The cosmological implications of high-redshift, massive galaxy clusters.

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Shaun Hotchkiss University of Helsinki: Hoyle et al 2011 (+ in prep)

Cape Town: 23/08/2011

Overview

- The LCDM model
- Galaxy Clusters
- -as probes of cosmology
- -as extreme objects
- Observational motivation: extreme objects
- Theory: non-Gaussian cluster mass function
- The cluster sample
- The XMM Cluster Survey
- What we did; Analysis and results using >M,>z
- What we found; Possible explanations, Systematics
- What others thought: Related work
- Why we were all wrong: Understanding the >M,>z question
- New, correct analysis and results
- Conclusions + future work

ΛCDM

The concordance cosmological model LCDM, stands for Lambda (repulsive energy density) Cold Dark Matter(non-relativistic matter, transparent to E.M. radiation). It is built on the assumptions that the universe is well describe by Einstein's gravity, and that it is homogeneous and isotropic. The model parameters are determined by some observations, and then used to predict a vast number of other observations, with remarkable accuracy.

Measured cosmological parameters							
Tests of geometry							
Probe	Reference	Parameters					
		Ω_b	Ω_{DM}	Ω_Λ	$H_0^\star$	σ_8
CMB	Dunkley et al. (2009)	0.0441 ± 0.003	0.214 ± 0.027	0.742 ± 0.030	$71.9^{+2.6}_{-2.7}$	0.796 ± 0.036
CMB + BAO + SNe	Dunkley et al. (2009)	0.0462 ± 0.002	0.233 ± 0.013	0.721 ± 0.015	70.1 ± 1.3	0.817 ± 0.026
SNe Ia	Astier et al. (2006)	0.31 ± 0.21		0.80 ± 0.31	–	–
SNe Ia + BAO	Astier et al. (2006)	0.27 ± 0.02		0.75 ± 0.08	–	–
BAO + SNe + CMB	Percival et al. (2007)	0.252 ± 0.027		0.743 ± 0.047	–	–
Tests of the growth of structure							
Clusters + CMB	Rozo et al. (2009)	0.265 ± 0.016		$1 - \Omega_m$	–	0.807 ± 0.020

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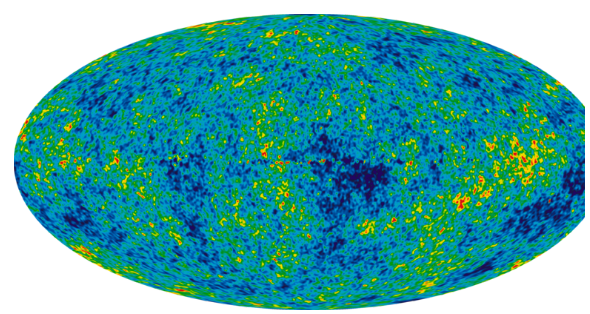
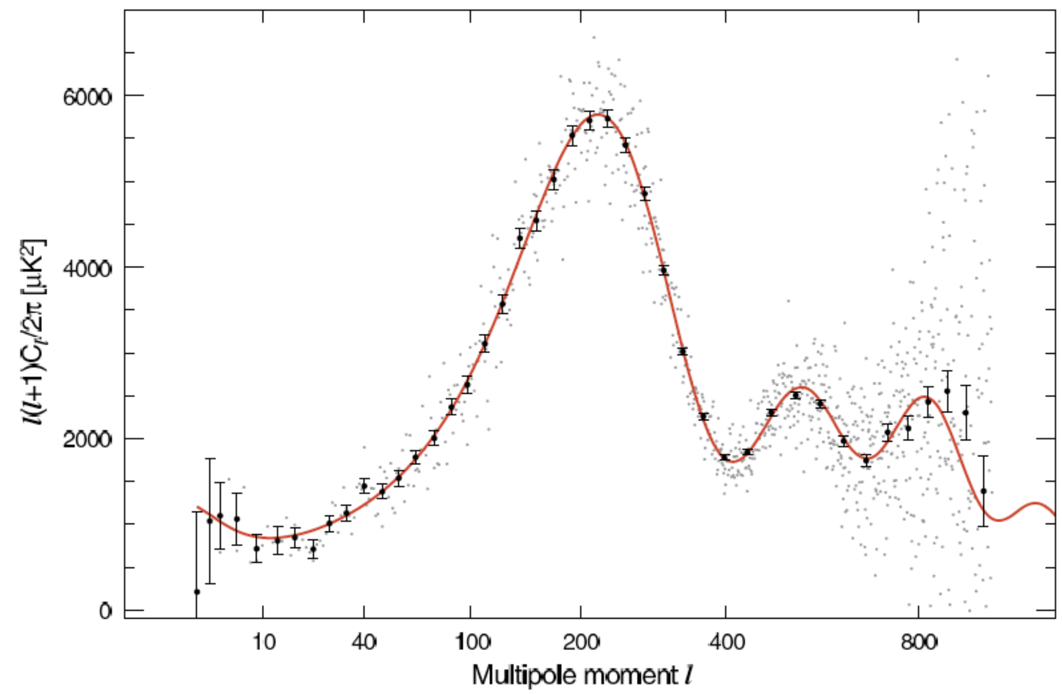
The CMB is the relic radiation left over after the Big Bang, and has almost the same temperature in every direction on the sky. There are tiny Gaussian temperature fluctuations of size ~10^{-5}. The CMB suggests that the Universe is geometrically flat.

All galaxies and clusters of galaxies grew out of these initial variations in the density field





Dunkley et al 2009

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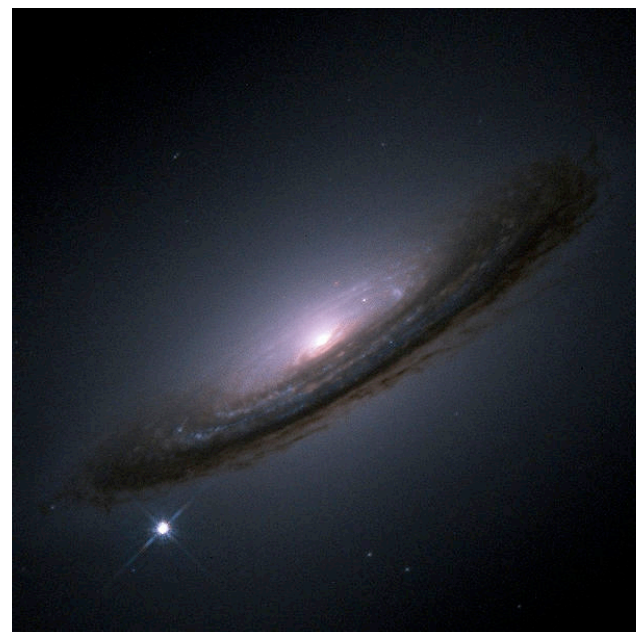
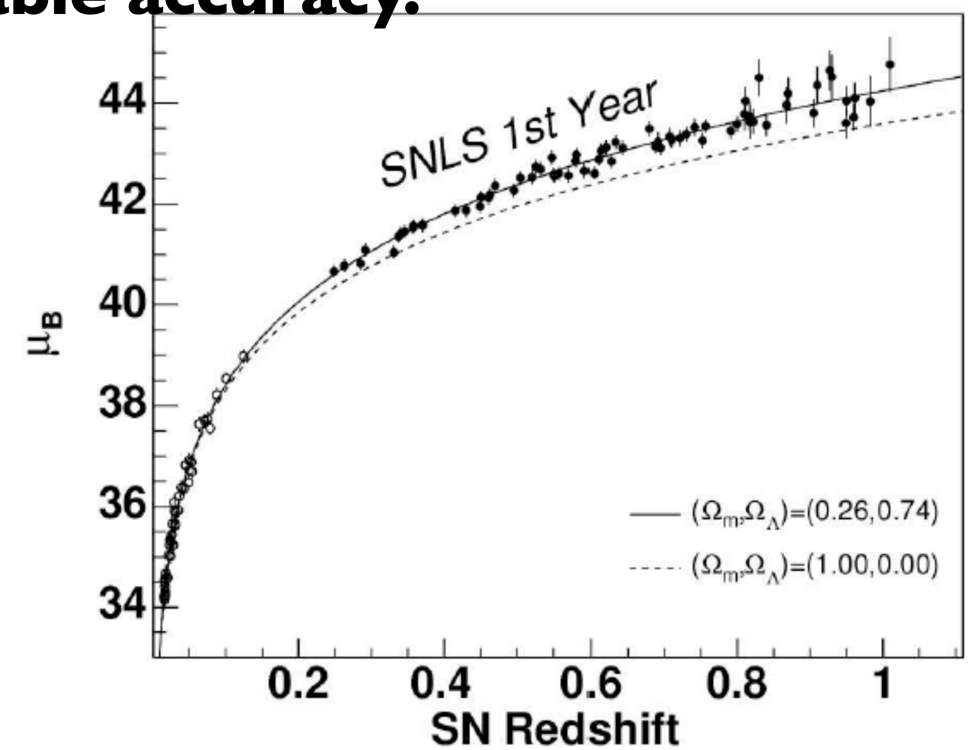
Certain types of Supernova an be used as "standardizable candles" which act as an independent measure of distance. They suggest that he Universe is accelerating in its expansion.





Astier et al 2006

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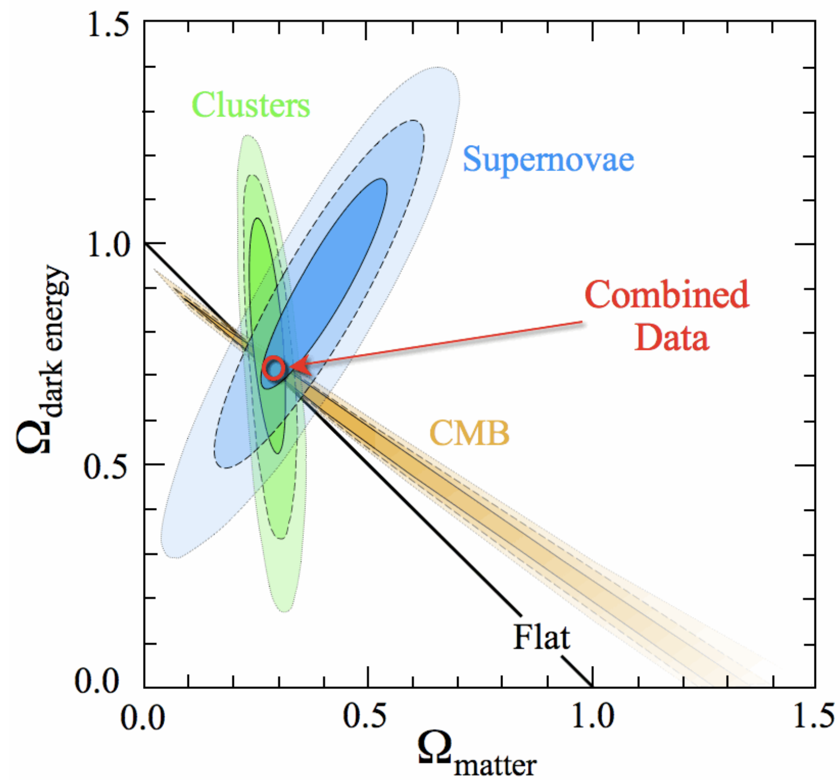
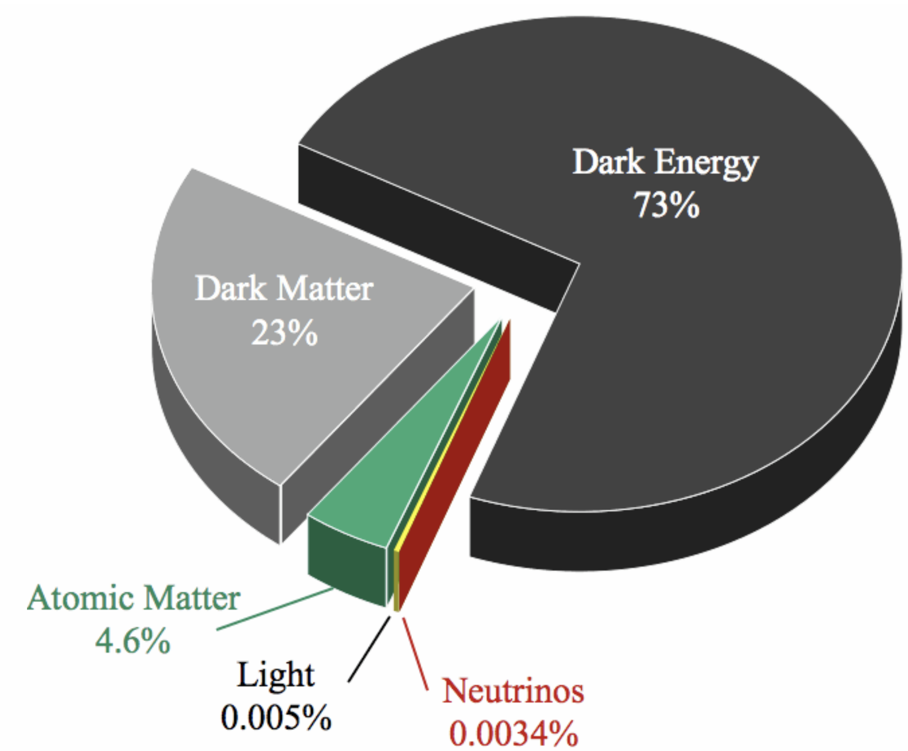
These probes (and others) determine the values of the cosmological parameters.





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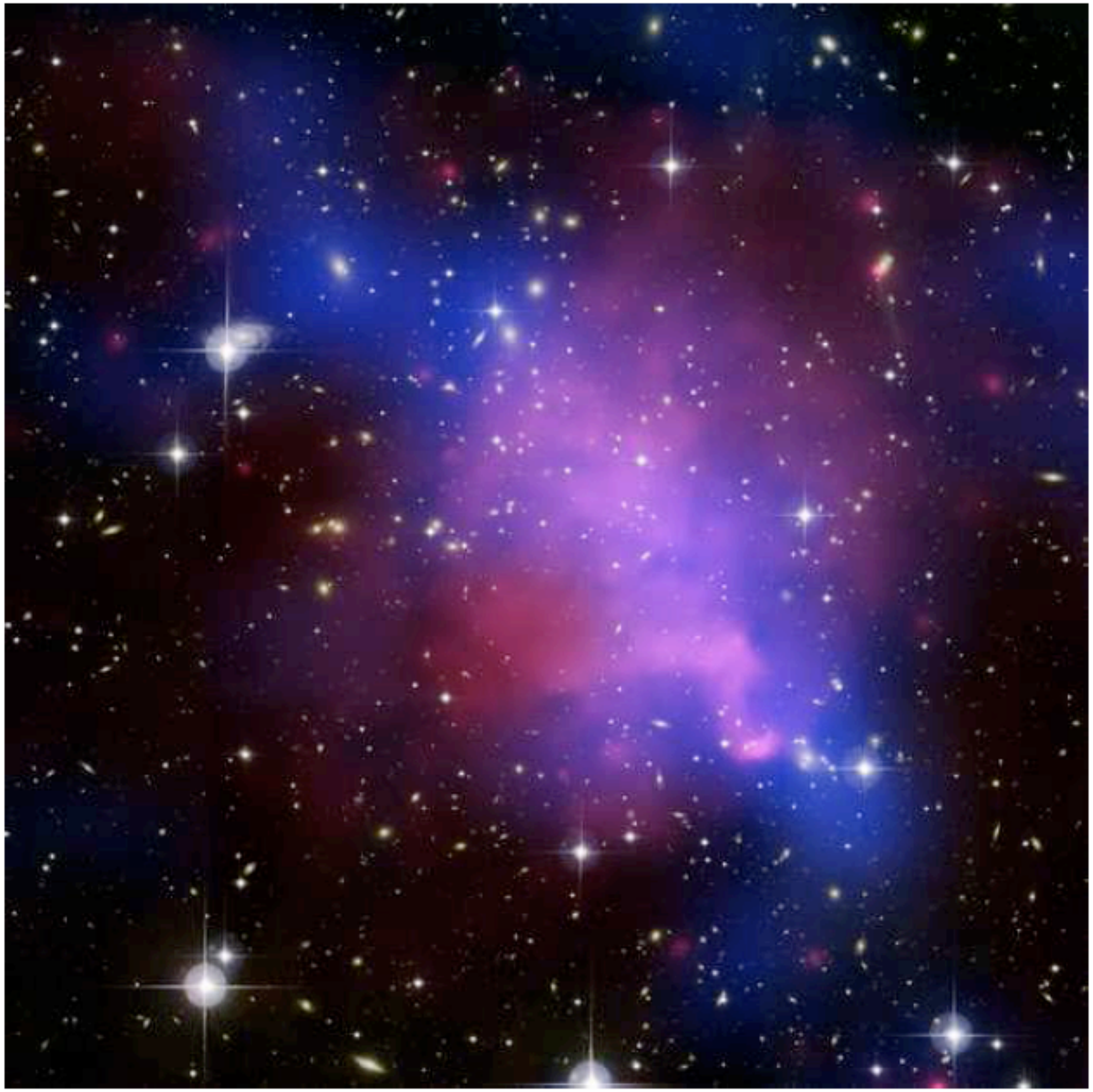

Credit: X-ray: NASA/CXC/UVic./A.Mahdavi et al.
Optical/Lensing: CFHT/UVic./A.Mahdavi et al.

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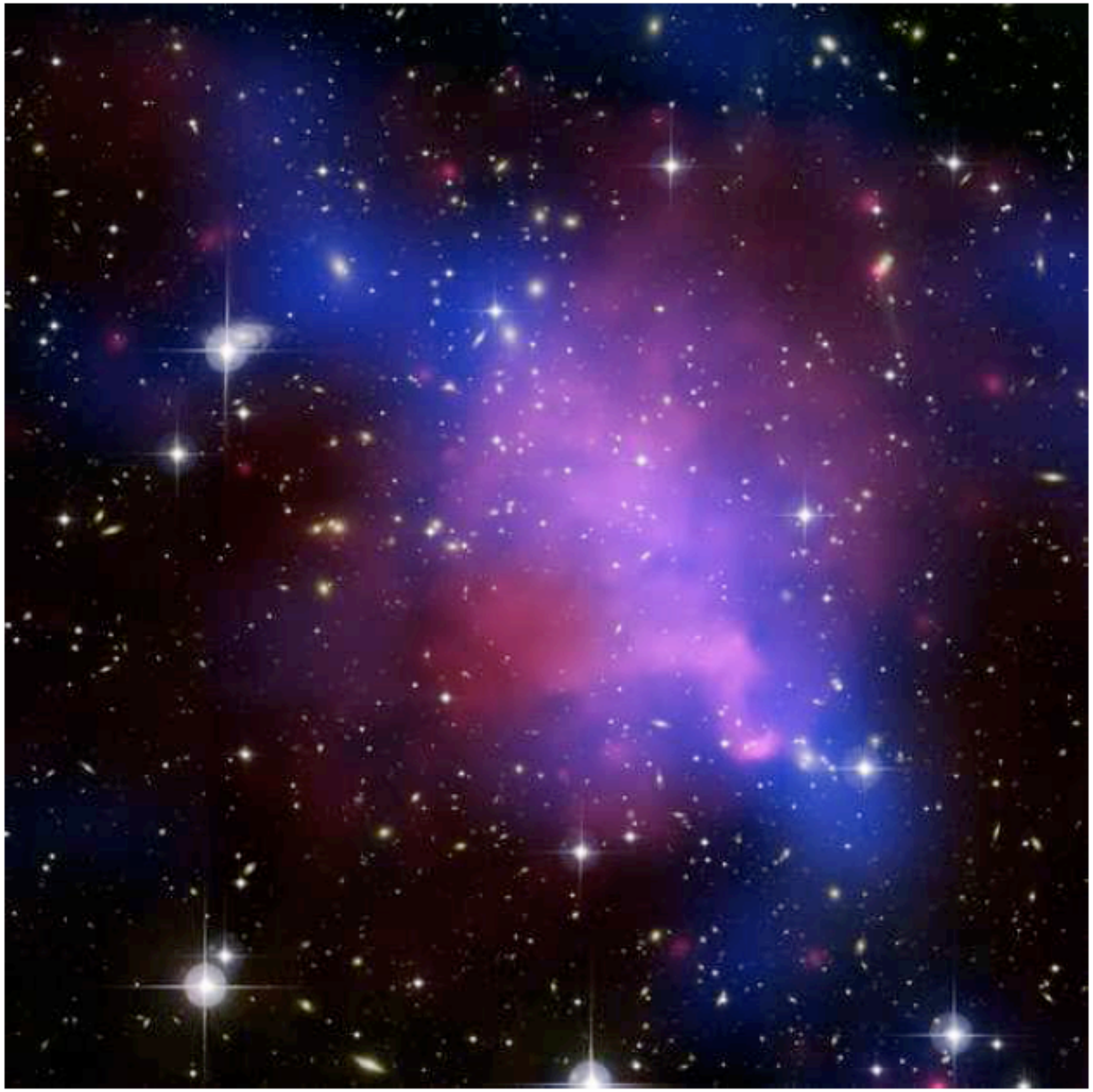

Need mass estimates before we can constrain cosmology.

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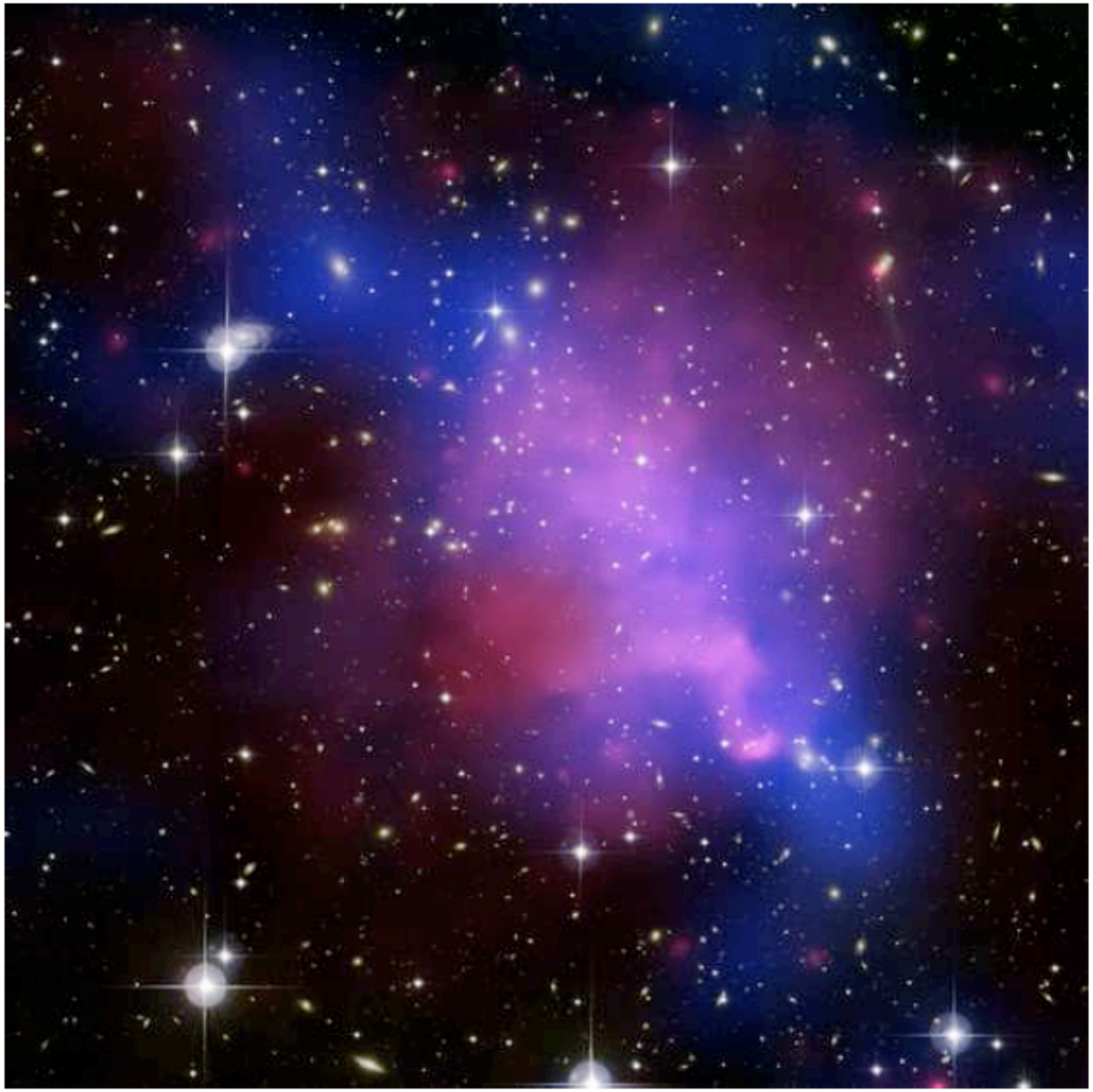

Clusters are detected at various wavelengths using different techniques.

