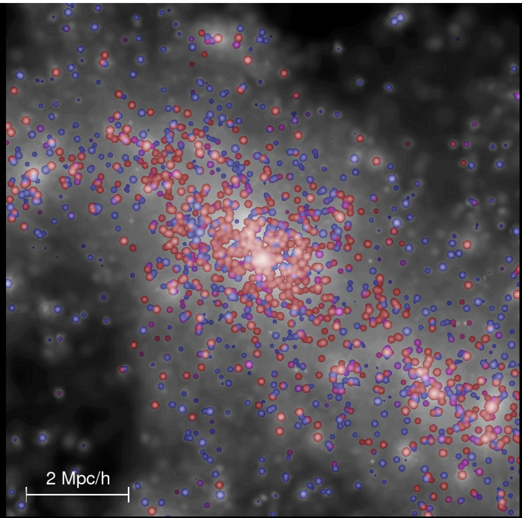
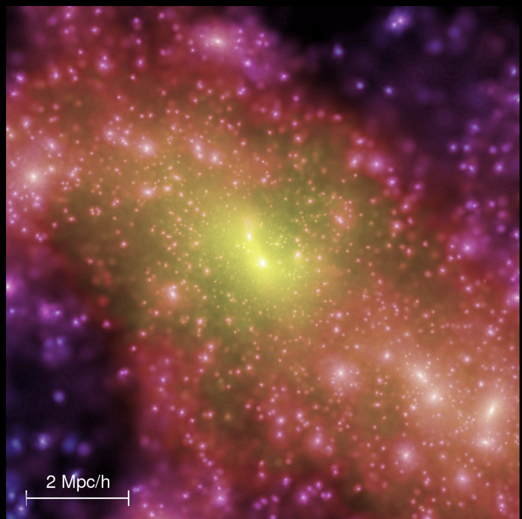
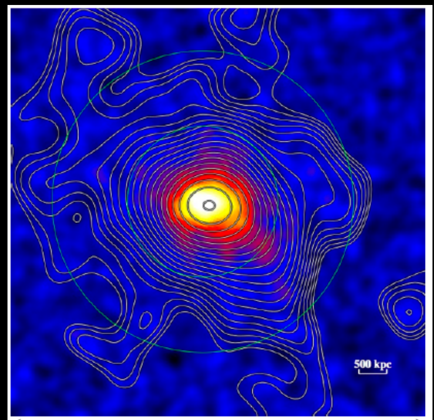
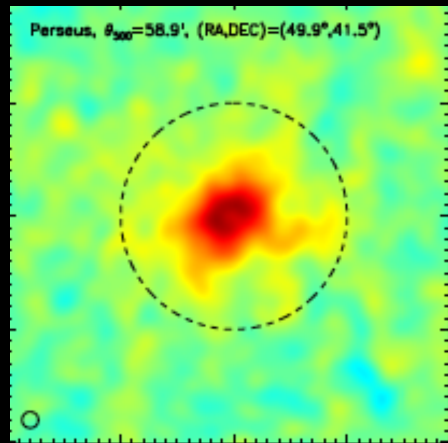
Cosmology with Galaxy Clusters

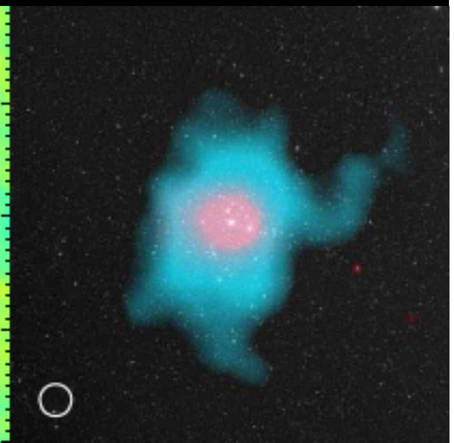
José Alberto Rubiño-Martín (IAC)







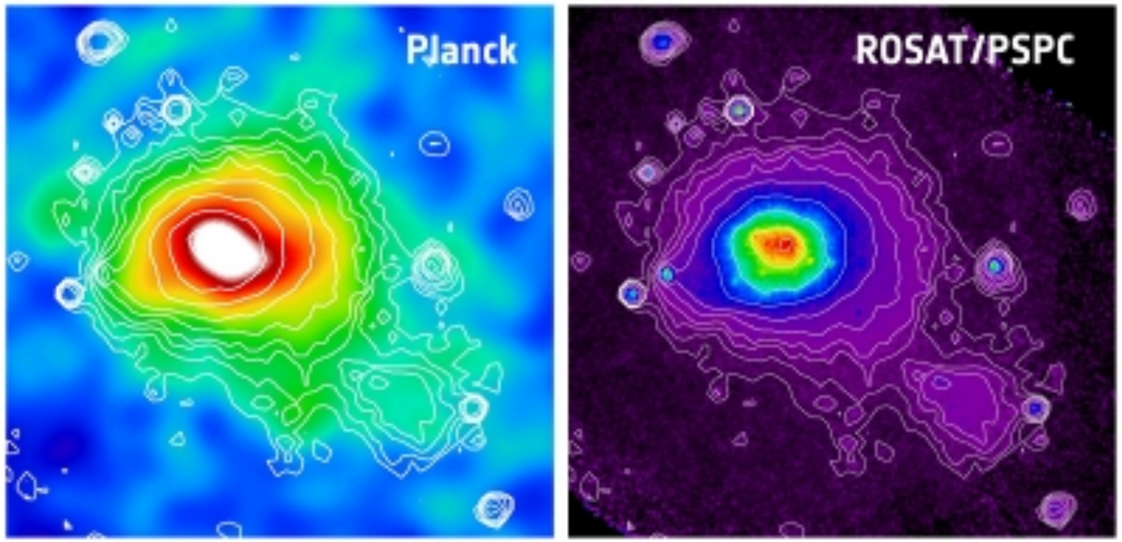




Meeting on Fundamental Cosmology

Fuerteventura, 5-6 June 2014

Three faces of galaxy clusters



Cosmology with galaxy clusters

Main key methods (see Carlstrom et al. 2002; Allen et al. 2011):

❖ **Halo counts and clustering**.

$$\overline{N}(M_a, z_i) \equiv \overline{N}_{ai} = \frac{\Delta\Omega_i}{4\pi} \int_{z_i}^{z_{i+1}} dz \frac{dV}{dz} \int_{\ln M_a}^{\ln M_{a+1}} d\ \ln M \frac{dn}{d\ \ln M}$$

❖ Determination of the **baryon (gas) fraction** and the physical density of matter in clusters of galaxies. Clusters are fair samples of the Universe**.**

$$f_{\rm gas}(z) = \Upsilon(z) \left(\frac{\Omega_{\rm b}}{\Omega_{\rm m}}\right)$$

❖ Determination of the **Hubble constant (H_0)** or distances (**$d_A(z)$**) from measurements of clusters of galaxies. Combining the SZ measurements (ΔT_{SZ} α $\int n_e T_e dl$) , and X-ray measurements (L_X α $\int n_e^2 T_e^{1/2} dV$).

$$d_{\rm A} \propto \left(\frac{y_{\rm obs}}{y_{\rm pred}}\right)^2$$

❖ Angular thermal **Sunyaev-Zeldovich power spectrum** (e.g. Komatsu & Seljak 2002)

$$C_\ell \propto \int dz \frac{dV}{dz} \int d\ln M \frac{dn}{d\ \ln M} \tilde{y}^2(M, z, \ell).$$

❖ **Bispectrum and 1-pdf of the thermal Sunyaev-Zeldovich maps**.

❖ Determination of **peculiar velocities**. Large-scale velocity fields in the Universe (e.g. bulk flows).

Cosmological constraints from galaxy clusters

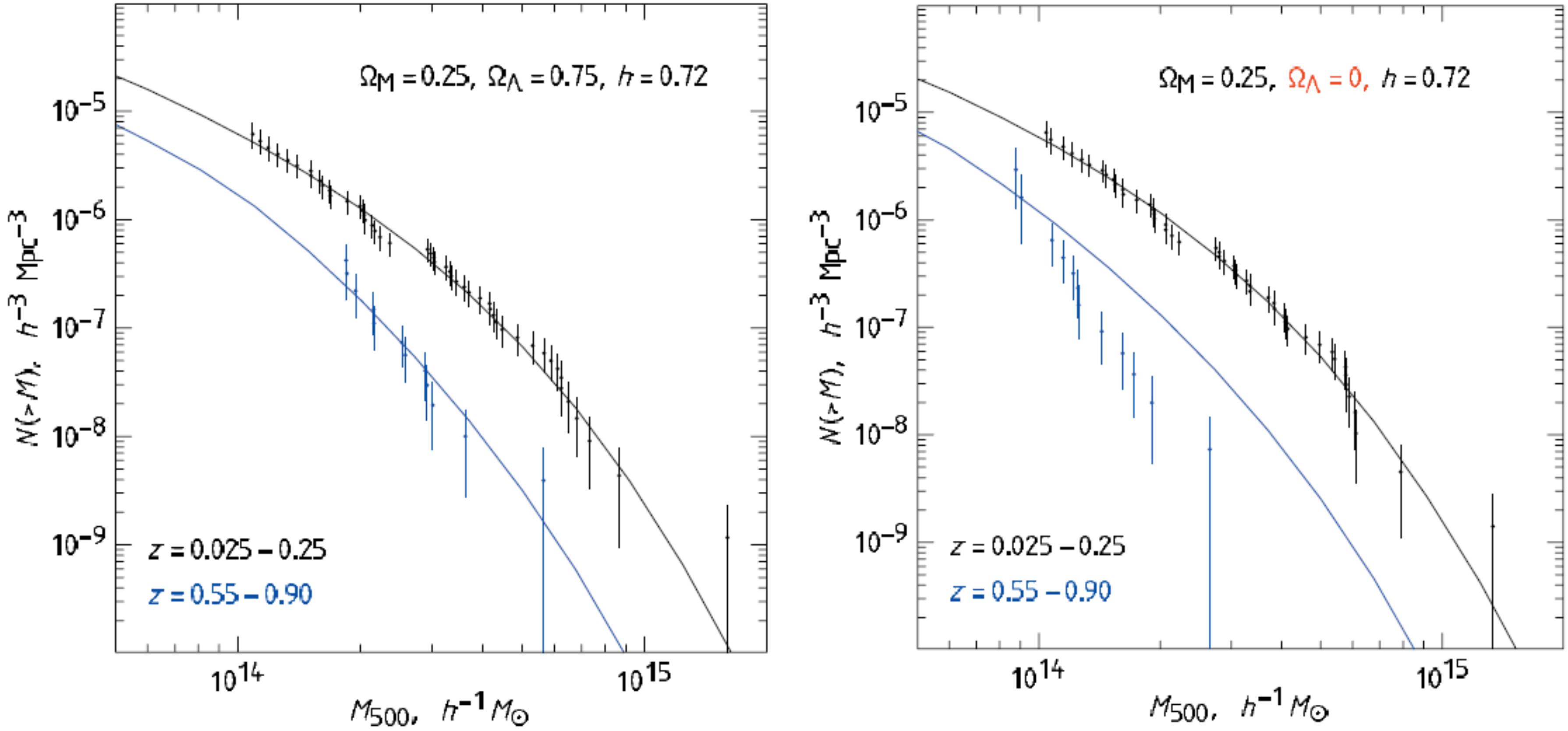
Status of the field in 2011 (from Allen et al. 2011).

Reference[c]	Data	σ_8	Ω_m	Ω_{DE}	w	b
Local abundance and evolution[d]						
M10	X-ray	0.82 ± 0.05	0.23 ± 0.04	$1 - \Omega_m$	-1.01 ± 0.20	
V09	X-ray	0.81 ± 0.04	0.26 ± 0.08	$1 - \Omega_m$	-1.14 ± 0.21	
Local abundance only						
R10	optical	0.80 ± 0.07	0.28 ± 0.07	$1 - \Omega_m$	-1	
H09	X-ray	0.88 ± 0.04	0.3	$1 - \Omega_m$	-1	
Local abundance and clustering						
S03	X-ray	$0.71^{+0.13}_{-0.16}$	$0.34^{+0.09}_{-0.08}$	$1 - \Omega_m$	-1	
Gas-mass fraction						
A08	X-ray		0.27 ± 0.06	0.86 ± 0.19	-1	
A08	X-ray		0.28 ± 0.06	$1 - \Omega_m$	$-1.14^{+0.27}_{-0.35}$	
E09	X-ray		0.32 ± 0.05	$1 - \Omega_m$	$-1.1^{+0.7}_{-0.6}$	
L06	X-ray+SZ		$0.40^{+0.28}_{-0.20}$	$1 - \Omega_m$	-1	
XSZ distances						
B06	X-ray+SZ		0.3	$1 - \Omega_m$	-1	$0.77^{+0.11}_{-0.09}$
S04	X-ray+SZ		0.3	$1 - \Omega_m$	-1	0.69 ± 0.08

References:

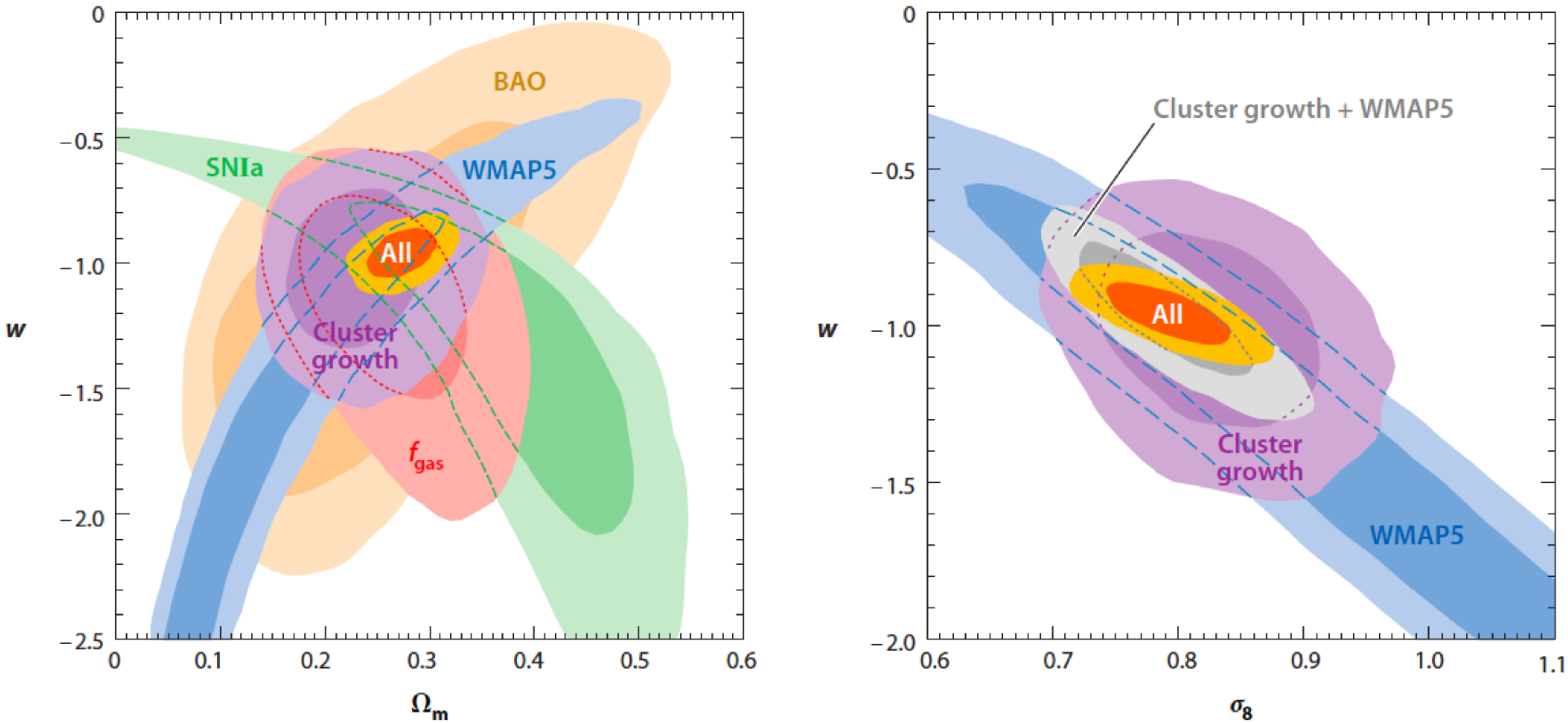
[c]A08 = Allen et al. (2008); B06 = Bonamente et al. (2006); E09 = Ettori et al. (2009); H09 = Henry et al. (2009); L06 = LaRoque et al. (2006); M10 = Mantz et al. (2010b); R10 = Rozo et al. (2010); S03 = Schuecker et al. (2003); S04 = Schmidt, Allen & Fabian (2004); V09 = Vikhlinin et al. (2009b).

Cluster mass function vs. cosmological model



Chandra Cluster Cosmology Project
Vikhlinin et al., 2009

Constraints from cluster growth and fgas



Growth of a statistically complete sample of 238 X-ray luminous ROSAT clusters (Mantz et al. 2010). Simultaneous fitting for cosmological parameters and scaling relations.

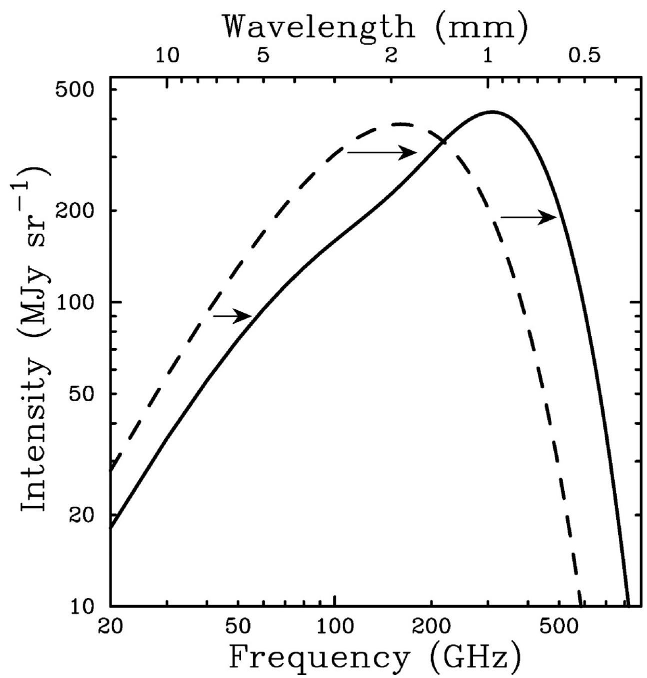
The Sunyaev-Zeldovich effect

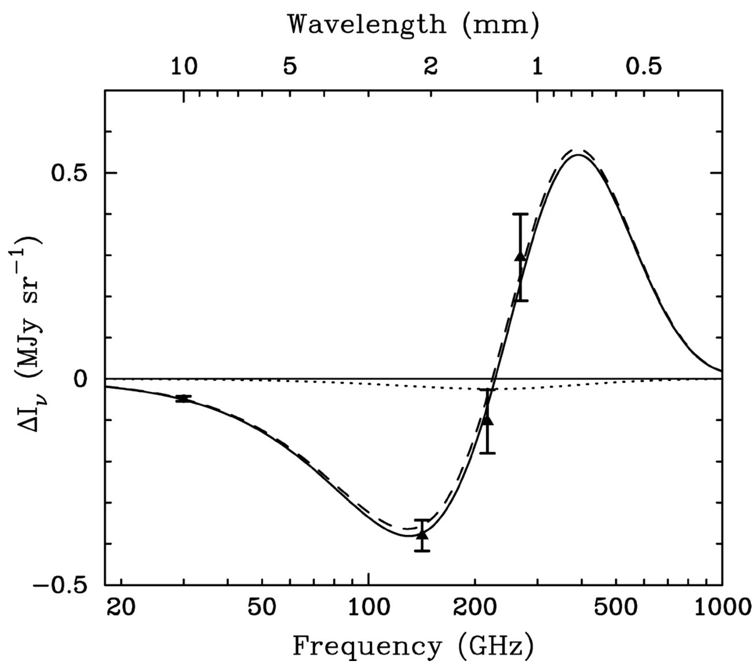
R. A. Sunyaev

Ya. B. Zeldovich

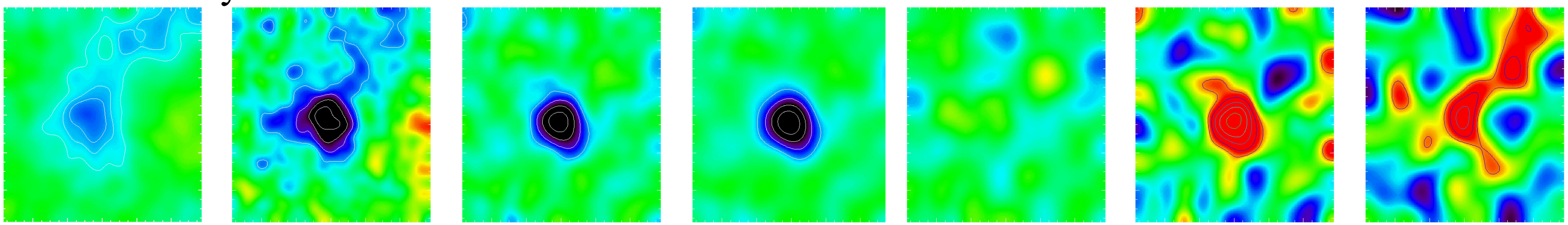
❖ Inverse Compton scattering of CMB photons off hot electrons.

