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

Ben Hoyle, Raul Jimenez, Licia Verde, ICC-IEEC University of Barcelona, University of Helsinki: Hoyle et al 2011 (+ in prep)

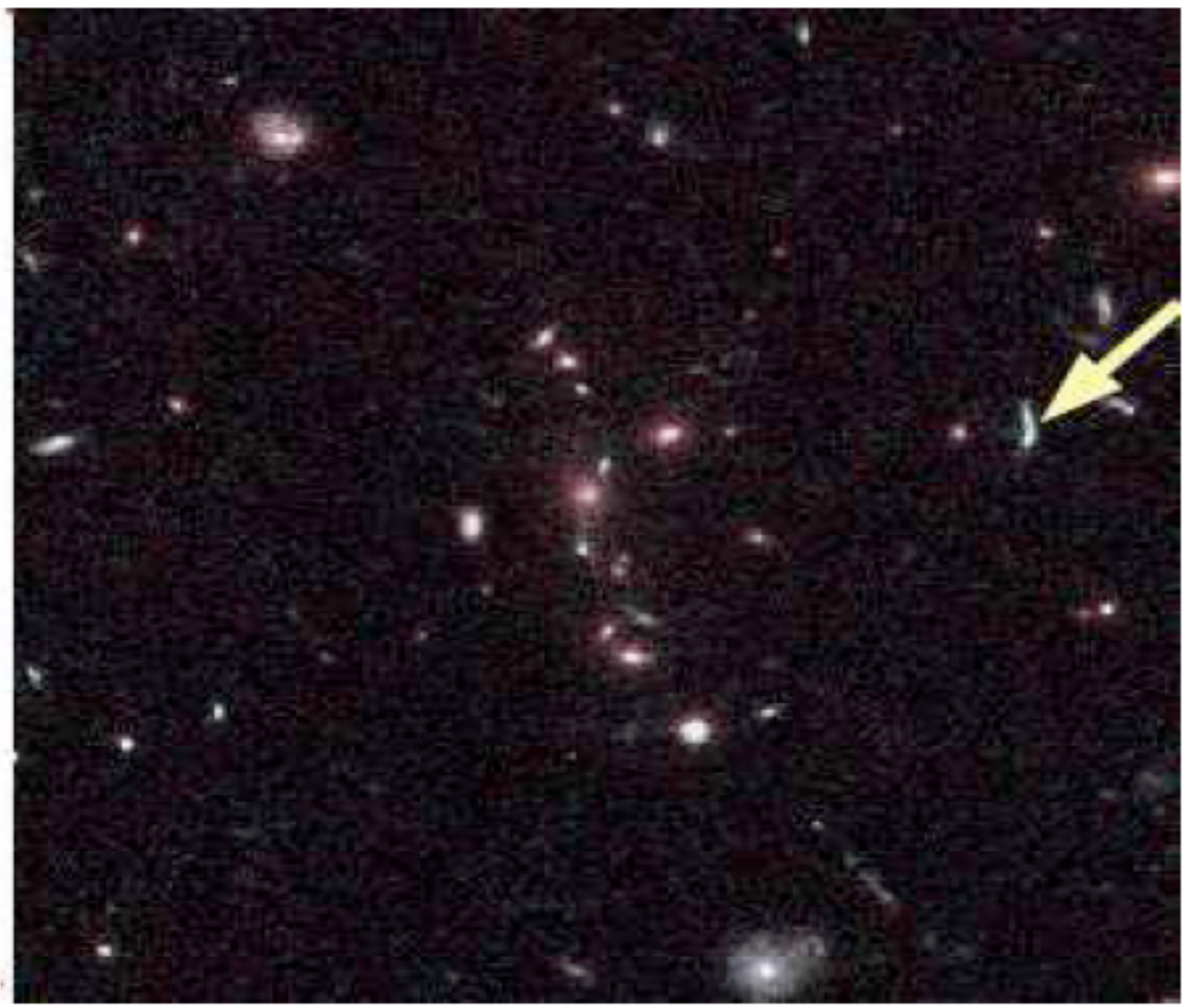
Santander SZ clusters: 28/06/2011

Overview

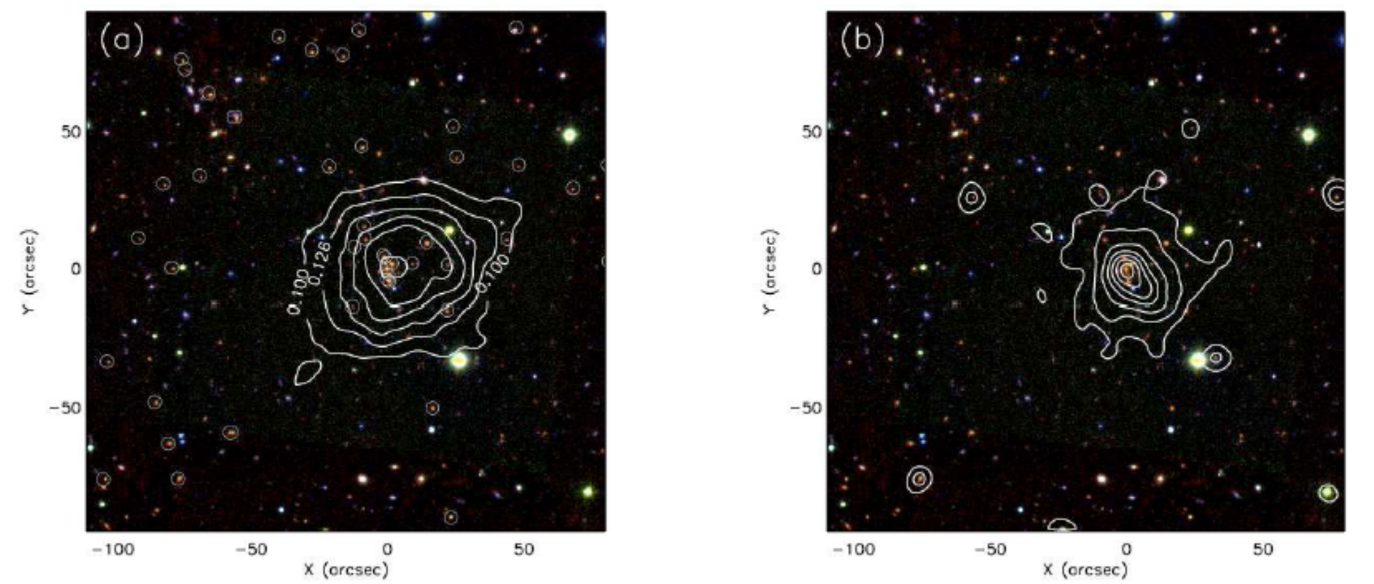
- Observational motivation
- Theory
- The cluster sample
- The XMM Cluster Survey
- Analysis and Results
- Possible explanations: Systematics
- Other work
- New Analysis and Results
- Conclusions

Motivation: observations of XMMJ2235

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



Jee at al 2009



$$M_{200} = 7.7 \pm 1.3 \times 10^{14}\ M_{\odot}$$

$$M_{200} = 7.7^{+4.4}_{-3.3} \times 10^{14}\ M_{\odot}$$

$$z = 1.4$$

How likely was this cluster to be observed?

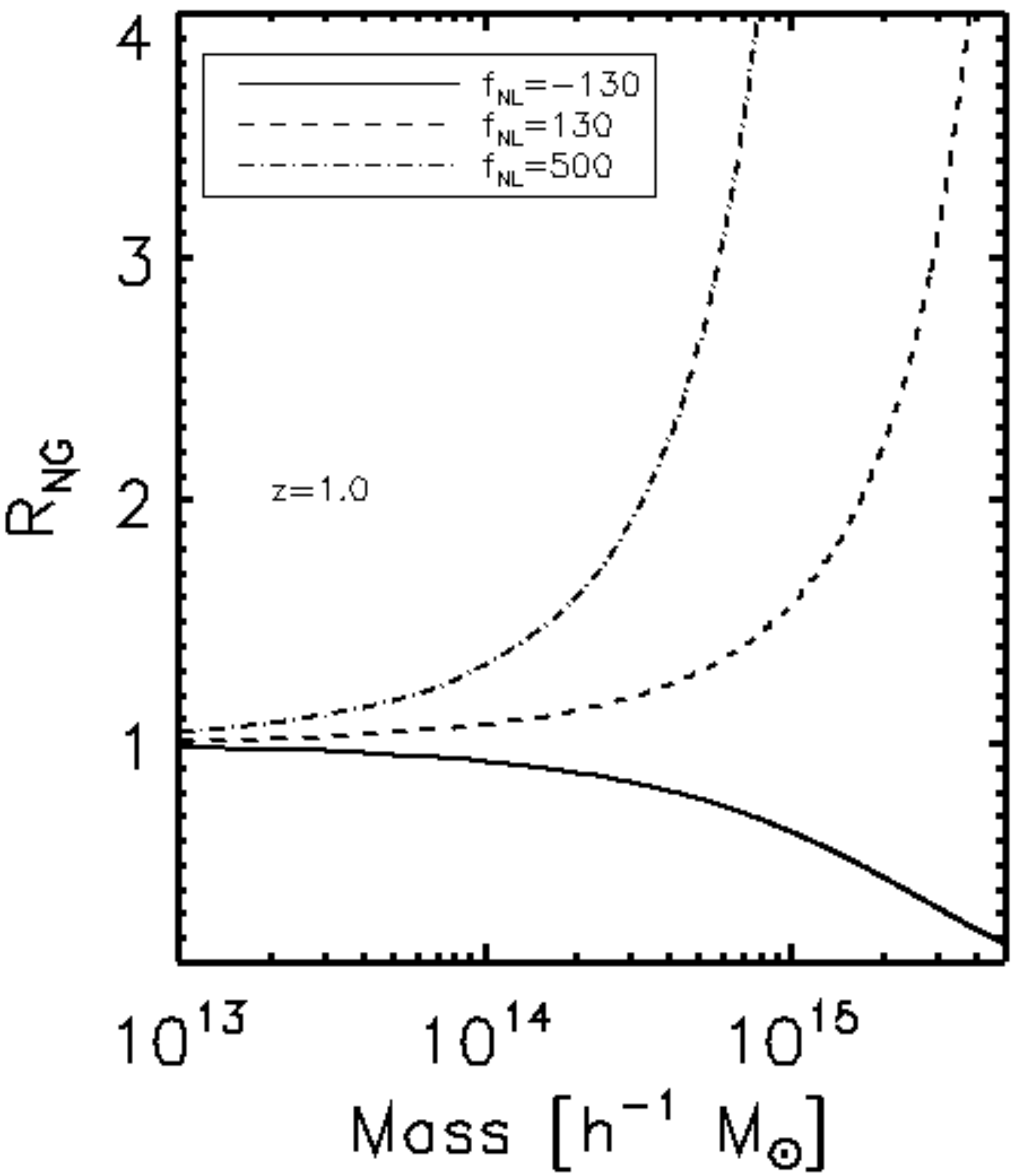
- **The expected number in the full sky ~7.**
- **Footprint was 11 square degrees XMM X-ray survey, 0.02% of sky.**
- **Poisson sample from (0.0002*7) >1 only 1.4%**

Jimenez & Verde 2009 showed values of fnl~150 relieves tension with XMM J2235.

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.

