High-redshift, massive, galaxy clusters in LCDM.

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Shaun Hotchkiss University of Helsinki.

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

LMU Munich 21/2/2012

Overview

- Galaxy Cluster surveys as cosmological probes
- The XMM Cluster Survey
- Individual Galaxy Clusters as extreme objects
- Early analysis >M,>z & misunderstandings
- A critical look at the >M,>z question
- Updated analysis and results
- Exclusion curves
- 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.

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

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

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

Press & Schecter 1974

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

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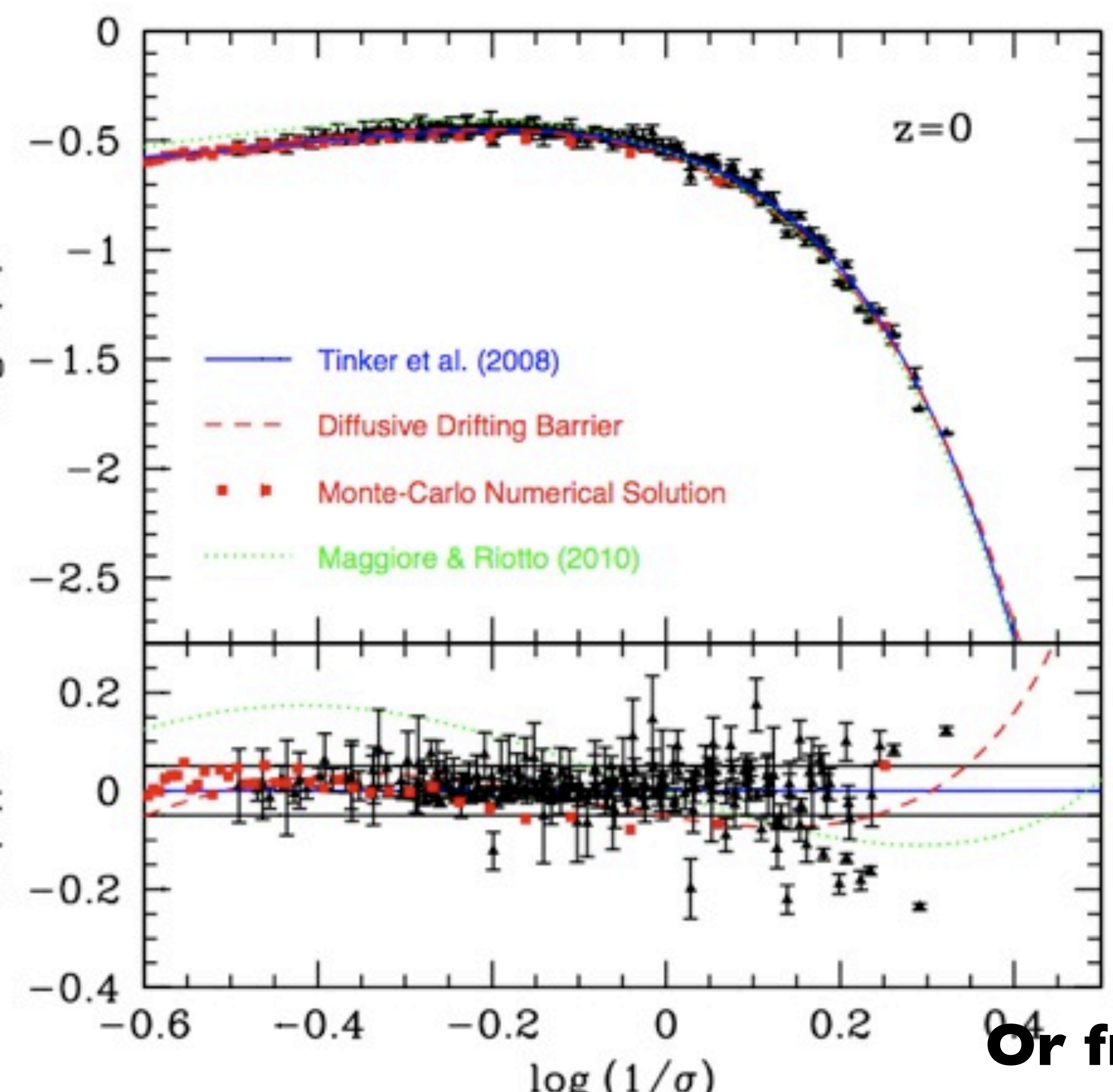

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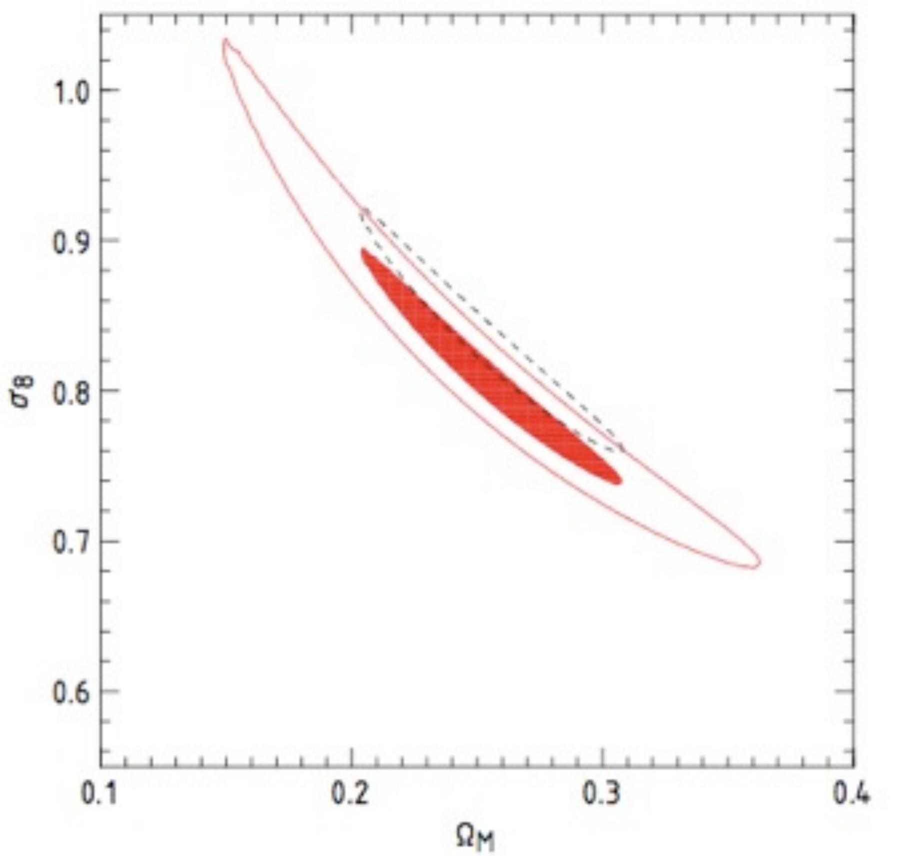
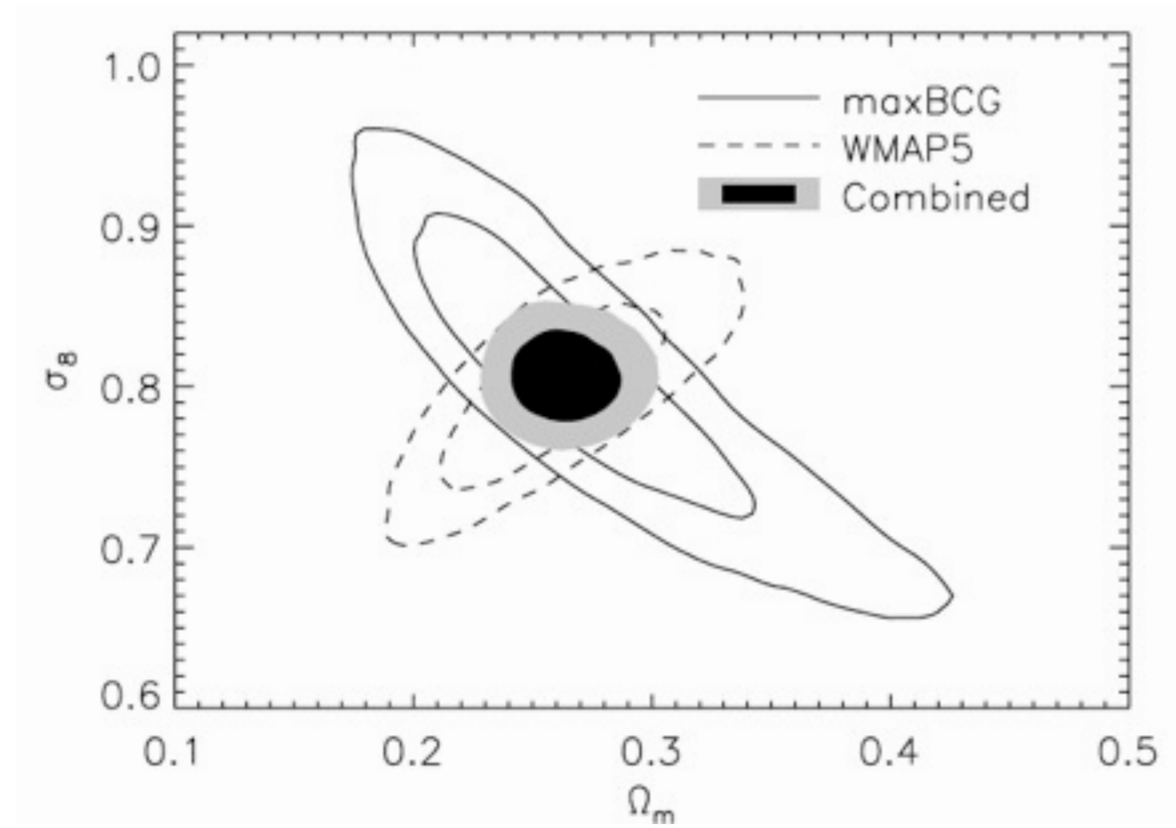
Or from first principles + fitting one parameter: Corasaniti & Ixandra Achitouv (PRD submitted) arXiv: 1107.1251 (& 1012.3468)

Cosmological constraints with many clusters



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



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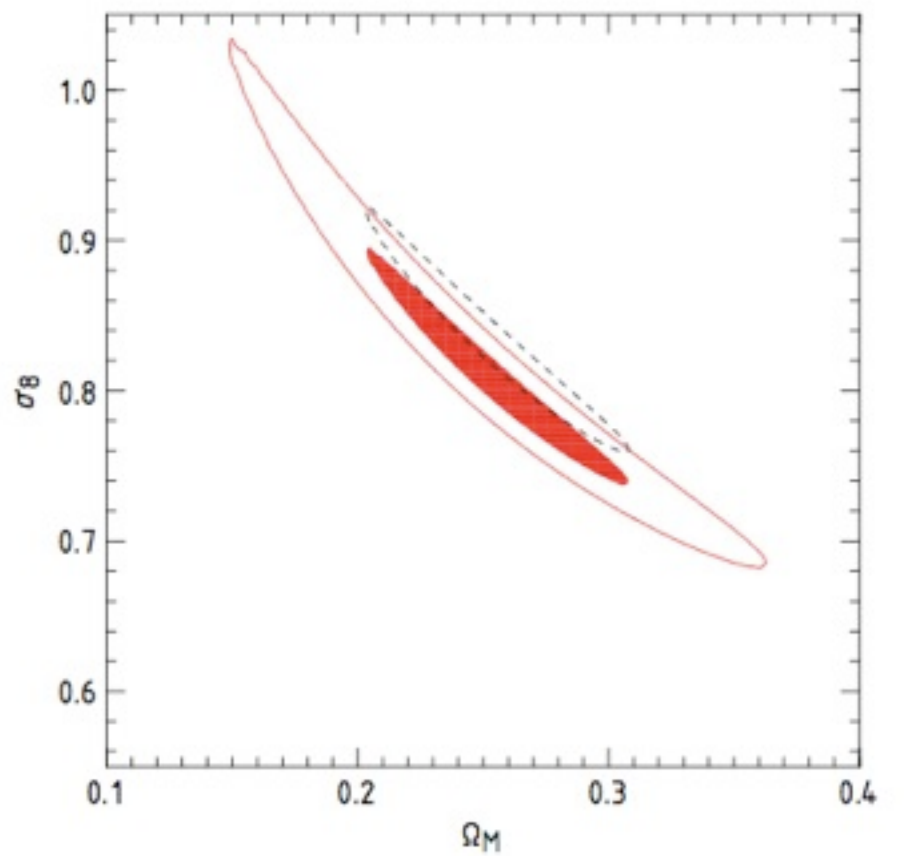

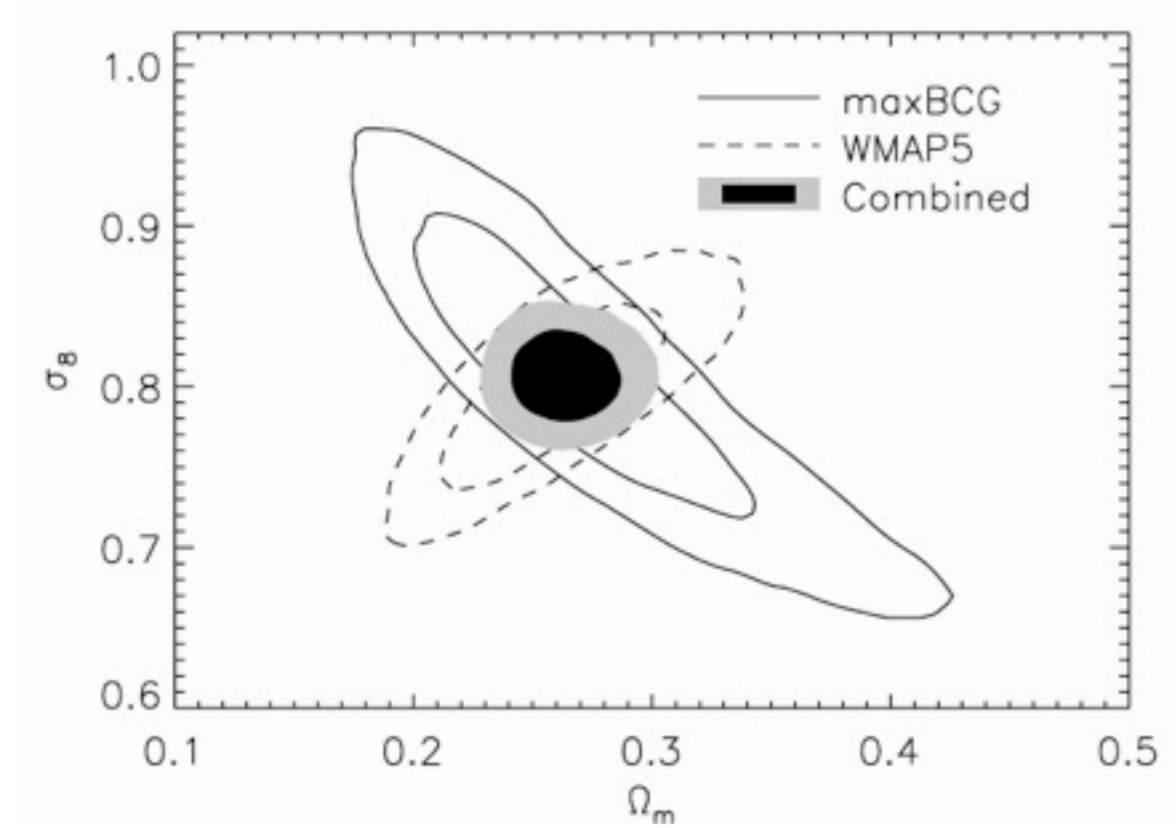

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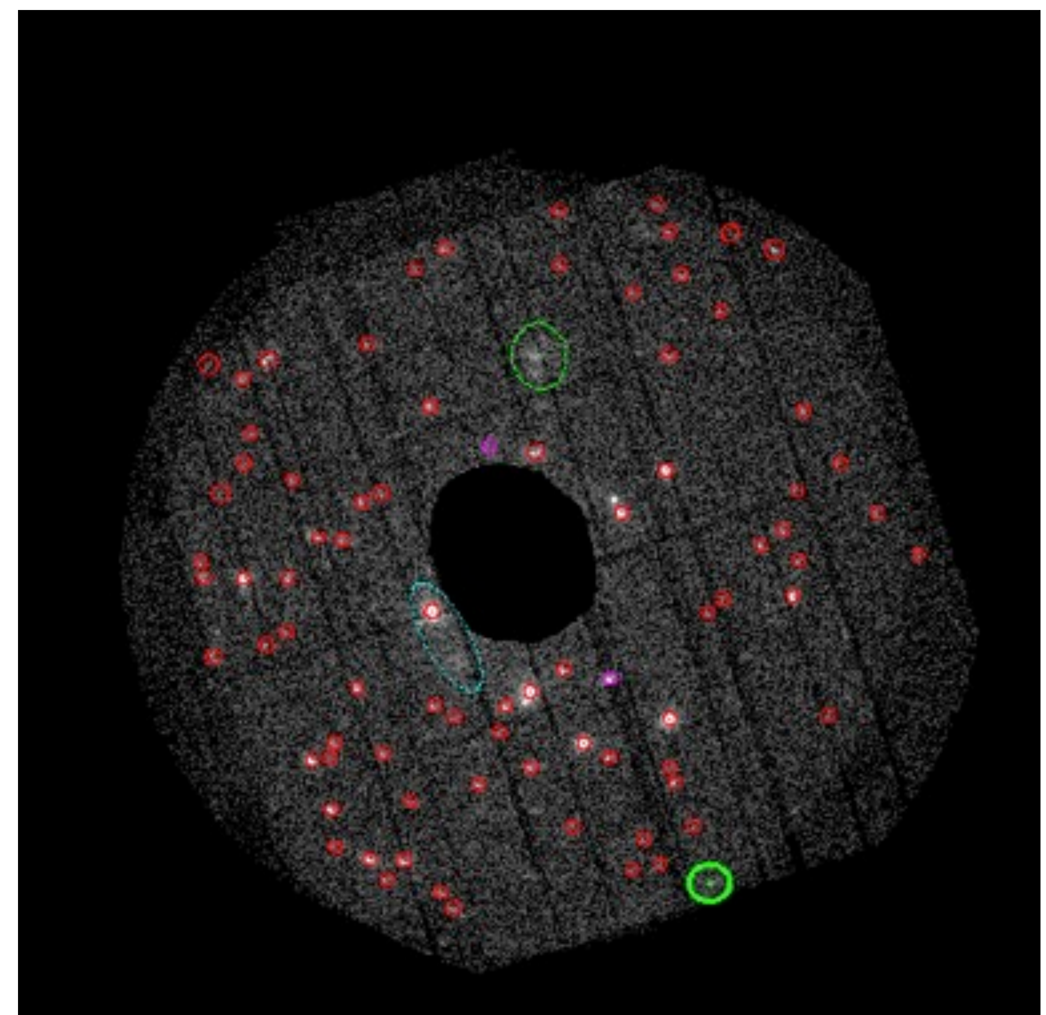
<u>Future cluster catalogues</u>
PanStarrs, DES ~100,000 optical
eROSITA ~10,000 X-ray

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

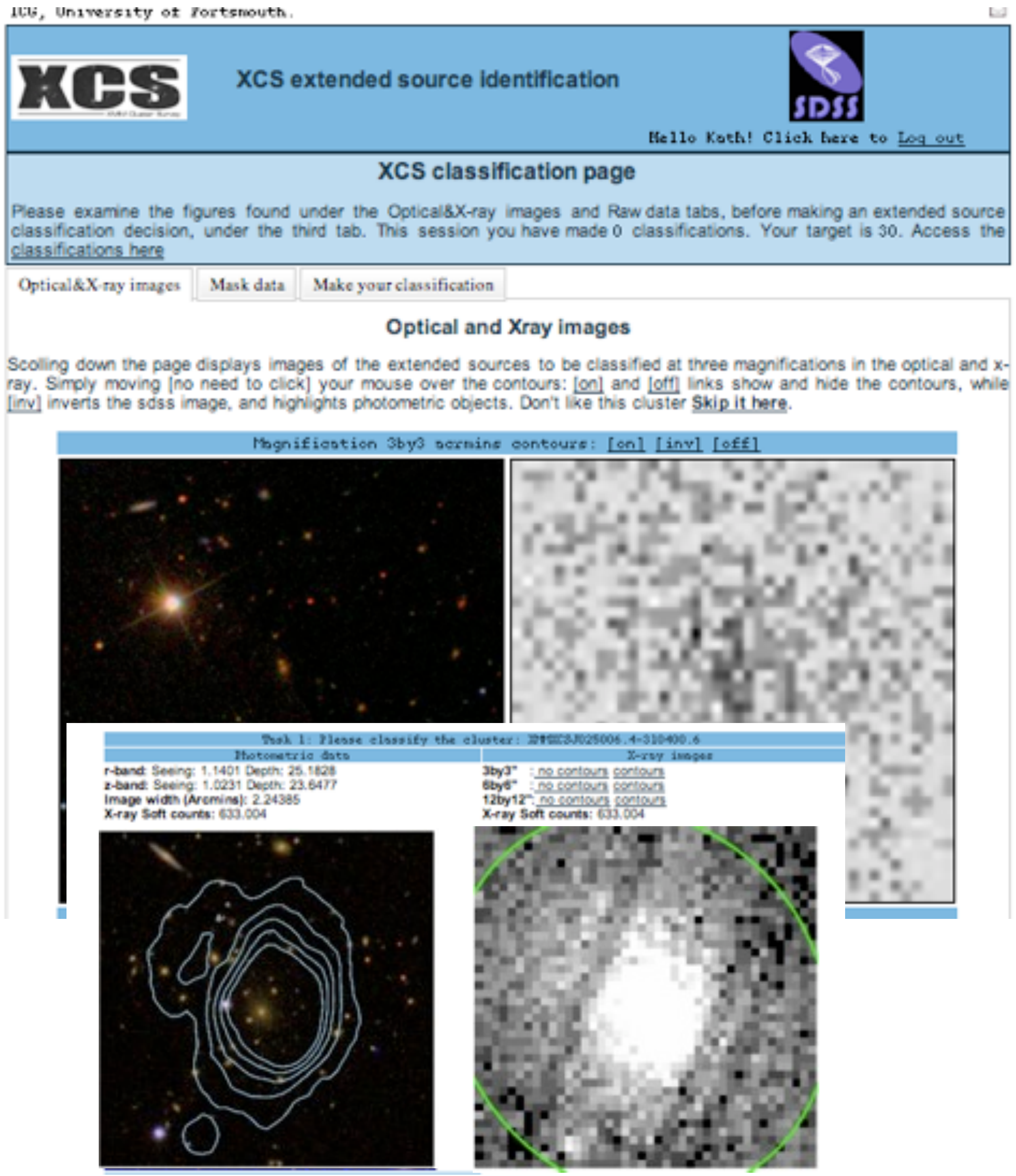
X-ray photon map + automated pipeline to detect point sources (red) extended sources (green).



The extended X-ray emission is produced by a cluster's ICM. However, we need optical identification and redshifts before the fluxes can be converted to temperatures/masses, and used for cosmology.

Algorithms paper, Lloyd-Davies et al. 2010

XCS: Cluster zoo



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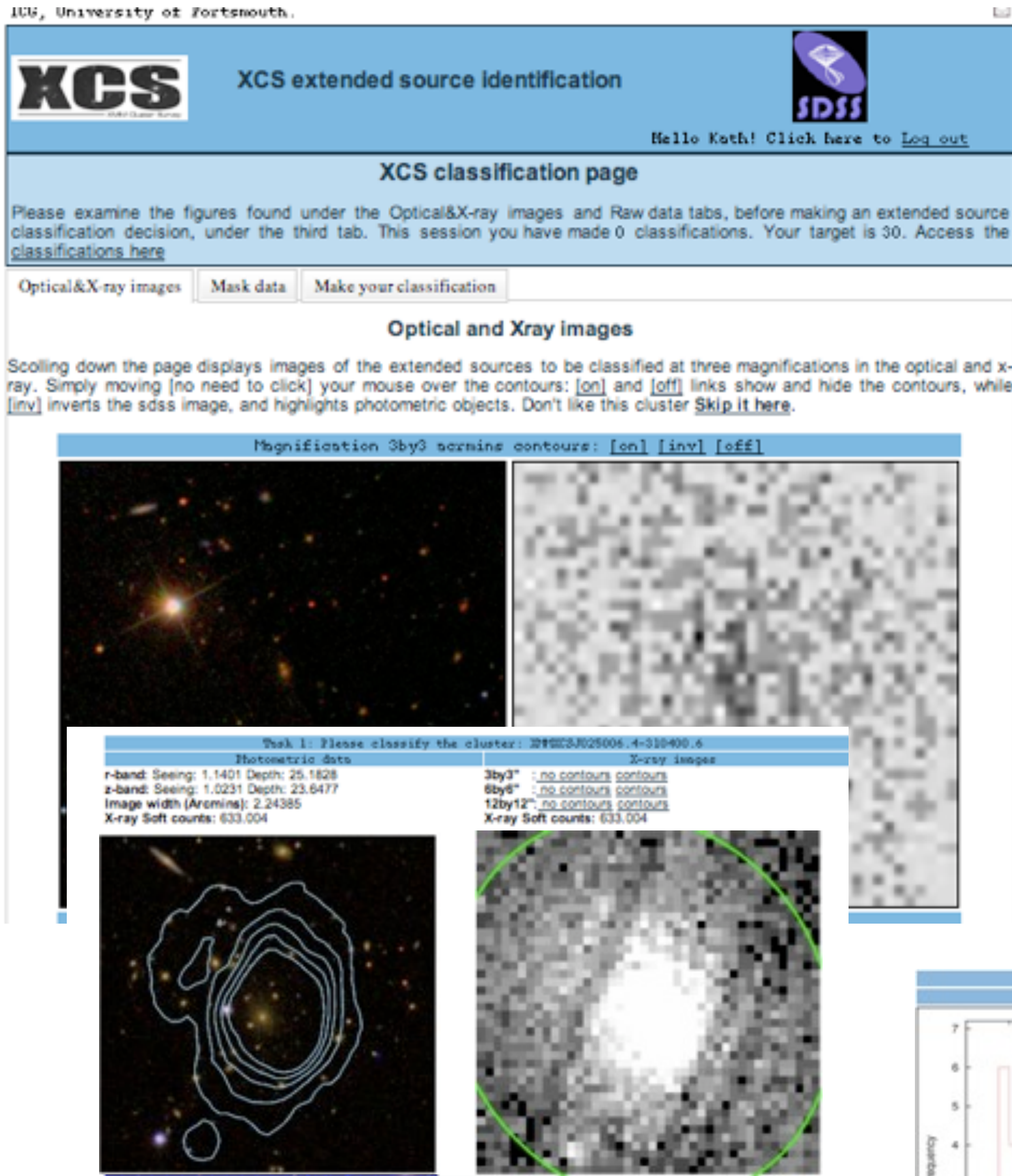

