Cluster cosmology with the Planck satellite

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on behalf of the Planck collaboration

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

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

Outline

I. **Clusters of galaxies and the Sunyaev-Zeldovich effect**

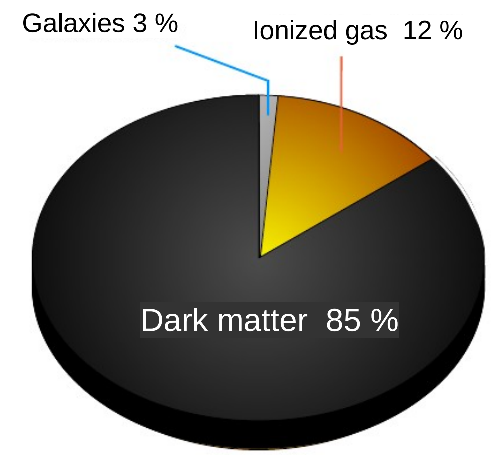
II. Measuring cluster thermal SZ with Planck

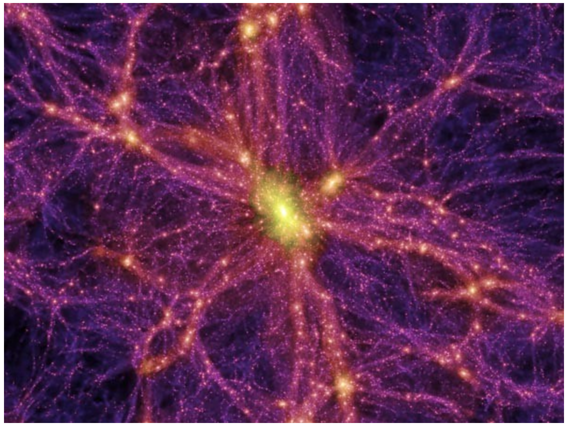
III. Cluster SZ cosmology with Planck

IV. Conclusions

Clusters of galaxies

- First observed by Zwicky in 1930's who inferred that their total mass was larger than the sum of its luminous components
- Largest gravitationally bound structures in the Universe
  - Dominated by dark matter
  - Most baryonic matter is in the form of gas, the Inter Cluster Medium (ICM)
  - Galaxies count for only 3 % of the total mass
- Formed by gravitational collapse at the intersection of cosmic filaments, correspond to massive dark matter halos
  - Self-similar scenario: clusters are scaled copies one of each others
  - However, baryonic physics plays a significant role
- Total mass 10^{13}- 10^{16} $M_{\odot}$, redshift $0 < z < 3$





Cluster observables

Cluster observables: detect them and/or measure their physical properties

Visible and IR emission

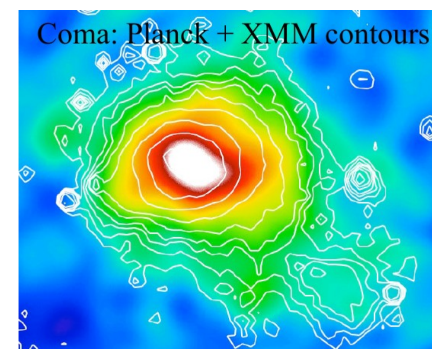
Light from stars in galaxies

Mass:
- Richness (number of galaxies)
- Luminosity profile
- Velocity dispersion
- Gravitational lensing

X-ray emission

Free-free emission from free electrons in the ICM

Density, temperature, entropy, mass:
- surface brightness
- spectroscopy



Sunyaev-Zeldovich effect

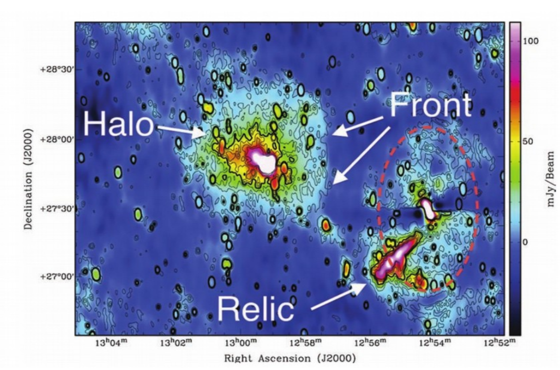
Interaction of hot electrons in the ICM with CMB photons

Pressure, mass, shocks:
- Compton parameter

Radio emission

Non thermal emission from accelerated particles

Shocks:
- Surface brightness

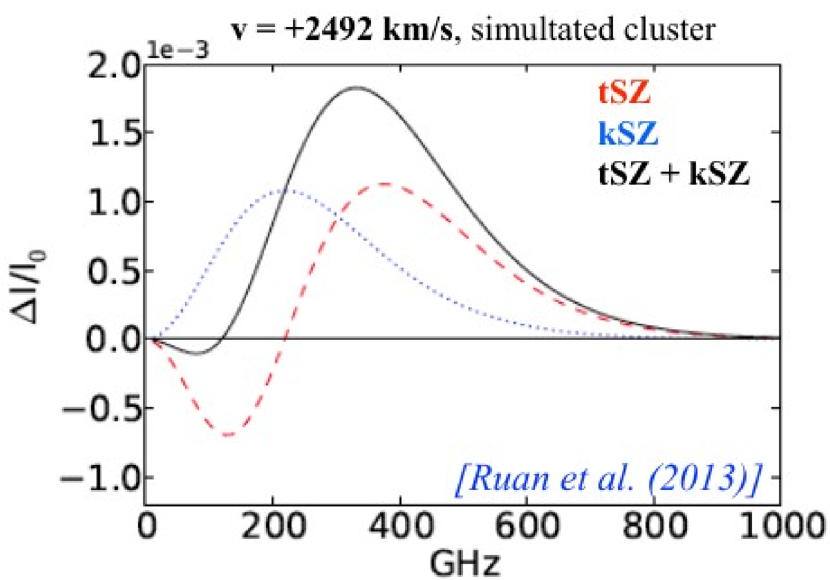


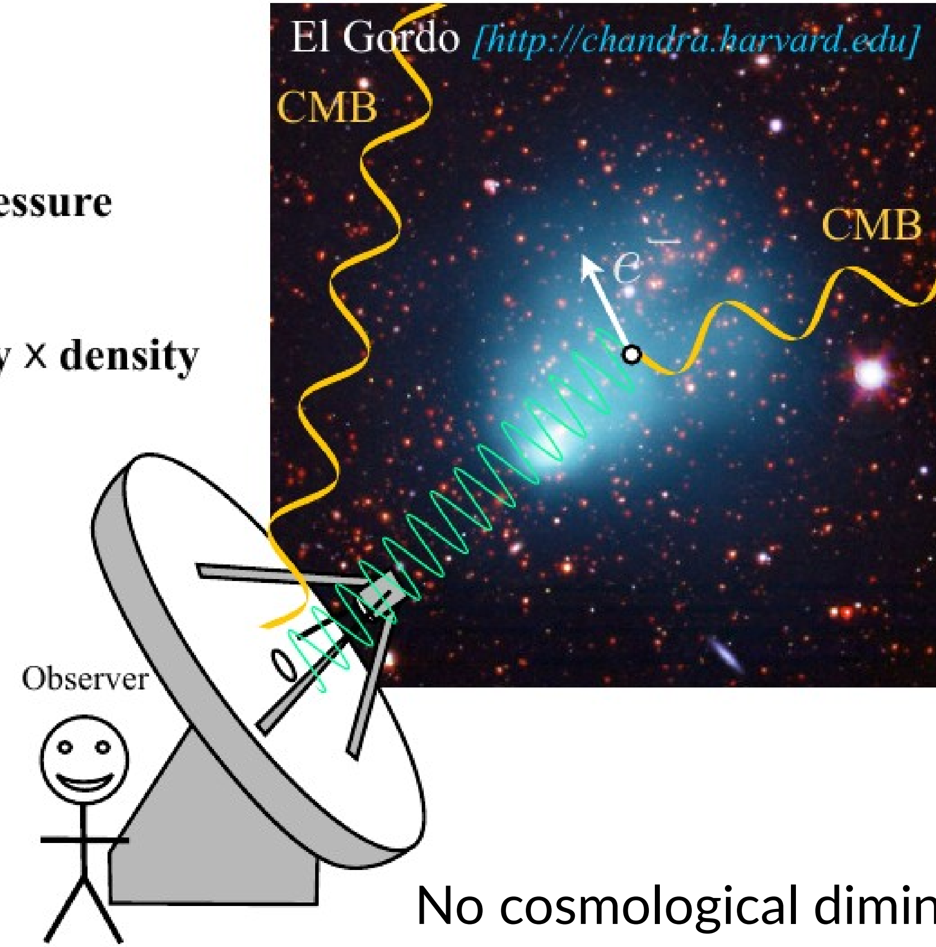
Sunyaev-Zeldovich effect

- **tSZ** = CMB spectral distortion from interaction with clusters' hot electrons
- **kSZ** = CMB Doppler shift from bulk motion of electrons (typically ~ tSZ/10)

$$\frac{\Delta I_\nu}{I_0} = f_\nu \; y_{\mathrm{tSZ}} + g_\nu \; y_{\mathrm{kSZ}}$$

$$\begin{cases} y_{\mathrm{tSZ}} = \dfrac{\sigma_{\mathrm{T}}}{m_e c^2} \displaystyle\int P_e \, d\ell & \Rightarrow \quad \textbf{Pressure} \\ y_{\mathrm{kSZ}} = \sigma_{\mathrm{T}} \displaystyle\int \dfrac{-v_z}{c} n_e \, d\ell & \Rightarrow \quad \textbf{Velocity} \times \textbf{density} \end{cases}$$





