Cosmological parameters from Strong-Lensing in galaxy-clusters

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Atelier Dark Energy – May 18th, 2020

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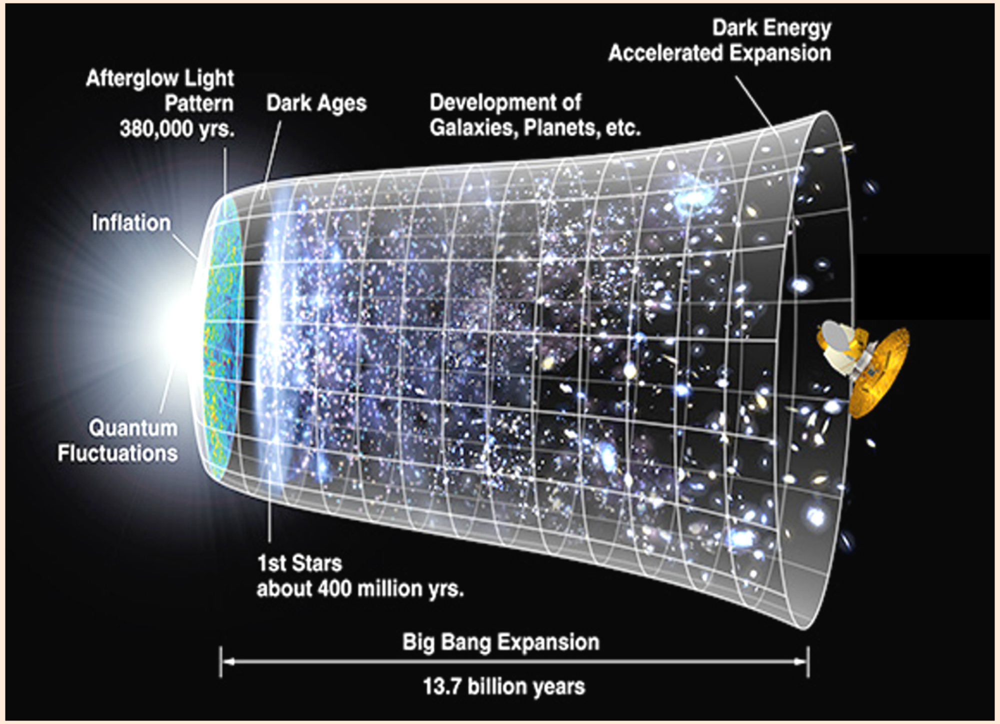
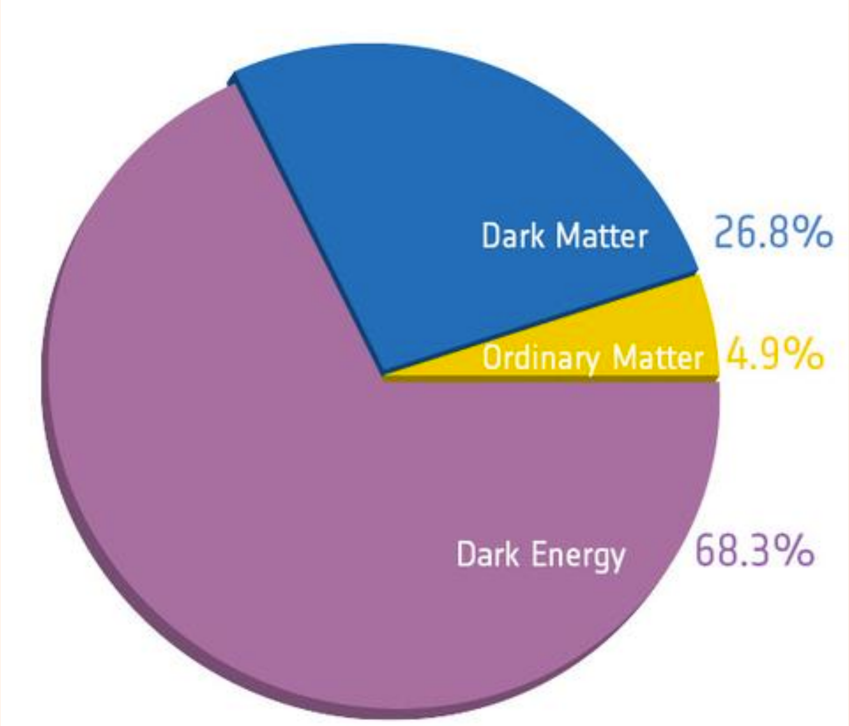
THE BROAD PICTURE



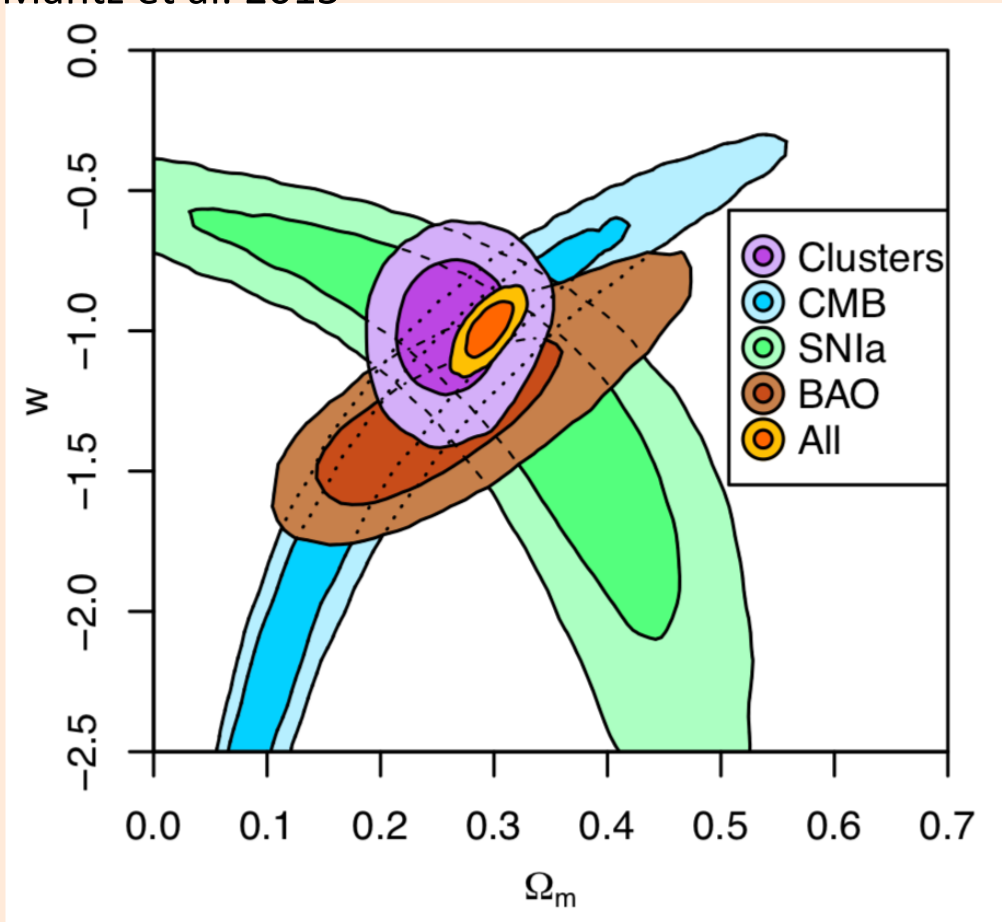


Dark energy

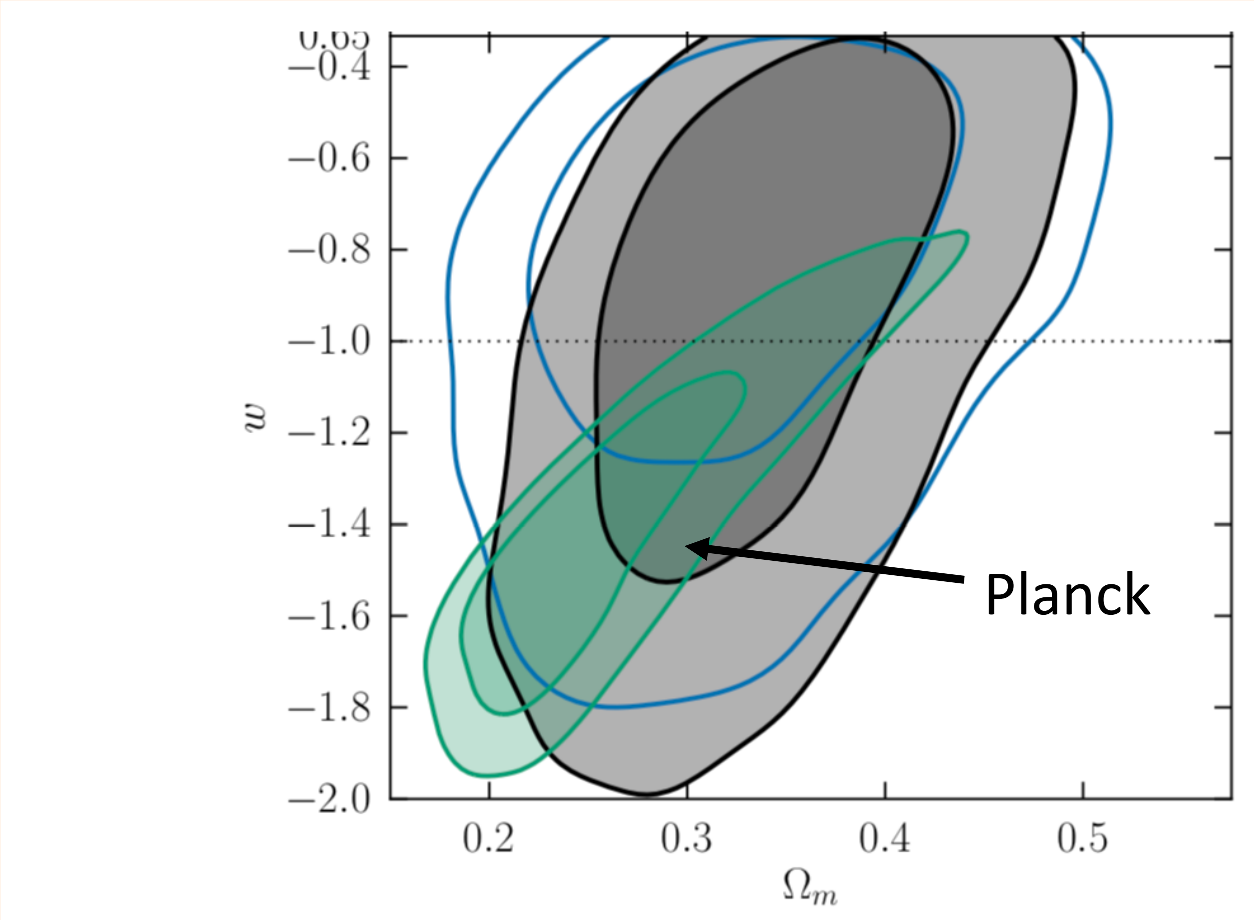
- Explains the recent acceleration of Universe expansion
- Slows down the formation of cosmological structures

Today's results on DE

Mantz et al. 2015



Dark Energy Survey Collab., Troxel et al. 2018

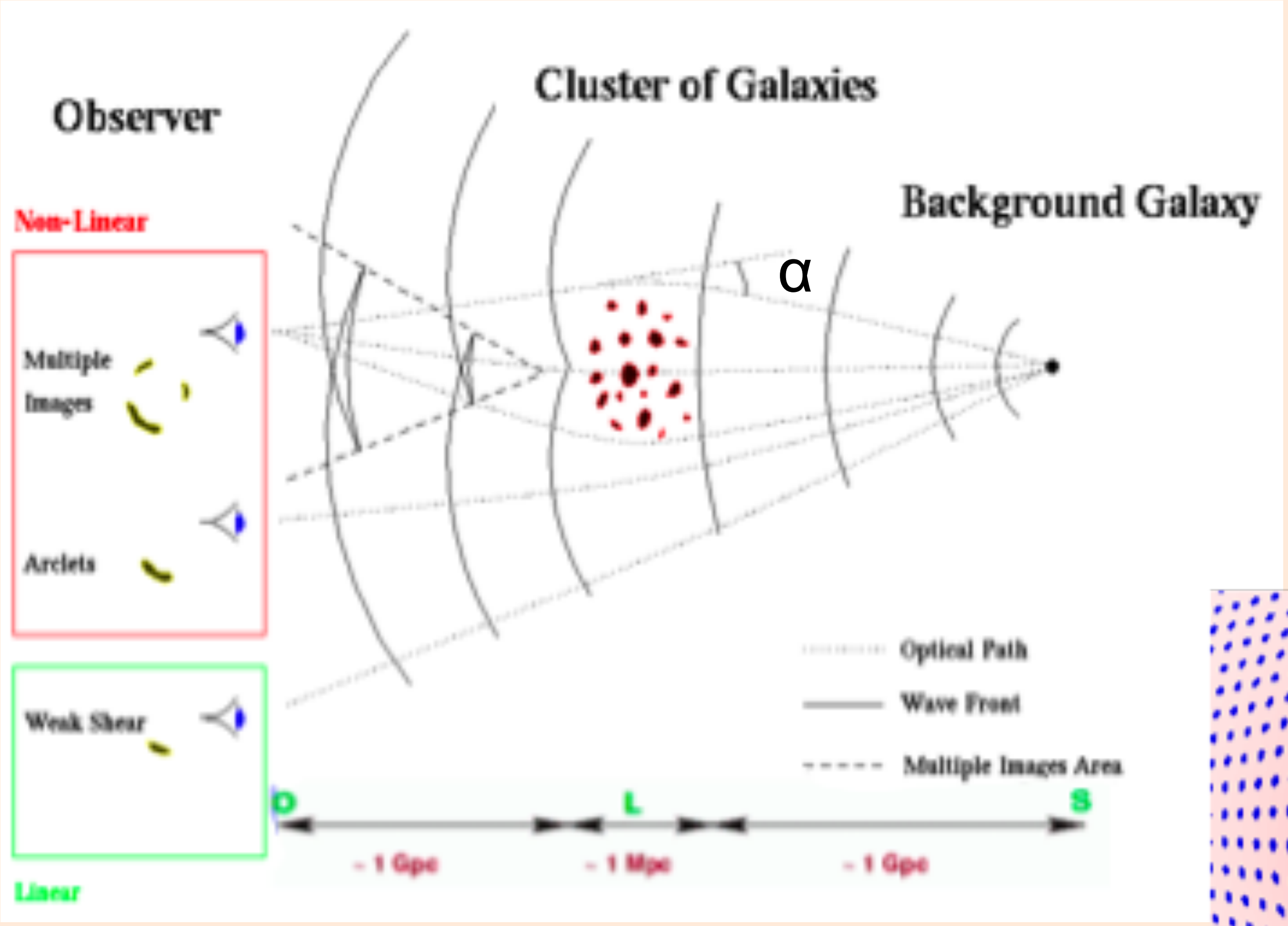


Planck measurements are at z ~ 1100, but Ω_m is calculated at z = 0 with a DE model (e.g. wCDM)

