High-redshift, massive, galaxy clusters in LCDM.

Ben Hoyle LMU observatory
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Hoyle et al (2011, PRD) & (2011, JCAP) & in prep.

LMU Munich 21/2/2012

Overview

- Observational cosmology
- Galaxy Cluster surveys as cosmological probes
- The XMM Cluster Survey
- Individual Galaxy Clusters as extreme objects
- Early analysis >M,>z analysis & results
- Systematics & bias
- A critical look at exclusion curves
- A critical look at the >M,>z question
- Updated analysis and results
- Conclusions + future work

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.

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

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

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

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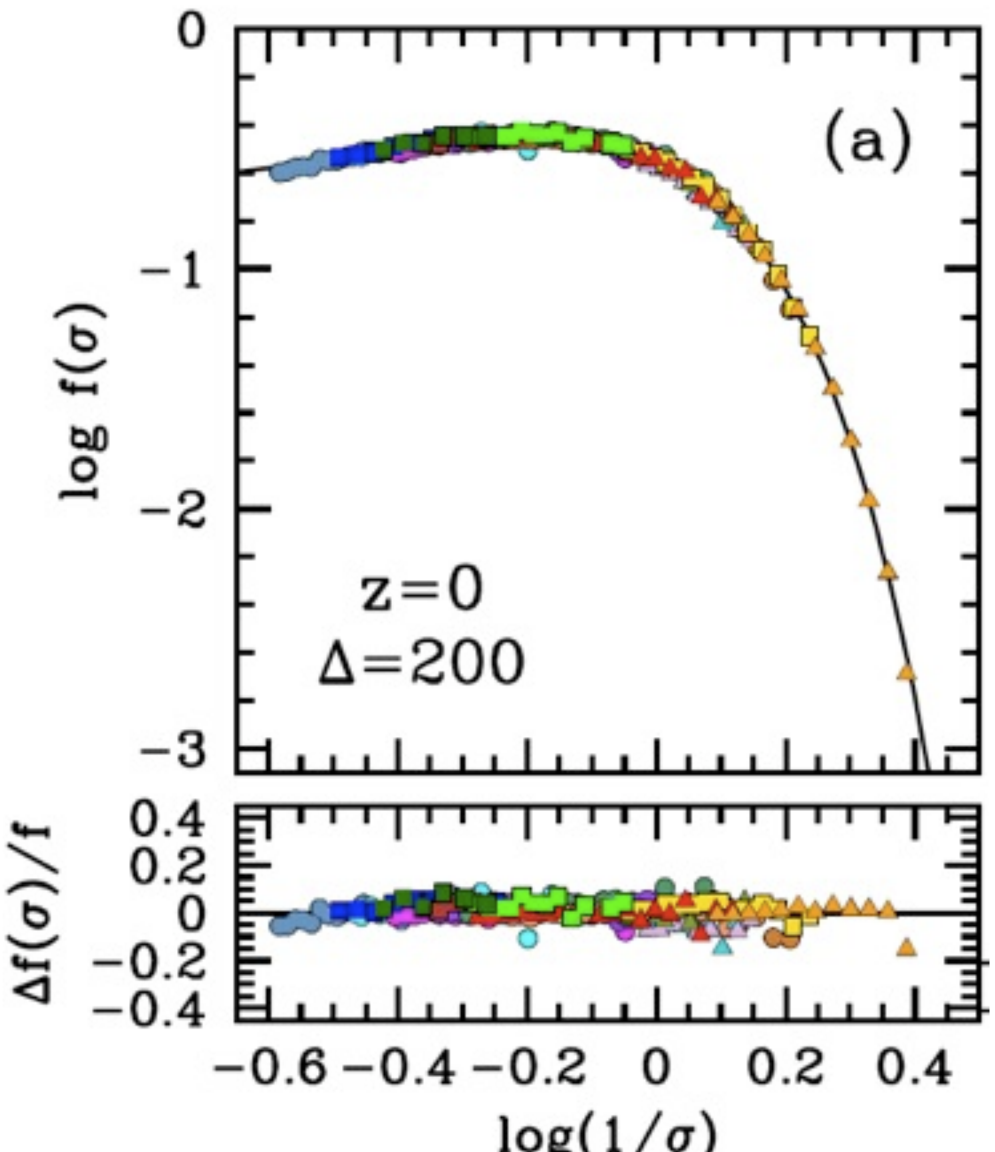

Tinker et al. 2008

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Now, fitting functions are calibrated to large N-body dark matter only simulations (e.g., Jenkins et al 2002, Tinker et al 2008)

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a}+1\right]e^{-c/\sigma^2} \qquad \frac{dn}{dM} = f(\sigma)\,\frac{\bar{\rho}_m}{M}\,\frac{d\ln\sigma^{-1}}{dM}.$$

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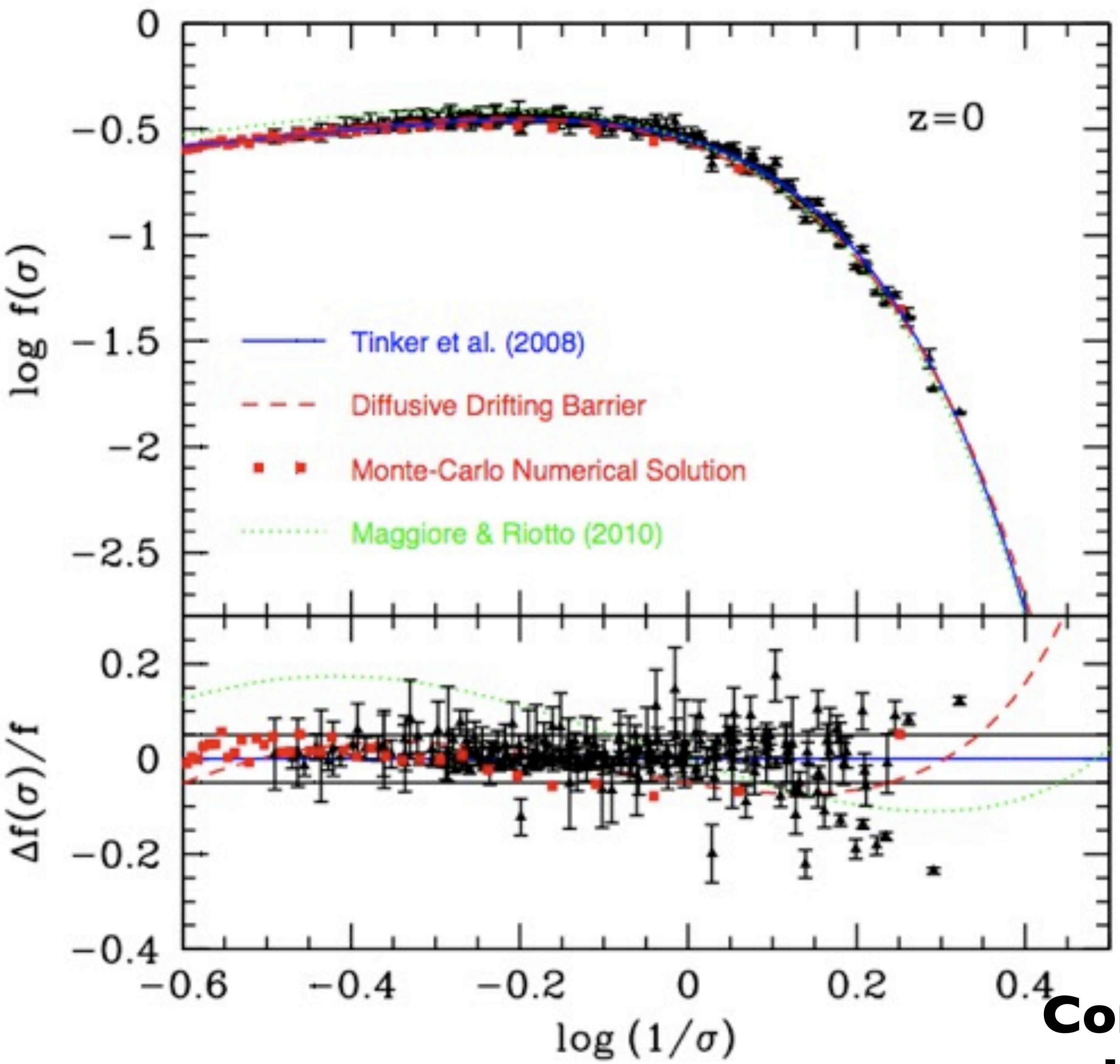

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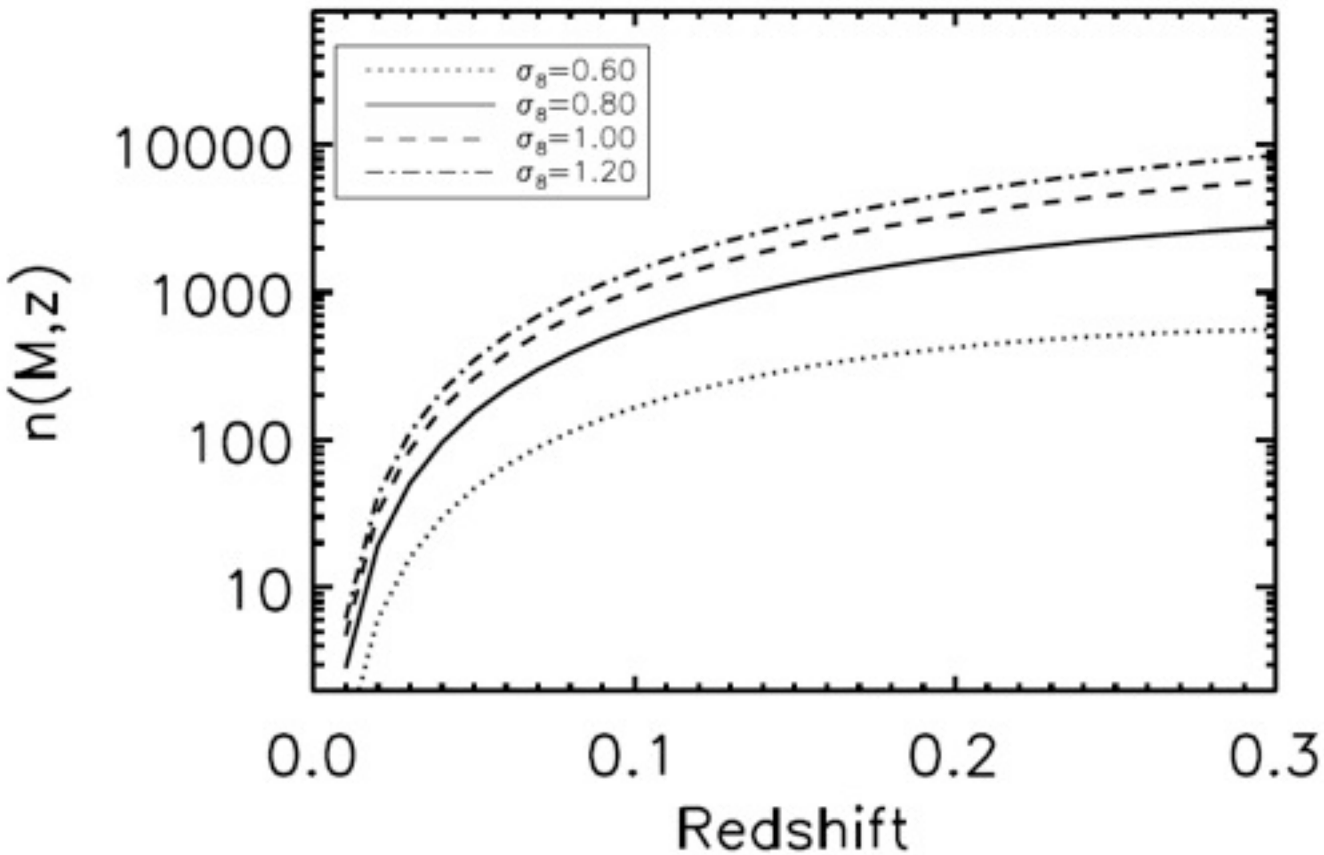
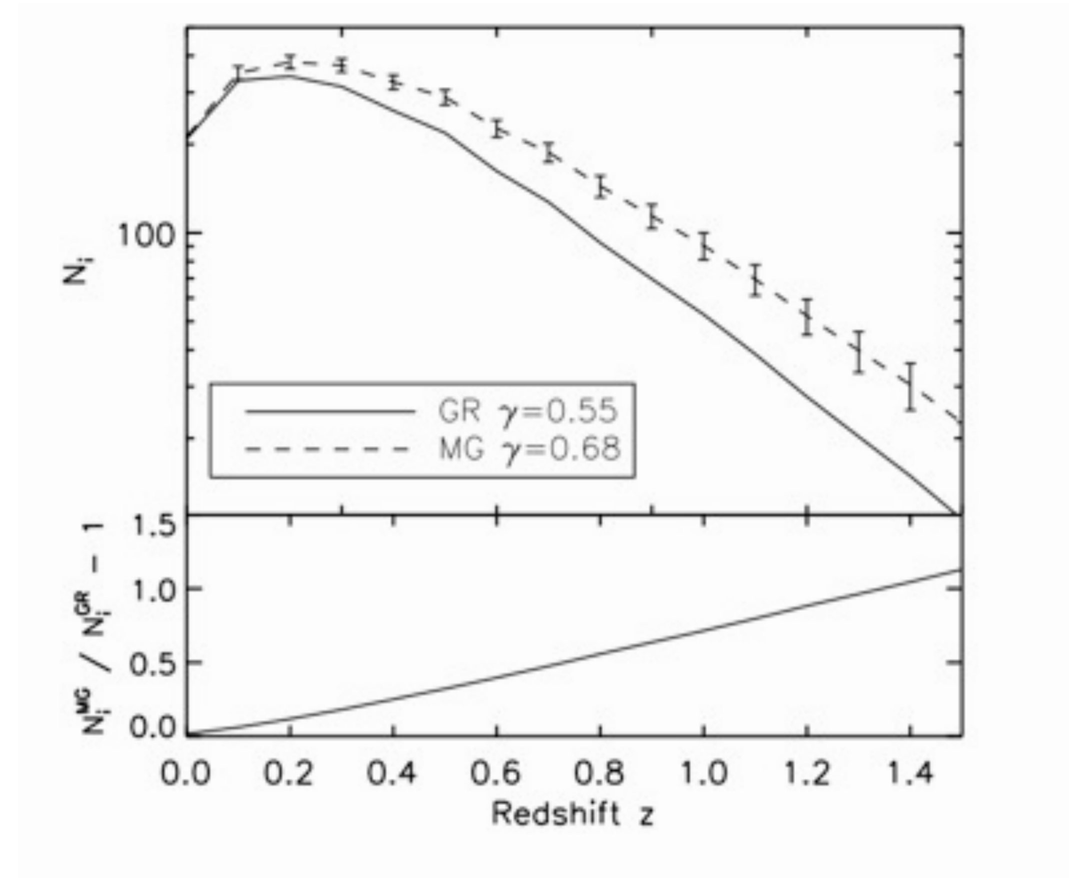
Corasaniti & Ixandra Achitouv (PRD submitted) arXiv: 1107.1251 (& 1012.3468)

The CMF with cosmological parameters/models





Shapiro, BH, et al 2010

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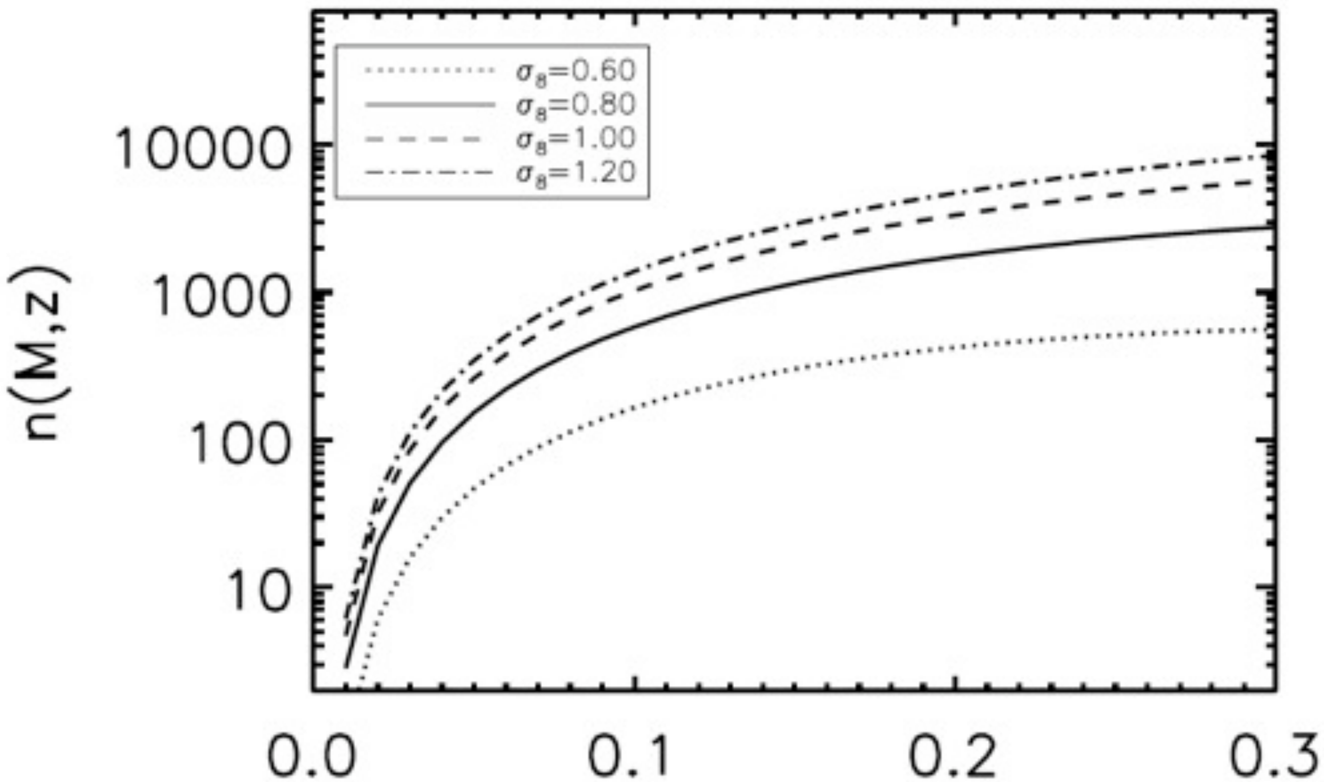

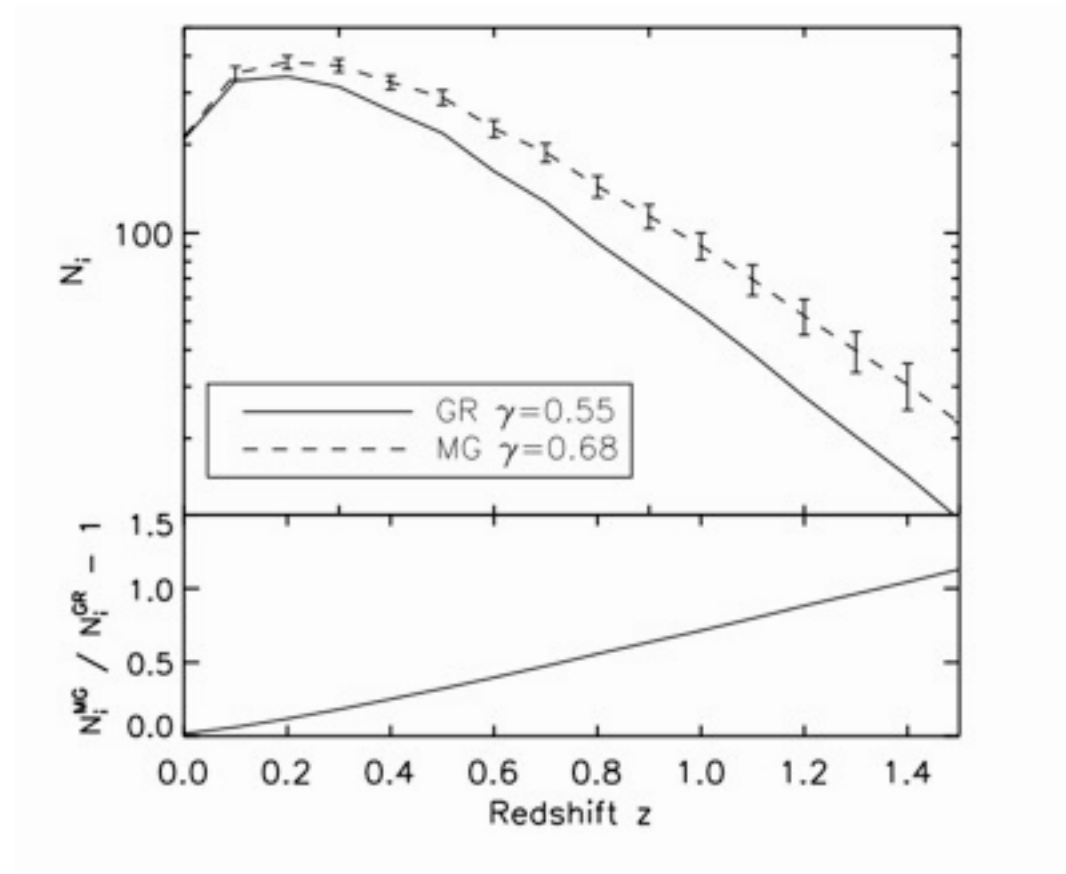

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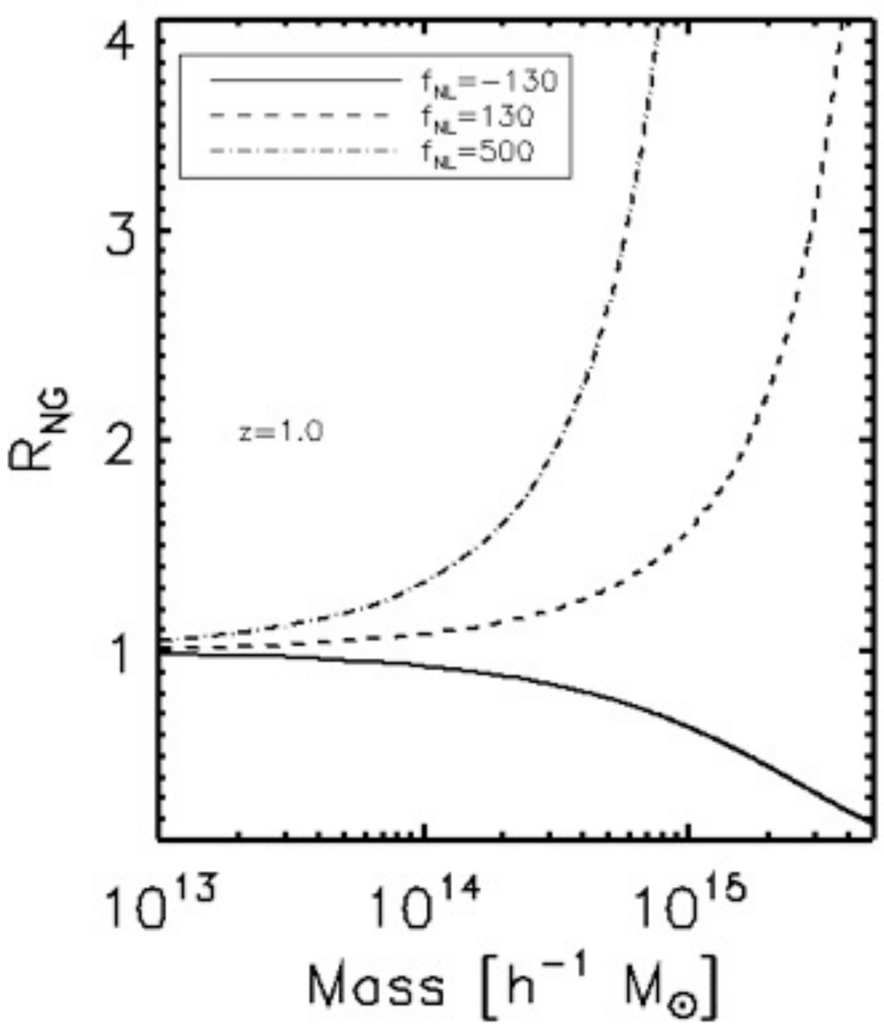
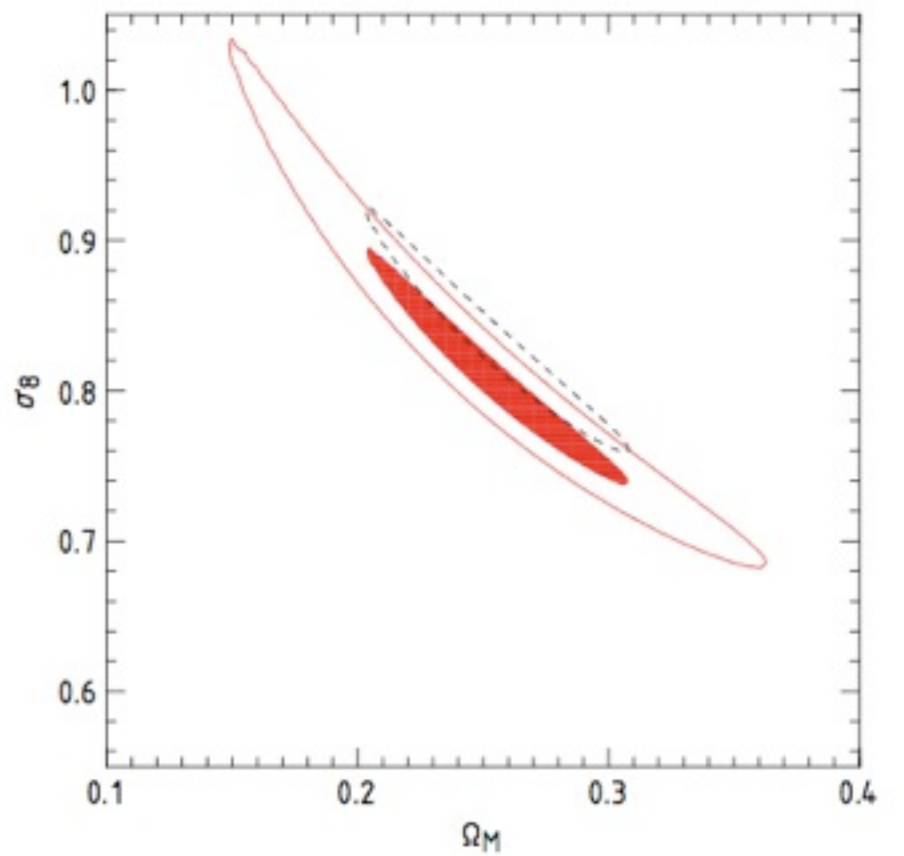


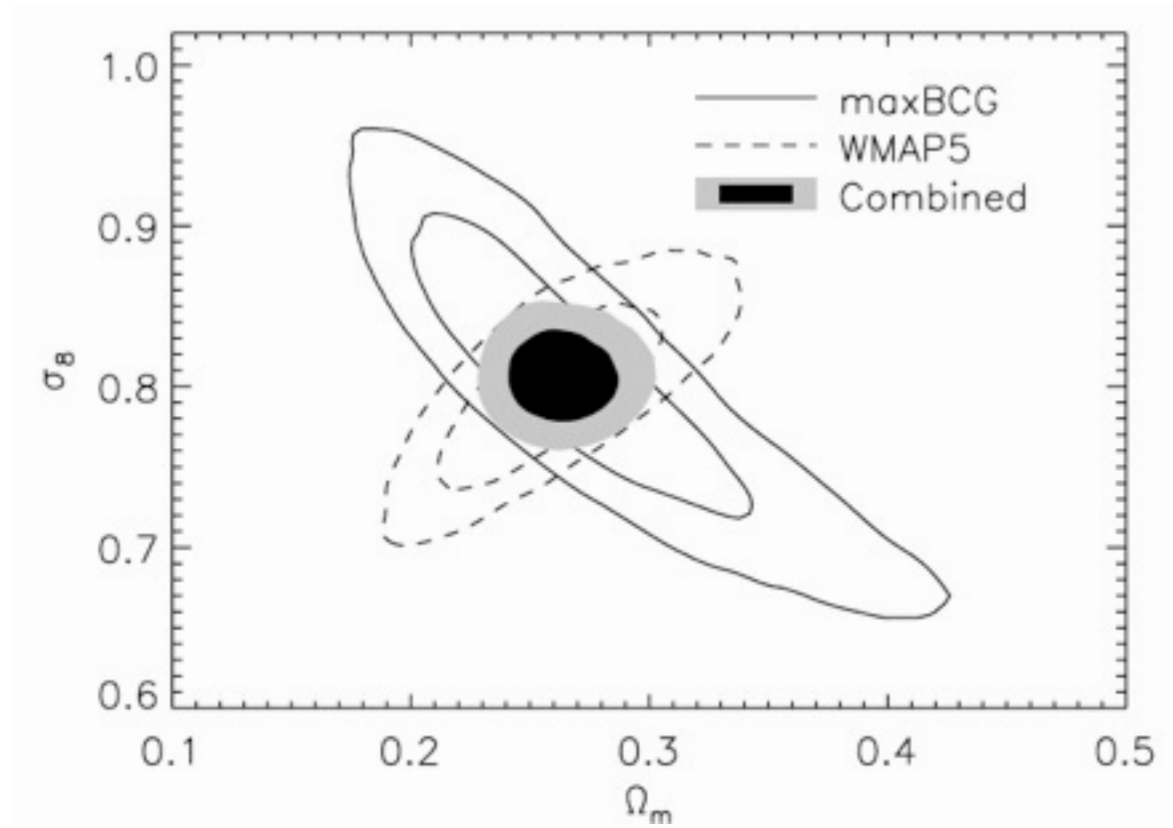
$$\mathcal{R}_{NG}(S_{3,M}, M, z) = \frac{n(M, z, f_{\rm NL})}{n_G(M, z, f_{\rm NL} = 0)}$$

