Cosmology with Galaxy Clusters

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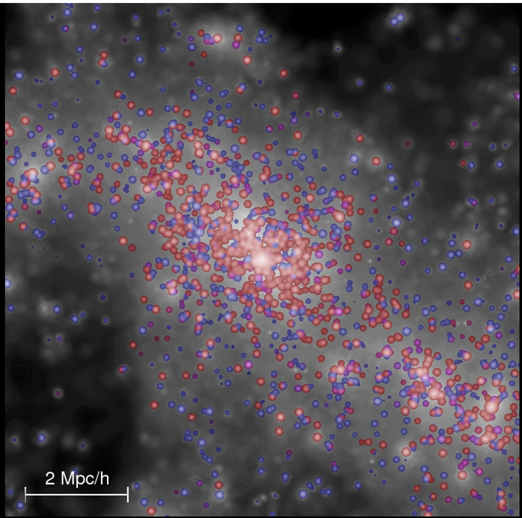
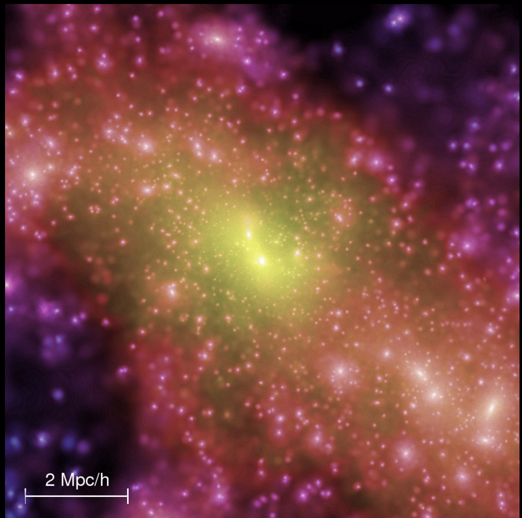
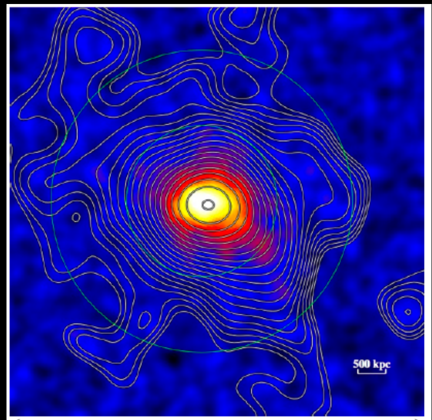
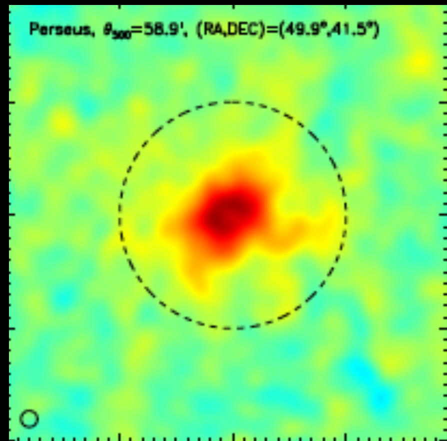
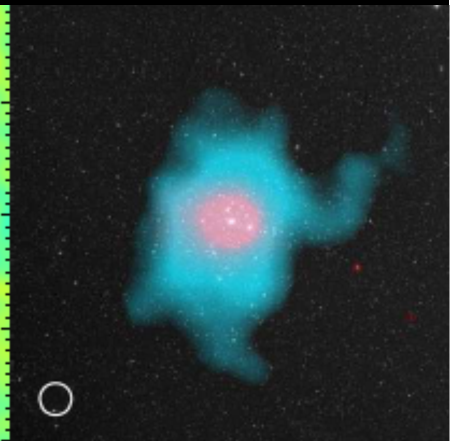






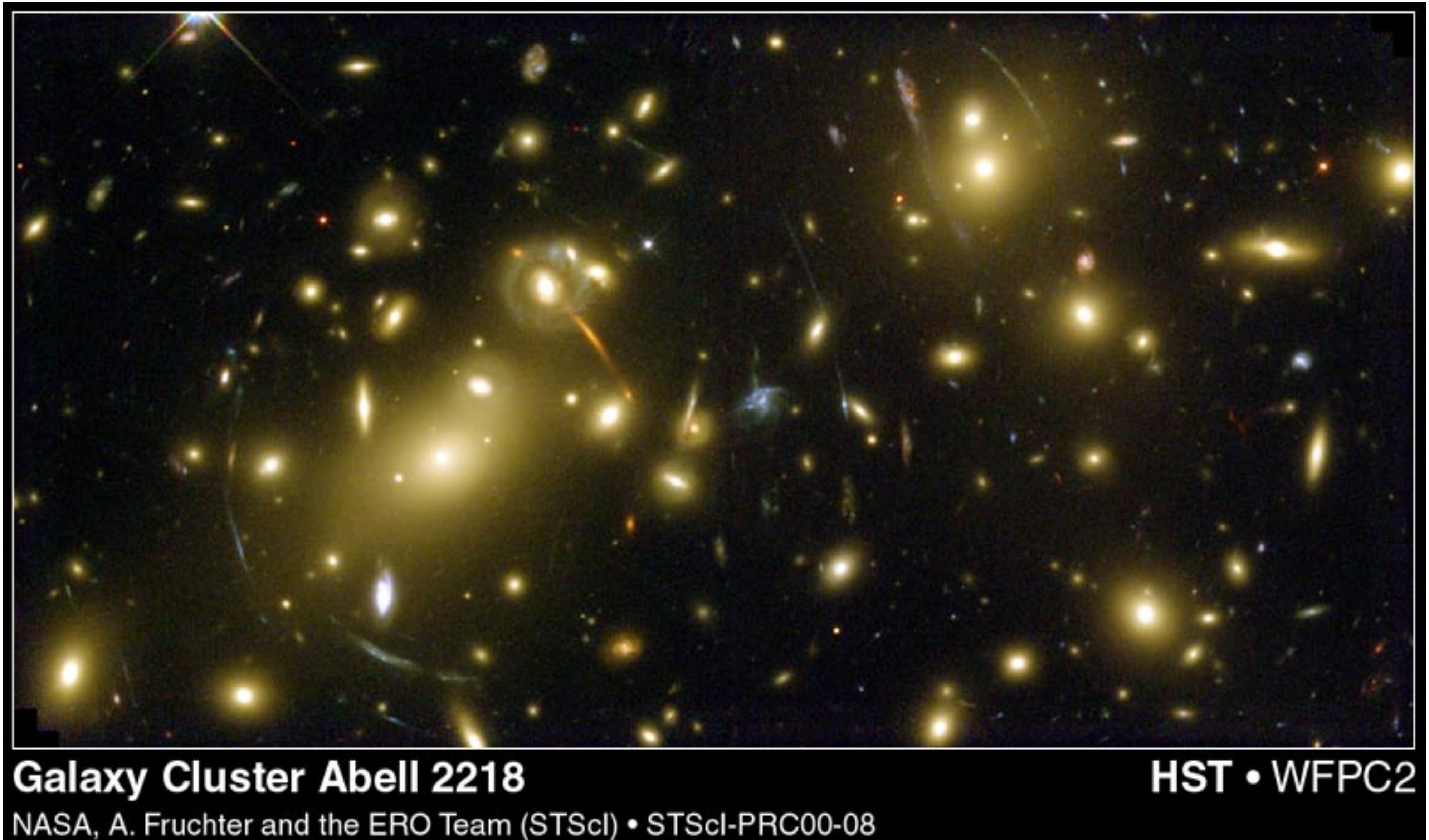




LAPIS 2018: La Plata International School on Astronomy and Geophysics

"Cosmology in the era of large surveys"

La Plata, Argentina. 23-27 April 2018.



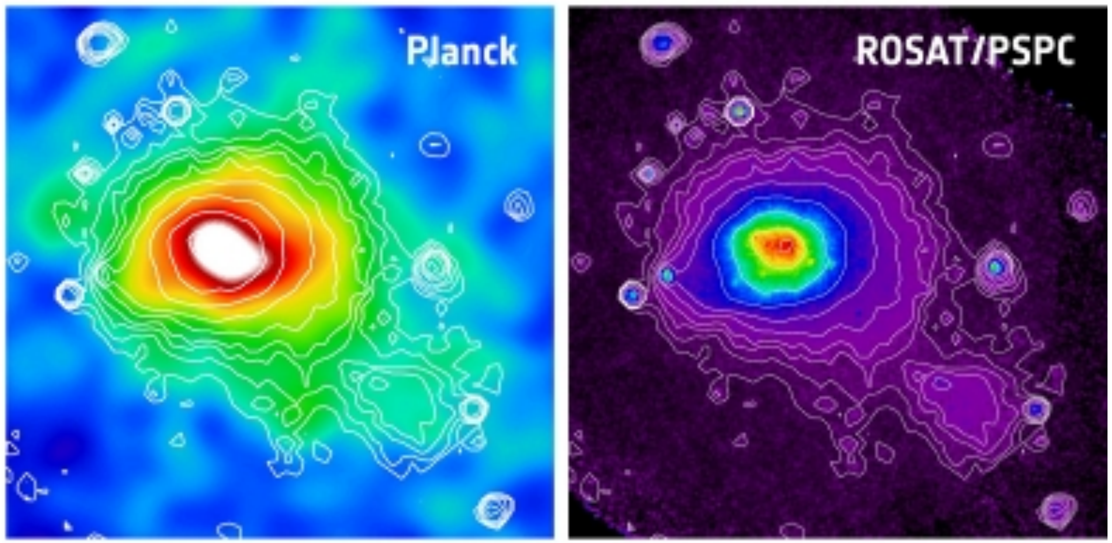
Thousands of galaxies with v ~ 1000 km/s

Hot **intergalactic gas** with Te ~ 3 – 10 KeV

Distant galaxies are gravitationally ***lensed*** by A 2218

Gravitational potential defined by "invisible" ***dark matter***

Three faces of galaxy clusters



1E 0657-558: The "bullet" cluster

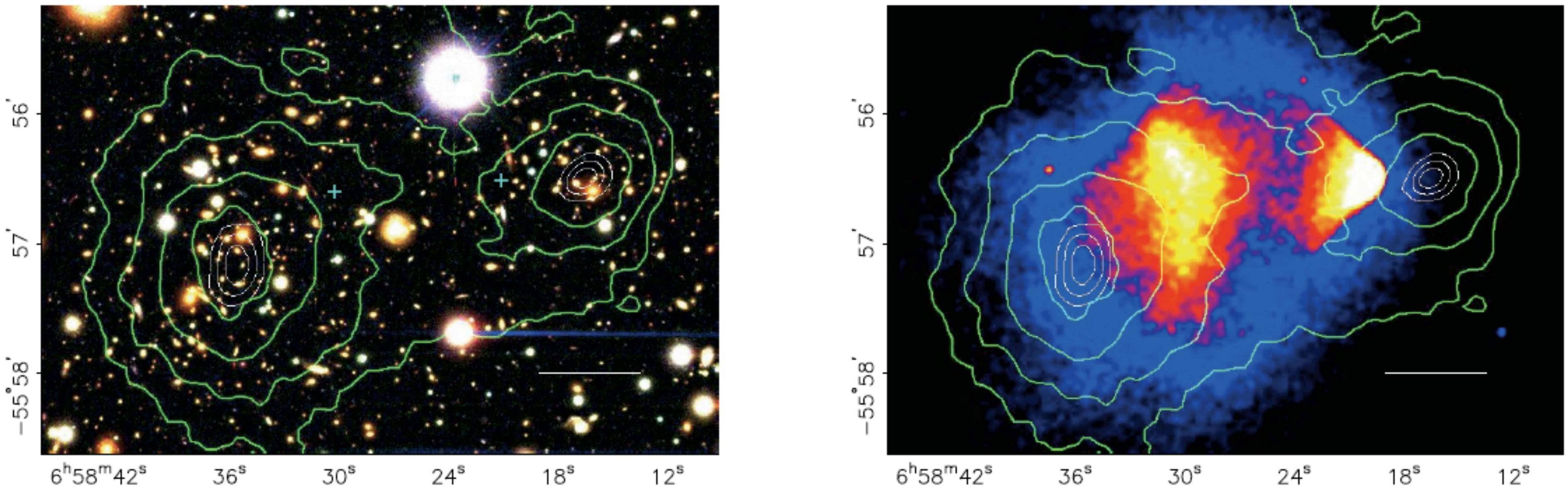


FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with the outer contour levels at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue plus signs show the locations of the centers used to measure the masses of the plasma clouds in Table 2.

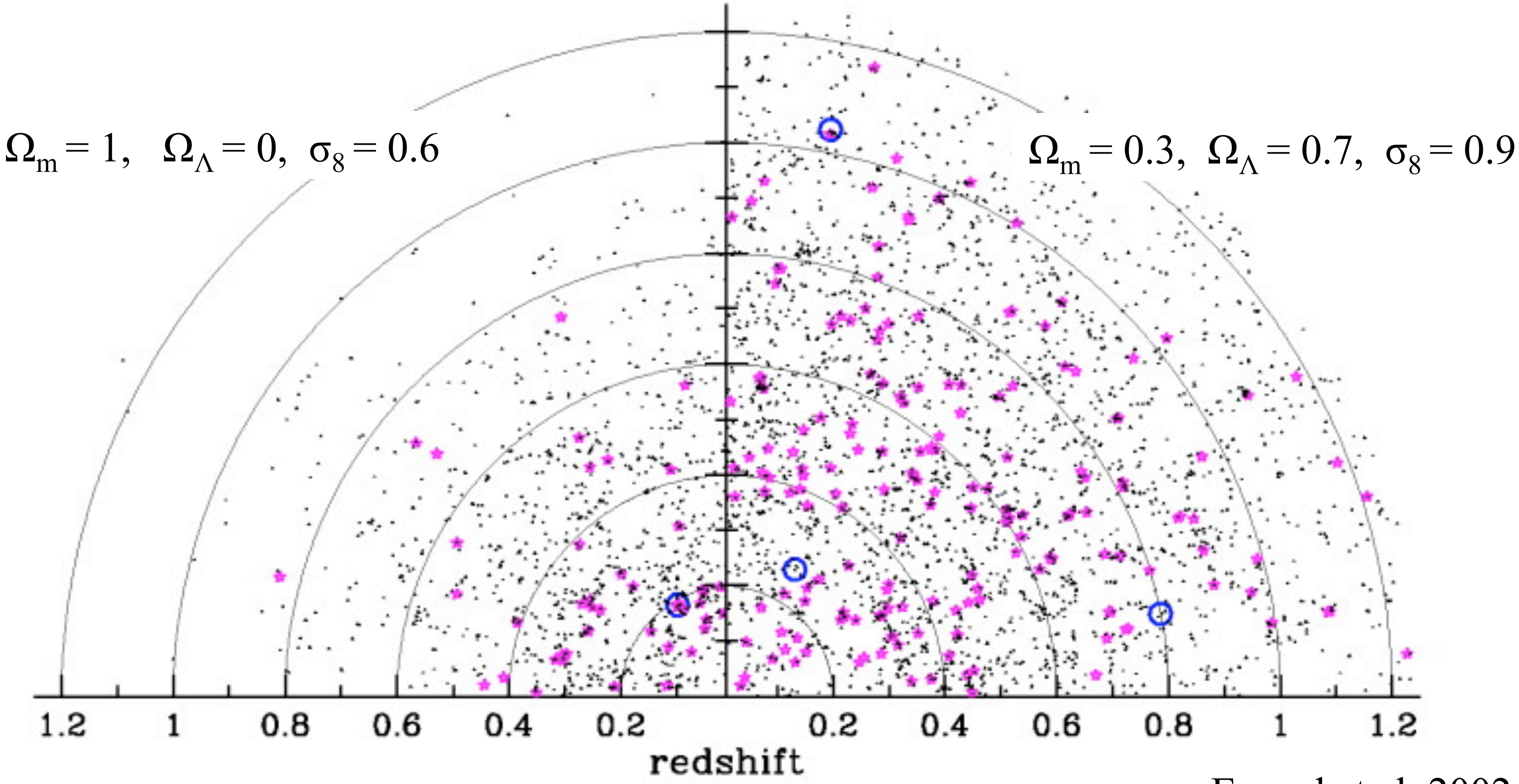
Evidence of dark matter: At a statistical significance of 8σ, the spatial offset of the center of the total mass from the center of the baryonic mass peaks cannot be explained with an alteration of the gravitational force law.

(Clowe et al. 2006)

Cosmology with cluster mass function

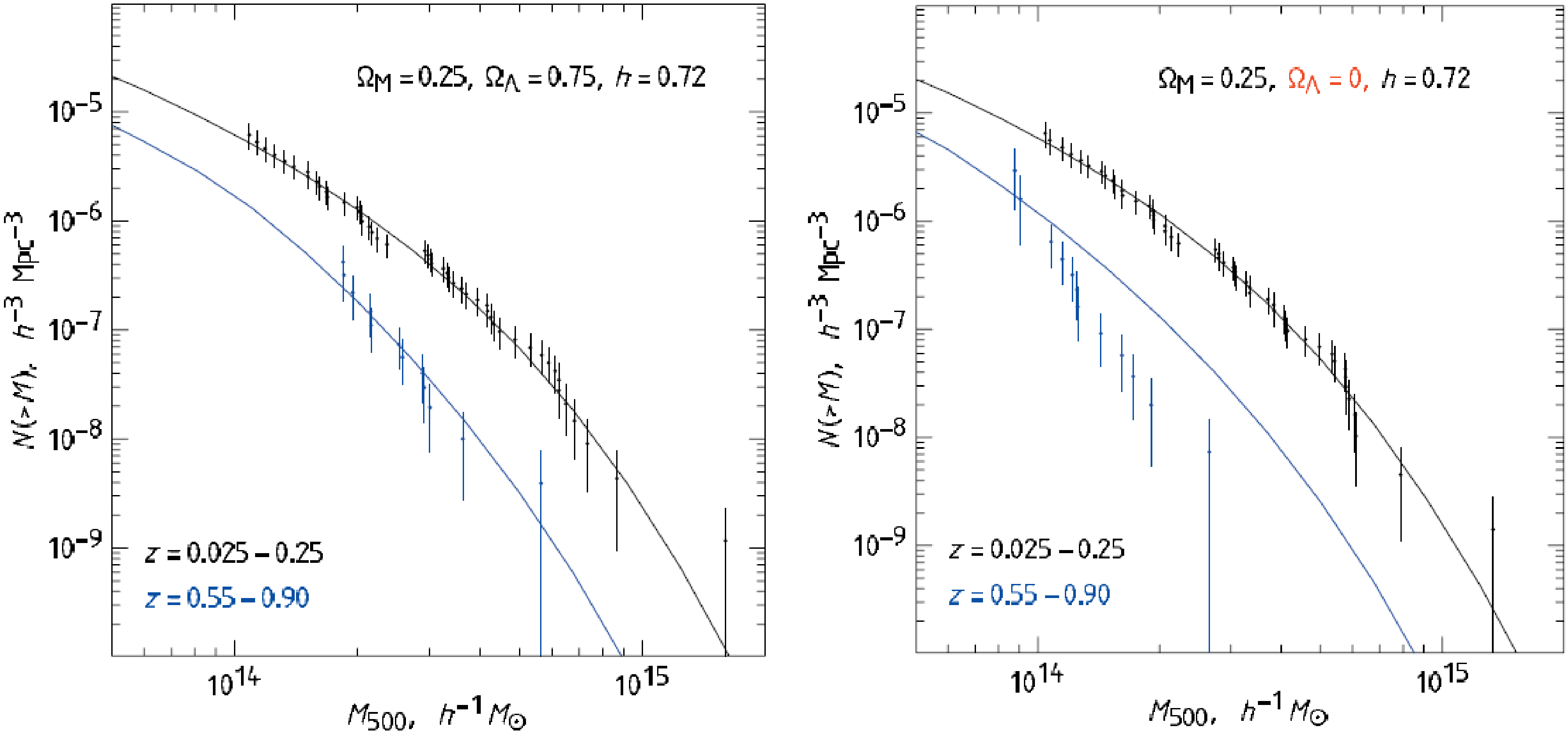
$N(M, z)$ depends on Ω_m, σ_8 [Ω_b, n, h, Ω_Λ]

(blue: $M_{200}>10^{15}\,h^{-1}M_\odot$, pink: $M_{200}>10^{14.5}-10^{15}\,h^{-1}M_\odot$, black= $M_{200}>10^{14}-10^{14.5}\,h^{-1}M_\odot$)



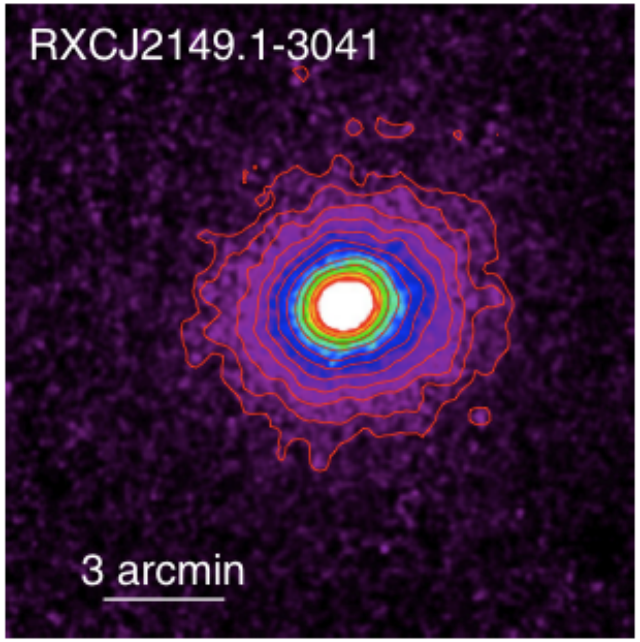
Evrard et al. 2002

Cluster mass function vs. cosmological model



Chandra Cluster Cosmology Project
Vikhlinin et al., 2009

Weighting galaxy clusters

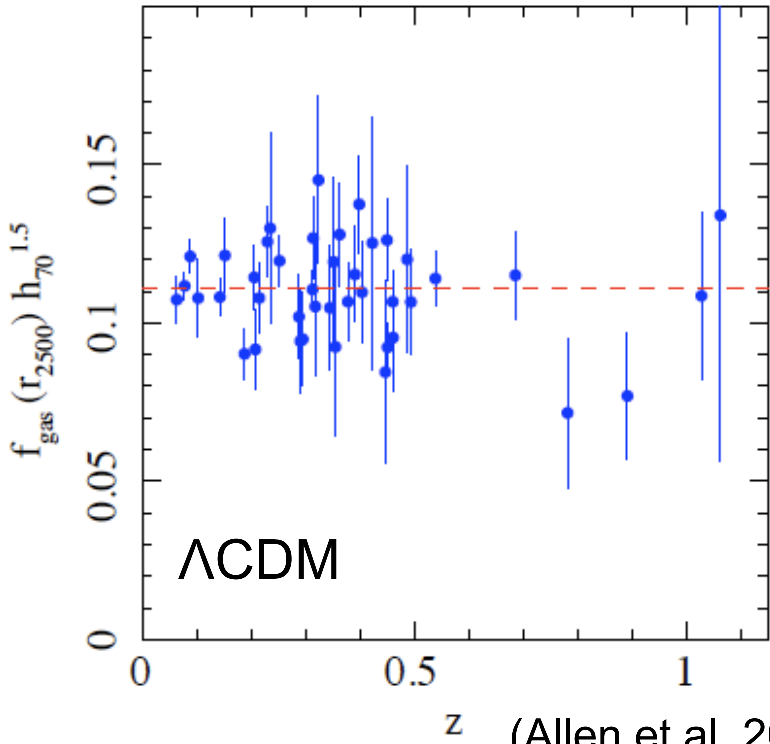


(85% DM; 15% hot X-ray gas)

- X-ray emission weights M_{gas}.
- Total mass (Hydrostatic Equilibrium):

$$M(r) = -\frac{kT}{G\mu m_p}\left[\frac{d\ln n_e}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$

(valid for relaxed systems).



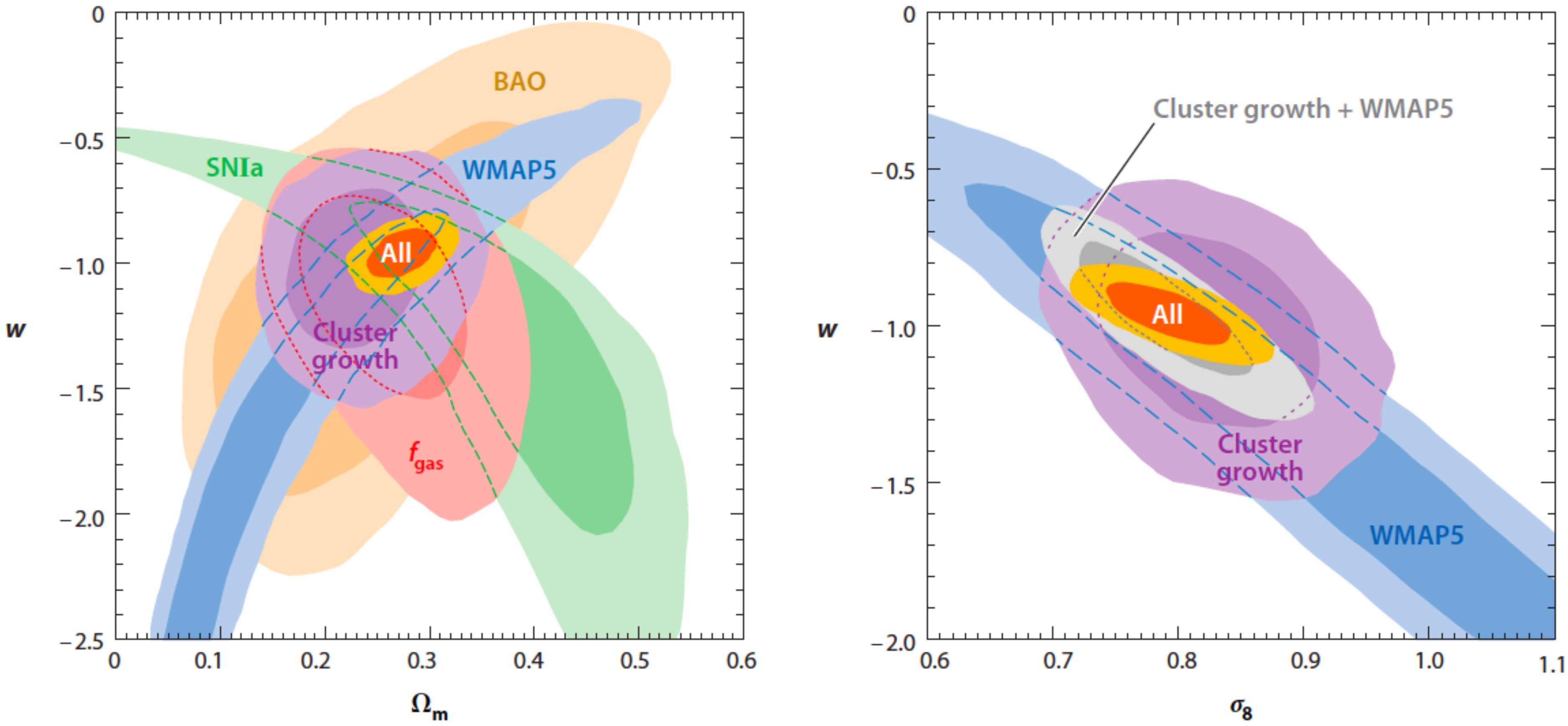
(Allen et al. 2008)

Clusters are fair samples of the Universe: f_{gas} can be used as a proxy for the universal ratio, Ω_b/Ω_m.

For a flat cosmology:

$$\Omega_m = 0.28 \pm 0.06 \text{ and } w = -1.14 \pm 0.31$$

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.

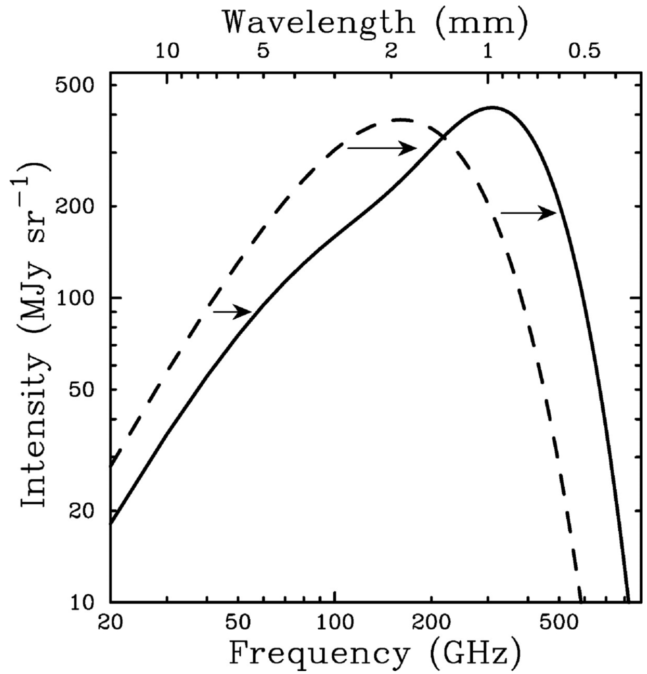
The Sunyaev-Zeldovich effect

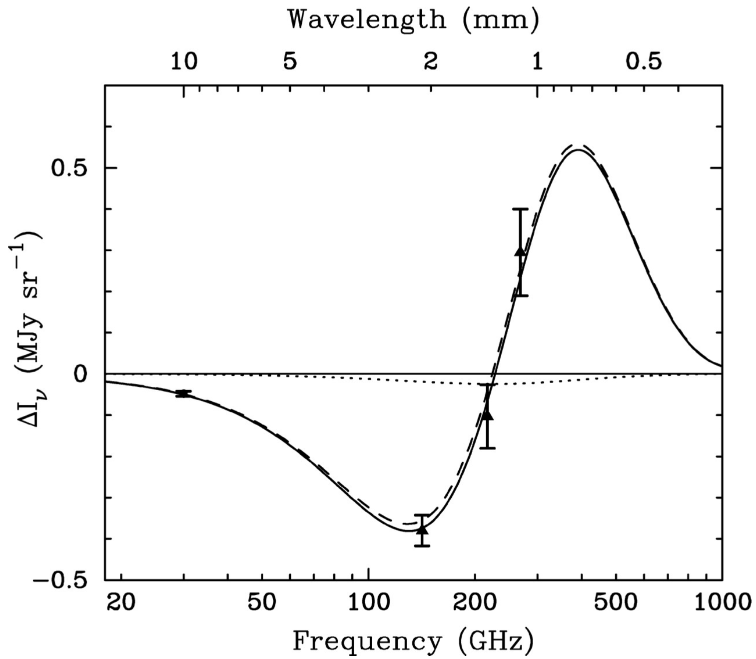
R. A. Sunyaev

Ya. B. Zeldovich

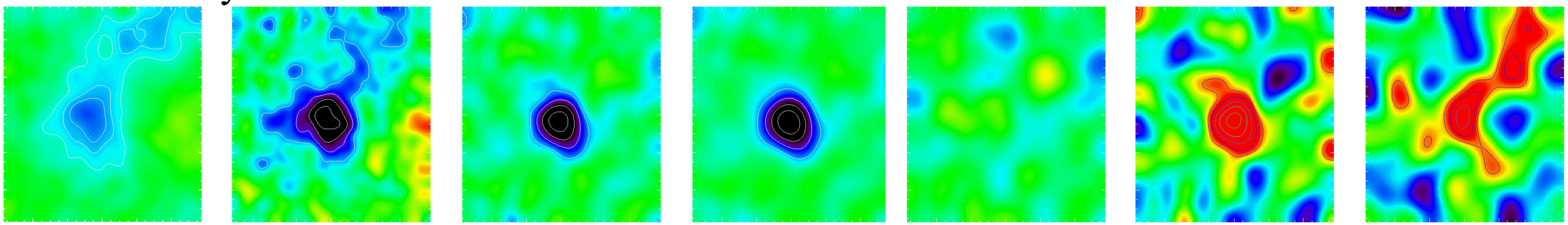
❖ Inverse Compton scattering of CMB photons off hot electrons.

❖ <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

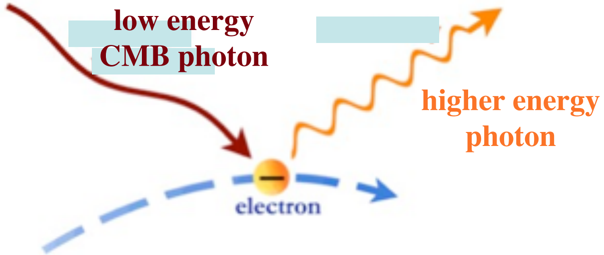
Ya. B. Zeldovich

Some notes:

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

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

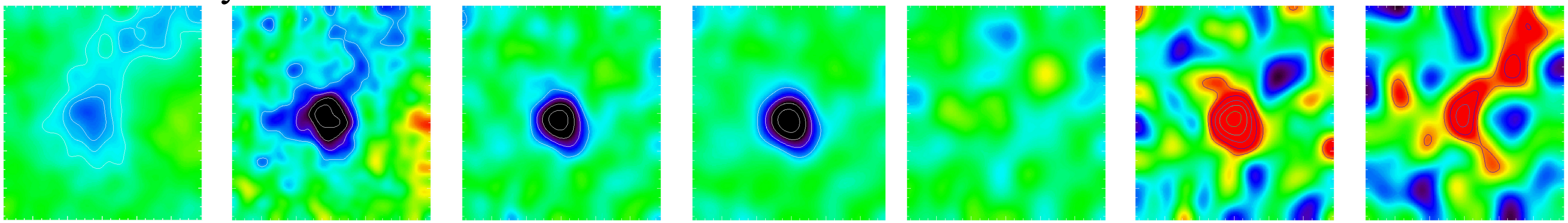
$$y = \frac{\sigma_T}{m_e c^2} \int_l (P_{th} = k_B n_e T) dl$$



❖ 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



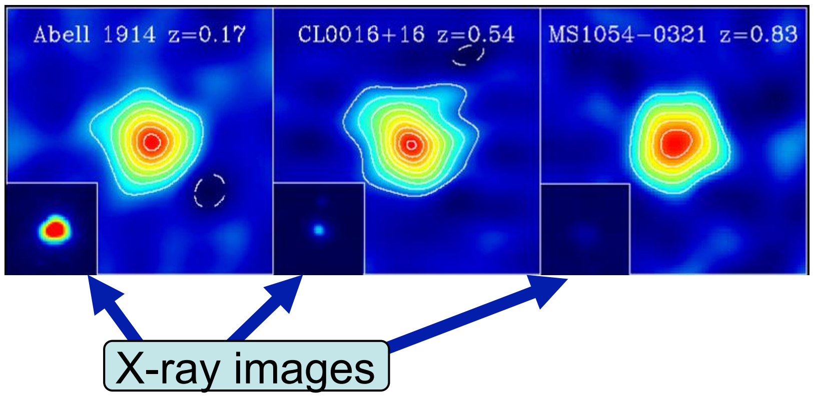
The Sunyaev-Zeldovich effect

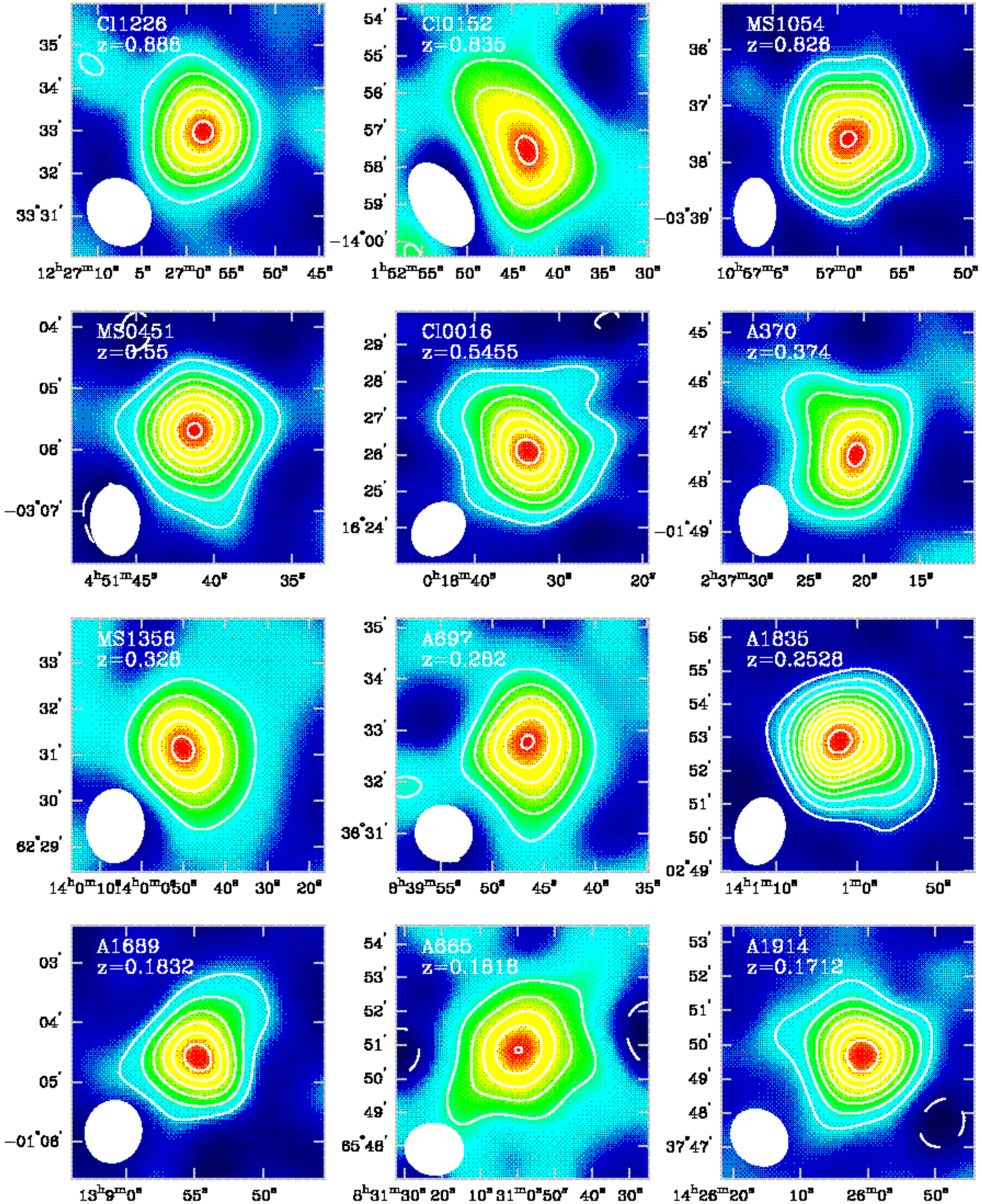
❖ The differential brightness of the SZ effect is **independent of redshift.** Only the physical parameters of the cluster appear in the Comptonization parameter.

