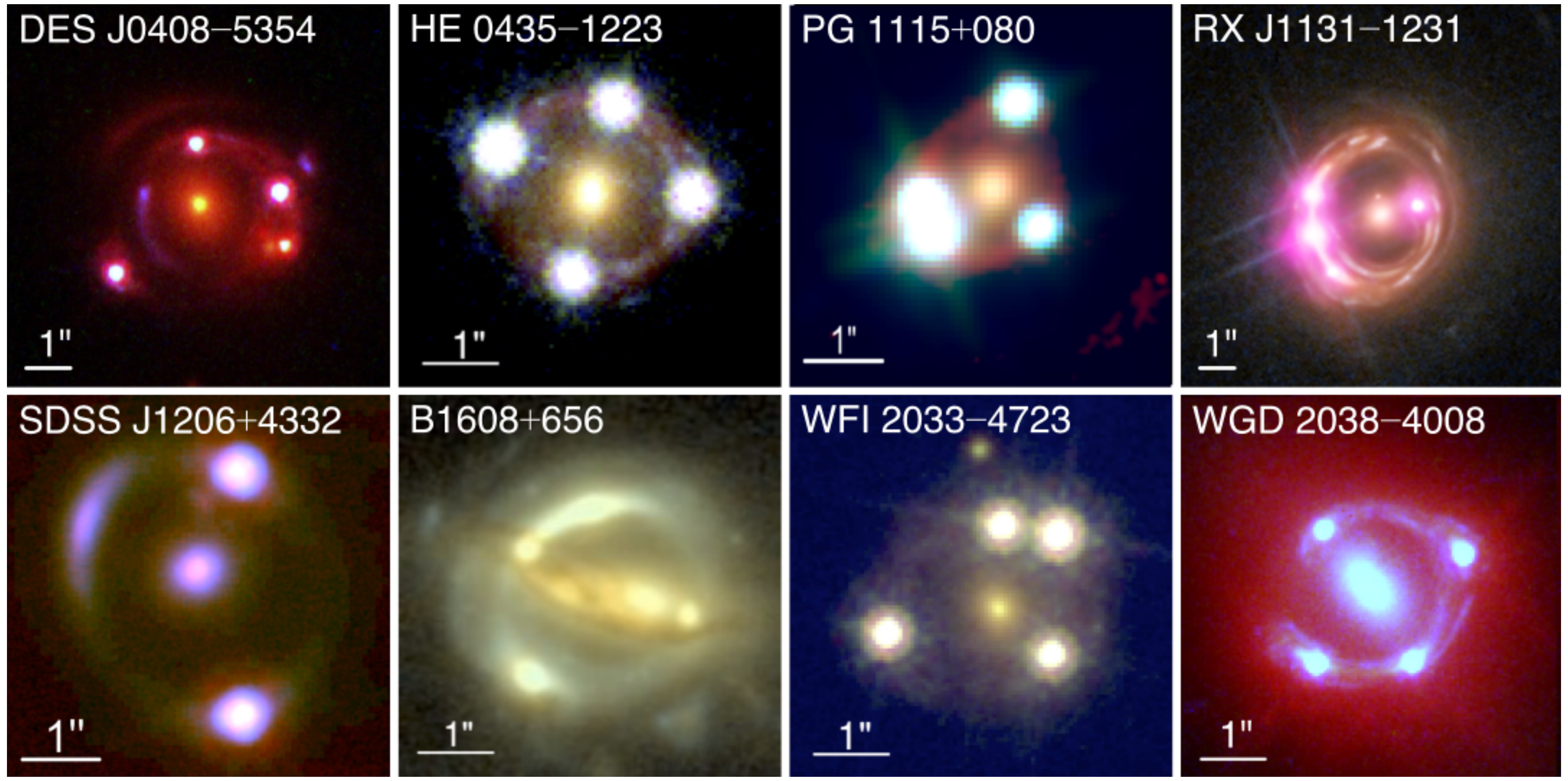
Precision kinematics of lens galaxy for precision measurement of H_0 using time-delay cosmography



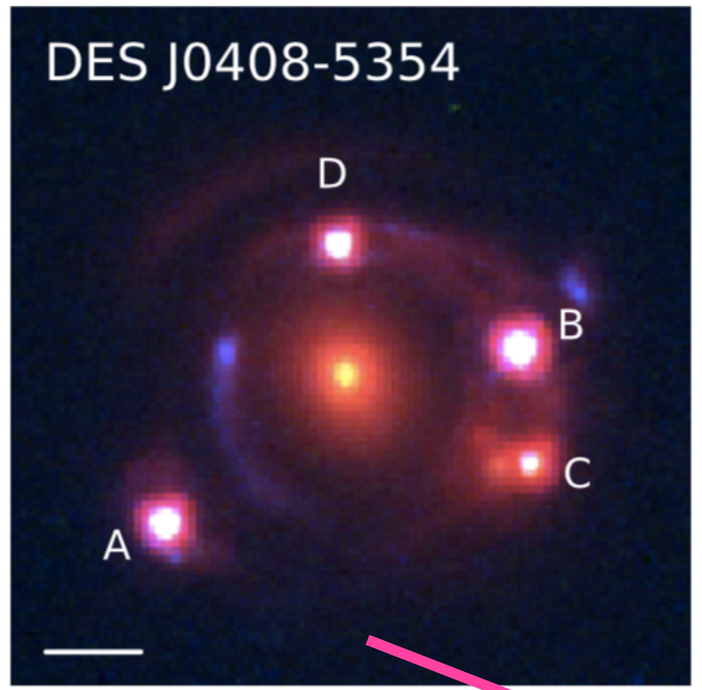
Pritom Mozumdar
University of California, Los Angeles
with
TDCOSMO collaboration

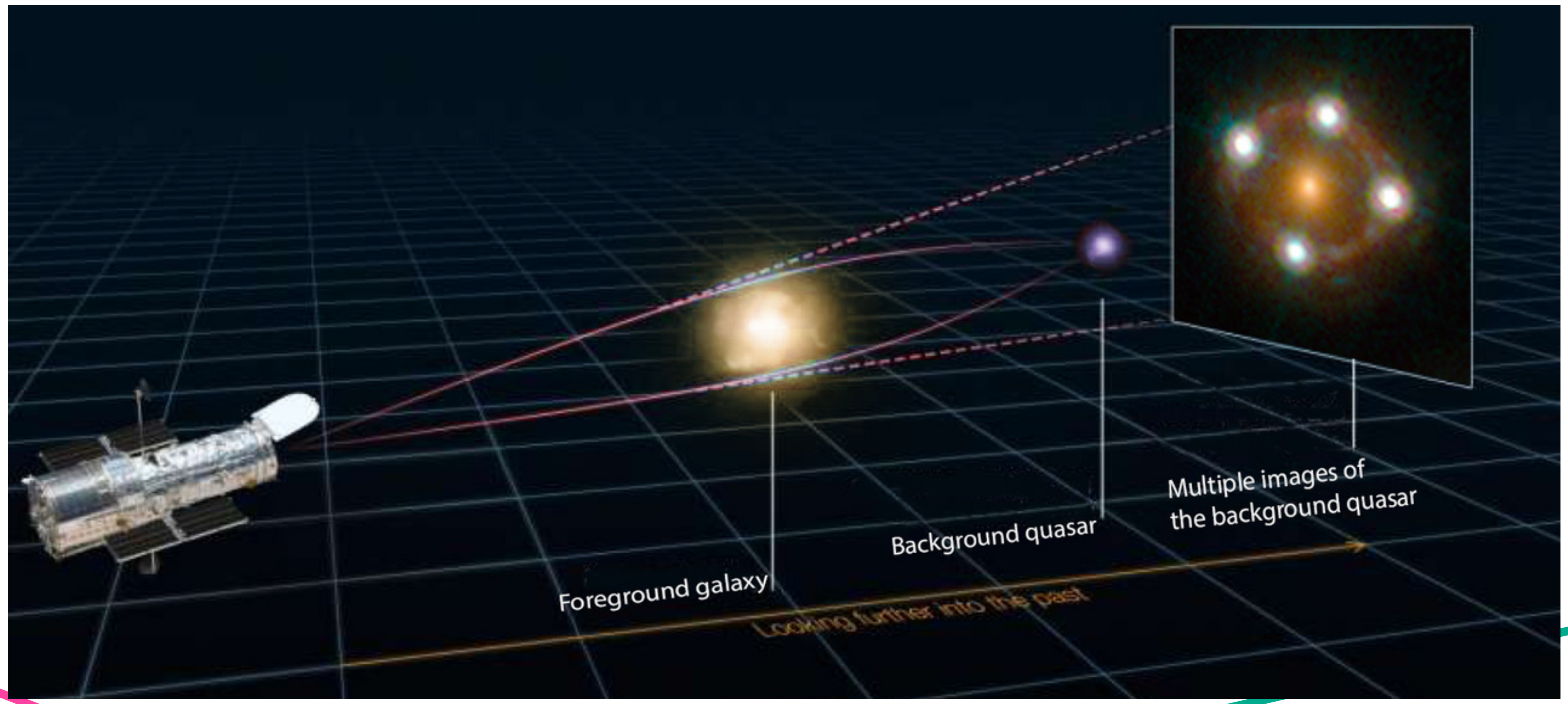
Outline :

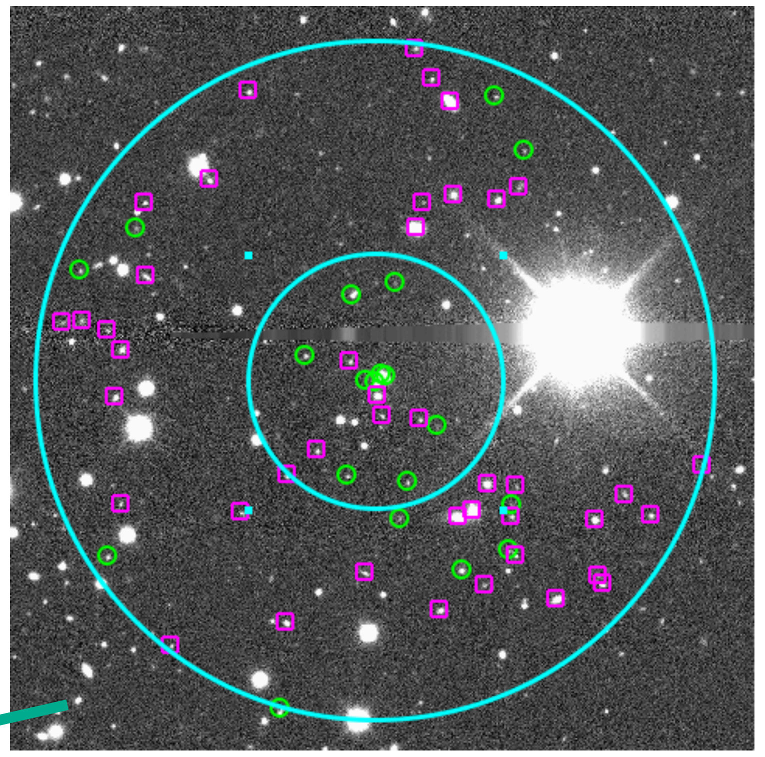
- Why kinematics is integral for precision H_0 - a tale of two degeneracies.
- How to improve precision on measured kinematics?
    - Improving random error budget
    - Improving systematic error budget

Recap: Measuring H_0 using time-delay cosmography

Hi-resolution imaging







Photometric survey, spectroscopic survey, *N*-body simulation

External convergence

Fermat potential difference

Treu & Shajib (2023)

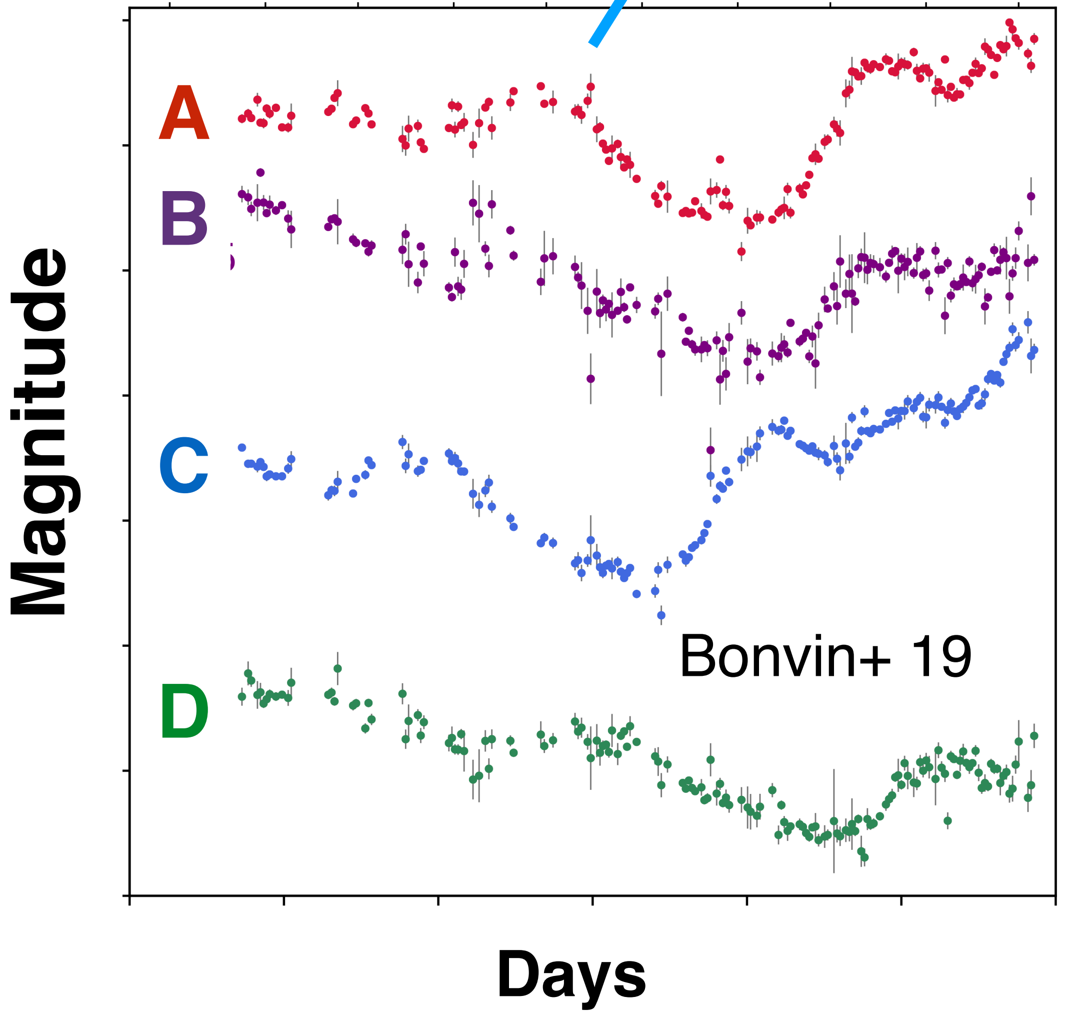
$$H_0 = \frac{\Delta\tau_{\rm model}(1-\kappa_{\rm ext})\lambda_{\rm int}}{\Delta t}\,\frac{f_k(0,z_{\rm d},\Theta)\,f_k(0,z_{\rm s},\Theta)}{f_k(z_{\rm d},z_{\rm s},\Theta)}.$$

