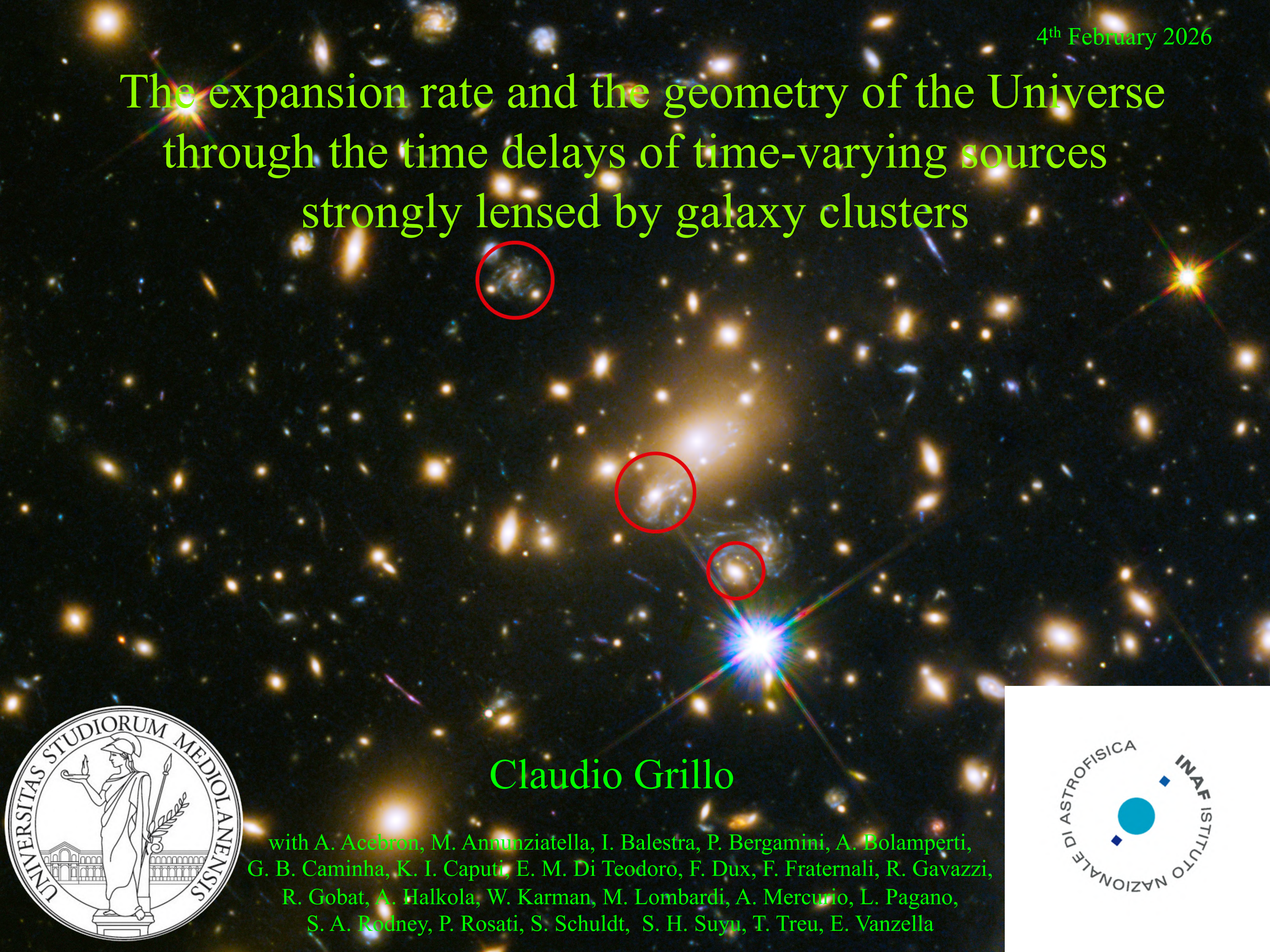


4th February 2026

The expansion rate and the geometry of the Universe through the time delays of time-varying sources strongly lensed by galaxy clusters

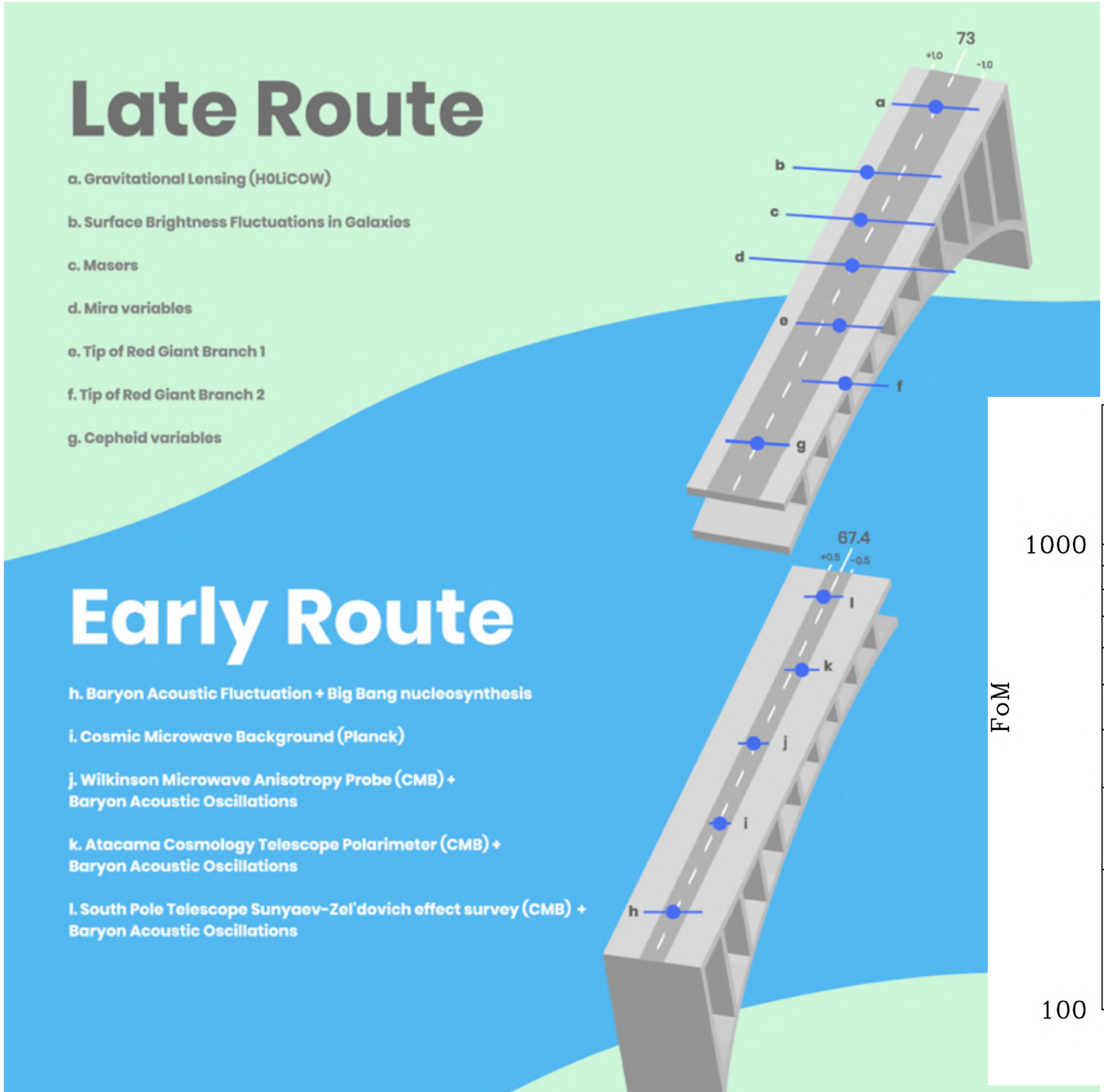
Claudio Grillo

with A. Acebron, M. Annunziatella, I. Balestra, P. Bergamini, A. Bolamperti, G. B. Caminha, K. I. Caputi, E. M. Di Teodoro, F. Dux, F. Fraternali, R. Gavazzi, R. Gobat, A. Halkola, W. Karman, M. Lombardi, A. Mercurio, L. Pagano, S. A. Rodney, P. Rosati, S. Schuldt, S. H. Suyu, T. Treu, E. Vanzella

UNIVERSITAS STUDIORUM MEDIOLANENSIS

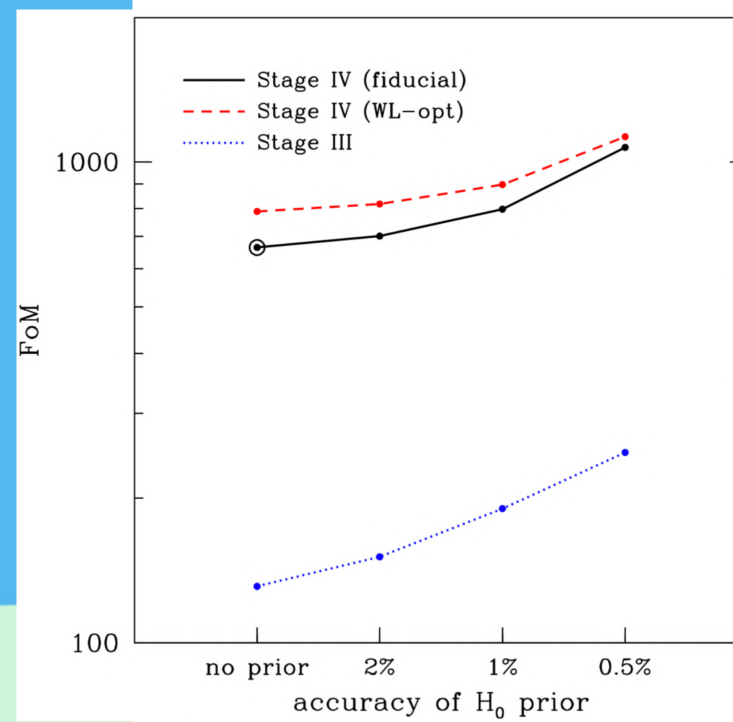
INAF ISTITUTO NAZIONALE DI ASTROFISICA

The H_0 problem



Riess 2019, NatRP, 2, 10

- Knowing the value of H_0 to ~1% will increase by ~40% the FoM of any stage-IV cosmological experiment, like Rubin and Euclid



Weinberg, Mortonson, Eisenstein, et al. 2013, PhR, 530, 87

Refsdal's idea in 1964

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

Sjur Refsdal

(Communicated by H. Bondi)

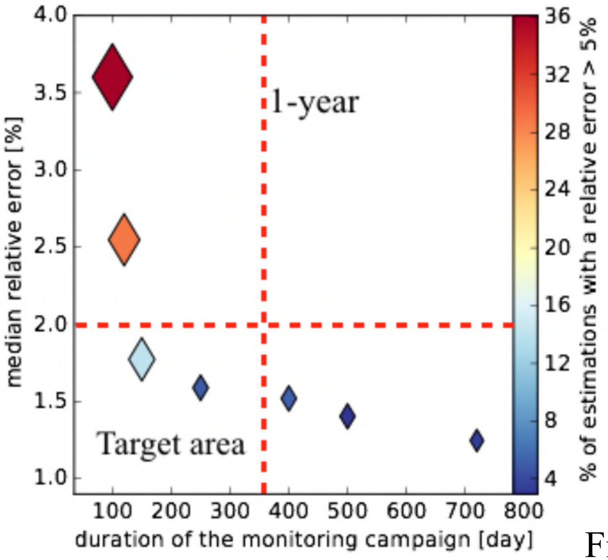
(Received 1964 January 27)

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.

Refsdal S. 1964, MNRAS, 128, 307

Where we stand



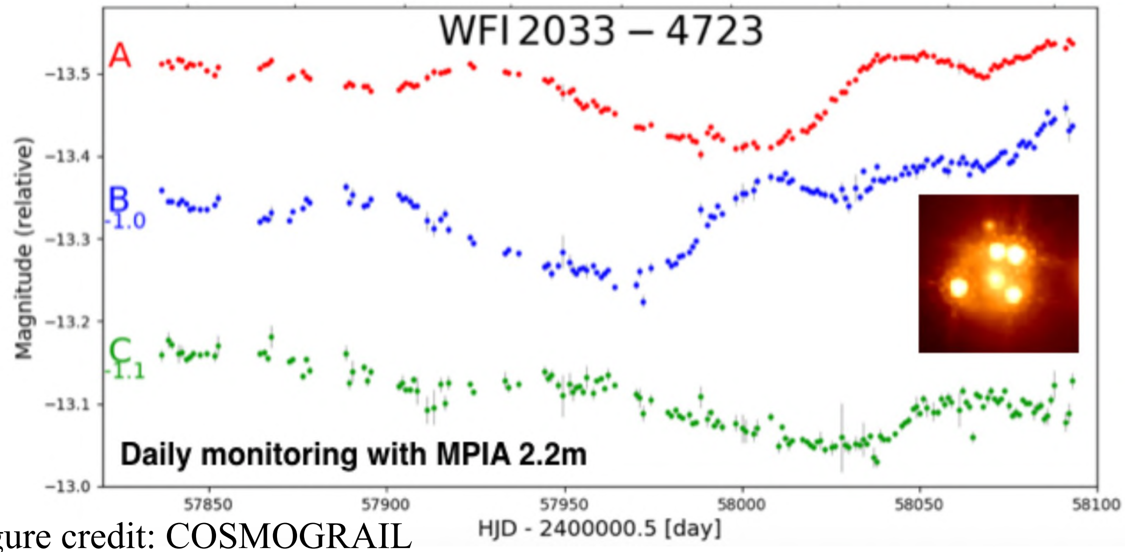


Figure credit: COSMOGRAIL

- COSMOGRAIL (COSmological MOnitoring of GRAvItational Lenses; PI: Courbin): LP with VST since P103 (4 periods; total 728 hours): time delays in 6 more galaxy-scale strong lenses
- H0LiCOW (H_0 Lenses in COSMOGRAIL's Wellspring; PI: Suyu) H_0 measured with 2.4% precision from 6 galaxy-scale strong lenses

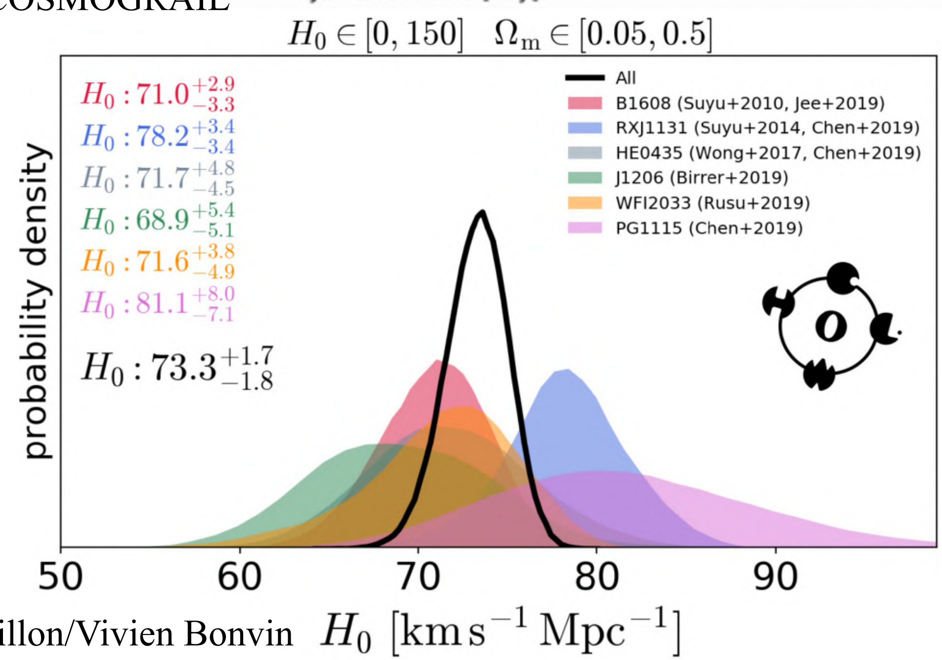


Figure credit: Martin Millon/Vivien Bonvin

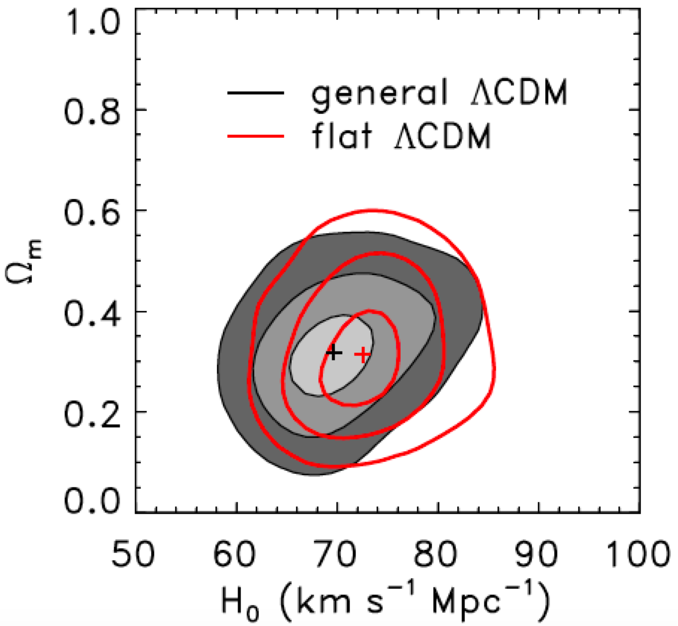
Wong, Suyu, Chen, et al. 2020, MNRAS, 498, 1420

Why strong lensing in galaxies and galaxy clusters?

❖ We can measure the expansion rate and the geometry of the Universe

✓ Image positions at different redshifts ➔ Ω_m, $\Omega_{\Lambda/DE}$, w

✓ Time delays of images of a source ➔ H_0, Ω_m, $\Omega_{\Lambda/DE}$, w



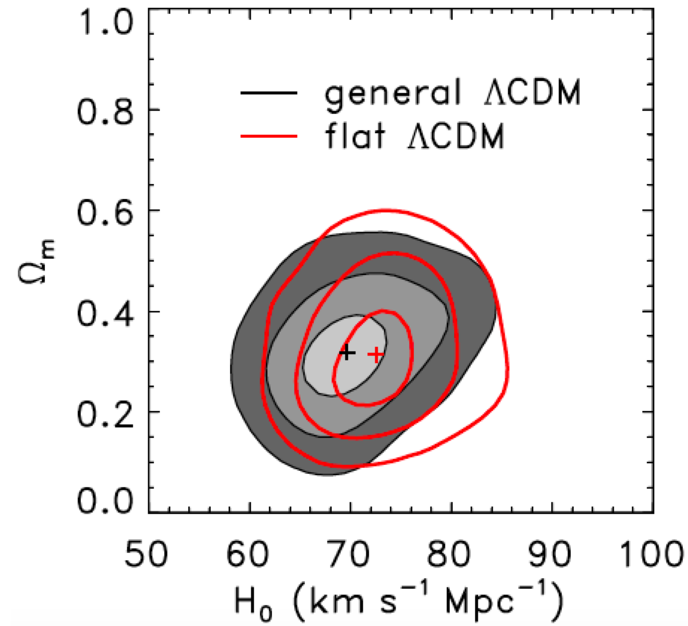
Grillo, Rosati, Suyu, et al. 2018, ApJ, 860, 94

Why strong lensing in galaxies and galaxy clusters?