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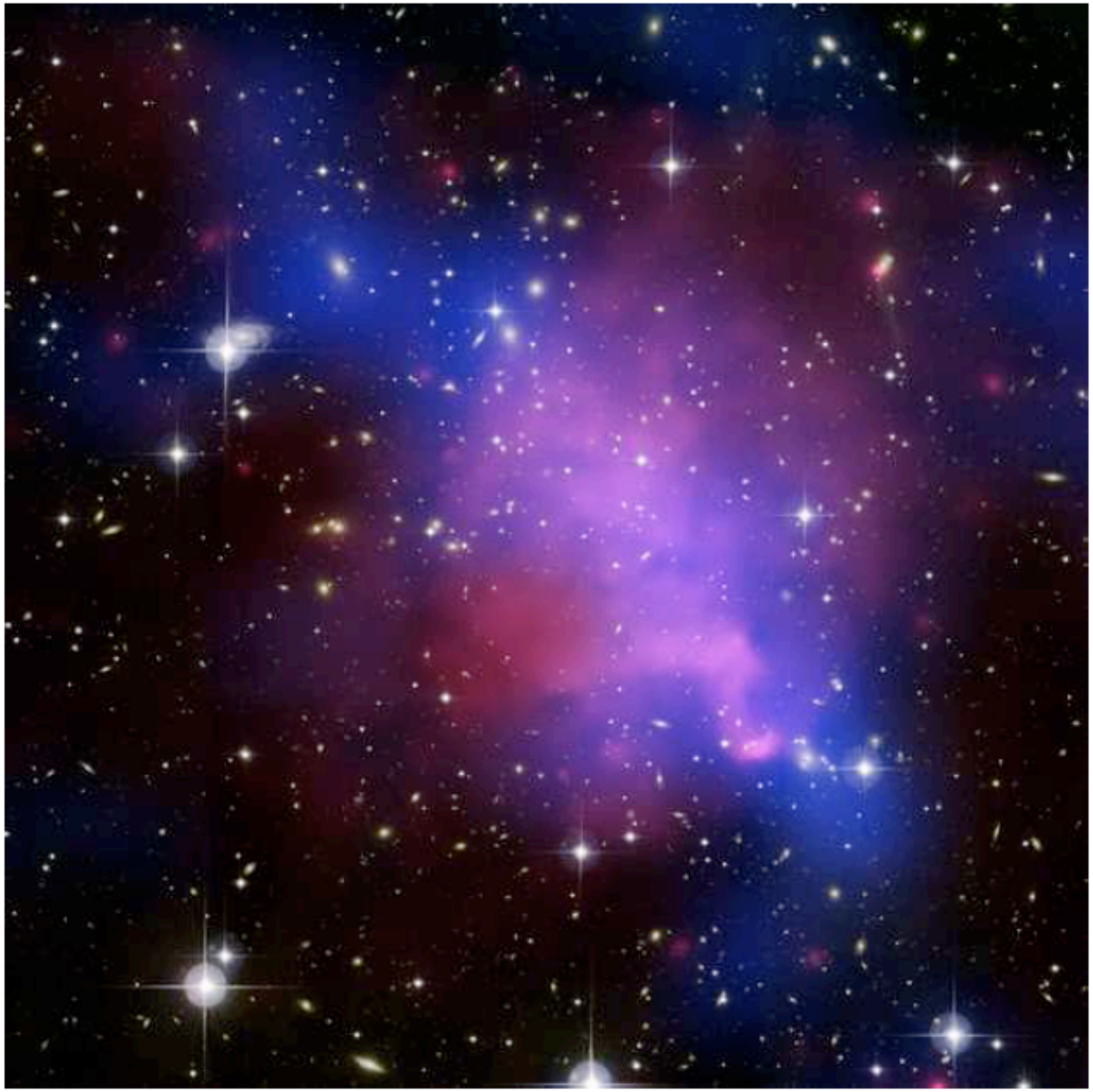

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Optical: Overdensity of (red-sequence) galaxies maxBCG (Koester et al 2007) using SDSS

$$N \sim 13 \times 10^3 \quad 0.1 < z < 0.3$$

$$M_{200}(N_{gal})$$

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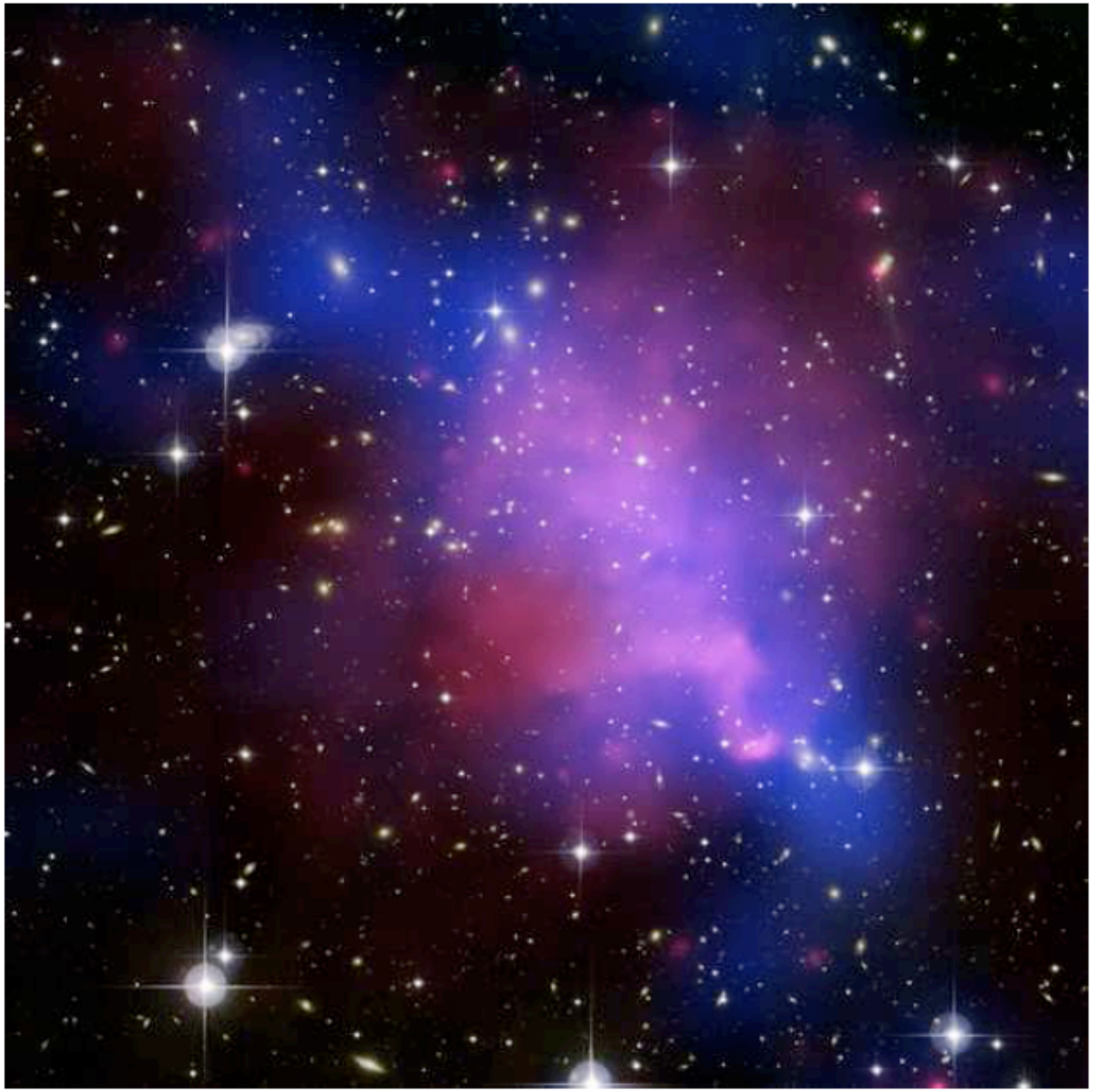

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N~ 500 $\quad 0.06 < z < 1.47$

$M_{200} \propto T_x^{1.5}$

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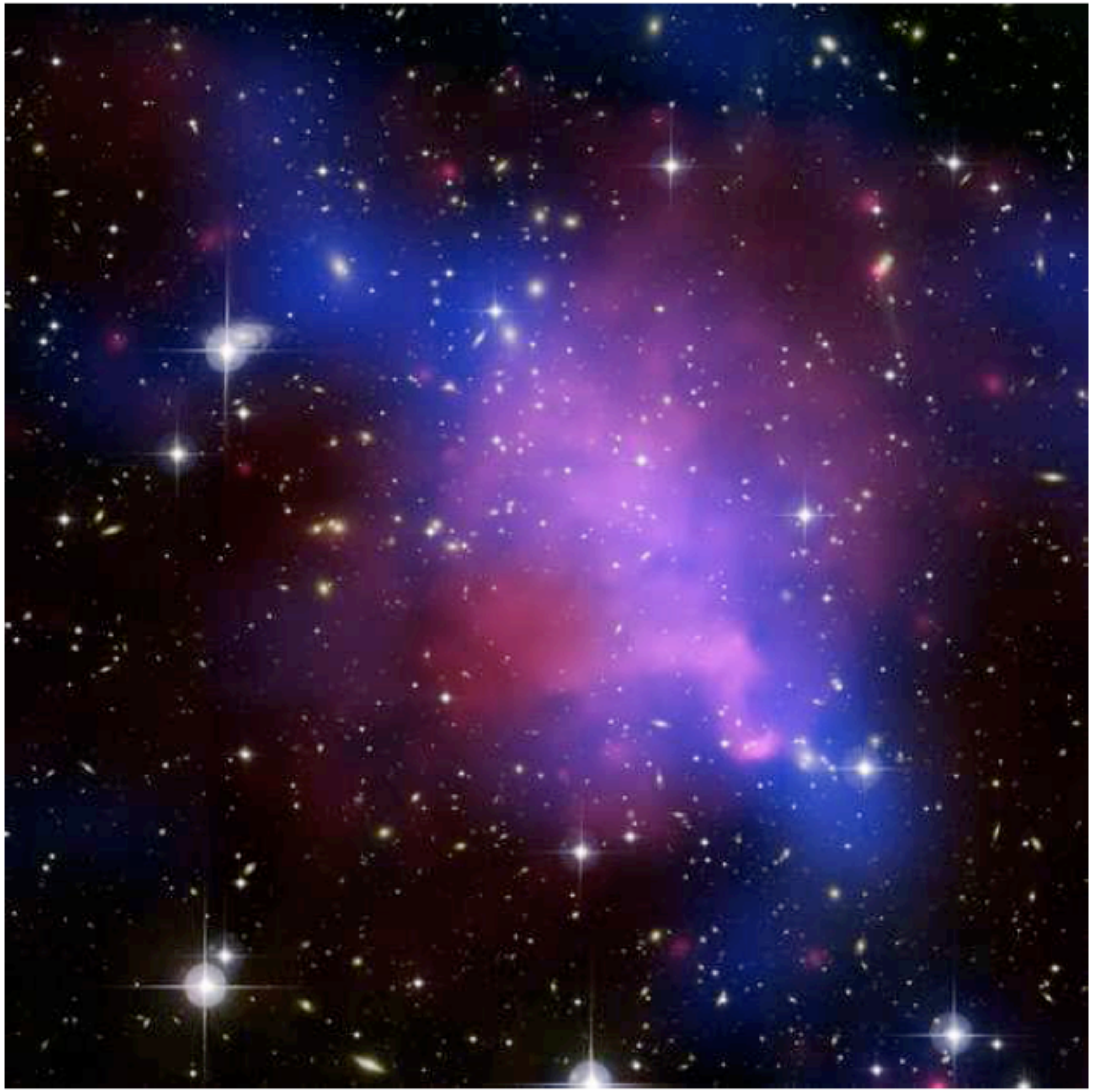

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$$M_{200} \propto T_x^{1.5}$$

CMB: The intra-cluster gas boosts the CMB energy (SZ effect) SPT (Williamson et al 2011)

$$N \sim 30 \quad 0.098 \leq z \leq 1.132$$

$$M_{200} \propto y(\rho_e, T_x)$$

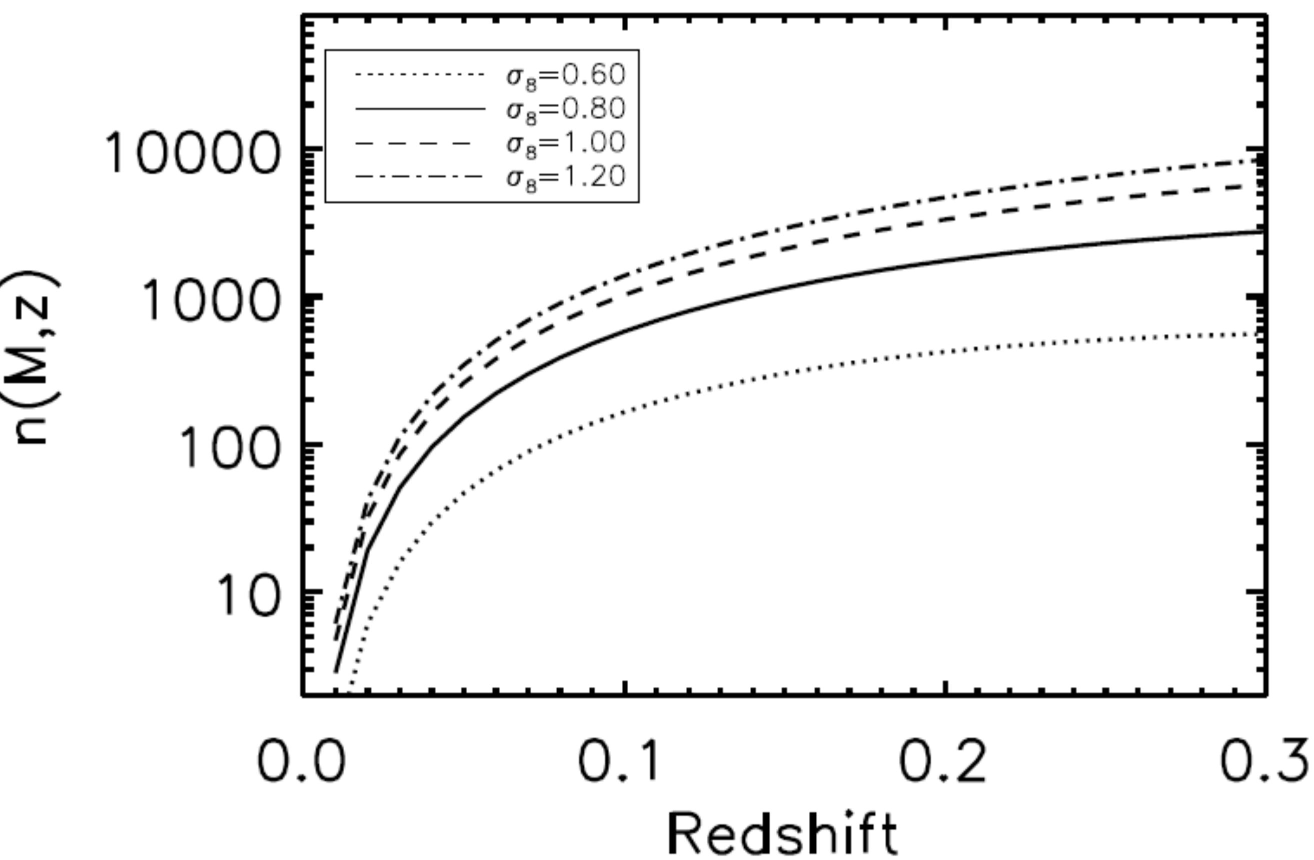
The theoretical cluster mass function

The mass function describes the number of clusters per unit mass, per unit redshift as a function of cosmological parameters.

$$n_G(M,z) = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M^2}\left|\frac{\mathrm{d}}{\mathrm{d}\ln M}\ln\sigma_M\right|\,\nu\,\exp -\nu^2/2\,.$$

$$\nu = \delta_{sc}/\sigma(M,z)$$

$$\sigma = \int P(k)\hat{W}(kR)k^2 dk,$$



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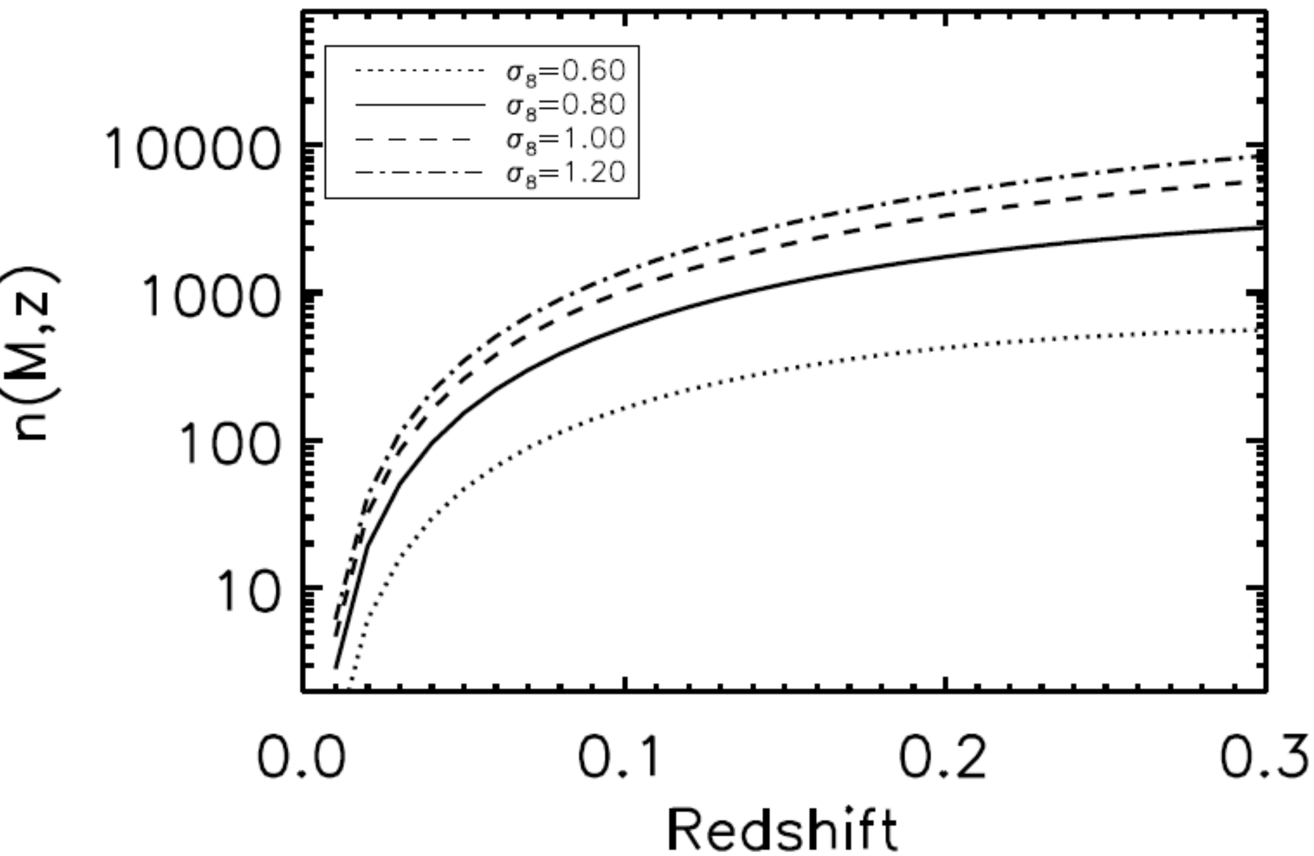

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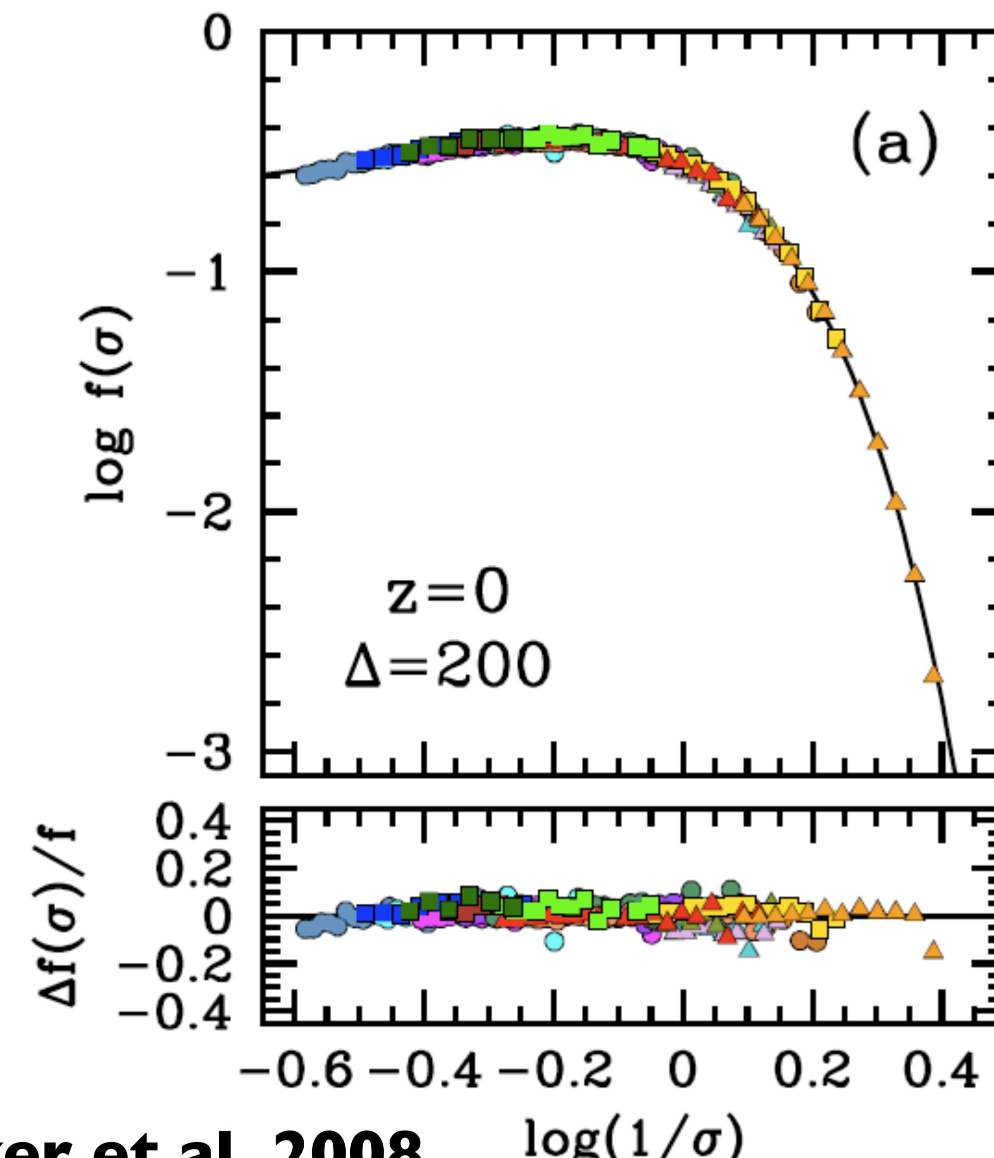


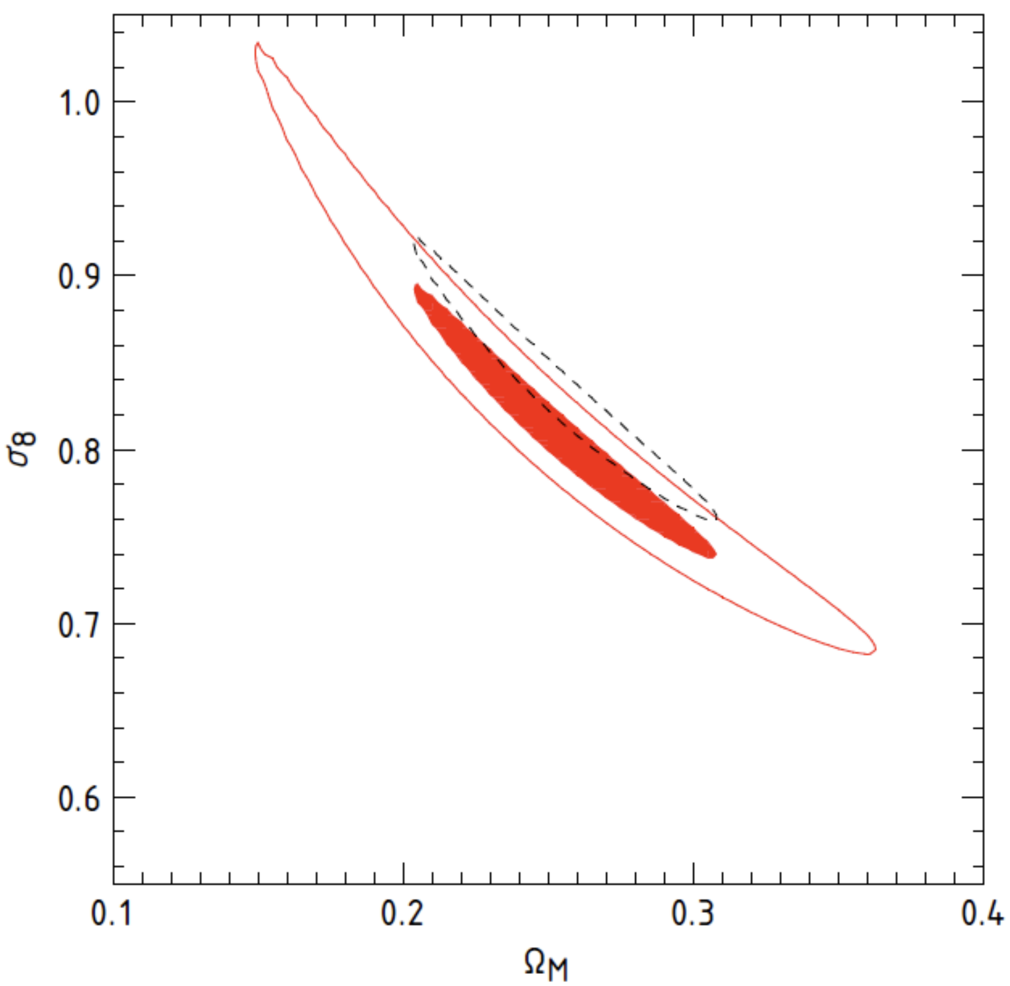
Tinker et al. 2008

Now, fitting functions are calibrated to large N-body dark matter only simulations (e.g., Jenkins et al 2002)

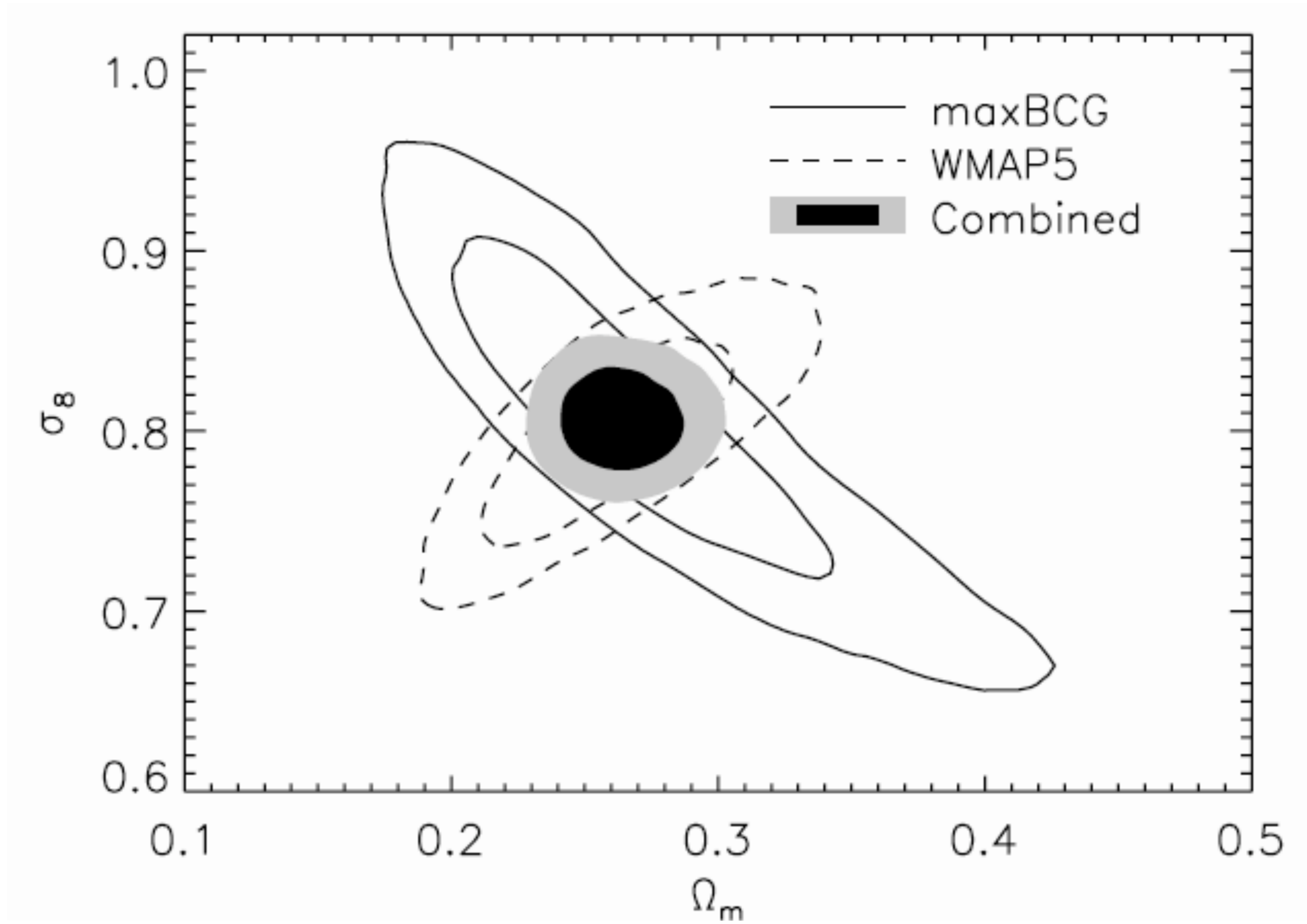
$$\frac{dn}{dM} = f(\sigma)\,\frac{\bar{\rho}_m}{M}\,\frac{d\ln\sigma^{-1}}{dM}.$$

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right]e^{-c/\sigma^2}$$

Using large samples of clusters to constrain cosmology



X-ray selected clusters: Vilhlinin et al. 2008



Optically selected clusters: Rozo et al. 2009

Individual clusters as “extreme object” cosmological probes

If we find a cluster which is considered “very rare”, we can use its existence to rule out a cosmological model (Mortonson et al 2010)

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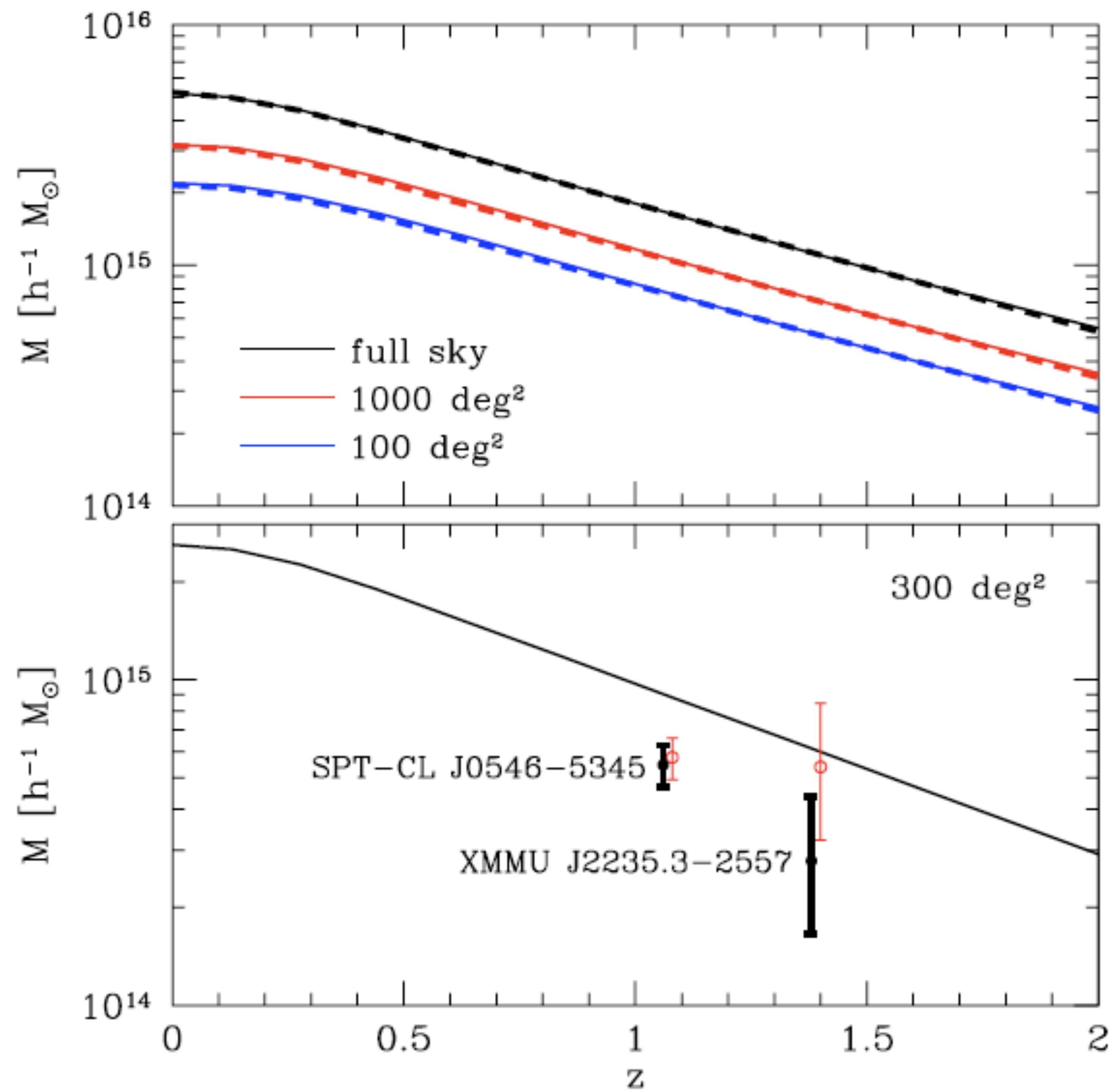
Given the (w)LCDM model with WMAP7 cosmological priors, we do not expect any cluster to sit above the curve at 95% (or some other specified) confidence.