Byrnes et al 2010 [arXiv:1007.4277]



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

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

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

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

Motivation: observations II - More massive clusters

SPT CL J0546-5345

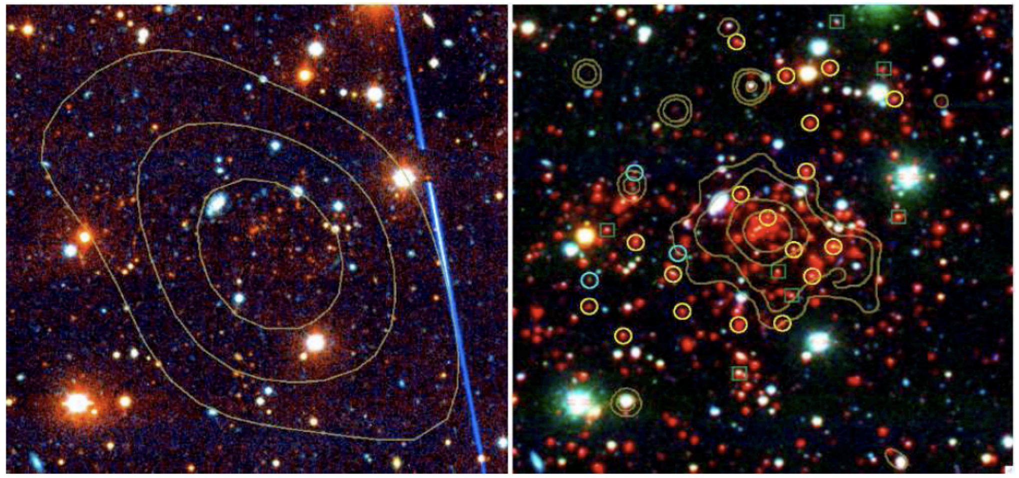


FIG. 1.— *Left:* Optical 4′ × 4′ color image (*grz*) of SPT-CL J0546-5345, with SZE significance contours overlaid (S/N = 2, 4, and 6). *Right:* False color optical (*ri*) + IRAC (3.6 μm) image of SPT-CL J0546-5345, with *Chandra* X-ray contours overlaid (0.25, 0.4, 0.85 and 1.6 counts per 2″ × 2″ pixel 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* is able to resolve substructure to the SW, which may be evidence of a possible merger. These images highlight the importance of IRAC imaging in studying the galaxies in high redshift, optically faint clusters. Spectroscopic early-type (late-type) members are indicated with yellow (cyan) circles. Green squares show the spectroscopic non-members.

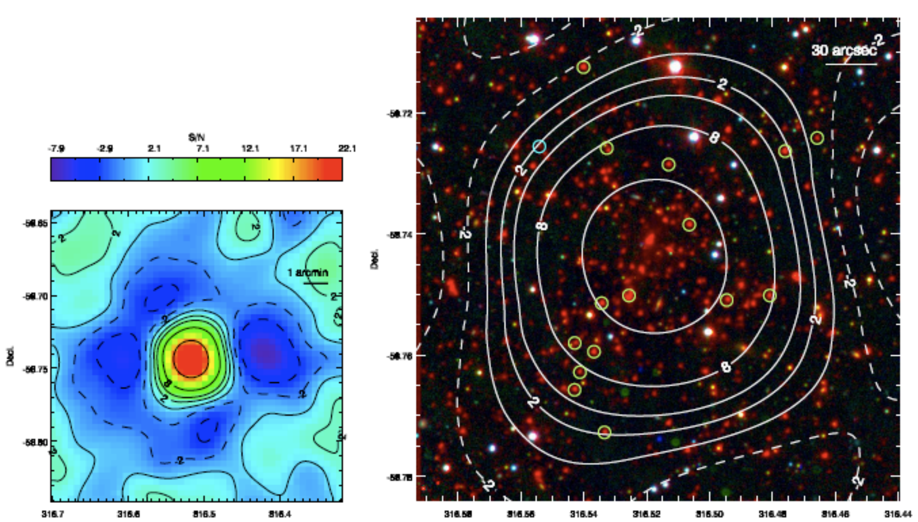
$$M_{200} \sim 10^{15}\, M_\odot \qquad z = 1.05$$

- **Expect to see one 18% of time**

Brodwin et al 2010

SPT-CL J2106-5844

Foley et al.



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

$$z = 1.13$$

- **Expect to see one 5.9% of time**

Foley et al 2011

More clusters.

Are these clusters consistent with LCDM?

B.H., Jimenez, Verde 2010, See also Mortonson et al 2010, Enqvist, Hotchkiss, Taanila 2011, Hotchkiss 2011, B.H. et al in prep.

- **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
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→'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) not SZ (ActPol ~1000). All X-ray clusters detected or redetected with XMM Cluster Survey

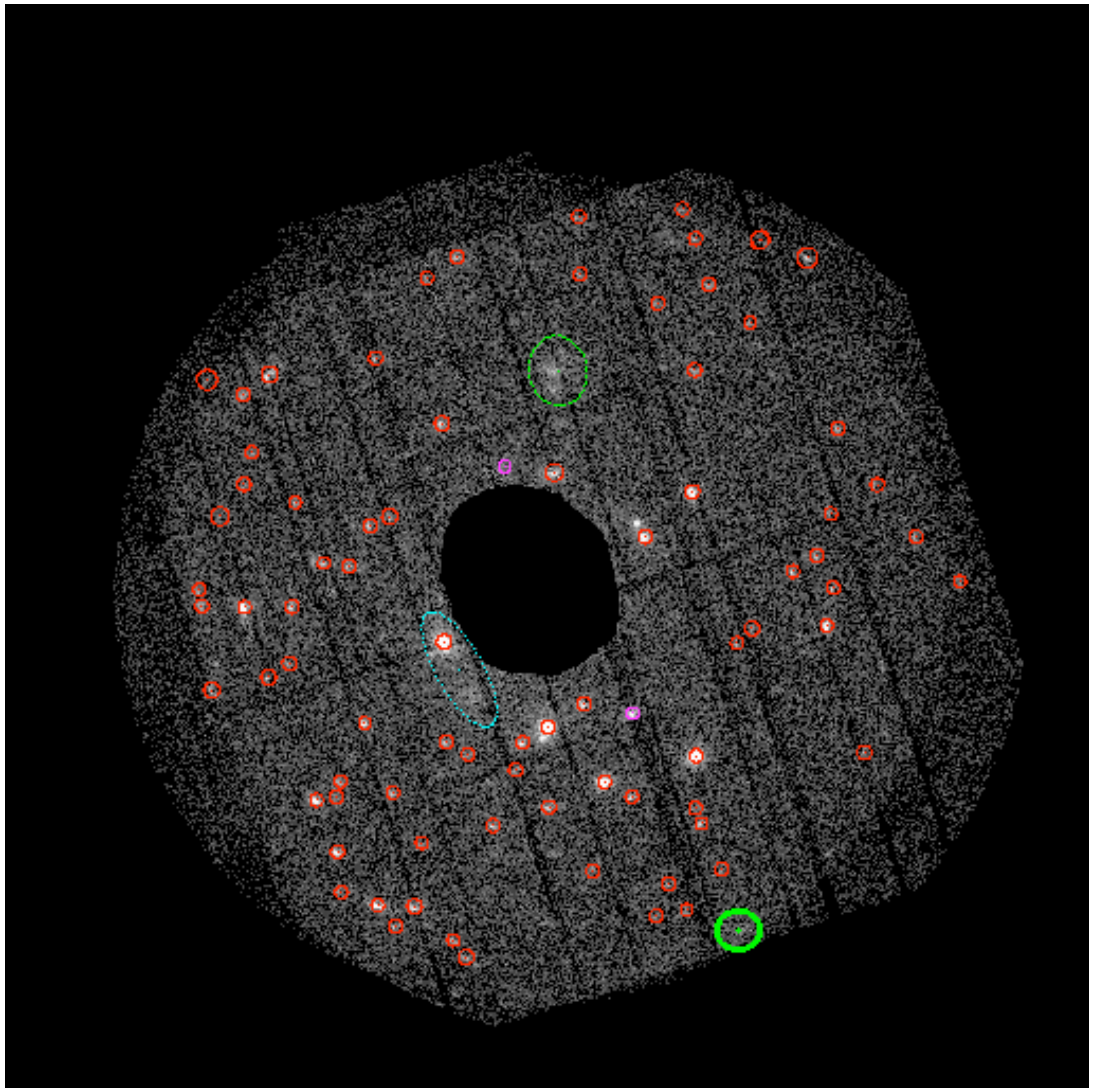
XCS:

XMM Cluster Survey

Members: Kathy Romer [P.I], John P. Stott, Claire Burke, 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.

- The XMM Cluster Survey aims to mine the XMM science archive for galaxy clusters

X-ray emission 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 and masses.



Algorithms paper, Lloyd-Davies et al. 2010 (arXiv:1010.0677)

See Matt's talk for all the juicy details.

Recent data release,
Mehrtens et al. arXix:1106.3056
503 clusters, spanning $0.06<z<1.46$
438 have x-ray temperatures

More Clusters. Data sample

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Conservative assumptions

Footprints; If there was overlap between the surveys, we conservatively assumed each X-ray survey had it's own unique footprint

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

Analysis & Results I

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

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

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

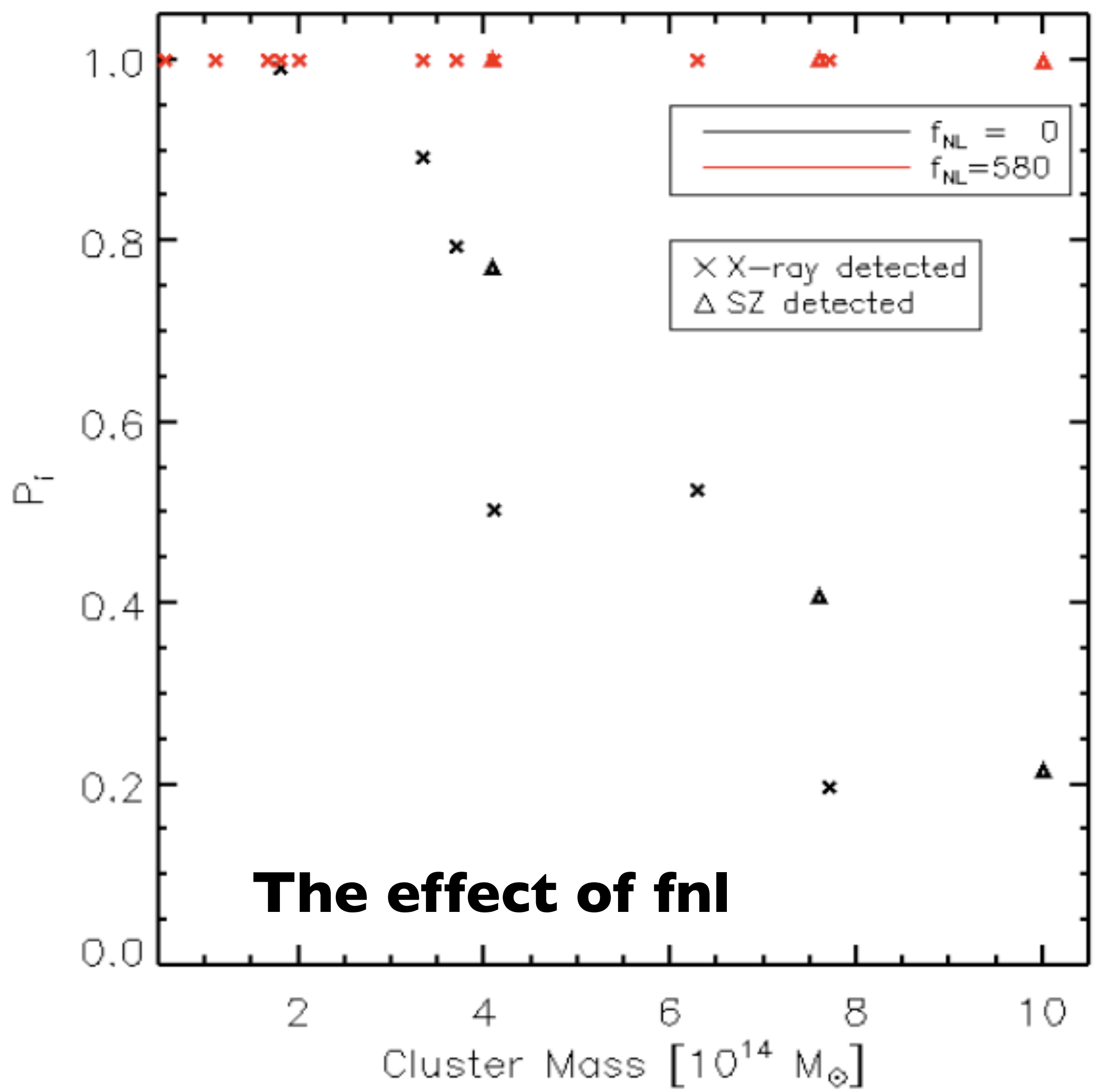
The probability P_i ,that cluster "i" exists is $\mathrm{Number}(P^O(A_s) \geq 1)/10^4)$