No cosmological diming

➡ **SZ = probe for intracluster gas**

SZ experiments

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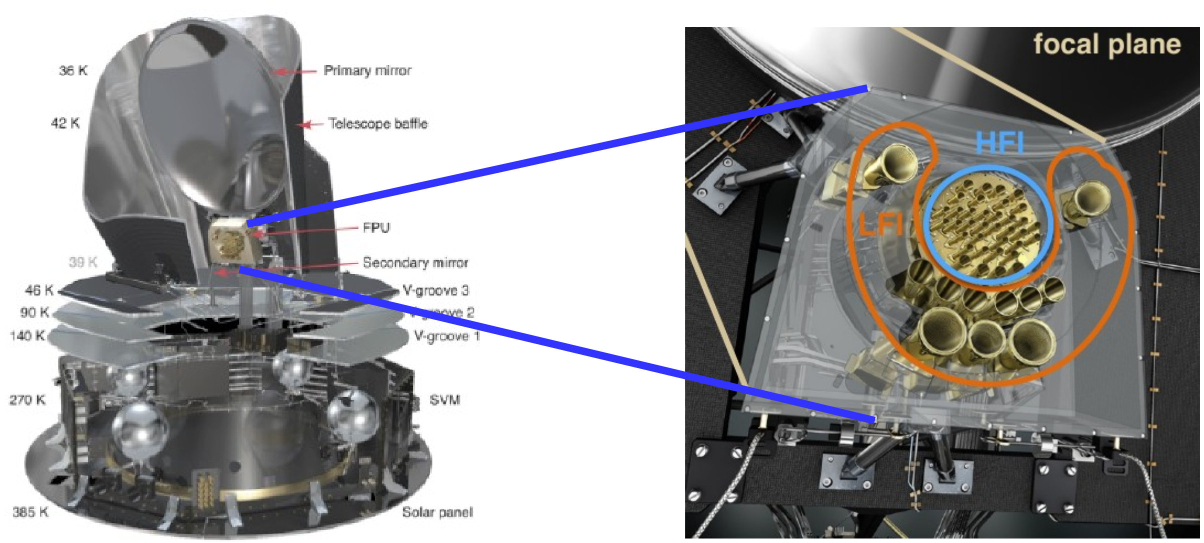
The PLANCK satellite

- 3rd generation of satellites for CMB studies (after COBE and WMAP)
- Launched by ESA on 14th of May 2009 from Lagrange L2 point
  Operated continuously from 12th August 2009 to 23rd October 2013
- 1.5 m telescope, complex cryogenic system: V-grooves, sorption cooler,
- 2 independent cryogenic instruments:
  - **LFI**, radiometers 30-70 GHz, cooled down to 18 K
  - **HFI**, bolometers 100-857 GHz, cooled down to 100 mK3
- Full sky coverage in 6-7 months, () full-sky surveys for HFI (LFI)



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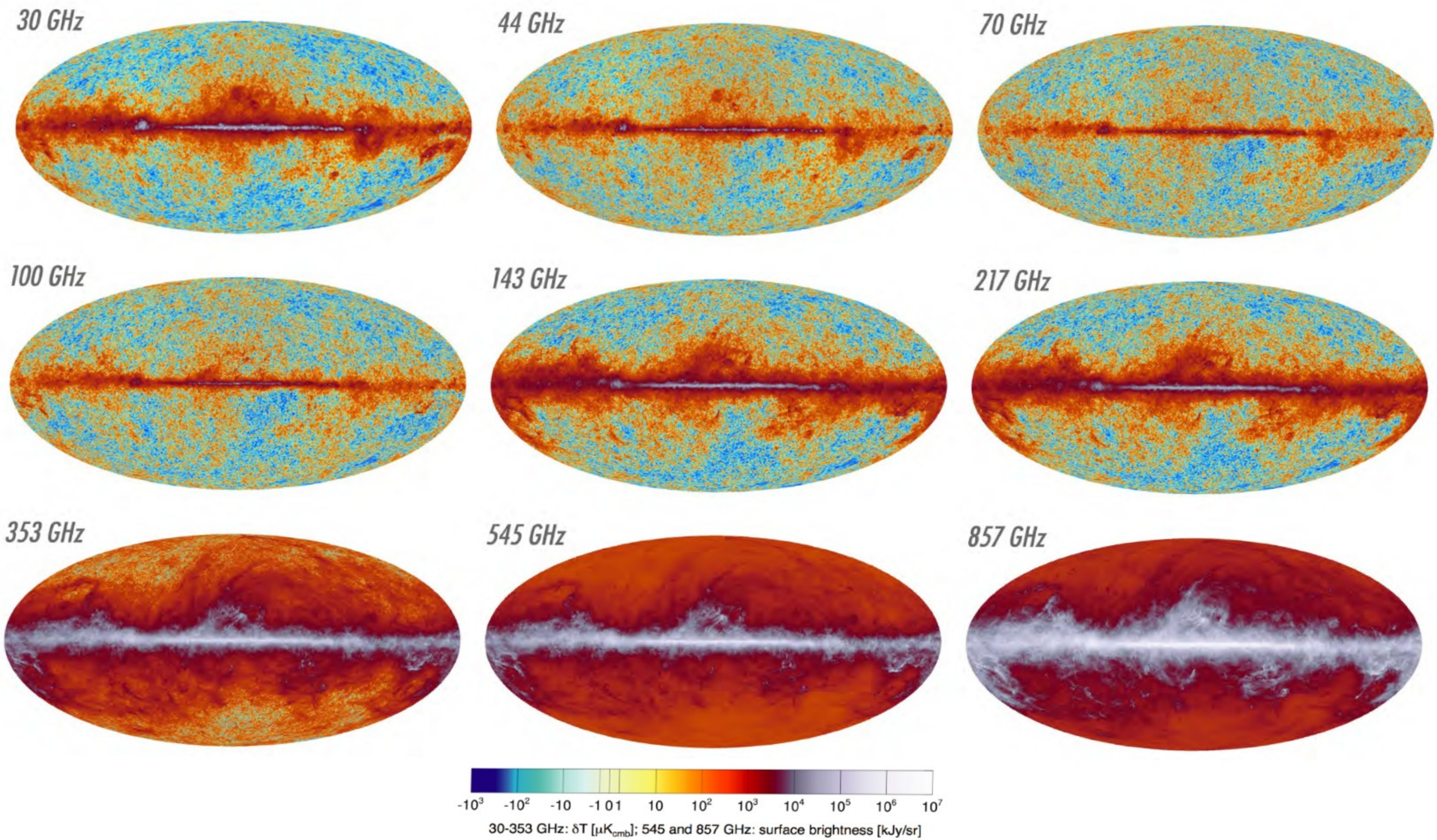
	30	44	70	100	143	217	353	545	857
Resolution (arcmin)	32	28	13	9	7	4.7	4.5	3.8	3.6
Sensitivity (μK_{CMB} $s^{1/2}$)	146	173	152	23	20	28	116	814	23798

[Planck 2015 results: I]

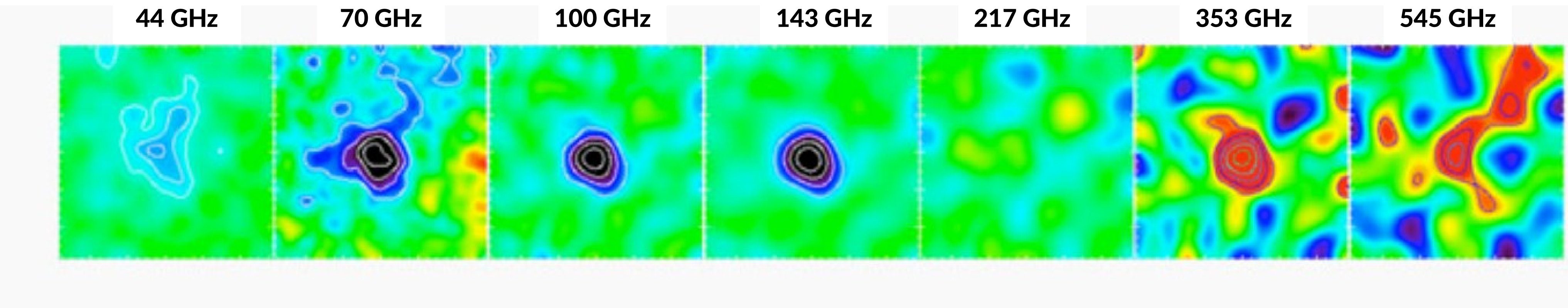
Planck satellite maps



[Planck 2015 results: I]

SZ with the Planck satellite

Planck satellite has been specifically designed to extract the tSZ signal on clusters