❖ In mm, a clusters at z=0.88 appears as bright as a cluster at z=0.17.

❖X-ray brightness of the cluster decreases with redshift as $(1+z)^4$

$$L_X \propto \int n_e^2 T_e^{1/2} dV$$





(Carlstrom et al. 2001)

X-Ray emission ~ Ne^2 L, CMB y ~ NeL. It is possible to find L and to measure angular dimension, i.e. to find the **distance** to the cluster and **Hubble constant** **for an object at any distance**

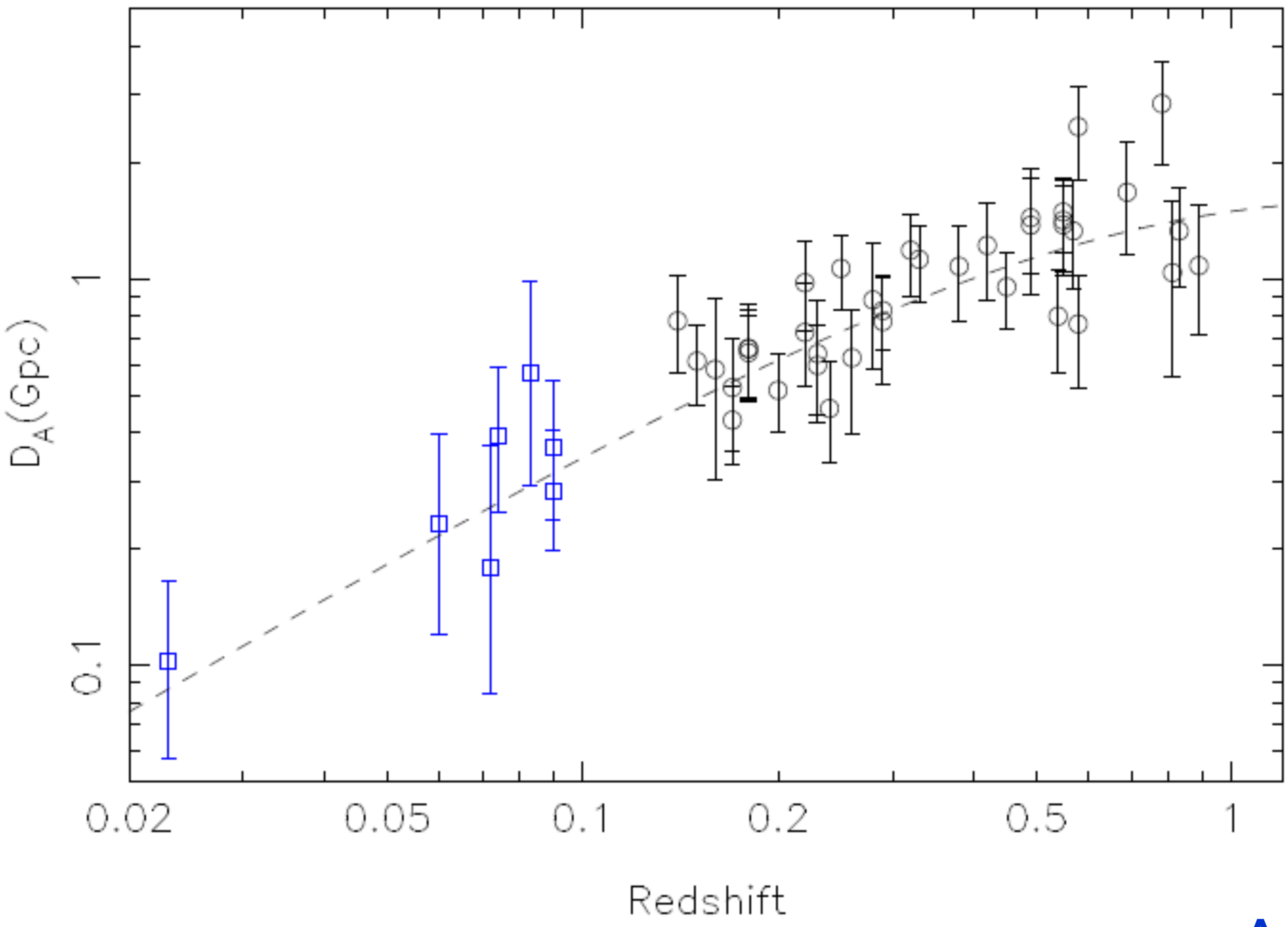


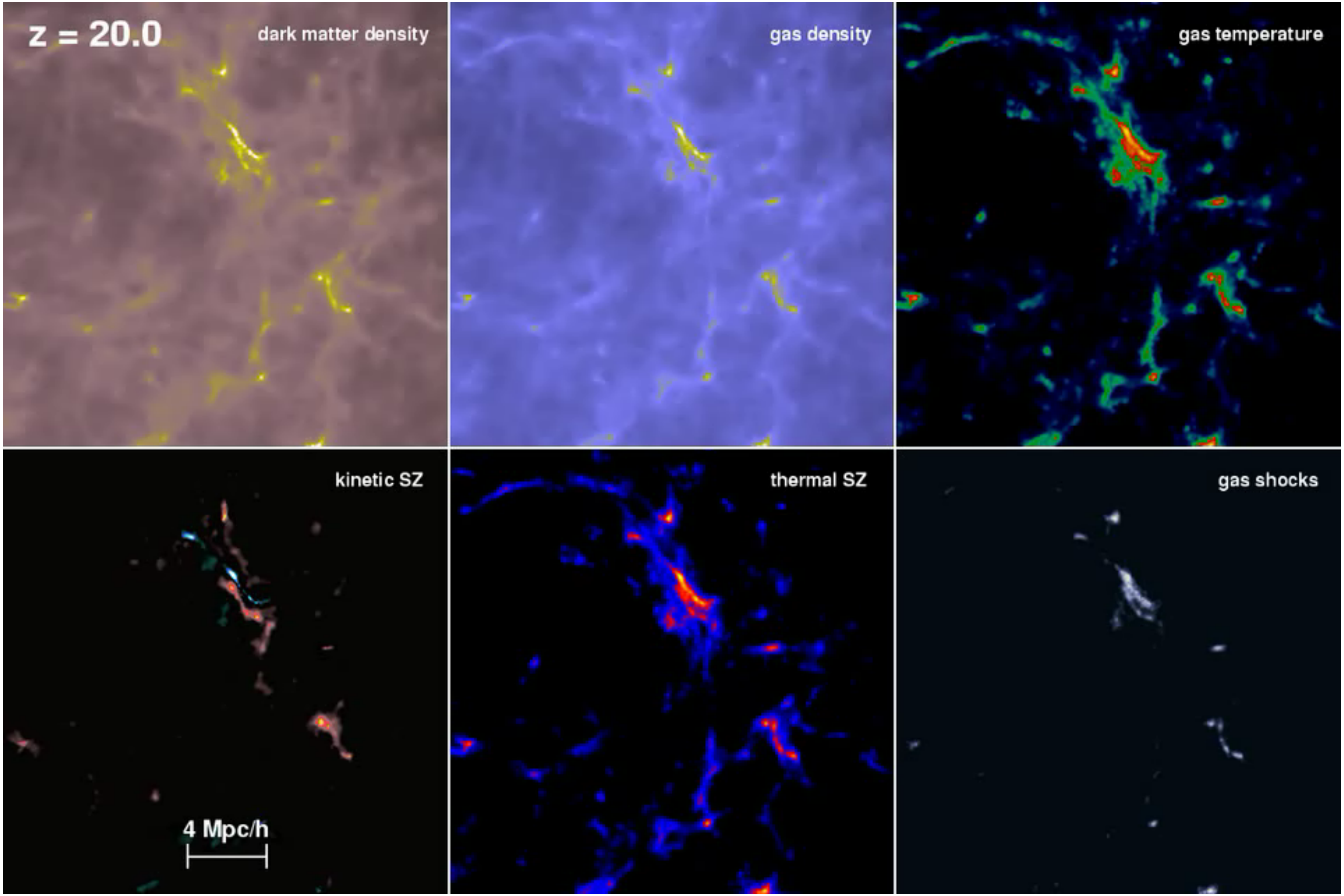
Fig. 3.— Angular diameter distances of the 38 clusters (open circles). The error bars are the total statistical uncertainties, obtained by combining the X-ray and SZE data modelling uncertainties (Table 2) and the additional sources of random error described in Section 3.3 and Table 3. The

Bonometto et al, 2005

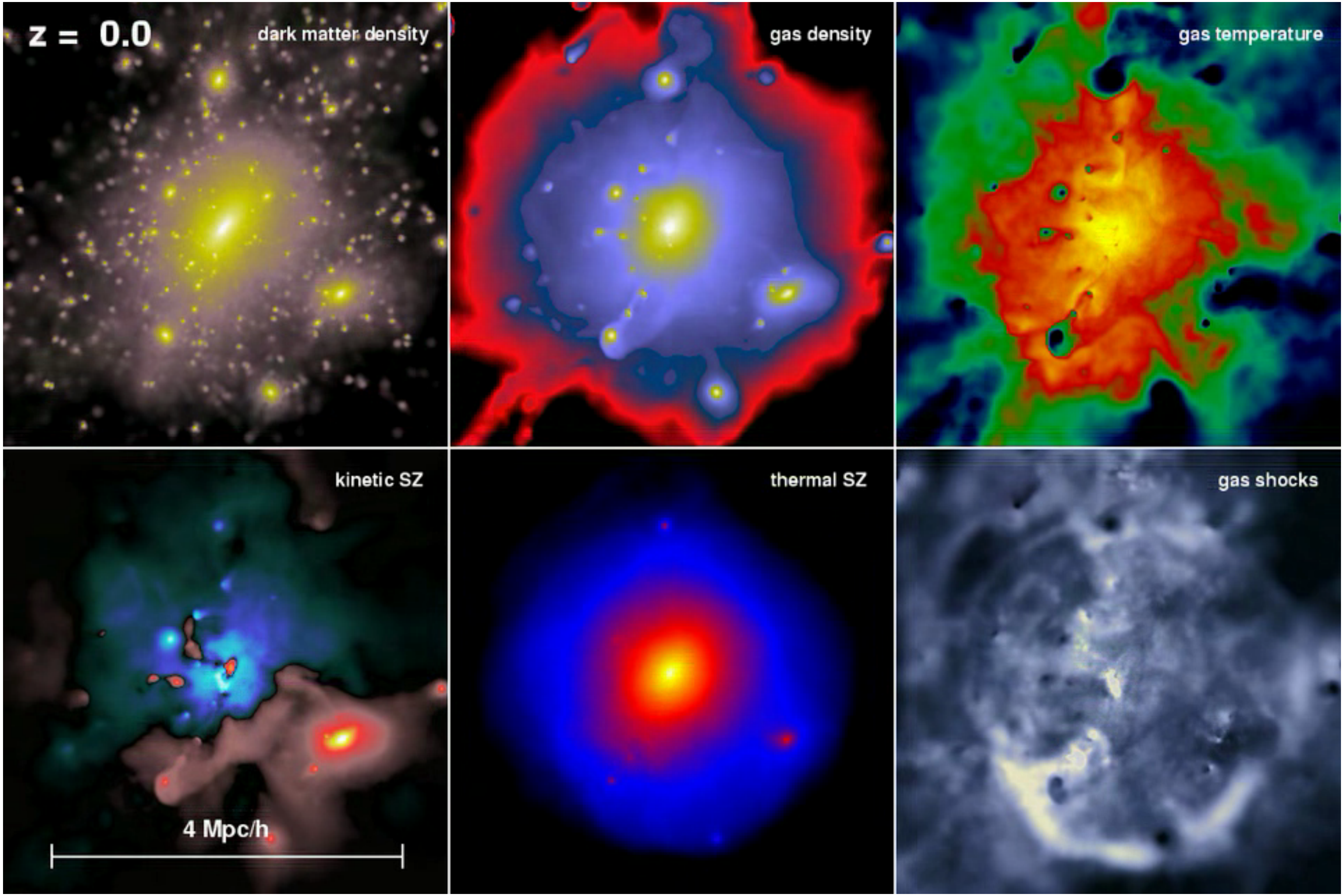
38 clusters measured by BIMA and CHANDRA

A lot of physics !!!

SZE in simulations



SZE in simulations



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** (Rubiño-Martin & Sunyaev 2003).

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

Cosmological constraints from galaxy clusters

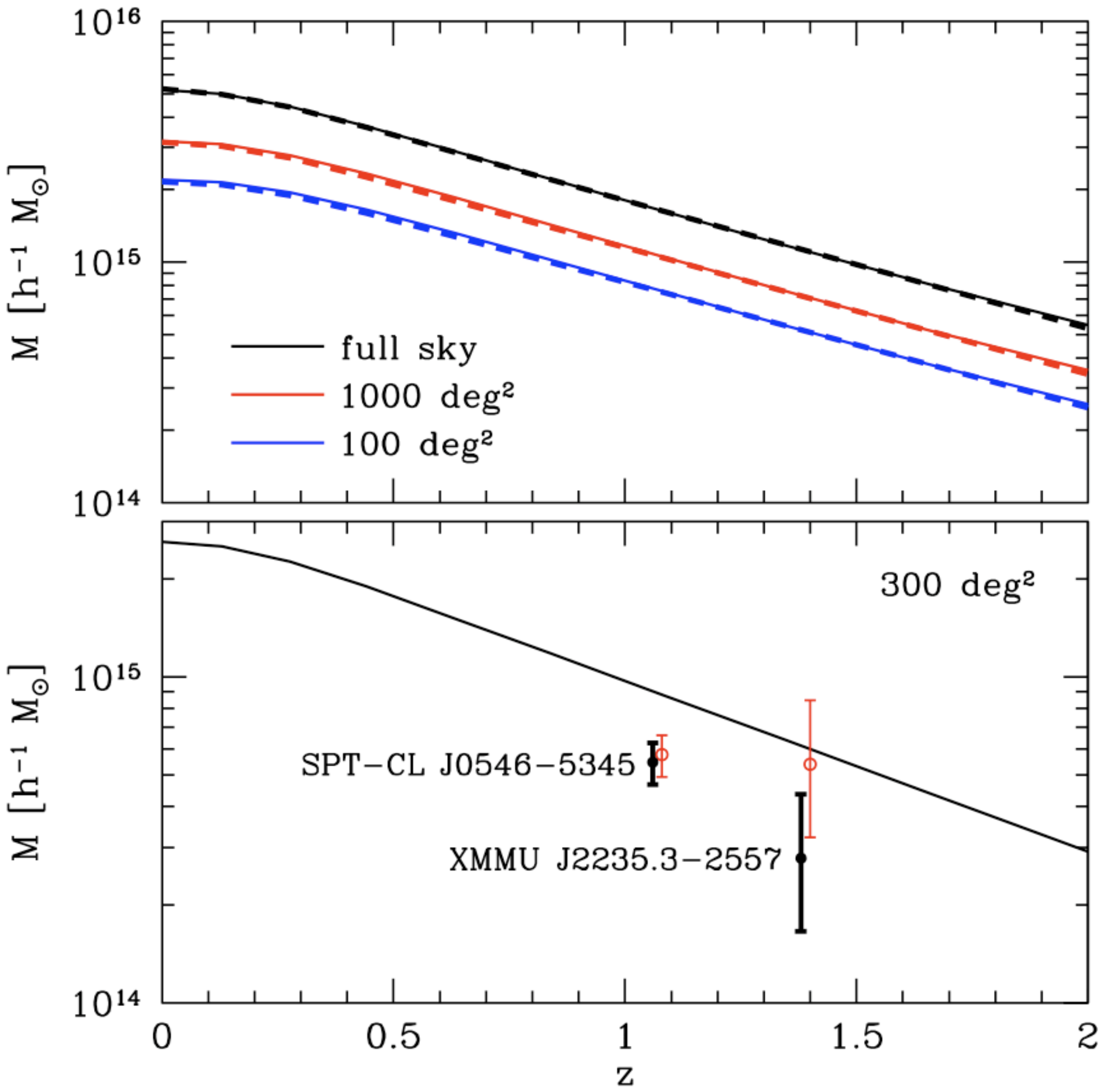
Status of the field in 2011 (from Allen et al. 2011).

Reference[c]	Data	σ_8	Ω_m	Ω_{DE}	w	h
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).

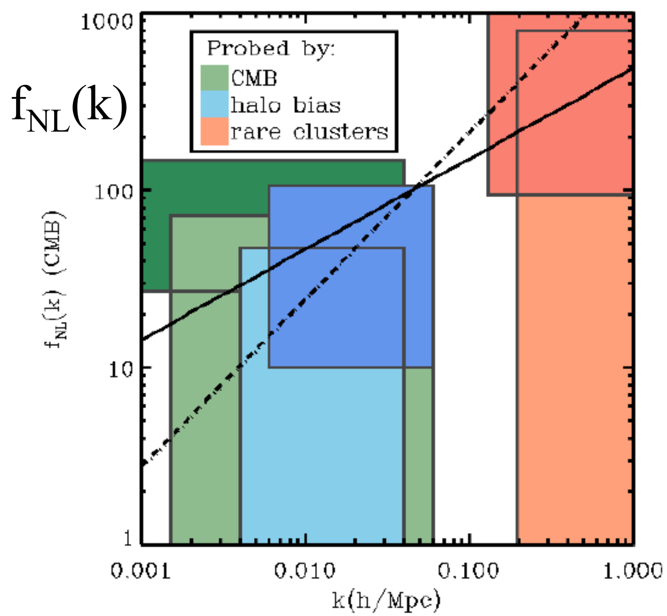
Falsifying ΛCDM with Cluster Counts



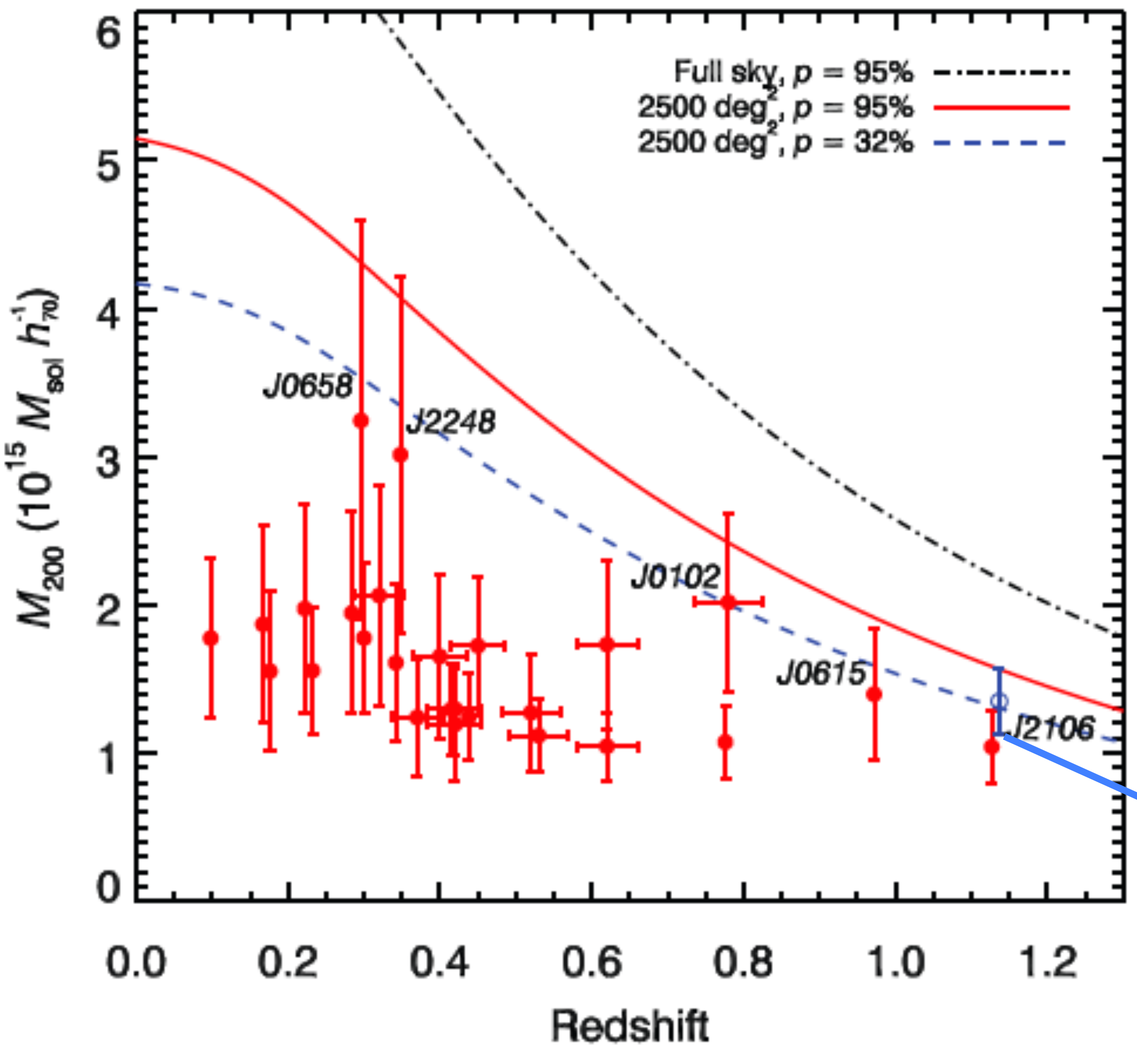
○ High-mass, high-redshift clusters tests extreme tail of the matter power spectrum.

○ 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)



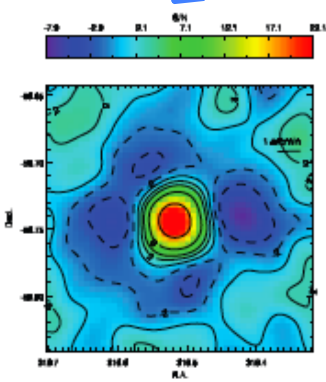
Falsifying ΛCDM with Cluster Counts

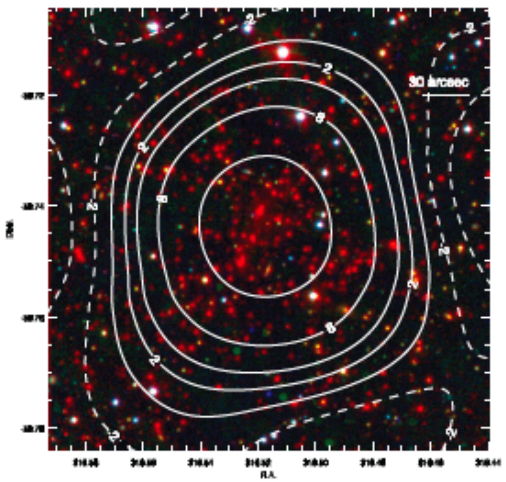


The 26 most significant (most massive) clusters over the full 2500 deg^2 SPT survey (Williamson et al. 2011).

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, PSZ1 and PSZ2 samples

II. Validation of the catalogues

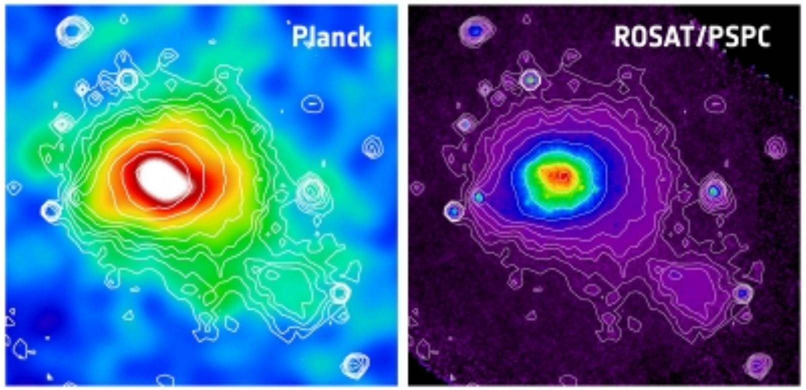
III. XMM-Newton and optical follow-up efforts.

II. **Cosmology with Planck SZ cluster counts**

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

III. **Cosmology with the y-map**.

IV. **Kinetic SZ effect.**



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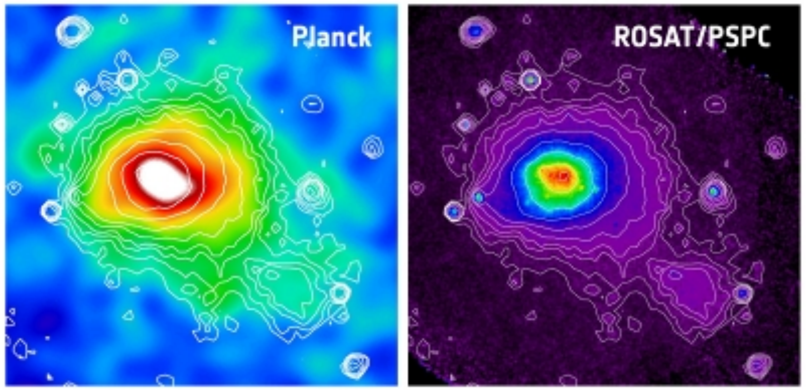
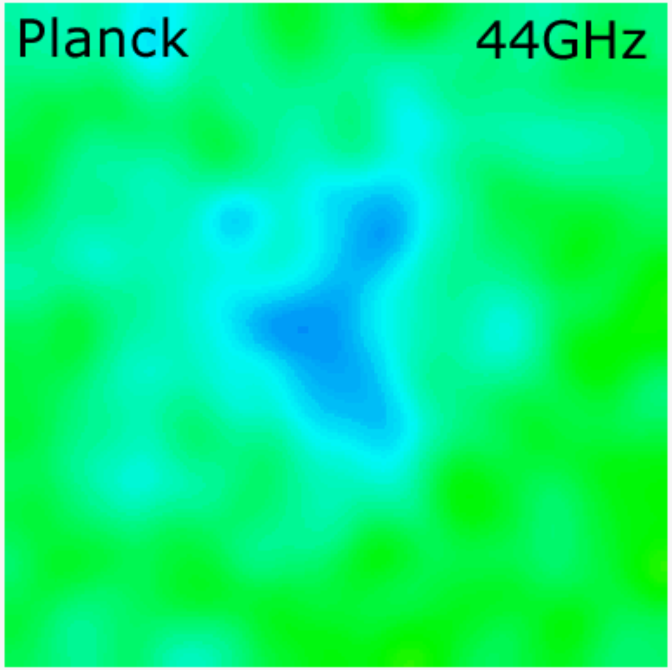
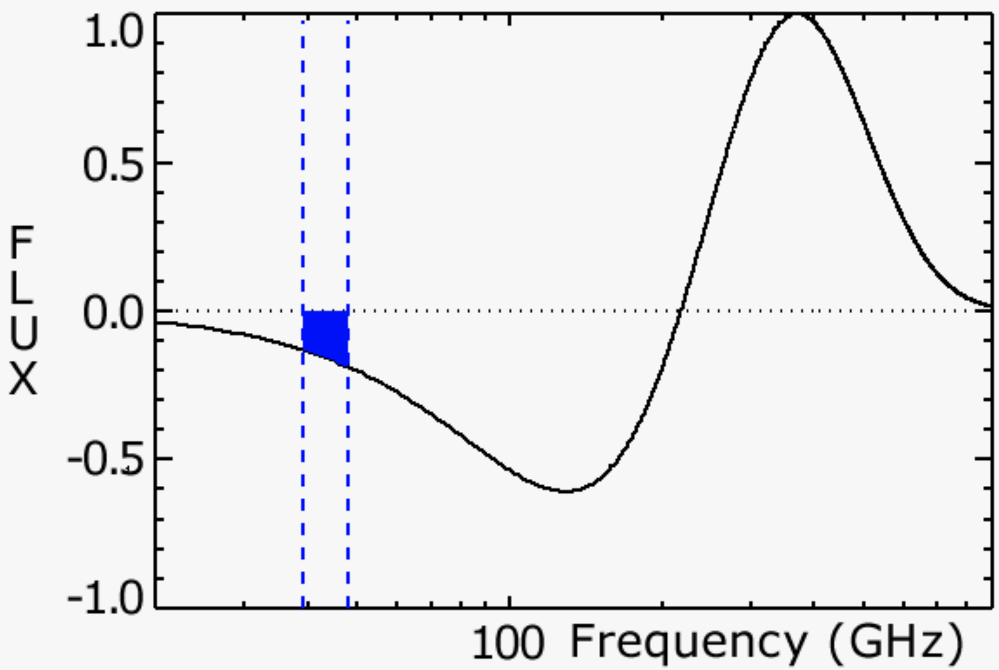


Planck: Uniqueness for SZ studies

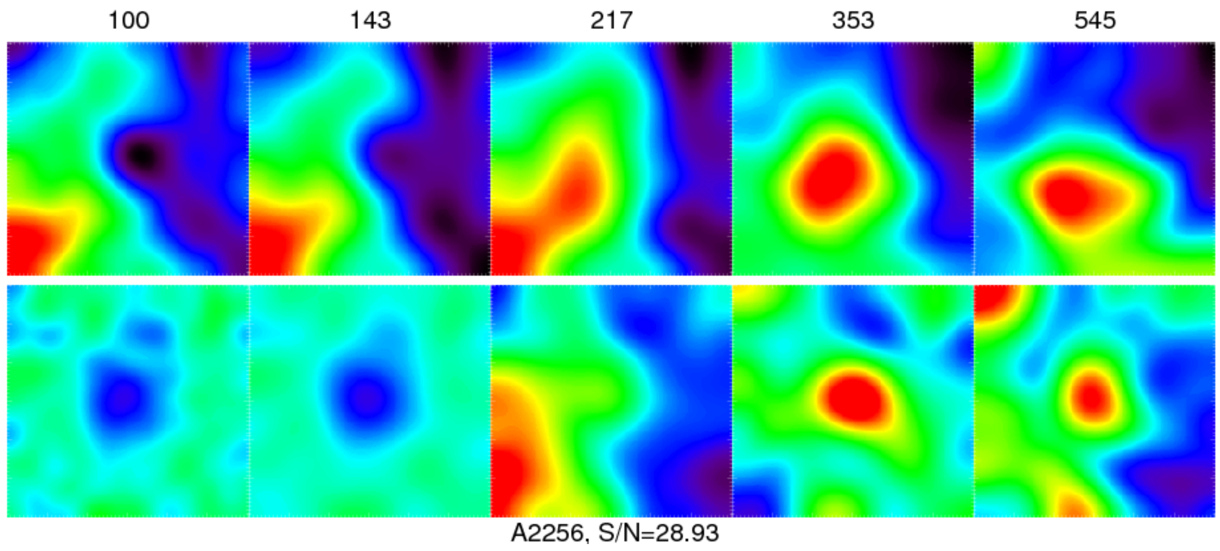
- **First all-sky SZ survey.** (Last all-sky survey for clusters was ROSAT in 1992)
- Frequency range from 30GHz to 857GHz, with a channel at 217GHz.
- Blind detection of the positive effect.

➔PLANCK, designed from start to measure SZ.





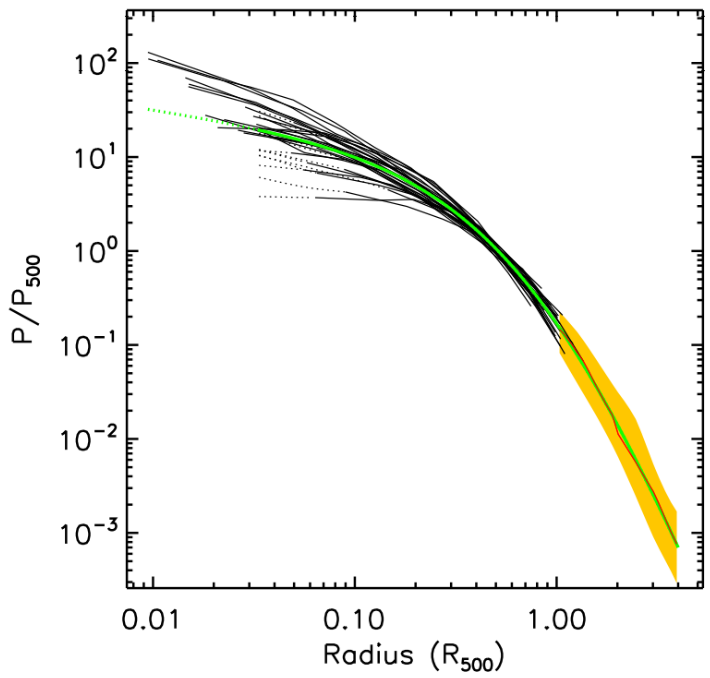
Cluster identification with PLANCK



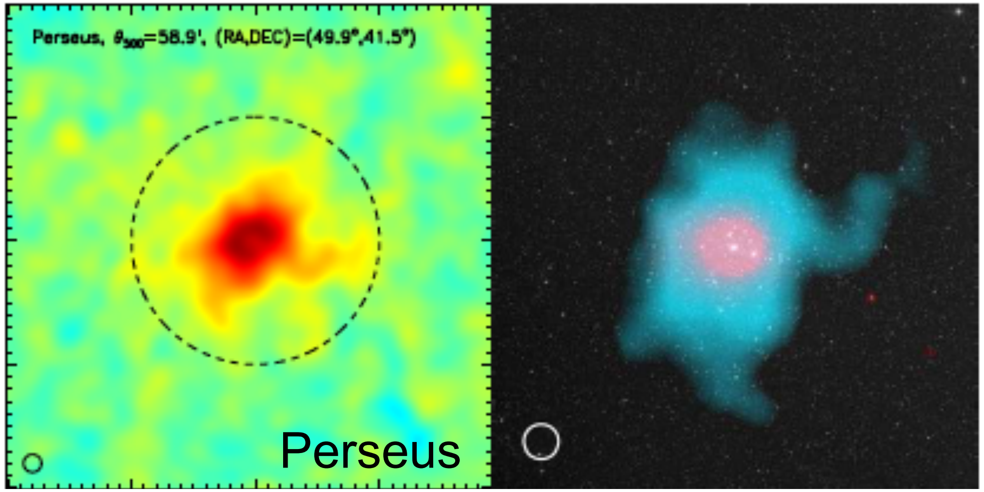
Raw maps

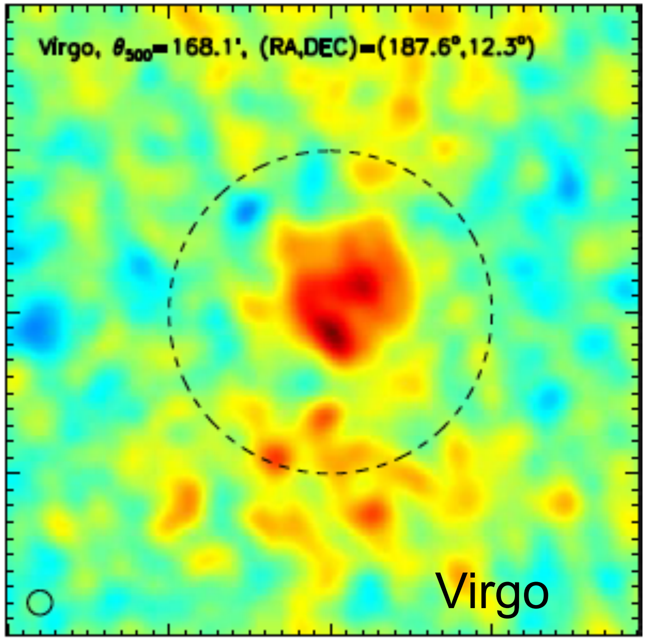
Cleaned maps (correcting for dust and CMB emission)

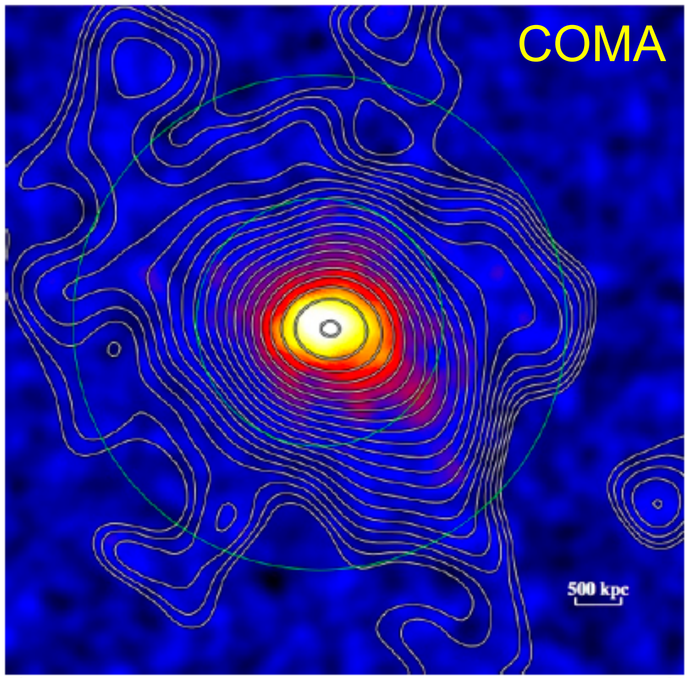
• Low significance of detections in individual cleaned frequency maps.
• **Adapted extraction technique: Matched Multi-Filter** (Herranz et al. 2002; Melin et al. 2006) enhances SZ signal over other components:
  • known spectrum: non-relativistic SZ.
  • known cluster shape: GNFW pressure profile (Arnaud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

