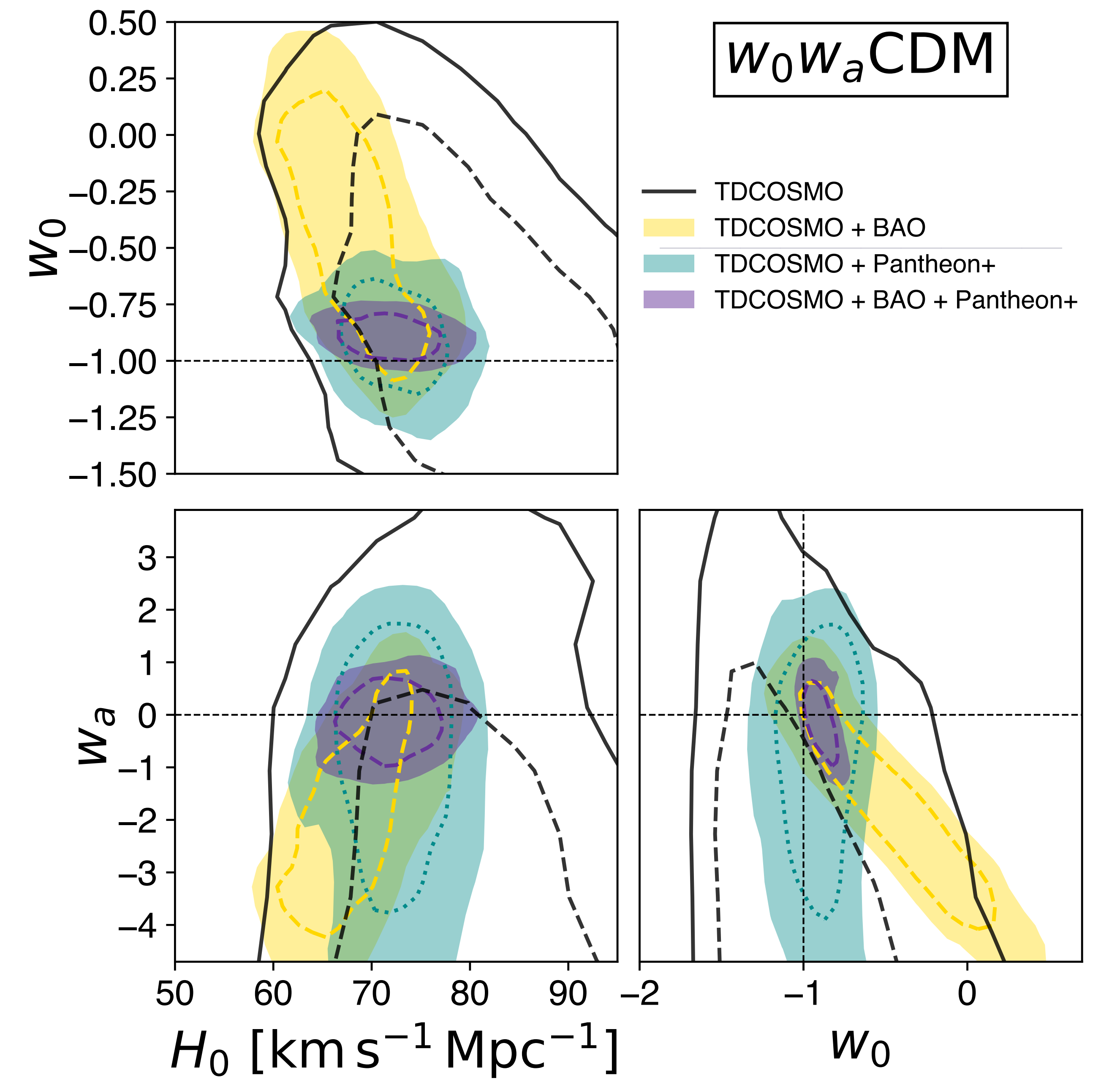
TDCOSMO 2025 +DESI-BAO:

$$H_0 = 71.8^{+3.0}_{-3.2}\ \mathrm{km.s^{-1}.Mpc^{-1}}$$
$$w = -0.93^{+0.08}_{-0.06}$$

ΛCDM extensions:

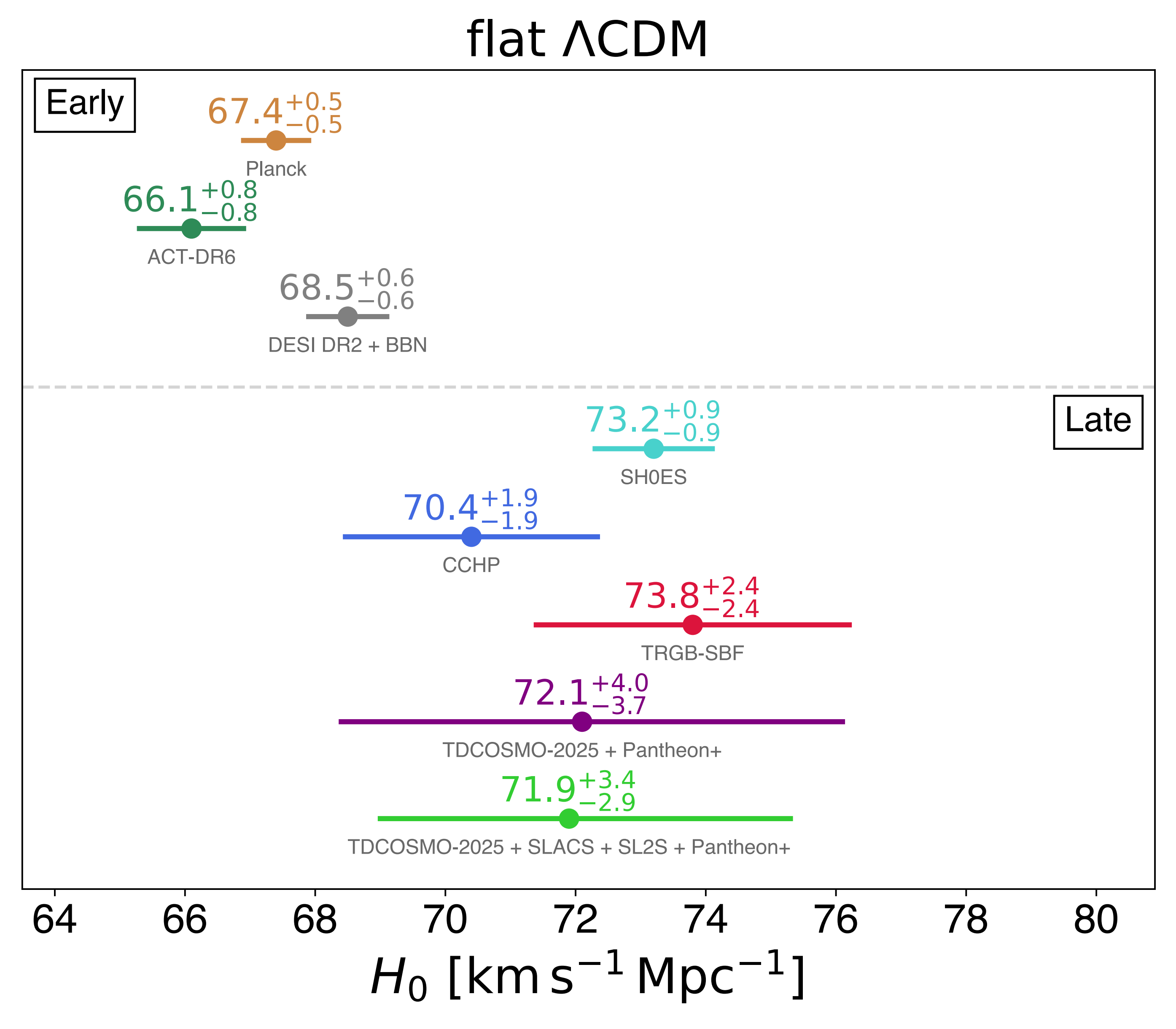
TDCOSMO 2025 + DESI-BAO + Pantheon+:

$$H_0 = 72.0^{+3.2}_{-3.2}\ \mathrm{km.s^{-1}.Mpc^{-1}}$$
$$w_0 = -0.90^{+0.07}_{-0.06}$$
$$w_a = -0.11^{+0.47}_{-0.49}$$



From TDCOSMO Collaboration et al. (2025)

Hubble Tension:



From TDCOSMO Collaboration et al. (2025)