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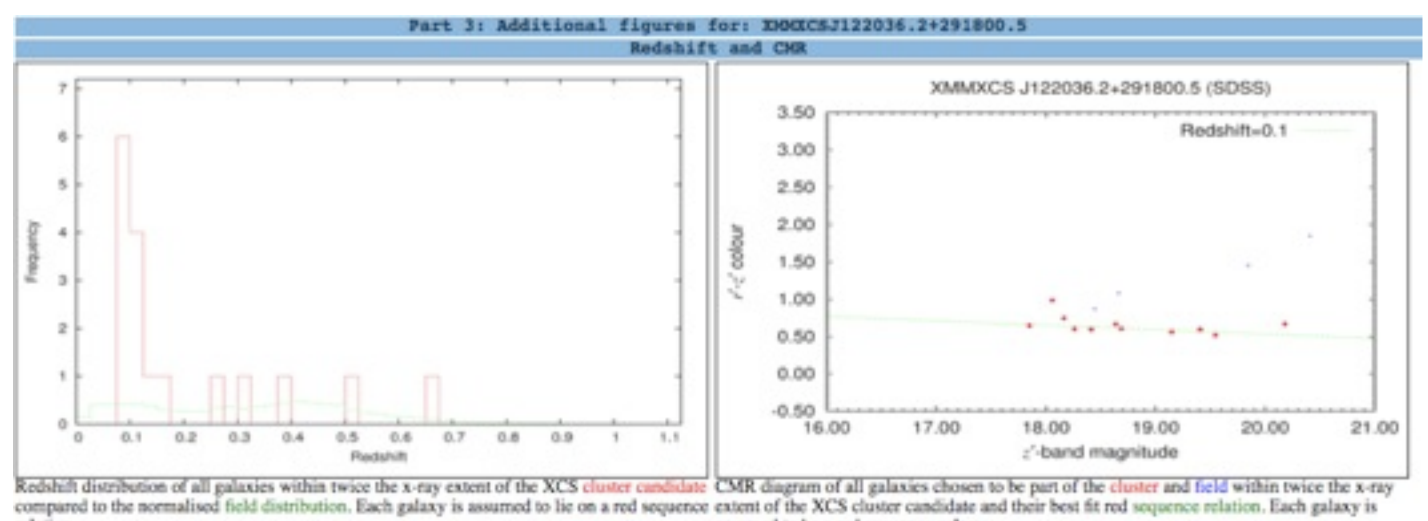
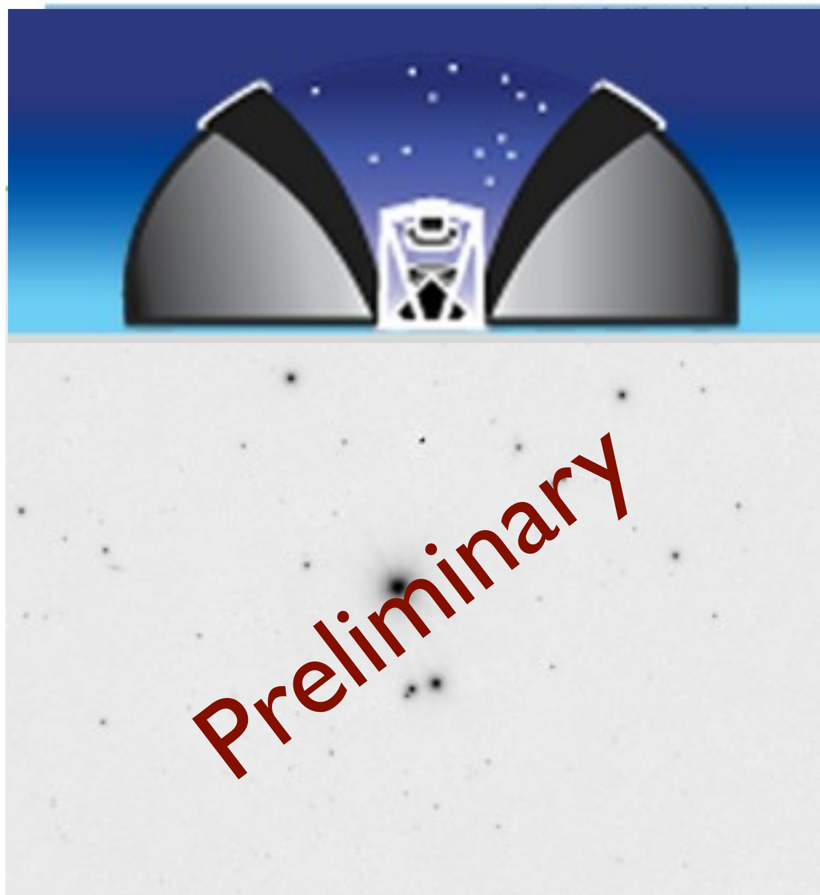
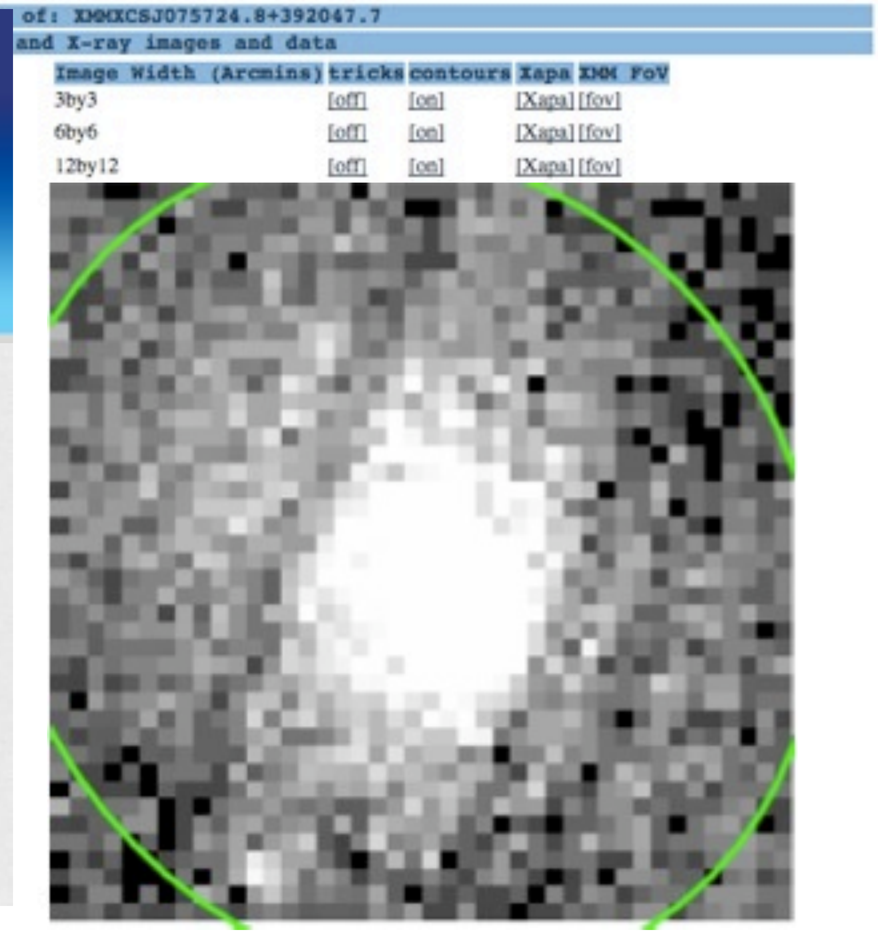


Redshift histograms Color-Magnitude diagrams

XCS: Future Cluster zoos

Pan-STARRS
PS1 Science Consortium



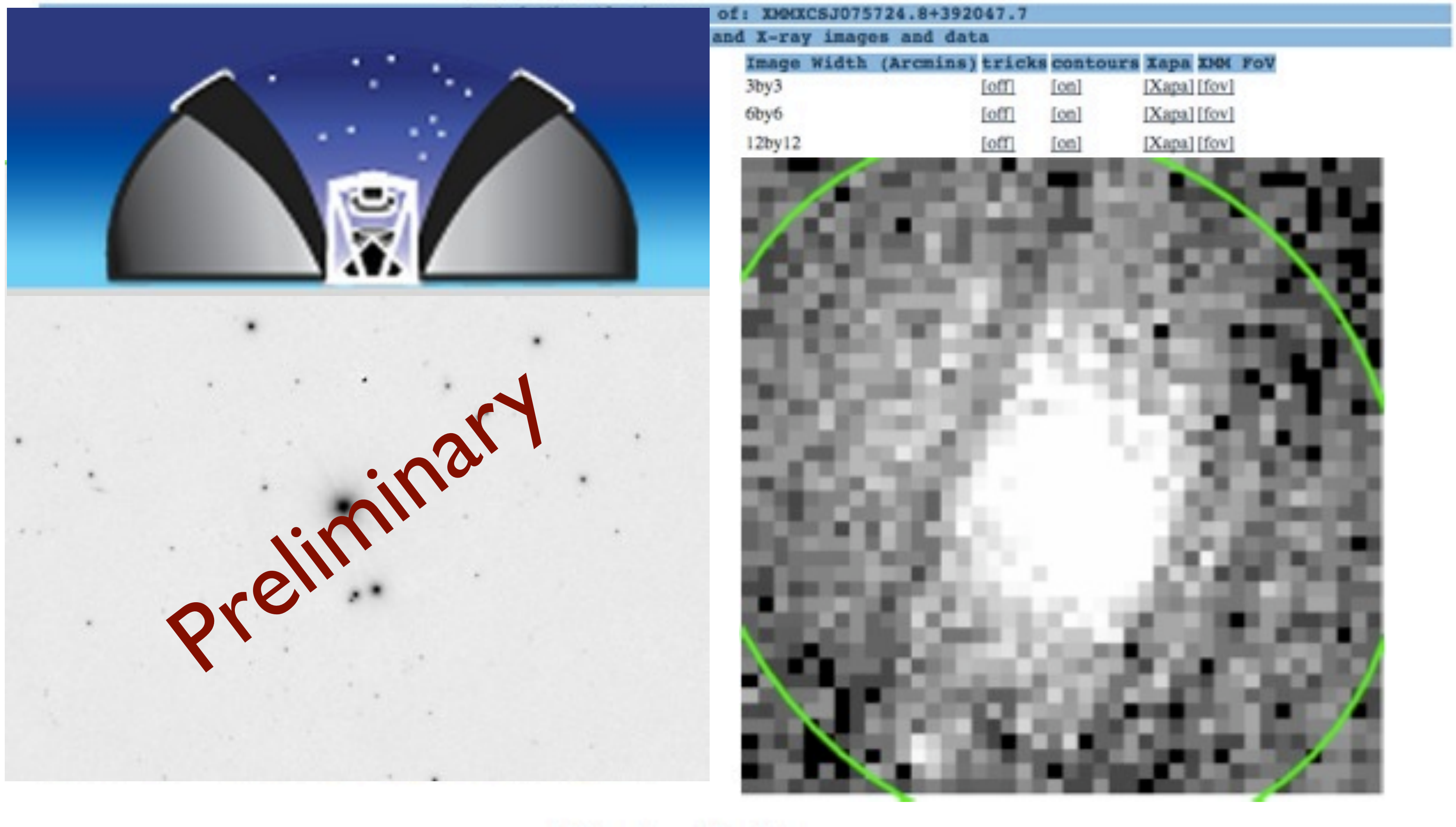


Cluster Zoo with XCS & PanStarrs Full sky data (Johannes, Tommaso, Jochen + others?)

High redshift optical + photoz + X-ray masses

HOD, mass-optical scaling relations for medium/high redshift X-ray selected clusters, with ~temperature/ mass estimates

XCS: Future Cluster zoos



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HETDEX Hobby-Eberly Telescope Dark Energy Experiment

THE DARK ENERGY SURVEY

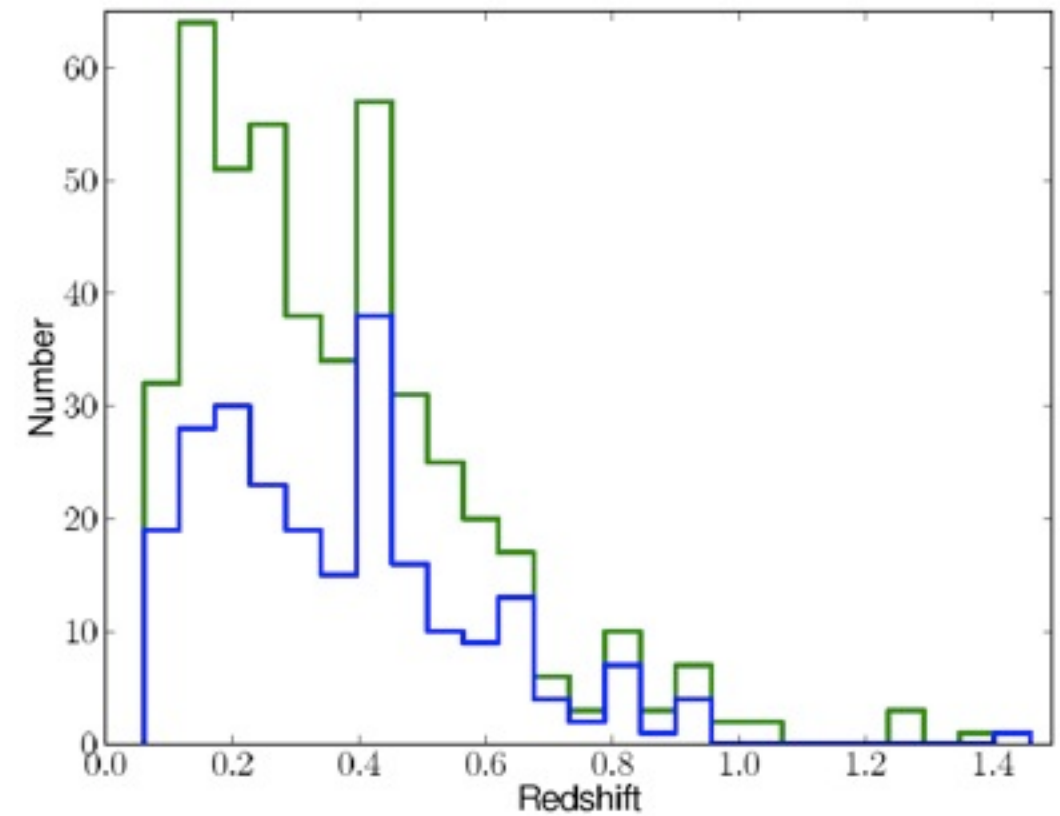
planck

eROSITA

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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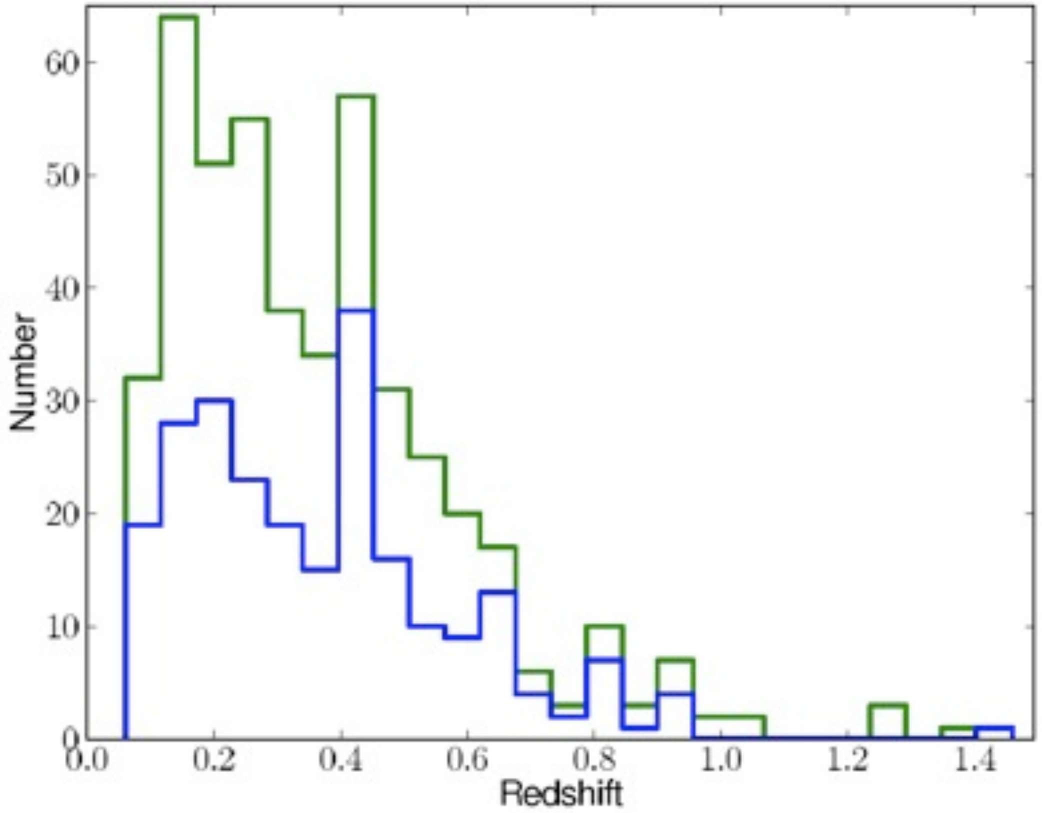
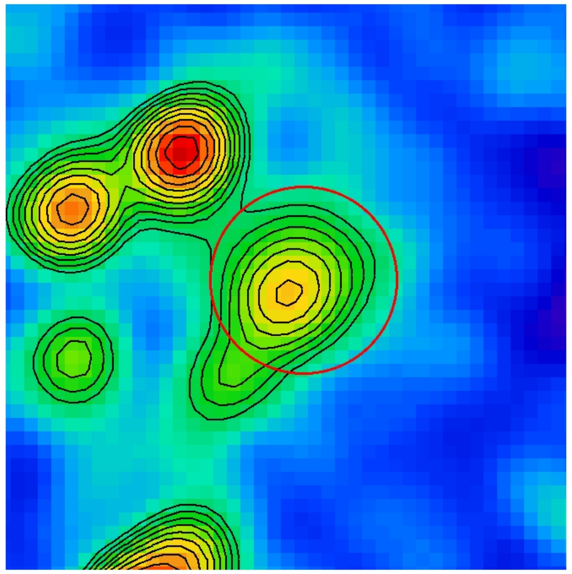
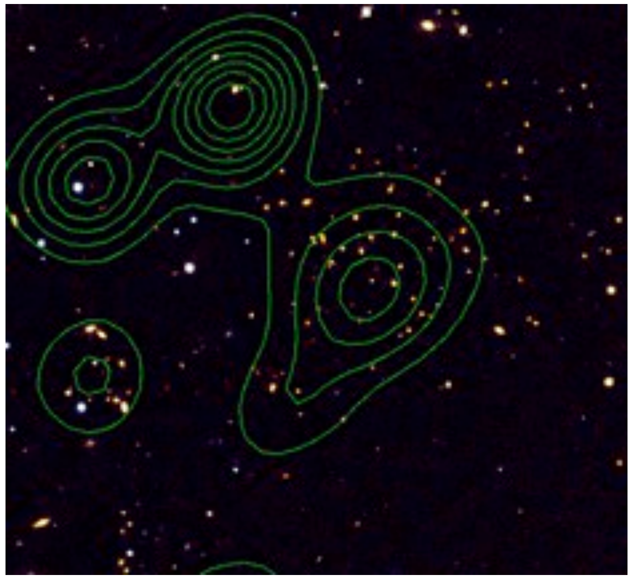


<u>XMMXCS J2215</u>
Was the highest redshift X-ray selected cluster, z=1.46 (Stanford et al. 2006, Hilton et al. 2007, 2008)





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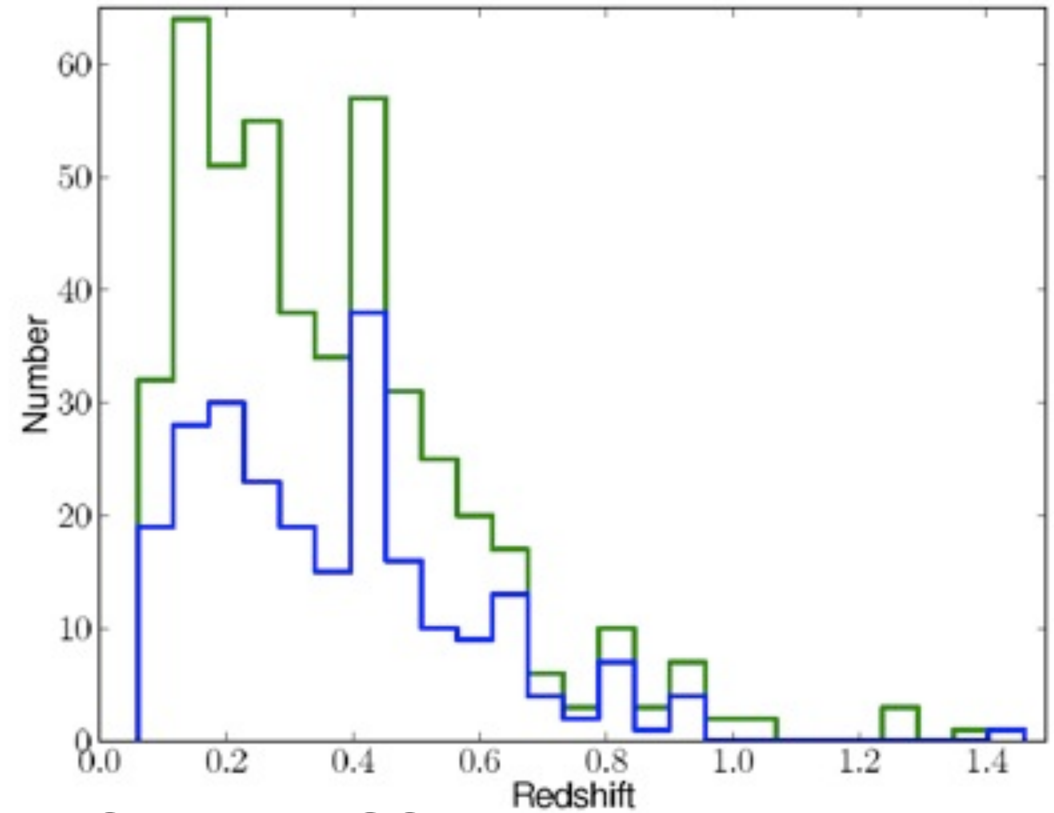

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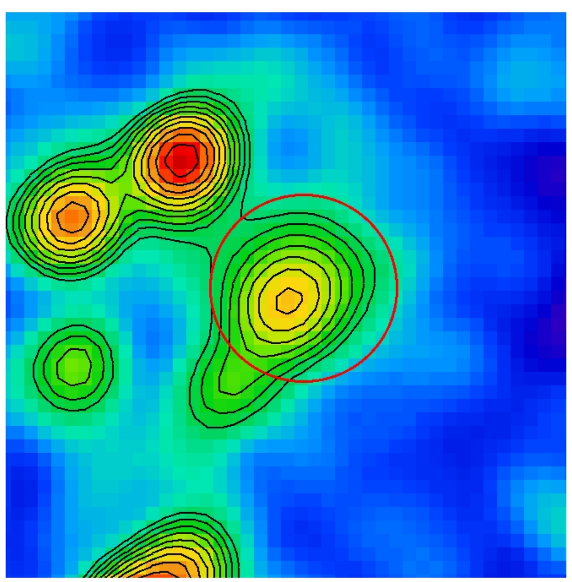
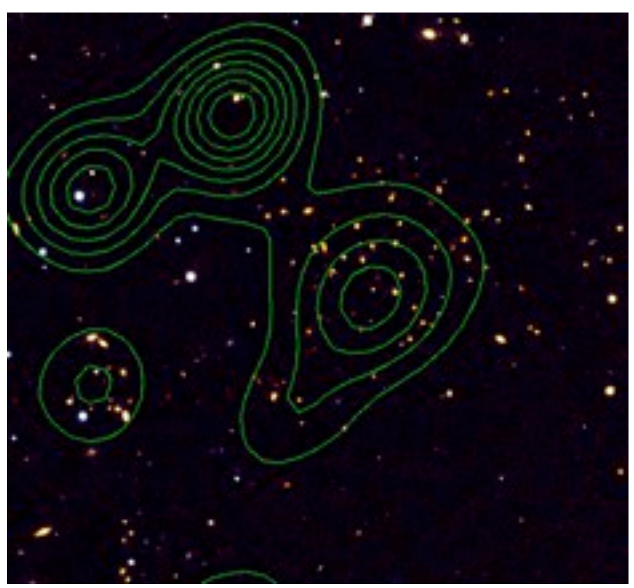




Now z=2.07, Gobat et al. 2011

<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=1.4
Hilton et al. 2009
Forecasting cosmological and cluster scaling-relation parameter constraints:
Sahlen et al. 2008

Individual clusters as extreme objects

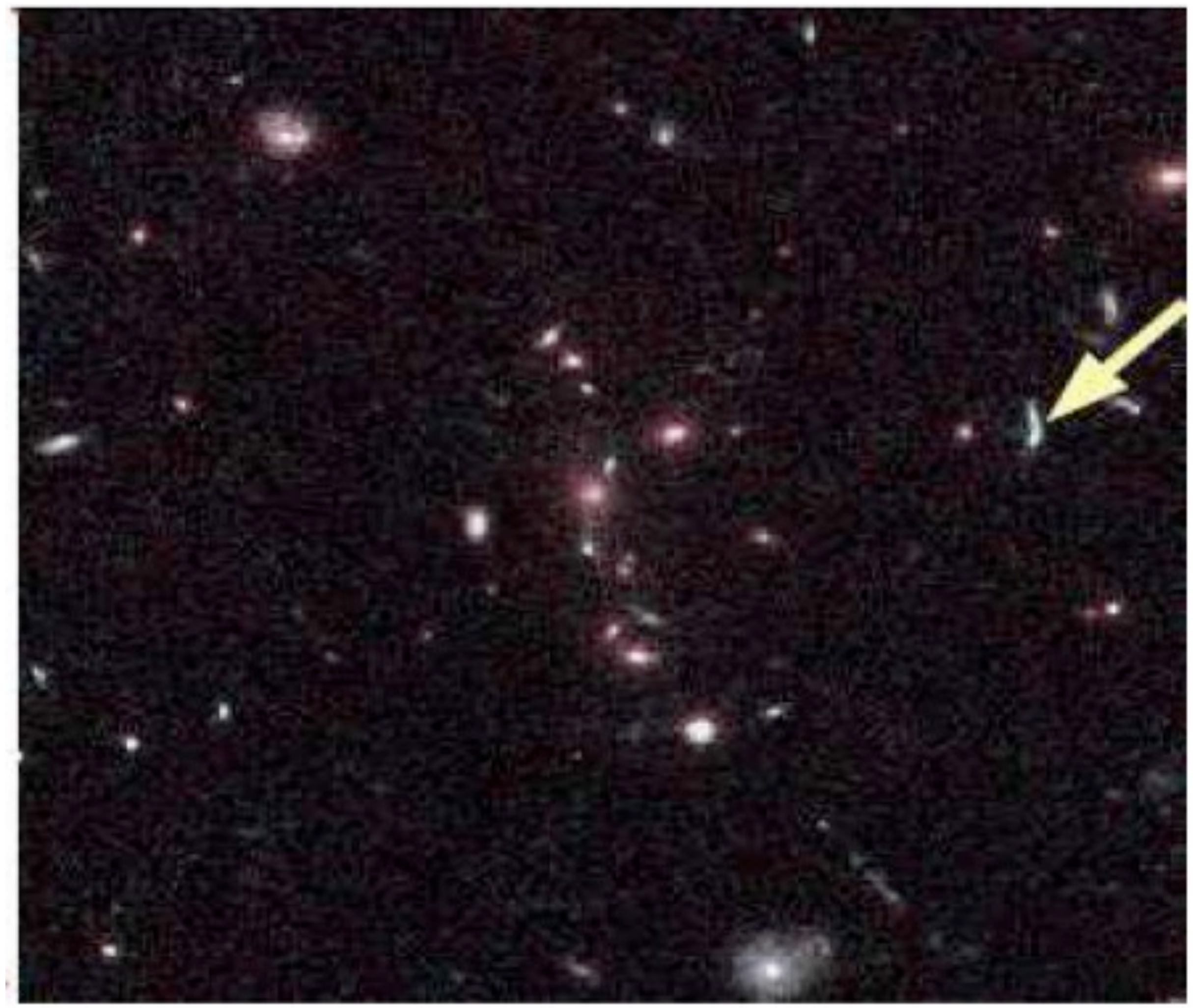
Individual clusters as extreme objects

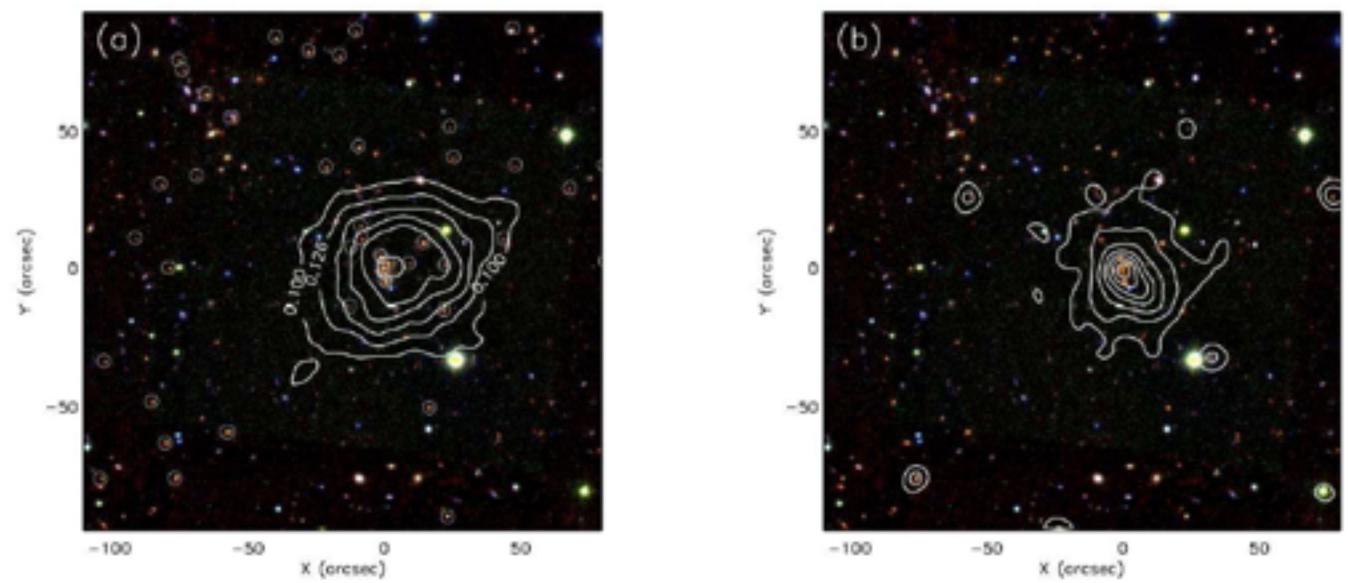
Cluster catalogues with many hundreds or thousands of clusters can be to constrain cosmology, but so can individual "pink elephant" or extreme clusters.