❖ <u>Net gain of energy of the photons</u>, so the blackbody spectrum of the CMB is distorted (y-distortion).





A2319 seen by PLANCK



44 GHz | 70 GHz | 100 GHz | 143 GHz | 217 GHz | 353 GHz | 545 GHz

The Sunyaev-Zeldovich effect

R. A. Sunyaev

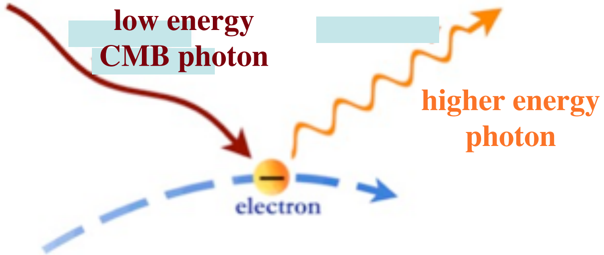
Ya. B. Zeldovich

Some notes:

❖ Differential brightness of the effect is independent of the redshift.

❖ The effect measures electron pressure along the line of sight:

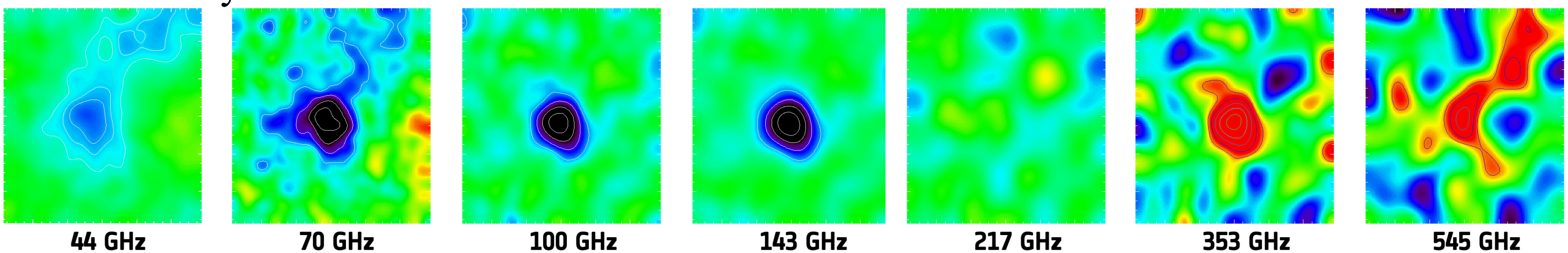
$$y = \frac{\sigma_T}{m_e c^2} \int_l (P_{th} = k_B n_e T) dl$$



❖ We will be interested in total SZ flux: $Y = \int y d\Omega$ which is proportional to $M_{gas}/d_A^2(z)$.

❖ There is also a kinetic effect (peculiar velocities wrt the CMB rest frame).

A2319 seen by PLANCK



Galaxy clusters from the ACT survey

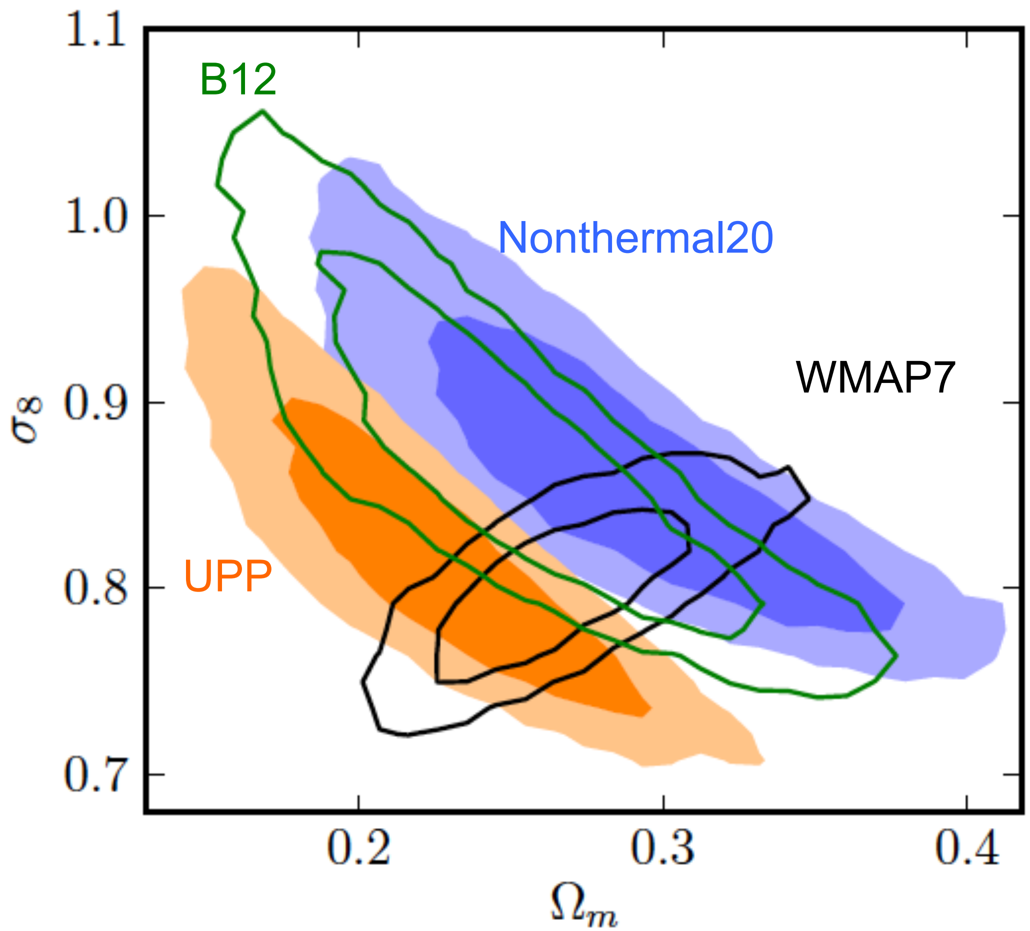
- **Hasselfield et al. (2013)**: catalog selected from 504deg^2 survey.
- ACT maps at 148GHz.
- 68 candidates, 19 new discoveries

Scalings relations:

UPP – Arnaud et al (2010)

B12 – Recalibration using Bode et al. (2012) simulations.

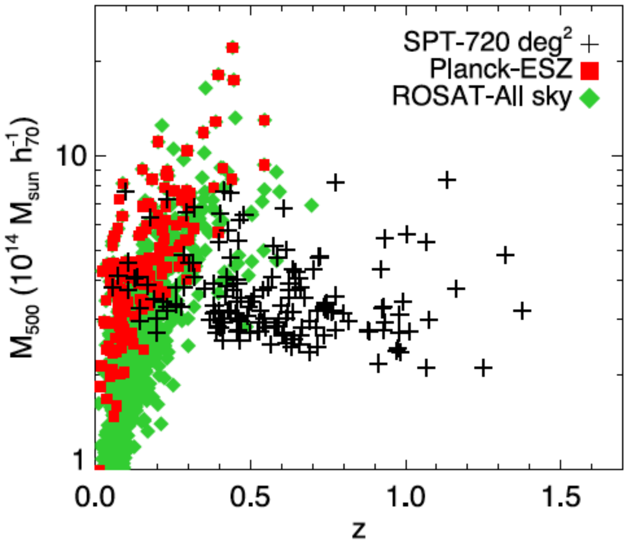
Nonthermal20 – Recalibration using one model from Trac et al. (2011).

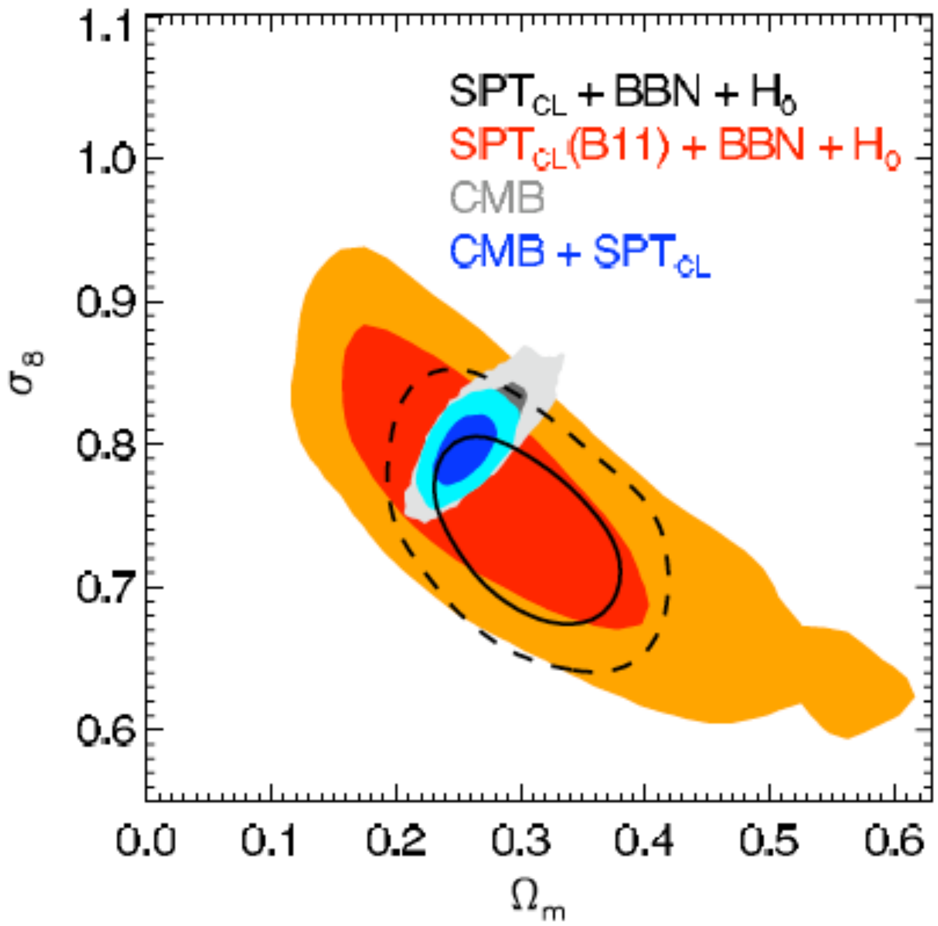


Data set	$\Omega_c h^2$	Ω_m	Parameter (wCDM) σ_8	h	w
Without ACT Cluster Data					
WMAP7	0.111 ± 0.006	0.259 ± 0.096	0.832 ± 0.134	0.753 ± 0.131	-1.117 ± 0.394
WMAP7 + SNe	0.111 ± 0.006	0.276 ± 0.020	0.791 ± 0.042	0.697 ± 0.016	-0.969 ± 0.054
Dynamical Mass Constraints					
WMAP7 + ACTcl(dyn)	0.116 ± 0.005	0.237 ± 0.080	0.921 ± 0.108	0.792 ± 0.119	-1.306 ± 0.356
WMAP7 + ACTcl(dyn) + SNe	0.115 ± 0.004	0.289 ± 0.017	0.835 ± 0.034	0.691 ± 0.014	-1.011 ± 0.052

Galaxy clusters from the SPT survey

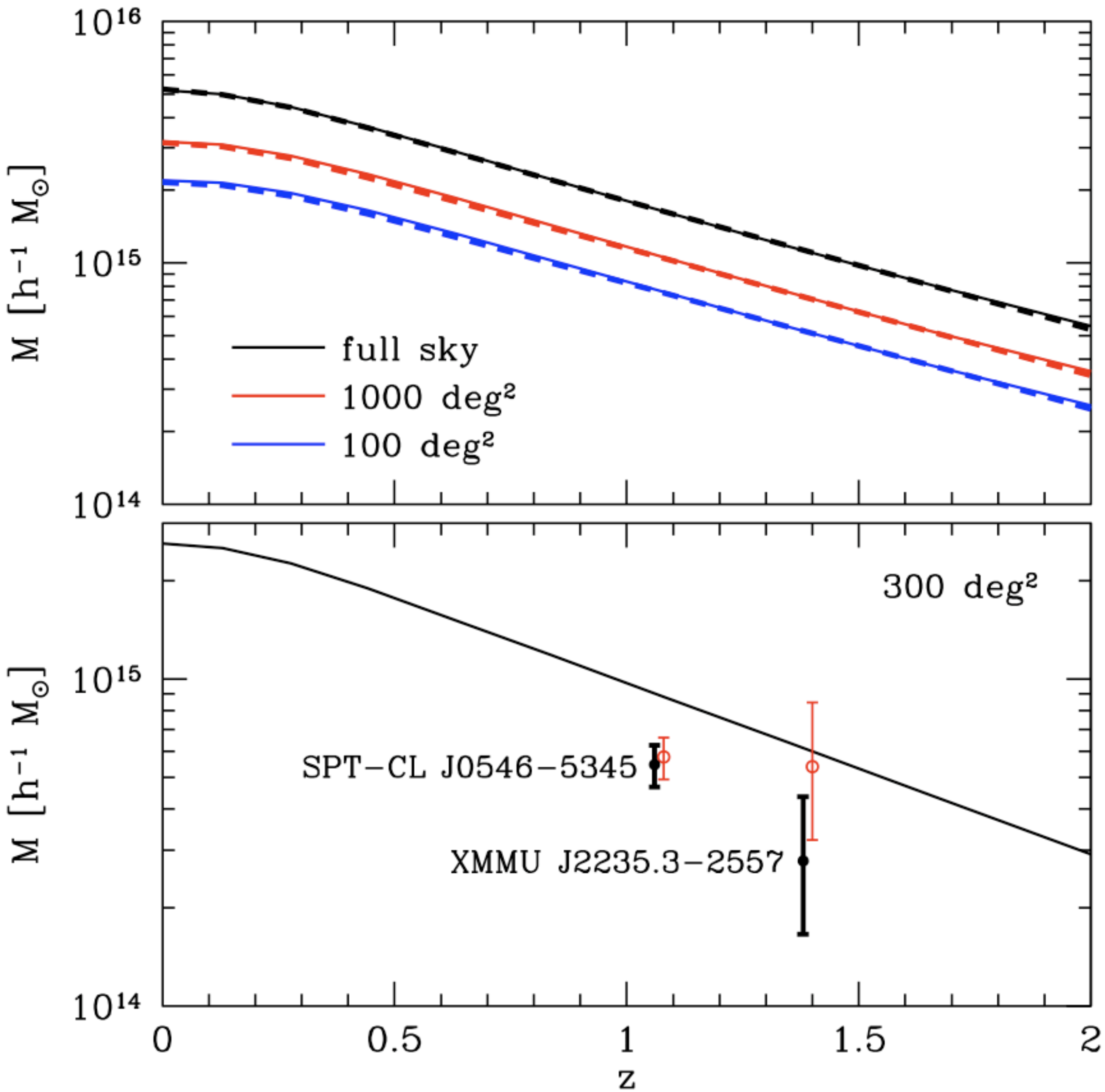
- **Reichard et al. (2013)**: catalog selected from 720 deg^2 SPT survey.
- SPT maps at 150GHz and 95GHz.
- 224 candidates, 158 confirmed (117 new discoveries).
- Scaling laws from Vikhlinin et al. (2009).



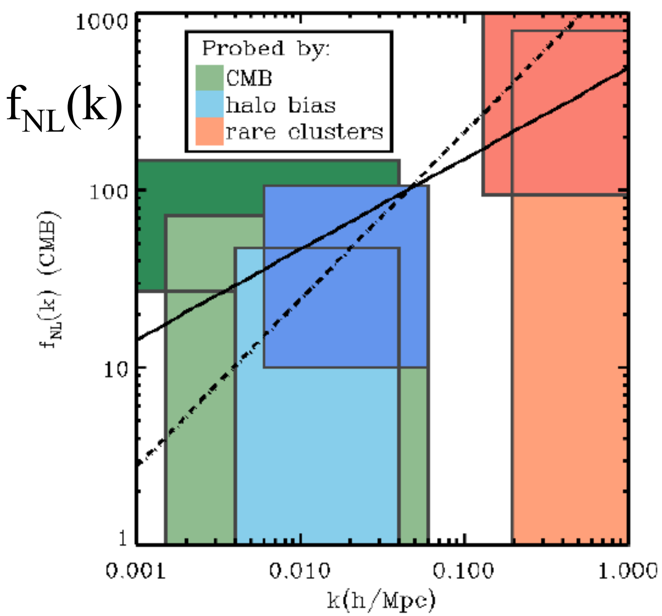


	ΛCDM		wCDM		$\sum m_\nu$	
	CMB	+SPT_{CL}	CMB + BAO + H_0 + SNe	+ SPT_{CL}	CMB + BAO + H_0	+ SPT_{CL}
$\Omega_c h^2$	0.1109 ± 0.0048	0.1086 ± 0.0031	0.1140 ± 0.0041	0.1104 ± 0.0029	0.1113 ± 0.0030	0.1113 ± 0.0025
σ_8	0.808 ± 0.024	0.798 ± 0.017	0.840 ± 0.038	0.807 ± 0.027	0.775 ± 0.041	0.766 ± 0.028
Ω_m	0.267 ± 0.026	0.255 ± 0.016	0.269 ± 0.014	0.262 ± 0.013	0.274 ± 0.016	0.275 ± 0.015
H_0	70.71 ± 2.17	71.62 ± 1.53	71.20 ± 1.49	71.15 ± 1.51	69.83 ± 1.36	69.76 ± 1.31
w			-1.054 ± 0.073	-1.010 ± 0.058		
$\sum m_\nu$ (95% CL)					<0.44	<0.38

Falsifying ΛCDM with Cluster Counts



- High-mass, high-redshift clusters tests extreme tail of the matter power spectrum.
- Even a single massive cluster could indicate tension with ΛCDM (Mortonson, Hu, Huterer 2010).
- Large non-Gaussianity in the initial conditions can influence the large scale structure (Dalal et al. 2008). See Hoyle, Jimenez & Verde (2011)



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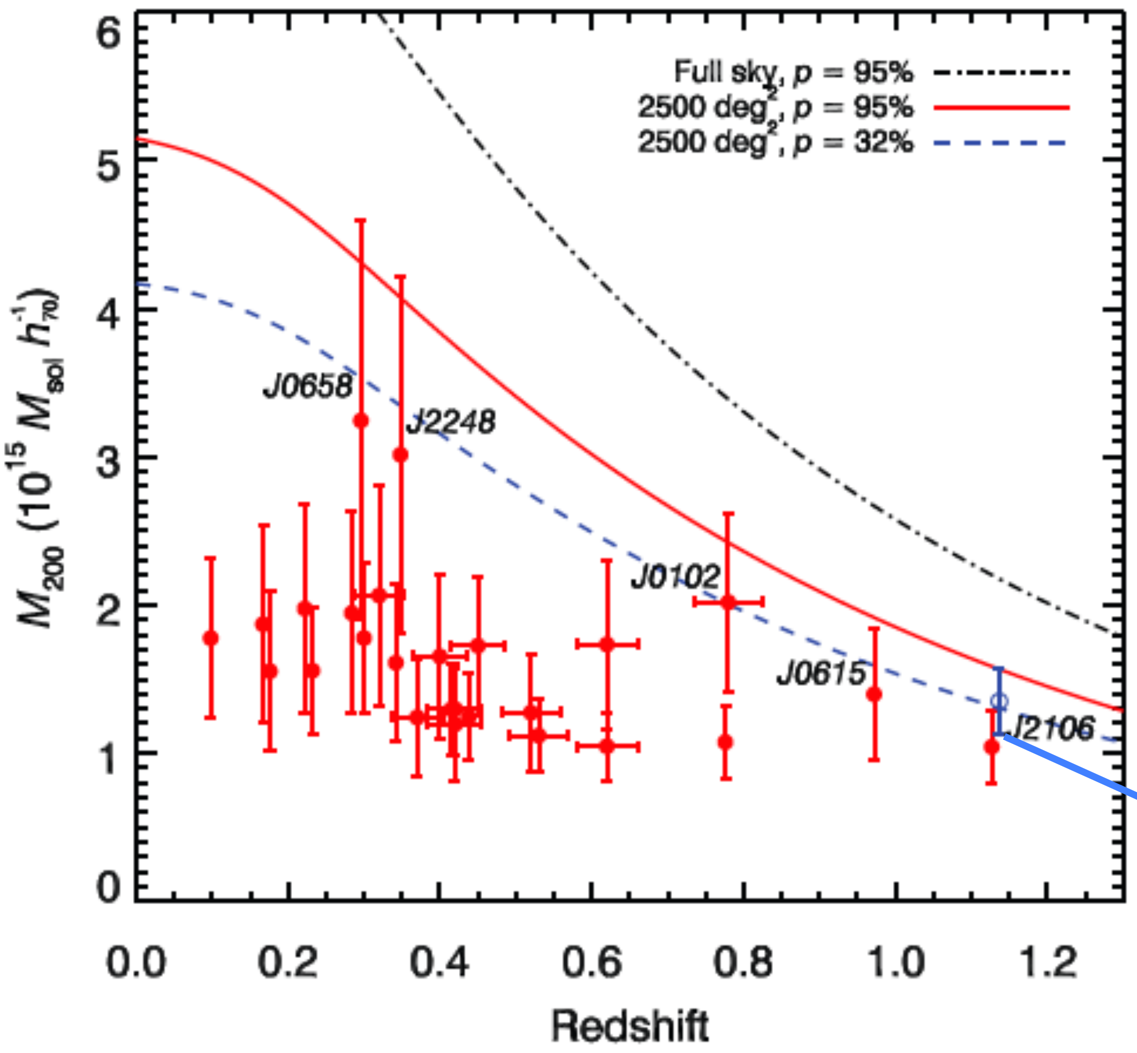
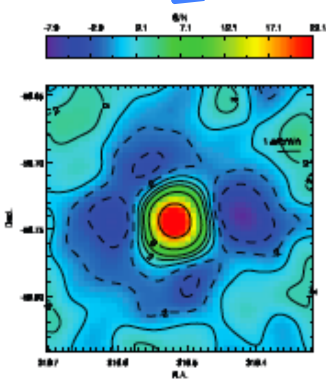
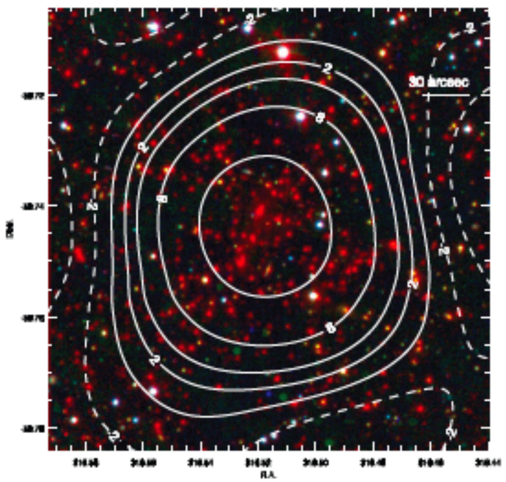


The 26 most significant (most massive) clusters over the full 2500 deg^2 SPT survey (Williamson et al. 2011).