❖ We can measure the expansion rate and the geometry of the Universe

✓ Image positions at different redshifts ➔ Ω_m, $\Omega_{\Lambda/DE}$, w

✓ Time delays of images of a source ➔ H_0, Ω_m, $\Omega_{\Lambda/DE}$, w



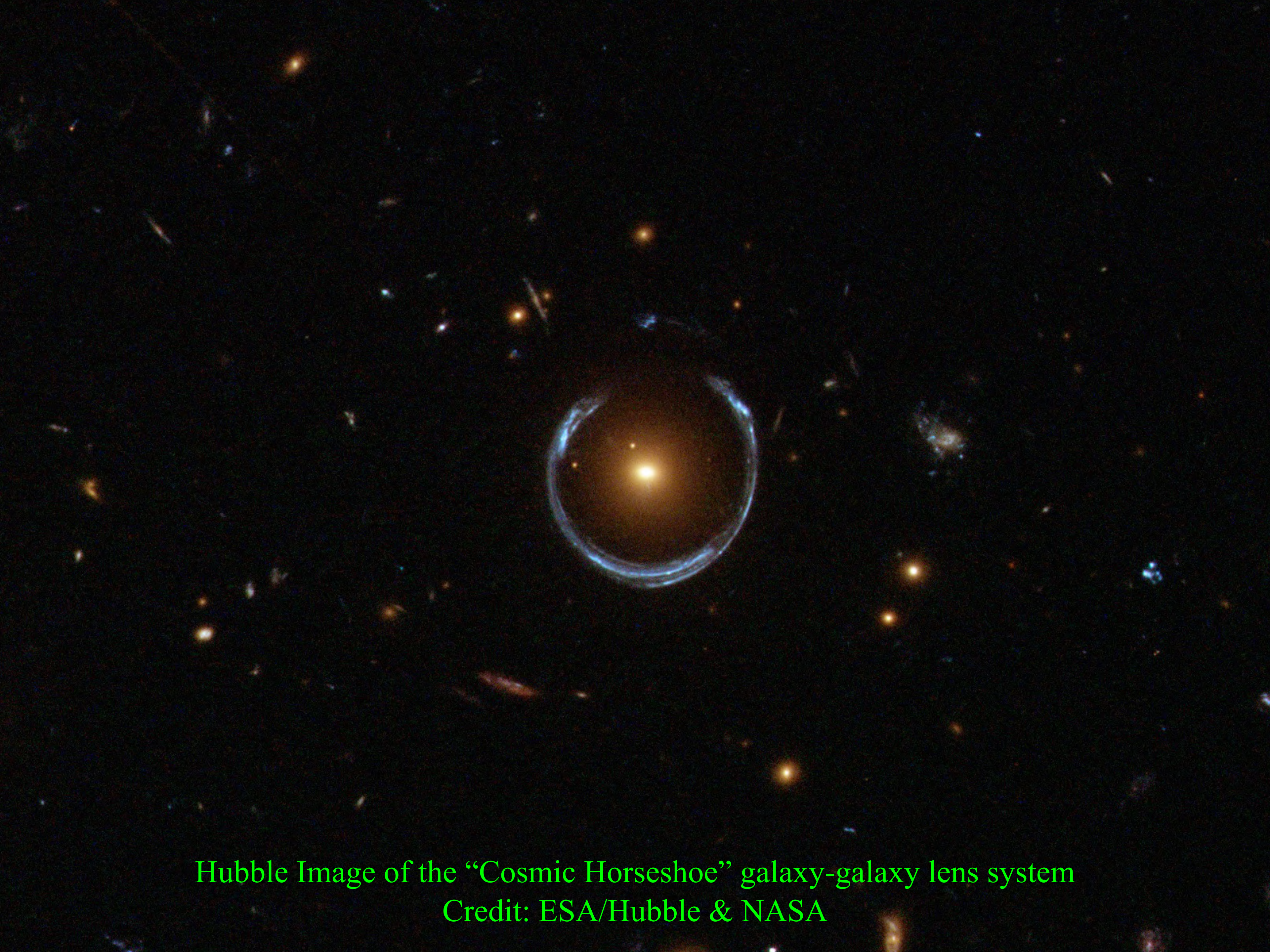
Grillo, Rosati, Suyu, et al. 2018, ApJ, 860, 94

❑ Well-known physics (General Relativity)

❑ No priors (completely independent) from other techniques

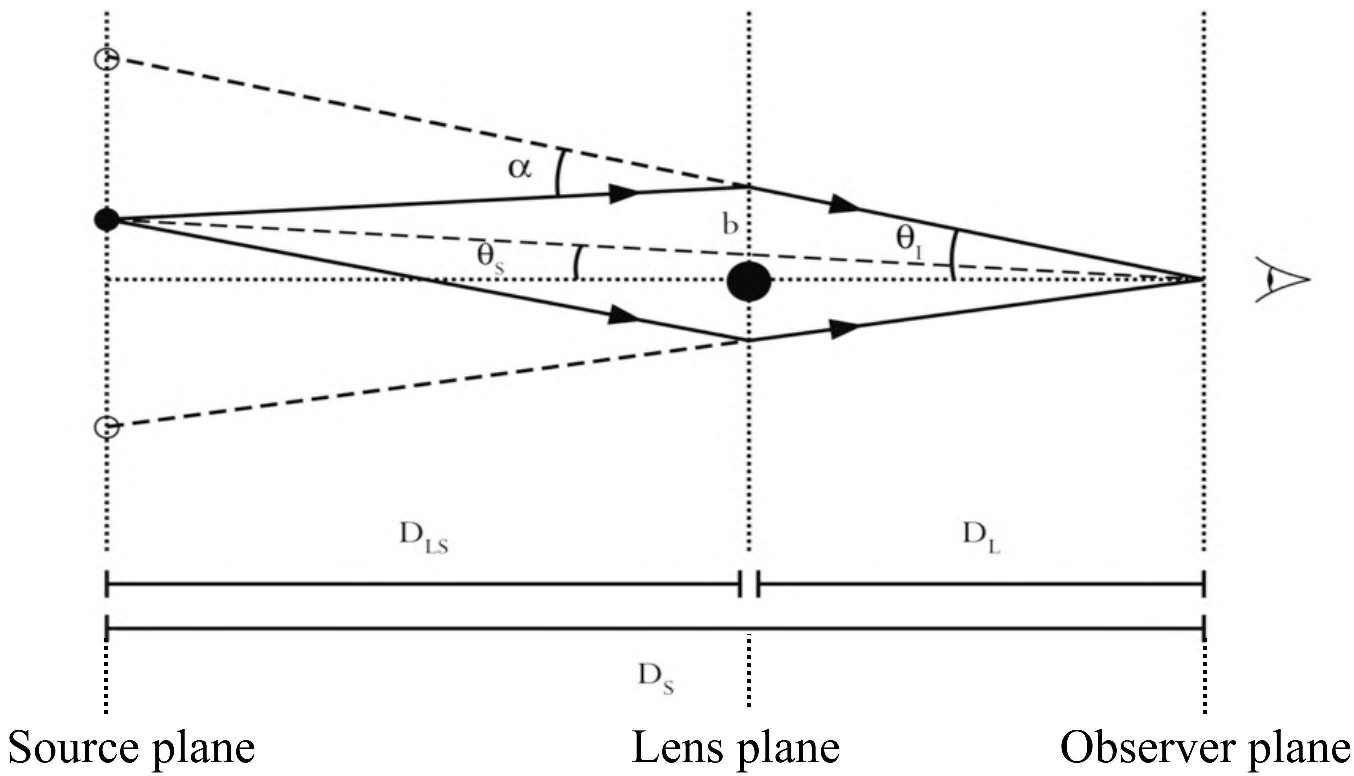
❑ One-step method, without intermediate calibrations

❑ “Mid-universe” probe

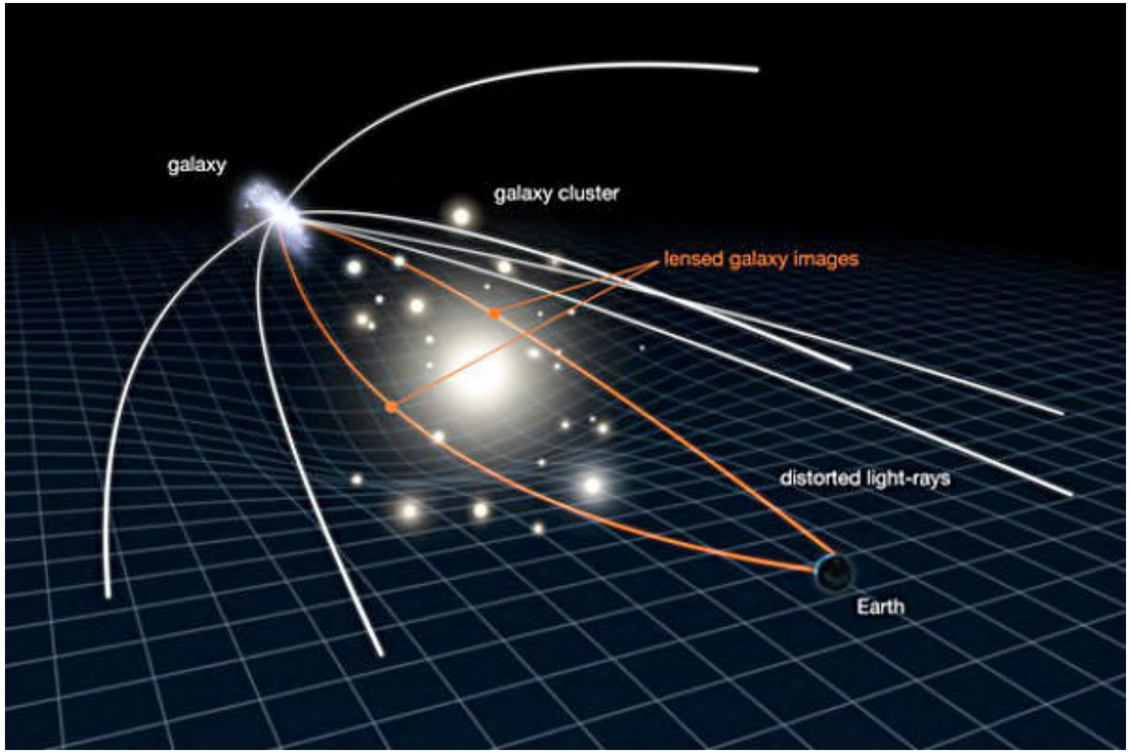


Hubble Image of the “Cosmic Horseshoe” galaxy-galaxy lens system
Credit: ESA/Hubble & NASA

Strong gravitational lensing I



Gravitational lensing time delay



Time delay between 2 images: $\Delta t_{i_1 i_2} = \frac{D_{\Delta t}}{c} \Delta \phi_{i_1 i_2}$

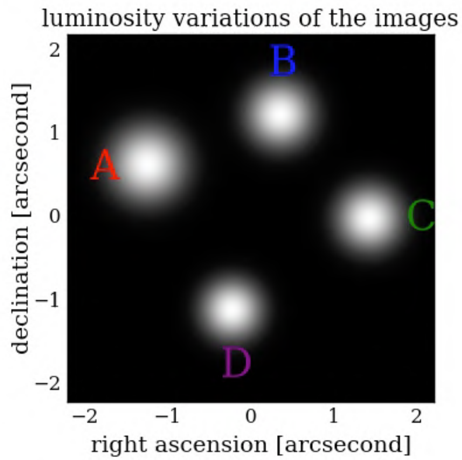
✓ Simple geometry and well-understood physics

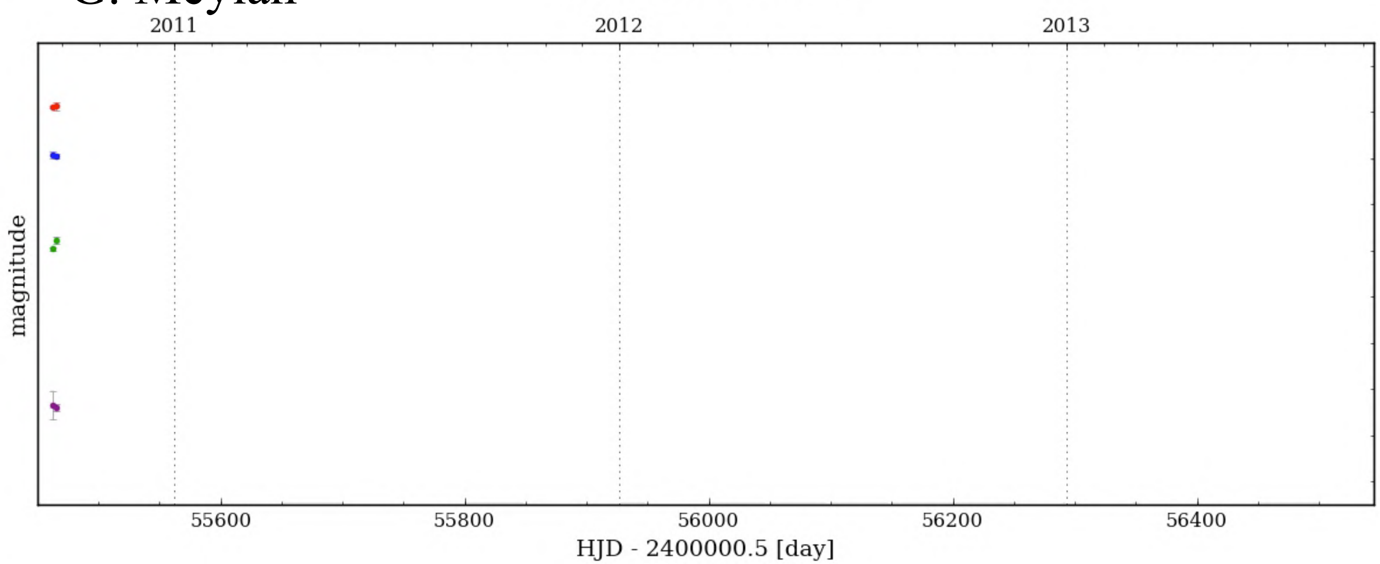
Time-delay distance: $D_{\Delta t}(z_{\rm d}, z_{\rm s}) = (1 + z_{\rm d}) \frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}}$

✓ One-step measurement of a cosmological distance, thus of H_0

Time delay measurements I

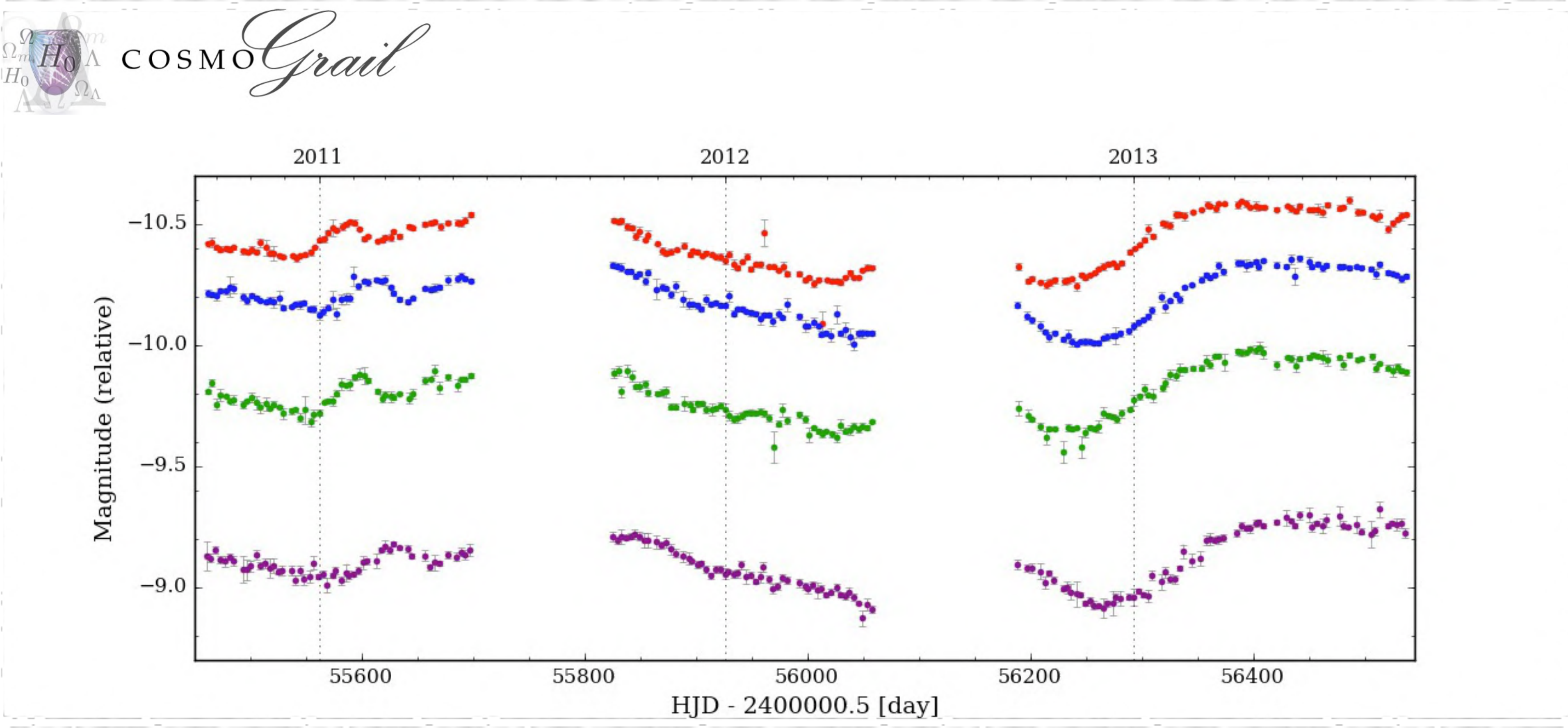
COSmological
MOnitoring of
GRAv**I**tational
Lenses;
PI: F. Courbin,
G. Meylan





