Institute for Advanced Study
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Planck results on the baryon content of Dark Matter halos

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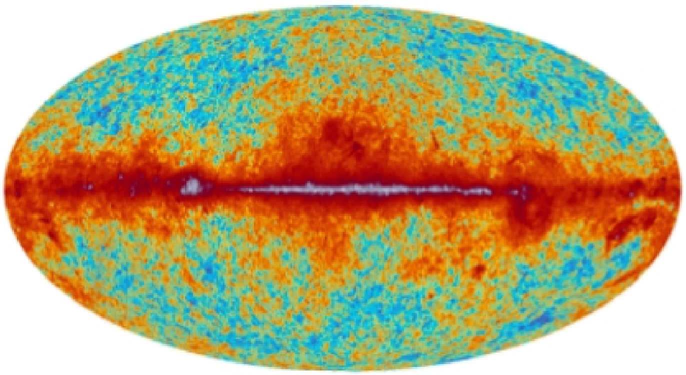
Max Planck Institute for Astrophysics
and the Planck Collaboration

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

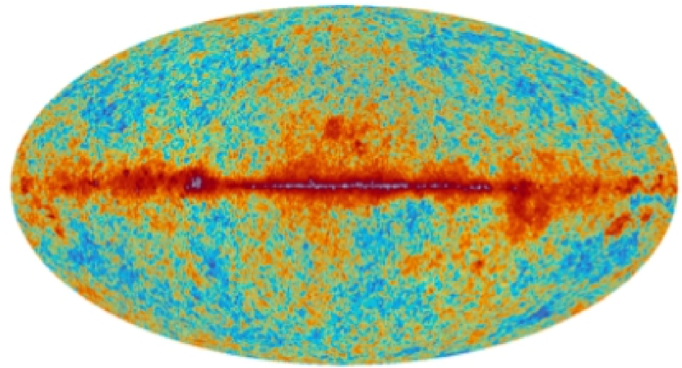
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

The nine *Planck* maps

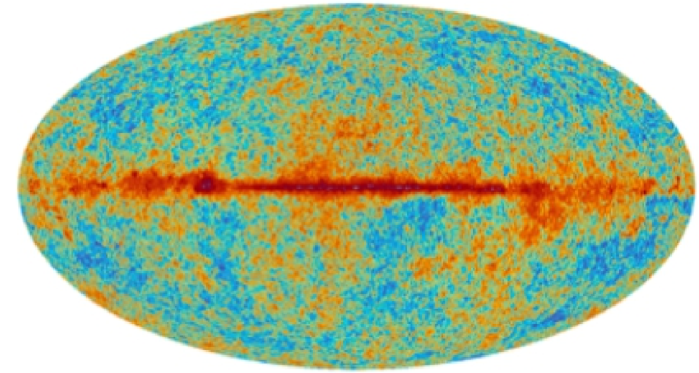
30 GHz



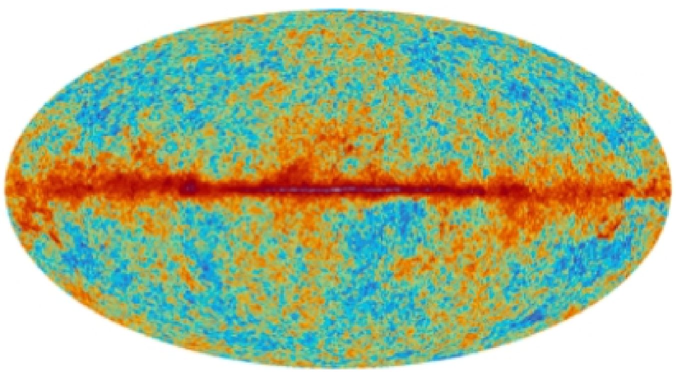
44 GHz



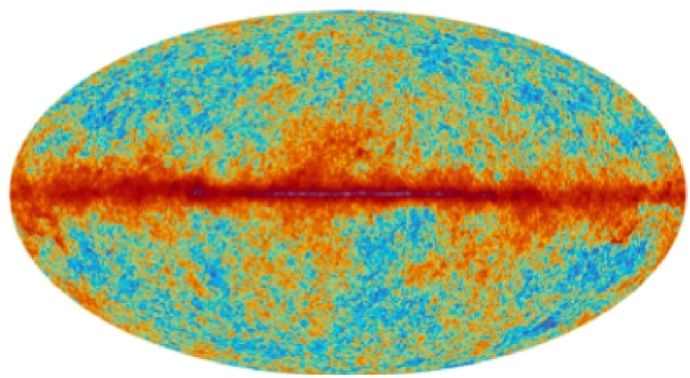
70 GHz



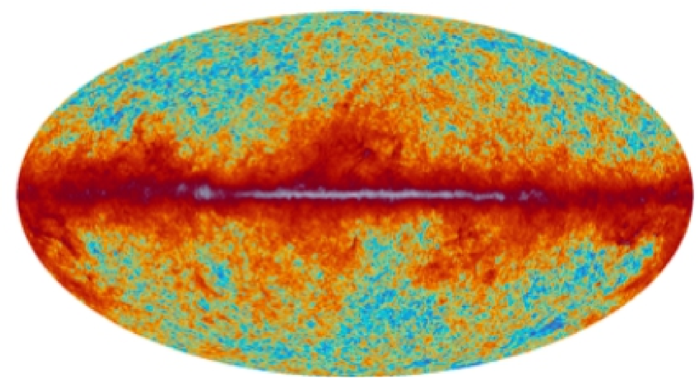
100 GHz



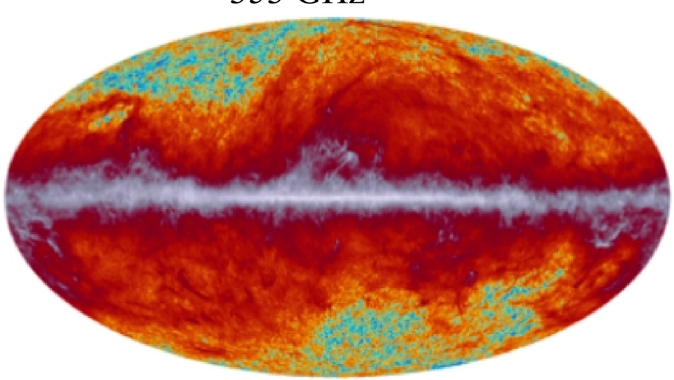
143 GHz



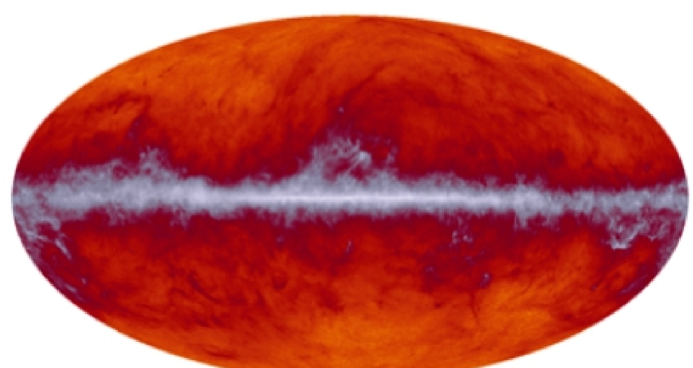
217 GHz



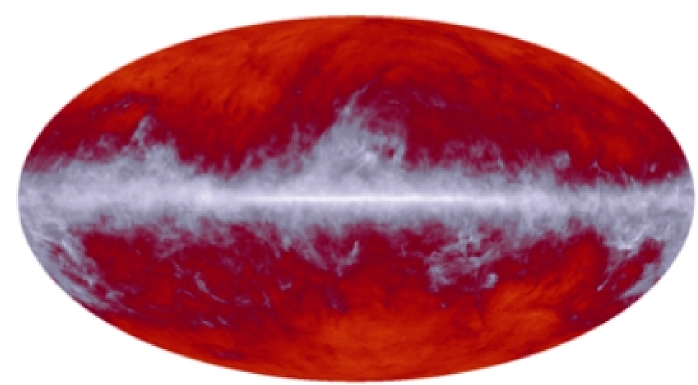
353 GHz



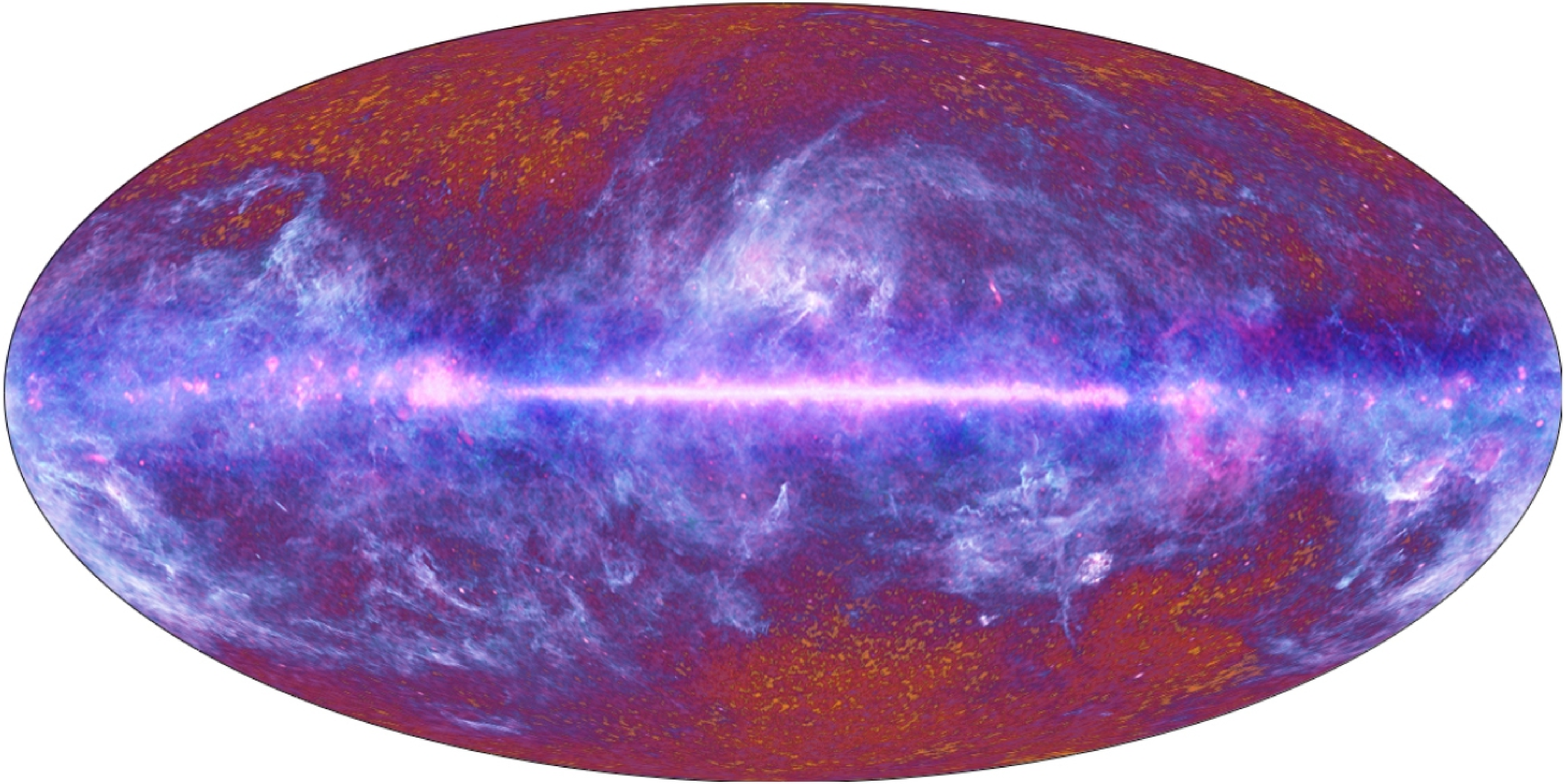
545 GHz



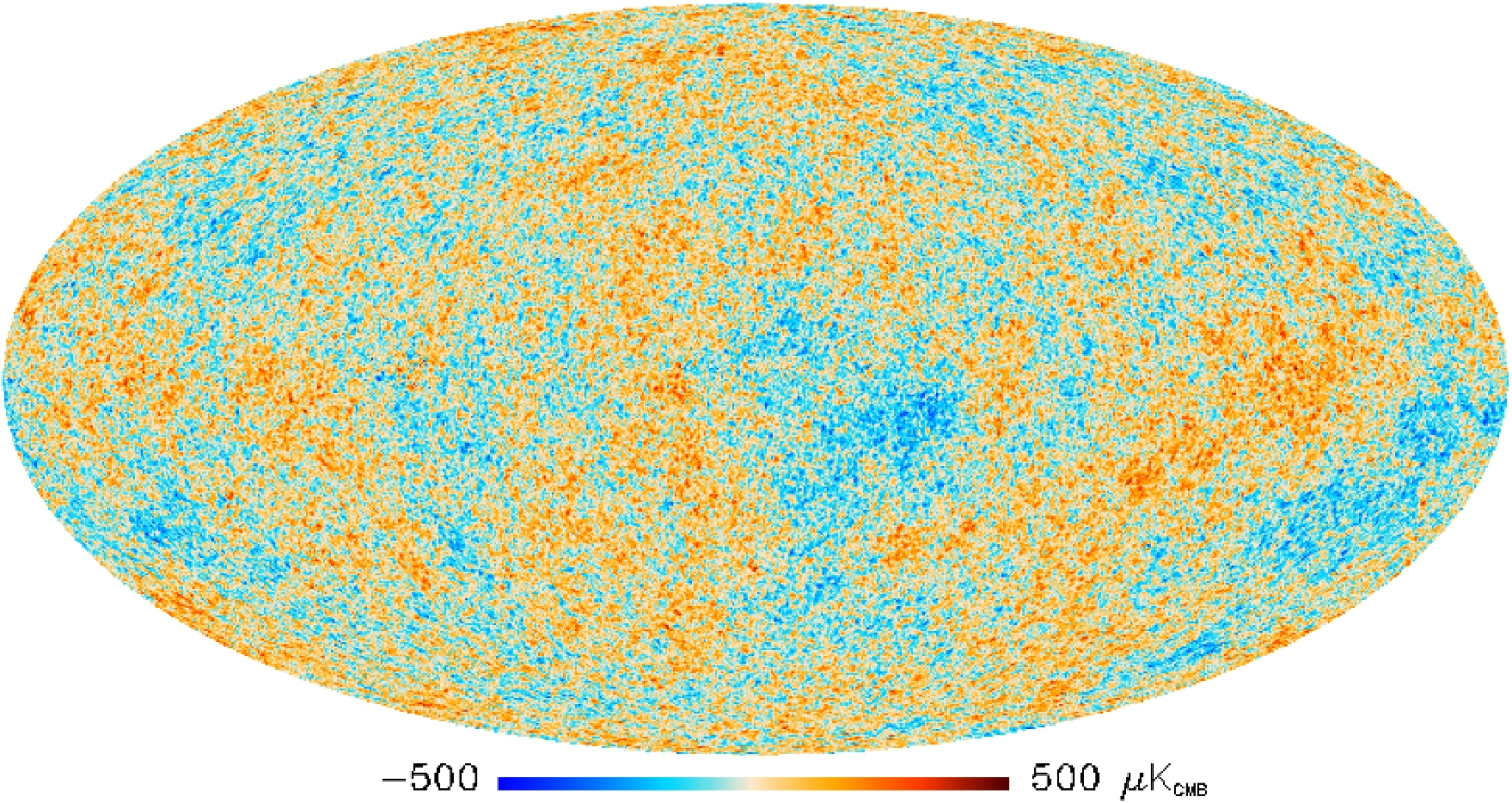
857 GHz



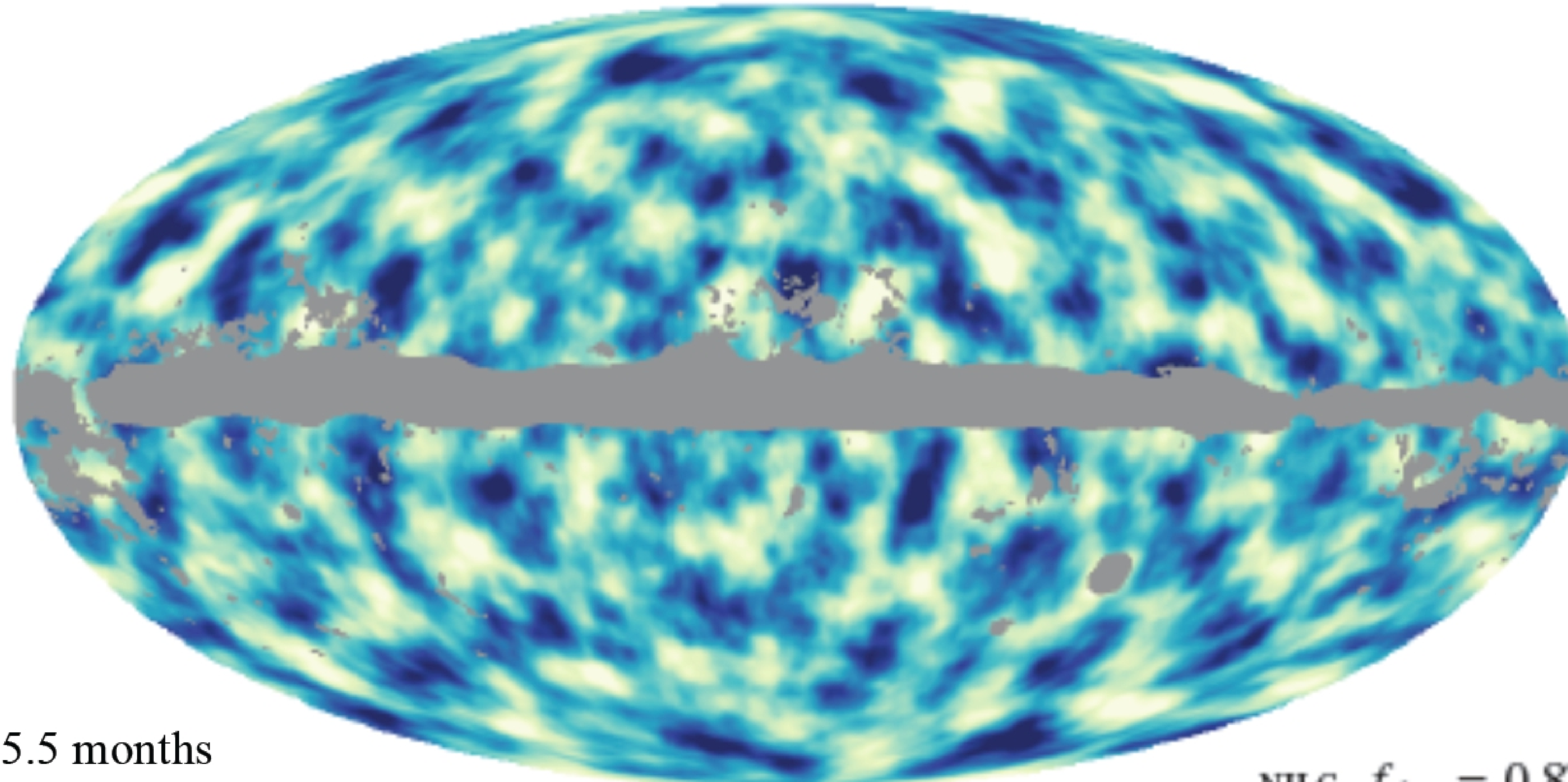
Public sky map after the first survey



CMB map after the first 2.5 surveys



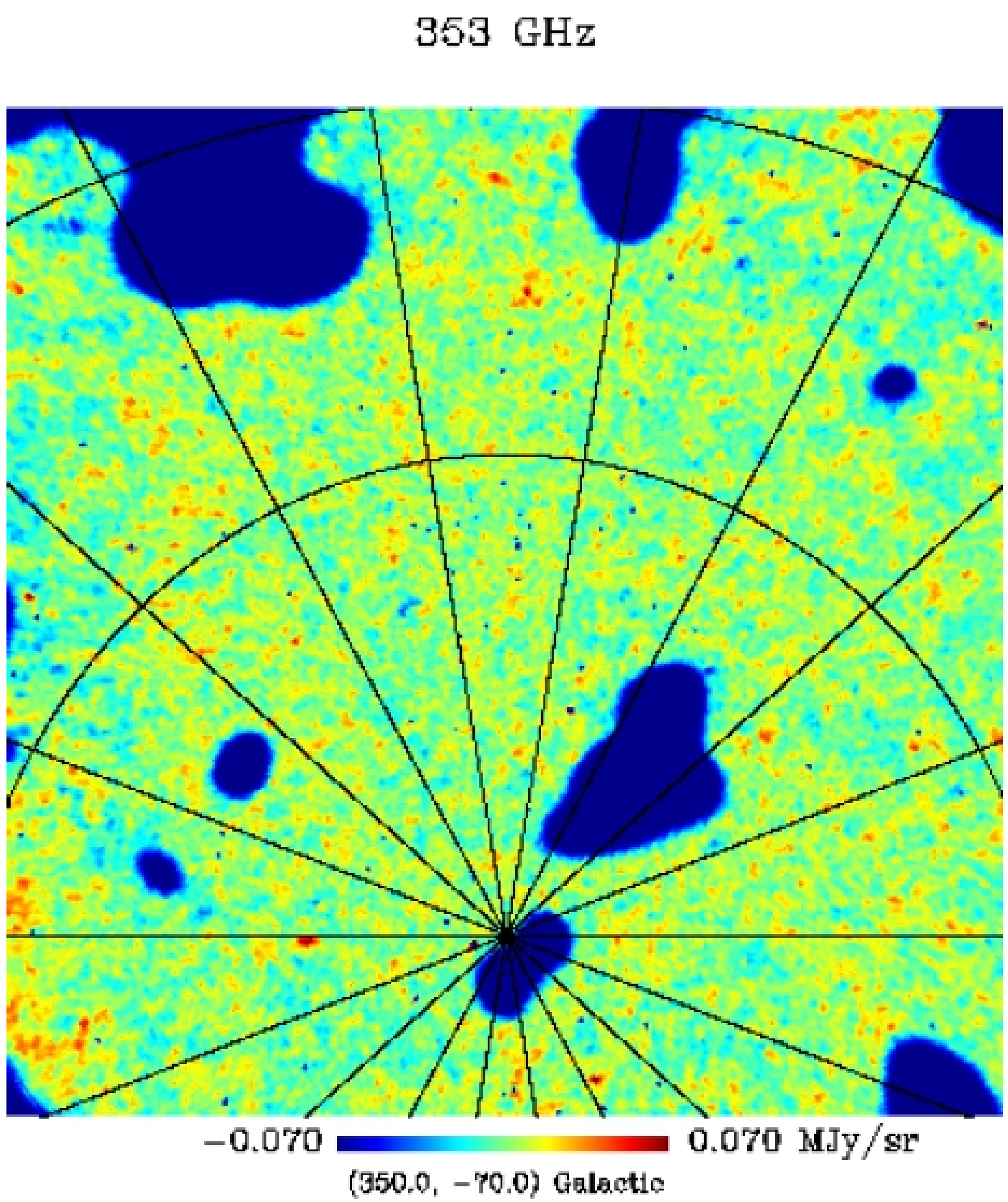
Lensing mass map from the first 2.5 surveys



