The cosmological implications of massive, high redshift galaxy clusters

Ben Hoyle, Raul Jimenez, Licia Verde, ICC-IEEC University of Barcelona, University of Helsinki: astro-ph/1009.3884 (accepted PRD)

Aday Robiana (ICC Barcelona), David Bacon (ICG Portsmouth), Kath Romer (Sussex) , Matt Hilton (Nottingham), Ed Lloyd-Davies (Sussex), Nicola Mehrtens (Sussex), Martin Sahlen (Stockholm University)

The XMM Cluster Survey.

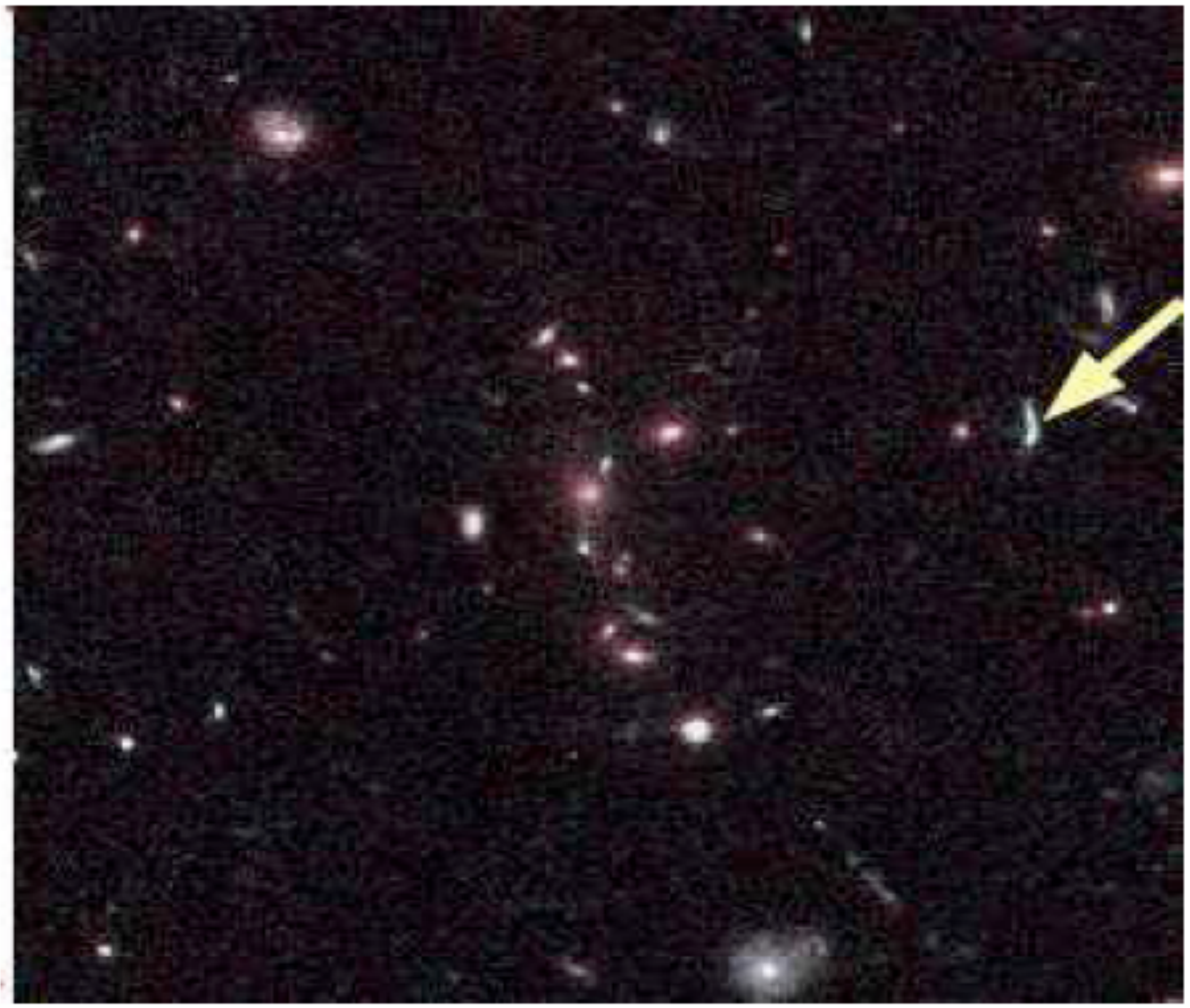
PONT AVINGNON 20/4/2011

Overview

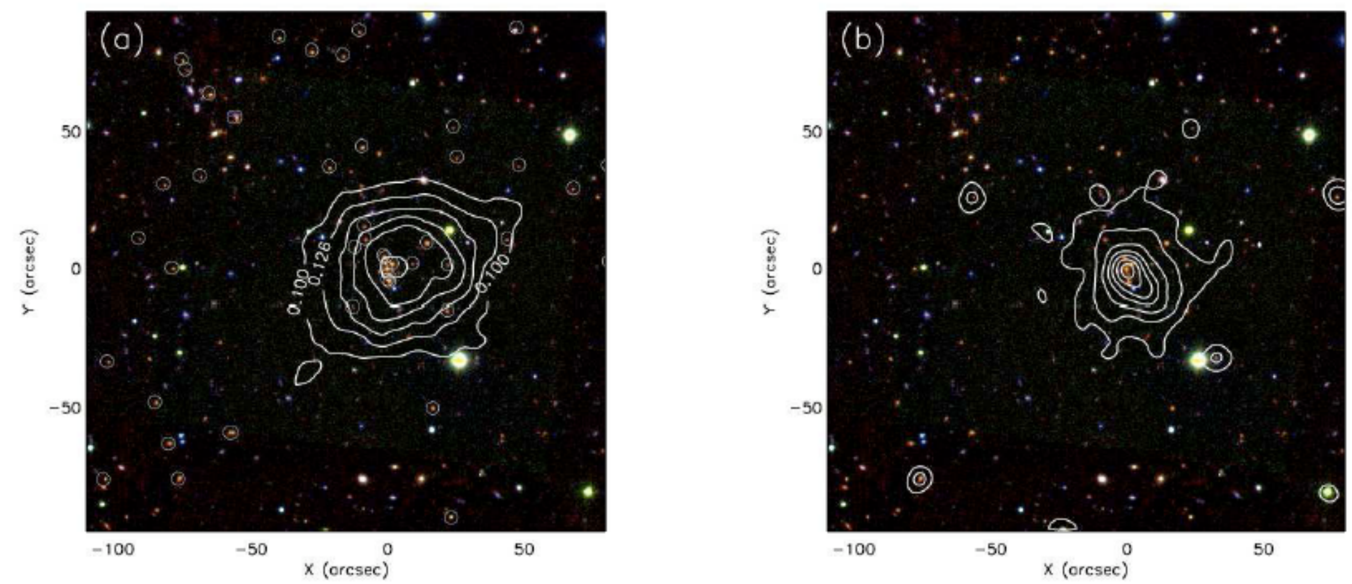
- Observational motivation
- The cluster sample
- The XMM Cluster Survey
- Analysis and Results
- Possible explanations: Systematics
- Conclusions

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?

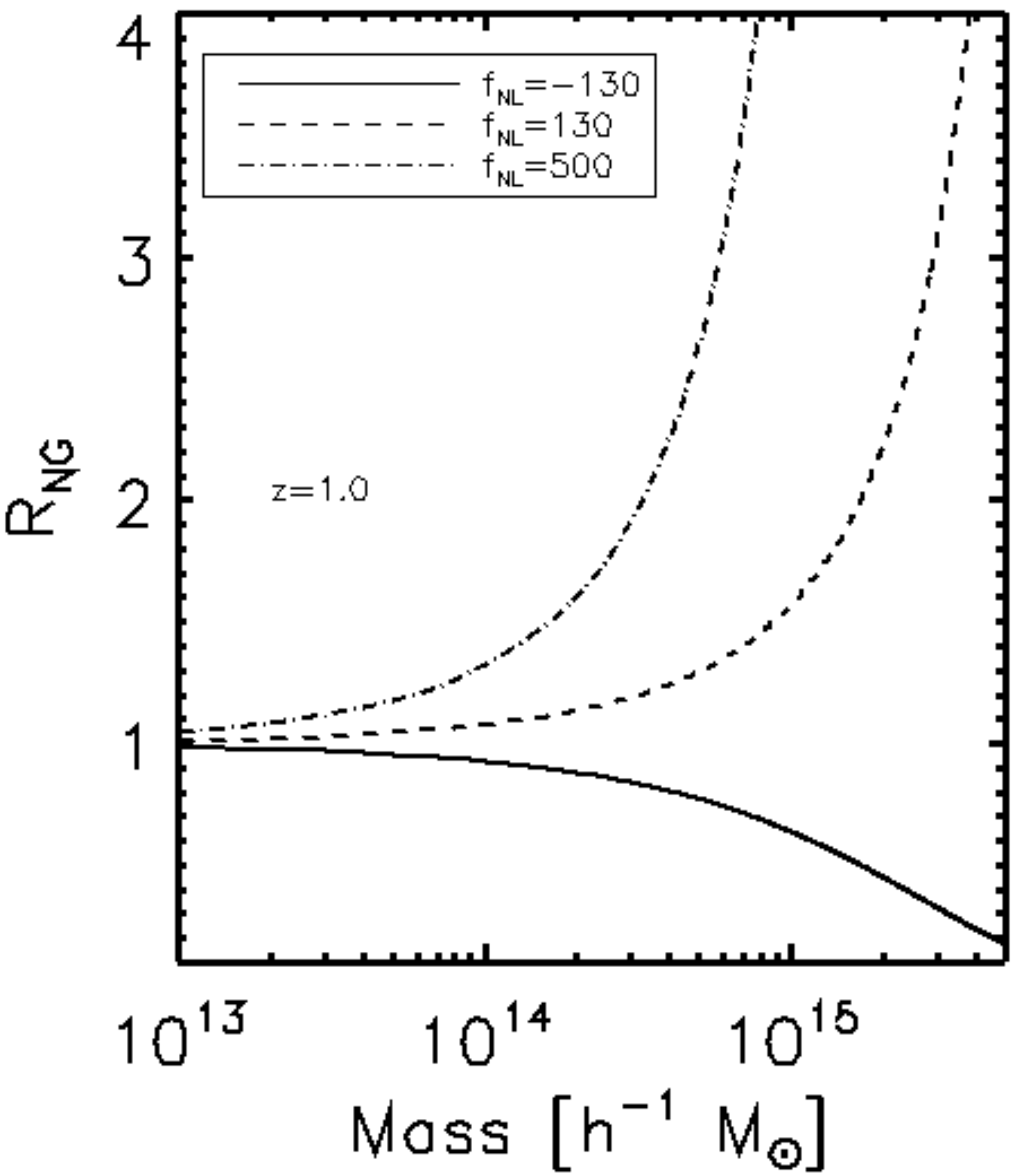
- **The expected number in the full sky ~7.**
- **Footprint was 11 square degrees XMM X-ray survey, 0.02% of sky.**
- **Poisson sample from (0.0002*7) >1 only 1.4%**

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]