E.g., Ixandra Achitouv & Corasaniti 1207.4796

Cosmological constraints with many clusters



~100 X-ray selected clusters:
Vikhlinin et al. 2008



~13,000 maxBCG (SDSS DR5) optically selected clusters:
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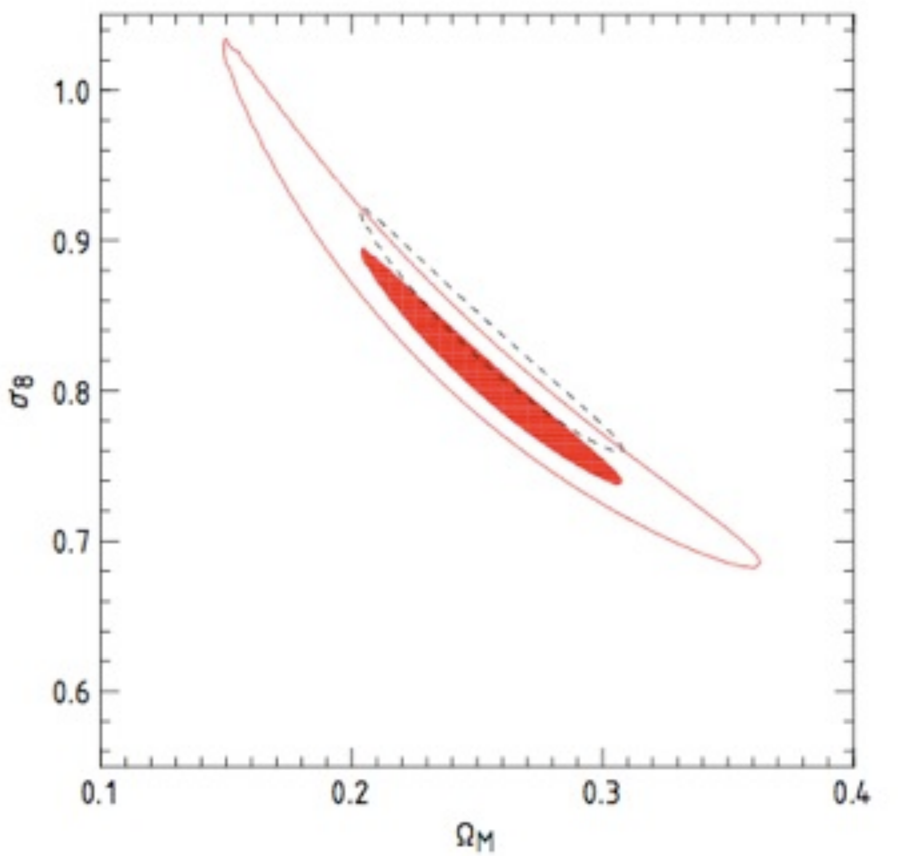

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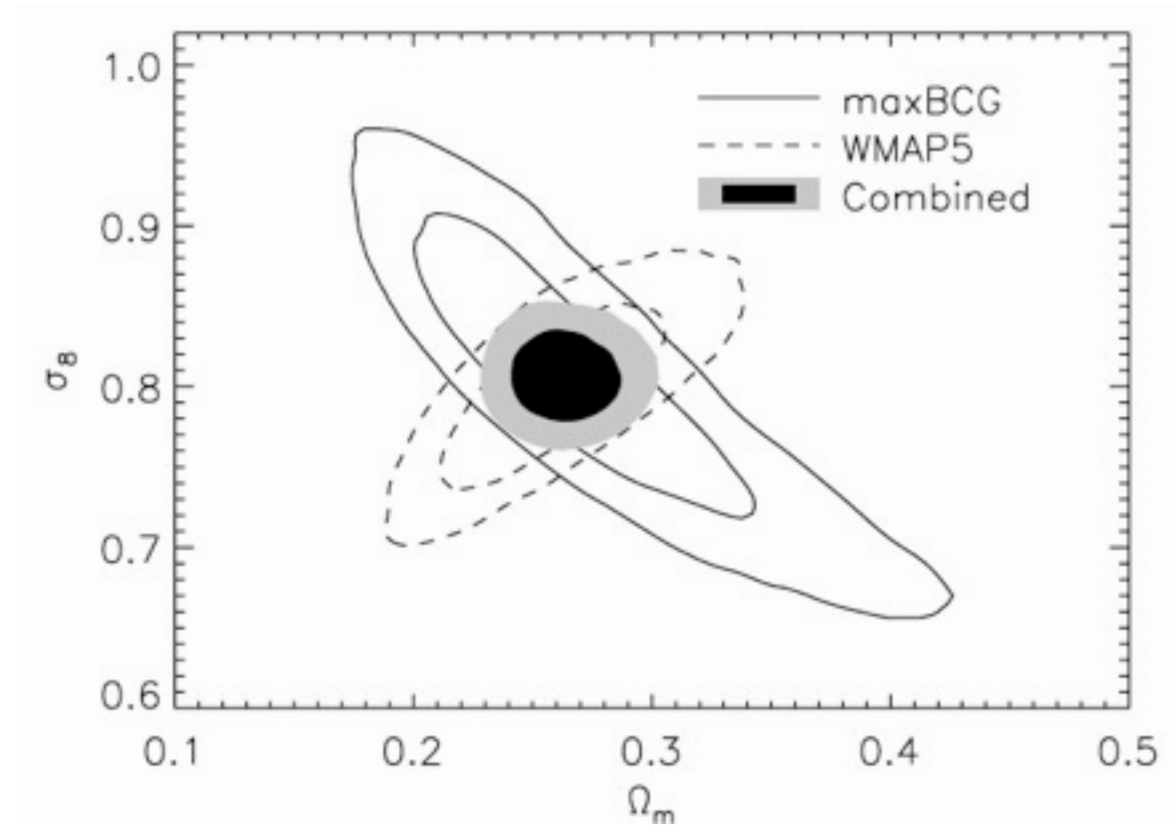

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<u>Other cluster catalogues</u>
Now available:
gmBCG ~55,000 (SDSS DR7)
XMM Cluster Survey ~500 (XCS DR1)

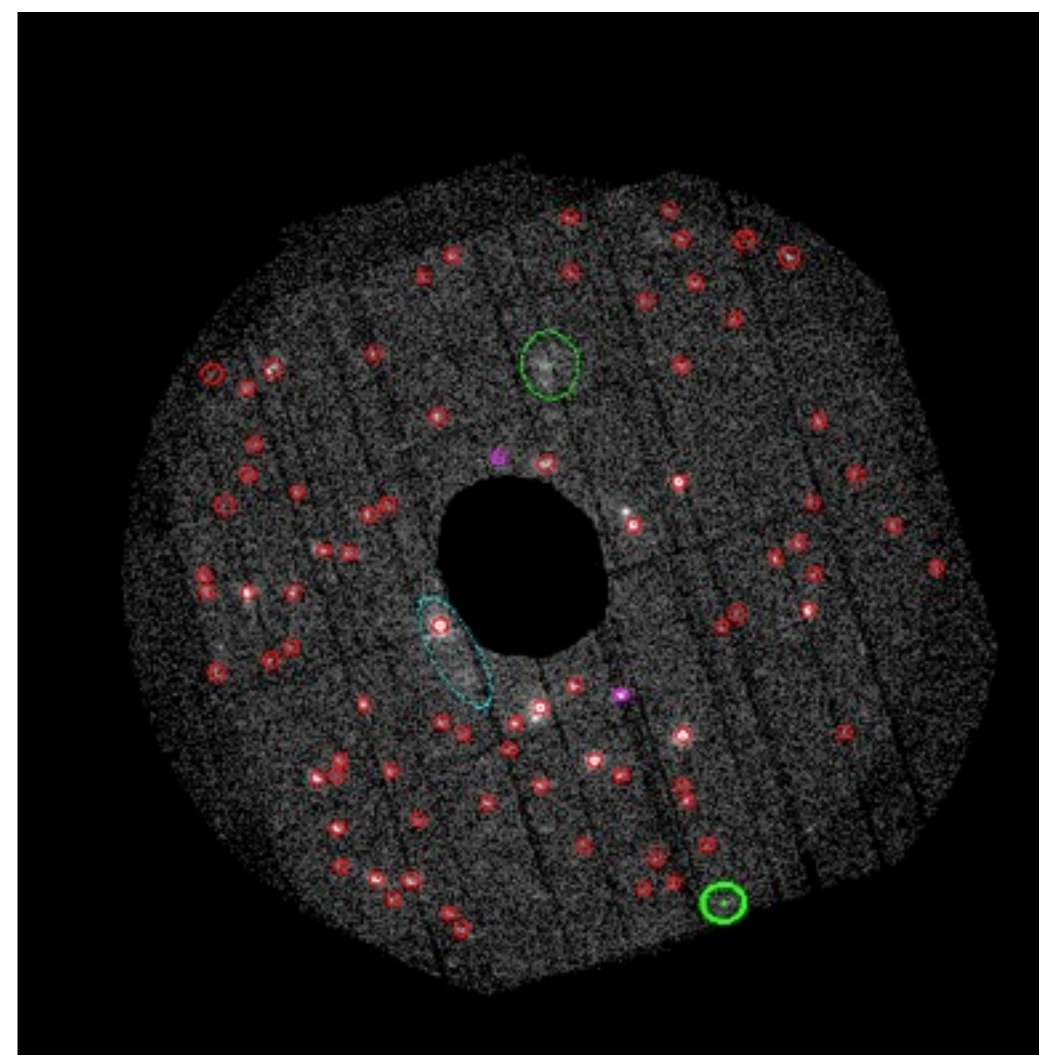
Gangkofner, Giannantonio, Weller... in prep

Future:
DES ~100,000 optical
eROSITA ~10,000 X-ray

XCS: Identifying and classifying extended sources

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

X-ray photon map + automated pipeline to detect point sources (red) and extended sources (green).



X-ray emission (from the ICM) is the smoking gun, but it's not enough. Need optical identification and redshifts (X-ray redshift difficult) before the fluxes can be converted to temperatures/masses.

Algorithms paper, Lloyd-Davies et al. 2010

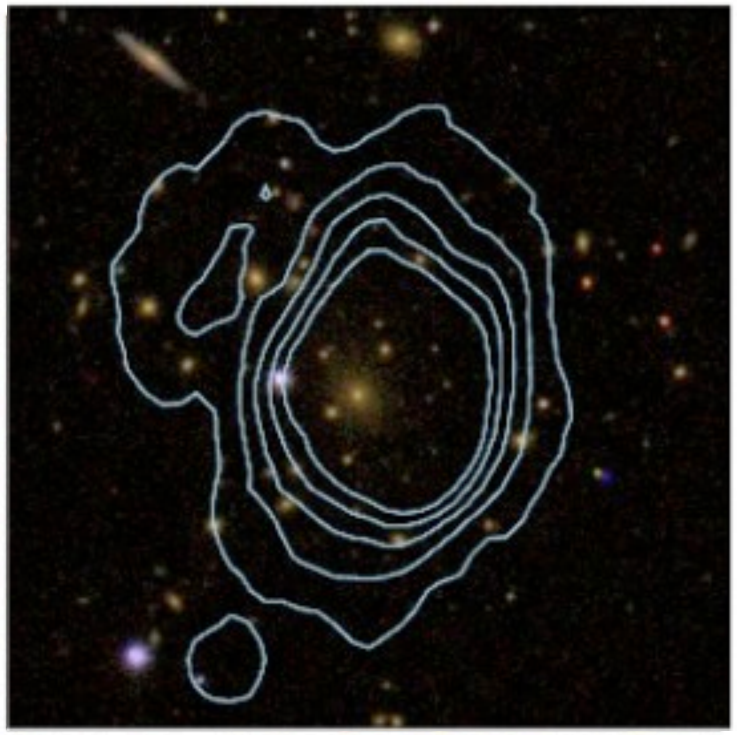
XCS: Cluster zoo

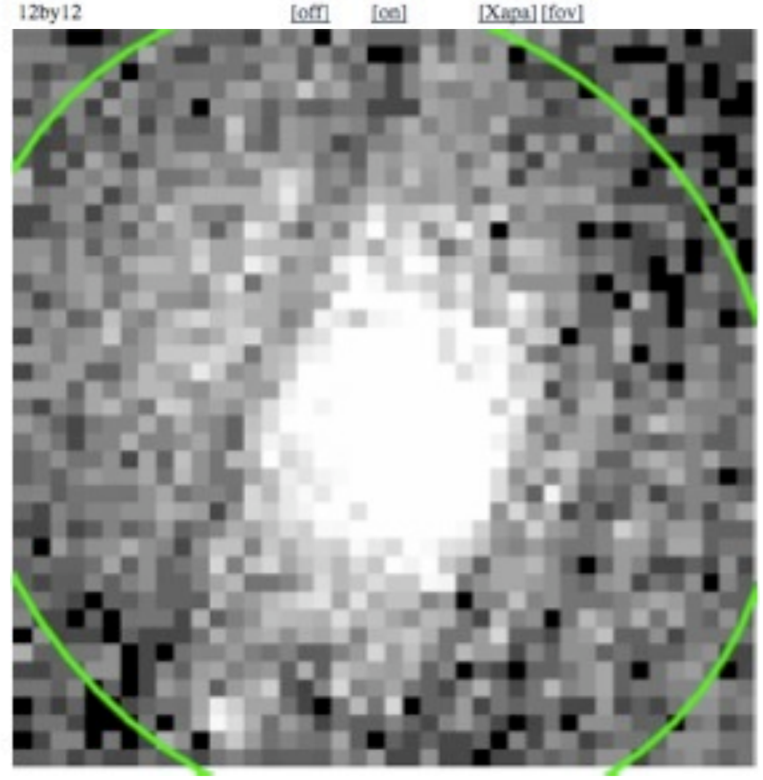
Part 1:View the images of: XMMXCSJ075724.8+392047.7

Photometric images and X-ray images and data

X-ray Soft counts 200.942

Image Width (Arcmins)	tricks	contours	Xapa	XMM FoV
3by3	[off]	[on]	[Xapa]	[fov]
6by6	[off]	[on]	[Xapa]	[fov]
12by12	[off]	[on]	[Xapa]	[fov]





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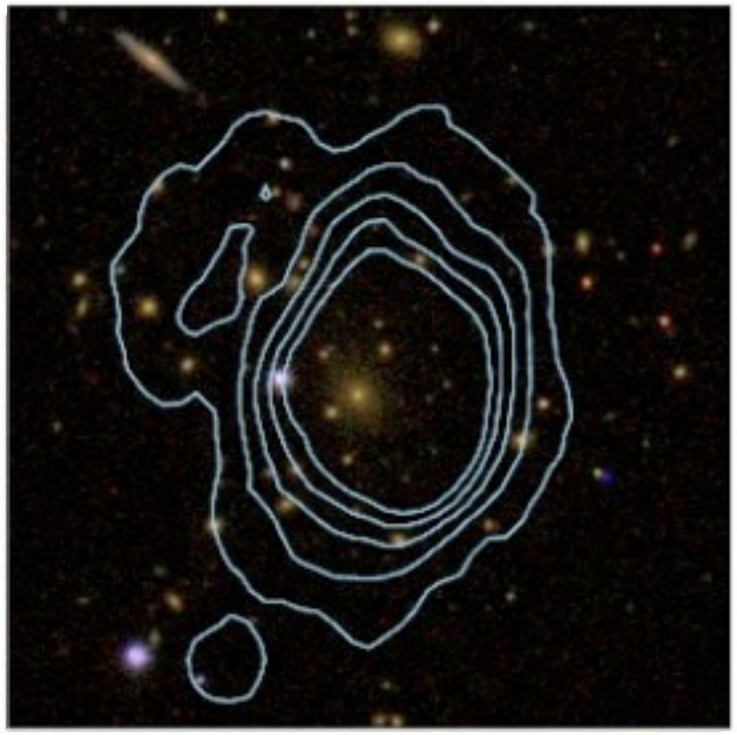
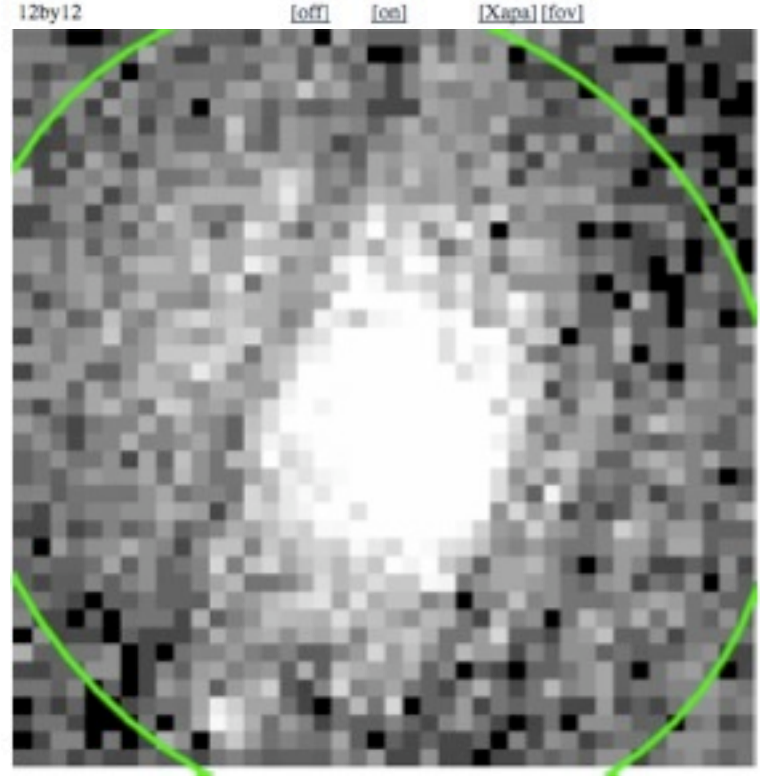
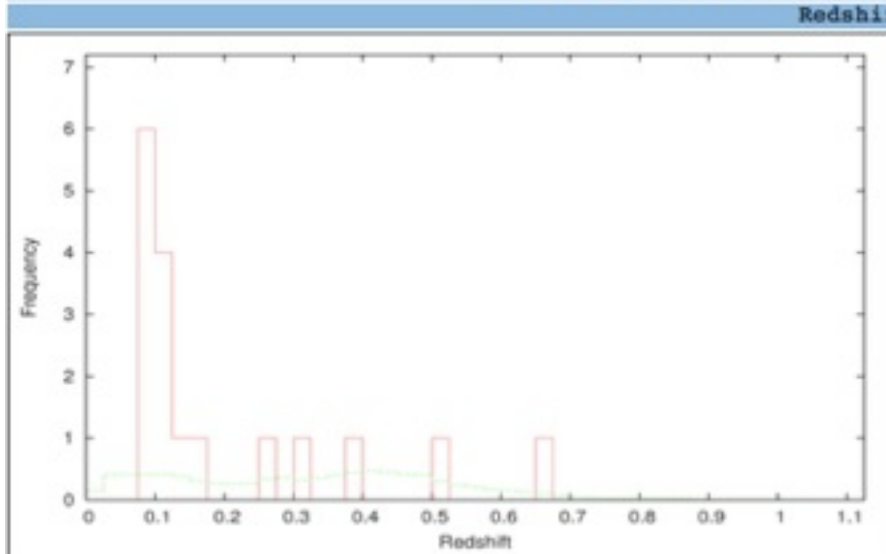


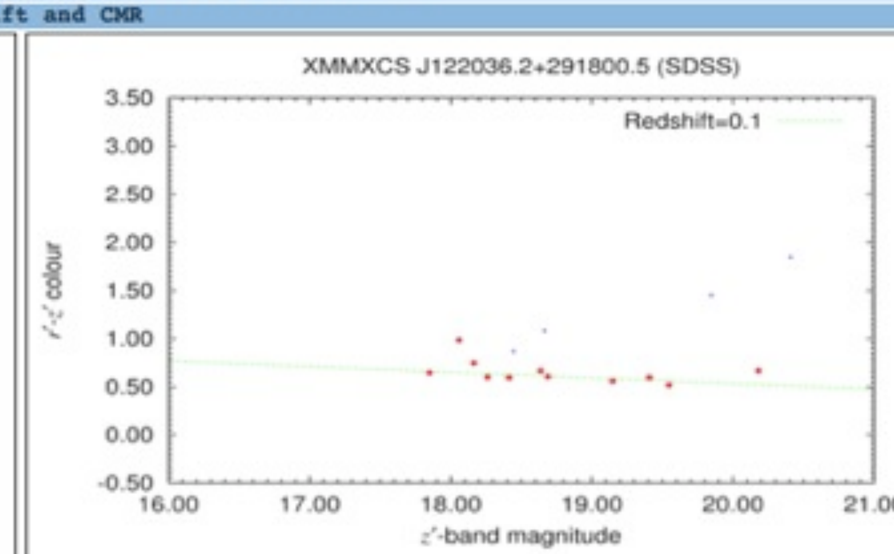


Part 3: Additional figures for: XMMXCSJ122036.2+291800.5

Redshift and CMR



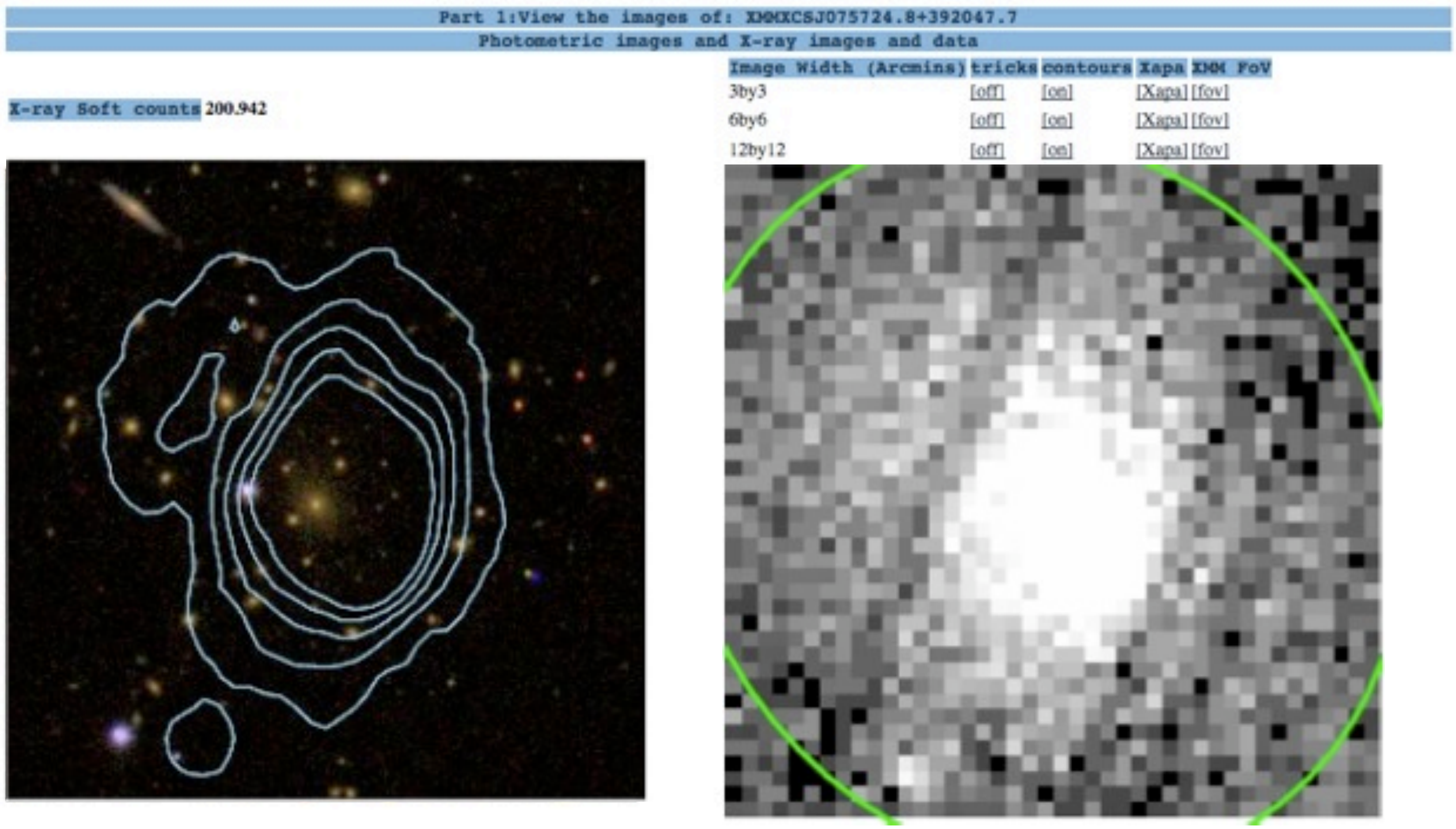
Redshift distribution of all galaxies within twice the x-ray extent of the XCS cluster candidate compared to the normalised field distribution. Each galaxy is assumed to lie on a red sequence relation.



CMR diagram of all galaxies chosen to be part of the cluster and field within twice the x-ray extent of the XCS cluster candidate and their best fit red sequence relation. Each galaxy is assumed to be a red sequence galaxy.

Redshift histograms Color-Magnitude diagrams

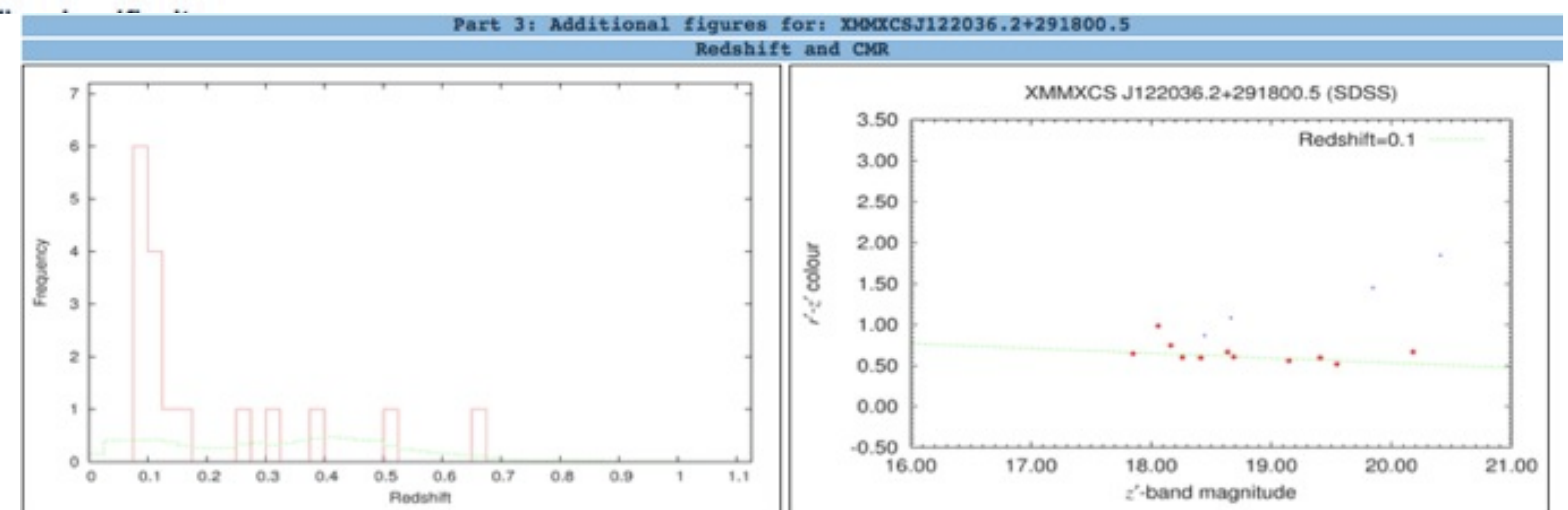
XCS: Cluster zoo



Cluster Zoo with XCS & PanStarrs data (Johannes Koppenhoefer, Tommasco Gianntonion, Jochen Weller + others?)

