7th Galileo Xu-Guangqui meeting
Pescara — July 11, 2025

Exploiting galaxy clusters as powerful cosmological probes through strong gravitational lensing

Giorgia Di Rosa
PhD student @ University of Ferrara

M. Lombardi, P. Bergamini, C. Grillo, P. Rosati, L. Bazzanini, A. Acebron, M. Meneghetti, D. Abriola, S. Schuldt, M. Fogliardi, G. Angora, A. Mercurio, E. Venzella et al.

GRAVITATIONAL LENSING

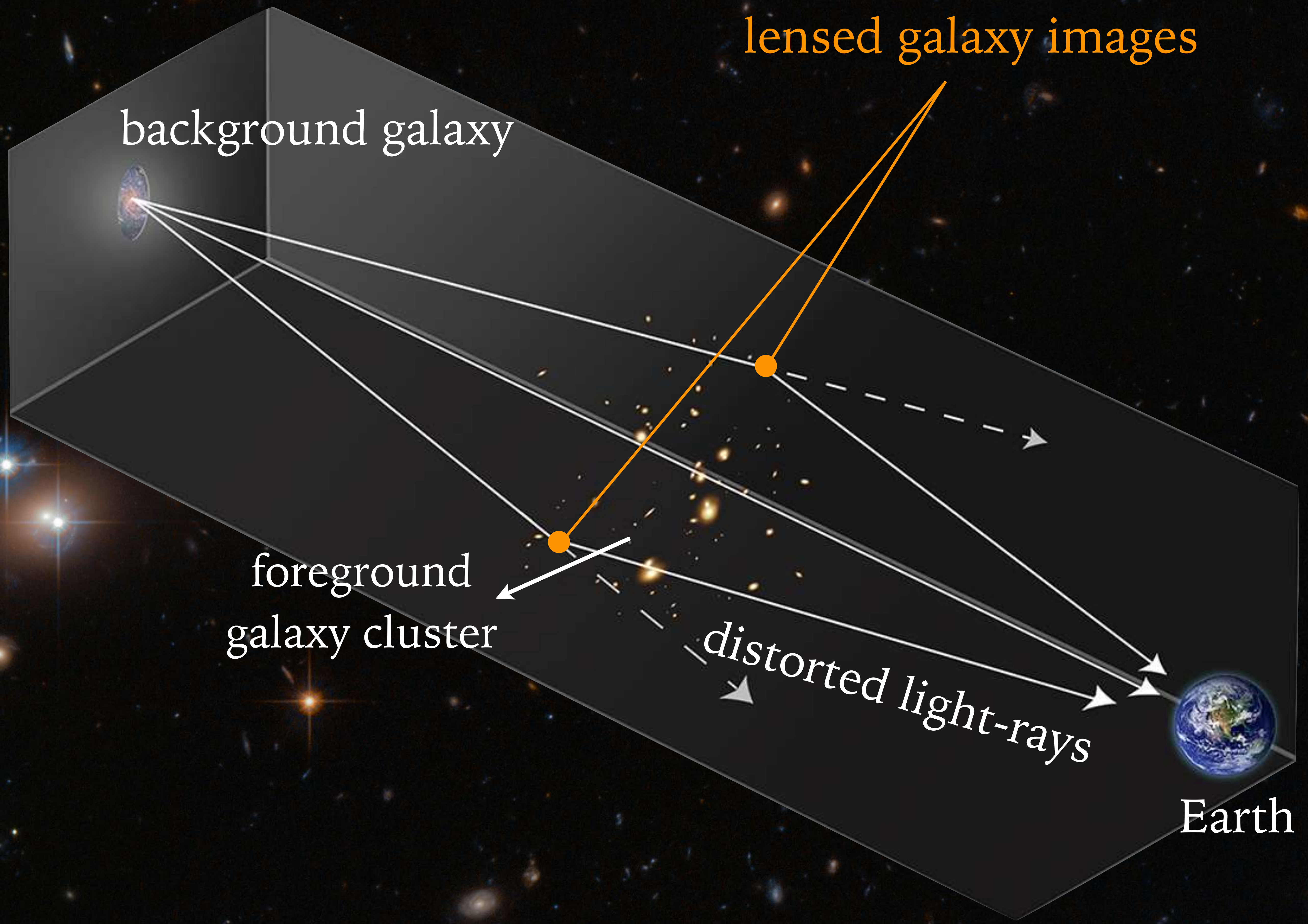
One of the most powerful means to investigate how matter is distributed within different scales of the Universe

Strong Lensing (SL) occurs if:

- source, lens and observer are closely aligned
- the lens is sufficiently dense (supercritical) → galaxies and central region of galaxy clusters

Effects:

- production of distinct and resolvable multiple images of the same background source
- amplification, magnification and distortion of the multiple images
- time delays between multiple images



GRAVITATIONAL LENSING

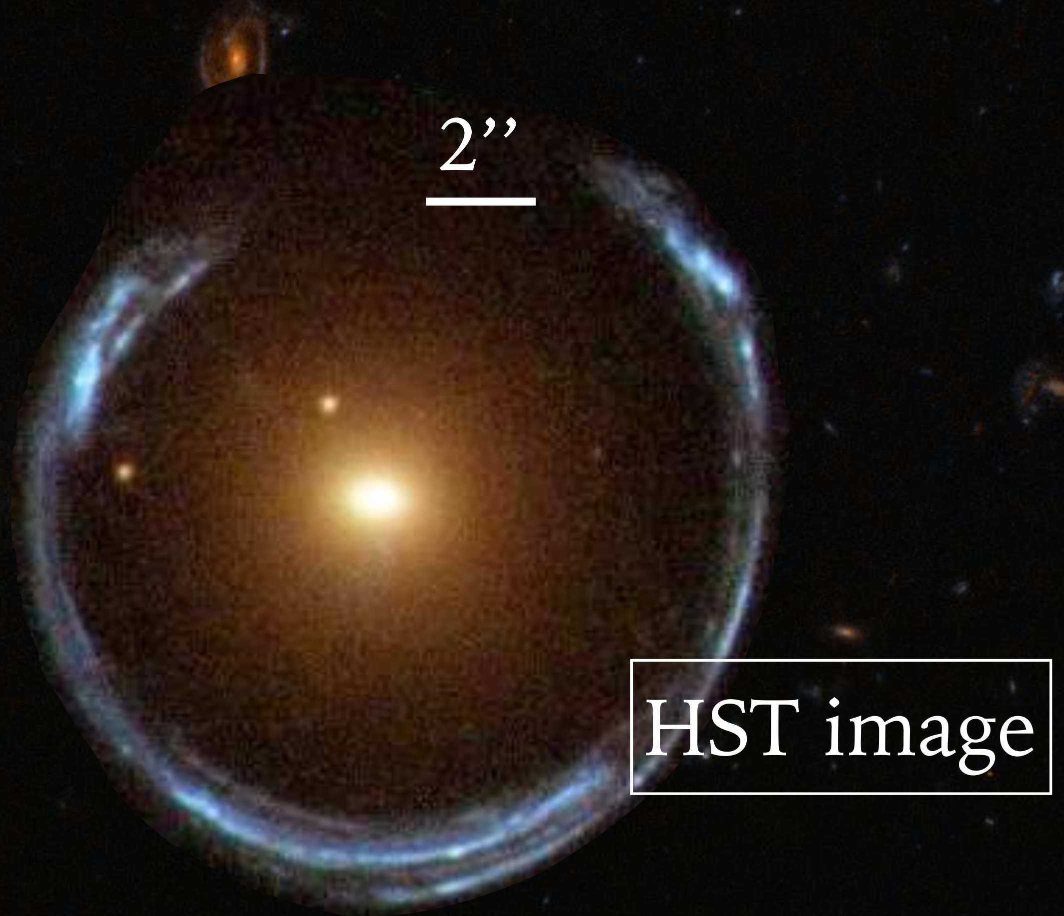
One of the most powerful means to investigate how matter is distributed within different scales of the Universe

Strong Lensing (SL) occurs if:

- source, lens and observer are closely aligned
- the lens is sufficiently dense (supercritical) → galaxies and central region of galaxy clusters

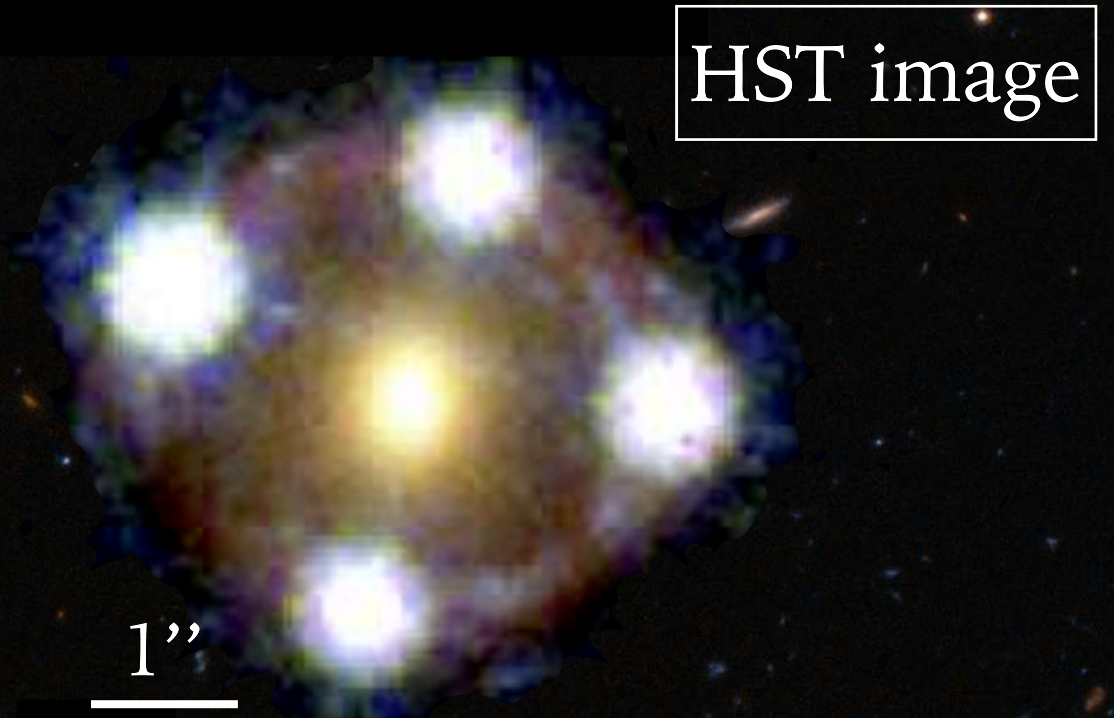
Effects:

- production of distinct and resolvable multiple images of the same background source
- amplification, magnification and distortion of the multiple images
- time delays between multiple images



Einstein ring

[redacted]



[redacted]

Einstein cross

GRAVITATIONAL LENSING

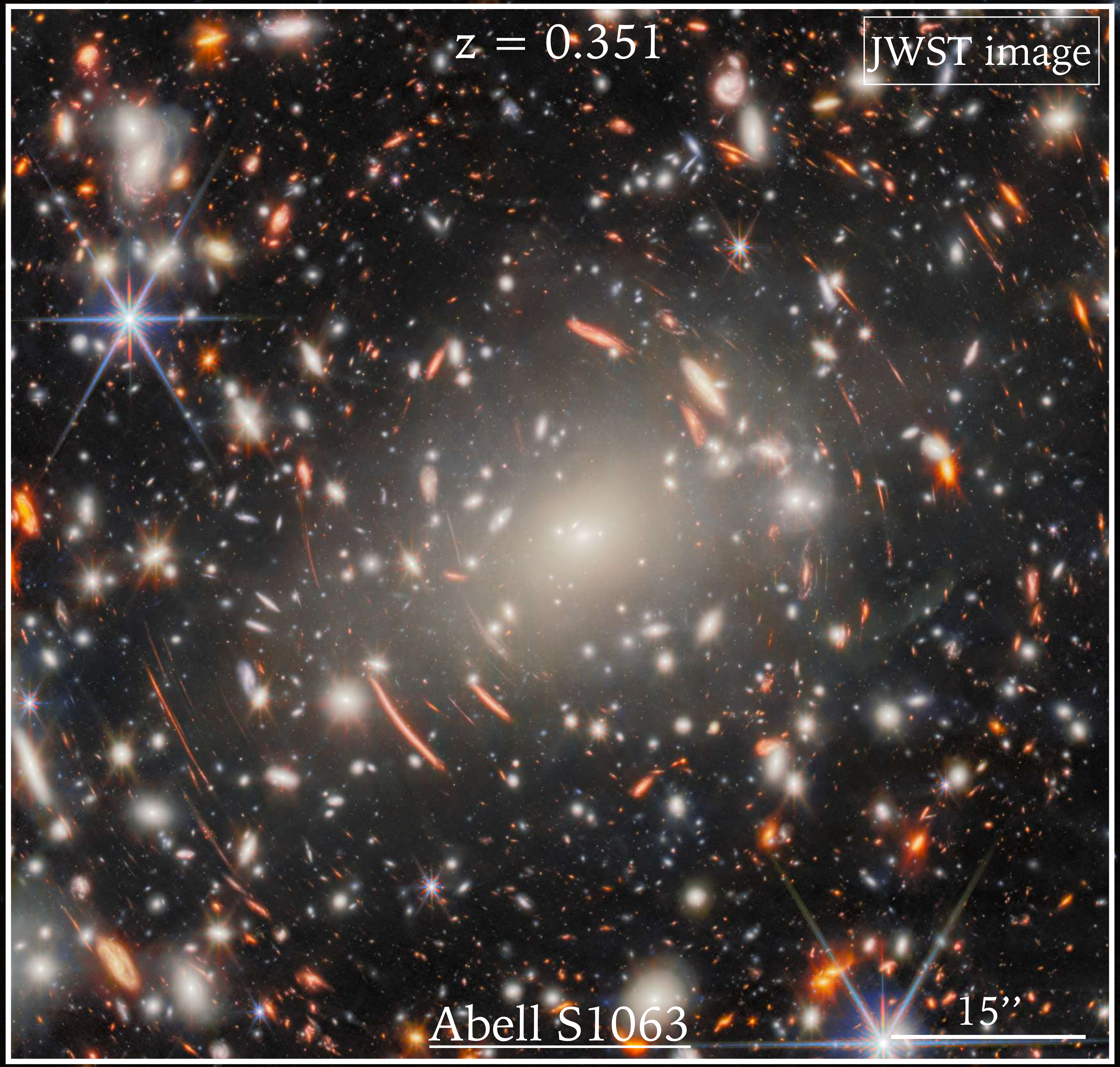
One of the most powerful means to investigate how matter is distributed within different scales of the Universe

Strong Lensing (SL) occurs if:

- source, lens and observer are closely aligned
- the lens is sufficiently dense (supercritical) → galaxies and central region of galaxy clusters

Effects:

- production of distinct and resolvable multiple images of the same background source
- amplification, magnification and distortion of the multiple images
- time delays between multiple images



