Cosmological constraints with galaxy cluster strong lenses

Max-Planck-Institut für Astrophysik

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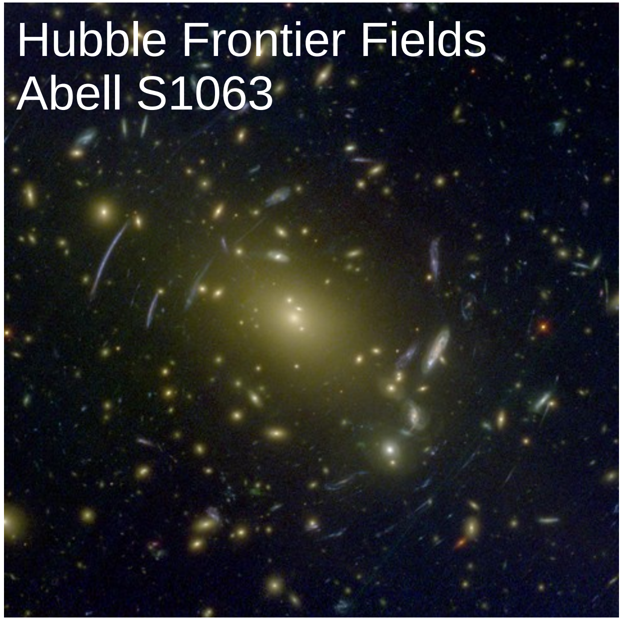
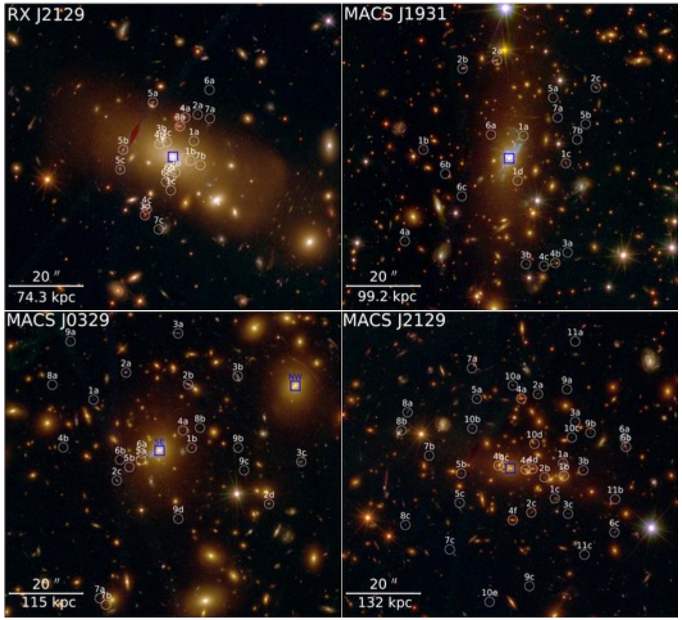
in collaboration with:

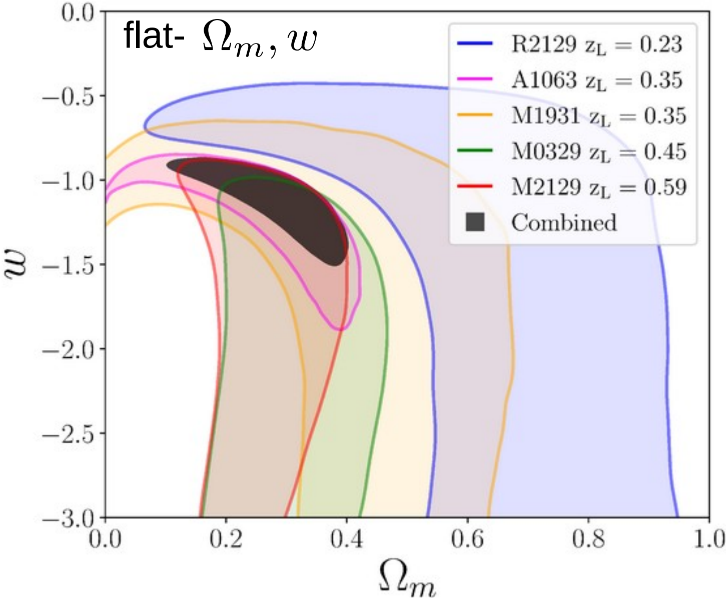
Sherry Suyu, Claudio Grillo, Piero Rosati, et al.

GCCL
GERMAN CENTRE FOR COSMOLOGICAL LENSING

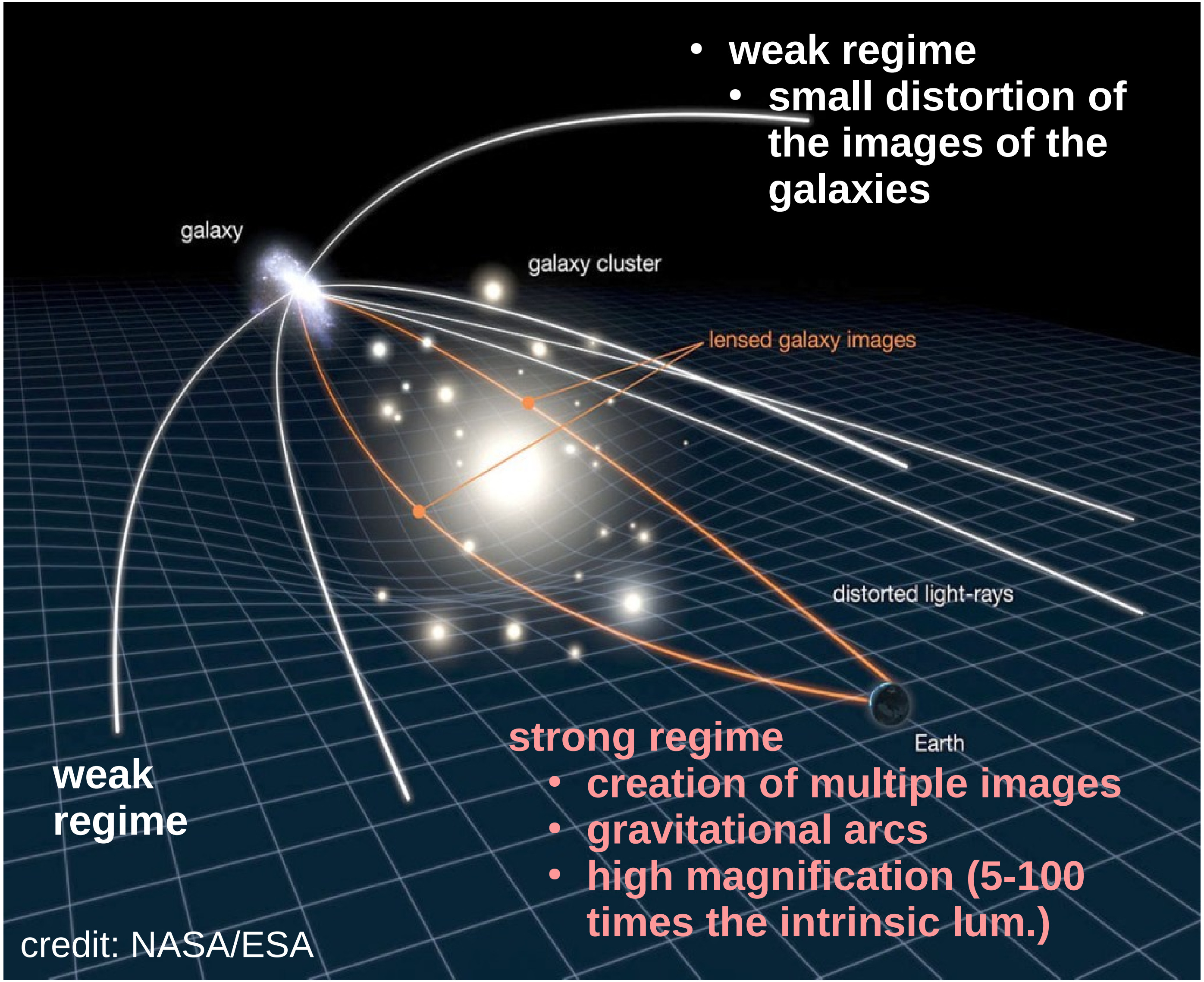




Caminha+2022 A&A, 657, 83
arXiv:2110.06232



Galaxy cluster strong lensing (SL)



Deflection of the light of a background galaxy by a massive object: galaxies, galaxy clusters, stars

Measure the mass distribution of these systems
- Does not depend on any assumption of the dynamical state or baryonic processes

Probe the background geometry of the Universe
- Angular diameter distances

Magnifications preserves surface brightness:

$$\mu \equiv \frac{\mathrm{A_{observed}}}{\mathrm{A_{intrinsic}}}$$

Allow us to observe very faint and distant object

Why do we need robust SL models?

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Galaxy clusters carry valuable information about the Universe

- Details of the mass distribution: DM content, inner slope, substructures, etc
- Cosmography with SL: background geometry, H_0 with measured time-delays
- Gravitational telescopes: detect the most faint objects in the Universe

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These studies demand highly accurate strong lensing models

- High-resolution photometry (HST) is important but not enough
- Spectroscopic confirmation of multiple images and cluster members is necessary
  - No missidentifications of multiple images and remove extra degeneracies

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Great progress in recent years thanks to coordinated programmes

- Imaging: ~1300 HST orbits on ~70 clusters at the redshift range of z = [0.2 0.9]
  - Cluster Lensing and Supernova Survey with Hubble - CLASH (25 clusters, ~27 mag depth, 16 filters)
  - Hubble Frontier Fields – HFF (6 clusters, ~29 mag depth, 7 filters)
  - Reionization Lensing Cluster Survey – RELICS (41 clusters, ~27 mag depth, 7 filters)

  - Spectroscopy
    - CLASH-VLT (VIMOS LP), GLASS and **MUSE** (~20 clusters and increasing)

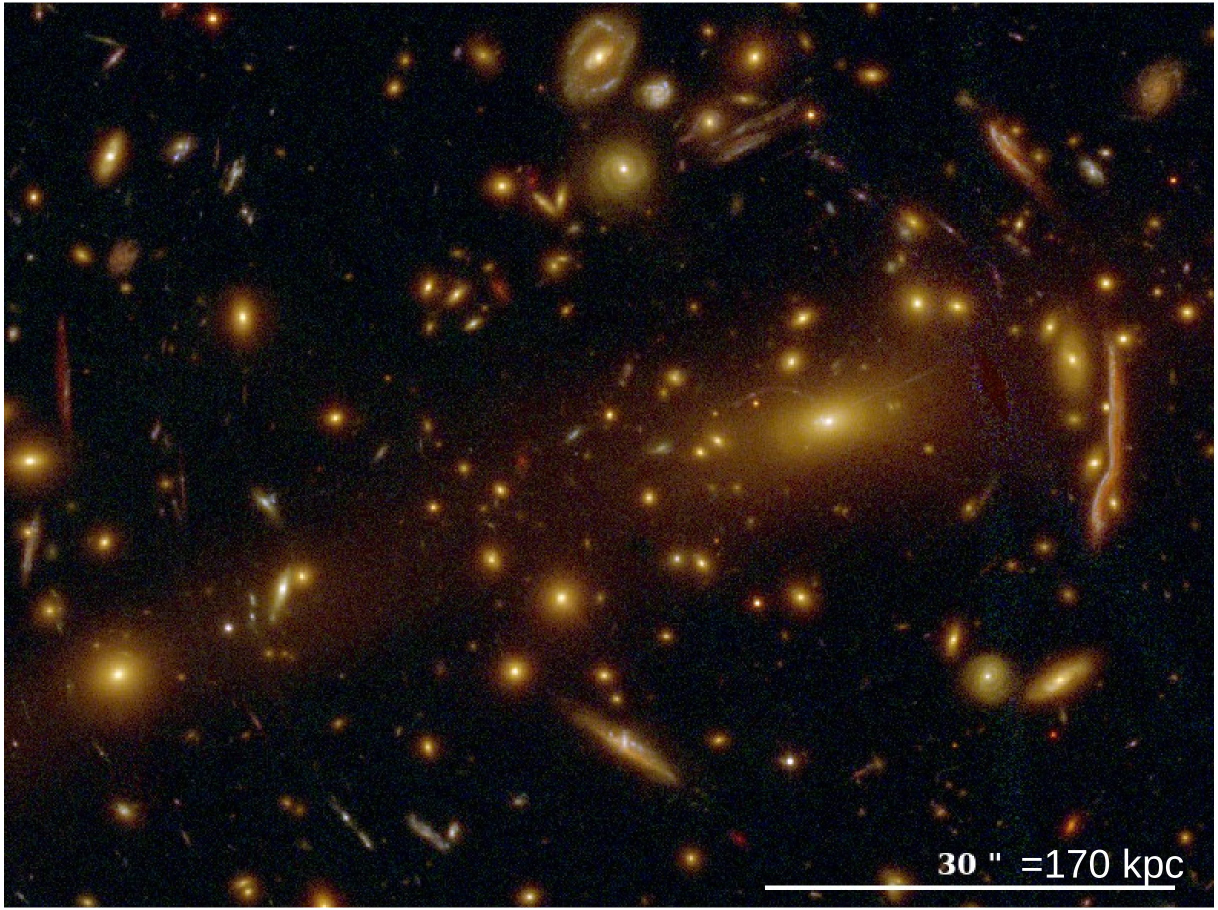
Focus on mass profiles and on constraints of the background cosmology of the Universe

$$\Omega_m, \Omega_k, w(z) \quad (\text{where}\, w = P/\rho)$$

Galaxy cluster strong lensing (SL)

MACSJ 1206
zcluster = 0.44

HST – CLASH
photometry 0.4 – 1.6 μm



Multiple images from the same background source are used to constraint the lensing model

