

TDCOSMO-2025

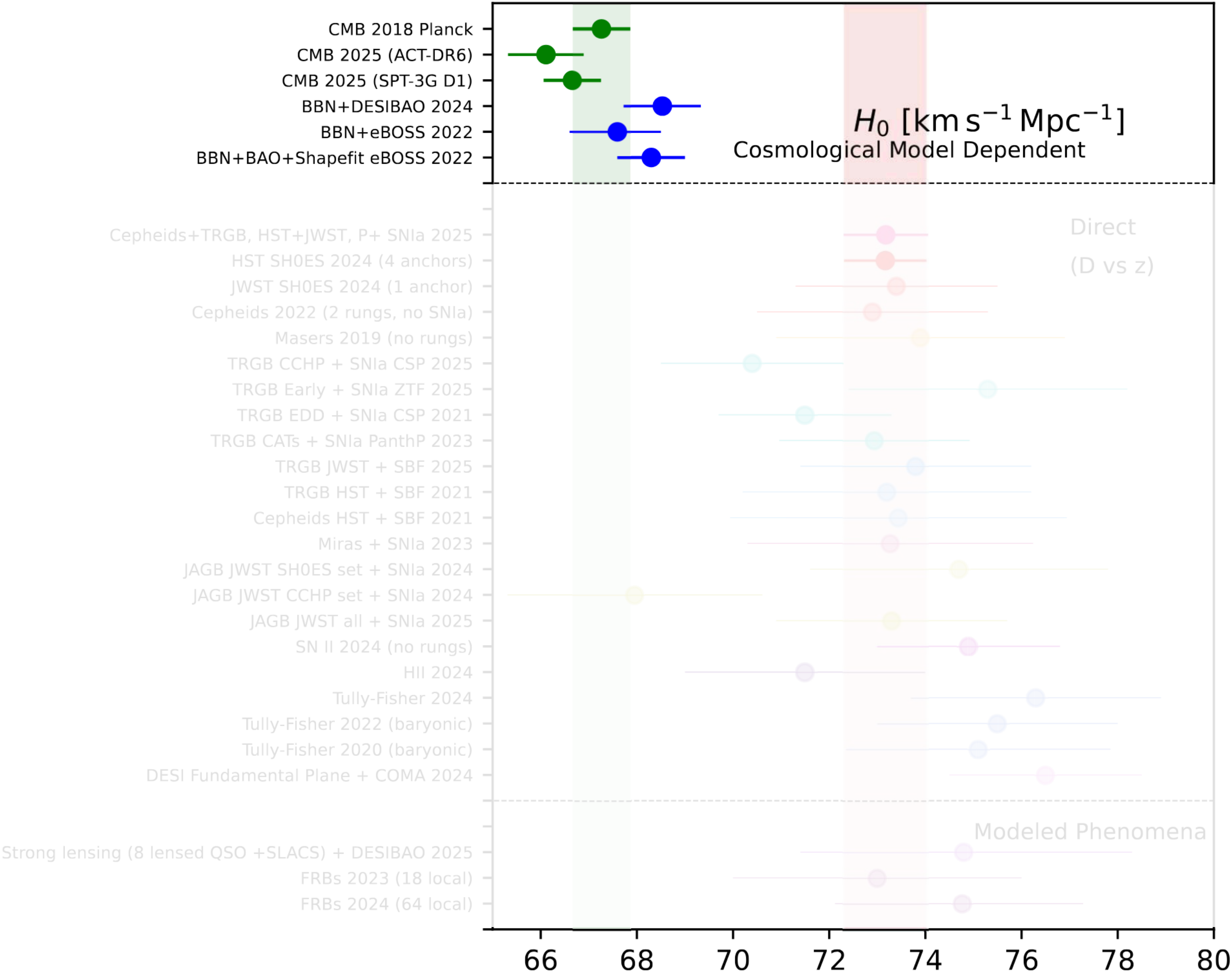
Cosmological constraints from strong lensing time delays

Aymeric Galan (MPA)

On behalf of the TDCOSMO collaboration

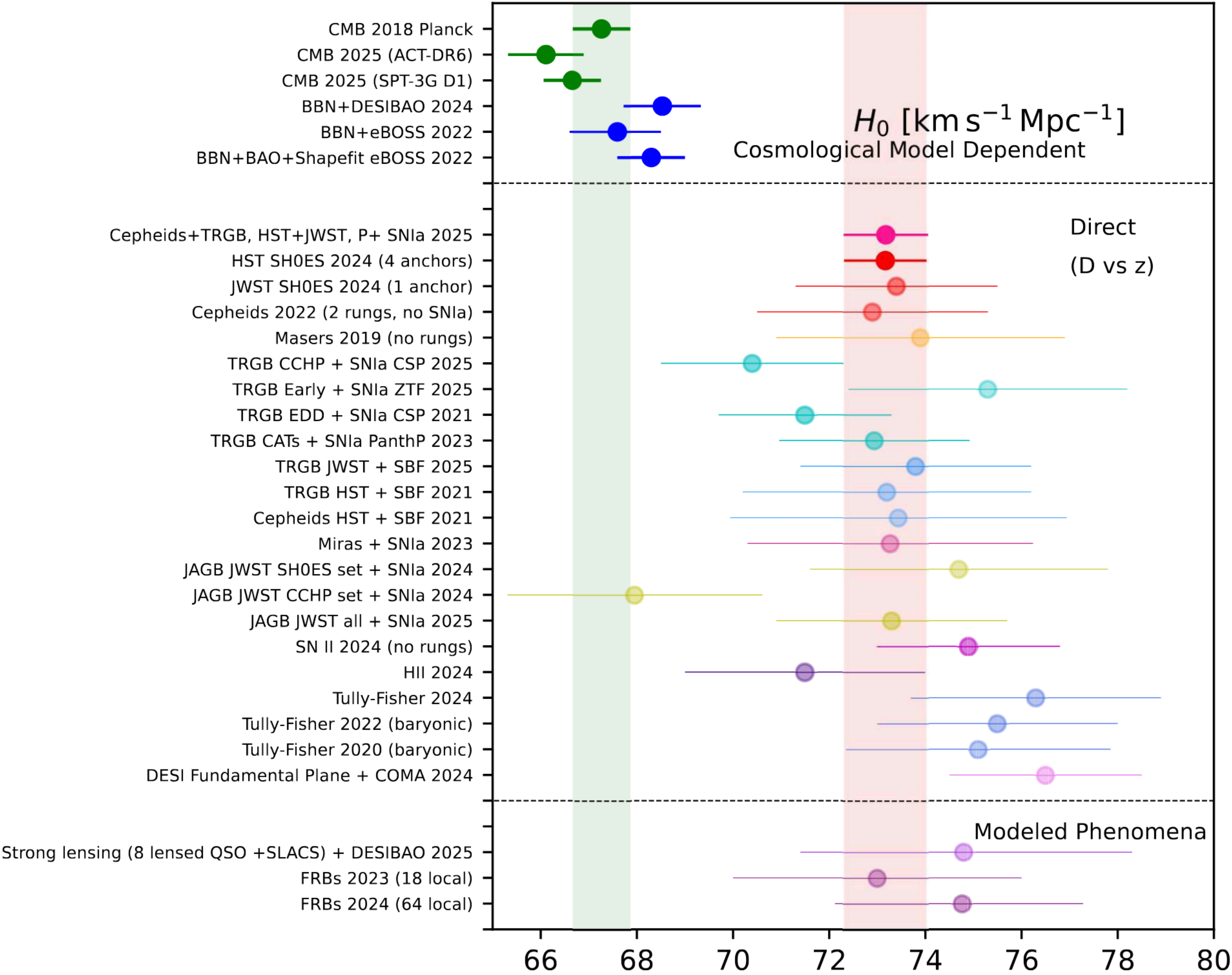
We always need methods independent from each others

Di Valentino et al. 2025

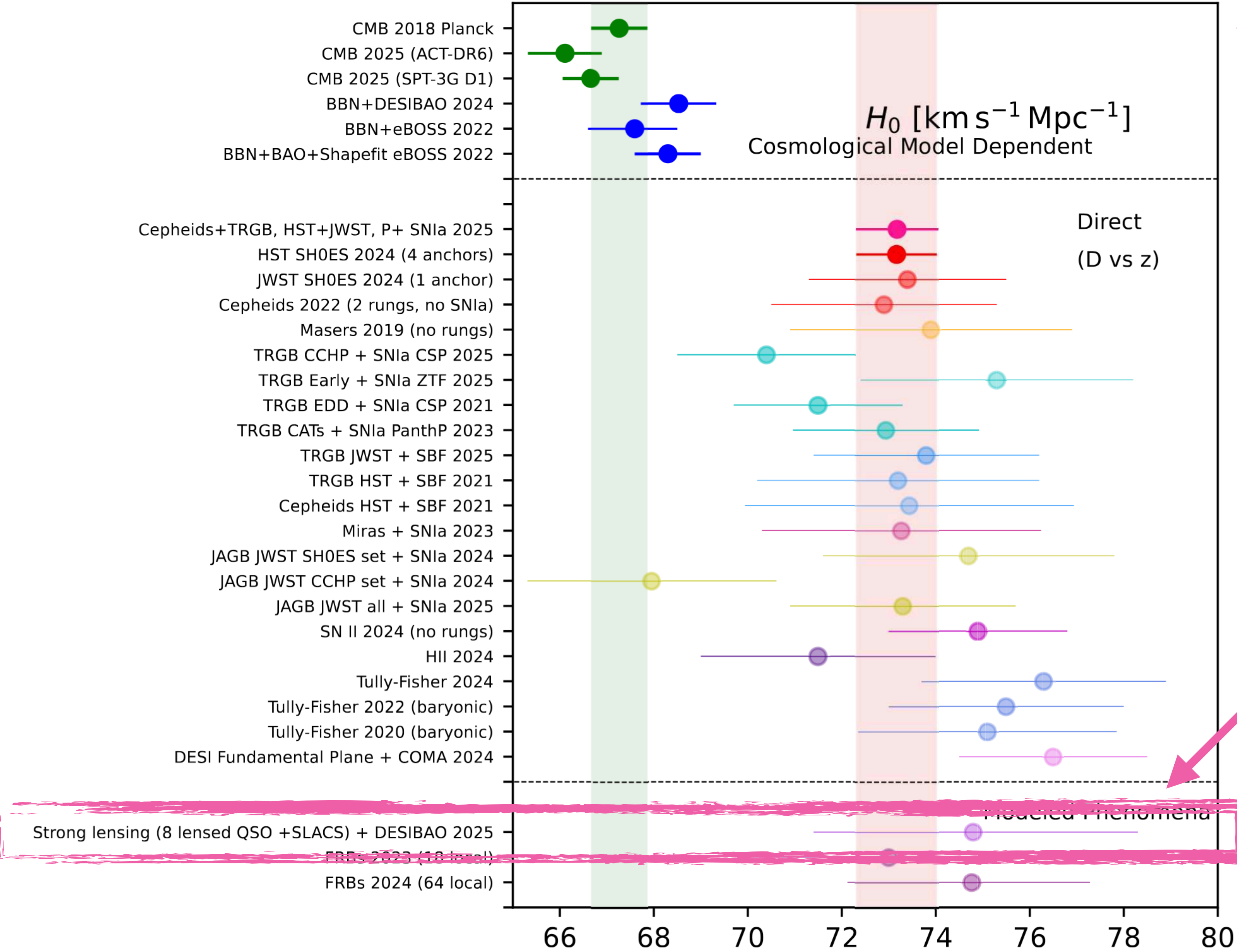


We always need methods independent from each others

Di Valentino et al. 2025

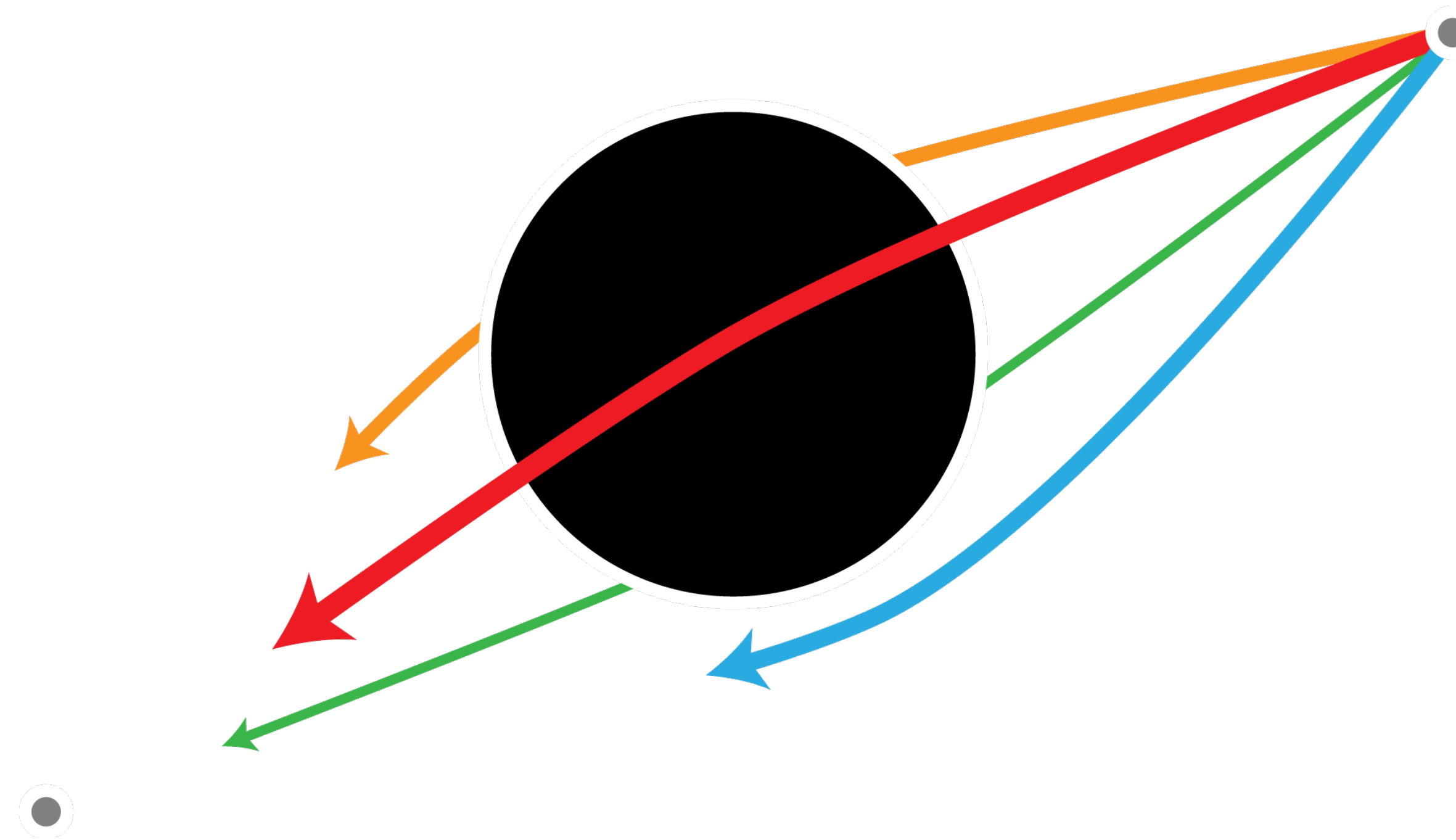


We always need methods independent from each others



Di Valentino et al. 2025

This talk:
time-delay cosmography
with strongly lensed quasars
(TDCOSMO collaboration)

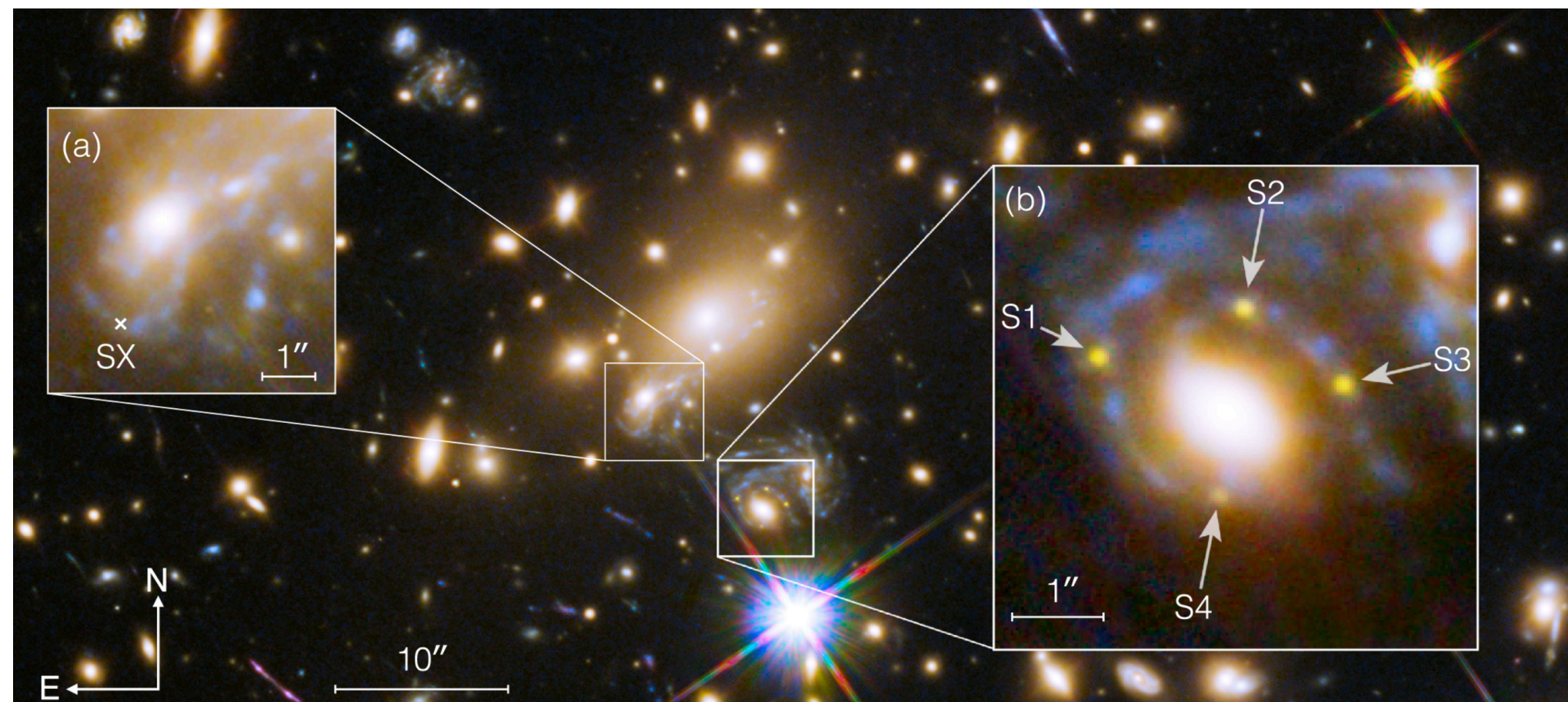


Time-delay cosmography is direct, without calibration and competitive by measuring ratios of angular diameter distances from single objects.

Time-delay cosmography is also visually appealing

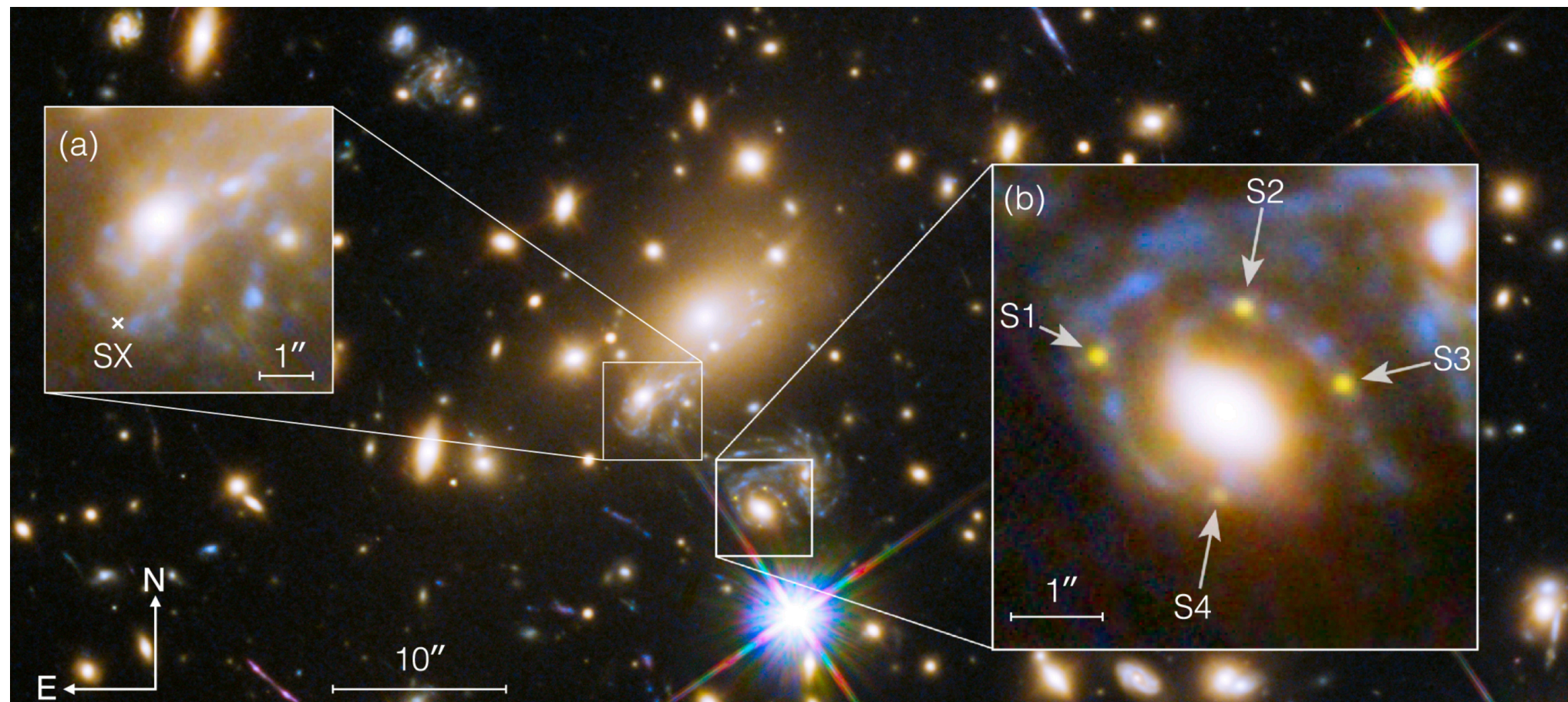
Time-delay cosmography is also visually appealing

Strongly lensed SN « Refsdal » (cluster scale)

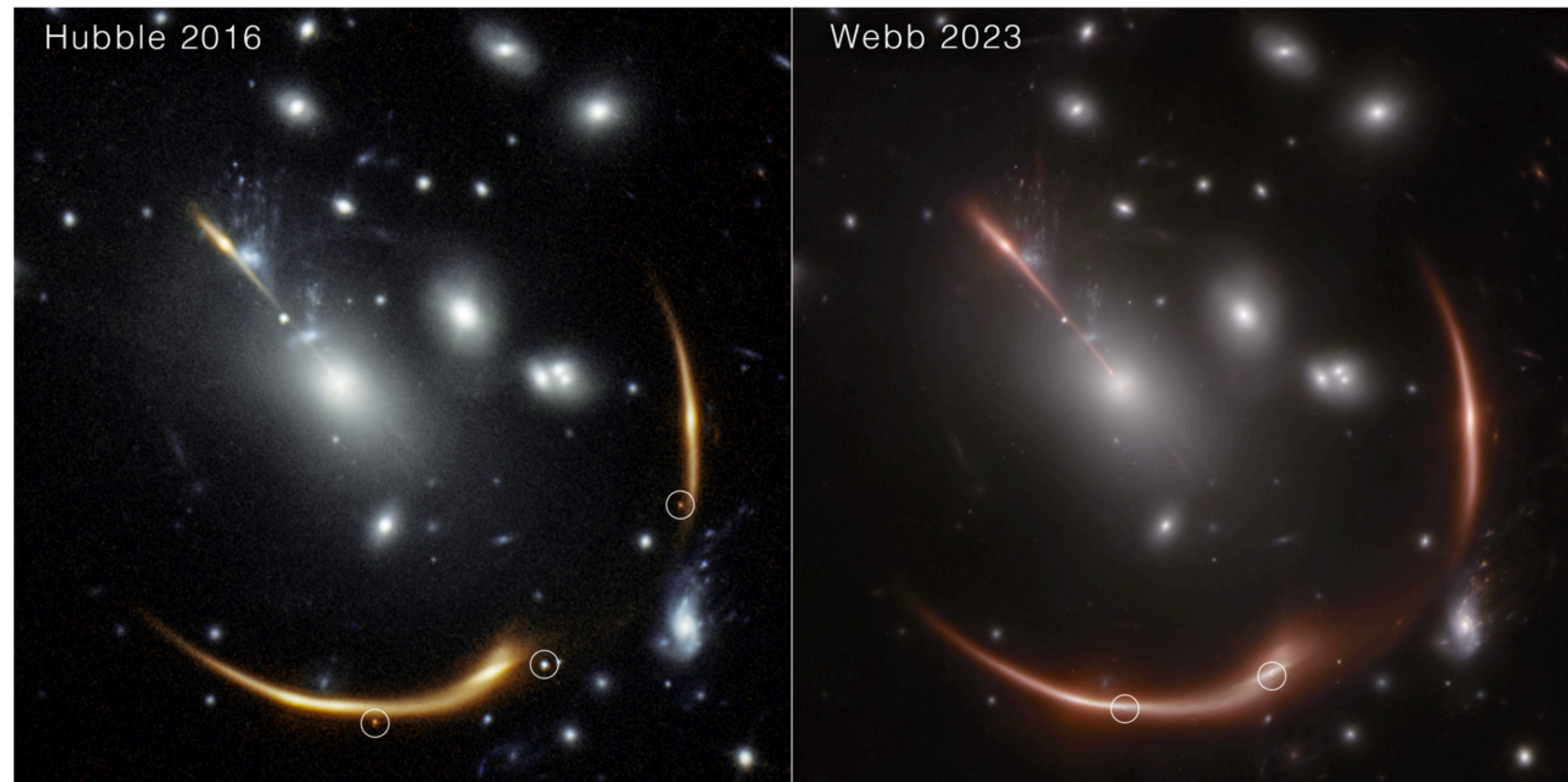


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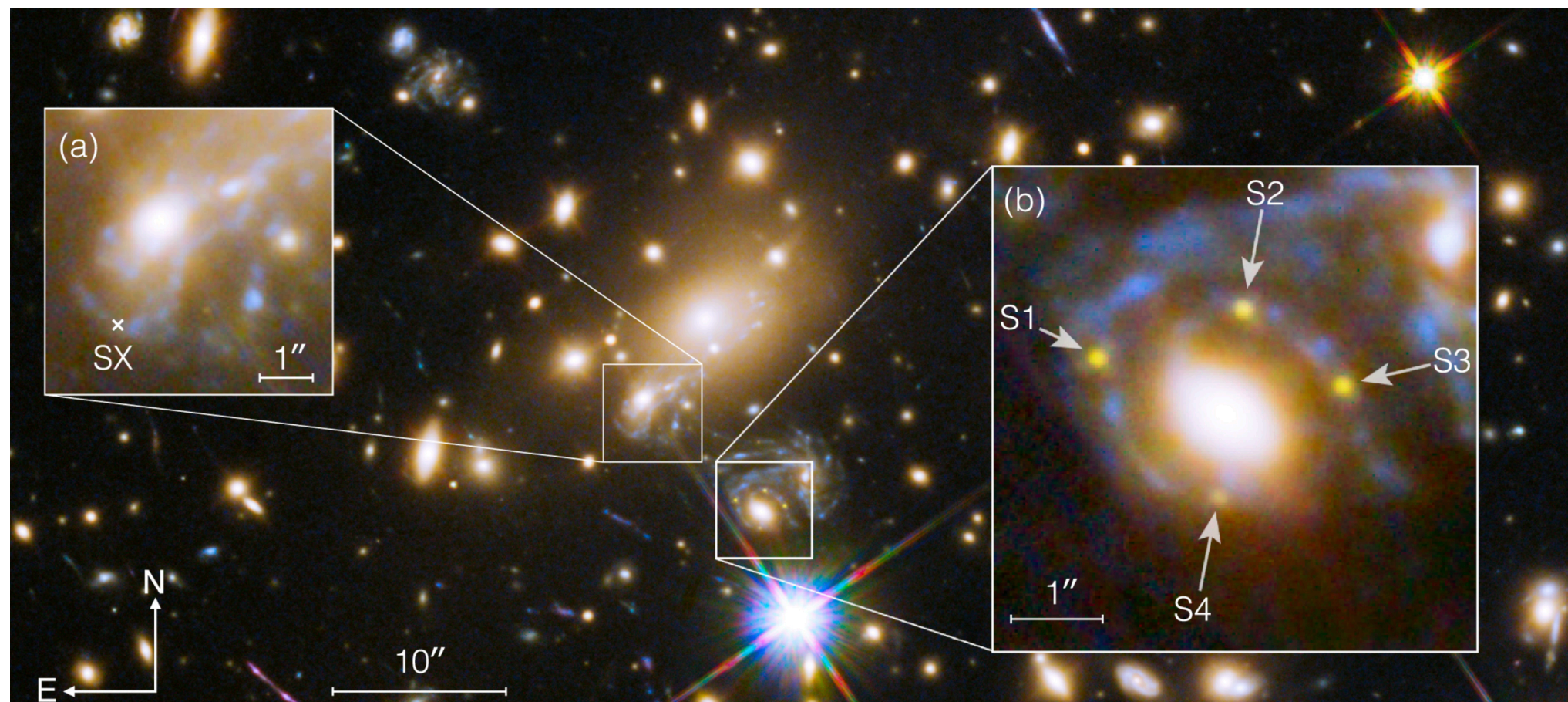


Strongly lensed SNe « Requiem » & « Encore » (cluster scale)

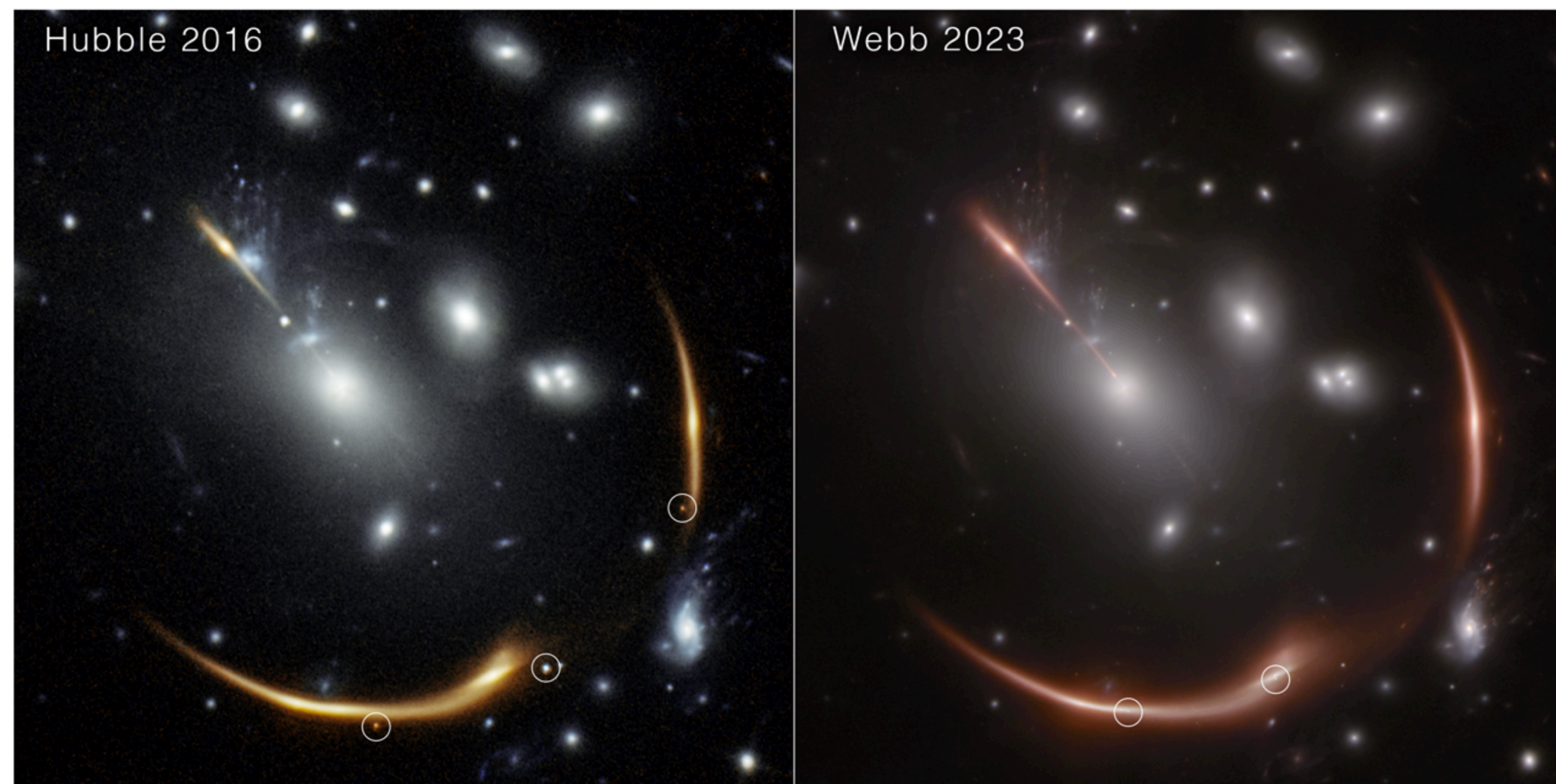


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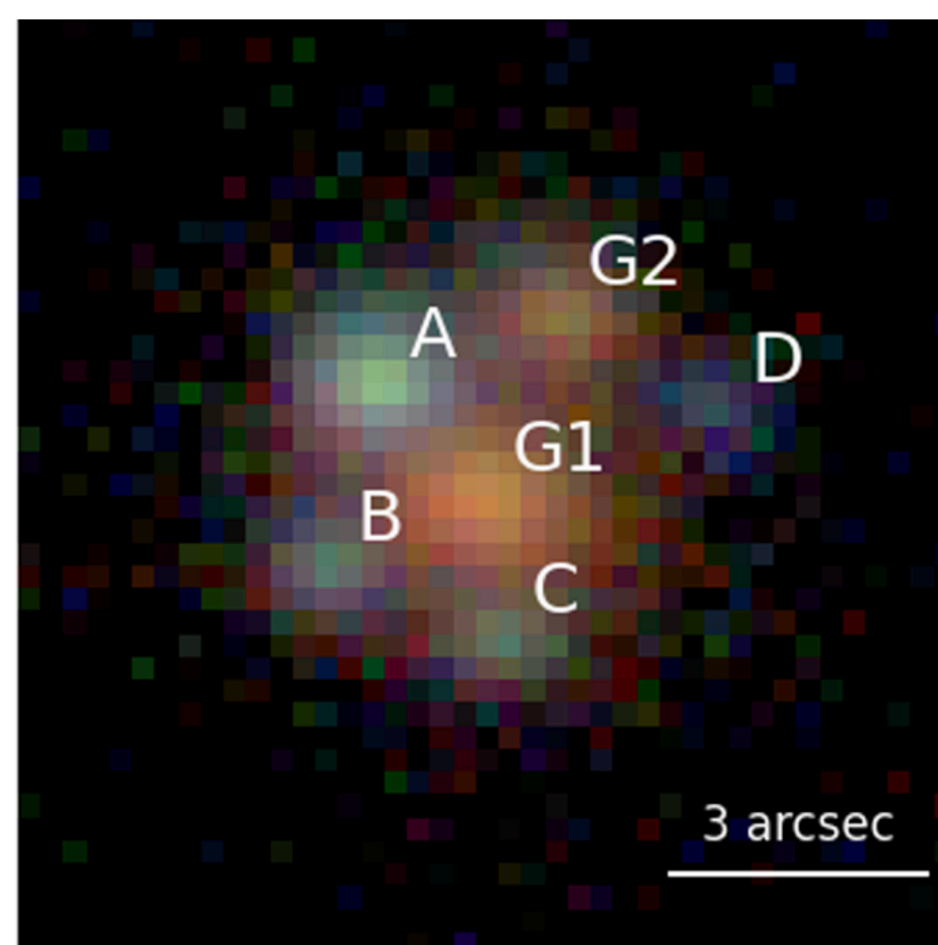


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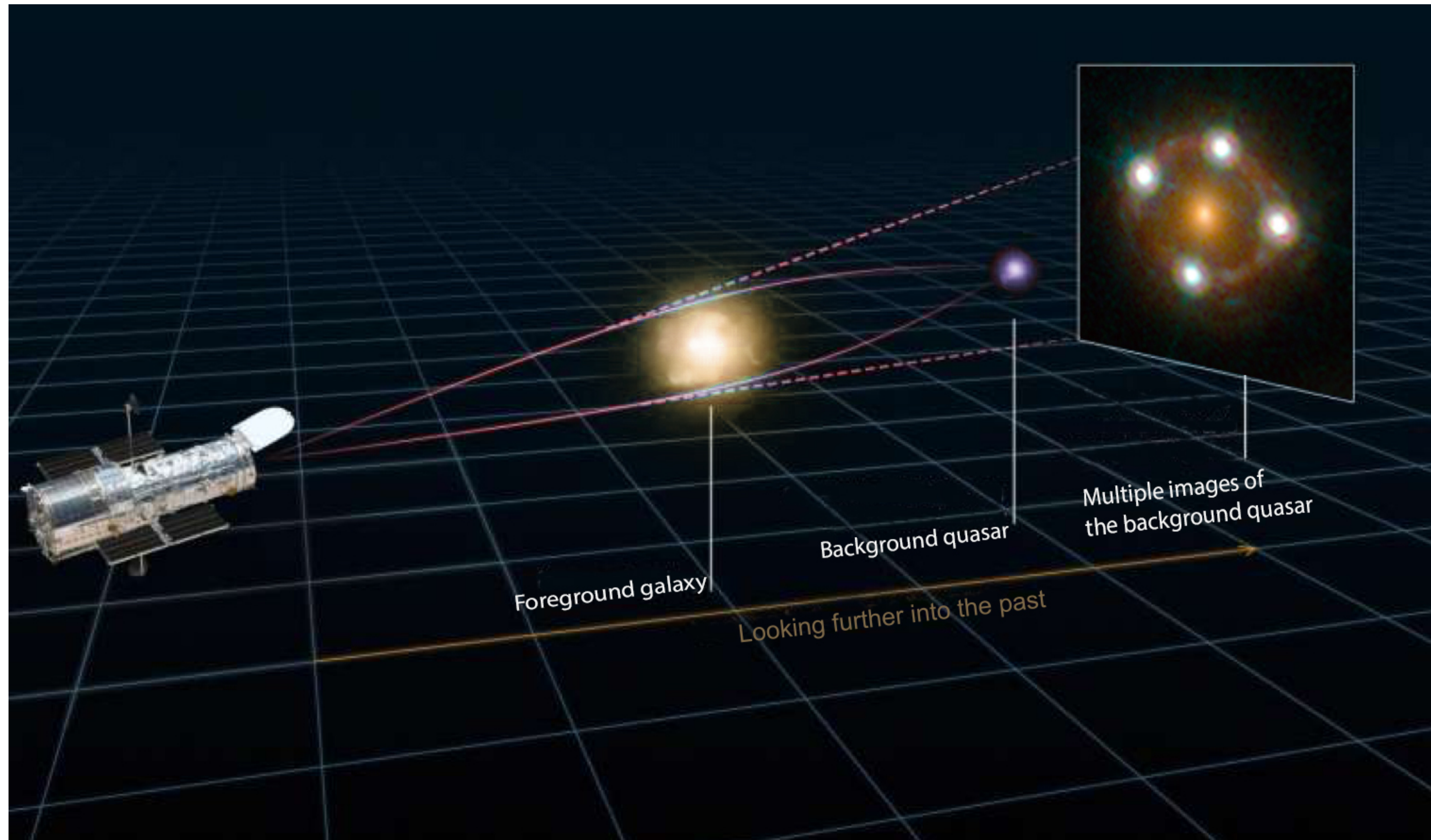
Strongly lensed SLSN « Winny » (galaxy scale)

! just discovered !

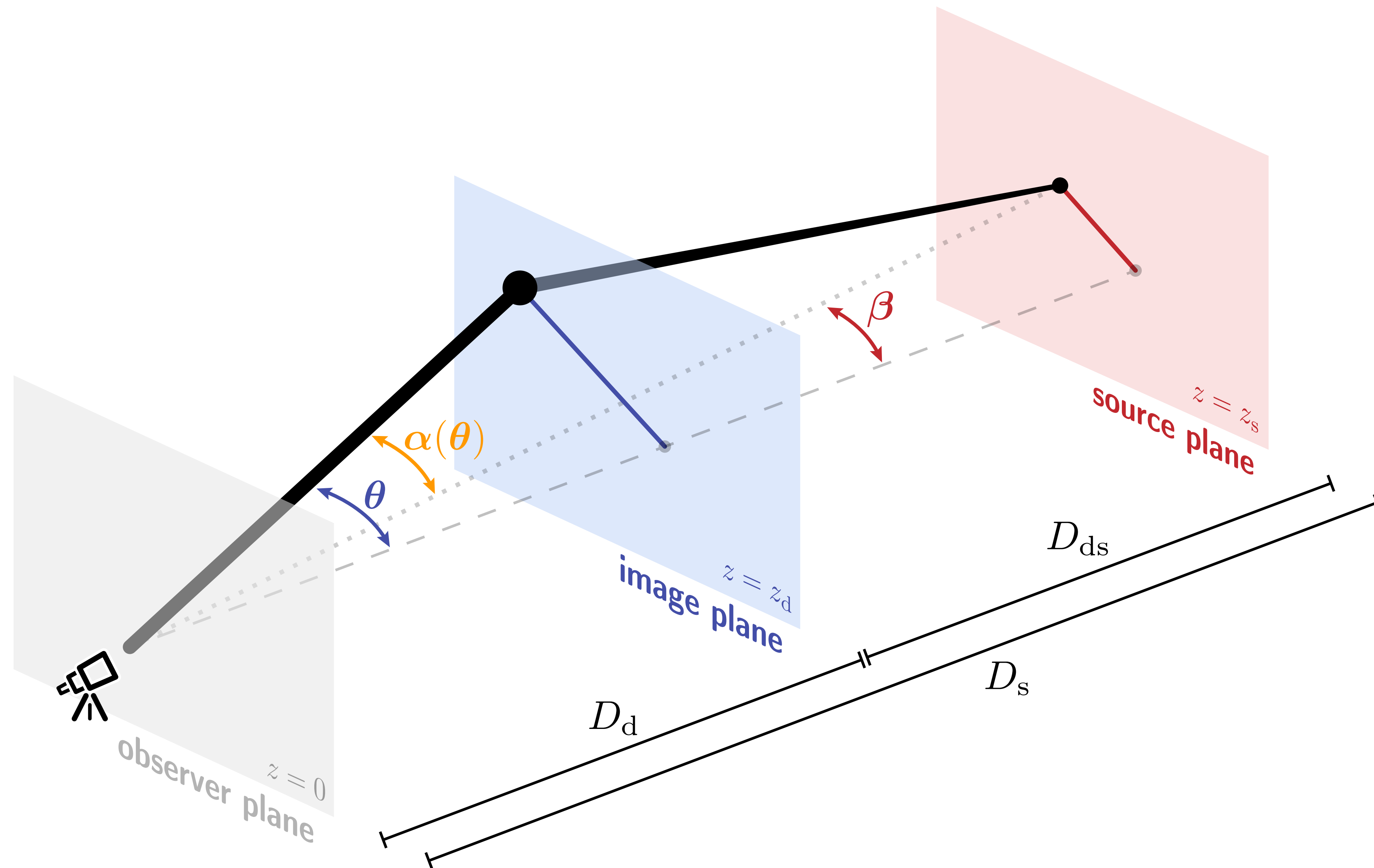


*Taubenberger et al. 2025
(See also Johansson et al. 2025)*

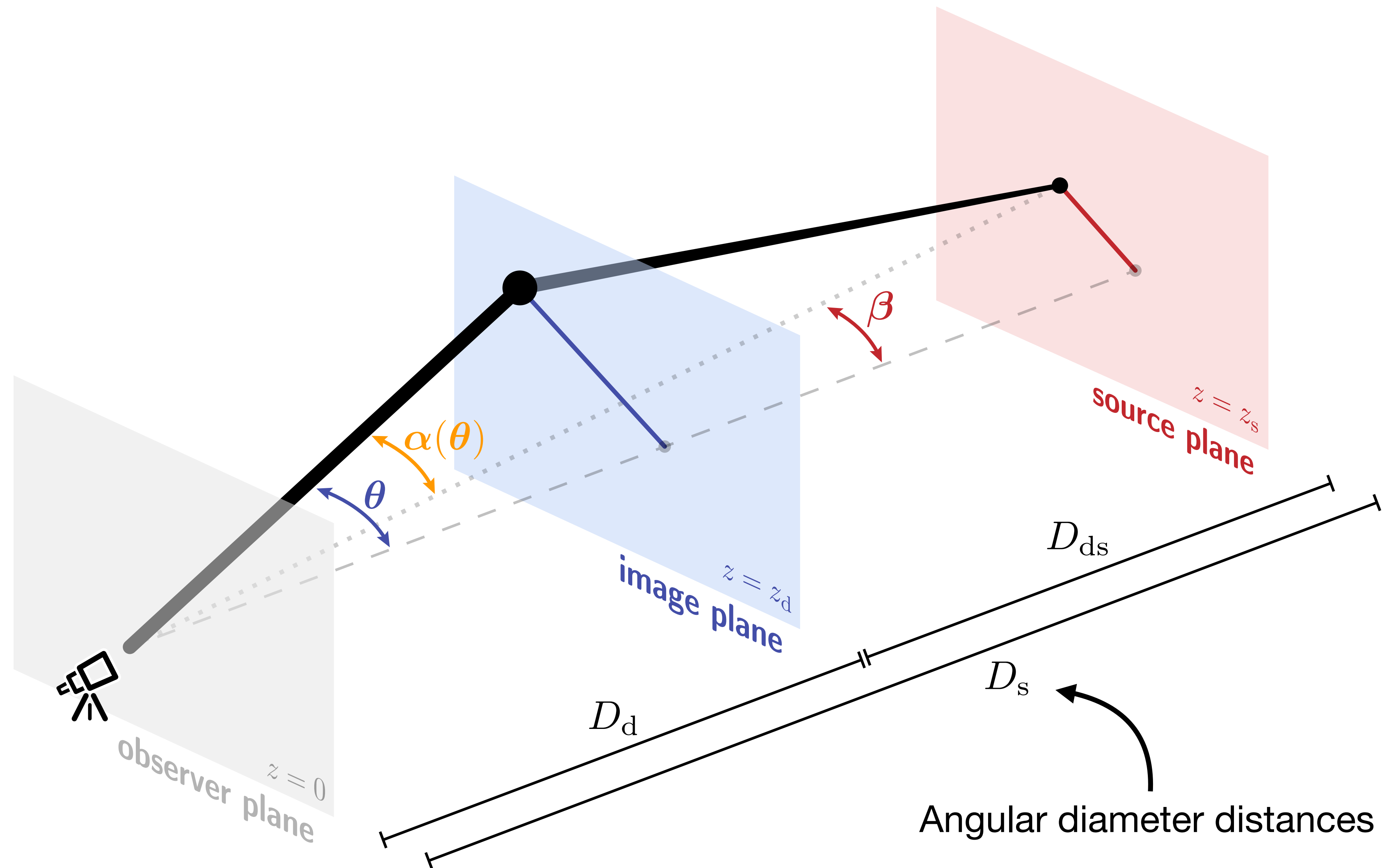
Strongly lensed quasars



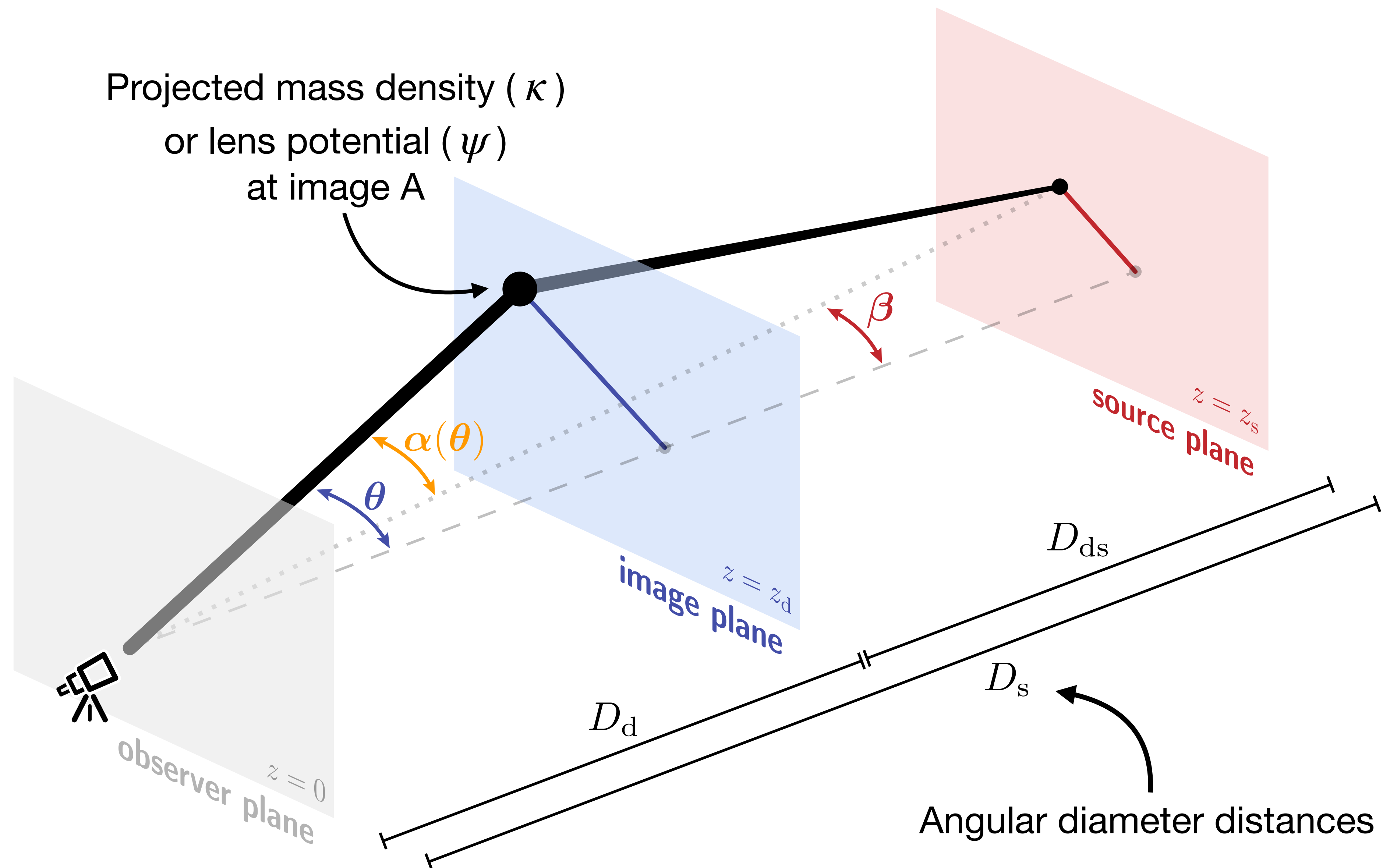
Strongly lensed quasars (schematic view)



