DARK ENERGY WITH CLUSTER STRONG LENSING

Eric Jullo – NPP Fellow since 01/2009

Jet Propulsion Laboratory

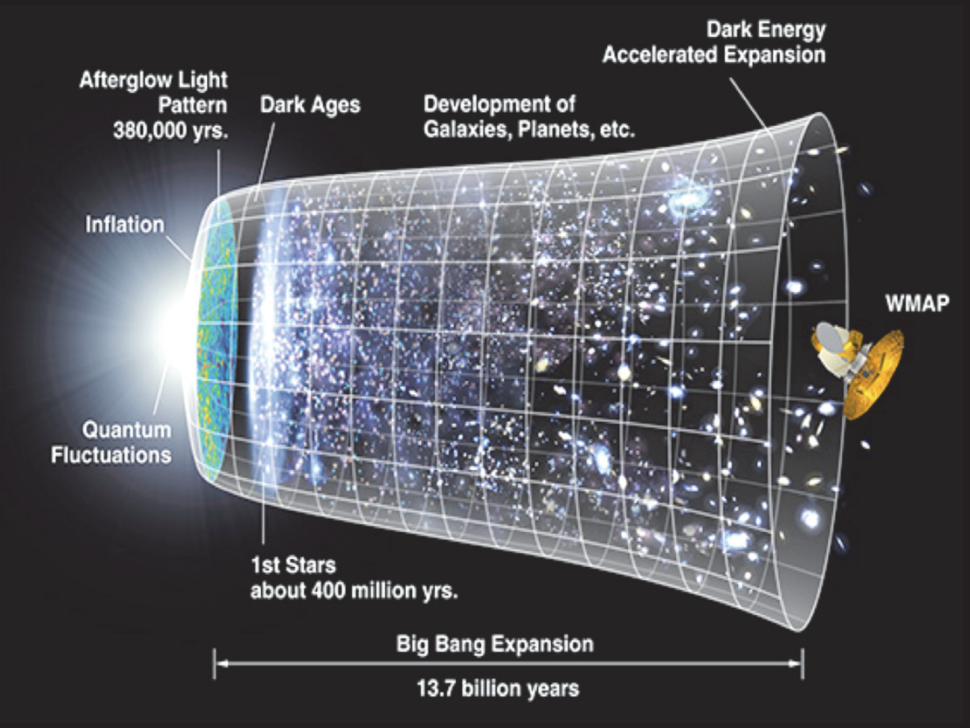
Collaborators: Jean-Paul Kneib (Marseille), Priyamvada Natarajan (Yale), Anson D'Aloiso (Yale), Marceau Limousin (Marseille), Johan Richard (Lyon), Carlo Schimd (Marseille)

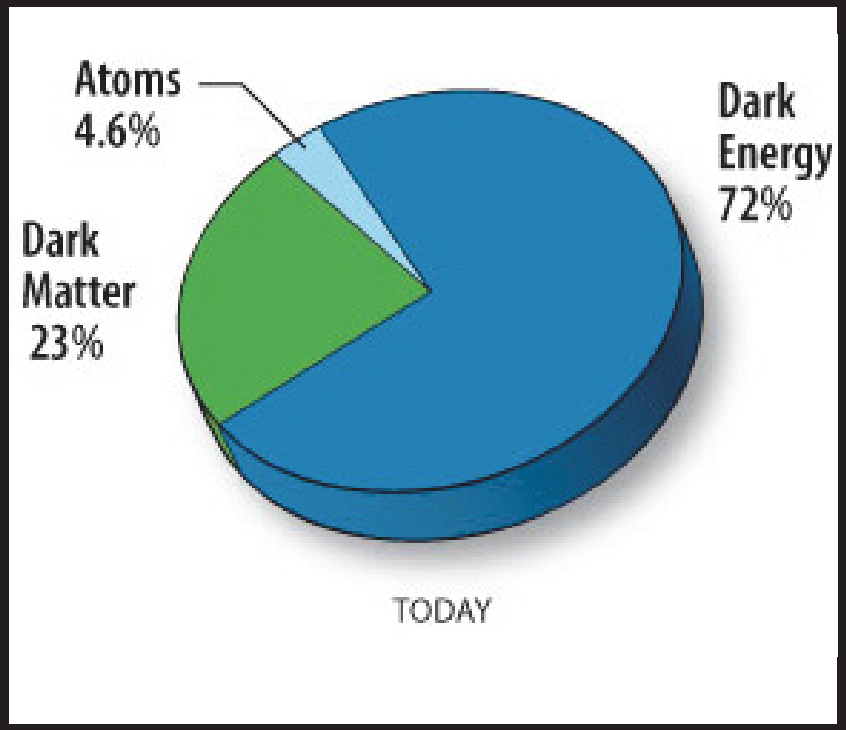
Postdoc Seminar Series --- JPL --- April 21st

OUTLINE

- A few words about Dark Energy
- Looking for galaxy clusters
- How gravitational lensing helps mapping dark matter in galaxy clusters?
- Cosmography with SL in galaxy clusters
- Future prospects

THE BROAD PICTURE

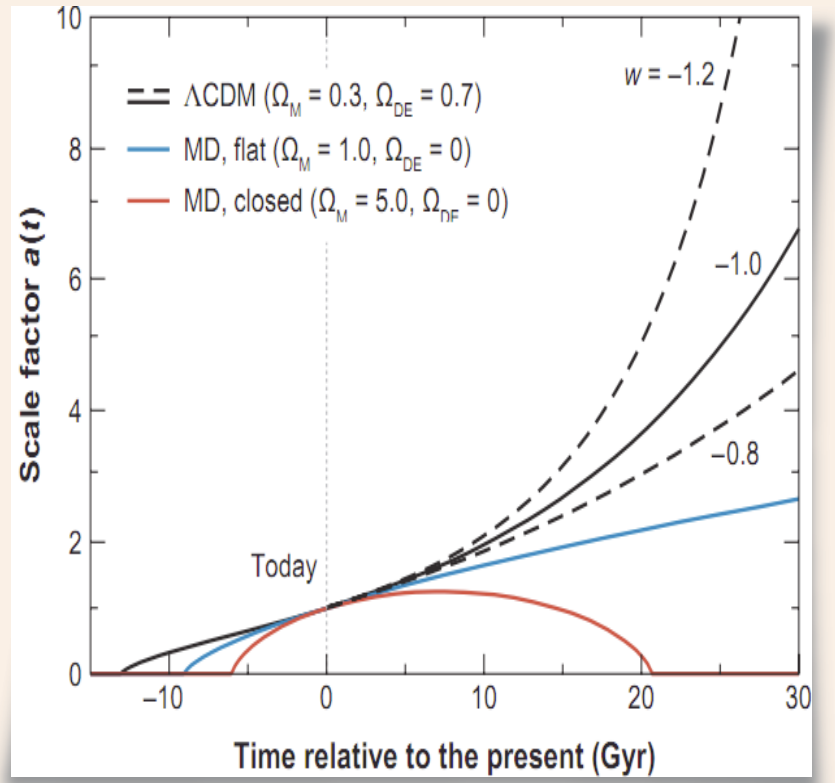


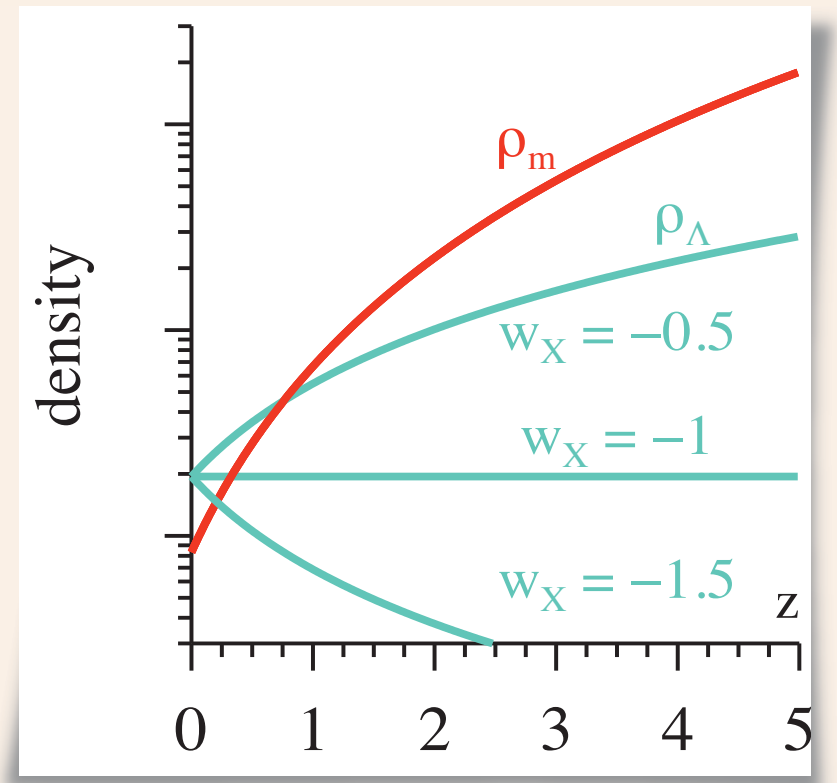


Dark energy

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

BIG CRUNCH, BIG RIP OR BIG FREEZE?





$$\Omega_k + \Omega_m + \Omega_\Lambda = 1$$

$$\Omega_\Lambda(z) = \Omega_\Lambda (1+z)^{3(w_X+1)}$$

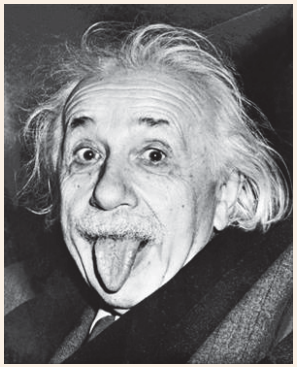
DE Equation of state parameter $w_X = P_X / \varrho_X$

DARK ENERGY MOTIVATIONS

Dark energy ensues from the Equivalence Principe

Gravity = Curvature = Acceleration

Einstein (1916) $$G_{\mu\upsilon} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\upsilon}$$



Dark energy is either:

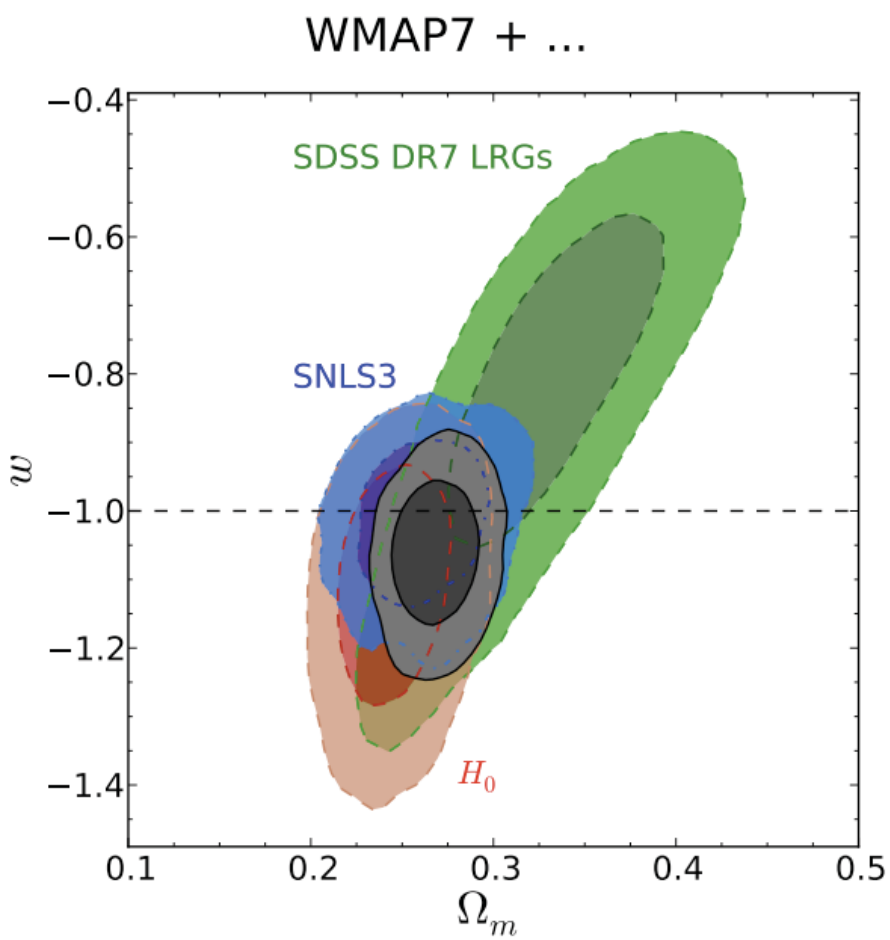
Vacuum energy ➔ 10^{120} discrepancy (fine-tuning!)

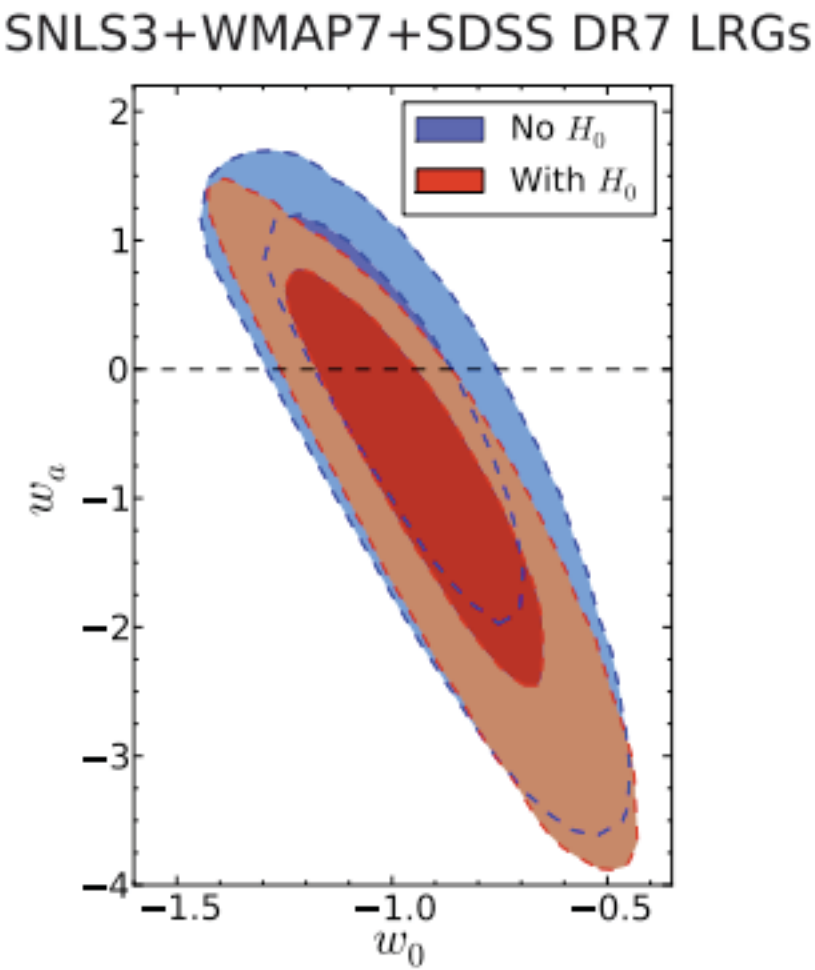
Cosmological constant ➔no underlying physics

Scalar field ➔ w(z), clustering DE? DE-matter inter.

