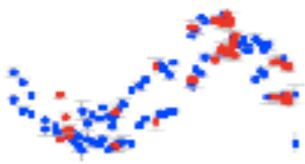
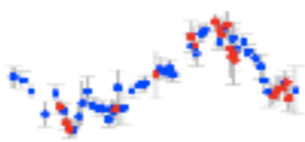
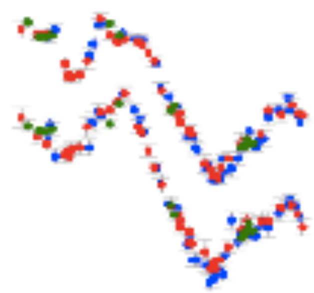
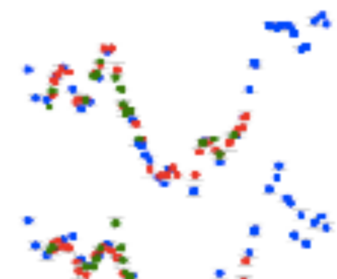
Measuring H_0 with Quasar Time Delays

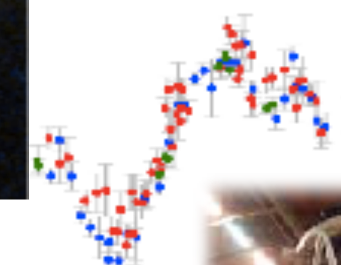
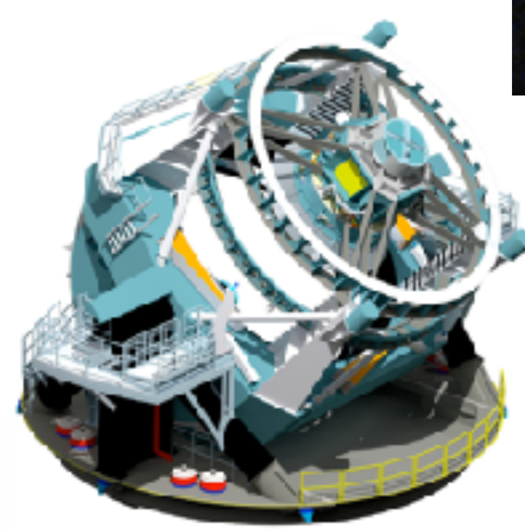
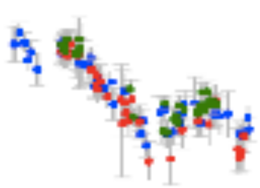
Frédéric Courbin (EPFL, Switzerland)

For the COSMOGRAIL, H0LiCOW, STRIDES and SHARP collaborations



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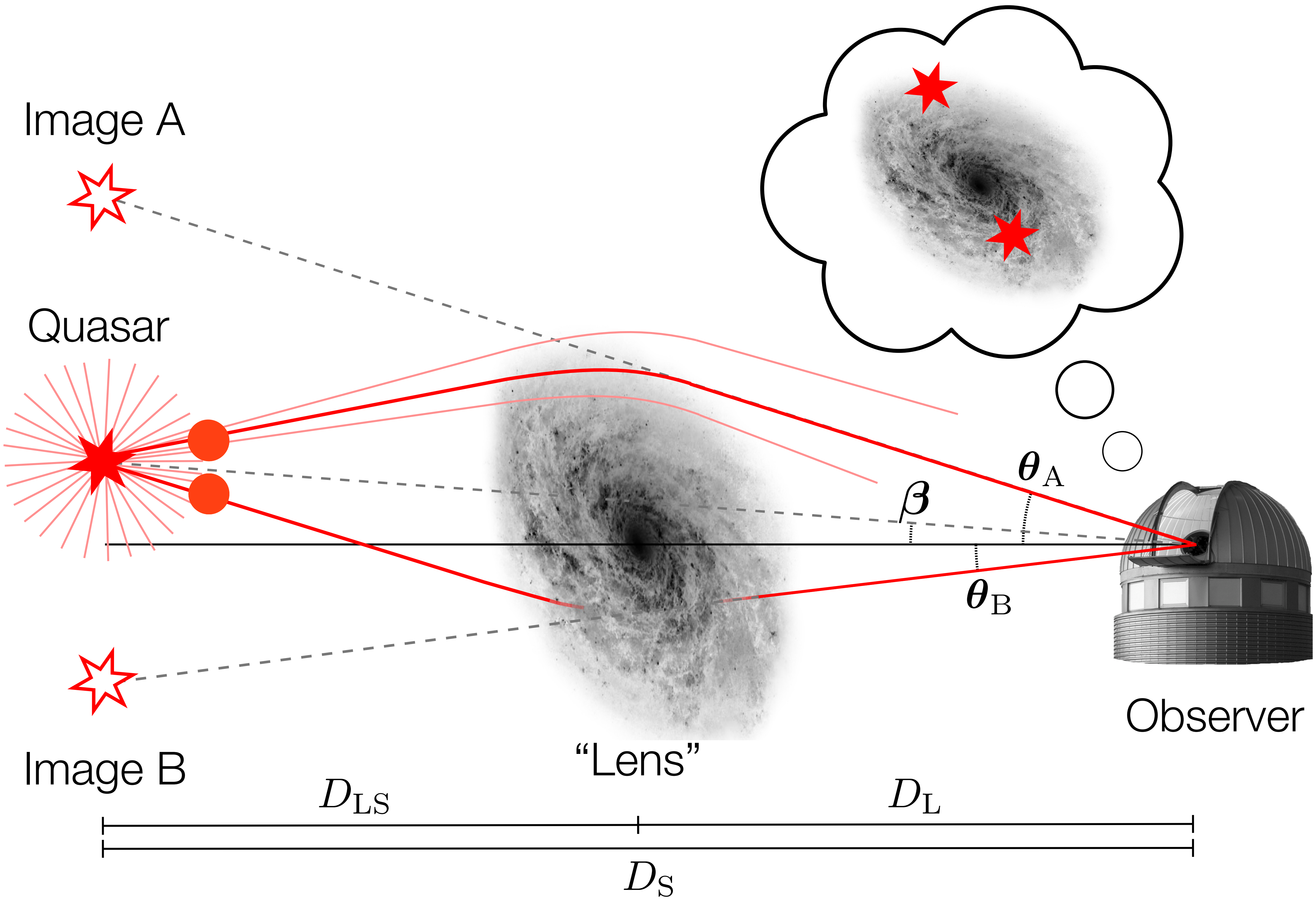
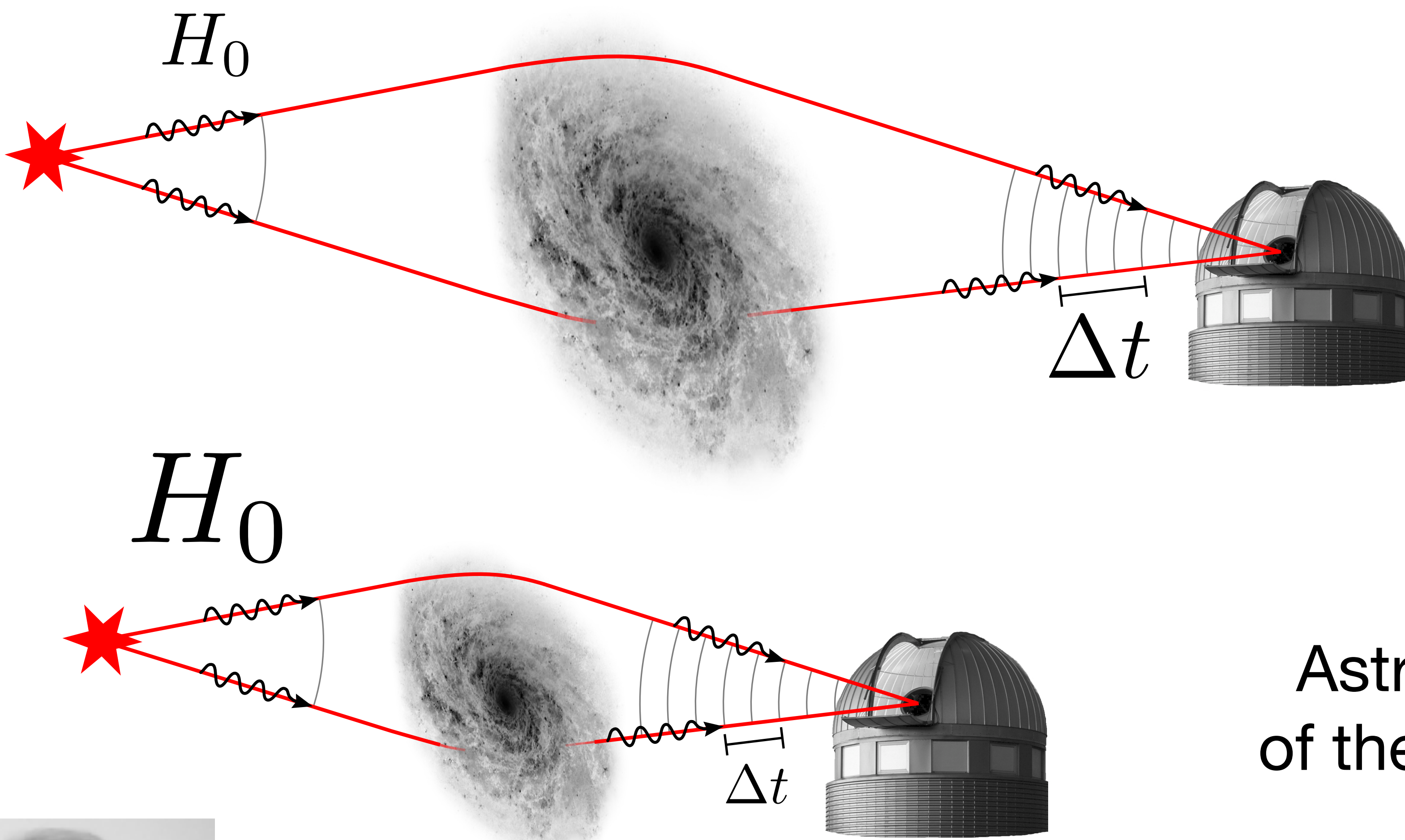
Chicago - October 2019

Time Delays in Strongly Lensed Quasars



Time Delays Measure the Hubble Constant H_0



Lens potential at the images

Source position (unconstrained)

Astrometry of the images

$$\Delta t = \frac{1+z_{\rm L}}{c}\underbrace{\frac{D_{\rm L}D_{\rm S}}{D_{\rm LS}}}_{\propto 1/H_0}\cdot\Delta\left(\frac{1}{2}|\vec{\theta}-\vec{\beta}|^2-\psi(\vec{\theta})\right)$$

Time delays provide a *single-step* and *independent* constraint on H_0.