If we observe a rare cluster, we can determine how much of the model parameter space can be excluded by identifying the appropriate line which runs through it.



Mortonson et al 2010

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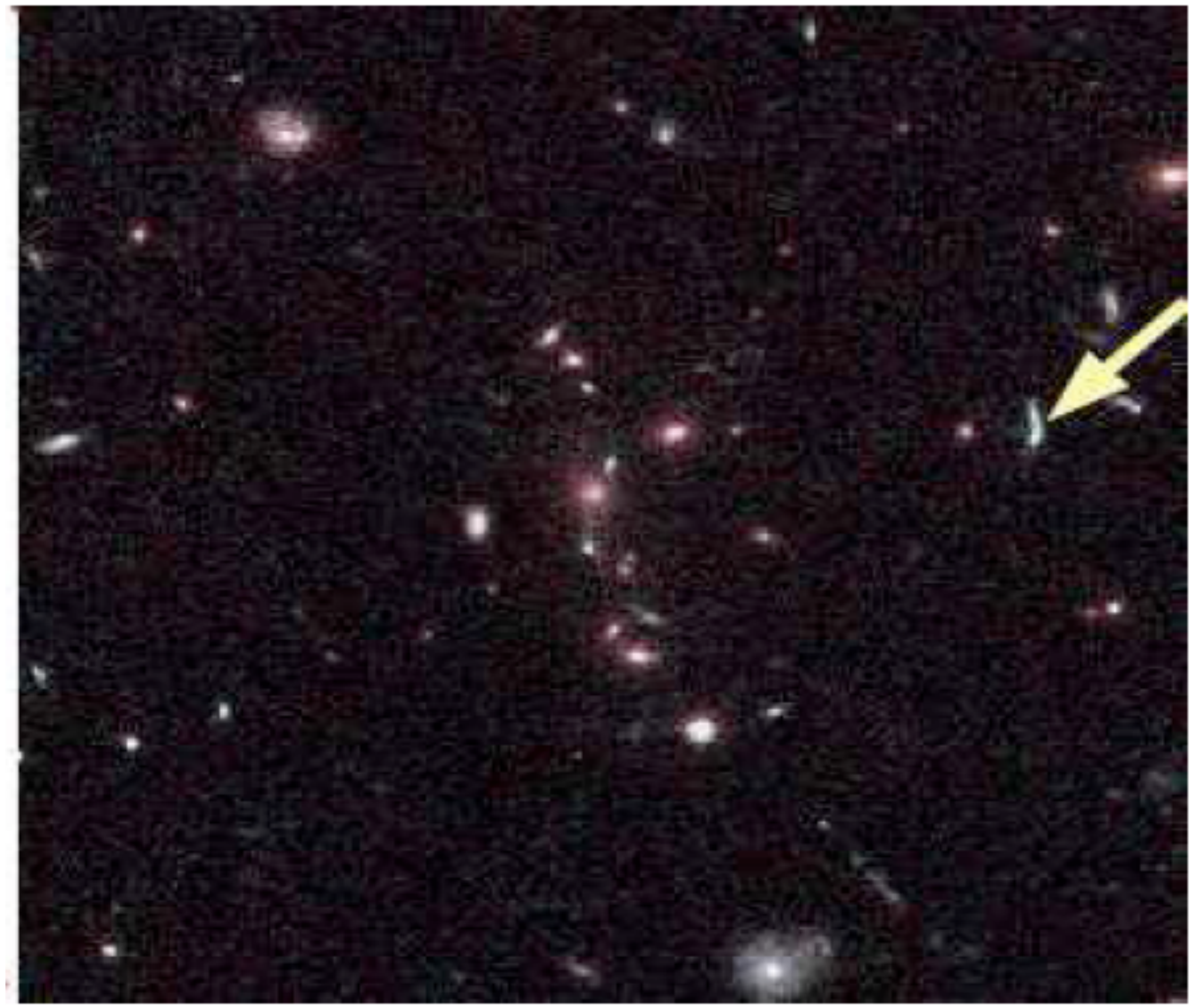
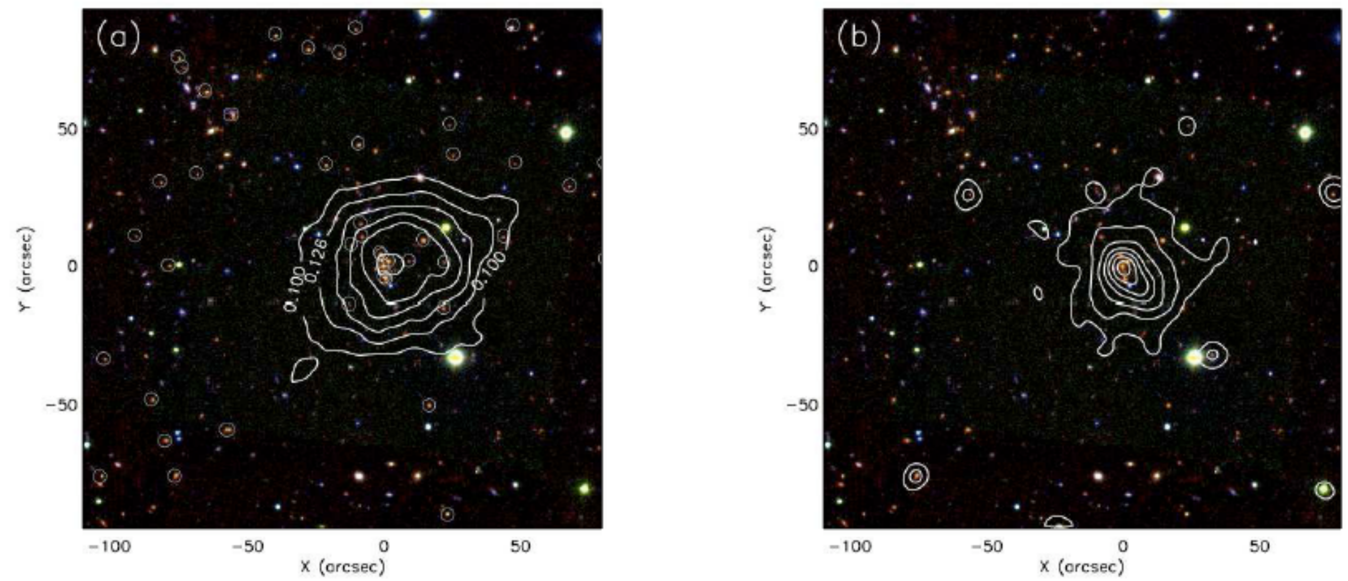
Motivation: observations of XMMJ2235

Some recent observations have called into question some of the underlying assumptions of the LCDM model + WMAP priors on the cosmological parameters. E.g., A very massive clusters of galaxies at high redshift, was statistically unlikely to have been observed.





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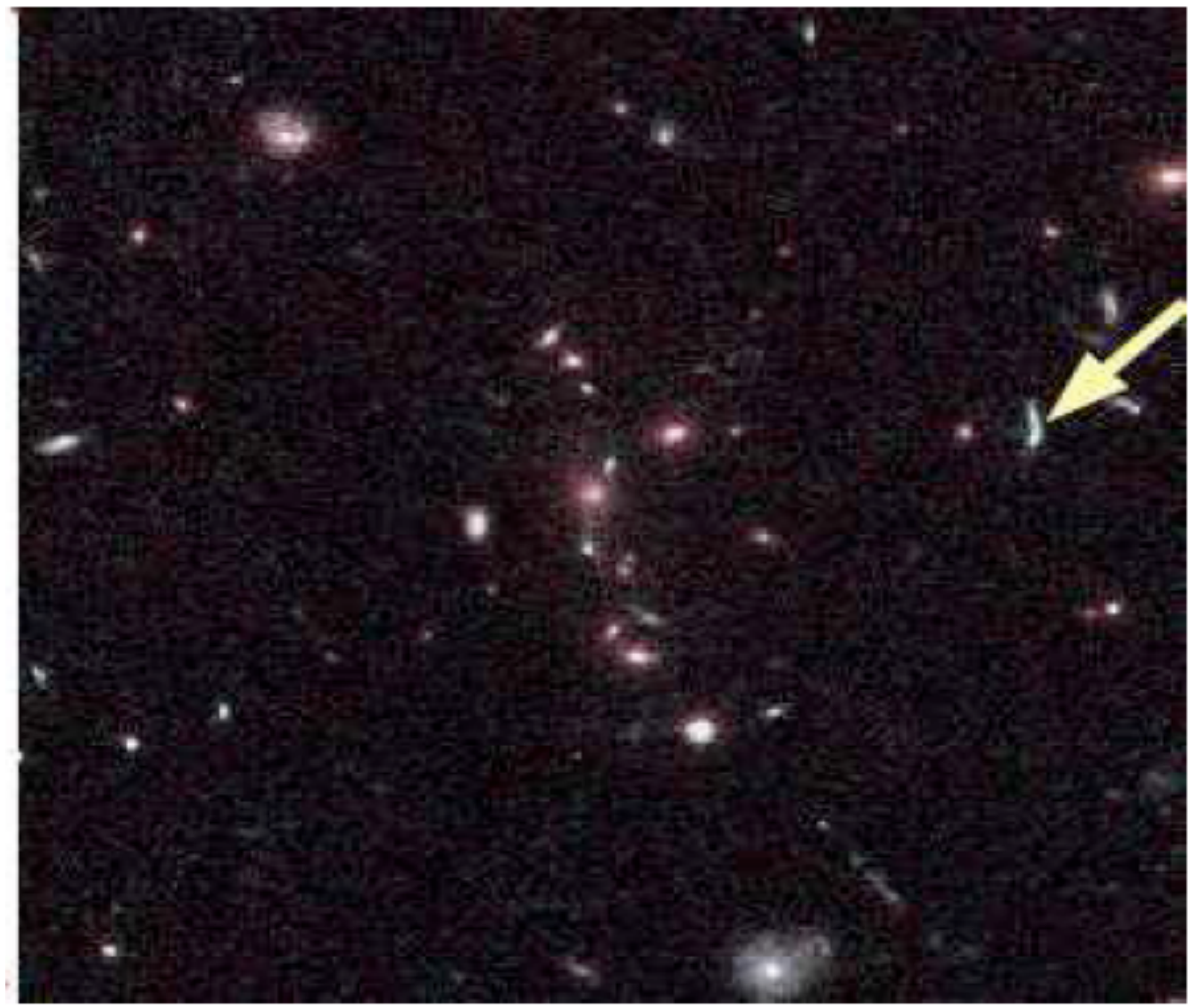

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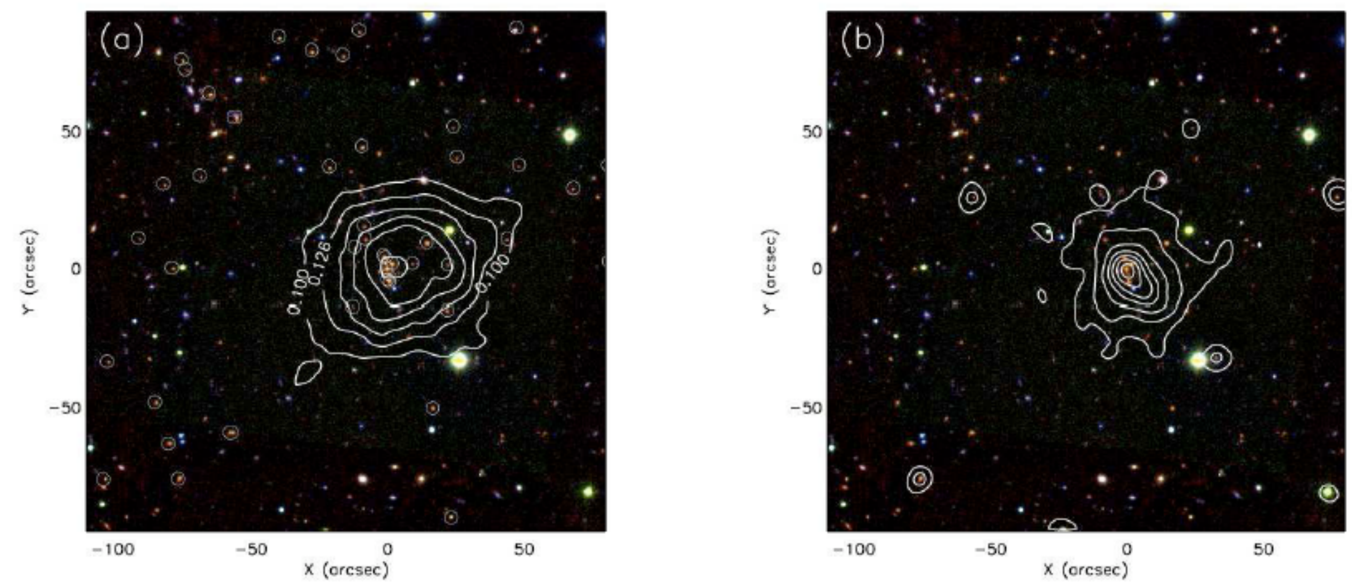

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<u>How likely was this cluster to exist >M >z?</u>

- **How many clusters would do we expect to find at >M,>z**
- **The expected number in the full sky ~7.**
- **Footprint was 11 square degrees XMM X-ray survey, 0.02% of sky.**
- **Poisson sample from (0.0002*7) >1 only 1.4%**

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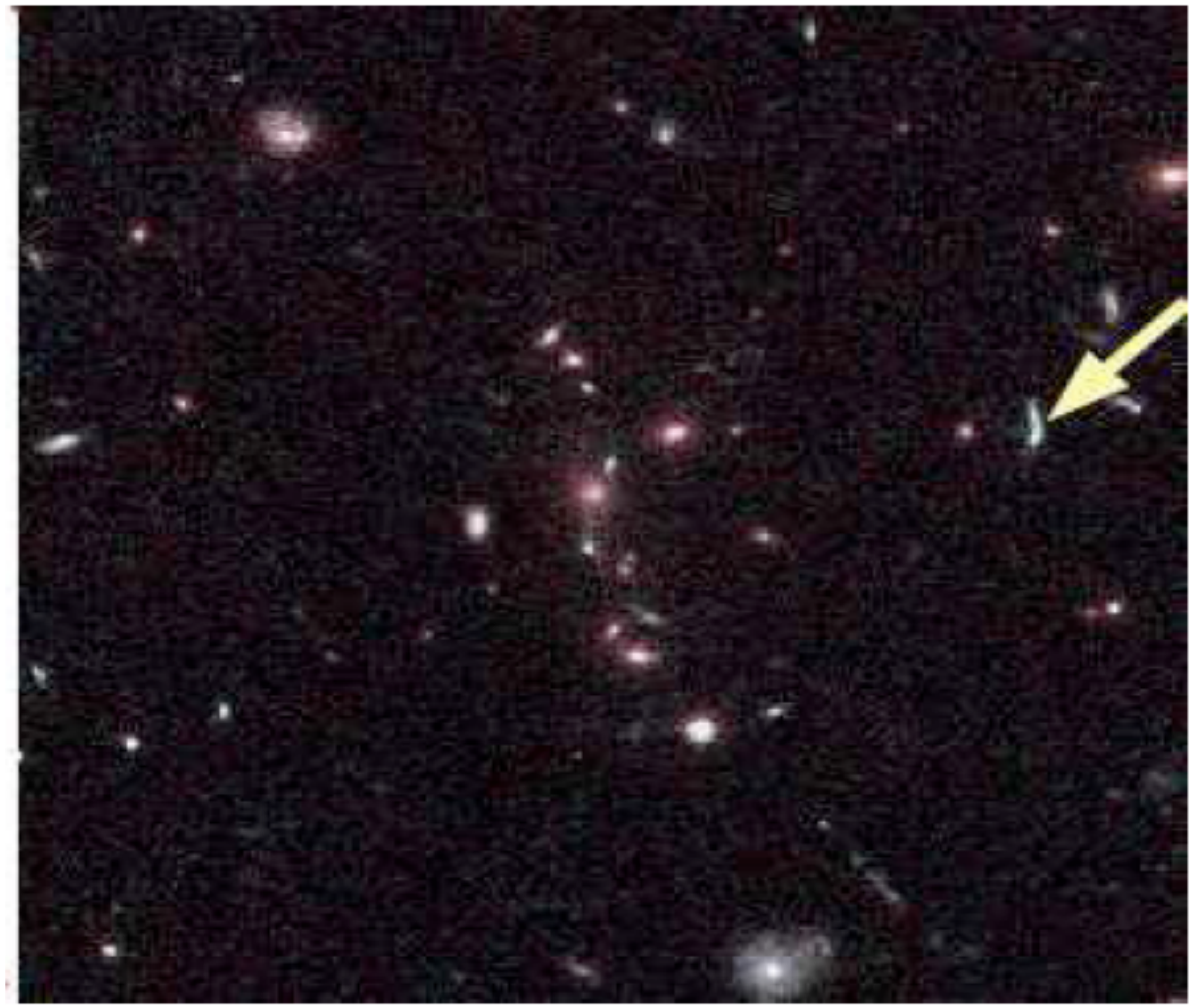

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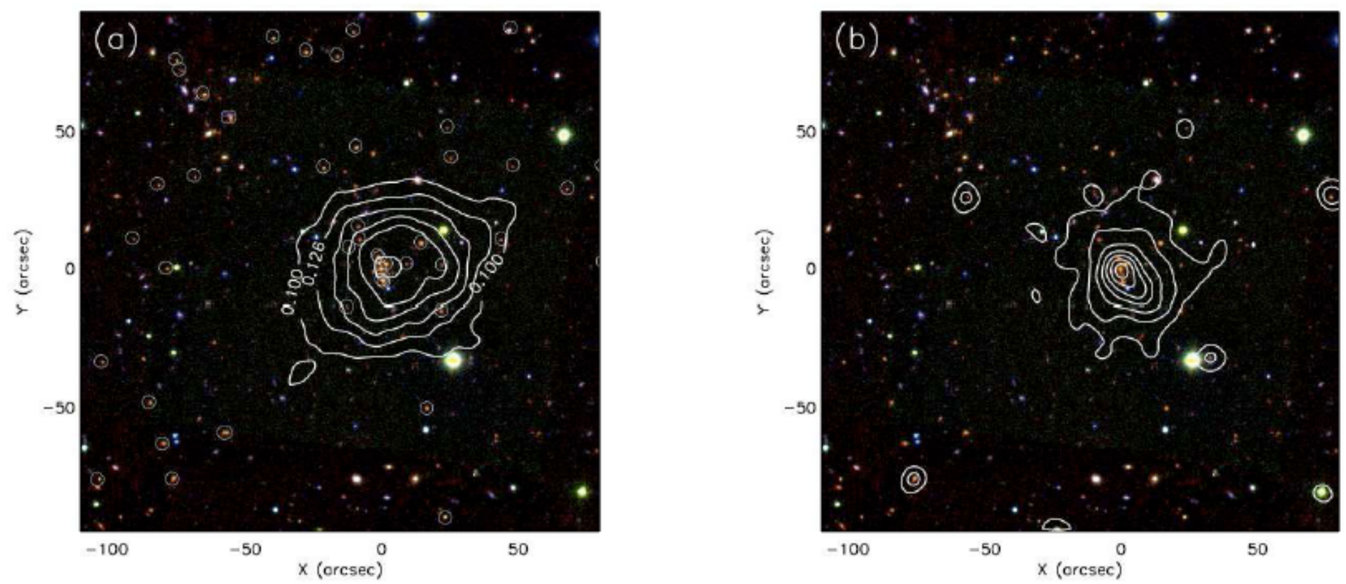

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**Jimenez & Verde 2009 showed fnl~150 relieves tension.
Cayon et al 2010 fnl=360,fnl>0 at 95%**

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Motivation: theory, a window to the early Universe

Using today's data, (not some future experiment e.g. LISA-like) we can make a measurement of the amount of primordial non-Gaussianity (fnl) of the initial density perturbations, which can tell us about the various types of scalar field interactions during inflation/reheating/preheating.

$$\Phi = \phi + f_{\rm NL}\left(\phi^2 - \langle\phi^2\rangle\right) \ .$$

<u>Hand wavy theory for observers</u>

Within the (perturbed) Lagrangian for the scalar fields in the early universe:

$$\Pi^3,\ (\partial\Pi)^3,\ \Pi(\partial\Pi)^2,\ \Pi_1\Pi_2\Pi_1\ \rightarrow f_{NL}(k)(n_{NG}) \sim ?$$

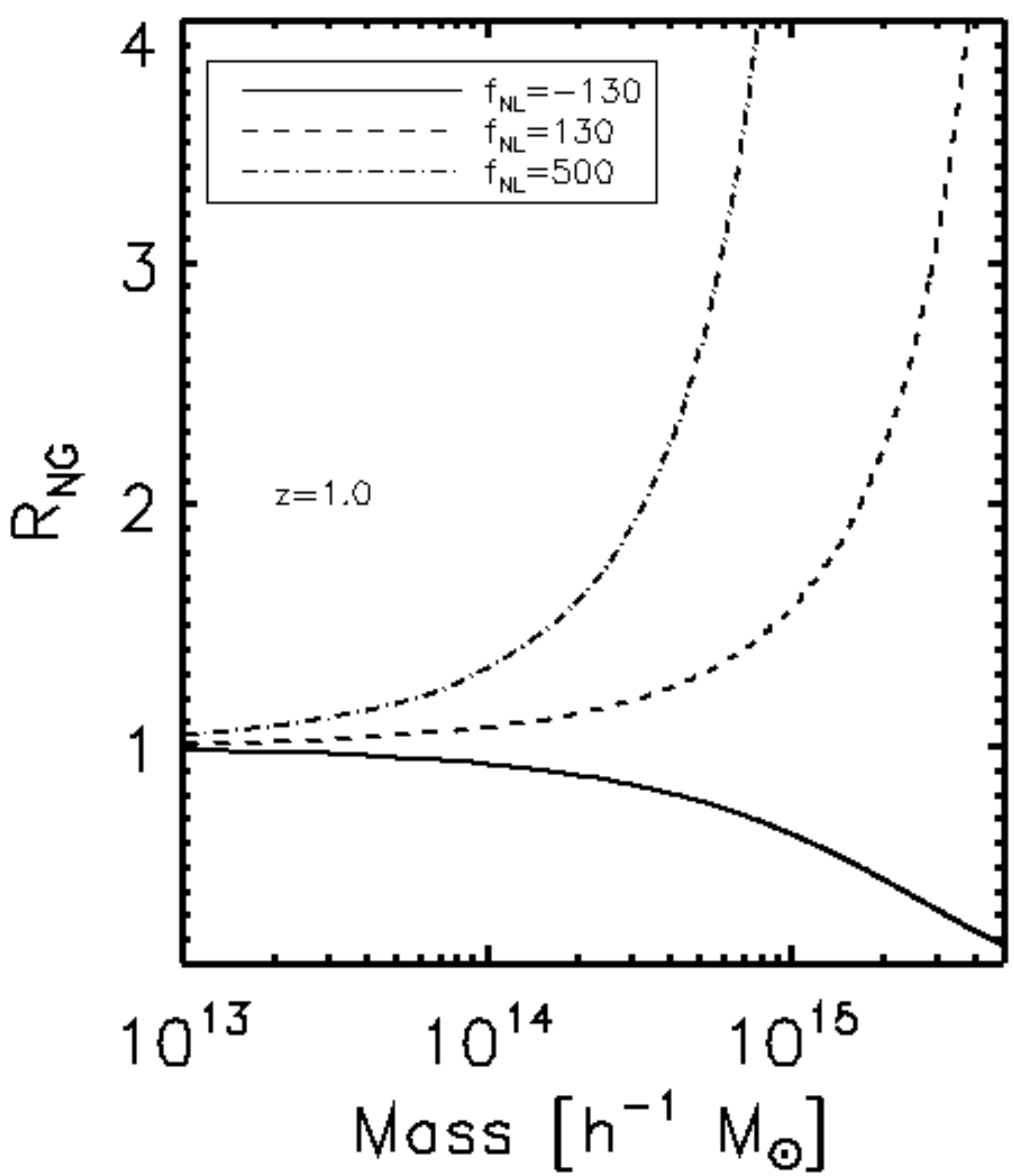
A single, multiply coupled field or two (or more) couple fields generate the bispectrum and can produce large non-Gaussianities (skewness) with scale dependence. See e.g., Byrnes et al 2010 [arXiv:1007.4277]

Modifying the mass function with non-Gaussianity

We can change the number of expected clusters by allowing some fnl which modifies the cluster mass function.

$$n_G(M,z) = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M^2}\left|\frac{\mathrm{d}}{\mathrm{d}\ln M}\ln\sigma_M\right|\,\nu\,\exp-\nu^2/2\,.$$

$$\mathcal{R}_{NG}(S_{3,M},M,z) = \frac{n(M,z,f_{\rm NL})}{n_G(M,z,f_{\rm NL}=0)}$$



Solved in the Press-Schecter type formalism by Matarrese, Verde, Jimenez 2002, LoVerde et al 2007, Maggiore et al 2009, D'Amico et al 2010 etc.