New gravitational physics➔beyond GR

TODAY'S RESULTS ON DE



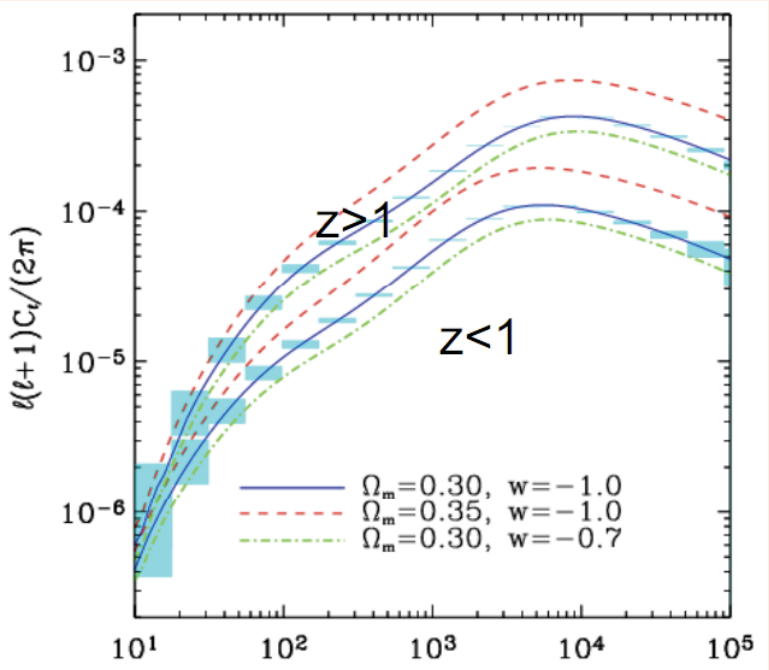


Sullivan+ 2011

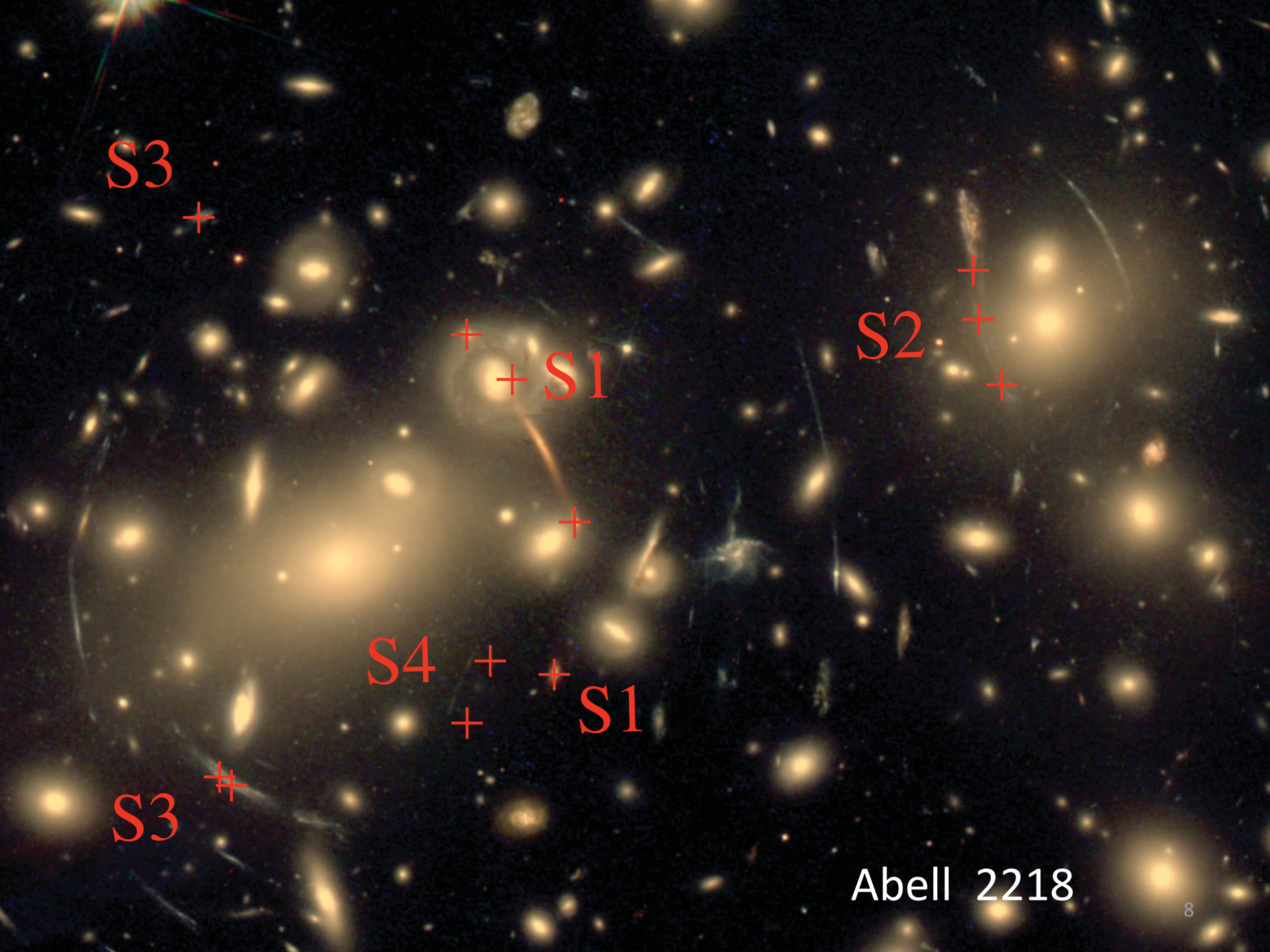
THE BEST DE PROBE: WEAK LENSING

- Map the 3D distribution of Dark Matter in the Universe
- Measures the mass without assumptions in relation between mass and light
- Most sensitive probe to Dark Energy, provided systematic errors are corrected

➢ Need measurements of galaxy shape and photometric redshifts

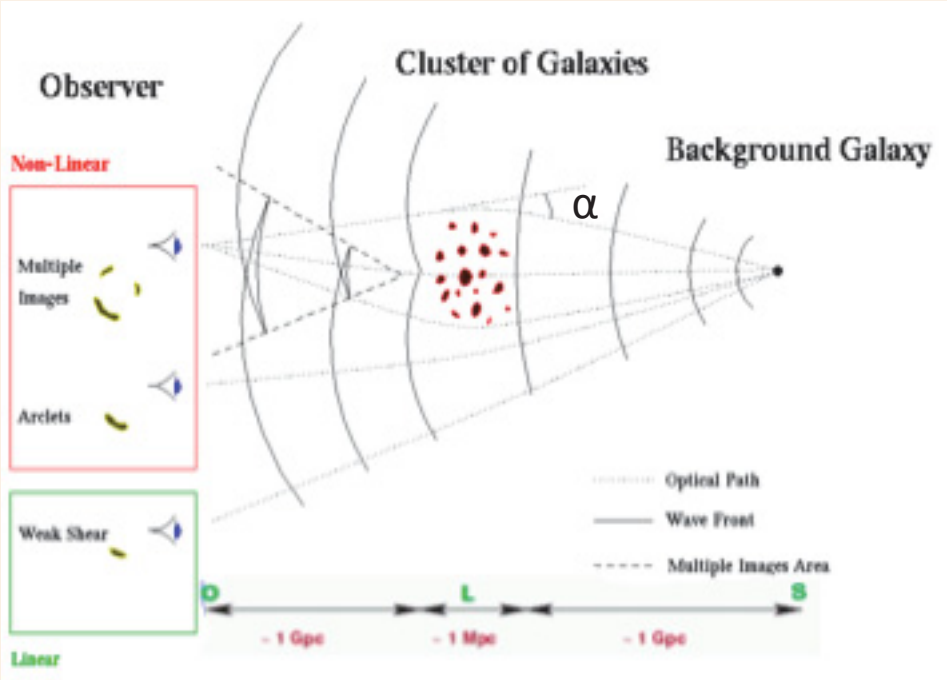


Dark matter power spectrum in 2 redshift bins



Abell 2218

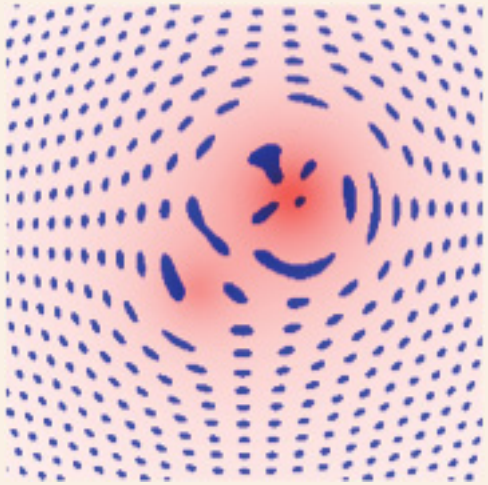
GRAVITATIONAL LENSING



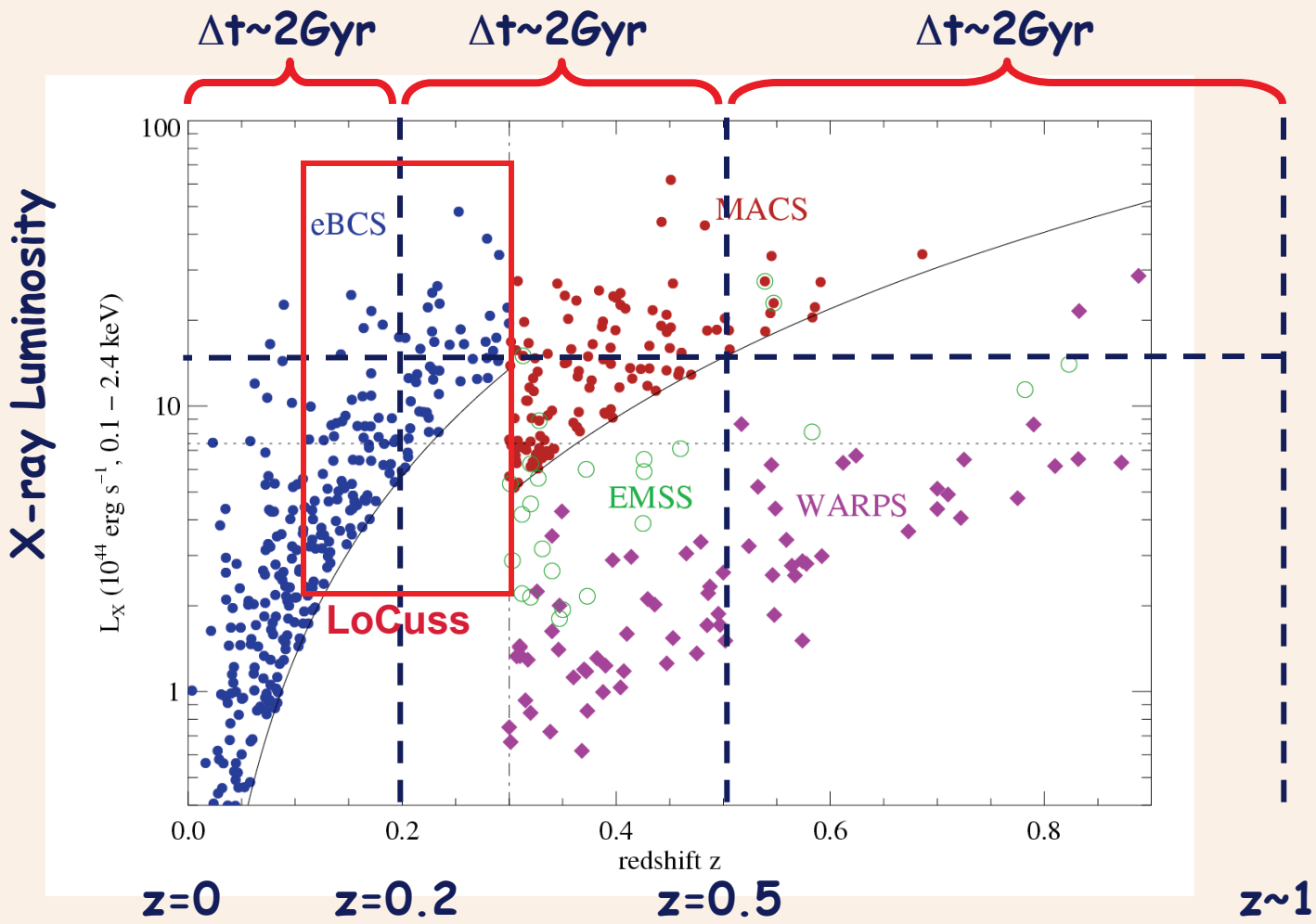
$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi(\theta_I)$$

Cosmology

mass



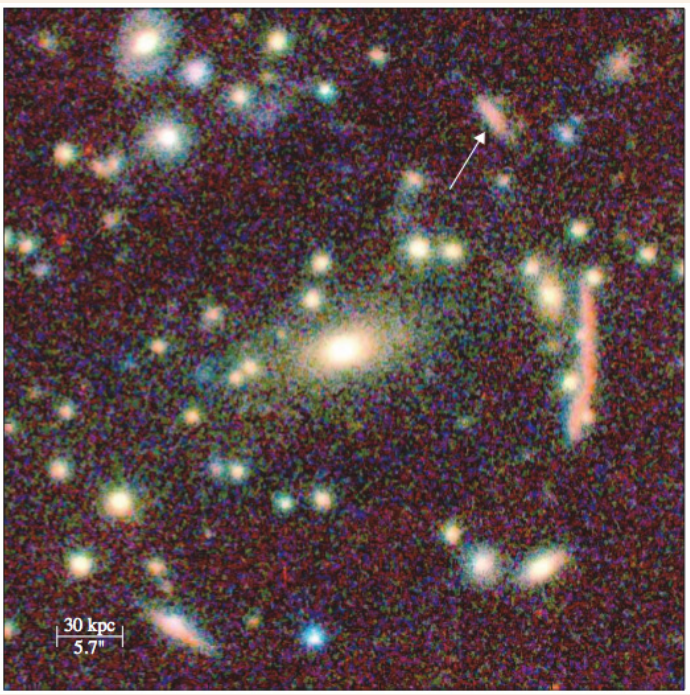
MASSIVE X-RAY SELECTED CLUSTER



HST MACS SURVEY

- ~130 MACS clusters (z>0.3), HST, Subaru, Chandra, ground-based spectroscopy follow-up
  - Find many strong lensing clusters (>50% show SL)
  - Constrain cluster masses individually and in a statistical way with ultimately possible cosmological implications

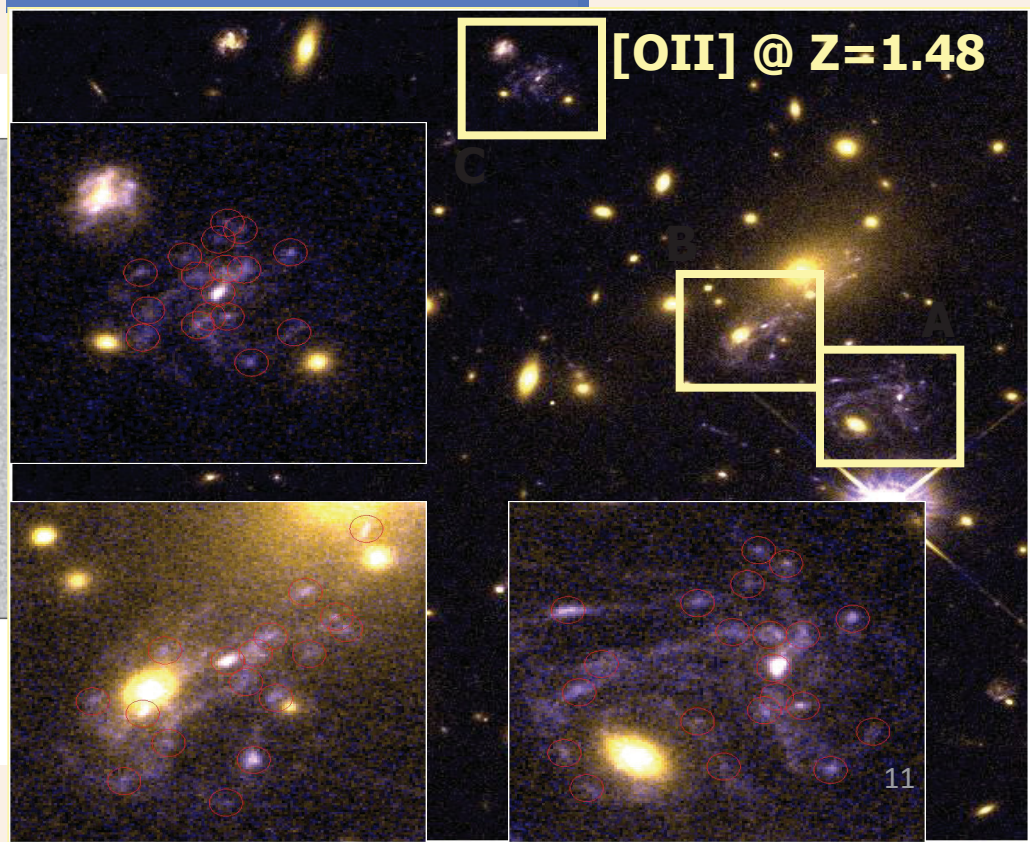
MACSJ1206.2-0847



Ebeling et al 2009

MACSJ1149.5+2233

Smith et al 2009



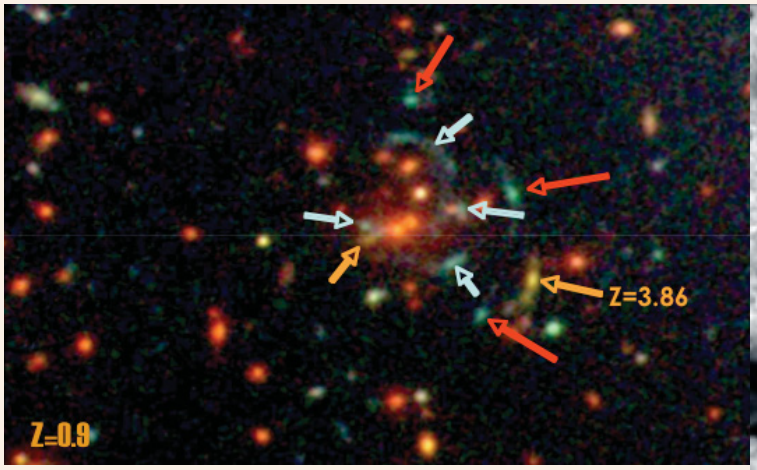
OPTICALLY SELECTED STRONG LENSING CLUSTERS

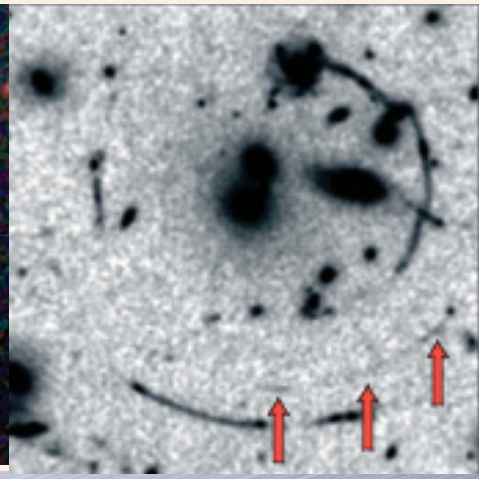
RCS-1 (Rz survey ~90 deg^2), 5 arcs (Gladders et al 2003) found by visual inspection