High redshift optical + photoz + X-ray masses

HOD, mass-optical scaling relations



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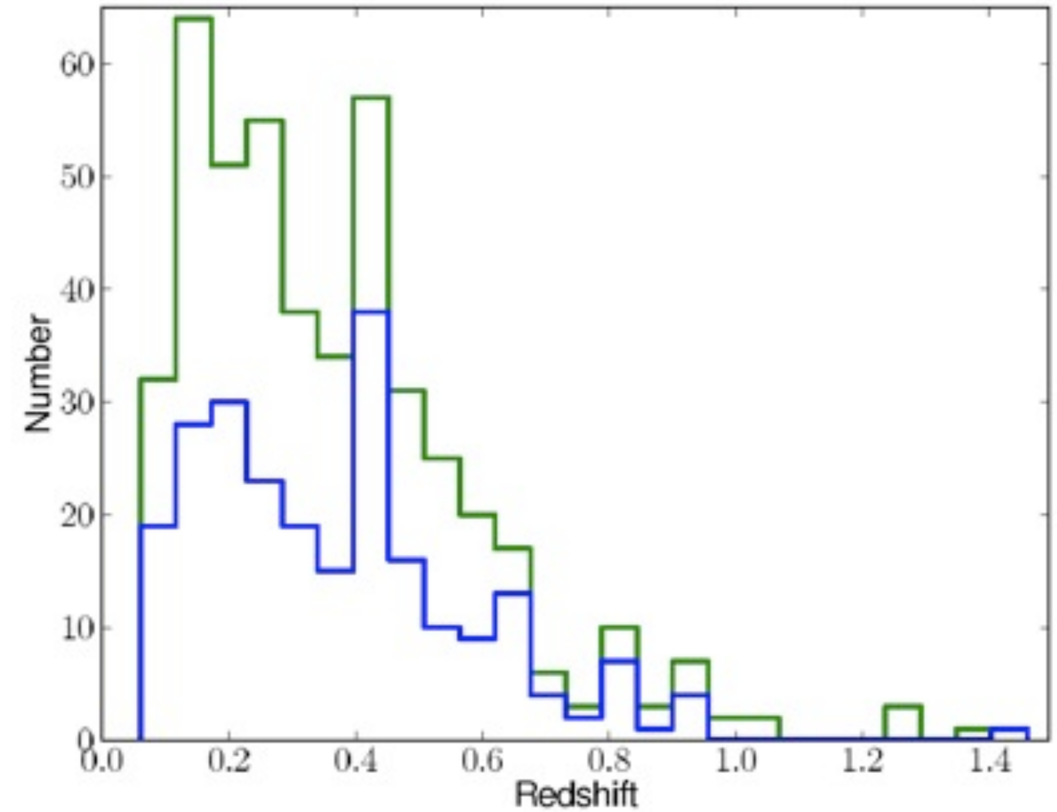
XCS: Recent achievements

Recent Data release, Mehrtens et al. 2011

503 clusters, spanning 0.06<z<1.46
402 have X-ray temperatures



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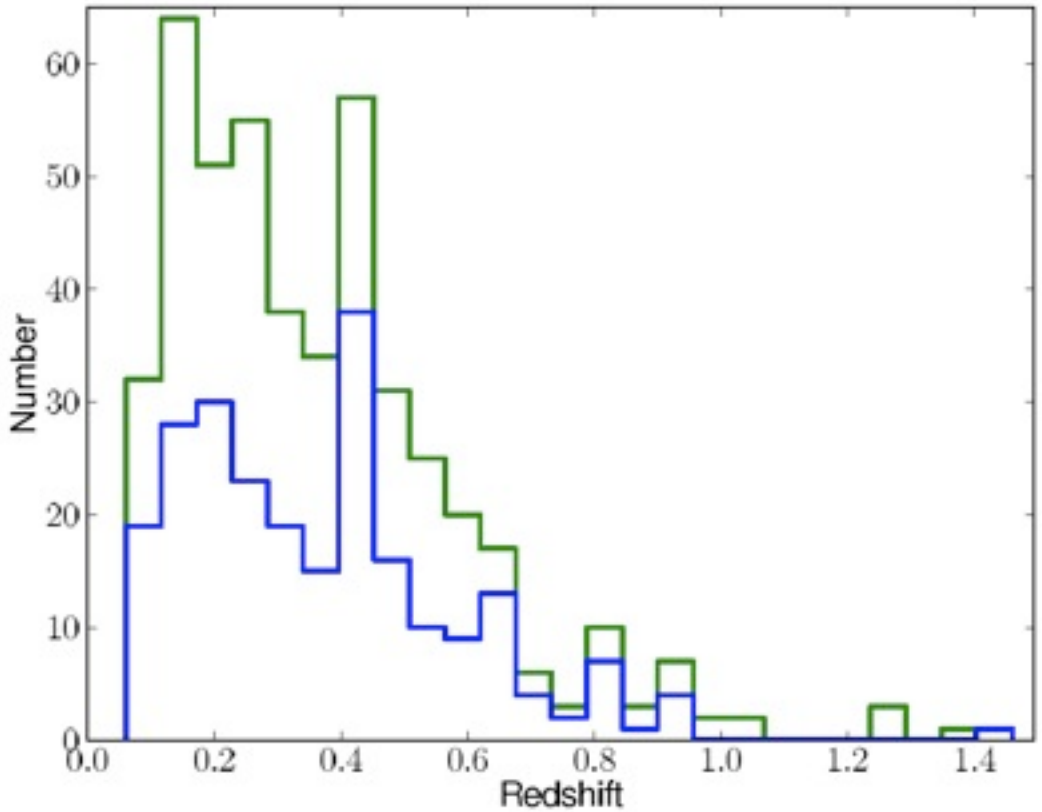
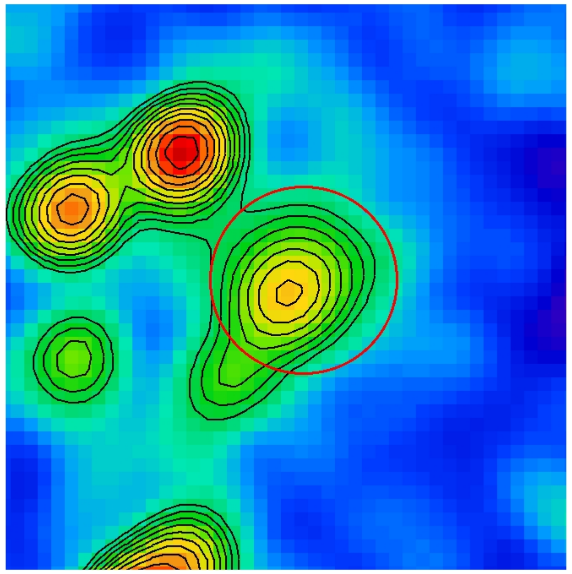
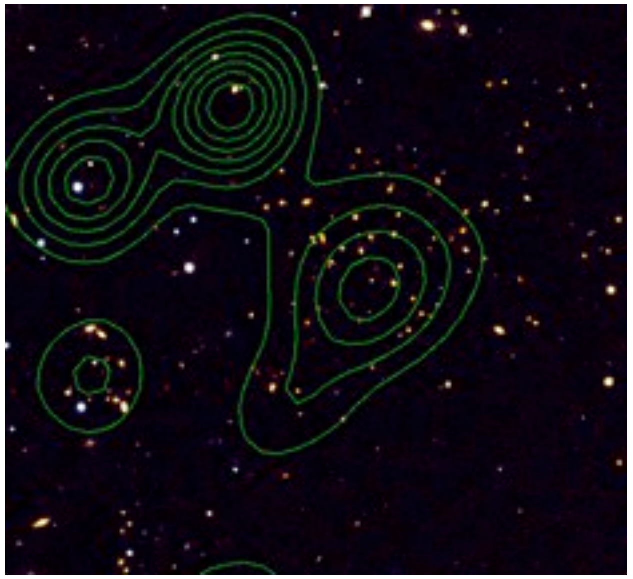


XMMXCS J2215
Was the highest redshift X-ray selected cluster, z=1.46 (Stanford et al. 2006, Hilton et al. 2007, 2008)





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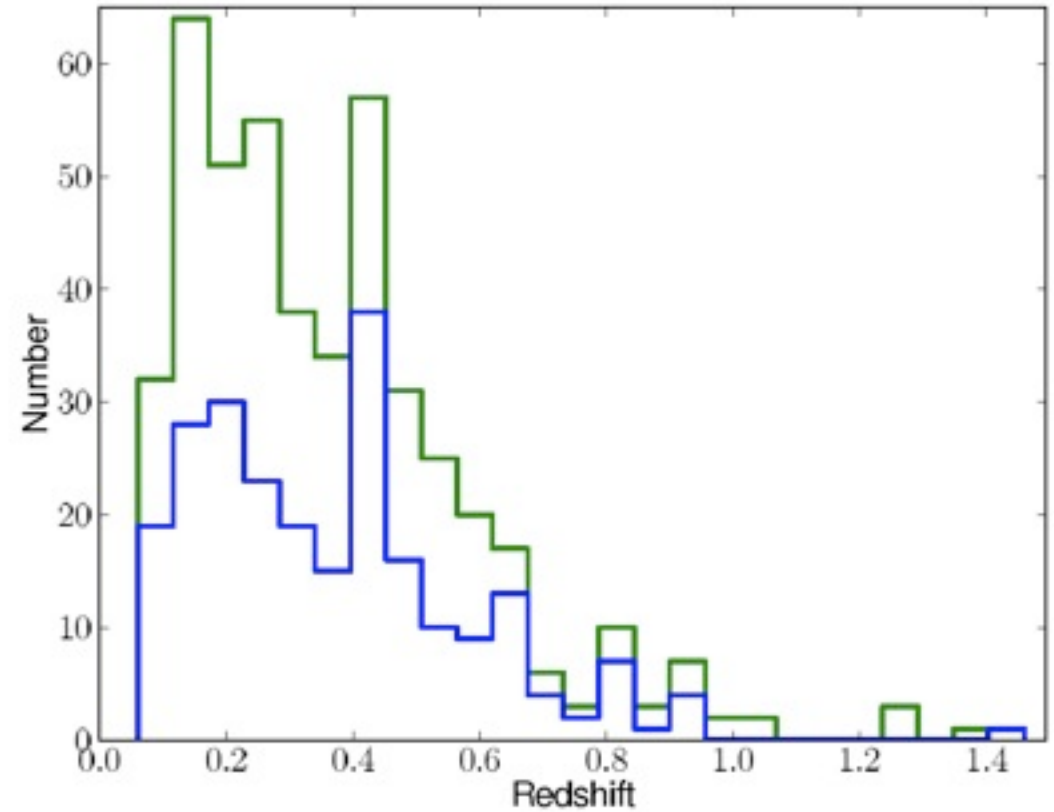

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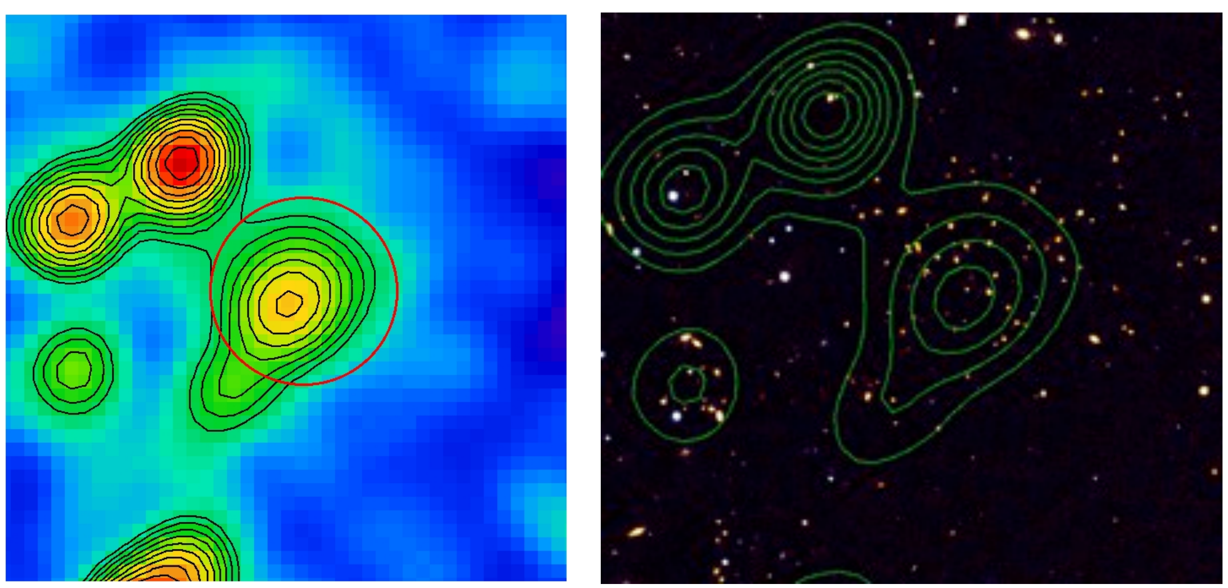
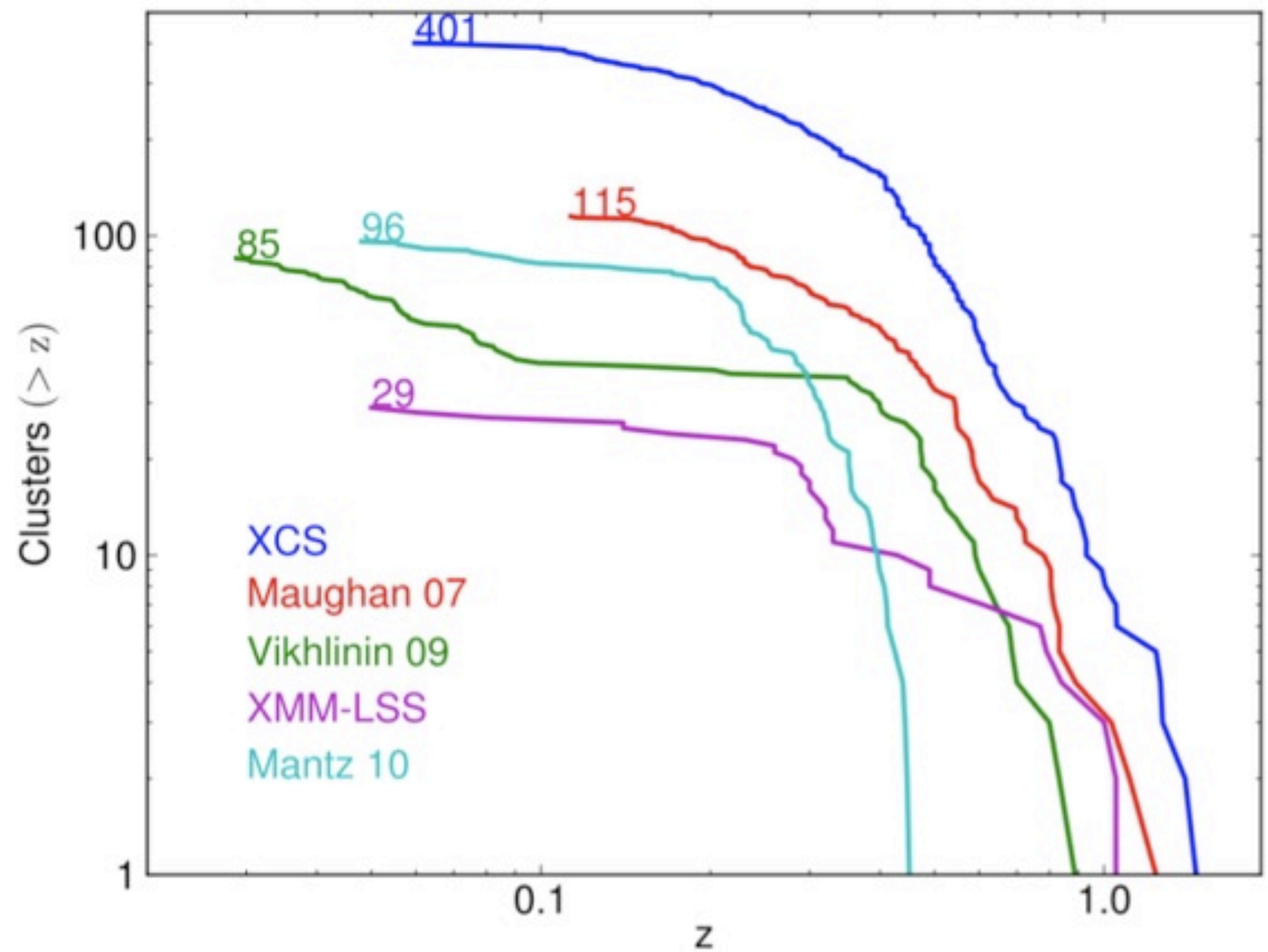


Now z=2.07, M~5-8.10^13 SolMass, Gobat et al. 2011

<u>Some XCS papers</u>

The Stellar Mass Assembly of Fossil Galaxies:
Harrison et al. arXiv:1202.4450
The interplay between the BCG and the ICM via AGN feedback:
Stott et al. 2012
Predicted overlap with the Planck Clusters:
Viana et al. 2011
AGN and Starburst Galaxies in XMMXCS J2215.9-1738 at z=1.46:
Hilton et al 2010
The build up of stellar mass in BCG at high redshift:
Stott et al. 2010
Galaxy Morphologies and the Color-Magnitude Relation in J2215 at z=1.46:
Hilton et al. 2009
Forecasting cosmological and cluster scaling-relation parameter constraints:
Sahlen et al. 2008

XCS: Comparison with other X-ray surveys



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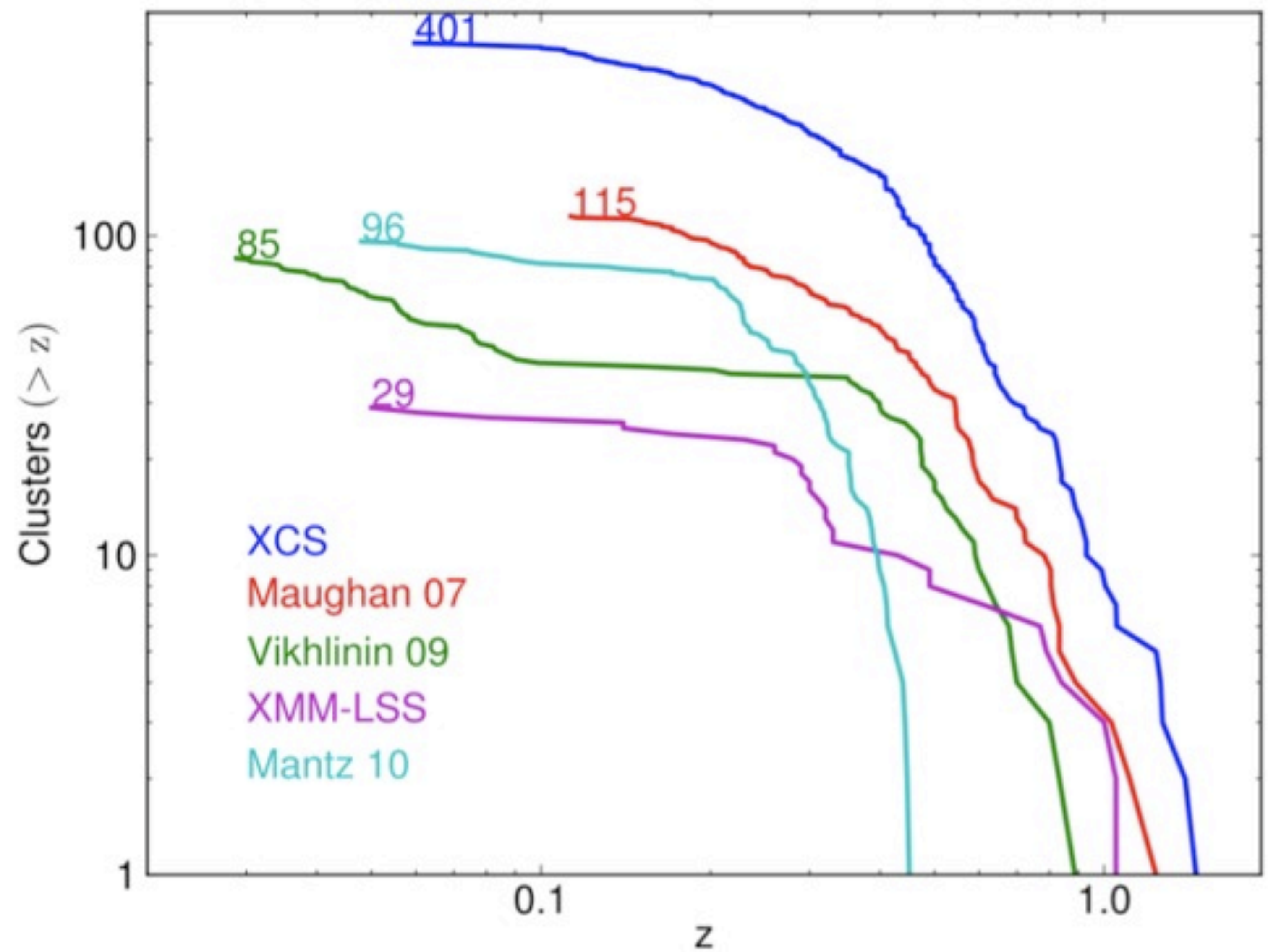


<u>The Future</u>

- **XMM lifetime extended to work past 2013**
- **Analyzing more XMM photon maps**
- **Obtaining more cluster redshifts**
- **Future data releases soon**
- **Cosmology from XCS DR1**

Data available: http://www.xcs-home.org/

Individual clusters as extreme objects

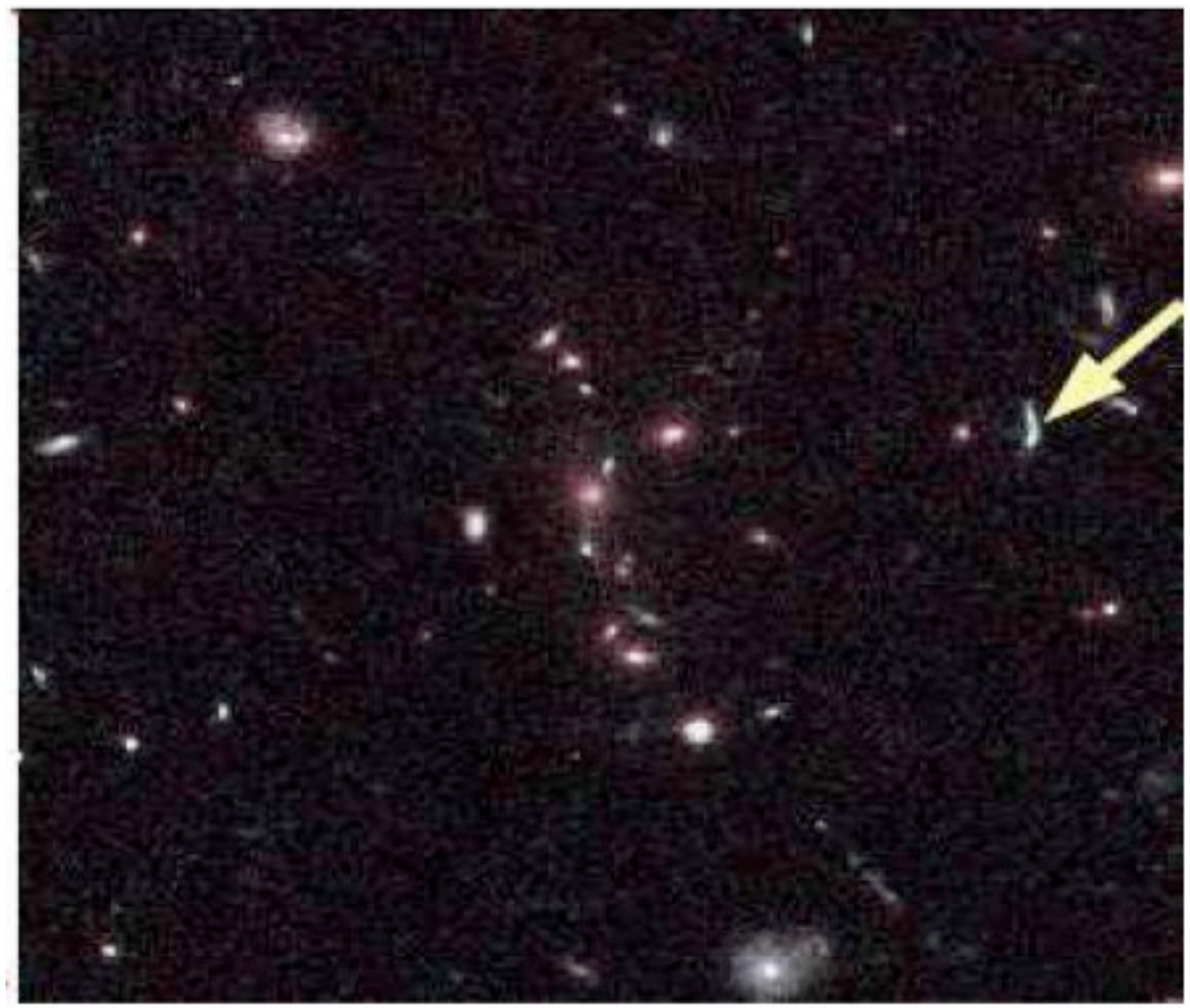
Individual clusters as extreme objects

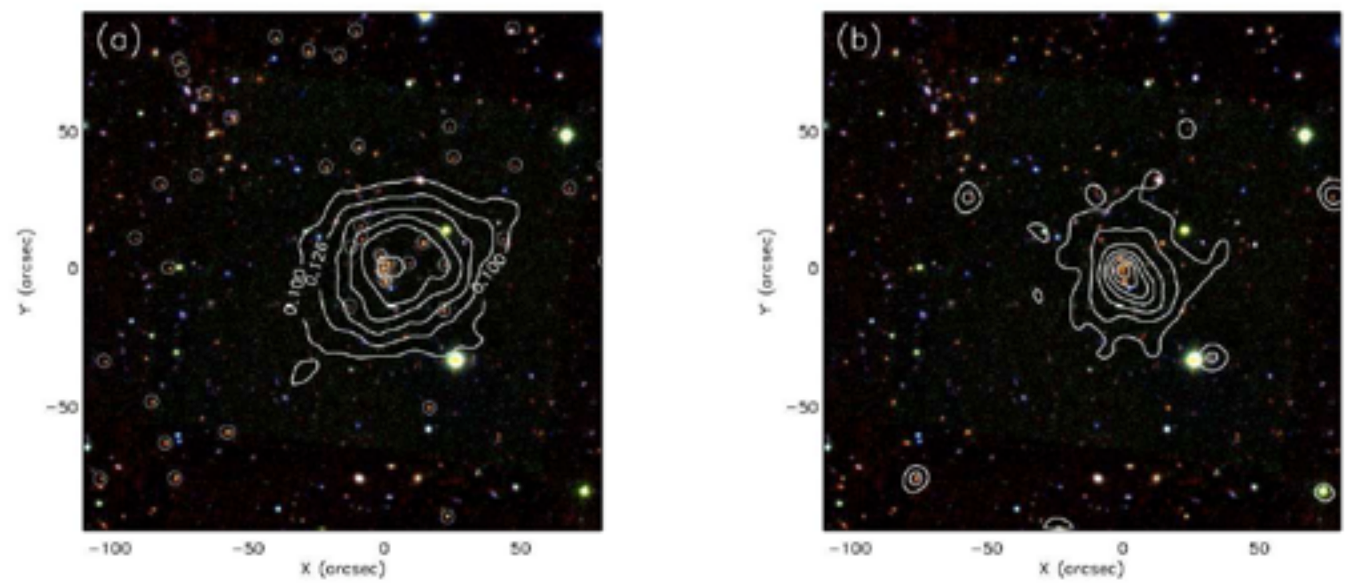
Cluster catalogues with many hundreds or thousands of clusters can be to constrain cosmology, but so can individual "pink elephant" or extreme clusters.

If observations of such clusters are statistically very unlikely to have occurred, maybe there is some tension with our understanding of the cosmological model.

Individual clusters as extreme objects

The observations of XMMJ2235 appeared to cause tension with the LCDM model + WMAP priors on the cosmological parameters. A very massive clusters of galaxies at high redshift, was statistically unlikely to have been observed.