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

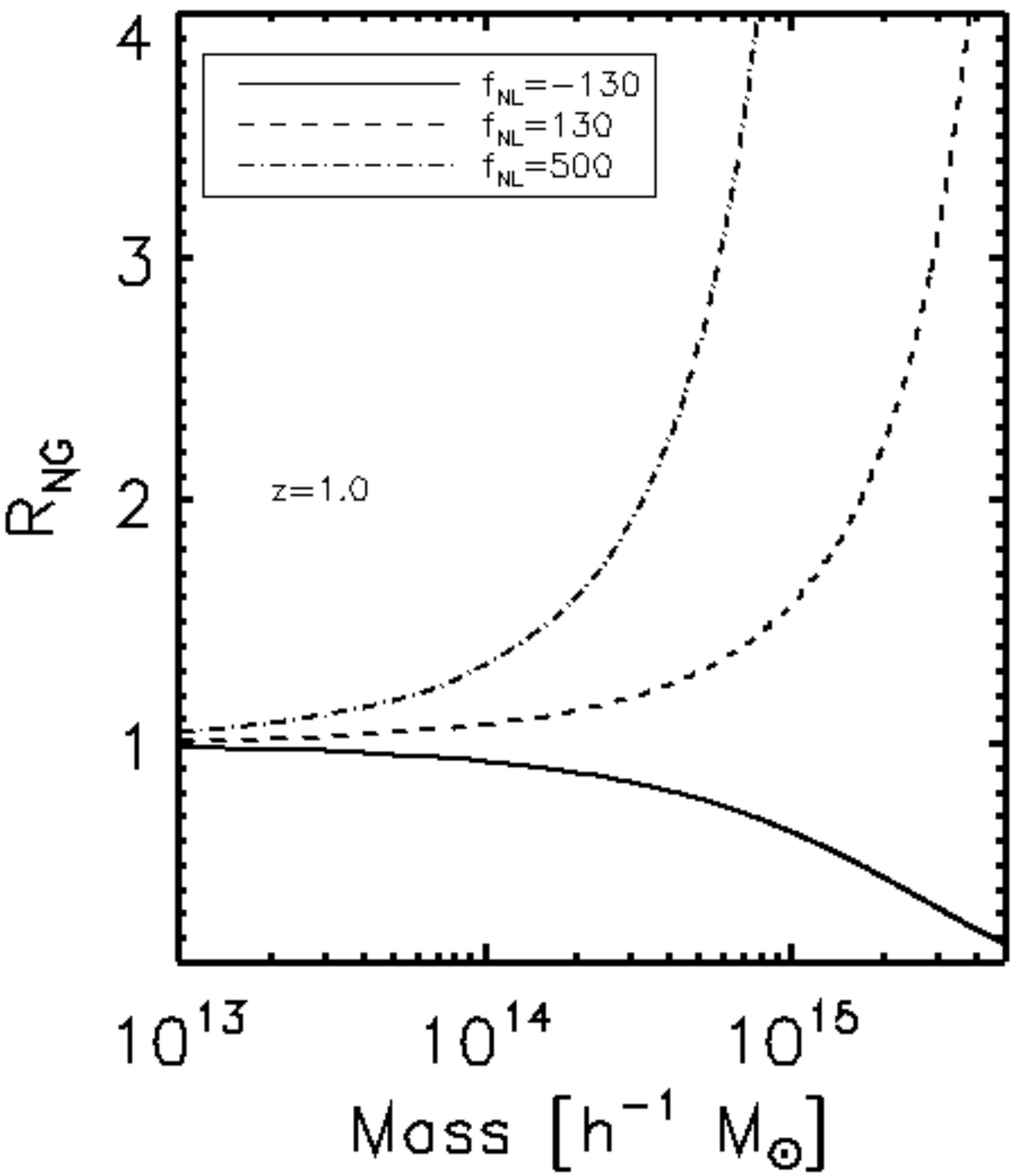
$$\mathcal{R}_{NG}(S_{3,M}, M, z) \quad = \quad \frac{n(M, z, f_{\rm NL})}{n_G(M, z, f_{\rm NL} = 0)}$$

Ask me later for details.

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]



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

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

~~**Ask me later for details.**~~

Ask someone else later for details.

Motivation: observations II - More massive clusters

SPT CL J0546-5345

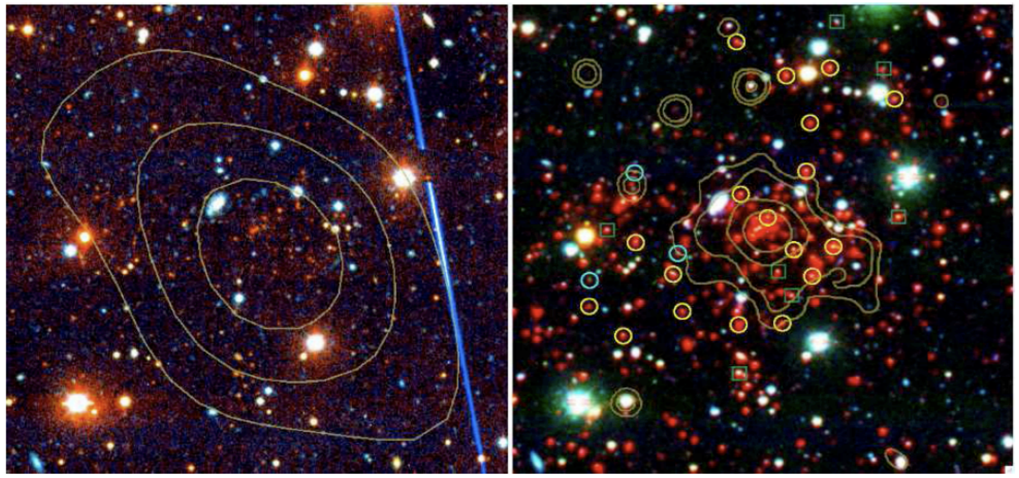


FIG. 1.— *Left:* Optical $4' \times 4'$ color image (grz) of SPT-CL J0546-5345, with SZE significance contours overlaid (S/N = 2, 4, and 6). *Right:* False color optical (ri) + IRAC (3.6 μm) image of SPT-CL J0546-5345, with *Chandra* X-ray contours overlaid (0.25, 0.4, 0.85 and 1.6 counts per $2'' \times 2''$ 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* 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.

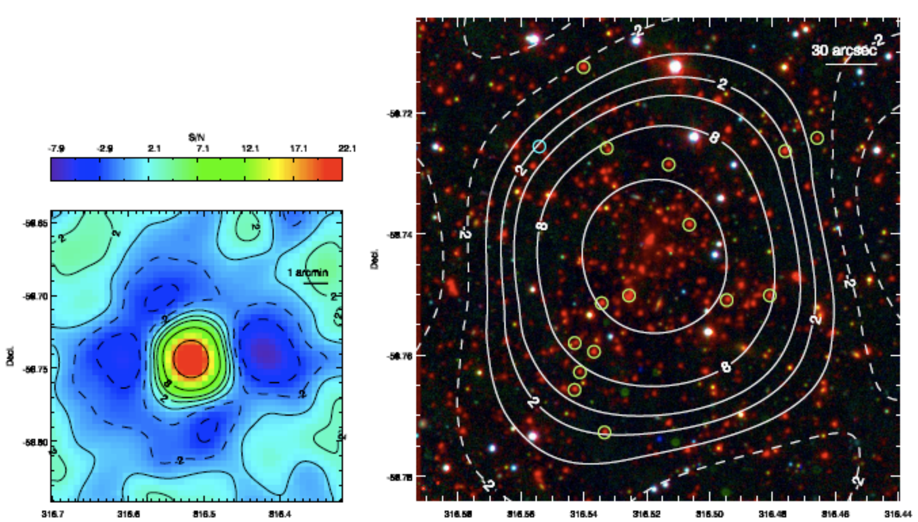
$$M_{200} \sim 10^{15}\, M_\odot \quad z = 1.05$$

- **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?

Hoyle, Jimenez, Verde arXiv:1009.3884 [accepted PRD], See also Enqvist, Hotchkiss, Taanila arXiv:1012.2732

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

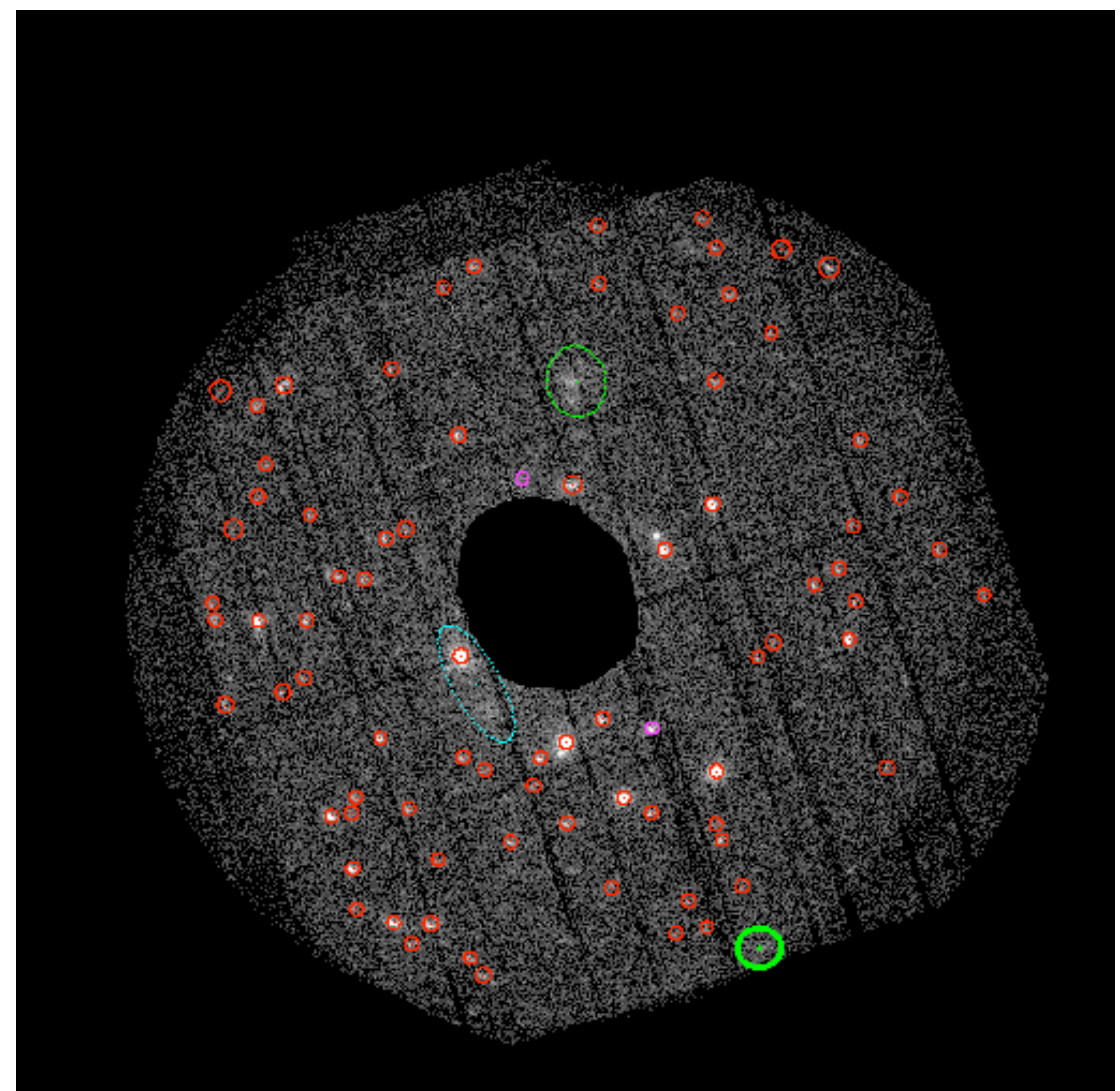
XCS:

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.