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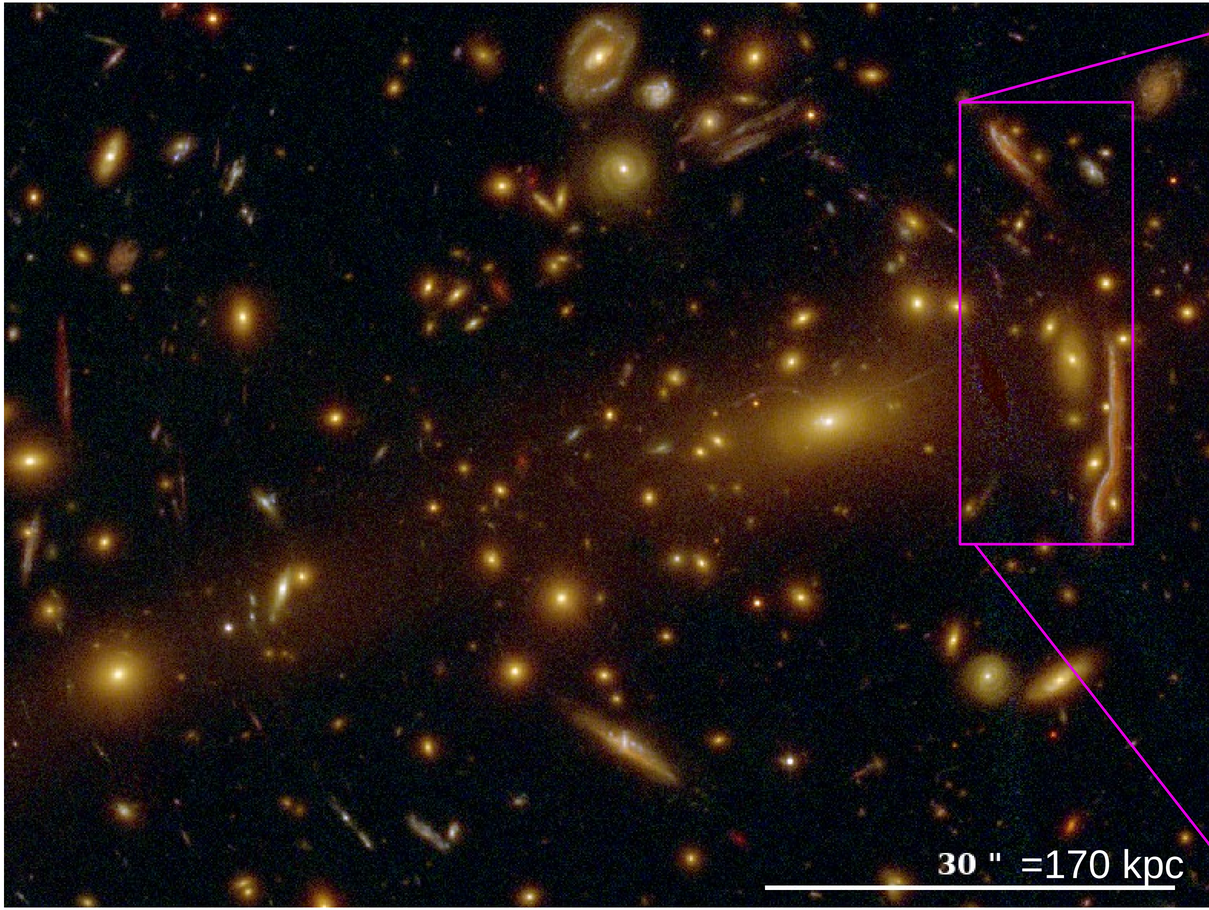

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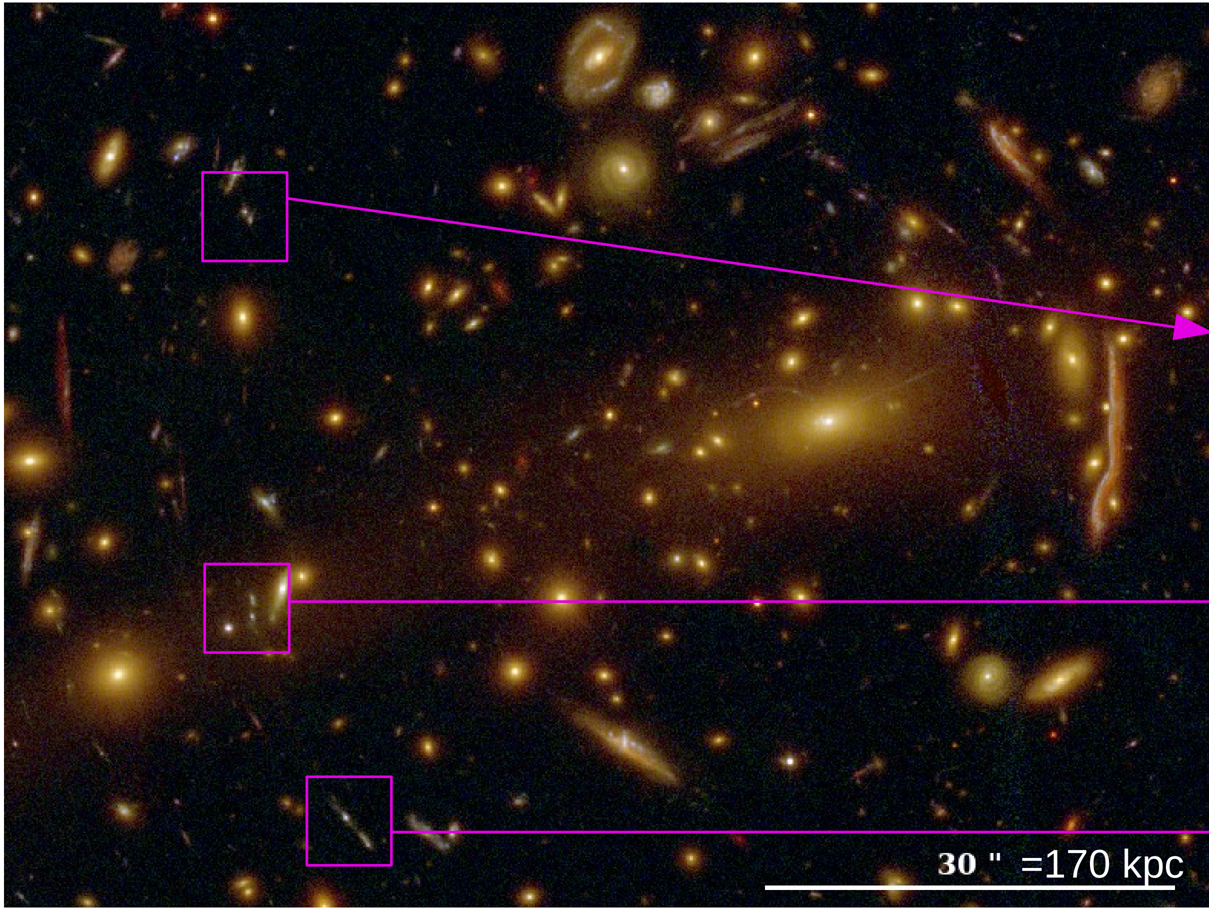
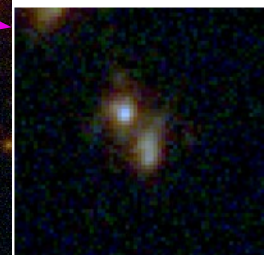
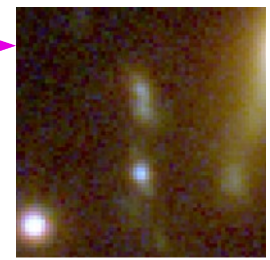
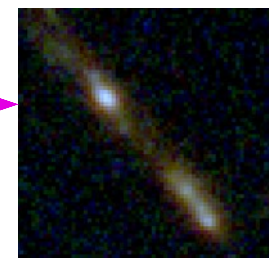


Not so obvious cases.

- Need spectroscopy to confirm multiple images
- We do not know the redshift







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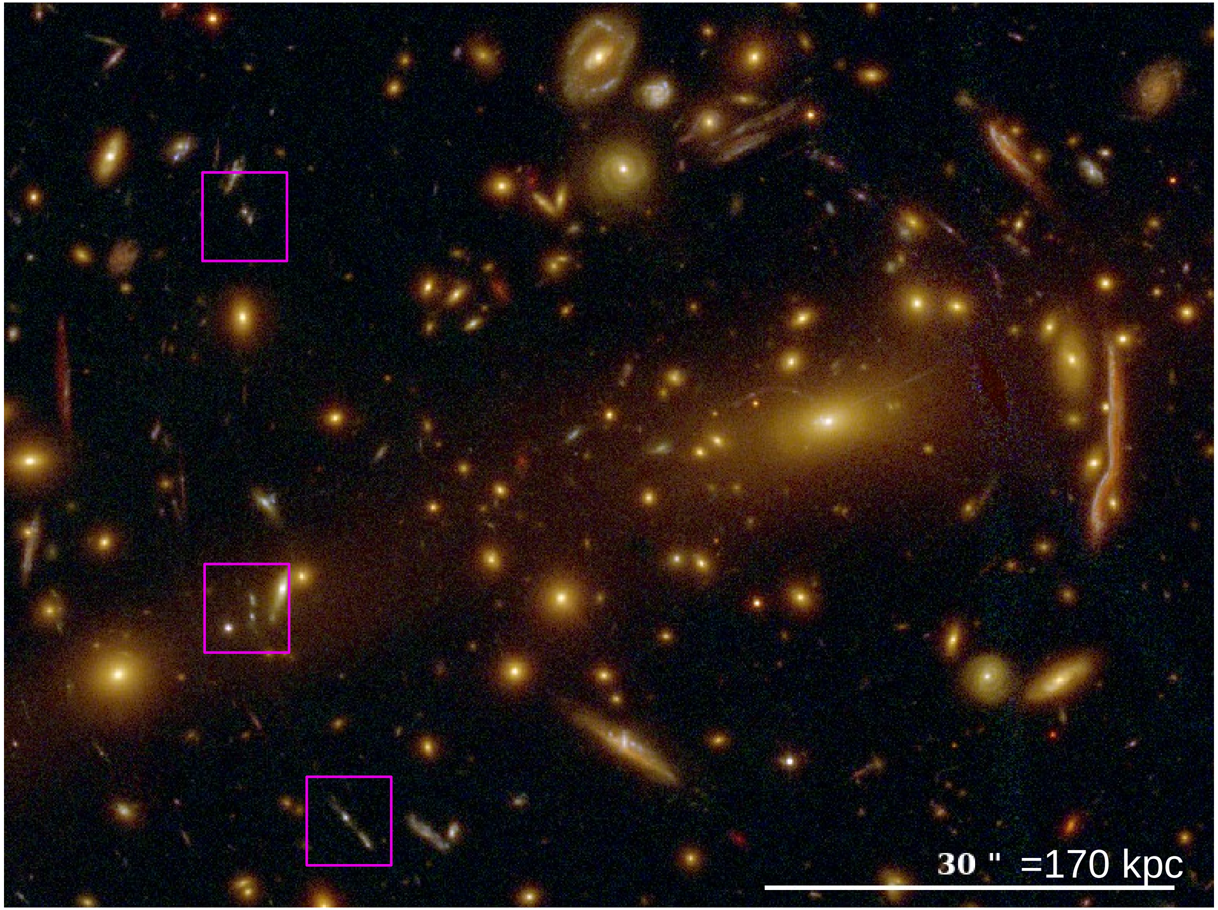

Not so obvious cases.

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- We do not know the redshift

Need high quality spectroscopy

Galaxy cluster strong lensing (SL)

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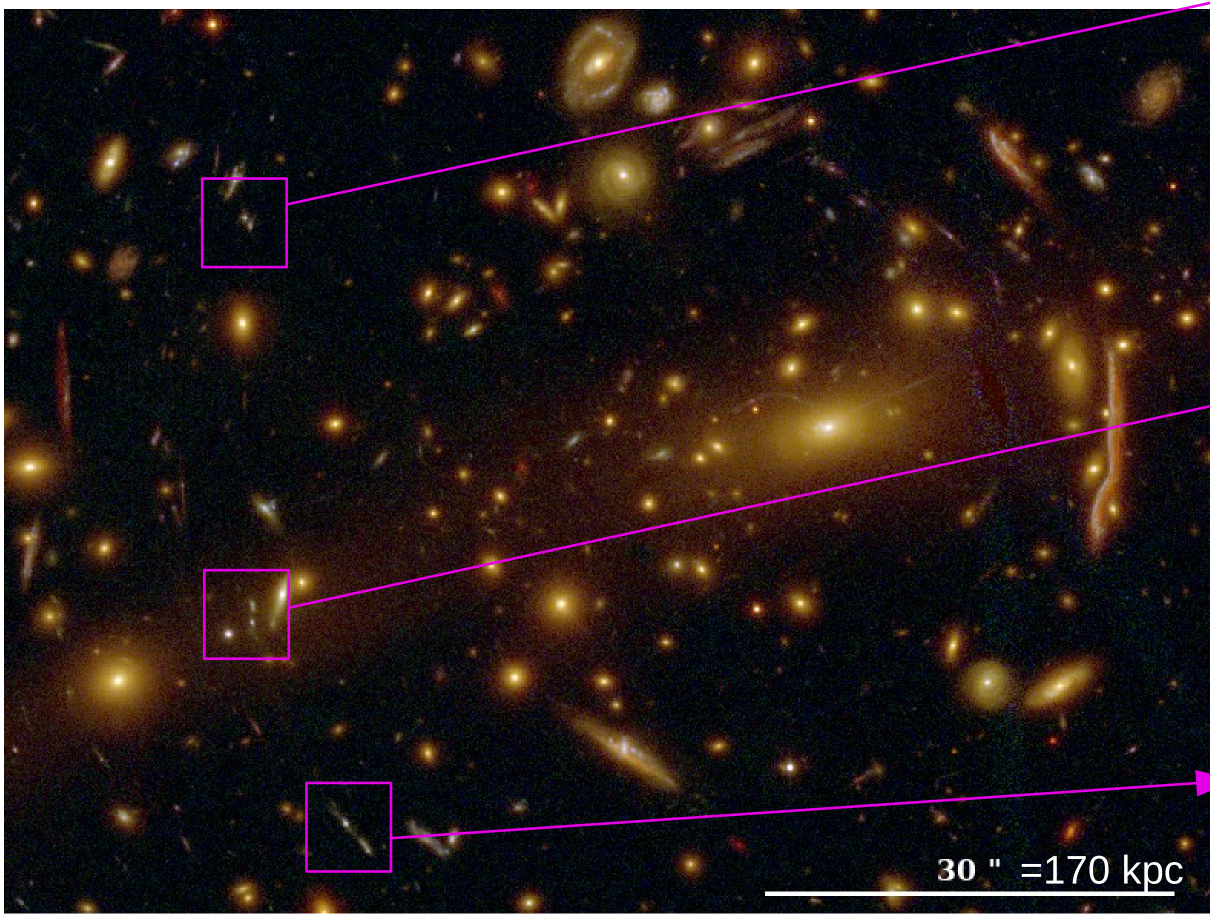

