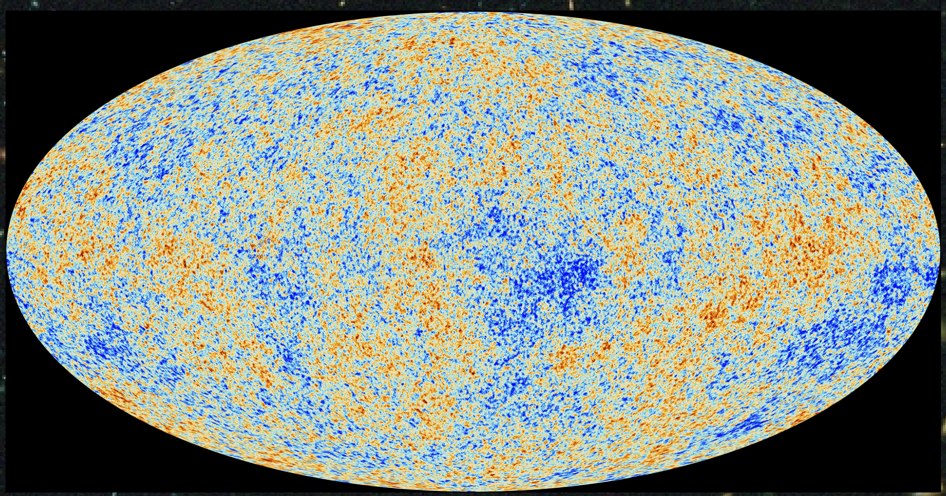
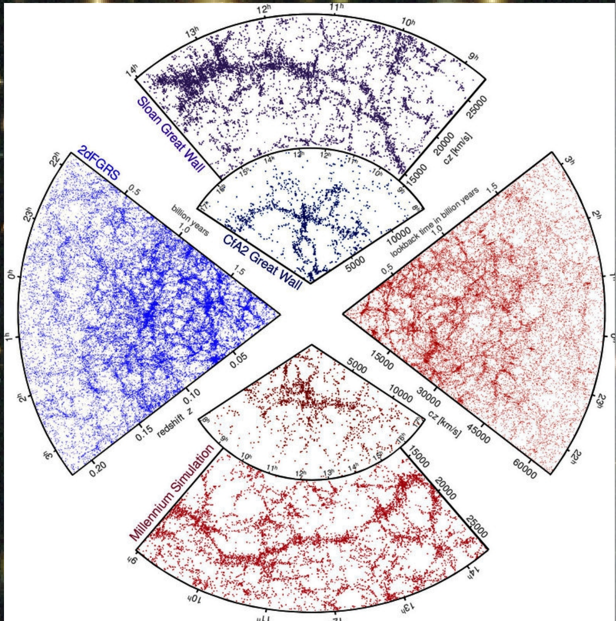


RAS, December 2015

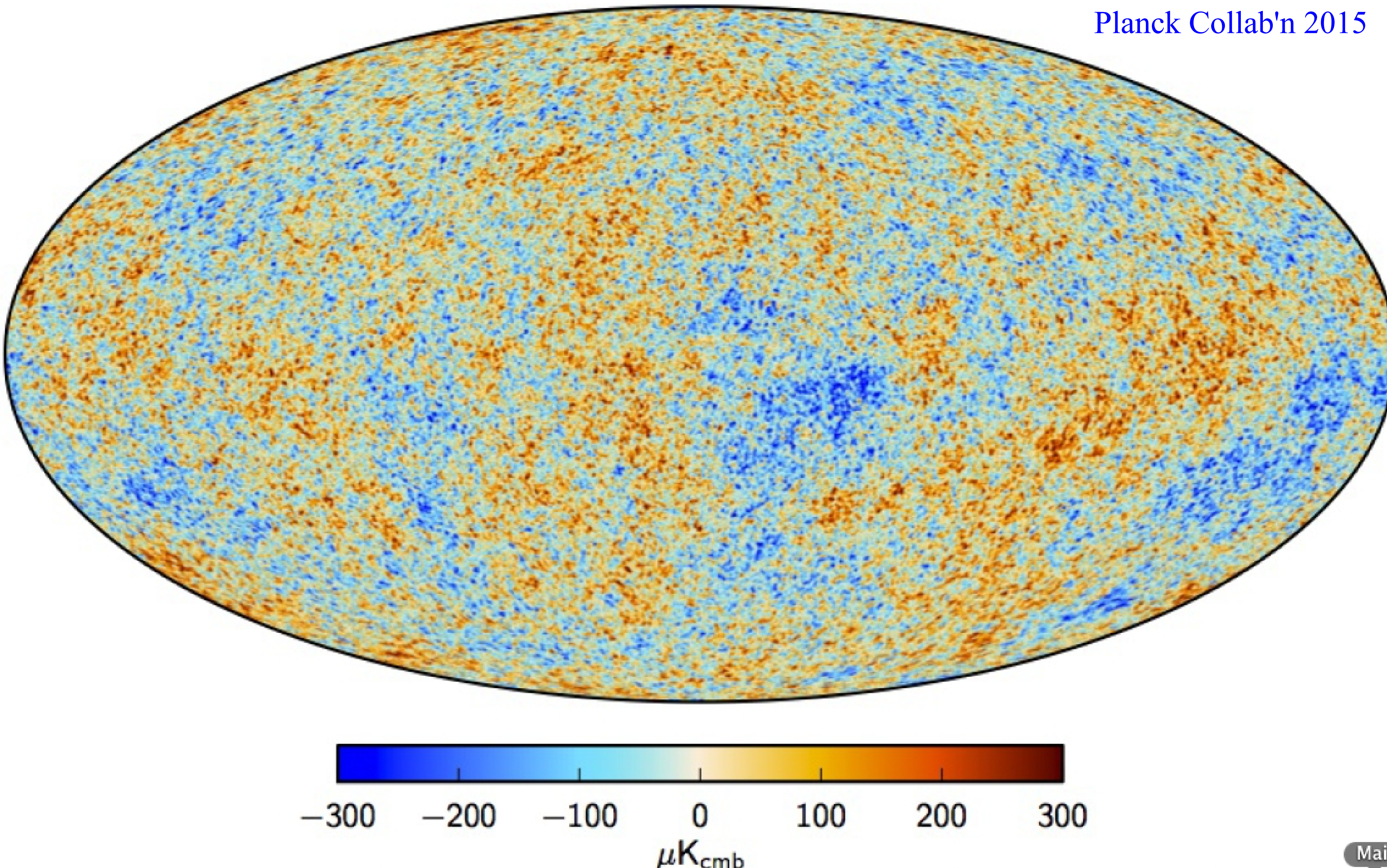
Cluster cosmology: a theoretical view



Simon White
Max Planck Institute for Astrophysics

CMB map from the full *Planck* mission

Planck Collab'n 2015



The six parameters of the base ΛCDM model

Planck Collab'n 2015

Parameter	TT+lowP 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04077 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.079 ± 0.017	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.094 ± 0.034	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049	0.9667 ± 0.0040

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80σ detection of nonbaryonic DM using *only* z ~1000 data!

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Total baryon density measured to 1%

80σ detection of nonbaryonic DM using *only* z ~1000 data!

One parameter extensions of the base ΛCDM model

Planck Collab'n 2015

Parameter	TT, TE, EE	TT, TE, EE+lensing+ext
Ω_K	$-0.040^{+0.038}_{-0.041}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.492	< 0.194
$N_{\rm eff}$	$2.99^{+0.41}_{-0.39}$	$3.04^{+0.33}_{-0.33}$
$Y_{\rm P}$	$0.250^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.0987	< 0.113
w	$-1.55^{+0.58}_{-0.48}$	$-1.019^{+0.075}_{-0.080}$

One parameter extensions of the base ΛCDM model

Planck Collab'n 2015

Curvature is <0.5% of current energy density

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Sum of ν masses < 4 times experimental lower limit

Uses of clusters in cosmology

Cluster abundance to measure fluctuation amplitude σ_8

Cluster abundance evolution to measure Ω_m

Cluster baryon fraction to estimate Ω_b/Ω_m

Cluster distribution to estimate power spectrum of LSS

Cluster core structure as a test of the nature of DM

Clusters as laboratories for galaxy evolution processes

Uses of clusters in cosmology

Cluster abundance to measure fluctuation amplitude σ_8

Non-gaussianities, ν masses

Cluster abundance evolution to measure Ω_m

Cluster baryon fraction to estimate Ω_b/Ω_m

Cluster distribution to estimate power spectrum of LSS

Cluster core structure as a test of the nature of DM

Clusters as laboratories for galaxy evolution processes

Uses of clusters in cosmology

Cluster abundance to measure fluctuation amplitude σ_8

Problem: converting cluster observables (L, T,...) to mass

Cluster abundance evolution to measure Ω_m

Problem: possible evolution of the L-M or T-M relations

Cluster baryon fraction to estimate Ω_b/Ω_m

Problems: clumping, extrapolation to R_{200}

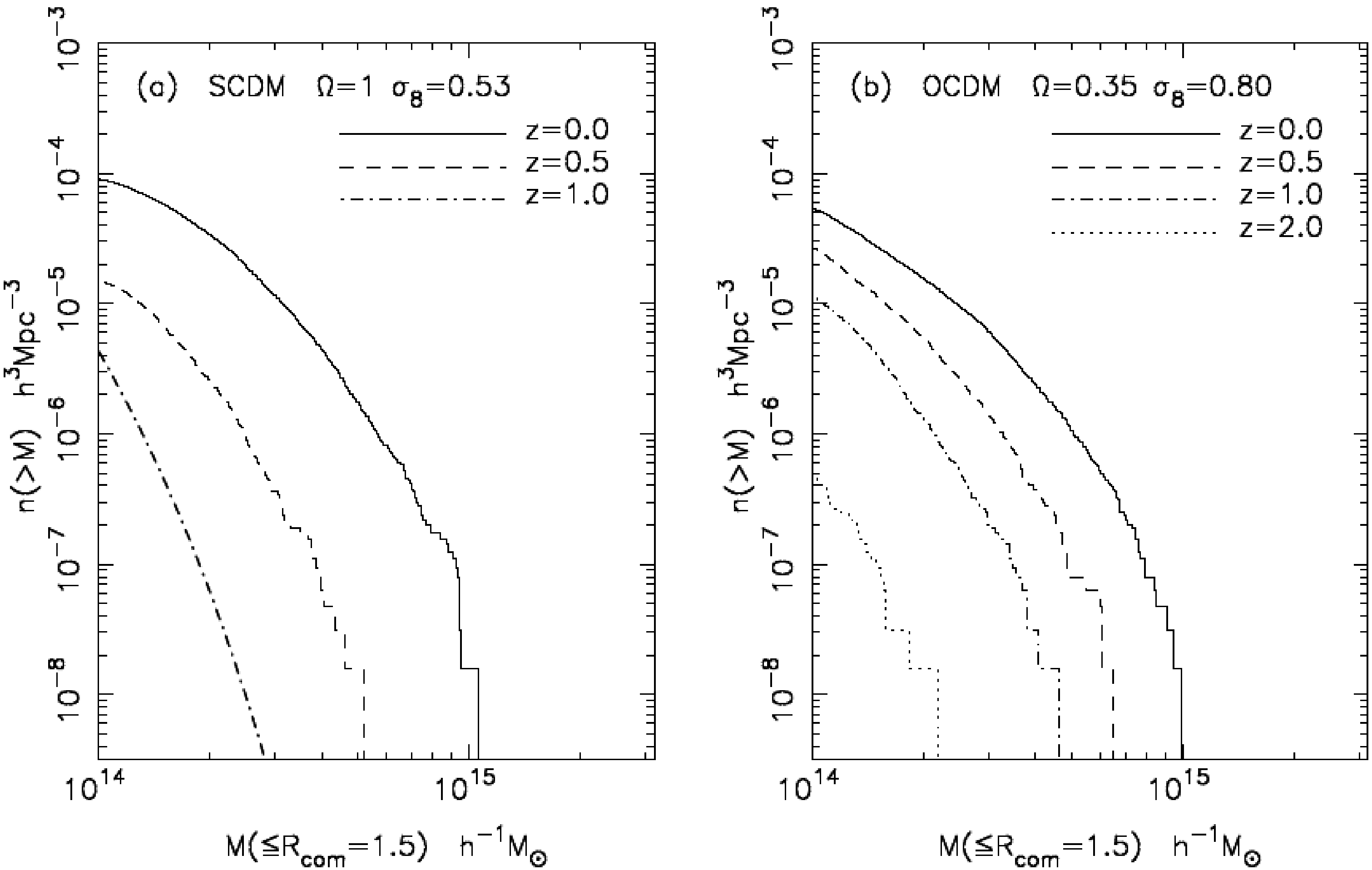
Cluster distribution to estimate power spectrum of LSS

Problem: sparse sampling

Cluster core structure as a test of the nature of DM

Problem: How does cD assembly affect DM profile?