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 exist.





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$$z = 1.4$$

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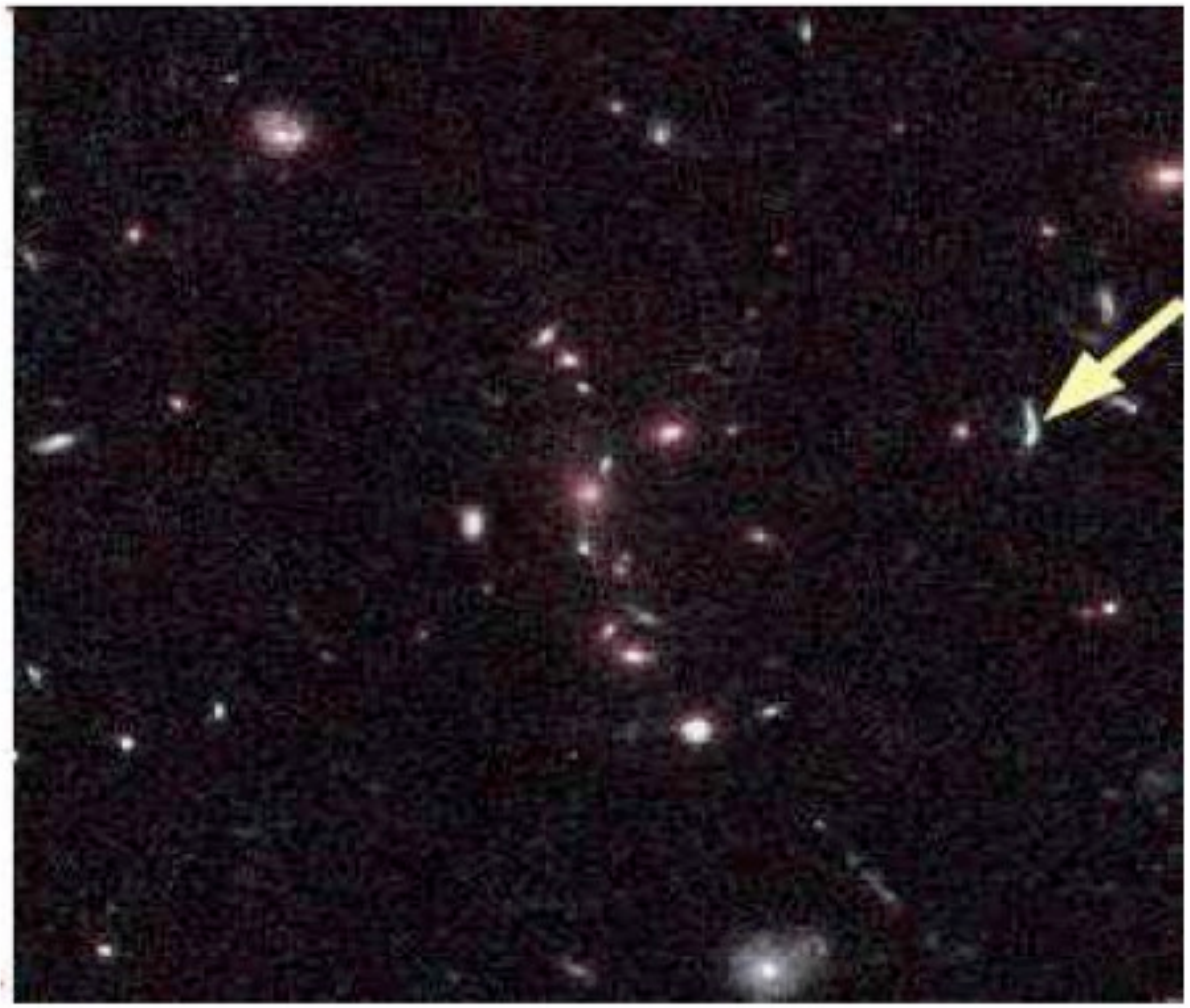

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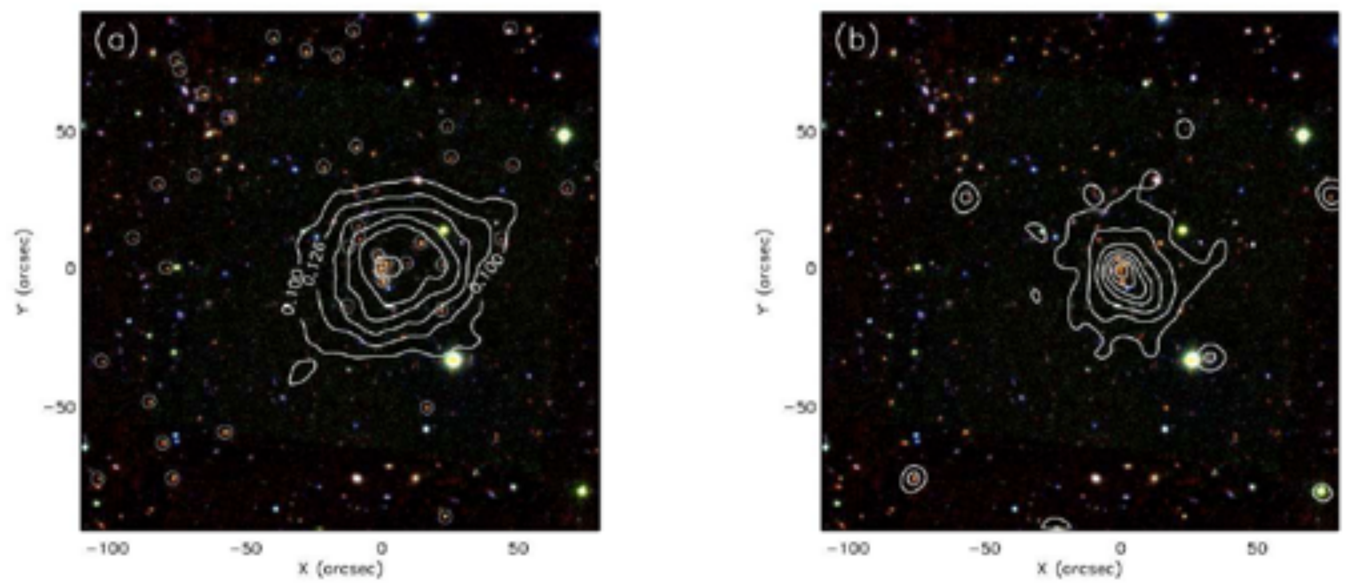

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<u>How likely was this cluster to exist >M >z?</u>

- **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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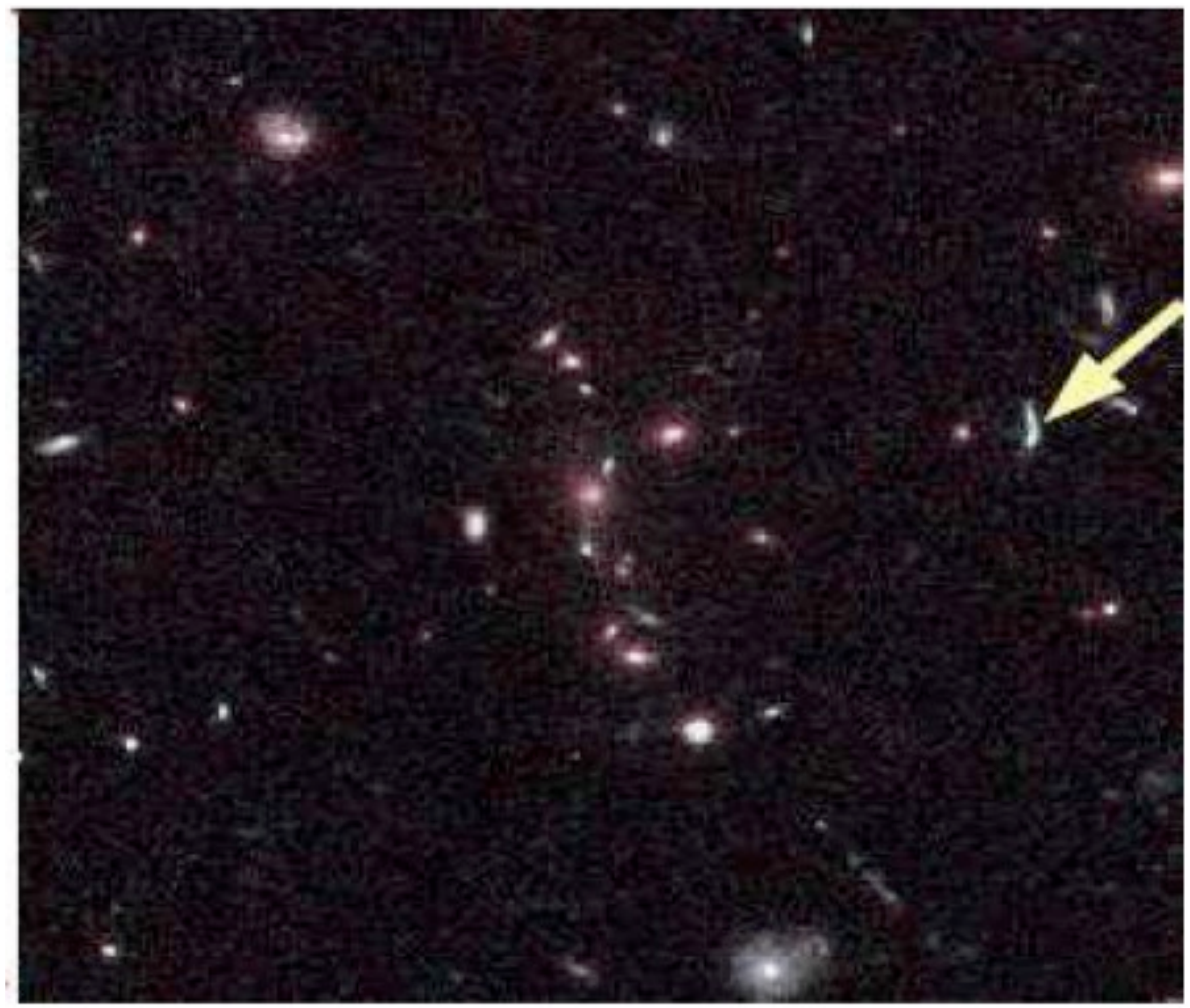

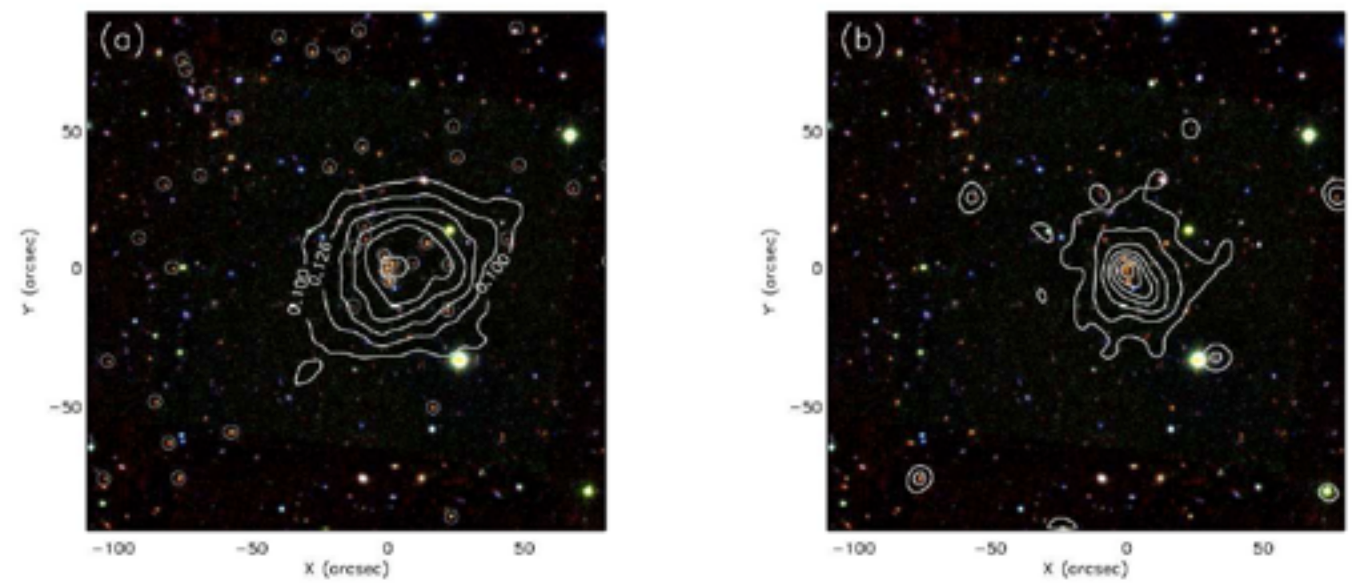

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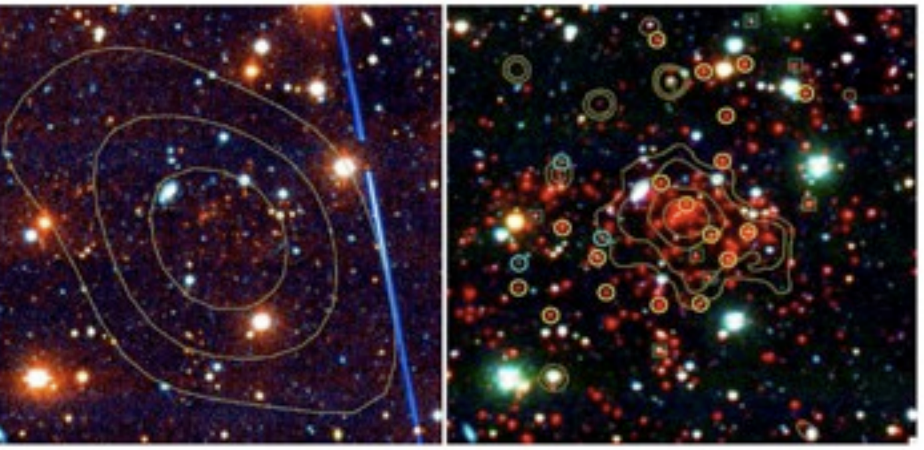
Jimenez & Verde 2009 showed fnl~150 relieves tension.
Cayon et al 2010 fnl=360,fnl>0 at 95%.

Observations of more "rare" clusters



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SPT CL J0546-5345

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

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Brodwin et al 2010

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We just got lucky.

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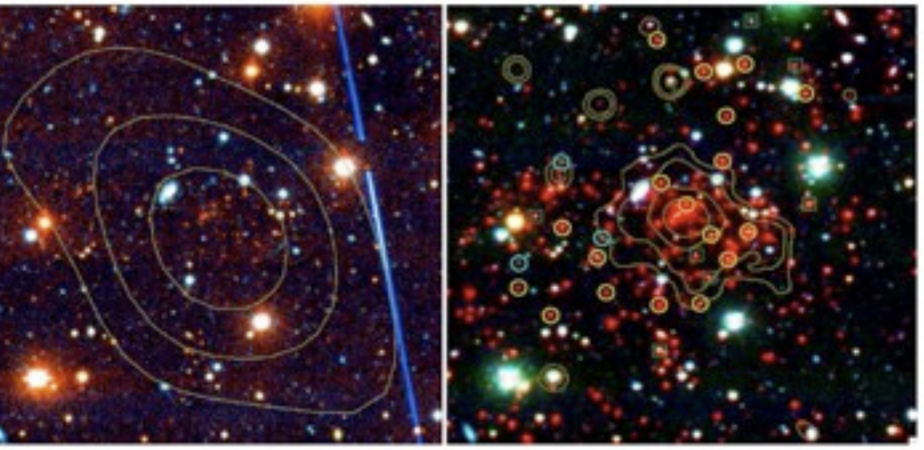

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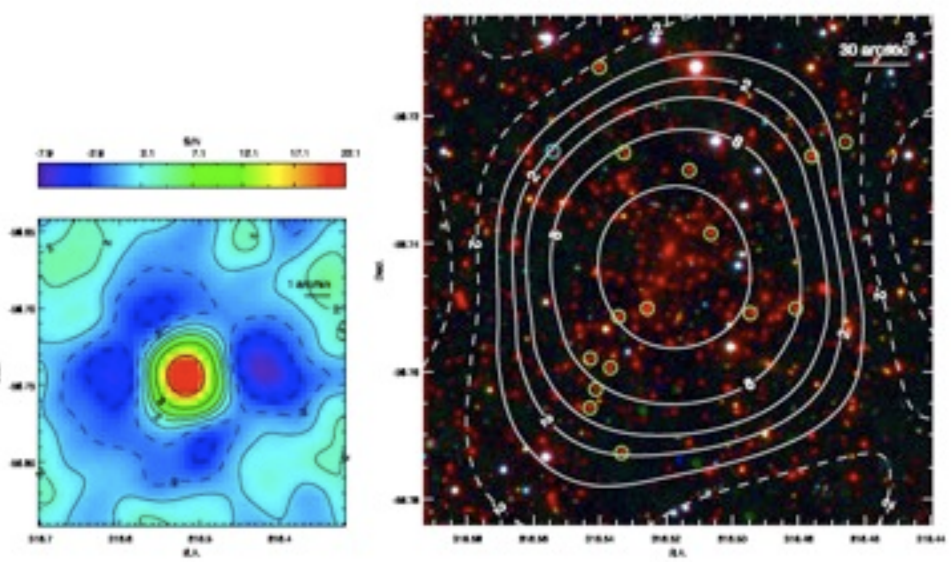

SPT-CL J2106-5844

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

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Foley et al 2011

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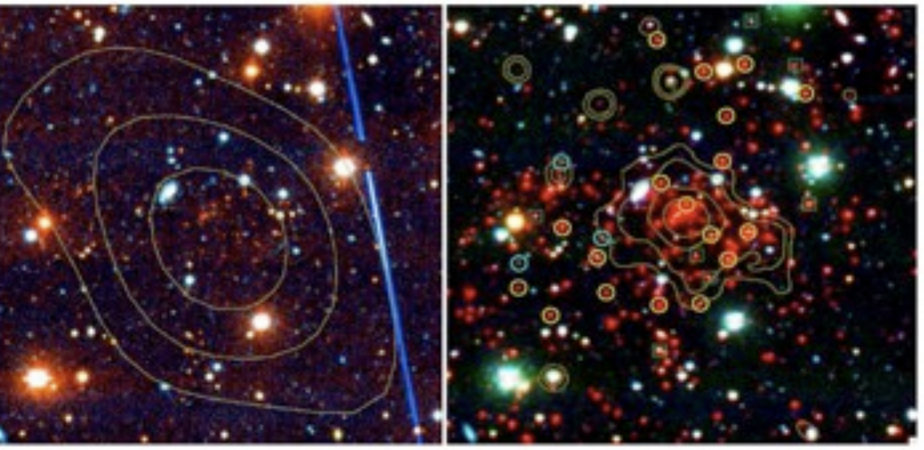
Observations of more “rare” clusters



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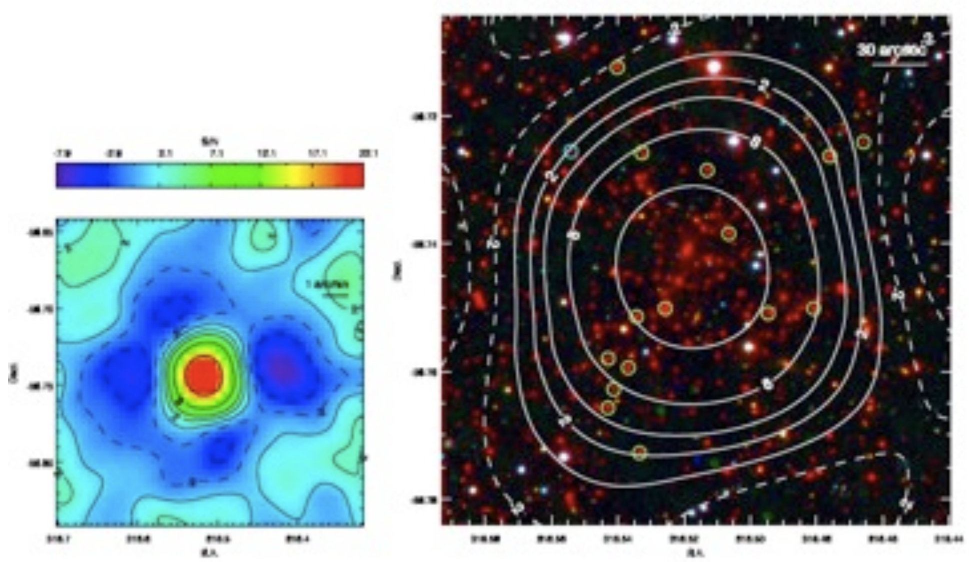

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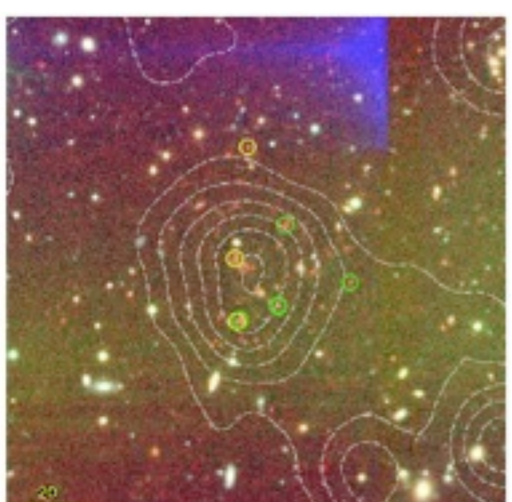

XMMUJ0044.0-2033

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

$$z = 1.57$$

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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BH, Jimenez, Verde 2011

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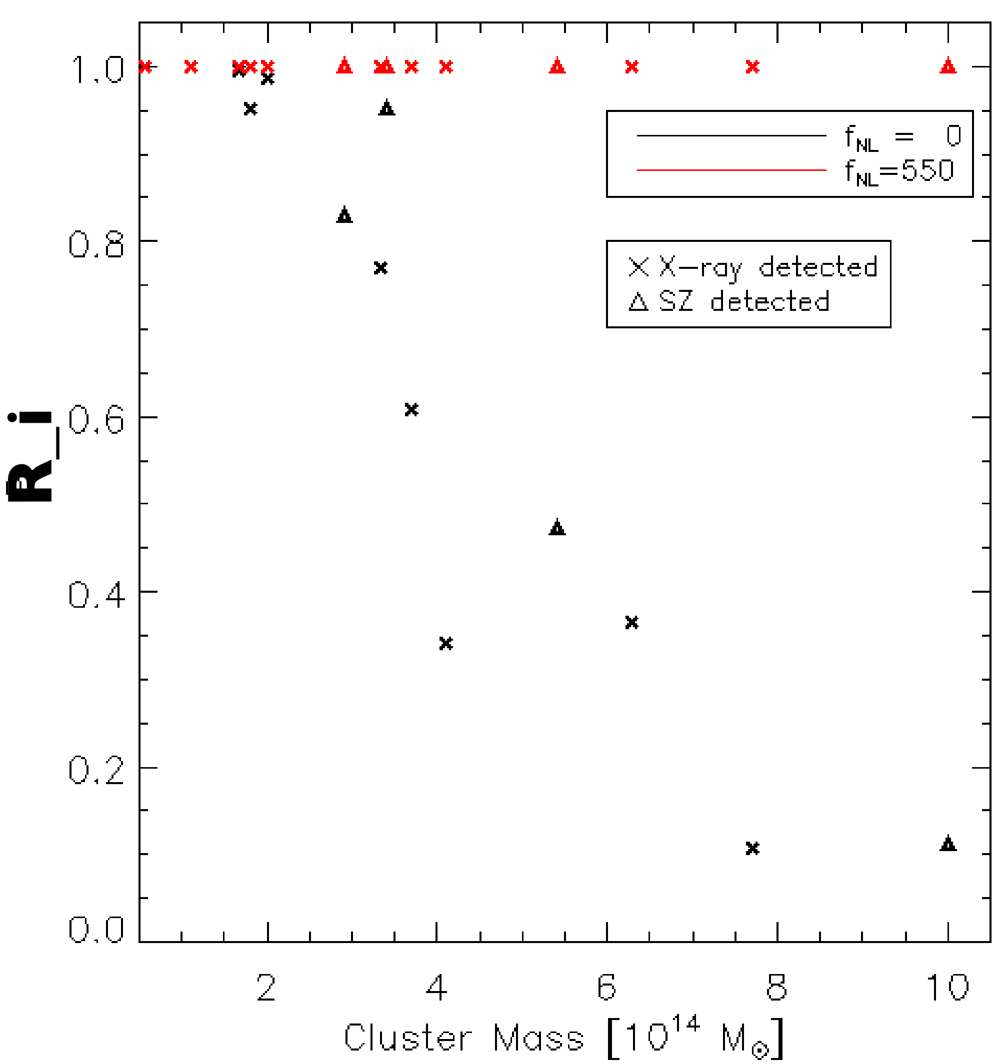

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The >M,>z analysis (uncalibrated)

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
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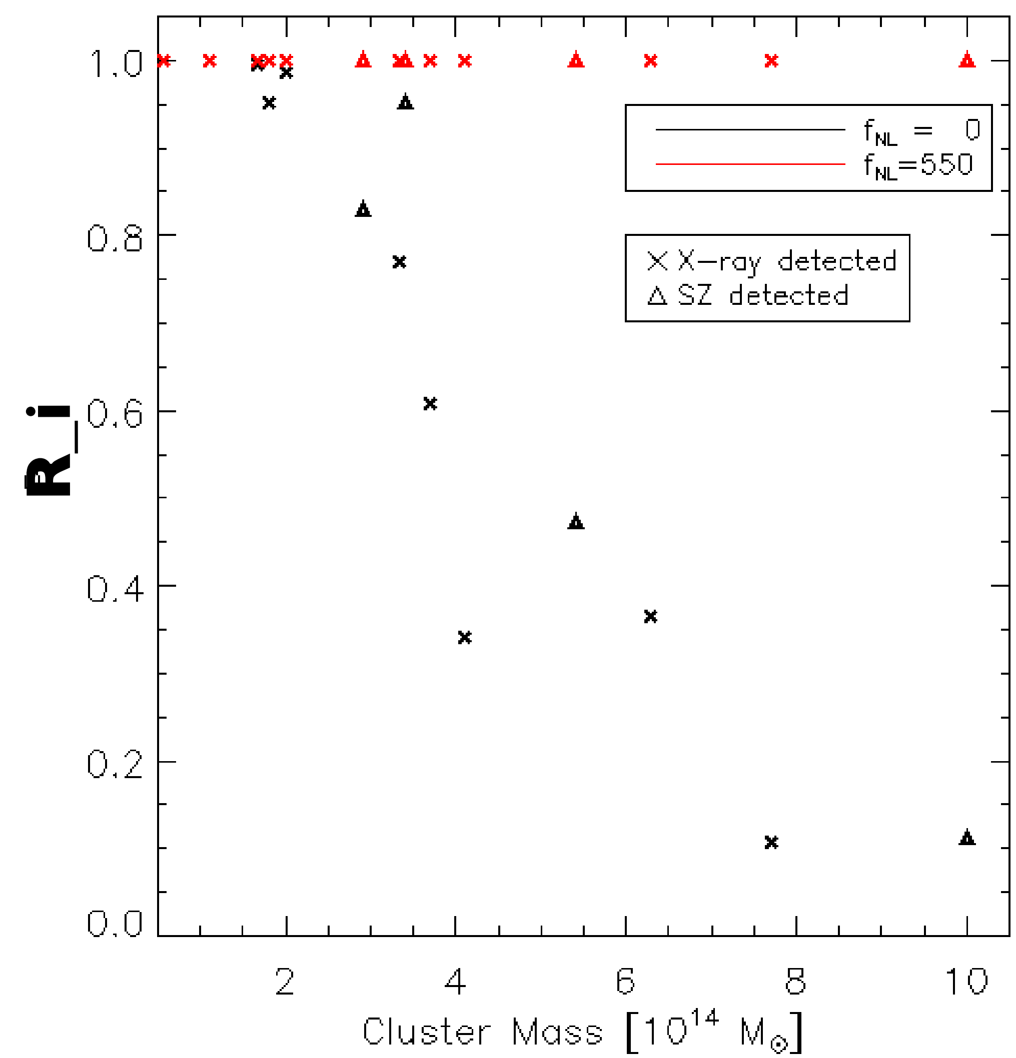

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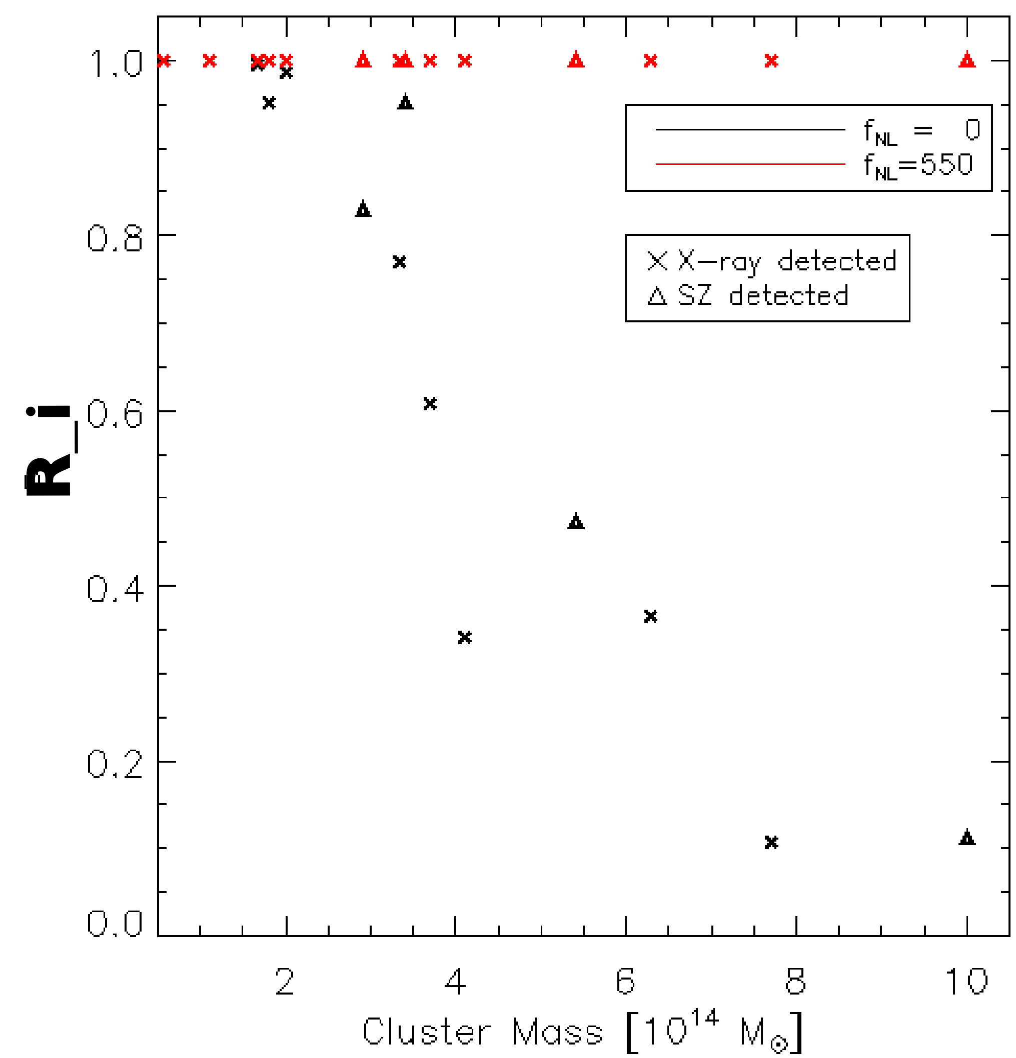

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1) Non-standard cosmology

2) some misunderstanding of these probabilities.