Example of RX J1131-123

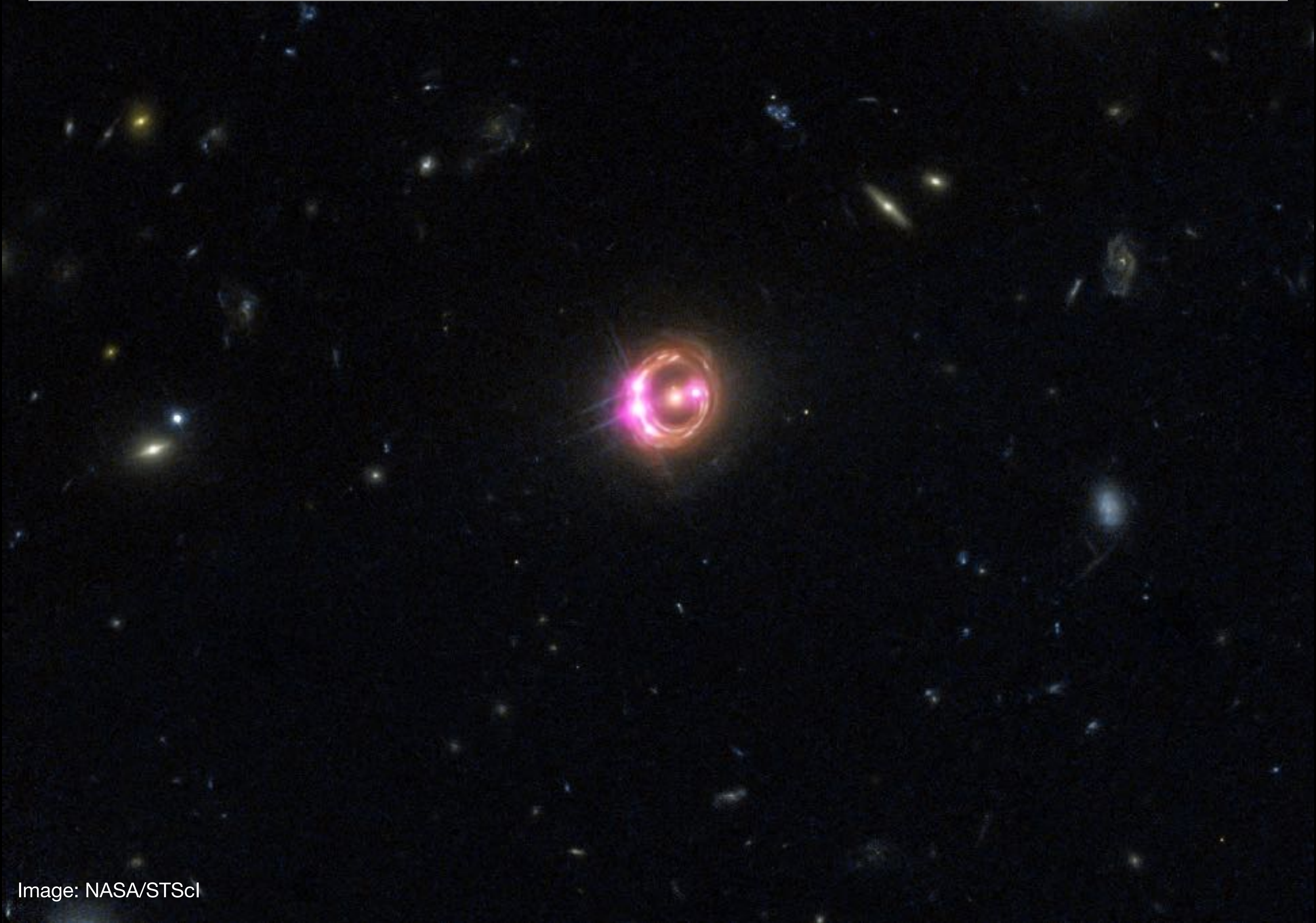


Image: NASA/STScI

Example of RX J1131-123

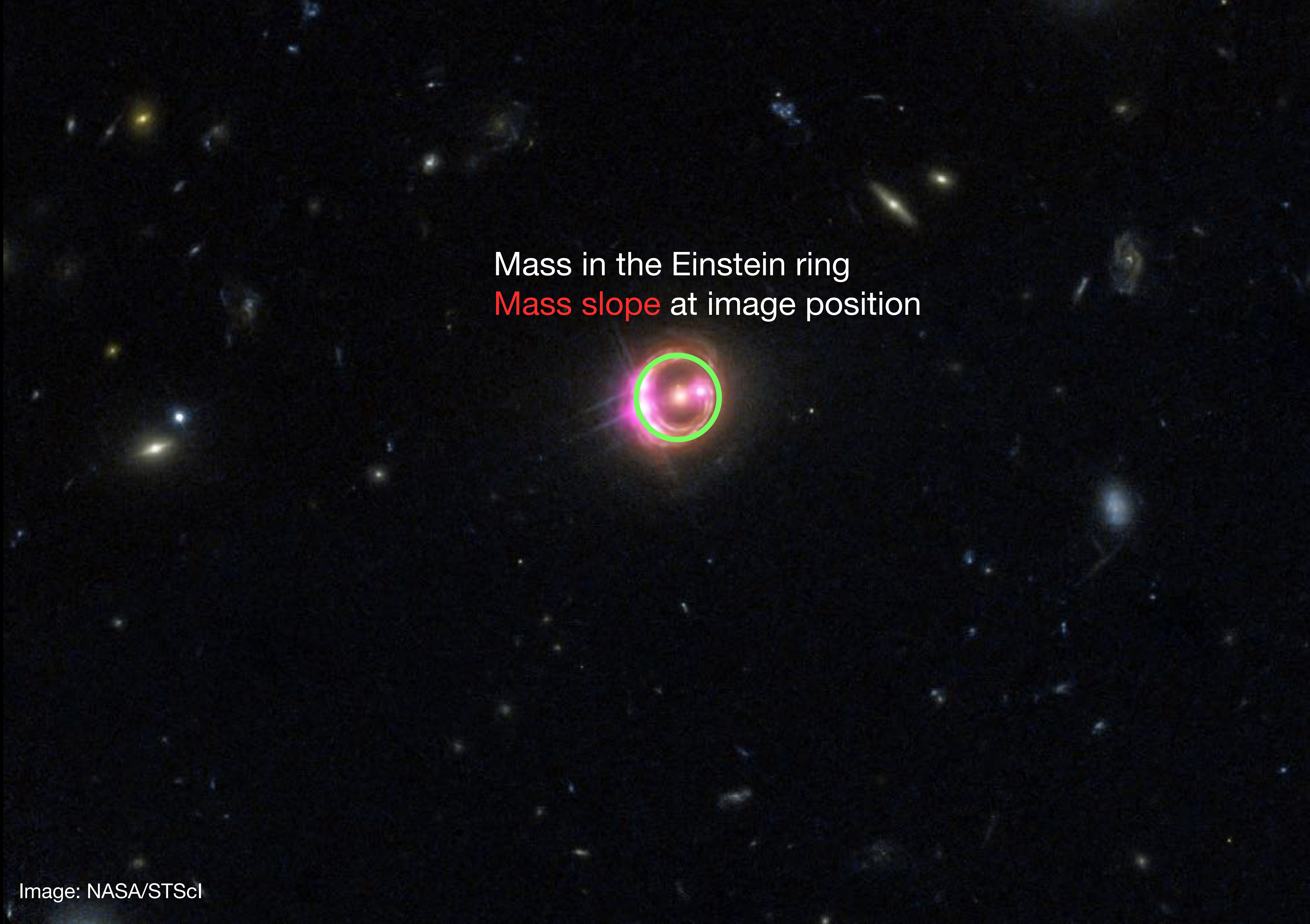


Image: NASA/STScI

Example of RX J1131-123

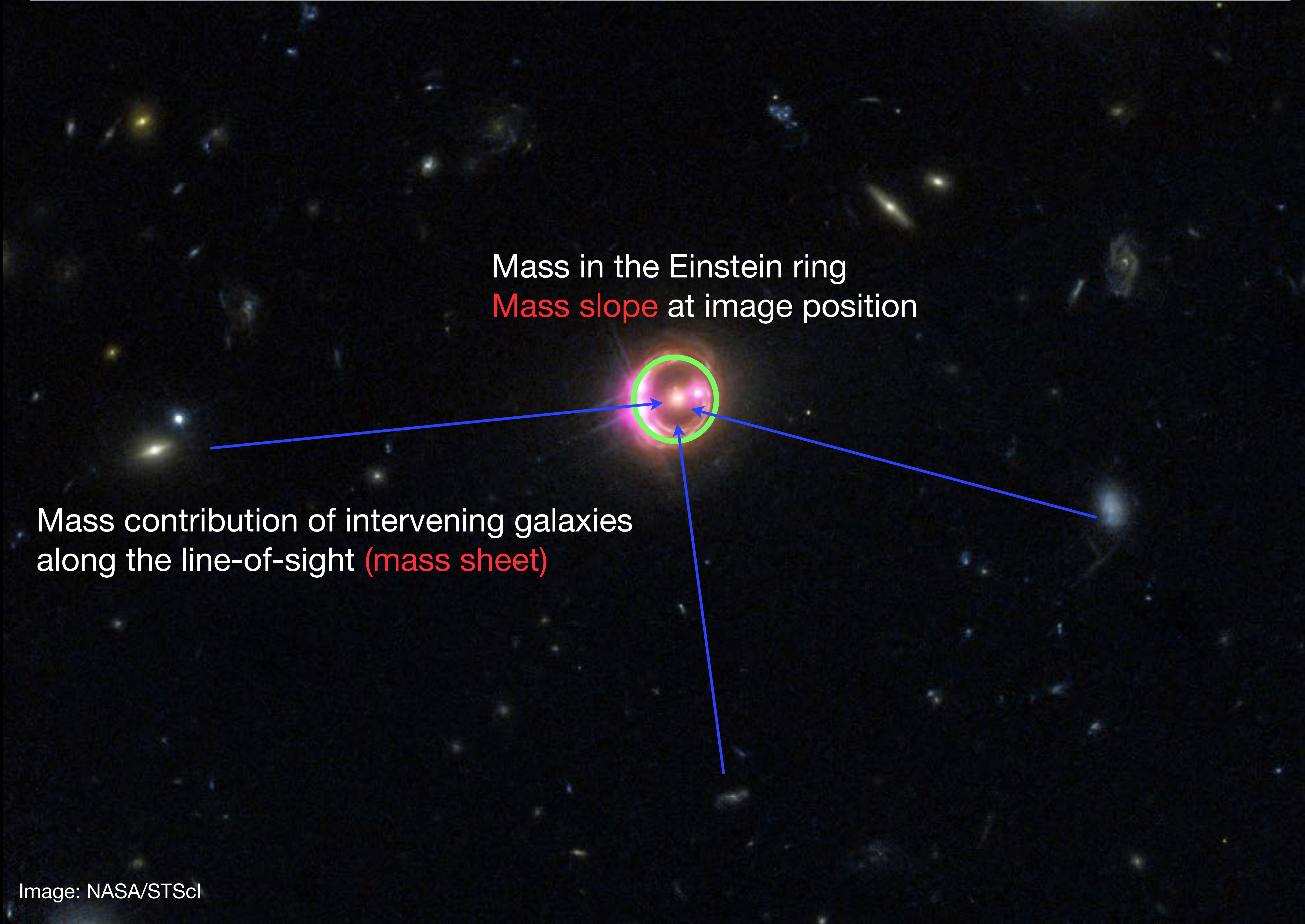


Image: NASA/STScI

What's Needed and State of the Art

	PAST
Time delays measurements	15-30%
Mass model for the lens	- Simplistic models - Few constraints
Environment of the lens	- External shear
Line of Sight contribution	- External shear

What's Needed and State of the Art

	PAST	NOW
Time delays measurements	15-30%	1-5%
Mass model for the lens	- Simplistic models - Few constraints	- Flexible elliptical models - Deep sharp HST/AO images - Lens dynamics
Environment of the lens	- External shear	- Include nearby companions - Multiplane lensing - Photo and spectro z
Line of Sight contribution	- External shear	- Galaxy counts - Cosmological simulations - Weak lensing

- **BLIND Analysis** !

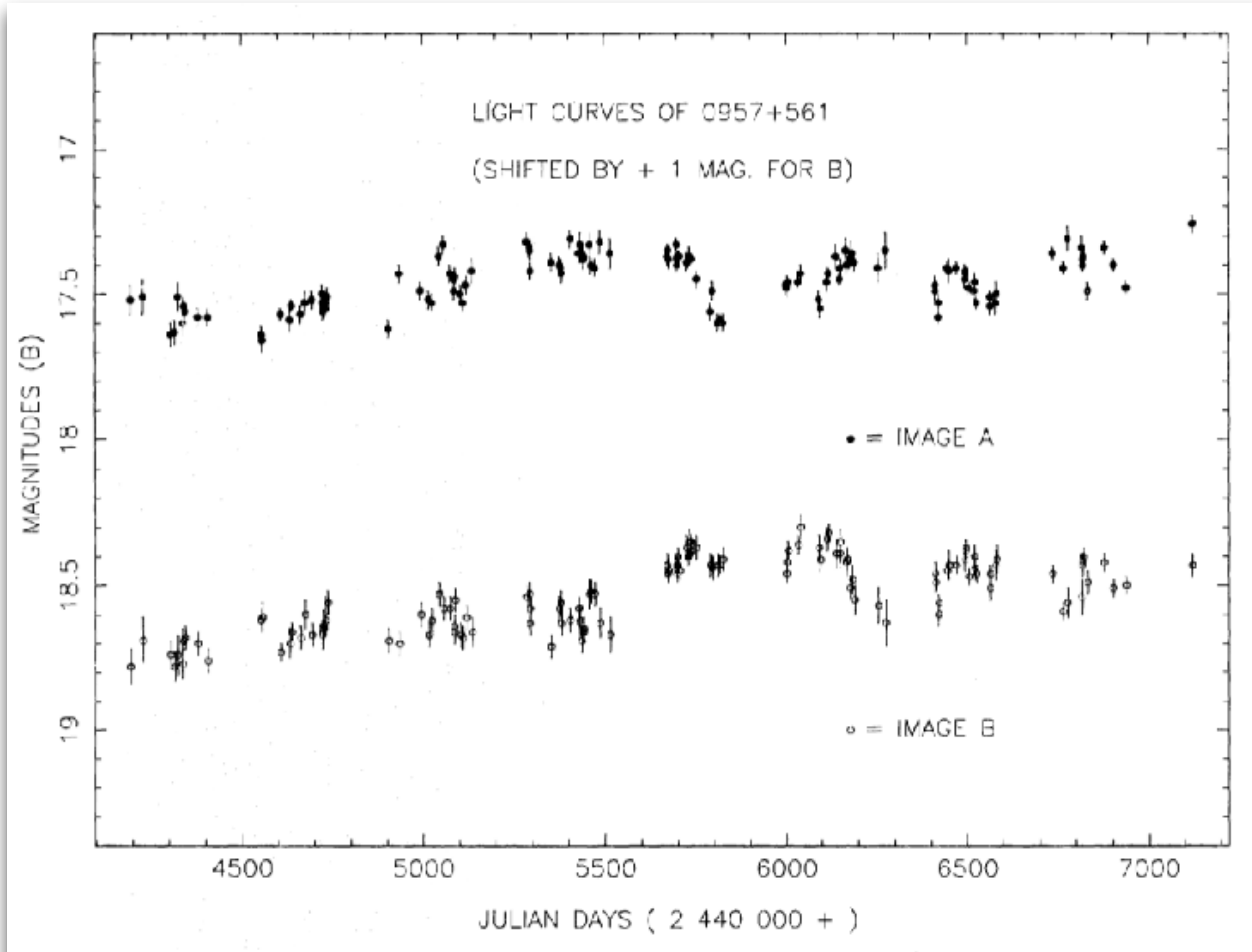
Time Delay Measurements

Past Measurements of Time Delays (1989-1992)

Q0957+561 « controversy » in the early 90s

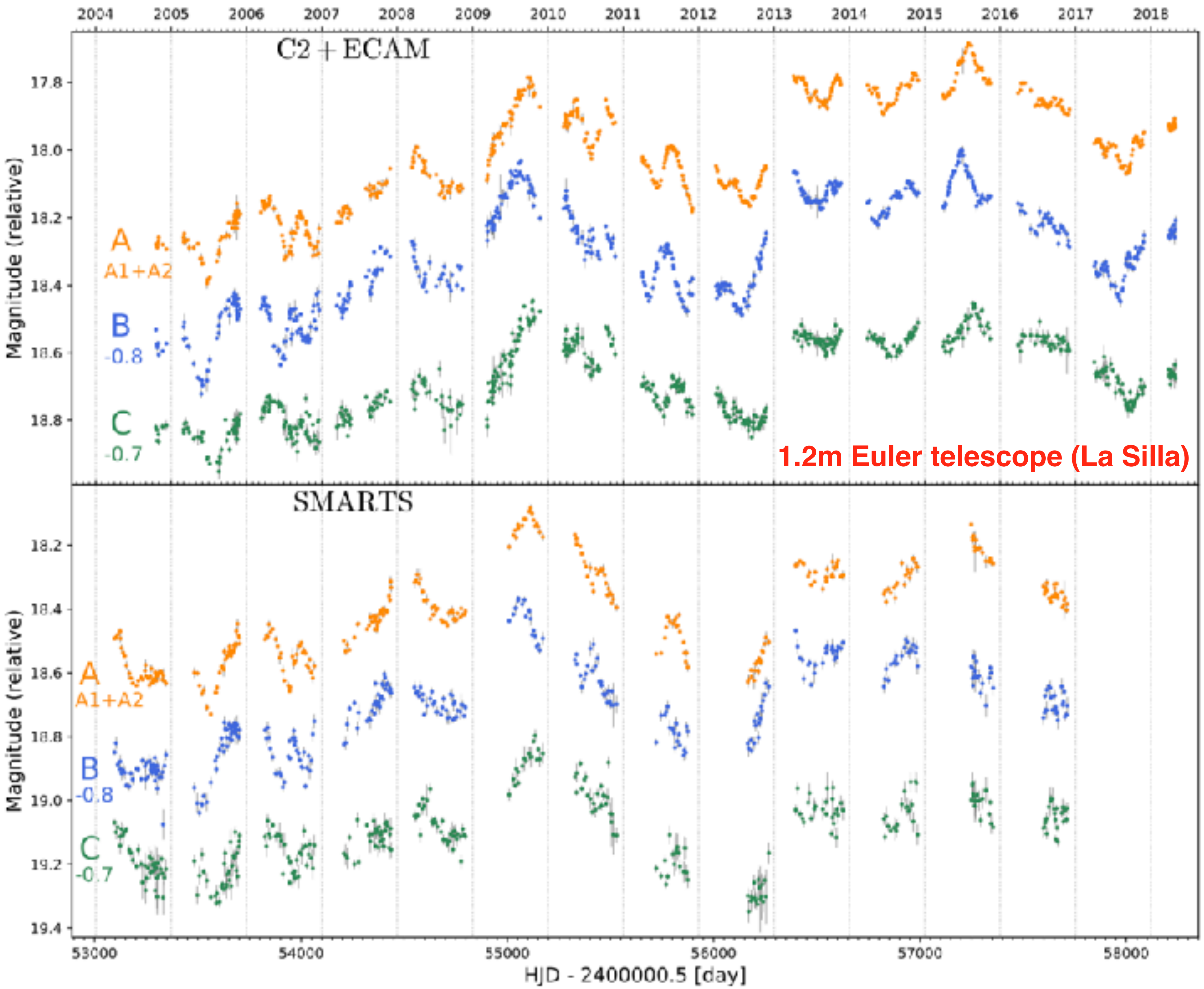
- **Vanderriest et al. 1989, A&A, 215, 1**: optical monitoring: Δt = **415** ± 20 days
- **Schild 1990, AJ, 100, 1771**: optical monitoring: Δt = **405** days
- **Lehar et al. 1992, ApJ, 384, 453**: radio monitoring at the VLA Δt = **513** ± 40 days

Past Measurements of Time Delays (1989-1992)



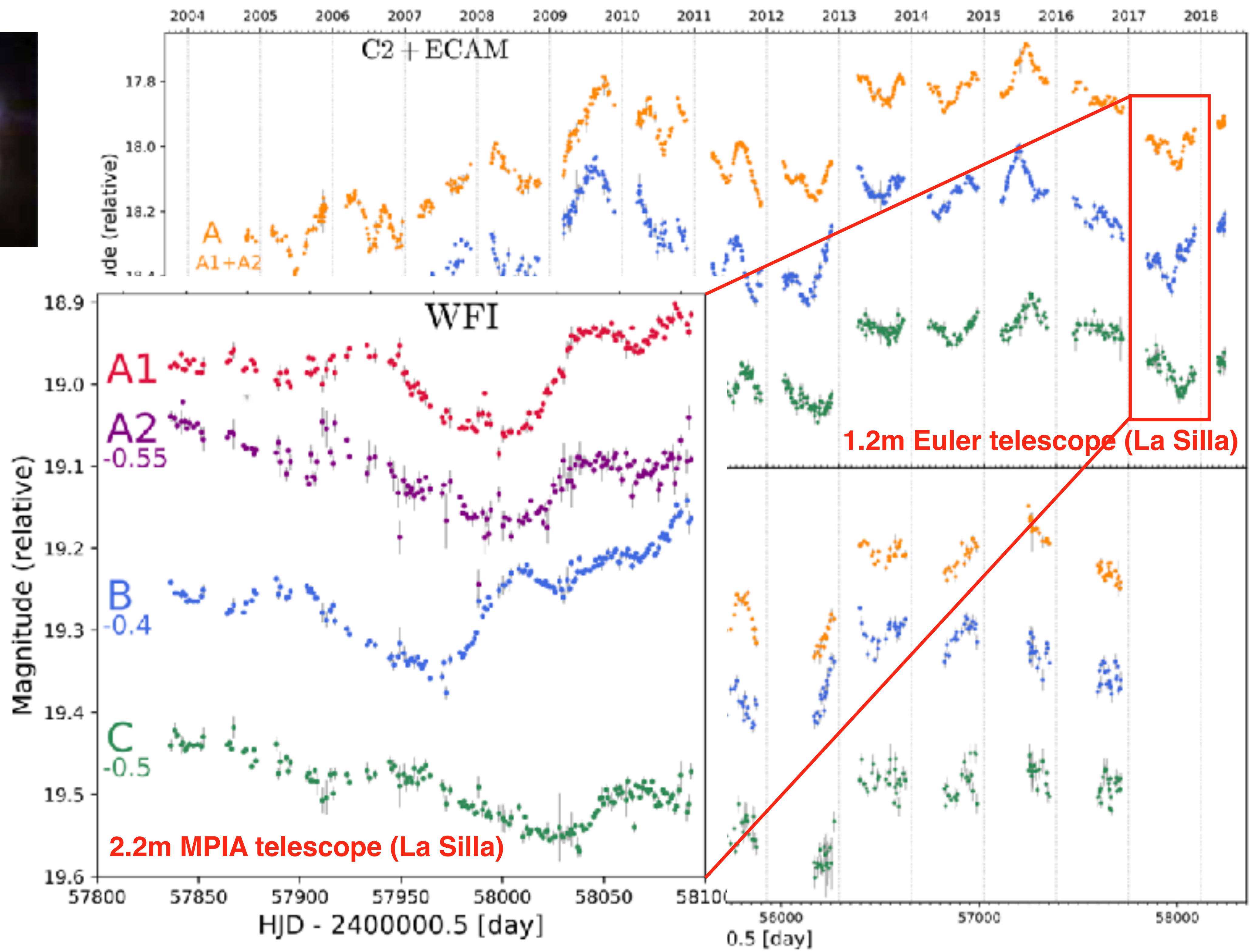
Vanderriest et al. (1989, A&A, 215, 1)

COSMOGRAIL Light Curves of WFI2033-4723



Bonvin et al. 2019, arXiv:1905.08260

MPIA 2.2m Light Curves of WFI2033-4723

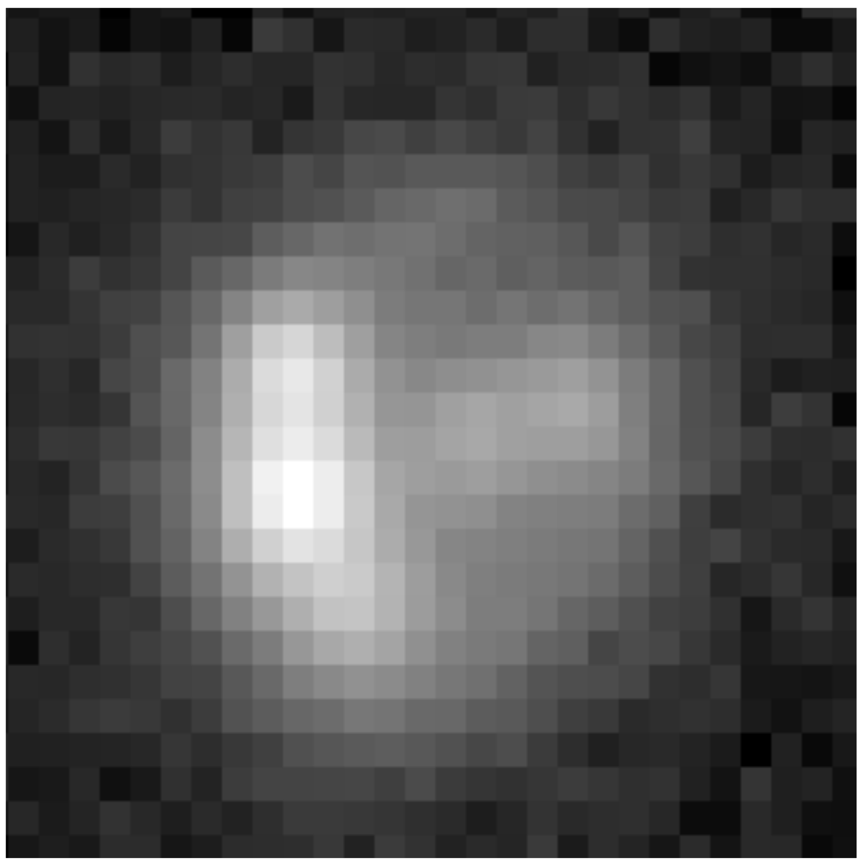


Bonvin et al. 2019, arXiv:1905.08260

2- Constraining the Mass Slope

Imaging Data for RX J1131-123

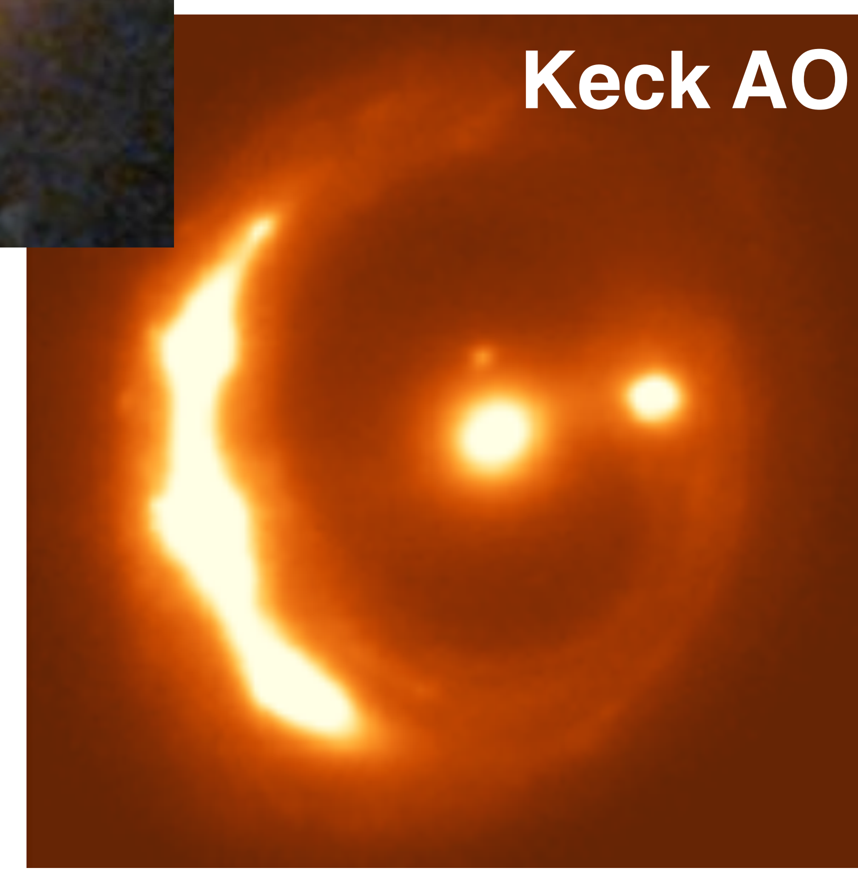
PAST



Ground-based seeing-limited

Lensing constraints restricted to astrometry of the lensed images

NOW



+ MUSE @VLT
+ OSIRIS @Keck

For detailed analyses of Keck AO imaging see Chen et al. (2019, arXiv1907.02533)

