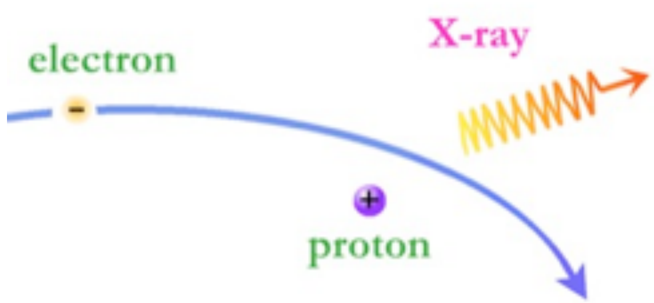
Physics of galaxy clusters from Sunyaev-Zeldovich observations

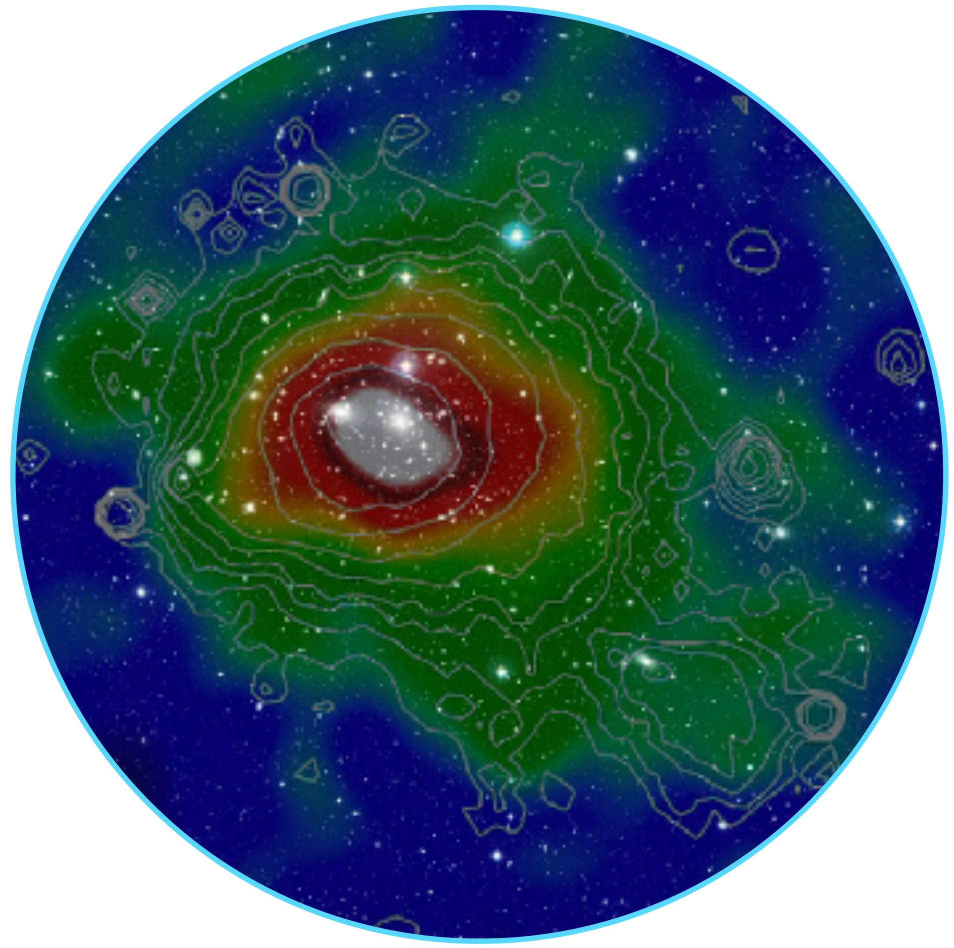
Etienne Pointecouteau

IRAP
(Toulouse, France)