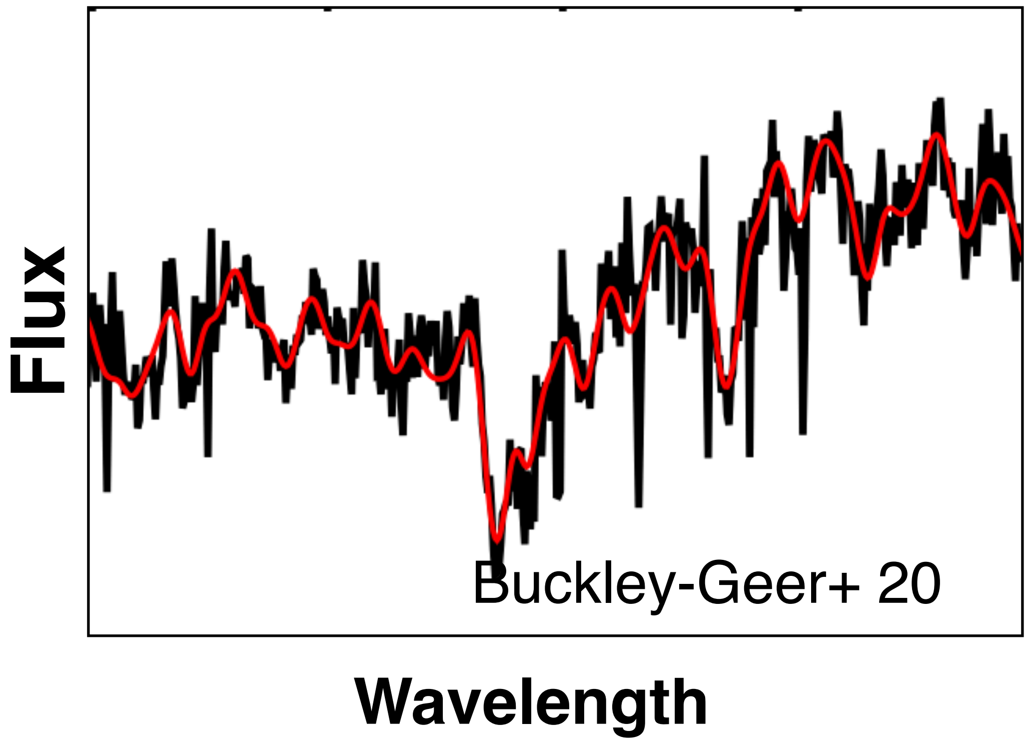
Term depending on density parameters in cosmological distance

Time delays

Deviation from mass model parametrization

Long-term monitoring with 1- or 2-m telescopes

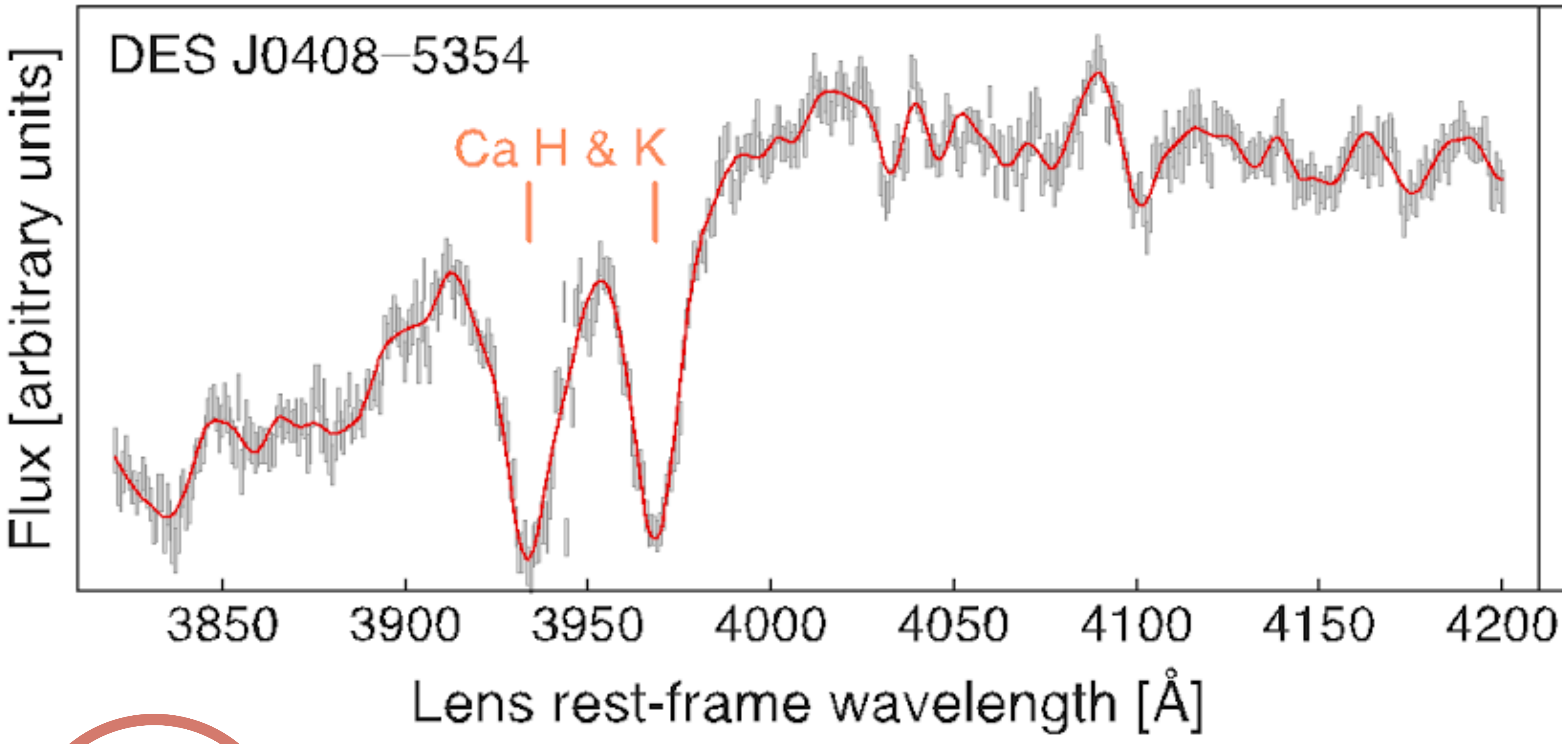




Ground/Space based Slit/IFU spectroscopy

We need 4 ingredients to infer H_0 :

- Time Delays Measurement
- Lens Modelling
- External Convergence
- Stellar kinematics

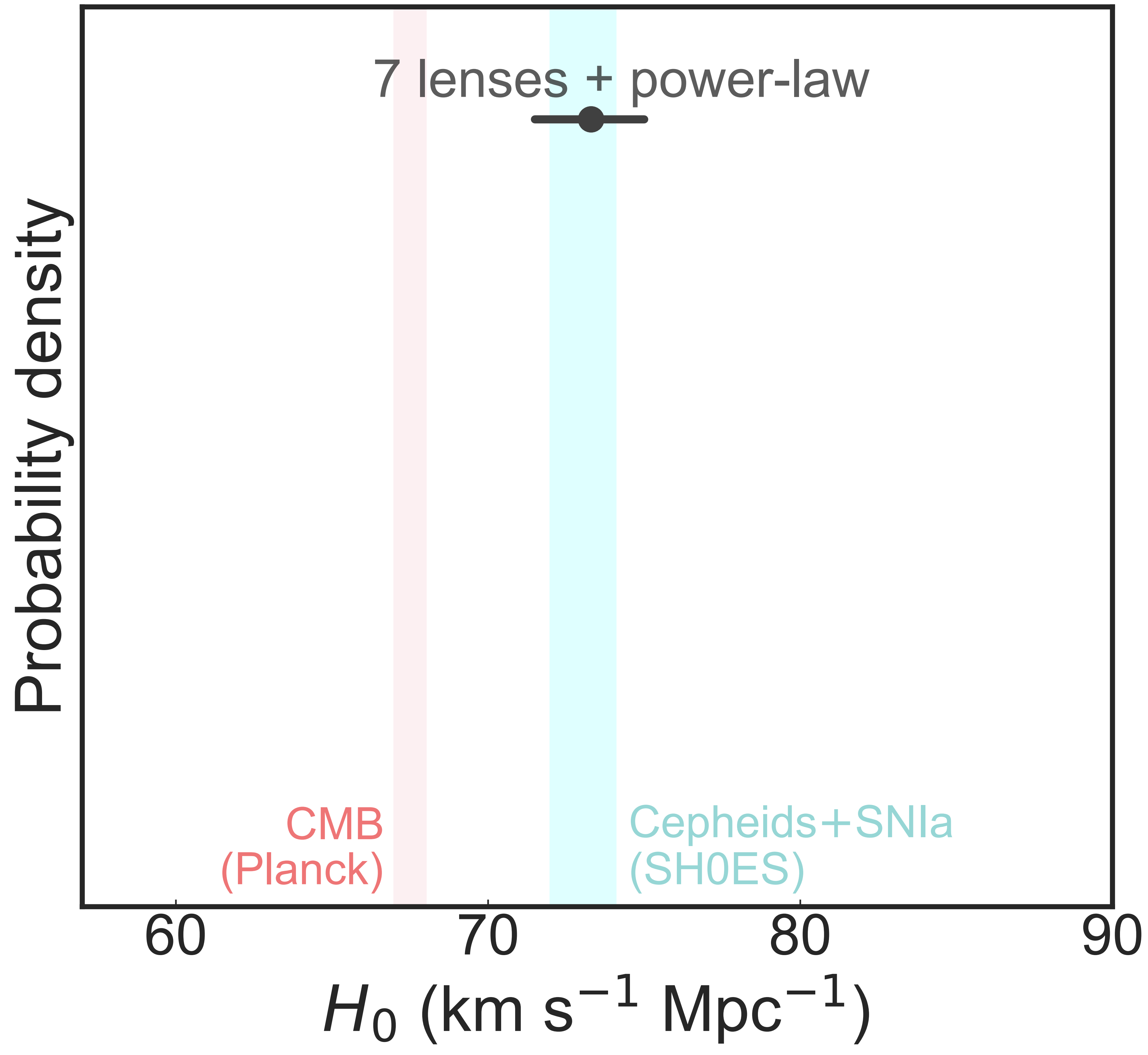


$$H_0 = \frac{\Delta\Phi_{\text{model}}(1-\kappa_{\text{ext}})\lambda_{\text{int}}}{\Delta t} f(z_d, z_s, \Omega_m, \Omega_s, \ldots)$$

From lens galaxy spectra and dynamical modeling

Lensing-only perspective of the Hubble tension

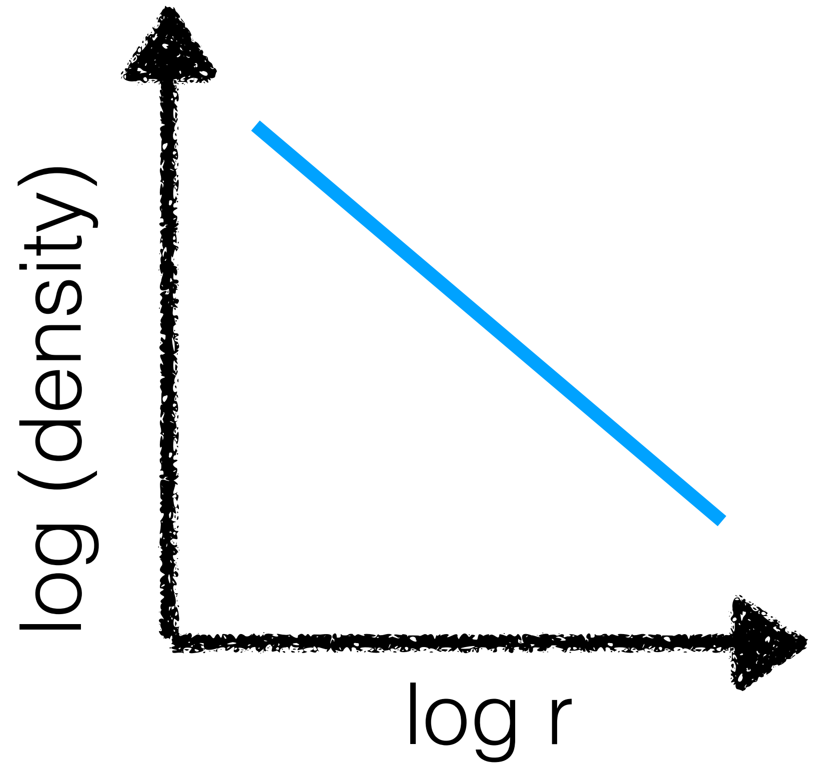
ΛCDM model (Cosmology) ⟷ ? Power-law mass model (Astrophysics)

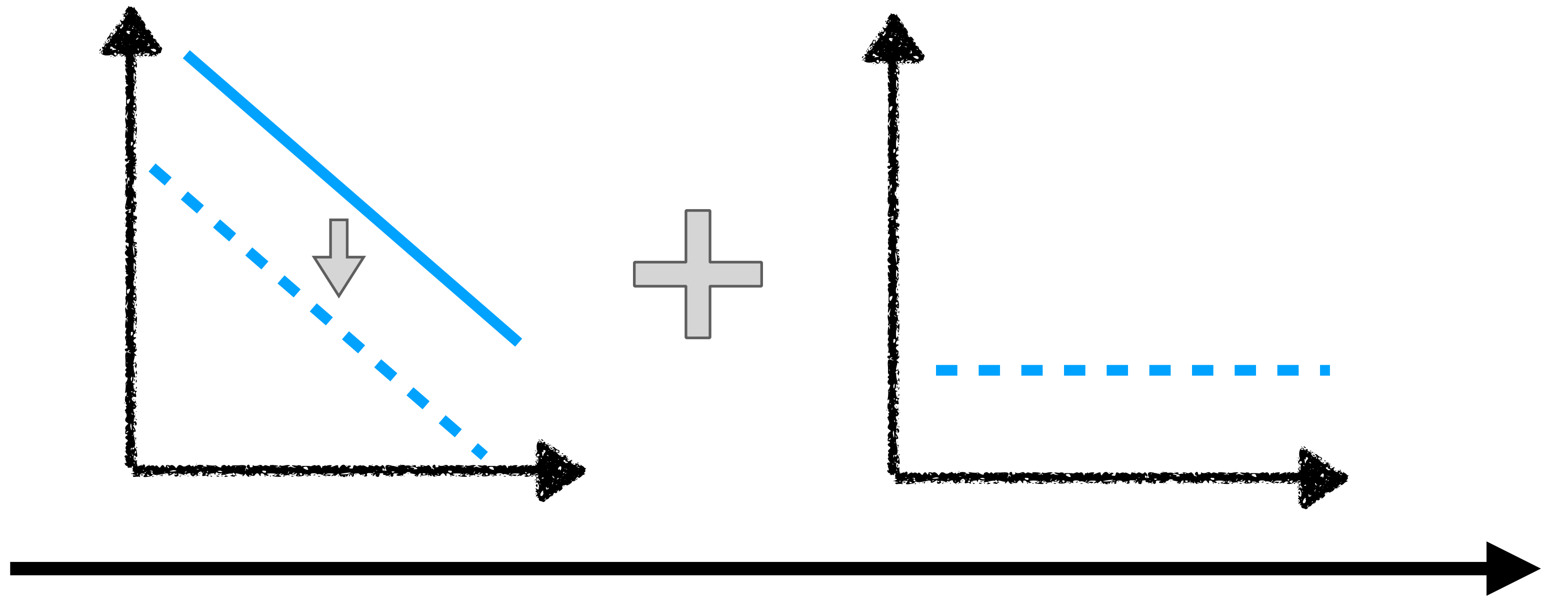


Millon+ 20

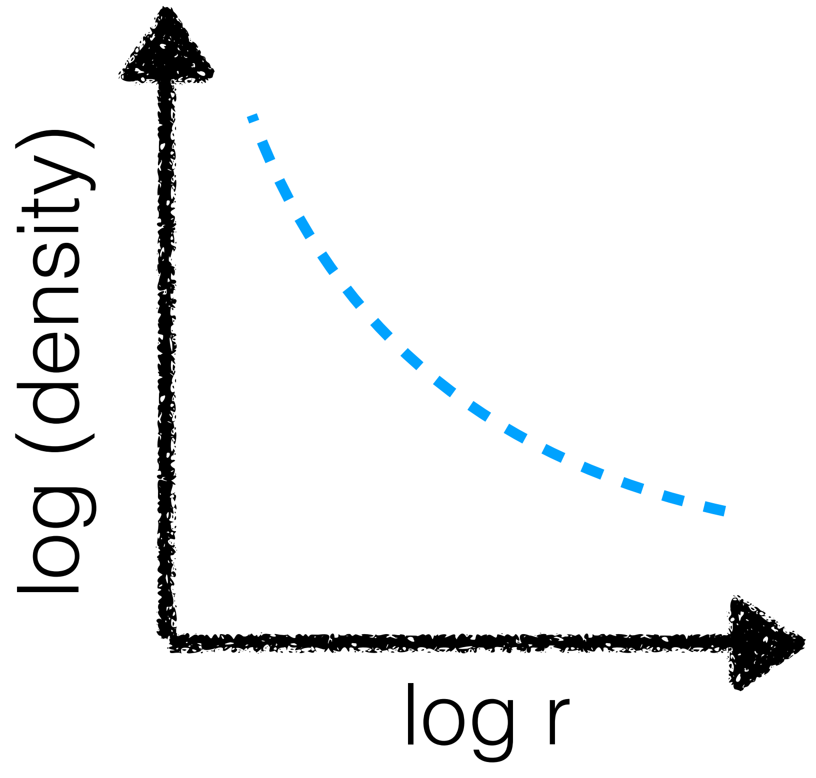
Mass-sheet degeneracy (MSD) in lensing

$$\Sigma \to \Sigma' = \lambda\Sigma + (1 - \lambda)$$





Changes predicted potential difference and thus H_0.