Clusters as laboratories for galaxy evolution processes

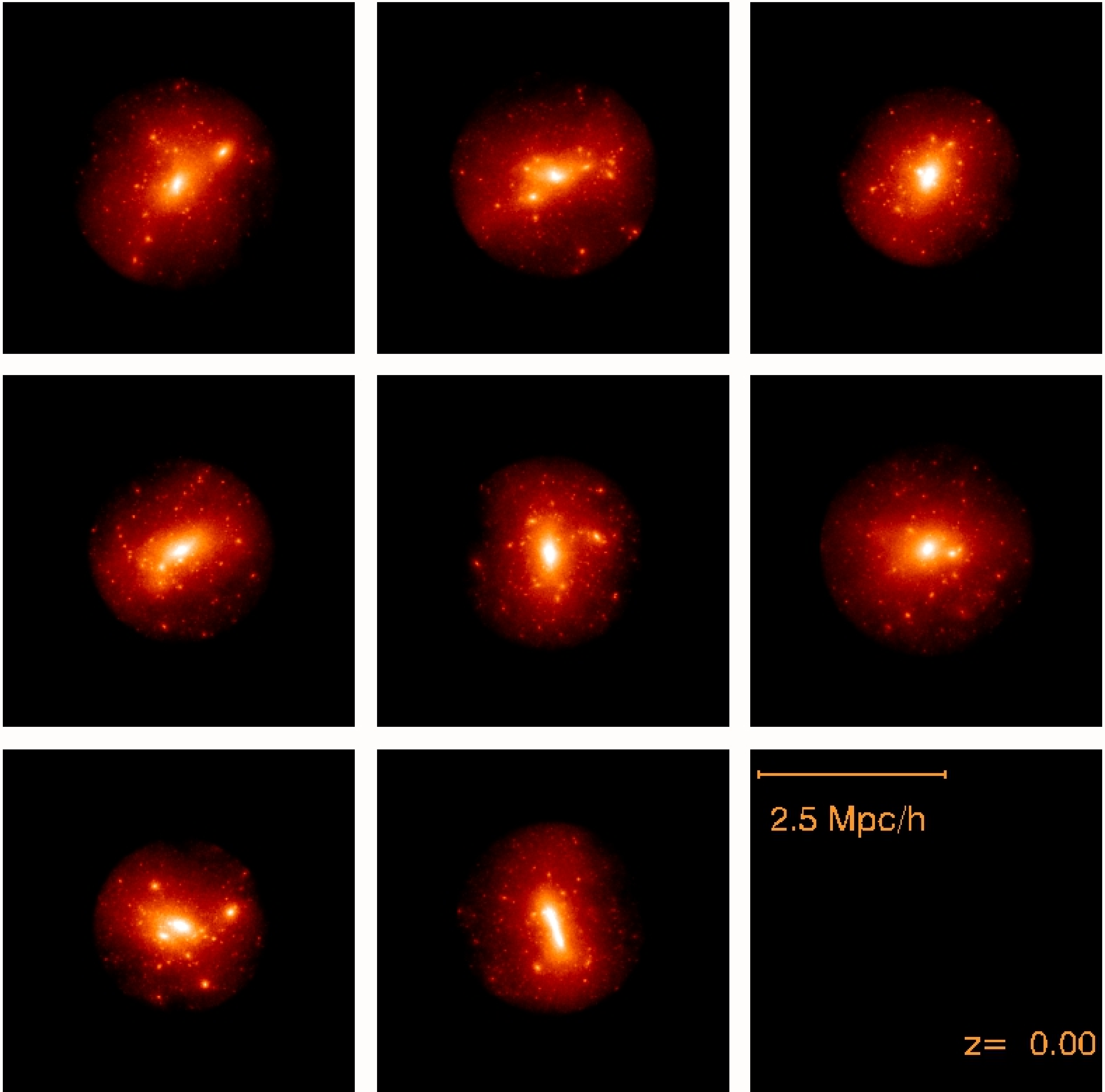


Bahcall, Fan & Cen 1997

For ΛCDM models cluster abundances at a given redshift set a single parameter.

Cluster evolution sets σ_8 and Ω_m separately

We show that the evolution of the number density of rich clusters of galaxies breaks the degeneracy between Ω (the mass density ratio of the universe) and σ_8 (the normalization of the power spectrum), $\sigma_8\,\Omega^{0.5} \simeq 0.5$, that follows from the observed present-day abundance of rich clusters. The evolution of high-mass (Coma-like) clusters is strong in $\Omega = 1$, low-σ_8 models (such as the standard biased CDM model with $\sigma_8 \simeq 0.5$), where the number density of clusters decreases by a factor of $\sim 10^3$ from $z = 0$ to $z \simeq 0.5$; the same clusters show only mild evolution in low-Ω, high-σ_8 models, where the decrease is a factor of ~ 10. This diagnostic provides a most powerful constraint on Ω. Using observations of clusters to $z \simeq 0.5 - 1$, we find only mild evolution in the observed cluster abundance. We find $\Omega = 0.3 \pm 0.1$ and $\sigma_8 = 0.85 \pm 0.15$ (for $\Lambda = 0$ models; for $\Omega + \Lambda = 1$ models, $\Omega = 0.34 \pm 0.13$). These results imply, if confirmed by future surveys, that we live in a low-density, low-bias universe.



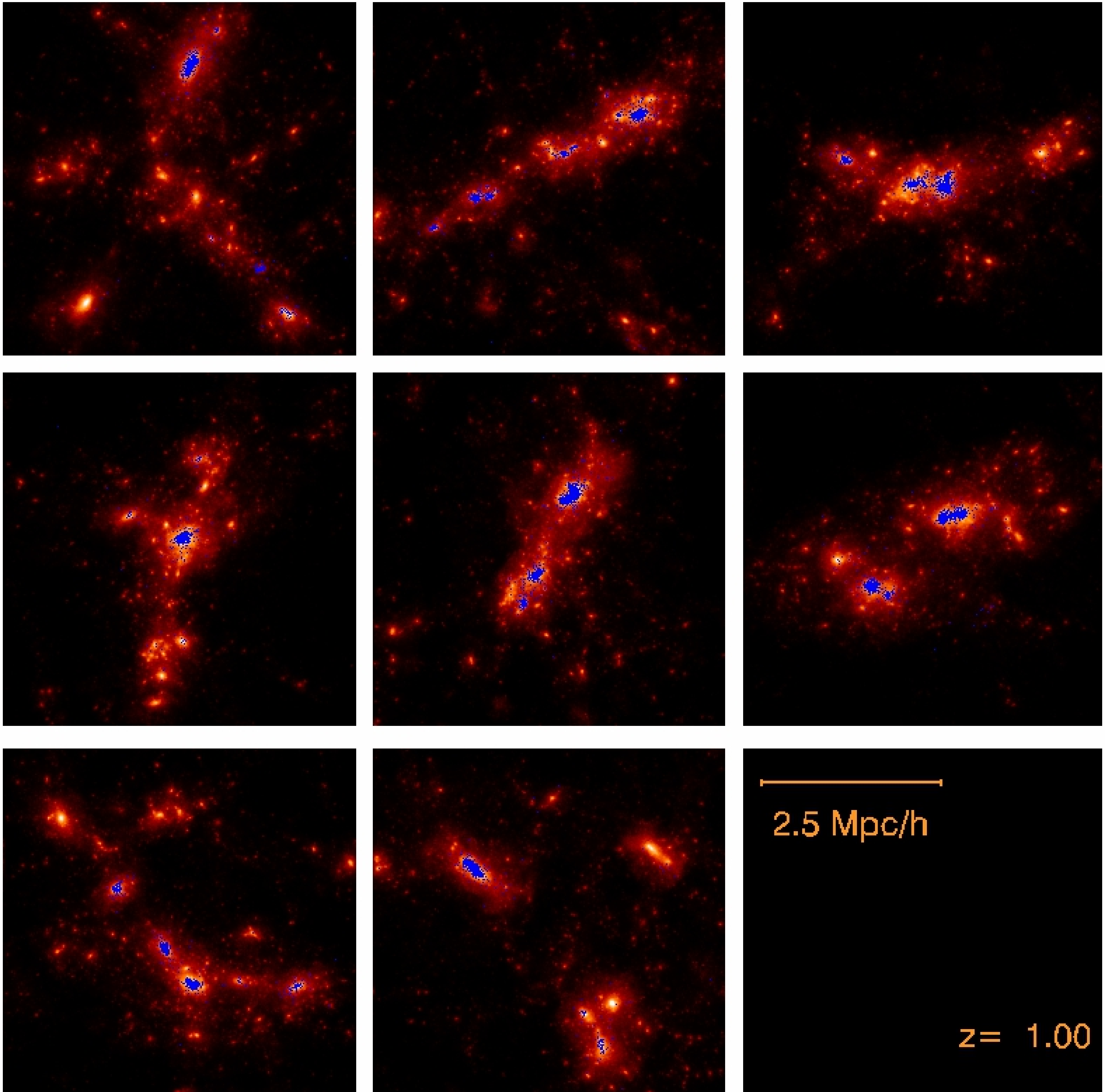
Cluster structure in ΛCDM

'Concordance' cosmology

Final cluster mass $\sim 10^{15}\,M_\odot$

Only DM within R_{200} at $z = 0$ is shown

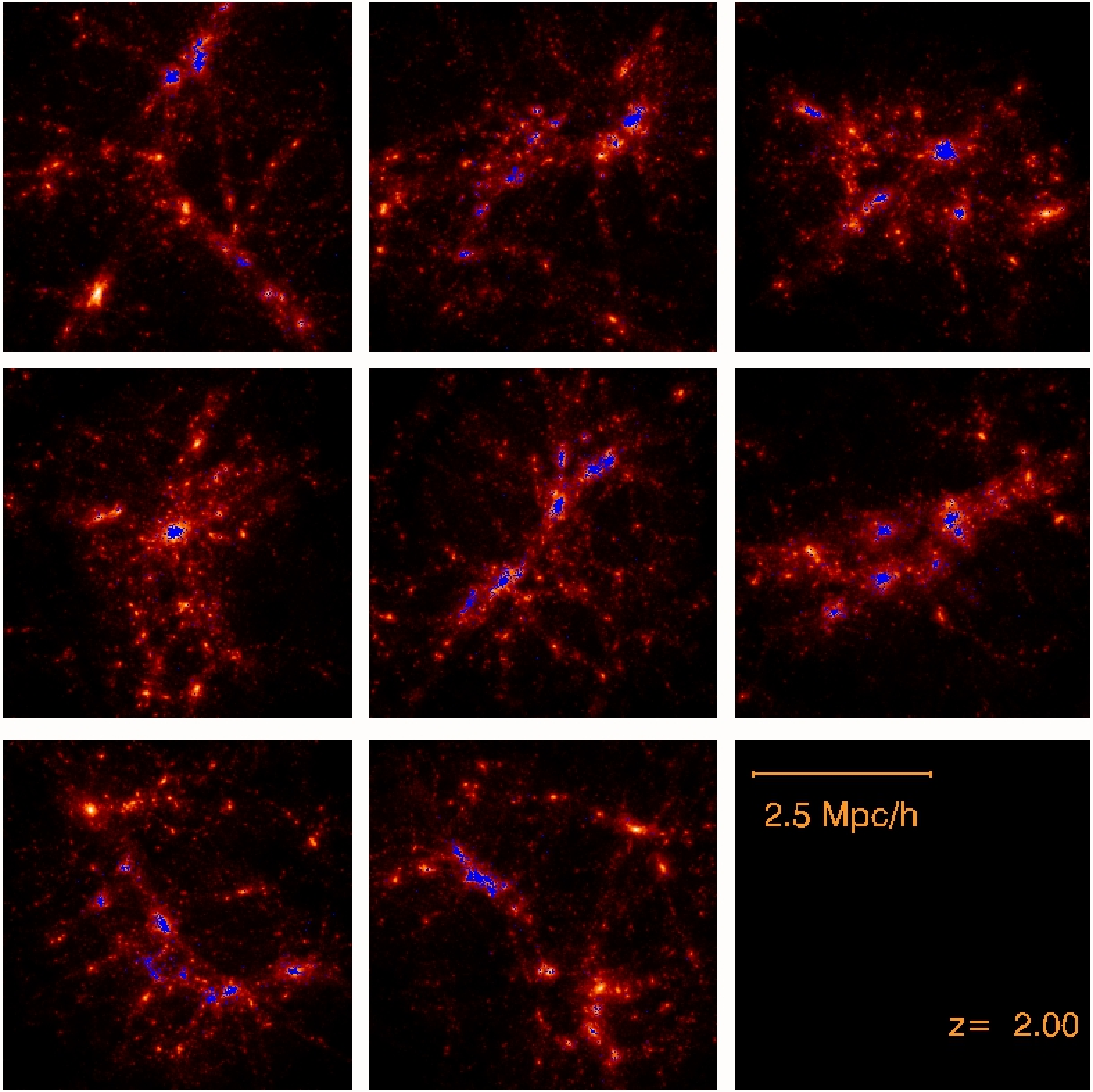
Cluster structure in ΛCDM



'Concordance' cosmology

Final cluster mass ~$10^{15}\,M_\odot$

DM within 20kpc at z = 0 is shown blue



Cluster structure in ΛCDM

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Final cluster mass $\sim 10^{15} M_\odot$