Mass Slope of Lens Galaxy

Arrival time surfaces
in the image plane

Normalized mass profile
κ = projected mass density
in units of the critical mass

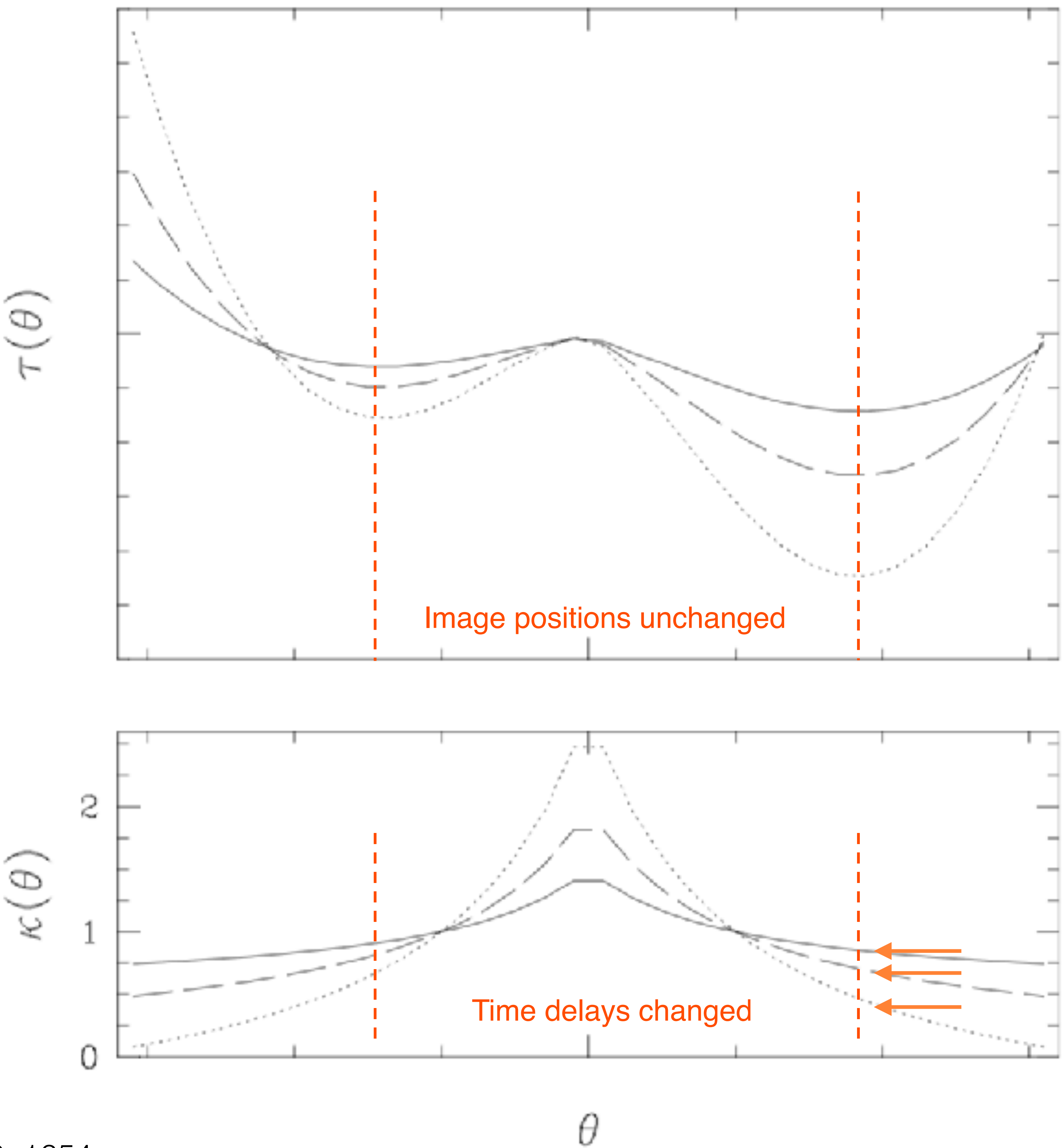
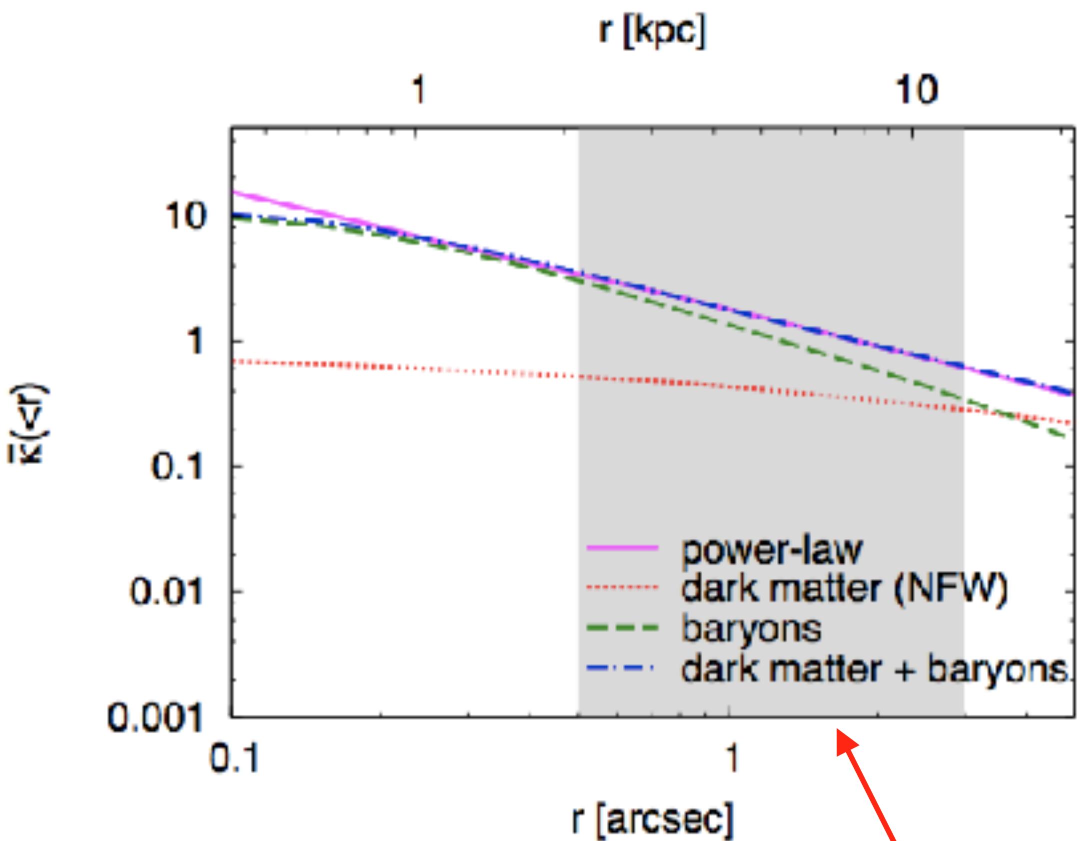
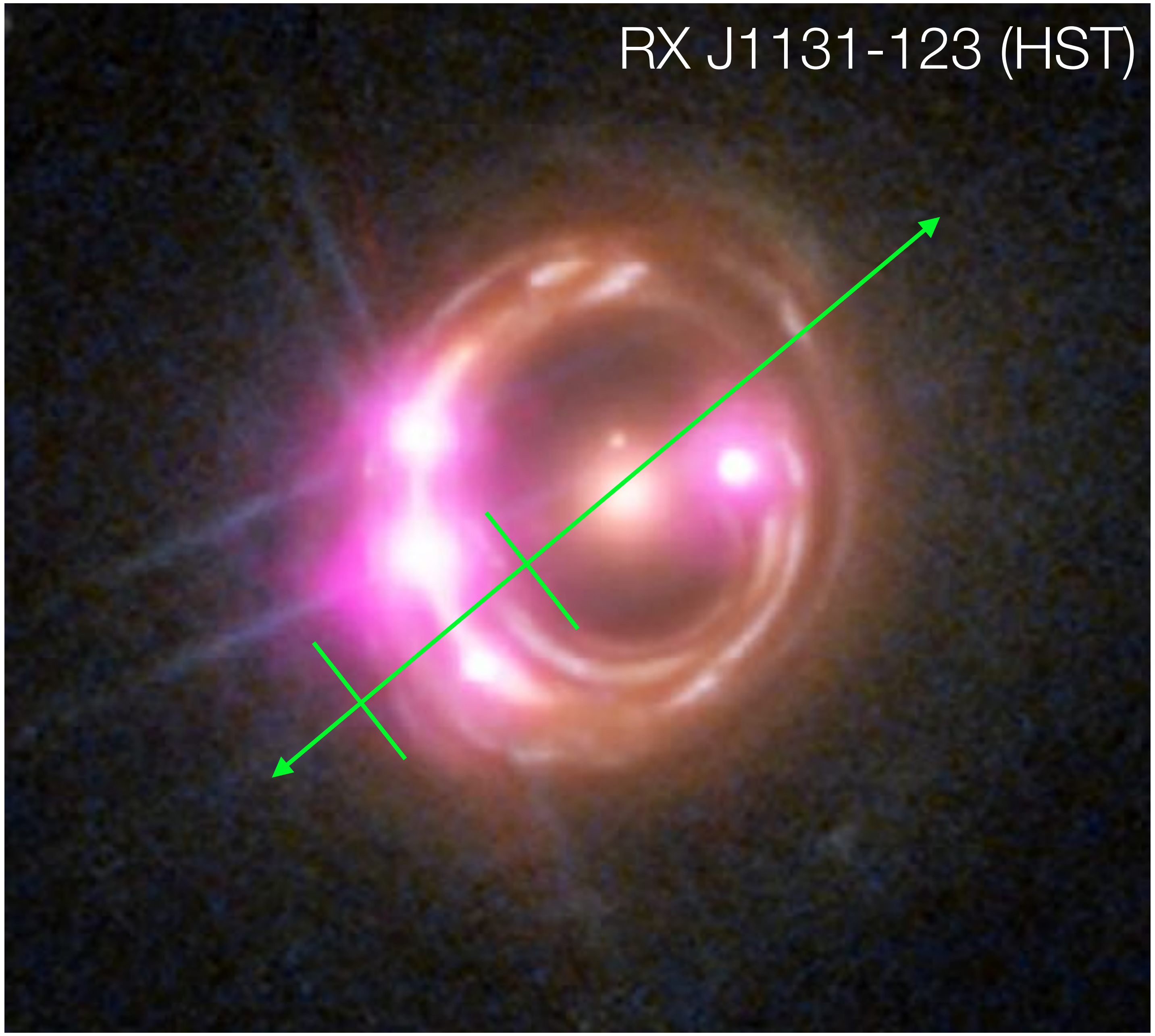


Figure adapted from Saha, 2000, AJ 120, 1654

Constraining Models with Thick Rings !



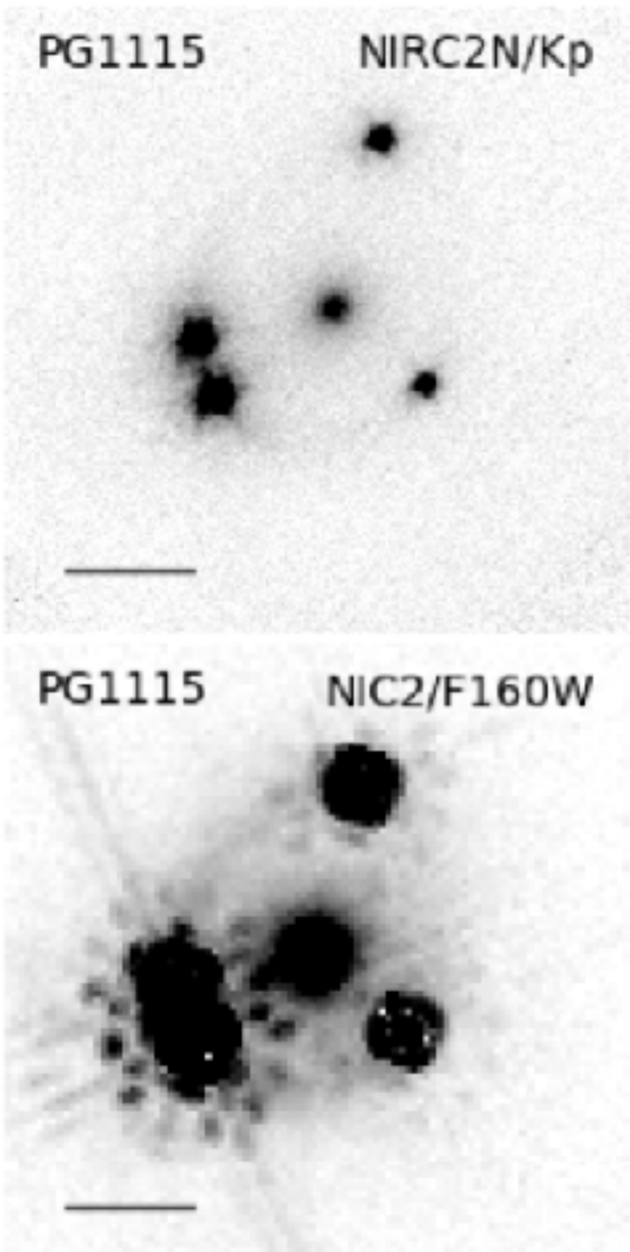


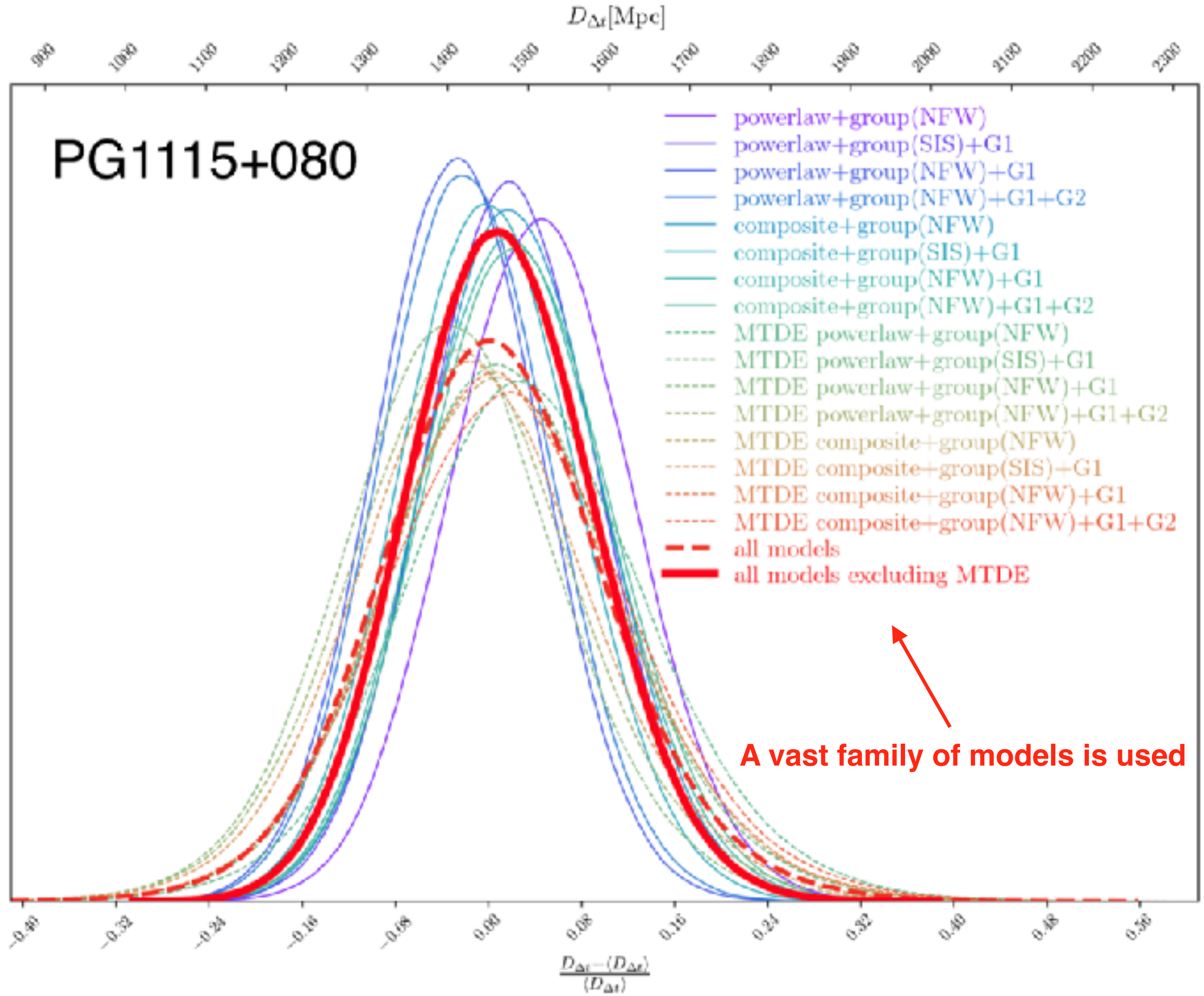
Lensing constraints come from all pixels covered by the Einstein ring formed by the quasar host.

Suyu et al. (2014, ApJ, 788, L35)

Blind Analysis !

Results of the unblinding process are **published as they are !**





Chen et al. (2019, arXiv1907.02533)

3- Effect of Line of Sight

Mass-sheet Degeneracy (Line-of-Sight Contribution)

Mass along the line of sight brings extra mass inside the Einstein radius.

