

Lessons learnt from SN Refsdal



Claudio Grillo

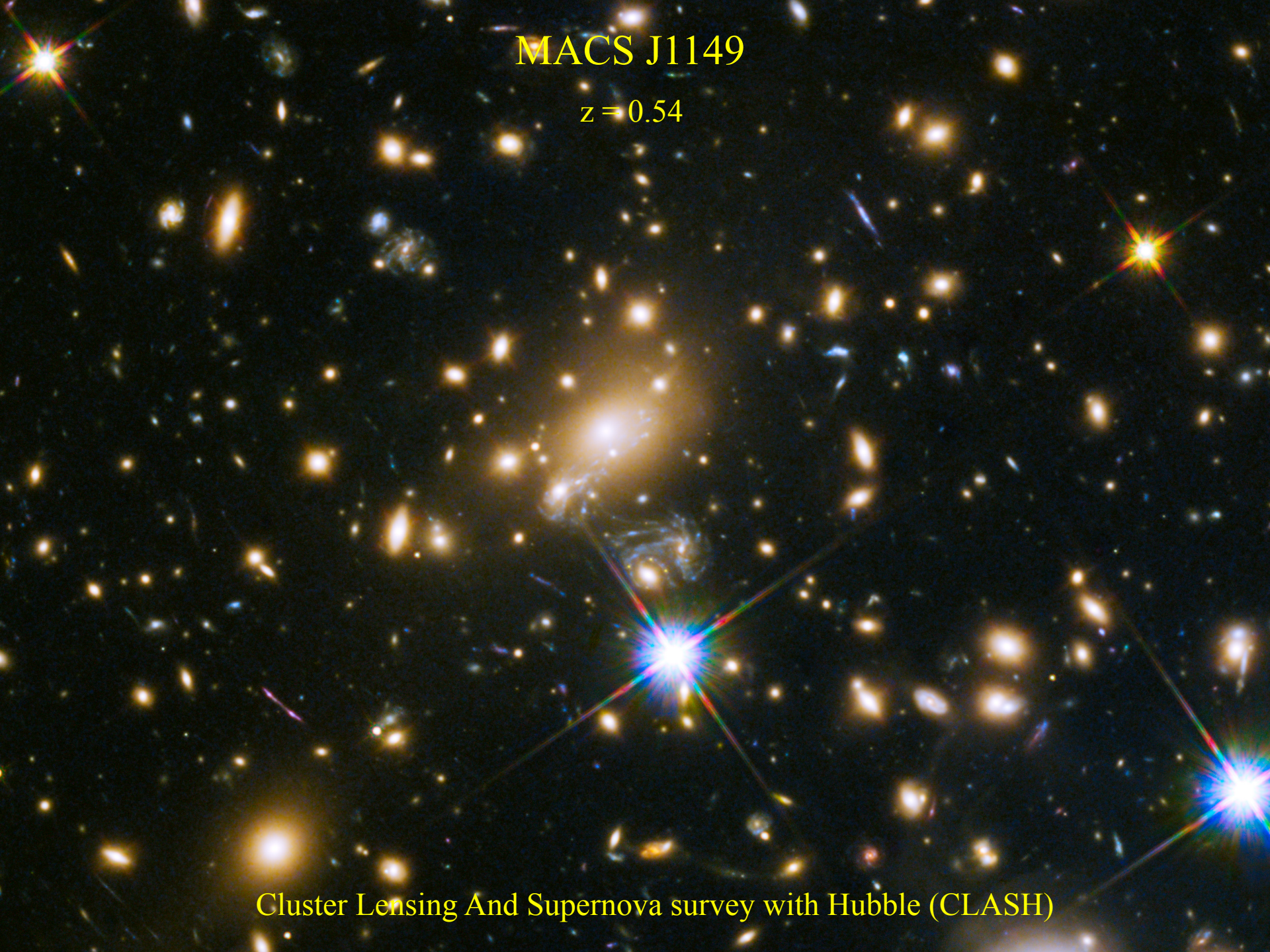
with A. Acebron, M. Annunziatella, I. Balestra, P. Bergamini, A. Bolamperti,
G. B. Caminha, K. I. Caputi, E. M. Di Teodoro, F. Dux, F. Fraternali, R. Gavazzi,
R. Gobat, A. Halkola, W. Karman, M. Lombardi, A. Mercurio, L. Pagano,
S. A. Rodney, P. Rosati, S. Schuldt, S. H. Suyu, T. Treu, E. Vanzella



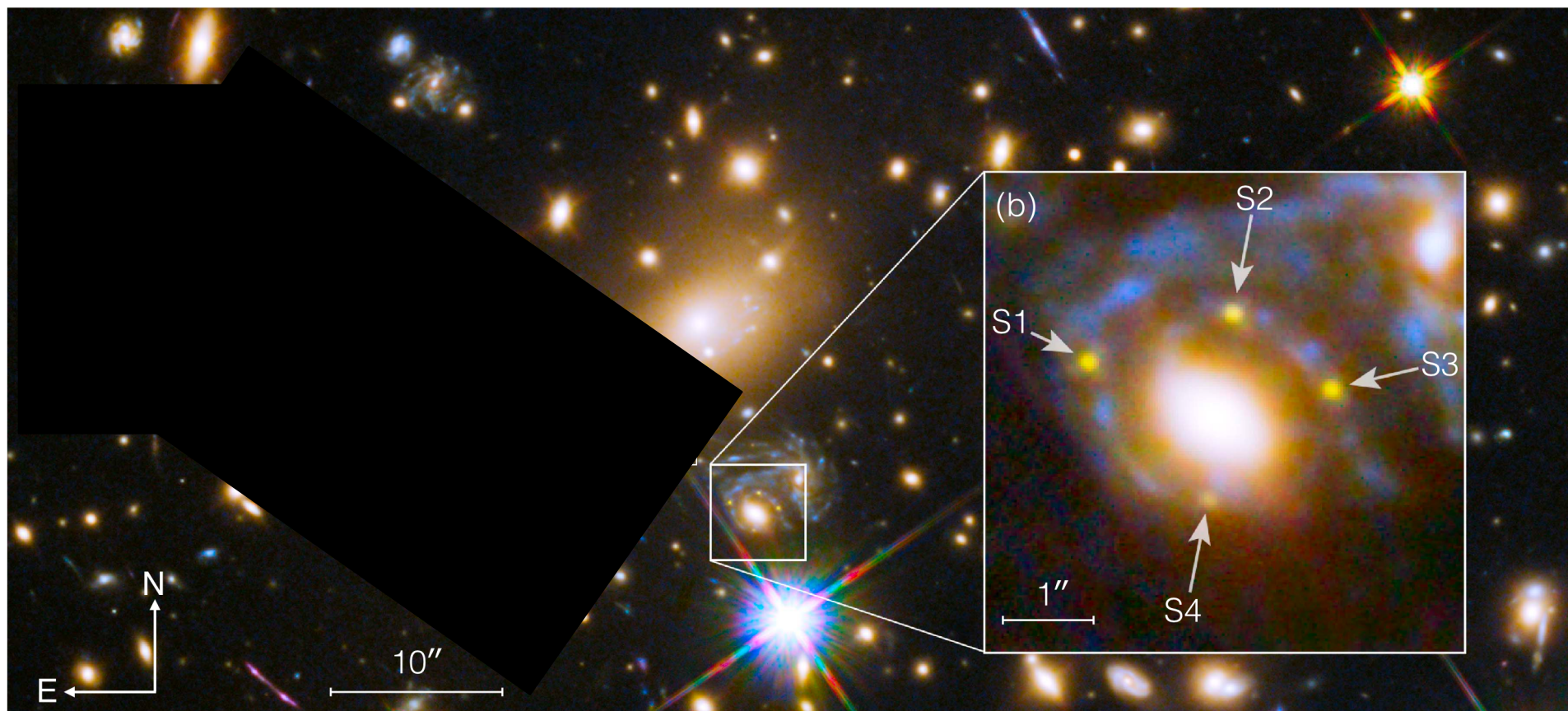
MACS J1149

$z = 0.54$

Cluster Lensing And Supernova survey with Hubble (CLASH)



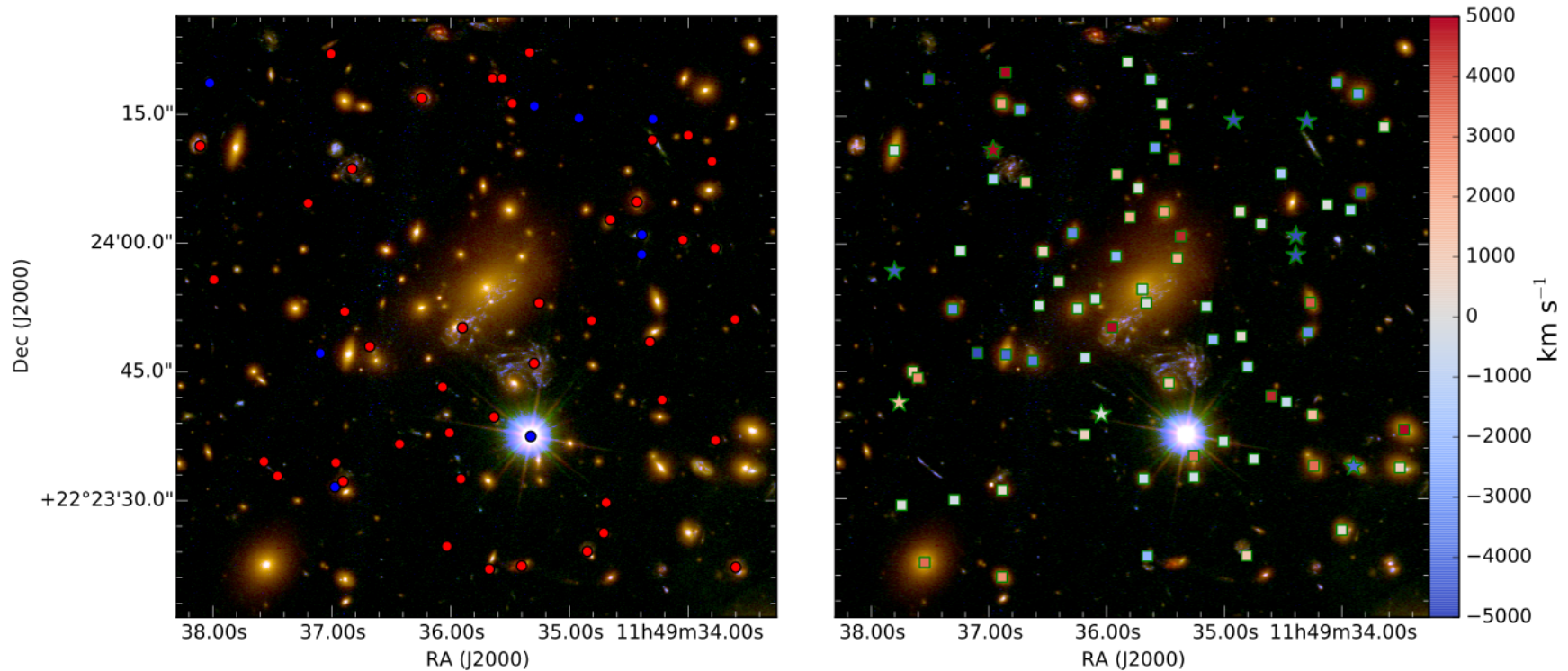
The first multiply-imaged spatially-resolved SN ('SN Refsdal') I



Einstein cross ($\approx 2''$ 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