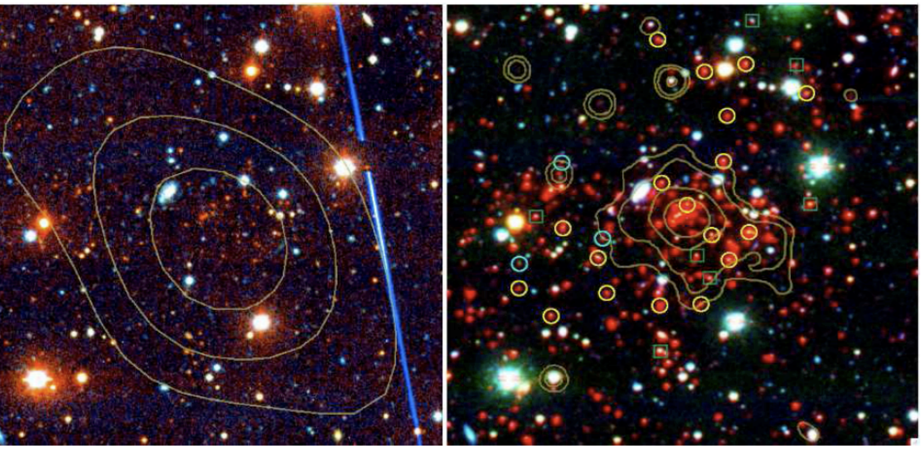
$$\mathcal{R}_{NG}(M,z,f_{NL}) = \exp\left[\delta_{ec}^3\frac{S_{3,M}}{6\sigma_M^2}\right]\times \left|\frac{1}{6}\frac{\delta_{ec}}{\sqrt{1-\frac{\delta_{ec}S_{3,M}}{3}}}\frac{dS_{3,M}}{d\ln\sigma_M}+\sqrt{1-\frac{\delta_{ec}S_{3,M}}{3}}\right|,$$

The normalised skewness of the smoothed density field

$$S_{3,M} = f_{NL}\,S_{3,M}^{f_{NL}=1}$$

Rng enable other, better calibrated mass functions to be used (e.g., Jenkins et al 2000, Tinker et al 2008, Wagner et al 2010).

Motivation: observations II - More “rare” clusters



ft: Optical 4′ × 4′ color image (*grz*) of SPT-CL J0546-5345, with SZE significance contours overlaid (S/N = 2, 4, and 6).
lor optical (*ri*) + IRAC (3.6 μm) image of SPT-CL J0546-5345, with *Chandra* X-ray contours overlaid (0.25, 0.4, 0.85 and
2″ × 2″ pixel per 55.6 ks in the 0.5-2 keV band). North is up, east is to the left. Due to its high angular resolution, *Chandra*
lve substructure to the SW, which may be evidence of a possible merger. These images highlight the importance of IRAC
dying the galaxies in high redshift, optically faint clusters. Spectroscopic early-type (late-type) members are indicated with
circles. Green squares show the spectroscopic non-members.

SPT CL J0546-5345

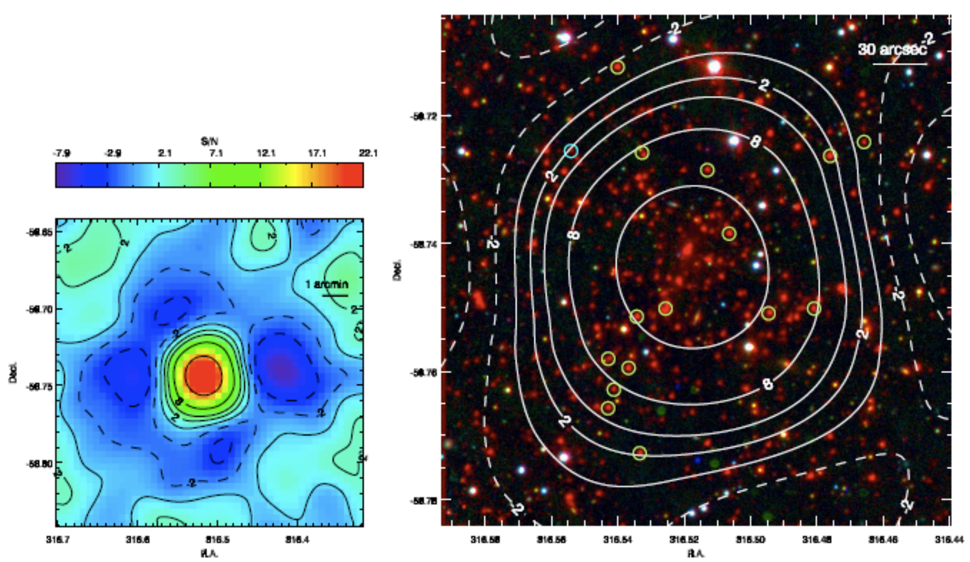
$$M_{200} \sim 10^{15}\, M_\odot$$

$$z = 1.05$$

Brodwin et al 2010

- **Expect to see one 18% of time in the >M,>z sense**

Foley et al.



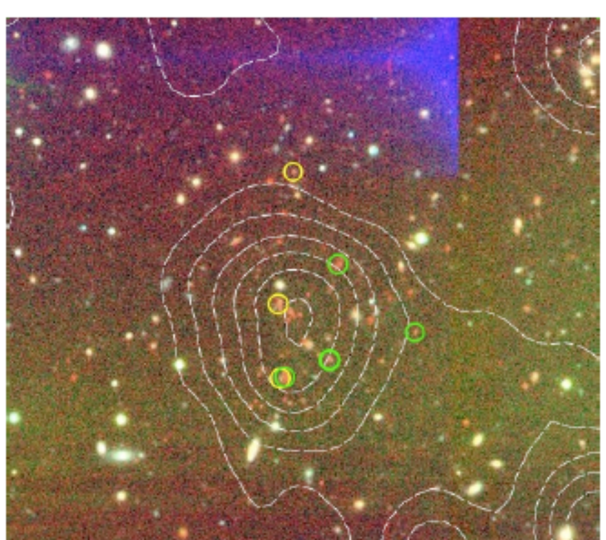
SPT-CL J2106-5844

$$M_{200} = 1.27 \times 10^{15}\, h^{-1}\, M_\odot!$$

$$z = 1.13$$

Foley et al 2011

- **Expect to see one 5.9% of time in the >M,>z sense**



XMMUJ0044.0-2033

$$3.5 < M < 5 \times 10^{14} M_\odot$$

$$z = 1.57$$

Santos et al 2011

- **Expect to see one <10% of time in the >M,>z sense**

Are we just getting lucky?

More clusters.

Are these clusters consistent with LCDM using the >M,>z test?

B.H., Jimenez, Verde 2010 PRD.83.103502

- **Spectroscopic redshifts >1**

- **3 SZ detected '*'**
- **11 X-ray detected '+'**

Cluster Name	Redshift	M_{200} $10^{14}M_{\odot}$	Method
'WARPSJ1415.1+3612' +	1.02	$3.33^{+2.83}_{-1.80}$	Velocity dispersion
'SPT-CLJ2341-5119' *	1.03	$7.60^{+3.94}_{-3.94}$	Richness
'XLSSJ022403.9-041328' +	1.05	$1.66^{+1.15}_{-0.38}$	X-ray
→'SPT-CLJ0546-5345' *	1.06	$10.0^{+6.00}_{-4.00}$	Velocity dispersion
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'SXDF-XCLJ0218-0510' +	1.62	$0.57^{+0.14}_{-0.14}$	X-ray

The next generation of cluster samples will be found by X-ray (eRosita ~ 100,000 clusters) not SZ (ActPol ~1000 clusters). All X-ray clusters detected or re-detected with XMM Cluster Survey

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- Theory: non-Gaussian mass function
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- The XMM Cluster Survey
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- What we found; Possible explanations, Systematics
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- Why we were all wrong: Understanding a bias
- New, correct analysis and results
- Conclusions

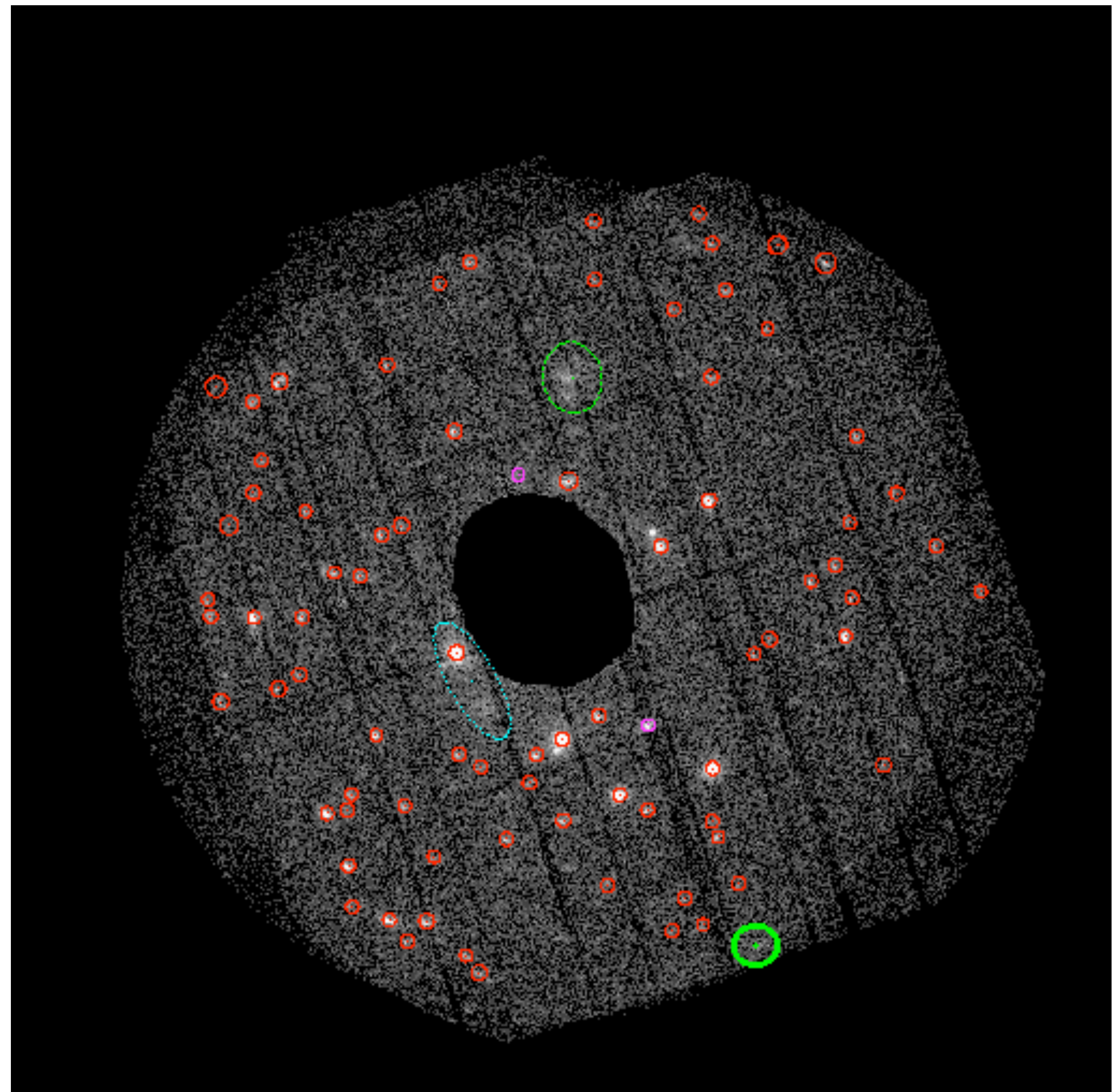
XMM Cluster Survey

Members: Kathy Romer [P.I], E. J. Lloyd-Davies, Mark Hosmer, Nicola Mehrtens, Michael Davidson, Kivanc Sabirli, Robert G. Mann, Matt Hilton, Andrew R. Liddle, Pedro T. P. Viana, Heather C. Campbell, Chris A. Collins, E. Naomi Dubois, Peter Freeman, Ben Hoyle, Scott T. Kay, Emma Kuwertz, Christopher J. Miller, Robert C. Nichol, Martin Sahlen, S. Adam Stanford, John P. Stott

- **The XMM Cluster Survey (XCS) aims to mine the XMM Newton X-ray telescope science archive images for galaxy clusters**
- **The science goals of the XCS are:**
  - **To measure cosmological parameters σ_8, Ω_M, Ω_Λ to 5, 10 and 15 per cent accuracy respectively**
  - **To study the evolution of the cluster gas (i.e., the luminosity—temperature relation) to high redshift**
  - **To provide a sample of high redshift clusters that can be used to test theories of cluster galaxy formation and evolution**

XCS: Finding and classifying extended sources

Using an automated pipeline (Lloyd-Davies et al 2010) which downloads the archival X-ray photon map, masks for bad pixels, stars etc., and detects point sources (red) and extended sources (green)

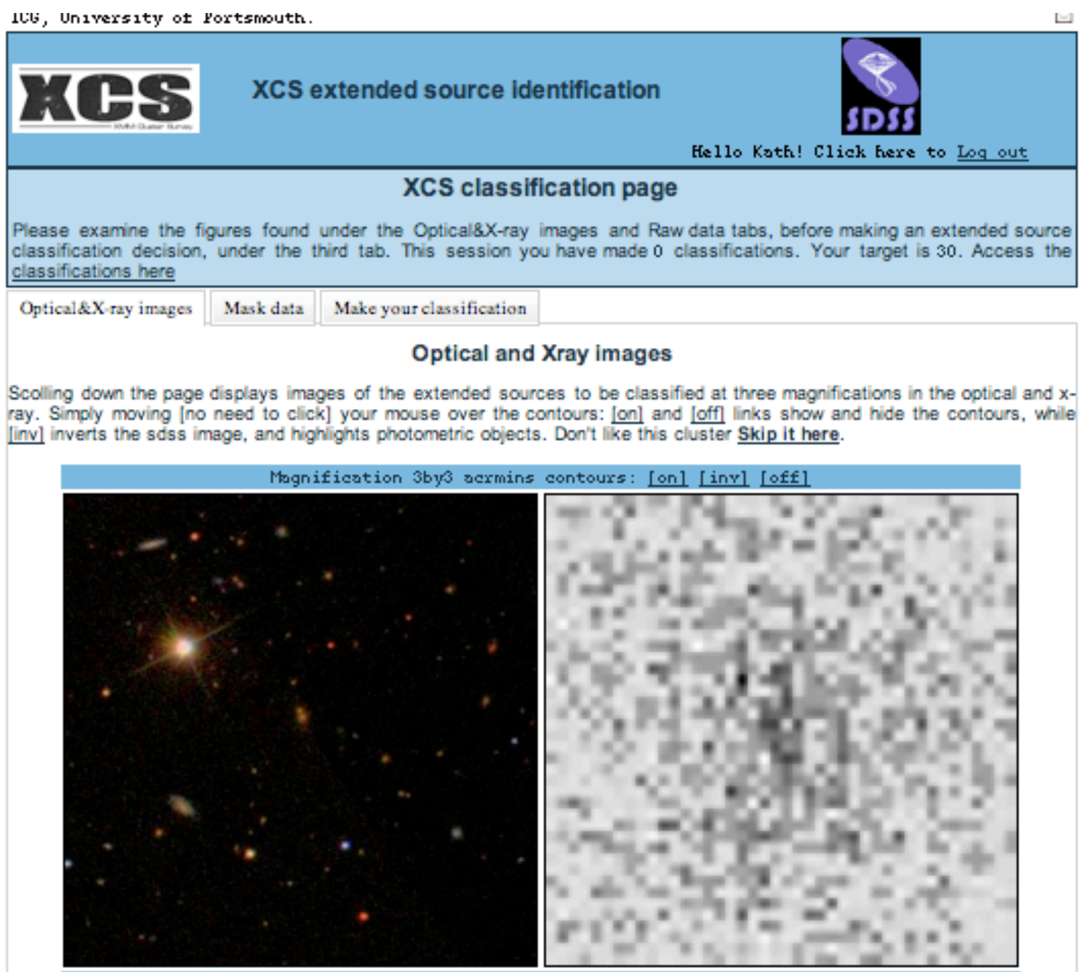


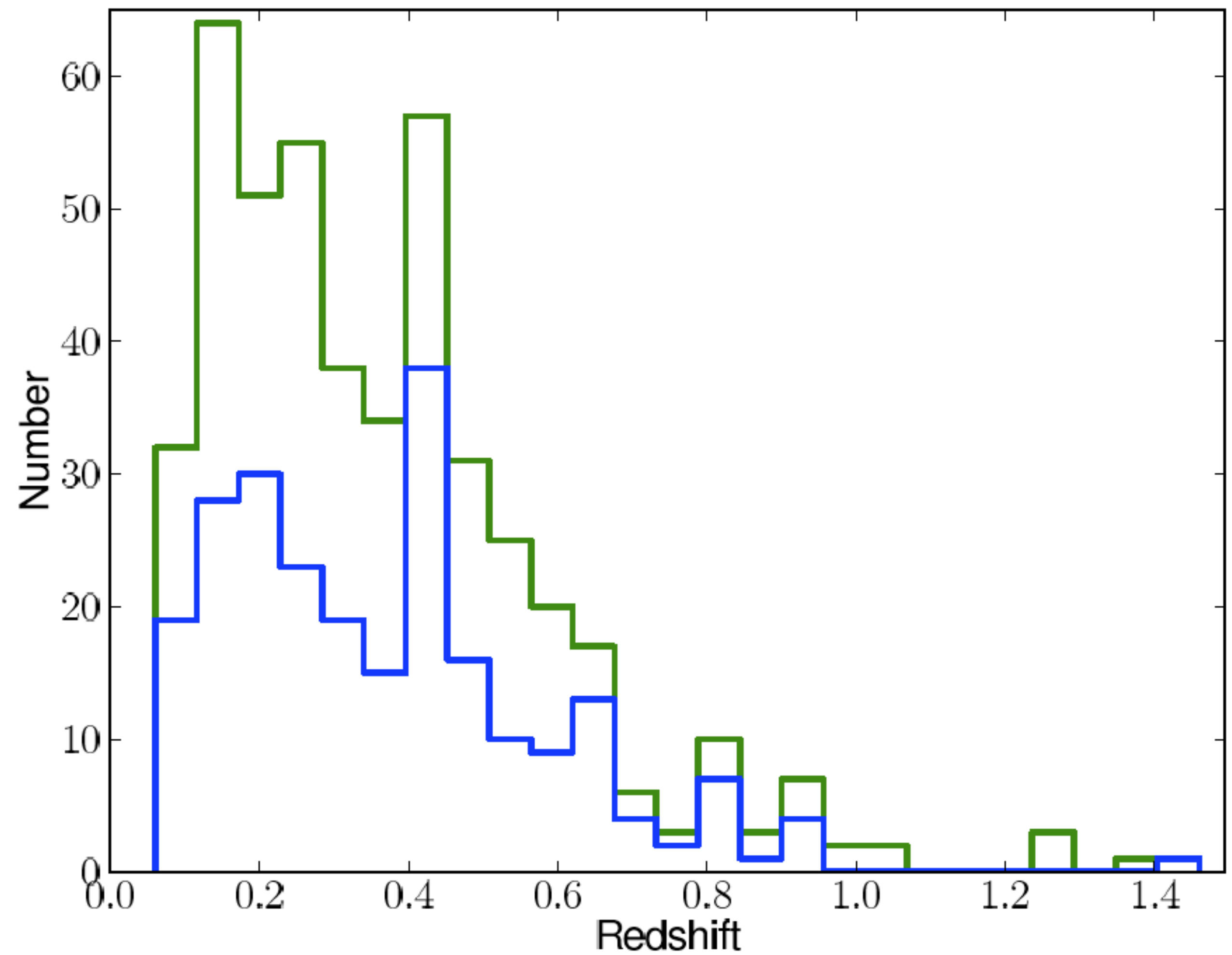
Extended X-ray emission is evidence of a galaxy cluster, but it's not enough. Need optical identification, and redshifts (X-ray redshifts difficult) before the fluxes can be converted to temperatures and masses.

XCS: Optical Followup

Purity with Cluster Zoo

All clusters multiply classified by experts to determine purity.





503 clusters, spanning 0.06<z<1.46
438 have x-ray temperatures

Recent data release, Mehrtens et al. arXix:1106.3056

XCS:

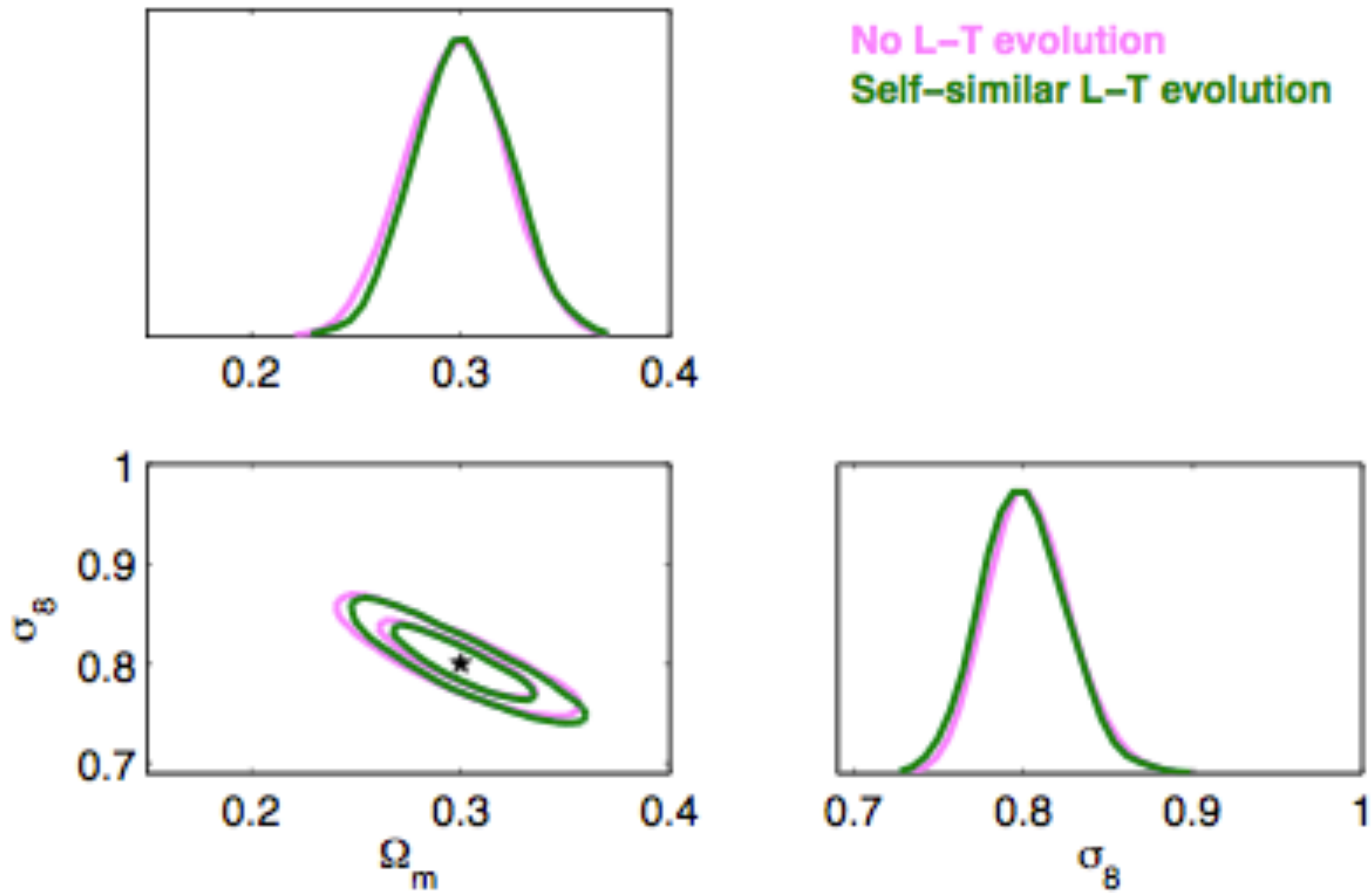
Current X-Ray Cluster Surveys

Stockholm University

Survey	Data	Clusters	Redshift range
HIFLUGCS	ROSAT	63	0.005 – 0.2
Maughan et al.	Chandra	115	0.1 – 1.3
O'Hara et al.	Chandra	70	0.18 – 1.24
400d	ROSAT/Chandra	86	0.35 – 0.9
XMM-LSS	XMM	29	0.05 – 1.05
Mantz et al.	ROSAT/Chandra	238	0.05 – 0.45
Peterson et al.	Chandra/XMM	723	0 – 1 ?
XCS_{300} (230 □°)	XMM	450	0.003 – 1.457

Martin Sahlen

XCS Cosmology predictions



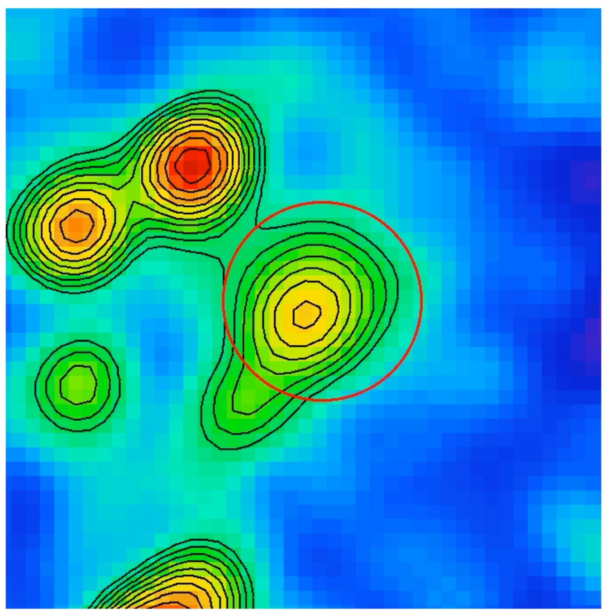
- XCS predictions based on LCDM mock catalogue, XCS selection function (need to know LT relation), and MT relation
- Parameters derived from n(M,z) (Sahlen et al. 2009)

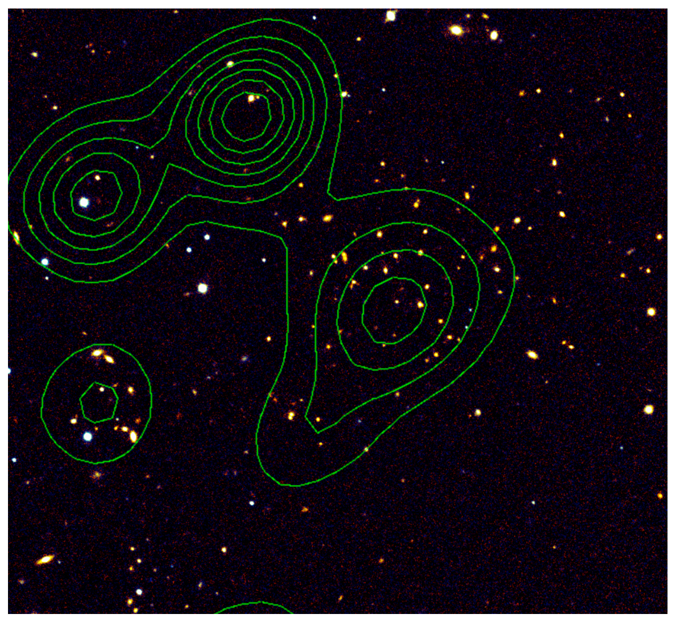
Martin Sahlen

XCS: Other XCS achievements

XMMXCS J2215

Was the highest redshift X-ray selected cluster, z=1.46 (Stanford et al. 2006, Hilton et al. 2007, 2008)



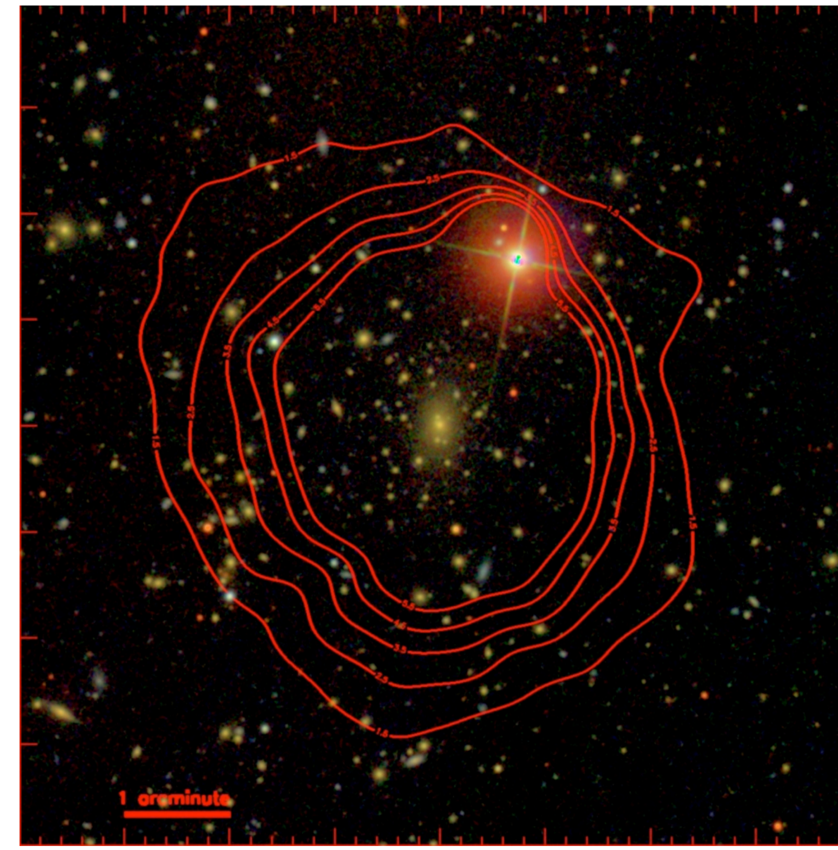


Now z=2.07, M~5-8.10^13 SolMass, Gobat et al arXiv:1011.1837

503 clusters, spanning 0.06<z<1.46
438 have x-ray temperatures

Recent Data release, Mehrtens et al. arXix:1106.3056

Fossil groups



- **15 Fossil Groups**
- **z<0.25**
- **0.9-6.6 keV**
- **Galaxy evolution**

Harrison et al (submitted)

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More Clusters. Data sample

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Conservative assumptions

Footprints; There was overlap between the surveys, but we conservatively assumed each X-ray survey had it's own unique footprint, resulting in a 300 sq. deg. footprint.