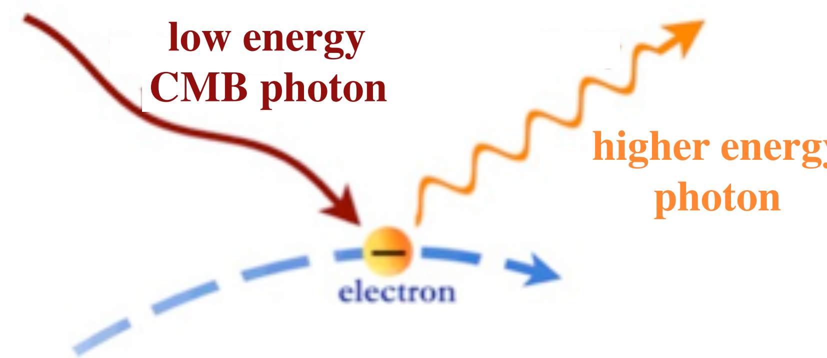
Intra-cluster gas emission

Bremsstrahlung





Inverse Compton scattering



$$E_X \propto \int_V n_e^2 \Lambda(T) dV$$

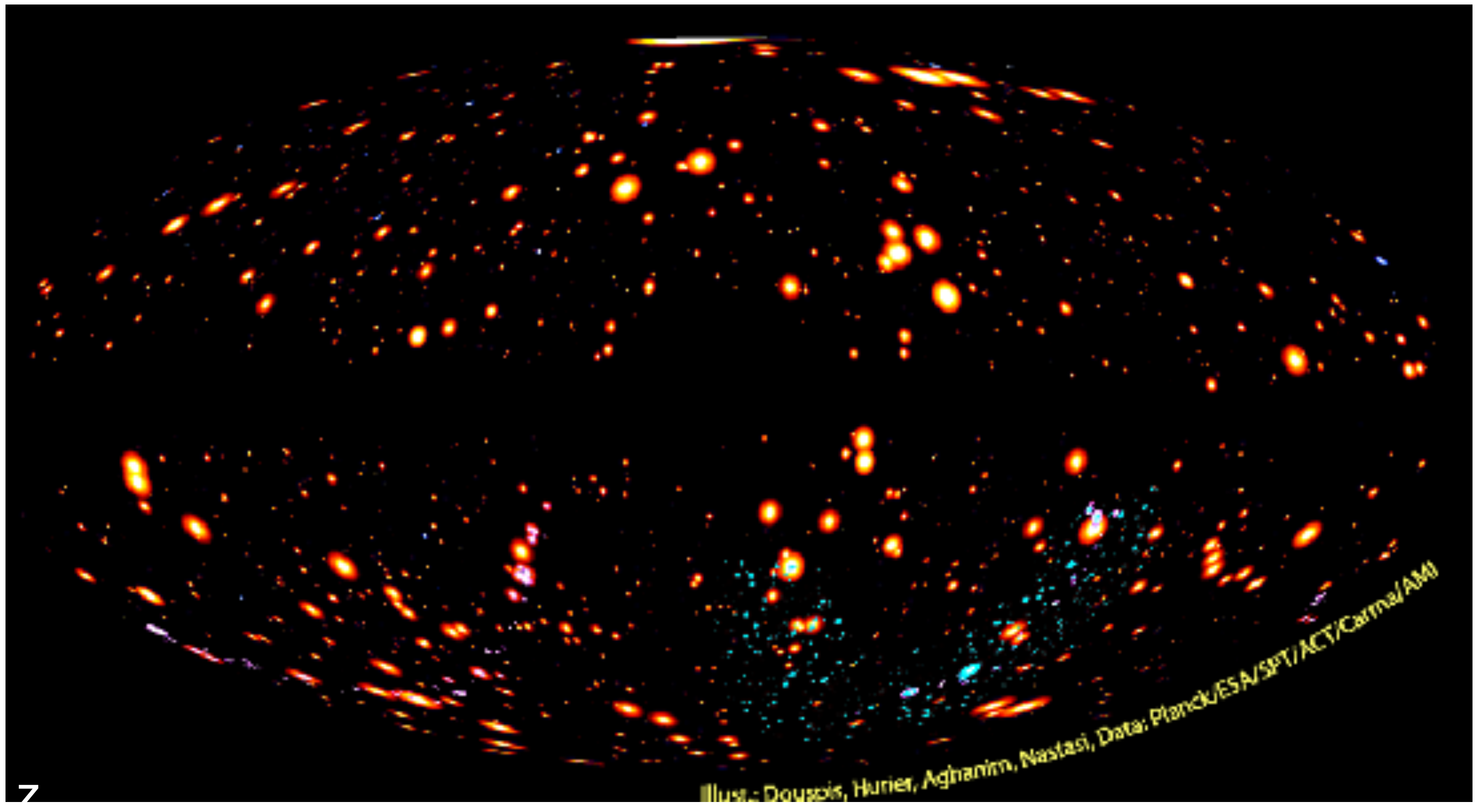
→ X-ray emission

$$F_\nu \propto \int_\Omega (P = n_e T) d\Omega$$

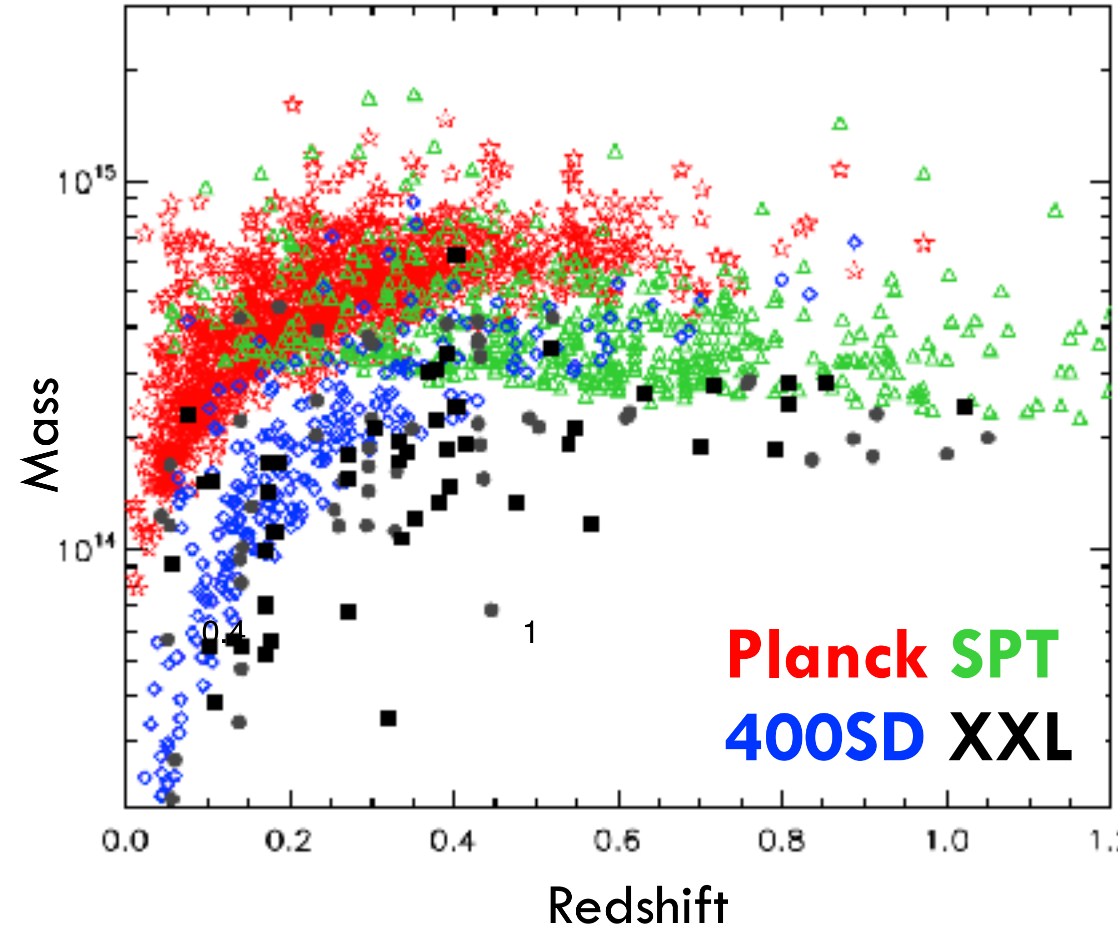
→ Sunyaev-Zeldovich effect

Two independent probes of the same physical component

SZ and X-ray surveys



(XXL — see Pacaud+16)

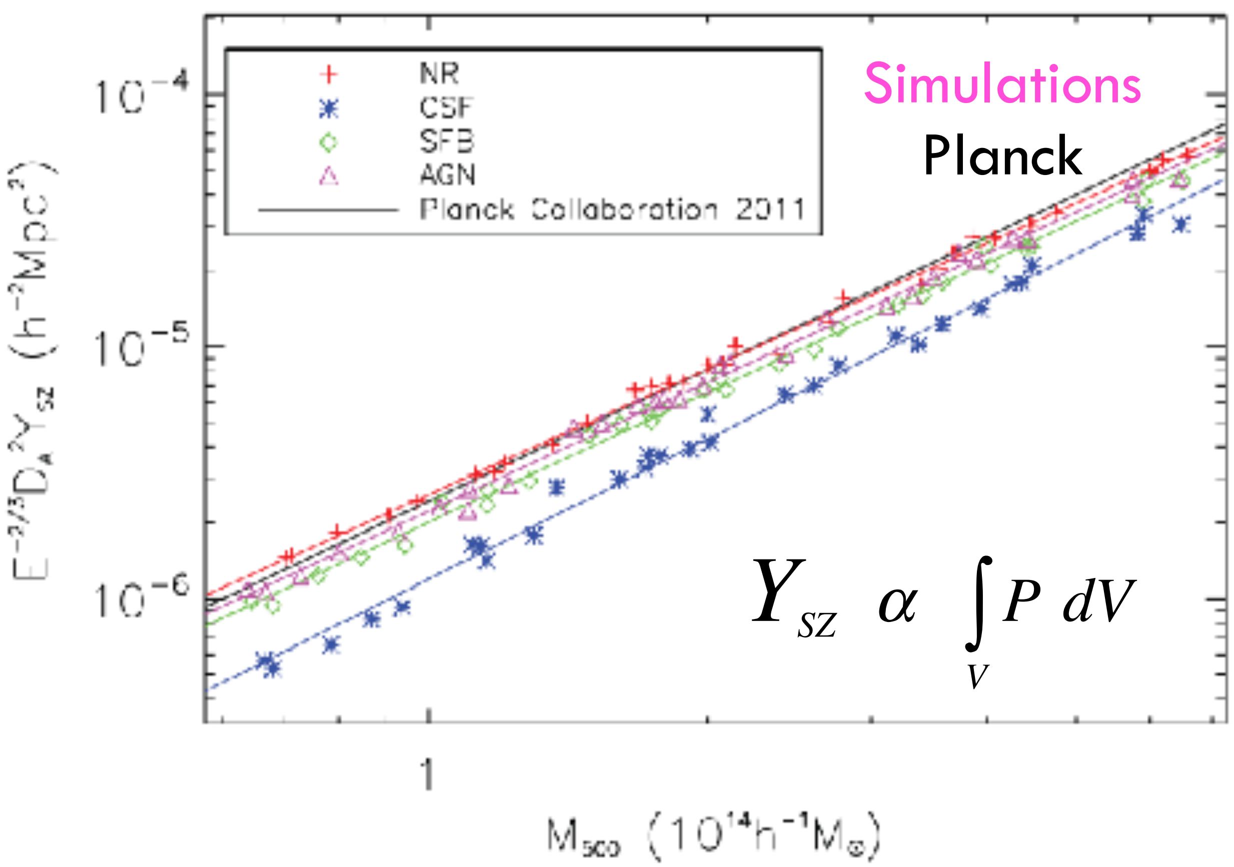


ACT	PLANCK	SPT
1,5’	4.5-10’	1.6’
91	1963	747
Hasselfield+13	Planck Coll.+11+13+15	Bleem+15

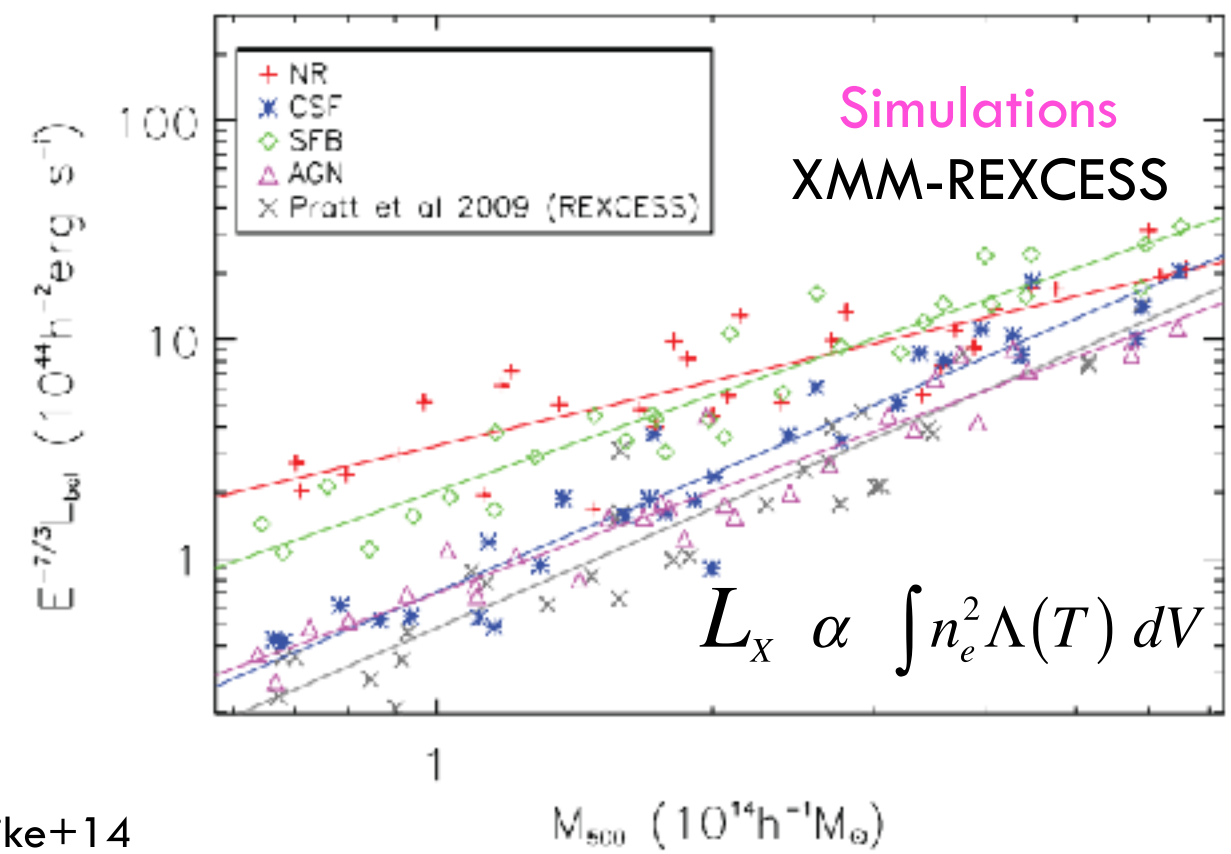
No redshift dimming for SZ
X-rays find lower mass halos