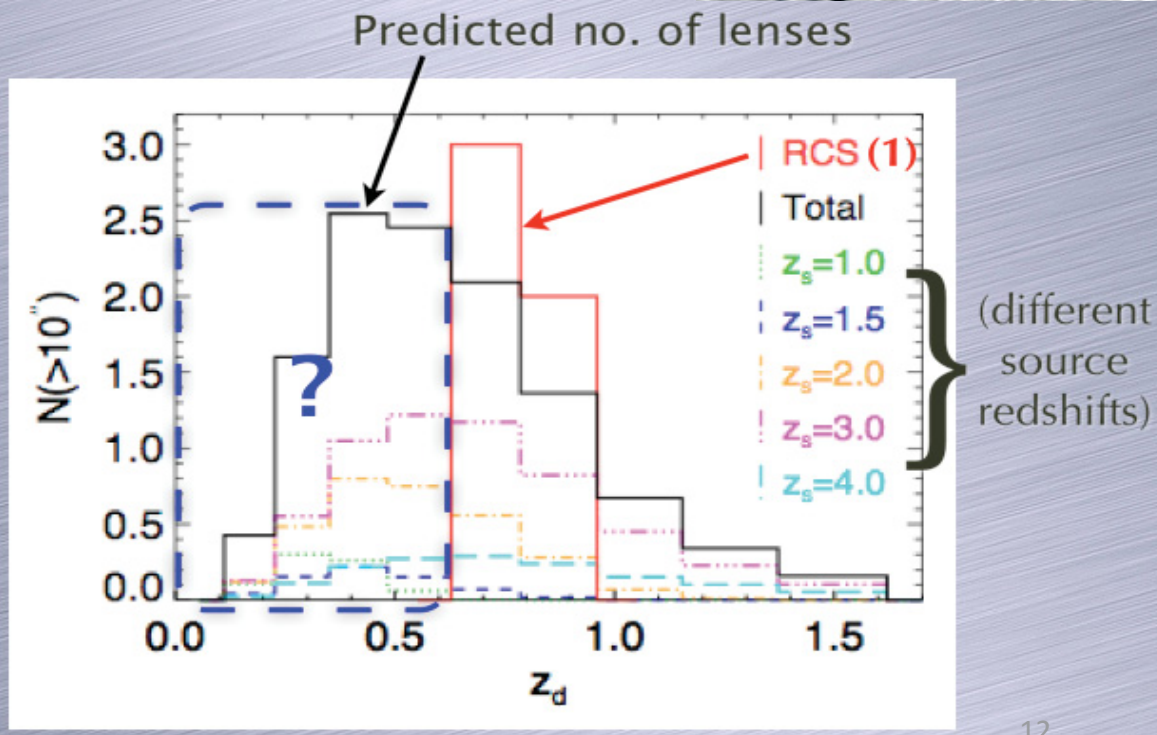
CFHT-LS wide (150 deg^2 provides a few arcs in clusters): Cabanac et al 2007

RCS-2 ~830 deg^2 provide better stat a few tens

SDSS Altogether more than 200 clusters identified with bright arcs (Gladders et al 2009, Oguri et al 2009)







Hennawi et al. 2007

THE SDSS GIANT-ARC SURVEY

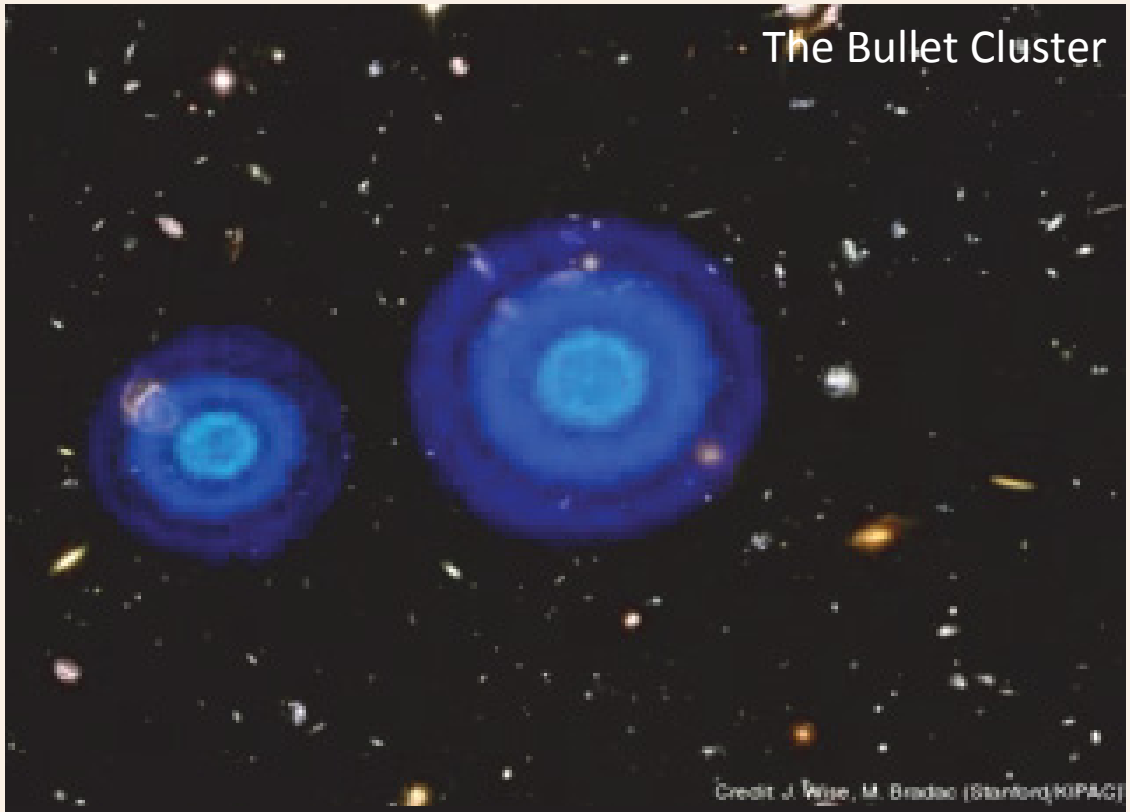
Hennawi+ 07, 08; Oguri+ 09; Gladders+ 10

MASS DISTRIBUTION MEASUREMENT

- How do we measure mass ?
- Central mass profile ? => learn about DM and baryon interactions
- Large scale mass profile and substructures ? => structure formation paradigm, halo models
- Case of mergers => probe nature of DM
- Comparison of the distribution of the different components => scaling relations, cluster thermodynamics

GALAXY CLUSTERS

What is a cluster made of	Observable
• 80% dark matter	SL/WL
• 15% hot gas (~10^7 K)	Xray/SZ
• 5% stars	Kinematic



Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al; Movie: KIPAC/J. White/M. Bradac

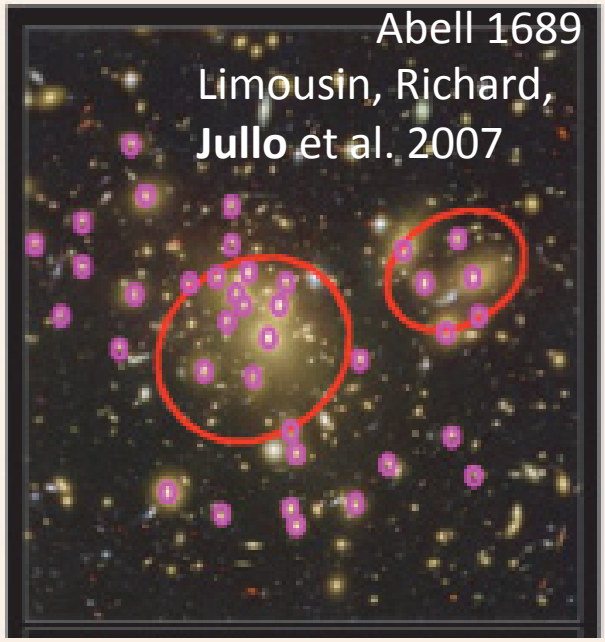
STRONG LENSES MODELS

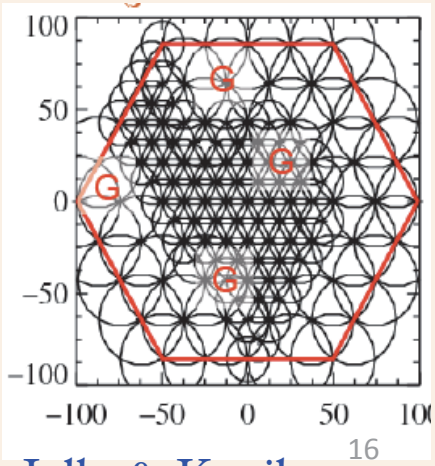
Problem

How to reproduce the observed multiple images?

I develop a public lensing code called LENSTOOL[1]

Observational models	Grid-based models
Decomposition into halos + $M \propto L^{\alpha}$ for the galaxies	Decomposition into pixels + $M \propto L^{\alpha}$ for the galaxies
Simple clusters	Complex clusters
Few contraints	Lots of constraints
Good fit with few constraints	Better fit with lots of constraints
Fast	Slow

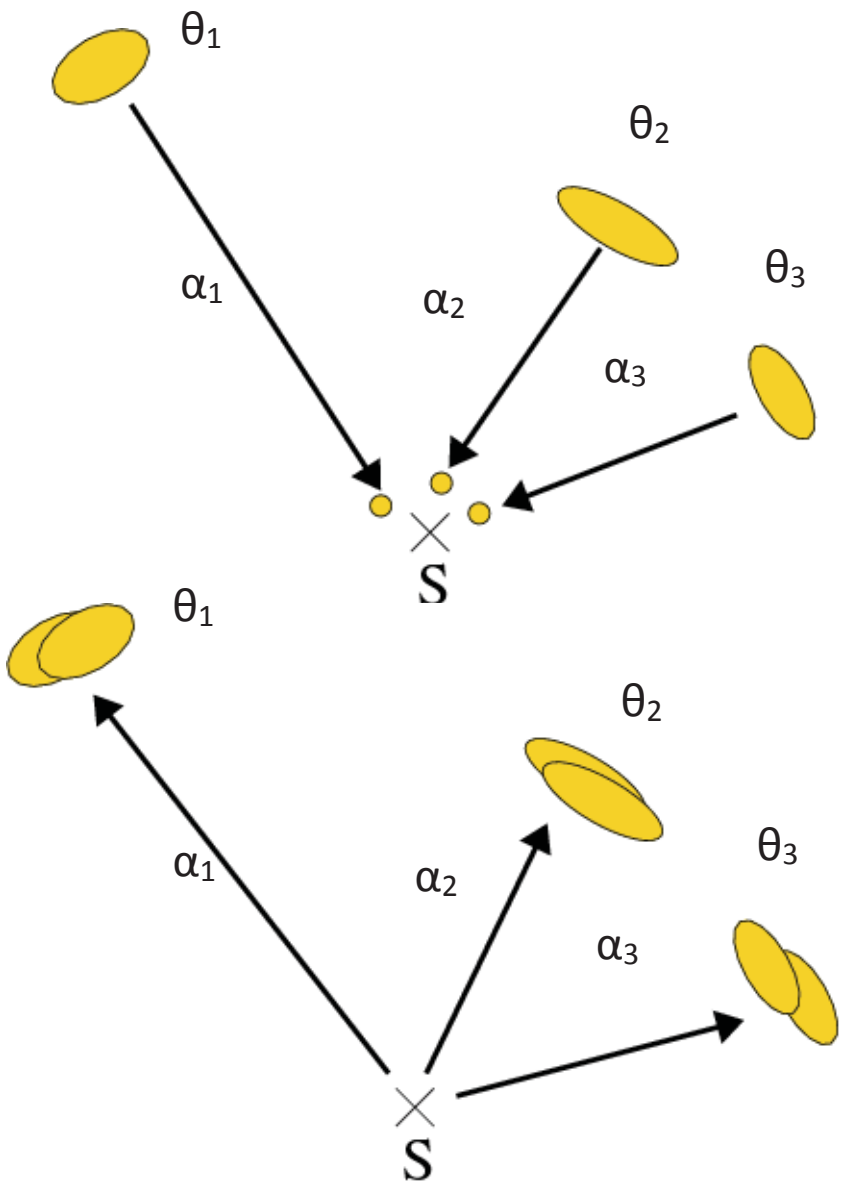




Jullo & Kneib 2009

[1] http://www.oamp.fr/cosmology/lenstool

STRONG LENSING FIT



- Multiple images of a single source
- Multiple images identification with
  - Same color
  - Same redshift
  - Same features (bright knots)
  - Be symetric to each others
- The model is validated when predicted and observed images fall at the same location

BAYESIAN INFERENCE

Phil Marshall's PhD, 2003

χ^2 definition for a system of images

$$\chi_i = \sum \frac{\theta_{obs} - \theta_{pred}}{\sigma_{ij}}$$

Assuming Gaussian errors

$$P(d \mid s, M) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-\chi^2}{2}\right)$$

Prior knowledge

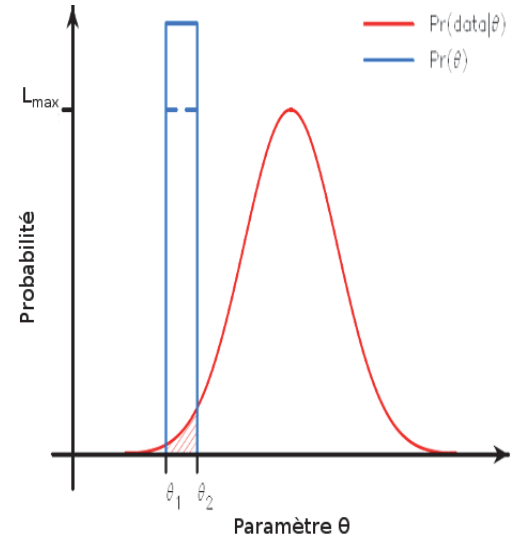
- Light map
- Xray map
- Velocity field of galaxies