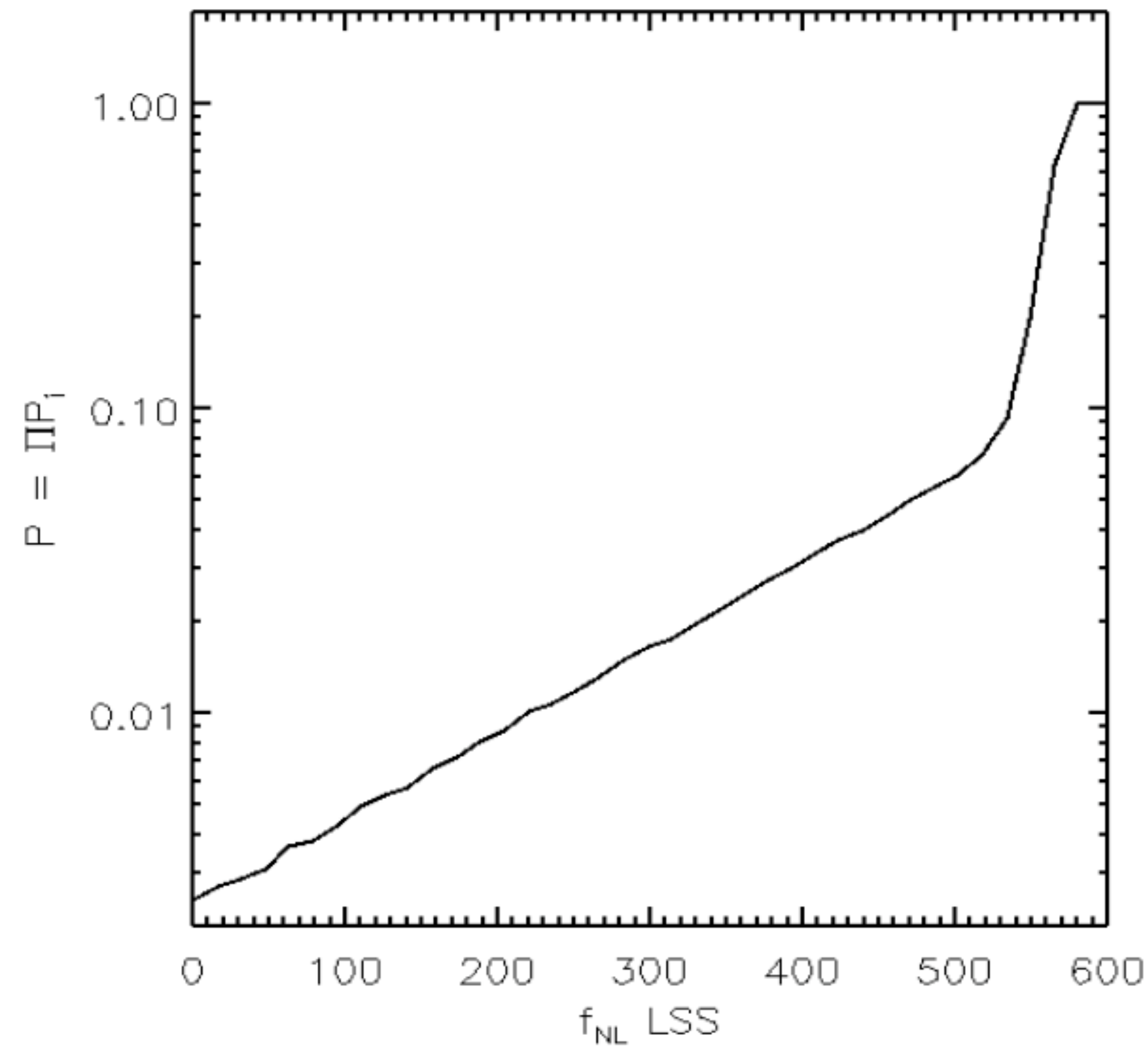
The probability, that the ensemble of cluster exists is $P(f_{\rm NL}, C) = \Pi P_i$

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

Analysis & Results I

Fixed cosmological parameters to best fit WMAP 5





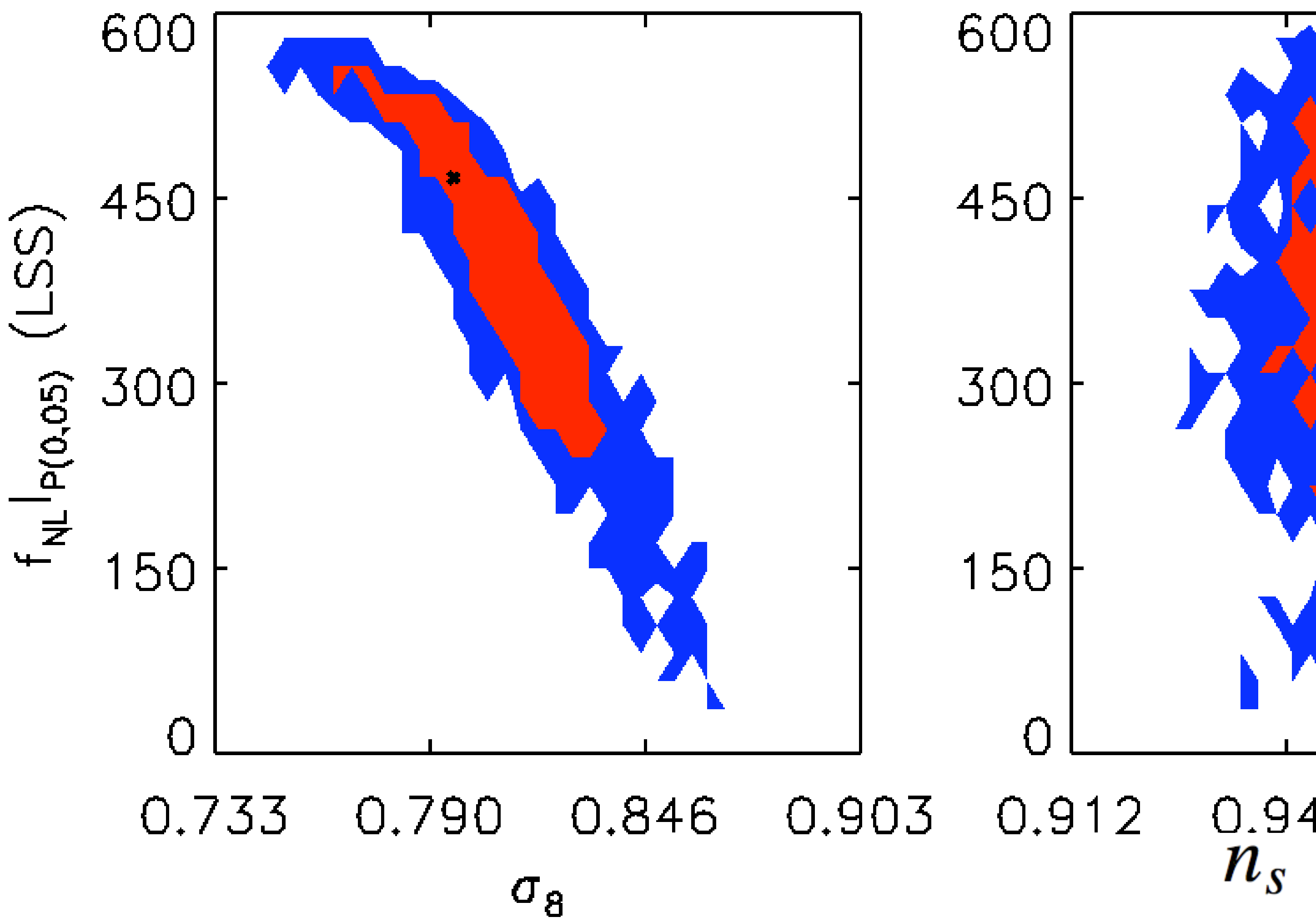
We determine the value of fnl where P=0.05
i.e., the value of fnl that contains 95% of the probability

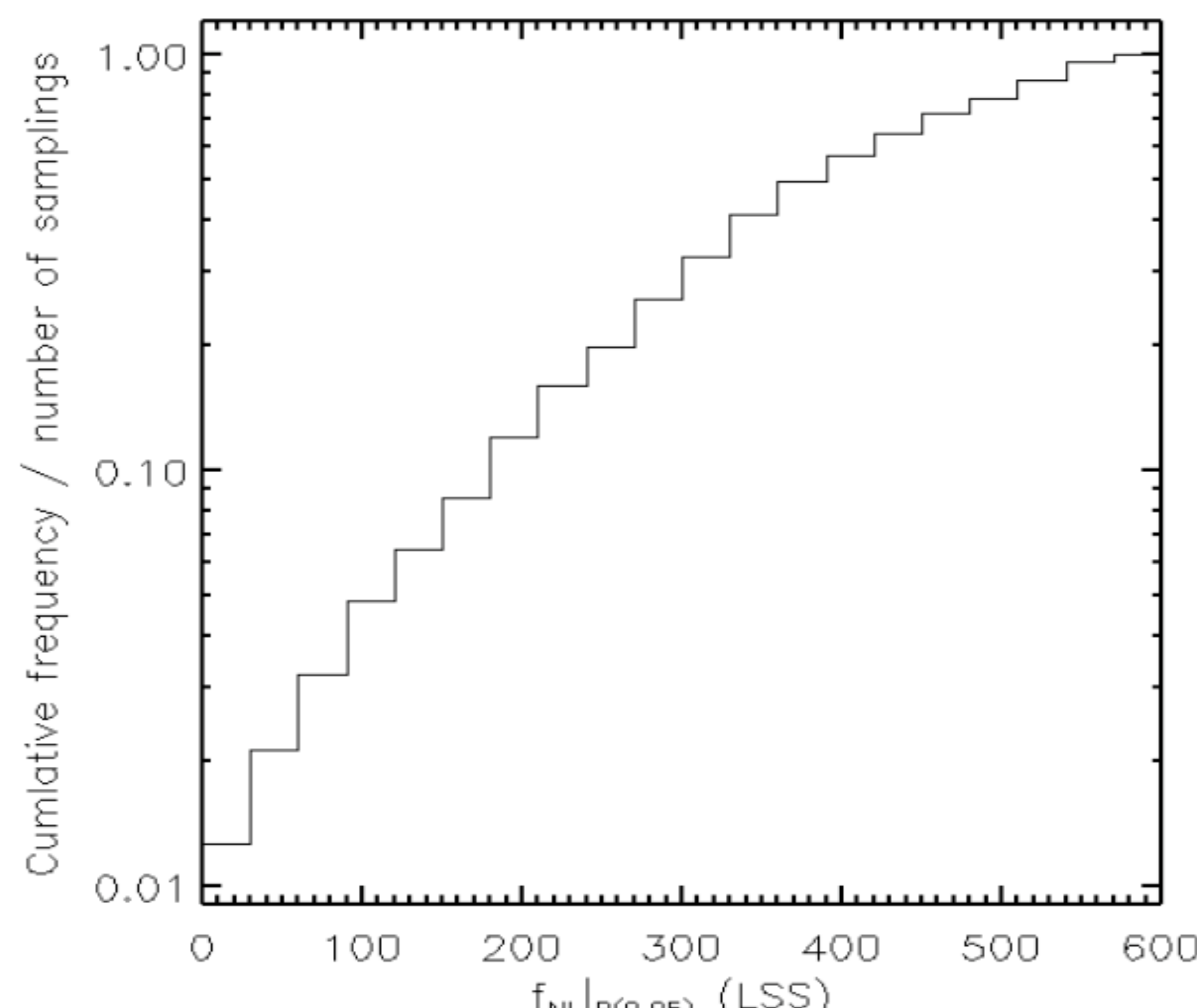
$$f_{\rm NL}|_{P(0.05)}$$

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

Analysis & Results I

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





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

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

Reality Check!

Is this a detection of +ve fnl, or are there systematics 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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Do we understand the mass function (with fnl, e.g., Tinker) at high mass and redshift well enough?