Fits HST imaging well

Fits HST imaging equally well

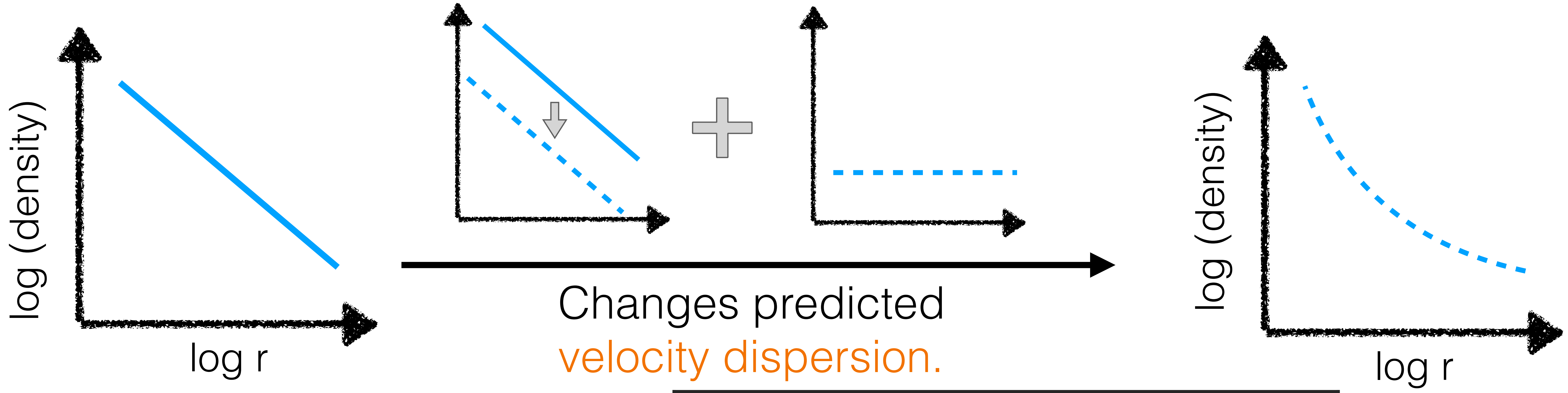
Not power law

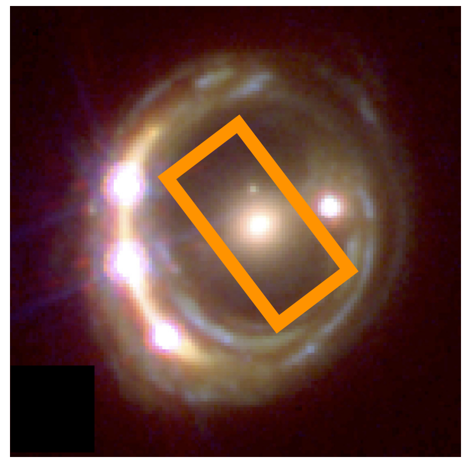
Power-law model implicitly breaks the MSD.

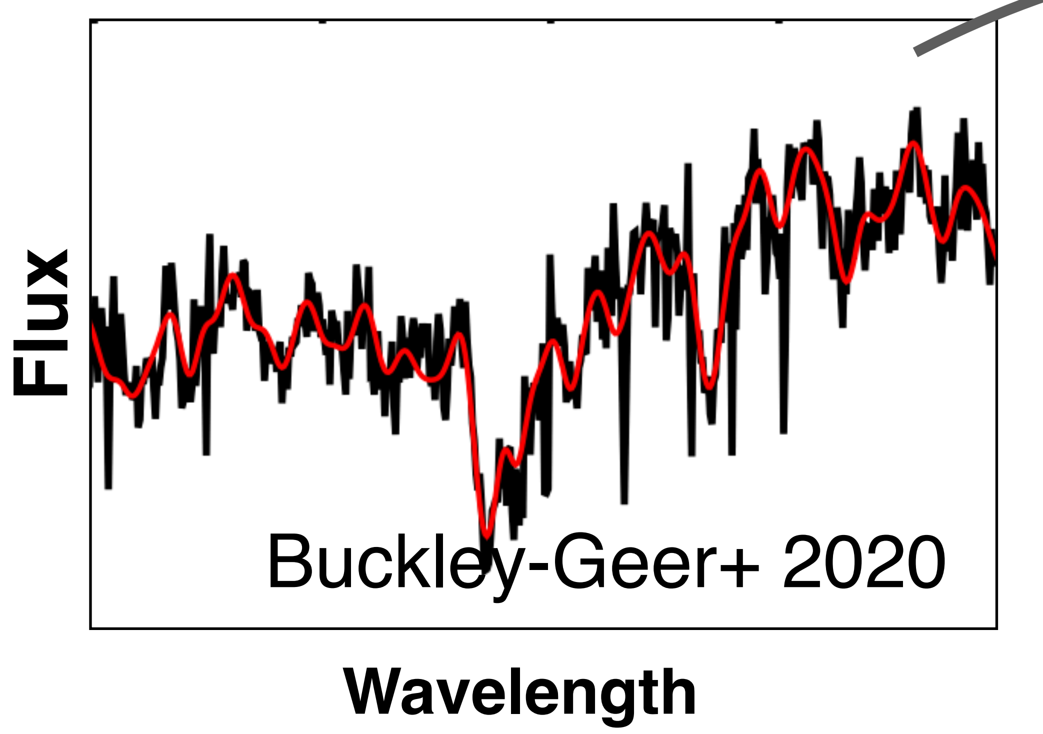
If the true mass profile is not a power law, then H_0 would be biased.

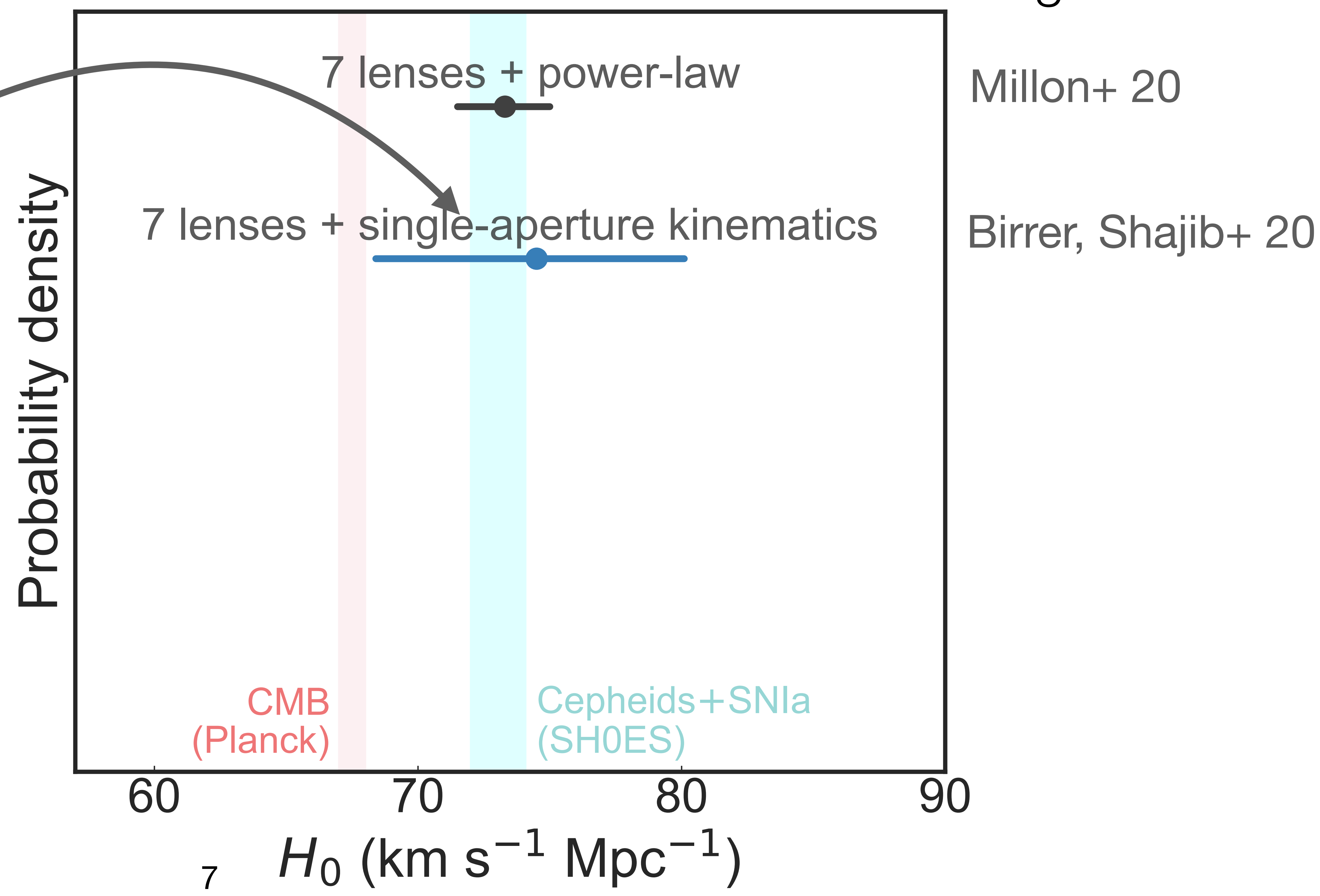
Mass-sheet degeneracy (MSD) in lensing

$$\Sigma \rightarrow \Sigma' = \lambda\Sigma + (1 - \lambda)$$

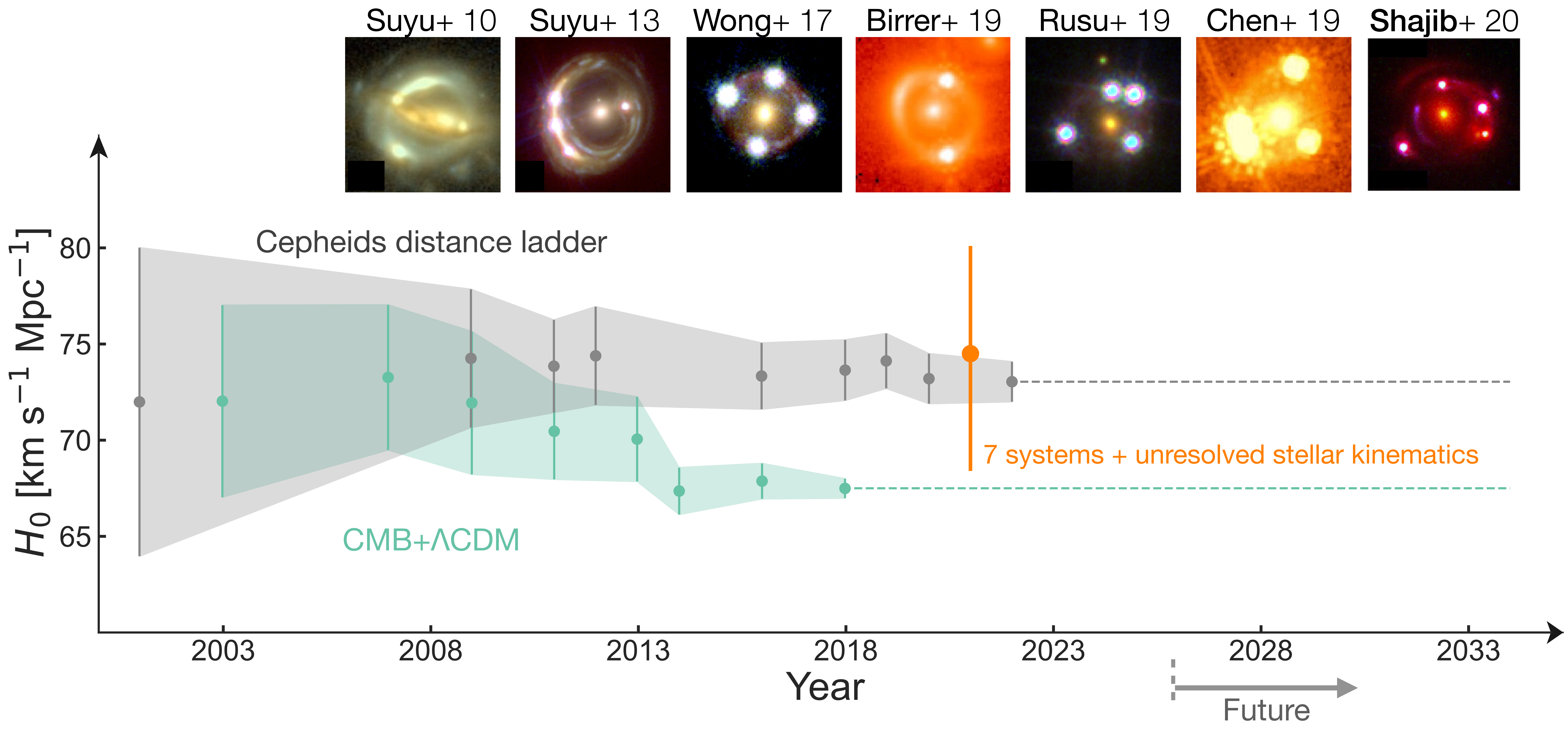






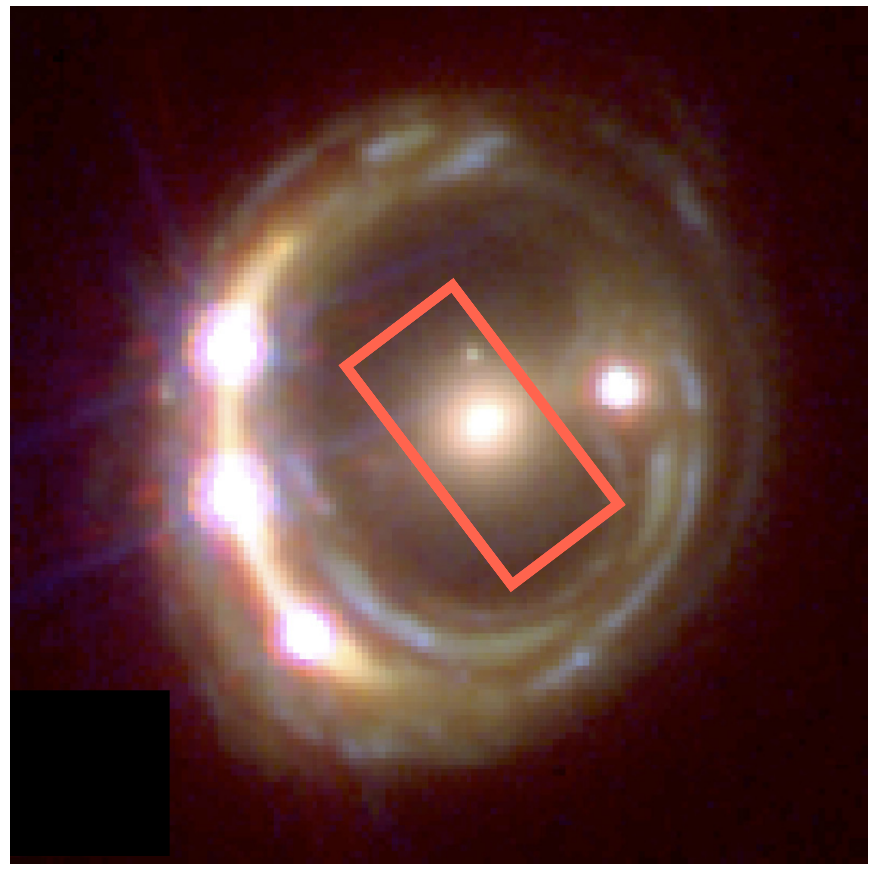


In 2020, the TDCOSMO collaboration measured H_0 blindly to 8% from 7 systems with the mass-sheet degeneracy constrained using kinematics.