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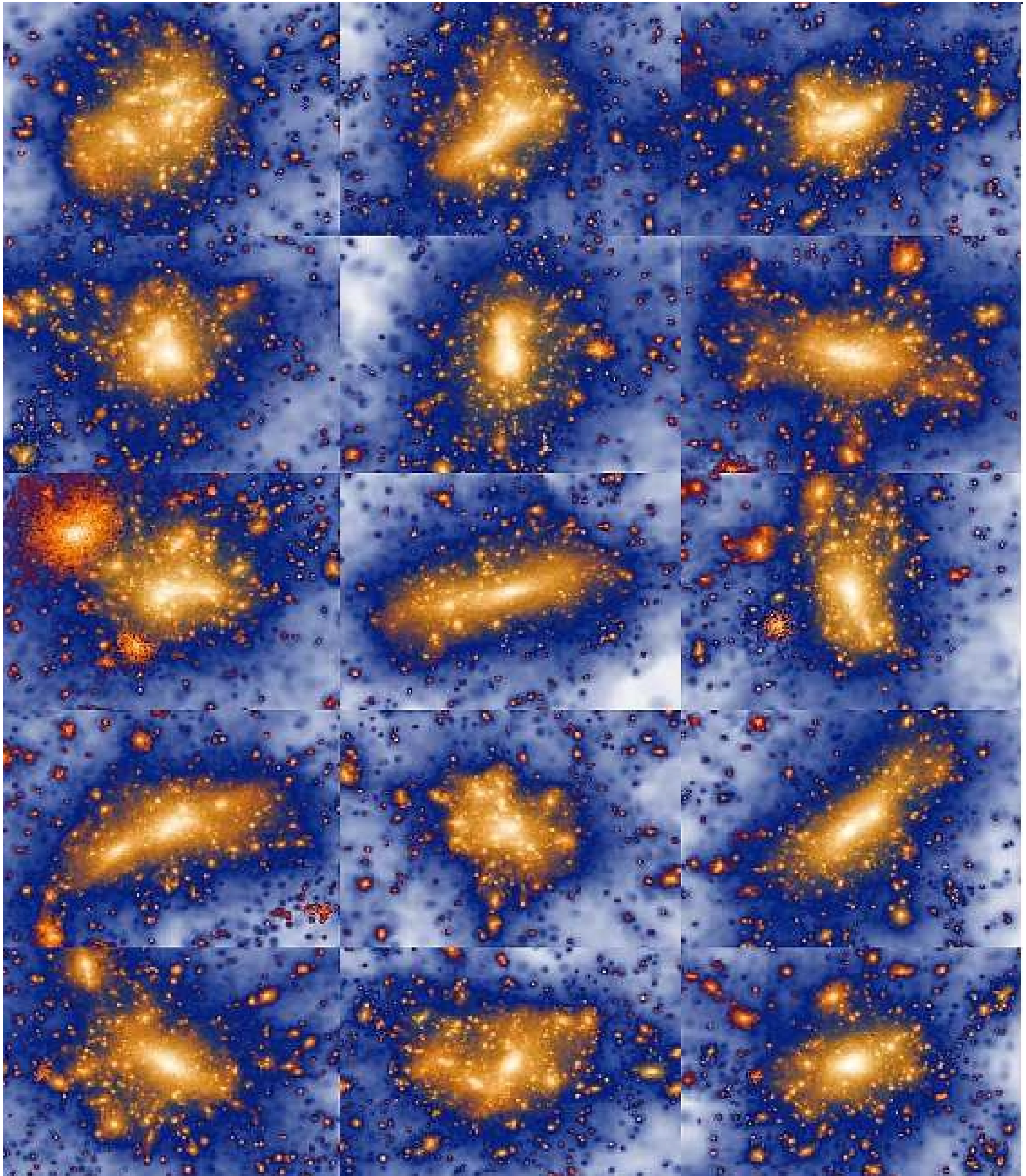
The fifteen most massive clusters in the Millennium-XXL



A $(4.3\ \mathrm{Gpc})^3$ DM-only simulation with high enough resolution to simulate galaxy formation in post-processing.

Extreme objects often look “weird”

5 Mpc

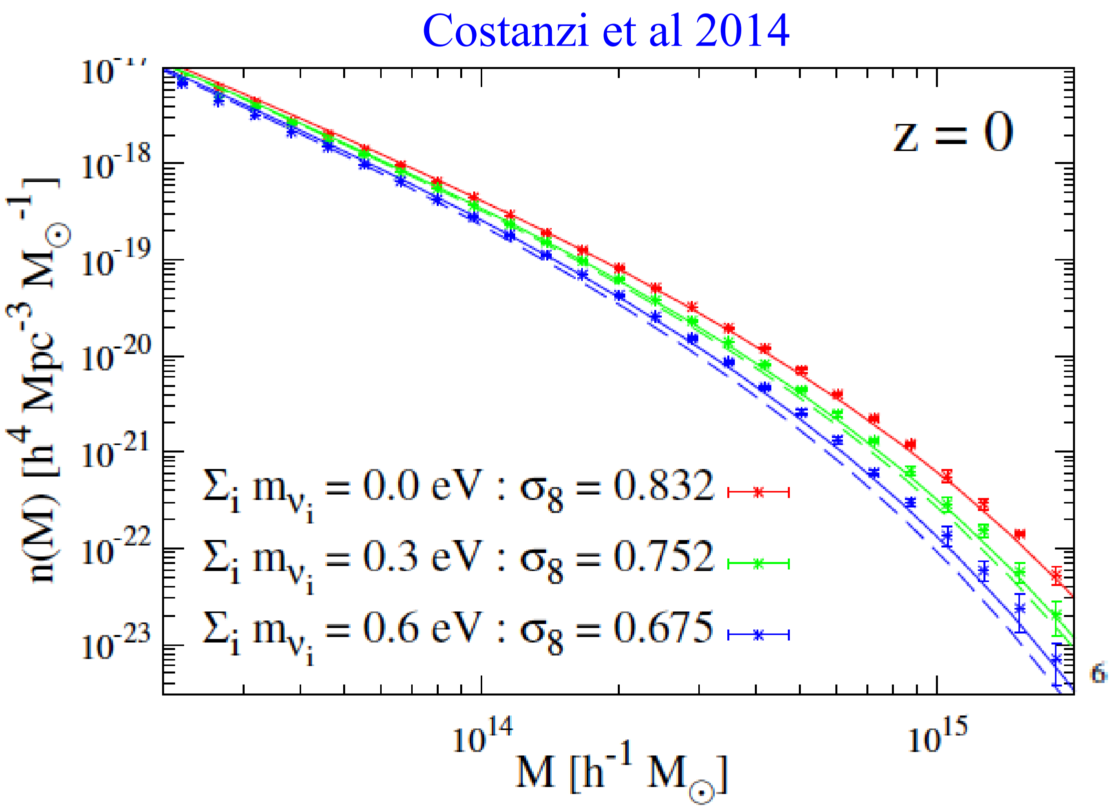
“Precision” cluster abundances?

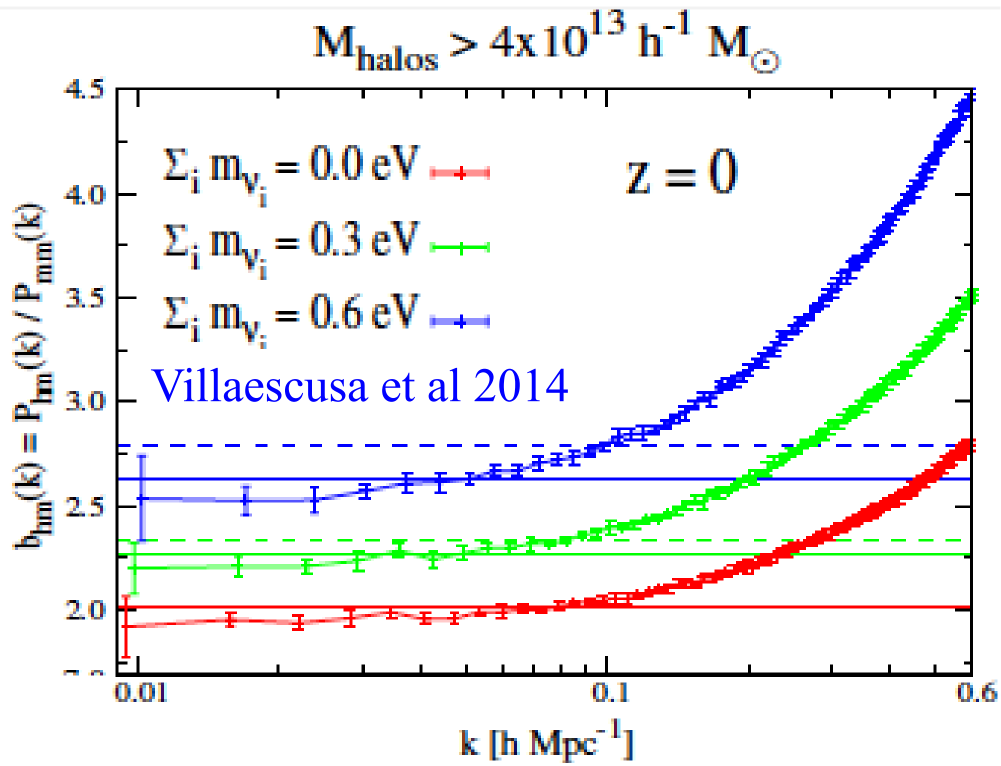
- Abundances as a function of **<u>mass</u>** can be calculated imprecisely from theory and measured precisely from (large enough) simulations
- They depend on the definition of mass (FoF, SO, M_{vir}, M_{200}....)
- Simulated abundances depend on <u>baryonic</u> physics (~5% in mass)
- Abundances are measured for samples selected observationally by
  Richness/optical flux, X-ray flux, SZ flux, lensing signal...
- … and as a function of <u>observationally inferred</u> mass, from
  N_{opt}, σ_{gal}, L_X, T_X, Y_X, Y, M_{lens}....

→ They depend sensitively on the Mass–Observable scaling relations both through sample selection and through mass estimation.

normalisations
slopes
(correlated) scatter

Neutrino effects on cluster abundance and clustering

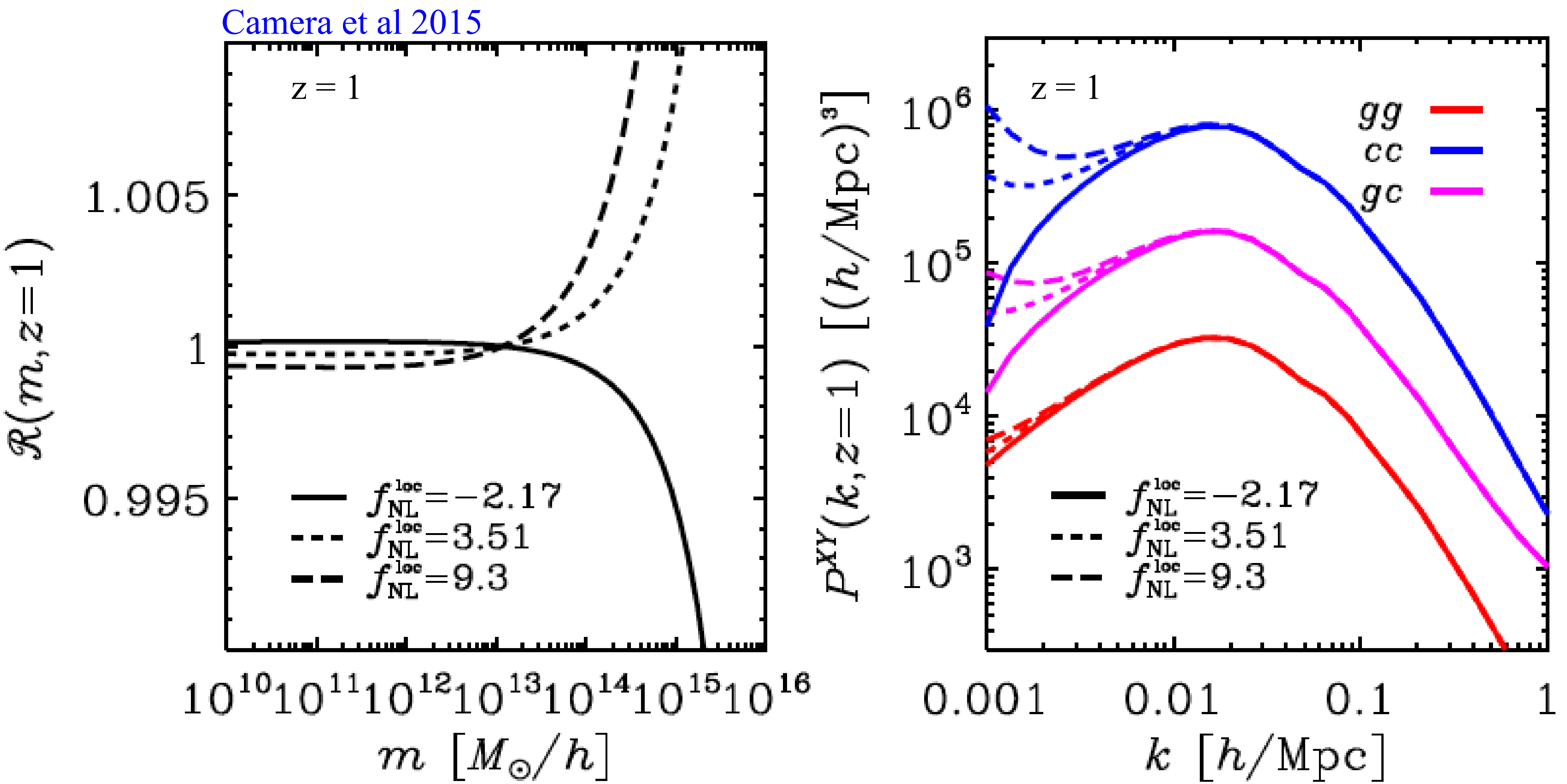




Non-negligible ν masses reduce the abundance of massive clusters for given CMB signal. $\Sigma\, m_\nu = 0.3$ eV is equivalent to a ~15% shift in mass