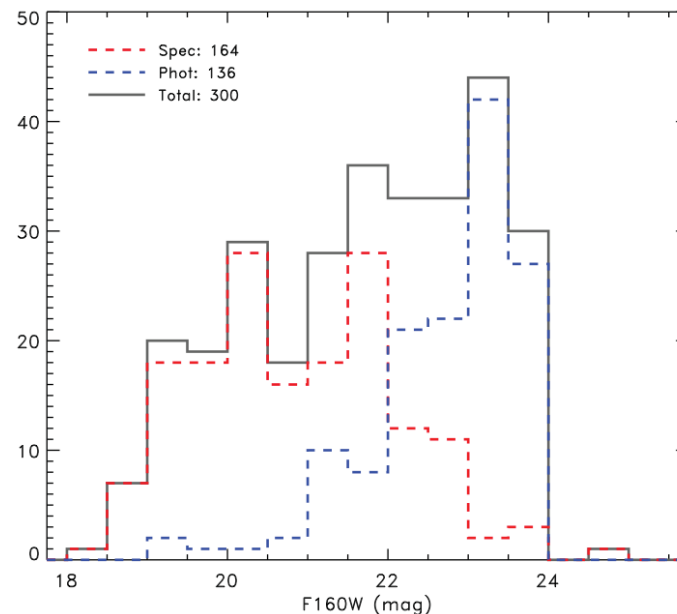
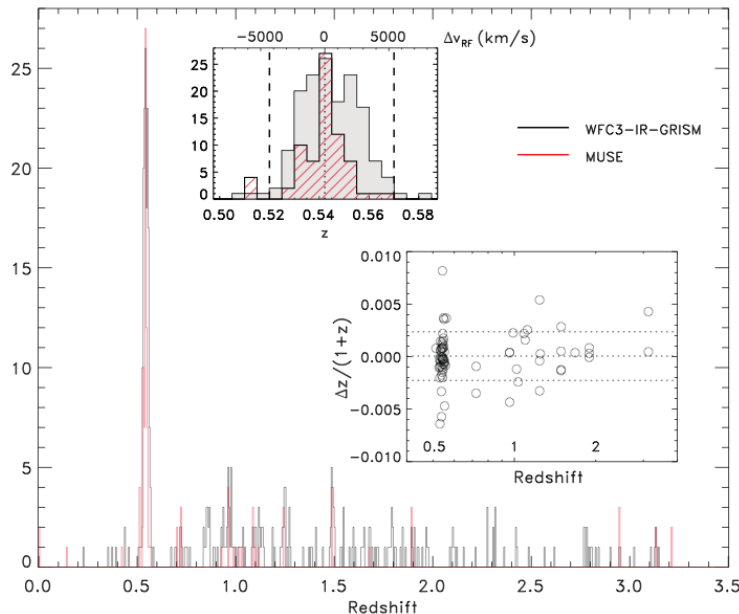
Grillo, Karman, Suyu, et al. 2016, ApJ, 822, 78



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

Our best-fitting strong lensing model I



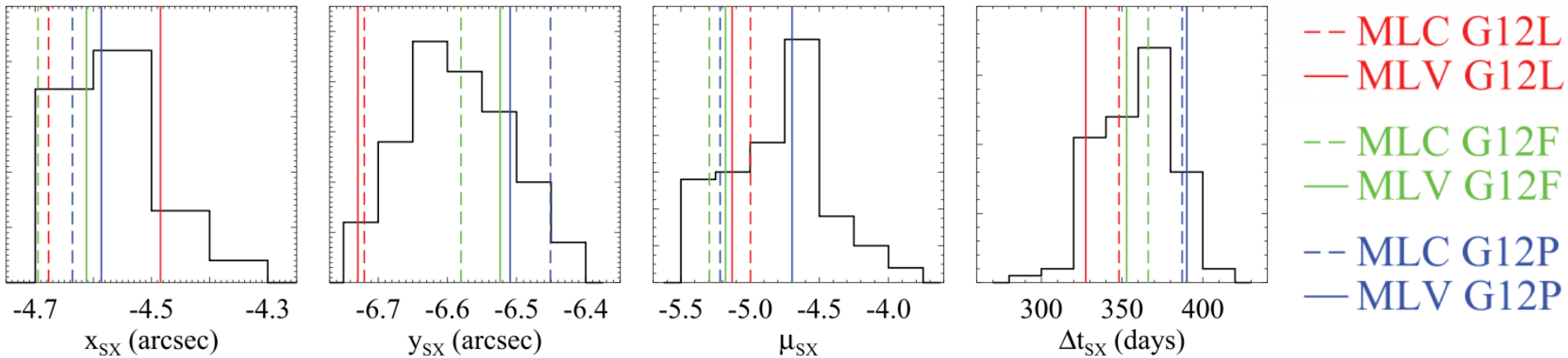
- 88 reliable multiple images from 10 different background sources (7 spectroscopic, z from 1.240 to 3.703, and 3 photometric) and 18 distinct knots in the SN Refsdal host
- 300 cluster members (CMs): 164 spectroscopic and 136 photometric
 - We adopt truncated isothermal profiles for the 300 CMs and 3 cored elliptical isothermal profiles for the cluster haloes
- We scale the CM profiles with the F160W: $\sigma_0 \sim L^{0.35}$ & $r_t \sim L^{0.5} \rightarrow M_T \sim \sigma_0^2 r_t \sim L^{0.7} L^{0.5} = L^{1.2}$
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

Our best-fitting strong lensing model II

ID	Model	χ^2	dof	rms (arcsec)
MLC G12L	3PIEMD + 300dPIE ($M_T L^{-1} = k$)	5094	97	0.49
MLV G12L	3PIEMD + 300dPIE ($M_T L^{-1} \sim L^{0.2}$)	5039	97	0.49
MLC G12F	3PIEMD + 298dPIE ($M_T L^{-1} = k$) + 2dPIE	1511	89	0.27
MLV G12F	3PIEMD + 298dPIE ($M_T L^{-1} \sim L^{0.2}$) + 2dPIE	1441	89	0.26
MLC G12P	3PIEMD + 298dPIE ($M_T L^{-1} = k$) + 2SPLE	3324	89	0.40
MLV G12P	3PIEMD + 298dPIE ($M_T L^{-1} \sim L^{0.2}$) + 2SPLE	3335	89	0.40

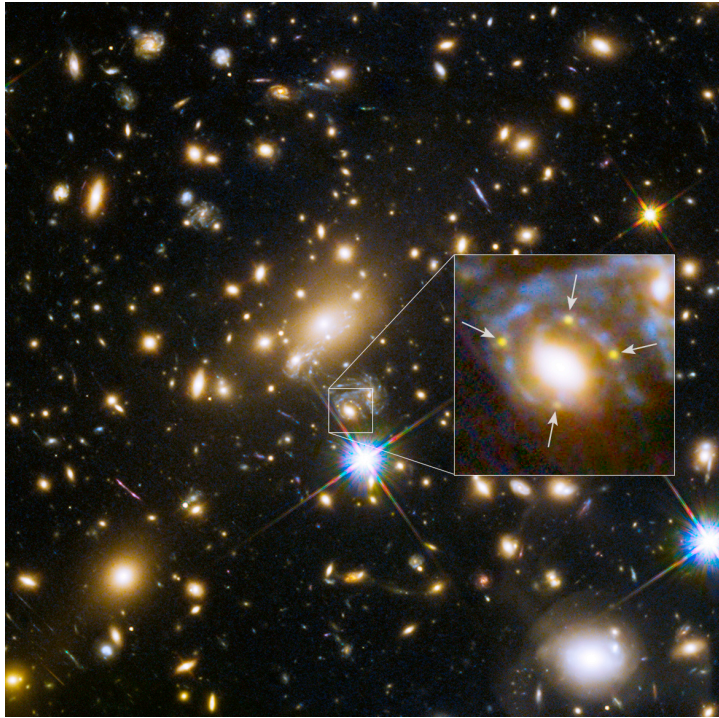
✓ Several different cluster total mass models are tested

Parameter	MLC G12L	MLV G12L	MLC G12F	MLV G12F ^a	MLC G12P	MLV G12P	MLV G12F ^b
x_{SX}^{c} (arcsec)	-4.68	-4.48	-4.70	-4.61	-4.64	-4.59	-4.59 [-4.66, -4.50]
y_{SX}^{c} (arcsec)	-6.72	-6.73	-6.58	-6.52	-6.45	-6.51	-6.59 [-6.66, -6.52]
μ_{SX}	-5.0	-5.1	-5.3	-5.2	-5.2	-4.7	-4.8 [-5.3, -4.5]
$\Delta t_{\text{SX}}^{\text{d}}$ (days)	348	328	366	353	387	390	361 [334, 381]

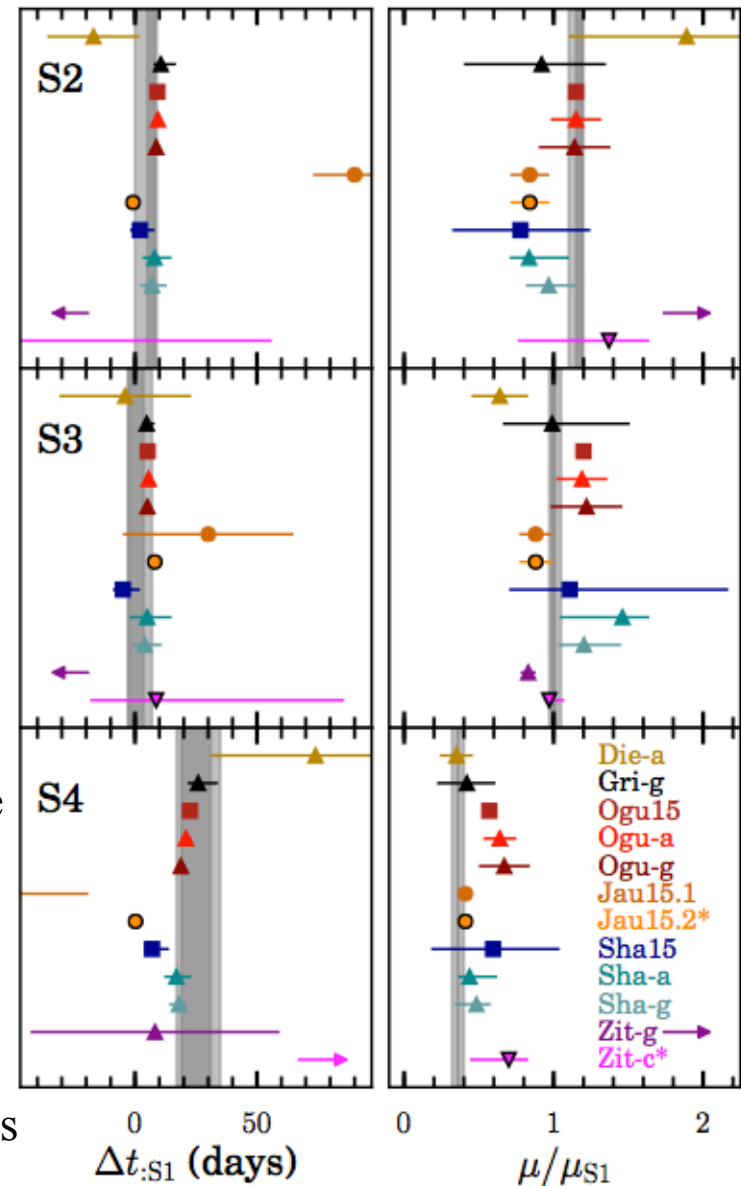


✓ Statistical and systematic uncertainties for the magnification and time delay of SX are similar