GRAVITATIONAL LENSING

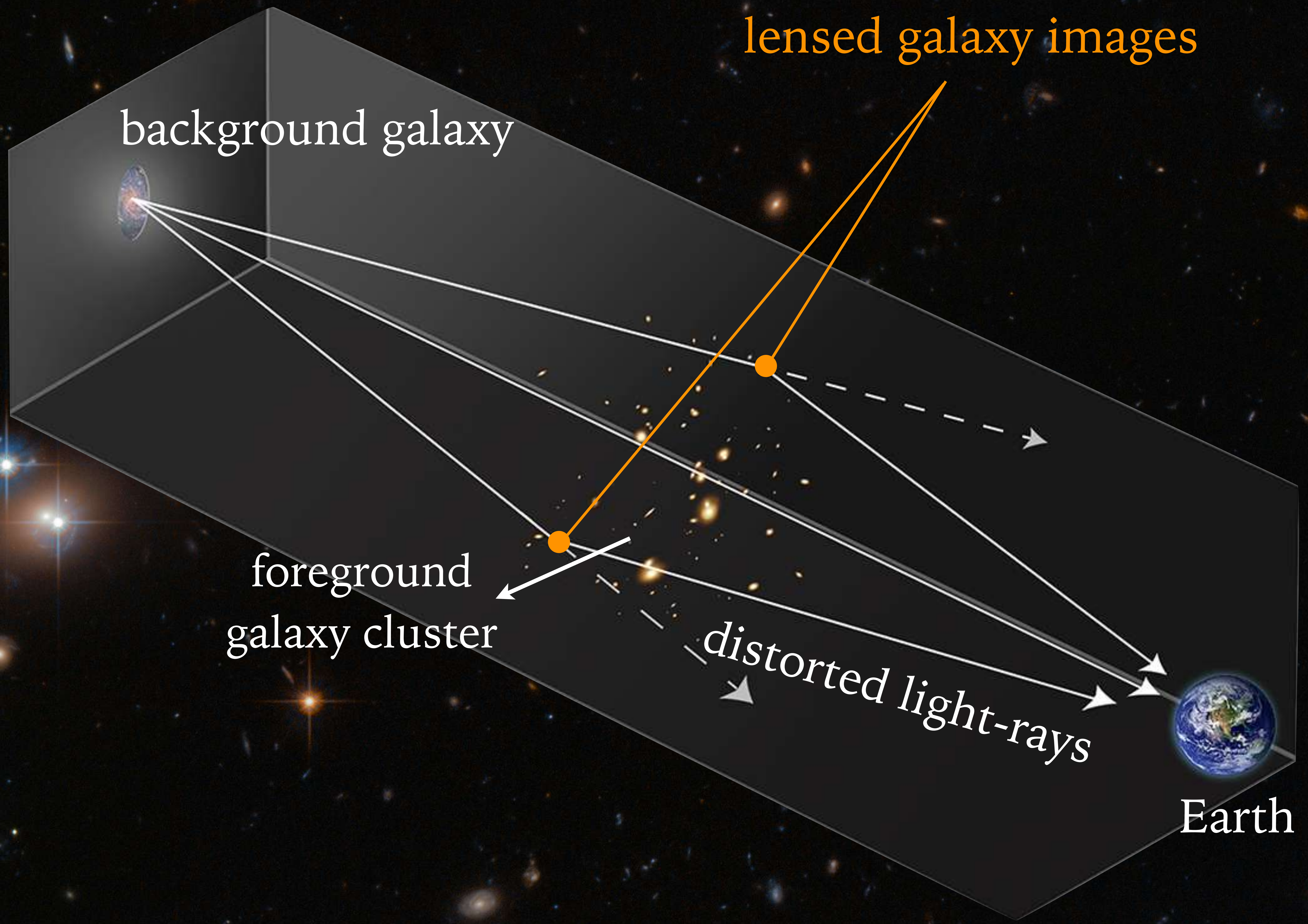
One of the most powerful means to investigate how matter is distributed within different scales of the Universe

Strong Lensing (SL) occurs if:

- source, lens and observer are closely aligned
- the lens is sufficiently dense (supercritical) → galaxies and central region of galaxy clusters

Effects:

- production of distinct and resolvable multiple images of the same background source
- amplification, magnification and distortion of the multiple images
- time delays between multiple images



GRAVITATIONAL LENSING

One of the most powerful means to investigate how matter is distributed within different scales of the Universe

Strong Lensing (SL) occurs if:

- source, lens and observer are closely aligned
- the lens is sufficiently dense (supercritical) → galaxies and central region of galaxy clusters

Effects:

- production of distinct and resolvable multiple images of the same background source
- amplification, magnification and distortion of the multiple images
- time delays between multiple images

→

- reconstruct the **total mass distribution** of the lens
- detect and study **distant and faint sources**
- estimate **cosmological parameters**

Time-delay cosmography

ON THE POSSIBILITY OF DETERMINING HUBBLE'S PARAMETER AND THE MASSES OF GALAXIES FROM THE GRAVITATIONAL LENS EFFECT*

Sjur Refsdal

(Communicated by H. Bondi)

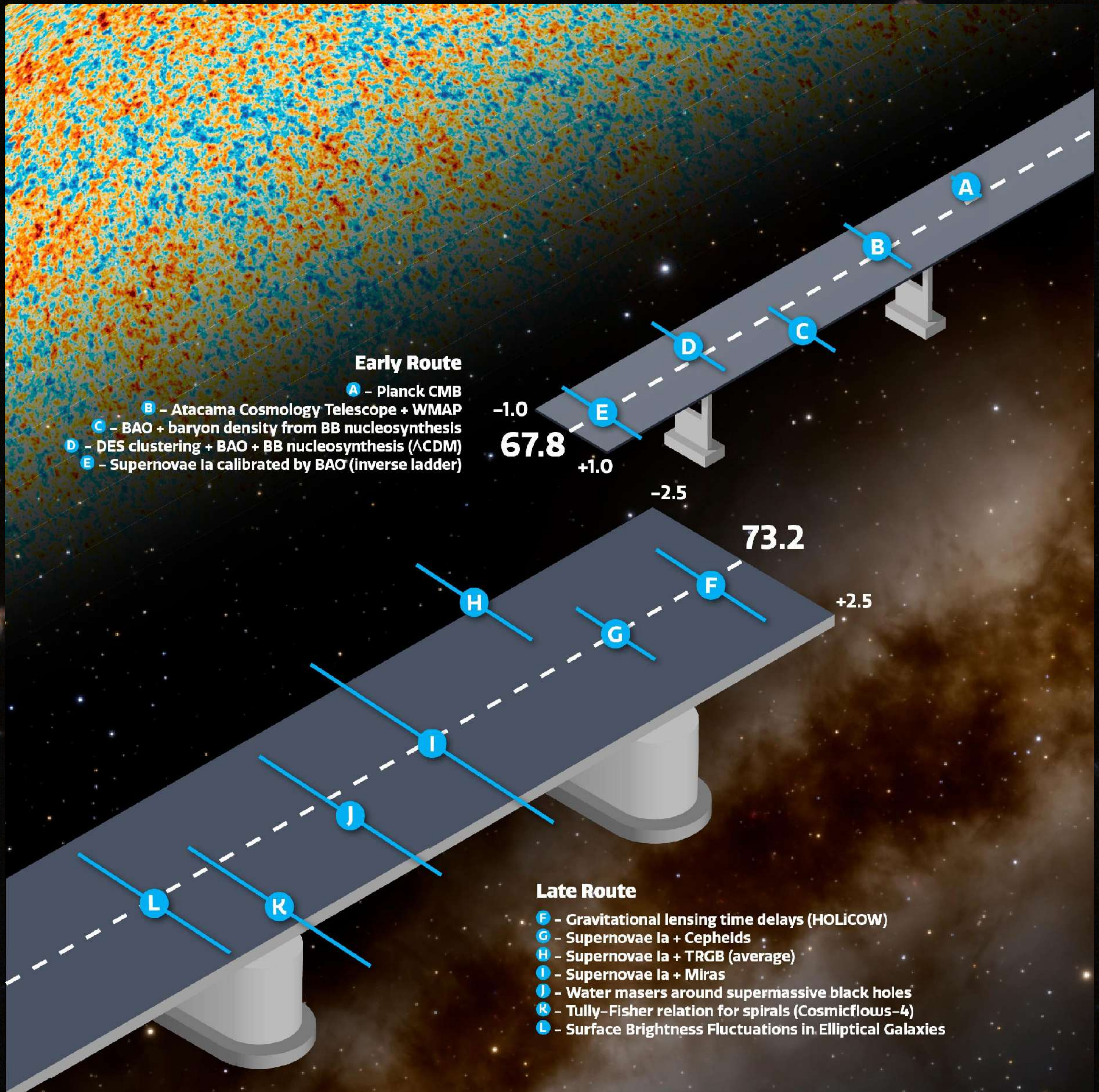
(Received 1964 January 27)

Summary

The gravitational lens effect is applied to a supernova lying far behind and close to the line of sight through a distant galaxy. The light from the supernova may follow two different paths to the observer, and the difference Δt in the time of light travel for these two paths can amount to a couple of months or more, and may be measurable. It is shown that Hubble's parameter and the mass of the galaxy can be expressed by Δt, the red-shifts of the supernova and the galaxy, the luminosities of the supernova "images" and the angle between them. The possibility of observing the phenomenon is discussed.

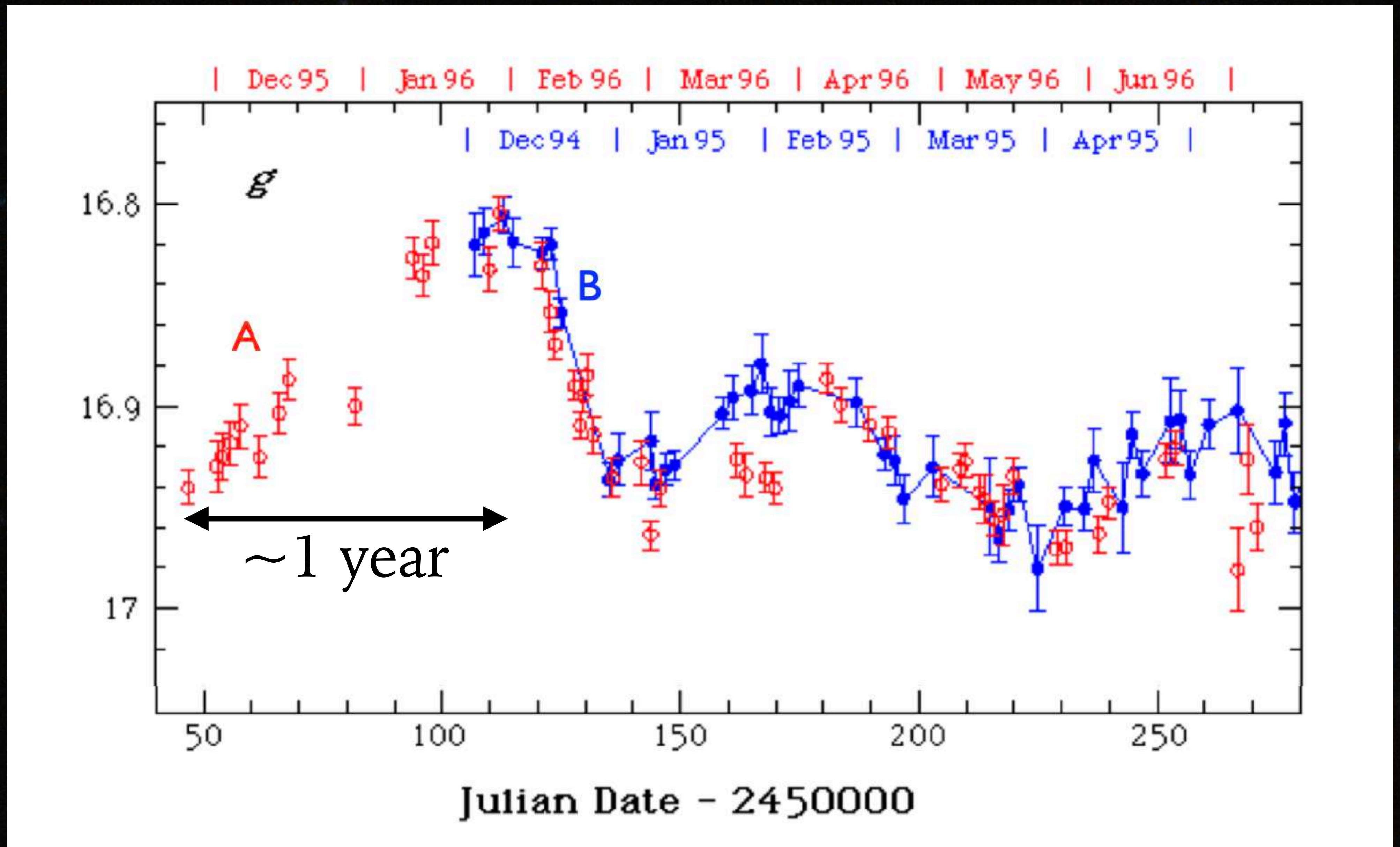
Time-delay cosmography

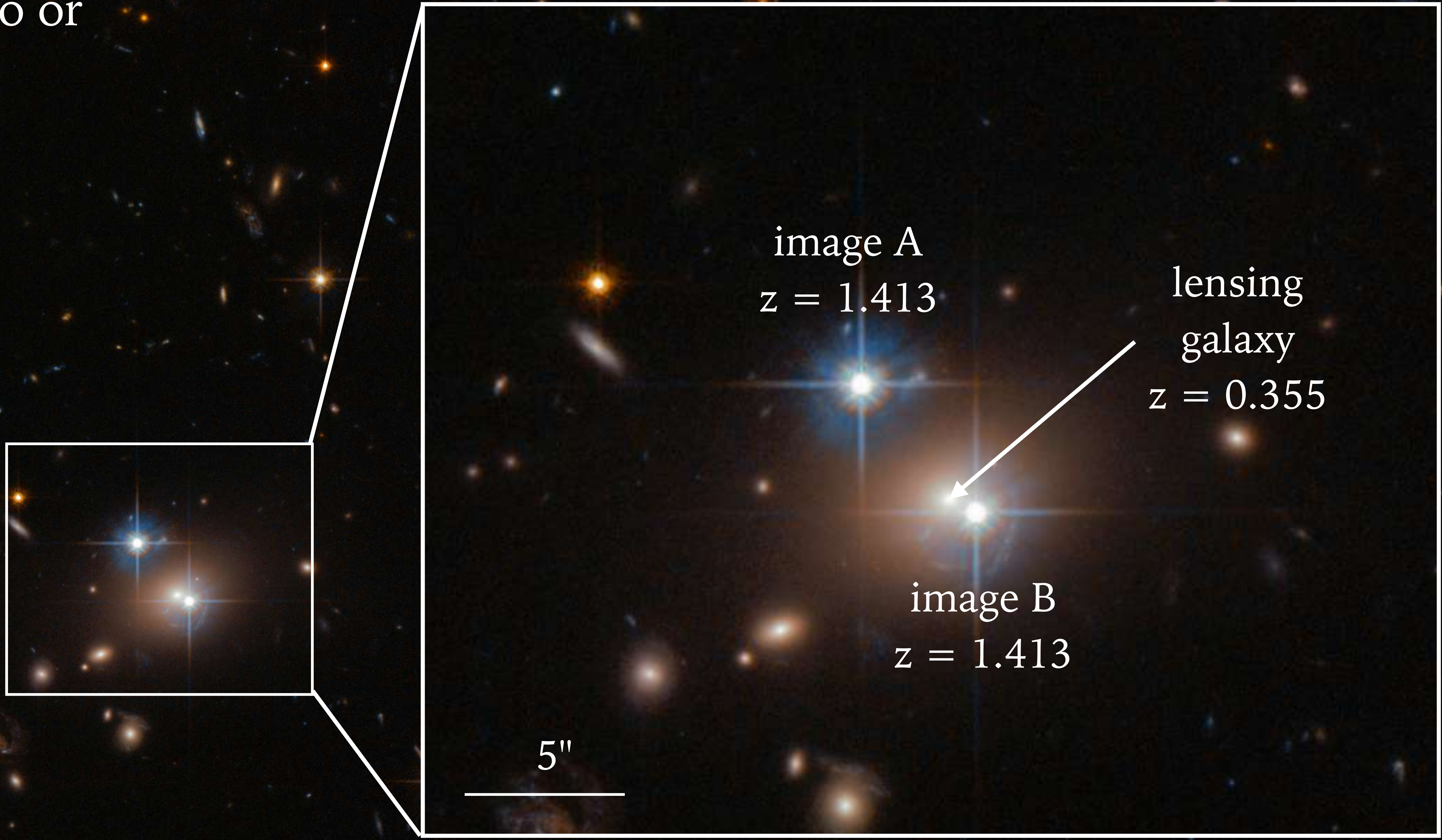
The Hubble tension



Time-delay cosmography

If a <u>variable background source</u> is lensed into two or more images, we can measure the time-delay between their light curves.