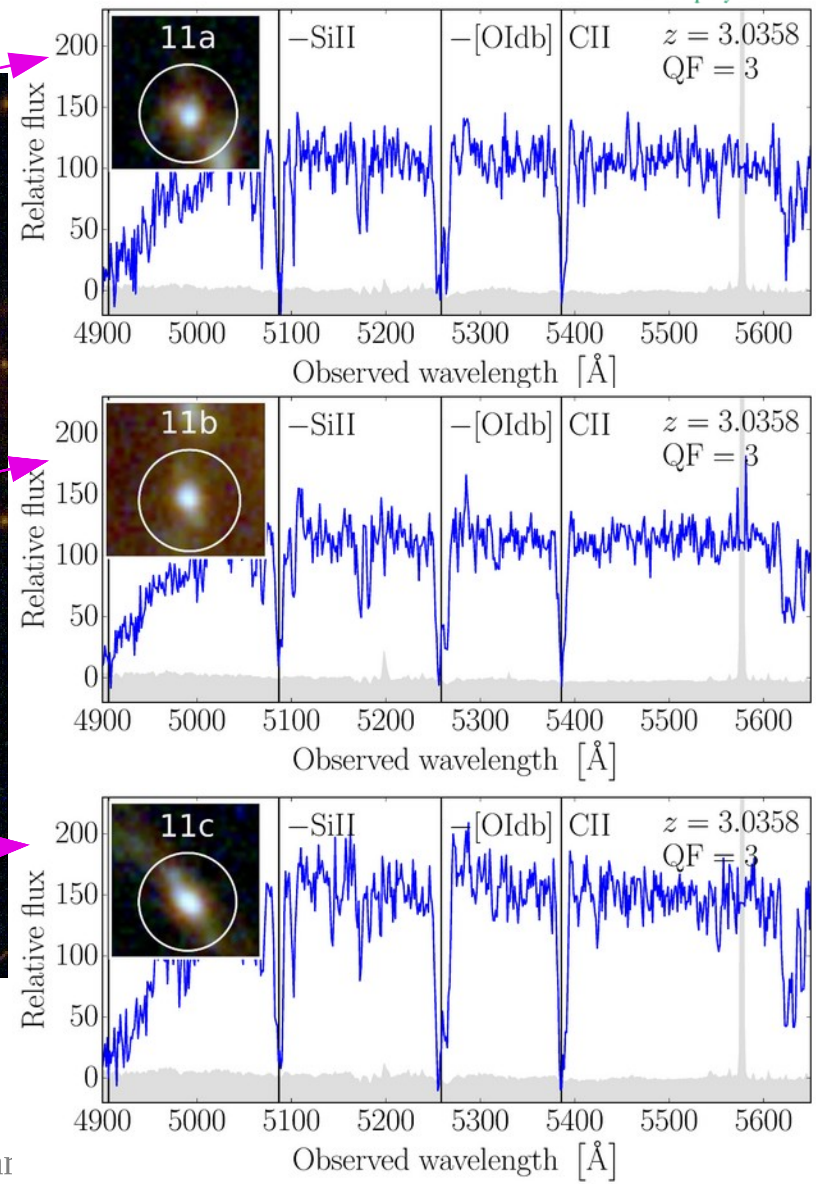

Clean sample of multiple images
→ Clean sample of model constraints

Spectroscopy in galaxy cluster fields

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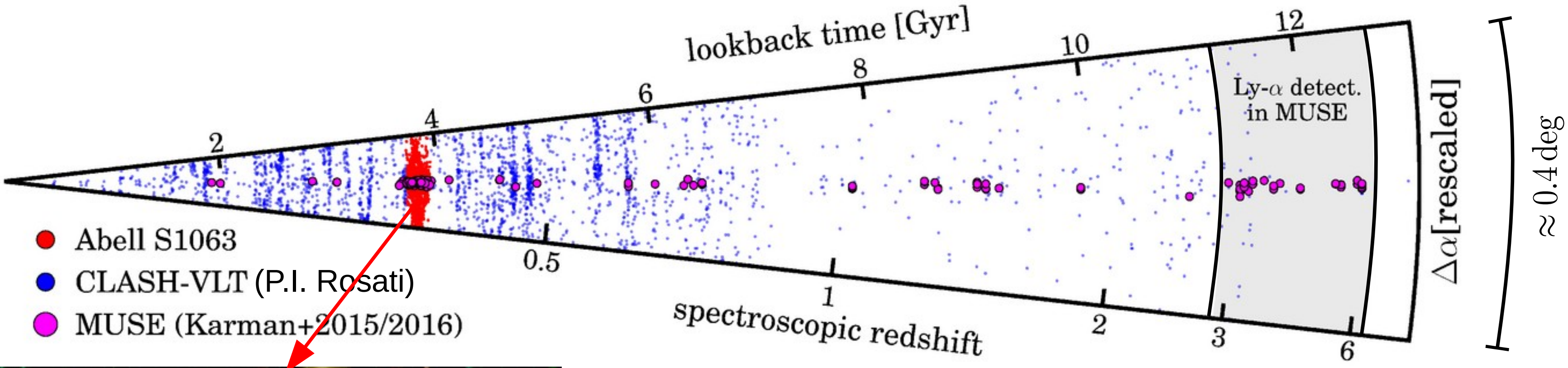

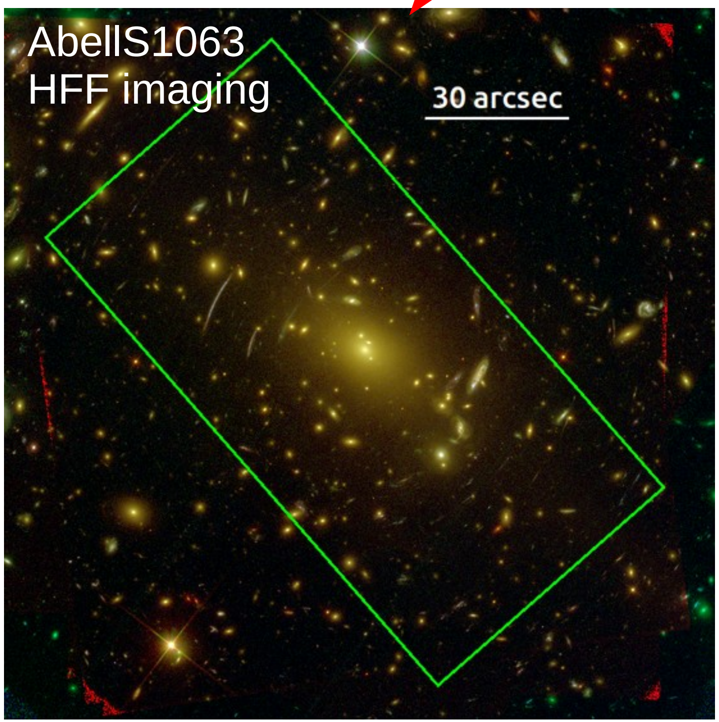

The Multi Unit Spectroscopic Explorer (MUSE) at VLT

Integral field spectroscopy over an area of 1 sq-arcmin

- No source pre-selection over this large area

Ideal to map galaxy cluster cores and confirm and identify many new multiple images when comparing to standard slit spectroscopy

Wavelength coverage of 4750Å – 9350Å

- Can confirm sources at redshifts out to z=6.7

Spatial pixel size of 0.2 arcsec, psf limited 0.6–1.0 arcsec

- Can spatially resolve emission/absorption lines

Spectral resolution of ~2.3 Å

MUSE observations of galaxy cluster

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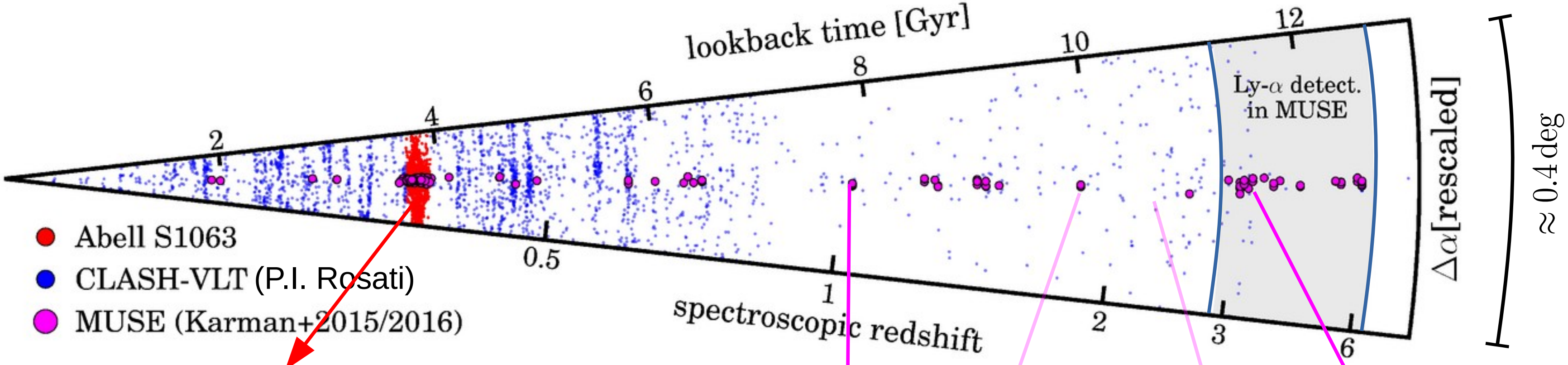
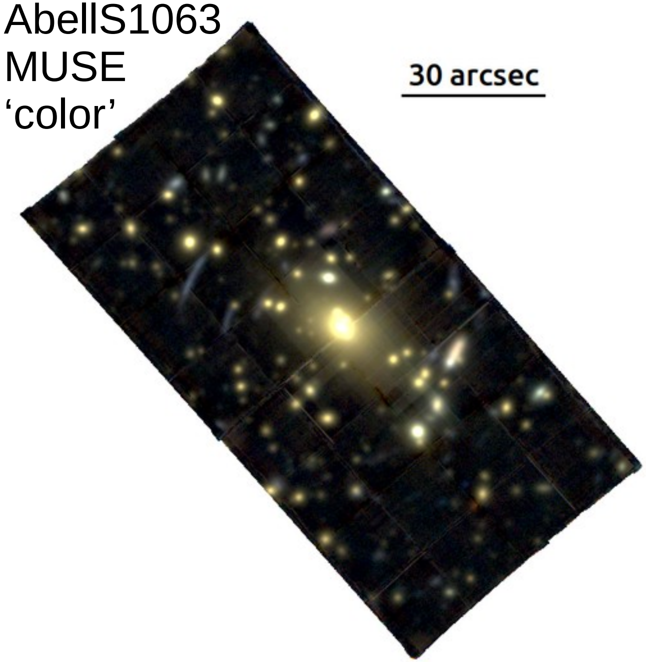
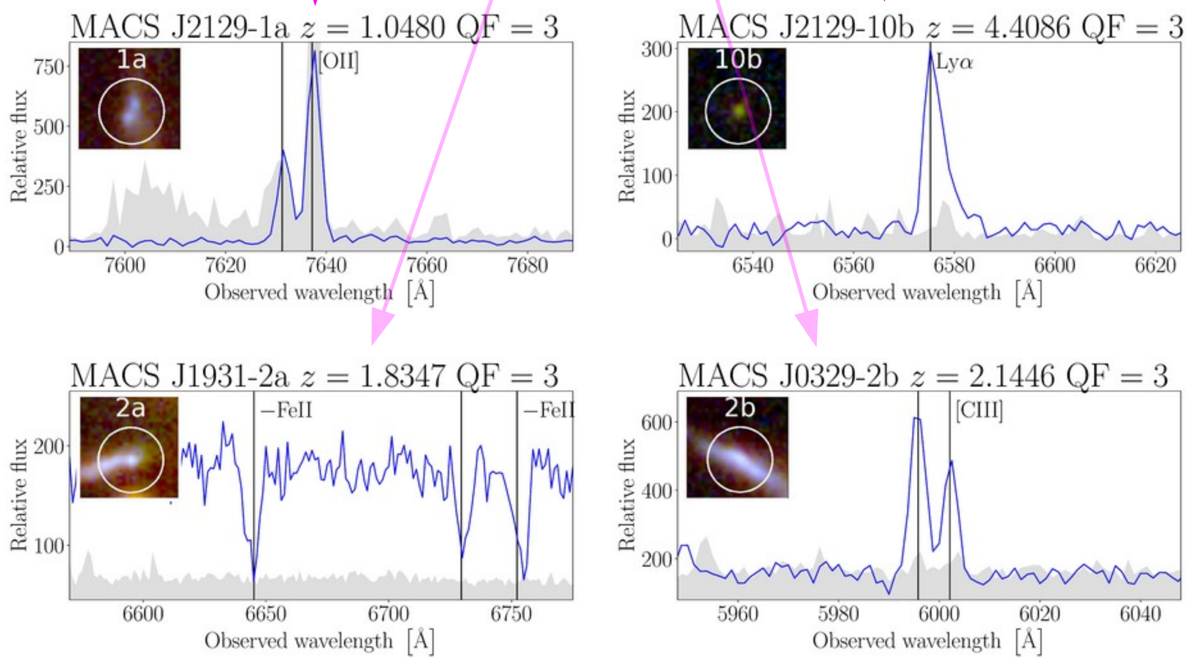


AbellS1063
MUSE
'color'

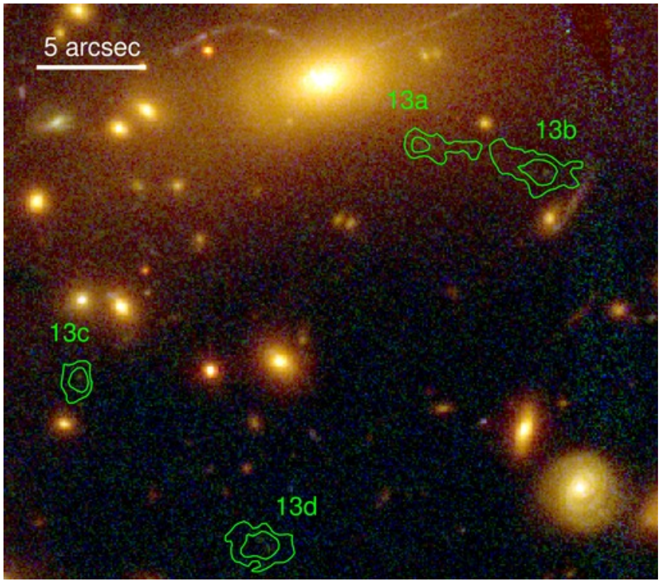


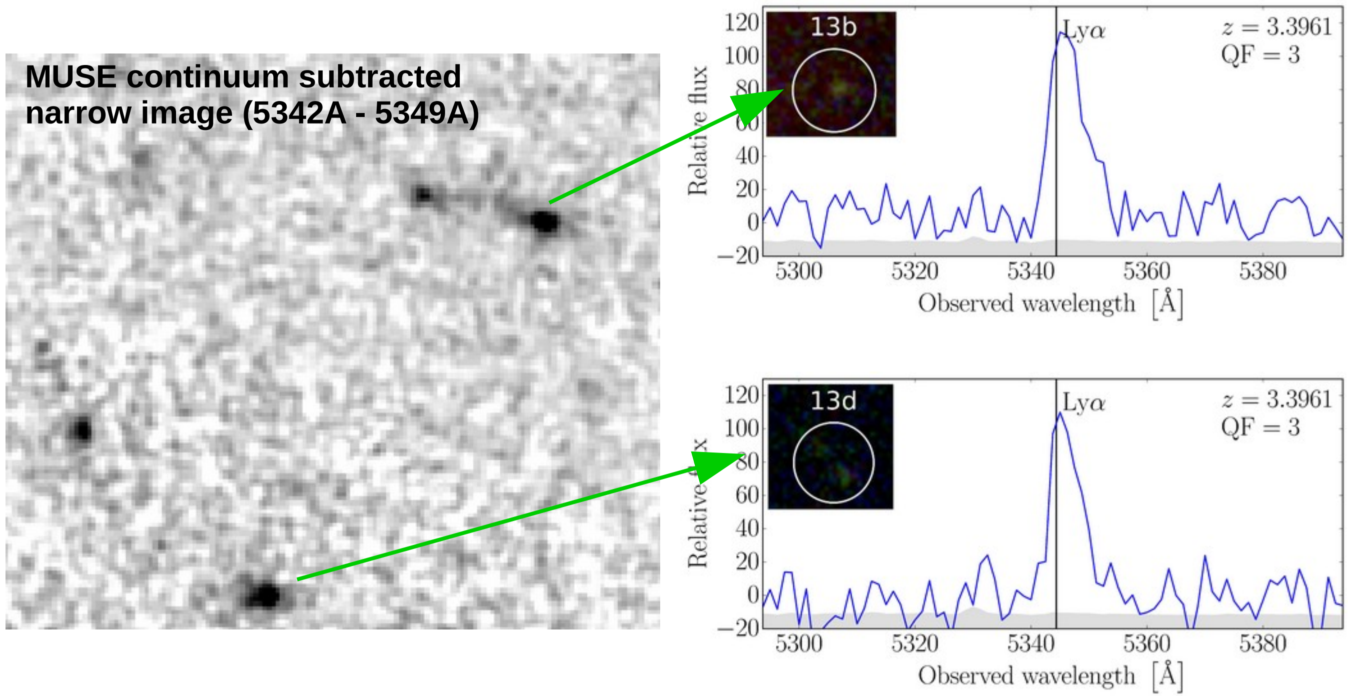


MUSE observations of galaxy cluster

Integral field spectroscopy allows us to detect HST-“dark” Lyman-alpha emitters
- ➔ Some are also multiply lensed adding additional SL constraitns

