COSMOLOGY WITH CLUSTERS: FIRST RESULTS FROM HFF

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Yale

Collaborators

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- **ILLUSTRIS** Lars Hernquist, Mark Vogelsberger, Volker Springel and the Illustris collaboration
- **Urmila Chadayammuri** (***poster**)
- Anson D'Aloisio
- Massimo Meneghetti

Cosmology with cluster-lenses

Lensing tests of dark matter – comparison with LCDM simulations

- Mass profiles of clusters: **concentration**
- **Substructure: abundance, profiles, spatial distribution**
- Density profiles of DM halos: inner and outer slopes
- Shapes of dark matter halos
- Higher order statistics: flexion, correlation function of substructure – pencil beam surveys, P(k)
- Science by stacking

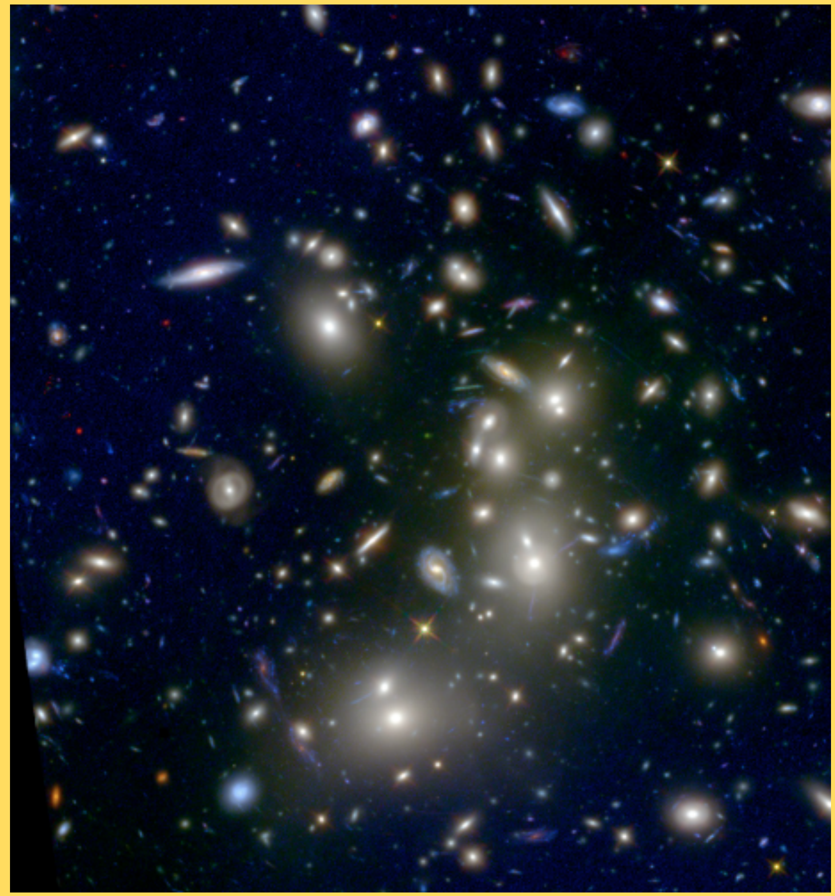
Lensing constraints on dark energy

- **Cosmography with strong lensing (CSL)**
- Triplet statistics

Lensing tests of the standard world model

- Primordial Non-Gaussianity (Arc-statistics)
- Growth of Structure and Structure Formation