15.5 months
S/N<1

NILC, $f_{\mathrm{sky}} = 0.87$

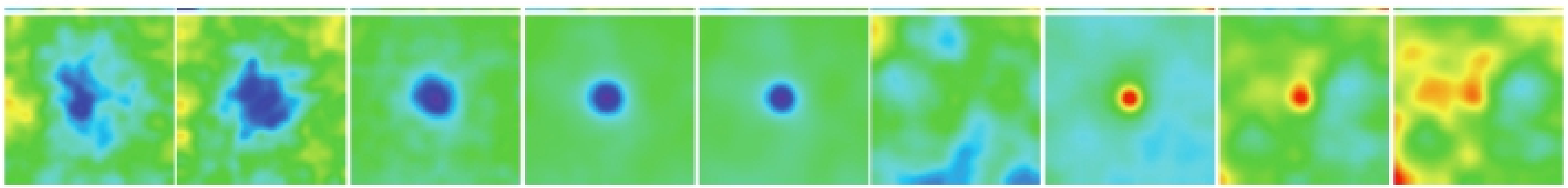
CIB map from the first 2.5 surveys



A projection of the cosmic star-formation history, re-radiated by dust.

The correlation with the projected mass map is detected at a level of 47 σ !

Detecting the (hot) baryons with *Planck*



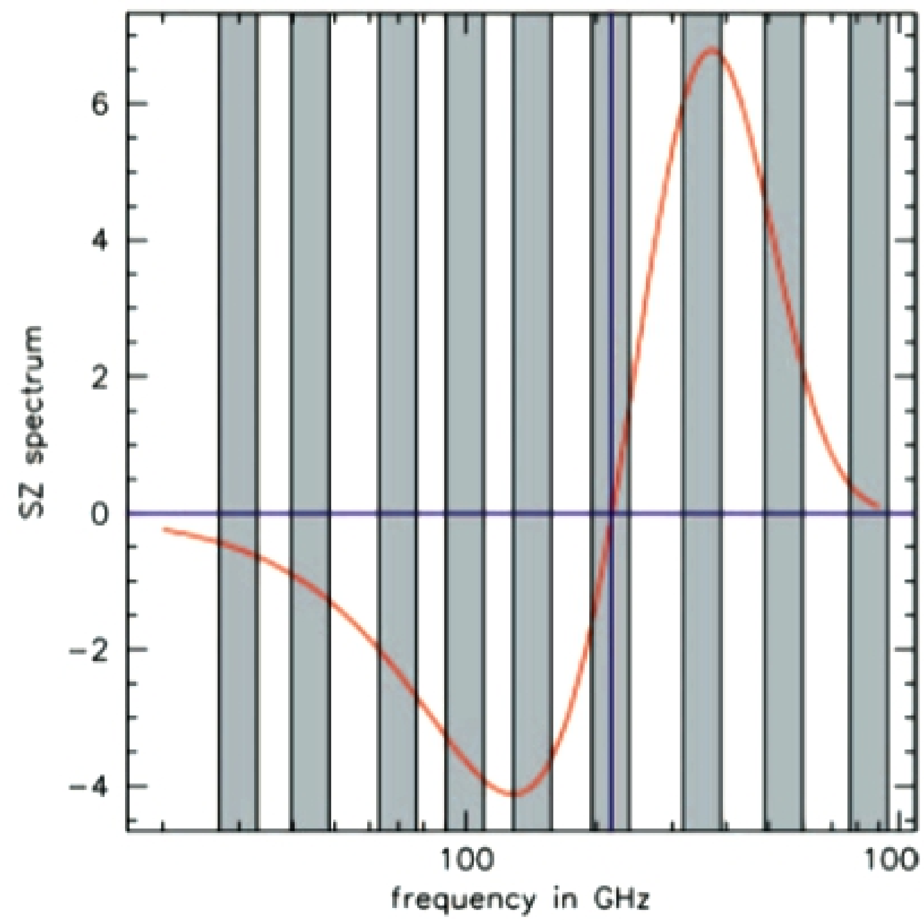
Planck can detect hot gas against the CMB through the spectral distortion introduced by Compton scattering,

$$\Delta i_\nu(\hat{n}) = y(\hat{n}) j_\nu \,,$$

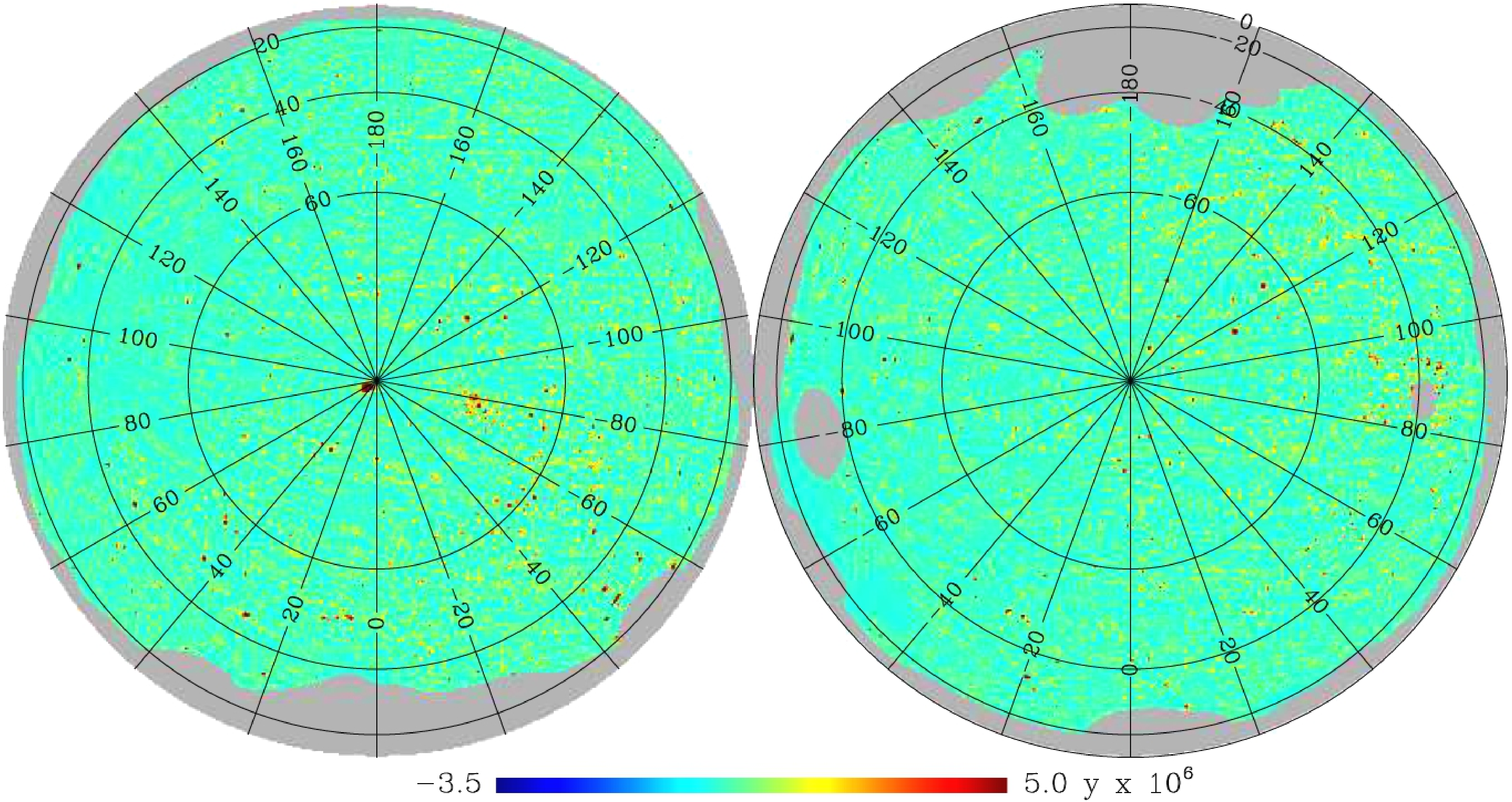
where j_ν is a characteristic spectral shape and y is the line-of-sight integral

