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

**Ben Hoyle, Raul Jimenez, Licia Verde, ICC-IEEC University of Barcelona, Shaun Hotchkiss University of Helsinki: Hoyle et al 2011 (PRD) and arXiv: 1108.5458 (JCAP sumbitted) + in prep)**

**Stockholm: 13/09/2011**

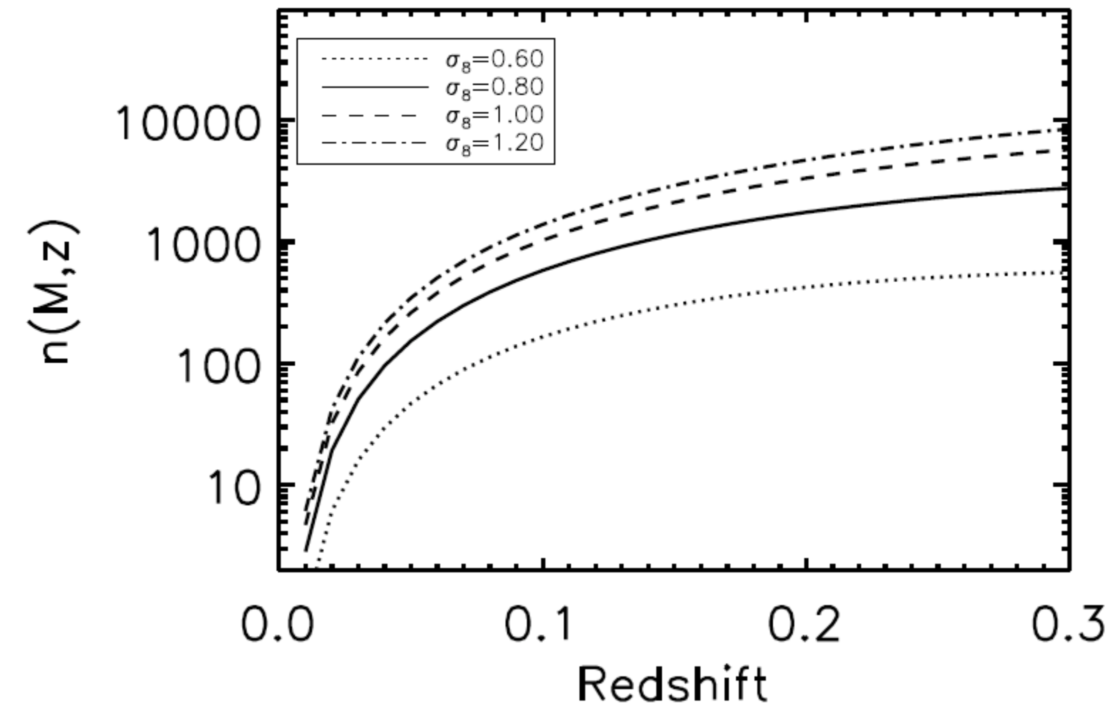
# Overview

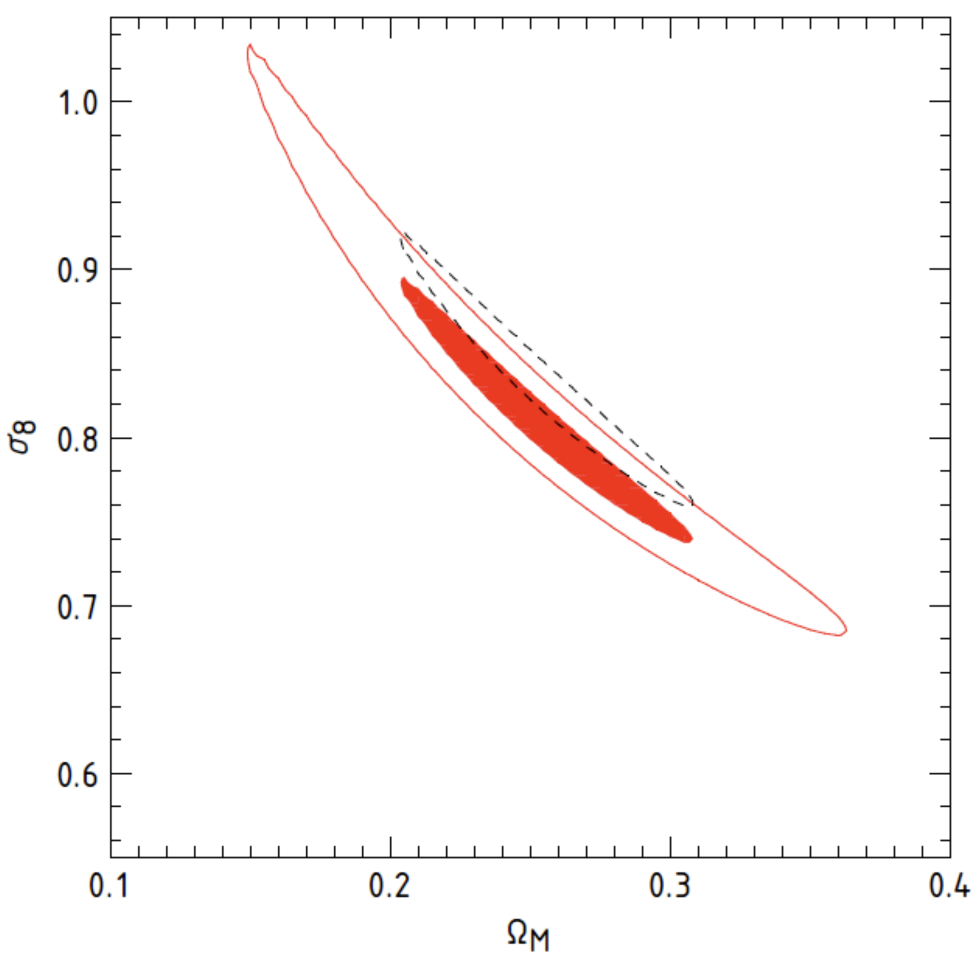
- Using galaxy clusters as extreme objects
- A critical look at the common exclusion curves
- Observational motivation: extreme objects
- Theory: non-Gaussian cluster mass function
- The observed cluster sample
- The XMM Cluster Survey
- Our previous >M,>z analysis & interesting results
- Possible explanations; systematics & bias
- A critical look at the >M,>z analysis
- New (correct) analysis and results
- Conclusions + future work

# Using large samples of clusters to constrain cosmology

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

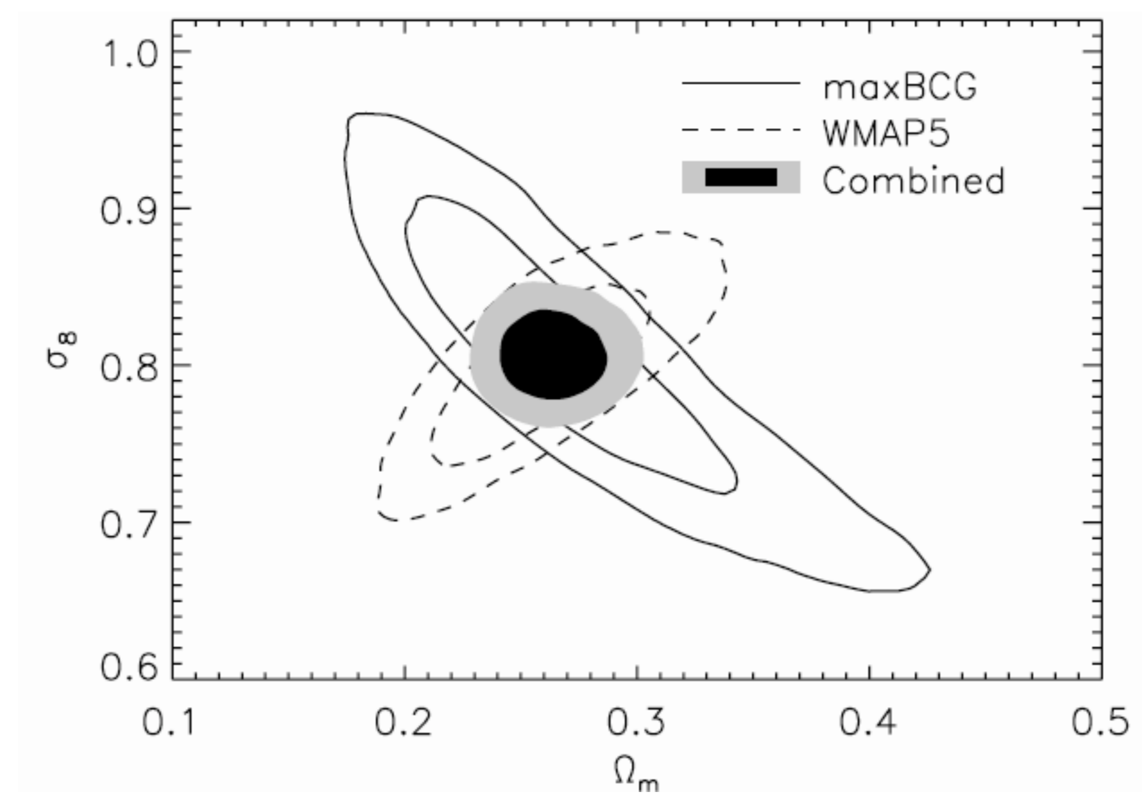
$$n_G(M,z) = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M^2}\left|\frac{\mathrm{d}}{\mathrm{d}\ln M}\ln\sigma_M\right|\,\nu\,\exp -\nu^2/2\,.$$




**X-ray selected clusters: Vilhlinin et al. 2008**

$N \sim 10^2$




**Optically selected clusters: Rozo et al. 2009**

$N \sim 13 \times 10^3$

# Individual clusters as "extreme object" probes of cosmology.

**If we find a cluster which is considered "very rare", we can use its existence to rule out a cosmological model using exclusion curves (Mortonson et al 2010, Hotchkiss 2011)**

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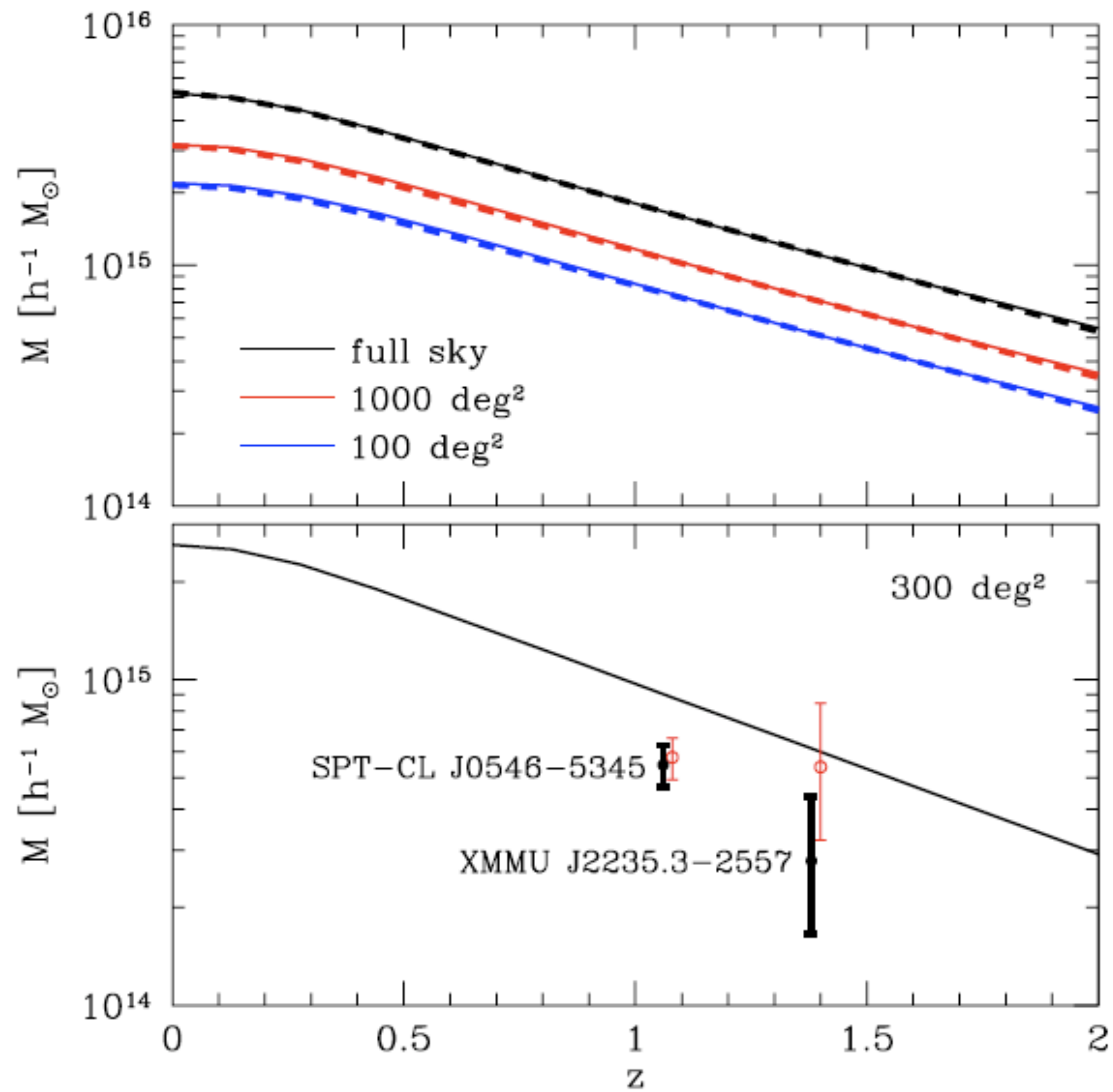
**Given the (w)LCDM model with WMAP7 cosmological priors, we do not expect any cluster to sit above the curve at 95% or some other specified confidence, (after fixing for selection functions and bias)**

**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**

# A closer look at >M,>z exclusion curves

**The exclusion curves are an excellent way to test for tension using only one cluster, after assumptions about survey geometry & selection functions have been made. Once fixed for following bias (See Hotchkiss 2011)**

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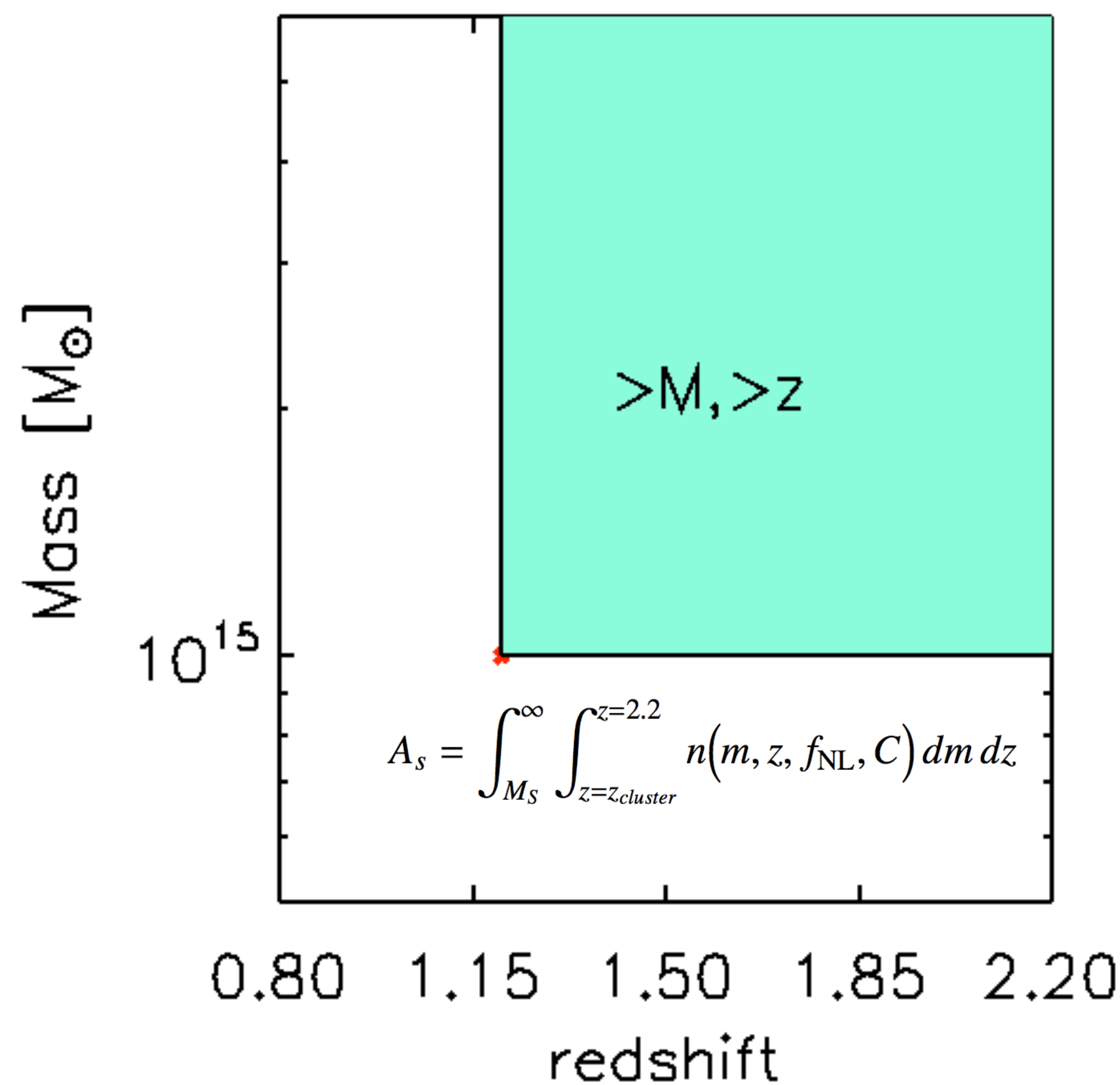