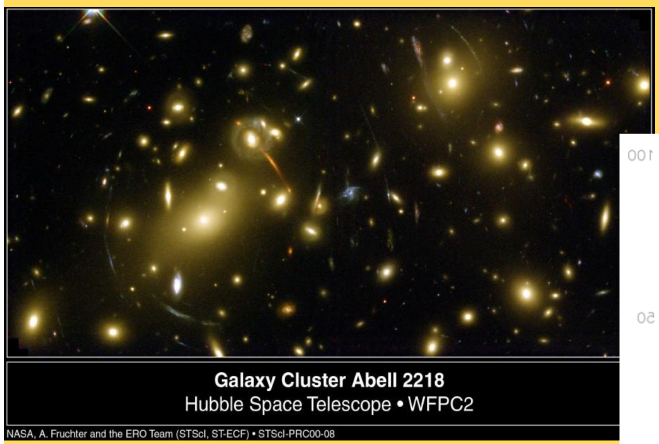
FF CLUSTERS MACS0416 & Abell2744

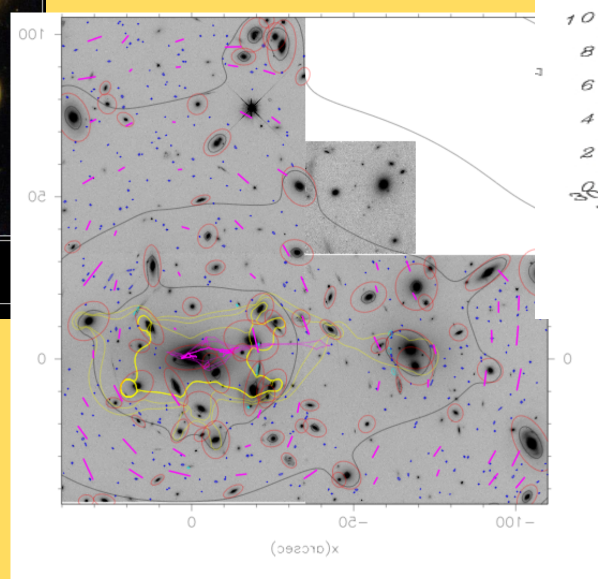


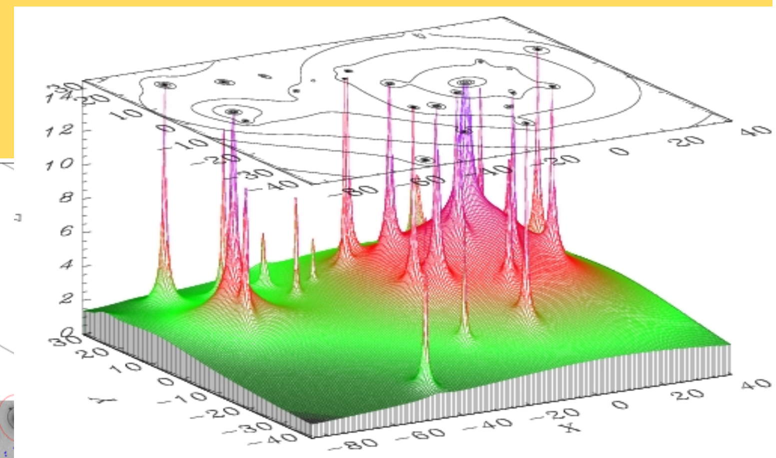
Jauzac+ 2014a,b CATS

MAPPING SUBSTRUCTURE IN CLUSTER LENSES

$$\Phi_{cluster} = \sum_i \Phi_{smooth} + \sum_n \Phi_{perturbers}$$

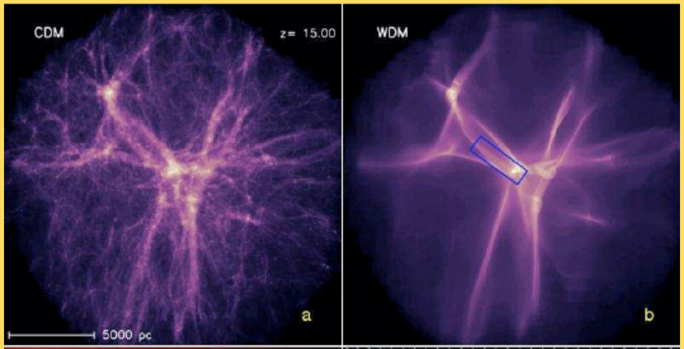






PN & Kneib 1997; PN+ 2005; 2009; 2011

Granularity of DM - substructure

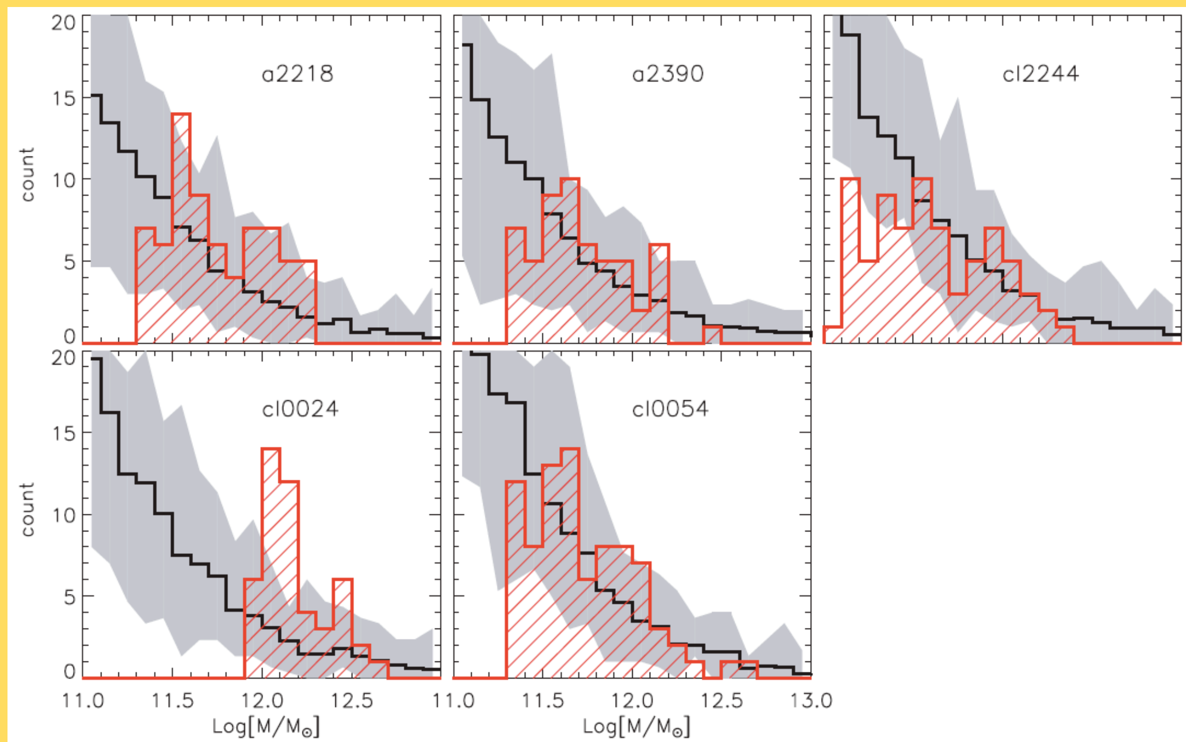


dependence on the nature of DM

substructure is reduced – small halos are heated as they move through larger ones, and tend to dissolve and merge into the larger structure in all self-interacting dark matter models