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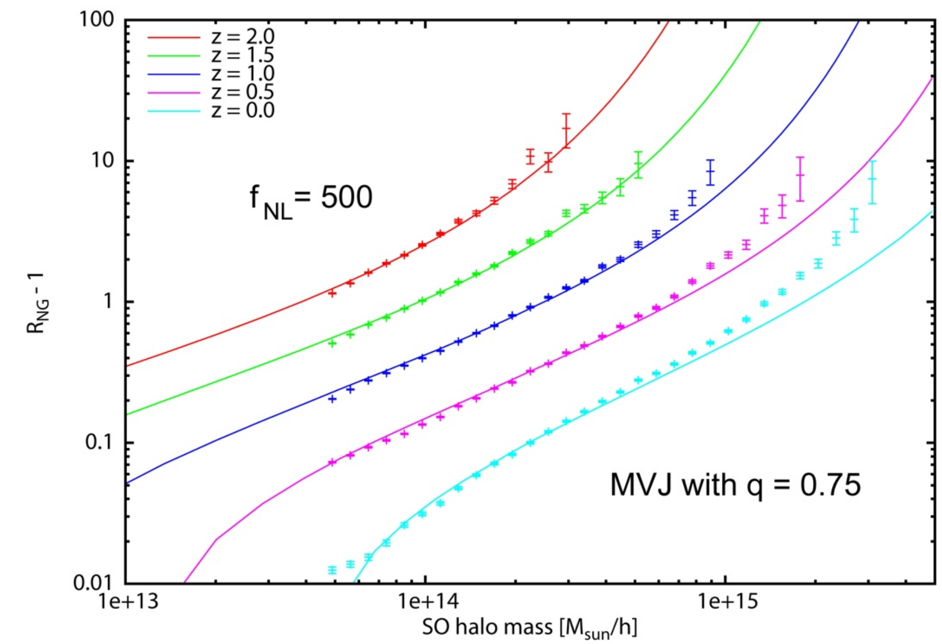

Non-Gaussian mass function fit to N-body simulations
Volume: 40 x (2.4 Gpc/h)^3
Number of Particles: 40 x 768^3
Spherical-overdensity halos with "virial" masses
Difference for very large halo masses might be due to fnl^2 effects.

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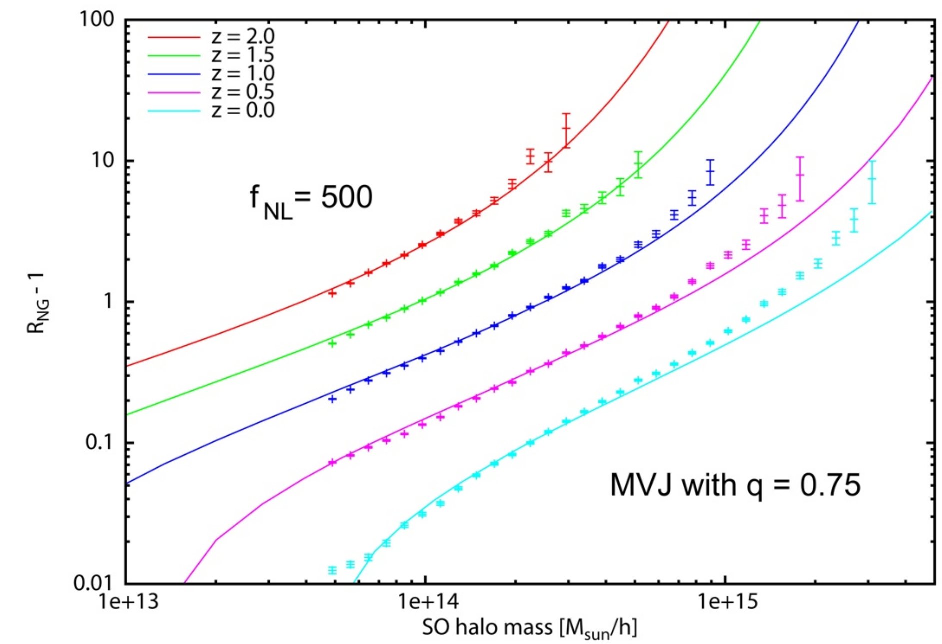
If every mass measurement was 1.5 sigma higher than the "true" value, then all tension is relieved. But all independent mass estimates must be systematically, equally wrong.



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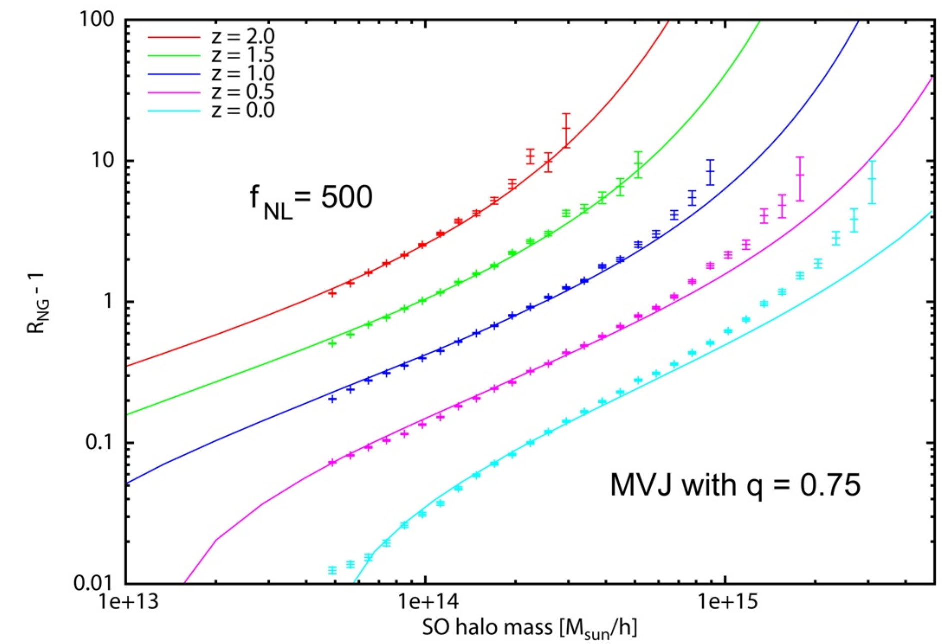
Failed HST WL proposal :([PI BH].



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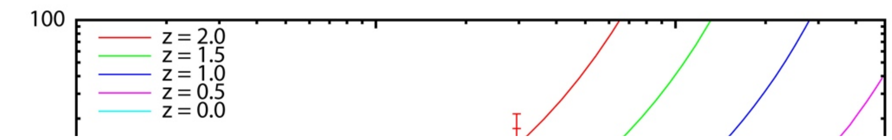

Cluster Name	Redshift	M_{200} $10^{14} M_{\odot}$	Method	Footprint	Mass reference
RCS0221-0321	1.02	$1.80^{+1.30}_{-0.70}$	WL	100.	[16]
RCS0220-0333	1.03	$4.80^{+1.80}_{-1.30}$	WL	100.	[16]
WARPSJ1415+3612	1.03	$4.70^{+2.00}_{-1.40}$	WL	100.	[16]
RCS2345-3632	1.04	$2.40^{+1.10}_{-0.70}$	WL	100.	[16]
XLSSJ022403.9-041328	1.05	$1.66^{+1.15}_{-0.38}$	X-ray	100.	[30]
RCS2156-0448	1.07	$1.80^{+2.50}_{-1.00}$	WL	100.	[16]
RCS0337-2844	1.10	$4.90^{+2.80}_{-1.70}$	WL	100.	[16]
ISCSJ1432+3332	1.11	$4.90^{+1.60}_{-1.20}$	WL	100.	[16]
RDCSJ0910+5422	1.11	$5.00^{+1.20}_{-1.00}$	WL	100.	[16]
XMMUJ2205-0159	1.12	$3.00^{+1.60}_{-1.00}$	WL	100.	[16]
RXJ1053.7+5735(West)	1.14	$2.00^{+1.00}_{-0.69}$	X-ray	100.	[30]
XLSSJ0223-0436	1.22	$7.40^{+2.50}_{-1.80}$	WL	100.	[16]
RDCSJ1252-2927	1.24	$6.80^{+1.20}_{-1.00}$	WL	100.	[16]
ISCSJ1434+3427	1.24	$2.50^{+2.20}_{-1.10}$	WL	100.	[16]
ISCSJ1429+3437	1.26	$5.40^{+2.40}_{-1.60}$	WL	100.	[16]
RDCSJ0849+4452	1.26	$4.40^{+1.10}_{-0.90}$	WL	100.	[16]
RDCSJ0848+4453	1.27	$3.10^{+1.00}_{-0.80}$	WL	100.	[16]
ISCSJ1432+3436	1.35	$5.30^{+2.60}_{-1.70}$	WL	100.	[16]
ISCSJ1434+3519	1.37	$2.80^{+2.90}_{-1.40}$	WL	100.	[16]
XMMUJ2235-2557	1.39	$7.30^{+1.70}_{-1.40}$	WL	100.	[16]
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SPT-CLJ0546-5345	1.06	$7.95^{+0.92}_{-0.92}$	Mixed	2500	[3]
SPT-CLJ2106-5844	1.13	$12.7^{+2.10}_{-2.10}$	SZ	2500	[10]

Jee et al 2011

- Gurvan Basin HST WL.

Related works

Mortonson et al 2010

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

- **Very conservative footprints and mass estimates.**
- **Insensitive treatment of multiple clusters**
- **Caution using this if know SF.**

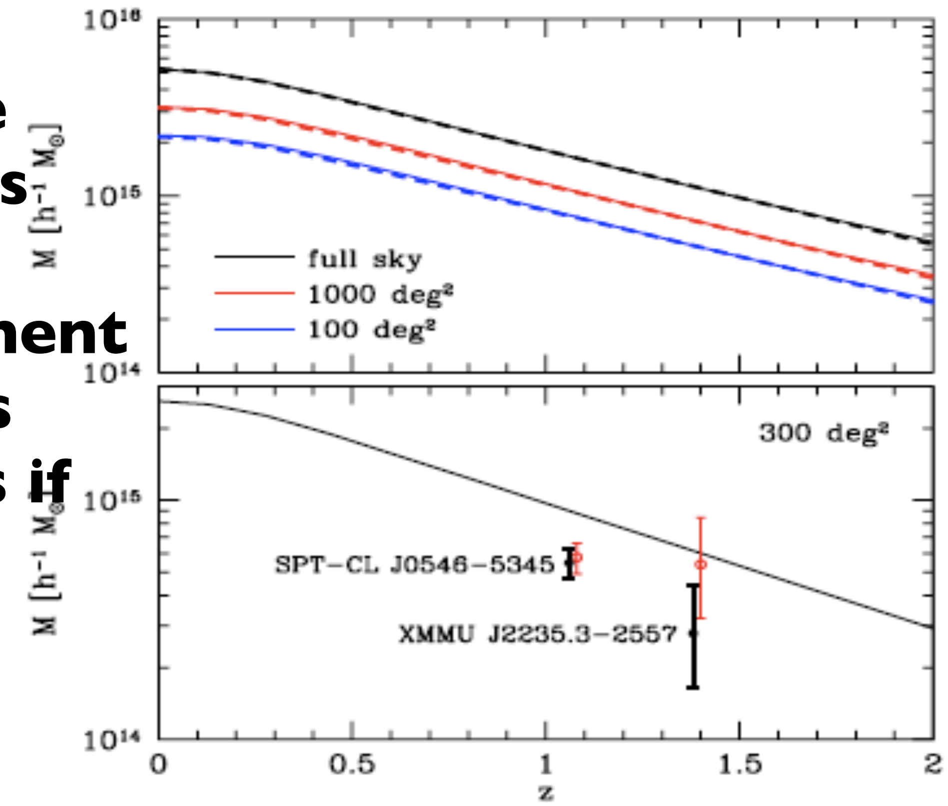

FIG. 4. $M(z)$ exclusion curves. Even a single cluster with (M, lying above the relevant curve would rule out both ΛCDM an quintessence. *Upper panel:* flat ΛCDM 95% joint CL for bo sample variance and parameter variance for various choices of sk fraction $f_{\rm sky}$ from the MCMC analysis (thin solid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