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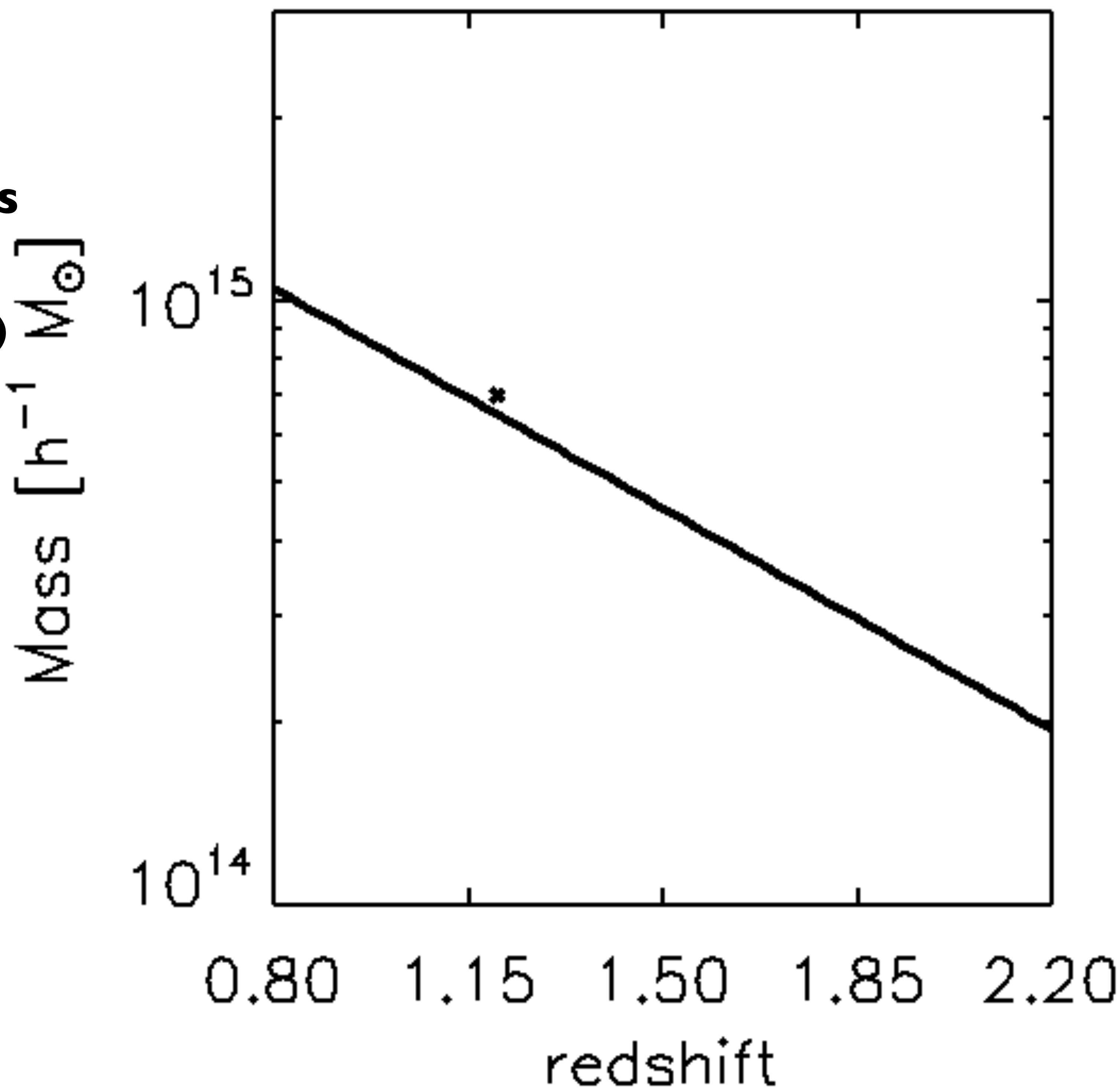

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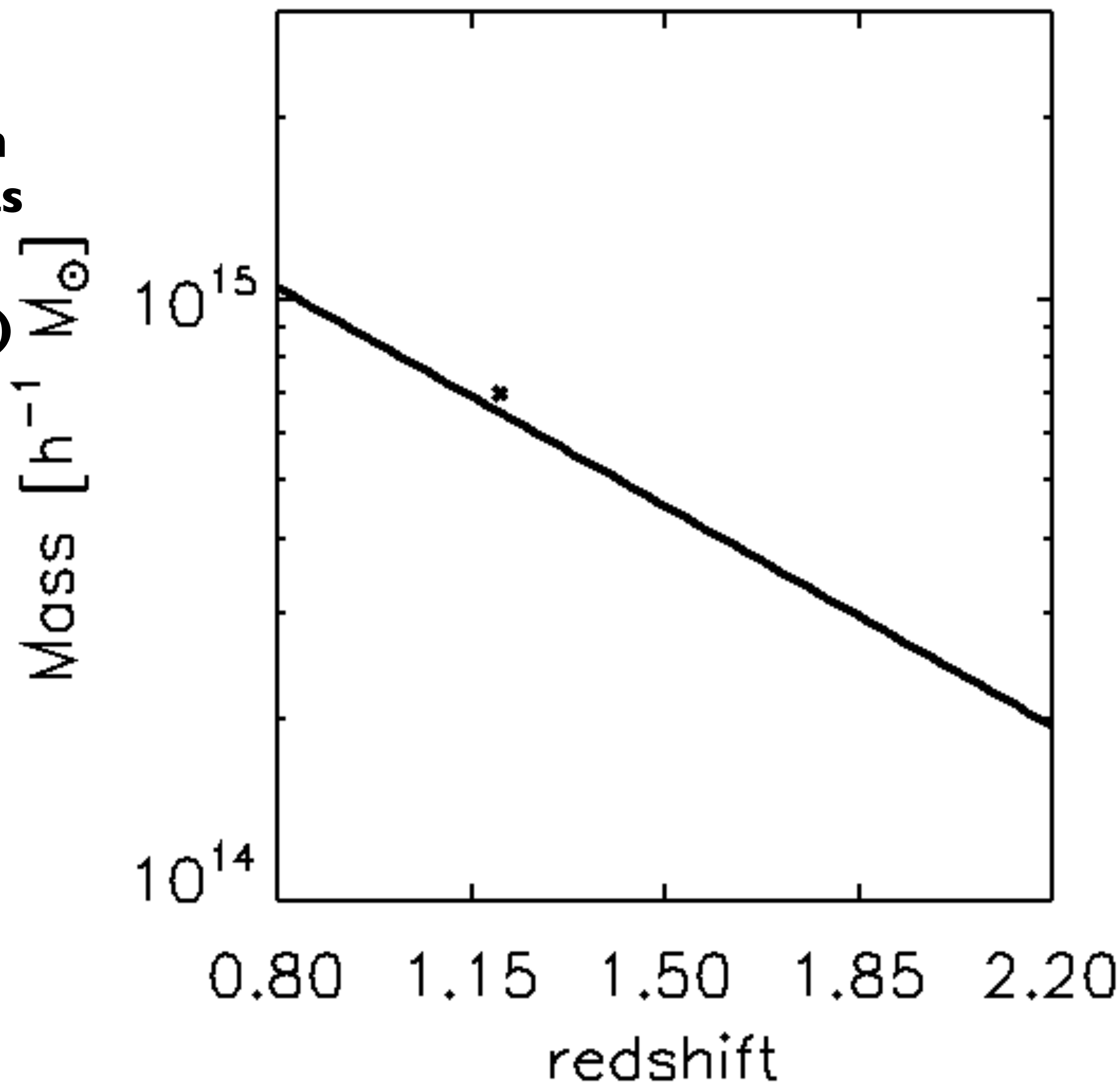

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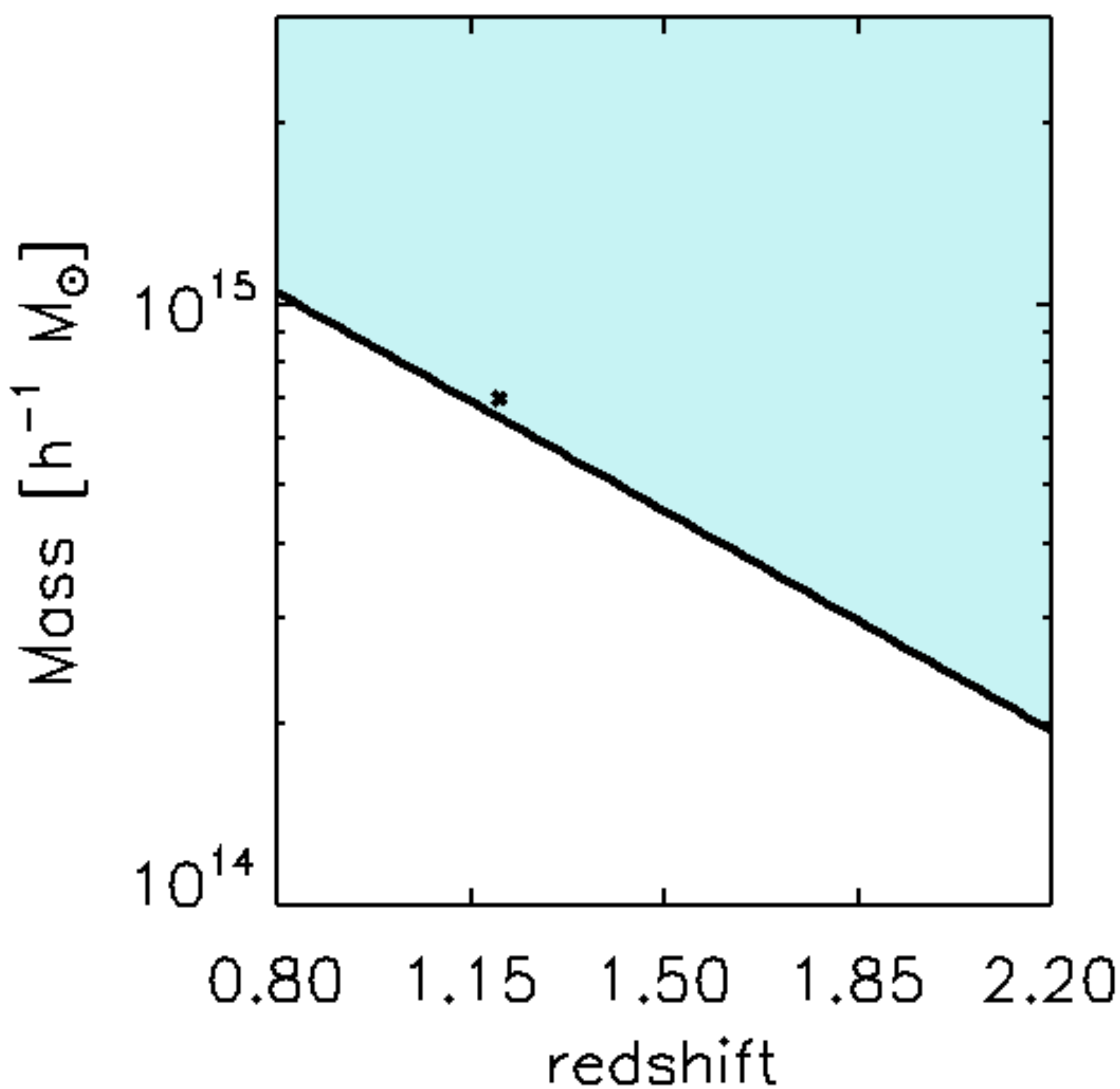

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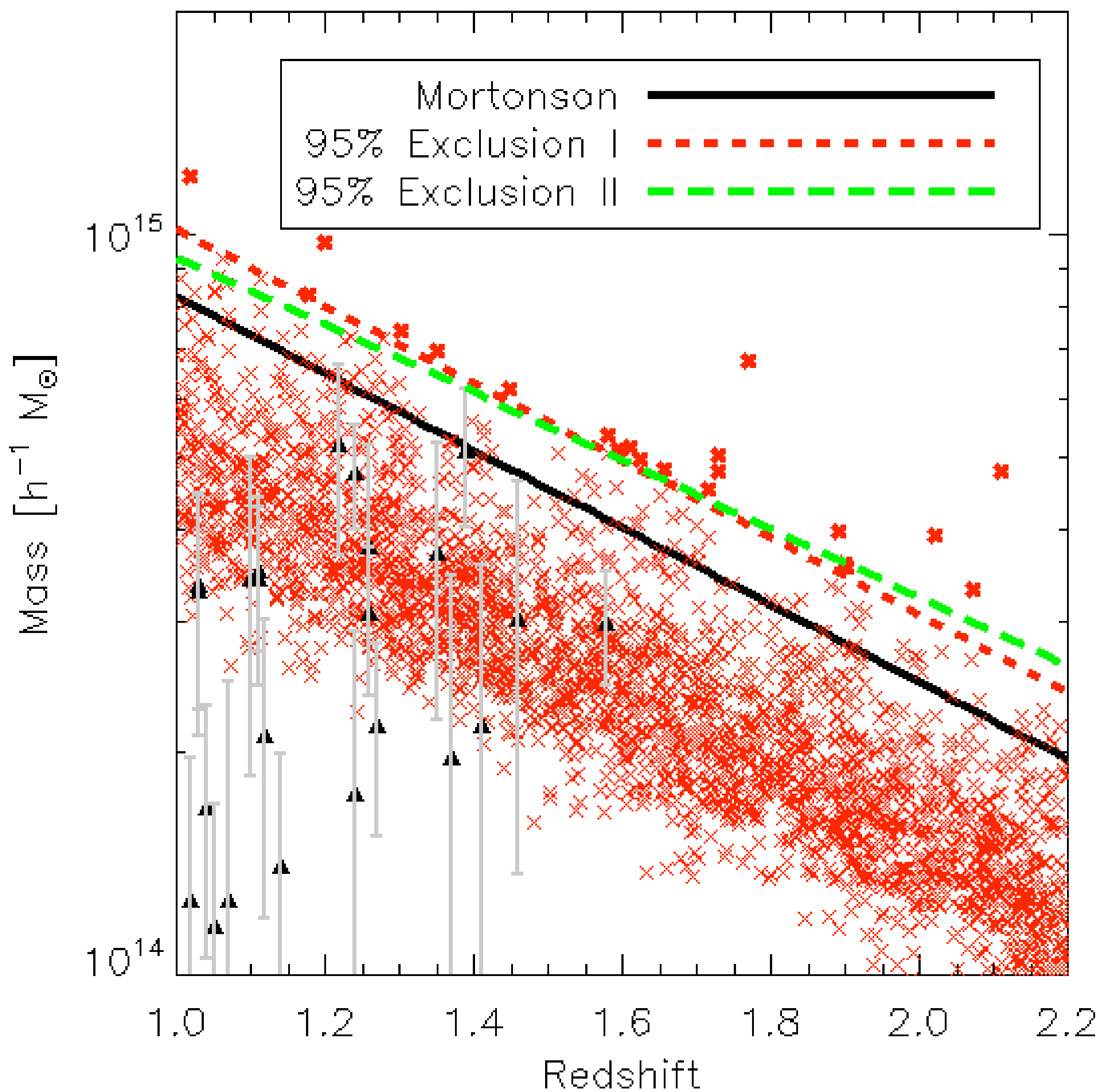