No DE at z ~ 1100 => little constraints on w from Planck

=> dependency w -- Ω_m in Planck results

STRONG GRAVITATIONAL LENSING

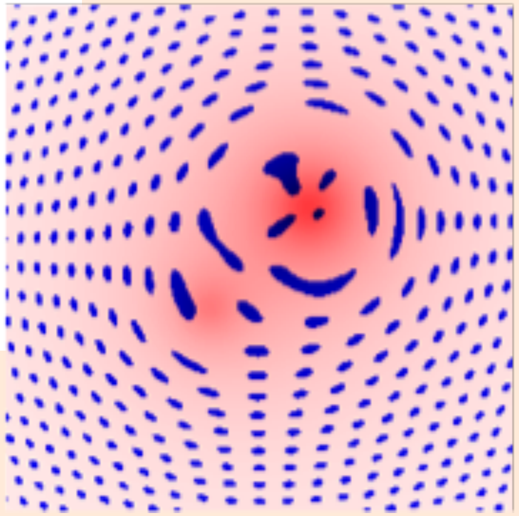


Deflection angle

$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi(\theta_I)$$

Cosmology

mass



Cosmology

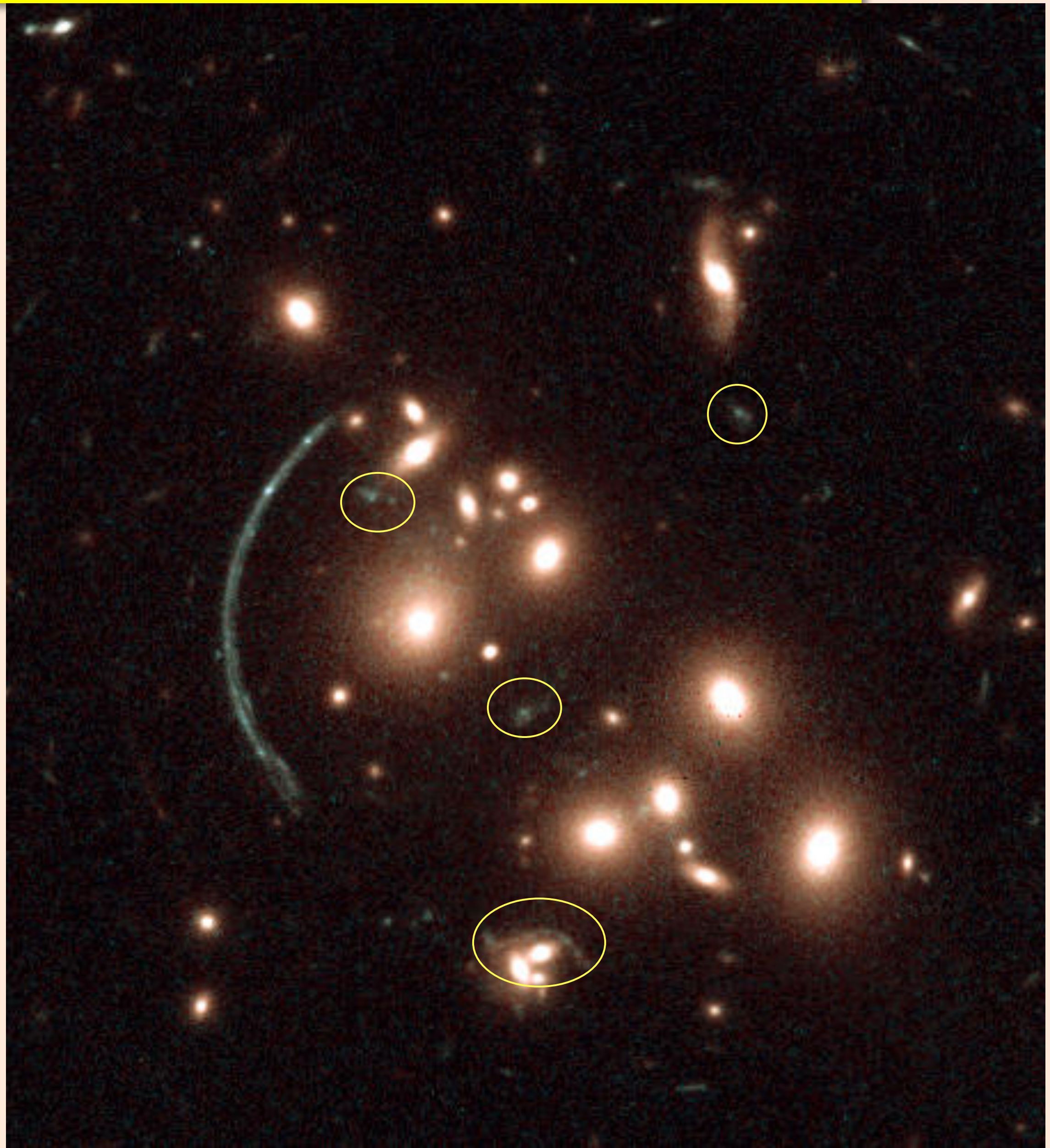
$$D_{AB} = \frac{1}{1+z_S} \int_{z_A}^{z_B} \frac{c\,dz}{H(z)}$$

Mass – Poisson Equation

$$\Delta\varphi = 4\pi G\Sigma$$

HOW TO IDENTIFY MULTIPLE IMAGES ?

Extreme distortion: Giant arcs are the merging of 2 or 3 (or possibly more) multiple images



Giant arc in Cl2244-04, z=2.24, Septuple image

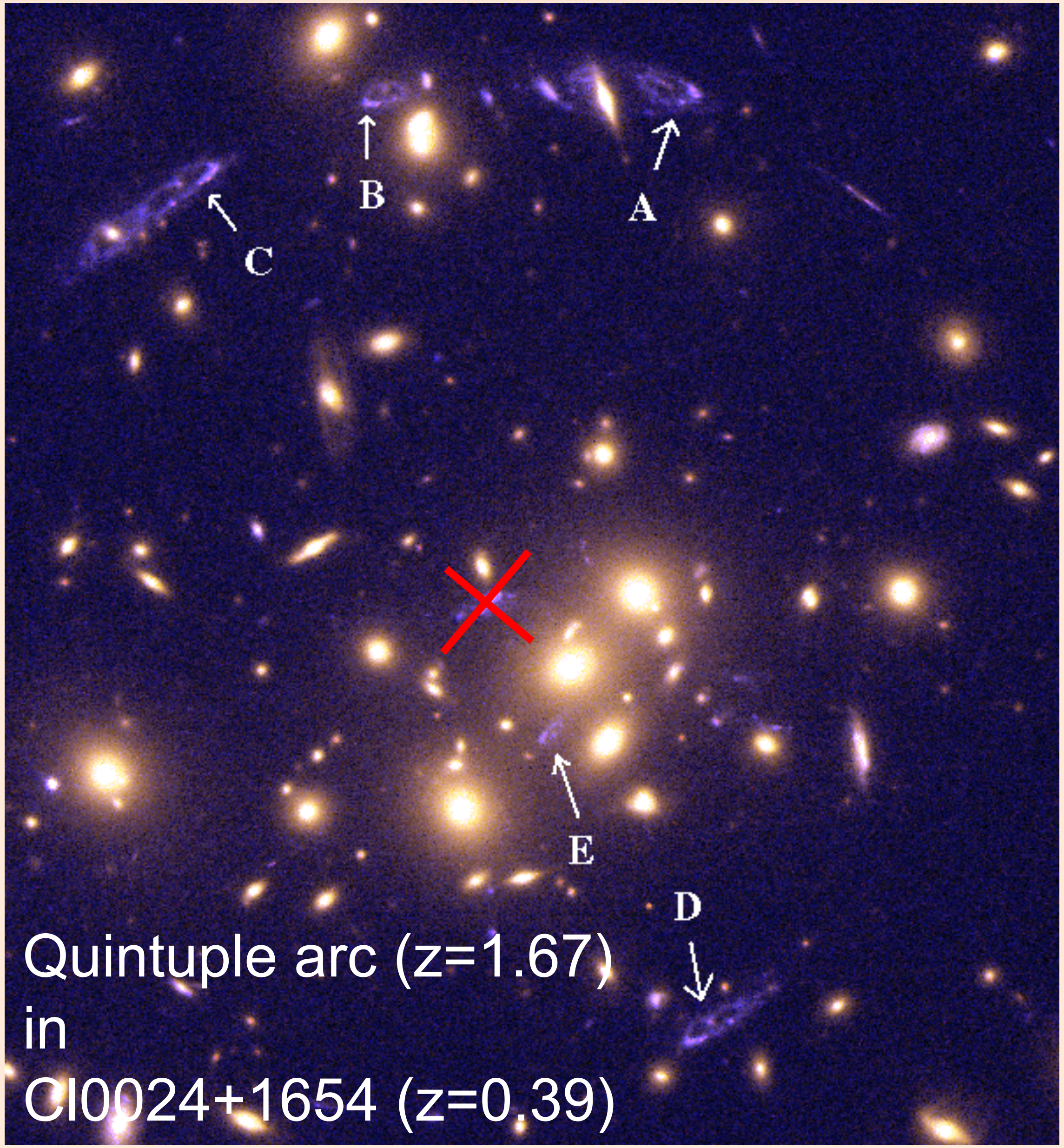
HOW TO IDENTIFY MULTIPLE IMAGES ?

Color and Morphology:

Lens model can help for the identification when different solution are possible

Finding multiple images in clusters :

- is an iterative process
- make take several weeks of computing time
- requires confirmation by multiple groups of people



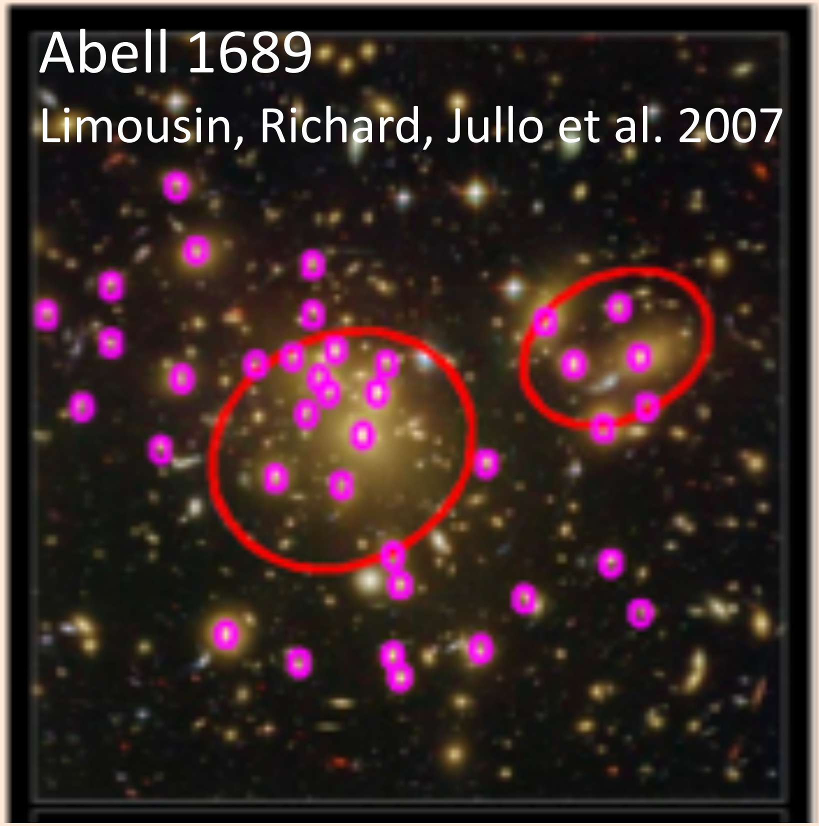
STRONG LENSES MODELS

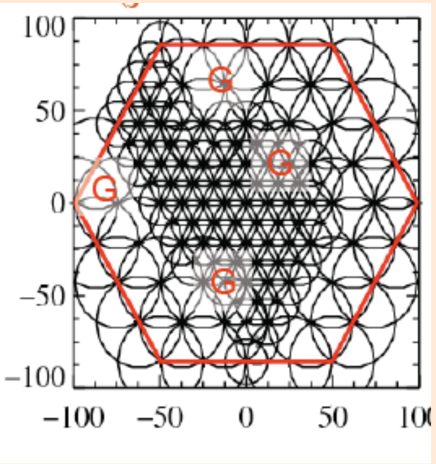
Problem
How to reproduce the observed multiple images?

We maintain a public lensing code called LENSTOOL[1]

$$\phi_{tot} = \phi_{cluster} + \Sigma_i \phi^i_{halos}$$

Physicaly motivated models	Agnostic Grid-based models
Decomposition into halos + luminosity scal. rel. for the galaxies	Decomposition into pixels + luminosity scal. rel. for the galaxies
Simple clusters	Complex clusters (substruc., filaments)
Few contraints	Lots of constraints (SL and WL)
Good fit with few constraints	Better fit with lots of constraints





Jullo & Kneib 2009

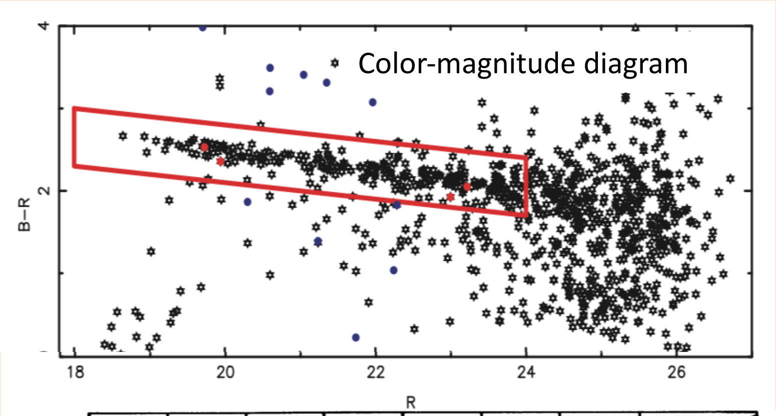
1 https://projects.lam.fr/lenstool

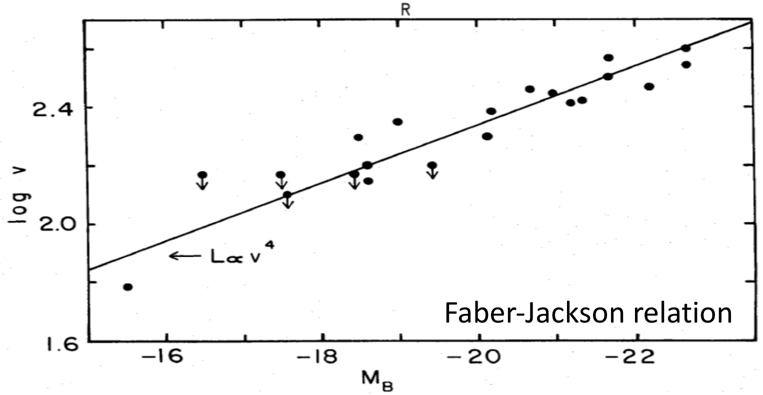
Properties of Galaxies in Clusters

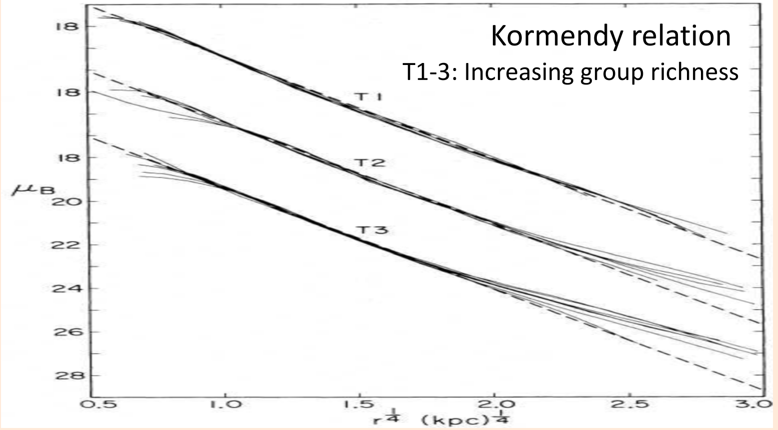
Galaxies in clusters have similar formation history