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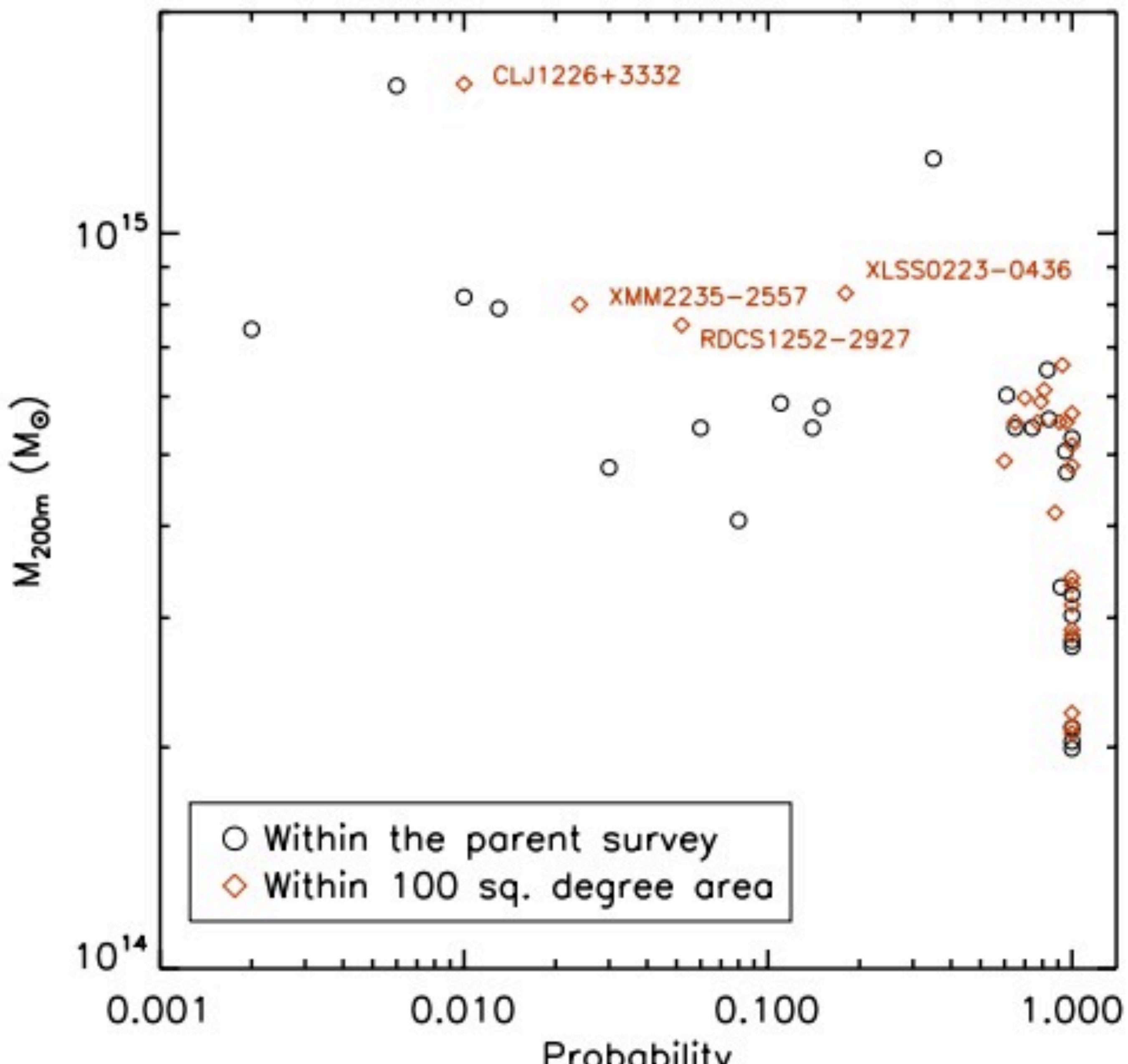
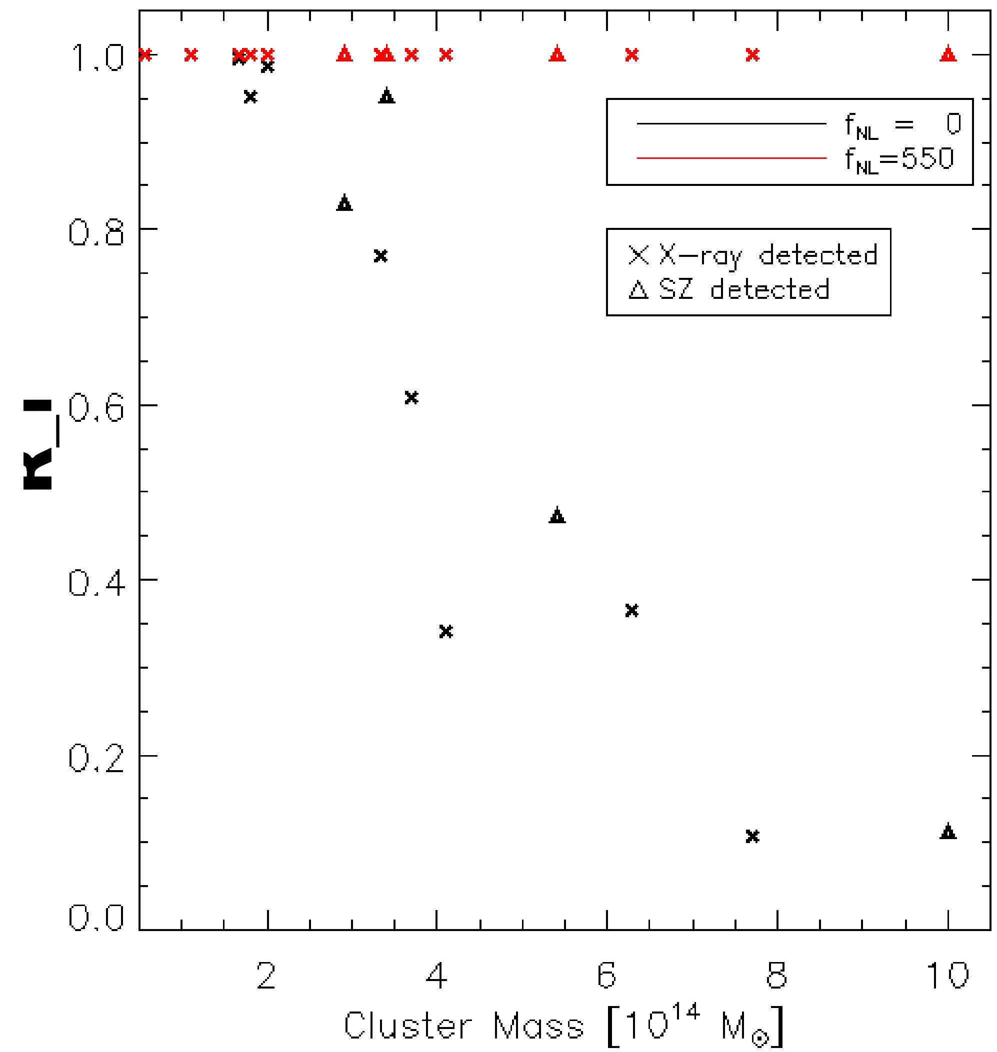


Jee et al (2011) updated cluster sample.

BH, Jimenez, Verde 2011



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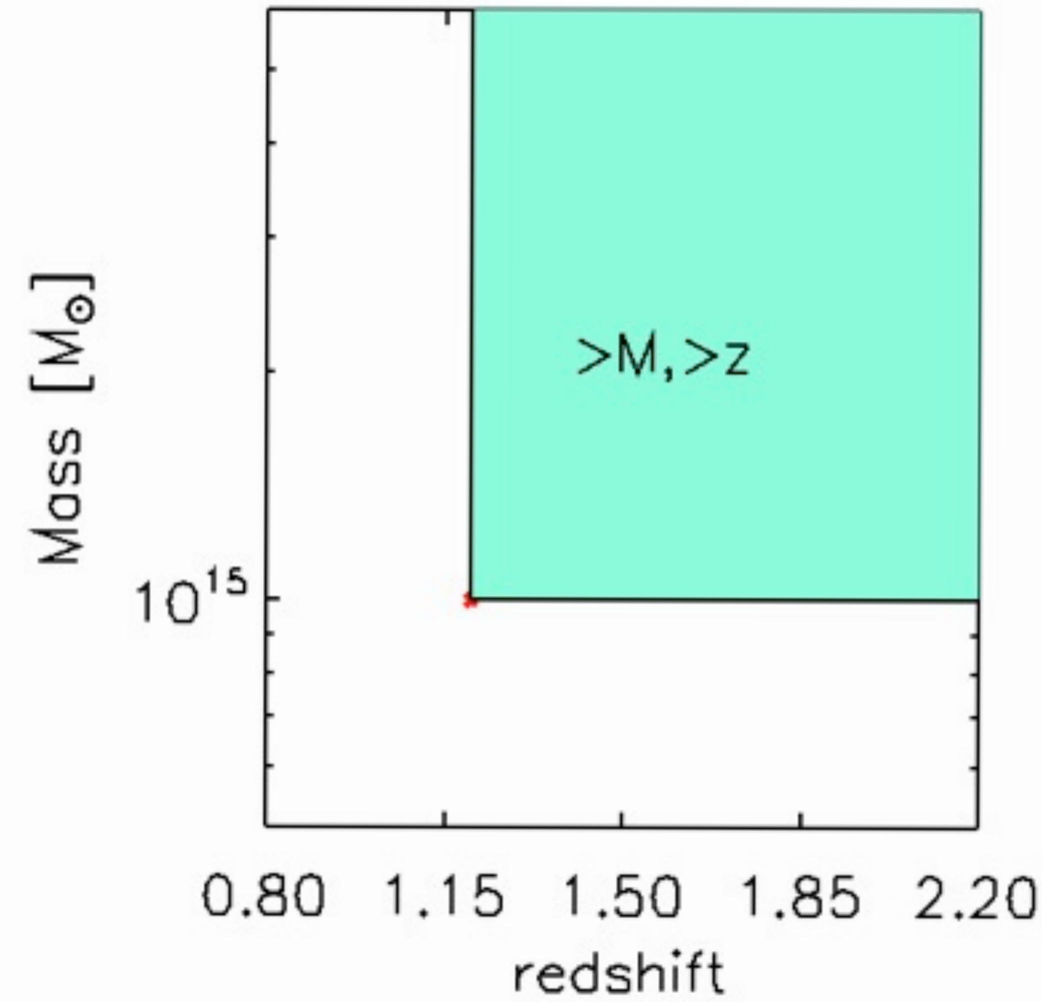

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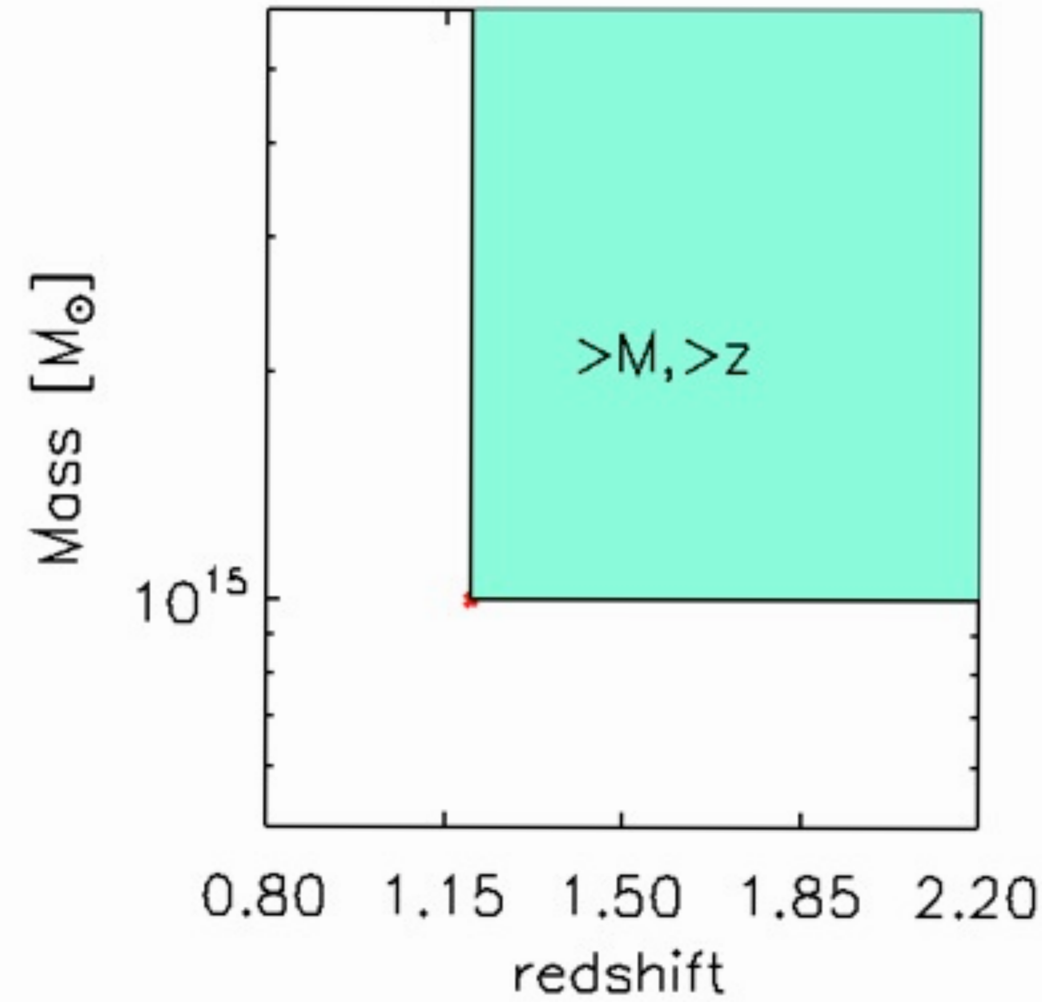

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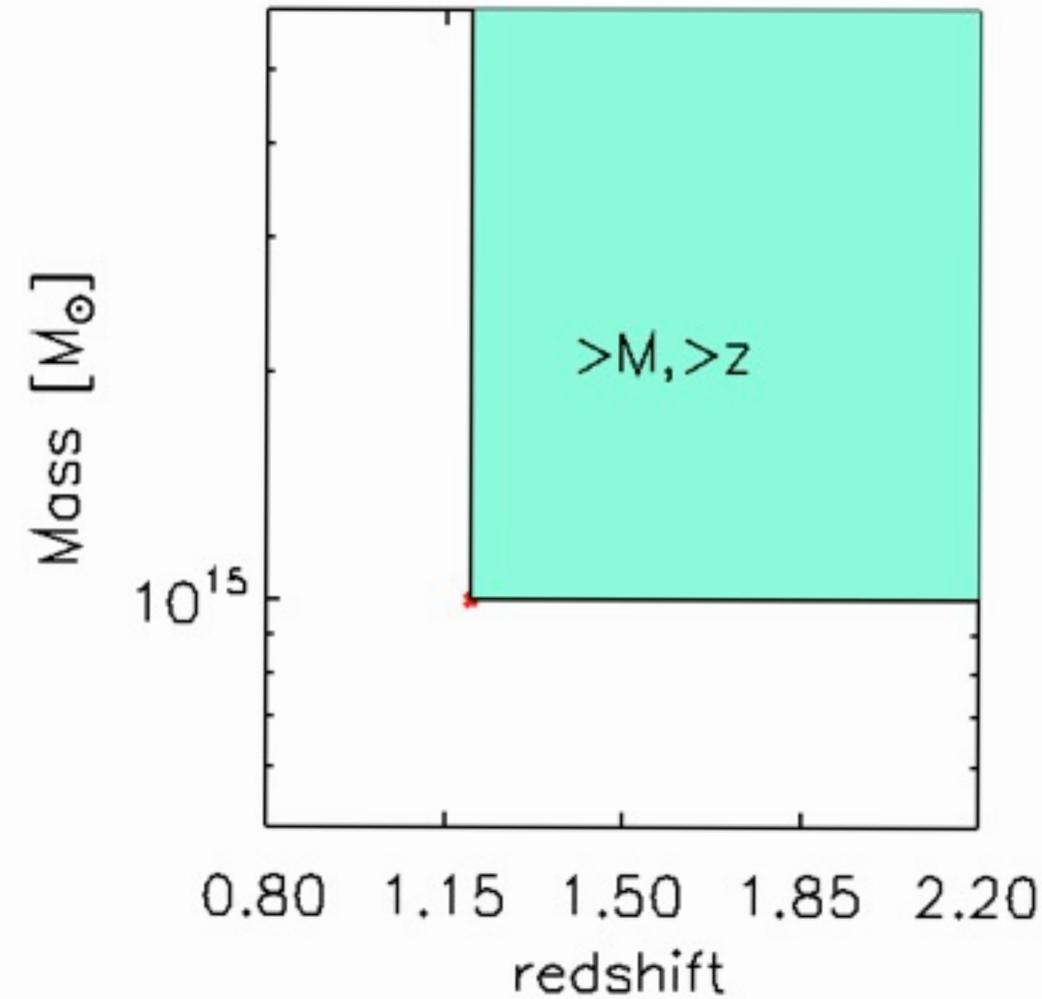

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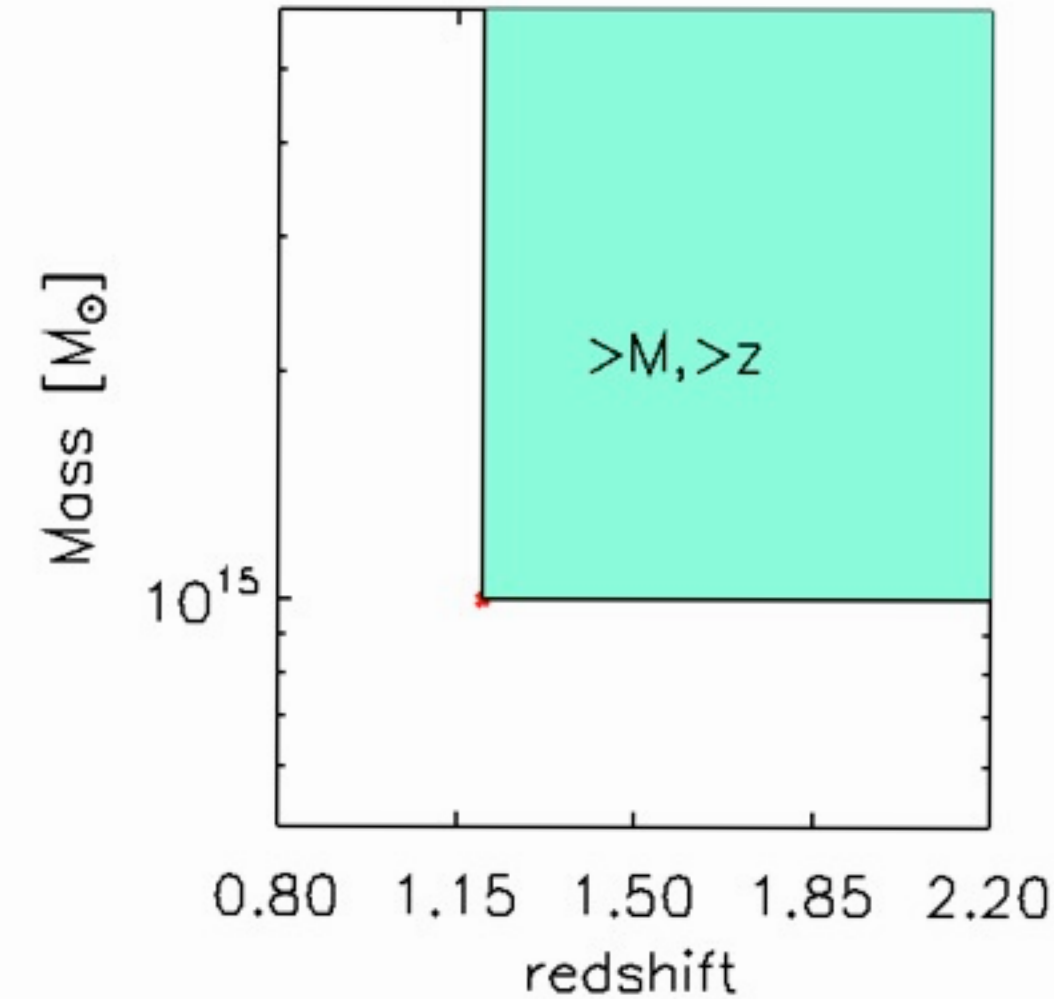

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The "existence probability" R, is given by

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

Unbiasing/Calibrating the >M,>z statistic 1

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

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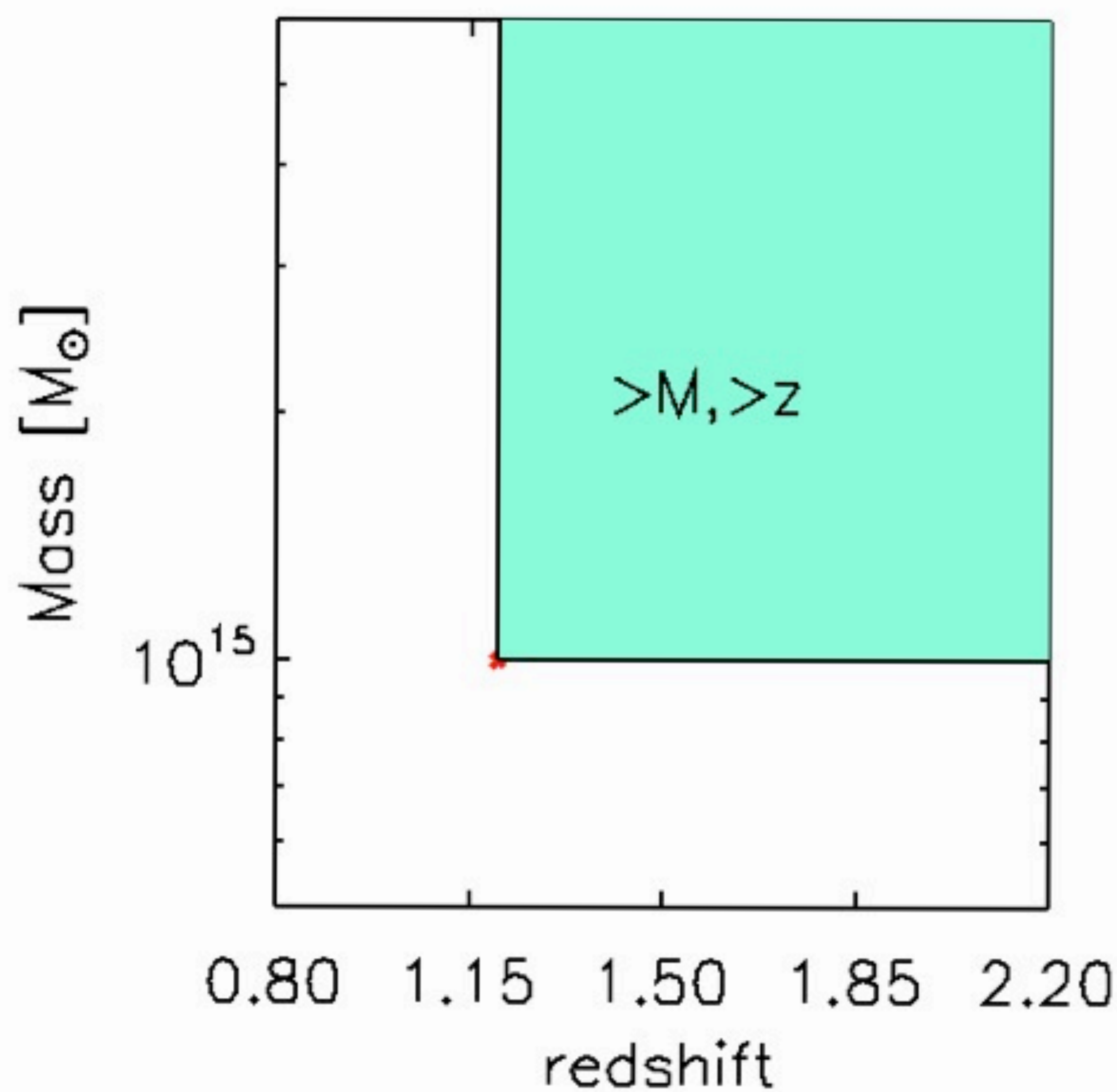

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Why should we restrict ourselves to the easily calculated, but arbitrary, >M,>z contours, e.g, what dictates that the box should be placed at right angles to the (M,z) axis, or have straight instead of curved boundaries? One could simply modify the >M,>z box and obtain a new "existence probability" R* which would be equally as 'justified' as the original existence probability R.