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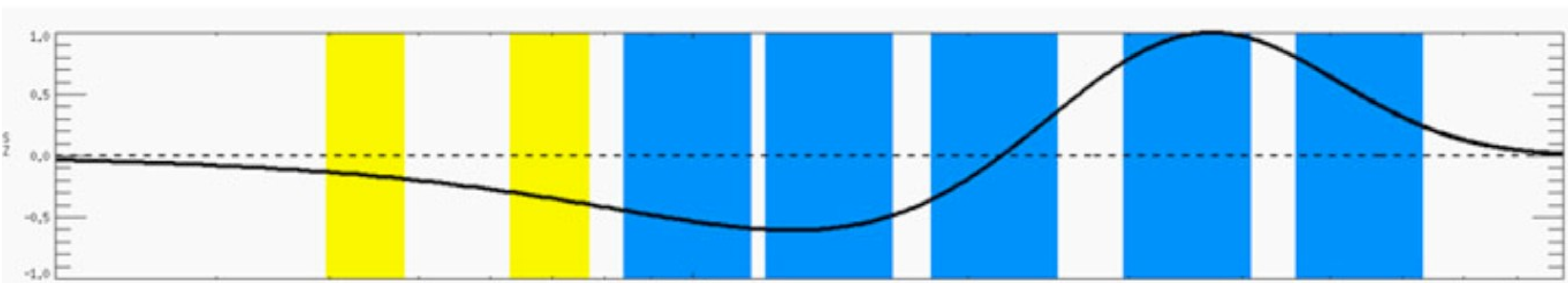
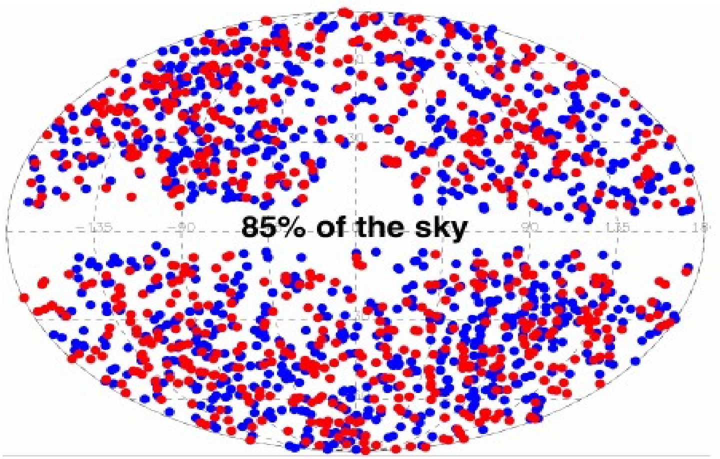
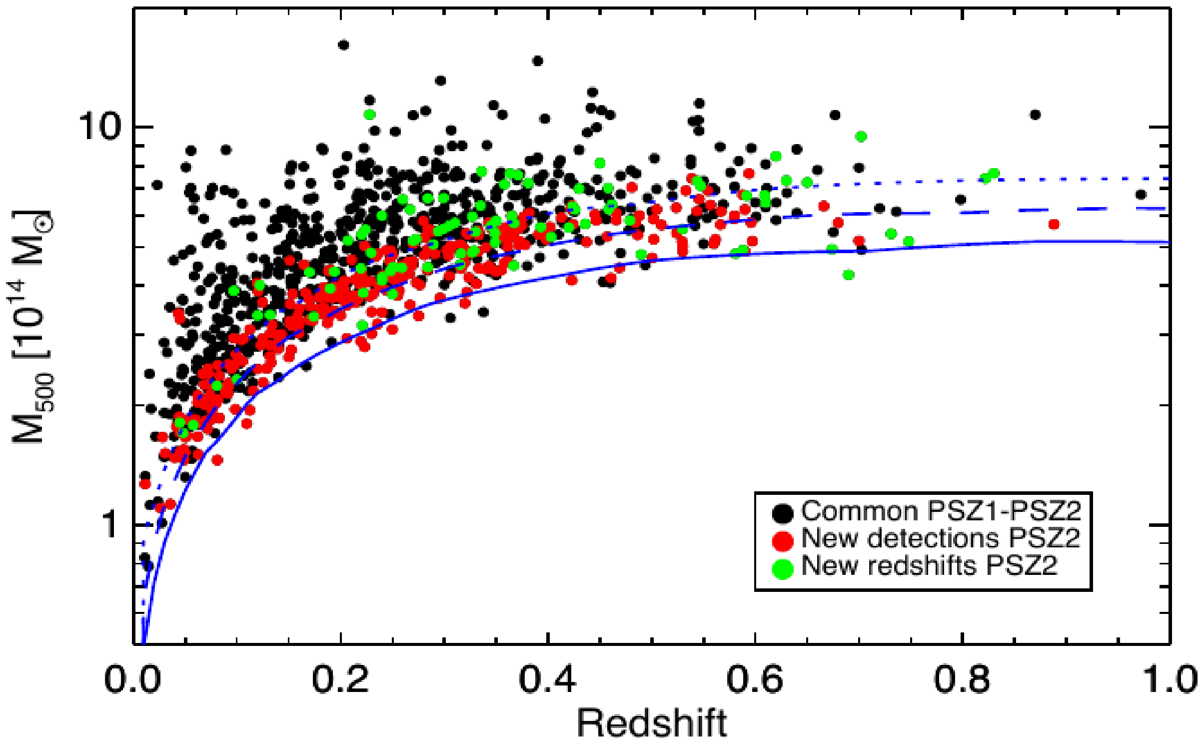


Use both specific cluster size and shape as well as spectral form

Planck cluster sample

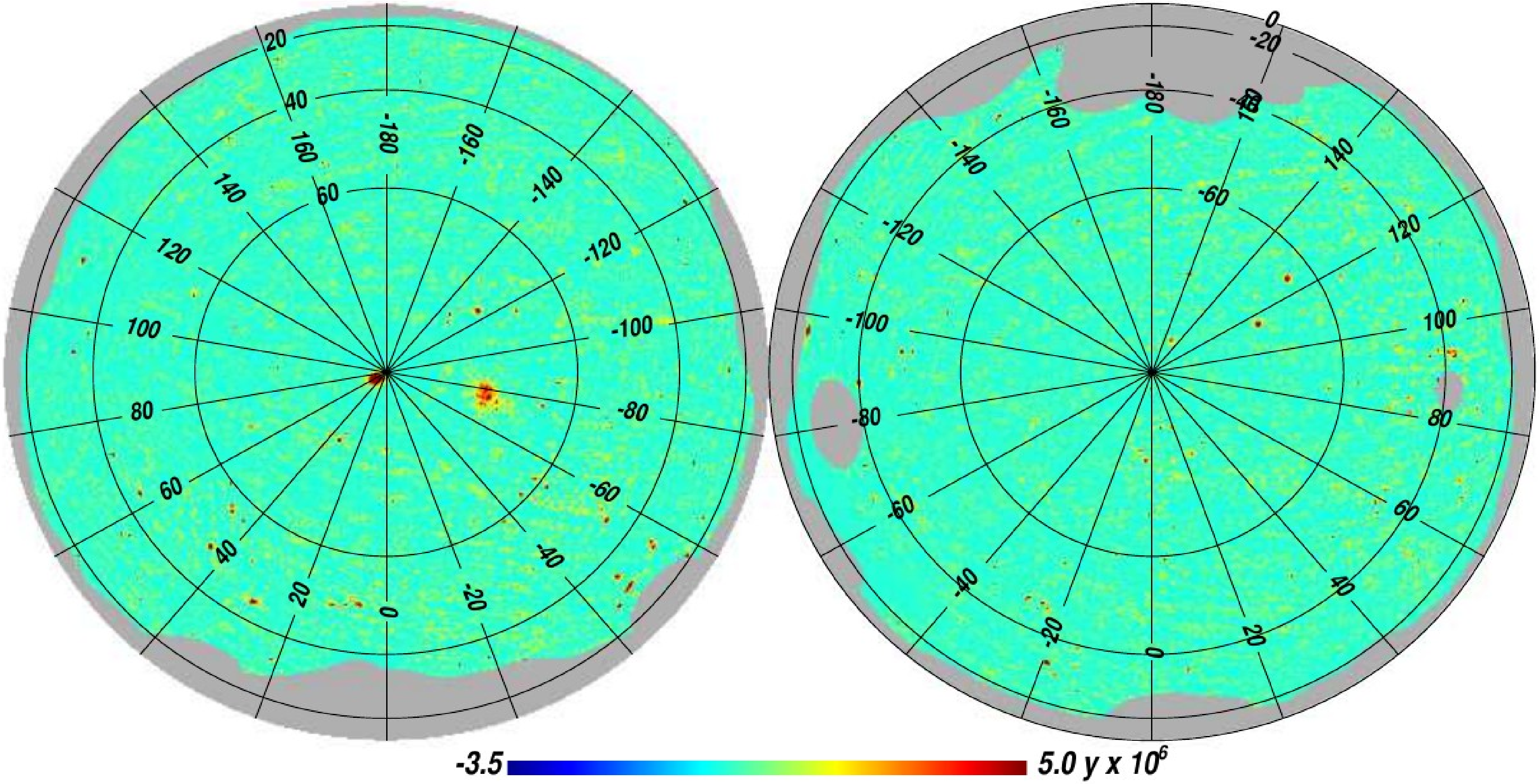
- Use specific multi-scales and multi-wavelengths filters to detect clusters
- Three catalogs has been released: ESZ(2011), PSZ1 (2013), PSZ2 (2015)
- PSZ2: 1653 clusters detected
- 1203 confirmed from existing surveys and follow-up programs in X-rays (XMM newton) and optical/IR (several telescopes)





Compton parameter map (y-map)

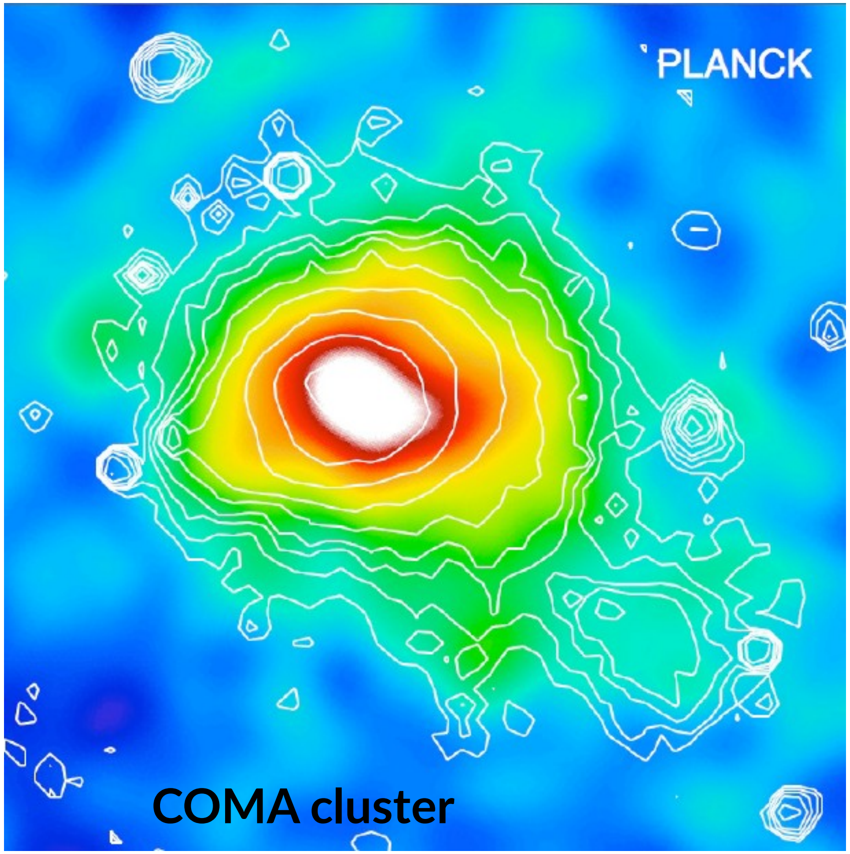
- Develop adapted component separation algorithms: **MILCA** and **NILC** preserve tSZ signal and nullify CMB emission
- First full-sky map of the tSZ emission