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$$z = 1.4$$

Jee at al 2009

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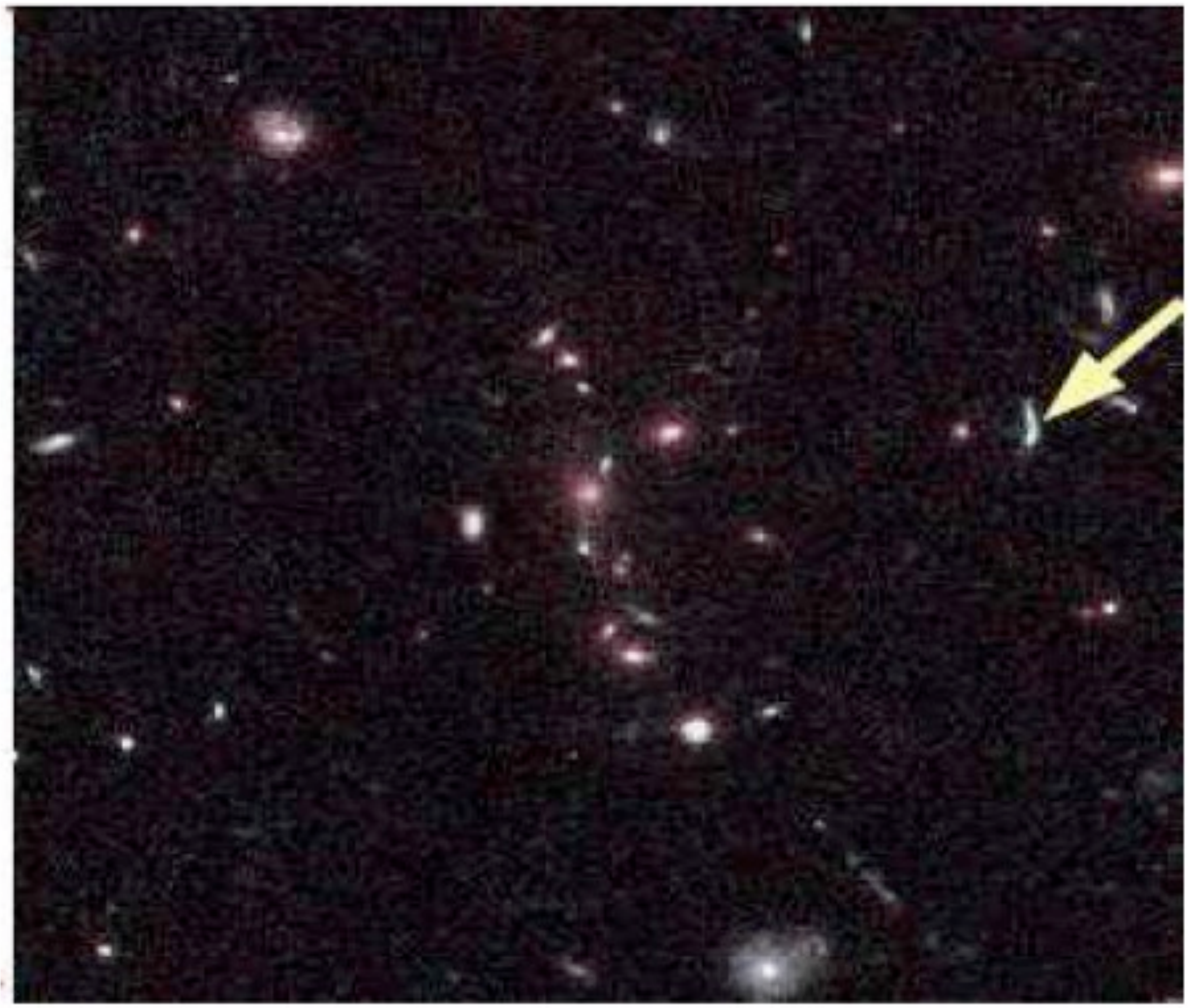

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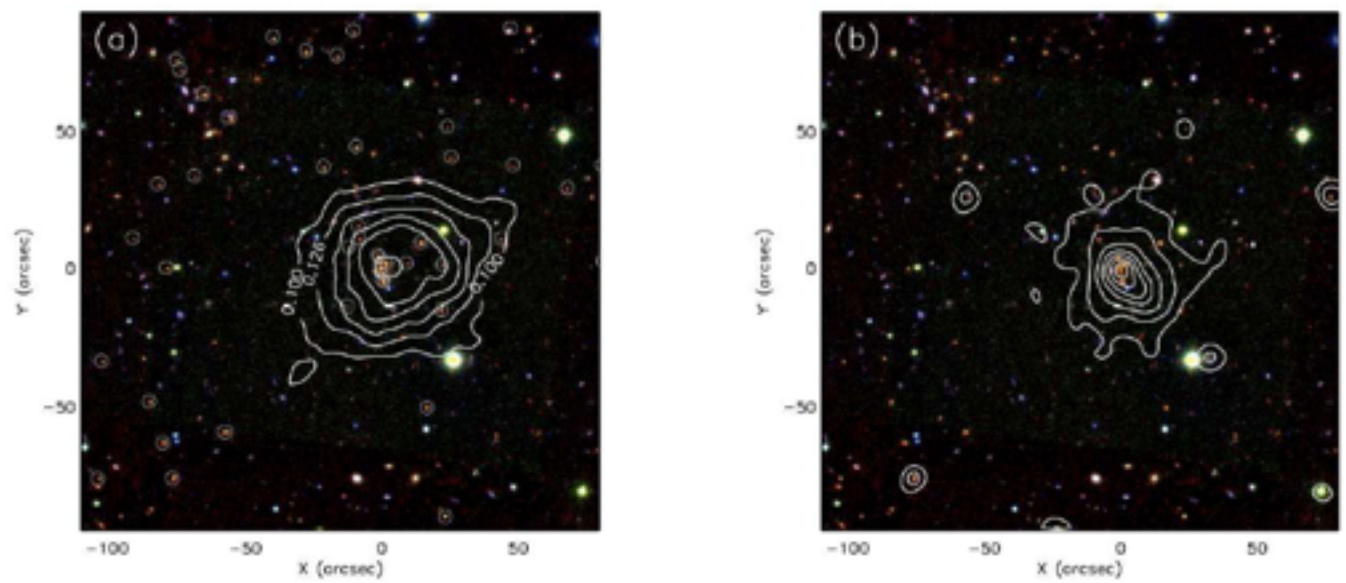

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- **How many clusters would do we expect to find at >M,>z**
- **The expected number in the full sky ~7.**
- **Footprint was 11 square degrees XMM X-ray survey, 0.02% of sky.**
- **Poisson sample from (0.0002*7) >1 only 1.4%**

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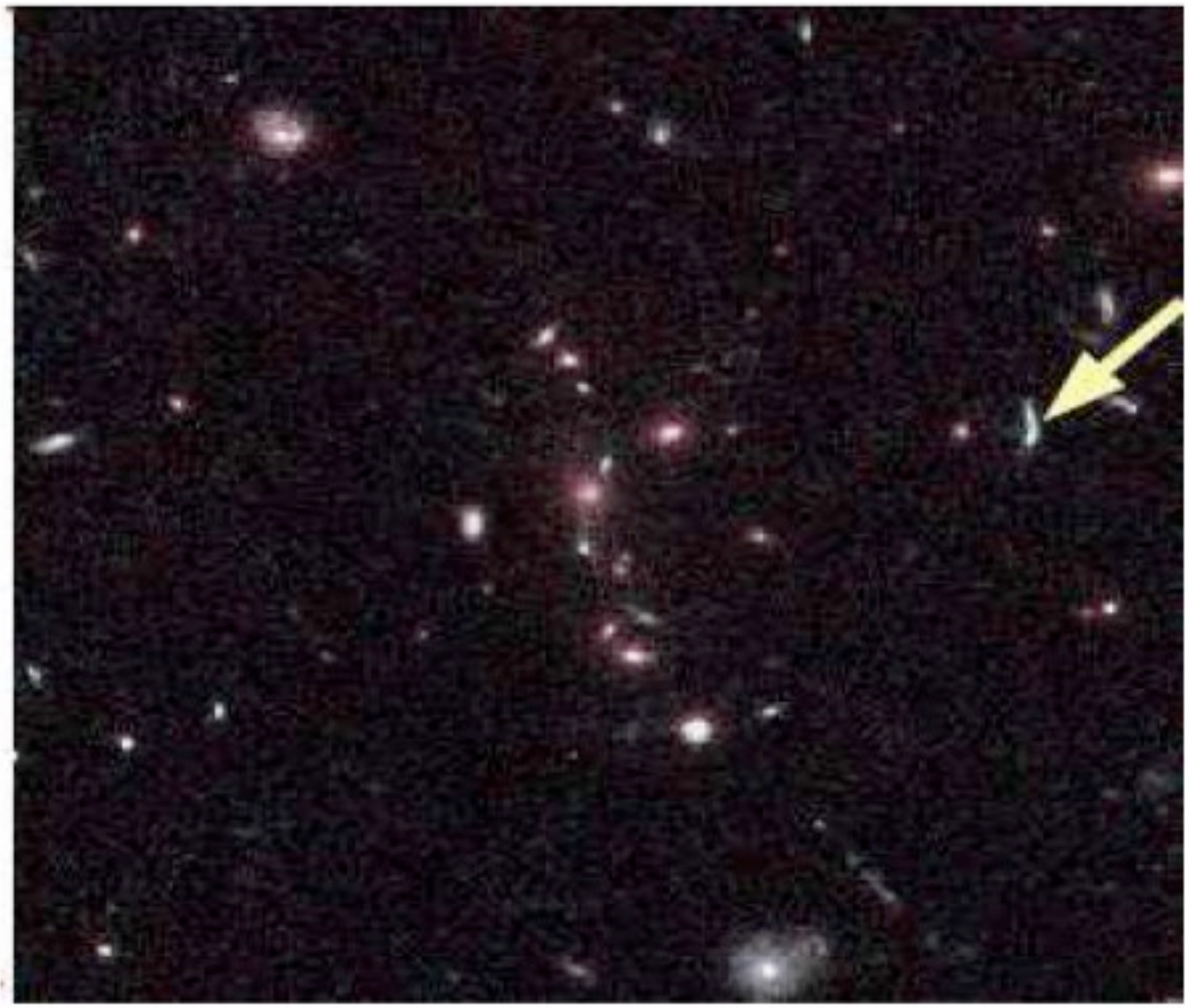

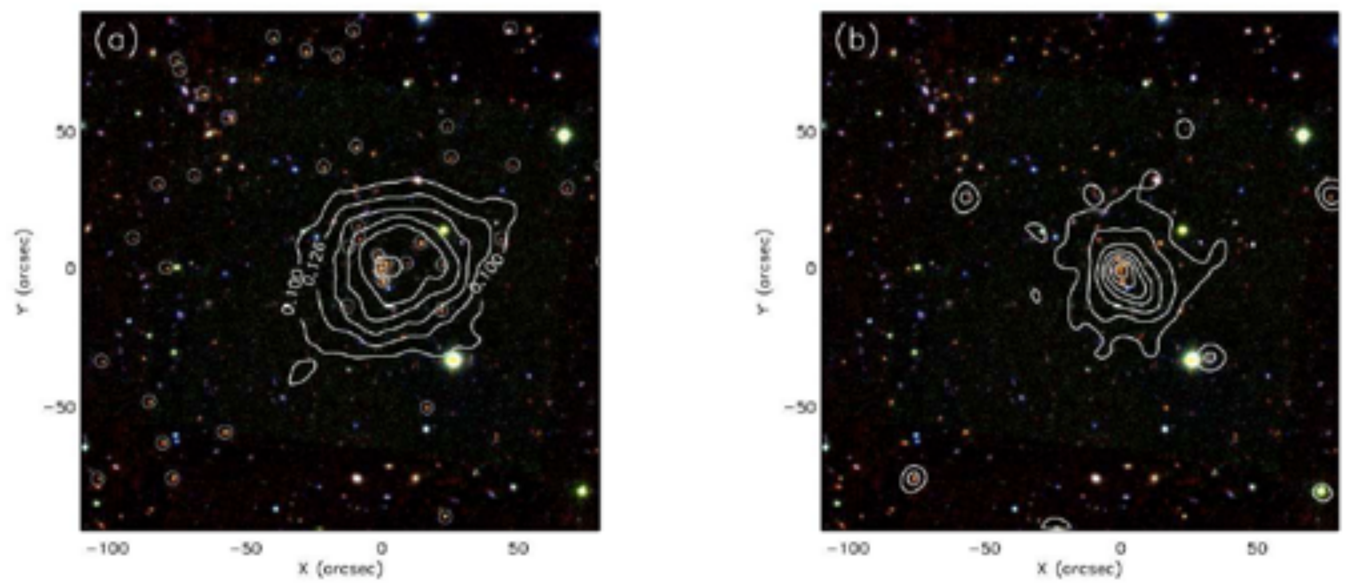

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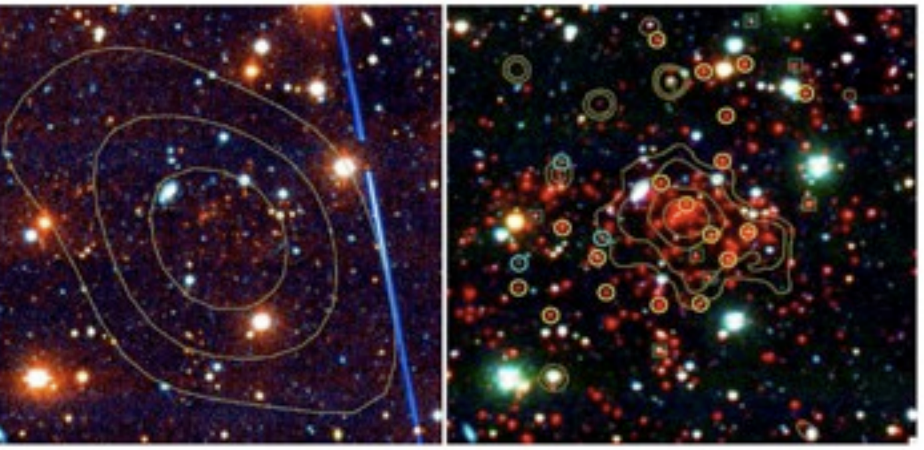
Jimenez & Verde 2009 showed fnl~150 relieves tension.
Cayon et al 2010 fnl=360,fnl>0 at 95%

Observations of 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). olor 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 ircles. 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**

We just got lucky.

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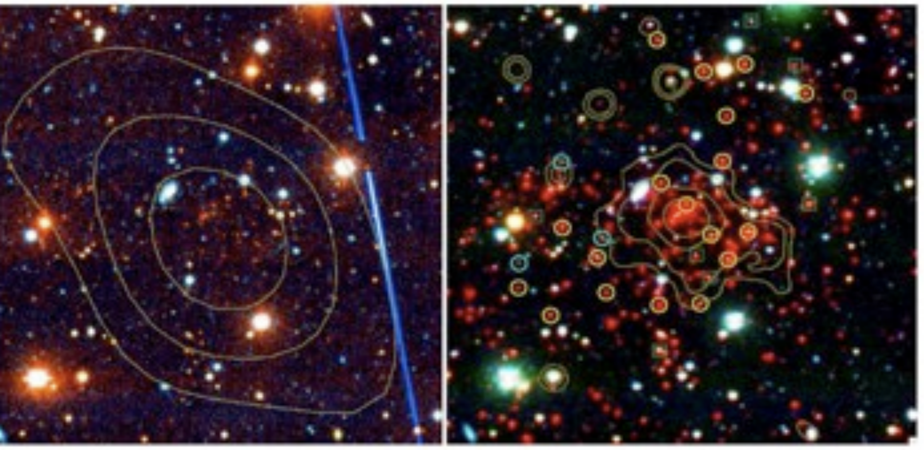

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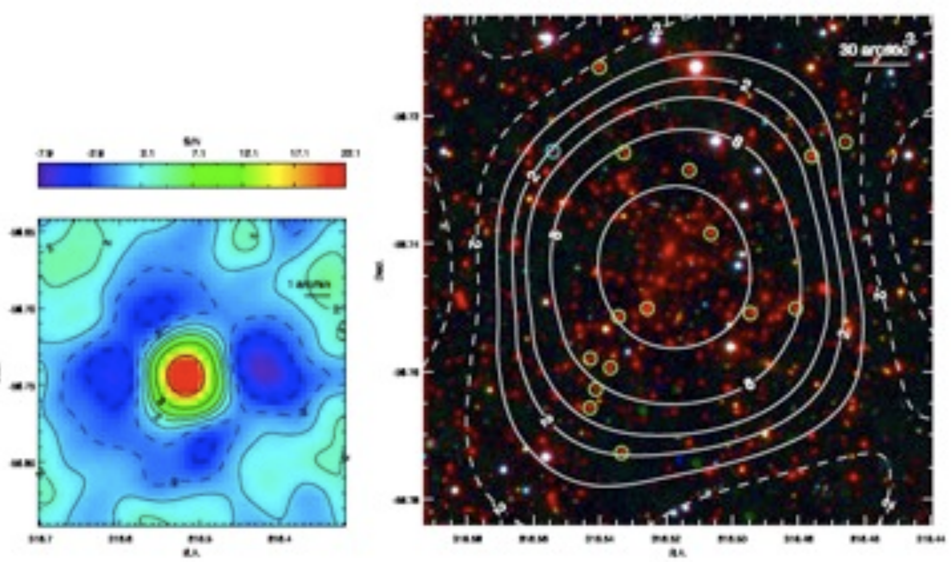


SPT-CL J2106-5844

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

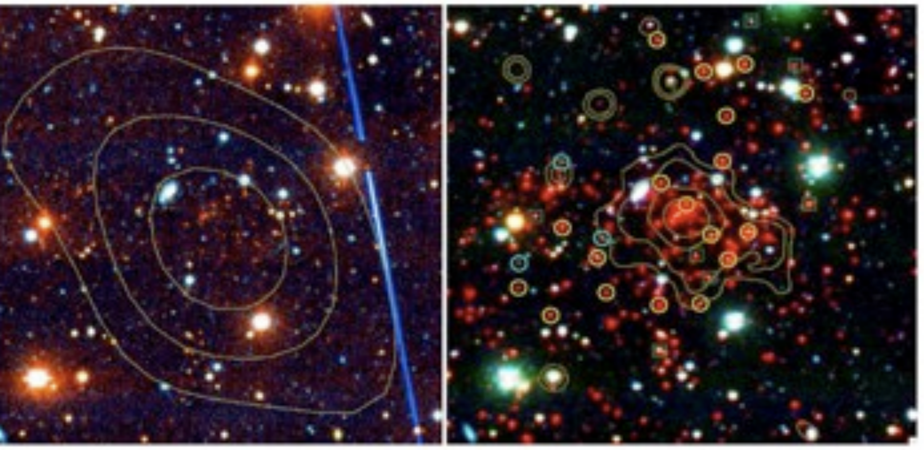
$z = 1.13$

Foley et al 2011

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

We got very lucky.

Observations of more "rare" clusters



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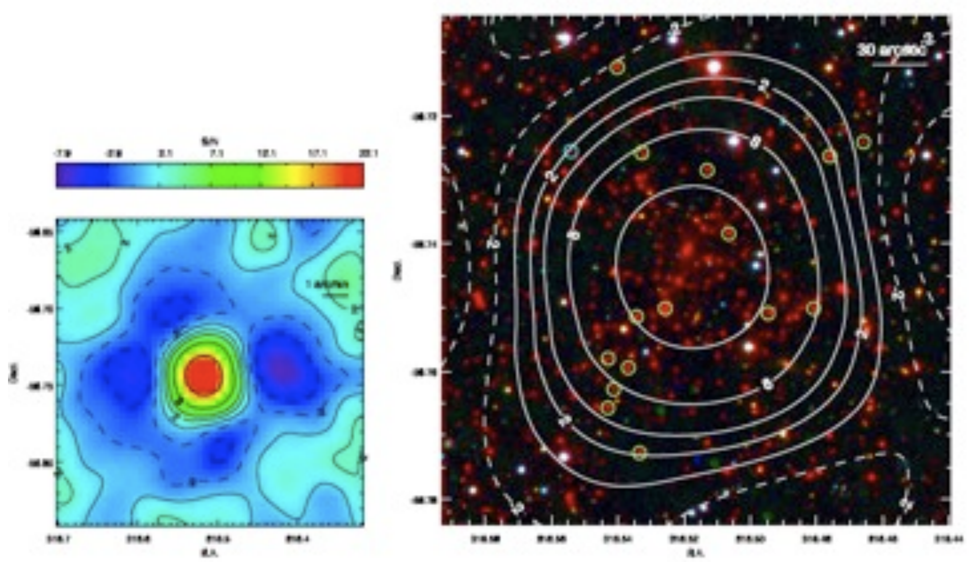
Foley et al.



SPT-CL J2106-5844

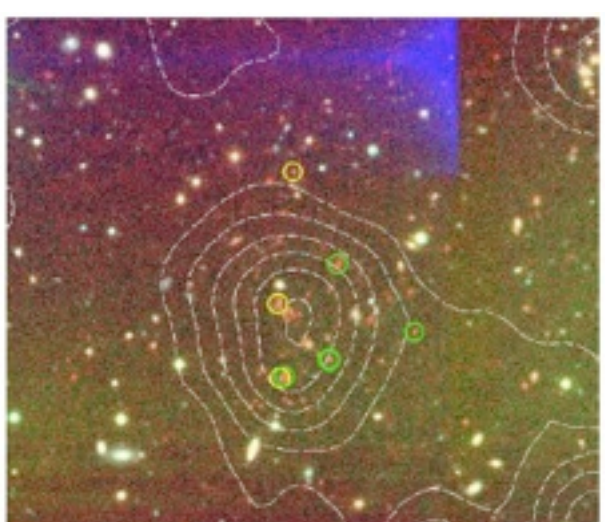
$M_{200} = 1.27 \times 10^{15}\, h^{-1}\, M_\odot!$

$z = 1.13$

Foley et al 2011

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

We got very lucky.



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**

Hey, we also got lucky!

The >M,>z analysis (uncalibrated)

Quantifying luck.

BH, Jimenez, Verde 2011

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
'SPT-CLJ2342-5411' *	1.08	$4.08^{+2.53}_{-2.53}$	Richness
'RDCSJ0910+5422' +	1.10	$6.28^{+3.70}_{-3.70}$	X-ray
'RXJ1053.7+5735(West)' +	1.14	$2.00^{+1.00}_{-0.70}$	X-ray
'XLSSJ022303.0043622' +	1.22	$1.10^{+0.60}_{-0.40}$	X-ray
'RDCSJ1252.9-2927' +	1.23	$2.00^{+0.50}_{-0.50}$	X-ray
'RXJ0849+4452' +	1.26	$3.70^{+1.90}_{-1.90}$	X-ray
'RXJ0848+4453' +	1.27	$1.80^{+1.20}_{-1.20}$	X-ray
→'XMMUJ2235.3+2557' +	1.39	$7.70^{+4.40}_{-3.10}$	X-ray
'XMMXCSJ2215.9-1738' +	1.46	$4.10^{+3.40}_{-1.70}$	X-ray
'SXDF-XCLJ0218-0510' +	1.62	$0.57^{+0.14}_{-0.14}$	X-ray

+ conservative assumptions

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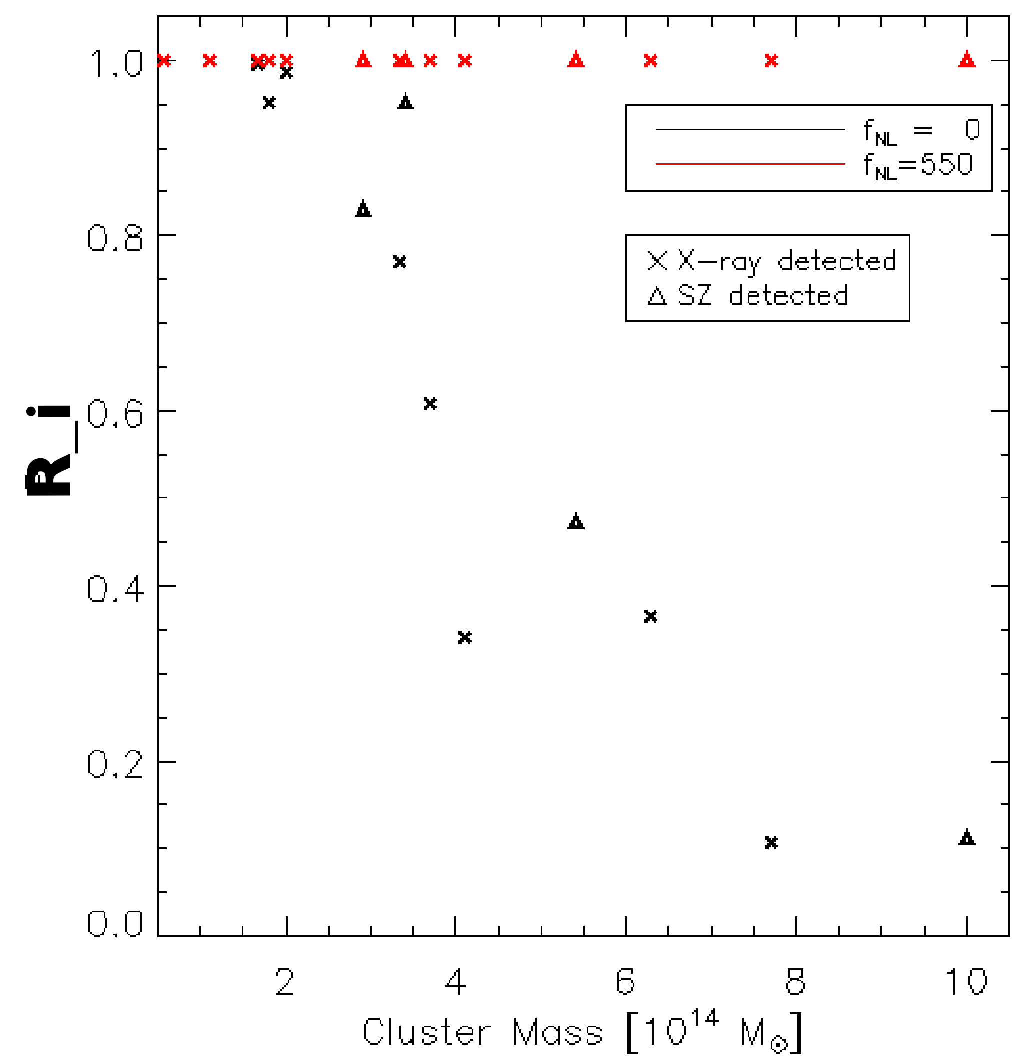

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We assumed that the probability, that an ensemble of N clusters exists is

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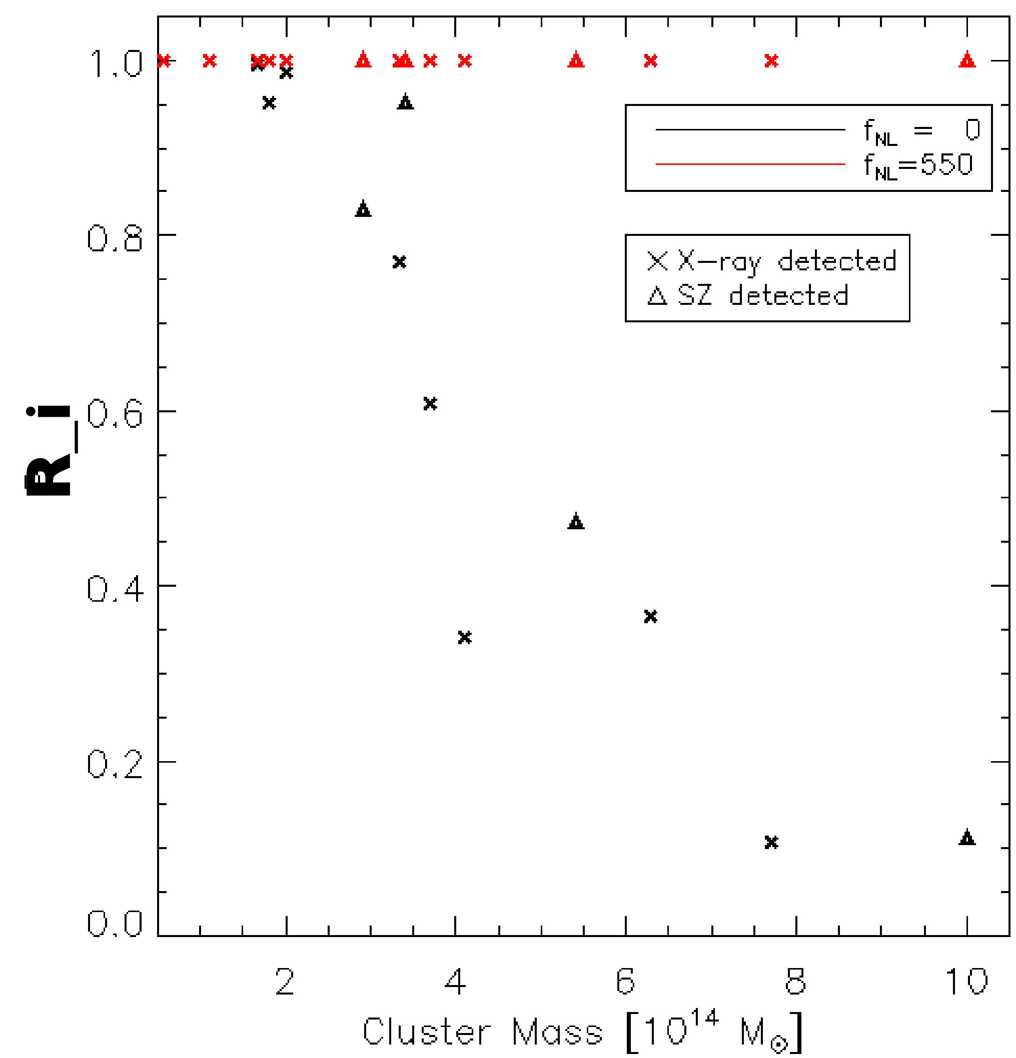

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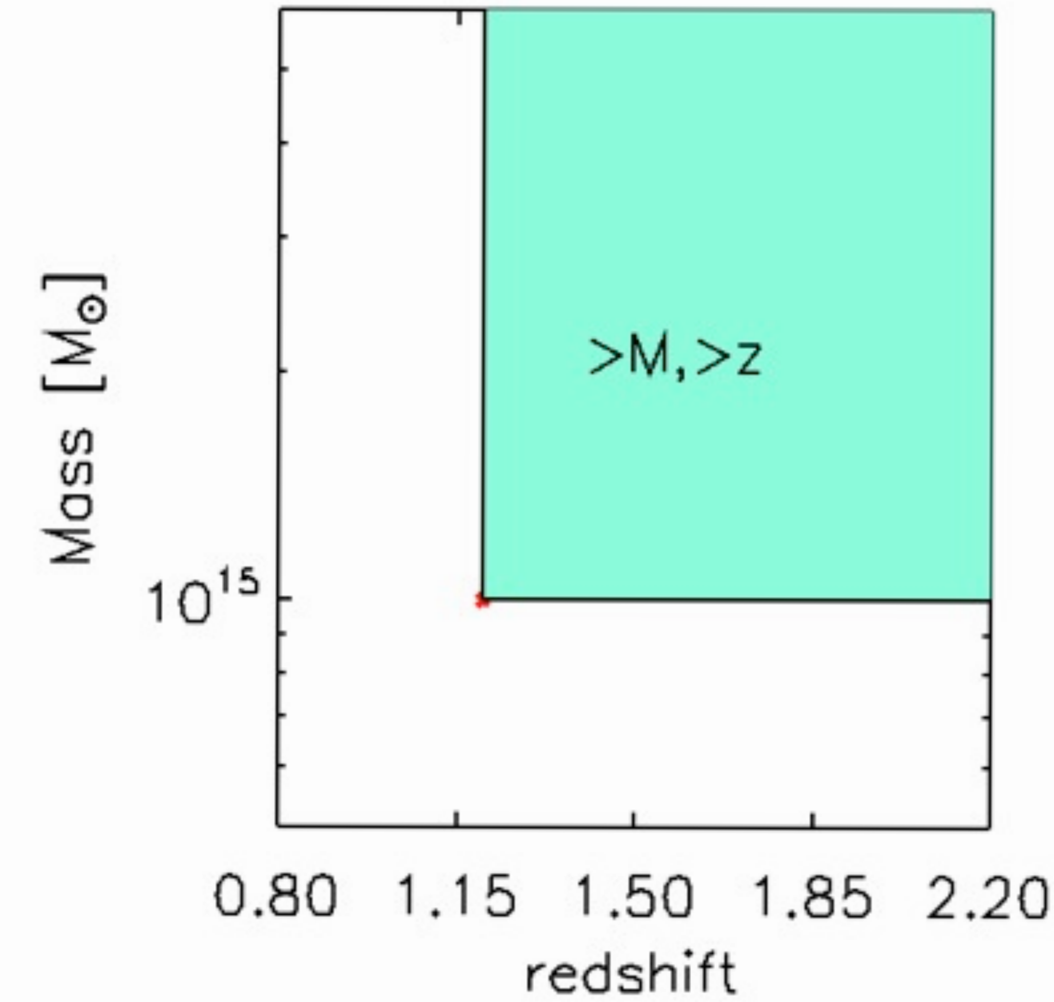
Using the >M,>z analysis, it appeared as though these clusters were very unlikely. Possible explanations:

$$f_{\rm NL} > 123; \quad \sigma_8 \geq 0.9;$$

The >M,>z analysis

The >M,>z analysis begins by assuming that we would have also observed any cluster with greater mass, or greater redshift than an observed cluster.