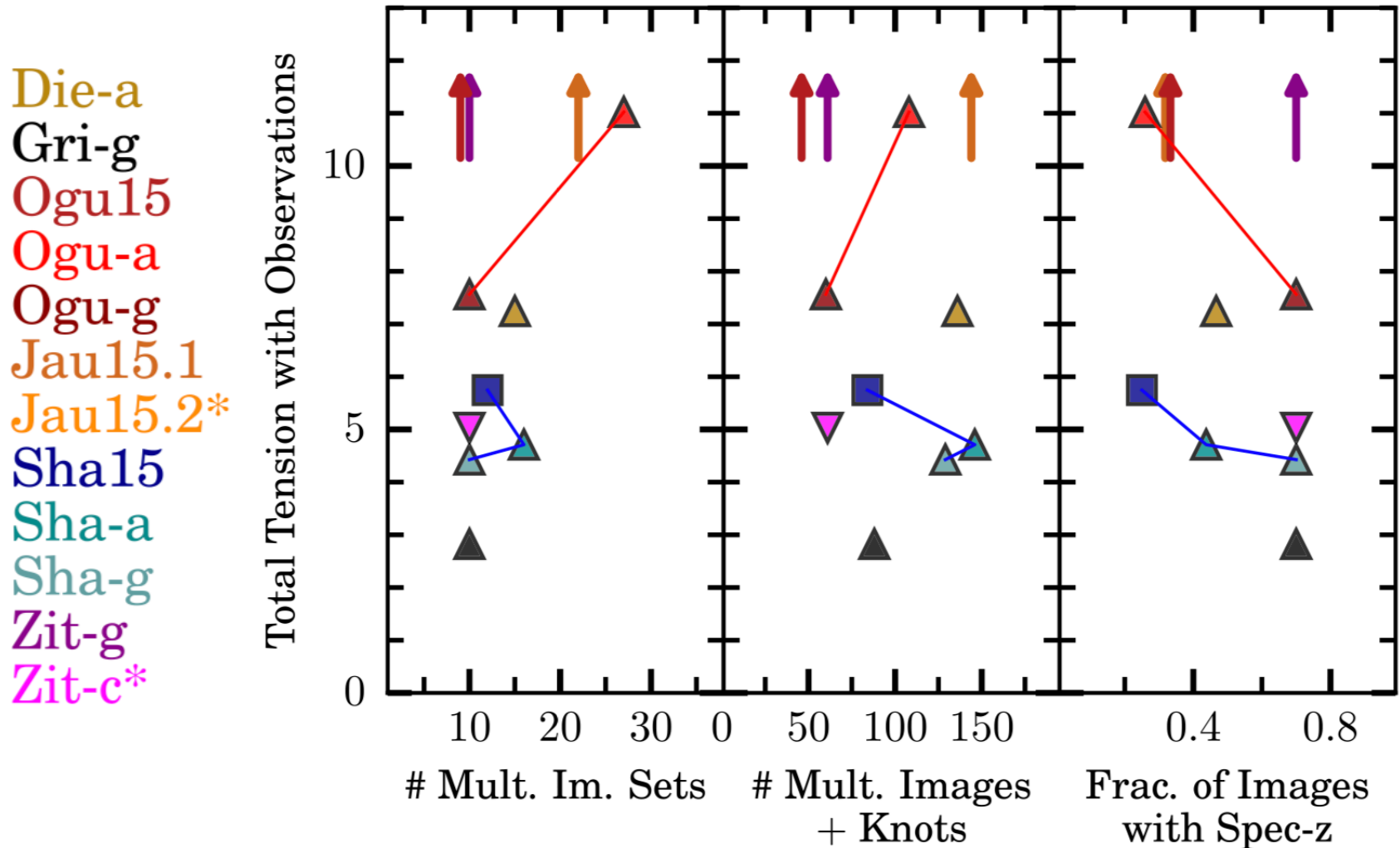
SN Refsdal's follow-up and true blind tests of model predictions I



- ❖ MUSE and GLASS data to build refined strong lensing models and predict the future appearance
Treu, Brammer, Diego, et al. 2016, ApJ, 817, 60
- ❖ S2-S4 relative (to S1) time delays and magnifications measured
Rodney, Strolger, Kelly, et al. 2016, ApJ, 820, 50
- ❖ Excellent agreement with some model predictions
Grillo, Karman, Suyu, et al. 2016, ApJ, 822, 78



SN Refsdal's follow-up and true blind tests of model predictions II

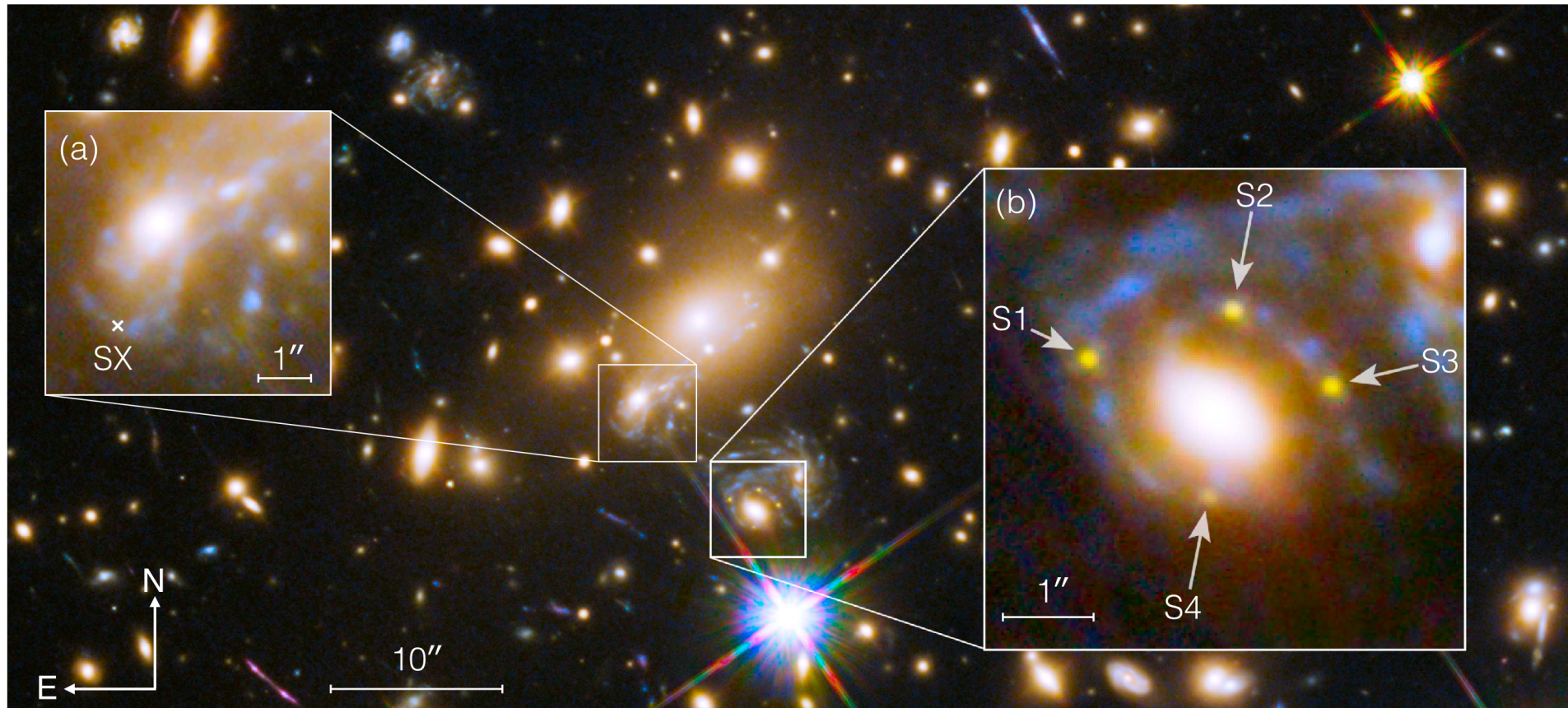


Rodney, Strolger, Kelly, et al. 2016, ApJ, 820, 50

❖ Excellent agreement with some model predictions

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

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



- Einstein cross ($\approx 2''$ 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

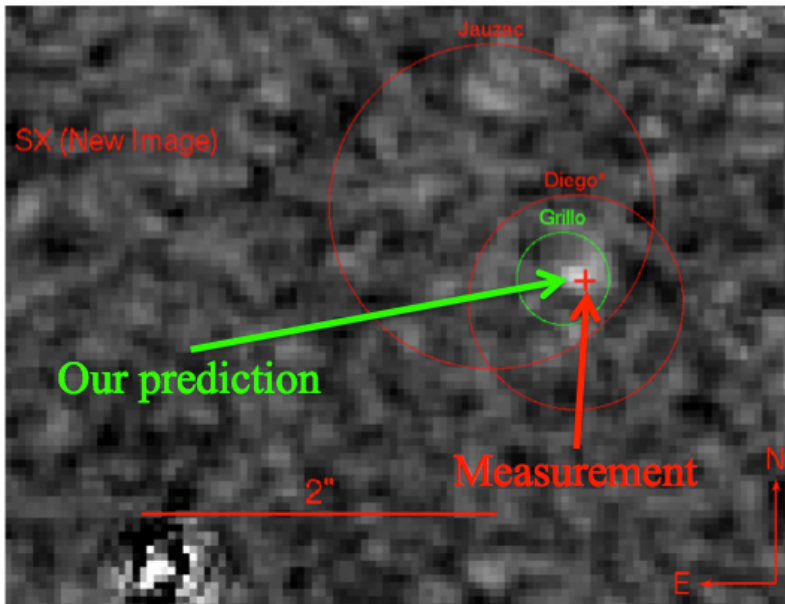
Kelly, Rodney, Treu, et al. 2016, *ApJ*, 819, 8

The reappearance of SN Refsdal

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

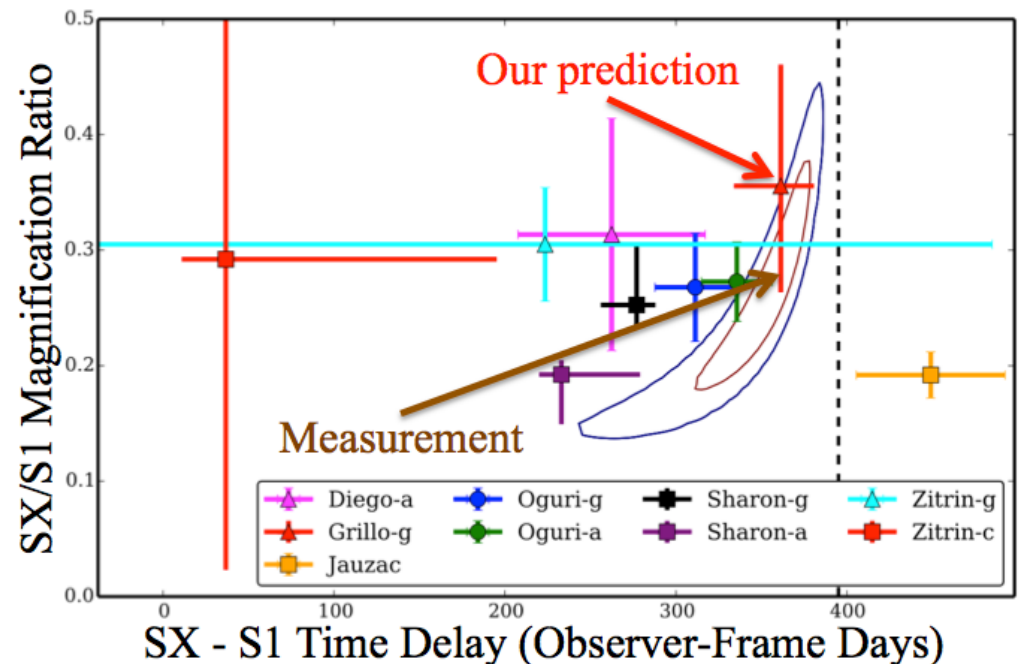
Grillo, Karman, Suyu, et al. 2016, ApJ, 822, 78