Cluster galaxies have similar colors

$\Rightarrow$ color-magnitude diagram







Cluster galaxies follow:

- Faber-Jackson(1976) relation between velocity and luminosity
- Kormendy(1977) relation between size and luminosity

USUAL MATTER DENSITY PROFILES

Isothermal sphere

$$\rho = \rho_0/\tilde{R}$$

$$\rho_0 = \frac{\sigma^2}{2\pi G}$$

PIEMD (Kassiolo,1993)

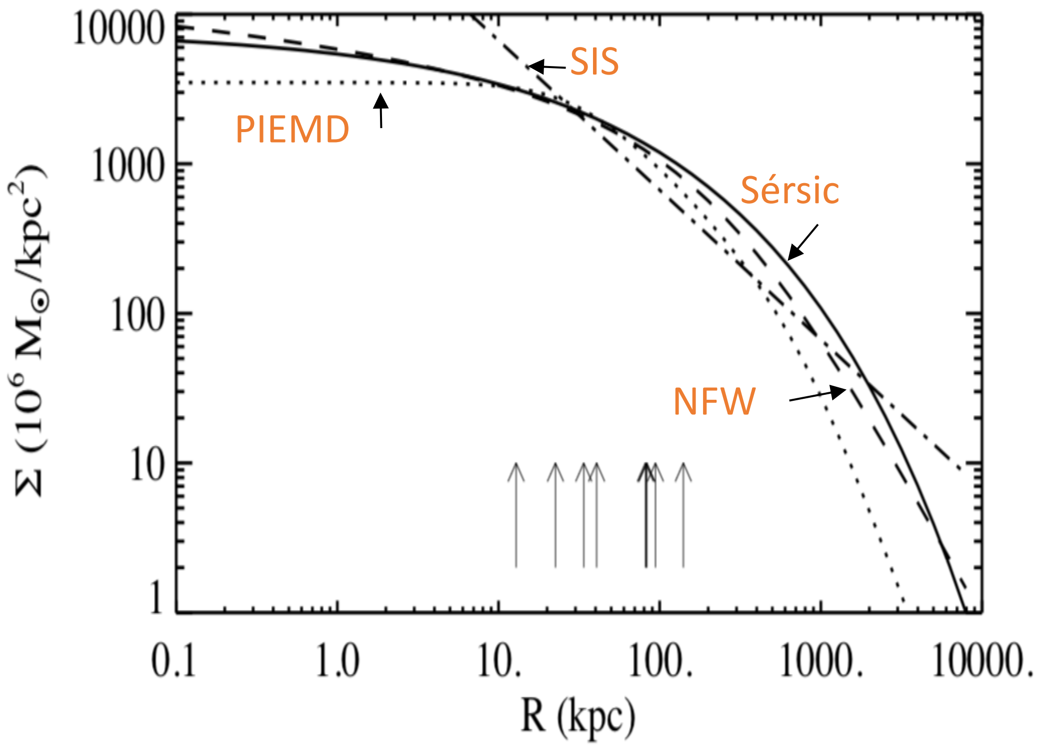
$$\rho = \frac{\rho_0}{(1+\frac{\tilde{R}^2}{r_c^2})(1+\frac{\tilde{R}^2}{r_{cut}^2})}$$

$$\rho_0 = \frac{\sigma_\infty^2}{2\pi G r_c^2}$$

Navarro, Frenk, White (1996)

$$\rho = \frac{\delta_c \rho_c}{\frac{\tilde{R}}{r_s}(1+\frac{\tilde{R}}{r_s})^2}$$

$$\delta_c = \frac{200}{3}\frac{c^3}{\ln(1+c)-c/(1+c)}$$



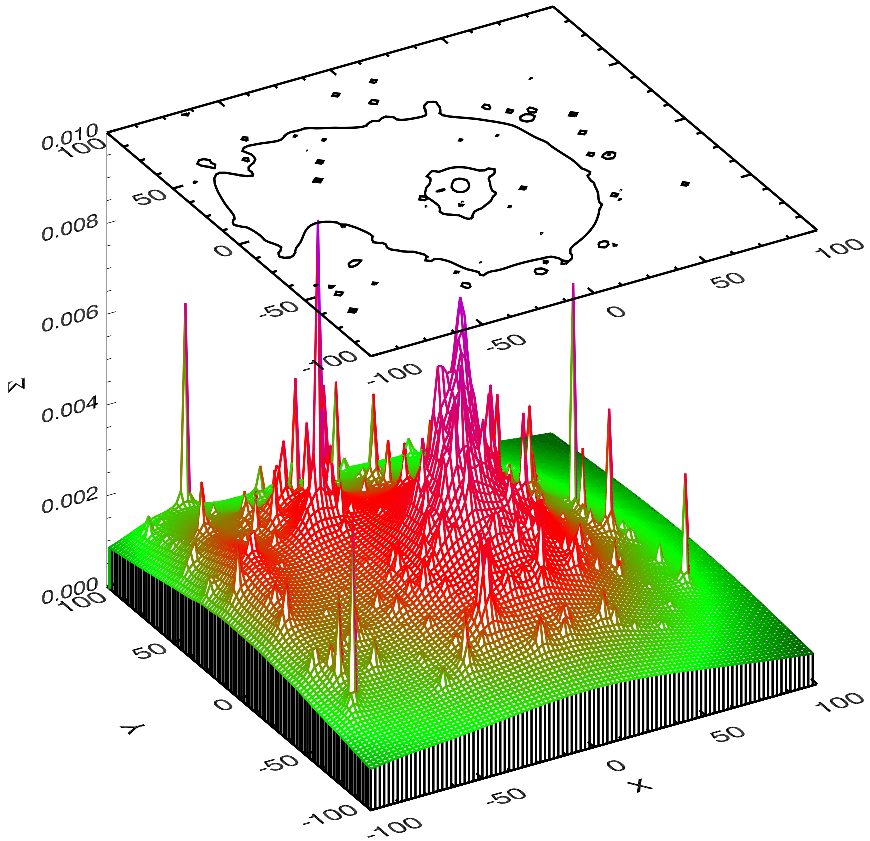
Sérsic (1963)

$$\ln\left(\frac{\Sigma}{\Sigma_e}\right) = -bn\left[\left(\frac{\tilde{R}}{R_e}\right)^{\frac{1}{n}} - 1\right]$$

$$bn \simeq 2n - \frac{1}{3} + \frac{4}{405n} + \frac{46}{25515n^2}{}^{d}$$

Galaxy scale components model

- For each galaxy scale lens potential, we model the total (stars+DM) matter density profile.



- We assume the following scaling relation between galaxy luminosity and total subhalo mass (PIEMD model):

$$\sigma = \sigma_*(\frac{L}{L_*})^{1/4} \qquad r_{cut} = r^*_{cut}(\frac{L}{L_*})^{\eta}$$

- Hence:

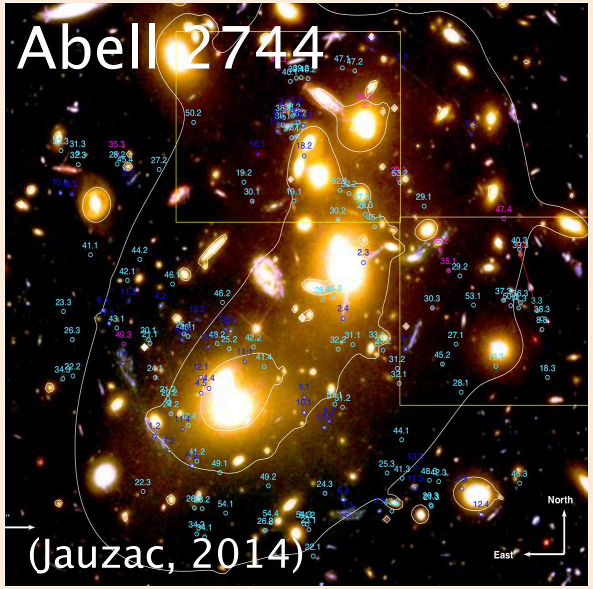
$$\frac{M}{L} \propto L^{\eta-1/2}$$

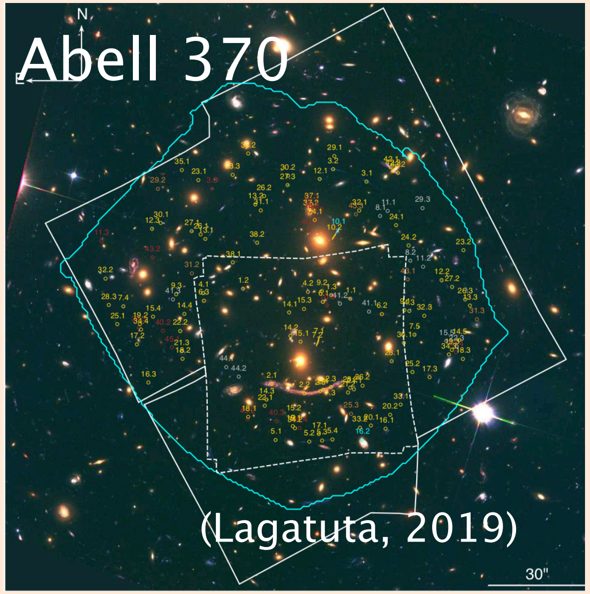
$\eta = 1/2$ Constant M/L

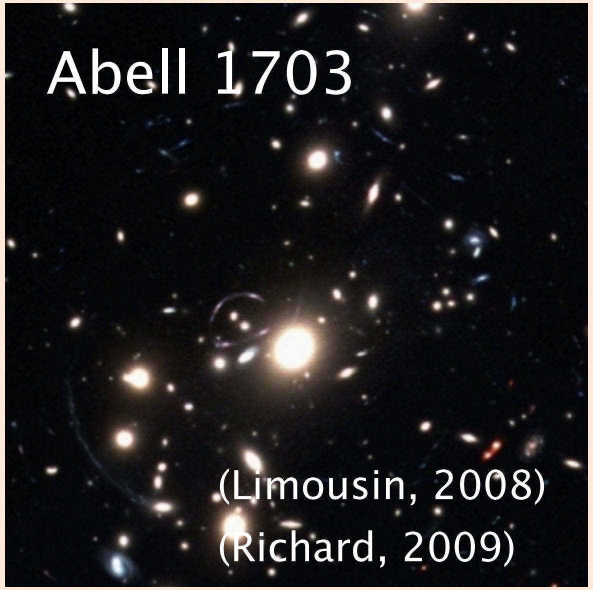
$\eta = 0.8$ FP scaling

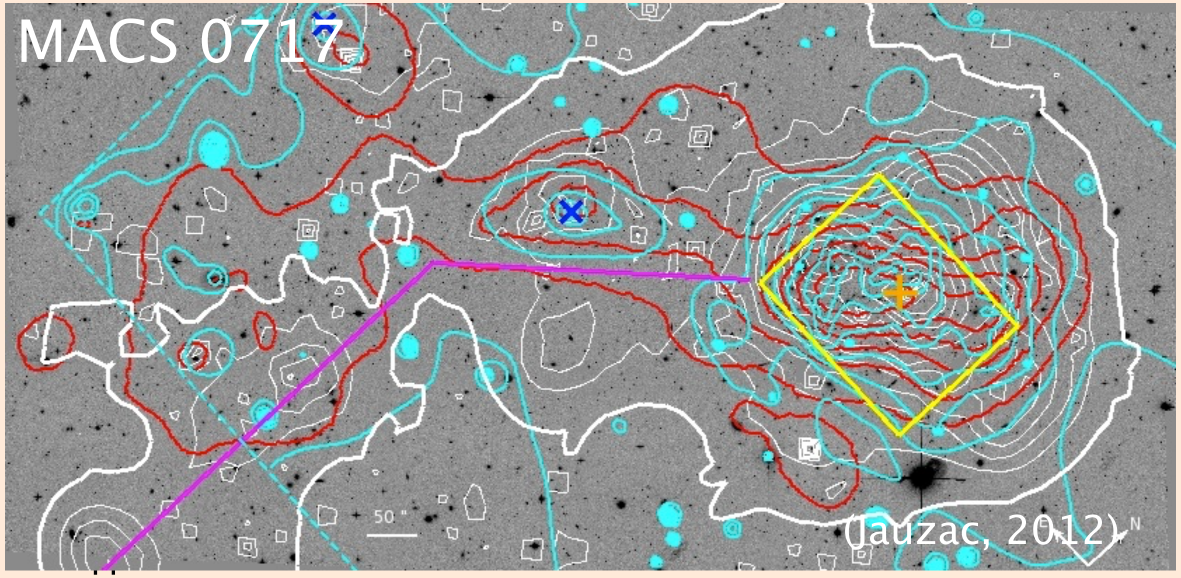
See Paraficsz et al. 2016

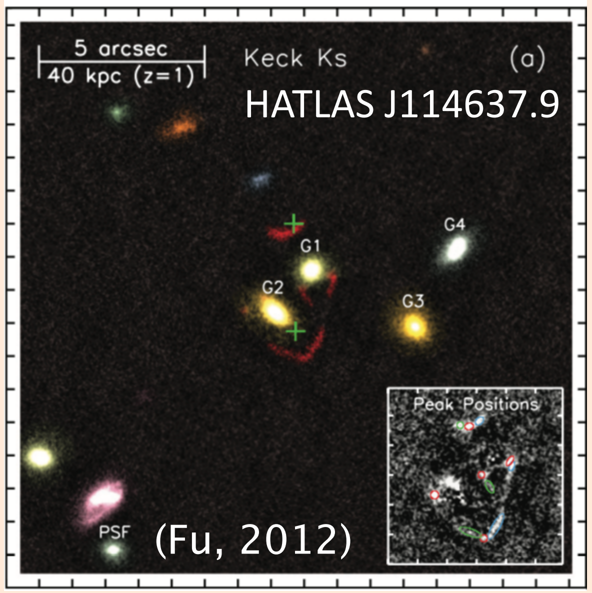
SOME CLUSTERS MODELED WITH LENSTOOL









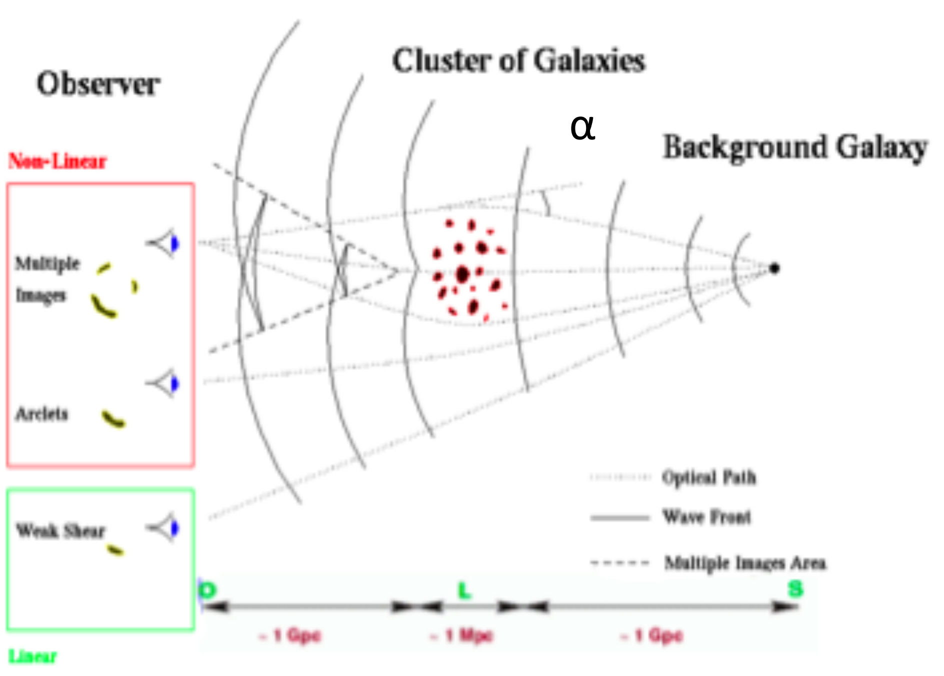


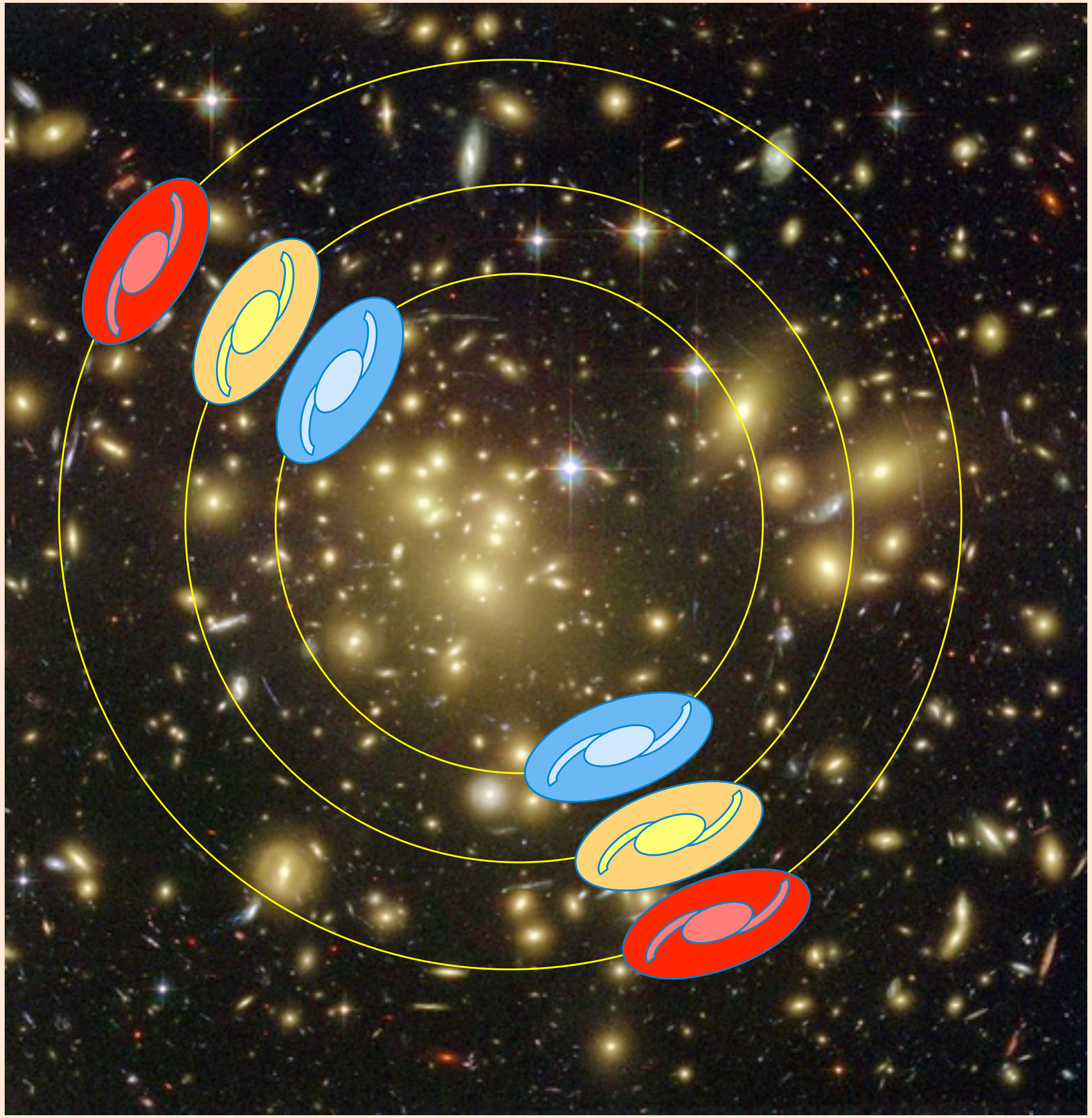
⇒ About 60 strong-lensing models available on Lenstool webpage

COSMOLOGY WITH STRONG LENSING

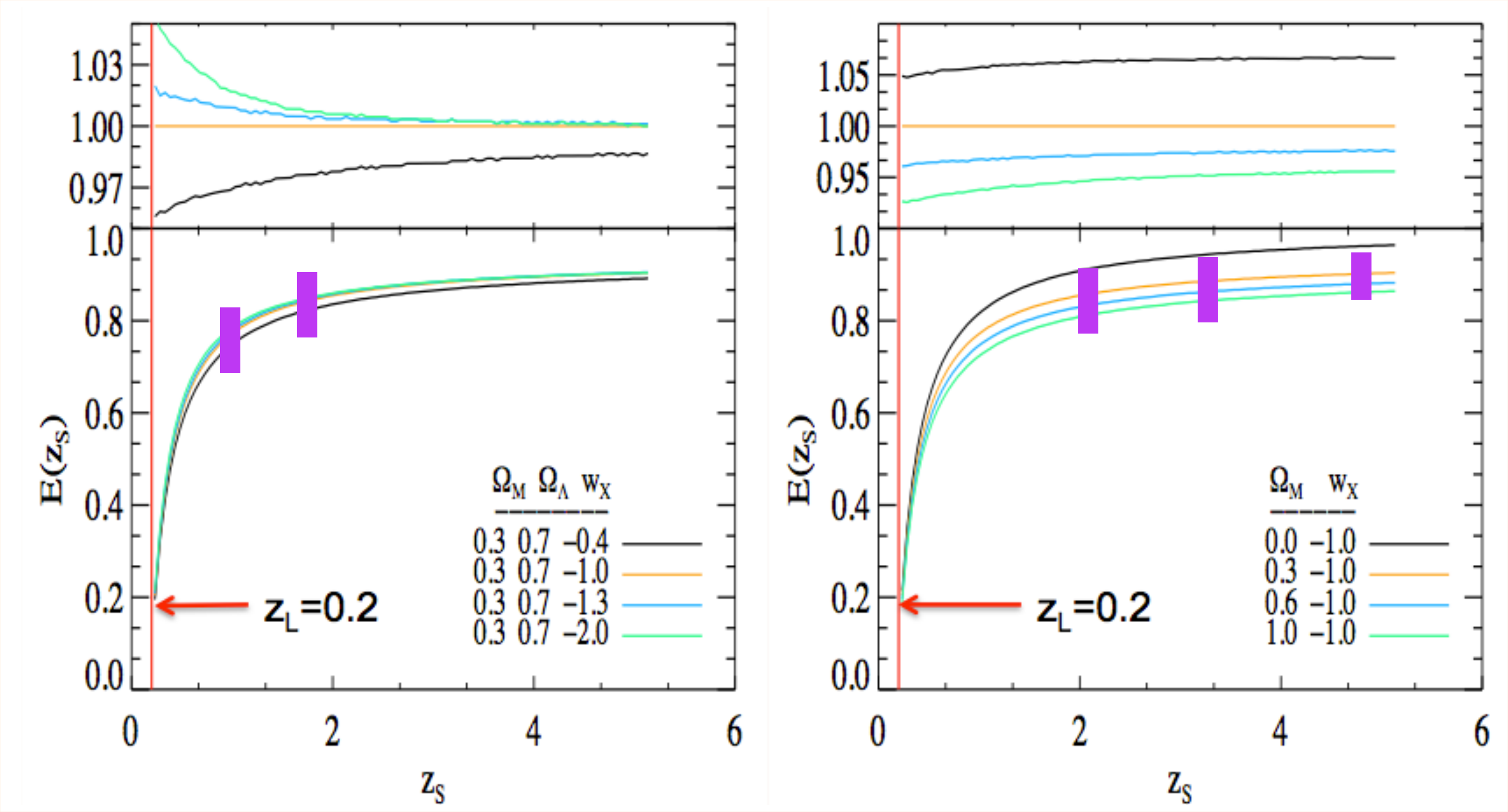
$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi(\theta_I)$$

Cosmology mass





EFFICIENCY RATIO E=DLS/DOS



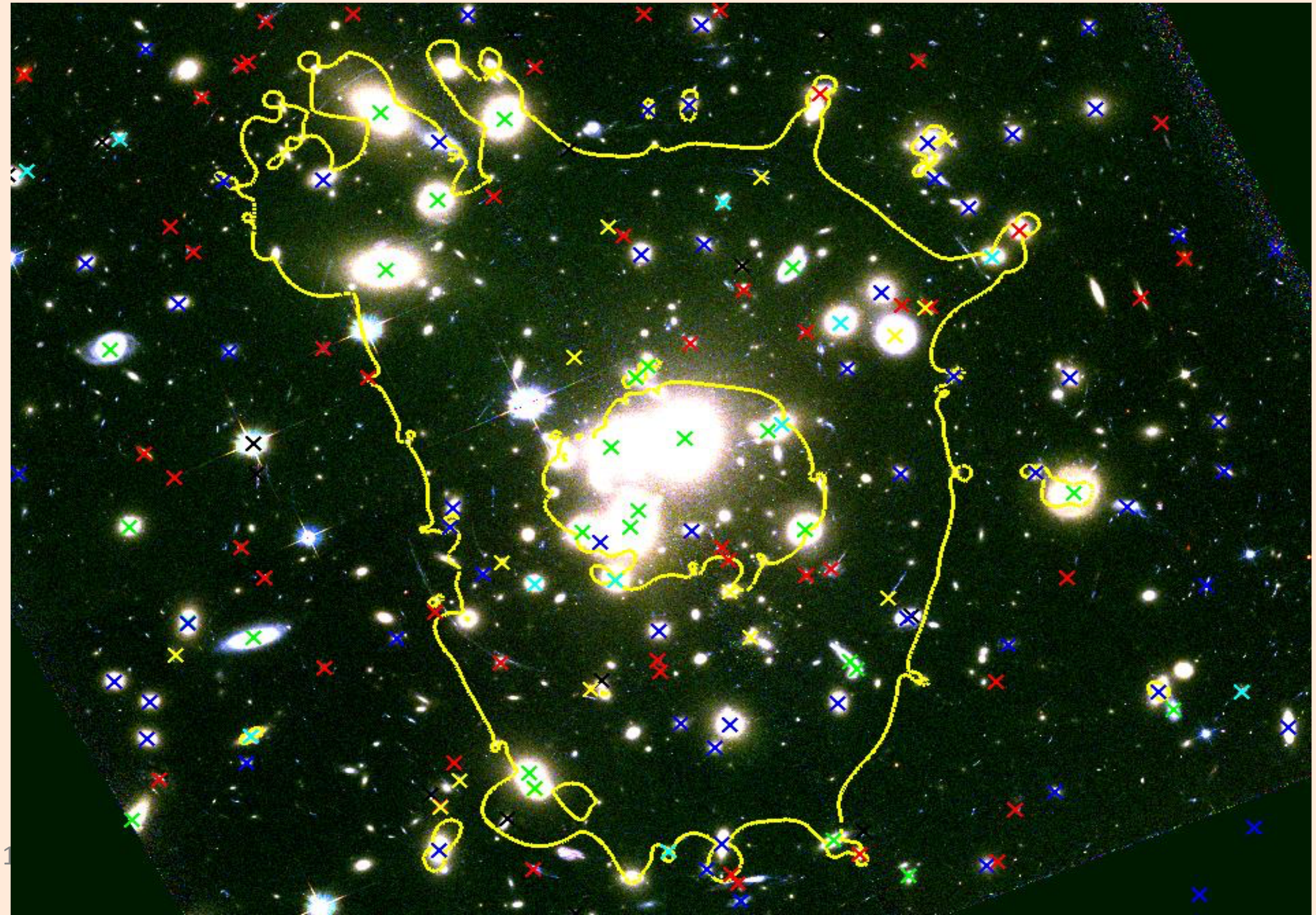
w_X effect

Ω_m effect

COSMOGRAPHY WITH ABELL 1689

Made possible thanks to:

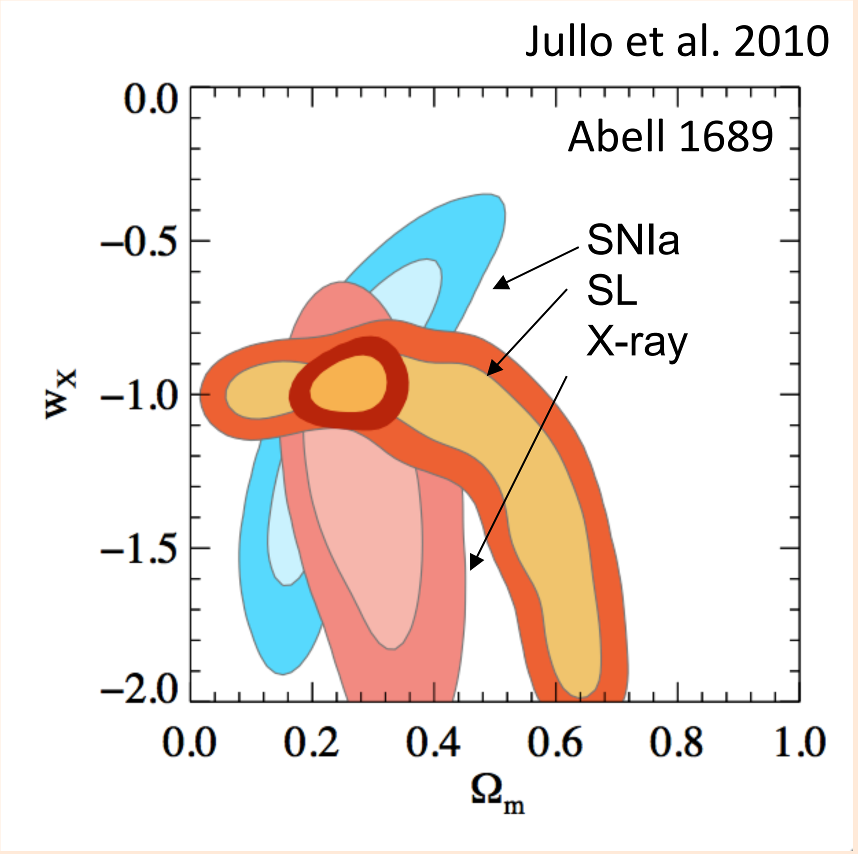
- Many previous models and multiple image identifications
- Massive spectroscopic surveys (2003-2006) [Richard et al 2011]
- 43 multiple image systems, 24 with spectro-z with 1.1 < z < 4.9



