H_0 Measurement by Gravitational Lens Time Delays

Presented by: WeiLeong Tee
Date: 11/24/2020

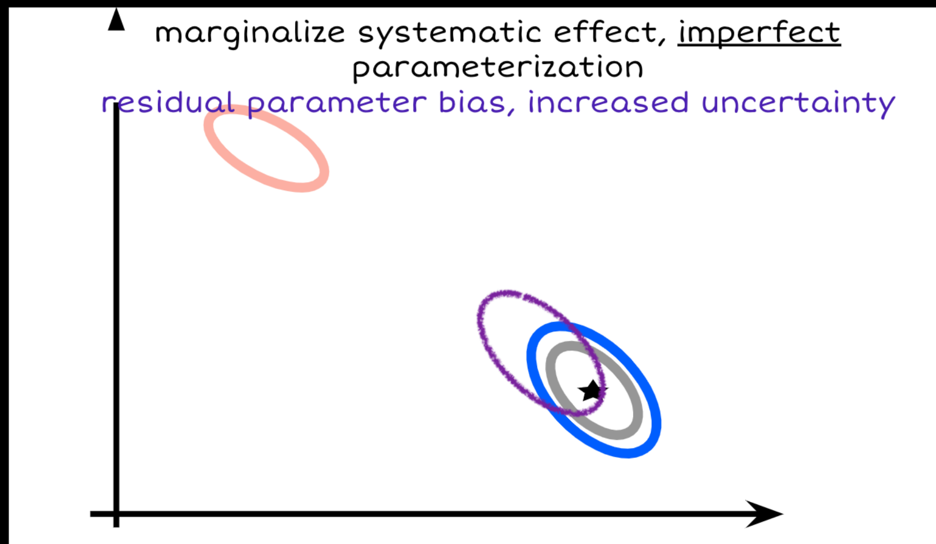
Outline

- Understand the idea of gravitational time-delayed cosmography
- Information needed & explore possible systematic errors
- Comparison between different H_0 measurements

Ways to Measure Cosmological Distance

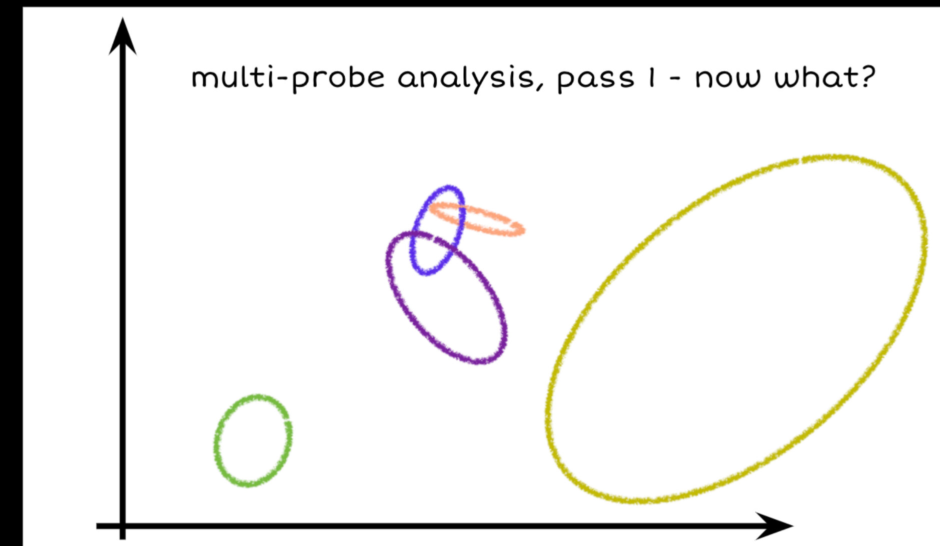
- Luminosity:
  - Type Ia supernovae + Periods of Cepheid variable stars in local galaxies: SN is standard candles, and calibrated by Cepheid to infer distance
- Geometry:
  - Baryon Acoustic Oscillations in the galaxy clustering power spectrum + Fluctuations in the Cosmic Microwave Background radiation
  - Gravitational lens time delays

The Trouble with Systematics

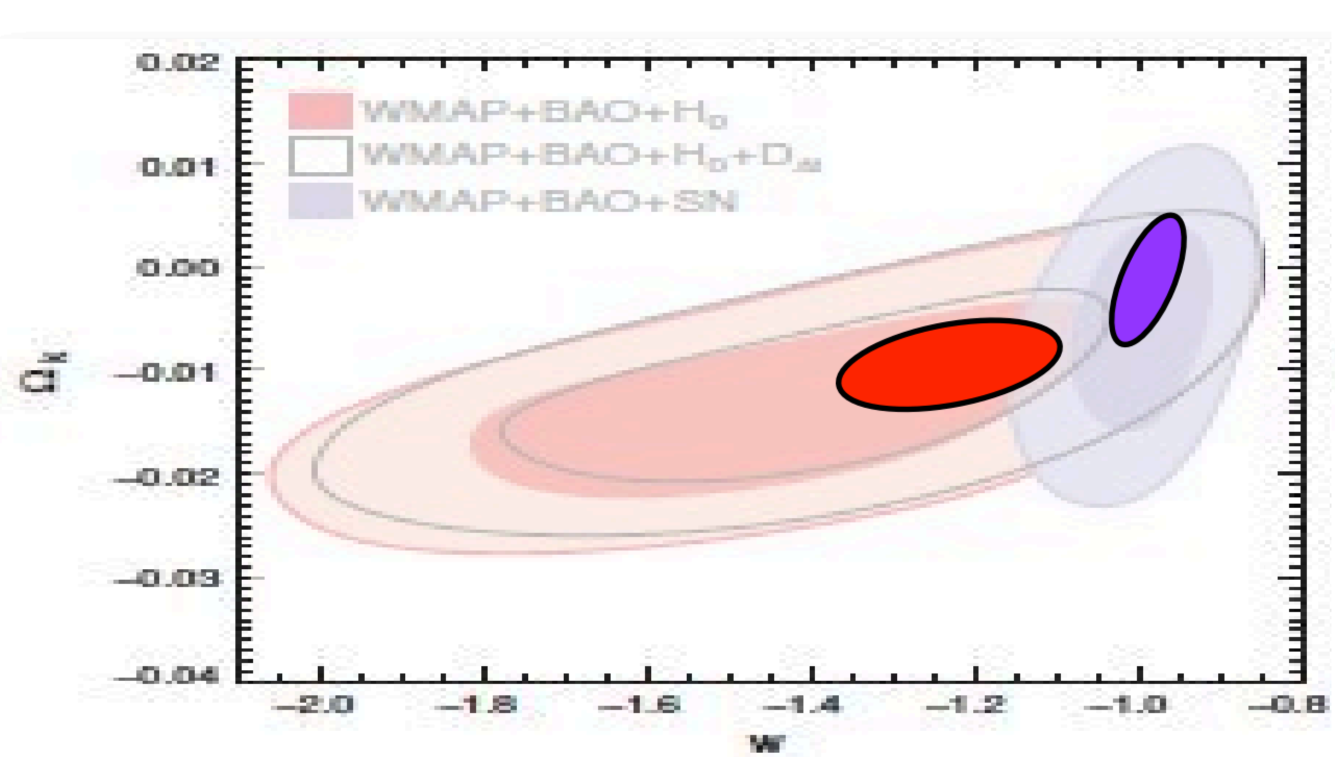


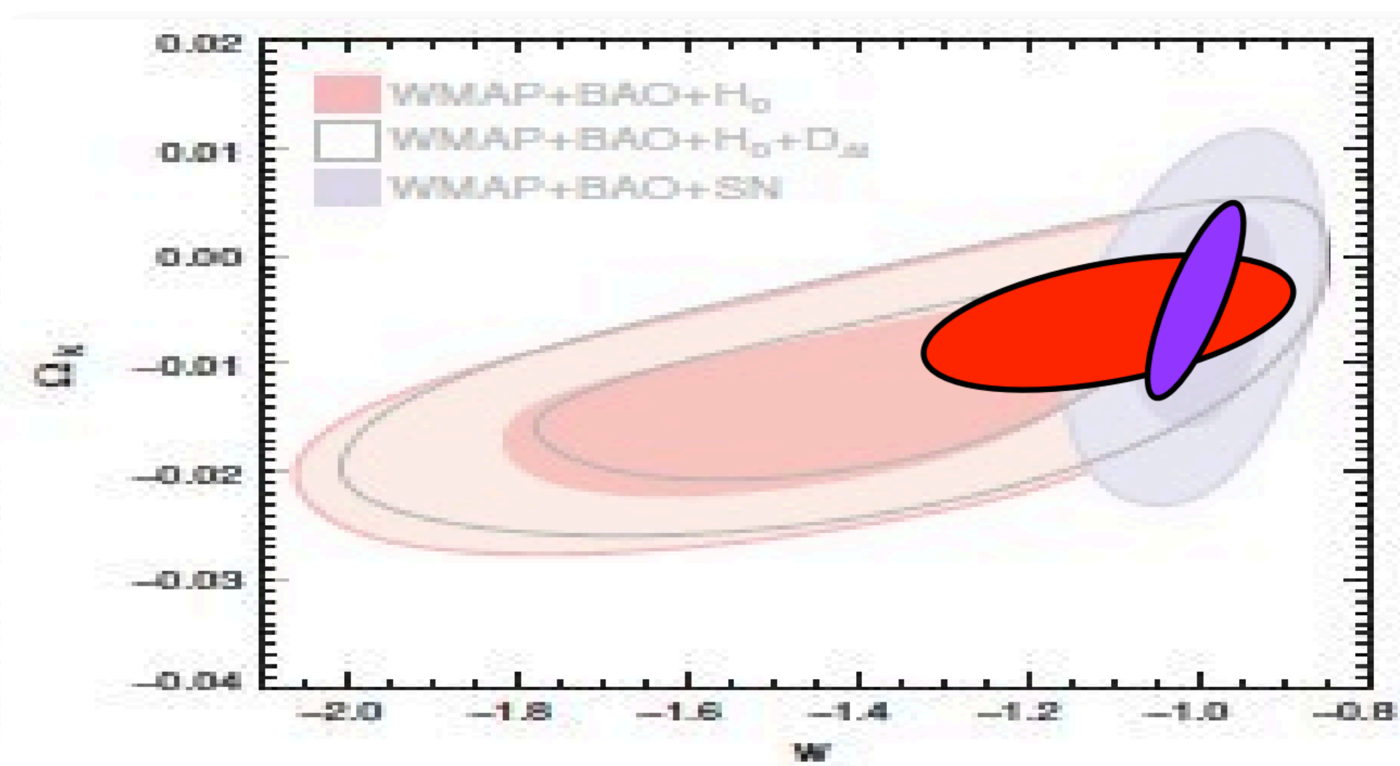
imperfect IA mitigation examples: Krause,TE, Blazek16

Unknown Systematics? vs. New Physics?