Twin Quasar Q0957+561
[Walsh et al., 1979]

Time-delay cosmography

Time delays between multiple images of variable background sources allow the geometry and the expansion rate (H_0) to be constrained:

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

geometrical + gravitational (Shapiro) time delay

$$\Delta t_{ij}(\vec{\theta}, \vec{\beta}) = \frac{1}{H_0} f(\Omega_M, \Omega_{DE}, w, z_l, z_s)\ \Delta\Phi_{Fij}(\vec{\theta}, \vec{\beta})$$

Δt_{ij} ↓ this can be measured

$\frac{1}{H_0}$ ↓ this can be inferred!

$\Delta\Phi_{Fij}$ ↓ this depends on ψ and ψ'

AN ACCURATE AND PRECISE MASS MODEL IS REQUIRED FOR TIME-DELAY COSMOGRAPHY!

Strong Lensing Modelling

→ from the images to the mass $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$

$$\vec{\alpha} = \frac{D_{\rm ds}}{D_{\rm s}} \frac{2}{c^2} \int \vec{\nabla}_{\perp} \phi dl$$

- Parametric approach

The total mass distribution of the lens cluster is described as the sum of different contributions:

- cluster-scale halos (DM + intra-cluster medium)
- galaxy-scale halos (DM + baryons)
- additional components (external shear, foreground/background galaxies)

$$\phi_{\rm tot} = \sum_i \phi_i^{\rm halo} + \sum_i \phi_j^{\rm gal} + \phi_{\rm ext}$$

Each component is described by a certain profile specified by some parameters.

Strong Lensing Modelling

→ from the images to the mass $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$

- Model optimization

Parameter inference is typically performed in a Bayesian framework, with MCMC methods used to sample the posterior probability distribution. The analysis aims to identify the parameter set that maximizes the posterior, consistent with the specified priors and the likelihood function:

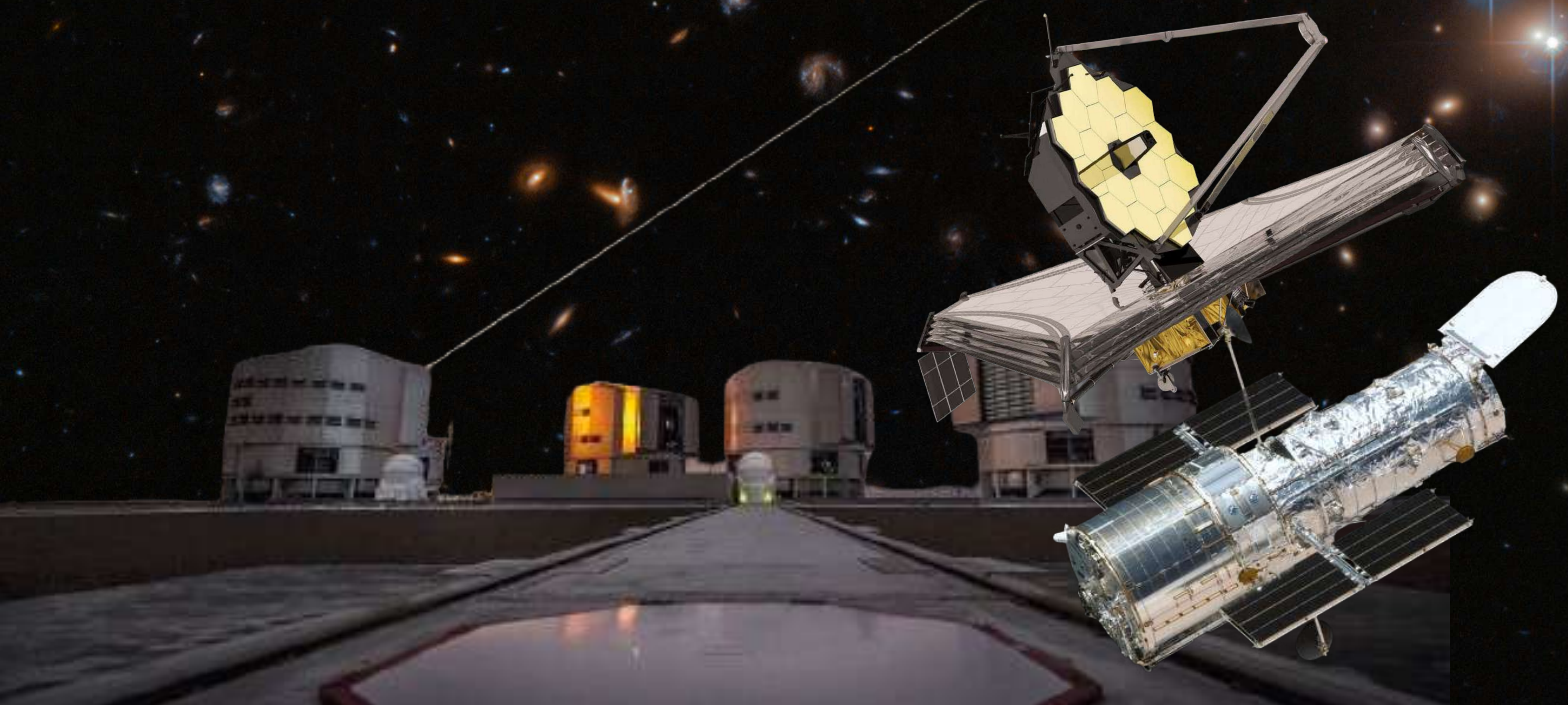
$$\mathscr{L} = P(D \,|\, x(\boldsymbol{\theta})) = \prod_{i=1}^{N} \frac{1}{\prod_j \sigma_{ij}\sqrt{2\pi}} \exp^{-\chi_i^2/2} \qquad \chi_i^2 = \sum_{j=1}^{n_i} \frac{[x_{\rm obs}^j - x^j(\boldsymbol{\theta})]^2}{\sigma_{ij}^2}$$

Strong Lensing Modelling

→ from the images to the mass $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$

Multiple images provide observational constraints of different nature:

- astrometric constraints (positions)
- photometric constraints (fluxes)
- temporal constraints (time-delay between multiple images of the same variable background source)



Imaging campaigns:

- Hubble Space Telescope (HST) (ESA/NASA)
  - Cluster Lensing and Supernova Survey with Hubble (CLASH)
  - Hubble Frontier-Fields (HFF)
  - Reionization Lensing Cluster Survey (RELICS)
- James Webb Space Telescope (JWST) (NASA)
  - Ultra-deep NIRCam and NIRSpec Observations of a Massive Cluster Lensing Field (UNCOVER)
  - Grism Lens-Amplified Survey from Space (GLASS-JWST)
  - CAnadian NIRISS Unbiased Cluster Survey (CANUCS)
  - Strong LensIng and Cluster Evolution program (SLICE)

Spectroscopic campaigns:

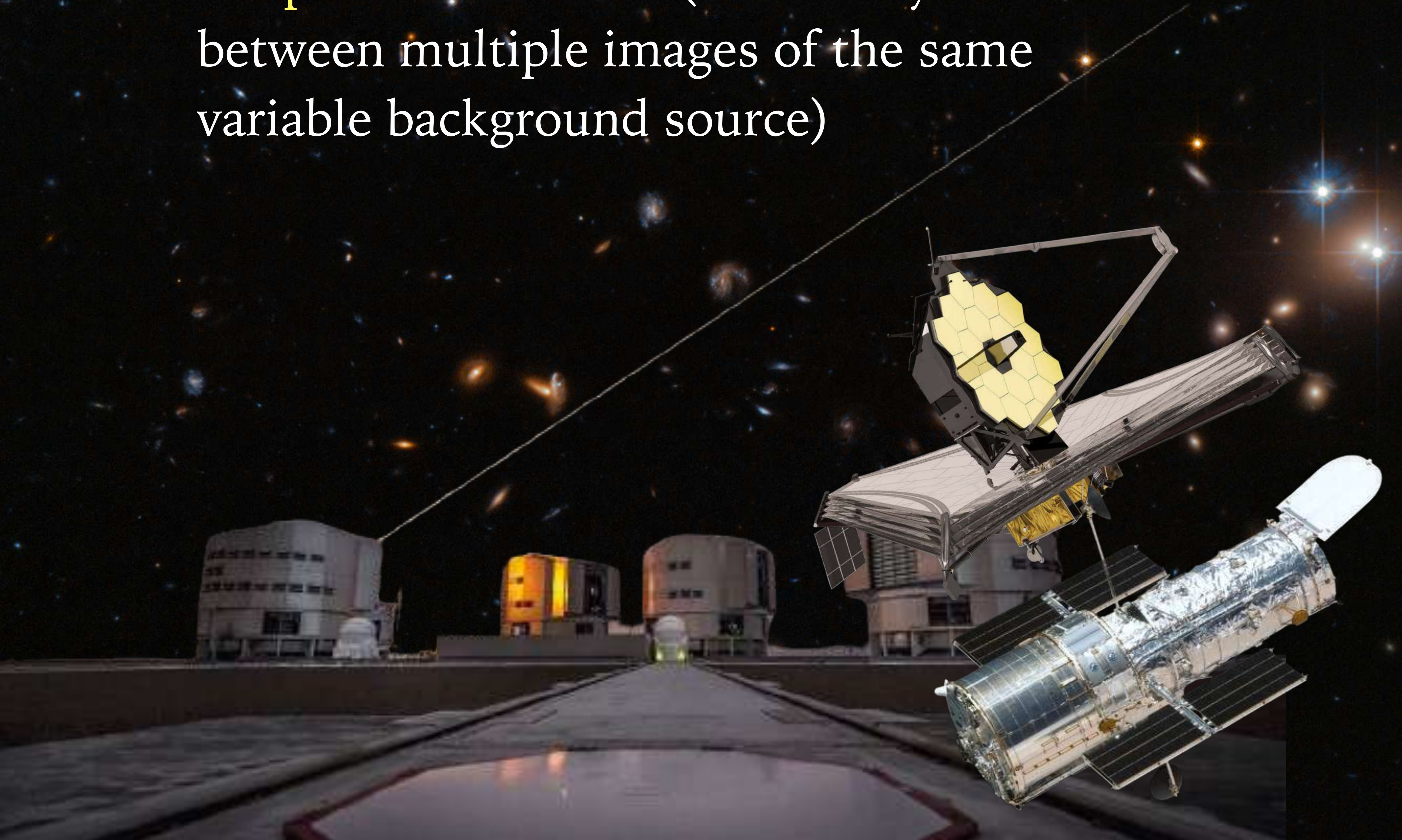
- Very Large Telescope (VLT) (ESO)
  - CLASH - VLT
  - Multi Unit Spectroscopic Explorer (MUSE)

Strong Lensing Modelling

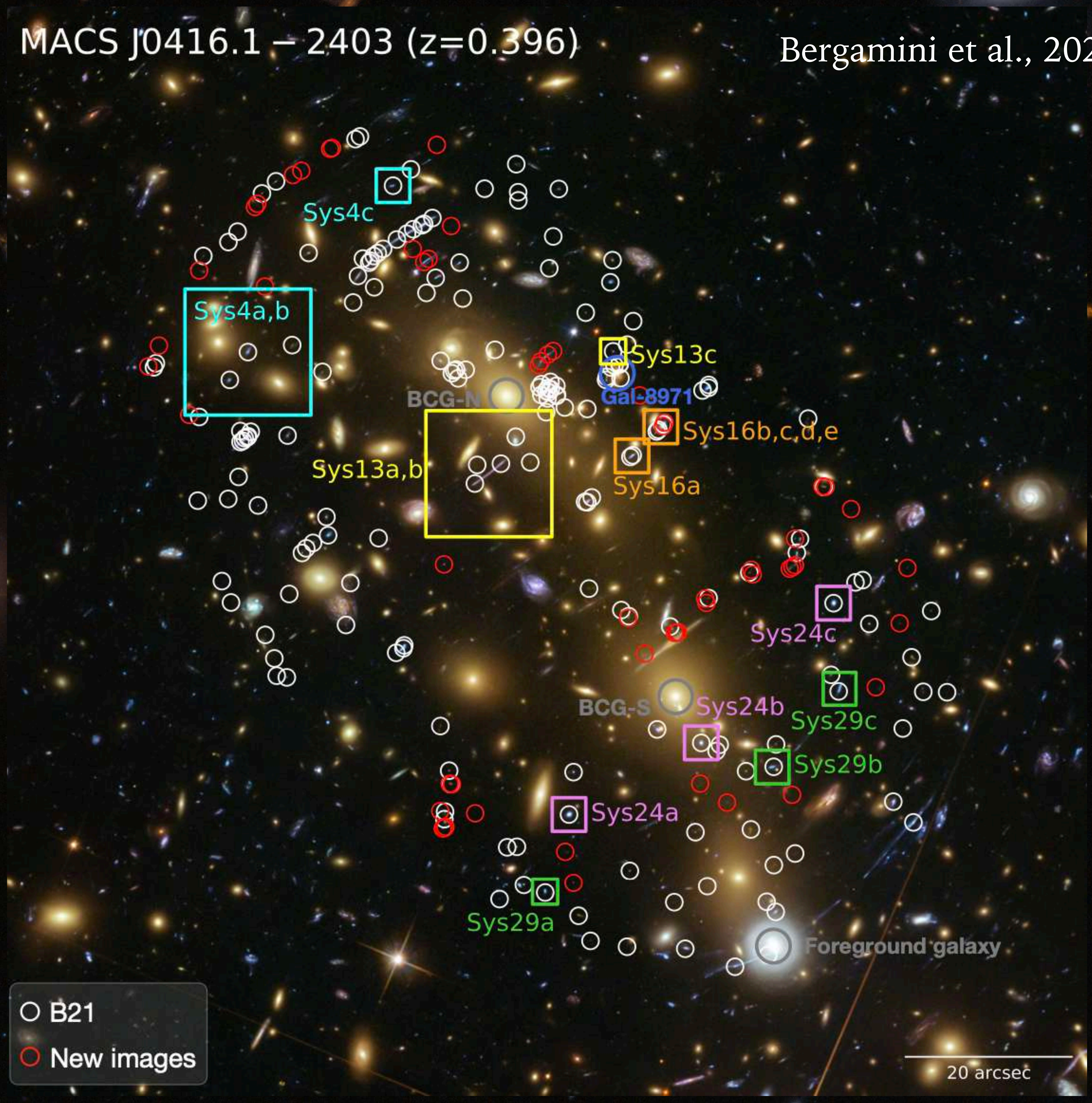
→ from the images to the mass $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$

