The Legacy of *Planck* for Cluster Cosmology

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Things I Will Not Talk About

Gas content of massive galaxies (see Simon White's talk).

Physics of the intra-cluster medium in nearby galaxy clusters (Planck 2012, Int. Res. Paper X).

Detection of gas bulk-flows via kSZ (Planck 2015, paper XXXVII).

- opens the door to constraining modified gravity models with kSZ data (also talk by Michael Niemack's talk).

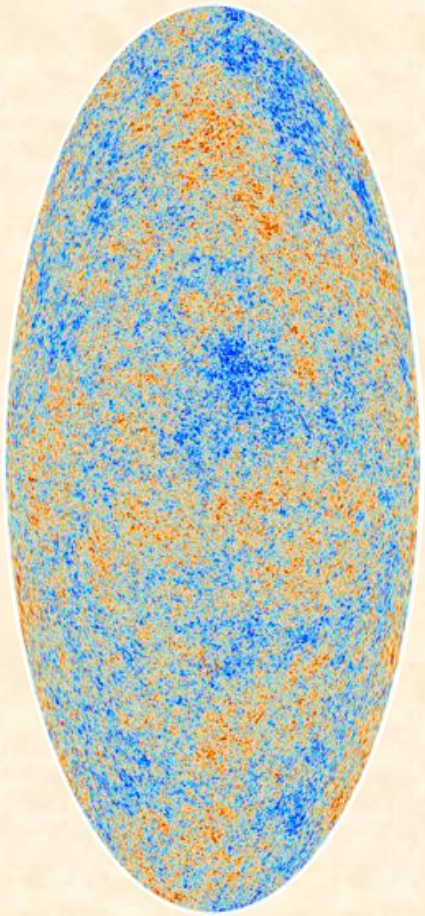
Identification of high z (z=2-4) protoclusters.
(Planck 2012, Int. Res. Paper XXVII, also talk by Hervé.Dole).

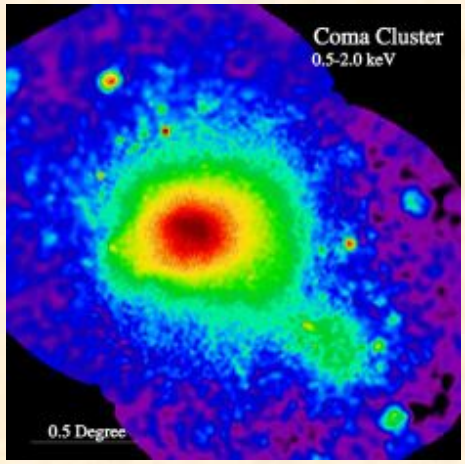
and more…

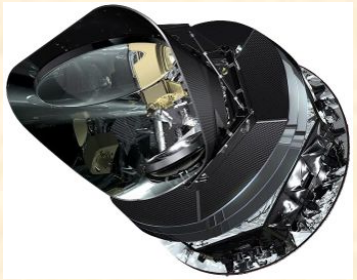
Focus on cluster studies with SZ effect.

Planck as an *SZ* Experiment

Planck detects galaxy clusters through the SZ effect.







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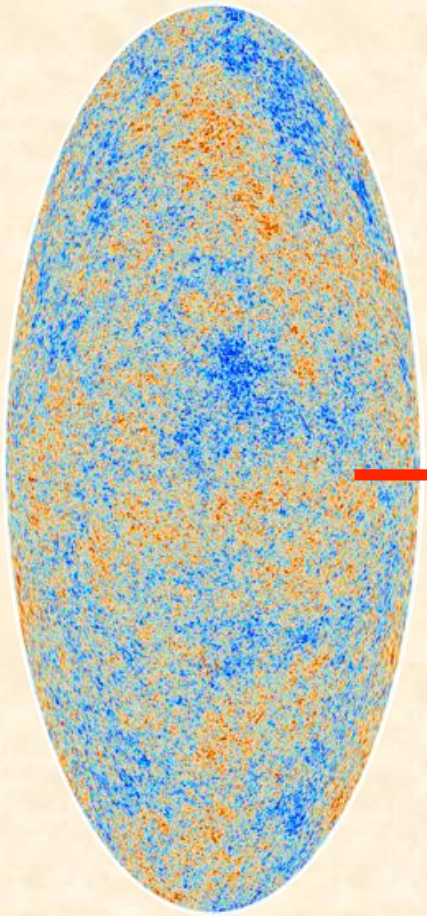
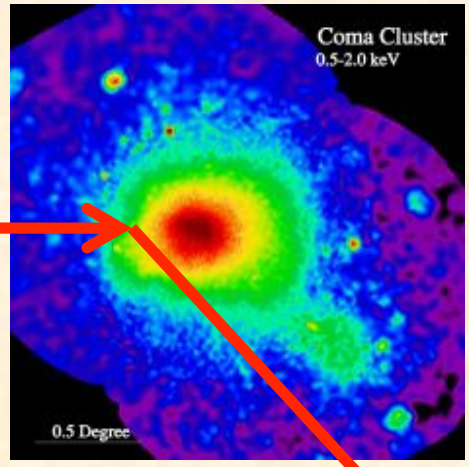
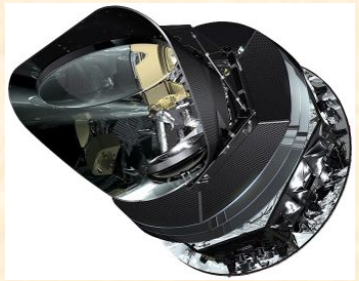
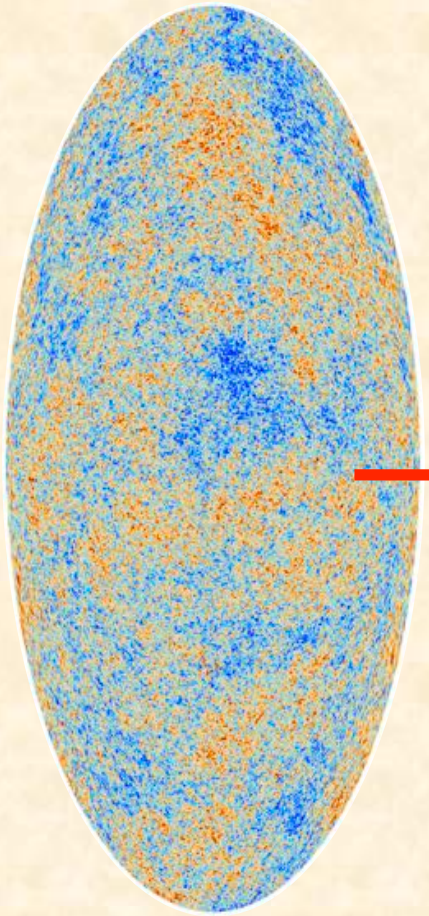


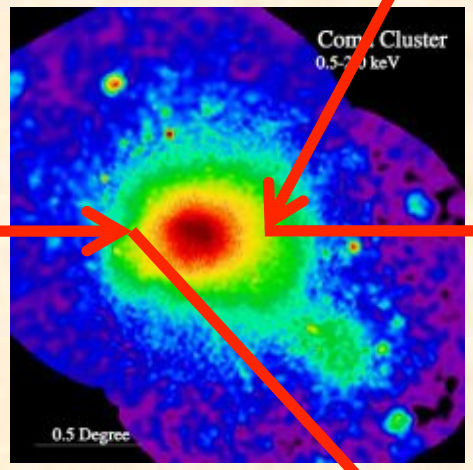


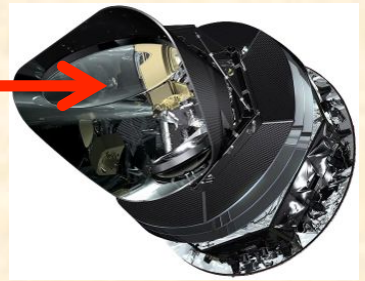


Net effect:

A fraction of the photons arrive with higher energy.







The *SZ* Effect

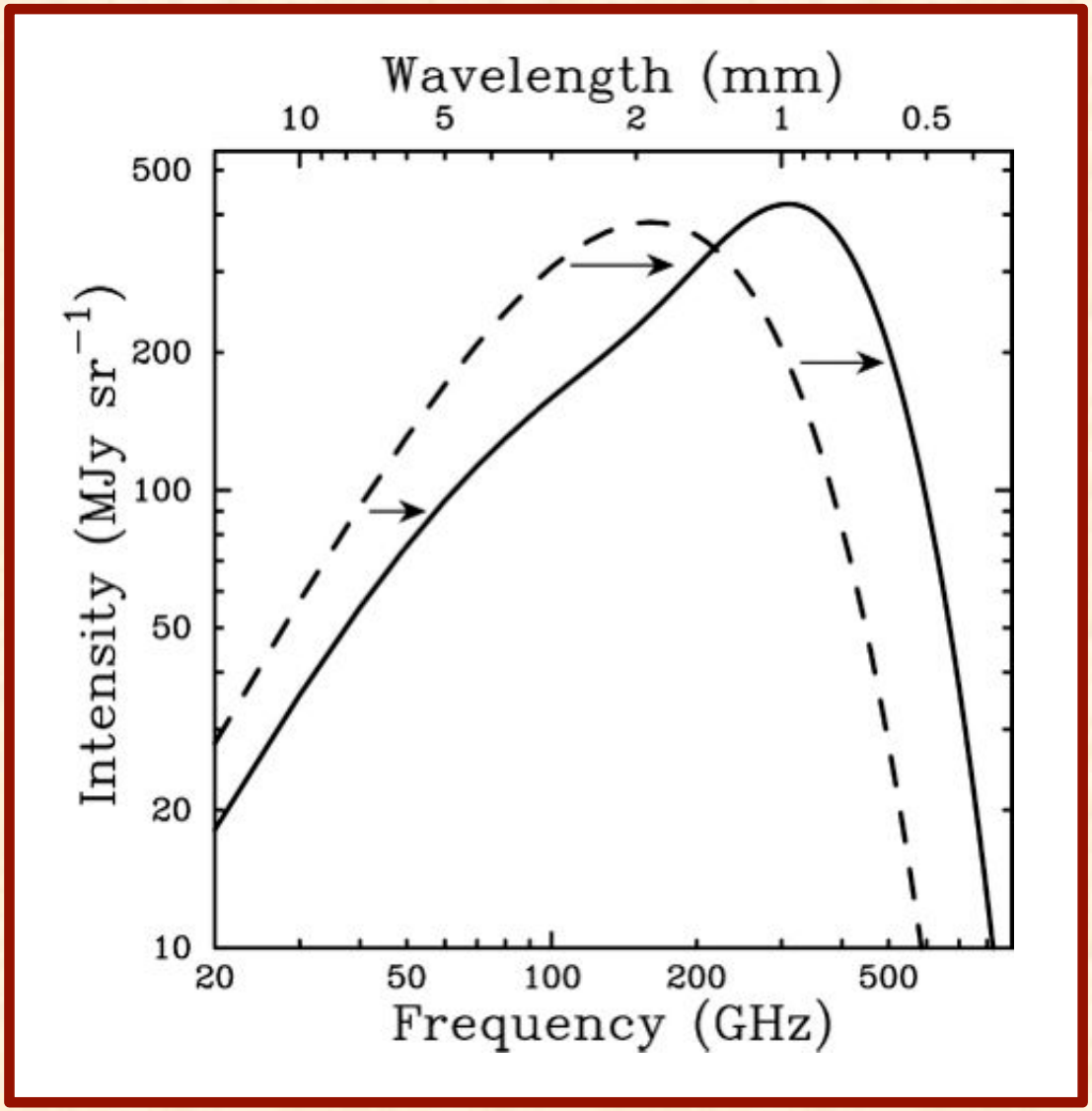
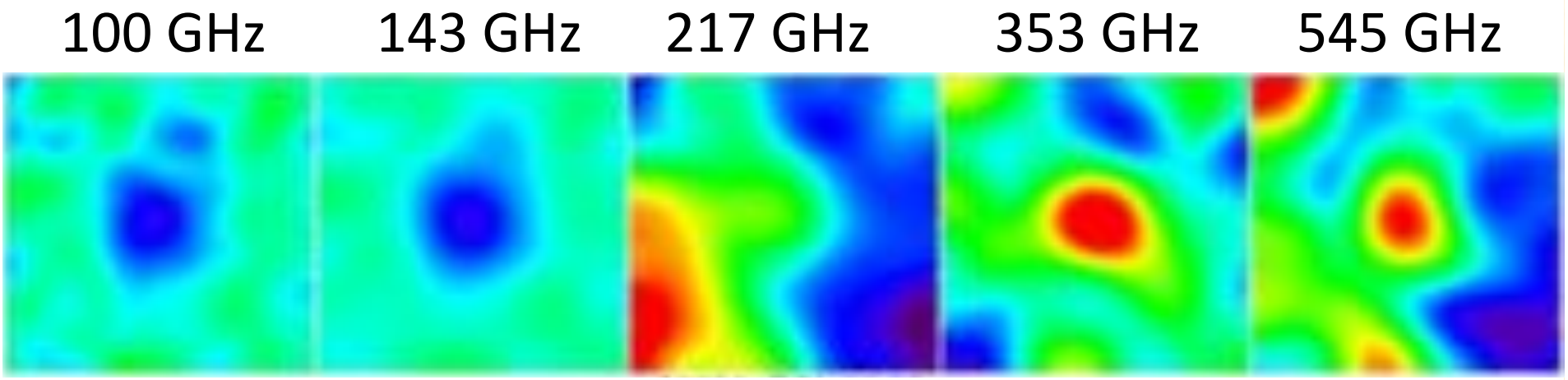


Figure courtesy of Erik Reese.

The *SZ* Effect

Abell 2256



Planck collaboration 2011

Planck in the Context of Other SZ Experiments

Planck is not the only SZ data set today.

Planck in the Context of Other SZ Experiments

Planck and ACT/SPT are highly complementary.