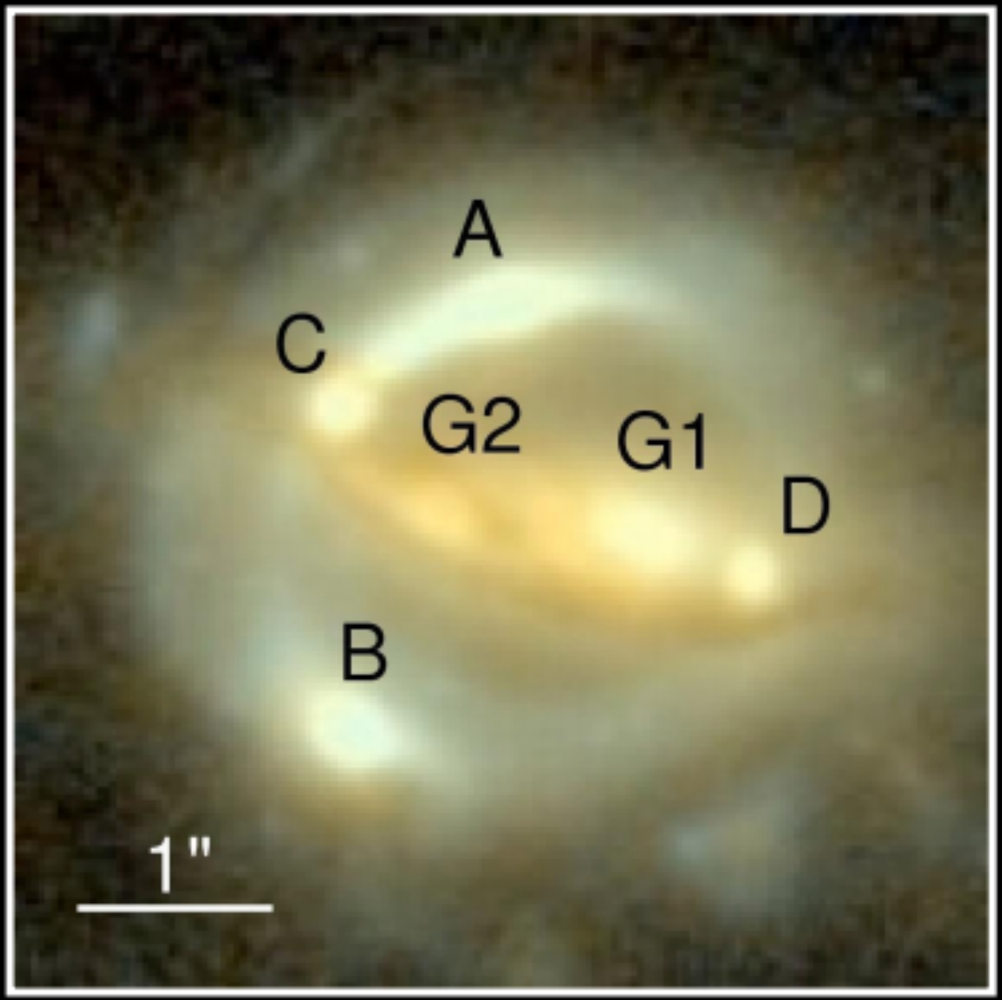


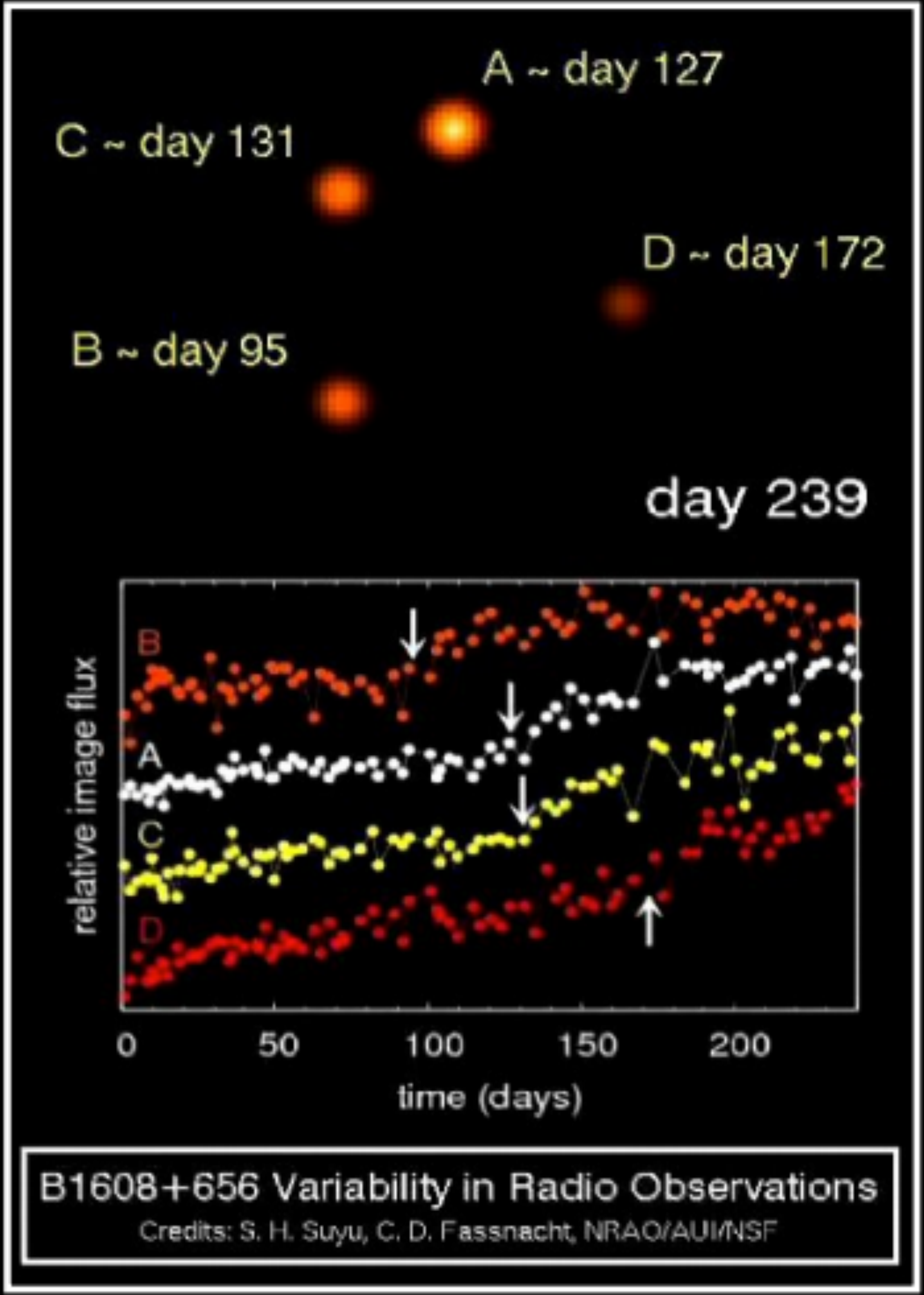
With multiple independent datasets, all have roughly competitive precision in at least one parameter.





Principles of Gravitational Lens Time Delays





Point like, variable source: QSO, AGN
Different path lengths, different travel times

Time Delay Cosmography

- Time delay distance: $D_{\Delta t} \equiv (1 + z_d)\dfrac{D_d D_s}{D_{ds}}$

- Time delay: $\Delta t_{AB} = \dfrac{D_{\Delta t}}{c}\Delta\phi_{AB}$

  $\Delta\phi_{AB}$: Difference of Fermat potentials related to lens mass distribution

- $\phi(\theta) \equiv \dfrac{(\theta - \beta)^2}{2} - \psi(\theta)$

  θ : Image position

  β : (unobservable) source position

  ψ : lensing potential

Deflection angle:

$\alpha(\theta) \equiv \nabla\psi(\theta)$

Convergence:

$\kappa(\theta) = \dfrac{1}{2}\nabla^2\psi(\theta)$

Time Delay Cosmography

- Time delay distance: $\boxed{D_{\Delta t}} \equiv (1+z_d)\frac{D_d D_s}{D_{ds}} \propto H_0^{-1}$

measurements

- Time delay: $\boxed{\Delta t_{AB}} = \frac{D_{\Delta t}}{c}\boxed{\Delta\phi_{AB}}$ lens modelling

  $\Delta\phi_{AB}$: Difference of Fermat potentials related to lens mass distribution

- $\phi(\theta) \equiv \frac{(\theta-\beta)^2}{2} - \psi(\theta)$

  θ : Image position

  β : (unobservable) source position

  ψ : lensing potential

Deflection angle:

$\alpha(\theta) \equiv \nabla\psi(\theta)$

Convergence:

$\kappa(\theta) = \frac{1}{2}\nabla^2\psi(\theta)$

Information Needed

Observations

- Imaging
- Spec z_d & z_s
- Time delays of multiple quasar images
- Lensed arcs
- Lens galaxy stellar kinematics
- Lens environment/LOS

Observational constraints

Modelling

Modelling Systematics

Lens Mass Model +

- Source position
- Intensity
- Source surface brightness distribution

Blind likelihood analysis on all cosmological parameters and distances

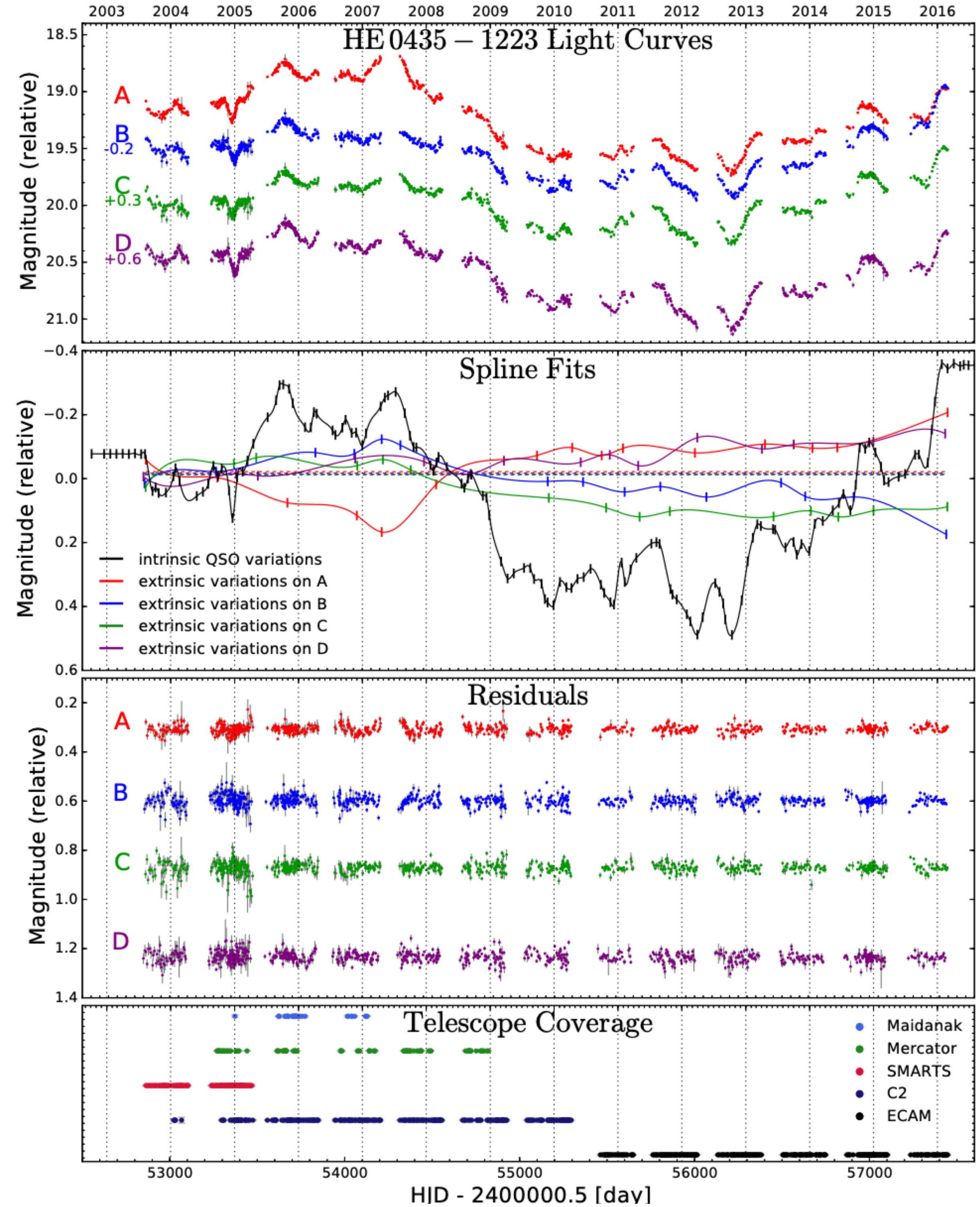
Best cosmological parameters set

Observations

- Imaging
- Spec z_d & z_s
- Time delays of multiple quasar images
- Lensed arcs
- Lens galaxy stellar kinematics
- Lens environment/LOS

Observational constraints

H0LiCOW Lens Samples



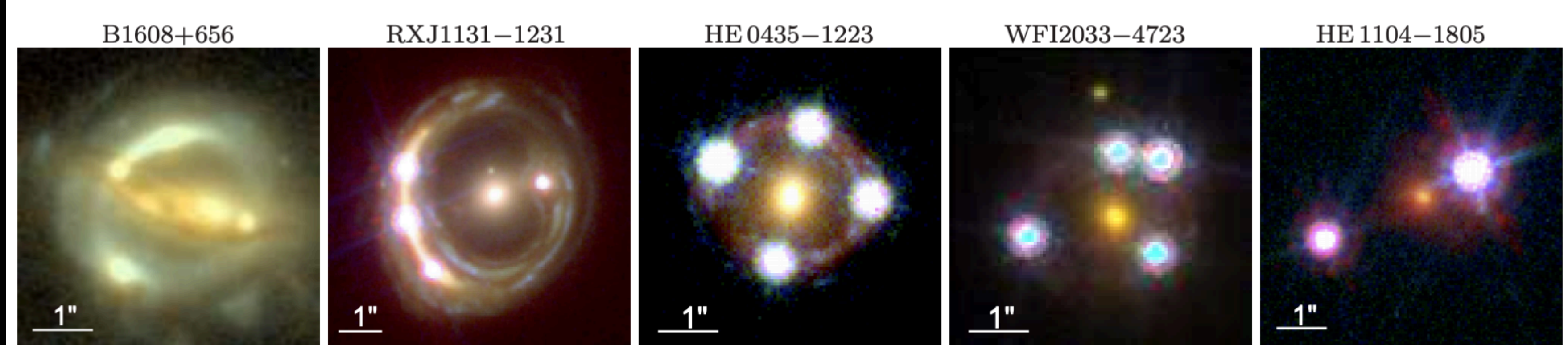


Figure 1. H0LiCOW lens sample, consisting of four quadruply lensed quasar systems in various configurations and one doubly lensed quasar system. The lens name is indicated above each panel. The color images are composed using 2 (for B1608+656) or 3 (for other lenses) *HST* imaging bands in the optical and near-infrared. North is up and east is left.

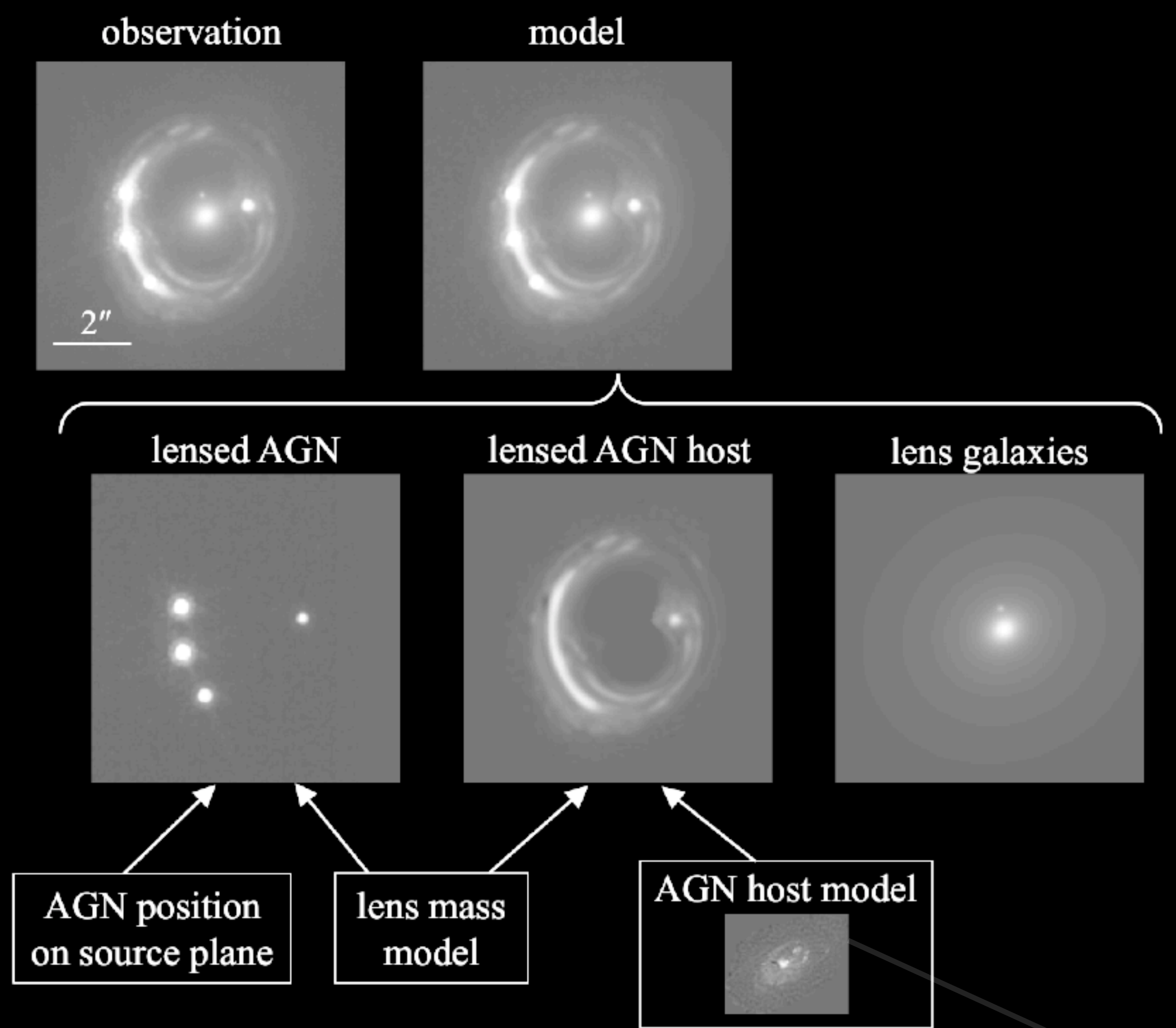


Fig. 3 Illustration of lens mass modeling of the gravitational lens RXJ1131−1231. Top left is the observed *HST* image. Top middle panel is the modeled surface brightness of the lens system, which is composed of three components shown in the second row: lensed AGN images (left), lensed AGN host galaxy (middle), and foreground lens galaxies (right). The bottom row shows that a mass model is required together with the AGN source position and AGN host galaxy surface brightness, to model the lensed AGN and lensed AGN host images. See the text and Suyu et al [2013, 2014] for more details.