- ◆ 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



SX Position

- ◆ 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

Measuring the value of the Hubble constant I

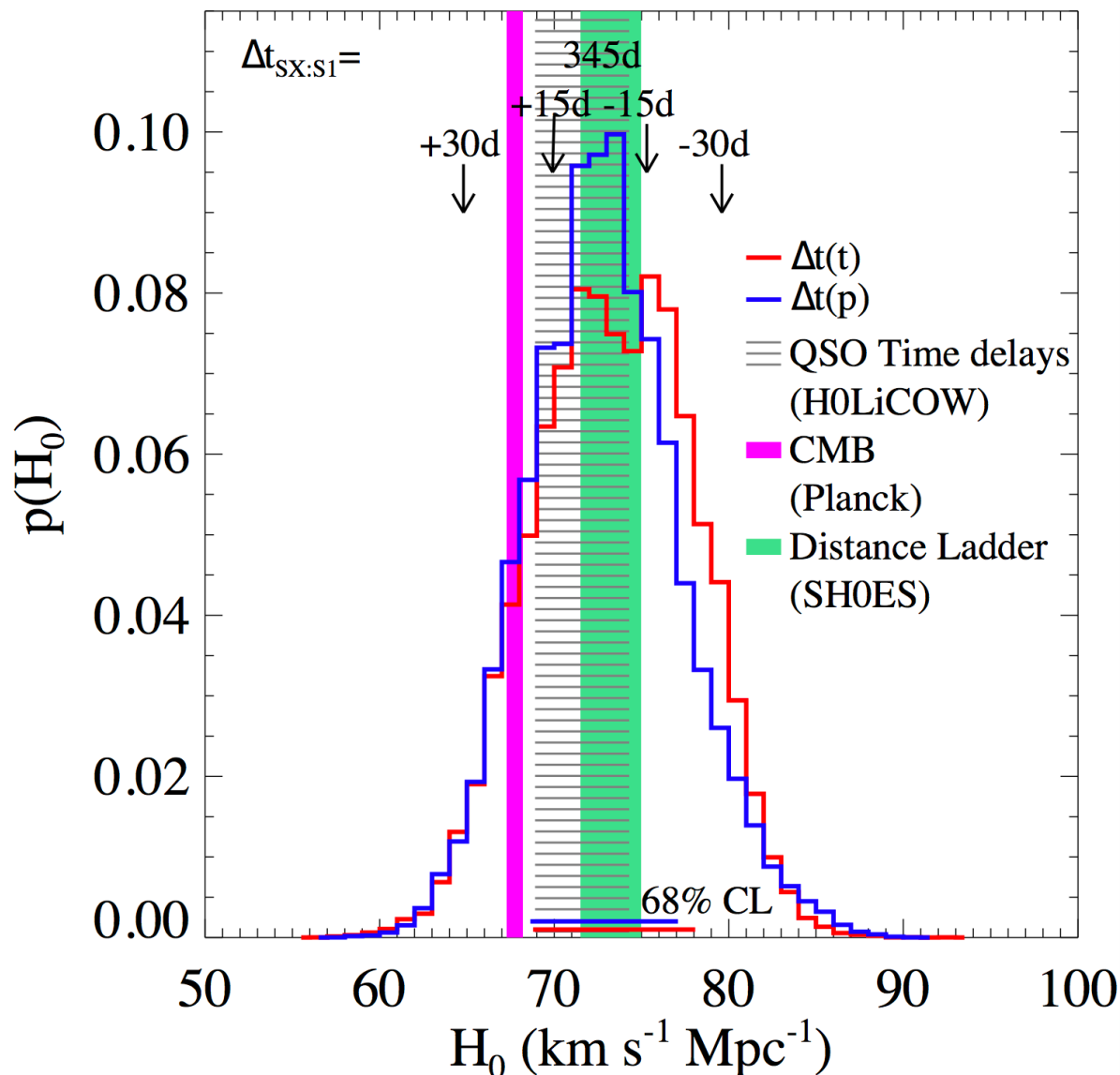
- ❖ We include the S2-S4 and SX time-delay measurements in the modelling and optimise both the cluster mass distribution and the cosmological model

ID	$\Delta t_{S2:S1}^a$ (days)	$\Delta t_{S3:S1}^a$ (days)	$\Delta t_{S4:S1}^a$ (days)	$\Delta t_{SX:S1}^b$ (days)	χ_{pos}^2	χ_{td}^2	χ_{tot}^2	dof
$\Delta t(t)$	4 ± 4	2 ± 5	24 ± 7	345 ± 10	88.1	1.4	89.5	93
$\Delta t(p)$	7 ± 2	0.6 ± 3	27 ± 8	345 ± 10	88.9	1.2	90.1	93

ID	H_0	1σ	2σ	3σ
$\Delta t(t)$	73.5	$+4.6$ -4.7	$+8.4$ -8.8	$+12.4$ -13.1
$\Delta t(p)$	72.8	$+4.3$ -4.1	$+9.5$ -8.0	$+14.1$ -11.5

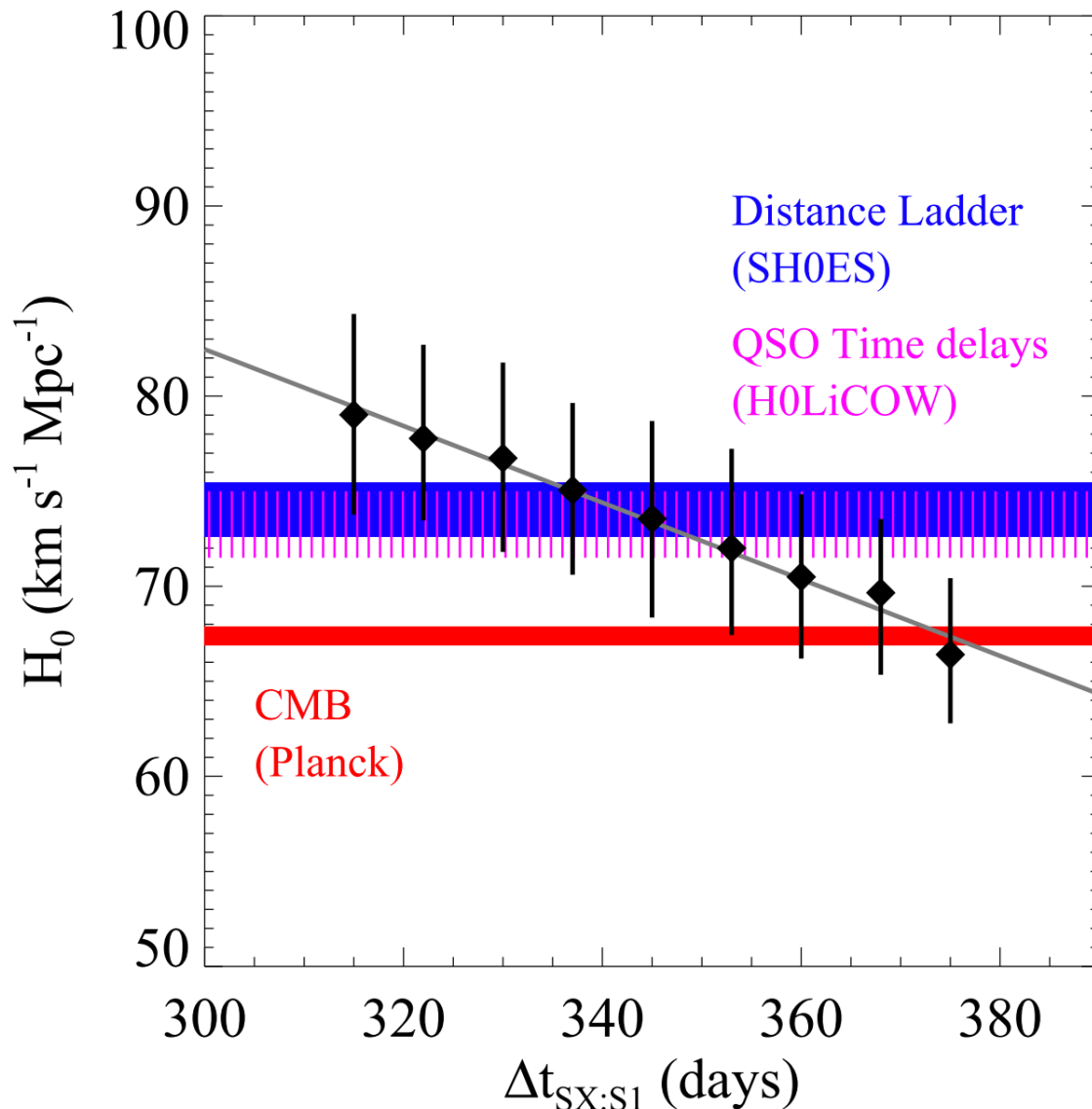
- ❖ In a flat Λ CDM model, we can infer the value of H_0 with a $\sim 6\%$ statistical error, **without any priors from other cosmological experiments**

Measuring the value of the Hubble constant II



- ❖ These results are complementary to and potentially competitive with those of other cosmological probes
- ❖ Shifts of $\sim 4\%$ (15d) or $\sim 9\%$ (30d) in the time-delay of SX translate into $\sim 4\%$ or $\sim 9\%$ differences in the estimate of H_0
- ❖ Reducing the error to $\sim 2\%$ or $\sim 1\%$ on the time-delay of SX decreases the error on the estimate of H_0 to $\sim 5\%$

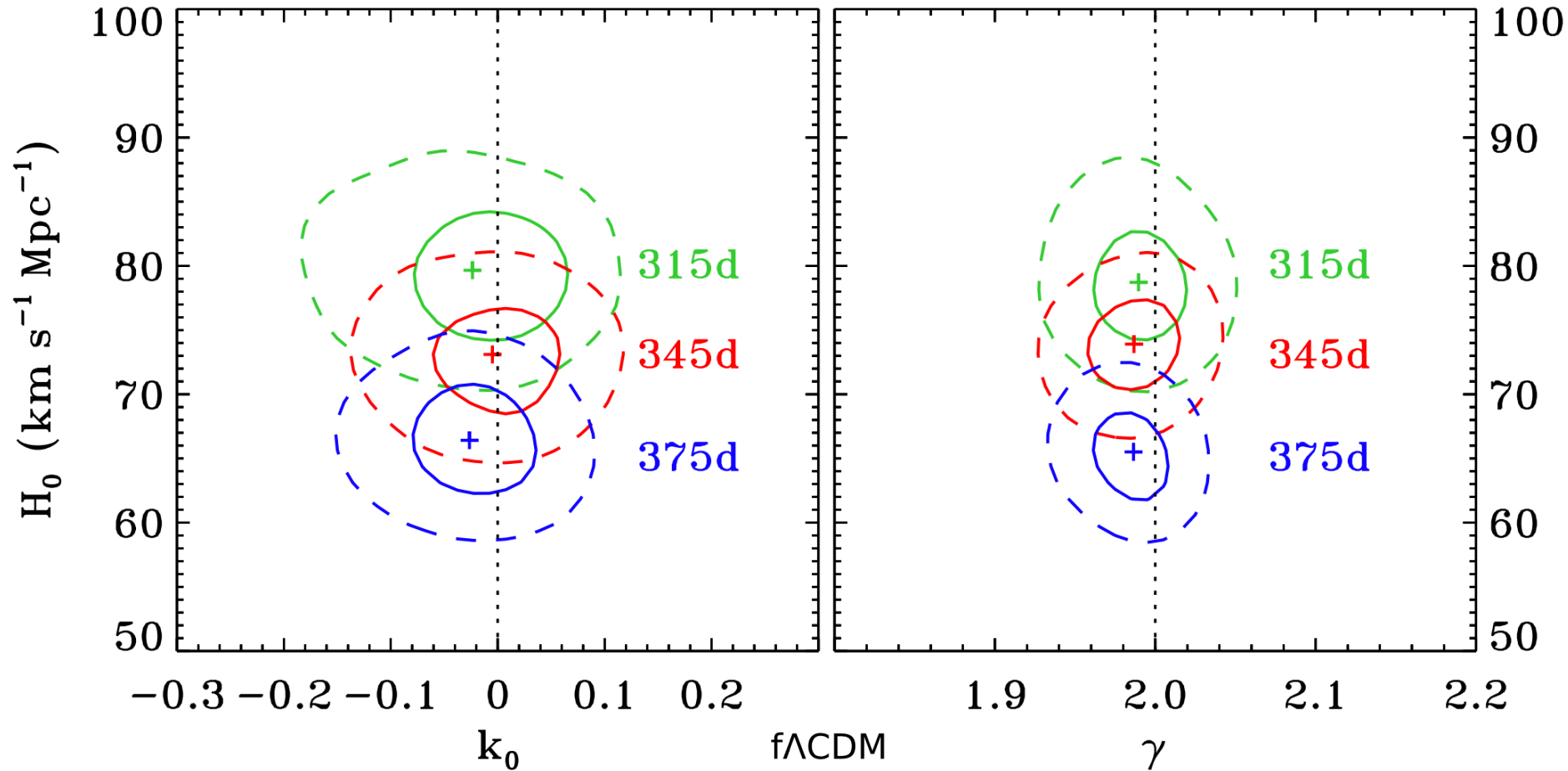
Measuring the value of the Hubble constant III



* In a flat Λ CDM model, a time delay between SX and S1 of 376 days provides a H_0 value of $(67 \pm 4) \text{ km}^{-1} \text{ s}^{-1} \text{ Mpc}^{-1}$

* True blind prediction!