Mass limited surveys up to high z

Sample selection



Pike+14

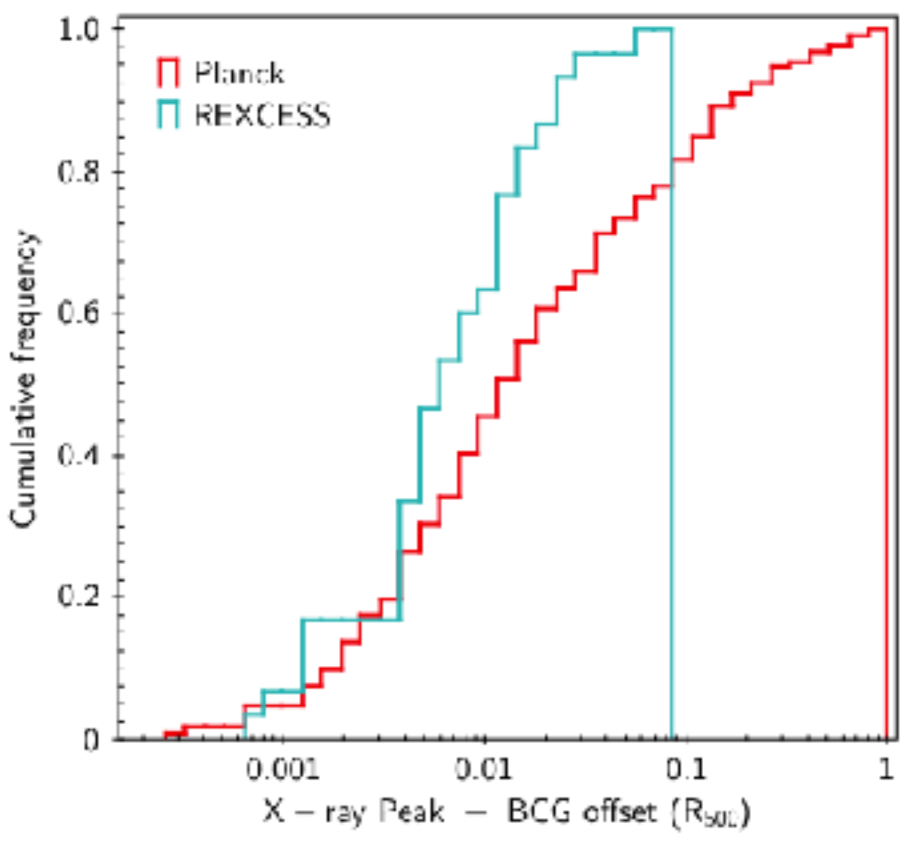


Weak dependence on non-grav. physics
Low scatter Y_{SZ} - M relation

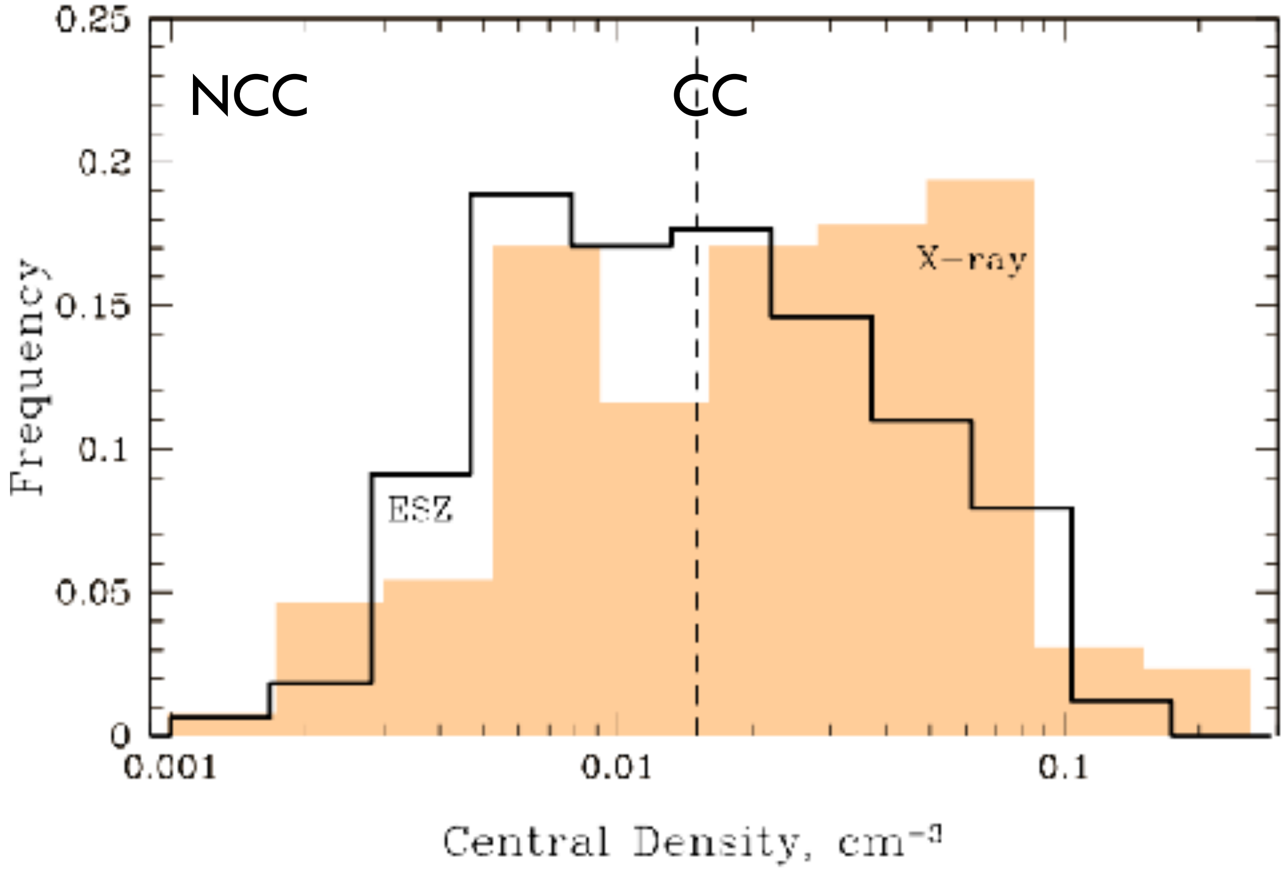
Strong dependence on non-grav. physics
High scatter L_X - M relation

Expected to be closer to (unbiased) mass selection

The cluster population



Rossetti+16



Andrade-Santos+17

Less CC clusters in *local* universe (over-represented in X-ray surveys)

More disturbed clusters

Close to mass selected, SZ catalogs up to z

⇒ **cluster formation and evolution**

⇒ **physics of the intra-cluster medium**

The SZ information

$$\frac{\Delta I_\nu}{I_0} = f(x, T_e)\, y_{tSZ} + f(x, v_z, T_e)\, y_{kSZ}$$

- Thermal SZ effect

$$y_{tSZ} = \frac{\sigma_T}{m_e c^2} \int P_e \, dl$$

Pressure

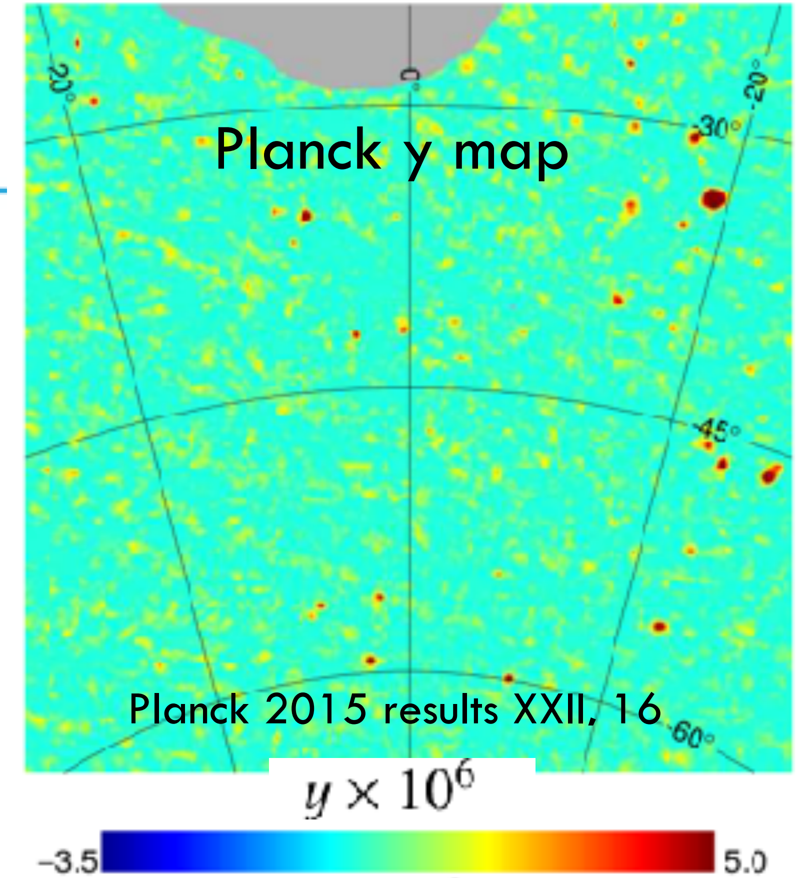
- Kinetic SZ effect

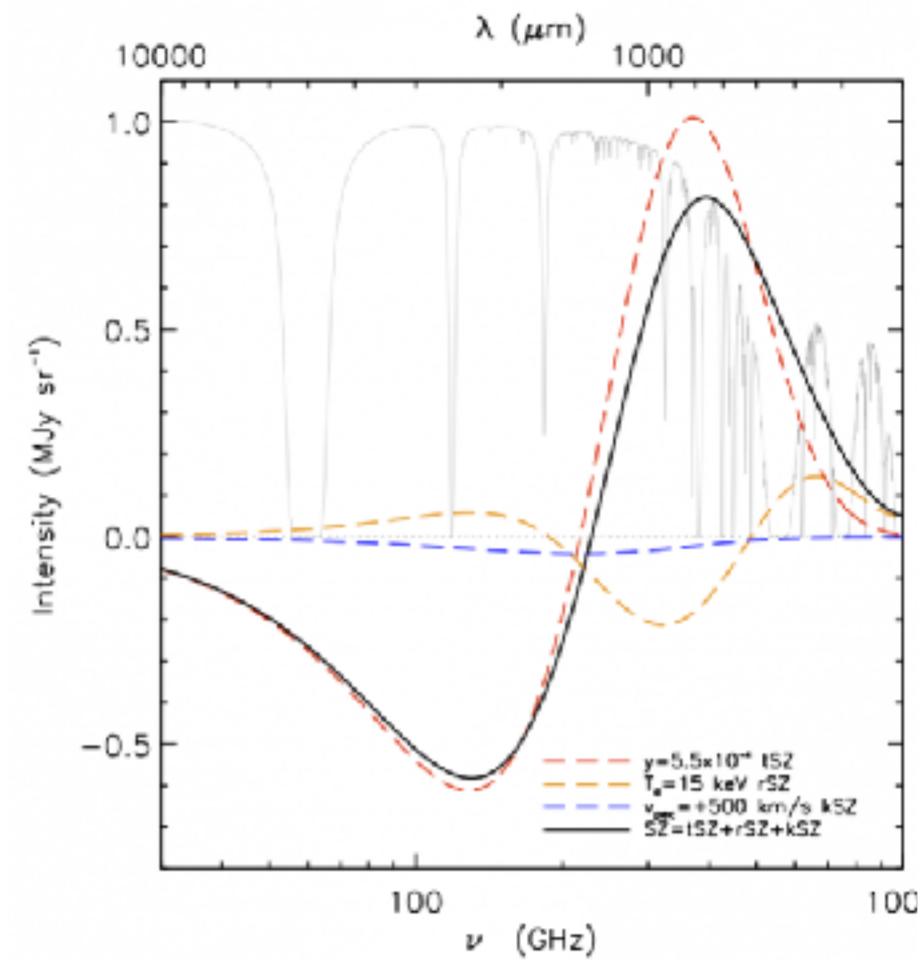
$$y_{kSZ} = \sigma_T \int -\frac{v_z}{c} n_e \, dl$$