$$y = k_{SZ} \int n_e \, T_e \, dl,$$

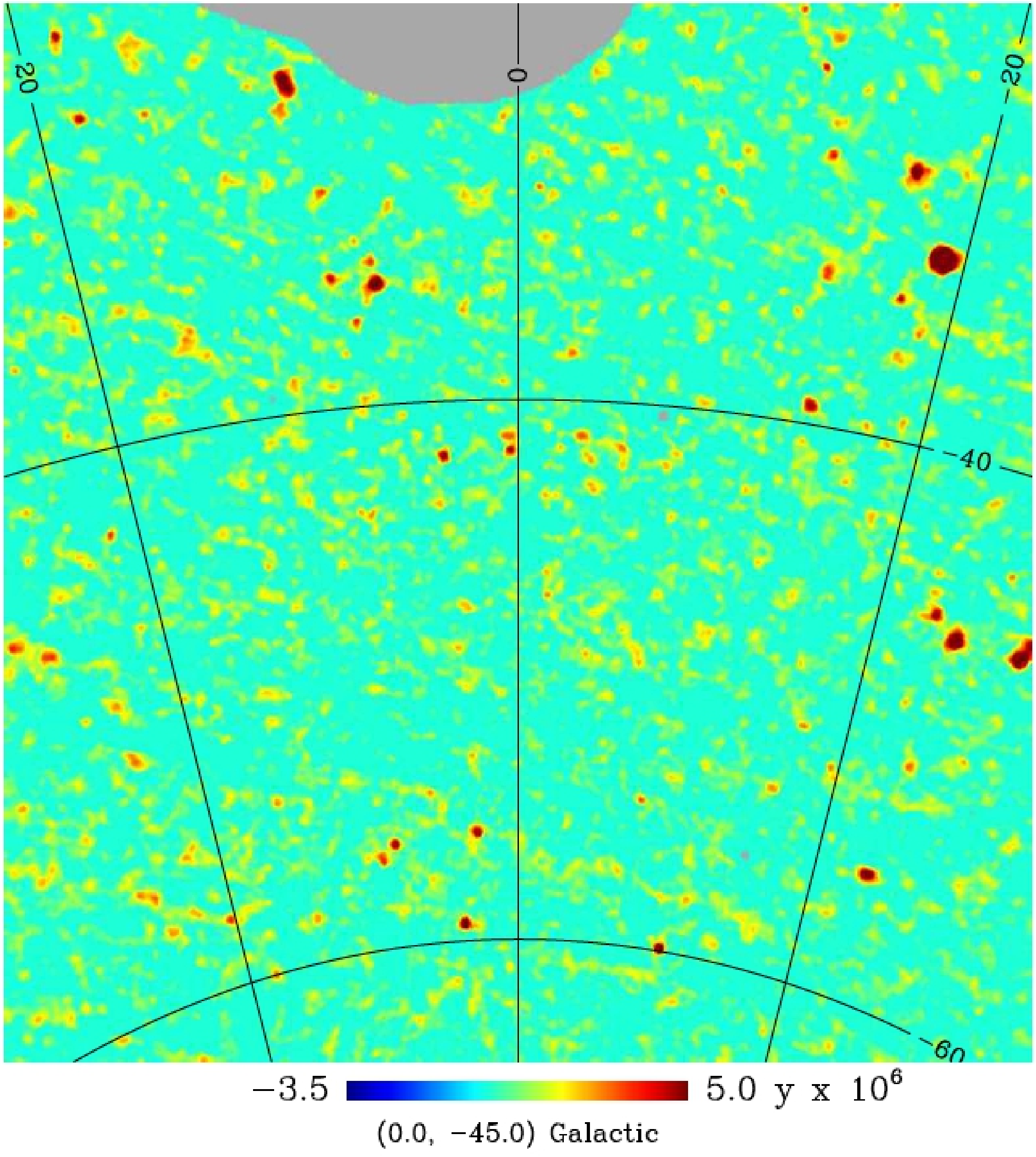
This is the Sunyaev-Zeldovich effect



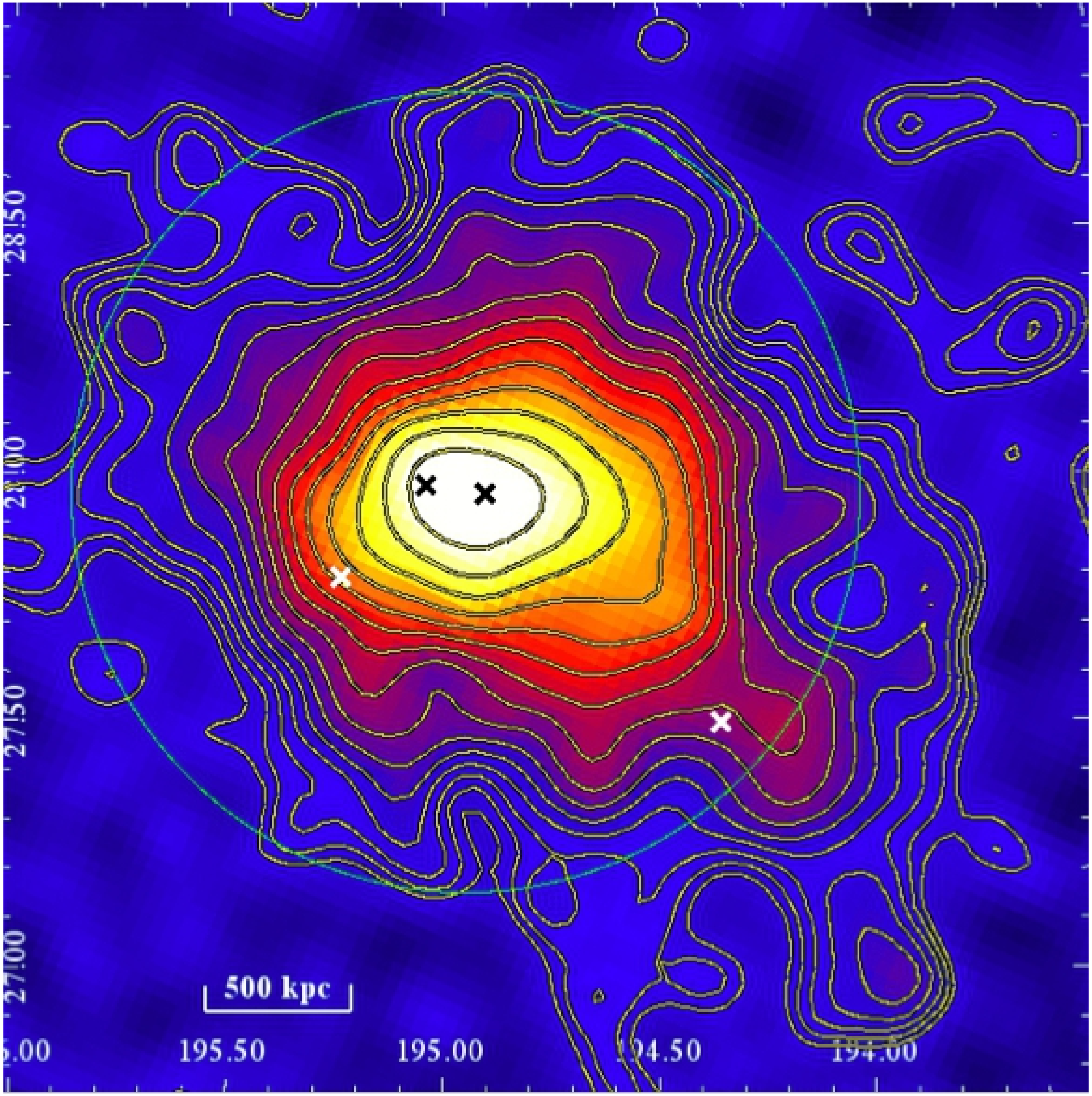
SZ map from the first 2.5 surveys



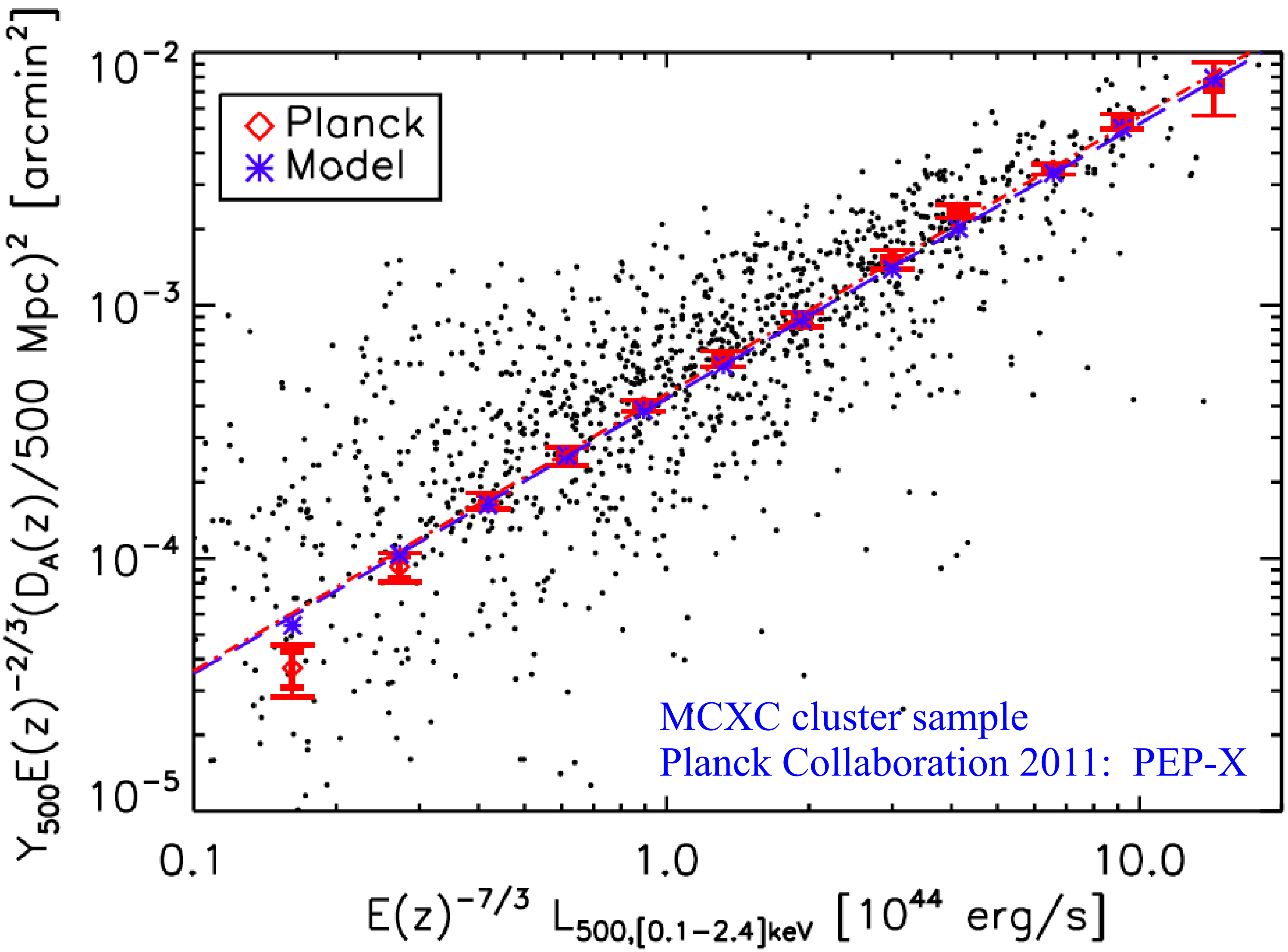
SZ map from the first 2.5 surveys



The Coma cluster



Planck estimate of Y – L_x relation



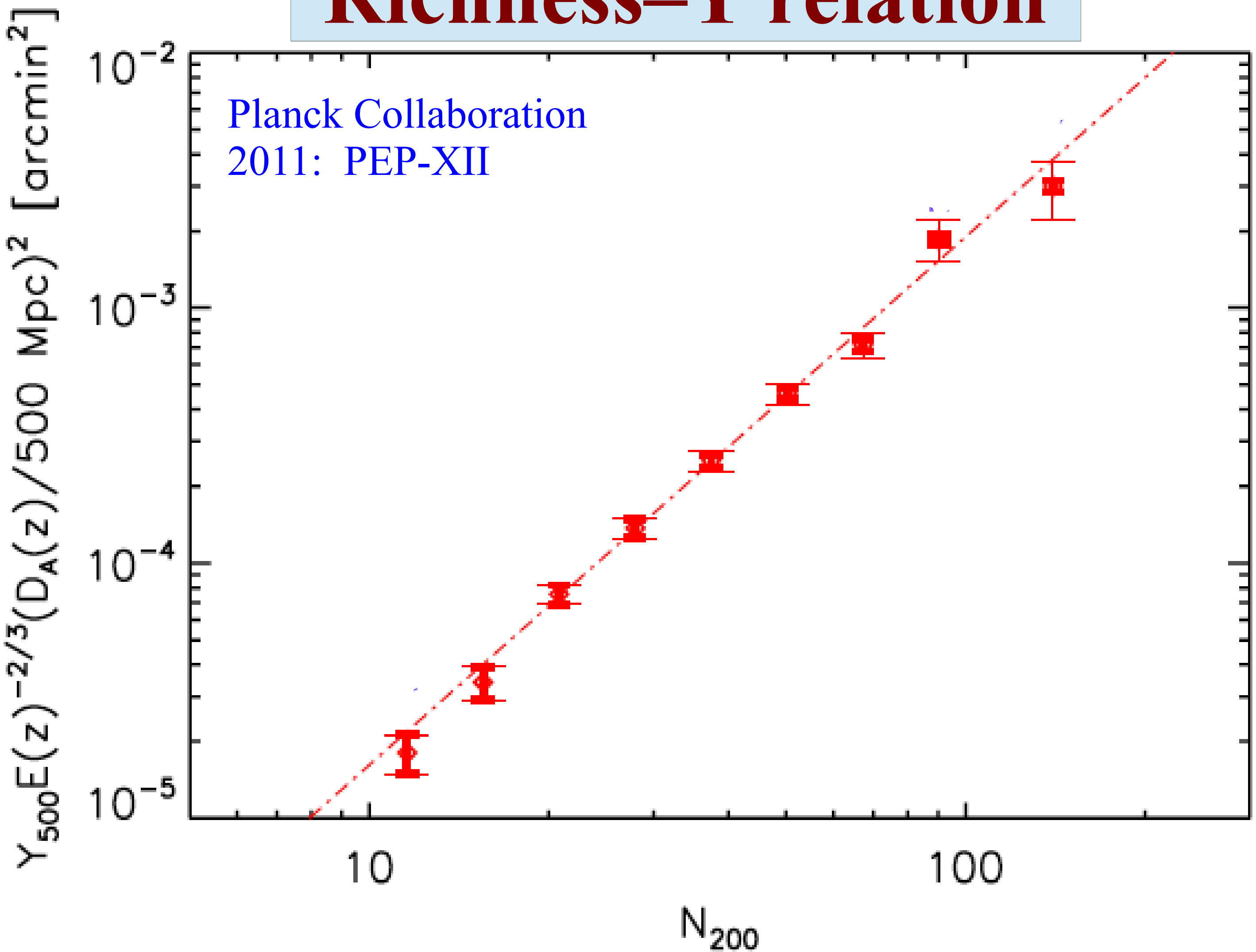
Model assumes $M \propto L_x^{0.61}$ and $Y \propto M^{1.78}$ based on bright X-ray clusters

For self-similar structure both imply baryon fractions decreasing with M

- Combination of Planck maps with wide-angle <u>optical</u> surveys allows high S/N detection of mean stacked signals due to
  - total mass (through lensing)
  - total hot gas content (through the SZ effect)
  - dust emission (through high frequency channels)
  - radio emission (through low-frequency channels)

- Here I will concentrate on results from stacking of SZ signals around objects defined from the Sloan Digital Sky Survey
  - cluster scaling relations for optically selected clusters
  - halo baryon content of dark halos down to galaxy scales

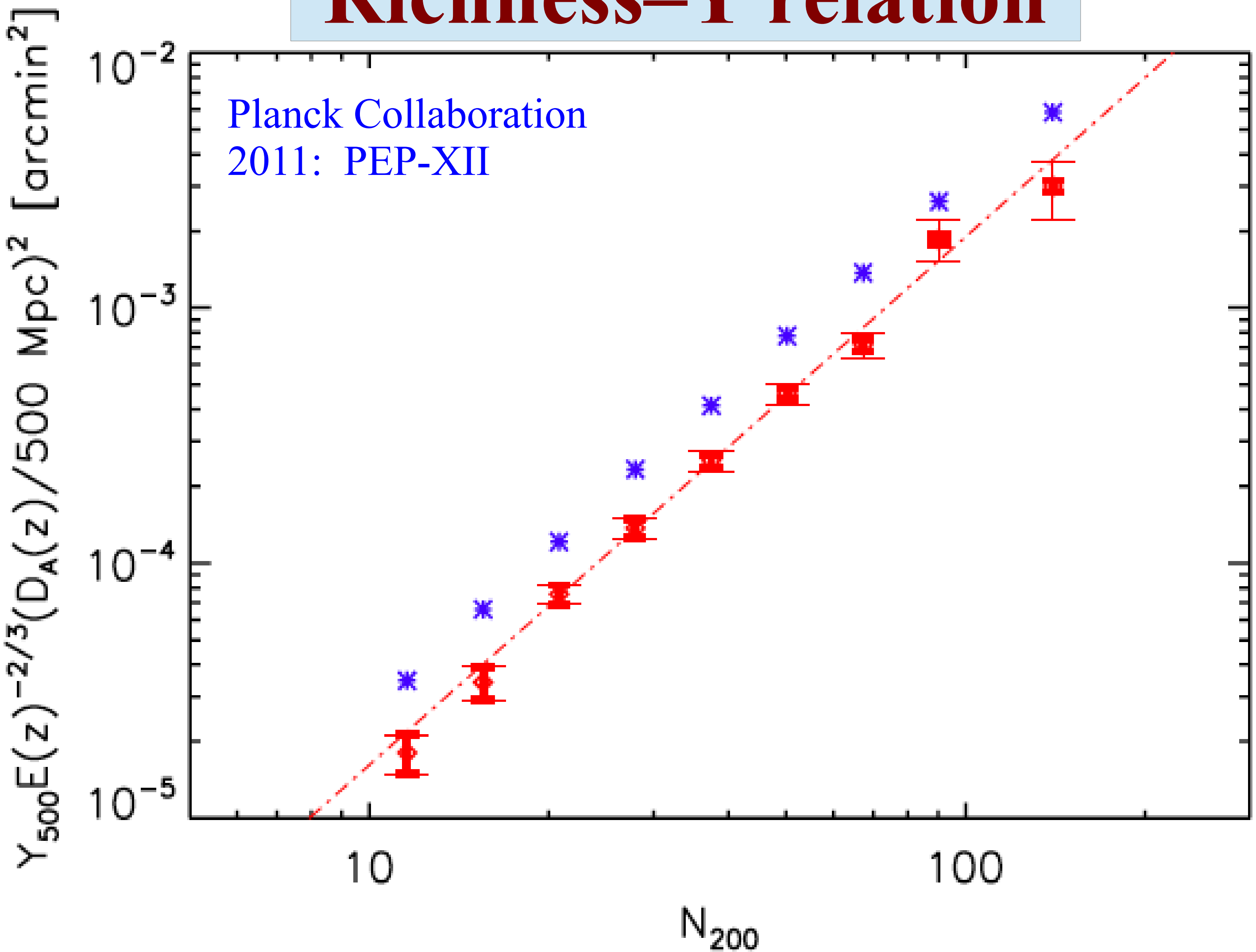
Richness–Y relation



The MaxBCG catalogue, based on SDSS/DR5 contains ~14,000 galaxy clusters with richness $N_{200} > 10$ over 7,500 squ.deg.

Stacking Planck SZ measurements based on a multi-frequency matched filter detects the mean $Y_{500} - N_{200}$ relation at high significance.

Richness–Y relation

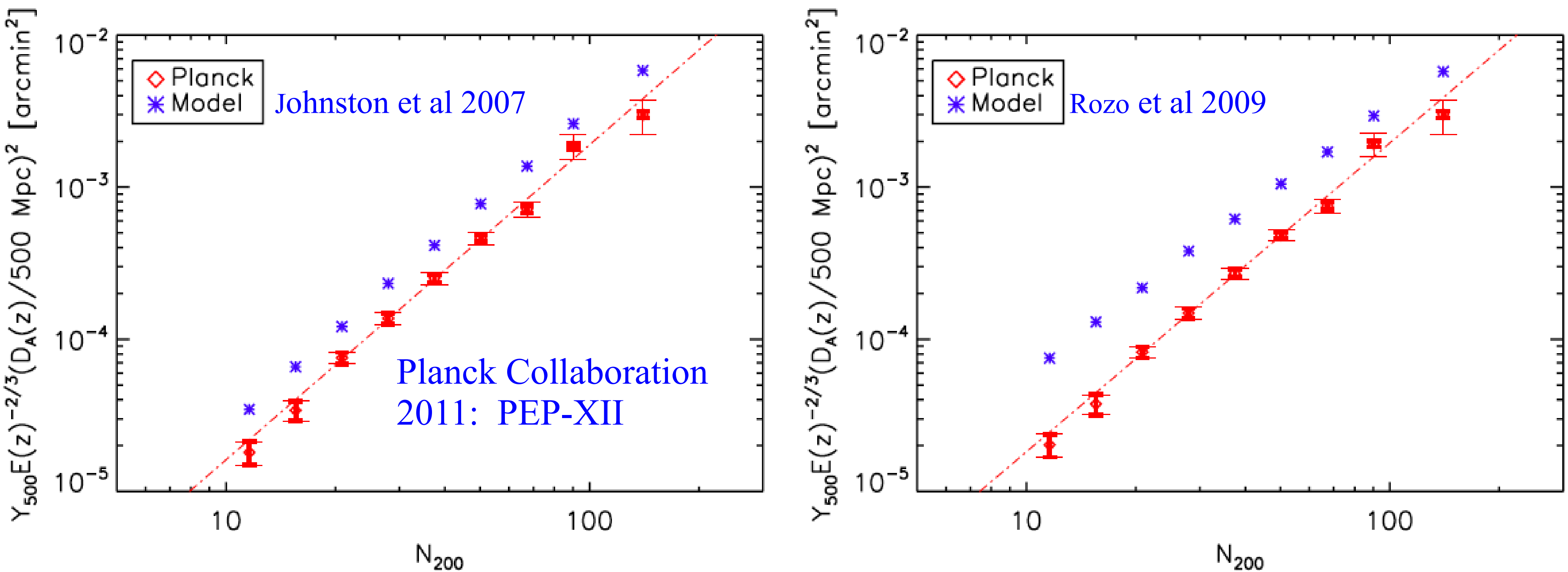


The result disagrees with the prediction from

N_{200} → M_{500} → $Y_{X,500}$ → Y_{500}

- N_{200} → M_{500}: gravitational lensing of maxBCG stacks (Johnston et al 2007)
- M_{500} → $Y_{X,500}$: universal pressure profile of Arnaud (2010)
- $Y_{X,500}$ → Y_{500}: assumed equal

Richness–Y relation



The result <u>disagrees</u> with the prediction from

N_{200} → M_{500} → $Y_{X,500}$ → Y_{500}

gravitational lensing of maxBCG stacks

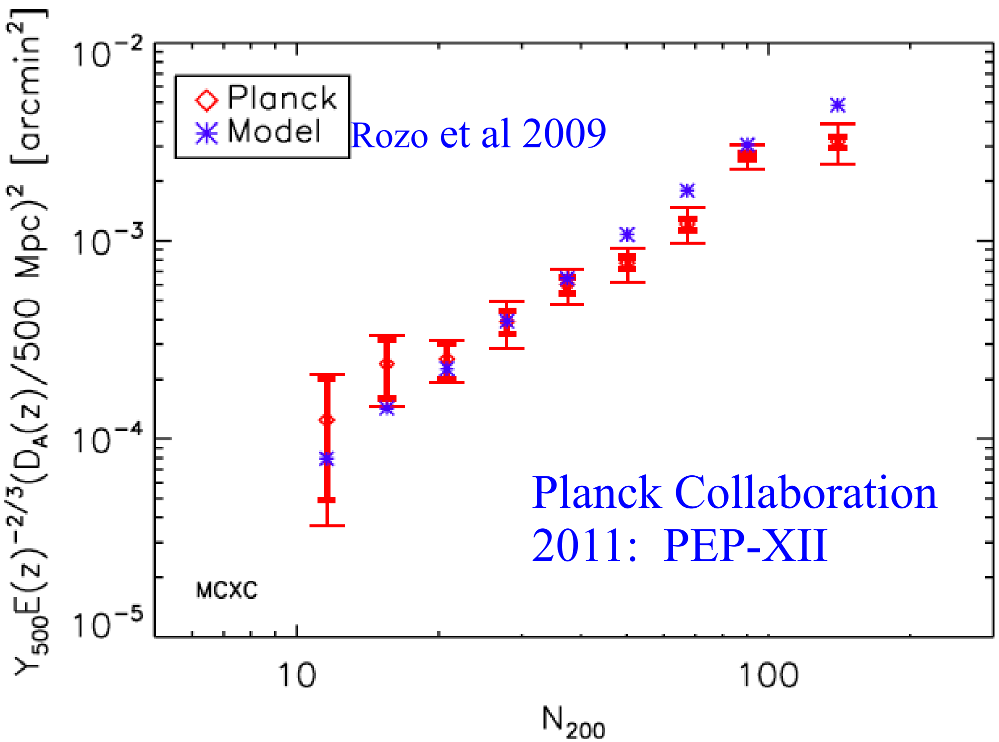
universal pressure profile of Arnaud (2010)

assumed equal

Richness–Y relation

Yet when sample is restricted to clusters which also appear in an X-ray selected sample, the discrepancy disappears

Malmquist bias transferred from the X-ray to the SZ!



The result now agrees with the prediction from

N_{200} → M_{500} → $Y_{X,500}$ → Y_{500}

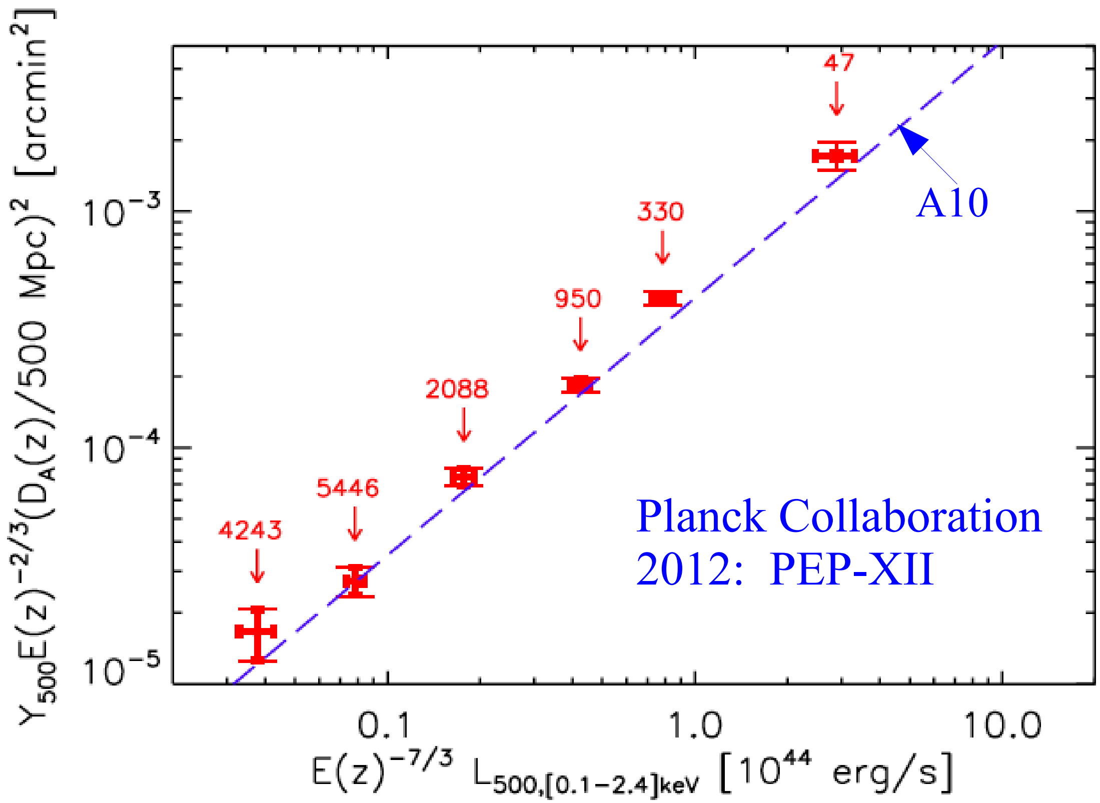
gravitational lensing of maxBCG stacks

universal pressure profile of Arnaud (2010)

assumed equal

$Y - L_X$ relation

Yet for stacks of given N_{200} in the full maxBCG sample, mean $L_{X,500}$ is related to mean Y_{500} as predicted by the Arnaud (2010) "universal" profile derived from X-ray clusters.



The Y – L relation is the same for X-ray-selected and non-X-ray-selected cluster samples

Thus the Malmquist bias in X-ray-selected samples shifts Y and L along the mean relation

Problems with scaling relations?

Cluster selection by optical, X-ray and SZ methods leads to samples with systematically different properties.

X-ray selection picks clusters which are systematically more regular and centrally concentrated than SZ selection which in turn picks clusters which are more regular than optical selection

These differences can shift scaling relations between observables, and between observables and a fiducial cluster mass, by amounts which are significant compared to cosmology dependences.

Such shifts are likely to be redshift-dependent and must be understood before cluster abundances can be used for cosmology

→ **Sample selection and calibration are critical.**
Scatter and evolution must be <u>fully</u> characterised

Problems with scaling relations?

Cluster selecti ... leads to samples with ...