$$\frac{dn}{dm} \propto m^{-1.8}$$

Comparison with LCDM simulations Millenium



Springel+ 05; PN, De Lucia & Springel 07; Gao & Theuns 2007; PN+2009

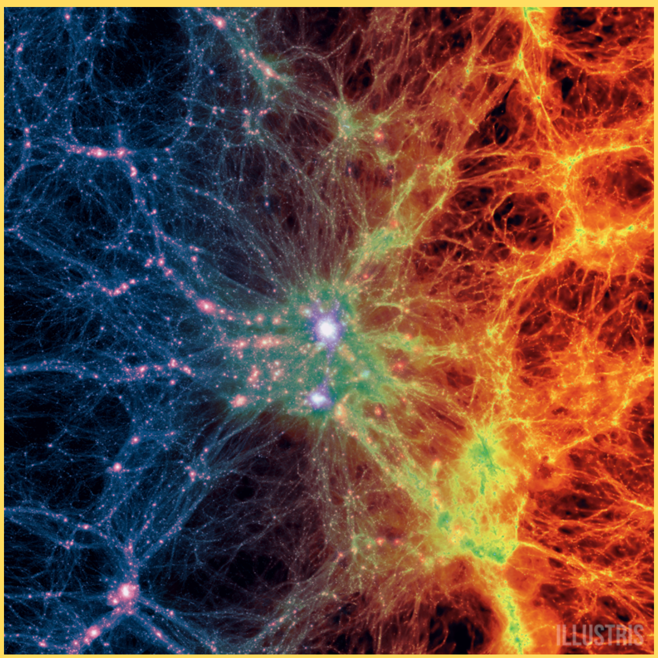
ILLUSTRIS

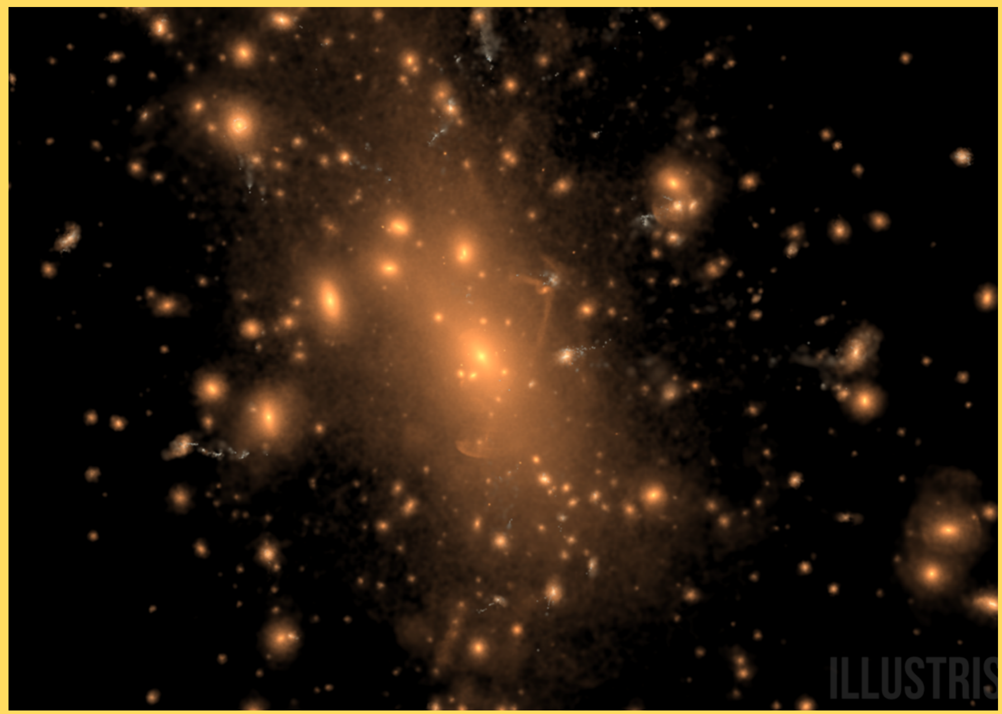
AREPO MOVING
MESH CODE

DM ONLY RUN
FULL PHYSICS RUN

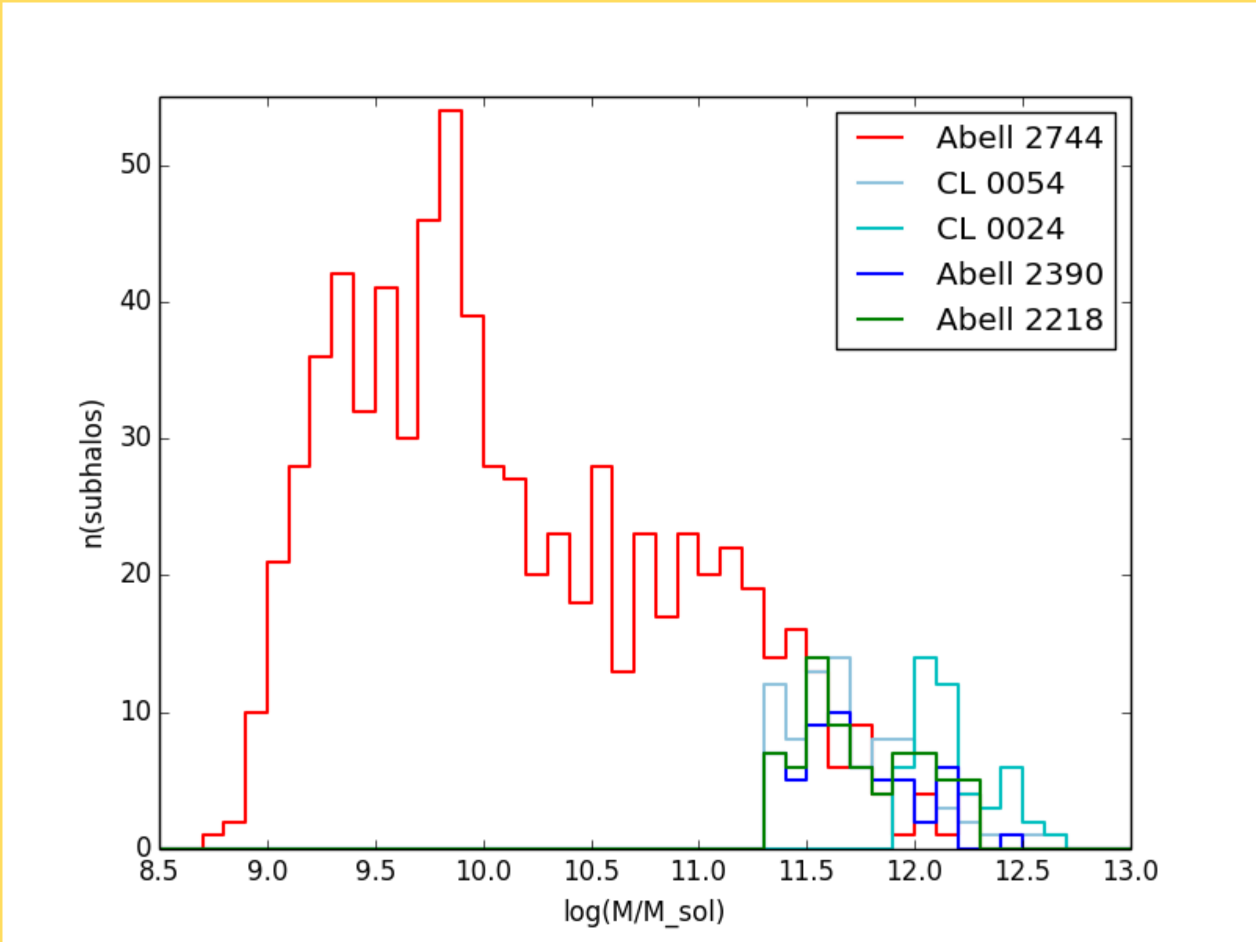
name	volume $[(\mathrm{Mpc})^3]$	DM particles / hydro cells / MC tracers	$\epsilon_{\mathrm{baryon}}/\epsilon_{\mathrm{DM}}$ [pc]	$m_{\mathrm{baryon}}/m_{\mathrm{DM}}$ $[10^5\,\mathrm{M}_\odot]$	$r_{\mathrm{cell}}^{\mathrm{min}}$ [pc]
Illustris-1	106.5^3	$3 \times 1,820^3 \cong 18.1 \times 10^9$	$710/1,420$	$12.6/62.6$	48
Illustris-2	106.5^3	$3 \times 910^3 \cong 2.3 \times 10^9$	$1,420/2,840$	$100.7/501.0$	98
Illustris-3	106.5^3	$3 \times 455^3 \cong 0.3 \times 10^9$	$2,840/5,680$	$805.2/4008.2$	273
Illustris-Dark-1	106.5^3	$1 \times 1,820^3$	$710/1,420$	$-/75.2$	–
Illustris-Dark-2	106.5^3	1×910^3	$1,420/2,840$	$-/601.7$	–
Illustris-Dark-3	106.5^3	1×455^3	$2,840/5,680$	$-/4813.3$	–

The initial conditions assume a LCDM cosmology consistent with WMAP-9 measurements, from which a linear power spectrum is used to create a random realization in a periodic box with side length 75 Mpc/h = 106.5 Mpc, at a starting redshift of 127. A series of simulations are run at different resolutions, and a second set is run with only dark matter. The main simulation initially has 1820^3 = 6,028,568,000 hydrodynamic cells, and the same number of DM particles and MC tracers (see table for more details, including mass resolutions and gravitational softening lengths). Evolving the main simulation to z=0 used 8,192 compute cores, a peak memory of 25 TB, and 19 million CPU hours.





Mapping substructure with the HST Frontier Fields

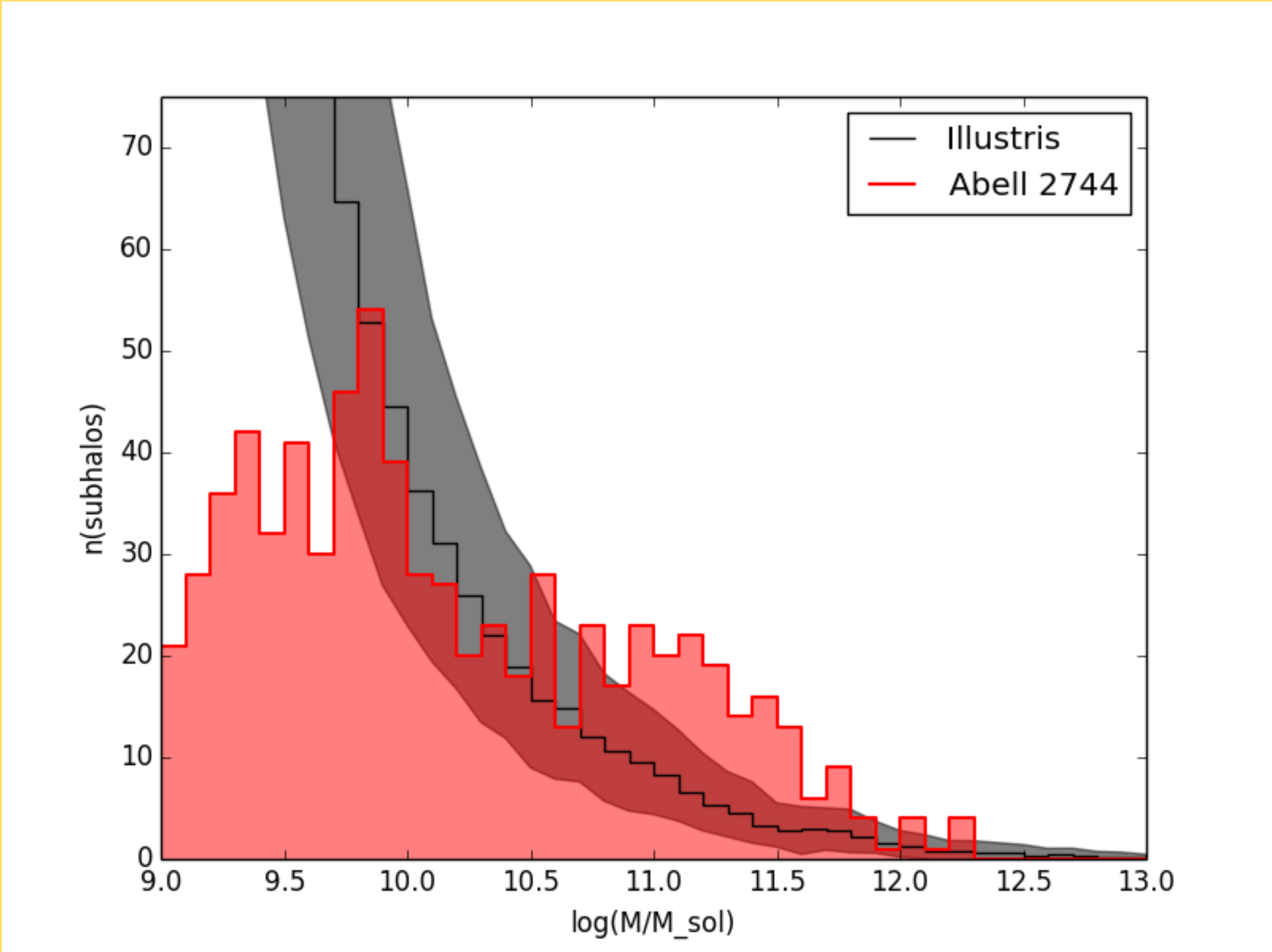


Jauzac+14 CATS

BEST FIT MODEL: d.o.f – 139, chi^2=2.04 and RMS = 0.69”