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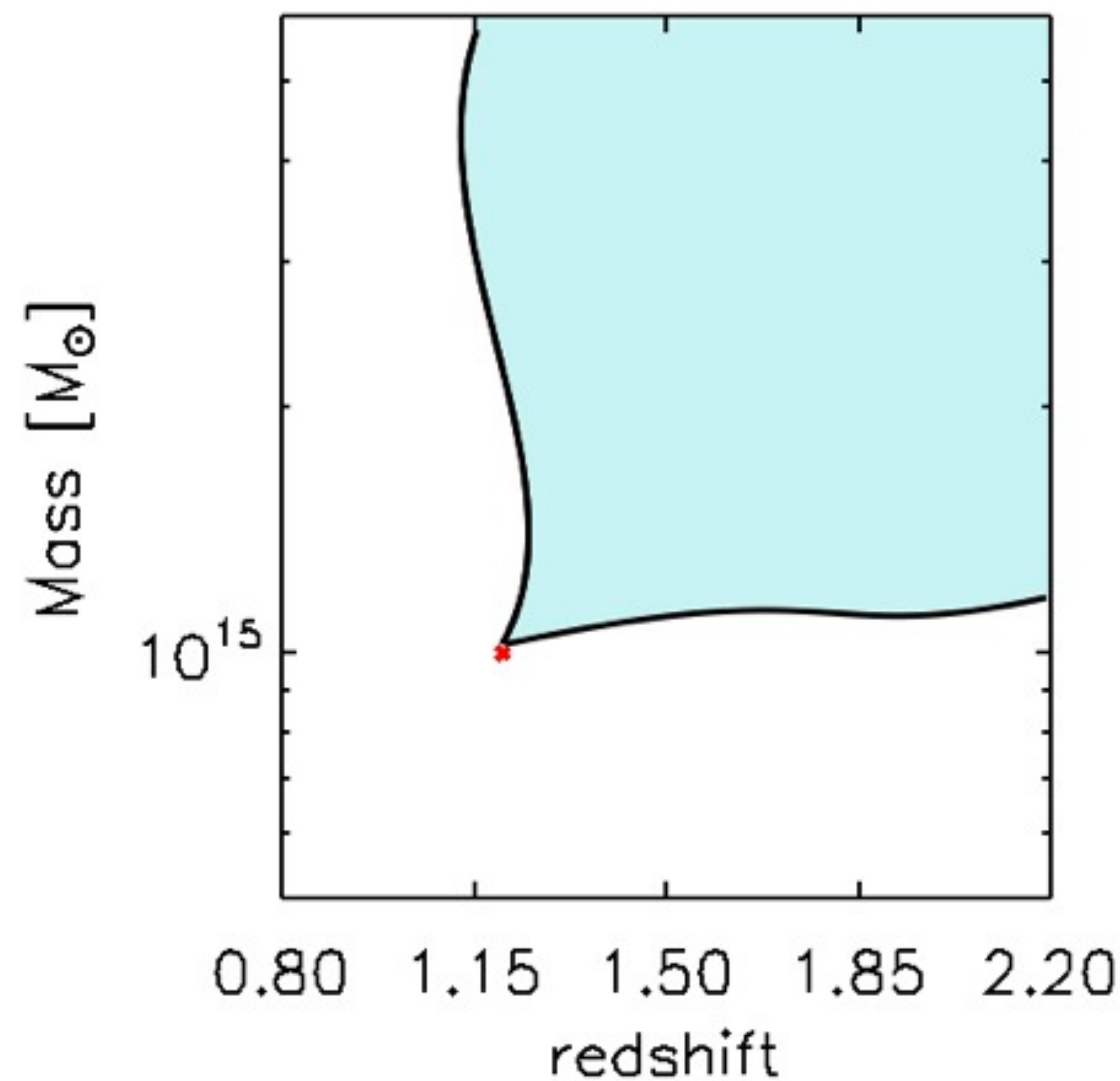

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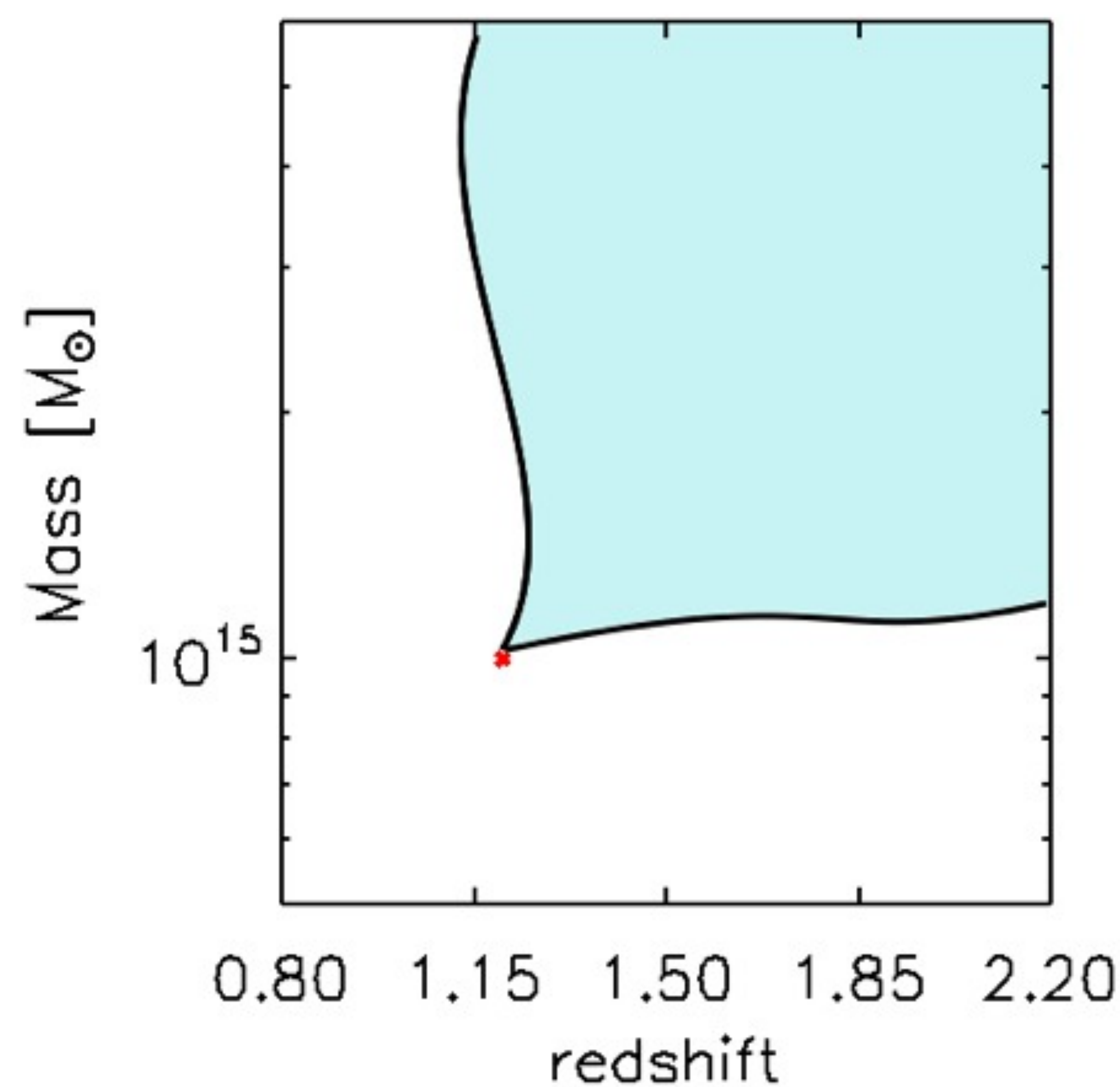
Once the above is understood, we can calculate the distributions of R found in simulations, compare it with R from observations, and then use the calibrated R to test for tension with LCDM.



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Playing the >M,>z game is only necessary if we don't know the selection function (sf) of a survey. For example Jee et al (2011) published a list of X-ray (actually SNe) selected clusters with weak lensing masses. They have a very complicated sf. Only the existence, not the absence, of clusters can constrain cosmology (contrast with e.g., SPT, maxBCG, R400d).

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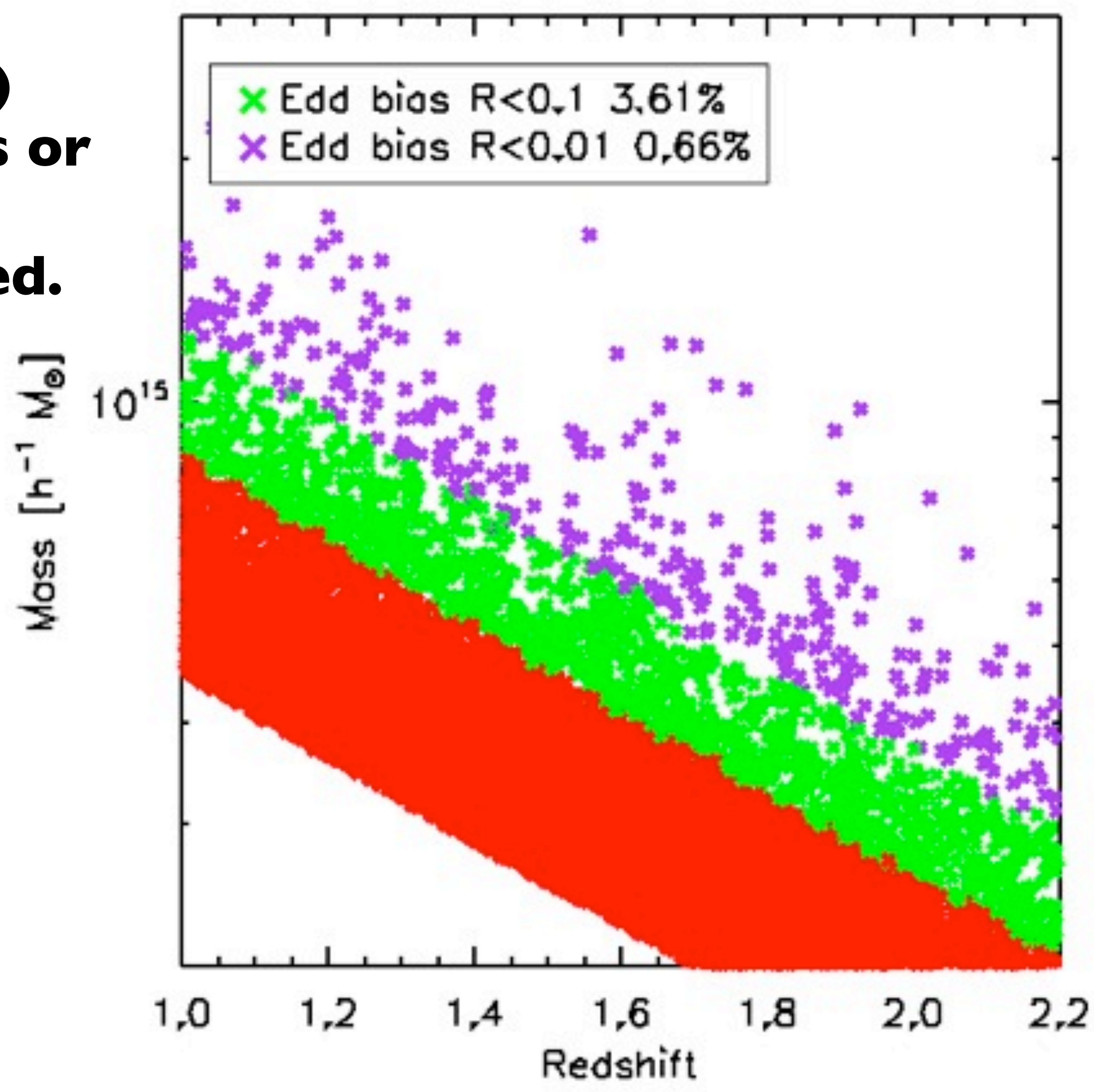

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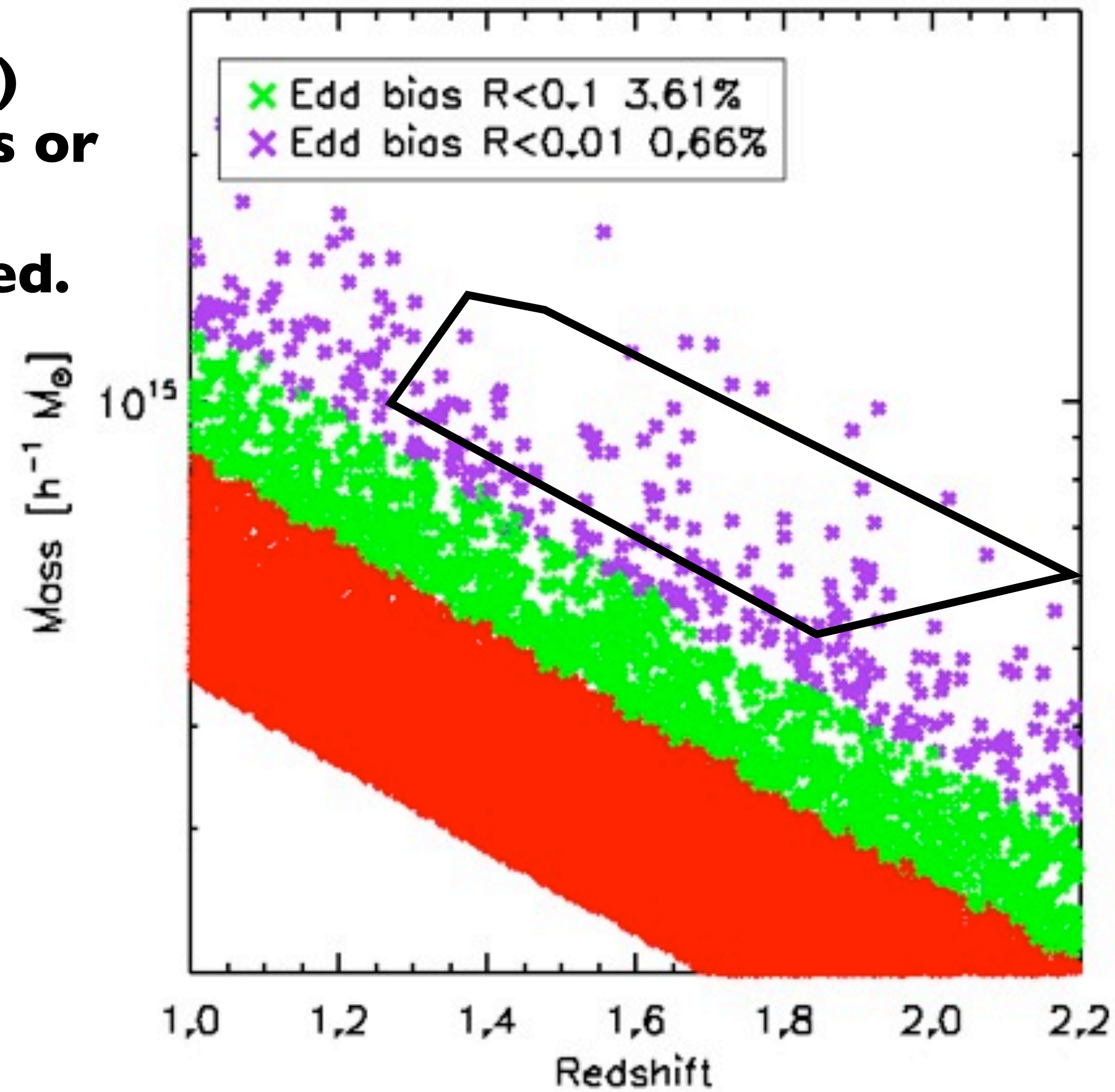

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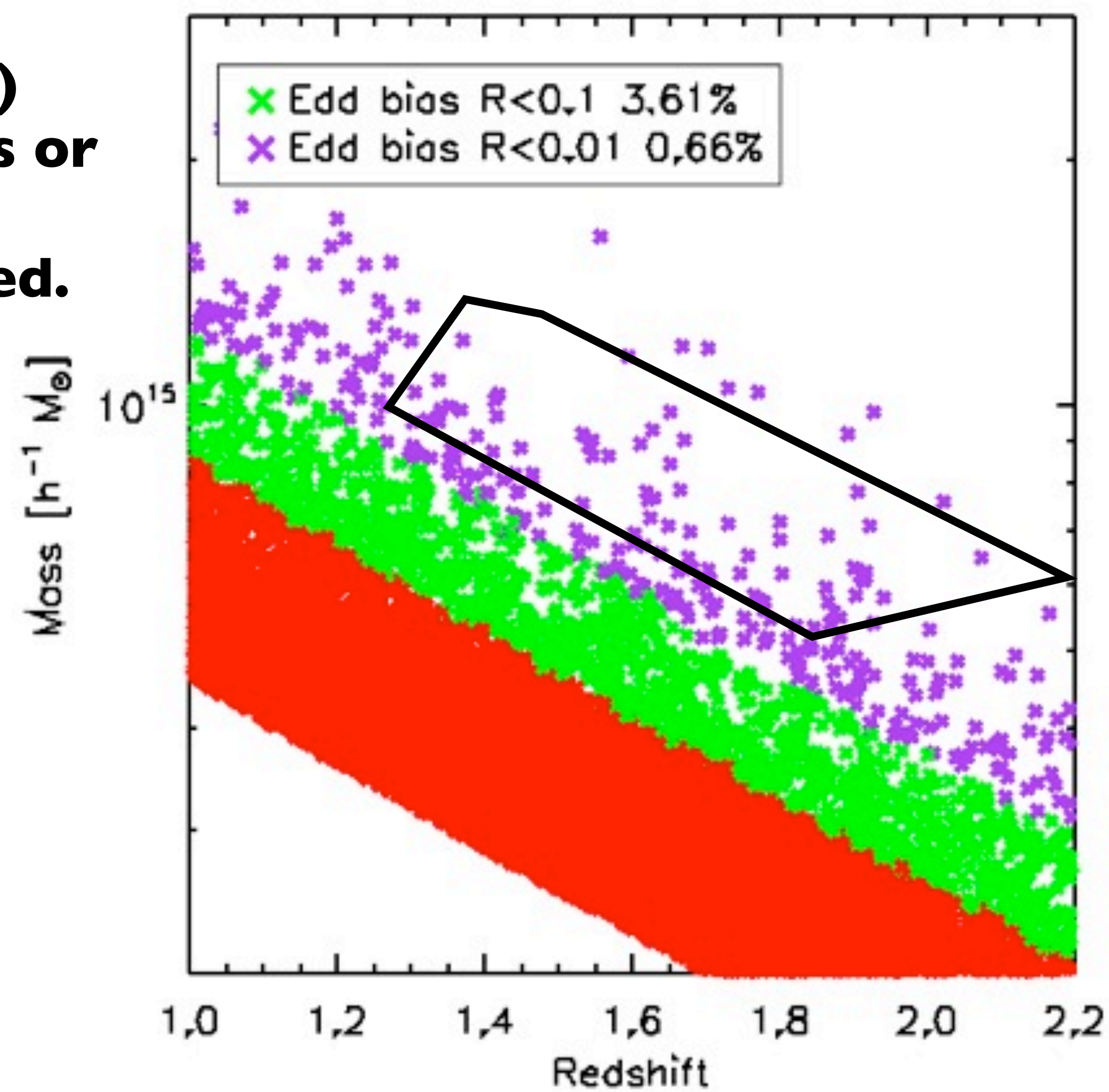


Note: To calibrate >M,>z analysis using simulated clusters, we must assume which part of the (M,z) plane has been "observed" (i.e., a sf).

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

Updated analysis/comparison: data

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

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

Redshift range of Jee 1.0<z<2.2

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

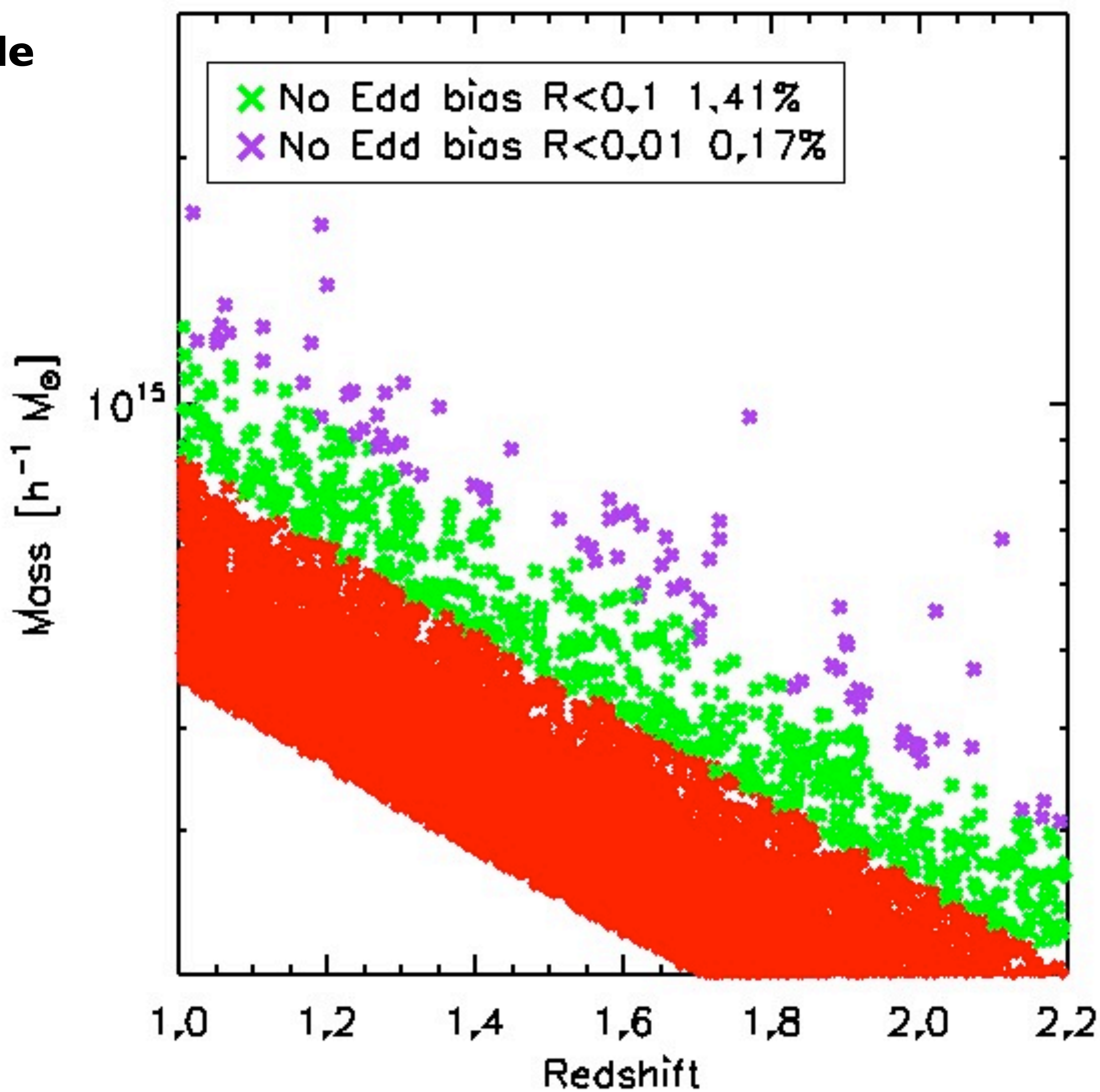
Cluster Name	Redshift	M_{200} $10^{14}M_\odot$	Method	$\tilde{R}$	Mass reference
RCS0221-0321	1.02	$1.80^{+1.30}_{-0.70}$	WL	0.992	[15]
WARPSJ1415+3612	1.03	$4.70^{+2.00}_{-1.40}$	WL	0.706	[15]
RCS0220-0333	1.03	$4.80^{+1.80}_{-1.30}$	WL	0.709	[15]
RCS2345-3632	1.04	$2.40^{+1.10}_{-0.70}$	WL	0.989	[15]
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]

Marginalize 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.

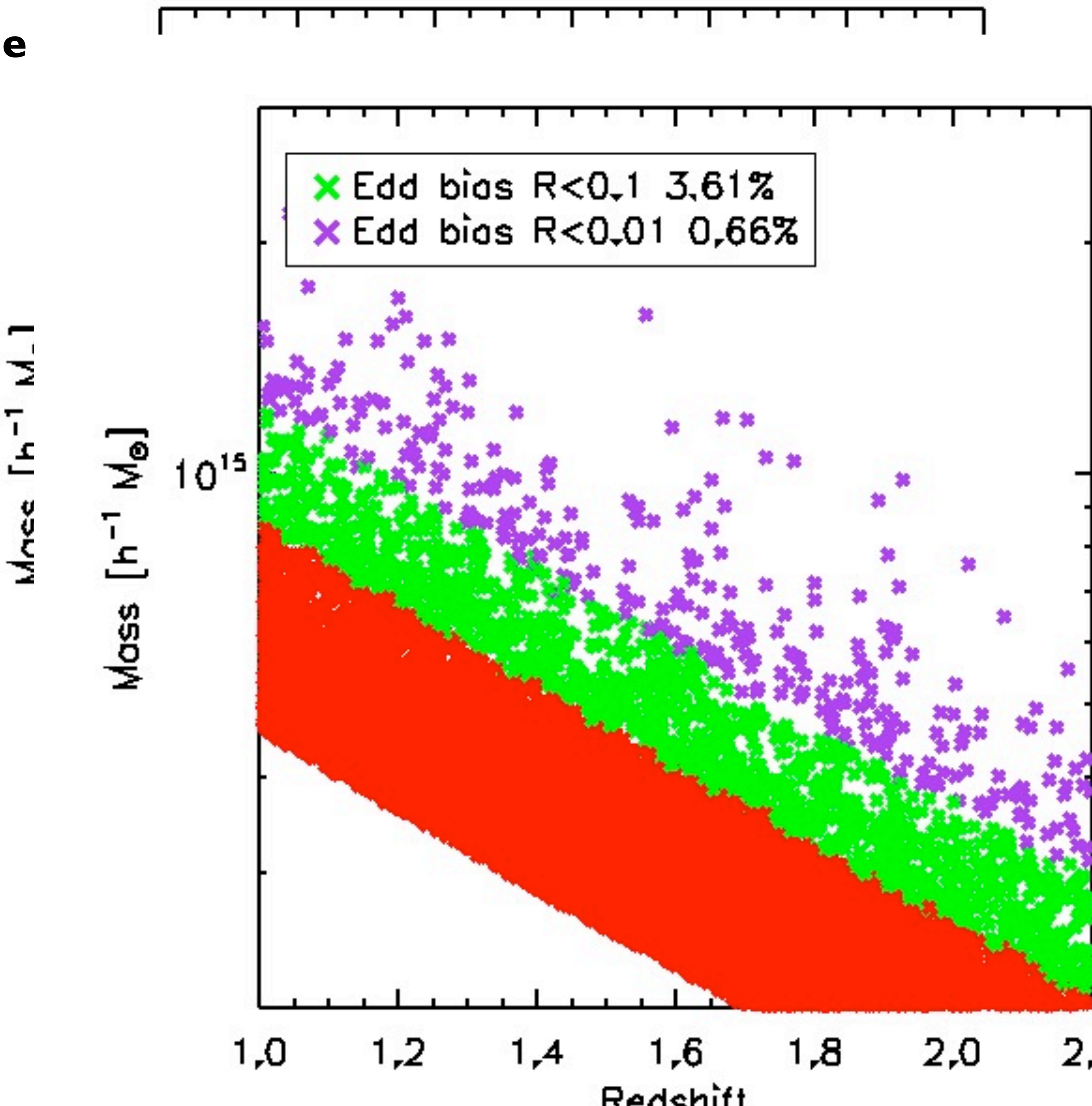


Correct analysis/comparison: simulations

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.