X-ray selectio ... ally more regular and ce ... n which in turn picks clusters ... election

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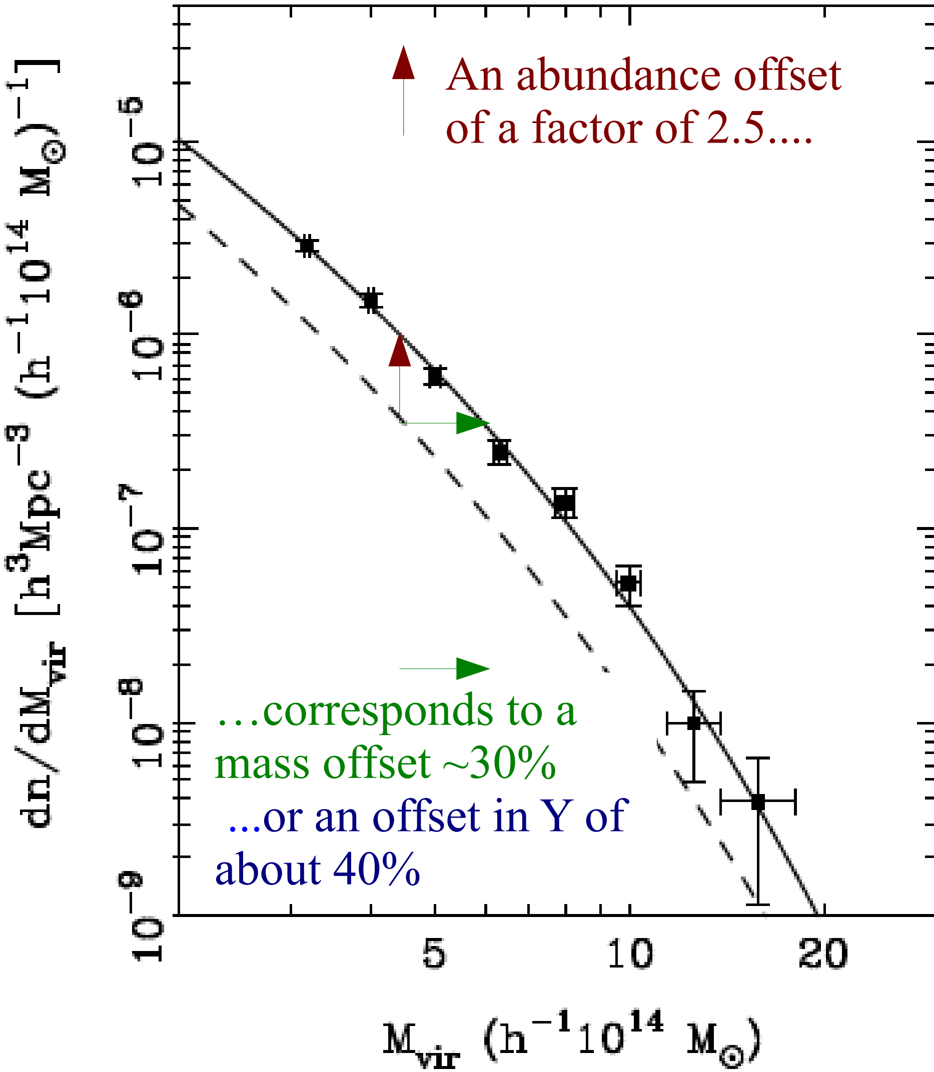


→ **Sample selection and calibration are critical.**
Scatter and evolution must be <u>fully</u> characterised

Millennium-XXL

Successor to the Millennium Run

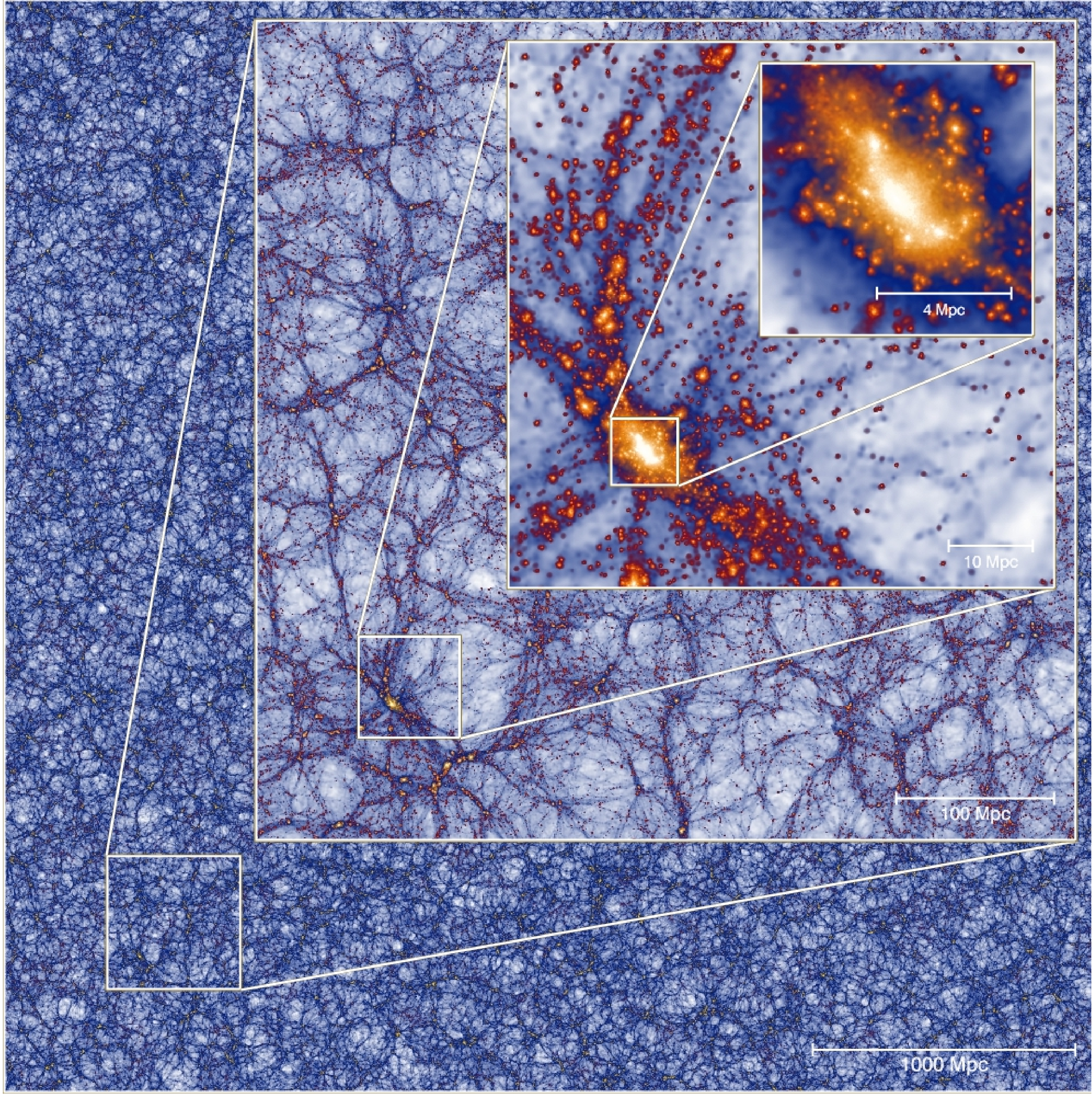
Same cosmology

30 times more particles

216 times more volume

~10^5 rich clusters!

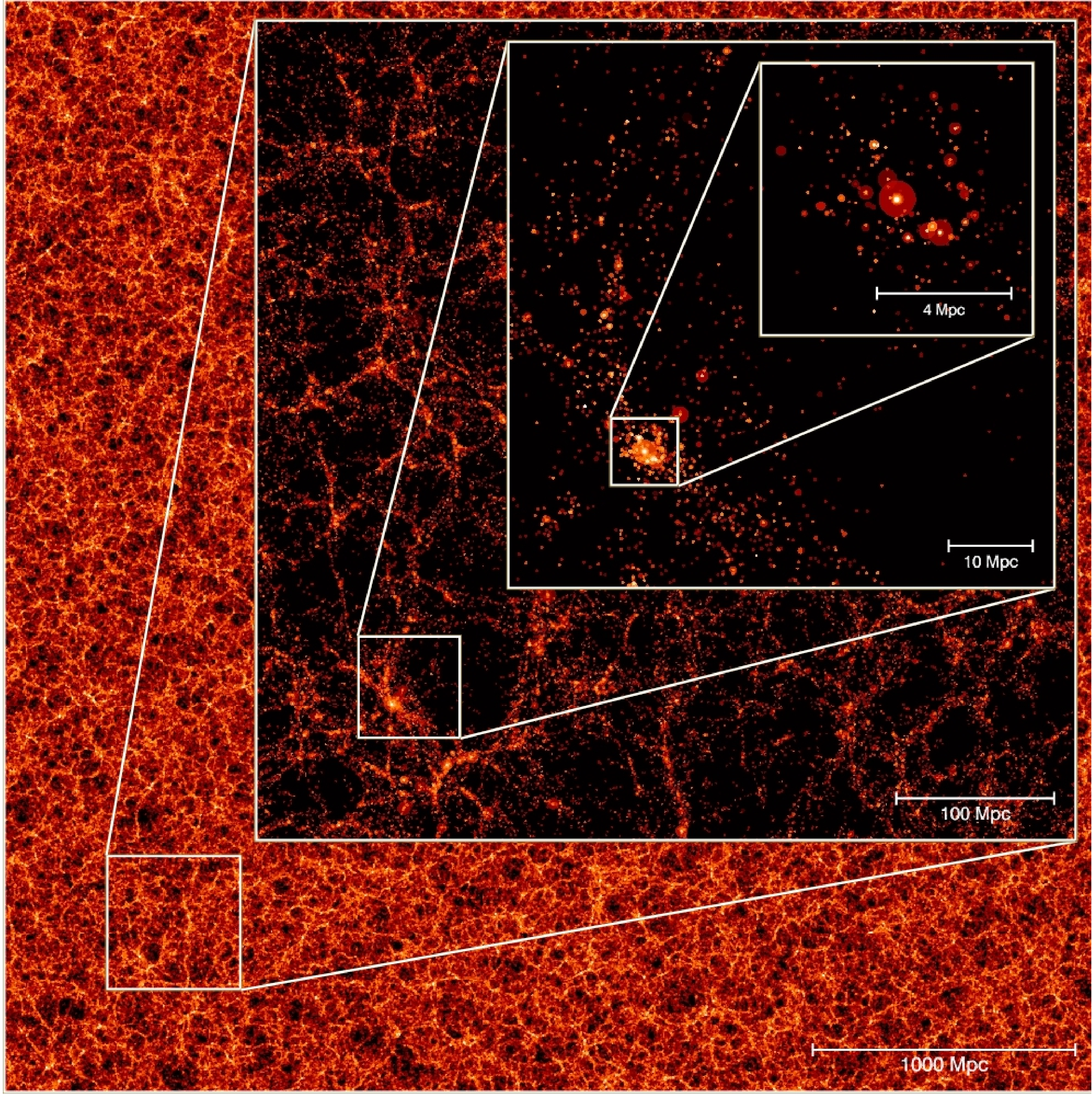
Angulo et al 2012



Millennium-XXL

Stored data allow simulation of the galaxy population down to 0.1 x Milky Way mass, though with less precision than in the MS

Allows clusters to be found directly in the galaxy distribution



Angulo et al 2012

Millennium-XXL

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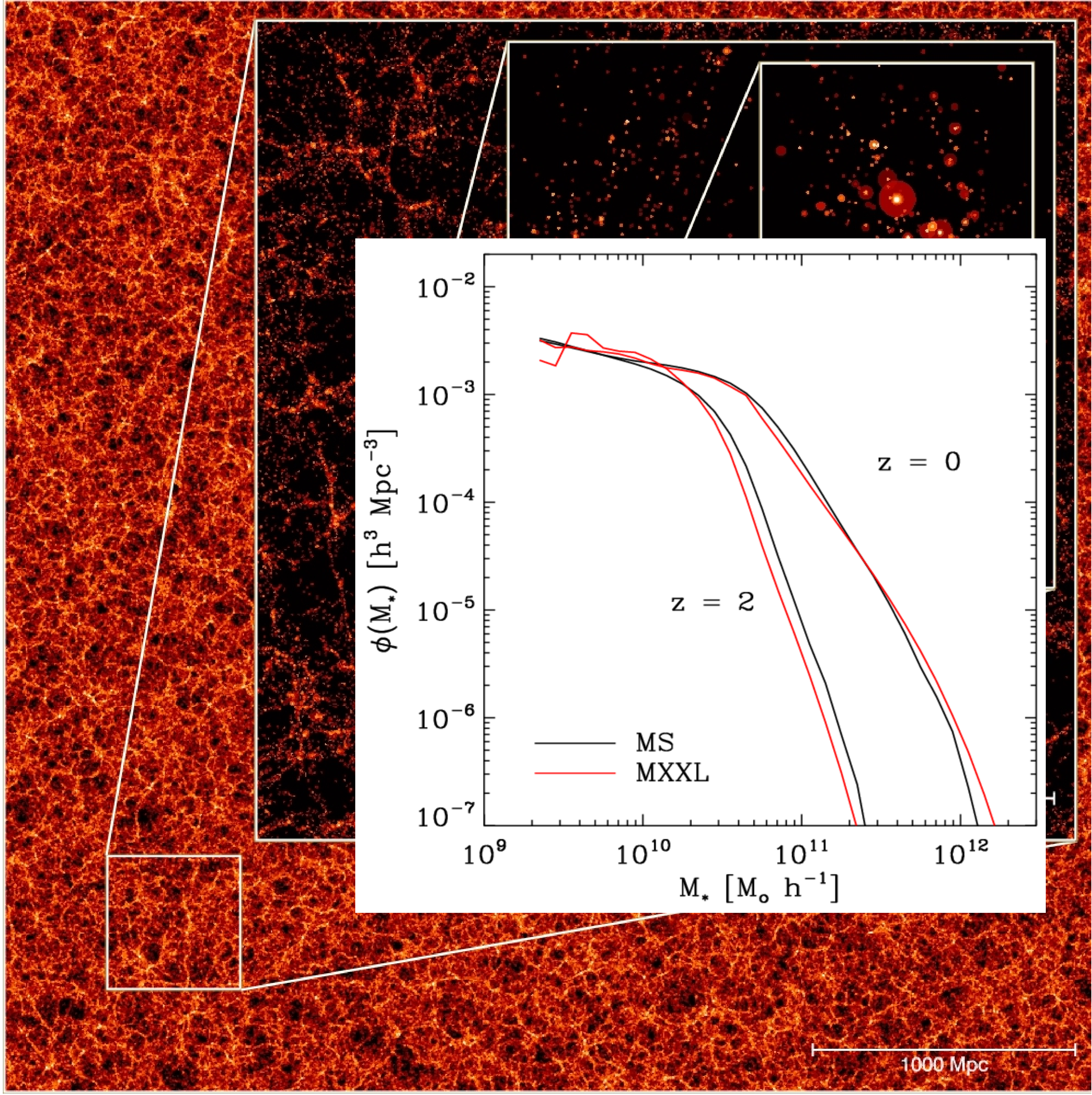
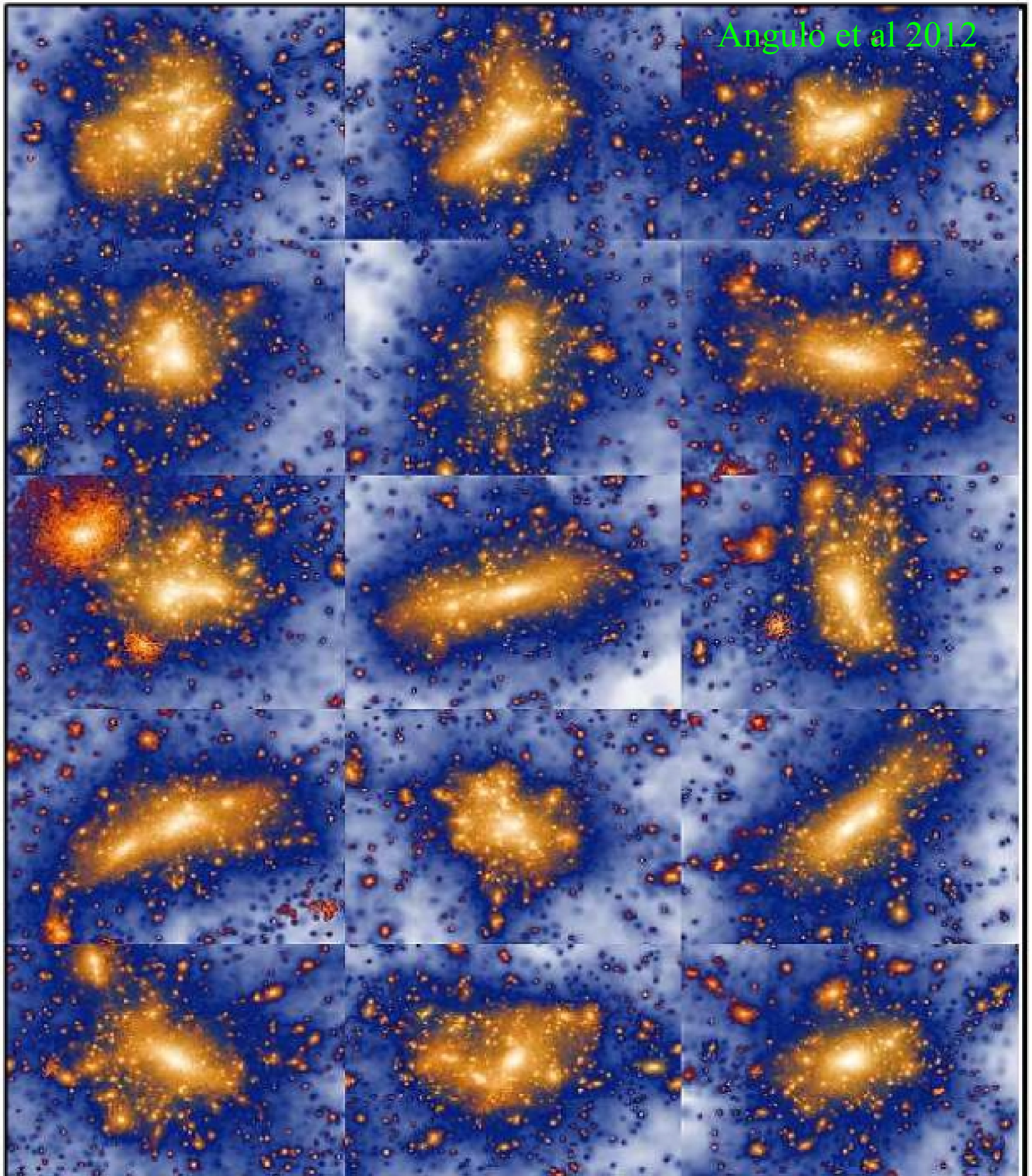


Angulo et al 2012



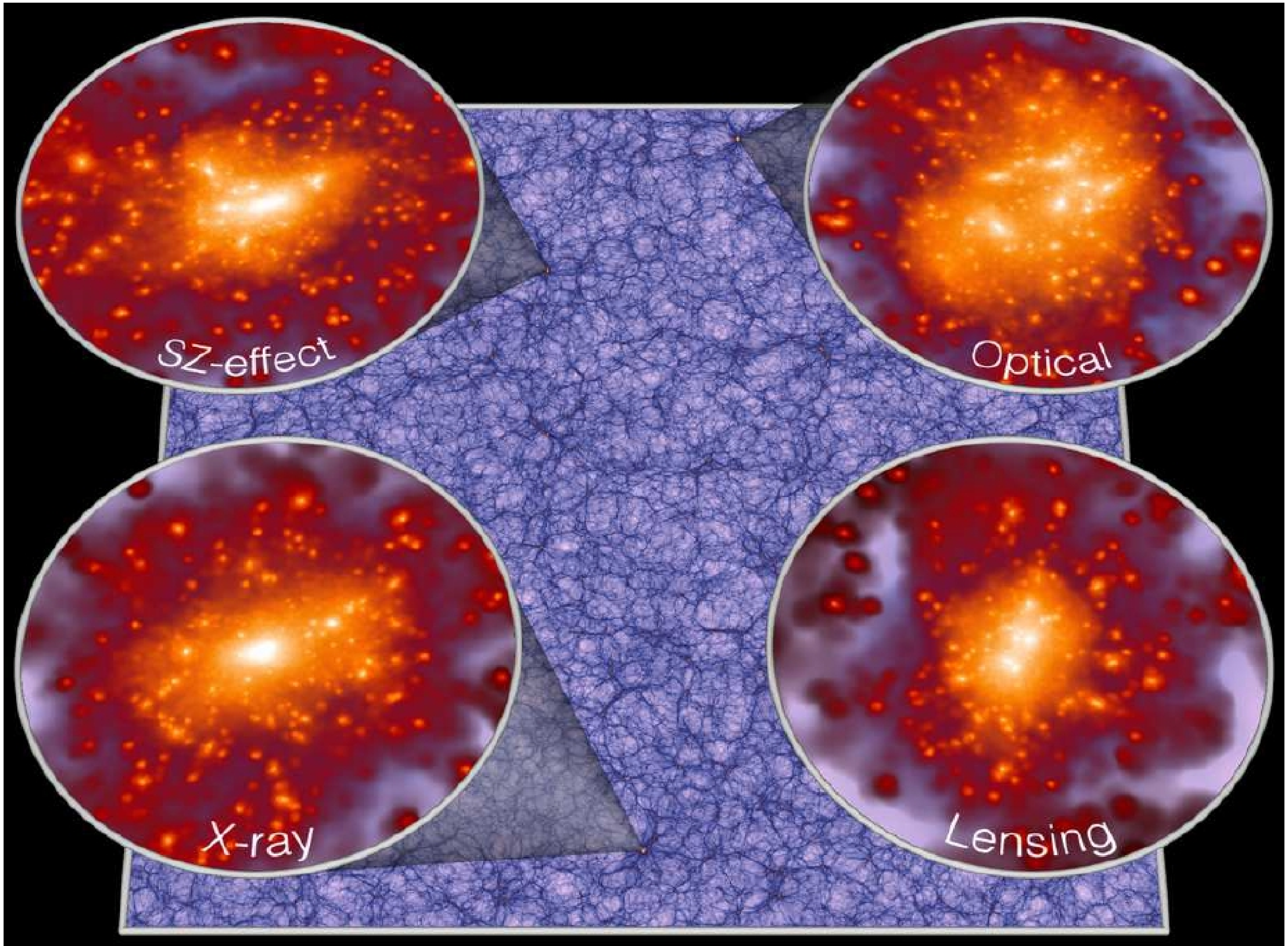
Scatter

Relations between mass measures show scatter because of:
(i) internal structure
(ii) orientation
(iii) environment
(iv) line-of-sight proj'ns