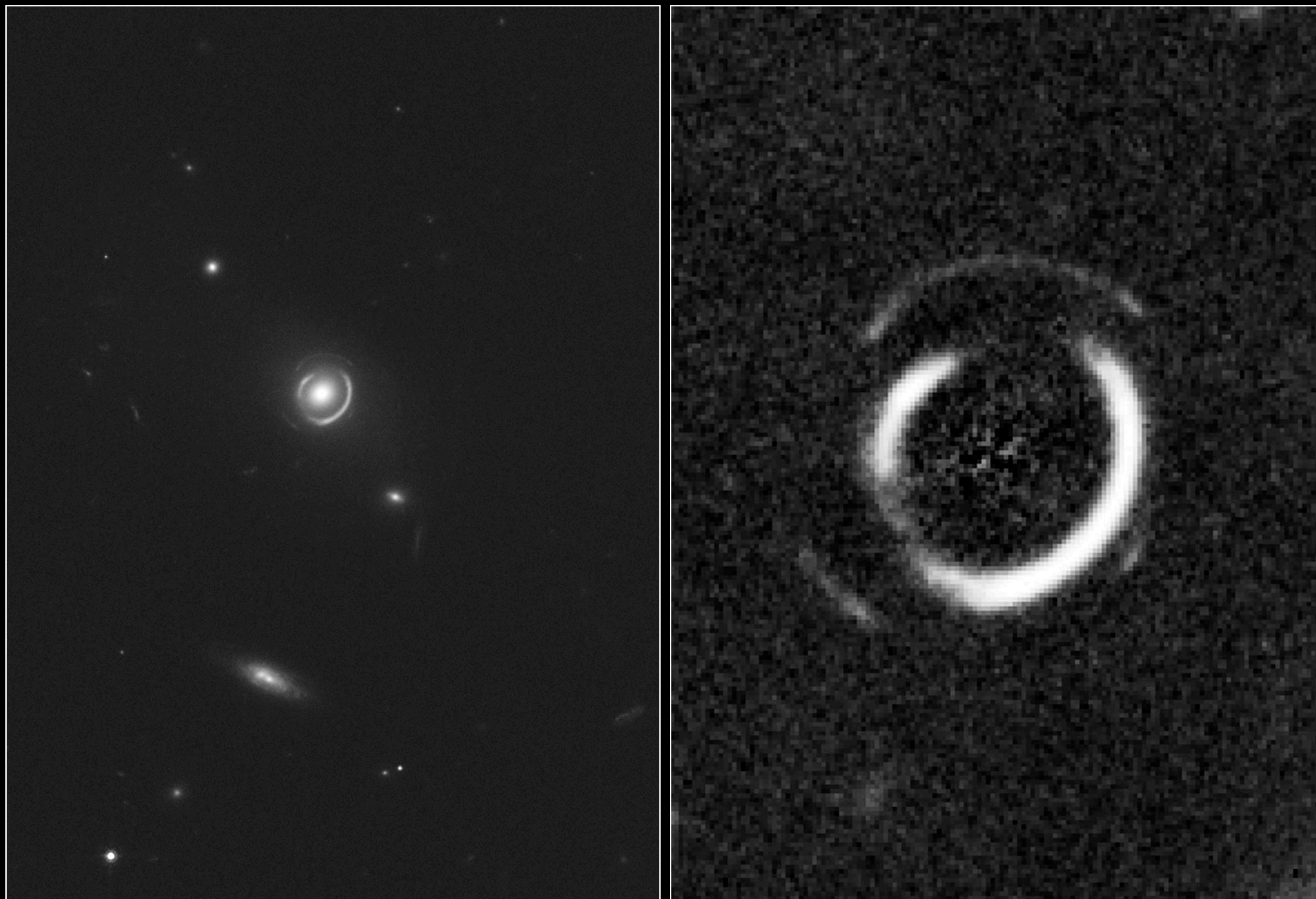
Credit: V. Bonvin

Time delay measurements II



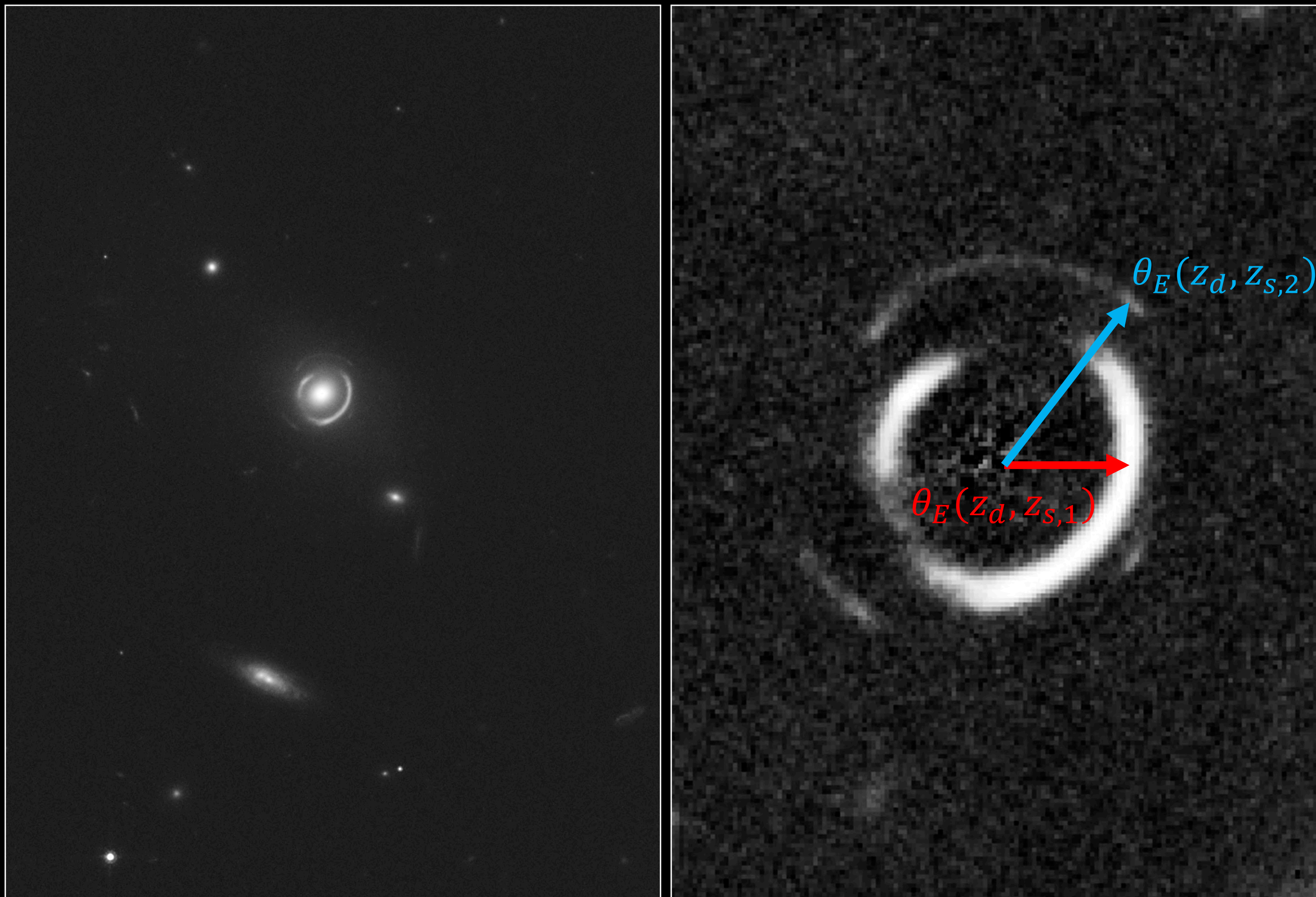
Credit: V. Bonvin

Double Einstein Ring SDSSJ0946+1006 *Hubble Space Telescope* ▪ ACS/WFC



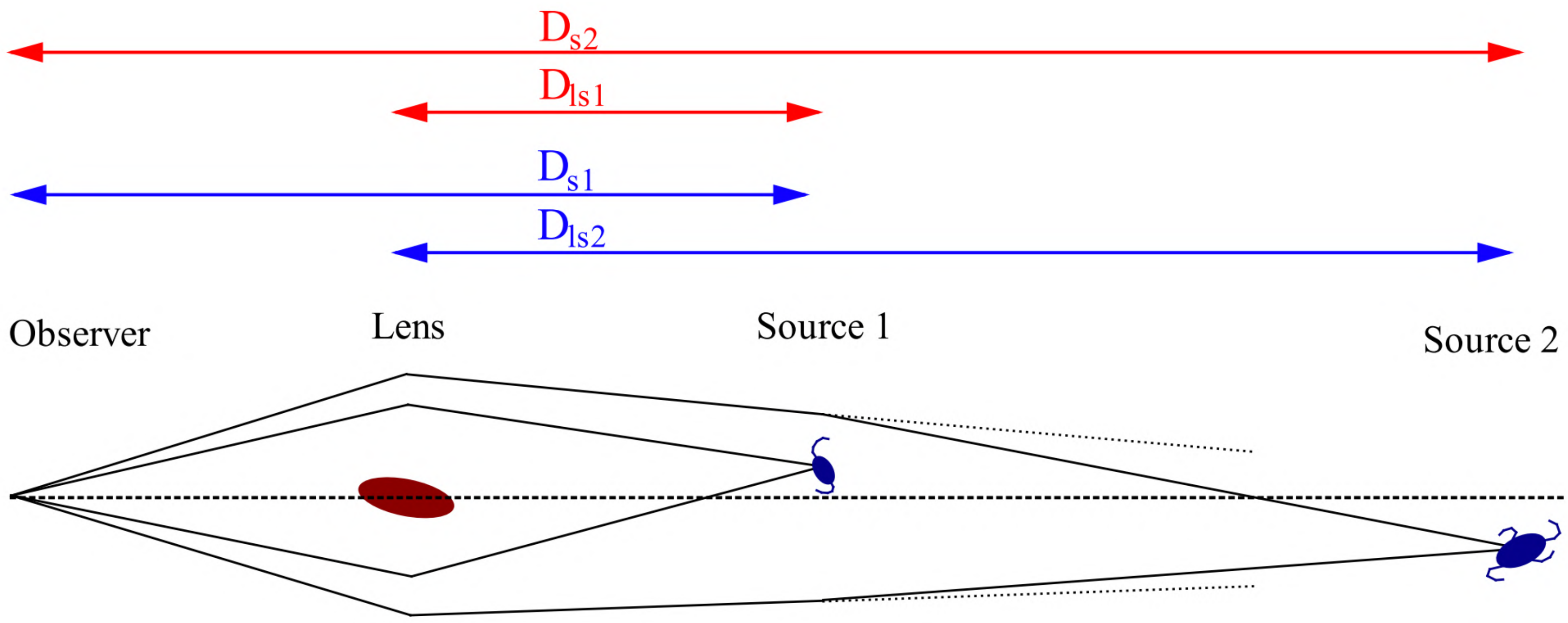
NASA, ESA, R. Gavazzi and T. Treu (University of California, Santa Barbara), and the SLACS Team STScI-PRC08-04

Double Einstein Ring SDSSJ0946+1006 *Hubble Space Telescope* ▪ ACS/WFC



NASA, ESA, R. Gavazzi and T. Treu (University of California, Santa Barbara), and the SLACS Team STScI-PRC08-04

Strong lensing with multiple sources



Collett & Auger 2014, MNRAS, 443, 969

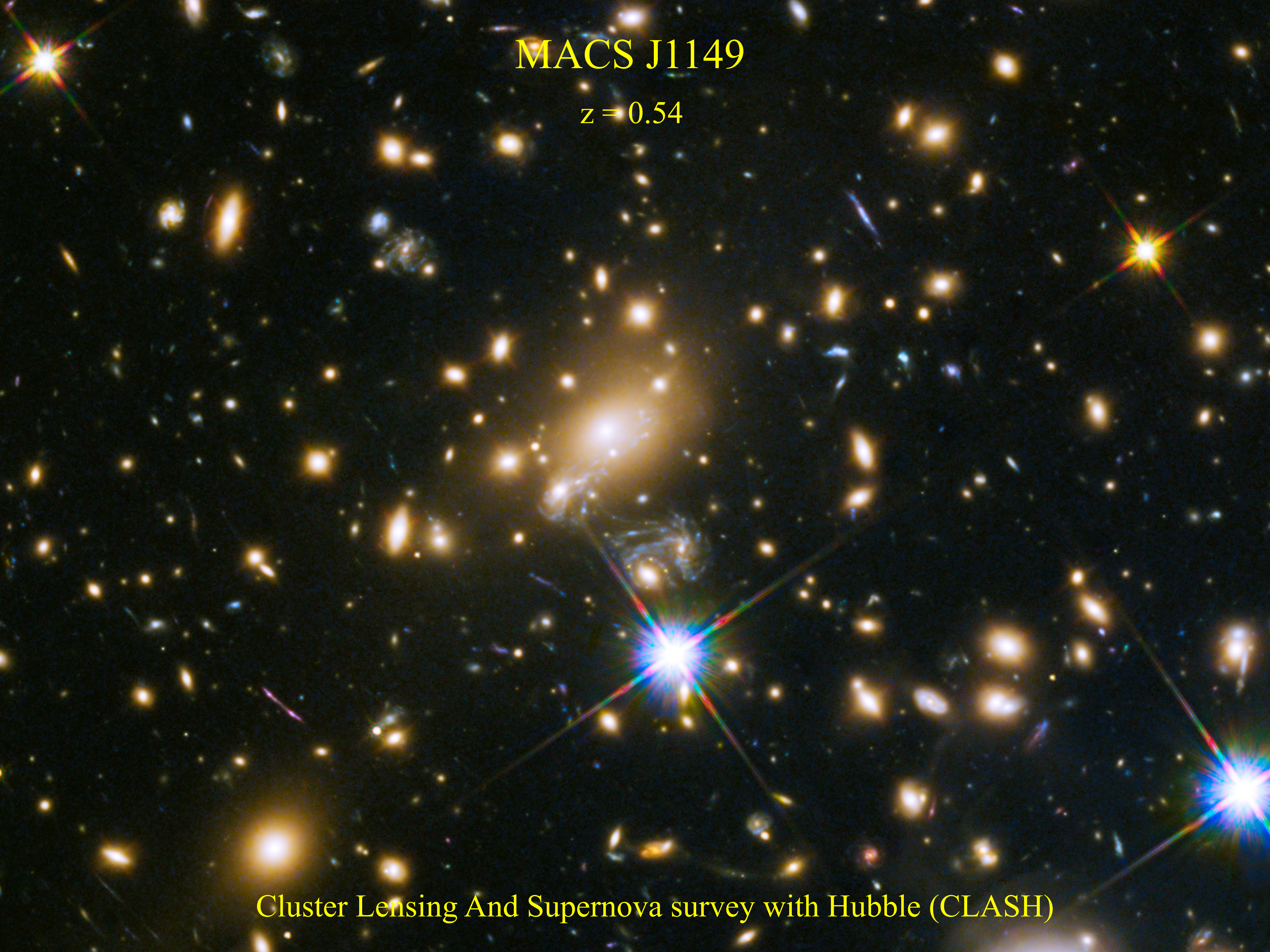
Einstein-radius ratio:

$$\frac{\theta_E(z_d, z_{s,1})}{\theta_E(z_d, z_{s,2})} = \sqrt{\frac{M[\theta_E(z_d, z_{s,1})]}{M[\theta_E(z_d, z_{s,2})]} \frac{D_{ds}(z_d, z_{s,1})}{D_s(z_{s,1})} \frac{D_s(z_{s,2})}{D_{ds}(z_d, z_{s,2})}}.$$

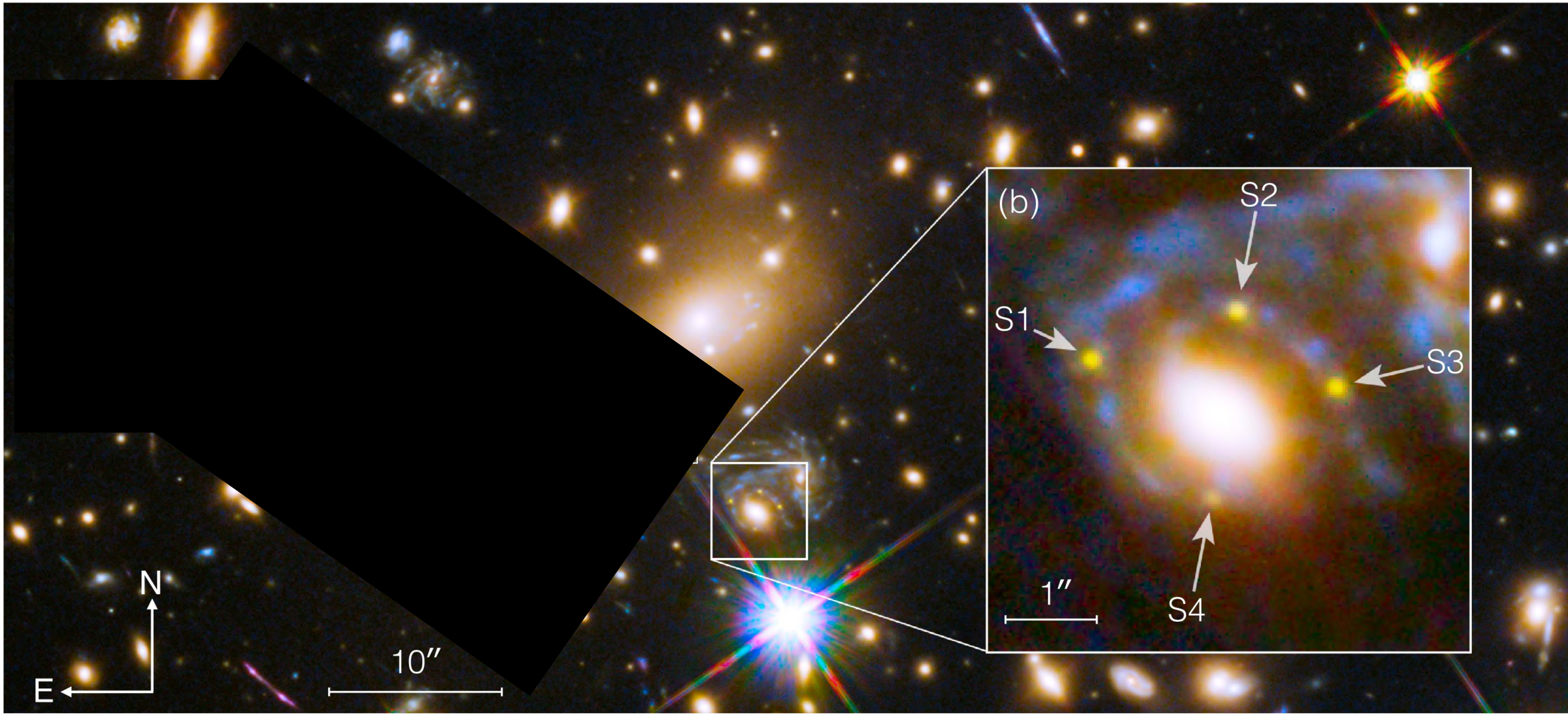
Family ratio:

$$\Xi(z_d, z_{s,1}, z_{s,2}) = \frac{D_{ds}(z_d, z_{s,1})}{D_s(z_{s,1})} \frac{D_s(z_{s,2})}{D_{ds}(z_d, z_{s,2})}$$

Bolamperti, Grillo, Caminha, et al. 2024, A&A, 692, 239


MACS J1149
z = 0.54
Cluster Lensing And Supernova survey with Hubble (CLASH)

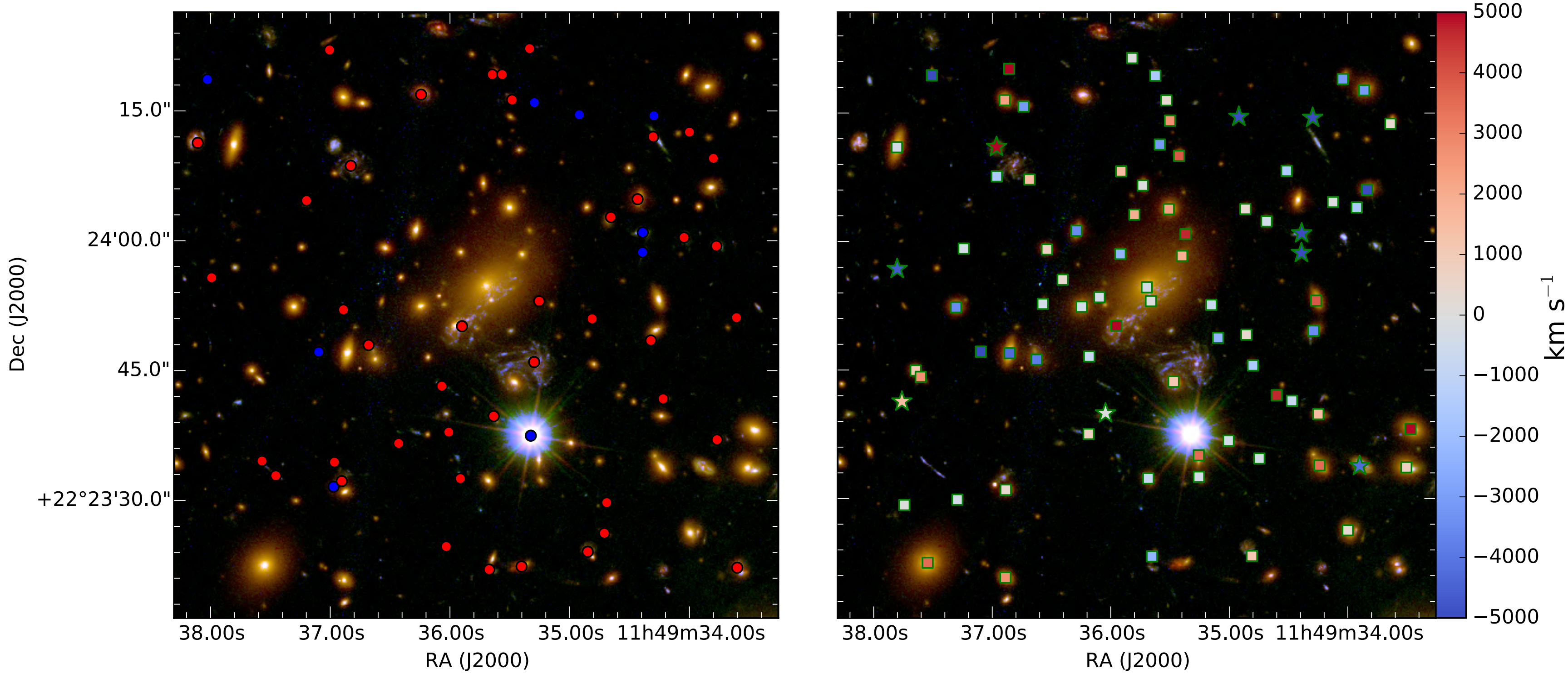
The first multiply-imaged spatially-resolved SN ('SN Refsdal') I



- Einstein cross (≈ 2" diameter), 4 multiple images (S1-S4), at z = 1.489, discovered in Nov. 2014

Kelly, Rodney, Treu, et al. 2015, Science, 347, 1123

The MUSE DDT proposal and data



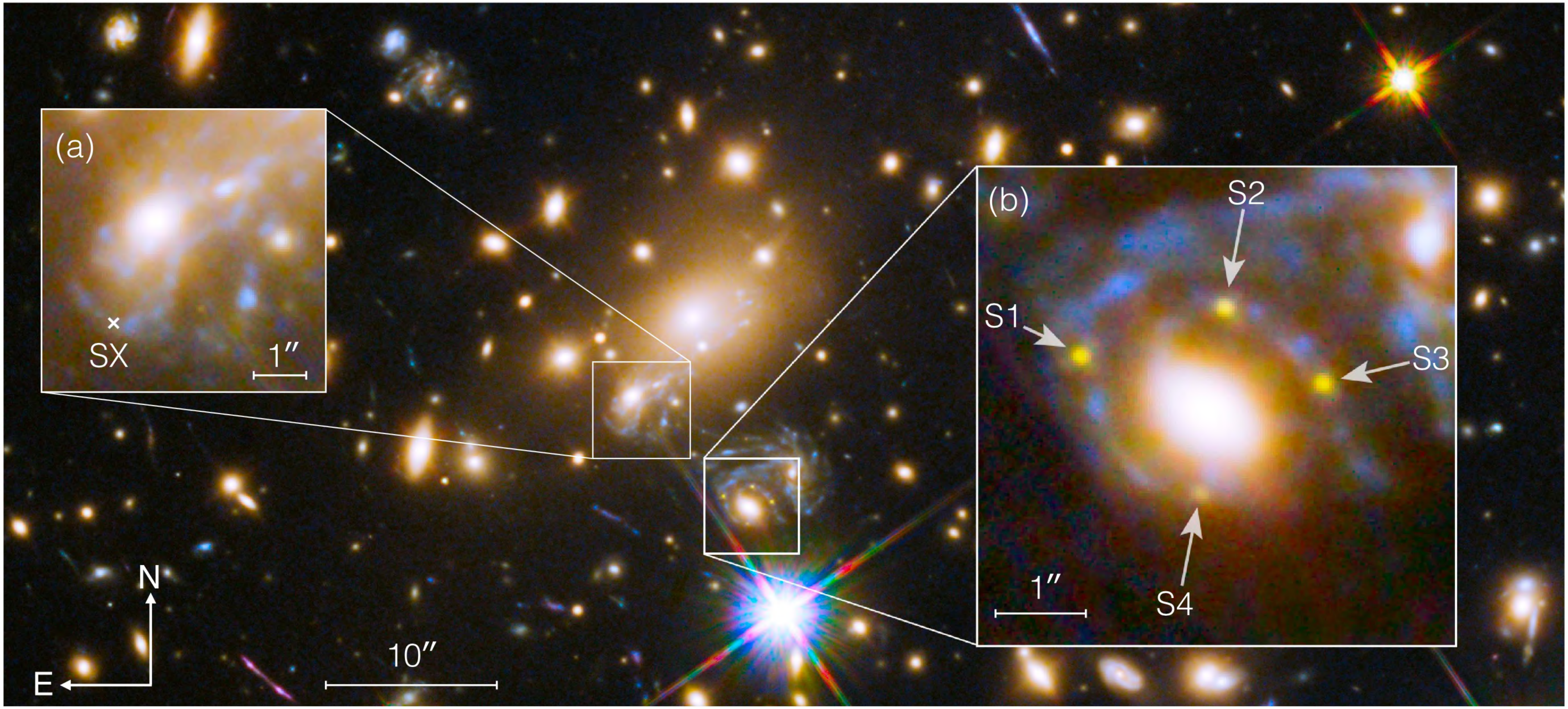
Grillo, Karman, Suyu, et al. 2016, ApJ, 822, 78

muse

MACS J1149 [1 pointing, 6 hr (4.8 hr total integration time], obtained in Feb.-Mar. 2015, with DDT 294.A-5032; PI: C. Grillo):