ACT/SPT

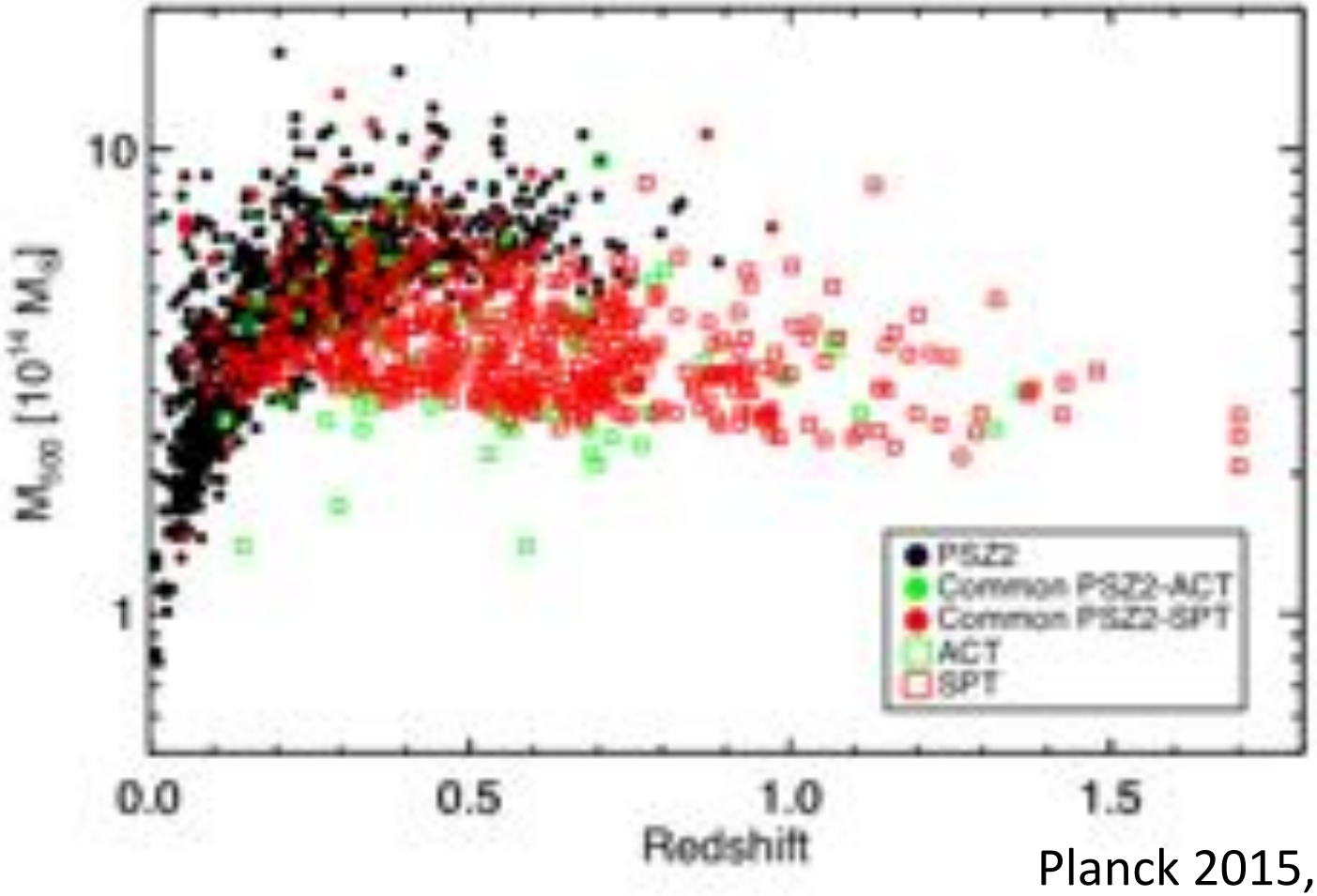
- Lower noise.
- Higher resolution.
- Higher redshift reach.

Planck

- Better frequency coverage
- All sky.
- Better overlap with existing data sets.
- Largest cluster catalog.

Planck in the Context of Other SZ Experiments

Selection is highly complementary.



Planck 2015, paper XXVII

Progress in SZ Cluster Detection is Astounding!

2009	SPT reports the first blind detection of clusters in SZ (Staniszewski et al. 2009).
2011	Planck releases its Early SZ cluster catalog: 189 cluster candidates. SPT/ACT have each detected tens of clusters.
2015	Planck releases its 2nd cluster catalog. 1653 detections. SPT/ACT each have several hundred detections.