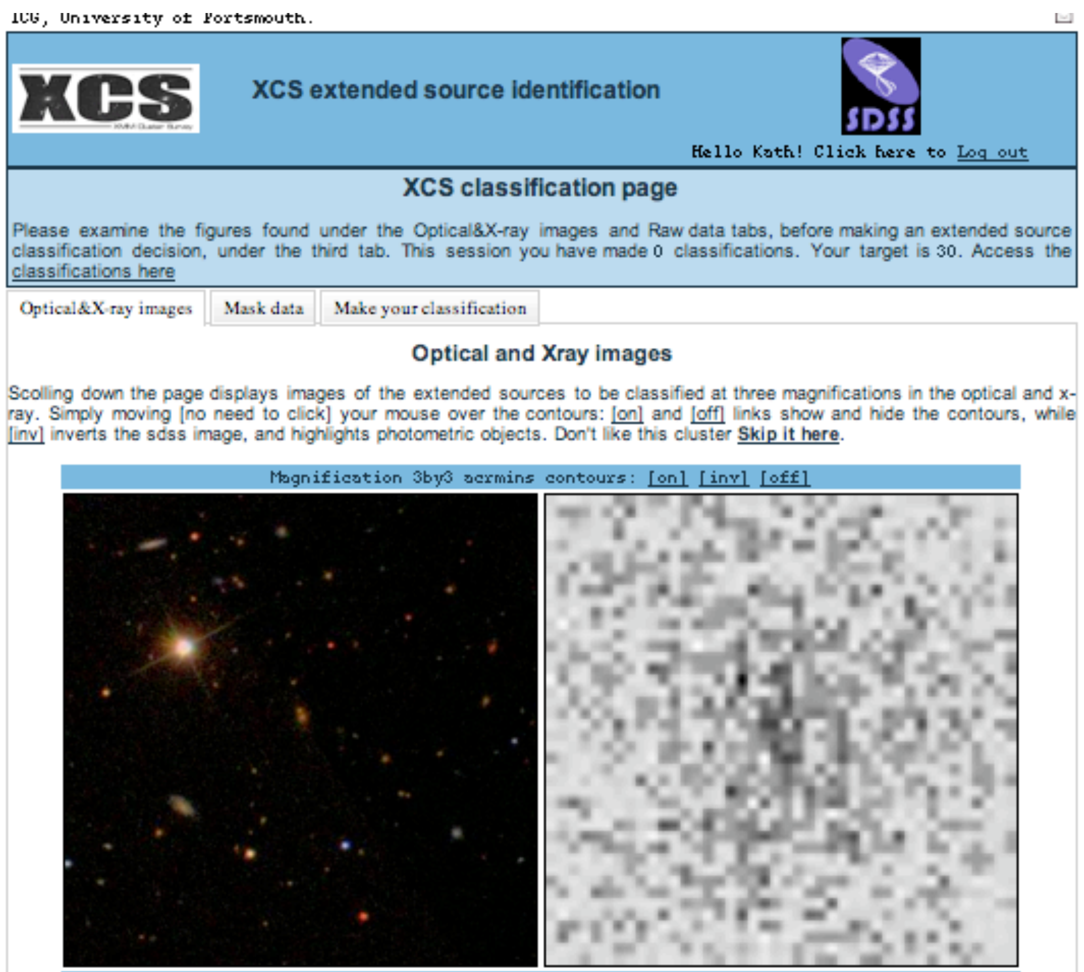


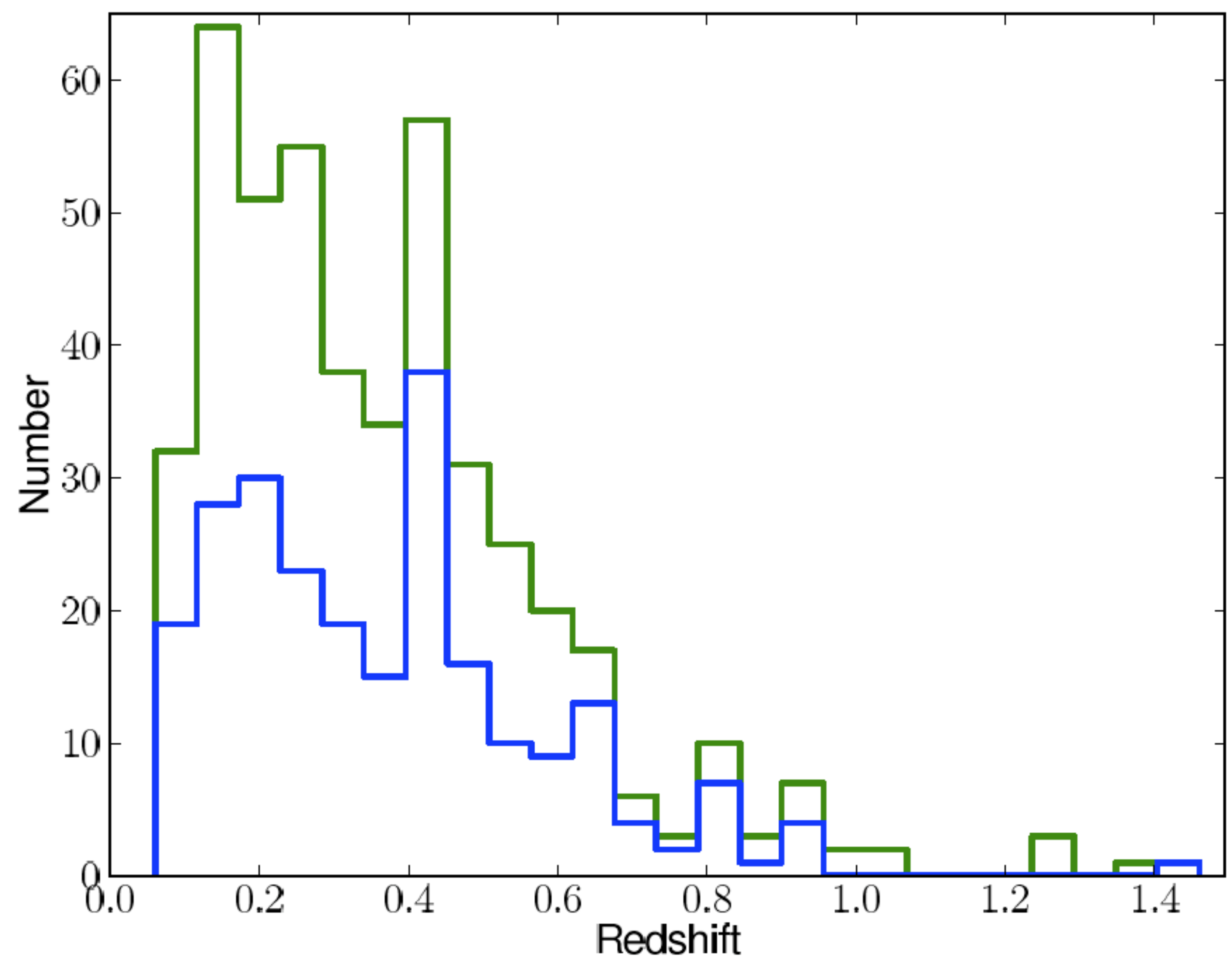
Algorithms paper, Lloyd-Davies et al. 2010 (arXiv:1010.0677)

XCS: Optical Followup

Purity with Cluster Zoo

All clusters multiply classified by experts to determine purity.





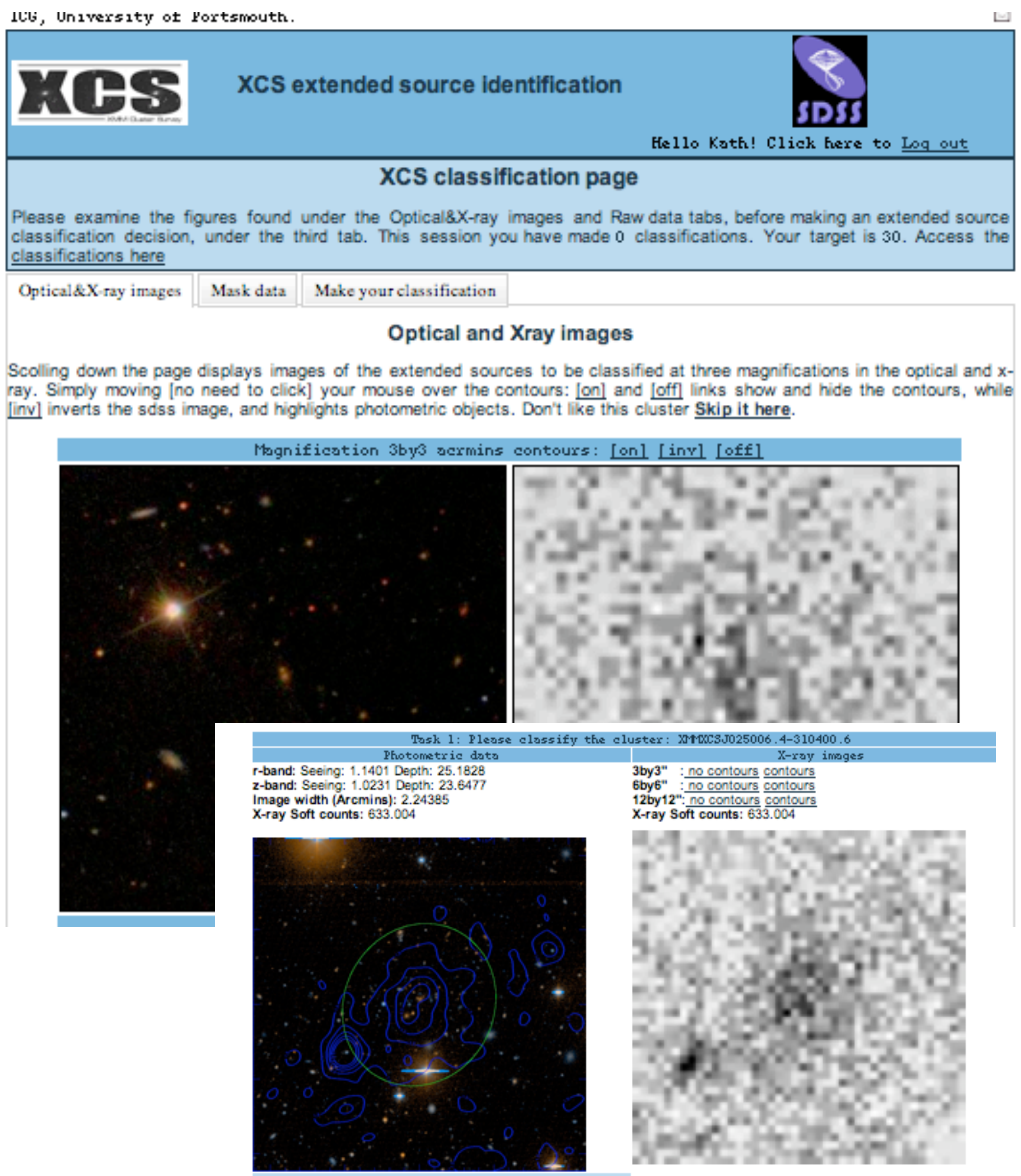
503 clusters, spanning 0.06<z<1.46
438 have x-ray temperatures

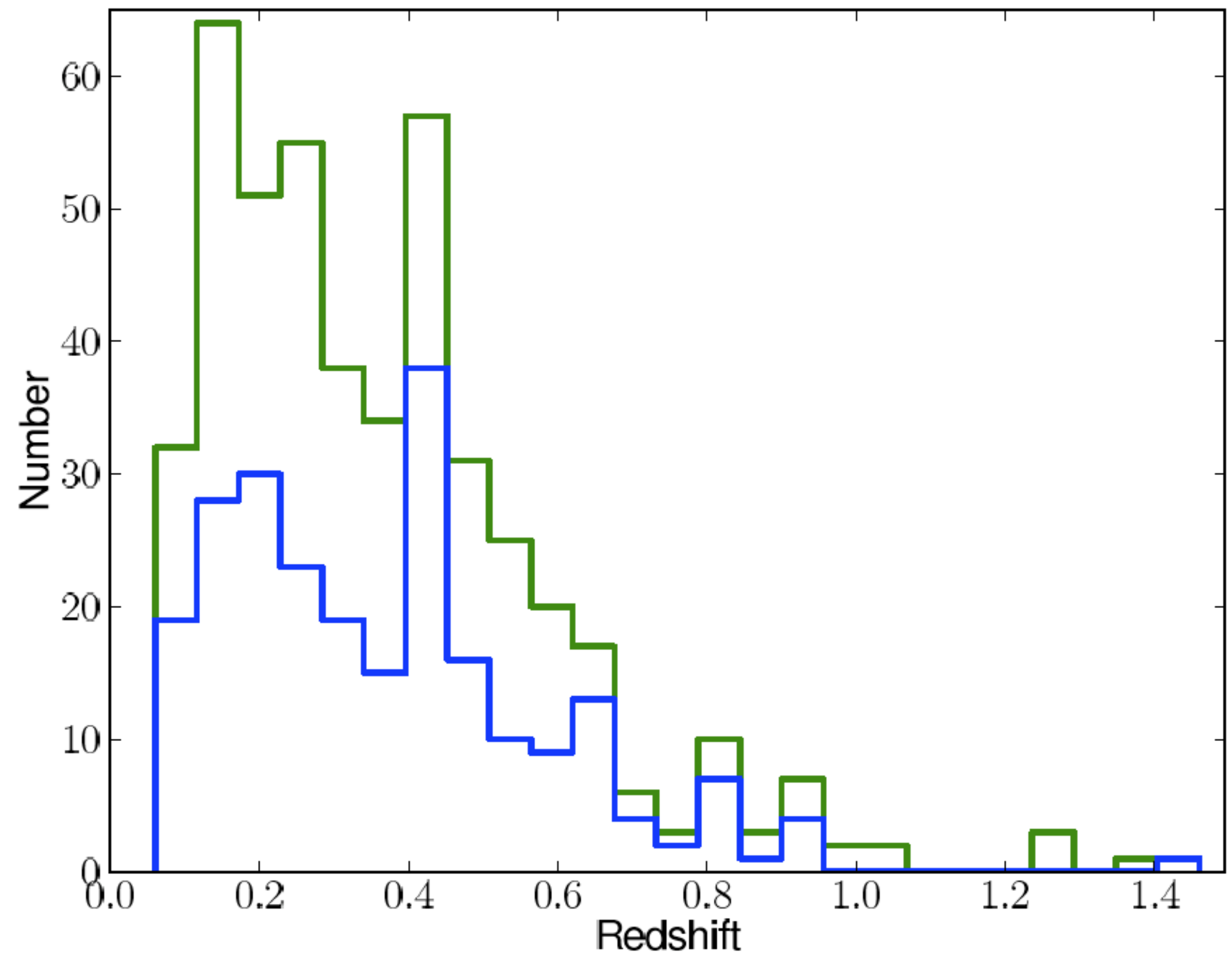
Data release, Mehrtens et al. in prep (very soon!)