They find:

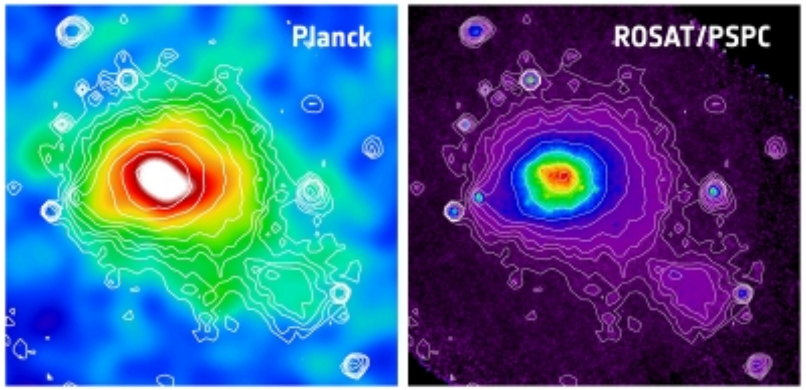
- 7% chance of finding SPT-CL J2106-5844 (z=1.133)
- Consistency with ΛCDM.
- Consistency with initial Gaussian density fluctuations.





Galaxy cluster physics and cosmology with PLANCK

I. The Sunyaev-Zeldovich effect and the Planck survey
   I. The ESZ and PSZ1 samples
   II. Validation of the catalogues
   III. XMM-Newton and optical follow-up efforts.
   IV. Cosmology with Planck SZ cluster counts
II. Baryons in clusters and Cluster masses. Scaling laws.
III. Cosmology with the y-map.
IV. Kinetic SZ effect.



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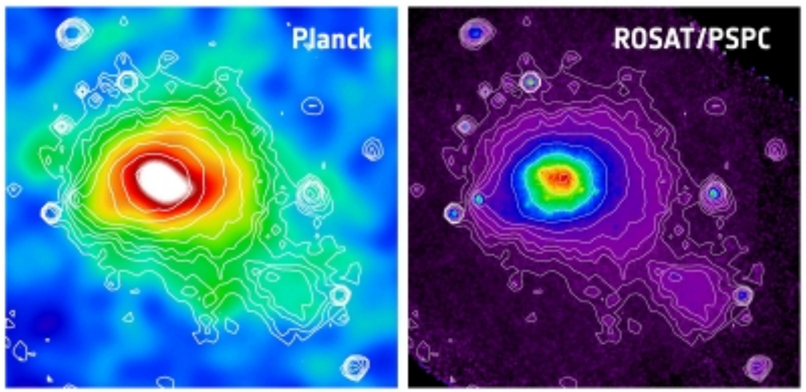
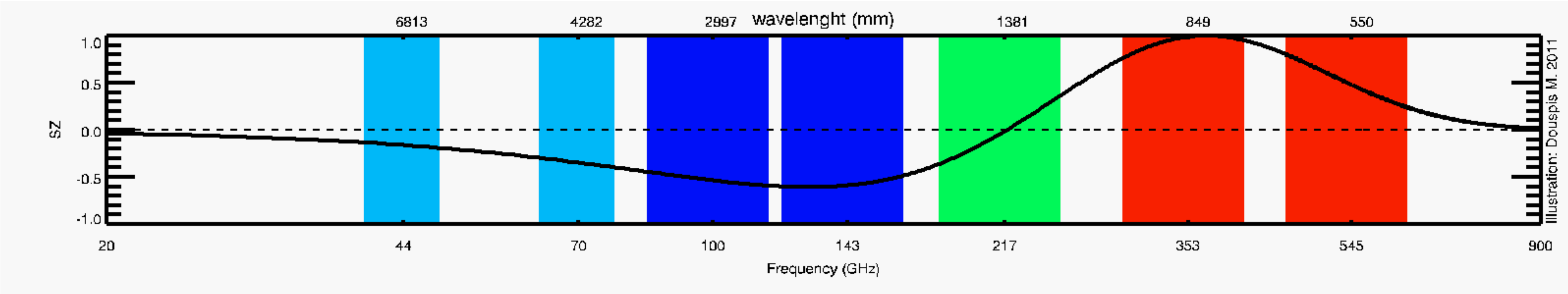
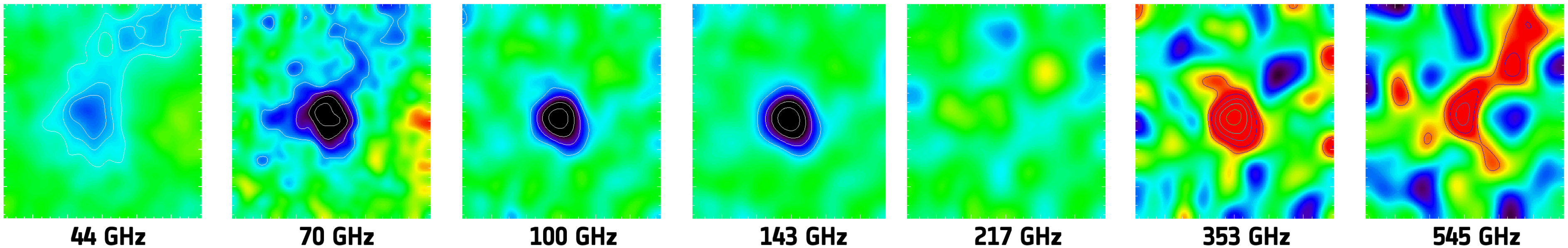


Planck: Uniqueness for SZ studies

- **First all-sky SZ survey.** (Last all-sky survey for clusters was ROSAT in 1992)
- Frequency range from 30GHz to 857GHz, with a channel at 217GHz.
- Blind detection of the positive effect.

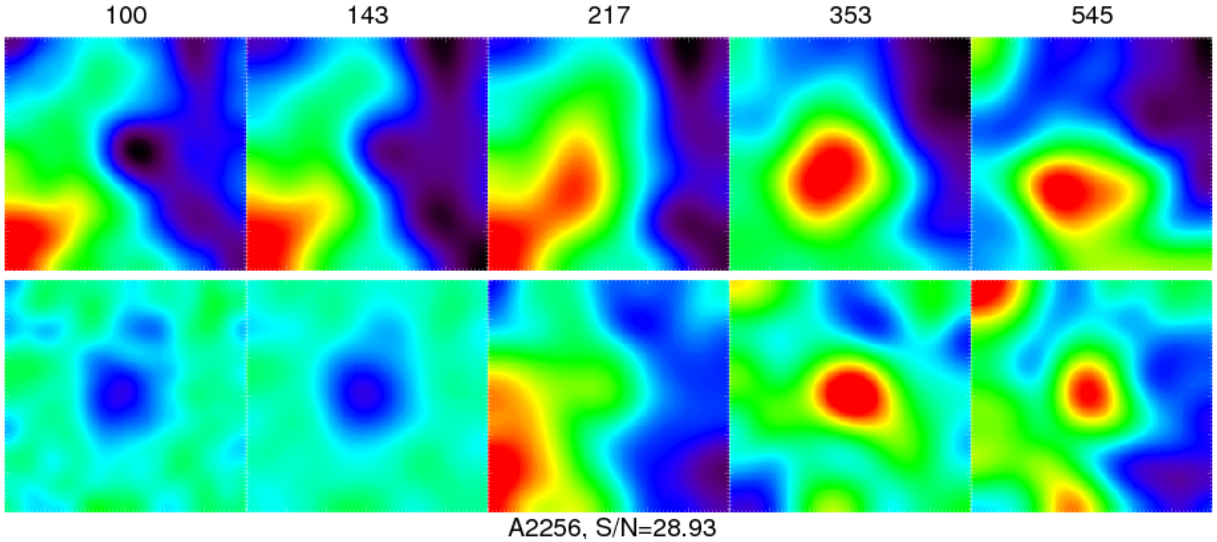
    ➔PLANCK, designed from start to measure SZ.





A2319 seen by PLANCK

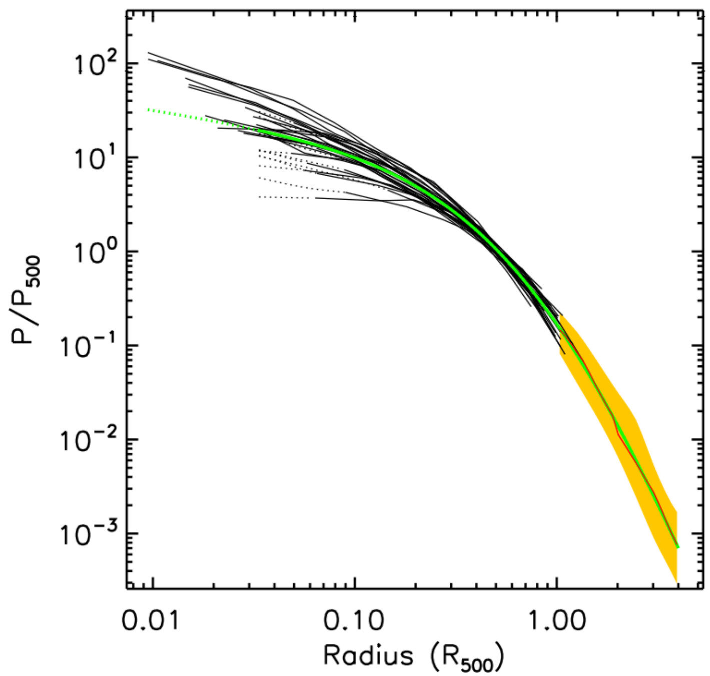
Cluster identification with PLANCK



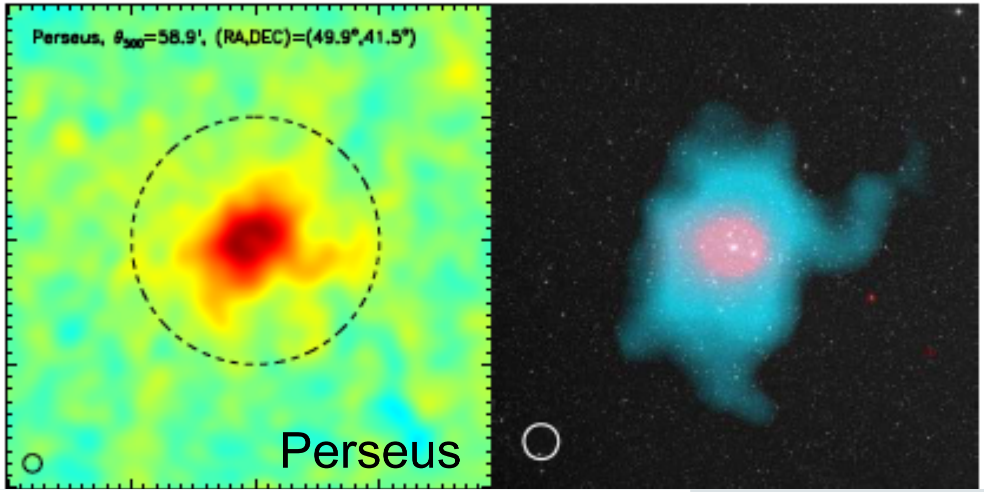
Raw maps

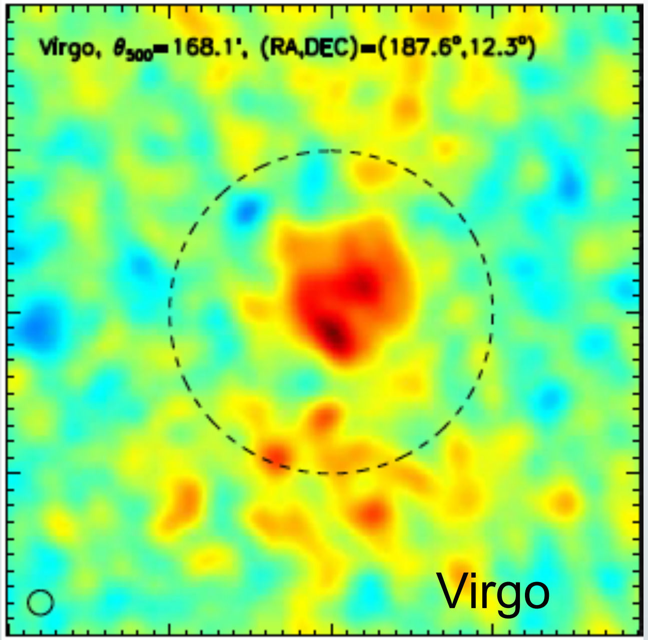
Cleaned maps (correcting for dust and CMB emission)

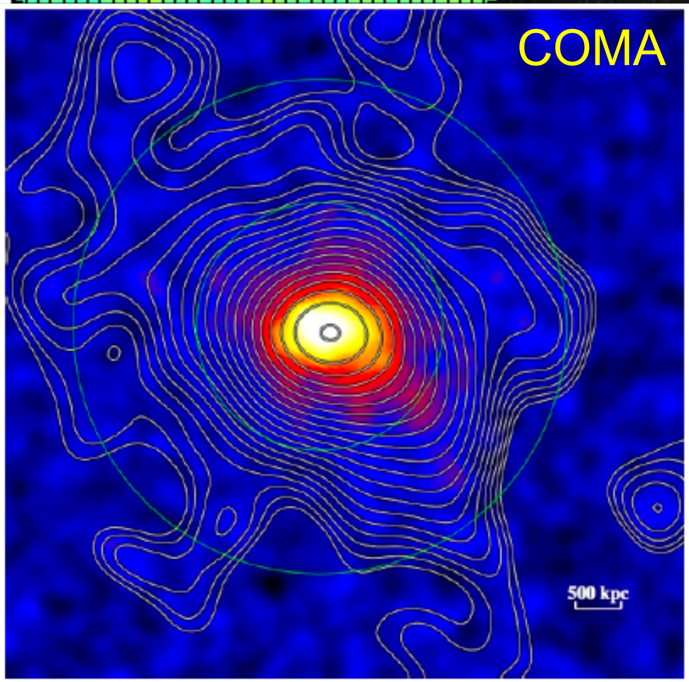
- Low significance of detections in individual cleaned frequency maps.
- **Adapted extraction technique: Matched Multi-Filter** (Herranz et al. 2002; Melin et al. 2006) enhances SZ signal over other components:
    - known spectrum: non-relativistic SZ.
    - known cluster shape: GNFW pressure profile (Arnaud et al. 2010)