Velocity

Reflect the state of the gas in the potential well

A probe of gravitational physics

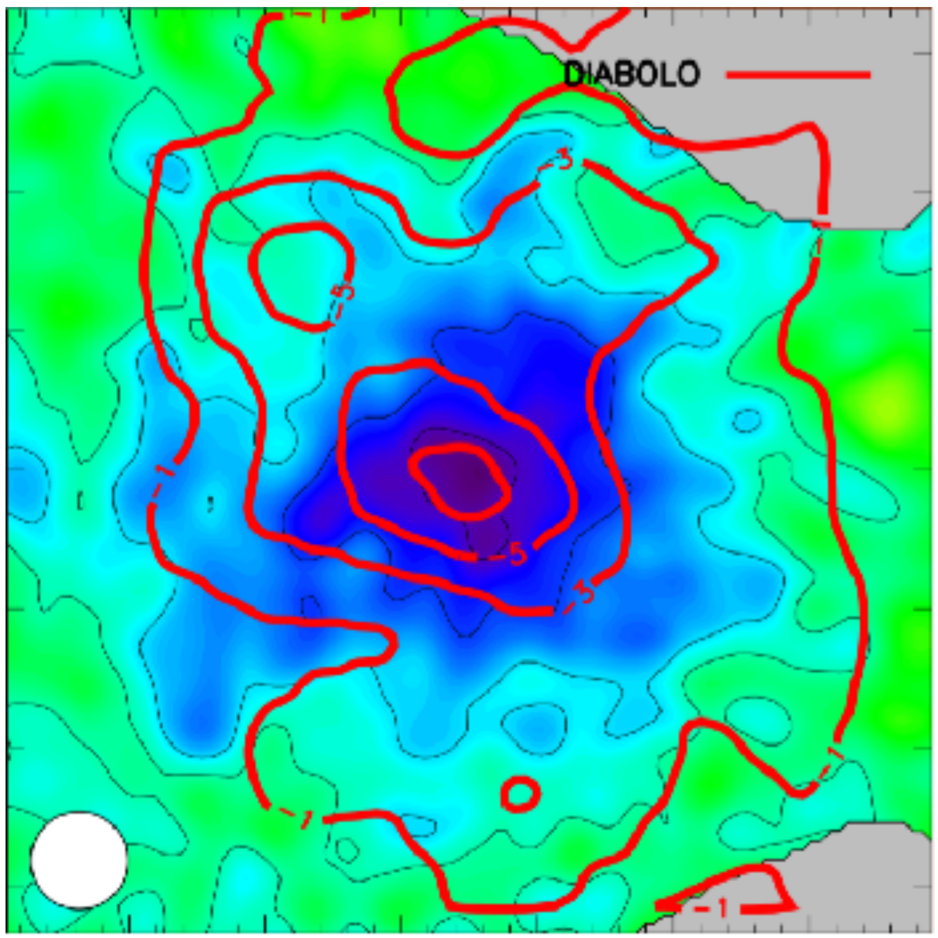




Imaging the SZ effect

The benchmark — RXJ1347-1145 (z=0.45)

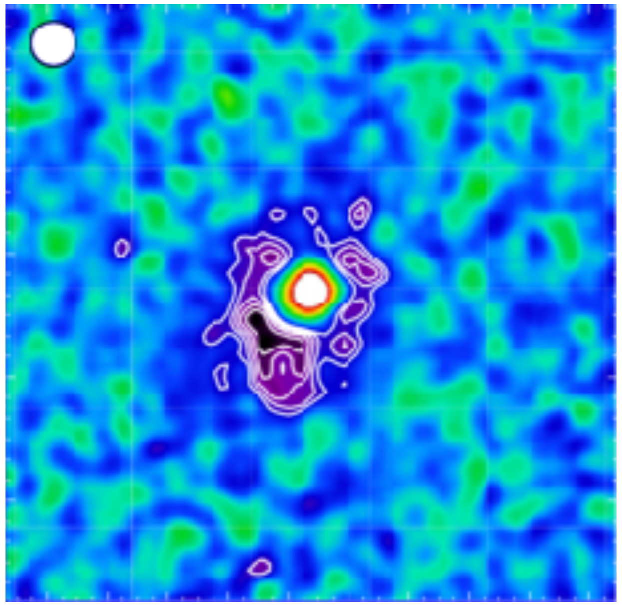
3.5 arcmin



Adam+2014

NIKA-1 @ IRAM 30m
150 GHz, 18" FWHM

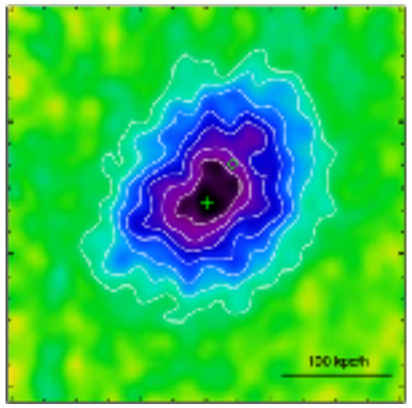
2.3 arcmin



Mason+10, Korngut+11

MUSTANG-1 @ GBT 100m
90 GHz, 9" FWHM

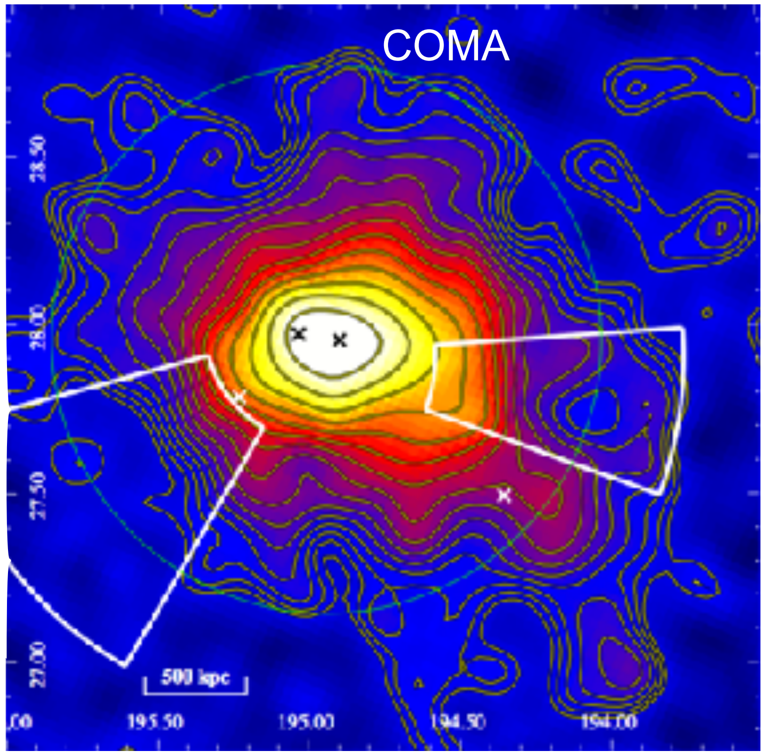
1.5 arcmin



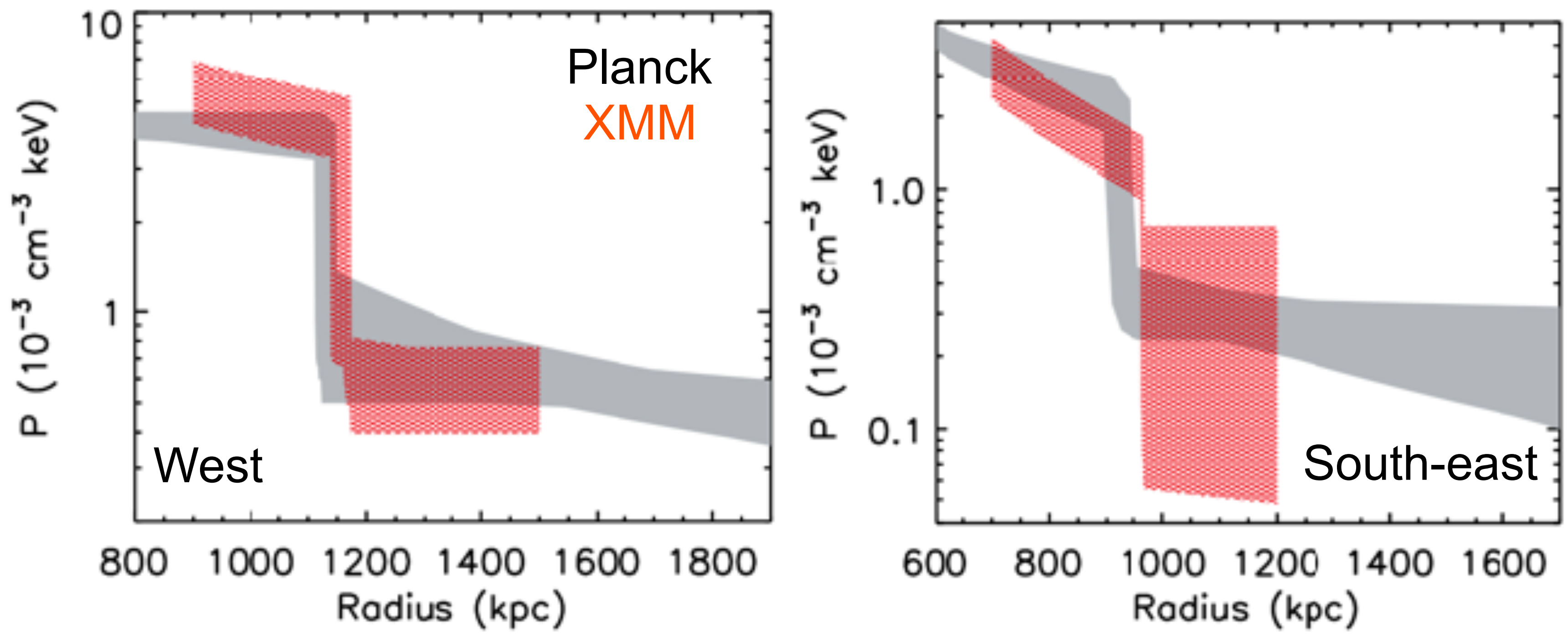
Kitayama+16

ALMA
90 GHz, 5" FWHM

Physics of merging clusters: shocks



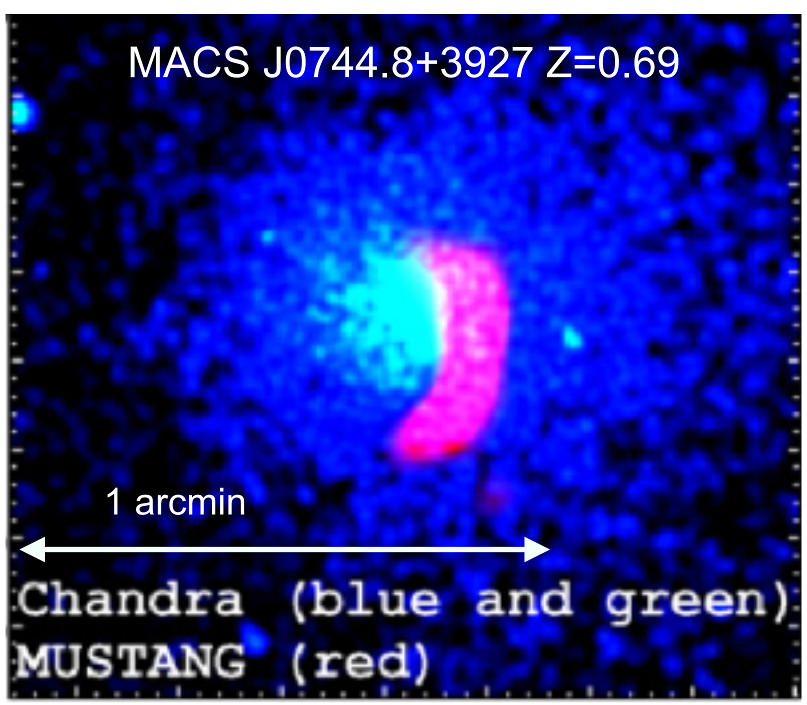
Planck Int. Result X, 2013



Mach number:

M_W = 2.03 [+0.09,−0.04]

M_{SE} = 2.05 [+0.25,-0.02]



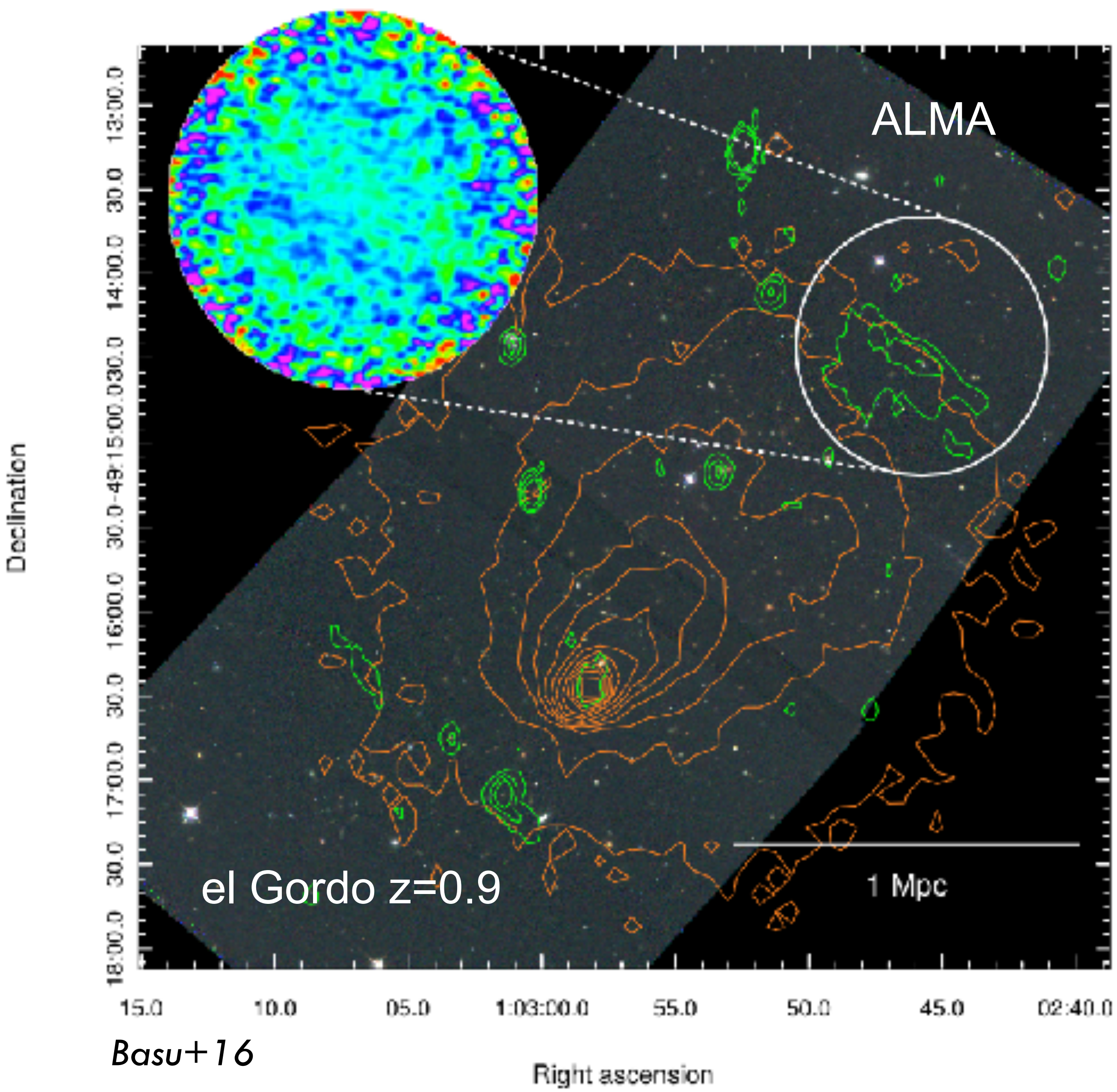
Korngut+11

Direct access to the gas pressure

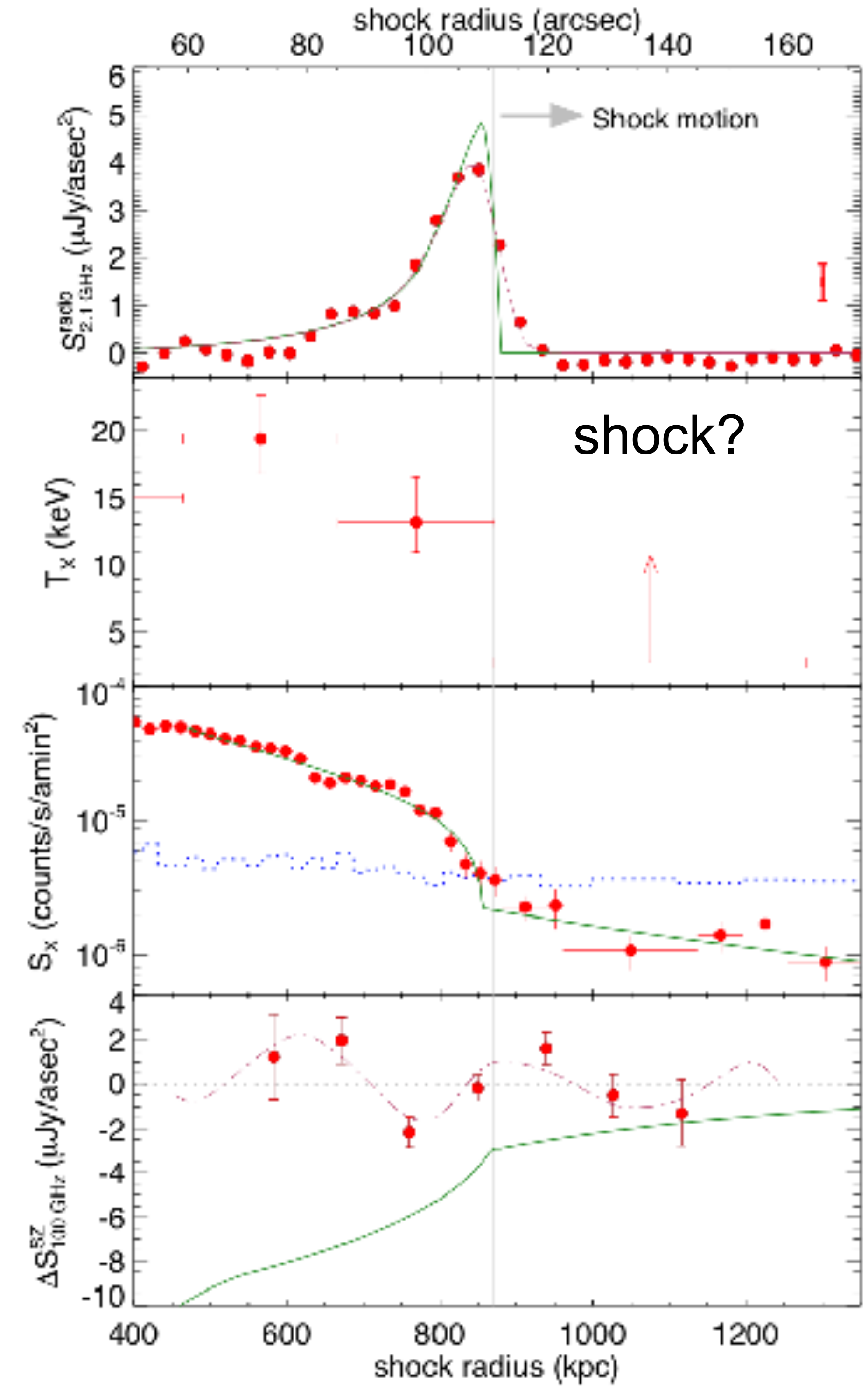
Better evidence of shocks

irap

Physics of merging clusters: radio relics

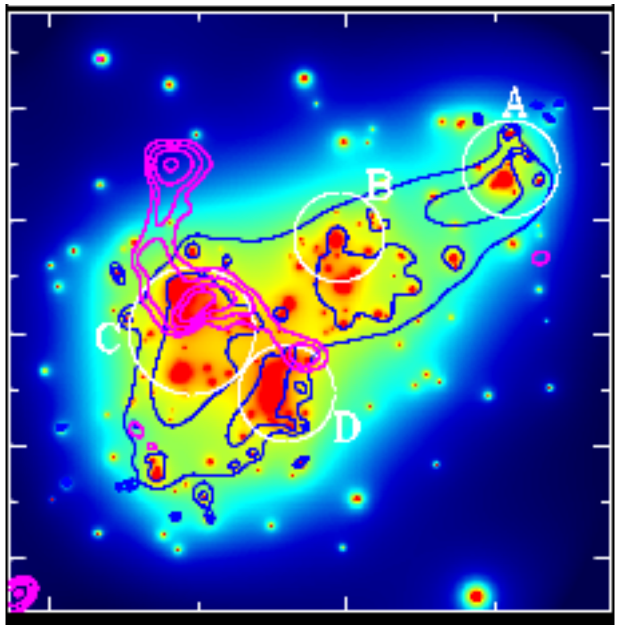


Basu+16

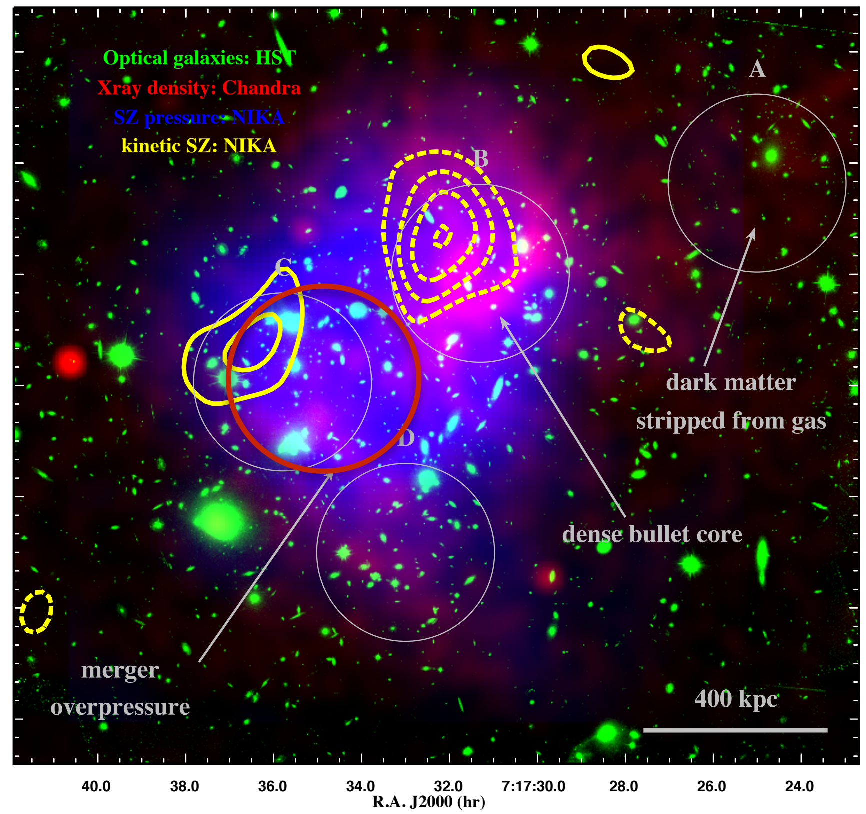


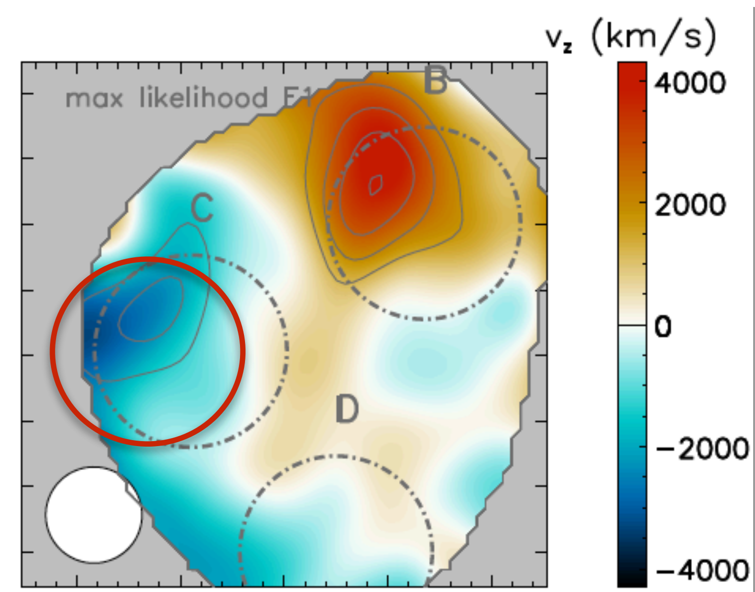
Unambiguous detection of P jump with radio ⇒ magnetic field