XCS: Optical Followup

Purity with Cluster Zoo

All clusters multiply classified by experts to determine purity.





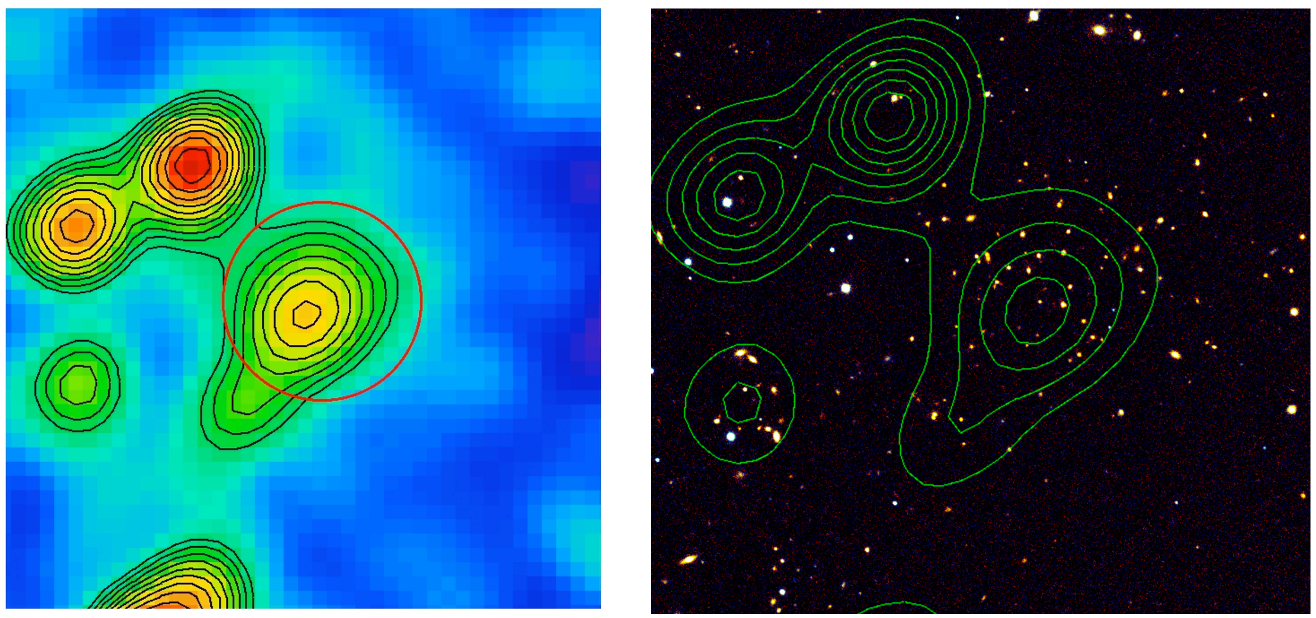
503 clusters, spanning 0.06<z<1.46
438 have x-ray temperatures

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

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)

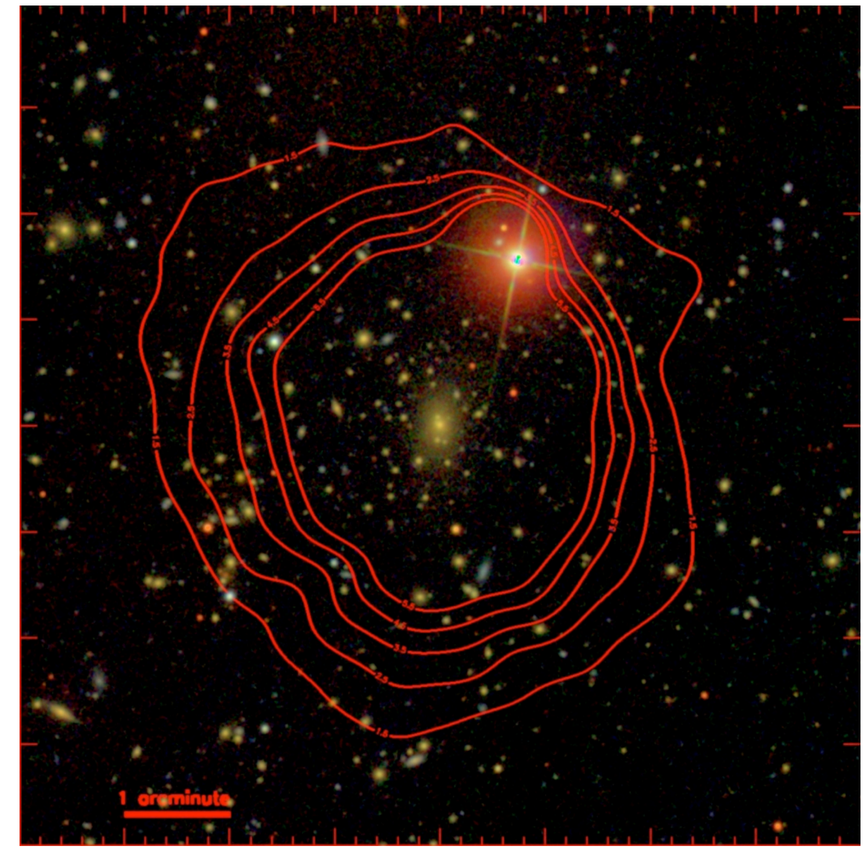


Now $z=2.07$, $M \sim 5\text{-}8.10^{13}$ SolMass, Gobat et al arXiv:1011.1837

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

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

Fossil groups



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

Harrison et al (in prep)

More Clusters. Data sample

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

<u>Conservative assumptions</u>

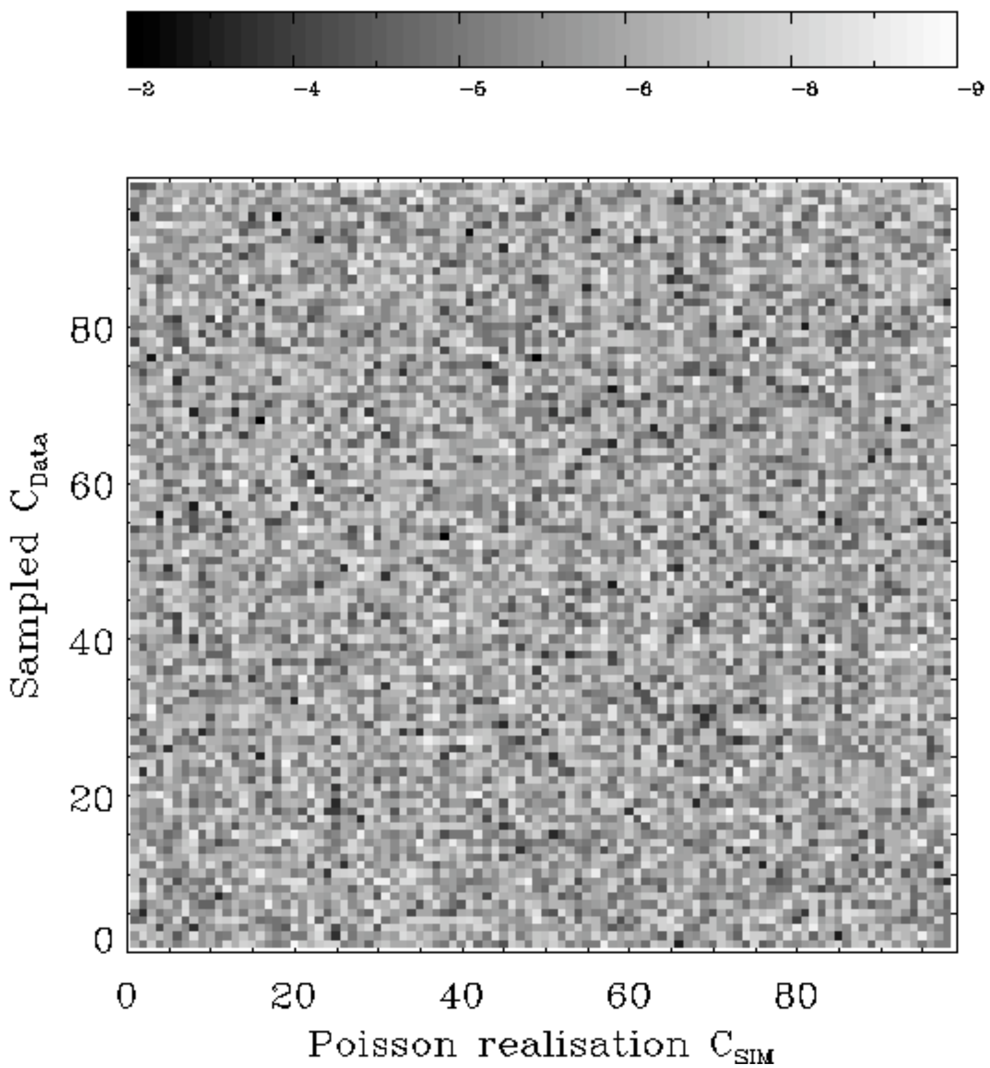
Footprints; If there was overlap between the surveys, we conservatively assumed each X-ray survey had it's own unique footprint

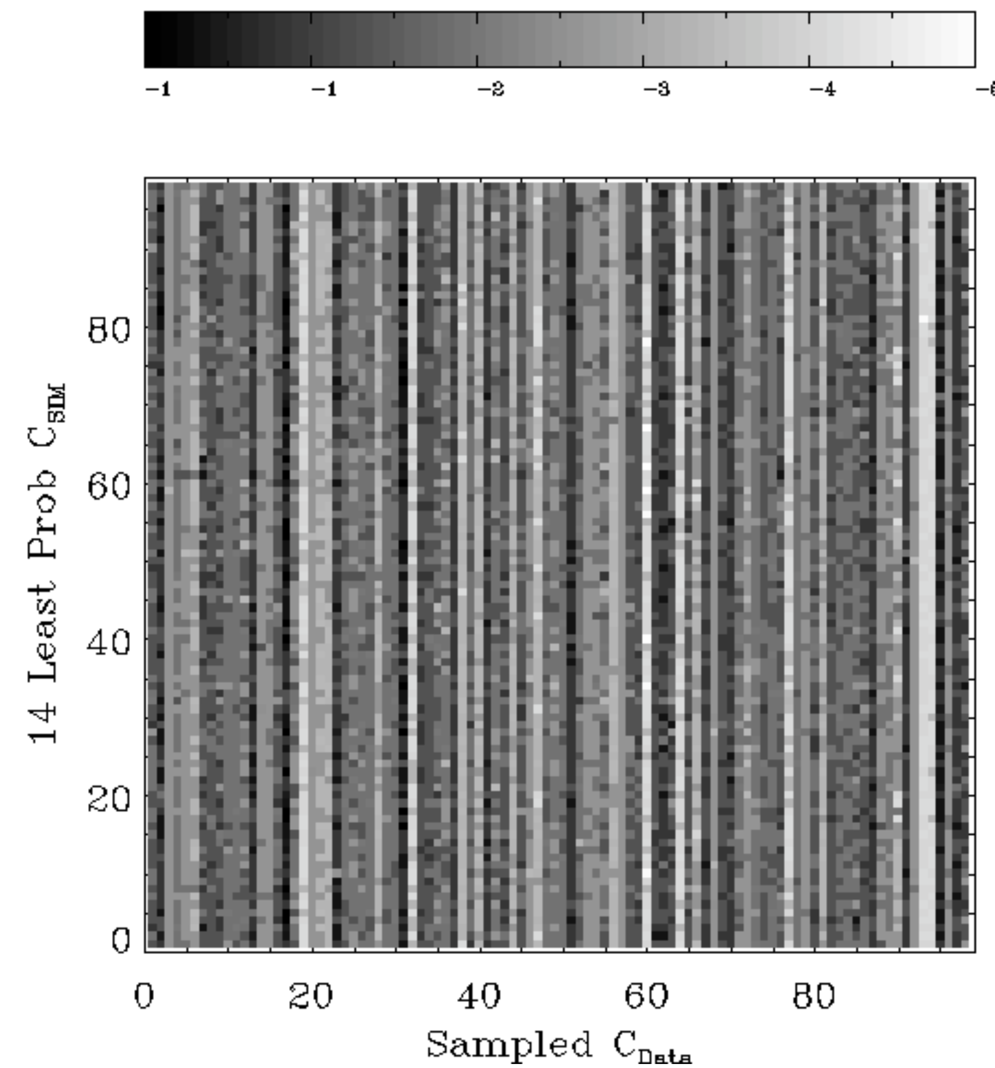
- **Survey volumes: We assumed all surveys had the redshift depth of the deepest survey z~2.2**
- **Selection functions: For each cluster, we assumed that any similar (>M) cluster at any higher redshift would have been detected.**
- **Mass estimates: We chose to use the cluster mass and error which gave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

Analysis & Results I

Comparing theory with observations: 2d K-S test.