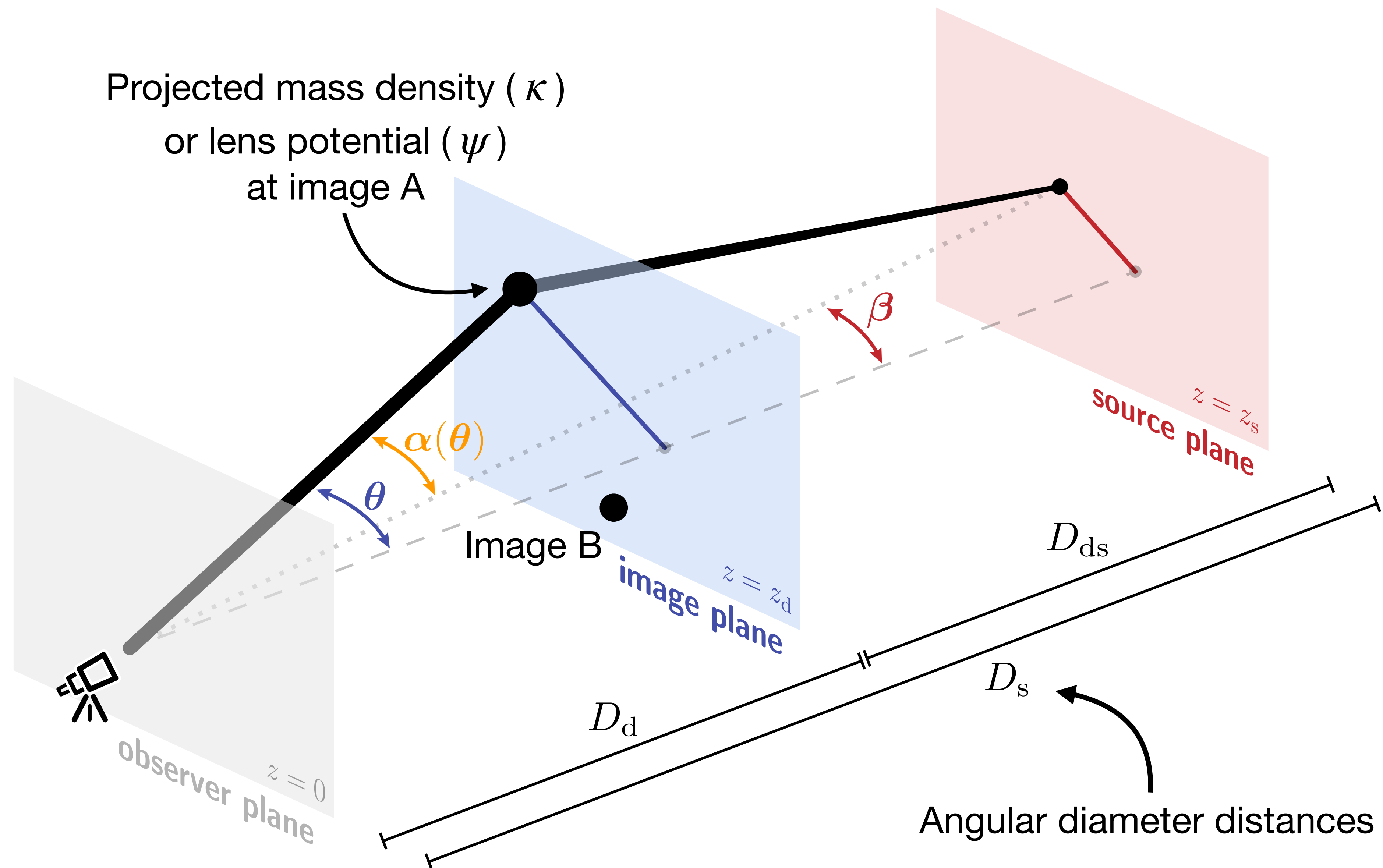
Strongly lensed quasars (schematic view)



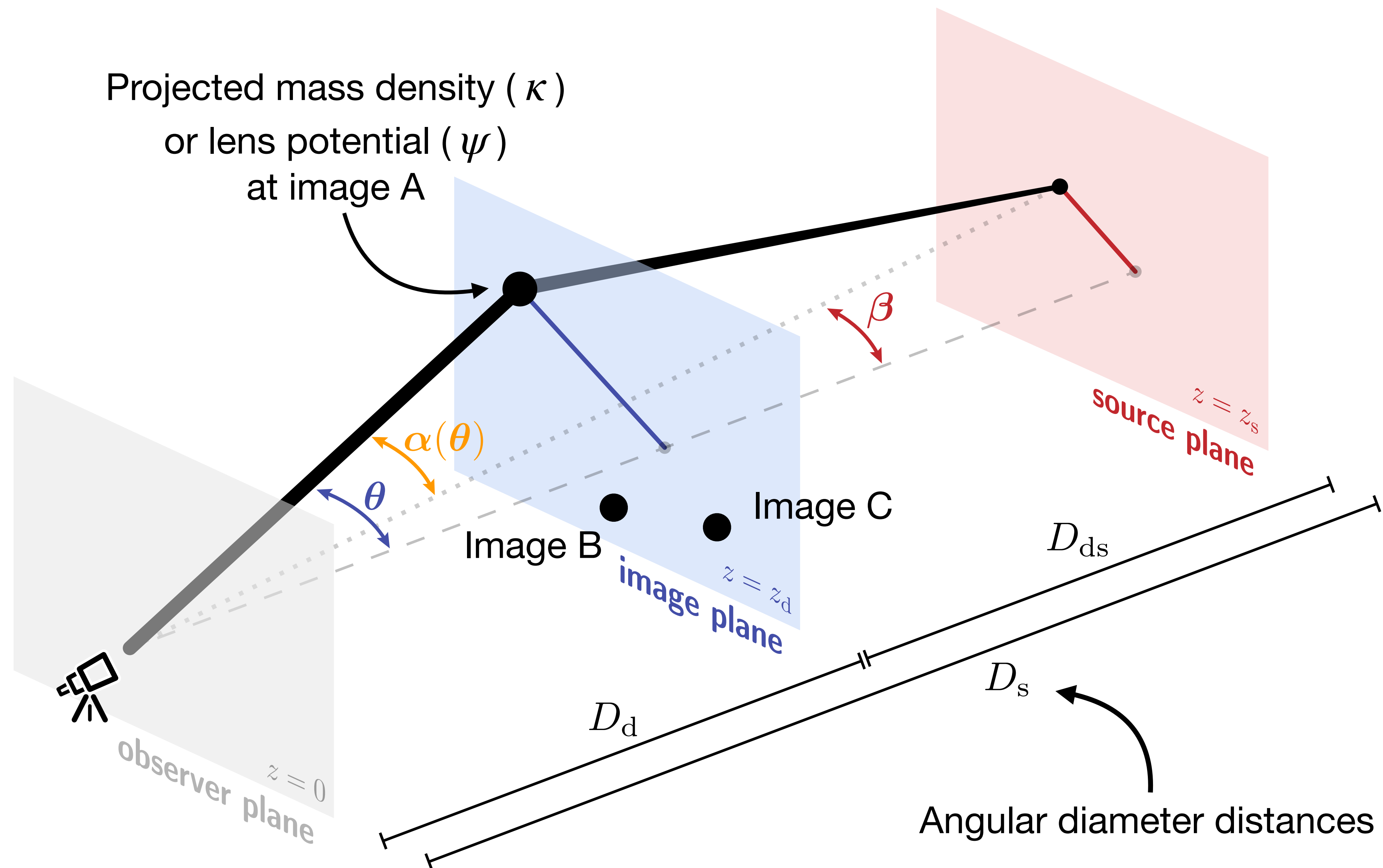
Strongly lensed quasars (schematic view)



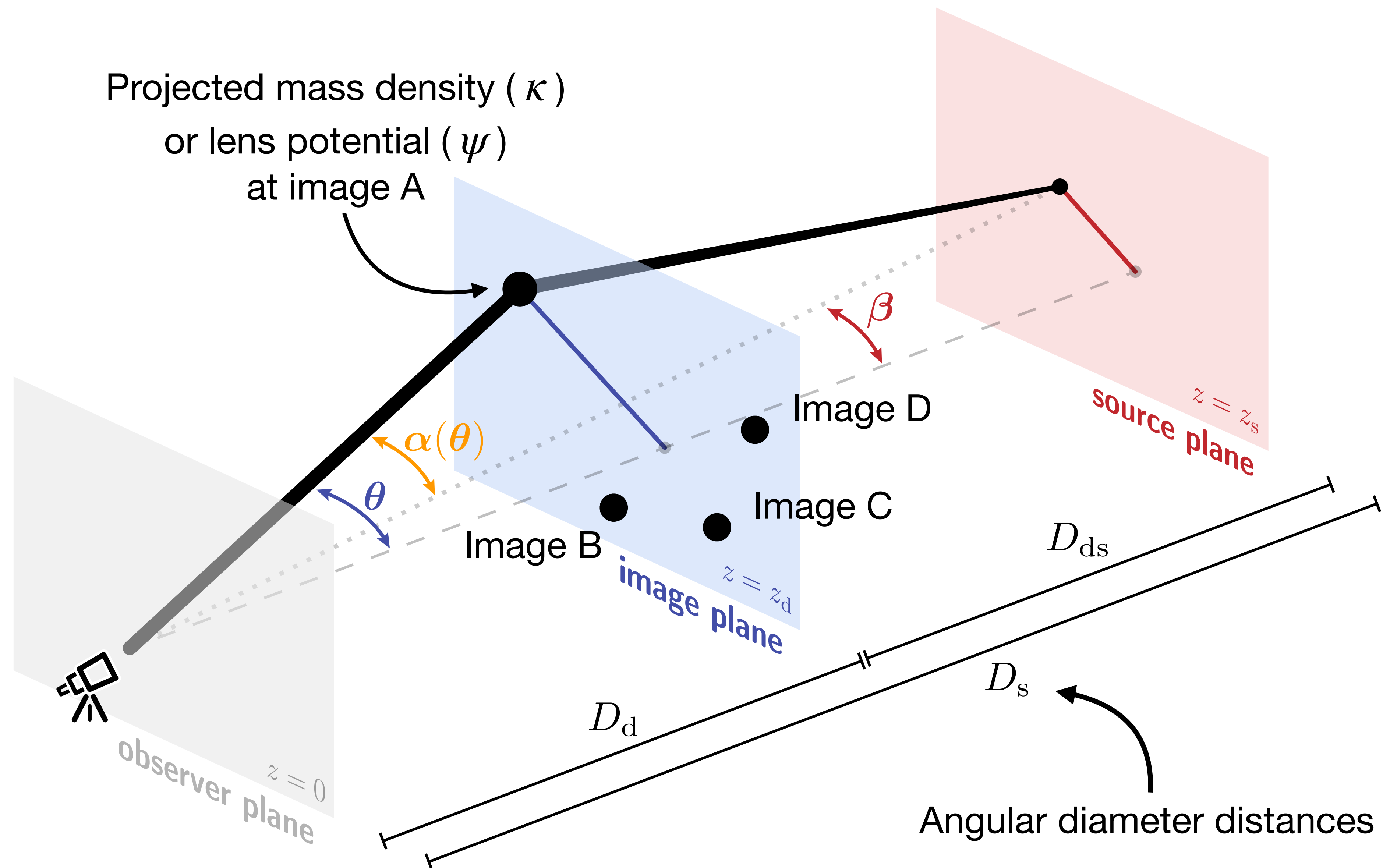
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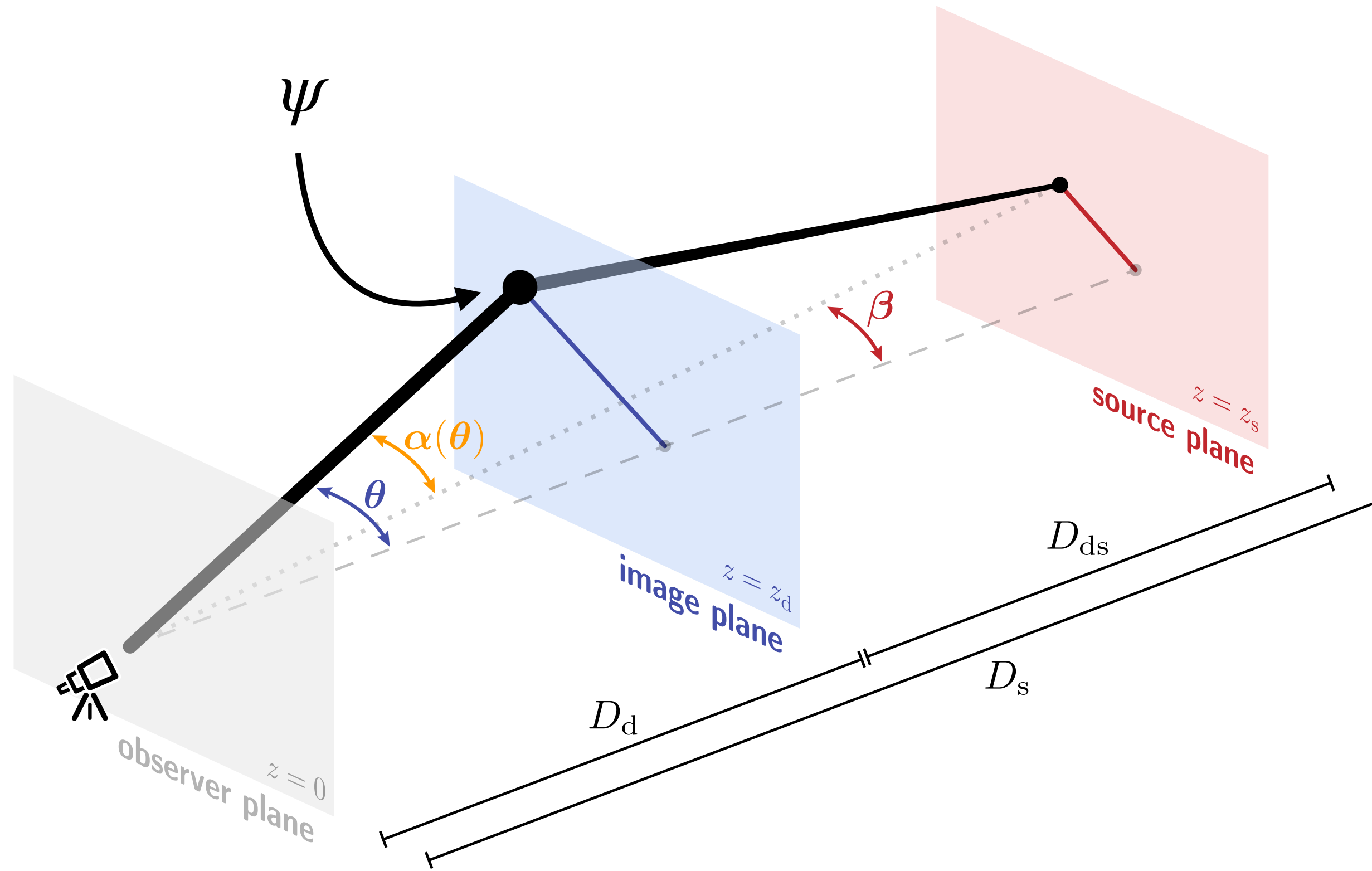
Strongly lensed quasars (schematic view)



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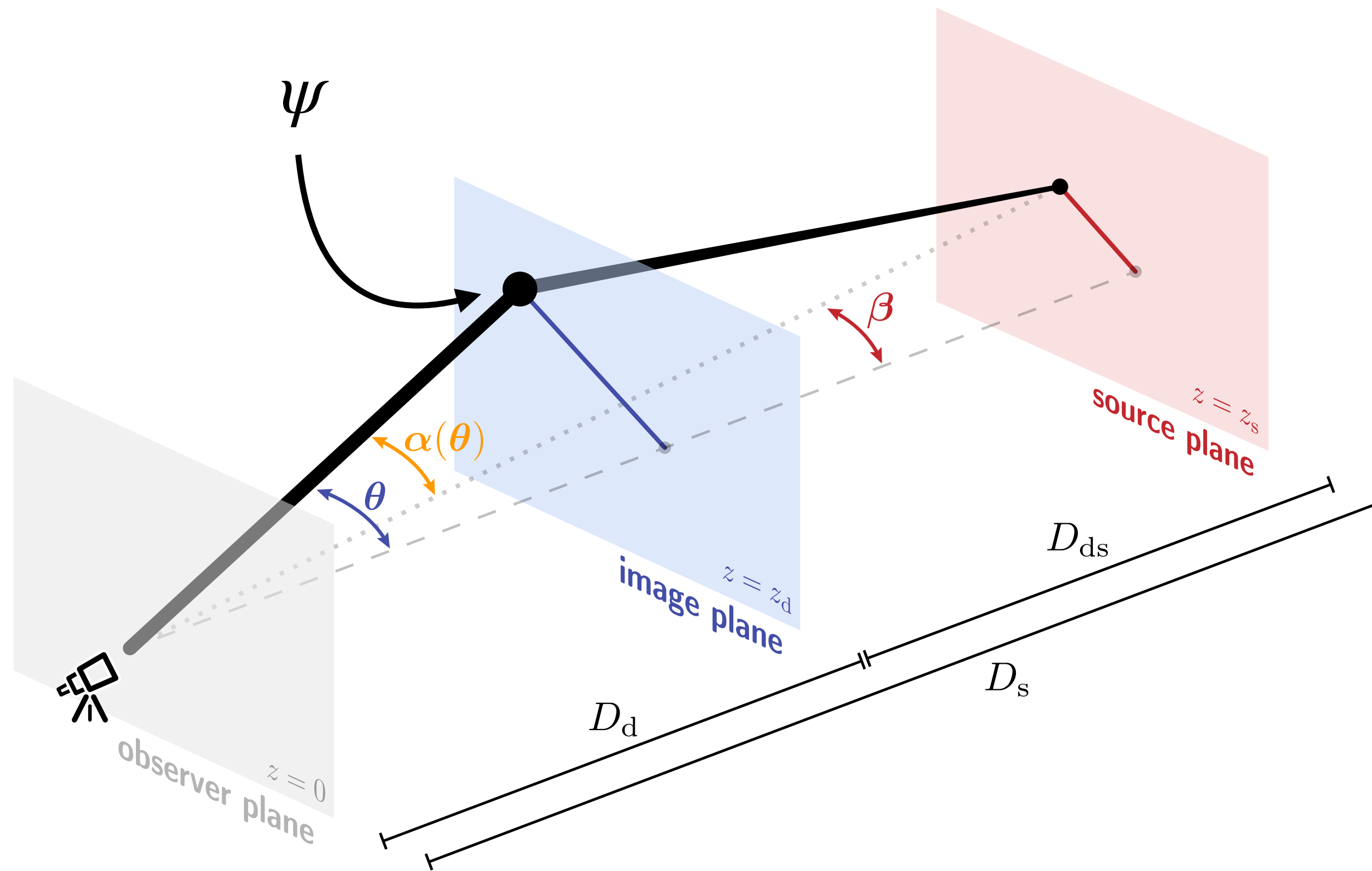
Basic principle of time-delay cosmography



Equation of the time delay (Δt):

$$\Delta t_{AB} \frac{c}{\Delta \phi_{AB}} = D_{\Delta t} \propto H_0^{-1}$$

Basic principle of time-delay cosmography



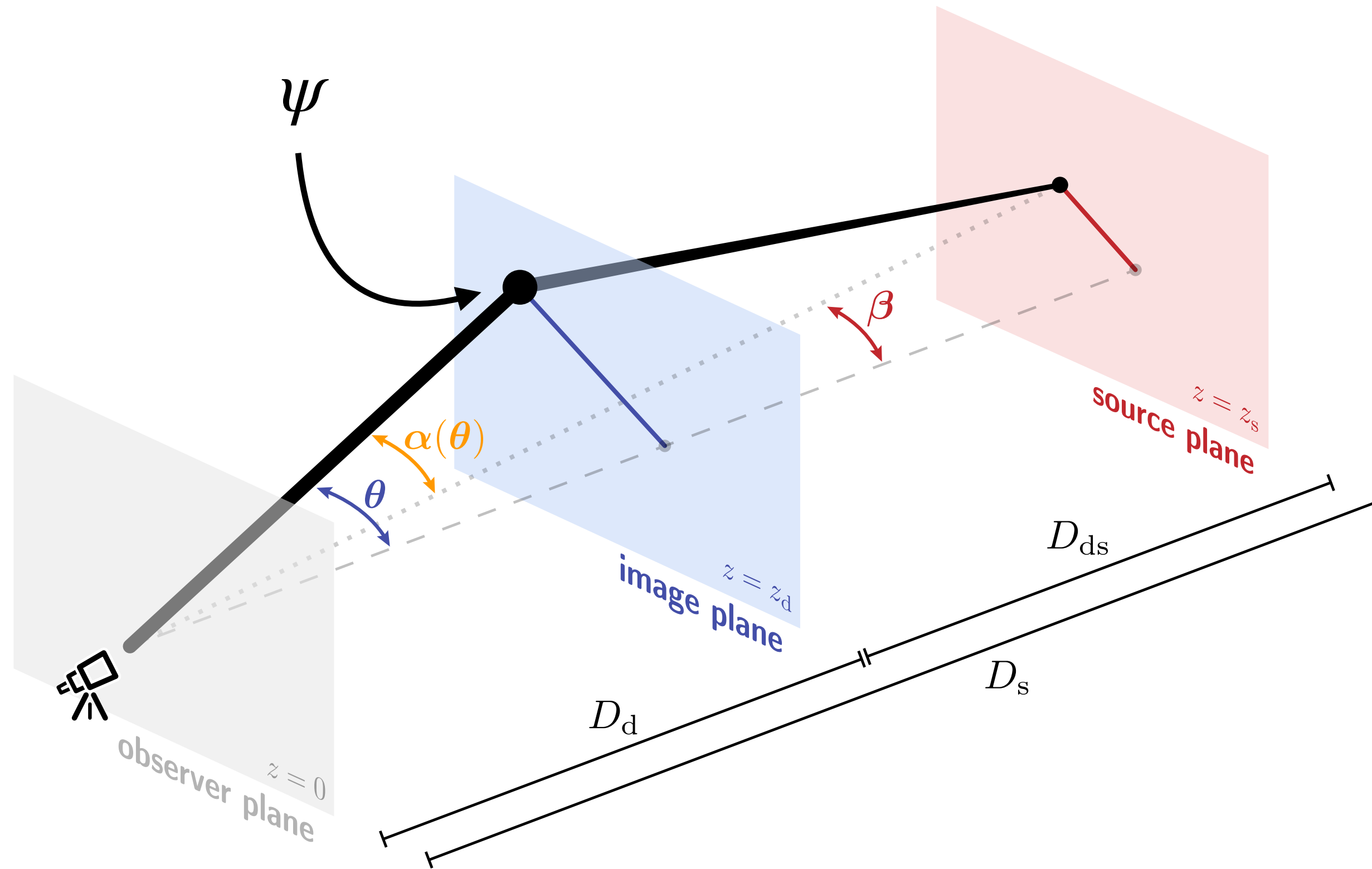
Time-delay
(between two images A and B)

$$\Delta t_{AB}$$

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Basic principle of time-delay cosmography



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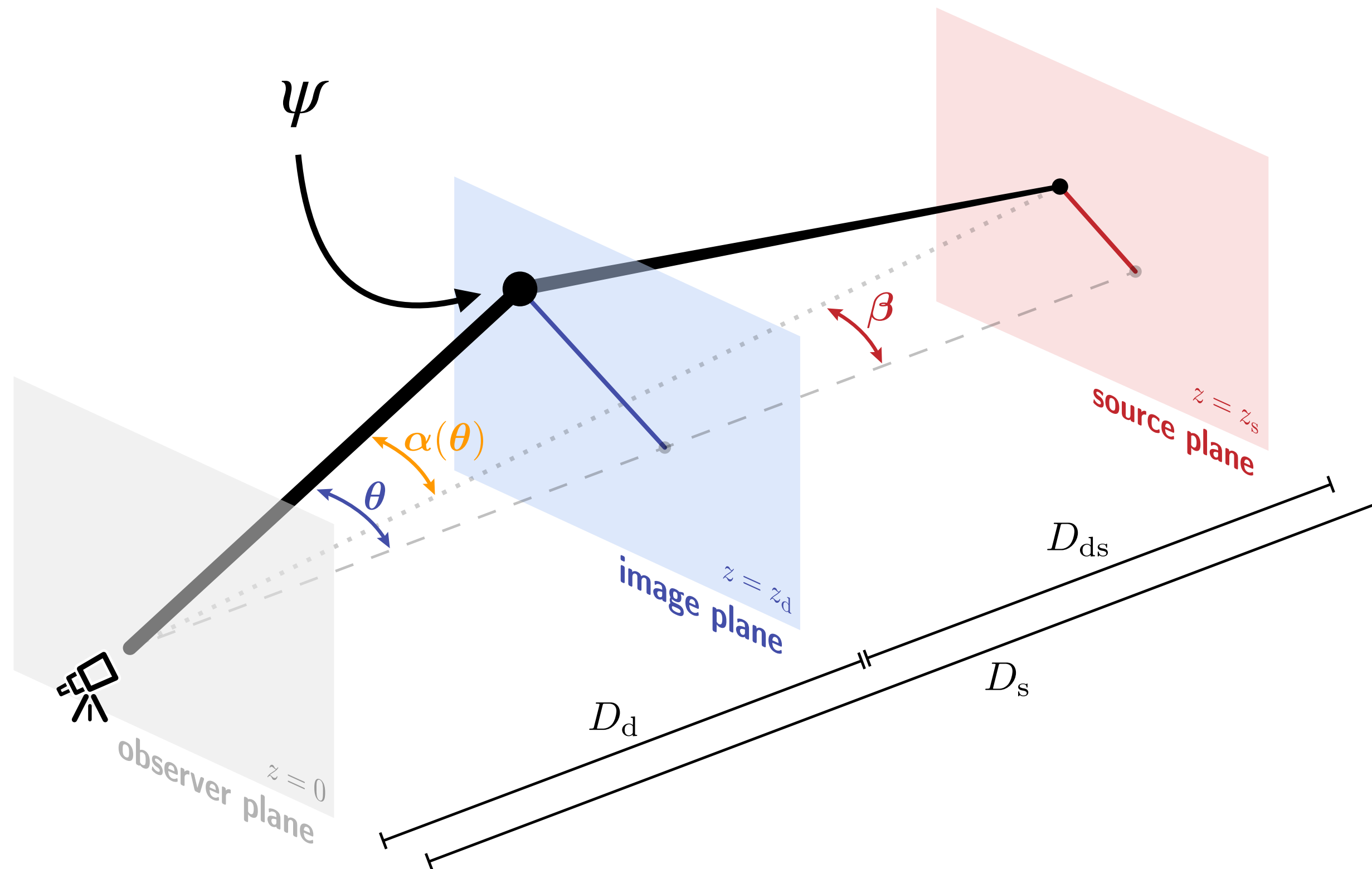
Time-delay
(between two images A and B)

$$\Delta t_{AB}$$

Time-delay distance

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

Basic principle of time-delay cosmography



Equation of the time delay (Δt):

$$\Delta t_{AB} \frac{c}{\Delta \phi_{AB}} = D_{\Delta t} \propto H_0^{-1}$$

Time-delay
(between two images A and B)

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Time-delay distance

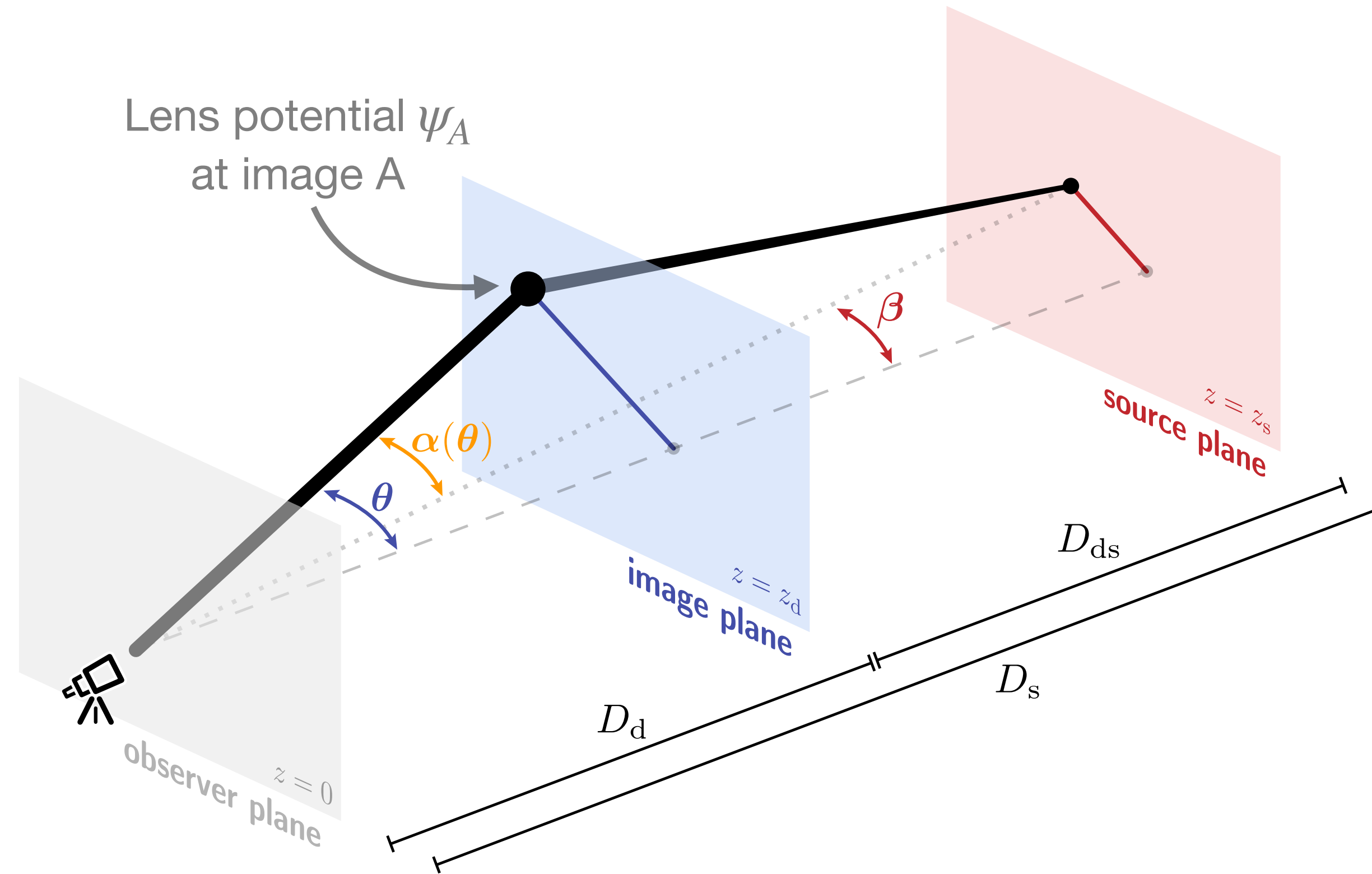
$$D_{\Delta t} \equiv (1 + z_d) \frac{D_d D_s}{D_{ds}}$$

Differential Fermat potential

$$\Delta \phi_{AB} \equiv \phi_A - \phi_B$$

$$\phi_A = \frac{(\theta_A - \beta)^2}{2} - \psi_A$$

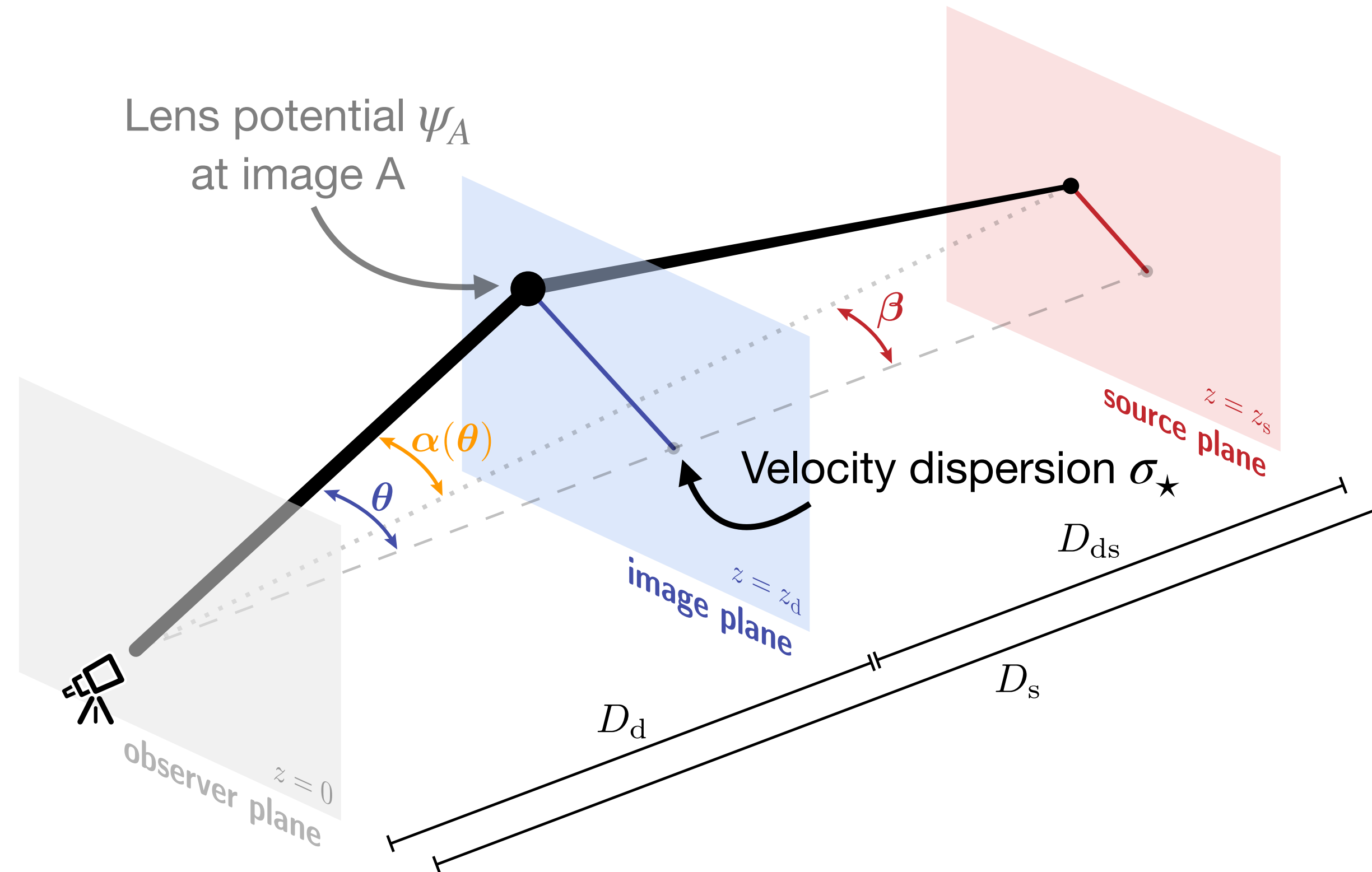
The modern version of time-delay cosmography



Equation of the time delay (Δt):

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The modern version of time-delay cosmography



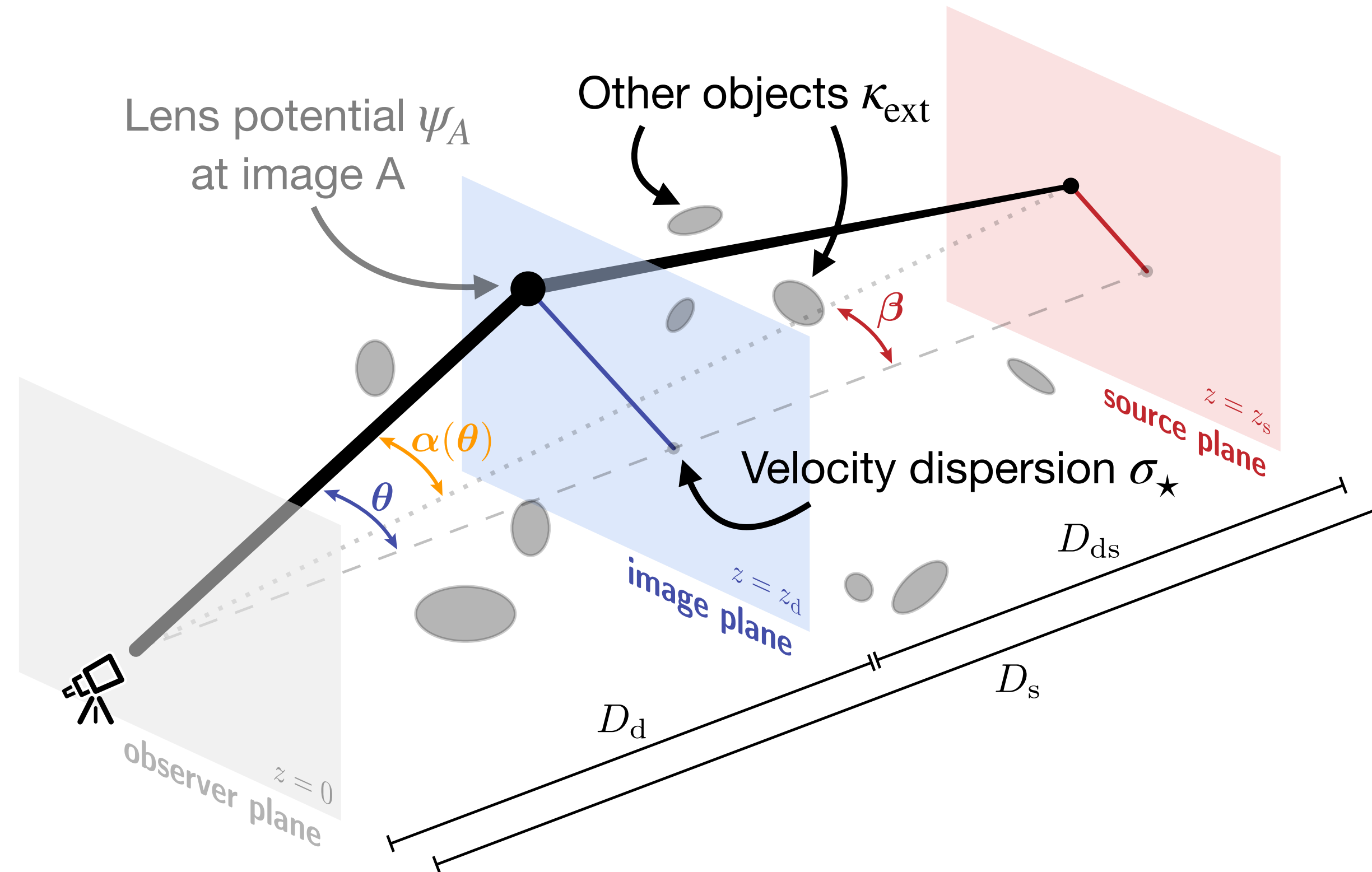
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Velocity dispersion of stars
in the lens galaxy ($\sigma_\star$):

$$\frac{D_s}{D_{ds}} = \frac{\sigma_\star^2}{c^2 J_d}$$

The modern version of time-delay cosmography



Equation of the time delay (Δt):

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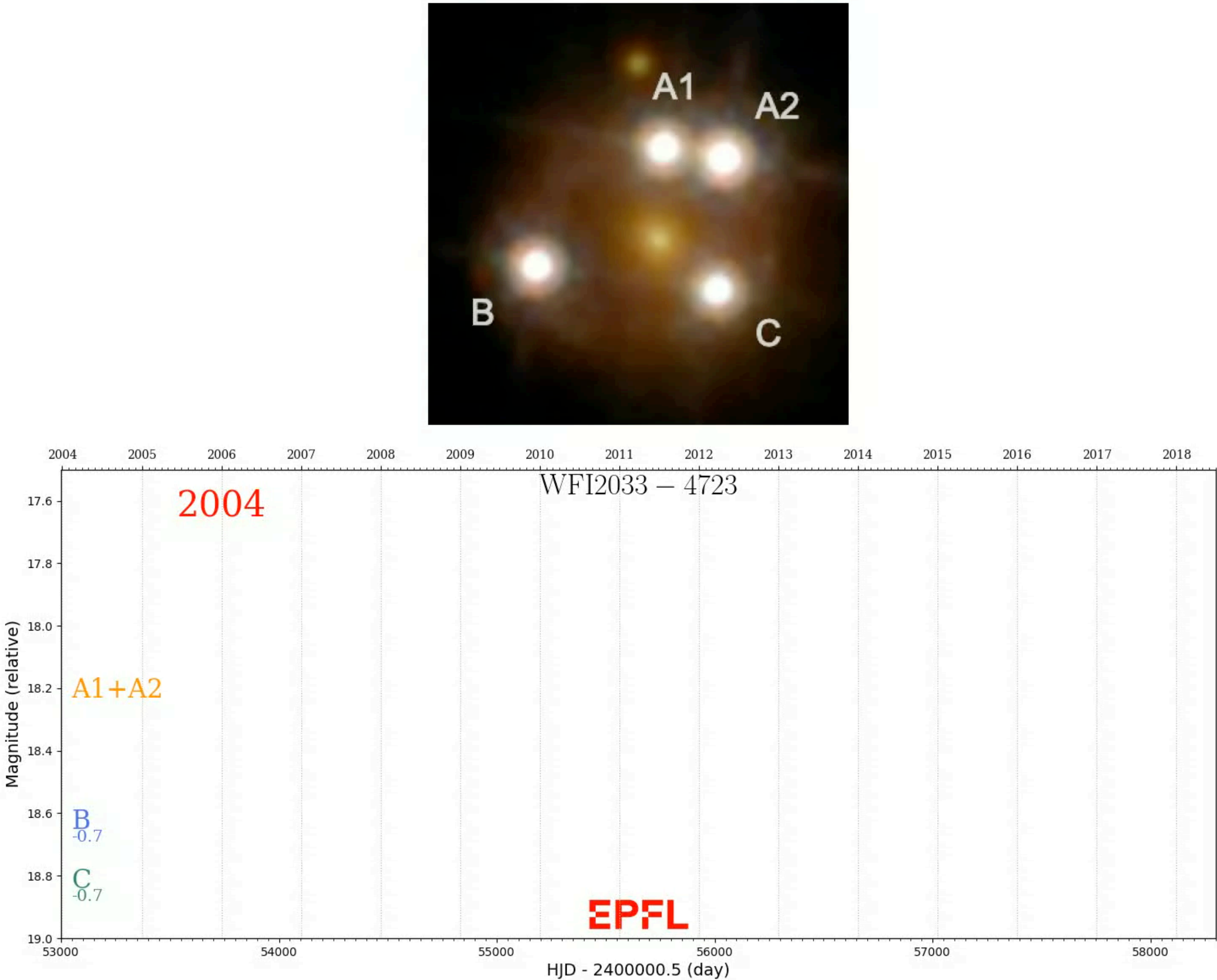
$$\frac{D_s}{D_{ds}} = \frac{\sigma_\star^2}{c^2 J_d}$$

Other massive objects along
the line of sight (κ_{ext})

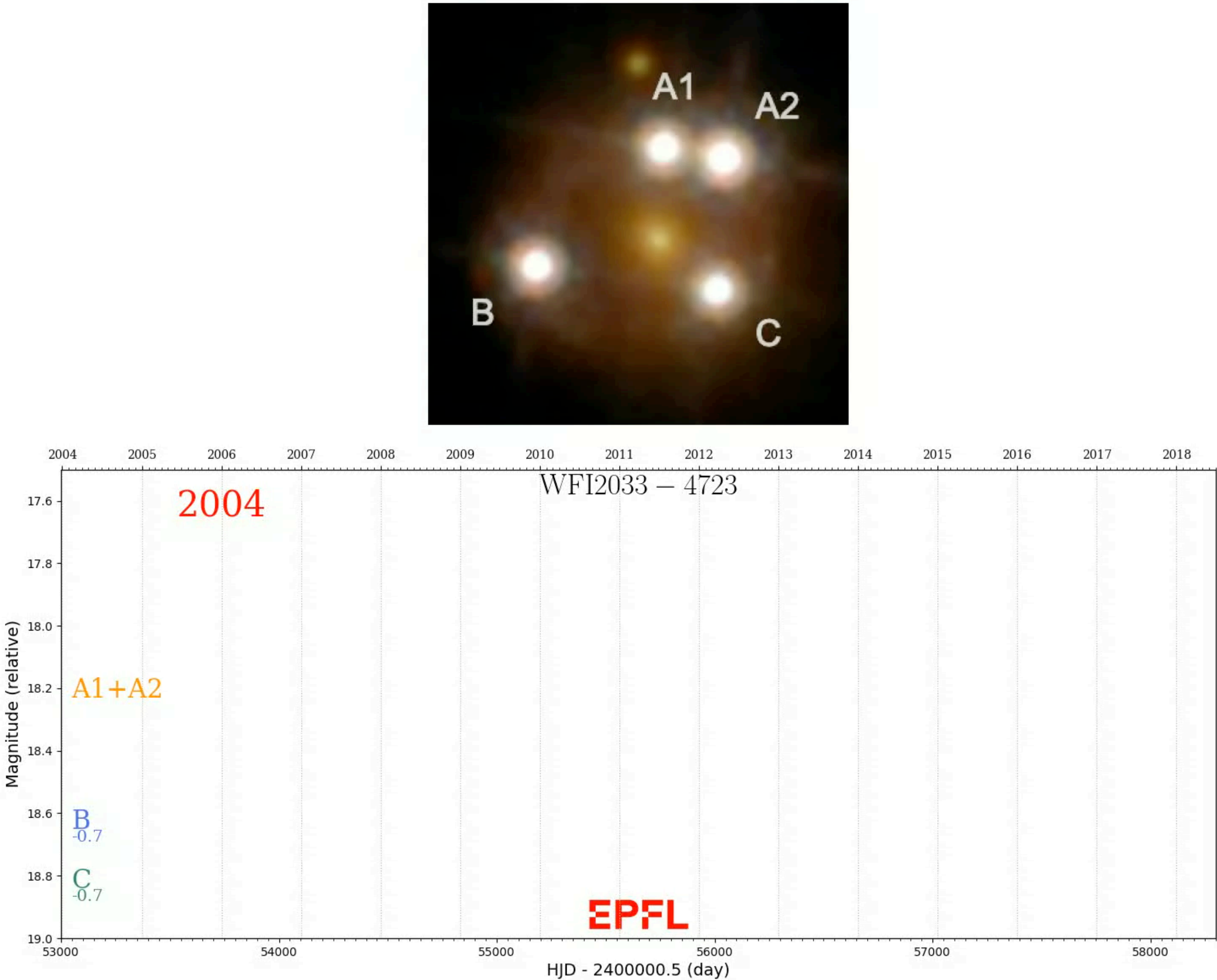
$$D_{\Delta t}^{\text{true}} = \frac{D_{\Delta t}}{1 - \kappa_{\text{ext}}}$$