A Multi-Wavelength view of Galaxy Clusters with Planck

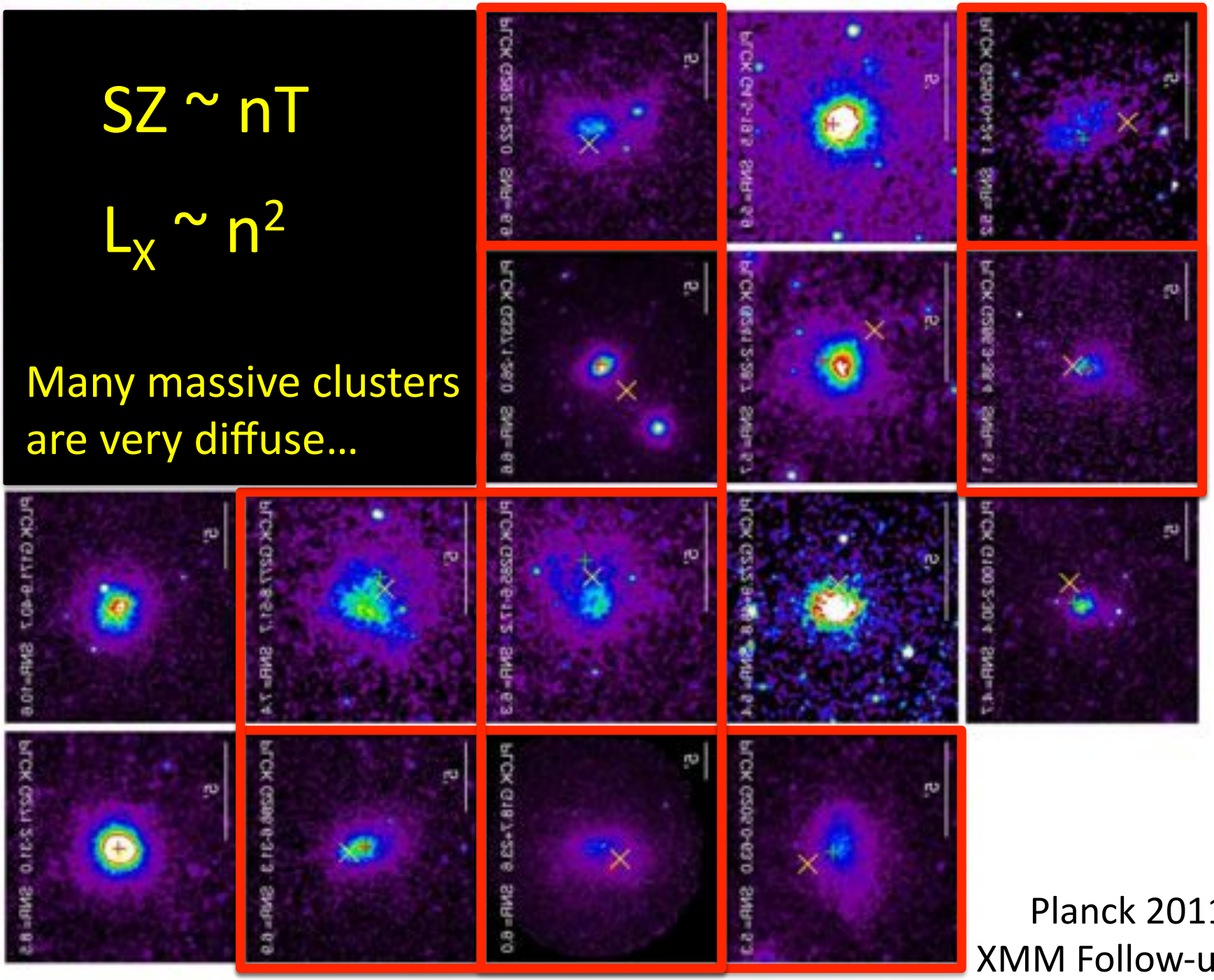
Planck 2011:
XMM Follow-up

Planck 2011:
XMM Follow-up

$SZ \sim nT$

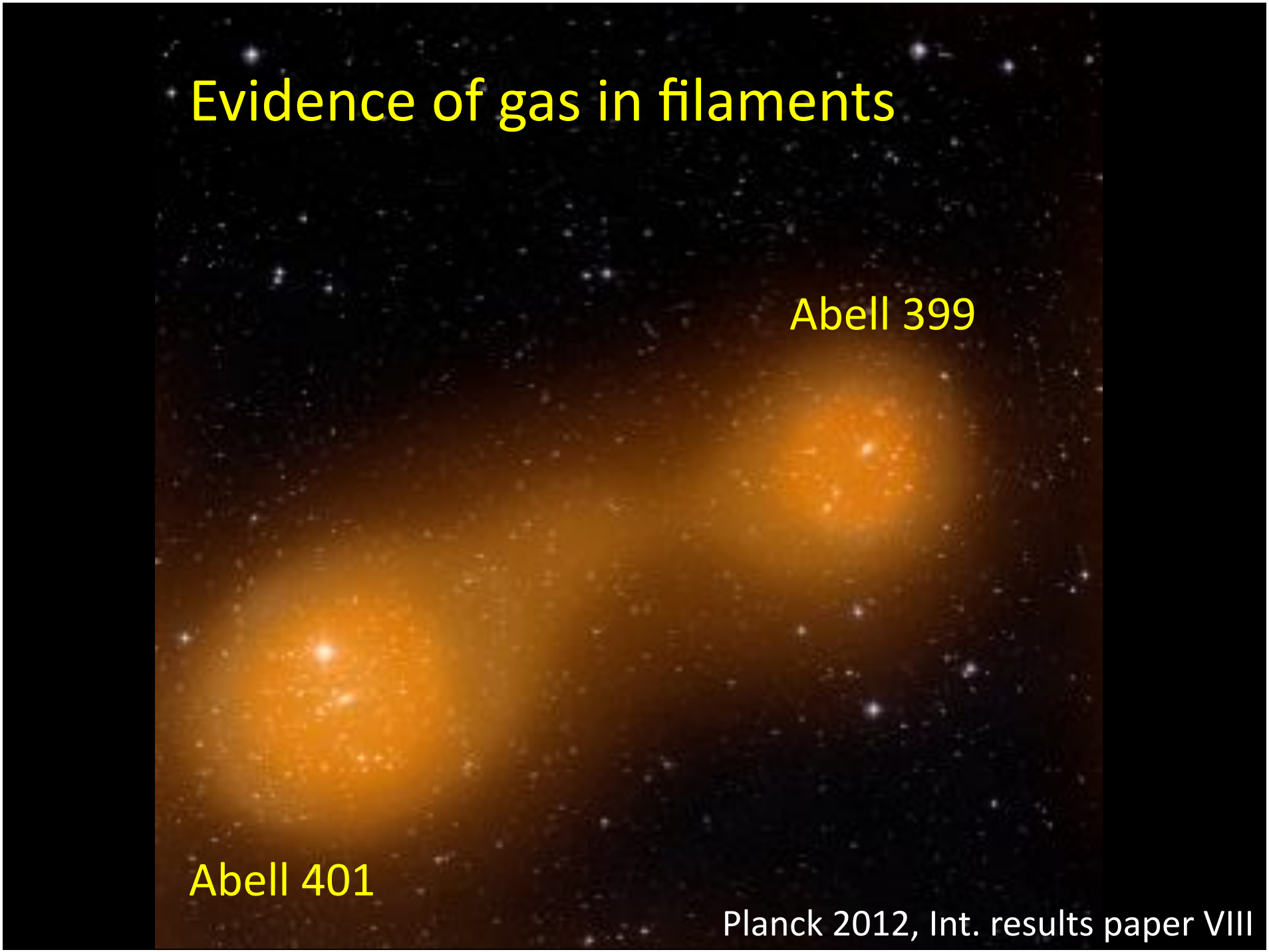
$L_X \sim n^2$

Many massive clusters are very diffuse…



Planck 2011:
XMM Follow-up

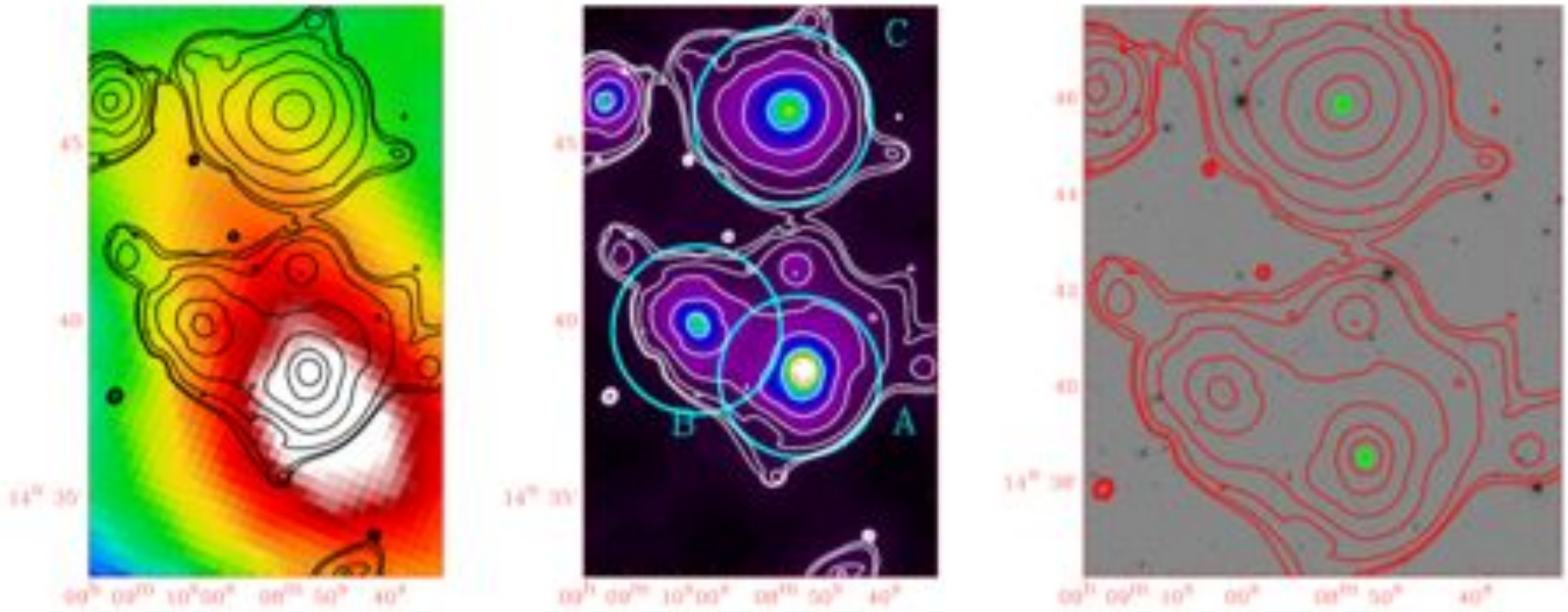
Evidence of gas in filaments



Planck 2012, Int. results paper VIII

Dynamically Interesting Objects

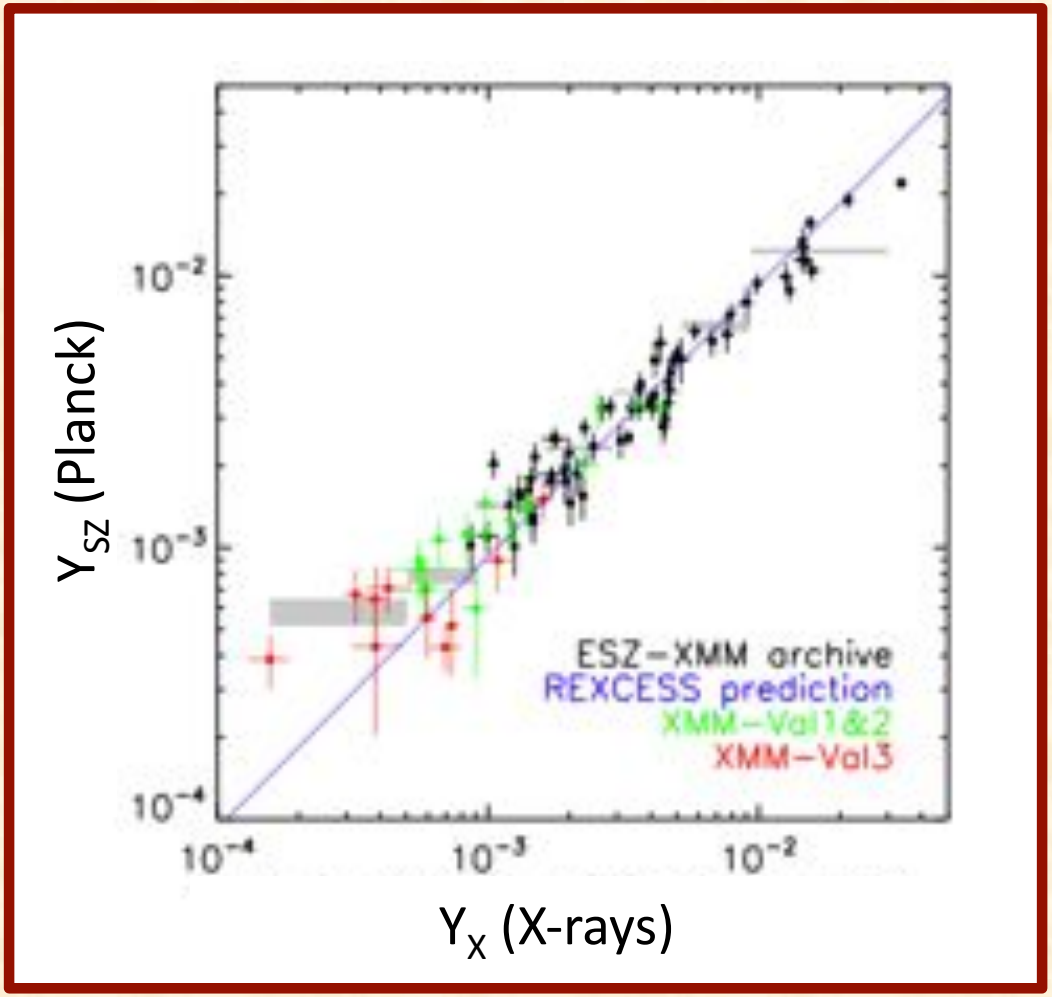
PLCKG214.6+37.0: The Birth of a Massive Galaxy Cluster



Planck 2012, Int. Res. Paper VI

Cluster Scaling Relations

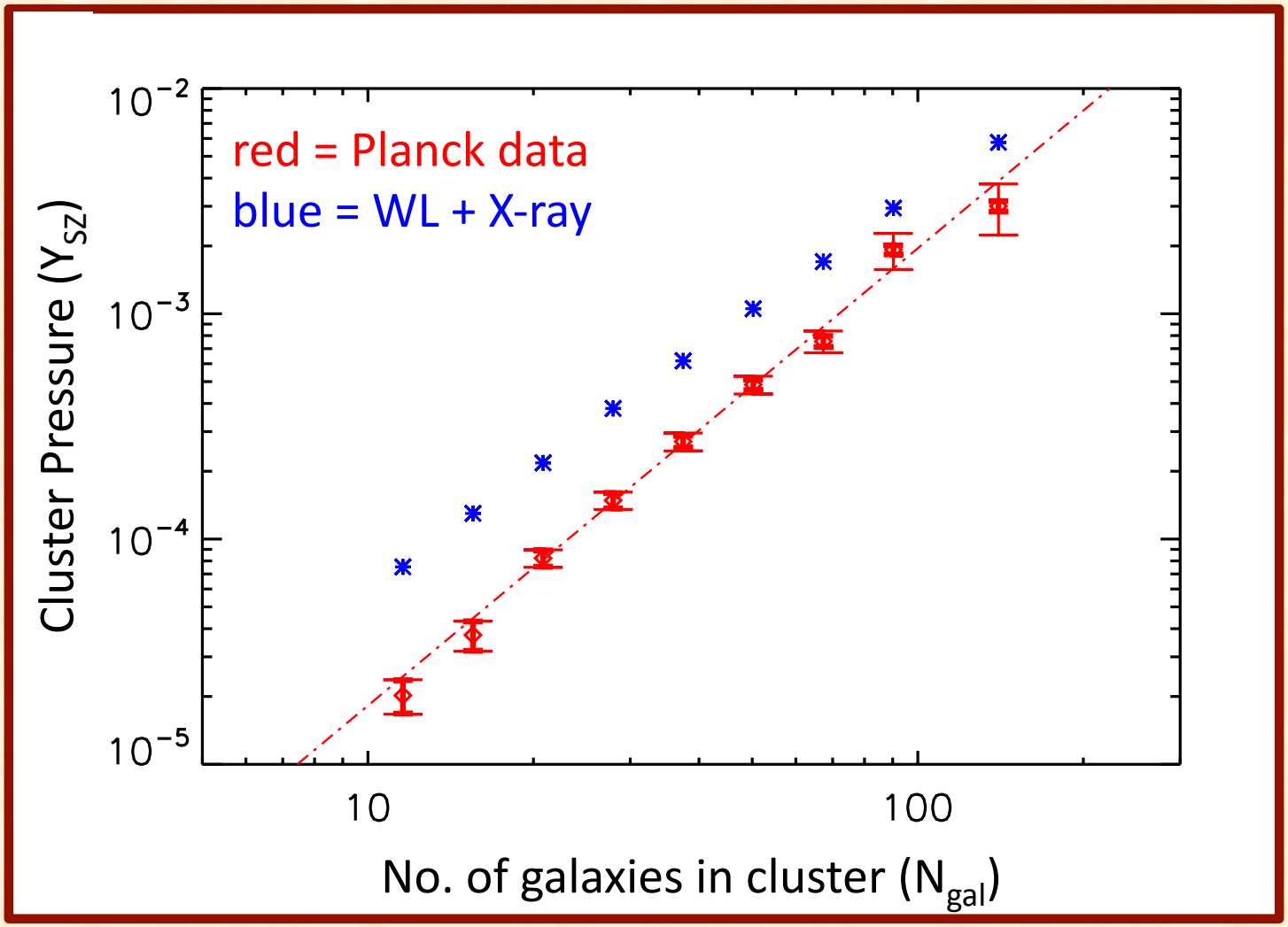
X-ray and SZ give consistent pictures of the intra-cluster gas.



Planck 2012, Int. Res. Paper I

Interesting Puzzle!

Comparison to optical clusters reveals tension.



Planck 2011, Optical Scaling Relations

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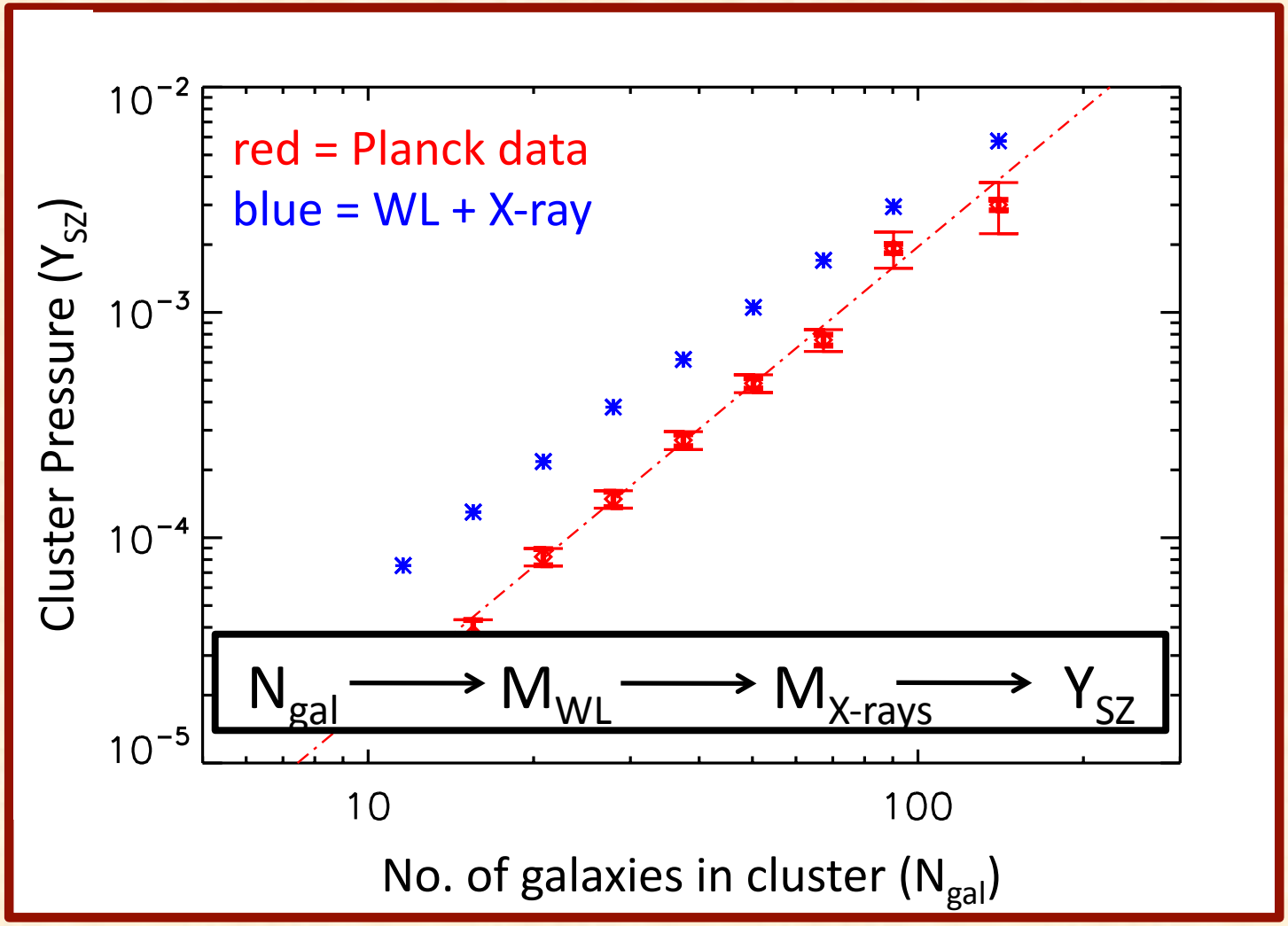
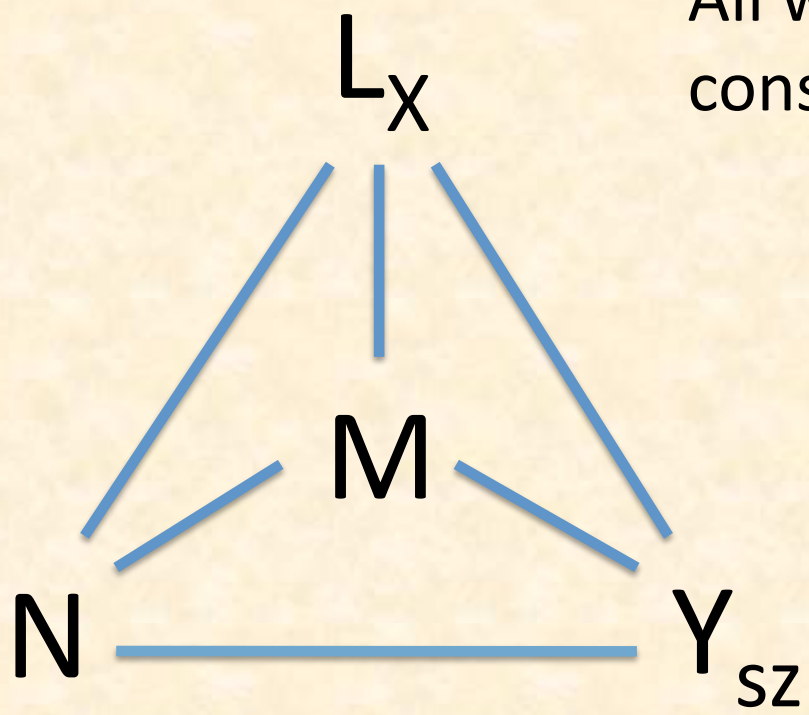


Planck 2011, Optical Scaling Relations

Look at Optical+X-rays+SZ for the First Time



All wave-lengths must be consistent with each other.

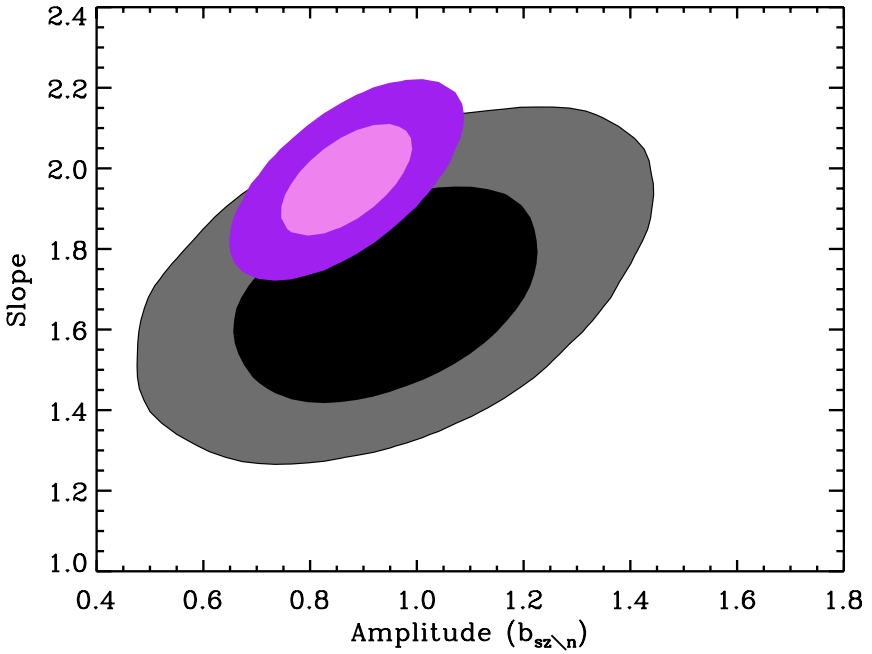
- Abundance data (Optical *and* X-ray)
- WL data
- L_X data
- Y_{SZ} data (Integrated pressure)

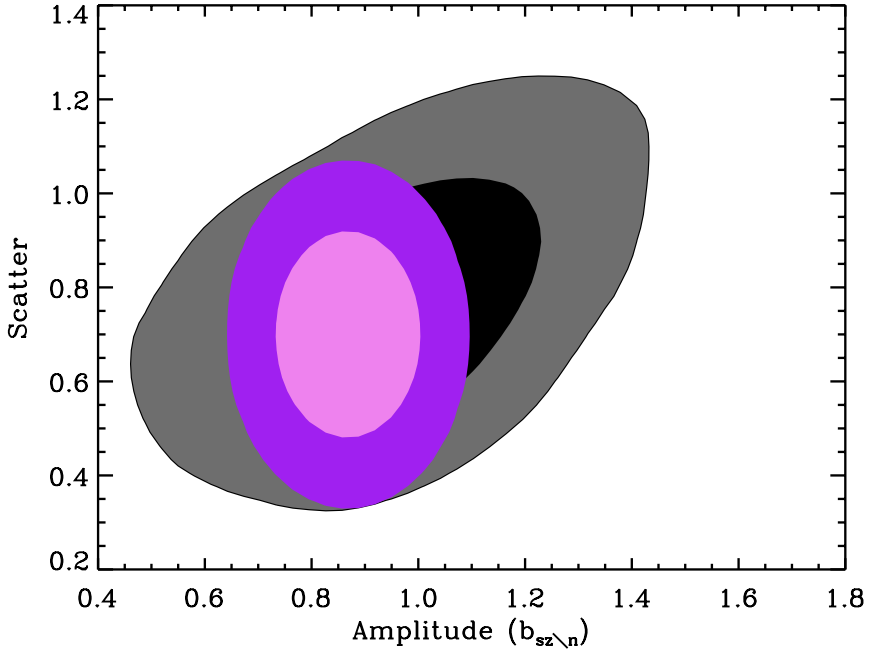
Tension traced to systematics in mass calibration.