- ❑ 117 secure redshifts
- ❑ 6 foreground galaxies
- ❑ 68 cluster members ($z_d = 0.542$)
- ❑ 30 background galaxies
- ❑ 7 systems (4 LAEs) with 18 multiple images
- ❑ Highest z: 3.703

The first multiply-imaged spatially-resolved SN ('SN Refsdal') II

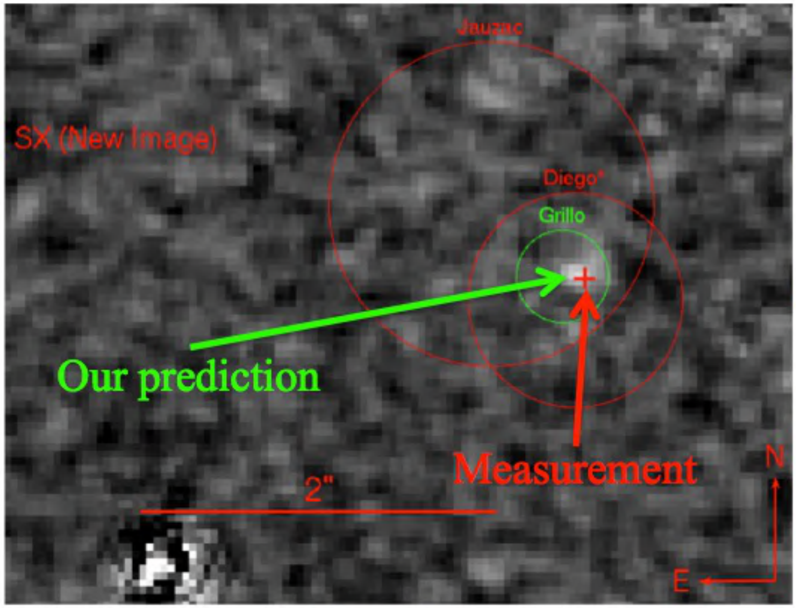


- Einstein cross (≈ 2" diameter), 4 multiple images (S1-S4), at z = 1.489, discovered in Nov. 2014

Kelly, Rodney, Treu, et al. 2015, Science, 347, 1123

- Reappearance, SX, detected in Dec. 2015

Kelly, Rodney, Treu, et al. 2016, ApJ, 819, 8



SX Position

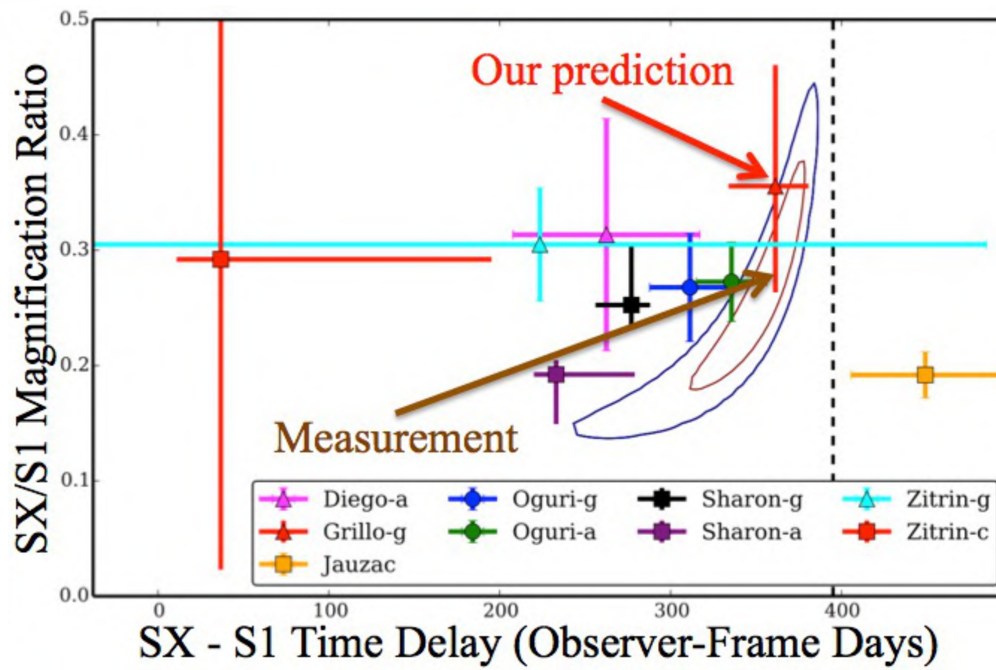
The reappearance of SN Refsdal

Kelly, Rodney, Treu, et al. 2016, 819, 8

Grillo, Karman, Suyu, et al. 2016, ApJ, 822, 78

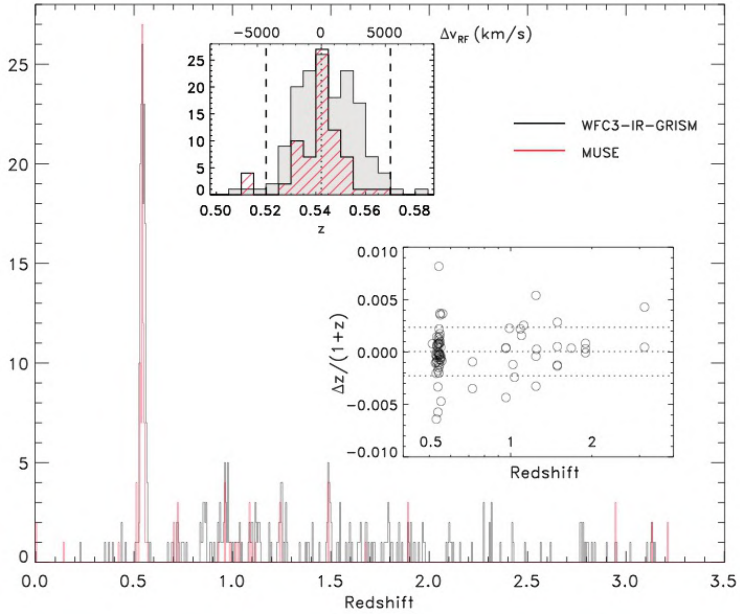
- The appearance of a distant supernova at a specific sky position and time successfully predicted in advance!
- Our model could predict the position, flux, and time delay within 1σ CL

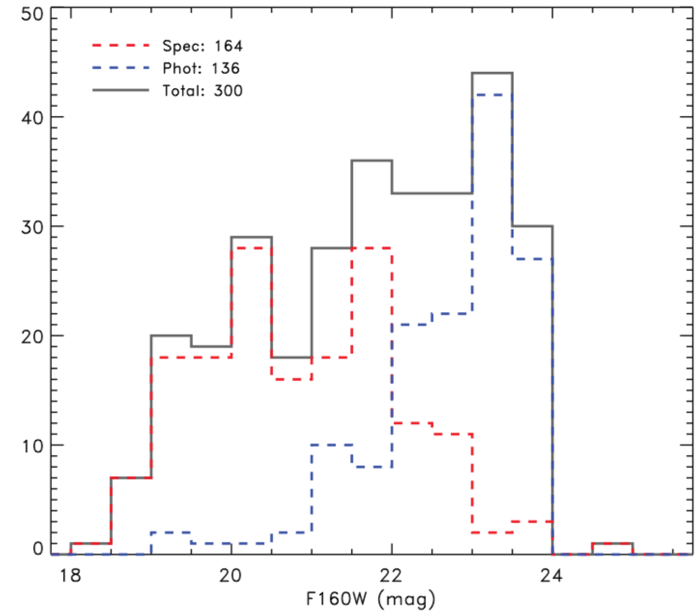
- If our strong lensing models can provide accurate predictions, our cluster total mass (dark matter+baryons) maps are likely to be very accurate!



Treu, Brammer, Diego, et al. 2016, ApJ, 817, 60

Our best-fitting strong lensing model

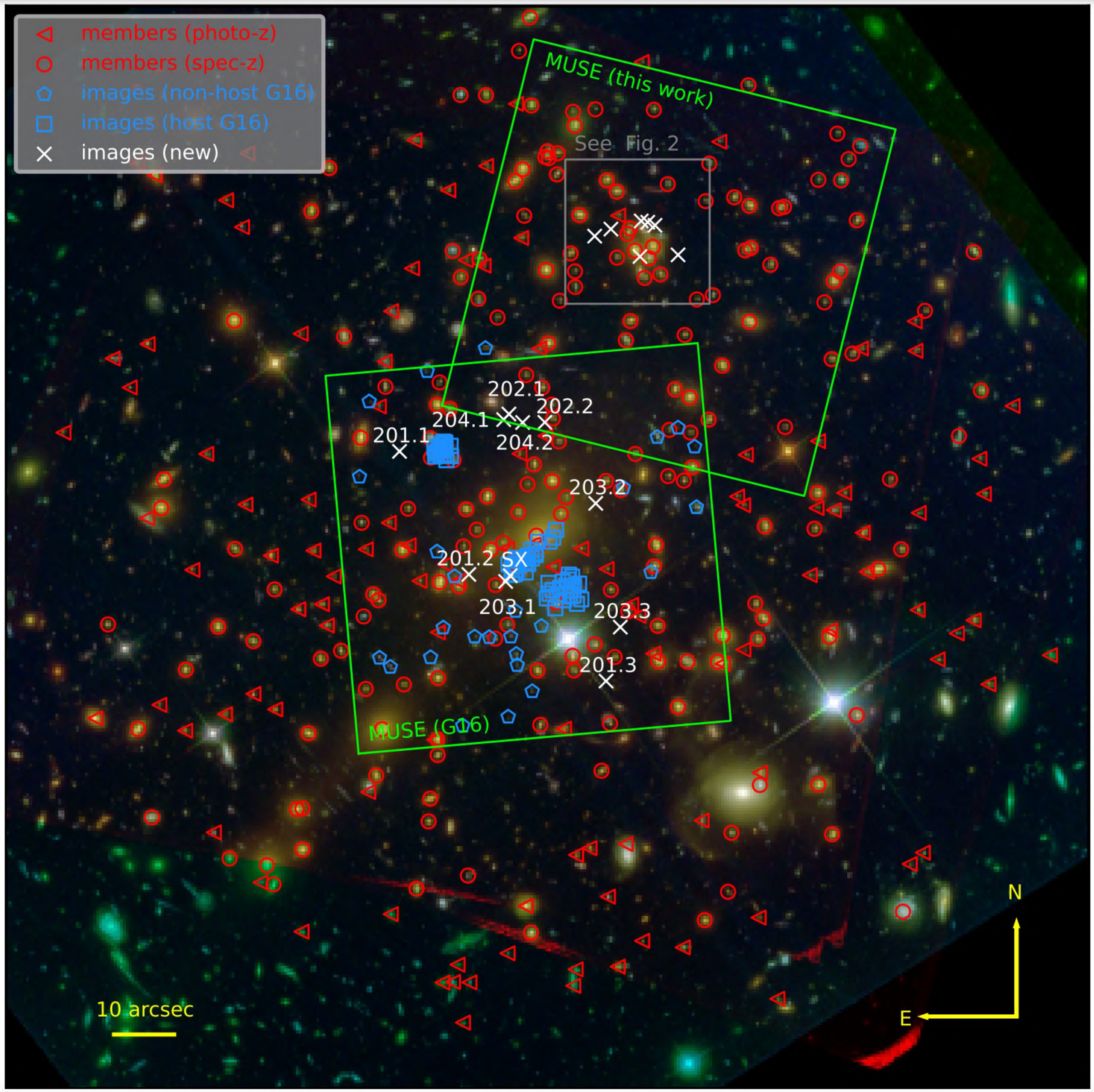




- 88 reliable multiple images from 10 different background sources (7 spectroscopic, z from 1.240 to 3.703, and 3 photometric) and 18 distinct knots in the SN Refsdal host
- 300 cluster members (CMs): 164 spectroscopic and 136 photometric
- We adopt truncated isothermal profiles for the 300 CMs and 3 cored elliptical isothermal profiles for the cluster haloes
- We scale the CM profiles with the F160W: $\sigma_0 \sim L^{0.35}$ & $r_t \sim L^{0.5}$ ➔ $M_T \sim \sigma_0^2 r_t \sim L^{0.7} L^{0.5} = L^{1.2}$ Mimic the Fundamental Plane M_T/L relation
- Strong lensing modelling with GLEE (Suyu & Halkola 2010; Suyu et al. 2012)
- The rms offset between observed and model-predicted multiple image positions is 0.26”

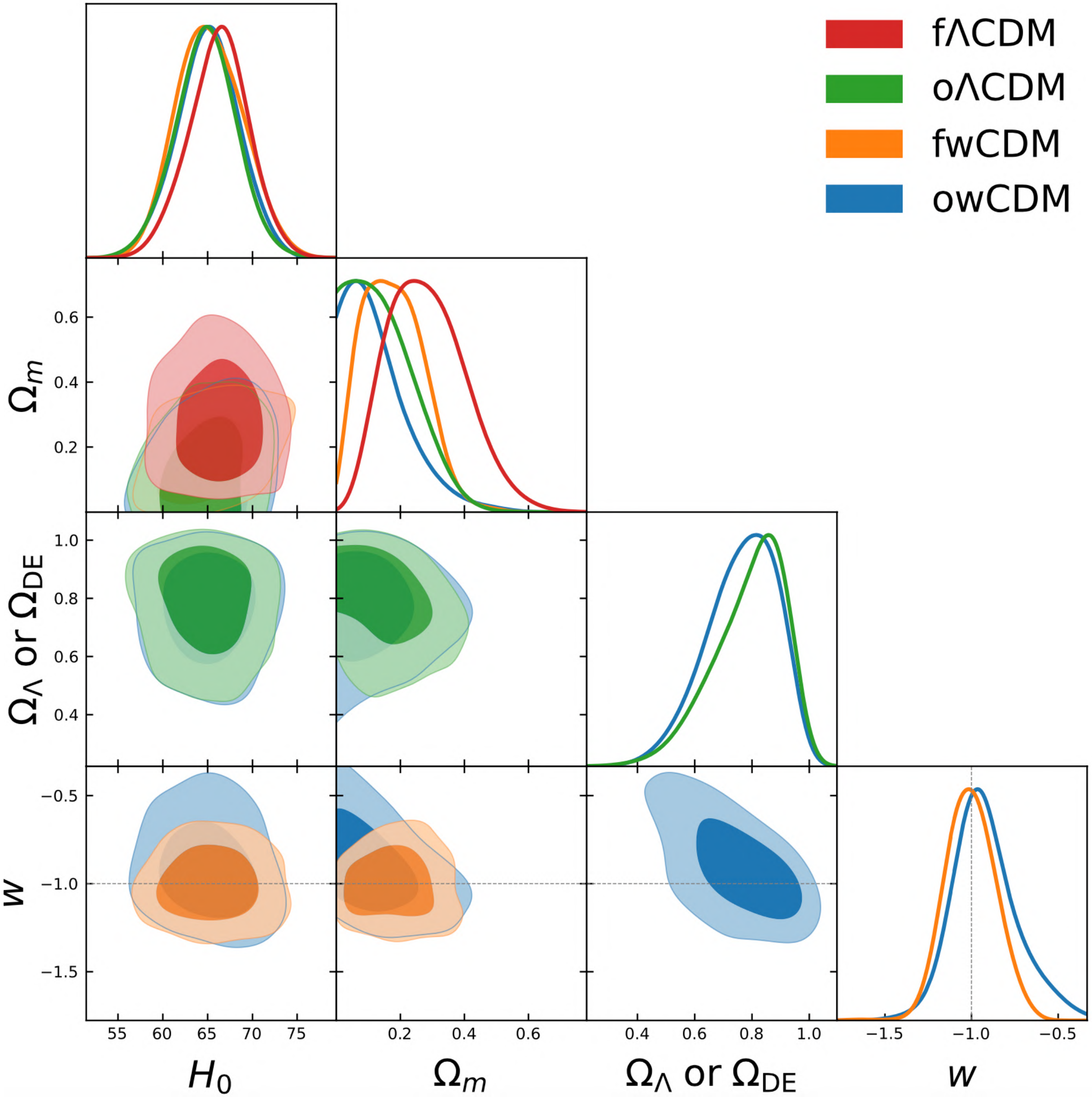
Grillo, Karman, Suyu, et al. 2016, ApJ, 822, 78

Improved strong lensing model of MACS J1149



Schuldt, Grillo, Caminha, et al. 2024, A&A, 689, 42

Measuring the values of the cosmological parameters I



❖ The measurements are very robust and do not depend significantly on the assumed cosmological model

❖ These results are complementary to and potentially competitive with those of other cosmological probes

Grillo, Pagano, Rosati & Suyu, 2024, A&A, 684, 23

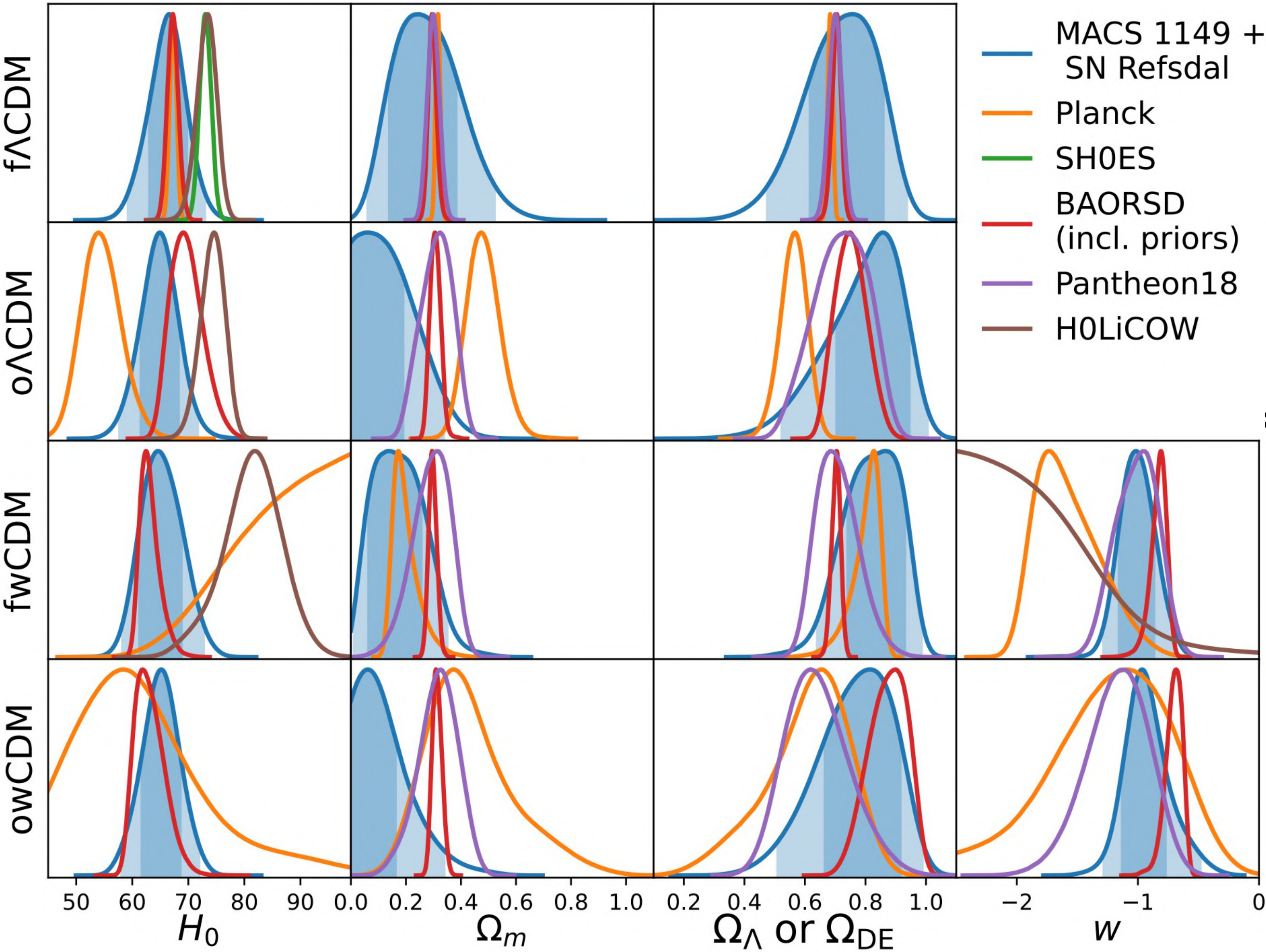
Measuring the values of the cosmological parameters II