This can be estimated in different ways:

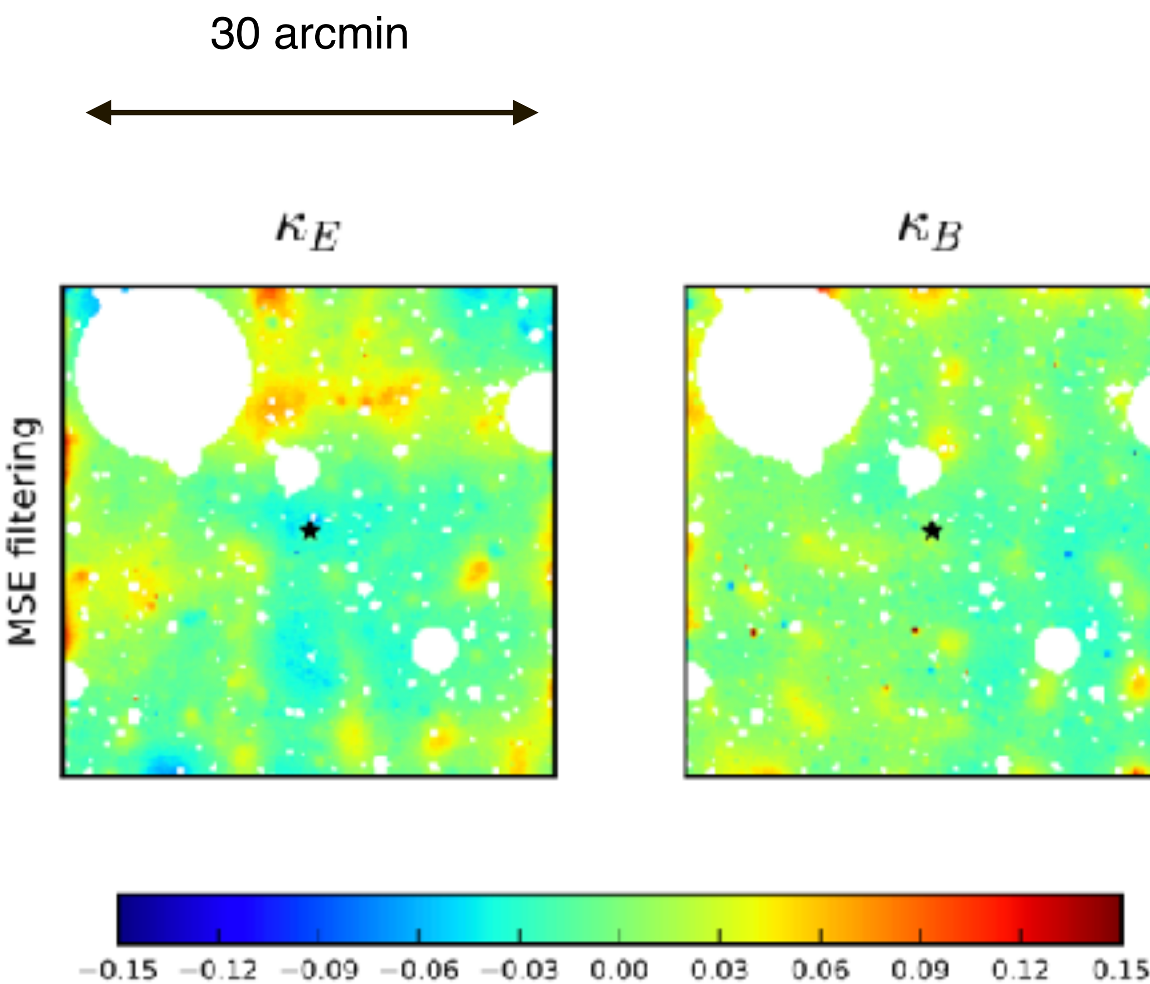
- Using galaxy counts in lens fields and compare with the general field (Fassnacht et al. 2006, ApJ, 642, 30)

- Using weighted galaxy counts (Collett et al. 2013, MNRAS 432, 679; Greene et al. 2013, ApJ, 768, 39)

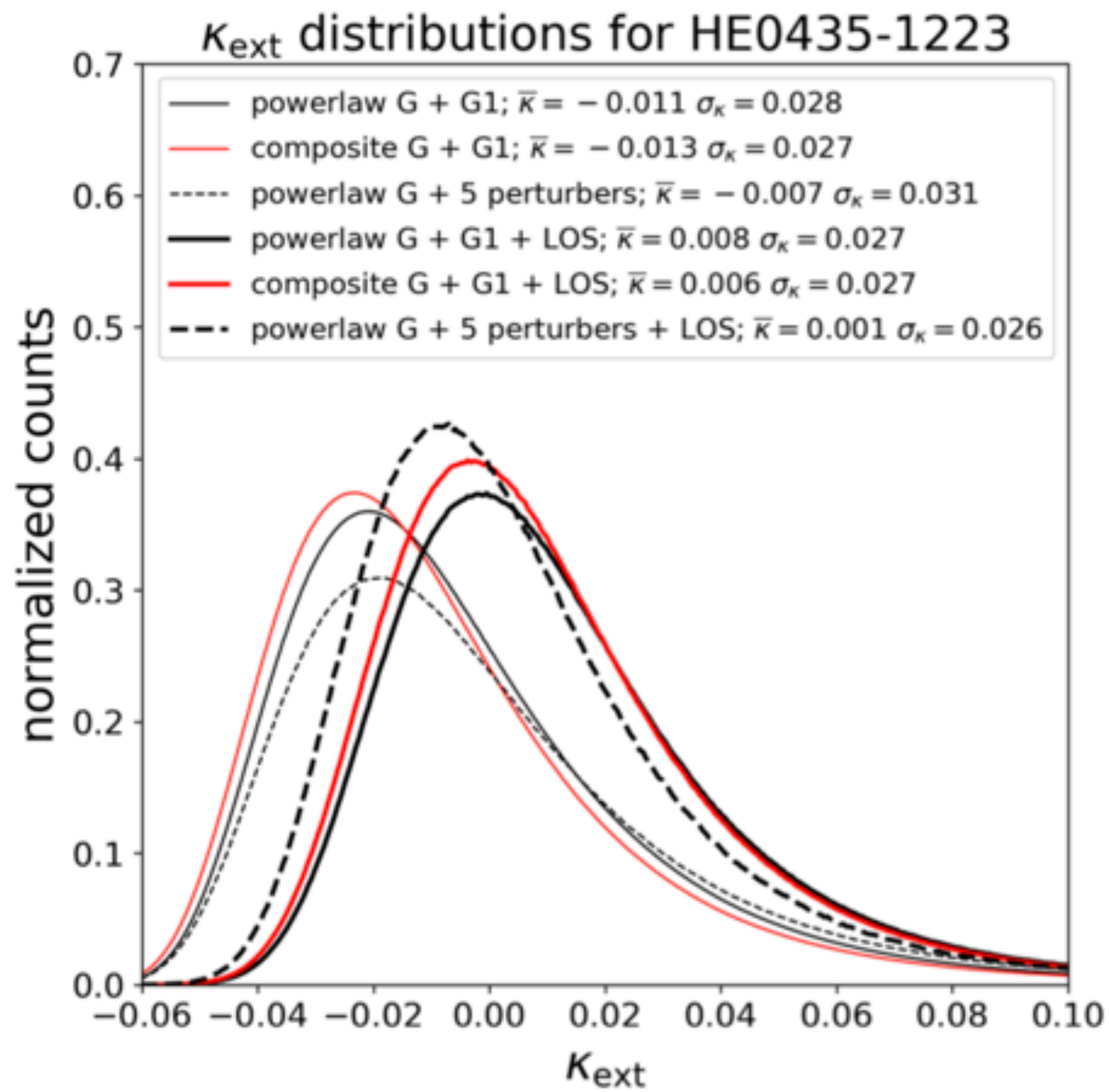
- Calibrating with cosmological simulations (e.g. Suyu et al. 2013, ApJ, 766, 70)

- Using weak lensing maps (e.g. Tihhonova et al. 2018, MNRAS, 477, 5657)

LoS contribution: Galaxy Counts and Weak Lensing

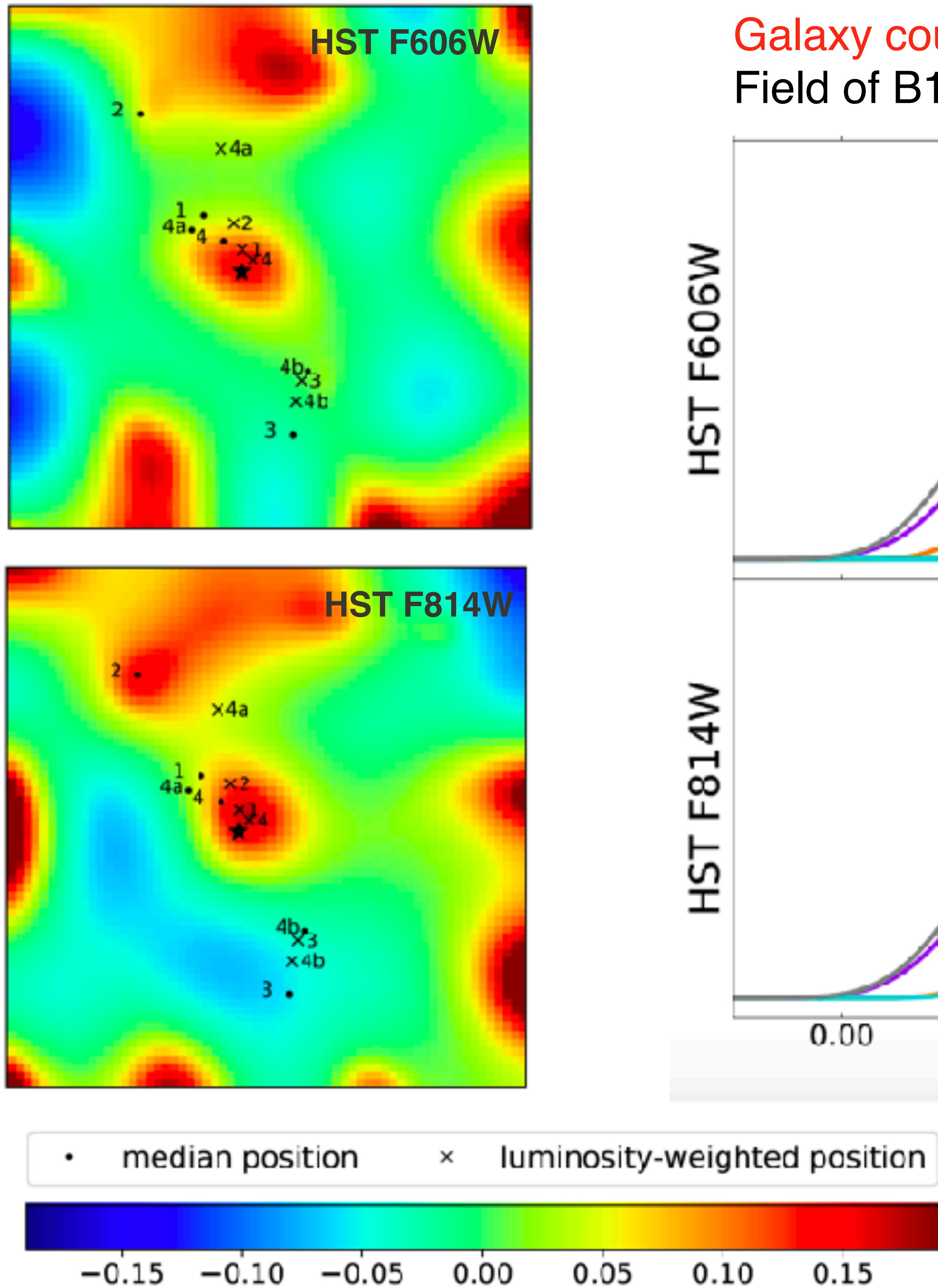


From weak lensing
Tihhonova et al. (2018, MNRAS 477, 5657)



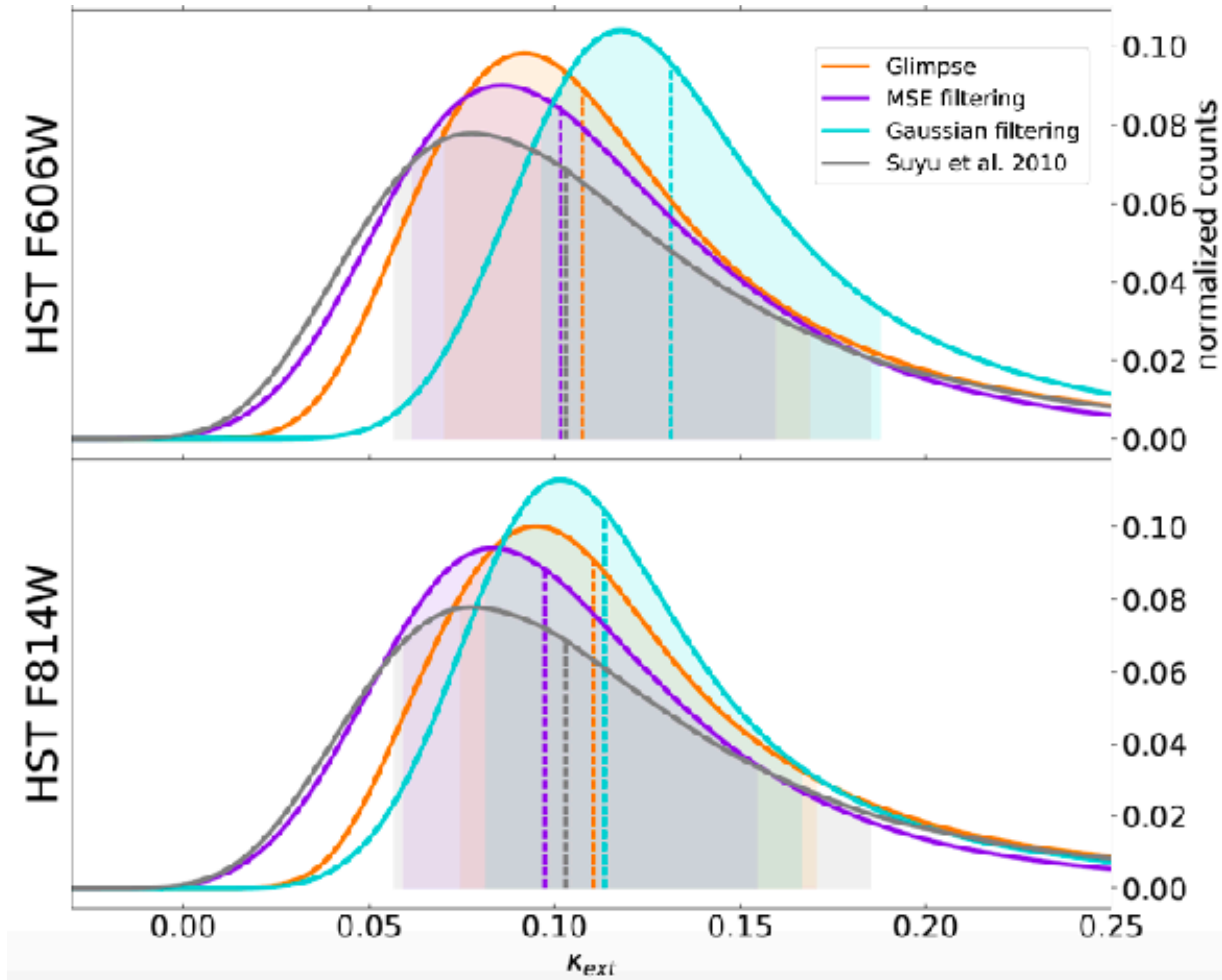
From galaxy counts
Chen et al. (2019, arXiv1907.02533)

LoS contribution: Galaxy Counts and Weak Lensing



Galaxy counts and weak lensing agree !