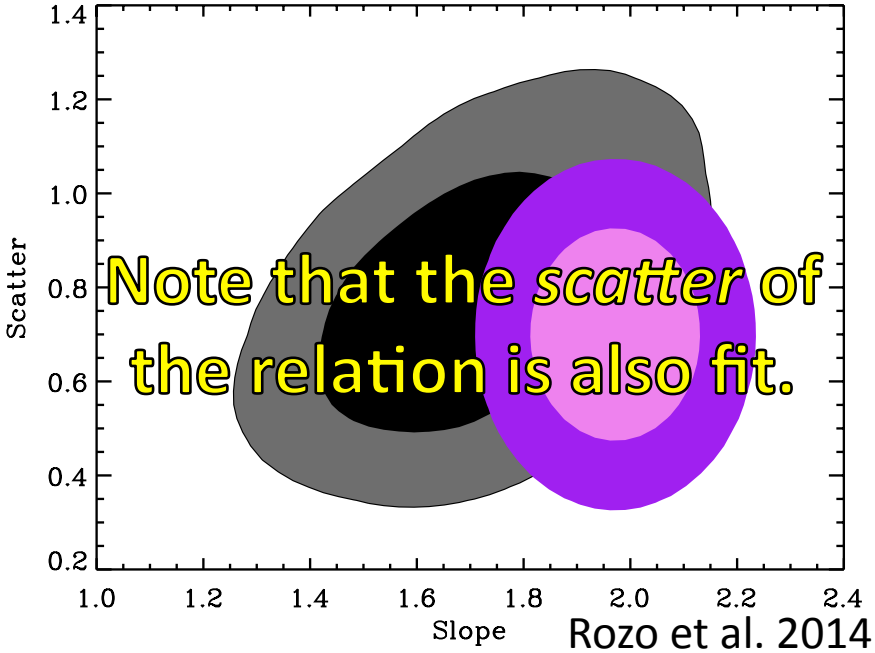
Predicted tension between Planck clusters and CMB.

Rozo et al. 2014

SZ-Optical Scaling Relations







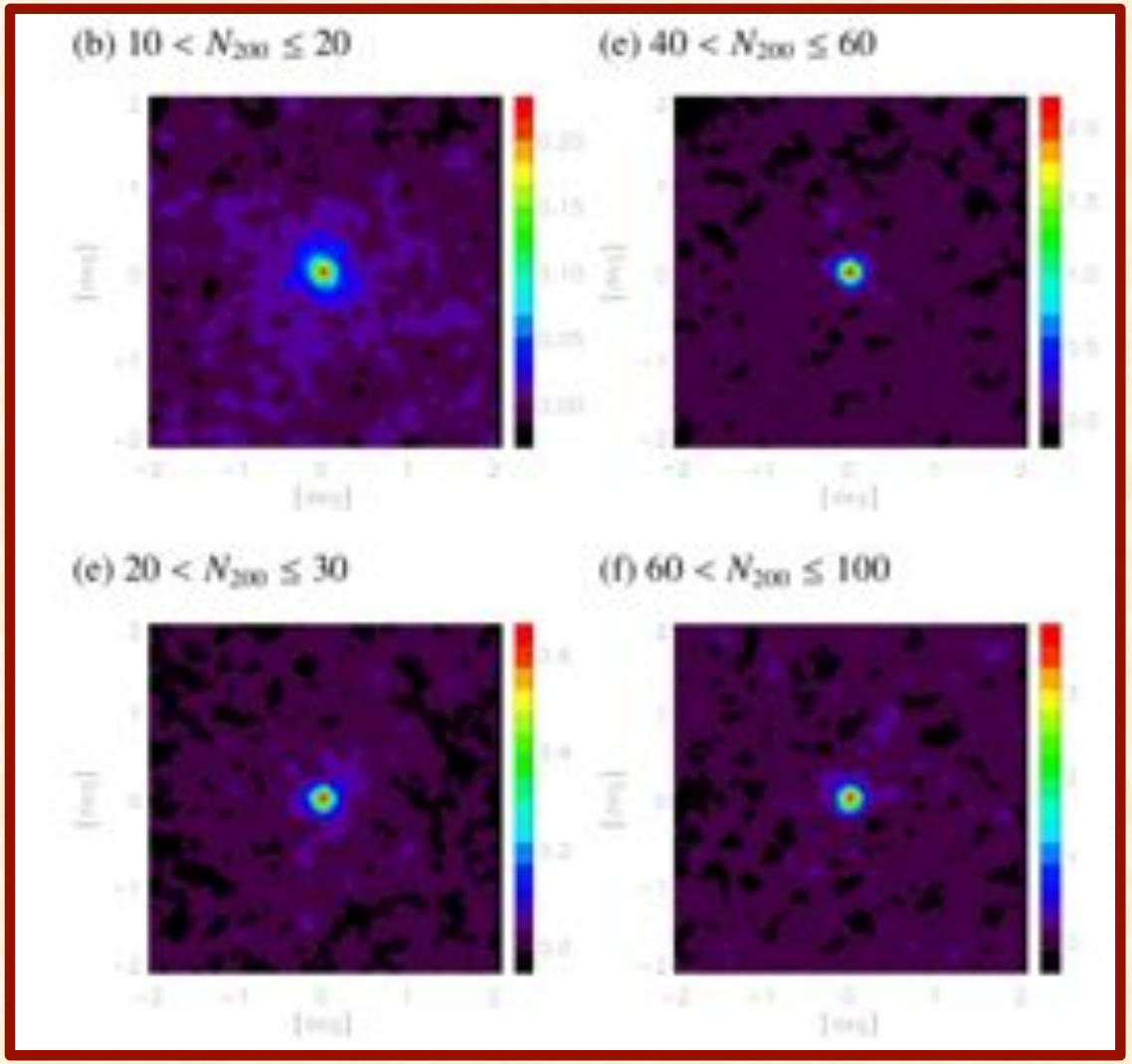
Note that the *scatter* of the relation is also fit.

Rozo et al. 2014

Enabling a Multi-Wavelength View of Future Catalogs

SZ-maps are publicly available.

Especially relevant for future surveys (e.g. DESI).

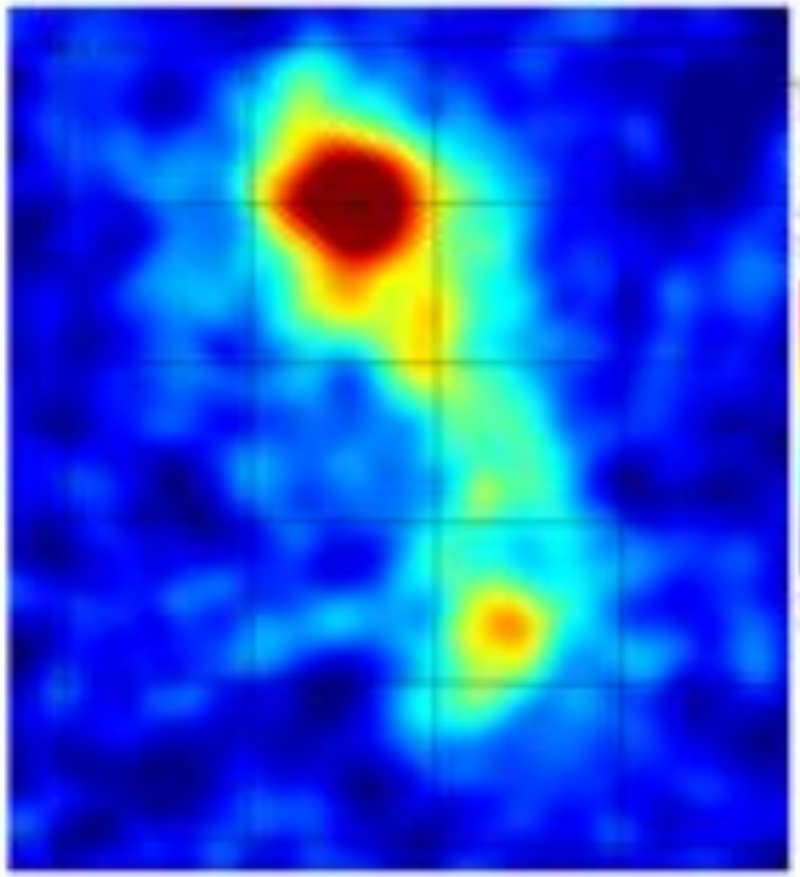


Wen et al. 2012 clusters.

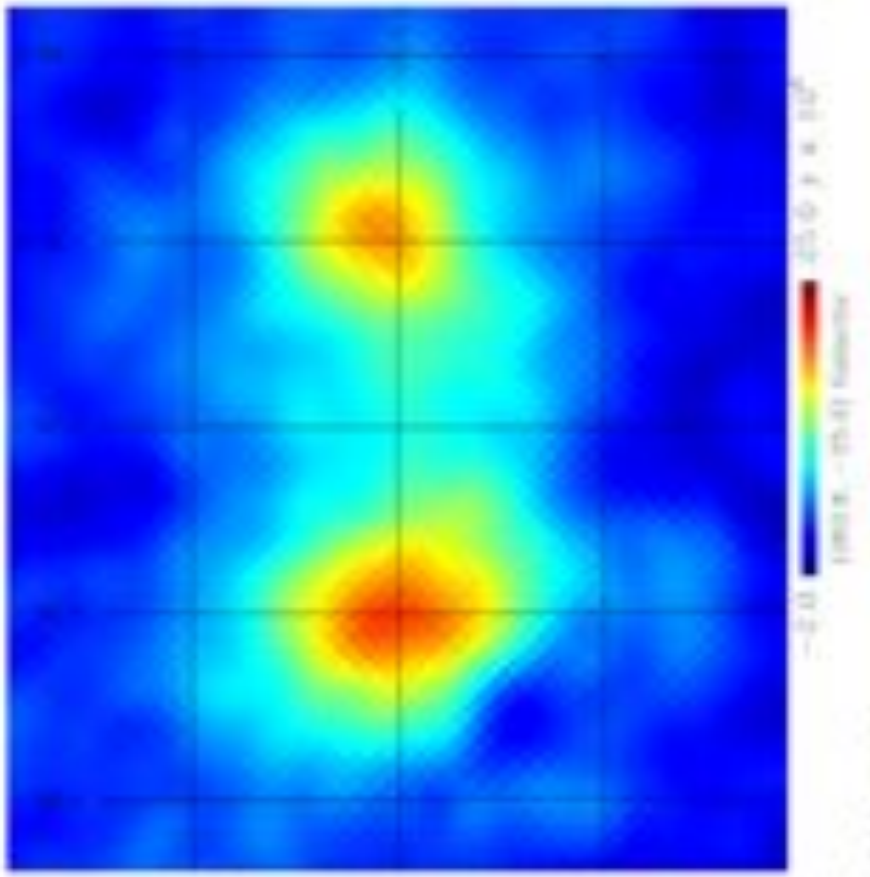
Planck 2015, Paper XXII

Gas Bridges in Planck *y*-Maps

Shapley Supercluster



A3395-A3391 Merger



Planck 2015, Paper XXII

Cluster Cosmology with Planck

Planck Cluster Cosmology

No. of clusters *as a function of* ***mass*** is a sensitive probe of σ_8, Ω_m.

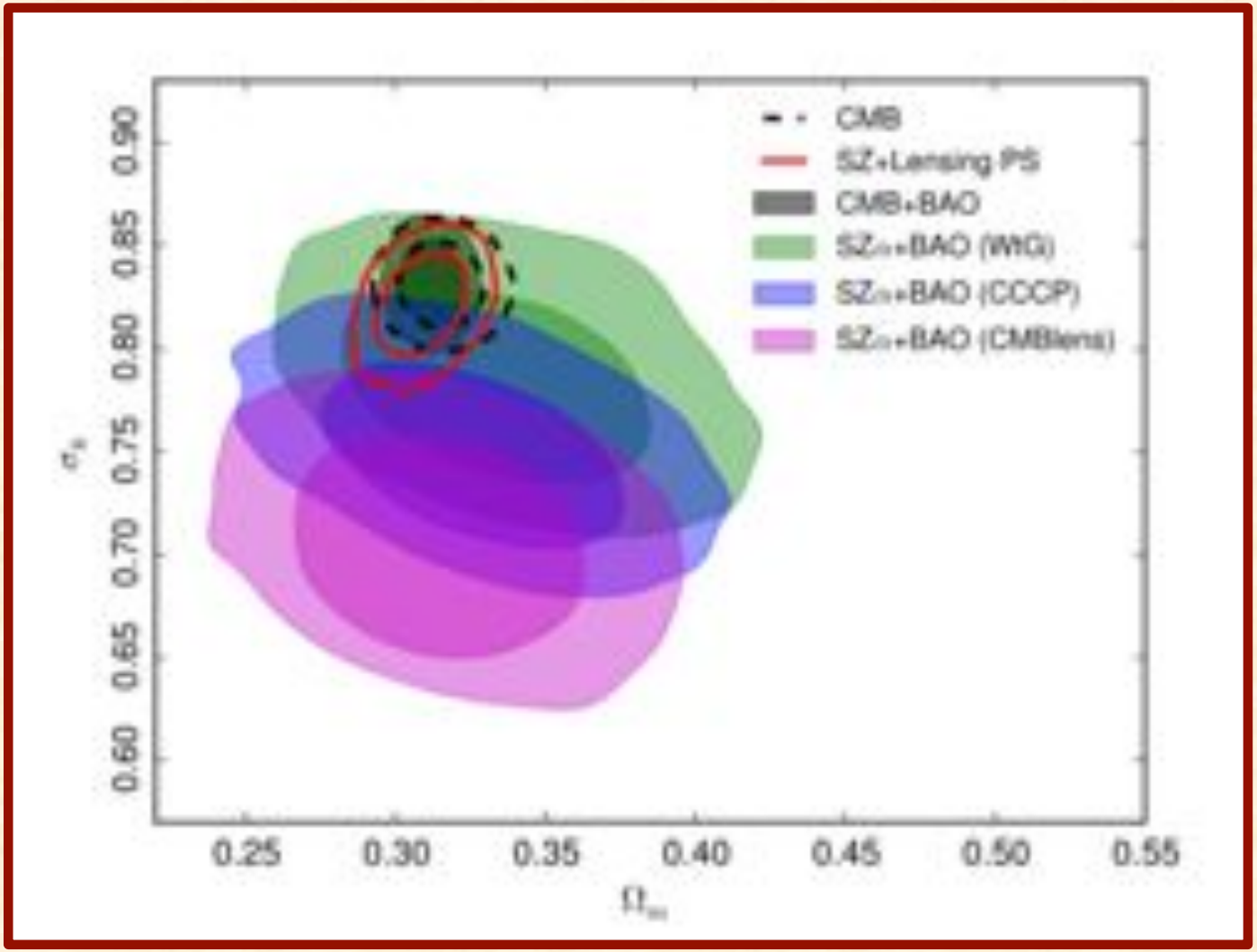
More massive cluster = higher σ_8, $\Omega_{m.}$

Planck finds the clusters via SZ.