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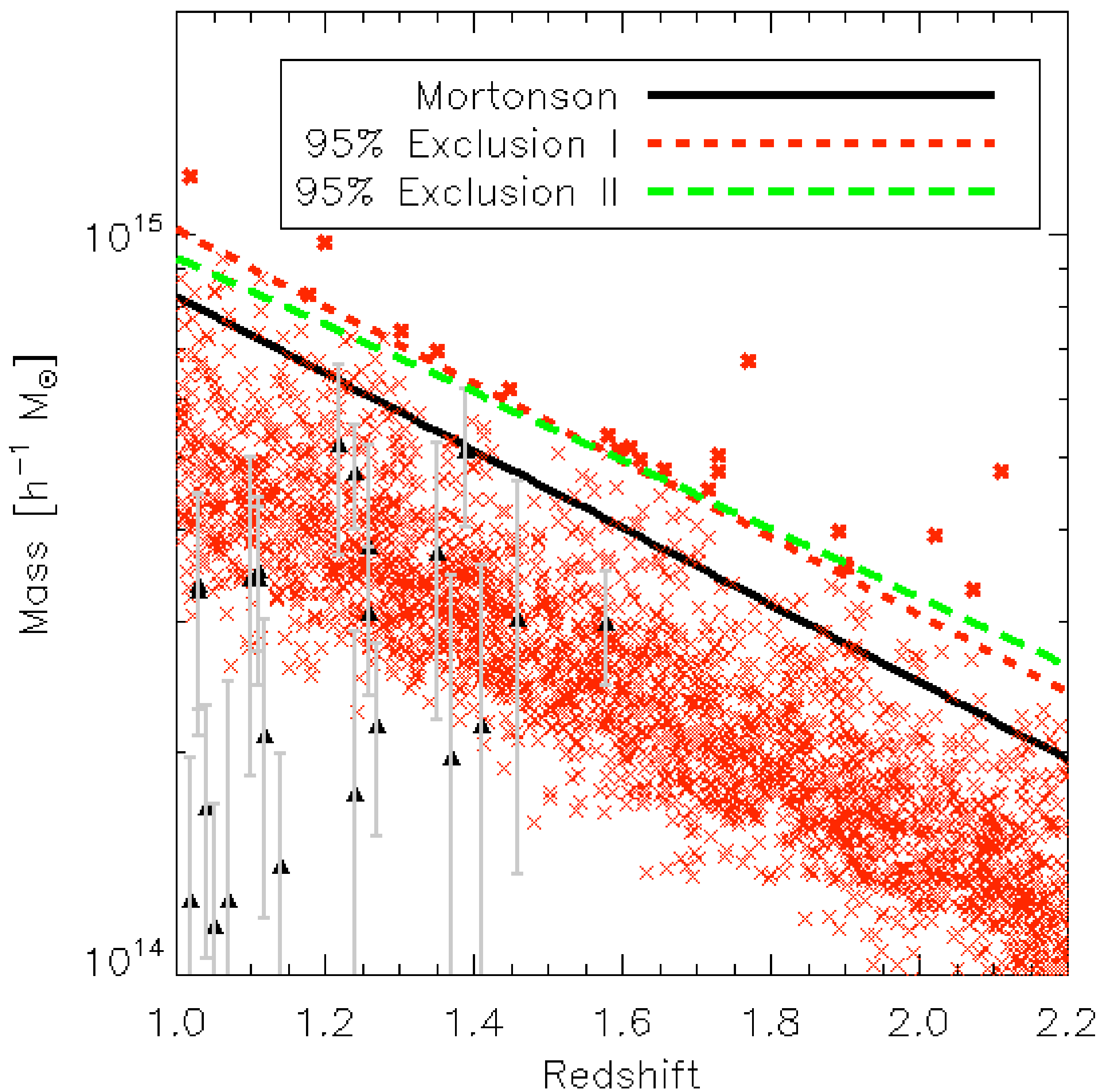
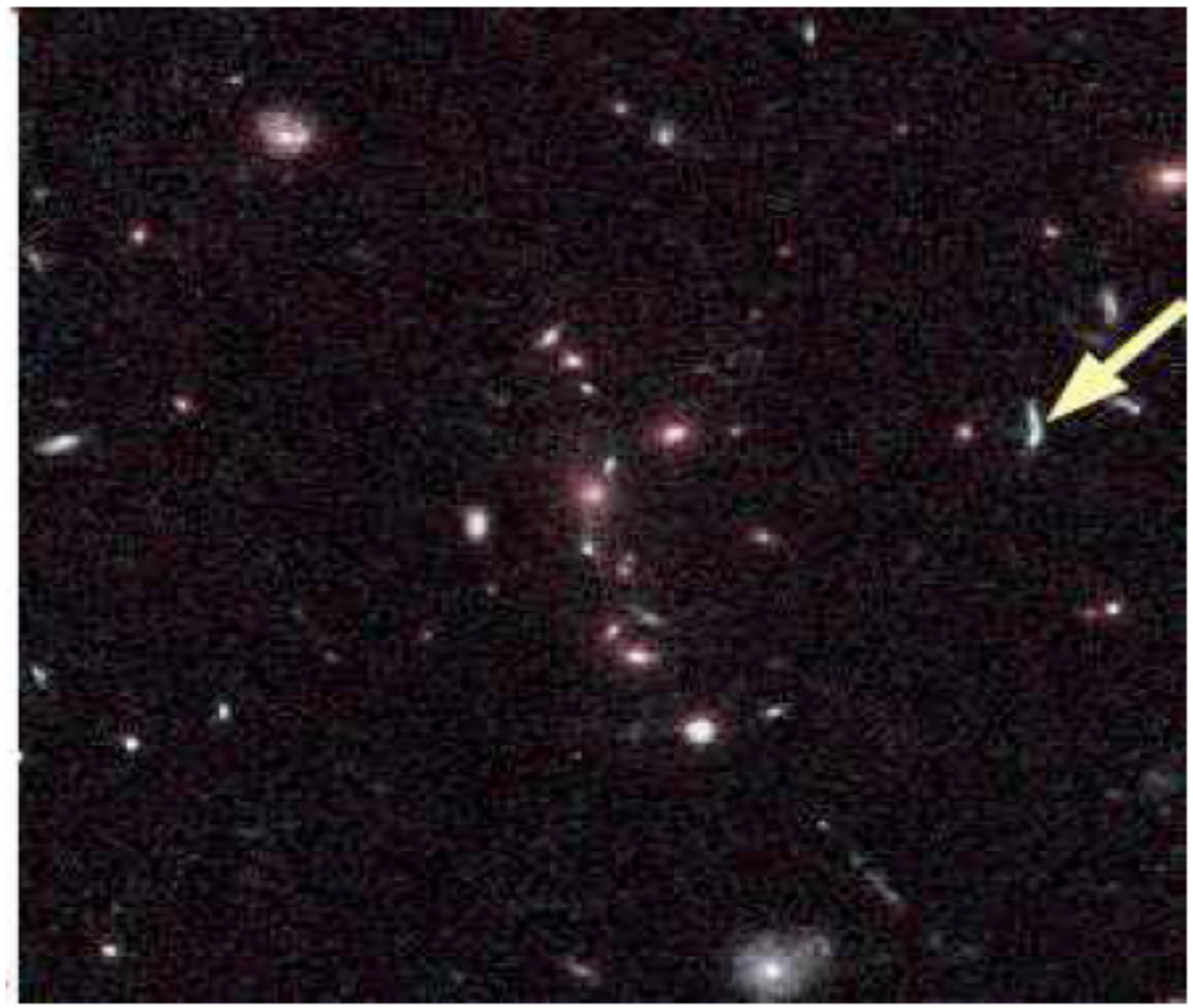
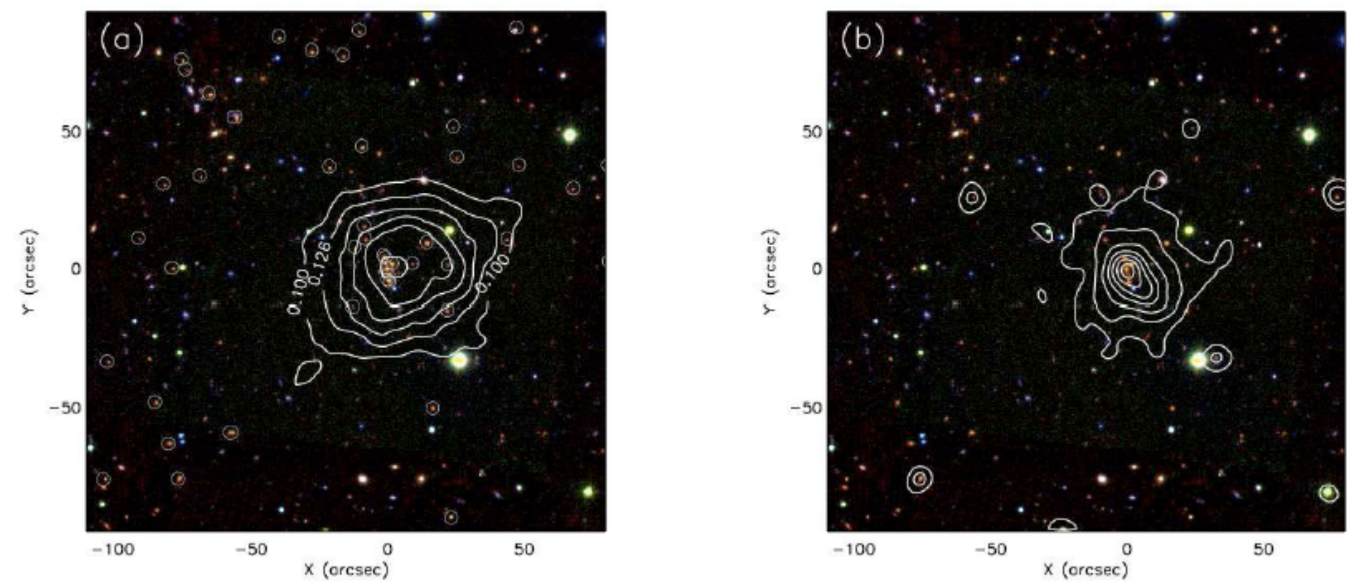
- **But, this line is arbitrary!**



# Motivation: observations of an extreme object

**The observations of XMMJ2235 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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$$z = 1.4$$

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**Jee at al 2009**

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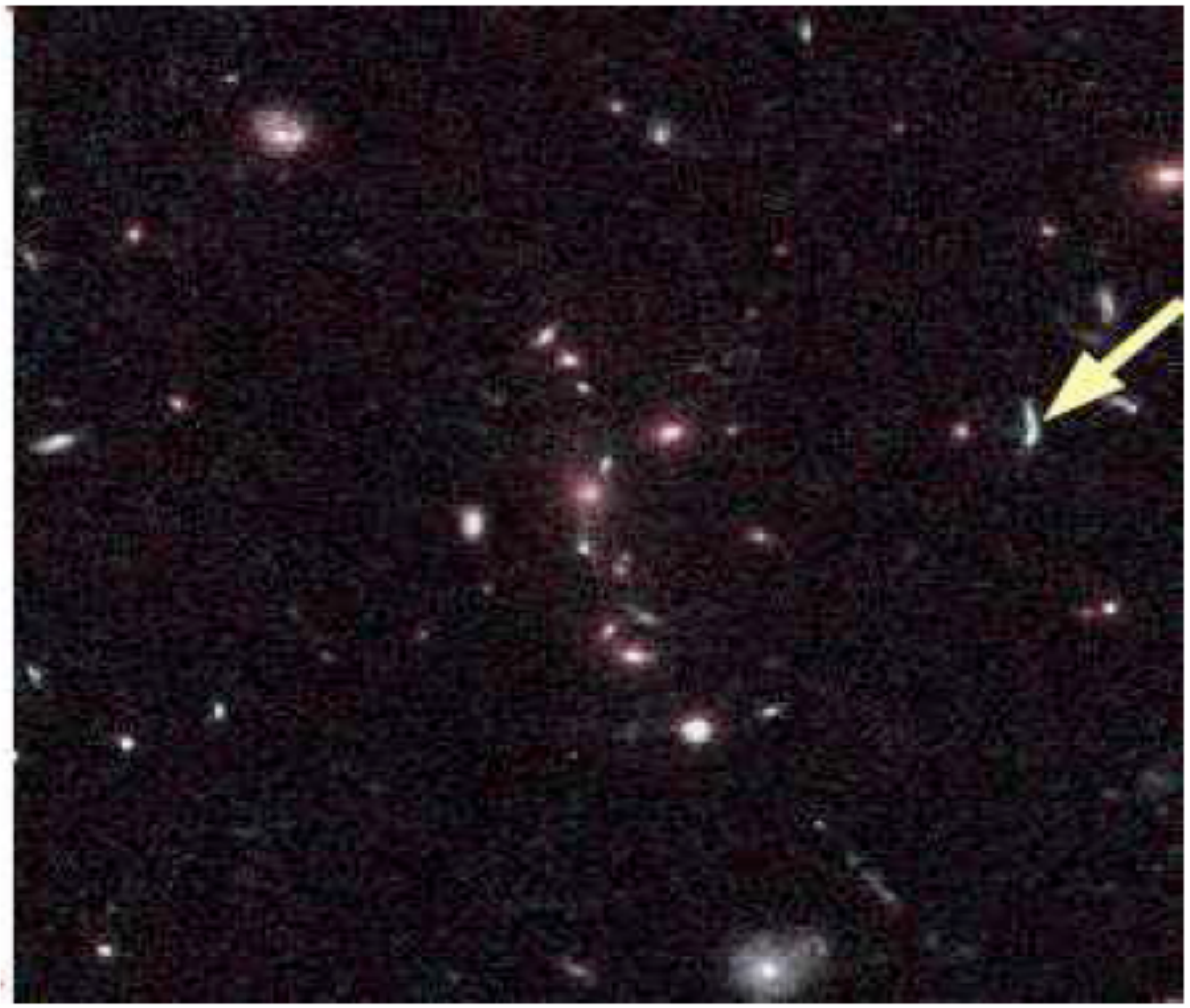

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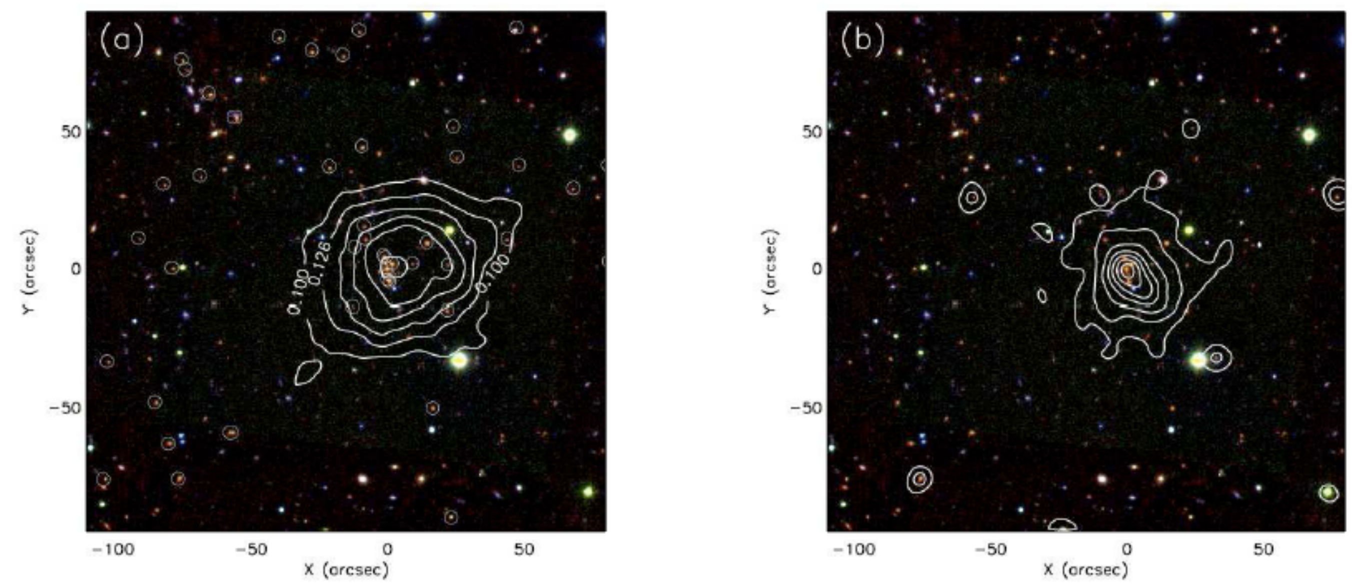


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**<u>How likely was this cluster to exist >M >z?</u>**

- **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.**
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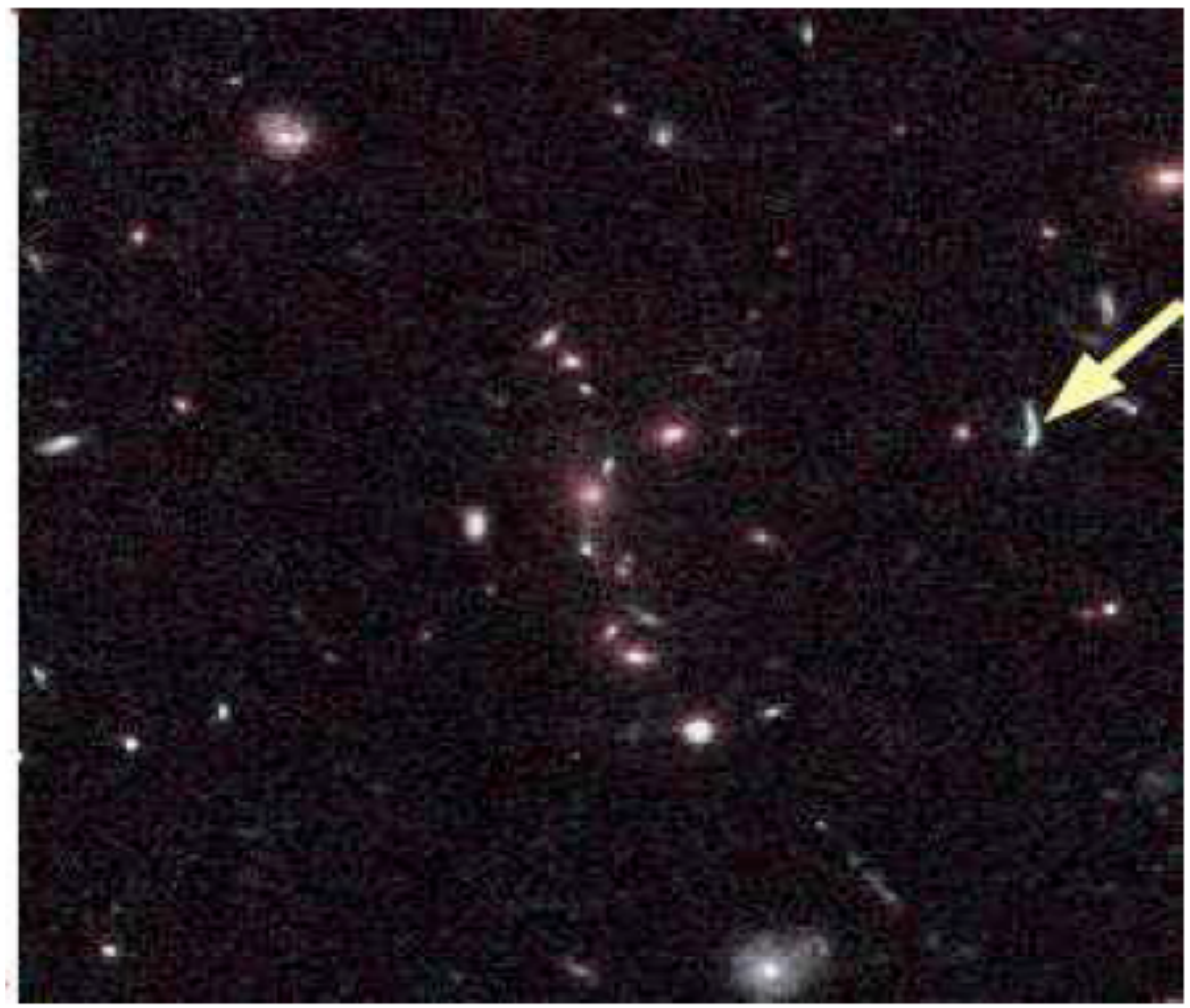