Modelling

Modelling Systematics

Lens Mass Model +

- Source position
- Intensity
- Source surface brightness distribution

- Degeneracy of radial profile slope of lens galaxy with $D_{\Delta t}$
- Lens arcs provides information on lens mass distribution (Require high precision cosmography)
- Mass-sheet degeneracy

Mass-sheet Degeneracy

Convergence:

$$\kappa(\theta) = \frac{1}{2}\nabla^2\psi(\theta)$$

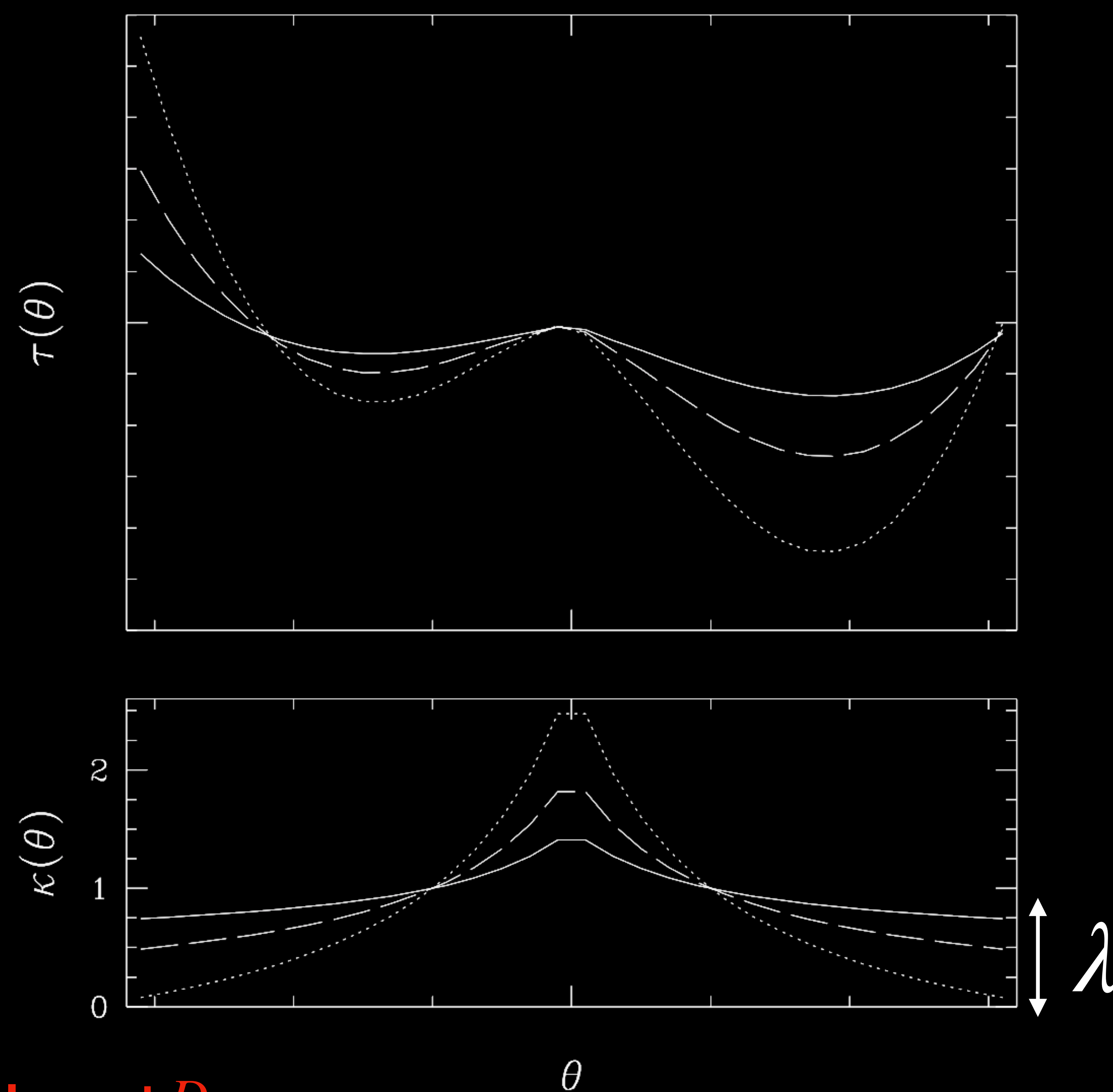
$$\kappa_\lambda = \lambda + (1-\lambda)\kappa$$

- **Adding extra "mass-sheet" and rescale with $1-\lambda$ gives same mass within Einstein radius**
- **Observed image morphology and brightness invariant under shifting the background source coordinate by $1-\lambda$**

$$\phi_\lambda(\theta;\beta) = (1-\lambda)\phi(\theta;\beta) + f(\beta)$$

$$\Delta t_\lambda(\theta) = (1-\lambda)\Delta t(\theta)$$

Impact $D_{\Delta t}$



Mass-sheet Degeneracy

Convergence:

$$\kappa(\theta) = \frac{1}{2}\nabla^2\psi(\theta)$$

$$\kappa_\lambda = \lambda + (1-\lambda)\kappa$$

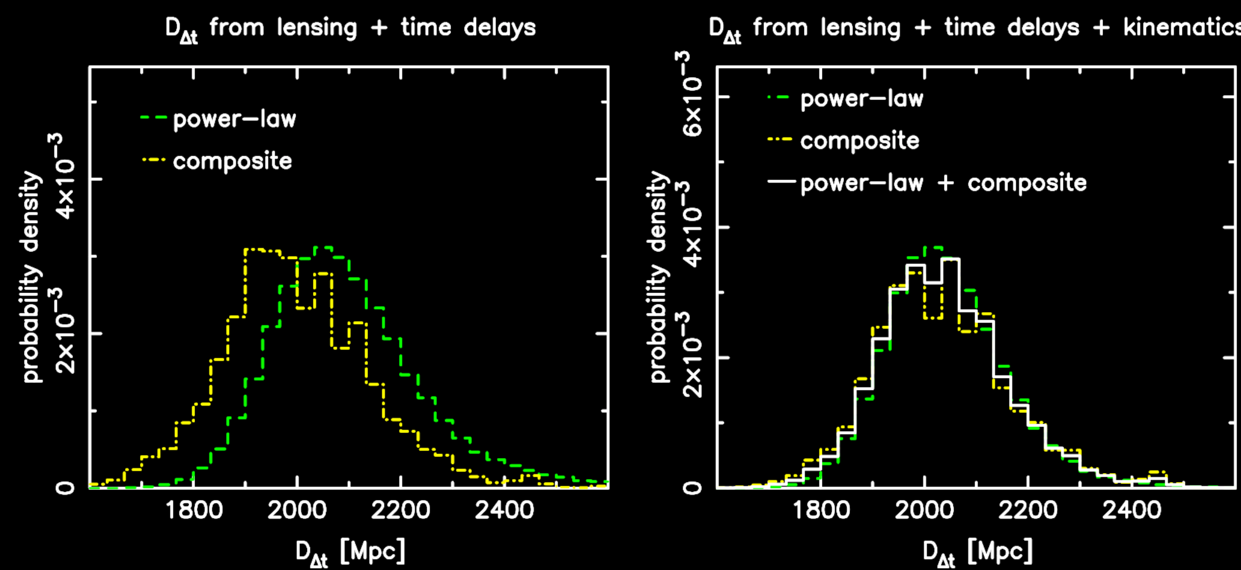


Figure 4. Time-delay distance, $D_{\Delta t}$, for the power-law model (dashed) and the composite model of baryons and dark matter (dot-dashed) in the UH_0 cosmology. The left panel is based on only the lensing and time-delay data, whereas the right panel includes the information from the lens velocity dispersion. The stellar kinematic information on the lens galaxy helps break lens model degeneracies, yielding very similar $D_{\Delta t}$ distributions for the two lens models. The combined PDF of $D_{\Delta t}$ is shown as solid in the right panel.