Needs additional external data to calibrate the mass of the galaxy clusters.

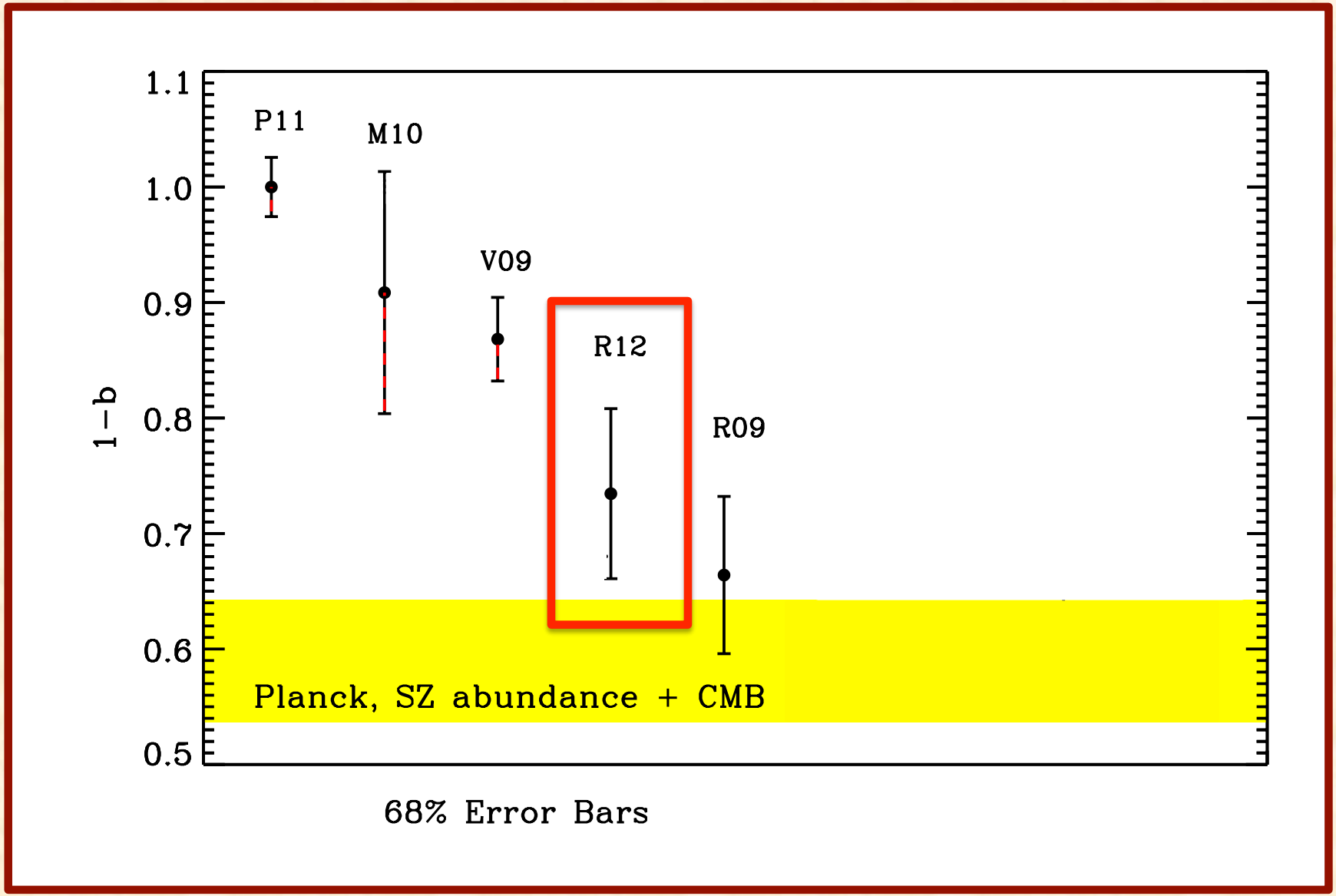
(note quite true, will come back to this).

Planck Results



Planck 2015, Paper XXIV

How Much Does a Cluster Weigh?



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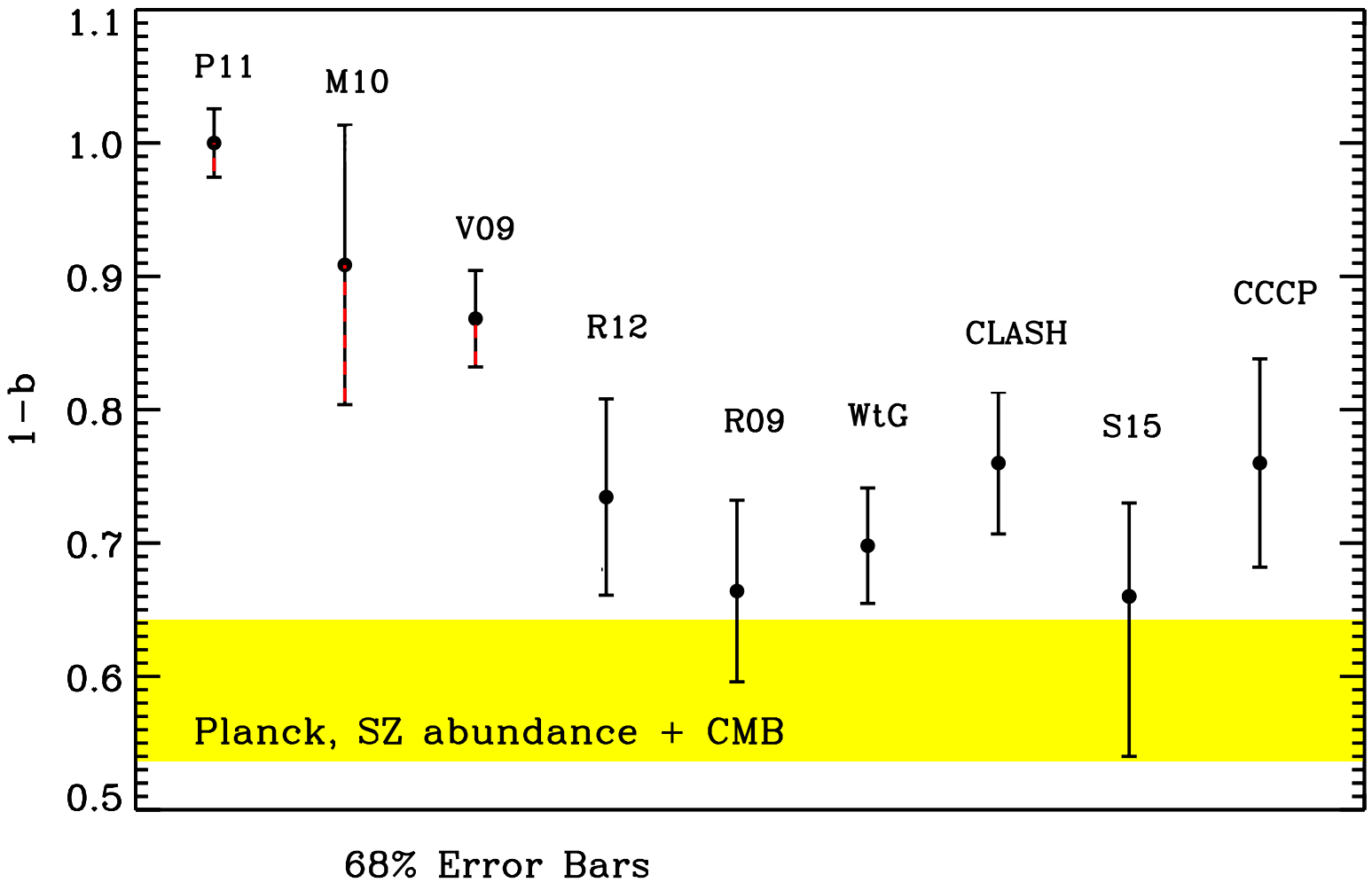

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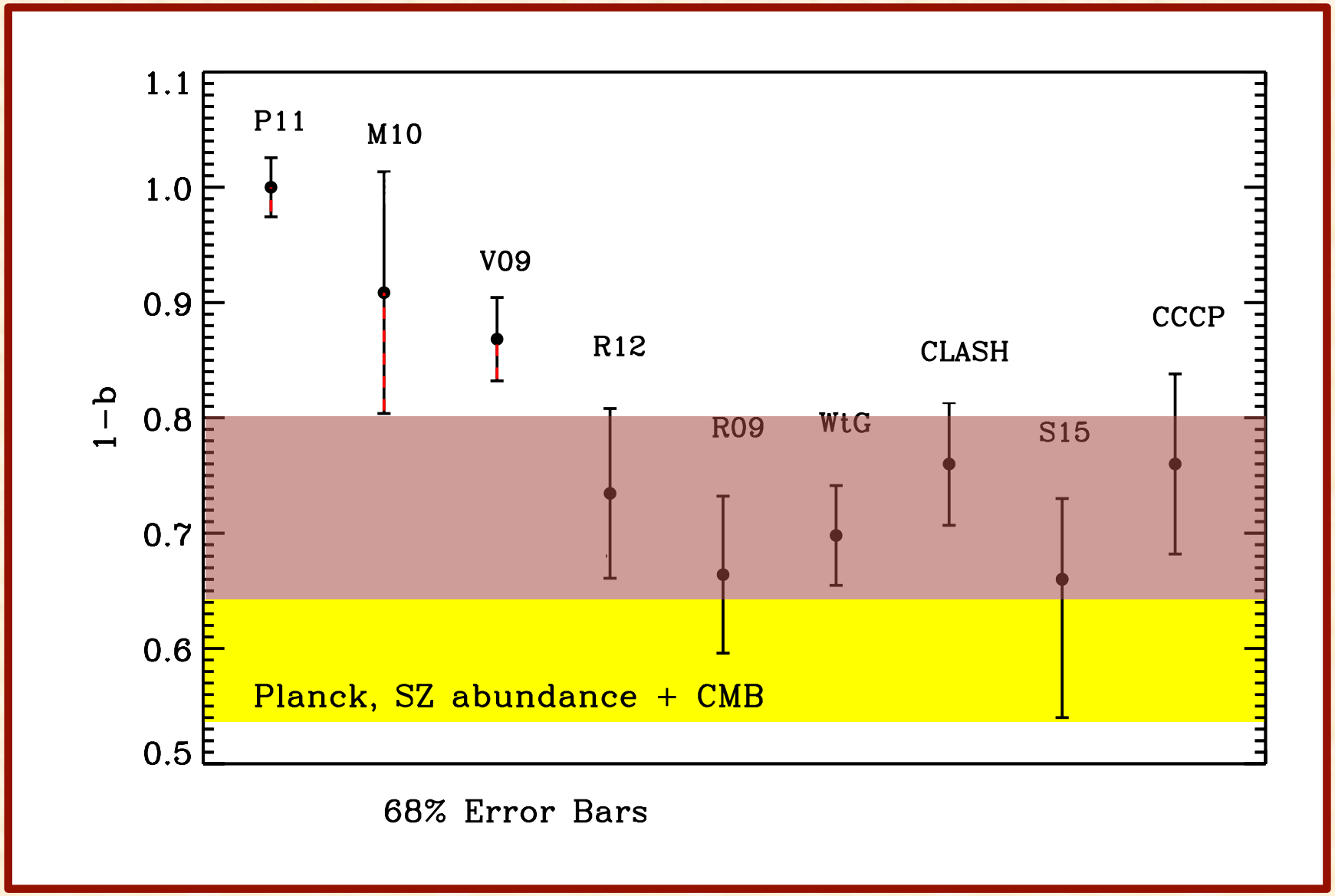