Tests of systematics and robustness of the results I



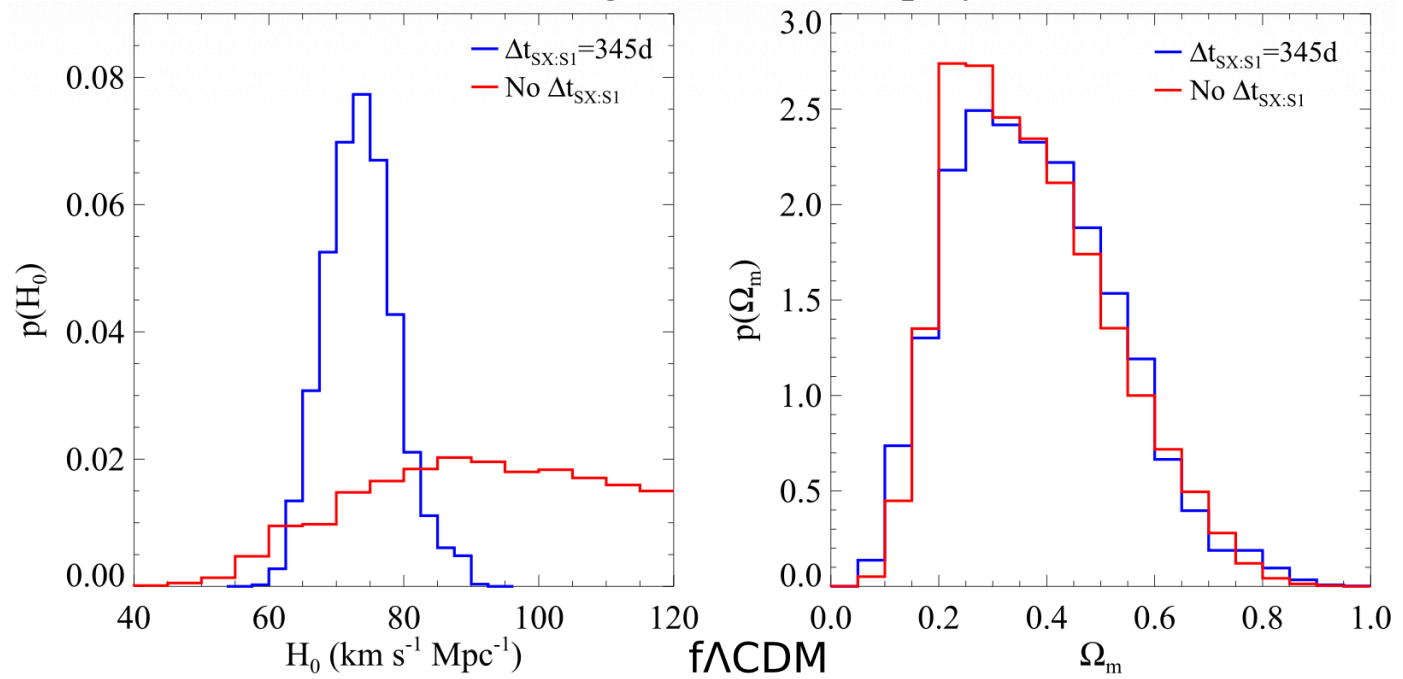
○ Systematic effects do not introduce any significant bias and statistical uncertainties dominate the total error budget

Tests of systematics and robustness of the results II

$\Delta t_{\text{SX:S1}}$	Model	H_0	Ω_m
345 days	s1	73.5 ± 4.3	0.37 ± 0.15
	s2	73.5 ± 4.7	0.40 ± 0.15
	s3	72.3 ± 4.3	0.34 ± 0.13
	s4	73.5 ± 4.2	0.36 ± 0.15
	s5	72.9 ± 4.3	0.38 ± 0.17

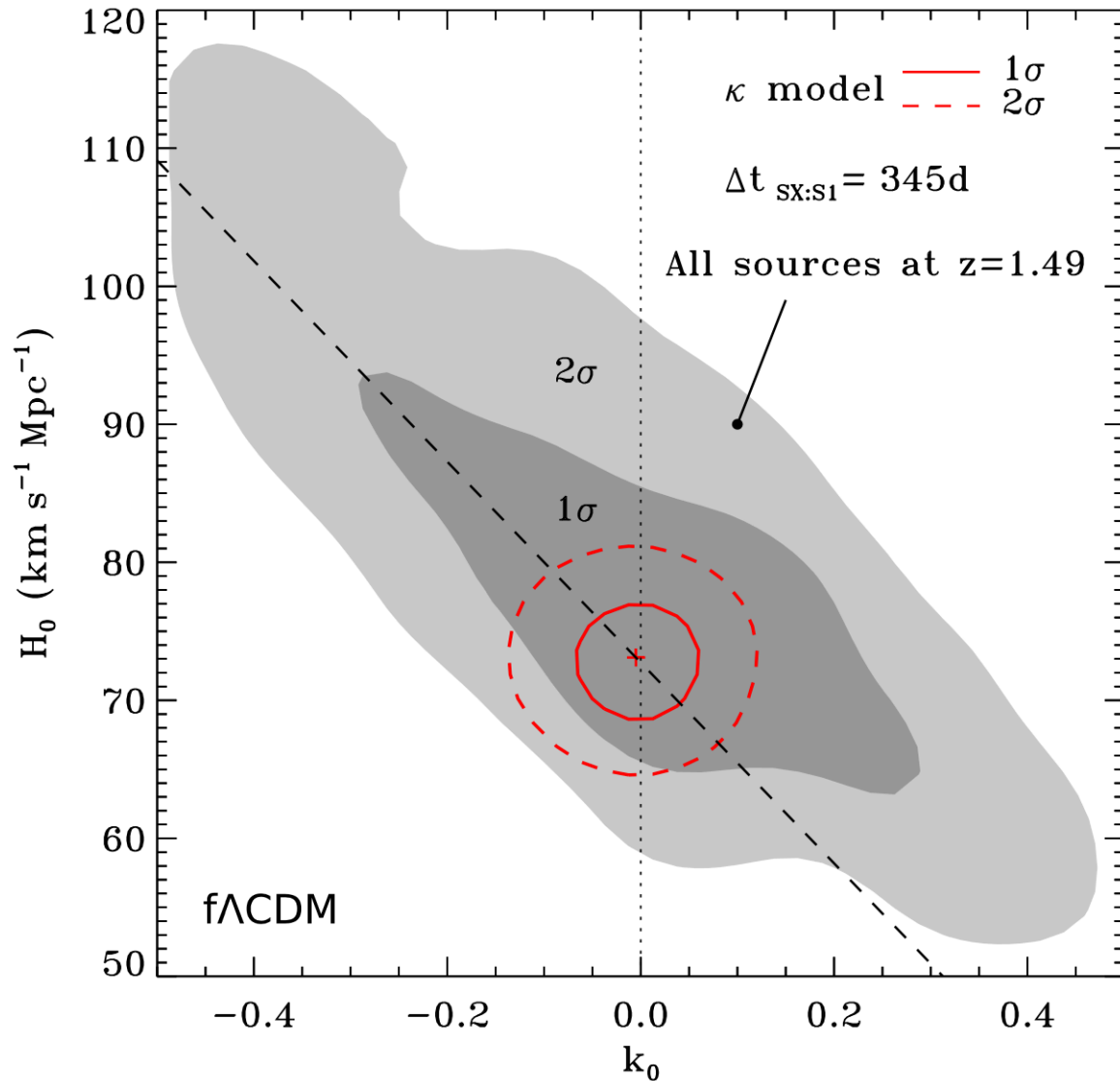
Λ CDM

- The scatter in the cluster member scaling relations also plays a minor role on the error budget



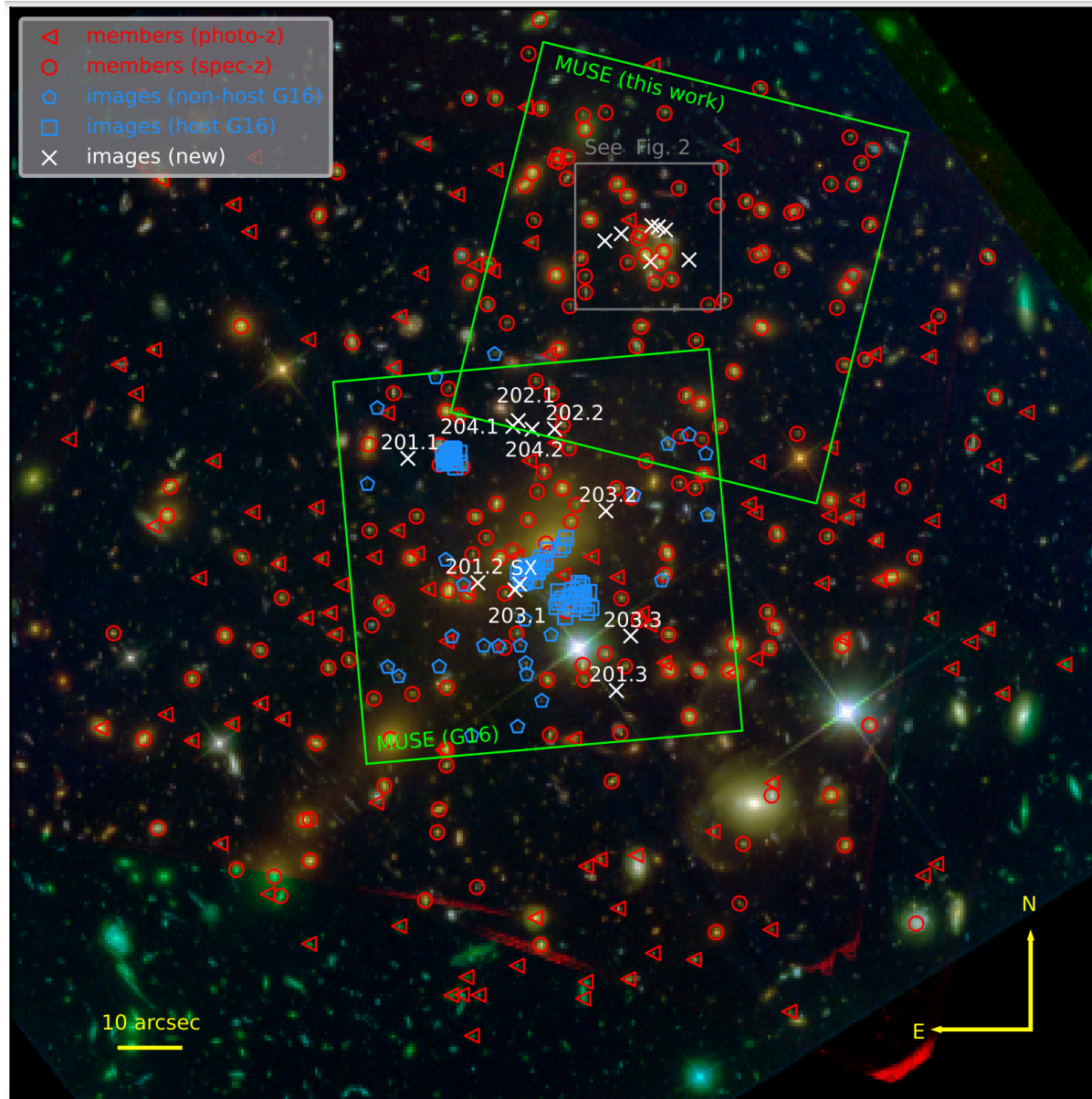
- The longest time delay of SX is crucial to measure the value of H_0 but not that of Ω_m
Grillo, Rosati, Suyu et al. 2020, ApJ, 898, 87