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	$0.76^{+0.15}_{-0.10}$	$-0.92^{+0.15}_{-0.21}$

- In all models, the value of H_0 can be measured with $\lesssim$6% statistical error
- In flat and open *w*CDM models, the value of *w* can be measured with a ~20% statistical error

Grillo, Pagano, Rosati & Suyu, 2024, A&A, 684, 23

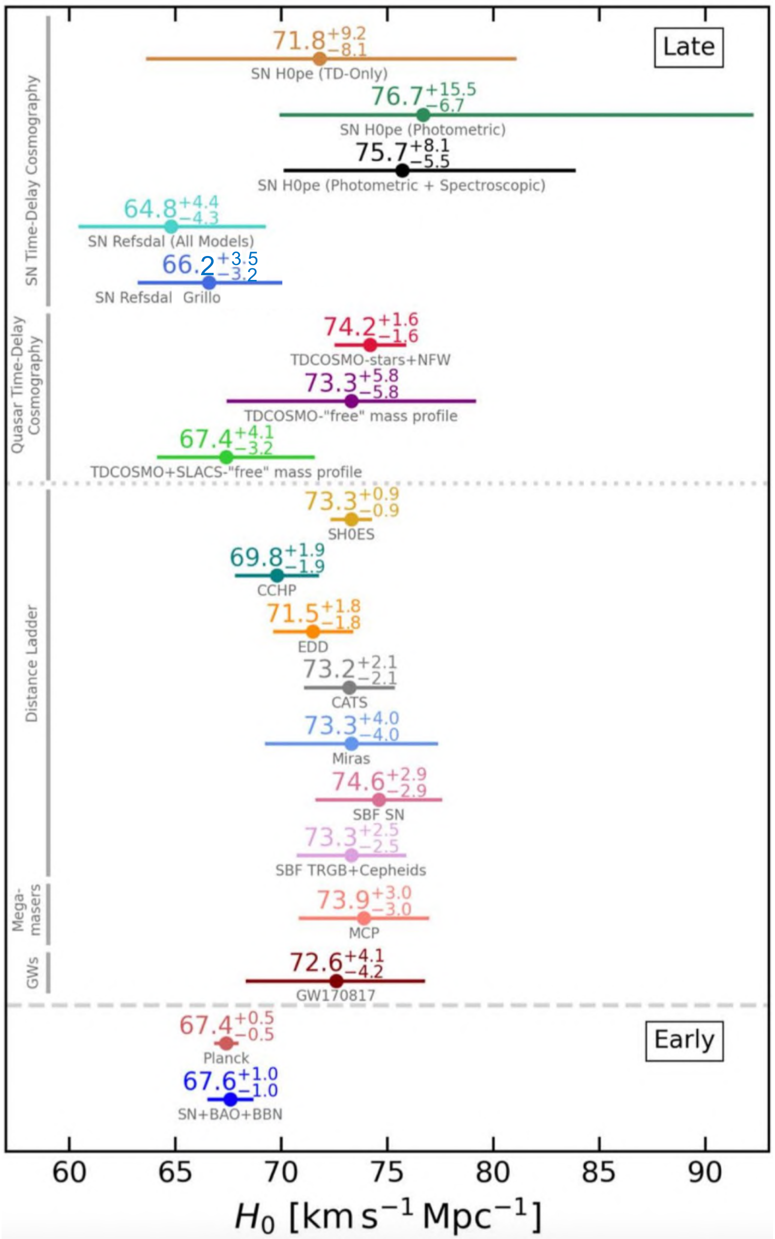
Comparison with other cosmological probes



❑ No other single probe can measure simultaneously all parameters

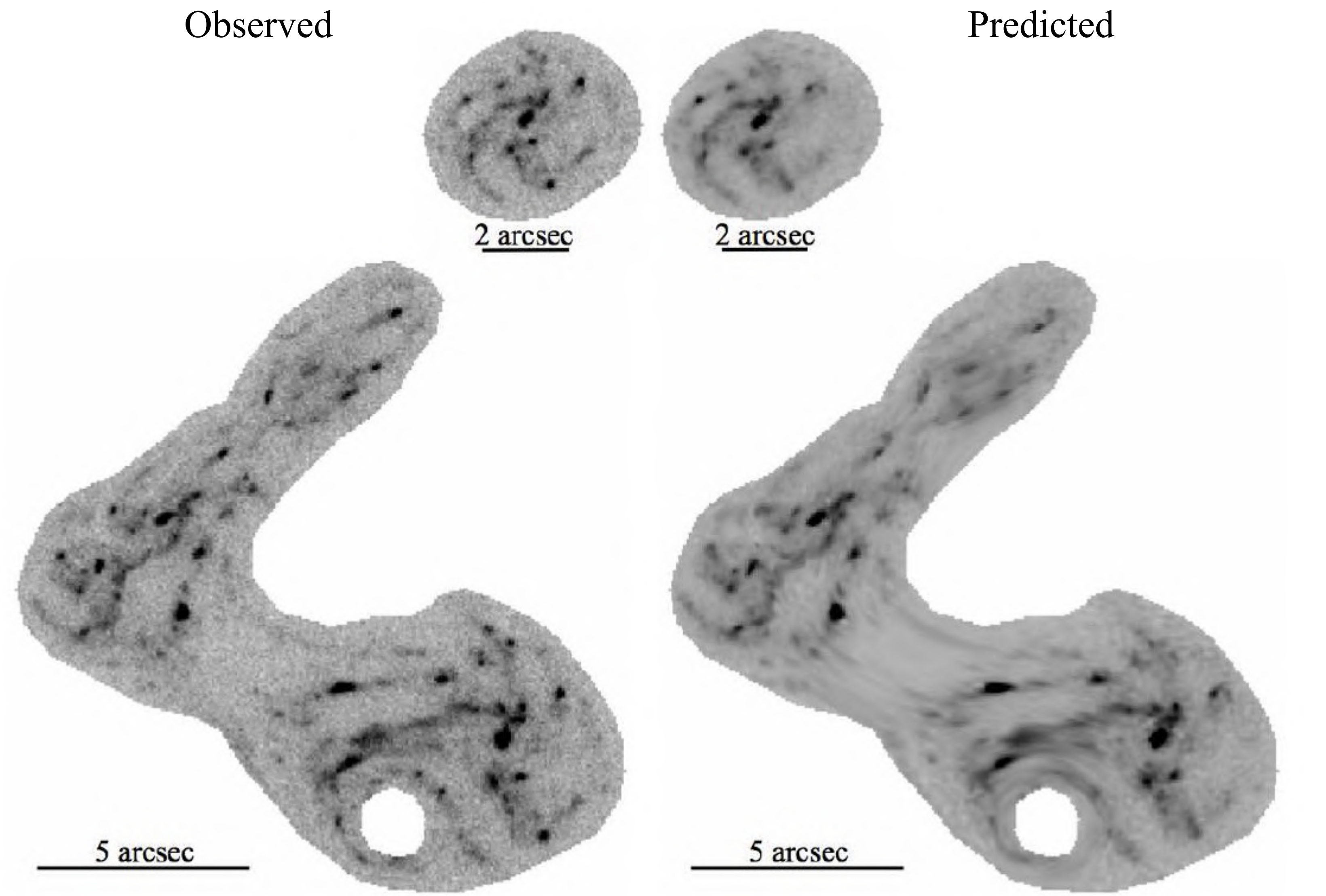
Grillo, Pagano, Rosati & Suyu, 2024, A&A, 684, 23

Comparison with other H_0 measurements



adapted from Pascale, Frye, Pierel, et al. 2025, ApJ, 979, 13

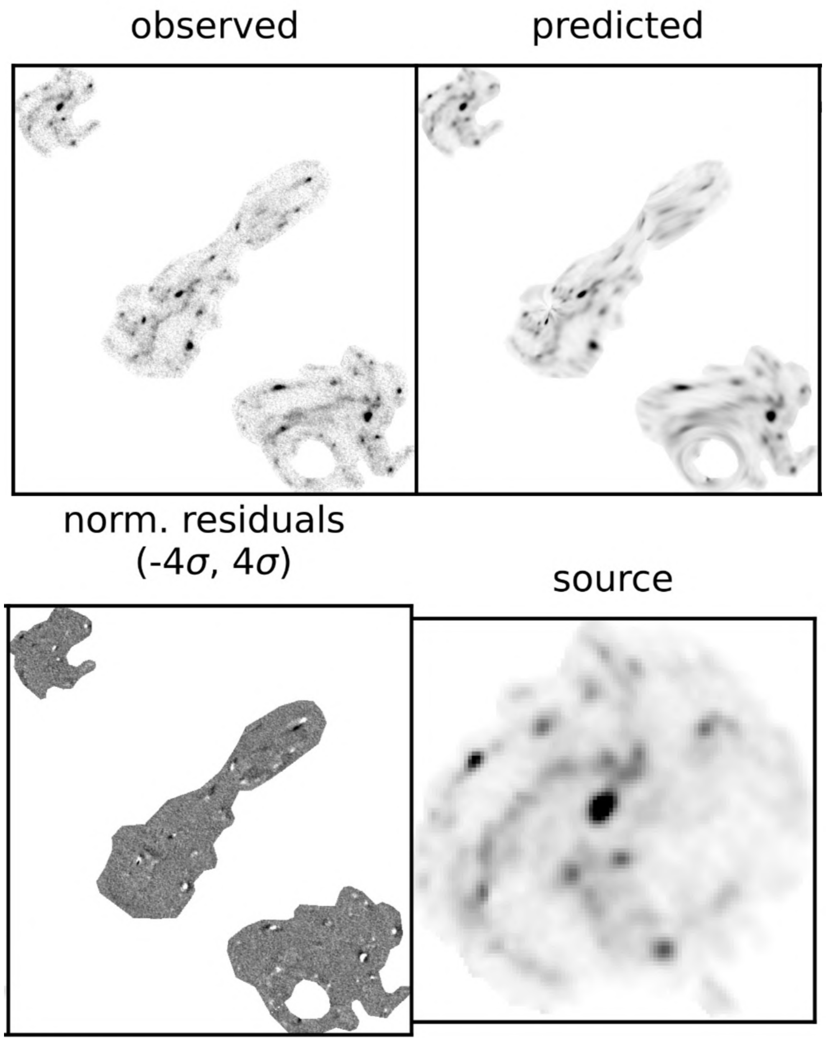
The SN Refsdal host I

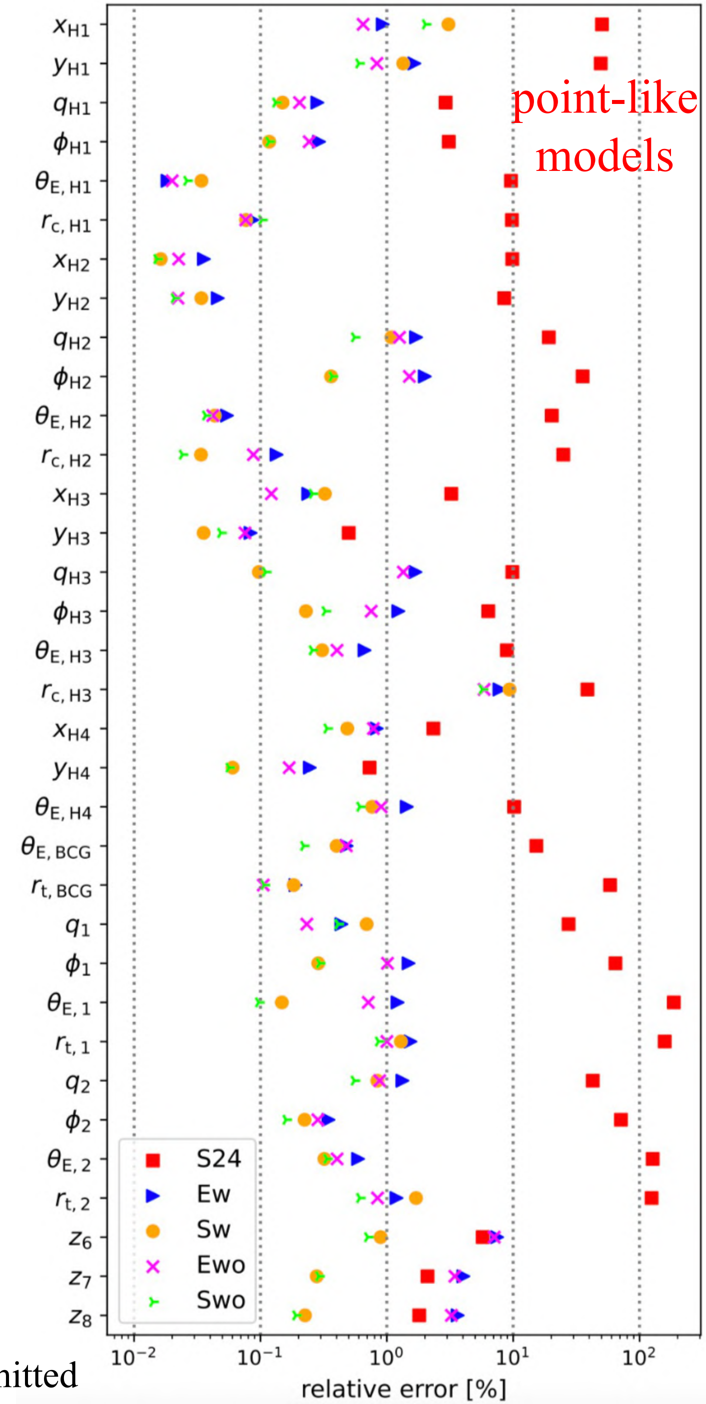


- The surface brightness of the SN host is nicely reconstructed by our best-fitting model

Grillo, Karman, Suyu, et al. 2016, ApJ, 822, 78

The SN Refsdal host II



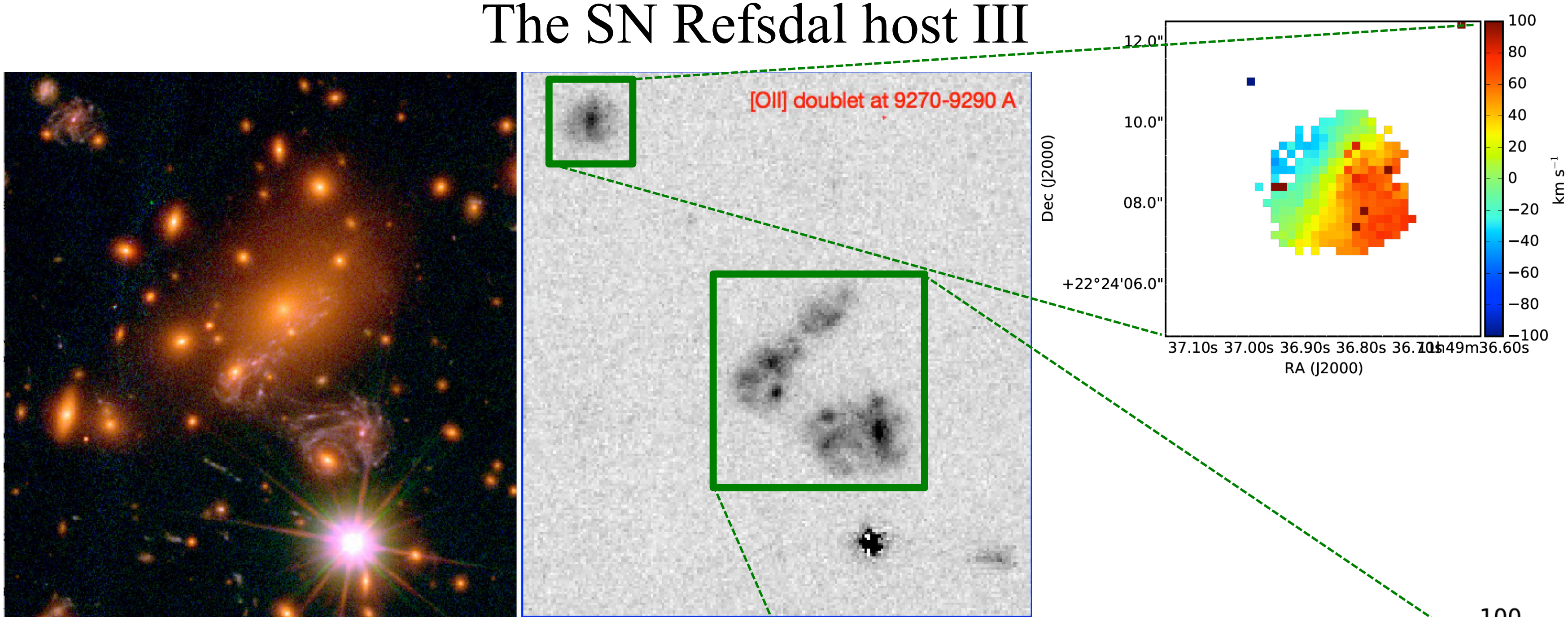


✧ ~77000 HST pixels

✧ Relative errors on the lensing model parameters reduced by 1 or 2 orders of magnitude

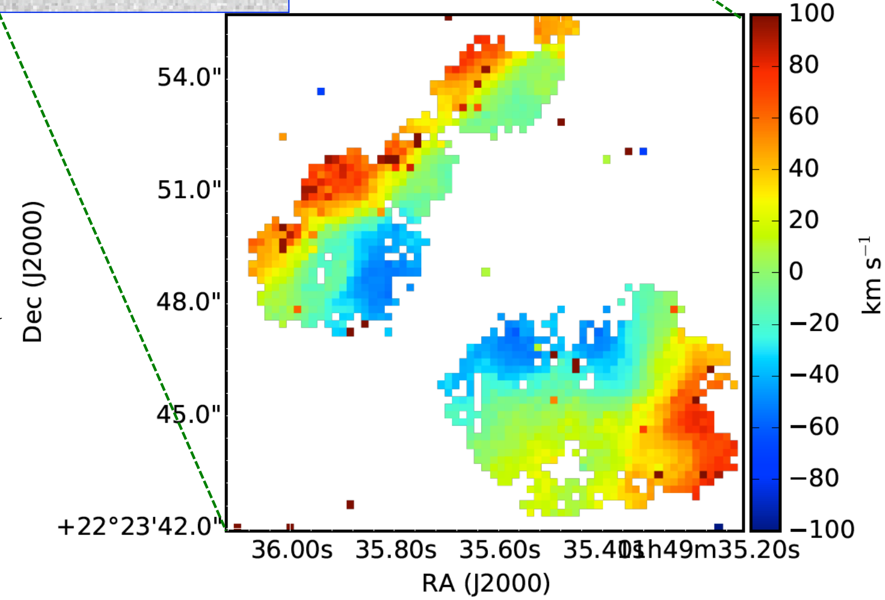
Schuldt, Grillo, Acebron, et al., submitted

The SN Refsdal host III



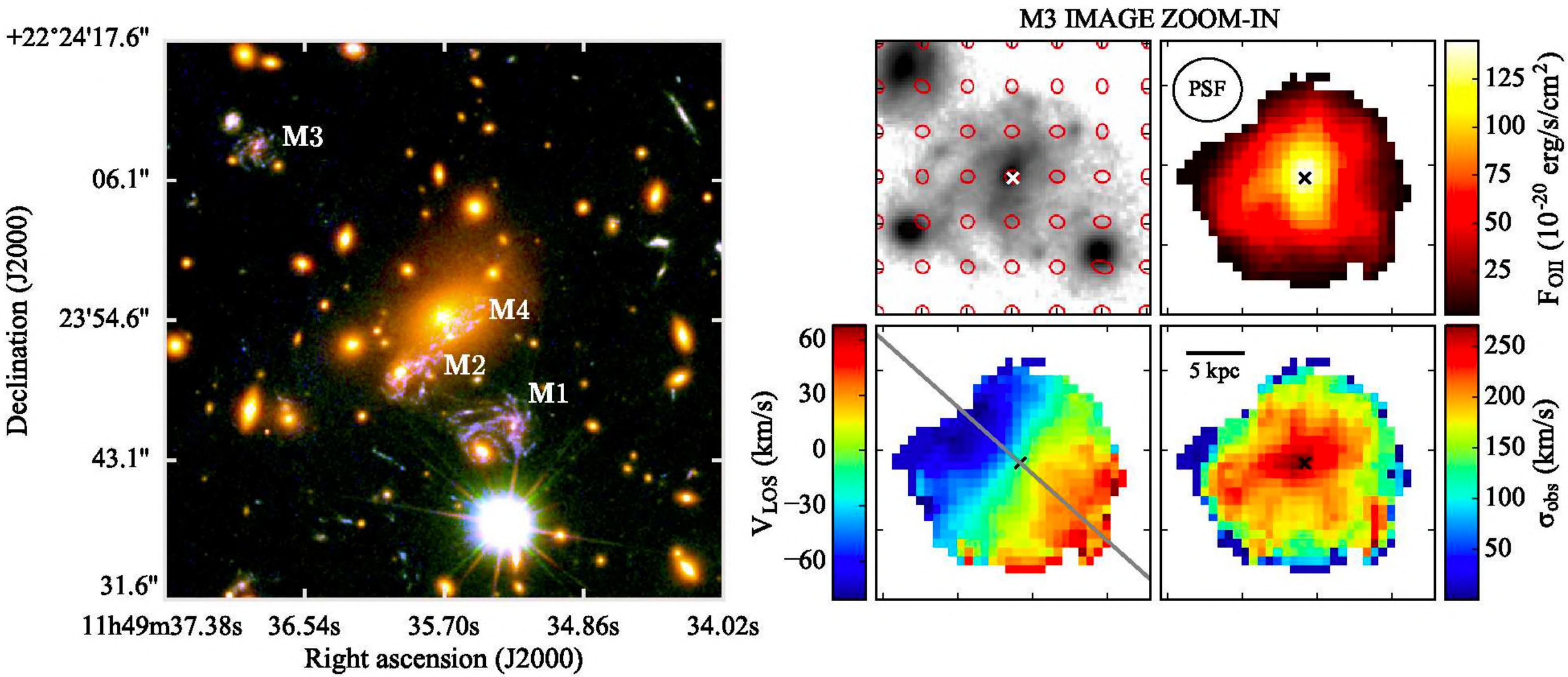
- Strong [OII] emission at $z = 1.489$

- The [OII] velocity map shows a clear and symmetrical rotation pattern with peak values of ~80 km s^{-1}