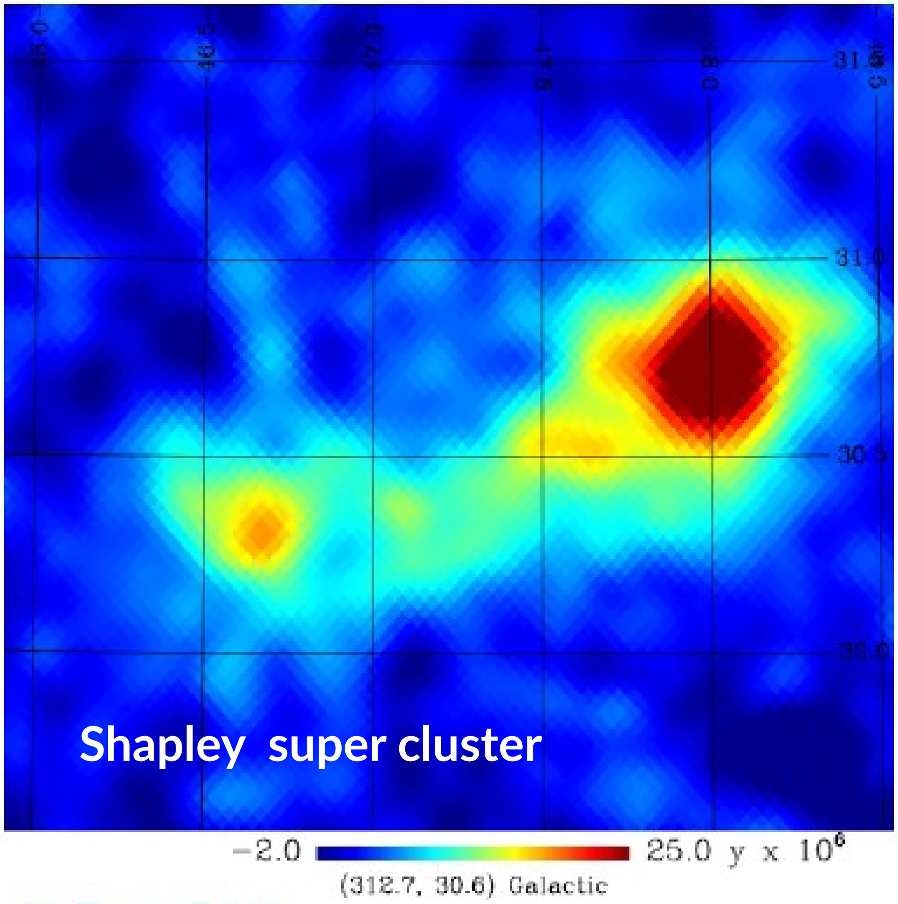
[Planck 2015 results: XXII]

Compton parameter map II

High sensitivity nearby clusters tSZ maps



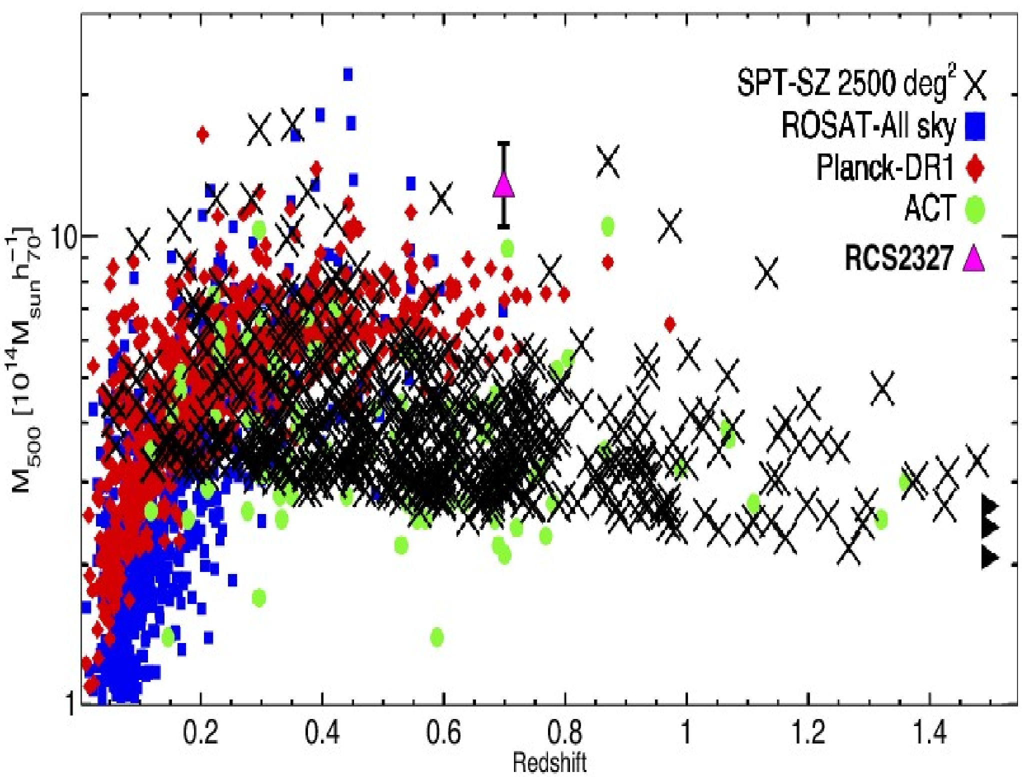
Complex interacting systems



[Planck 2015 results: XXII]

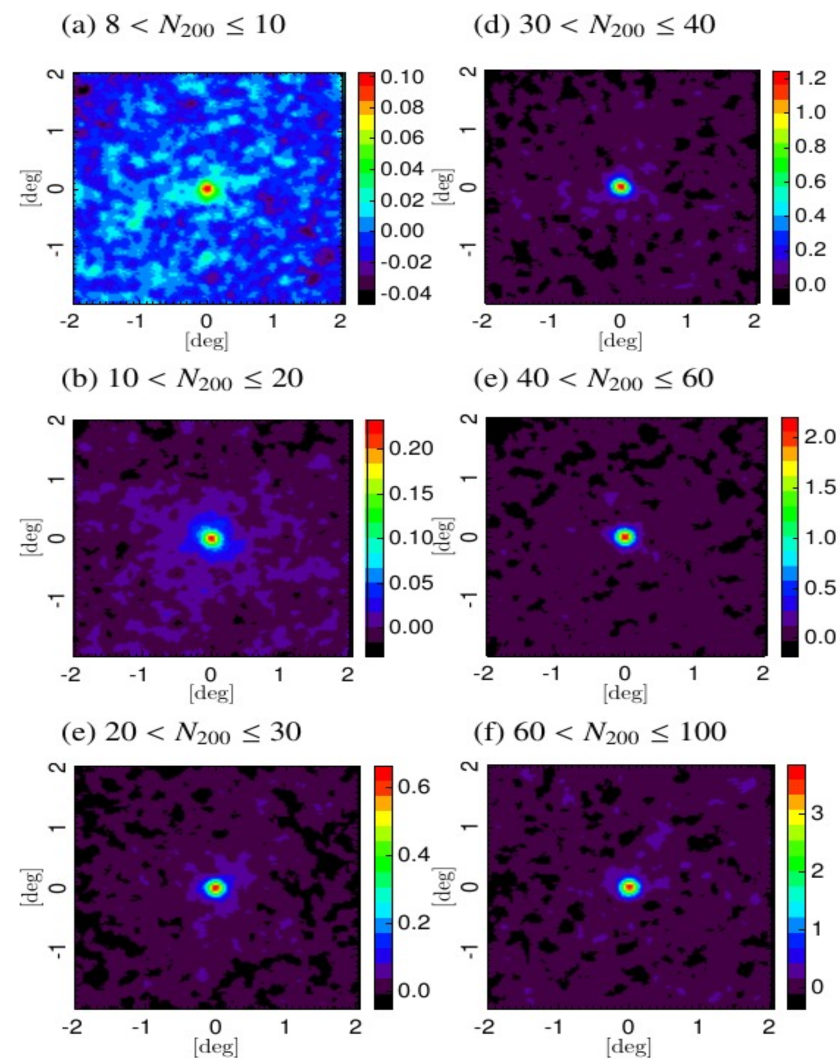
Multi-wavelength comparisons

Xray vs SZ



Planck 2015 results XXII
Wen +2011

SDSS8 vs Planck SZ



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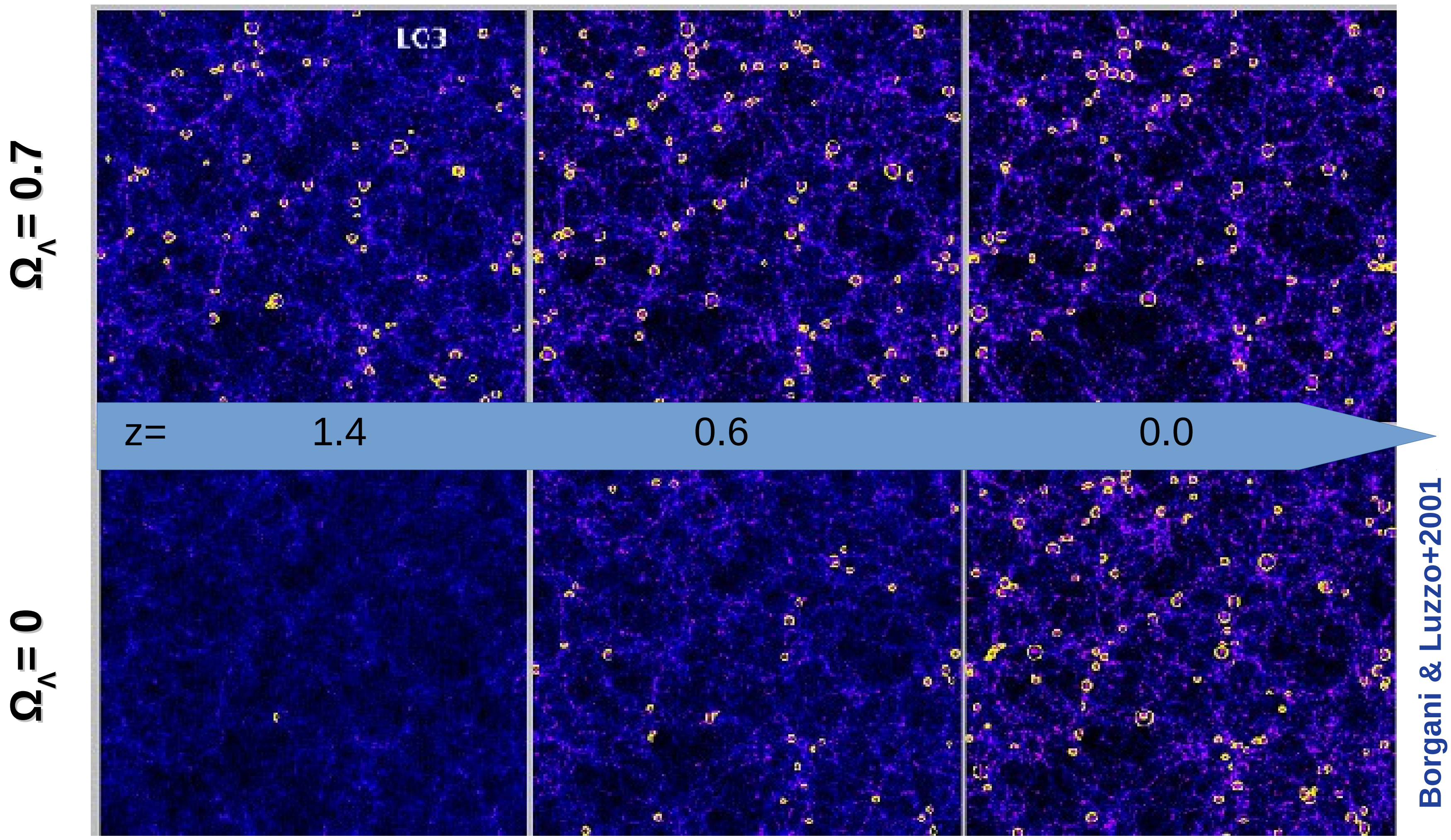
Cosmology with clusters