Measuring the time delays

Time delays from (possibly decade-long) monitoring campaigns

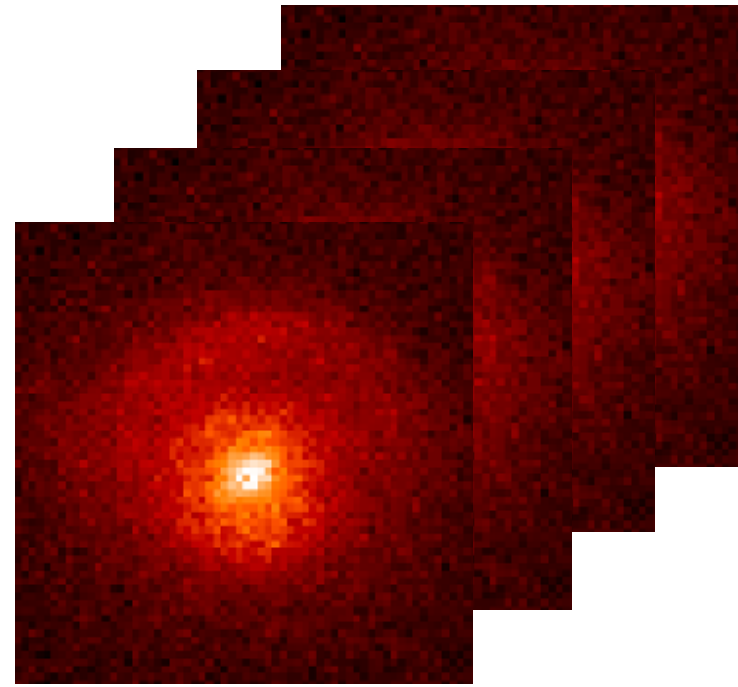


Time delays from (possibly decade-long) monitoring campaigns

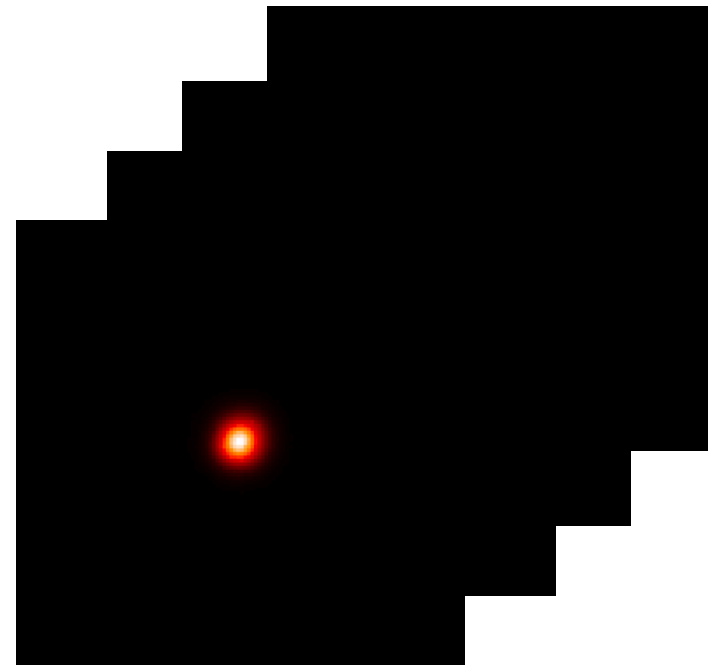


Extracting the light curves

Multi-epoch data



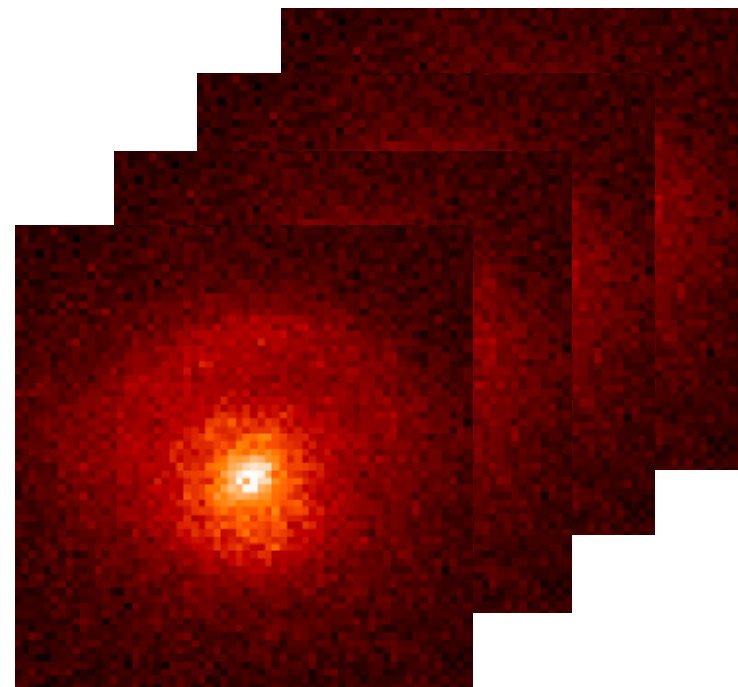
PSF for each epoch



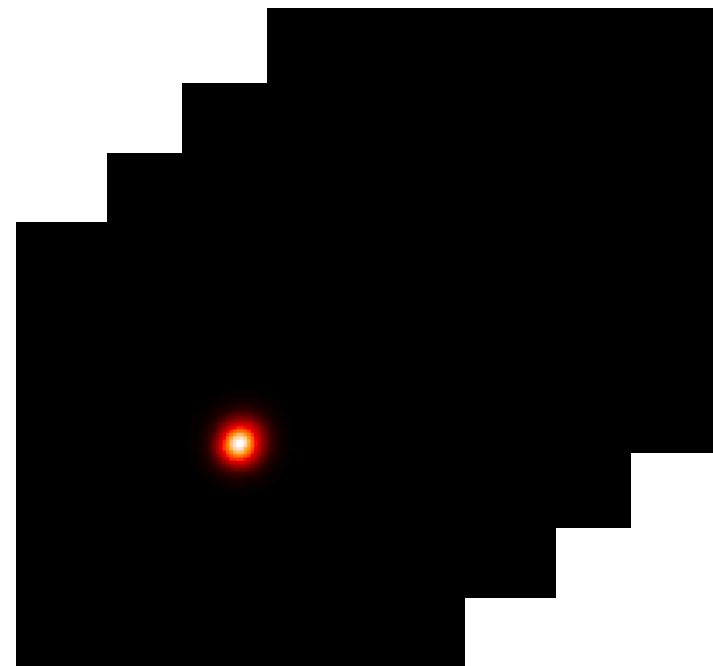
(Michalewicz et al. 2023, Millon et al. 2024)

Extracting the light curves

Multi-epoch data

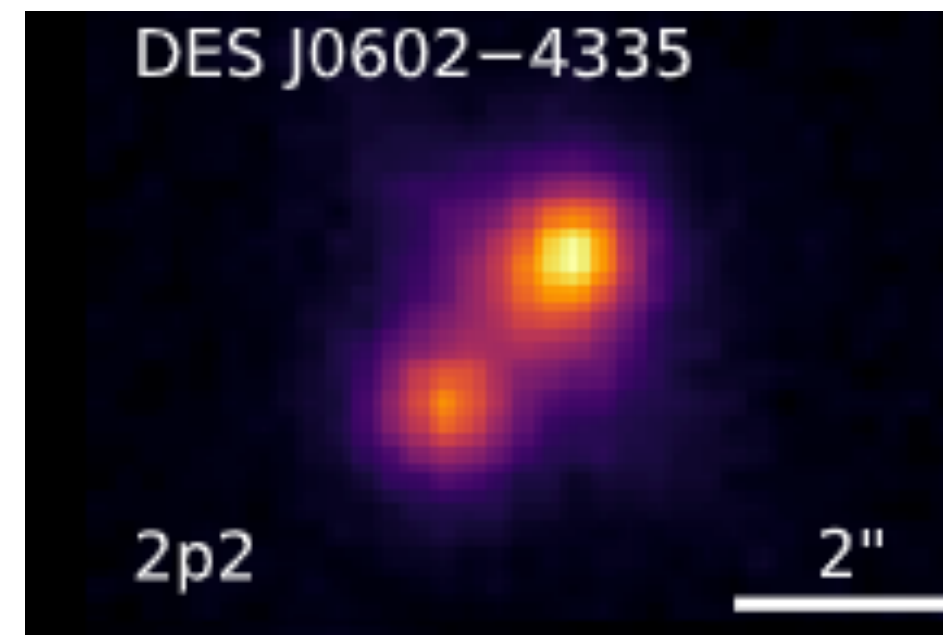


PSF for each epoch

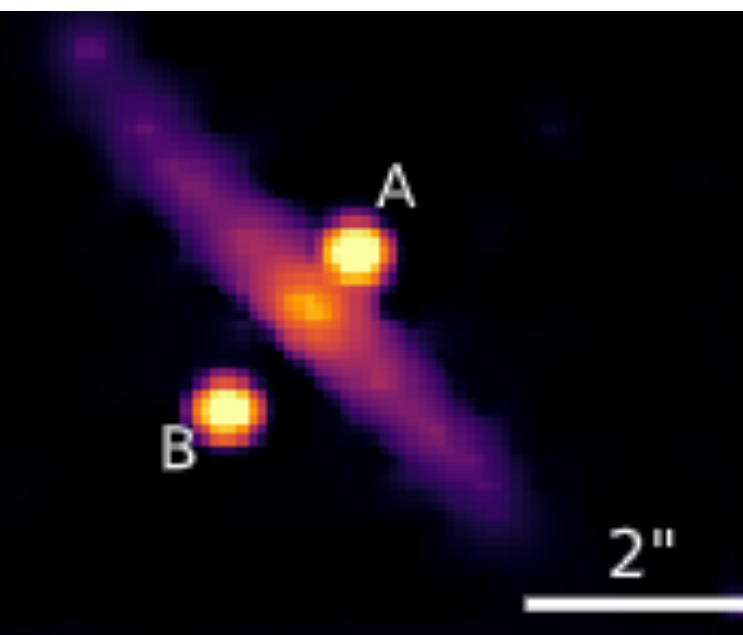


(Michalewicz et al. 2023, Millon et al. 2024)

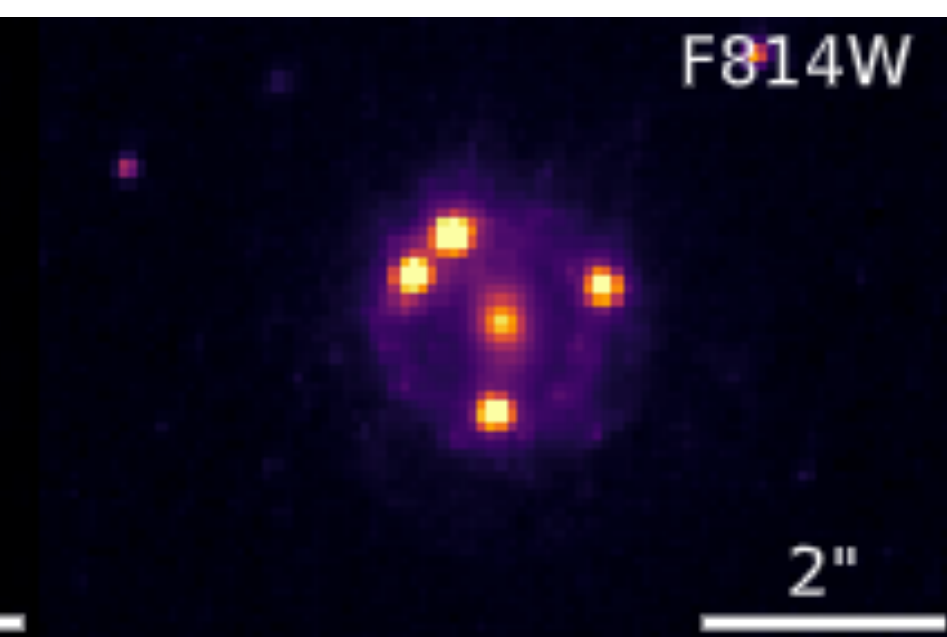
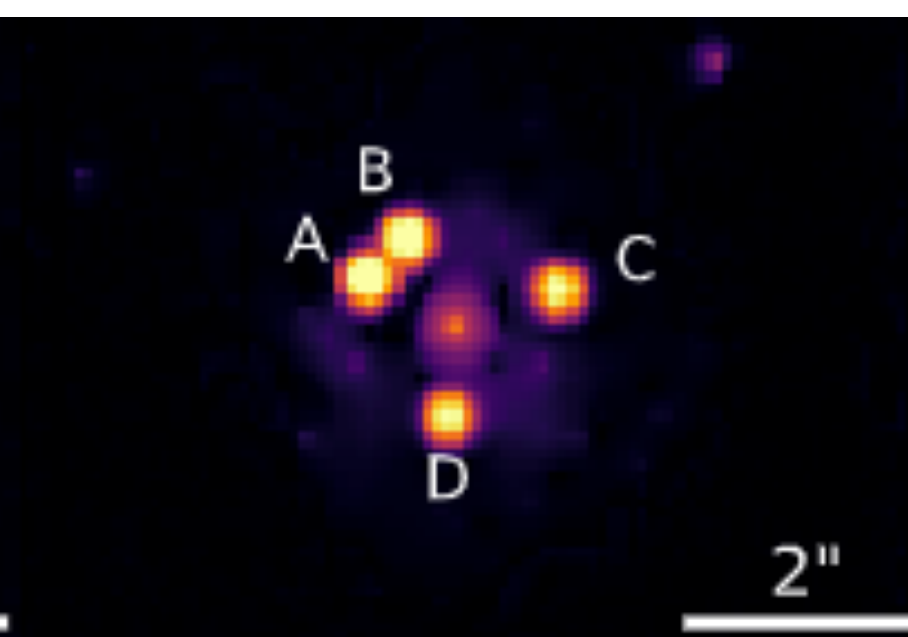
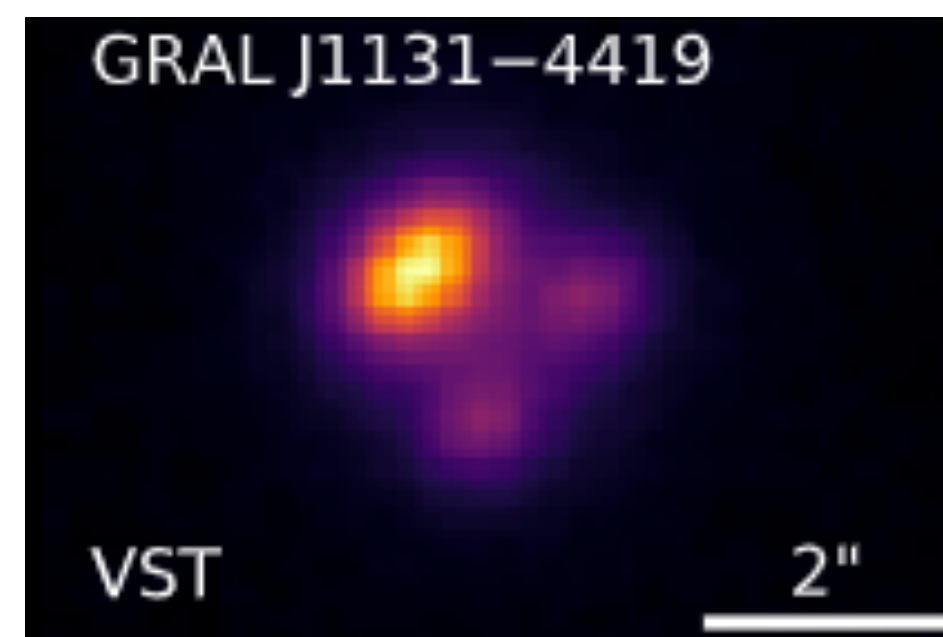
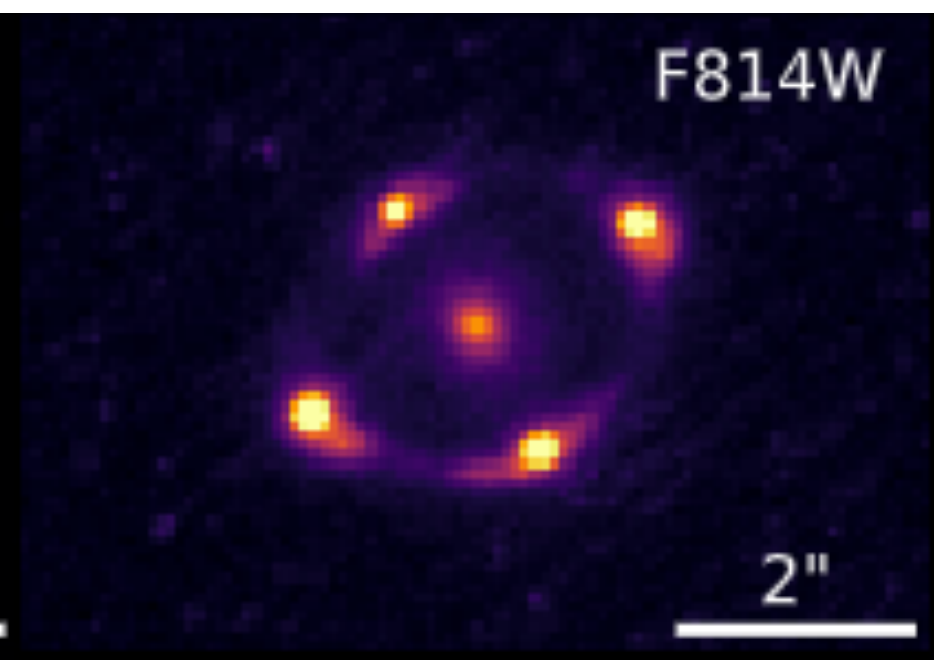
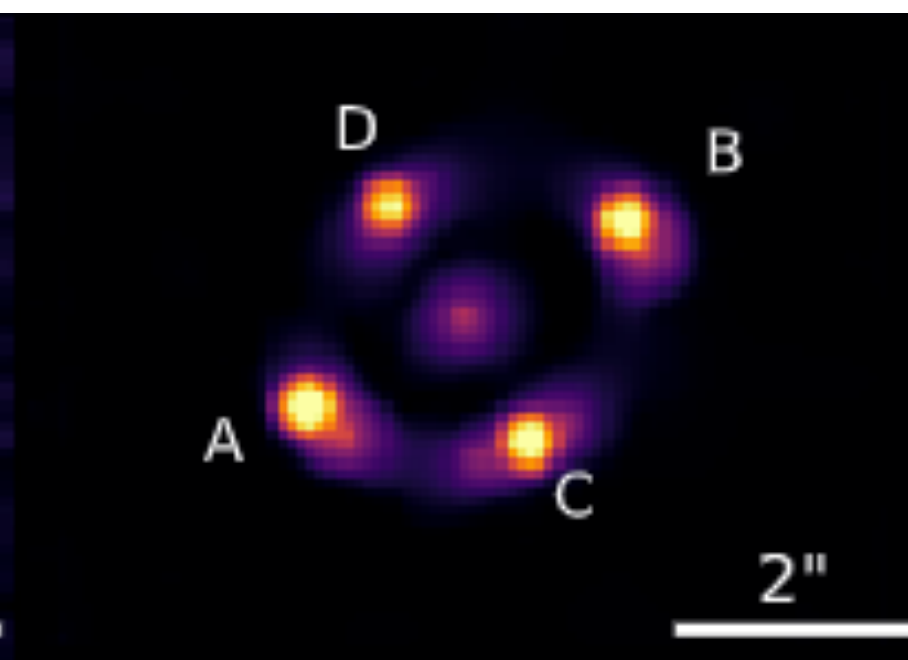
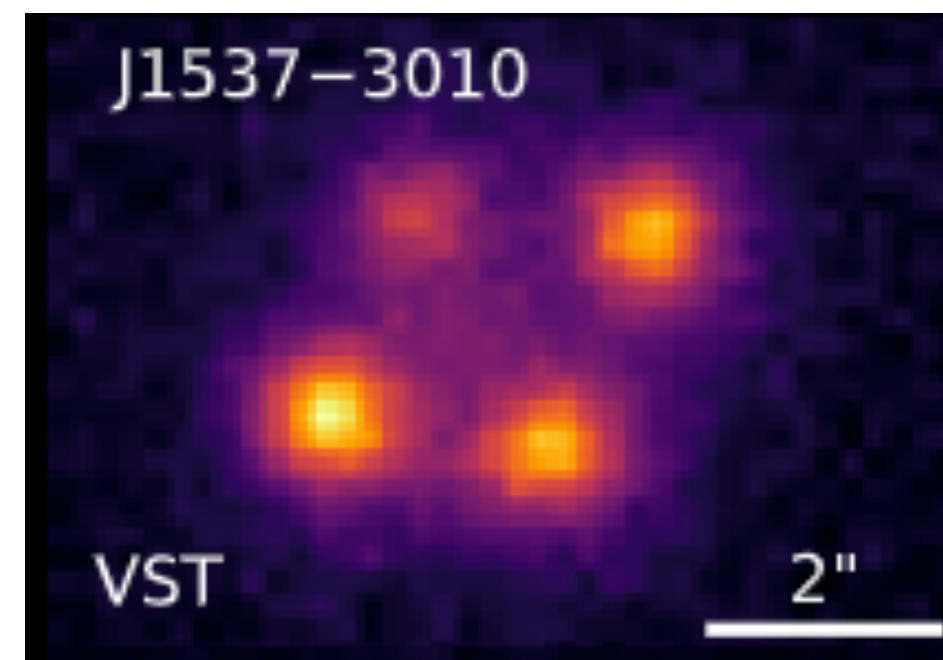
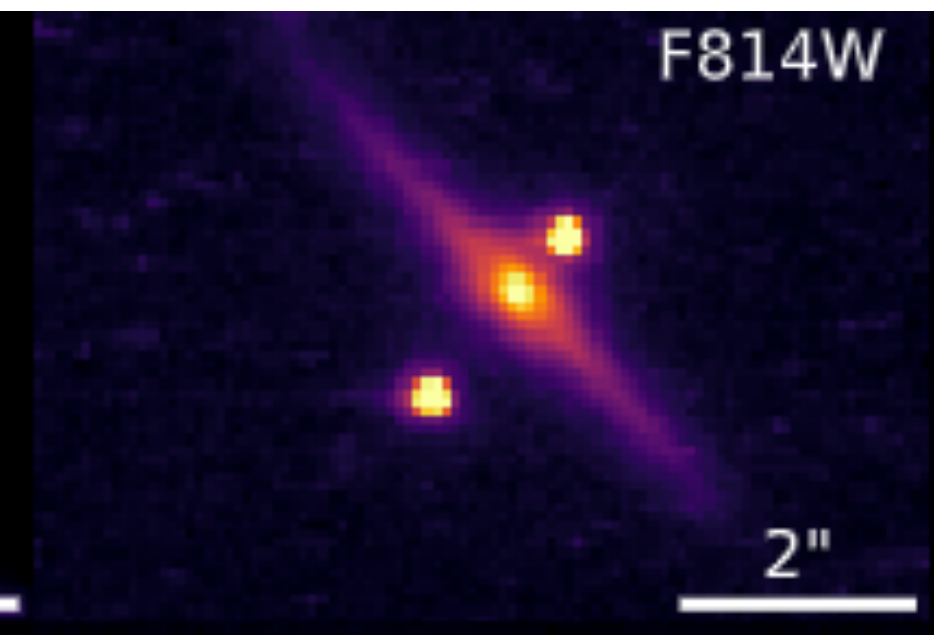
Original data (res: $\sim 0.9''$)



STARRED (res: $0.21''$)



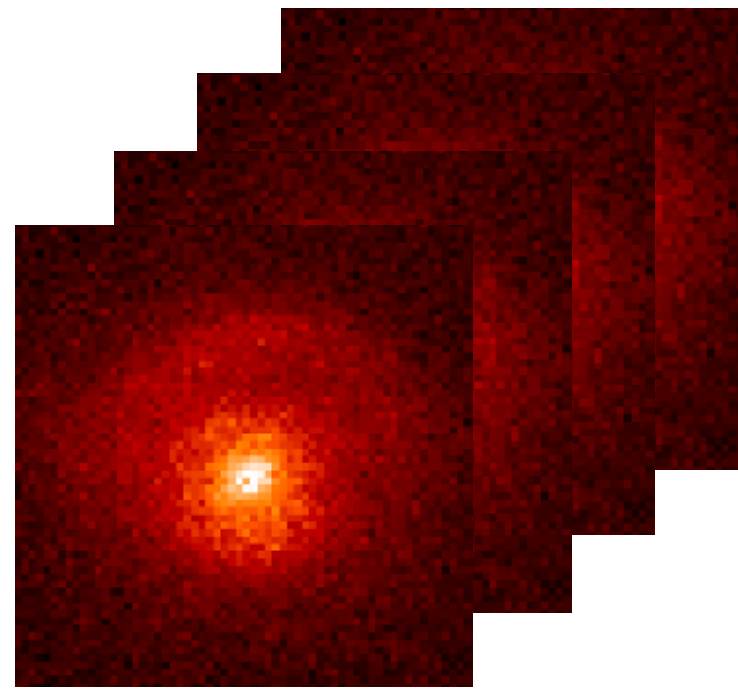
HST (res: $0.07''$)



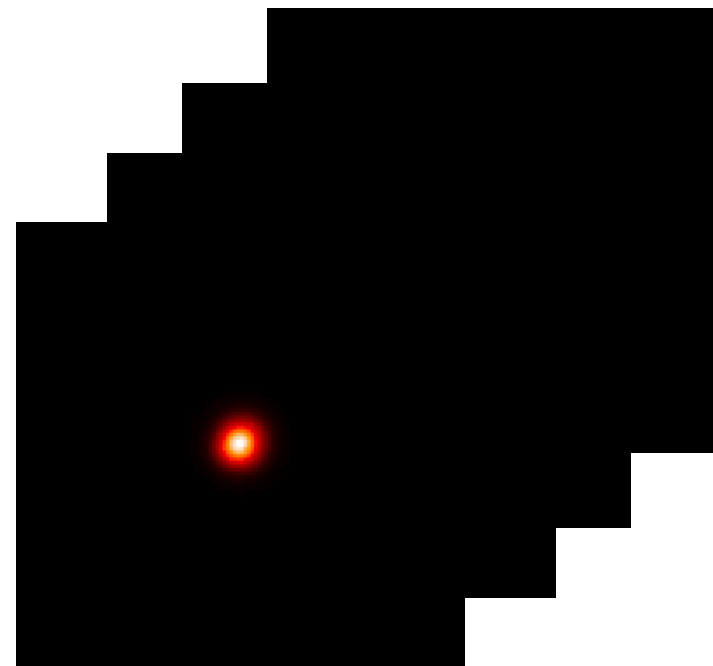
Dux et al. (2025)

Extracting the light curves

Multi-epoch data



PSF for each epoch



(Michalewicz et al. 2023, Millon et al. 2024)

Deconvolution, PSF modeling + photometry: STARRED

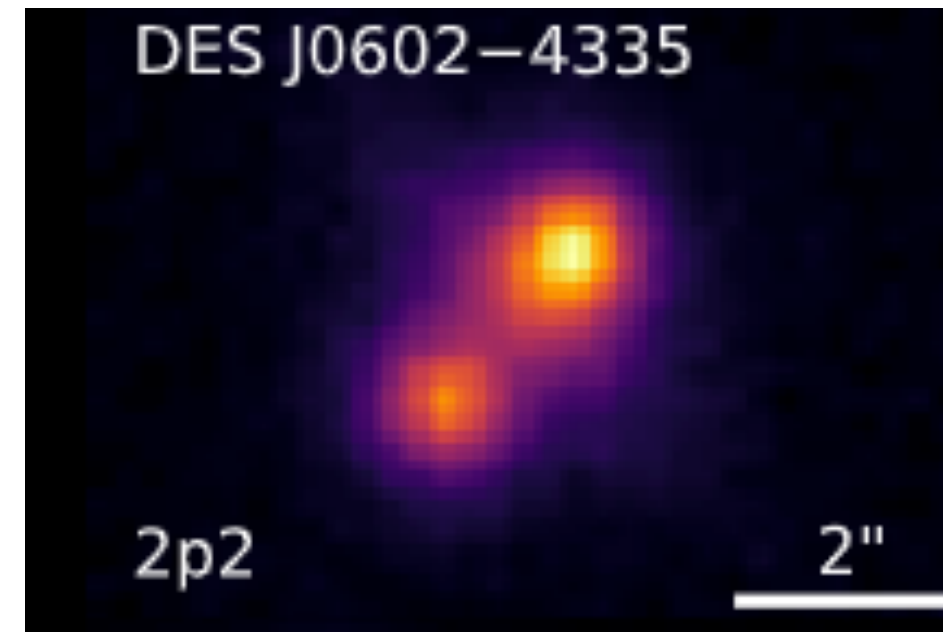
<https://gitlab.com/cosmograil/starred>

Automated pipeline: lightcurver

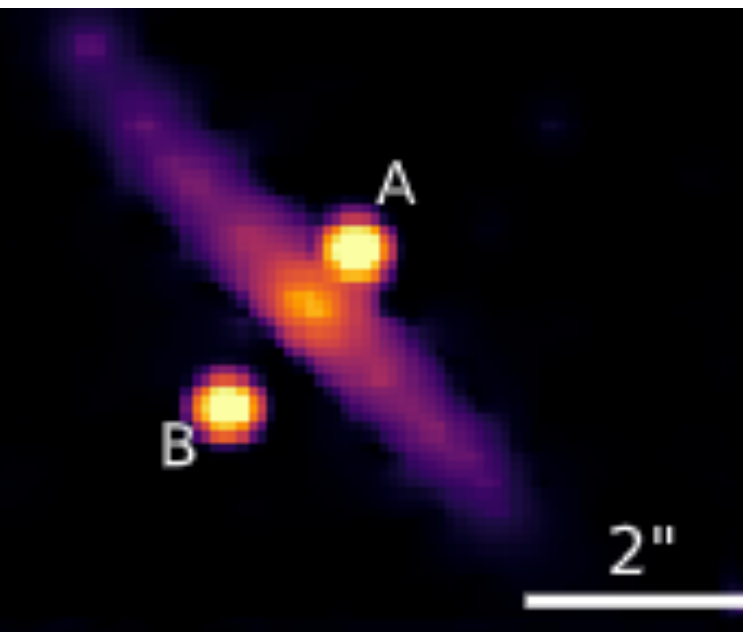
<https://github.com/duxfrederic/lightcurver>



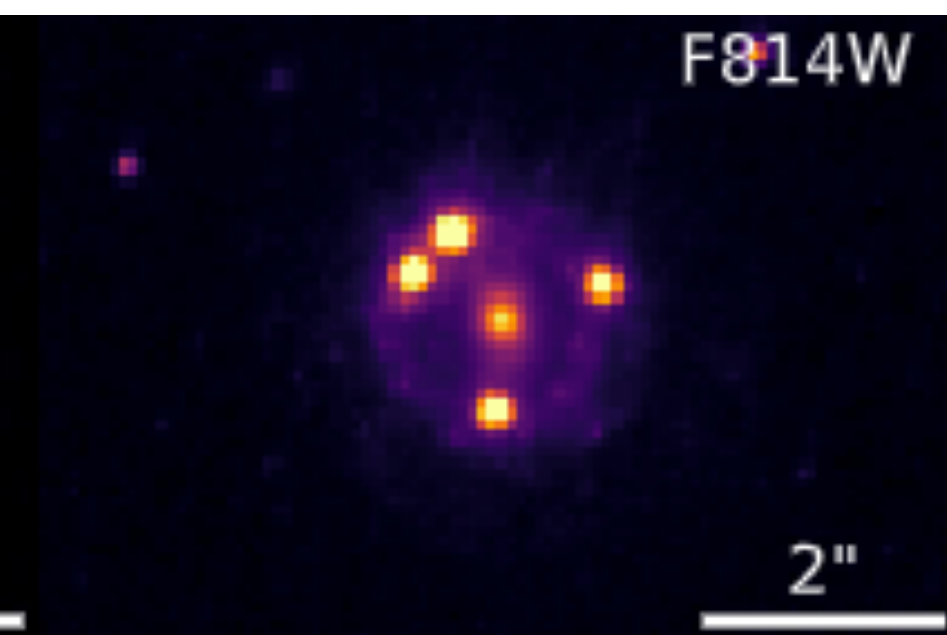
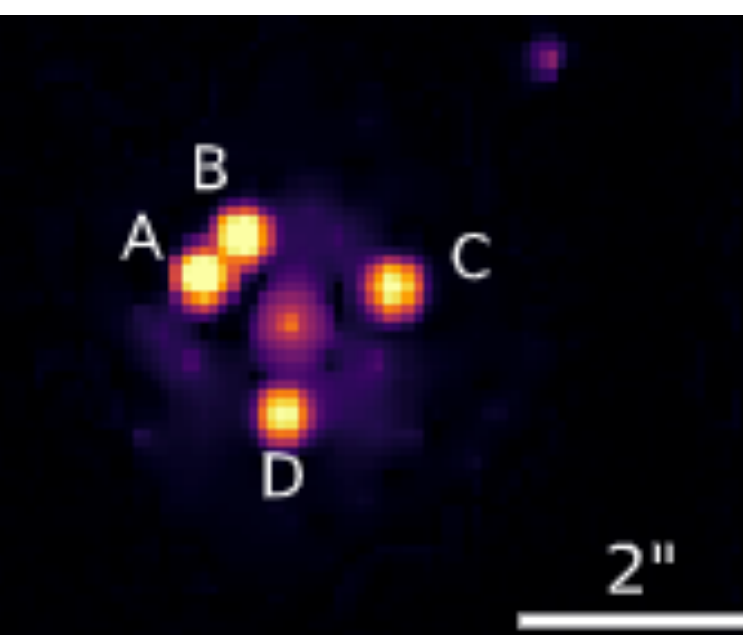
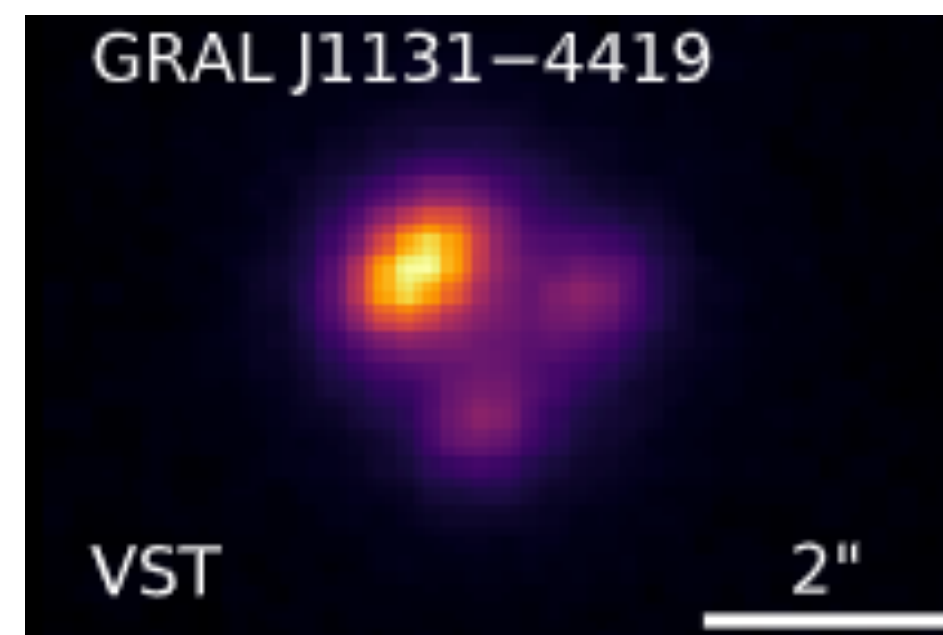
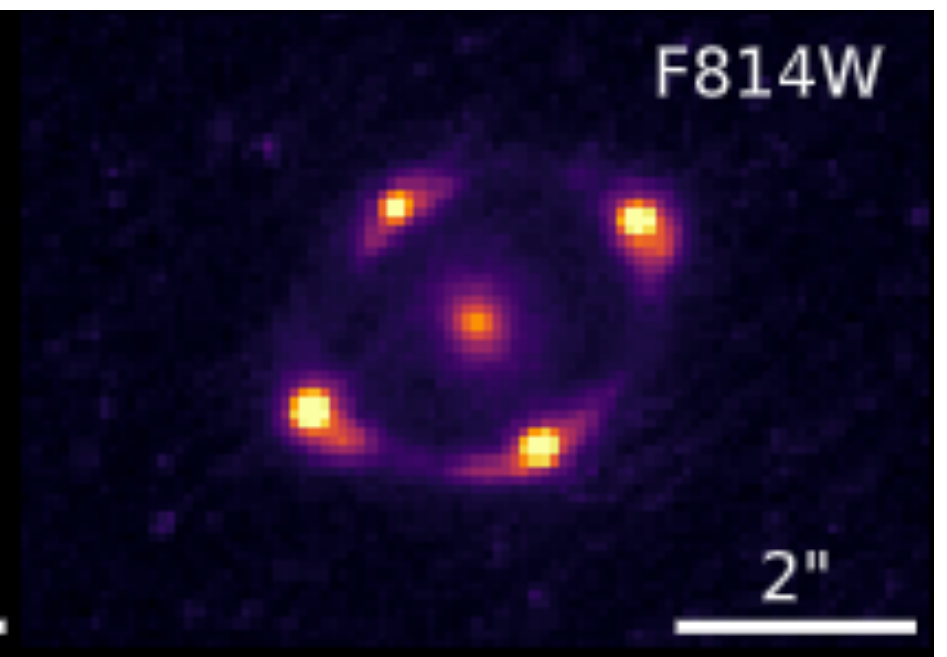
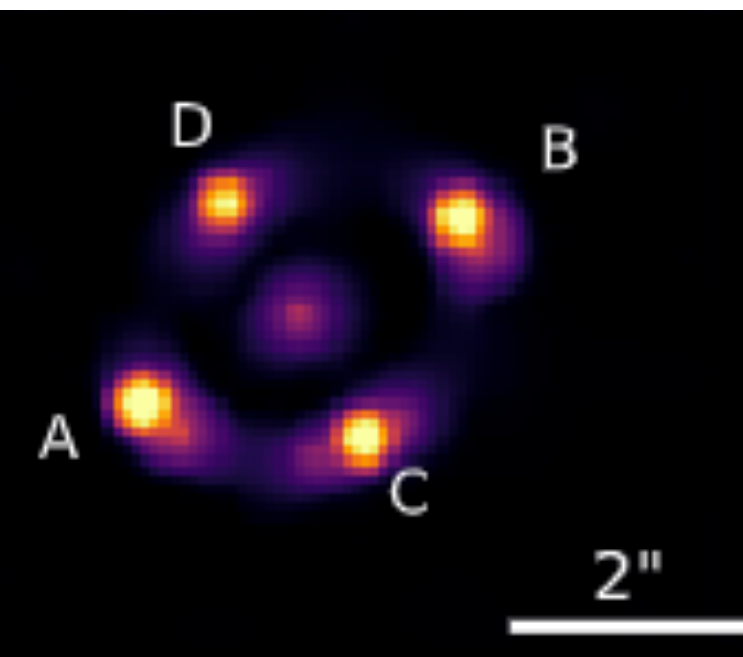
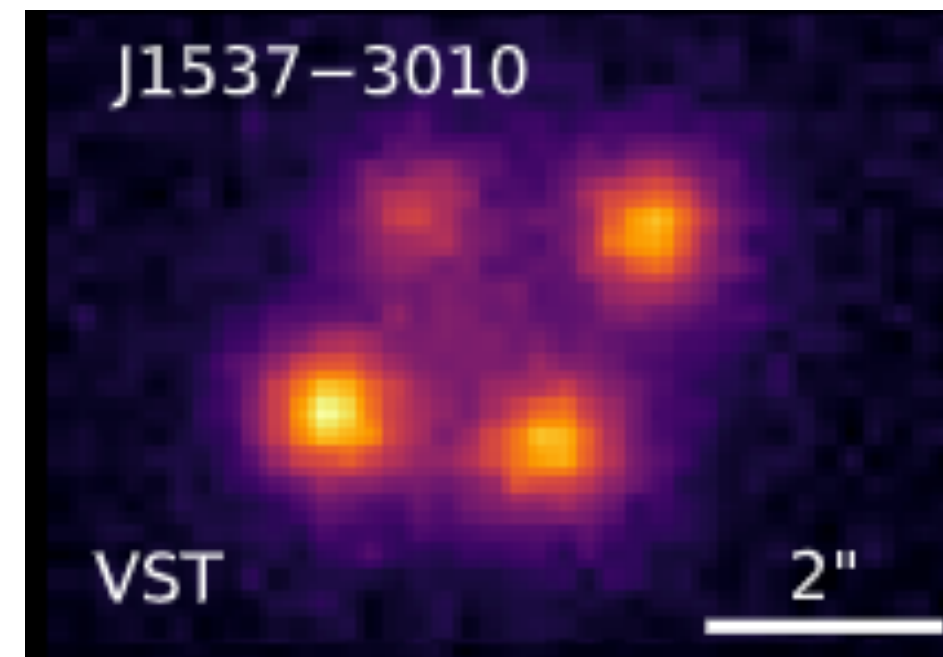
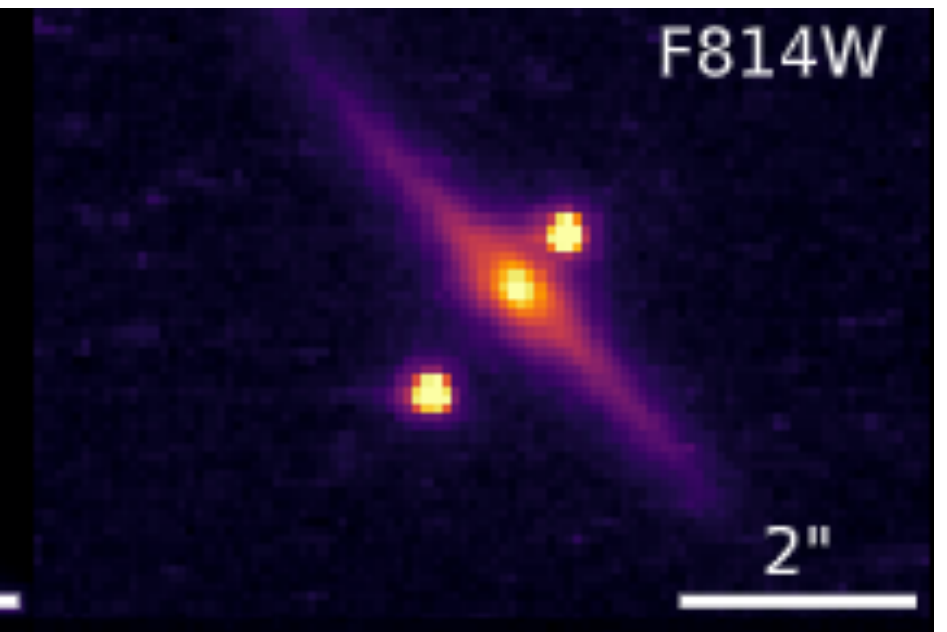
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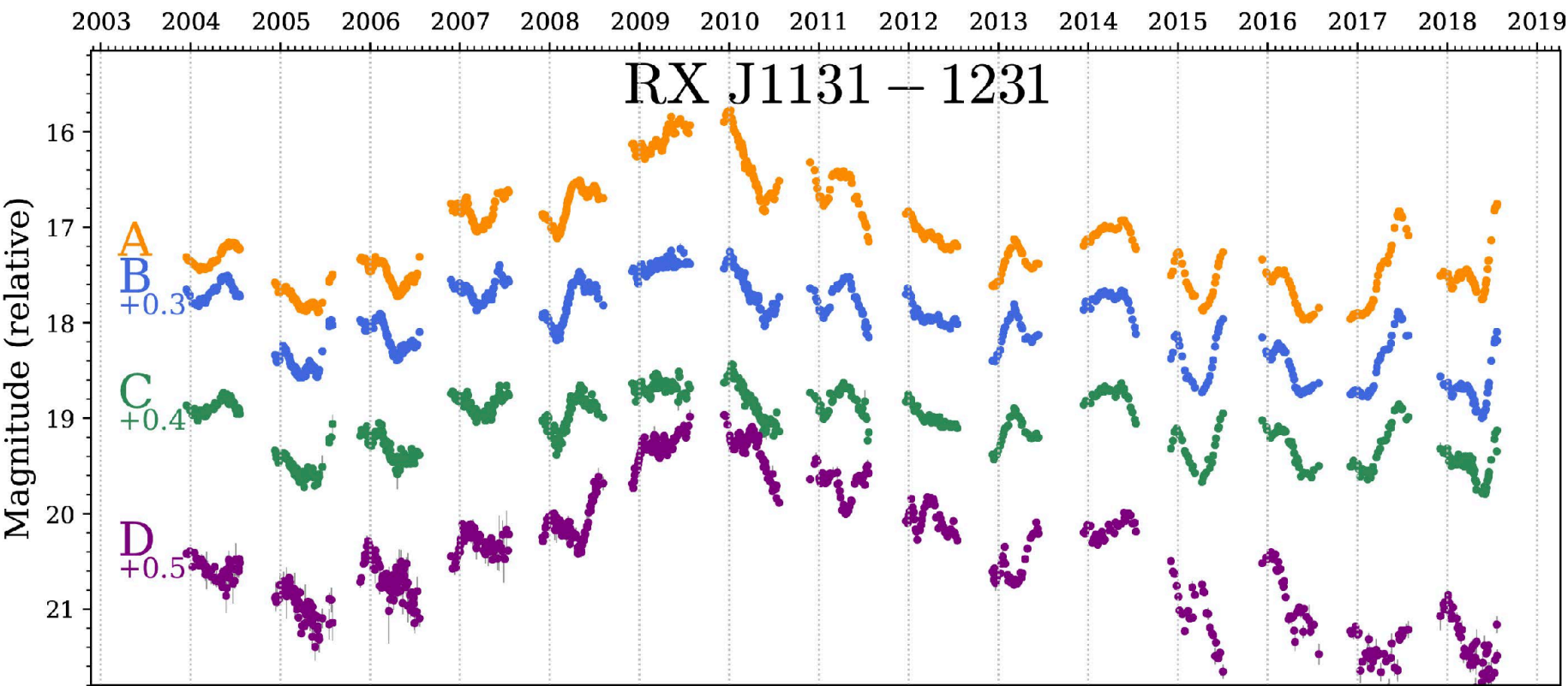


HST (res: $0.07''$)