Multiple images provide observational constraints of different nature:

- astrometric constraints (positions)
- photometric constraints (fluxes)
- temporal constraints (time-delay between multiple images of the same variable background source)



Bergamini et al., 2022

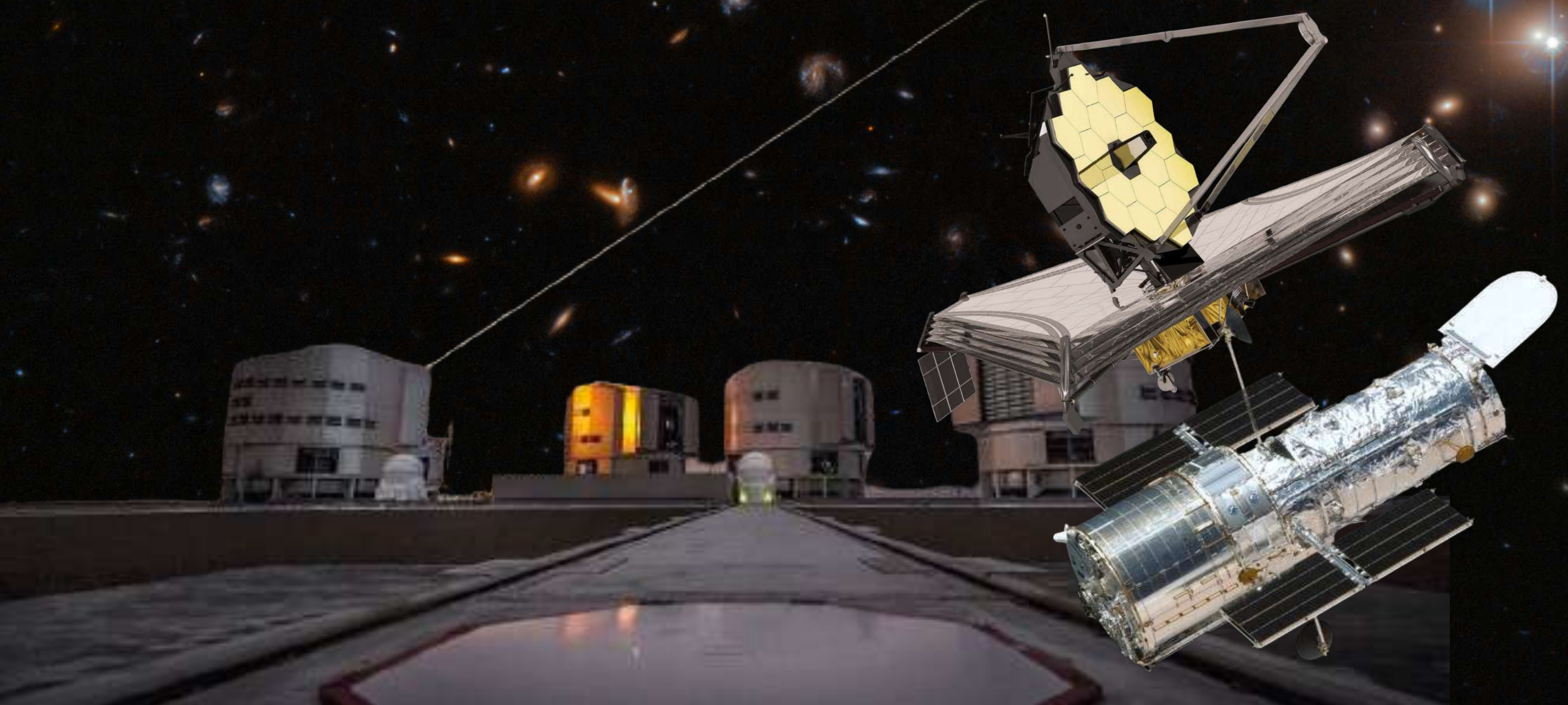


Strong Lensing Modelling

→ from the images to the mass $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$

Multiple images provide observational constraints of different nature:

- astrometric constraints (positions)
- photometric constraints (fluxes)
- temporal constraints (time-delay between multiple images of the same variable background source)



Imaging campaigns:

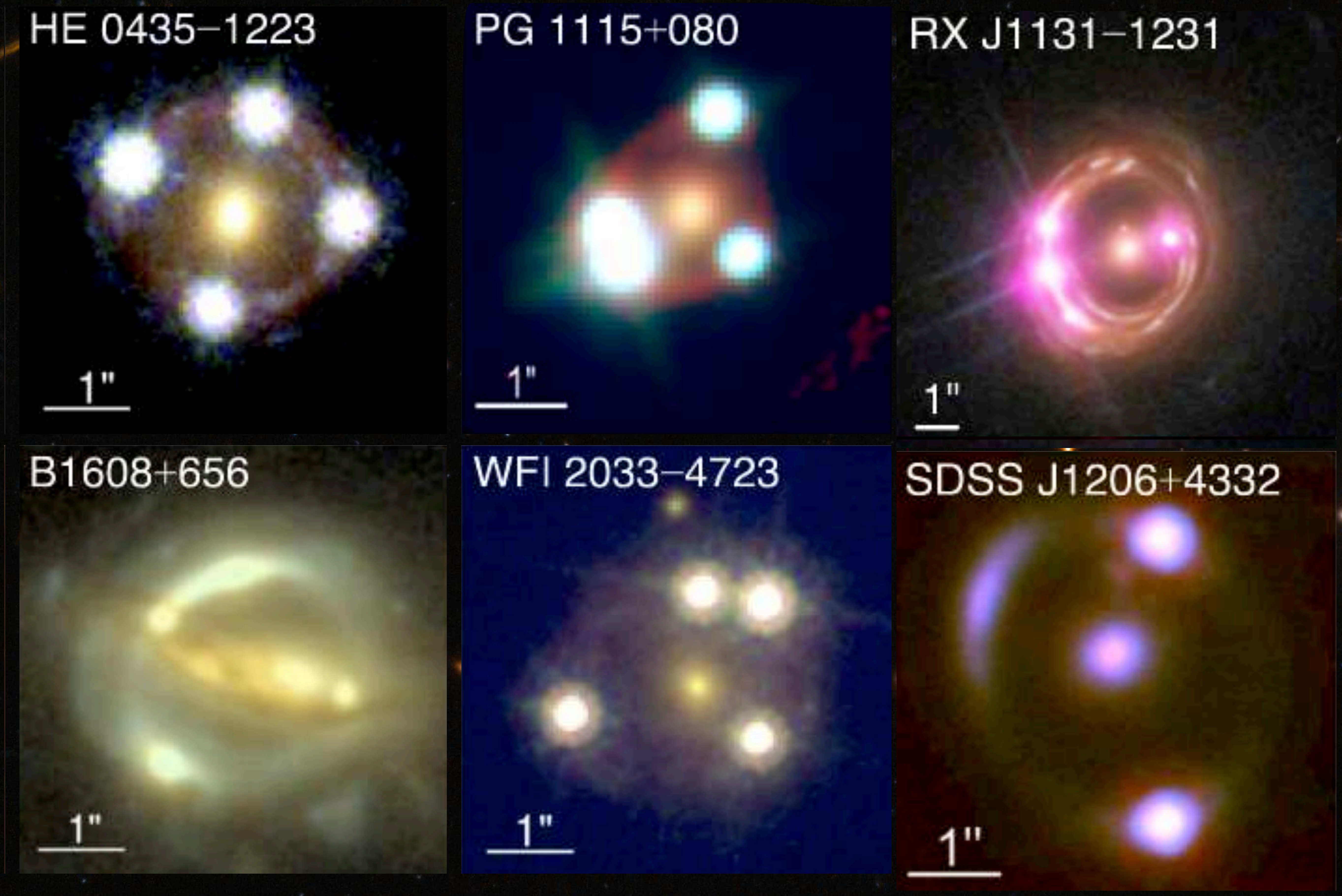
- Hubble Space Telescope (HST) (ESA/NASA)
  - Cluster Lensing and Supernova Survey with Hubble (CLASH)
  - Hubble Frontier-Fields (HFF)
  - Reionization Lensing Cluster Survey (RELICS)
- James Webb Space Telescope (JWST) (NASA)
  - Ultra-deep NIRCam and NIRSpec Observations of a Massive Cluster Lensing Field (UNCOVER)
  - Grism Lens-Amplified Survey from Space (GLASS-JWST)
  - CAnadian NIRISS Unbiased Cluster Survey (CANUCS)
  - Strong LensIng and Cluster Evolution program (SLICE)

Spectroscopic campaigns:

- Very Large Telescope (VLT) (ESO)
  - CLASH - VLT
  - Multi Unit Spectroscopic Explorer (MUSE)

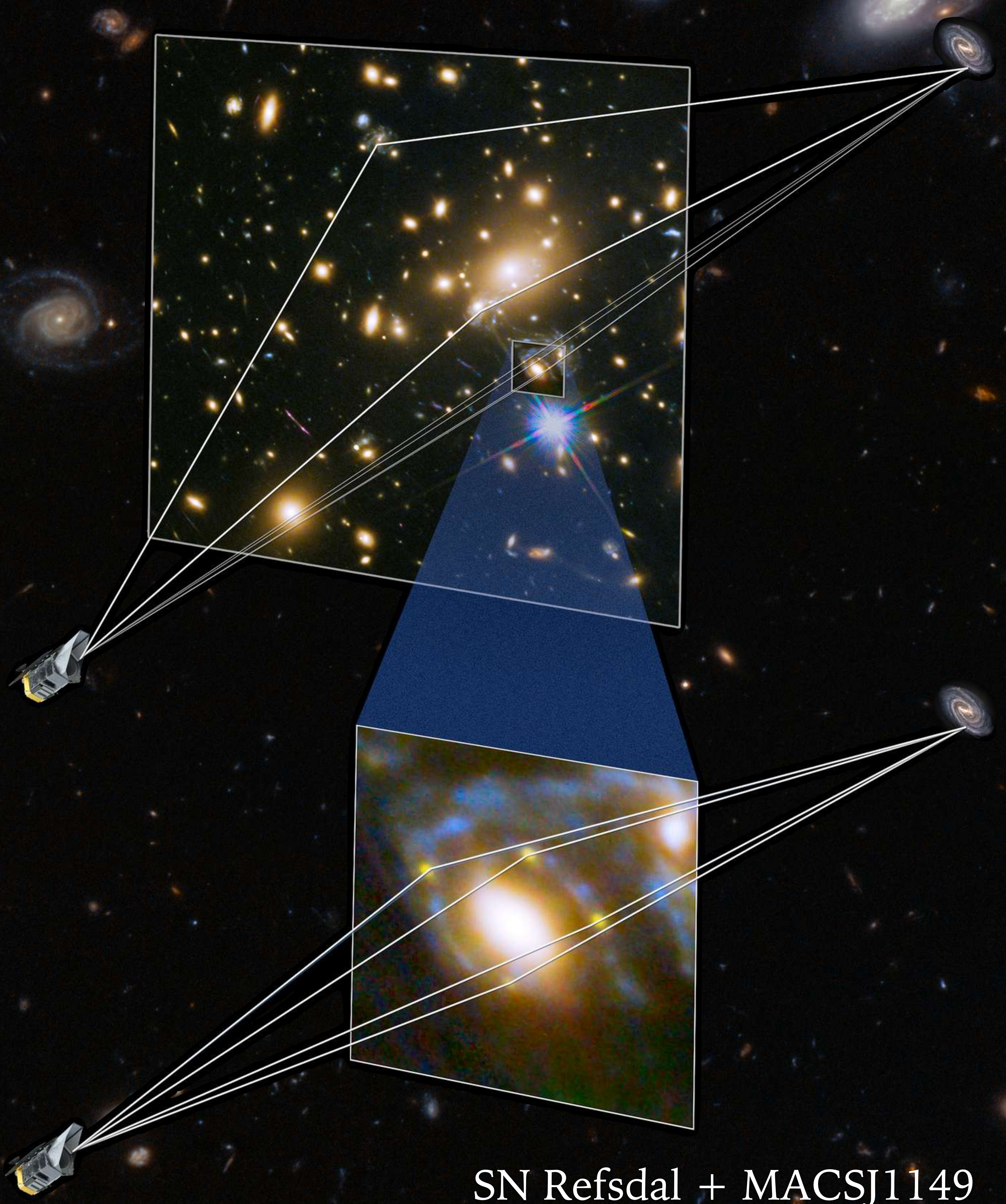
Time-delay cosmography

GALAXY-SCALE



H0LiCOW collaboration
[Wang et al., 2019]

CLUSTER SCALE



SN Refsdal + MACSJ1149
[Grillo et al., 2024]

The landmark case of SN Refsdal strongly lensed by the galaxy cluster MACSJ1149

CLASH+GLASS observations of MACSJ1149 [Kelly et al., 2015]

z_{lens}=0.542, z_{host}=1.489

The landmark case of SN Refsdal strongly lensed by the galaxy cluster MACSJ1149

CLASH+GLASS observations of MACSJ1149 [Kelly et al., 2015]

z_{lens}=0.542, z_{host}=1.489

The landmark case of SN Refsdal strongly lensed by the galaxy cluster MACSJ1149

CLASH+GLASS observations of MACSJ1149 [Kelly et al., 2015]

$z_{\mathrm{lens}}=0.542$, $z_{\mathrm{host}}=1.489$

The landmark case of SN Refsdal strongly lensed by the galaxy cluster MACSJ1149

CLASH+GLASS observations of MACSJ1149 [Kelly et al., 2015]

z_{lens}=0.542, z_{host}=1.489

MACS J1149.5 +2223
(z = 0.542)

The landmark case of SN Refsdal strongly lensed by the galaxy cluster MACSJ1149

CLASH+GLASS observations of MACSJ1149 [Kelly et al., 2015]

z_{lens}=0.542, z_{host}=1.489

The landmark case of SN Refsdal strongly lensed by the galaxy cluster MACSJ1149

CLASH+GLASS observations of MACSJ1149 [Kelly et al., 2015]

z_{lens}=0.542, z_{host}=1.489

The landmark case of SN Refsdal strongly lensed by the galaxy cluster MACSJ1149

CLASH+GLASS observations of MACSJ1149 [Kelly et al., 2015]