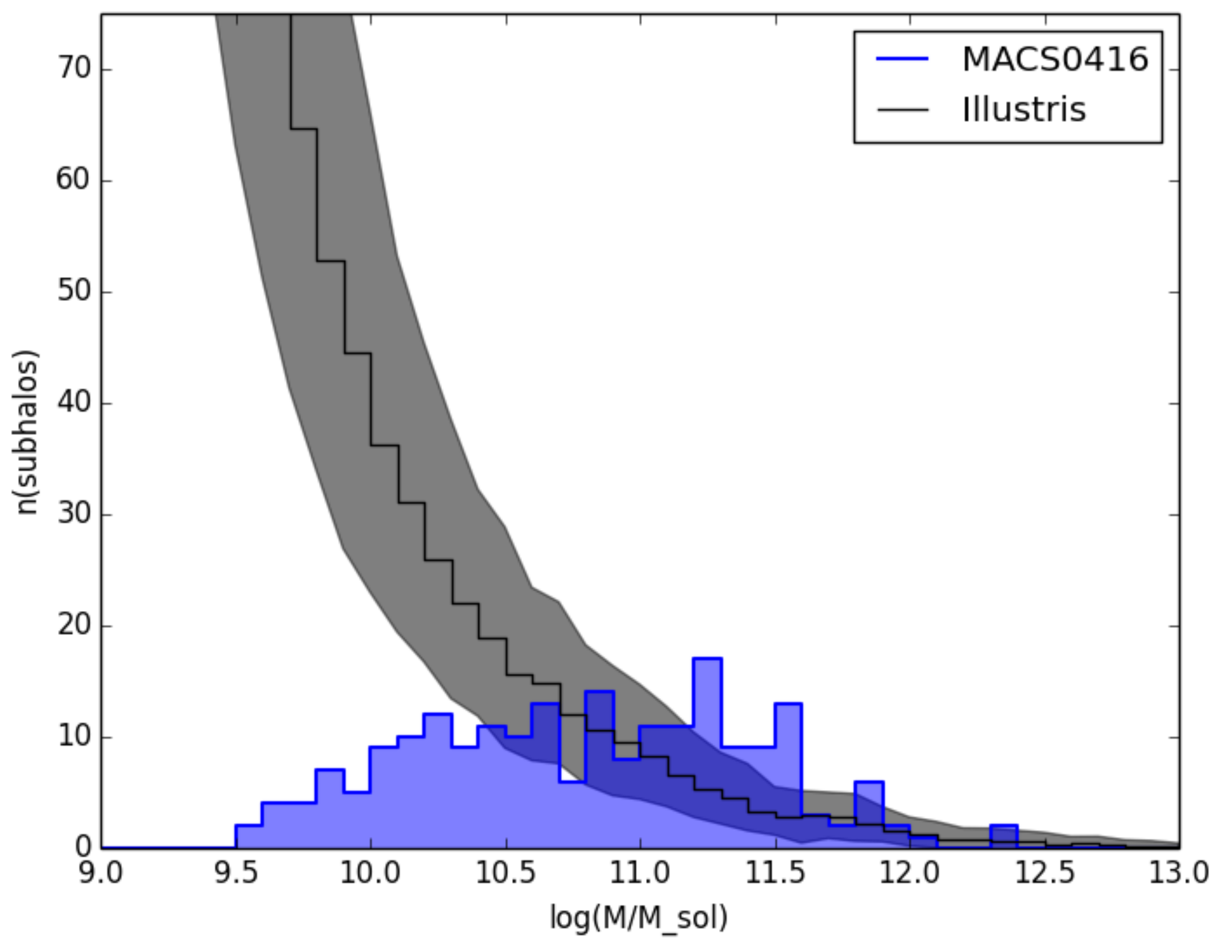
51 image families, 159 images, 2 large scale PIEMDs + 733 cluster galaxies

Comparison with Illustris LCDM clusters



The subhalo mass function

Comparison with Illustris LCDM clusters



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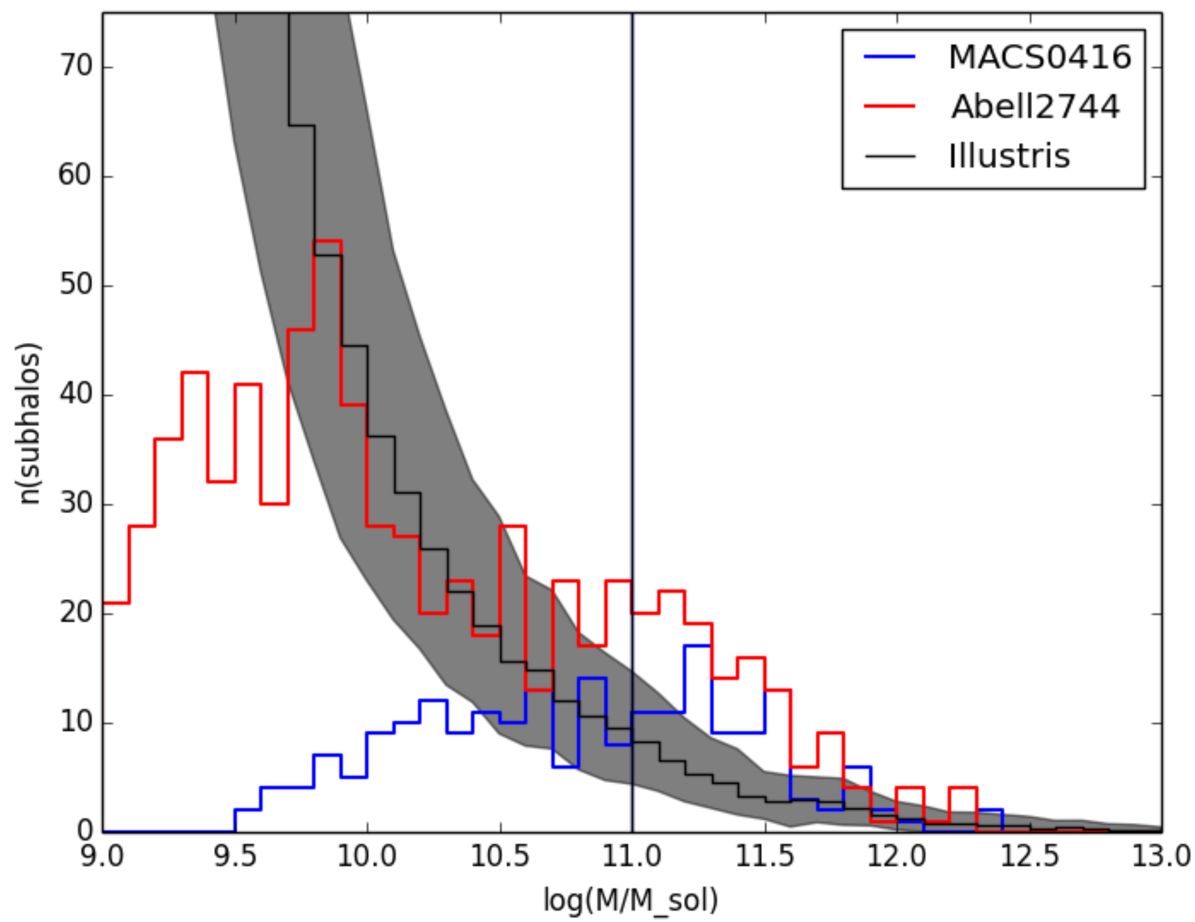