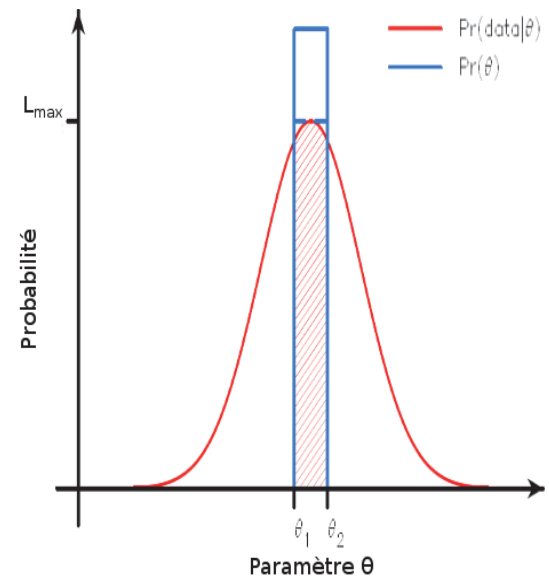
Bayes theorem

$$P(s \mid d, M) = \frac{P(d \mid s, M) P(s \mid M)}{P(d \mid M)}$$

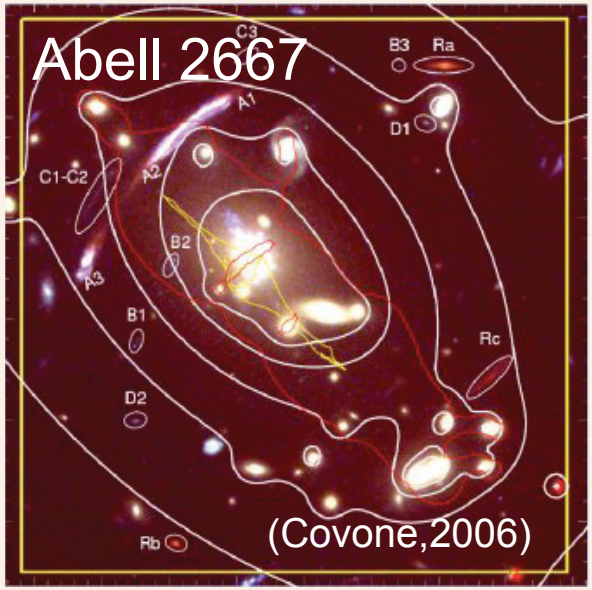
Optimisation Algorithms: Annealing, Mixing distribution

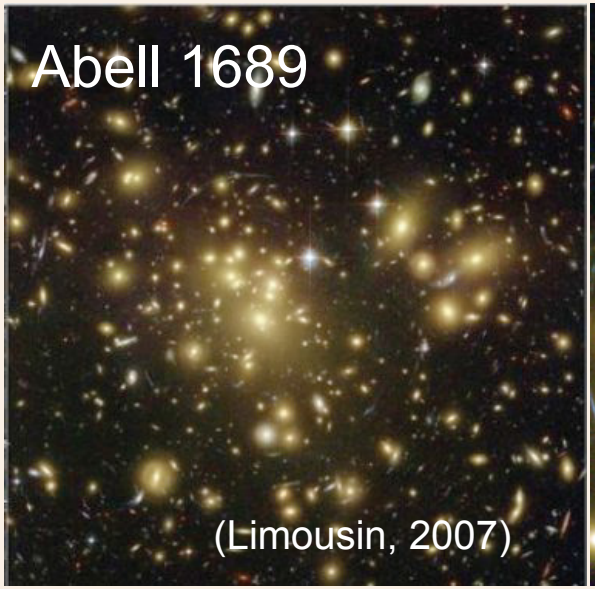
Bayesian Evidence to rank models

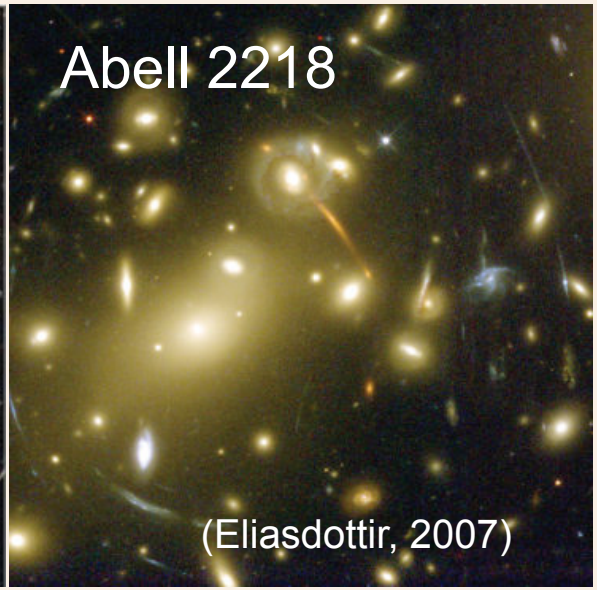


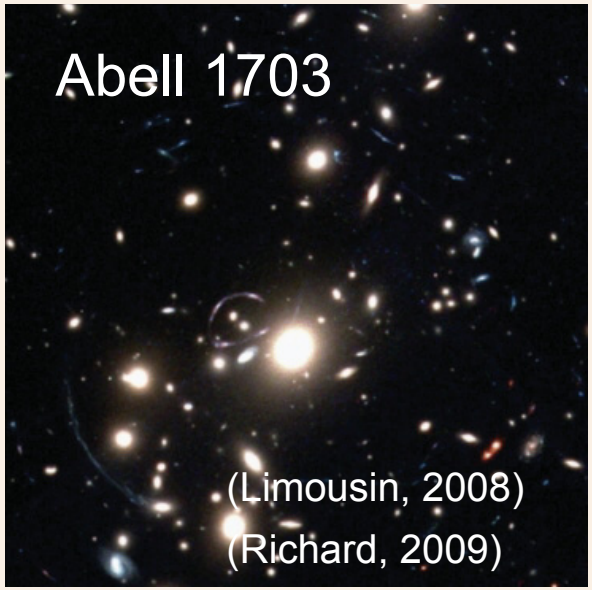


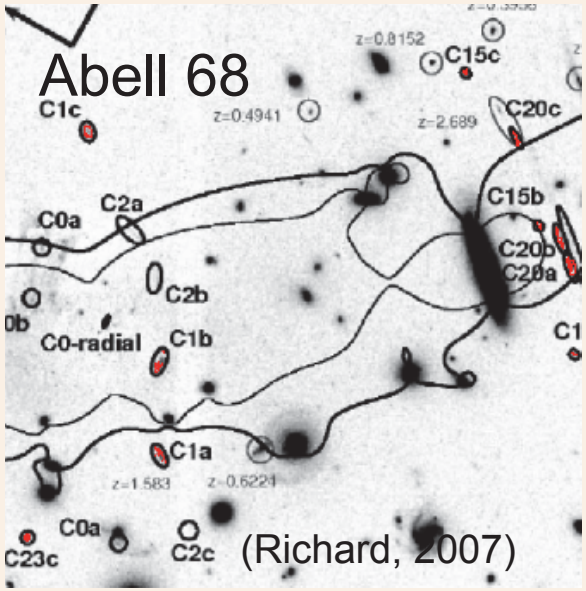
SOME CLUSTERS MODELED WITH LENSTOOL

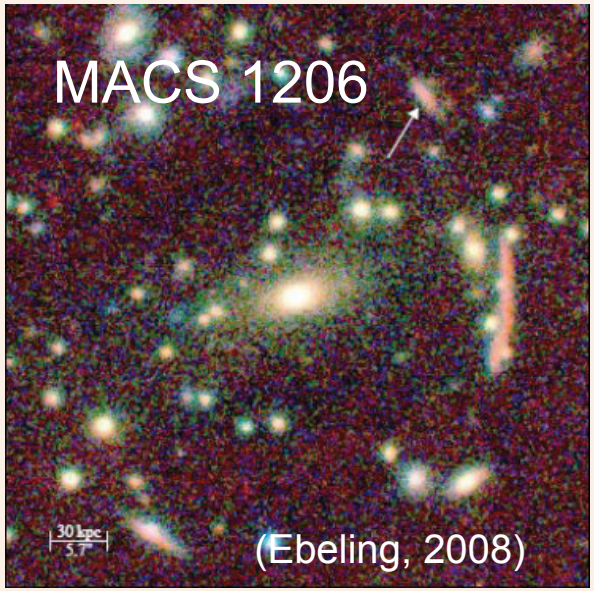




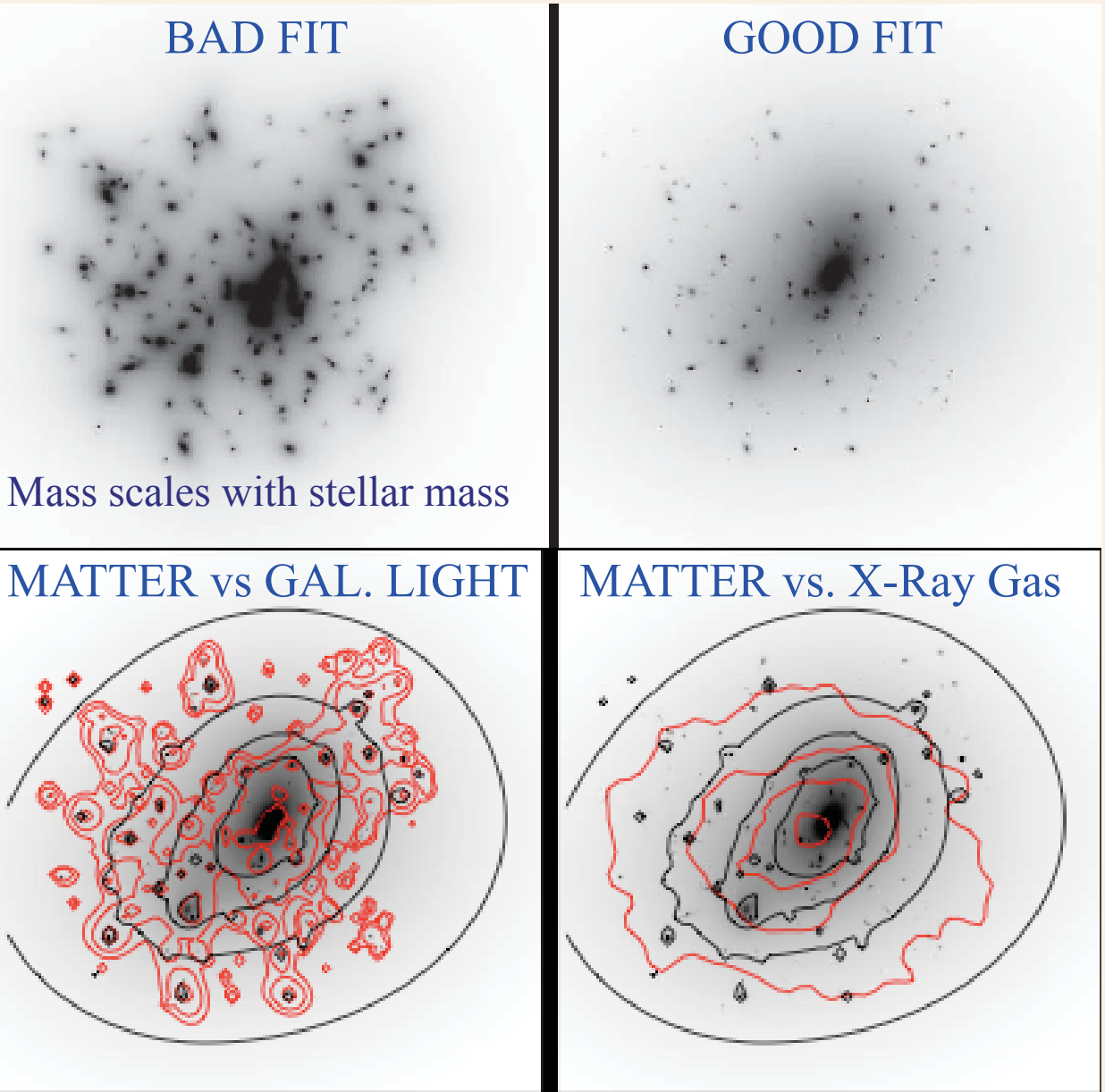








WHERE IS THE MATTER IN A2218?



Strong Lensing constraints in Abell 2218:

- Mass distribution proportional to the stellar mass produce a BAD FIT to the lensing data
- Require large scale mass distribution (cluster DM)
- Important difference between DM , Galaxy distribution and X-ray gas (different physics)
- But, scaling relation should exists

Eliasdottir et al. 2009

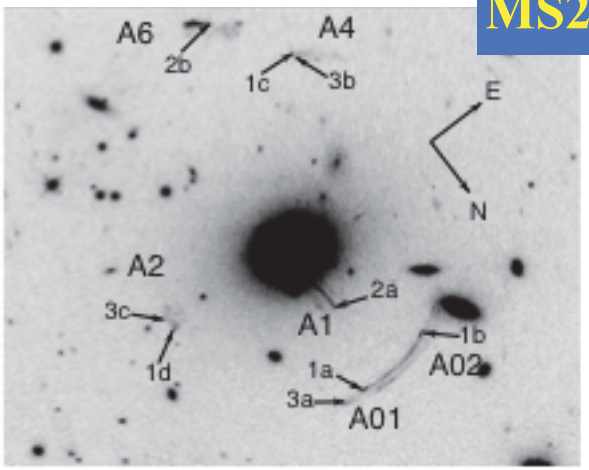
MASS PROFILE OF CLUSTERS (SL+DYNAMICS)

- DM simulation predicts a universal profile; what is observed in the inner core?

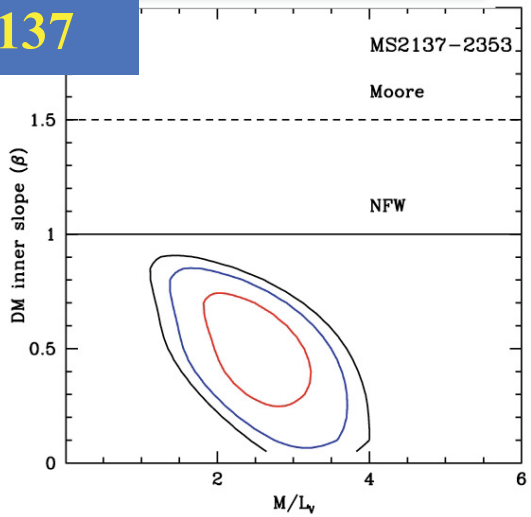
- Combination of strong lensing (radial and tangential arcs) + dynamical estimates from the cD galaxies

- Some degeneracies, but indication of a flatter profile than canonical NFW: -0.5<beta<-1
- "Flat" core found in other clusters (RCS0224, Cl0024)

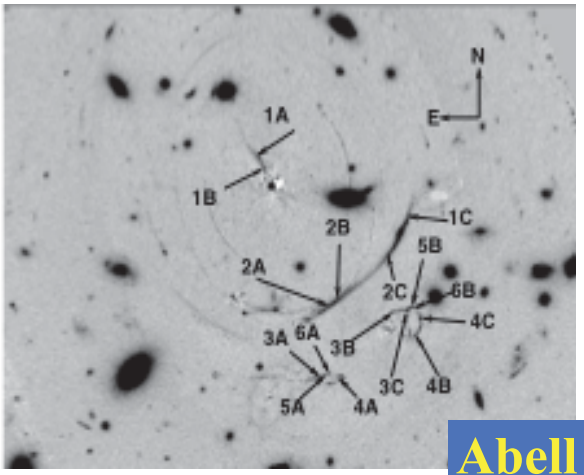
- Possibly probe DM & Baryon coupling?