Breaking the mass-sheet degeneracy

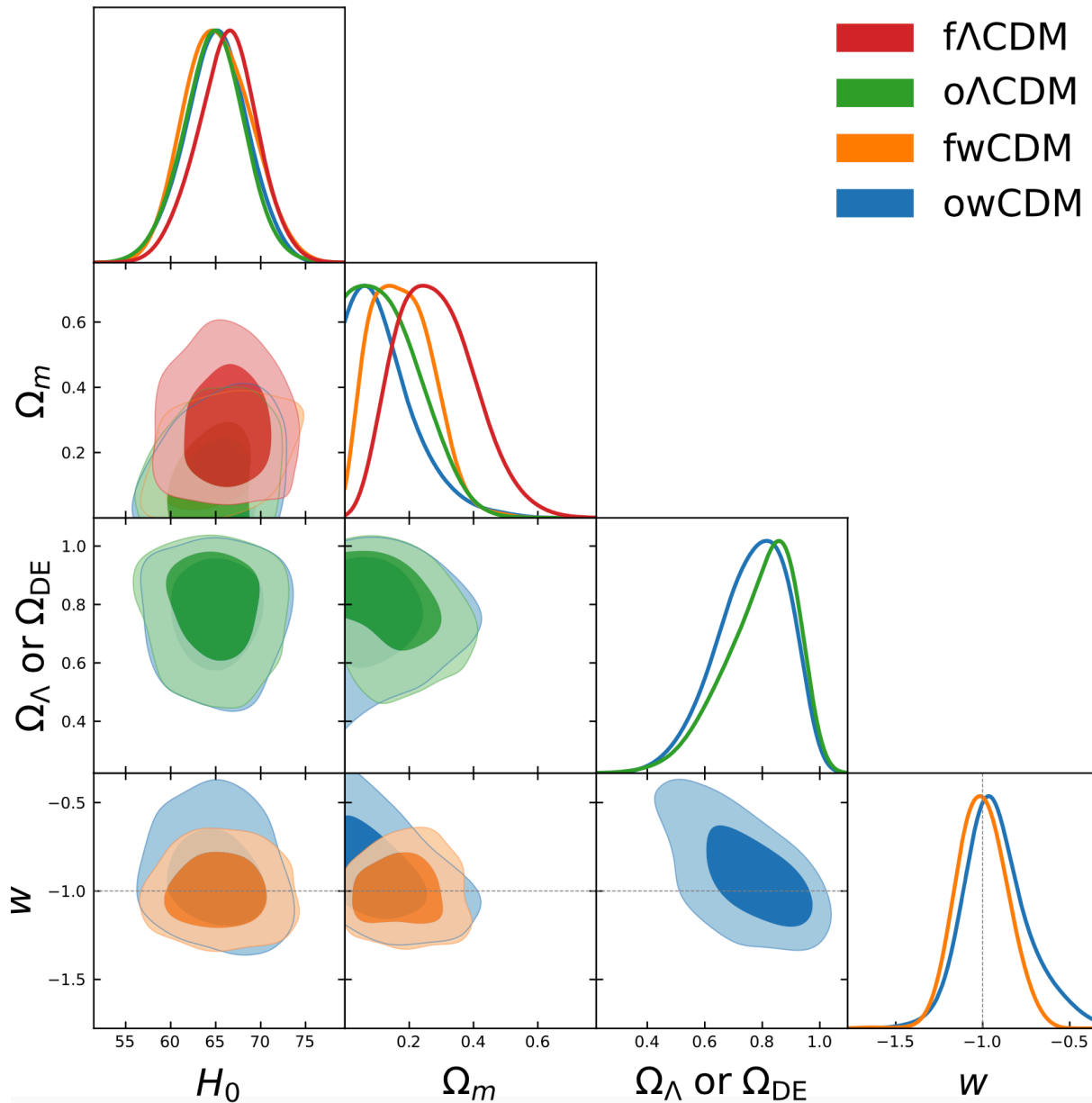


○ Having multiple images of sources at different redshifts breaks the mass-sheet degeneracy

Improved strong lensing model of MACS J1149



Measuring the values of the cosmological parameters I



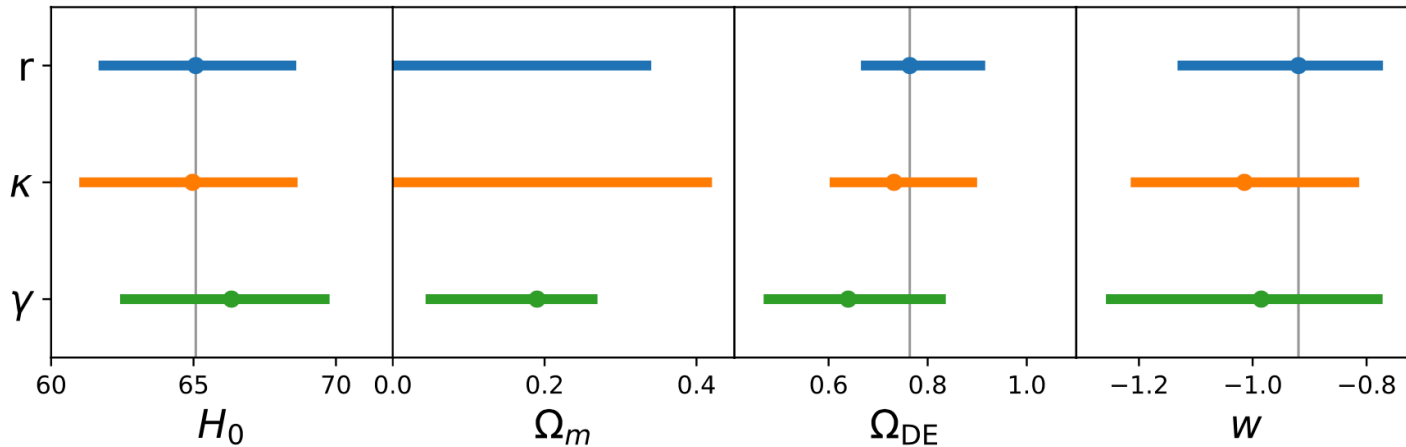
❖ The measurements are very robust and do not depend significantly on the assumed cosmological model

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

Measuring the values of the cosmological parameters II

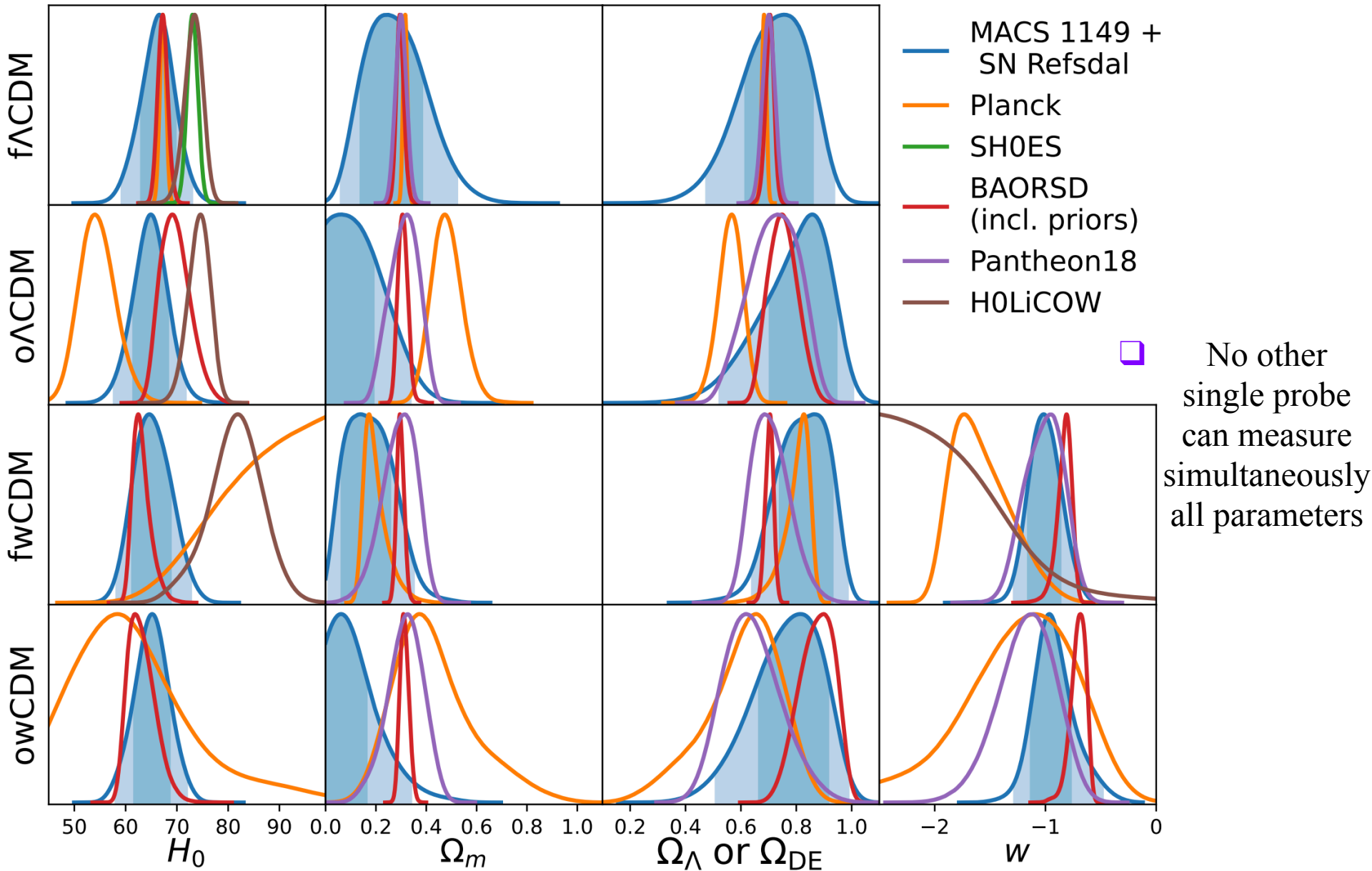
Model	H_0 (km s ⁻¹ Mpc ⁻¹)	Ω_m	Ω_Λ or Ω_{DE}	w
Λ CDM	$66.2^{+3.5}_{-3.2}$	$0.28^{+0.10}_{-0.14}$	$0.72^{+0.14}_{-0.10}$	$\equiv -1$
$o\Lambda$ CDM	$64.8^{+3.5}_{-3.3}$	< 0.34	$0.79^{+0.16}_{-0.09}$	$\equiv -1$
f_w CDM	$65.3^{+3.5}_{-4.1}$	$0.18^{+0.08}_{-0.11}$	$0.82^{+0.12}_{-0.08}$	$-1.00^{+0.14}_{-0.15}$
ow CDM	$65.1^{+3.5}_{-3.4}$	< 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 $\sim 20\%$ statistical error