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Enqvist et al 2010

- **Agreed with us!**
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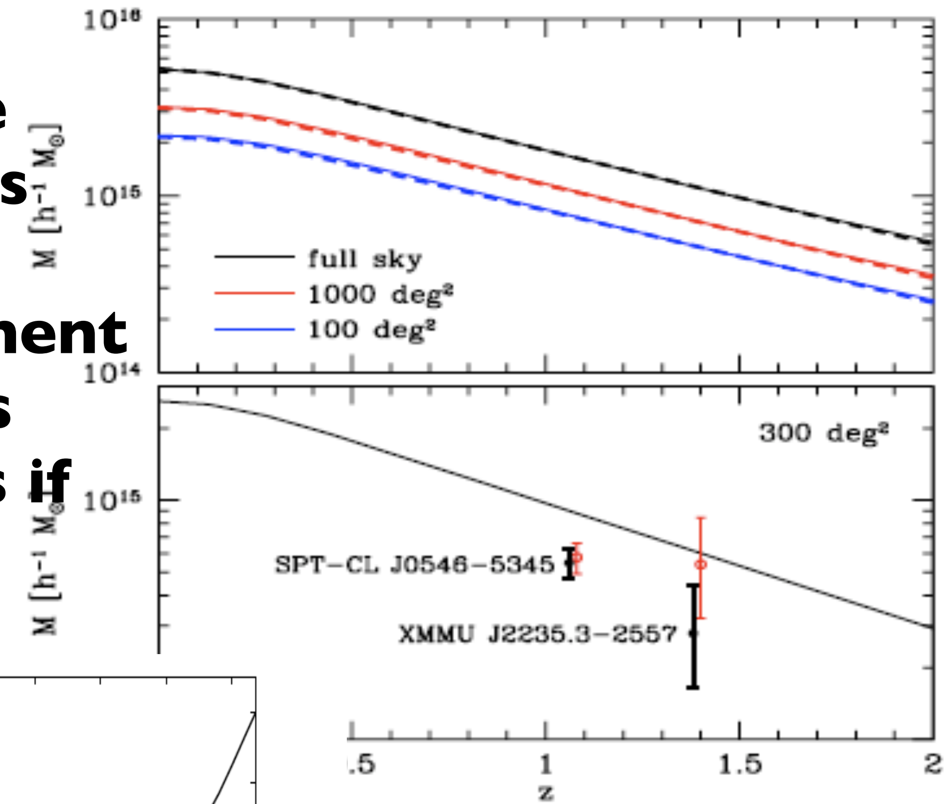

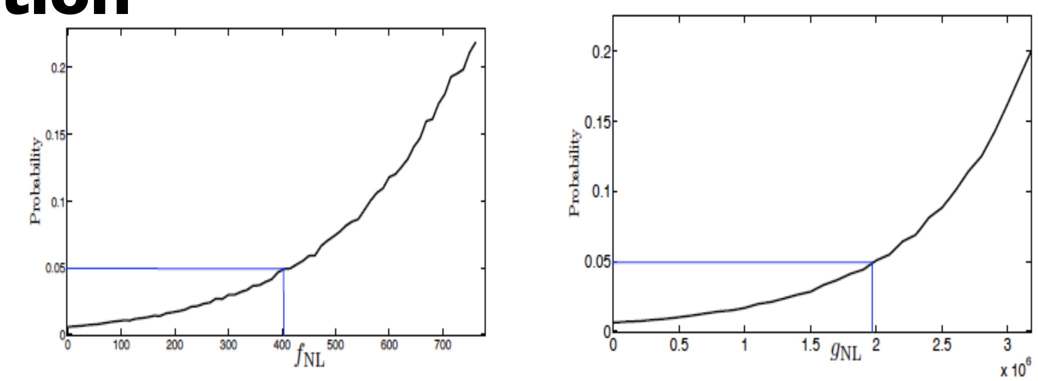

(a) The probability that the ensemble of clusters in table 1 could exist as a function of $f_{\rm NL}$.

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

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

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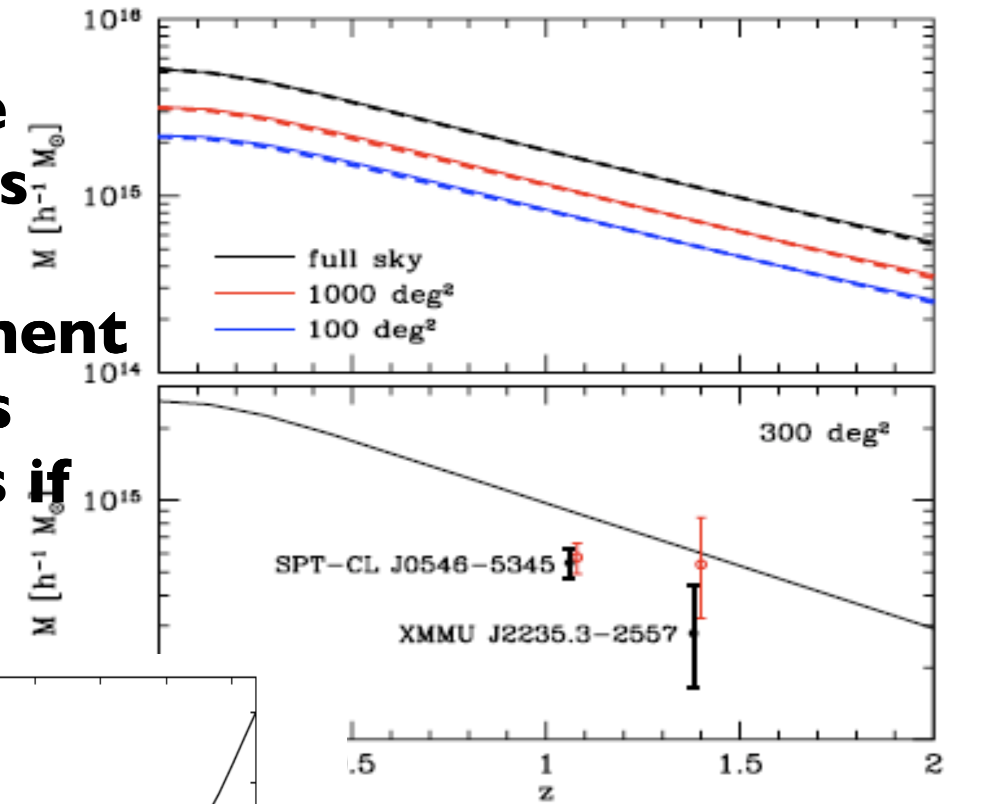

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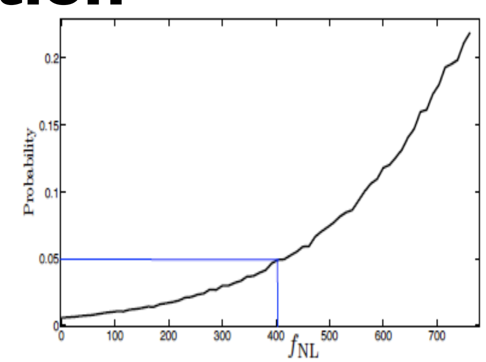

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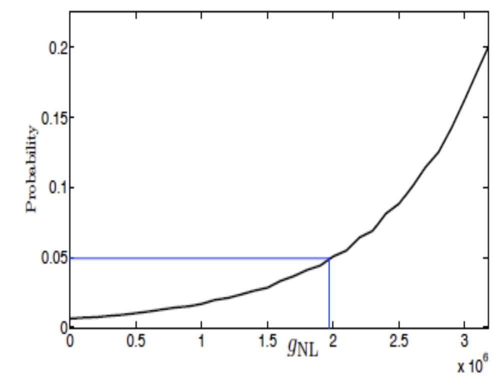
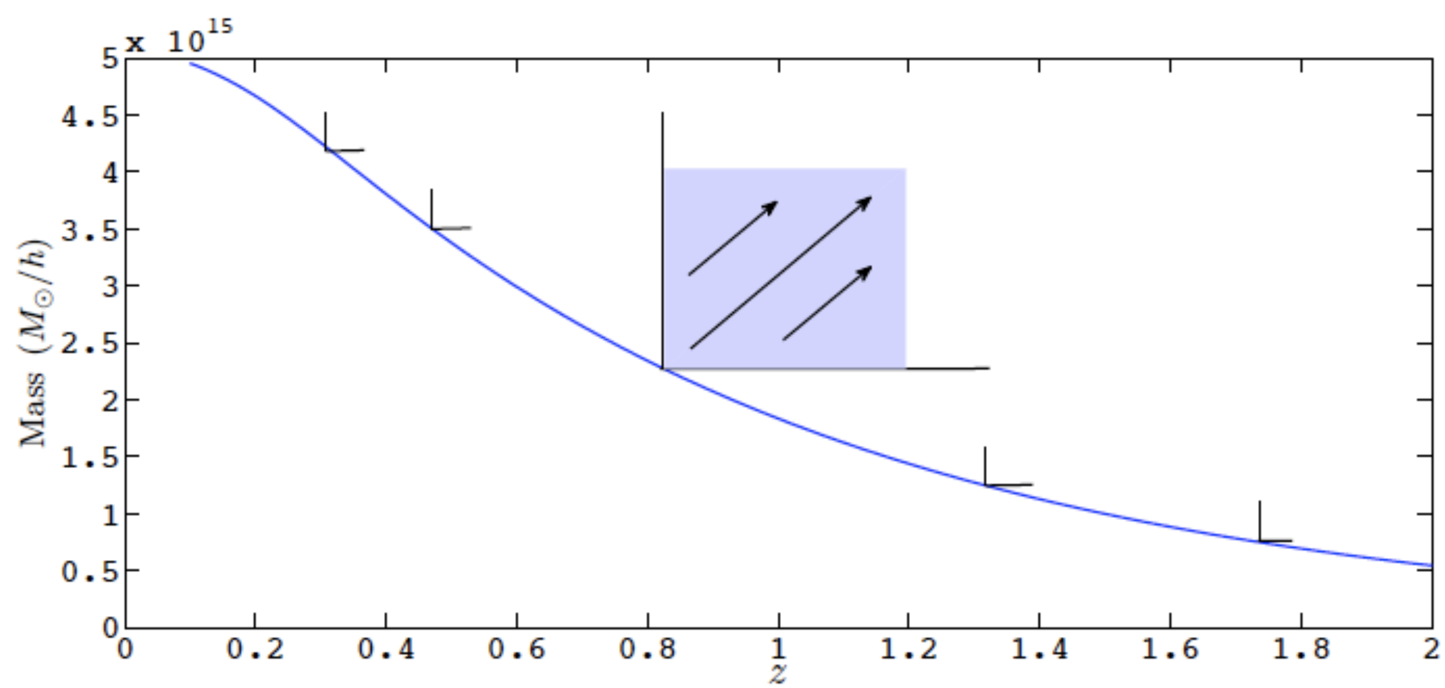


(b) The probability that the ensemble of clusters in table 1 could exist as a function of $g_{\rm NL}$, with $f_{\rm NL} \lesssim 50$.

Hotchkiss arXiv: 2011

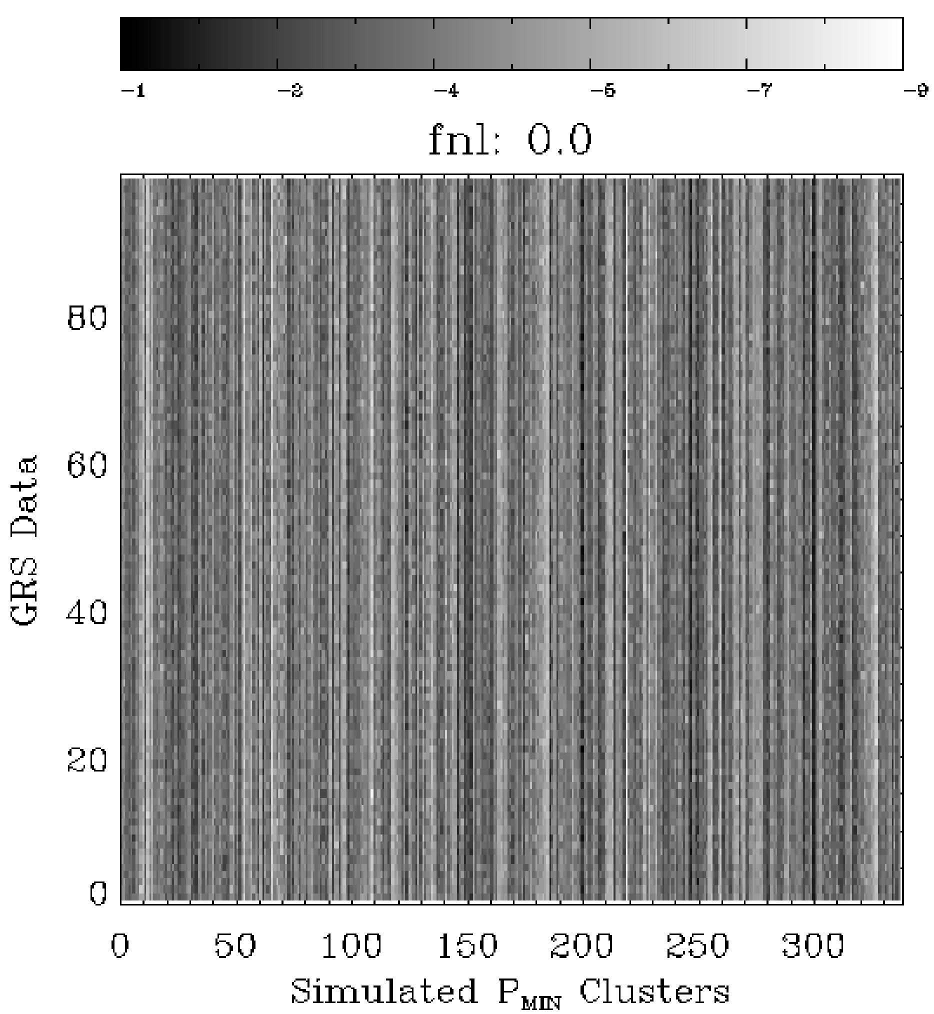
- **Higher probability, but assumed the selection function was known. Integrated above the curve.**
- **If the observed clusters were consistent with being the Least Probable clusters, ->no tension with WMAP7 LCDM.**
- **If observed clusters random selection -> still caused tension.**



Analysis & Results II

Comparing the clusters with the LP simulated clusters: 2d K-S test.