Neutrino masses also cause the bias of clusters to shift and become scale-dependent

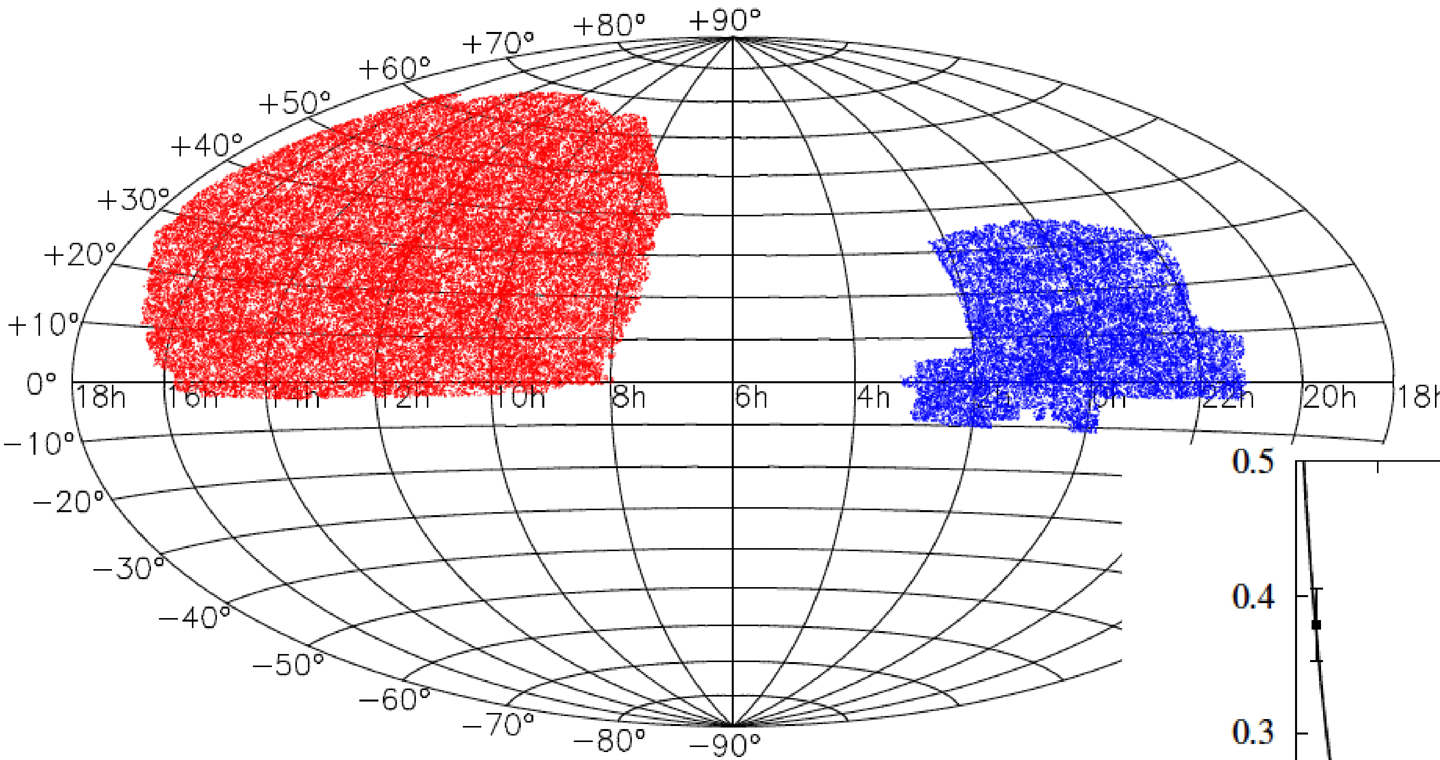
Primordial nongaussianity affects abundances and clustering



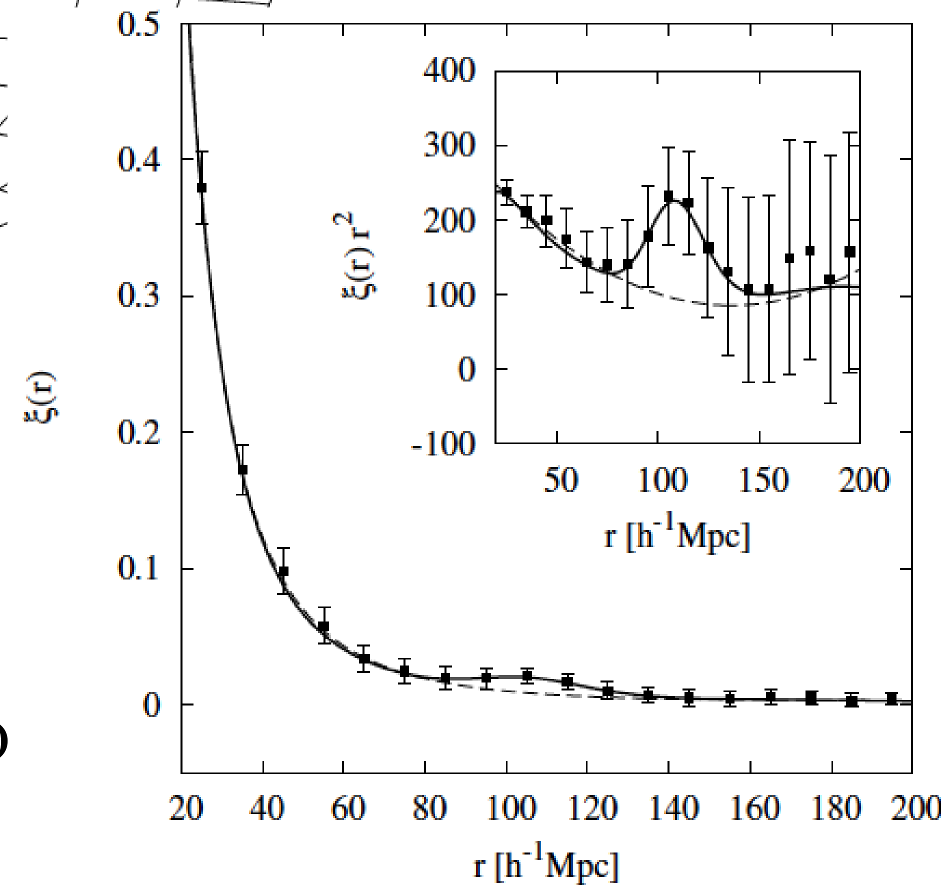
Levels of (local) nongaussianity allowed by *Planck* affect abundances at the 1% level for log M > 14.5, and power spectra for k < 0.01 h/Mpc