- **Adding extra "mass-sheet" and rescale with $1-\lambda$ gives same mass within Einstein radius**
- **Observed image morphology and brightness invariant under shifting the background source coordinate by $1-\lambda$**

$$\phi_\lambda(\theta;\beta) = (1-\lambda)\phi(\theta;\beta) + f(\beta)$$

1. **Studies of the lens environment, to estimate $\kappa_{\rm ext}$ due to mass structure (galaxy density) along the line of sight to the strong lensing system.**
2. **Stellar kinematics/velocity dispersion of strong lens galaxy, provides an independent mass measurement within the effective radius to complement the lensing mass enclosed within the Einstein radius.**

$$\Delta t_\lambda(\theta) = (1-\lambda)\Delta t(\theta)$$

Impact $D_{\Delta t}$

$$D_{\Delta t} = \frac{D_{\Delta t}^{\rm model}}{1-\kappa_{\rm ext}}$$

Inferring Cosmological Parameters

Let $\pi = \{H_0, \Omega_{\rm m}, \Omega_\Lambda, w\}$ **(cosmological parameters)**

Observer data sets:
$d_{\rm HST}$, Δt, σ, $d_{\rm LOS}$

$\xi = \{\pi, \nu\}$ **(all = cosmological + nuisance parameters (lens model + break degeneracy))**

Goal: Obtain the posterior probability distribution function (PDF) of the model parameters ν **given the data,** $P(\xi \,|\, d_{\rm HST}, \Delta t, \sigma, d_{\rm LOS}, A)$ **by marginalized over the nuisance parameters**

$$P(\pi \,|\, d_{\rm HST}, \Delta t, \sigma, d_{\rm LOS}, A) = \int d\nu \; P(\xi \,|\, d_{\rm HST}, \Delta t, \sigma, d_{\rm LOS}, A)$$

A = Discrete set of assumptions make about the model form, data modeling, set-up, treatment etc.

Prior

$$P(\xi \,|\, d_{\rm HST}, \Delta t, \sigma, d_{\rm LOS}, A) \propto P(d_{\rm HST}, \Delta t, \sigma, d_{\rm LOS} \,|\, \xi, A) \boxed{P(\xi \,|\, A)}$$

$$P(d_{\rm HST}, \Delta t, \sigma, d_{\rm LOS} \,|\, \xi, A) = \underbrace{P(d_{\rm HST} \,|\, \xi, A)}_{\text{imaging}} \underbrace{P(\Delta t \,|\, \xi, A)}_{\text{light curve}} \underbrace{P(\sigma \,|\, \xi, A)}_{\text{stellar kinematics}} \underbrace{P(d_{\rm LOS} \,|\, \xi, A)}_{\text{lens environment}}$$

Modelled $D_{\Delta t}$

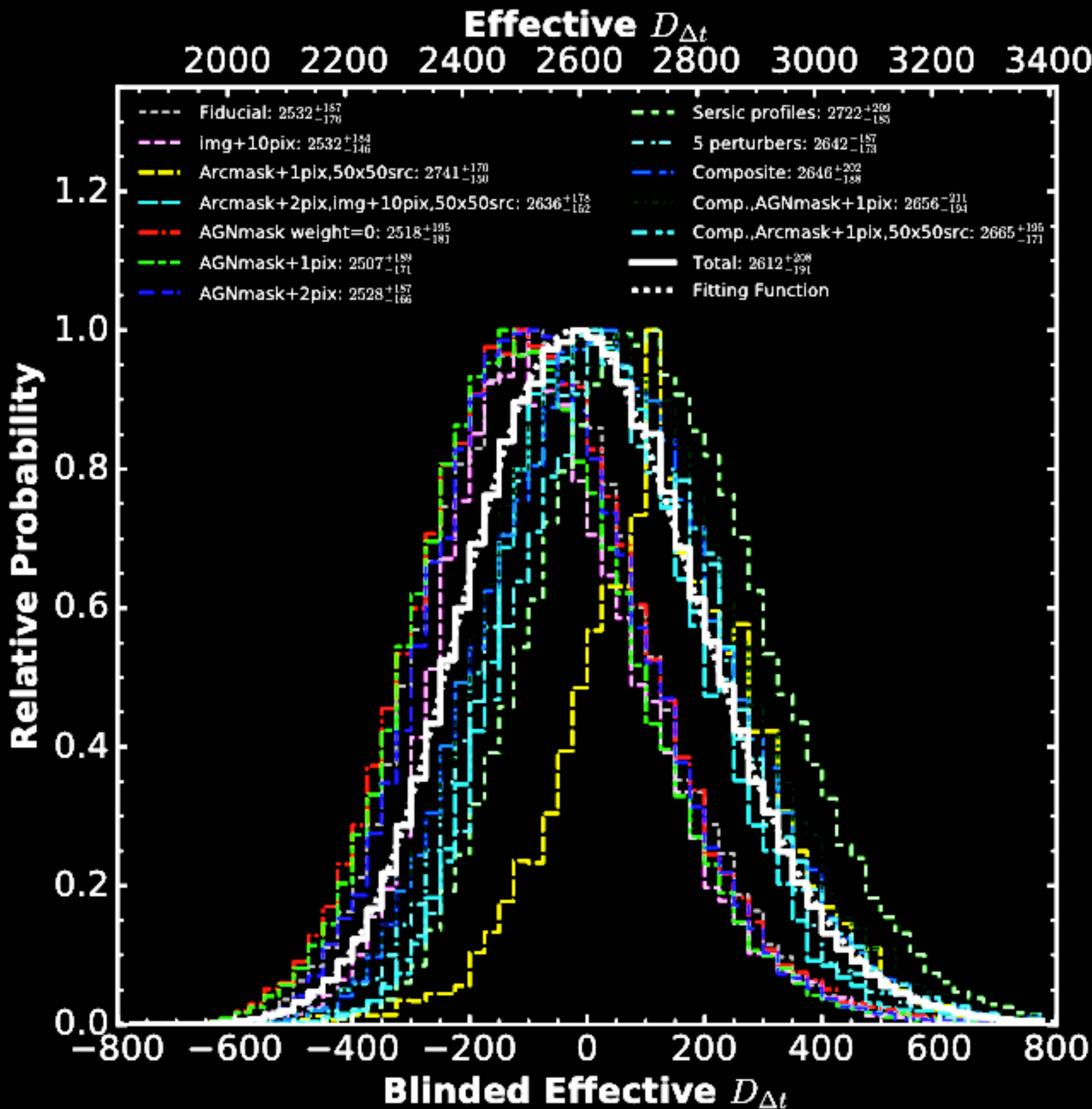
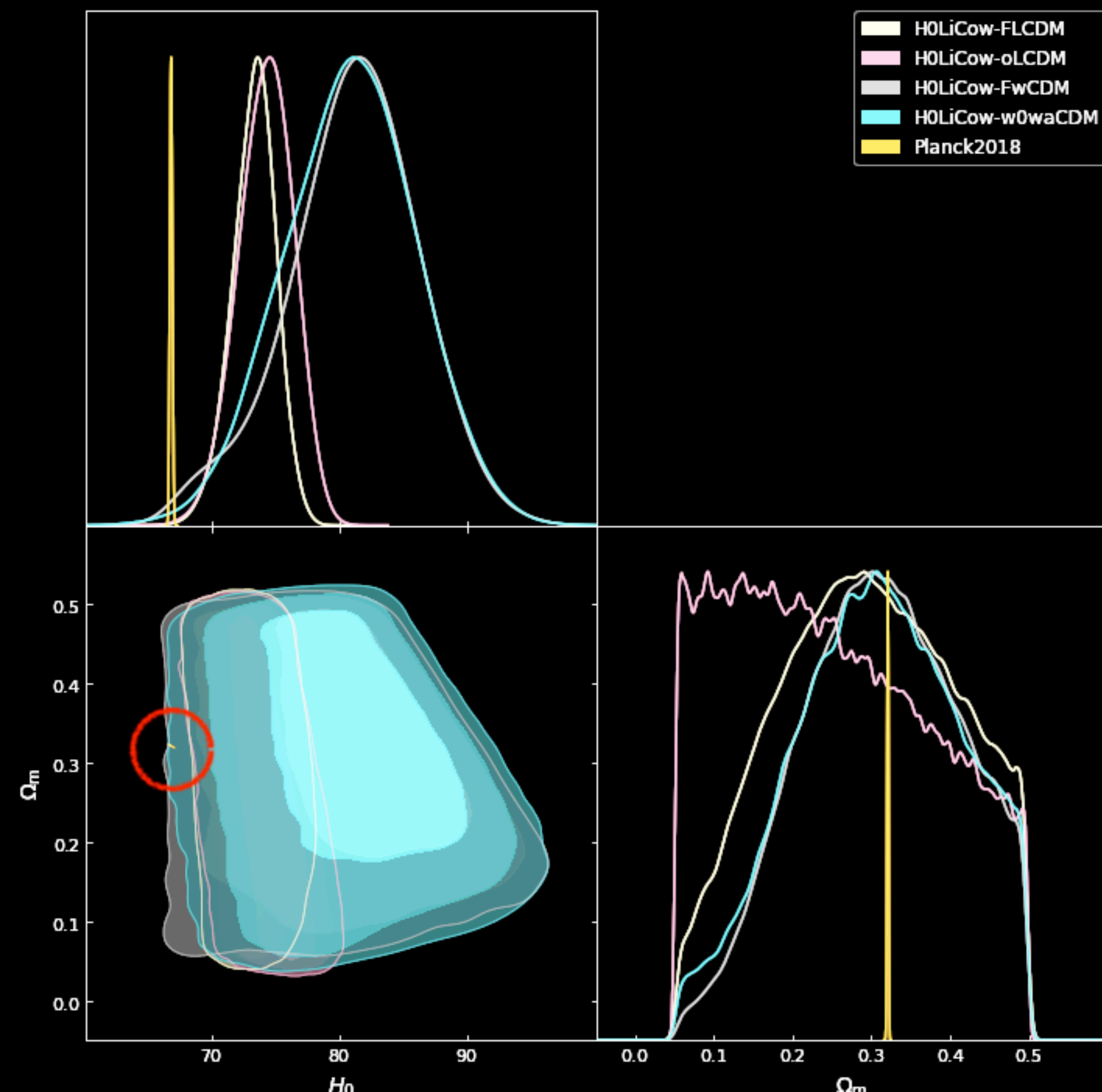