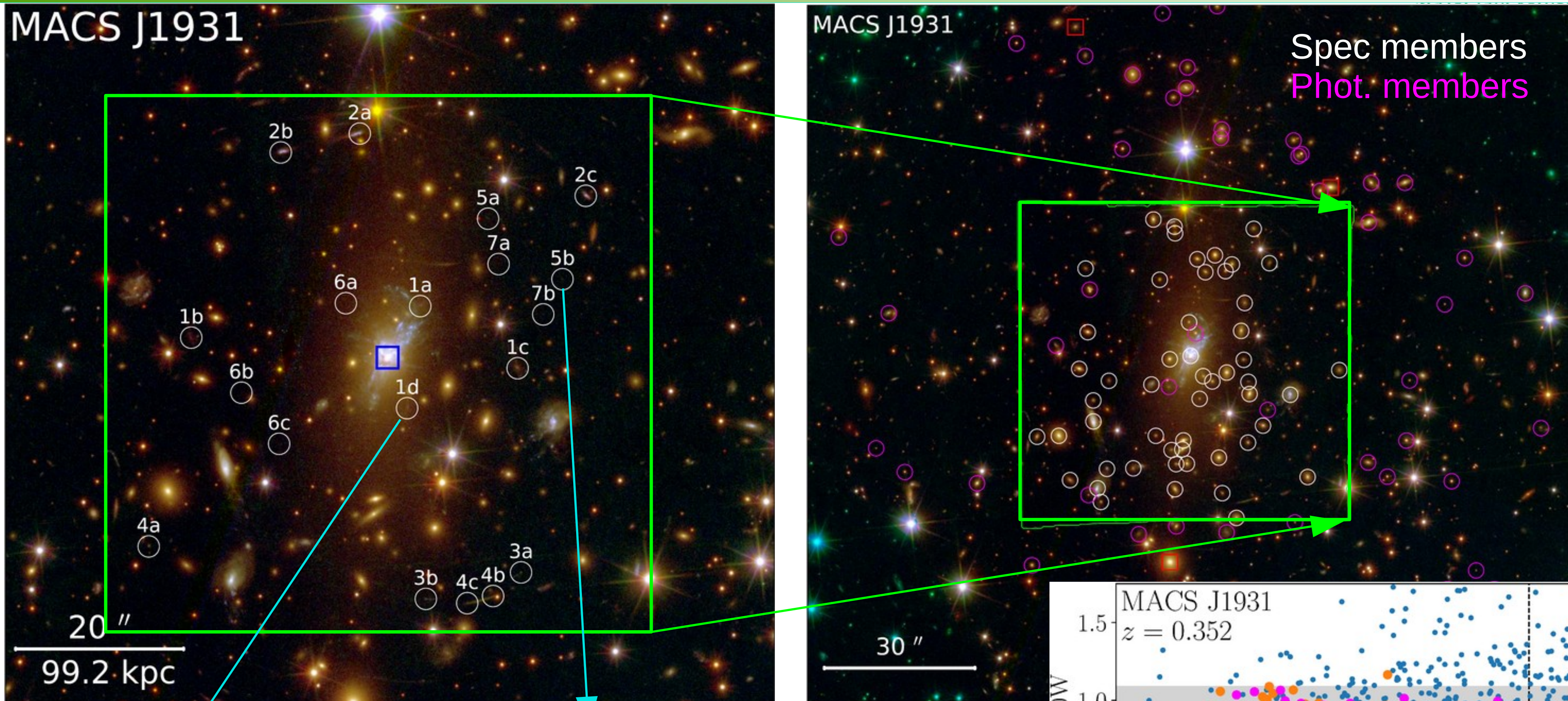
MACS 1206

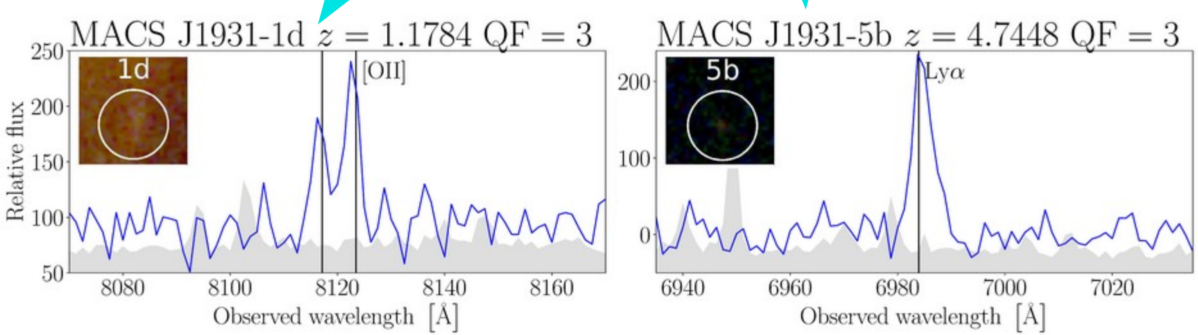


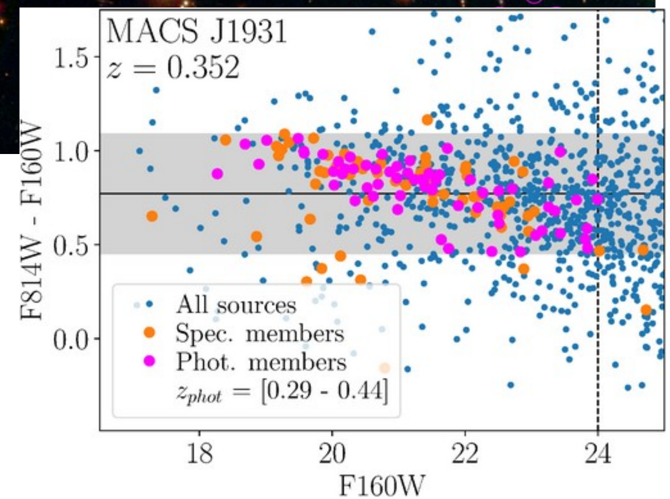


MUSE is more efficient than HST in obtaining redshift and even detecting multiple image families in some cases

Spectroscopic information into the SL model







SL parametric modeling

Multiple images are used as model constraints, using the software *lenstool*

- The diffuse component:
  - dark matter, gas and ICL
  - PIEMD and gNFW profile(s)
- Members based on extensive spectroscopy
  - Isothermal profiles
  - Mass-to-light scaling relation

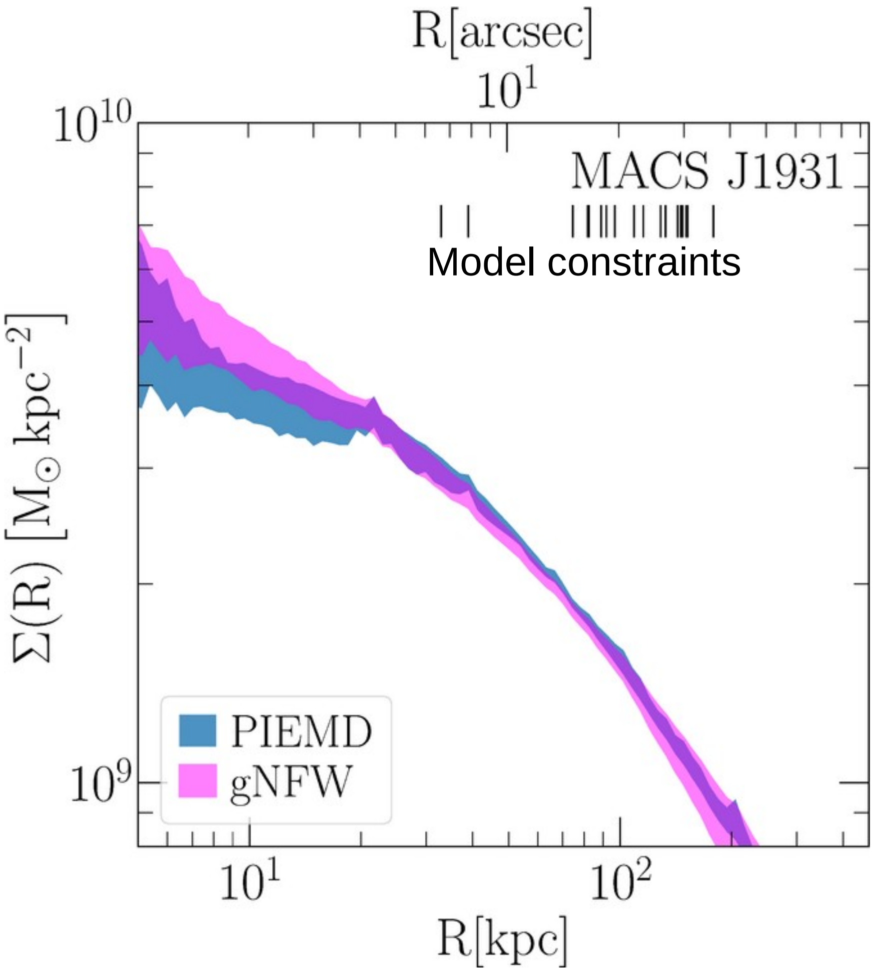
$$\psi_{\text{total}} = \sum \psi_{\text{diffuse}} + \sum \psi_{\text{members}}$$

$$\sigma_i^{\text{members}} = \sigma^{\text{reference}} \left(\frac{L_i}{L_0}\right)^{\alpha}$$

$$r_{\text{cut},i}^{\text{members}} = r_{\text{cut}}^{\text{reference}} \left(\frac{L_i}{L_0}\right)^{\beta}$$

Robust against different parameterizations

- Deviates only in regions with no model constraints



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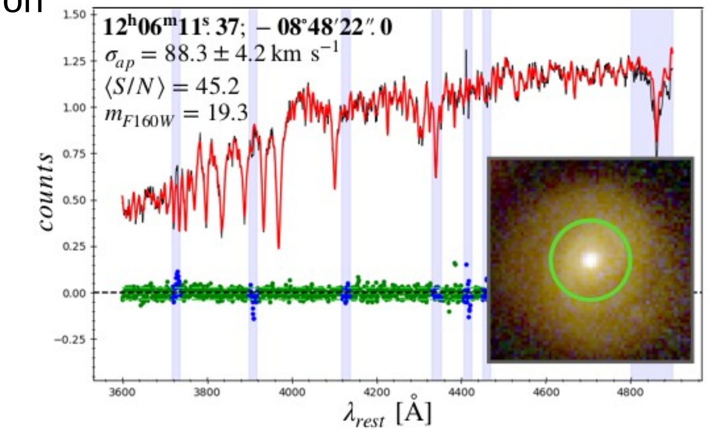
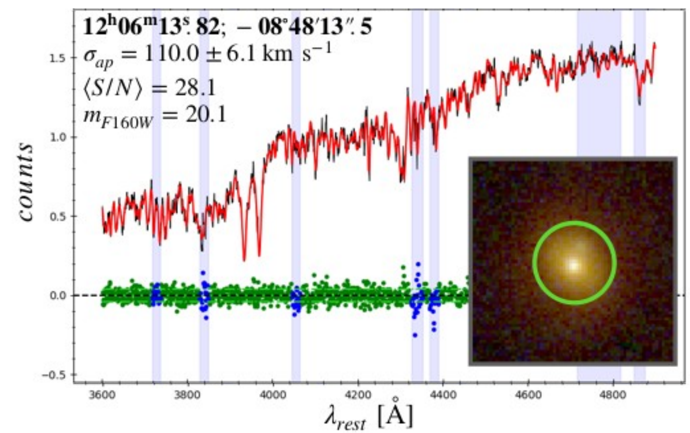
Validation using velocity dispersion measurements