Prospects for Improvement

Significantly Large SZ Samples will Appear in the Near Future

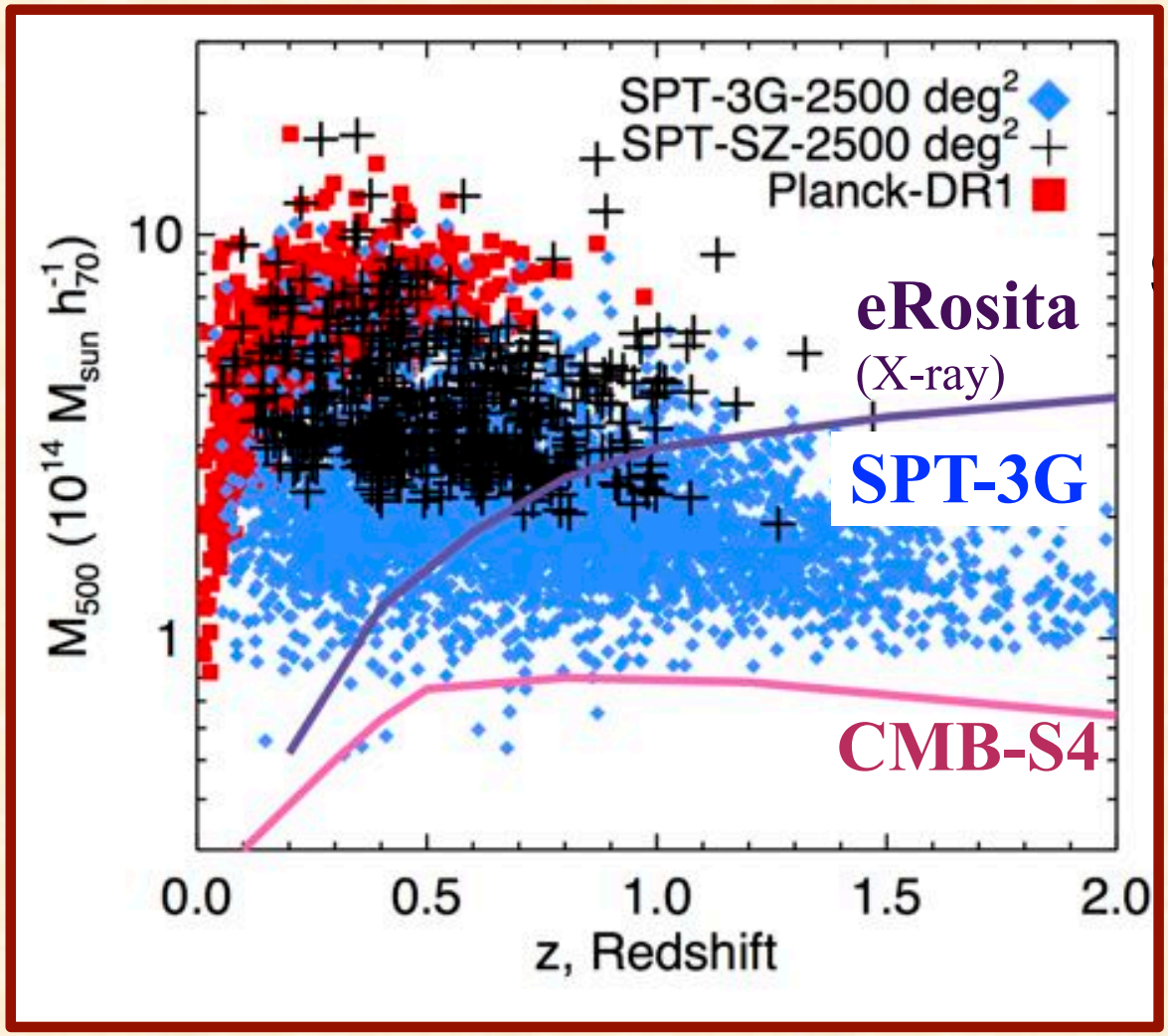
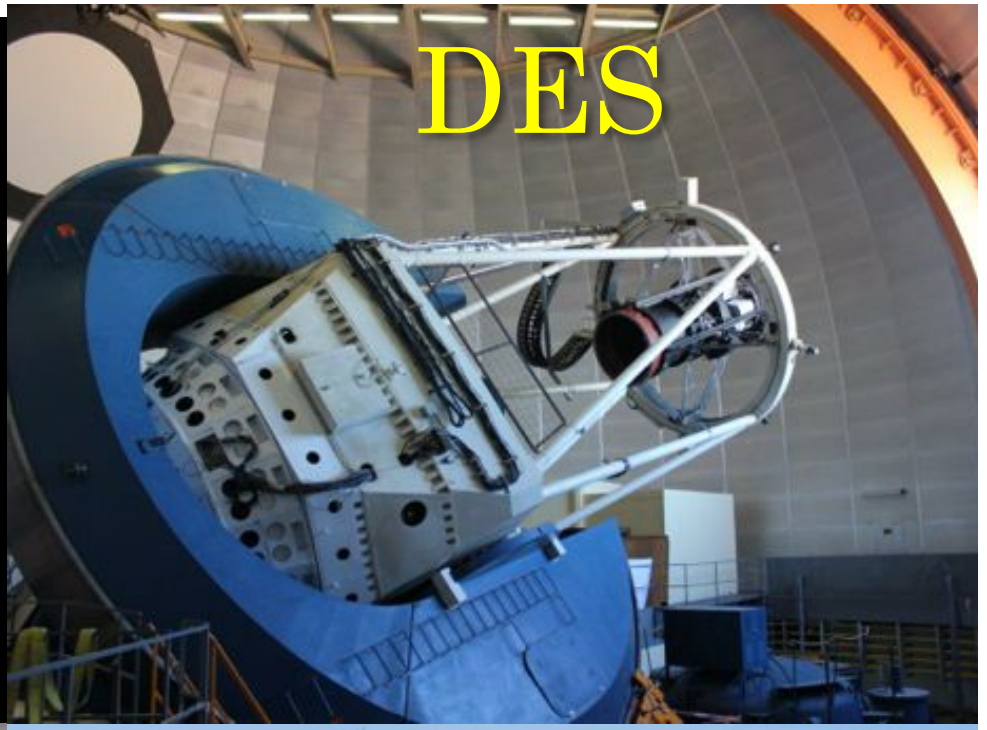
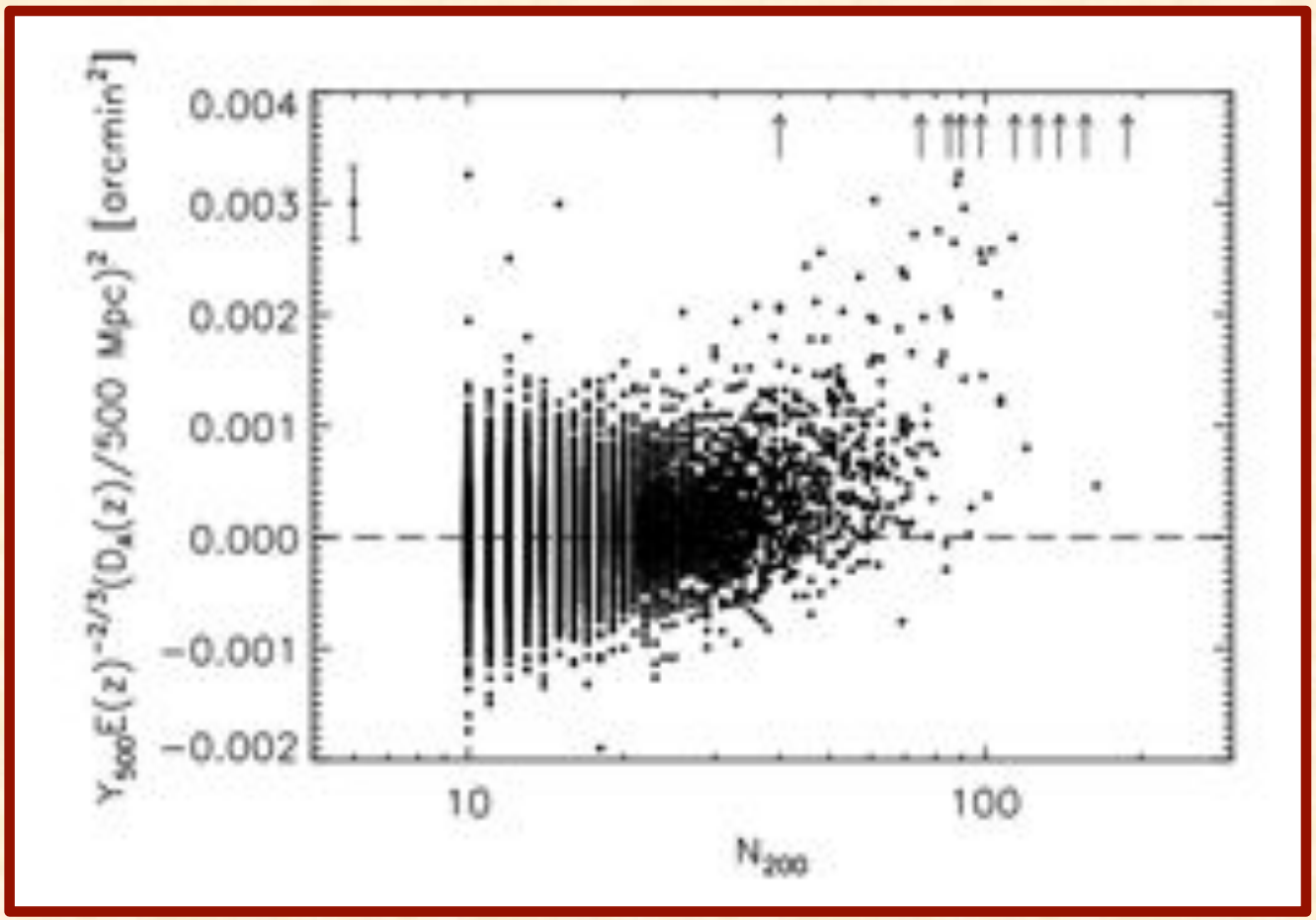


Figure courtesy of Lindsay Bleem.

Prospects for Improvement



Much Higher Quality Optical Clusters Catalogs Available!



Planck 2011, Optical Scaling Relations.

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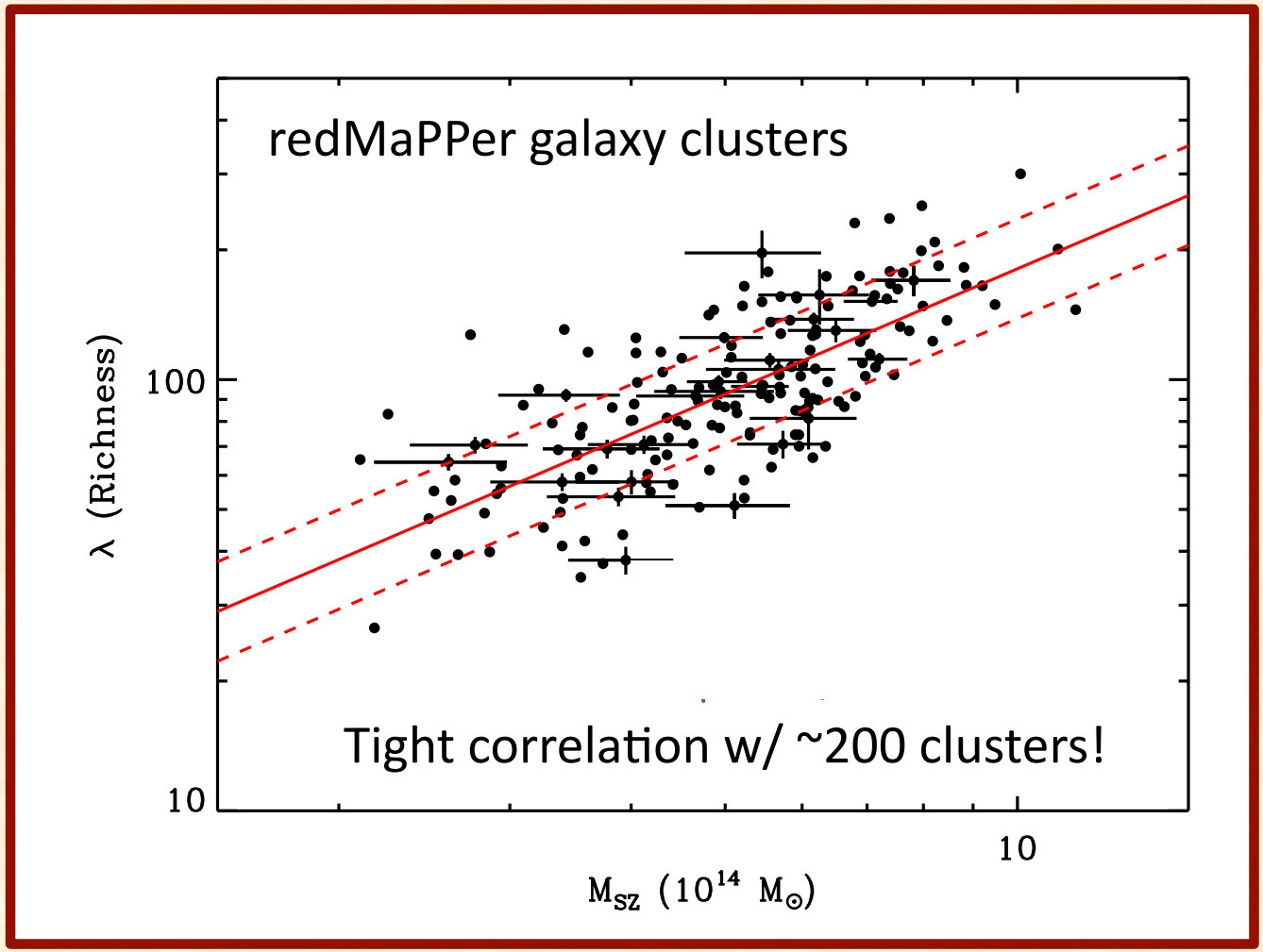
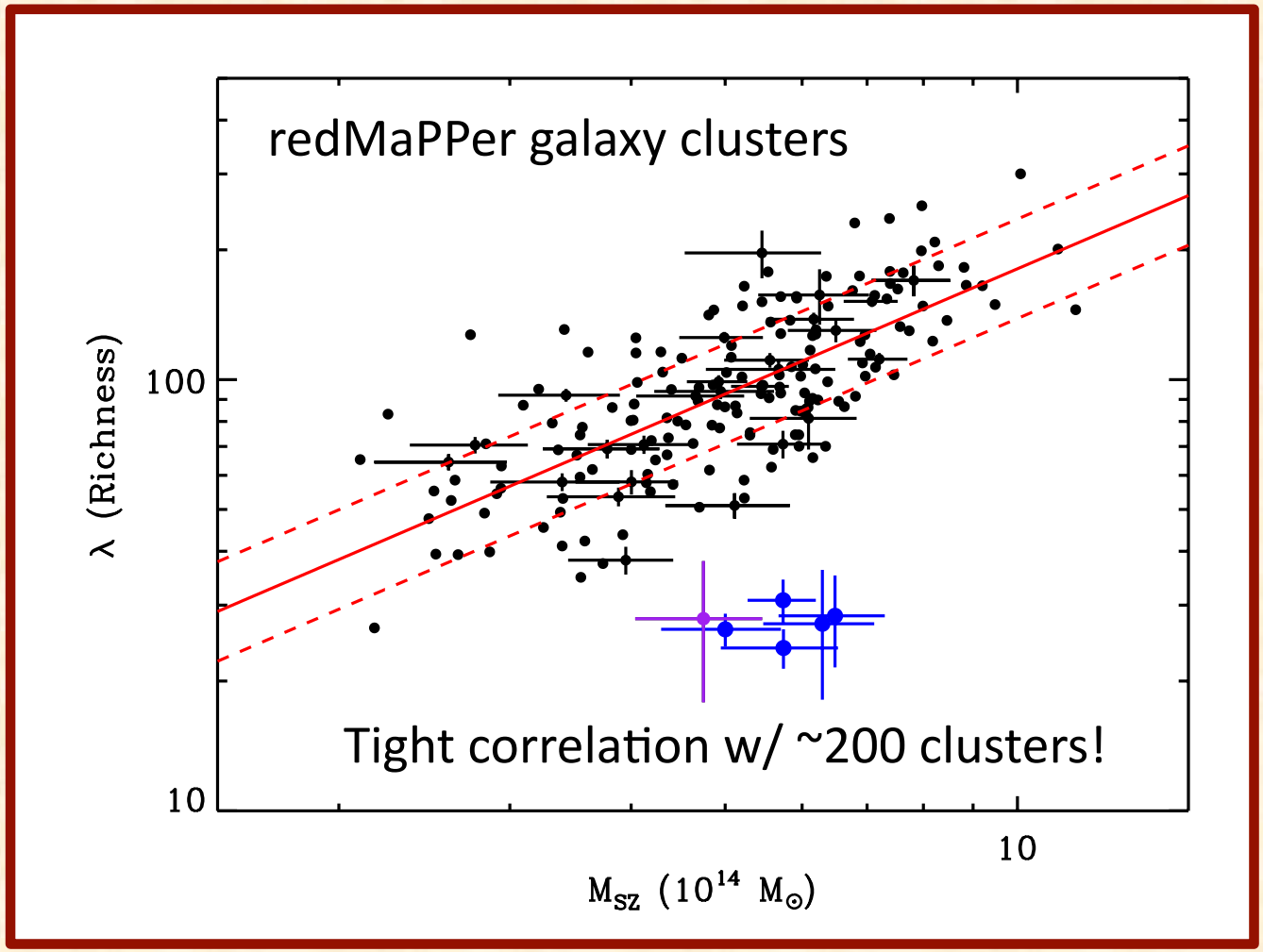