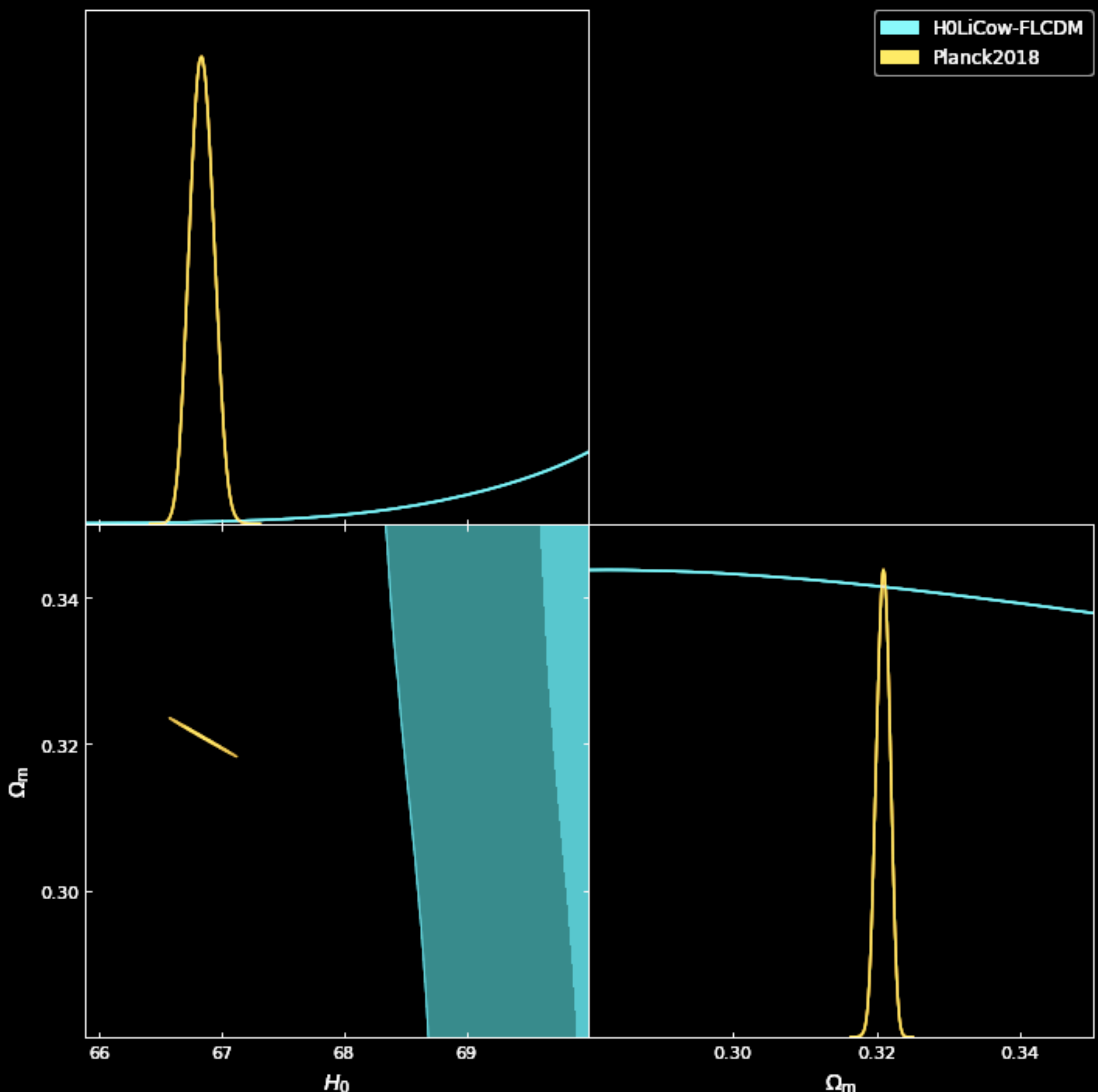
Figure 8. PDF of $D_{\Delta t}$ for the various models, as indicated by the legend. The median and 68% quantile of each distribution is given. The thick black line represents the sum of all the distributions, which accounts for the various systematic uncertainties. The dotted black line is the skewed lognormal distribution (Equation (17)) fit to the final distribution. The bottom x-axis shows the blinded result, which is obtained by subtracting the median of the combined PDF from the absolute $D_{\Delta t}$ values. The top x-axis shows the true $D_{\Delta t}$ values. Throughout our blind analysis, the top x-axis was hidden until our analysis was finalized.

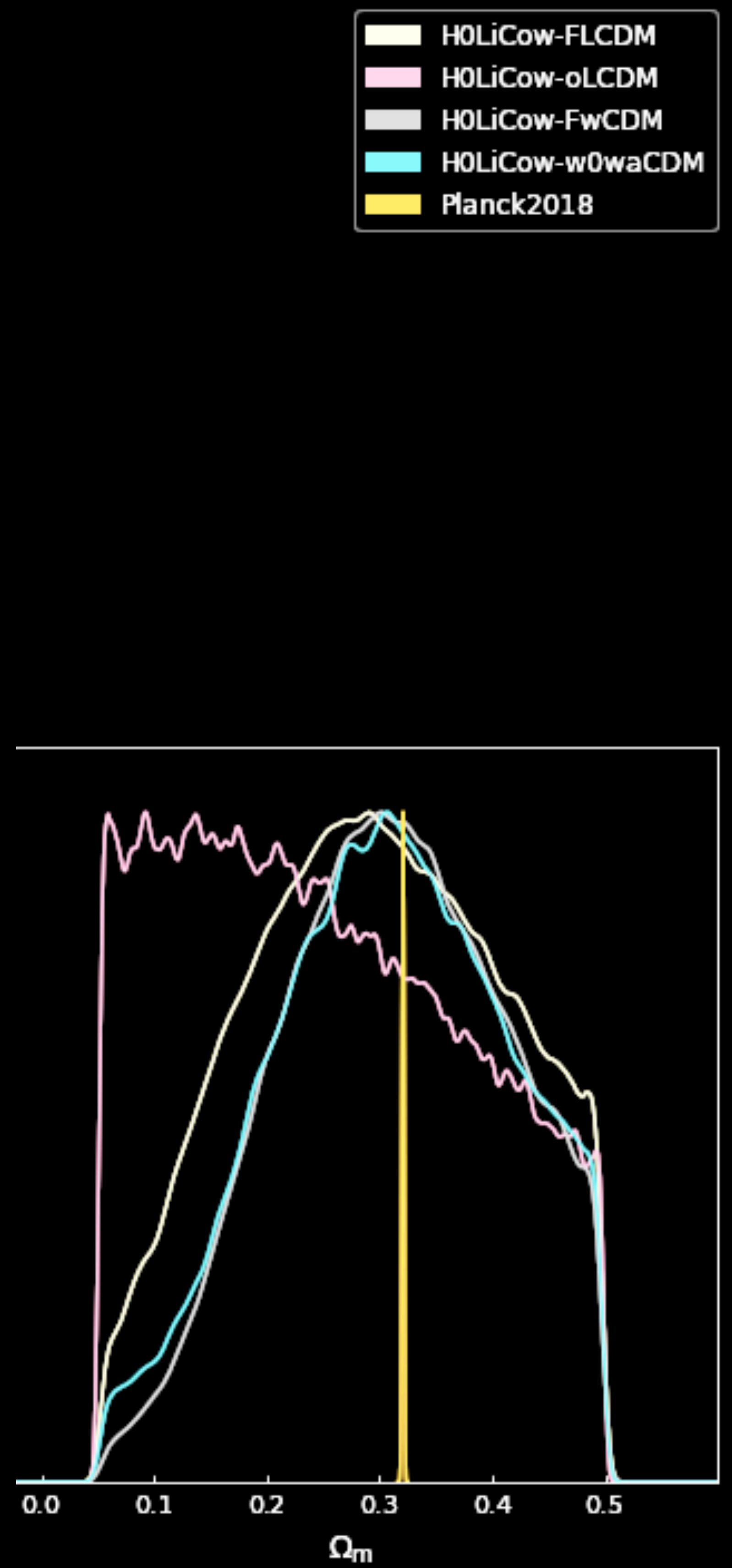
Choices in modeling lead to small offsets in time delay distance.
These models can be averaged over, before unblinding