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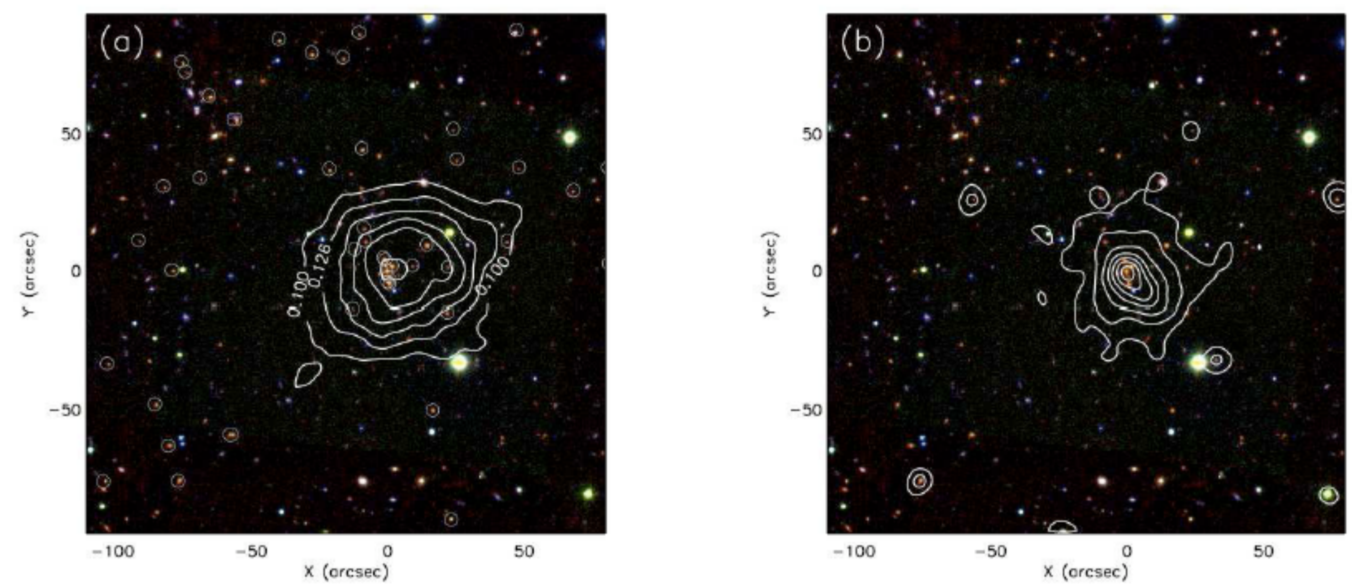


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**Jimenez & Verde 2009 showed fnl~150 relieves tension. Cayon et al 2010 fnl=360,fnl>0 at 95%**

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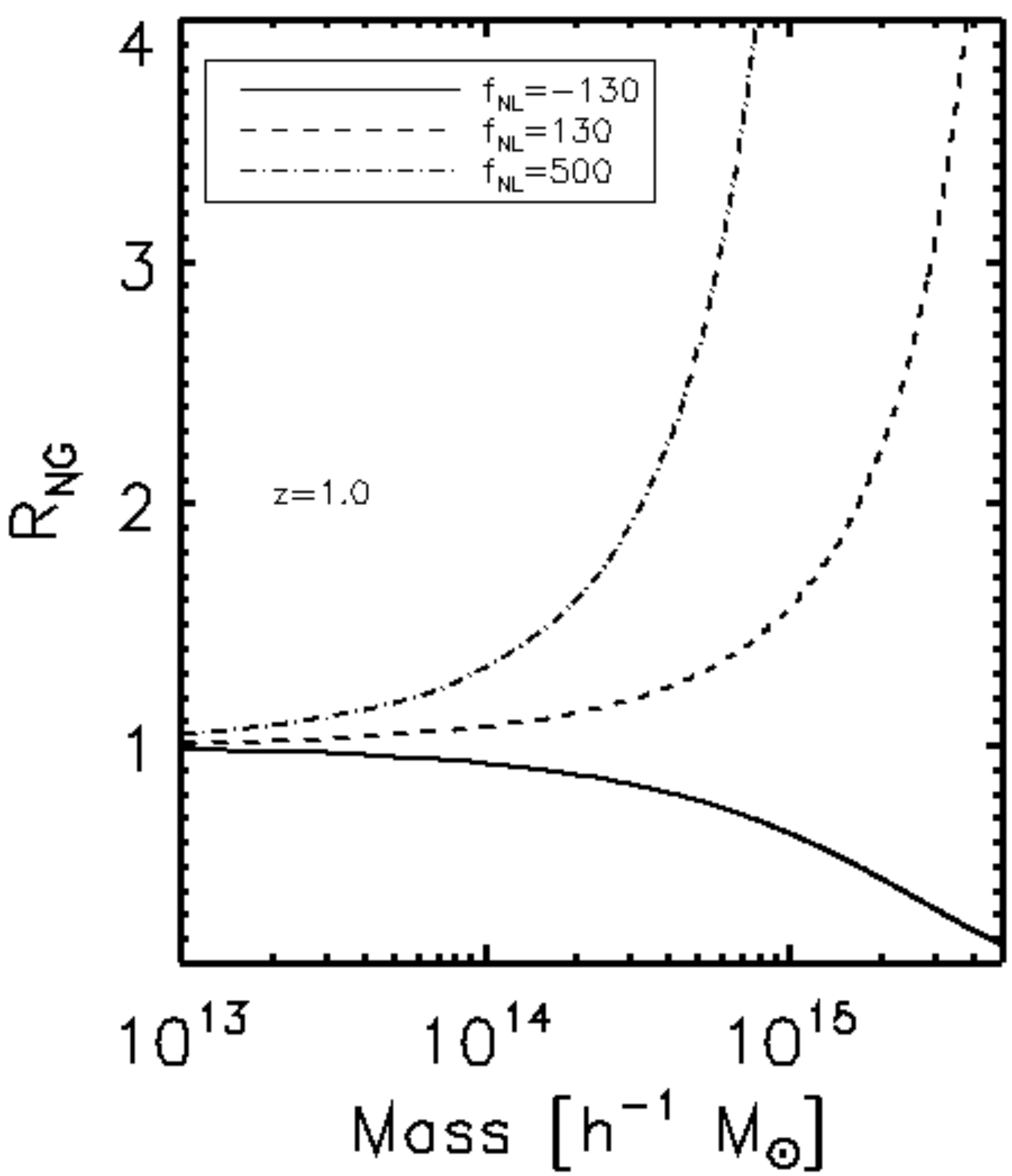
# Motivation: theory, a window to the early Universe

**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.**

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

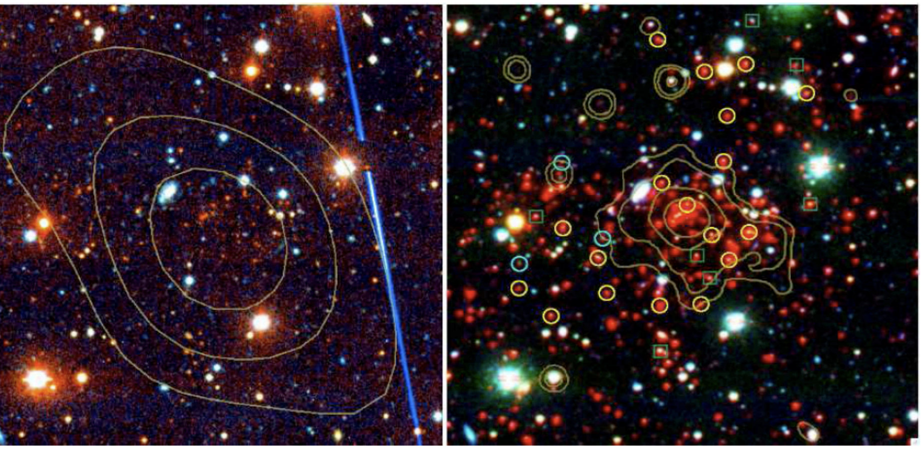



**fnl and cluster abundances**

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

**Solved in the Press-Schecter type formalism by Matarrese, Verde, Jimenez 2002 (extenions: LoVerde et al 2007, Maggiore et al 2009, D'Amico et al 2010, Paranjape, Gordon, Hotckiss 2011, etc...)**

# Motivation: observations II - More “rare” clusters



*eft:* Optical $4' \times 4'$ 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 $\mu$m) image of SPT-CL J0546-5345, with *Chandra* X-ray contours overlaid (0.25, 0.4, 0.85 and $2'' \times 2''$ 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**

**Are we just getting lucky?**

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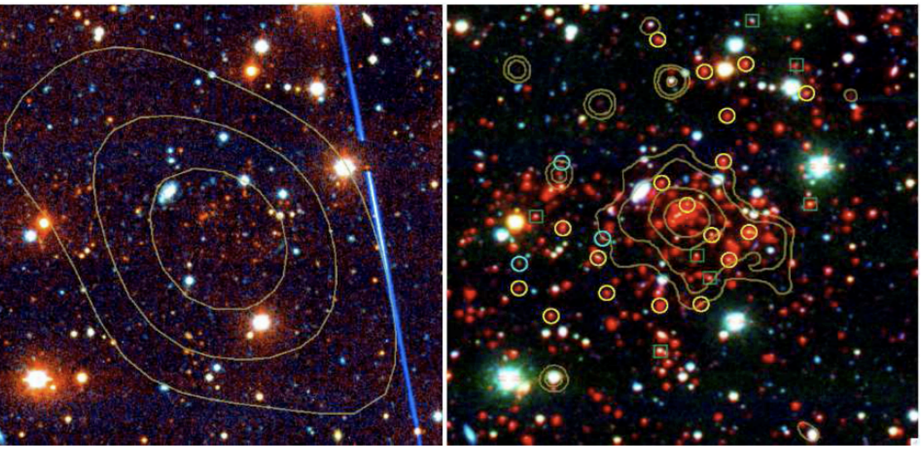

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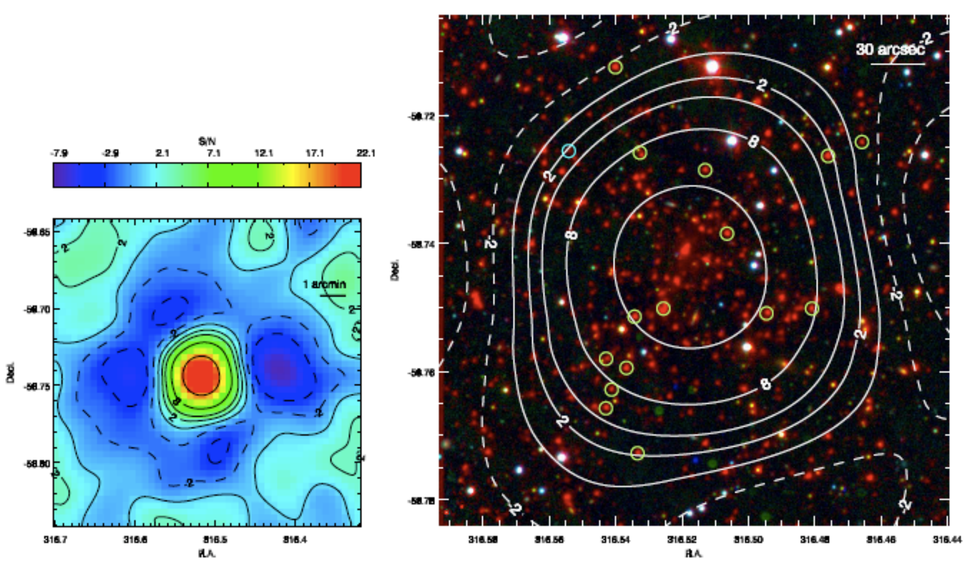


**SPT-CL J2106-5844**

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

$$z = 1.13$$

**Foley et al 2011**

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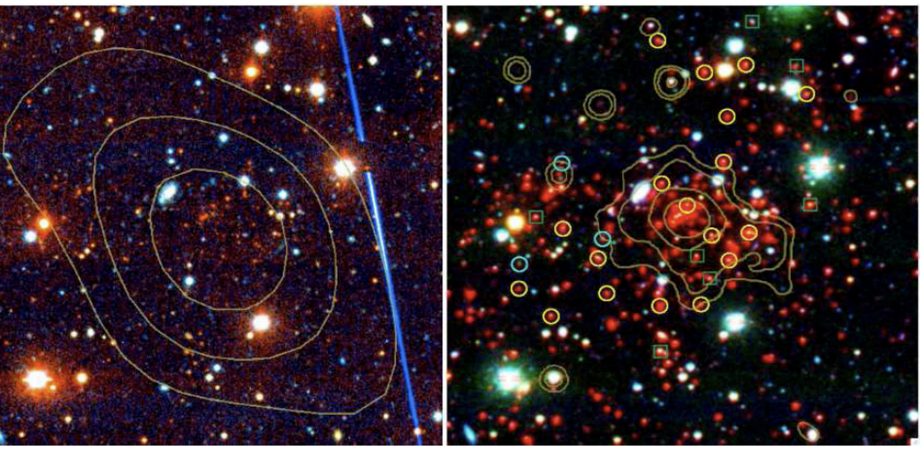

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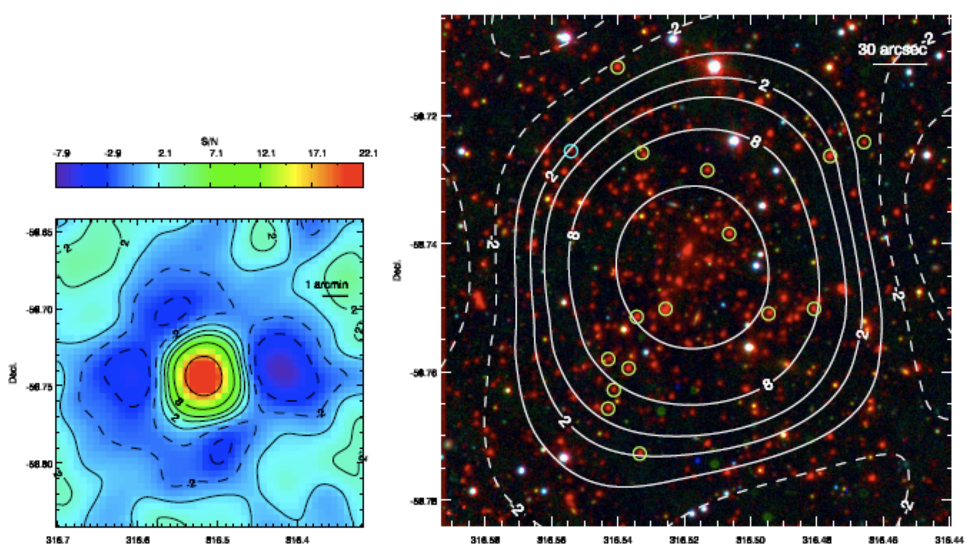


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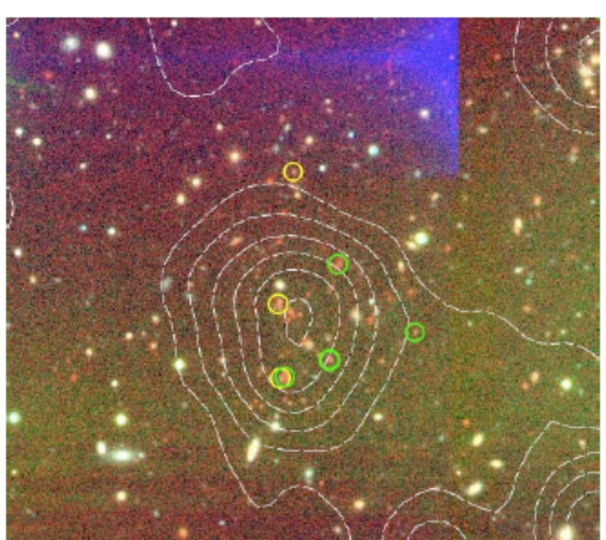


**XMMUJ0044.0-2033**

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

$$z = 1.57$$

**Santos et al 2011**

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

**Are we just getting lucky?**

# More clusters.

**How lucky are we being? Are high-redshift, massive 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 |
| '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 |

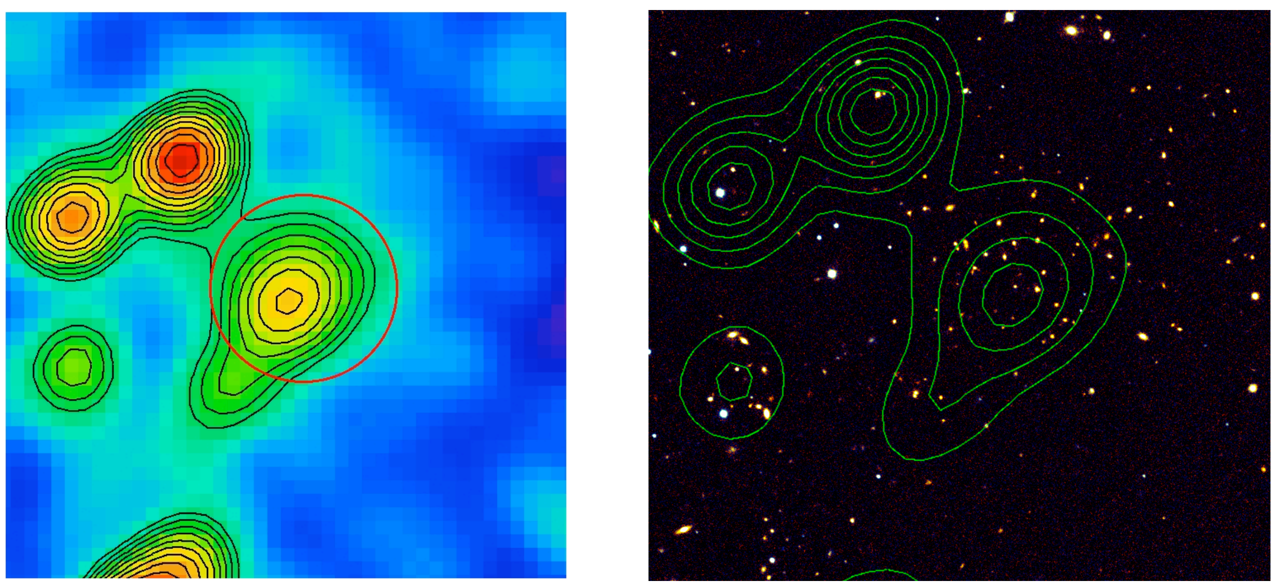
**The next generation of cluster samples will be found by X-ray (eRosita ~ 100,000 clusters) not SZ (ActPol ~1000 clusters). All X-ray clusters detected or re-detected with XMM Cluster Survey**