Planck 18; Riess+ 22; Birrer, **Shajib**+ 20

But unresolved velocity dispersion brings it’s own problem



Mass model

$$\rho(r) \approx r^{-\gamma}$$

Anisotropy model

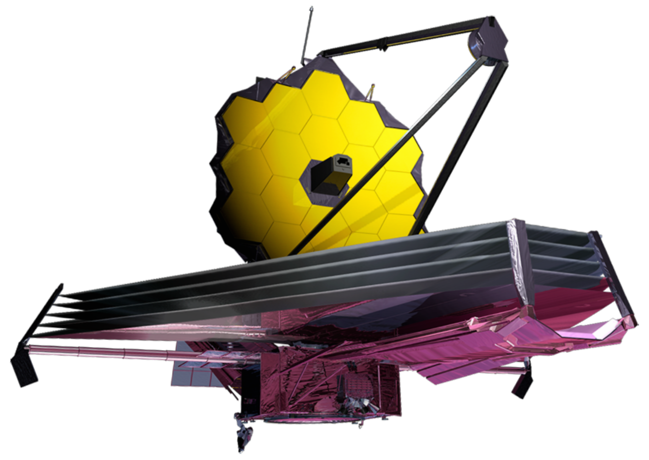
$$b = 1 - \frac{\sigma_z}{\sigma_R}$$

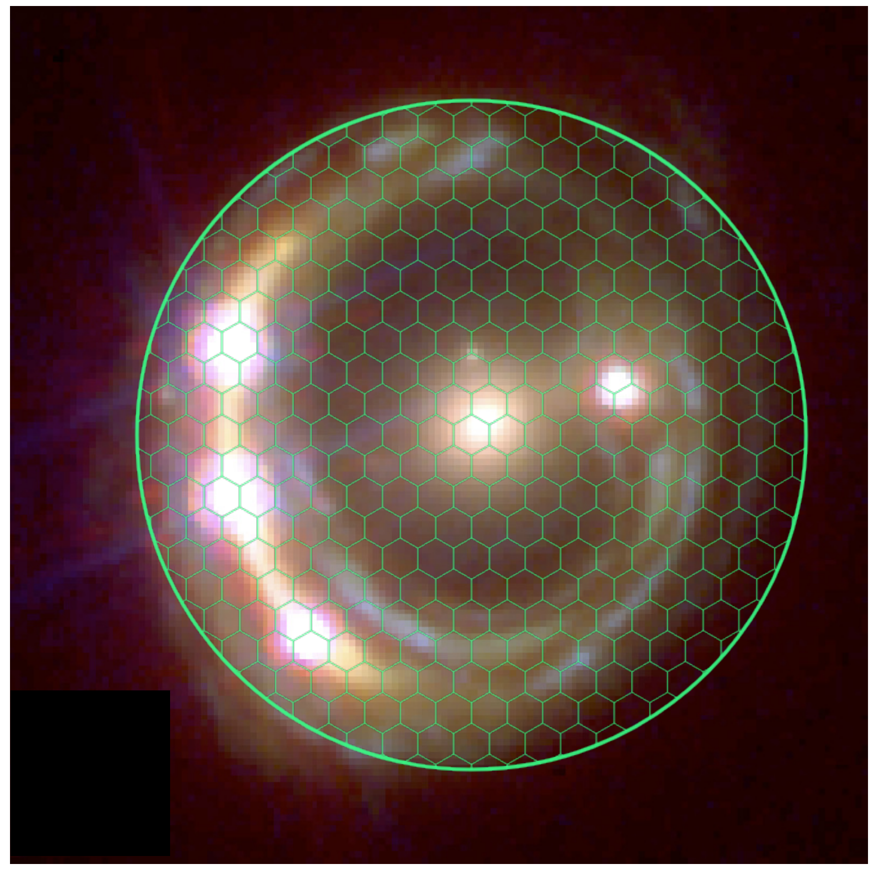
$$\frac{\zeta\ \left(b\overline{v_z^2} - \overline{v_\phi^2}\right)}{R} + \frac{\partial\left(b\zeta\ \overline{v_z^2}\right)}{\partial R} = -\zeta\ \frac{\partial\Phi}{\partial R}$$

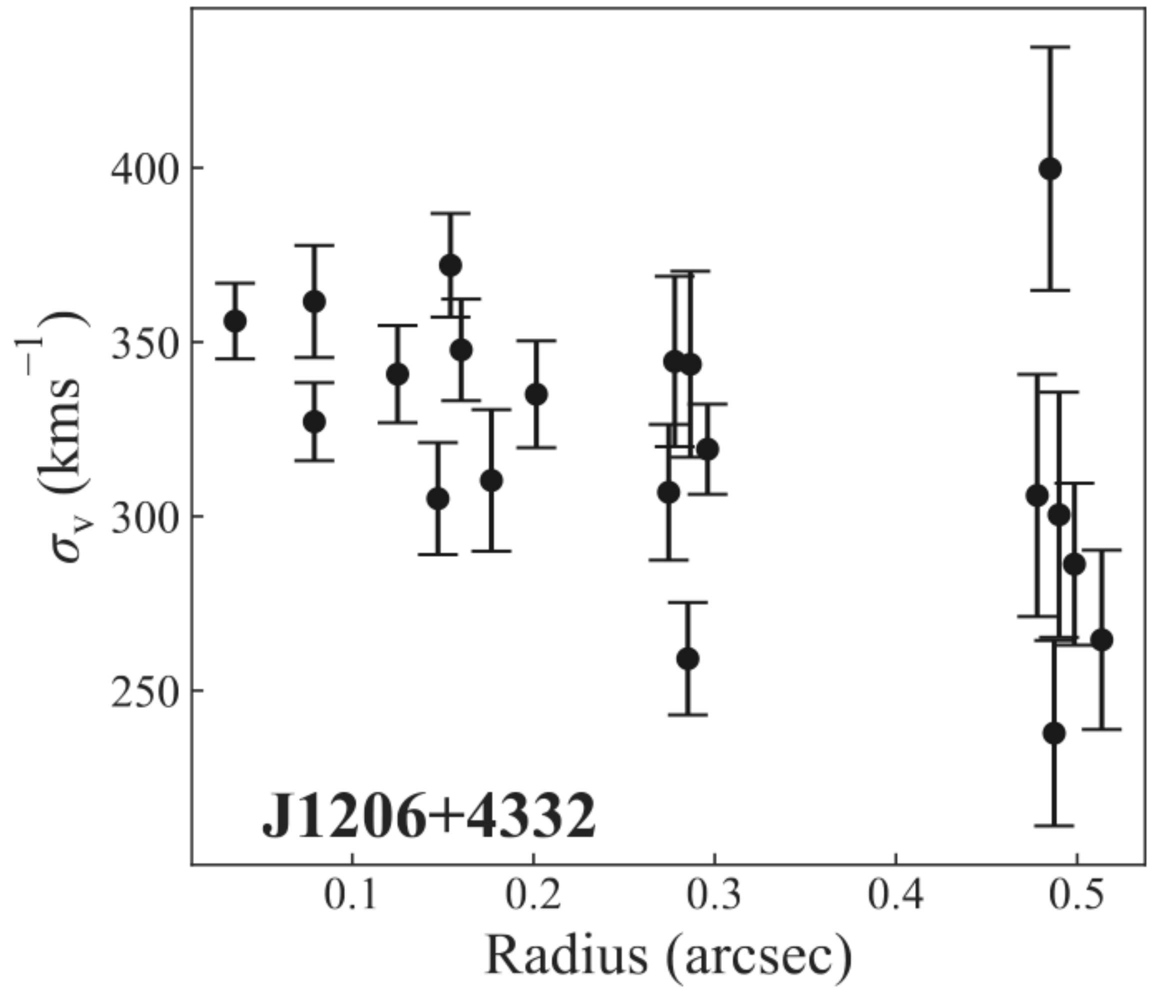
$$\frac{\partial\left(\zeta\ \overline{v_z^2}\right)}{\partial z} = -\zeta\ \frac{\partial\Phi}{\partial z},$$

Introduce Mass-Anisotropy degeneracy

Resolved velocity dispersion breaks both MSD and MAD







Mass model

$$\rho(r) \approx r^{-\gamma}$$

Anisotropy model

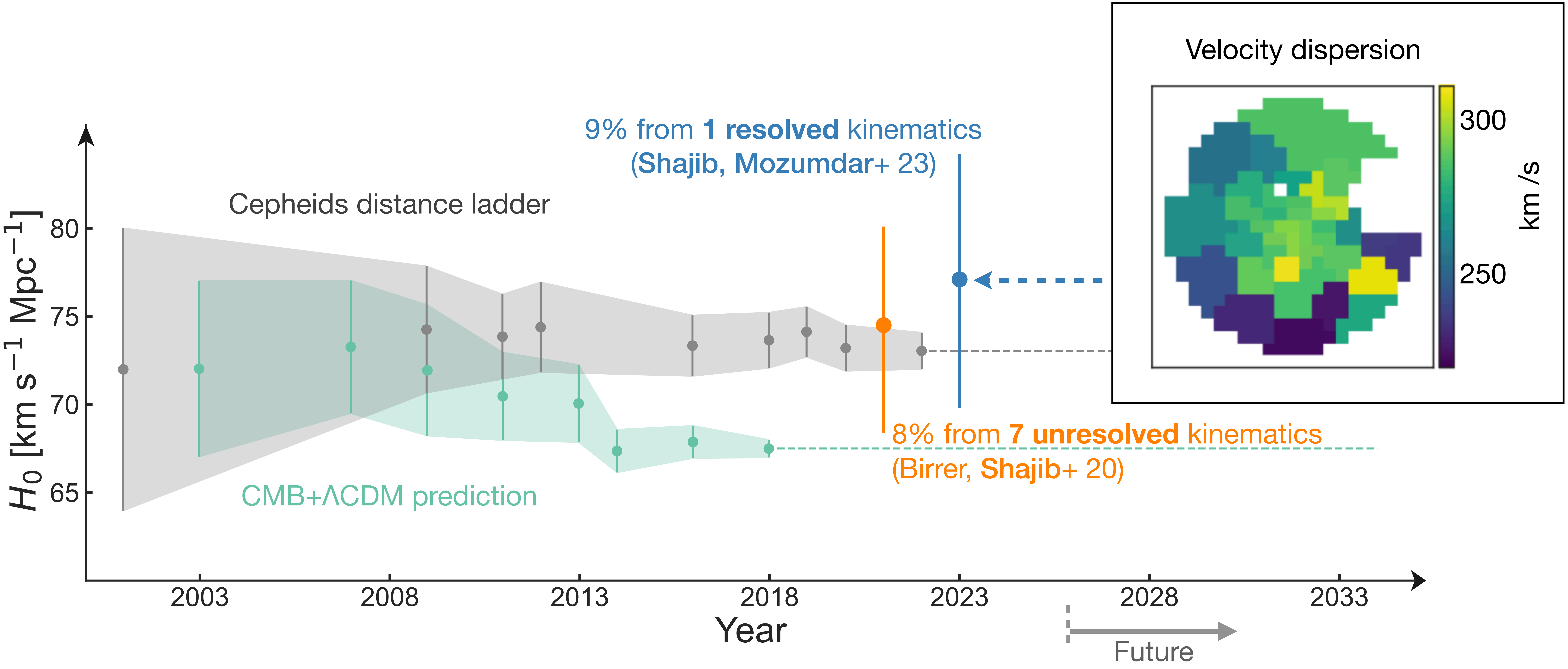
$$b = 1 - \frac{\sigma_z}{\sigma_R}$$

$$\frac{\zeta\ (b\overline{v_z^2} - \overline{v_\phi^2})}{R} + \frac{\partial\left(b\zeta\ \overline{v_z^2}\right)}{\partial R} = -\zeta\ \frac{\partial \Phi}{\partial R}$$

$$\frac{\partial\left(\zeta\ \overline{v_z^2}\right)}{\partial z} = -\zeta\ \frac{\partial \Phi}{\partial z},$$

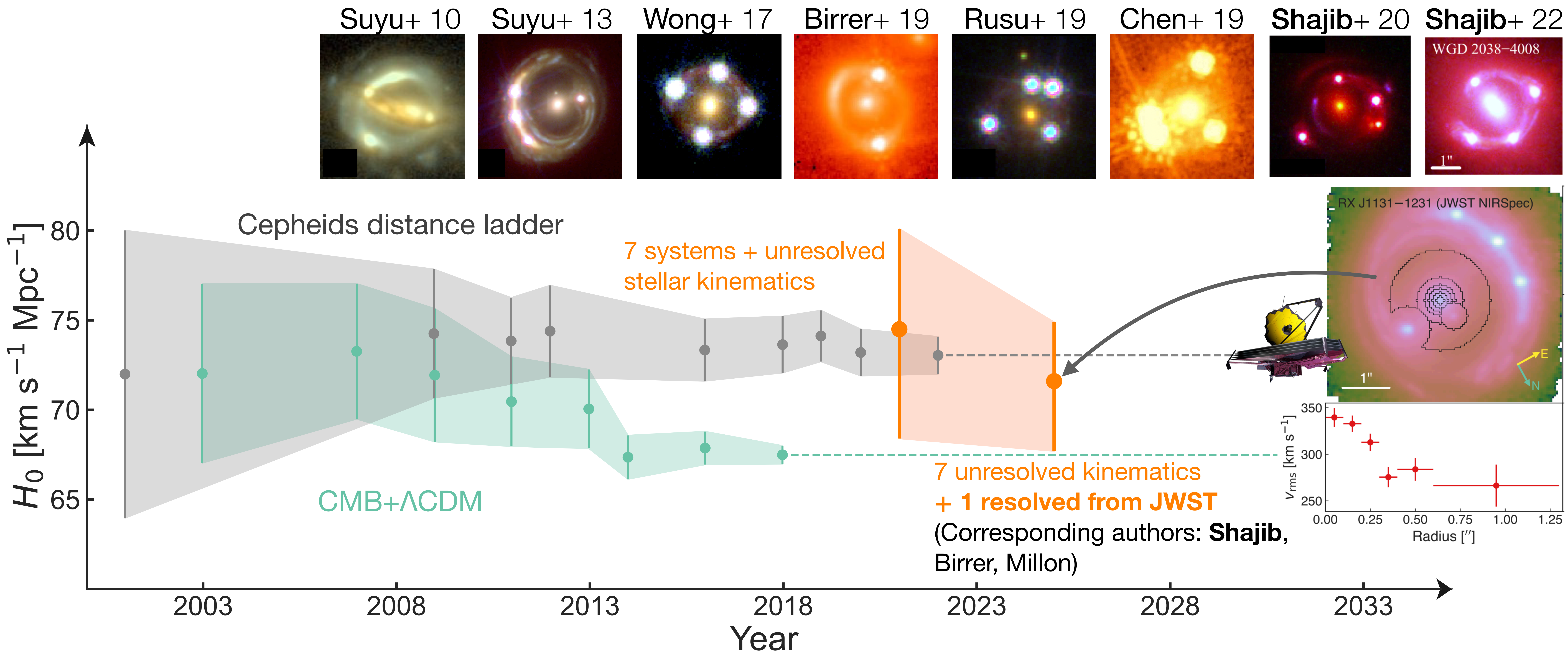
Mass-Anisotropy degeneracy (MAD)

Spatially resolved stellar kinematics constrain *H_0* to 9% from only one time-delay lens.