Grillo, Karman, Suyu, et al. 2016, ApJ, 822, 78

The SN Refsdal host IV



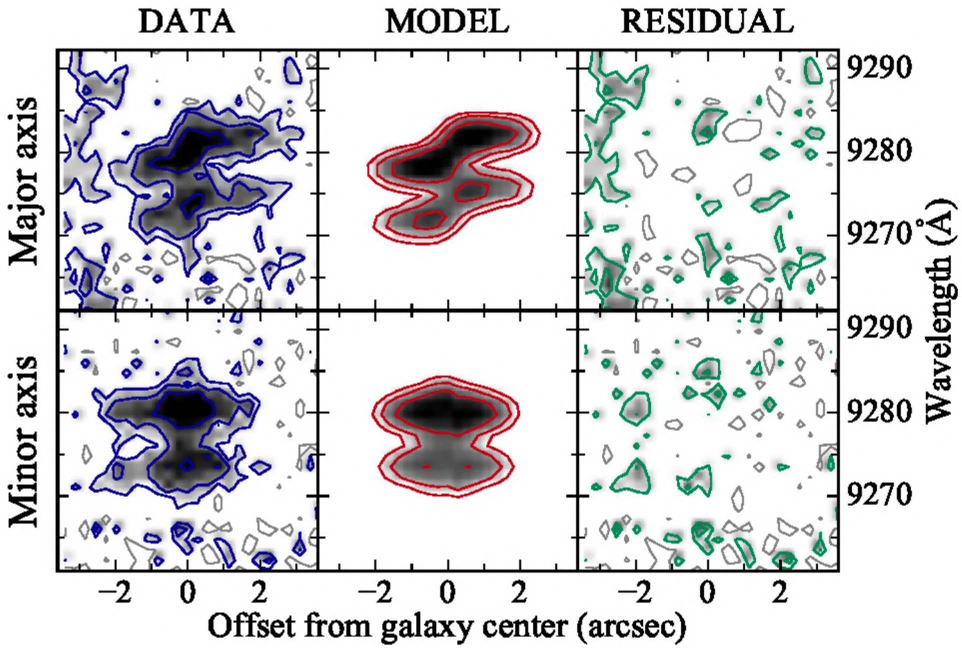
- M3 image used for the kinematic modelling, least distorted image ($\mu \sim 4$)
- Moment maps by fitting a double Gaussian to each spatial pixel in the [OII] data-cube (uncorrected for observational biases)

$$I(\lambda) = G_1(A_1, m_1, \sigma_1) + G_2(A_2, m_2, \sigma_2) = $$
$$= G_1(A_1, m_1, \sigma\ ) + G_2(\kappa A_1, m_1 + \Delta\lambda, \sigma)$$

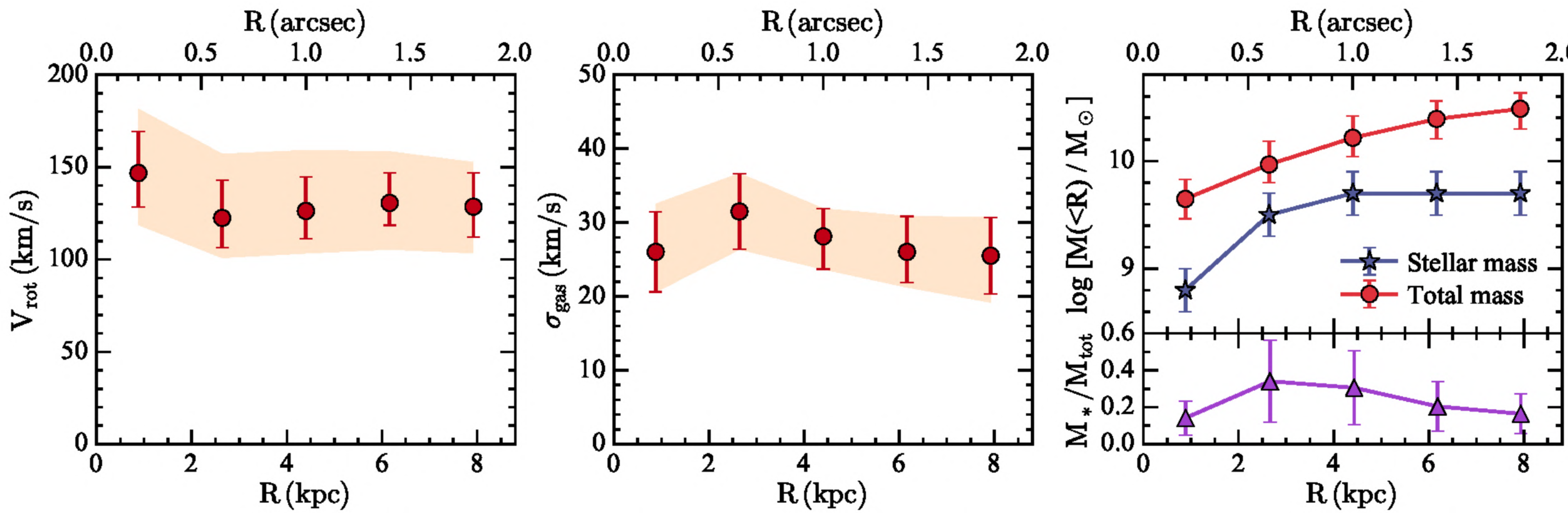
- Kinematic modelling with a modified version of ^{3D}Barolo (Di Teodoro & Fraternali 2015)
  - Disk galaxy decomposed in a number of 3D tilted rings: (x_0, y_0), i, ϕ, z, $V_{\rm rot}$, $\sigma_{\rm gas}$

Di Teodoro, Grillo, Fraternali et al. 2018, MNRAS, 476, 804

The SN Refsdal host V

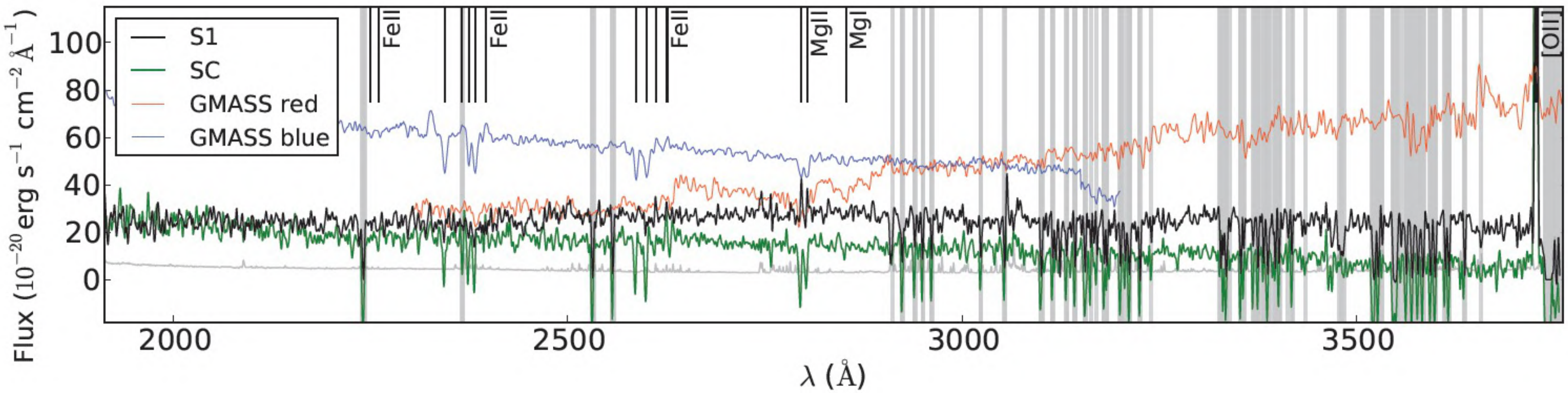


- ✓ Position-velocity diagrams: model consistent with the observations
- ✓ V: steeply rising+flat; σ: ~flat
- ✓ $V_{\rm flat} = 128^{+29}_{-19}$ km/s ; $\sigma = 27^{+5}_{-5}$ km/s
- ✓ From SED fitting: $M_* = 5 \times 10^9$ M$_\odot$ & SFR = 1−6 M$_\odot$/year
- ✓ Stellar-to-total mass ratio ~ 0.2 ± 0.1
- ✓ SN Refsdal host is a regular star-forming, mildly turbulent, rotation-dominated (V/σ ~ 5) spiral galaxy in the 4 Gyr old Universe

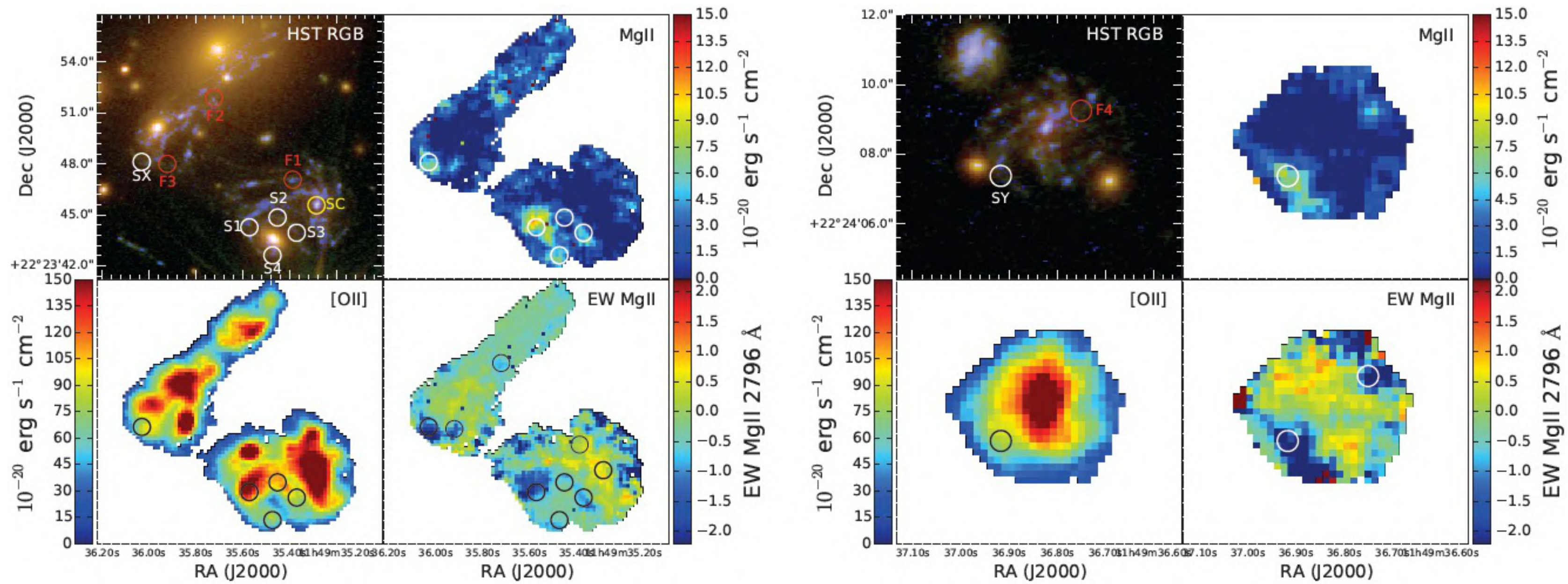


Di Teodoro, Grillo, Fraternali et al. 2018, MNRAS, 476, 804

The SN Refsdal host VI



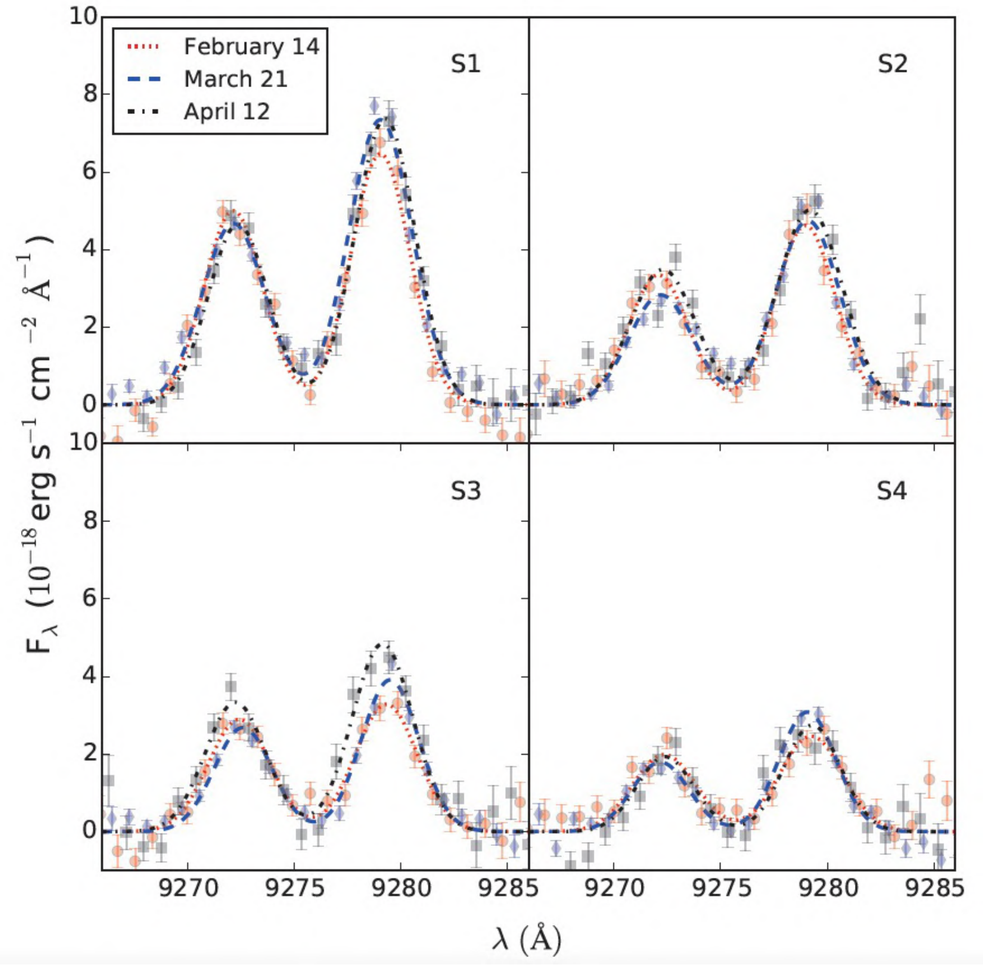
✧ FeII and MgII lines very different at the position of S1 and at the centre of the SN host



✧ The MgII doublet emission reveals a highly-ionized region surrounding the SN Refsdal

Karman, Grillo, Balestra et al. 2016, A&A, 585, 27

The SN Refsdal



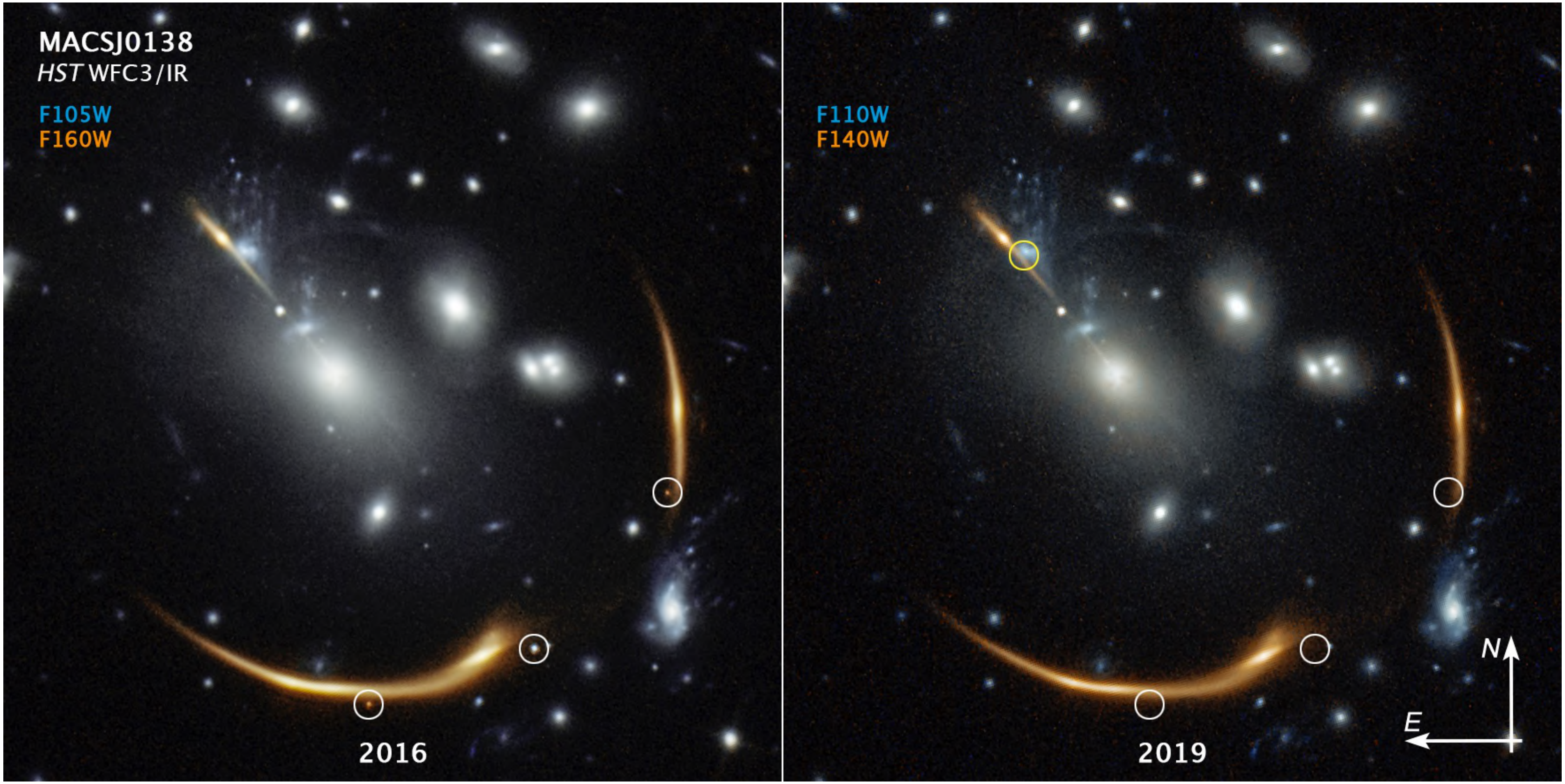
Pos.	Feb. 14th	Mar. 21st	Apr. 12th
		(10^{-18} erg s^{-1}cm^{-2})	
S1	40.1±3.9	44.8±2.8	42.5±5.7
S2	28.0±4.7	28.6±2.2	32.6±6.5
S3	22.4±4.1	22.4±2.6	29.2±6.3
S4	16.3±6.6	16.3±2.1	15.6±5.5

- No variability of the [OII] lines over periods of 35 and 57 days

- Either there is no variation in the luminosity of the SN over this period, or the SN contribution to the [OII] emission is lower than the sensitivity of our observations