# Recent XCS achievements

**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

**XMMXCS J2215**

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

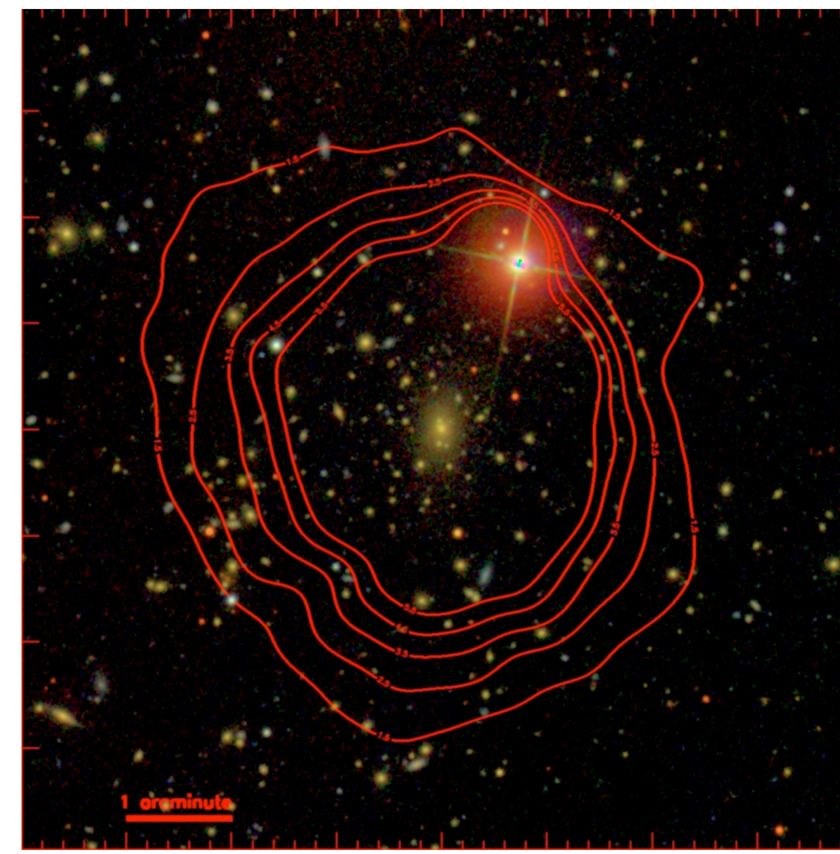


**Now z=2.07, M~5-8.10^13 SolMass, Gobat et al arXiv:1011.1837**

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

**Algorithm paper: Lloyd-Davies et al 2010**
**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)**

# Analysis >M,>z 1

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**Very Conservative assumptions**

**Footprints; 300 sq. deg. footprint.**

**Survey volumes: 1.0<z<2.2**

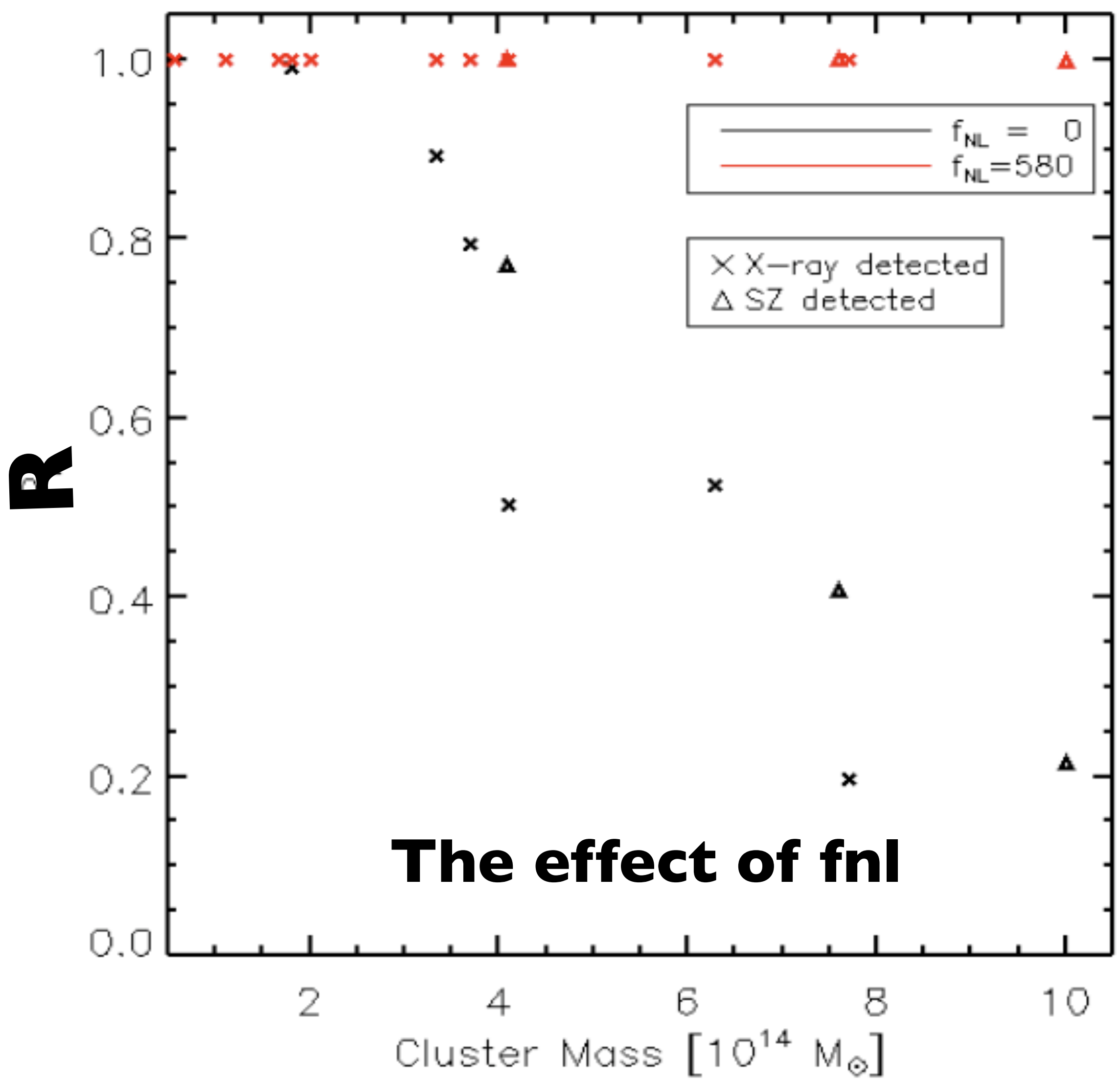
**Selection functions: For each cluster, we assumed that any similar (>M) cluster at any higher redshift (>z) would have been detected.**

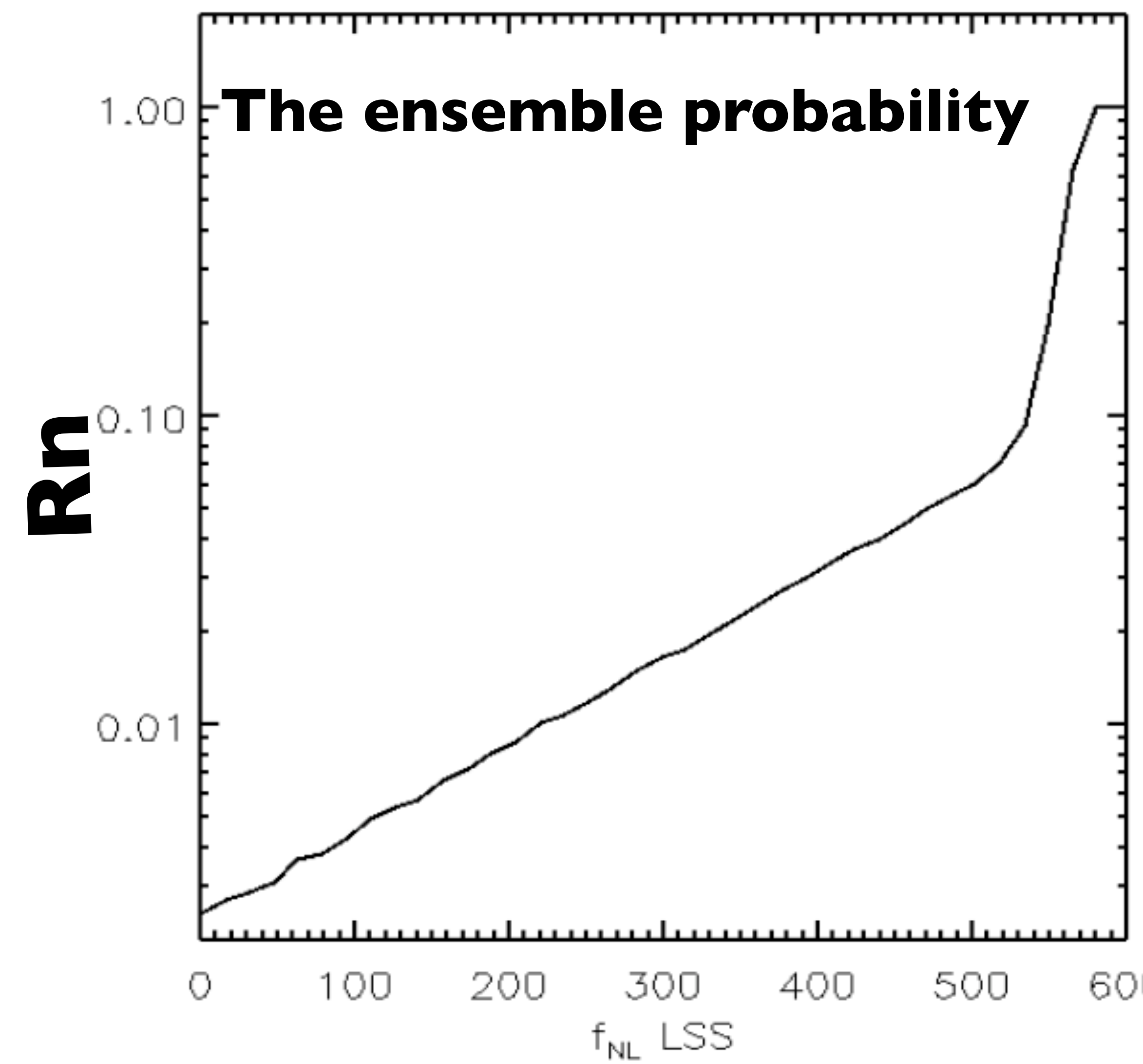
**Mass estimates: We chose to use the cluster mass and error which gave the least tension with LCDM.**

**Calculate (>M,>z) R for each cluster, multiply R values together to get ensemble probability Rn**

# Results >M,>z: I

**Calculate (>M,>z) R for each cluster, multiply R values together to get ensemble probability Rn**




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

**Marginalize over cosmological parameters assuming WMAP 5 priors**

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

**Corroborated by Enqvist, Hotchkiss, Taanila 2010.**

# Reality Check!

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

# Possible explanations: Systematics

**<u>1) Cosmological parameters.</u>**

- **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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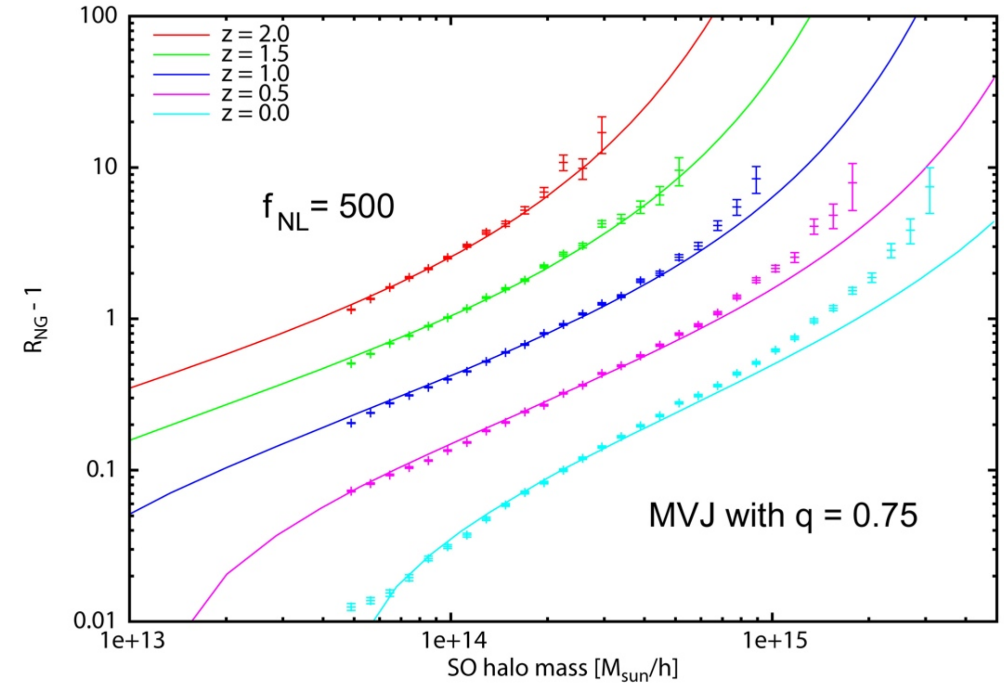


**Non-Gaussian mass function fit to N-body simulations**
**Volume: 40 x (2.4 Gpc/h)^3**
**Number of Particles: 40 x 768^3**
**Spherical-overdensity halos with "virial" masses**
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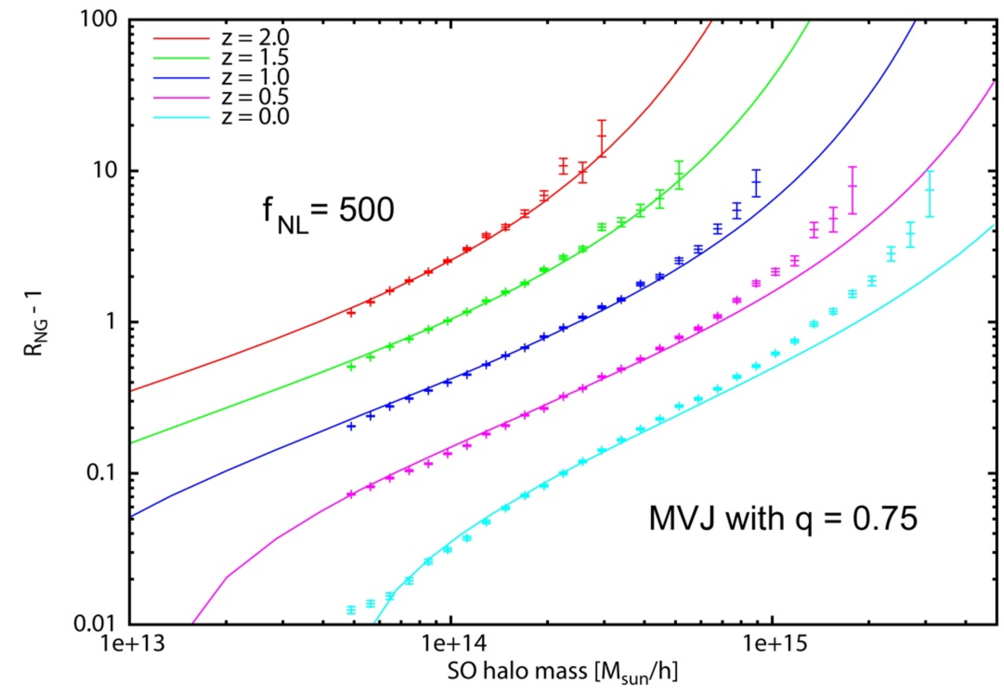


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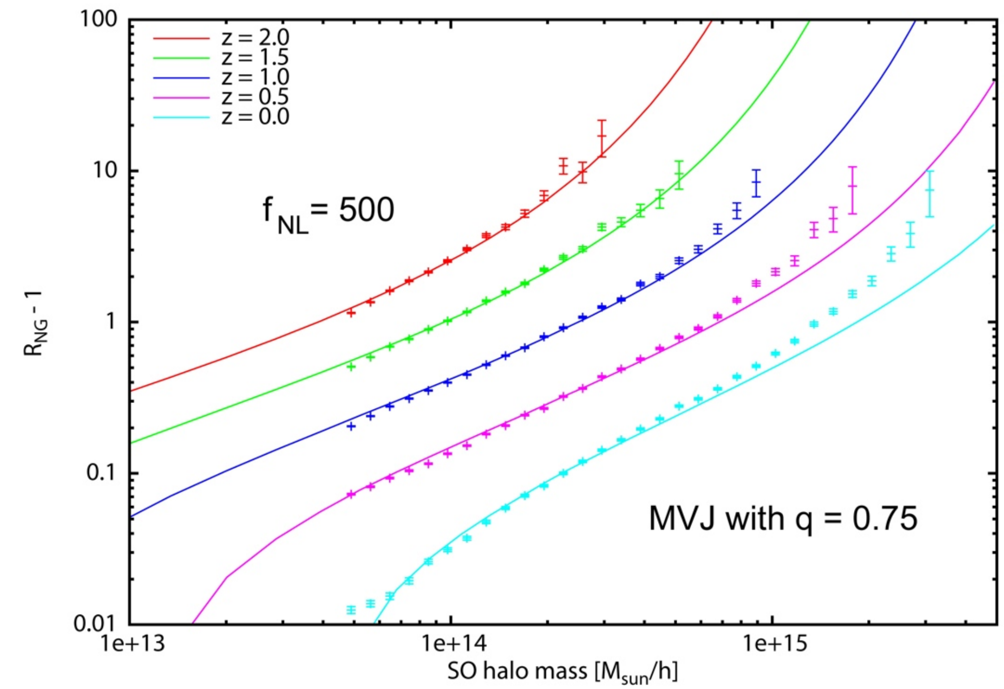