Field of B1608: HST and Subaru imaging

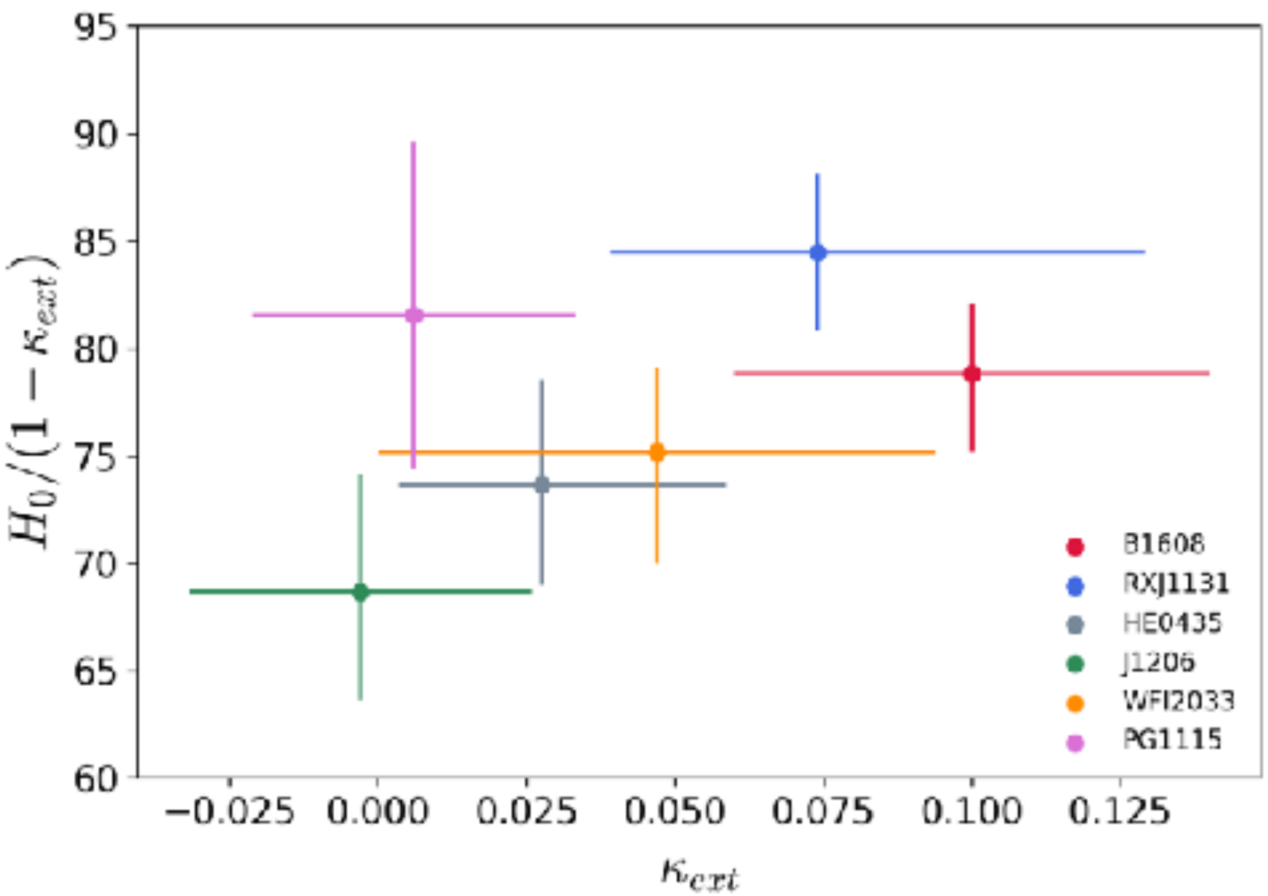


Tihhonova et al. 2019, submitted

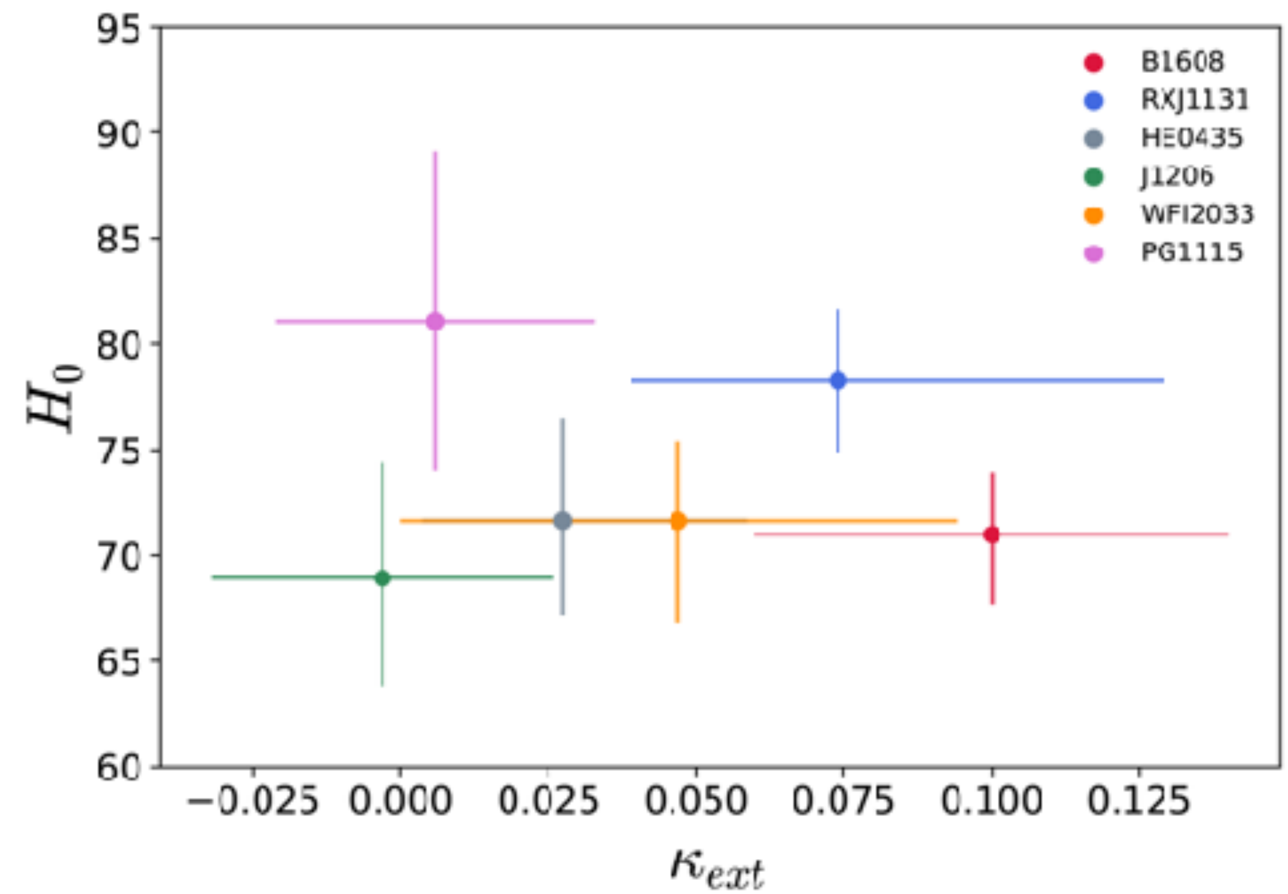
Current Values of External Convergence

No obvious correlation between H_0 and external convergence among the 6 fields analyzed so far.

Before correction

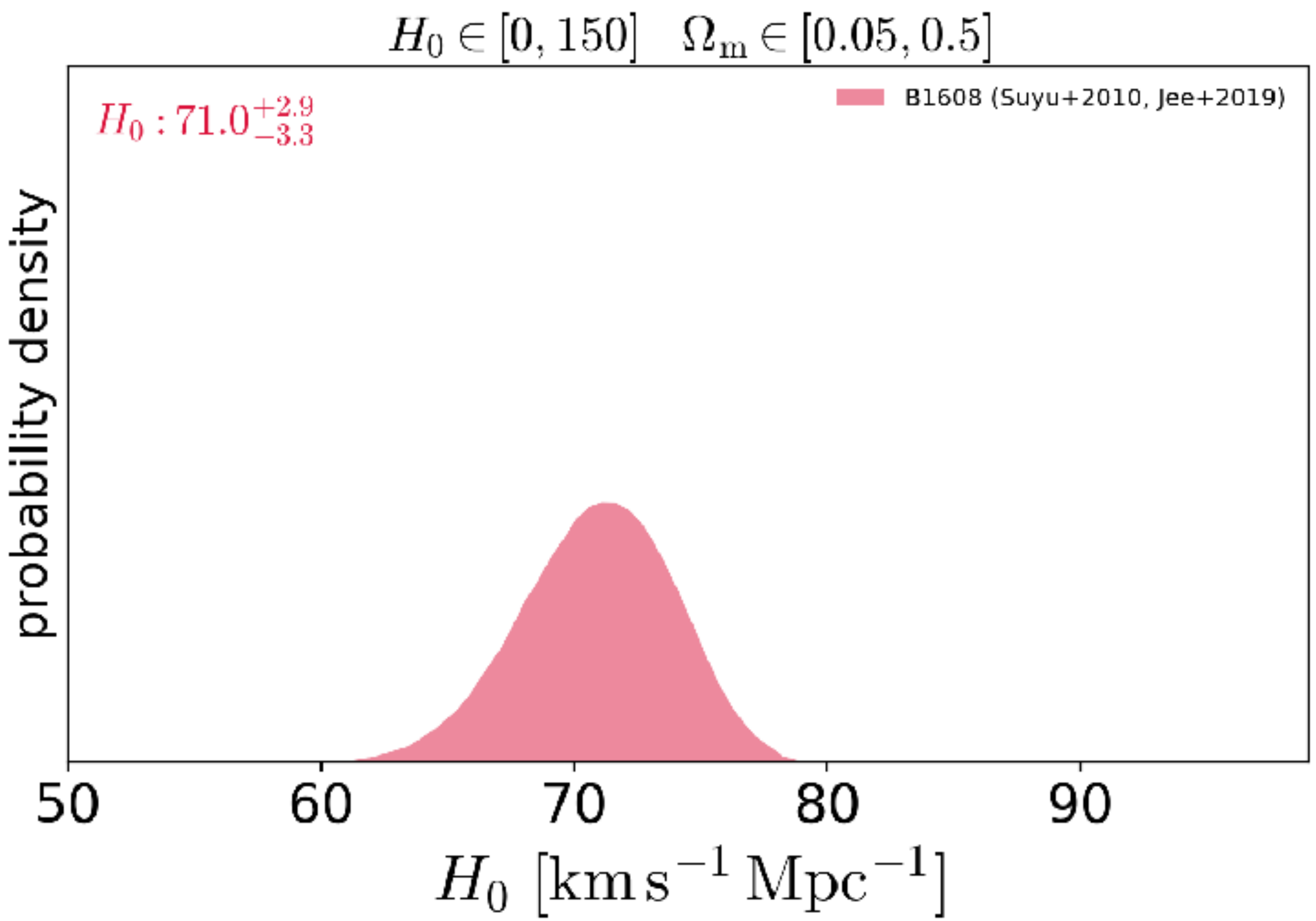


After correction

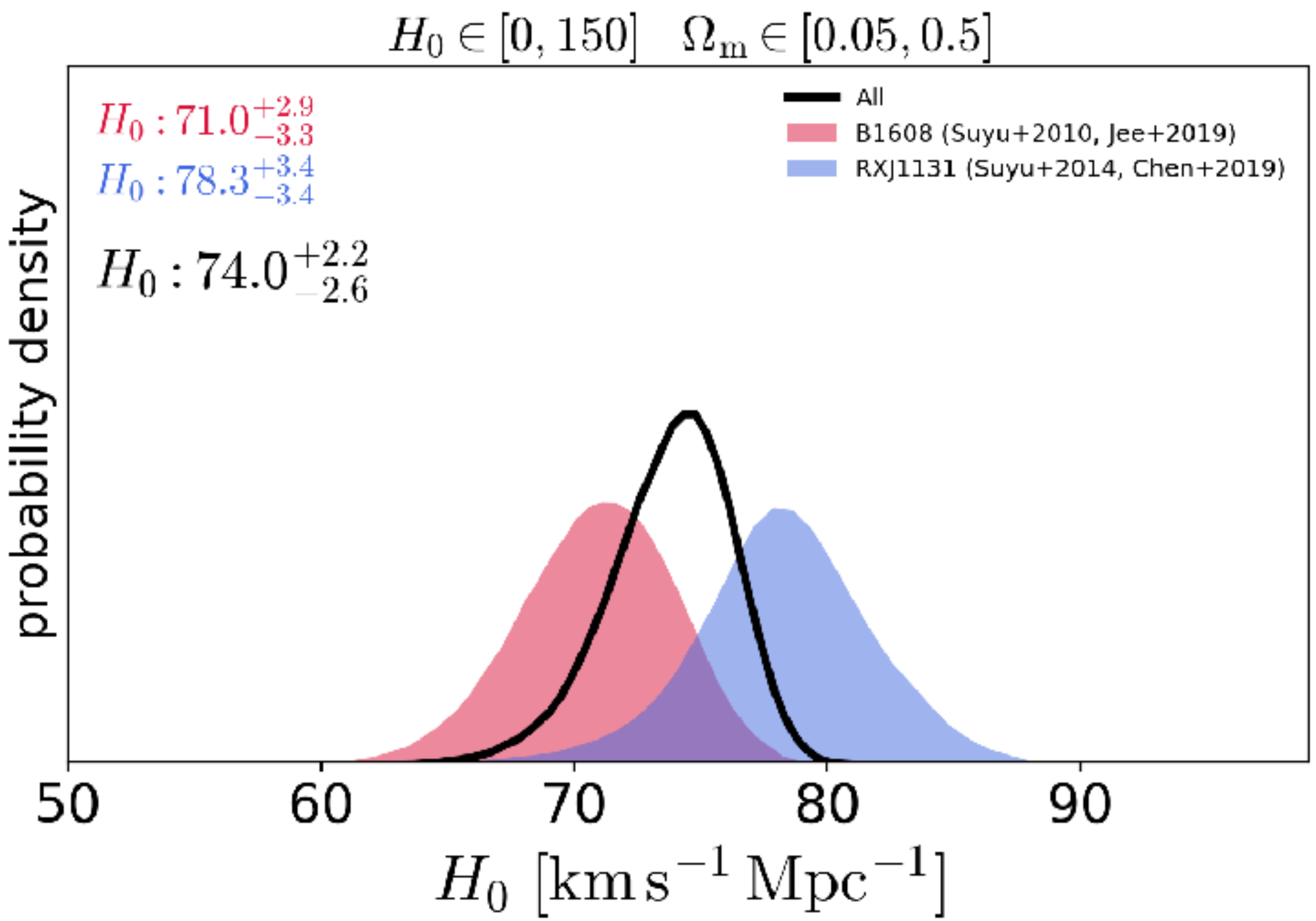


Millon et al. 2019, in prep

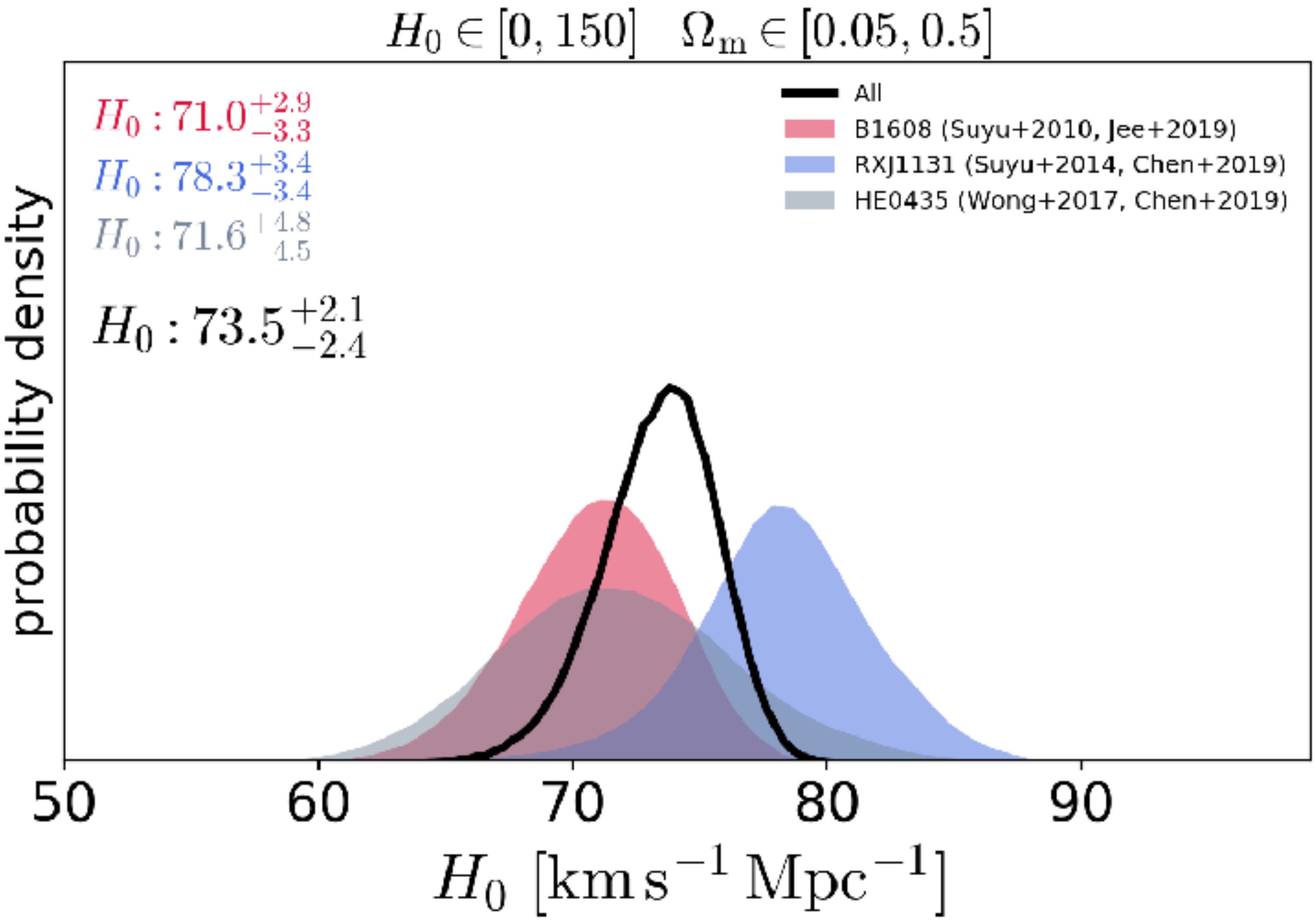
Cosmology Results for 1 Lens in flat lambda-CMD



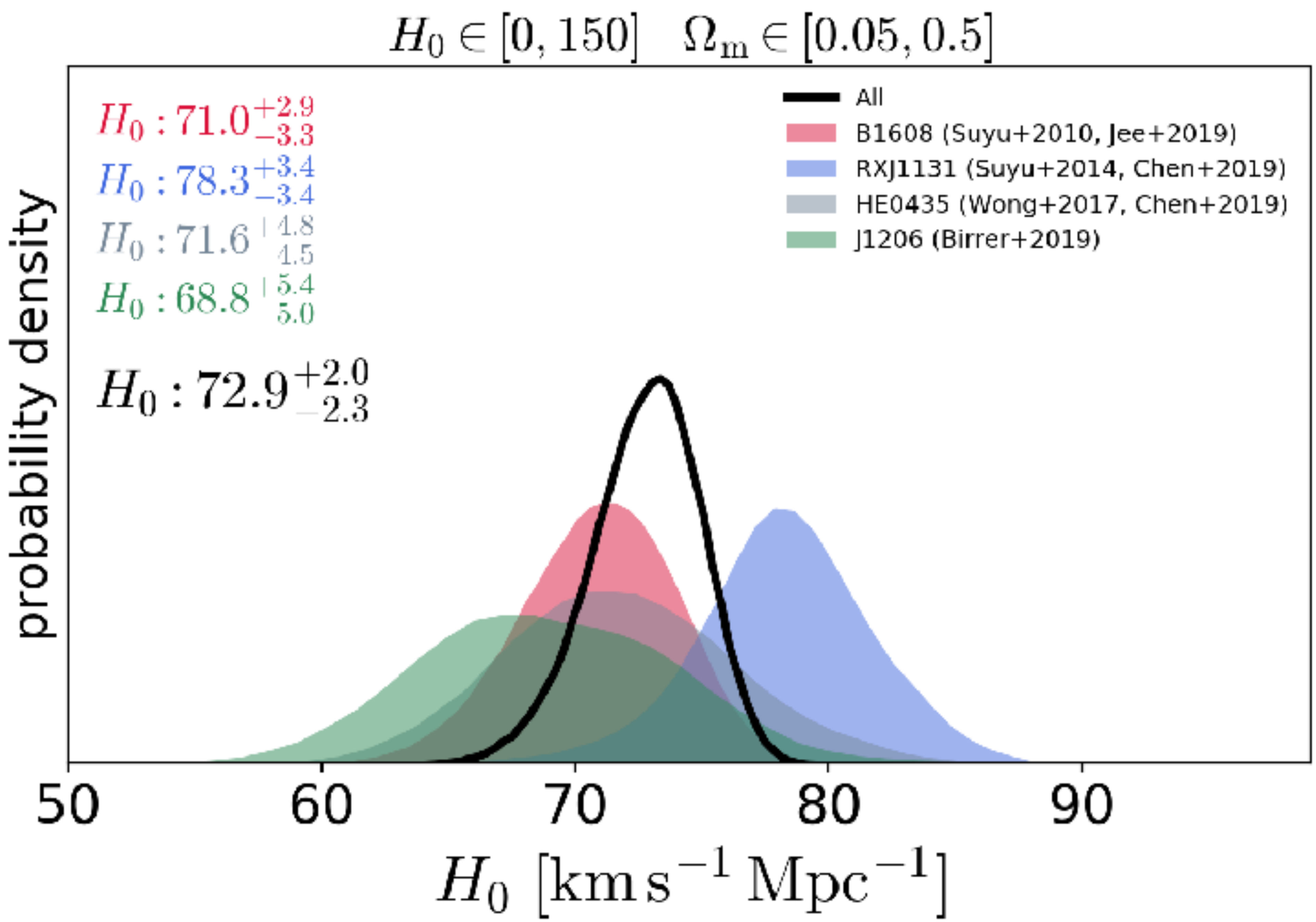
Cosmology Results for 2 Lenses in flat lambda-CMD