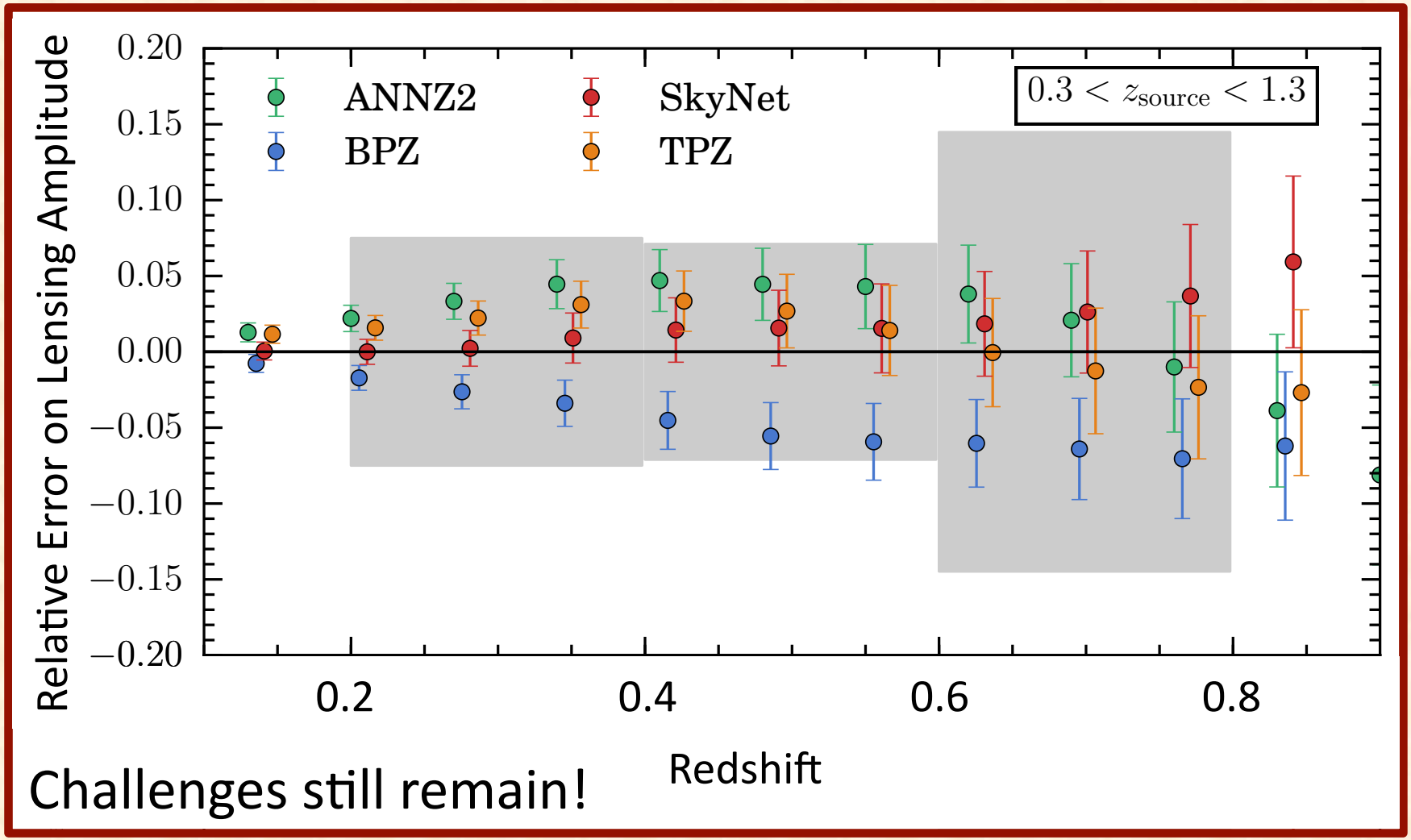
Rozo et al. 2015

Multi-wavelength is Critical to Characterize Clusters!



Rozo et al. 2015

Photoz Systematics in DES



Challenges still remain!

Bonnet et al. 2015

Planck Cluster Cosmology

No. of clusters *as a function of* ***mass*** is a sensitive probe of σ_8, Ω_m.

More massive cluster = higher σ_8, $\Omega_{m.}$

Planck finds the clusters via SZ.

Needs additional external data to calibrate the mass of the galaxy clusters.

(note quite true, will come back to this).

CMB Lensing

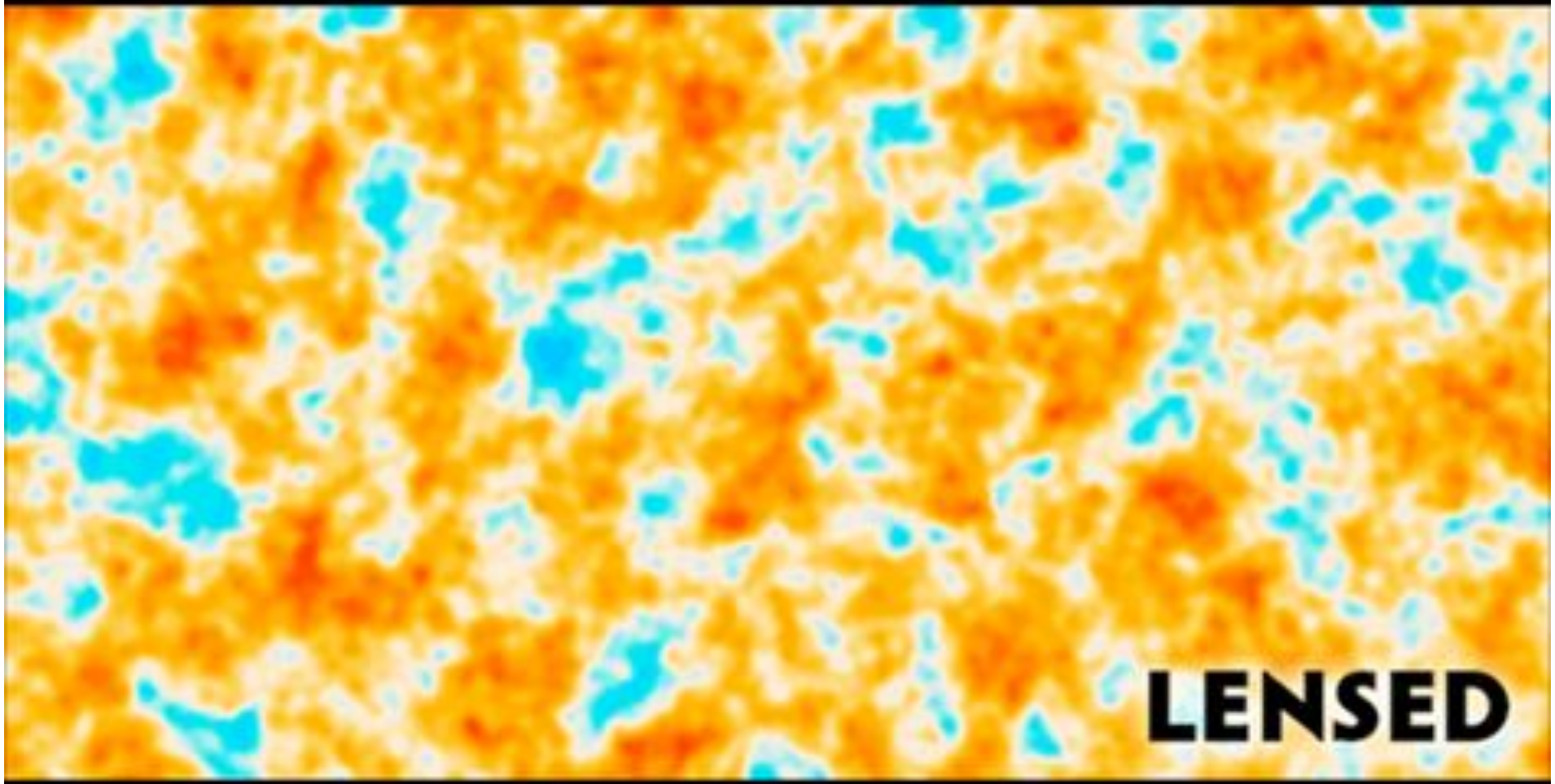
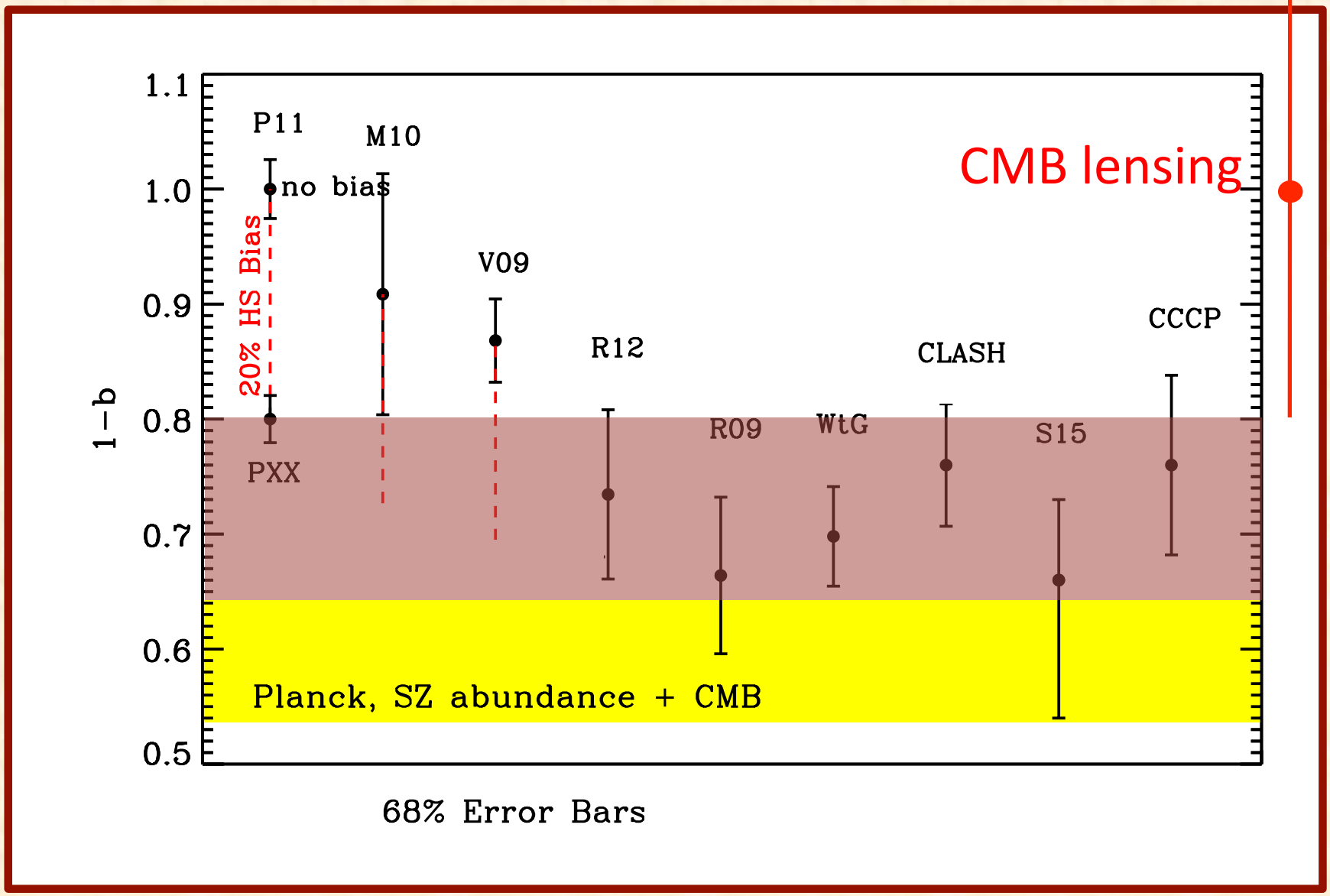
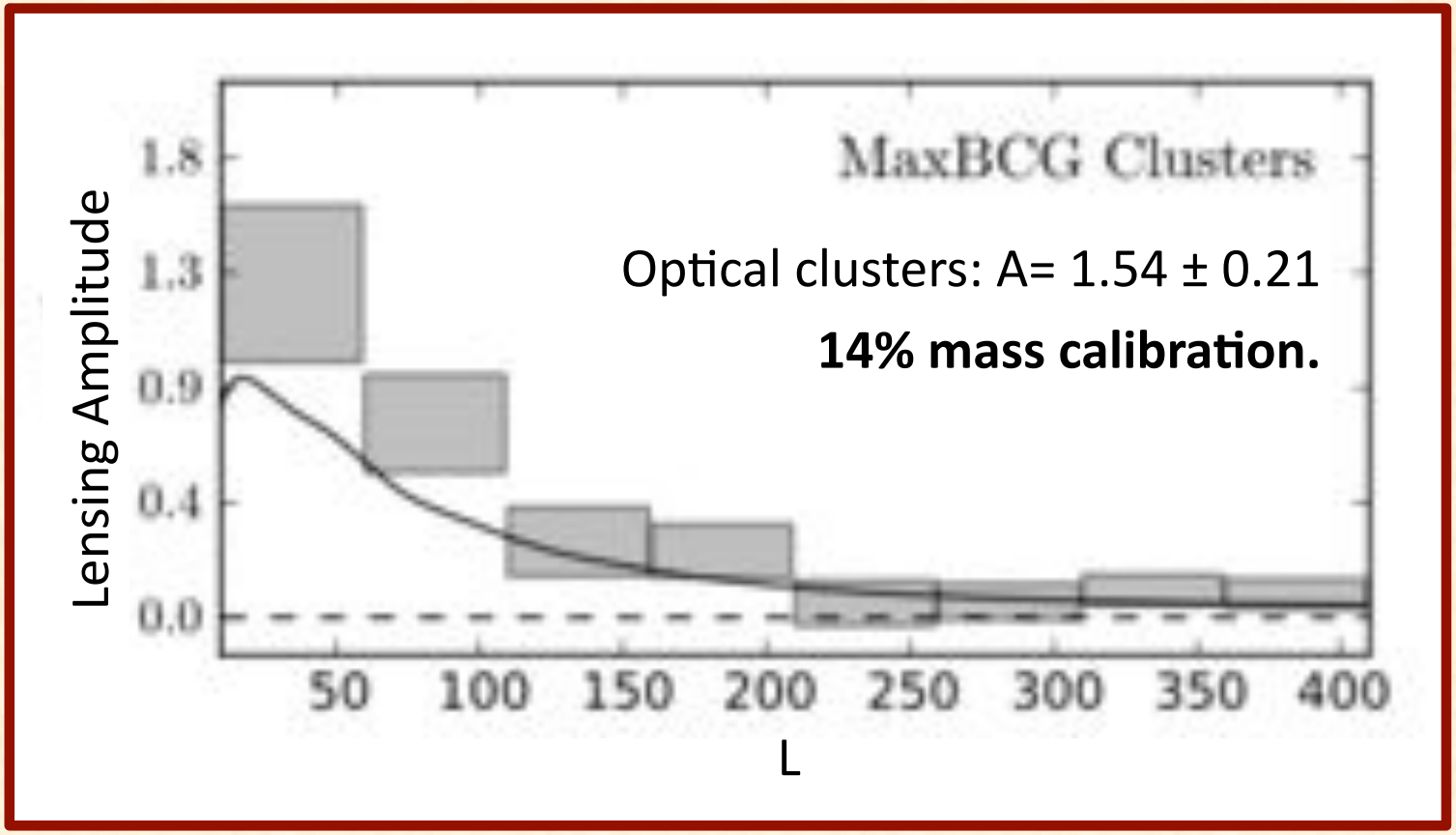


Image credit: ESA/NASA/JPL-Caltech

How Much Does a Cluster Weigh?