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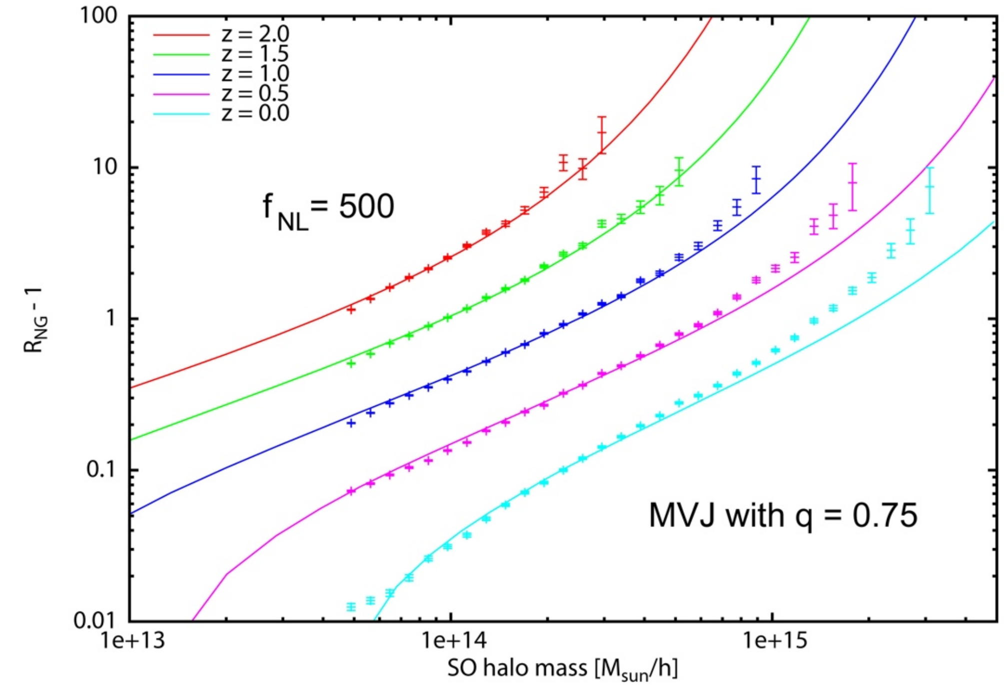


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## 4) Biased analysis?

Some discussions in the community. Is the analysis correct? Most of the literature has been asking this >M,>z question.

# A critical look at the >M,>z statistic 1

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 level of tension with a model is caused by the existence of this cluster(s)?"

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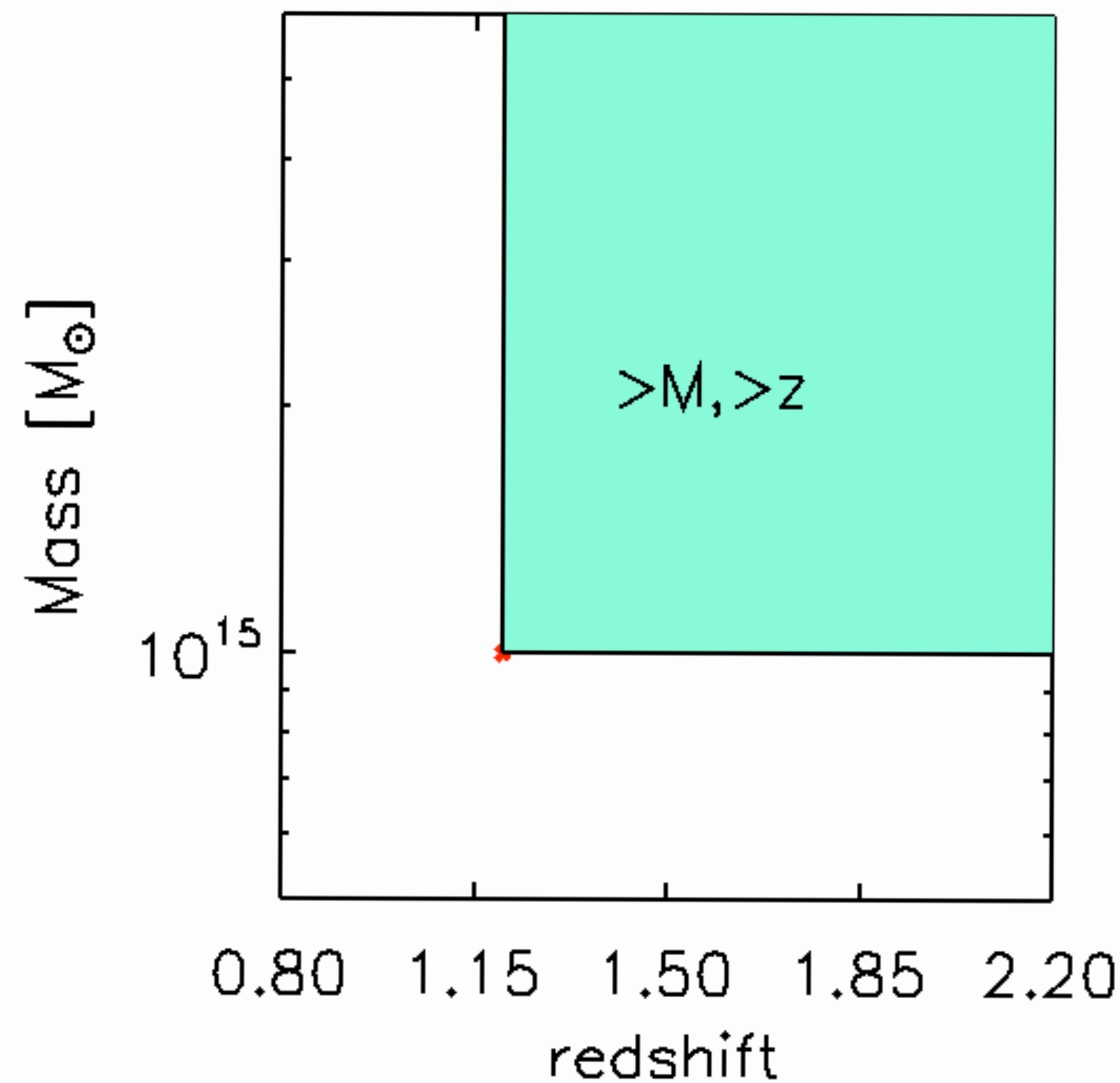

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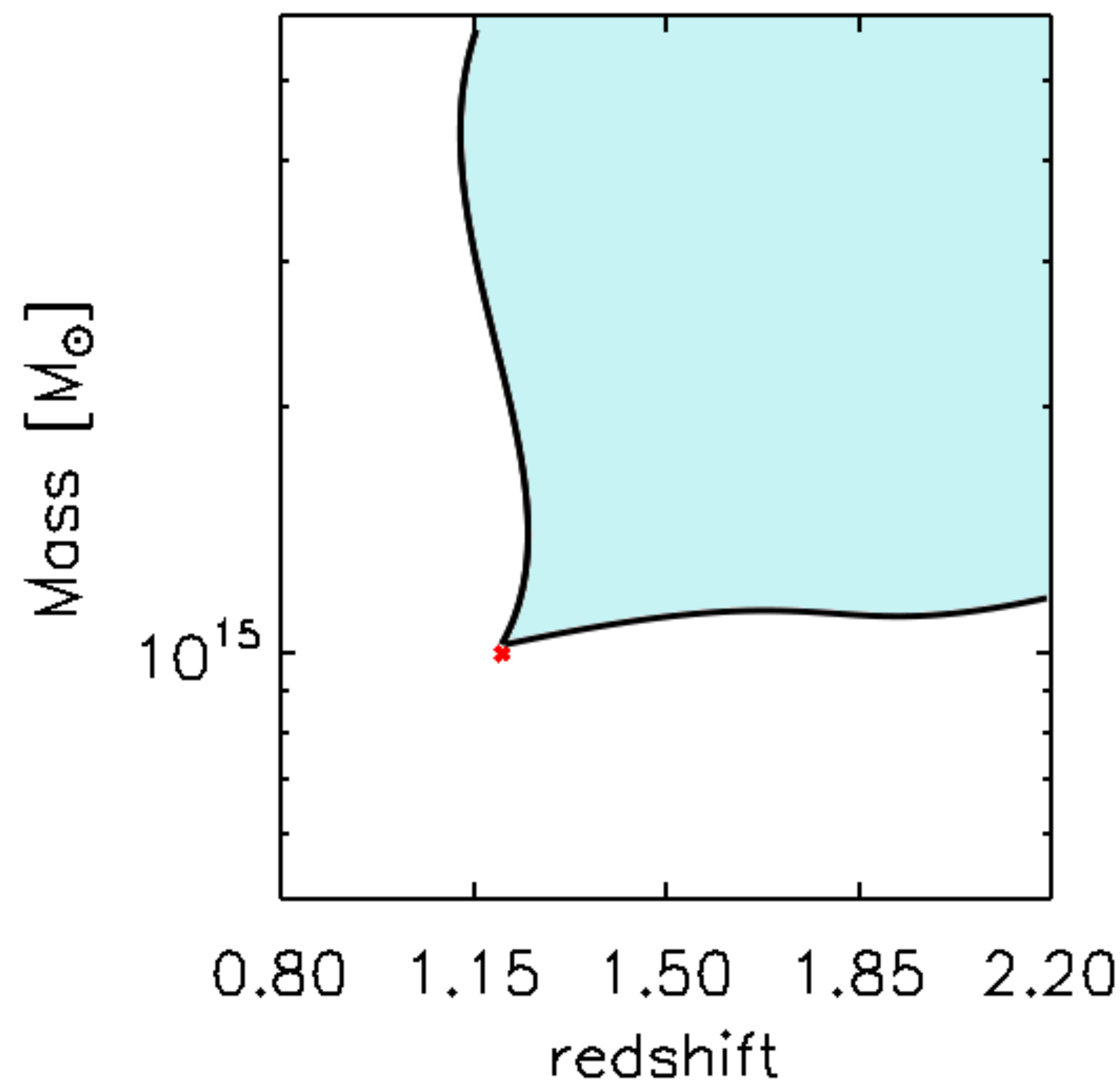

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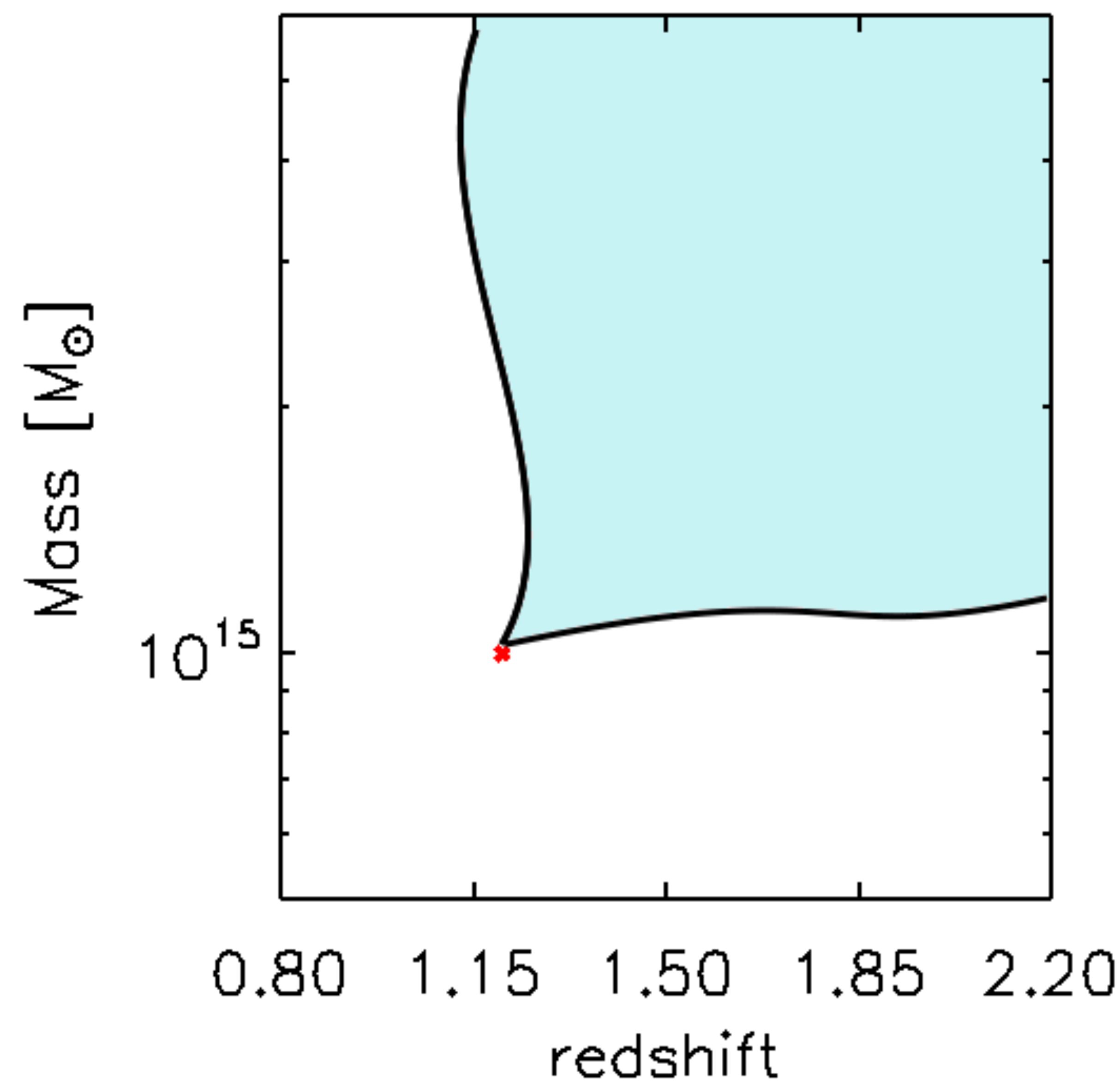
**Once the above is understood, we can simply calibrate R on simulations, and then use it to test for tension.**



# A critical look at the >M,>z statistic 11

**<u>Using R to measure tension with a model</u>**

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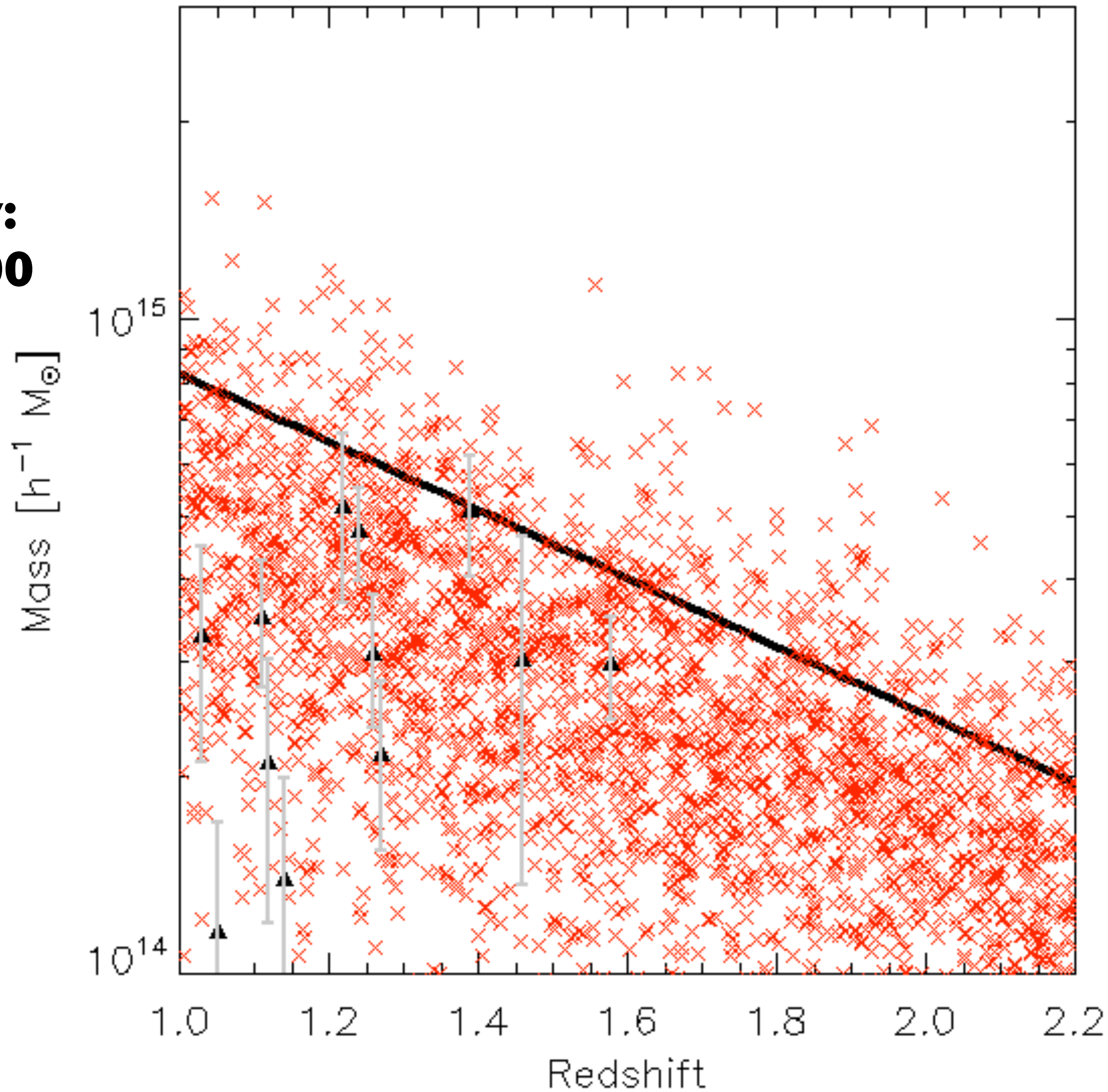
**For example, assuming the survey geometry: M>1e14 Msol, 2.2>z>1.0, and a footprint of 100 sq. deg, We Poisson sampled from the mass function.**