Relations to observable mass proxies show <u>additional</u> scatter because of:
(v) extra astrophysics
(vi) observational error

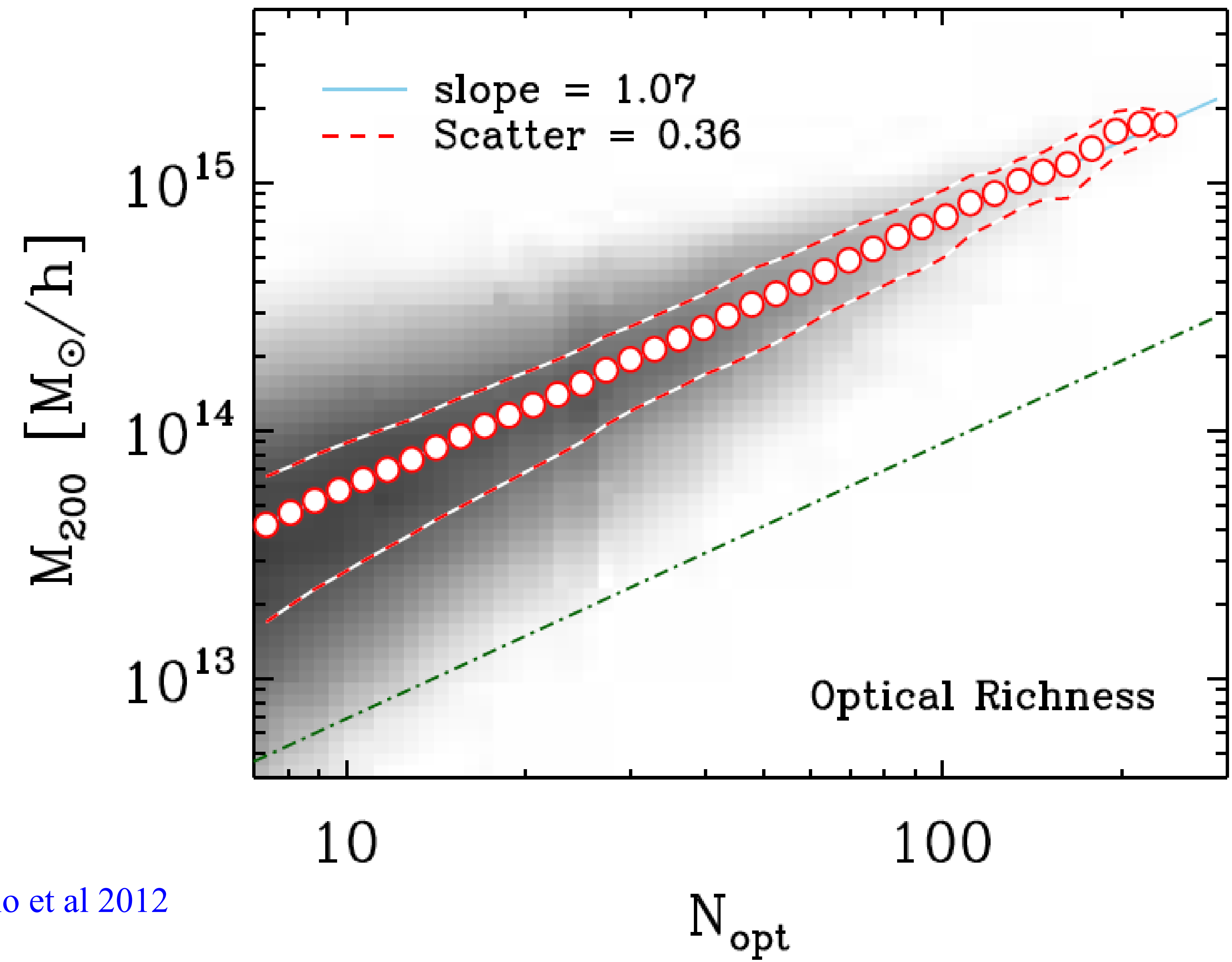
MXXL surrogates for cluster observables

By using the mass and galaxy distributions, assuming $\rho_{gas} \propto \rho_{DM}$, and $T_{gas} \propto T_{vir,DM}$, one can construct surrogate observables corresponding to: (a) optical richness; (b) X-ray lum'y; (c) SZ signal; (d) lensing strength



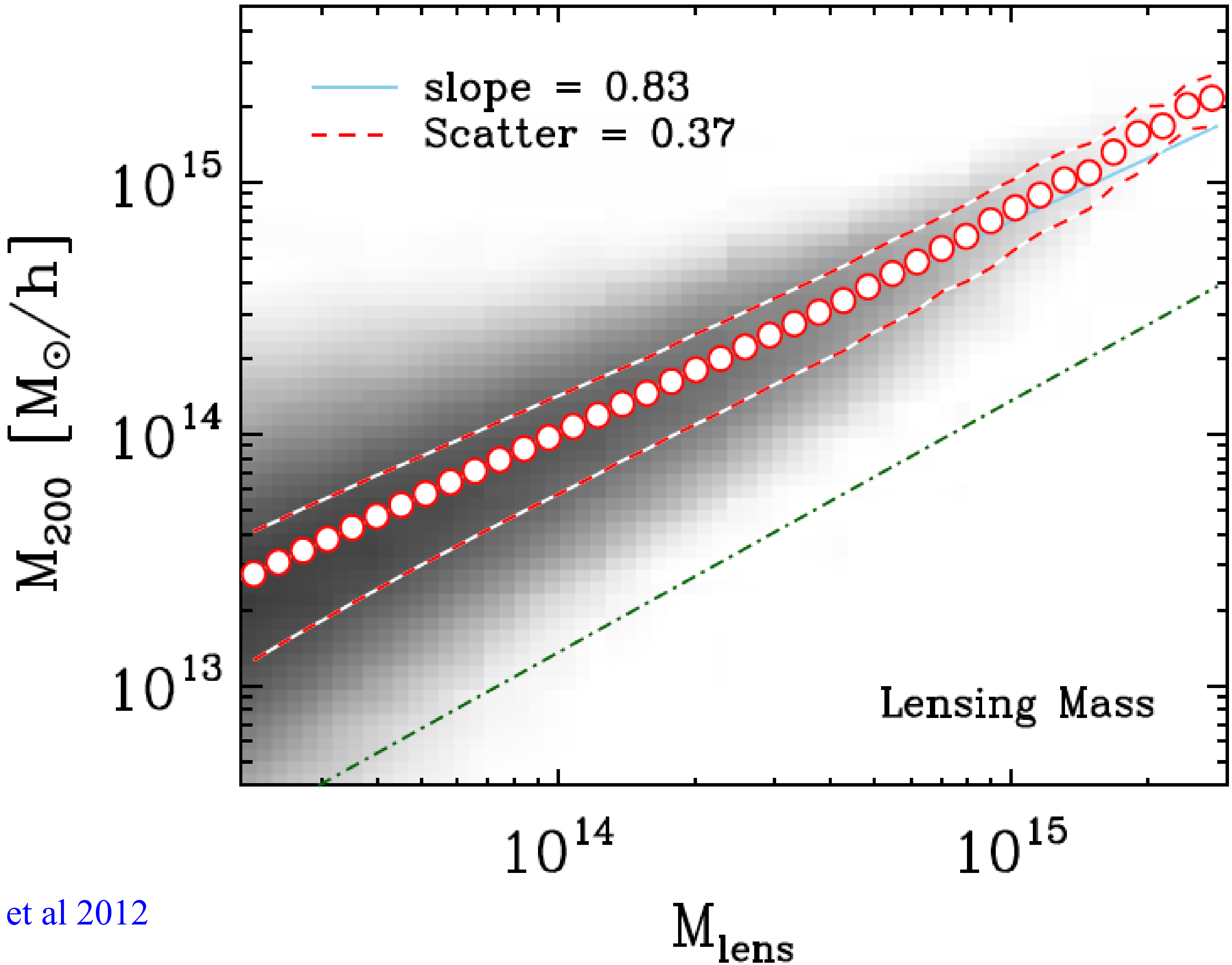
Angulo et al 2012

Scatter between mass and proxy in the MXXL



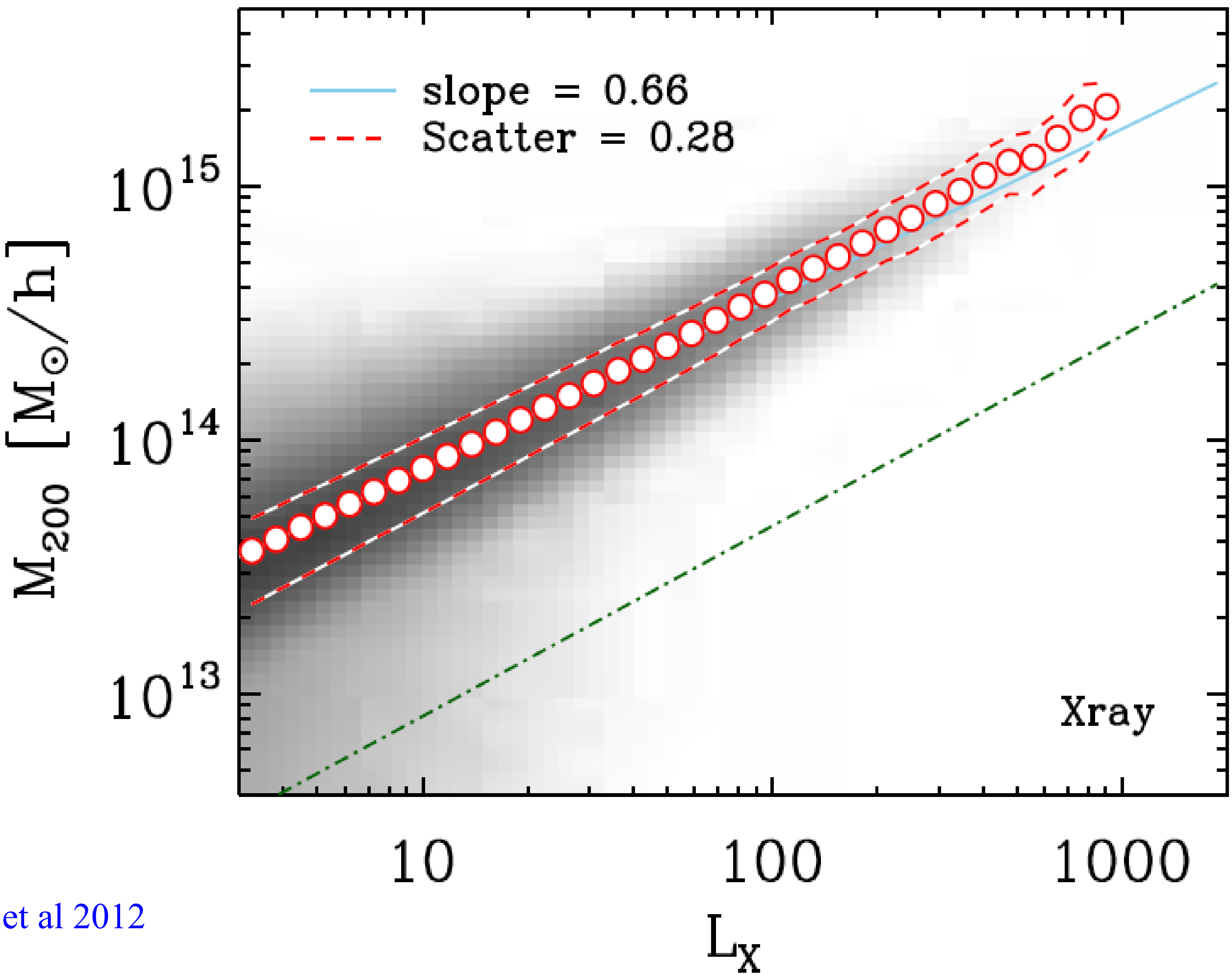
Angulo et al 2012

Scatter between mass and proxy in the MXXL



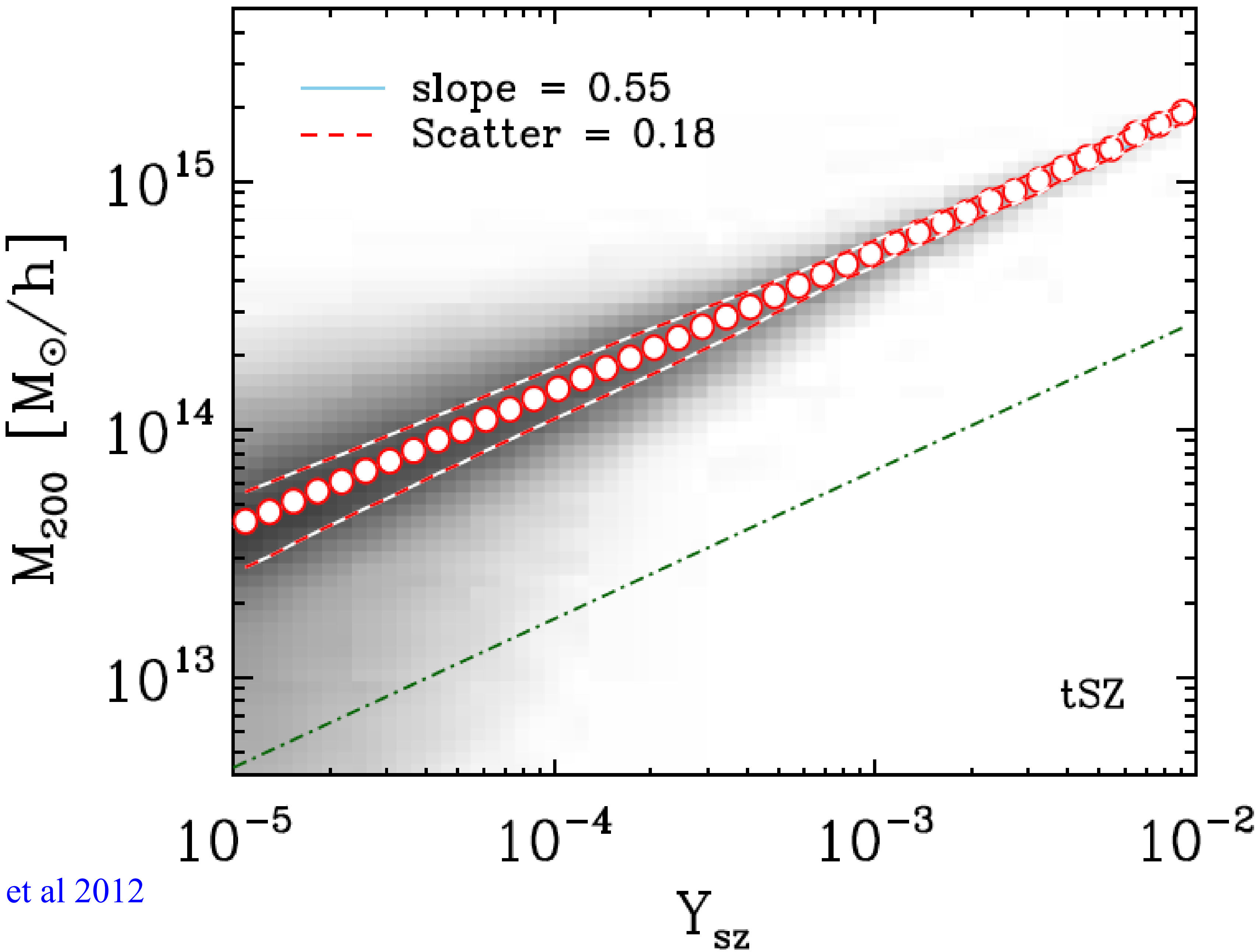
Angulo et al 2012

Scatter between mass and proxy in the MXXL



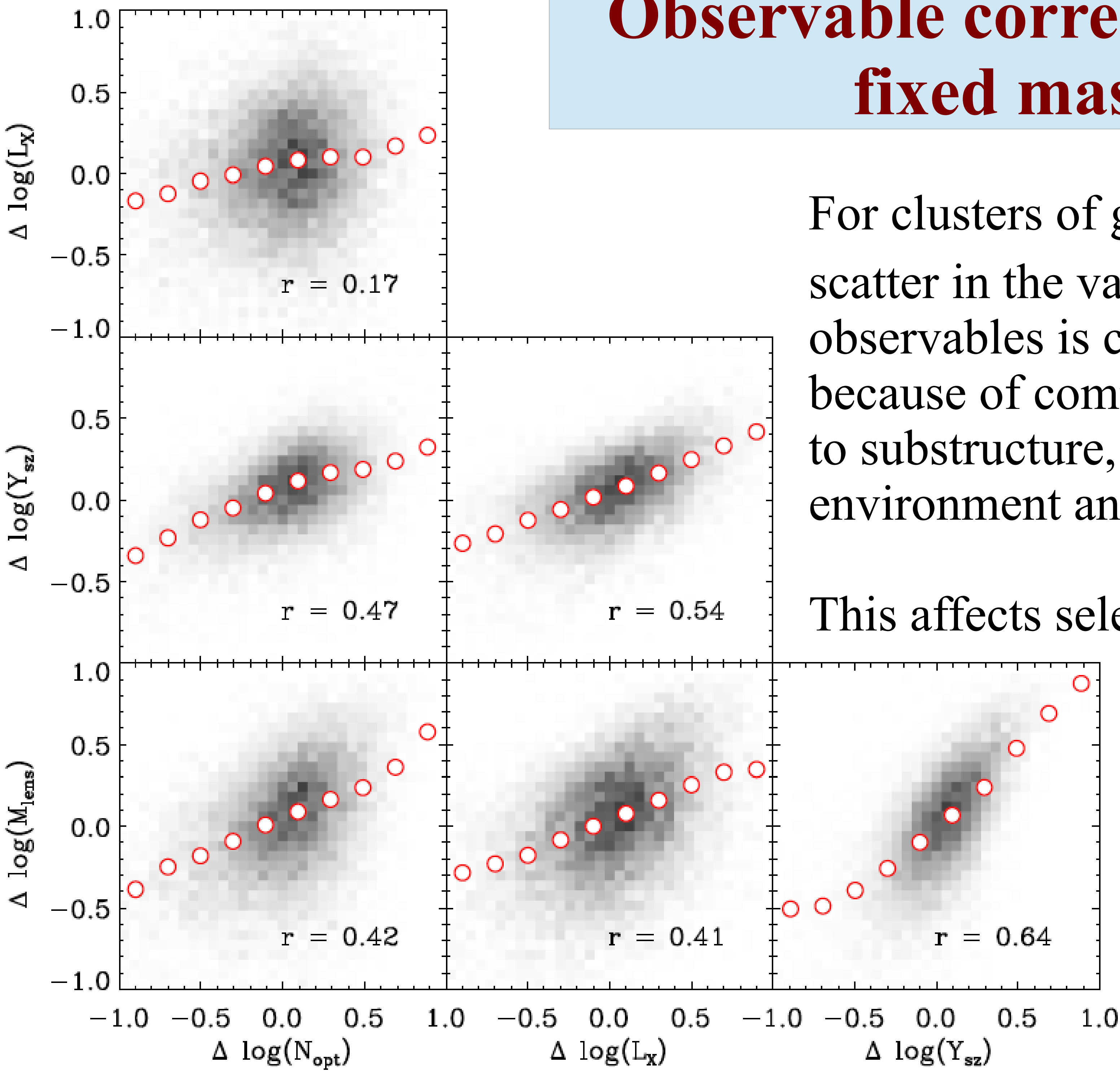
Angulo et al 2012

Scatter between mass and proxy in the MXXL



Angulo et al 2012

Observable correlations at fixed mass

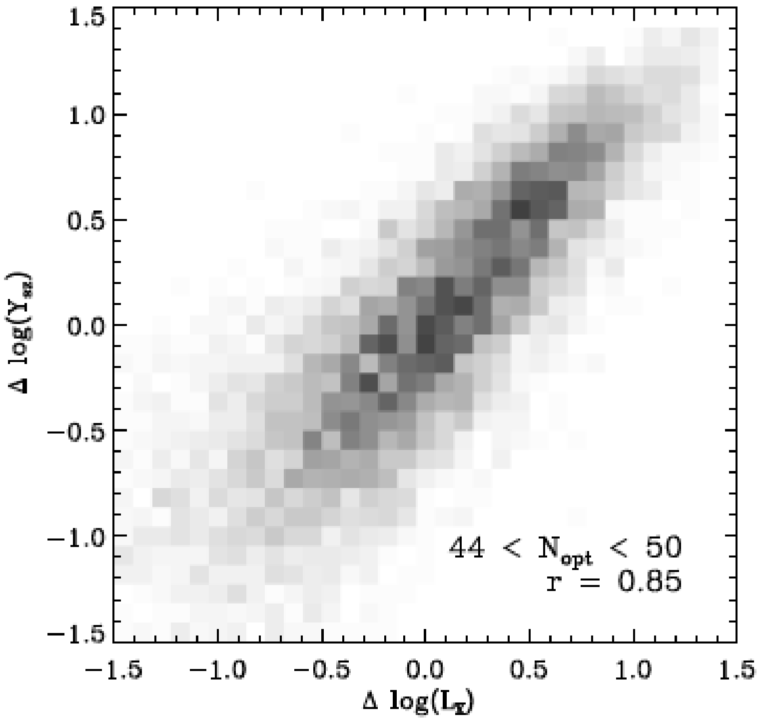


For clusters of given M_{200}, the scatter in the values of the observables is correlated because of common sensitivity to substructure, orientation, environment and projection.