The 2d KS test determines if two 2d data sets are drawn from the same parent population. We Poisson sample from the theoretical mass function, and compare the resulting distribution in the (M,z) plane of the LP clusters from each simulation with each other (varying WMAP7 cosmology) and with the data.



Results

- **The simulated LP clusters are consistent with each other (P=0.2)**
- **The simulated LP clusters are not consistent with the data (P=0.001) .**

-> Tension with LCDM still remains.

Conclusions/Future work

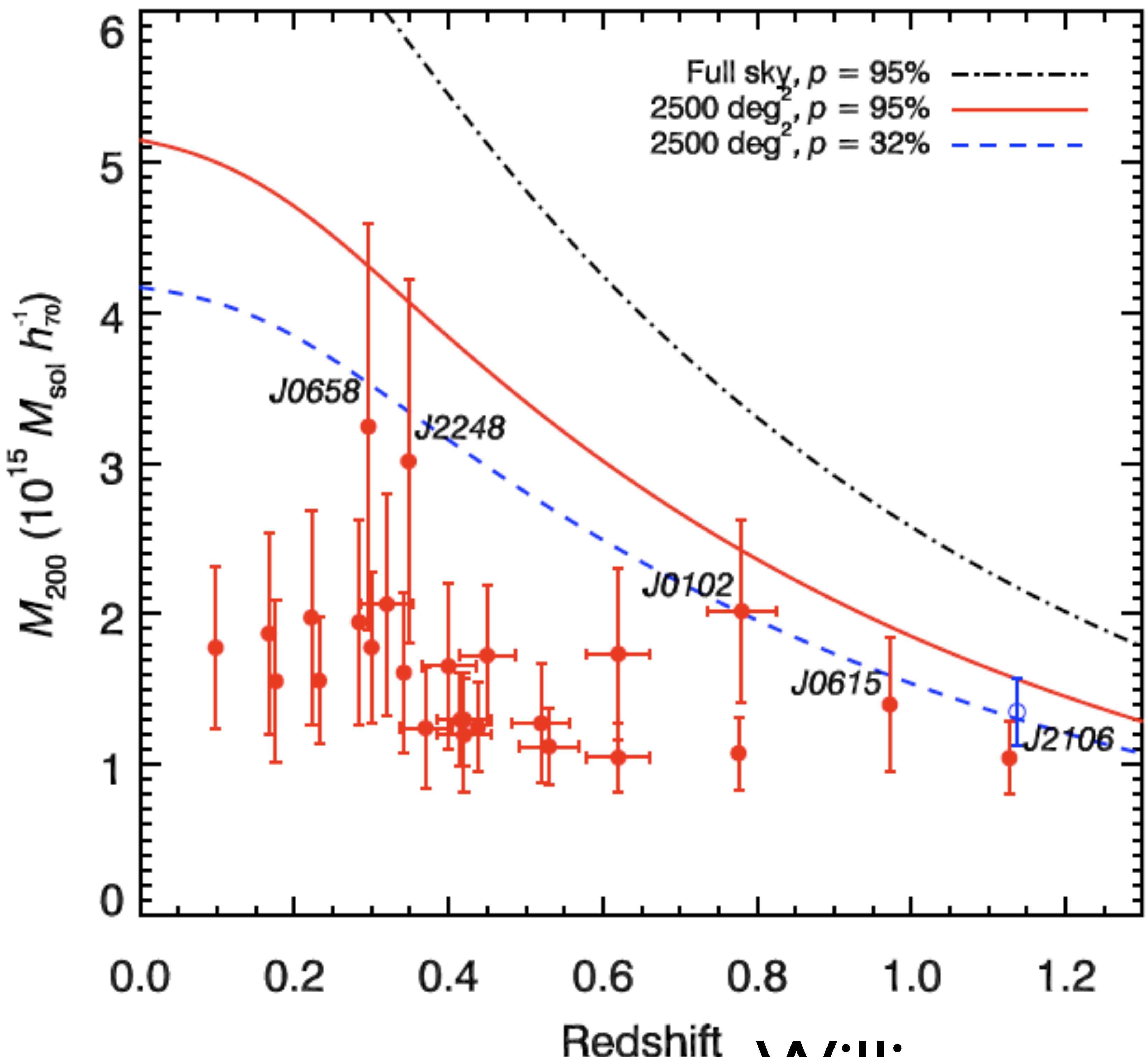
These clusters still pose a question to LCDM with WMAP priors on cosmological parameters.

$\sigma_8 = 0.9$ **or** $M_{TRUE} = M_{OBS} - 1.5 \times \Delta M$ **or** $f_{\rm NL}|_{P(0.05)} \gtrsim 123$ at the 95%

or **mass function uncertainty.**

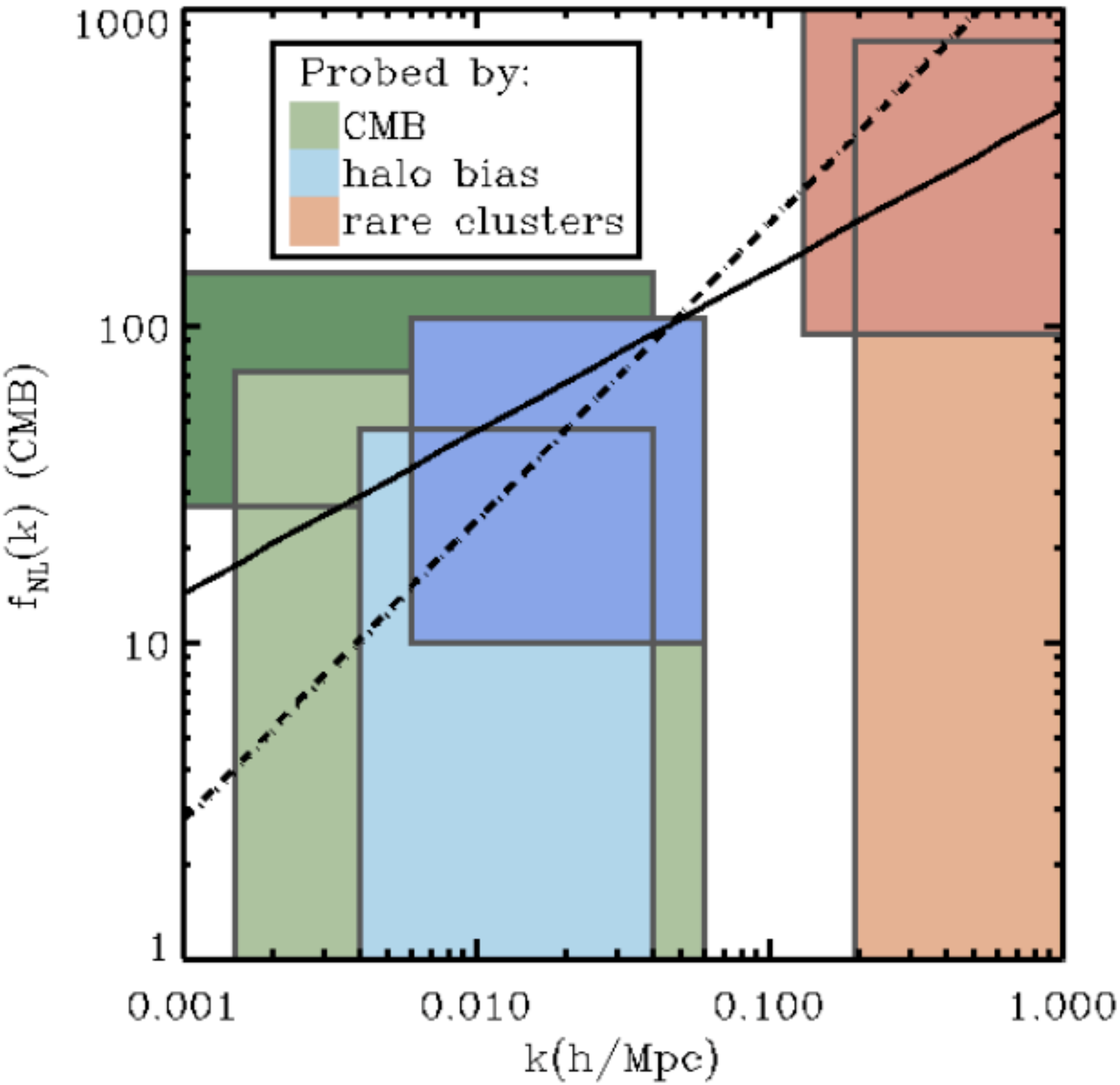
- **Built a list of high redshift clusters.**
- **Conservative footprint/survey/completeness/mass assumptions.**
- **Attempted to quantify the tension with LCDM.**
- **Showed how fnl or systematics can reduce tension, and work to reduce systematics.**
- **No consensus as to the level of tension, or how to quantify it.**
- **A more rigorous approach to quantifying tension and parameter estimation is developed in Hoyle et al (in prep)**

- **But, more high redshift, massive clusters are being found ~weekly. SPT release/Planck /XCS, so we need a framework to understand what they tell us about LCDM**



Williamson et al 2011

If fnl, then Scale Dependent non-Gaussianity



WMAP CMB, scales 0.04 h/Mpc

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

Yadev & Wandelt 2008

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

Komatsu et al 2011

Halo bias, scales 0.1 h/Mpc

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

Xia et al 2010

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

Slozar et al 2008

Galaxy Clusters, scales 0.4 h/Mpc

$$449 \pm 286 \text{ at } 1\,\sigma$$

Cayon et al 2010

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

Hoyle et al 2010

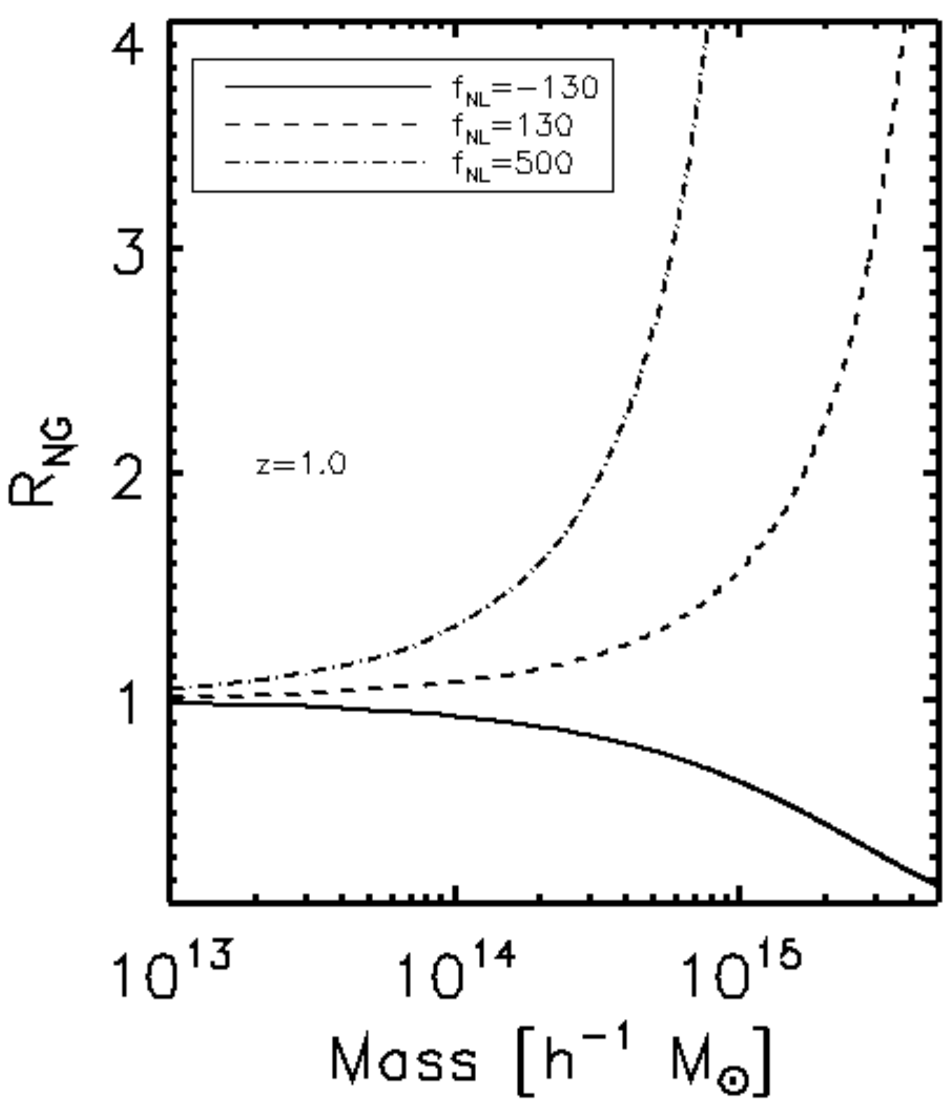
$$f_{\rm NL} = f^*_{\rm NL}\left(\frac{k}{k^*}\right)^{n_{NG}} \qquad n_{NG} = 0.50 \pm 0.19 \qquad n_{NG} = 0.95 \pm 0.23$$