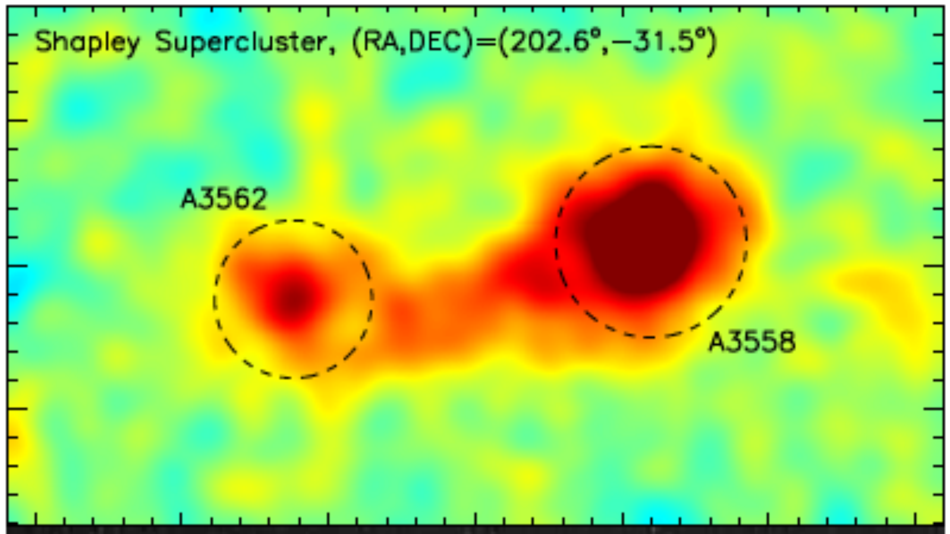


Planck SZ cluster catalogue



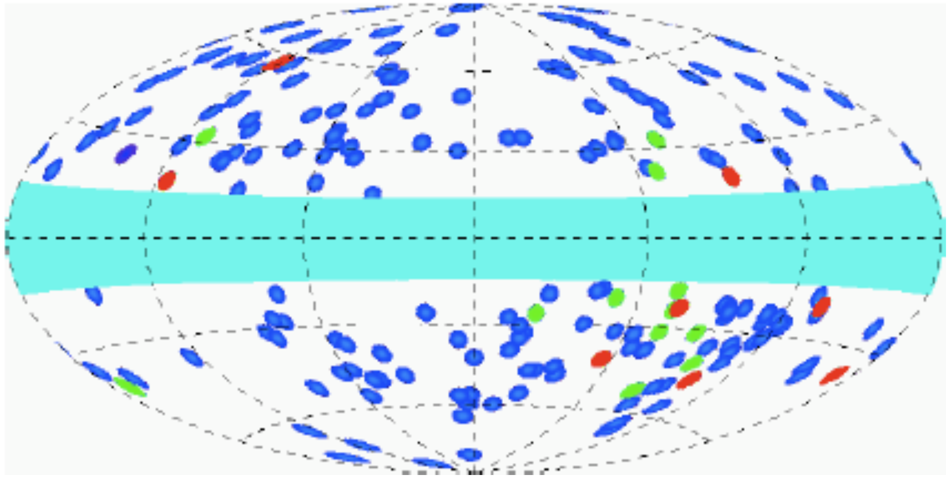




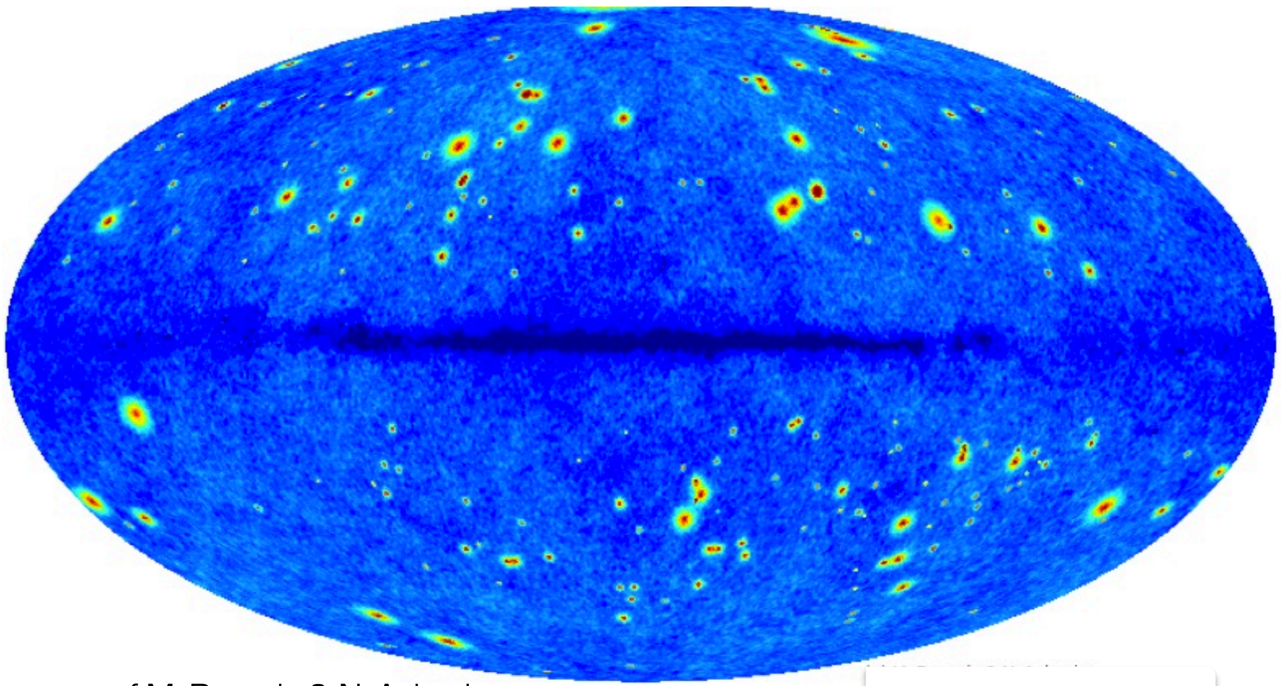


Planck Early Results: the all-sky ESZ cluster sample

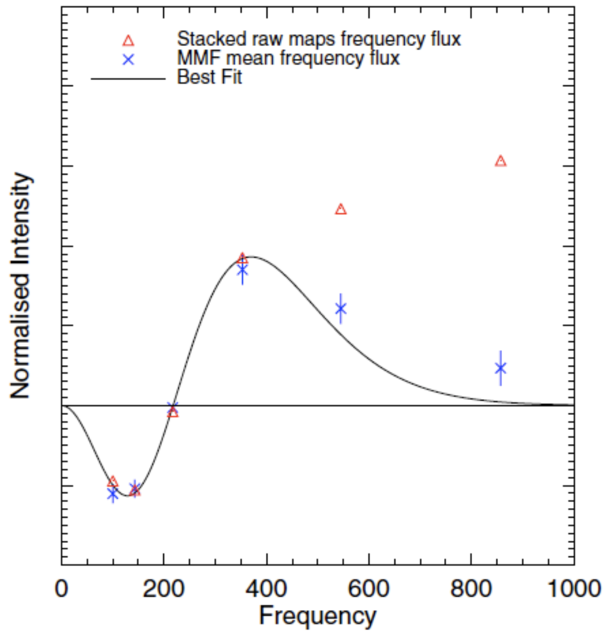
- **Early SZ sample: a high reliability sample** from the first 10 months of observations.
- **189** candidates in total (with |b| >14deg and MMF type **S/N from 6 to 29** => **purity > 95%**)
- 169 candidates identified with known X-ray or optical clusters. For ~80% of them, Planck provides the first SZ measure.
- 20 candidates new clusters.



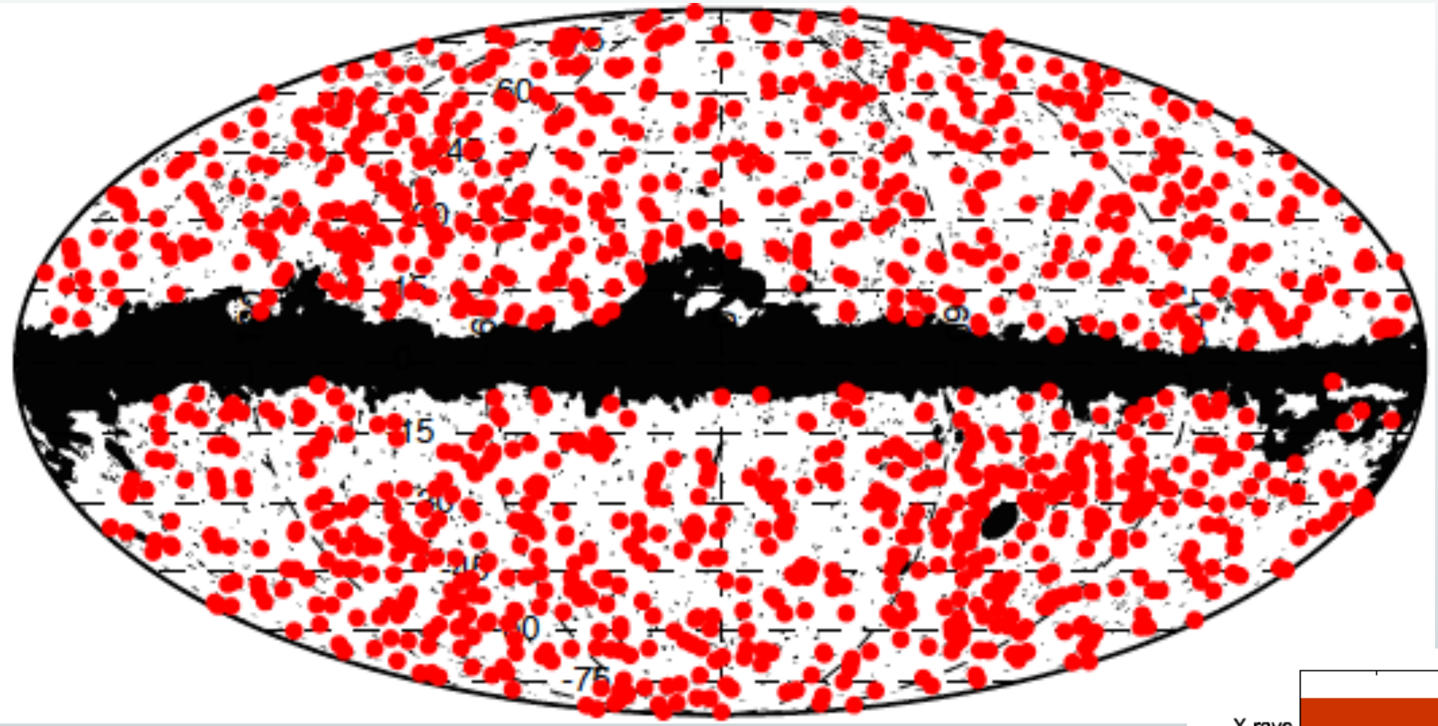
(Planck Collaboration VIII, 2011)

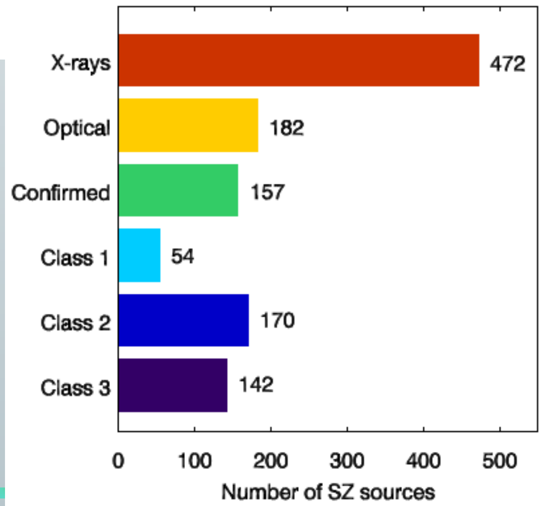


Courtesy of M. Douspis & N. Aghanim



Planck SZ cluster catalogue (PSZ1)



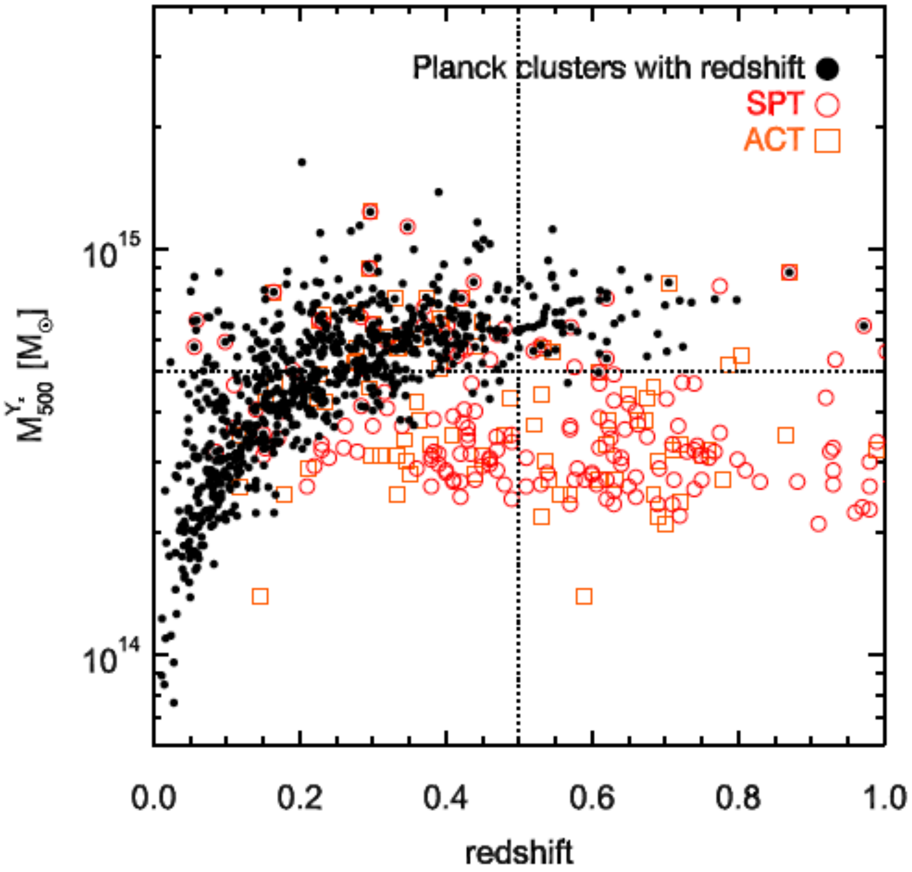


- Based on nominal mission data. Published in March 2013.
- New all-sky catalogue of 1227 SZ sources, the largest to date.
- Confirmed galaxy clusters: 861 (of which 178 are new).
- Candidate clusters: 366.
- Mass and redshift estimates for 813 clusters.

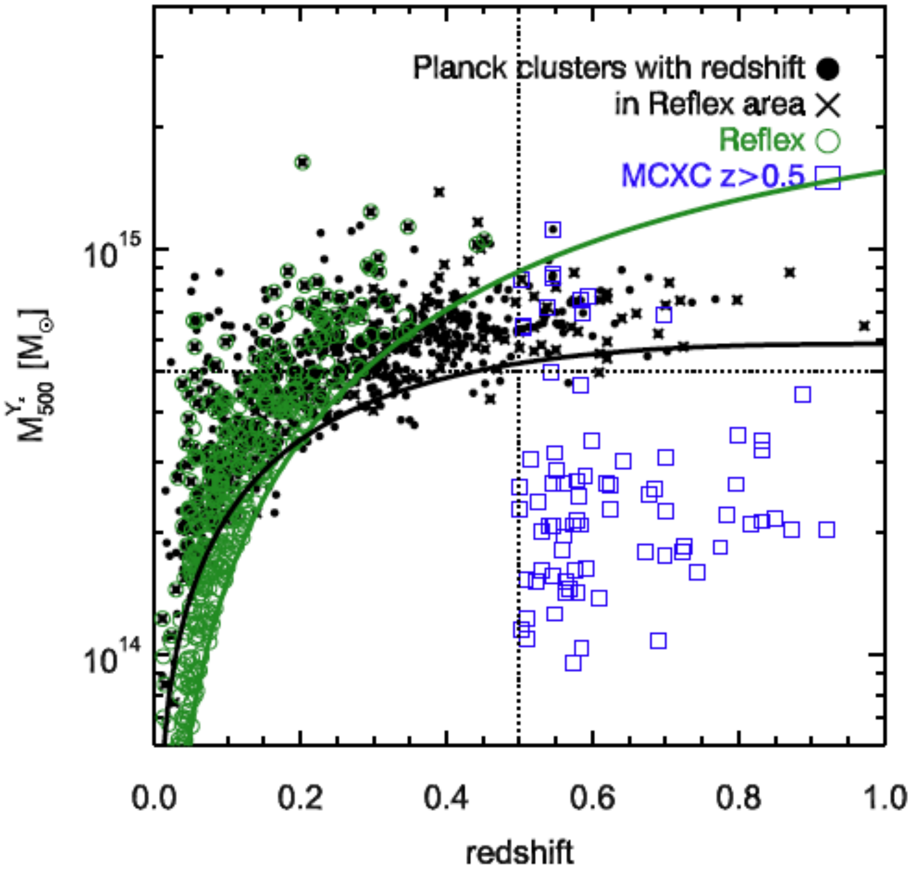
(Planck Collaboration XXIX 2013)

PSZ1 vs other surveys

Mass – redshift space



PSZ1 sample compared to other SZ samples



PSZ1 clusters previously known in X-rays

Planck´s unique capability **to detect rarest and most massive clusters** over the whole sky.

Validation of the SZ samples

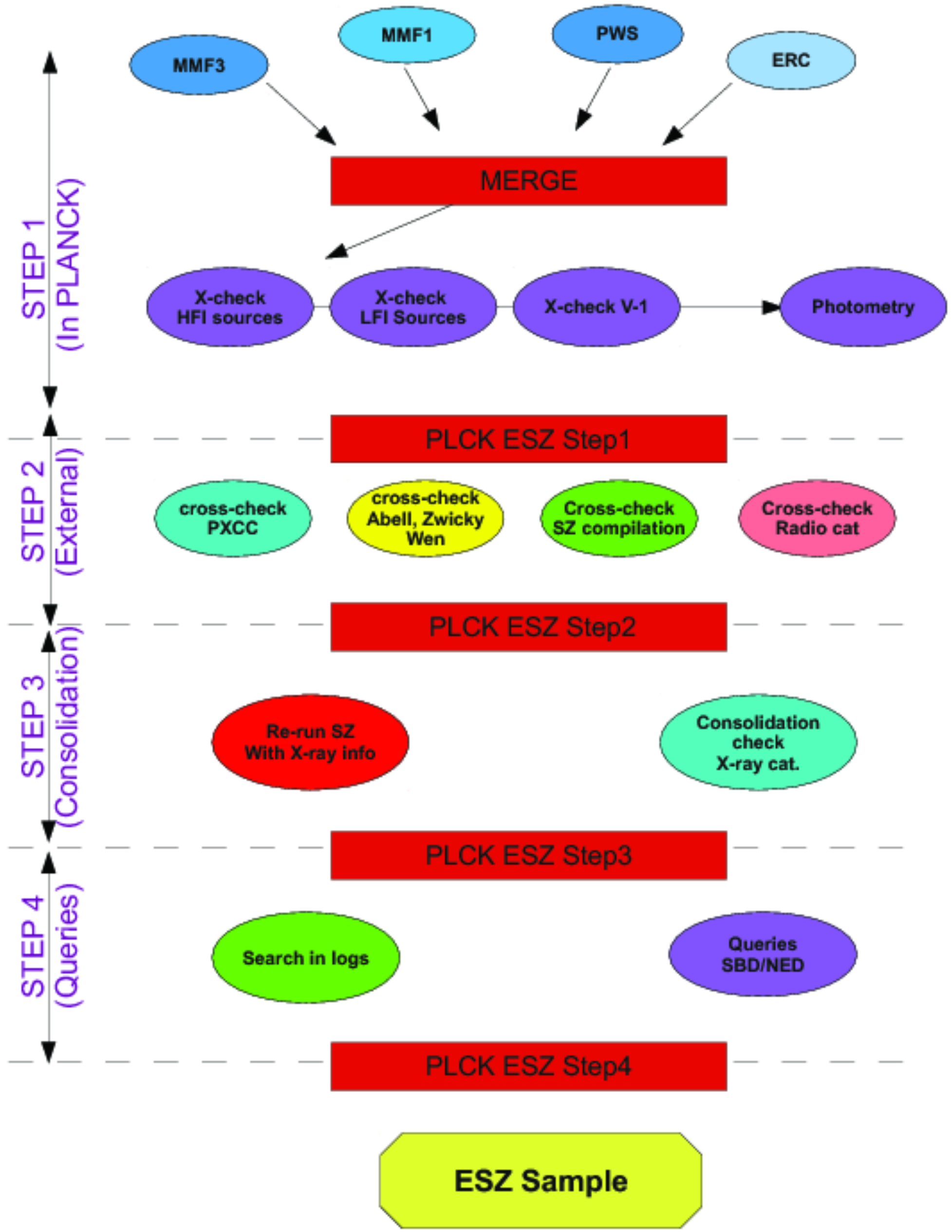
Planck internal quality assessment

- Redundant detection of candidates
- Search for and rejection of solar system objects, artefacts, galactic sources, etc.

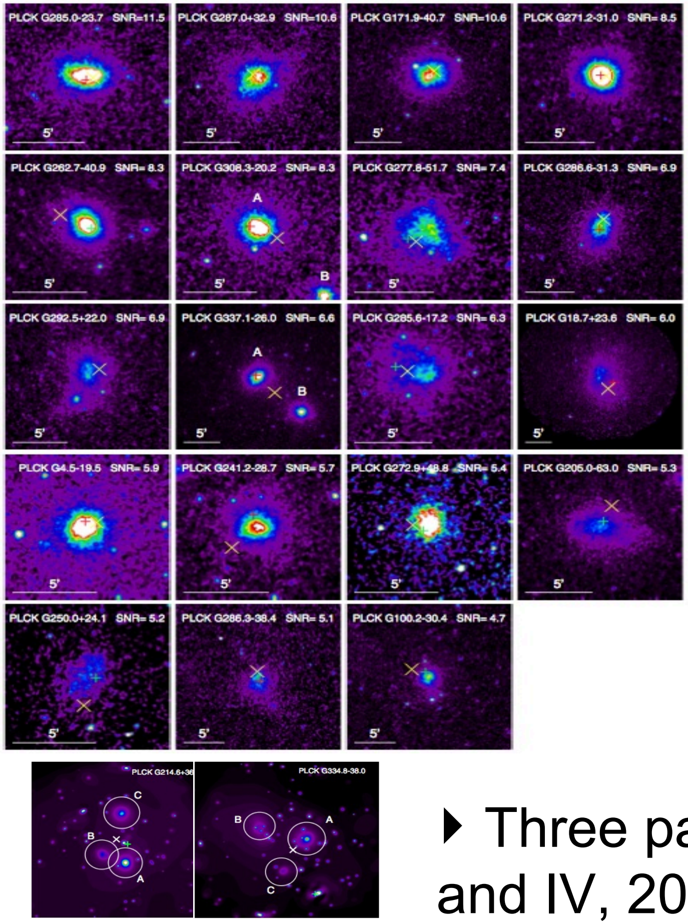
Identification with known clusters from ancillary data

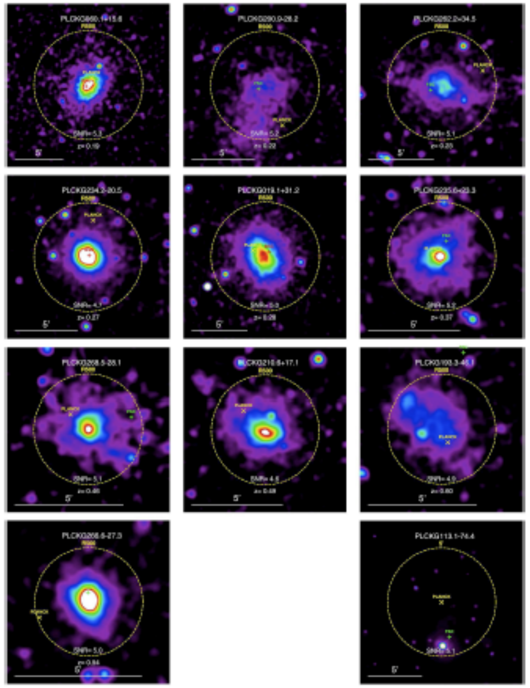
Multi-frequency follow-up programme for confirmation of SZ candidates:

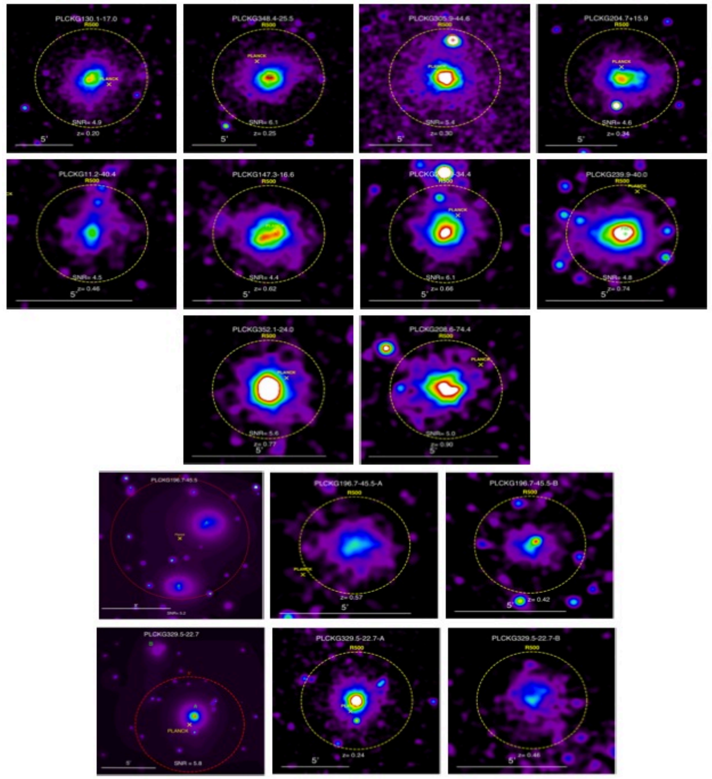
- Optical (ENO, ESO, Palomar)
- SZ (AMI).
- X-rays, with XMM-Newton



XMM-Newton follow-up/validation programme



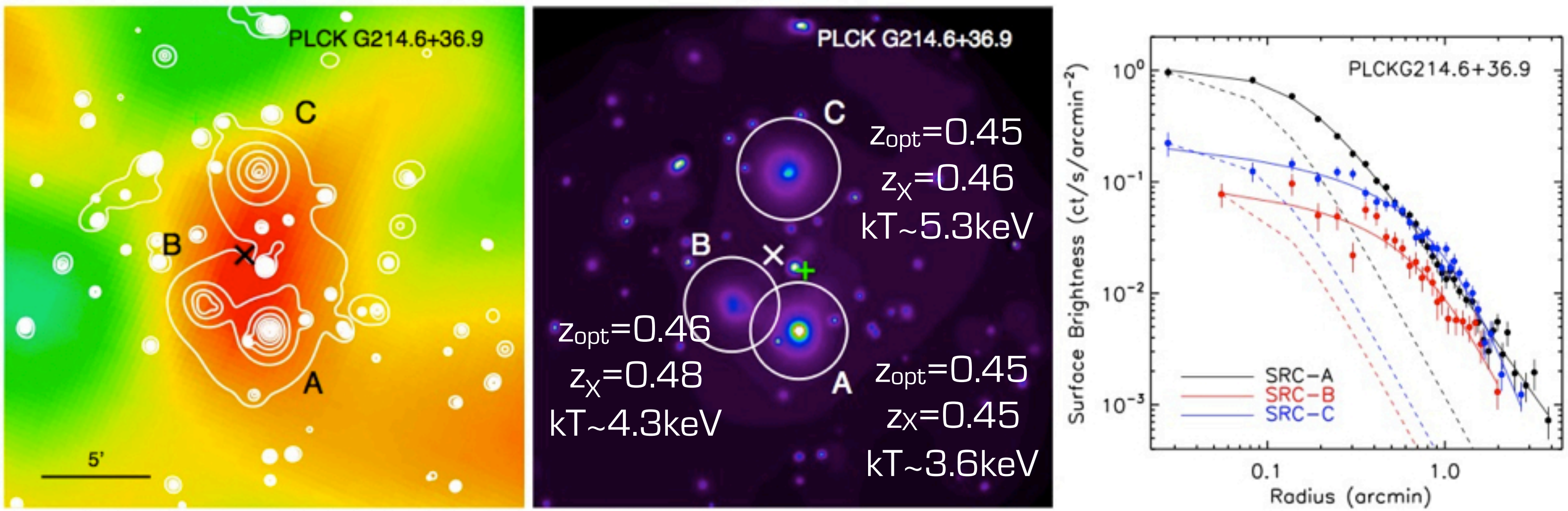




- Three papers (Early Paper IX 2011, Intermediate Papers I and IV, 2012).
- High success rate (>85% are real candidates)
- 51 targets confirmed
- 70% disturbed morphologies (compared to 30% for X-ray selected clusters, see e.g. REXCESS)
- 4 double and 2 triple systems (12% multiple systems)

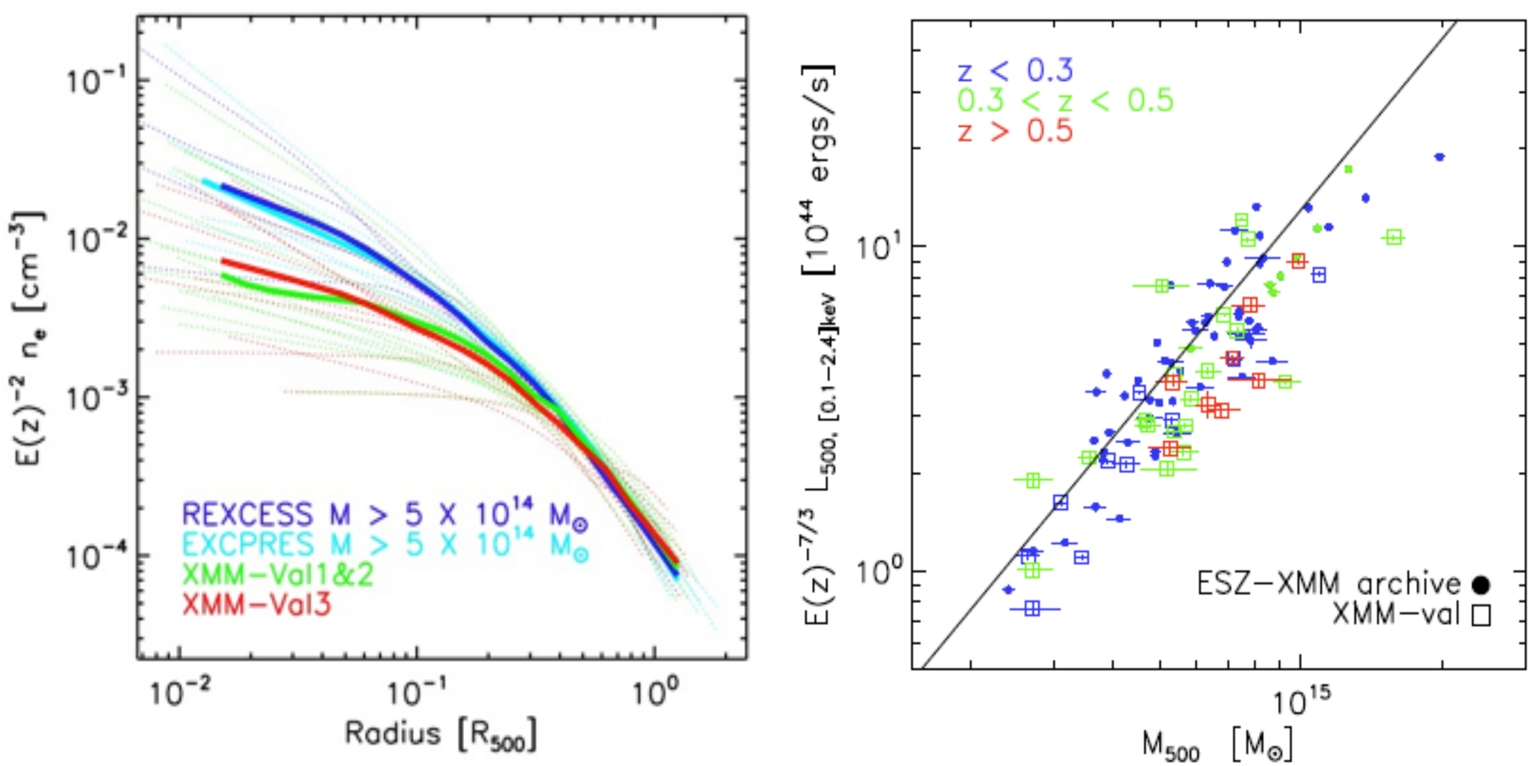
Multiple systems

Blind SZ detection of super-clusters (SC)



Physics : probably boosted by merger shocks?
Cosmology: how many ? must we take SC in the 'selection' function?

Physical characterization of Planck clusters

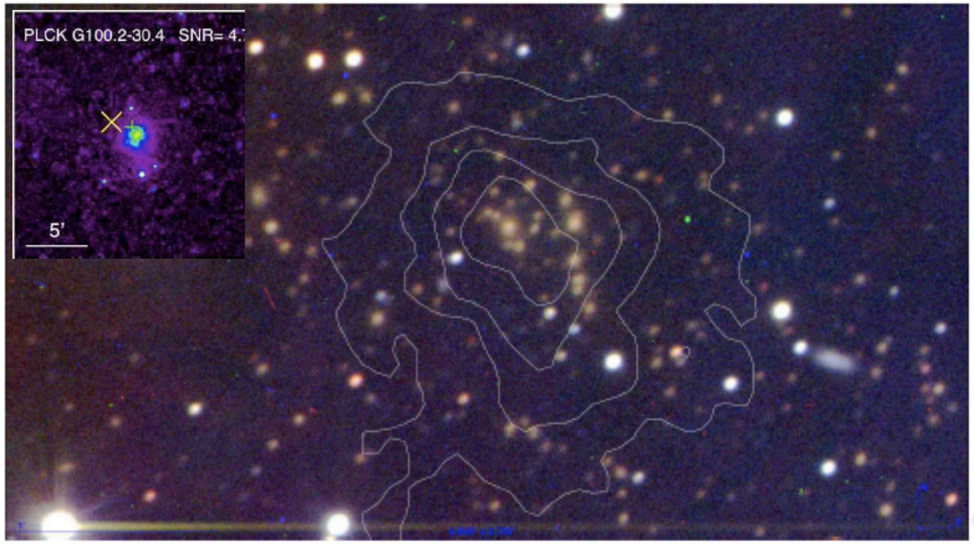


- Large variety of dynamical states with **new clusters more disturbed and (X-ray) under-luminous** (at all redshifts)

Strong synergy between Planck and XMM data

Optical Follow-up of Planck clusters

ENO/IAC80

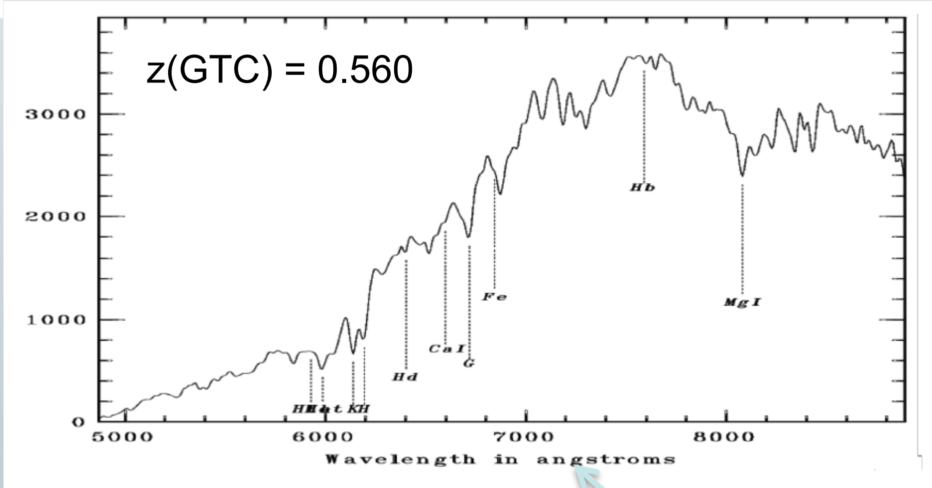


Optical follow-up and validation programmes (>300 candidates) in:

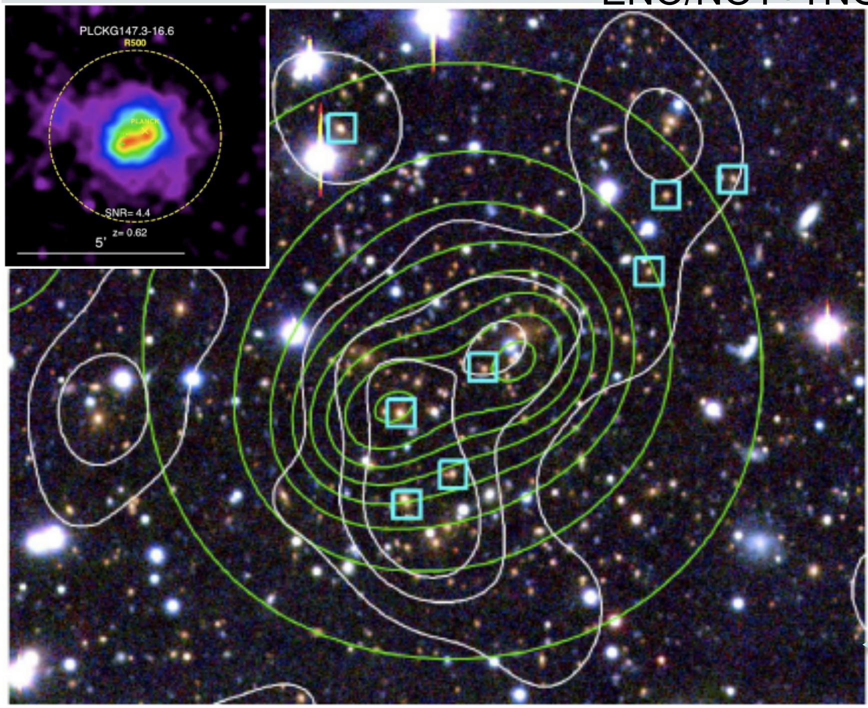
- Canary Islands Observatories
- ESO
- Palomar
- RTT

z(Fe K) = 0.31
z_{phot}=0.34±0.03

ENO/GTC

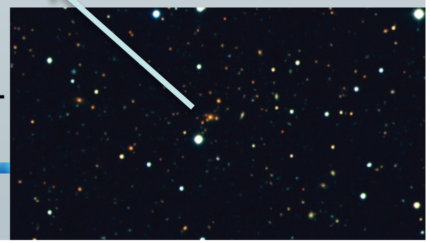


ENO/NOT+TNG

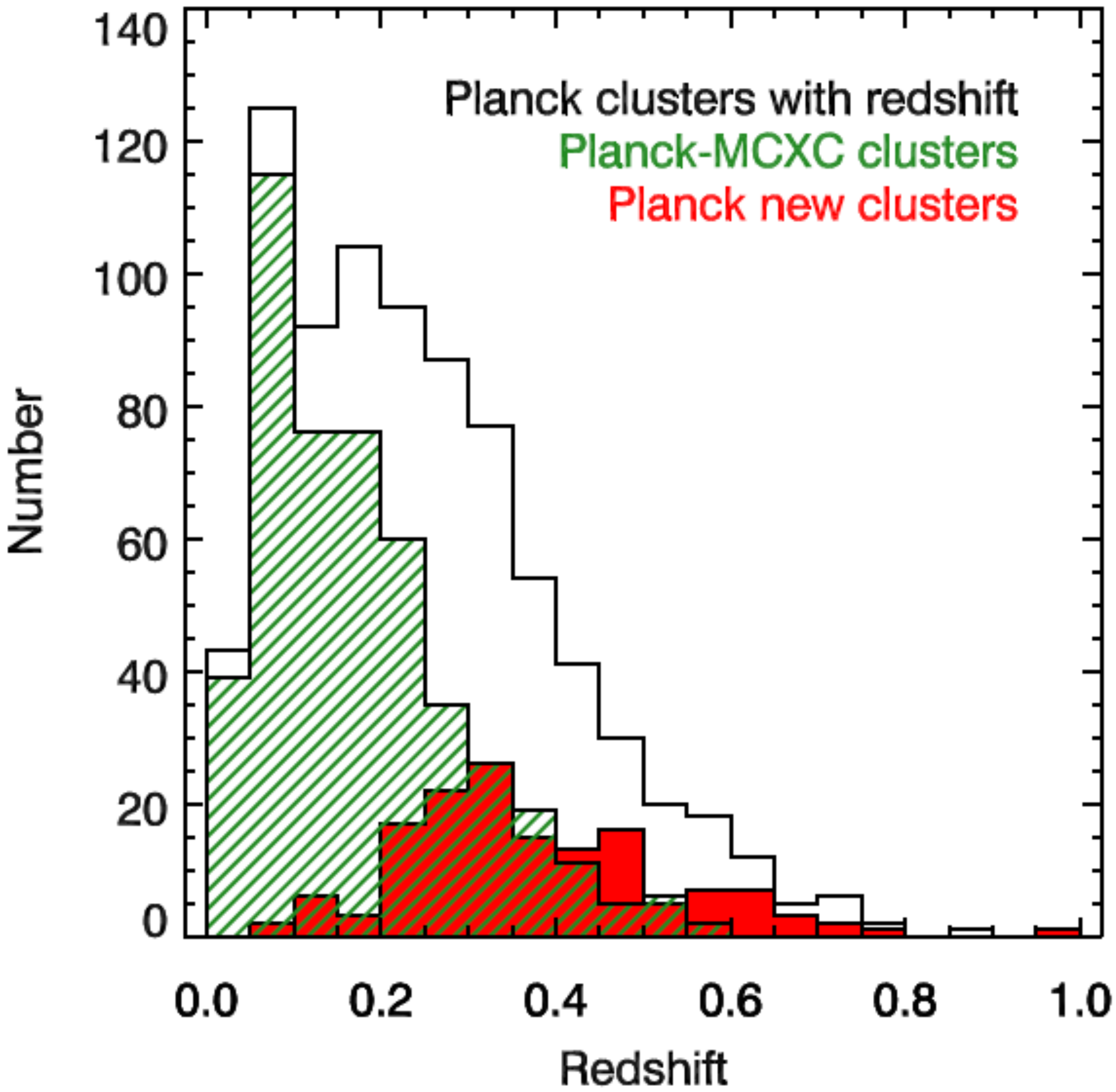


z(Fe K) = 0.62
z_{spec} = 0.66±0.05
(Gemini)