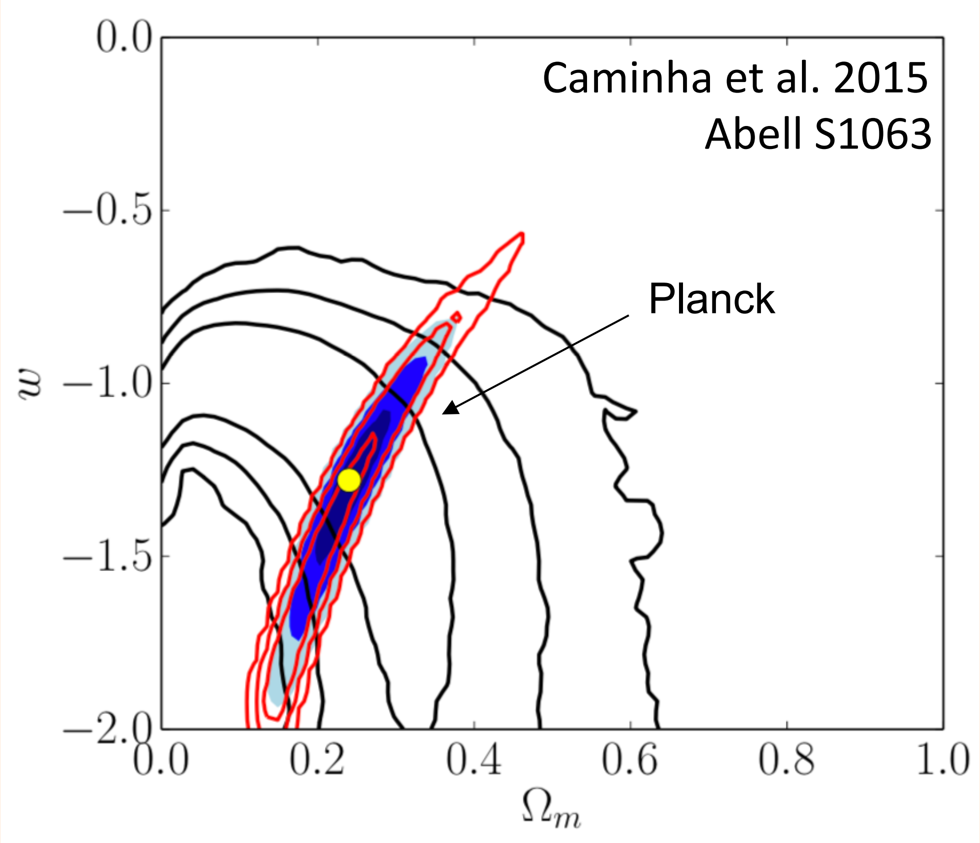
Broadhurst et al 2005
Halkola et al 2007
Limousin, et al. 2007
Richard et al. 2007
Frye et al 2007
Leonard et al 2007
Jullo & Kneib 2009
Coe et al 2010

X KECK/LRIS
X VLT/FORS
X CFHT/MOS
X MAGELLAN /LDSS2
X Litterature

Current CSL constraints on wCDM model



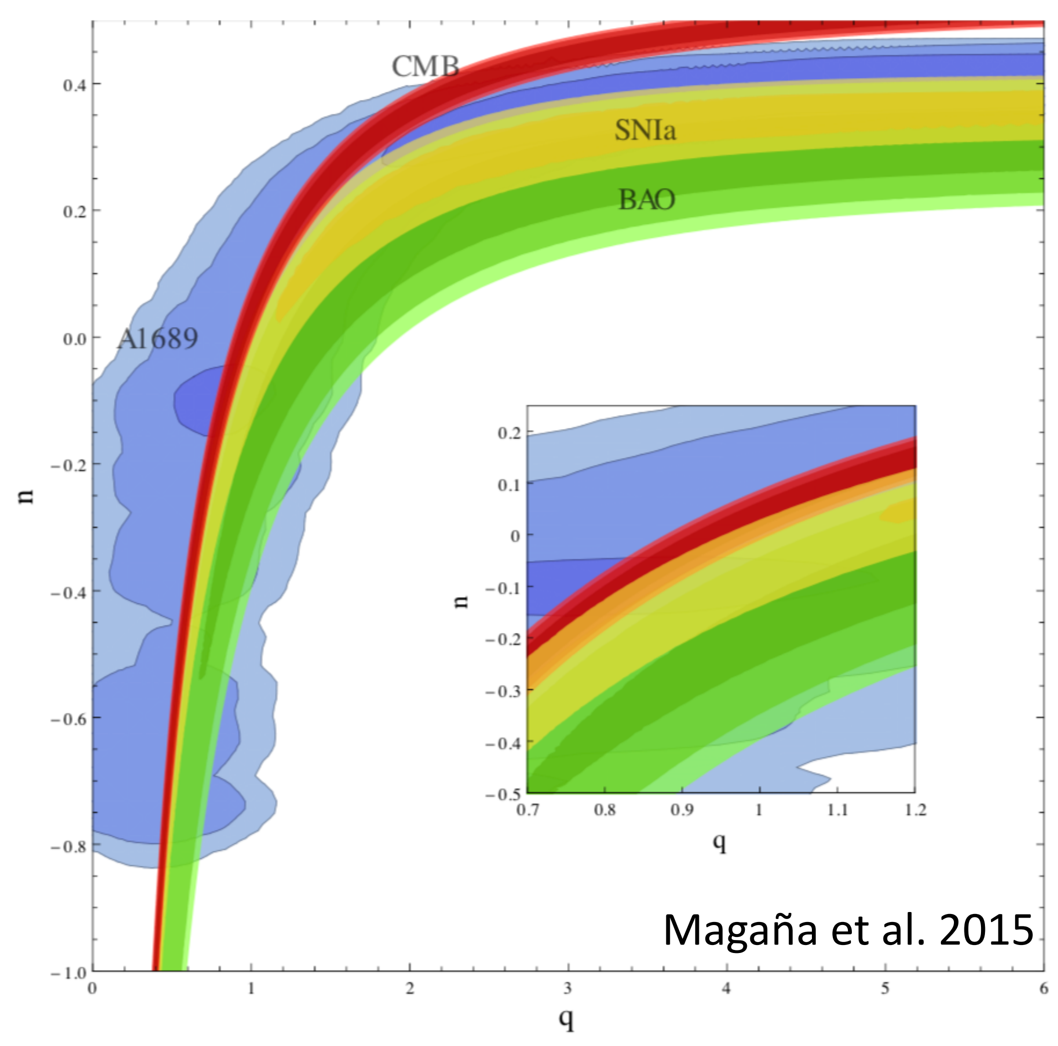
- 12 sources, 43 multiple images
- 24 z-spec in redshift range 1 < z < 5



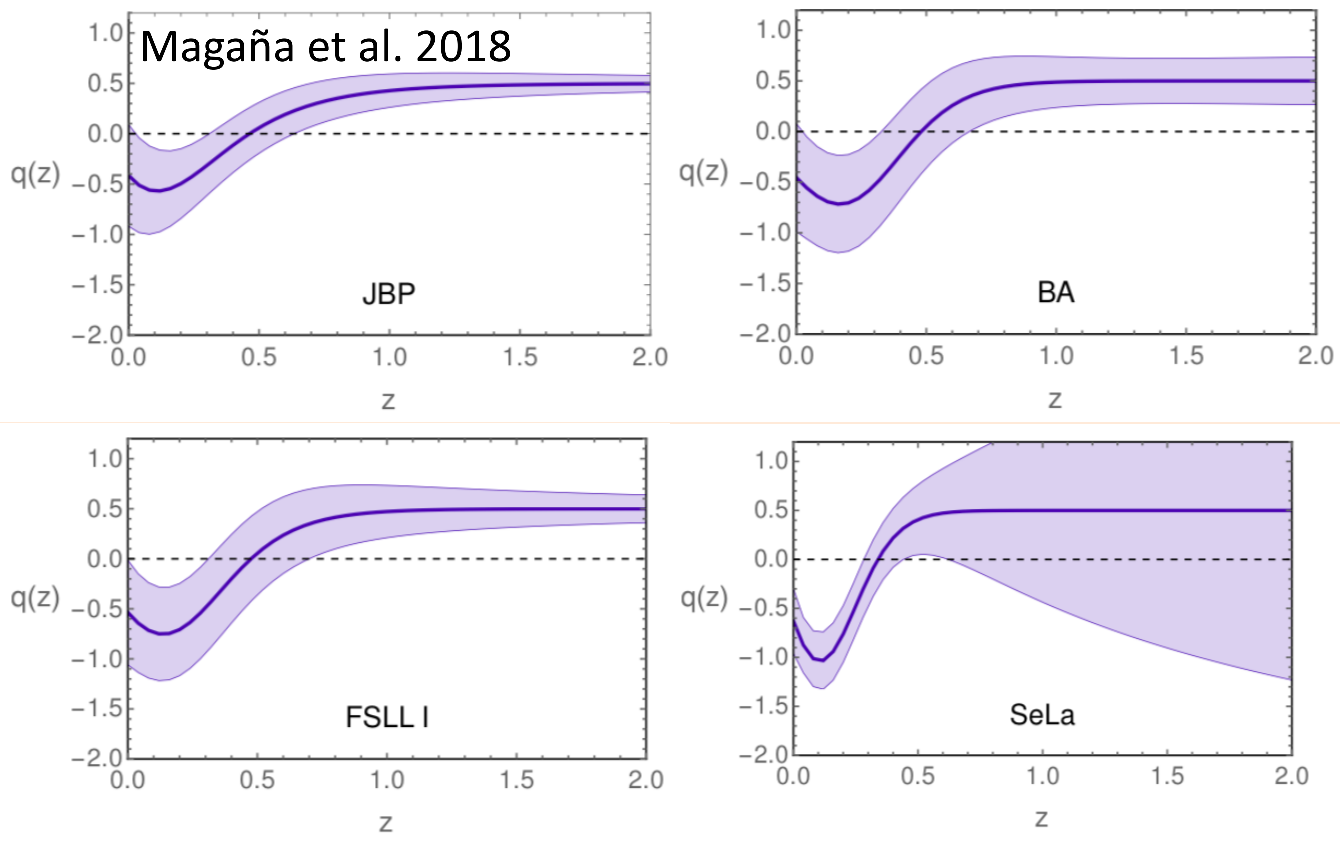
- 16 sources, 47 multiple images
- 24 z-spec in redshift range 1 < z < 6

=> Constraints depend on discarding outliers, and estimating model uncertainties

ALTERNATIVE DARK ENERGY MODELS

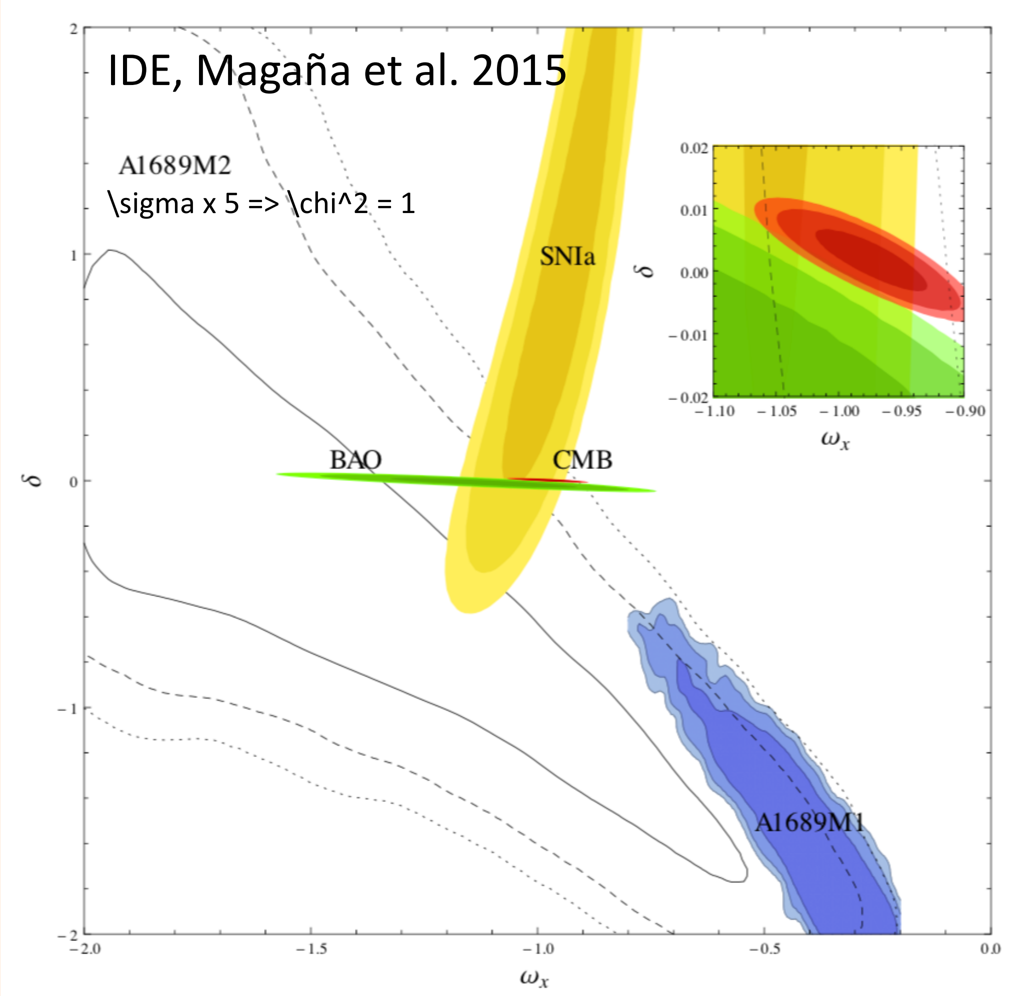


Modified polytropic Cardasian model (MPC)



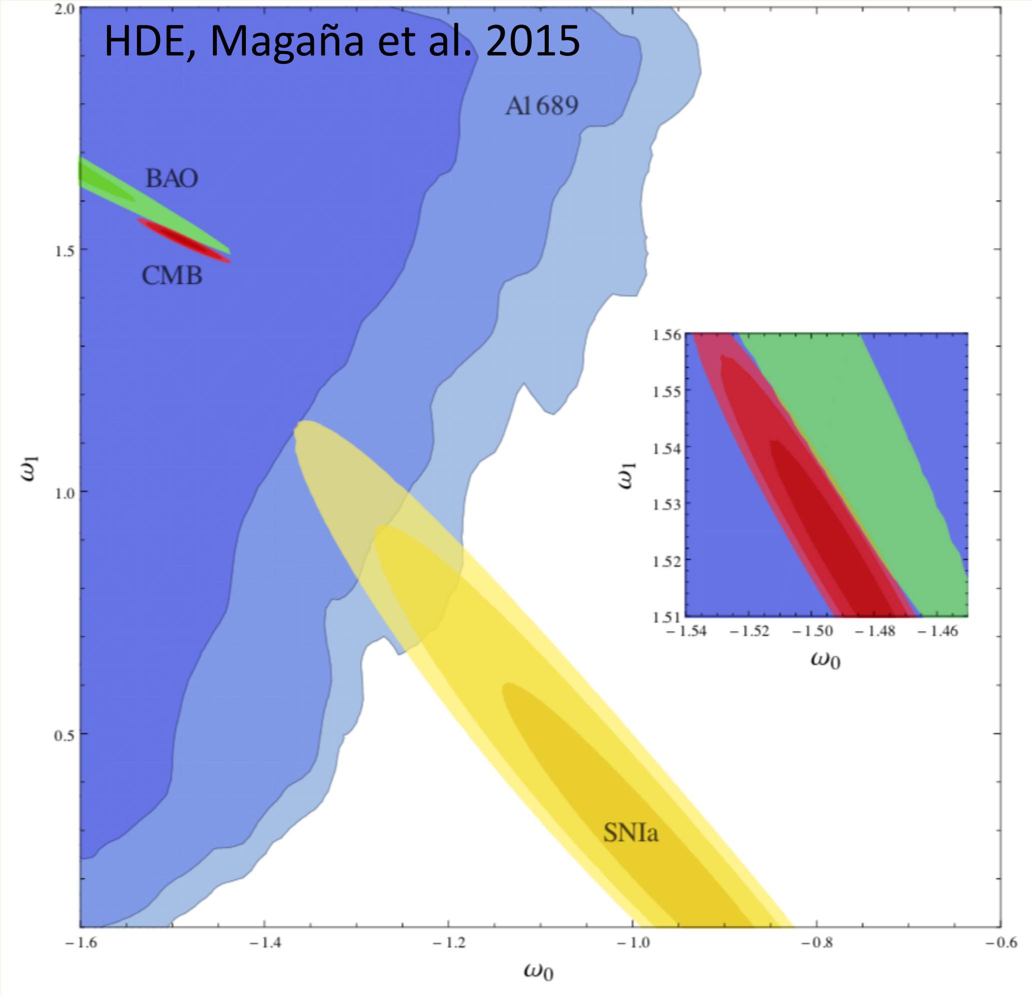
Chevallier-Polarski-Linder	FOM=61	Jassal-Bagla-Padmanabhan	8936
Interacting Dark Energy	1971	Barbosa-Alcaniz	5089
Holographic dark energy	15143	Feng-Shen-Li-Li	6544
Modified Polytropic Cardassian	65	Sendra-Lazkoz	1517

UNSOLVED ISSUES ...???