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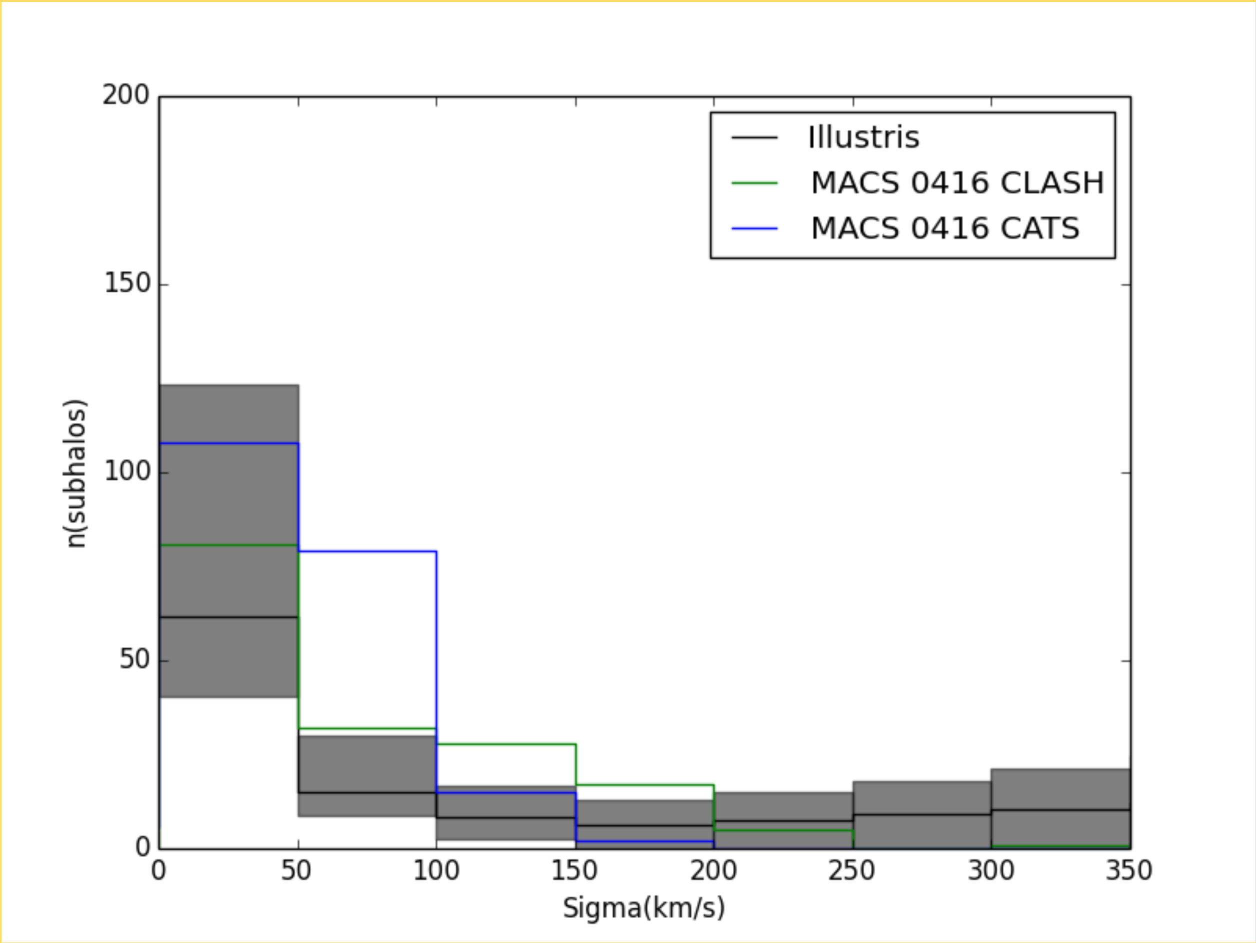
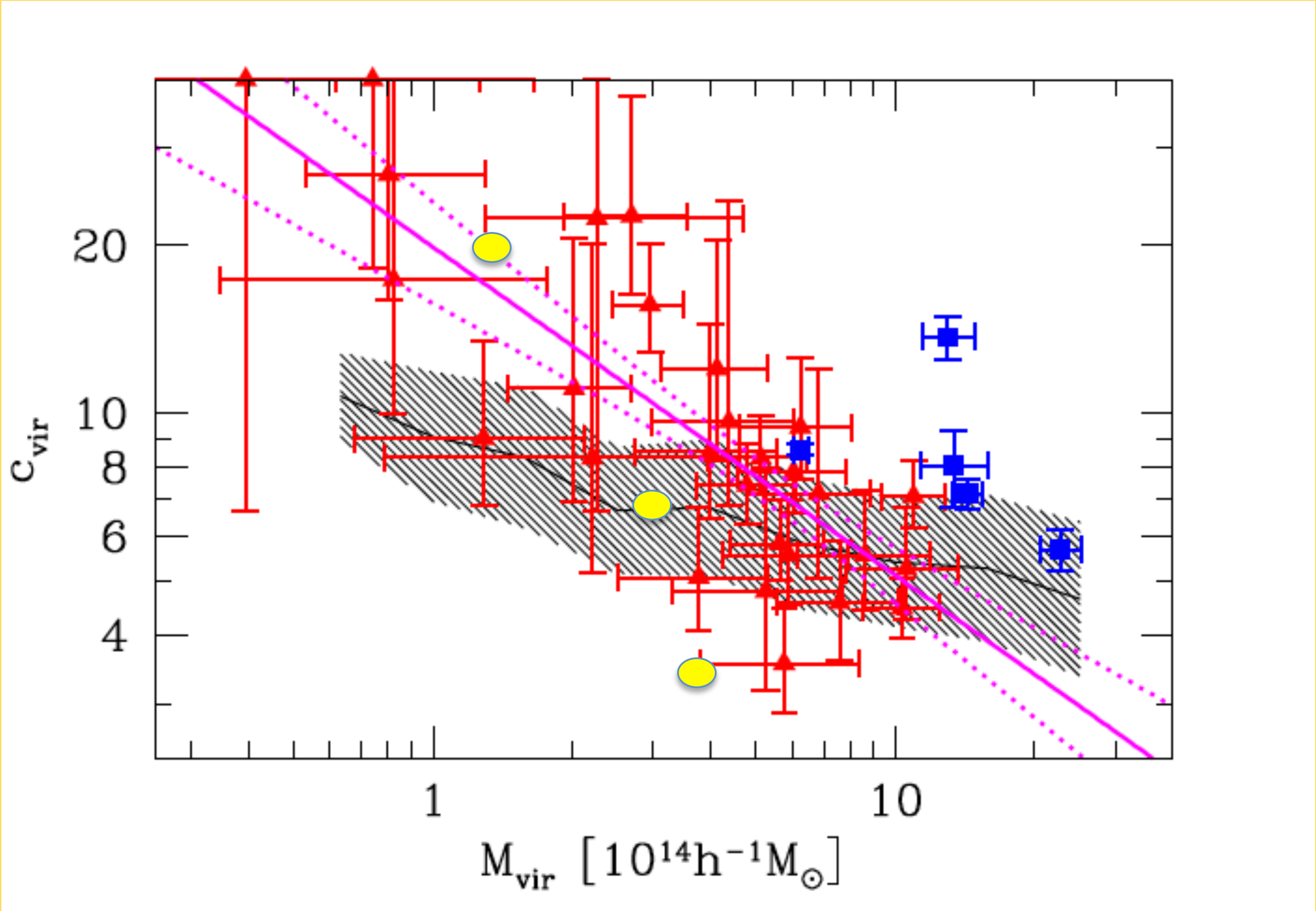
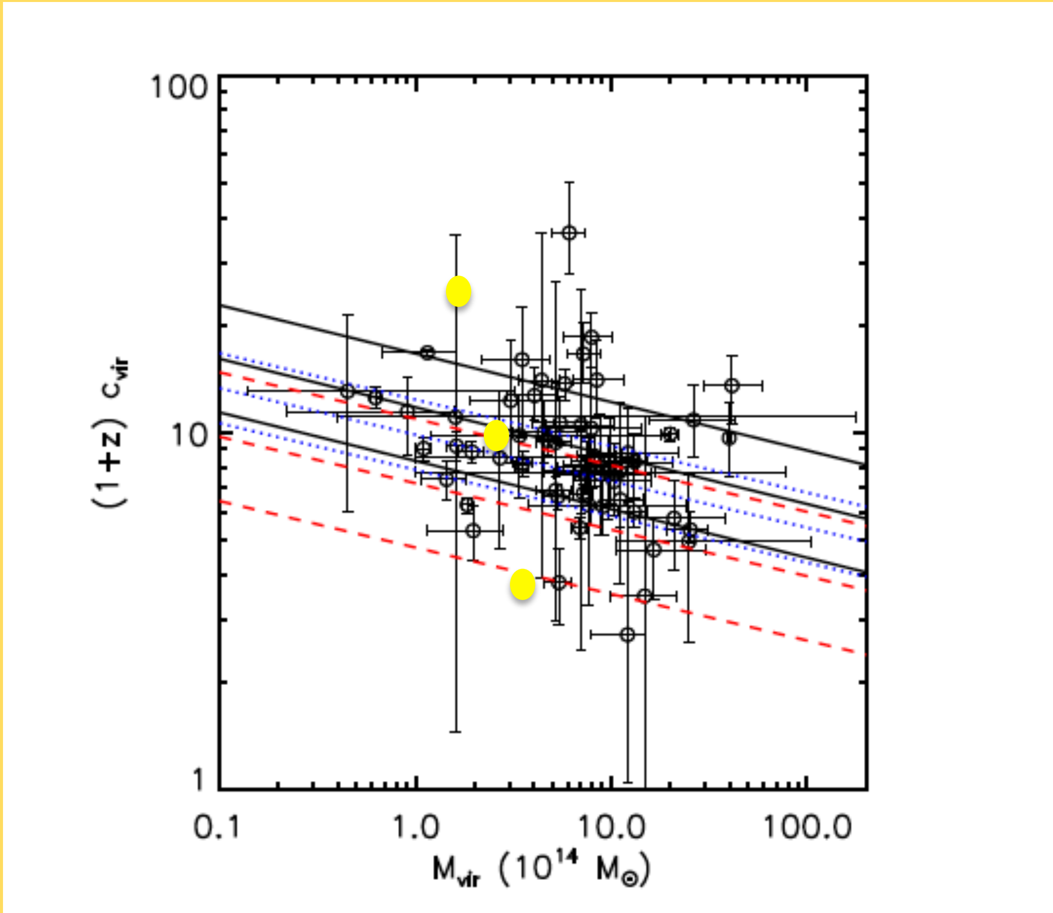