Physics of merging clusters: gas motion



Mroczkowski+2012





Adam+2016

MACS J0717.5+3745 at z=0.55

A triple merger system with a complex dynamics

$$\frac{\Delta I_\nu}{I_0} = f(x,T_e)\, y_{tSZ} + g(x,v_z,T_e)\,\sigma_T \int -\frac{v_z}{c}\, n_e \, dl$$

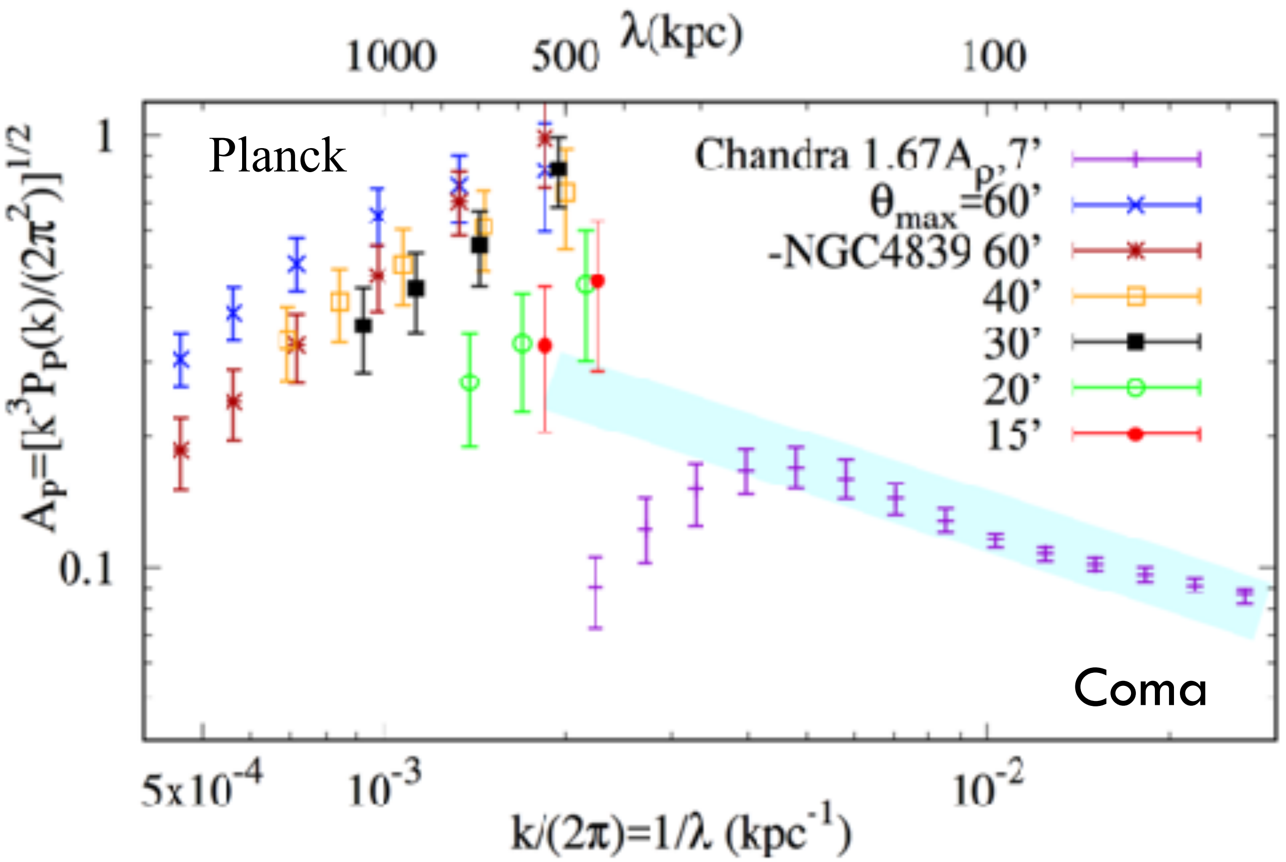
First detection by Bolocam (Sayers+2013)

First imaging by NIKA (Adam+16)

Separate kSZ and tSZ with 2 bands

To be combined with X-ray (density)