Cluster distribution in mass and redshift depends on cosmological parameters

A bit of tSZ cluster cosmology theory

Cluster number counts

$$\frac{dN}{dz} = \int d\Omega \int dM_{500}\, \hat{\chi}(z, M_{500}, l, b) \frac{dN}{dz\, dM_{500}\, d\Omega}$$

tSZ power spectrum

$$C_\ell^{1\text{halo}} = \int_0^{z_{\max}} dz \frac{dV_c}{dz d\Omega} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_\ell(M,z)|^2$$

Universe properties:

Volume of the Universe

Mass and redshift cluster distribution

Cluster properties and dynamical state:

Hydrostatic to total mass bias

Cluster pressure distribution

tSZ flux to hydrostatic mass relation

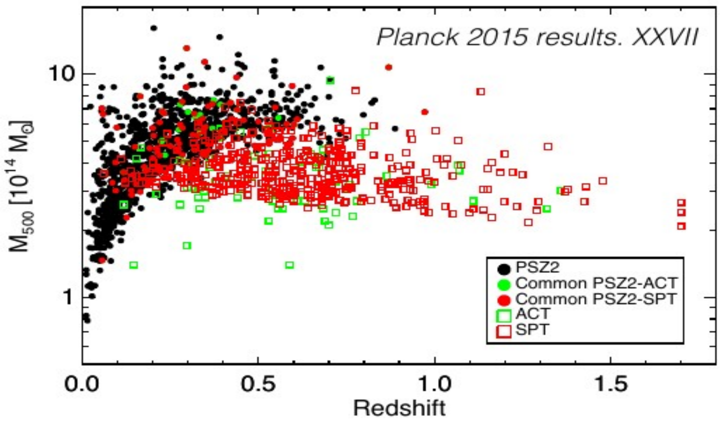
Data analysis

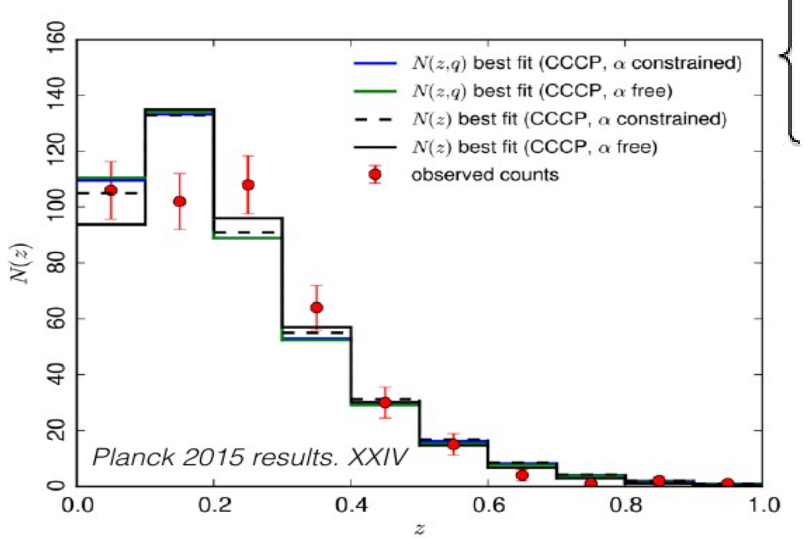
Cluster selection function

Noise distribution in the y-map

Planck tSZ cluster cosmology I

Cluster number counts





$$\frac{dV_c}{dz d\Omega}$$ (H0,Ωm,ΩΛ,Ων) Volume

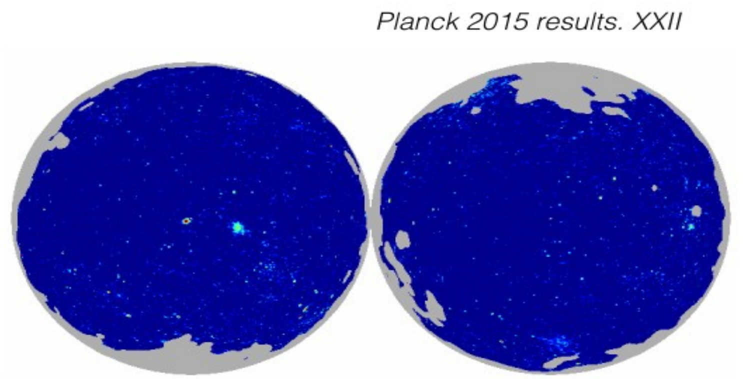
$$\frac{dn(\sigma_8, \Omega_m)}{dM}$$ Mass function

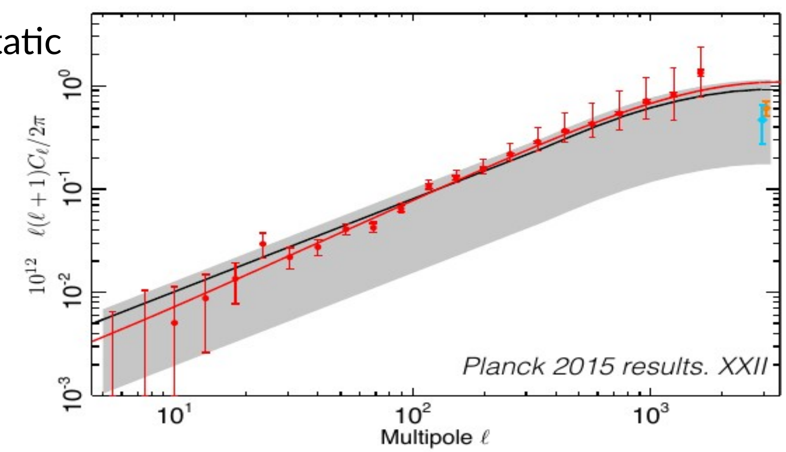
$P_e(r)$ Pressure profile

$Y_\Delta = A M_\Delta^\alpha$ Scaling relation

$M_{tot}^{HE} = (1-b) M_{tot}$ Hydrostatic bias

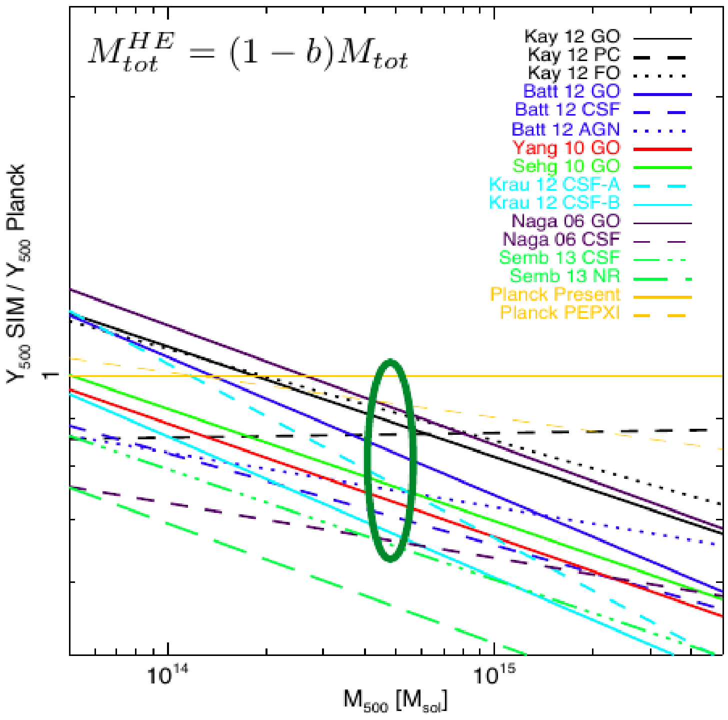
tSZ power spectrum





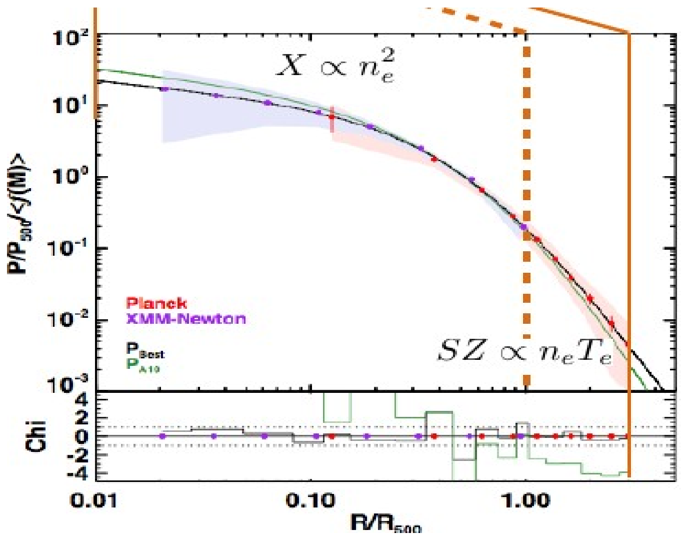
A bit of cluster complexity

- Hydrostatic bias and mass function from hydrodynamic cosmological simulations



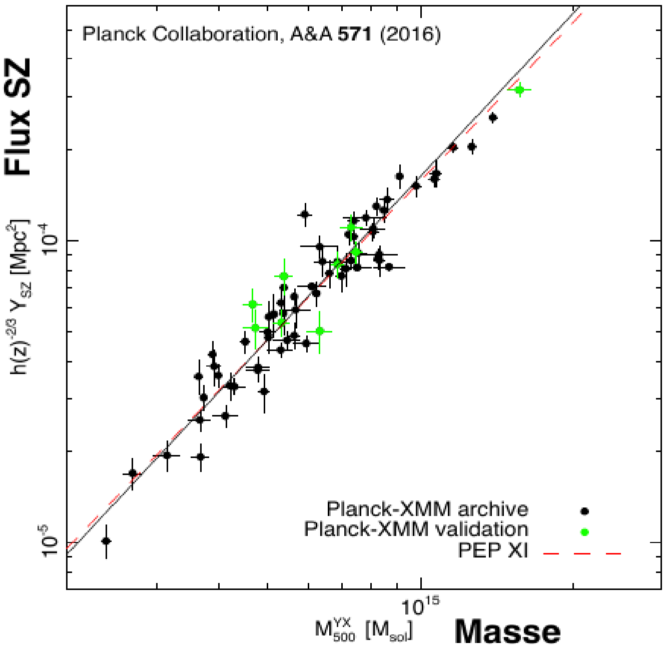
[Planck 2013 results XX]