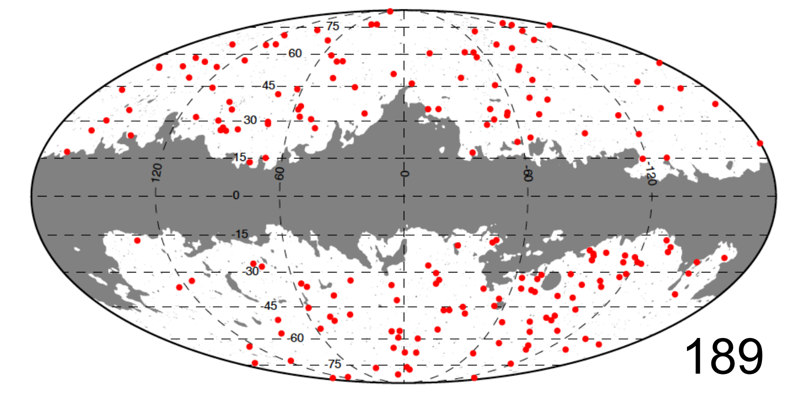
ENO/INT



Planck SZ follow-up program

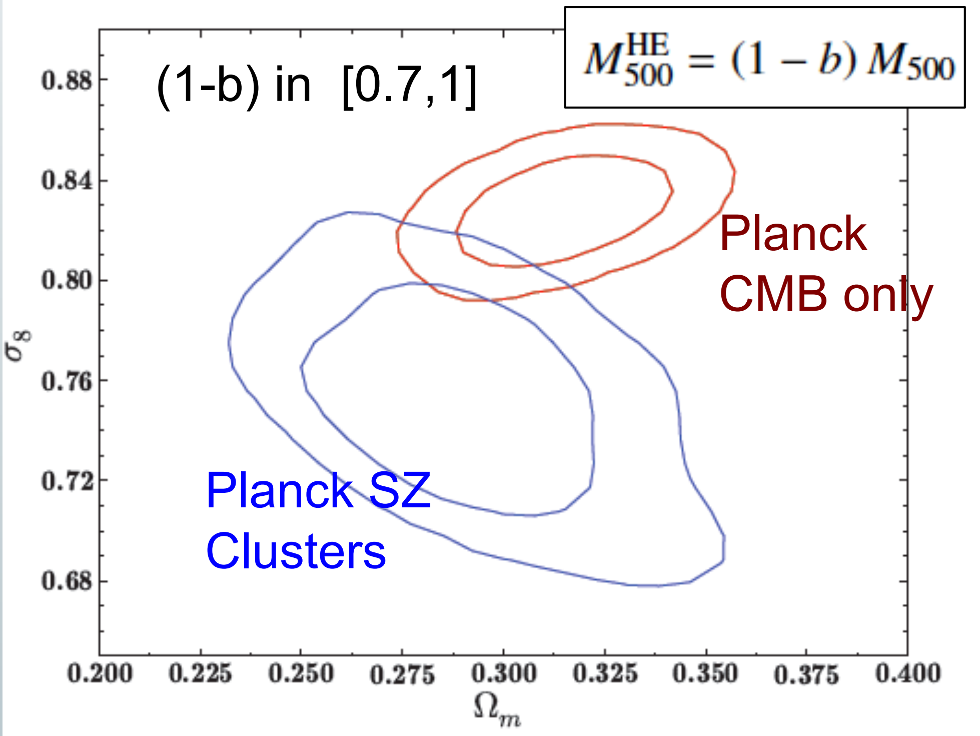


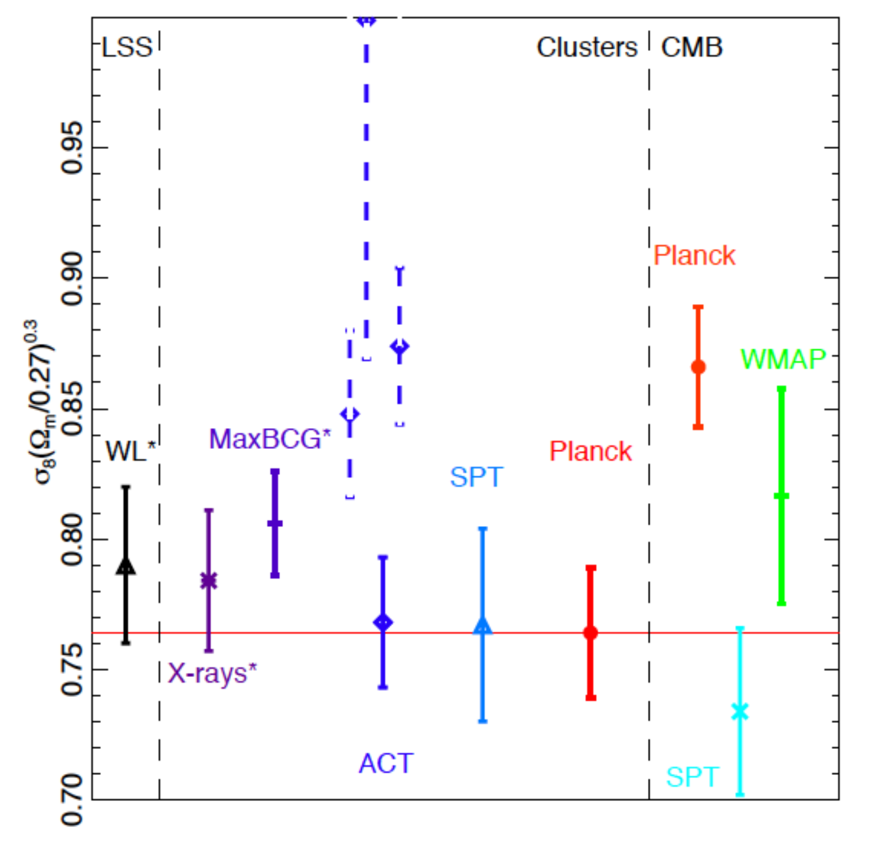
Cosmology with galaxy clusters



Observations: N(z)

Theoretical Ingredients: halo mass function, scaling relations to predict M and z; completeness and selection function of the survey.





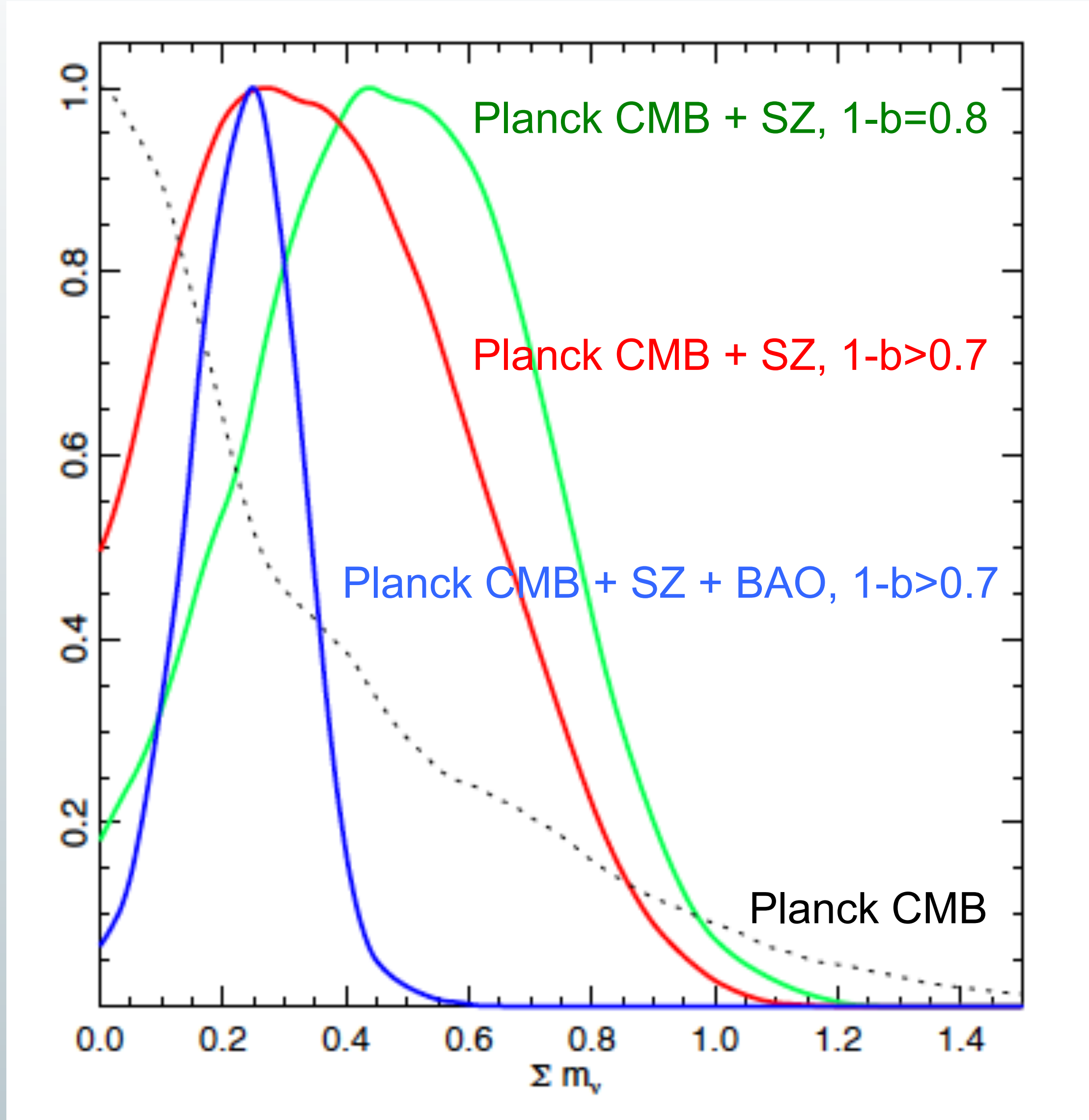
Cosmology with galaxy clusters

- Tension between the CMB and the SZ clusters result.
- The cluster result depends critically on the value of (1-b).
- But there is consistency between Planck and other SZ surveys.

Experiment	CPPP[a]	MaxBCG[b]	ACT[c]	SPT	*Planck* SZ
Reference	Vikhlinin et al. (2009b)	Rozo et al. (2010)	Hasselfield et al. (2013)	Reichardt et al. (2013)	This work
Number of clusters	49+37	~13000	15	100	189
Redshift range	[0.025, 0.25] and [0.35, 0.9]	[0.1, 0.3]	[0.2, 1.5]	[0.3, 1.35]	[0.0, 0.99]
Median mass ($10^{14}h^{-1}M_\odot$)	2.5	1.5	3.2	3.3	6.0
Probe	$N(z, M)$	$N(M)$	$N(z, M)$	$N(z, Y_X)$	$N(z)$
S/N cut	5	$(N_{200} > 11)$	5	5	7
Scaling	Y_X–T_X, M_{gas}	N_{200}–M_{200}	several	L_X–M, Y_X	Y_{SZ}–Y_X
$\sigma_8(\Omega_m/0.27)^{0.3}$	0.784 ± 0.027	0.806 ± 0.033	0.768 ± 0.025	0.767 ± 0.037	0.764 ± 0.025

[a] The degeneracy is $\sigma_8(\Omega_m/0.27)^{0.47}$.
[b] The degeneracy is $\sigma_8(\Omega_m/0.27)^{0.41}$.

Cosmology with galaxy clusters



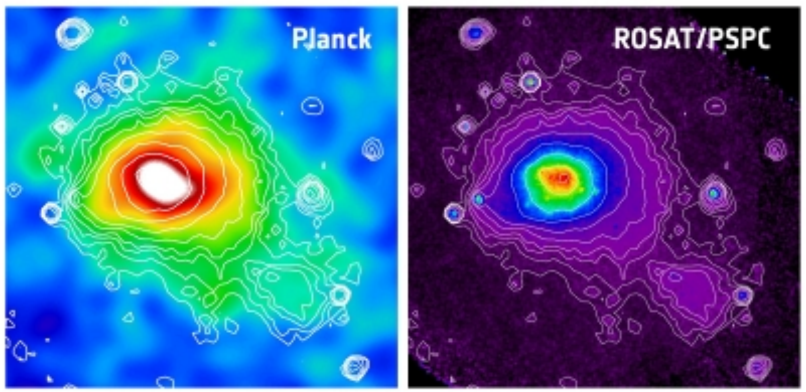
Galaxy cluster physics and cosmology with PLANCK

I. The Sunyaev-Zeldovich effect and the Planck survey
  I. The ESZ and PSZ1 samples
  II. Validation of the catalogues
  III. XMM-Newton and optical follow-up efforts.
  IV. Cosmology with Planck SZ cluster counts

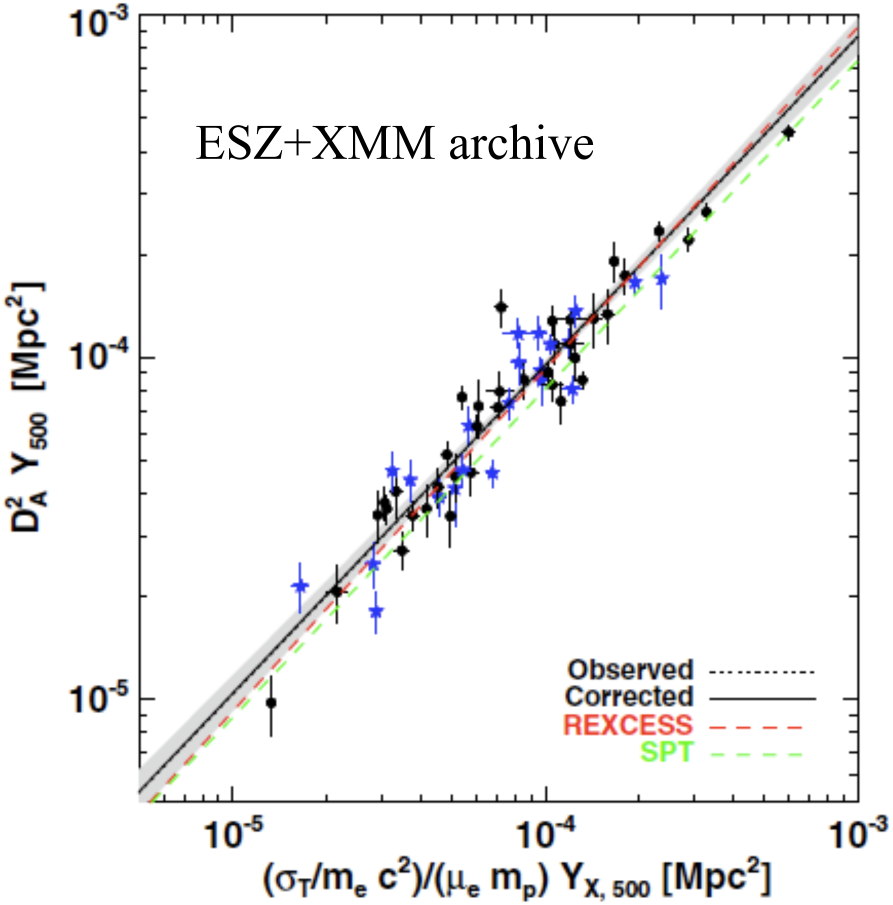
II. Baryons in clusters and Cluster masses. Scaling laws.

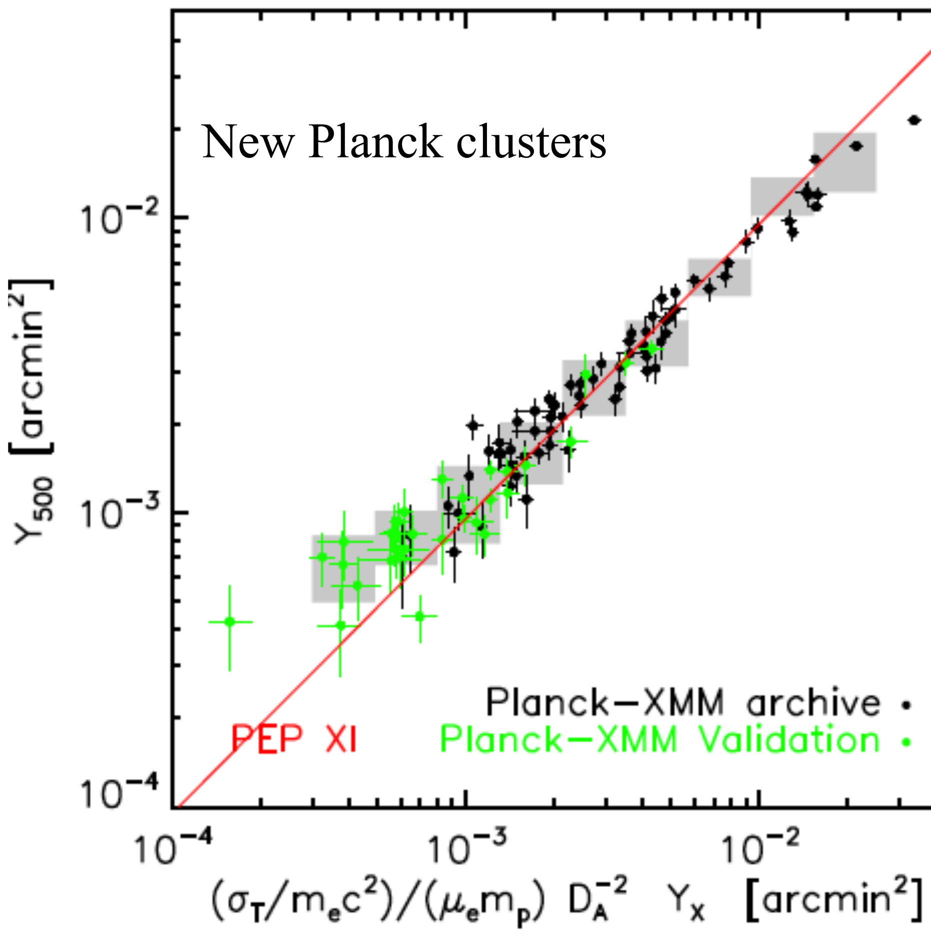
III. Cosmology with the y-map.

IV. Kinetic SZ effect.



SZ vs X-ray scaling relations



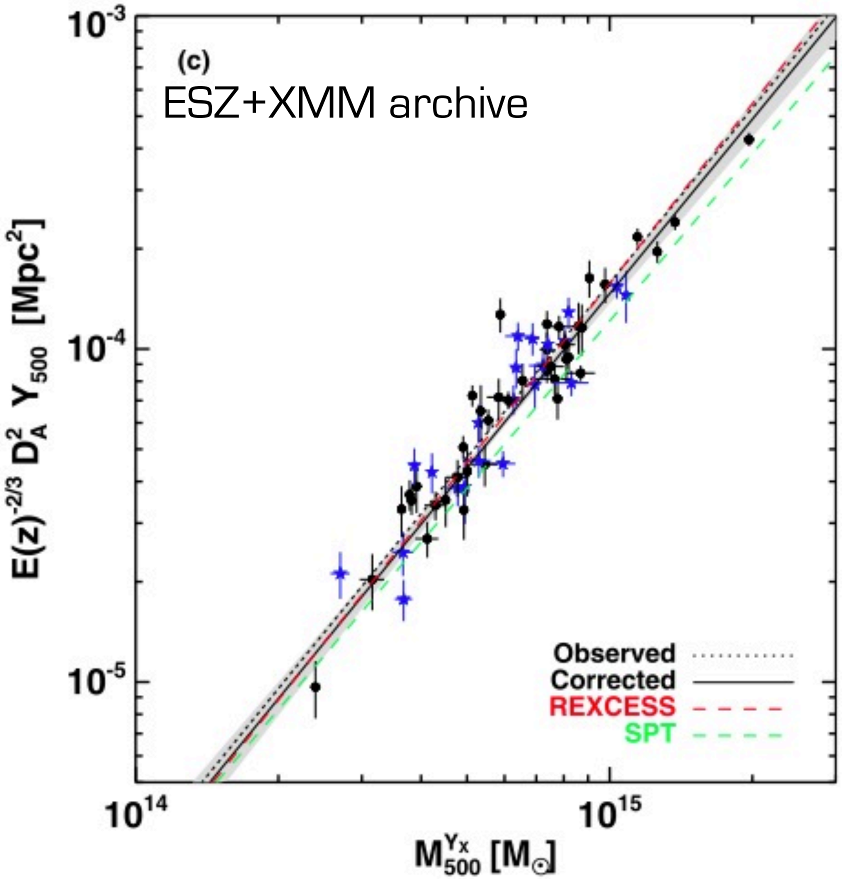


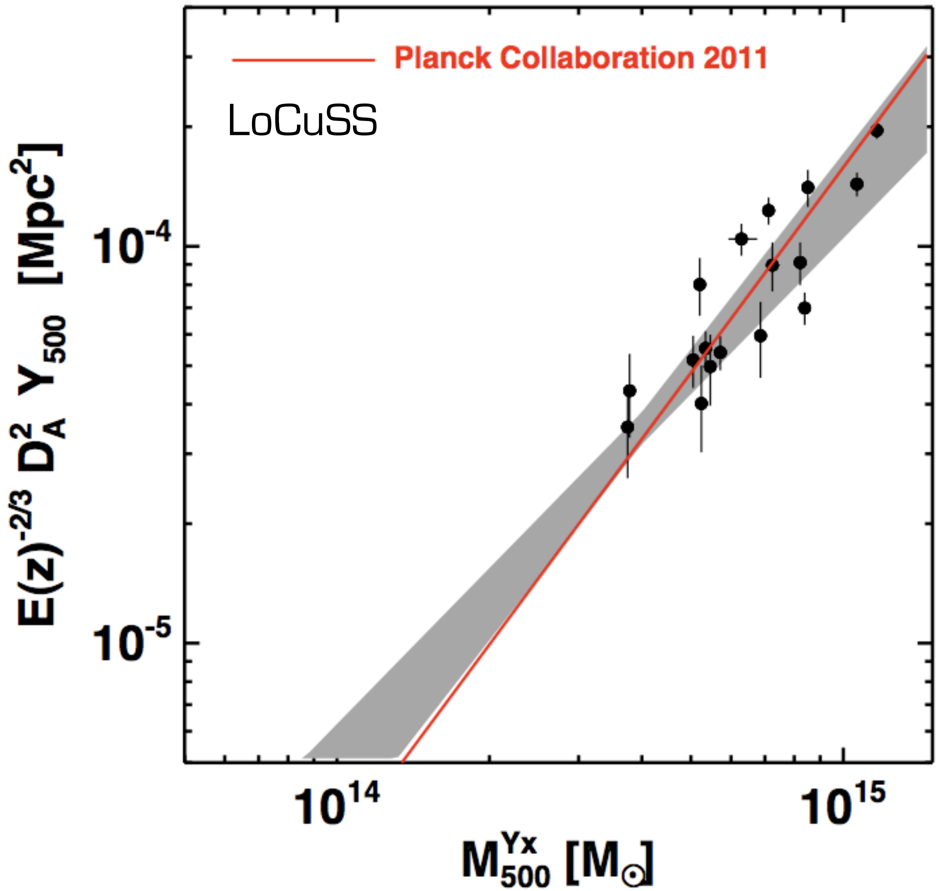
$Y_X = M_{gas,500} T_X$

Agreement between X-ray-based predicted (Y_X) and measured SZ signals (Y_{SZ}), at least within R_{500}.