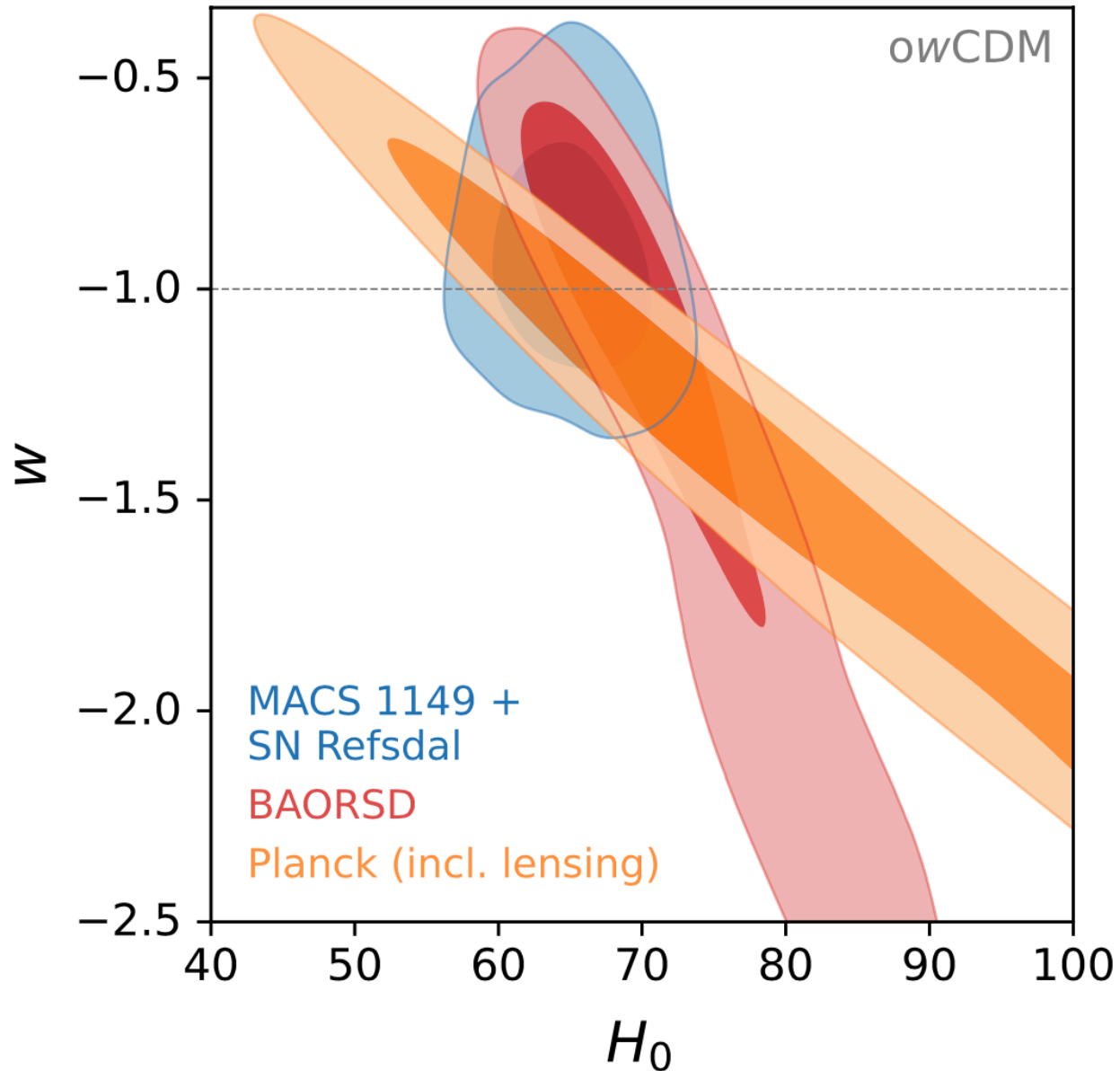


- Systematic effects do not introduce any significant bias and statistical uncertainties dominate the total error budget

Comparison with other cosmological probes I



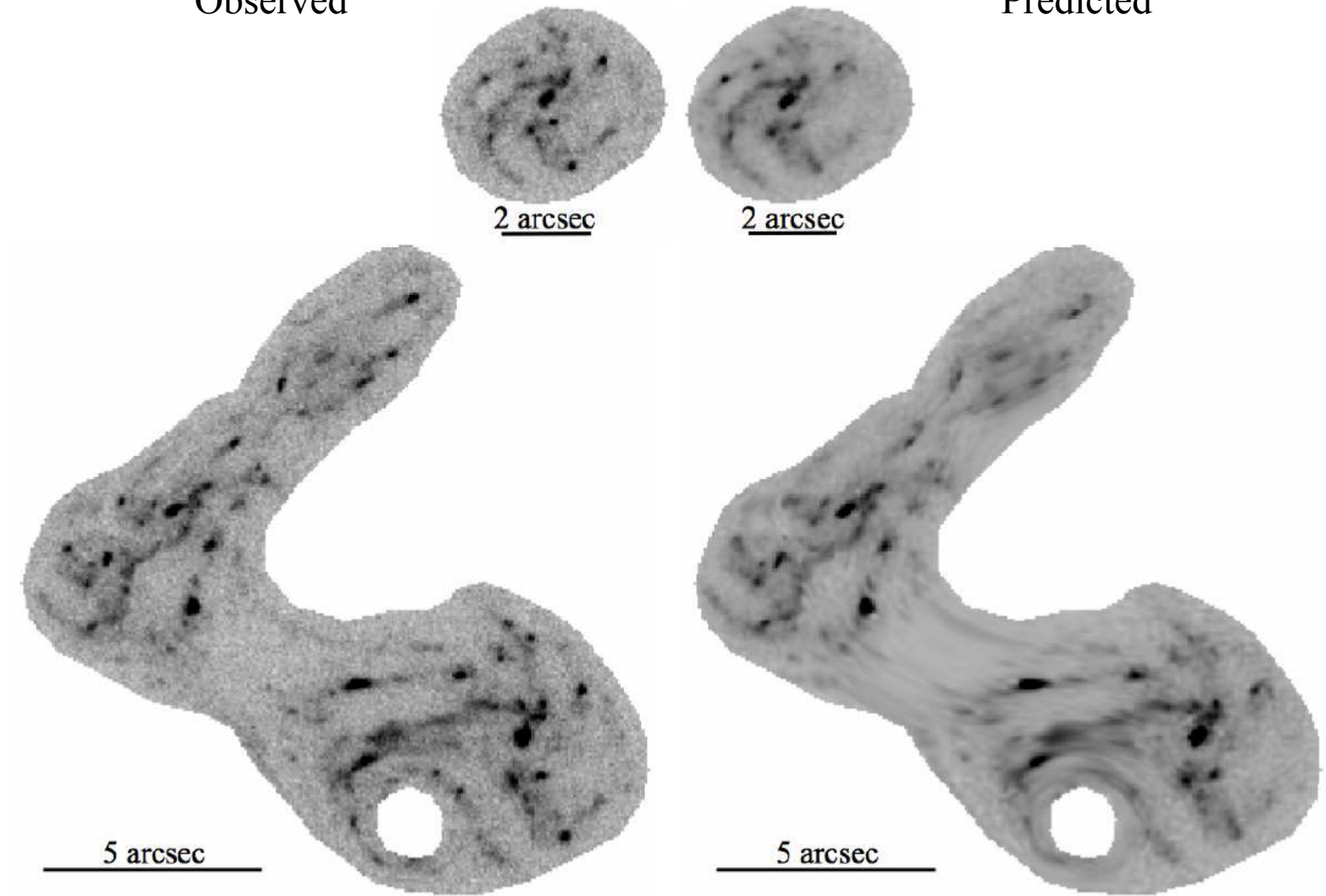
Comparison with other cosmological probes II



The SN Refsdal host I

Observed

Predicted



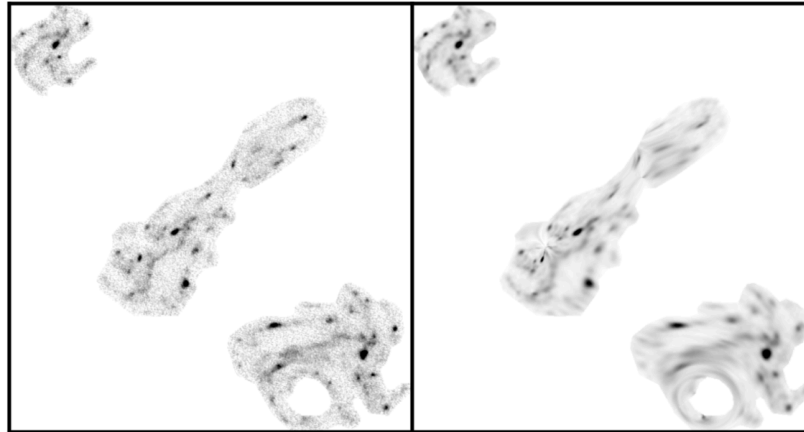
□ The surface brightness of the SN host is nicely reconstructed by our best-fitting model

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

The SN Refsdal host II

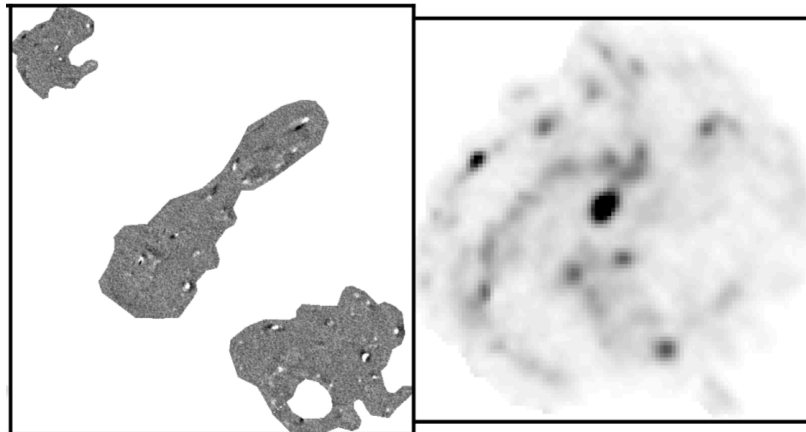
observed

predicted



norm. residuals
(-4σ , 4σ)