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**We found that the ``Least Probable'' (LP) cluster from each separate simulation has a spread of existence probabilities from 0.001<R<0.339 at 95%**

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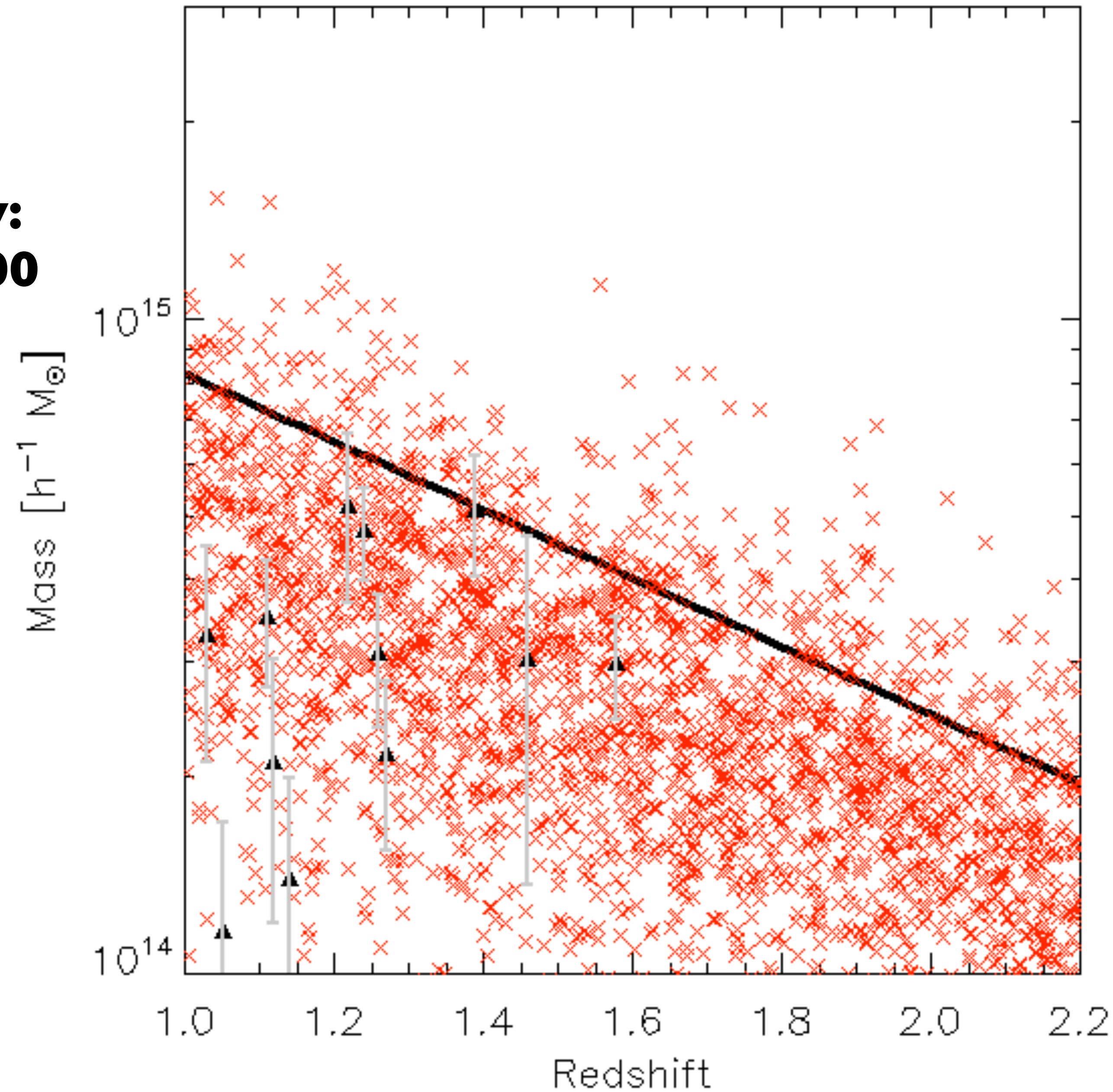

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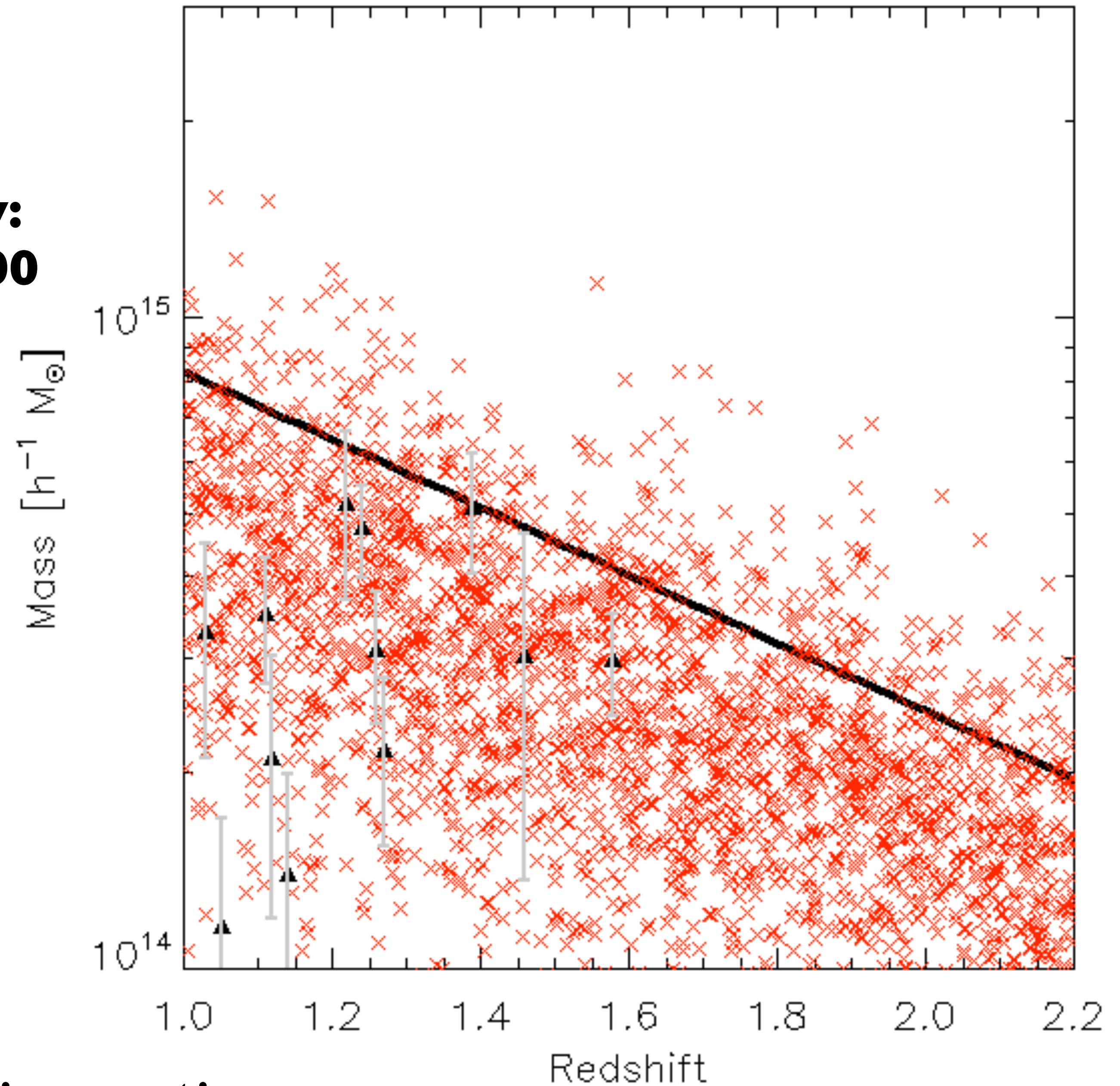


**Using R to measure tension with a model**

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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 'n' clusters, we can extend this analysis by multipling each R together, Rn, and comparing with Rn LP or Rn random clusters from simulations.**

# Correct analysis/comparison

| Cluster Name | Redshift | $M_{200}$ $10^{14}M_\odot$ | Method | $\tilde{R}$ | Mass reference |
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| RCS0221-0321 | 1.02 | $1.80^{+1.30}_{-0.70}$ | WL | 0.992 | [15] |
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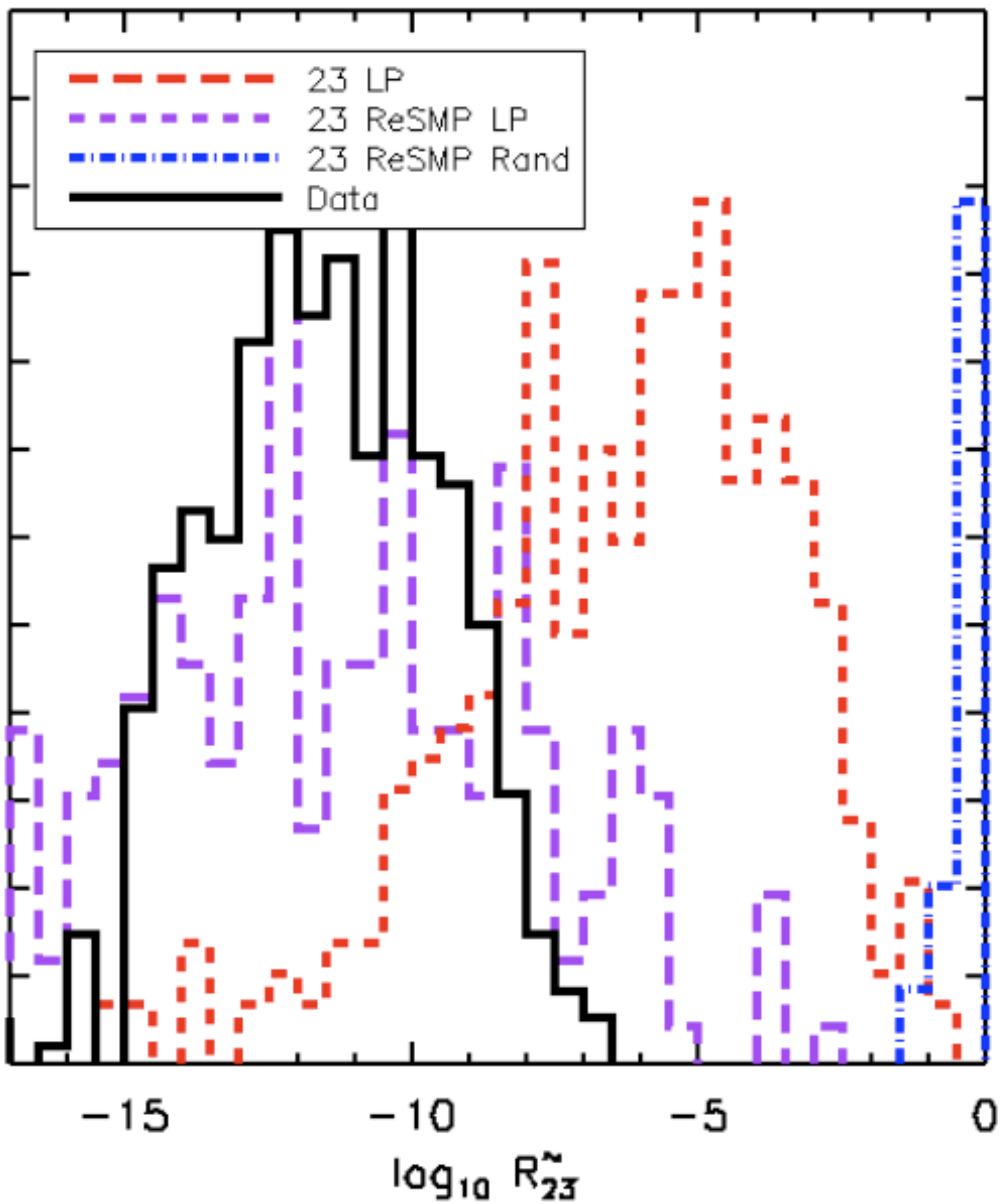


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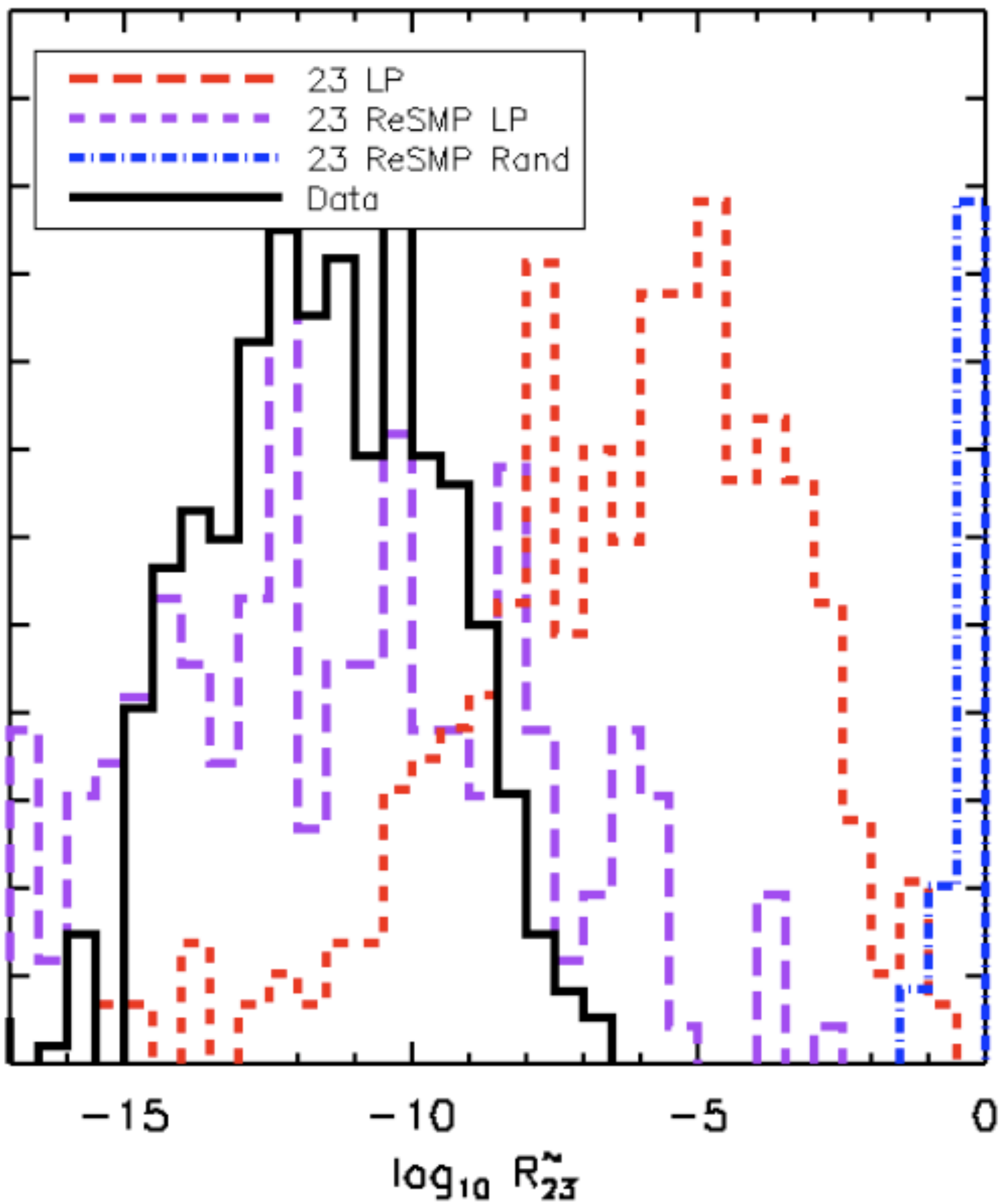