SL model disagrees with other probes

=> Lens model systematic error?



Sometimes, other probes disagree

=> Cosmological information or modelling systematics?

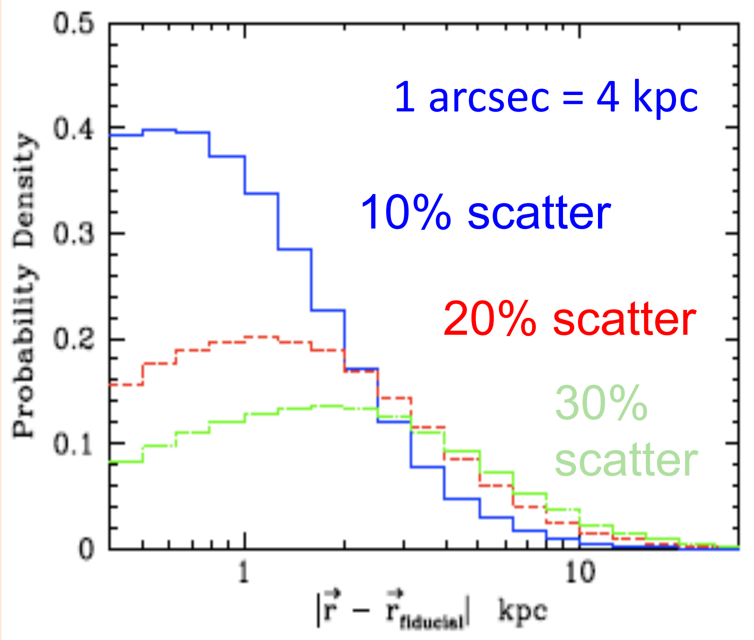
Galaxy modeling uncertainties

PIEMD parameters
+20% scatter

$$
\begin{cases}
\sigma_0 = \sigma_0^\star \left(\dfrac{L}{L^\star}\right)^{1/4}, \\
r_{\rm core} = r_{\rm core}^\star \left(\dfrac{L}{L^\star}\right)^{1/2}, \\
r_{\rm cut} = r_{\rm cut}^\star \left(\dfrac{L}{L^\star}\right)^{\alpha}.
\end{cases}
$$

The total mass of a subhalo scales then as:

$$M = (\pi/G)(\sigma_0^\star)^2 r_{\rm cut}^\star (L/L^\star)^{1/2+\alpha},$$

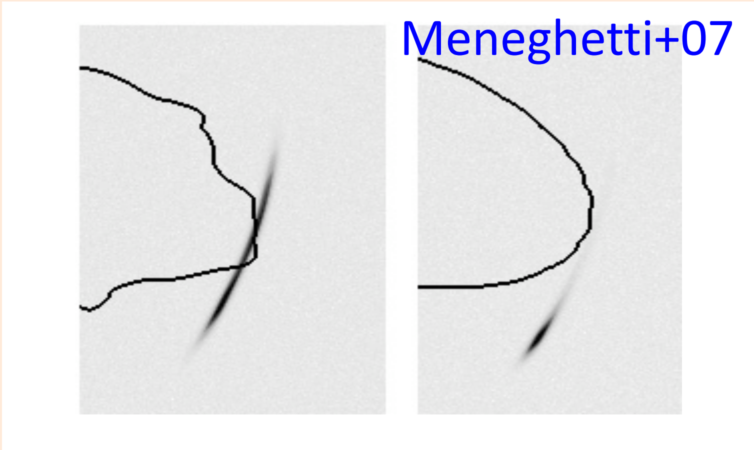


Simulations: D'Aloisio & Natarajan 2010

For A1689, this lead to a scatter on the image position of ~ 1 kpc ~ 0.25"

=> Scatter different for each image

=> Images must be weighted in χ^2 INDIVIDUALLY (not the usual approach). Specific to each cluster



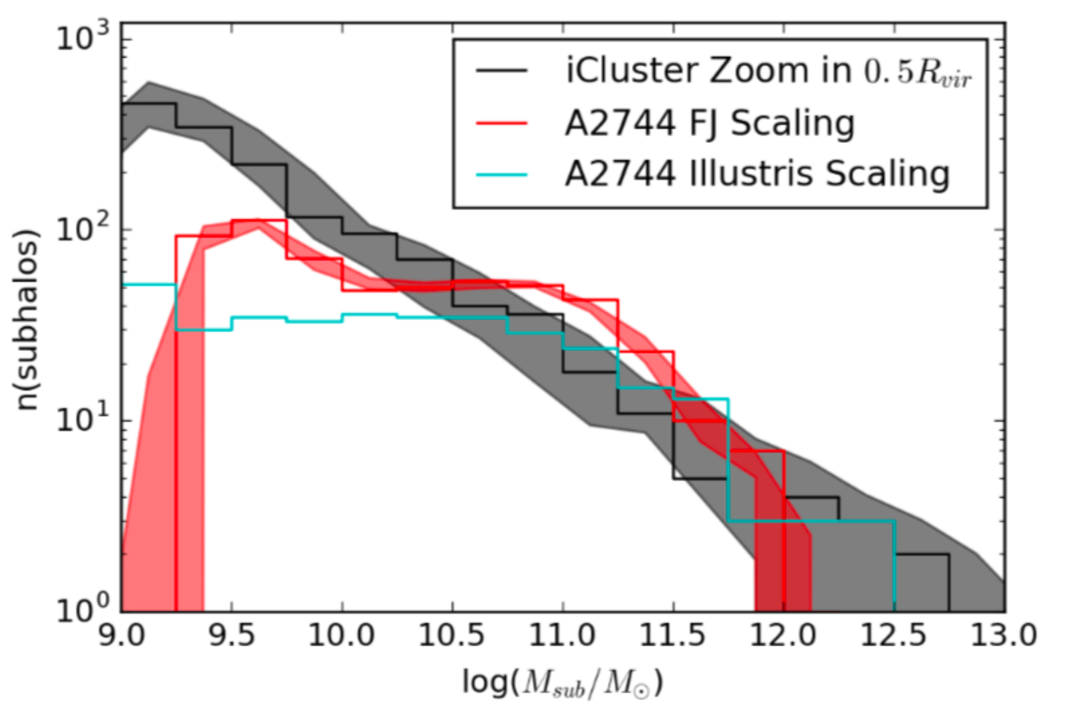
CURRENT OBSERVATIONAL KNOWLEDGE

Strong lensing in clusters allows to constrain the M/L ratio of satellite galaxies (i.e. cluster member galaxies)

Natarayan et al. 2017

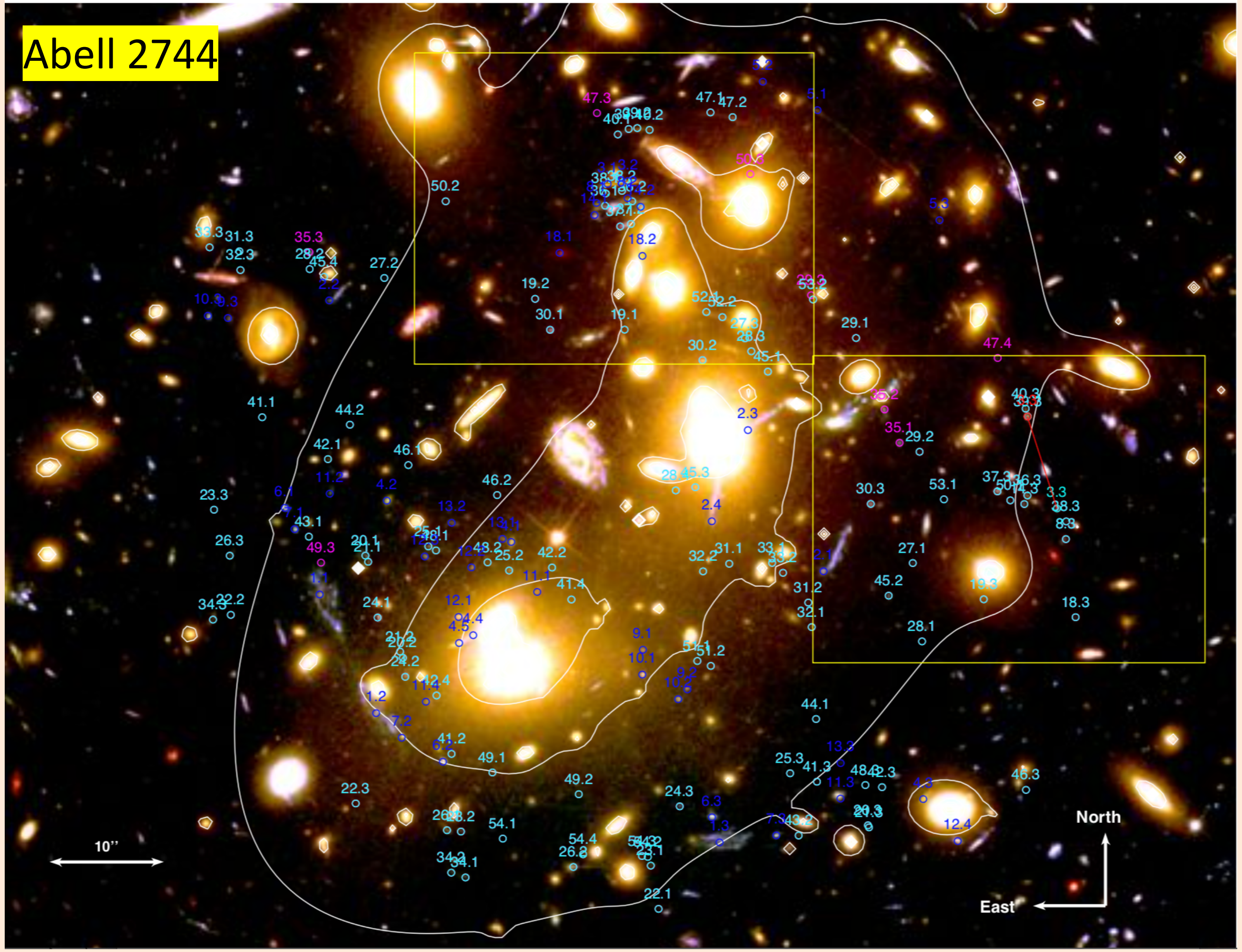
$$\sigma_0 = \sigma_0^\star \left(\frac{L}{L^\star}\right)^{1/4} \qquad r_{\rm cut} = r_{\rm cut}^\star \left(\frac{L}{L^\star}\right)^{\alpha}$$

$$M = (\pi/G)(\sigma_0^\star)^2 r_{\rm cut}^\star (L/L^\star)^{1/2+\alpha}$$



=> Better agreement with Illustris empirical scaling

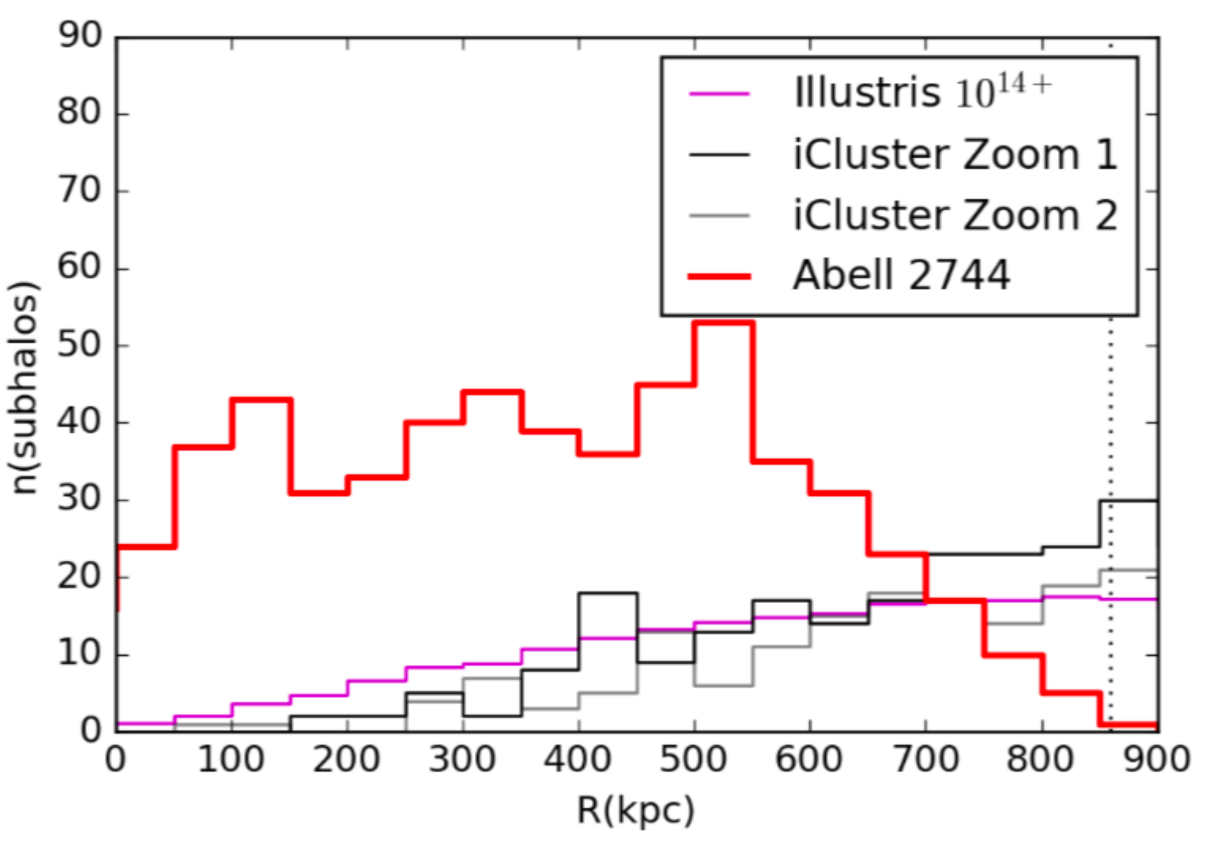
>150 multiple images in HST Frontier Field cluster, Jauzac et al. 2014