[Planck intermediate results V (2013)]

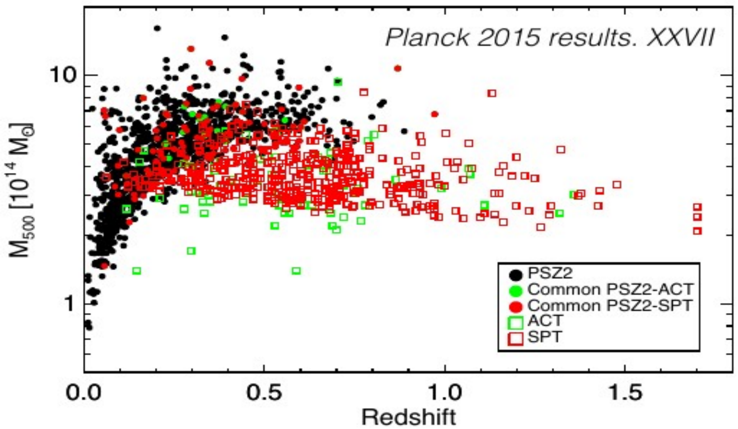


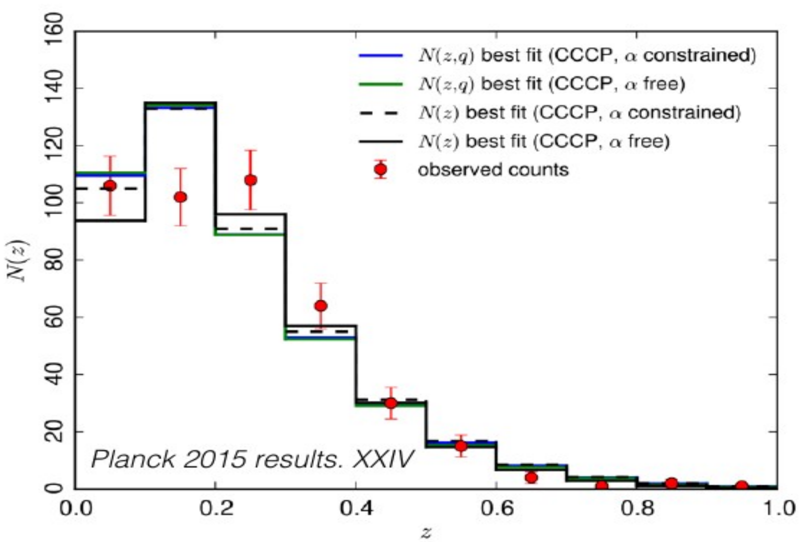
- Pressure profile from tSZ (Planck), X-rays (XMM) low redshift clusters

- Scaling relation from tSZ (Planck), X-rays (XMM) low redshift clusters

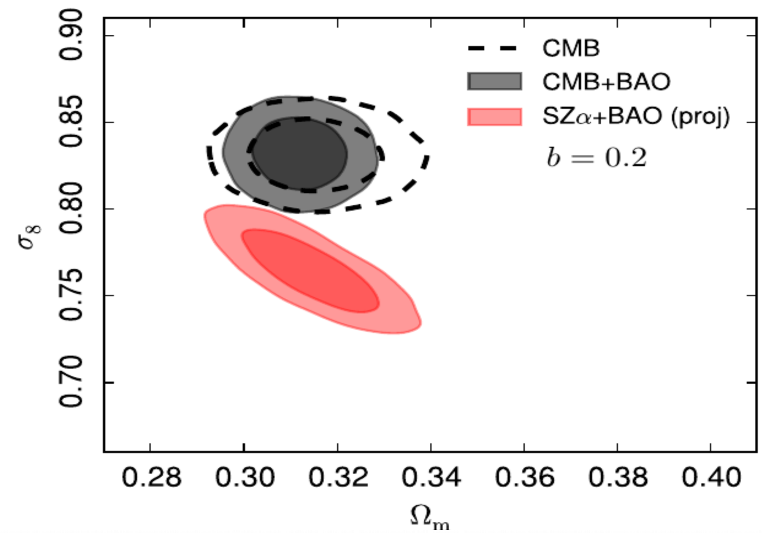


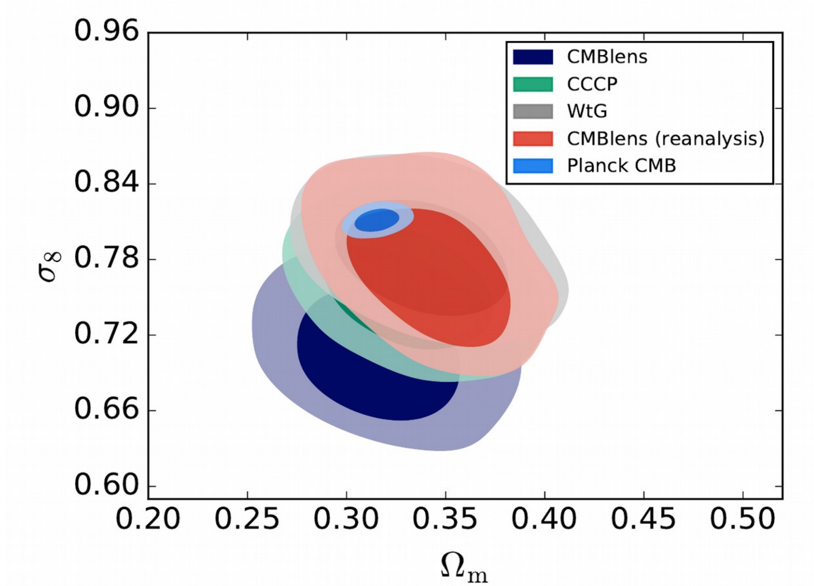
Cluster number counts





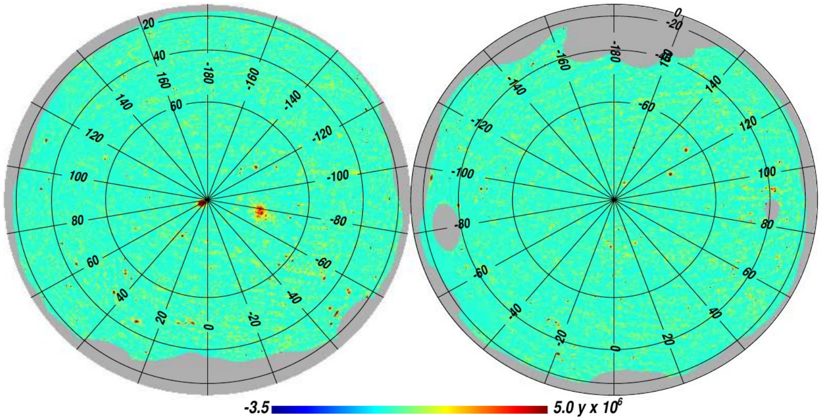
[Planck 2015 results: XXVII]

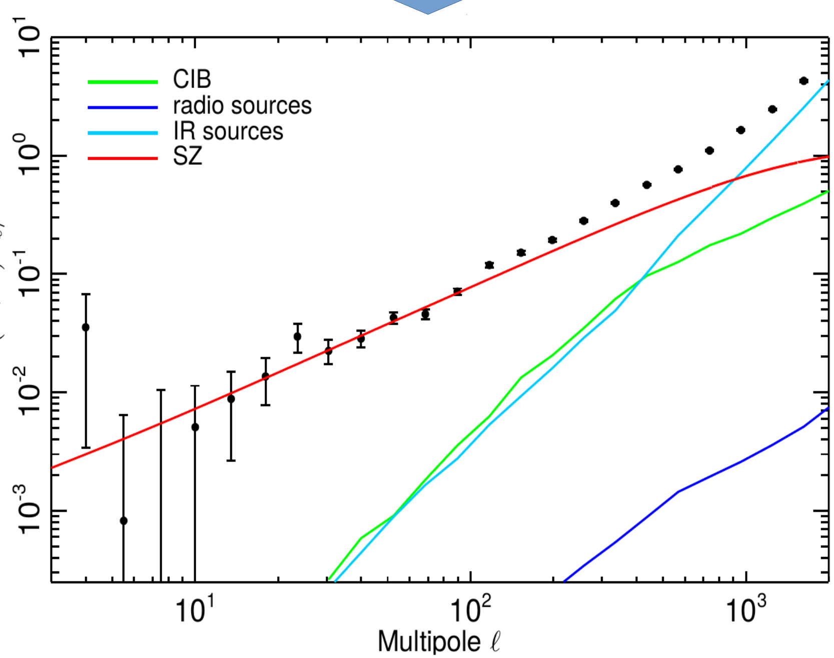


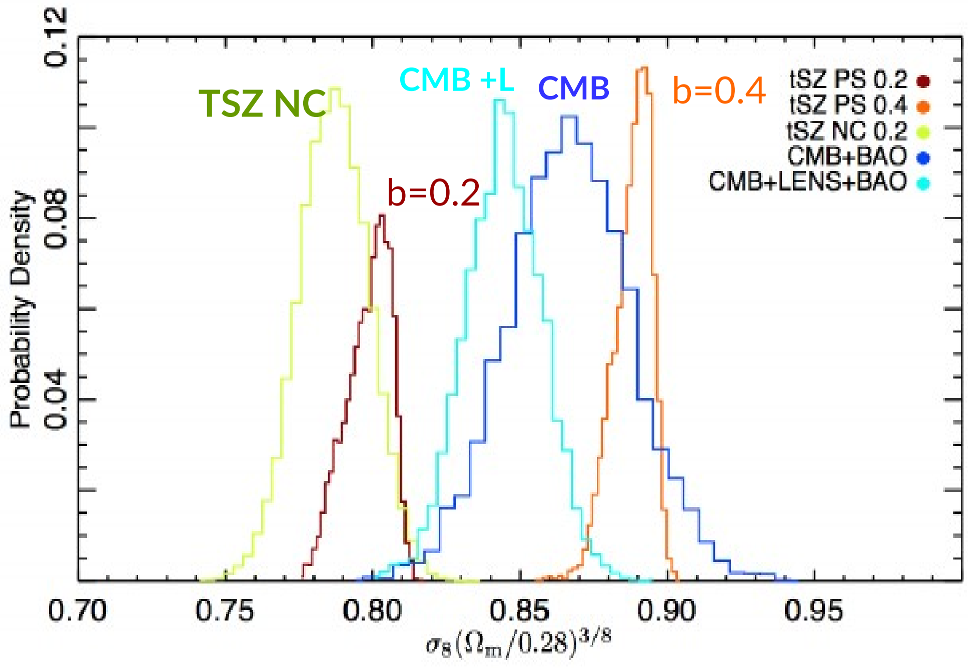


[Planck 2018 results: I]