→ "Precision" cluster results will require marginalising over $f_{\rm NL}$

First >3σ detection of BAO in the cluster distribution

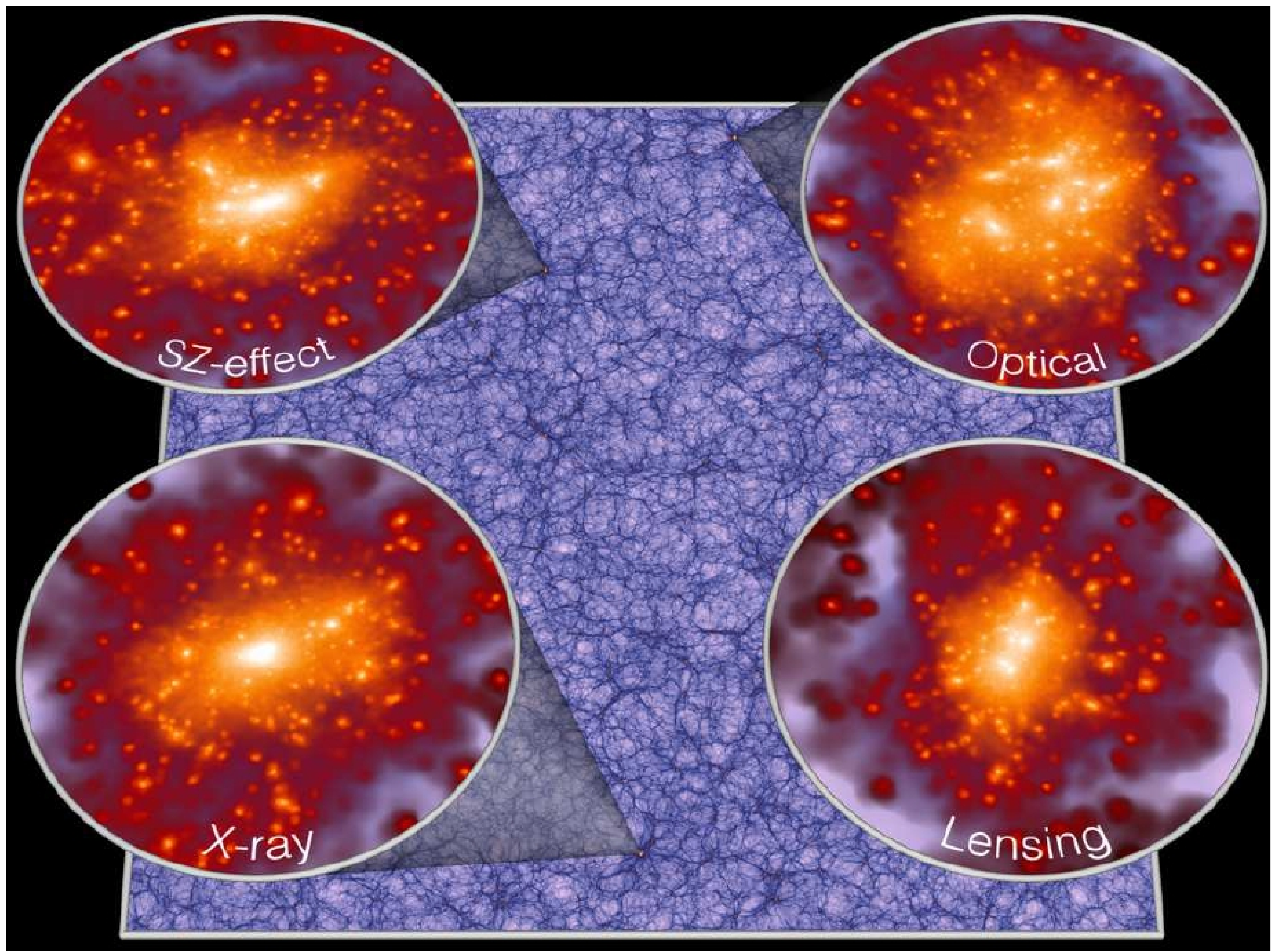


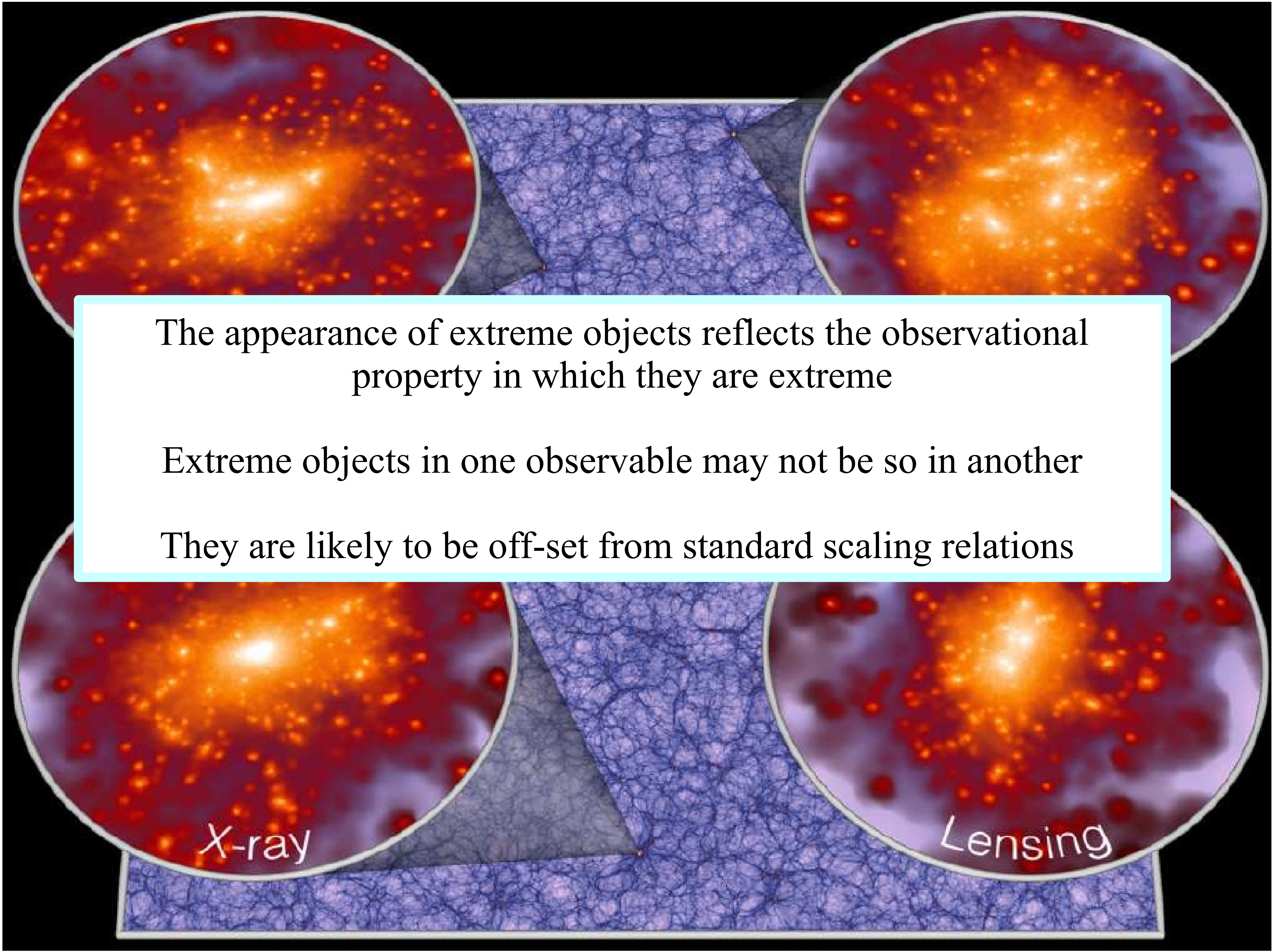
Hong et al 2015



79,000 clusters with $0.05 < z < 0.5$ found in SDSS/DR12 photometry and with spectroscopic redshifts from BOSS

Detection is at 3.9σ (c.f ~55σ for the BAO position for BOSS/DR12 LowZ galaxies)

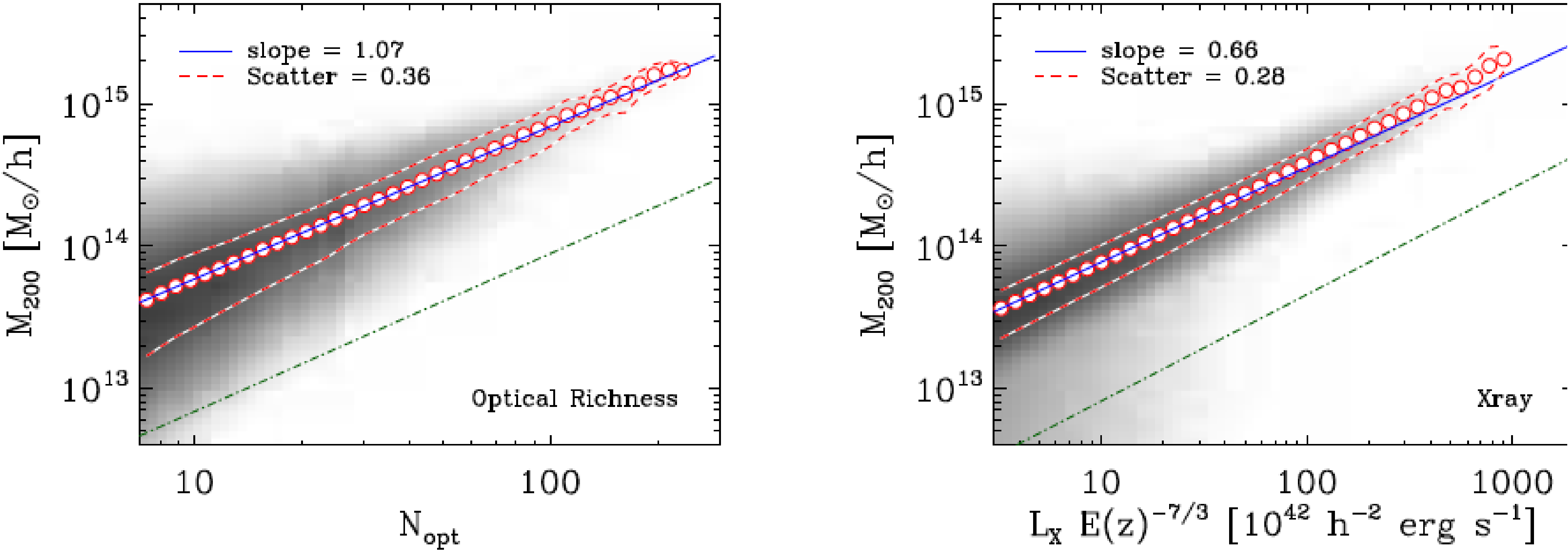

SZ-effect
Optical
X-ray
Lensing



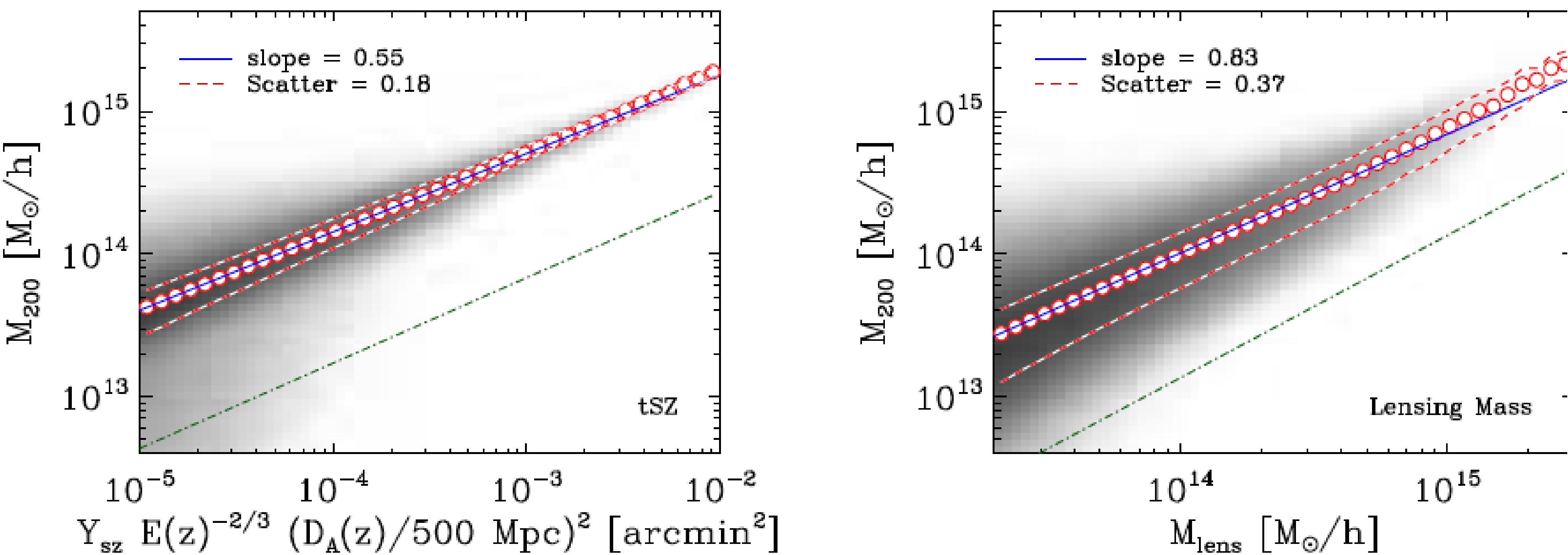
The appearance of extreme objects reflects the observational property in which they are extreme

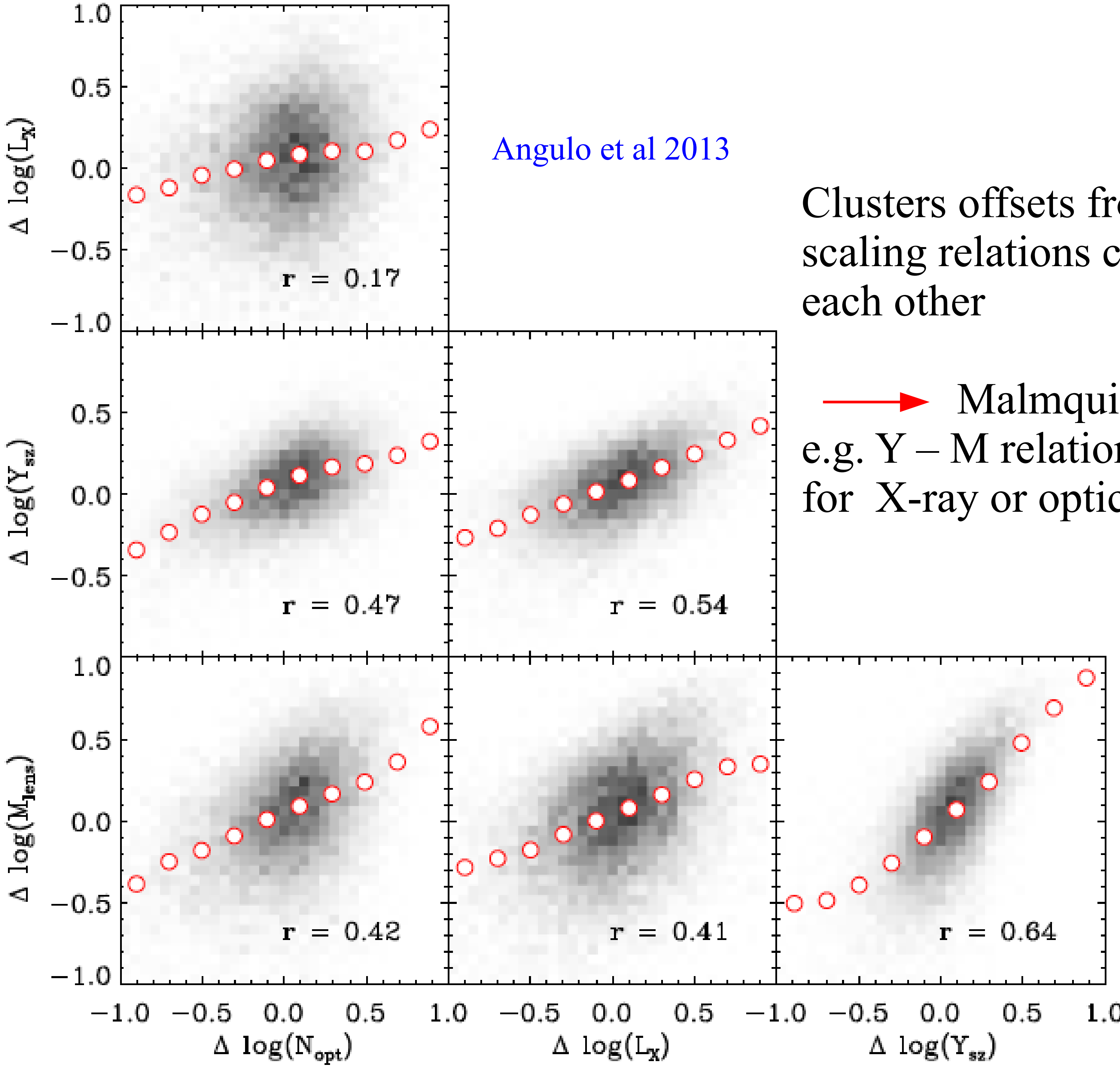
Extreme objects in one observable may not be so in another