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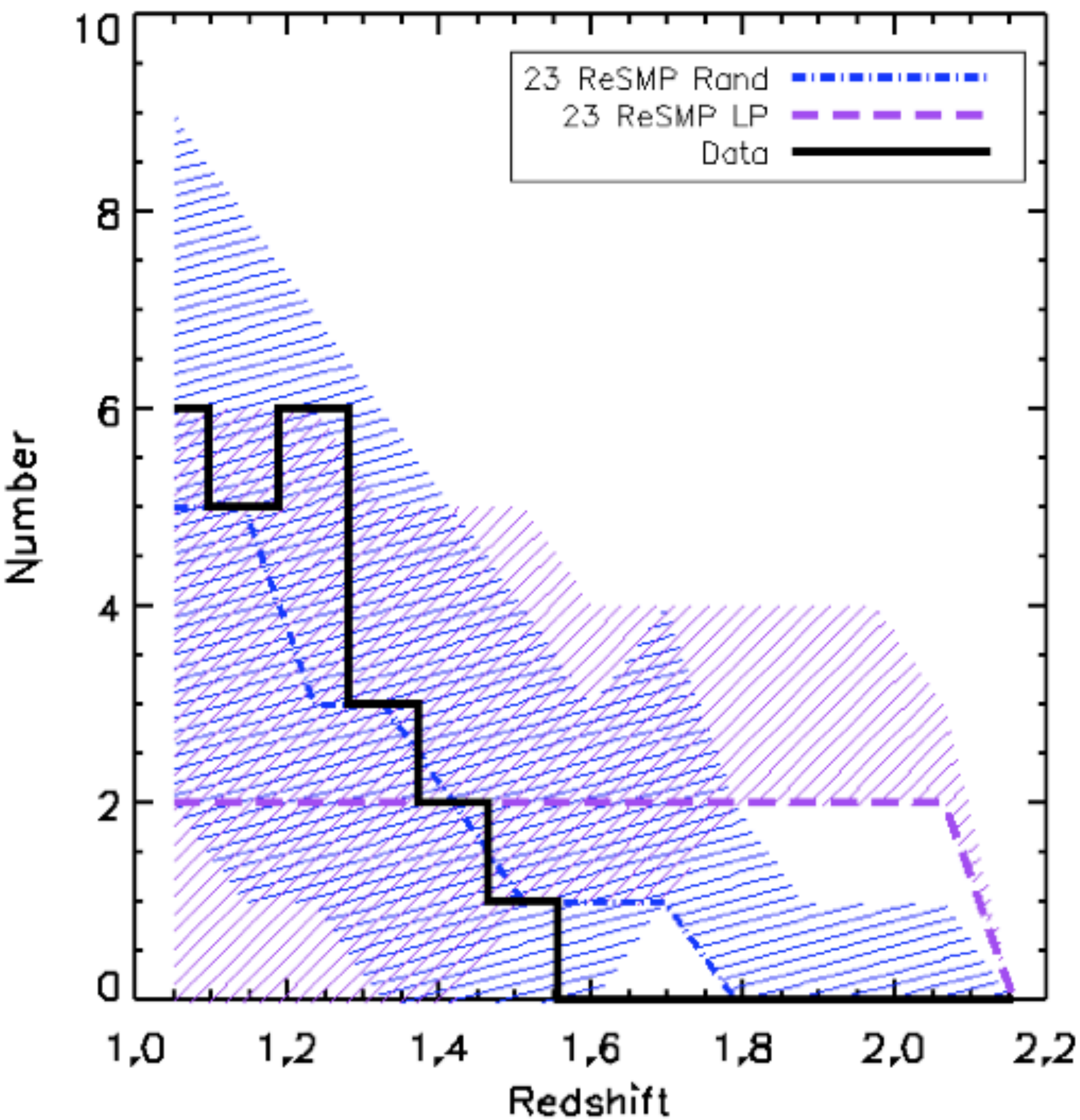
**see also Hotchkiss 2011**

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

- **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.**

**Recall: If LP no Rn tension, if random lots of Rn tension**

# 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.**

**However, if the observed clusters are consistent with a random selection of clusters (from simulations), then the (>M,>z) R statistic is very discrepant, the redshift distributions are consistent, but the 2dK-S test probabilities are very low.**

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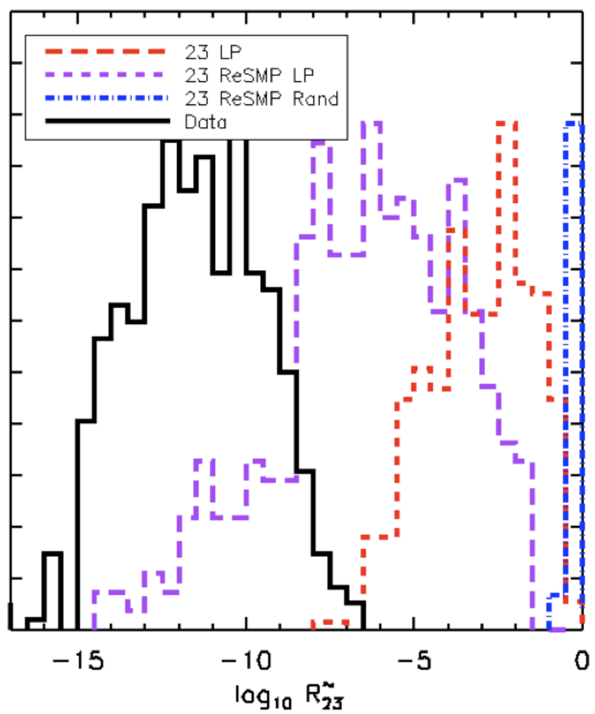
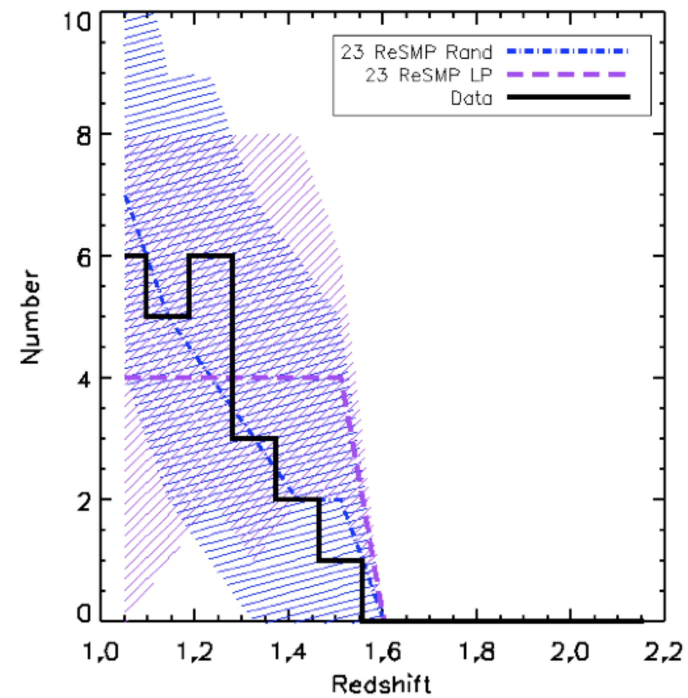
**However, if the observed clusters are consistent with a random selection of clusters (from simulations), then the (>M,>z) R statistic is very discrepant, the redshift distributions are consistent, but the 2dK-S test probabilities are very low.**

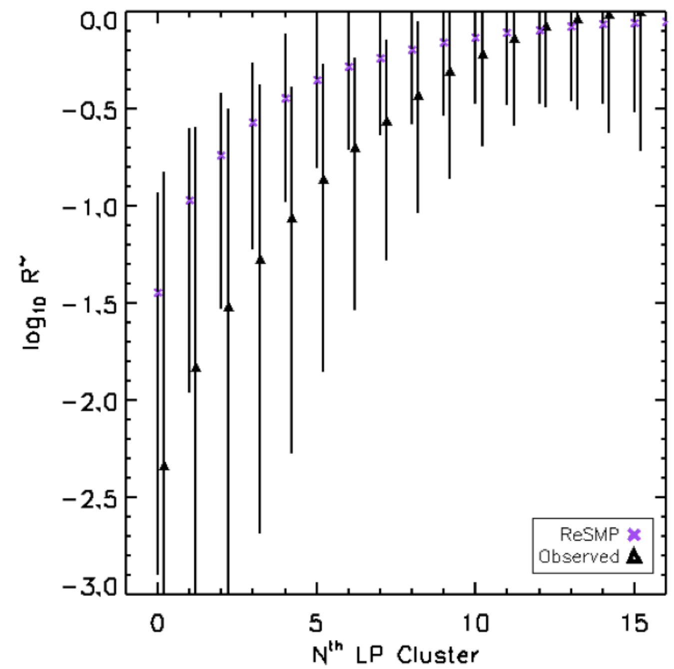
**What could cause such a signal?**

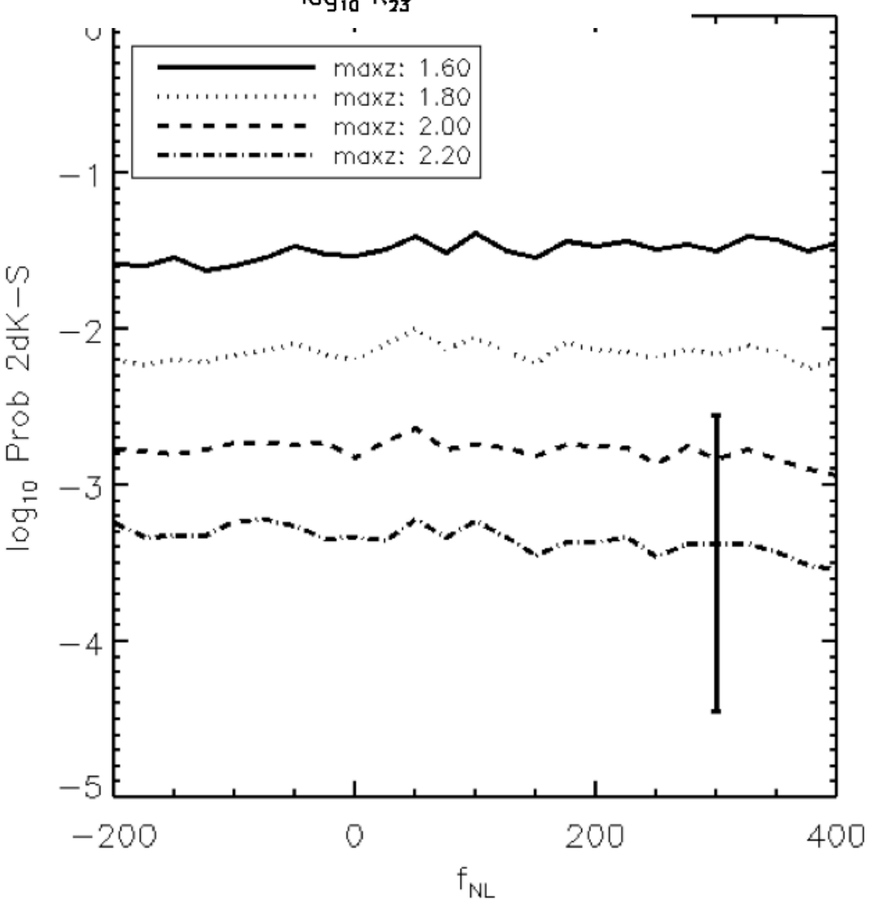
# Possible (unphysical?) causes.

**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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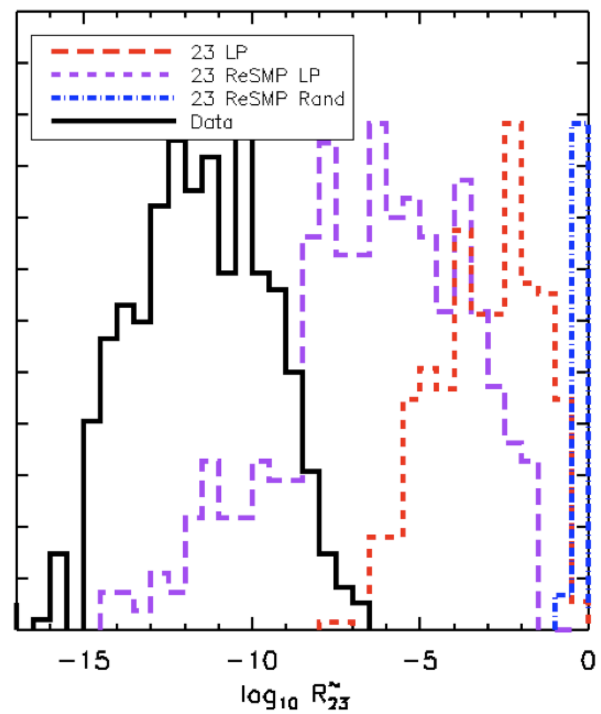


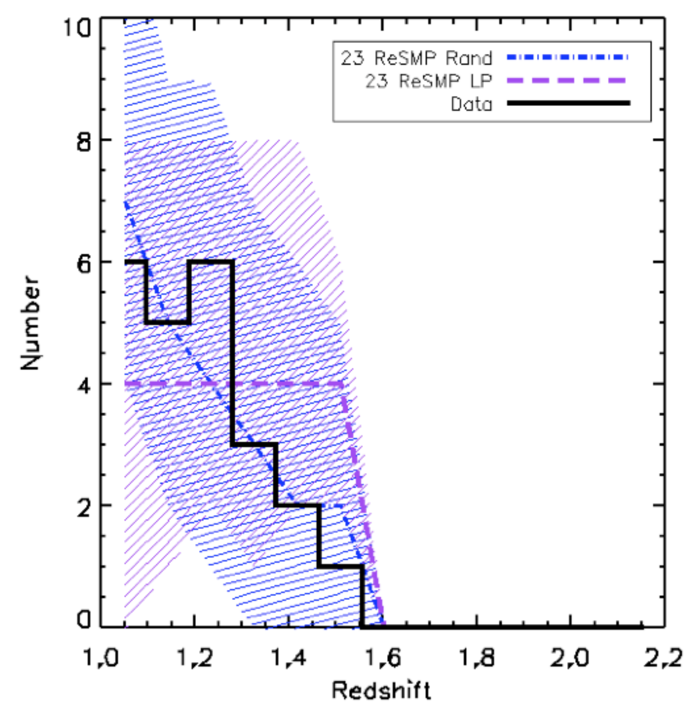


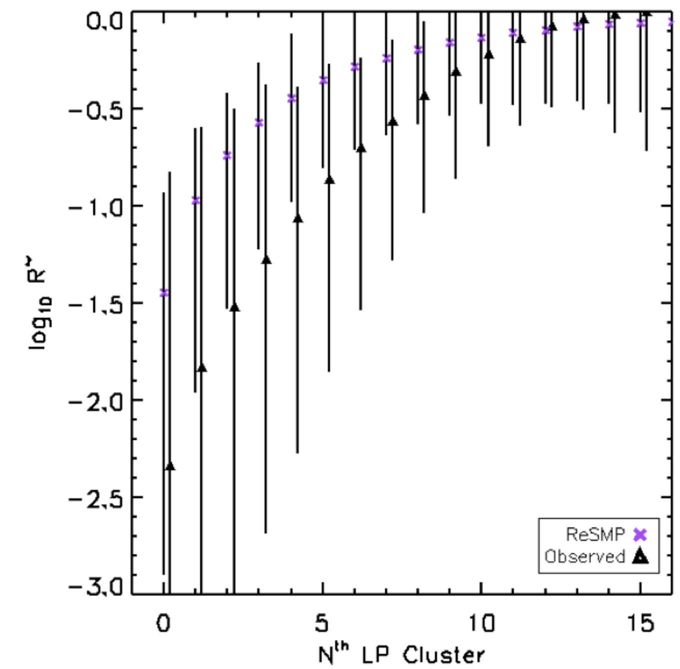


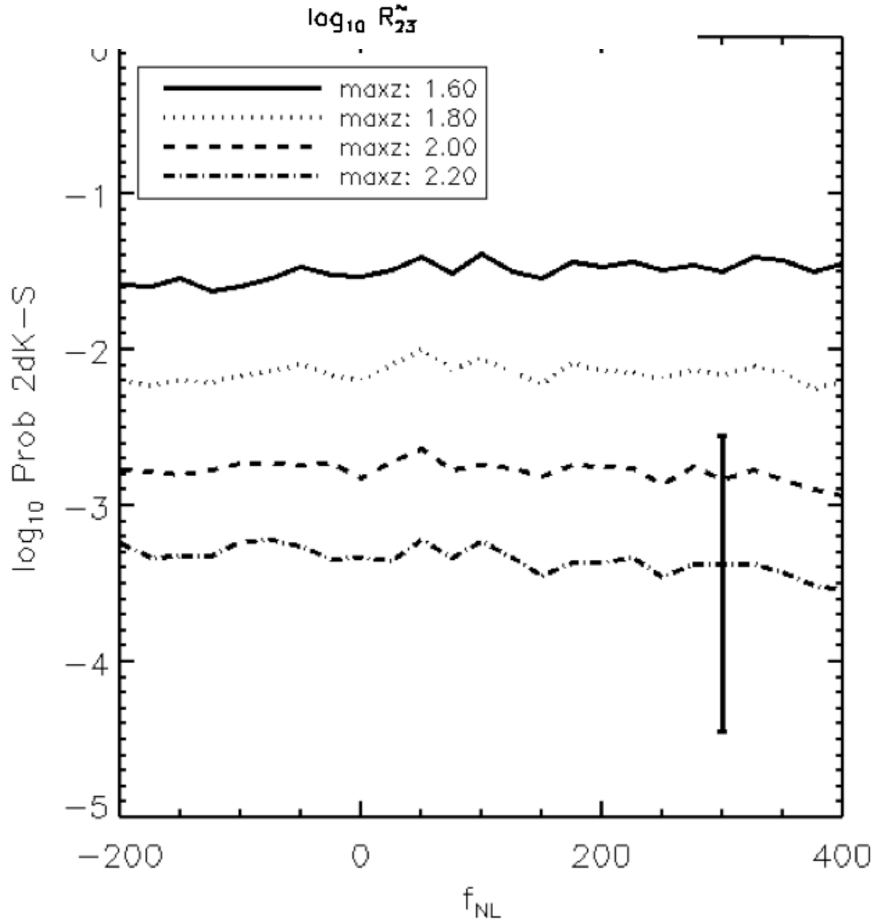


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**Follow up work: To use samples of clusters with an unknown selection function to bound cosmological parameters (Hoyle et al, in prep.)**

# Summary

- Identified the >M,>z question was biased.
- Built a list of all (23) high-redshift (z>1) massive (M>10^14 solar mass) clusters.
- Used the most robust mass estimates.
- Used a realistic footprint/survey geometry.

- Compared observed clusters with distributions of simulated clusters including the Eddington bias, and uncertainties in cosmological parameters (assuming WMAP7 priors).

- Quantified the tension with LCDM, using the >M,>z statistic, redshift histograms, 2dK-S test.
- Showed how fnl cannot reduce the tension when properly compared to simulations.

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

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