Lo Verde et al 2008

Modifying the mass function with non-Gaussianity

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

$$n_G(M,z) = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M^2}\left|\frac{\mathrm{d}}{\mathrm{d}\ln M}\ln\sigma_M\right|\,\nu\,\exp-\nu^2/2\,. \qquad \mathcal{R}_{NG}(S_{3,M},M,z) = \frac{n(M,z,f_{\rm NL})}{n_G(M,z,f_{\rm NL}=0)}$$



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

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

The normalised skewness of the smoothed density field

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

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

Motivation: theory, a window to the early Universe

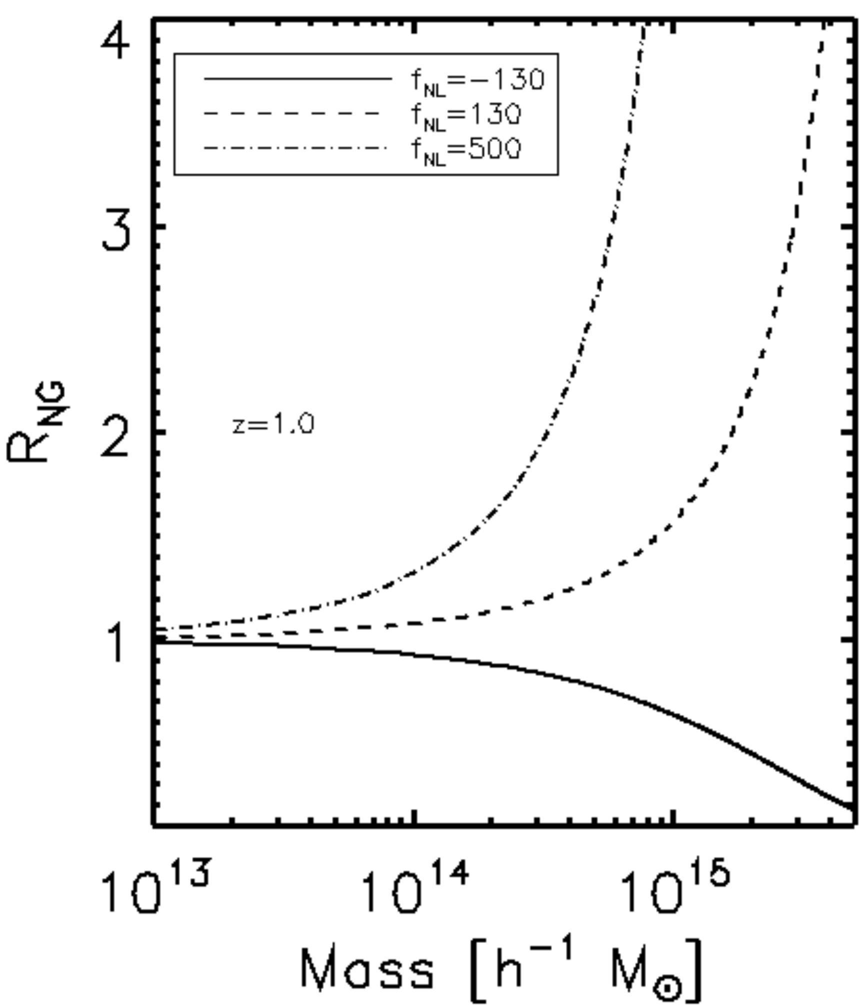
Using today's data, (not some future experiement e.g. LISA-like) we can make a measurement of the primodial non-Gaussianity (fnl) which can tell us about the various types of scalar field interactions during inflation/reheating/preheating.

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

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

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

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



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

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

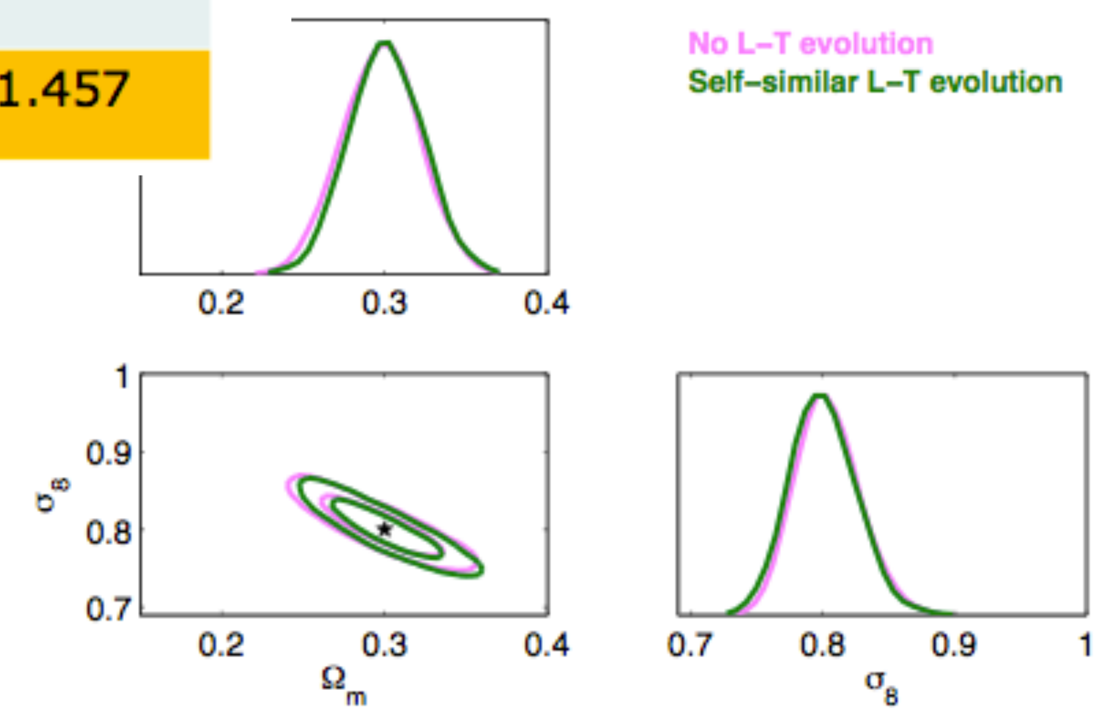
$$\mathcal{R}_{NG}(S_{3,M}, M, z) \ = \ \frac{n(M,z,f_{\rm NL})}{n_G(M,z,f_{\rm NL}=0)}$$

XCS:

Current X-Ray Cluster Surveys

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

Forcast papers:
Cosmological constraints



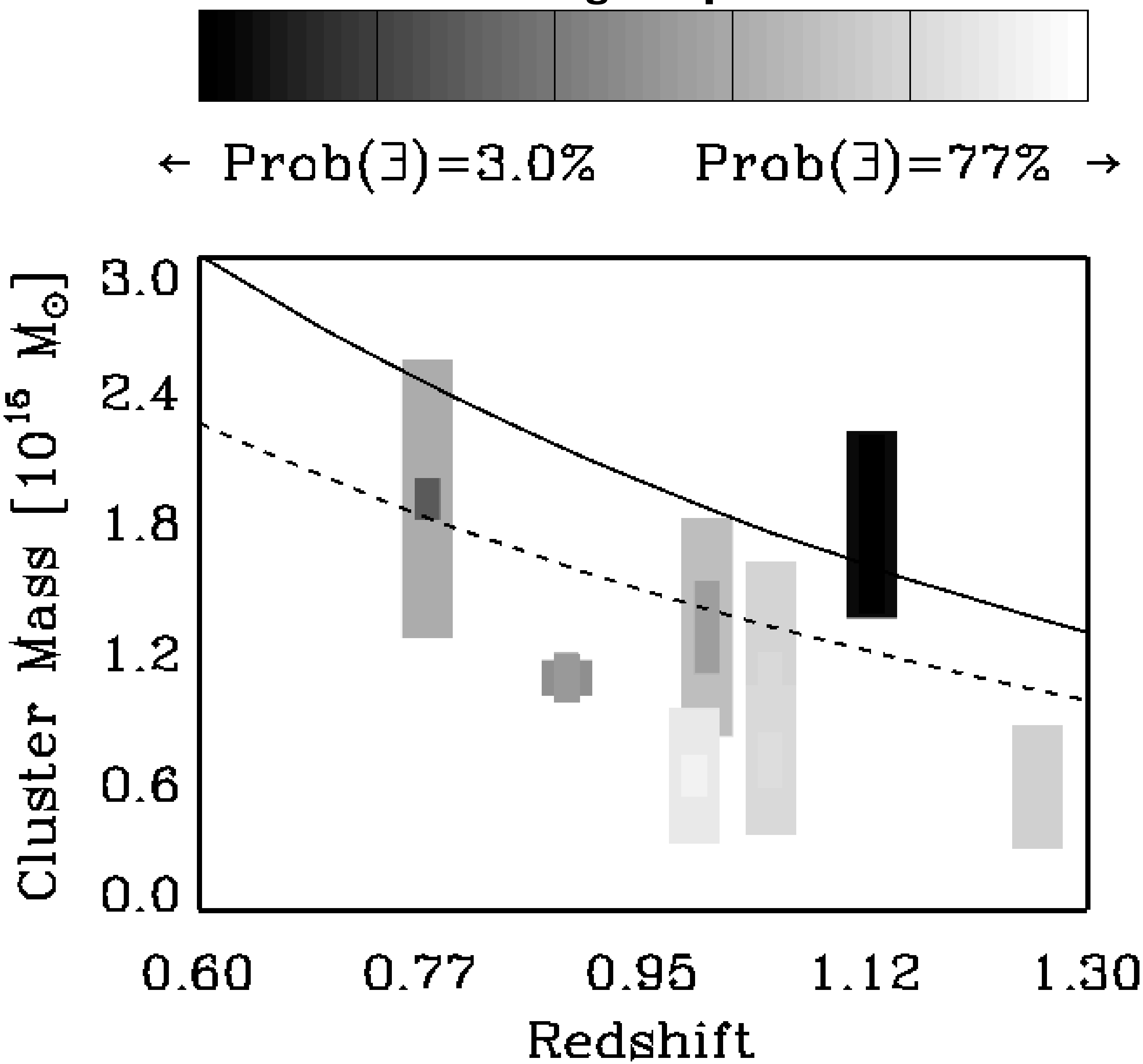
Martin Sahlen et al 2009, and in prep.

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

Data release, Mehrtens et al. in prep (very soon!)