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An abundance number is calculated

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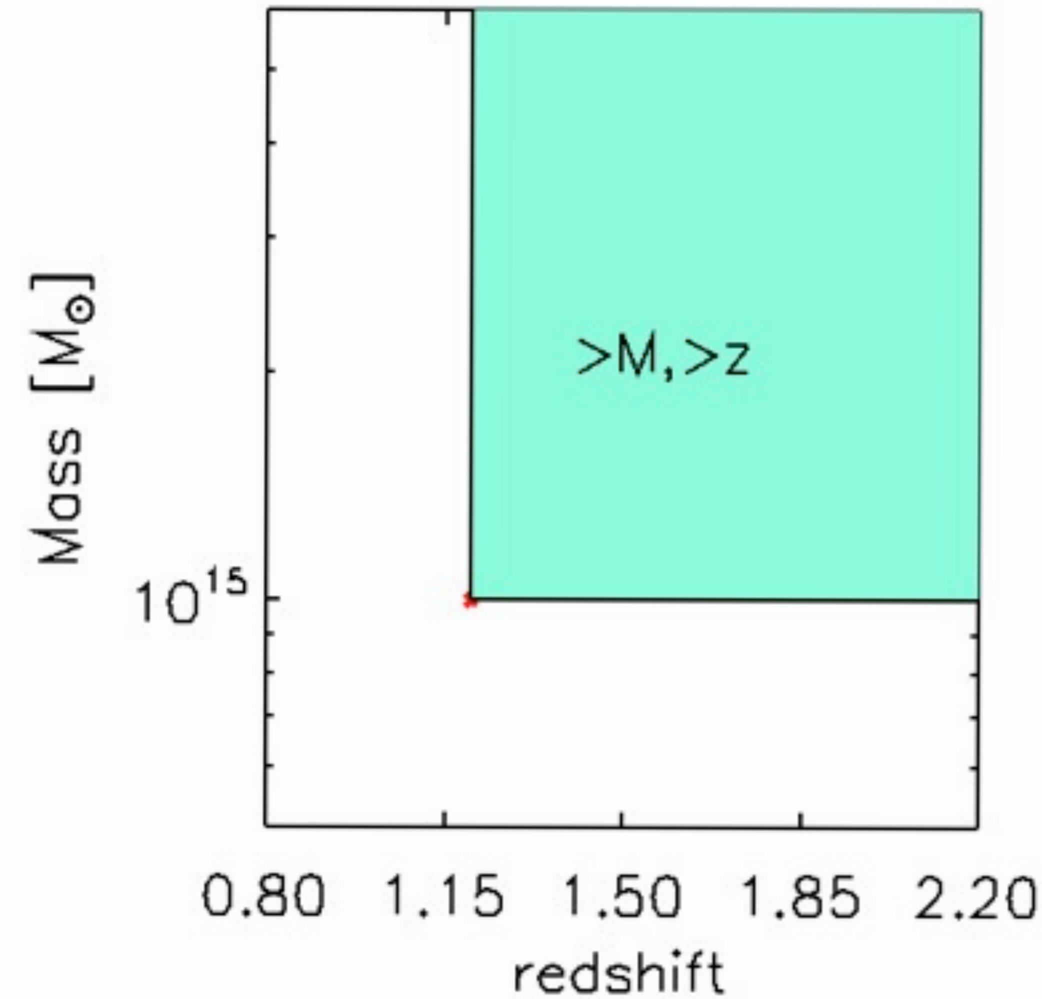

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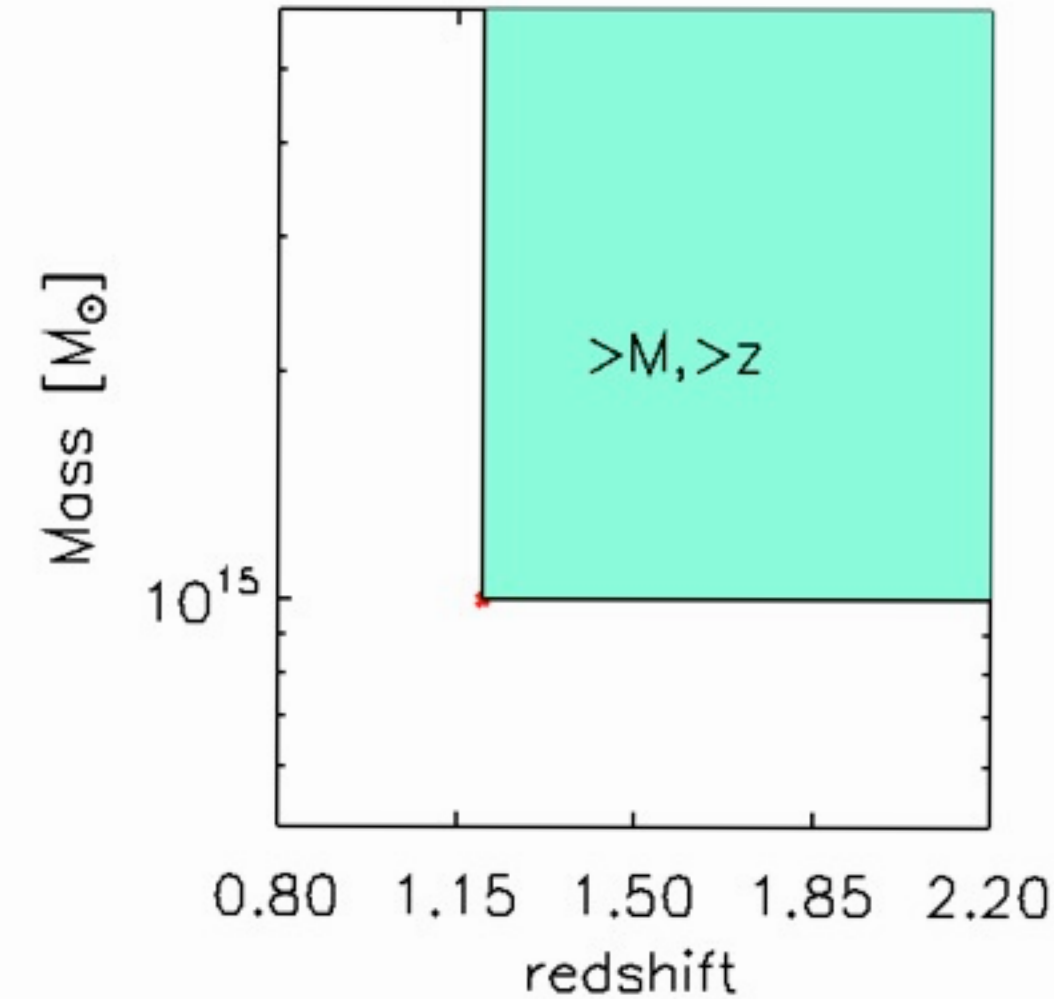

We Poisson sample from As many (1e4) times.

If the Poisson sample is >1, the cluster exists in this realisation.
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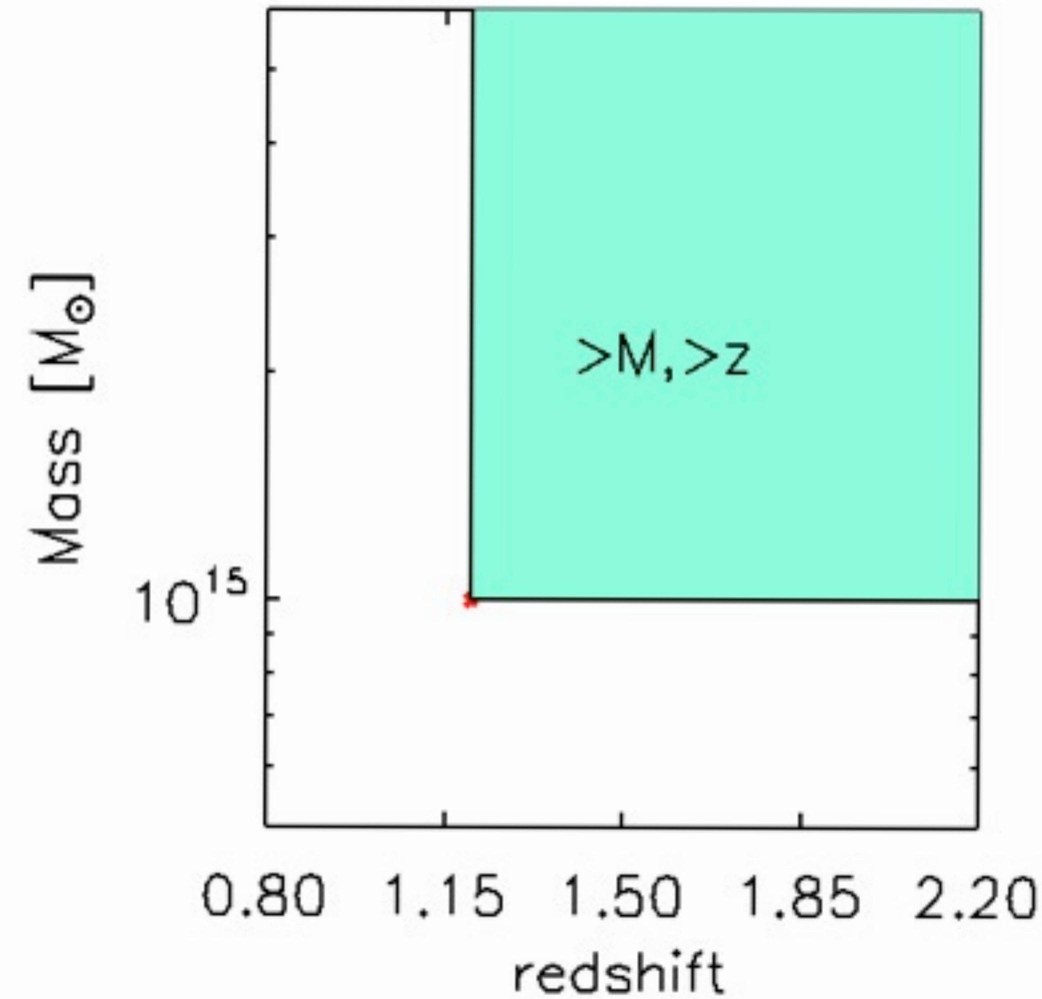

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The “existence probability” R, is given by

$$R = \quad \text{Number}(P^O(A_s) \geq 1)/10^4)$$

Unbiasing/Calibrating the >M,>z statistic 1

The bias in a nutshell: In previous literature, the question, a) What is the probability of finding a cluster(s) in this >M,>z box? referred to as "existence probability" R has been used as a proxy for what we actually want to know, b) "What is the probability of this cluster(s) existing in our cosmological model?"

When stated like this, one can see that a) does not imply b). (see Hotchkiss 2011)

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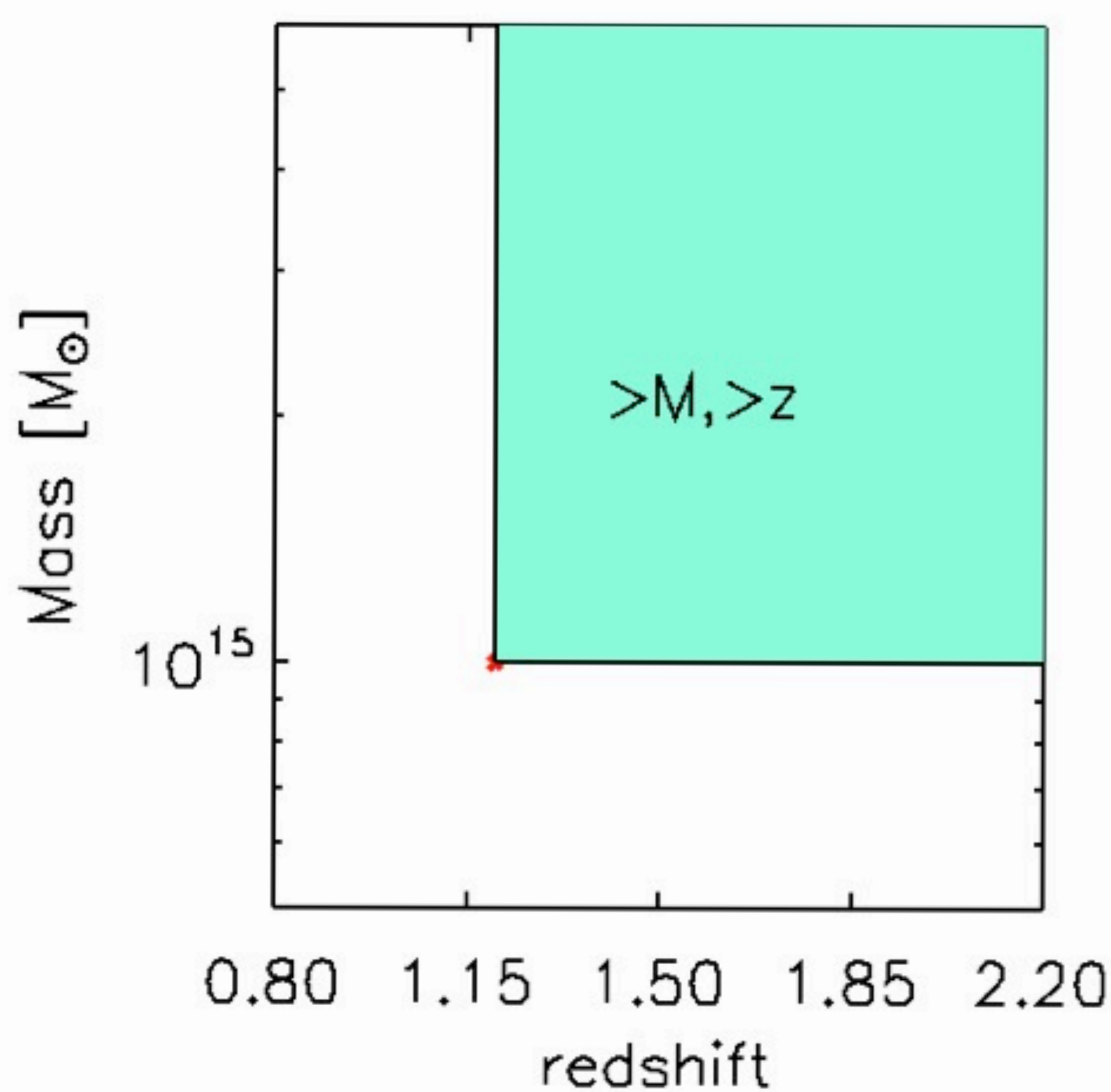

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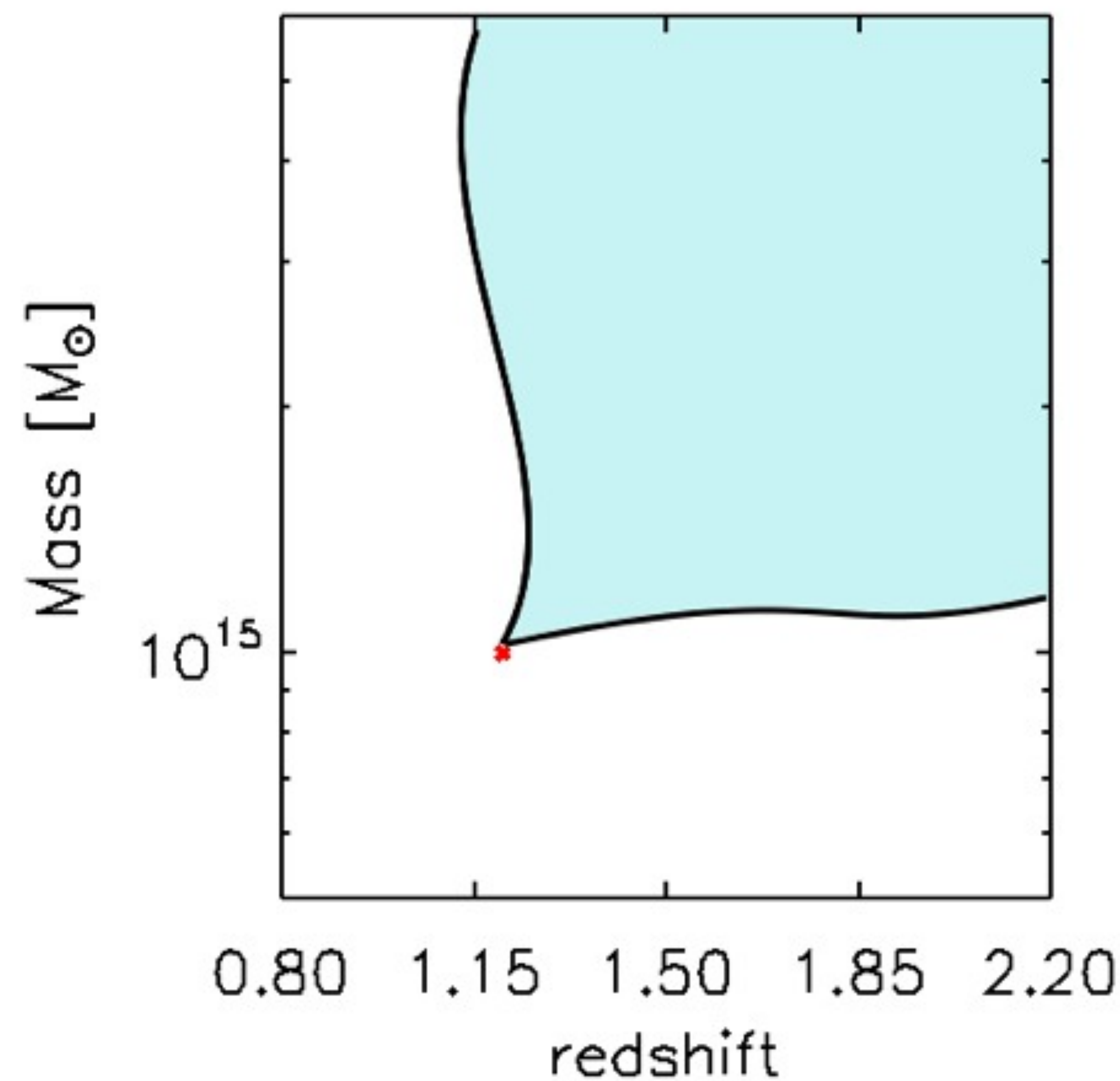
<u>Why this is wrong</u>

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, or have straight instead of curved boundaries? One could simply modify the >M,>z box 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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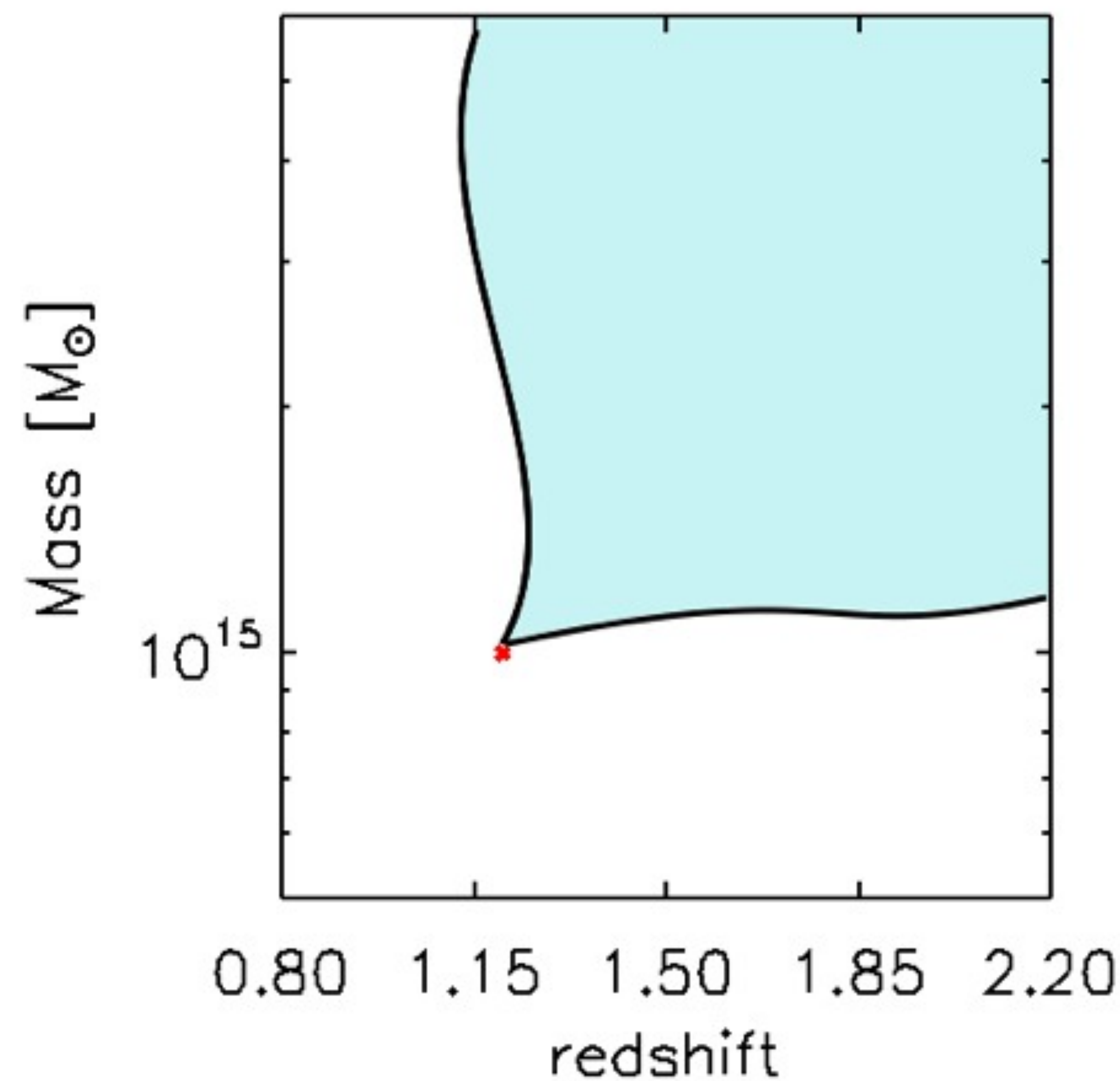
Once the above is understood, we can calibrate R using simulations, compare it with R from observations, and then use the calibrated R to test for tension with LCDM.



>M,>z exclusion curves (calibrated)

Remember, (once calibrated) exclusion curves can be used to test for tension using only one cluster.