Turbulence of the gas



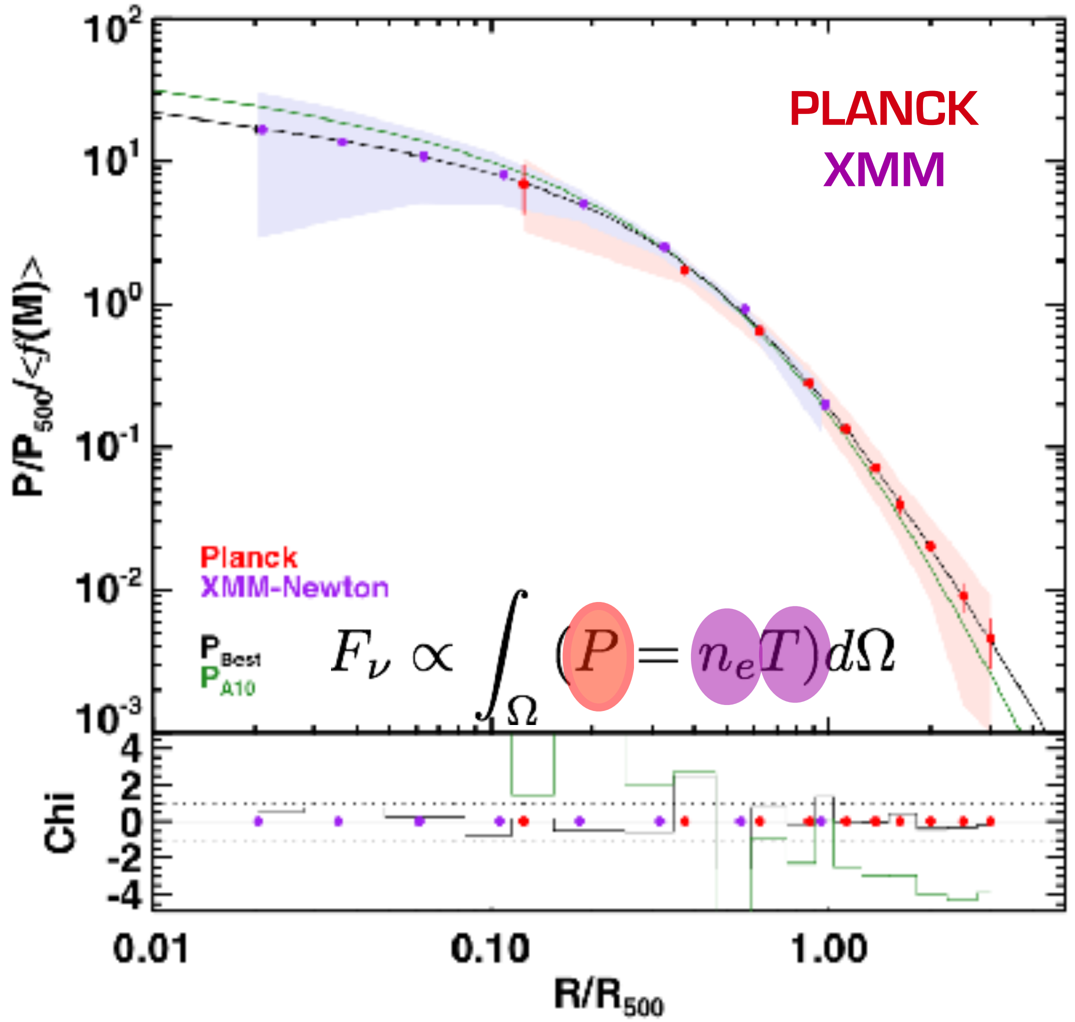
Khatri & Gaspari, 17

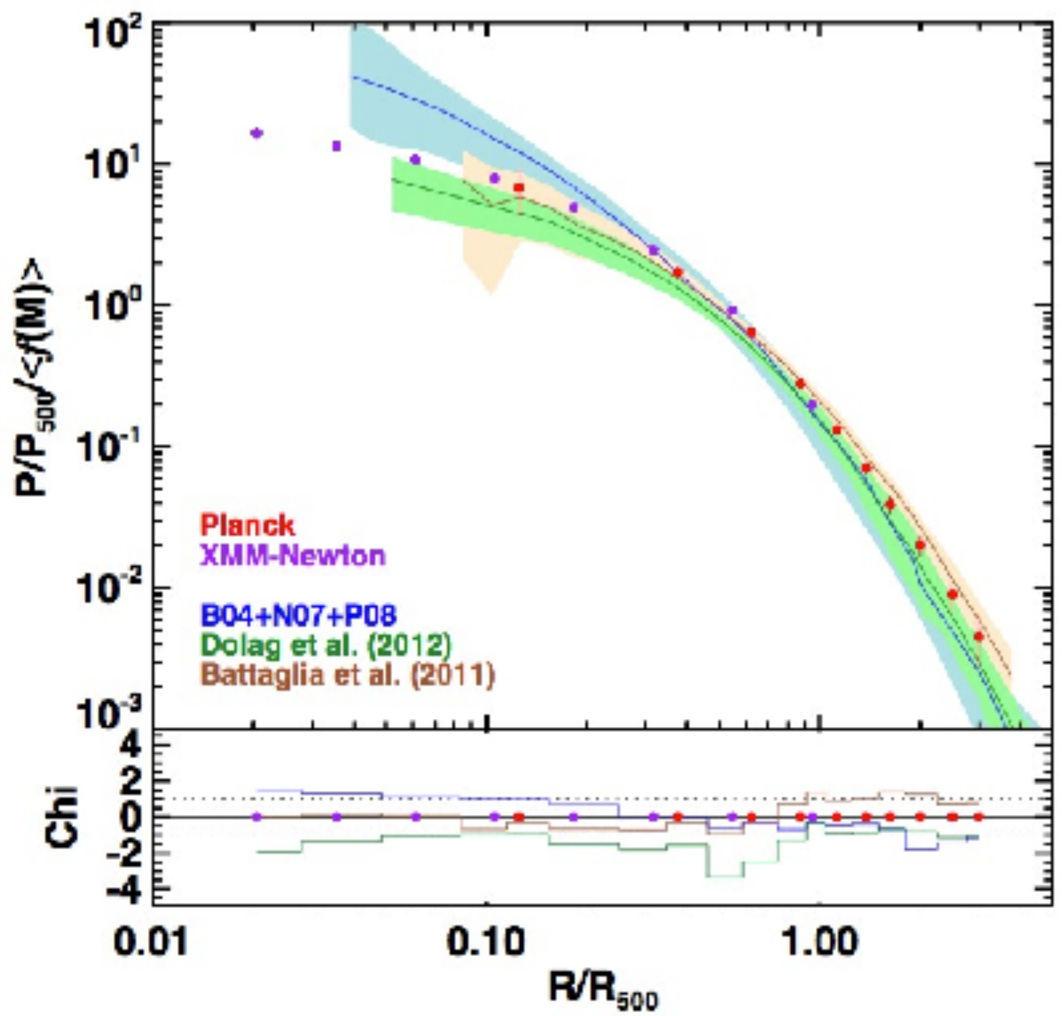
- Constrains on the turbulence power spectrum; peak at ~500 kpc scale
- Favour adiabatic mode (sound waves)
- Eturb/Eth ~ 0.34

From small scales X-ray fluctuations to large scales

Dissipation of energy through bulk motions and turbulent flows
Implication for thermalisation physics and Mass estimate

Pressure of the gas



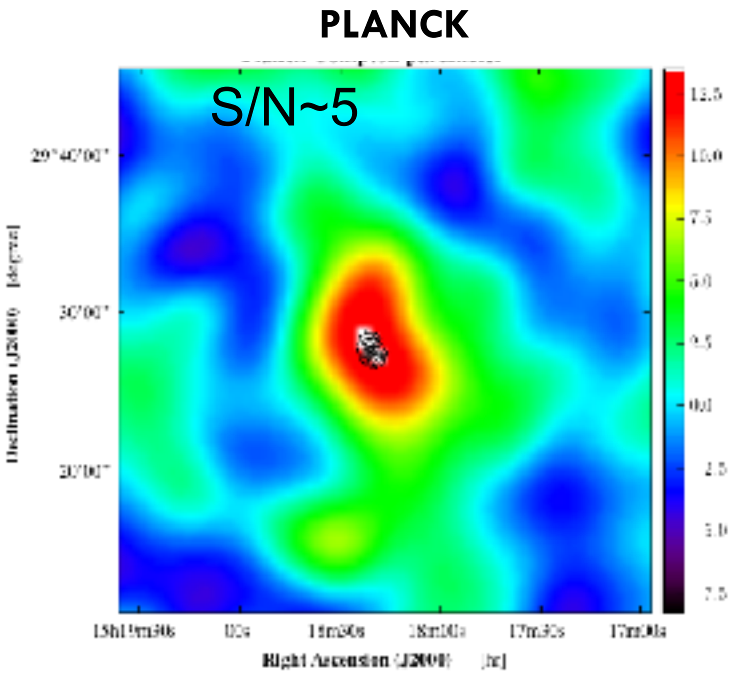


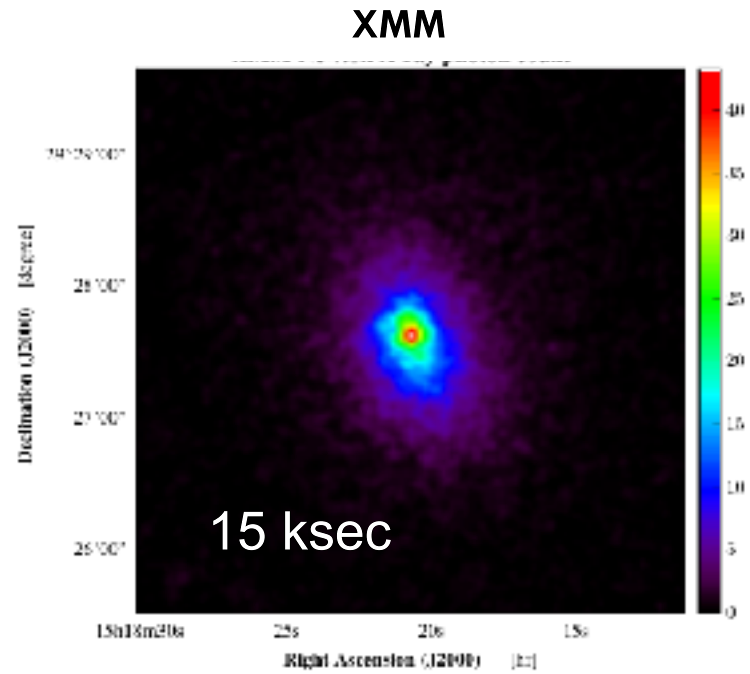
Planck Coll. 2013, Planck Int V

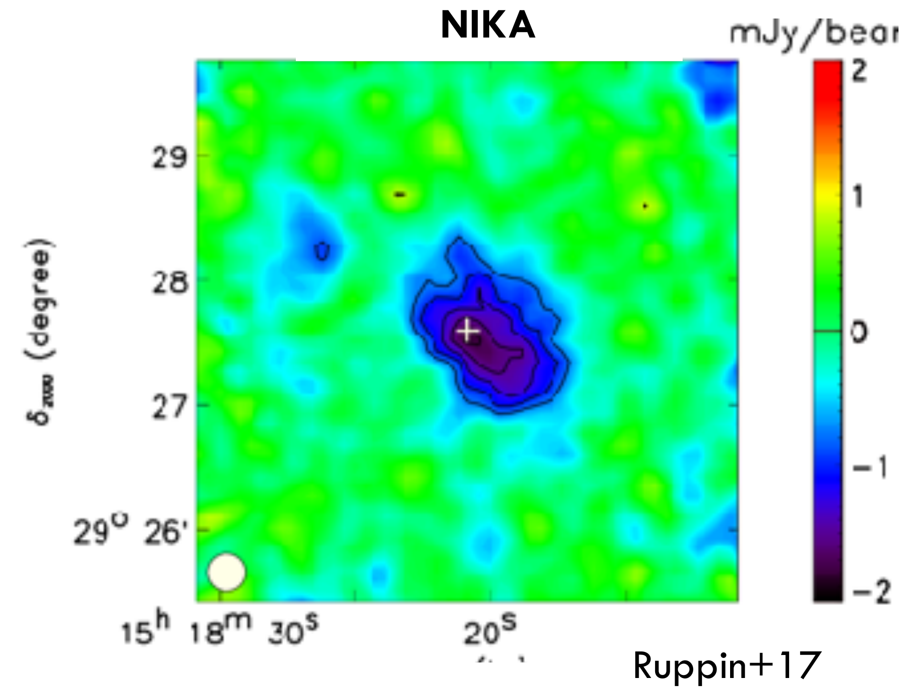
Profile from 0.02 to 3 R_{500} from X-ray +SZ