Planck 18; Riess+ 22

In 2025, the TDCOSMO collaboration measured H_0 blindly to 5% from 8 systems with the mass-sheet degeneracy constrained using kinematics.



Planck 18; Riess+ 22; **TDCOSMO Collaboration 2025**

Improving systematic error budget:

$$G_{\mathrm{mod}}(ln\lambda) = \sum_{n=1}^{N} w_n \left\{ [T_n(ln\lambda) * \mathscr{L}_n(cln\lambda)] \sum_{k=1}^{K} a_k \mathscr{P}_k(ln\lambda) \right\} + \sum_{l=0}^{L} b_l \mathscr{P}_l(ln\lambda) + \sum_{j=1}^{J} c_j S_j(ln\lambda)$$

Model spectra

Wavelength

Template

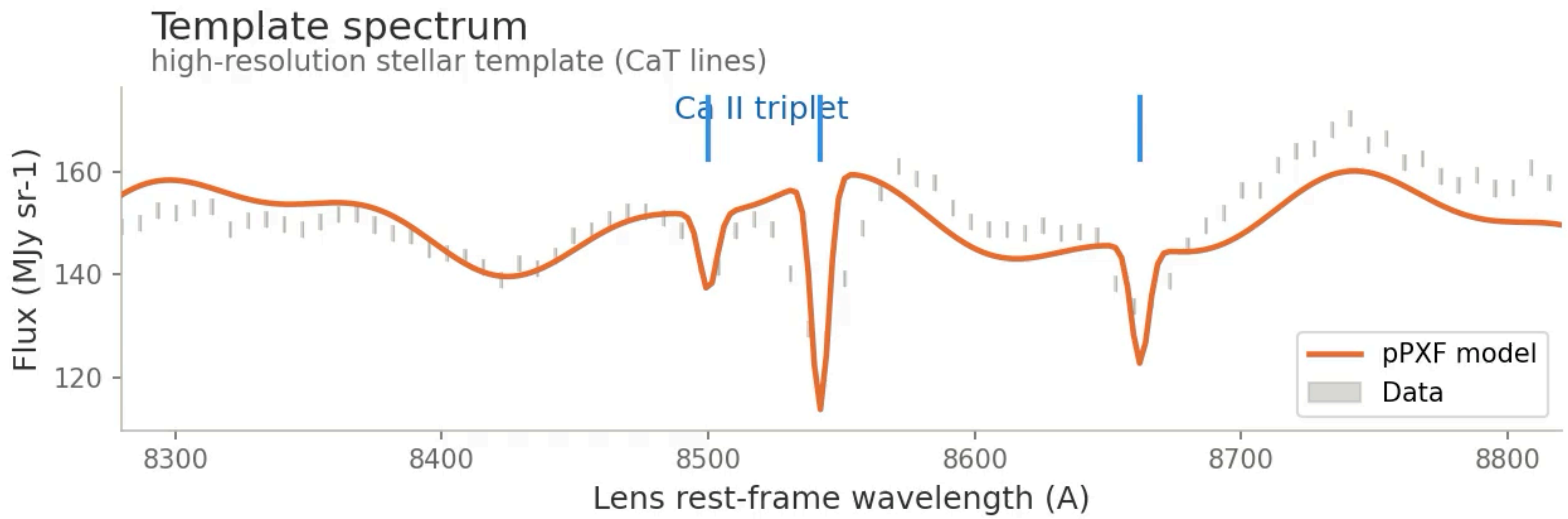
Instrument LSF

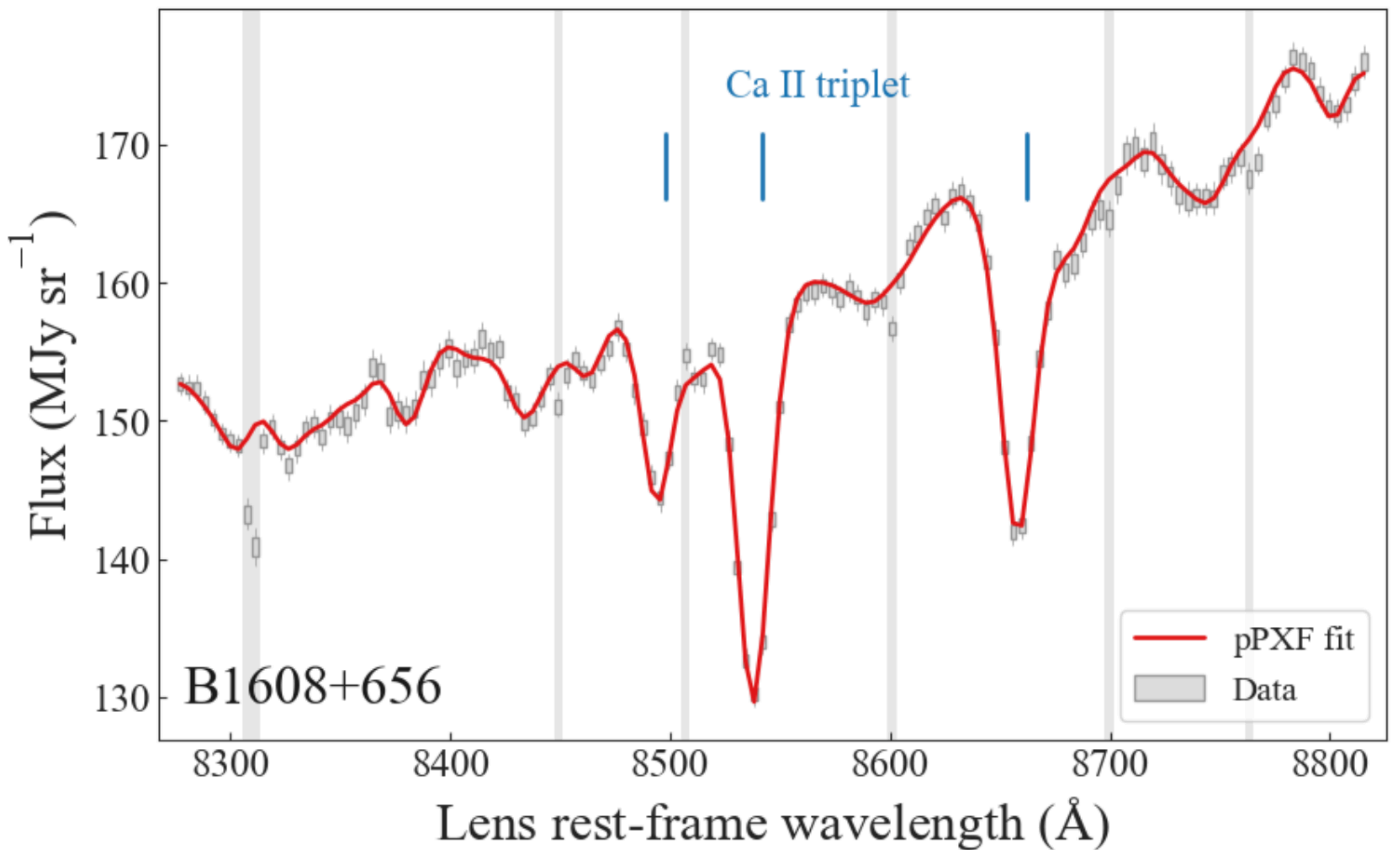
Multiplicative polynomial

Additive polynomial

Background

pPXF fit

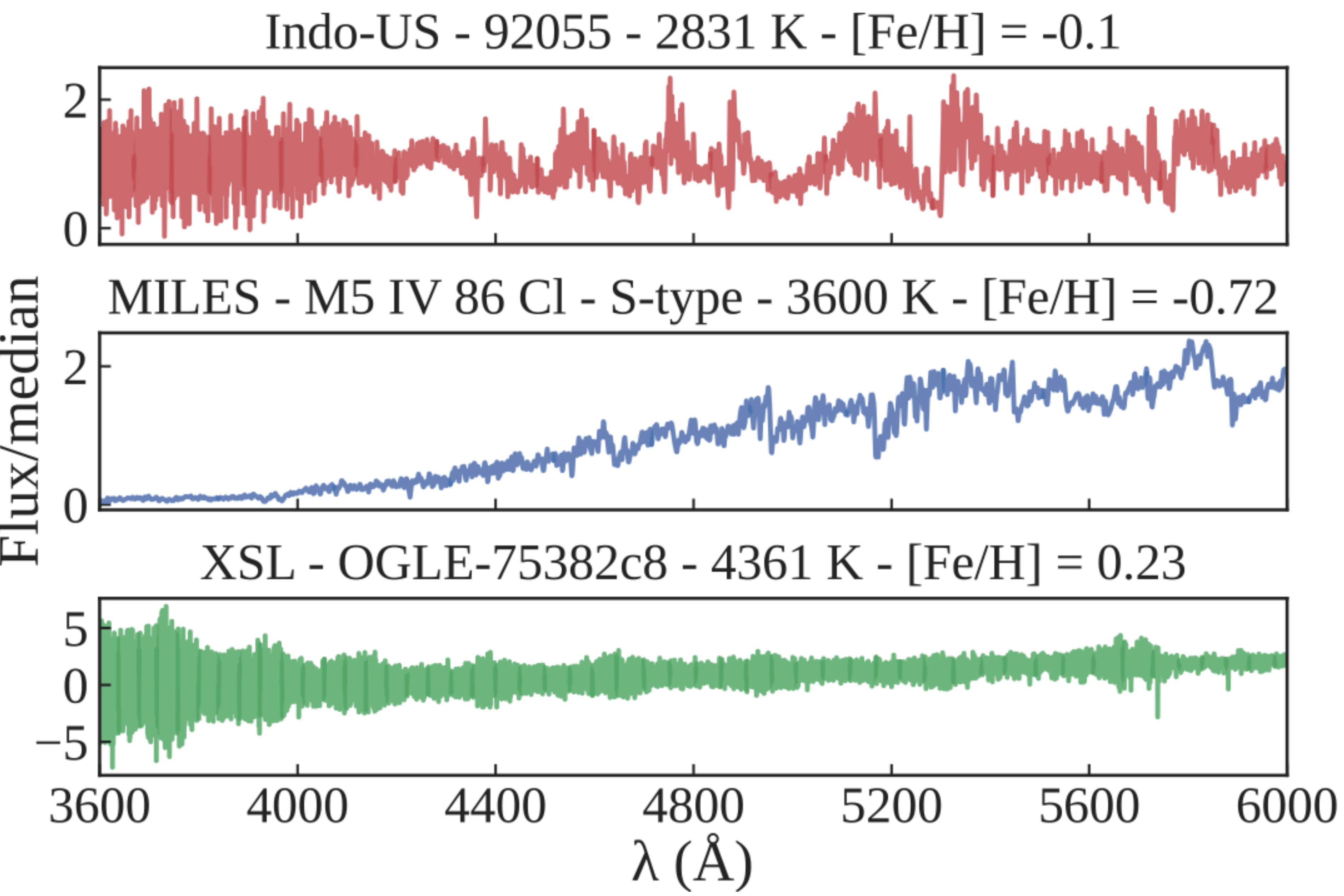


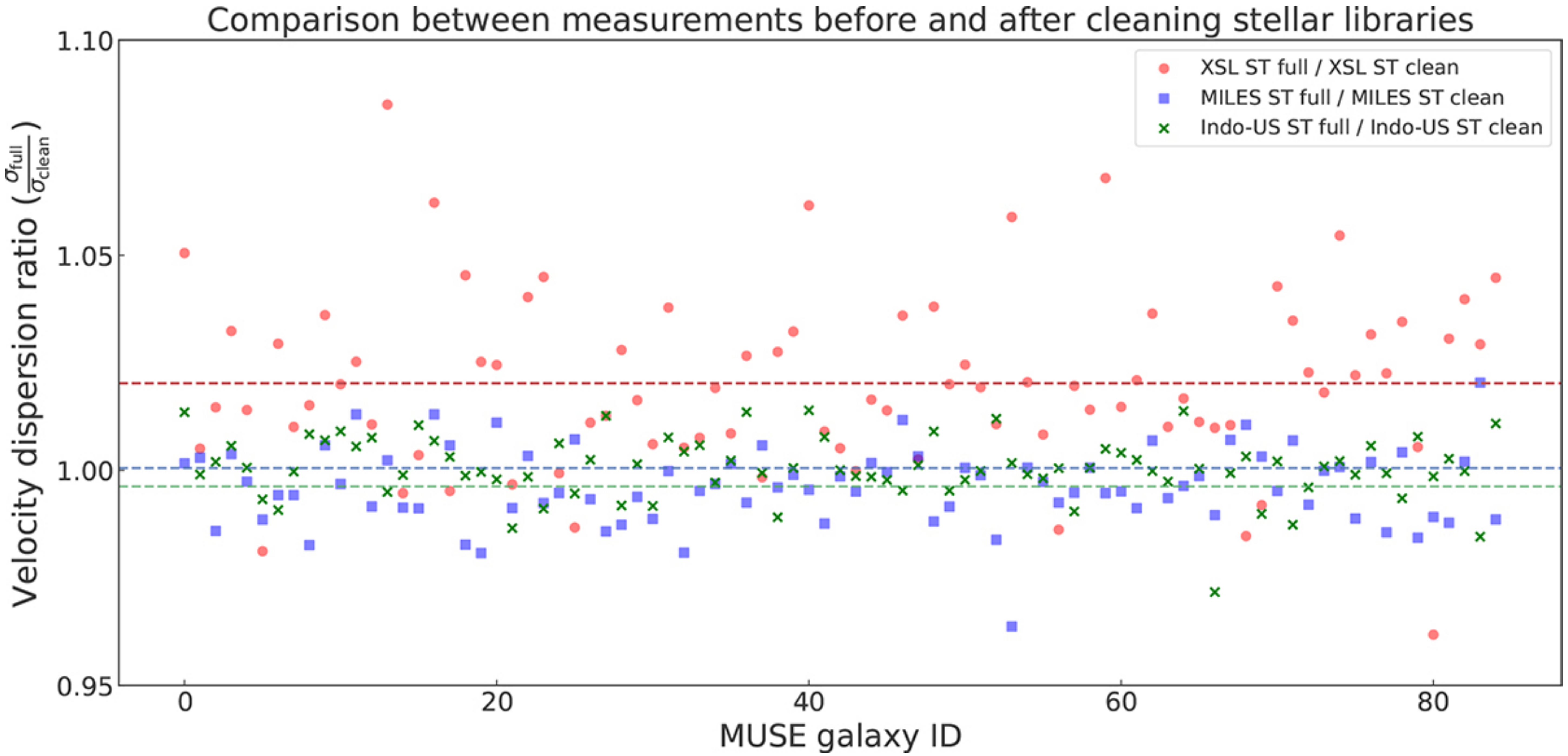


Bad templates provide bias fits:

$$G_{\mathrm{mod}}(ln\lambda) = \sum_{n=1}^{N} w_n \left\{ [T_n(ln\lambda) * \mathscr{L}_n(cln\lambda)] \sum_{k=1}^{K} a_k \mathscr{P}_k(ln\lambda) \right\} + \sum_{l=0}^{L} b_l \mathscr{P}_l(ln\lambda) + \sum_{j=1}^{J} c_j S_j(ln\lambda)$$

Examples of rejected templates





Step	# MILES	# XSL	# Indo-US
Initial	985	830	1273
After library authors' cuts [(a)]	801	530	1273
With T_{eff} and Fe/H [(b)]	790	522	1006
After a visual inspection	**789**	**496**	**992**