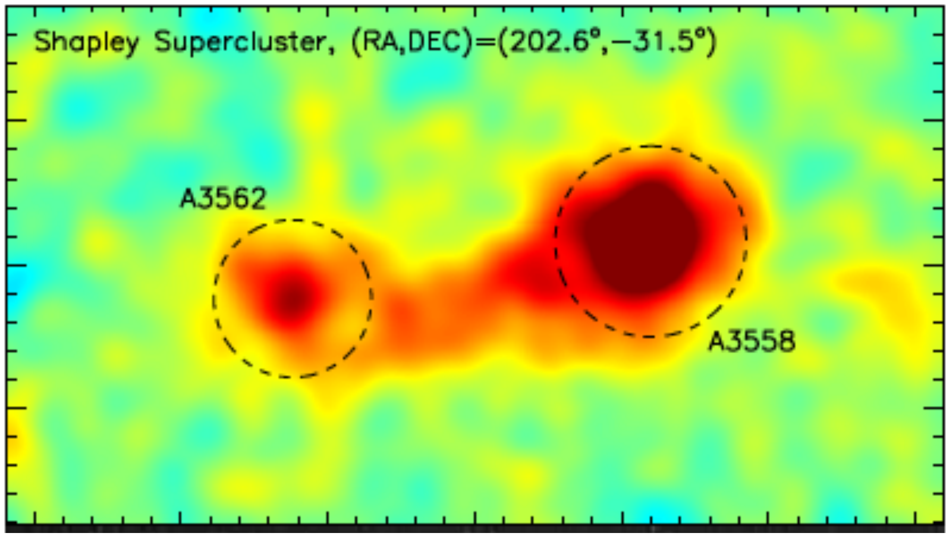


Planck SZ cluster catalogue



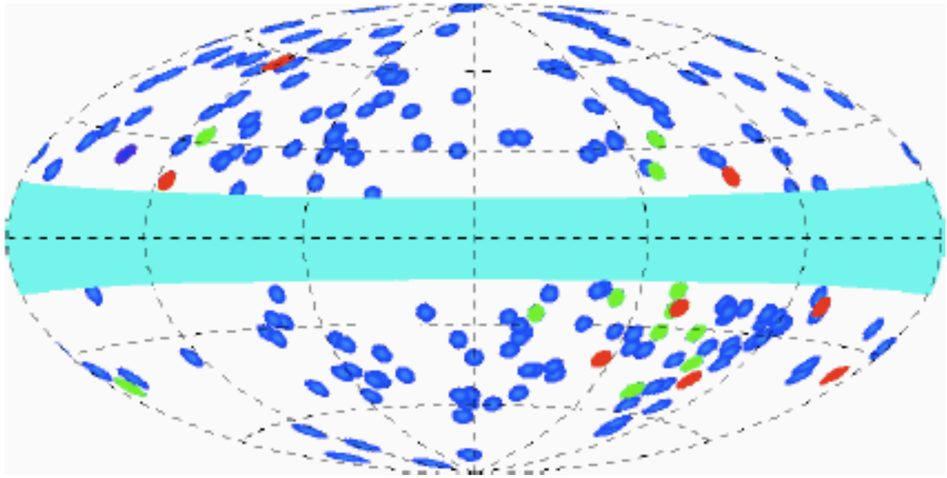




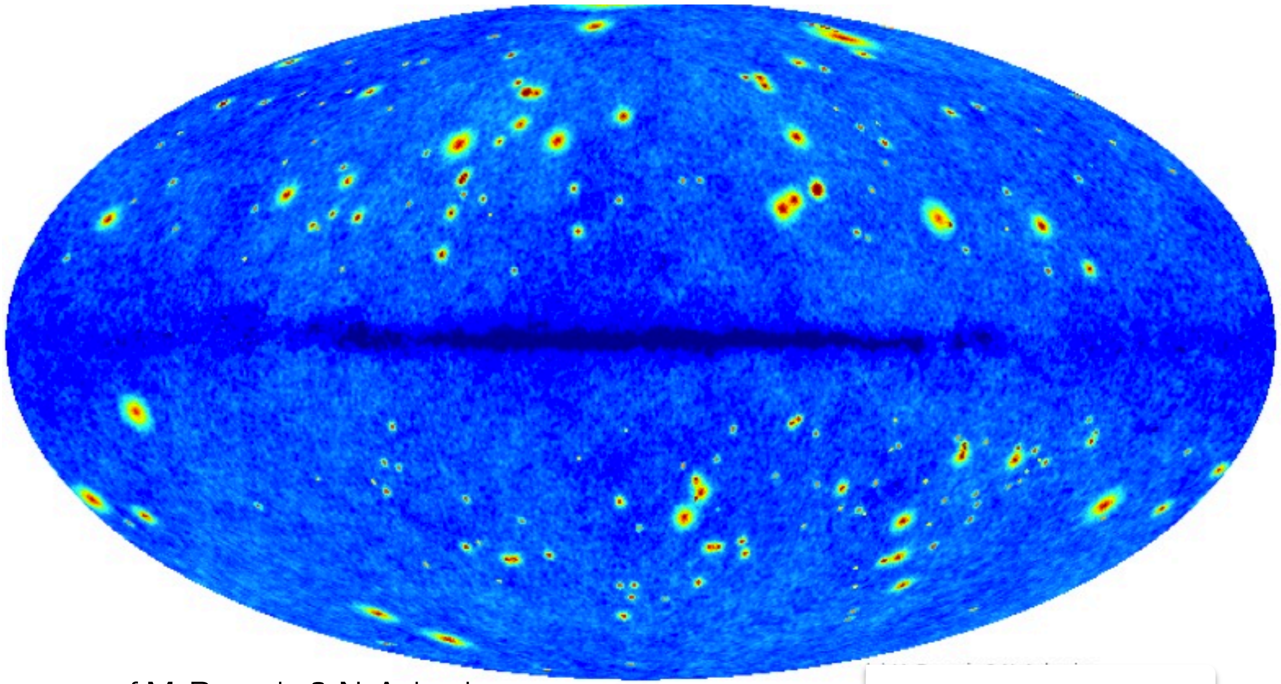


Planck Early Results: the all-sky ESZ cluster sample

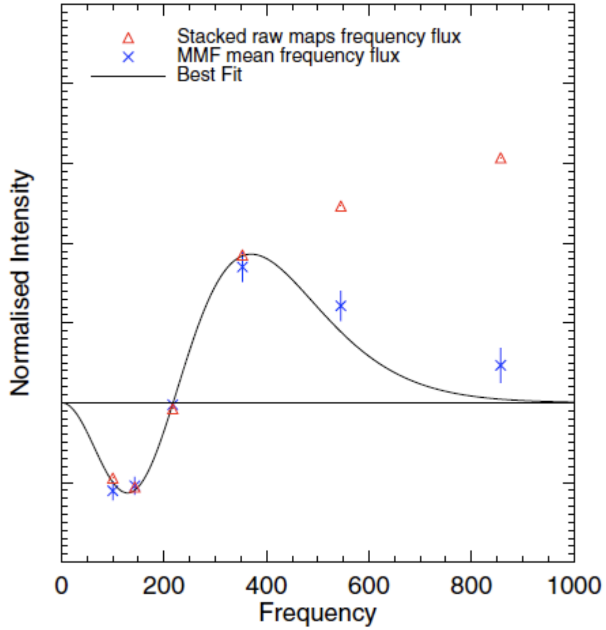
- **Early SZ sample: a high reliability sample** from the first 10 months of observations.
- **189** candidates in total (with |b| >14deg and MMF type **S/N from 6 to 29** => **purity > 95%**)
- 169 candidates identified with known X-ray or optical clusters. For ~80% of them, Planck provides the first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



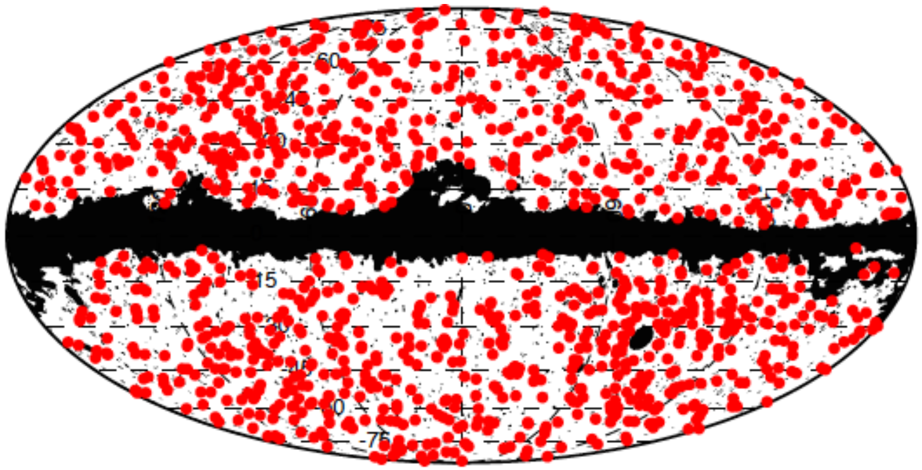
(Planck Collaboration VIII, 2011)



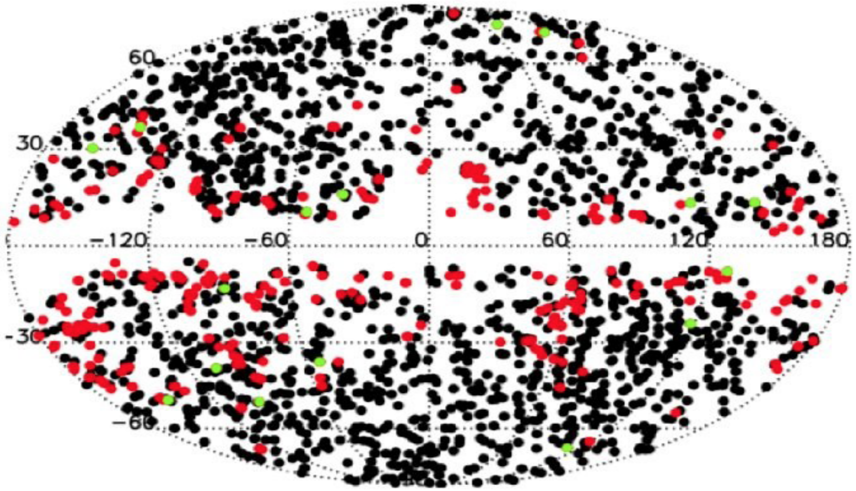
Courtesy of M. Douspis & N. Aghanim



Planck cluster catalogues (PSZ1 & PSZ2)



PSZ1 (Planck Collaboration XXIX 2014)

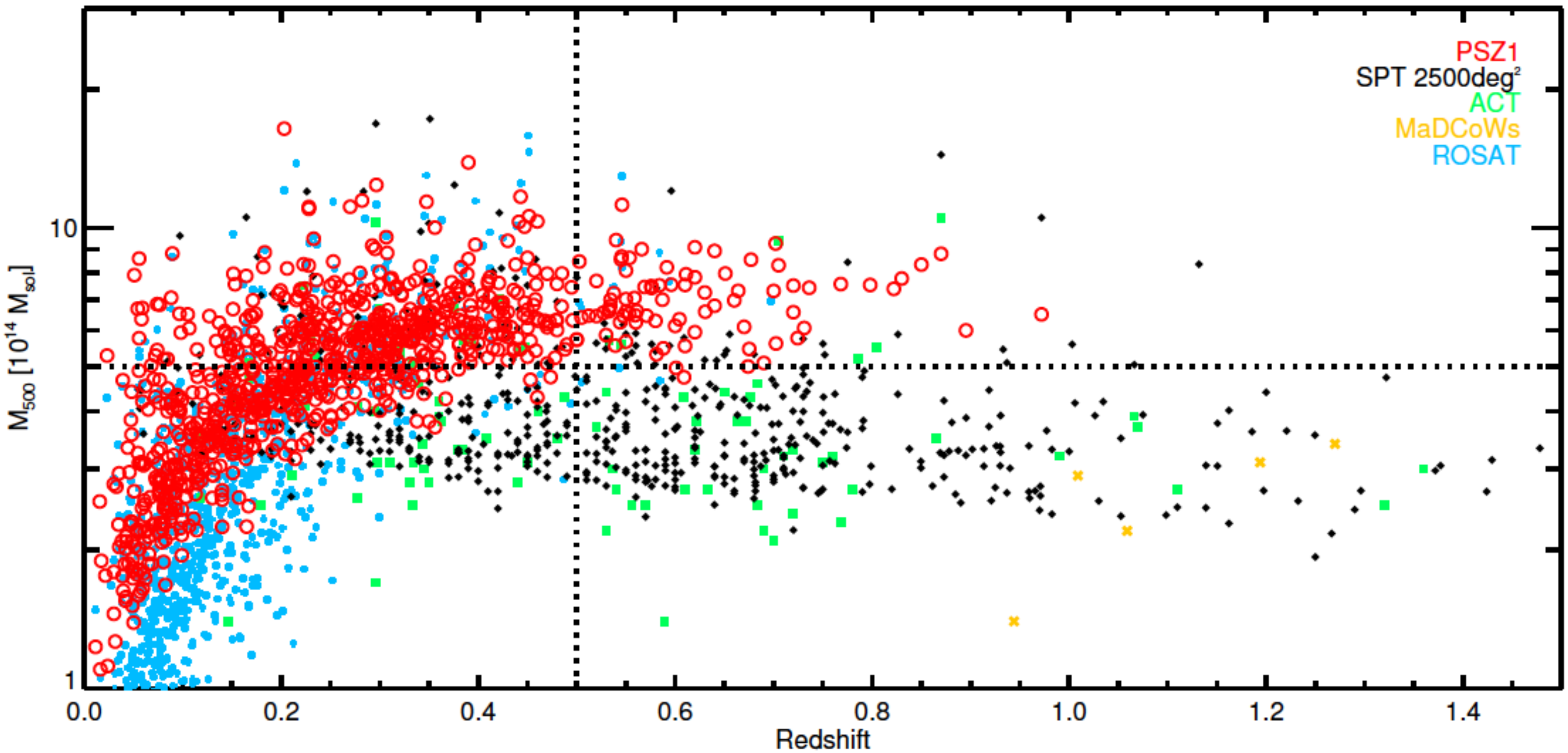


PSZ2 (Planck Collaboration XXVII 2016)

Sample	PSZ1 2013	PSZ1 2015	PSZ2	Common	New PSZ2
Union	1227	1227	1653	937	716
Intersection	546	546	827	502	325
Confirmed	861	947	1203	820	383
Candidates	366	292	546	99	447
Low reliability	142	131	143	39	104

Properties of SZ catalogues

Mass – redshift space



SZ selected clusters → no redshift dimming →quasi mass-selected

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

→Access to high M – z region: less sensitive to gas modeling & rare objects

SPT & ACT catalogs: higher z & lower masses

Validation of the SZ samples

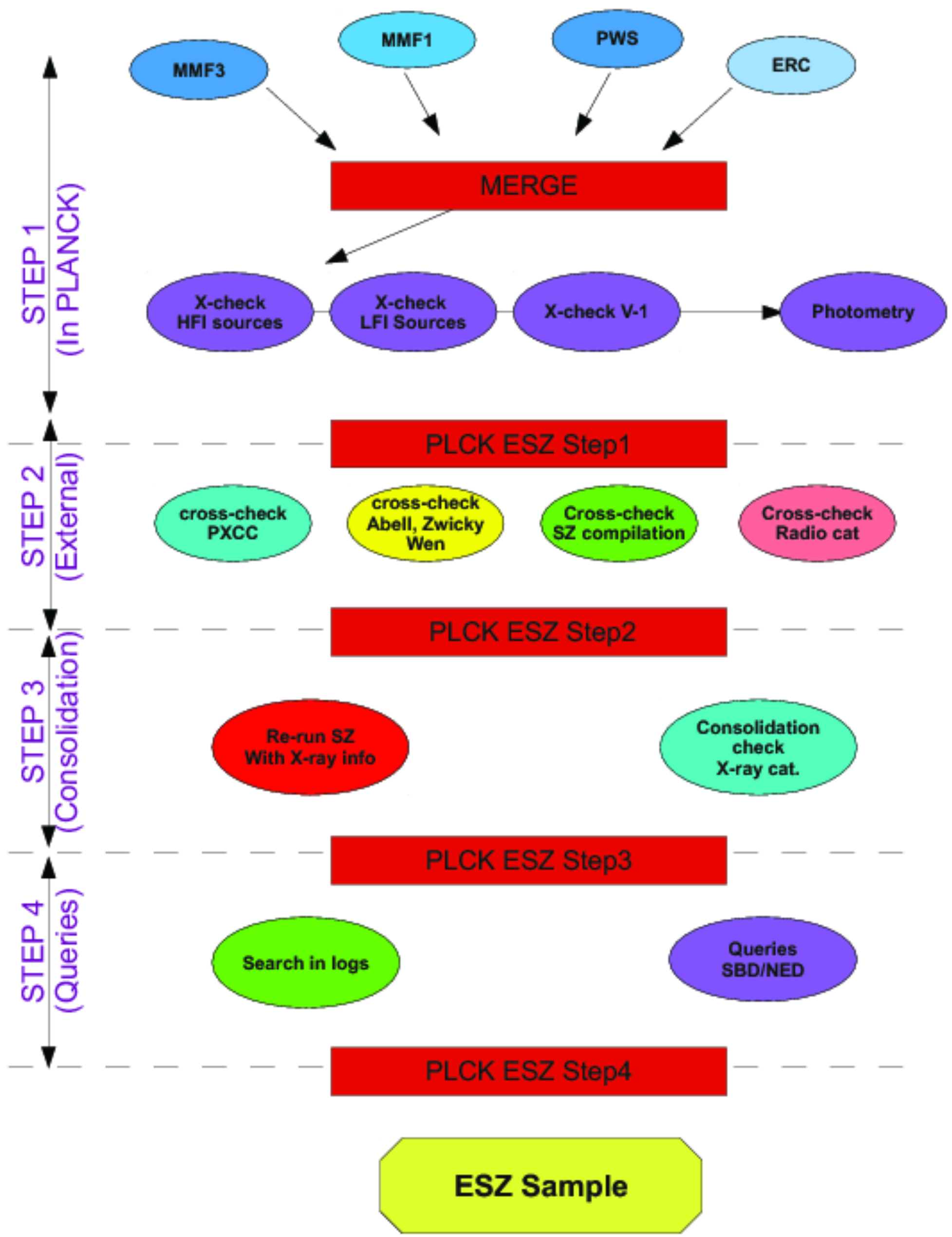
Planck internal quality assessment

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

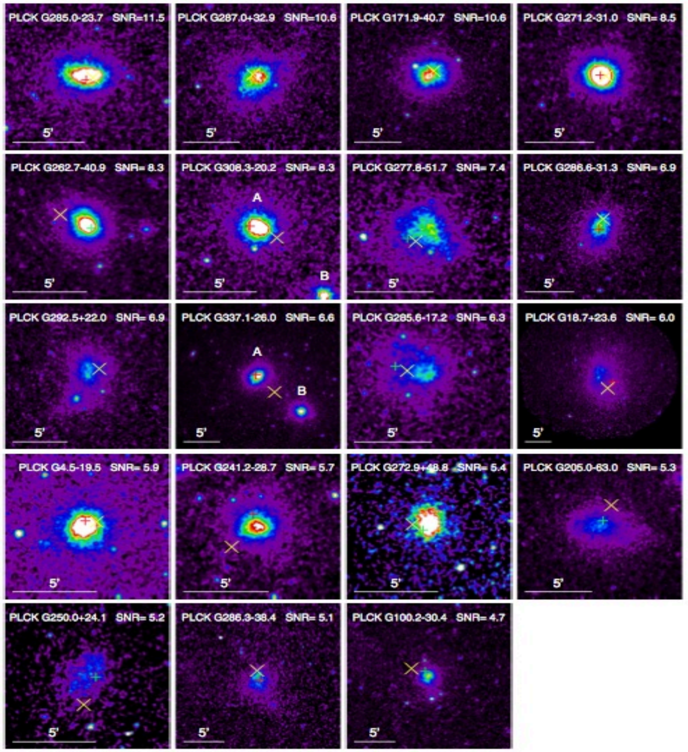
Identification with known clusters from ancillary data

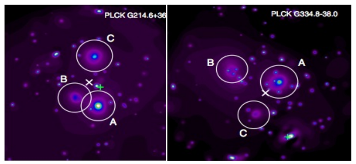
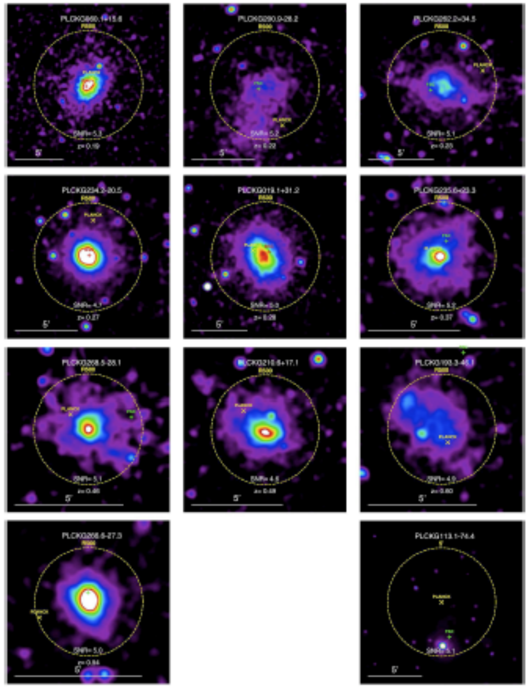
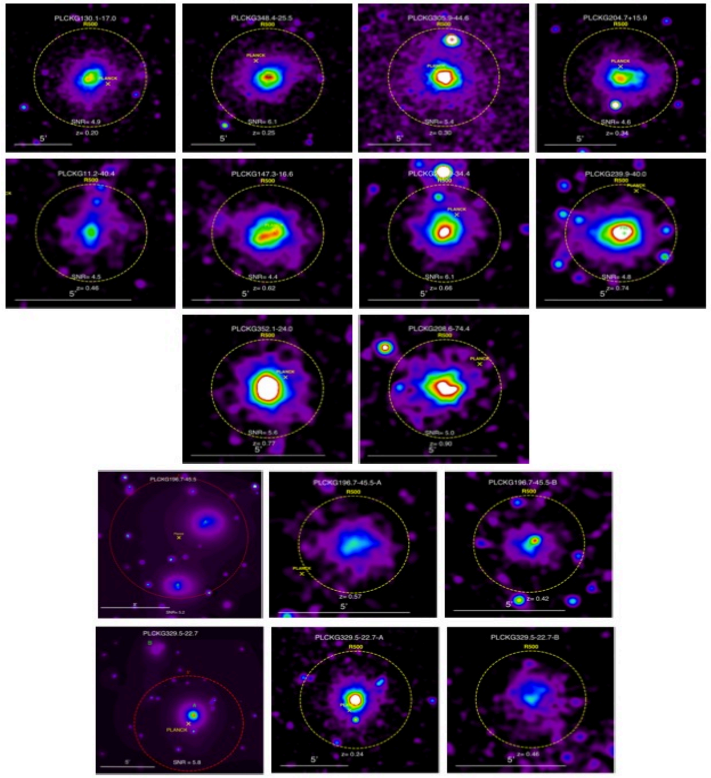
Multi-frequency follow-up programme for confirmation of SZ candidates:

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



XMM-Newton follow-up/validation programme

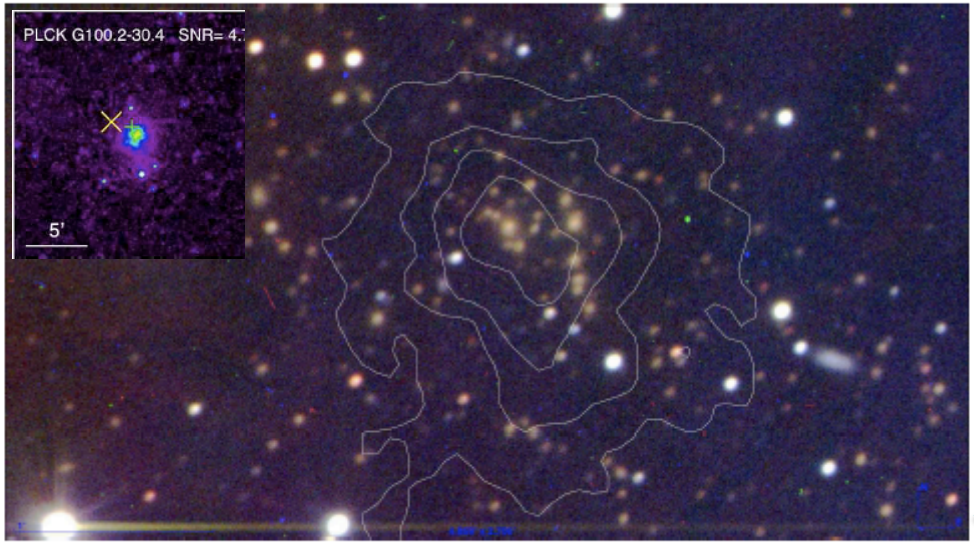


- Three papers (Early Paper IX 2011, Intermediate Papers I and IV, 2012).
- High success rate (>85% are real candidates)
- 51 targets confirmed
- 70% disturbed morphologies (compared to 30% for X-ray selected clusters, see e.g. REXCESS)
- 4 double and 2 triple systems (12% multiple systems)

Optical Follow-up of Planck clusters

ENO/IAC80



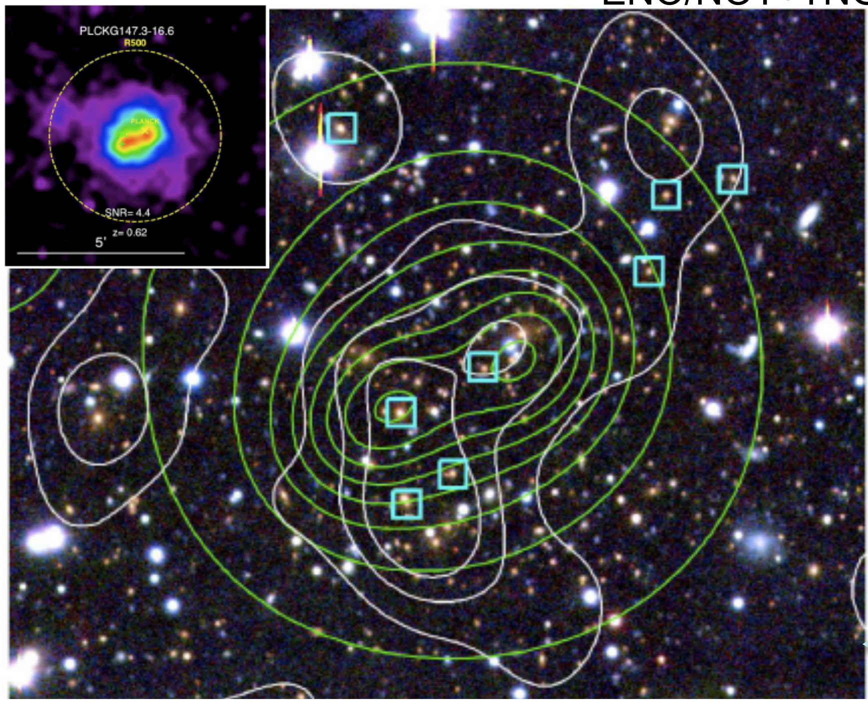
Follow-up observations (>200 confirmed) in:

- Canary Islands Observatories
- ESO (NTT, 2.2m)
- Palomar
- RTT

Two large programs: **ESO-LP** (PI: Aghanim) and **ITP** (PI: Rubiño-Martin). Plus dedicated observations at **RTT** (PI: R. Burenin).

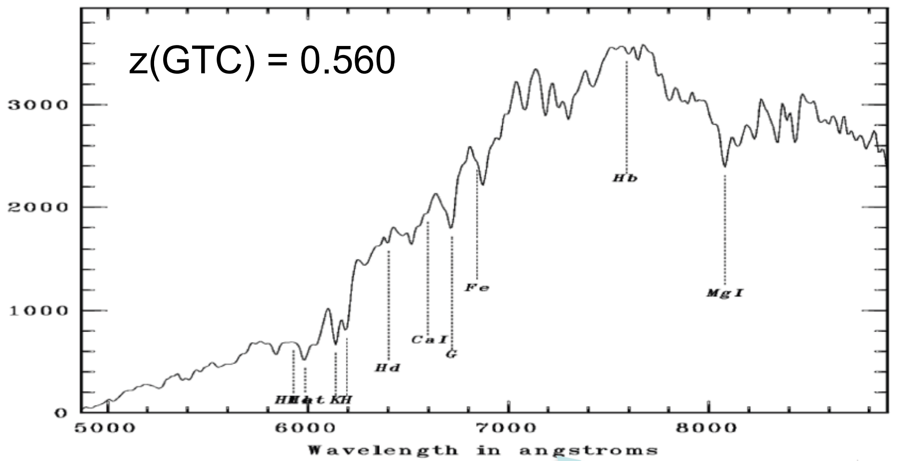
z(Fe K) = 0.31
z_{phot}=0.34±0.03

ENO/NOT+TNG

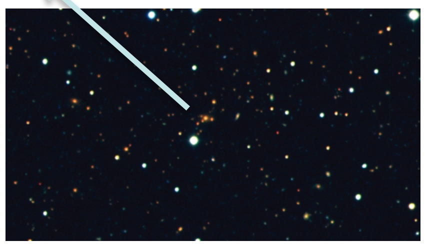


z(Fe K) = 0.62
z_{spec} = 0.66±0.05
(Gemini)

ENO/GTC

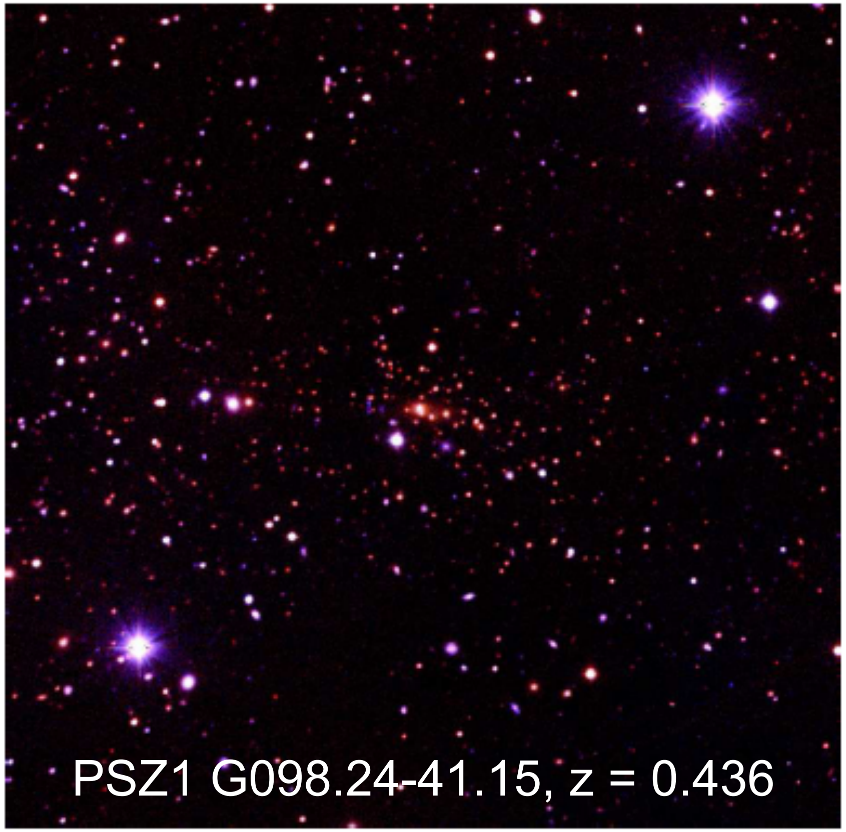


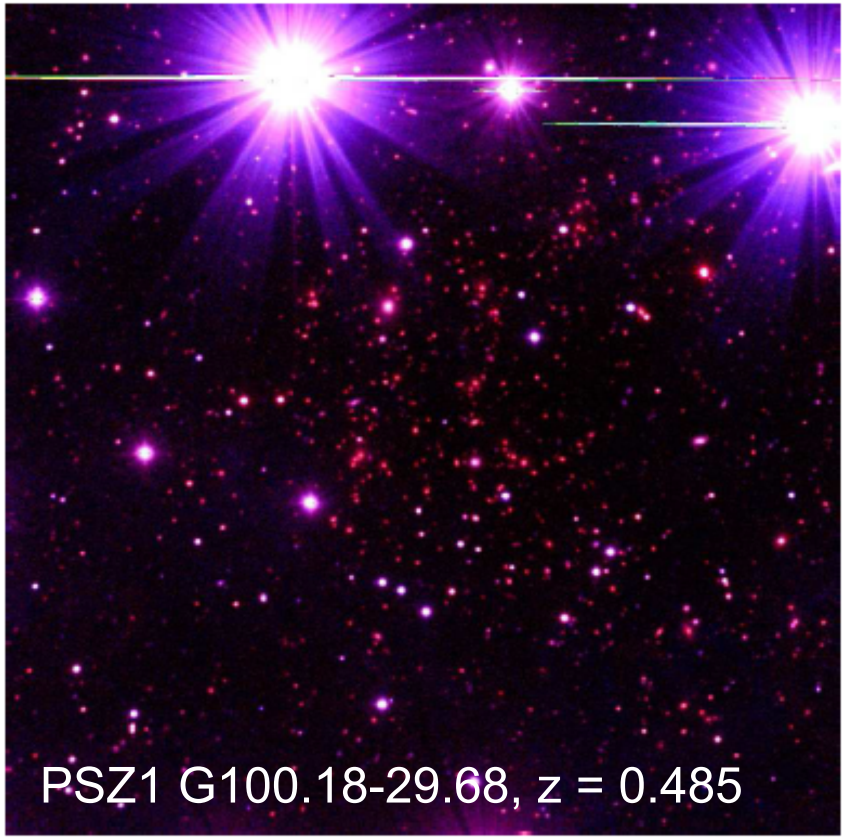
ENO/INT



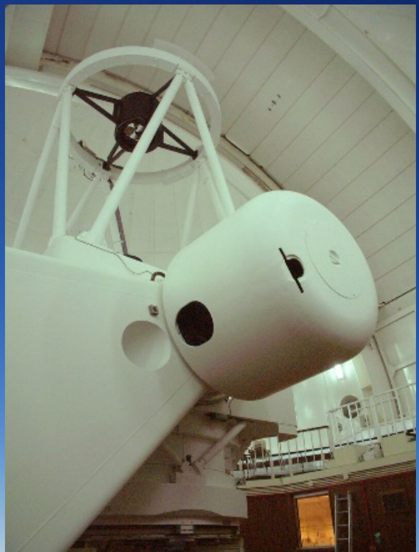
Optical follow-up. RTT programme.

- Observations with the Russian-Turkish 1.5-m telescope (RTT150). Some observations of distant clusters were done at the 6-m Bolshoy Telescope Azimutal'ny (BTA) of the Special Astrophysical Observatory of the Russian Academy of Sciences.
-The redshifts of 65 Planck clusters were measured spectroscopically and 14 more were measured photometrically.
- See details in Planck Collaboration Int. XXVI (2014), arXiv: 1407.6663.





Optical follow-up of Planck SZ sources from the Canary Island Observatories



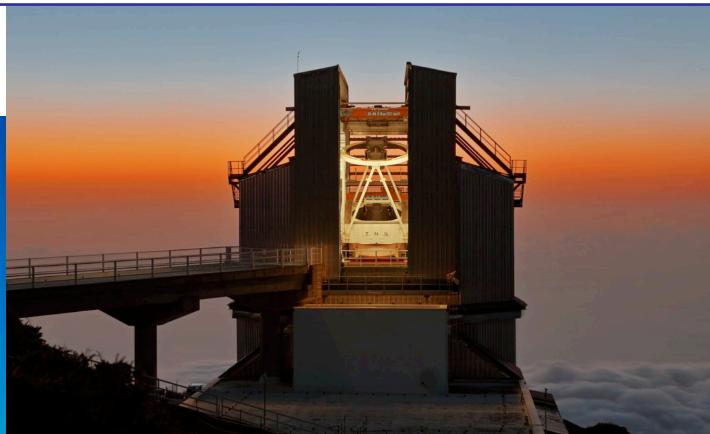
PI: J. A. Rubiño
Postdoc: R. Barrena
PhD: A. Ferragamo
A. Aguado
D. Tramonte

CoI: R. Genova
Postdocs in the past:
A. Streblyanska
H. Lietzen
A. Hempel

Optical follow-up. Canary Islands observatories

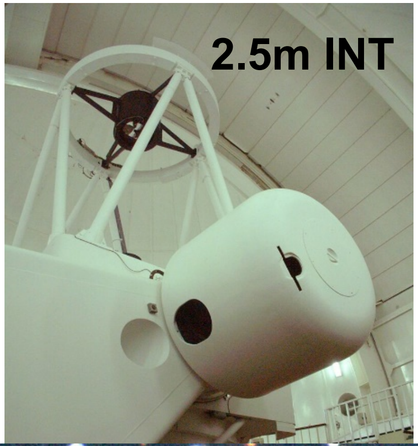
ITP 13B-15A: **>80 nights** observing time at GTC, INT, TNG and WHT telescopes
LP 15B-17A. **>40 nights** using INT, TNG and GTC telescopes.