Poisson sampling of the theoretical cluster mass function (assuming best-fit WMAP5 cosmological parameters), to build 100 sets of 'simulated' clusters in (M,z) plane. Compare distributions of the simulated clusters with data after marginalizing (sampling) from the mass and mass error 100 times, using the 2d K-S test. Are they drawn from the same parent population? If yes, P ~ 0.1 - 1.0





The observed clusters:

- **Do not appear to be drawn from a Poisson sampling of the mss fn:** $P \sim 10^{-6.2}$
- **Reference, comparing simulated clusters with simulated clusters:** $P \sim 10^{-0.8}$
- **Not consistent with being the 14 least probable objects:** $P \sim 10^{-2.5}$
- **Not located in a particular region of (M,z) plane (systematics):** $P \sim 10^{-1.7}$

Analysis & Results II

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.

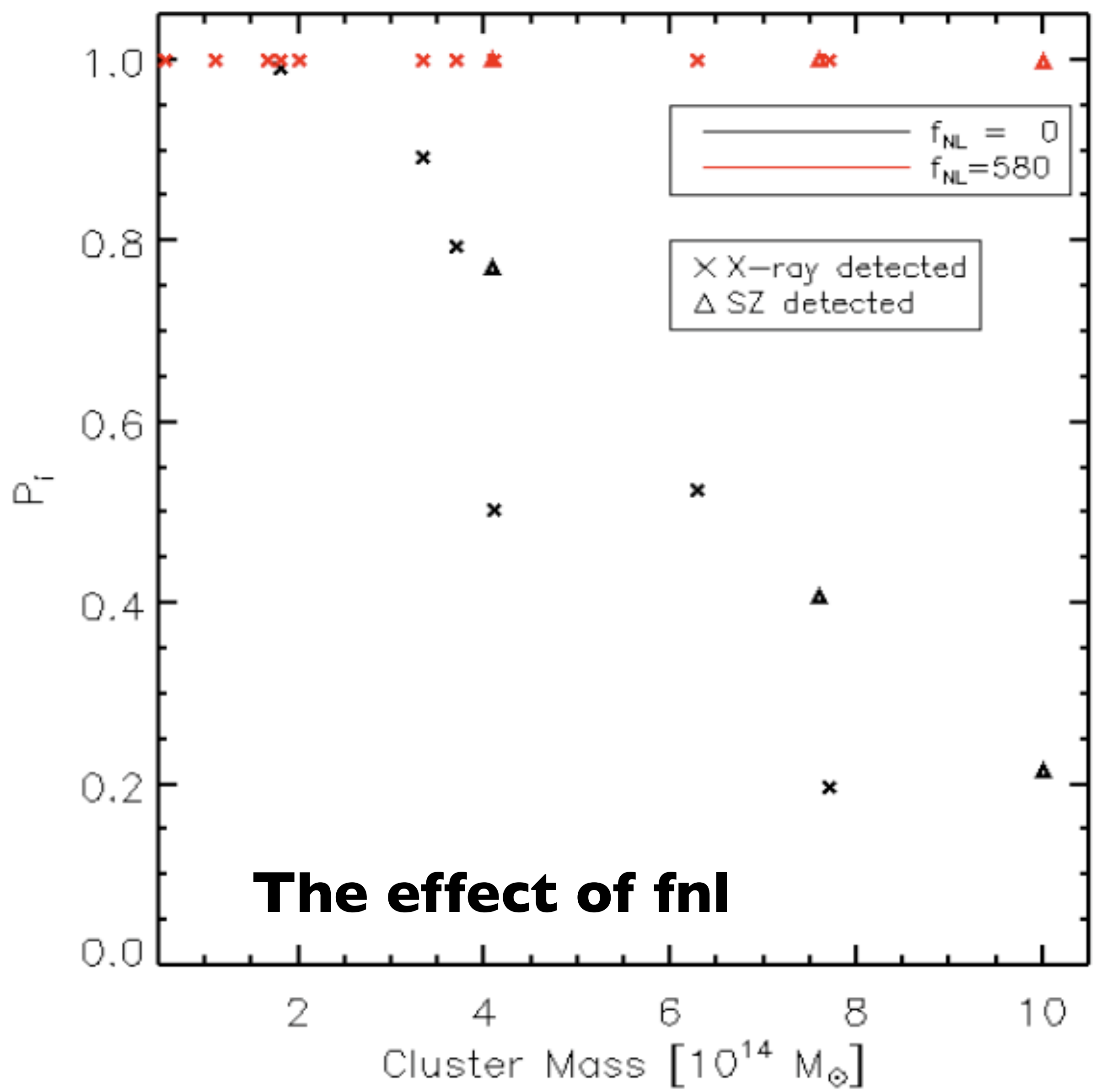
The probability P_i ,that cluster "i" exists is $\mathrm{Number}(P^O(A_s) \geq 1)/10^4)$

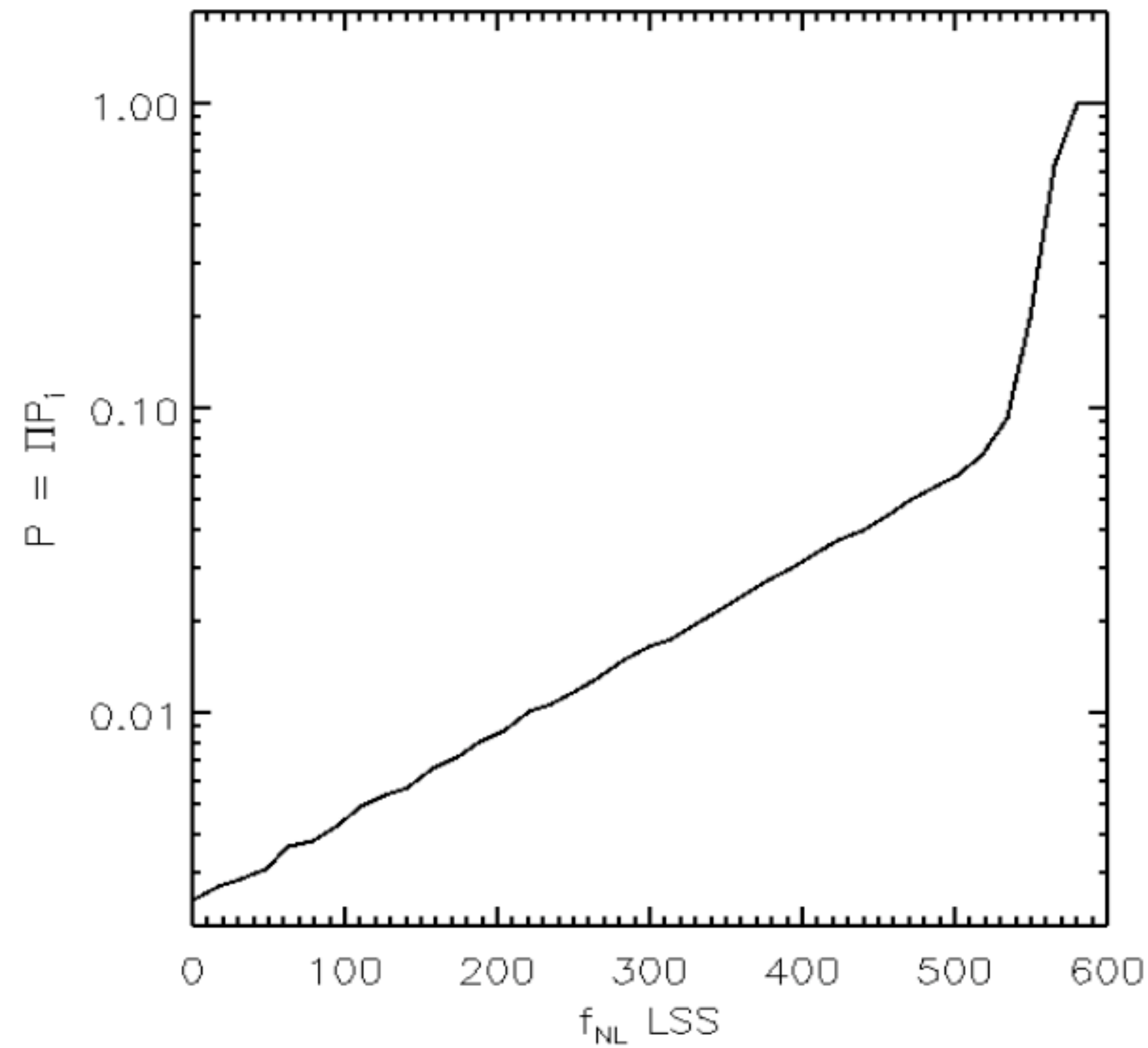
The probability, that the ensemble of cluster exists is $P(f_{\rm NL}, C) = \Pi P_i$