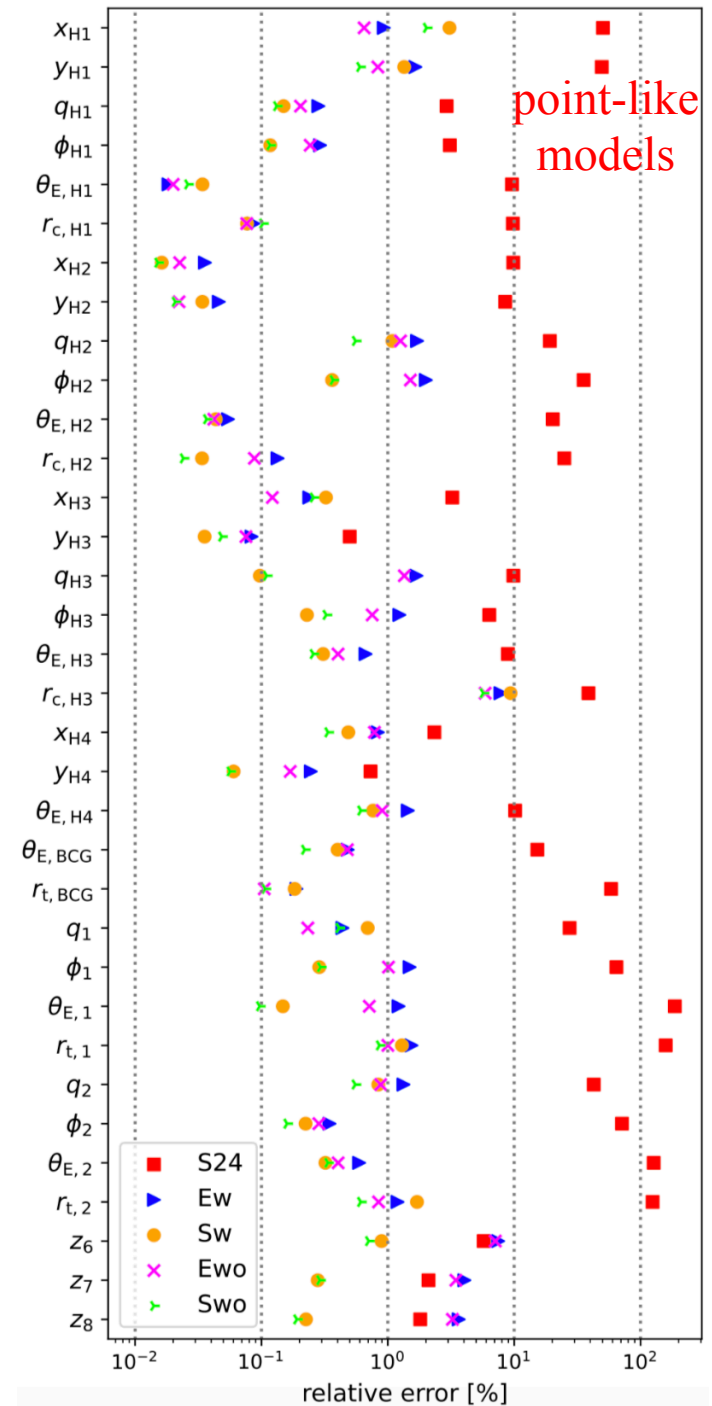
source



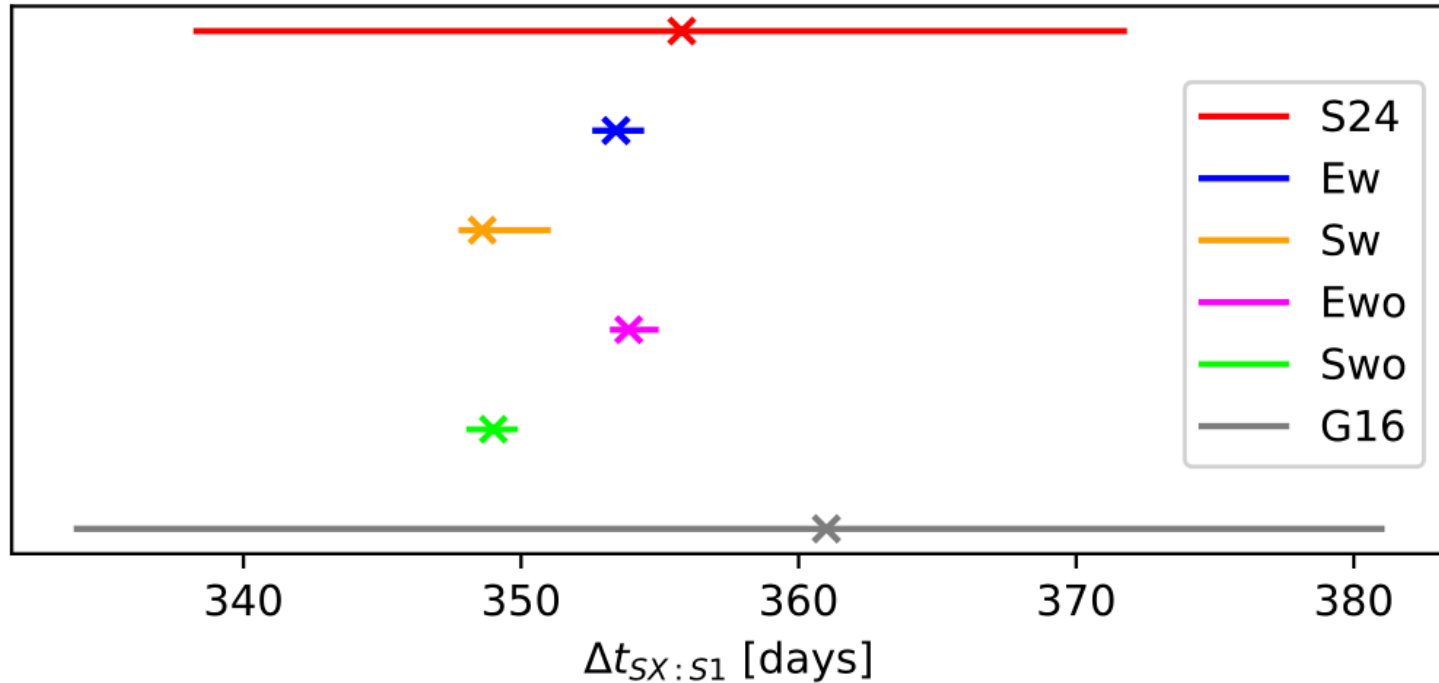
~ 77000 HST pixels

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

Schuldt, Grillo, Acebron, et al. 2026, A&A, 707, 370



The SN Refsdal host III



- ◇ The statistical uncertainty on the model-predicted time delay of SX reaches the sub-percent level
- ◇ The relative weighting of the point-like multiple image positions and flux distribution of the SN host introduces some systematic effects

Lessons learnt from SN Refsdal

Accurate and precise cosmographic measurements from SN Refsdal would have not been possible without:

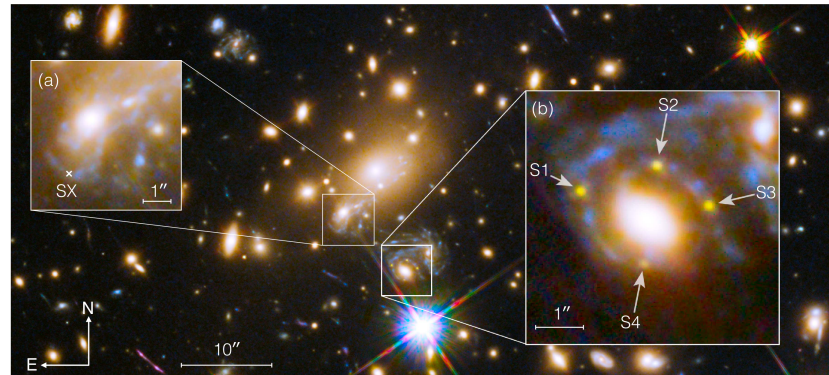
- pure sample of (spectroscopic) cluster members with detailed photometry
- secure sample of (spectroscopically confirmed) multiple images
- extended redshift range for the background sources
- multiple images covering a large area of the cluster
- angularly close pairs of multiple images
- multiple images radially elongated in the cluster core
- many secure knots identified and modelled in the SN host

Important technicalities:

- test different cluster total mass models
- model fluxes and time-delays estimated at the model-predicted positions of the multiple images
- rescaling of the positional errors of the multiple images to get $\chi^2_{\text{tot}} \sim \text{dof}$

The VST proposal I

- Targets: ~25 brightest LSST QSOs/SNe lensed by galaxies/galaxy clusters (7 years, from P4)
~18 galaxy-scale systems
~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 $r \sim 20$ mag targets $\rightarrow$ 30 min. with VST, per object per epoch (including overheads)
- Requested time: ~ 2 hours (including overheads) per night for 7 years
 $\rightarrow$ 4620 hours (including overheads) over 7 years
- 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

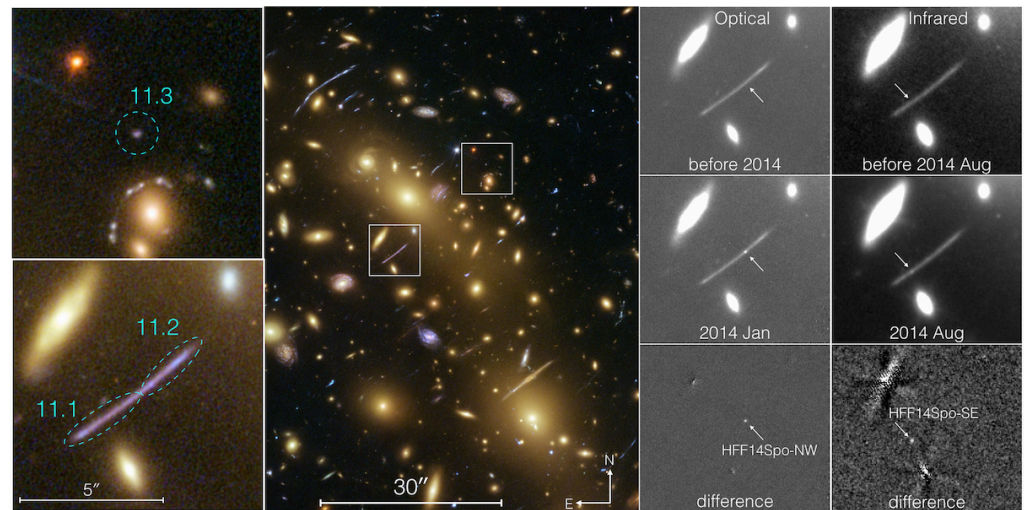
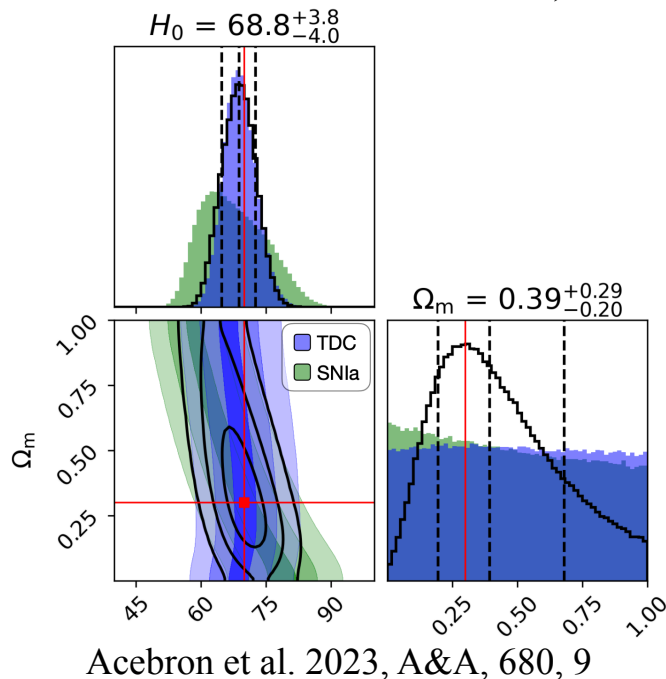
The VST proposal II

Why the VST?

To measure time delays with $\sim 2\%$ 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.



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)

The team

A. Acebron, G. Angora, M. Annunziatella, L. Bazzanini,
P. Bergamini, A. Bolamperti, M. Bronikowski, M. Brescia,
F. Courbin, M. D'Addona, G. Di Rosa, F. Dux, C. Giocoli,
G. Granata, C. Grillo, M. Lombardi, M. Meneghetti,
A. Mercurio, U. Mestric, M. Millon, L. Pecoraro,
T. Petrushevska, R. Ragusa, P. Rosati, S. Schuldt,
S. H. Suyu, E. Vanzella

✓ 27 people with different seniority

✓ 7 different countries

✓ 17 INAF (staff/affiliated) scientists from 3 INAF centres

✓ 5 LSST PIs + LSST scientists



COSMOGRAIL PI + H0LiCOW PI



Italian core members of (galaxy cluster) strong lensing



The team has years of experience in the analysis of photometric data
from optical telescopes and in the modelling of strong lenses



Some team members are also very actively participating to the Euclid mission,
which will provide complementary data and results