tSZ power spectrum & high order statistics



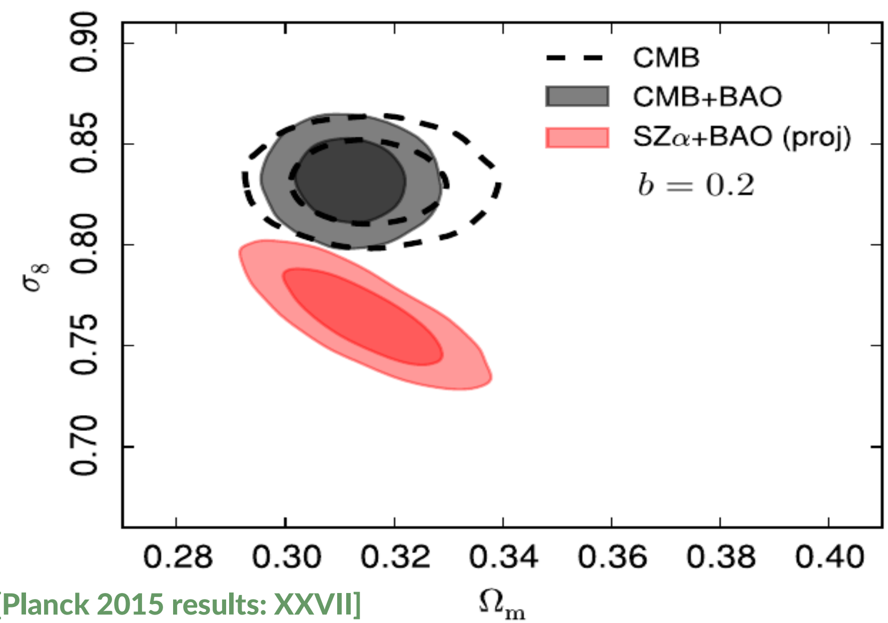




[Planck 2015 results: XXV]

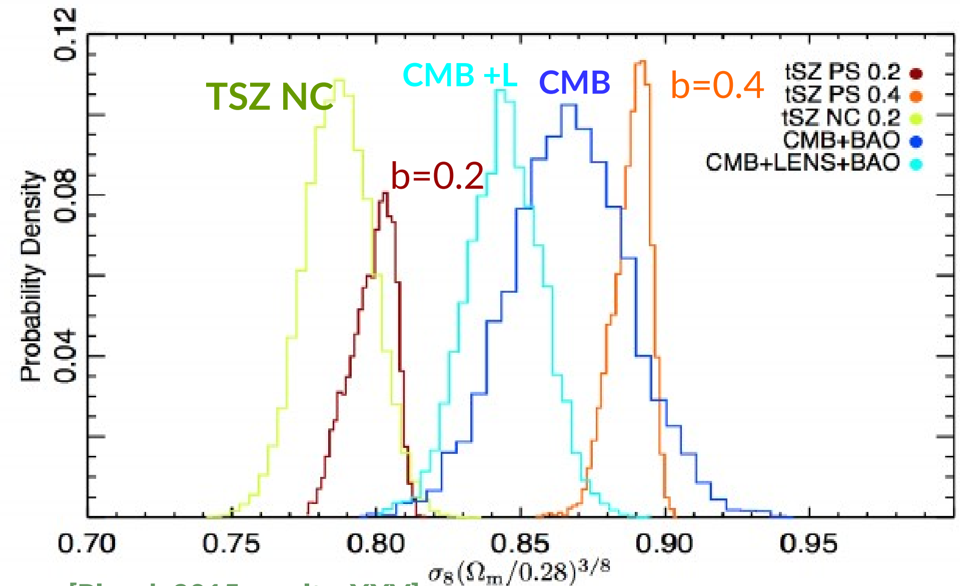
tSZ Planck cosmology summary

Cluster number counts



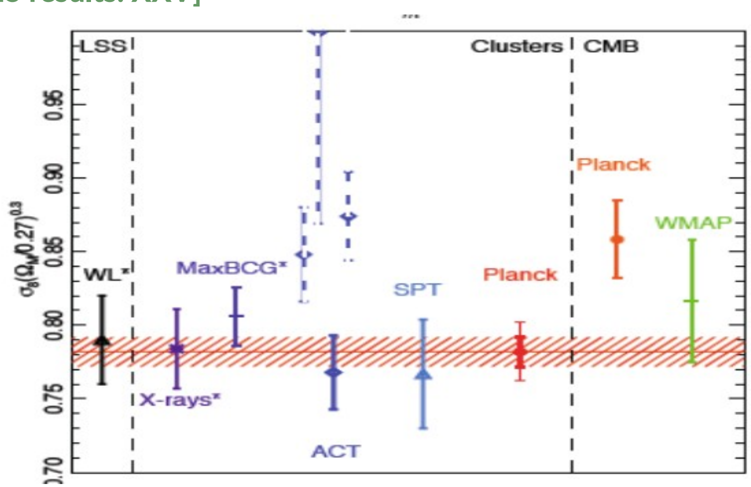
[Planck 2015 results: XXVII]

tSZ power spectrum

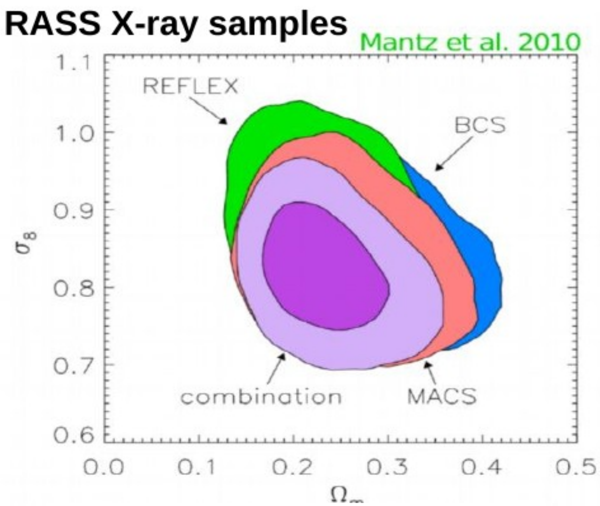


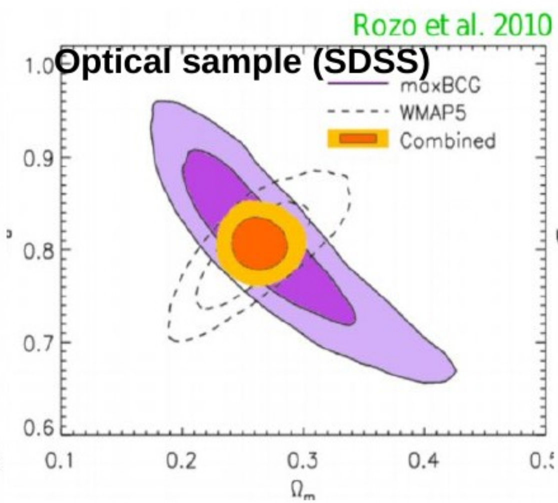
[Planck 2015 results: XXV]

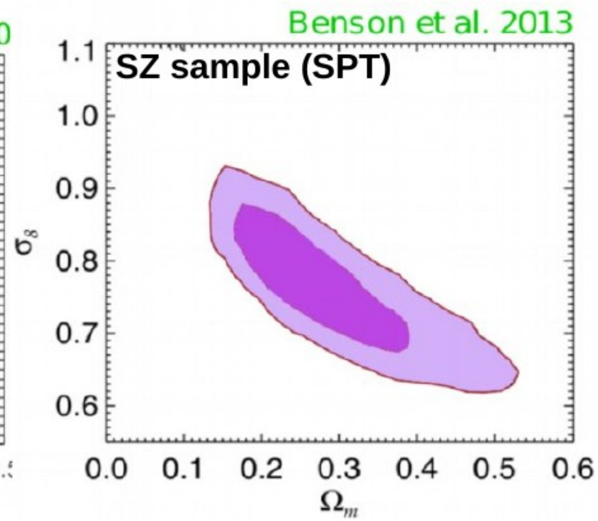
- 2-σ tension between CMB and tSZ derived cosmological parameters
- This is also true for other cluster observables
- Need to understand cluster physics: hydrostatic bias, condition for hydrostatic equilibrium, shocks in the ICM, non thermal pressure, …
- Need to cross check mass function definitions