Concentration-Mass Relation



Oguri+ 2011; Ishigaki+ 2014

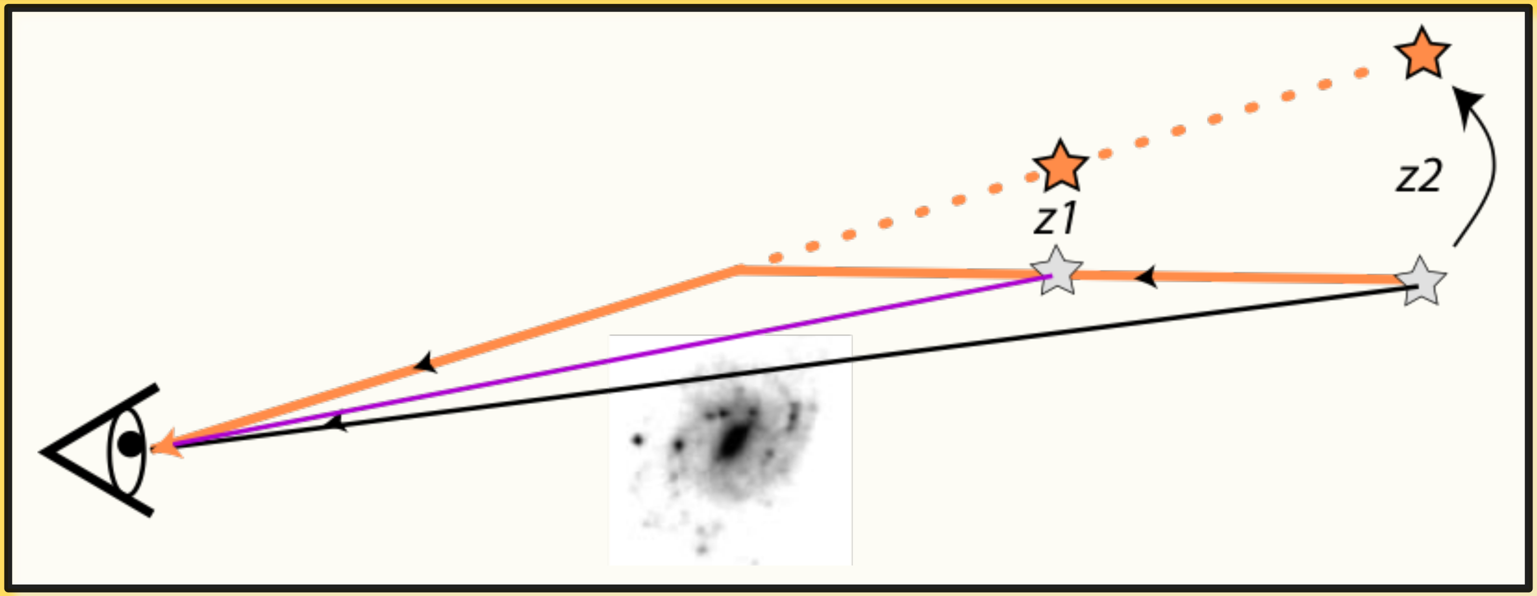
Concentration-Mass Relation



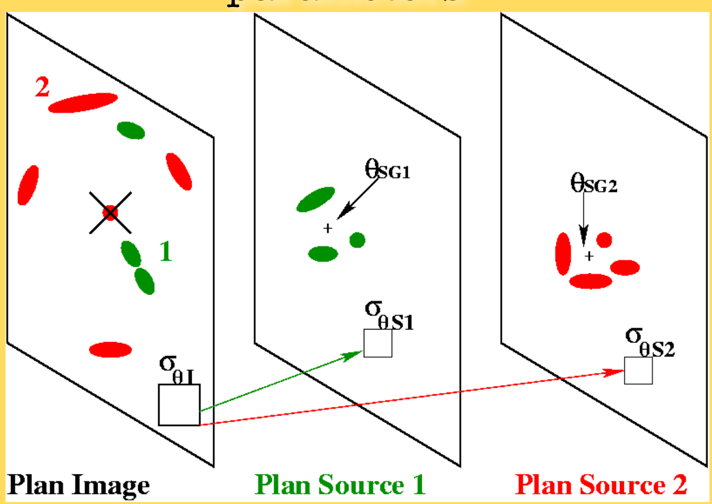
$$c_{\rm vir} = \frac{14.5 \pm 6.4}{(1+z)} \left(\frac{M_{\rm vir}}{1.3 \times 10^{13}\, h^{-1}\, M_\odot} \right)^{-0.15 \pm 0.13}$$

Bullock+ 2001
Hennawi+ 2007
Comerford & PN 2007

Einstein radii at multiple source redshifts



Ratio of the position of multiple images,depends on mass distribution and cosmological parameters