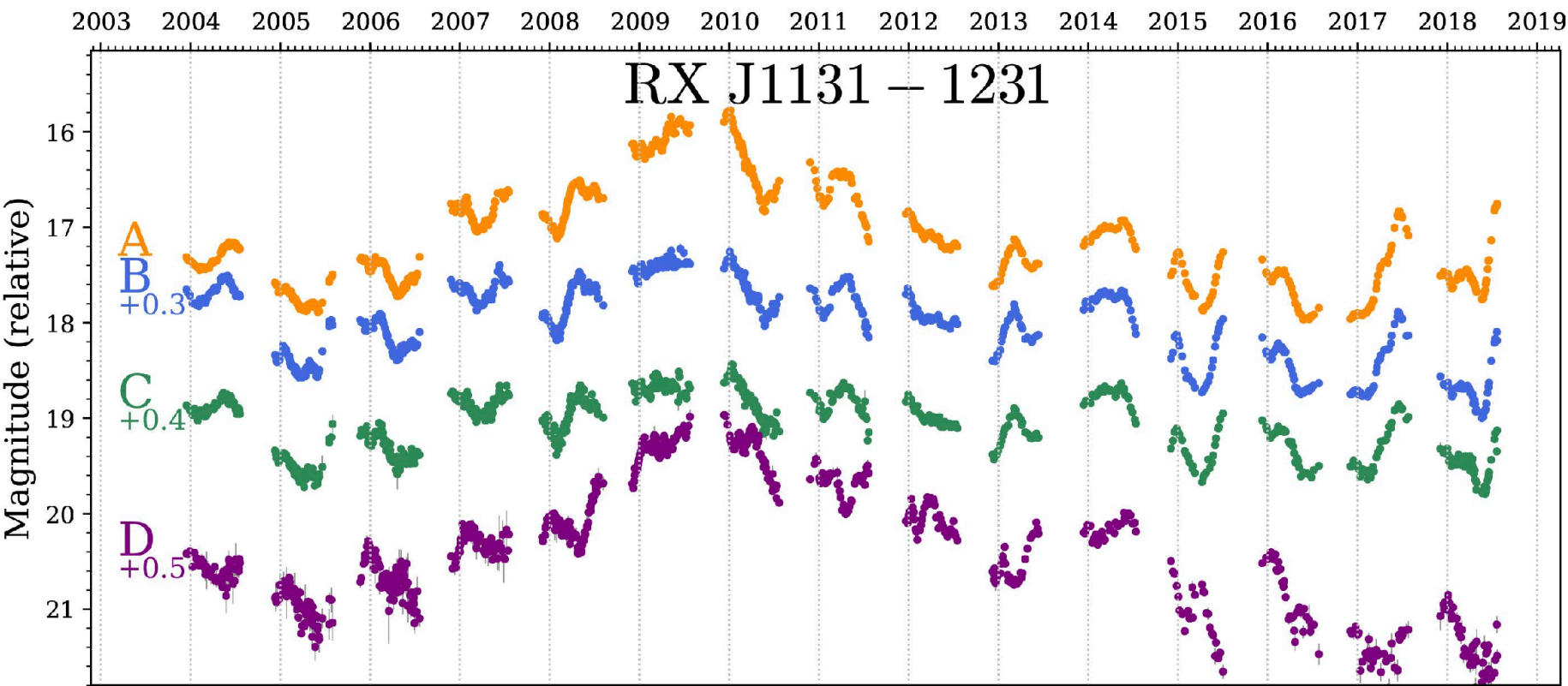
Dux et al. (2025)

Time delays via curve shifting

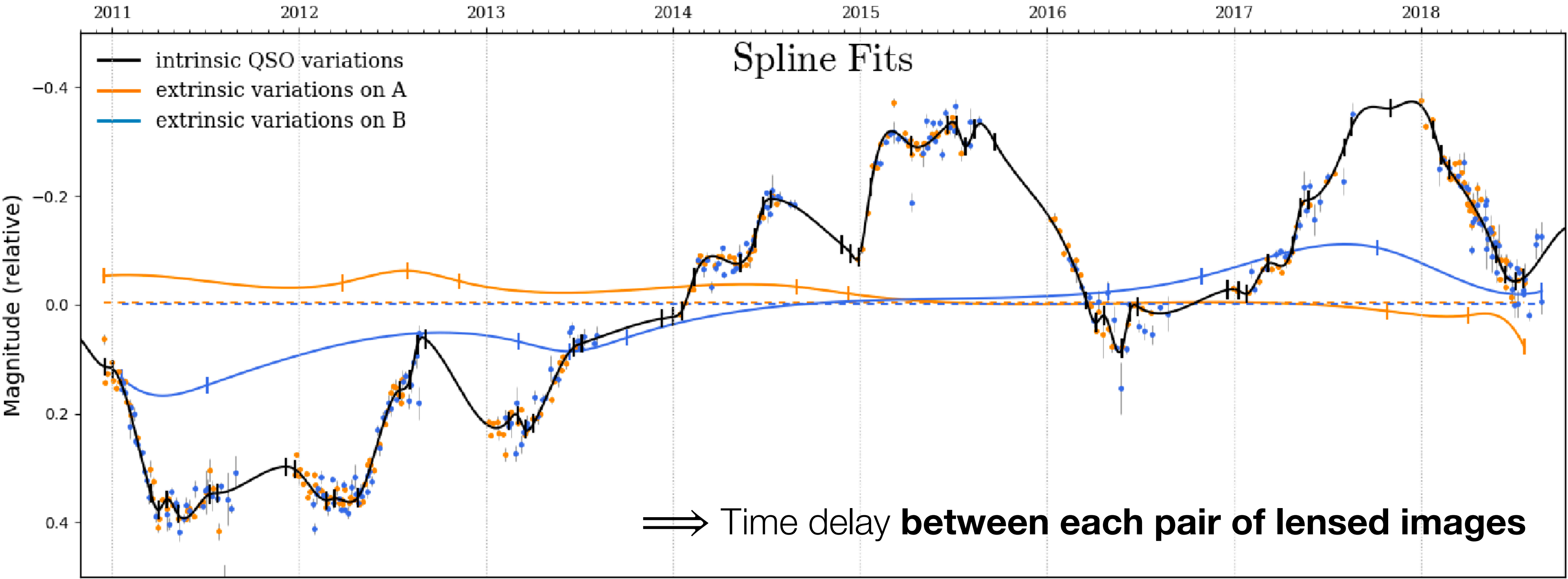


Millon et al. 2020

Time delays via curve shifting



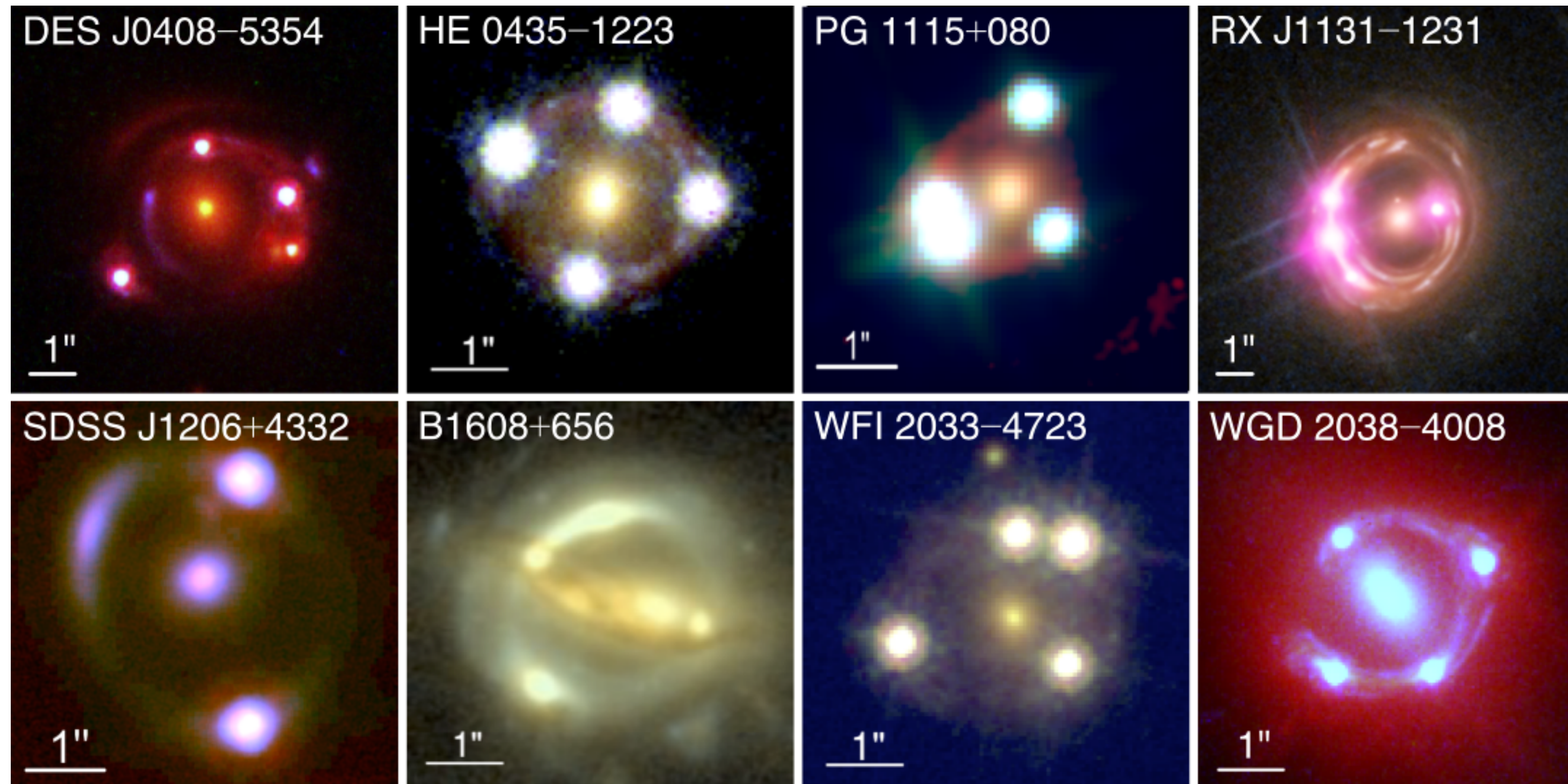
Millon et al. 2020



Modeling the lens' Fermat potential

High-resolution and high signal-to-noise images are required

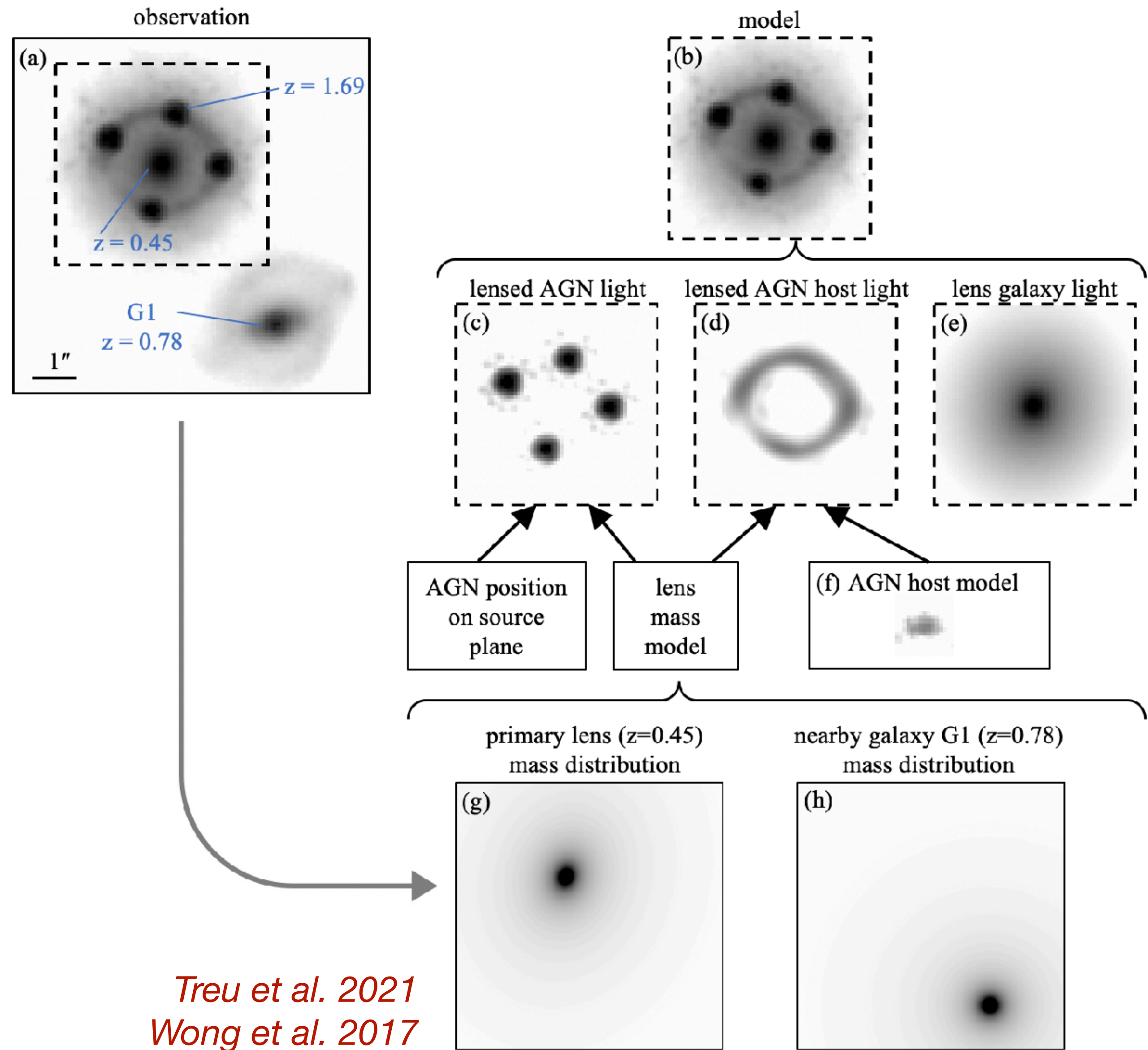
Typical instruments: HST, 10m-class telescopes with Adaptive Optics (AO), and now JWST



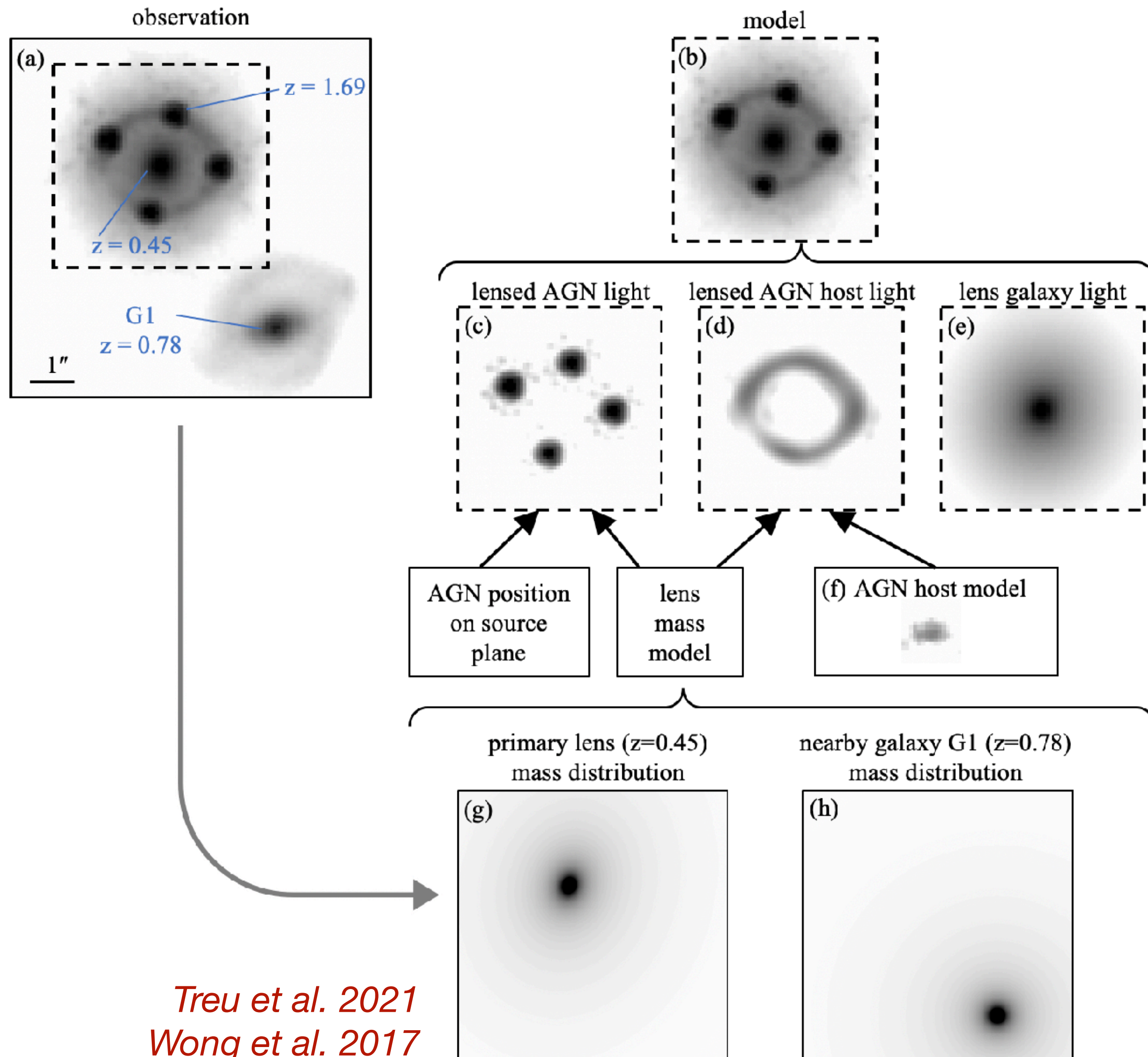
TDCOSMO collaboration et al. 2025

⇒ Forward modeling of the imaging data to evaluate the Fermat potential

Lens modeling of high-resolution images



Lens modeling of high-resolution images



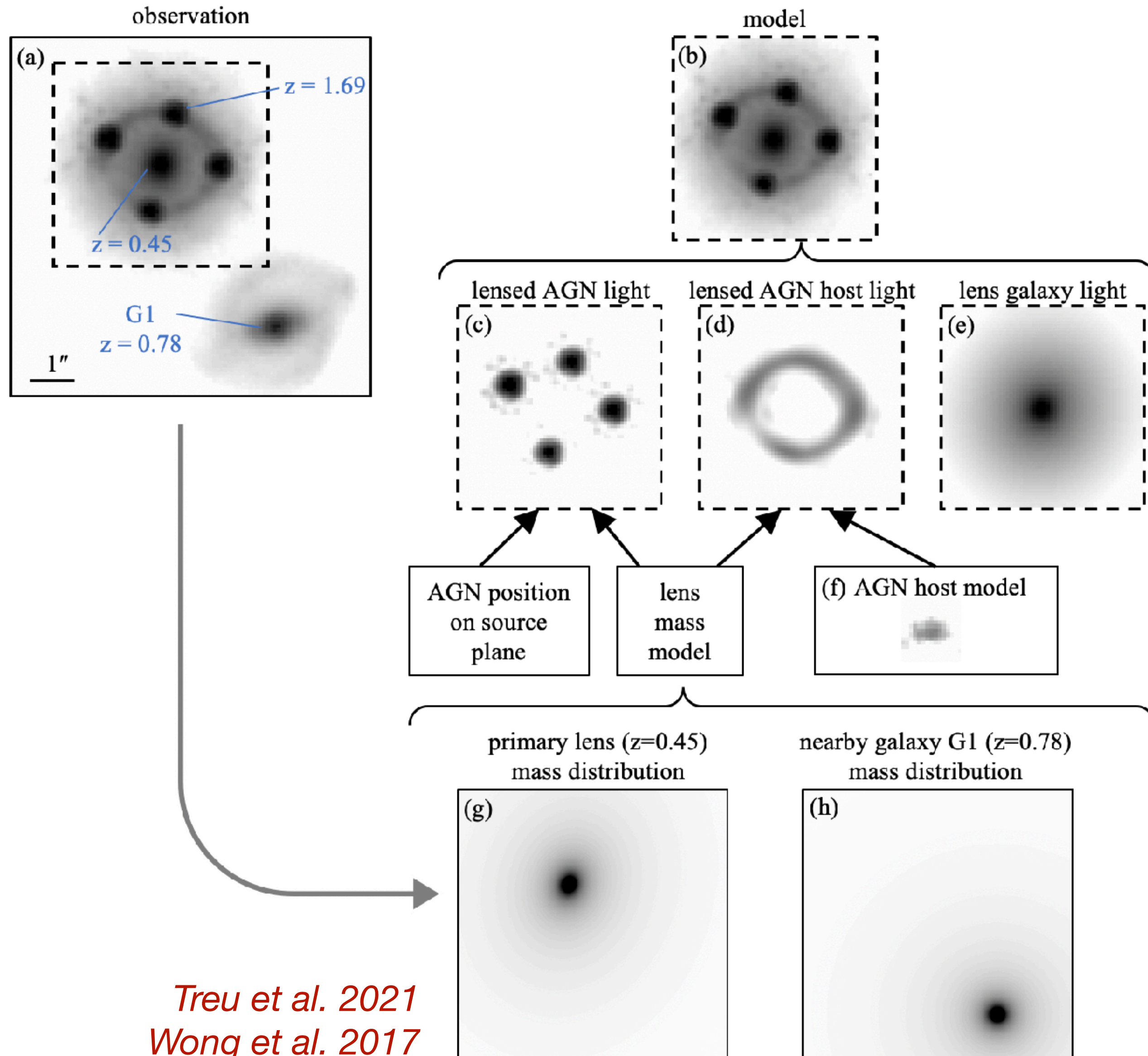
Treu et al. 2021
Wong et al. 2017

Assumptions regarding the mass distribution of the lens

Elliptical « power law »
total mass distribution

« Composite »
mass distribution
(dark matter + stars)

Lens modeling of high-resolution images

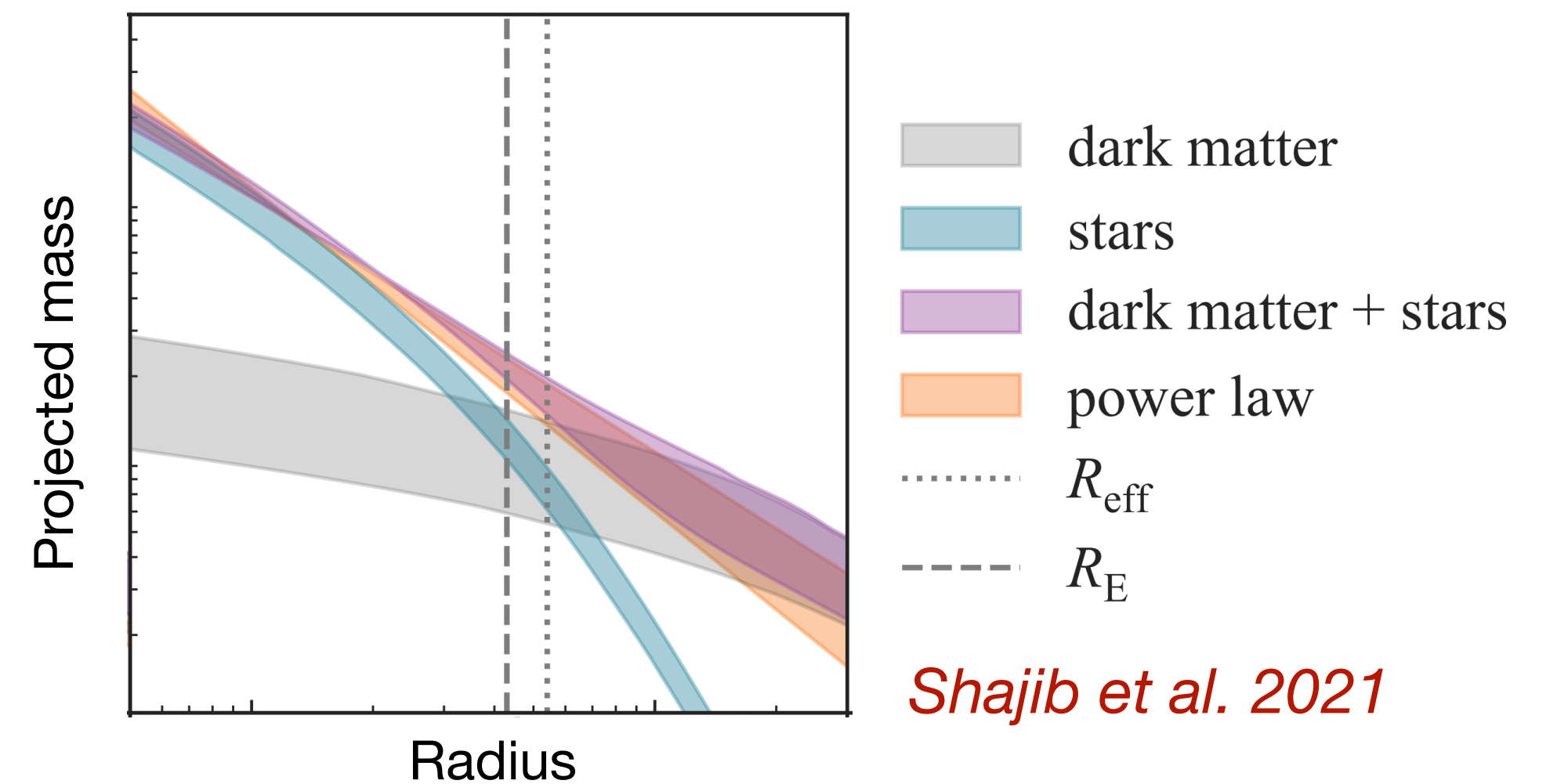


Assumptions regarding the mass distribution of the lens

Elliptical « power law »
total mass distribution

« Composite »
mass distribution
(dark matter + stars)

Radial mass profile of the lens galaxy



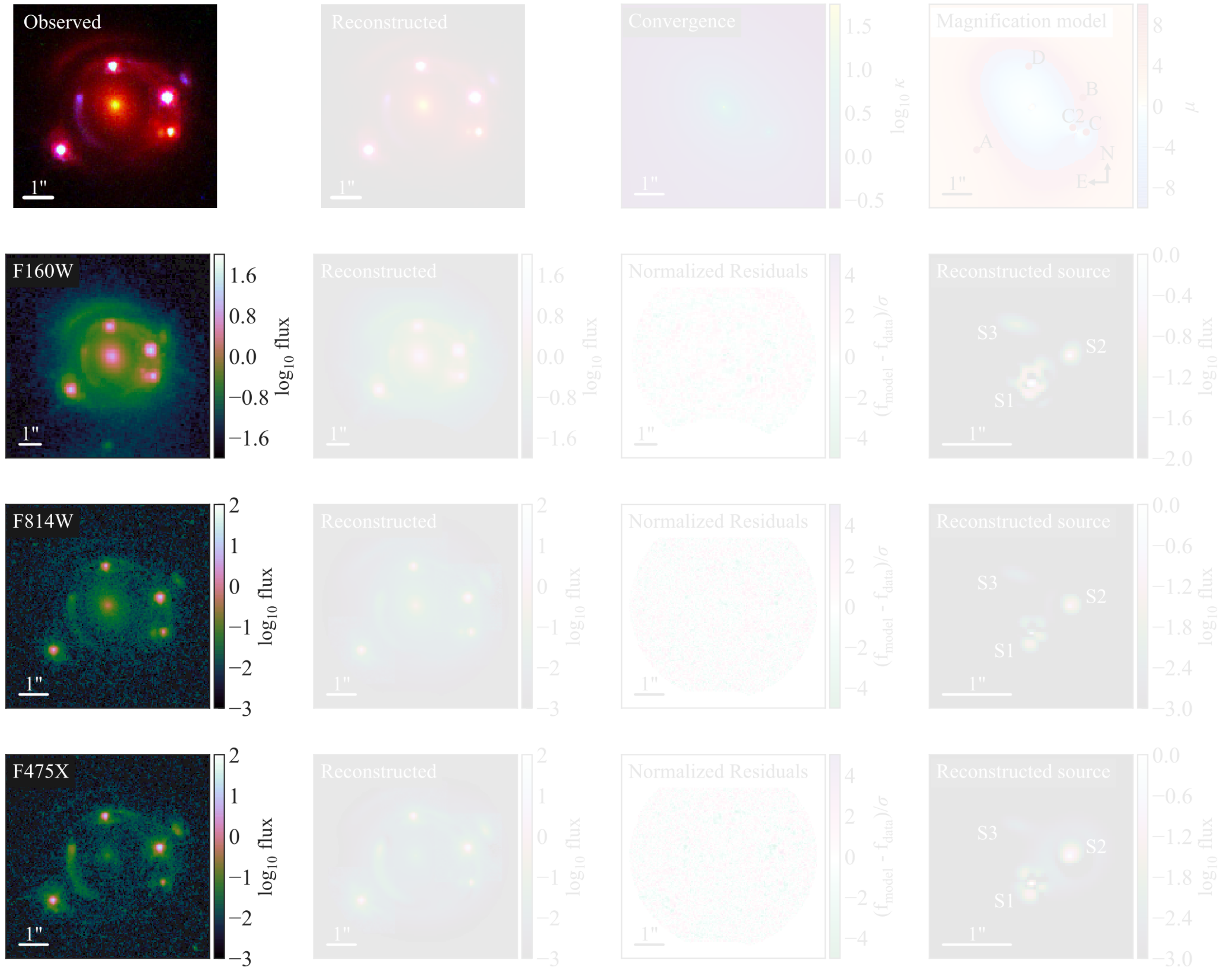
Lens modeling of high-resolution images

So far using two software packages
(Lenstronomy & GLEE)

Near-infrared →

Red →

Blue →



Shajib et al. 2019

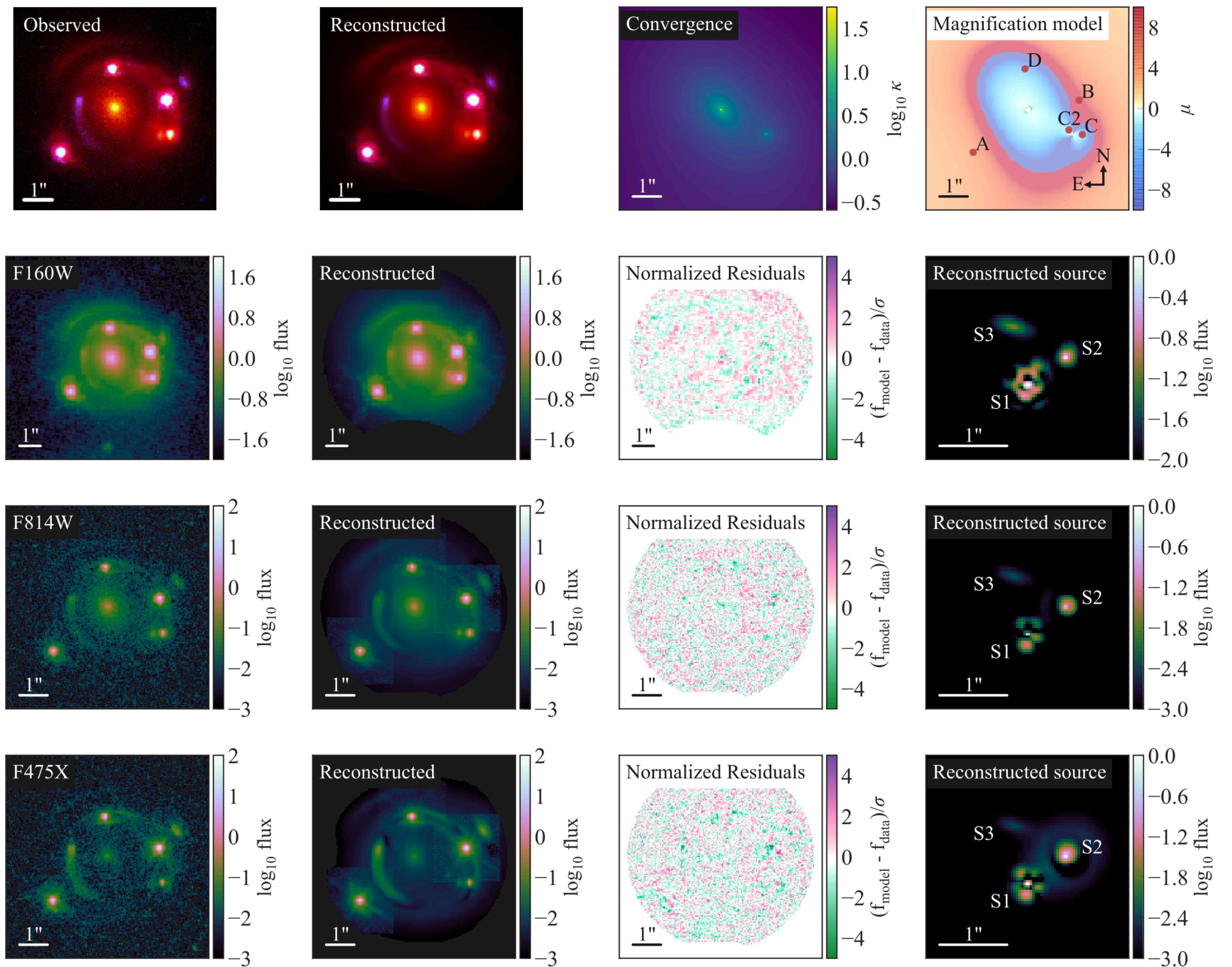
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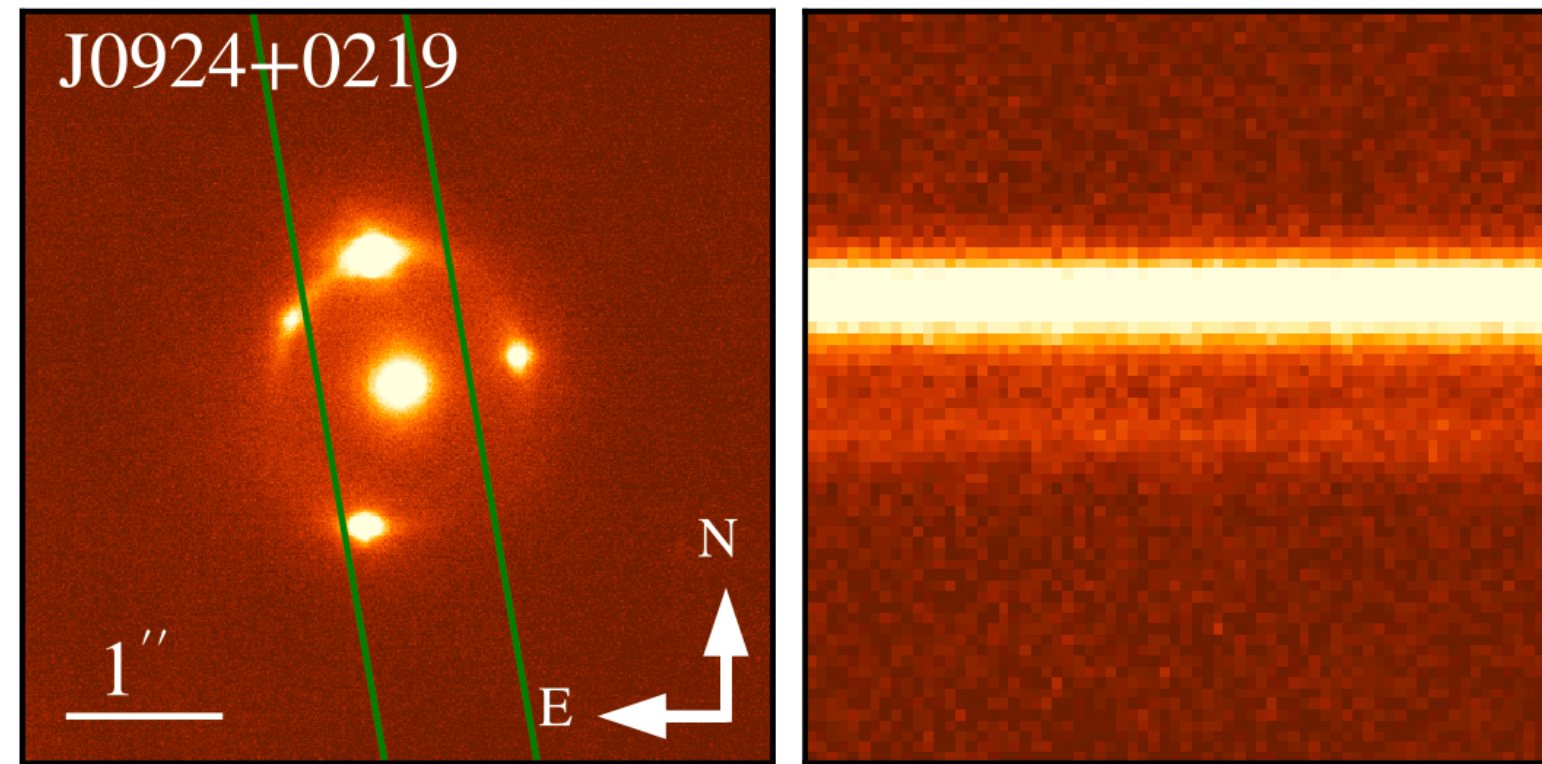


Shajib et al. 2019

Modeling the lens' stellar kinematics

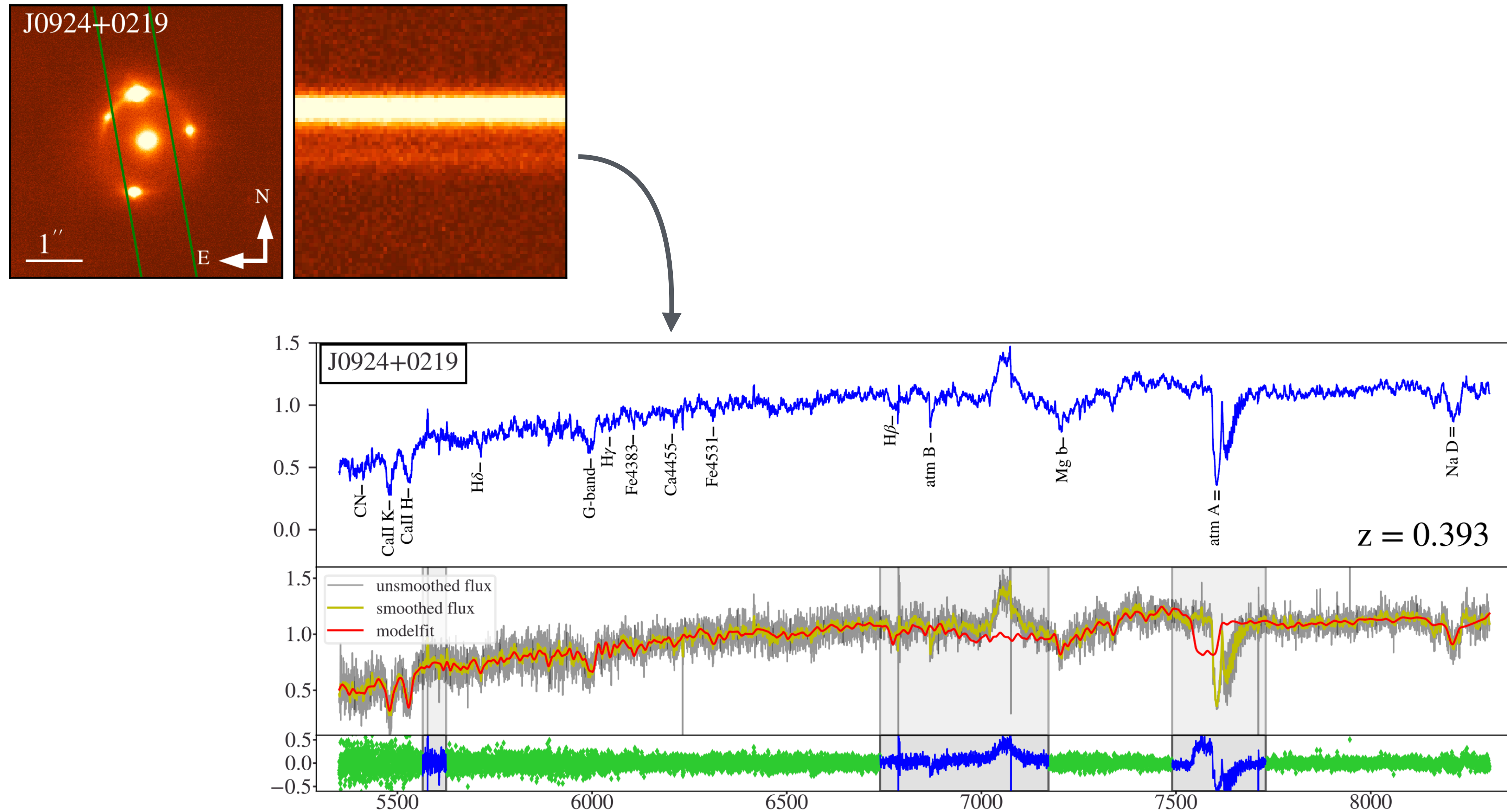
Measuring stellar kinematics

Mozumdar et al. 2023



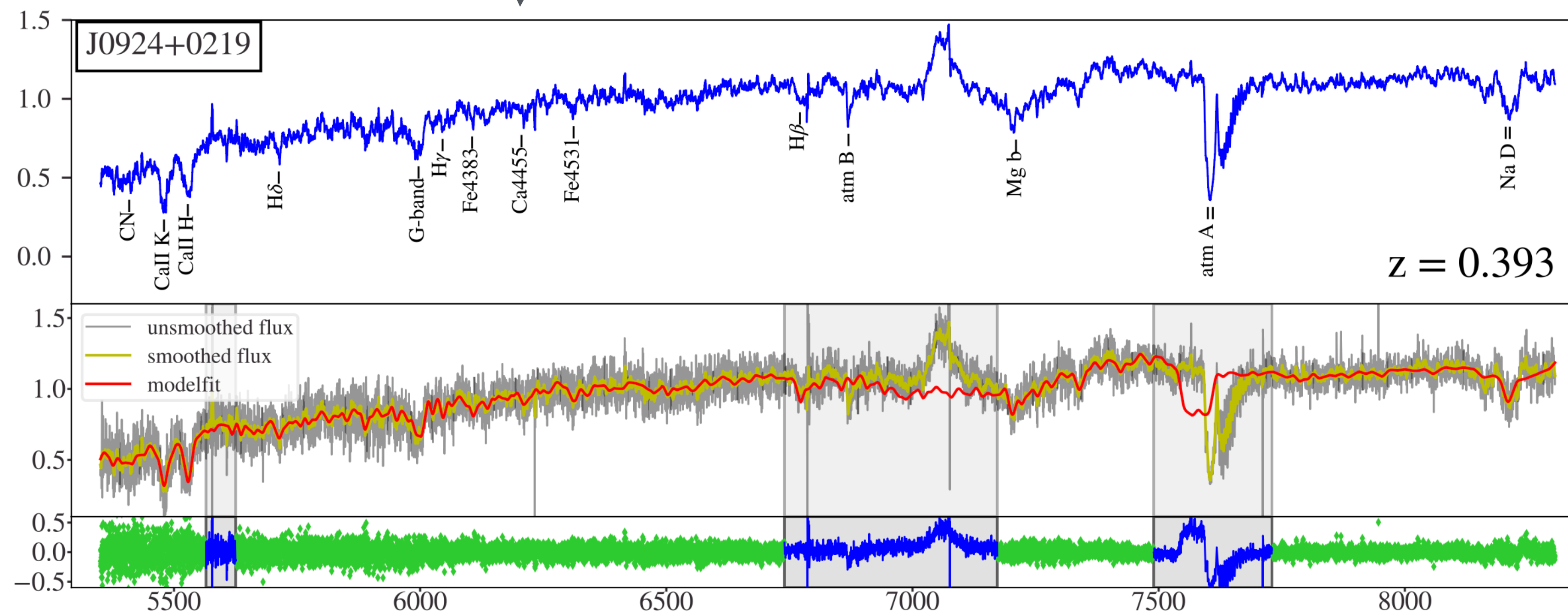
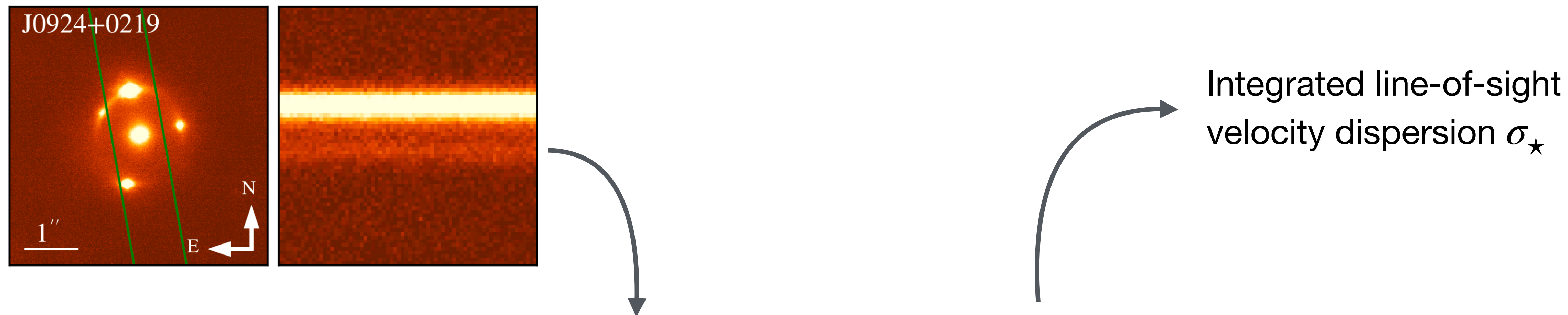
Measuring stellar kinematics

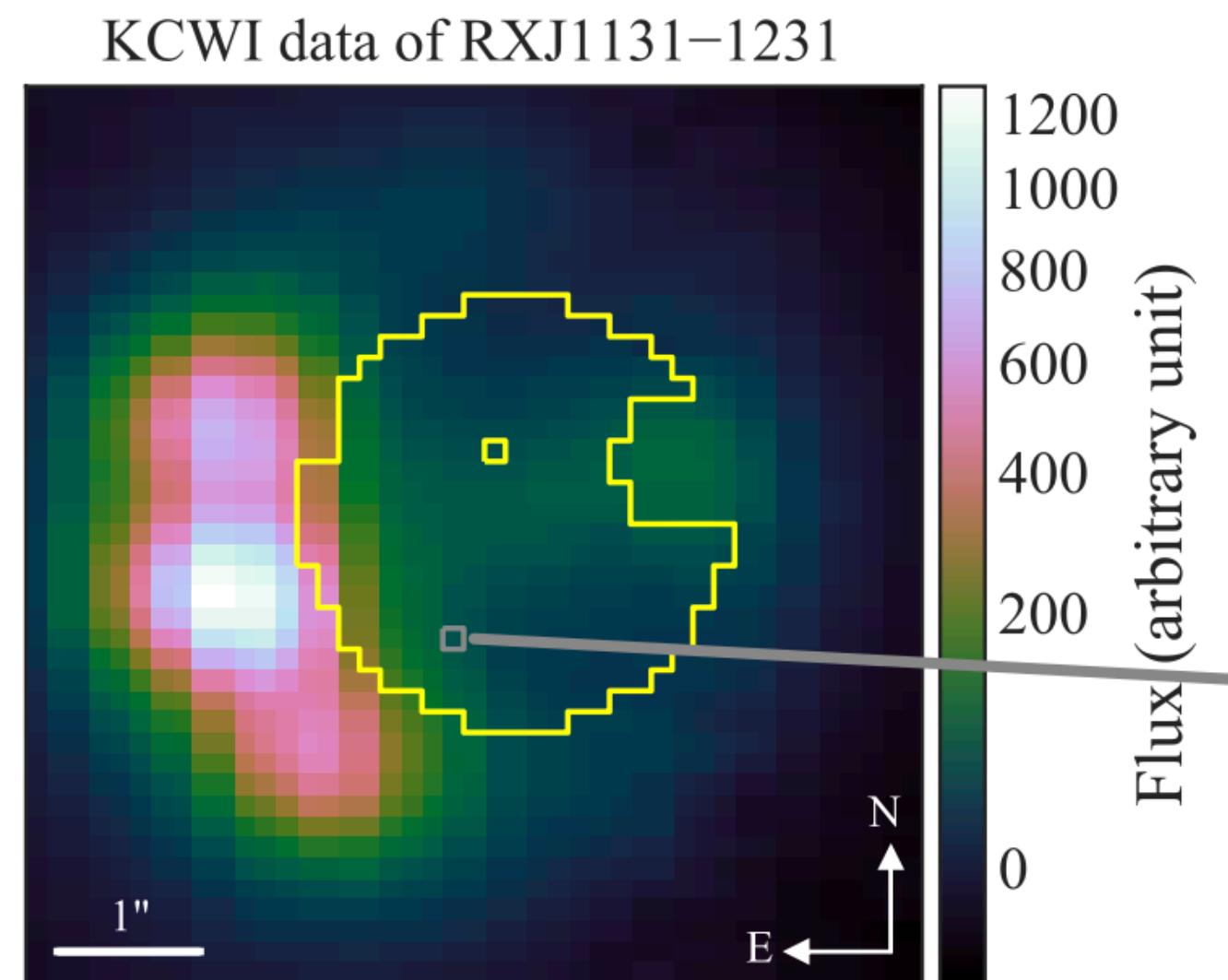
Mozumdar et al. 2023



Measuring stellar kinematics

Mozumdar et al. 2023

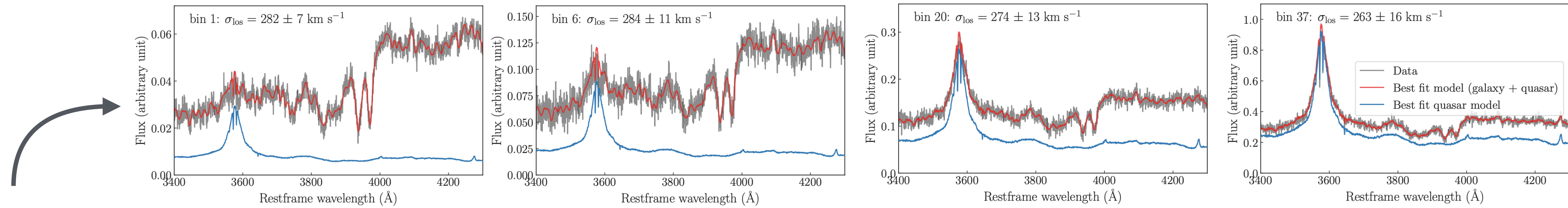




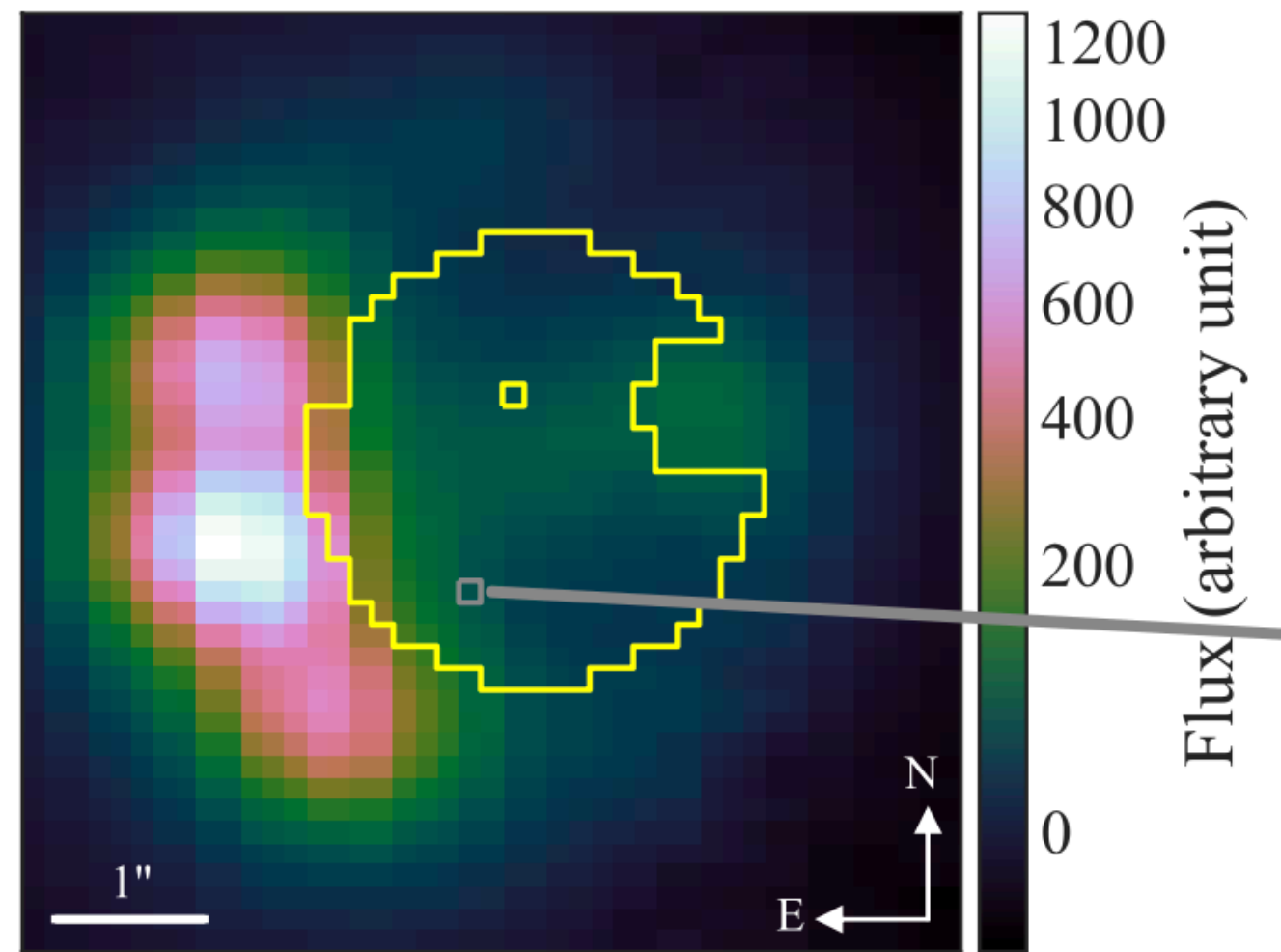
Shajib et al. 2023

⇒ Instead of measuring $\sigma_{\star}$ only around the center of the lens galaxy, we get a 2D map of it!