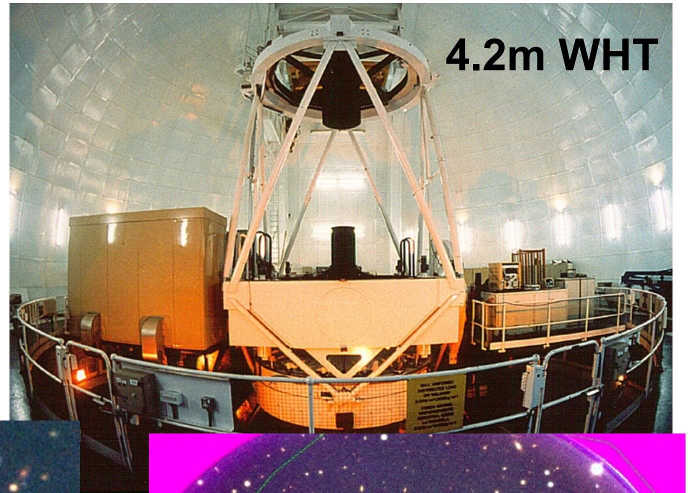
TELESCOPE	INSTRUMENTS	MODE
2.5m INT	WFC (34’x34’)	griZ photometry
4.2m WHT	ACAM (8’x8’ imaging,R~700)	griZ photometry. Long-slit spectroscopy
3.5m TNG	DOLORES (R~600)	MOS spectroscopy
10.4m GTC	OSIRIS (R~800)	Long-slit spectroscopy. MOS spectroscopy

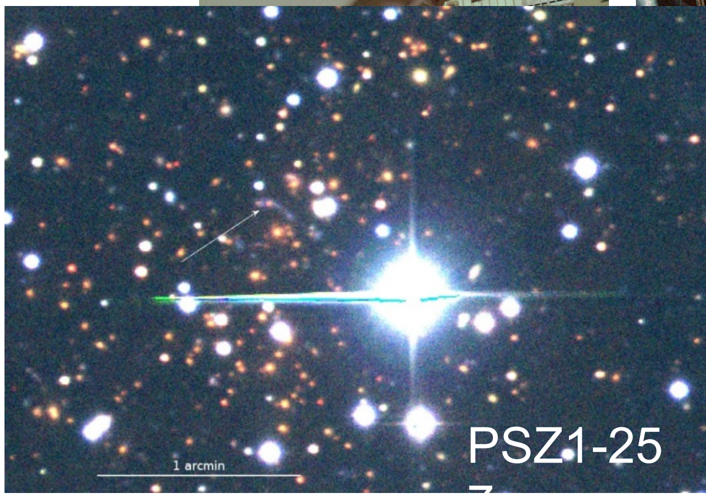



Optical validation: observational strategy

Cluster identification - Imaging



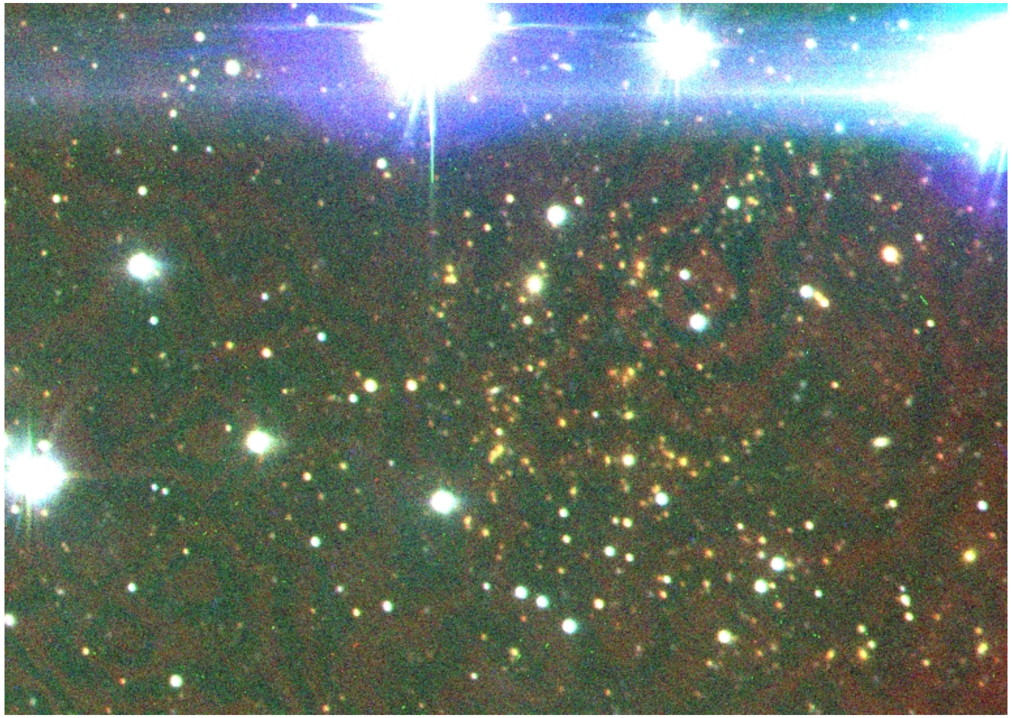




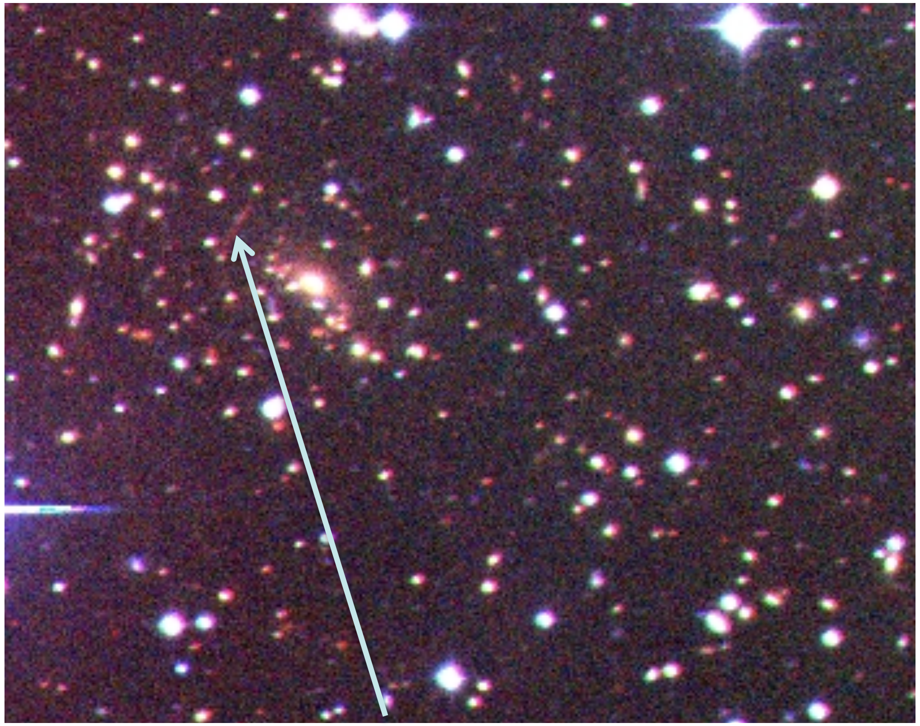
90% Complete	FOV	Texp / band	g-band	r-band	i-band
IAC80	10'x10'	3000s	22.5	21.8	21.3
WFC / INT	33'x33'	1500s	23.5	22.7	22.0
ACAM / WHT	8'x8'	900s	24.6	23.7	23.2

Optical follow-up. ITP programme.

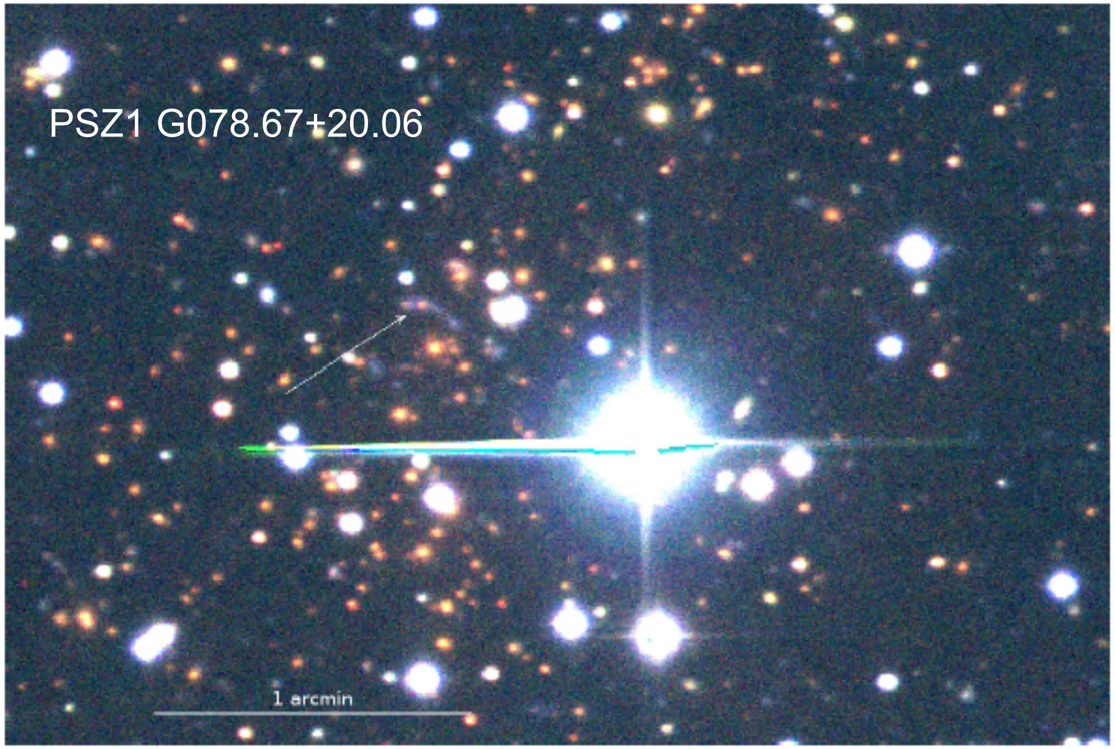
Imaging: 11 nights per year in INT and WHT telescopes. More than 100 clusters imaged per year.

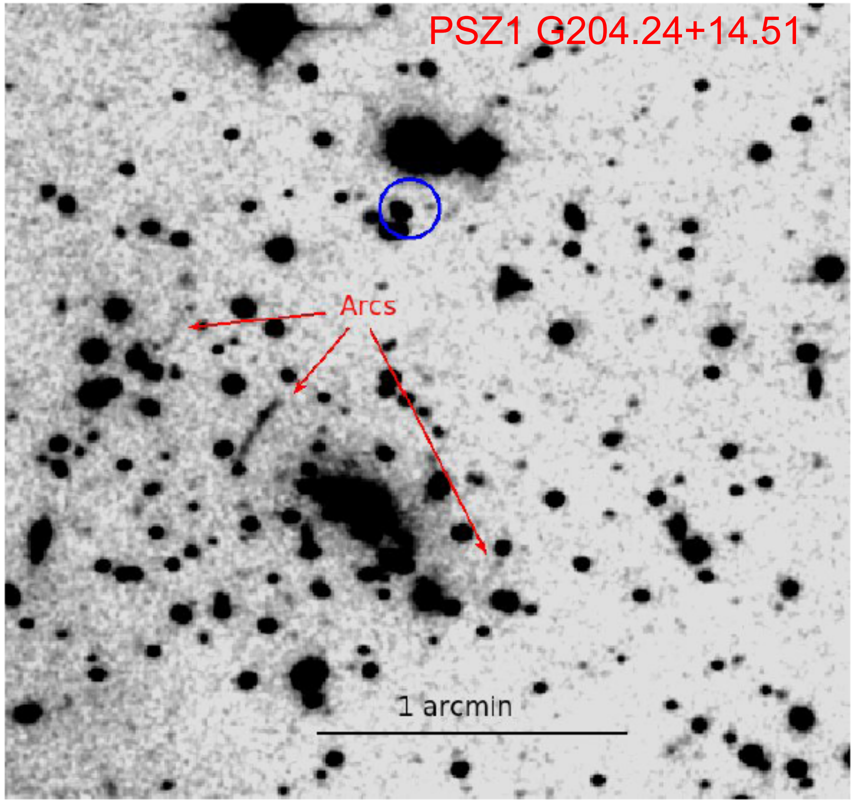


RGB image of PSZ1 G100.18-29.68. (Z_{phot}=0.485)

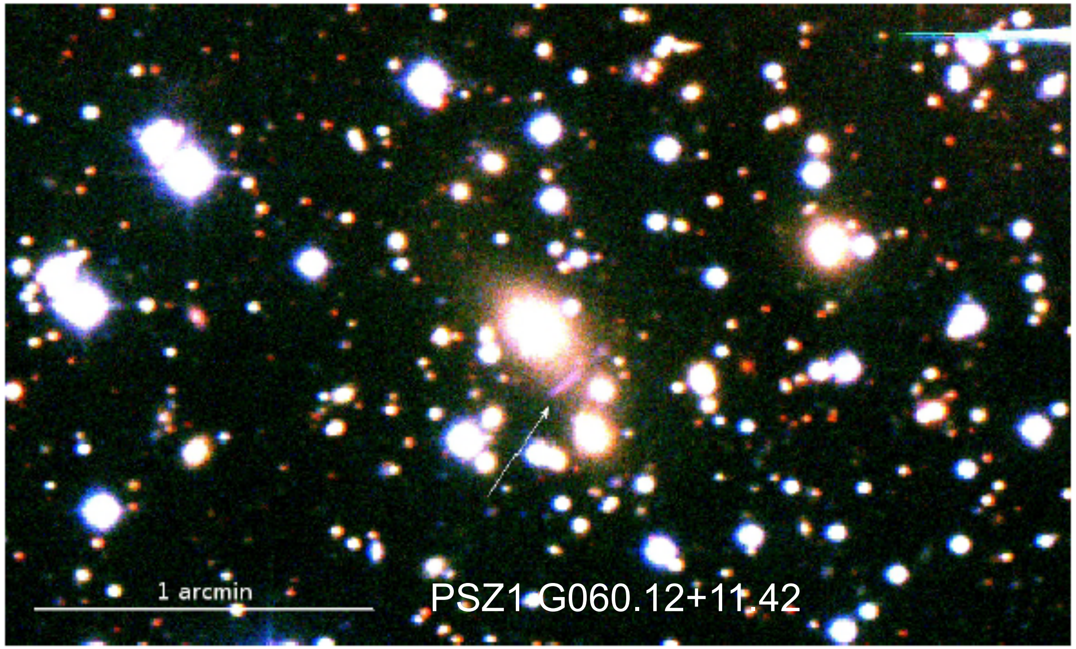


Cluster with arcs (Z_{phot} >0 .6)


PSZ1 G078.67+20.06
1 arcmin

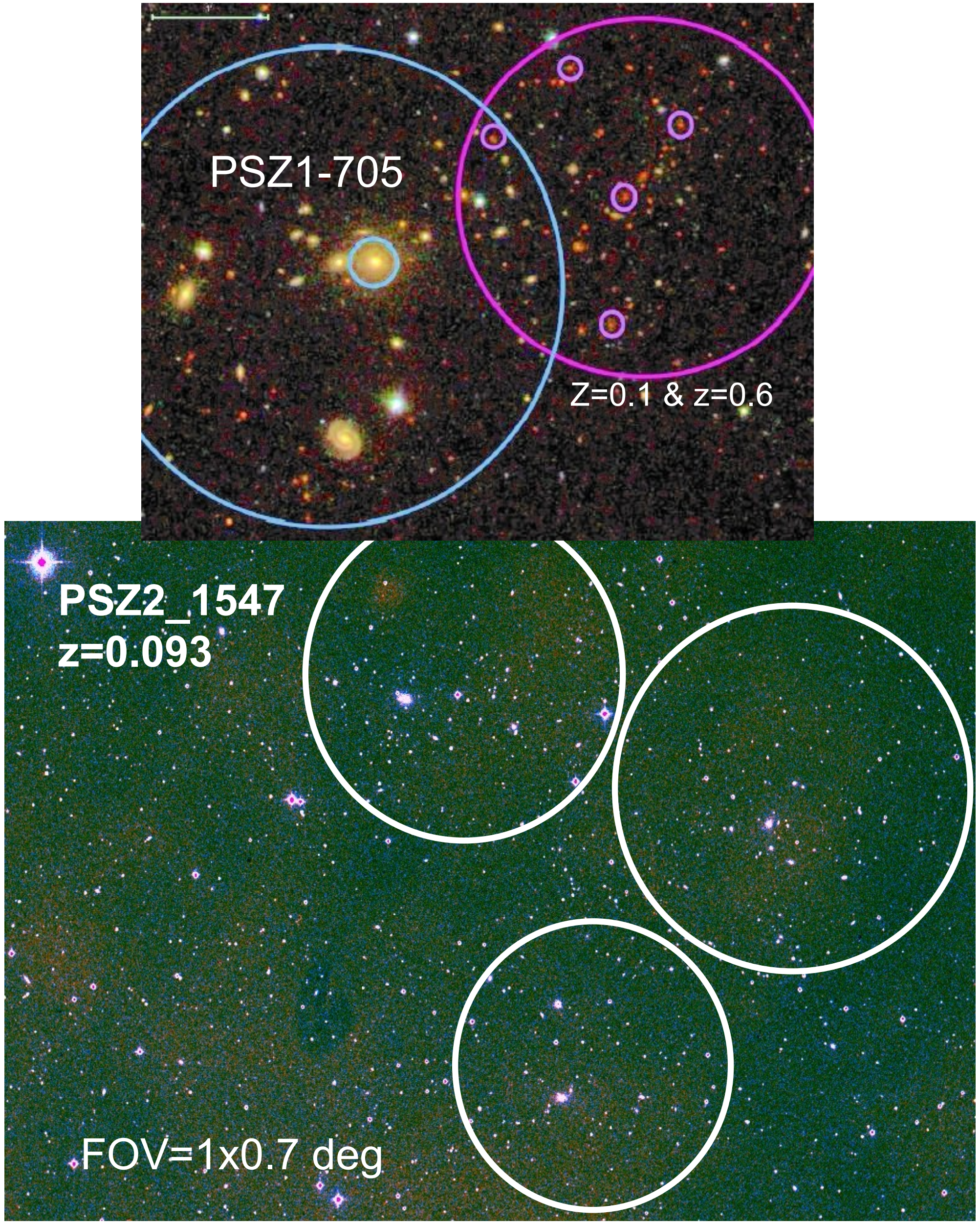

PSZ1 G204.24+14.51
Arcs
1 arcmin

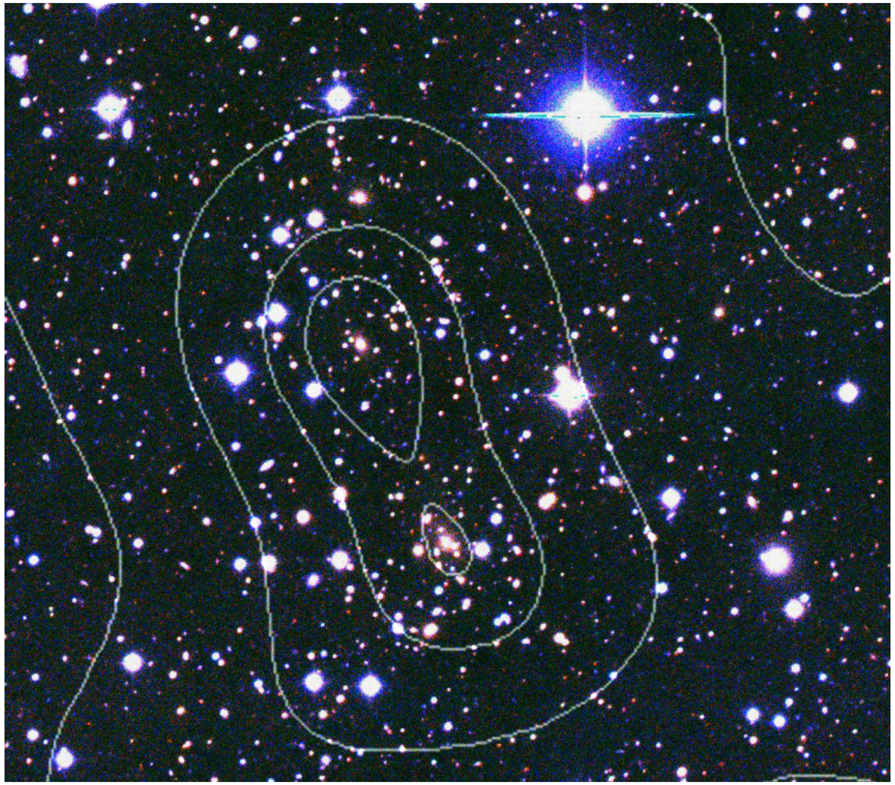
Arcs


1 arcmin
PSZ1 G060.12+11.42

Optical follow-up. ITP programme.

Imaging: 11 nights per year in INT and WHT telescopes. More than 100 clusters imaged/year.

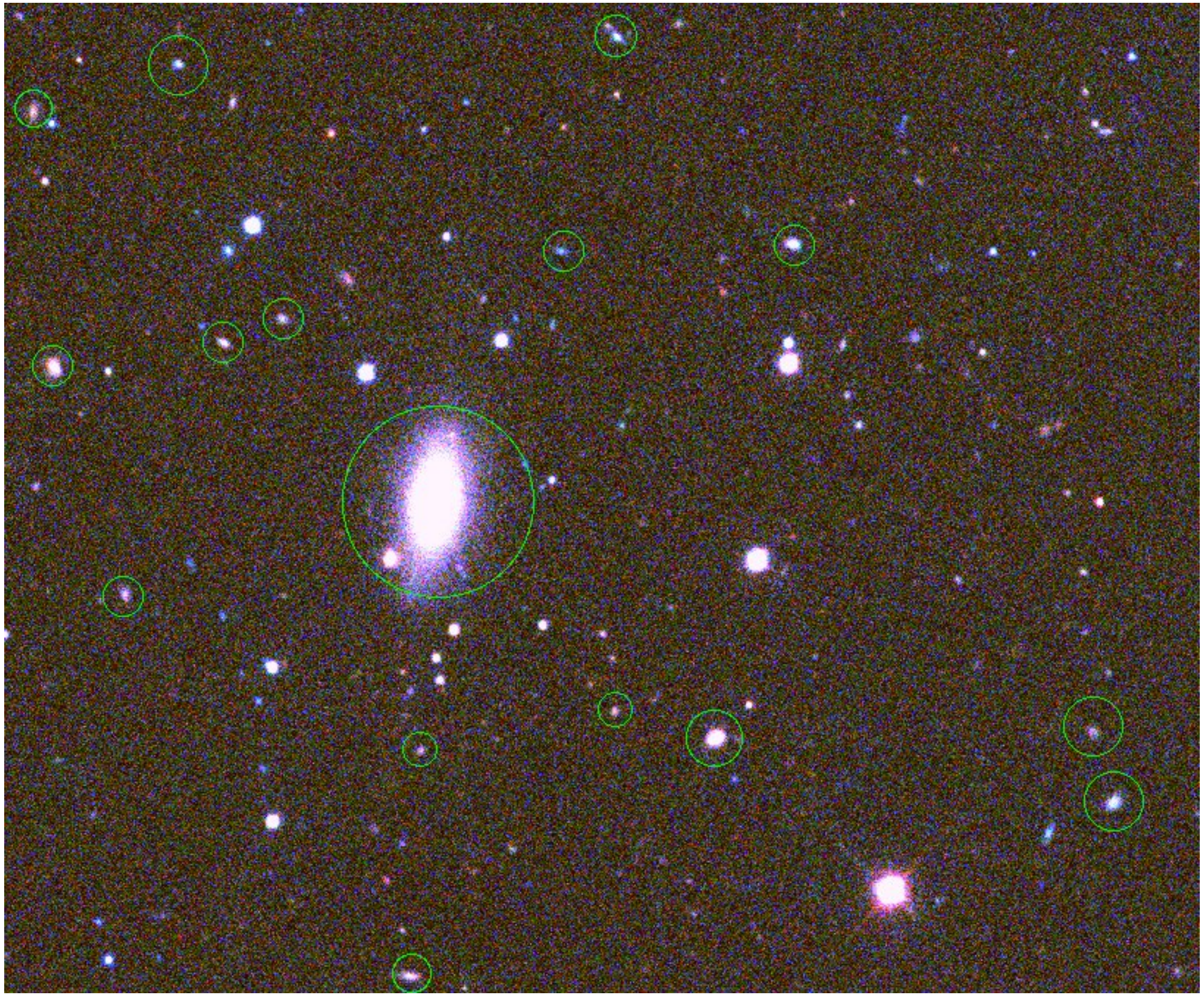




Multiple examples of clusters with sub-structure or multiple systems.
Top: On top of the RGB image, the contours correspond to the density levels of (photometrically selected) cluster members (Z_{spec} = 0.3).

Optical follow-up. ITP programme.

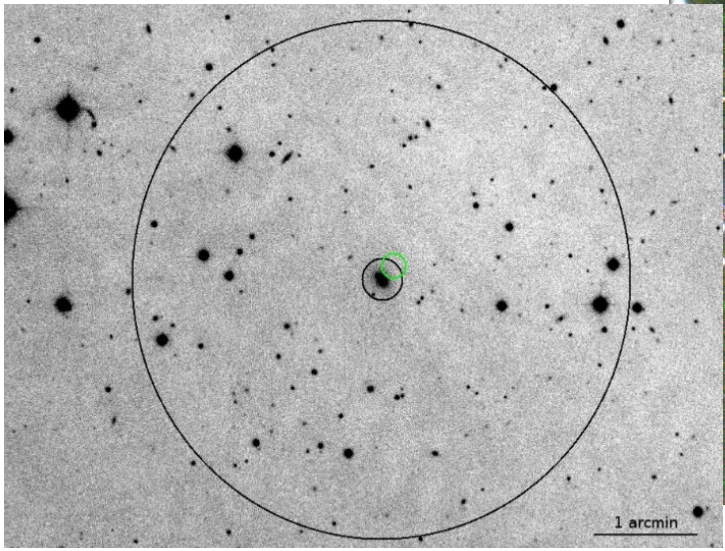
Imaging: More than 100 clusters imaged per year.



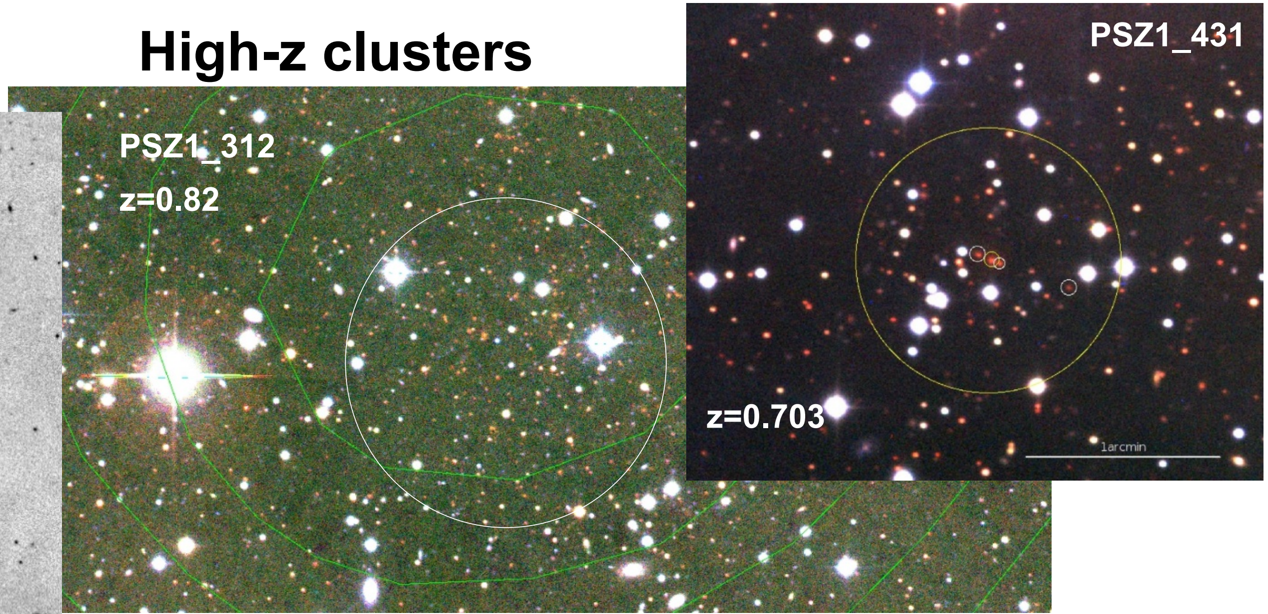
Several identifications correspond to **Fossil groups** (e.g. Jones et al. 2013; Voevodkin et al. 2010)

Figure shows a case with Zspec=0.0336.

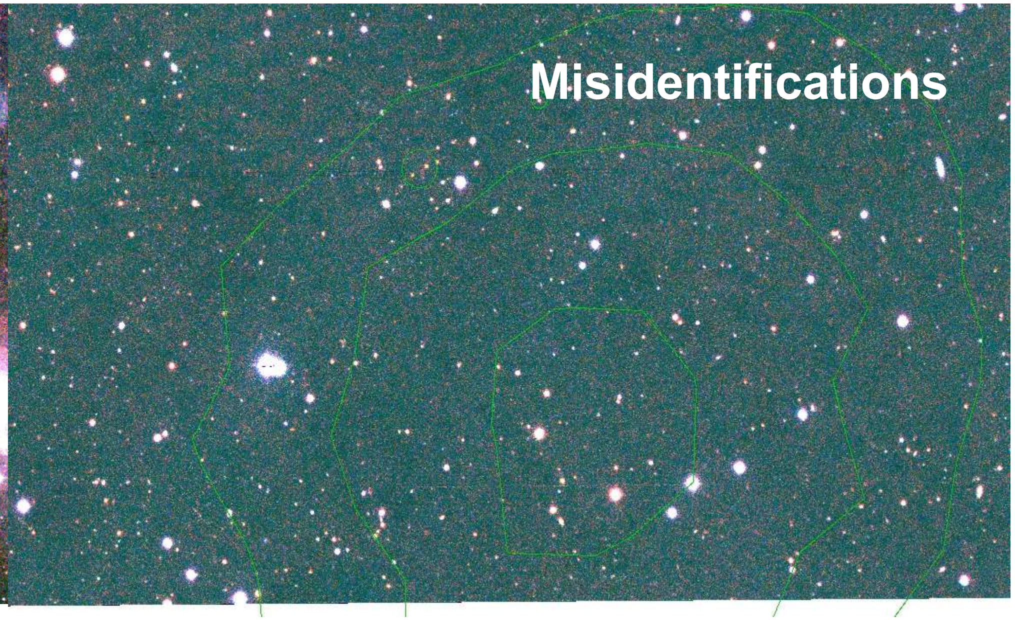
Fossil systems



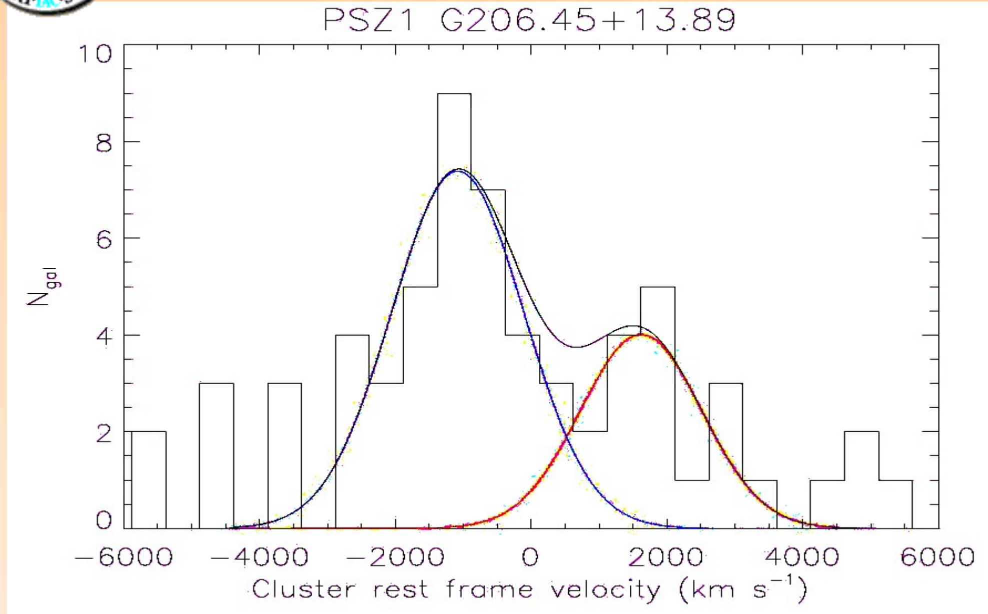
High-z clusters

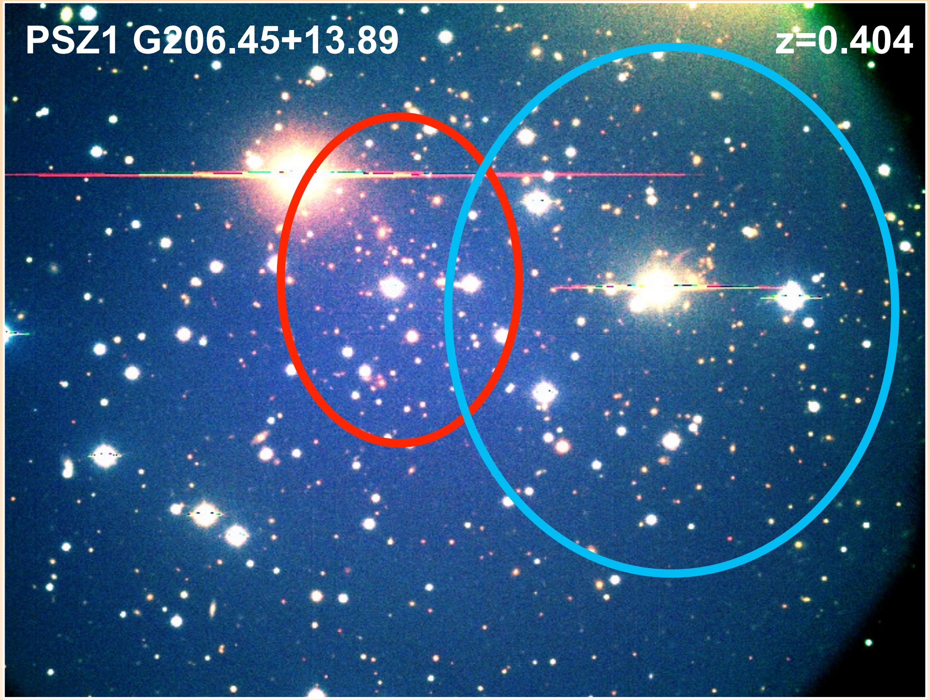


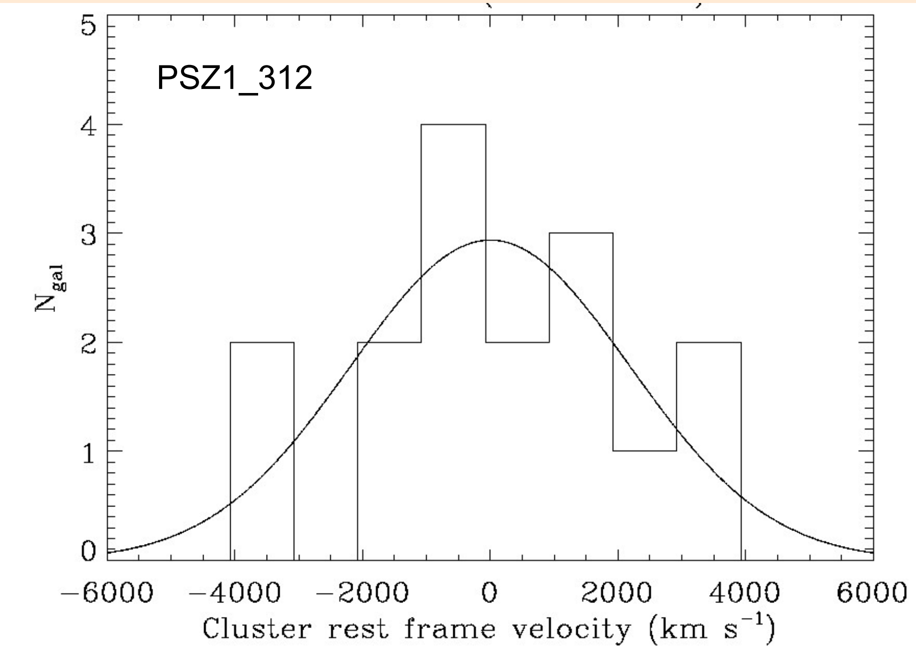
Non-detections (~5%)

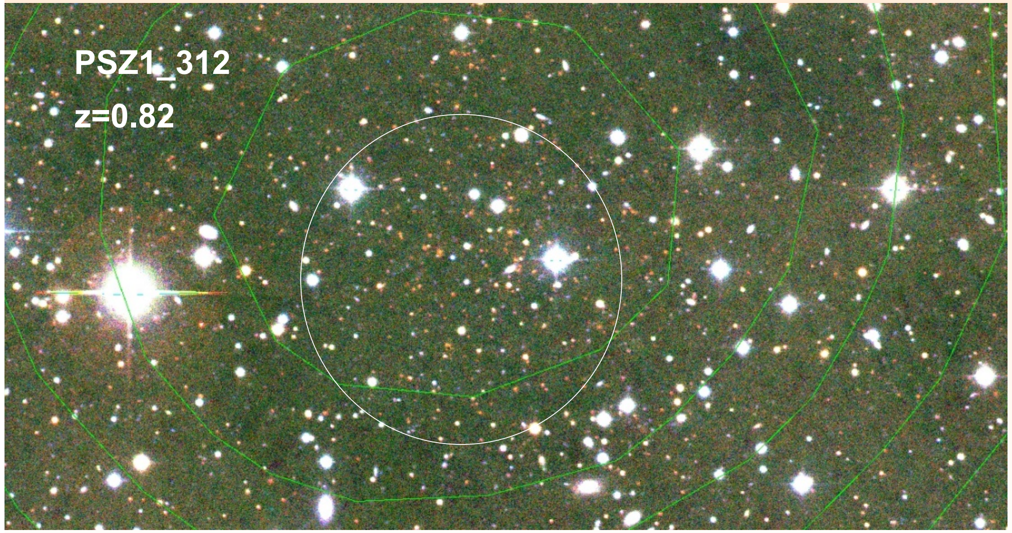


Velocity dispersion and possible substructures









Optical follow-up. Canary Islands observatories

ITP paper accepted/submitted (PSZ1):

- Planck Collaboration XXXVI (2016). 78 sources. 2016A&A...586A.139P.
- Barrena et al. (2018): 115 SZ sources during the 1st year of ITP. arXiv180305764B.