Bergamini+2019 A&A 631, A130





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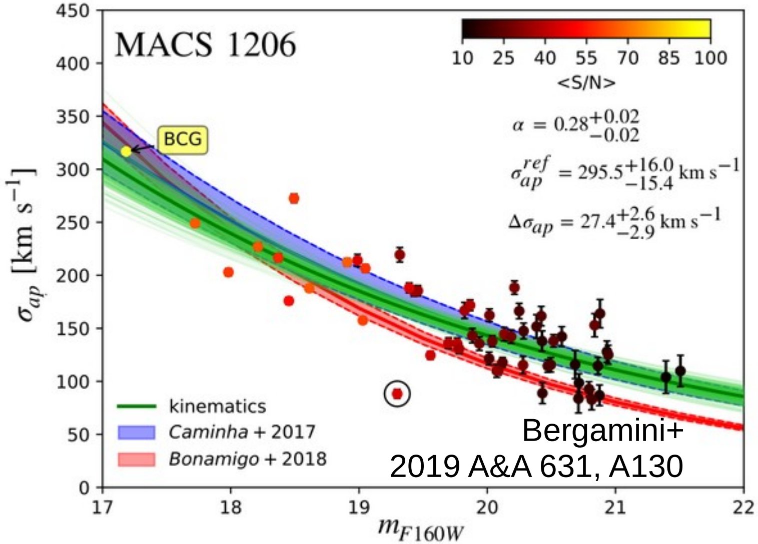
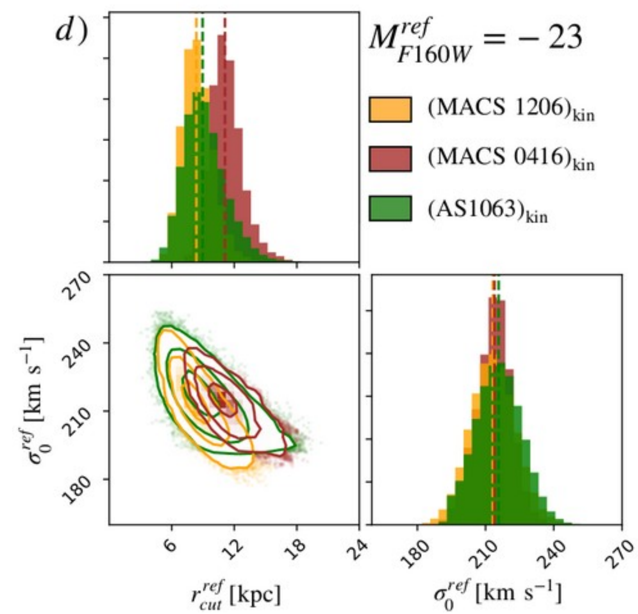
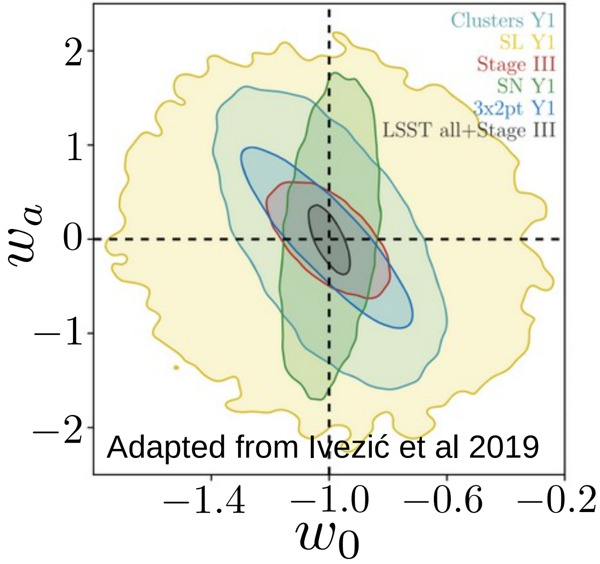




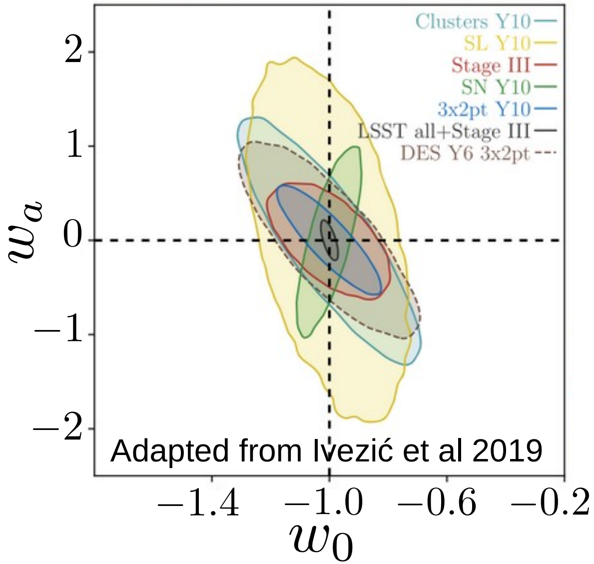
Galaxy cluster strong lensing cosmography

- Sensitive to the dark energy equation of state, Ω_m, Ω_k
  - ➔ Still plays a role in the concept and design of cosmological observations and surveys
- Not extensively explored in the literature
- Use the same SL models as mentioned before (no new data needed)
- Complementary to other observables

Forecast for LSST Year 1



Forecast for LSST Year 10



Cosmography with cluster strong lensing

In systems with only one source family the cosmological parameters are degenerated with the cluster mass normalization:

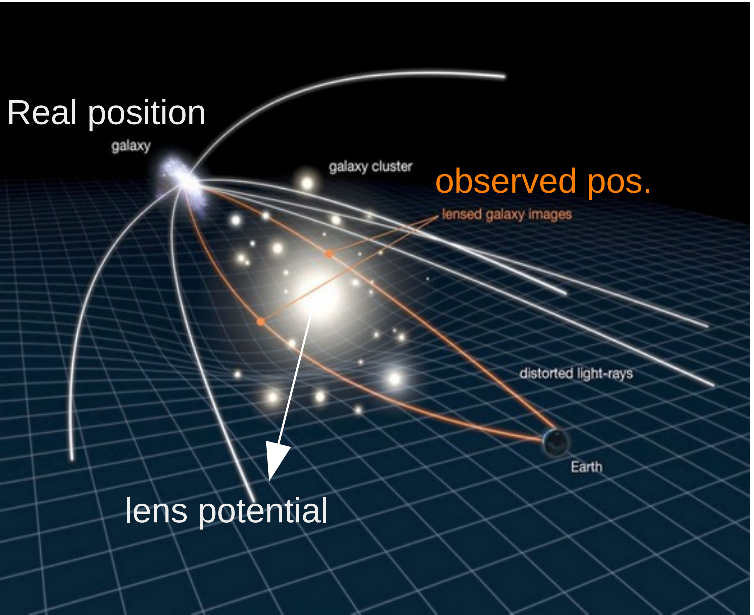
$$\vec{\theta} = k\vec{\beta} + \frac{2D_{LS}}{c^2 D_{OL} D_{OS}} \vec{\nabla}\psi\left(\vec{\theta}\right)$$

observed position

real position

lens potential
(mass distribution)

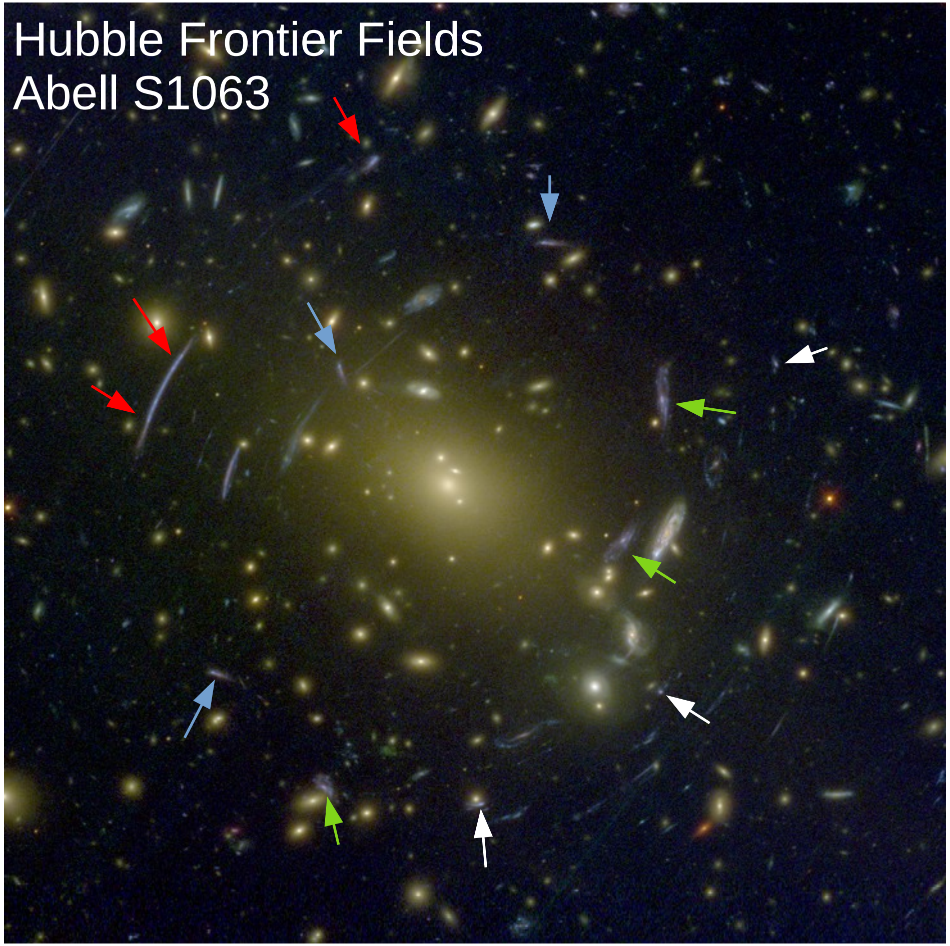
Angular diameter distances
- **Cosmological dependency**



Cosmography with cluster strong lensing

In systems with only one source family the cosmological parameters are degenerated with the cluster mass normalization:

$$\vec{\theta_N} = k\vec{\beta_N} + \frac{2D_{LSN}}{c^2 D_{OL} D_{OSN}} \vec{\nabla}\psi\left(\vec{\theta_N}\right)$$



Cosmography with cluster strong lensing

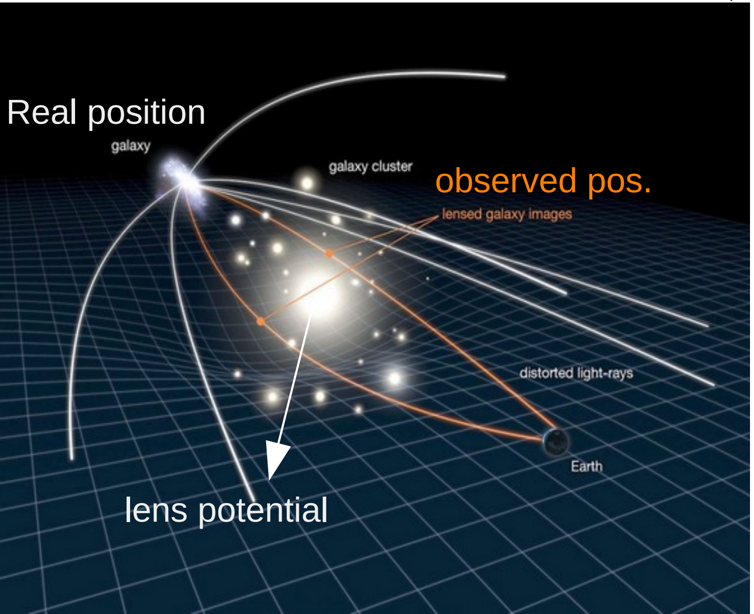
In systems with only one source family the cosmological parameters are degenerated with the cluster mass normalization:

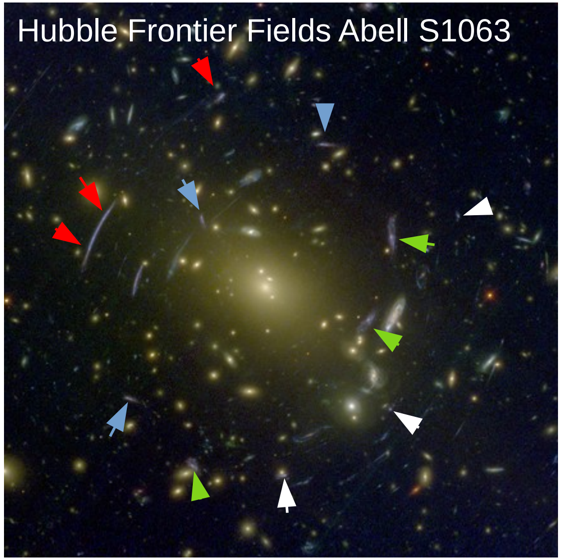
$$\vec{\theta_1} = k\vec{\beta_1} + \frac{2D_{LS1}}{c^2 D_{OL} D_{OS1}} \vec{\nabla}\psi\left(\vec{\theta_1}\right)$$

$$\vec{\theta_2} = k\vec{\beta_2} + \frac{2D_{LS2}}{c^2 D_{OL} D_{OS2}} \vec{\nabla}\psi\left(\vec{\theta_2}\right)$$

$$\vdots$$

$$\vec{\theta_N} = k\vec{\beta_N} + \frac{2D_{LSN}}{c^2 D_{OL} D_{OSN}} \vec{\nabla}\psi\left(\vec{\theta_N}\right)$$



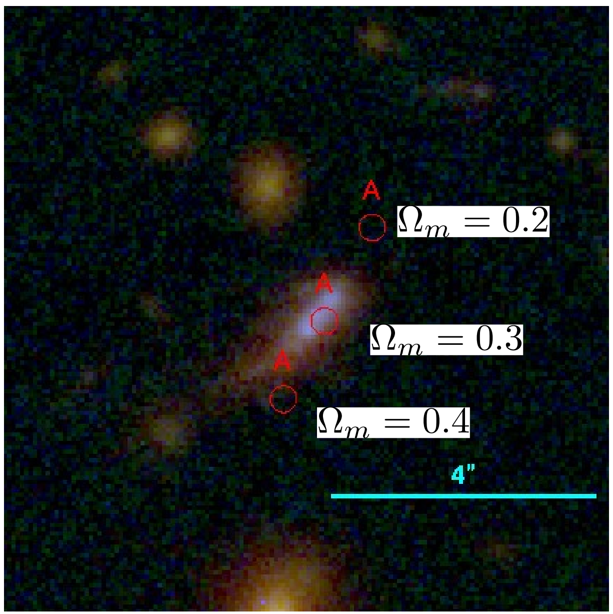


Cosmography with cluster strong lensing

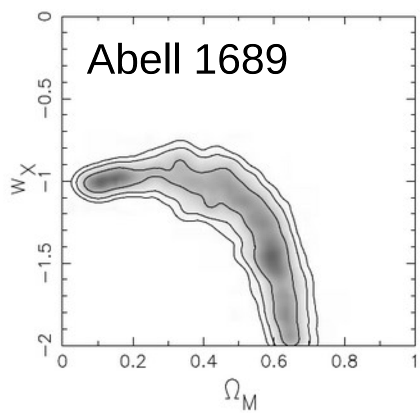
If we have more than one source in different redshifts it is possible to constrain not the mass distribution and the background cosmology.
The angular diameter distance ratios for 2 (or more) sources defines the ‘family ratio’

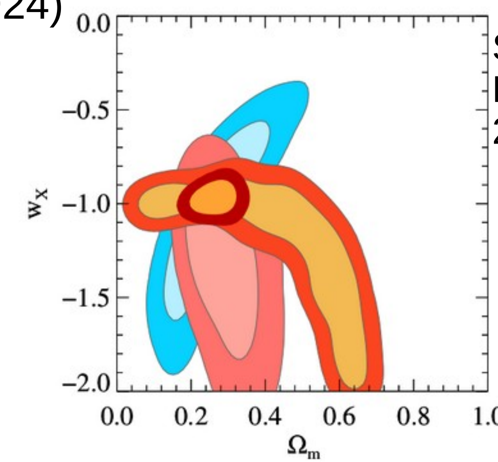
$$\Xi(z_L, z_{s1}, z_{s2}; \Omega_m, \Omega_k, w) \equiv \frac{D_{LS1}\, D_{OS2}}{D_{LS2}\, D_{OS1}}$$