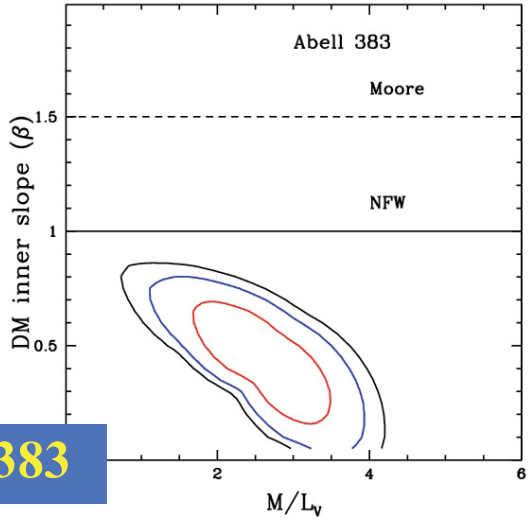


MS2137



New detailed modeling



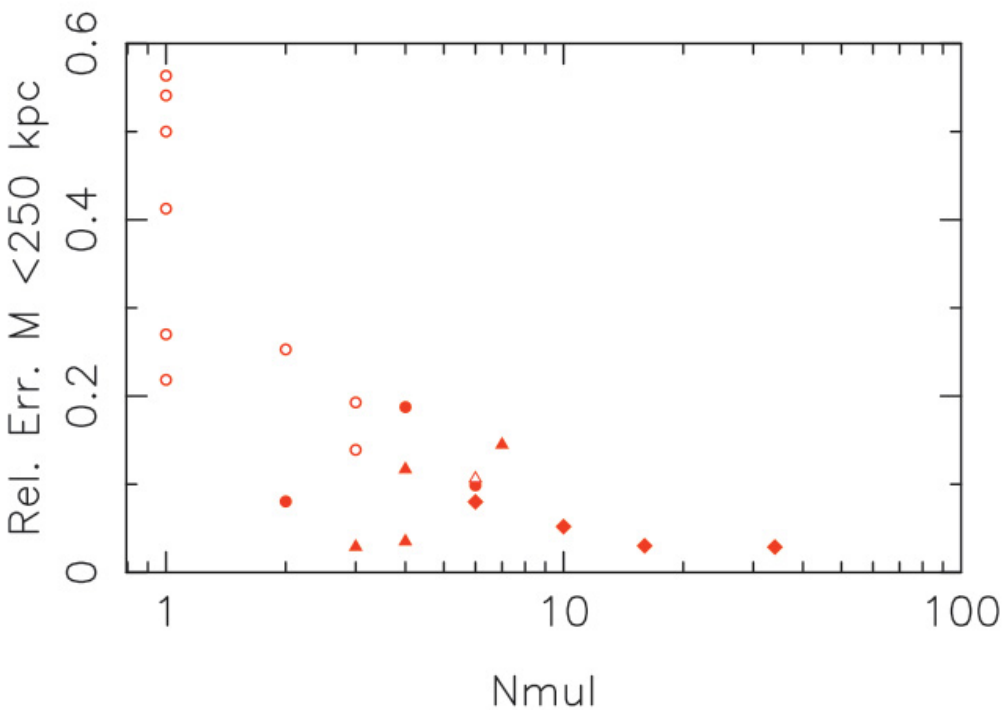


Abell 383

Sand, et al. 2007

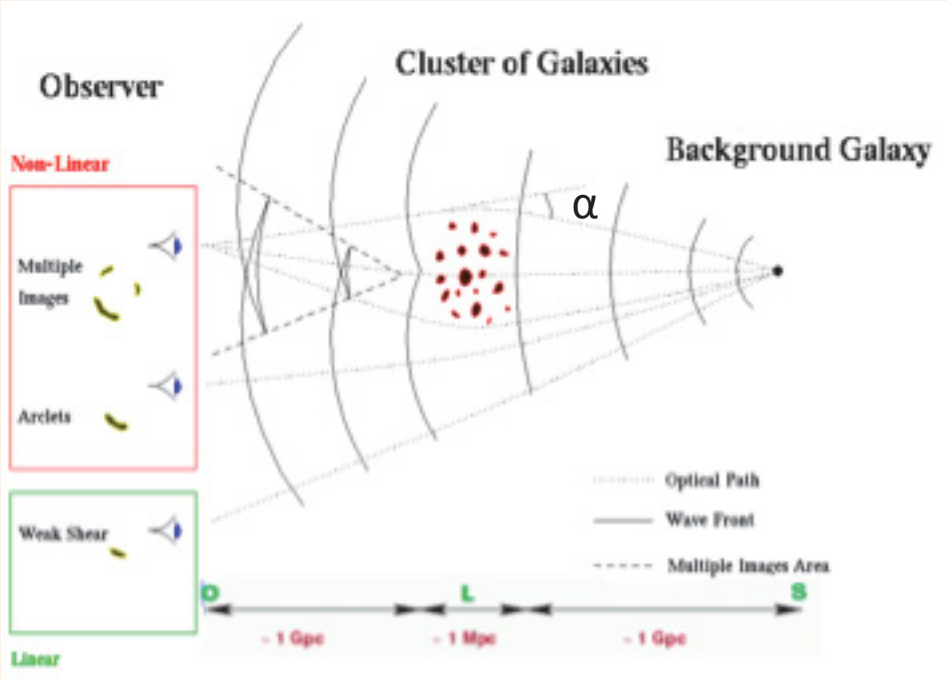
CLUSTER LENS MODEL ACCURACY ?

- **Mass model accuracy depends on the number of multiple images.**
- Mass accuracy limitations:
  - multiple images identification
  - redshift of multiple images
  - priors on the mass models (hence on the software used)
  - galaxy halos scaling relations
  - line of sight structures (can be modeled)



Cosmography

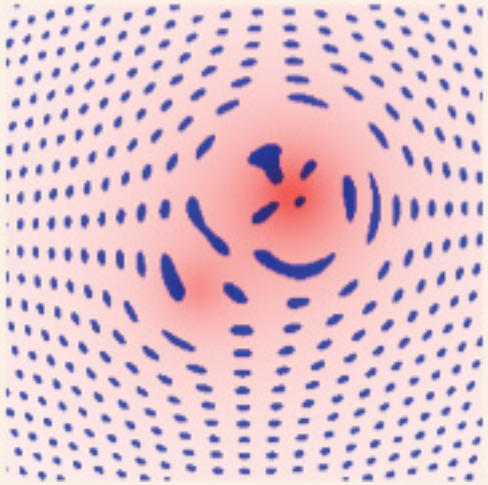
GRAVITATIONAL LENSING



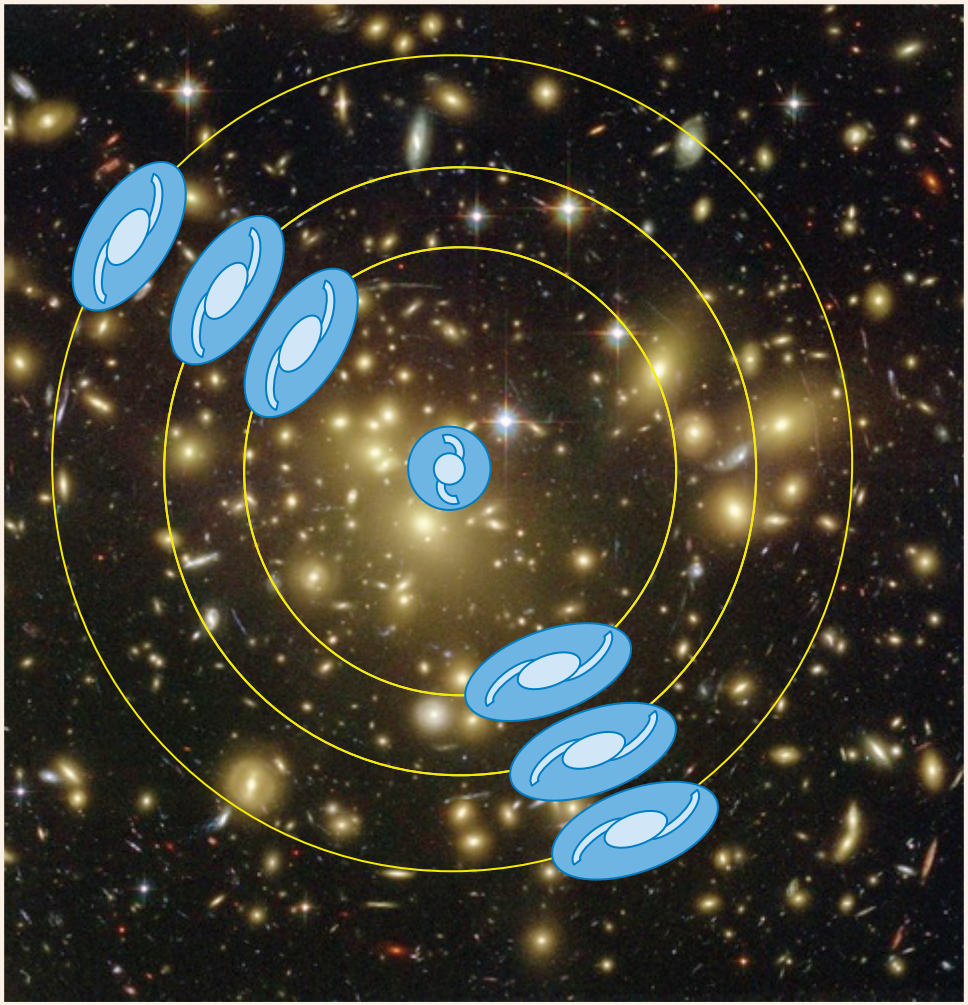
$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi(\theta_I)$$

Cosmology

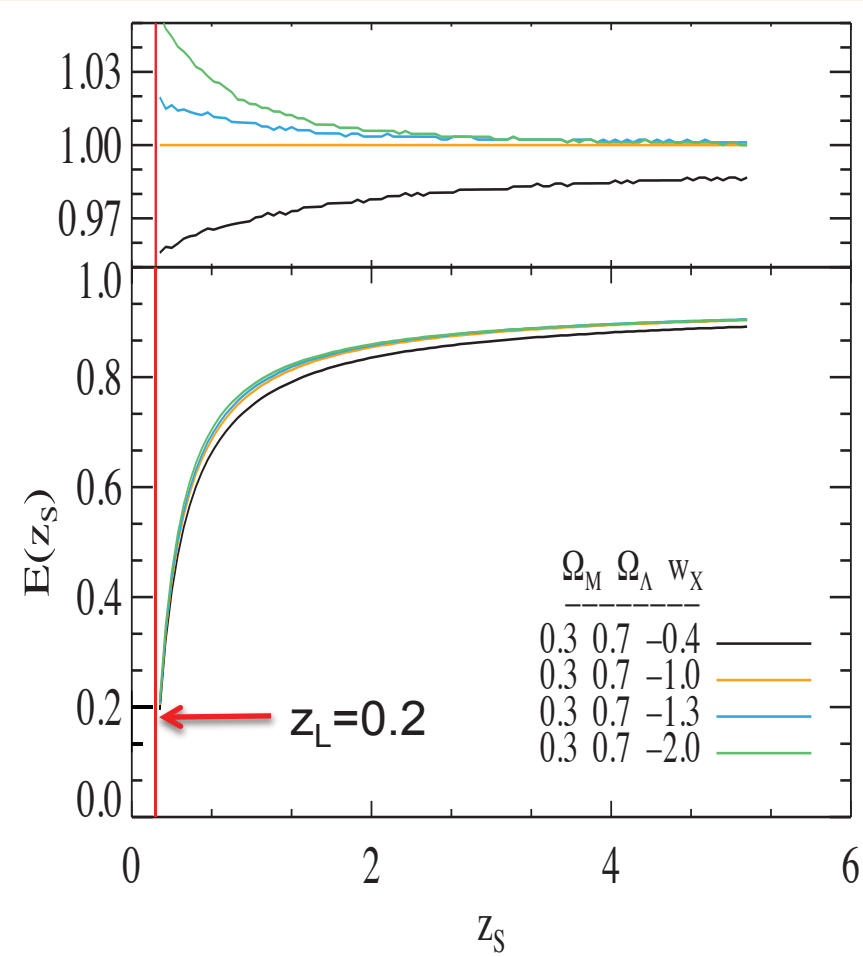
mass

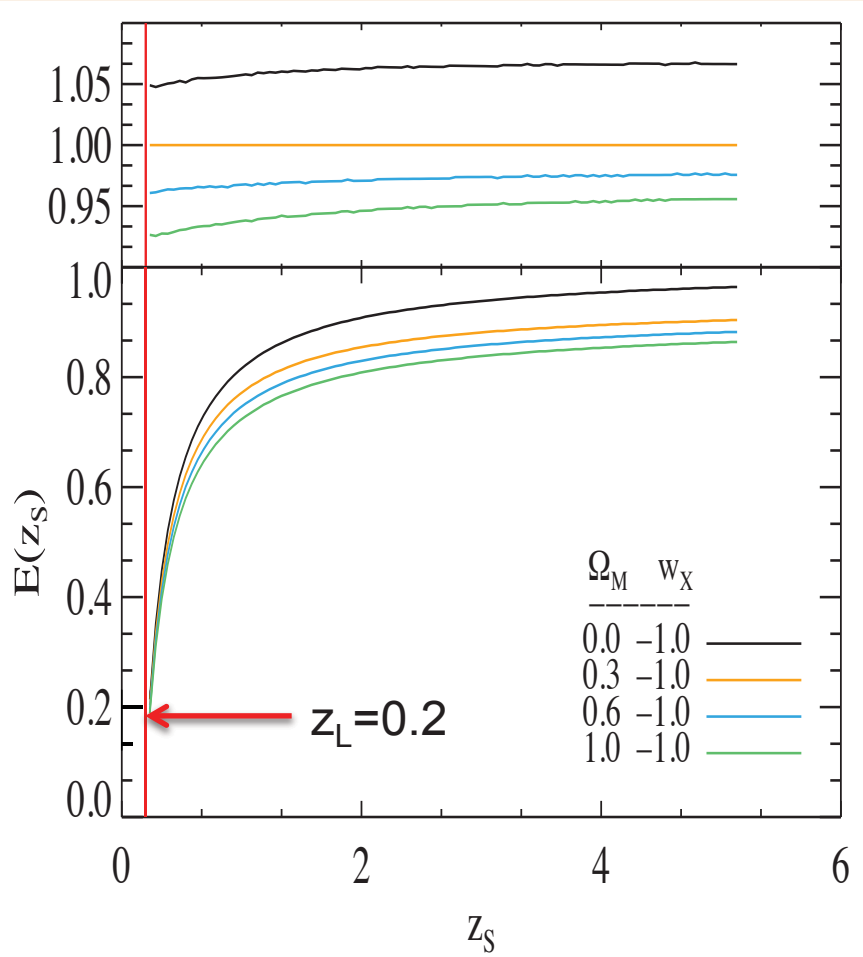


SCALING WITH COSMOLOGY OR MASS?



Efficiency ratio $E=D_{LS}/D_{OS}$





w_X effect

Ω_m effect

IT CAN BE SOLVED WITH SEVERAL REDSHIFTS

ISOTHERMAL SPHERE LENS lens at $z = z_L$; sources at z_{S1} & z_{S2}

$$R_{E_1} = \frac{4\pi\sigma^2}{c^2}\frac{D_{LS_1}}{D_{OS_1}} \qquad R_{E_2} = \frac{4\pi\sigma^2}{c^2}\frac{D_{LS_2}}{D_{OS_2}}$$

$$D_{ij} \equiv H_0 f(z_i, z_j, \Omega_M, \Omega_x, w_x)$$

$$\frac{R_{E_1}}{R_{E_2}} = [\frac{D_{LS_1}}{D_{OS_1}}][\frac{D_{OS_2}}{D_{LS_2}}]$$