$z_{\text{lens}}=0.542$, $z_{\text{host}}=1.489$

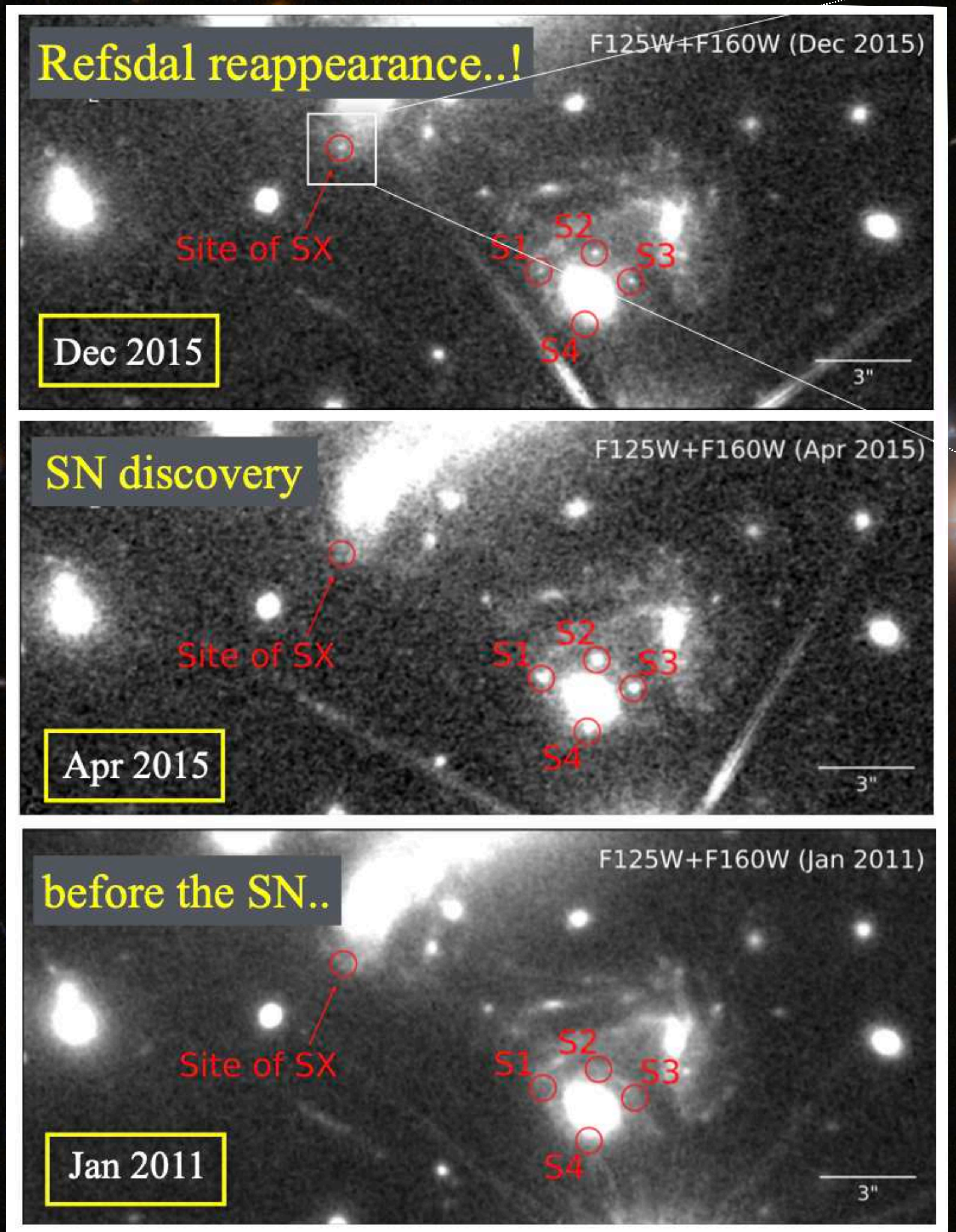
Time-delay cosmography

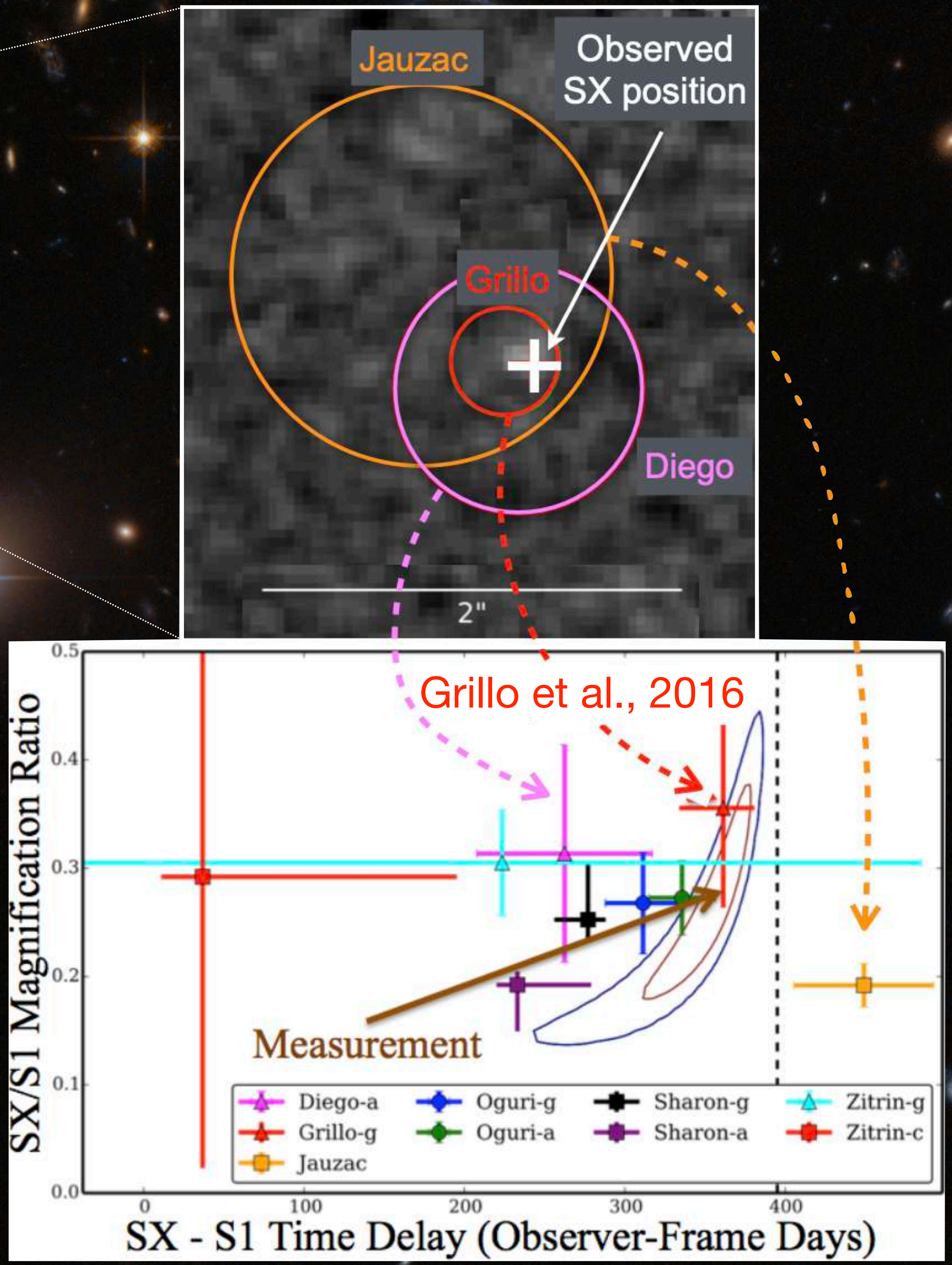
The landmark case of SN Refsdal strongly lensed by the galaxy cluster MACSJ1149

"REFSDAL" MEETS POPPER: COMPARING PREDICTIONS OF THE RE-APPEARANCE OF THE MULTIPLY IMAGED SUPERNOVA BEHIND MACSJ1149.5+2223

T. Treu et al., 2016

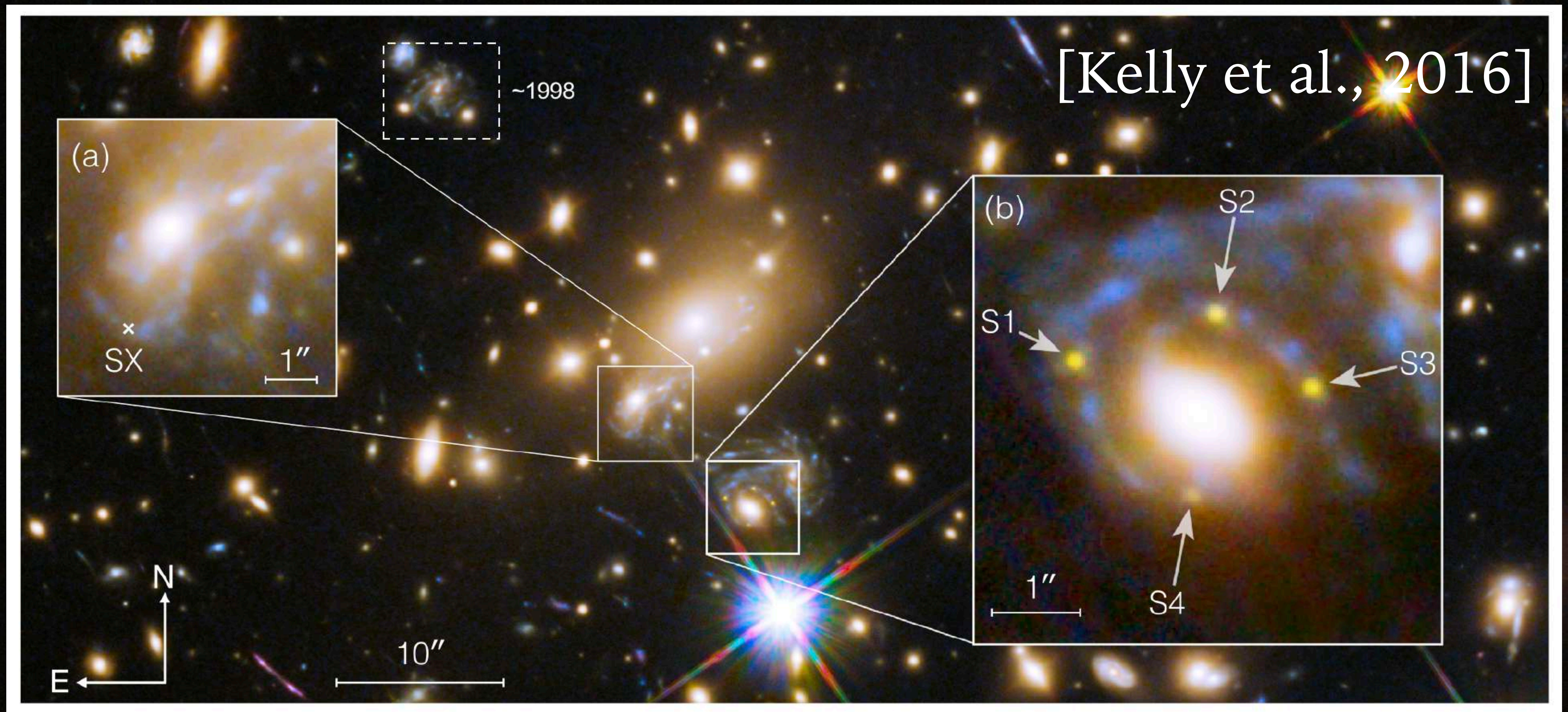
The Astrophysical Journal, Volume 817 (Jan 2016)





Time-delay cosmography

The landmark case of SN Refsdal strongly lensed by the galaxy cluster MACSJ1149



HST + MUSE/VLT

THE STORY OF SUPERNOVA "REFSDAL" TOLD BY MUSE
C. Grillo et al., 2016
The Astrophysical Journal, Volume 822 (May 2016)

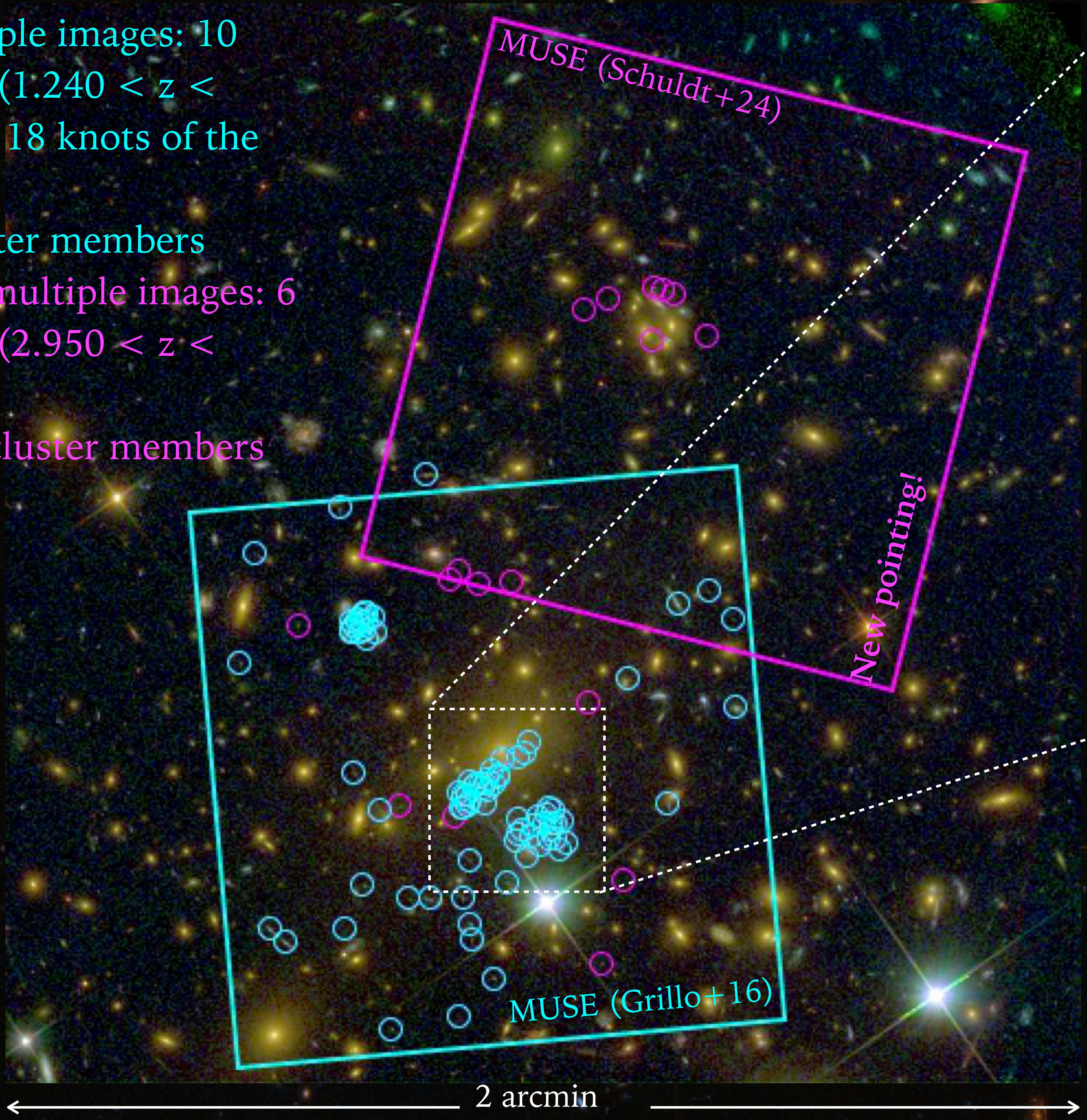
Measuring the Value of the Hubble Constant "à la Refsdal"
C. Grillo et al., 2018
The Astrophysical Journal, Volume 860 (Jun 2018)