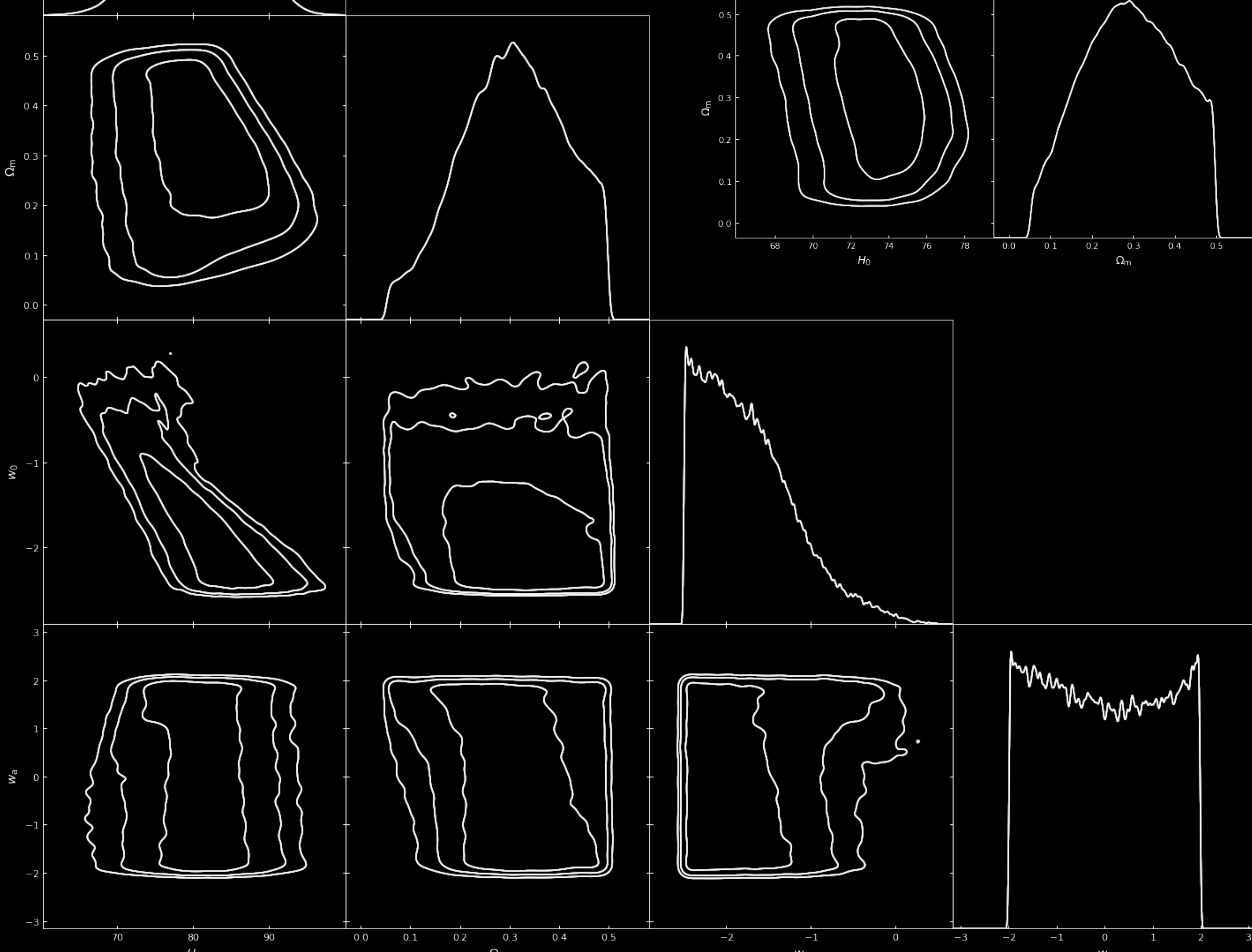
H_0 Measurement by Gravitational Lens Time Delays



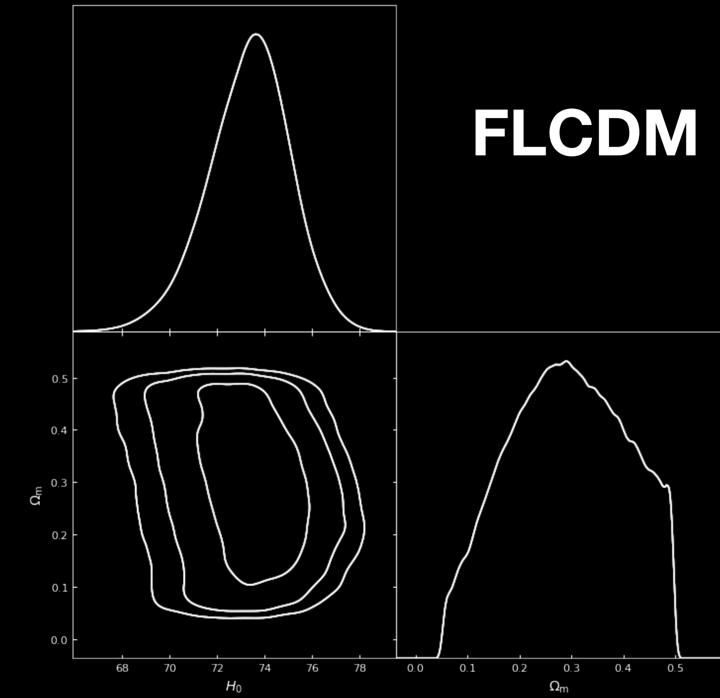
H_0 Measurement by Gravitational Lens Time Delays