Current SL models can predict the positions of multiple images with [0.3-0.7] arcsec precision



To probe the cosmology we need to constrain the cluster mass and cosmological parameters at the same time (Jullo+2010, Science, 329, 924)

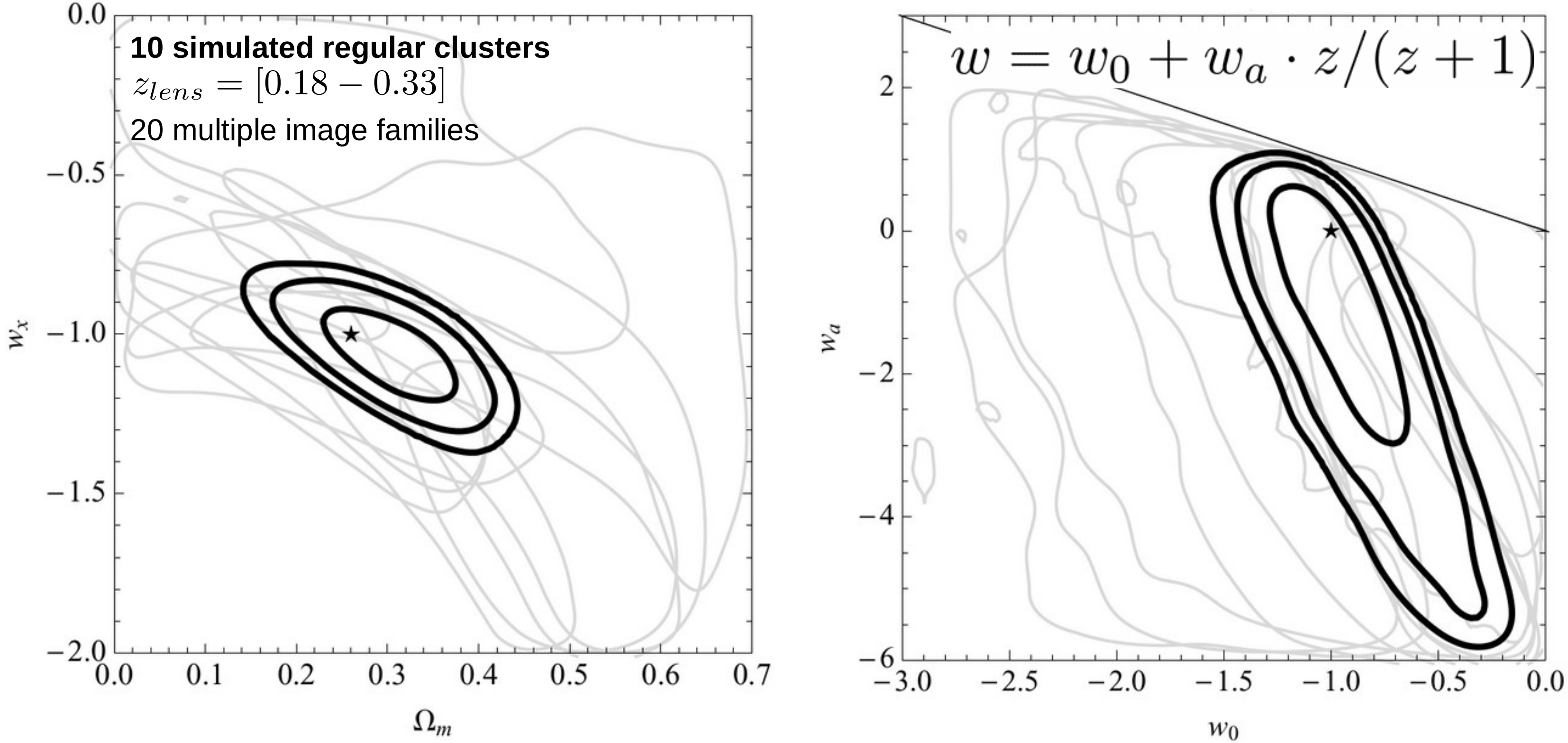




See also: Magaña+ 2015, 2018

Constraints using a sample of clusters

Simulations, D'Aloisio & Natarajan 2011 (see also Gilmore & Natarajan 2009)

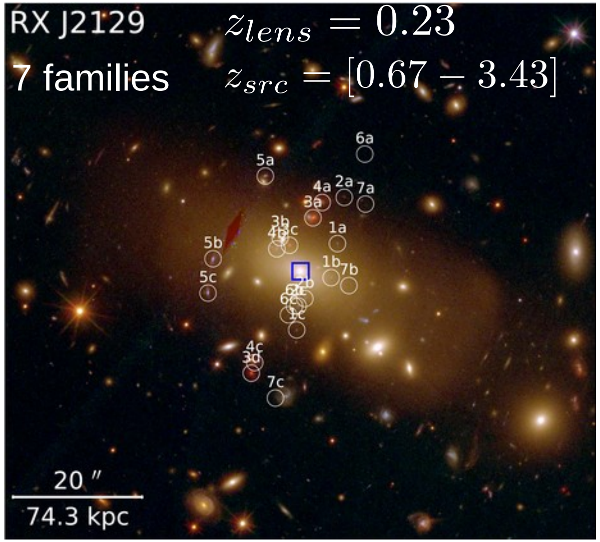


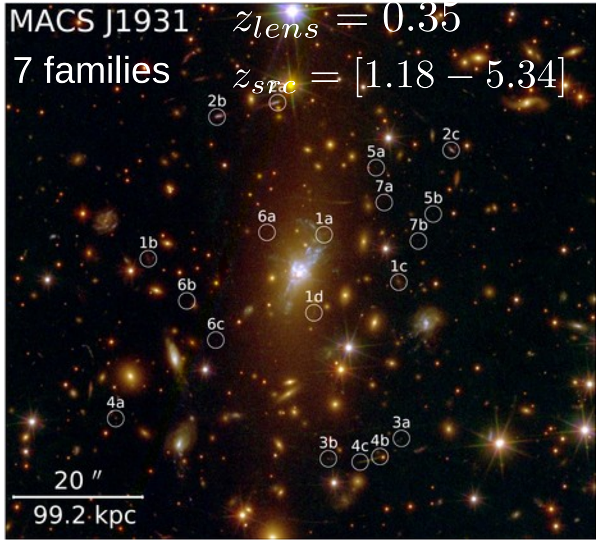
Mitigate possible systematic effects that might affect the individual clusters differently

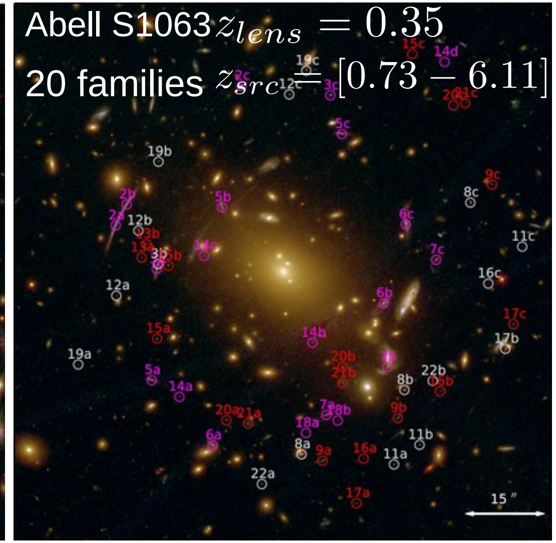
- Line-of-sight perturbers
- Cluster redshift and distribution of background sources
- Mass components external to the cluster cores

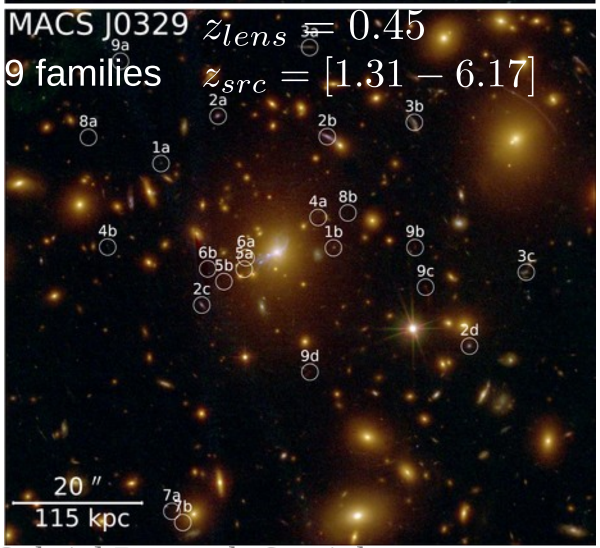
Our sample of strong lensing clusters

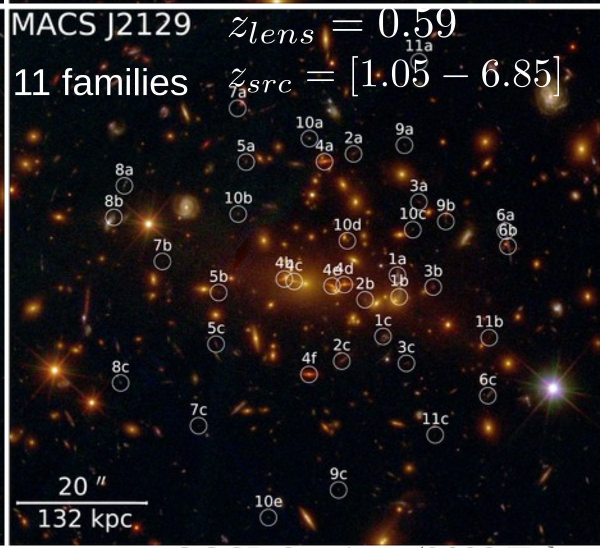
Five (regular) clusters with good spectroscopic coverage (MUSE) (Caminha+2016 and 2019)
→ Precise strong lensing models and well constrained mass distributions











$$z_{lens} = [0.23 - 0.59]$$

$$z_{sources} = [0.7 - 6.9]$$

7 – 20 families

High completeness of confirmed cluster members

Parametric models (using *lenstool*)
→ 8 – 16 free parameters to describe the mass distribution

Cosmography with cluster strong lensing

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We focus on four cosmologies based on the PLANCK public release (2020, A&A, 641, A6)

	free params.		fixed params.
base-	Ω_m	$\rightarrow$	$w = -1, \Omega_k = 0$
flat-	Ω_m, w	$\rightarrow$	$\Omega_k = 0, w_a = 0$
curv-	Ω_m, Ω_k	$\rightarrow$	$w = -1$
CPL-	Ω_m, w_0, w_a	$\rightarrow$	$\Omega_k = 0$

We also combine our SL constraints with CMB, BAO and SNe-Ia

→ Cluster SL cosmography is not as developed as these "classical" probes, but we are taking the steps to make it a competitive probe.

CPL cosmology: $\Omega_m, \Omega_k, w_0, w_a$,where $w = w_0 + w_a \cdot z/(z+1)$ (Chevallier & Polarski 2001 Linder 2003)

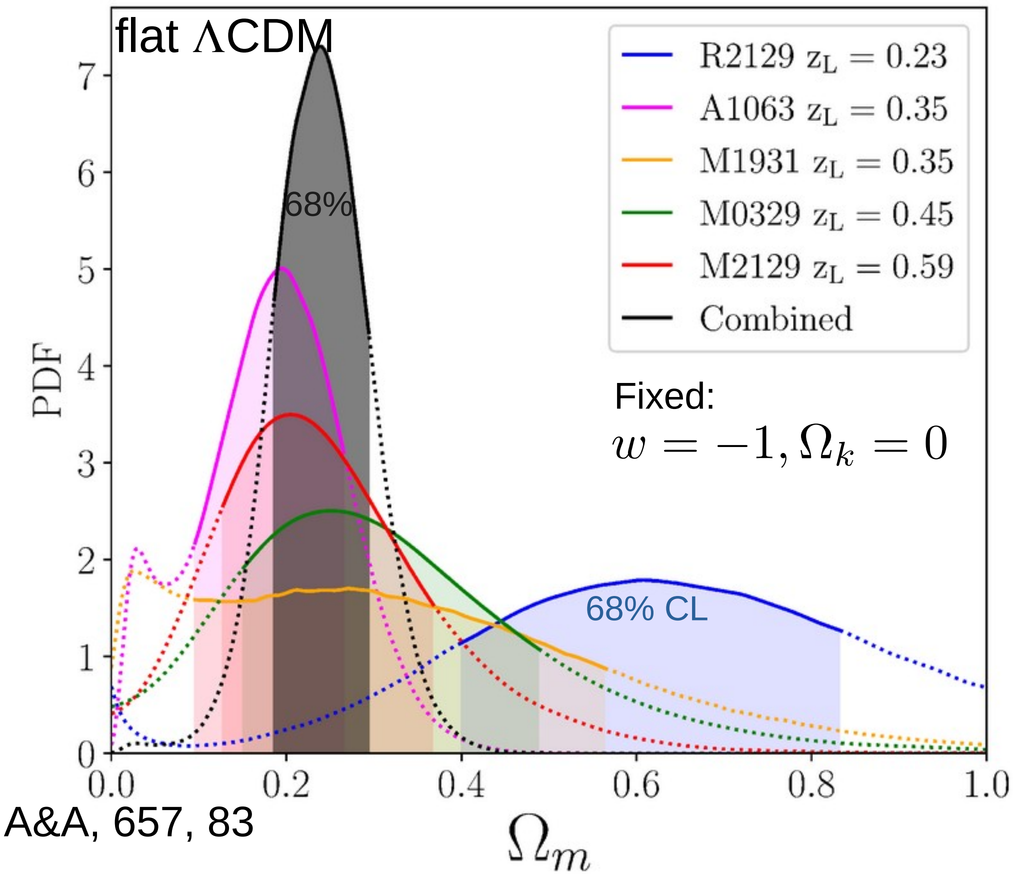
Base Ω_m Cosmology

Color curves: constraints from individual clusters

→ dashed regions are the 68% confidence regions

Grey curve: combined strong lensing constraints $\Omega_m = 0.24^{+0.06}_{-0.05}$

→ in agreement with PLANCK constraints ($\Omega_m = 0.32^{+0.01}_{-0.01}$)



Caminha+2022 A&A, 657, 83

R2129, $z_{\rm cluster} = 0.234$
$N_{\rm src} = 7$, $z_{\rm src} = [0.68 - 3.43]$

A1063, $z_{\rm cluster} = 0.348$
$N_{\rm src} = 20$, $z_{\rm src} = [0.73 - 6.11]$

M1931, $z_{\rm cluster} = 0.352$
$N_{\rm src} = 7$, $z_{\rm src} = [1.18 - 5.34]$

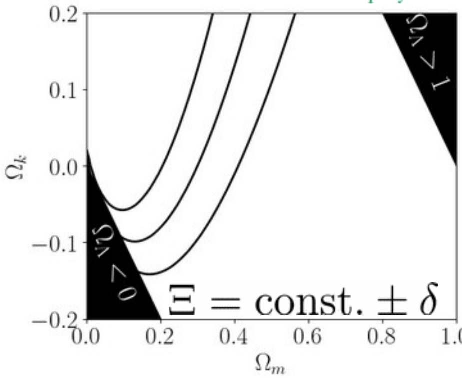
M0329, $z_{\rm cluster} = 0.450$
$N_{\rm src} = 9$, $z_{\rm src} = [1.31 - 6.17]$