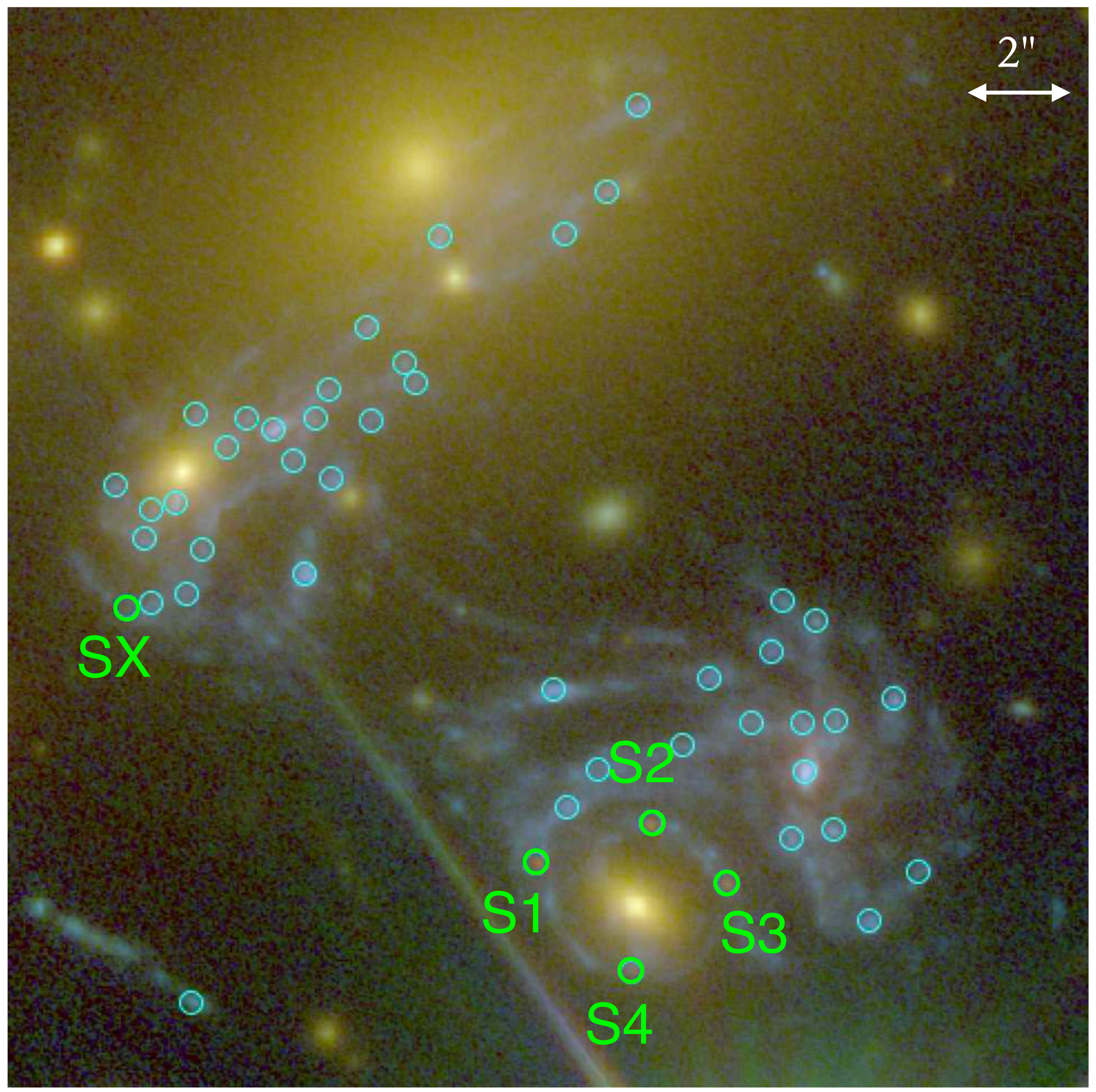
On the Accuracy of Time-delay Cosmography in the Frontier Fields Cluster MACS J1149.5+2223 with Supernova Refsdal
C. Grillo et al., 2020
The Astrophysical Journal, Volume 898 (July 2020)

Cosmography with supernova Refsdal through time-delay cluster lensing: Independent measurements of the Hubble constant and geometry of the Universe
C. Grillo et al., 2024
Astronomy & Astrophysics, Volume 684 (Jun 2018)

MACSJ1149: SL system

- 89 multiple images: 10 families ($1.240 < z < 3.703$) +18 knots of the SN host
- 300 cluster members
- 17 new multiple images: 6 families ($2.950 < z < 5.983$)
- 10 new cluster members



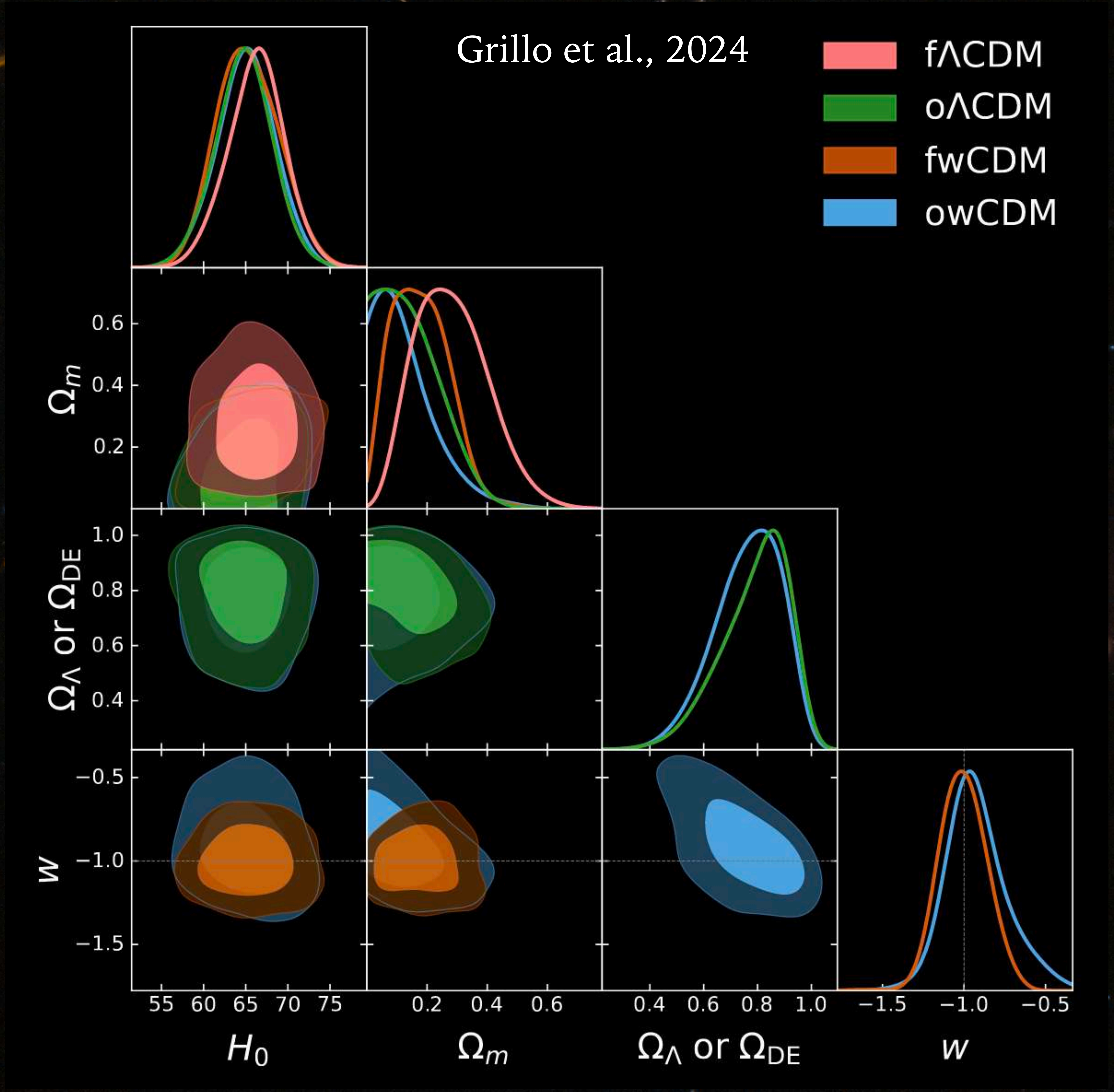


- Cluster redshift **z=0.542**
- 5 multiple images of SN Refsdal (**z=1.489**) (S1—S4 + SX)
- 4 measured time-delays [Kelly et al., 2023]

Cosmography with supernova Refsdal through time-delay cluster lensing: Independent measurements of the Hubble constant and geometry of the Universe

C. Grillo et al., 2024

Astronomy & Astrophysics, Volume 684 (Jun 2018)



Model	H_0 (km s^{-1} Mpc^{-1})	Ω_m	Ω_Λ or Ω_{DE}	w
fΛCDM	$66.2^{+3.5}_{-3.2}$	$0.28^{+0.10}_{-0.14}$	$0.72^{+0.14}_{-0.10}$	$\equiv -1$
oΛCDM	$64.8^{+3.5}_{-3.3}$	< 0.34	$0.79^{+0.16}_{-0.09}$	$\equiv -1$
fwCDM	$65.3^{+3.5}_{-4.1}$	$0.18^{+0.08}_{-0.11}$	$0.82^{+0.12}_{-0.08}$	$-1.00^{+0.14}_{-0.15}$
owCDM	$65.1^{+3.5}_{-3.4}$	< 0.34	$0.76^{+0.15}_{-0.10}$	$-0.92^{+0.15}_{-0.21}$