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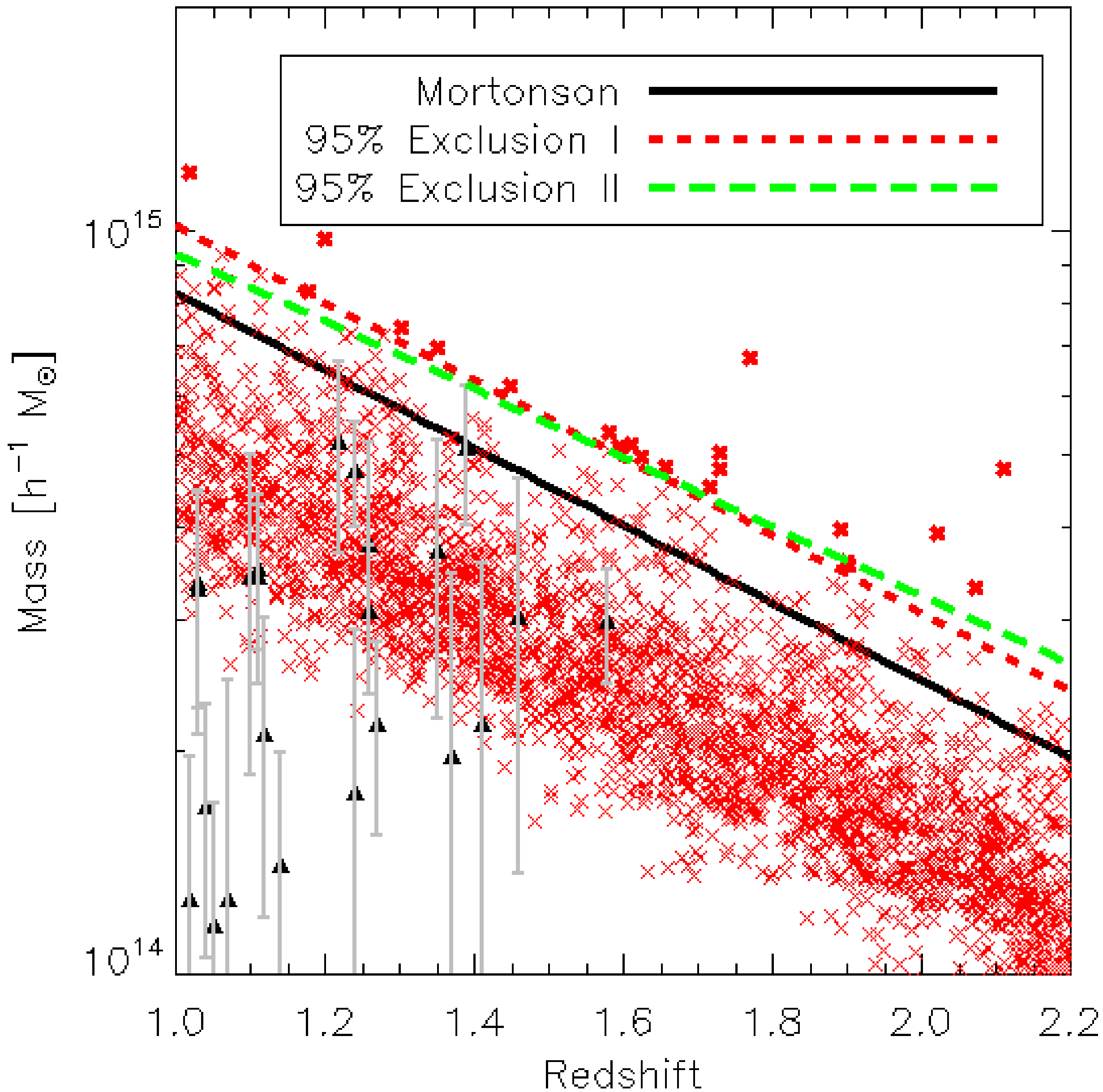

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- **Assume a sf /geometry**
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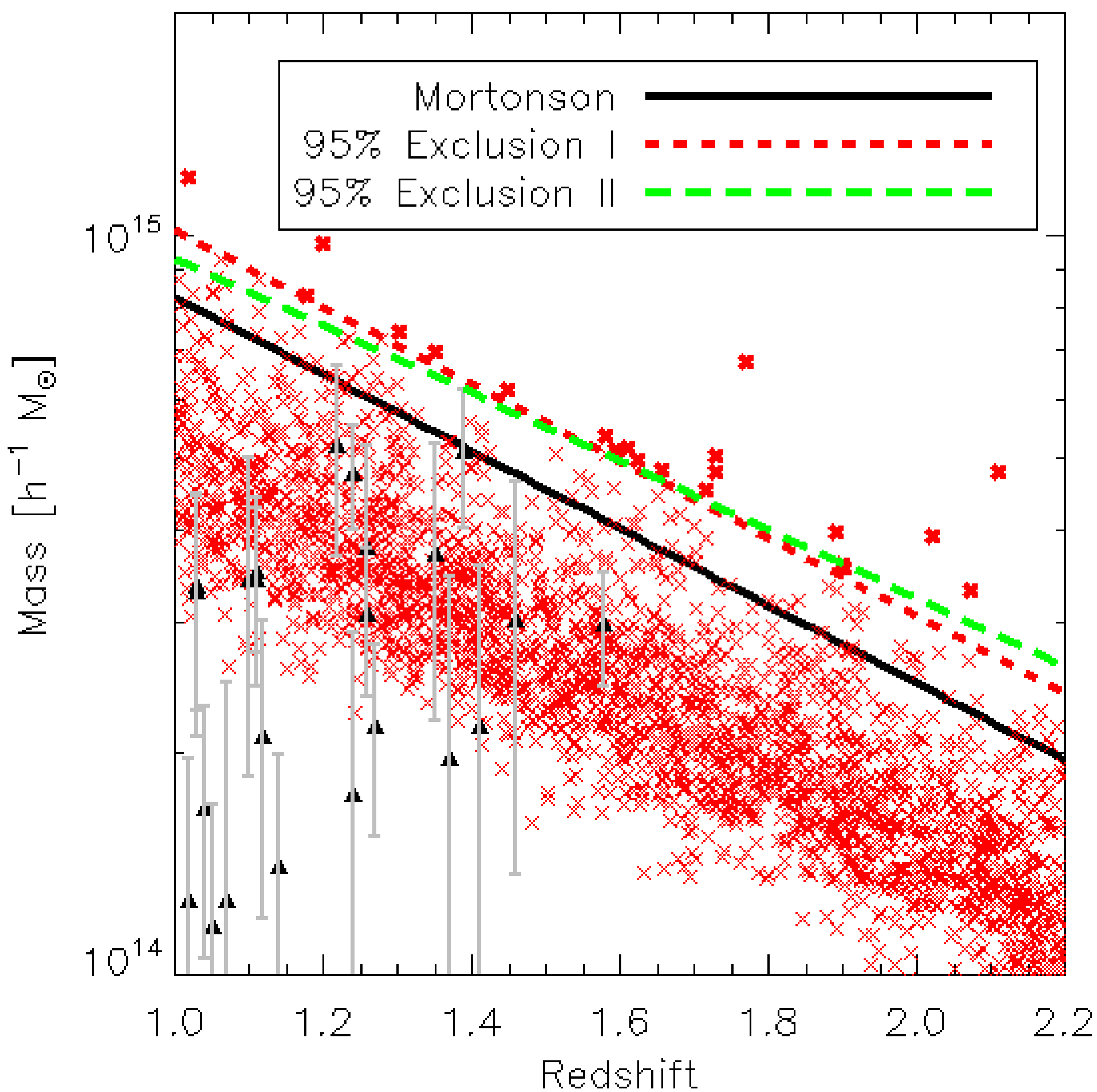
- **Draw a line which correctly excludes (e.g.) 95% of the simulated clusters**



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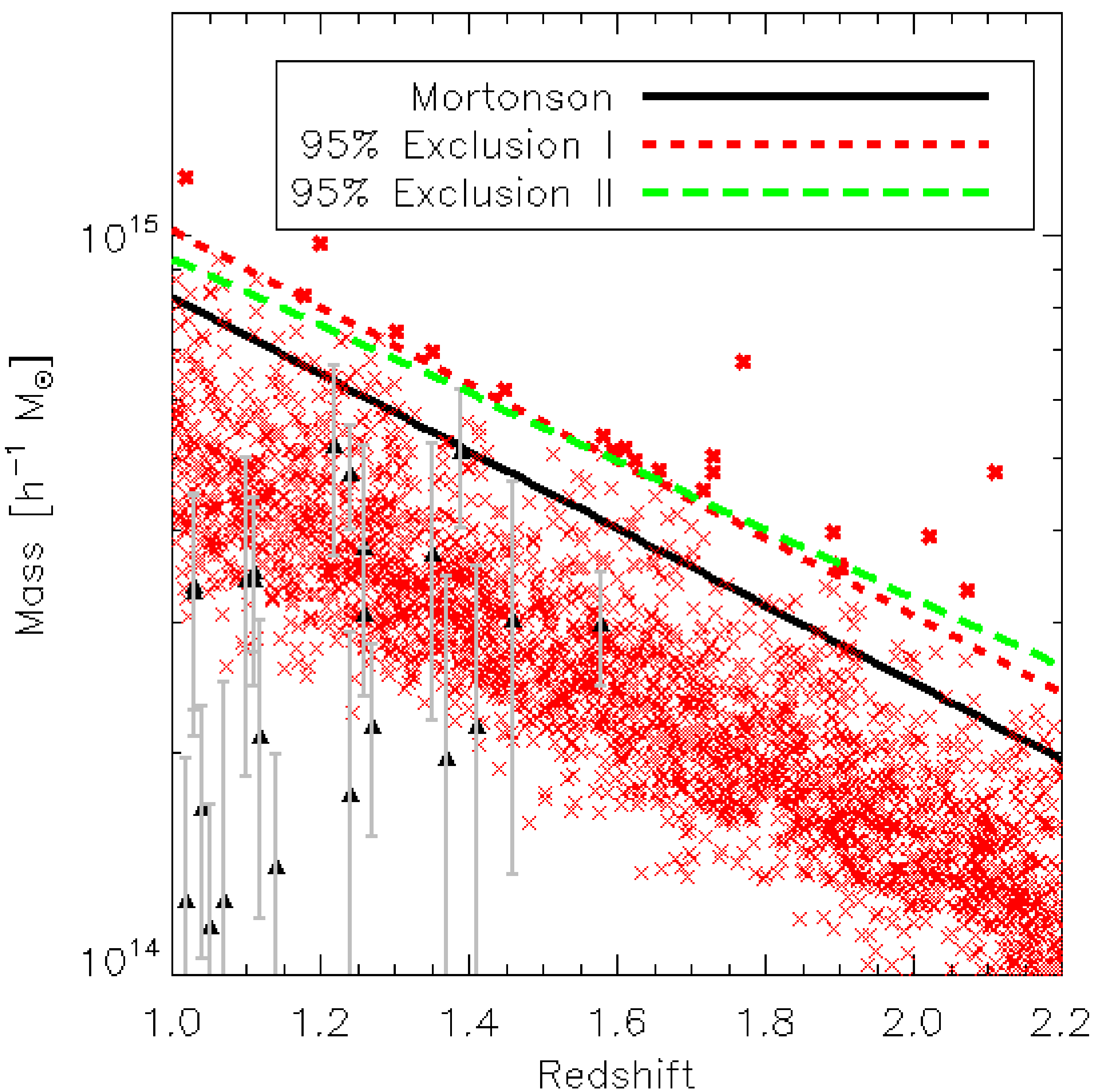
But, this line is arbitrary!

Any inferred exclusion significance must be quoted together with the metric.



(see also Hotchkiss 2011, and Harrison & Hotchkiss 1210.4369)

Notes on the >M,>z statistic

Playing the >M,>z game is only necessary if we don't know the selection function (sf) of a survey. X-ray/ Weak lensing (actually SNe) sample of clusters from Jee et al (2011), have a very complicated sf. Only the existence, not the absence, of clusters can constrain cosmology (as opposed to e.g., SPT, maxBCG, R400d).

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Extended sources not followed up => no redshifts or mass estimates.
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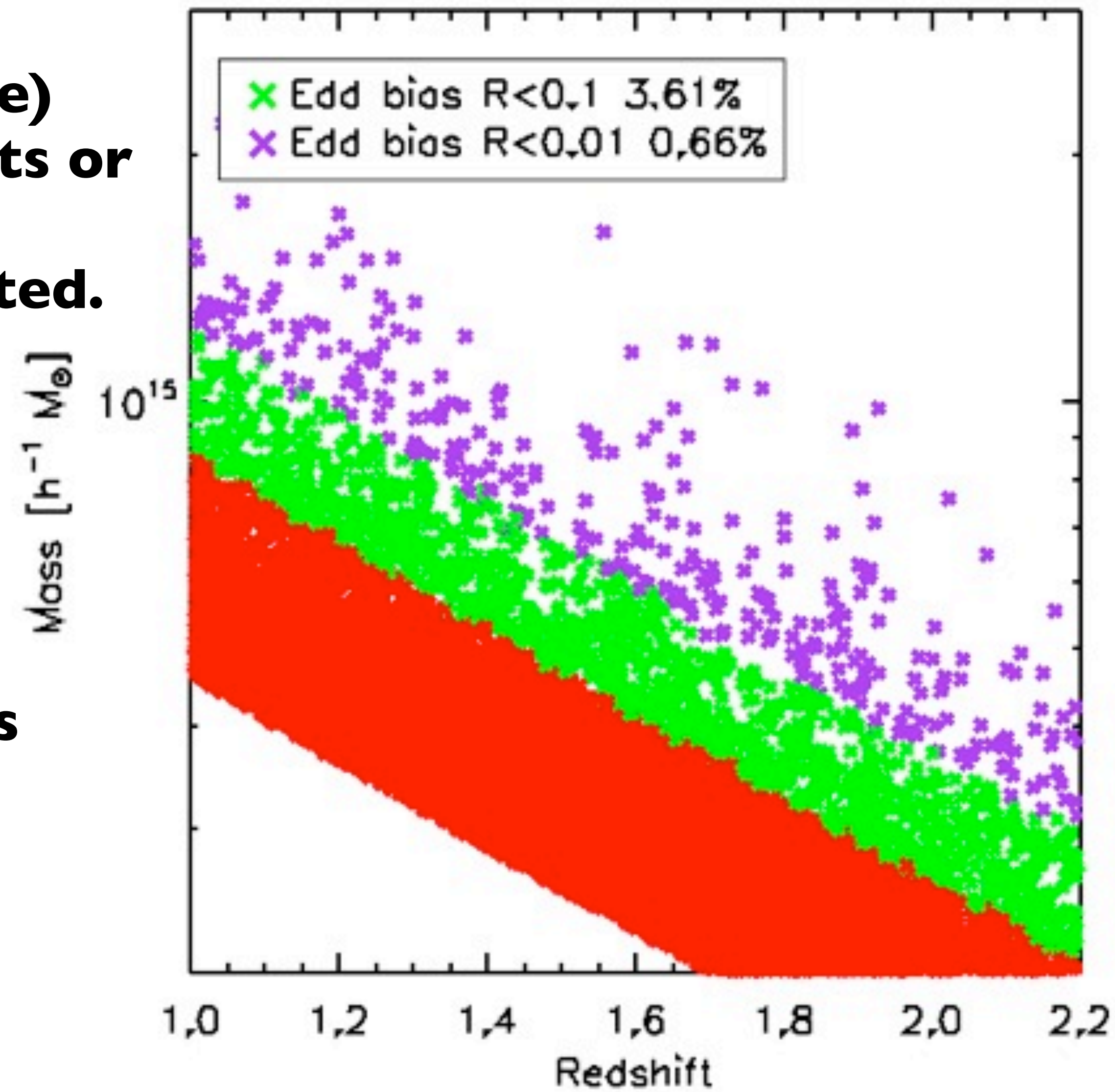

<u>But we still want to infer something!</u>
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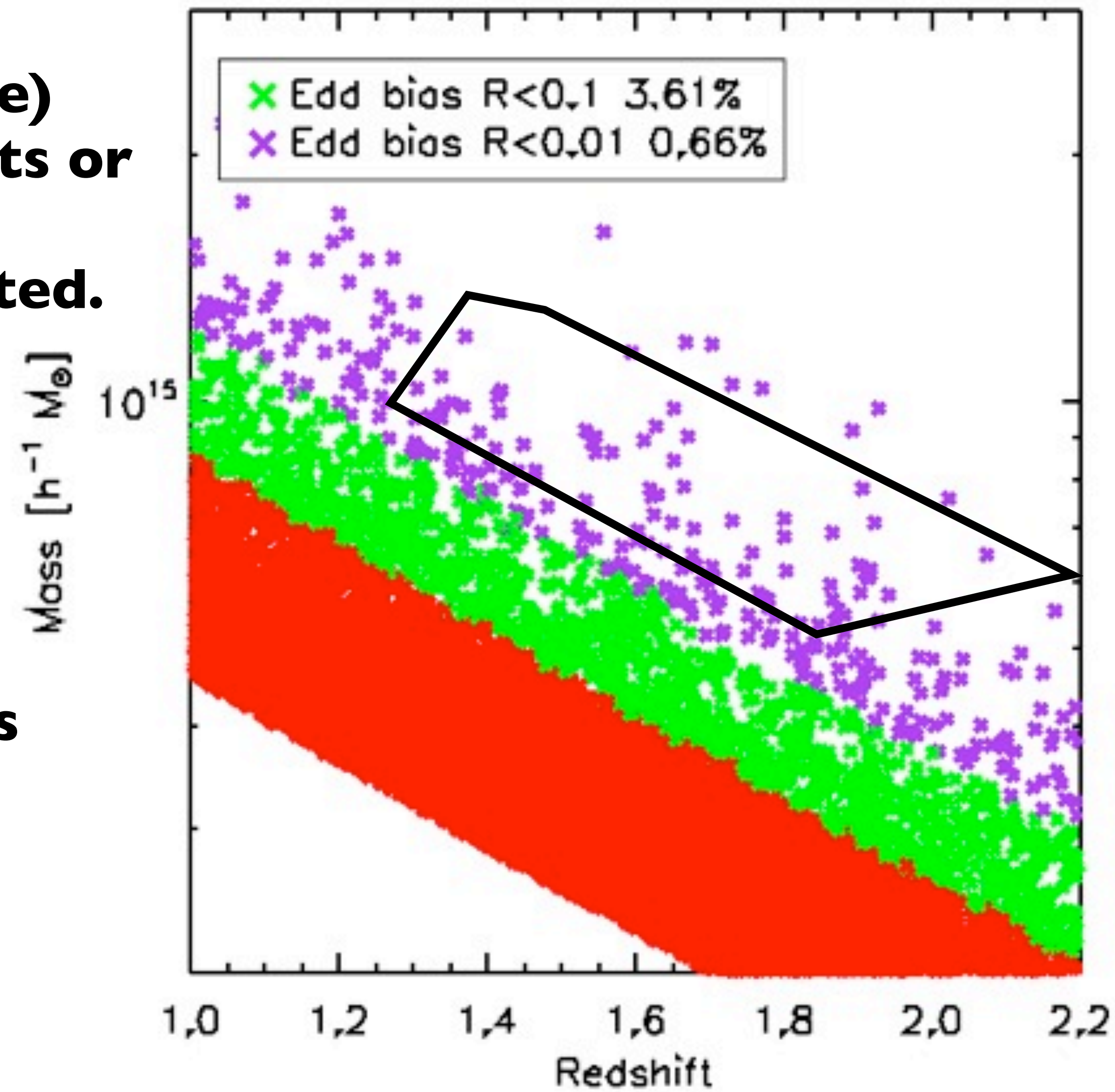

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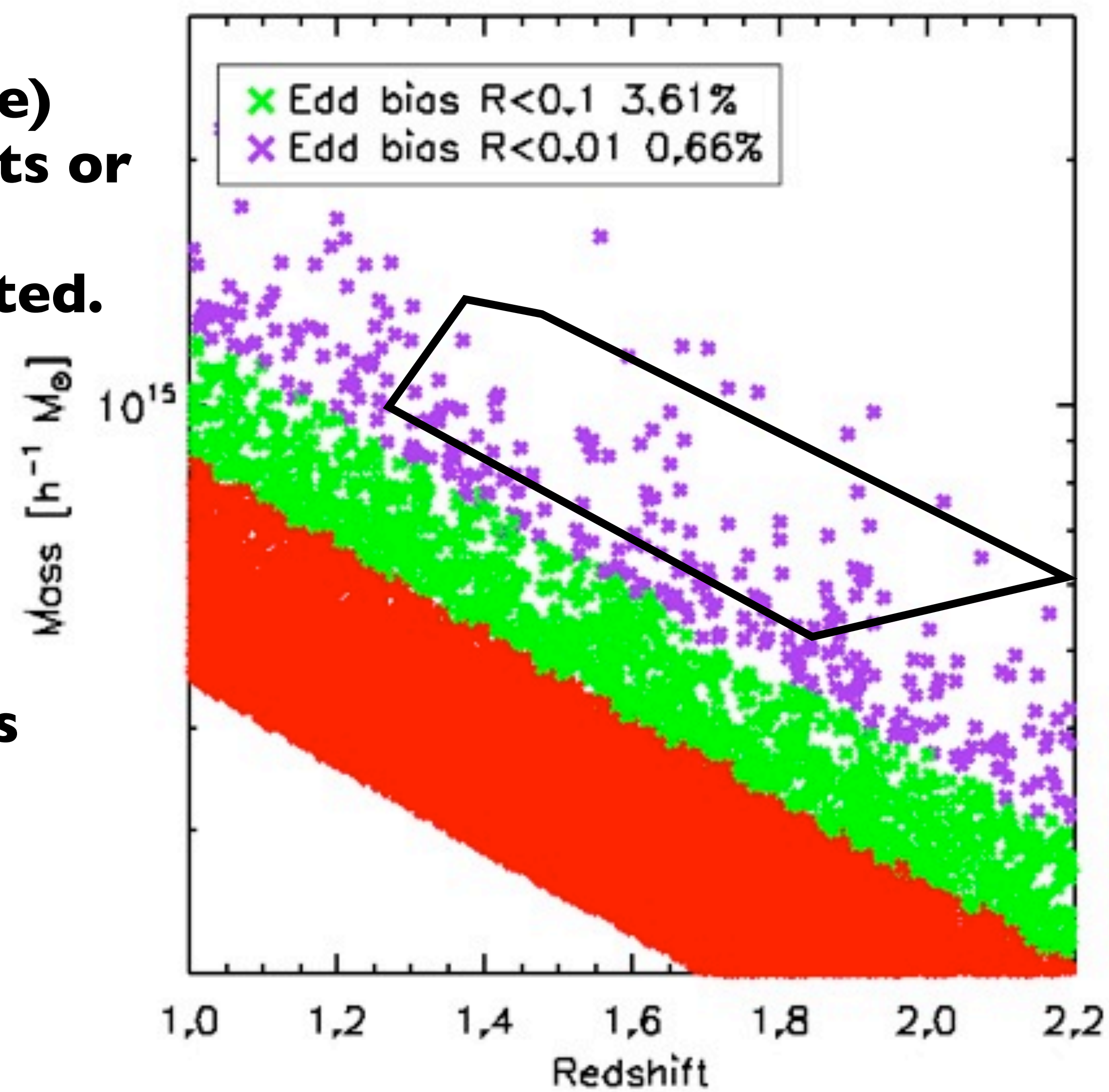

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Note: To calibrate >M,>z analysis using simulated clusters, we must assume which part of the (M,z) plane has been "observed" (i.e., a sf).

Ongoing work to recover cosmological constraints using weaker assumptions about the selection function (Hoyle et al, in prep)

Correct analysis/comparison: data

<u>Observations progressed</u>
Jee et al 2009, 2011, Santos et al 2011, Stott et al 2010

Realistic X-ray survey footprint 100 sq. deg. (Jee et al 2011)

Redshift range of Jee 1.0<z<2.2

Most precise mass measurement.

Still use the (>M,>z) R statistic but calibrate to simulations.

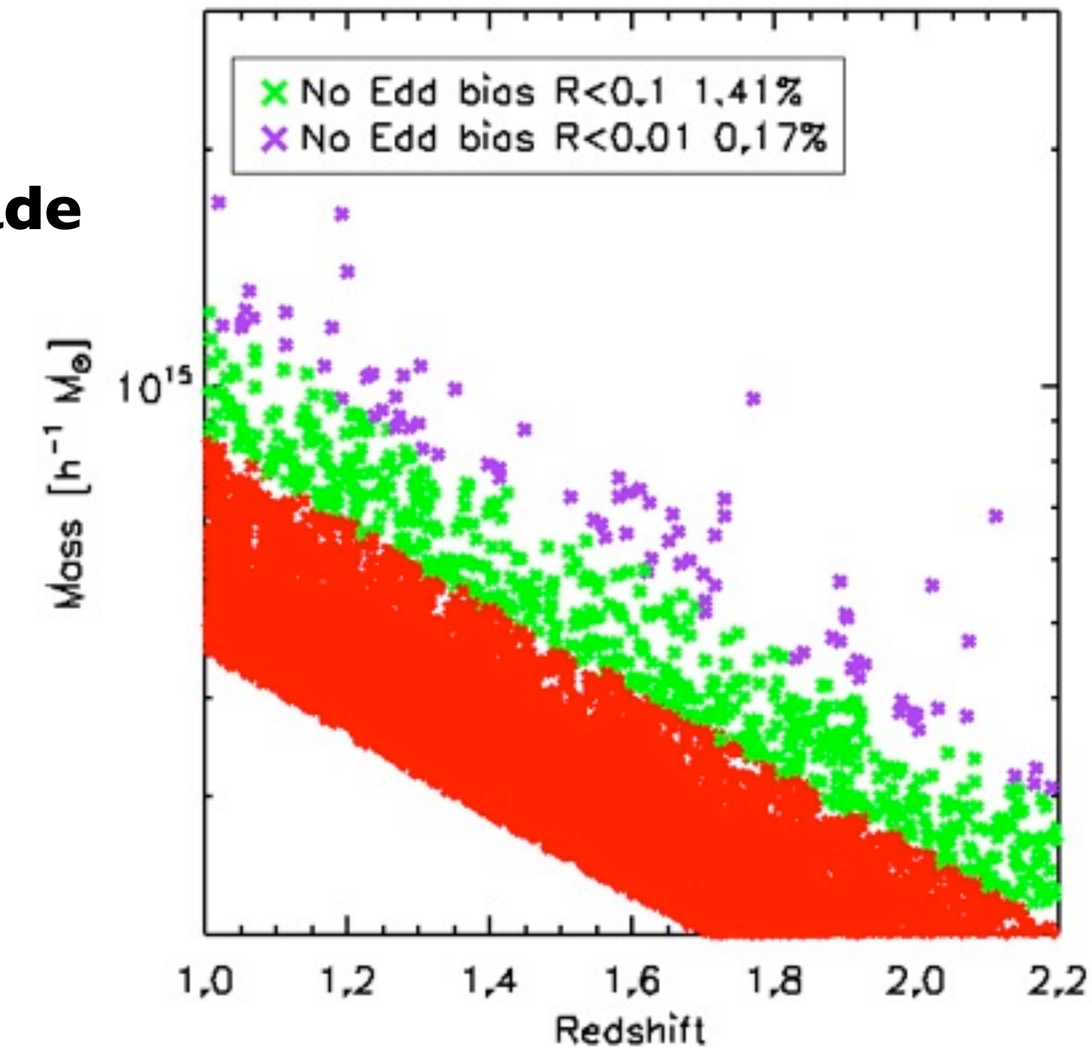
Cluster Name	Redshift	M_{200} $10^{14}M_\odot$	Method	$\tilde{R}$	Mass reference
RCS0221-0321	1.02	$1.80^{+1.30}_{-0.70}$	WL	0.992	[15]
WARPSJ1415+3612	1.03	$4.70^{+2.00}_{-1.40}$	WL	0.706	[15]
RCS0220-0333	1.03	$4.80^{+1.80}_{-1.30}$	WL	0.709	[15]
RCS2345-3632	1.04	$2.40^{+1.10}_{-0.70}$	WL	0.989	[15]
XLSSJ022403.9-041328*	1.05	$1.66^{+1.15}_{-0.38}$	X-ray	0.997	[31]
RCS2156-0448	1.07	$1.80^{+2.50}_{-1.00}$	WL	0.916	[15]
RCS0337-2844	1.10	$4.90^{+2.80}_{-1.70}$	WL	0.567	[15]
RDCSJ0910+5422	1.11	$5.00^{+1.20}_{-1.00}$	WL	0.595	[15]
ISCSJ1432+3332	1.11	$4.90^{+1.60}_{-1.20}$	WL	0.603	[15]
XMMUJ2205-0159	1.12	$3.00^{+1.60}_{-1.00}$	WL	0.888	[15]
RXJ1053.7+5735(West)	1.14	$2.00^{+1.00}_{-0.69}$	X-ray	0.989	[31]
XLSSJ0223-0436	1.22	$7.40^{+2.50}_{-1.80}$	WL	0.119	[15]
RDCSJ1252-2927	1.24	$6.80^{+1.20}_{-1.00}$	WL	0.094	[15]
ISCSJ1434+3427	1.24	$2.50^{+2.20}_{-1.10}$	WL	0.806	[15]
ISCSJ1429+3437	1.26	$5.40^{+2.40}_{-1.60}$	WL	0.327	[15]
RDCSJ0849+4452	1.26	$4.40^{+1.10}_{-0.90}$	WL	0.517	[15]
RDCSJ0848+4453	1.27	$3.10^{+1.00}_{-0.80}$	WL	0.839	[15]
ISCSJ1432+3436	1.35	$5.30^{+2.60}_{-1.70}$	WL	0.265	[15]
ISCSJ1434+3519	1.37	$2.80^{+2.90}_{-1.40}$	WL	0.636	[15]
XMMUJ2235-2557	1.39	$7.30^{+1.70}_{-1.40}$	WL	0.035	[15]
ISCSJ1438+3414	1.41	$3.10^{+2.60}_{-1.40}$	WL	0.584	[15]
XMMXCSJ2215-1738	1.46	$4.30^{+3.00}_{-1.70}$	WL	0.335	[15]
XMMUJ0044.0-2033**	1.57	$4.25^{+0.75}_{-0.75}$	X-ray	0.152	[30]

Margenalise over the mass error by sampling from each clusters' mass and error many times and calculate R for each sampled mass. This produces a distribution in R for each cluster.

BH, Jimenez, Verde, Hotchkiss (2011 JCAP)

Correct analysis/comparison: simulations

1) 450 sets of simulations made from Poisson sampling the mass function, varying cosmological parameters, assuming WMAP7 priors.

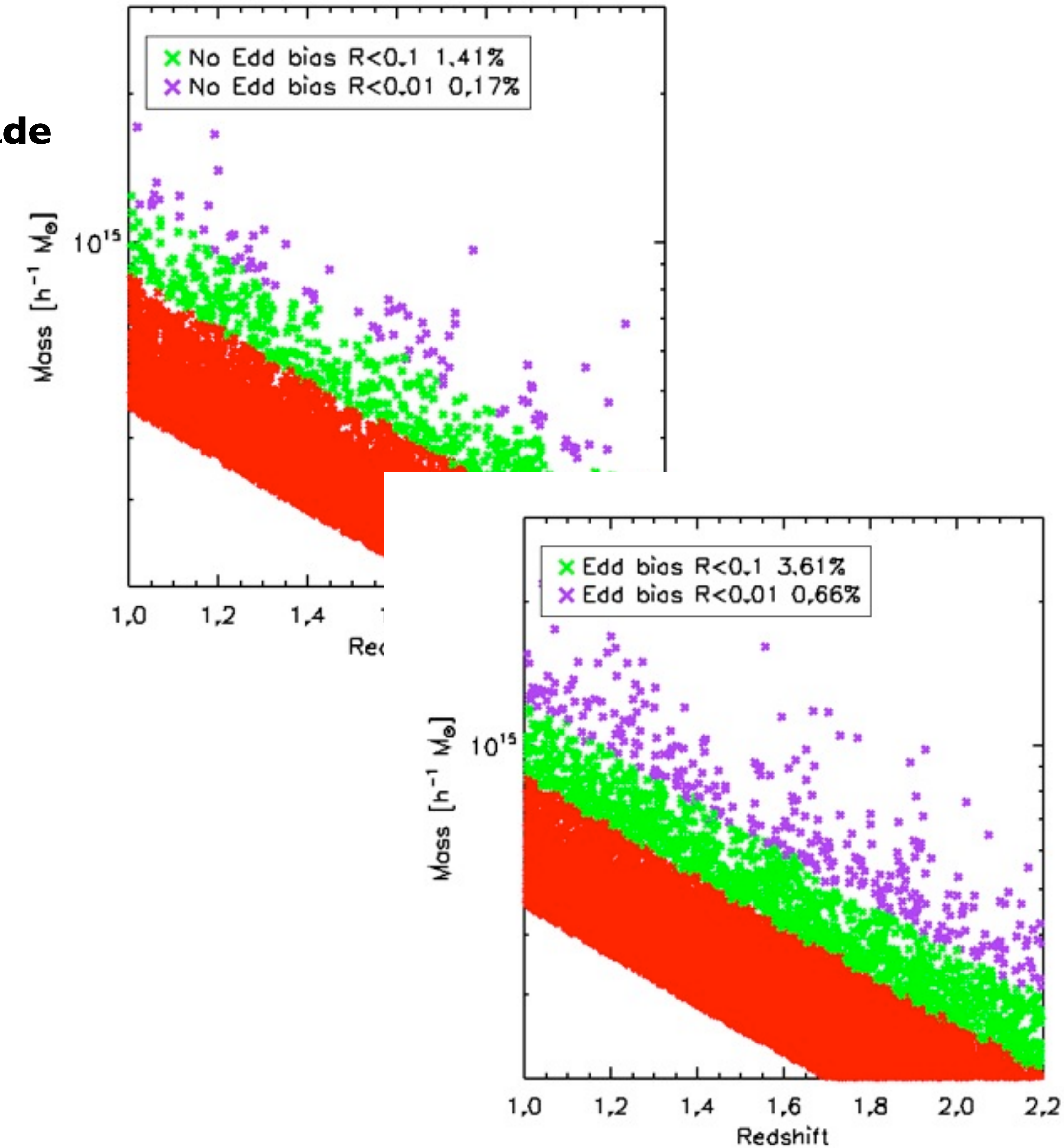


Correct analysis/comparison: simulations

1) 450 sets of simulations made from Poisson sampling the mass function, varying 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 (see Mortonson et al 2011).