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 II

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

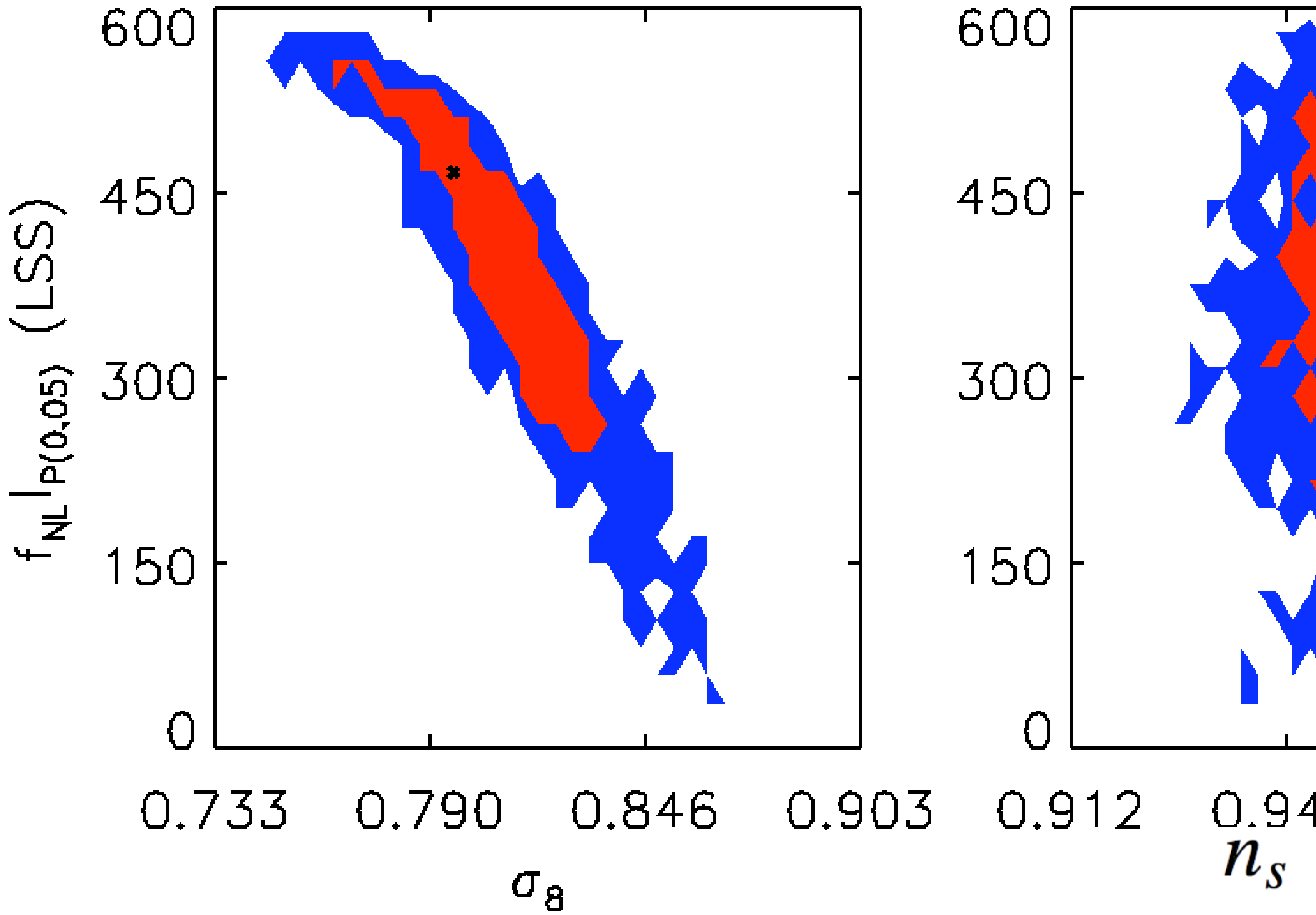
$$f_{\rm NL}|_{P(0.05)}$$

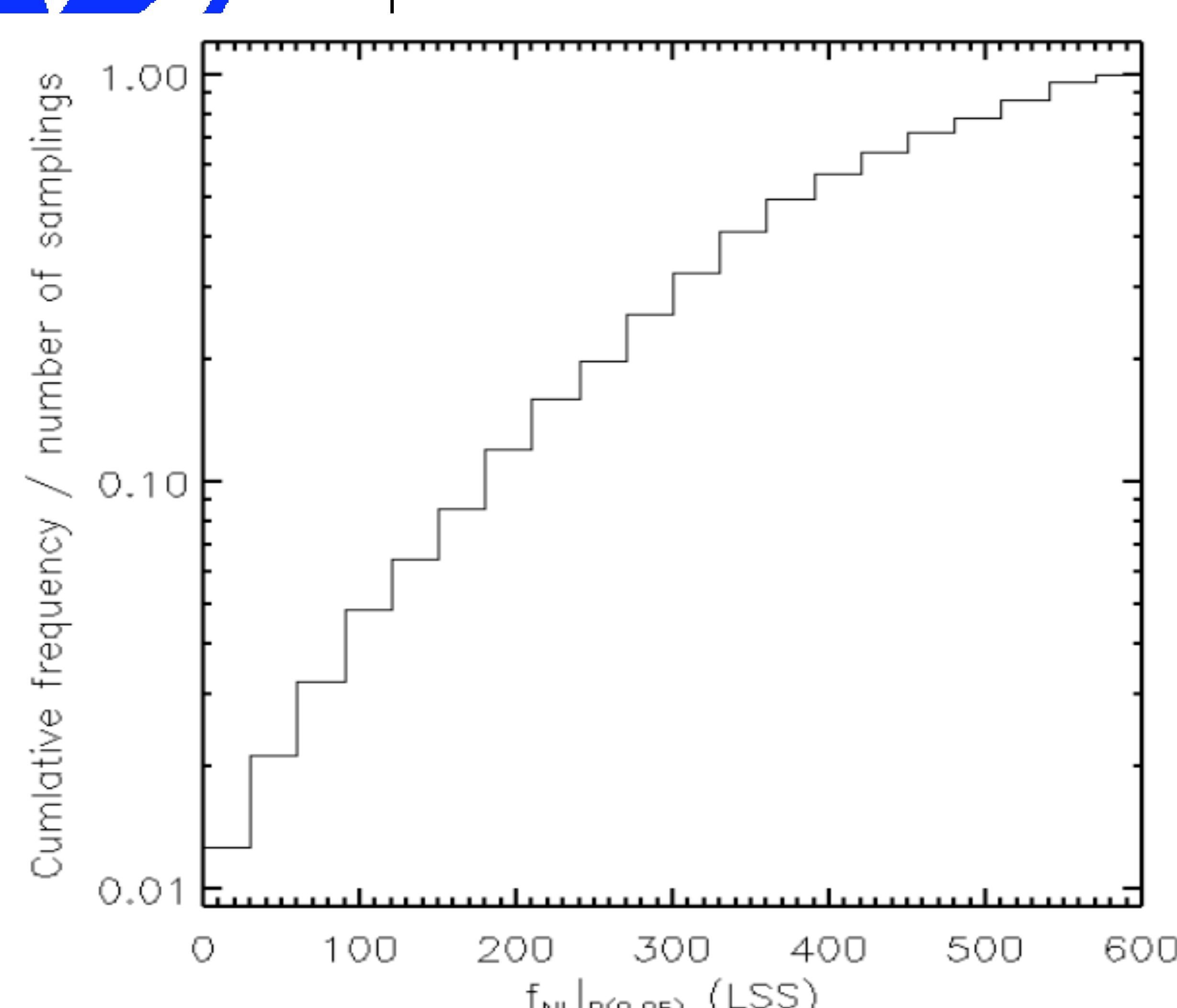
$$\text{At the 95\% confidence level, } f_{\rm NL} > 467$$

Enqvist et al 2010 arXiv:1012.2732 $f_{\rm NL} \gtrsim 410$

Analysis & Results II

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





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

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

<u>**Reality Check!**</u>

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

Possible explanations: Systematics I

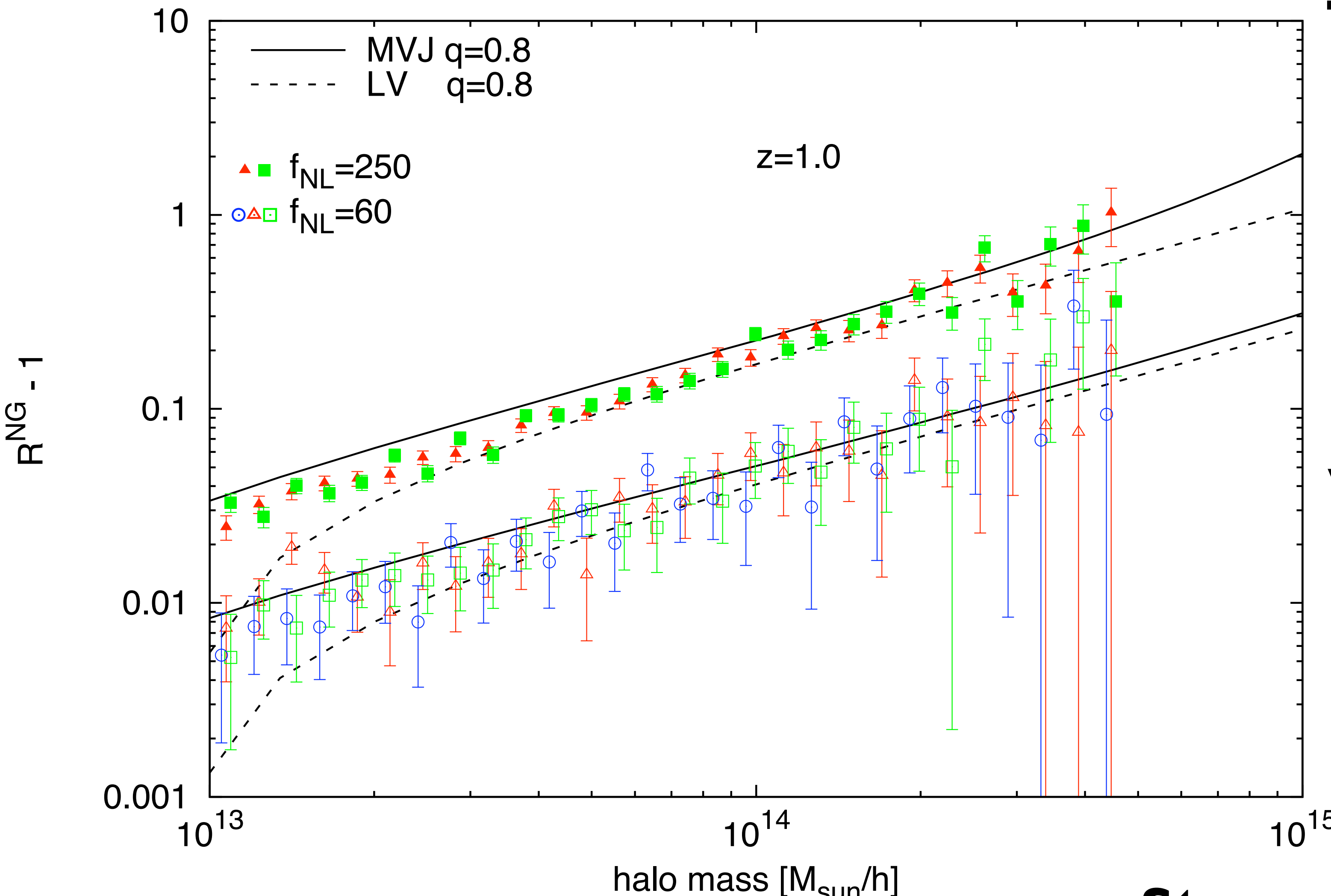
Cosmological parameters.

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

$$\sigma_8 = 0.801 \pm 0.03$$

Mass functions.

Do we understand the mass function (with fnl) at high mass and redshift well enough?



Theoretical/Computational:

Mass functions with fnl (gnl,tnl)
D'Amico et al 2010,
Lo Verde & Smith arXiv:1102.1439

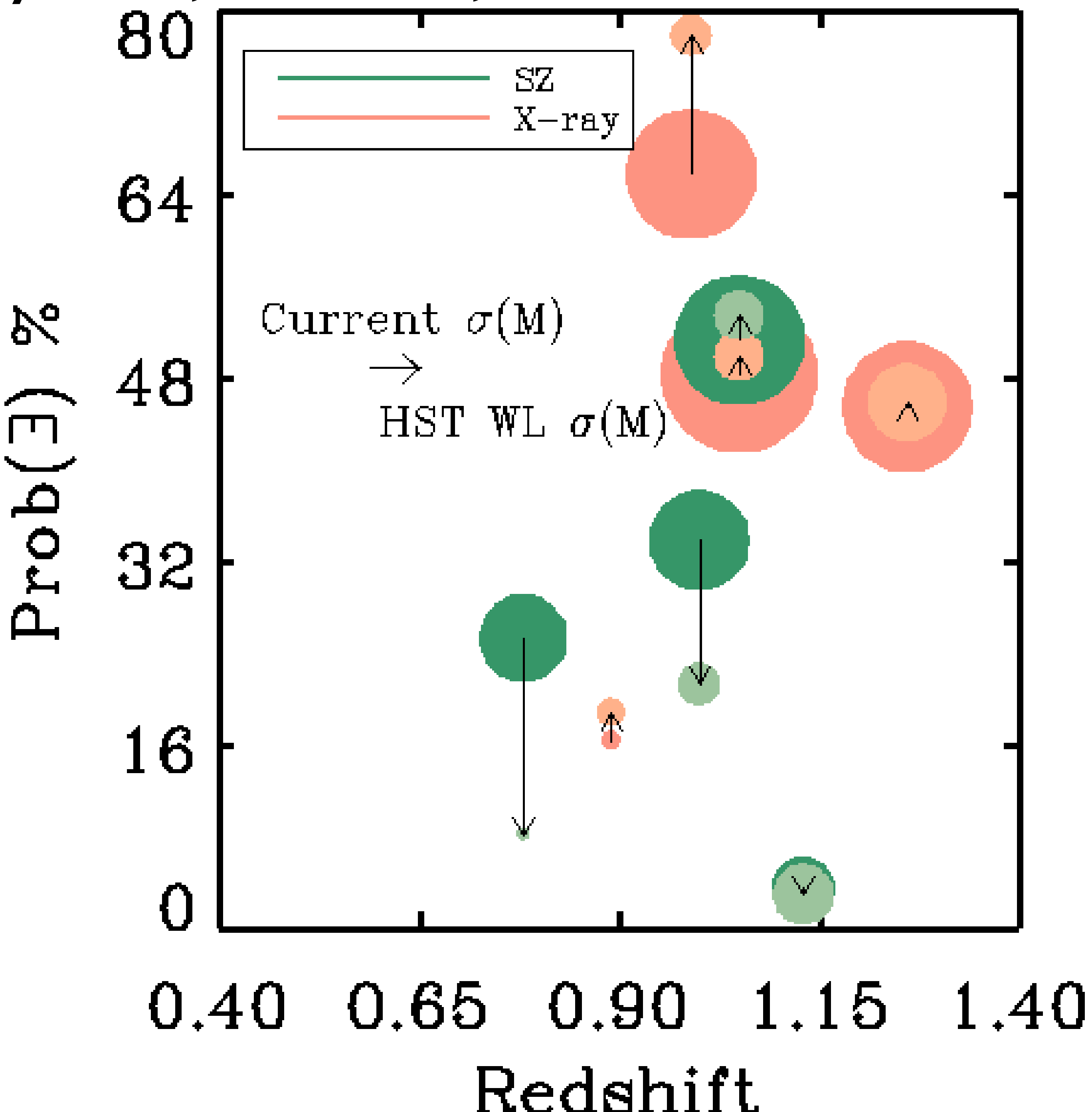
Non-Gaussian mass function fit to Nbody simulations (Christian Wagner et al 2010)

Stay awake for Christian's talk, up next..