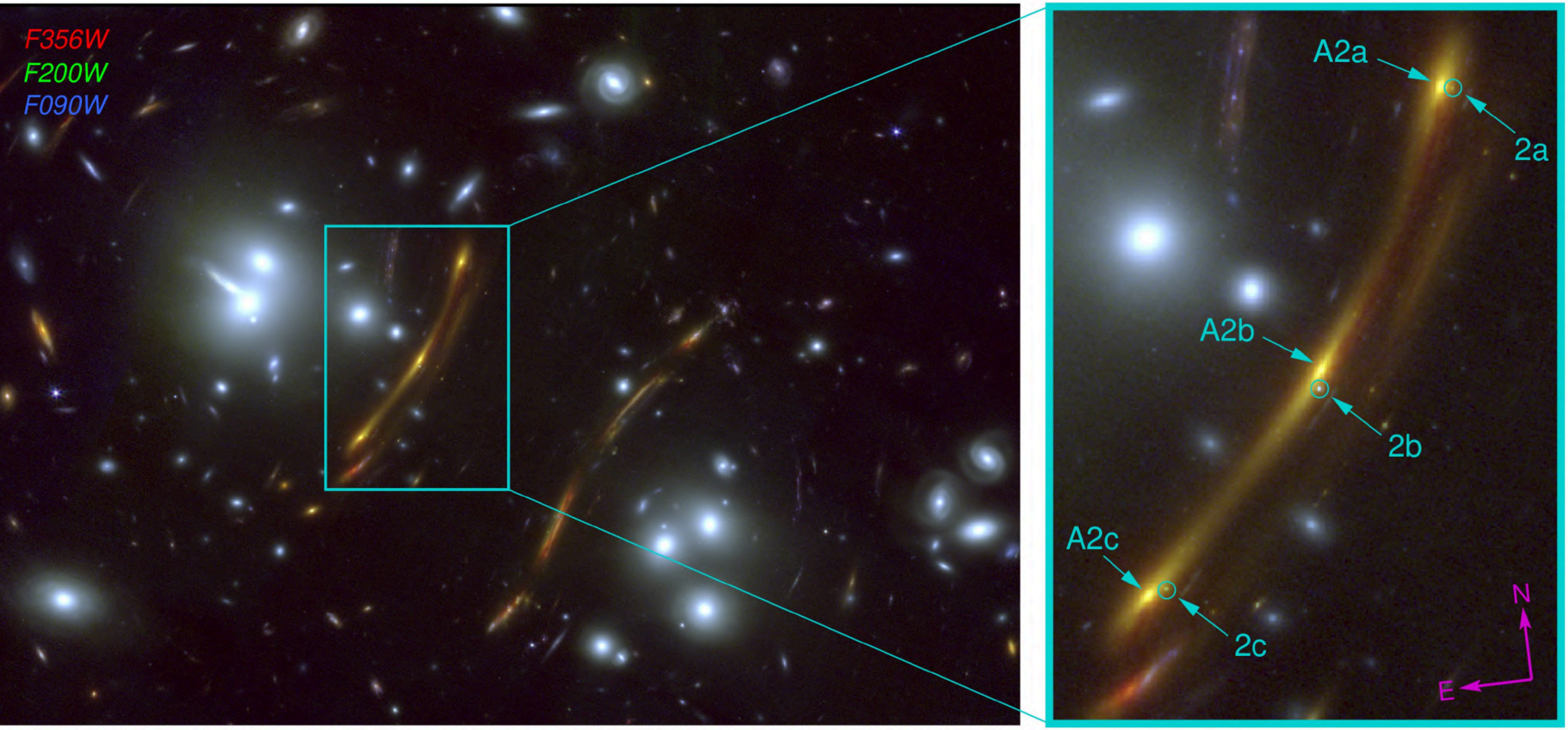
Karman, Grillo, Balestra et al. 2016, A&A, 585, 27

SN ‘Requiem’



Rodney, Brammer, Pierel et al. 2021, Nature Astronomy, 5, 1118

SN 'H0pe'



Frye, Pascale, Pierel, et al. 2024, ApJ, 961, 171

Pascale, Frye, Pierel, et al. 2025, ApJ, 979, 13

Grayling, Thorp, Mandel, et al., MNRAS, submitted

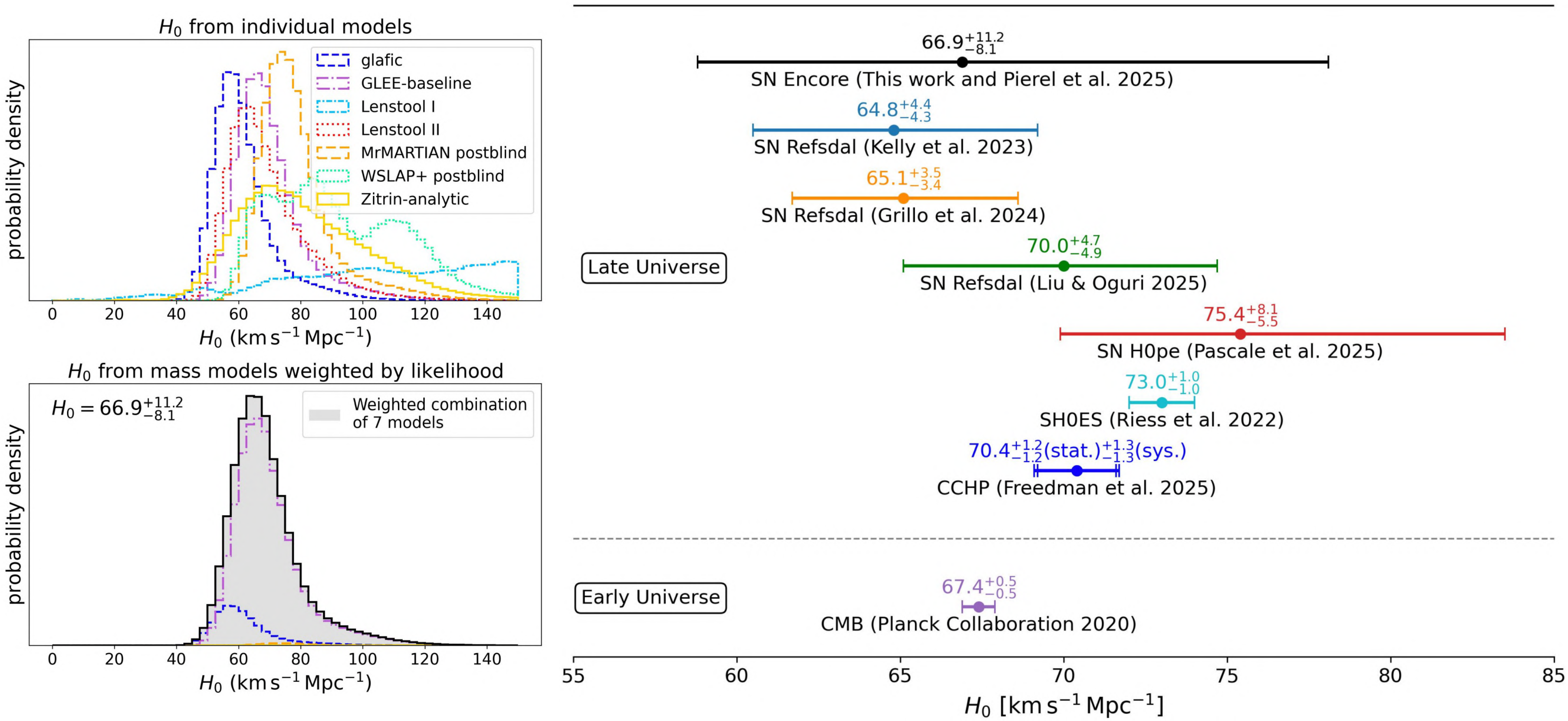
SN ‘Encore’

Pierel, Newman, Dhawan et al. 2024, ApJ, 967, 37

Pierel, Hayes, Millon, et al. 2026, ApJ, in press

Suyu, Acebron, Grillo, et al. 2026, A&A, in press

H_0 from SN Encore

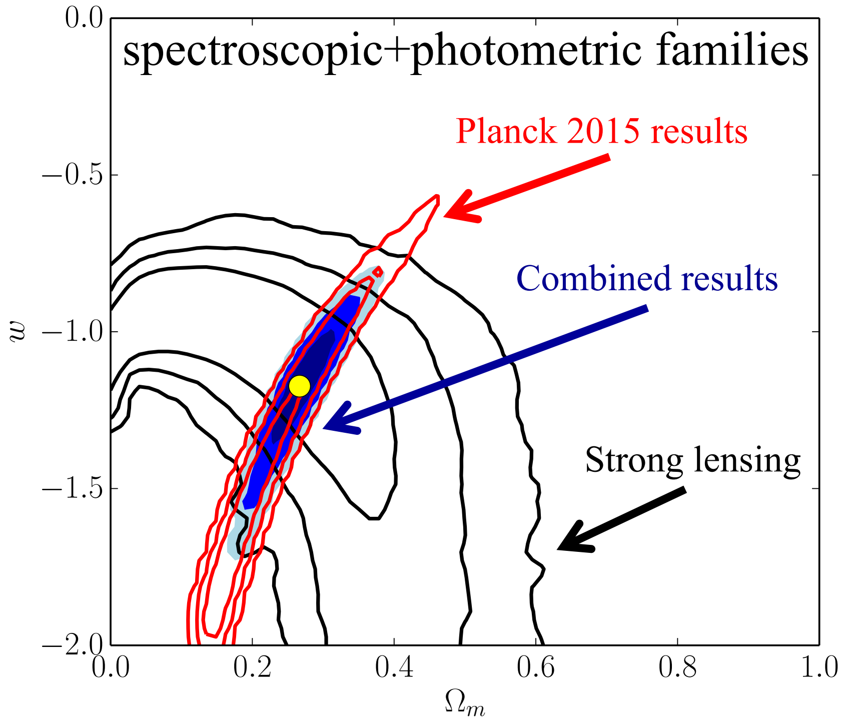


Suyu, Acebron, Grillo, et al. 2026, A&A, in press

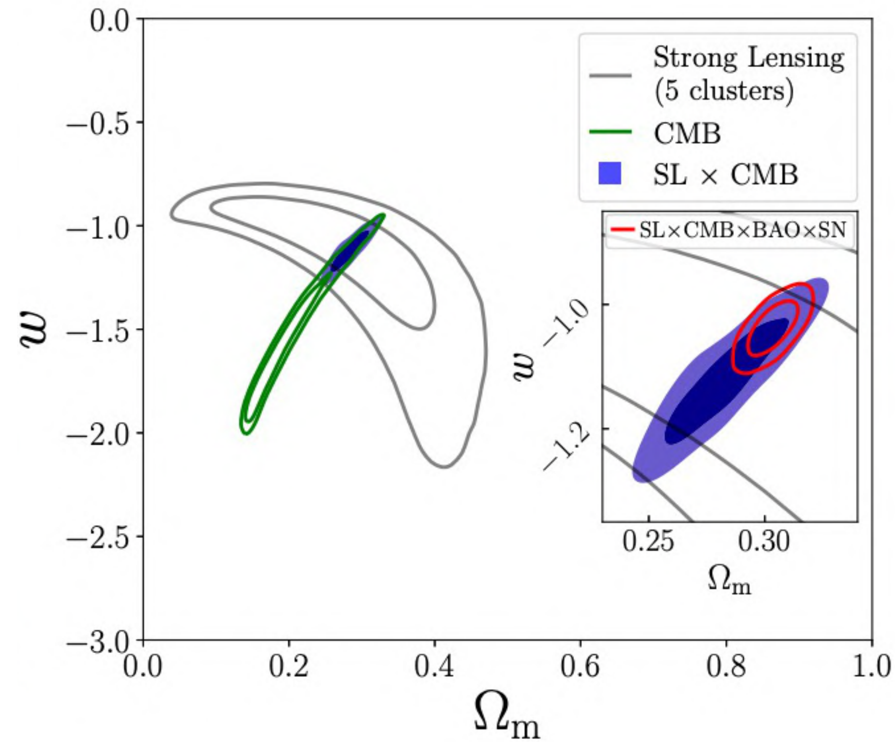
Pierel, Hayes, Millon, et al. 2026, ApJ, in press

Cluster cosmography without time delays I

- Family ratios of many sources covering an extended redshift range allow to measure cosmologically relevant quantities



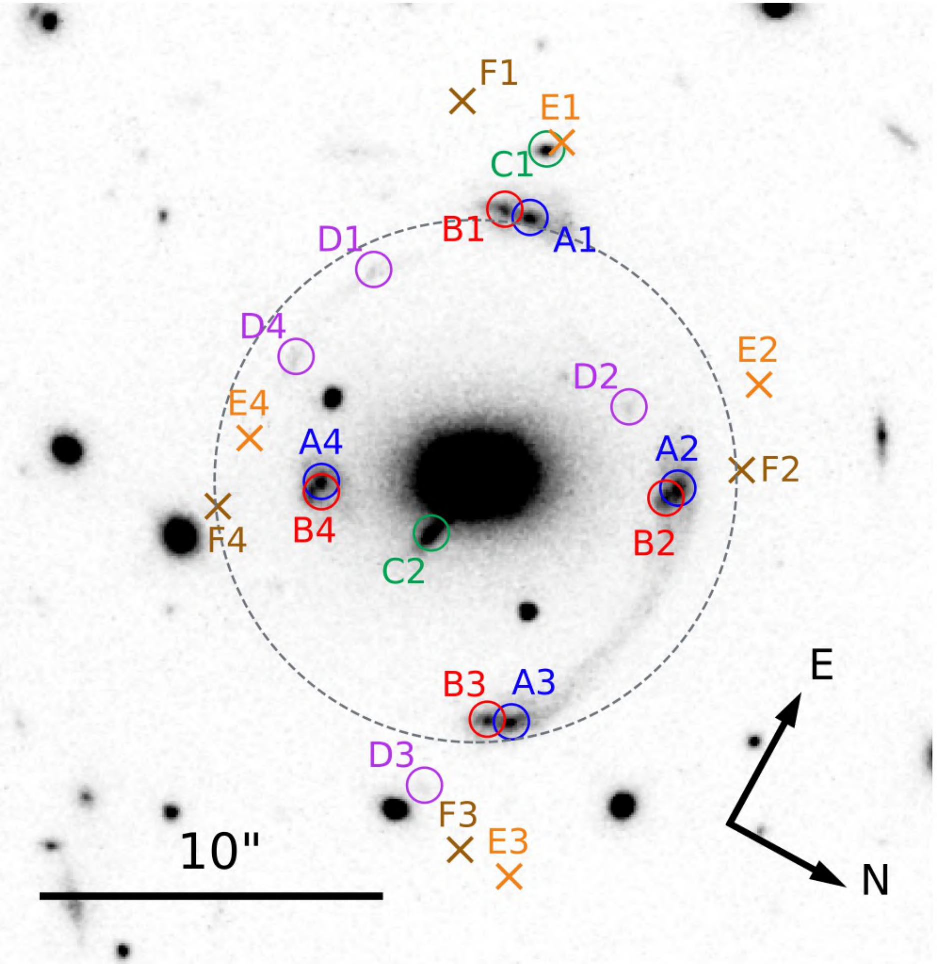
Caminha, Grillo, Rosati, et al. 2016, A&A, 587, 80

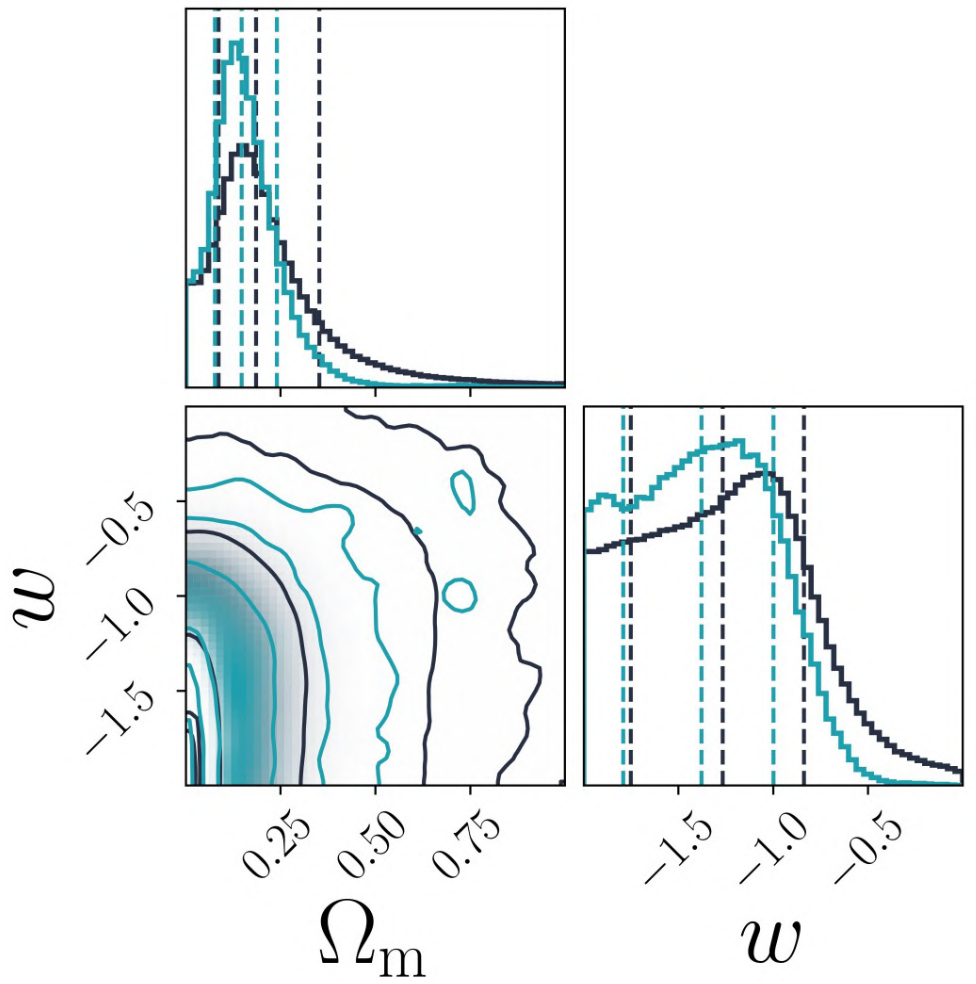


Caminha, Suyu, Grillo, et al. 2022 A&A, 657, 83

- A sample of 5 lens clusters with more than 50 spectroscopically confirmed strong lensing families provides, in a flat *w*CDM model, $\Omega_m = 0.30^{+0.09}_{-0.11}$ and $w = -1.12^{+0.17}_{-0.32}$

Cluster/Group cosmography without time delays II





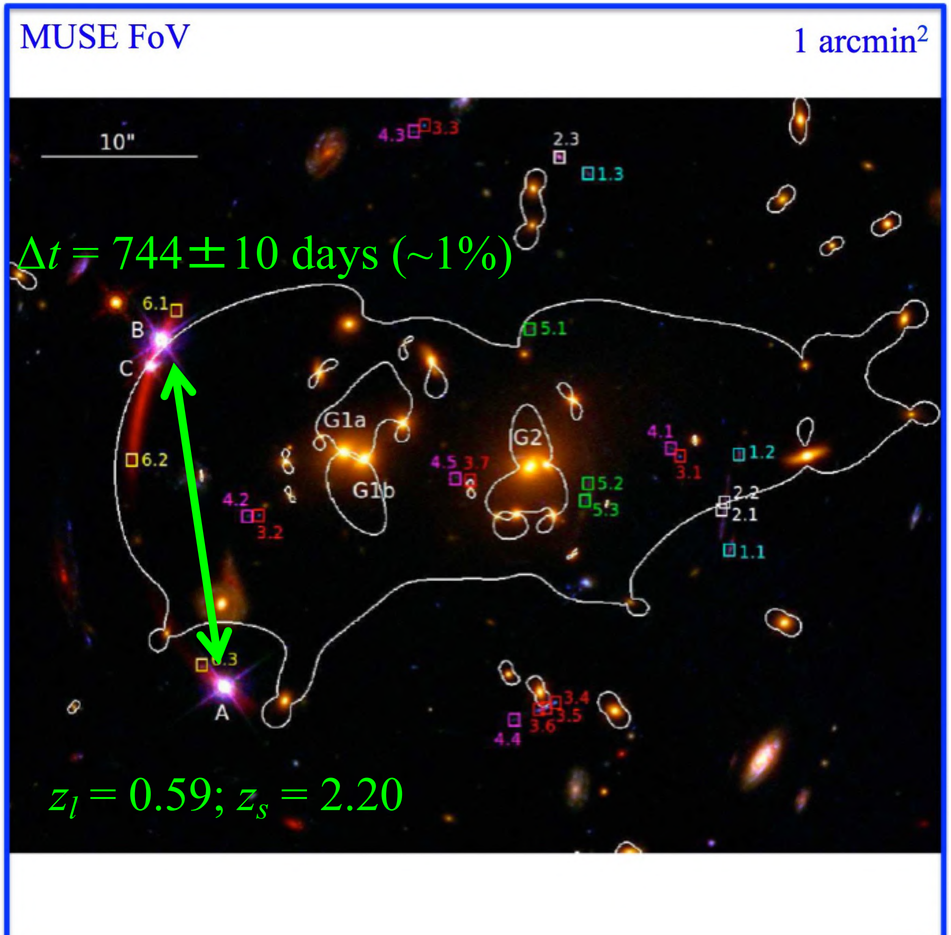
Bolamperti, Grillo, Caminha, et al. 2024, A&A, 692, 239

What's next?