ITP papers in preparation (PSZ1):

- Rubiño-Martín et al. (2018): ~71 SZ clusters observed in the 2nd year of ITP.
- Ferragamo et al. (2018a): Biases in velocity dispersion and mass estimators.
- Ferragamo et al. (2018b): Dynamical masses within Planck SZ sources.

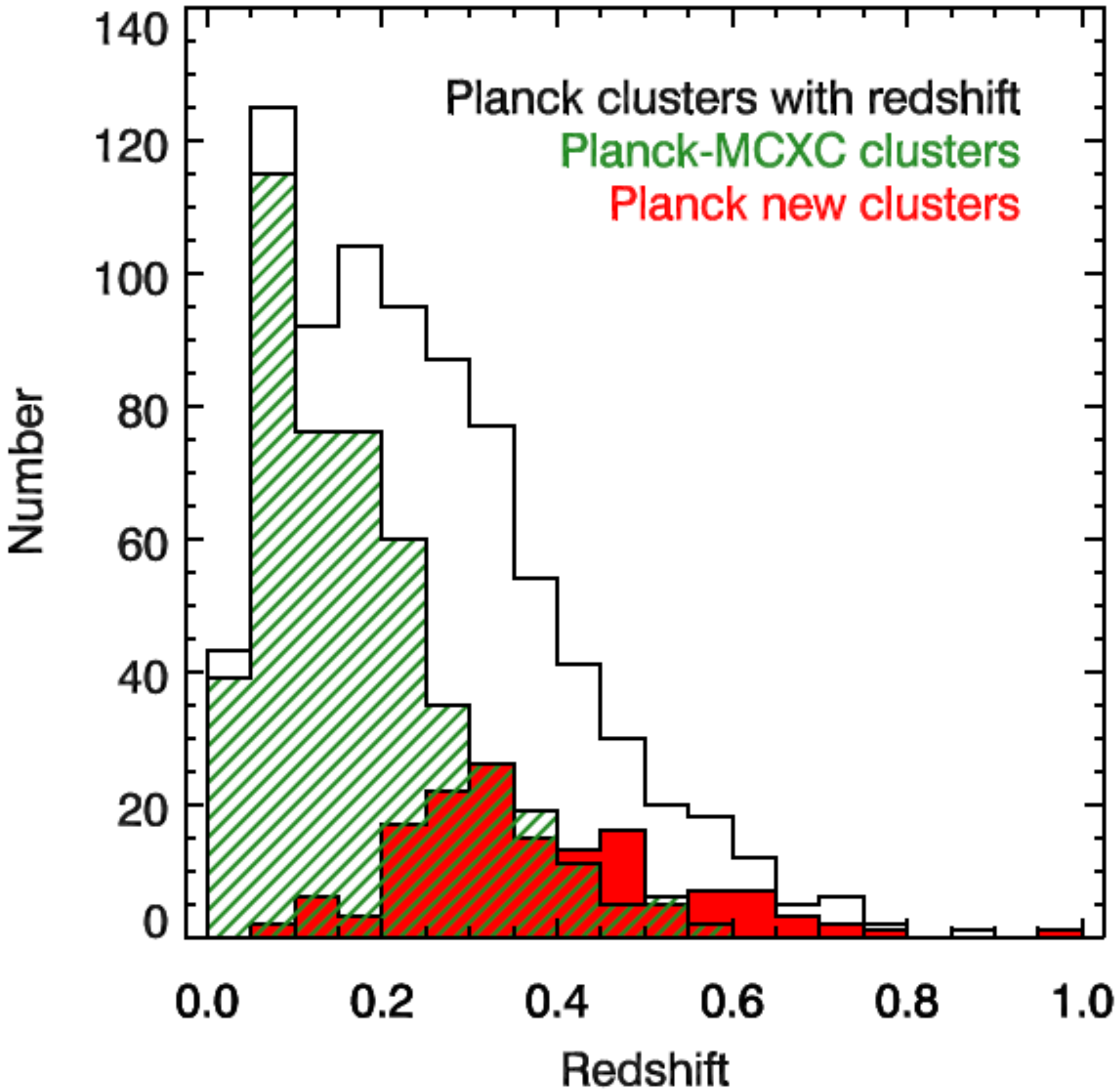
C128 papers submitted (PSZ2):

- Streblyanska et al. (2018): Characterization of a subsample of Planck SZ source cluster catalogues using optical SDSS DR12 data. arXiv180401356S.

C128 papers in preparation (PSZ2):

- Streblyanska et al. (2018b). SZ sources during the 1st year of C128 programme.
- Aguado et al. (2018). SZ sources during the 2nd year of C128 programme.

Planck SZ follow-up program



(Planck Collaboration XXIX 2014)

Galaxy cluster physics and cosmology with PLANCK

I. The Sunyaev-Zeldovich effect and the Planck survey

I. The ESZ, PSZ1 and PSZ2 samples

II. Validation of the catalogues

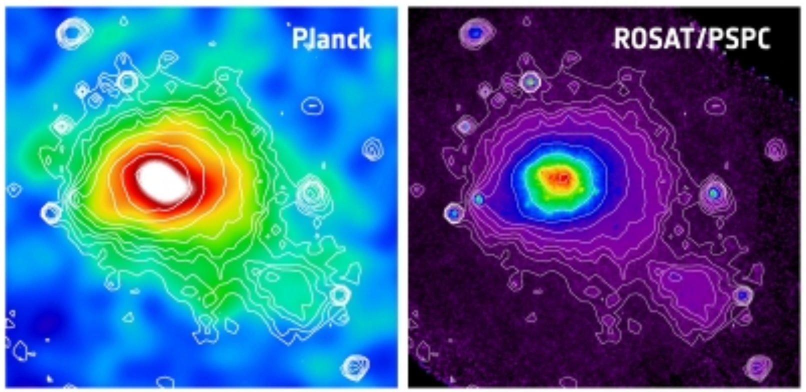
III. XMM-Newton and optical follow-up efforts.

II. **Cosmology with Planck SZ cluster counts**

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

III. **Cosmology with the y-map.**

IV. **Kinetic SZ effect.**



Cosmology with SZ from PLANCK: cluster counts

Ingredients:

- A *comoving volume element* $\dfrac{dV}{dz d\Omega}(z)$
- A *galaxy clusters mass function* $\dfrac{dn}{dM}(M, z)$
- A *survey selection function* $S(M, z)$

$$\frac{dN}{dz}(z) = \int_{4\pi} d\Omega \frac{dV}{dz d\Omega}(z) \int_0^{\infty} dM \frac{dn}{dM}(M, z) S(M, z)$$

Mass function. Number of DM haloes from simulations (Tinker et al. 2008).
Cosmology sample. Subset of the PSZ catalogues.
Selection function. Survey characteristics extracted from the noise maps.
Scaling laws (observables vs Mass).

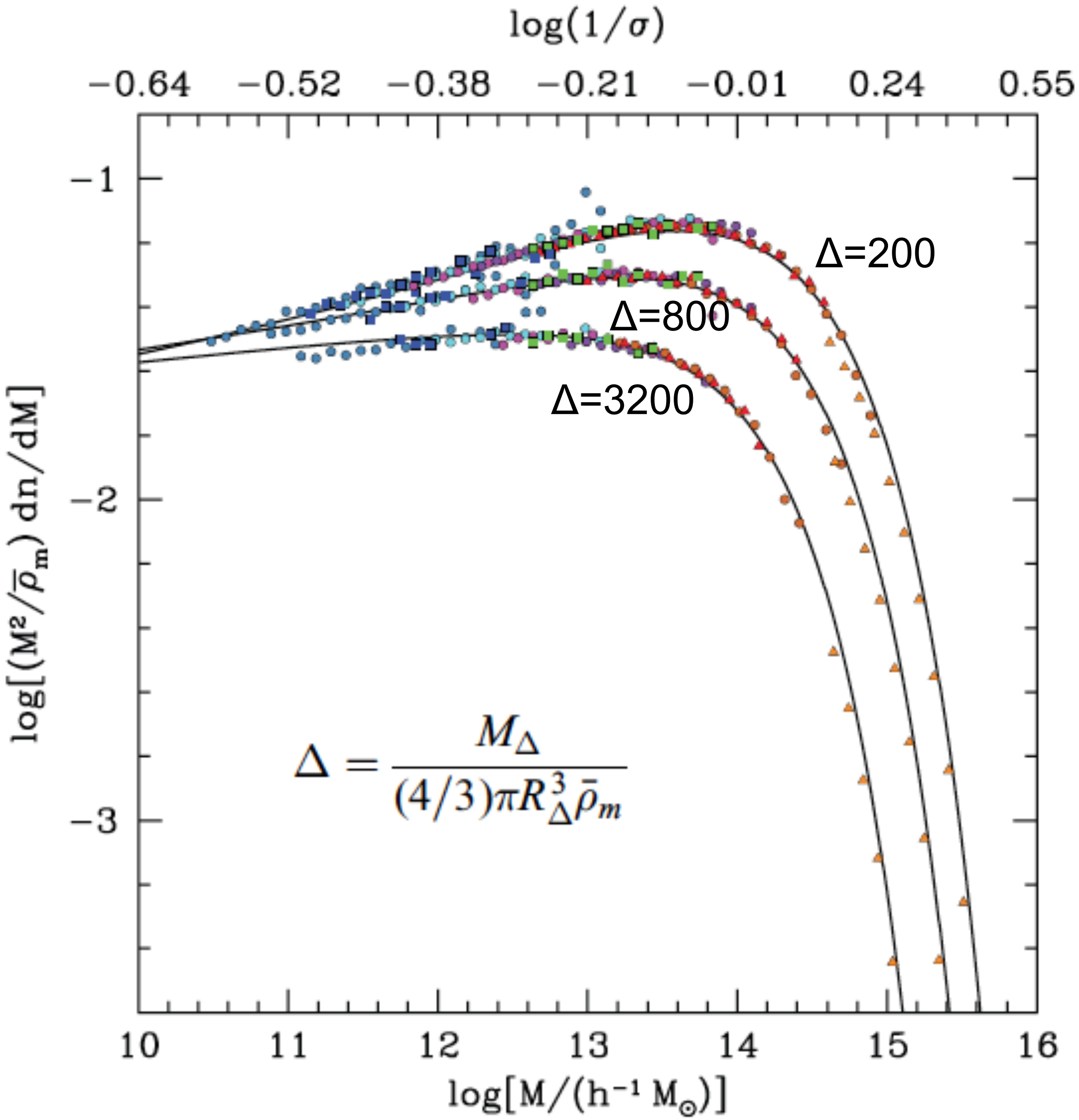
$$\chi_{\mathrm{erf}}(Y_{500}, \theta_{500}, l, b) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{Y_{500} - X\,\sigma_{Y_{500}}(\theta_{500}, l, b)}{\sqrt{2}\,\sigma_{Y_{500}}(\theta_{500}, l, b)}\right)\right]$$

Mass function of DM haloes

$$\frac{dn_u}{dm} = \frac{\rho_m}{m}\frac{d\ln\sigma^{-1}}{dm} f(\sigma, z)$$

Tinker et al. (2008):

$$f_{TA}(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right] e^{-c/\sigma^2}$$



Cosmology with SZ from PLANCK: scaling laws

Scaling laws (observables vs Mass).

Relate observable quantities and mass.

Mass proxies:

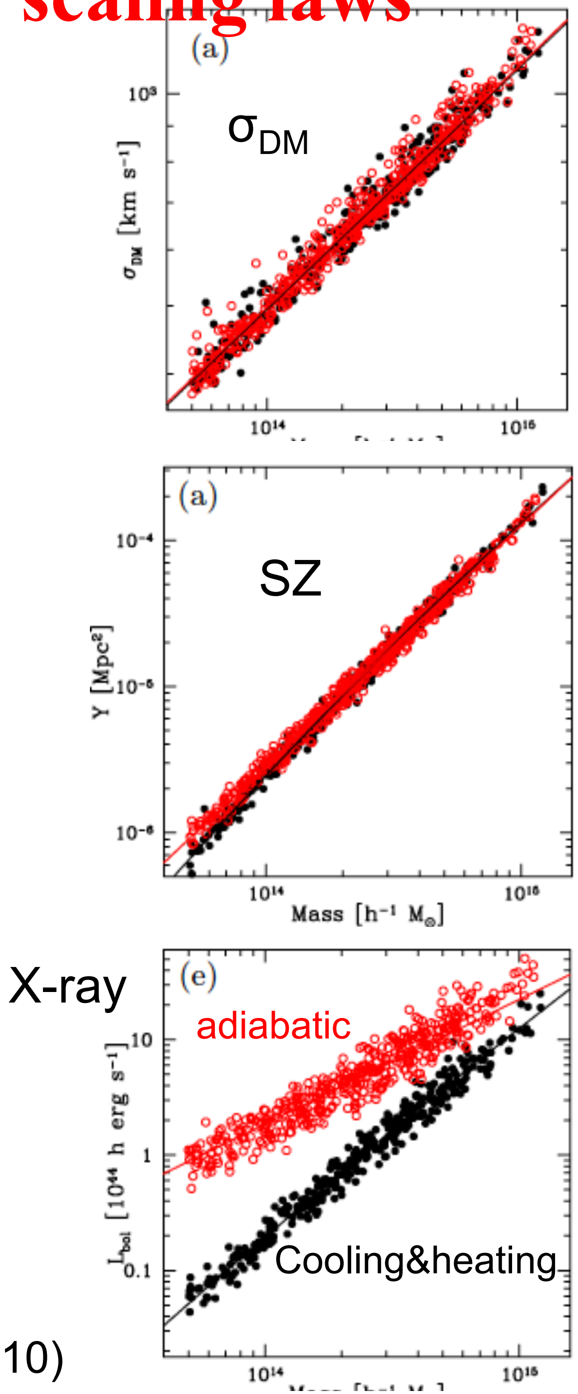
- X-rays (Mgas, T, Lx)
- Optical (richness, Loptical, velocity dispersion)
- SZ (Ysz flux).

Complex physics → simplified assumptions.

- Hydrostatic equilibrium
- No multi-temperature structure
- …

SZ: Weaker dependence →Low scatter Y_{SZ}-M relation (~unbiased selection).

X-rays: Stronger dependence on non-gravitational physics →High scatter L_X-M relation & bias



Stanek et al. (2010)

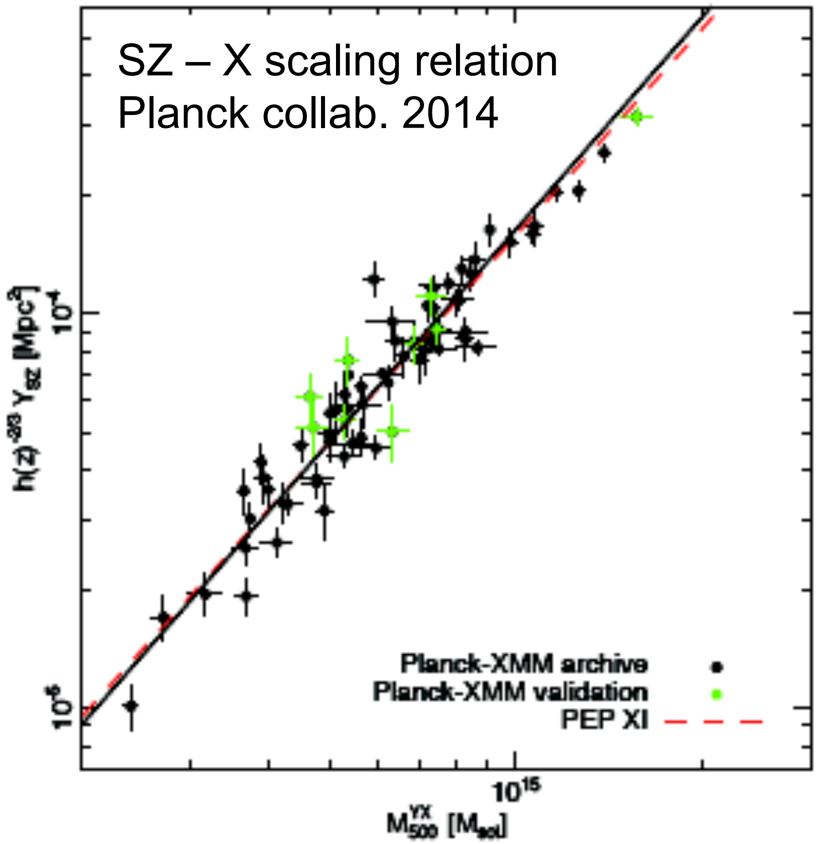
Cosmology with SZ from PLANCK: scaling laws

Use Ysz from Planck and the Yx-Mx estimated from X-ray data. → Y_{SZ}-M_X

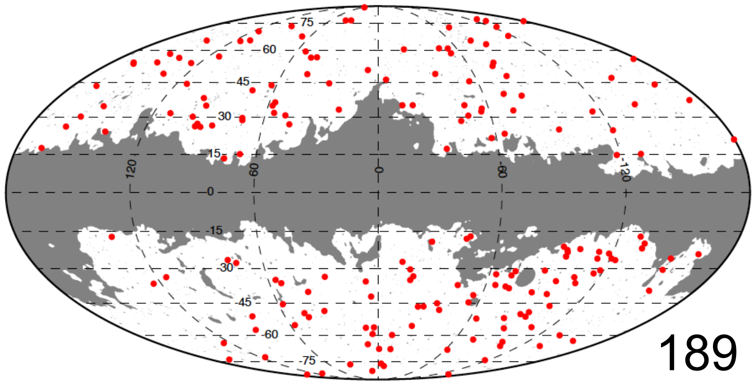
$$E^{-\beta}(z)\left[\frac{D_A^2(z)\,\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,M_\odot}\right]^{\alpha},$$

D_A is the angular-diameter distance
$E^2(z)=\Omega_m(1+z)^3+\Omega_\Lambda$

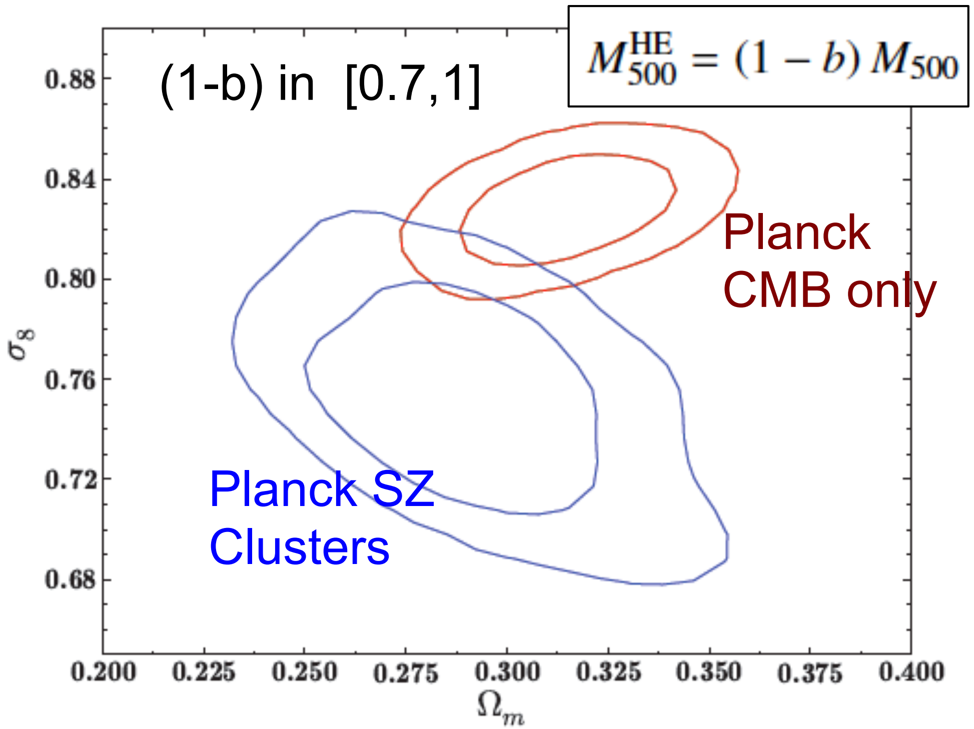
Mean bias between X-ray mass (based on HE) and true mass $\boxed{M_{500}^{\mathrm{HE}} = (1-b)\,M_{500}}$

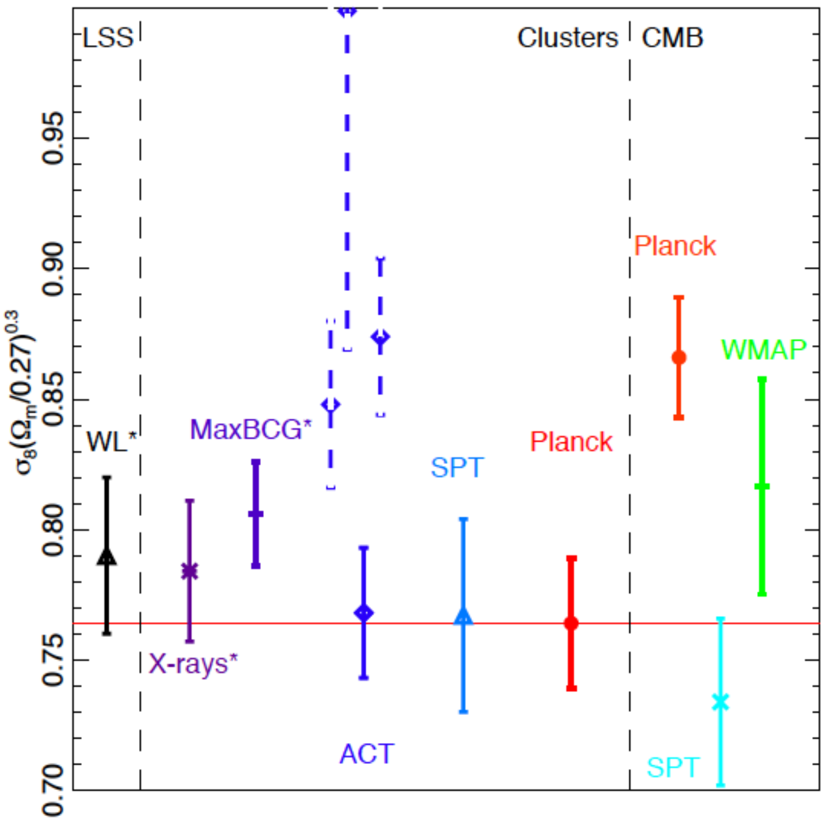


Cosmology with galaxy clusters (PSZ1)



Observations: N(z)
Theoretical Ingredients: halo mass function, scaling relations to predict M and z; completeness and selection function of the survey.
Tension in sigma8-OmegaM plane





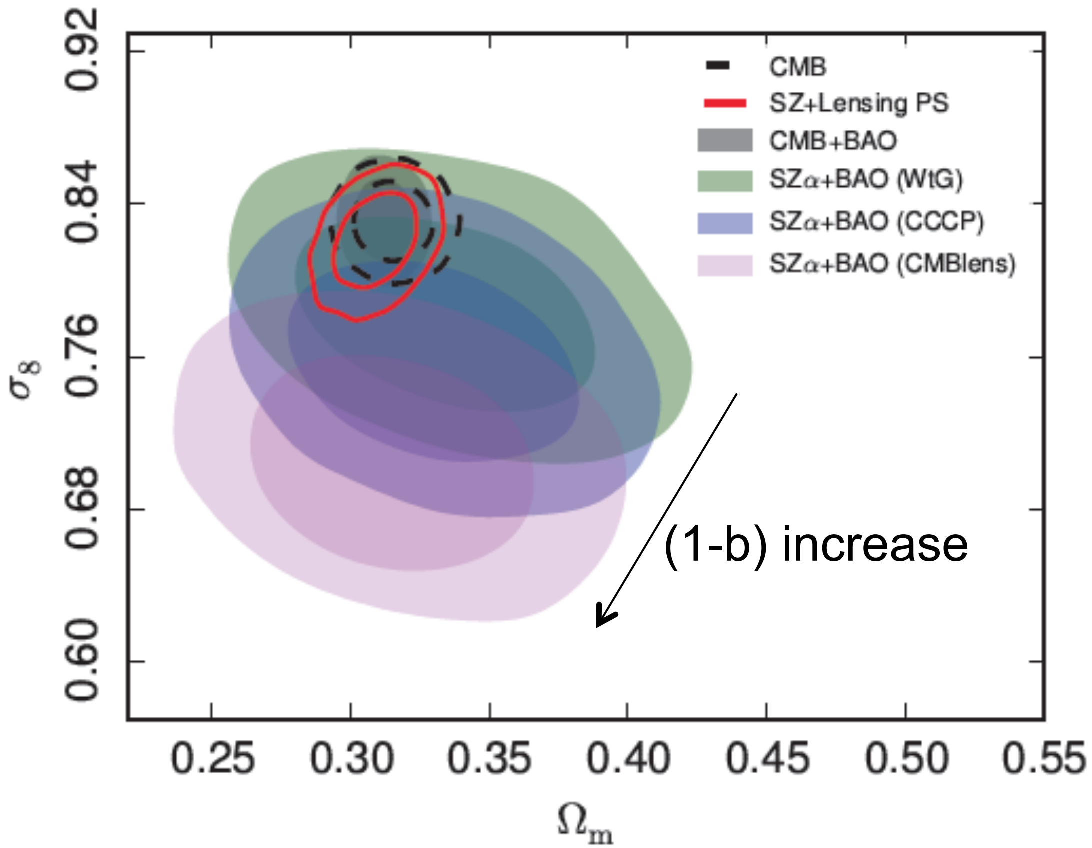
Cosmology with galaxy clusters (PSZ1)

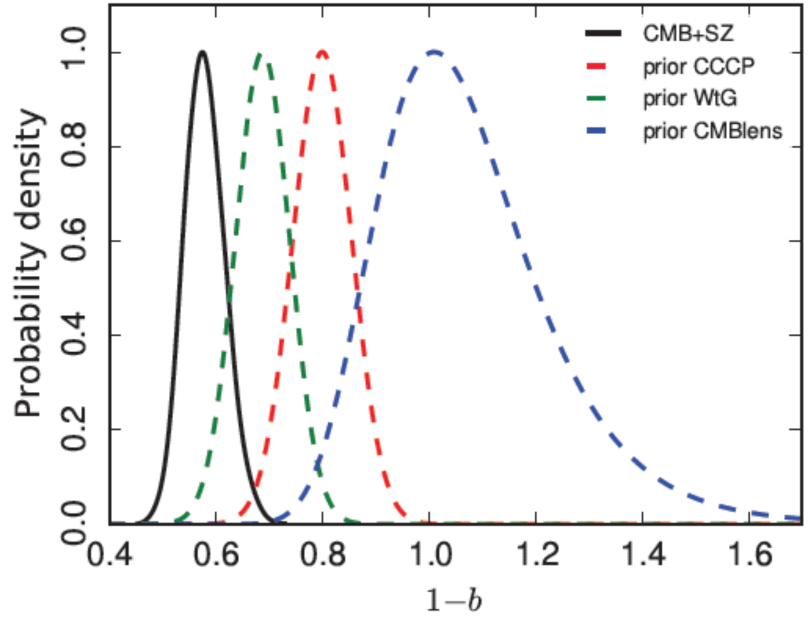
- Tension between the CMB and the SZ clusters result.
- The cluster result depends critically on the value of (1-b).
- But there is consistency between Planck and other SZ surveys.

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 $\sigma_8(\Omega_m/0.27)^{0.41}$.

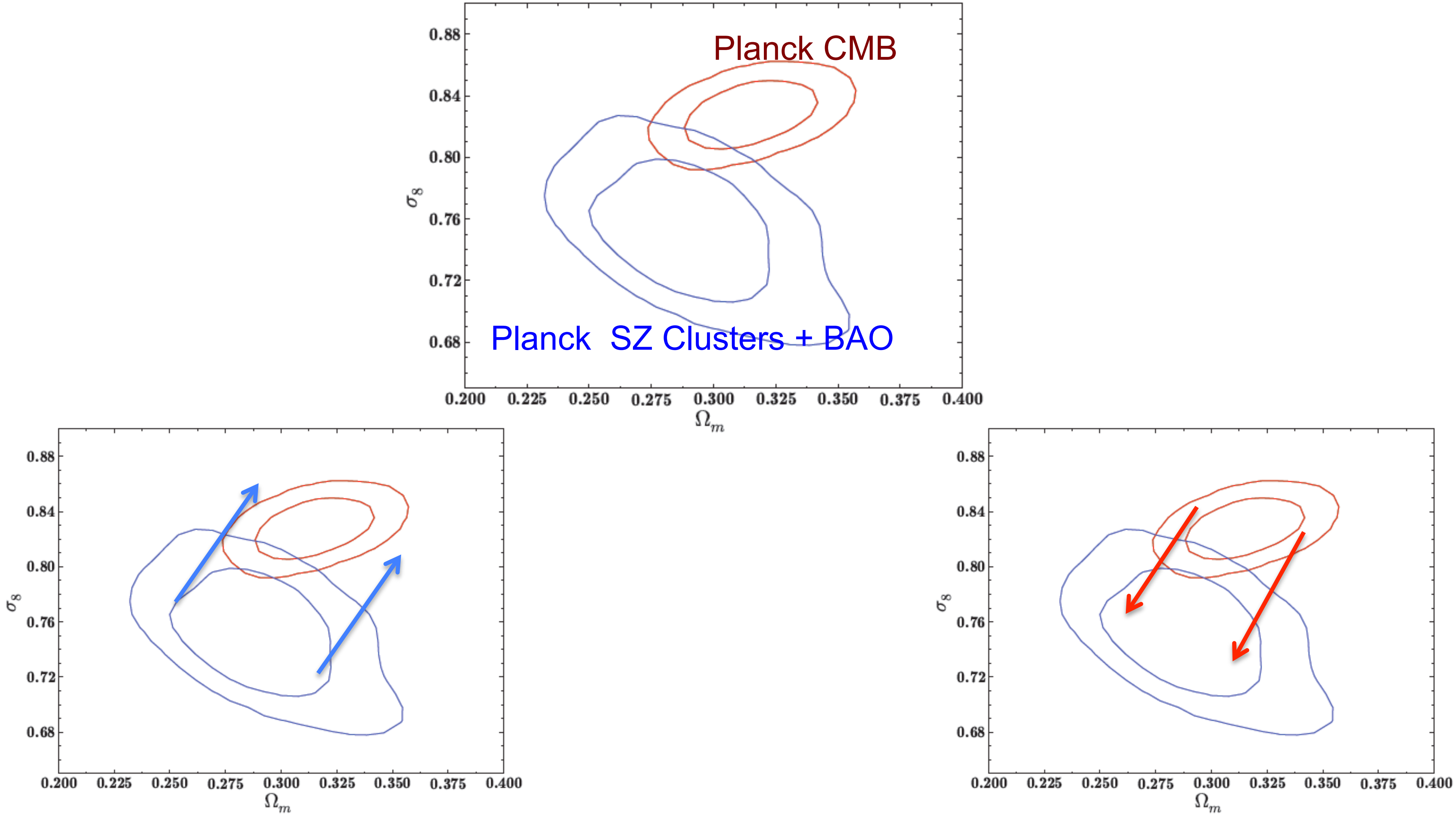
Cosmology with galaxy clusters (PSZ2)





- Planck Collaboration XXIV (2016) confirms the tension, using now PSZ2.
- Large sample (439 clusters with S/N>6 in PSZ2).
- Rescaling to weak lensing.
- CMB preferred mass bias (1-b)~0.58.

Reducing the Planck SZ – CMB tension



- Changes in scaling relation
- Change in bias

- Change transfer function, e.g. neutrinos.
- Change initial spectrum

Cosmology with SZ from PLANCK: scaling laws

Use Ysz from Planck and the Yx-Mx estimated from X-ray data. → Y_{SZ}-M_X

$$E^{-\beta}(z)\left[\frac{D_A^2(z)\,\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,M_\odot}\right]^\alpha$$

Mean bias between X-ray mass (based on HE) and true mass $\boxed{M_{500}^{\mathrm{HE}} = (1-b)\,M_{500}}$

Y_{SZ} – M_X rescaled relation

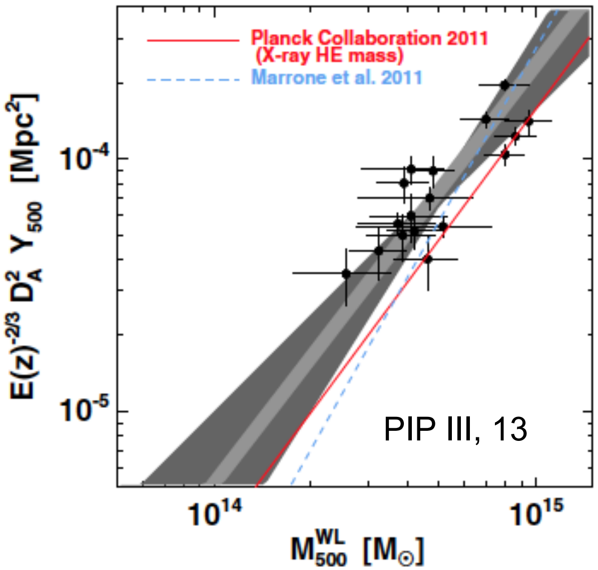
- Hydrodynamical simulations → (1-b) ~0.7 to 1.0
- Weak Lensing from WtG → (1-b)~0.68 (von der Linden et al. ‘14)
- Weak Lensing from PSZ2LenS → (1-b)~0.76 (Sereno et al. ‘17)
- Weak Lensing from CCCP → (1-b)~0.78 (Hoekstra et al. ‘15)
- CMB lensing mass → (1-b)~1 (Planck collab. ‘16)

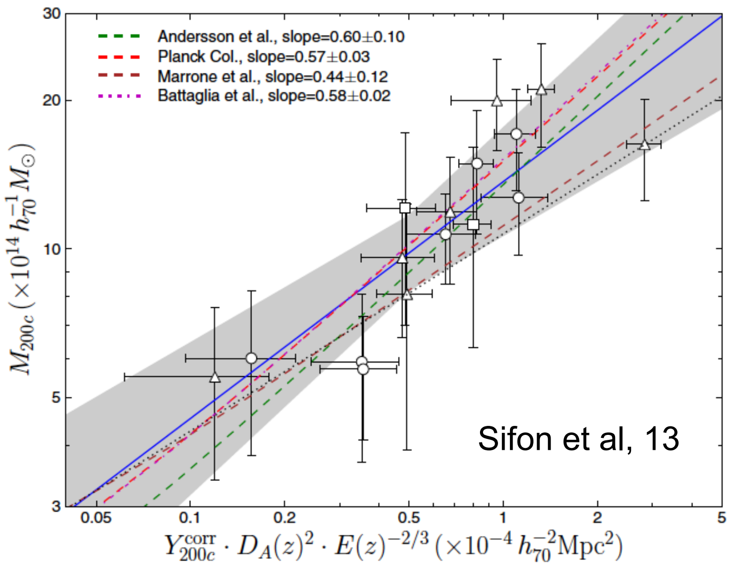
& many others

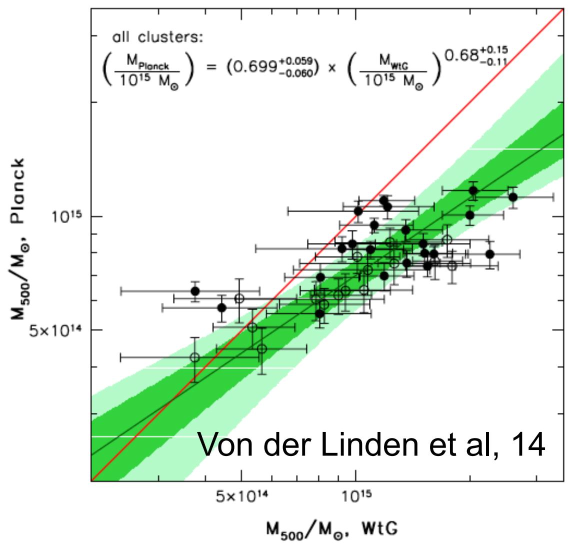
+ Mass estimates from velocity dispersions

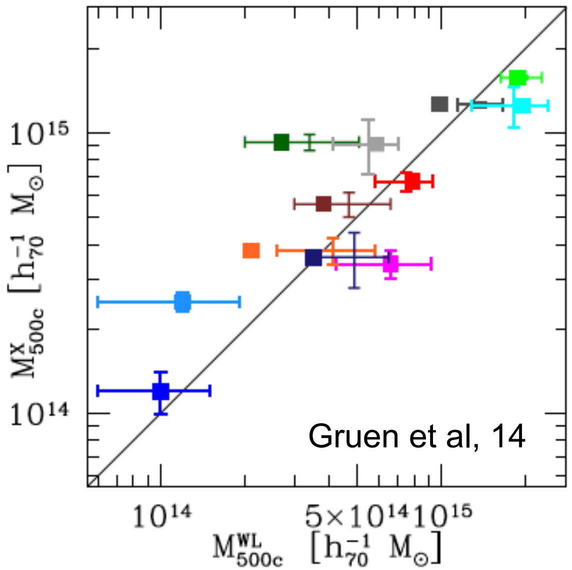
- Sifon et al. (2015) → (1-b)~1.10
- Ruehl et al. (2014).