LOS AND CSL CONSTRAINTS

$$\boldsymbol{\theta} = \boldsymbol{\beta} + \boldsymbol{\alpha}(\boldsymbol{\theta}, \xi; M)$$

$$\xi = \frac{D(0, z_l) D(z_l, z_s)}{D(0, z_s)} \equiv \frac{D_{ol} D_{ls}}{D_{os}}$$

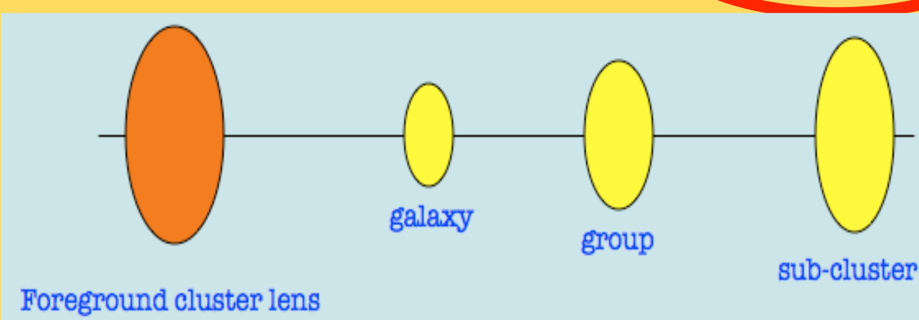
For multiple images of the same source

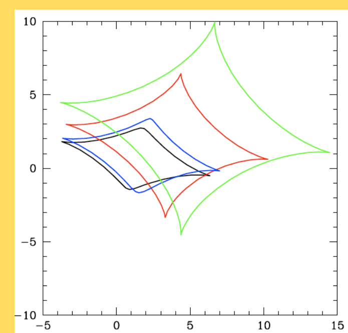
$$\boldsymbol{\beta}_f = \boldsymbol{\theta}_{f,i} - \boldsymbol{\nabla} \varphi_M(\boldsymbol{\theta}_{f,i}, \xi),$$

notation denotes the position of the i^{th} image of family f

Taking the ratio of 2 distinct families of multiple images

$$\left\{\frac{D_{ls1}}{D_{os1}} \frac{D_{os2}}{D_{ls2}}\right\} \frac{\sum_{i=1}^{m} \boldsymbol{\nabla} \phi_M(\boldsymbol{\theta}_{1,i})}{\sum_{j=1}^{n} \boldsymbol{\nabla} \phi_M(\boldsymbol{\theta}_{2,j})} = \frac{-m\boldsymbol{\beta}_1 + \sum_{i=1}^{m} \boldsymbol{\theta}_{1,i}}{-n\boldsymbol{\beta}_2 + \sum_{j=1}^{n} \boldsymbol{\theta}_{2,j}}.$$





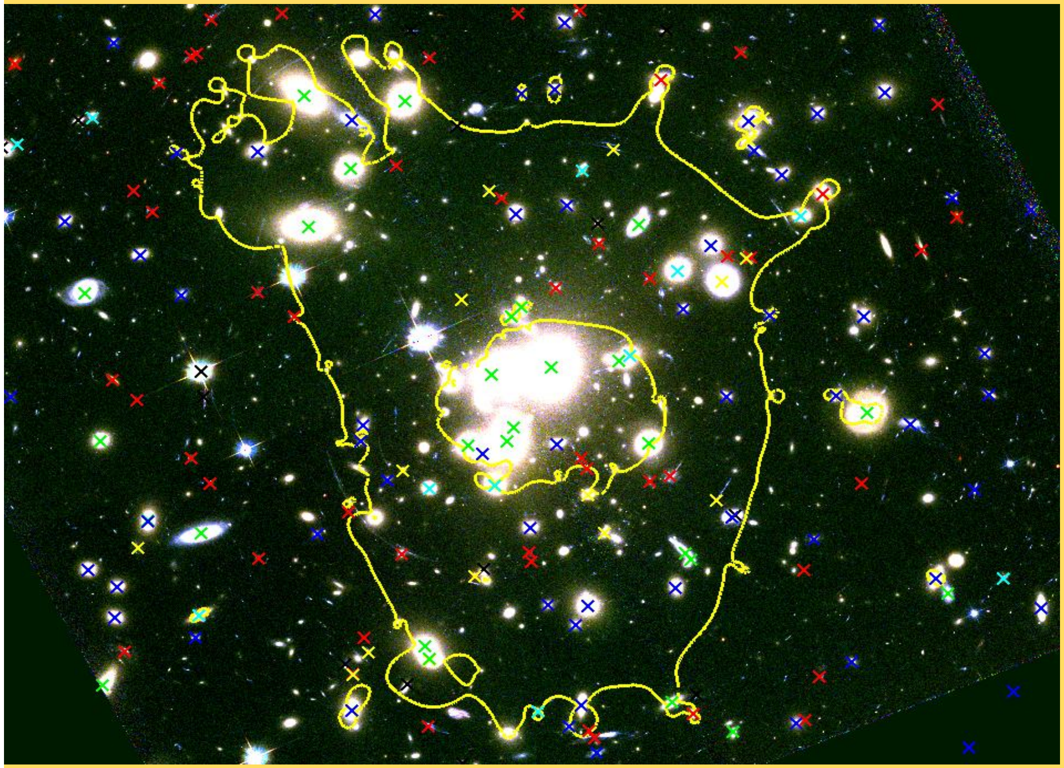
$$\Xi(z_l, z_{s1}, z_{s2}; \Omega_M, \Omega_X, w_X) = \frac{D(z_l, z_{s1})}{D(0, z_{s1})} \frac{D(0, z_{s2})}{D(z_l, z_{s2})}$$