Data upgrade: spatially resolved kinematics



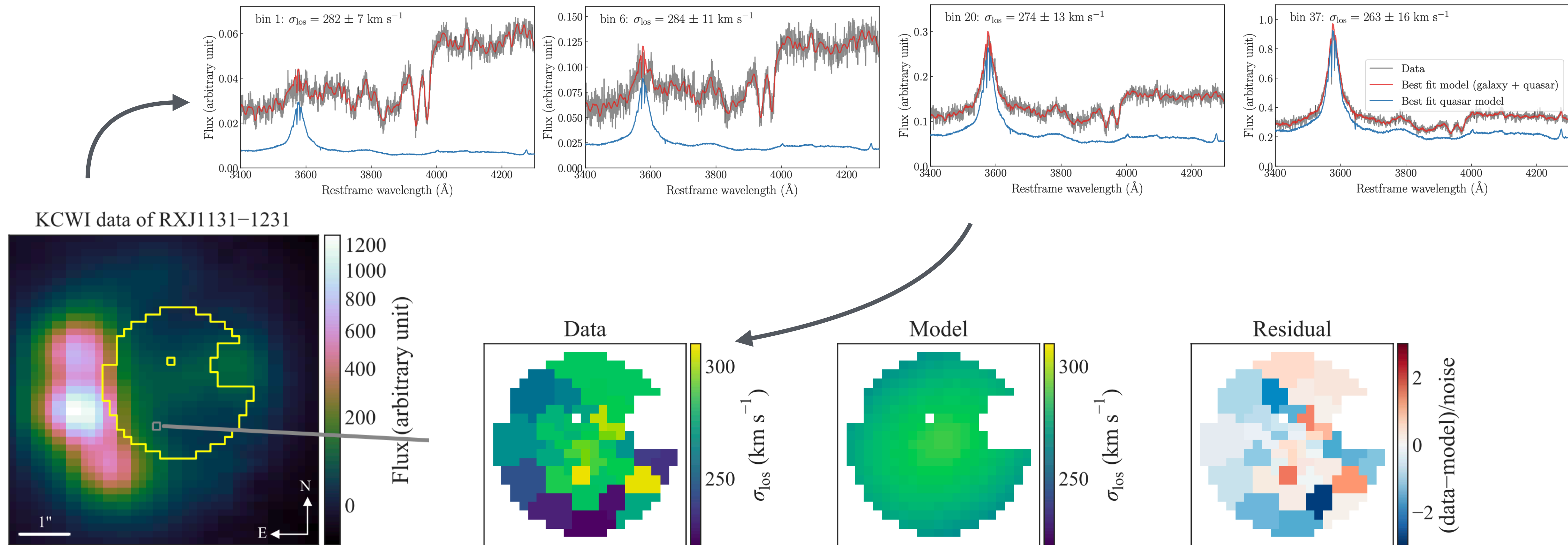
KCWI data of RXJ1131-1231



Shajib et al. 2023

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Data upgrade: spatially resolved kinematics



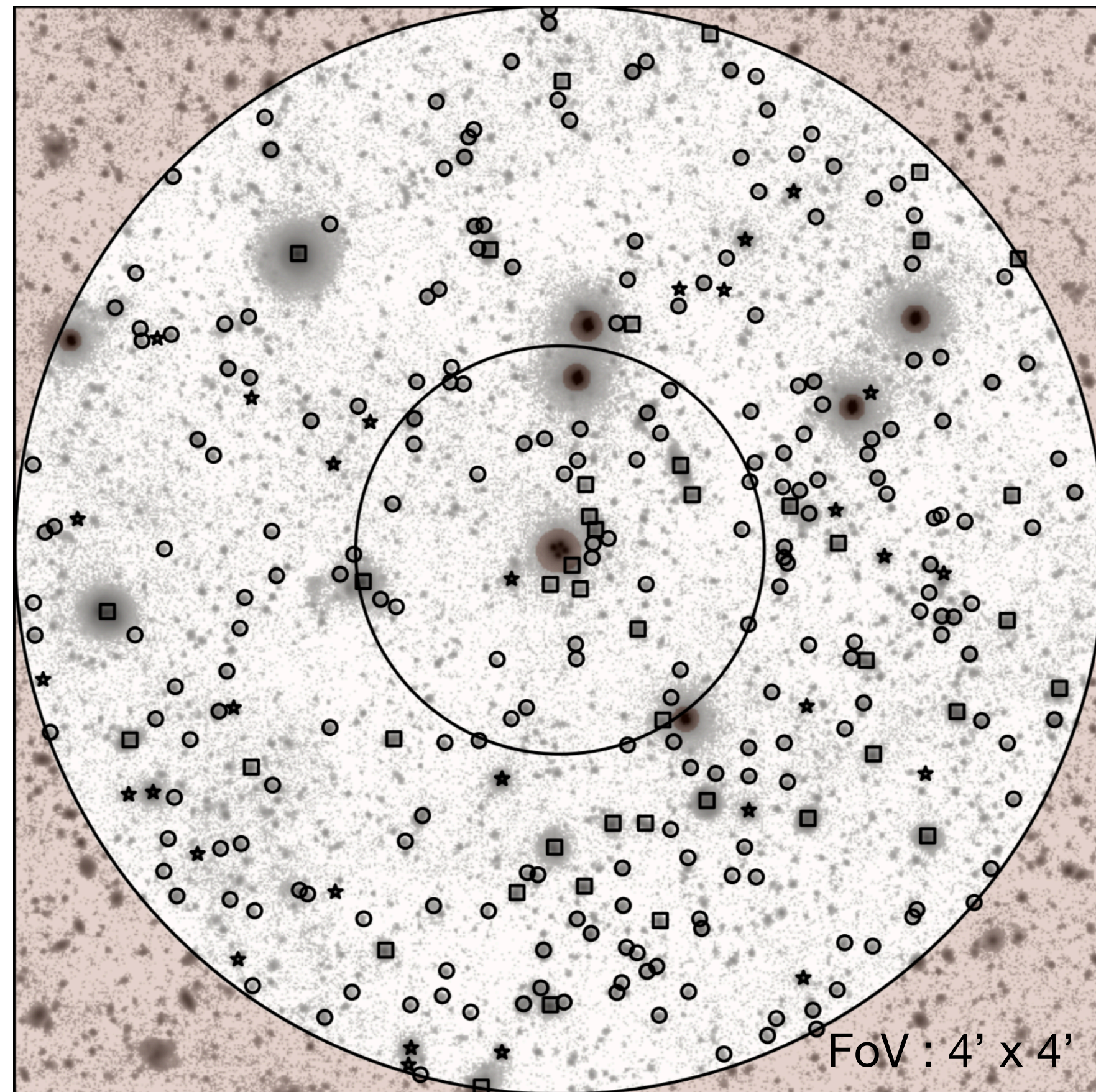
Shajib et al. 2023

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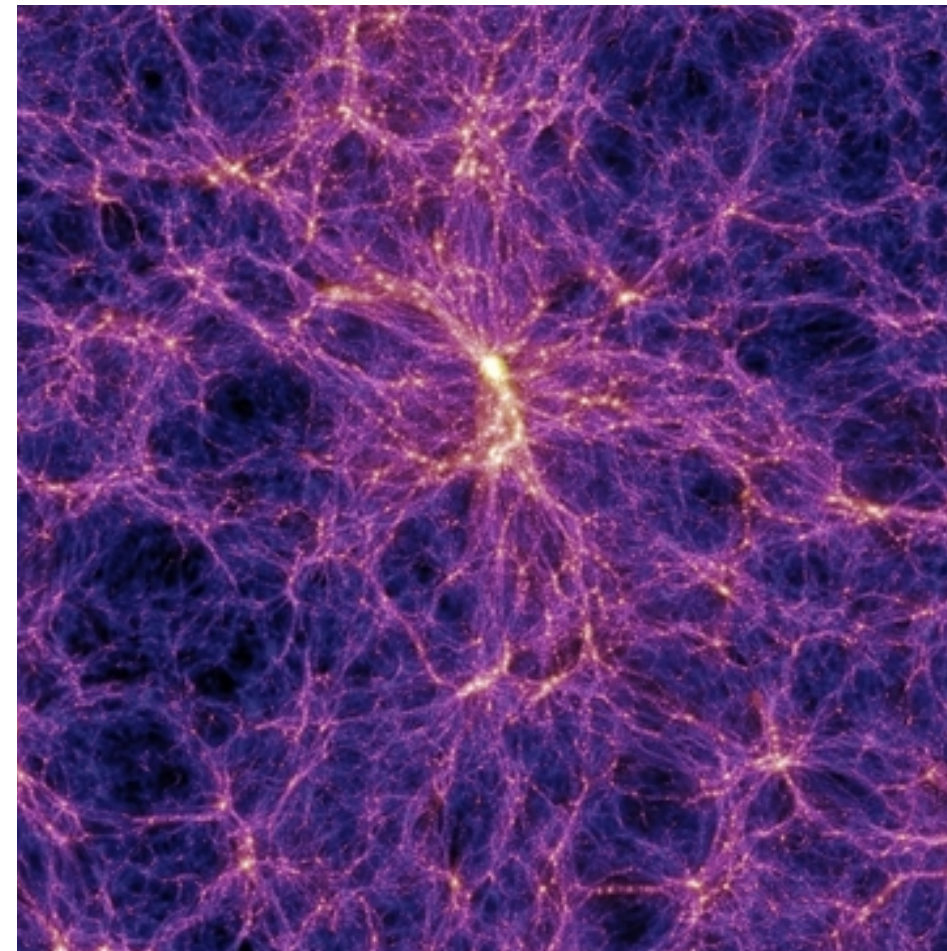
Estimating line-of-sight contributions

Measuring the external convergence

Option 1: Galaxy counts (ground-based + cosmo. sim.)

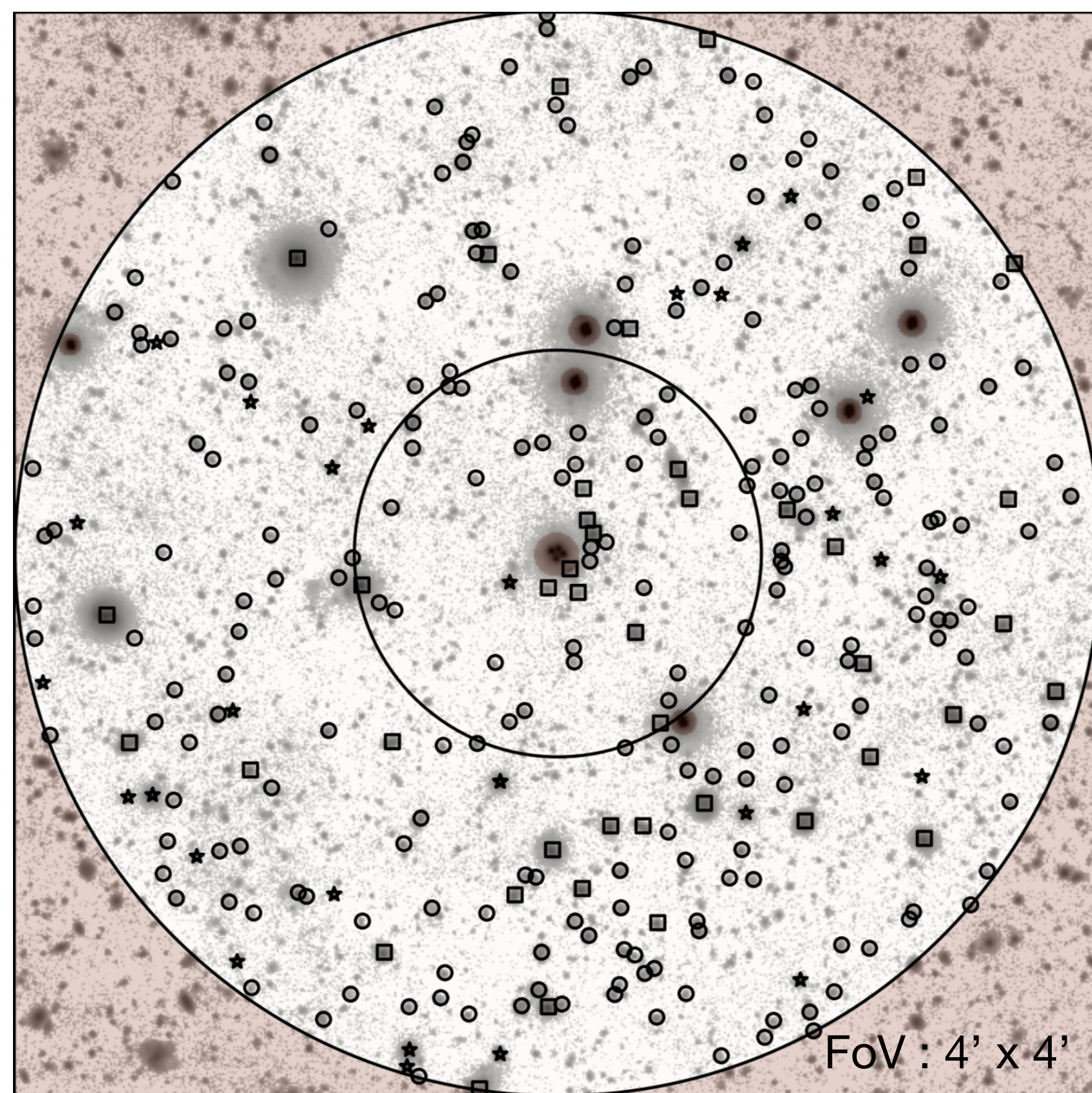


Rusu et al. (2017)

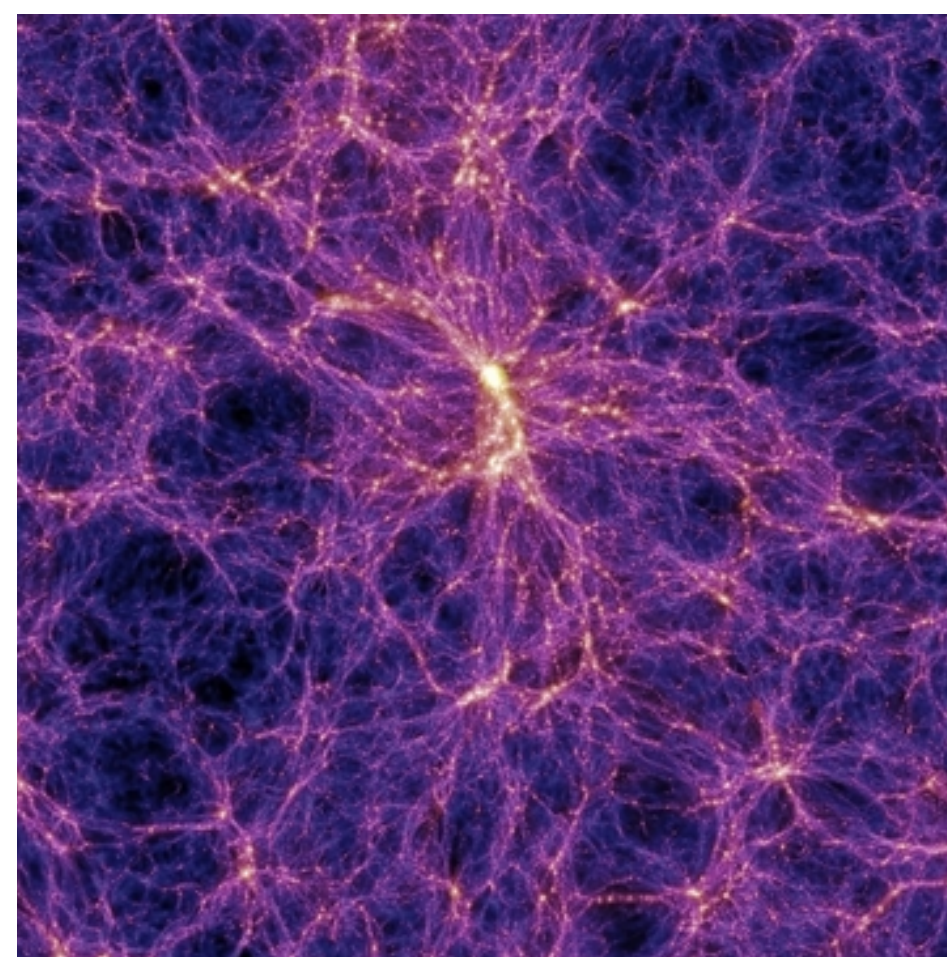


Springel et al. (2005)

Option 1: Galaxy counts (ground-based + cosmo. sim.)

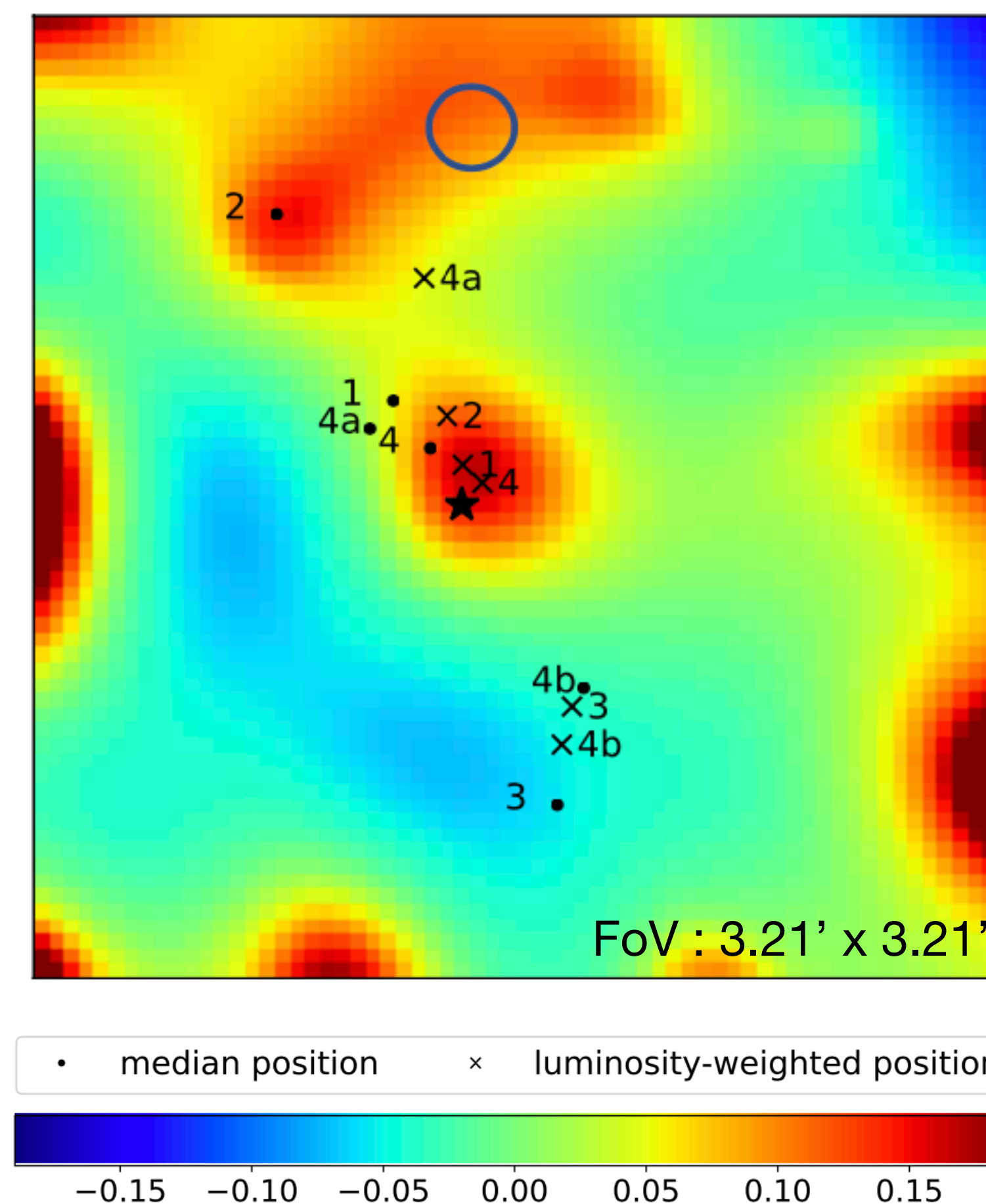


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Springel et al. (2005)

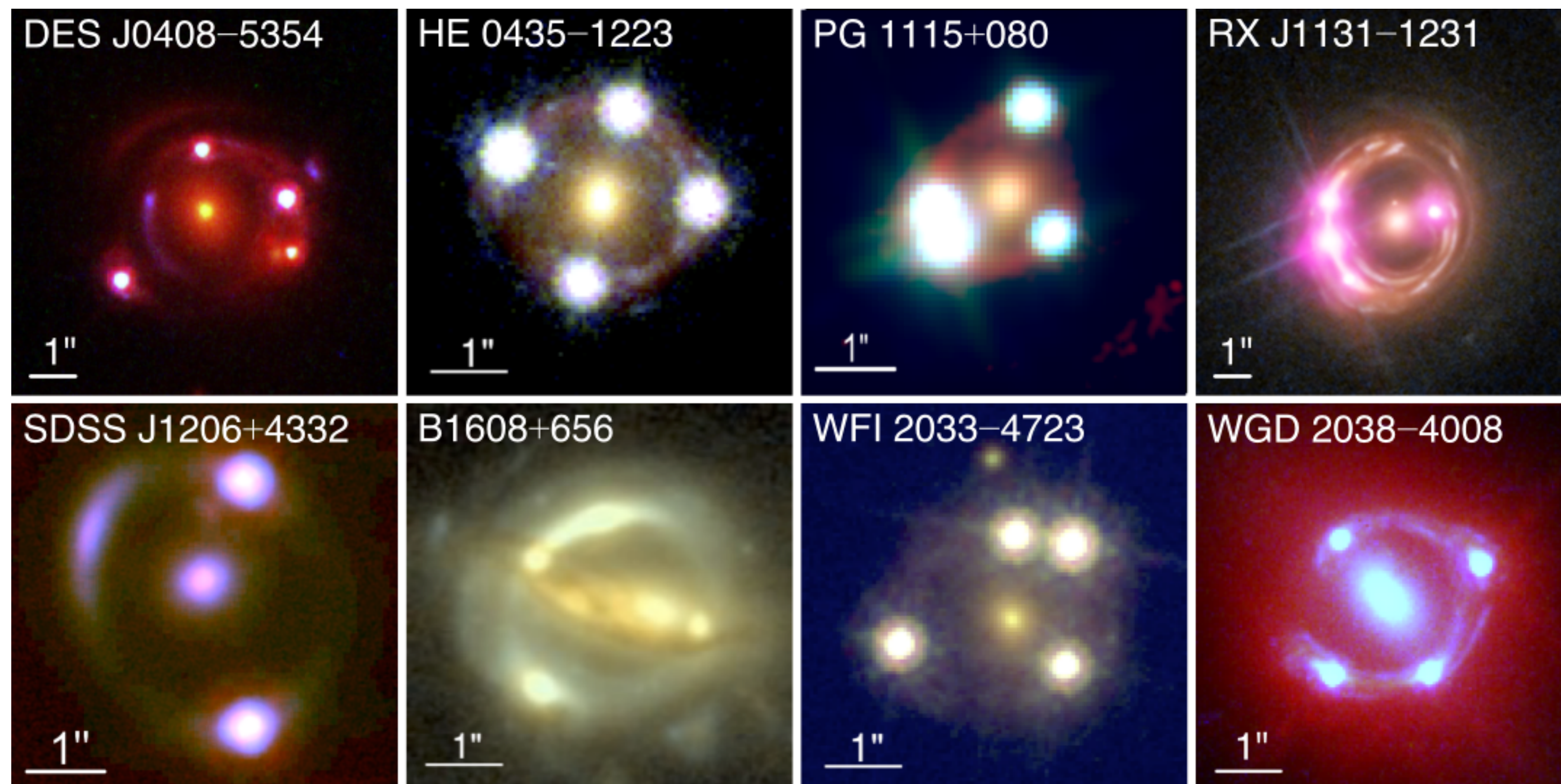
Option 2: Weak lensing (ground-based + HST)



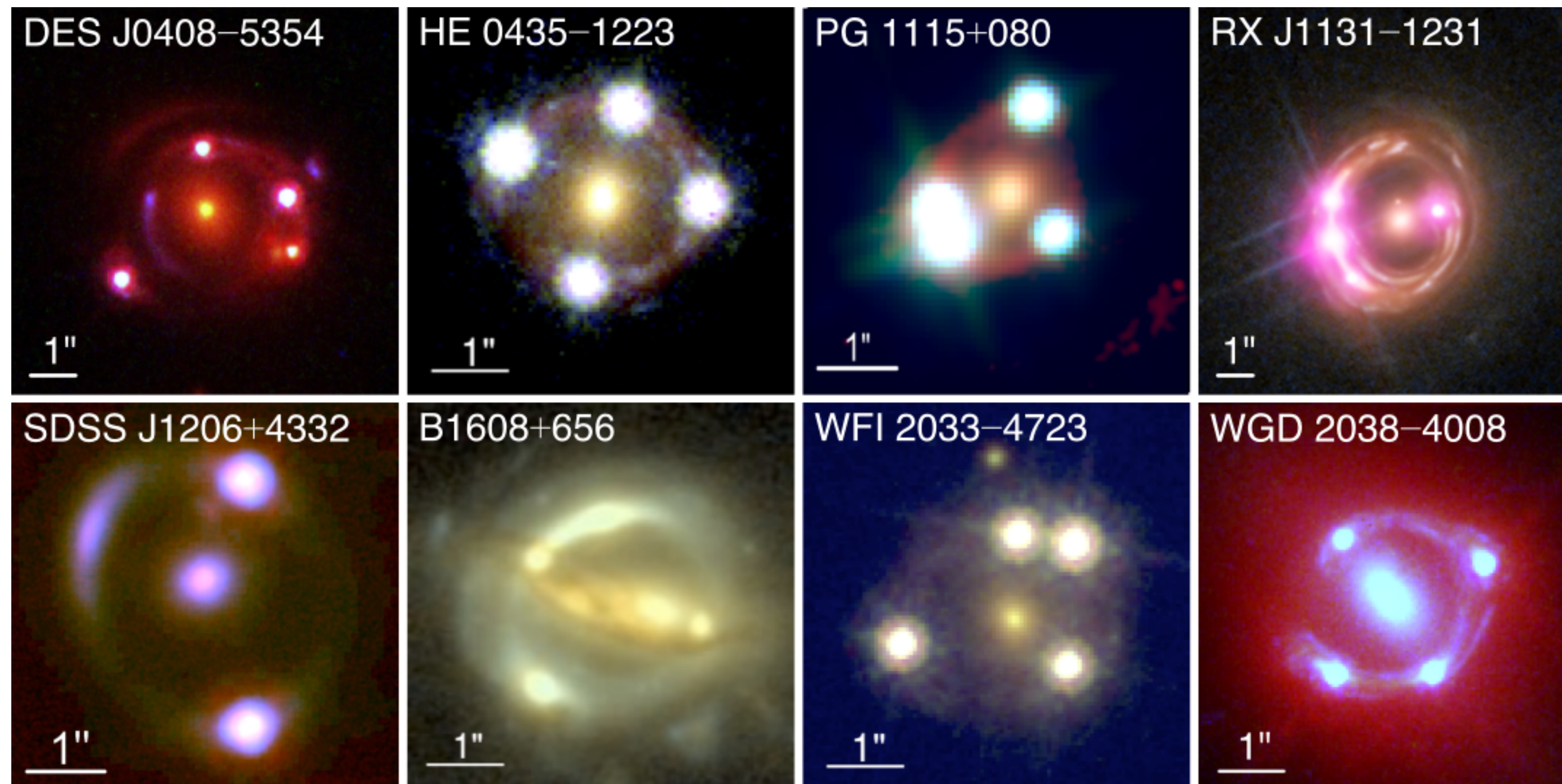
Tihhonova et al. (2020)

Inference of the Hubble constant H_0

Repeat the process for several systems and combine constraints



Repeat the process for several systems and combine constraints



Every part of each analysis — time delays, Fermat potential, etc. —
is **performed blindly** with respect to H_0 !
(except one lens historically)

Constraints on H_0

Constraints on H_0

H_0 measurements in flat Λ CDM - performed blindly

H0LiCOW XIII →

Wong et al. 2020

6 time-delay lenses

H0LiCOW (average of PL and NFW + stars/constant M/L)

$73.3^{+1.7}_{-1.8}$

TDCOSMO I →

Millon et al. 2020

7 time-delay lenses (6 H0LiCOW + 1 STRIDES)

TDCOSMO-1 (NFW + stars/constant M/L)

$74.0^{+1.7}_{-1.8}$

$74.2^{+1.6}_{-1.6}$
TDCOSMO-1 (power-law)

} Assertive assumptions
on the structure of galaxies
(power-law or DM+stars profiles)

Inference performed blindly

60 65 70 75 80

H_0 [km s⁻¹ Mpc⁻¹]

Relaxing the assumption on the density profile of galaxies

- The observed « bulge-halo conspiracy » may not be universal
⇒ Possible deviations from a power-law density profile

Relaxing the assumption on the density profile of galaxies

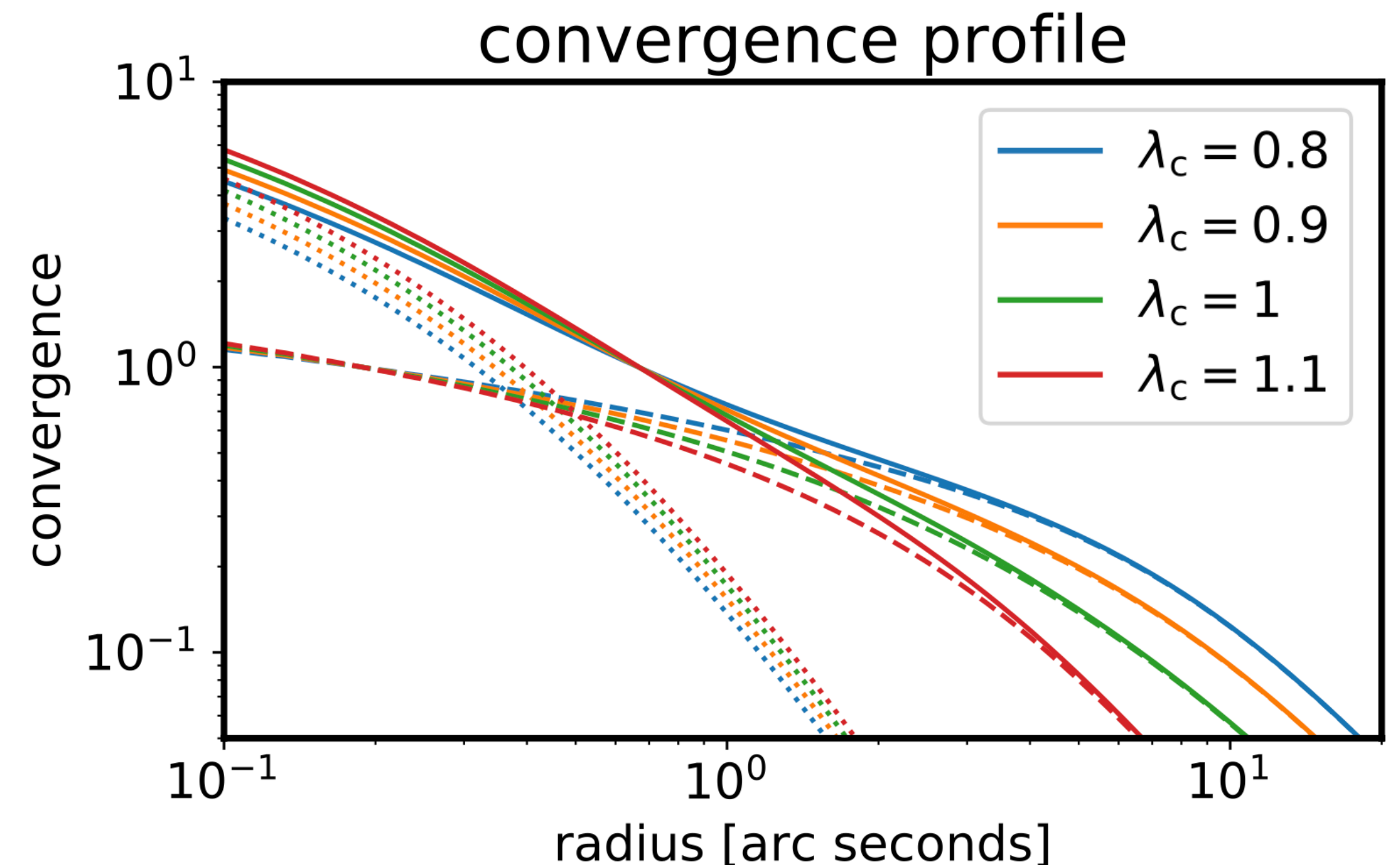
- The observed « bulge-halo conspiracy » may not be universal
⇒ Possible deviations from a power-law density profile
- Certain exotic DM models predict cores extending further out than typical Einstein radii
⇒ This *cannot* be constrained by strong-lensing data alone

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Mass-sheet transformed convergence profile:

$$\kappa_{\lambda_{\text{int}}} = \lambda_{\text{int}} \kappa_{\text{model}} + (1 - \lambda_{\text{int}}) \kappa_{\text{c}}$$



Birrer et al. 2020

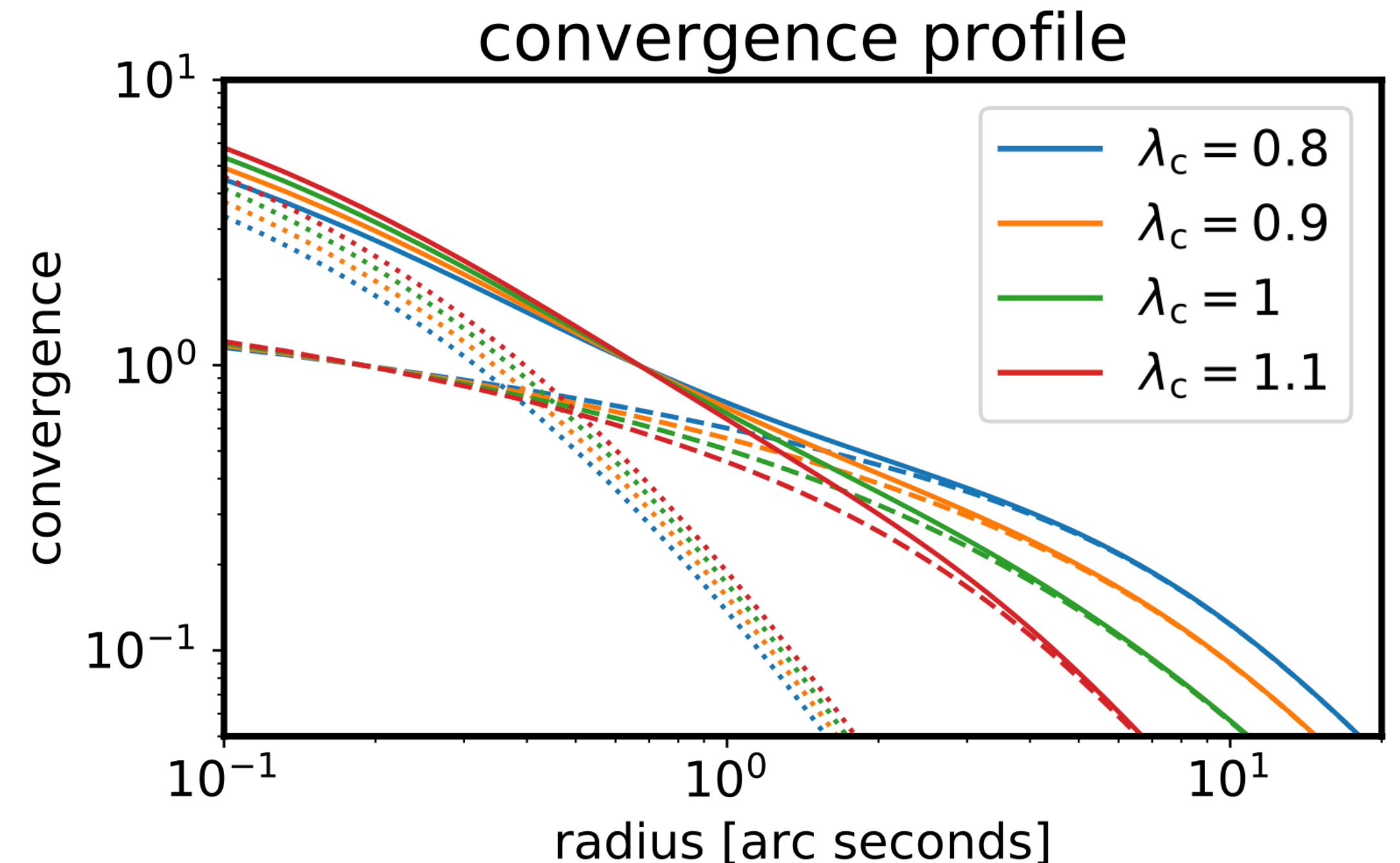
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⇒ **Internal mass-sheet parameter** λ_{int}
(external parameter already incorporated via κ_{ext})



Birrer et al. 2020

Constraints on H_0

H_0 measurements in flat Λ CDM - performed blindly

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Wong et al. 2020

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Millon et al. 2020

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TDCOSMO-1 (power-law)

TDCOSMO IV →

Birrer et al. 2020

7 time-delay lenses (+ 33 SLACS lenses)

kinematics-only constraints on mass profile

$74.5^{+5.6}_{-6.1}$

TDCOSMO-4

Assertive assumptions
on the structure of galaxies
(power-law or DM+stars profiles)

Conservative assumptions
on the structure of galaxies
(mass-sheet transformed profile)

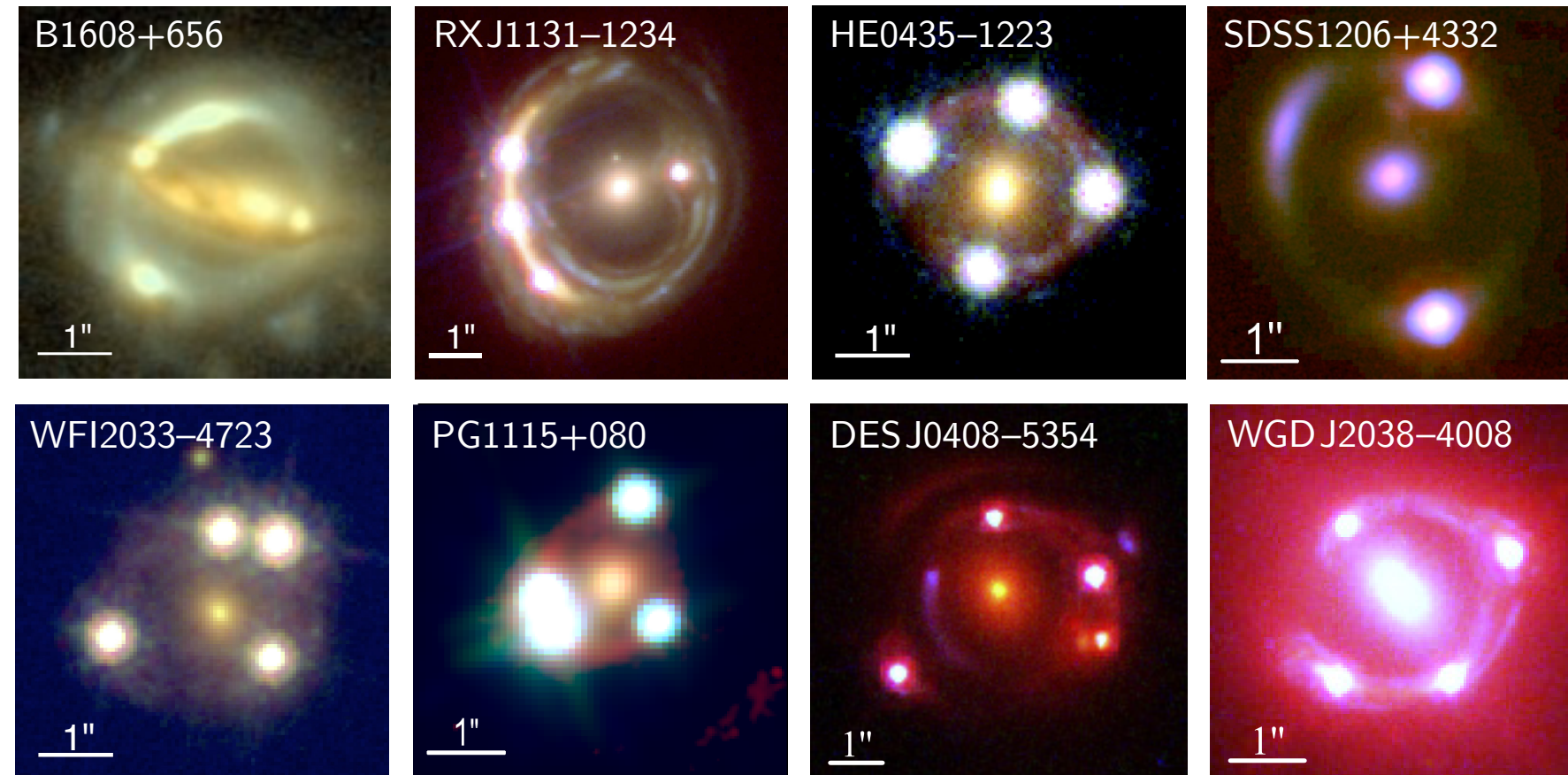
Inference performed blindly

60 65 70 75 80

H_0 [km s⁻¹ Mpc⁻¹]

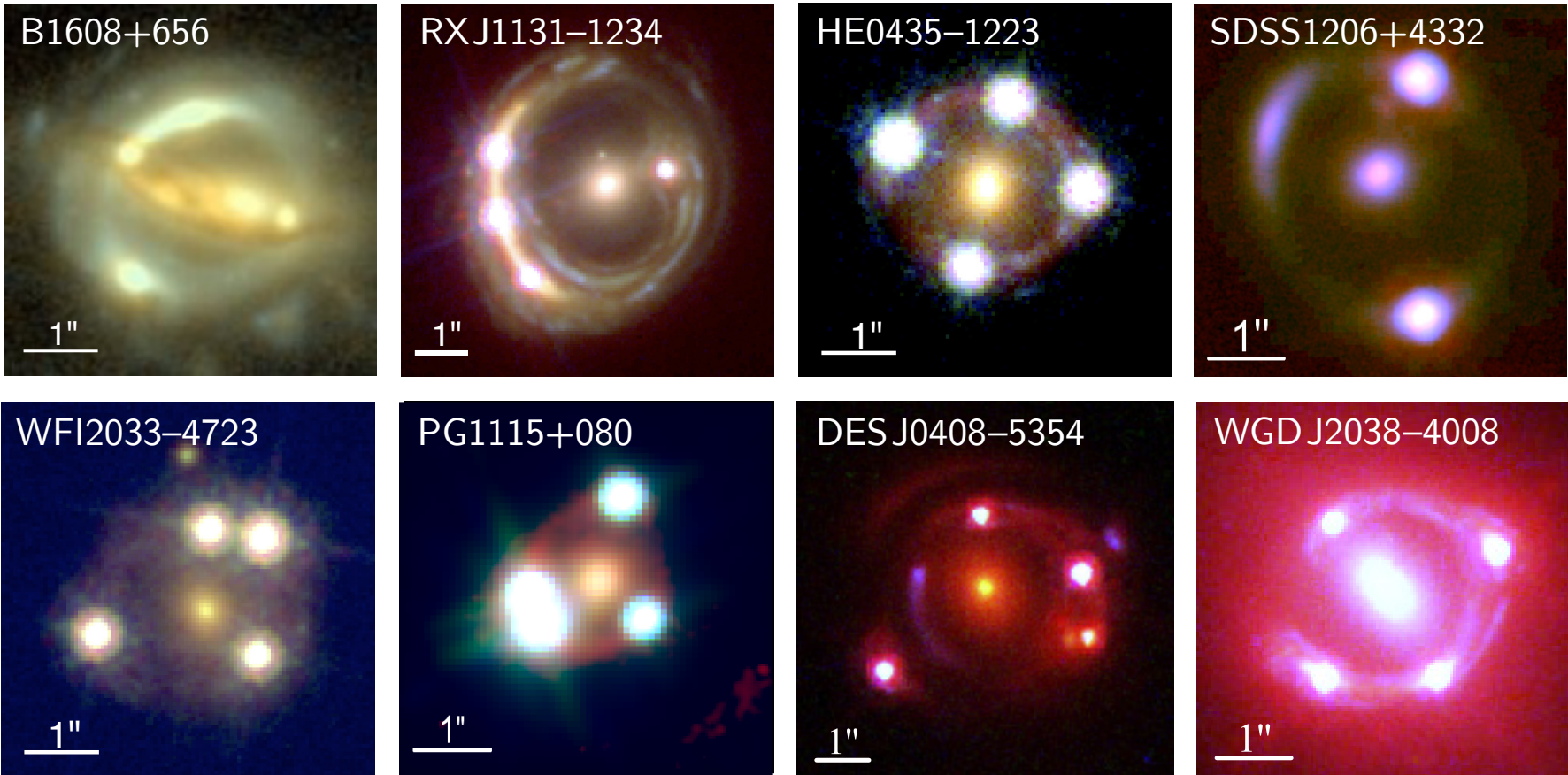
Inference of H_0 ... now jointly with galaxies density profile