They are likely to be off-set from standard scaling relations



Angulo et al 2013



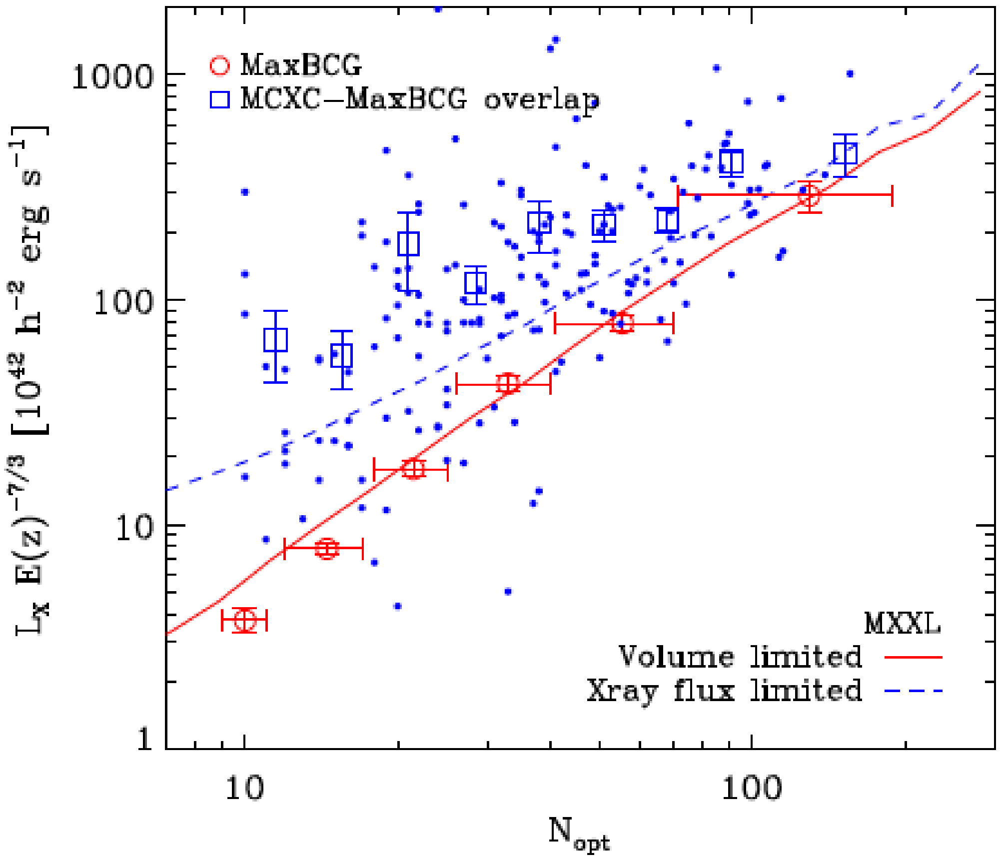


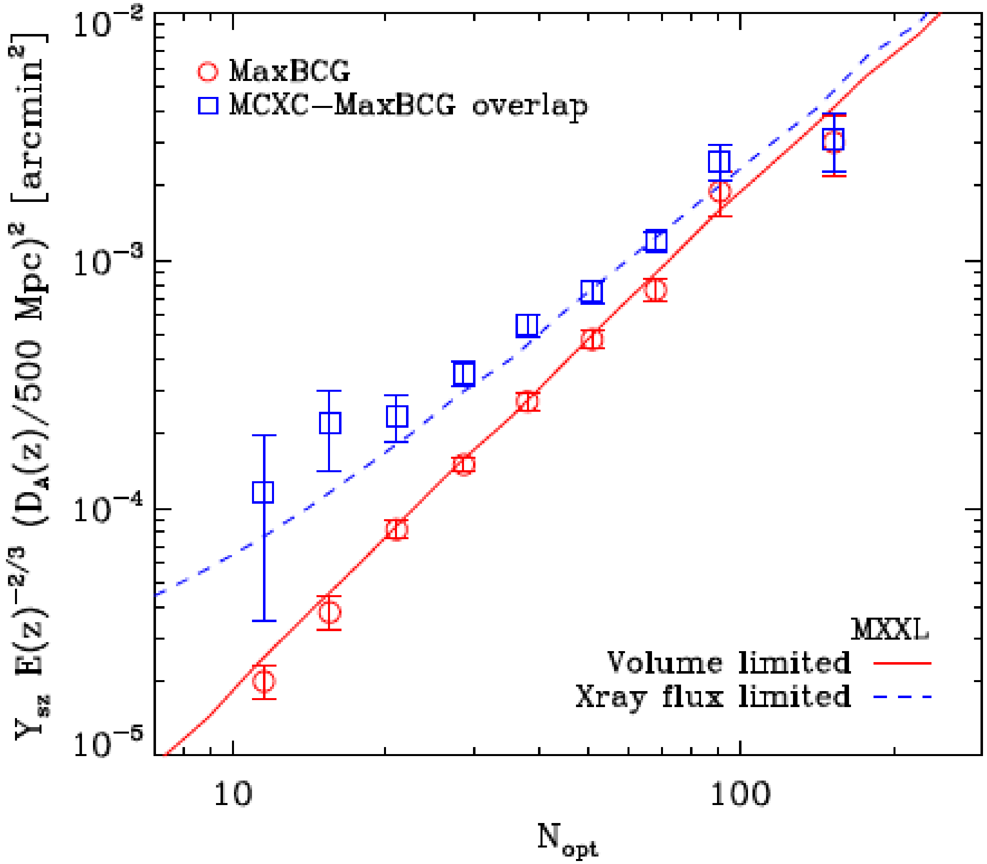
Angulo et al 2013

Clusters offsets from different scaling relations correlate with each other

→ Malmquist bias in, e.g. Y – M relations inferred for X-ray or optical samples

Angulo et al 2013



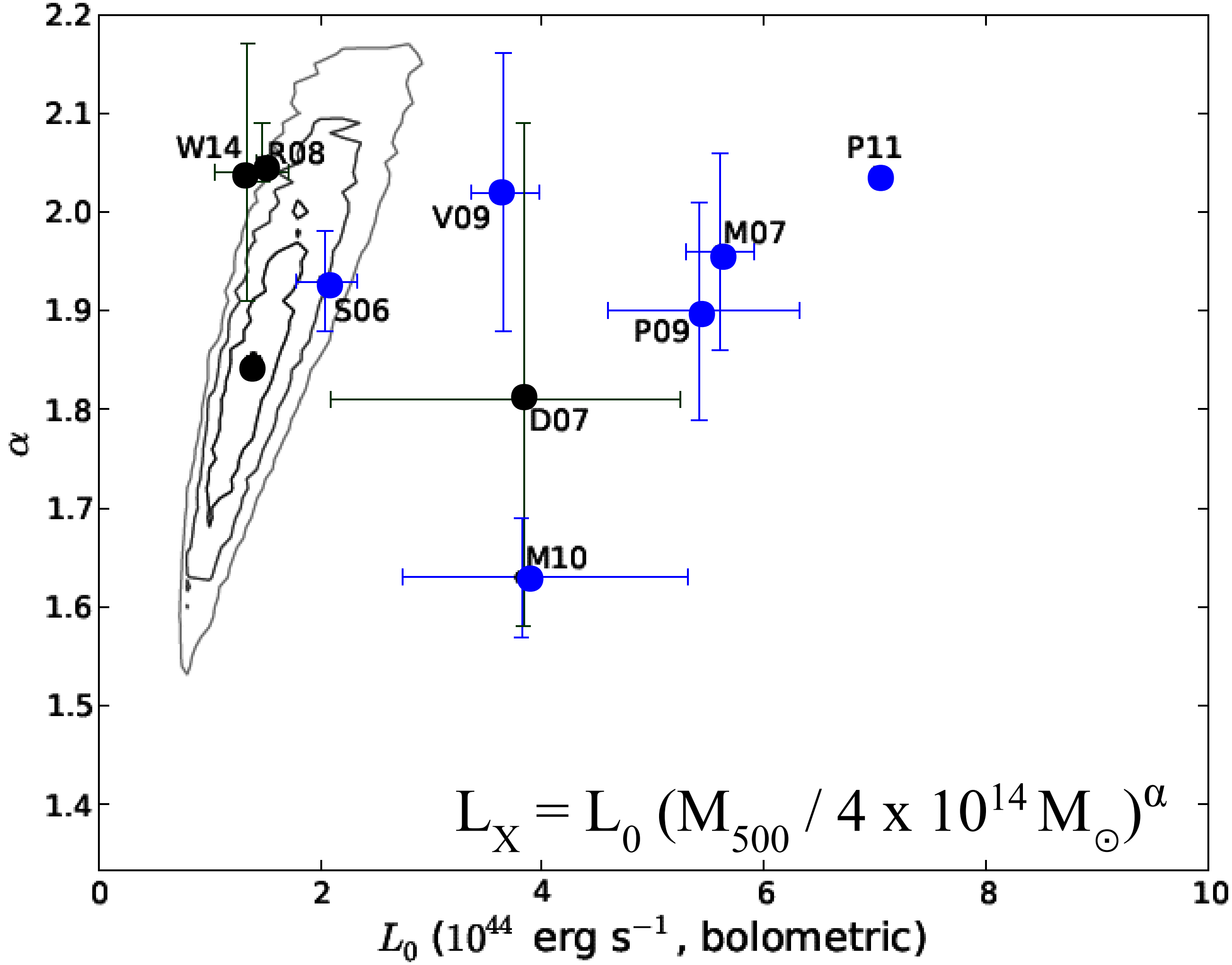


Scaling relations between observables depend on how the observational sample is selected.

This is predicted by the MXXL modelling and observed in maxBCG-ROSAT-Planck data.

The same is to be expected for observable-mass scaling relations.

Stacked Rosat X-ray signal from Locally Brightest Galaxies



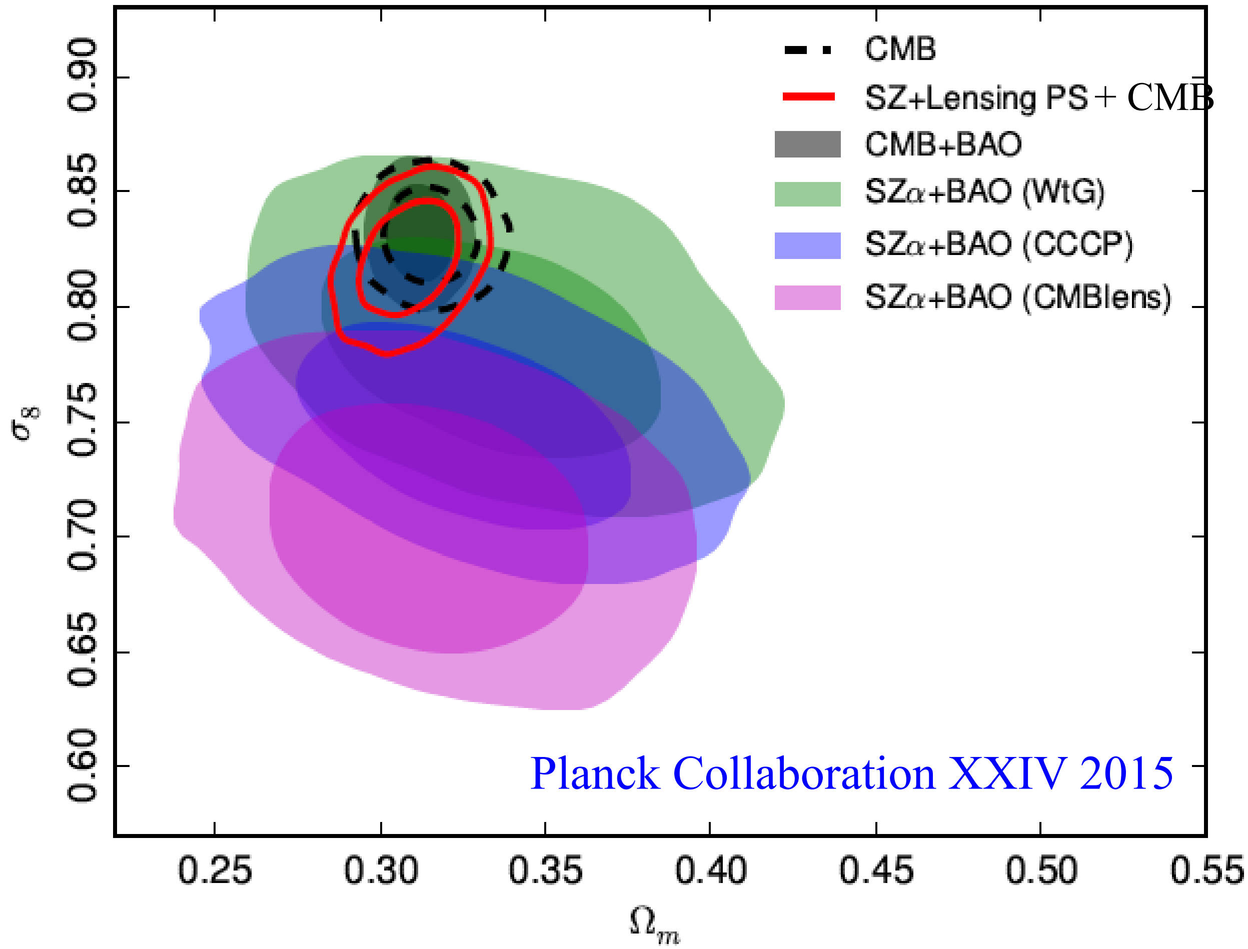
Anderson et al 2015

α = 4/3 is expected for self-similar halos with constant baryon fraction

X-ray luminosity grows much faster with mass than this

$L_X - M_{500}$ relation for LBG halos <u>agrees</u> with those for optically selected cluster samples (black symbols) but <u>disagrees</u> with most results for X-ray selected cluster samples (blue symbols)

Problems with cluster abundances?