HST proposal

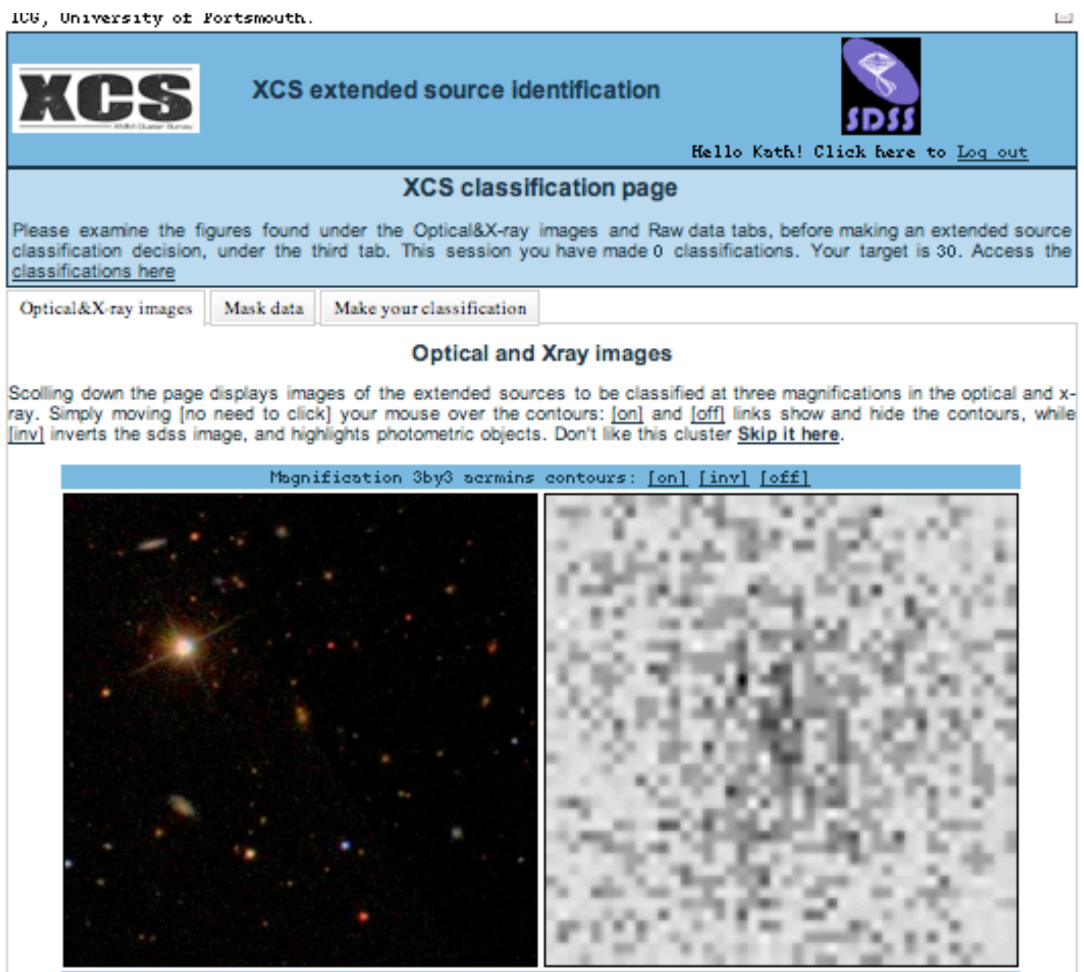
Mortonson et al type exclusion curves, and the change in Probability of existence with HST WL mass estimates assuming the peak mass value is unchanged.

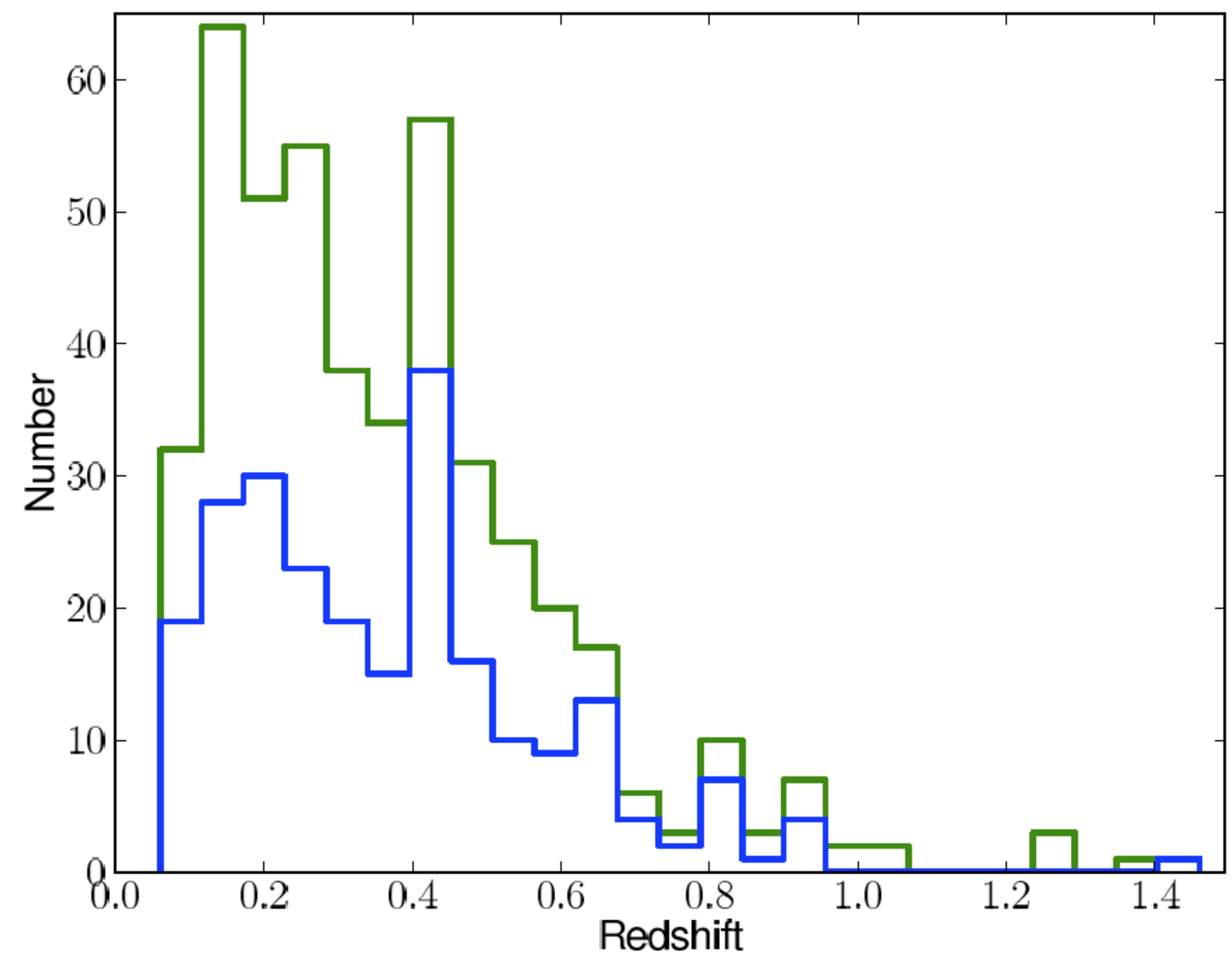


XCS: Optical Followup

Purity with Cluster Zoo

All clusters multiply classified by experts to determine purity.





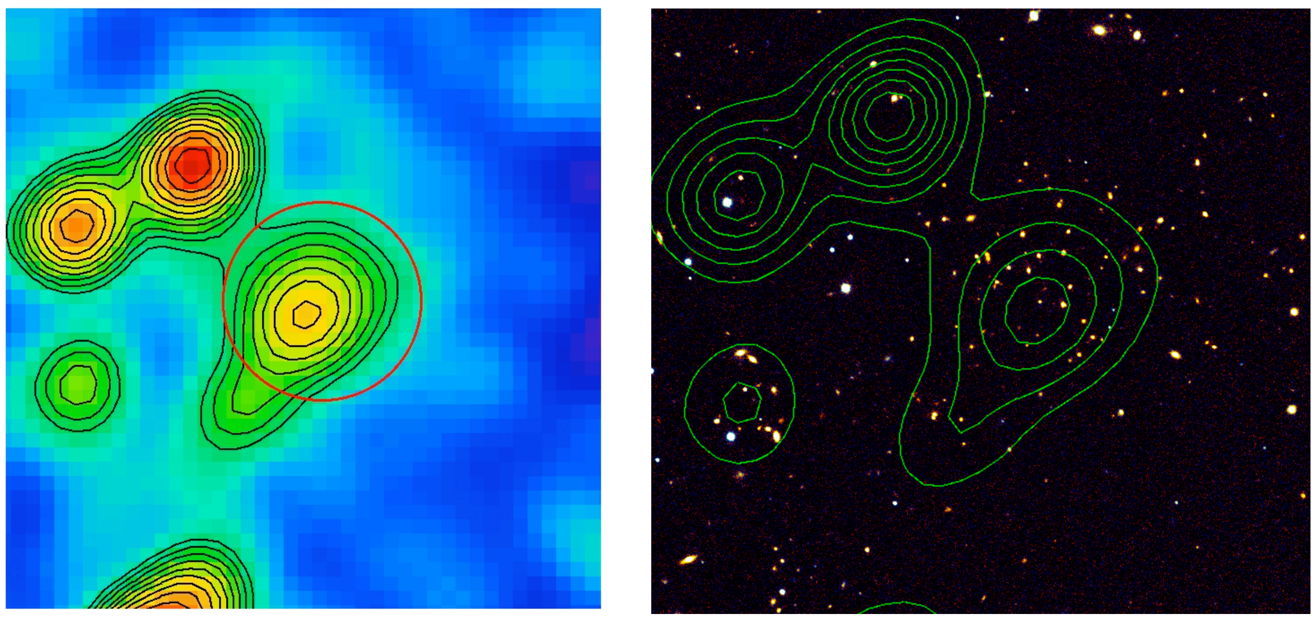
503 clusters, spanning 0.06<z<1.46
438 have x-ray temperatures

Recent data release, Mehrtens et al. arXix:1106.3056

XCS: Other results.

XMMXCS J2215

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

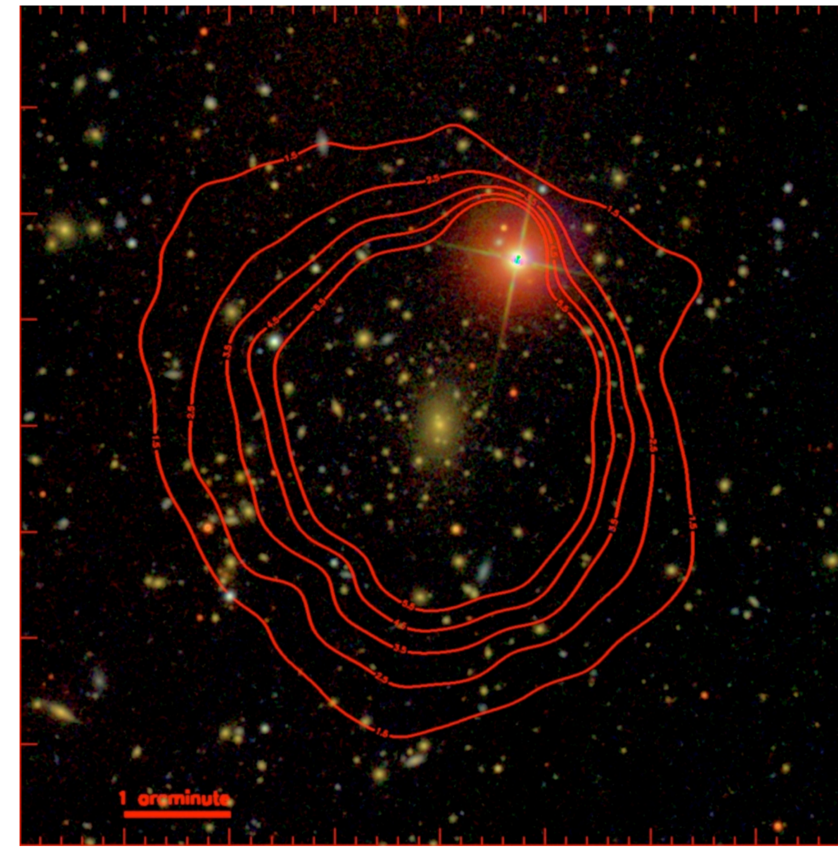


Now z=2.07, M~5-8.10^13 SolMass, Gobat et al arXiv:1011.1837

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

Recent Data release, Mehrtens et al. arXix:1106.3056

Fossil groups



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

Harrison et al (submitted)