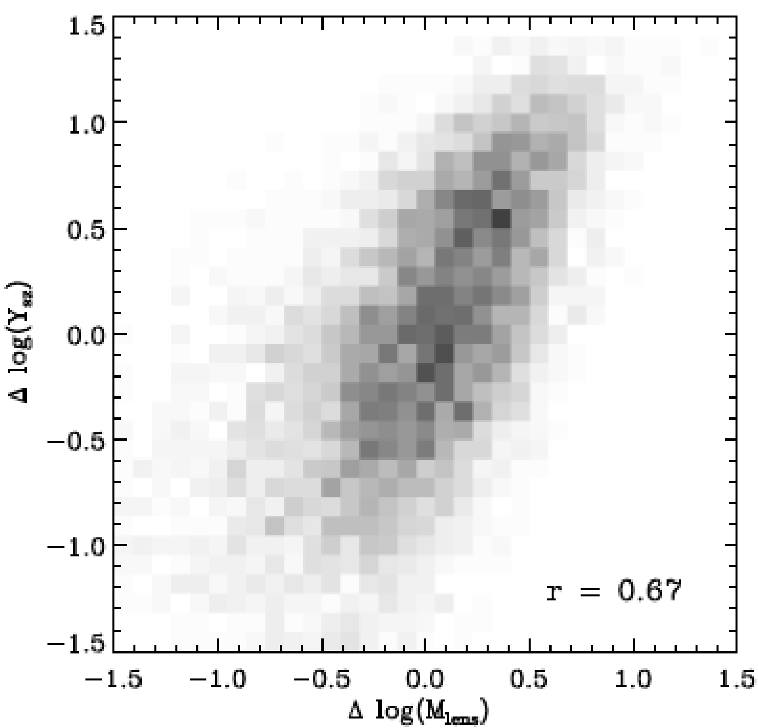
This affects selection biases

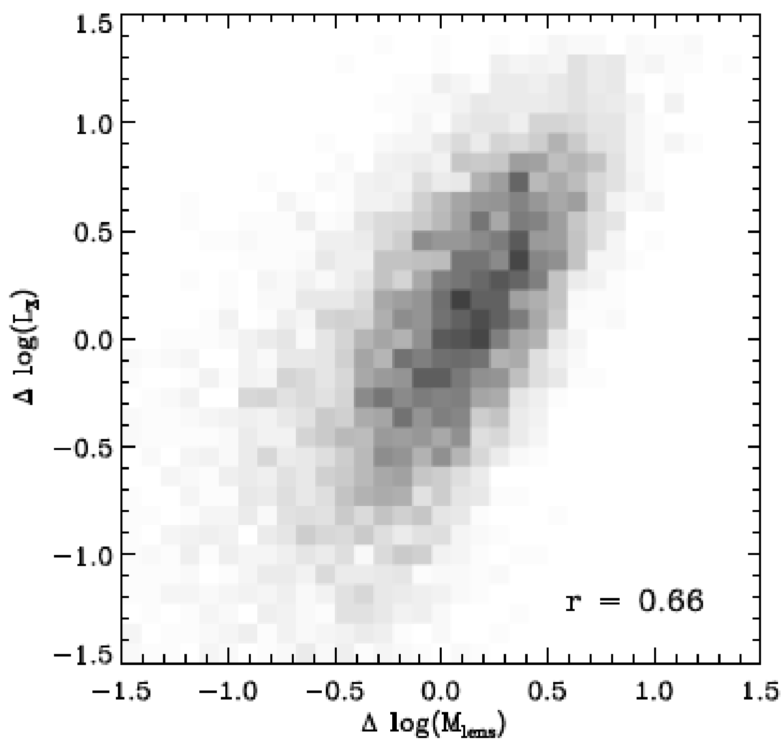
Angulo et al 2012

Observable correlations at fixed richness



For clusters of given <u>richness</u>, the correlated scatter in the values of the observables is larger because of the large scatter in the richness-mass relation caused by centering issues (e.g. picking the wrong central galaxy)





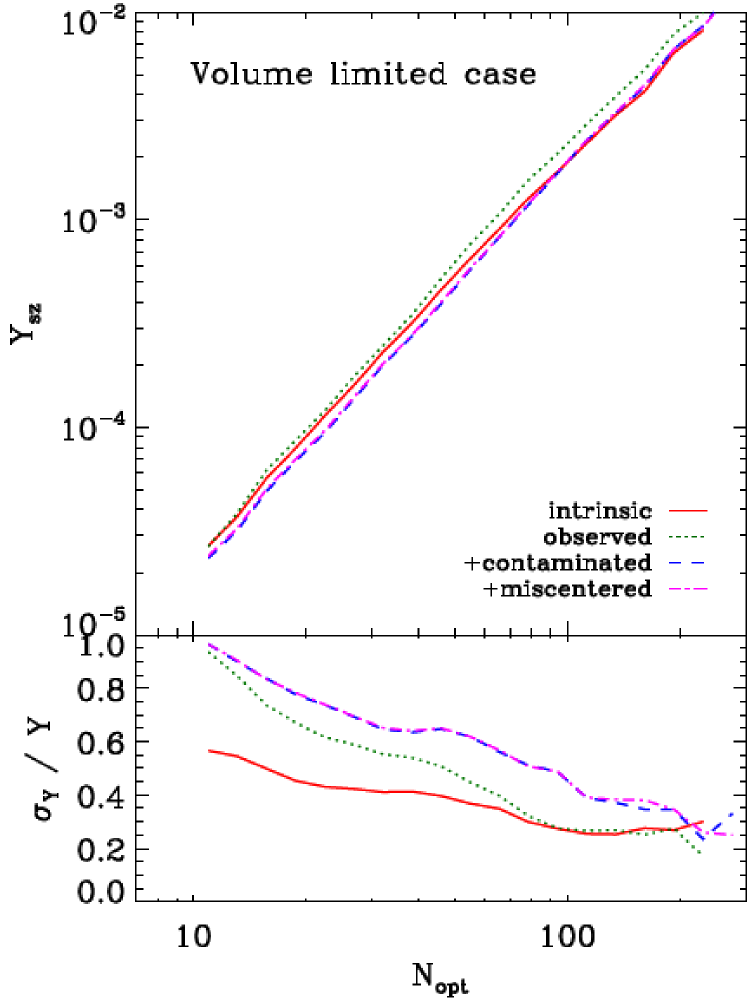
Angulo et al 2012

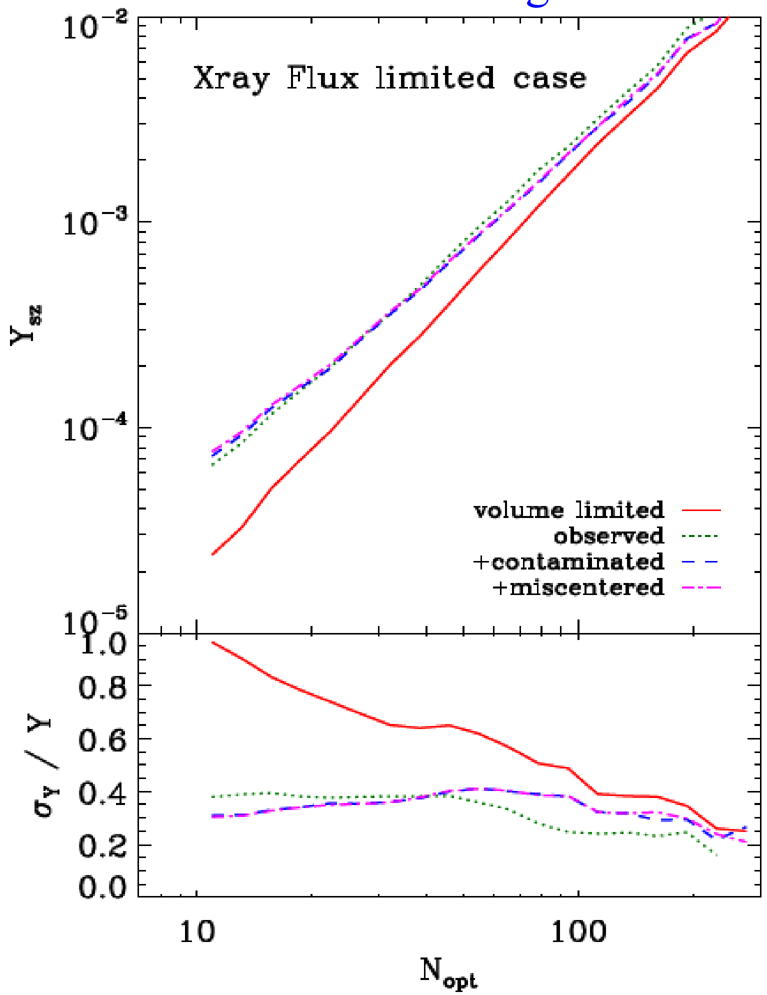
Scaling relations and sample selection

The scaling relations between observables (slope, normalisation and scatter) depend on how cluster samples are selected

This is an extension of Malmquist bias

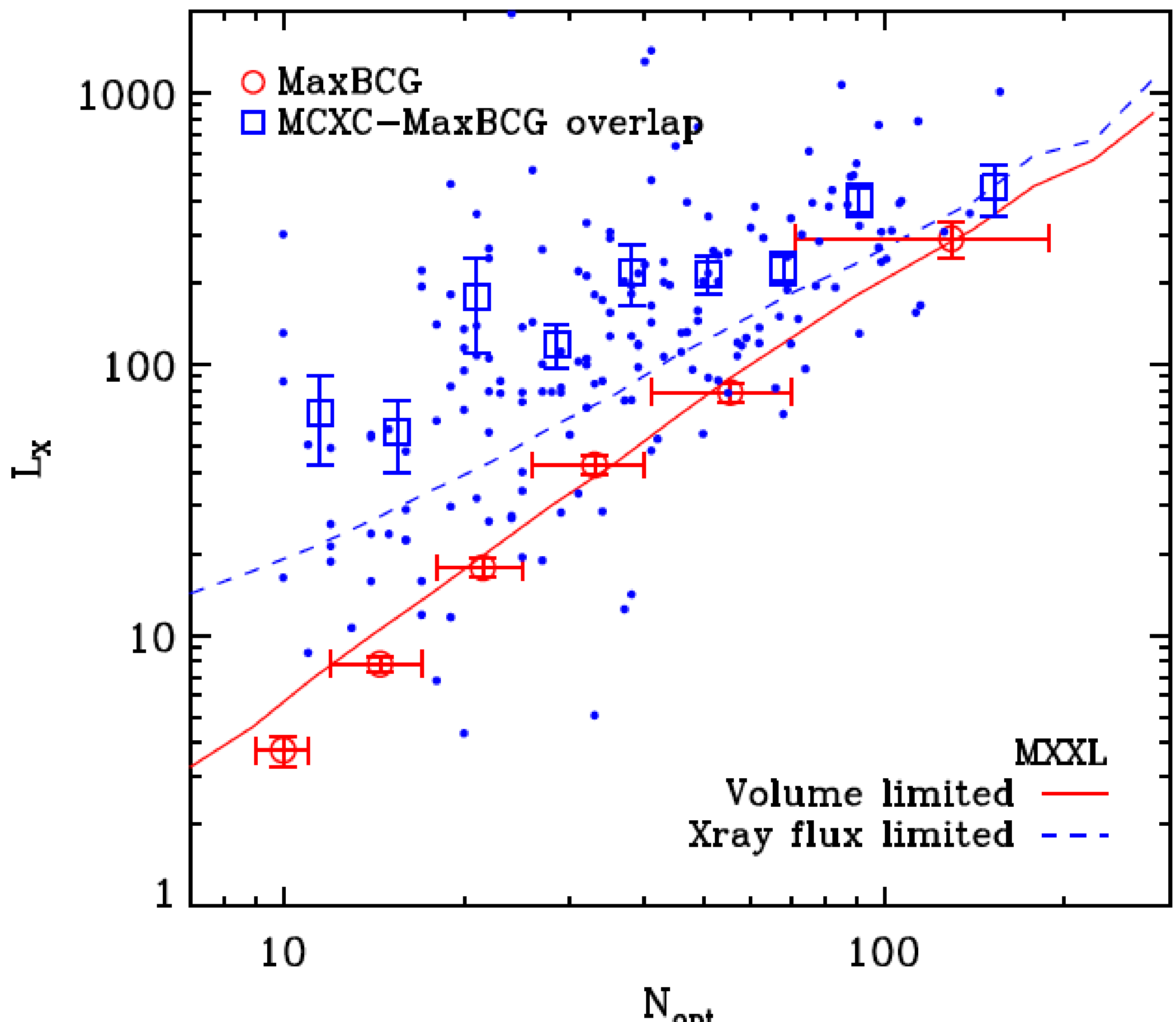
Angulo et al 2012





Scaling relations for maxBCG clusters

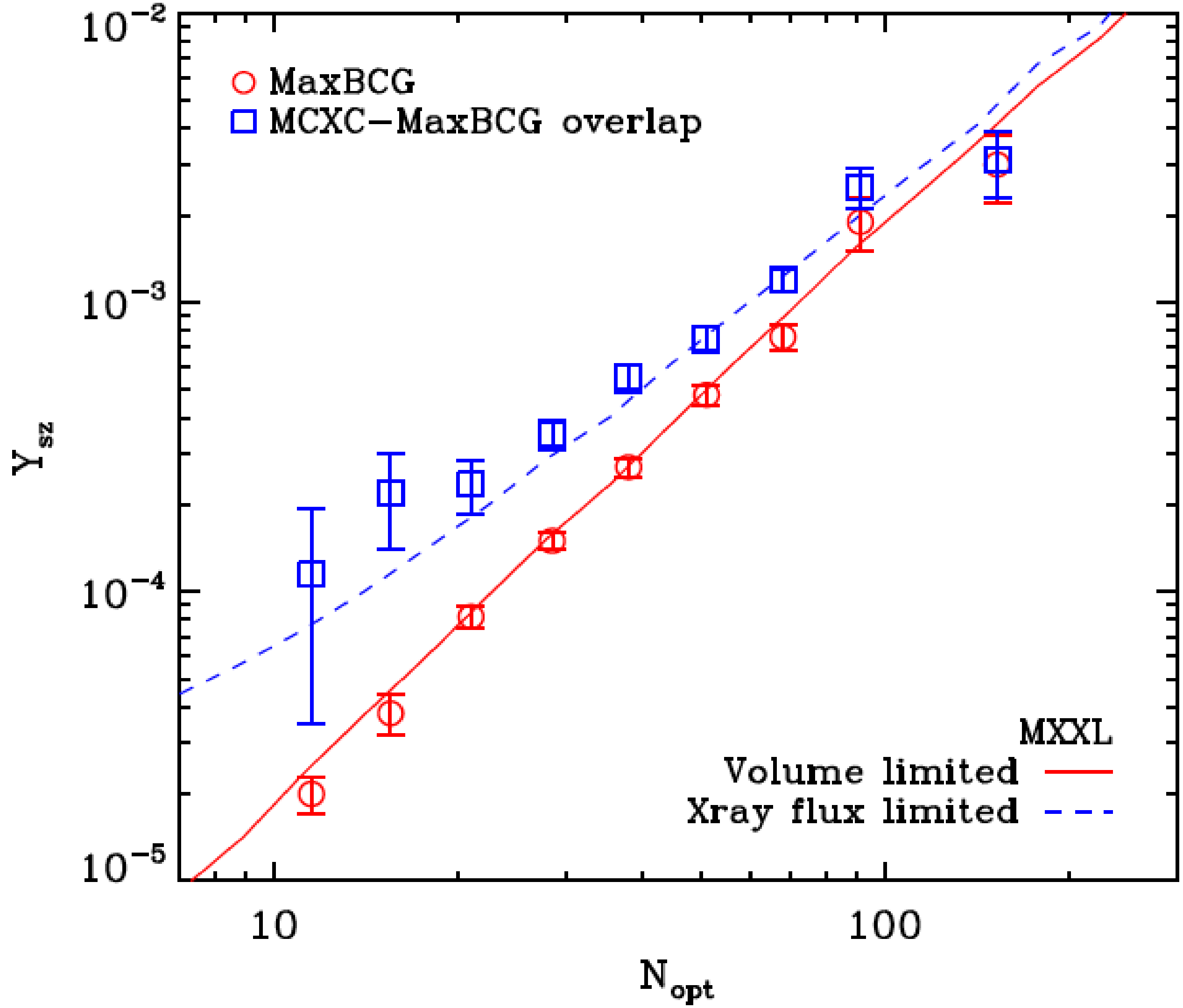
Clusters in the maxBCG catalog which are also in the MCXC catalog of X-ray clusters are systematically X-ray bright



Angulo et al 2012

Scaling relations for maxBCG clusters

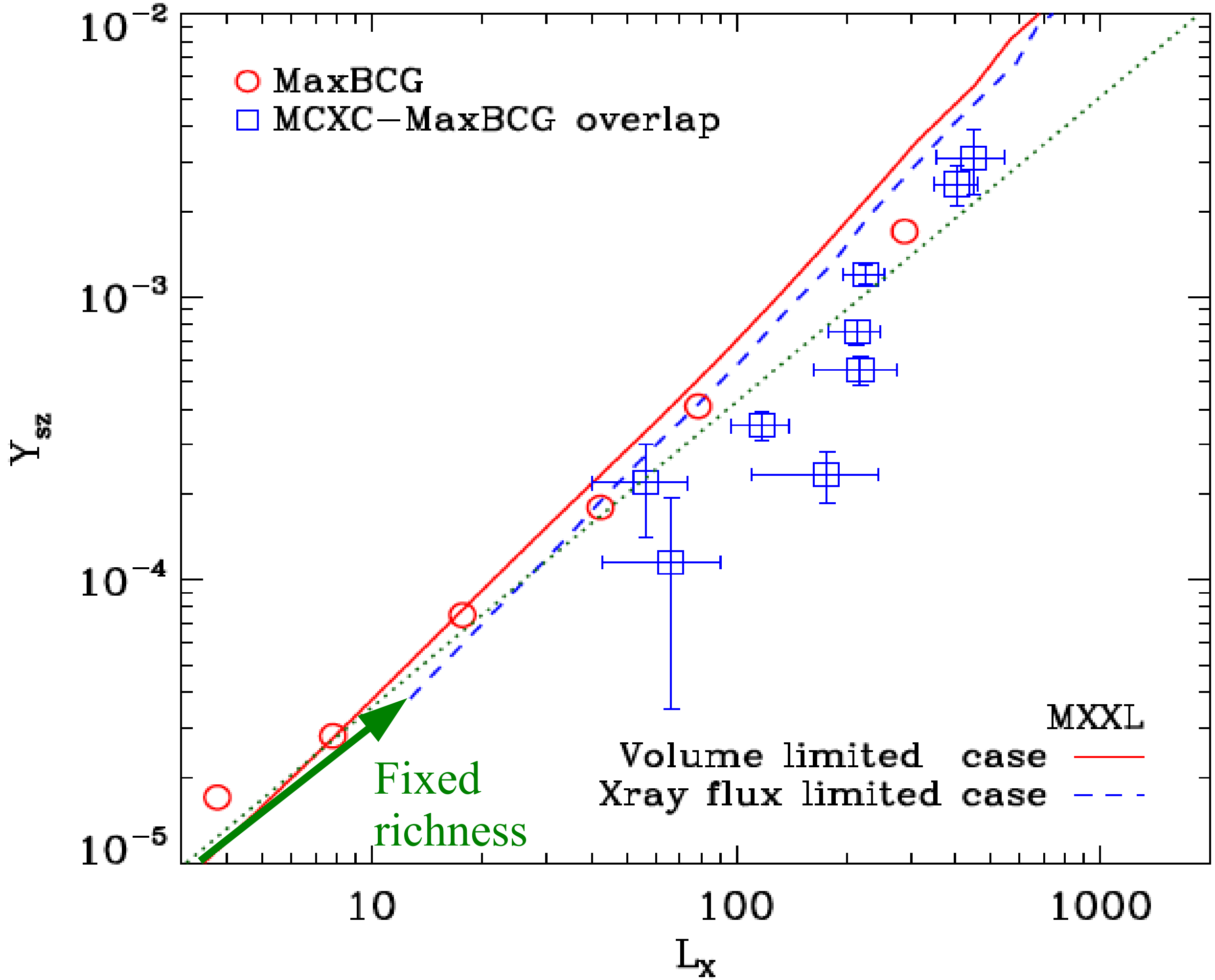
Clusters in the maxBCG catalog which are also in the MCXC catalog of X-ray clusters are also SZ bright. This is a result of transference of Malmquist bias