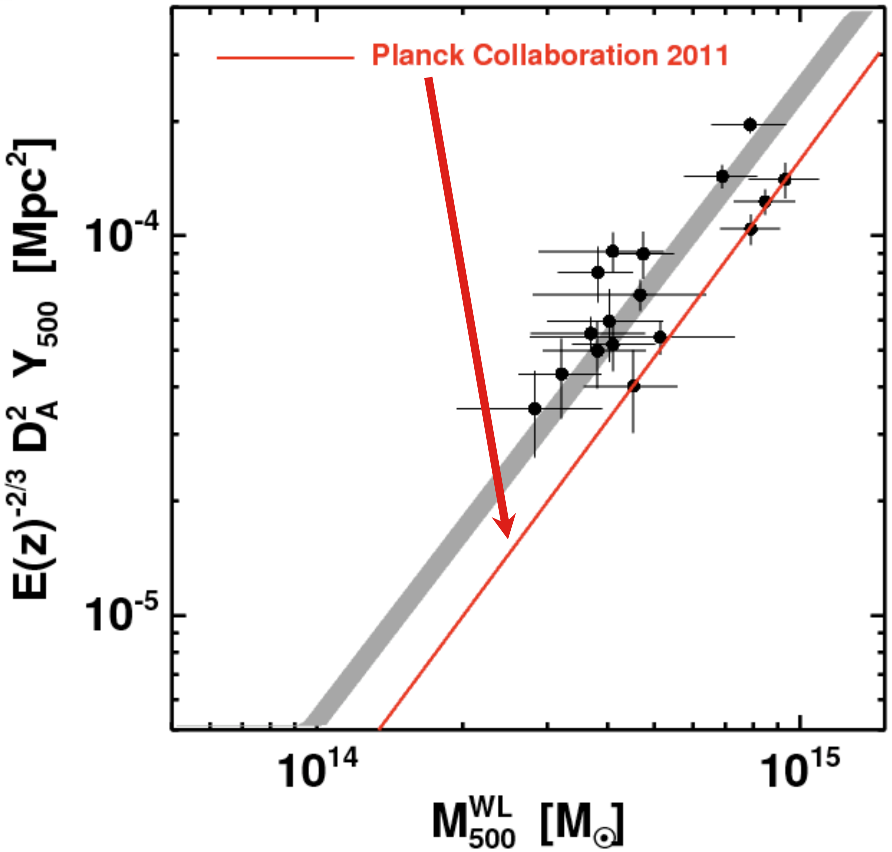
SZ mass proxy: Y_{SZ} - M

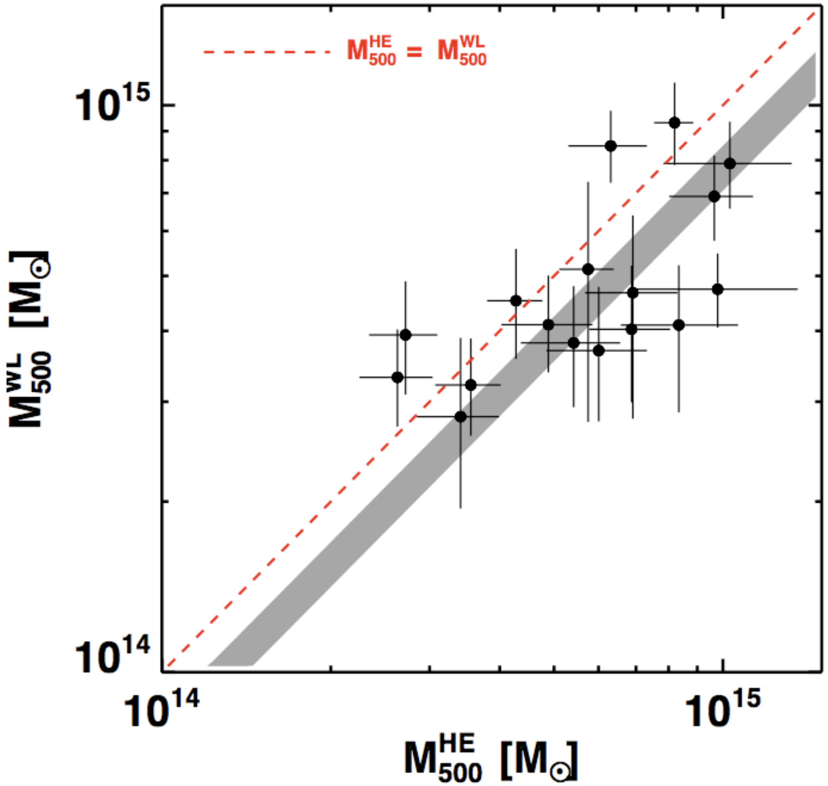
- SZ fluxes and HE X-ray masses agree





SZ signal and cluster masses





$$M_{500}^{WL} = (0.78 \pm 0.08)\, M_{500}^{HE}$$

HE X-ray masses larger than WL masses by 22 ± 8 % on average

Sample of 19 objects with WL measurements from Subaru

- not solved by appealing to HE bias
- WL concentration larger than X-ray
- Mis-centering introduces secondary mass normalisation effect
- Other effects from WL modelling, dilution...?

(Planck Collaboration Int III, 2013)

Missing hot baryons?

The Astrophysical Journal, 648:176–199, 2006 September 1

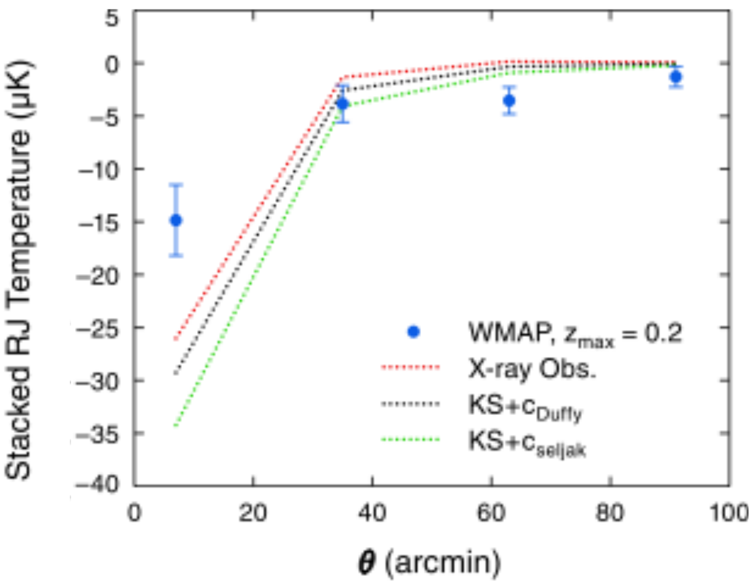
THE SUNYAEV-ZEL'DOVICH EFFECT IN A SAMPLE OF 31 CLUSTERS: A COMPARISON BETWEEN THE X-RAY PREDICTED AND *WMAP* OBSERVED COSMIC MICROWAVE BACKGROUND TEMPERATURE DECREMENT

Richard Lieu,[1] Jonathan P. D. Mittaz,[1] and Shuang-Nan Zhang[1,2,3,4]
Received 2005 October 6; accepted 2006 April 30

ABSTRACT

The *WMAP* Q-, V-, and W-band radial profiles of temperature deviation of the cosmic microwave background (CMB) were constructed for a sample of 31 randomly selected nearby clusters of galaxies in directions of Galactic latitude $|b| > 30°$. The profiles were compared in detail with the expected CMB Sunyaev-Zel'dovich effect (SZE) caused by these clusters, with the hot gas properties of each cluster inferred observationally by applying gas temperatures as measured by *ASCA* to isothermal β-models of the *ROSAT* X-ray surface brightness profiles, with the *WMAP* point-spread function fully taken into consideration. After co-adding the 31 cluster fields to significantly reduce the systematic and random uncertainties, it appears that *WMAP* detected the SZE in all three bands. Quantitatively, however, the observed SZE only accounts for about 1/4 of the expected decrement. The discrepancy represents too much unexplained extra flux: in the W band, the detected SZE corresponds on average to 5.6 times less X-ray gas mass within a 10′ radius than the mass value given by the *ROSAT* β-model. We critically examined how the X-ray prediction of the SZE may depend on our uncertainties in the density and temperature of the hot intracluster plasma,

(Lieu et al. 06
Komatsu et al. 11)



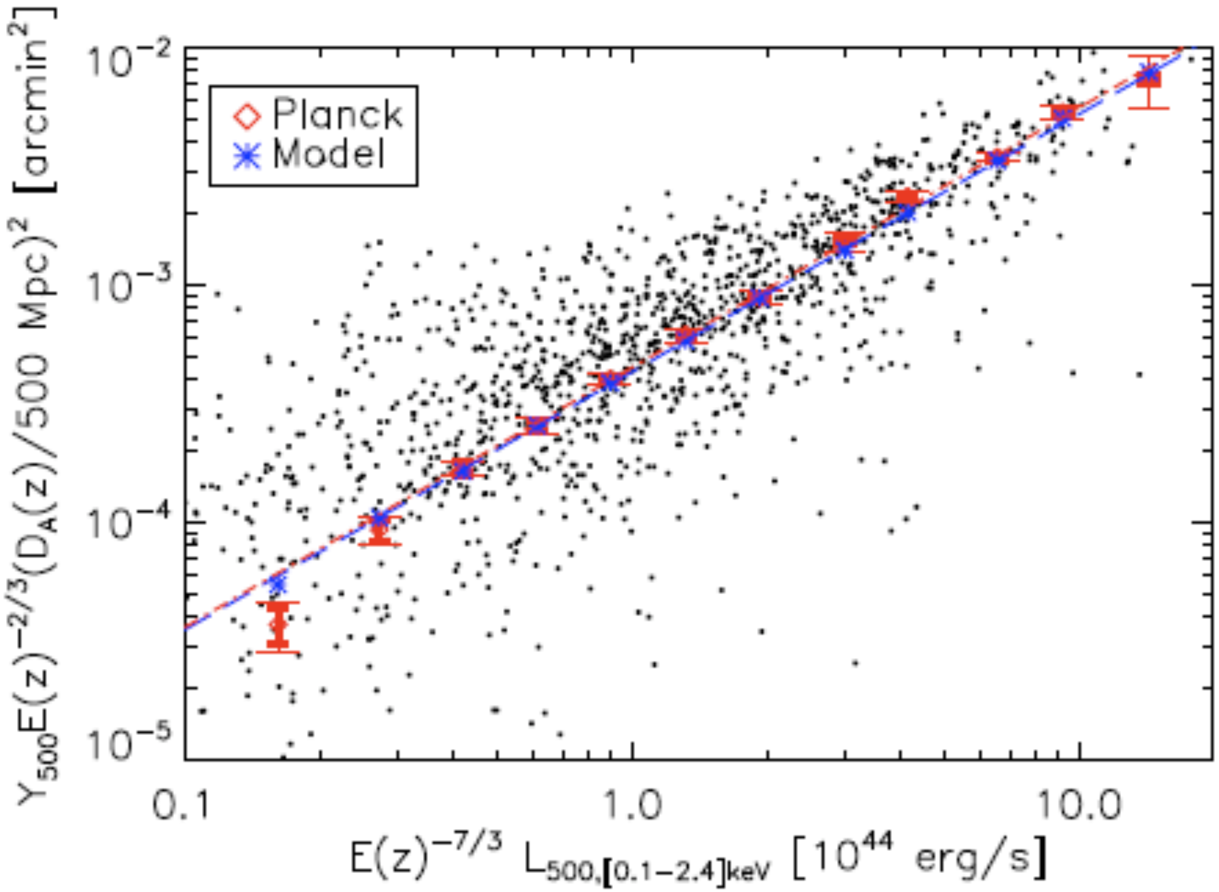
Accepted for Publication in the Astrophysical Journal Supplement Series
Preprint typeset using LaTeX style emulateapj v. 11/10/09

SEVEN-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (*WMAP*[1]) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

E. Komatsu[2], K. M. Smith[3], J. Dunkley[4], C. L. Bennett[5], B. Gold[5], G. Hinshaw[6], N. Jarosik[7], D. Larson[5], M. Nolta[8], L. Page[7], D. N. Spergel[3,9], M. Halpern[10], R. S. Hill[11], A. Kogut[6], M. Limon[12], S. S. Meyer[13], N. Odegard[11], G. S. Tucker[14], J. L. Weiland[11], E. Wollack[6], and E. L. Wright[15]
Accepted for Publication in the Astrophysical Journal Supplement Series

Zel'dovich (SZ) effect at the locations of known clusters of galaxies. The measured SZ signal agrees well with the expected signal from the X-ray data on a cluster-by-cluster basis. However, it is a factor of 0.5 to 0.7 times the predictions from "universal profile" of Arnaud et al., analytical models, and hydrodynamical simulations. We find, for the first time in the SZ effect, a significant difference between the cooling-flow and non-cooling-flow clusters (or relaxed and non-relaxed clusters), which can explain some of the discrepancy. This lower amplitude is consistent with the lower-than-theoretically-expected SZ power spectrum recently measured by the South Pole Telescope collaboration.

Missing hot baryons?

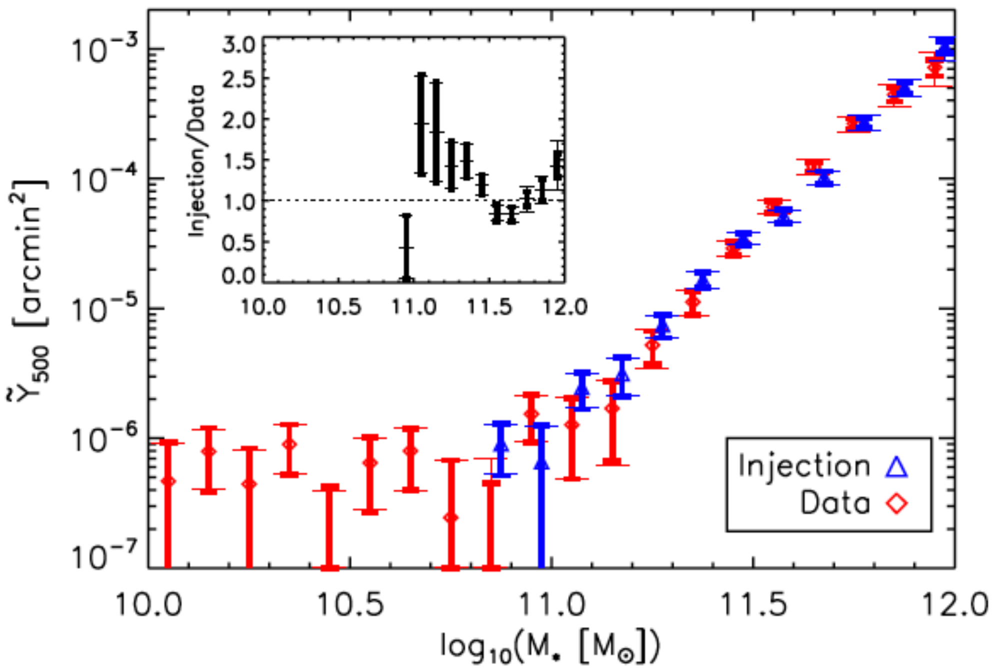


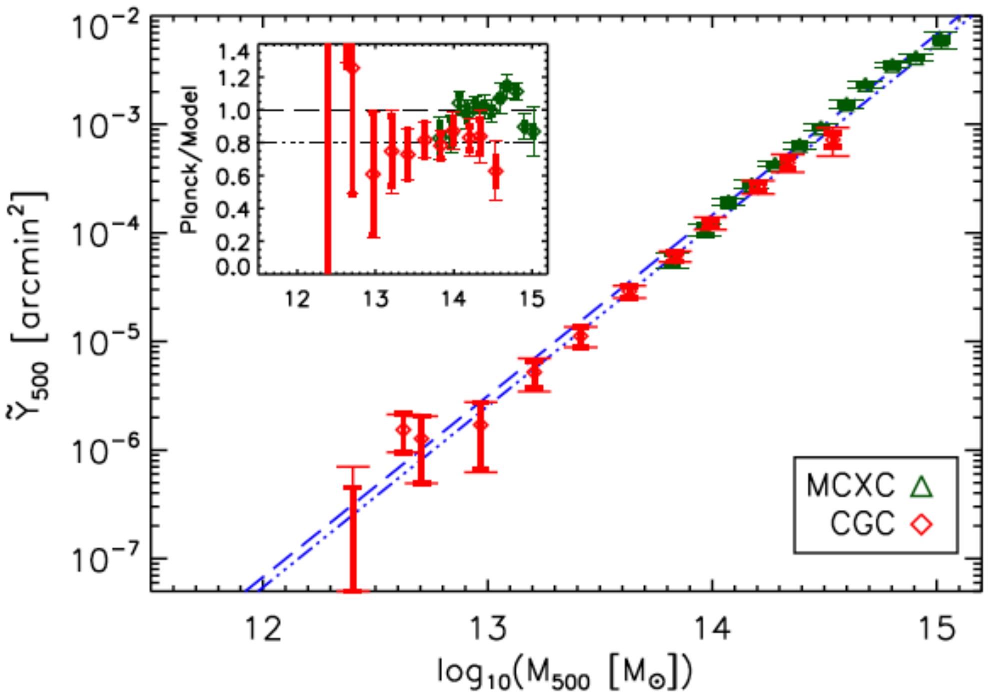
Use Multi-frequency Matched Filter (MMF) at positions of the ***Meta-Catalogue of X-ray detected Clusters*** *(~1600 MCXC clusters)*

- Statistical analysis of SZ - X-ray scaling relation
- Agreement between X-ray-based predicted (L_{500}-M_{500} and Y_{500}-M_{500}) and measured SZ signals.
- Planck shows that there are **no missing hot baryons** (a 5 years debate, closed because Planck error bars are about 10 times smaller than WMAP ones).

SZ – optical scaling relations: central galaxies

- Locally brightest galaxies selected from DR7.
- Semianalytic galaxy formation simulation (Guo et al. 2011) used to calibrate the purity and $M_\star$-M_h (stellar-to-halo mass) relation.





Planck sees about ¼ of all cosmic baryons in the form of hot gas. The new measurements multiply by a factor of 4 the amount of baryons detected by X-rays in clusters above 10^{14} Msun.