M2129, $z_{\rm cluster} = 0.587$
$N_{\rm src} = 11$, $z_{\rm src} = [1.05 - 6.85]$

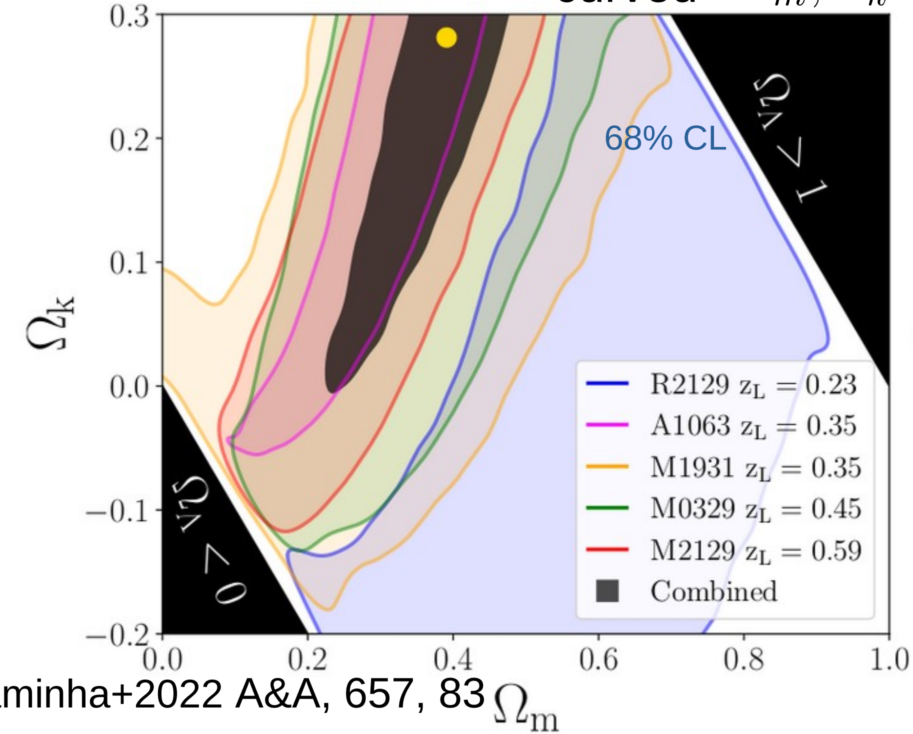
Constraints on the curvature

Confidence level contours follow the expected degeneracy.

→ Relatively week constraints on the curvature, $\Omega_k = 0.28^{+0.16}_{-0.21}$



curved- Ω_m, Ω_k



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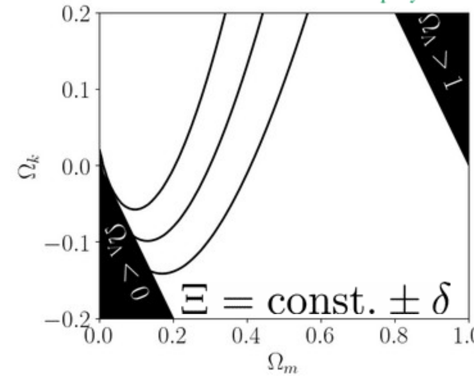
Constraints on the curvature

Confidence level contours follow the expected degeneracy.

→ Relatively week constraints on the curvature, $\Omega_k = 0.28^{+0.16}_{-0.21}$

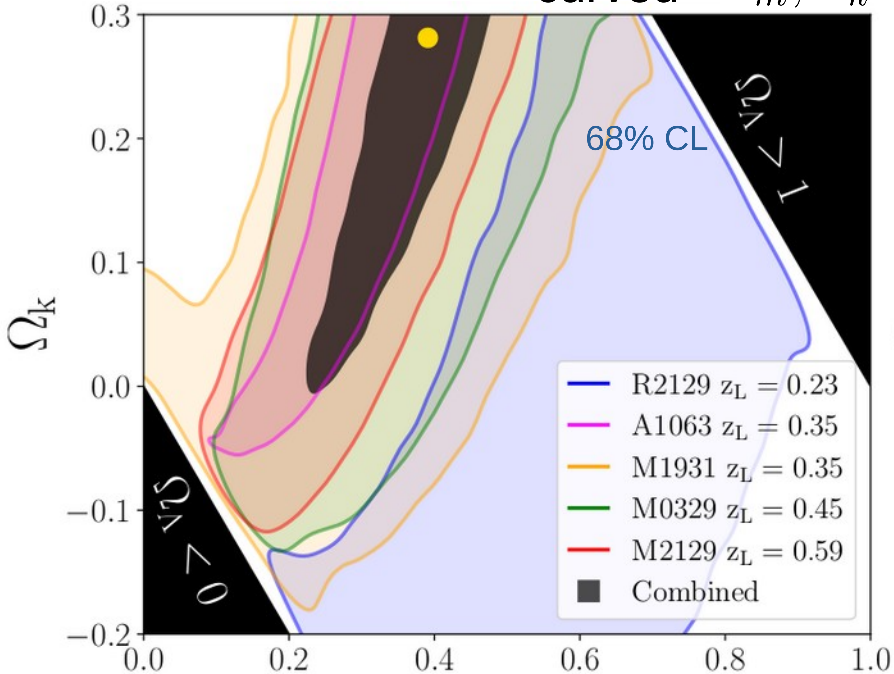
Great complementary when combining with other probes

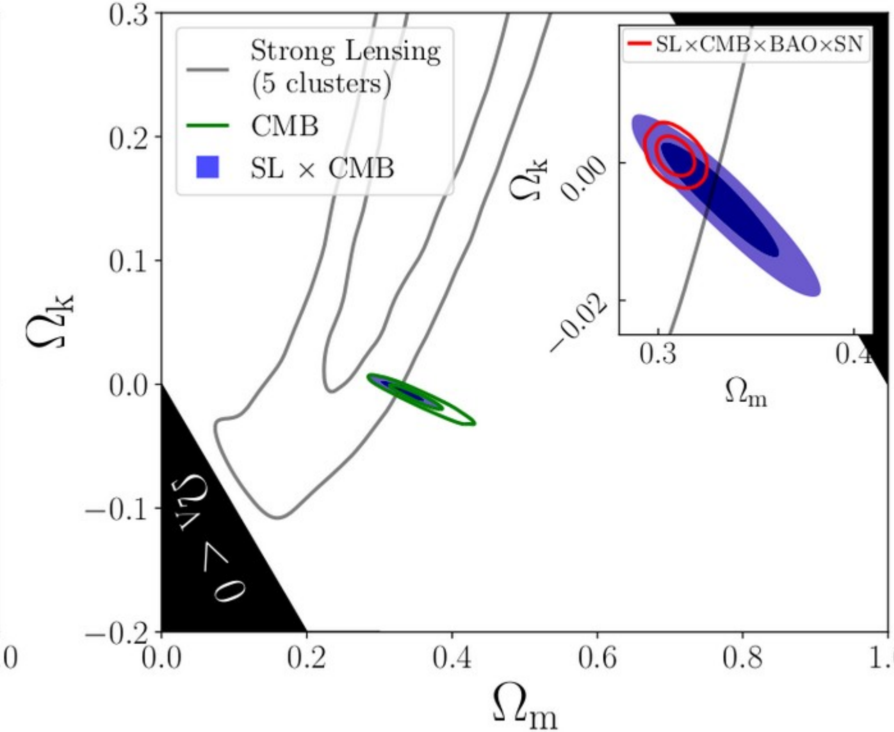
Strong lensing only → CMB only (PLANCK) → SL X CMB



$\Omega_m = 0.39^{+0.08}_{-0.11}$ $\Omega_k = 0.28^{+0.16}_{-0.21}$ → $\Omega_m = 0.35^{+0.03}_{-0.03}$ $\Omega_k = -0.01^{+0.01}_{-0.01}$ —**1.2** X smaller→ $\Omega_m = 0.33^{+0.02}_{-0.02}$ $\Omega_k = -0.005^{+0.005}_{-0.006}$

curved- Ω_m, Ω_k





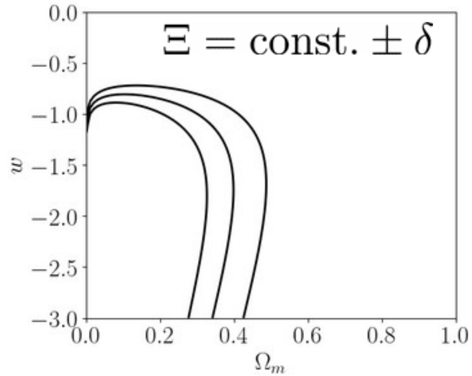
Caminha+2022 A&A, 657, 83 Ω_m

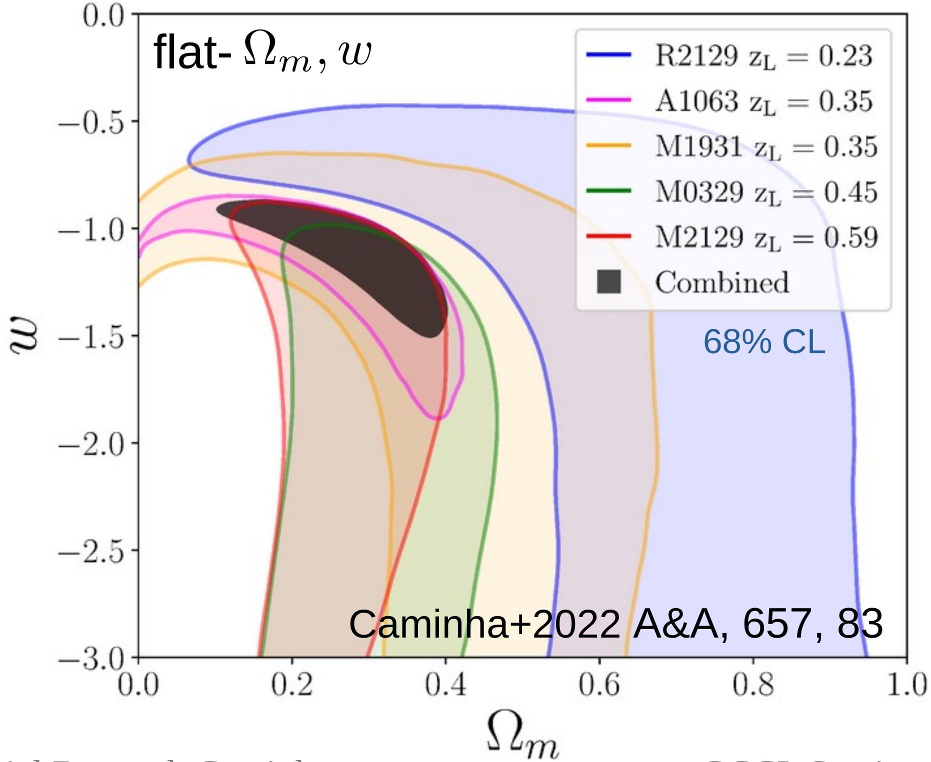
Constraints on the dark energy equation of state

Confidence level contours follow the expected degeneracy.

→ Promising constraints on w when combining all clusters

$$\Omega_m = 0.30^{+0.10}_{-0.10} \qquad w = -1.12^{+0.17}_{-0.32}$$





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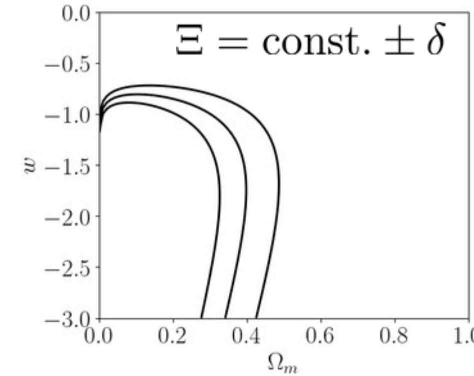
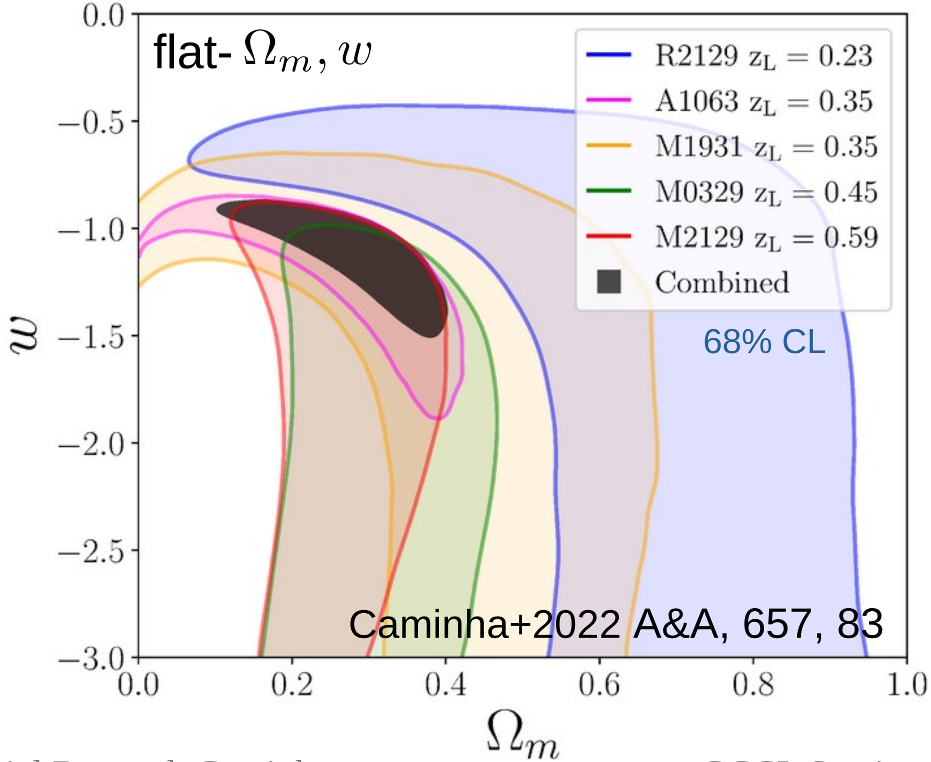
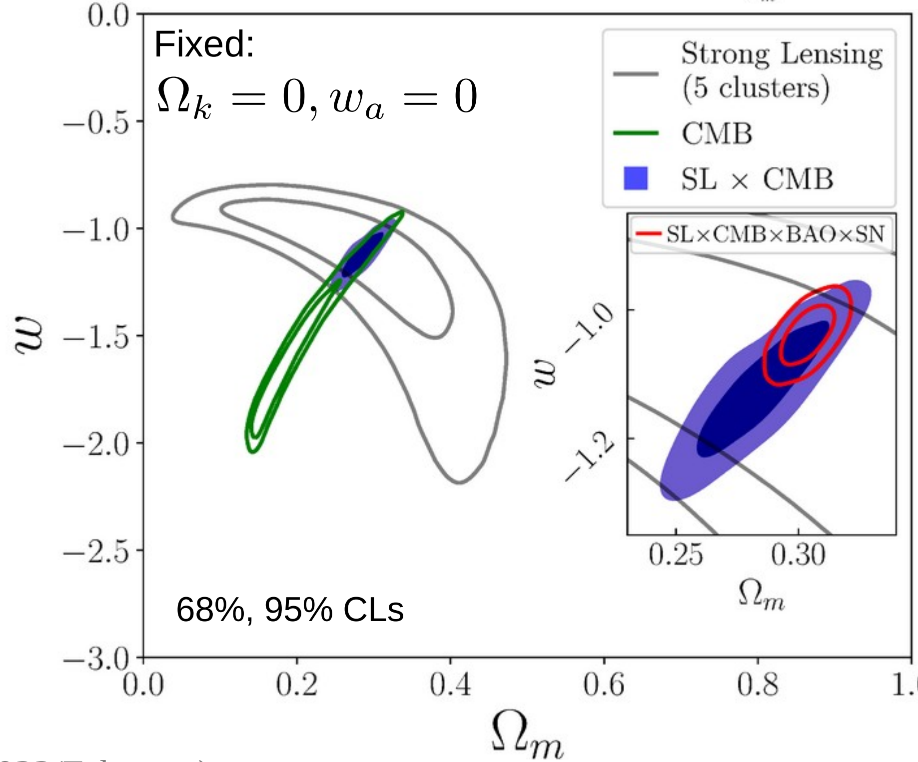


When comparing to PLANCK, the improvement on the figure of merit is **2.5** for Ω_m and **4.0** for w.