Angulo et al 2012

Scaling relations for maxBCG clusters

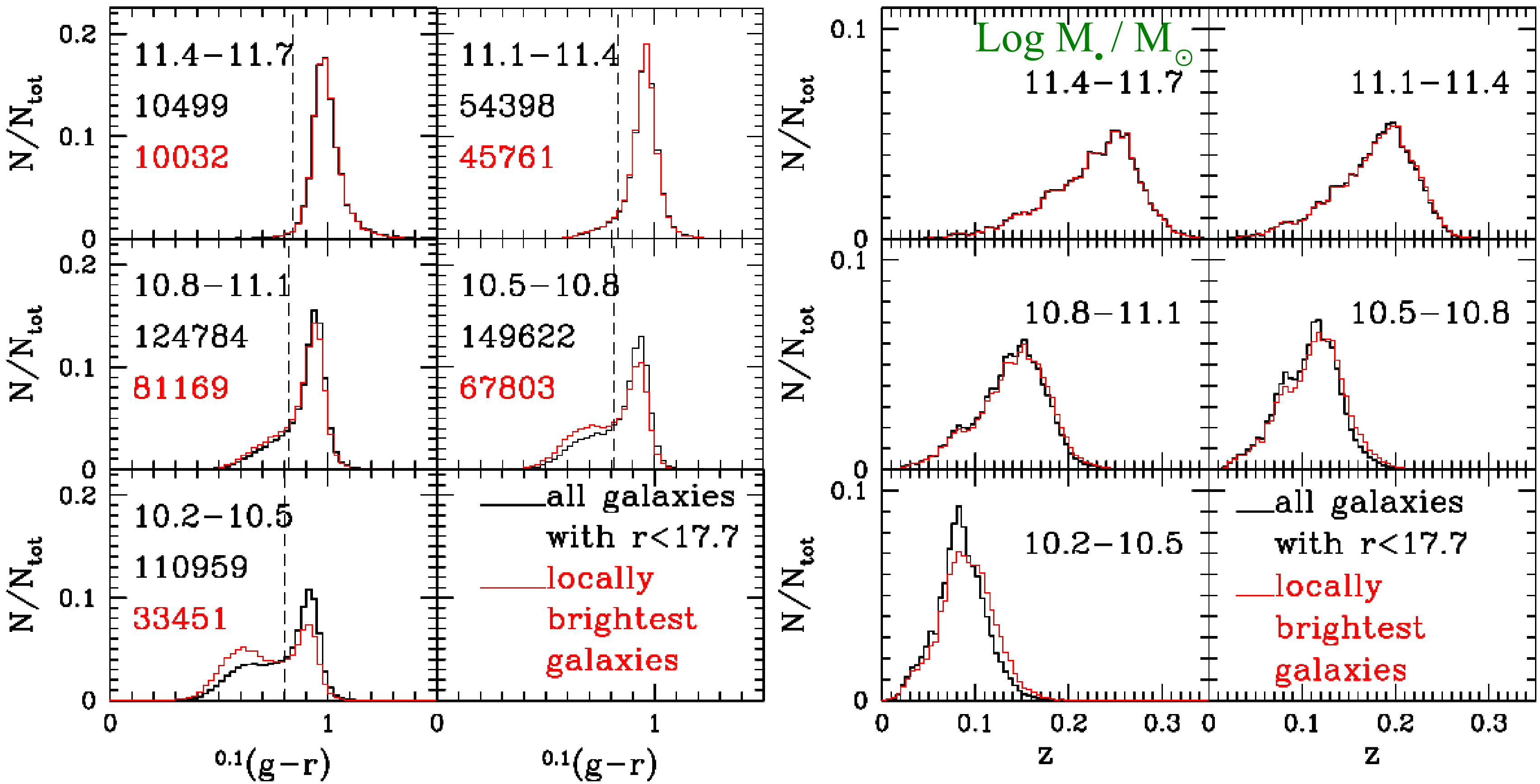
Clusters in the maxBCG catalog which are also in the MCXC catalog of X-ray clusters lie almost on the same L_X – Y relation as the rest of the sample. At given richness, X-ray selection increases both L_X and Y along the relation



Angulo et al 2012

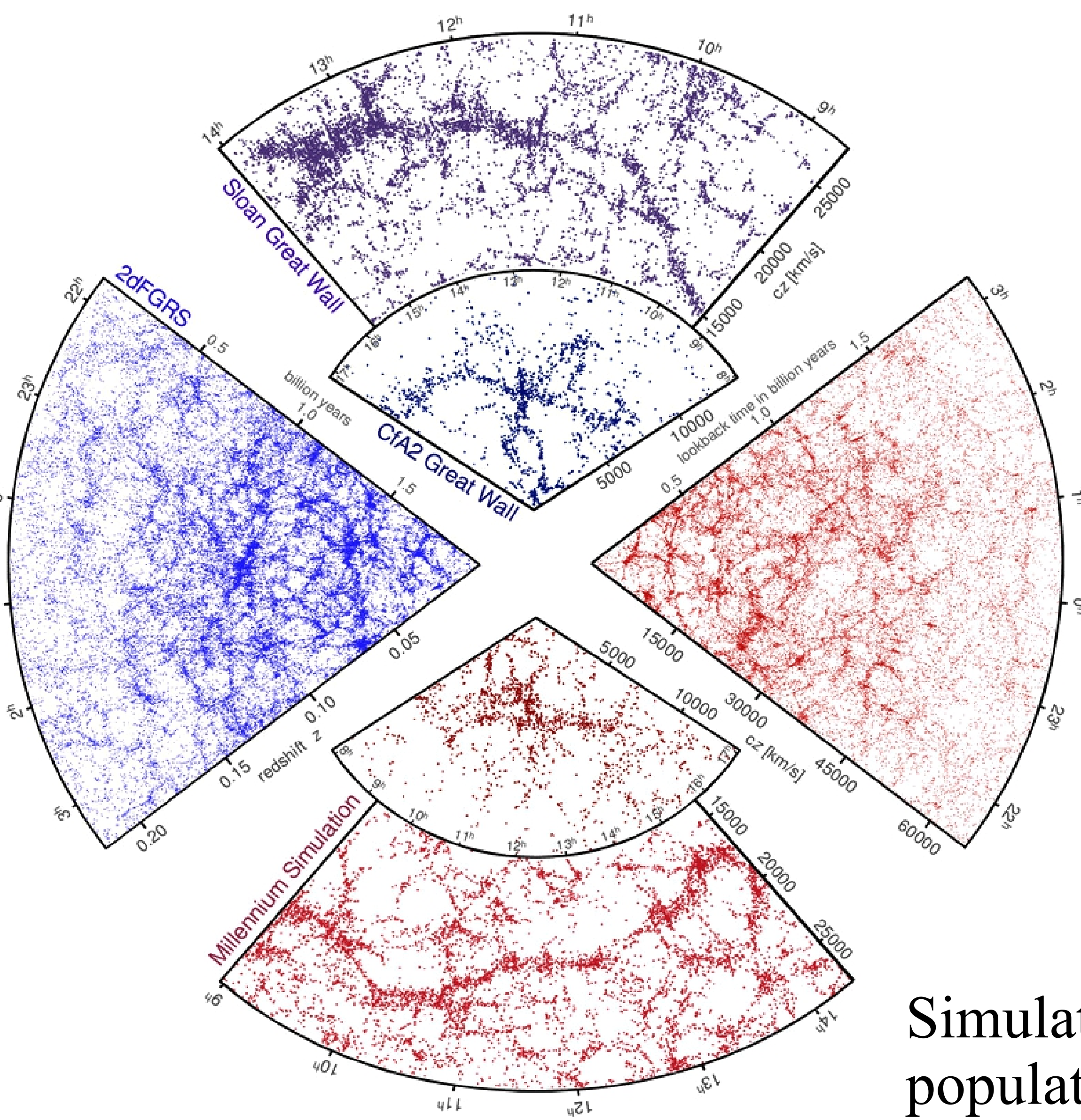
A complete sample of locally brightest galaxies

Planck Collaboration 2013: PIP-XI

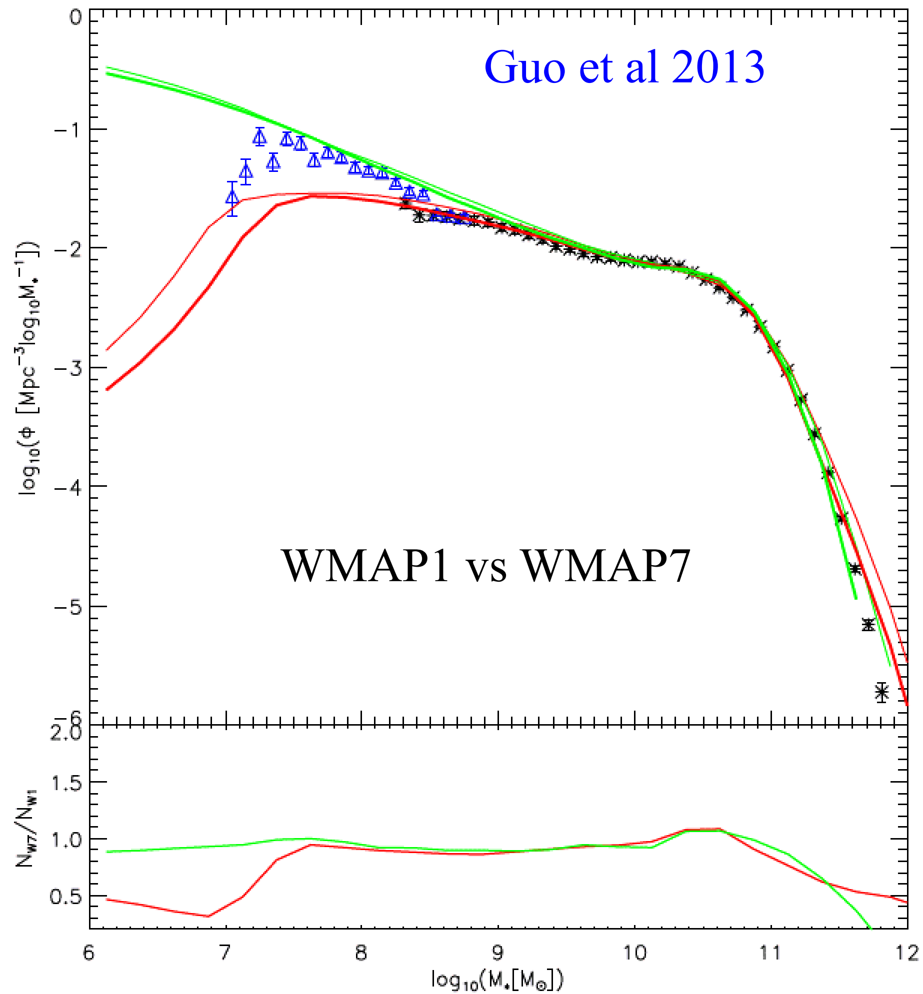


All SDSS/DR7 galaxies in the main spectroscopic sample with:
r < 17.7 (extinction-corrected Petrosian mag.), $z > 0.03$, and no brighter companion with $\Delta r_p < 1$ Mpc, $|c\Delta z| < 1000$ km/s in either the spectroscopic or photometric catalogues

Galaxy population simulations as calibrators



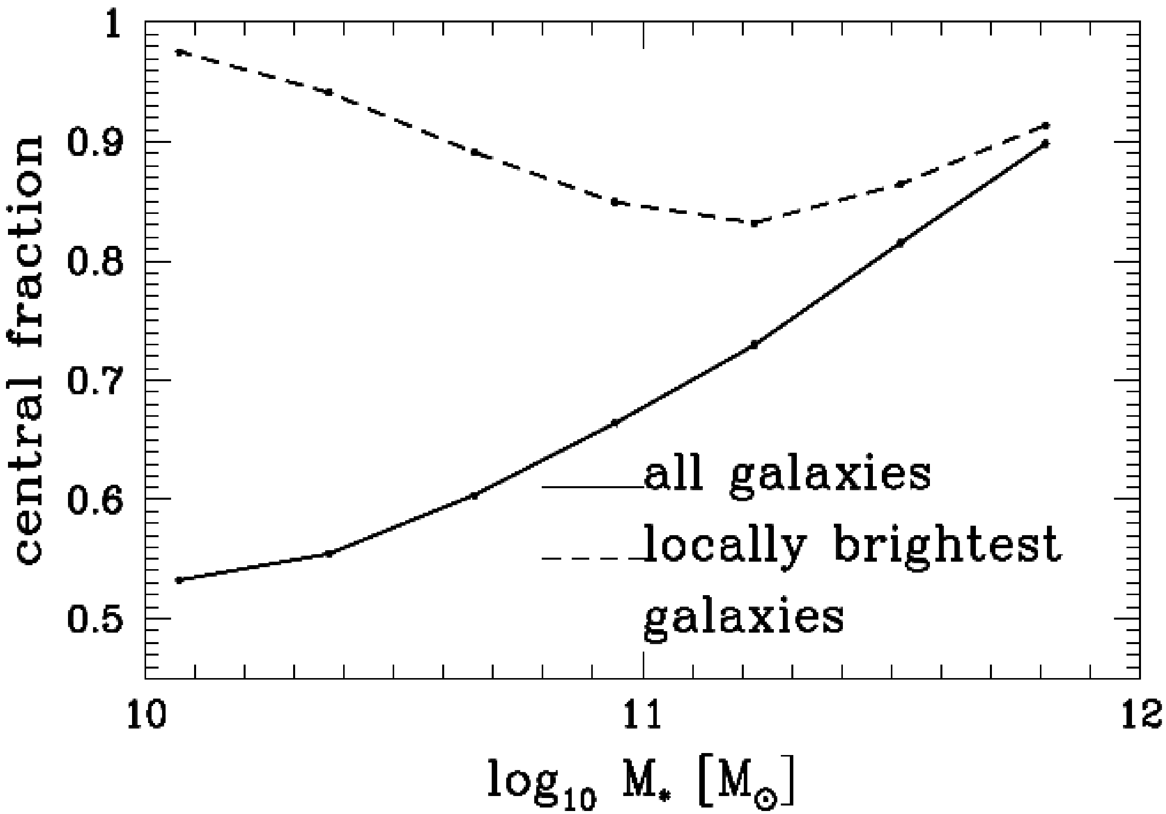
Springel et al 2006



Simulations of the formation of the galaxy population can reproduce the abundance and clustering of galaxies in any viable ΛCDM cosmology (here WMAP7)

LBG's are predominantly halo central galaxies

Planck Collaboration 2013: PIP-XI



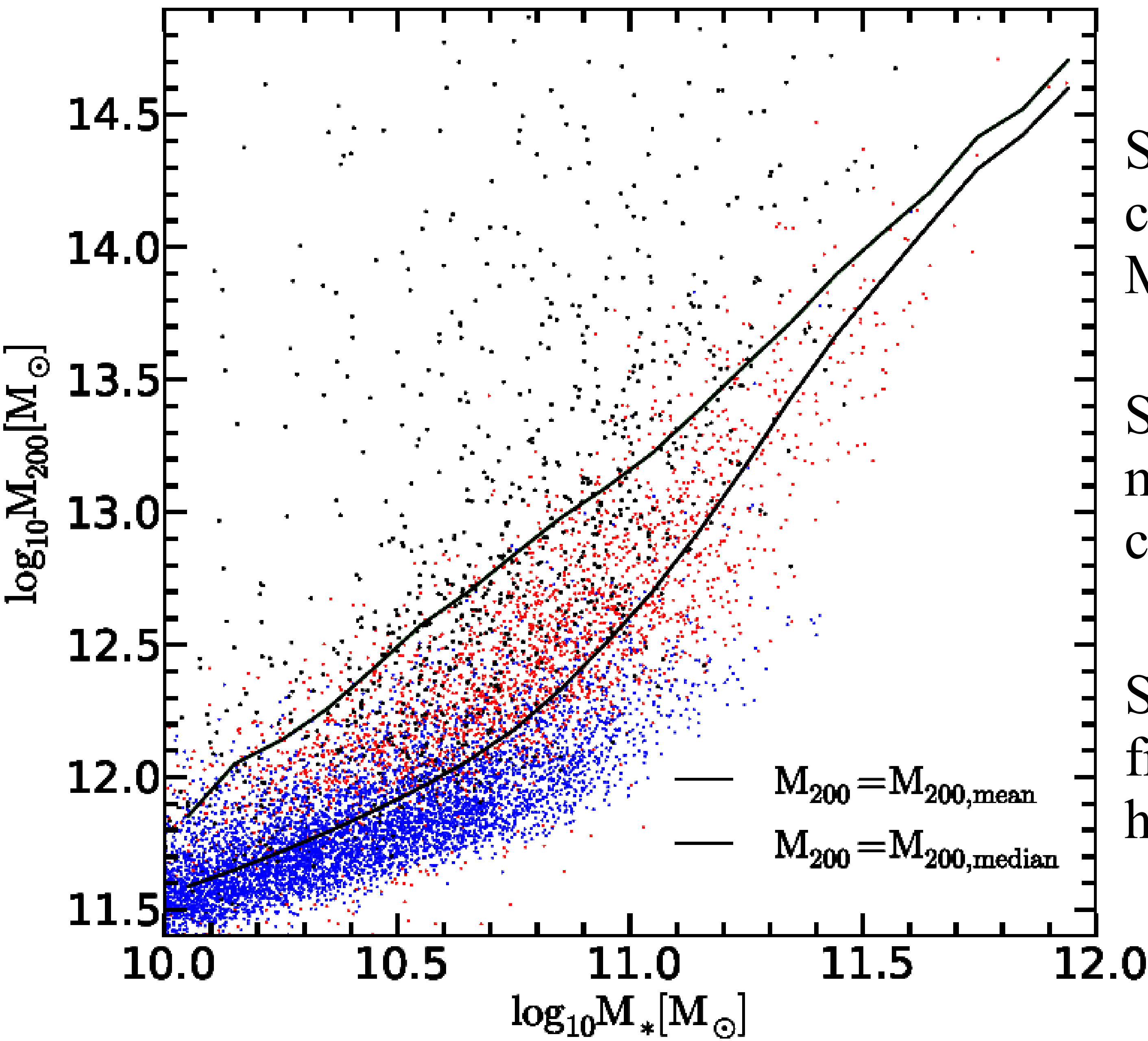
LBG's selected according to the observational criteria in a mock catalogue constructed from the Guo et al (2012) model of galaxy formation in the Millennium Simul'n (scaled to WMAP7)