Use 'cleaned' stellar library

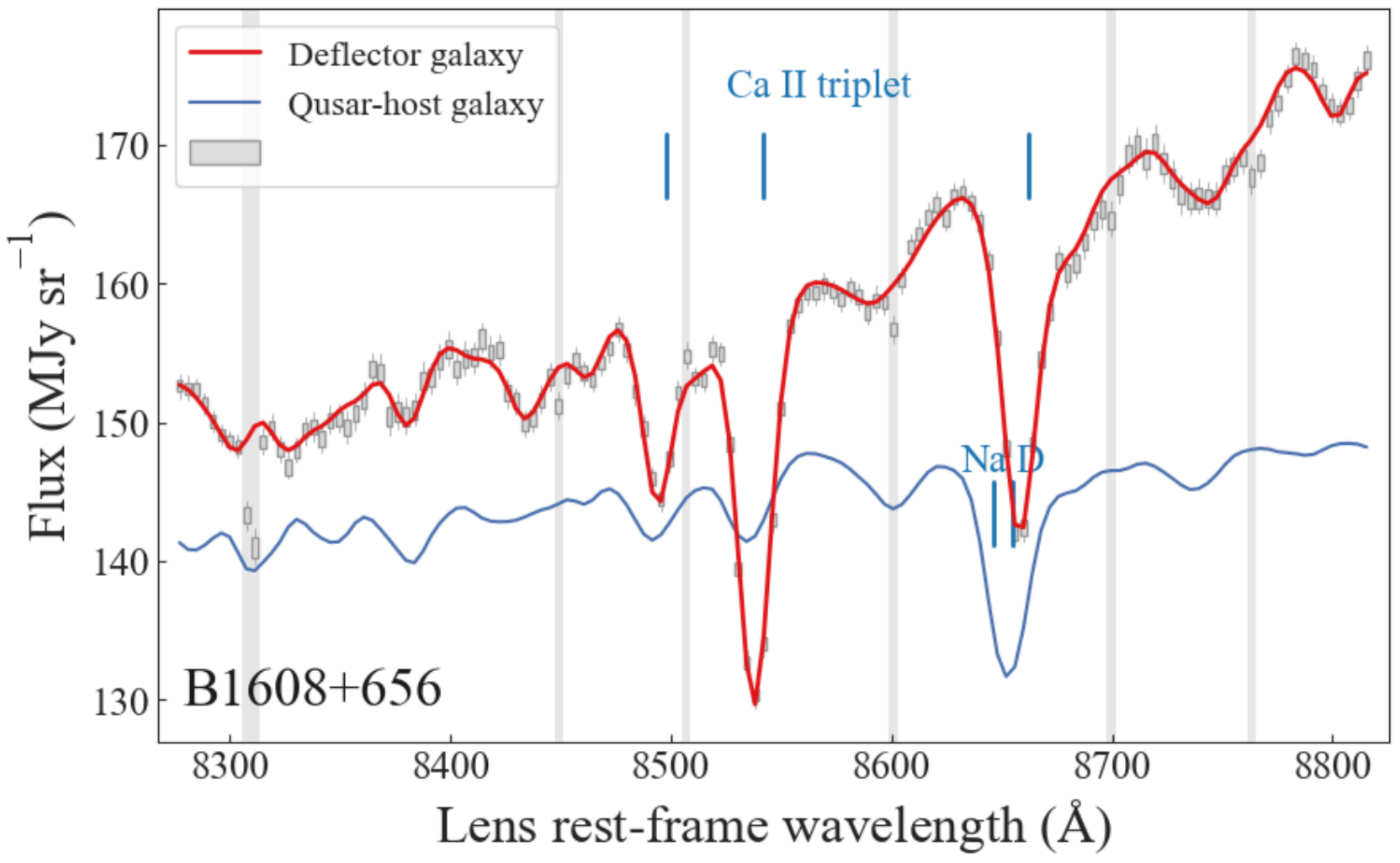
Marginalize measurements from all template libraries using Bayesian Information Criterion (BIC)

(Knabel & Mozumdar+2025)

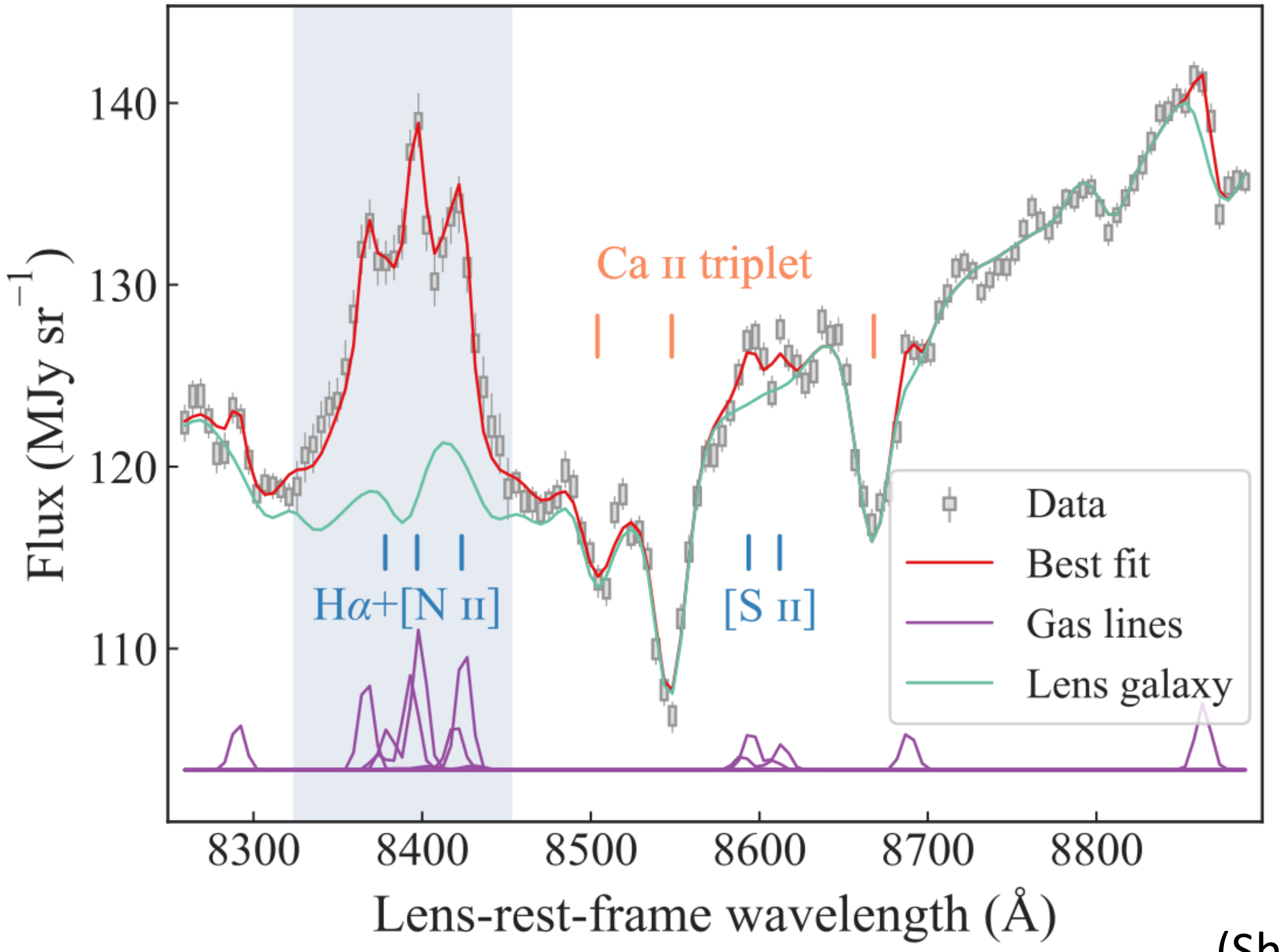
Improving systematic error budget:

$$G_{\rm mod}(ln\lambda) = \sum_{n=1}^{N} w_n \left\{ [T_n(ln\lambda) * \mathscr{L}_n(cln\lambda)] \sum_{k=1}^{K} a_k \mathscr{P}_k(ln\lambda) \right\} + \sum_{l=0}^{L} b_l \mathscr{P}_l(ln\lambda) + \sum_{j=1}^{J} c_j S_j(ln\lambda)$$

Observed spectra = Lens galaxy + Qusar-host galaxy + Quasar image



(Mozumdar+ 2026, inpreparation)



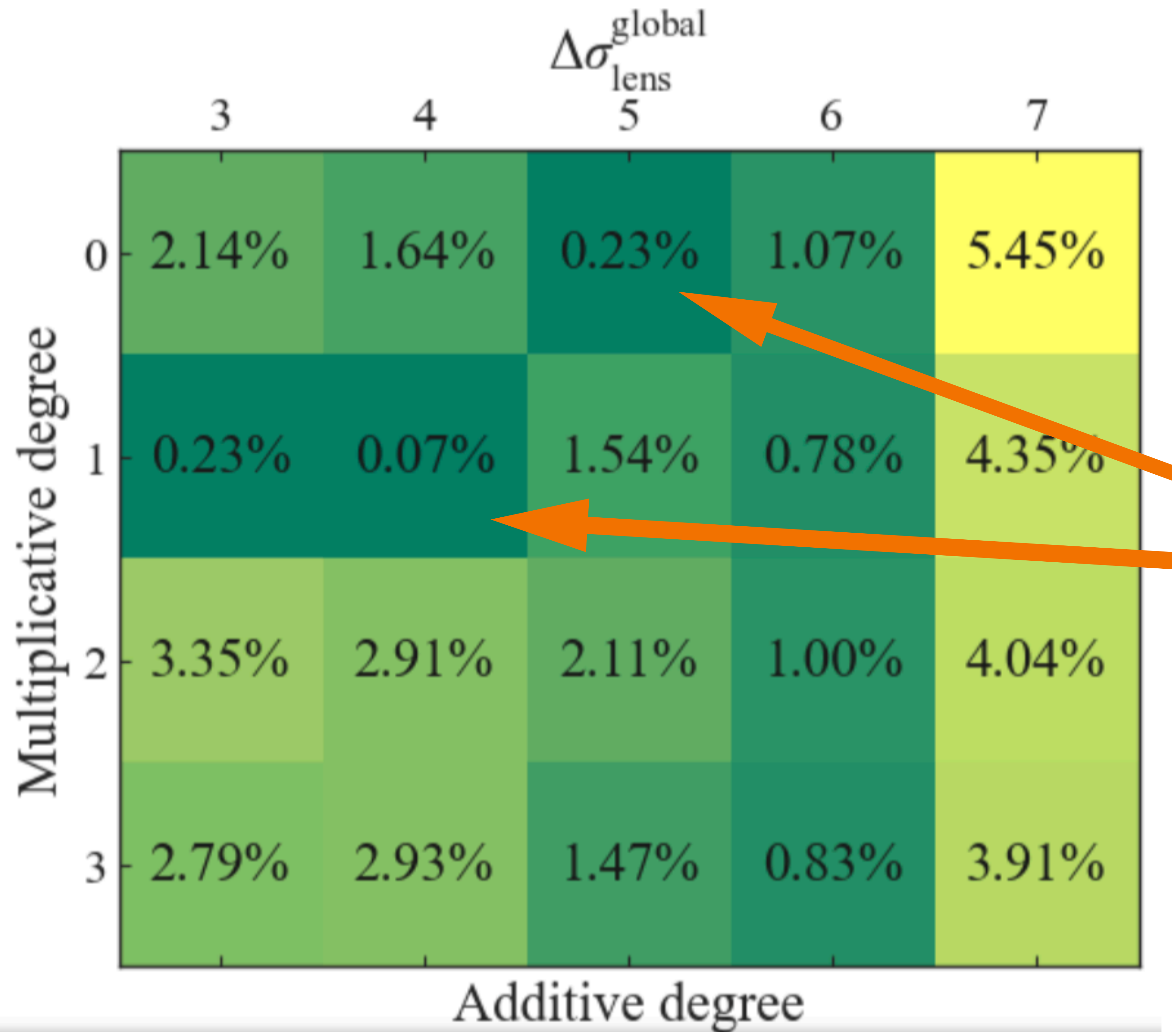
(Shajib+ 2026)

Include all three components in the pPXF fit

Improving systematic error budget:

$$G_{\mathrm{mod}}(ln\lambda) = \sum_{n=1}^{N} w_n \left\{ [T_n(ln\lambda) * \mathscr{L}_n(cln\lambda)] \sum_{k=1}^{K} a_k \mathscr{P}_k(ln\lambda) \right\} + \sum_{l=0}^{L} b_l \mathscr{P}_l(ln\lambda) + \sum_{j=1}^{J} c_j S_j(ln\lambda)$$

Polynomial order grid



In a prefect world, measurement from different template libraries should be same.

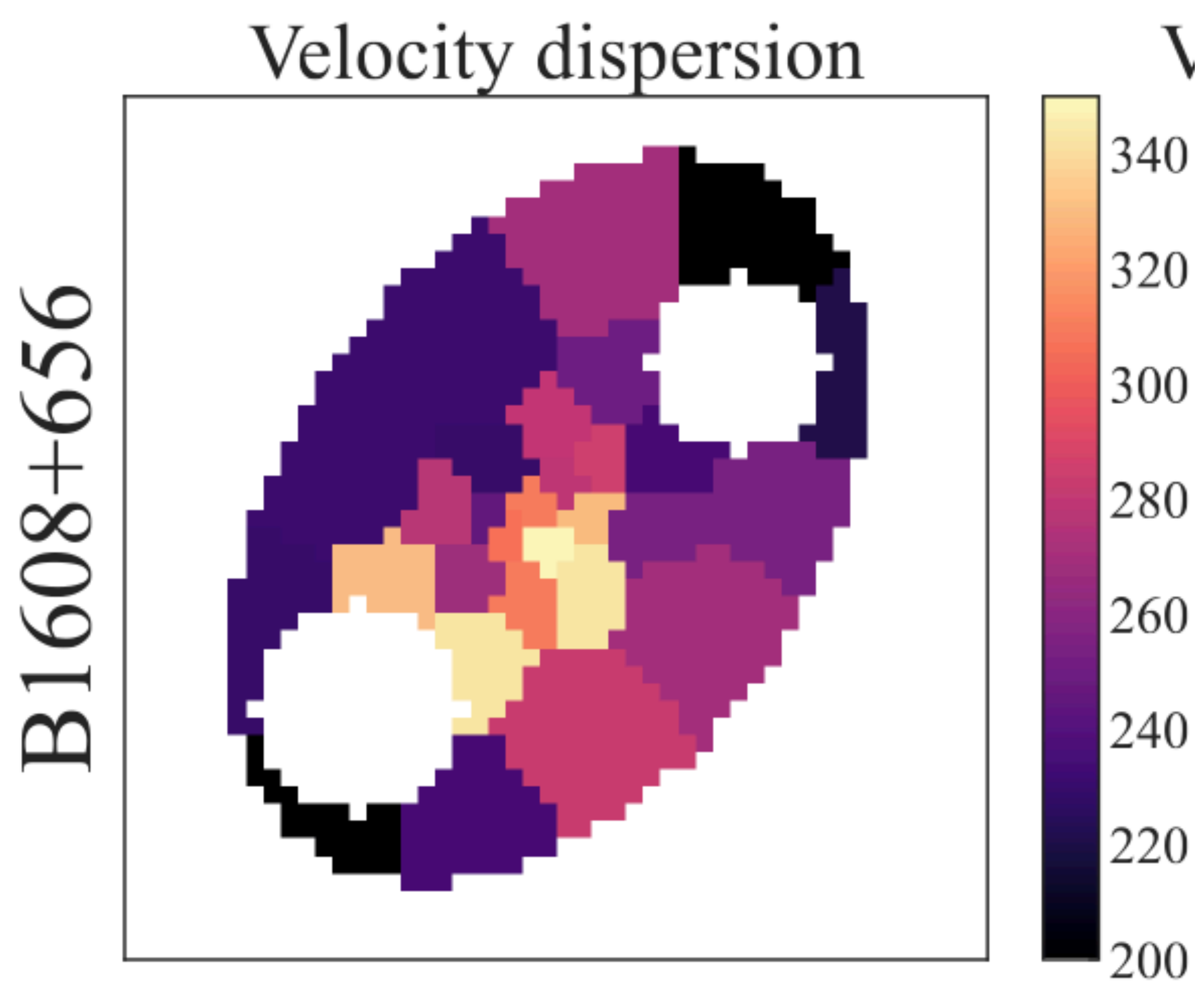
The optimal polynomial degree pair minimizes the scatter among measurements using different stellar libraries