- **Survey volumes: We assumed all surveys had the redshift depth of the deepest survey 1.0<z<2.2**
- **Selection functions: For each cluster, we assumed that any similar (>M) cluster at any higher redshift (>z) would have been detected.**
- **Mass estimates: We chose to use the cluster mass and error which gave the least tension with LCDM**

Analysis >M,>z

For each cluster "i", we sample S, from the mass and error 10,000 times. We calculate the expected abundance of clusters above each sampled mass and redshift using the theoretical cluster mass function.

$$A_s = \int_{M_S}^{\infty} \int_{z=z_{cluster}}^{z=2.2} n\left(m, z, f_{\rm NL}, C\right) dm\, dz$$

We Poisson sample P^O,from the expected abundance (As) for this realisation.
If the Poisson sample is >1, the cluster exists in this realisation.
If the Poisson sample is <1 the cluster does not exist in this realisation.

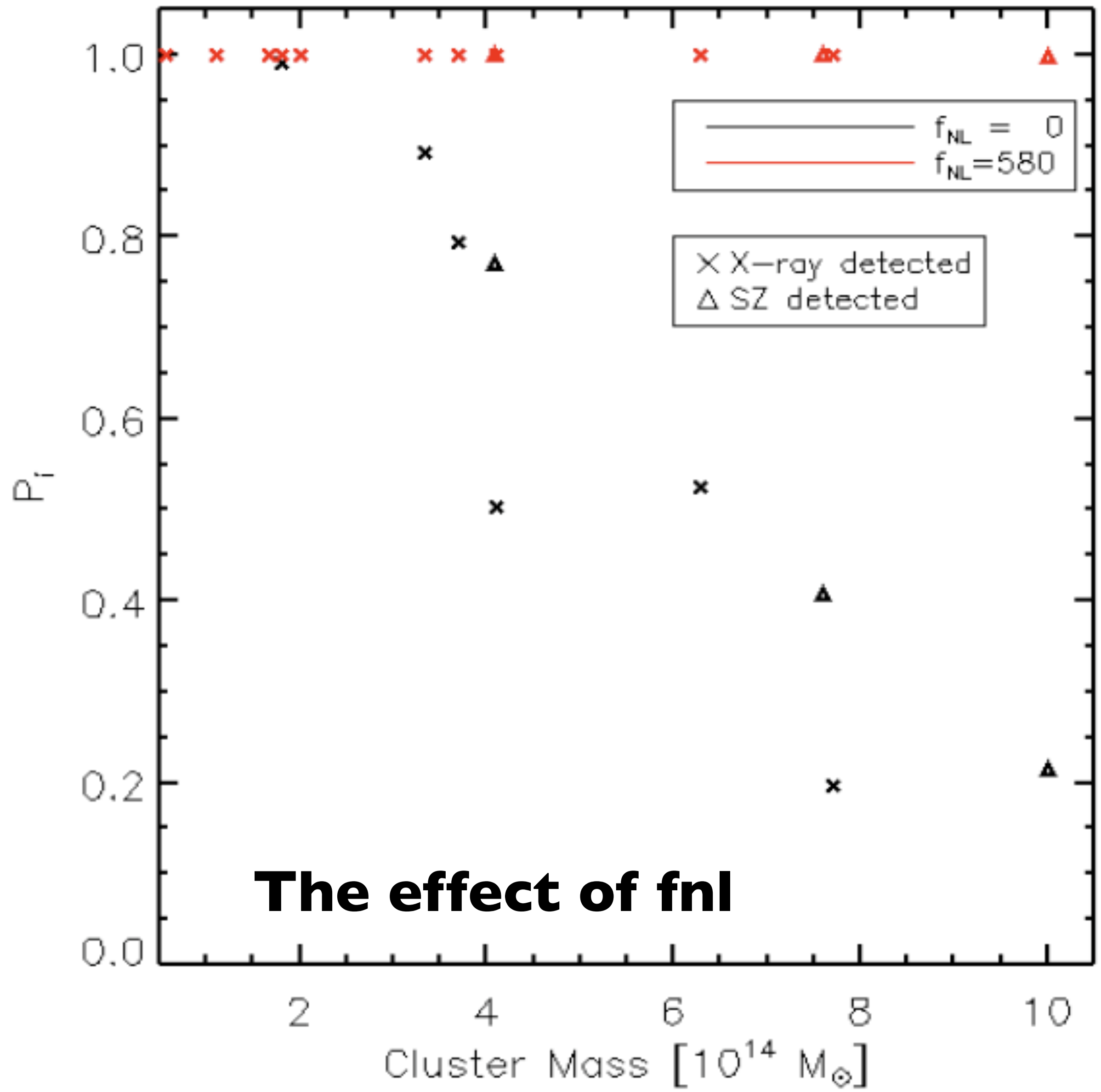
The probability P_i ,that cluster "i" exists is $\mathrm{Number}(P^O(A_s) \geq 1)/10^4)$

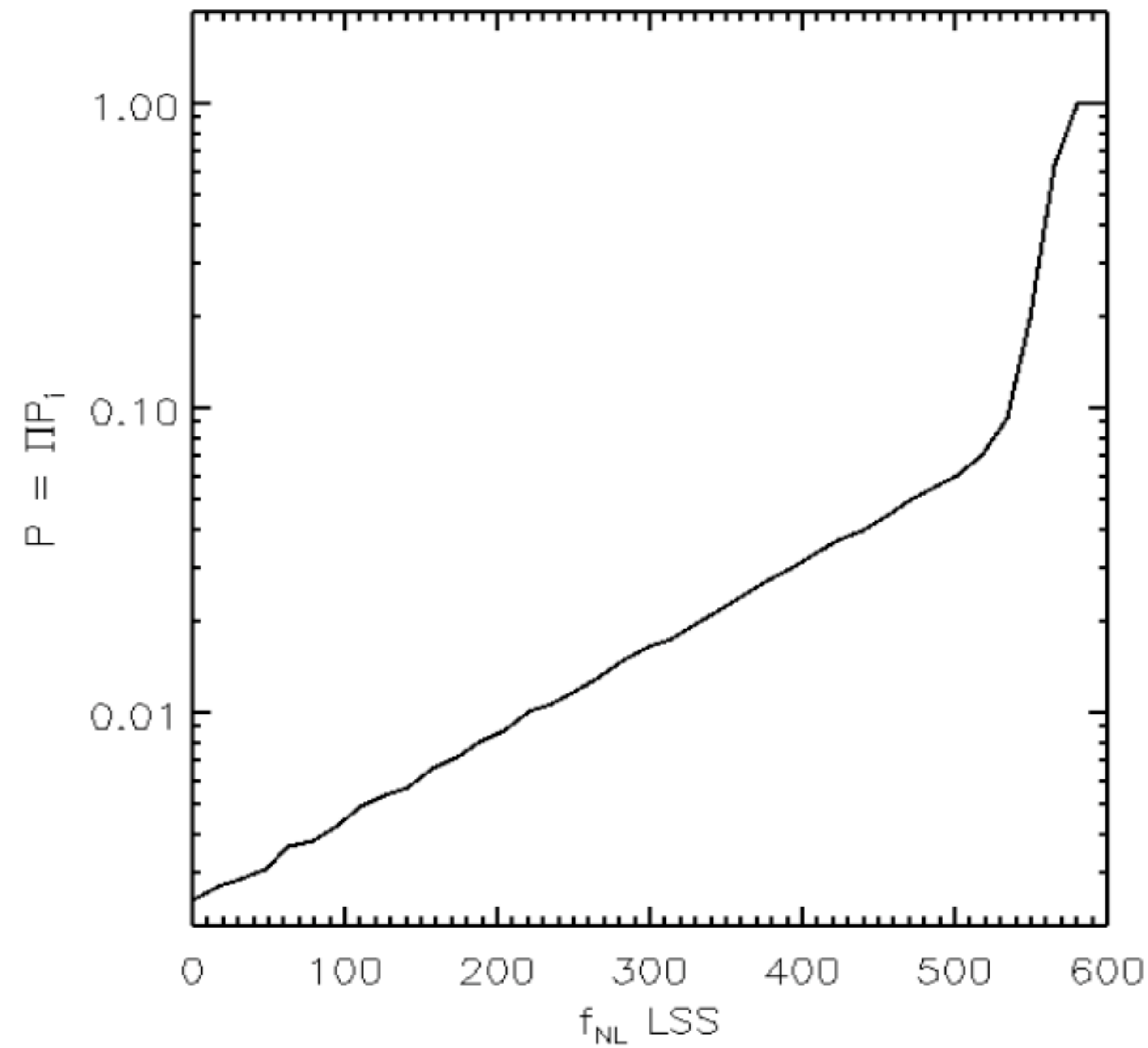
The probability, that the ensemble of cluster exists is $P(f_{\rm NL}, C) = \Pi P_i$

We multiply the probabilities, because the clusters are typically separated by vast redshifts, and positions on the sky. We therefore model them as being independent events.

Results >M,>z: I

Fixed cosmological parameters to best fit WMAP 5



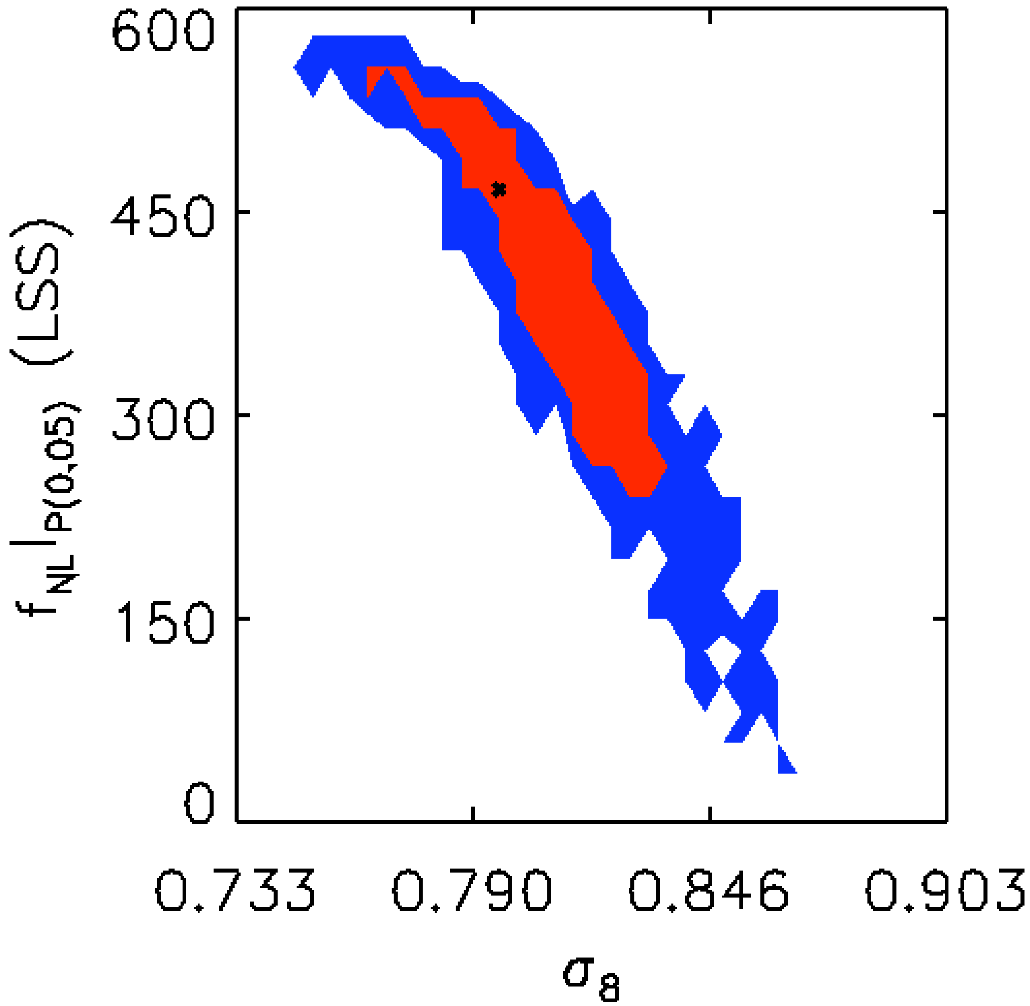


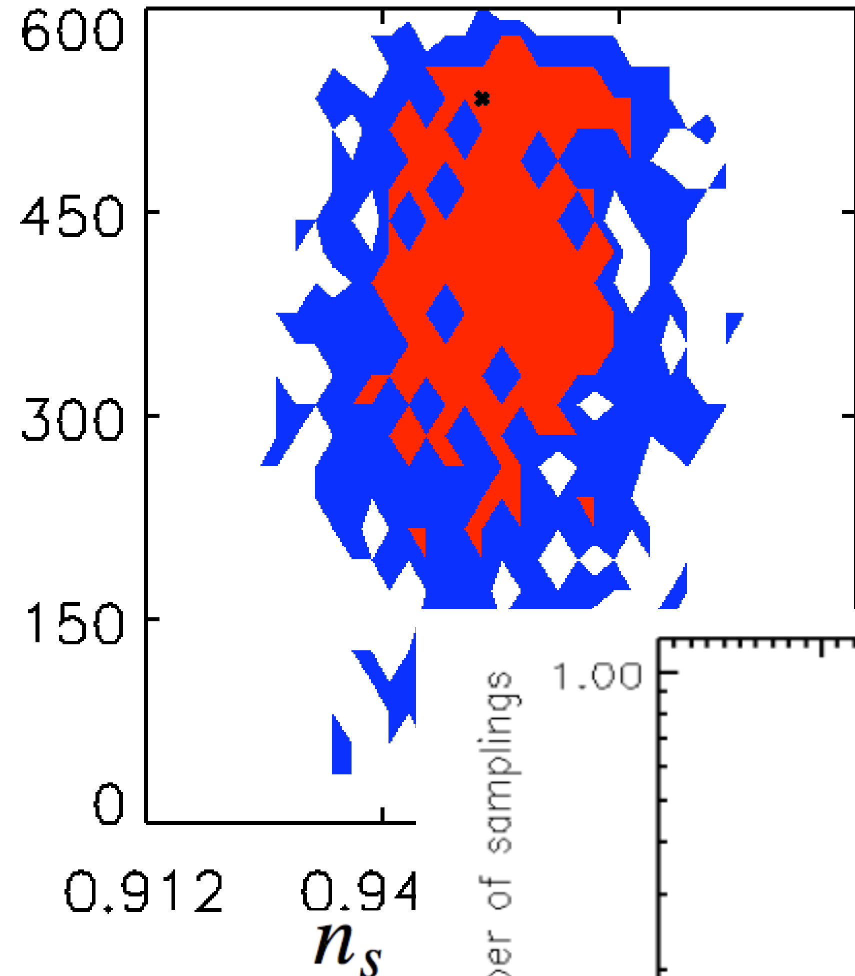
We determine the value of fnl where P=0.05
i.e., the value of fnl that contains 95% of the probability, denoted by $f_{\rm NL}|_{P(0.05)}$

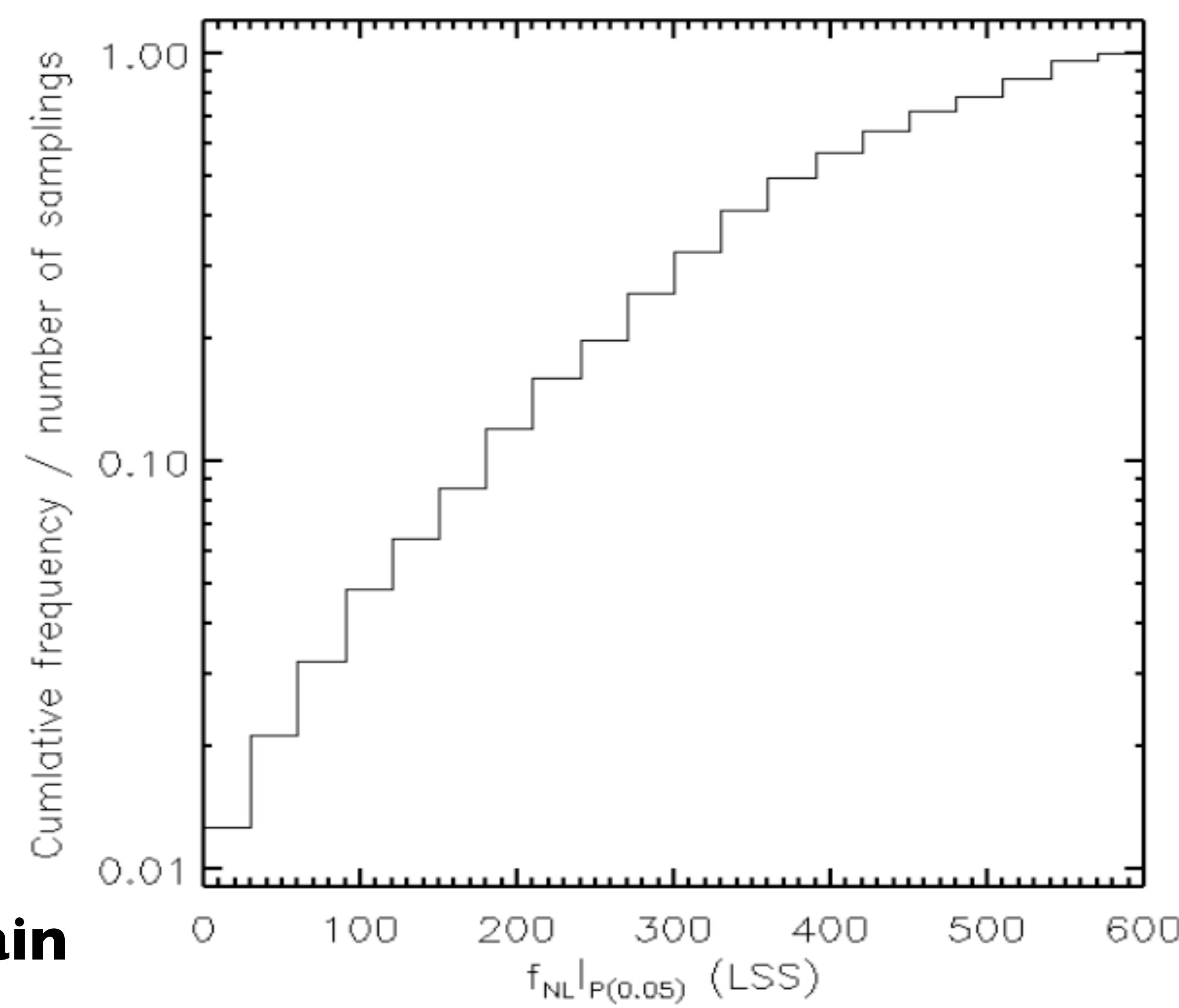
At the 95% confidence level, $f_{\rm NL} > 467$

Results >M,>z: II

Marginalising over parameters; $\Omega_M,\ \Omega_b,\ \Omega_\Lambda,\ \Omega_K,\ n_s,\ \sigma_8,\ H_0,\ w_0$







$f_{\rm NL}|_{P(0.05)} \gtrsim 123$ at the 95%

Note, this is a 95% value of a 95% statistic

<u>Reality Check!</u>

Is this a detection of +ve fnl, or are there systematics/biases which could also explain the presence of these clusters?

Possible explanations: Systematics

1) Cosmological parameters.

- **If** $\sigma_8 = 0.9$ **tension is removed.**
- **But CMB + LSS find (Komatsu et al 2011)**

$$\sigma_8 \;=\; 0.801 \pm 0.03$$

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2) Mass functions.

Do we understand the mass function (with/without non-Gaussianity) at high mass and redshift well enough?

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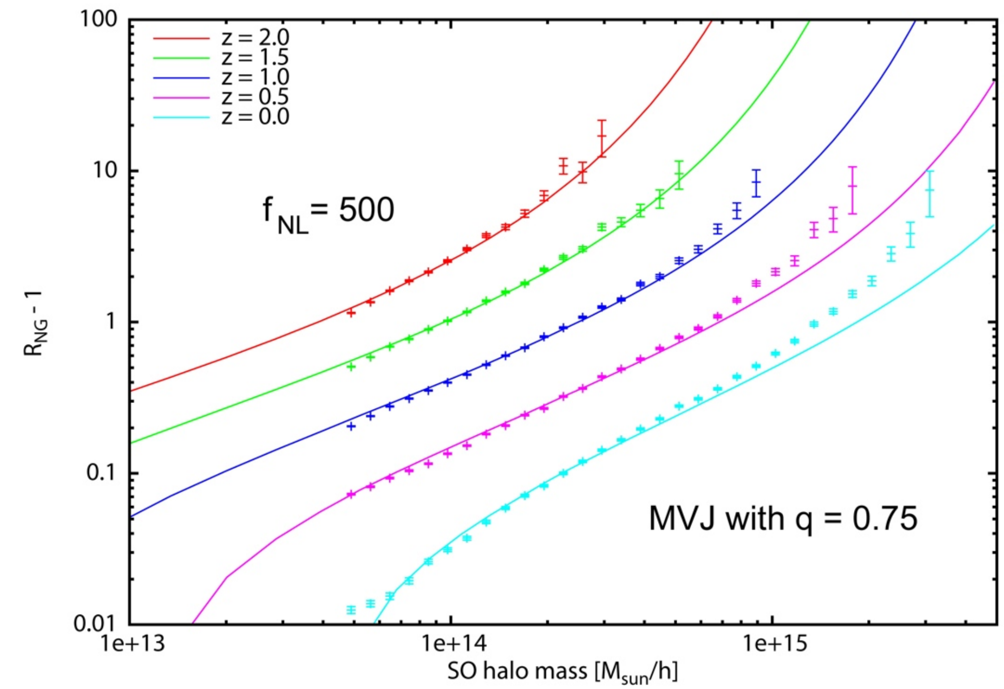
--Yes new simulation work by Christian Wagner fnl<500, z<1.5, M<5x10^14 Msol



Non-Gaussian mass function fit to N-body simulations
Volume: 40 x (2.4 Gpc/h)^3
Number of Particles: 40 x 768^3
Spherical-overdensity halos with "virial" masses
Difference for very large halo masses might be due to fnl^2 effects.

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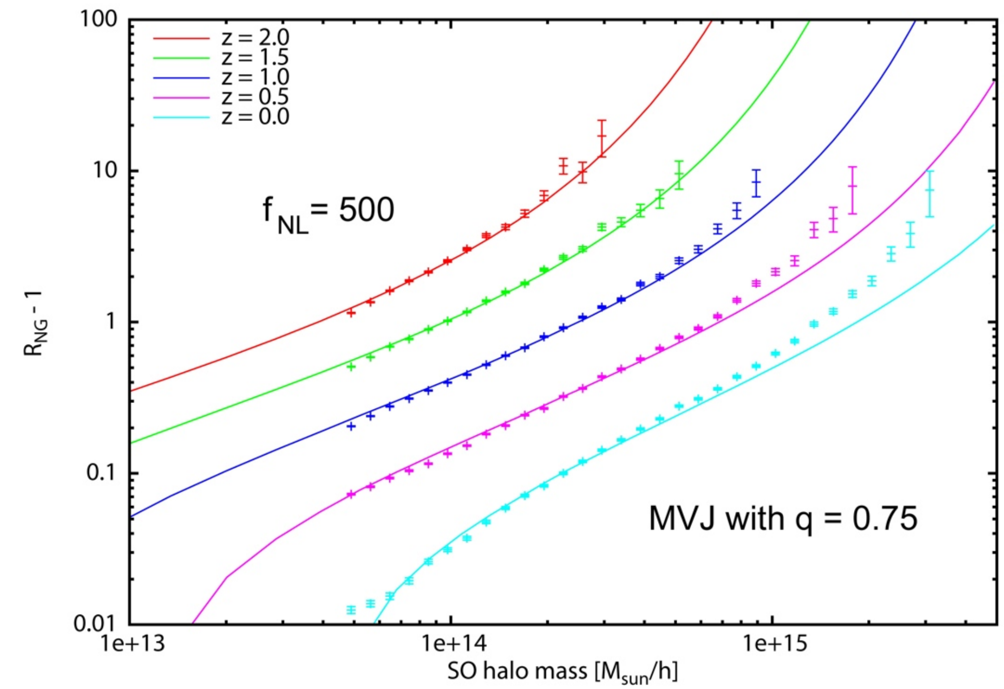
If every mass measurement was 1.5 sigma higher than the "true" value, then all tension is relieved. But all independent mass estimates must be systematically, equally wrong, and we chose mass measurements to relieve tension.