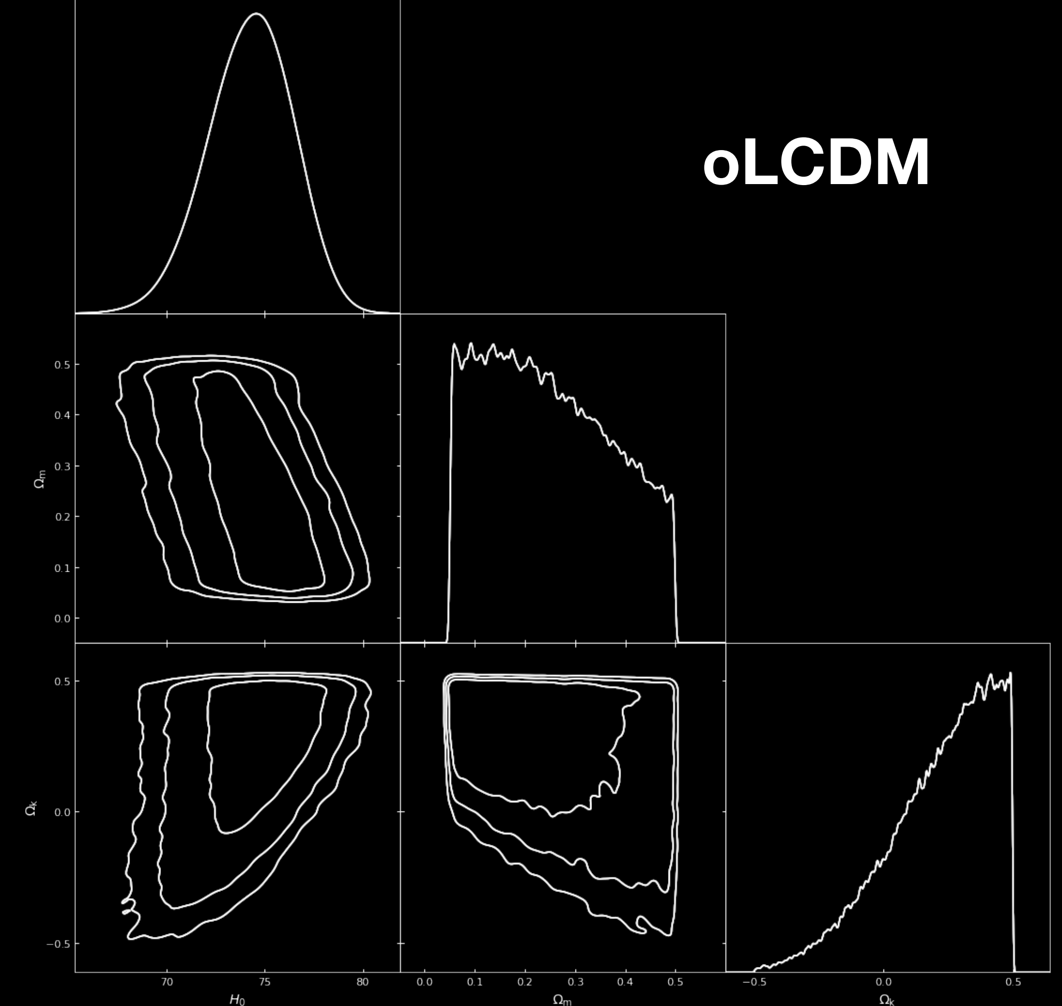




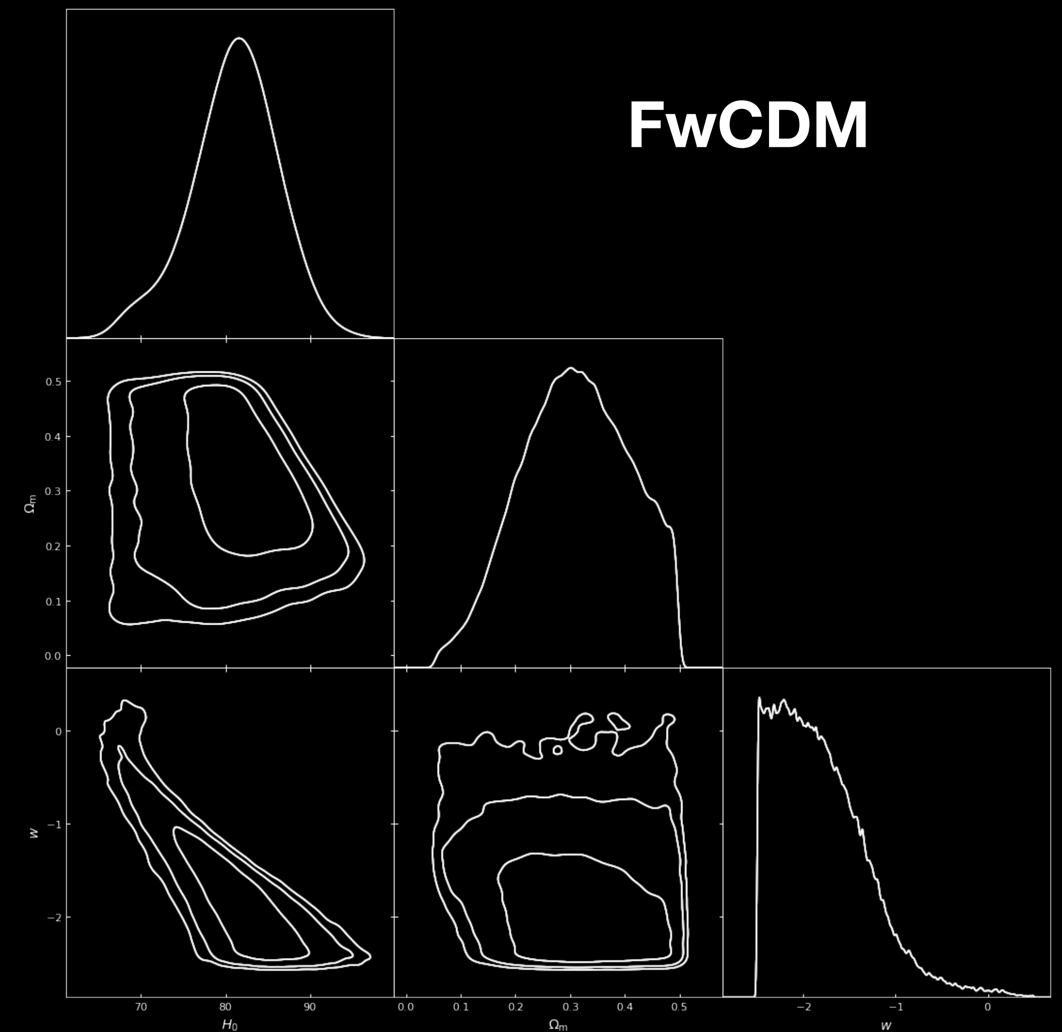
FLCDM



oLCDM



FwCDM



w0waCDM

H_0 Tension

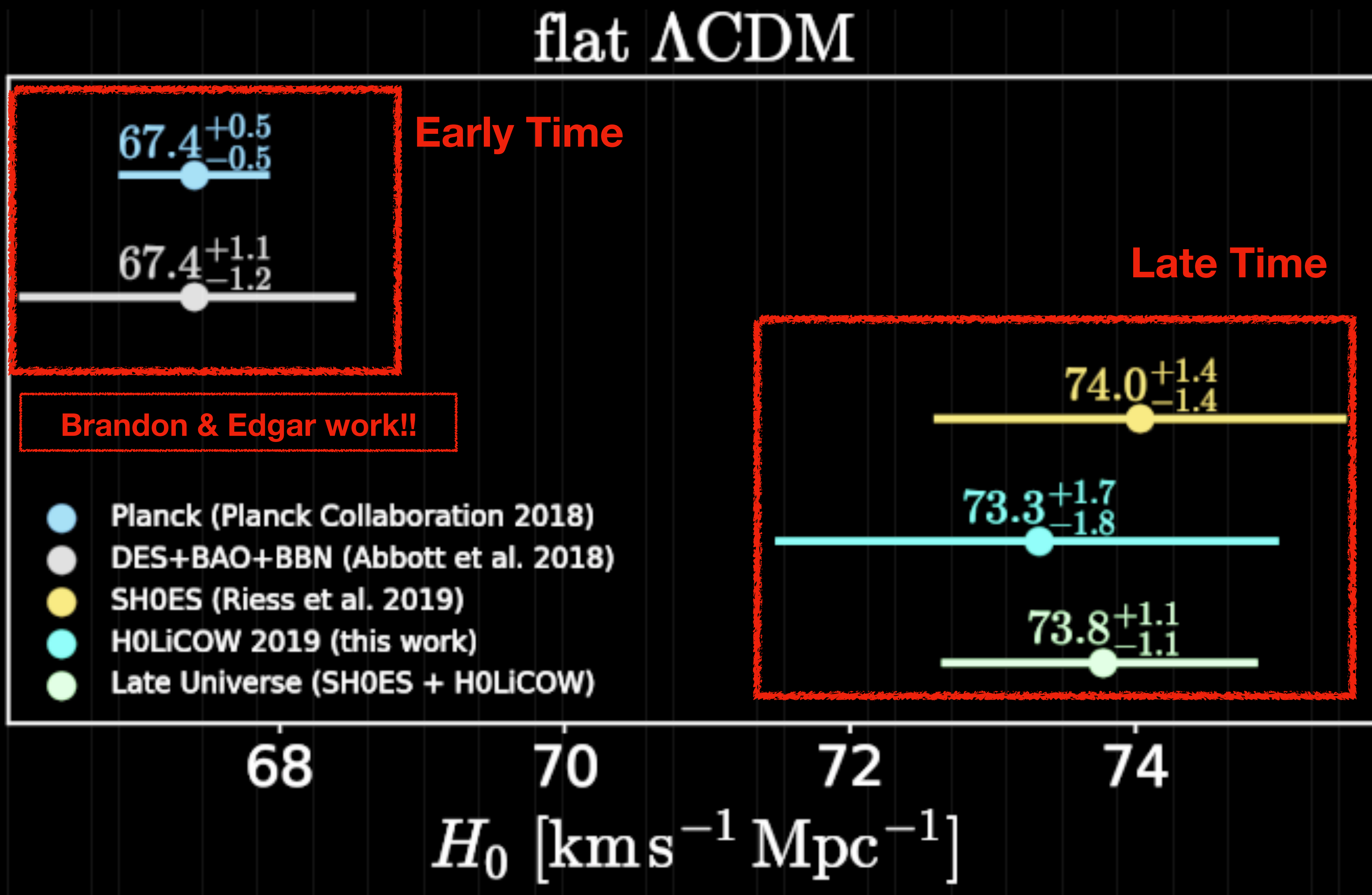
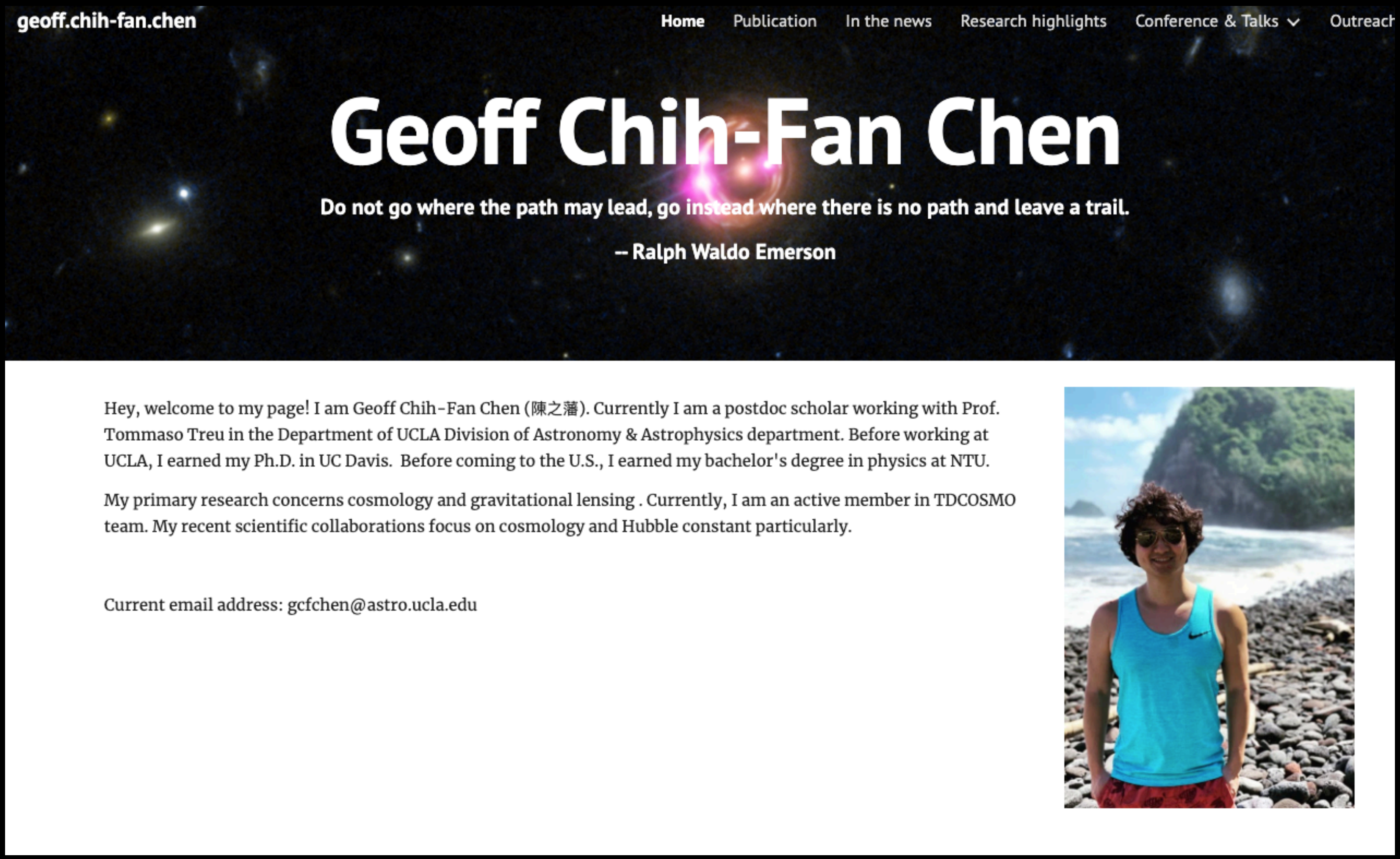


Figure 12. Comparison of H_0 constraints for early-Universe and late-Universe probes in a flat ΛCDM cosmology. The early-Universe probes shown here are from *Planck* (orange; Planck Collaboration et al. 2018b) and a combination of clustering and weak lensing data, BAO, and big bang nucleosynthesis (grey; Abbott et al. 2018b). The late-Universe probes shown are the latest results from SH0ES (blue; Riess et al. 2019) and H0LiCOW (red; this work). When combining the late-Universe probes (purple), we find a 5.3σ tension with *Planck*.

Special thanks to
Geoff Chih-Fan Chen (UCLA, H0LiCOW/TDCOSMOS)
on helping with the concept building process.



Thanks for paying attention!
I am happy to take any question!
(Although I may not know how to answer it)