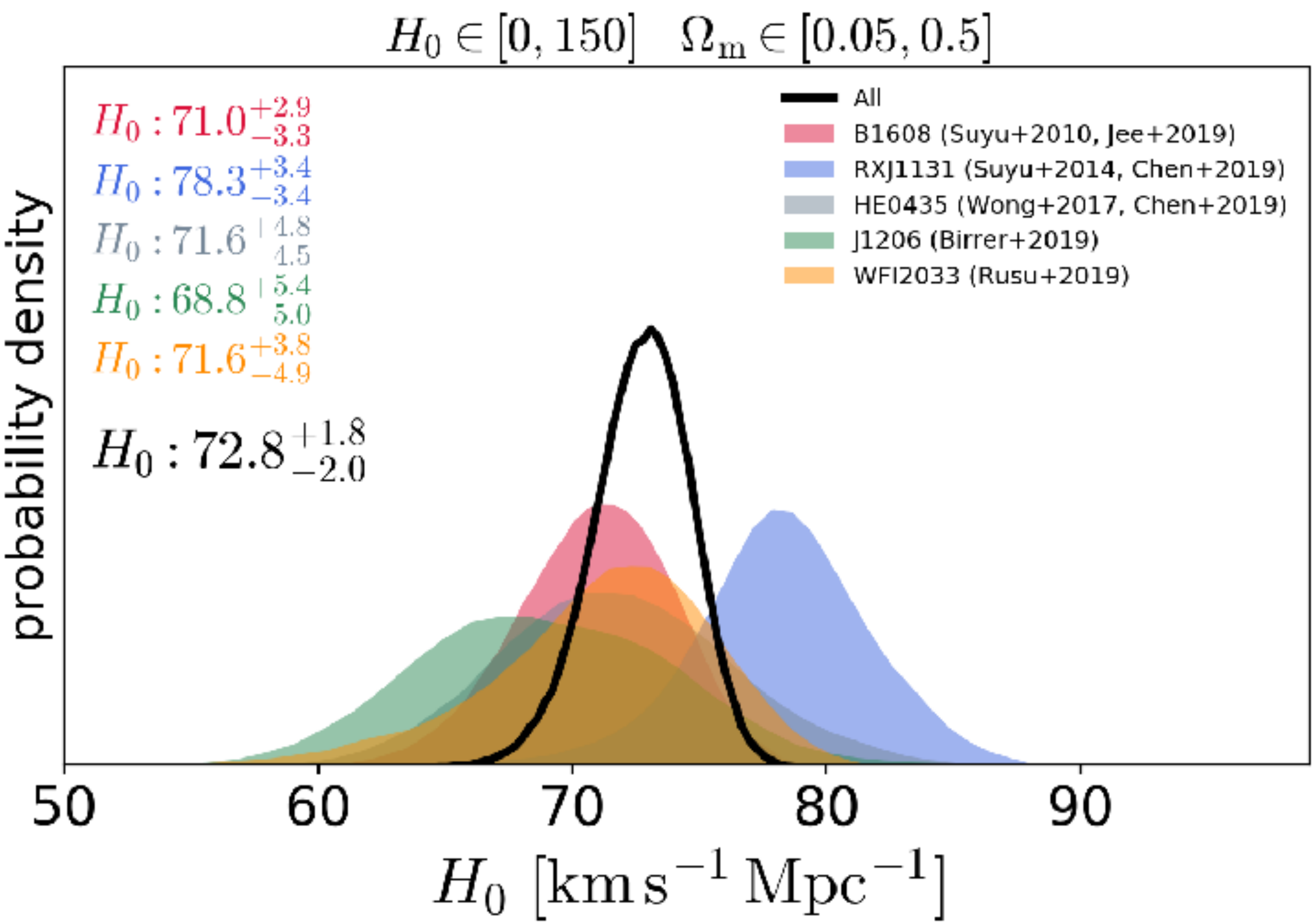
Cosmology Results for 3 Lenses in flat lambda-CMD



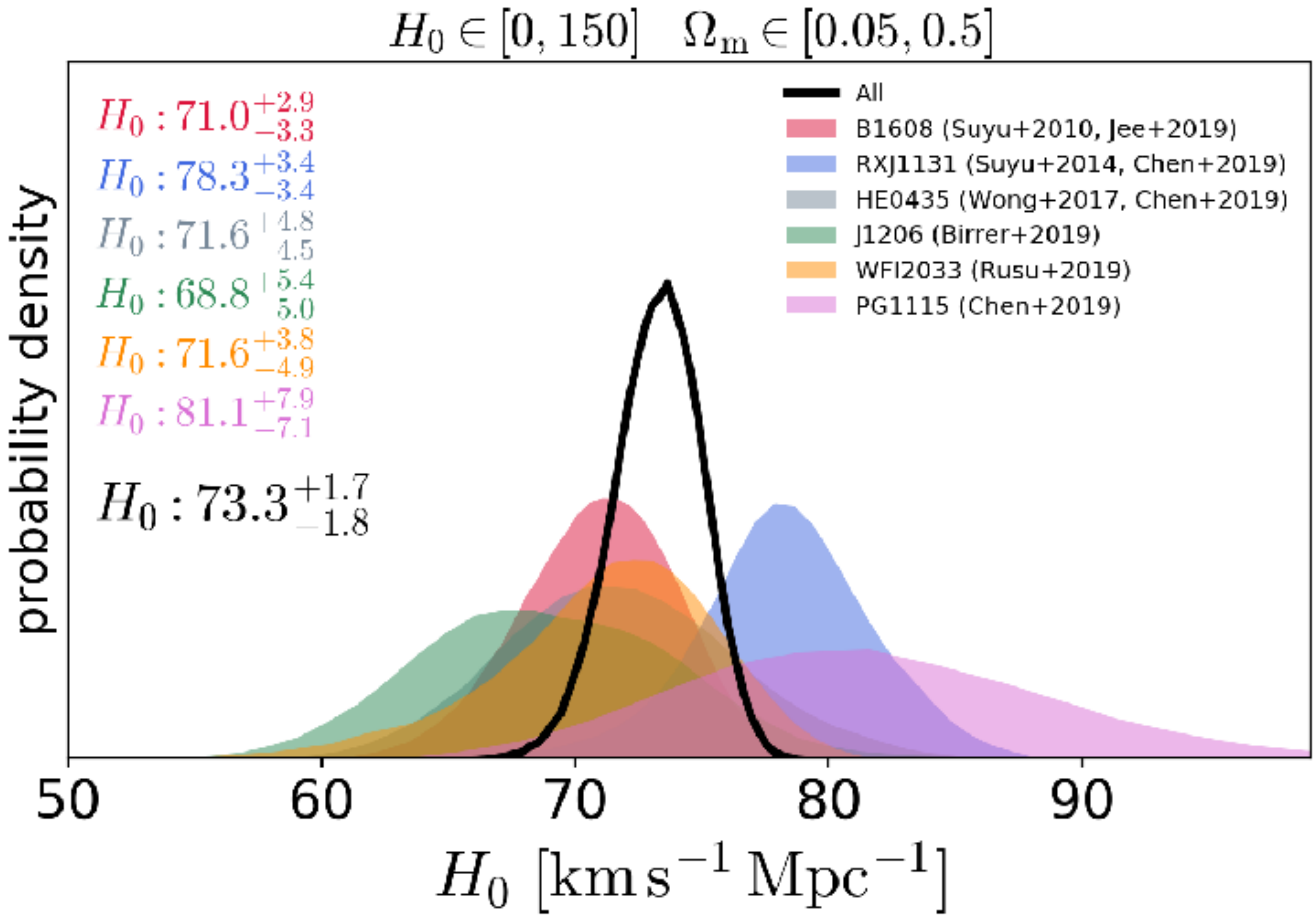
Cosmology Results for 4 Lenses in flat lambda-CMD



Cosmology Results for 5 Lenses in flat lambda-CMD



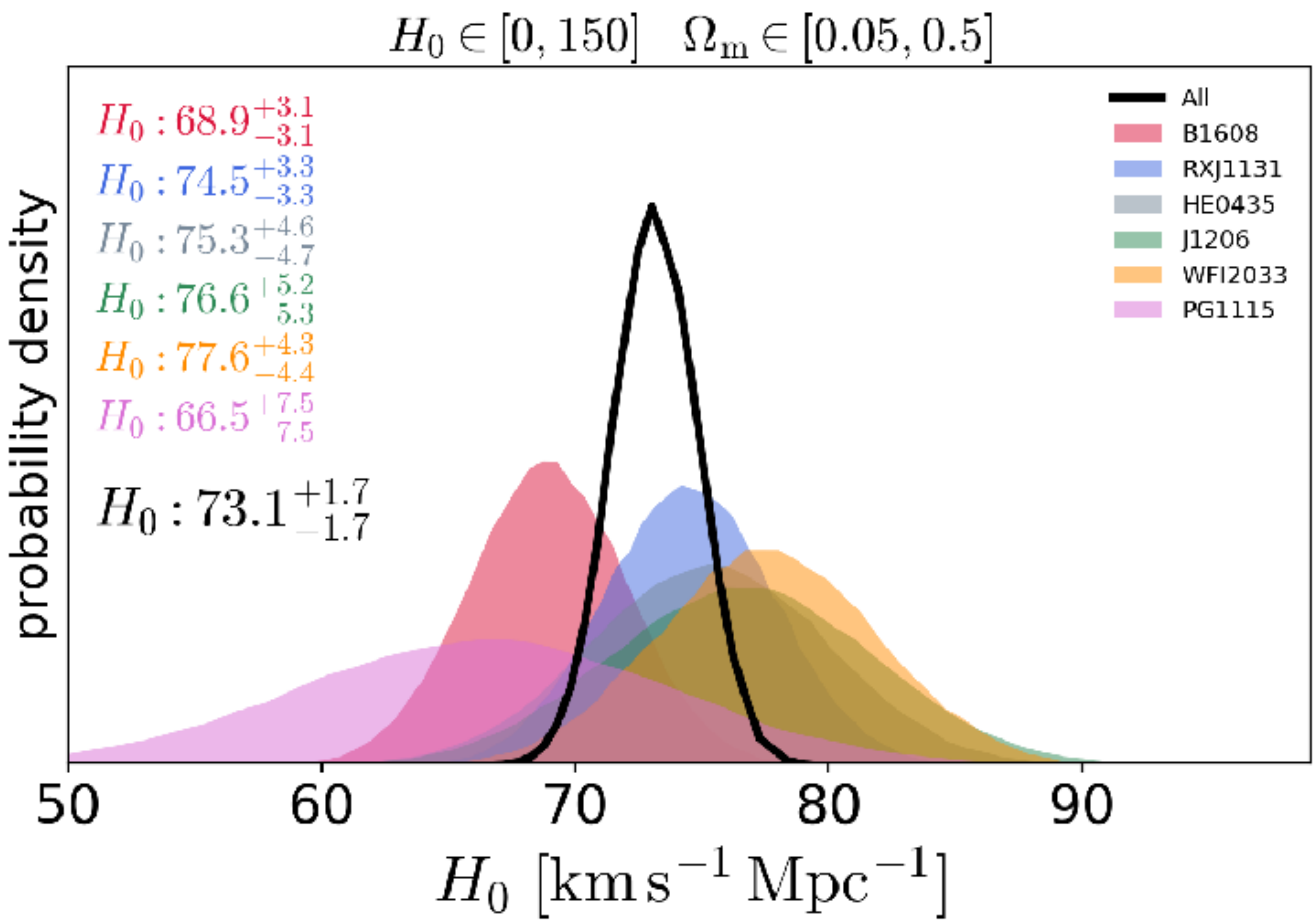
Cosmology Results for 6 Lenses in flat lambda-CMD



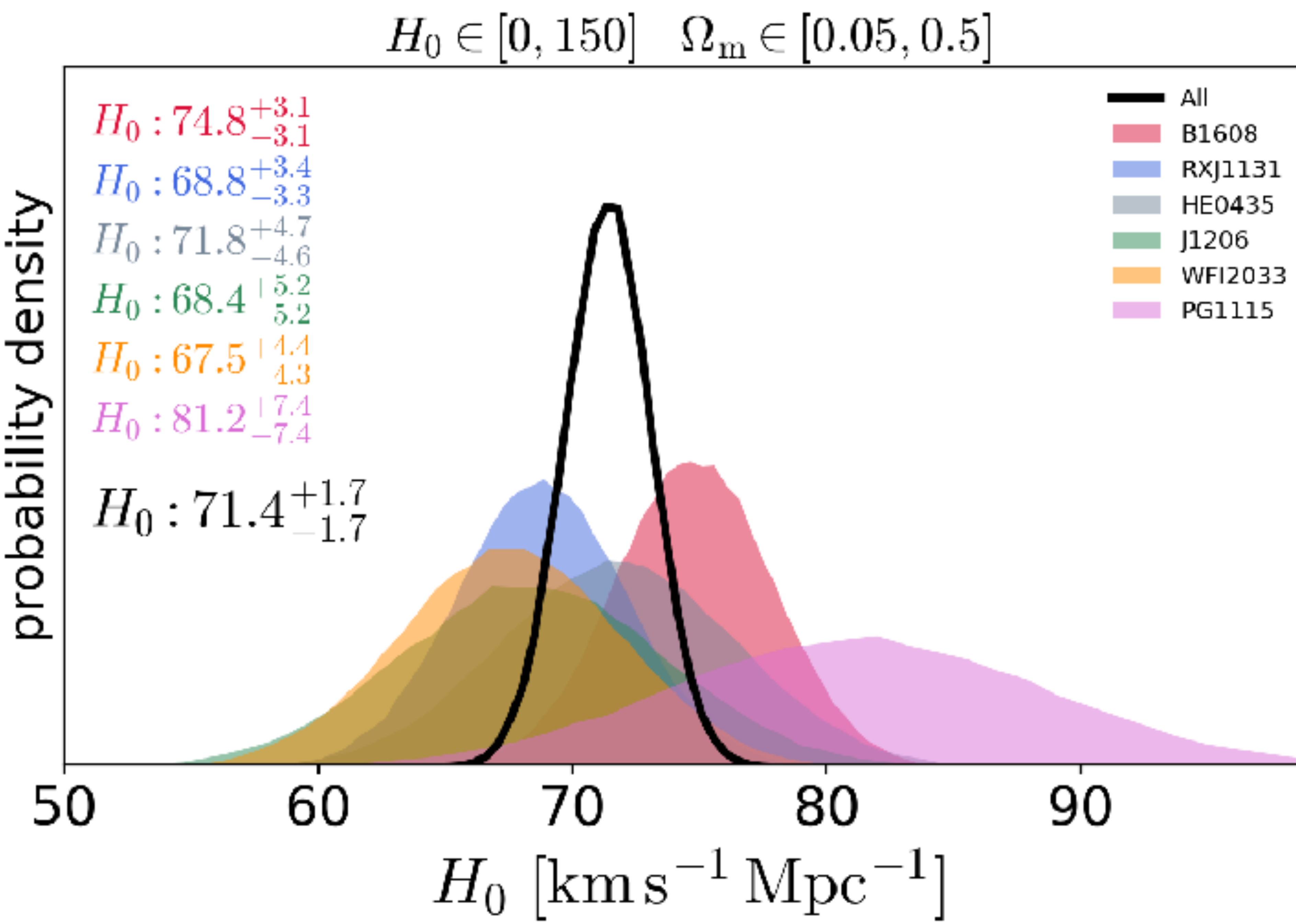
H0LiCOW XIII: milestone paper (Wong et al. 2019, arXiv1907.04869)

Are these statistically compatible with each other ?

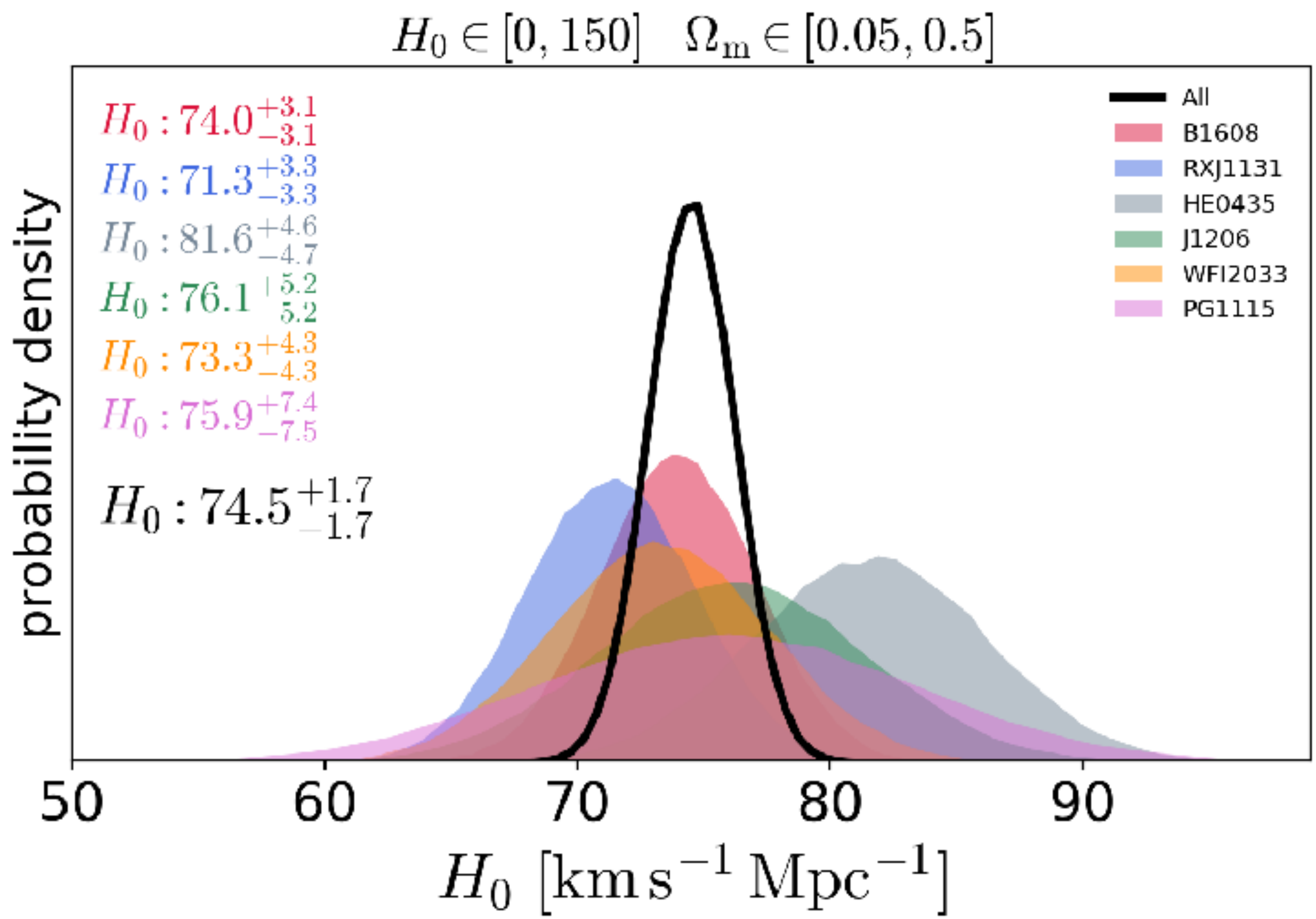
Random Realizations with 6 Lenses (fiducial: 73.3)