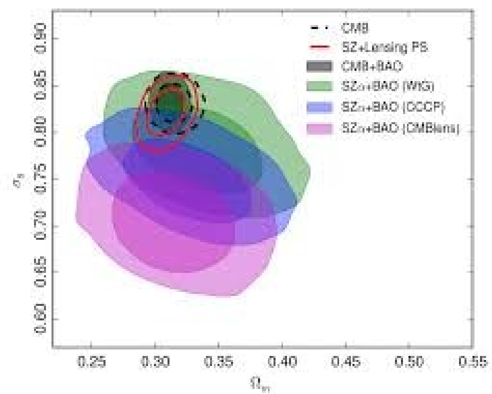


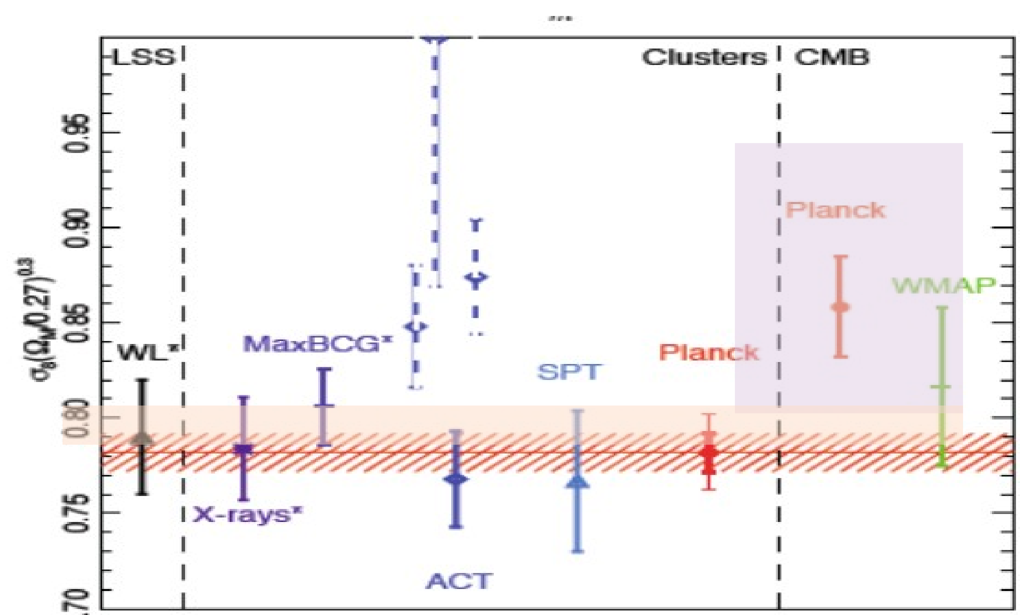
Multi-wavelength cluster cosmology











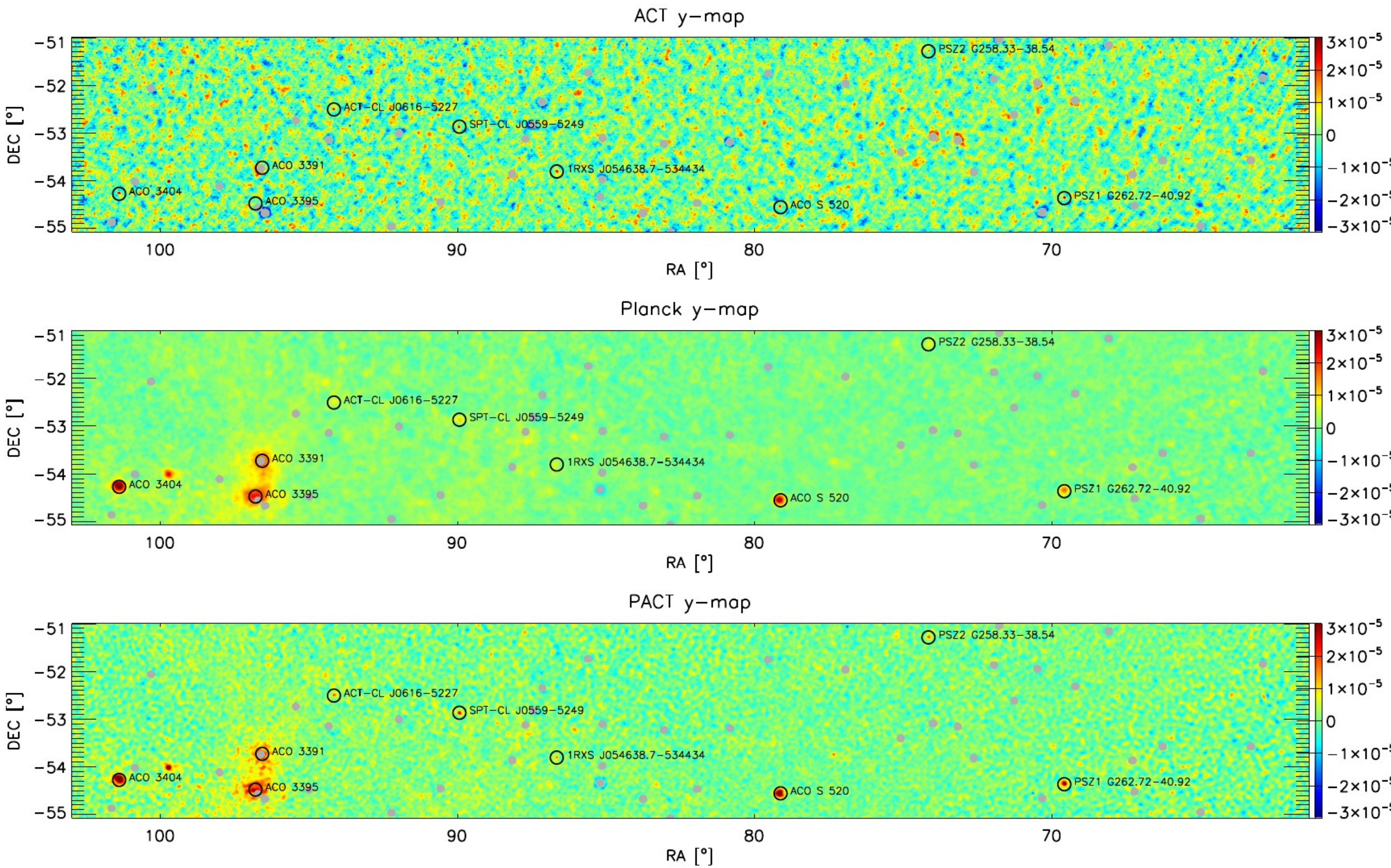
- Need to understand cluster physics: hydrostatic bias, condition for hydrostatic equilibrium, shocks in the ICM, non thermal pressure, …

Outline

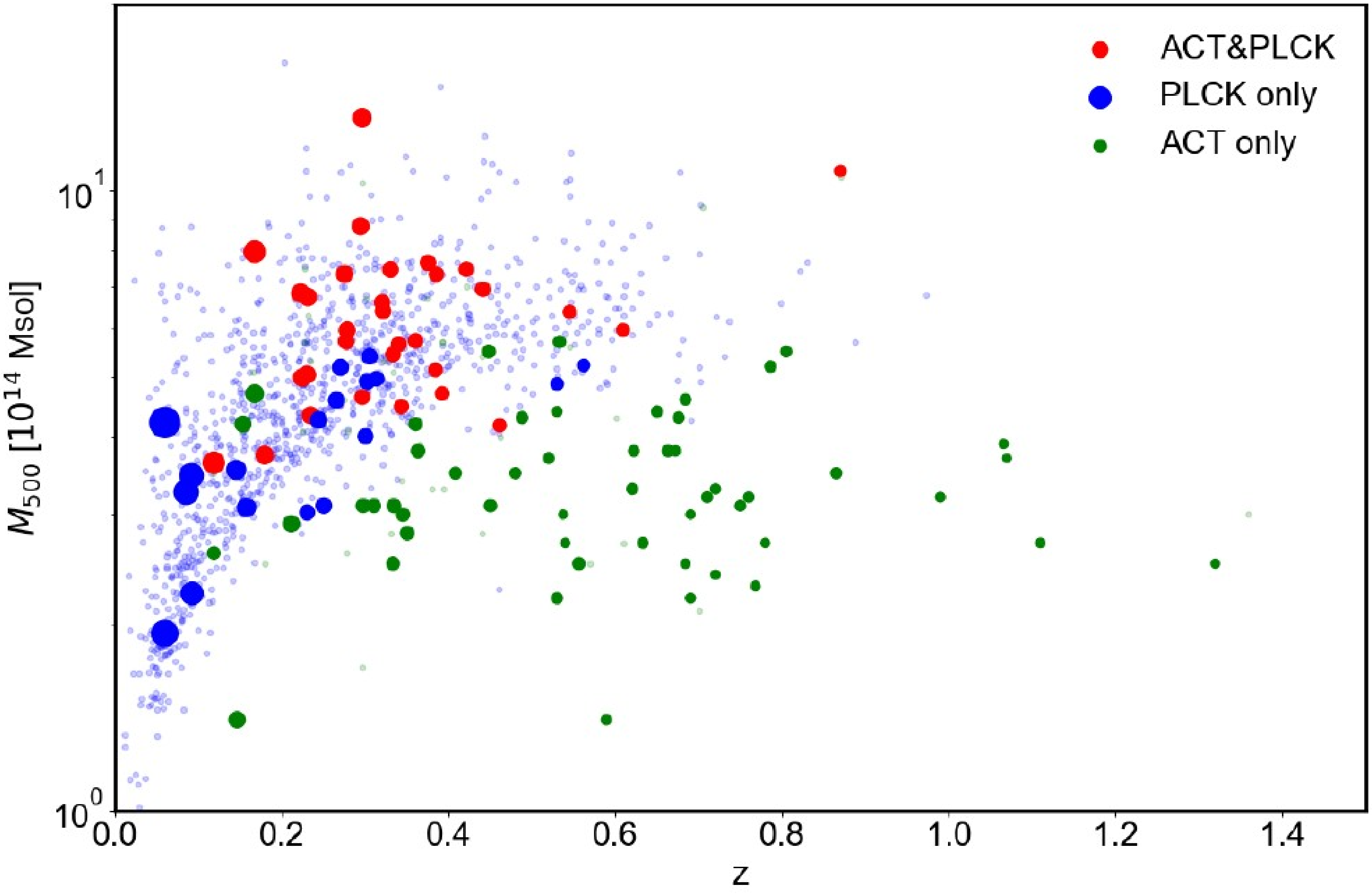
Conclusions

- Clusters of galaxies provide a cosmological probe of choice
- Large number of cluster observables can be used
- SZ effect opens a new window for the detection, study and cosmological use of clusters of galaxies
- Recent CMB experiments like Planck, ACT and SPT have released large catalogs of tSZ detected clusters making SZ cosmology possible
- SZ cluster cosmology, as for any other cluster observable, is in tension with CMB cosmology and seems to be limited by the knowledge of the mass-observable scaling relations
- Better understanding of cluster physics is needed to improve cosmology with clusters and eventually understand discrepancy with CMB cosmology
- Stay tune for more cluster cosmology in this conference: see Mayet, Ruppin, Bartalucci and Bolliet talks

PACT


ACT y−map
Planck y−map
PACT y−map
DEC [°]
RA [°]
ACT-CL J0616-5227
SPT-CL J0559-5249
ACO 3391
ACO 3404
ACO 3395
1RXS J054638.7-534434
ACO S 520
PSZ2 G258.33-38.54
PSZ1 G262.72-40.92

PACT


ACT&PLCK
PLCK only
ACT only
M_{500} [10^{14} Msol]
10^1
10^0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
z