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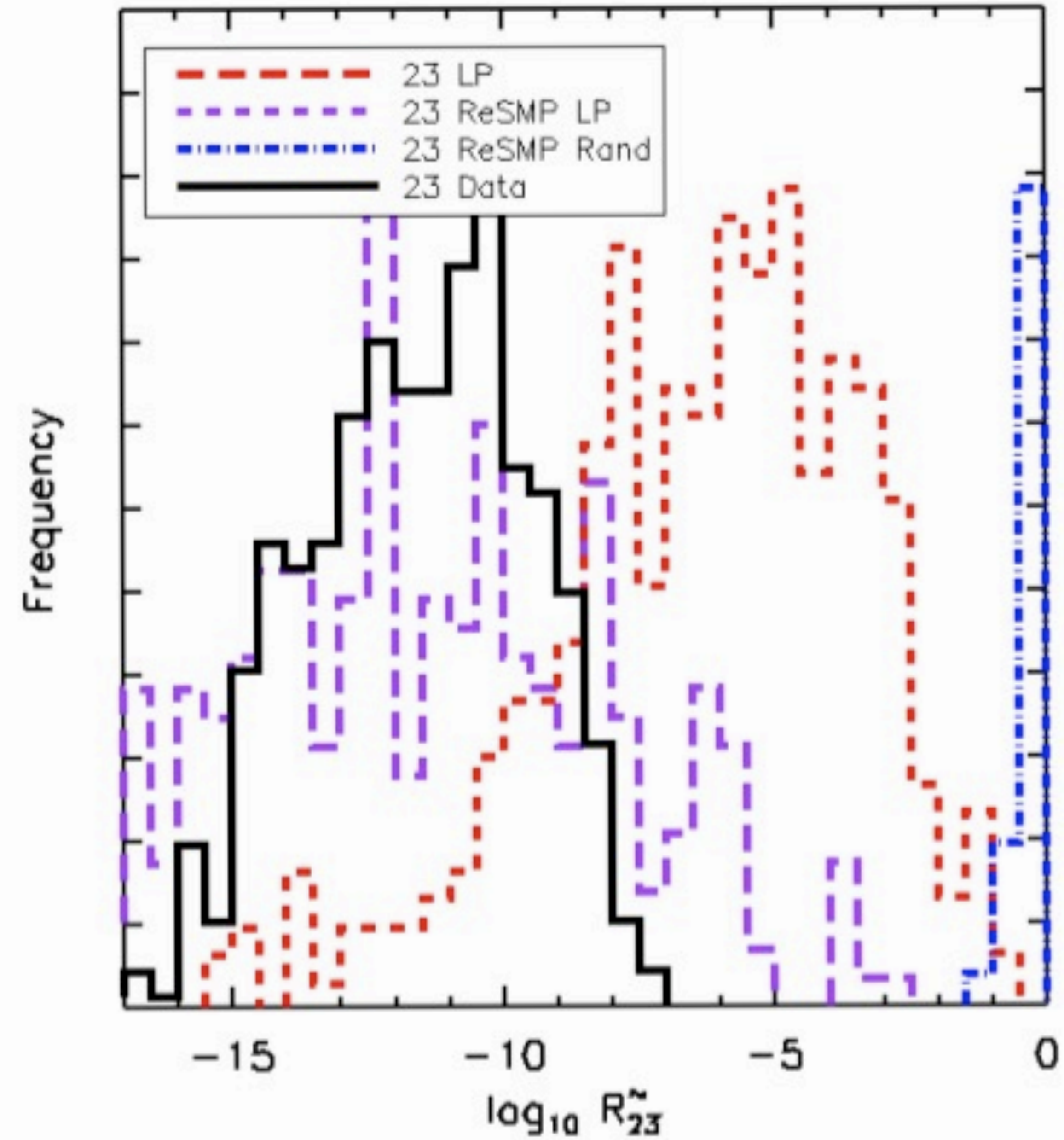

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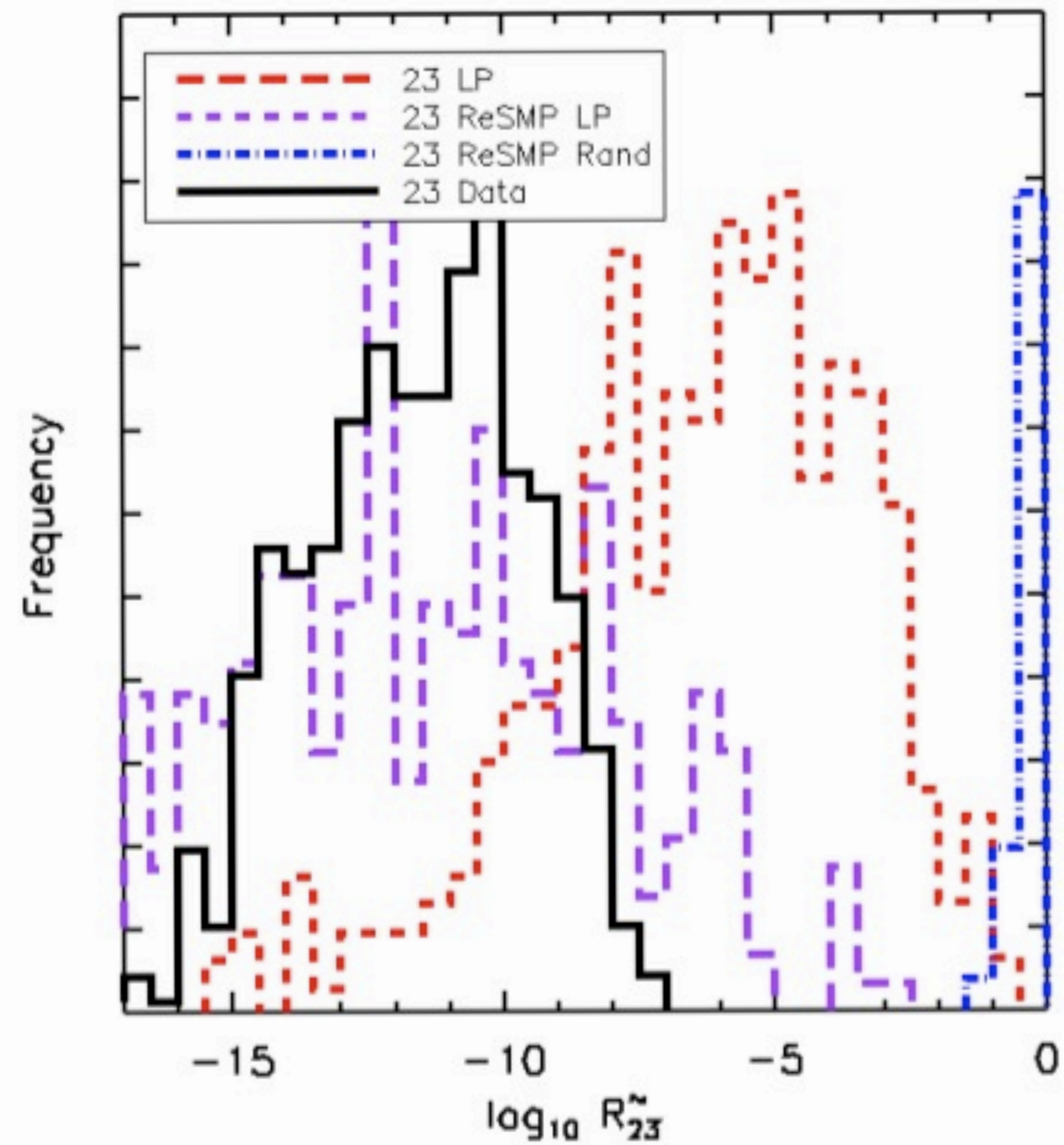

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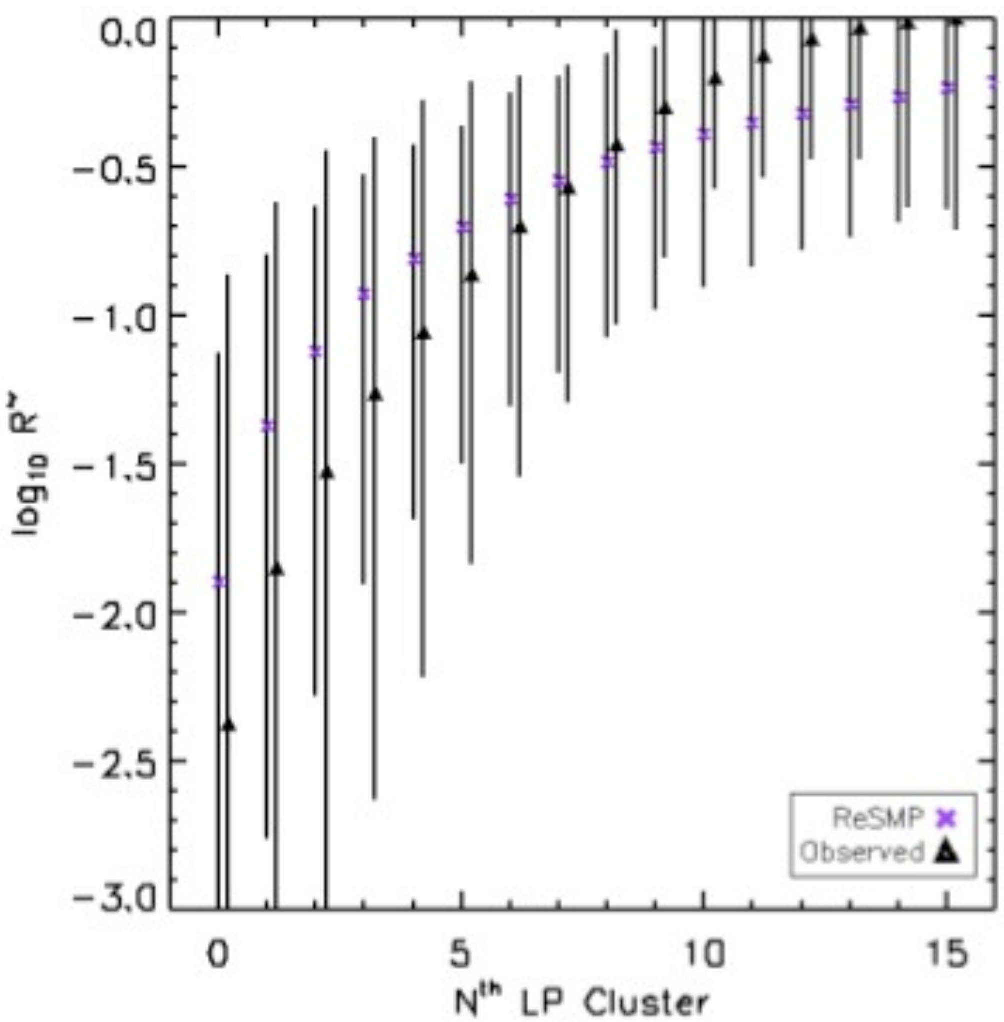

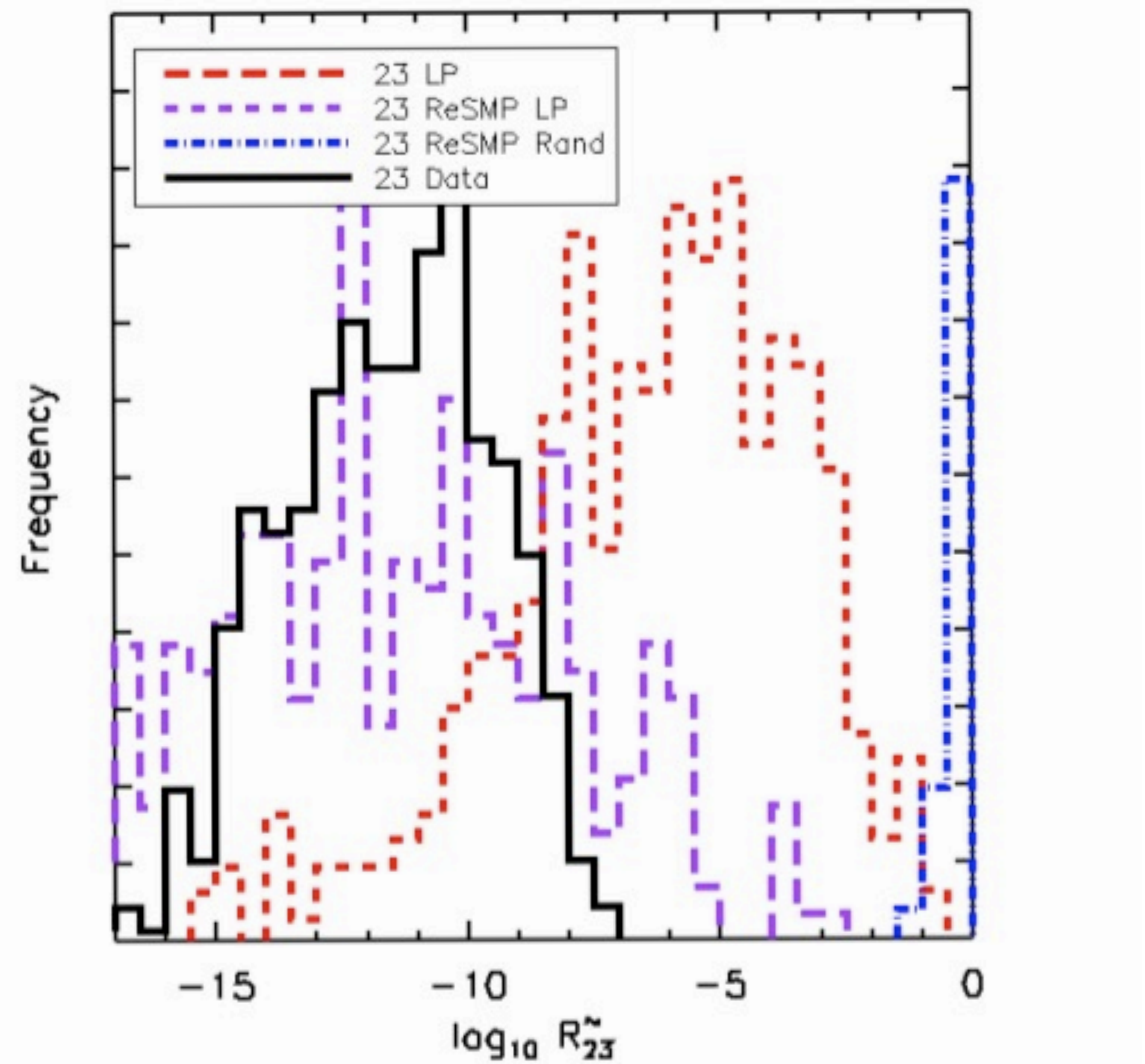

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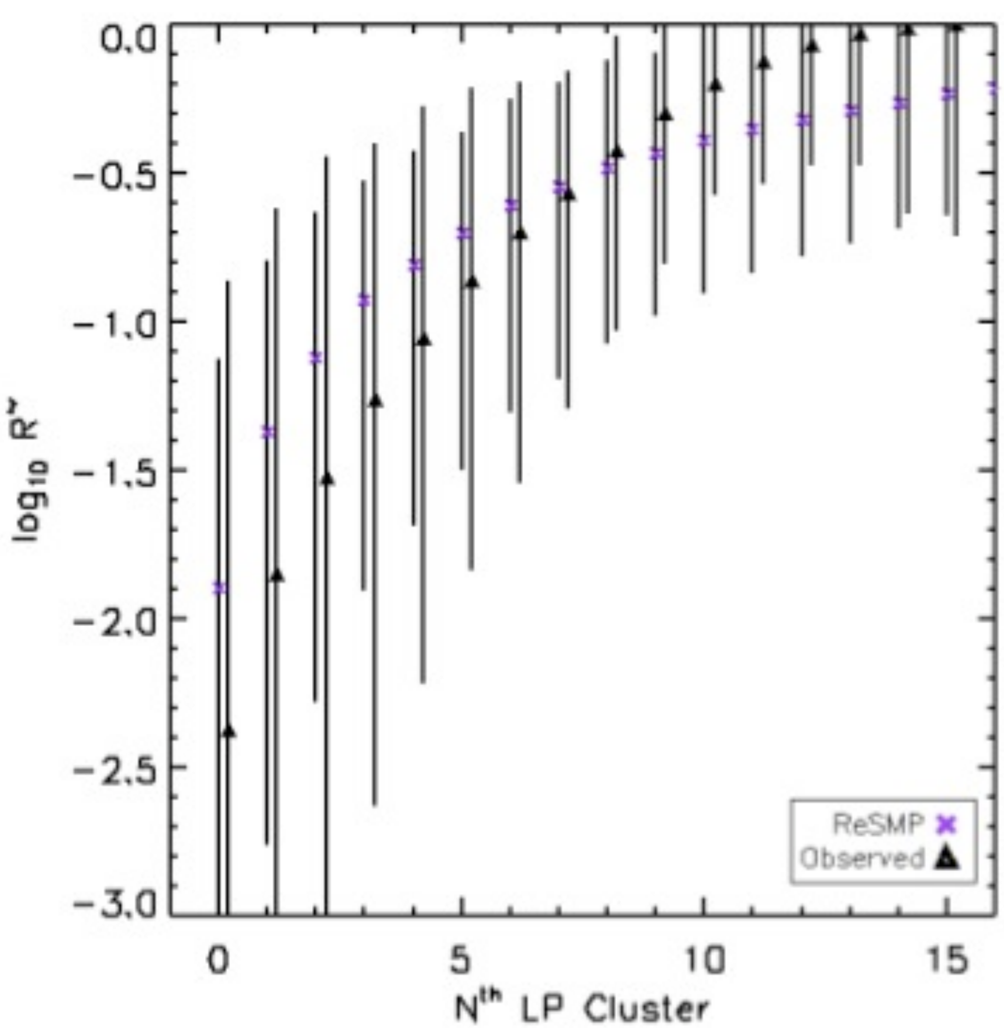

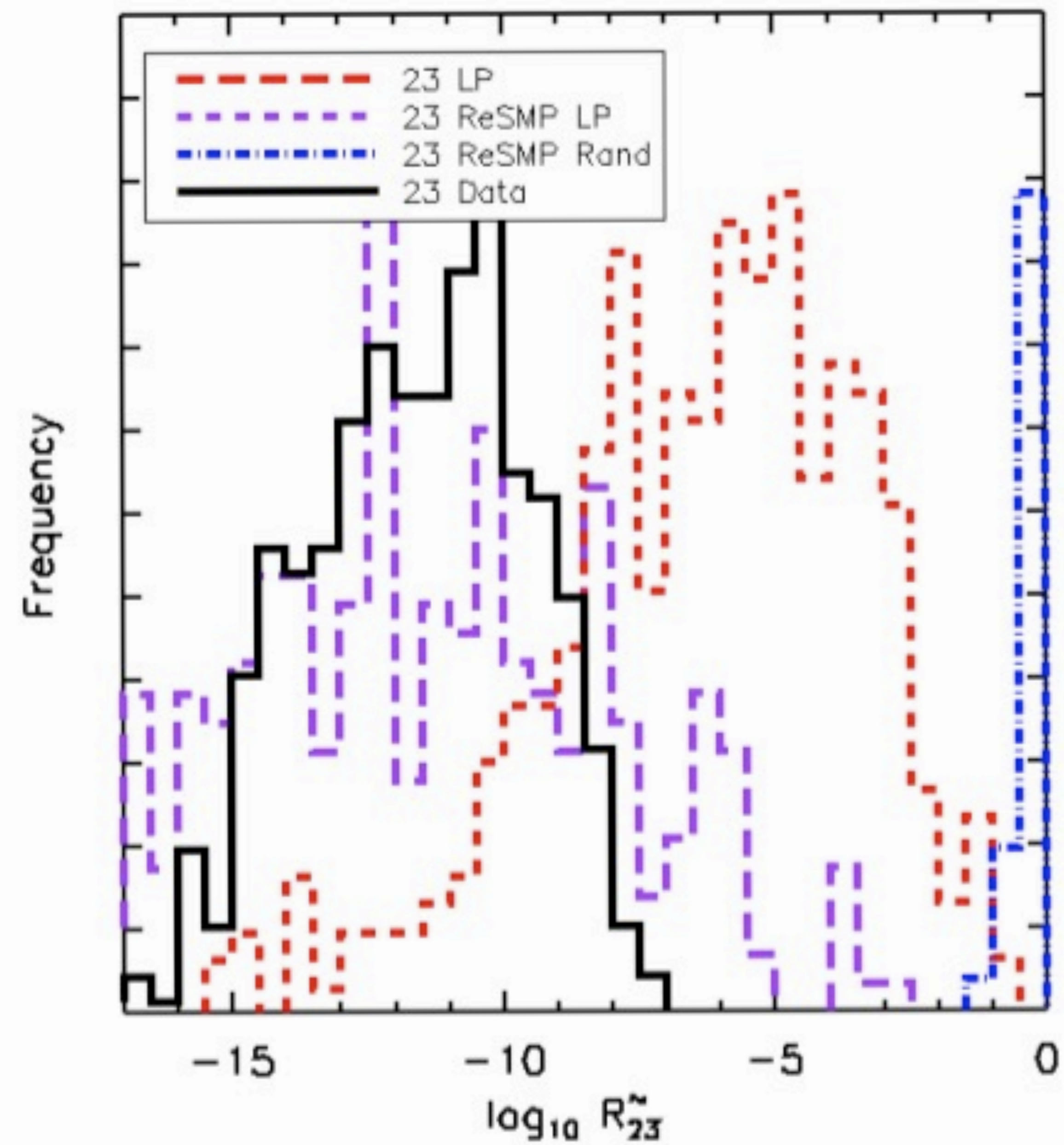

This analysis assumes the survey geometry of Jee et al.
1<z<2.2; footprint=100 sq. deg.

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.

However, we are be too conservative in the modeling of the survey geometry. More work needed to understand what this means for LCDM.

Related work, exclusion curves

Curves in the mass-redshift plane can be used to signal tension with individual 'rare' clusters, but can rule out a cosmological model. The (biased) idea was introduced in Mortonson et al (2010).

Harrison & Hotchkiss 2012 released (de-biased) code to create these curves in future claims of tension with individual clusters.

They also need to make assumptions about survey geometry.

The observed clusters provide no tension, e.g. with exclusion curves, with LCDM *assuming* the survey geometries examined here.

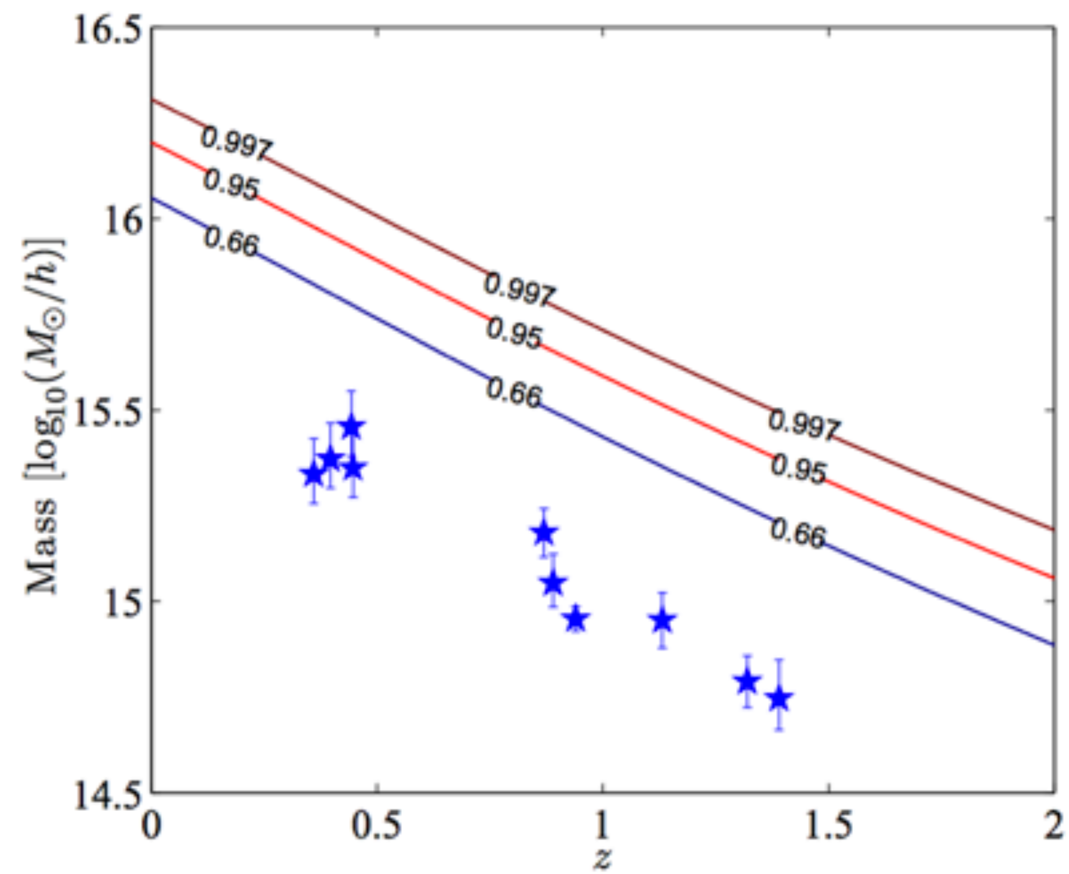

Figure 4. Rareness of currently observed clusters (using the $> mdV$ measure described in the text) corresponding to an idealised all-sky survey which is complete at masses above $m_{min} = 10^{14} M_\odot/h$ out to $z = 2$.

Harrison & Hotchkiss arXiv: 1210.4369

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Summary

- Individual “extreme” clusters can be used to rule out cosmological models
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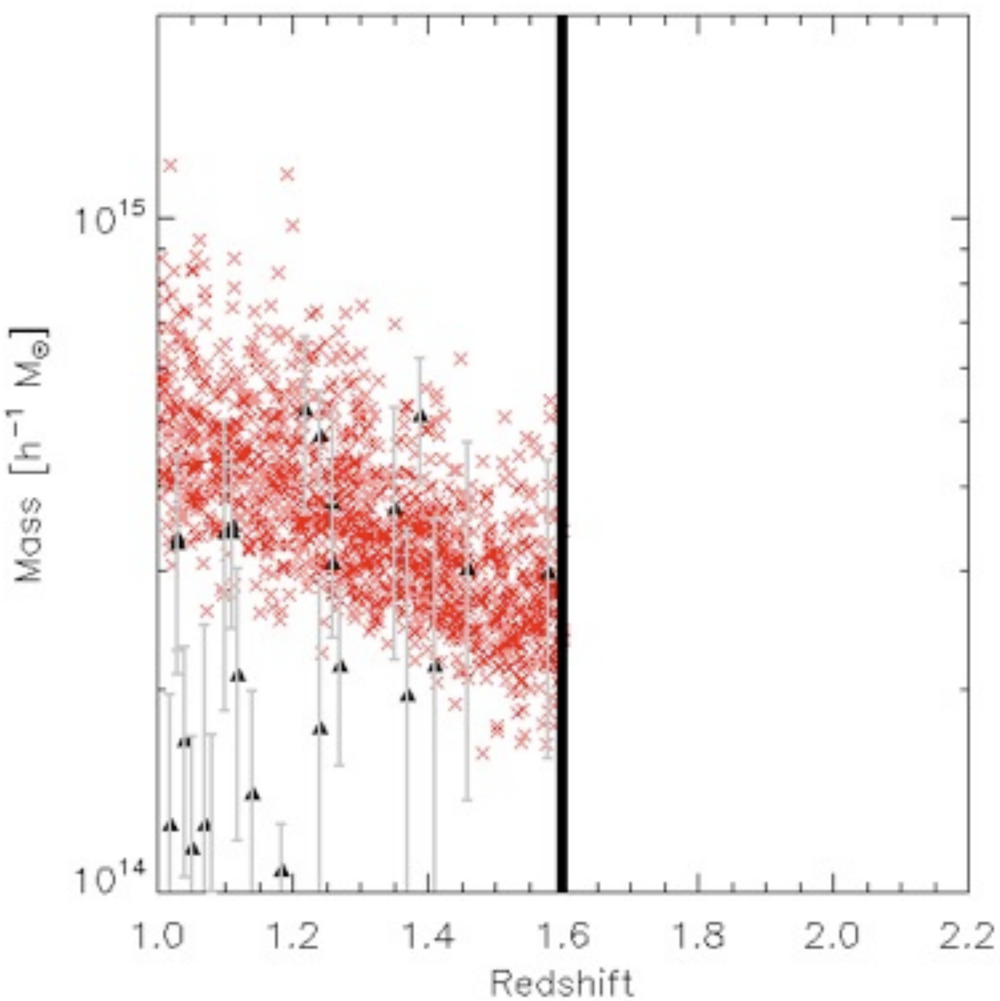
- More high-redshift, massive clusters are being found ~weekly. Planck/XCS/Panstarrs/DES, and will likely be found with future surveys (eROSITA).