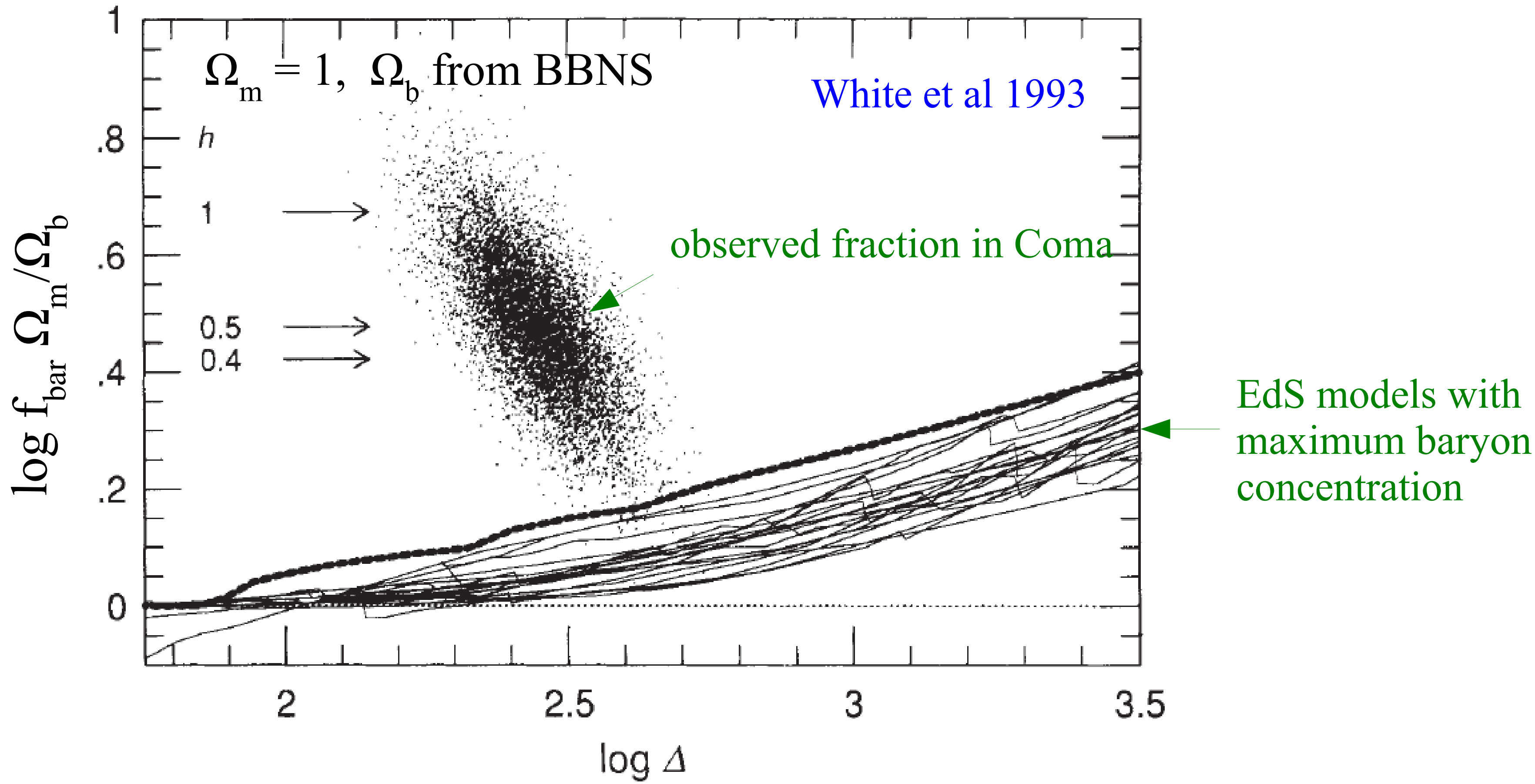


Effect of ν masses?

- Cluster counts as a function of SZ flux (or X-ray mass proxy) and z imply a lower σ_8 than *Planck* infers from primary CMB fluctuations

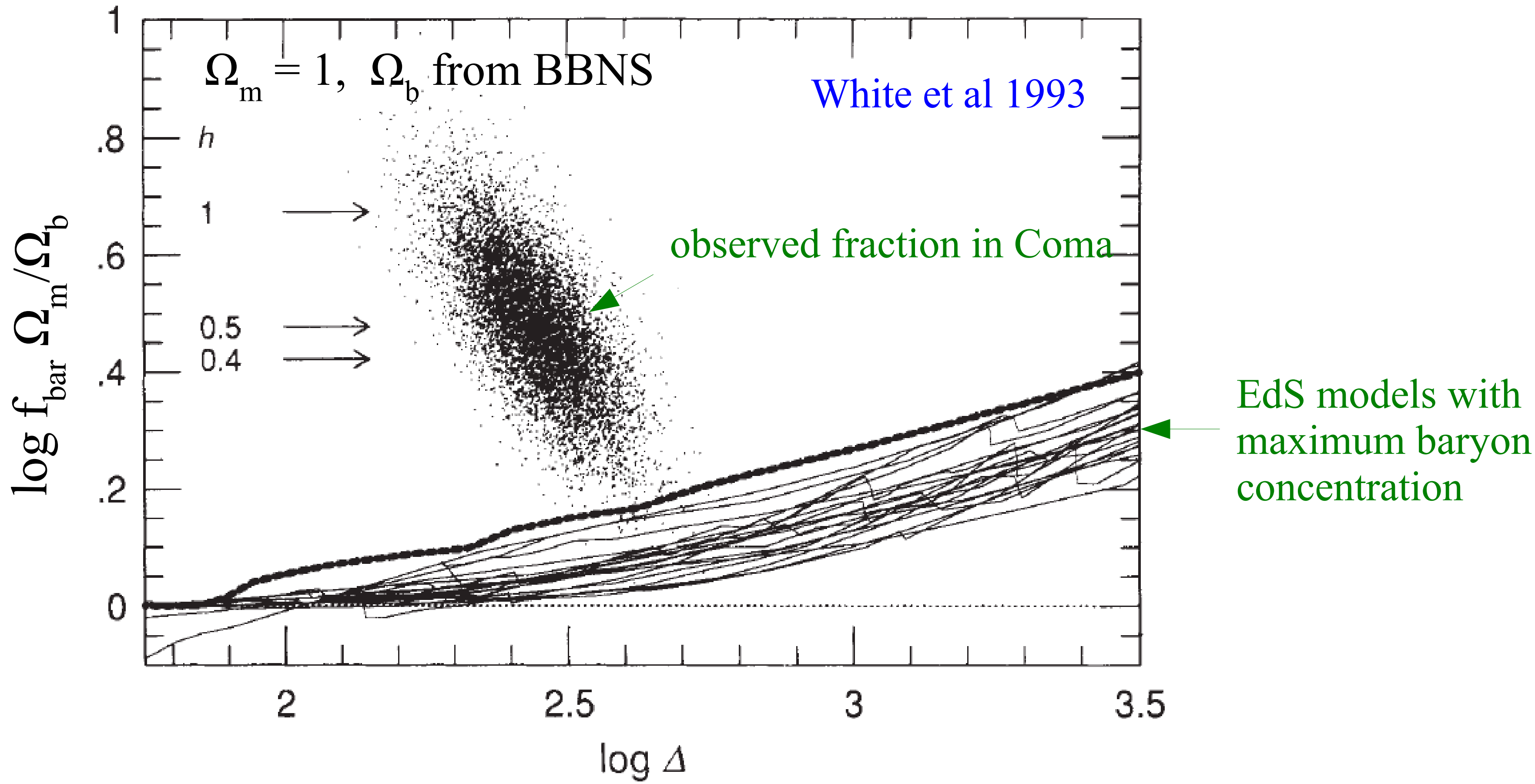
- This depends critically on the $M_h - Y$ or $M_h - Y_x$ calibration
  - – are calibrations obtained for the "right" clusters? –

The baryon fraction in galaxy clusters requires low Ω_m



Baryonic matter constitutes a larger fraction of the total mass of rich galaxy clusters than is predicted by a combination of cosmic nucleosynthesis considerations (light-element formation during the Big Bang) and standard inflationary cosmology. This cannot be accounted for by gravitational and dissipative effects during cluster formation. Either the density of the Universe is less than that required for closure, or there is an error in the standard interpretation of element abundances.

The baryon fraction in galaxy clusters requires low Ω_m



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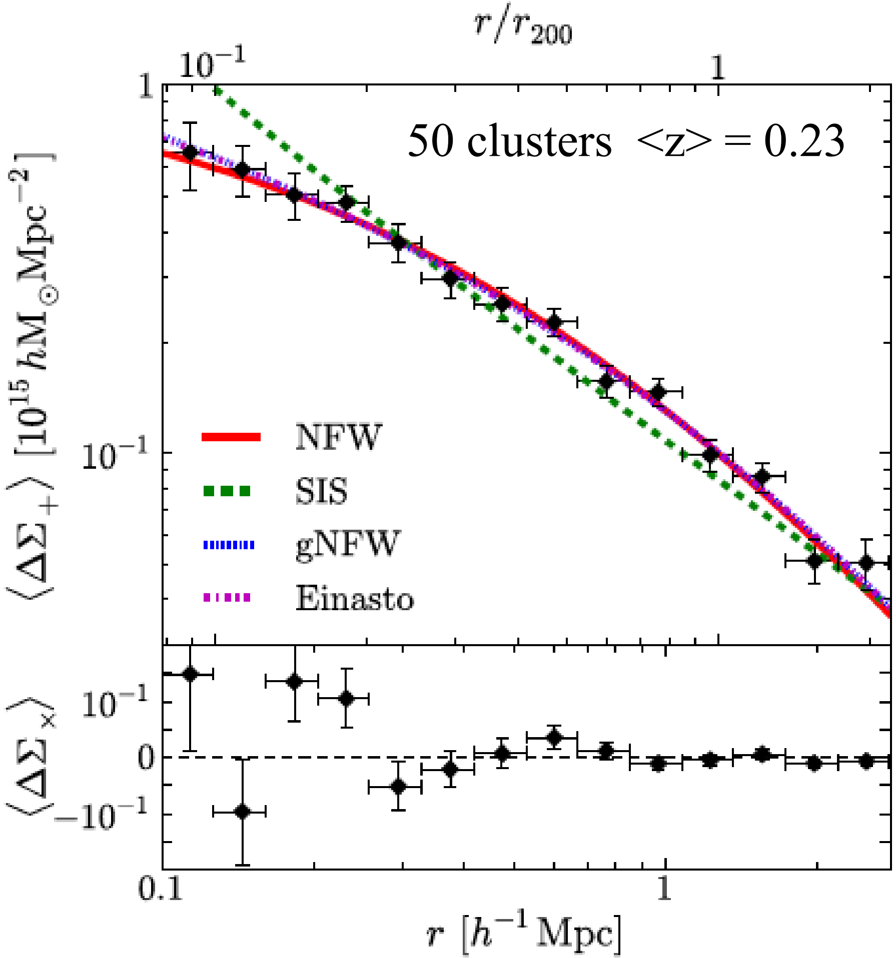
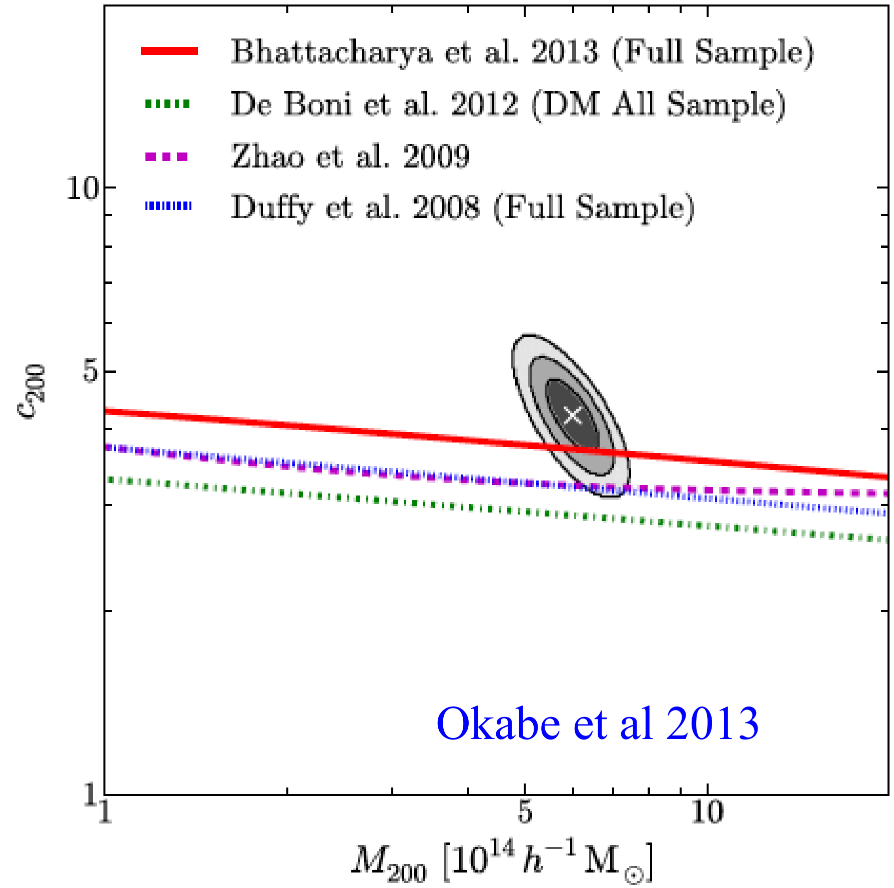
… but *Planck* has now measured Ω_m/Ω_b to 1%, finding agreement with BBNS