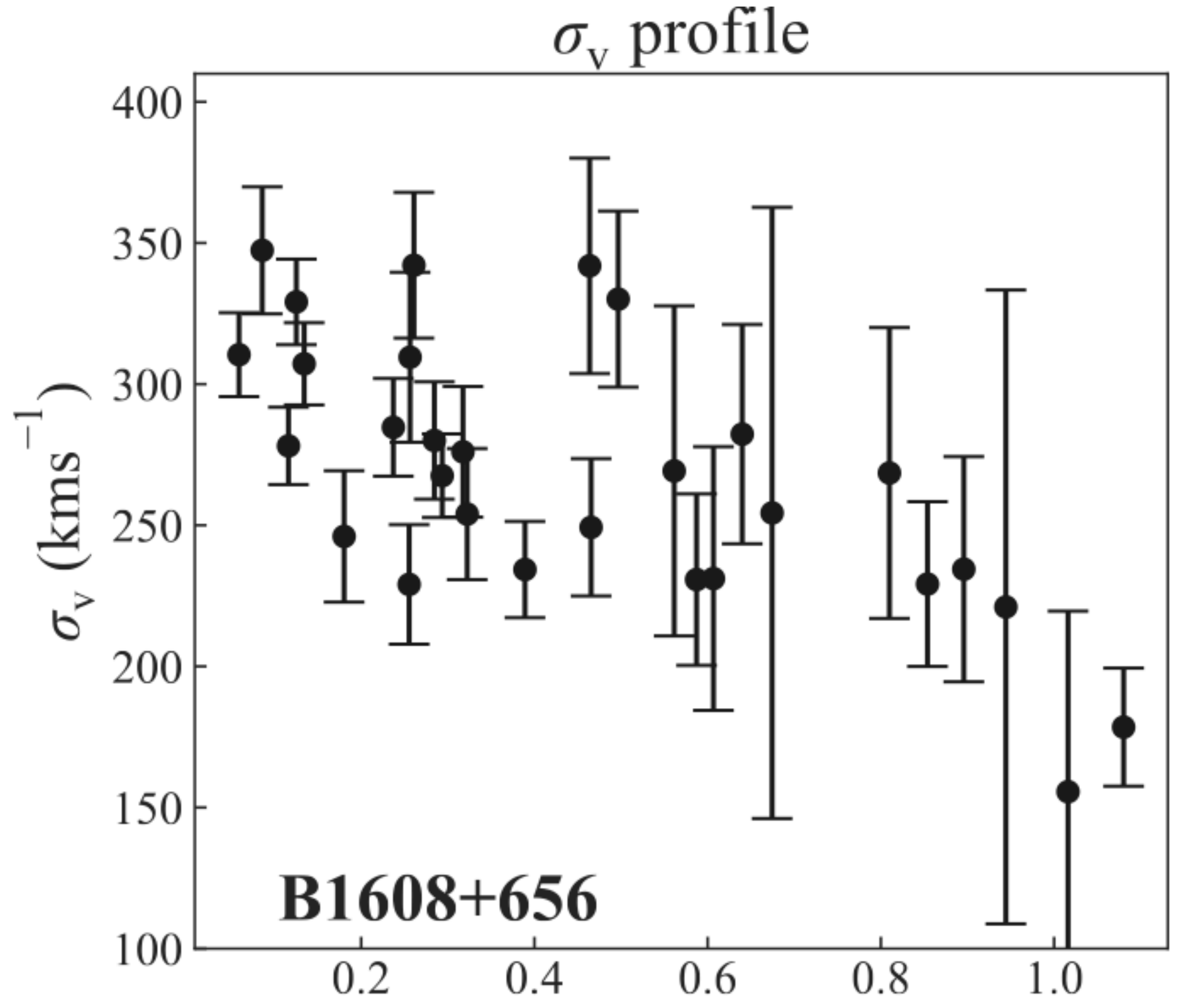
Improving systematic error budget:

$$G_{\rm mod}(ln\lambda) = \sum_{n=1}^{N} w_n \left\{ [T_n(ln\lambda) * \mathscr{L}_n(cln\lambda)] \sum_{k=1}^{K} a_k \mathscr{P}_k(ln\lambda) \right\} + \sum_{l=0}^{L} b_l \mathscr{P}_l(ln\lambda) + \sum_{j=1}^{J} c_j S_j(ln\lambda)$$

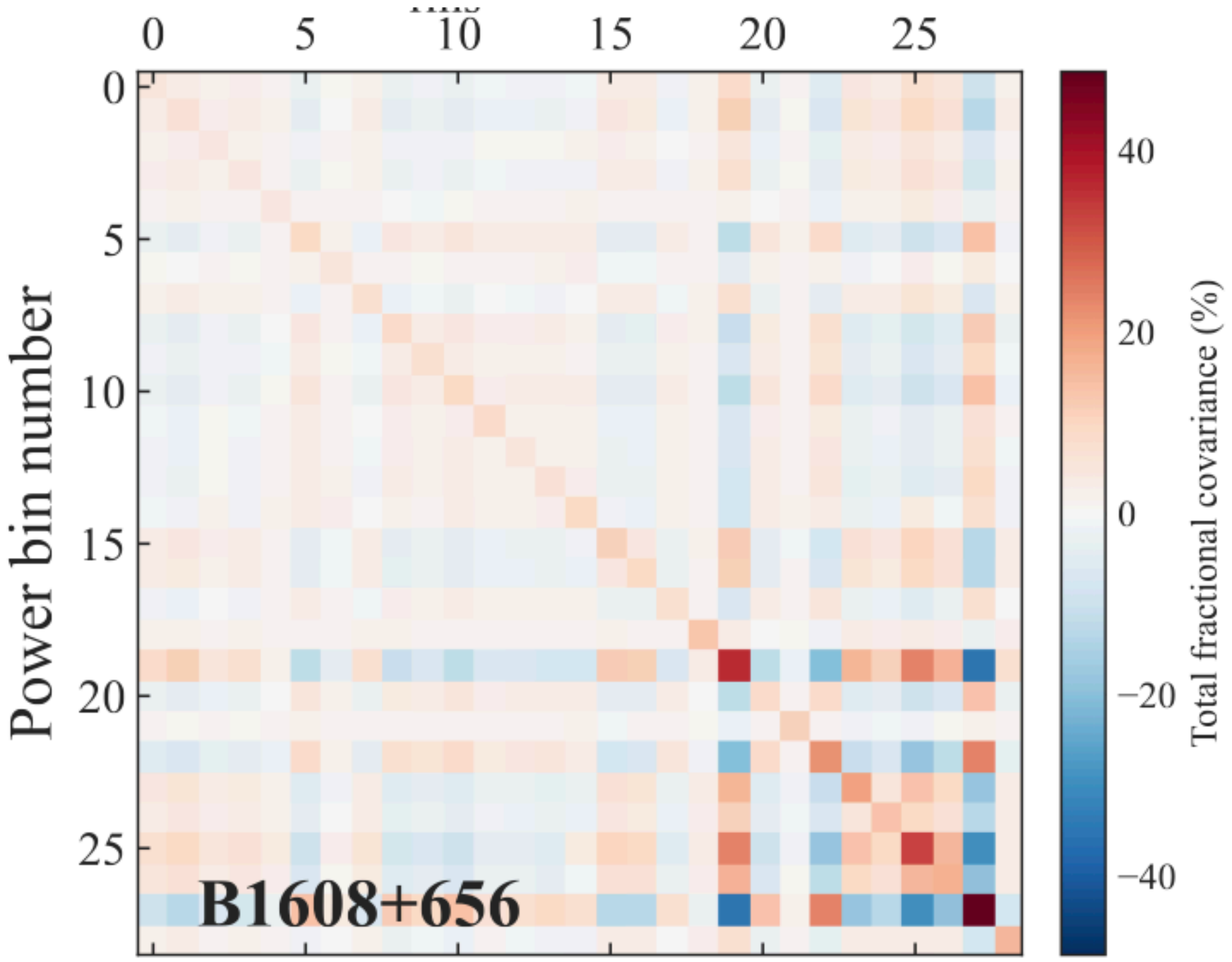
systematic source	choices
template library	Indo-US, XSL
polynomial degree ($a_{\rm deg}, m_{\rm deg}$)	B1608+656: [(0,4), (1,3), (1,6), (0,5)]
	J1206+4332: [(1,4), (2,6), (1,6), (0,5)]
outlier rejection threshold	2.50σ, 2.70σ

16 combination of systemic choice





Covariance Matrix



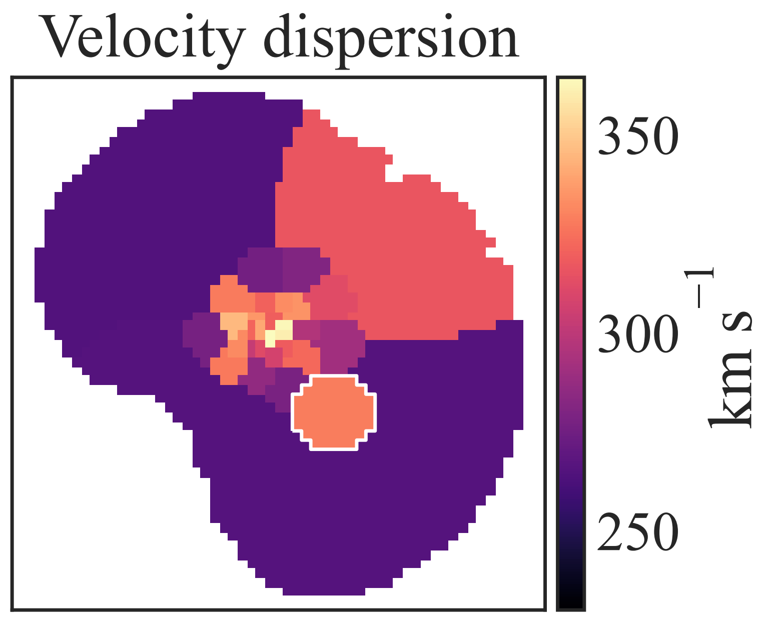
(Mozumdar+ 2026, in preparation)

Improving random error budget:

TDCOSMO 2025 JWST-IFU Sample

- Increase sample size with resolved kinematics -

TDCOSMO 2025: **1** JWST/IFU lens



RXJ1131-1231

Shajib+2026

Improving random error budget:

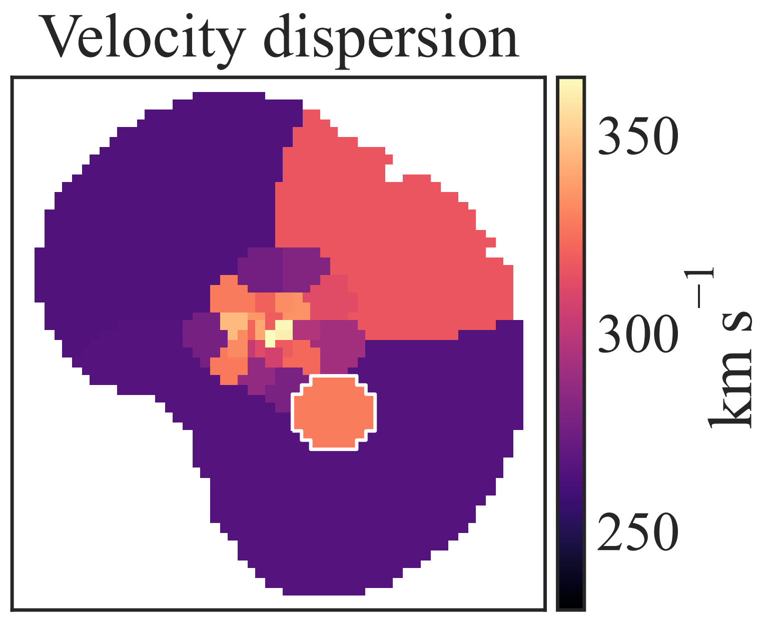
- Increase sample size with resolved kinematics -