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

Follow up work: Panstarrs/XCS/other matching, and to use samples of clusters with an unknown selection function to bound cosmological parameters (in prep.)

z<1.6 survey geometry

All clusters have z<1.6. Perhaps we were too conservative, comparing 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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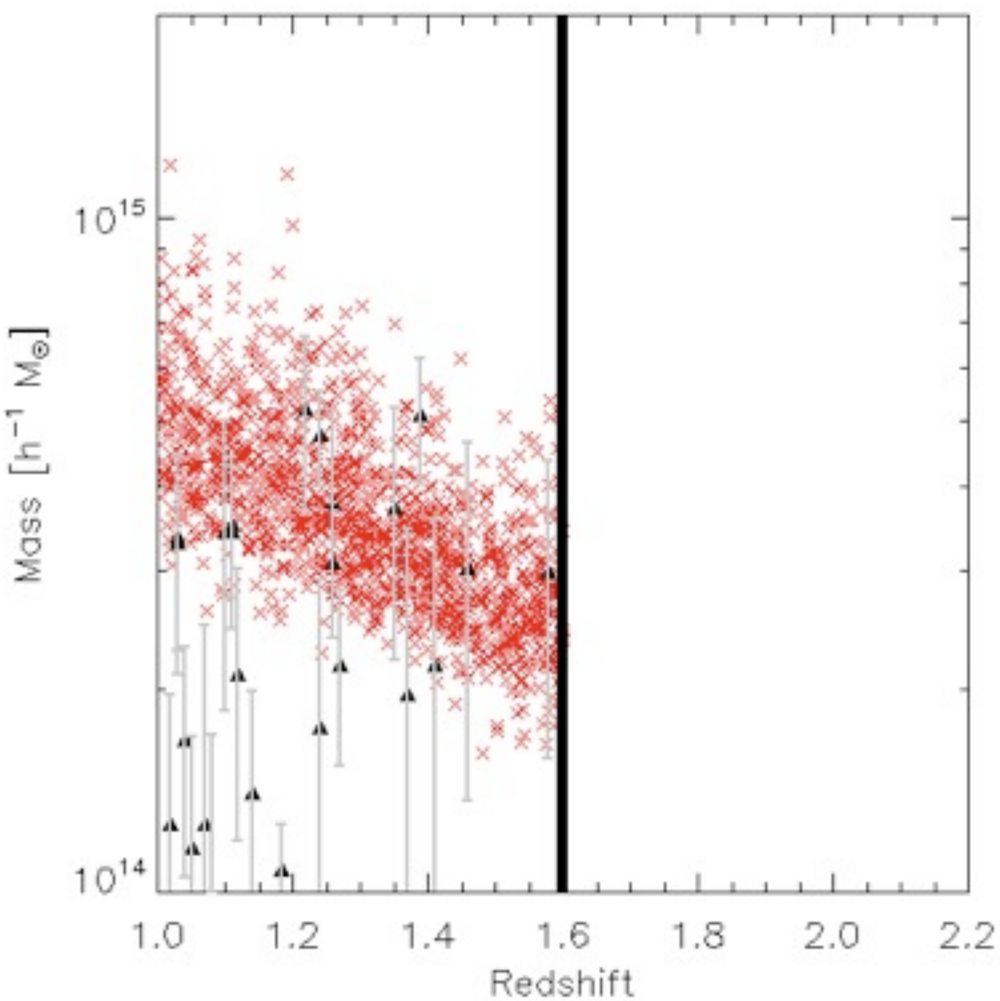

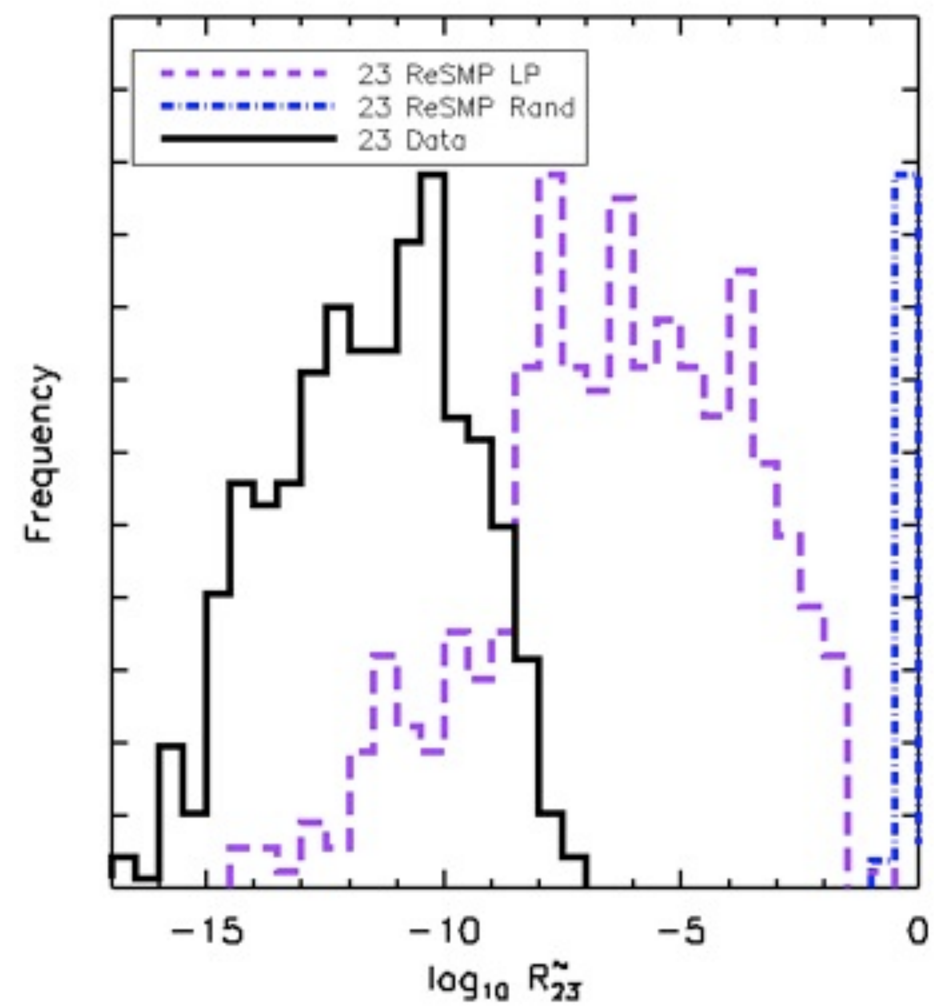

The comparison between observations and z<1.6 simulations still show consistency

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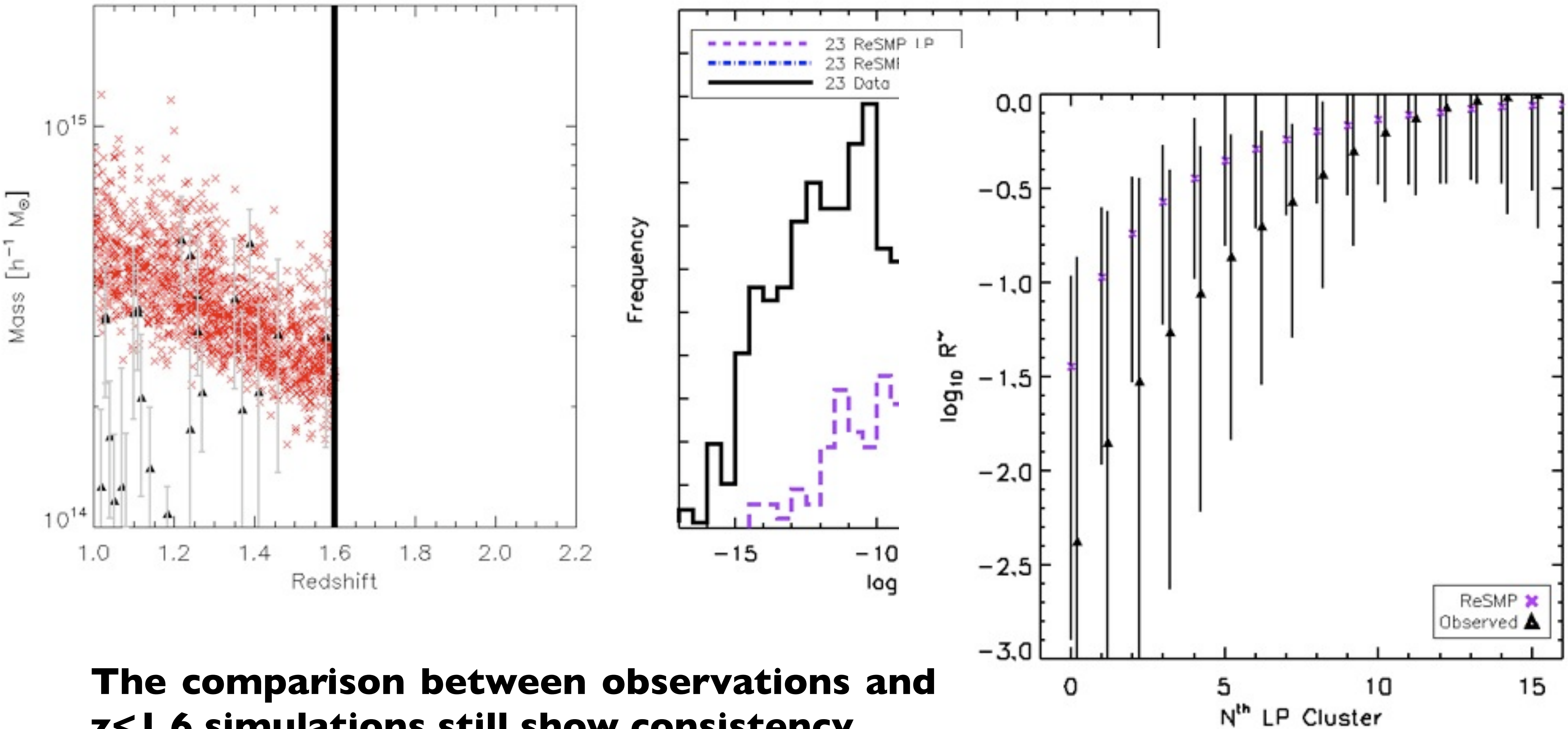

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Remember, (once calibrated) exclusion curves can be used to test for tension using only one cluster.

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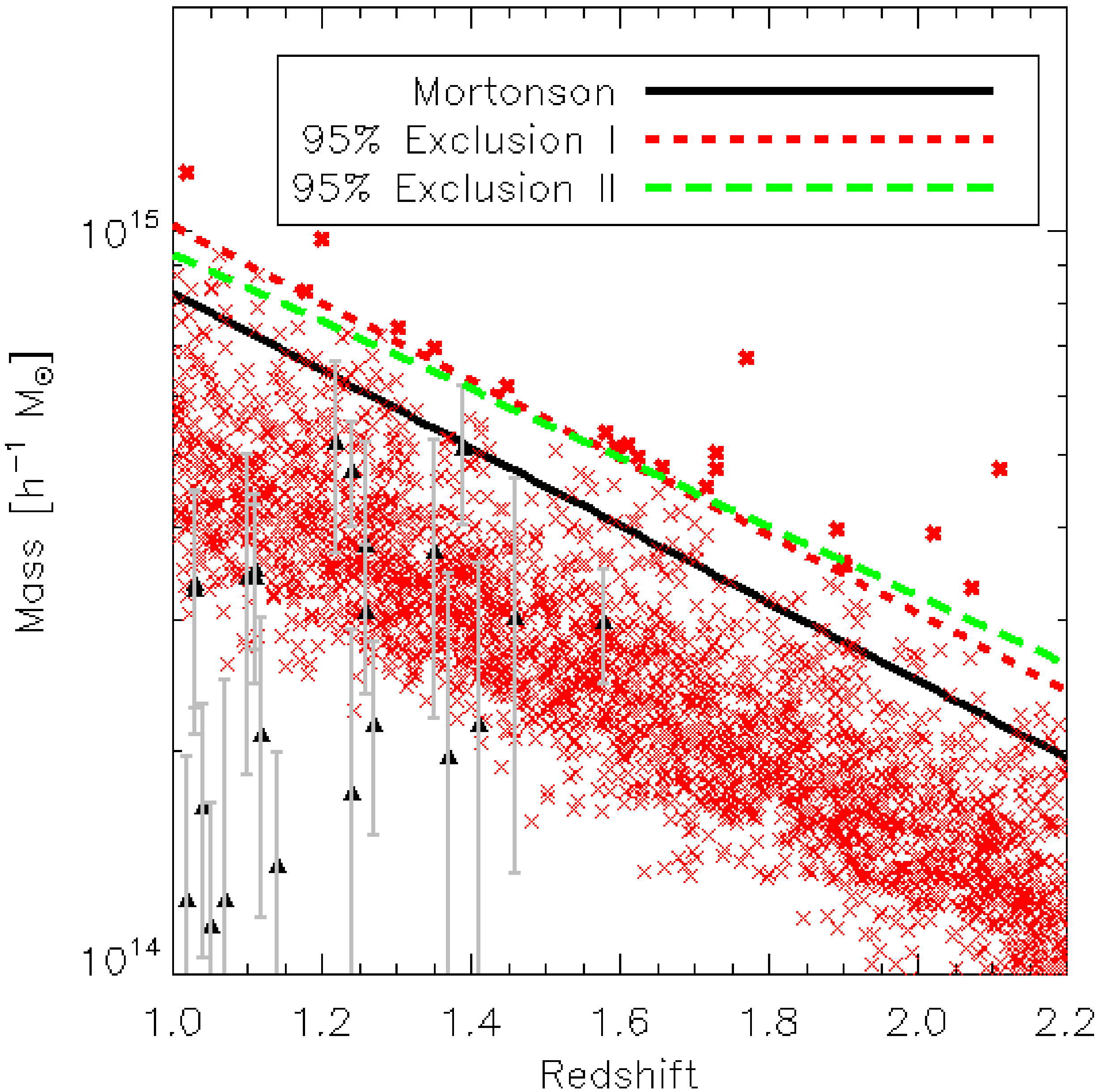

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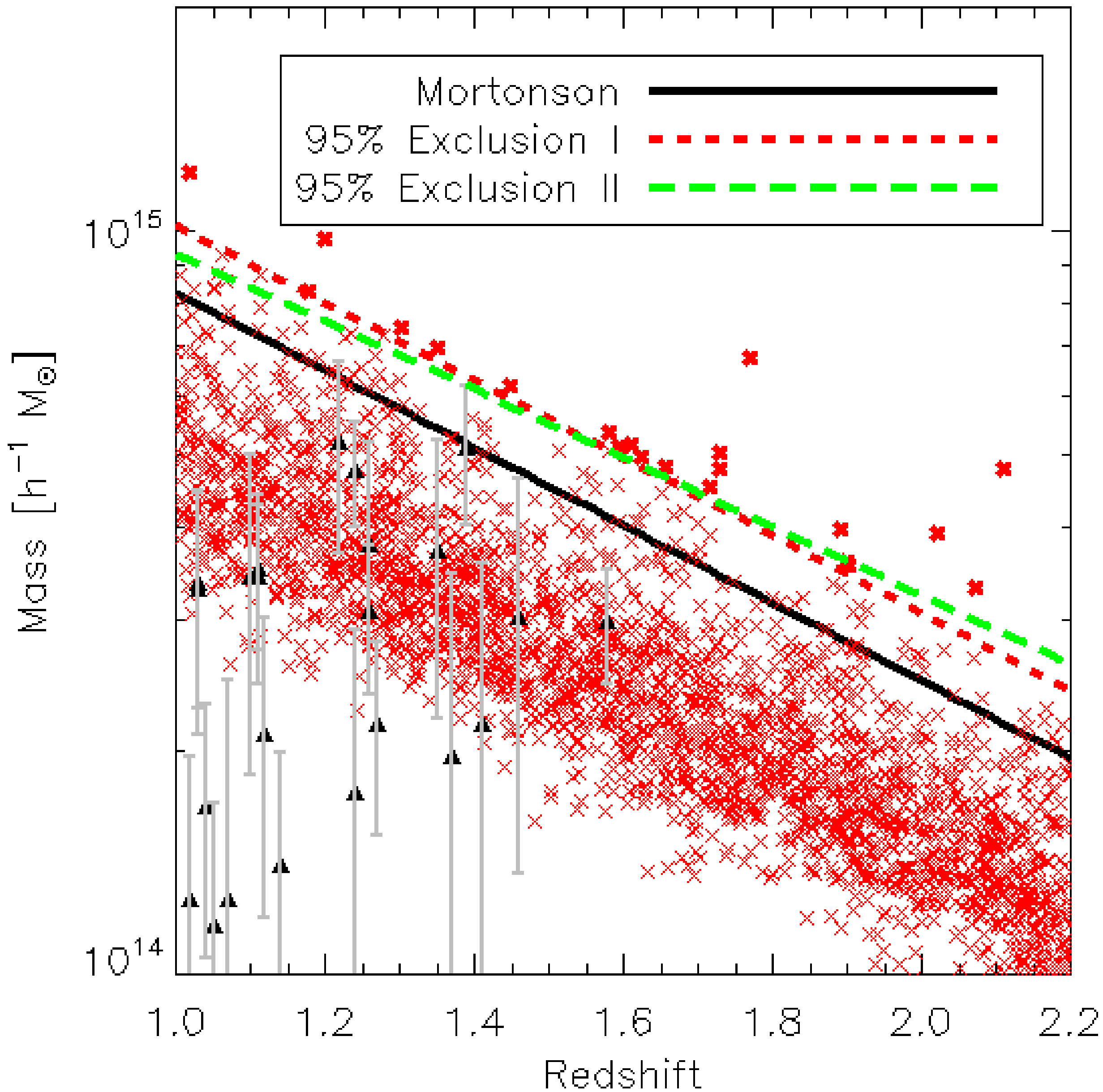

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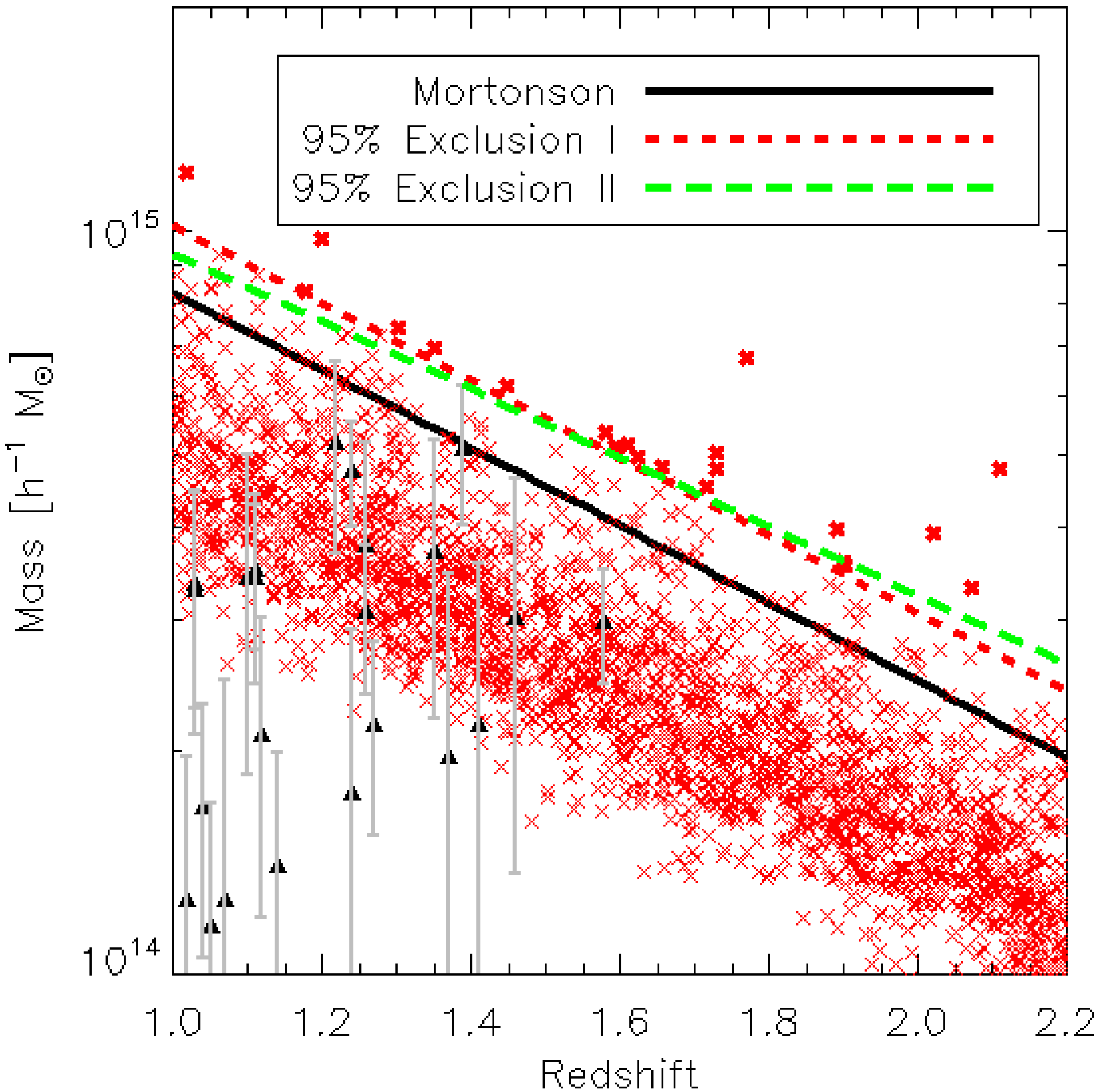
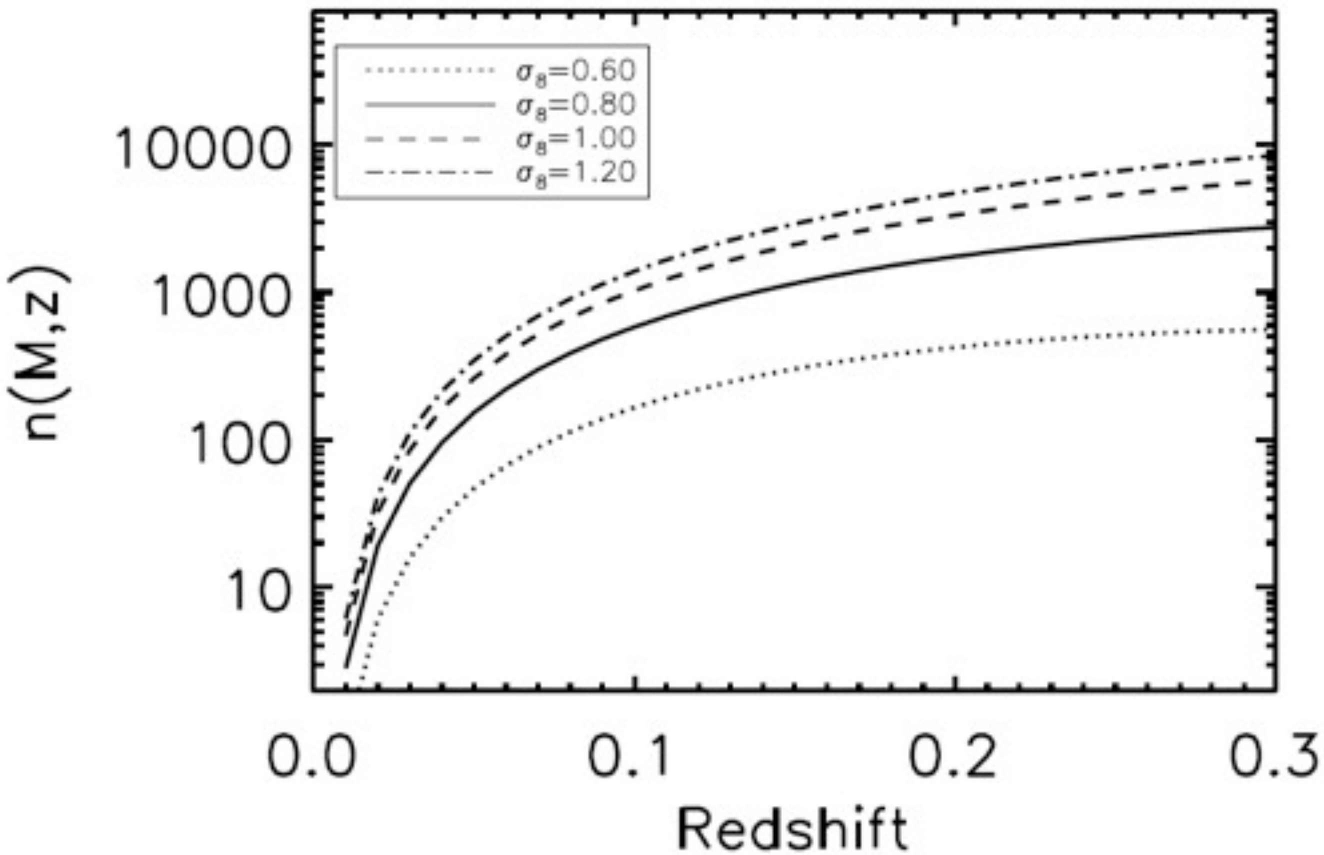
But, this line is arbitrary!

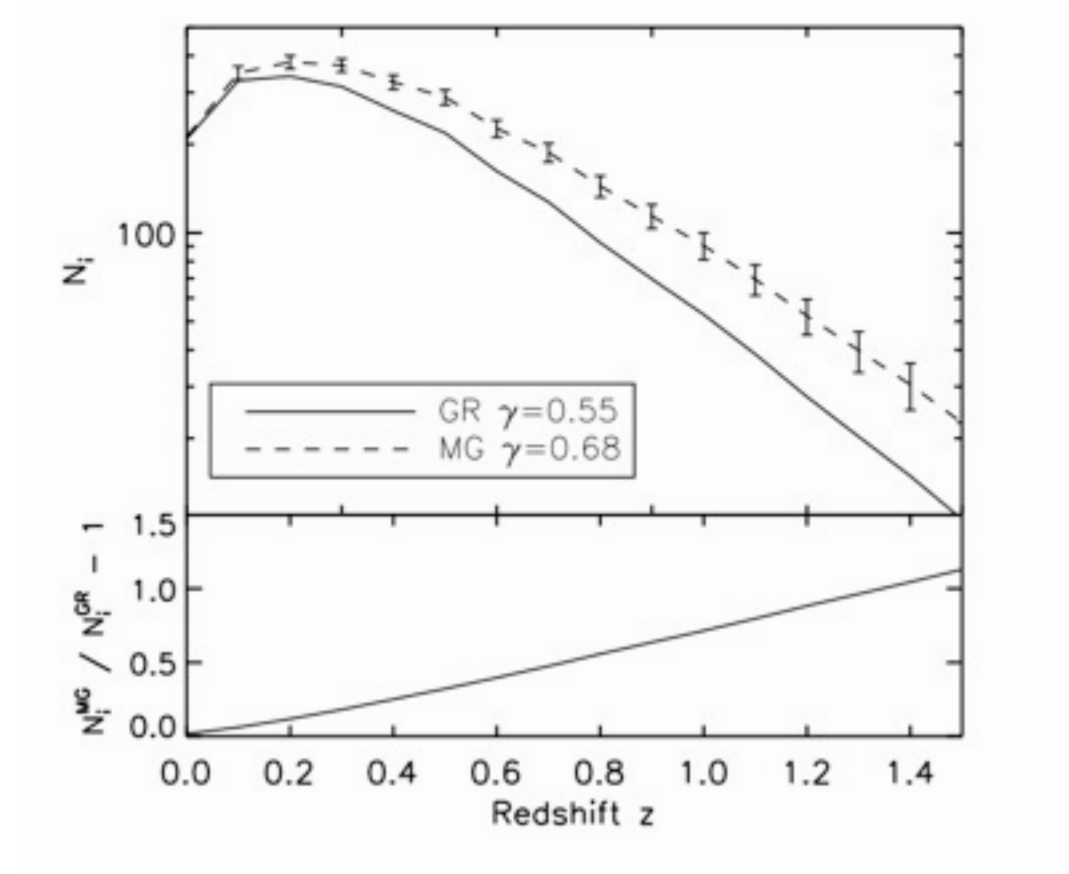
Any inferred exclusion significance must be quoted together with the metric.