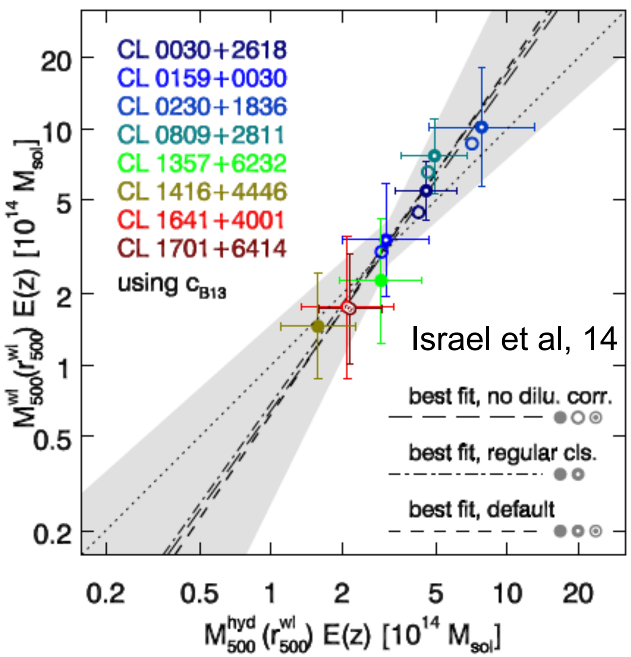
Weighting clusters and observable mass relation











M_X-M_{WL} and M_{dyn} not fully converged

Systematics on M-Y of 20-30%

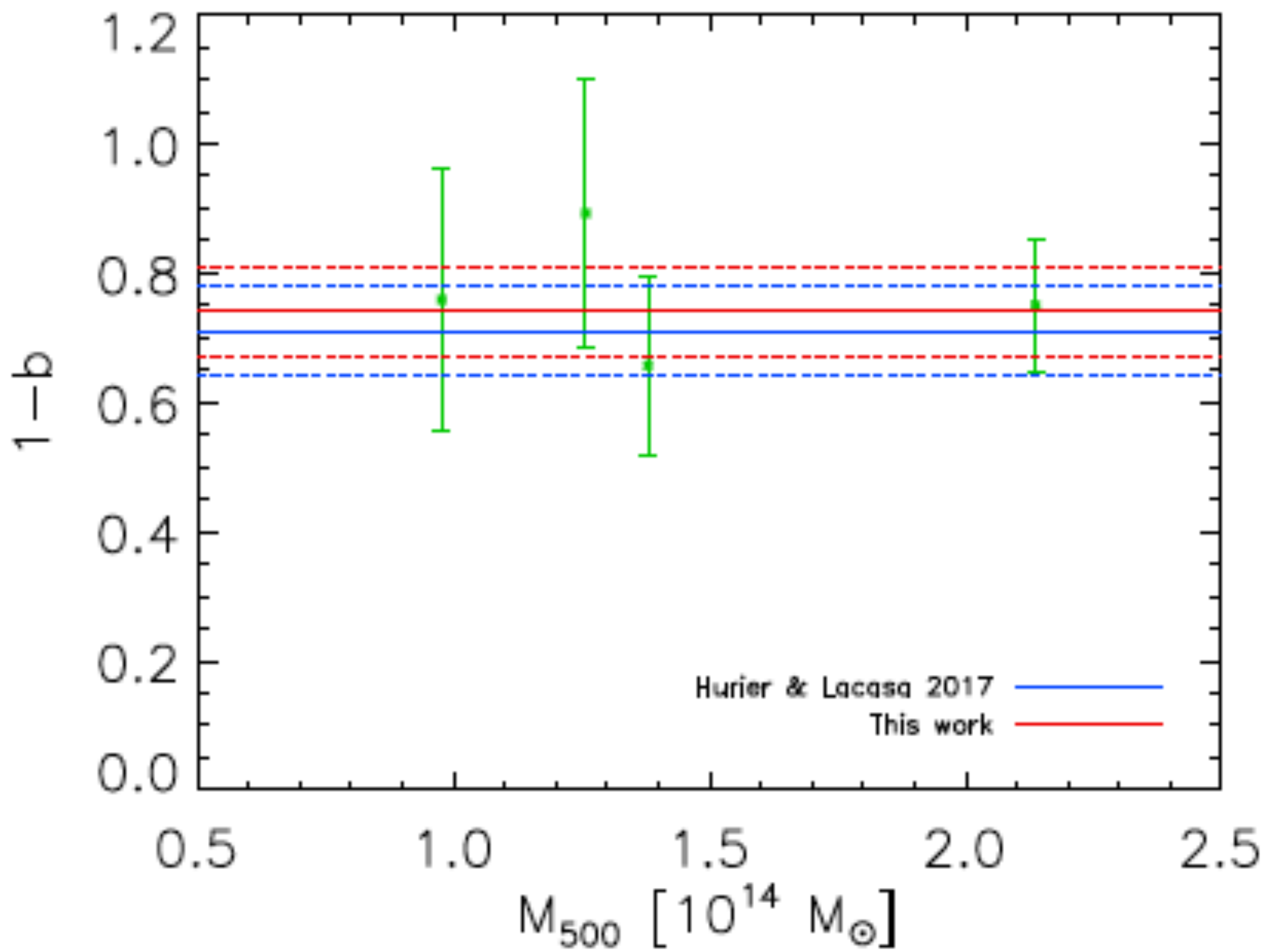
Update on (1-b) for clusters with SZ

CMB lensing data and SZ measurements.

Using the Compton y-map from Planck.

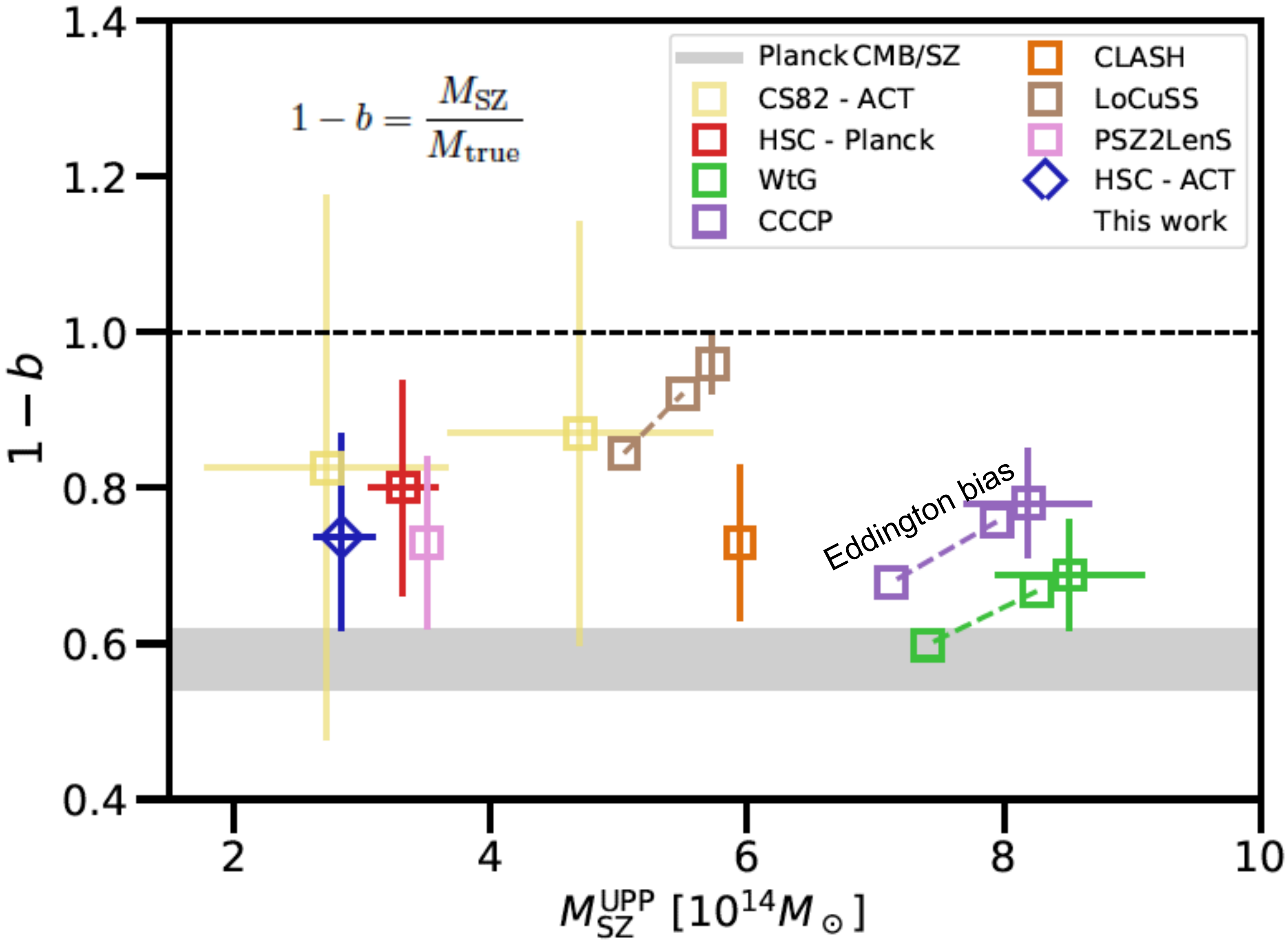
Stacked y signal on redmapper clusters, in four richness bins.

1-b = 0.74 +/- 0.07



(Hurier & Angulo 2018)

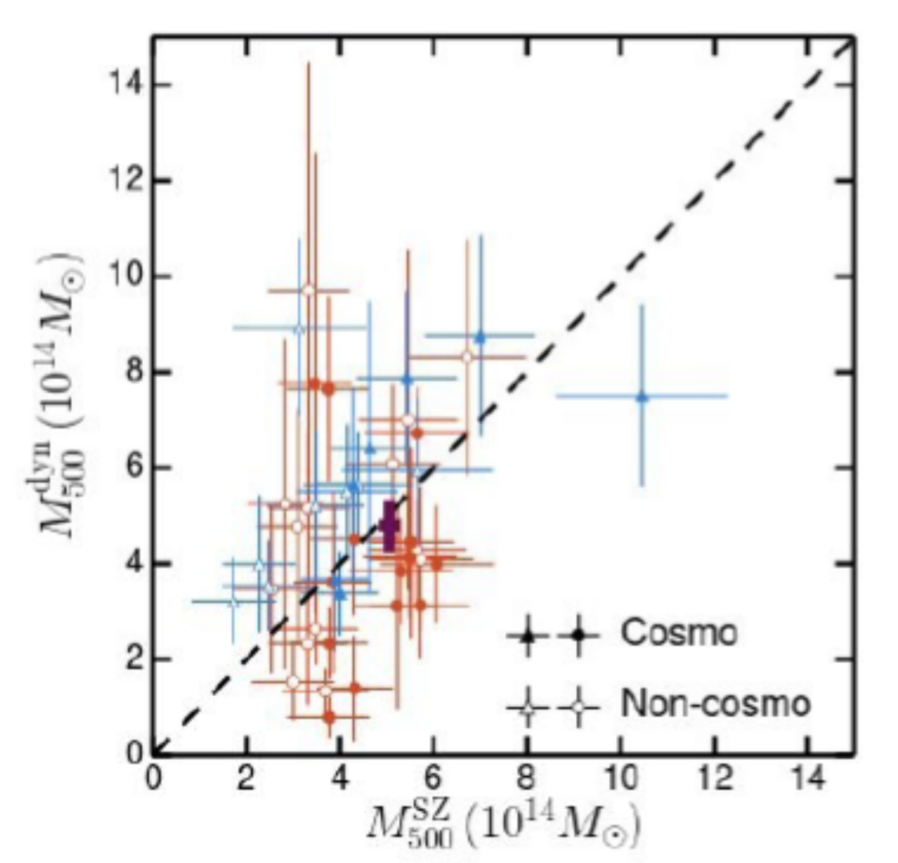
Update on (1-b) for clusters with SZ



(Miyatake et al. 2018, arxiv:1804.05873)
ACTPol clusters and HSC lensing

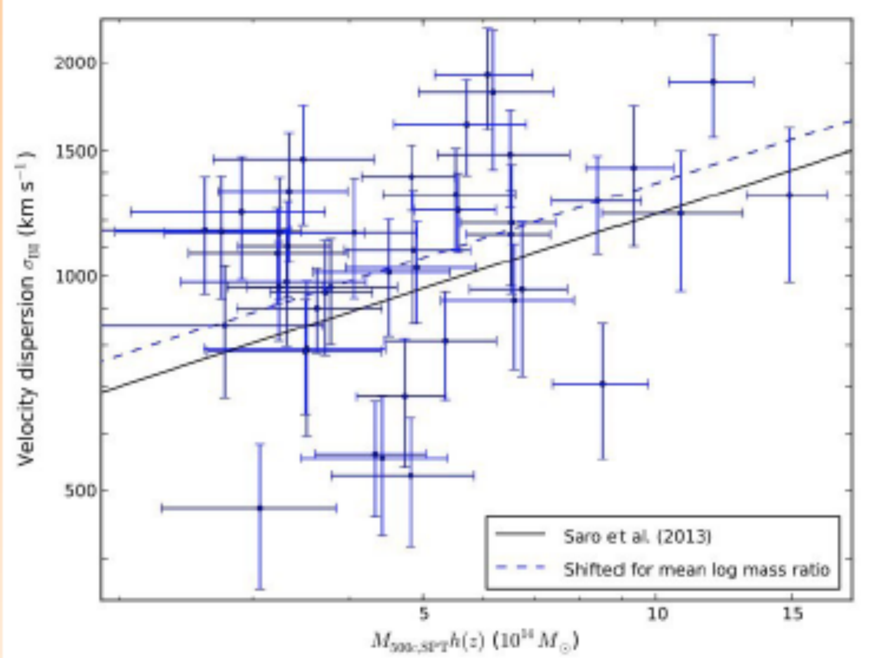
Dynamical cluster masses

ACT data (44 clusters)
Sifon et al. (2015)



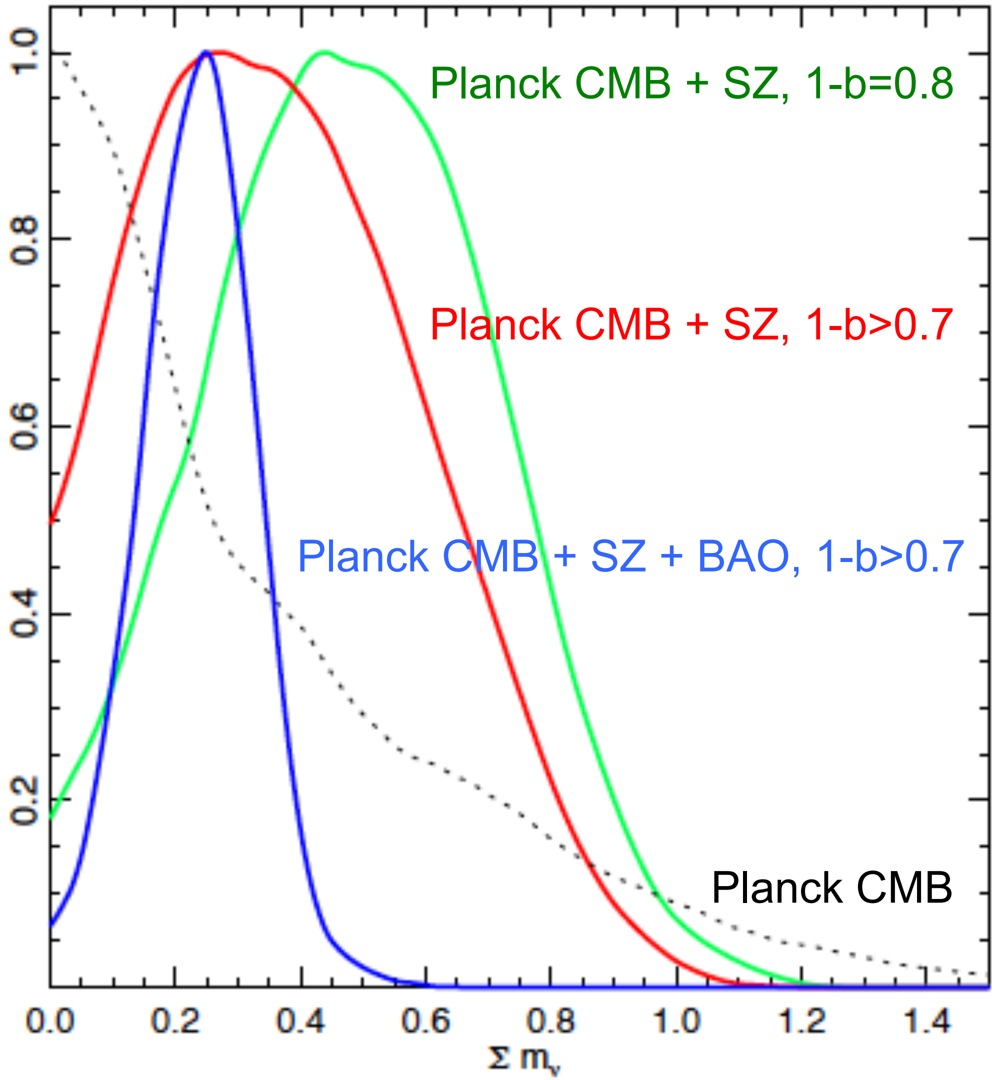
$$\frac{(1 - b_{\rm SZ})}{\beta_{\rm dyn}} = 1.10 \pm 0.13.$$

SPT data (19 clusters)
Ruel et al. (2014)

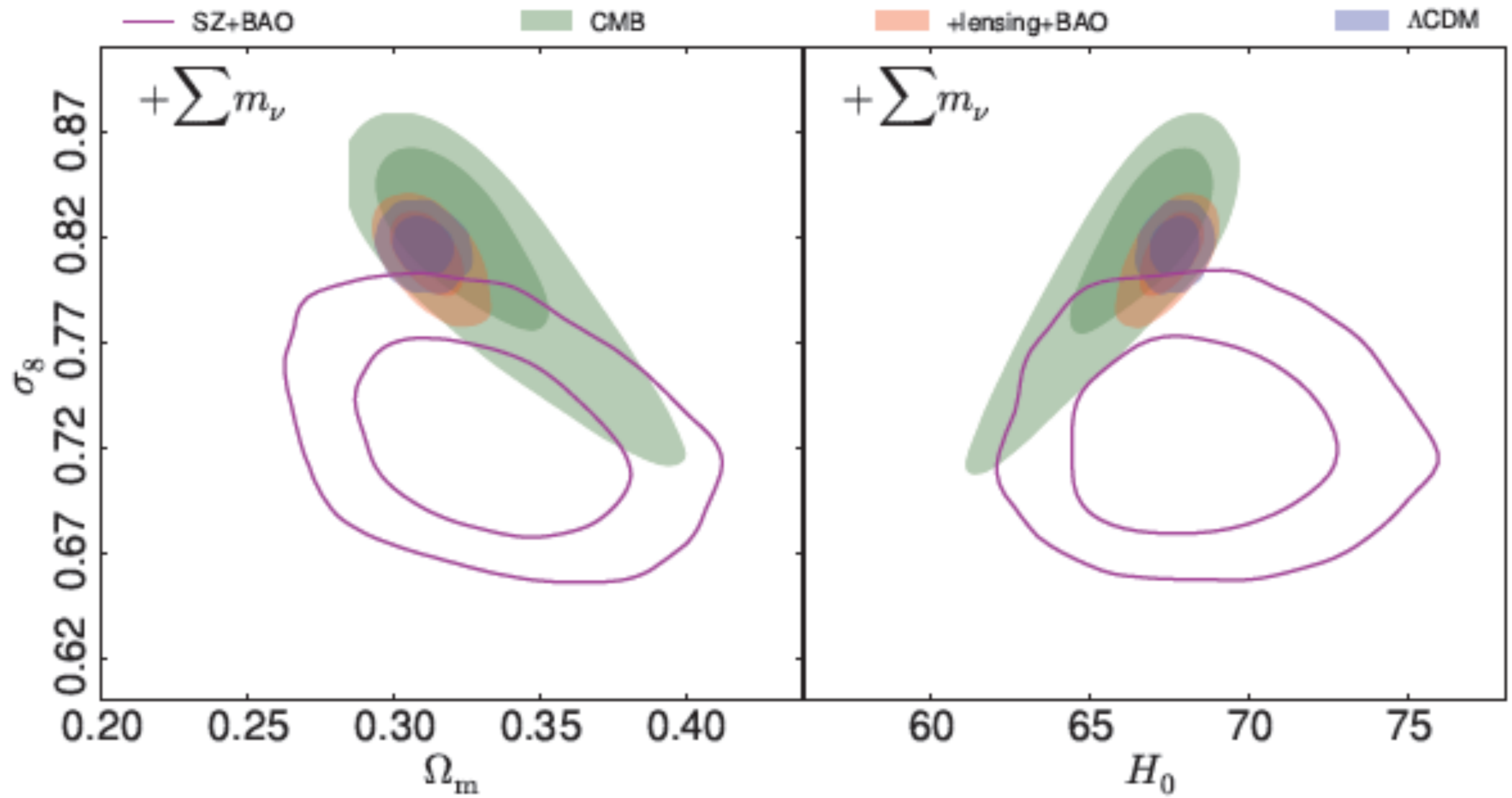


$$\langle \ln(M_{200c,\,\rm dyn}/M_{200c,\,\rm SPT}) \rangle = 0.33 \pm 0.10,$$

Constraints on neutrino masses (PSZ1)



Constraints on neutrino masses (PSZ2)



Planck Collaboration XXIV 2016

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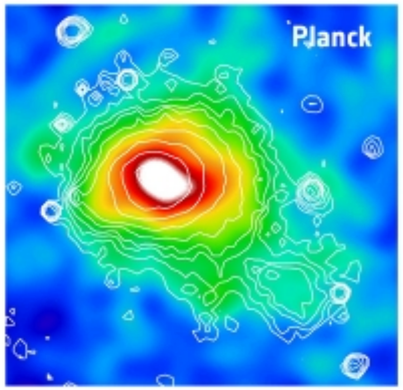
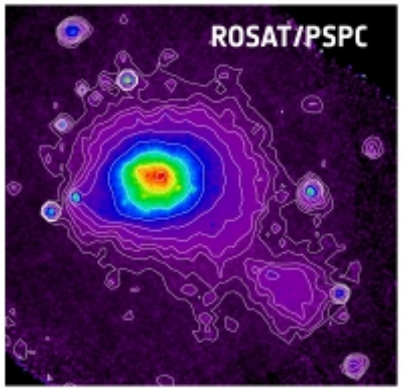
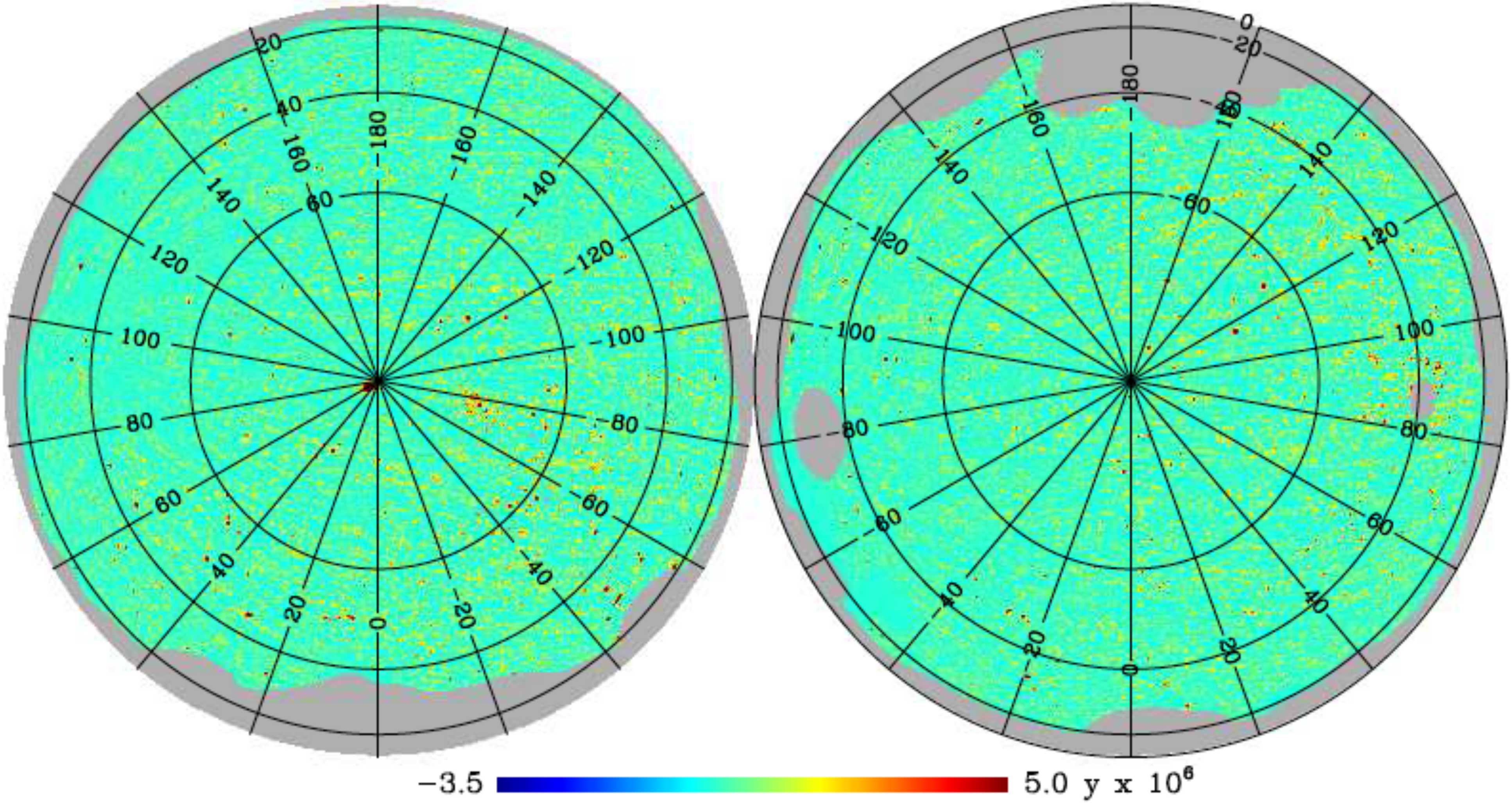
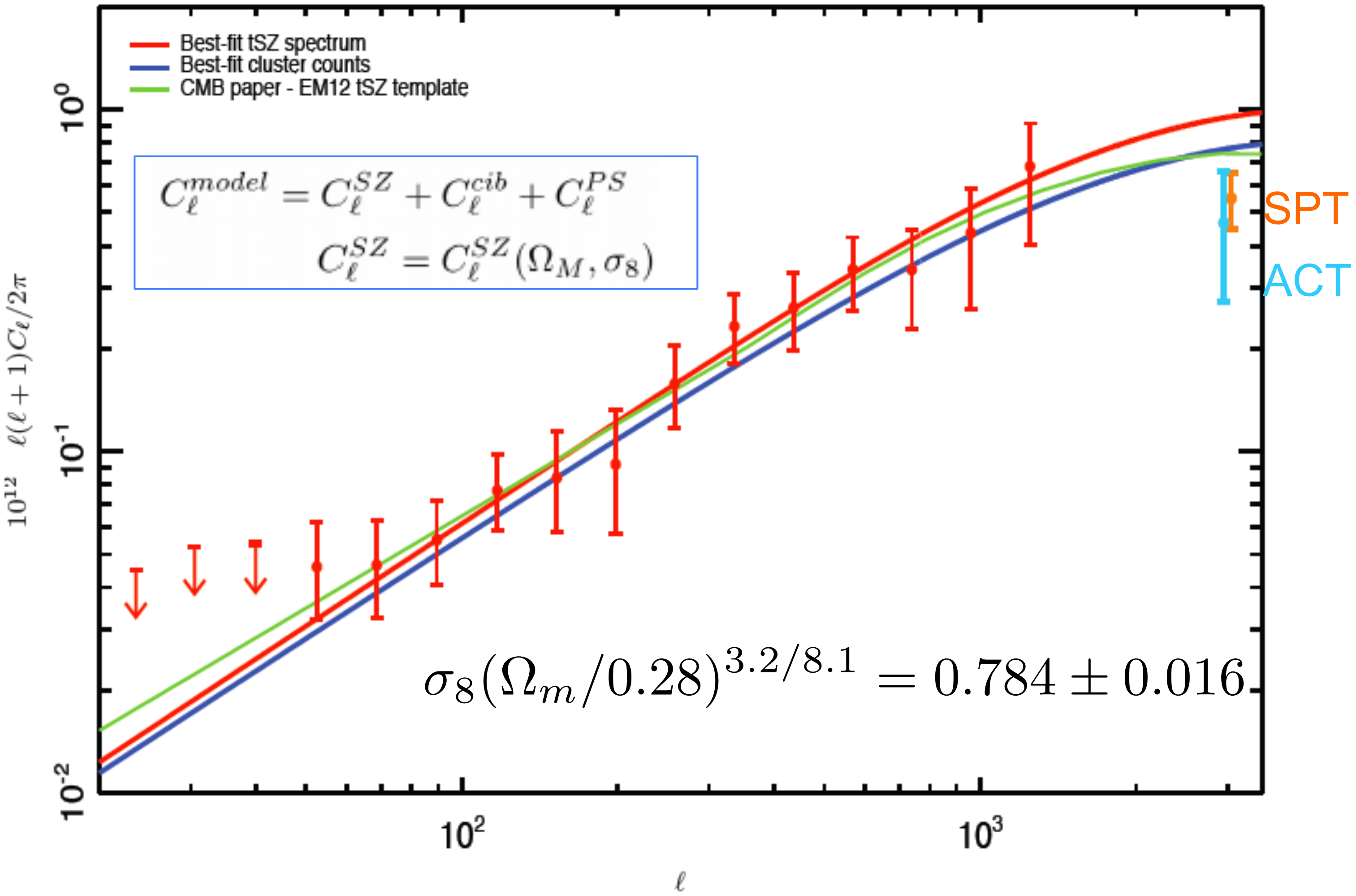




All-sky SZ map

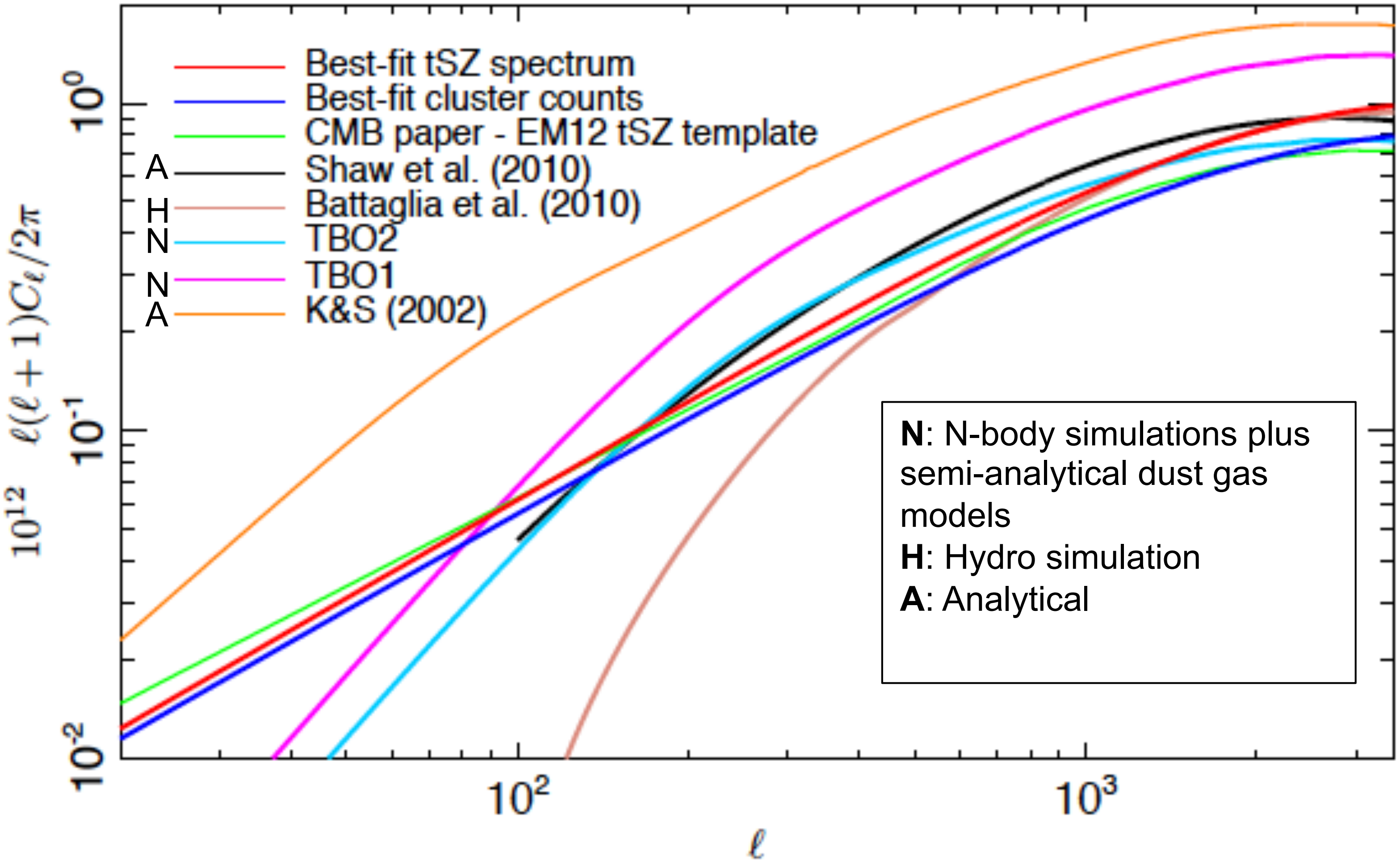


All-sky SZ map: power spectrum



- 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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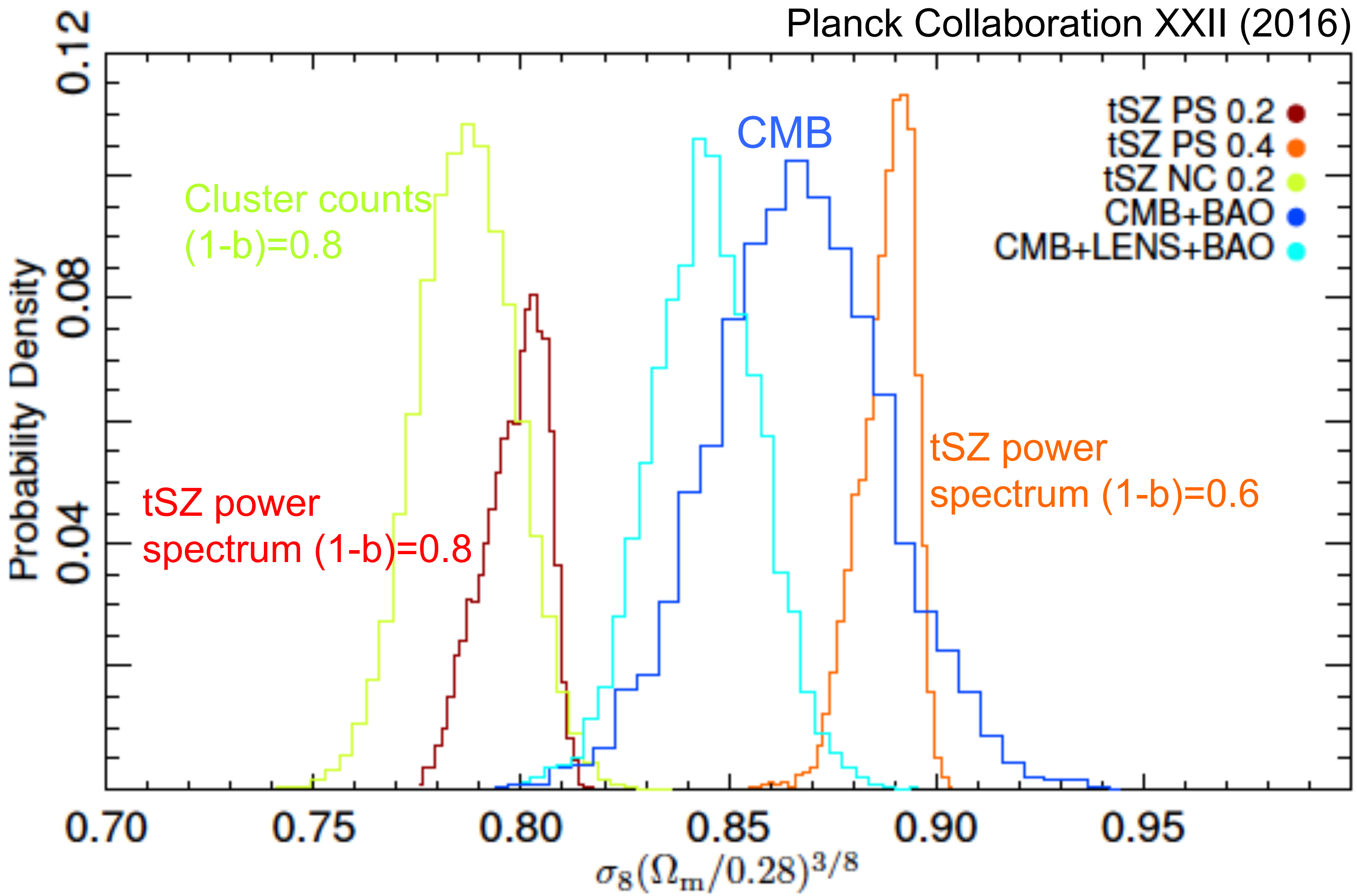
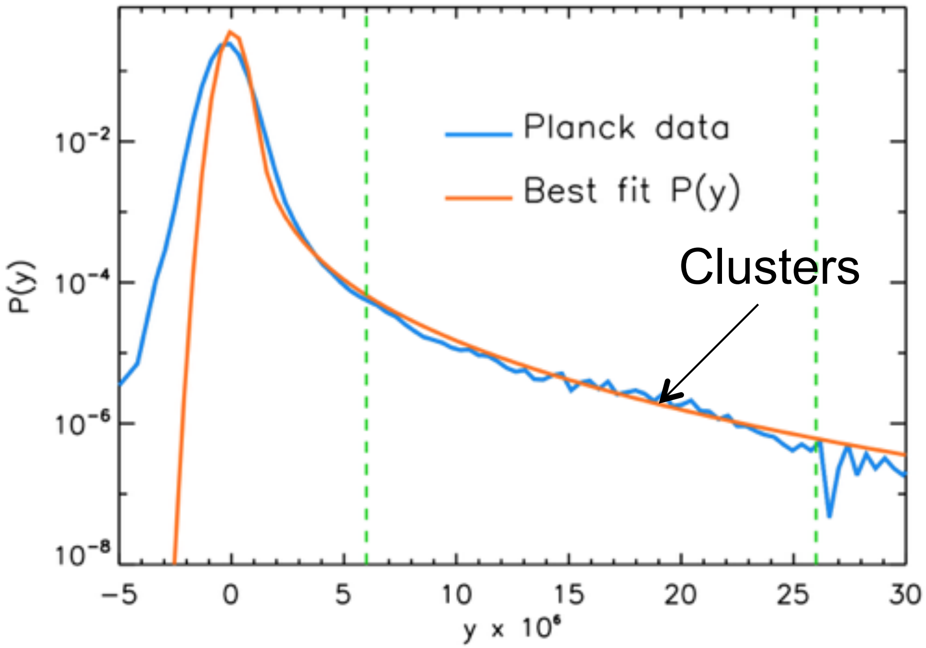
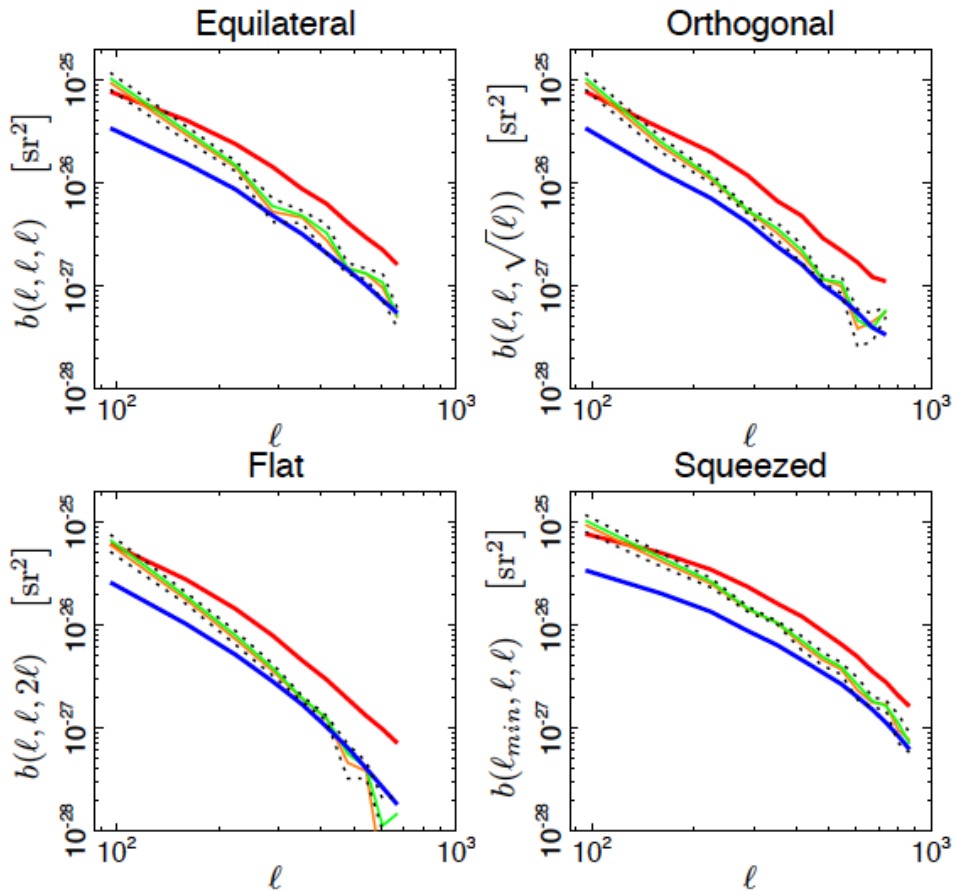
All-sky SZ map: power spectrum



Marginalised likelihood distribution for tSZ and CMB analyses → tension.