Time-delays + distance ratios

↓ H_0

↓ $\Omega_m, \Omega_\Lambda, w$

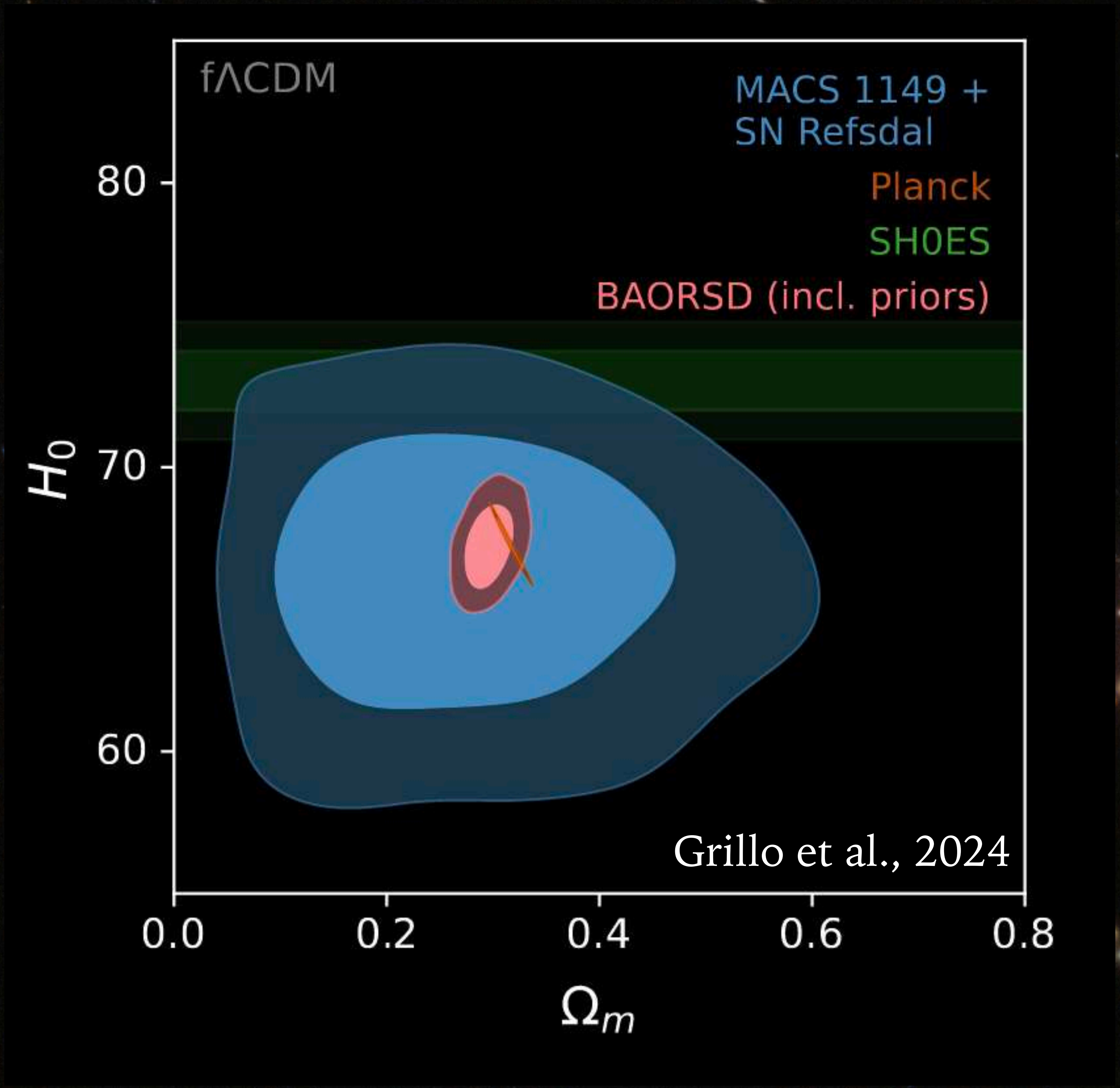
↓

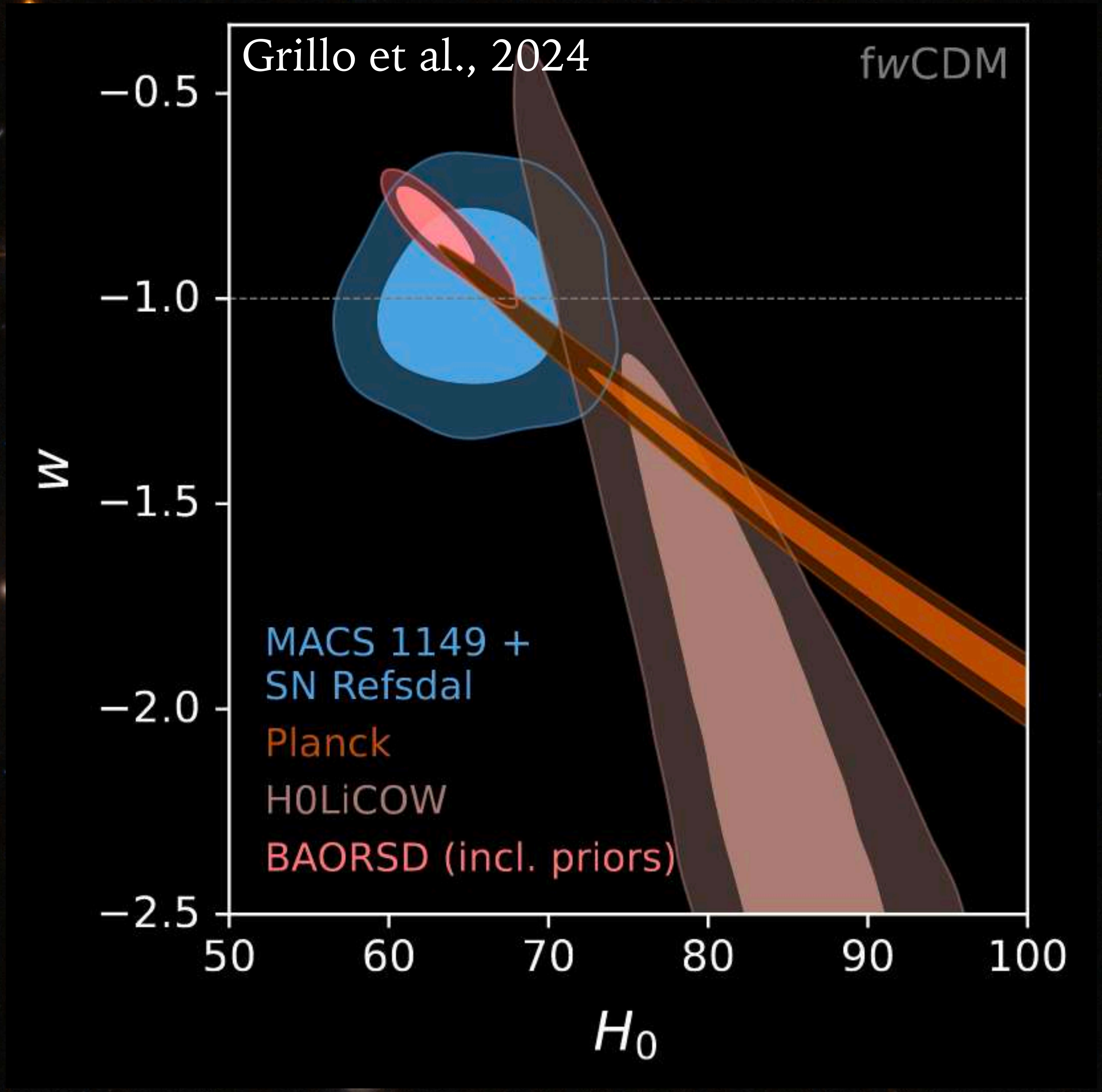
$$\eta = \frac{\left(\frac{D_{ds}}{D_s}\right)_{z_{S1}}}{\left(\frac{D_{ds}}{D_s}\right)_{z_{S2}}}$$

Cosmography with supernova Refsdal through time-delay cluster lensing: Independent measurements of the Hubble constant and geometry of the Universe

C. Grillo et al., 2024

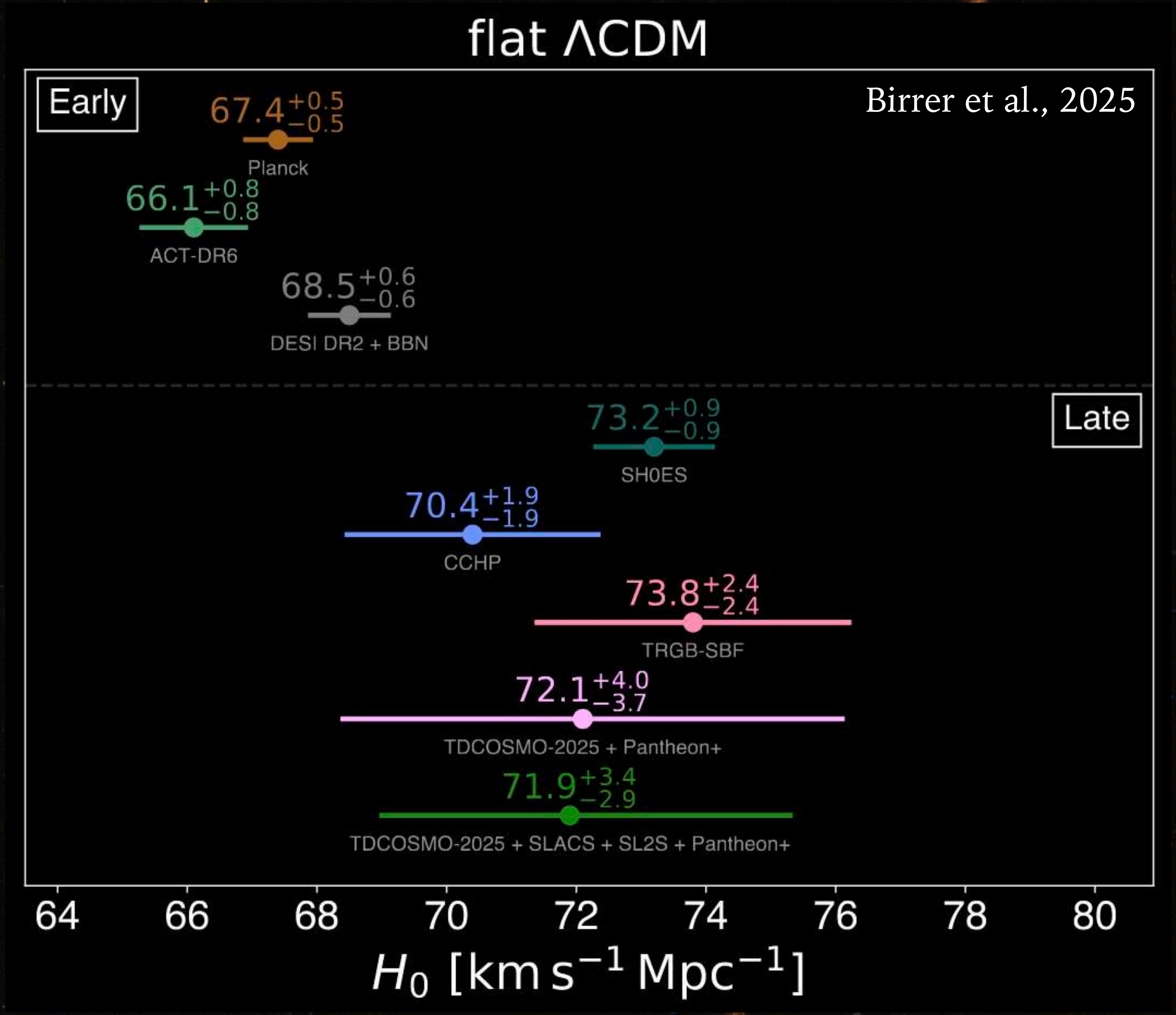
Astronomy & Astrophysics, Volume 684 (Jun 2018)





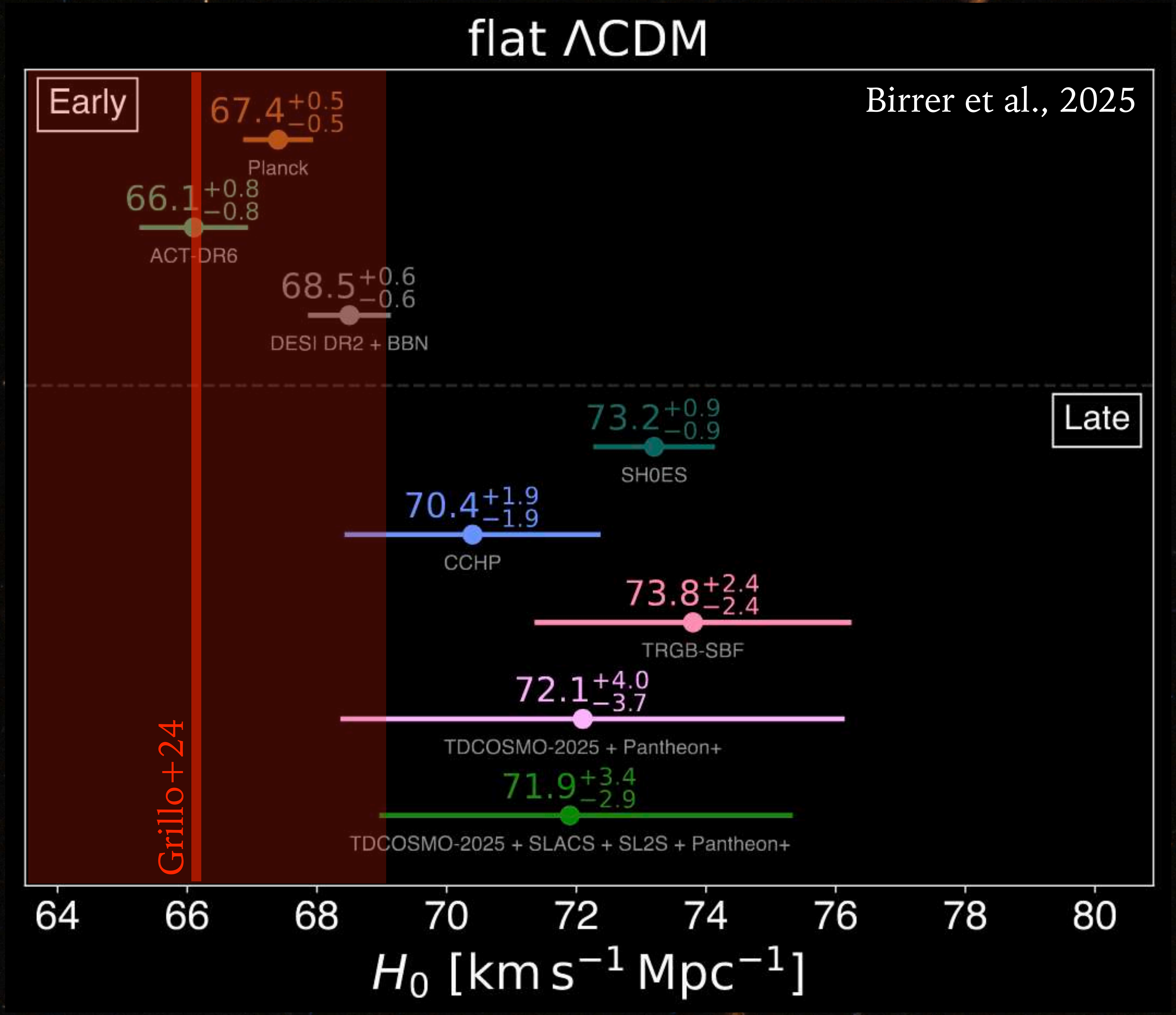
Time-delay cosmography

The Hubble tension



Time-delay cosmography

The Hubble tension



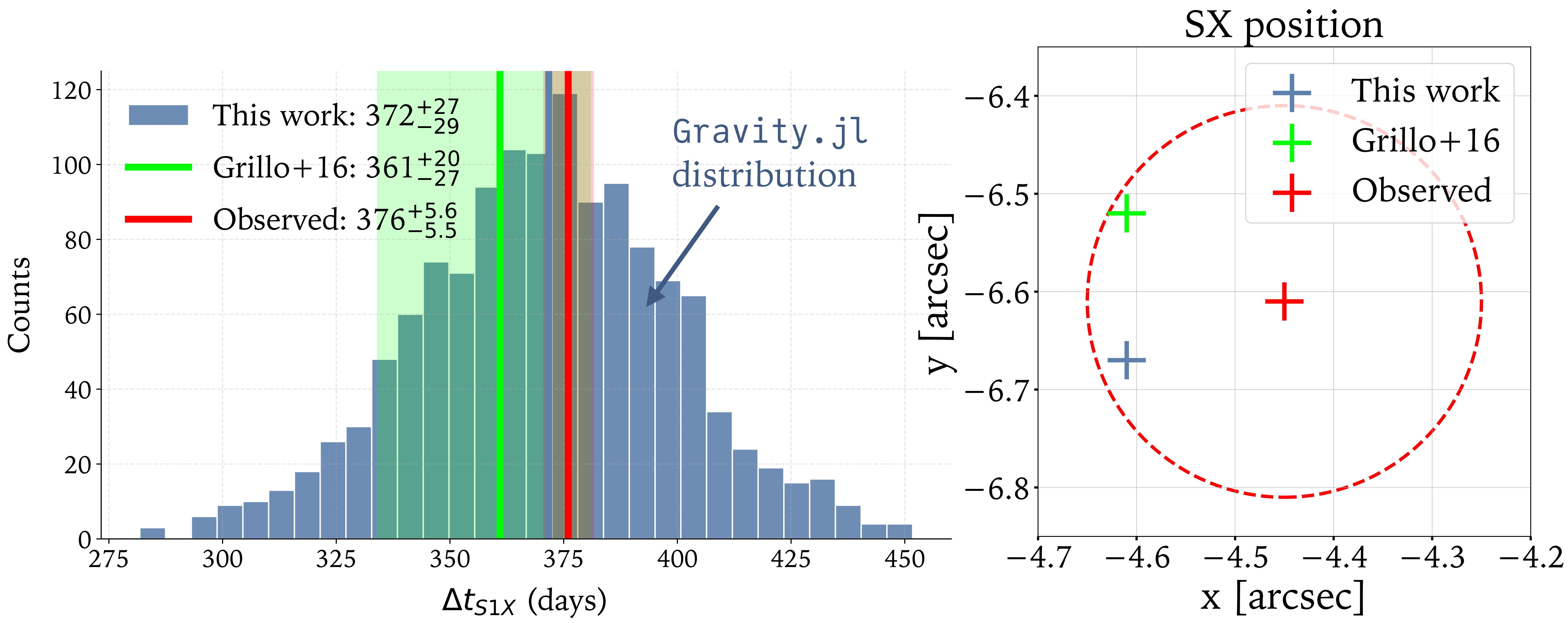
MACSJ1149: SL model with `Gravity.jl`

- ‼ New software to perform SL modelling [M. Lombardi, 2024]
- ‼ Fast: implemented in `Julia` (high-performance programming language)
- ‼ General/flexible: multi-plane lensing equations, arbitrary cosmology, different sources, many different algorithms

- Goal: apply `Gravity.jl` to cluster-scale time-delay cosmography (TDC)
- `Gravity.jl` is fast and efficient, but it’s new and must be tested
- MACSJ1149 as a representative test case: use the MACSJ1149 Refsdal lensing dataset to compare inferences on H_0 with other studies using different SL tools.