Possible explanations: Systematics II

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.

We are trying to obtain better mass estimates for a sample of high redshift clusters, with an HST proposal;
B.H. (P.I.), Aday Robiana, Licia Verde, Raul Jimenez, David Bacon, Martin Sahlen, Ed Lloyd-Davies, Kathy Romer, Matt Hilton, Nicola Mehrtens.



Conclusions

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

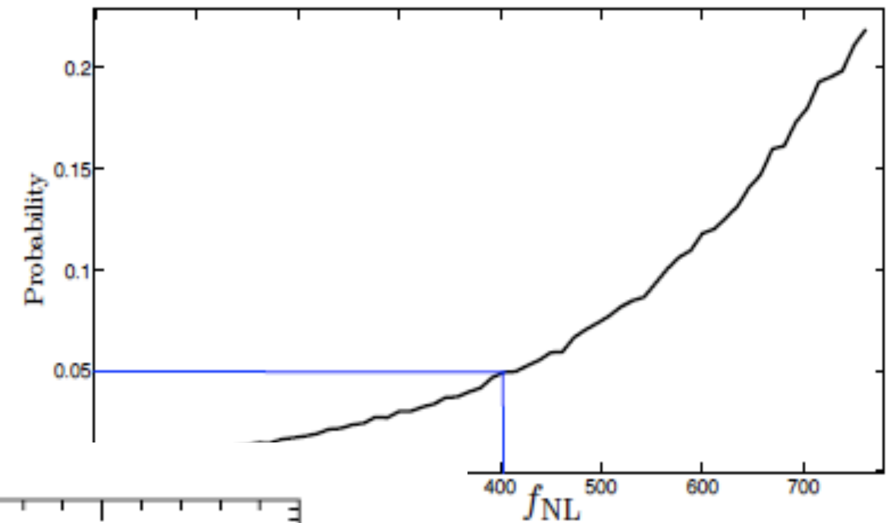
$\sigma_8 = 0.9$ **or** $M_{TRUE} = M_{OBS} - 1.5 \times \Delta M$ **or** $f_{\rm NL}|_{P(0.05)} \gtrsim 123$ at the 95%

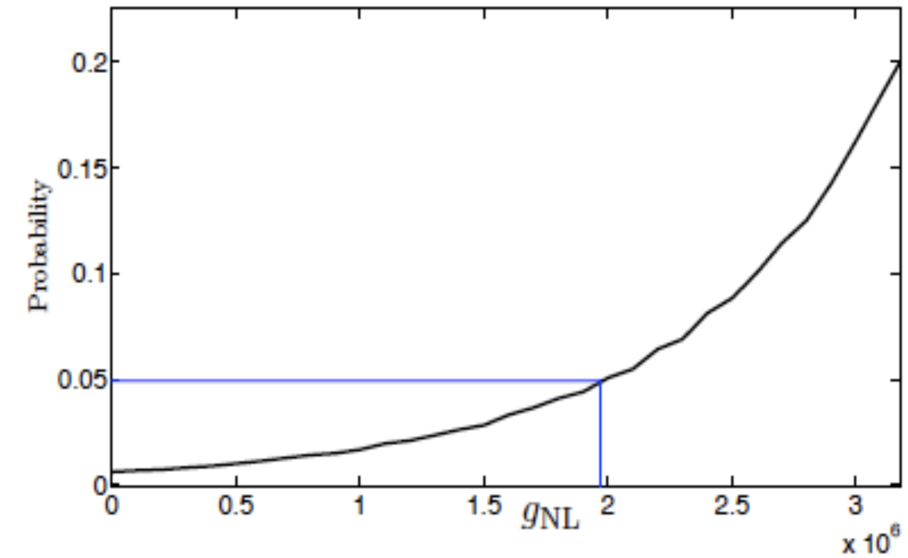
or mass function uncertainty.

- **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 (HST WL).**
- **No consensus as to the level of tension, or how to quantify it.**
- **Theoretical/Computation work ongoing.**

- **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**
- **Watch out for the 500 XCS clusters with temperatures!**

Extensions/Related work





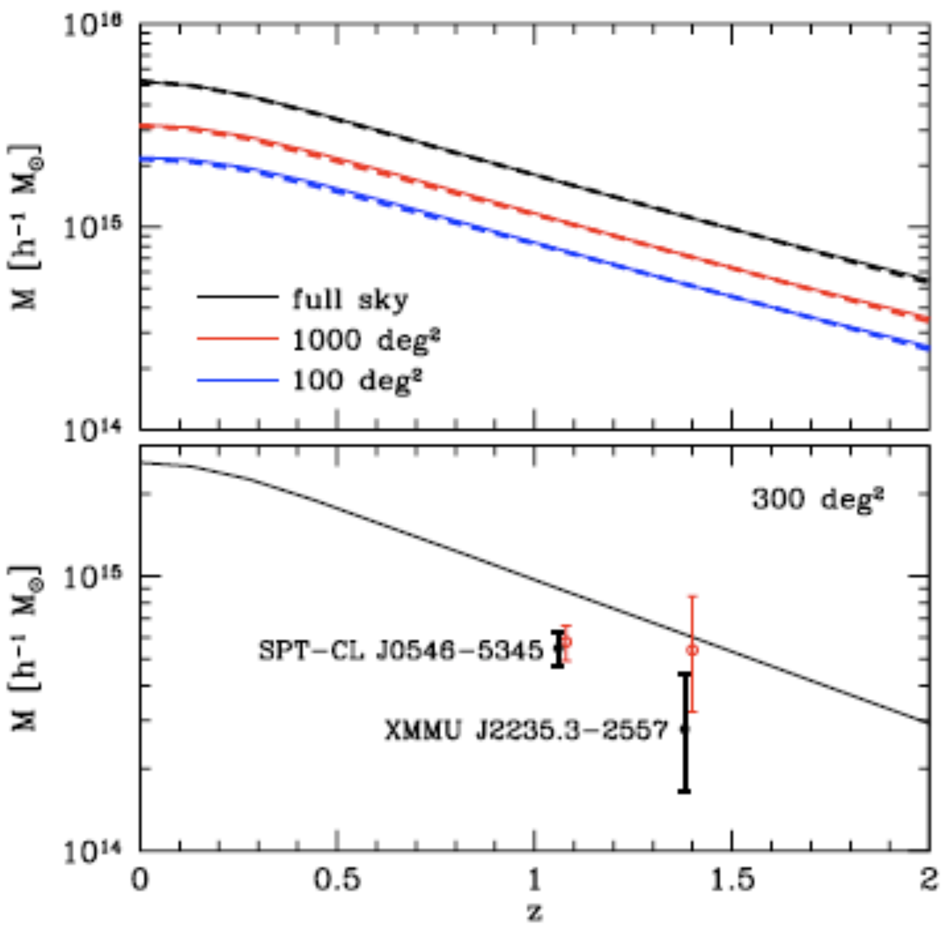
:he ensemble of clusters in (b) The probability that the ensemble of clusters in ta
:ction of $f_{\rm NL}$. ble 1 could exist as a function of $g_{\rm NL}$, with $f_{\rm NL} \lesssim 50$.

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

Enqvist et al 2010

Showed how the choice of mass function leads to instability for large masses/values of fnl, and extended for gnl.

Impose $f_{\rm NL} < 50 \rightarrow g_{NL} \sim 2 \times 10^6$



Mortonson et al 2010

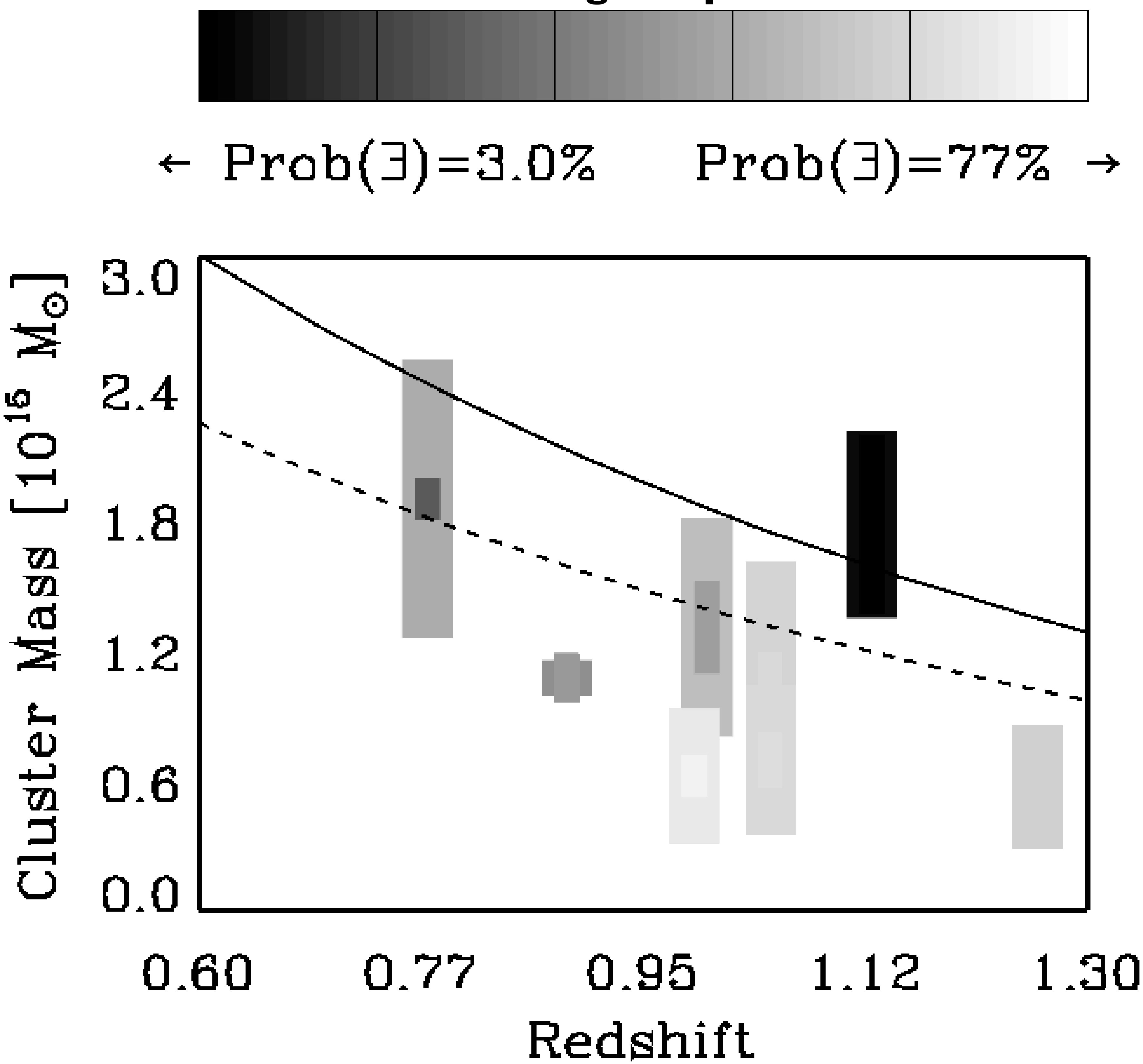
Provided a fitting function to describe how one cluster could rule out (w)LCDM, but underestimate constraining power of >1 clusters.