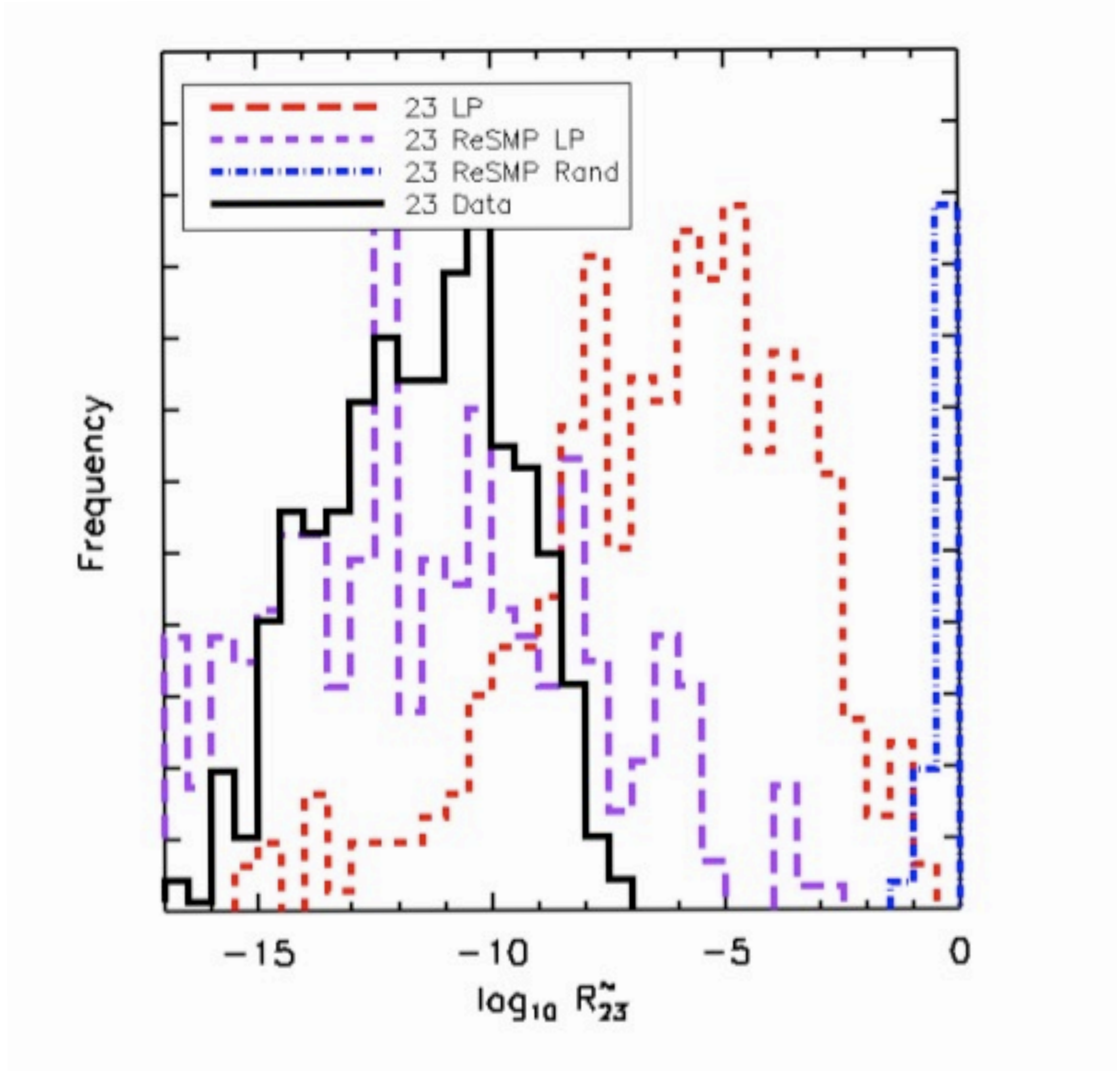
3) Calculate R for each cluster, identify the LP clusters in each simulation.



Calibrated analysis/comparison with sim.

We assumed that the combined R values, for an ensemble of N clusters is

$$R_N = \Pi_N R_i$$



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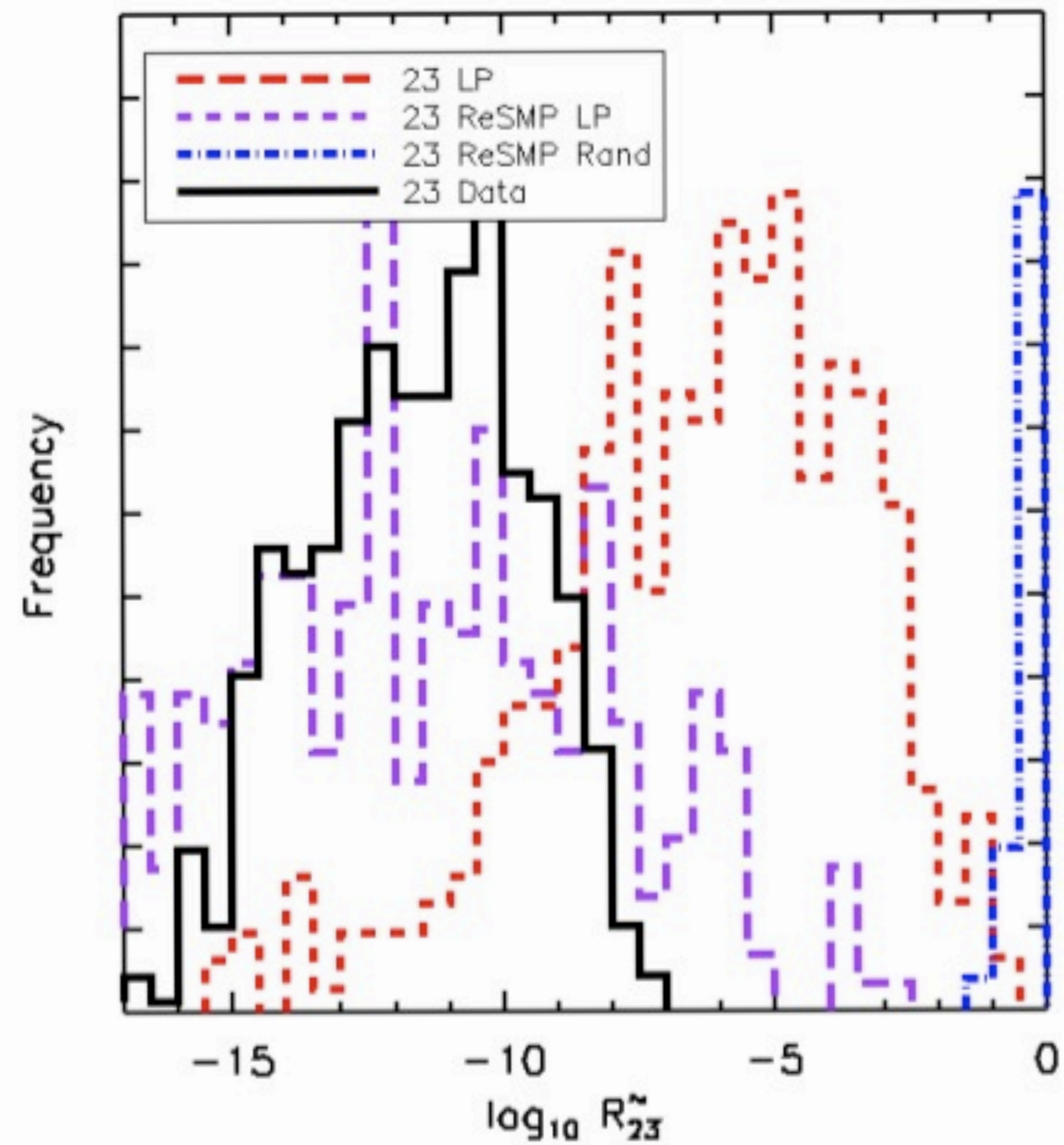
Using the >M,>z analysis, the observed clusters are in good agreement with LCDM.



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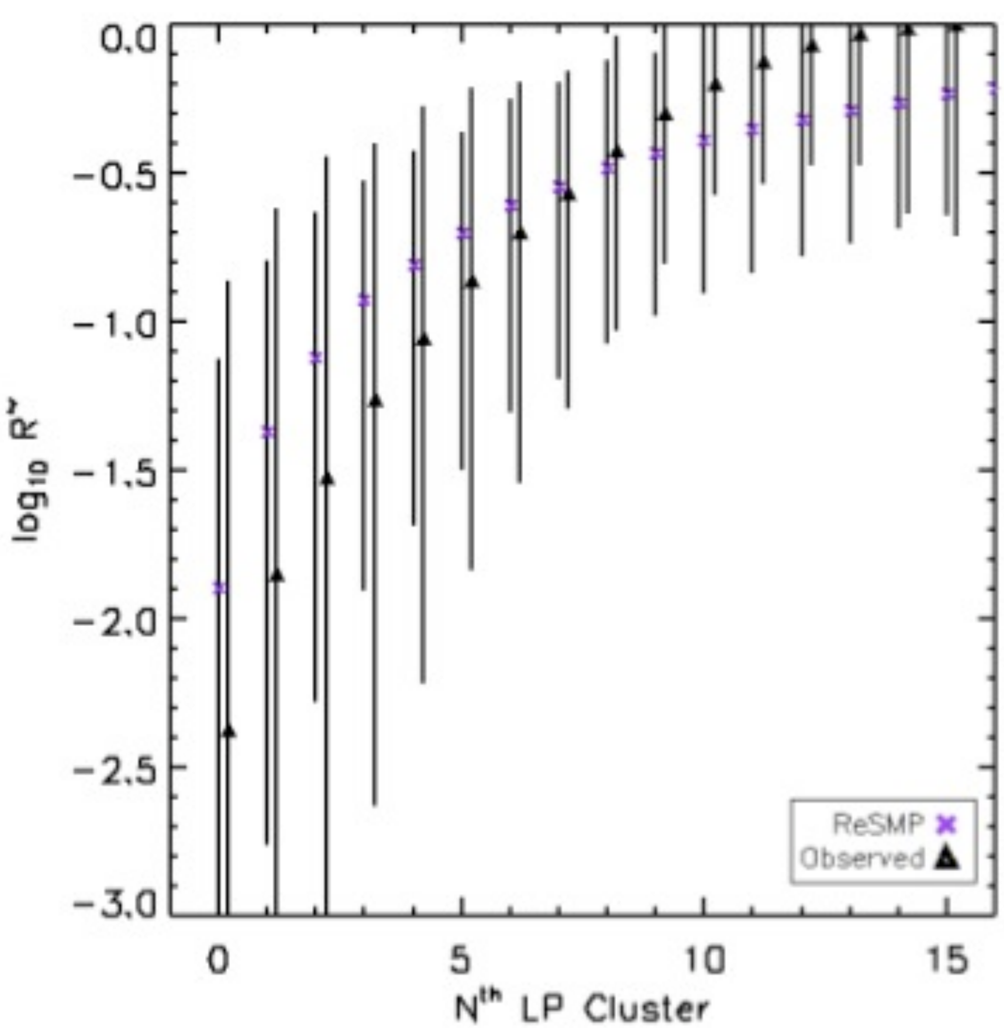

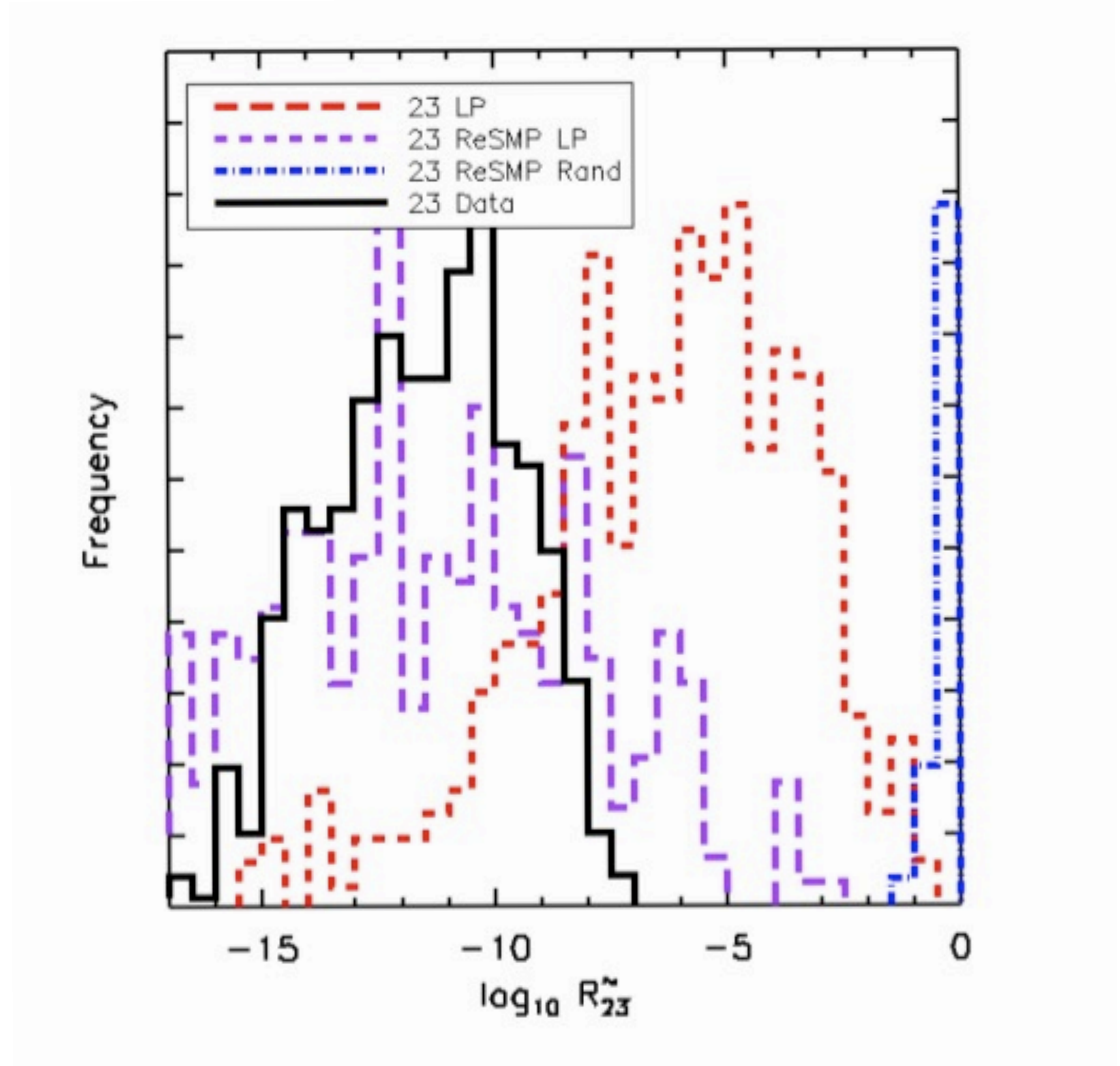

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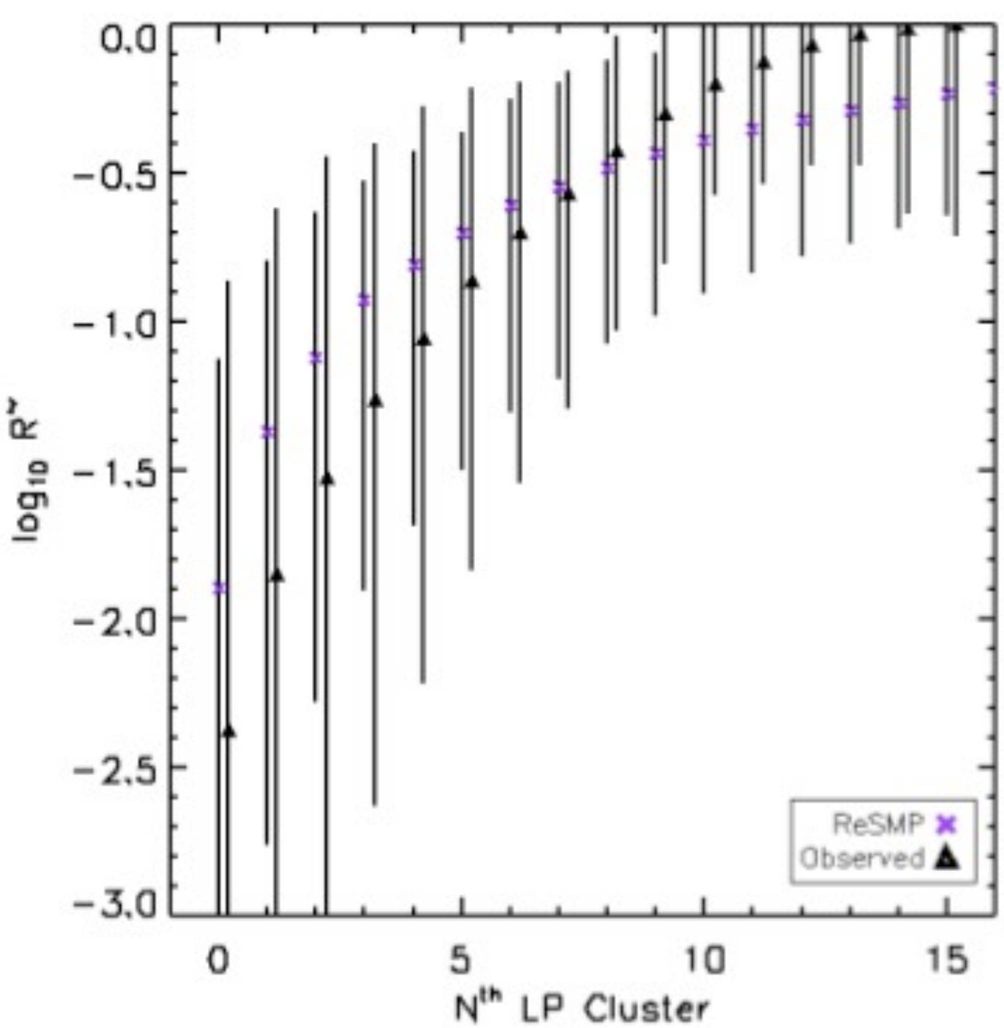
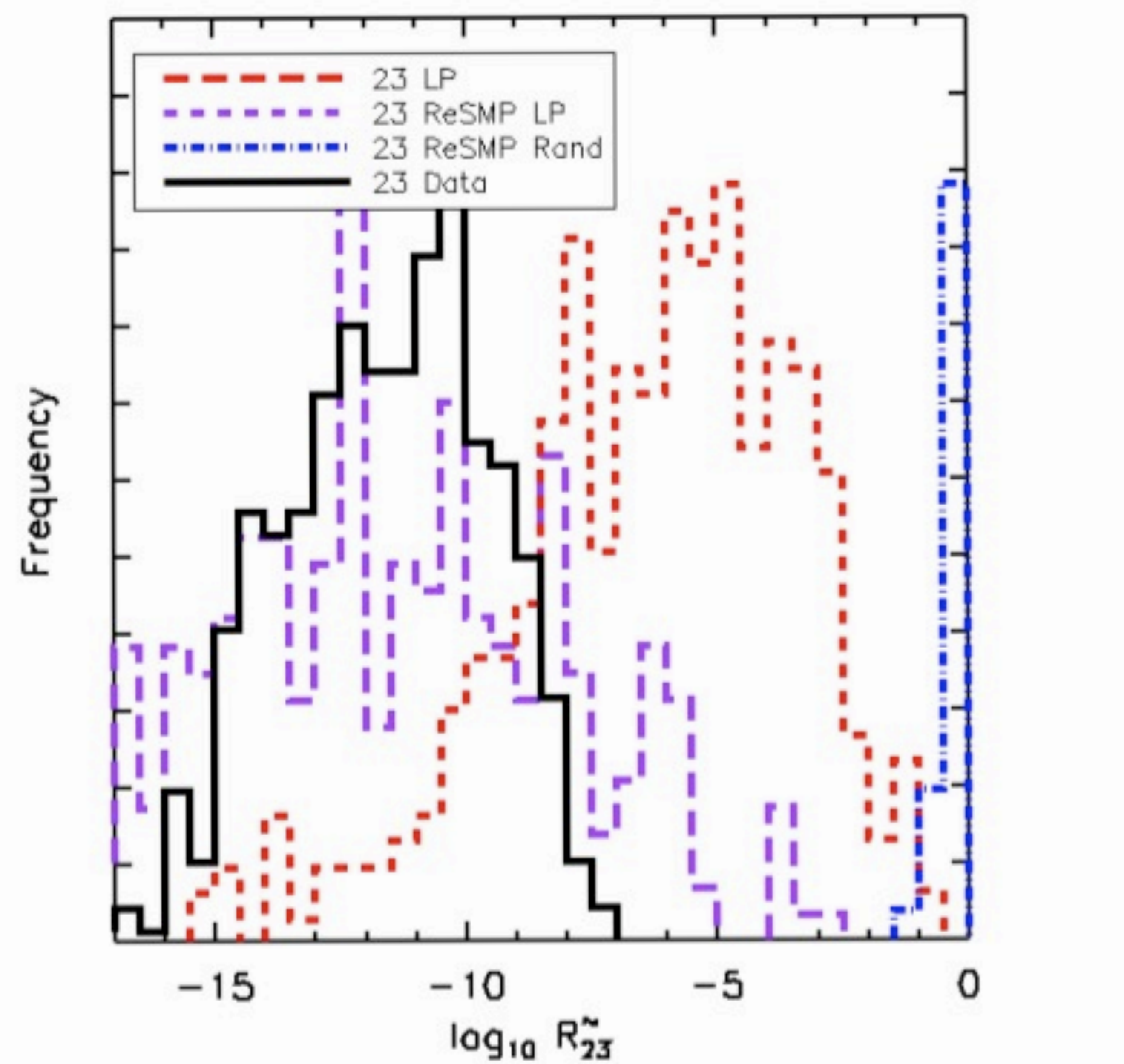
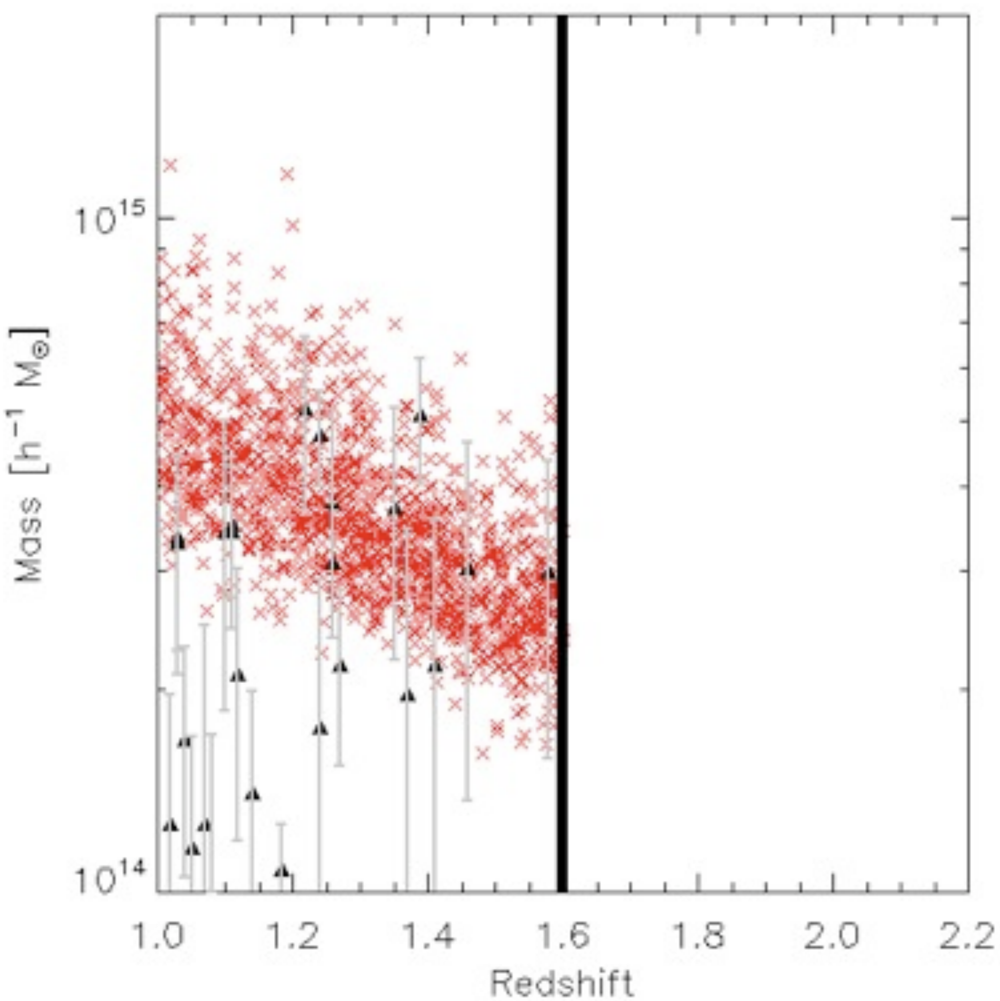




This analysis assumes the survey geometry of Jee et al. 1<z<2.2; footprint=100 sq. deg.

z<1.6 survey geometry

All clusters have z<1.6. Perhaps we were being unfair to compare the observed clusters (z<1.6) with simulated clusters between 1<z<2.2. We now modify the assumed survey geometry, by imposing a hard cut to the simulations.