All-sky SZ map: bispectrum and P(y)

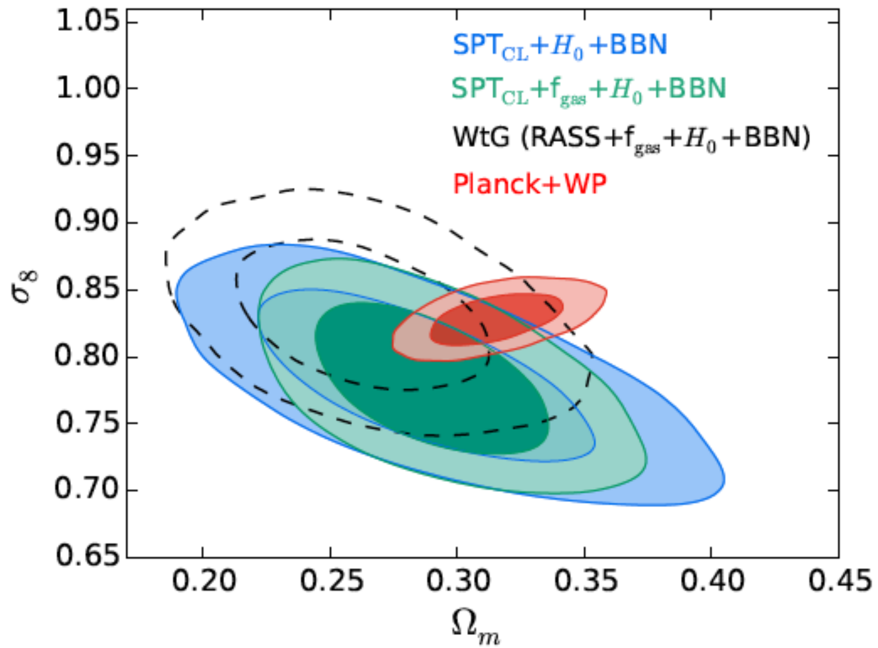


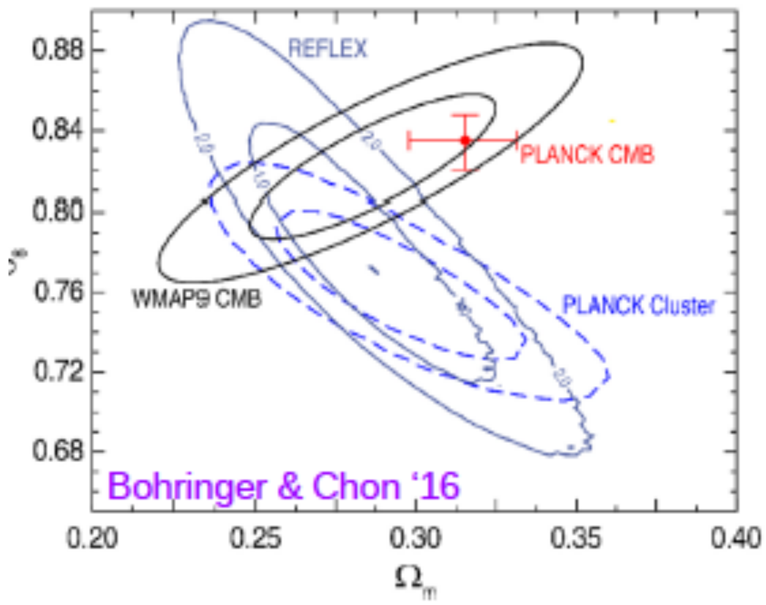


- Methodology proposed in Rubiño-Martin & Sunyaev (2003).
- Fit to the 1-pdf: σ_8=0.77±0.02 (68% CL). Planck Collab (2016)
- Un-normalized skewness: σ_8=0.78±0.02 (68% CL).
- Also applied to ACT (Wilson et al. 2013), giving σ_8=0.78±0.04.

Tension with CMB

Cosmological parameters from clusters and other surveys (I)

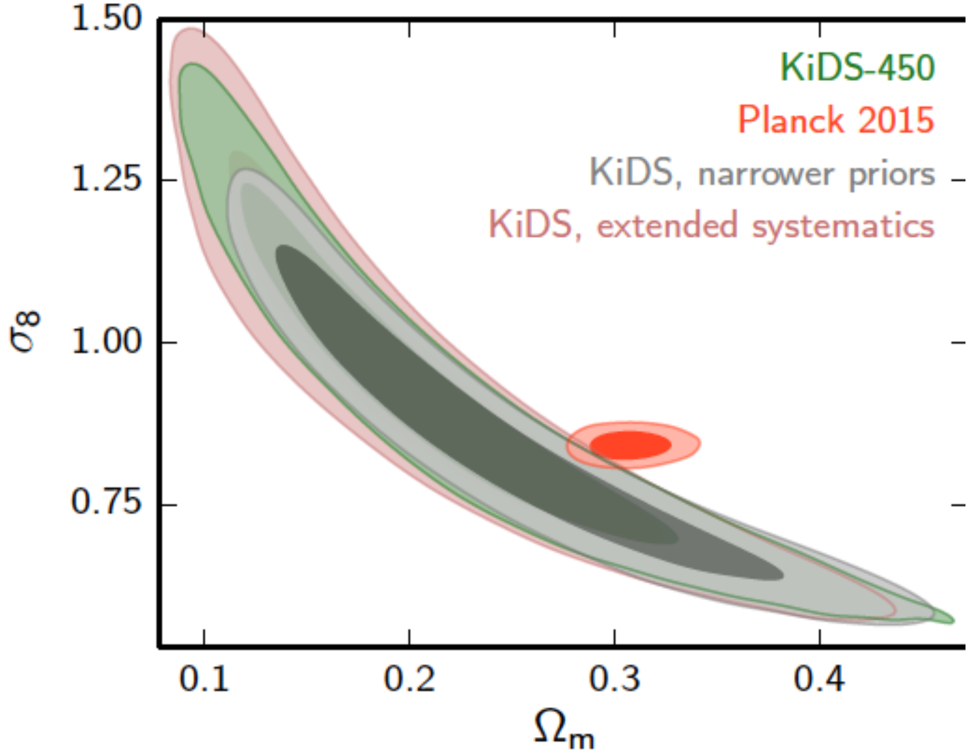




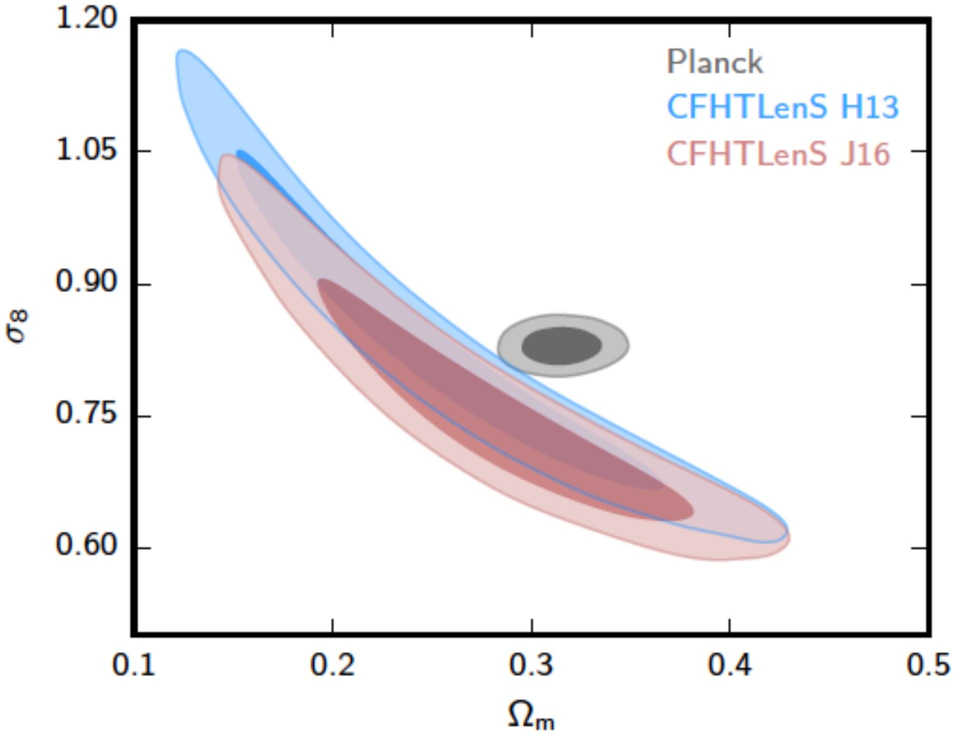
De Haan et al. (2016)
377 SPT clusters.
Lensing based priors for the normalization of the mass relation.

Bohringer & Chon (2016)
X-ray lum func of REFLEX-II.
In agreement with Planck clusters but tension with CMB

Cosmological parameters from clusters and other surveys (II)



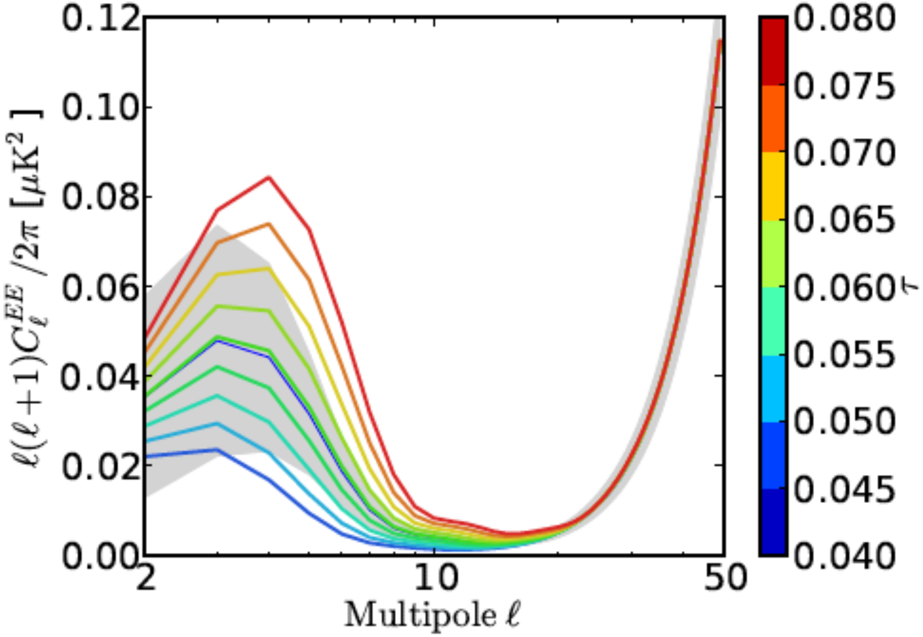
Joudaki et al. (2017)
KiDS-450. Weak lensing.

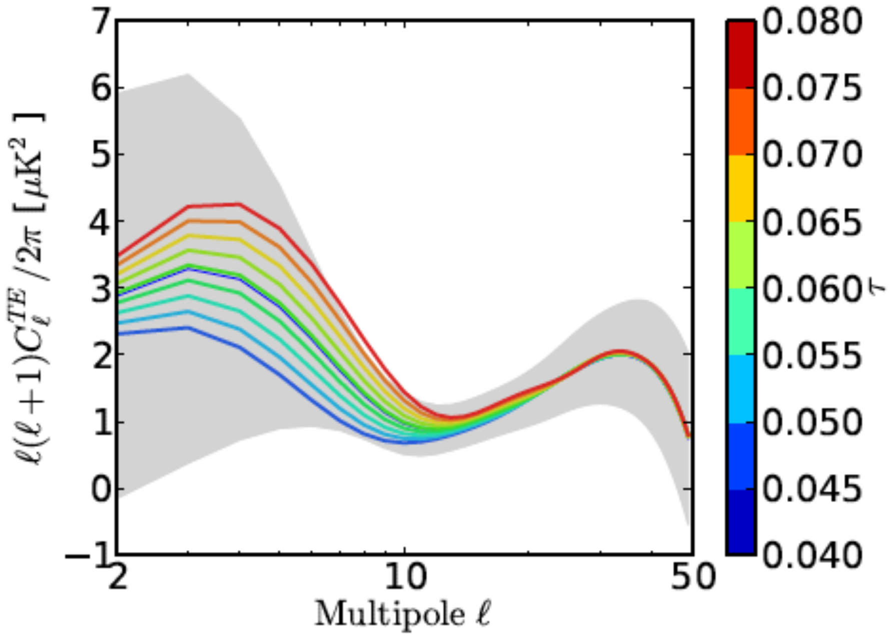


Joudaki et al. (2017b)
CFHTLenS. Cosmic shear tomography

~2sigma tension regardless of the cosmological datasets.

Reionization



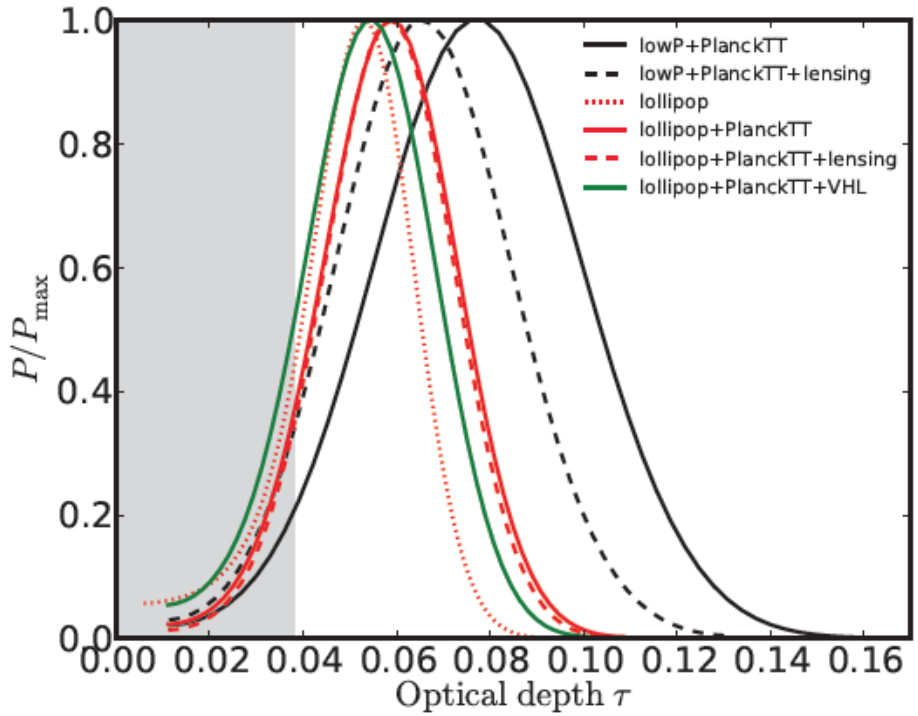


❖ Planck Collaboration XLVII (2016).

❖ $\tau = 0.058 \pm 0.012$ (assuming instantaneous reionization).

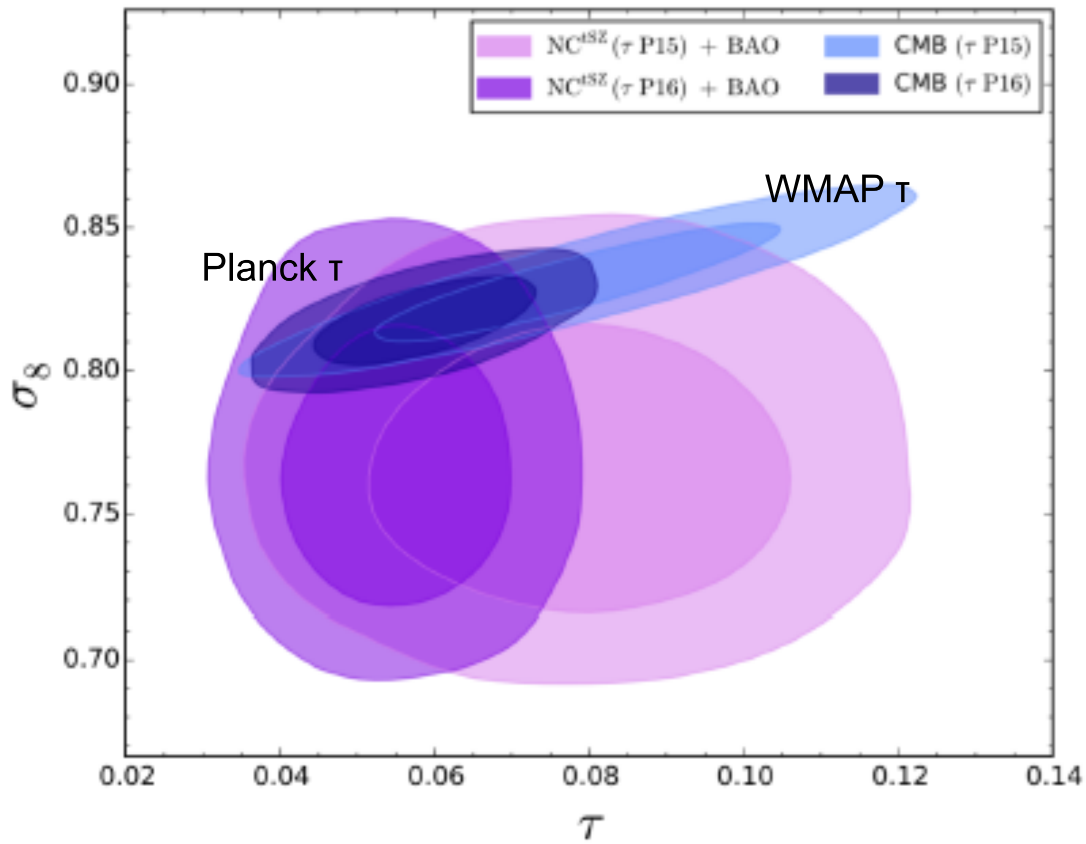
❖ Redshift of reionization is model dependent: z_{re}~8.5. Complementary to 21cm studies.

❖ Needed to break degeneracies with other parameters (r). Reduced tension between CMB and astrophysical probes of reionization.



Cosmological parameters from Planck SZ counts revisited (I)

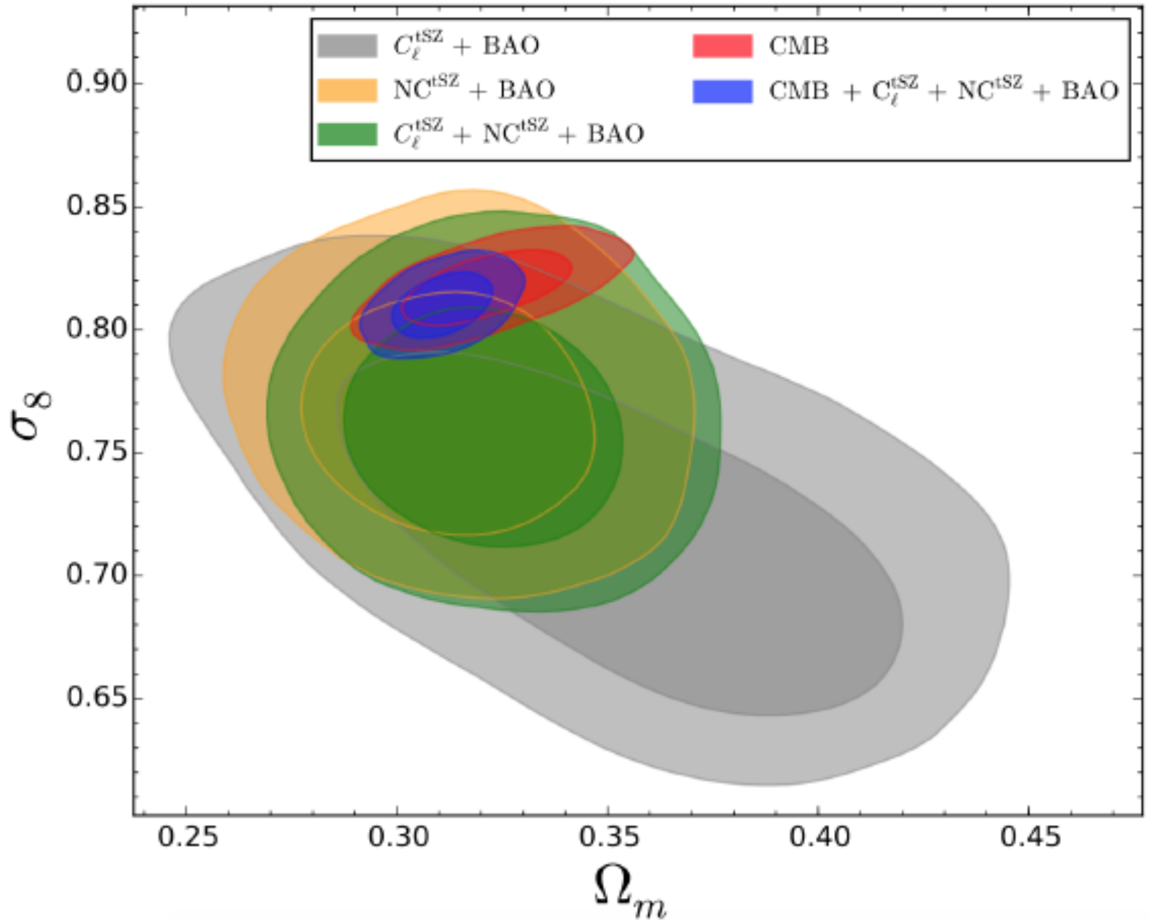
- SZ counts as in Planck Collab. 2016.
- Prior on mass bias from CCCP lensing (1-b)=0.78.
- New Planck low-l polarisation: τ = 0.058 ± 0.012



Salvati et al. (2017)

Cosmological parameters from Planck SZ counts revisited (II)

- SZ counts as in Planck Collab. 2016.
- Prior on mass bias from CCCP lensing (1-b)=0.78.
- New Planck low-l polarisation: τ = 0.058 ± 0.012
- Combinining Cluster counts + SZ power spectrum.

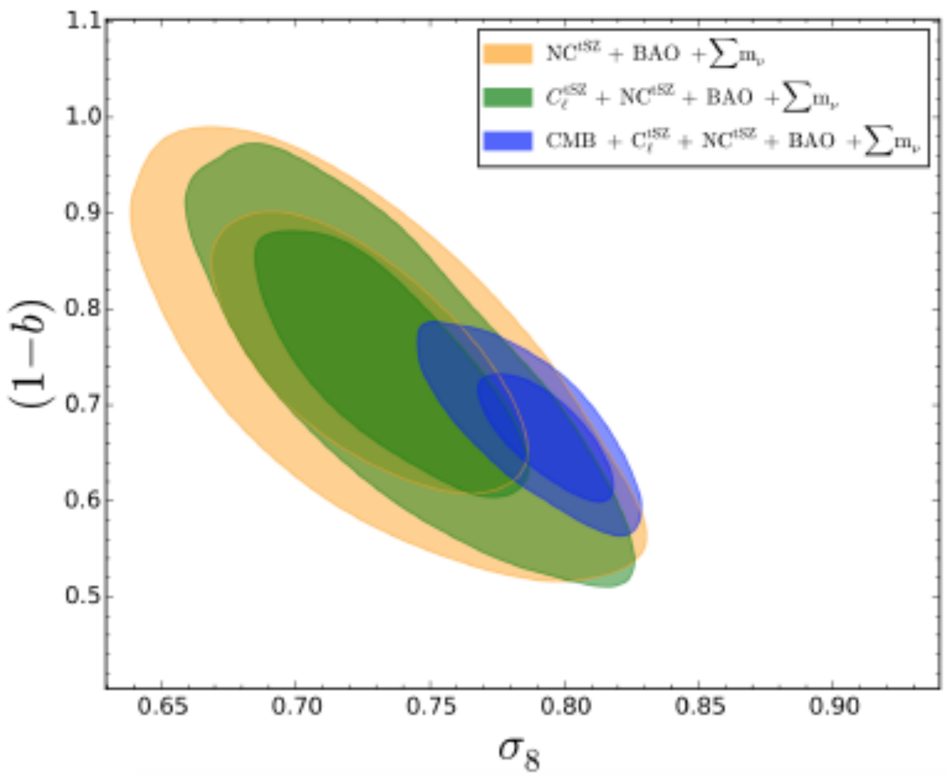


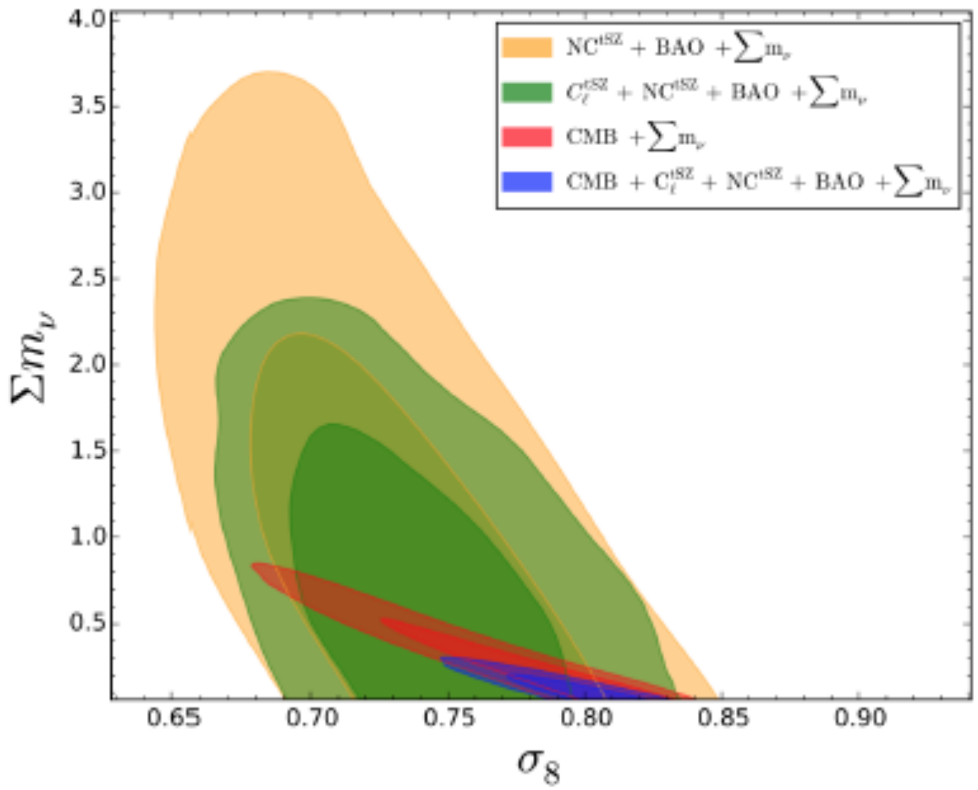
Tension in sigma8 reduced from ~2.4sigmas to ~1.5sigmas

Salvati et al. (2017)

Cosmological parameters from Planck SZ counts revisited (III)

Salvati et al. (2017)





Degeneracy between σ8 and mass bias →To reconcile CMB and tSZ counts & Cl, (1-b)~0.64 is needed.

Including massive neutrinos.
Σmv<0.19eV from CMB+ tSZ probes

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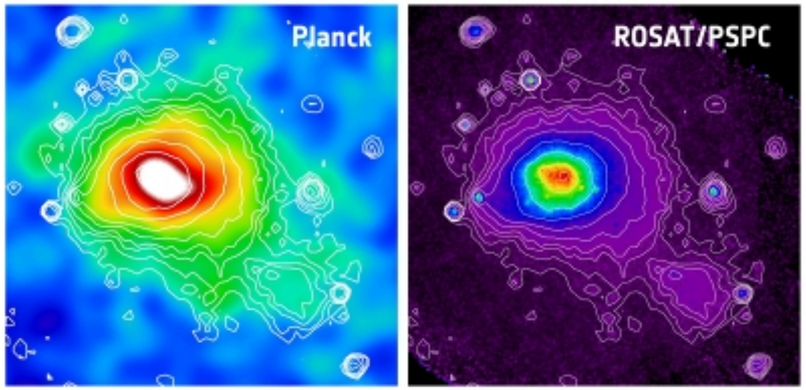
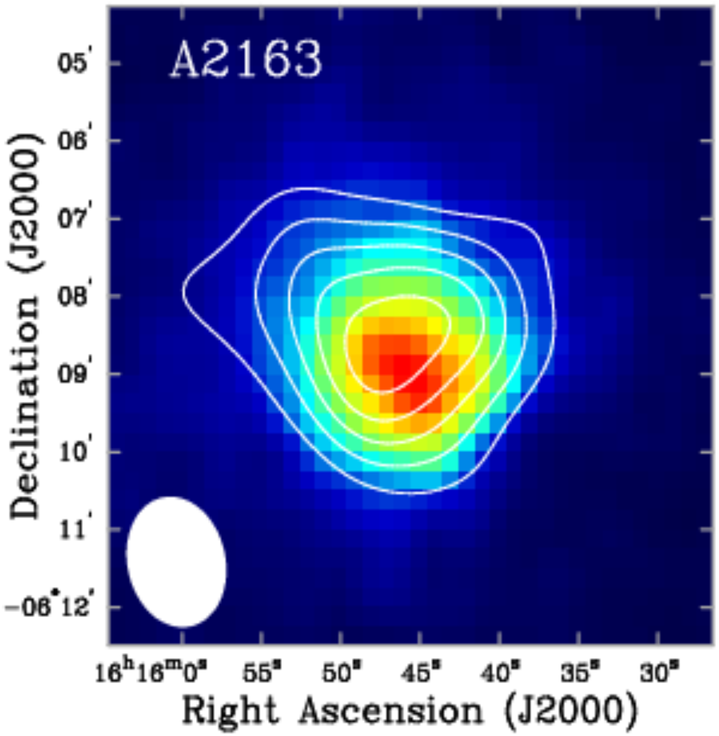


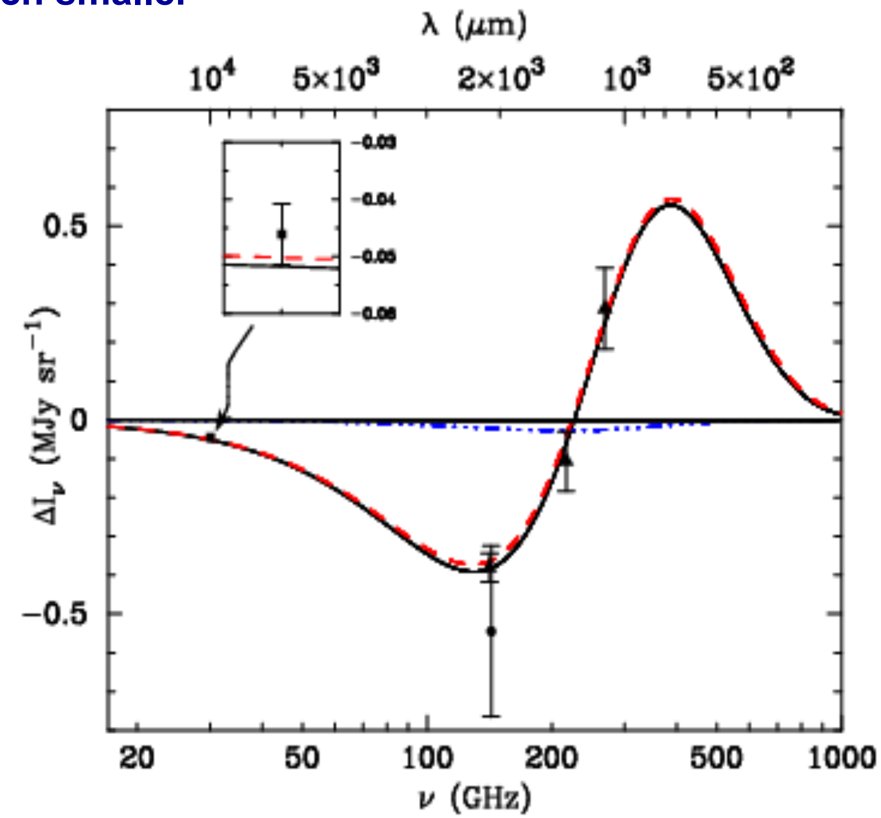
Kinetic Sunyaev-Zel´dovich Effect

- The kinetic effect arises if the scattering medium causing the thermal SZ is moving relative to the Hubble flow. The net effect is proportional to the **peculiar velocity projected along the line of sight.**

$$\frac{\delta T_{\rm kSZ}}{T_0} = -\tau_e \frac{v_{||}}{c}$$

- For the typical values of the gas temperature and the velocities <u>in clusters</u>, the **kSZ contribution is much smaller than the tSZ one**.





S.Church et al.

SuZie experiment (Berkeley, Stanford)

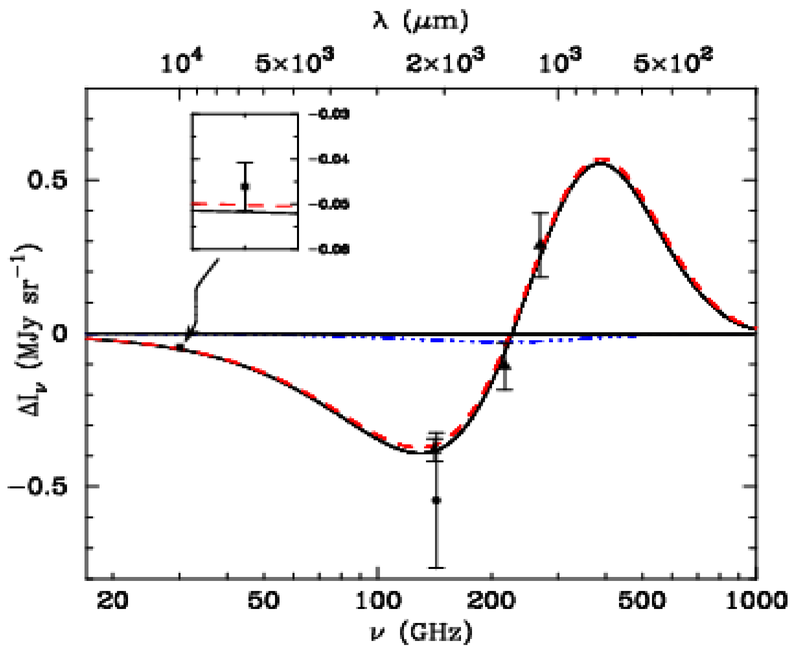
Peculiar velocity:

V= 415 +920 -760 km/s

Cluster MS1054 at redshift z=0.826

moving from us due to Universe expansion

with a velocity 54 % of speed of light (162 000 km/s).