DISCREPANCIES WITH SIMULATIONS

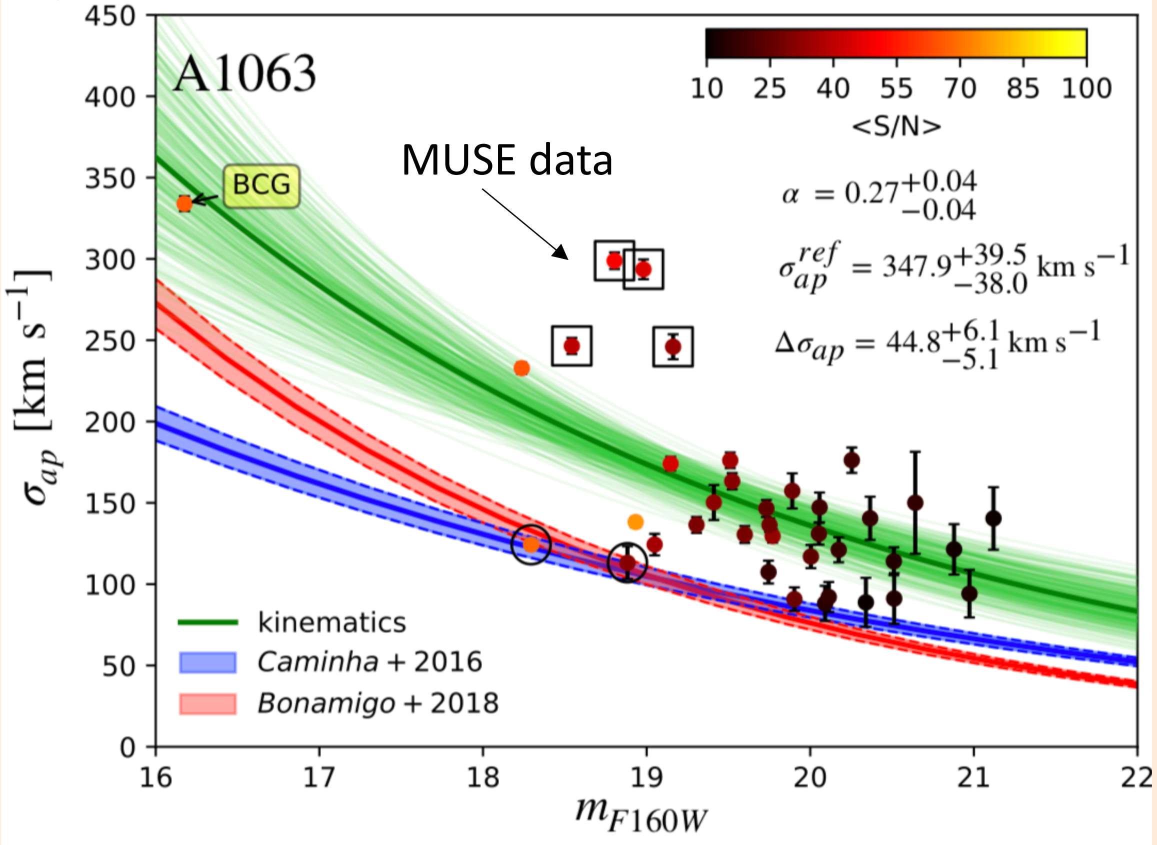
However, some uncertainties remain

Natarayan et al. 2017



Projected radial distances mismatch

Bergamini et al. 2019, *Comparison MUSE and HST SL-models*

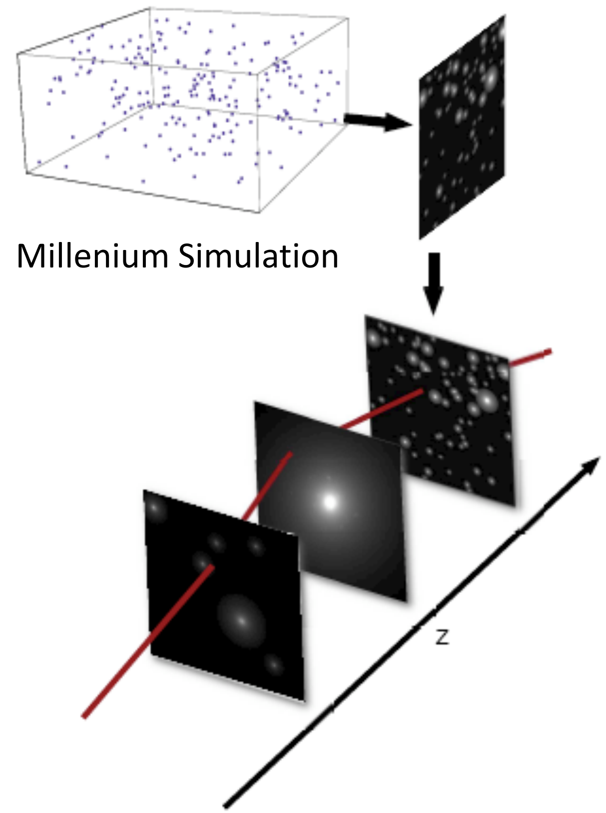


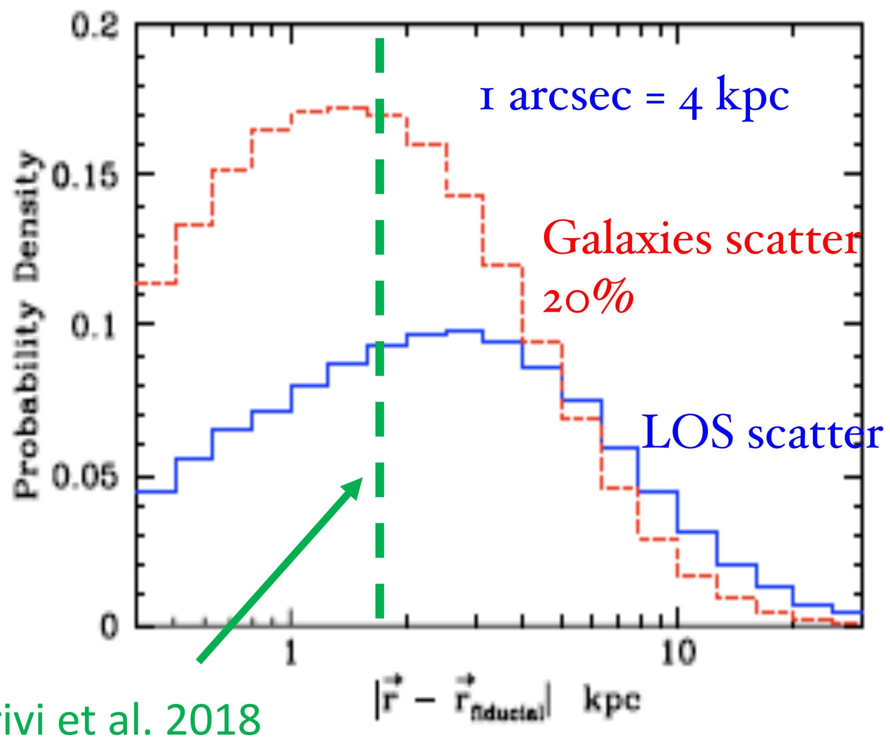
Outliers in the luminosity – σ_{ap} scaling relation

=> They can bias the lensing models

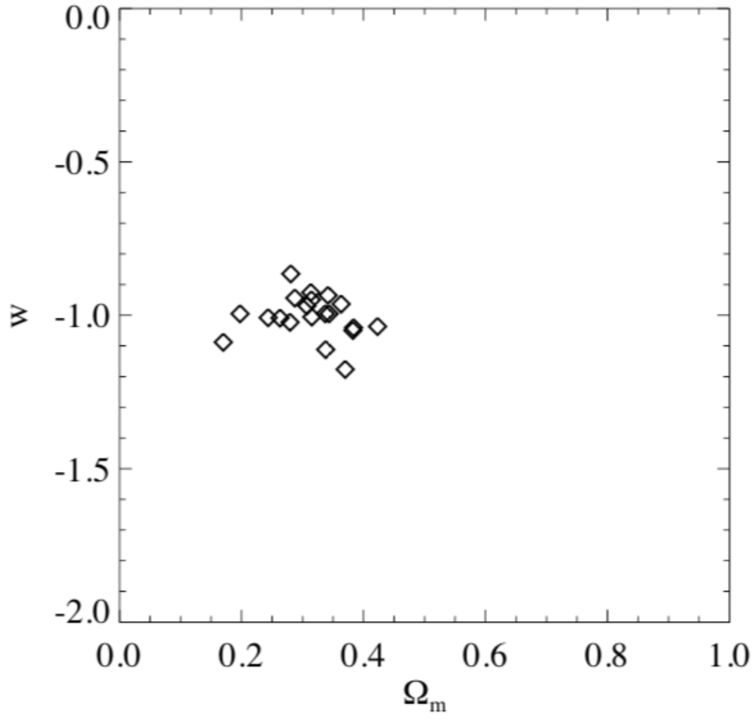
UNACCOUNTED STRUCTURES : LINE OF SIGHT

D'Aloisio & Natarajan, 2010





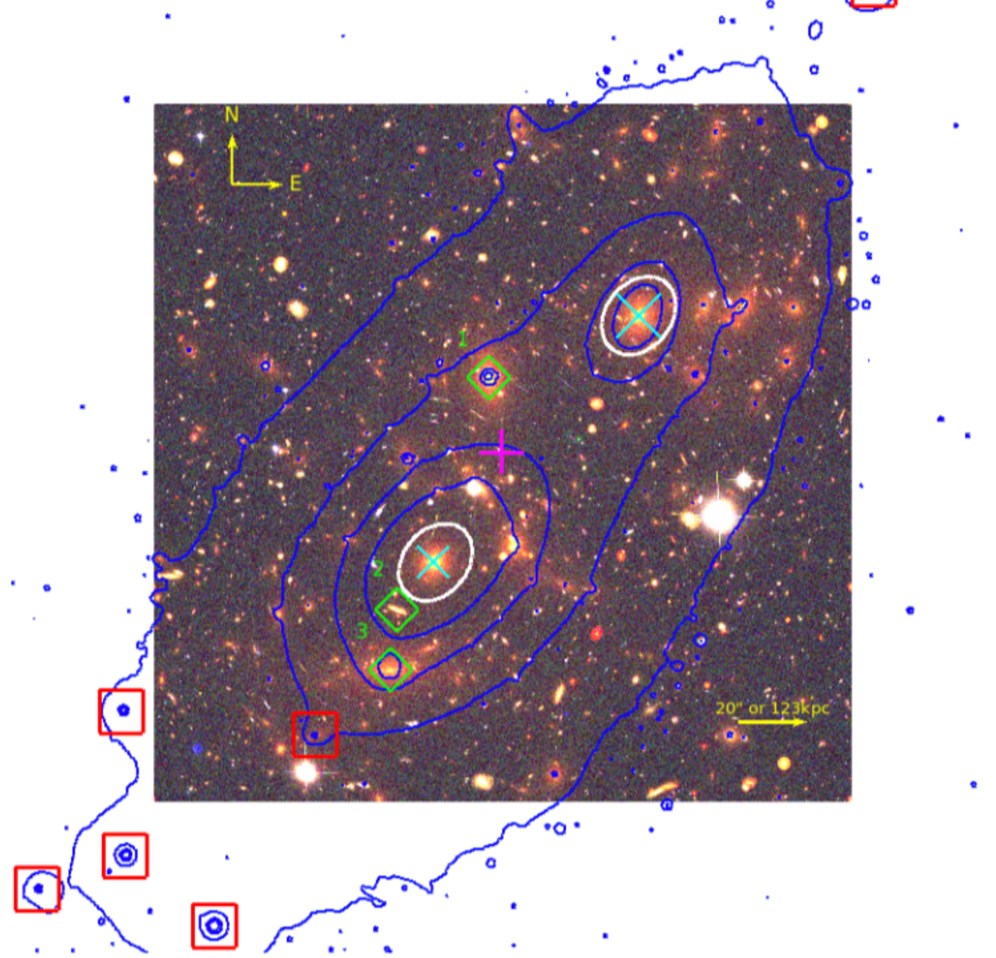
Caminha et al. 2017



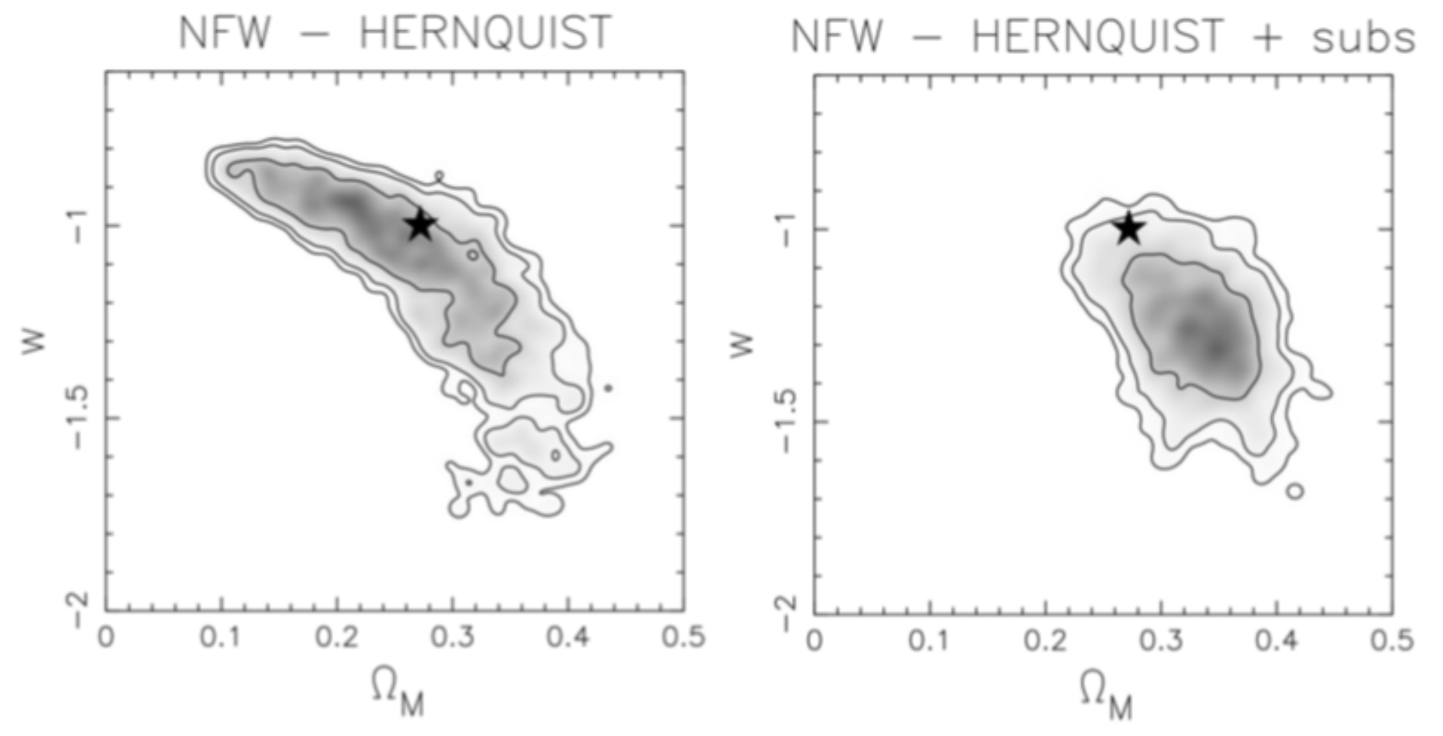
⇒ Agreement that line of sight structures effect is RMS ~ 0.3", similar to galaxy scatter