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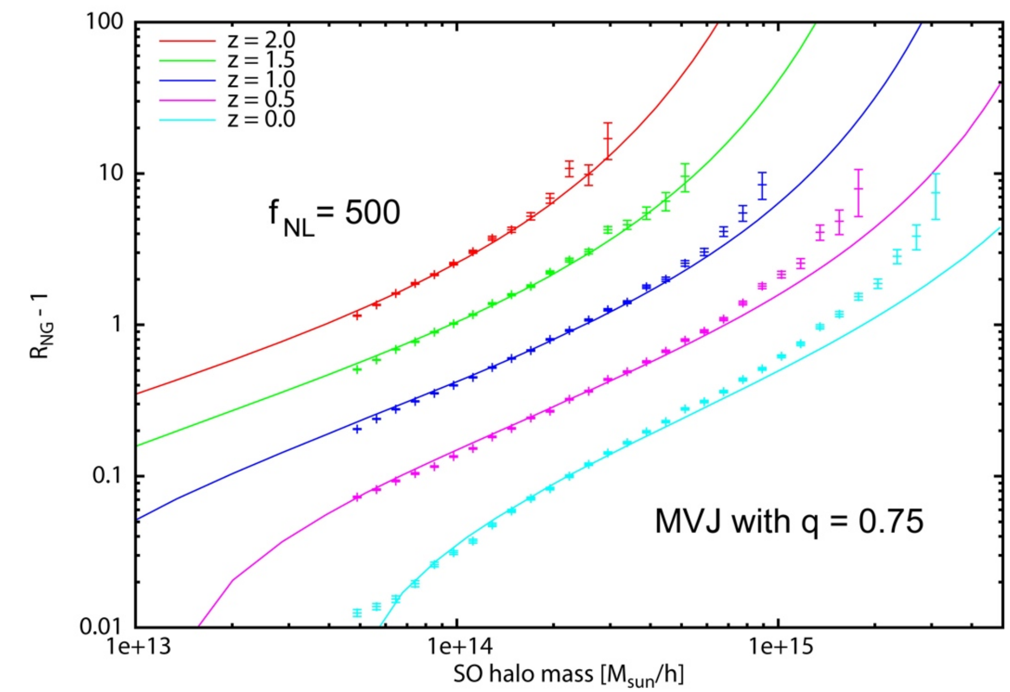
HST WL proposal to obtain better mass measurements of high-z cluster :([PI BH].



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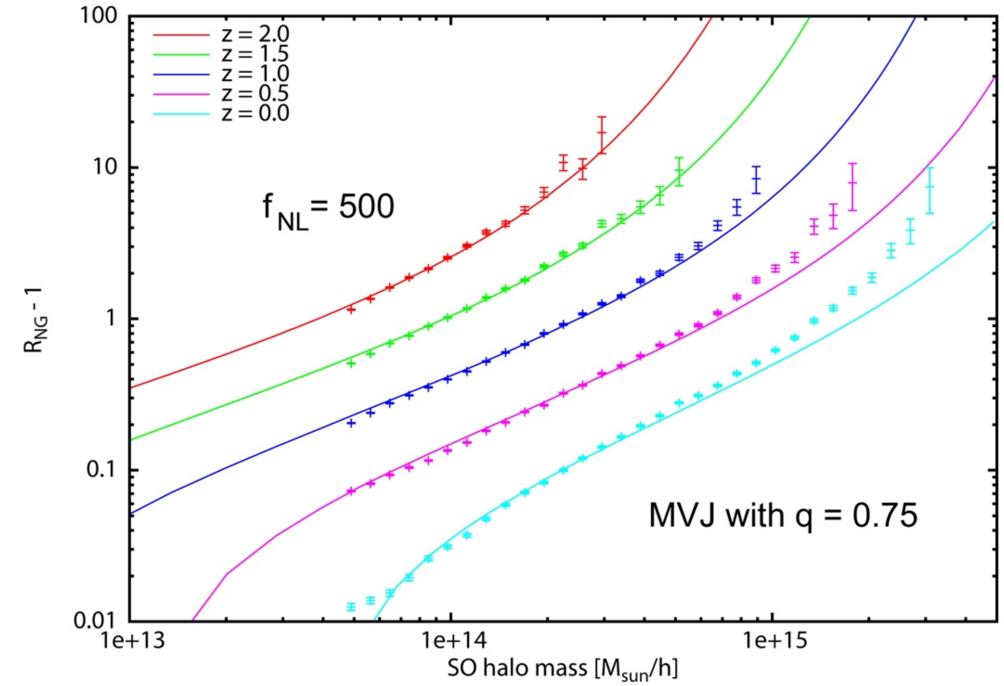

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4) Biased analysis.

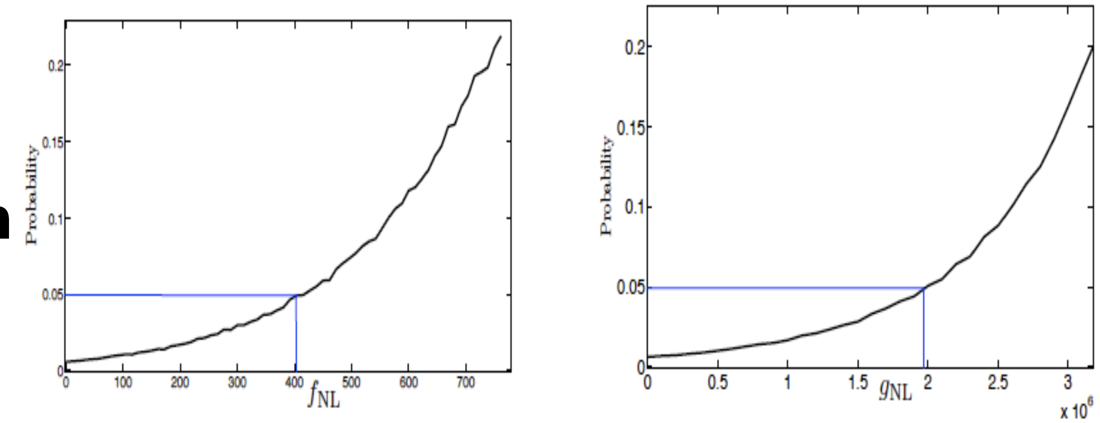
Some heated discussions: Mortonson, Jimenez,Verde,Hunterer,Hotchkiss,Hu..
Is the analysis correct? -- All literature have been asking >M,>z question.

Related works

Related works

Enqvist et al 2010

- **Agreed with us!**
- **Breakdown of the mass function**
- **Small fnl, consistent gnl**



(a) The probability that the ensemble of clusters in table 1 could exist as a function of $f_{\rm NL}$.

(b) The probability that the ensemble of clusters in table 1 could exist as a function of $g_{\rm NL}$, with $f_{\rm NL} \lesssim 50$.

Figure 6. Estimates for $f_{\rm NL}$ and $g_{\rm NL}$.

Related works

Enqvist et al 2010

- **Agreed with us!**
- **Breakdown of the mass function**
- **Small fnl, consistent gnl**

Mortonson et al 2010

- **Treatment of the Eddington bias**
- **Tension curve for 1 cluster.**
- **Very conservative footprints and mass estimates.**
- **Insensitive treatment of multiple clusters**

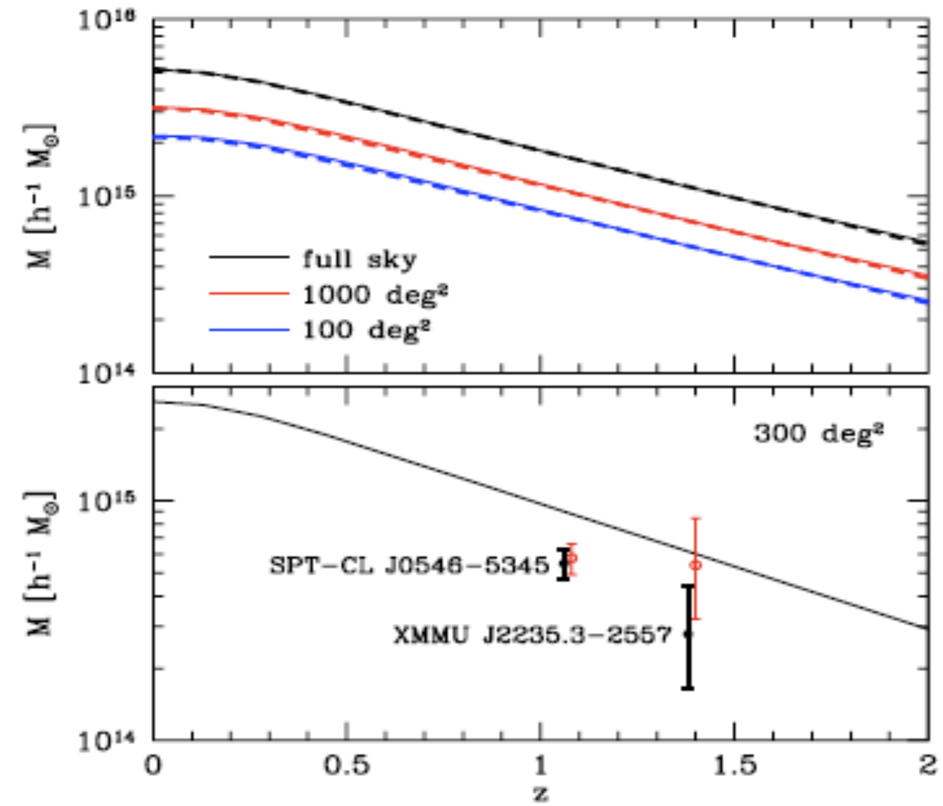


FIG. 4. $M(z)$ exclusion curves. Even a single cluster with (M, lying above the relevant curve would rule out both ΛCDM ar quintessence. *Upper panel:* flat ΛCDM 95% joint CL for bo sample variance and parameter variance for various choices of sl fraction $f_{\rm sky}$ from the MCMC analysis (thin solid curves) and usi the fitting formula from Appendix A (thick dashed curves; acc rate to $\lesssim 5\%$ in mass). *Lower panel:* Two of the most anomalo clusters detected to date, compared with the 95% joint CL excl sion curve for 300 deg^2 which approximates the total survey ar for each cluster. We show the X-ray determined masses with ar without Eddington bias correction (black solid points with thi error bars and red open points with thin error bars, respective offset in redshift by ± 0.01 for clarity).

The Eddington bias: Measurements (with an error) drawn from non-uniform distributions are biased because objects are more likely to be scattered in one particular direction than another. The shape of the theoretical cluster mass function means that low mass clusters are more likely to be scattered high, and masquerade as high mass clusters, than higher mass clusters are to be scattered low.

Related works

Enqvist et al 2010

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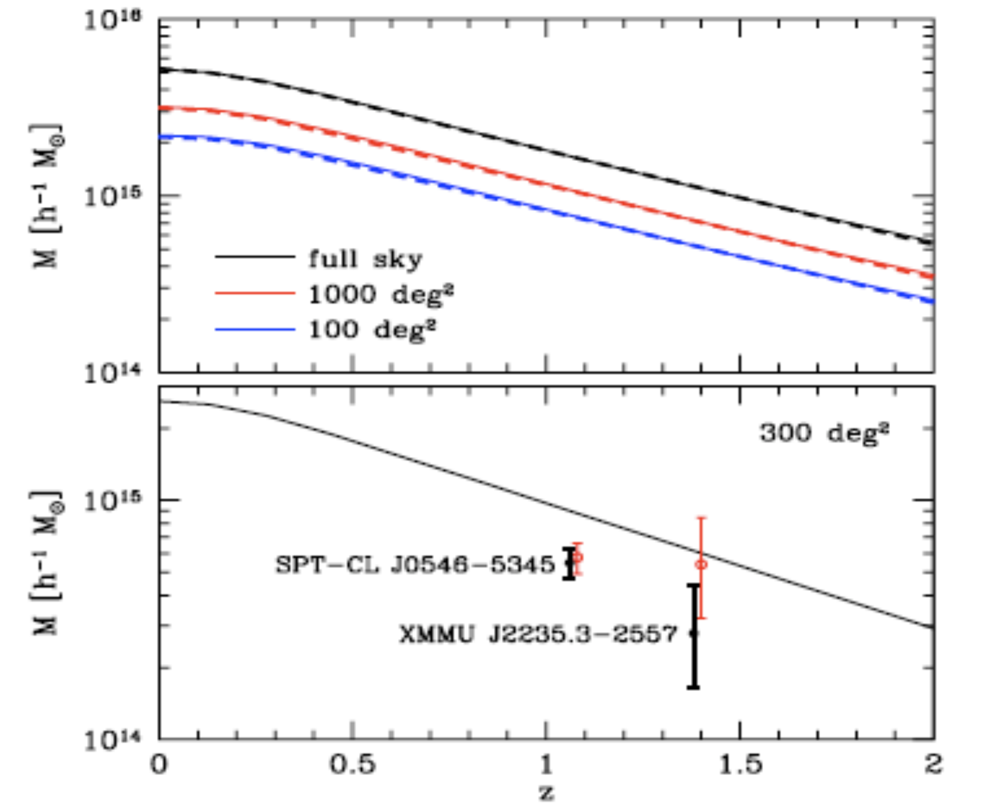
- **Small fnl, consistent gnl**



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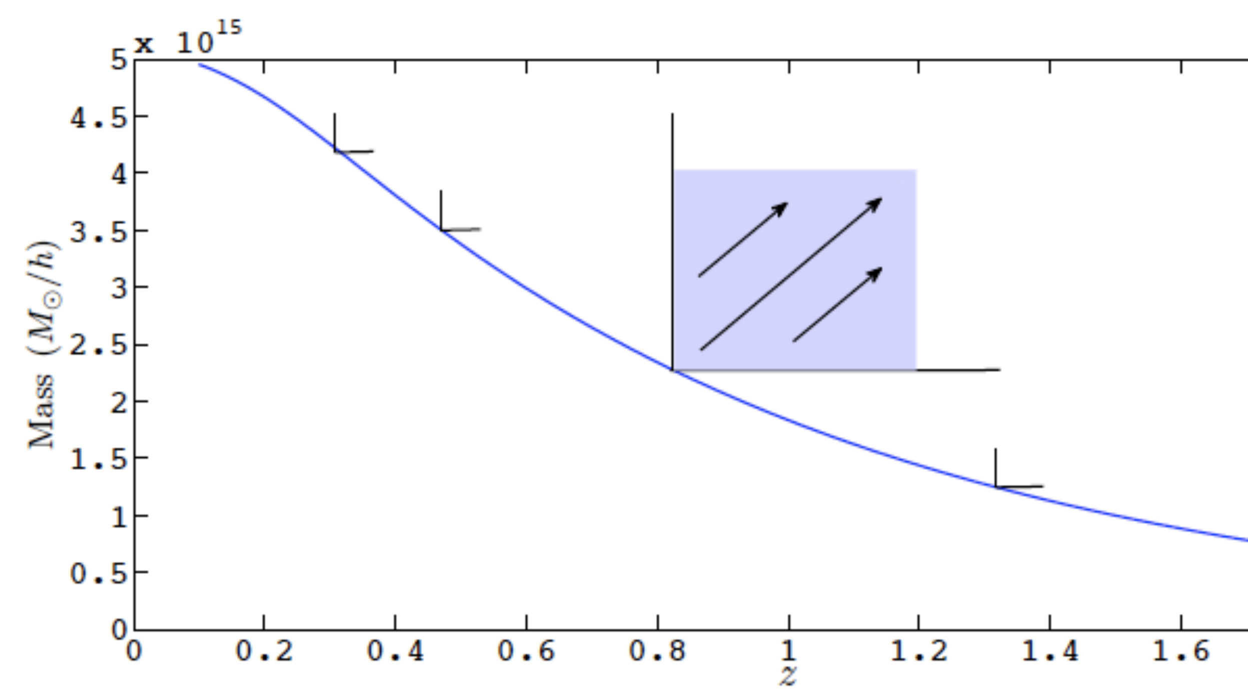
Mortonson et al 2010

- **Treatment of the Eddington bias**
- **Tension curve for 1 cluster.**

Hotchkiss 2011

- **Identified a bias, and fixed. Compared with Poisson samplings of the mass function. Assumed unrealistic 2500 sq. deg. WMAP7 best fit parameter values.**
- **If the observed clusters were consistent with being the Least Probable clusters = no tension with WMAP7 LCDM.**
- **If observed clusters random selection= still tension.**



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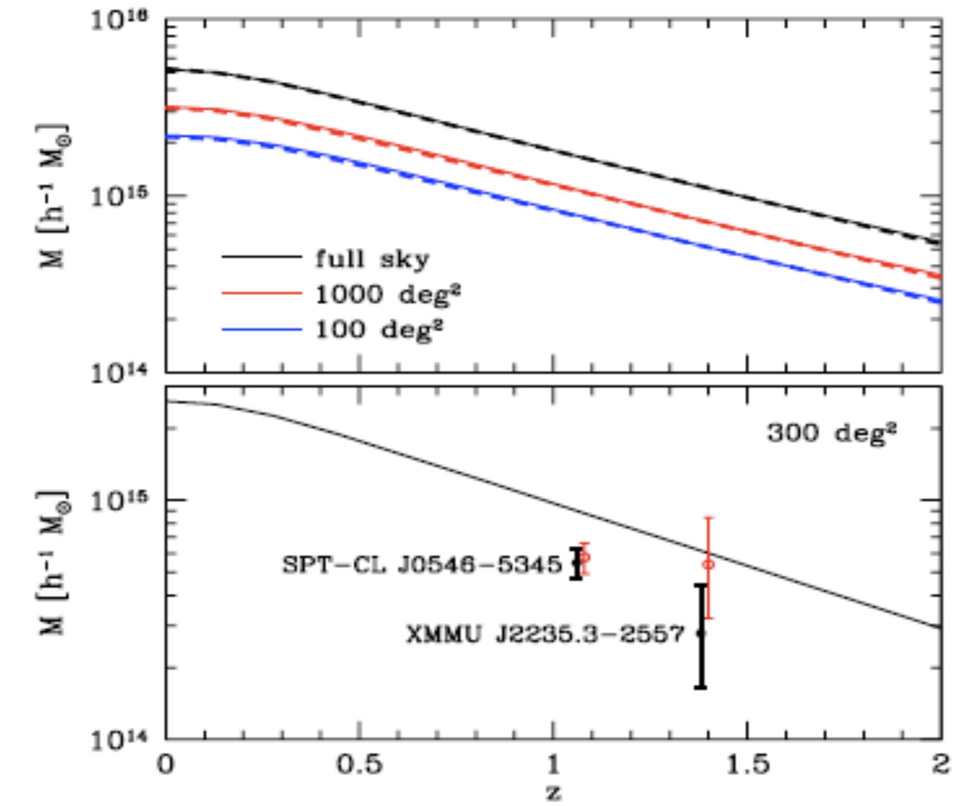

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>M,>z bias

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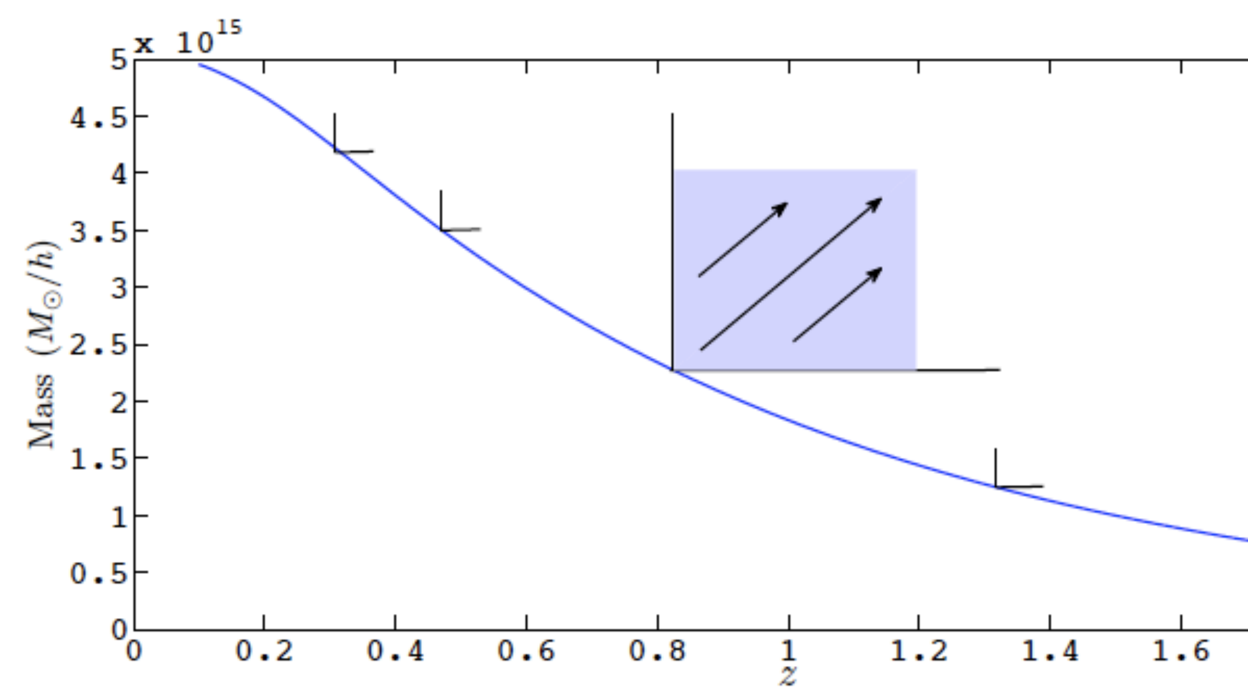

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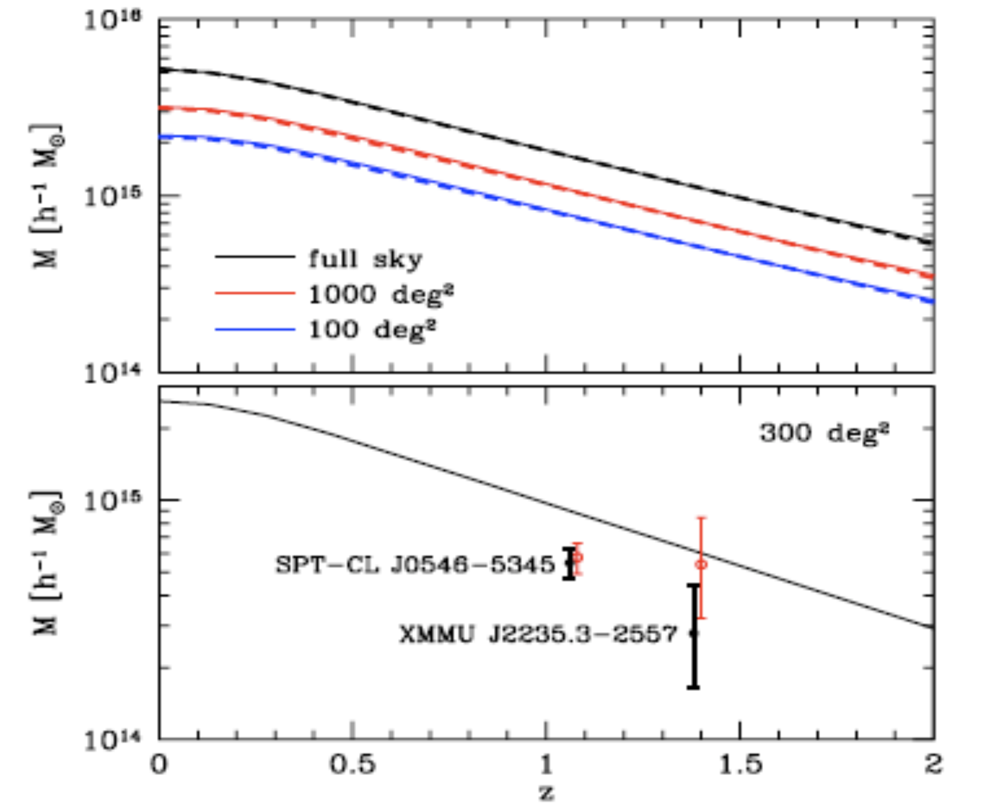

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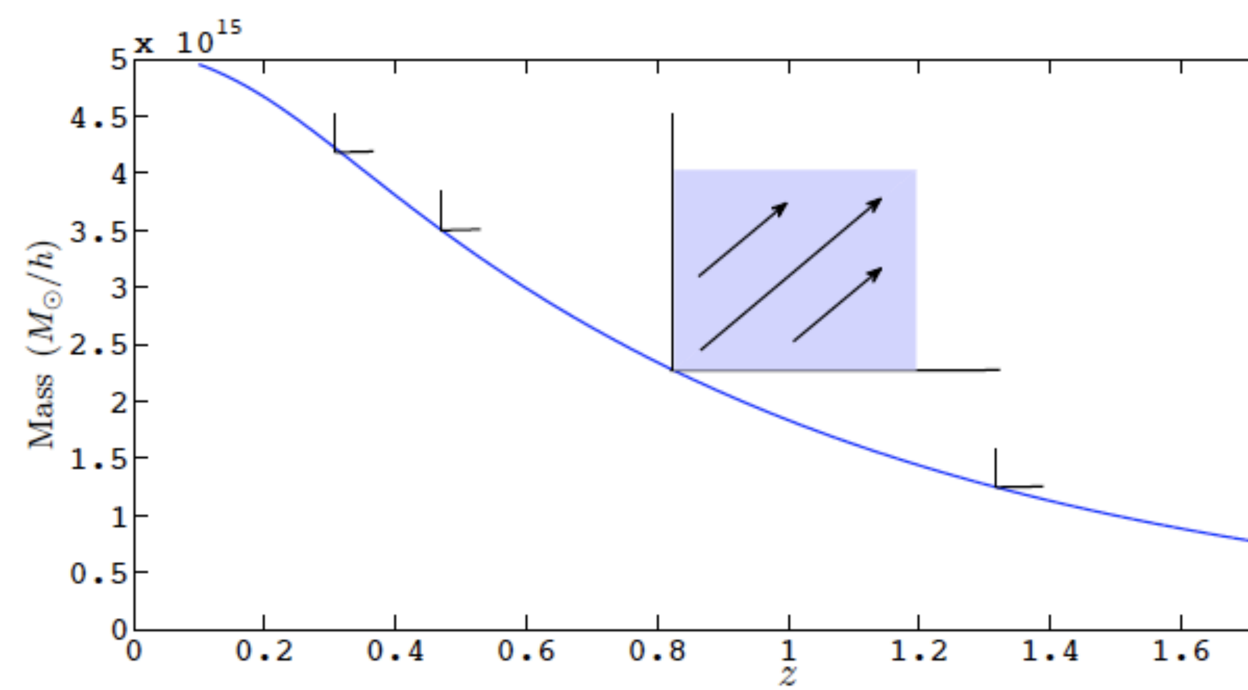

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In all previous literature the >M,>z "existence probability" R, has been used as a proxy for what we actually want to know, "What level of tension with a model is caused by the existence of this cluster?"