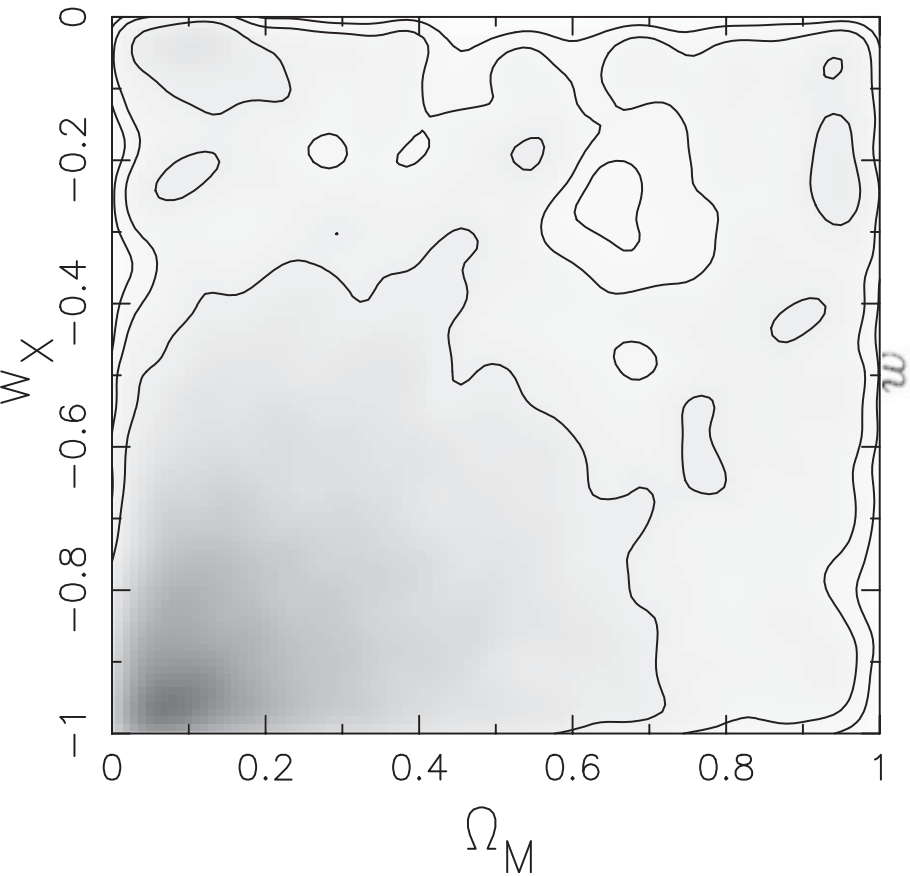
Obtained from data

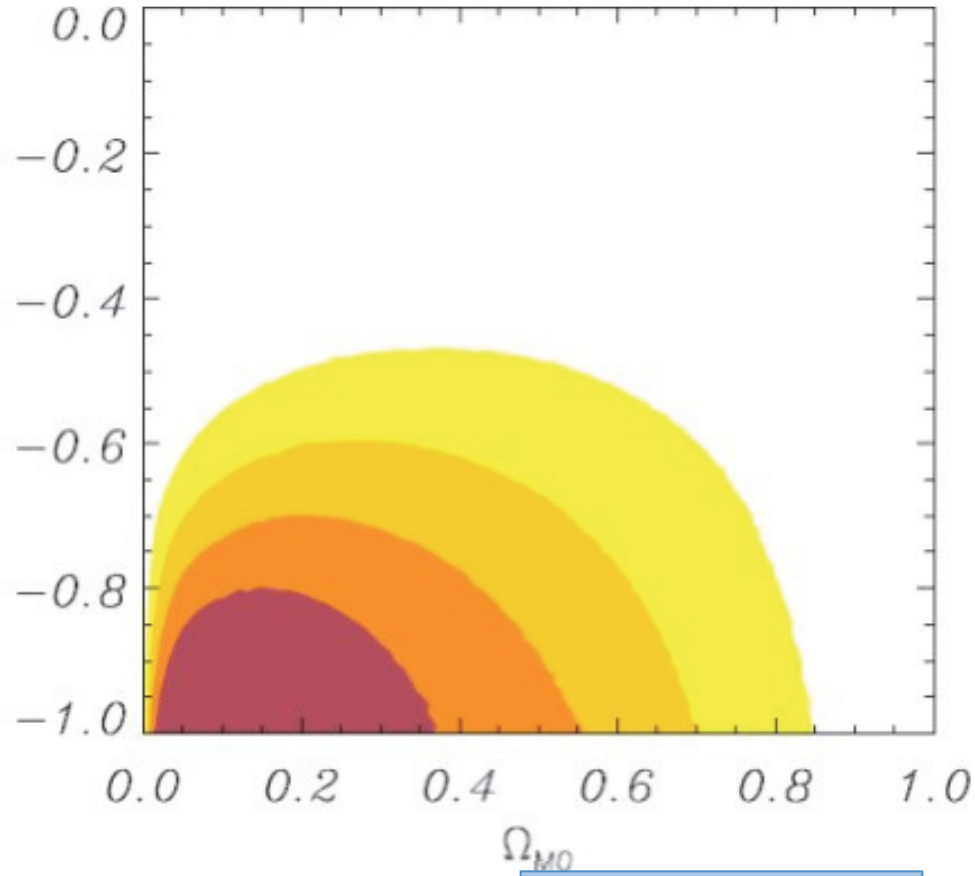
Solve for cosmological parameters

Requirements :

- spec-z & simple cluster & multiple images of several galaxies

A2218 RESULTS





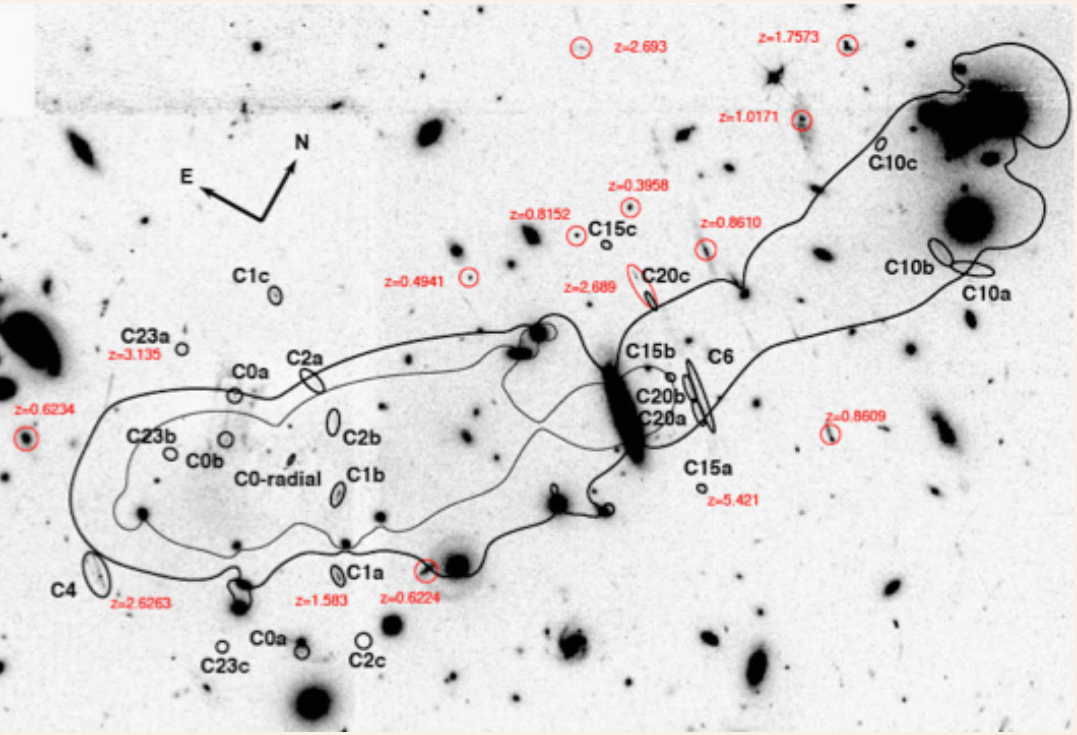
Soucail et al. 2004

$$\Omega_m < 0.7 \ , w_X < 0.4 \ @ \ 1\sigma$$

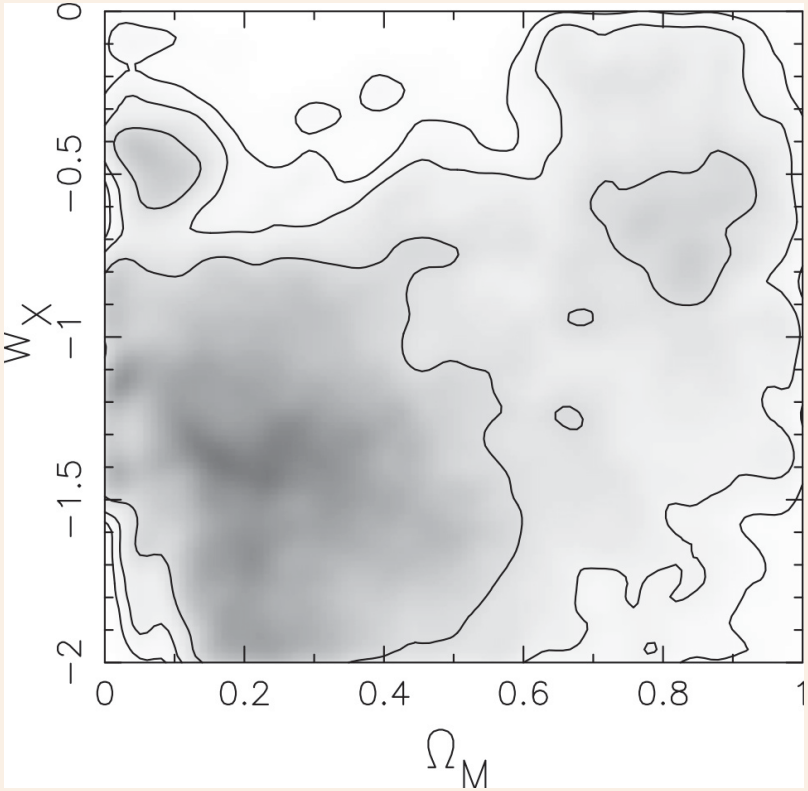
COSMOGRAPHY WITH ABELL 68

Mass model with 7 multiple image systems (5 with known redshifts).

Optimizing cosmography (Ω_M , w_X) for a flat Universe



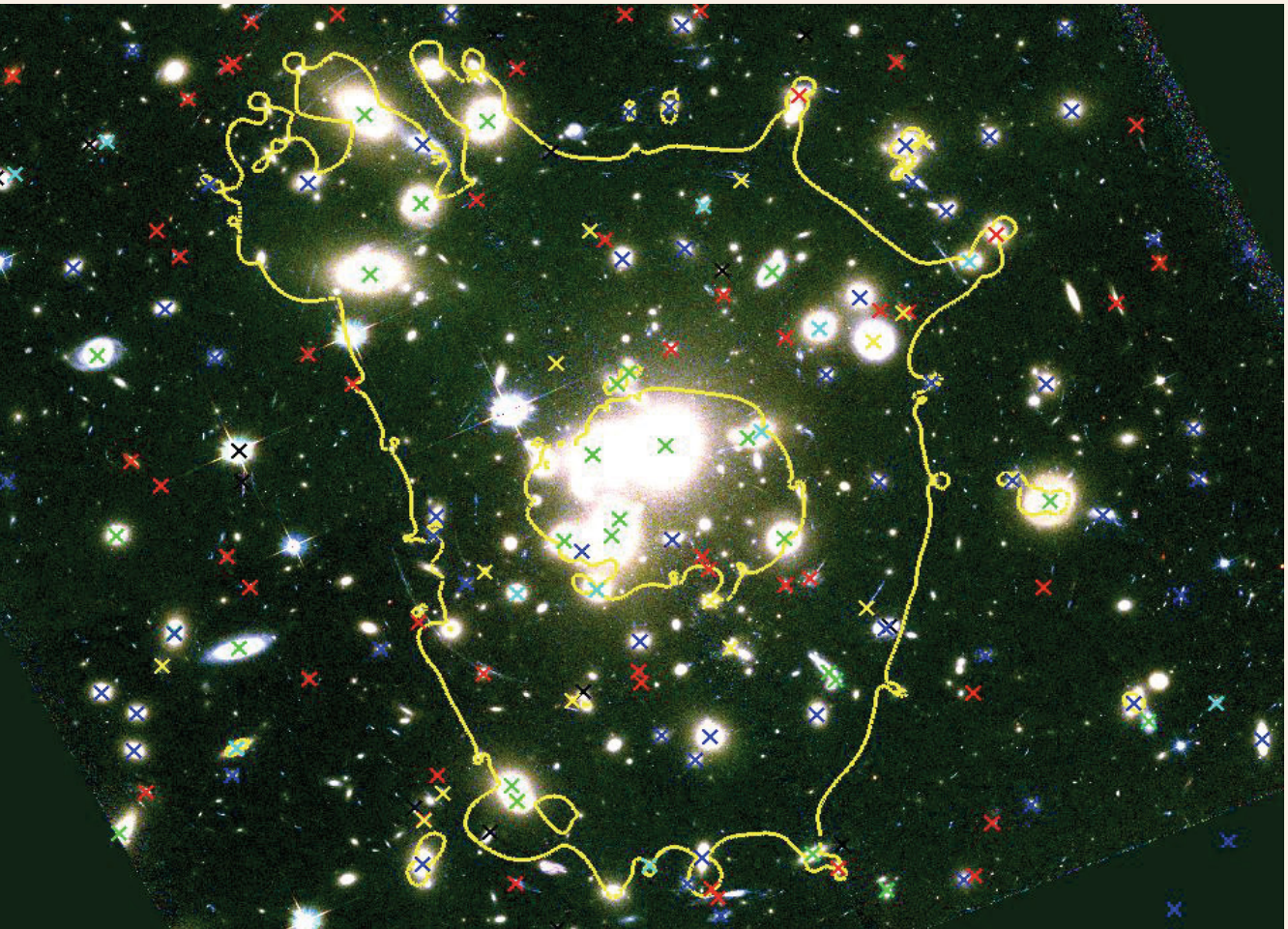
Richard et al 2007



EJ PhD 2008

COSMOGRAPHY WITH ABELL 1689

- **Mass models from different groups w. or w/o weak lensing**
- **Massive spectroscopic surveys (2003-2006) [Richard et al 2011]**
- **43 multiple image systems, 24 with spectro-z with $1.1 < z < 4.9$**

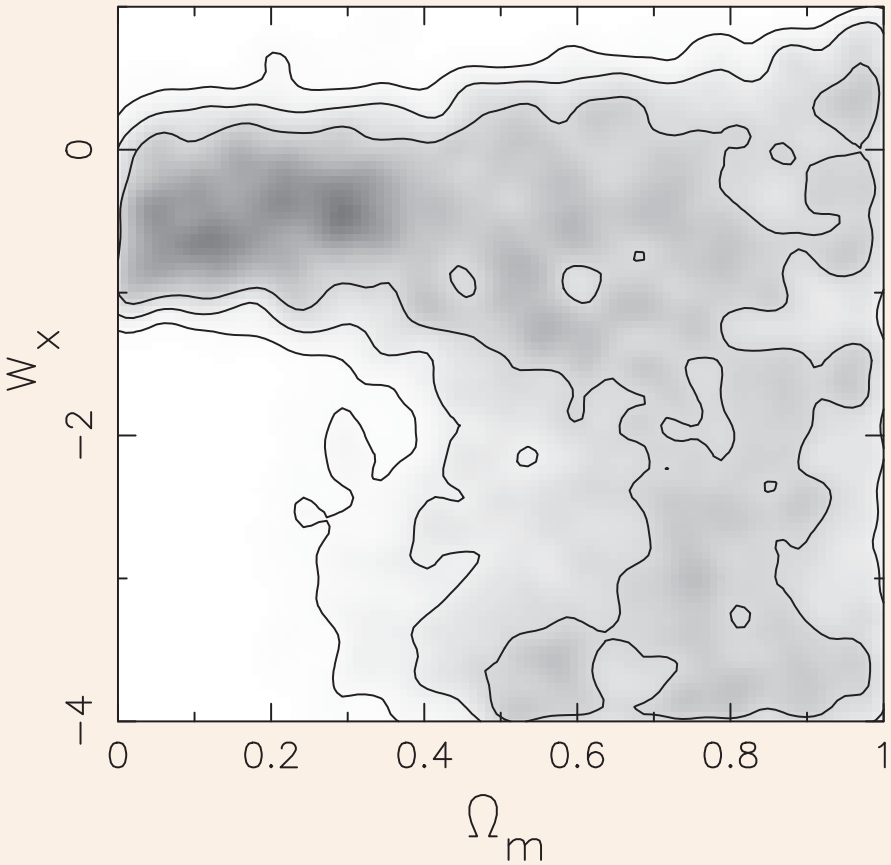


Broadhurst et al 2005
Halkola et al 2007
Limousin, et al. 2007
Richard et al. 2007
Frye et al 2007
Leonard et al 2007
Jullo & Kneib 2009
Coe et al 2010

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

RESULTS WITH ALL IDENTIFIED MULTIPLE IMAGES IN A1689

- All Images
  - potential misidentification
  - badly modeled images: locally complex mass distribution



ERRORS DUE TO GALAXIES MODELING

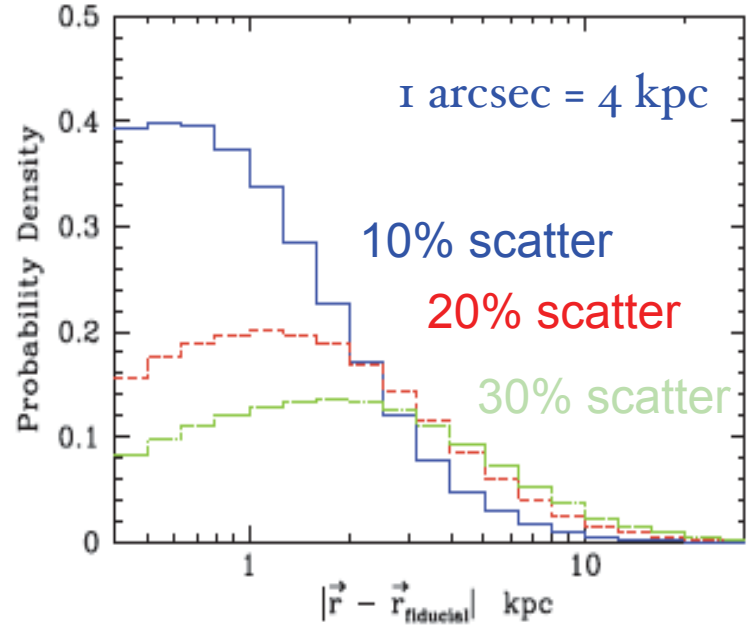
PIEMD parameters
20% scatter

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

The total mass of a subhalo scales then as:

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

Jullo+07



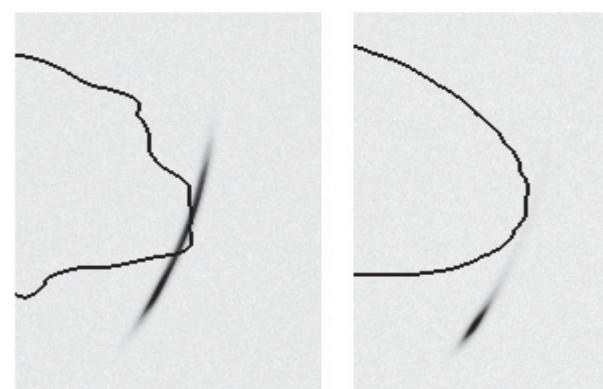
Simulations: D' Aloisio & Natarajan 10

For A1689

- Scatter in the scaling relations ~ 1"

– > Scatter for each image

– > Images are weighted in χ^2 INDIVIDUALLY



Meneghetti+07

ERRORS DUE TO DEFLECTIONS BY LOS STRUCTURES

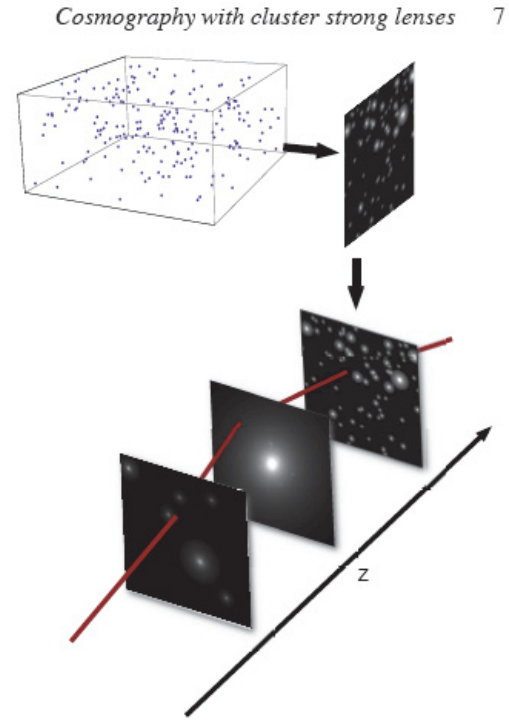
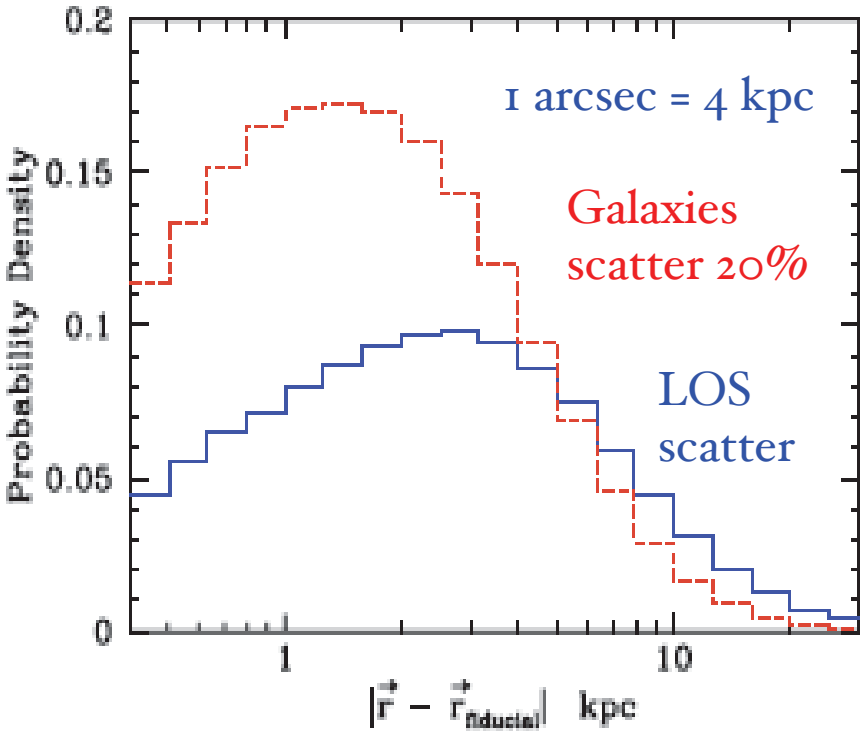


Figure 5. Schematic diagram illustrating the creation of lensplanes to quantify the effects of LOS halos. A rectangular slice of the Millenium Simula-



Simulations: D' Aloisio & Natarajan 10

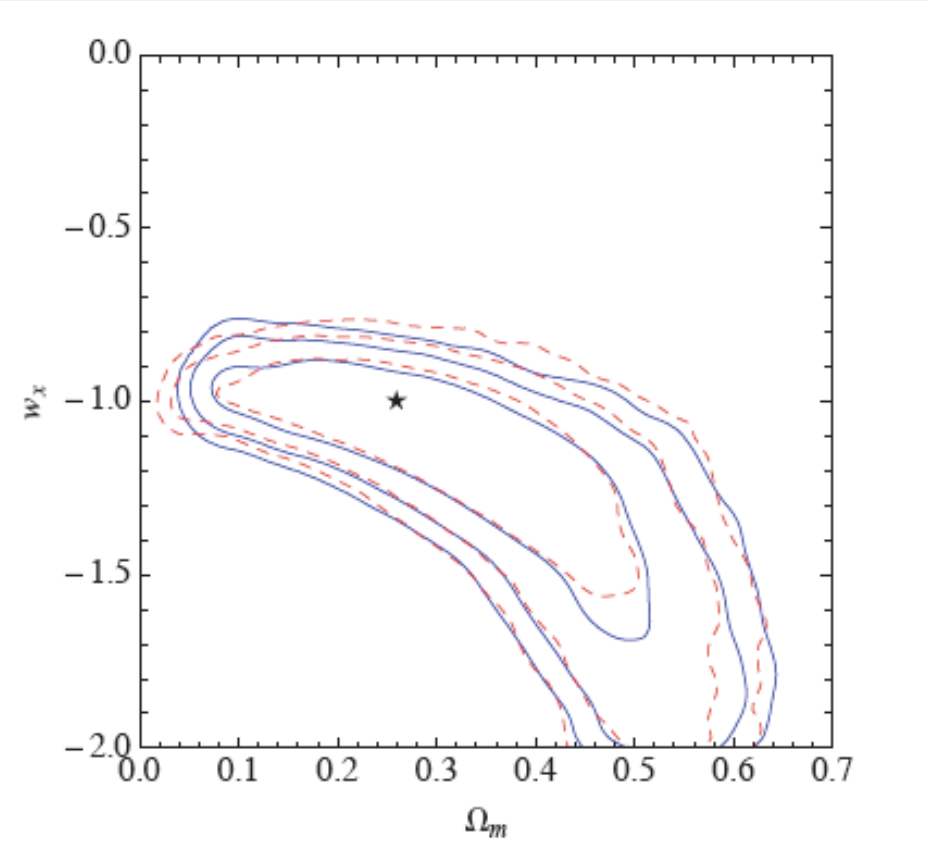
For A1689

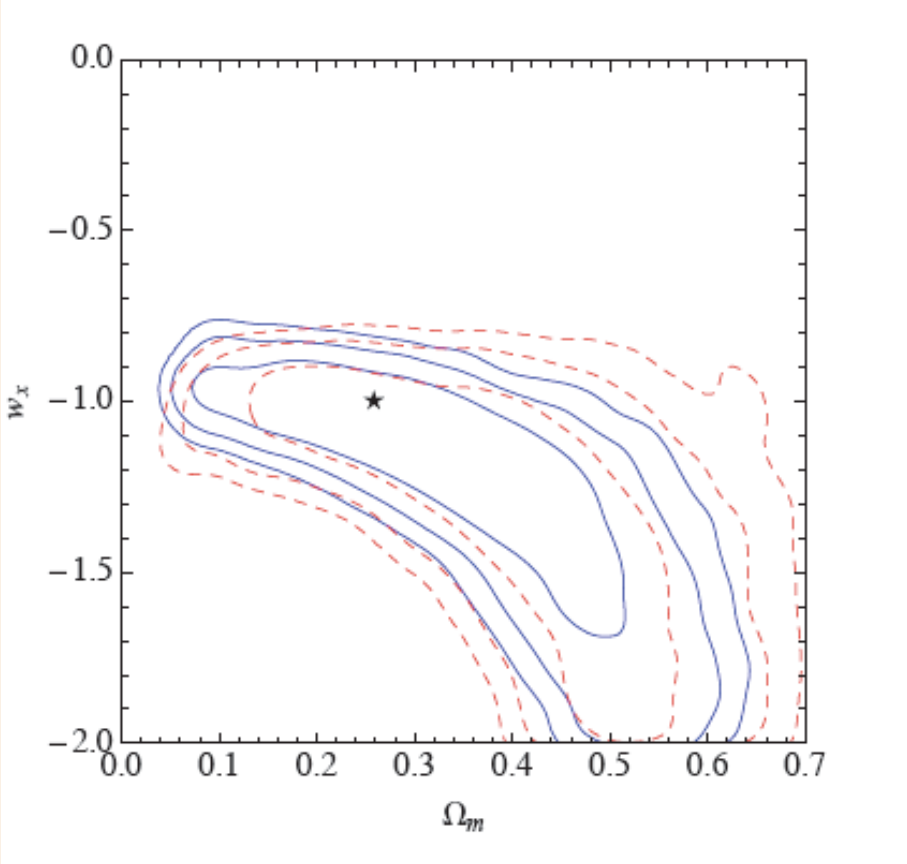
- 1" of scatter due to structures in the lens plane & along L.O.S.

Correlated LOS (infalling subclusters, filaments)

Uncorrelated LOS (primary contribution to the errors) ~

No bias due to choice of density profile, cluster bimodality

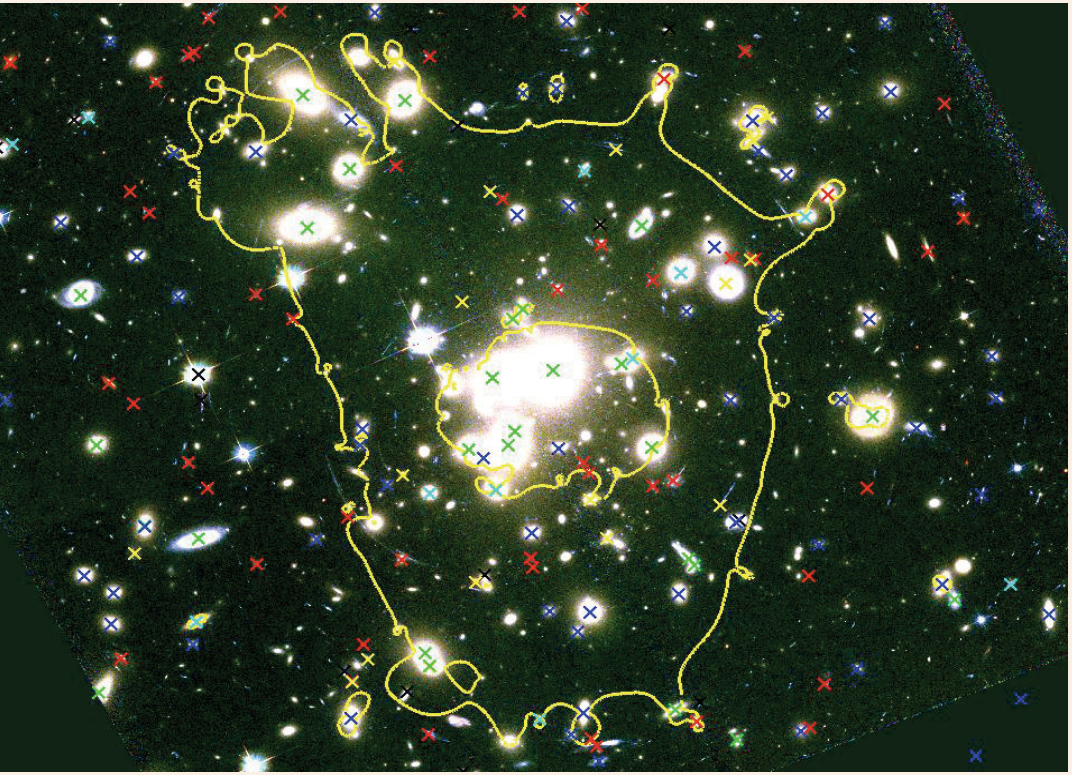




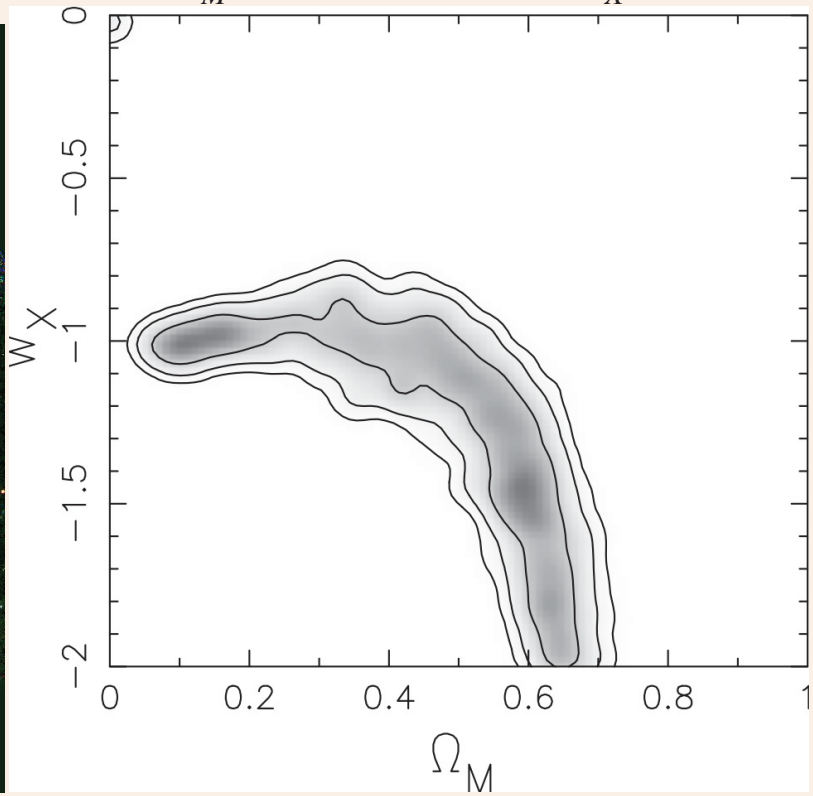
Not particularly sensitive to the inner slope/outer slope of the density profile
No bias from choice of profile NFW vs. PIEMD or bi-modality

COSMOGRAPHY WITH A1689

Mass model with 3 PIEMD potentials; 58 cluster galaxies
Bayesian optimization: 32 constraints, 21 free parameters;
RMS = 0.6 arcsec; 28 multiple images from 12 sources with spec z, flat Universe prior