(Planck Collaboration Int XI, 2014)

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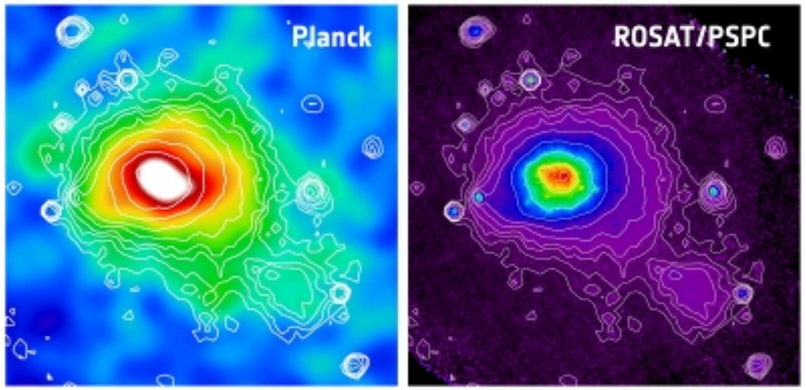
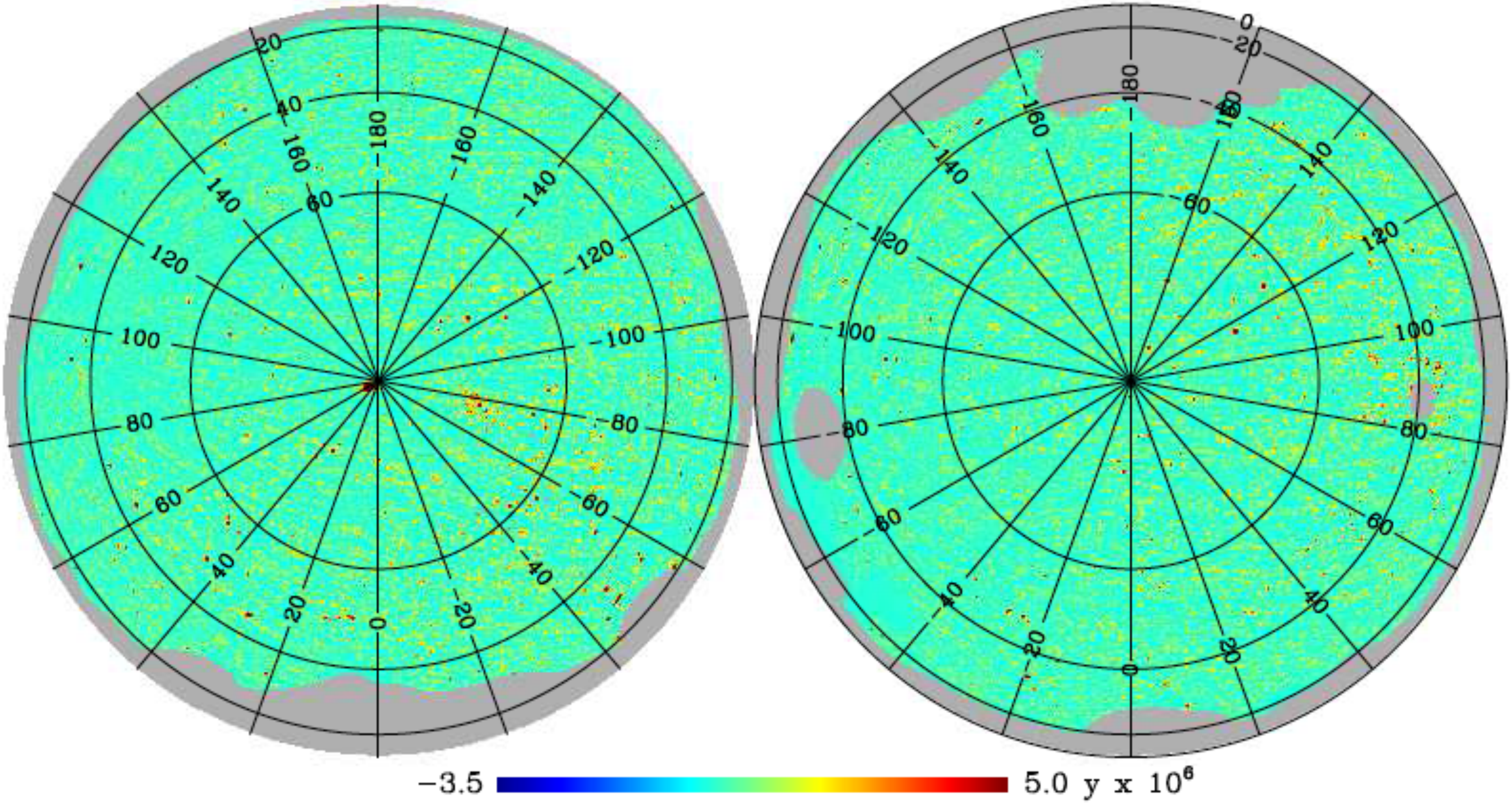
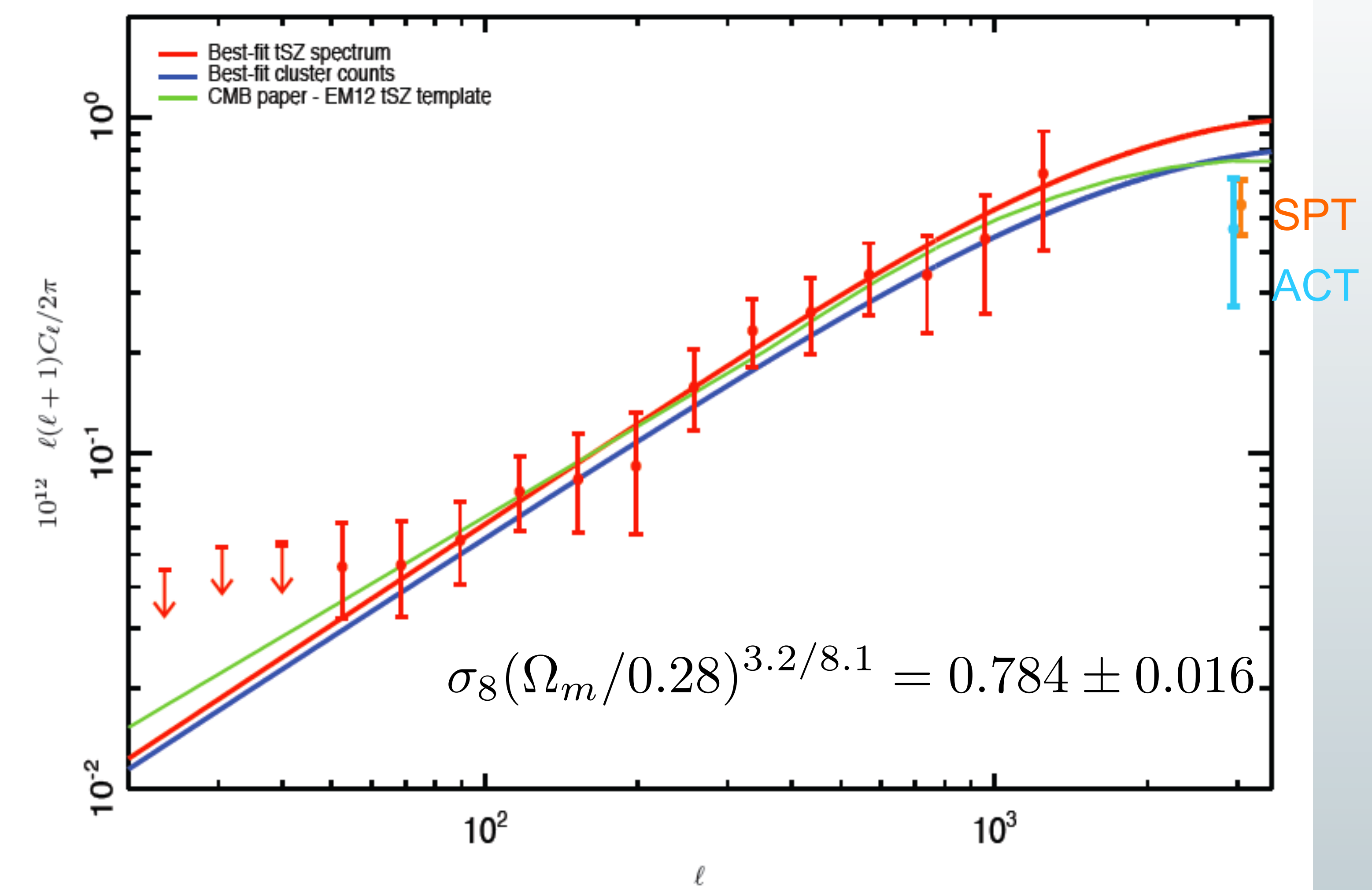


All-sky SZ map

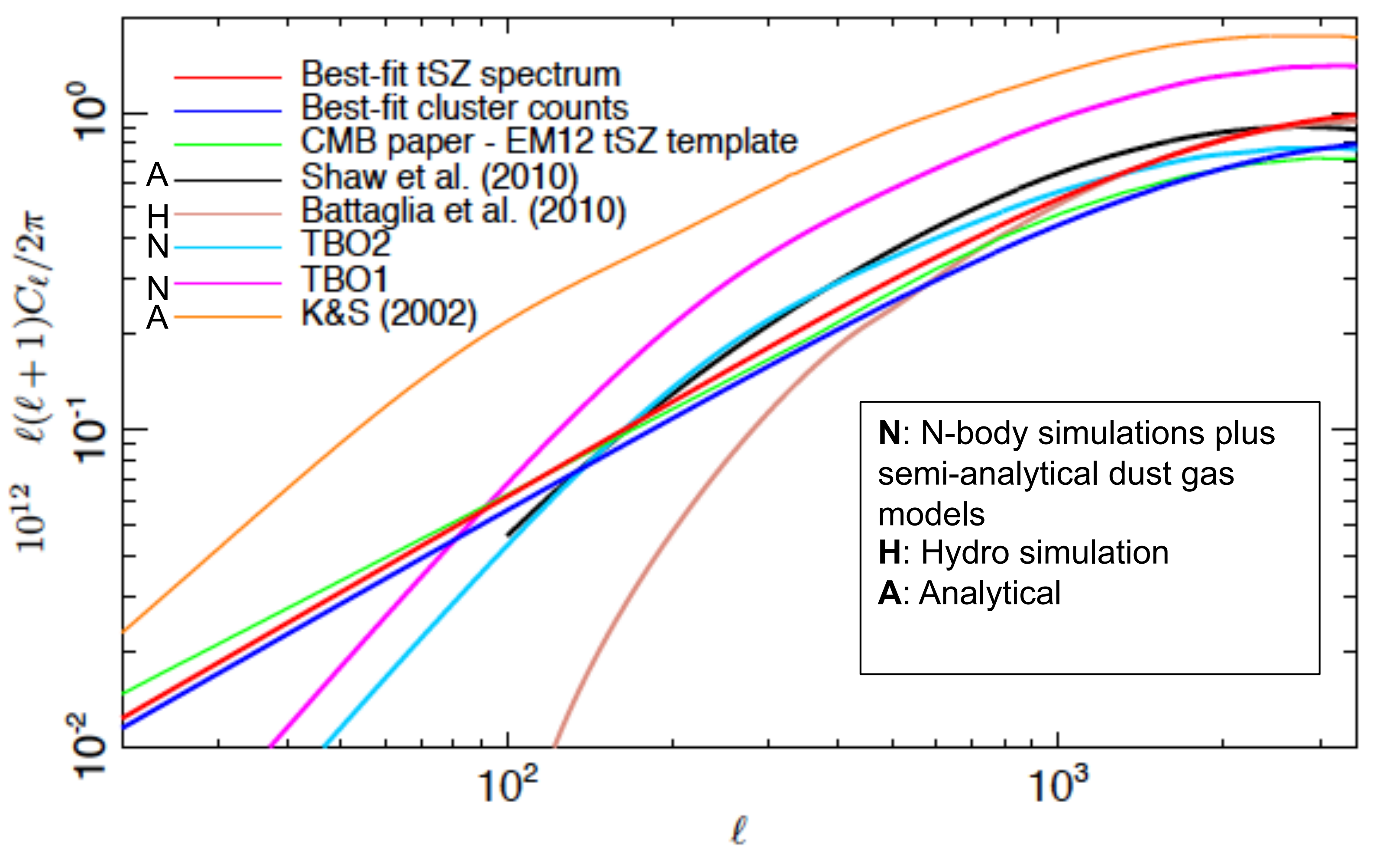


All-sky SZ map: power spectrum



- Angular Power spectrum of SZ map fully compatible with number counts.
- Planck probes the whole range of angular scales in the SZ power spectrum.

All-sky SZ map: power spectrum



- Angular Power spectrum of SZ map fully compatible with number counts.
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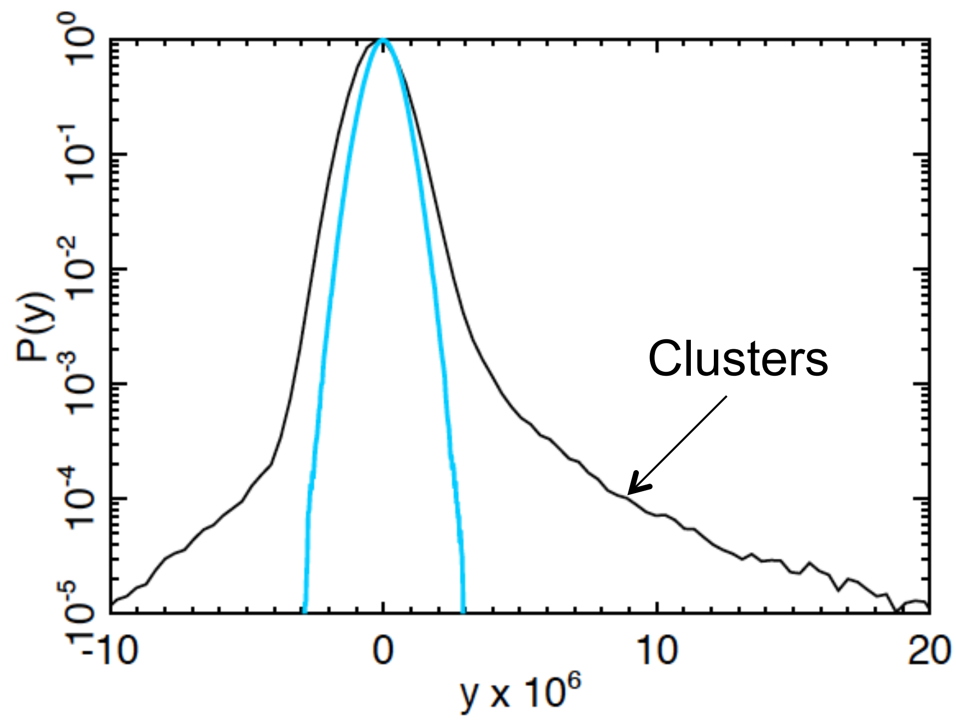
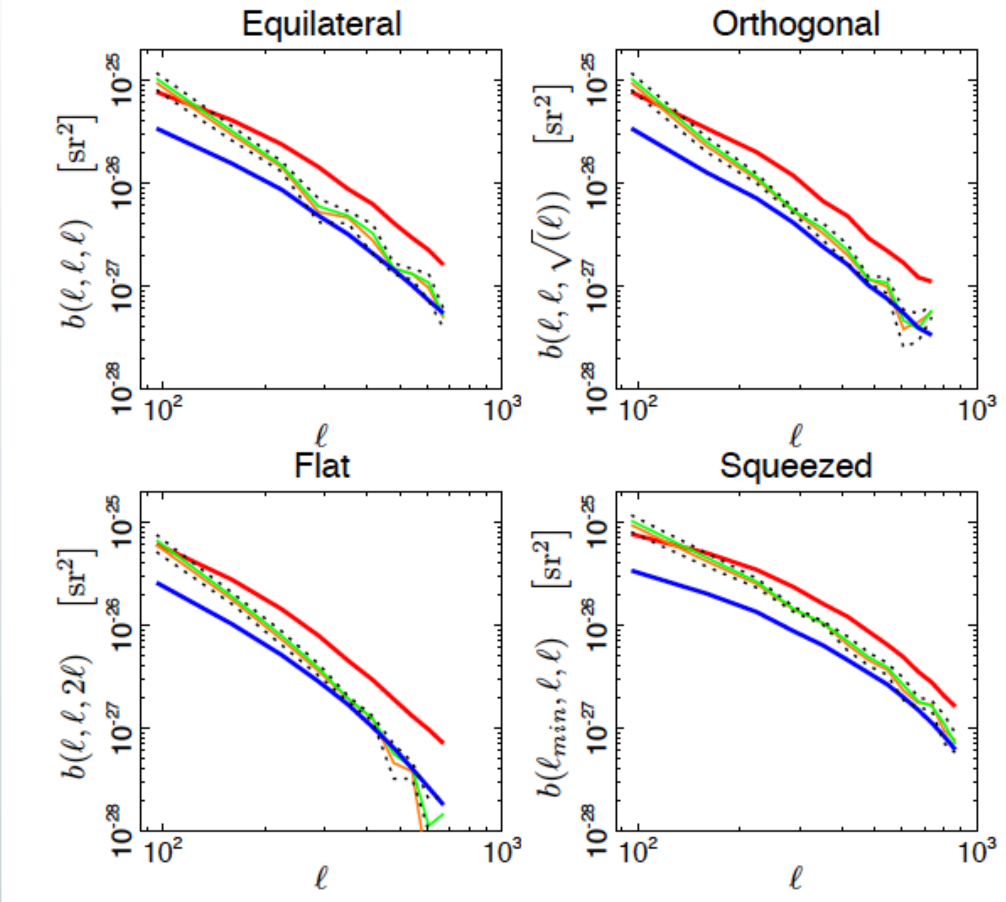
All-sky SZ map: bispectrum and P(y)





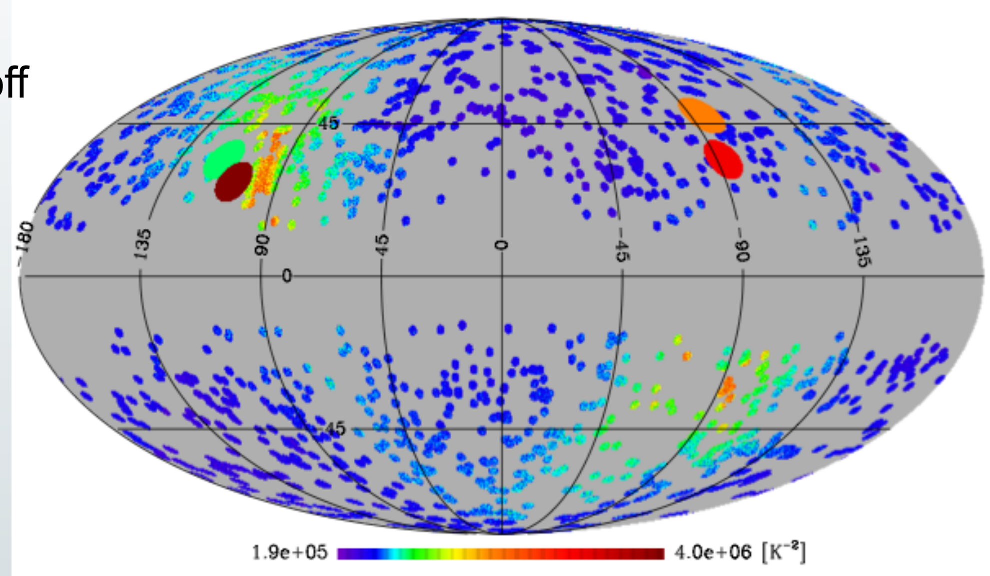
- Methodology proposed in Rubiño-Martin & Sunyaev (2003).
- Bispectrum of SZ map: σ_8=0.74±0.04 (68% CL).
- Un-normalized skewness: σ_8=0.779±0.015 (68% CL).
- Also applied to ACT (Wilson et al. 2013), giving σ_8=0.78±0.04.

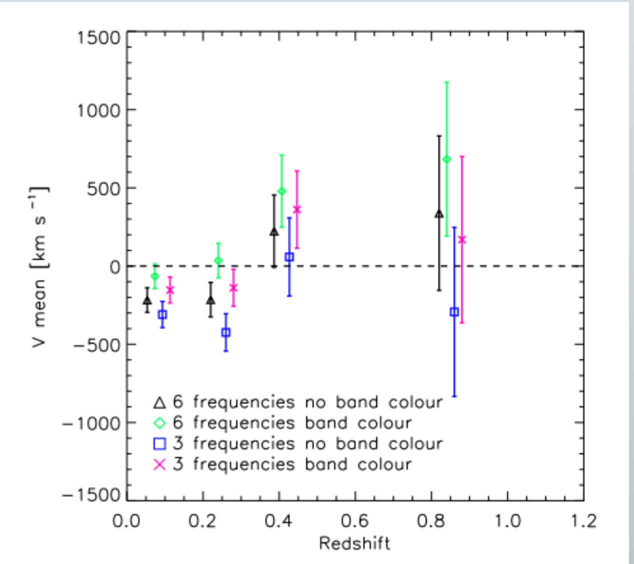
Kinetic Sunyaev-Zeldovich effect

• The kSZ effect expresses the Doppler kick experienced by CMB photons when scattering off rapidly moving electrons

$$\frac{\delta T}{T_0}(\hat{n}) = -\int dl\, \sigma_T\, n_e \frac{v_e \cdot \hat{n}}{c}$$

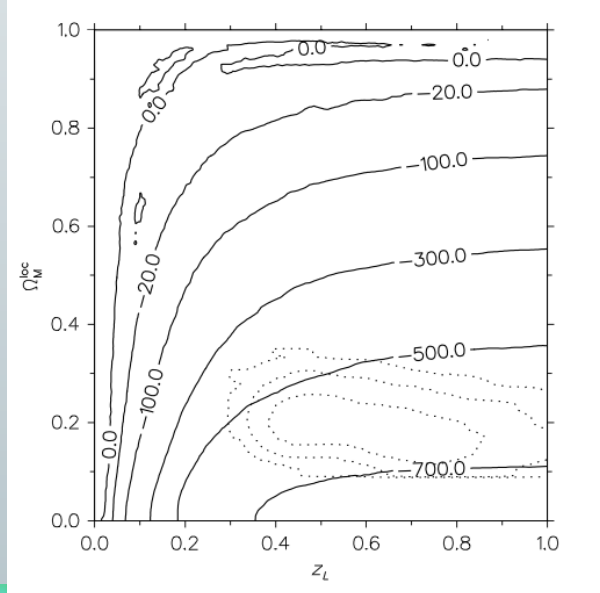
• The kSZ temperature anisotropies is independent of frequency, and it is sensitive to peculiar velocities.





• NO statistically significant kSZ monopole at any redshift bin (72 +/- 60 km s^{-1}), which rules out giant void models as alternative explanations to LCDM (see Goodman 1995; García-Bellido & Haugbolle 2008).

• No detection of kSZ dipole (=bulk flow).



Conclusions

- Clusters are a powerful tool for cosmological studies. They can constrain the cosmological model in multiple ways, providing complementary information to other LSS probes.
- Recent SZ catalogues provide excellent reference samples, but intensive follow-up programs are needed.
- PLANCK: all-sky SZ detection up to high redshifts ($0.2<z<1.0$)
  - PSZ1 clusters, largest sample of SZ for cosmological studies.
  - Ambitious follow-up program: X-rays, SZ and optical.
  - Unveiling a population of dynamically perturbed clusters @ $z>0.3$, possibly under-represented in X-ray surveys. Detection of new distant massive clusters.
  - New sample (PSZ2) to appear in Oct 2014.
- Overall view of ICM properties and mass content of galaxy clusters is a critical research area.
  - High precision calibration of the $Y_{SZ} - Y_X$ and $Y_{SZ} - L_X$ and $Y_{SZ} - M$
  - Understanding the biases of the different mass proxies.
- The future is very promising in this area (eROSITA, EUCLID, …).

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.

X name "The talk"