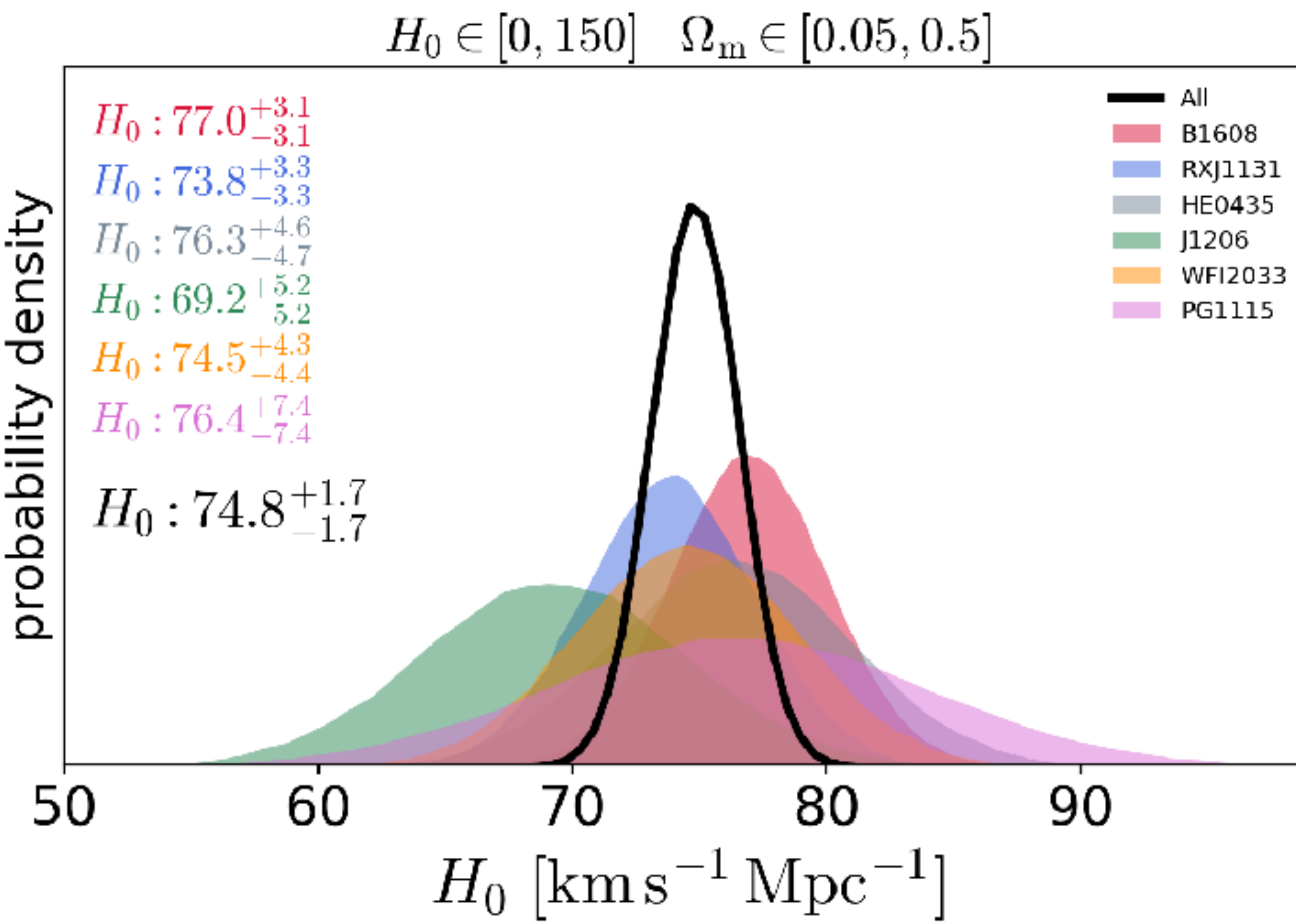
Random Realizations with 6 Lenses (fiducial: 73.3)



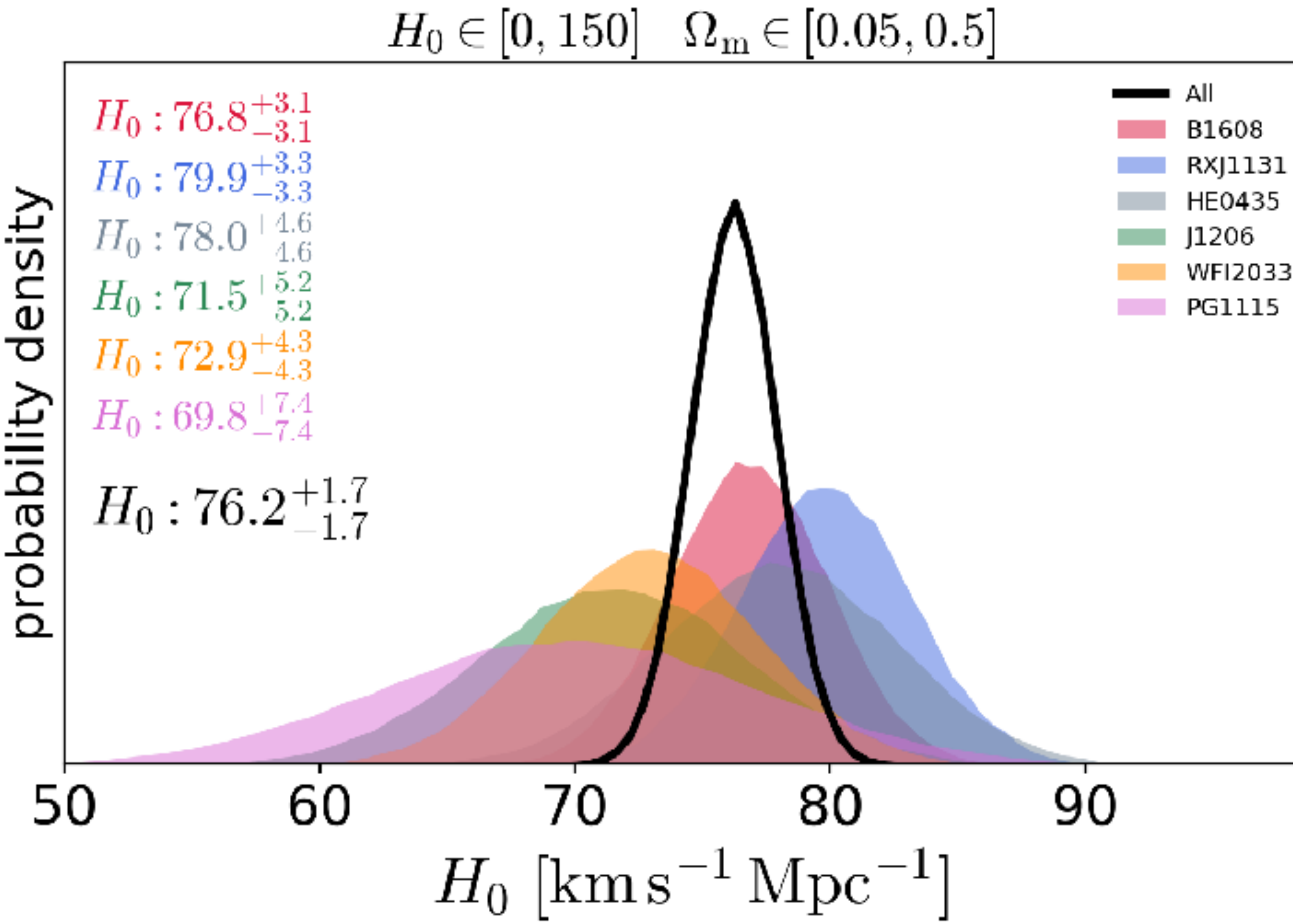
Random Realizations with 6 Lenses (fiducial: 73.3)



Random Realizations with 6 Lenses (fiducial: 73.3)

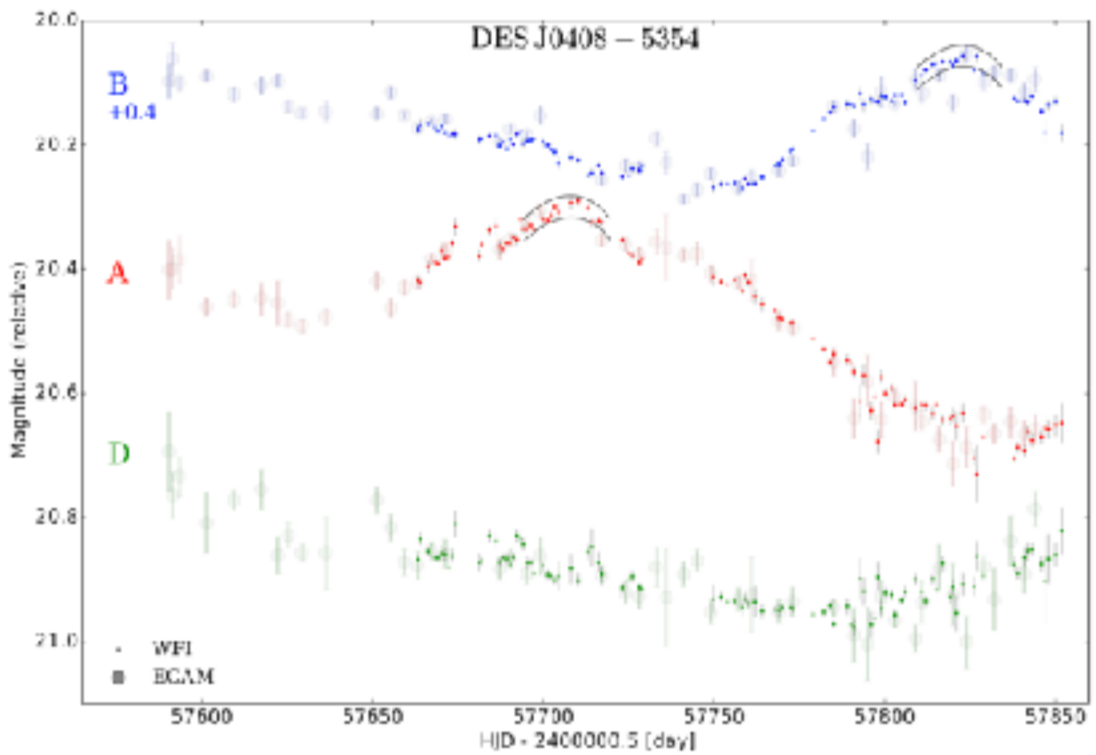


Random Realizations with 6 Lenses (fiducial: 73.3)



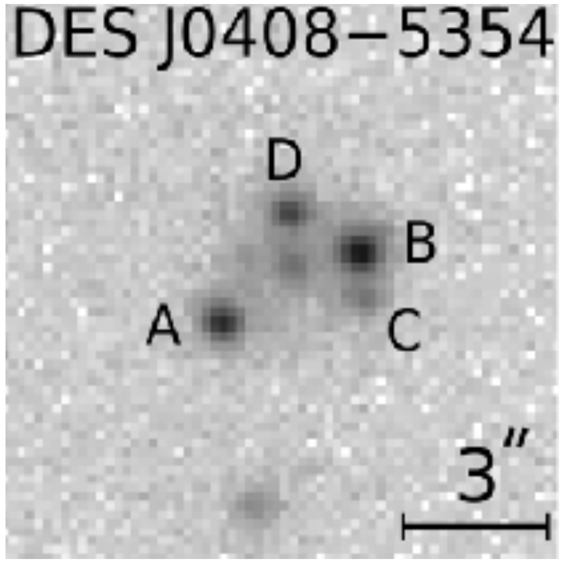
Latest Object from the Collaboration: DES J0408-5354

DES J0408-5354: Data



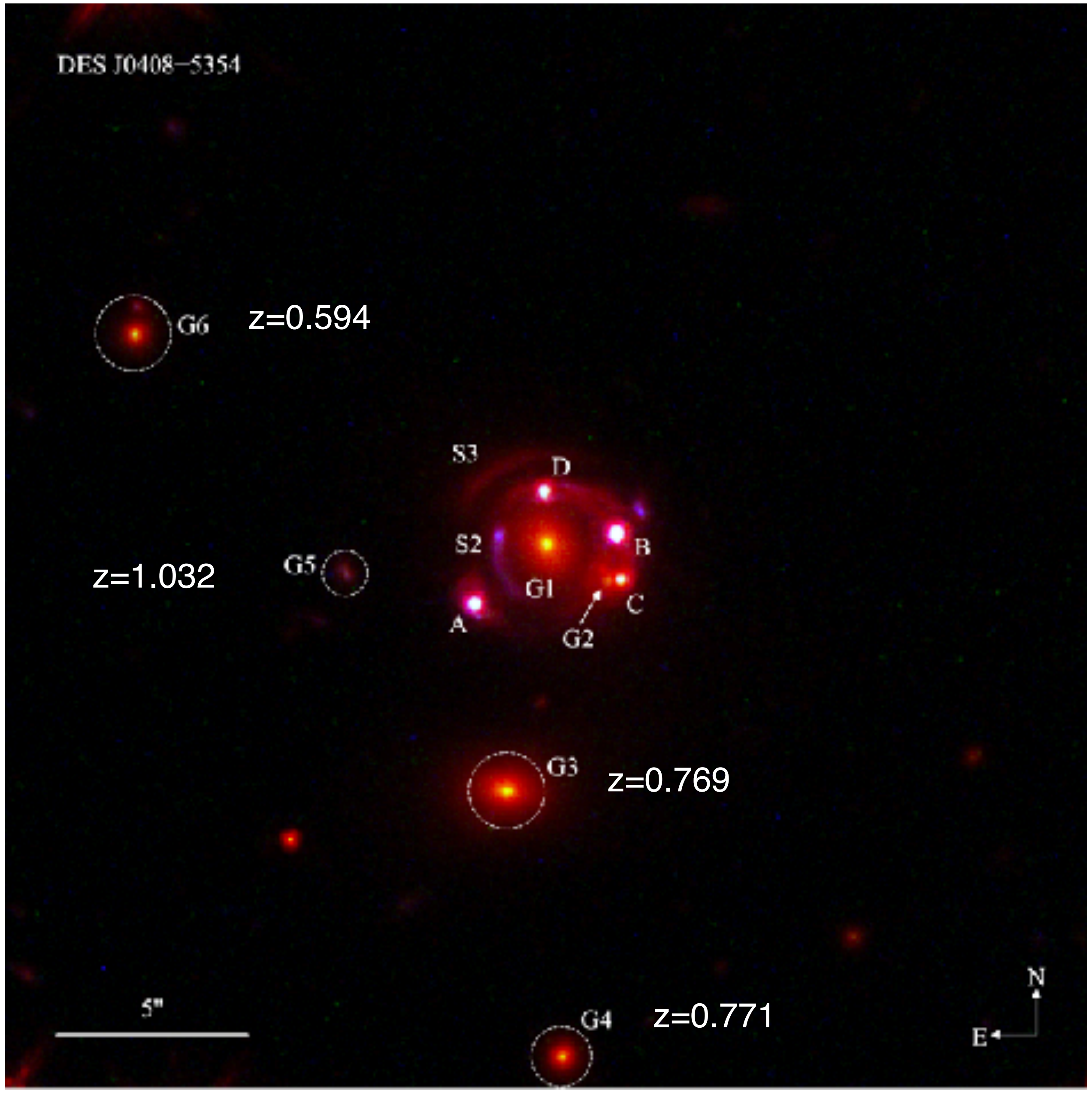
$\Delta t(AB) = 112.1 \pm 2.1$ days (1.8%)

MPIA 2.2m light curve and image



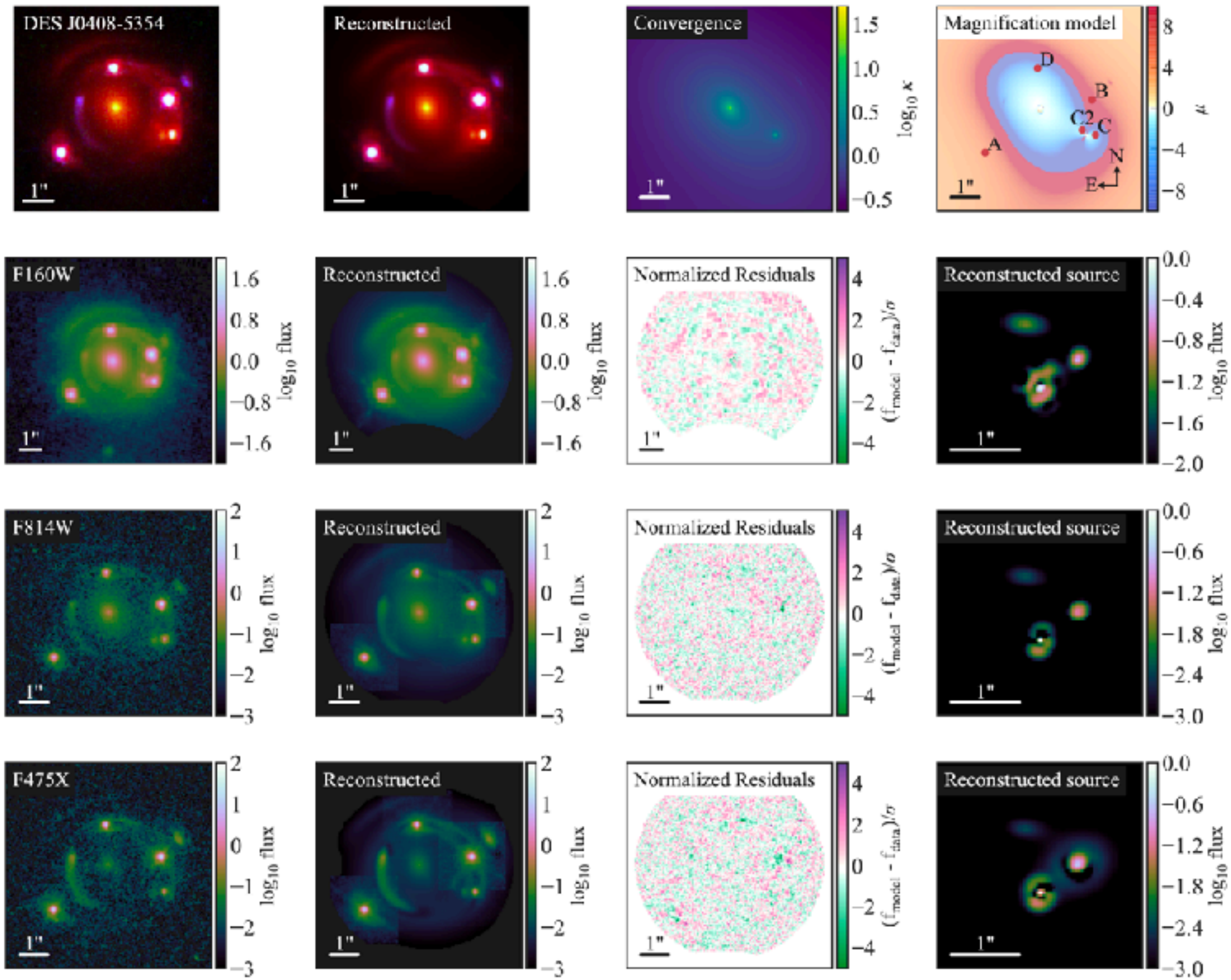
Time delays: Courbin et al. (2018)
Discovery: Lin et al. 2017