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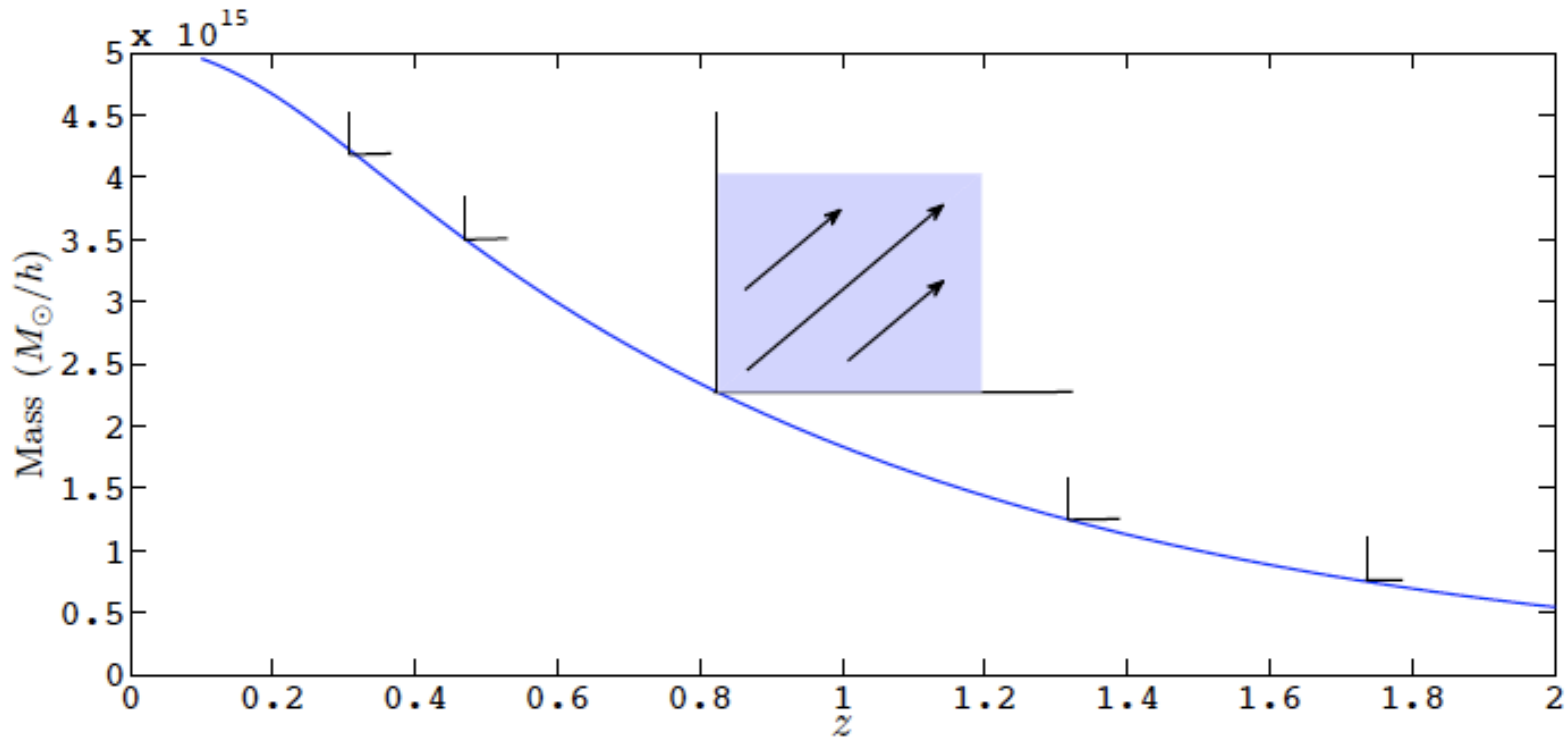
Why should we restrict ourselves to the easily calculated, but arbitrary, >M,>z contours, e.g, what dictates that the box should be placed at right angles to the (M,z) axis, and not at an incline of X%, or have curved instead of straight boundaries? One could simply squash the >M,>z box by X% and obtain a new existence probability R* which would be equally as 'justified' as the original existence probability R. The Universe doesn't care what we call "existence probability"



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Using R to measure tension with a model

Once the above is understood, we can simply calibrate R on simulations. For example, assuming survey geometry: mass >1e14 Msol, 2.2>z>1.0, and a footprint of 100 sq. deg, Poisson sample from the mass function and calculate R for each cluster. We find that the ``Least Probable'' (LP) cluster from each separate simulation has a spread of existence probabilities from 0.001<R<0.339 at 95% Also note that, randomly selected simulated clusters have 0.8<R<1.0 at 95%

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How we use R in practice

If we detected, followed up, and measured the mass of only one cluster C, we wouldn't know it were actually the least probable cluster until all others had been followed up. But, if Rc < 0.001 --> immediately claim tension. However, if Rc=0.1 (>>0.001) we cannot rule in/out tension, because we don't know which sample C was drawn from (random or LP), until further analysis/followup.

If we have detected multiple clusters, we can multiply each R together and compare with simulations.

Overview

- The LCDM model
- Galaxy Clusters
- -as probes of cosmology
- -as extreme objects
- Observational motivation: extreme objects
- Theory: non-Gaussian cluster mass function
- The cluster sample
- The XMM Cluster Survey
- What we did; Analysis and results using >M,>z
- What we found; Possible explanations, Systematics
- What others thought: Related work
- Why we were all wrong: Understanding the >M,>z question
- New, correct analysis and results
- Conclusions + future work

Correct analysis/comparison

Cluster Name	Redshift	M_{200} $10^{14}M_\odot$	Method	$\tilde{R}$	Mass reference
RCS0221-0321	1.02	$1.80^{+1.30}_{-0.70}$	WL	0.992	[15]
WARPSJ1415+3612	1.03	$4.70^{+2.00}_{-1.40}$	WL	0.706	[15]
RCS0220-0333	1.03	$4.80^{+1.80}_{-1.30}$	WL	0.709	[15]
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XLSSJ022403.9-041328*	1.05	$1.66^{+1.15}_{-0.38}$	X-ray	0.997	[31]
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Observations progressed

Jee et al 2009, 2011, Santos et al 2011, Stott et al 2010

Realistic X-ray survey footprint 100 sq. deg. Most precise mass measurement.

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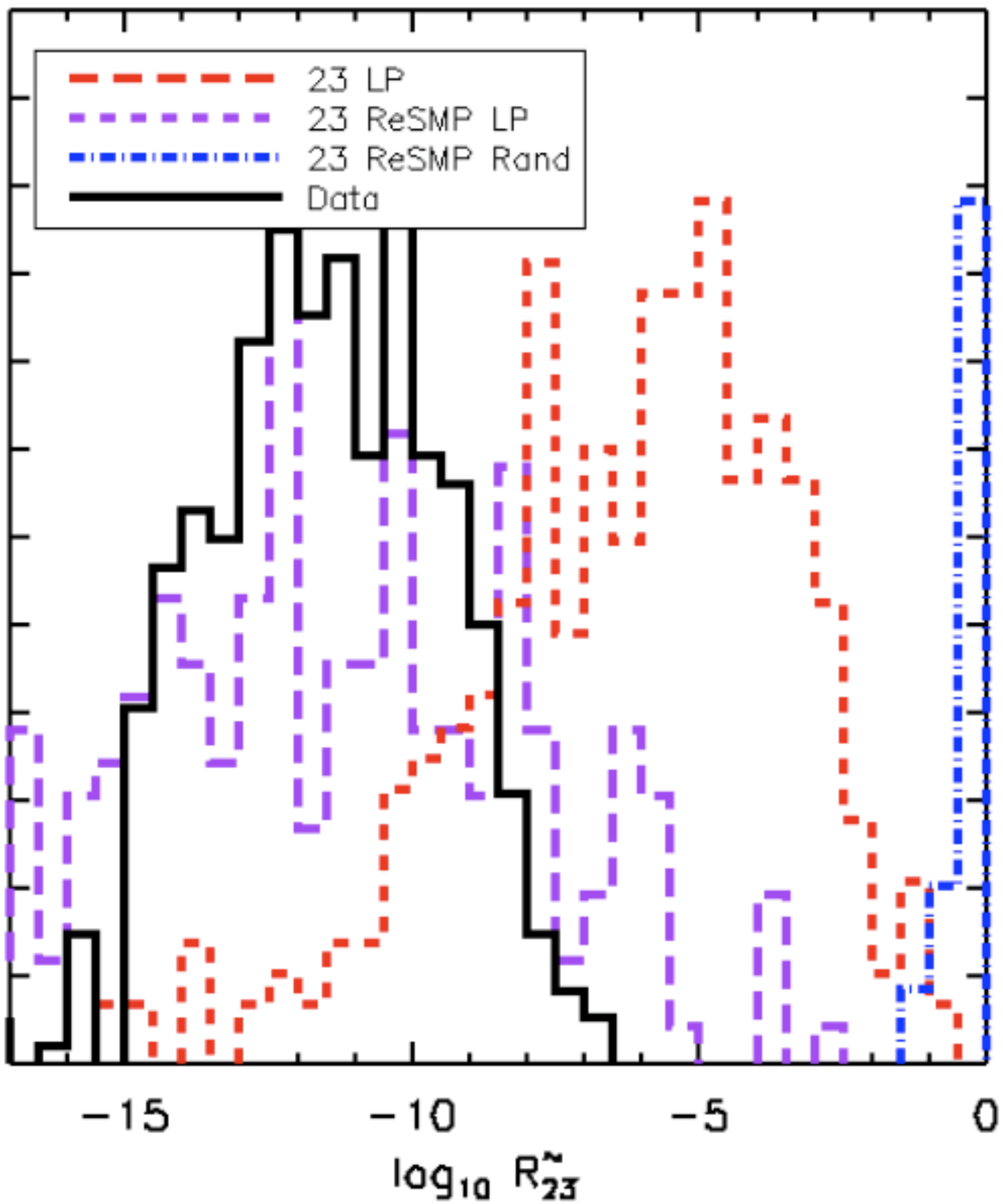
Realistic X-ray survey footprint 100 sq. deg. Most precise mass measurement.

Compare to improved simulations
1) 450 sets of Poisson samplings from mass function, vary cosmological parameters, assuming WMAP7 priors.

2) Assign each simulated cluster a 40% mass error and re-sampled the cluster mass. This accounts for the Eddington bias.
3) Calculate R for each cluster, identify the LP clusters.

The >M,>z statistic

We have observed 23 clusters, we sampling from the mass and error, and then multiply each R value together R_{23}, and then compare with simulations.



No R tension if the observed clusters are drawn from the LP re-sampled clusters.
Massive tension if the observed clusters are drawn from a random sample.
More work to determine which sample the clusters are drawn from.

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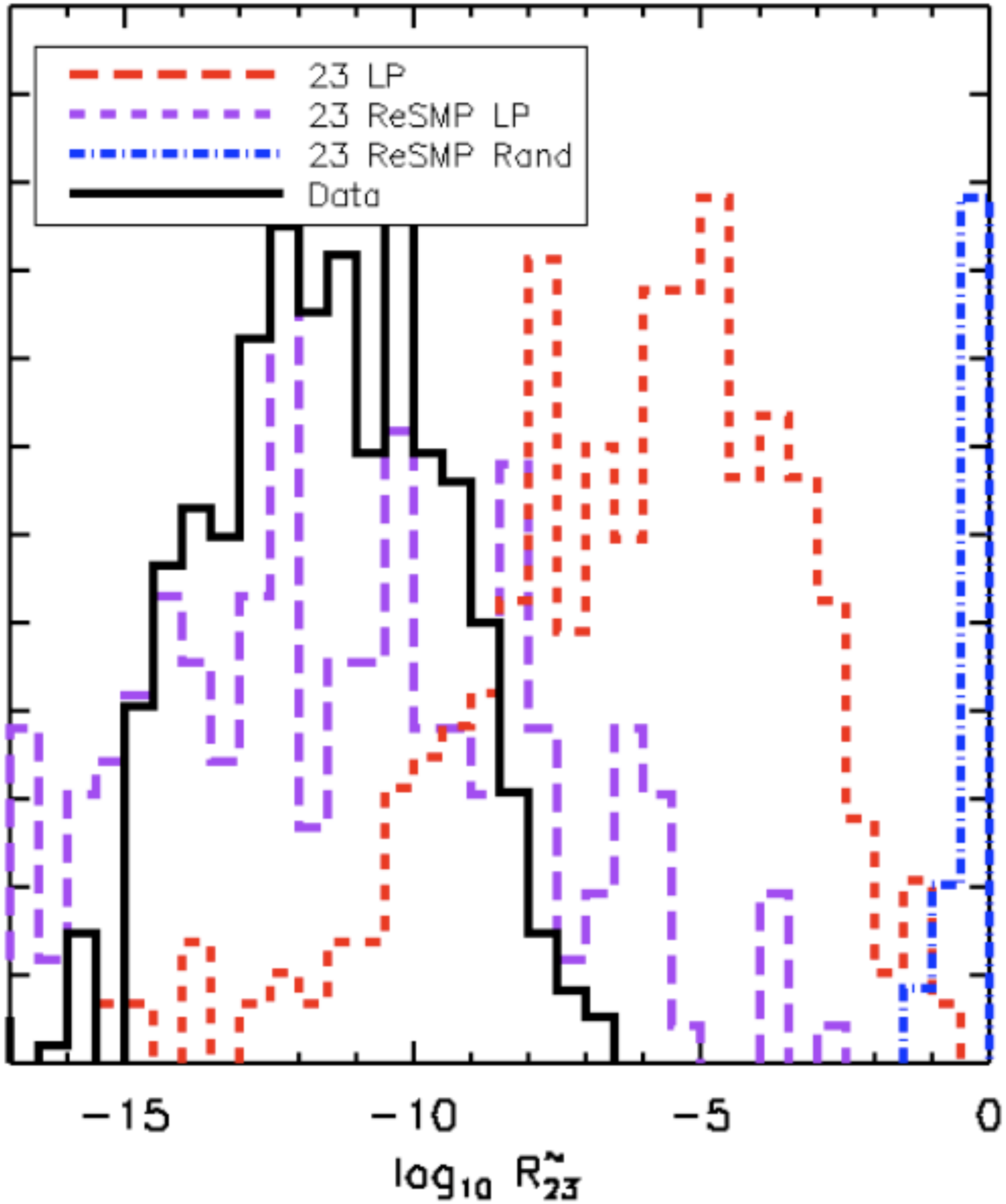
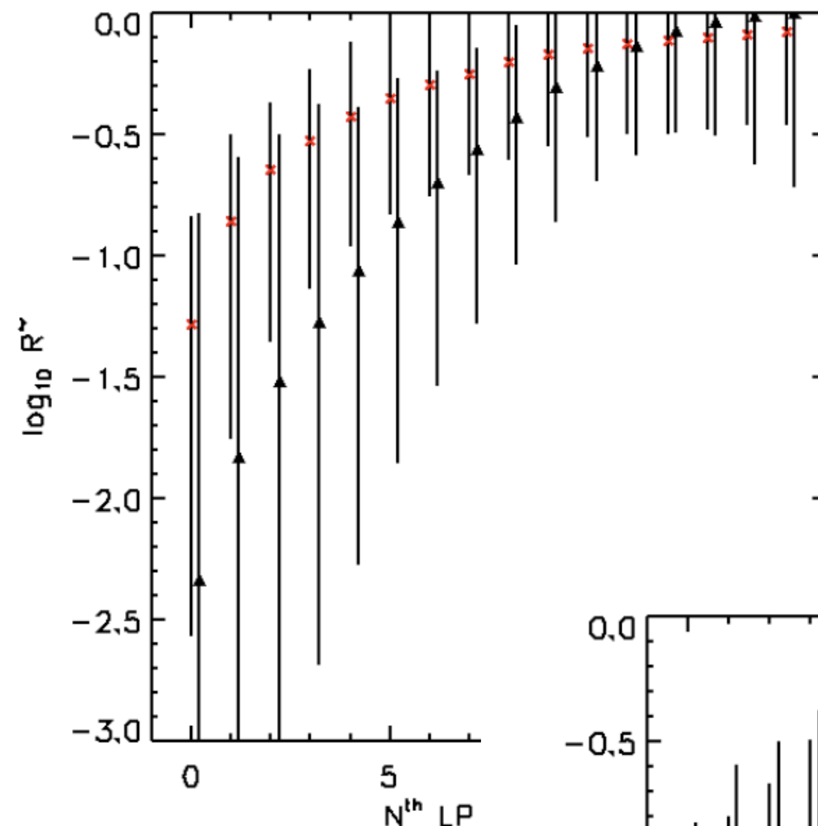
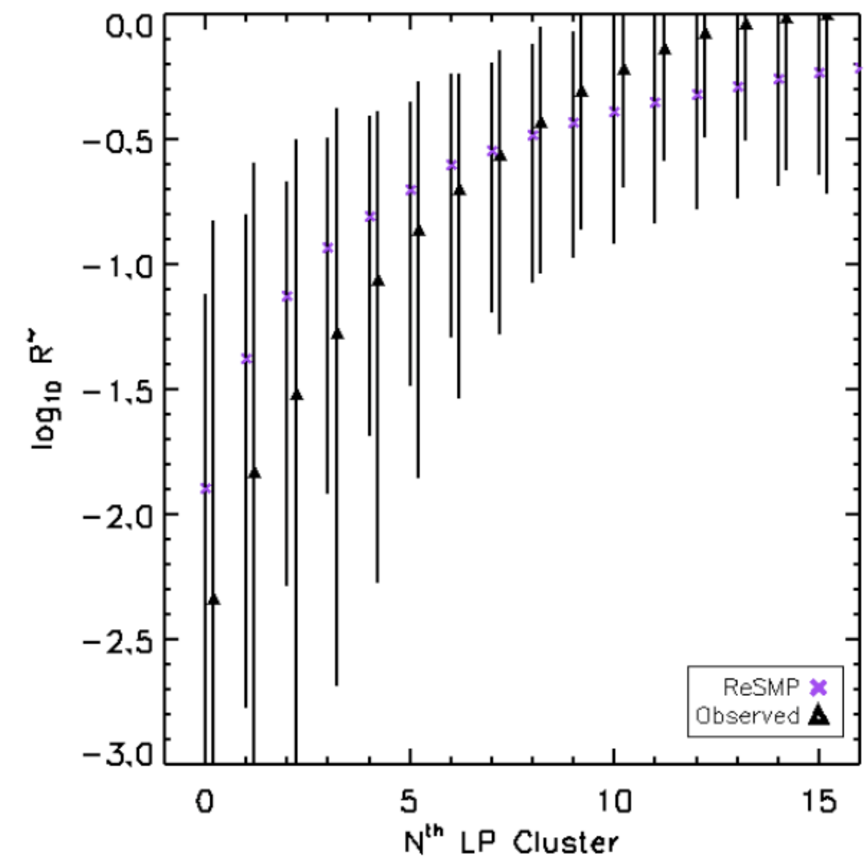




Rank each cluster by R and compare with simulations



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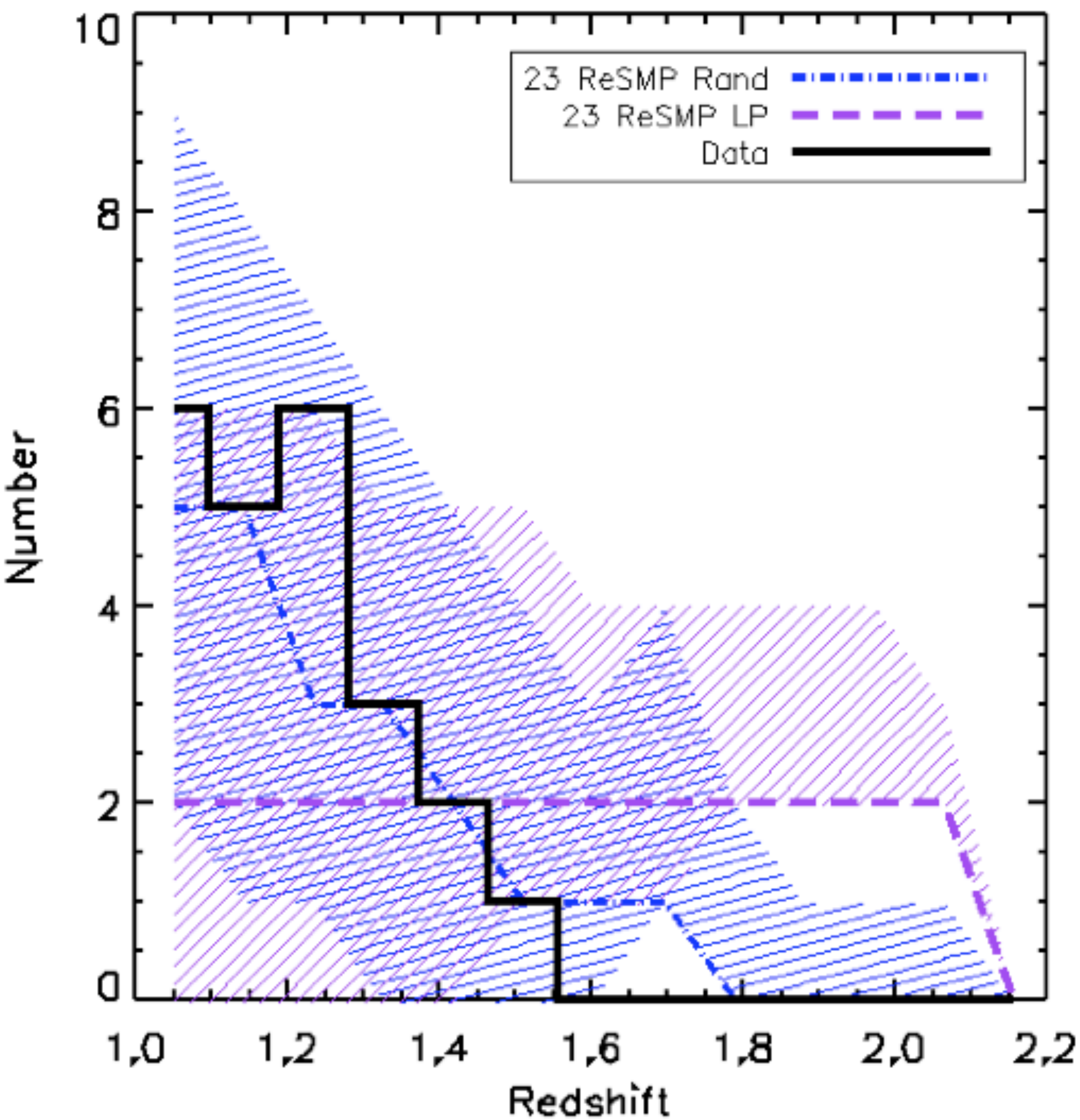
The distribution of clusters: I

To determine which sample of simulated clusters the observed clusters are consistent with, we compare the redshift histograms of the 23 observed clusters with sets of 23 randomly selected, and 23 LP (re-sampled) simulated clusters.



If the observed clusters were drawn from the LP clusters, we would expect ~8 of them to have z>1.6.

We observe 0.
Poisson Probability (0,8)=exp(-8)

The redshift distribution is better described by the randomly selected re-sampled simulated clusters

More rigorous testing of 2 two dimensional data sets: 2dK-S test.

Recall: If LP no R tension, if random lots of R tension

The distribution of clusters: II

The 2d Kolmogorov-Smirnov test calculates the probability of two 2d data sets being drawn from the same parent population. We compare the distribution in the (M,z) plane of the 23 LP clusters from each simulation with each other (varying WMAP7 cosmology) and with the data (after sampling from the mass and error), and 23 randomly selected simulated clusters with the data. P~0.2 means they are likely to be drawn from the same parent population.

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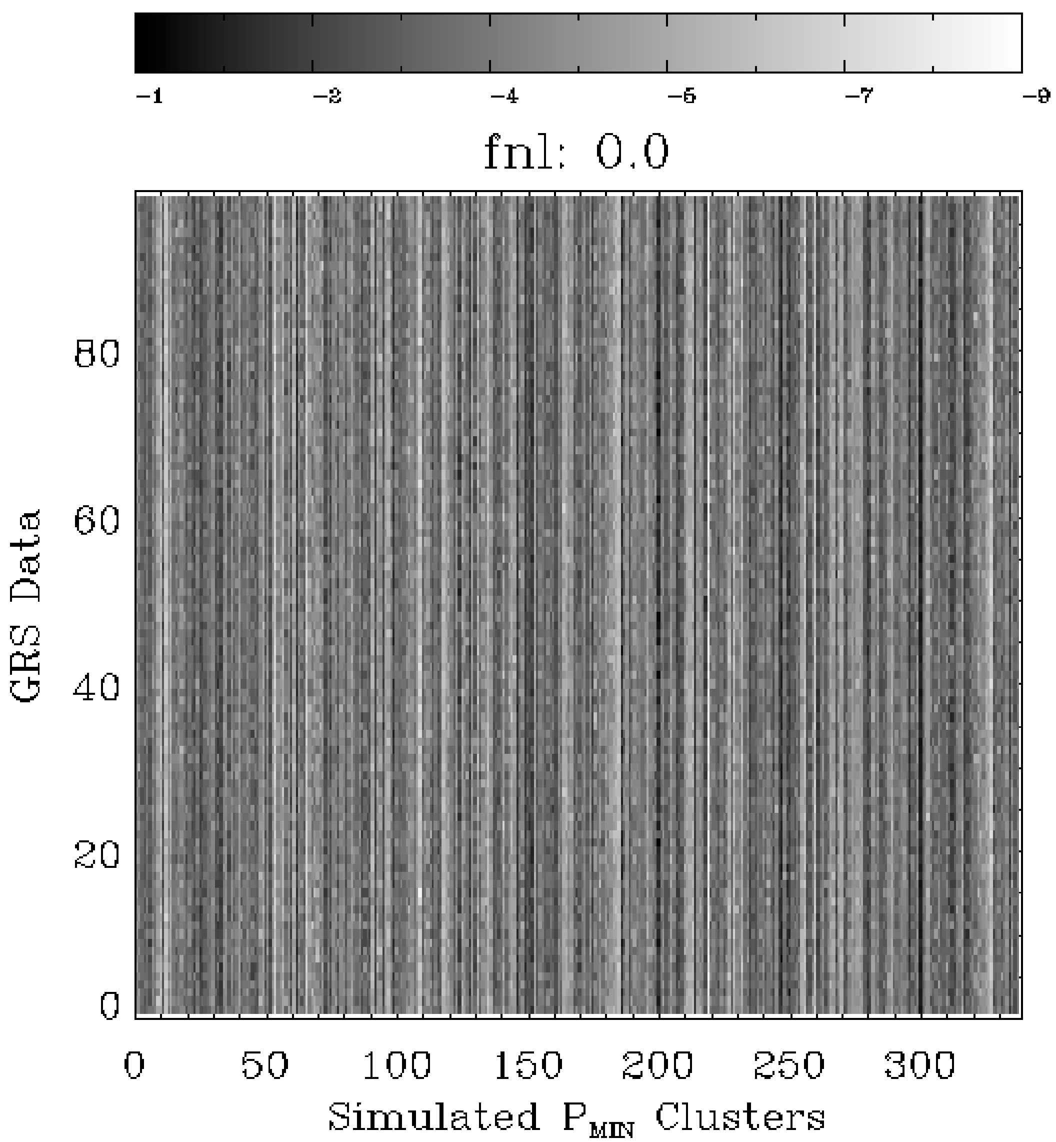

Results

- **The simulated LP clusters are consistent with each other (P=0.2, 10^{-0.7})**
- **The simulated LP clusters are not consistent with the observed clusters (P=0.001)**
- **But, the observed clusters are less likely still to be consistent with a randomly selected simulated clusters.**

S1(M,z)	S2(M,z)	$< \log P > f_{NL}^{-200}$	$< \log P > f_{NL}^{0}$
Sim P_{LP}	Sim P_{LP}	-0.79 ± 0.67	-0.81 ± 0.72
D^x	Sim P_{LP}	-3.24 ± 0.97	-3.33 ± 0.96
D^x	Sim P_{RAND}	-5.09 ± 1.08	-4.94 ± 1.08
S1(M,z)	S2(M,z)	$< \log P > f_{NL}^{200}$	$< \log P > f_{NL}^{400}$
Sim P_{LP}	Sim P_{LP}	-0.82 ± 0.70	-0.84 ± 0.73
D^x	Sim P_{LP}	-3.36 ± 0.94	-3.50 ± 0.91
D^x	Sim P_{RAND}	-4.85 ± 1.186	-4.70 ± 1.13

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Main results

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The (>M,>z) R statistic, tells us that if the observed clusters were consistent with being the LP clusters (compared with simulations), all tension has been removed. But the redshift distributions and the 2dK-S test, show that this is very unlikely.