TDCOSMO 2025: **1** JWST/IFU lens

TDCOSMO 2026: **6** JWST/IFU lens

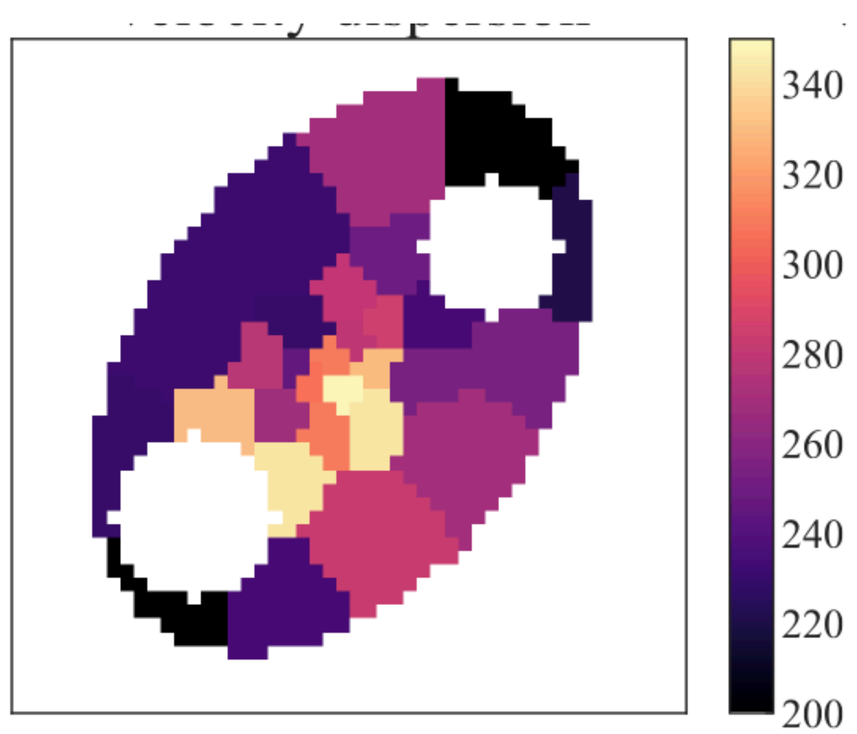
TDCOSMO 2026+: **16** JWST/IFU lens

TDCOSMO 2026 JWST-IFU Sample

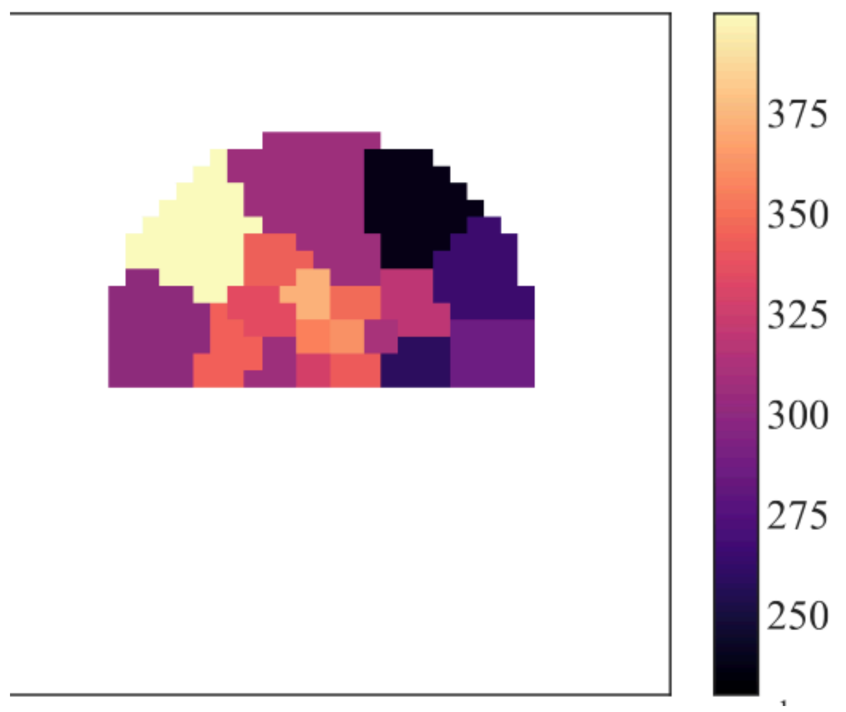


RXJ1131-1231

Shajib+2026

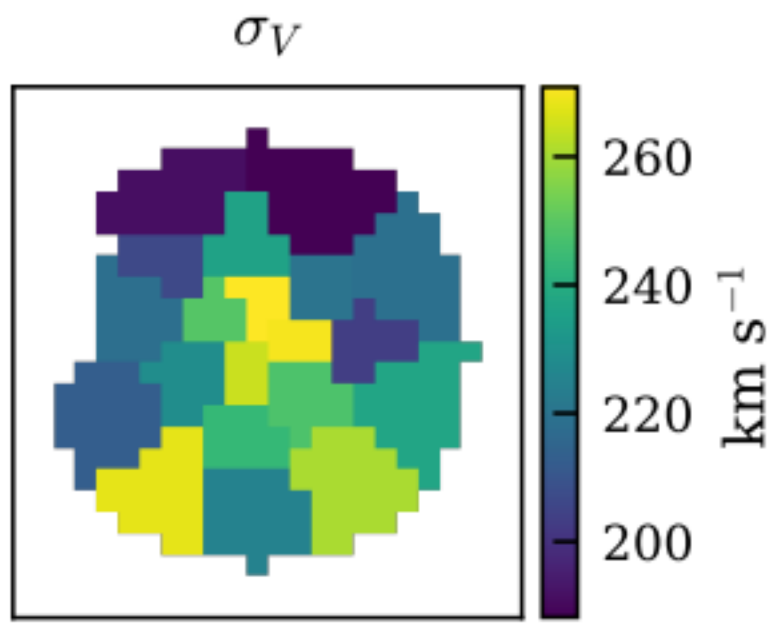


B1608+656

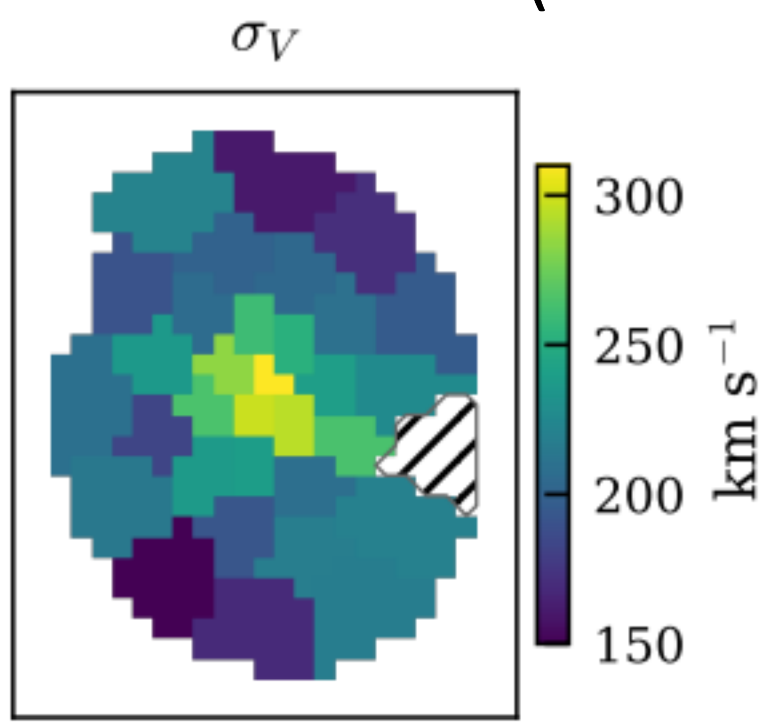


J1206+4332

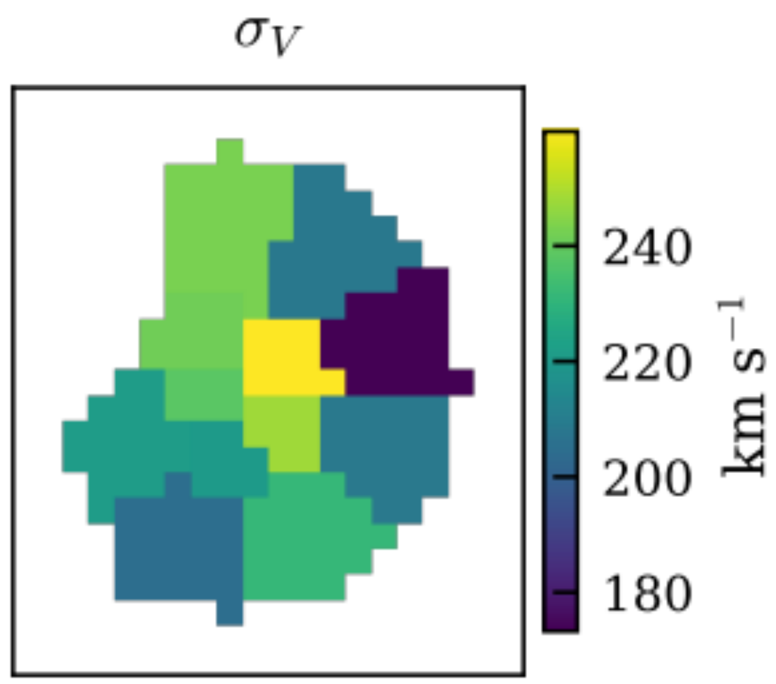
(Mozumdar+ 2026, in preparation)



HE0435-1223



PG1115+080



WFI2033-4723

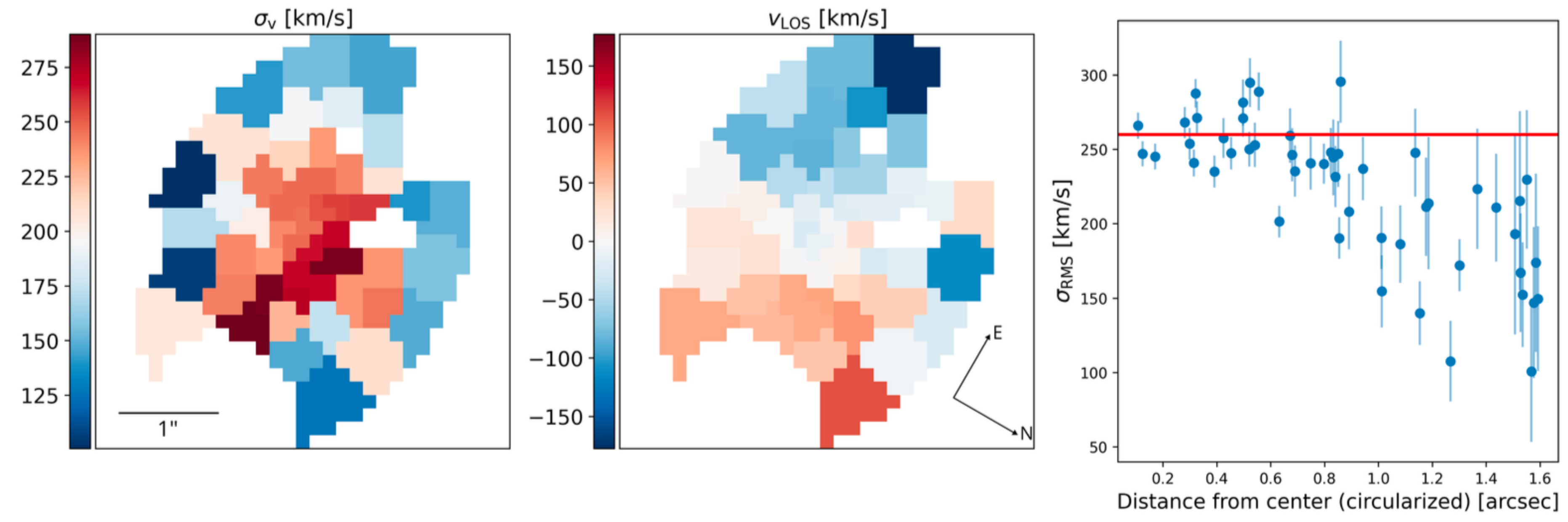
(Knabel+ 2026, in preparation)

We need perfect reduction of NIRSpec data cube - Check Shawn’s talk tomorrow

Improving random error budget:

Ground based IFU (Keck-KCWI and VLT/MUSE)

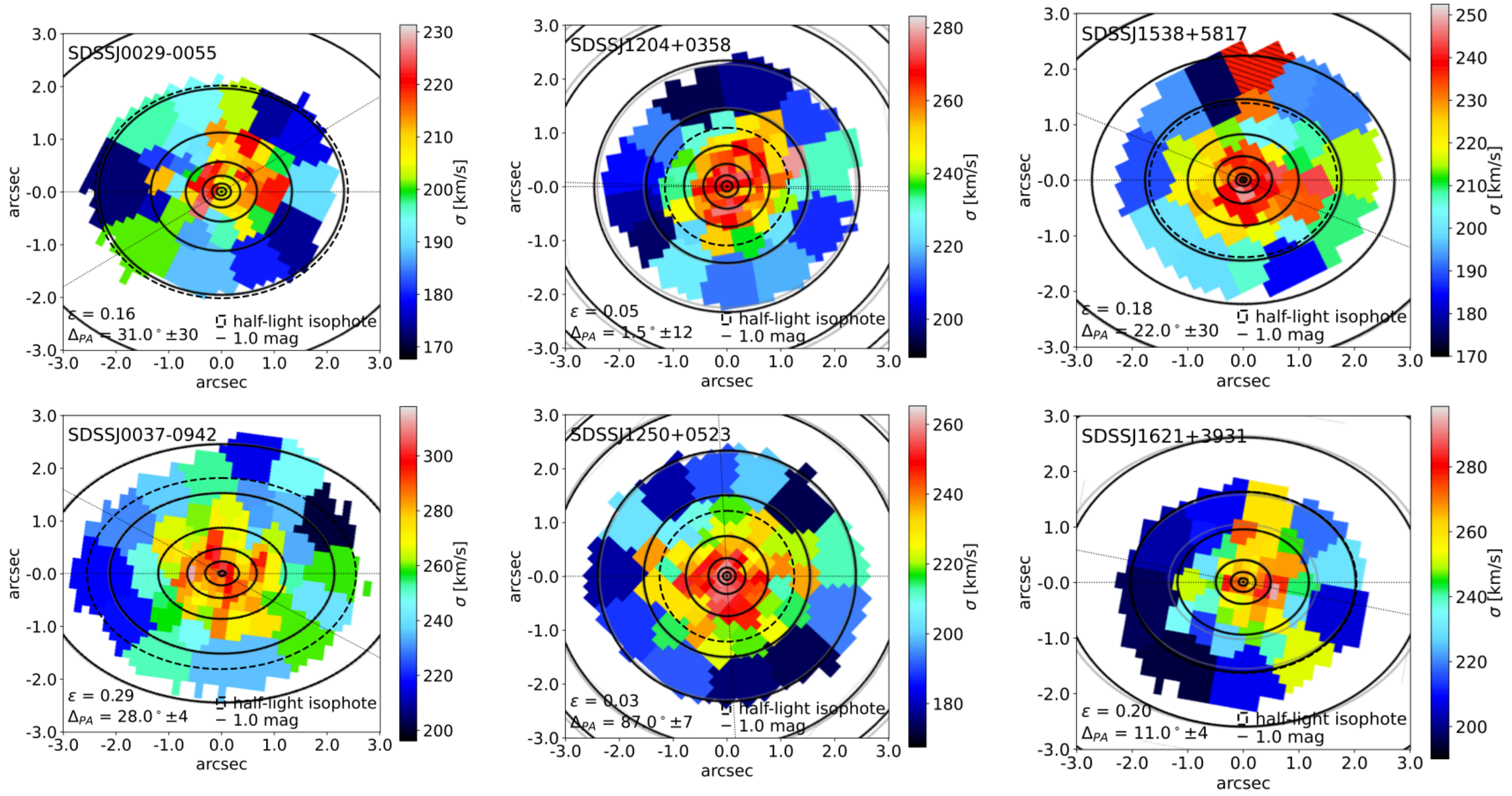
TDCOSMO 2026 - 3 KCWI/MUSE IFU



J1433+6007

Sheu+2026

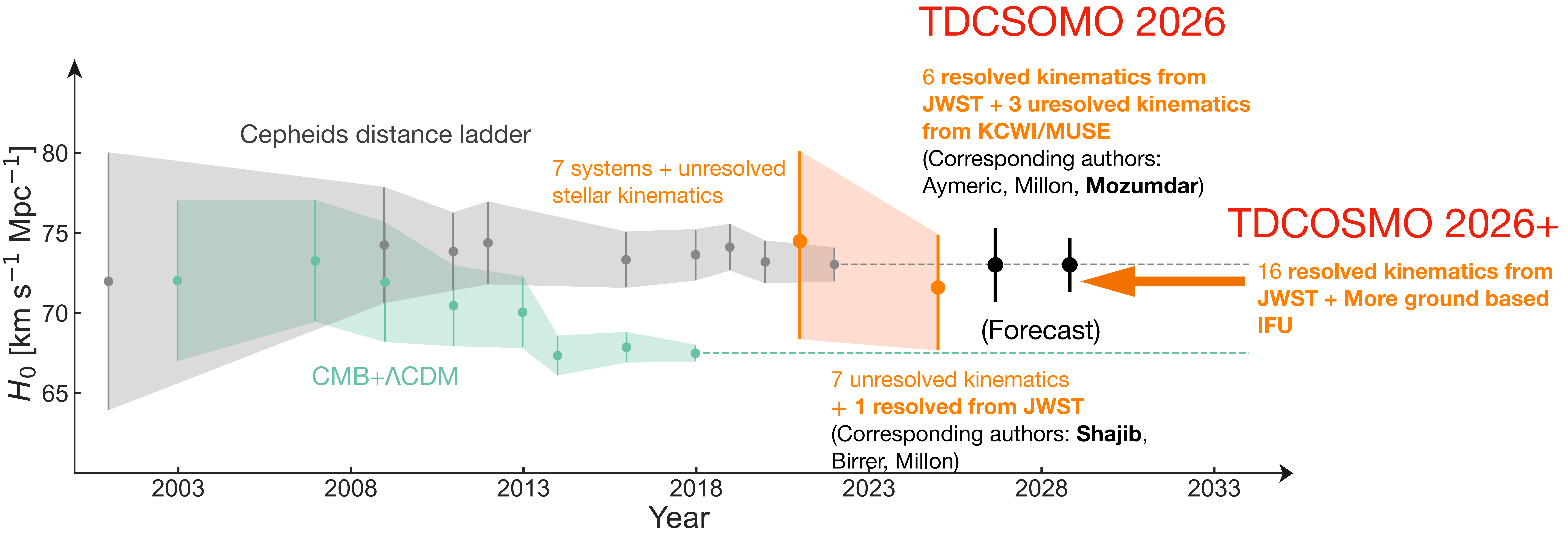
External dataset - SLACS and SL2S



(Knabel+ 2025)

Improving precision on H_0 to 2% level:

TDCOSMO 2026 is almost here - stay tuned !



Planck 18; Riess+ 22; **TDCOSMO Collaboration**

Summary :

- Precision kinematics is integral for precision H0 via time-delay cosmography, without any mass profile assumption.
- Resolved kinematics is most effective to alleviate both mass-sheet degeneracy (MSD) and mass-anisotropy degeneracy (MAD).
- We can control systematic uncertainty to ~1% level.
- We are improving random error budget by increasing sample size with JWST-IFU kinematics and ground based IFU kinematics.
- Time-delay cosmography can provide ~ 2% H_0, with 16 JWST based IFU data and plus other IFU and complementary datasets.