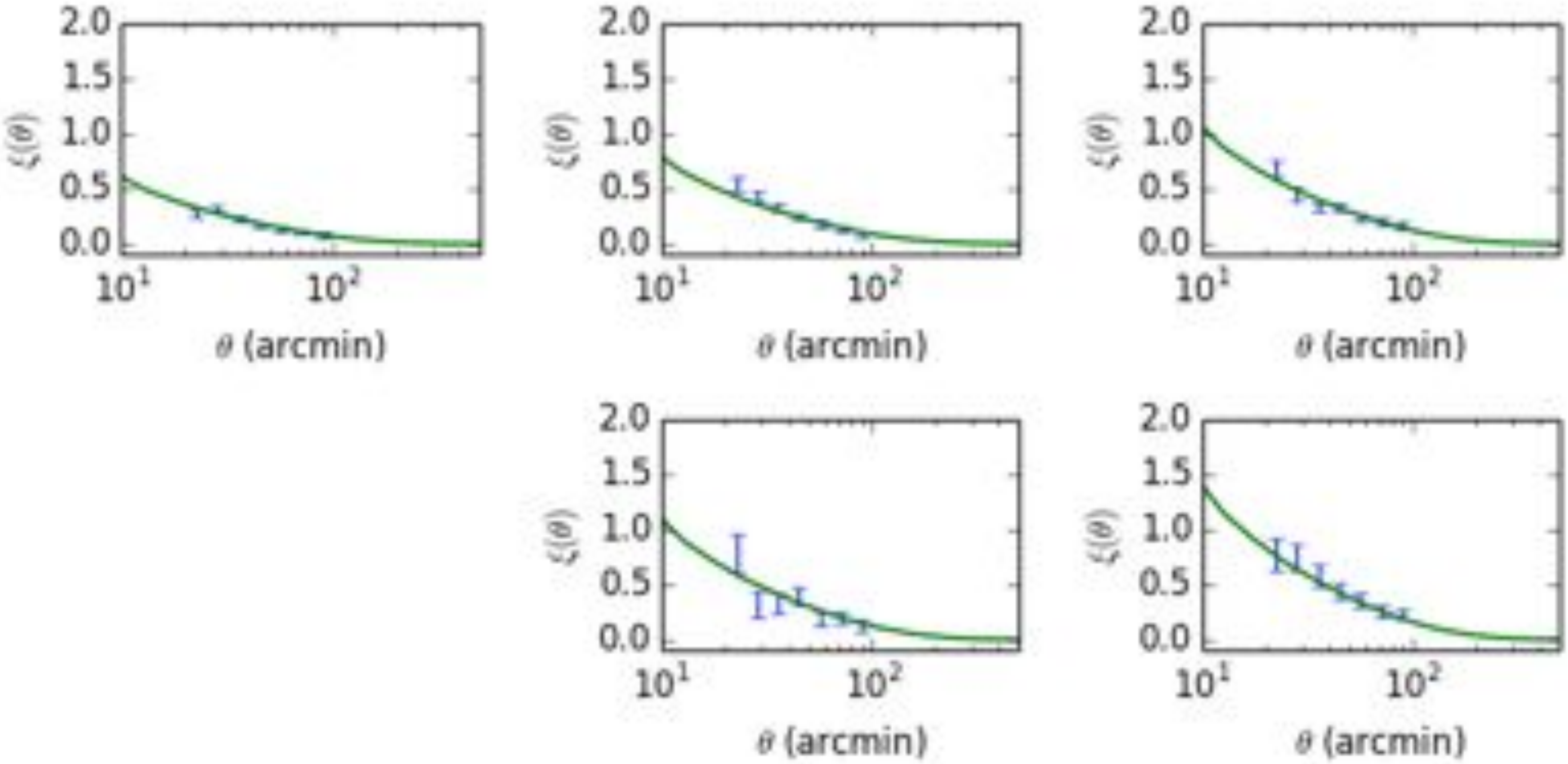


Most Powerful by Combining with External Catalogs

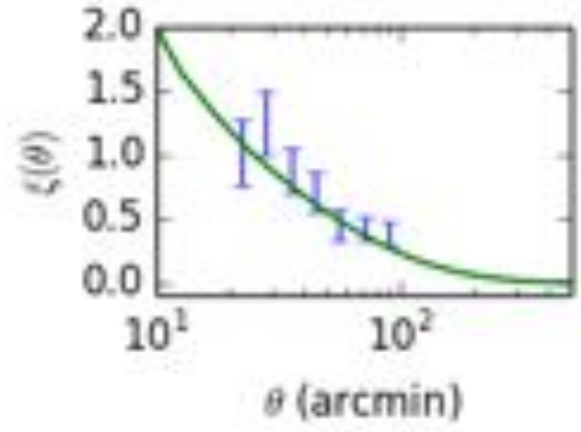


Factors of a few coming from new optical surveys.

Planck 2013, Paper XVII

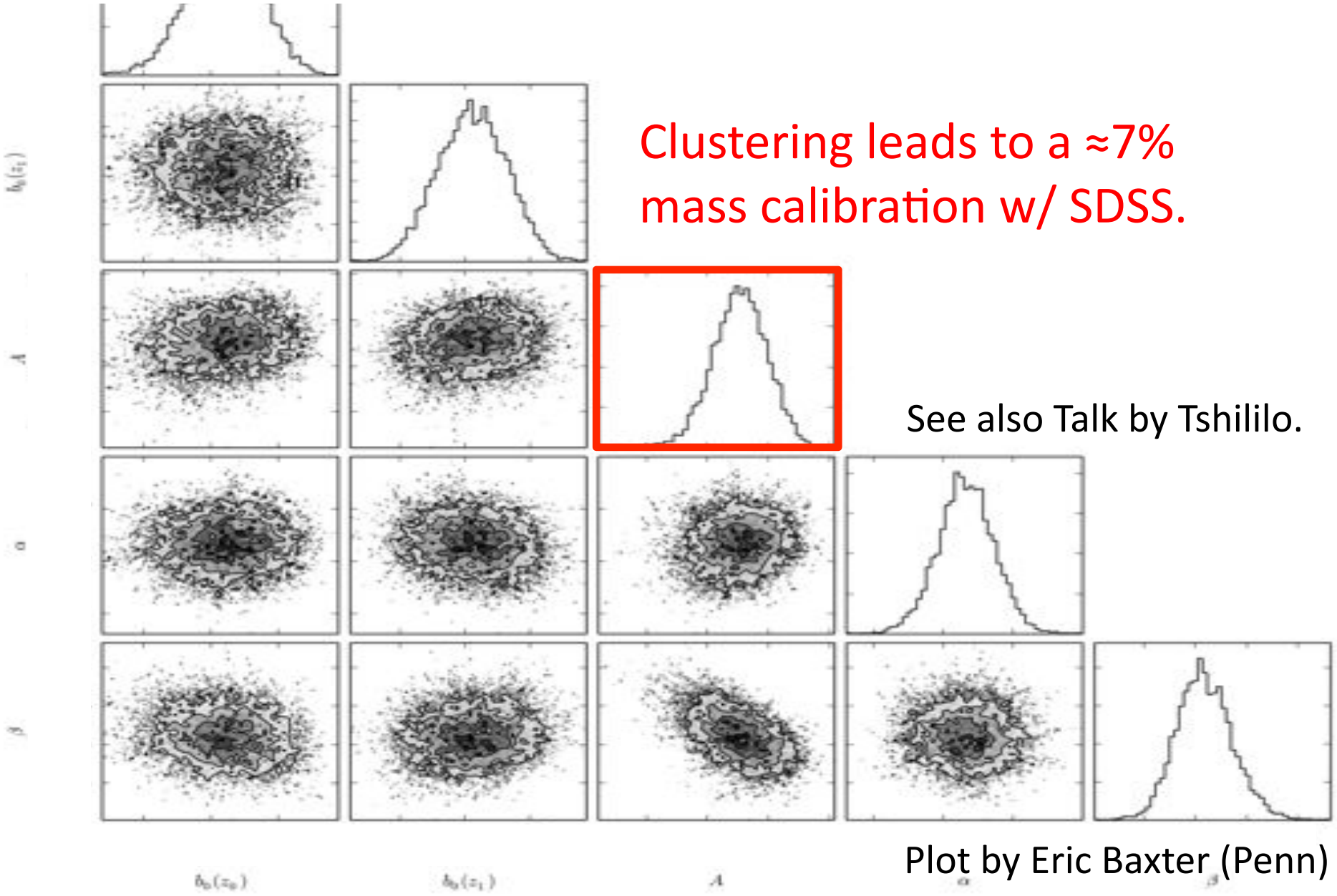


Mass Calibration via Cluster Clustering



Plot by Eric Baxter (Penn)

Clustering Mass Calibration

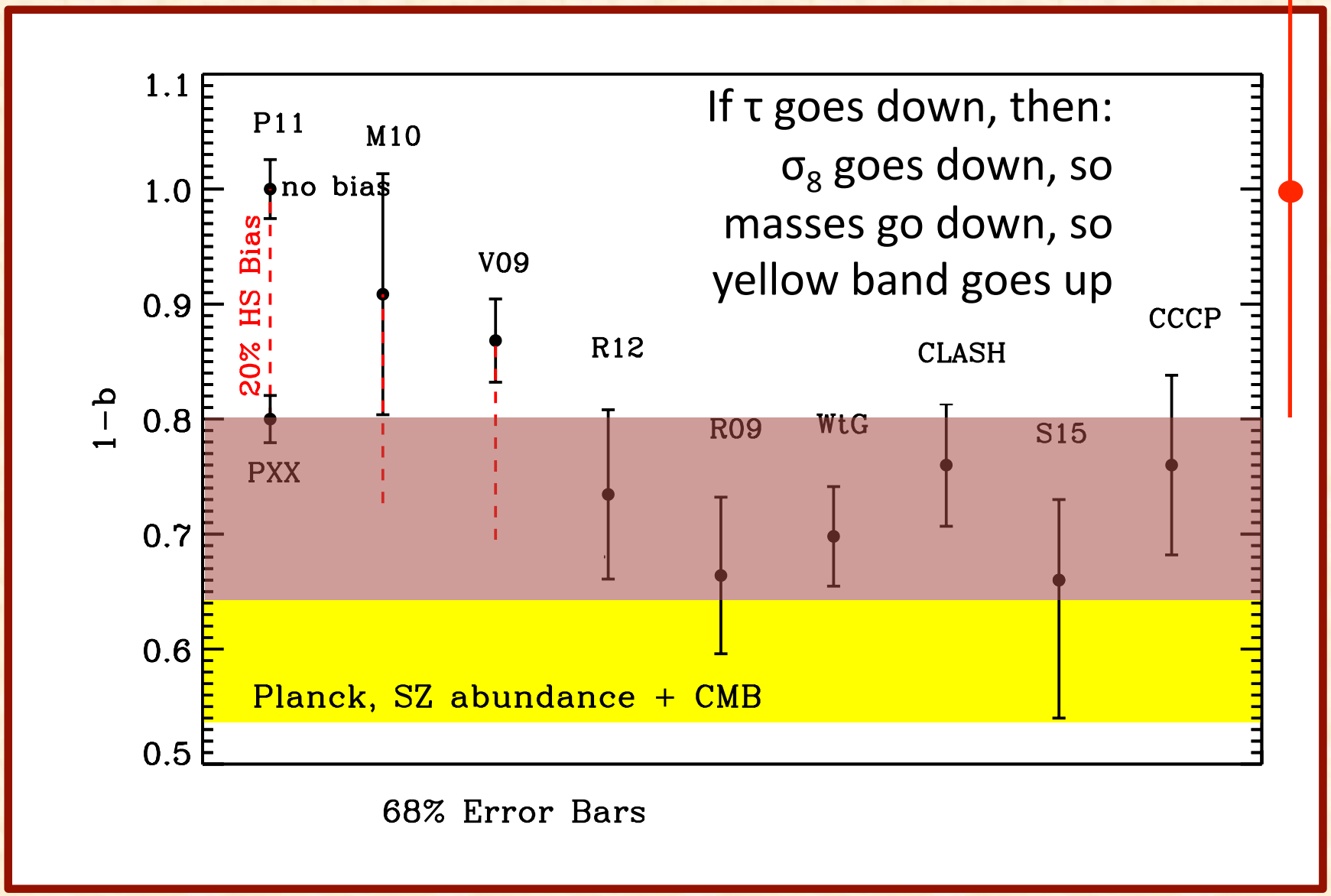


Clustering leads to a ≈7% mass calibration w/ SDSS.

See also Talk by Tshililo.

Plot by Eric Baxter (Penn)

Planck Band to Move Up in the Near Future?



Motivation: Plenary talk by Jean-Loup Puget

Summary

Planck+SPT+ACT have turned SZ from an interesting prediction/detection into a useful cosmological tool.

Largest SZ cluster catalog today: 1600+ systems!

Revealed large population of X-ray diffuse, dynamically interesting sample of massive clusters.

Revealed filament gas.

Provides *y*-maps for future analyses/surveys.

Summary

Expect Planck will have ushered in a new era of multi-wavelength cluster cosmology.

Planck highlighted importance of mass calibration for cluster cosmology.

Planck demonstrated the feasibility of CMB lensing for mass calibration (expect near future improvements!).

Other methods (cluster clustering) are coming, enabled by larger cluster samples.

Current cluster data consistent with CMB, but does suggest lower σ_8 and/or Ω_m.