Strongly lensed quasars



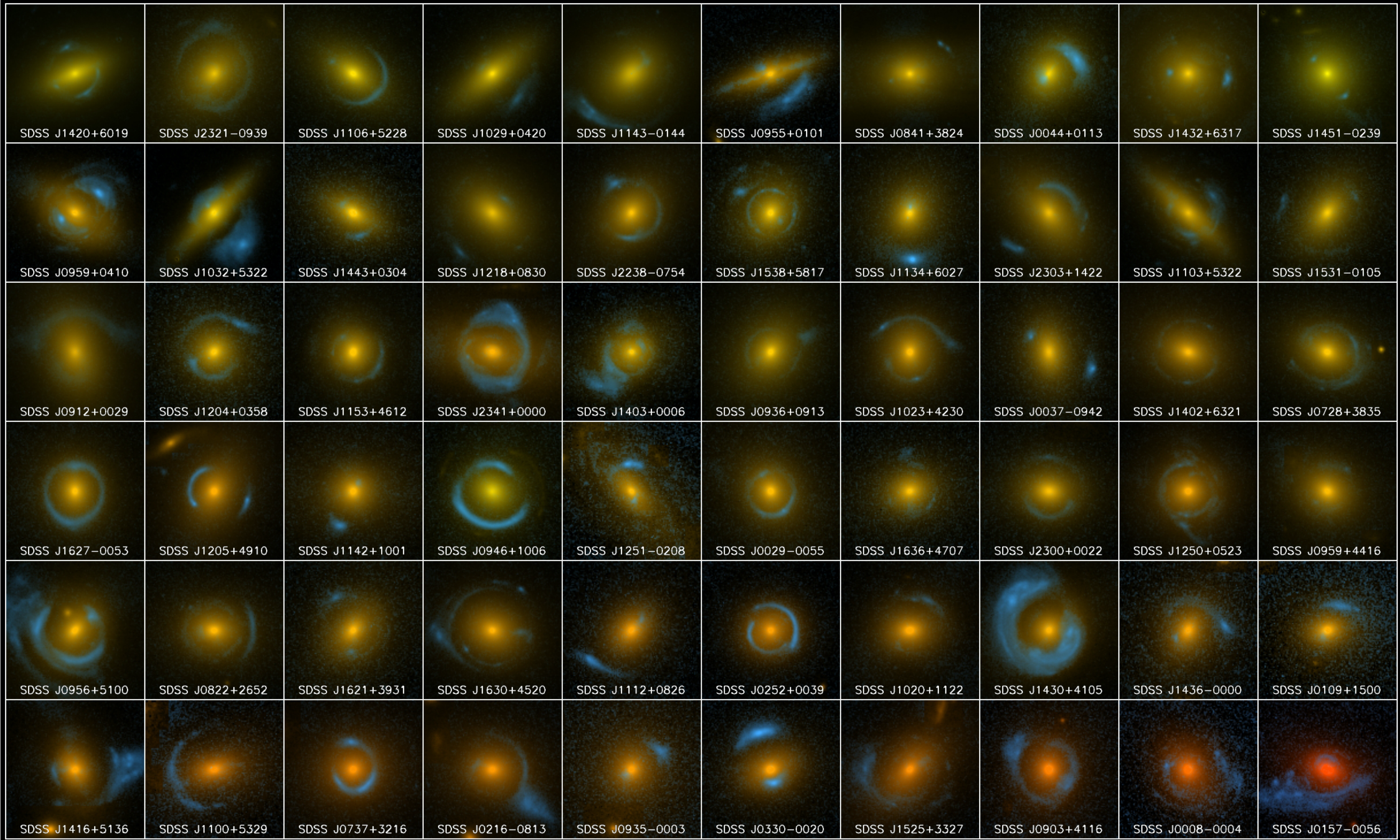
Inference of H_0 ... now jointly with galaxies density profile

Strongly lensed quasars



+

Non-time-delay systems with *similar* lenses (SLACS & SL2S samples)



SLACS: The Sloan Lens ACS Survey

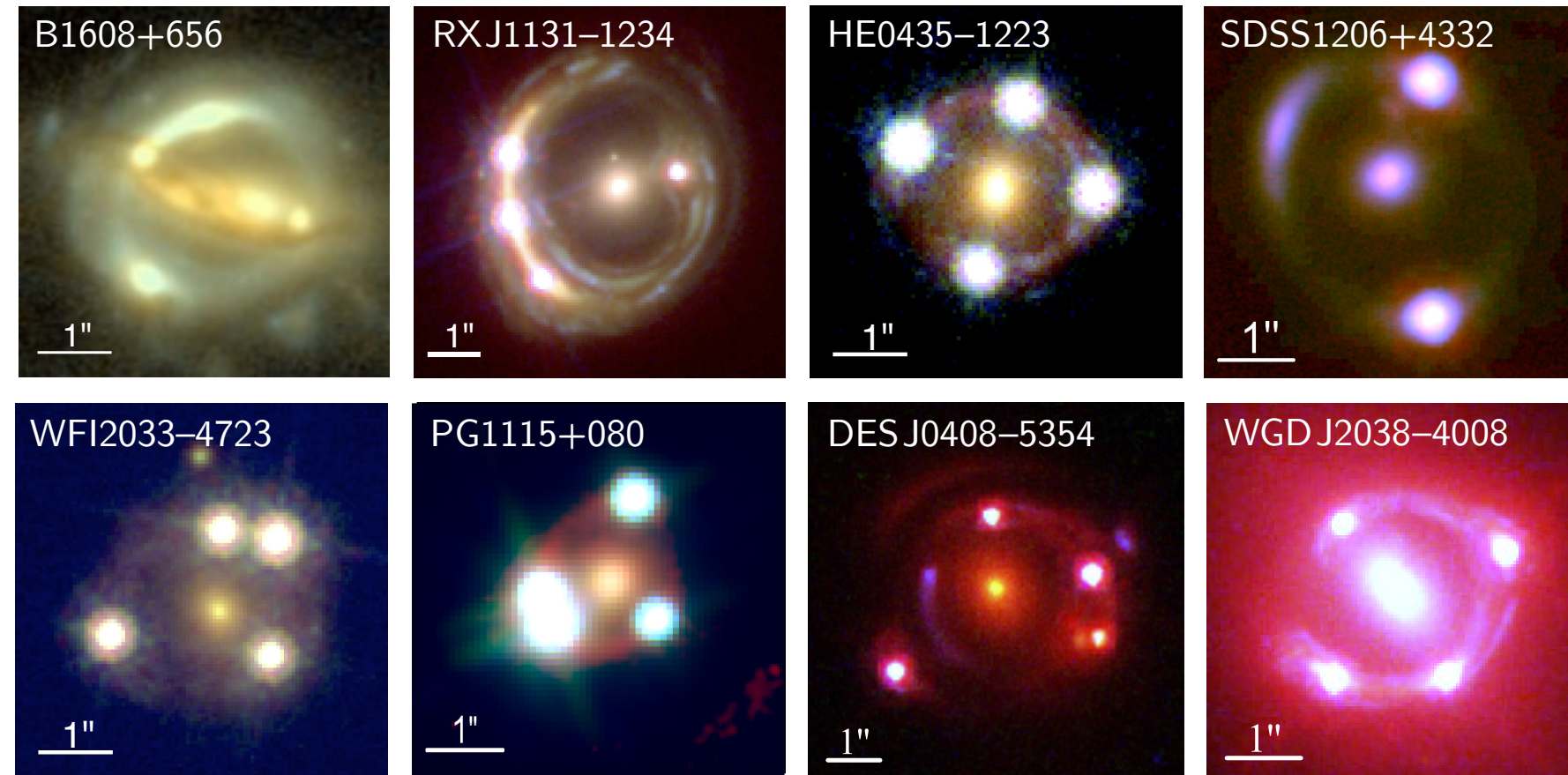
www.SLACS.org

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

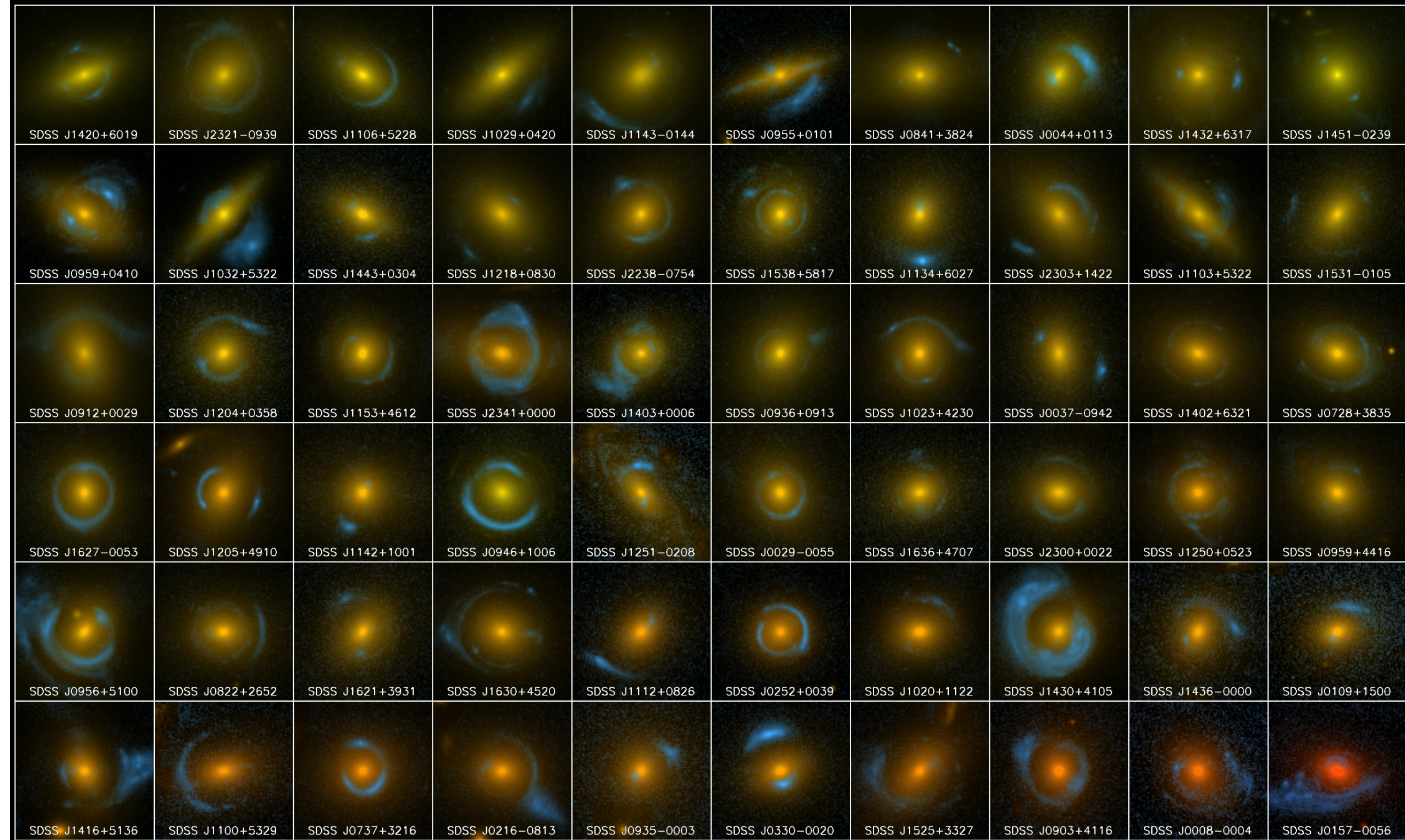
Inference of H_0 ... now jointly with galaxies density profile

Strongly lensed quasars

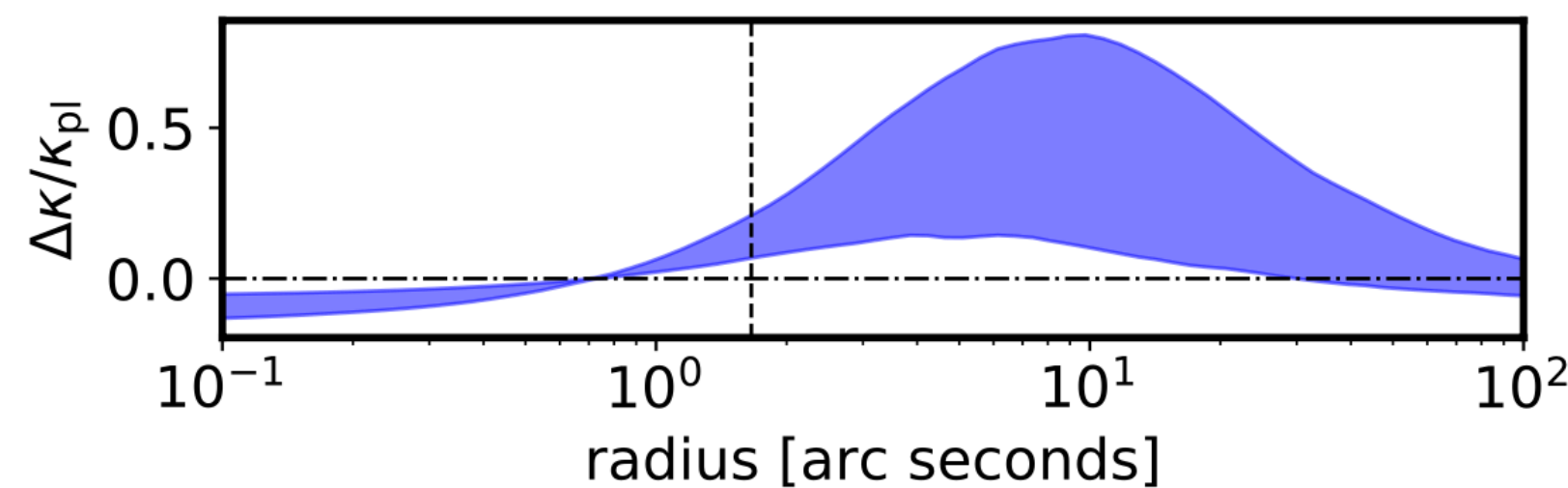
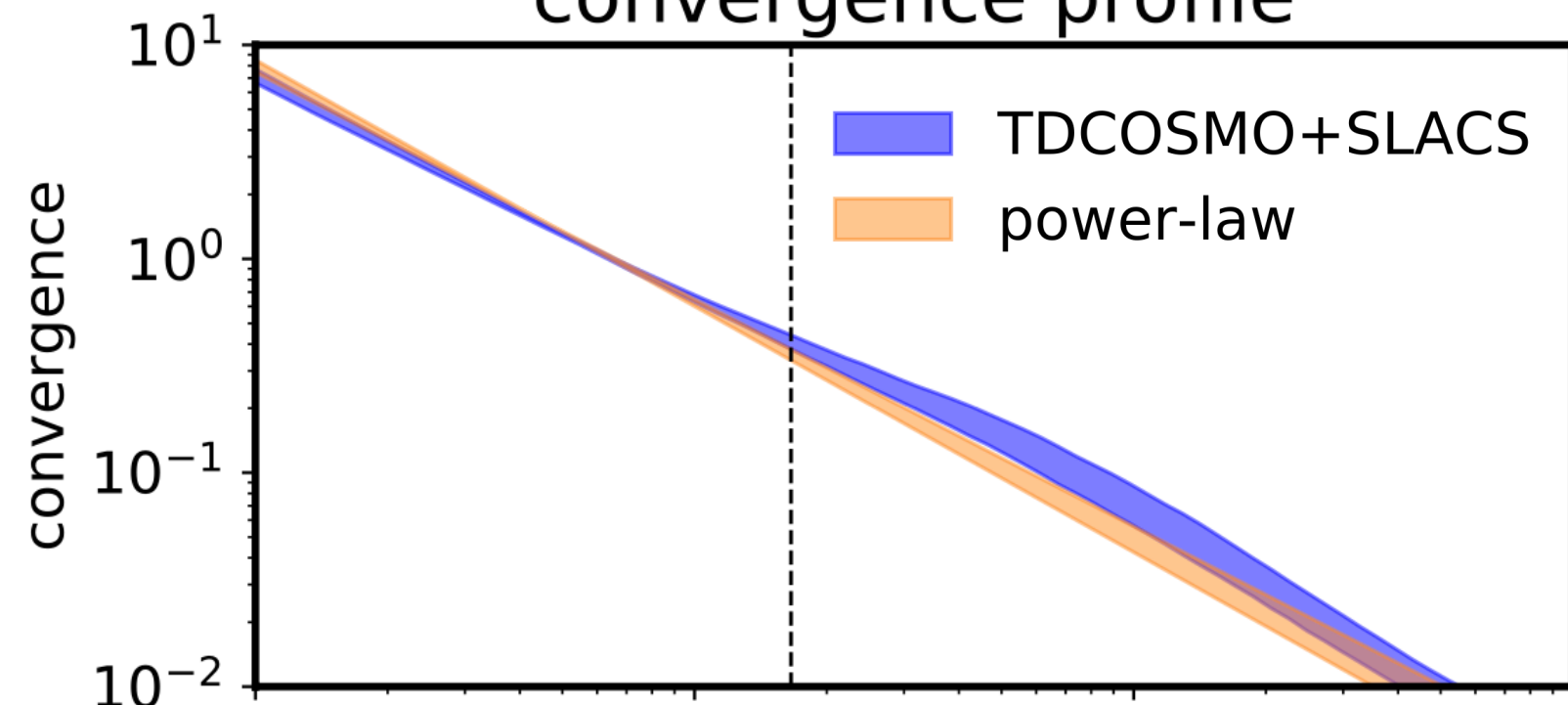


+

Non-time-delay systems with *similar* lenses (SLACS & SL2S samples)



convergence profile



TDCOSMO IV, Birrer et al. 2020

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

www.SLACS.org

Constraints on H_0

H_0 measurements in flat Λ CDM - performed blindly

H0LiCOW XIII →

Wong et al. 2020

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Millon et al. 2020

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TDCOSMO-1 (NFW + stars/constant M/L)

$74.0^{+1.7}_{-1.8}$

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TDCOSMO-1 (power-law)

TDCOSMO IV →

Birrer et al. 2020

7 time-delay lenses (+ 33 SLACS lenses)

kinematics-only constraints on mass profile

$74.5^{+5.6}_{-6.1}$

TDCOSMO-4

$67.4^{+4.1}_{-3.2}$

TDCOSMO-4 + SLACS

Assertive assumptions
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(power-law or DM+stars profiles)

Conservative assumptions
on the structure of galaxies
(mass-sheet transformed profile)

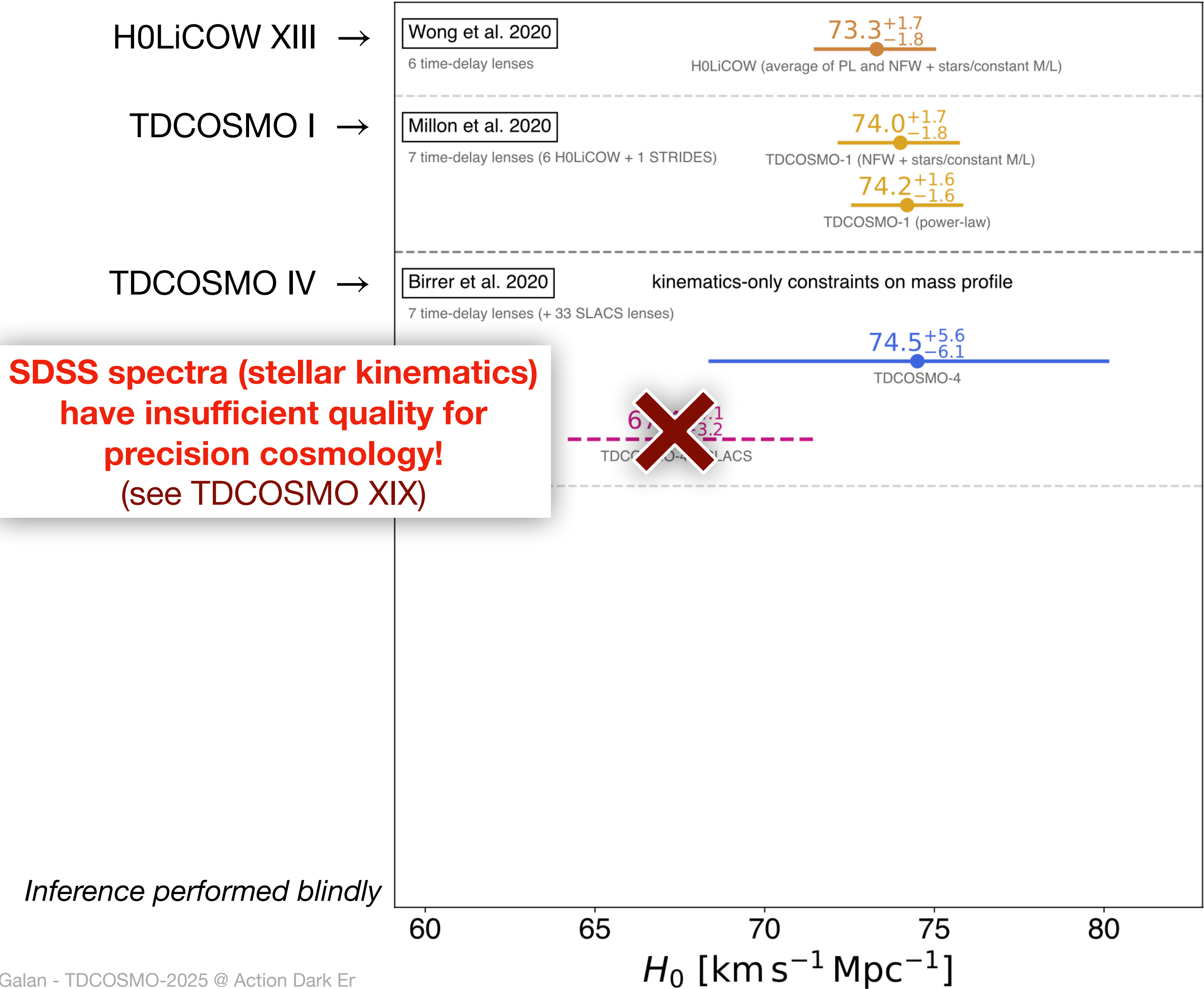
Inference performed blindly

60 65 70 75 80

H_0 [km s⁻¹ Mpc⁻¹]

Constraints on H_0

H_0 measurements in flat Λ CDM - performed blindly



Assertive assumptions
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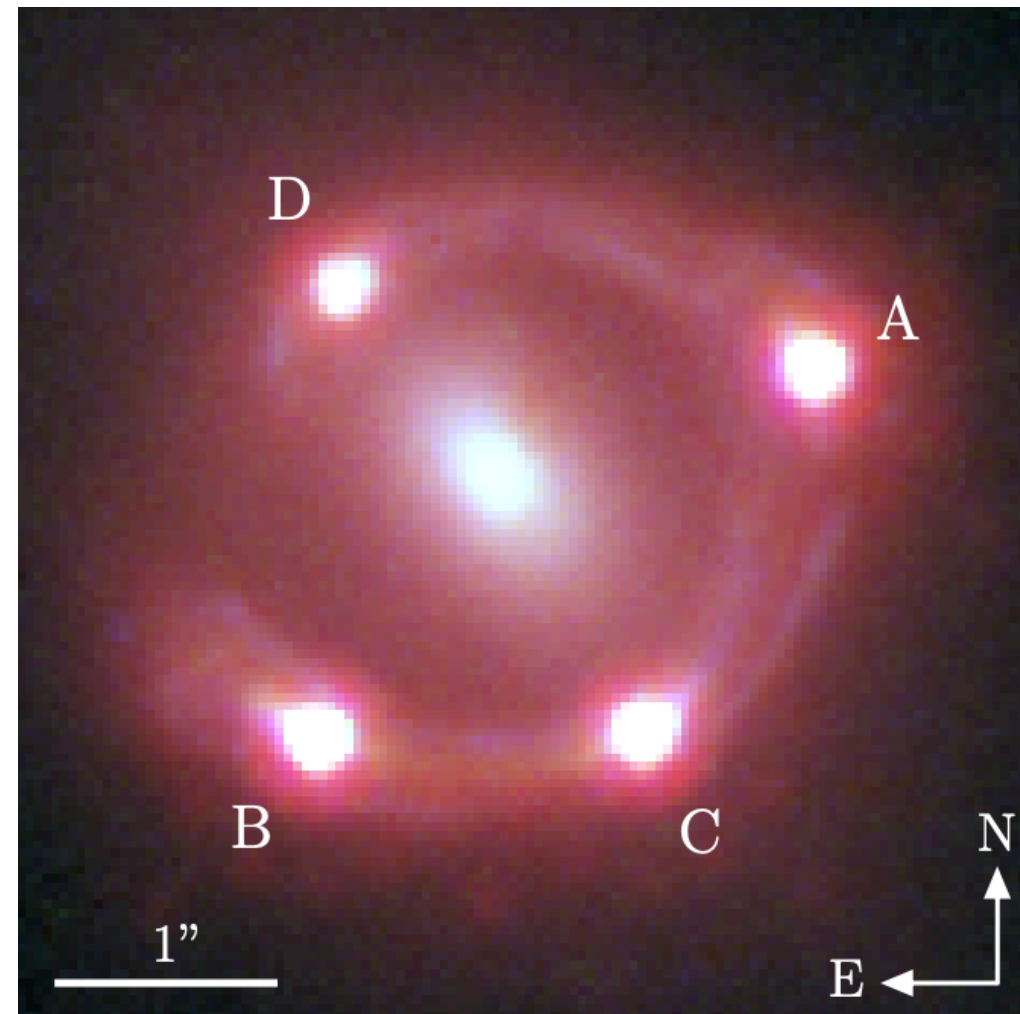
Inference of H_0

Joint inference of H_0 and galaxies' mass profiles

TDCOSMO-2025: What's new in the latest milestone

- New strongly lensed quasar: **WGD2038–4008**

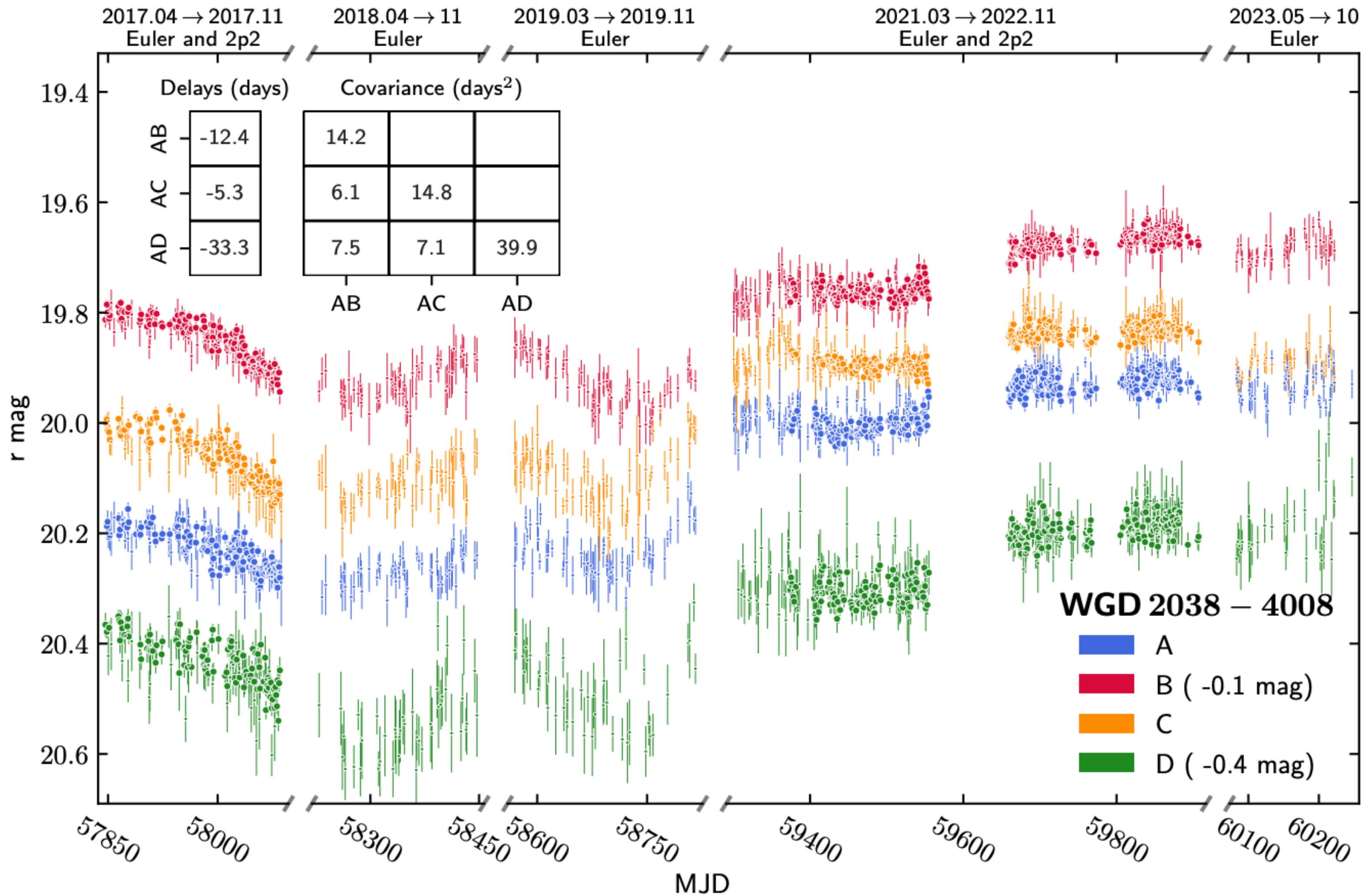
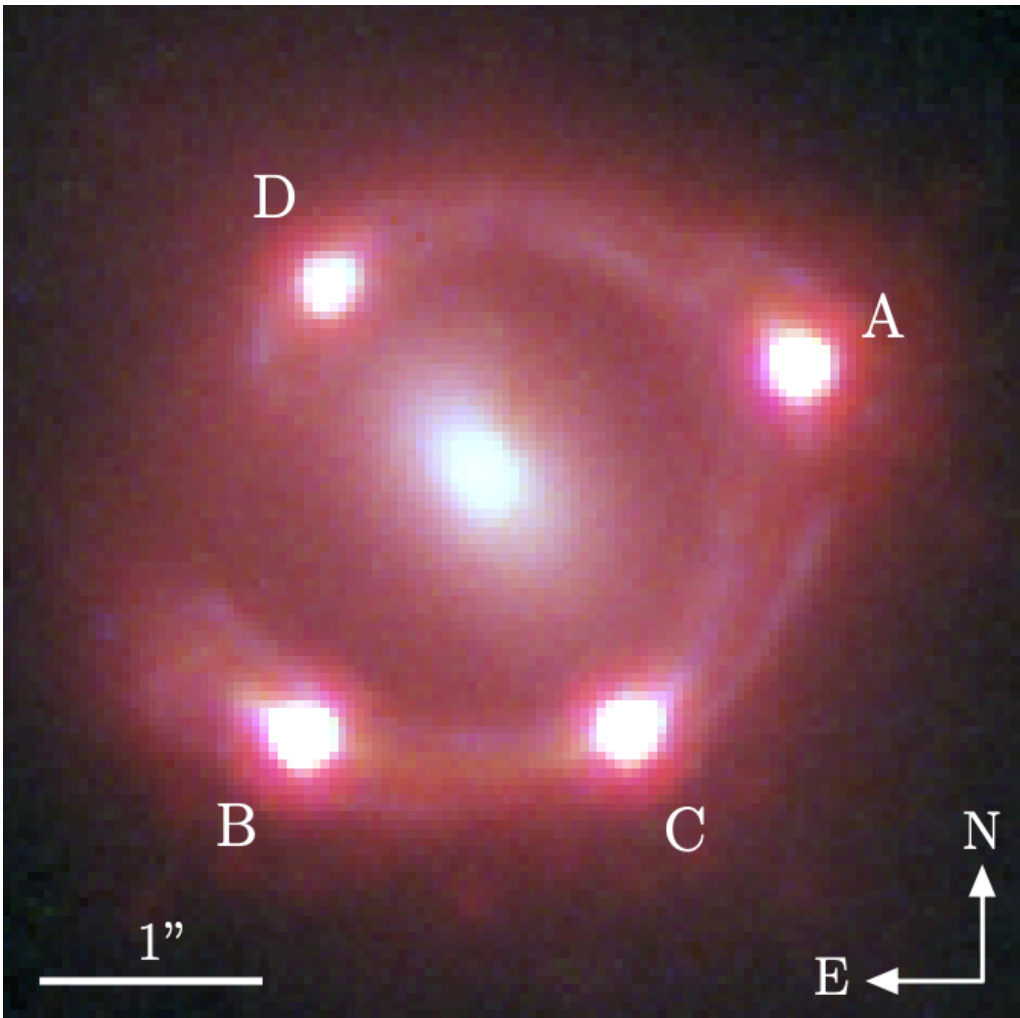
Wong et al. 2024



TDCOSMO-2025: What's new in the latest milestone

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Wong et al. 2024



TDCOSMO-2025: What's new in the latest milestone

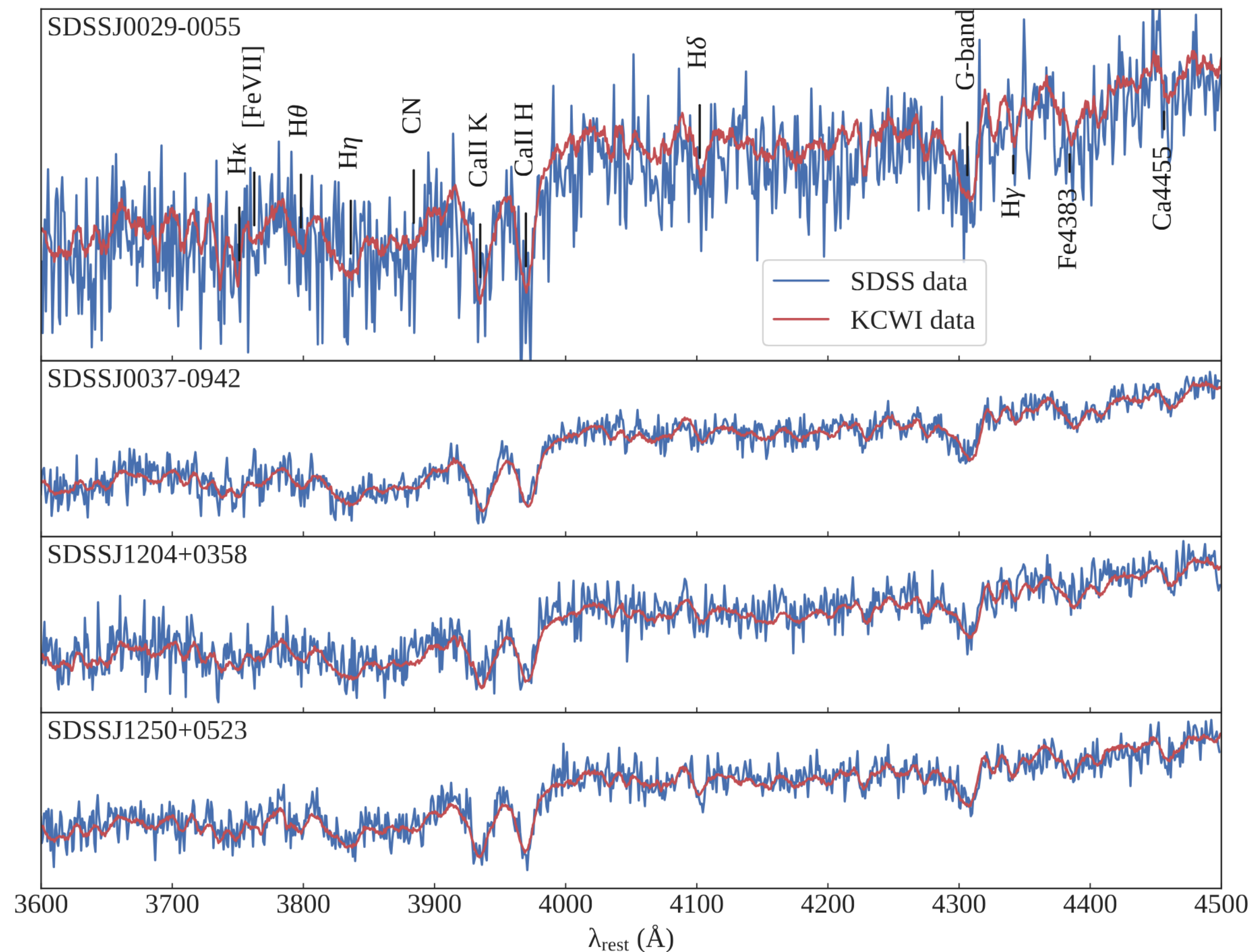
- Improved methods to infer **stellar velocity dispersions** at **$< 1\%$ accuracy**:

Knabel et al. 2025

- Improved methods to infer **stellar velocity dispersions at $< 1\%$ accuracy:**

Knabel et al. 2025

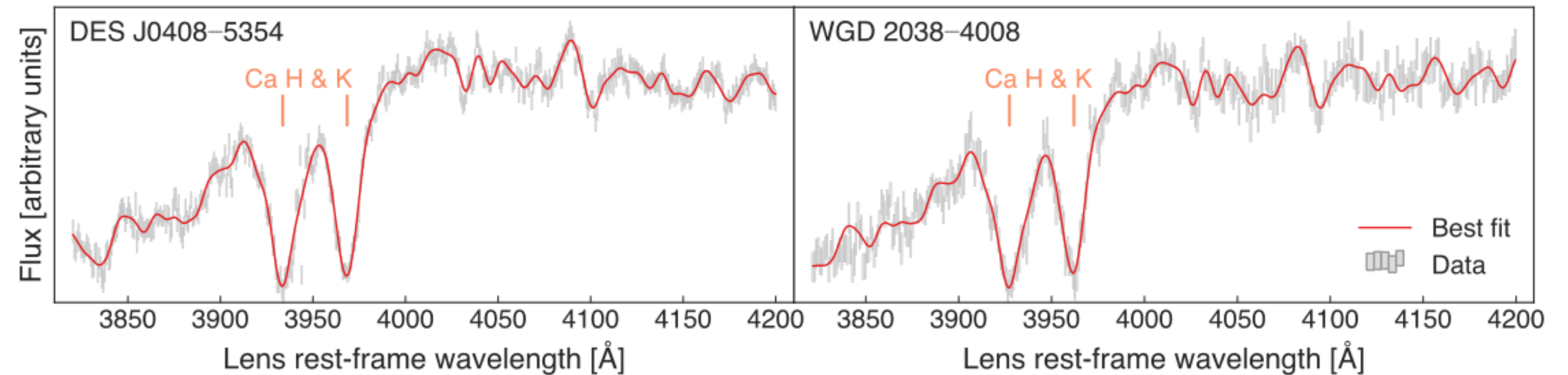
- ✓ Requires spectrum $S/N > 15 \text{ \AA}^{-1}$
- ✓ Cleaned spectral template libraries
- ✓ Marginalization over several libraries



- New spectroscopic data from JWST/Nirspec, Keck/KCWI and VLT/MUSE

TDCOSMO collaboration et al. 2025

VLT/MUSE *integrated* spectra →



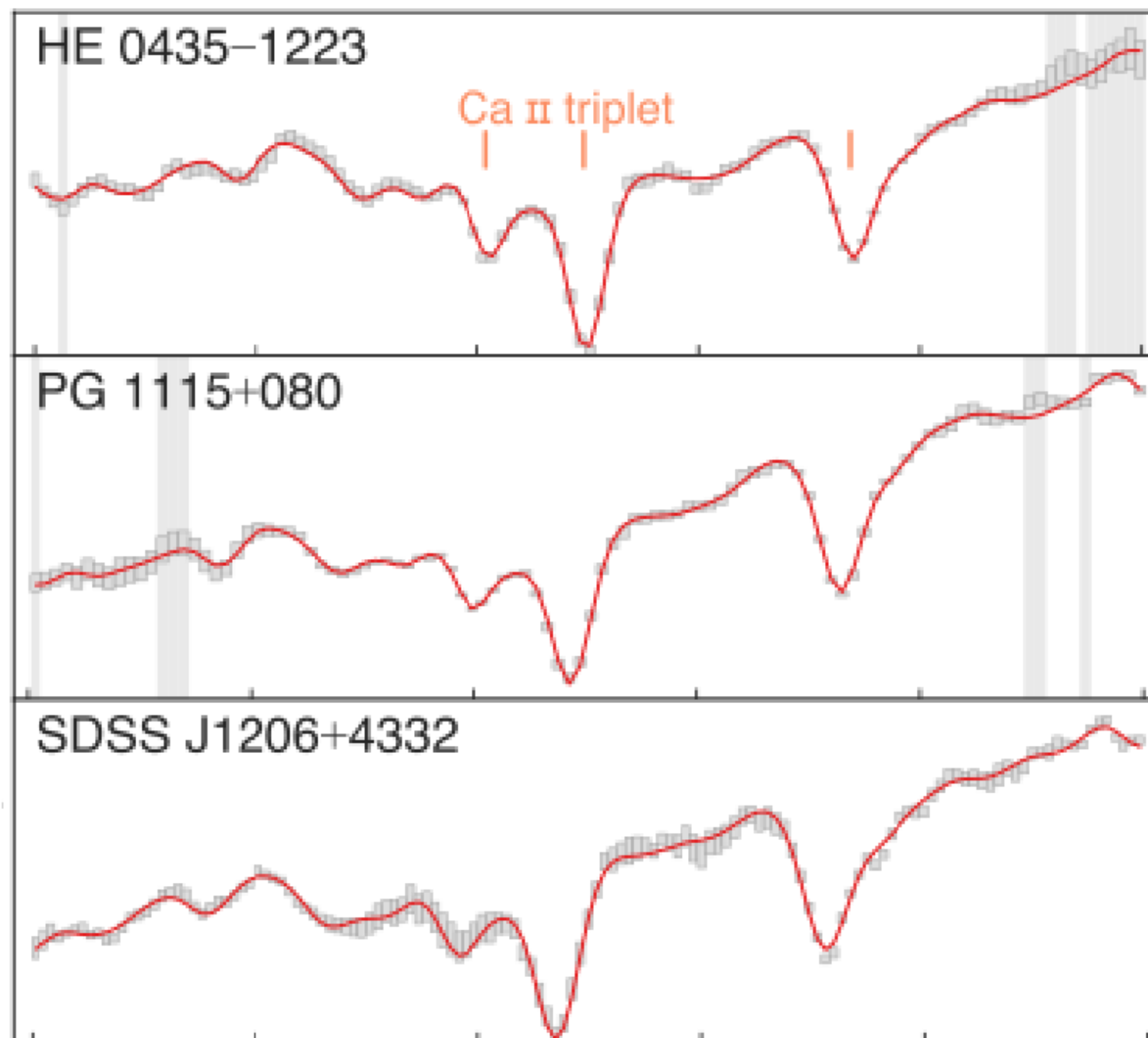
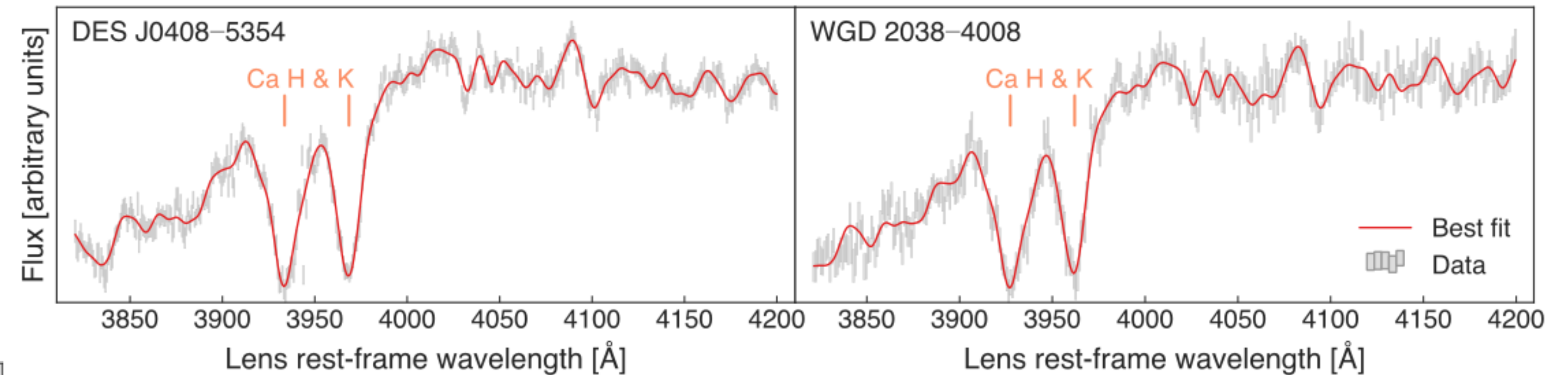
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TDCOSMO collaboration et al. 2025

VLT/MUSE *integrated* spectra →

JWST/NIRSpec *integrated* spectra



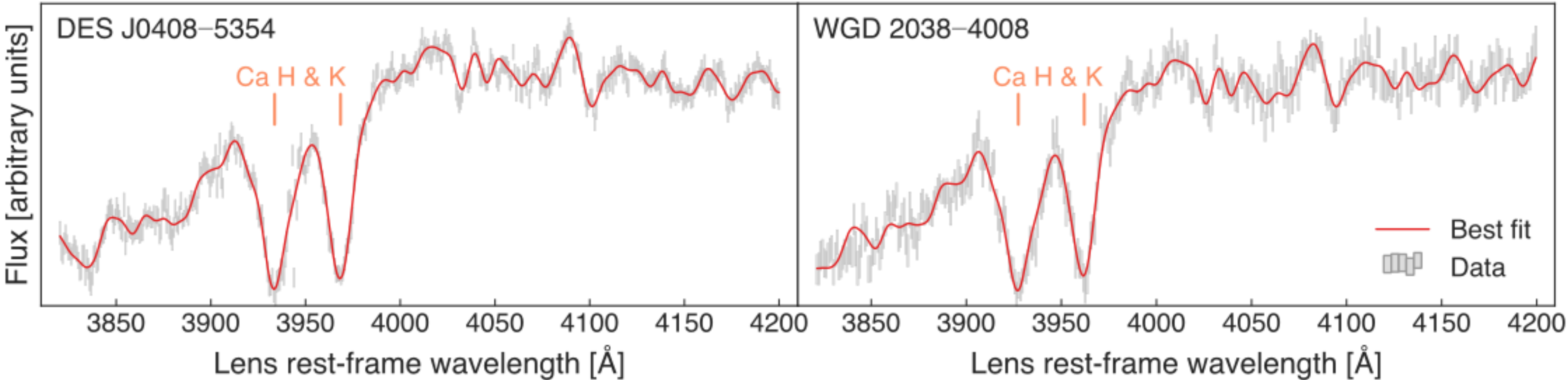
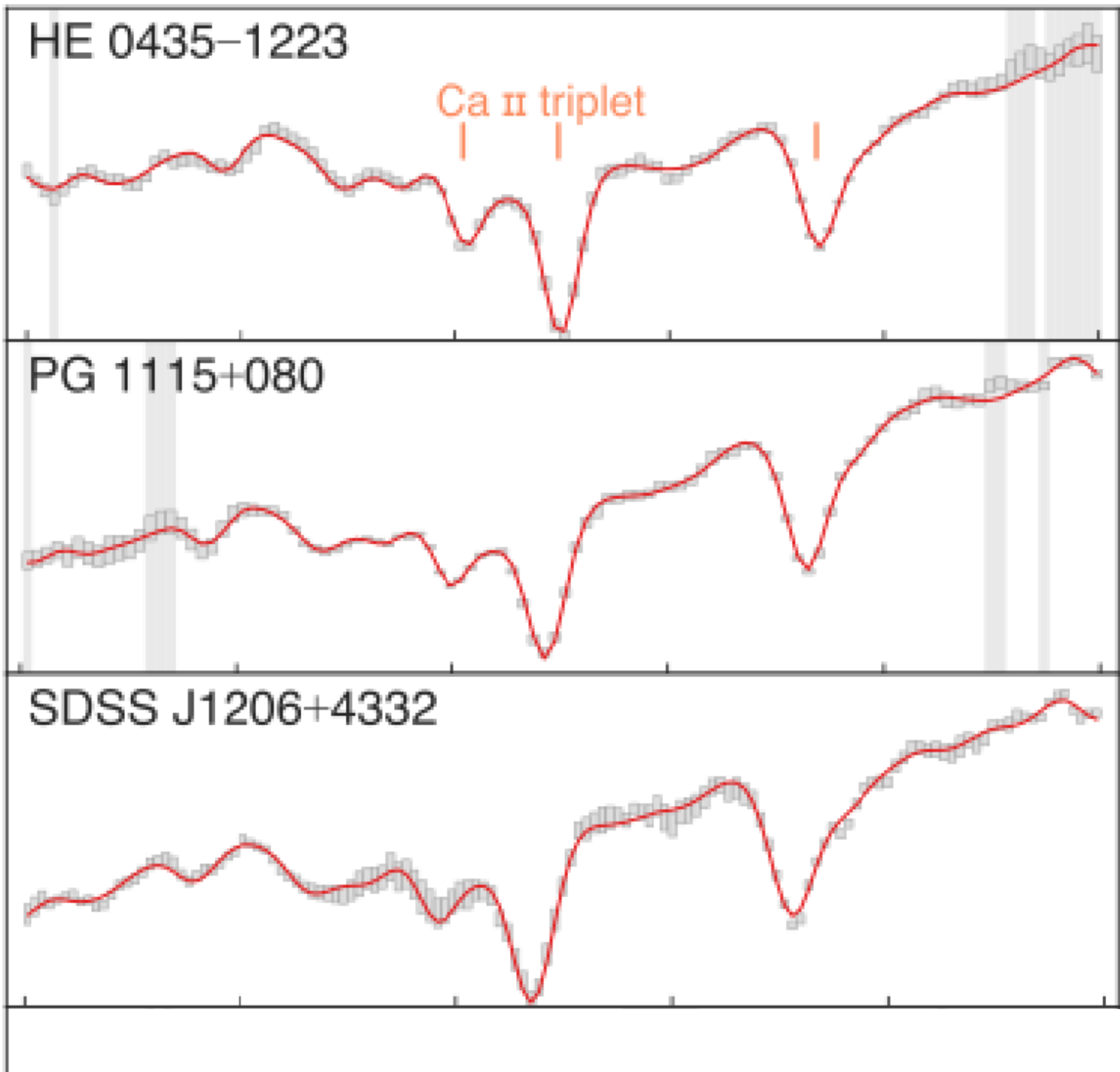
TDCOSMO-2025: What's new in the latest milestone