At least 83% of LBGs are the central galaxies of their dark haloes

2/3 of the rest are <u>brighter</u> than the central galaxy of their halo

LBG stellar mass is related to halo mass

Planck Collaboration 2013: PIP-XI



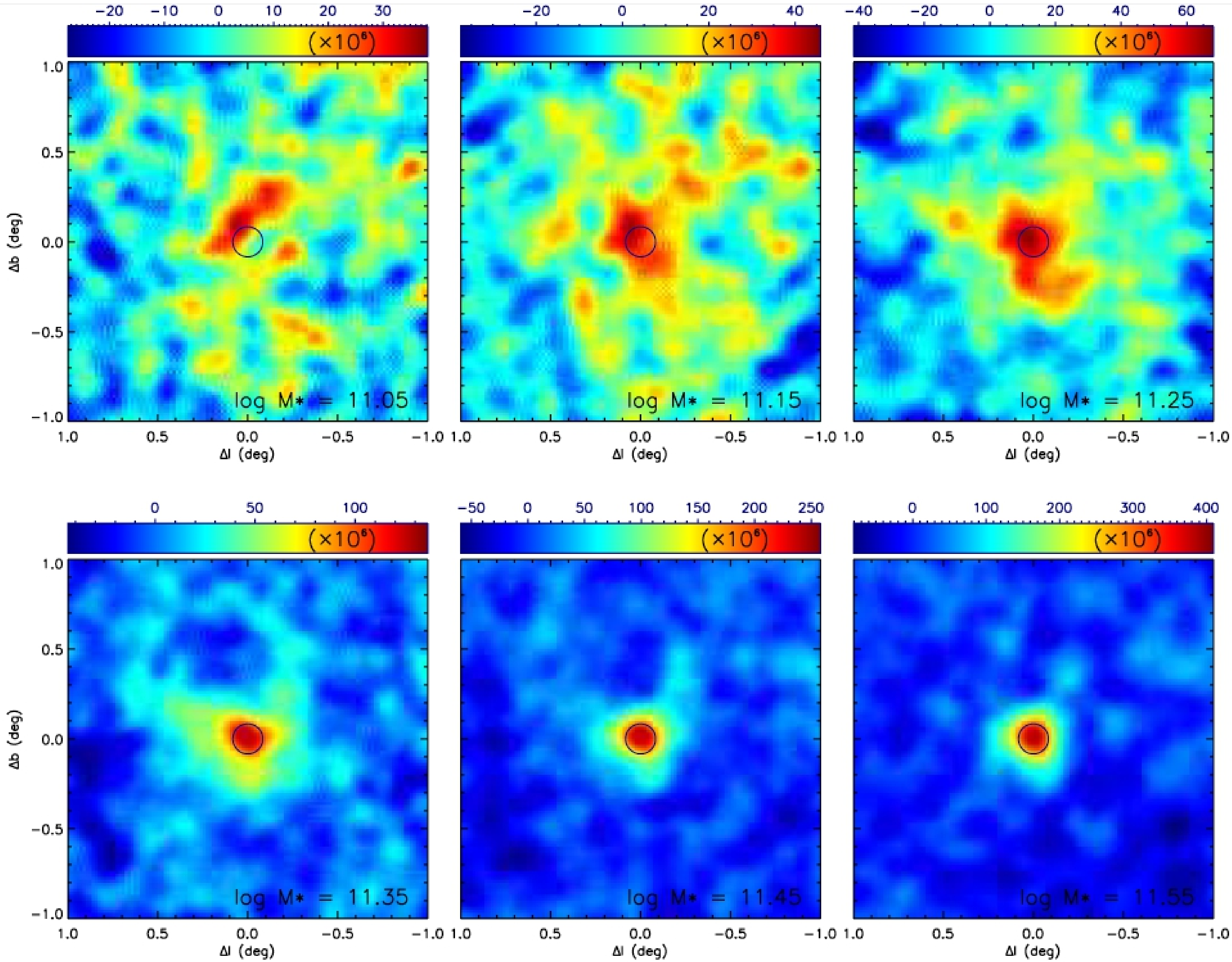
Star-forming and passive centrals lie on different M_* --M_h relations

Satellites tend to have more massive halos than centrals of the same M_*

Satellites are also offset from the centres of their halos

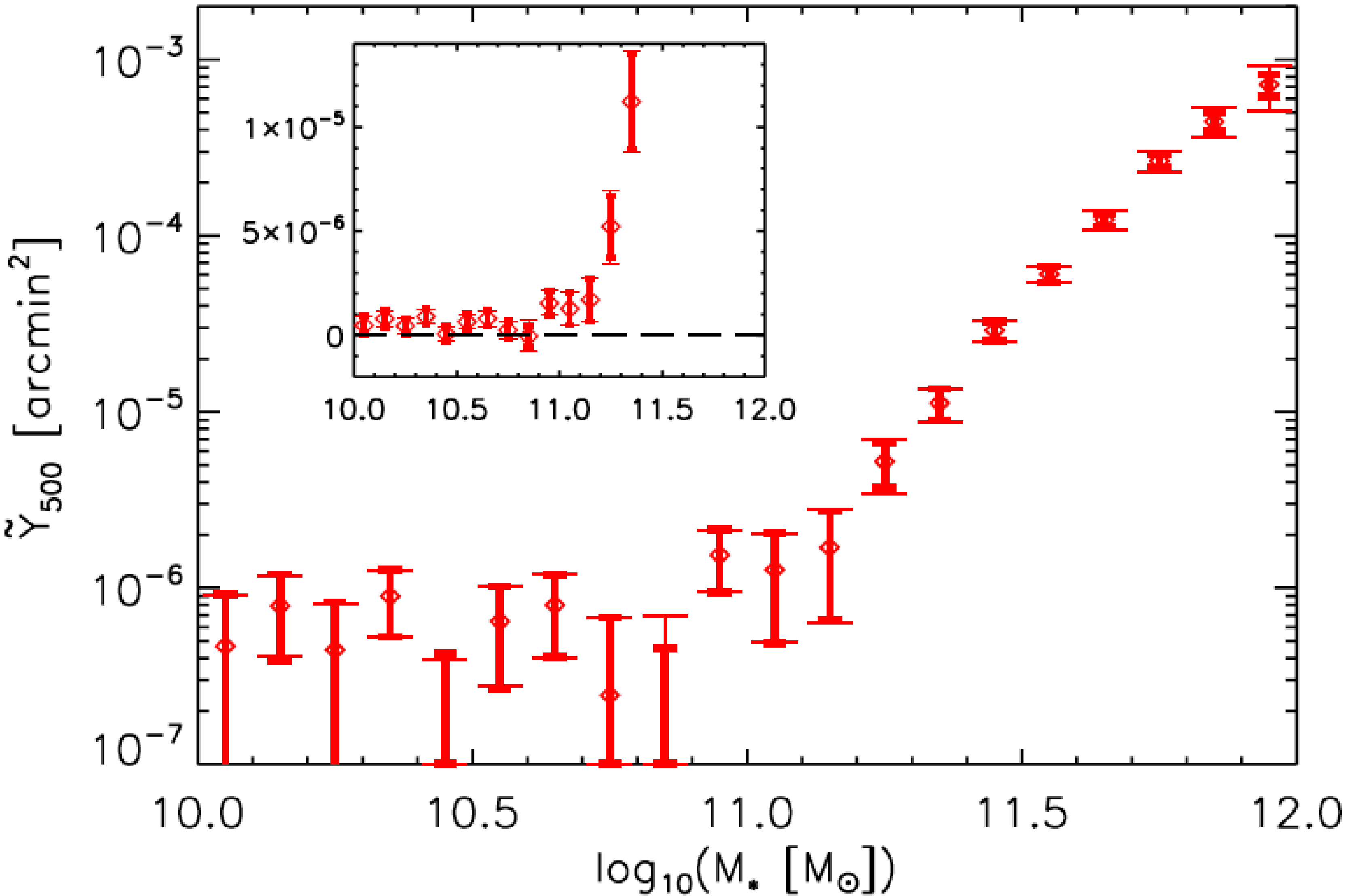
Stacked Planck y-maps for LBGs

Planck Collaboration 2013: PIP-XI



Mean Y_{500} as a function of M_* for LBGs

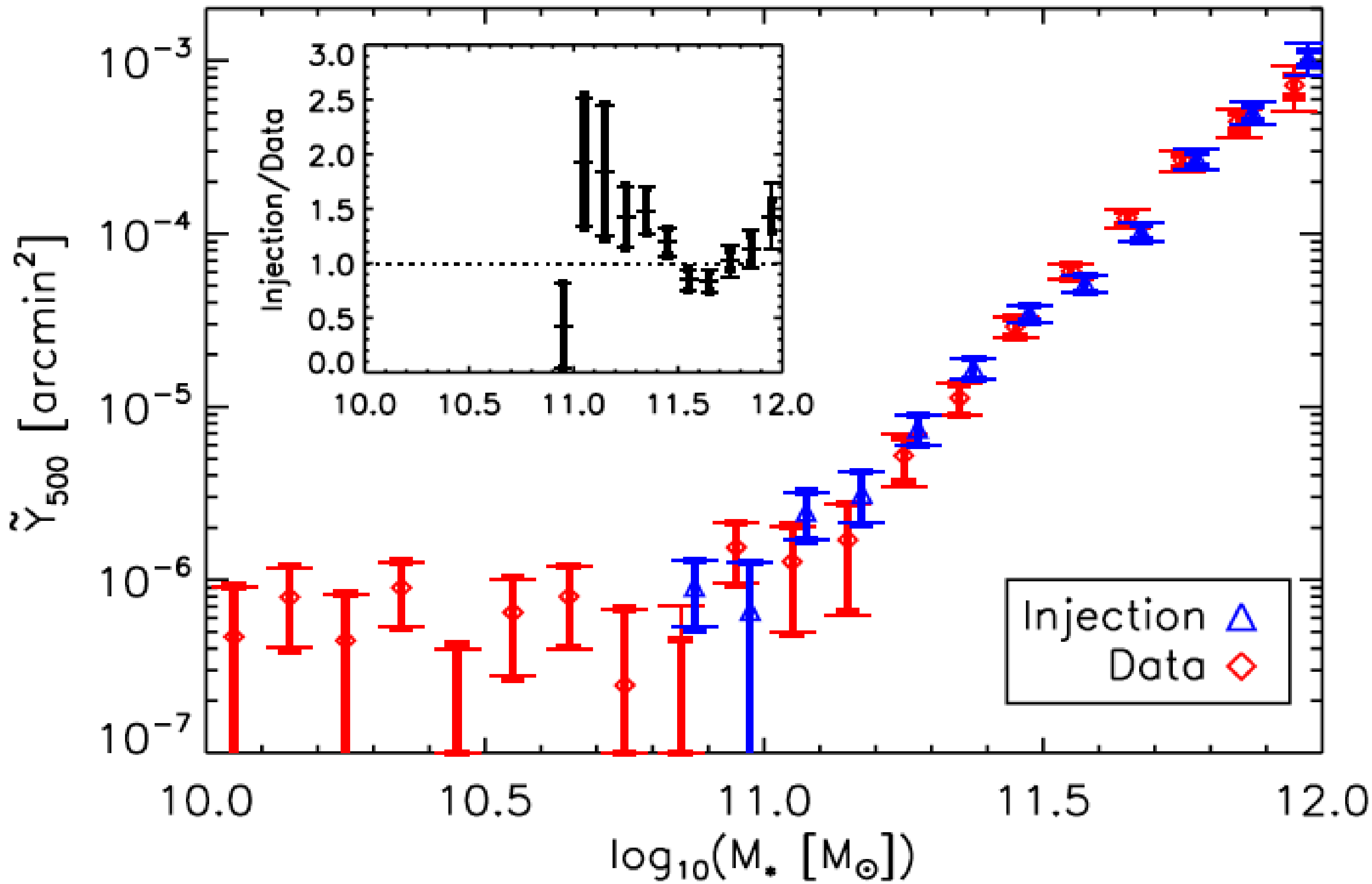
Planck Collaboration 2013: PIP-XI



Signal is detected down to $\log M_* / M_\odot \sim 11.0$

Mean Y–M_* expected for self-similar Y–M_h

Planck Collaboration 2013: PIP-XI



To each real LBG assign a random mock LBG of the same M_*

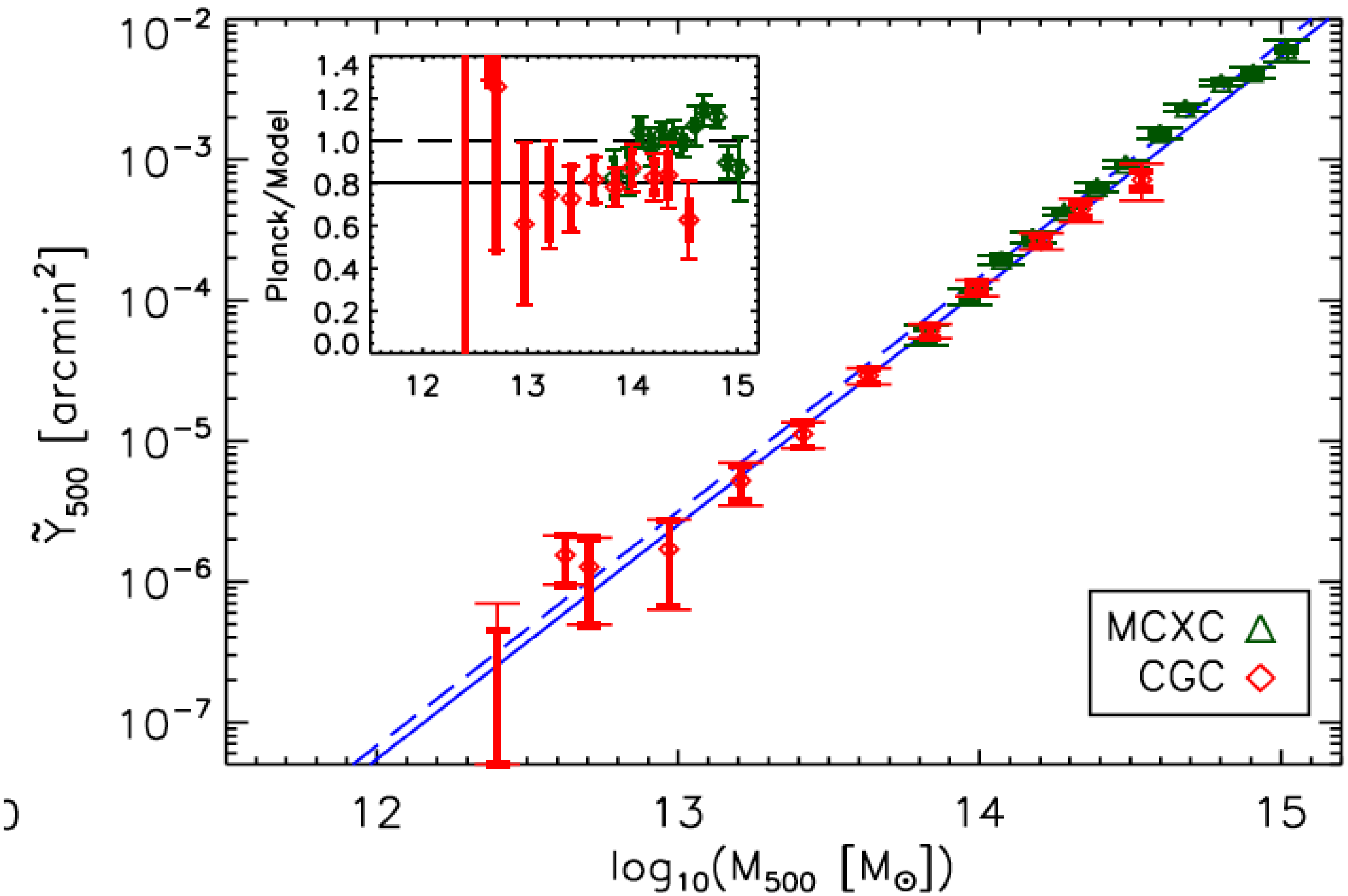
Use offset and M_h of mock LBG with $Y = A\, M_h^{\beta}$ + A10 profile

"Detect" using same filter as for observations, stack and compare

Fit for A and β → cosmic baryon fraction + self-similar β !

Inferred Y–M_h compared to X-ray cluster result

Planck Collaboration 2013: PIP-XI



LBG and MCXC results consistent to 20% – Malmquist bias in MCXC?
Scaling continues down to log M_h / $M_\odot$ ~ 12.5 <u>with no break</u>.
Planck has seen about 25% of all cosmic baryons in this SZ signal!

Conclusions

Cluster scaling relations and their evolution are the critical factor in using cluster abundances for cosmology

- Scatter in mass proxies can interact with sample selection to produce seriously biased results. The multi-dimensional scatter in the observables–mass relation must be fully modelled

Adopting a cosmology allows cluster physics to be studied

- By stacking LBGs, Planck detects Y down to $M_h \sim 10^{12.5}\, M_\odot$ with no break in the self-similar $Y - M_h$ scaling relation

- SZ-detected hot gas in halos accounts for ~25% of all baryons

- Future work should measure evolution in the $Y - M_h$ relation

Dependence of stacking on isolation criteria

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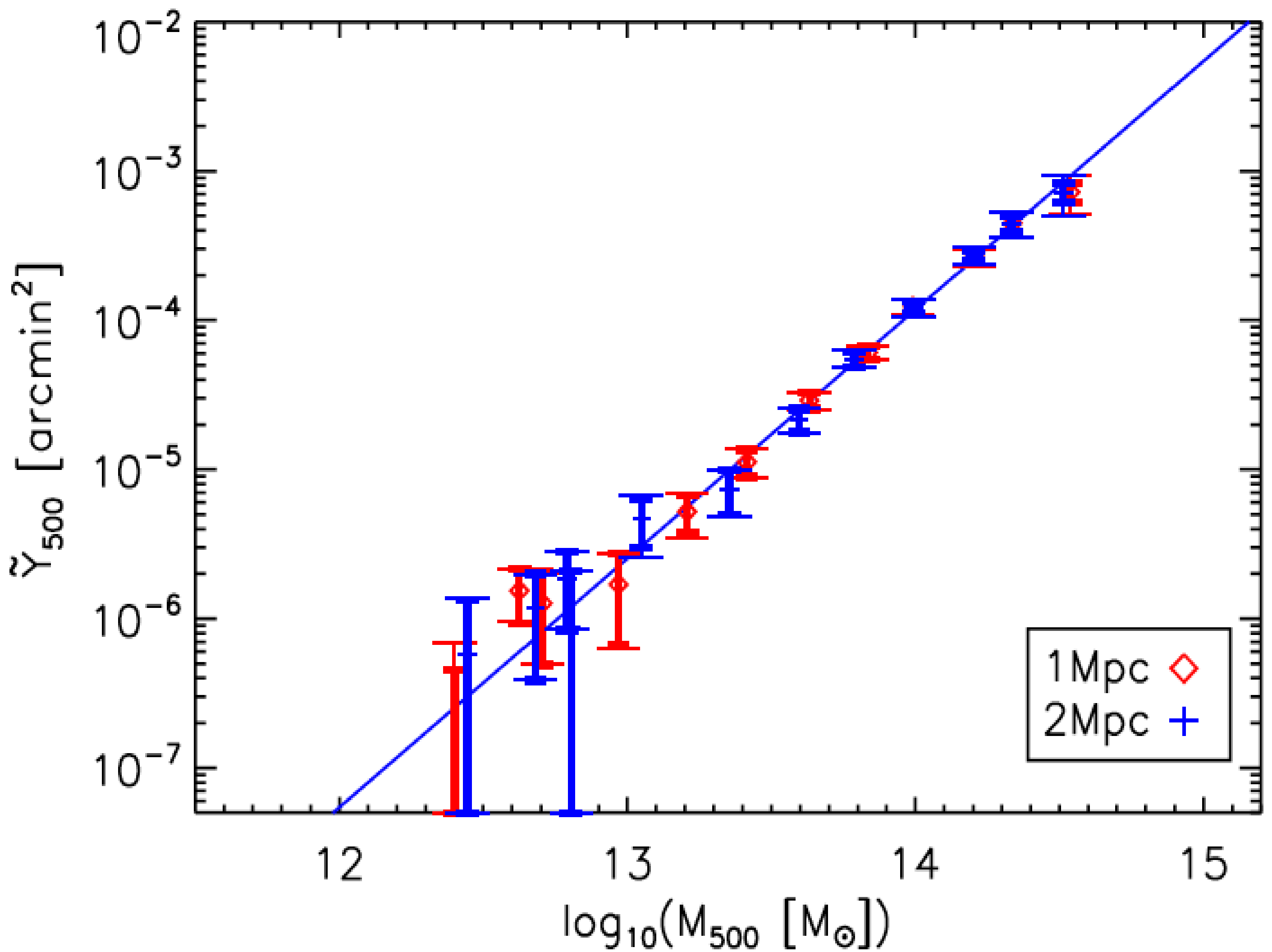

Changing LBG isolation criteria to $\Delta r_p < 2$ Mpc, $|c\Delta z| < 2000$ km/s has no systematic effect but reduces the sample, hence increases the noise

Halo mass distributions in bins of stellar mass

Planck Collaboration 2012: PIP-XI