FIG. 4. $M(z)$ exclusion curves. Even a single cluster with (M, z) lying above the relevant curve would rule out both ΛCDM and quintessence. *Upper panel:* flat ΛCDM 95% joint CL for both sample variance and parameter variance for various choices of sky fraction $f_{\rm sky}$ from the MCMC analysis (thin solid curves) and using the fitting formula from Appendix A (thick dashed curves; accurate to $\lesssim 5\%$ in mass). *Lower panel:* Two of the most anomalous

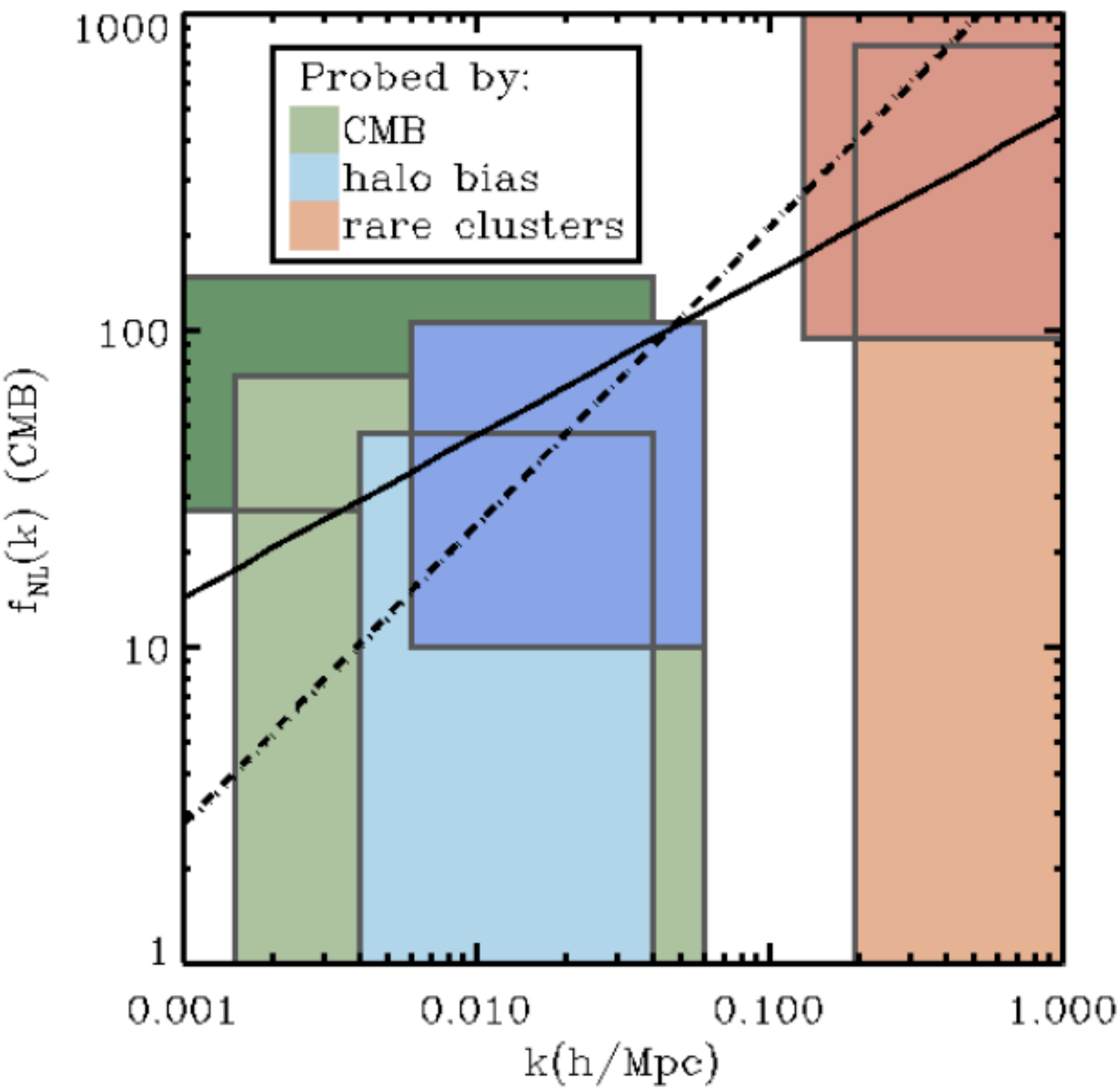
Or, non constant equation of state of dark energy, Baldi & Pettorino 2010

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.



Sexy Conclusions: Scale Dependent non-Gaussianity



WMAP CMB, scales 0.04 h/Mpc

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

Yadev & Wandelt 2008

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

Komatsu et al 2011

Halo bias, scales 0.1 h/Mpc

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

Xia et al 2010

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

Slozar et al 2008

Galaxy Clusters, scales 0.4 h/ Mpc

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

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

Hoyle et al 2010

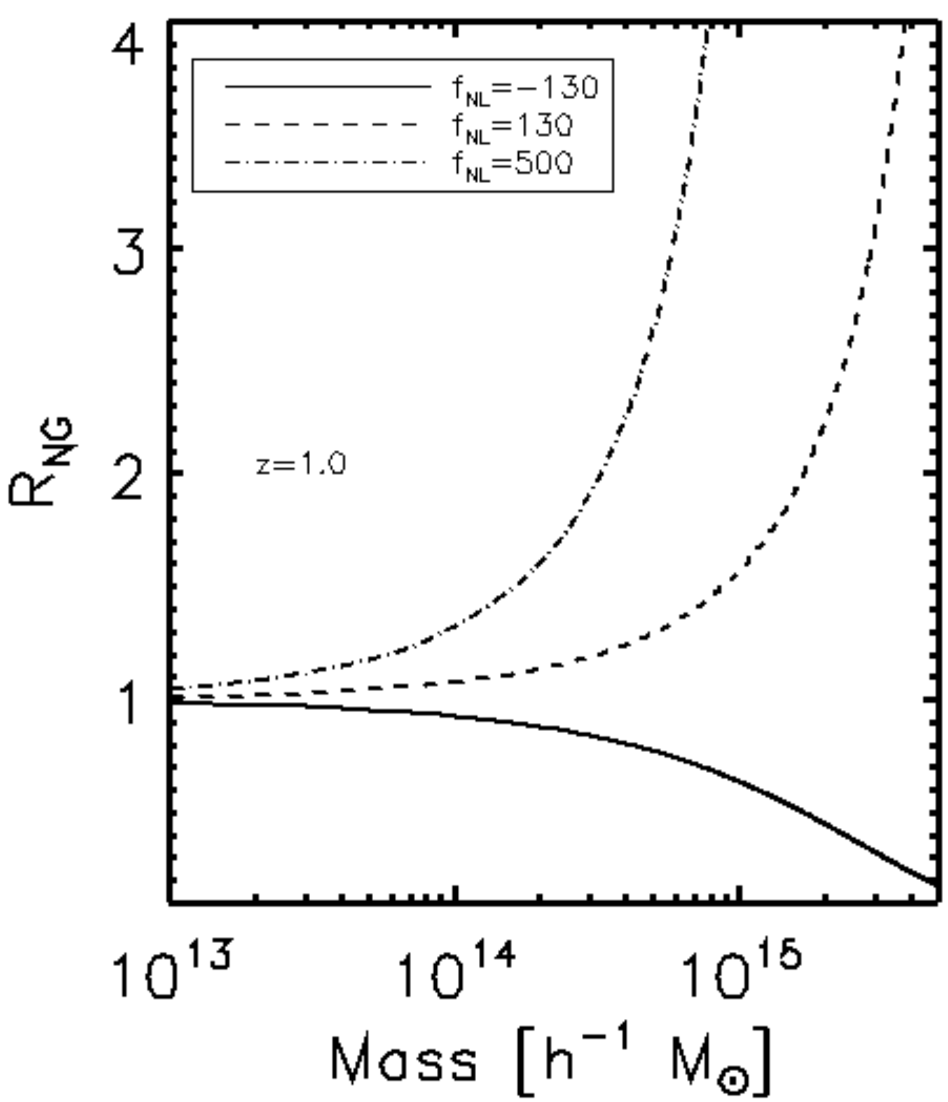
$$f_{NL} = f^*_{NL}\left(\frac{k}{k^*}\right)^{n_{NG}} \qquad n_{NG} = 0.50 \pm 0.19 \qquad n_{NG} = 0.95 \pm 0.23$$

Lo Verde et al 2008

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.

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



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

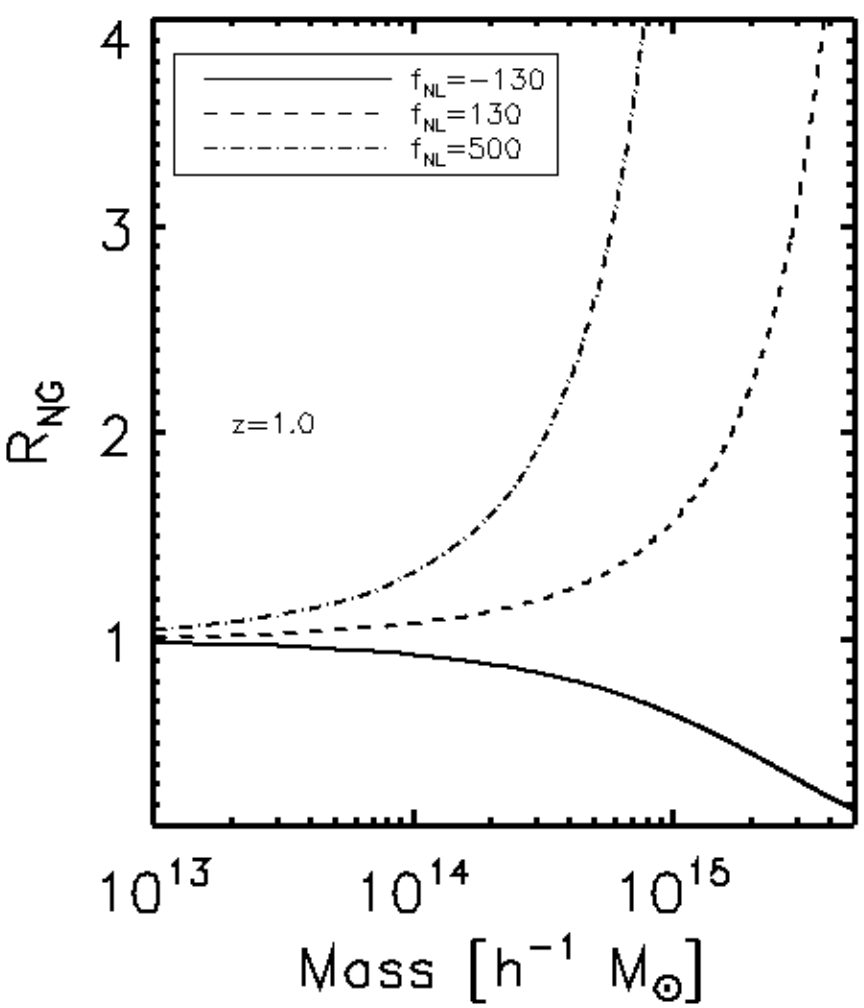
Using today's data, (not some future experiement e.g. LISA-like) we can make a measurement of the primodial non-Gaussianity (fnl) which can tell us about the various types of scalar field interactions during inflation/reheating/ preheating.

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

<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]

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

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

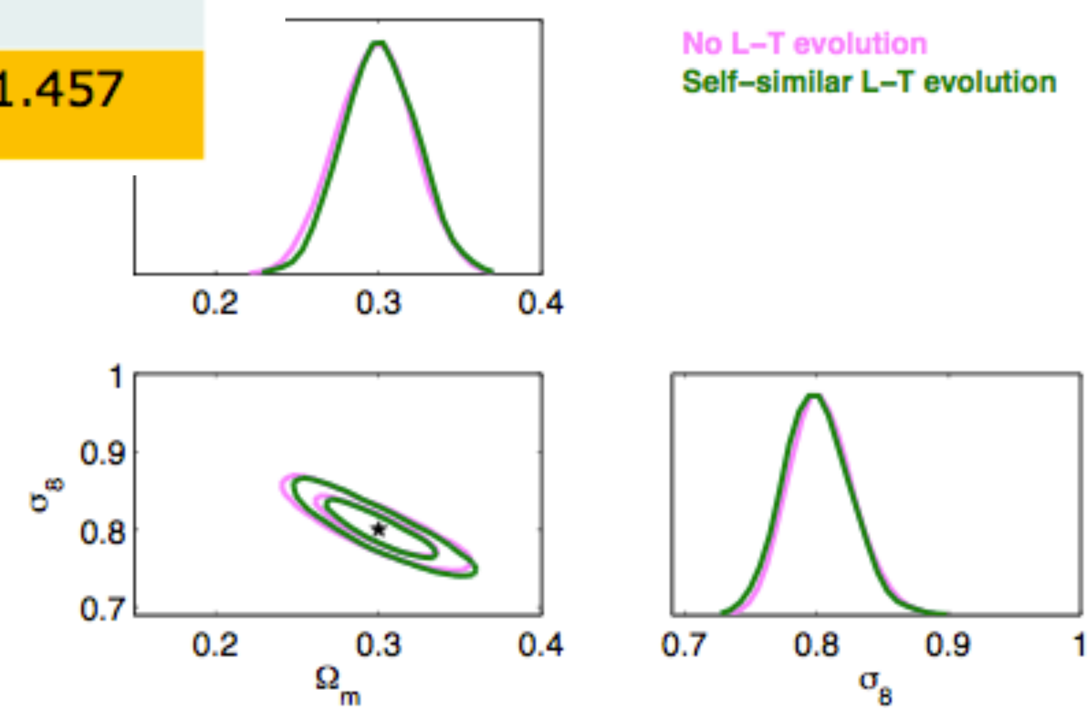
XCS:

Current X-Ray Cluster Surveys

Stockholm University

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

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!)