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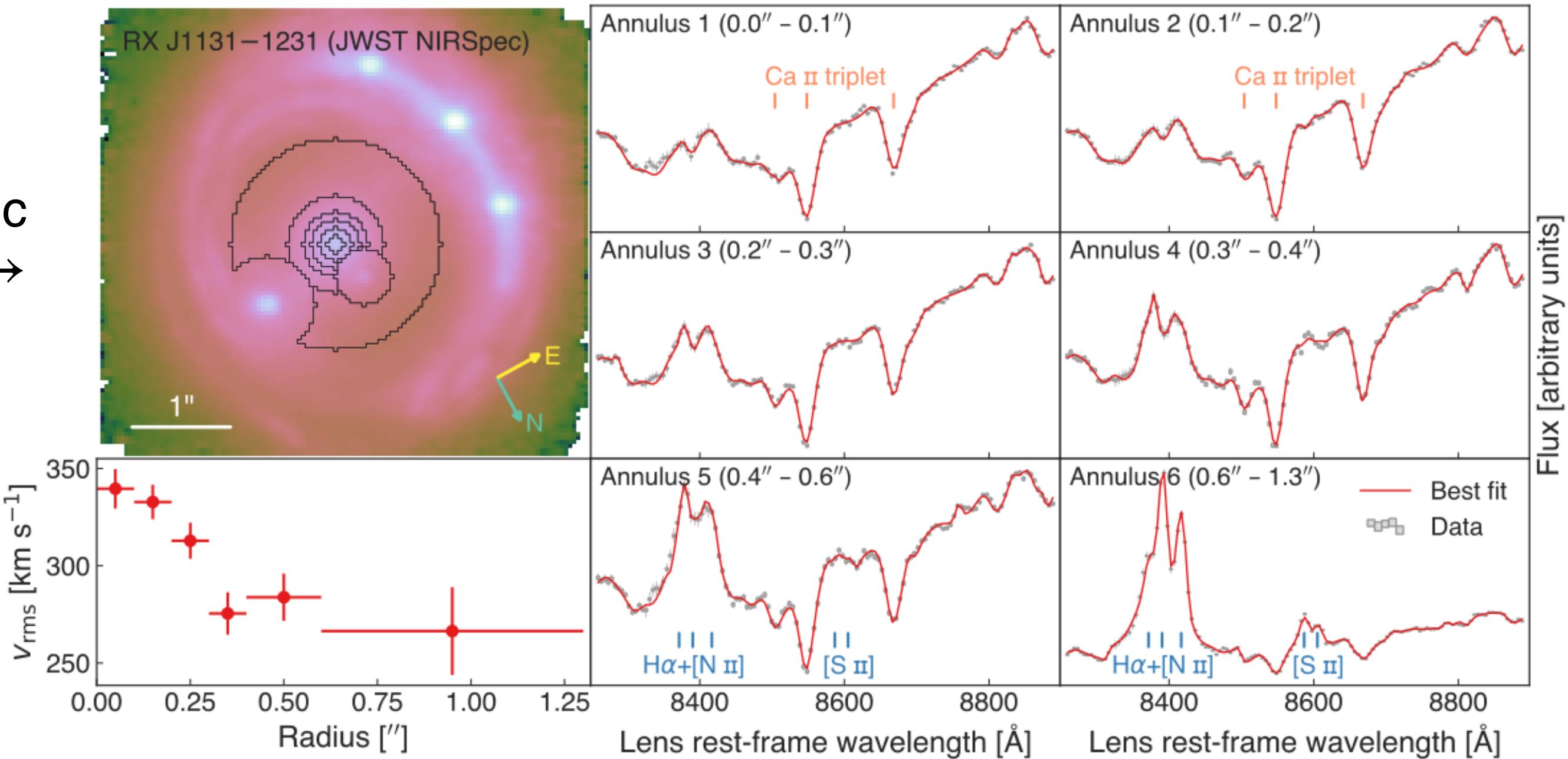
TDCOSMO collaboration et al. 2025

VLT/MUSE *integrated* spectra →

JWST/NIRSpec *integrated* spectra



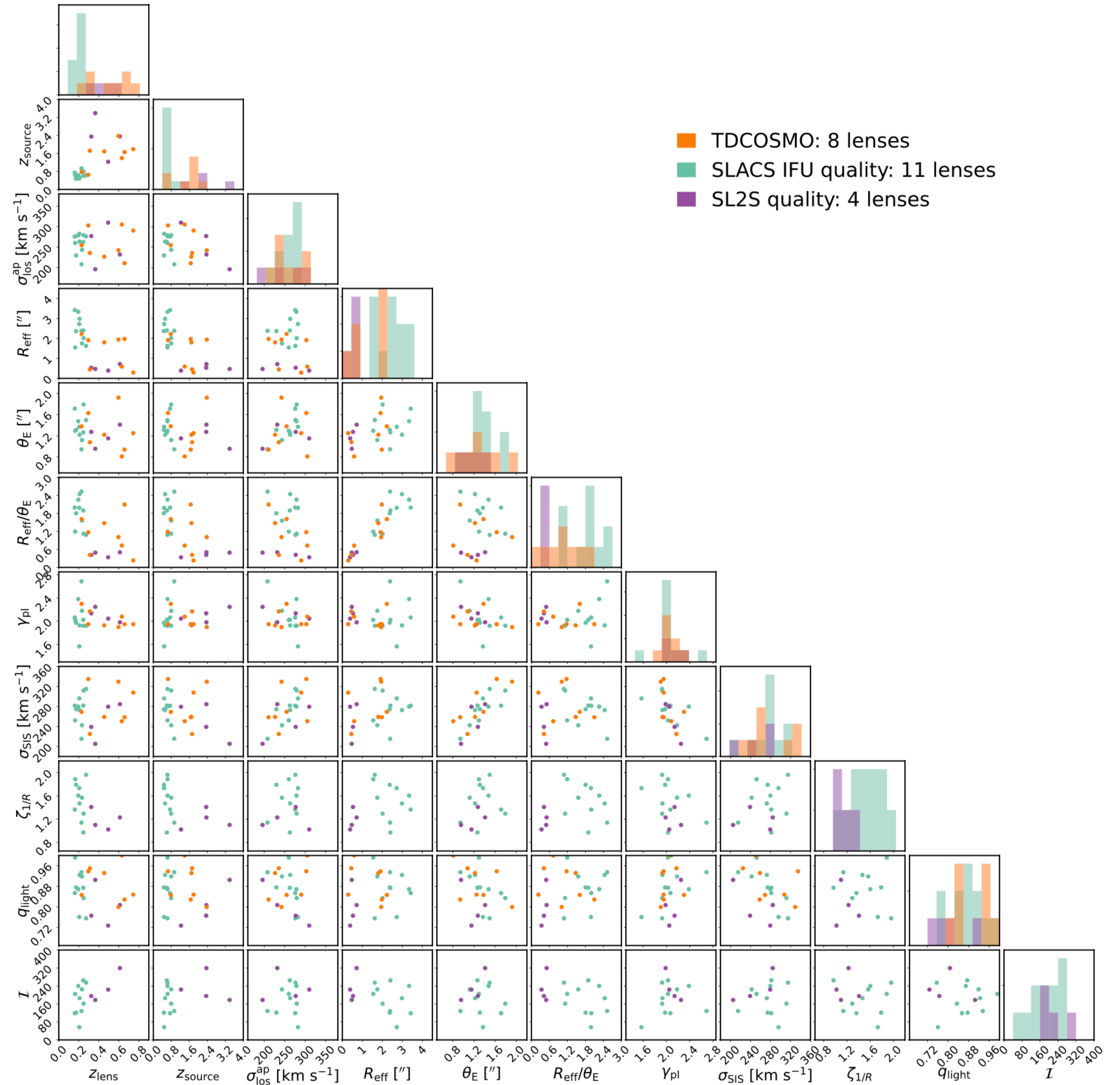
JWST/NIRSpec *resolved* spectra →



TDCOSMO-2025: What's new in the latest milestone

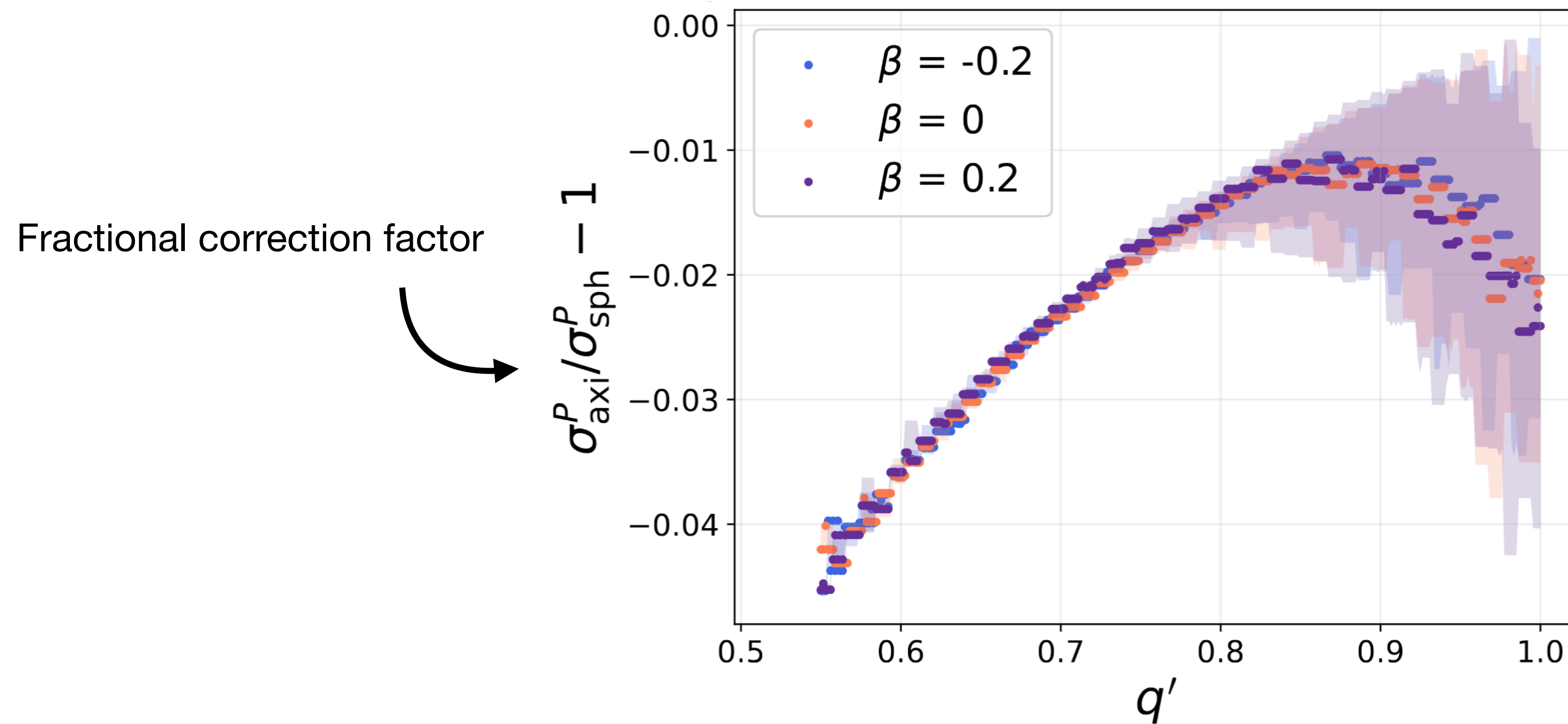
- Better selection and better data for non-time-delay lenses (SLACS, SL2S)

TDCOSMO collaboration et al. 2025



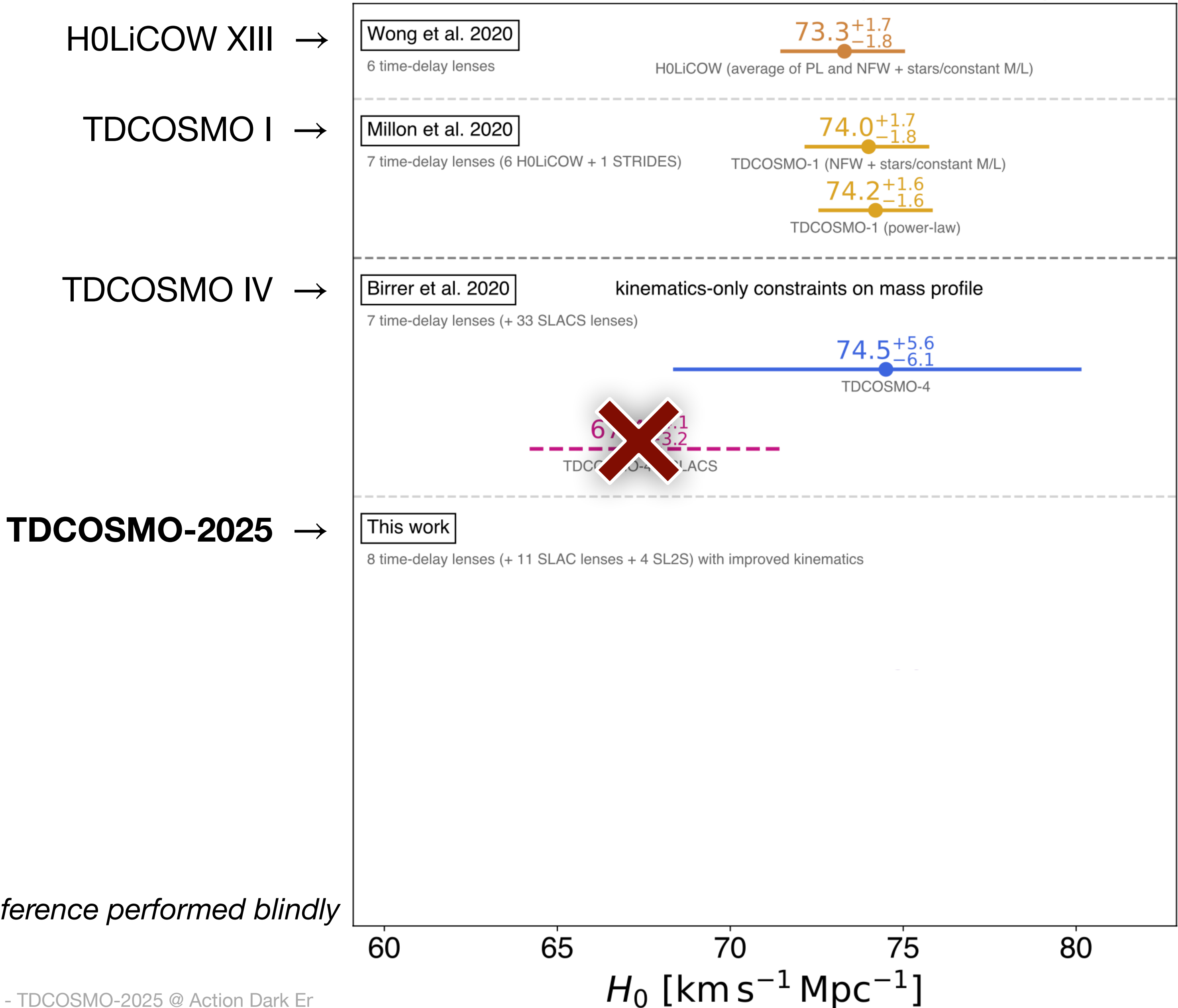
- Correction for **departure of sphericity** in stellar dynamics modeling

Huang et al. 2025



TDCOSMO-2025: Final constraints on H_0

H_0 measurements in flat Λ CDM - performed blindly

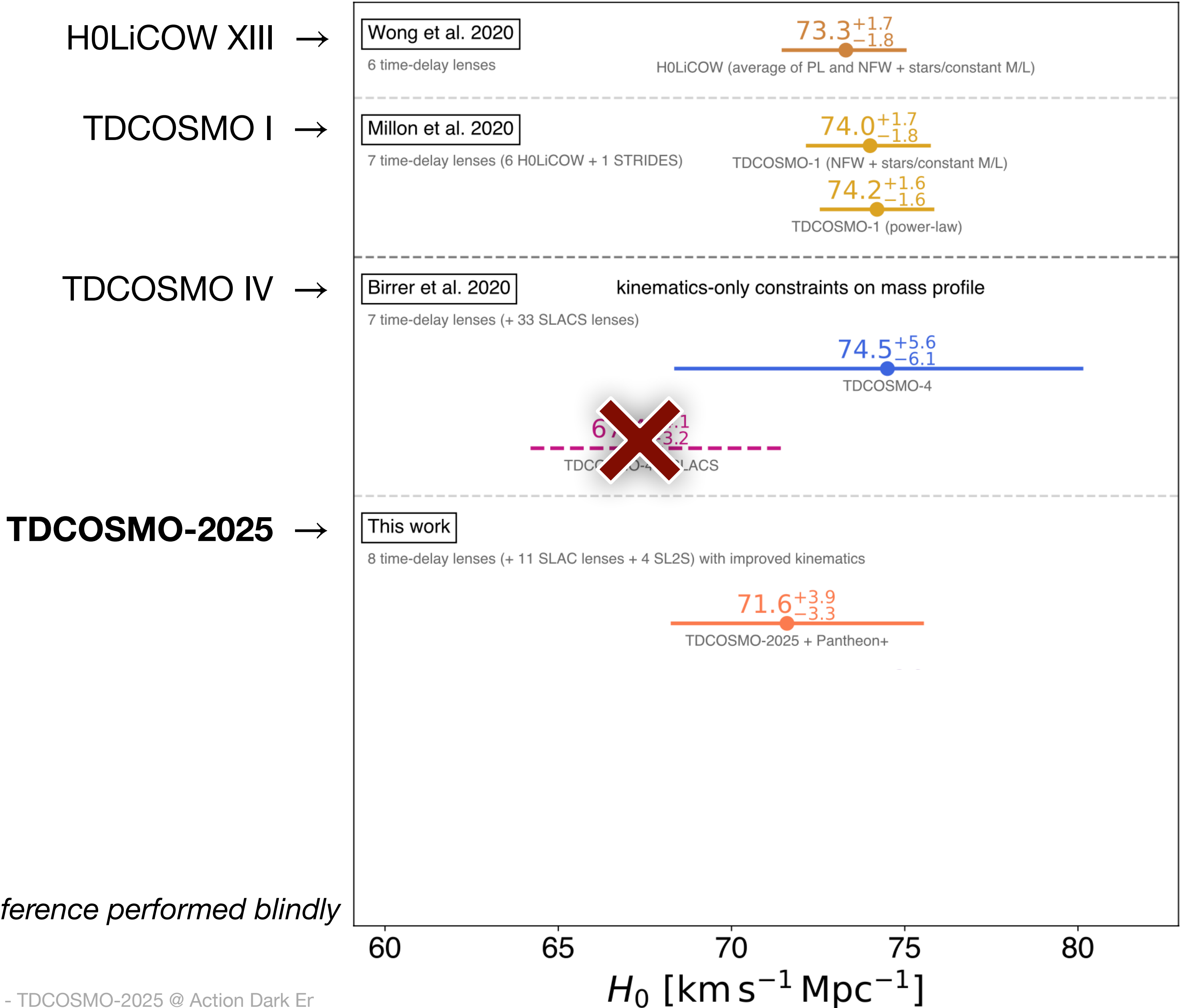


Assertive assumptions
on the structure of galaxies
(power-law or DM+stars profiles)

Conservative assumptions
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(mass-sheet transformed profile)

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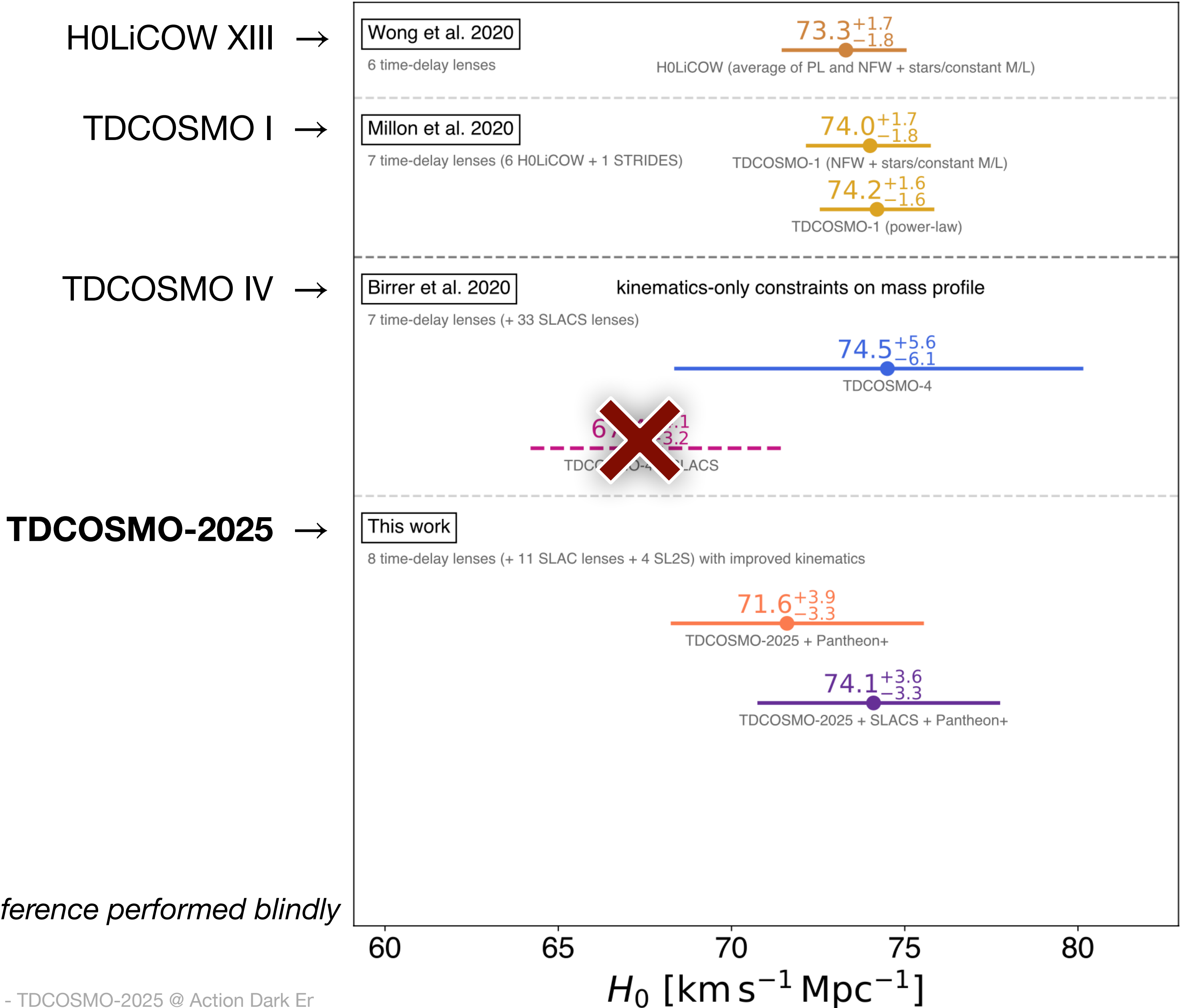


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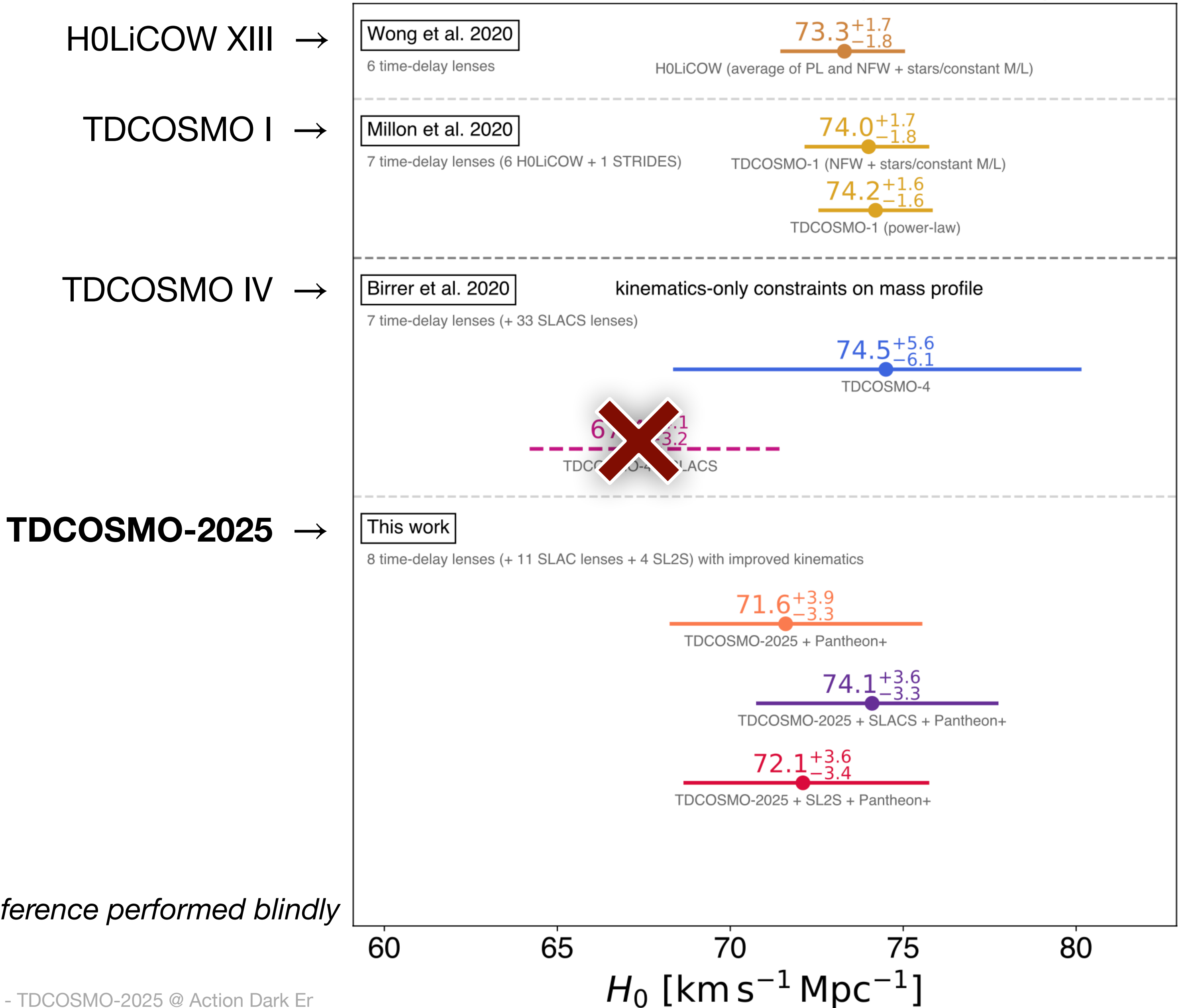


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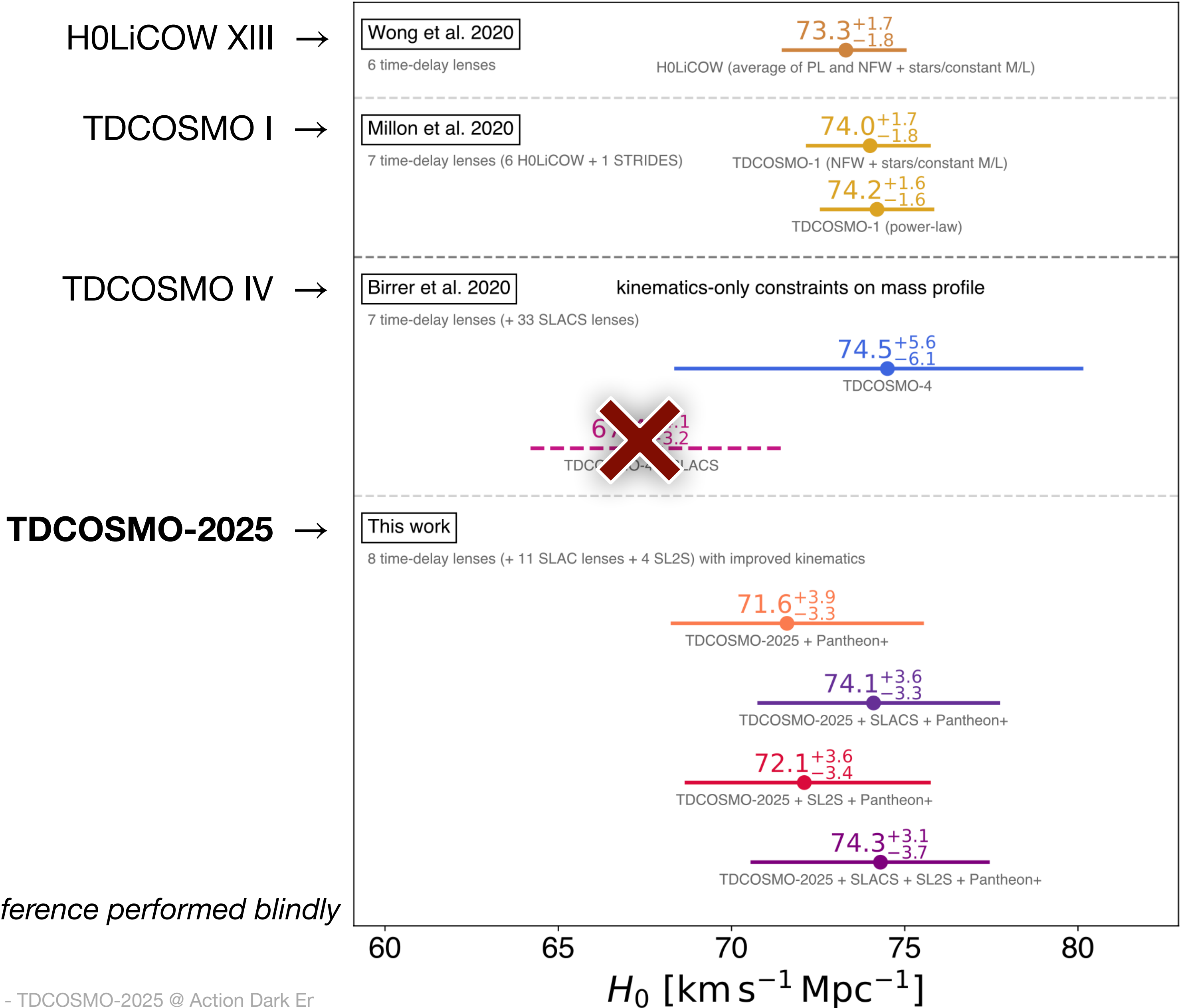


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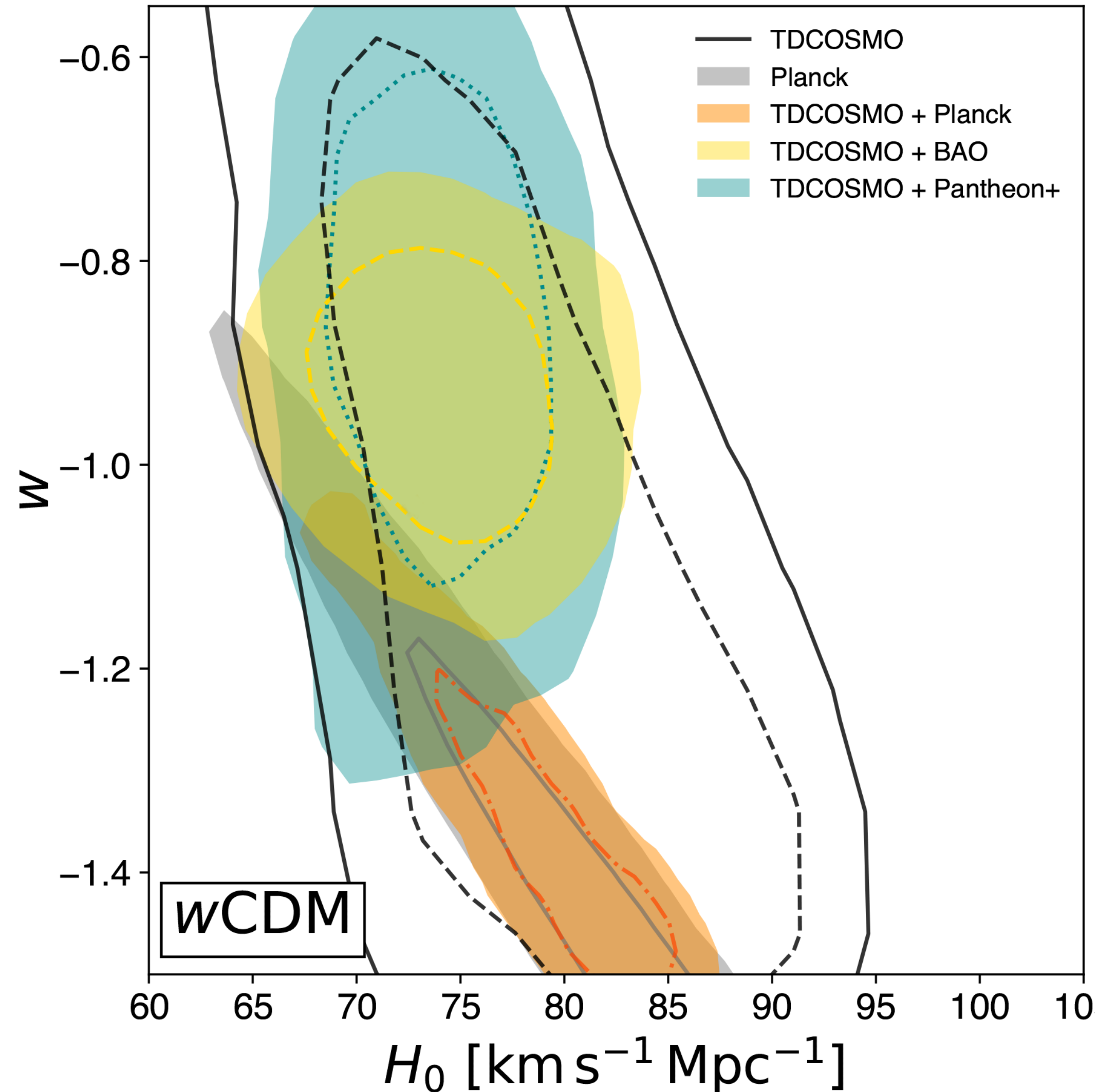
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TDCOSMO collaboration et al. 2025



TDCOSMO 2025 only:

$$H_0 = 78.0^{+6.6}_{-7.3} \text{ km.s}^{-1}.\text{Mpc}^{-1}$$

$$w = -1.12^{+0.44}_{-0.27}$$

TDCOSMO 2025 + Planck:

$$H_0 = 79.7^{+3.2}_{-4.3} \text{ km.s}^{-1}.\text{Mpc}^{-1}$$

$$w = -1.38^{+0.13}_{-0.08}$$

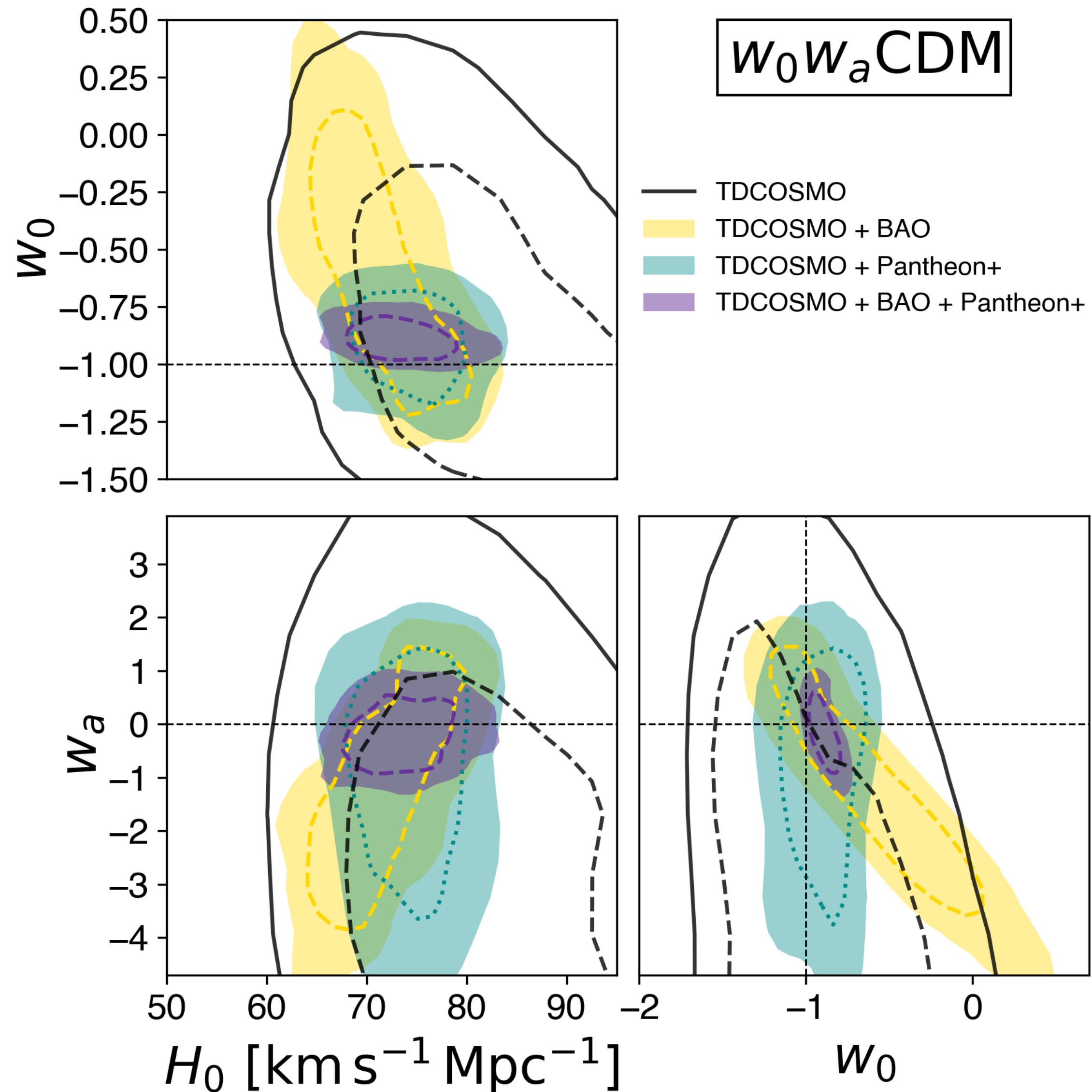
TDCOSMO 2025 +DESI-BAO:

$$H_0 = 74.0^{+3.4}_{-3.6} \text{ km.s}^{-1}.\text{Mpc}^{-1}$$

$$w = -0.93^{+0.08}_{-0.09}$$

TDCOSMO-2025: Constraints on other cosmological parameters

TDCOSMO collaboration et al. 2025



TDCOSMO 2025 + DESI-BAO + Pantheon+:

$$H_0 = 73.2^{+4.0}_{-3.0} \text{ km.s}^{-1}.\text{Mpc}^{-1}$$

$$w_0 = -0.89^{+0.06}_{-0.05}$$

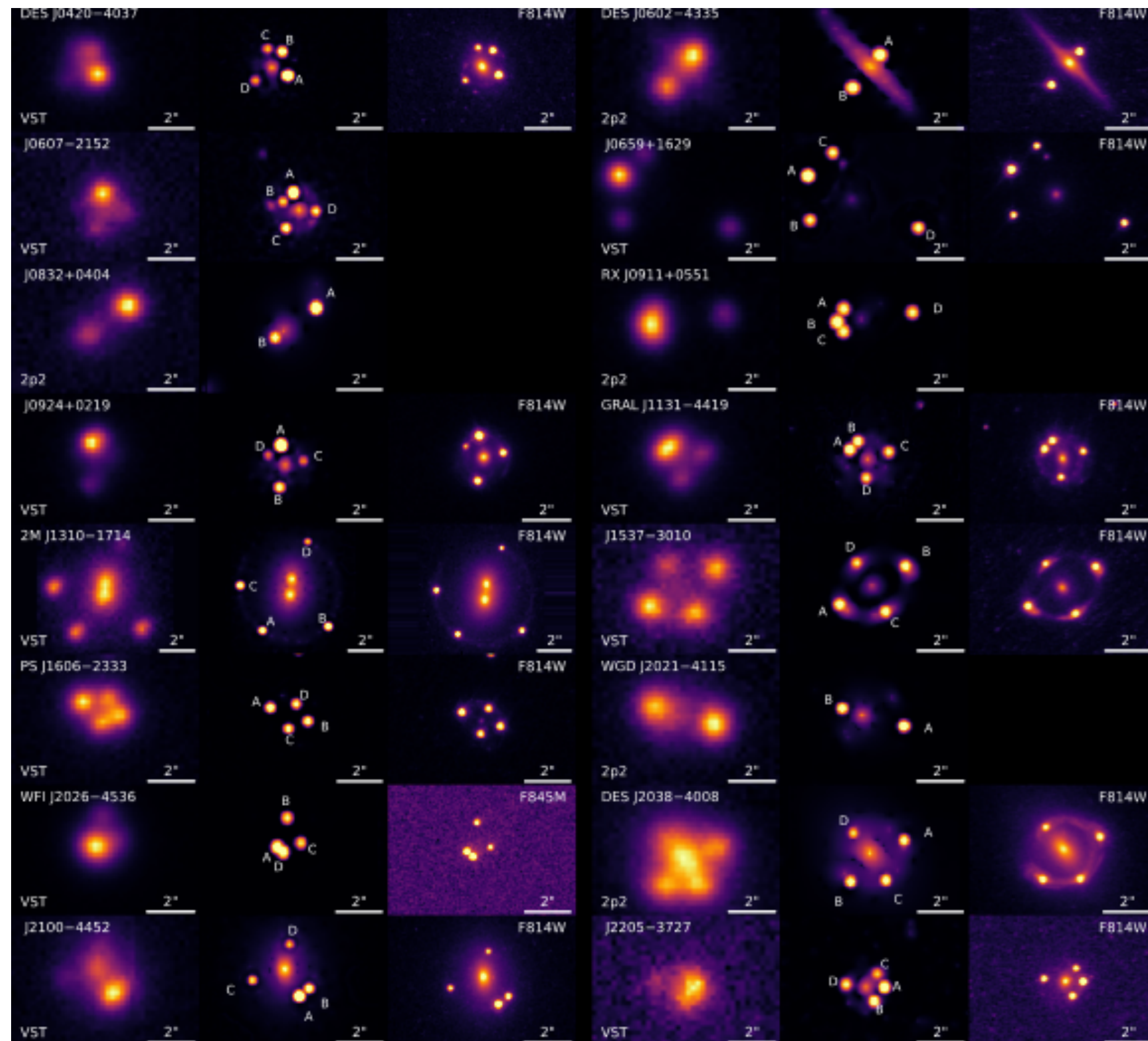
$$w_a = -0.20^{+0.49}_{-0.45}$$

Steps towards (even) better constraints

Some work in progress...

Some work in progress...

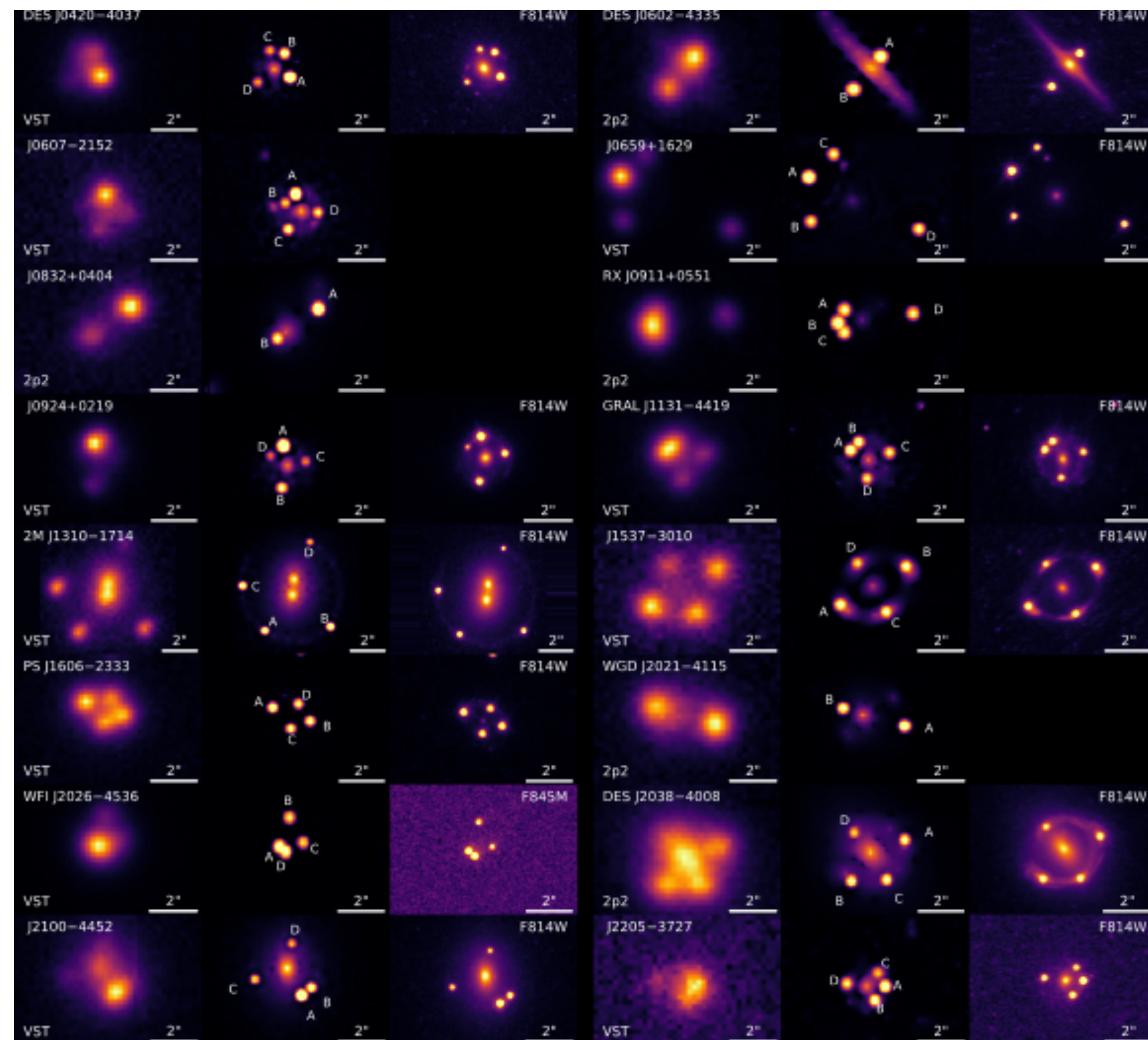
- New time delays for ~ 40 systems (up to 1%-level precision!)