MACSJ1149: SL model with `Gravity.jl`

1. Trying to reproduce Grillo et al., 2016 SL model (based on the SL tool GLEE)



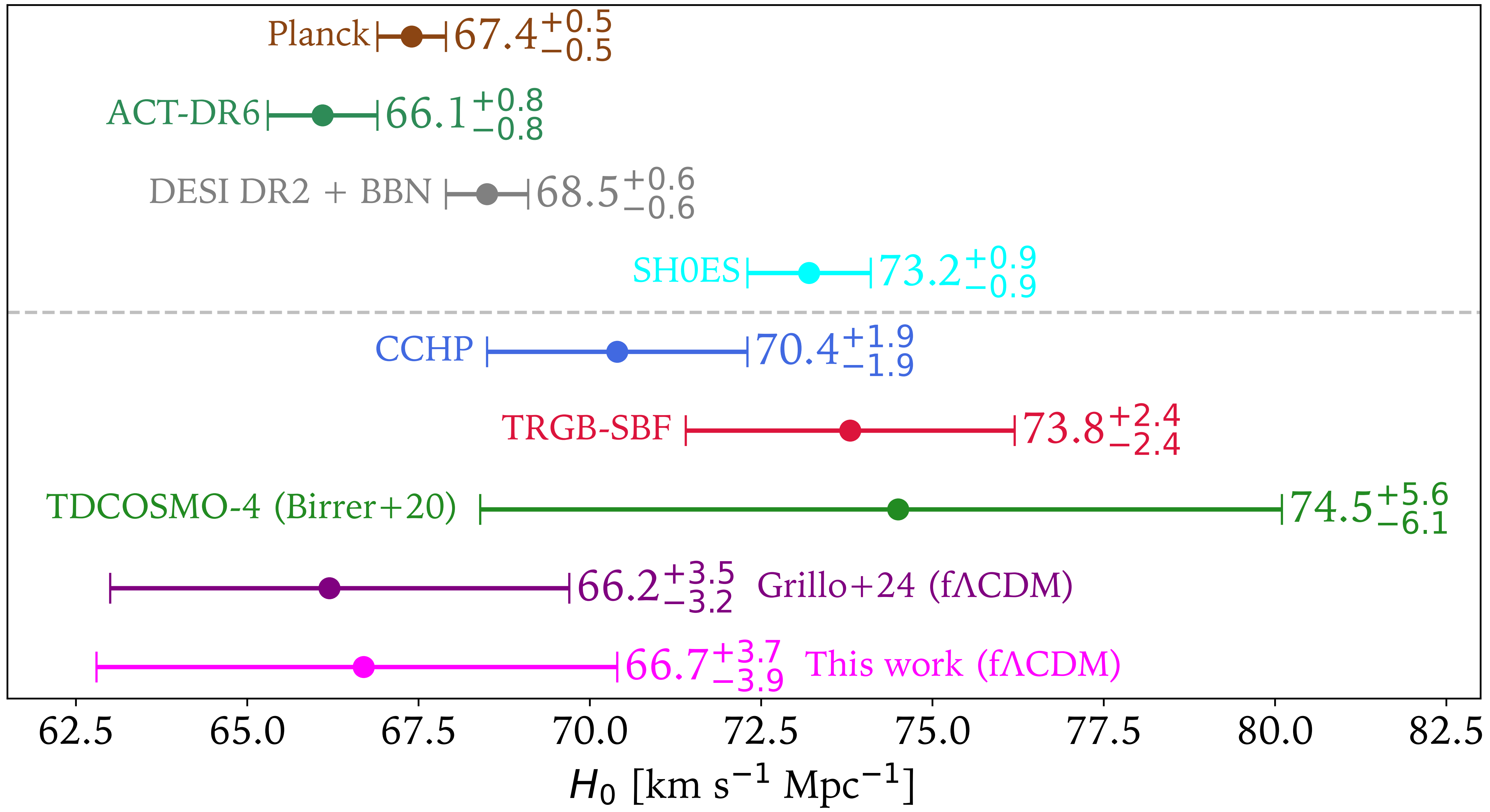
Predictions on SX: position and time-delay

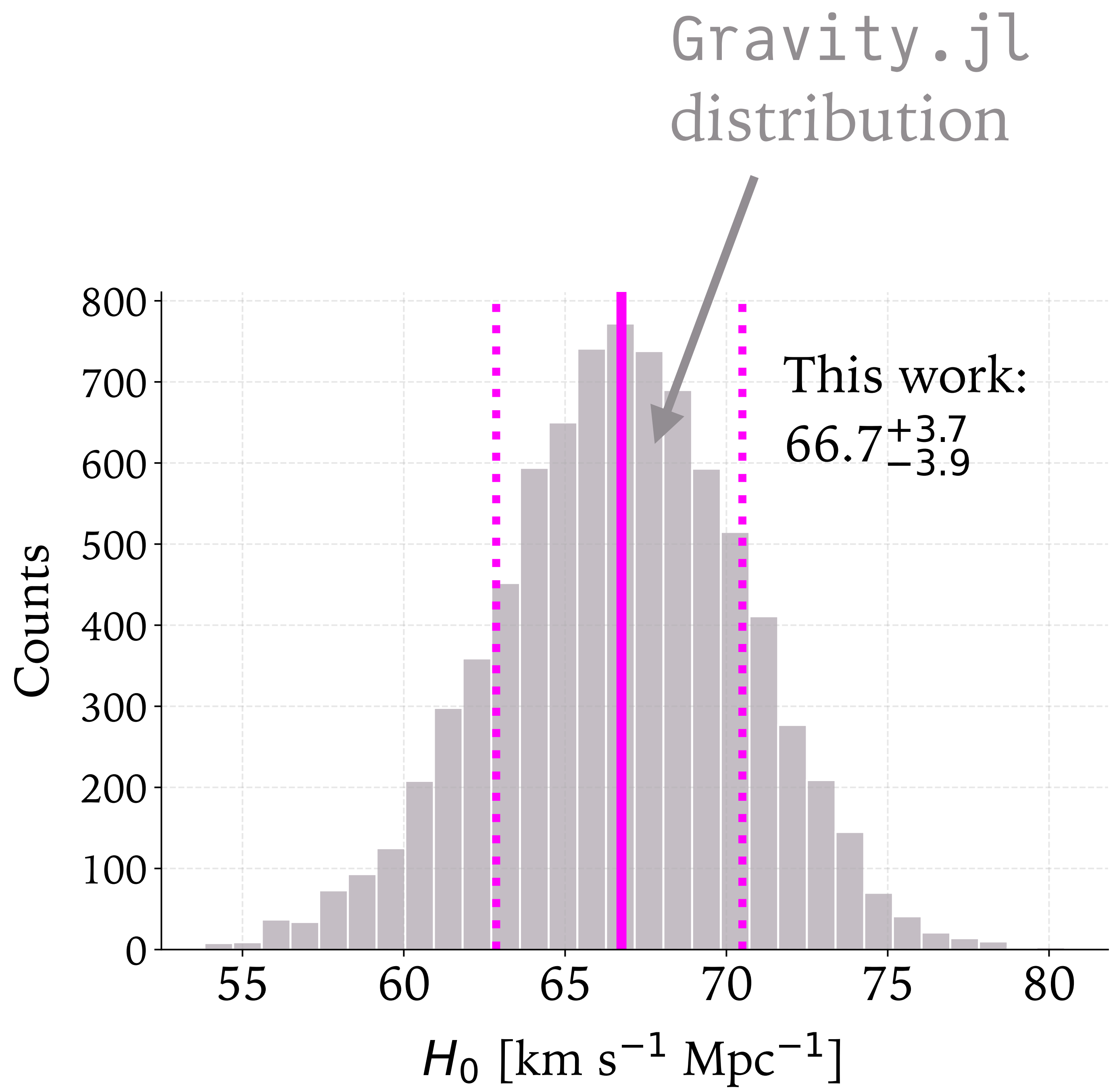
Our Gravity.jl model is able to reproduce Grillo et al., 2016 results!

MACSJ1149: SL model with `Gravity.jl`

2. With the same mass model, we include SX position and S1—SX time-delay measurements as additional constraints, leaving H_0 as a free parameter (flat ΛCDM with $\Omega_m = 0.3$).

Inference of H_0

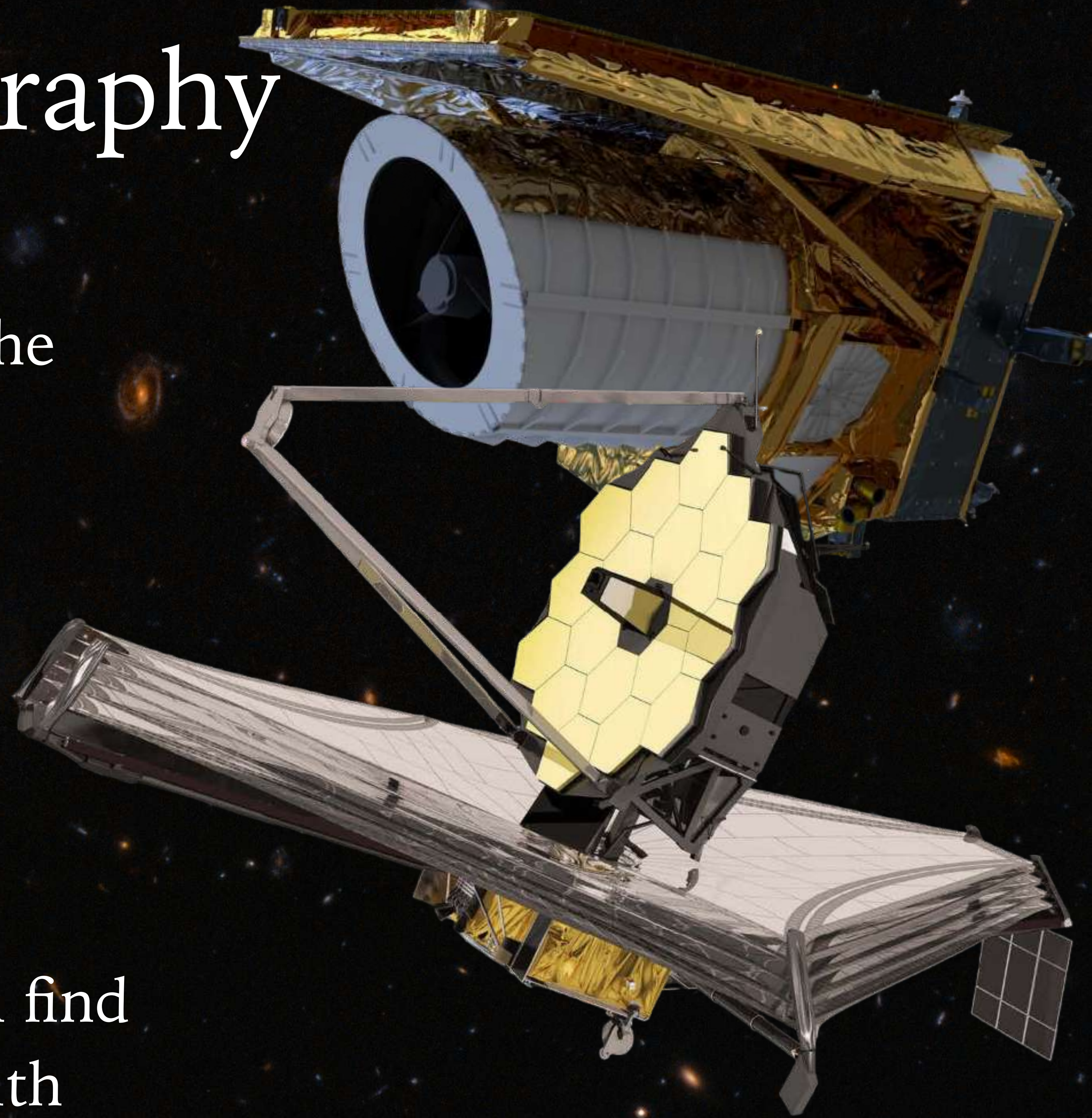




Posterior on H_0 for MACSJ1149 from `Gravity.jl`

Our Gravity.jl model is able to reproduce Grillo et al., 2024 results!

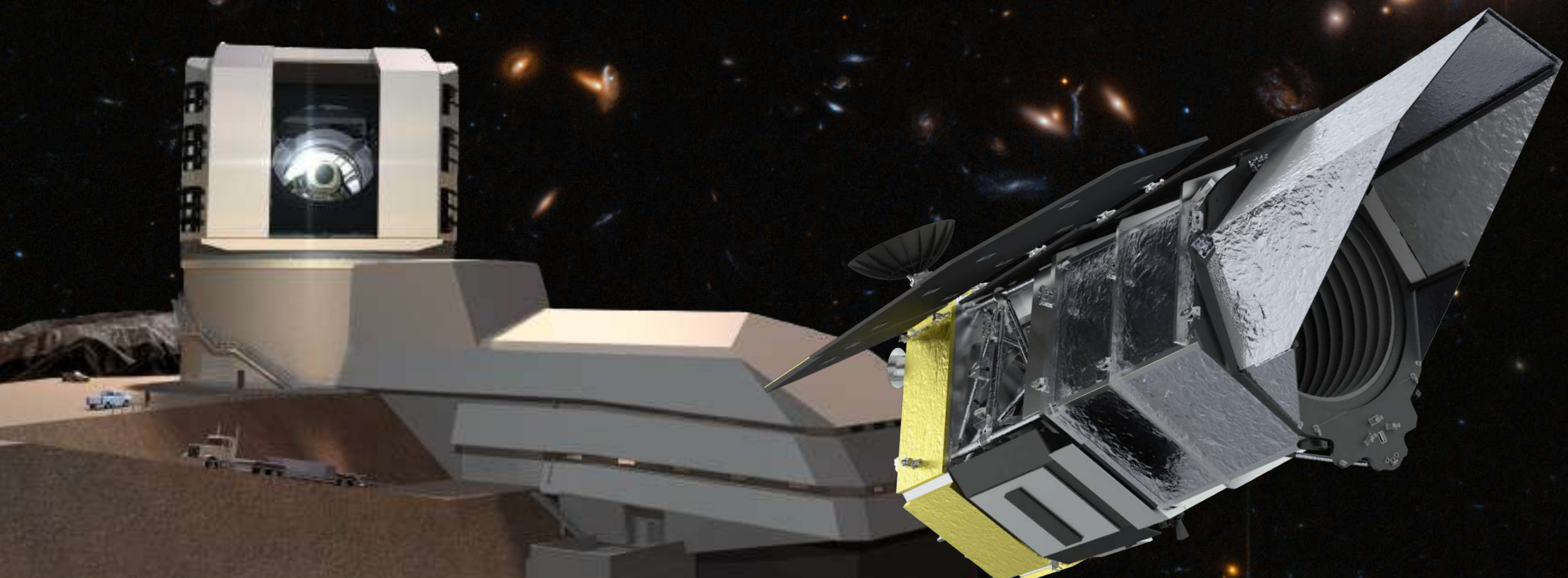
Future prospects for cosmography



`Gravity.jl` promises to be a competitive strong lens modelling package in the upcoming era of high-volume, high-quality SL data.

- James Webb Space Telescope will provide a number of SL constraints ~ 1000 in massive clusters vs $\lesssim$100 in the HST era

- Euclid (2023) and,
- Nancy Grace Roman Space Telescope (2027) will find thousands lenses (on galaxy and cluster scale) with multiply imaged quasars



- Vera Rubin Observatory (2025) will provide light curves of bright multiply imaged quasars, but also discover tens of lensed supernovae

Thanks for the attention!