→ constraints on cluster formation physics rather than cosmology

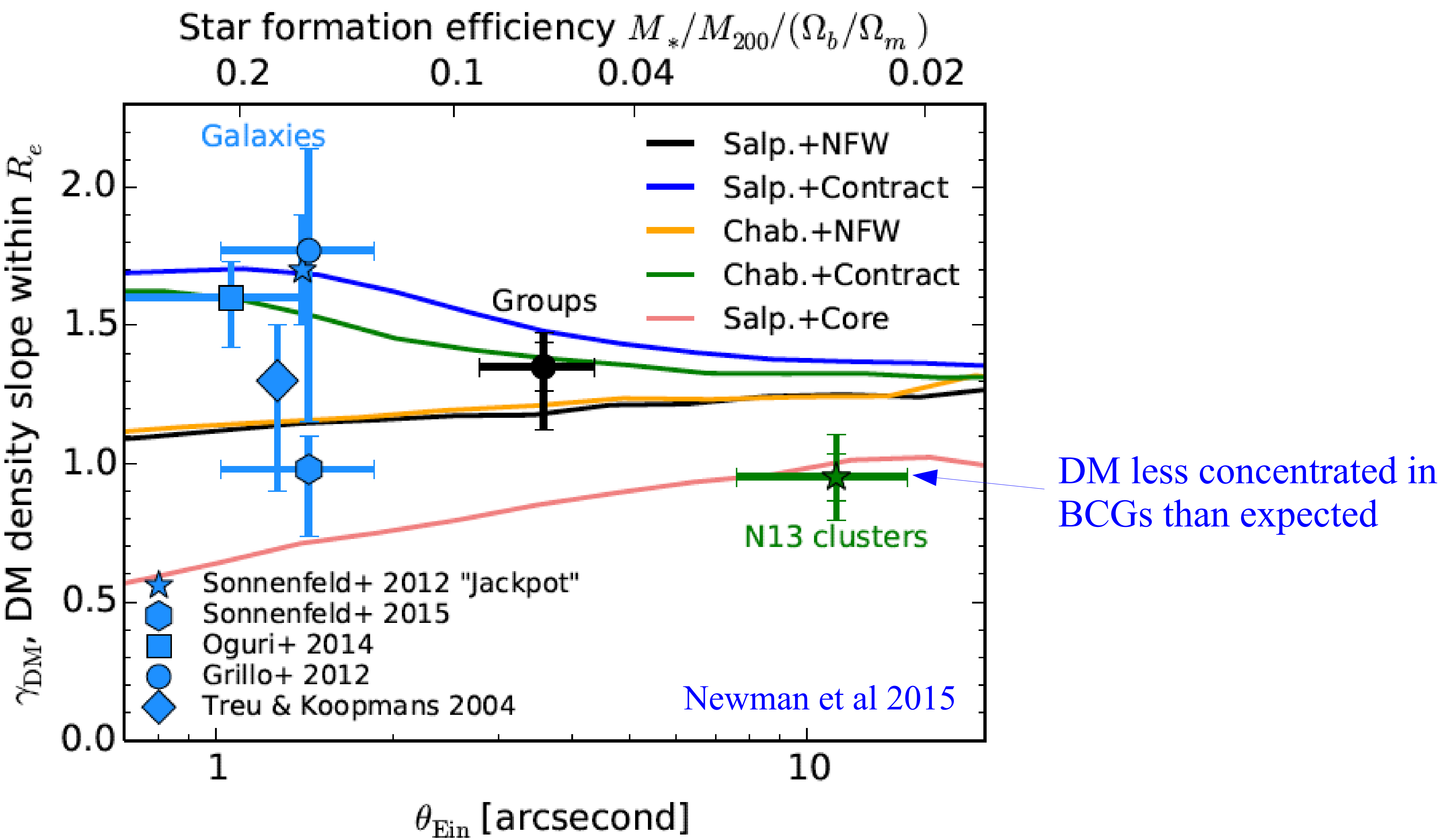
The mass profiles of massive galaxy clusters





- The mean density profile of rich clusters has the predicted ΛCDM shape
- This is effectively a one-parameter fit (the mean cluster mass)
- Using masses from abundance matching → a zero-parameter test!

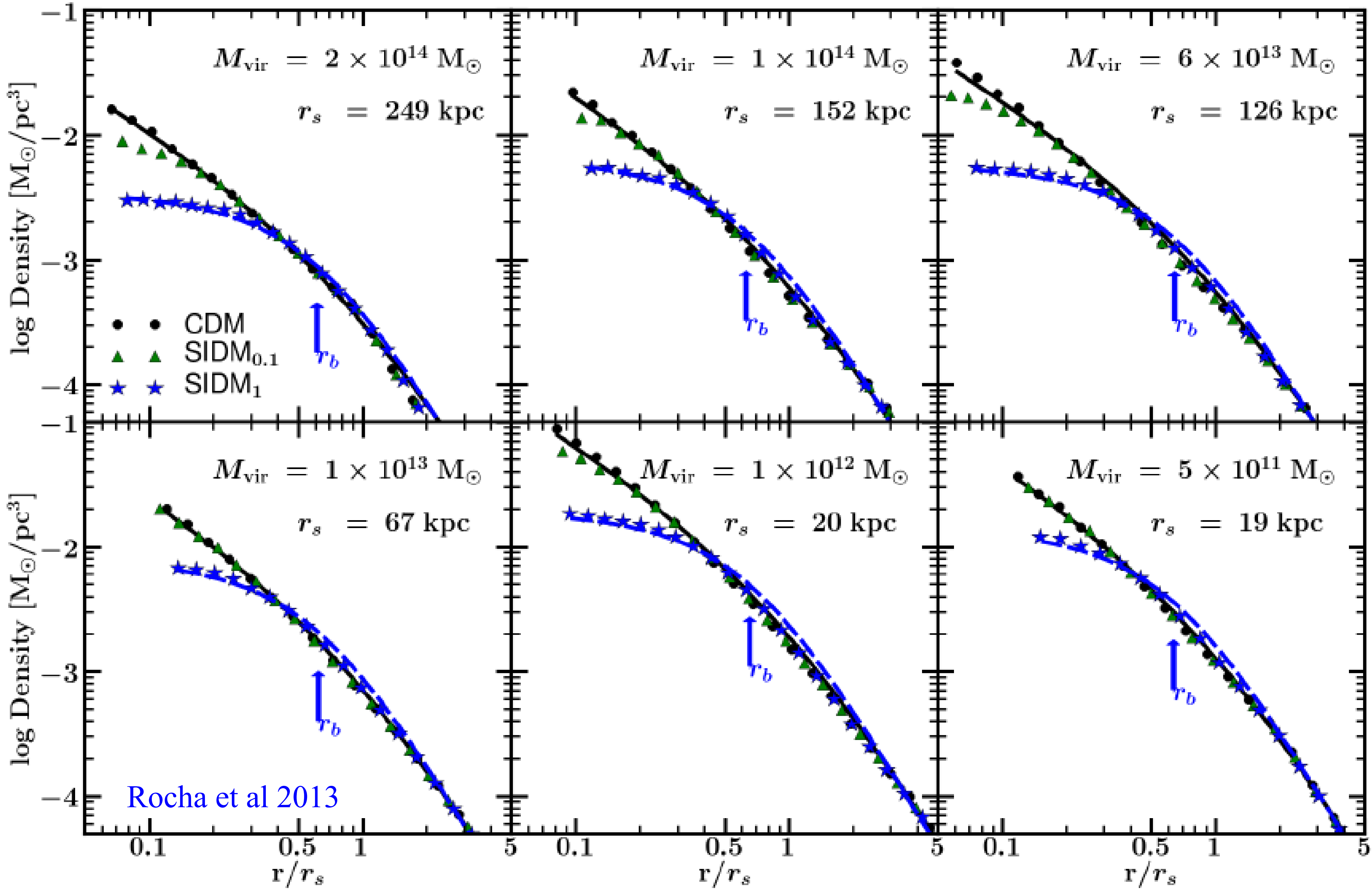
Dark matter profiles within cluster/group central galaxies



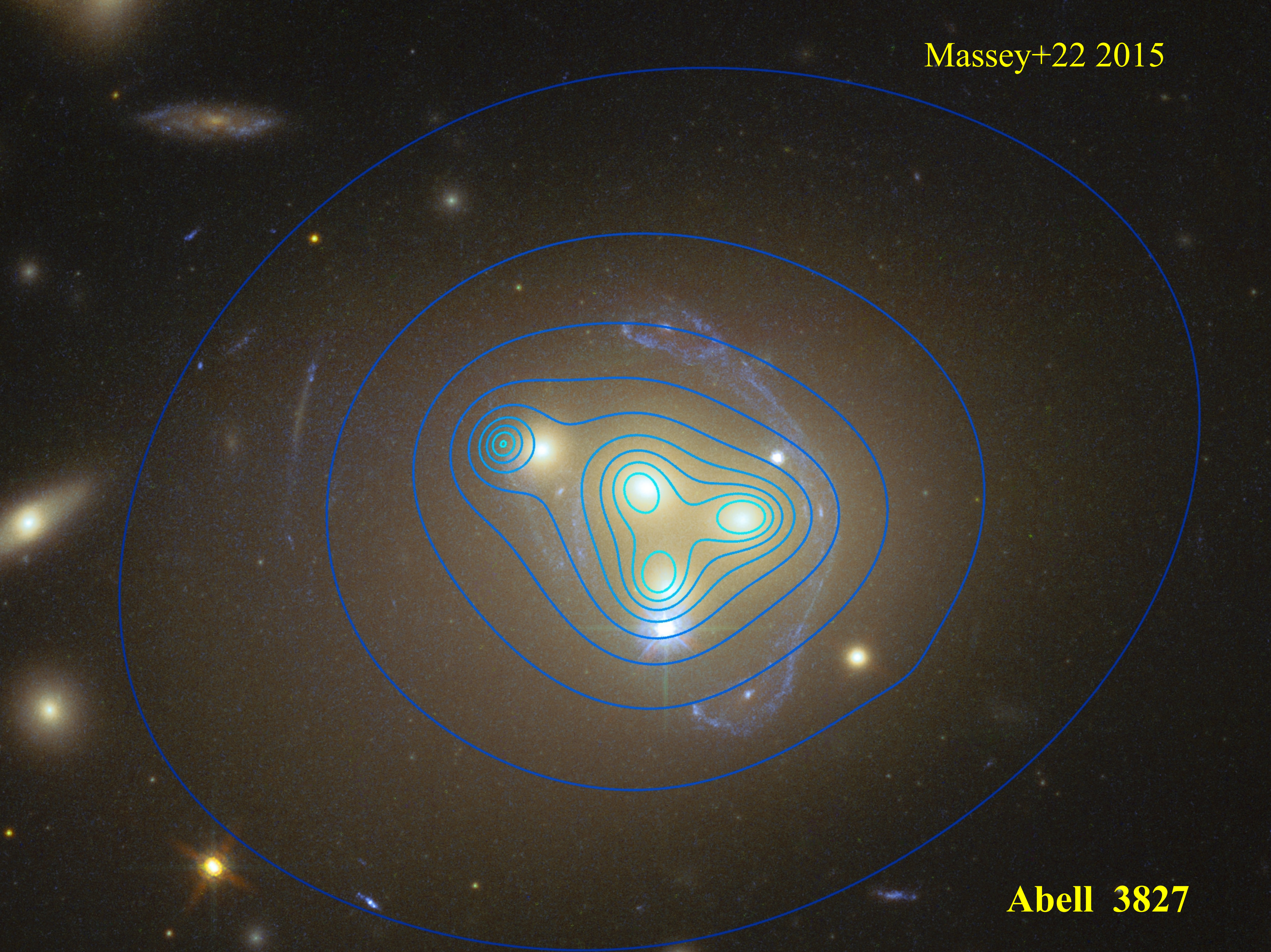
Strong lensing and kinematics constrain the total mass profile
Subtracting an estimate of the stellar mass profile constrains the DM profile

Bullet cluster structure implies a long mean-free-path for DM particles

→ constraints on self-interacting DM.



Velocity-independent elastic collision cross-sections $\sigma/m \sim 1\ cm^2/g$ result in Cores that are too big in both clusters and galaxies. $\sim 0.1\ cm^2/g$ looks OK.


Massey+22 2015
Abell 3827

Summary

- The level of precision already reached by CMB and galaxy BAO surveys has substantially "raised the bar" for cluster cosmology
- Cluster cosmology using abundances is no longer limited by sample size but by systematics in scaling relations and their evolution
- The scatter in scaling relations and correlated scatter between different scaling relations are important and affect current results
- Baryon effects on cluster properties cannot be ignored when aiming for precision results
- Cluster structure may encode significant information about the nature of dark matter