However its peculiar velocity

is less than 1000 km/s with respect to the reference frame in which the

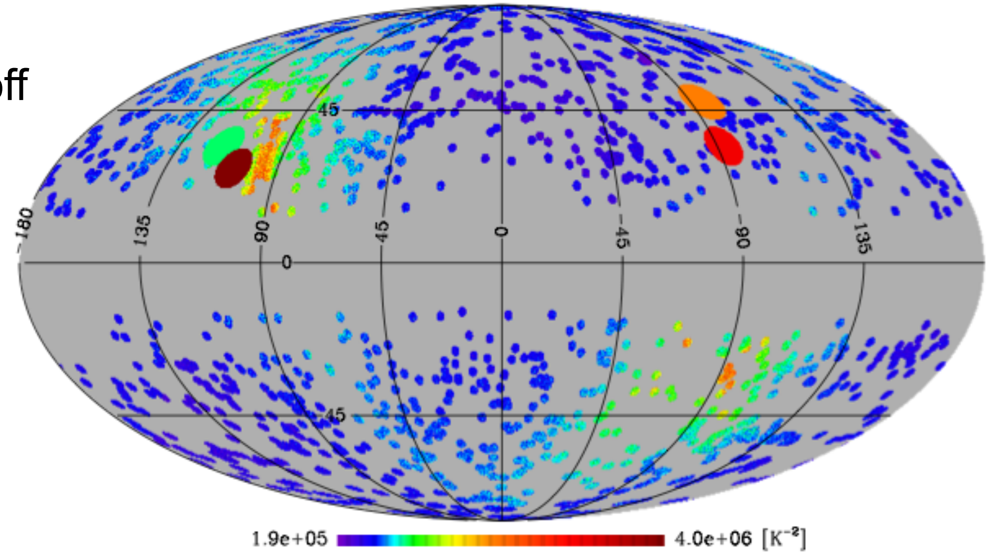
cosmic background radiation is isotropic (0.6% of Hubble recession velocity !!!).

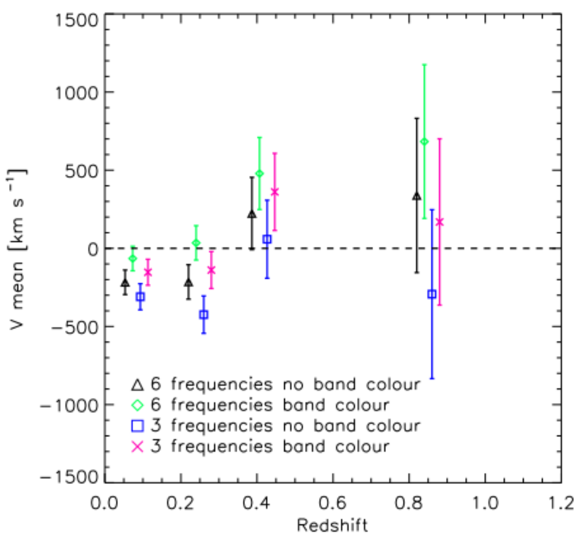
Kinetic SZ effect and Planck

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

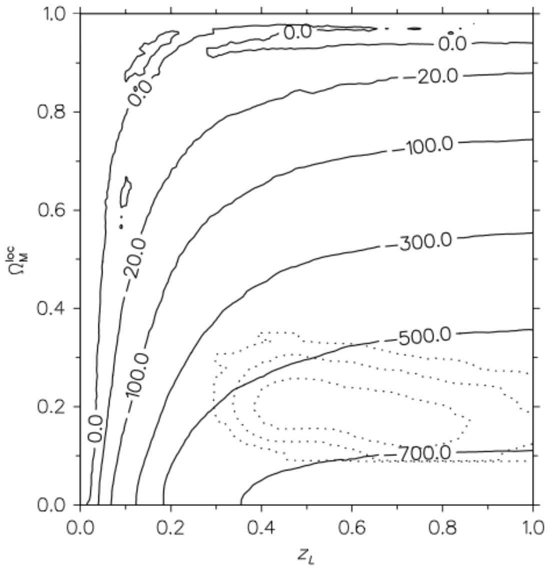
$$\frac{\delta T}{T_0}(\hat{\boldsymbol{n}}) = -\int dl\, \sigma_{\rm T}\, n_{\rm e} \frac{\boldsymbol{v}_{\rm e} \cdot \hat{\boldsymbol{n}}}{c}$$

- 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 e.g. giant void models as alternative explanations to ΛCDM (e.g. Goodman 1995; García-Bellido & Haugbolle 2008).
- No detection of kSZ dipole (=bulk flow).
- **Strongest evidence of univ. homogeneity below z=0.5.**

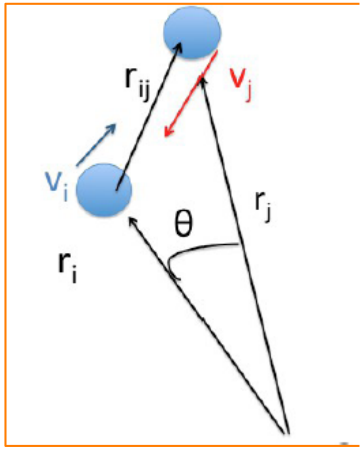


(Planck Collaboration Int XIII 2014)

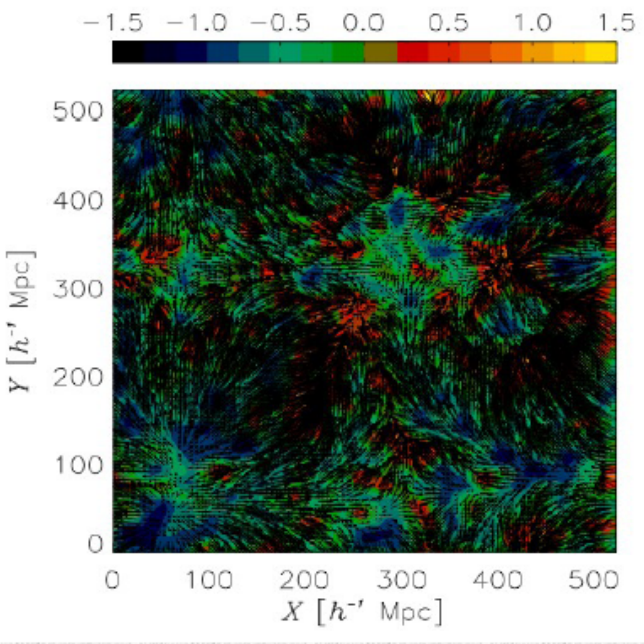
Measuring the Kinetic SZ effect

A) The kSZ pairwise momentum (Groth et al. 1981; Hand et al. 2012).

$$\hat{p}_{\mathrm{kSZ}}(r) = -\frac{\sum_{i<j}(\delta T_i - \delta T_j)\, c_{i,j}}{\sum_{i<j} c_{i,j}^2}$$



B) The kSZ correlation with the velocity field (Dedeo et al. 2005; Ho et al. 2010)



$$\frac{\partial \delta(\boldsymbol{x})}{\partial t} + \nabla \boldsymbol{v}(\boldsymbol{x}) = 0$$

We invert the density field into the peculiarvelocity field on large scales (via the continuity equation above), and cross correlate kSZ temperature estimates with the "expected" peculiar radial velocity:

$$<\delta T_{\mathrm{kSZ},\, i} \,.\, (\mathbf{v_j}.\mathbf{n_j})/\sigma> [r].$$

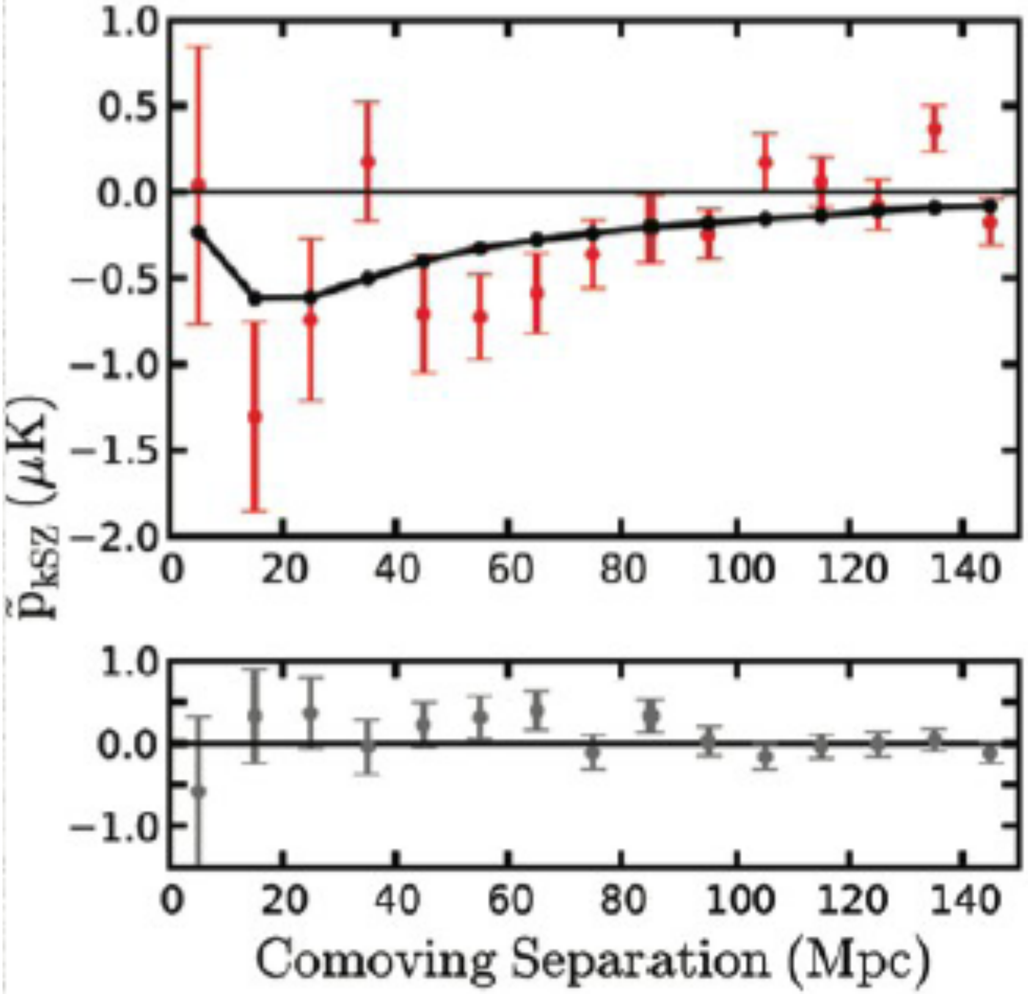
Planck Intermediate Results XXXVII (2015)

ACT's detection of kSZ pairwise momentum

Hand et al. (2012).

The *Atacama Cosmology Telescope* collaboration provided the first detection of the kSZ pairwise momentum by stacking pairwise momentum estimates of *filtered* maps at 145 GHz on the positions of ~5e13 M_sun LRGs identified by BOSS.

ACT **has FWHM~1.3** arcmin, where *Planck's* best angular resolution is close to **FHWM=5 arcmin.**



Planck detection of kSZ-velocity cross correlation

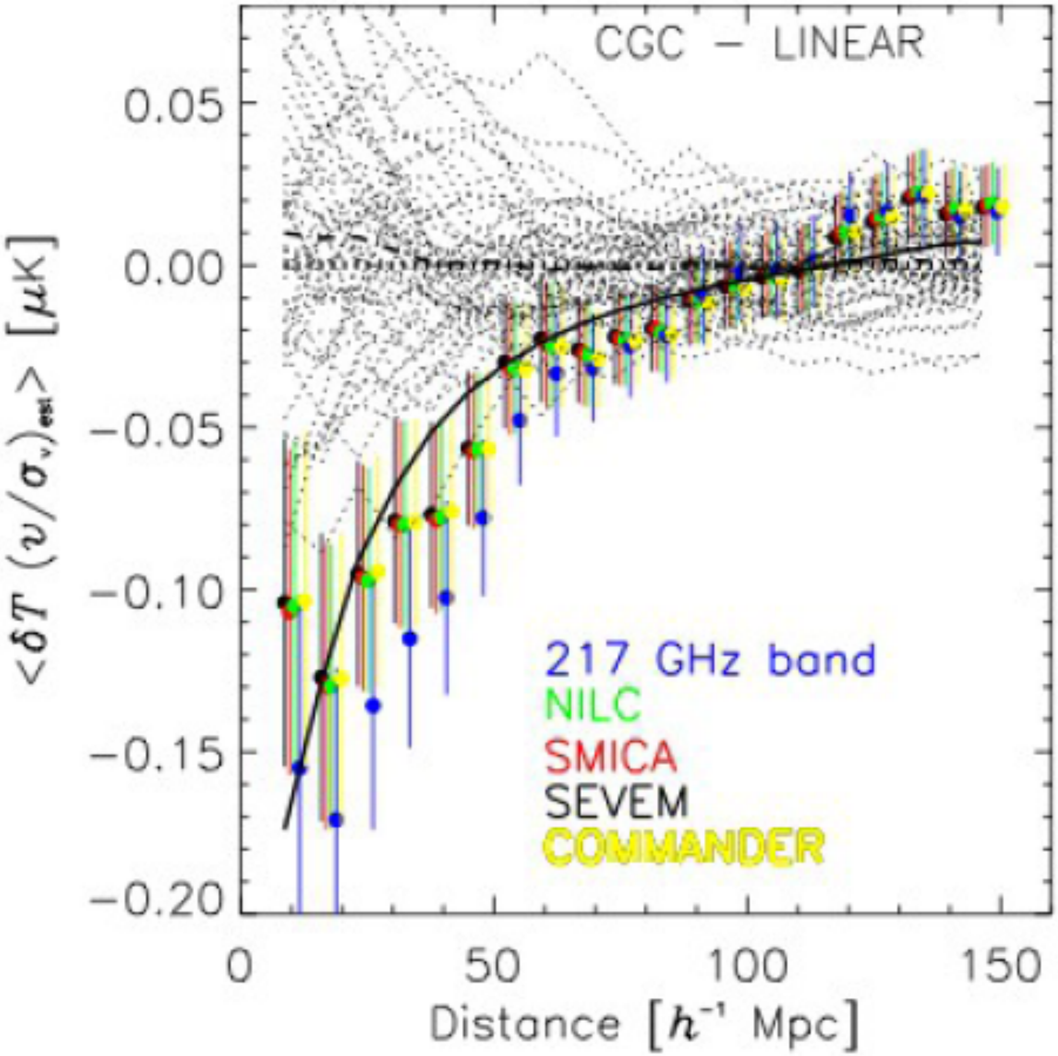
Planck Collaboration XXXVII (2015).

Sloan BCG sample

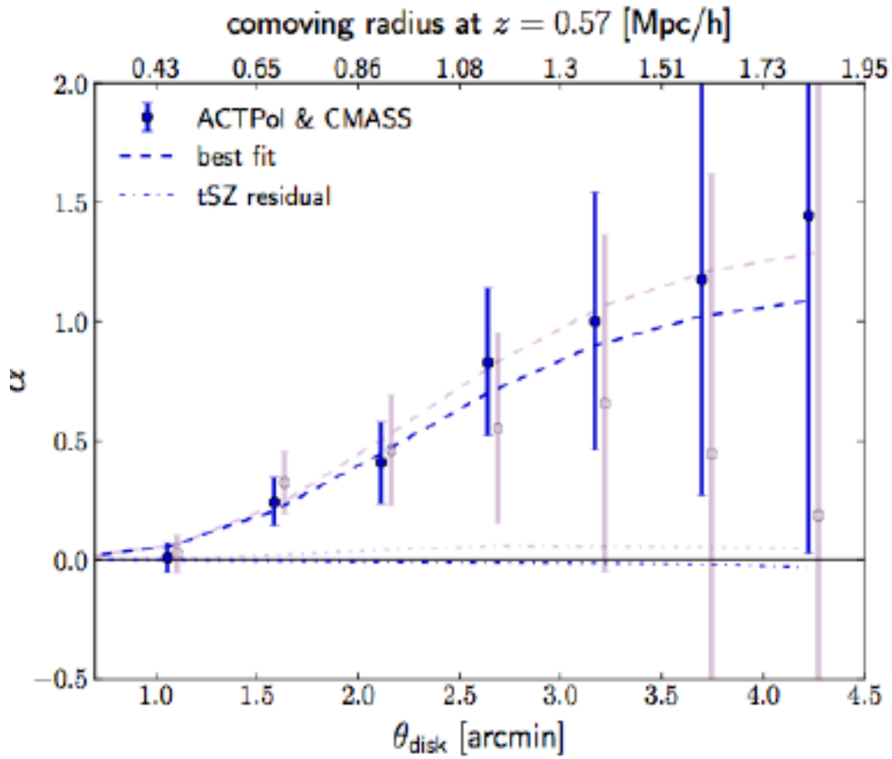
A) Detection of the kSZ pairwise momentum by *Planck* on Sloan local BCG sample.

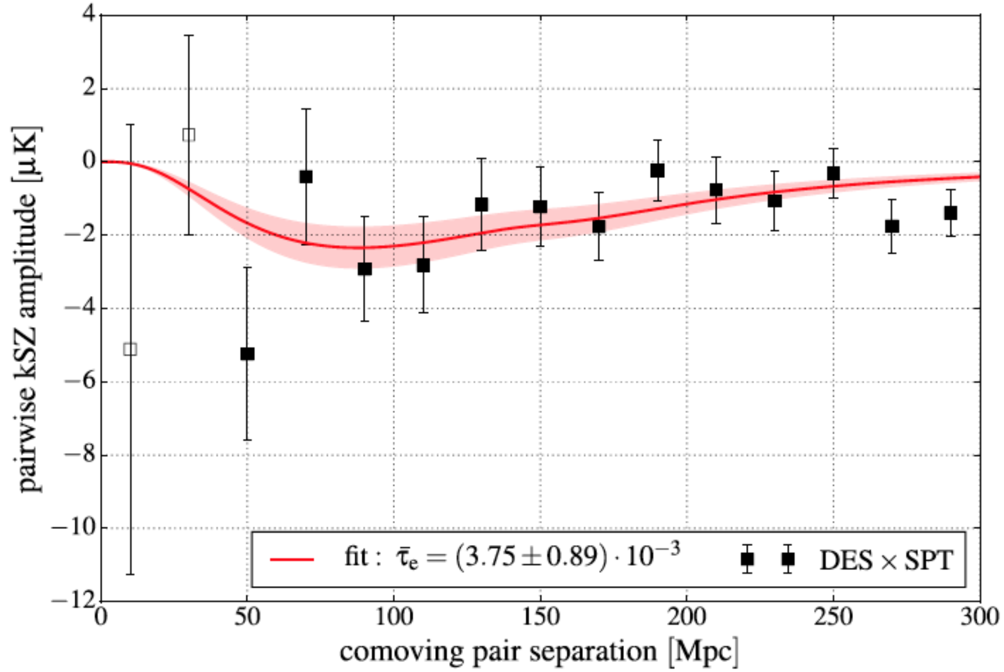
B) First detection of the kSZ – velocity cross-correlation. S/N=3.8.

Hernandez-Monteagudo et al. (2015) PRL. Finding the missing baryons around BCGs.



Latest results from high-resolution experiments like the South Pole Telescope (SPT) and the Atacama Cosmology Telescope Pol (ACTPol)

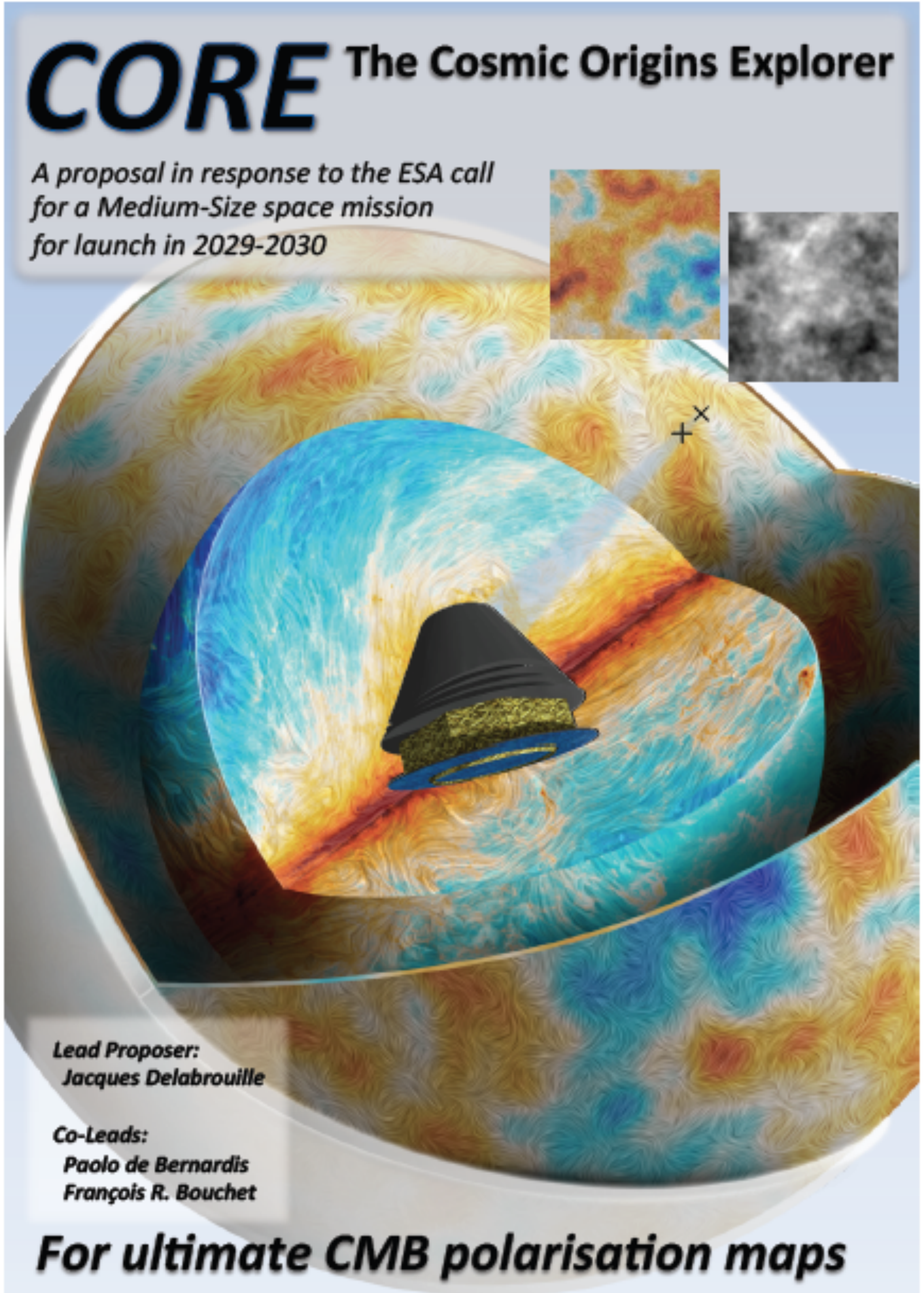




Schaan et al. (2016). ACTPol.
Velocity reconstruction from BOSS.
Detection of 3sigmas.
α = <δTobs / δTmodel >

Soergel et al. (2016). SPT.
DES YR1 cluster catalogue
Detection of ~4.2 sigmas

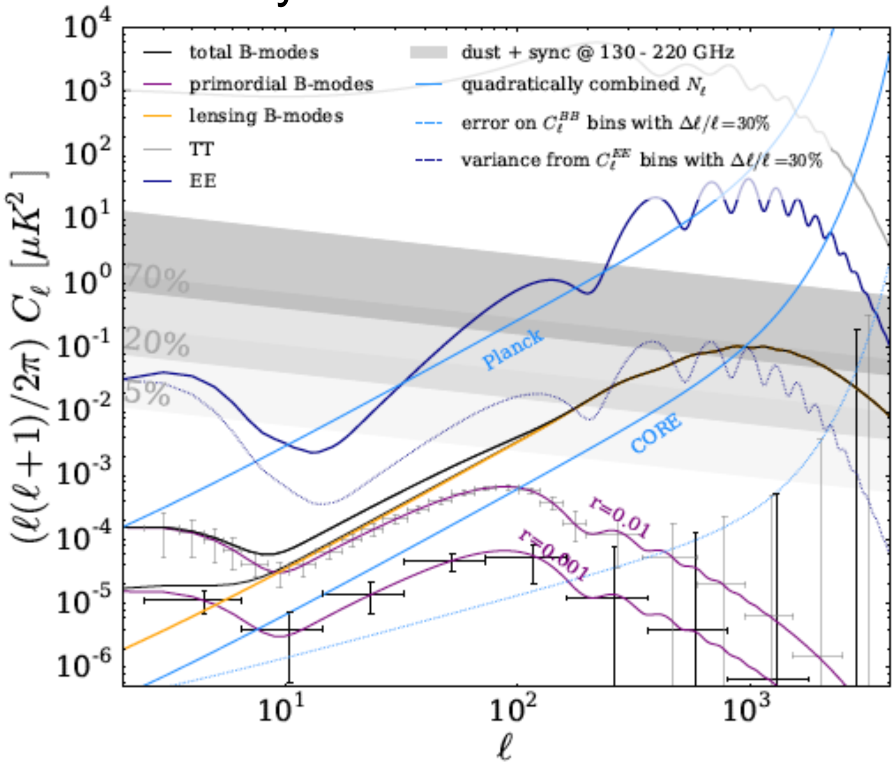
Future missions



Submitted to M5 ESA call, but not accepted.

Science case:

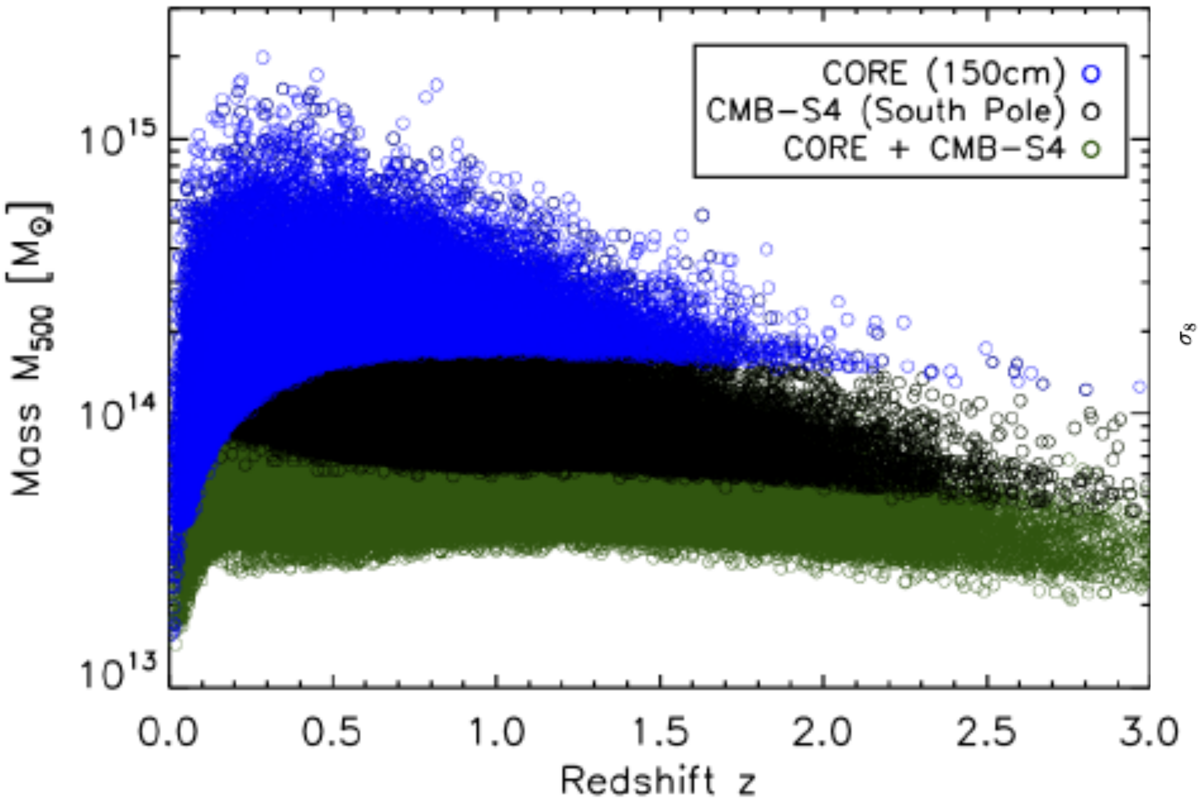
- Inflation
- Gravitational lensing (neutrino masses < 44meV).
- DE (FoM increased x10 wrt EUCLID)
- Neff with error <0.04
- Galaxy clusters.

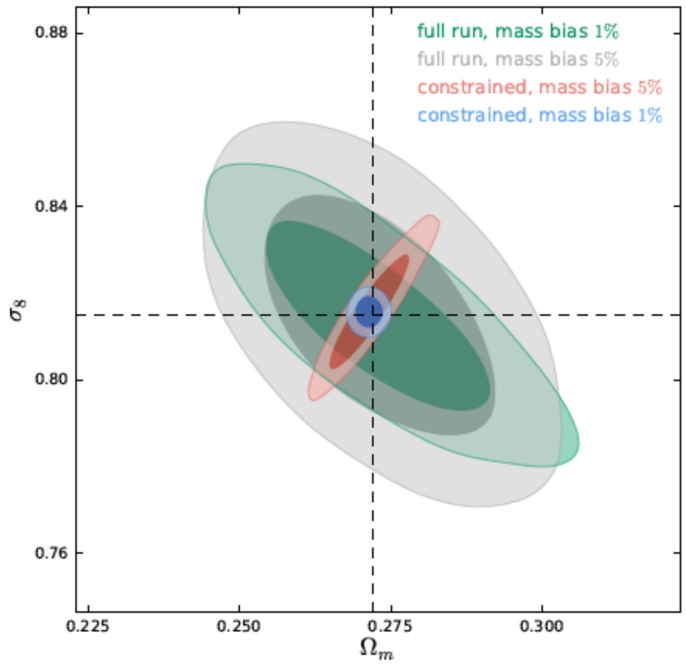


arXiv:170604516

Galaxy clusters with CORE

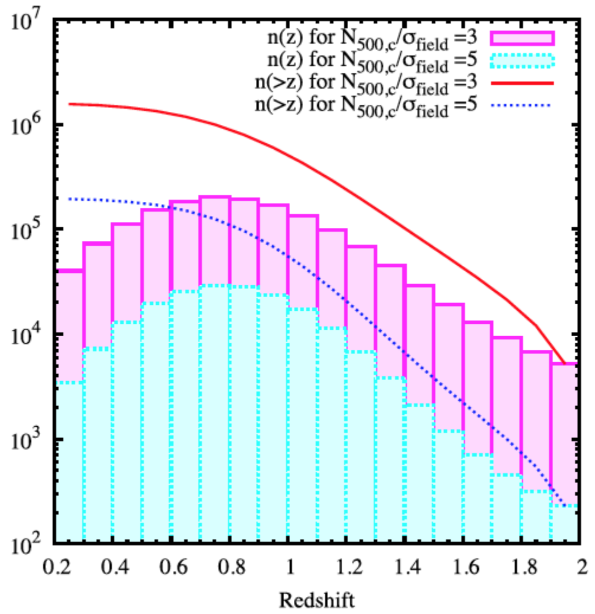
CORE mission concept with a 150 cm diameter primary mirror could detect of the order of 50,000 clusters through the thermal SZ effect.

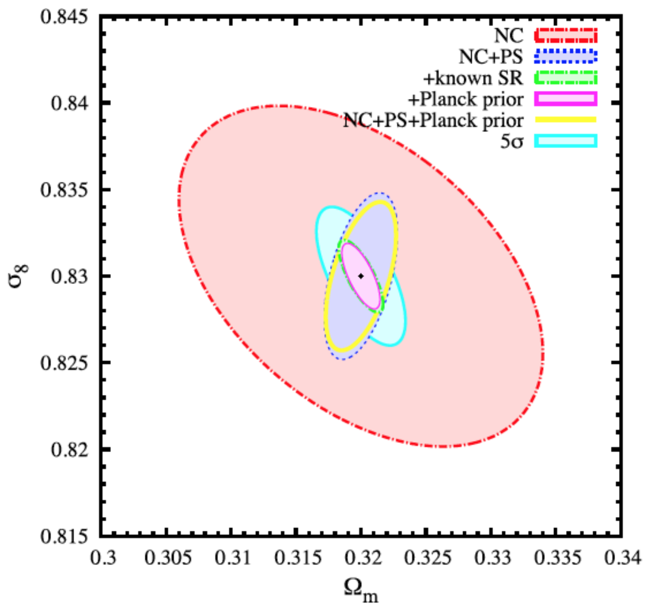




(Melin et al. 2018, JCAP)

Sector	Euclid Targets
Dark Energy	(i) Euclid *alone* to measure w_p and w_a to 2% and 10% (FoM_{DE} = 500) (ii) Look for deviations from $w = -1$, indicating a dynamical dark energy. (iii) Measure the cosmic expansion history to better than 10% for several redshift bins from $z = 0.5$ to $z = 2$.
Test of Gravity	(i) Measure the growth index, γ_m, to a precision better than 2%. (ii) Measure the growth rate to better than 5% for several redshift bins between $z = 0.5$ and $z = 2$ (iii) Separately constrain the two relativistic potentials Φ and Ψ (iv) Test the cosmological principle
Dark Matter	(i) Detect dark matter halos between a mass scale of $>10^{15}$ to $10^8\ M_\odot$ (ii) Accuracy of a few hundredths of an eV on the sum of neutrino masses, the number of neutrino species and the neutrino hierarchy. (iii) Measure the dark matter mass profile on cluster and galactic scales.
Initial Conditions	(i) Measure the matter power spectrum on a large range of scales in order to extract values for the parameters σ_8 and n to 1%; improve constraints on σ_8 and n by over a factor 30 and 2 respectively compared to Planck alone (ii) For extended models, improve constraints on n and α with respect to Planck alone by a factor 2. (iii) Measure the non-Gaussianity parameter f_{NL} to ± 10.



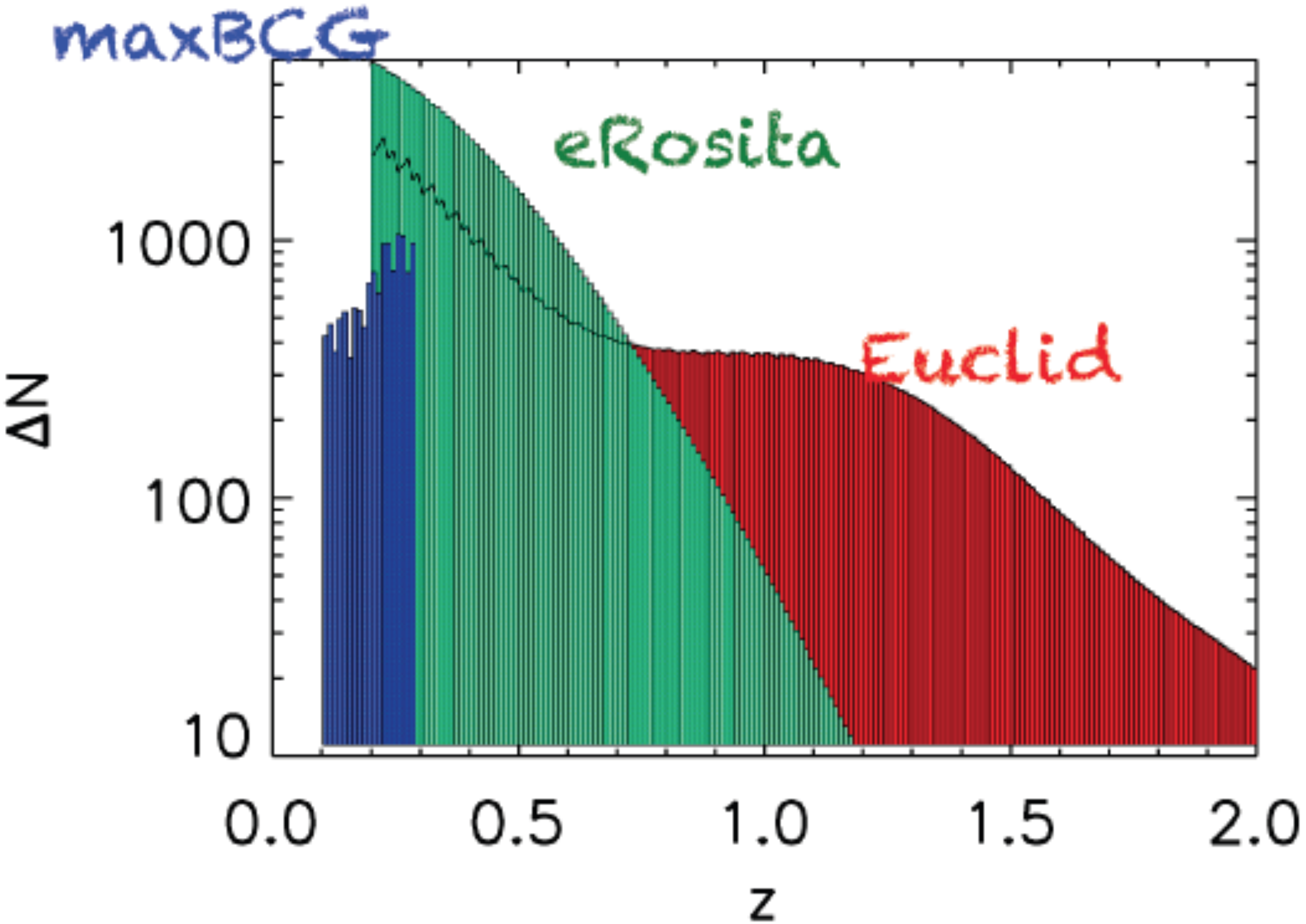


EUCLID will detect ~2x10^6 clusters at all redshifts.

Internal mass calibration from weak lensing and the dynamics of cluster galaxies.

(Sartoris et al. 2016)

EUCLID, eROSITA



15,000 deg^2

Euclid as a high redshift cluster finder

(slide from J. Weller)

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 ($0.2<z<1.0$)
  - Unveiling a population of dynamically perturbed clusters @ $z>0.3$, possibly under-represented in X-ray surveys. Detection of new distant massive clusters.
- 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, CORE?…)
  - DE evolution
  - Neutrino masses

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

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