Dux et al. 2025

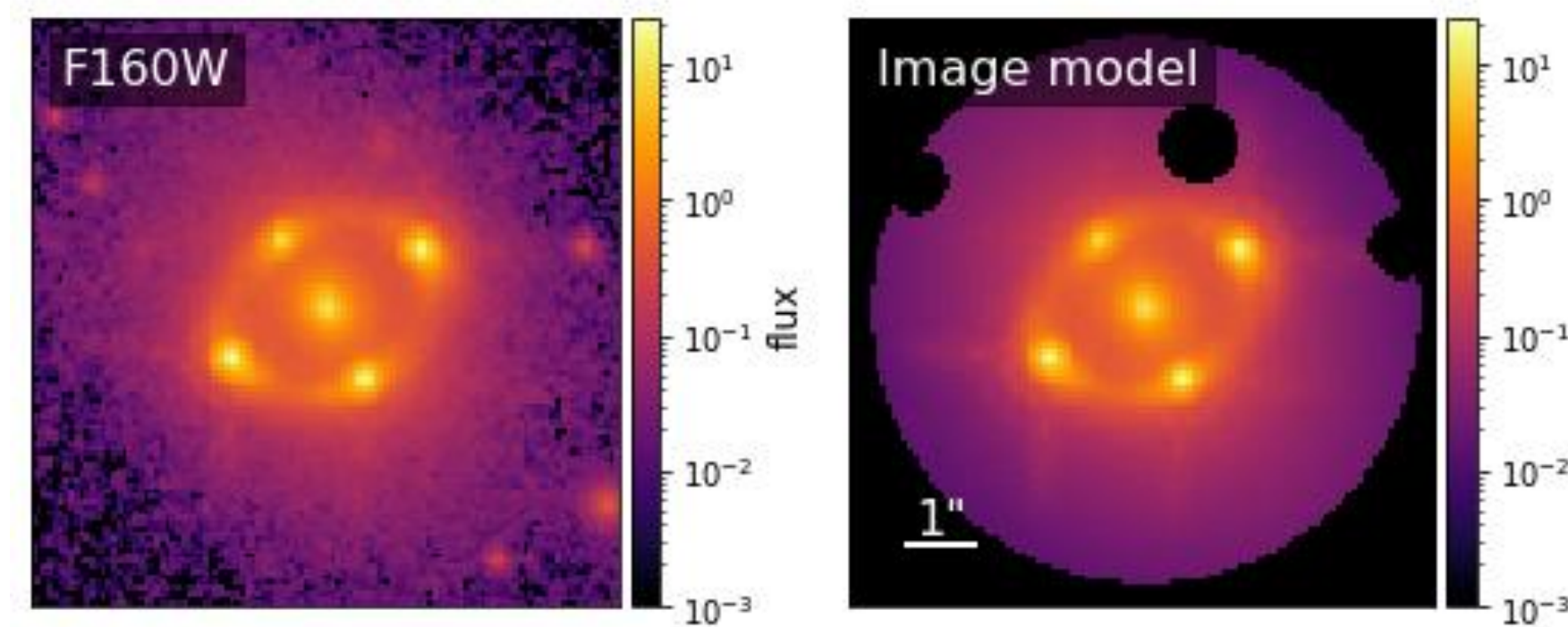
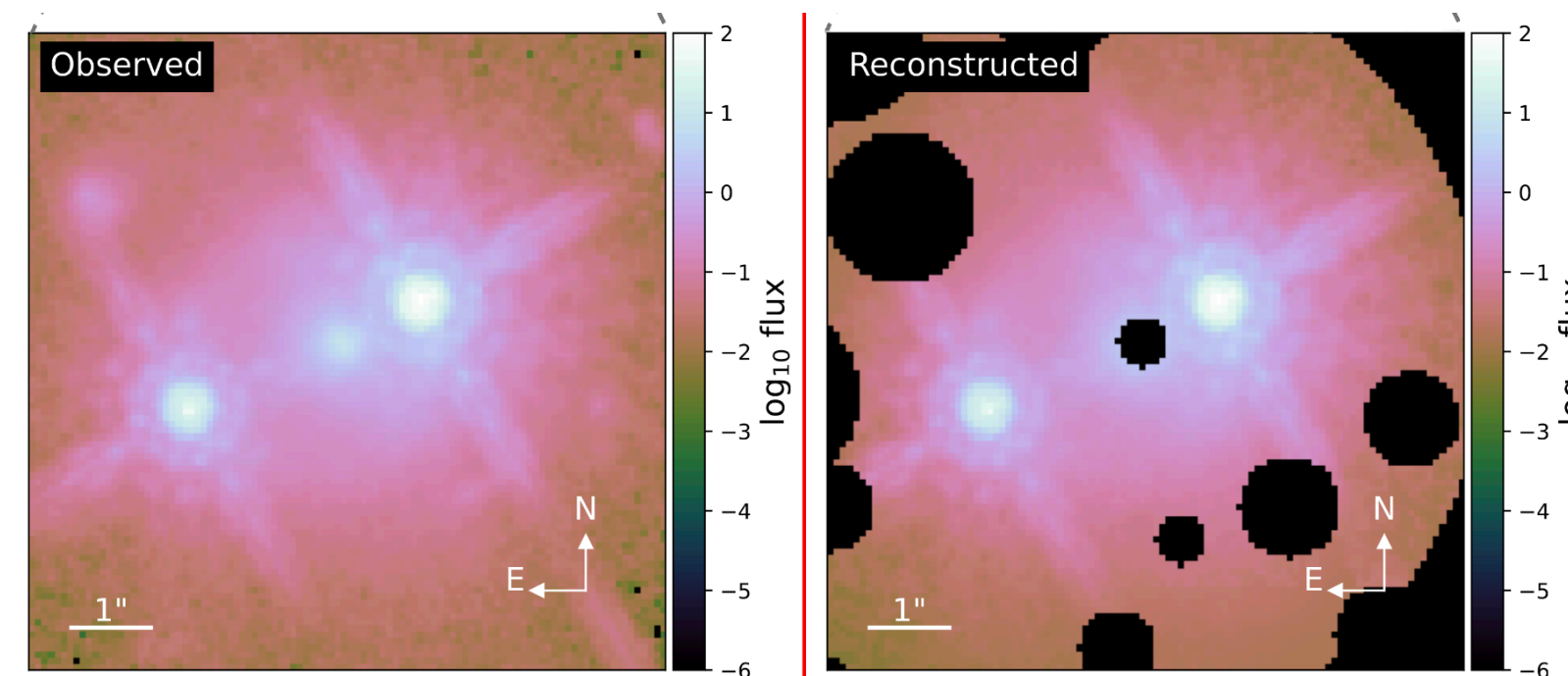
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- New strongly lensed quasars, including doubly lensed quasars



Dux et al. 2025

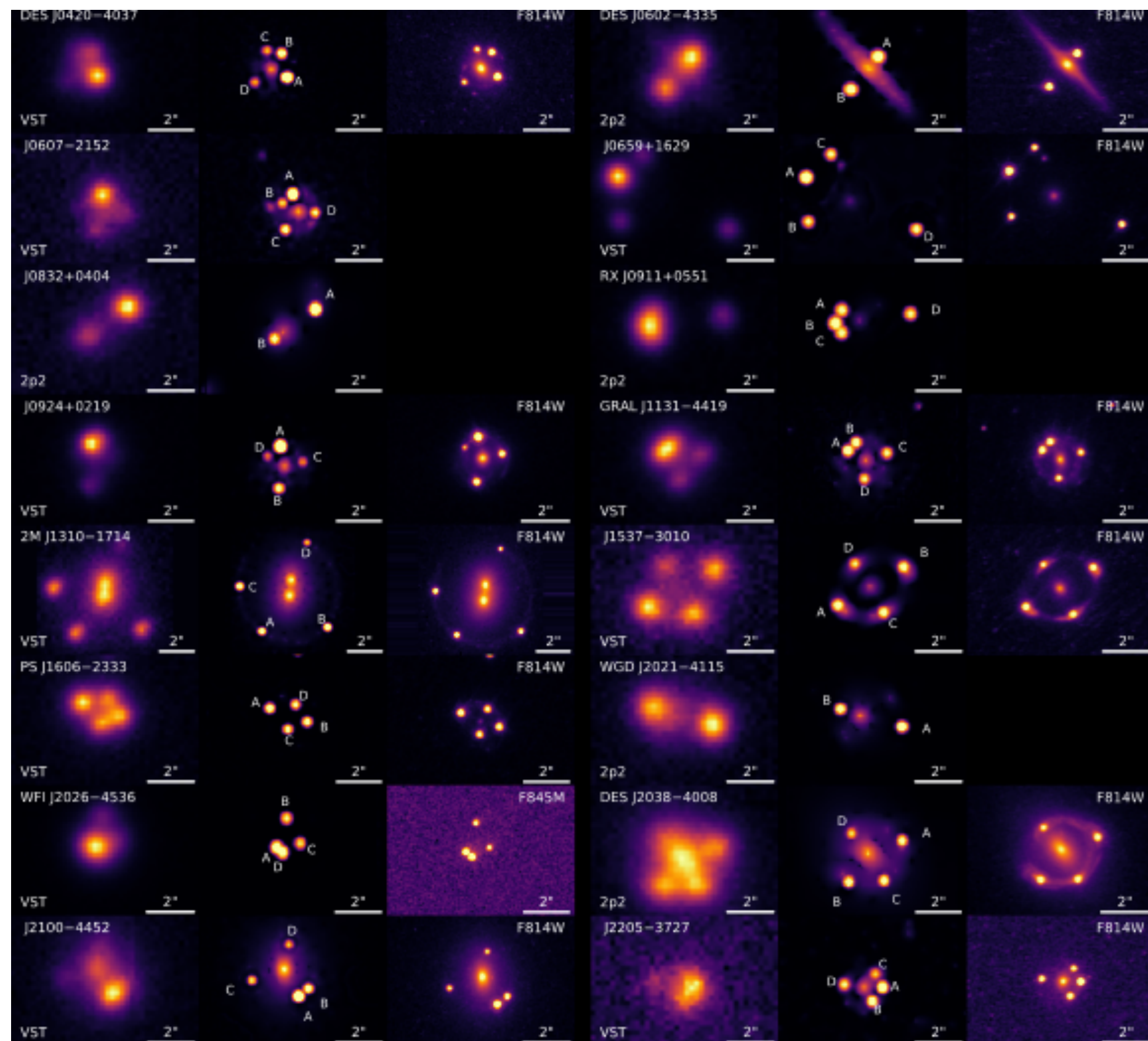
Paic et al. 2025



Galan et al. (in prep.)

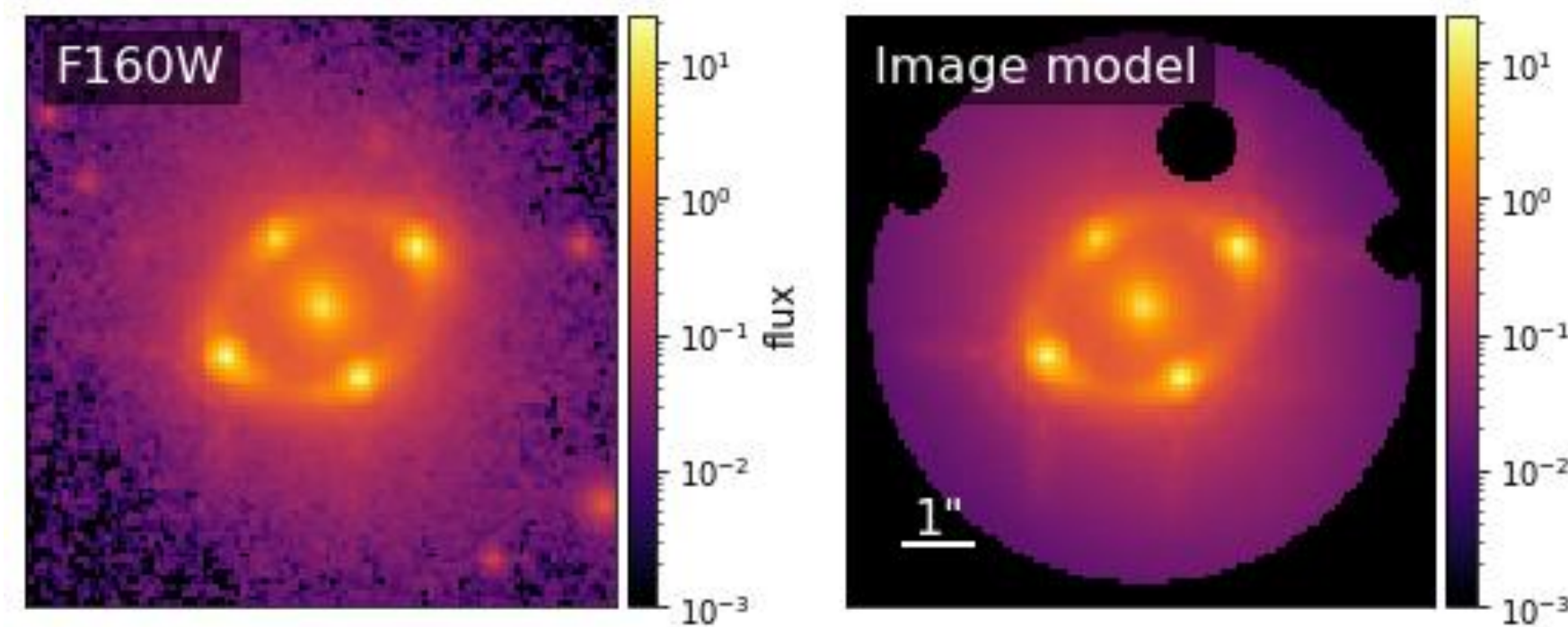
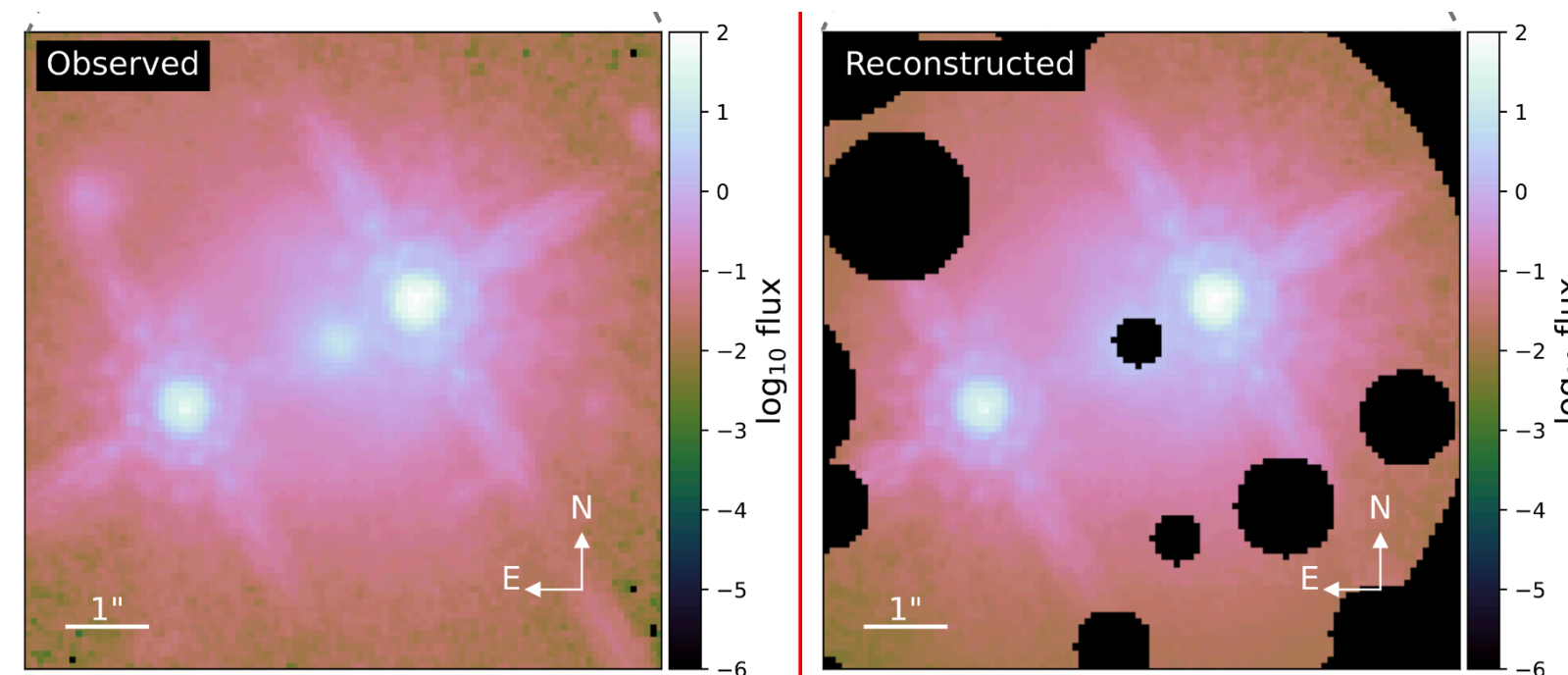
Some work in progress...

- New time delays for ~ 40 systems (up to 1%-level precision!)
- New strongly lensed quasars, including doubly lensed quasars
- Re-analysis of lensed quasars using new JWST/NIRCam data



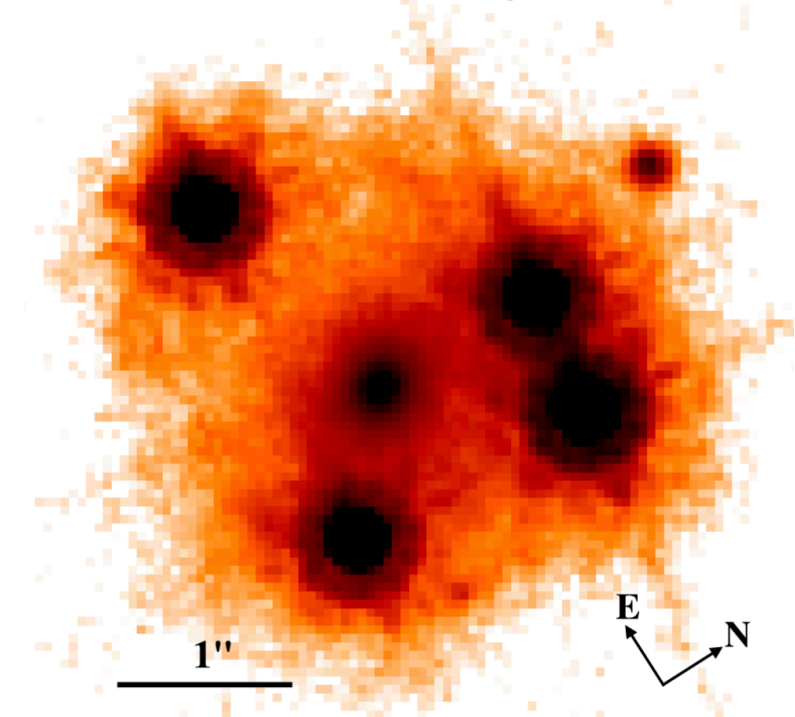
Dux et al. 2025

Paic et al. 2025

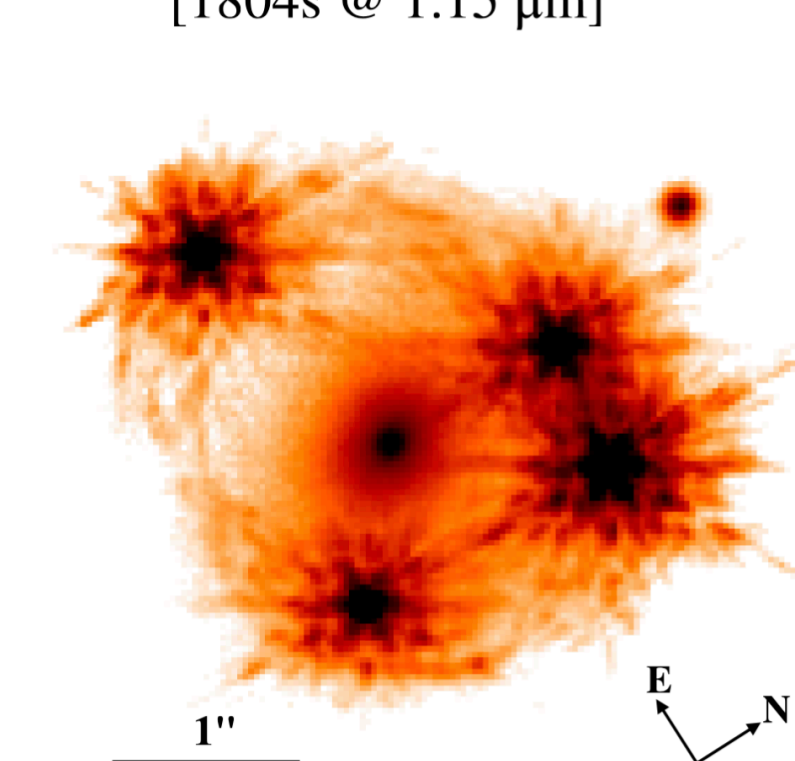


Galan et al. (in prep.)

HST ACS/F814W
[2085s @ 0.814 μm]



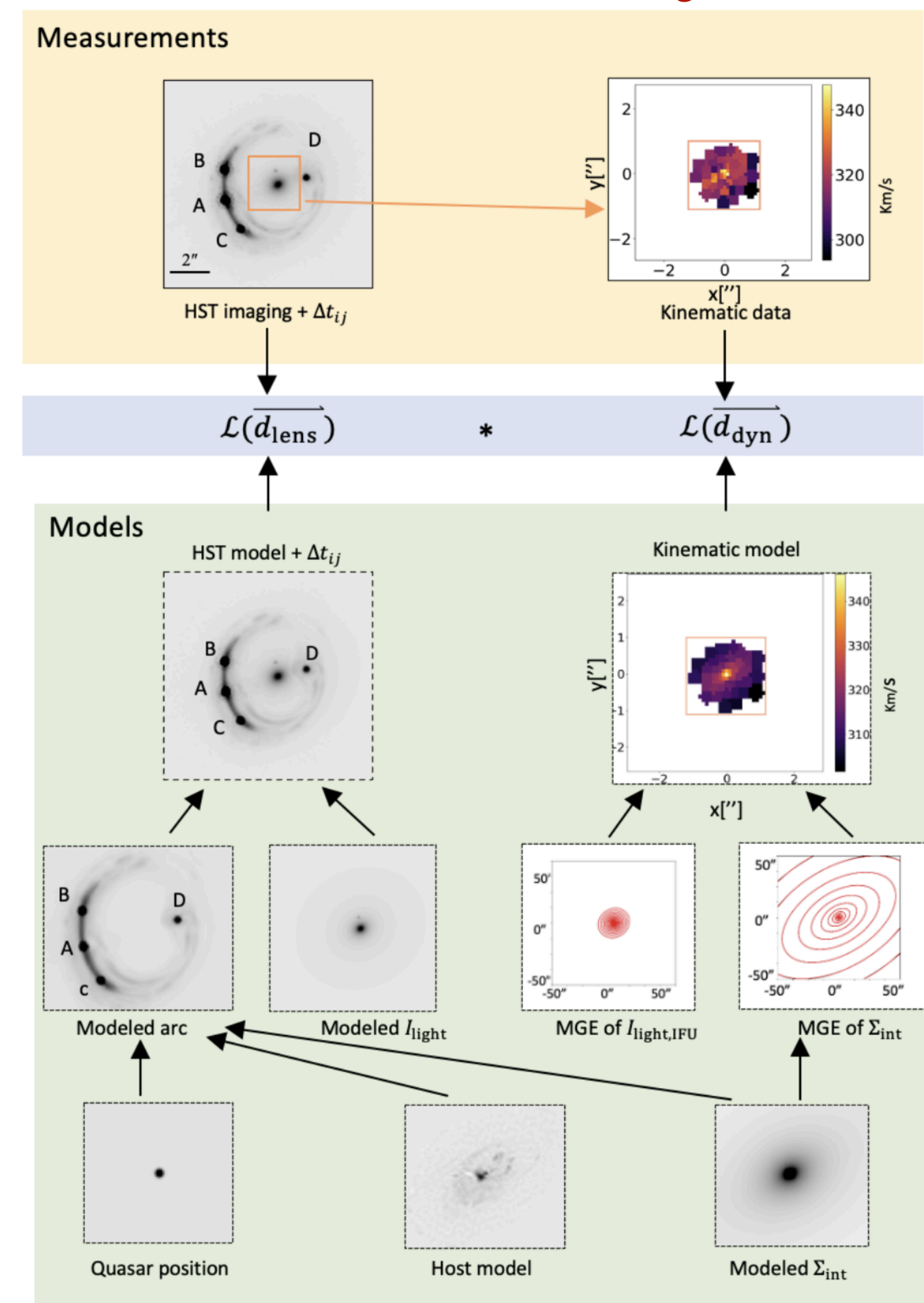
JWST NIRCam/F115W
[1804s @ 1.15 μm]



Williams et al. 2025

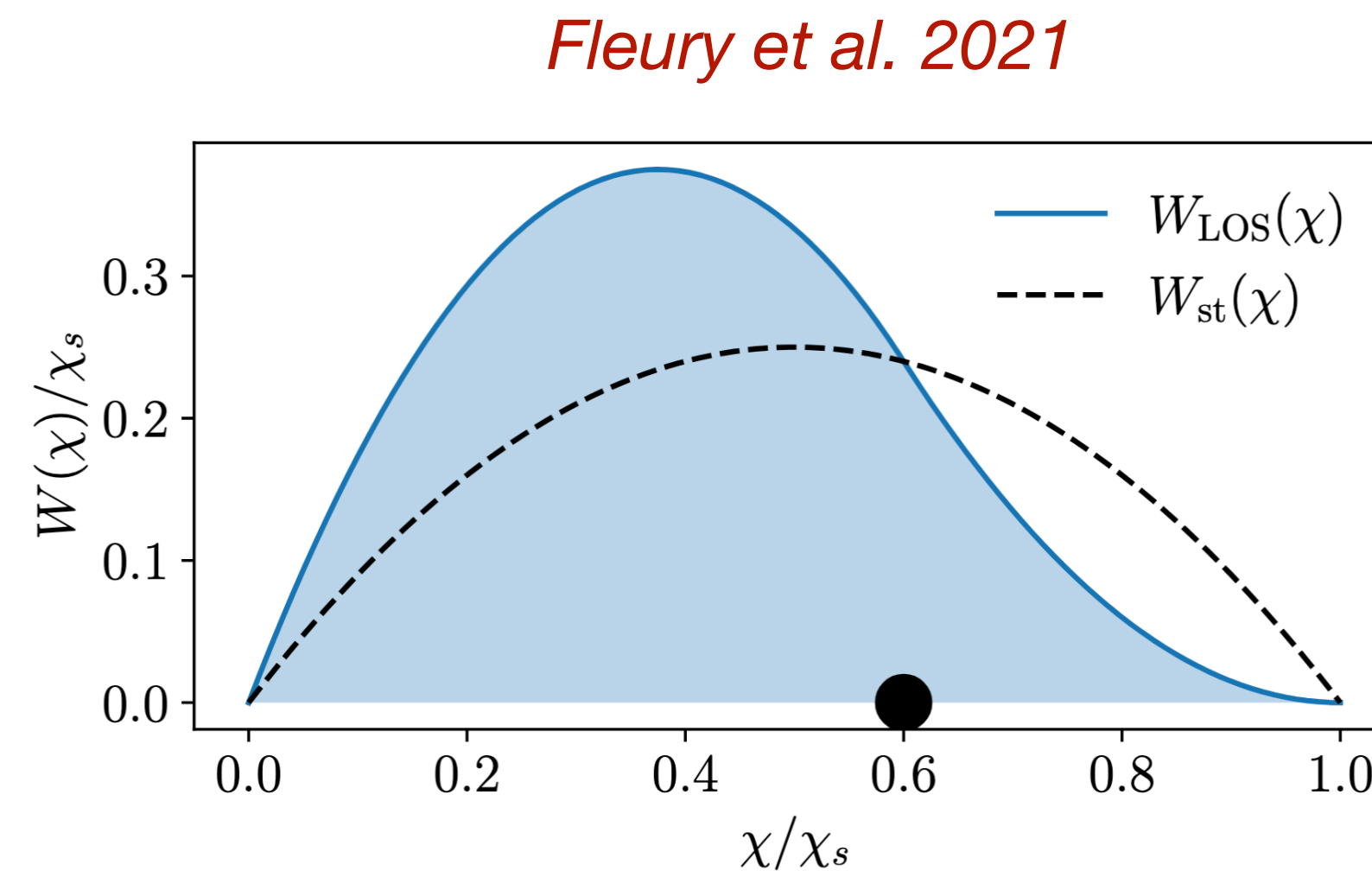
- **Joint modeling of lensing + resolved axisymmetric stellar kinematics**

Wang et al. 2025

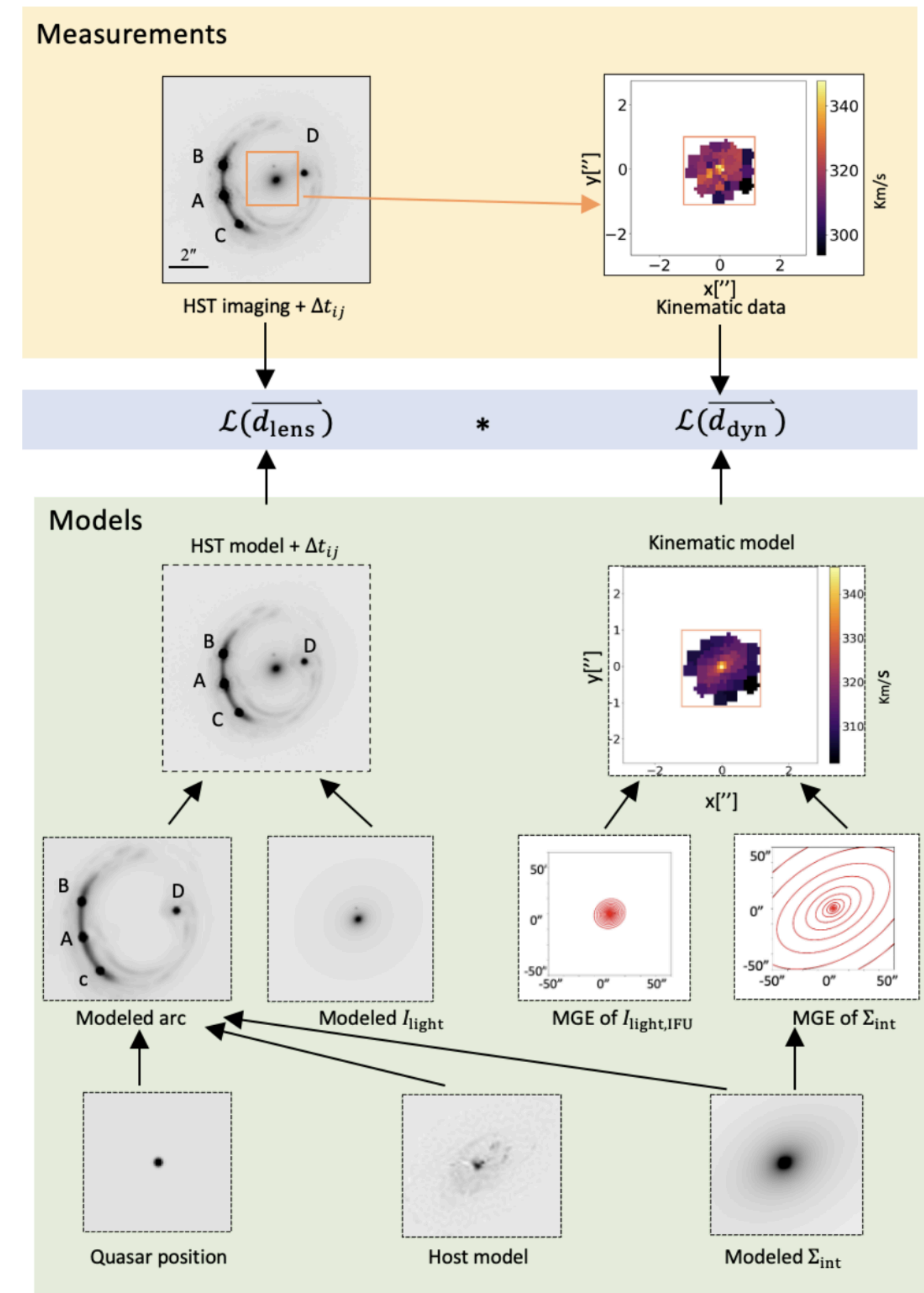


Some work in progress...

- Joint modeling of lensing + resolved axisymmetric stellar kinematics
- Better treatment of line-of-sight effects



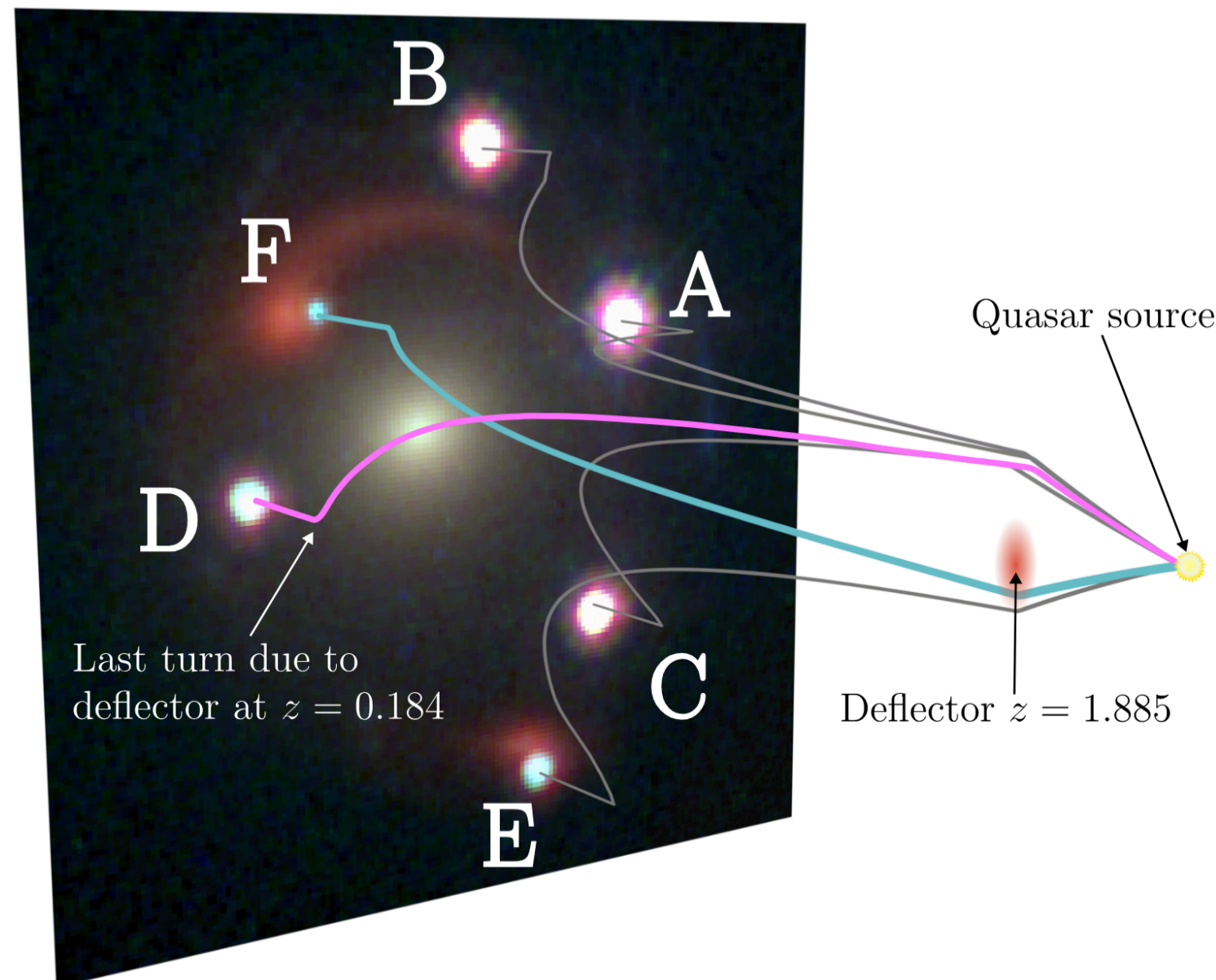
Wang et al. 2025



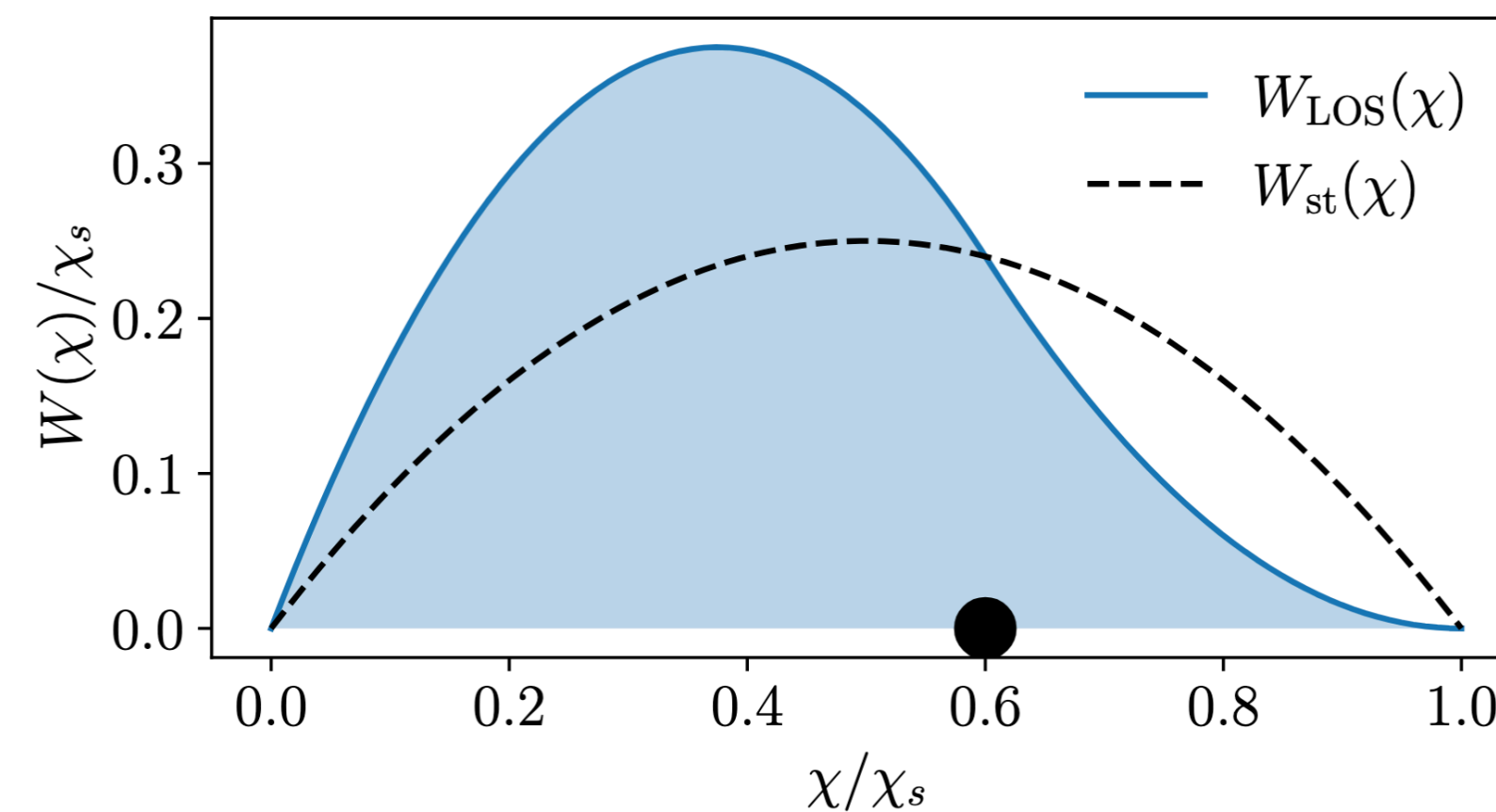
Some work in progress...

- **Joint modeling of lensing + resolved axisymmetric stellar kinematics**
- **Better treatment of line-of-sight effects**
- **Exotic systems: multi-source planes, zig-zag lenses**
(extra constraints on e.g. the DE equation of state)

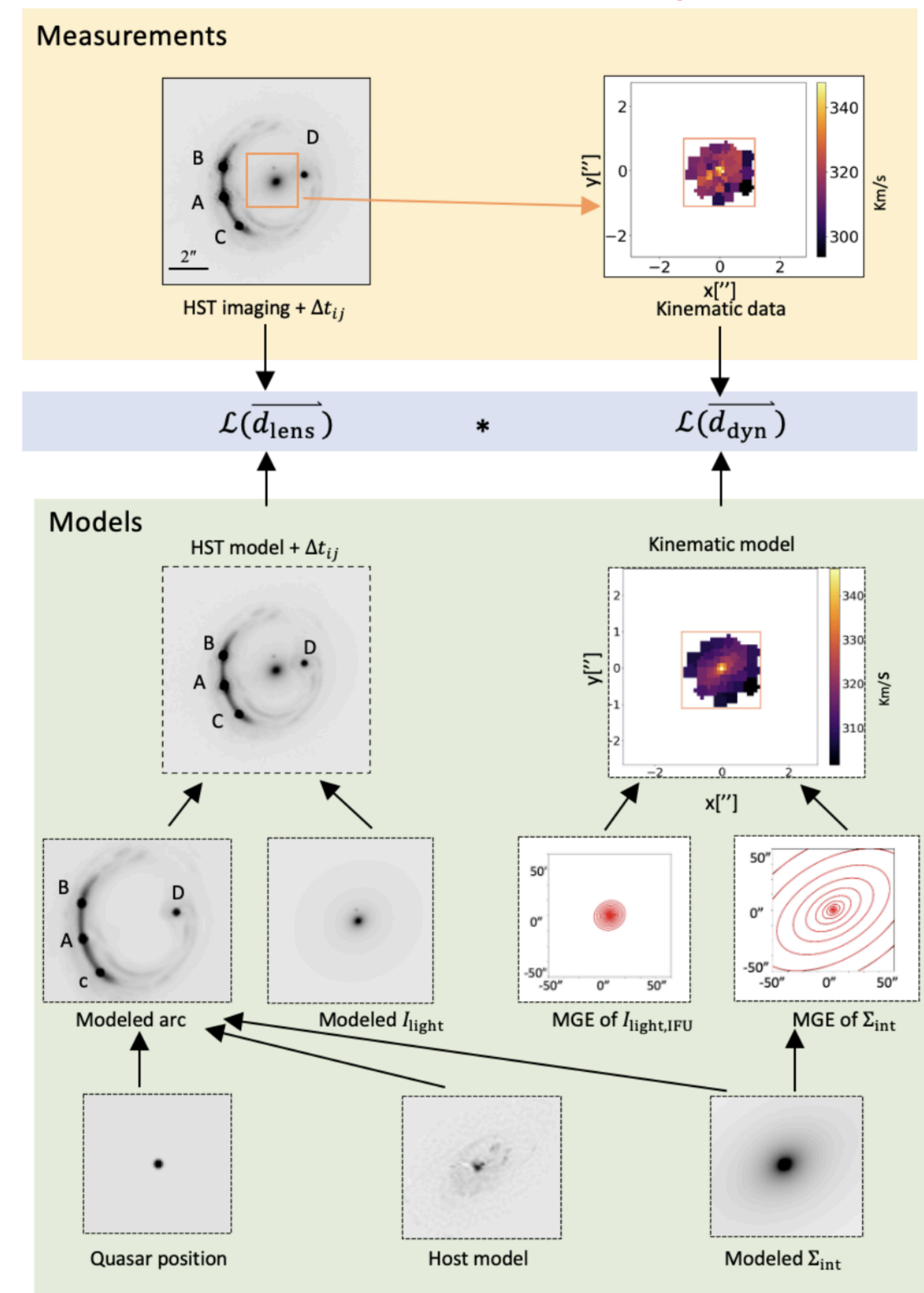
Dux et al. 2024



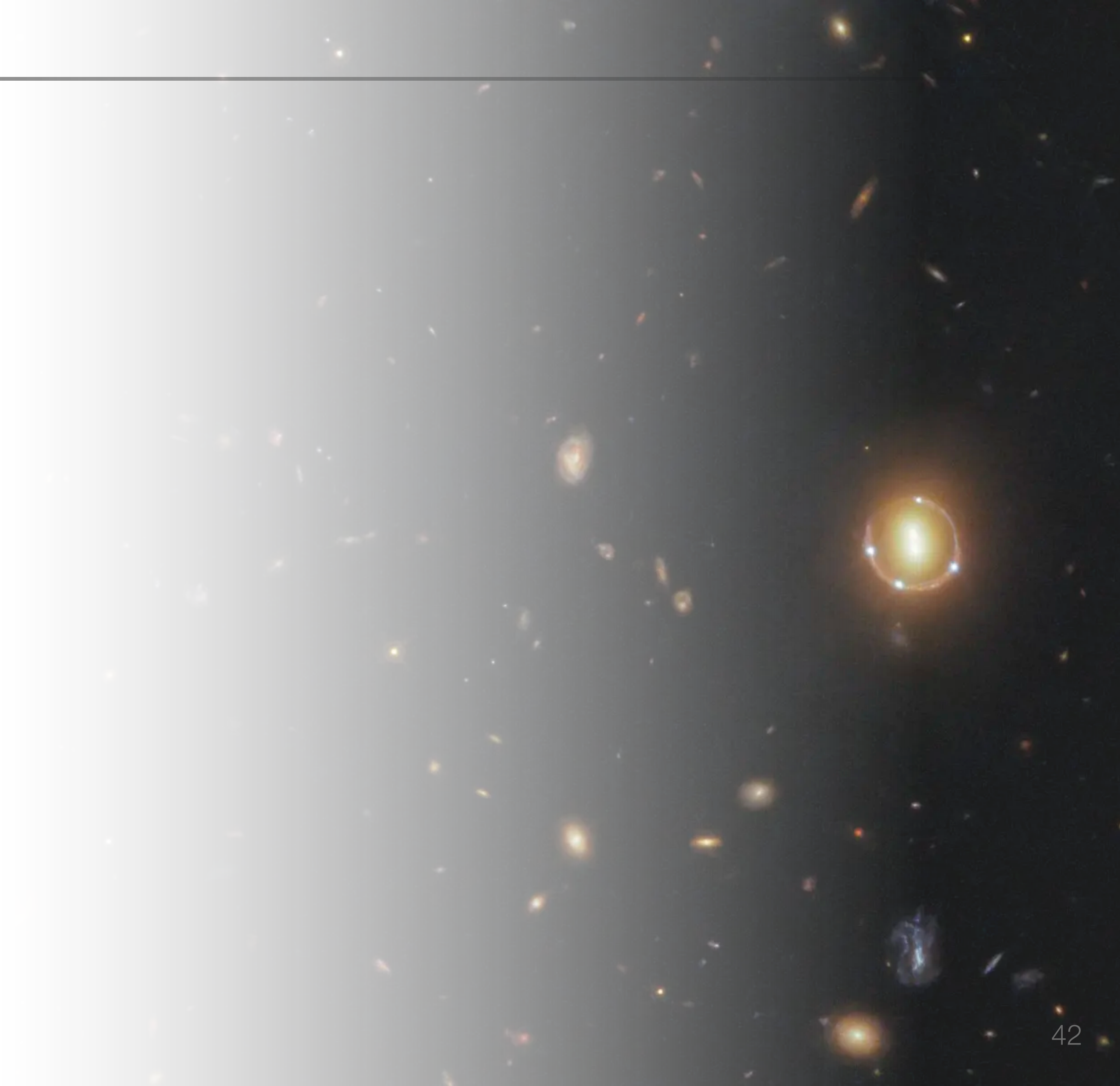
Fleury et al. 2021



Wang et al. 2025



Conclusions



- ▶ We use spatially resolved stellar kinematics to **relax assumptions on galaxies' mass profiles**, and explicitly address the MSD.

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- ▶ We developed a new methodology to guarantee **sub-percent systematic uncertainties** on kinematics measurements.
- ▶ We measure the Hubble constant **at $\sim 4\%$ precision**, in excellent agreement with e.g. SH0ES.
- ▶ Future TDCOSMO milestones will include **several new lenses**, JWST/NIRCam+NIRSpec analyses, full modelling of resolved stellar kinematics, and more.