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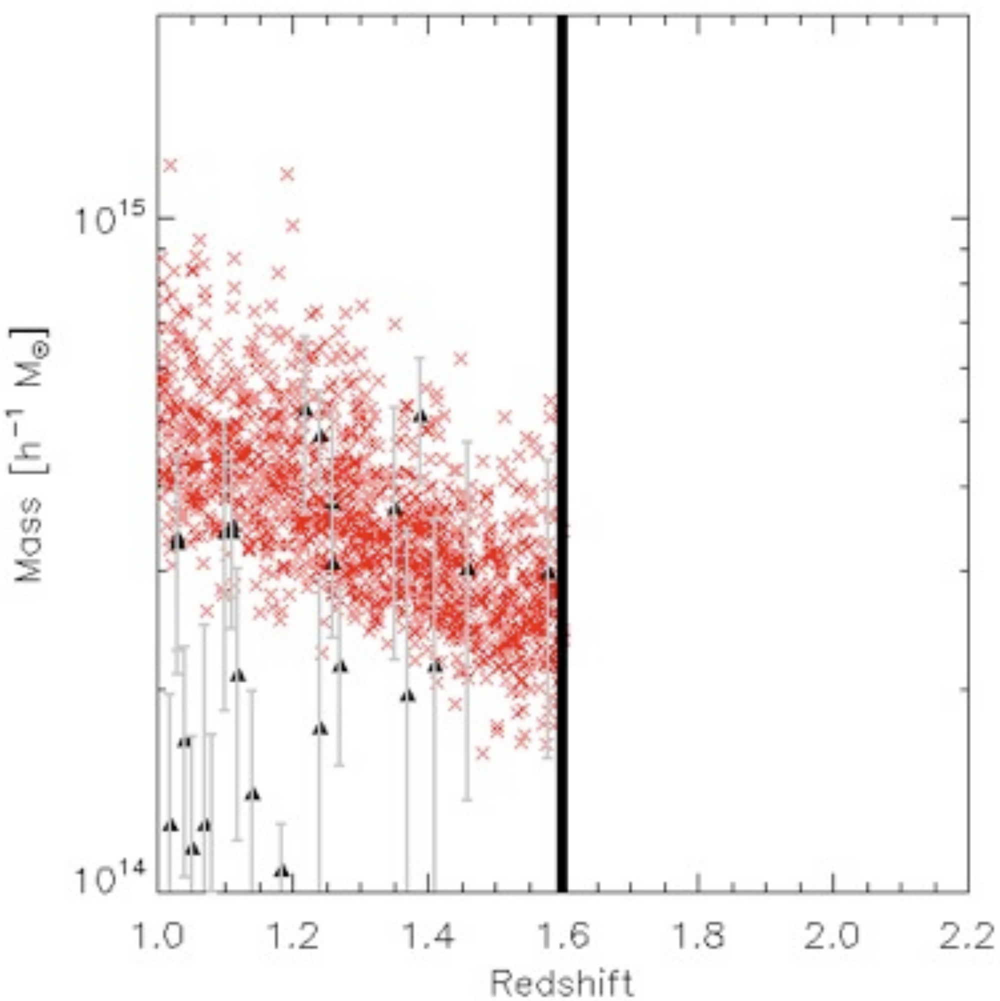

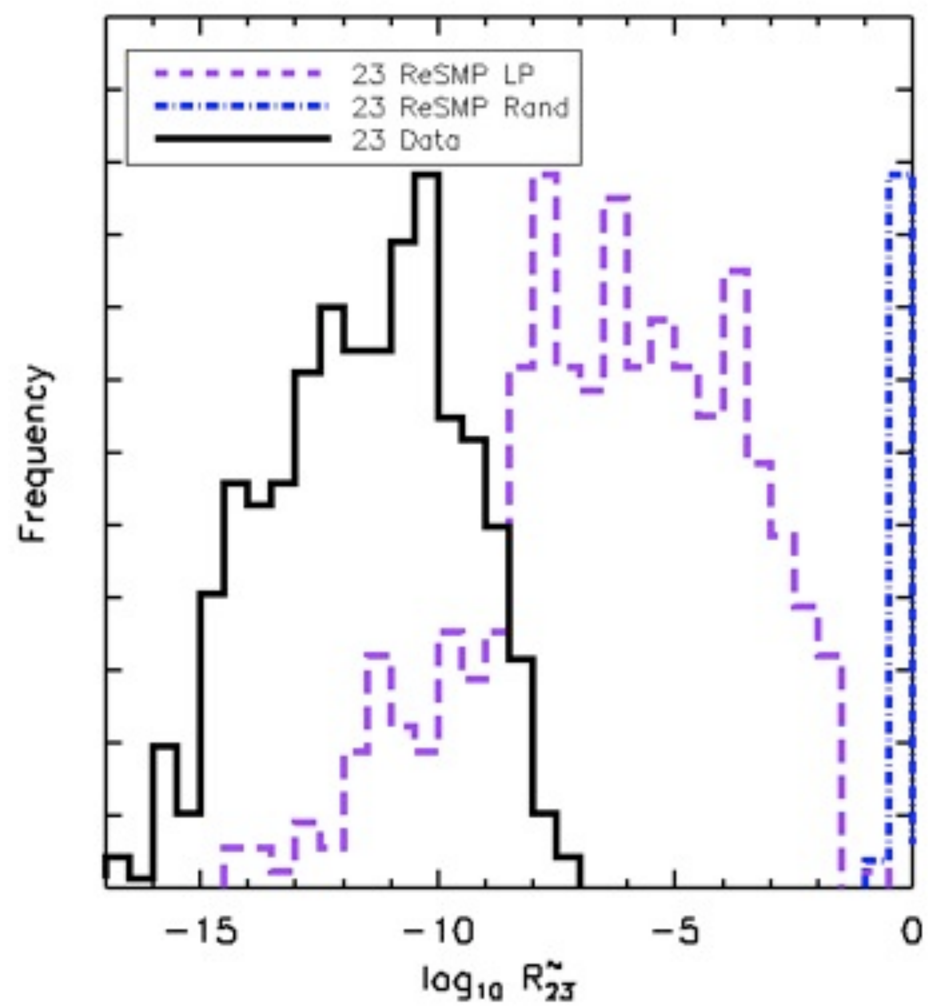

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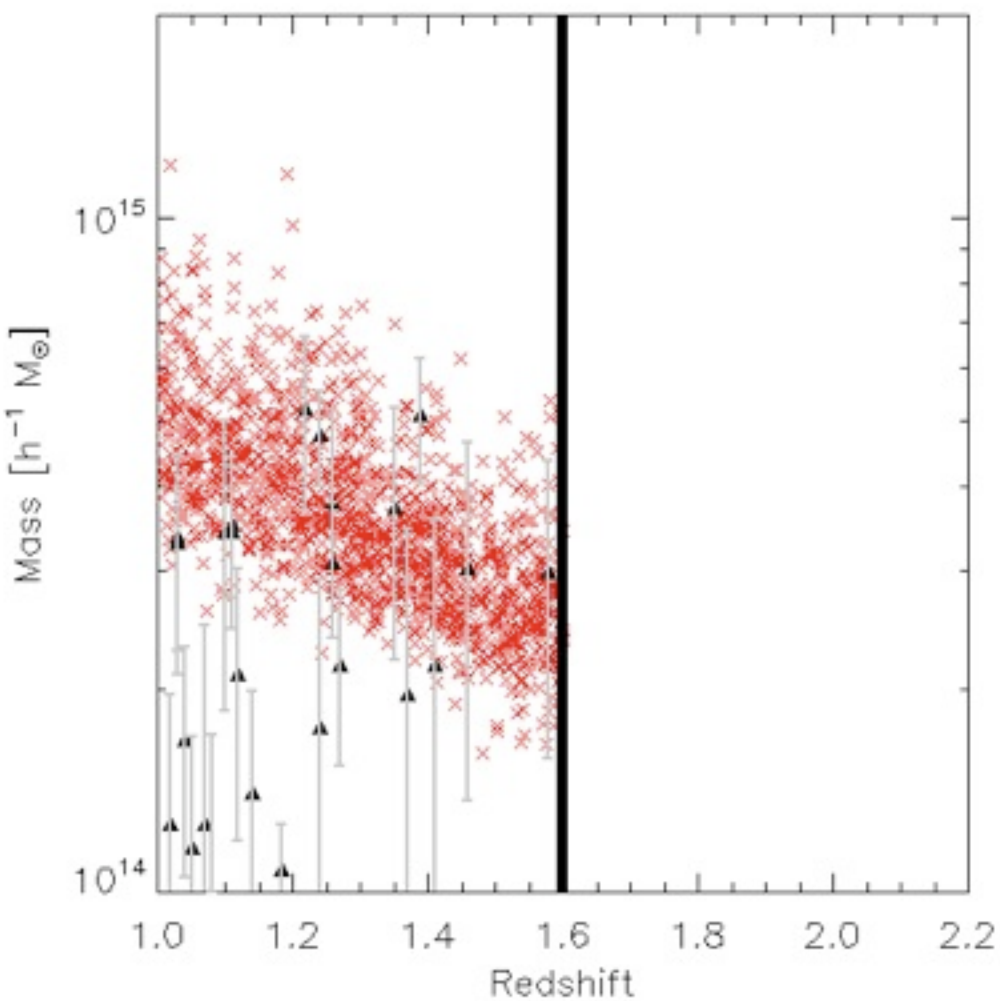

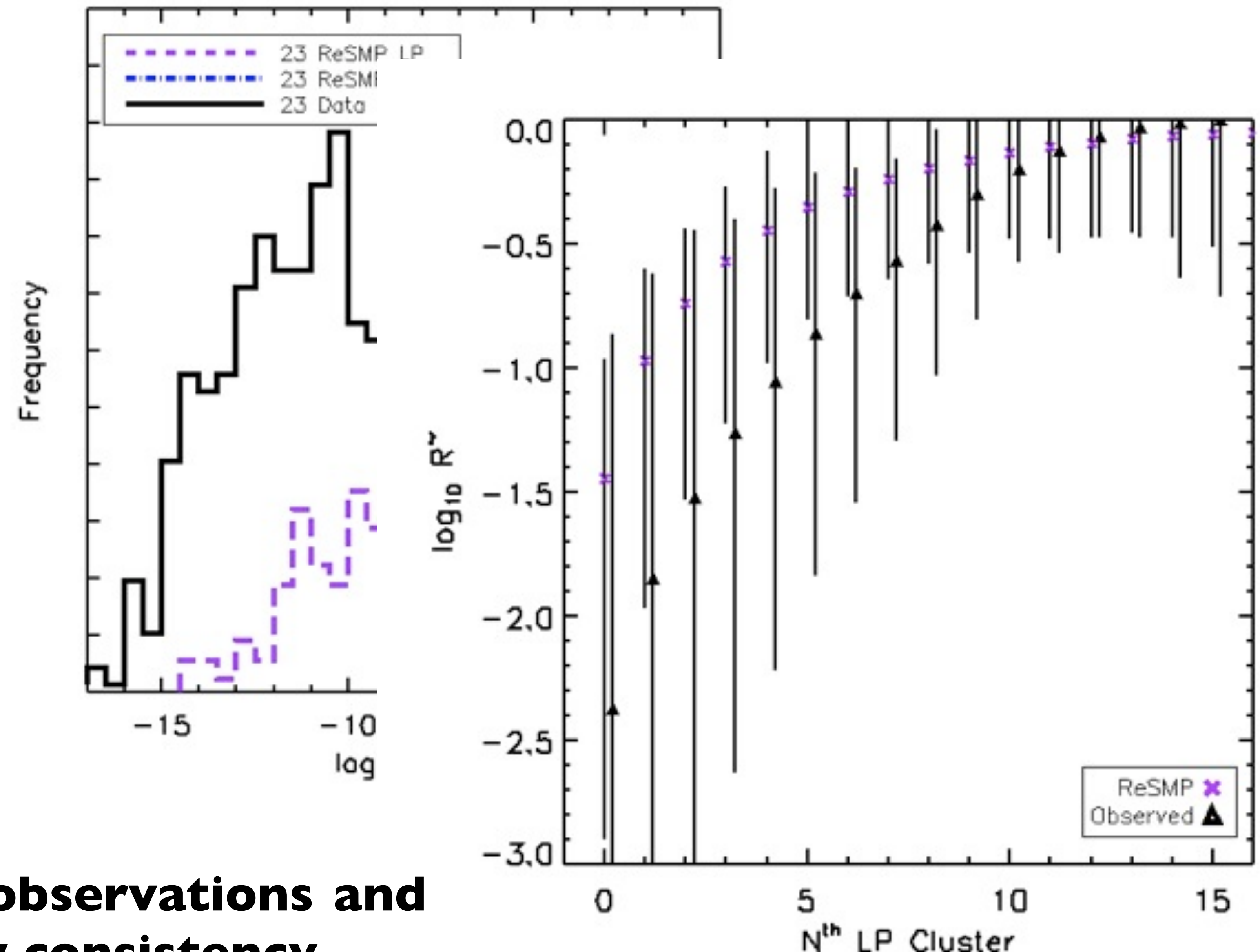

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Subsequent work

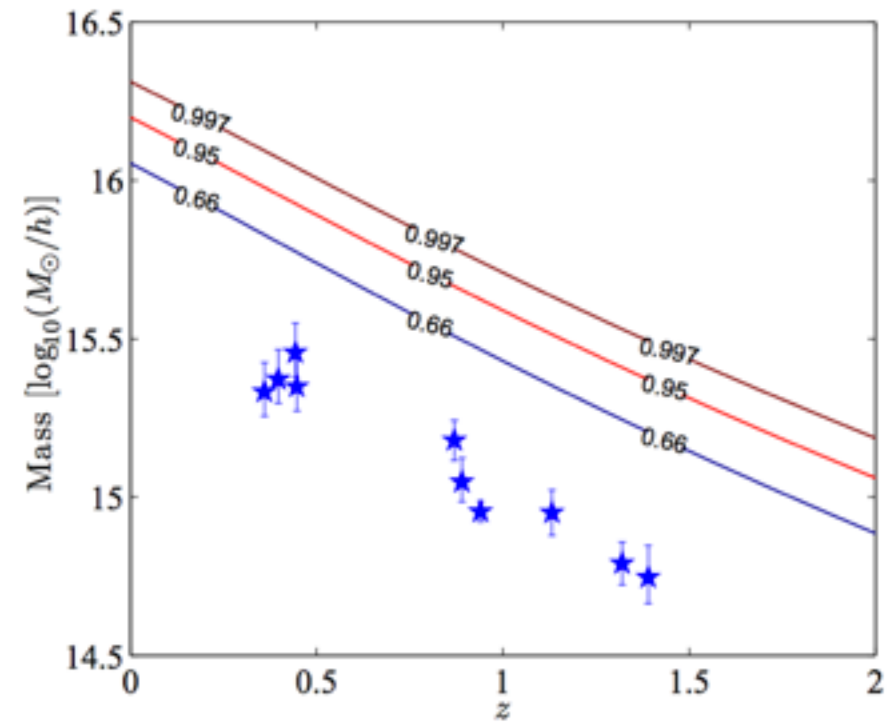


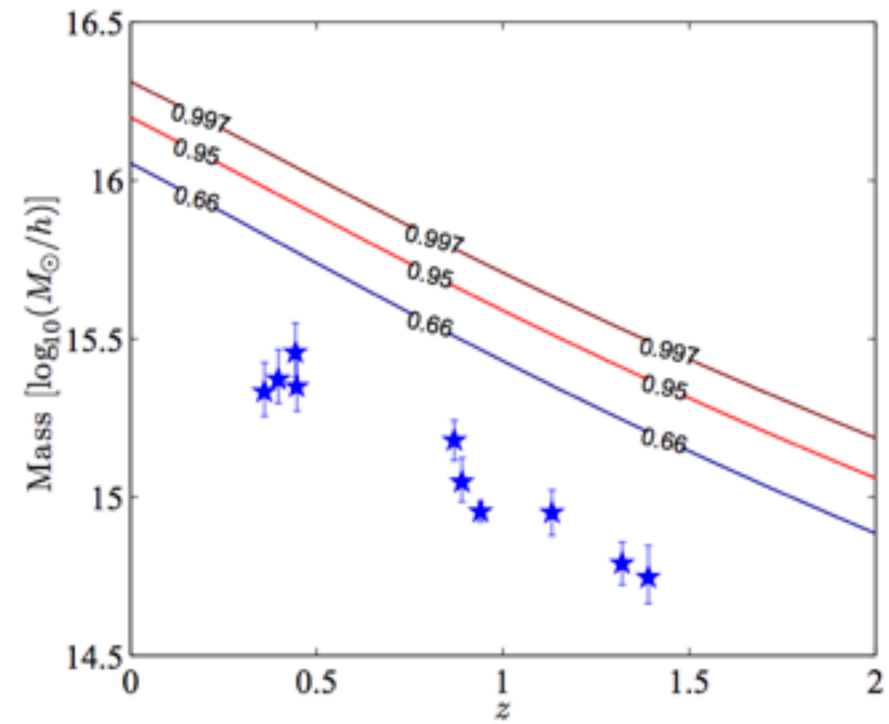
Figure 4. Rareness of currently observed clusters (using the $> mdV$ measure described in the text) corresponding to an idealised all-sky survey which is complete at masses above $m_{min} = 10^{14} M_\odot/h$ out to $z = 2$.

Harrison & Hotchkiss
arXiv: 1210.4369

Subsequent work

Harrison & Hotchkiss 2012 released code to compare the 'rareness' of clusters with different masses found at different redshfits, by transforming them to an "equivilant mass" at z=0 frame.

However, they also need to make assumptions about survey geometry.



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Main results

The calibrated R (>M,>z) statistic for the observed ensemble of clusters are consistent with R values for simulated clusters drawn from LCDM mass function, once the Eddington bias is considered.

The observed clusters provide no tension with LCDM with the survey geometries examined here.

However, we still may be being unfair to the clusters by assuming this survey geometry? More work needed.

Summary

- Surveys of clusters of galaxies are currently, and will be, powerful cosmological probes
- Individual “extreme” clusters can be used to rule out cosmological models
- Showed why the common measure of rareness (>M,>z) is meaningless unless calibrated to simulations.
- Addressed the calibration, and suggested fixes for the common exclusion curves.

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- Quantified the tension (or lack of) with LCDM, using the $>M$,$>z$ statistic.

- More high-redshift, massive clusters are being found ~weekly. Apex/Planck/XCS, and will likely be found with future surveys (eROSITA).

- High z selection functions can be difficult to quantify. In these cases we have begun to build a statistical framework to understand what individual or ensembles of clusters tell us about cosmological models.

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

Exclusion curves (uncalibrated)

Furthermore, we can define lines of constant R (>M,>z) in the mass-redshift plane, and use them to create exclusion curves. The exclusion curves can only be used for individual 'rare' clusters, but can rule out a cosmological model (Mortonson et al 2010).

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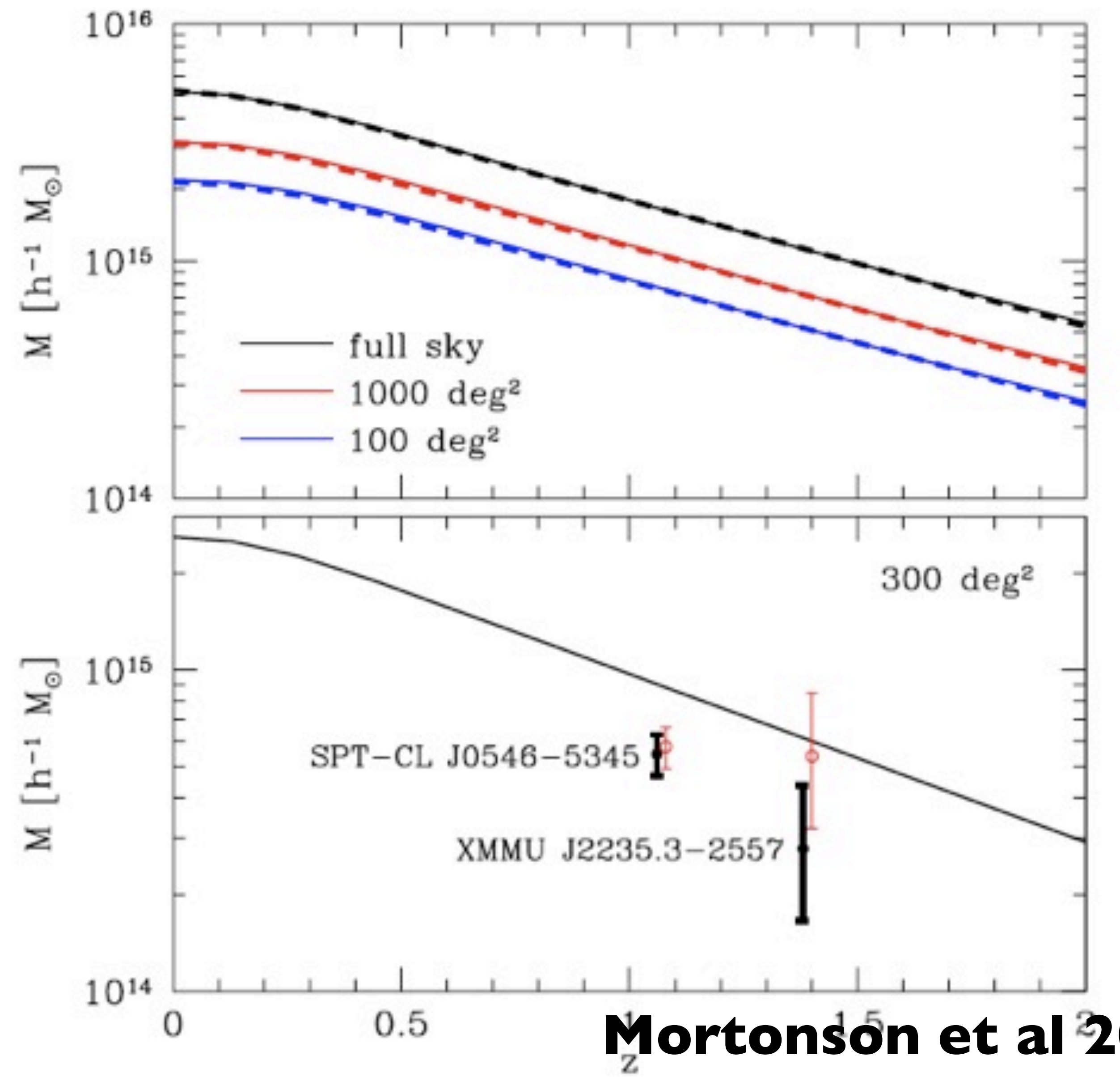
Given the (w)LCDM model with WMAP7 cosmological priors, we do not expect any cluster to sit above the curve at 95% or some other specified confidence.

These lines were created by tracing lines of constant R (existence probability >M,>z).



Mortonson et al 2010

More >M,>z analysis (uncalibrated)

TABLE 3
DISCOVERY PROBABILITY OF GALAXY CLUSTERS

Cluster name	Within Parent Survey
XMMXCS J2215-1738	0.96
XMMU J2205-0159	1
XMMU J1229+0151	0.61
WARPS J1415+3612	0.65
ISCS J1432+3332	0.14
ISCS J1429+3437	0.15
ISCS J1434+3427	1
ISCS J1432+3436	0.11
ISCS J1434+3519	1
ISCS J1438+3414	0.92
RCS 0220-0333	0.74
RCS 0221-0321	1
RCS 0337-2844	0.84
RCS 0439-2904	0.95
RCS 2156-0448	1
RCS 1511+0903	1
RCS 2345-3632	1
RCS 2319+0038	0.83
XLSS J0223-0436	0.01
RDCS J0849+4452	0.03
RDCS J0910+5422	0.06
RDCS J1252-2927	0.002
XMMU J2235-2557	0.013
CL J1226+3332	0.006
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Jee et al 2011

Improved (HST WL) cluster mass estimates & less conservative (more realistic) survey footprints.

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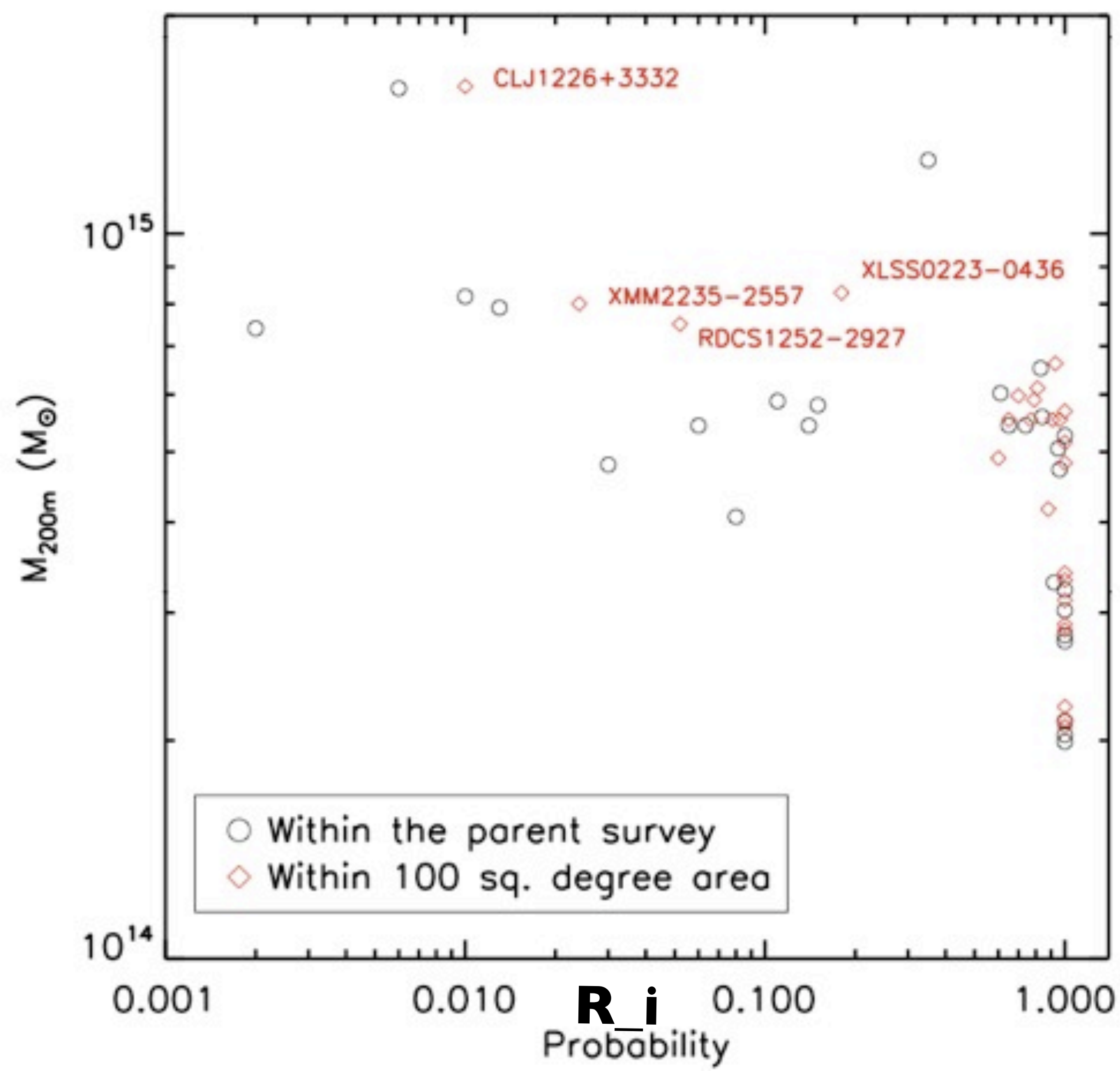

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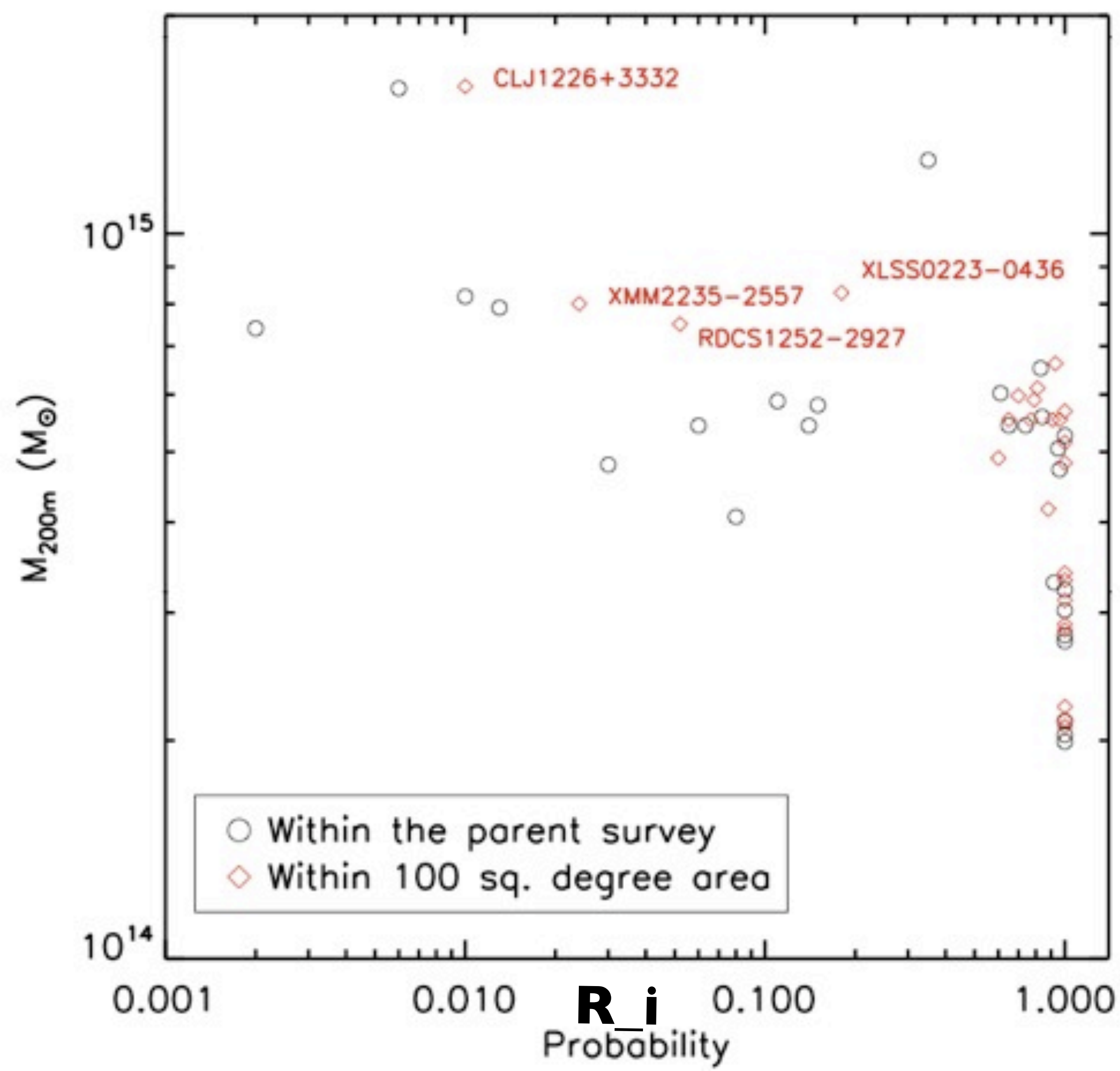

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Are these clusters really in tension with LCDM, or have we been goofing up? What's going on?