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

The CMF with cosmological parameters/models





Shapiro, BH, et al 2010

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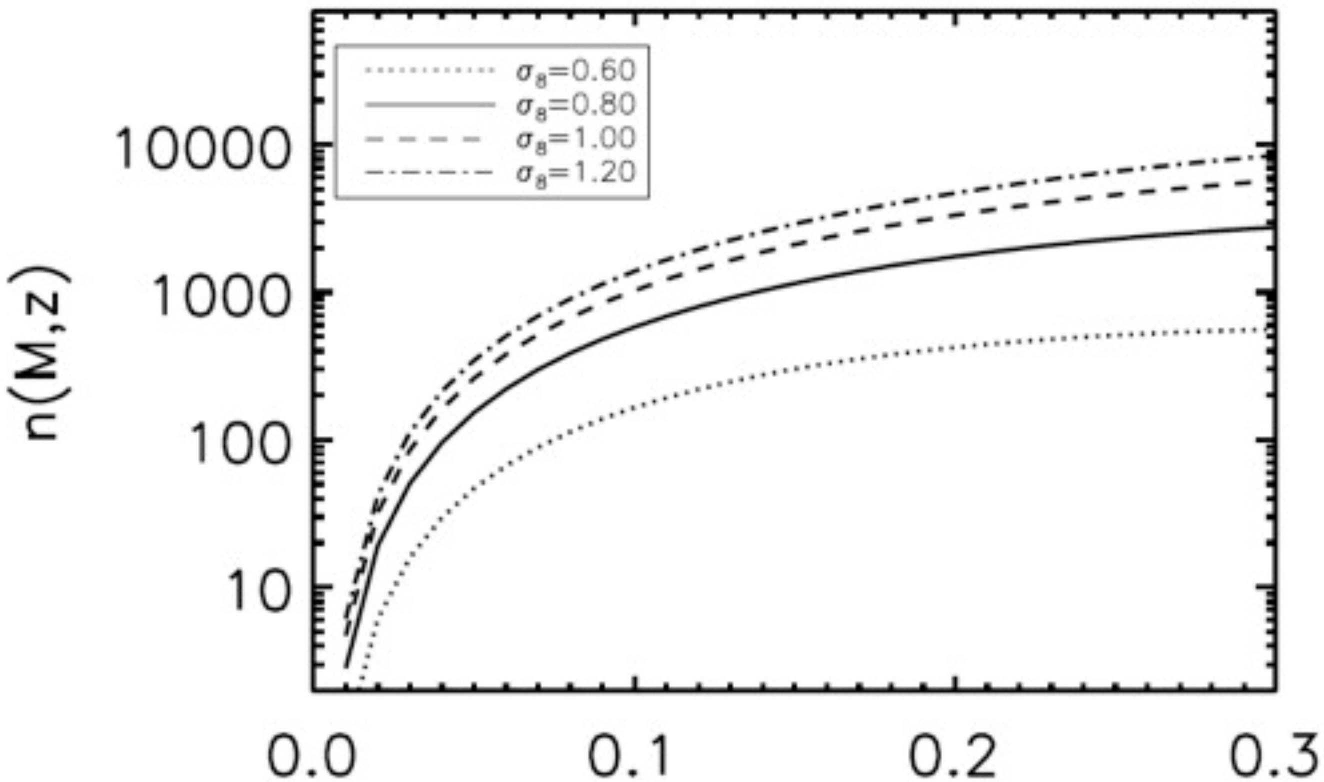

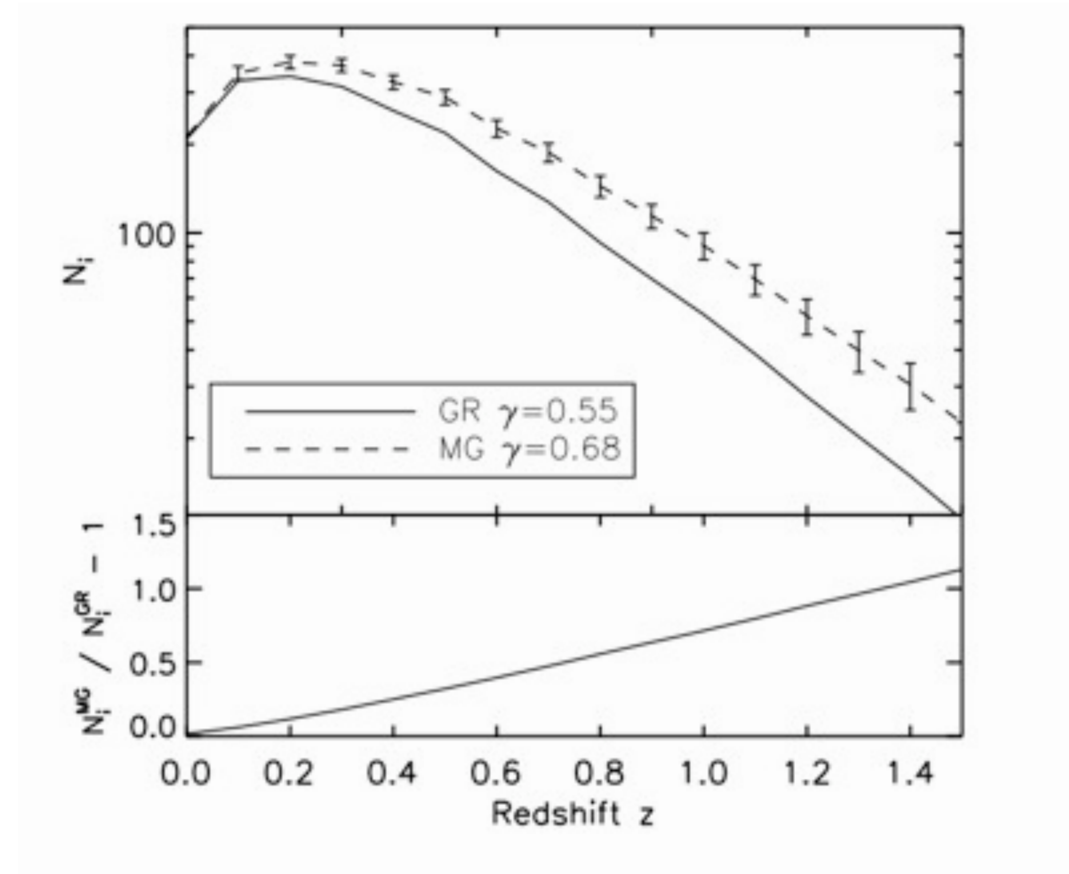

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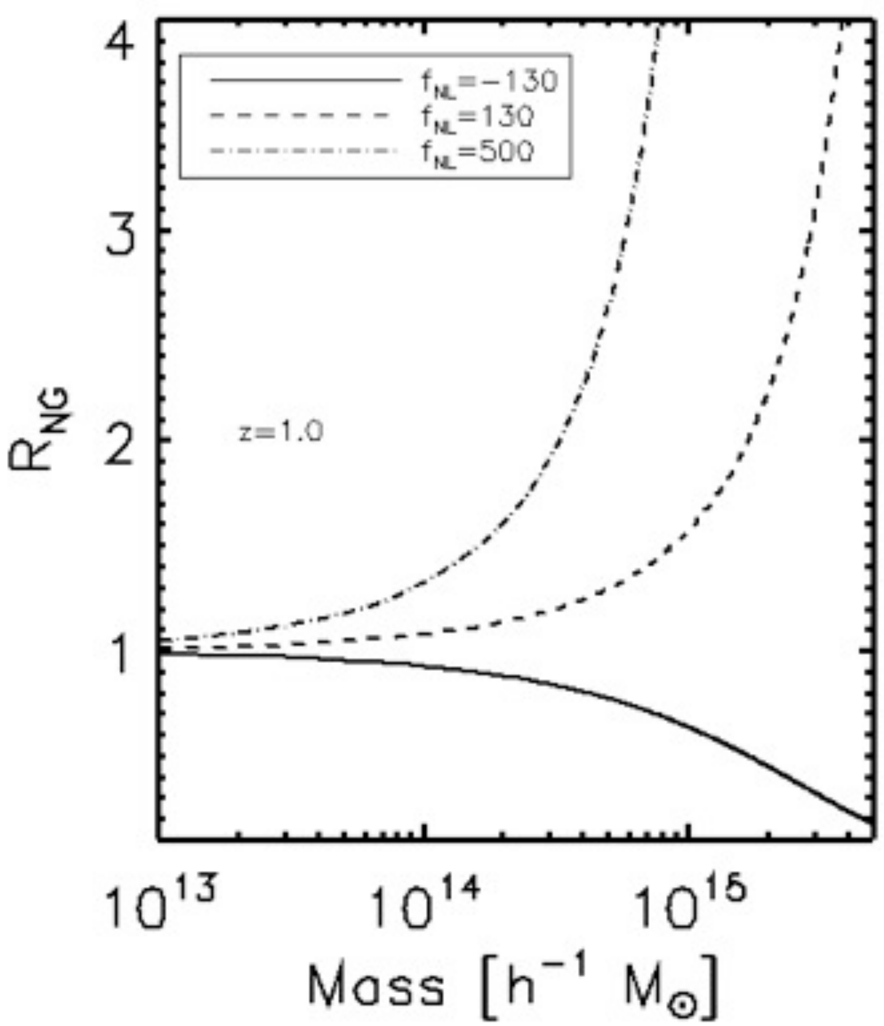

$$\mathcal{R}_{NG}(S_{3,M}, M, z) = \frac{n(M, z, f_{\rm NL})}{n_G(M, z, f_{\rm NL} = 0)}$$

E.g., Ixandra Achitouv & Corasaniti 2012, Wagner et al 2010

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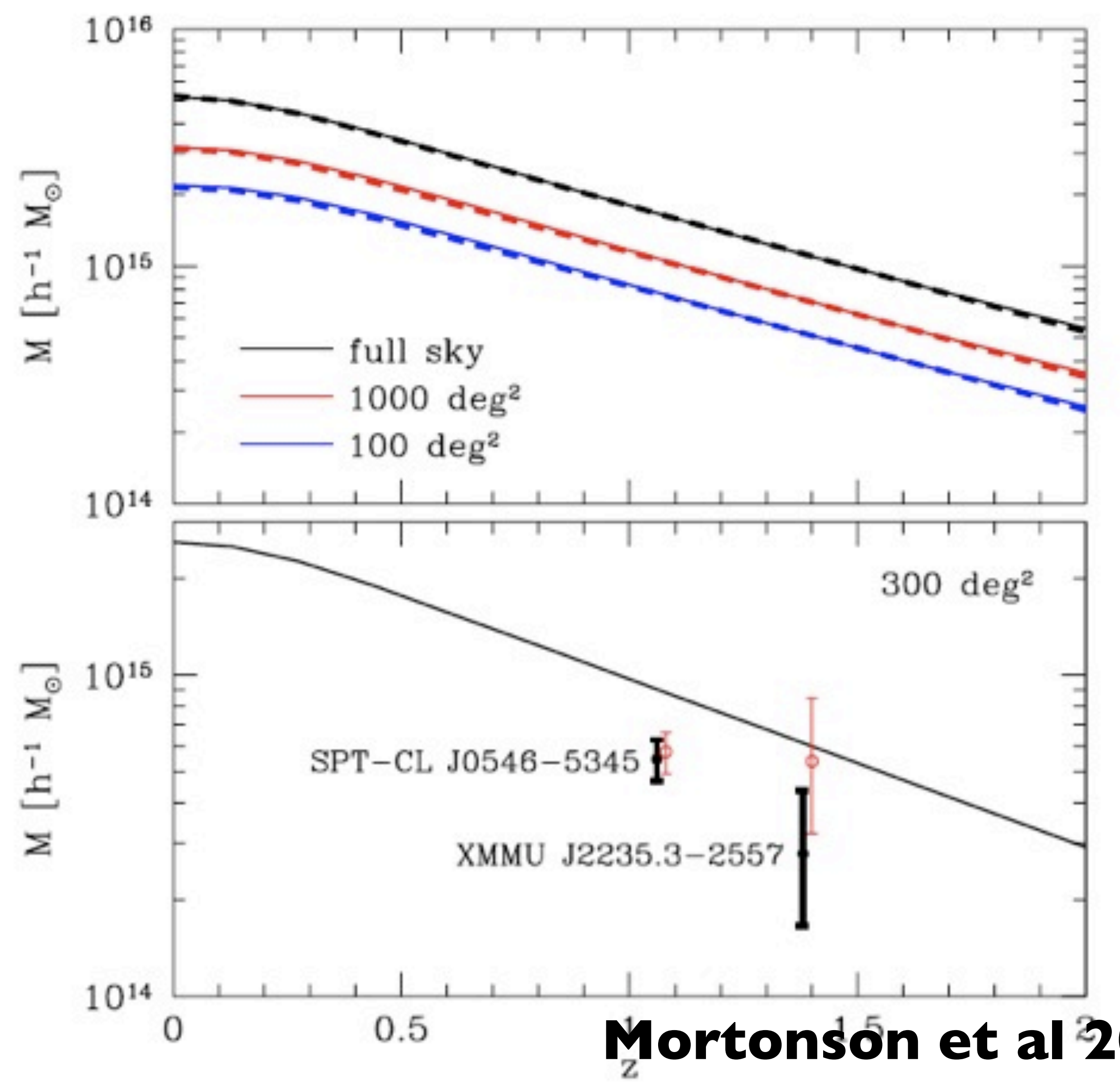
Given the (w)LCDM model with WMAP7 cosmological priors, we do not expect any cluster to sit above the curve at 95% or some other specified confidence.

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
MS 1054-0321	0.35
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Jee et al 2011

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

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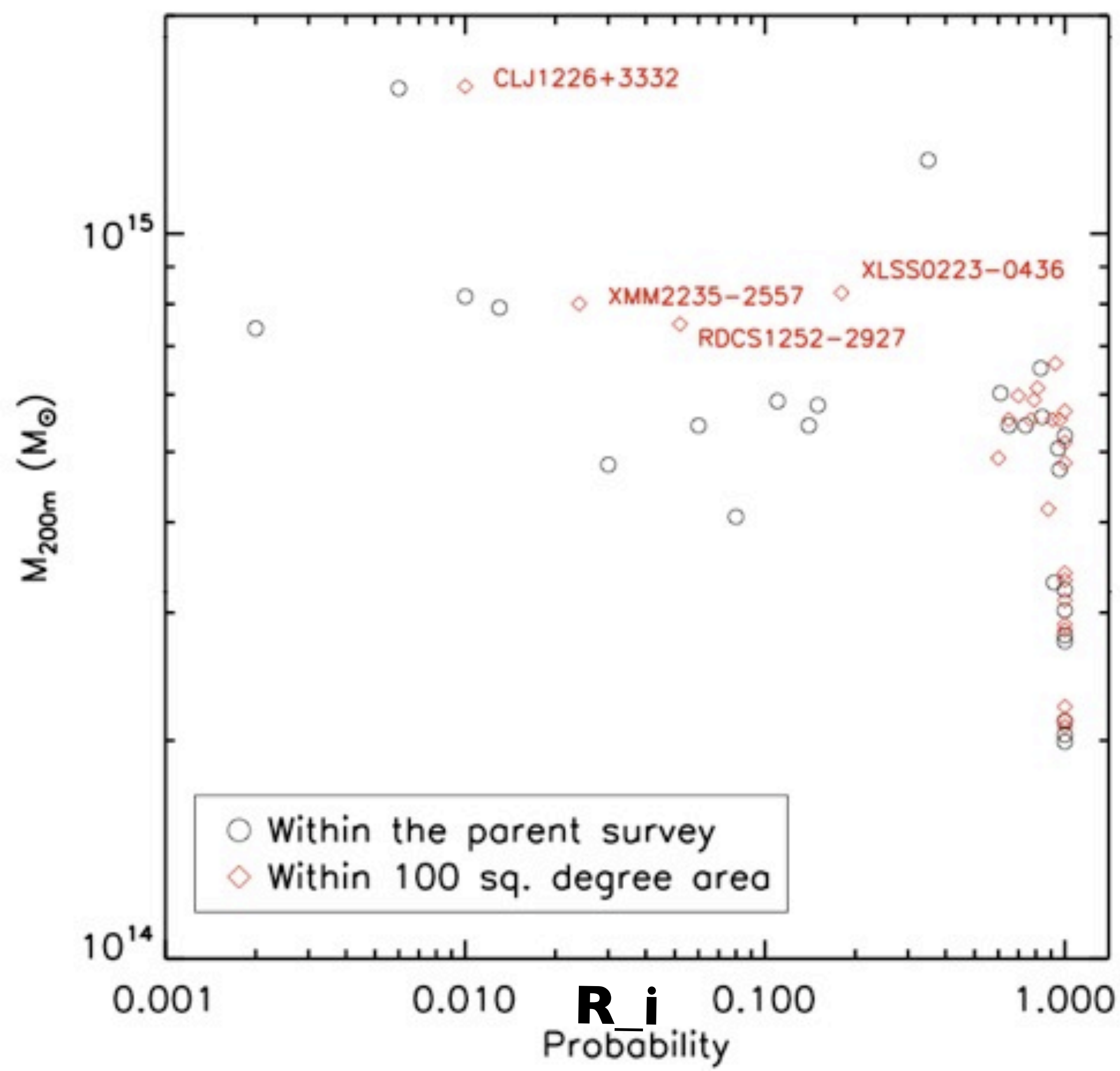

R_i

The ensemble of clusters was 'unlikely' to have been observed.

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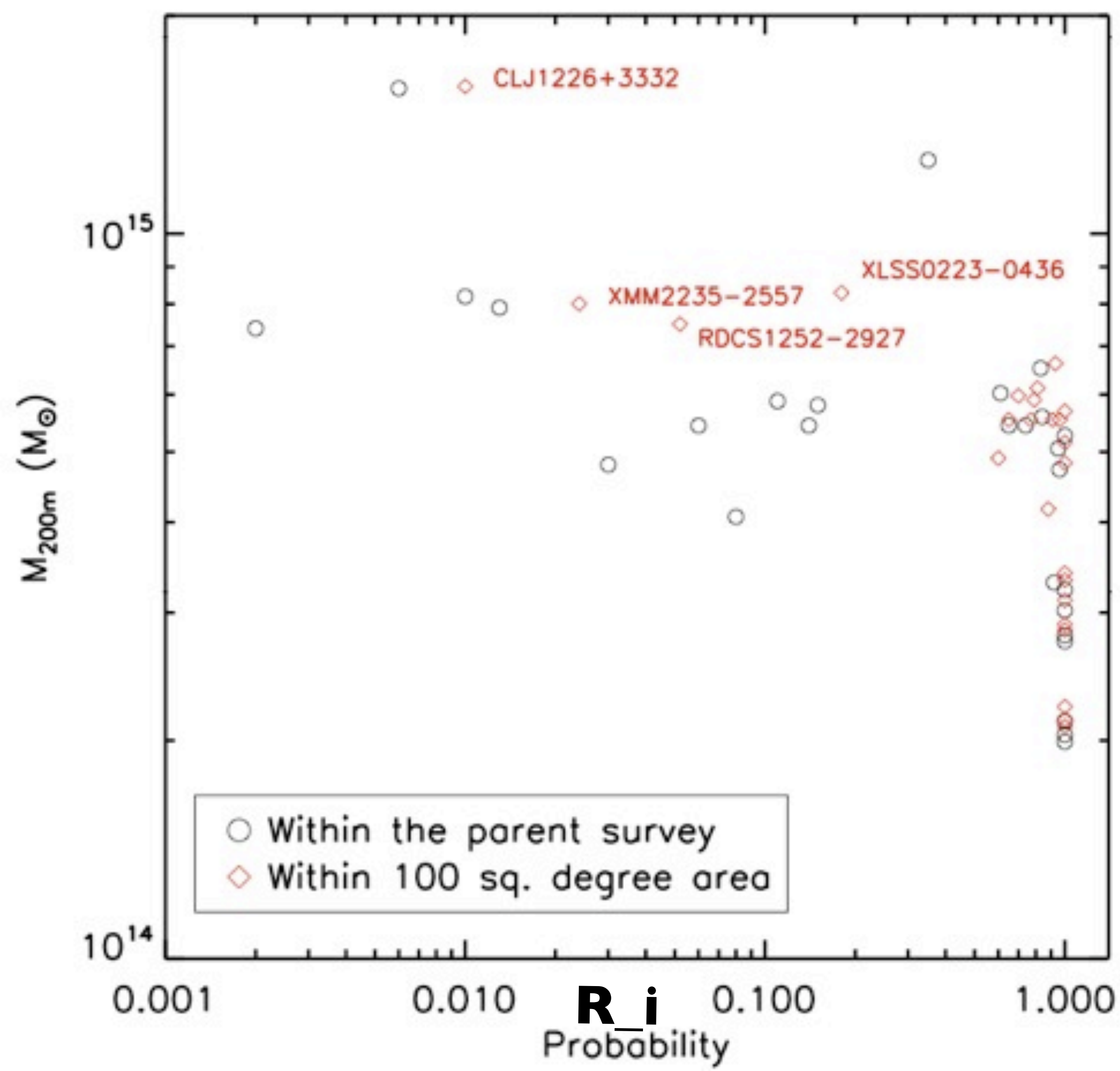

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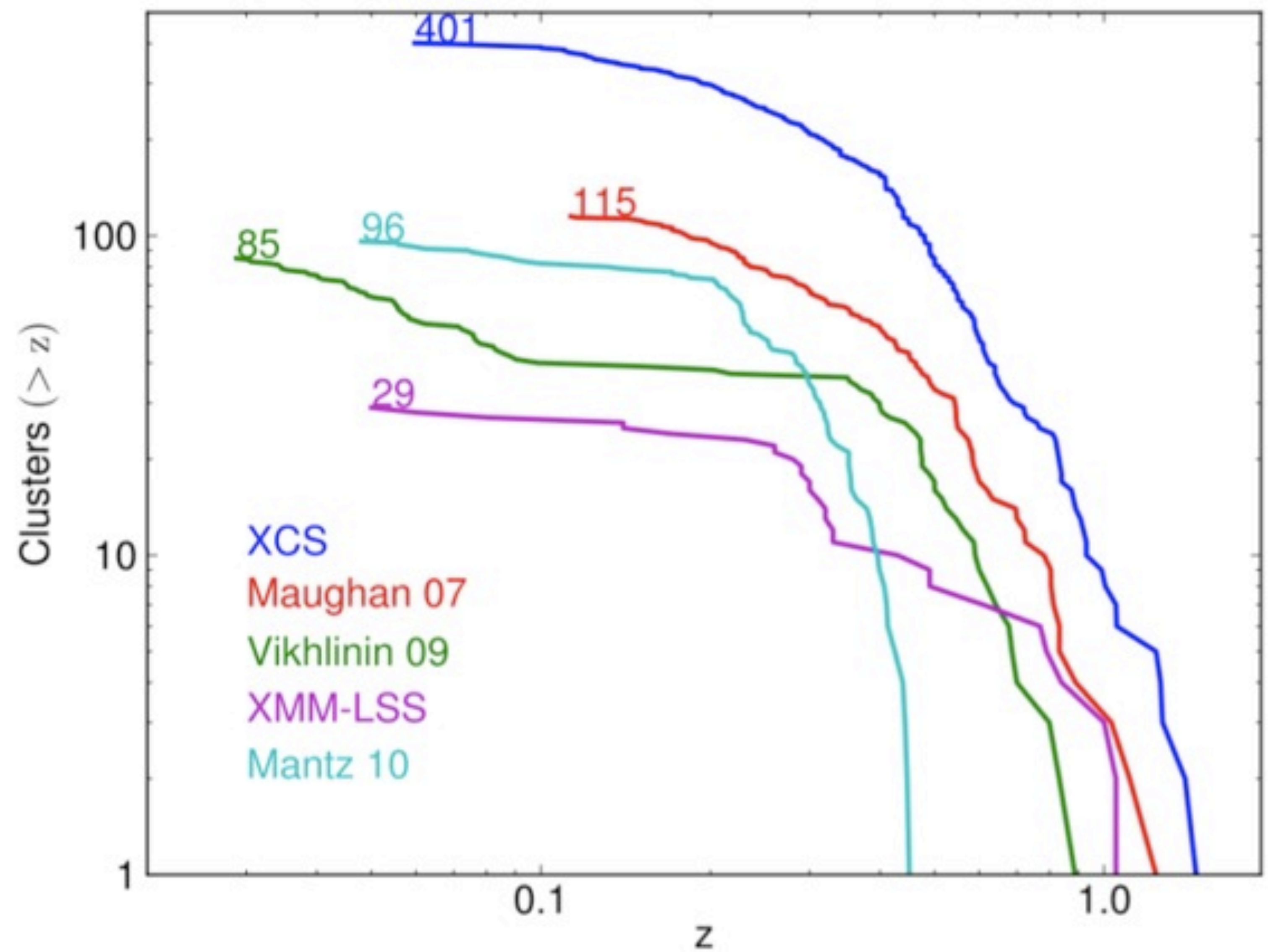
Are these clusters really in tension with LCDM, or have we been goofing up? What's going on?

XCS: Comparison with other X-ray surveys



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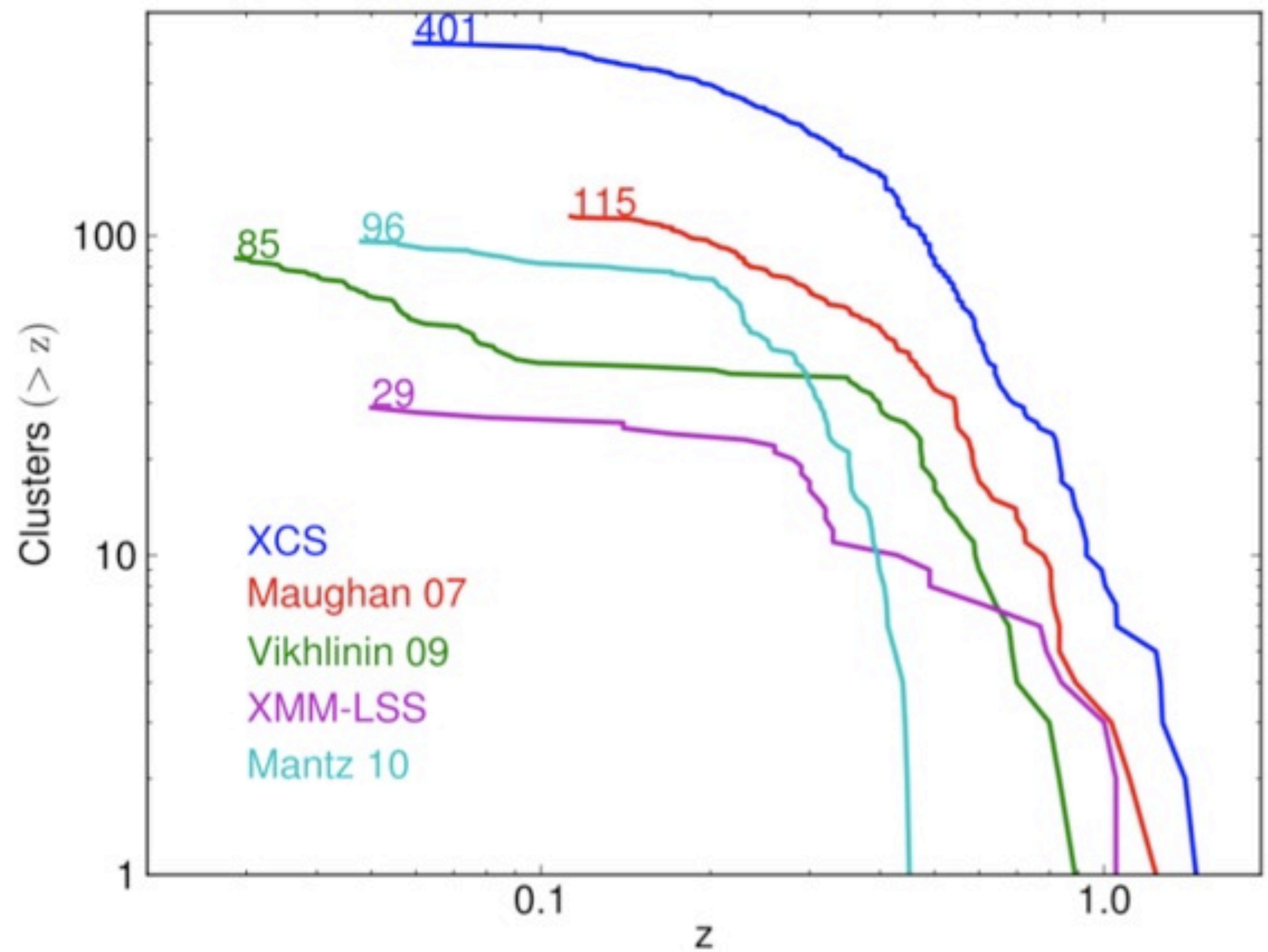


The Future

- **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/**

Galaxy cluster

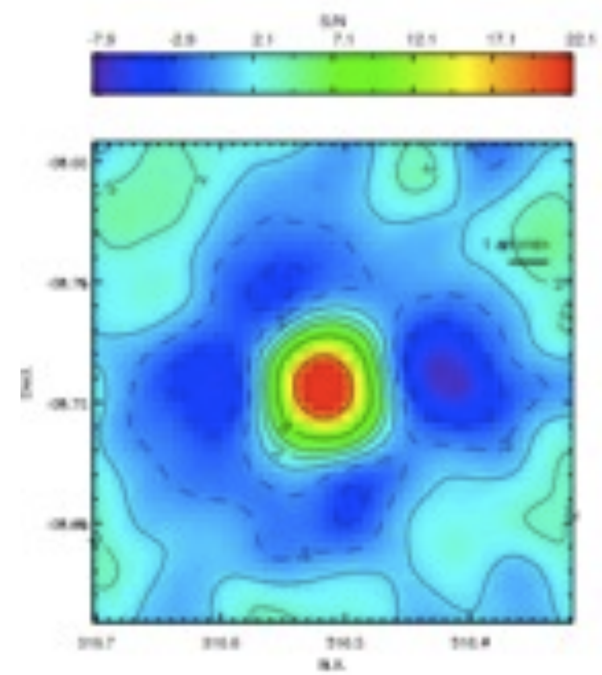
From Wikipedia, the free encyclopedia

It has been suggested that this article or section be merged into *Galaxy gr*
(Discuss) *Proposed since January 2012.*

A **galaxy cluster** is a structure that consists of hundreds of galaxies bound by gravity.[1] Galaxy clusters are much larger than galaxy groups. One of the key features of clusters is the Intracluster medium or ICM. The ICM consists of gas between the galaxies and has a temperature on the order of 7-9 keV. Clusters of galaxies should not be confused with star clusters such as open clusters, which are structures of stars *within* galaxies, as well as globular clusters, which typically orbit galaxies.

Name of the components	Mass fraction
Galaxies	1%
Intergalactic gas in ICM	9%
Dark matter	90%

www-xray.ast.cam.ac.uk



Foley et al 2012

Why use clusters, when we have WMAP?
Clusters probe the growth of structure, and so are complementary to geometry probes such as CMB.