SL X PLANCK ⟶ $\Omega_m = 0.28^{+0.02}_{-0.02} \quad w = -1.12^{+0.07}_{-0.07}$





Constraints on the equation of state evolution

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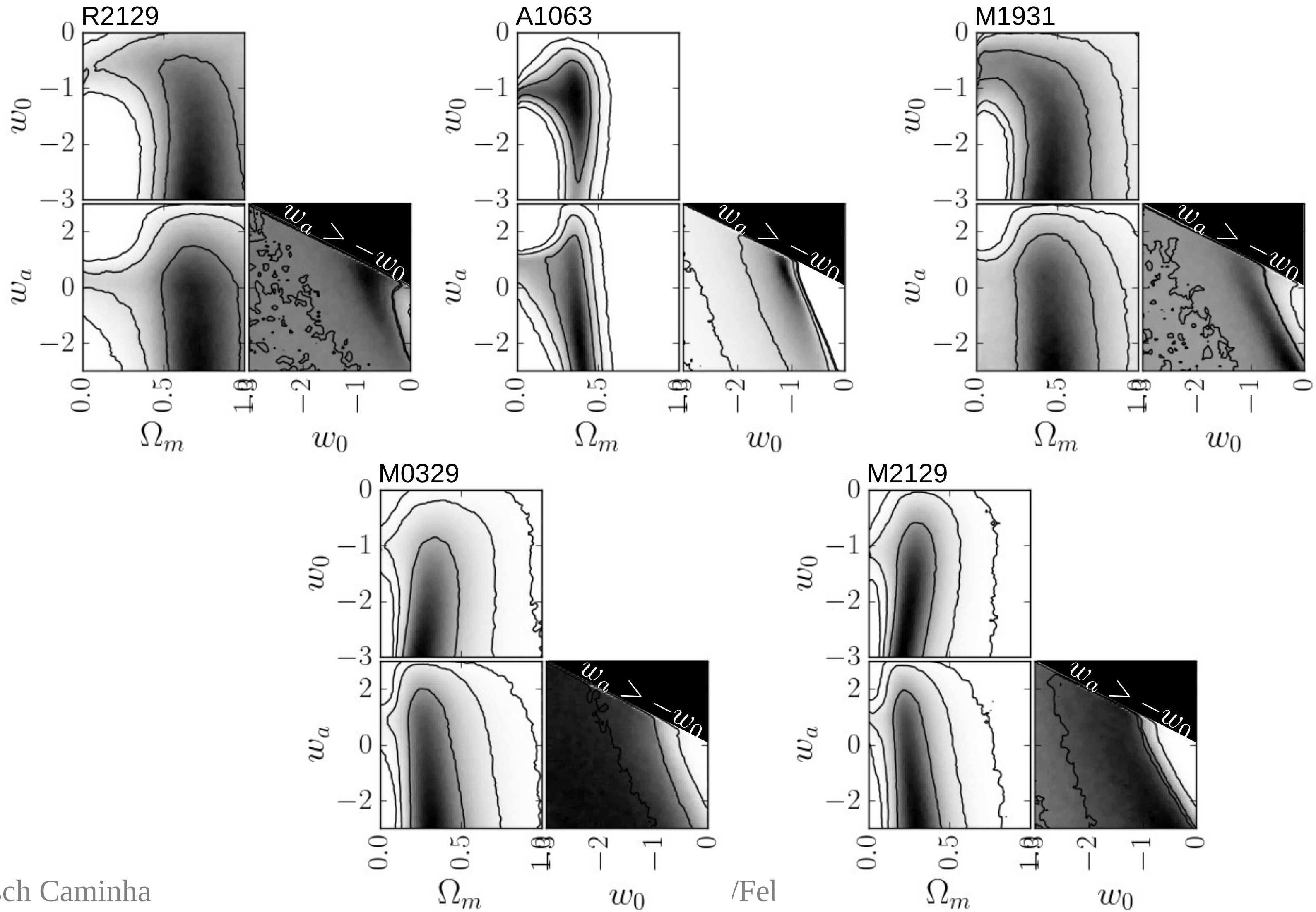
für Astrophysik

Increased number of cosmological parameters, but still very good complementary with other probes.

$$w = w_0 + w_a \cdot z/(z+1)$$



Constraints on the equation of state evolution

Max-Planck-Institut für Astrophysik

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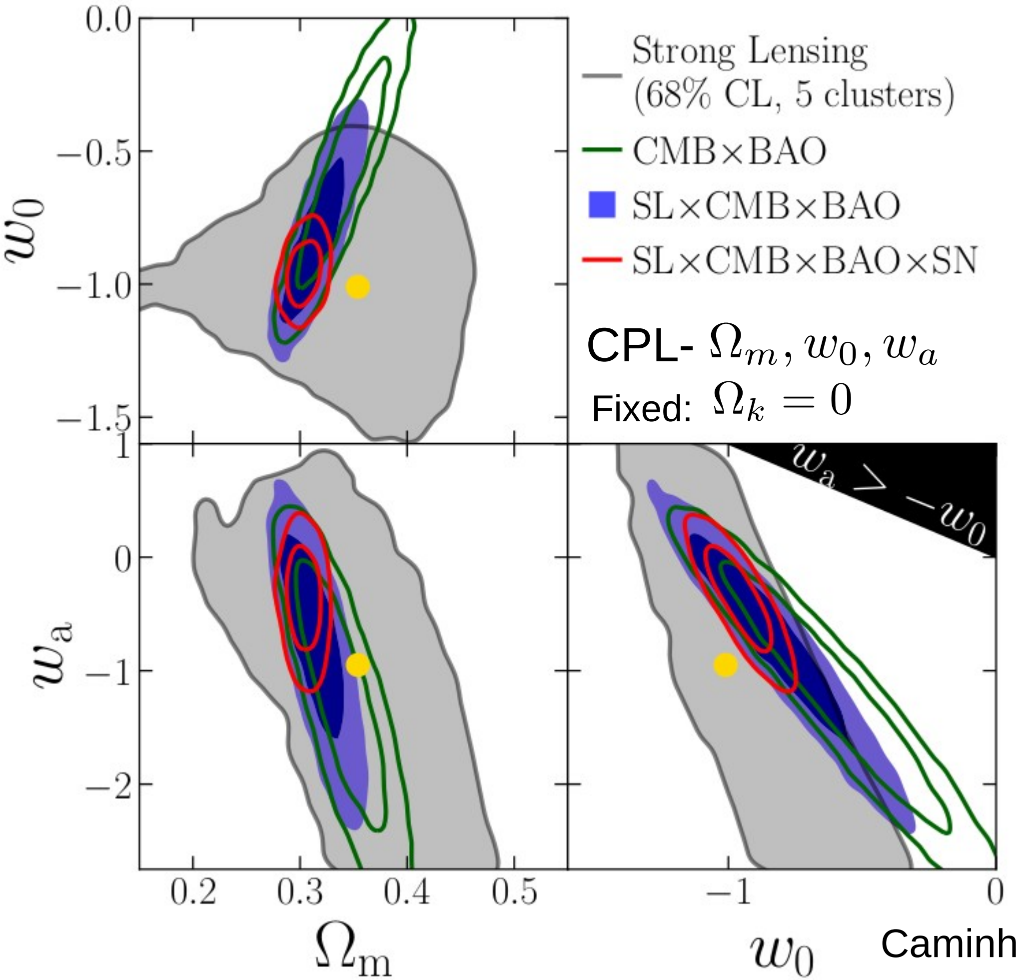

CPL- Ω_m, w_0, w_a

Fixed: $\Omega_k = 0$

SL only:

$\Omega_m = 0.35^{+0.07}_{-0.11}$ $w_0 = -1.01^{+0.33}_{-0.43}$

$w_a = -0.95^{+1.43}_{-1.31}$

PLANCK X BAO only:

$\Omega_m = 0.34^{+0.03}_{-0.03}$ $w_0 = -0.59^{+0.27}_{-0.28}$

$w_a = -1.23^{+0.76}_{-0.78}$

PLANCK X BAO X SL:

$\Omega_m = 0.32^{+0.02}_{-0.02}$ **(1.40)** $w_0 = -0.84^{+0.21}_{-0.19}$ **(1.36)**

$w_a = -0.71^{+0.56}_{-0.65}$ **(1.26)**

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Cosmological constraints summary

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→For a simple flat ΛCDM cosmology, most of the constraining power is from CMB

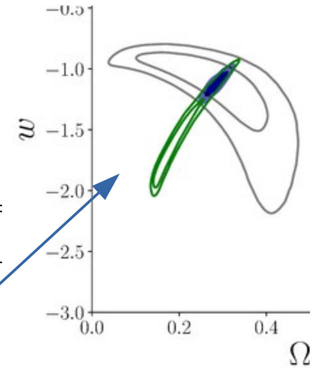
→Cluster SL cosmography improves significantly constraints on the equation of state for dark energy

→Cluster SL cosmography is not very sensitive to the curvature of the Unvierse when comparing to other probes

→Cluster SL cosmography is also efficient in probing the variation of the dark energy EoS as a function of redshift

Improvement on the 68% CL error bars

flat-ΛCDM	Ω_m	$\delta\Omega_m$				
SL	$0.239^{+0.056}_{-0.054}$	—				
CMB	$0.315^{+0.007}_{-0.007}$	—				
SL×CMB	$0.314^{+0.007}_{-0.007}$	1.01				
CMB×BAO×SN	$0.310^{+0.006}_{-0.005}$	—				
SL×CMB×BAO×SN	$0.310^{+0.006}_{-0.005}$	1.00				
flat-wCDM	Ω_m	$\delta\Omega_m$	w	δw		
SL	$0.296^{+0.086}_{-0.105}$	—	$-1.12^{+0.17}_{-0.32}$	—		
CMB	$0.186^{+0.057}_{-0.032}$	—	$-1.60^{+0.31}_{-0.23}$	—		
SL×CMB	$0.283^{+0.018}_{-0.018}$	2.52	$-1.12^{+0.07}_{-0.07}$	4.00		
CMB×BAO×SN	$0.306^{+0.008}_{-0.008}$	—	$-1.03^{+0.03}_{-0.03}$	—		
SL×CMB×BAO×SN	$0.303^{+0.007}_{-0.007}$	1.07	$-1.04^{+0.03}_{-0.03}$	1.07		
curved-ΛCDM	Ω_m	$\delta\Omega_m$	Ω_k	$\delta\Omega_k$		
SL	$0.391^{+0.076}_{-0.109}$	—	$0.2813^{+0.1588}_{-0.2082}$	—		
CMB	$0.352^{+0.023}_{-0.024}$	—	$-0.0106^{+0.0068}_{-0.0065}$	—		
SL×CMB	$0.330^{+0.021}_{-0.020}$	1.15	$-0.0048^{+0.0053}_{-0.0062}$	1.16		
CMB×BAO×SN	$0.309^{+0.006}_{-0.006}$	—	$0.0008^{+0.0020}_{-0.0020}$	—		
SL×CMB×BAO×SN	$0.308^{+0.006}_{-0.006}$	1.03	$0.0010^{+0.0020}_{-0.0020}$	1.00		
CPL	Ω_m	$\delta\Omega_m$	w_0	δw_0	w_a	δw_a
SL	$0.354^{+0.070}_{-0.105}$	—	$-1.01^{+0.32}_{-0.43}$	—	$-0.95^{+1.43}_{-1.31}$	—
CMB×BAO	$0.340^{+0.027}_{-0.027}$	—	$-0.59^{+0.27}_{-0.28}$	—	$-1.22^{+0.75}_{-0.78}$	—
SL×CMB×BAO	$0.315^{+0.019}_{-0.019}$	1.40	$-0.84^{+0.21}_{-0.19}$	1.36	$-0.71^{+0.56}_{-0.65}$	1.26
CMB×BAO×SN	$0.306^{+0.011}_{-0.011}$	—	$-0.96^{+0.09}_{-0.08}$	—	$-0.27^{+0.29}_{-0.33}$	—
SL×CMB×BAO×SN	$0.304^{+0.011}_{-0.010}$	1.03	$-0.96^{+0.09}_{-0.08}$	1.02	$-0.35^{+0.28}_{-0.33}$	1.01



Discussions

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- Cluster strong lensing is a continuously growing field with applications in cosmology
- Additional clusters will be included to improve the SL constraints

- SL cluster cosmography is a very powerful tool to constraint the background geometry of the Universe and complementary with other probes
  - The combination of different cluster strong lenses is particularly interesting to reduce systematics and to obtain better constraints
  - When combined with Planck constraints, we improve the figure of merit of the dark energy equation of state and dark matter density (by factors of up to 4.0 and 2.5)
  - The chains are publicly available
- Next generation of surveys, such as Rubin-LSST and Euclid will increase immensely the number of cluster strong lensing and the data-quality
  - → We need to better understand how to optimize the selection for spectroscopic followups
    - → Shallow in many systems, deep in few? Include time delay information to constraint also H_0
    - → It might not be necessary to obtain HST like image quality since we use only multiple images with spectroscopic confirmation

- Near future:
  - → JWST will observe cluster strong lenses and increase by a factor of 10 (or more) the number of model constraints in a few clusters