HST color image



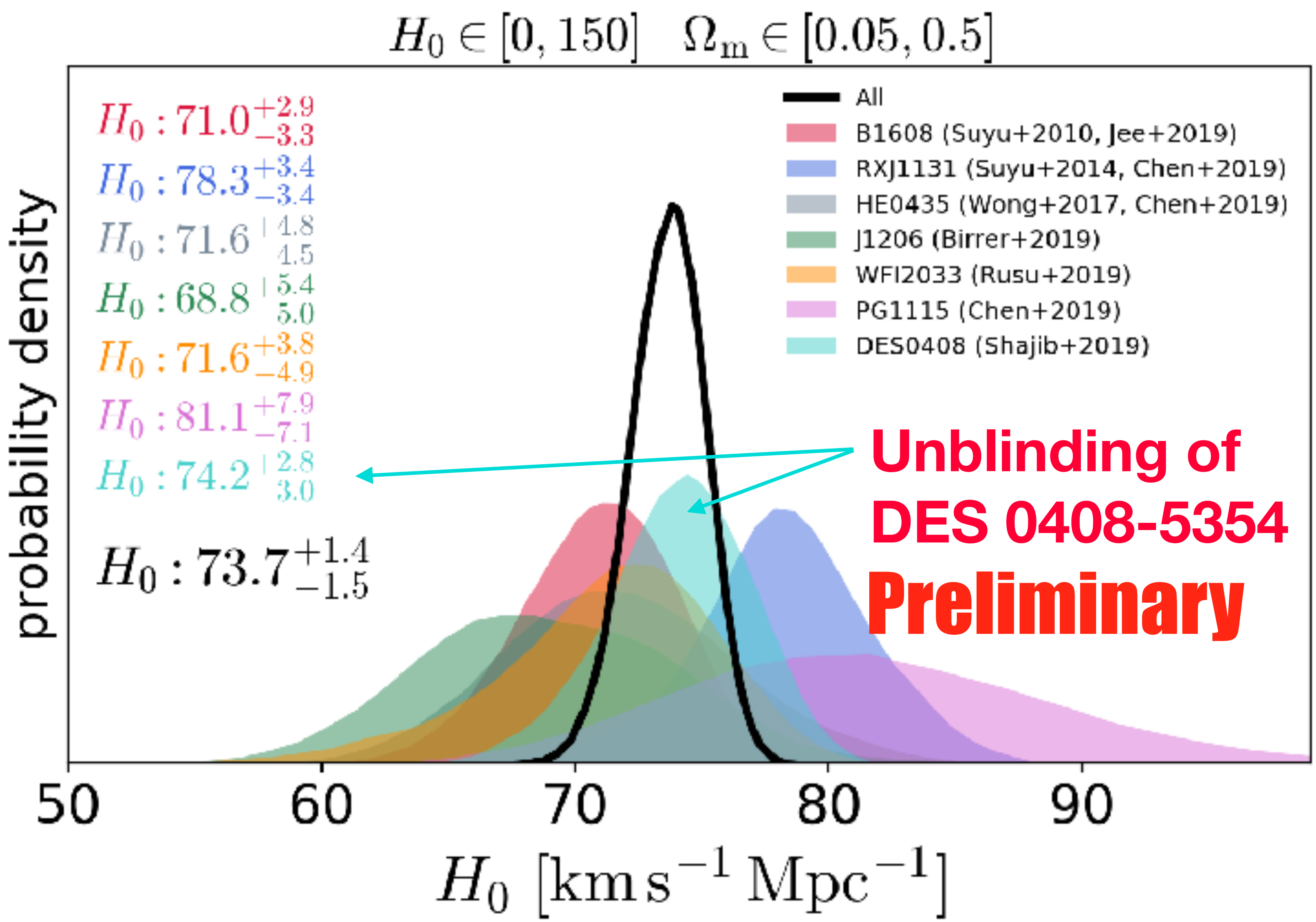
Shajib et al. (2019 arXiv1910.06306)

DES J0408-5354: Modeling with `Lenstronomy`



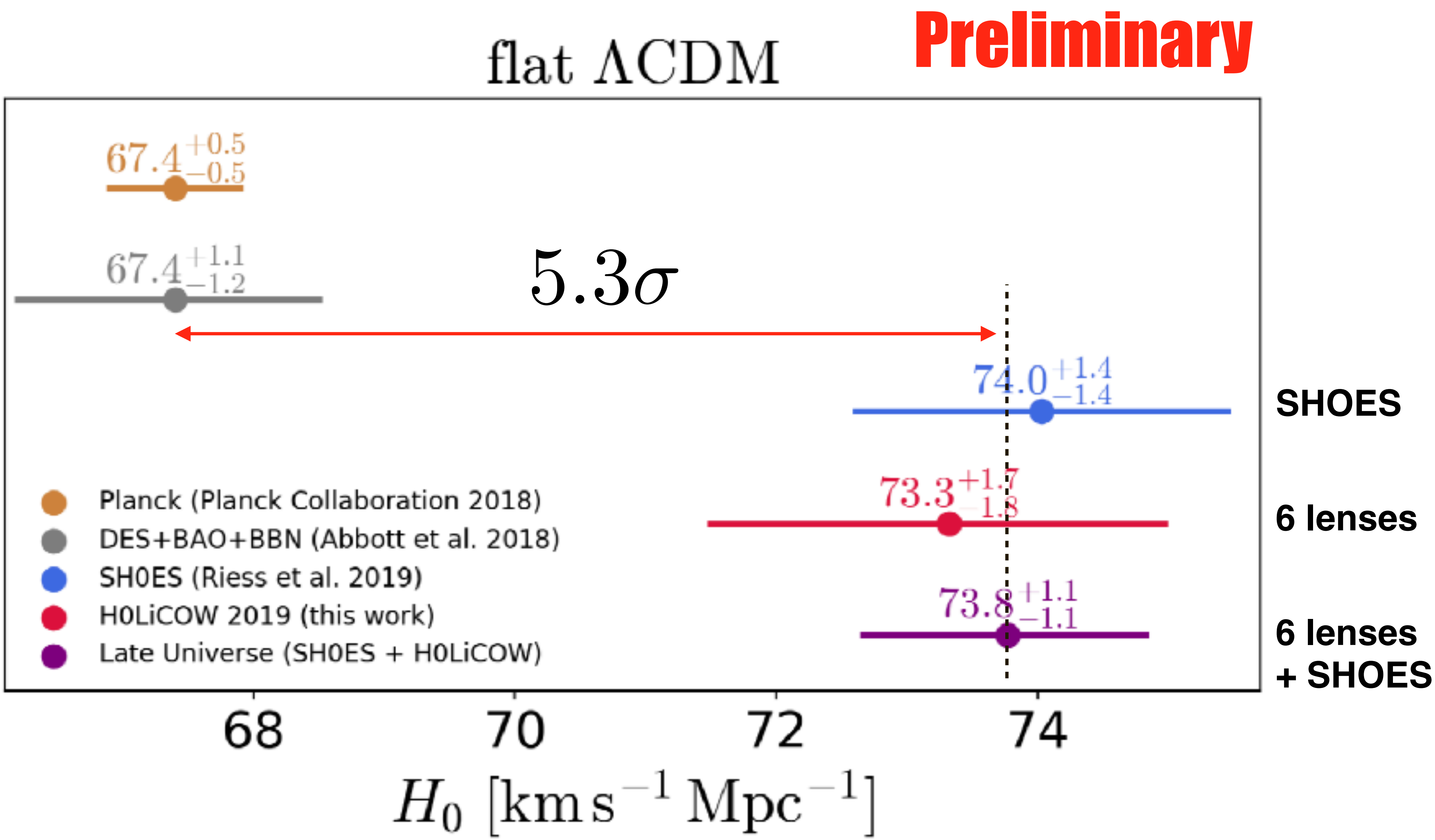
Shajib et al. (2019 arXiv1910.06306)

New Cosmology Results for 7 Lenses in flat lambda-CMD



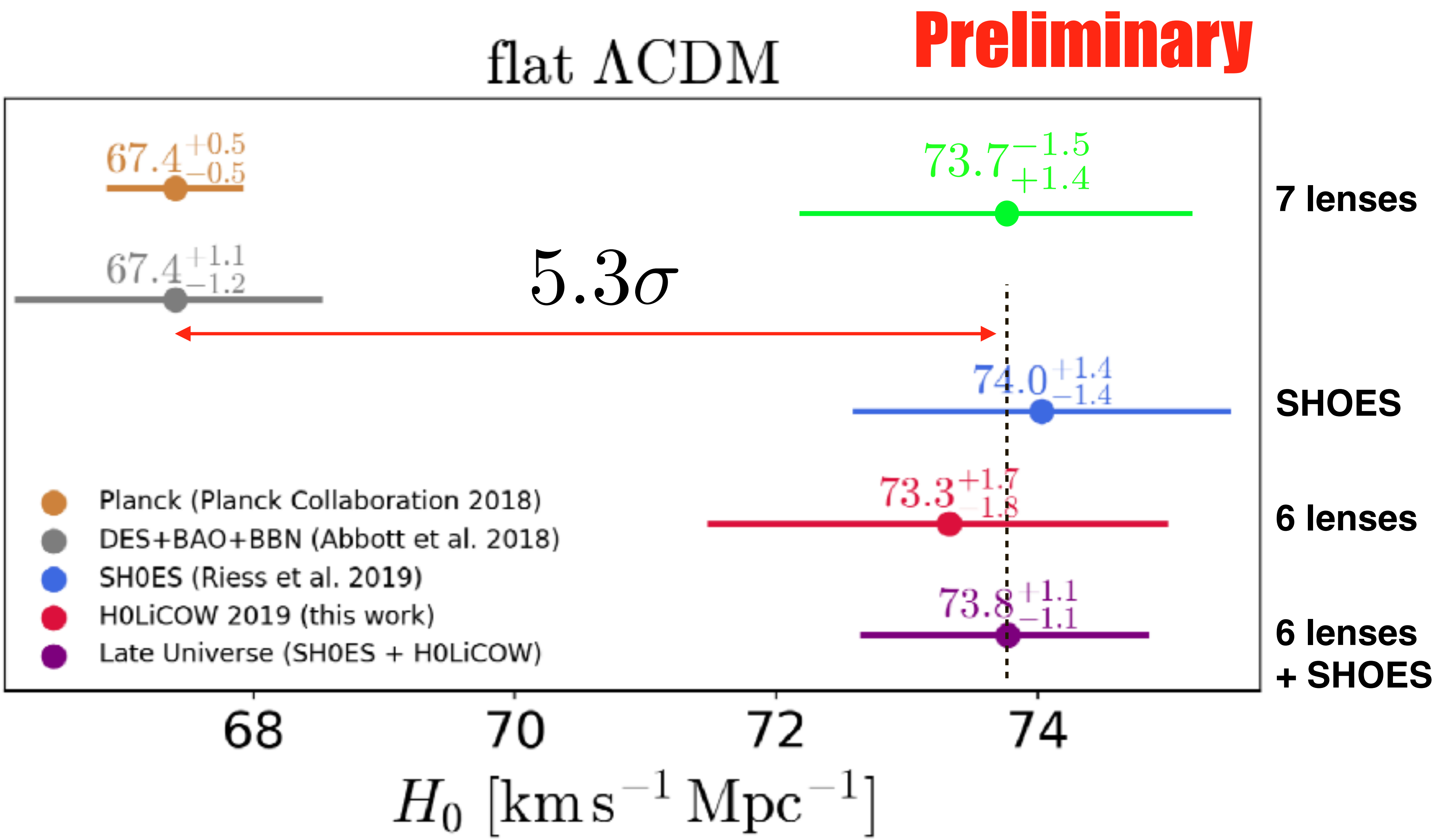
See also poster from **Anowar Shajib**

Cosmology Results for 6 Lenses in flat lambda-CMD



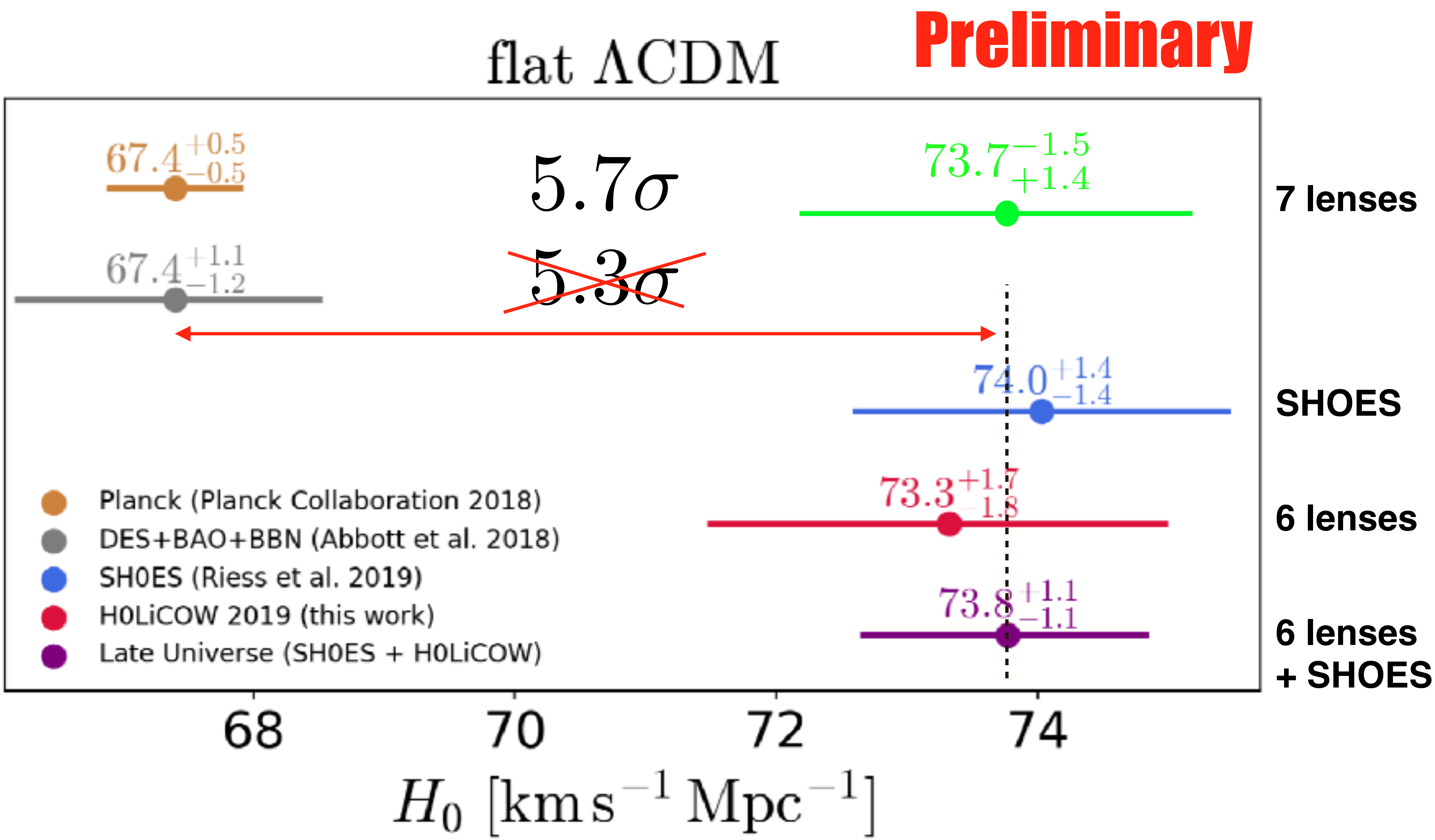
H0LiCOW XIII milestone paper by Wong et al. (2019, arXiv1907.04869)

Cosmology Results for 7 Lenses in flat lambda-CMD



Adding DES0408-5354 by Shajib et al. (2019, arXiv1910.06306)

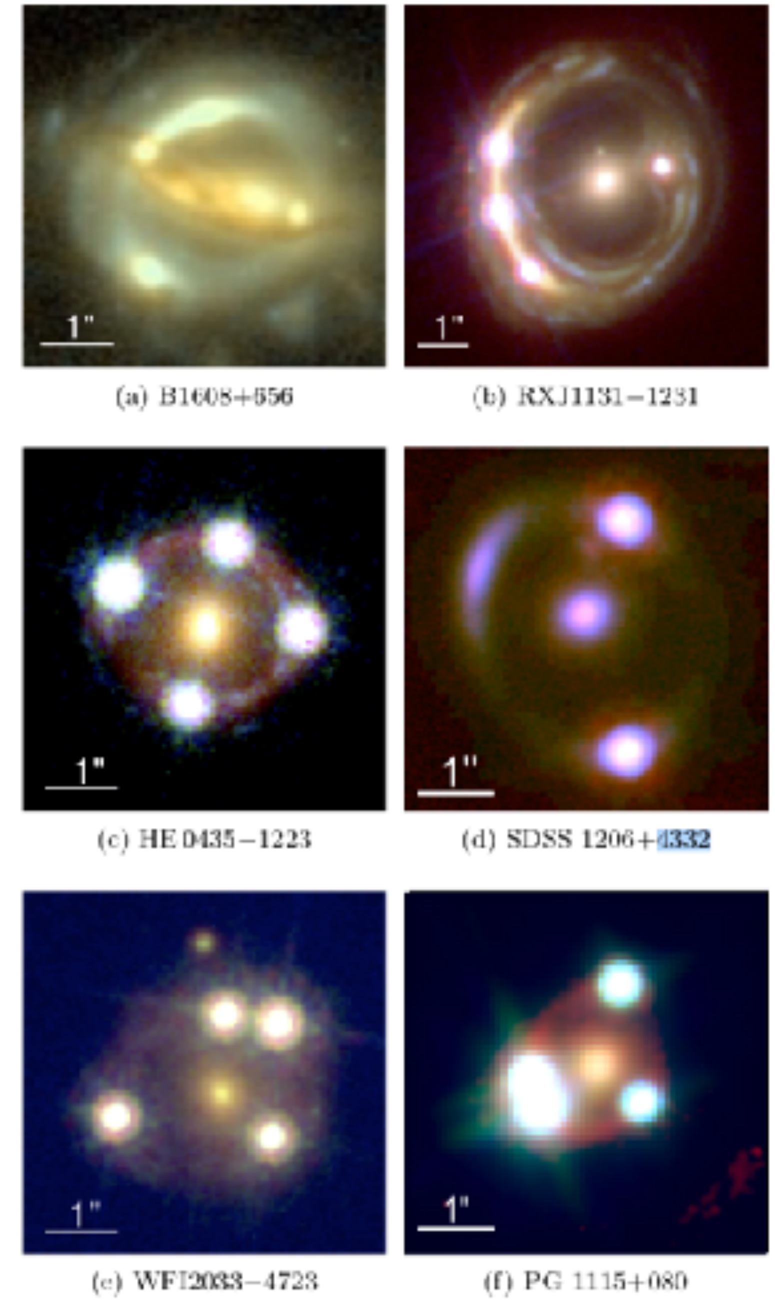
Cosmology Results for 7 Lenses in flat lambda-CMD



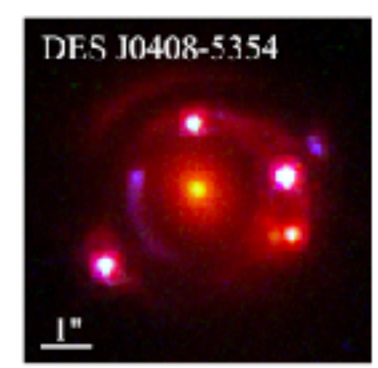
Now combining SHOES with 7 lenses

Summary

- Strong lensing time delays consist in an **absolute** distance indicator
- Time delays are measured to a few percents within 1 single season
- DES, KIDS, HSC, PanSTARSS EUCLID, LSST, Gaia, will discover hundreds of new suitable targets
- 7 lenses give H_0 with accuracy and precision comparable to supernovae and are independent
- In flat lambda-CDM $H_0 = 73.7 \pm 2.9$ km.s^{-1}.Mpc^{-1}
- A dozen of additional objects already « in the pipeline »
- **All analysis done blind!**



(a) B1608+656 (b) RXJ1131−1231 (c) HE 0435−1223 (d) SDSS 1206+4332 (e) WFI2033−4723 (f) PG 1115+080



More strong lensing results on posters by Akin Yildirim, Anowar Shajib & Chih-Fan Chen