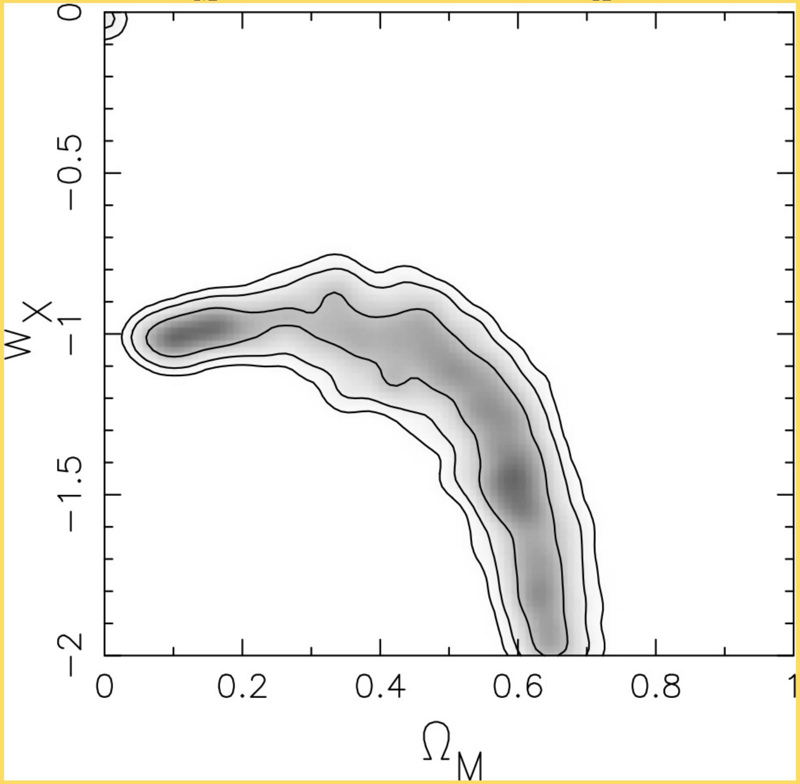
Gilmore & PN 08; D'Aloisio & PN 10

RESULTS FOR ABELL 1689

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

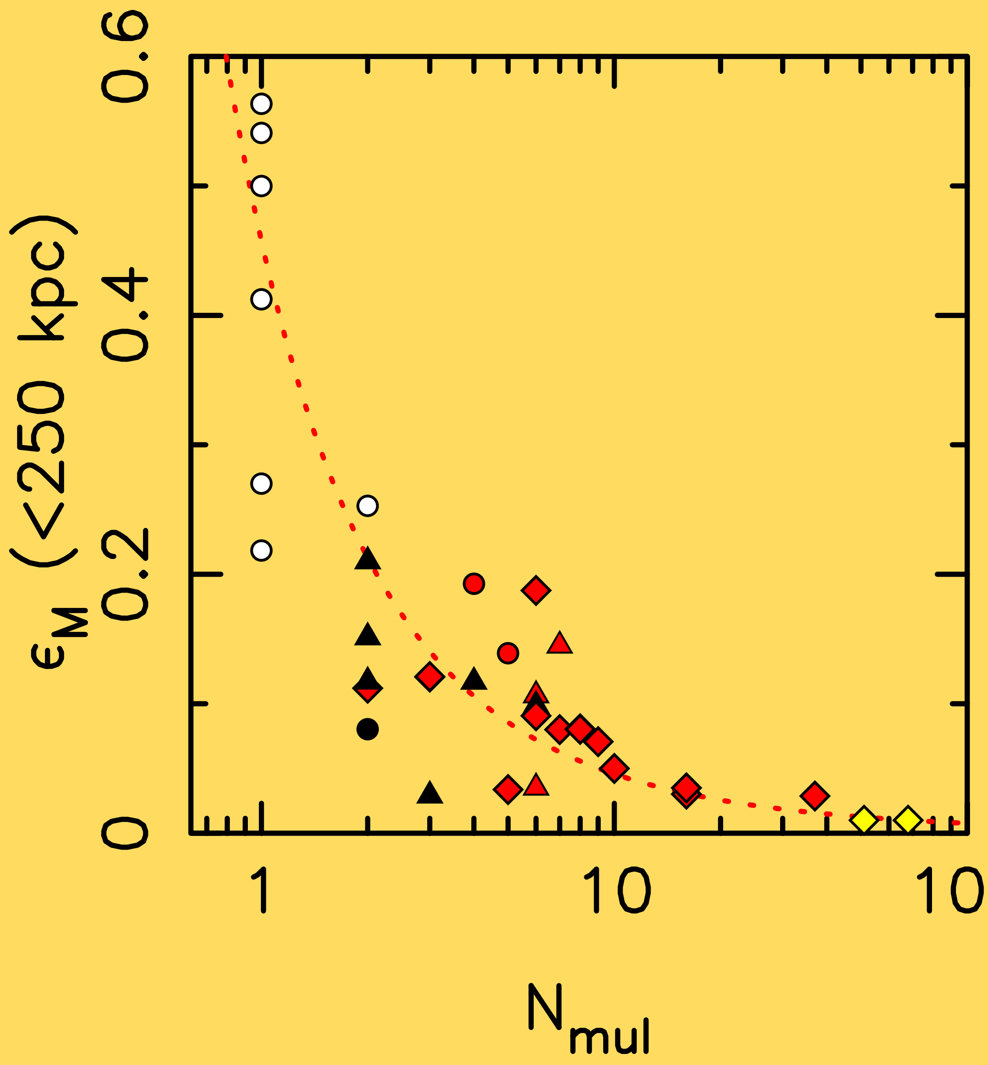
$0.1 \le \Omega_M \le 0.58; -1.57 \le w_X \le -0.85$

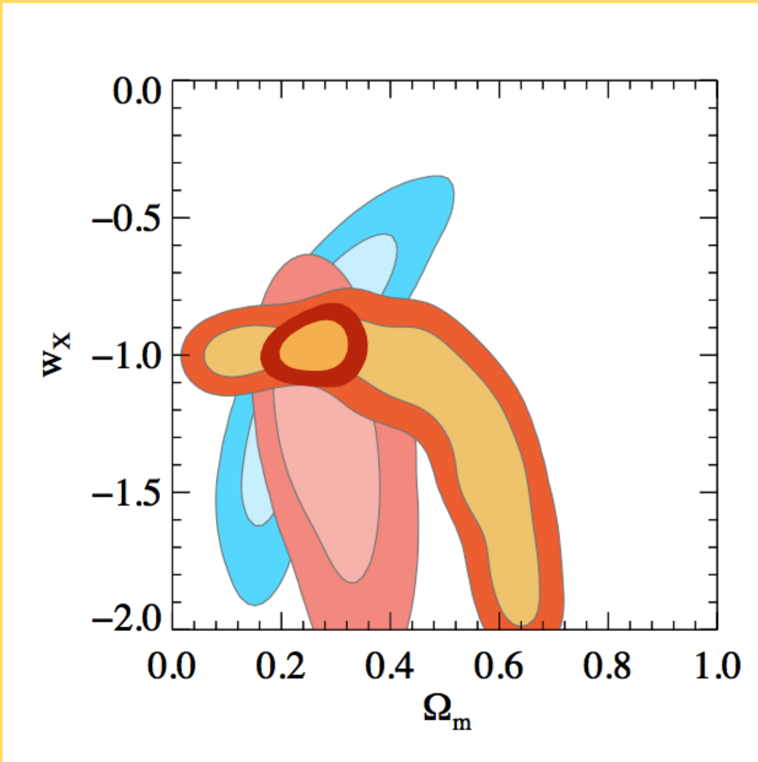




Broadhurst+ 05, Benitez+ 06; Halkola+ 06; Limousin+ 07
D'Aloisio & PN 10; Jullo & Kneib 09: Jullo+ 10

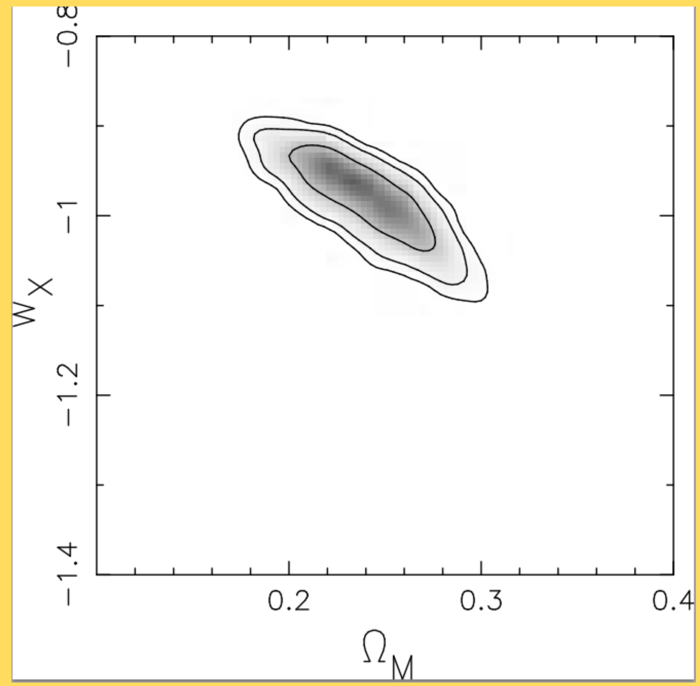
PRE-HFF COSMOGRAPHY





Cosmography with 100 multiple images

Optimized in the image plane with 242 image constraints (122 multiply imaged families)



Jullo+ 14 CATS

$$\Omega_M = 0.2395 \pm 0.0230 \quad w_X = 0.9691 \pm 0.0348$$

HFF COSMOGRAPHY

INPUTS NEEDED

Spectroscopic redshifts for as many multiple images
Central velocity dispersions for cluster galaxies
High fidelity mass models

KEY SYSTEMATICS

LOS SUBSTRUCTURE
Correlated LOS (infalling subclusters, filaments)
Uncorrelated LOS (primary contribution to the errors)

RELATING MASS TO LIGHT
Scatter in Scaling Relations

D'Aloisio & PN '10, '11, D'Aloisio, PN & Shapiro'14

MUSE Richard+ CATS, HST Grism GLASS