INFALLING STRUCTURES

Acebrón et al. 2017



ARES simulation (Meneghetti et al. 2016)



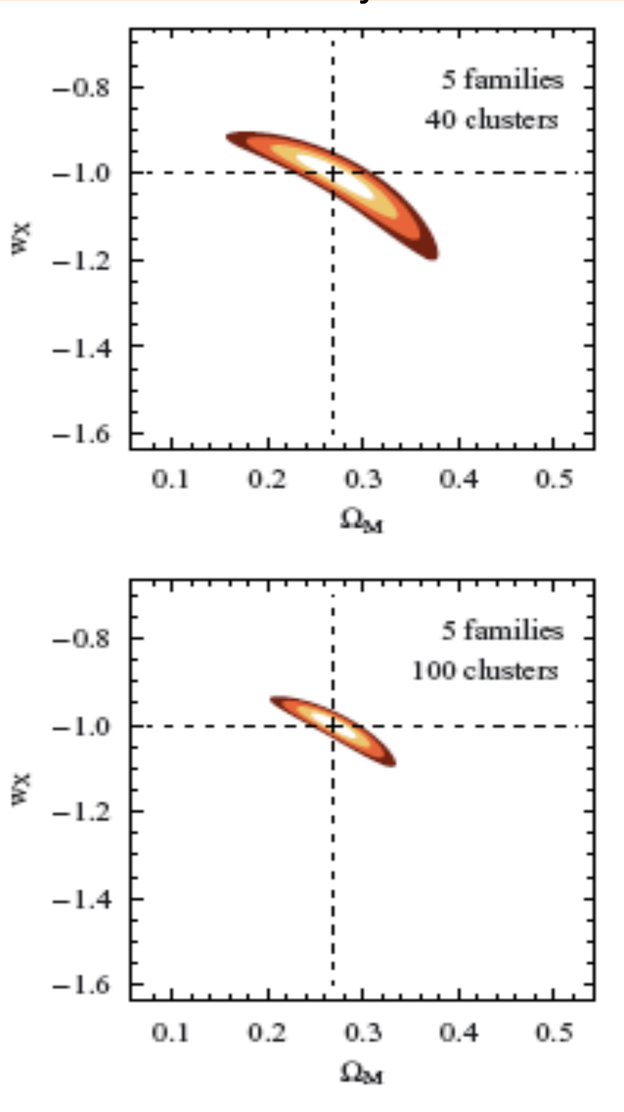
Adding subtructures

- Improves the cosmological precision
- Introduces a bias due to improper modeling

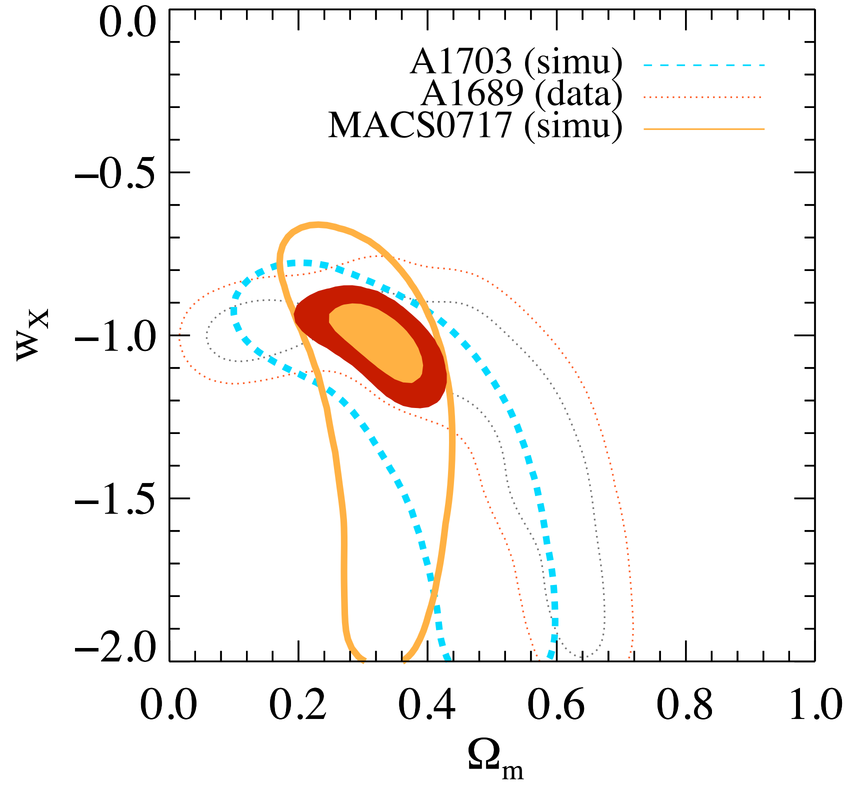
⇒Need to identify them better (weak-lensing)

COSMOLOGICAL FORECASTS

Gilmore & Natarajan 2009

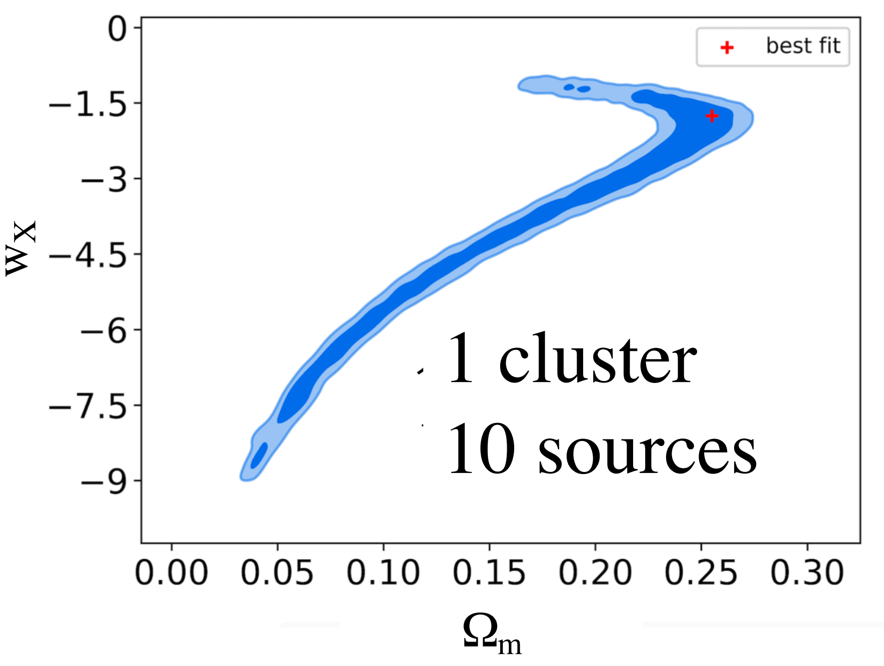


Simple simulation (not published)



Fit of a wCDM model on a simulated JBP model (Jassal, Bagla, Padmanabhan 2005)

Work in progress with Chinese colleagues



JBP model: rapid evolution of EoS at low-z

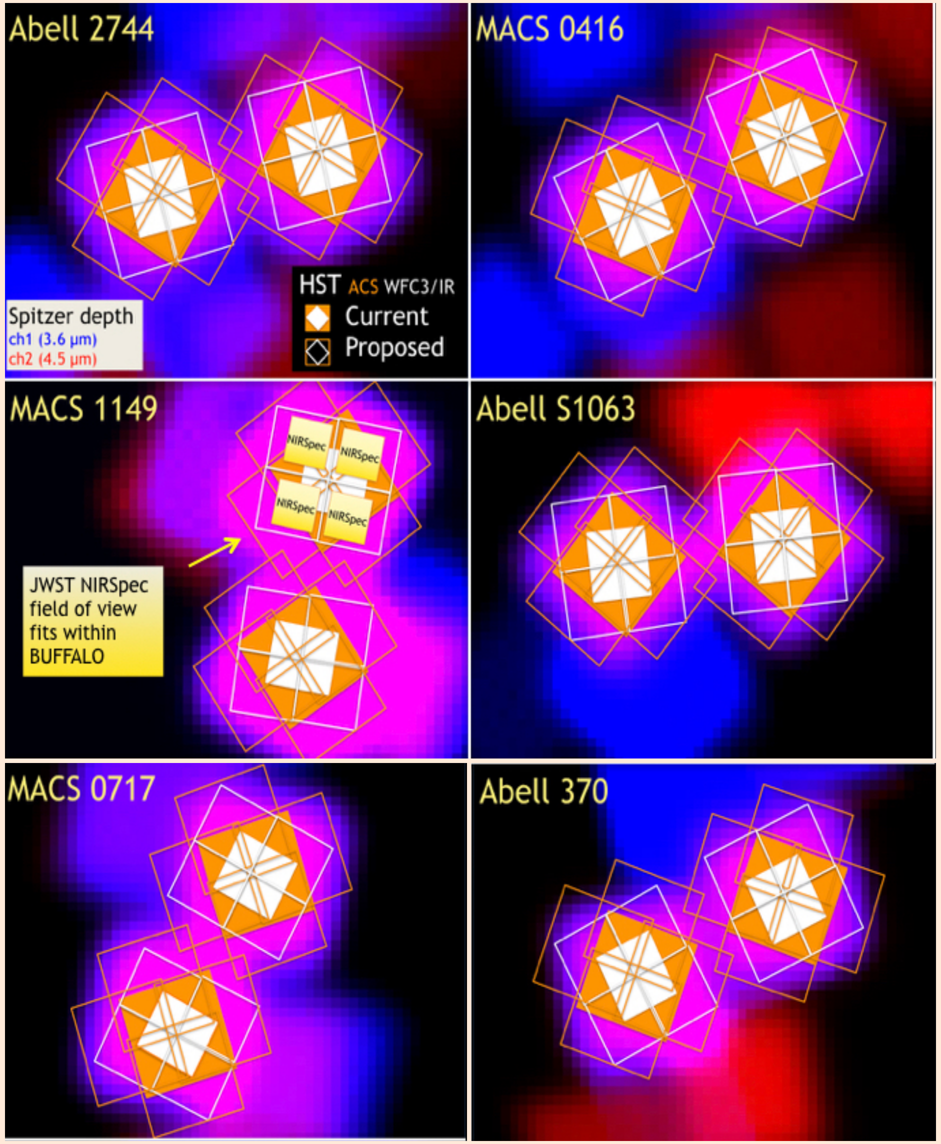
$w(z) = w_X + w_1 z / (1 + z)^2$

NEW SL DATASETS: BUFFALO

100 HST orbits to observe the outskirt of 6 massive HST Frontier Field clusters (PI. Steinhardt, Jauzac)

- Observations in 5 HST bands, 12 x 6 arcmin^2
- Prepare a statistical sample of galaxies at z > 7, to submit to JWST
- Study the evolution of clusters and member galaxies
- Dark-matter properties

- Treasury program (immediately public data)
- Ancillary data from Spitzer, Chandra, XMM, etc.



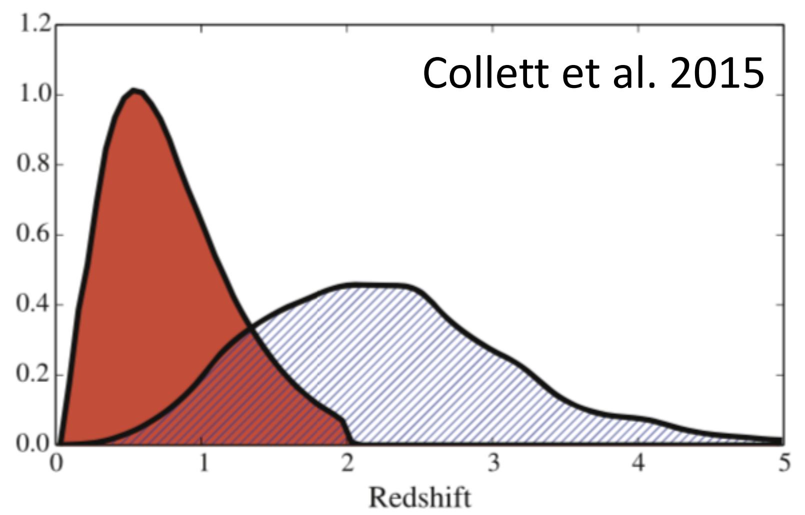
FORTHCOMING SL DATASETS

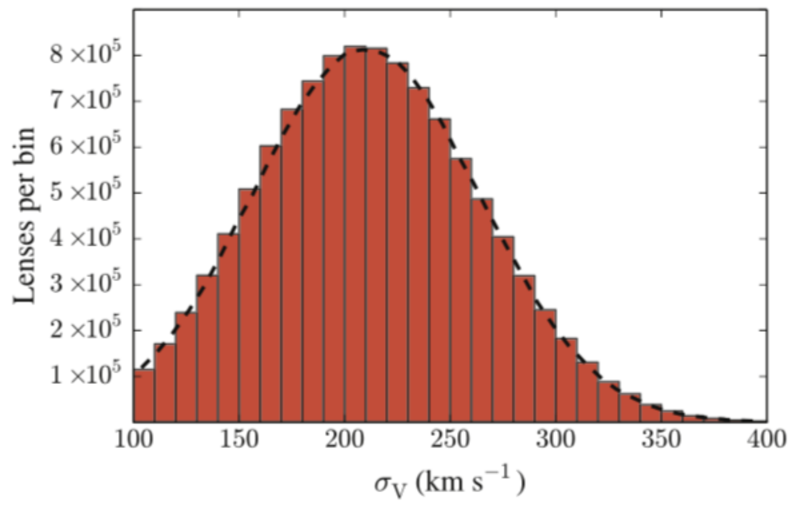
The fraction of lenses in groups and clusters is 14% and 4%, respectively (Oguri et al. 2006)

Assuming Poisson limited lens galaxy subtraction, Collett et al. 2015 estimate

- Euclid should discover 170,000 lenses => 23,800 in groups, 6800 in clusters
- LSST should discover 120,000 lenses => 16,800 in groups, 4800 in clusters
- Spectroscopic follow-up with 4MOST (PI: Collett, proposal)

There are on-going work to detect lenses with machine-learning in Euclid and LSST (e.g. Metcalf et al. 2016)





CONCLUSIONS

- Gravitational lensing in clusters can test dark energy models

- Currently, we are limited by systematic errors:
  - cluster member galaxies
  - line-of-sight perturbations,

- Recent hydro-simulations help derive empirical models of galaxy evolution in clusters to solve cluster member galaxies problem

- We need to get prepared for the forthcoming observational data.