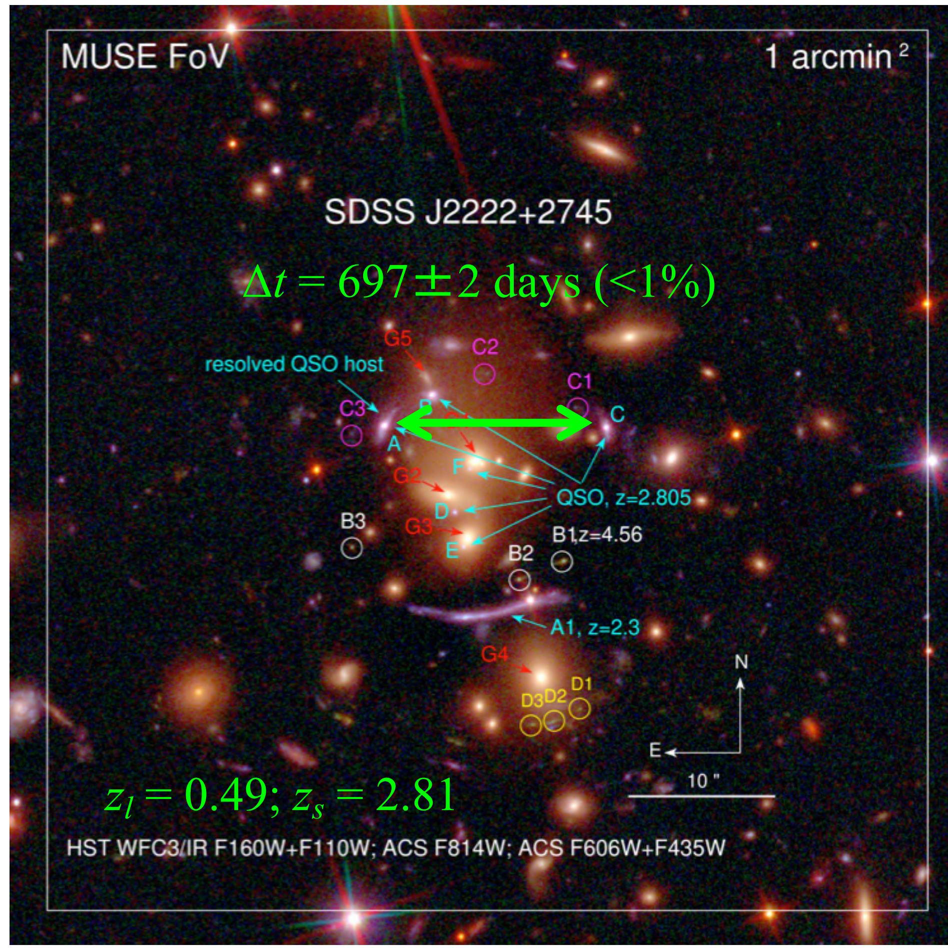
Currently, we know only a few (≤10) quasars and supernovae strongly lensed by galaxy clusters and with measured time delays

2 additional cluster lensing systems visible from Paranal now have VLT/MUSE data reduced (5 hours; PI: Grillo)

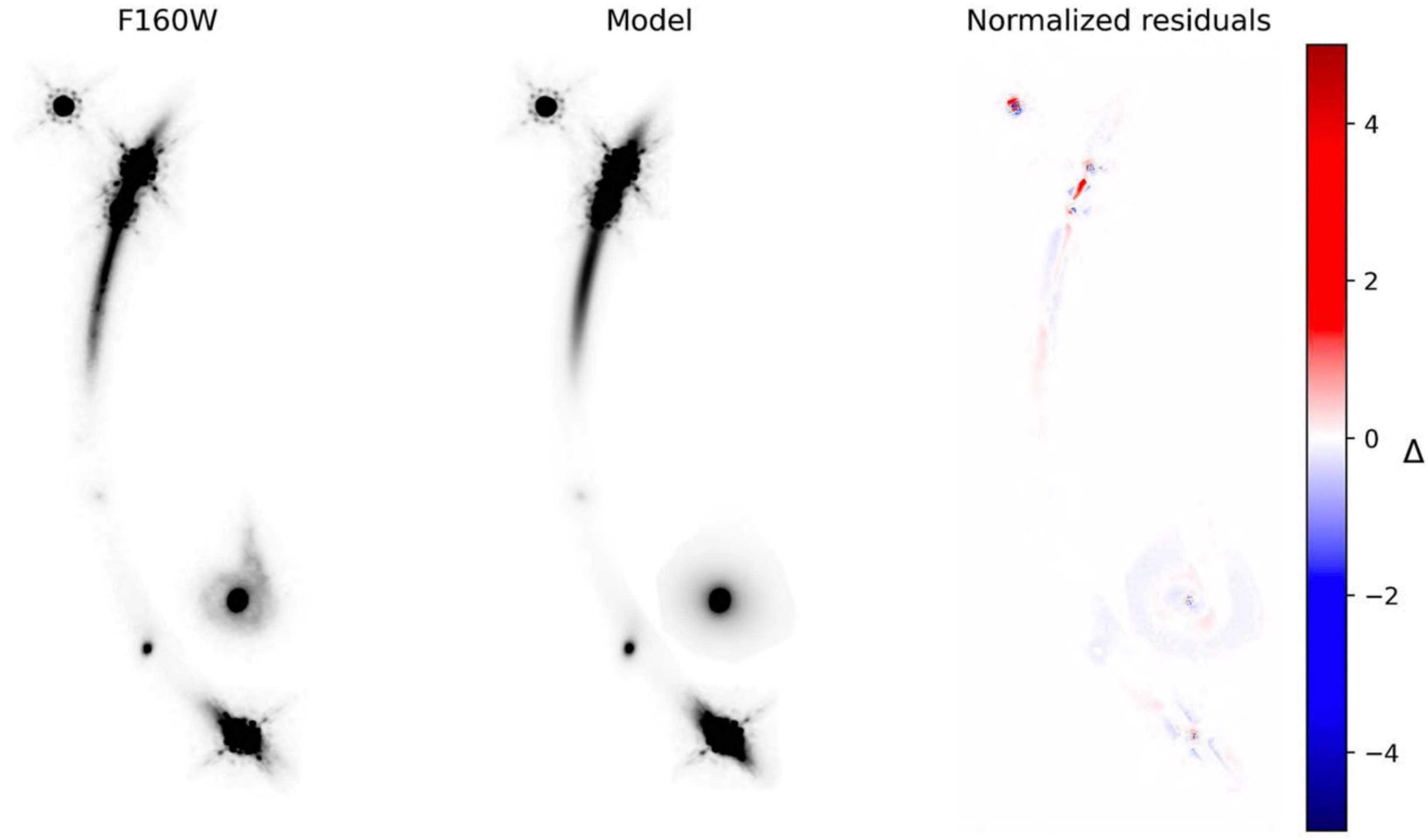
Acebron, Grillo, Bergamini, et al. 2022, ApJ, 926, 86



Acebron, Grillo, Bergamini, et al. 2022, A&A, 668, 142

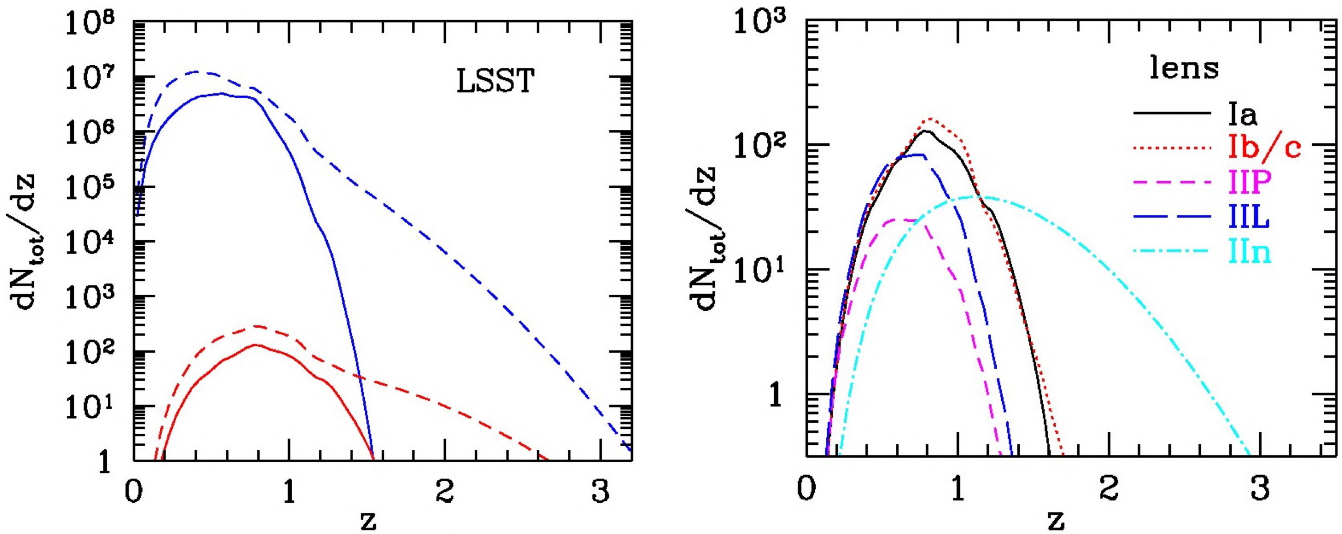


The QSO host



Acebron, Grillo, Suyu, et al. 2024, ApJ, 976, 110

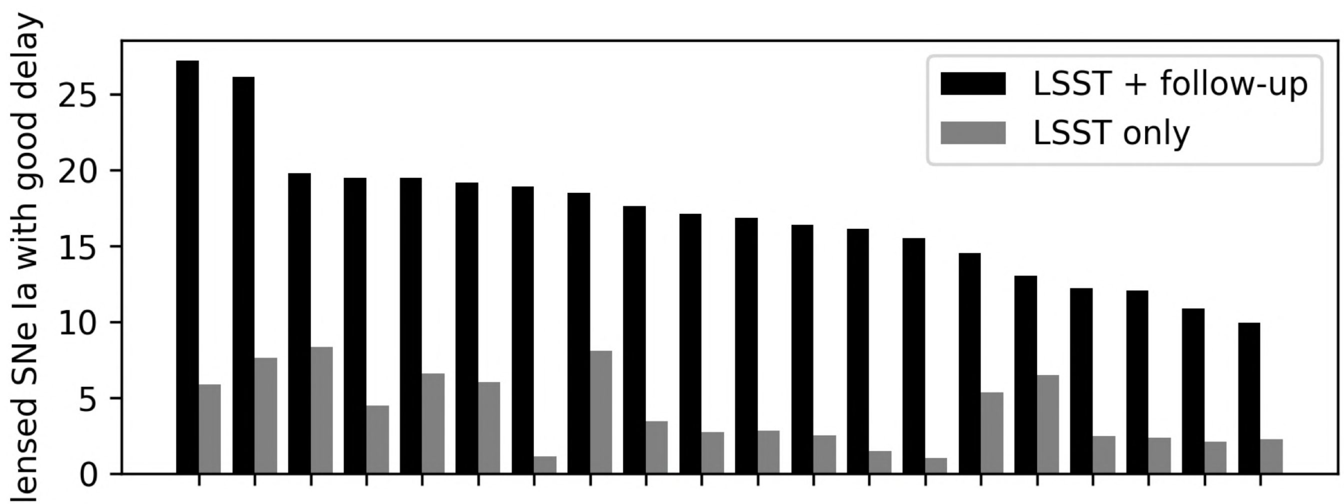
Future with Vera C. Rubin



Oguri & Marshall 2010, MNRAS, 405, 2579

- Rubin will discover thousands of new multiply-lensed QSOs and SNe

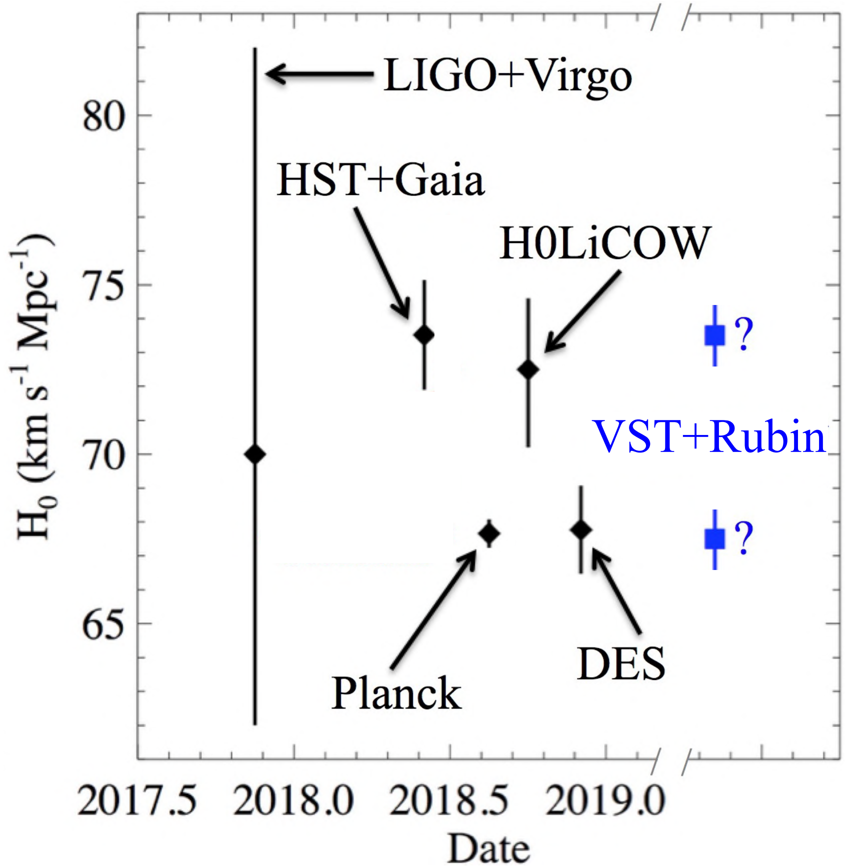
- Rubin only is not ideal for time-delay cosmography
- Rubin will benefit from additional dedicated monitoring



Huber, Suyu, Noebauer, et al. 2019, A&A, 631, 161

Why VST+Rubin for strong lensing in galaxies and galaxy clusters?

★ ~30 new multiply-imaged transient/variable sources from Rubin+VST with ~2% time-delay precision can result in a ~1% uncertainty on the cosmic expansion rate H_0

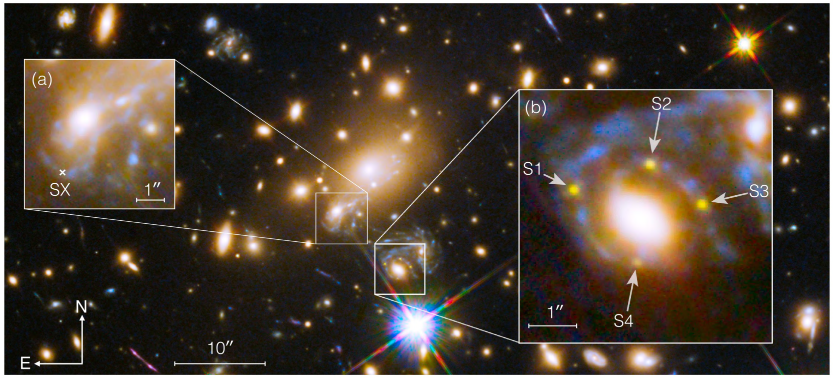


Our VST programme I

- Targets: ~40/30 brightest Rubin QSOs/SNe lensed by galaxies/galaxy clusters (8 years)

~30/23 galaxy-scale systems

~10/7 cluster-scale systems



- Observational strategy: 2 galaxies + 2 clusters per night (service mode is needed)
- Observing conditions: seeing < 1.4 arcsec, also in bright Moon conditions, clear sky
- Observational needs: high-cadence (daily), high S/N (~1000 per epoch) for *R* ~ 20 mag targets → 30 min. with VST, per object per epoch (including overheads)
- Allocated time: ~1.8 hours (including overheads) per night for 8 years (PI: C. Grillo) → **5228 hours** (including overheads) over **8 years**, started in **October 2024**
- Data reduction: Data will be downloaded daily and analysed with existing pipelines
- Results: Each lens galaxy (cluster) will be observed for a total of over 8(24) months

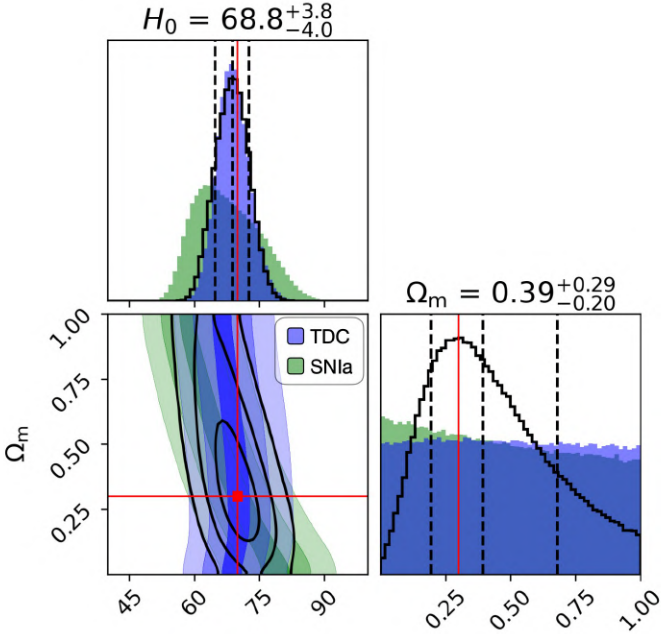
Our VST programme II

➢ Why the VST?

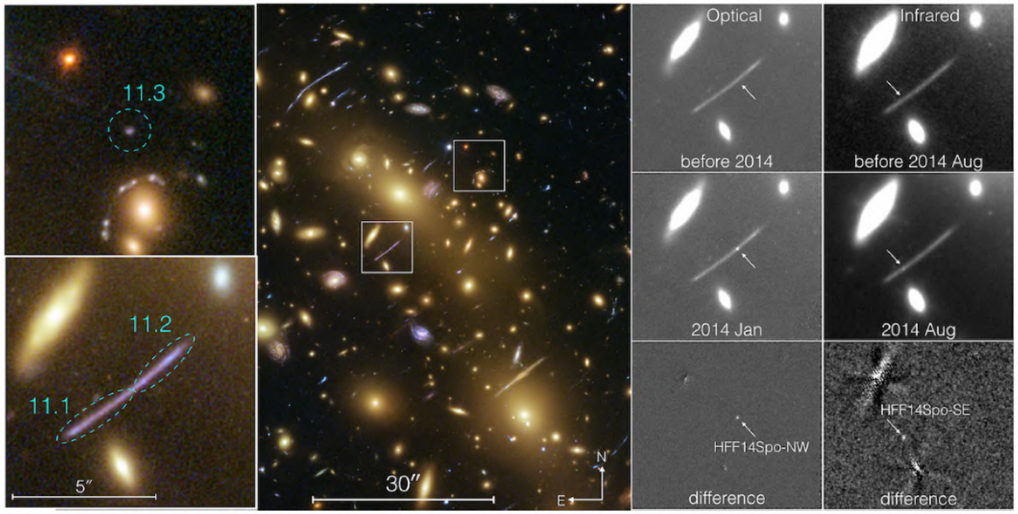
To measure time delays with ~2% errors, we need 1) the excellent PSF quality and 2) the stability of OmegaCAM, in addition to 3) good weather conditions

➢ Why the large FoV?

1) High-quality mass maps from weak lensing and possible mass structures along the line of sight. Crucial to accurate measurements of the cosmological parameters. 2) For the optical photometric calibration, many stars will enable a robust source variability measurement. 3) Search for SN Ia in cluster member galaxies. Independent estimates of the luminosity distances of the clusters. 4) Serendipitous (lensed and unlensed) new, interesting transients.



Acebron et al. 2023, A&A, 680, 9



Rodney et al. 2018, NatAs, 2, 324

★ A luminous blue variable or a recurrent nova at $z = 1.01$

★ Joint technique (black) of time-delay cosmography (blue) + SN Ia luminosity distance (green)

Final remarks

- Reliable (**!!!**) strong lensing analyses of galaxy clusters with time delays can lead to new exciting results on
  (1) the cosmic expansion rate and geometry
  (2) the cluster dark matter halo and sub-halo populations
  (3) the physical properties of distant sources

The new era of time delays in lens galaxy clusters will allow us to

- Measure the values of the most relevant cosmological quantities (H_0, Ω_m, $\Omega_{\Lambda/DE}$, w)
- Build robust high-resolution mass maps of the galaxy clusters
- Test the ΛCDM model (e.g., DM mass density profiles, stats of sub-haloes,…)

- High angular resolution and multiband imaging + spectroscopic redshifts + monitoring campaigns/surveys are necessary to
  - ✓ Select and model the cluster members, for accurate lensing analyses
  - ✓ Confirm several multiple image systems, allowing unbiased estimates of the cluster modelling parameters
  - ✓ Measure the time delays of the time-varying sources