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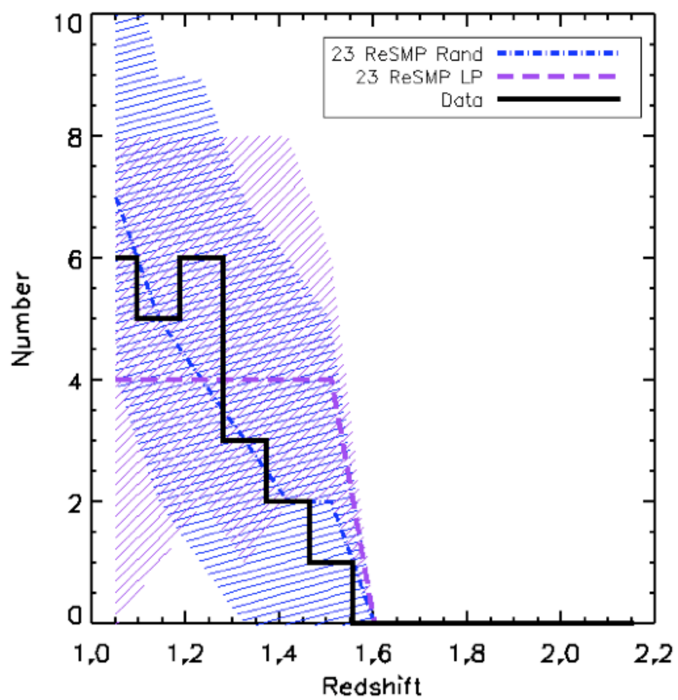
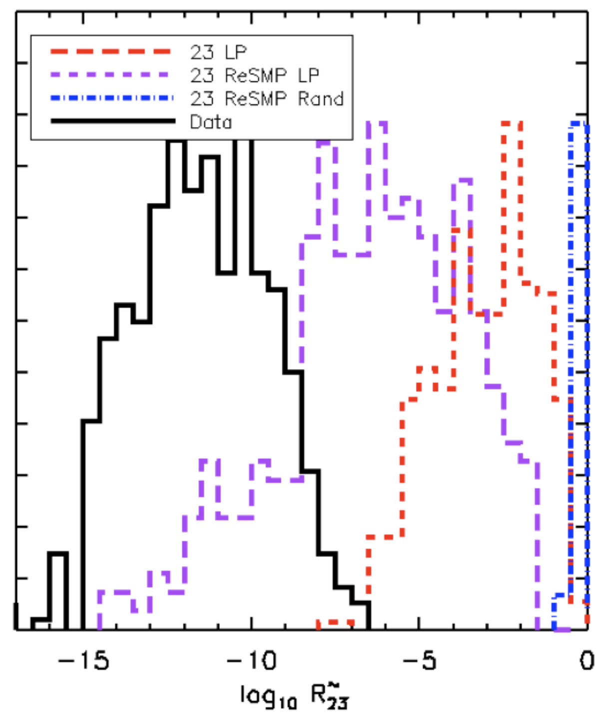
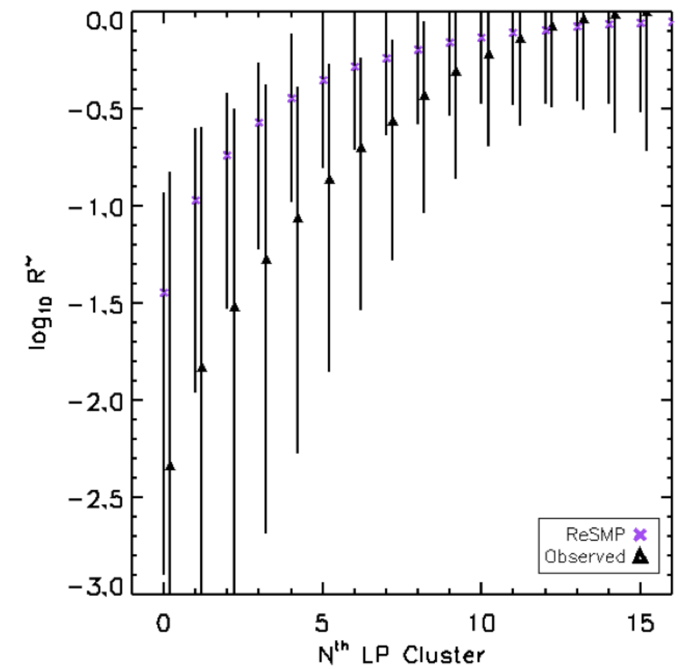
What could cause such a signal?

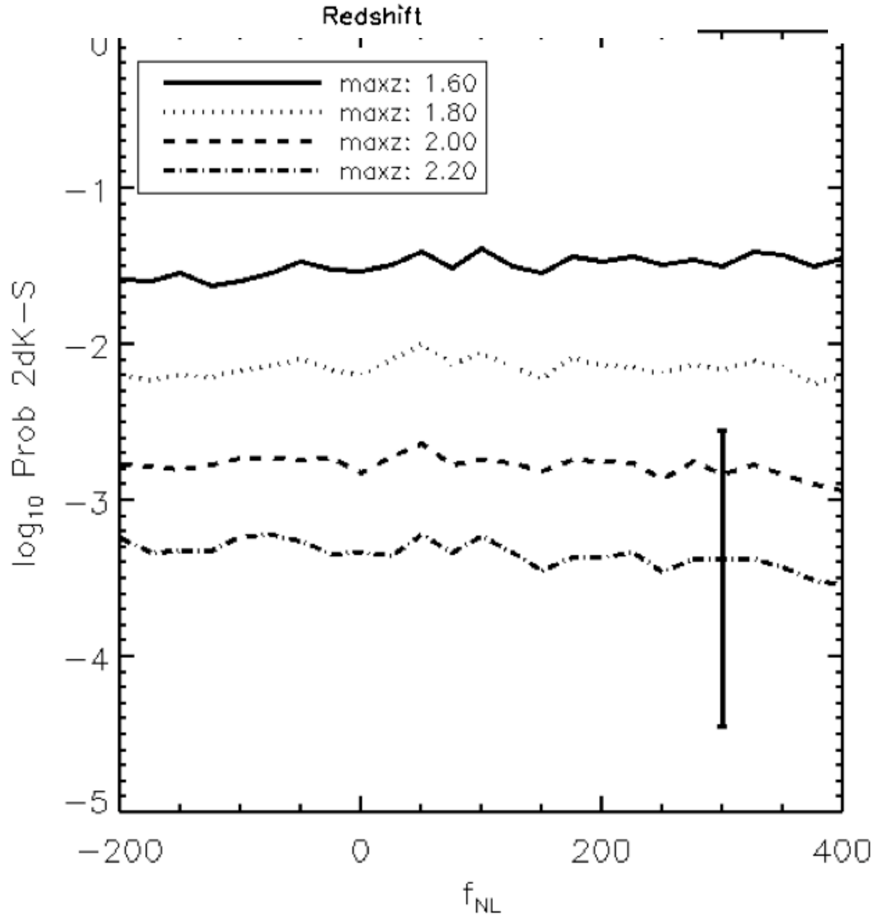
Possible (unphysical?) causes.

If there was a very strange selection bias, such that only z<1.6, massive clusters were detected, followed up to obtain spectroscopic redshifts, then the comparison between observations and simulations begins to agree.









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But recall, z=2.07, M~5-8.10^13 SolMass, Gobat et al arXiv:1011.1837

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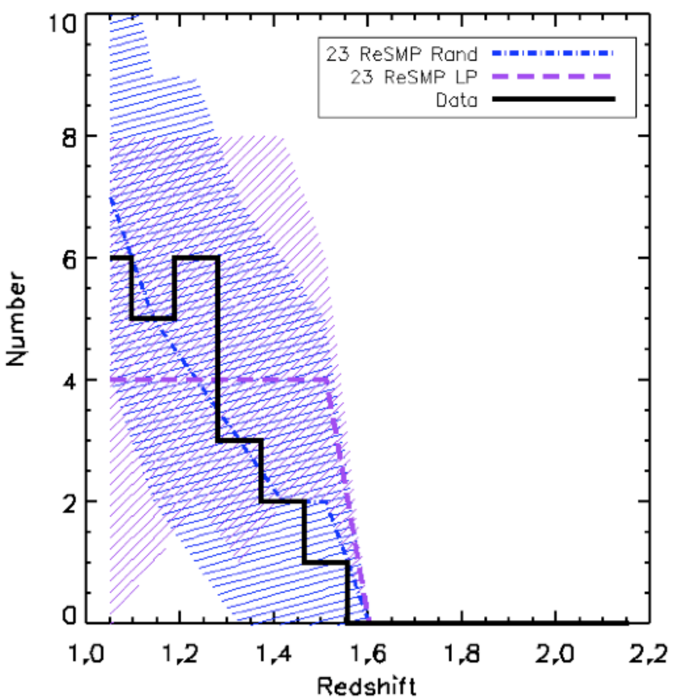

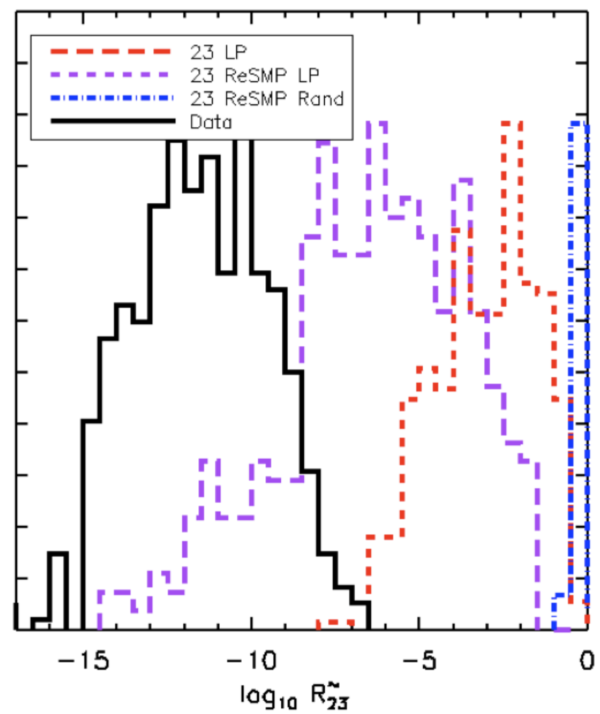

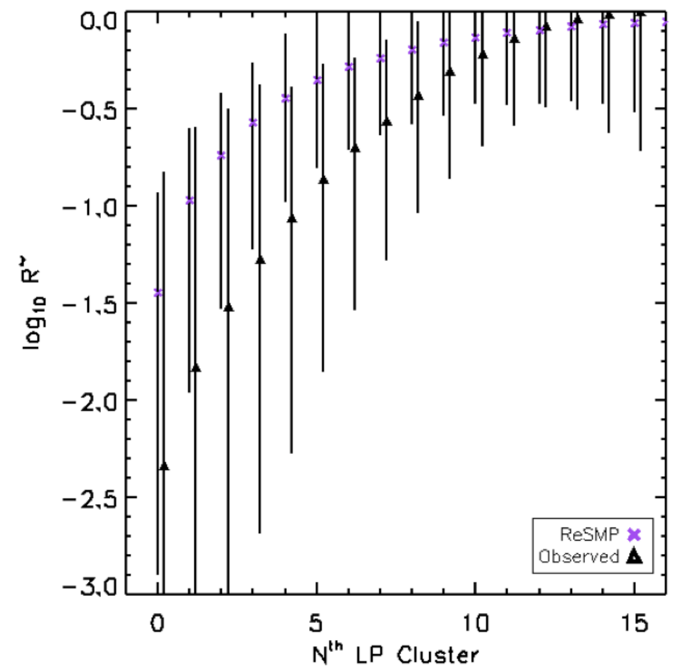

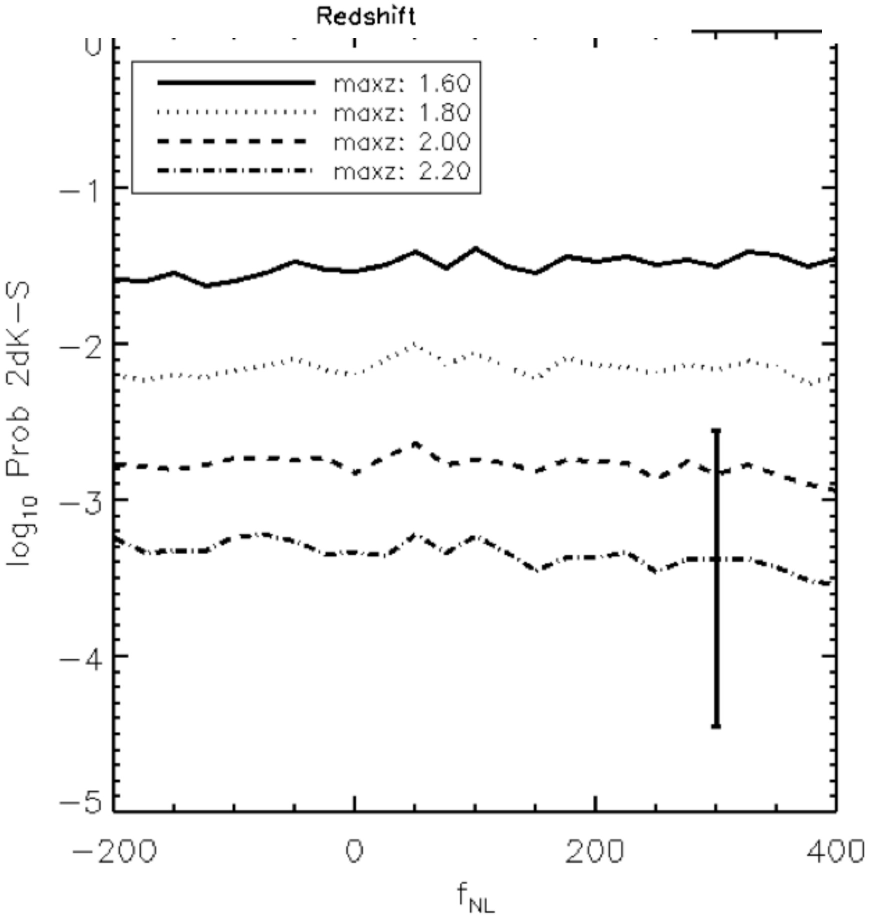

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Follow up work: To use samples of clusters with an unknown selection function to bound cosmological parameters (Hoyle et al, in prep.)

Summary

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- Used the most robust mass estimates.
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- Showed how fnl cannot reduce the tension when properly compared to simulations.

These clusters still appear to cause tension with LCDM assuming WMAP priors on cosmological parameters.

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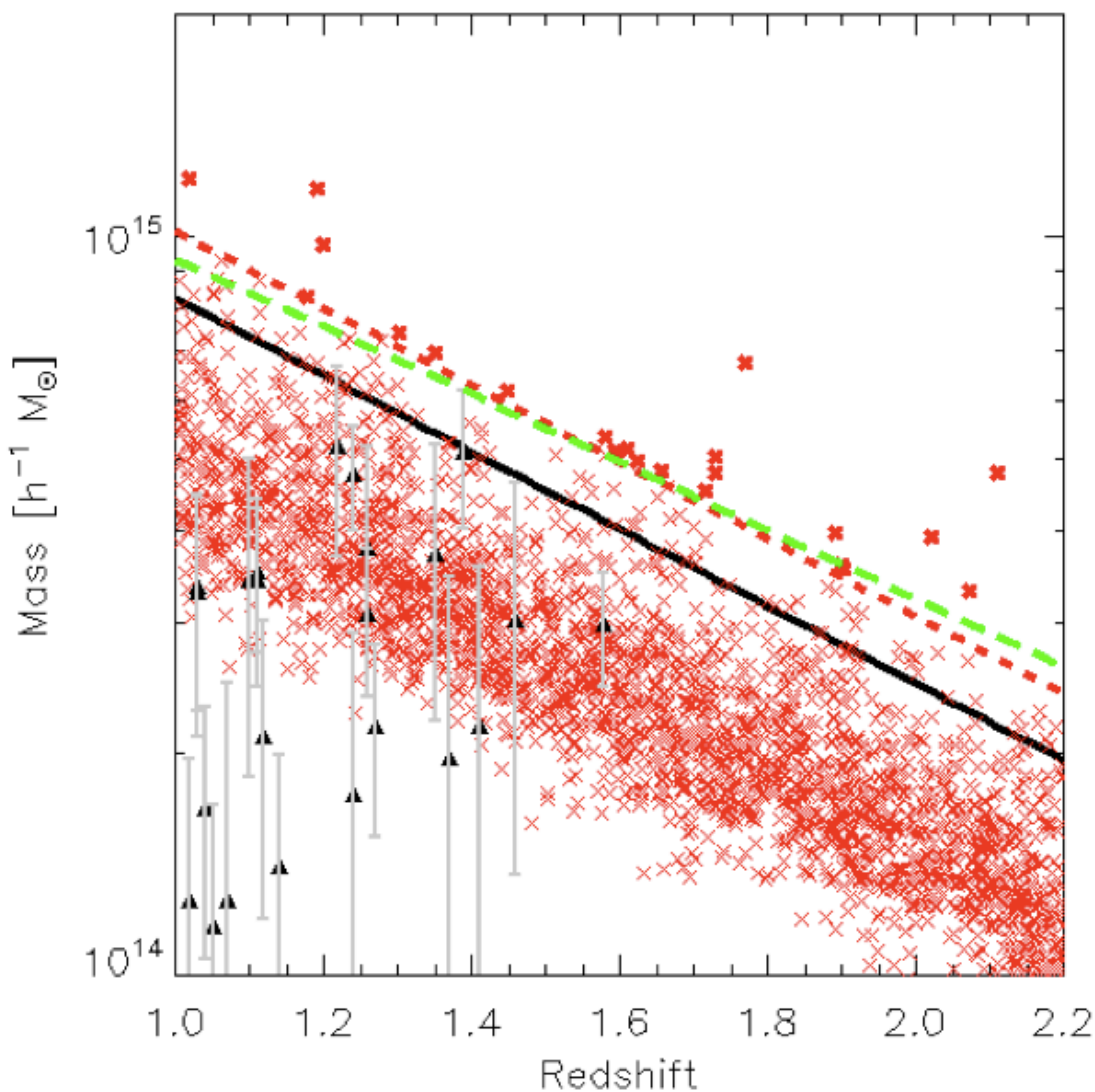
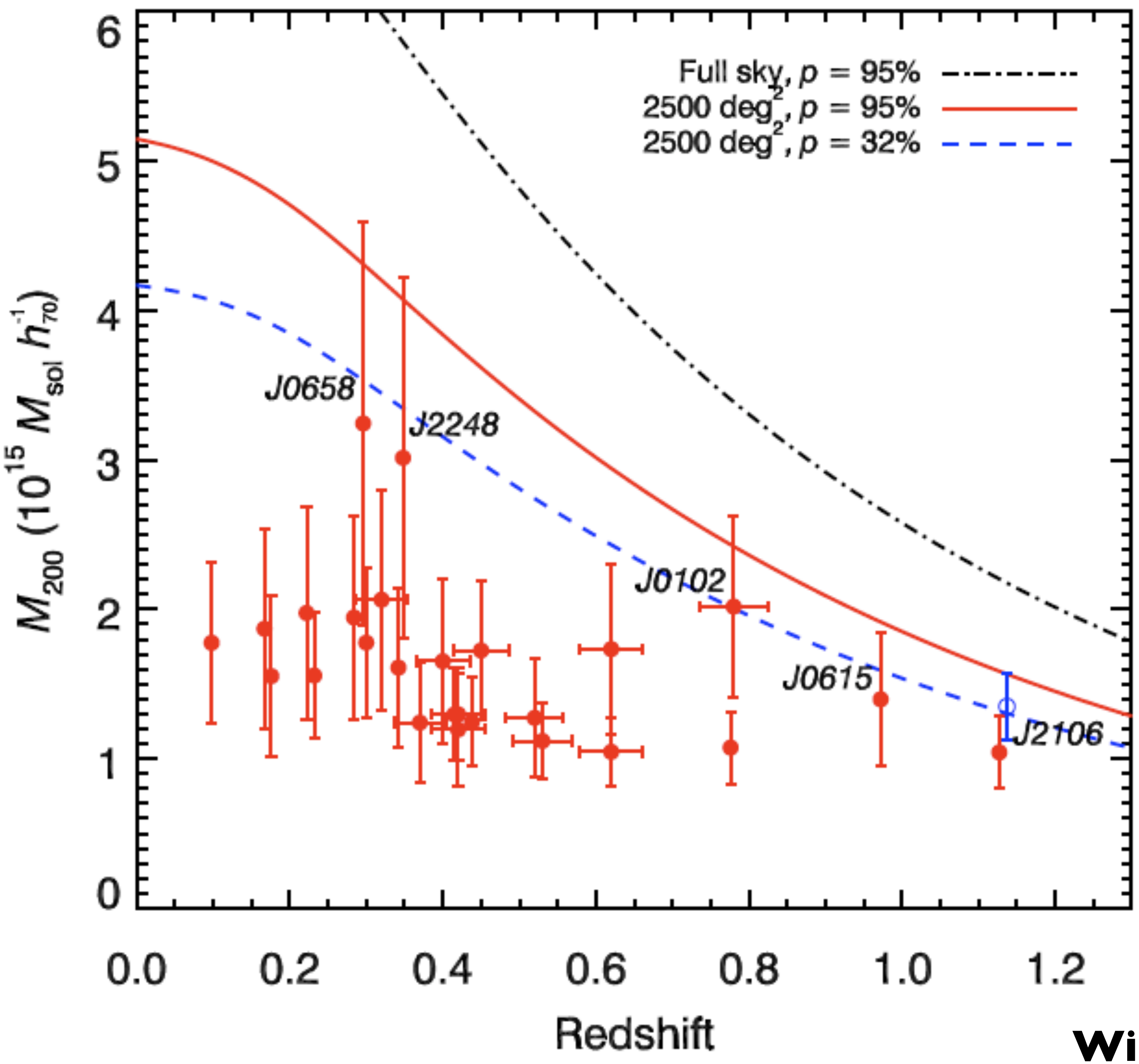
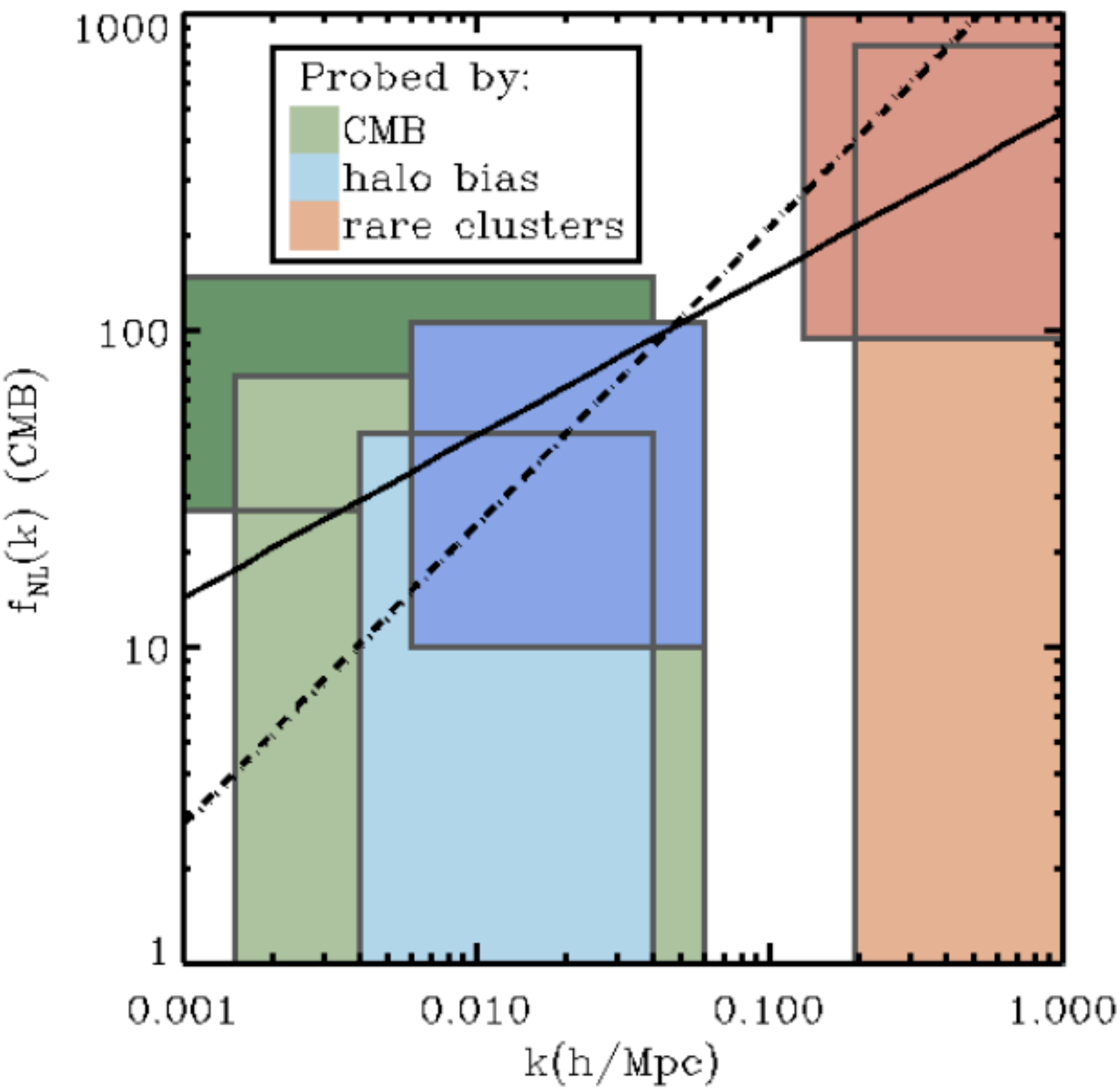


10^{15}
10^{14}
Mass $[h^{-1}\ M_{\odot}]$
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Redshift



Williamson et al 2011

Scale Dependent non-Gaussianity



WMAP CMB, scales 0.04 h/Mpc

$27 < f_{NL} < 147$, at the 95%

Yadev & Wandelt 2008

$f_{NL} = 32 \pm 21$ at $1\,\sigma$

Komatsu et al 2011

Halo bias, scales 0.1 h/Mpc

$10 < f_{NL} < 106$ at the 95%

Xia et al 2010

$-77 < f_{NL} < 47$ at the 95%

Slozar et al 2008

Galaxy Clusters, scales 0.4 h/ Mpc

449 ± 286 at $1\,\sigma$ **Cayon et al 2010**

$f_{NL}^{LSS}|_{P(0.05)} \gtrsim 123$ at the 95%

Hoyle et al 2010

$$f_{NL} = f_{NL}^{*}\left(\frac{k}{k^{*}}\right)^{n_{NG}} \qquad n_{NG} = 0.50 \pm 0.19 \qquad n_{NG} = 0.95 \pm 0.23$$

Lo Verde et al 2008