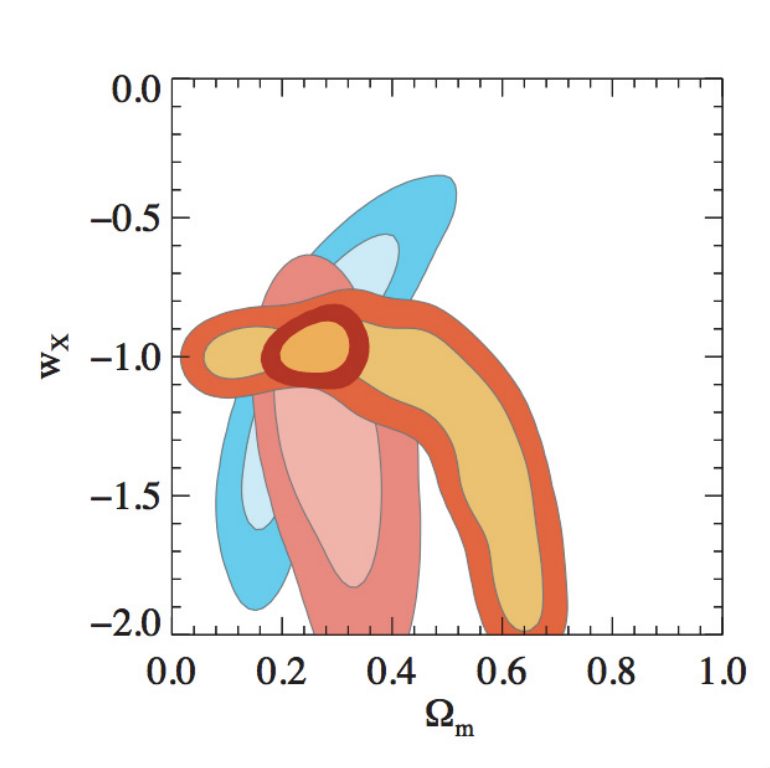


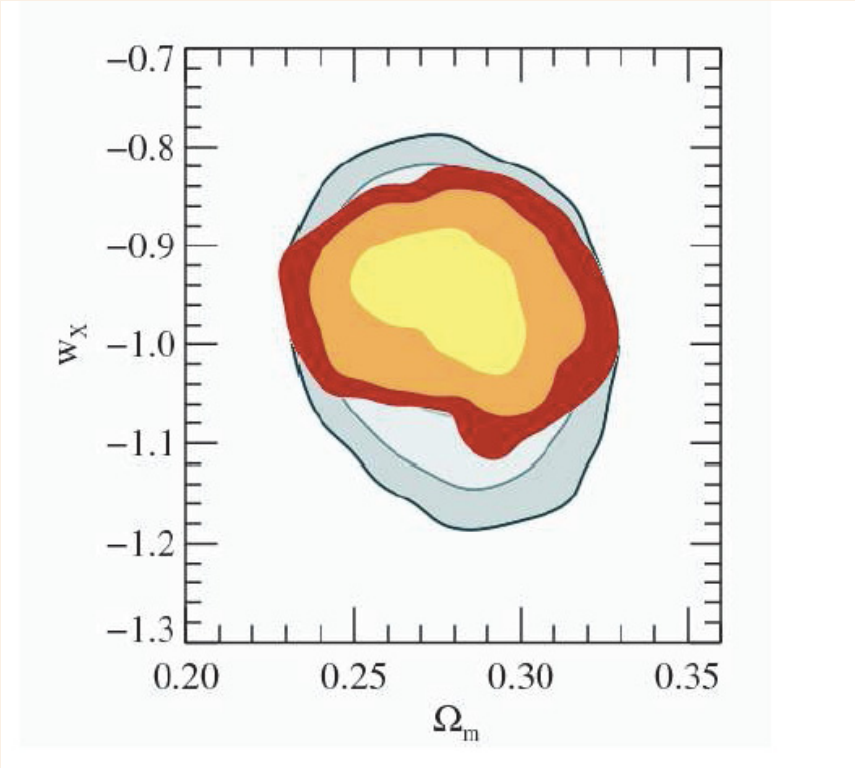
$0.1 \le \Omega_M \le 0.58; -1.57 \le w_X \le -0.85$



Jullo+ (Science, August 2010, 329, 924)

CURRENT CONSTRAINTS INCLUDING CSL

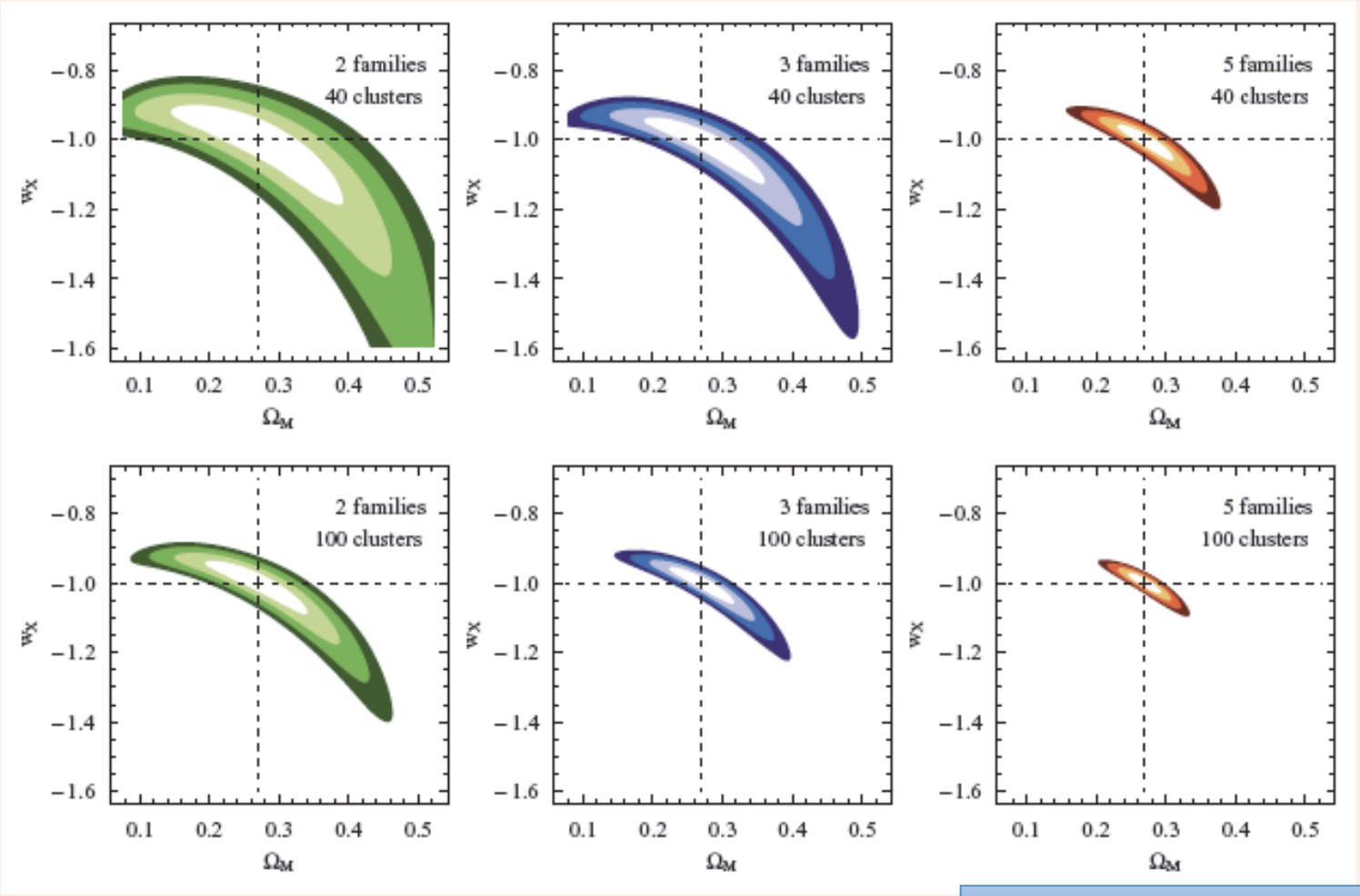




Combining X-ray clusters, WMAP5, strong lensing
competitive with WMAP5 + SNe + BAO

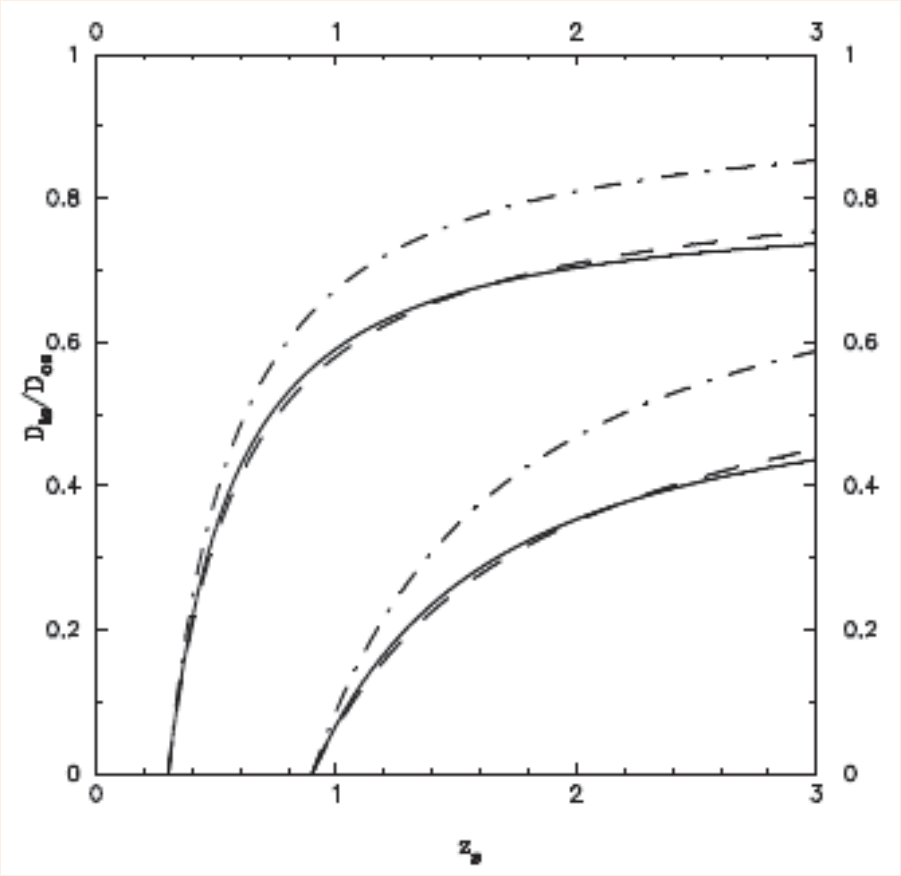
Jullo, PN, Kneib 2010

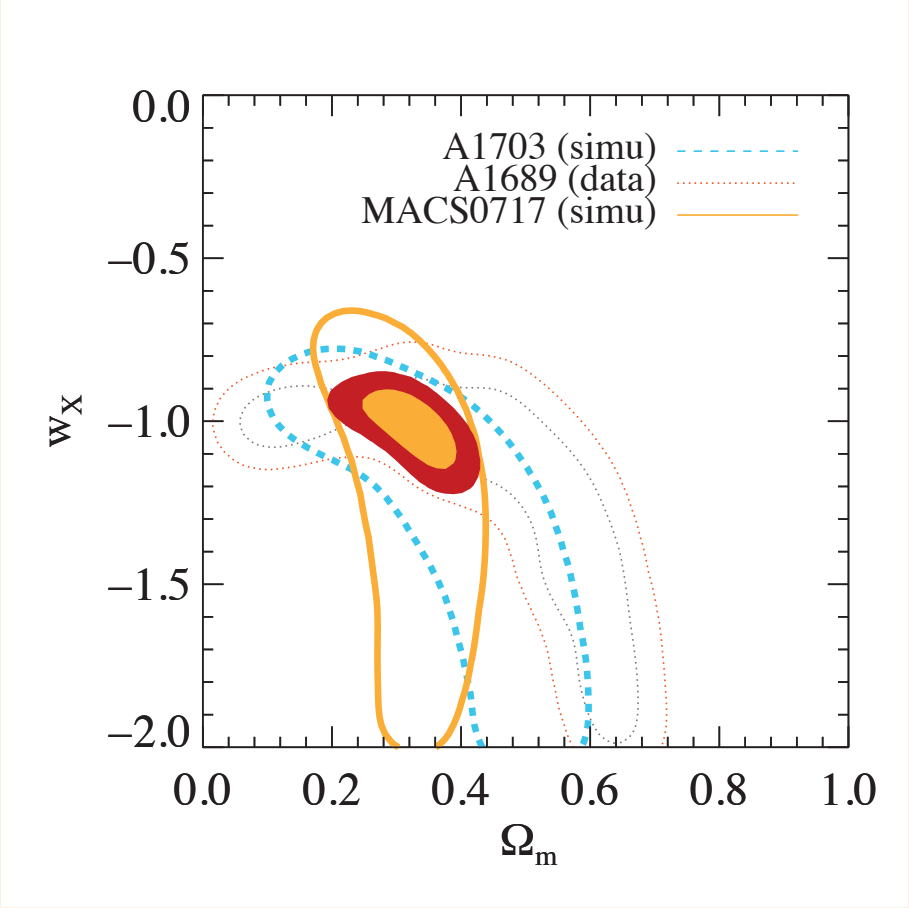
COMBINATION OF MANY CLUSTERS



Gilmore & Natarajan 2009

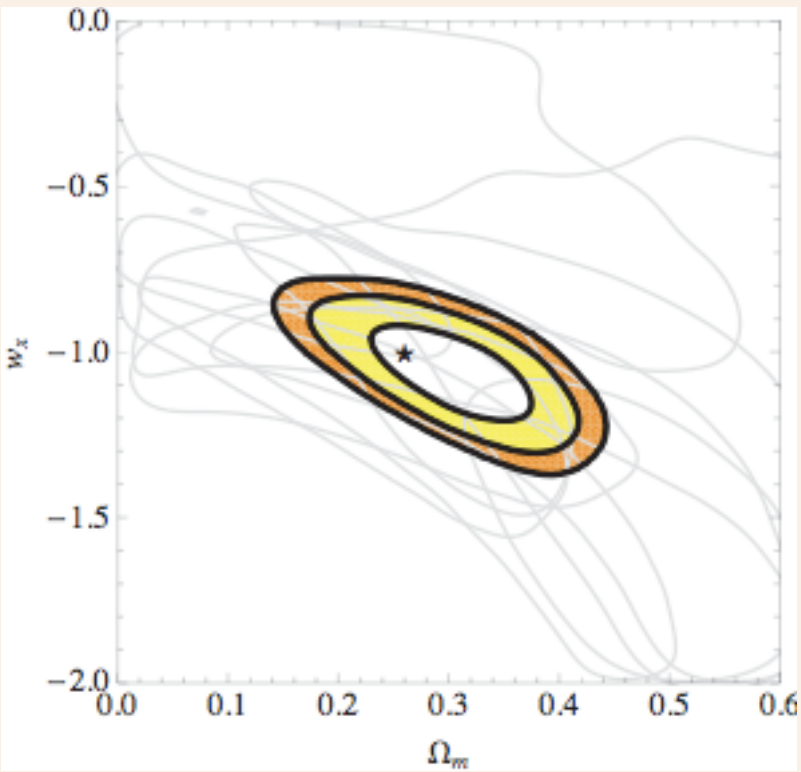
HIGH AND LOW-Z CLUSTERS



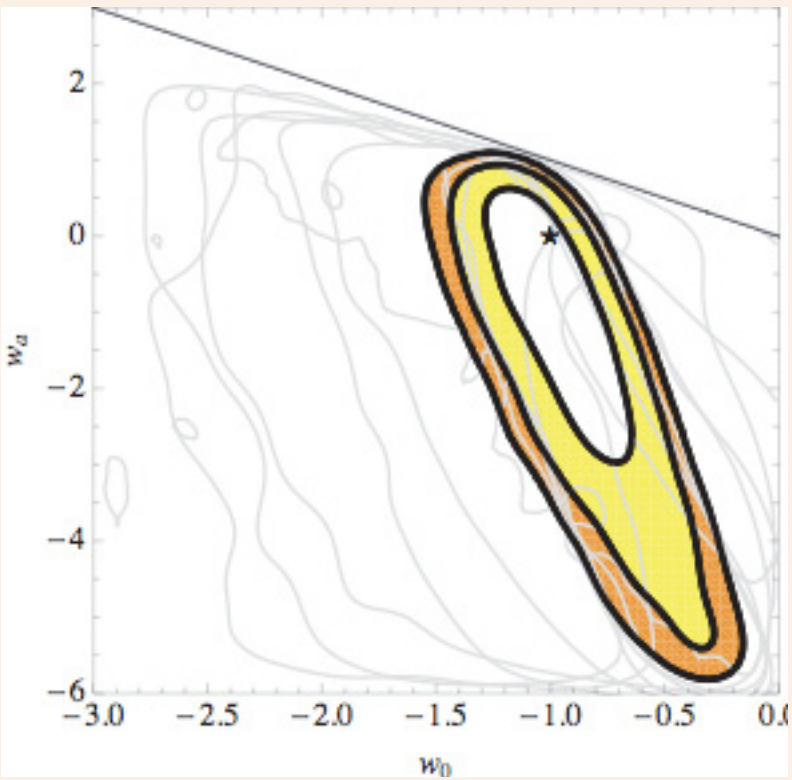


PROBING W(Z)

10 clusters, 20 families! Flat prior, input w = -1; evolving wa



D'Aloisio & Natarajan 2010



$$w_x = w_0 + w_a \frac{z}{(1+z)}$$

Chevallier, Polarski & Linder 01

FUTURE PROSPECTS

- *Cluster cosmography is a promising new (geometrical) cosmological probe* - Simple and likely Competitive
- Requirements:
  - HST multiband imaging (some progress: CLASH project & others) => dedicated large proposal proposed in Cycle 19 (PI: Kneib)
  - Ground based spectroscopy on 8-10m telescope (with current facilities & soon with ESO/VLT/MUSE)
- JWST may become a key player (deeper images & spectroscopy)
- *Complementary output: Mass distribution to the % level => unique way to characterize DM properties.*

The END

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