Probing the gas physics in the clusters' outskirts

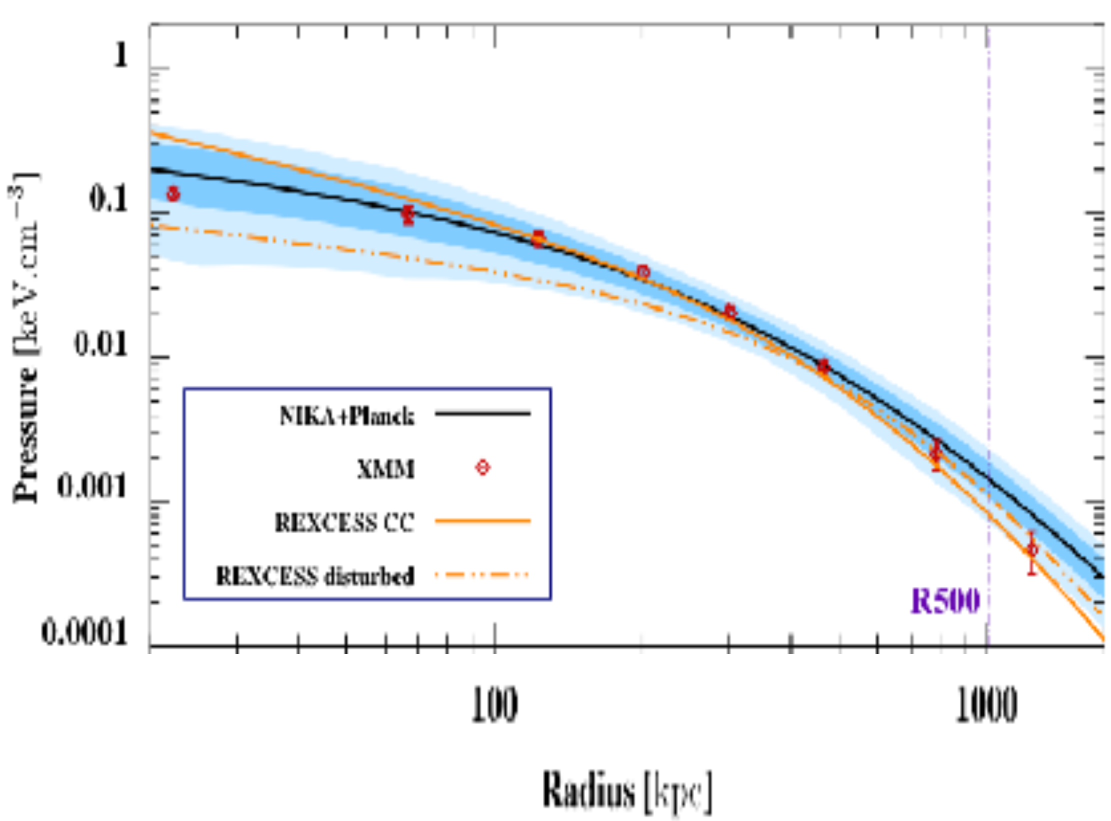
Pressure of the gas







Ruppin+17



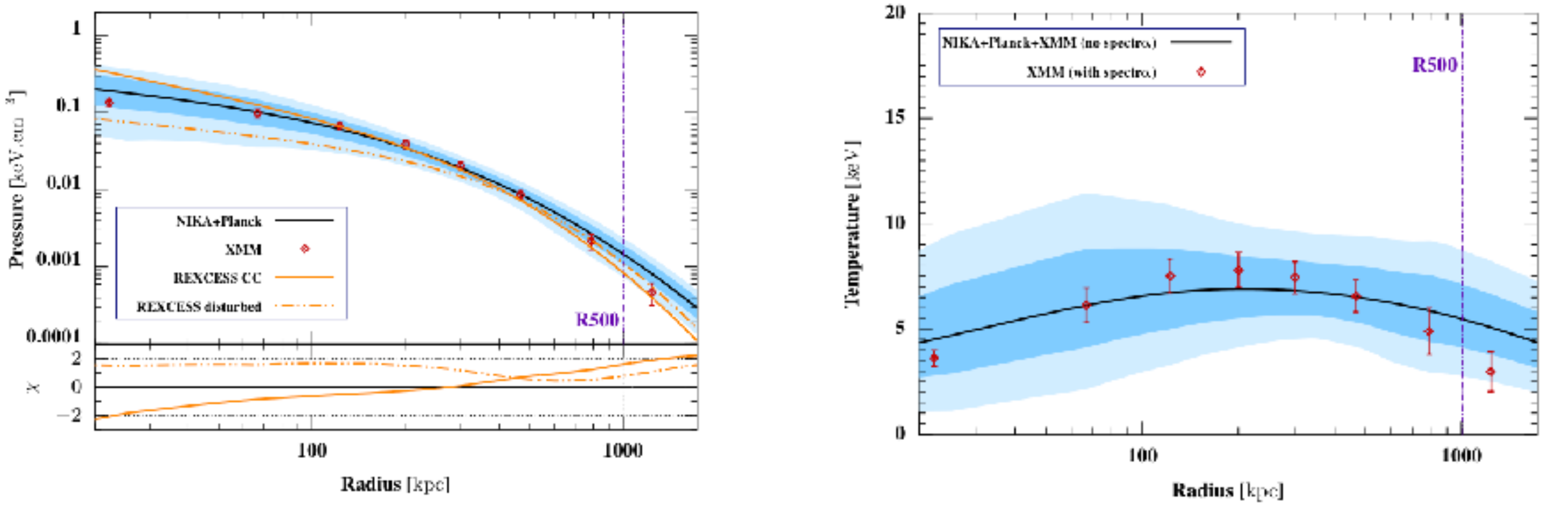
Ruppin+17

PSZ1 G045.85+57.71 z= 0.61

- Less steep radial decrease of SZ signal
- SZ imaging versus X-ray spectroscopy

SZ now competitive with X-ray

Joint X-ray and SZ profiles



Ruppin+17

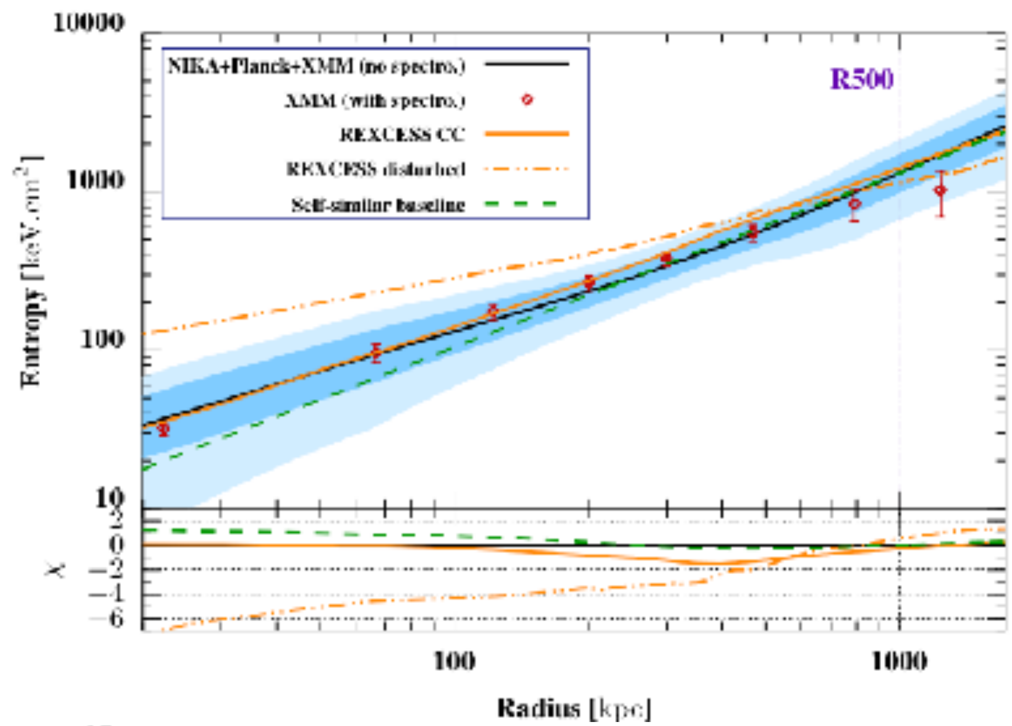
$$y_{tSZ} \equiv f(T_e)\int P_e \, dl \qquad\qquad P_e(r) \qquad\qquad T_{mw} \text{ and } n_e(r)$$

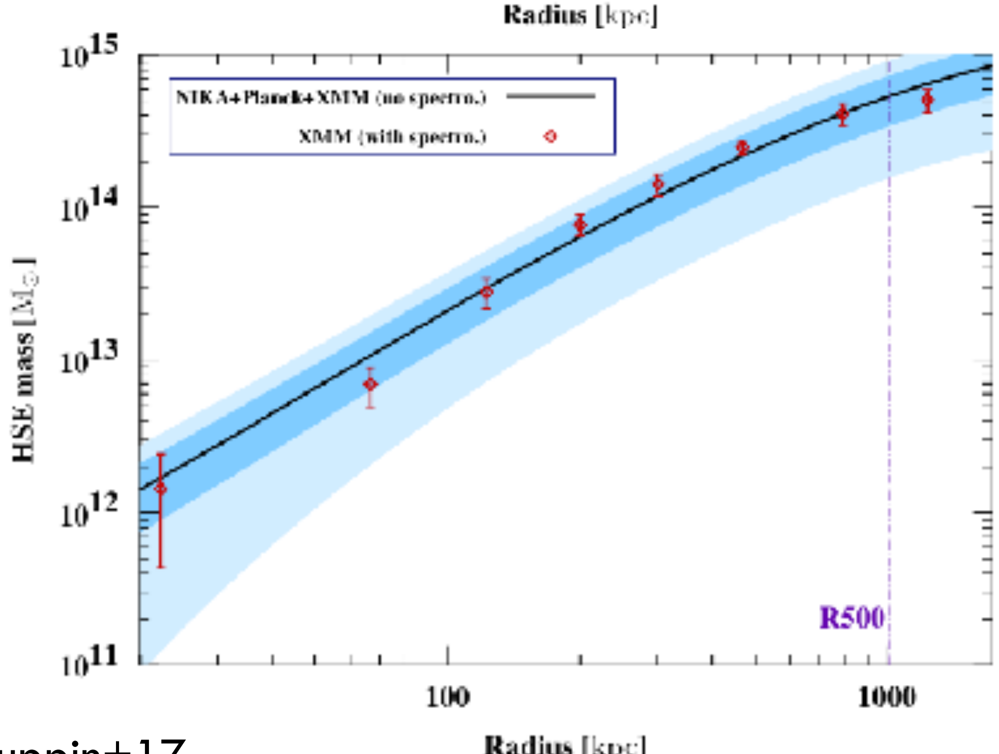
deprojection

$$S_X \equiv \int n_e^2 \Lambda(T_e)\, dl \qquad\qquad n_e^2(r) \qquad\qquad Q = \langle n_e^2 \rangle / \langle n_e \rangle^2$$

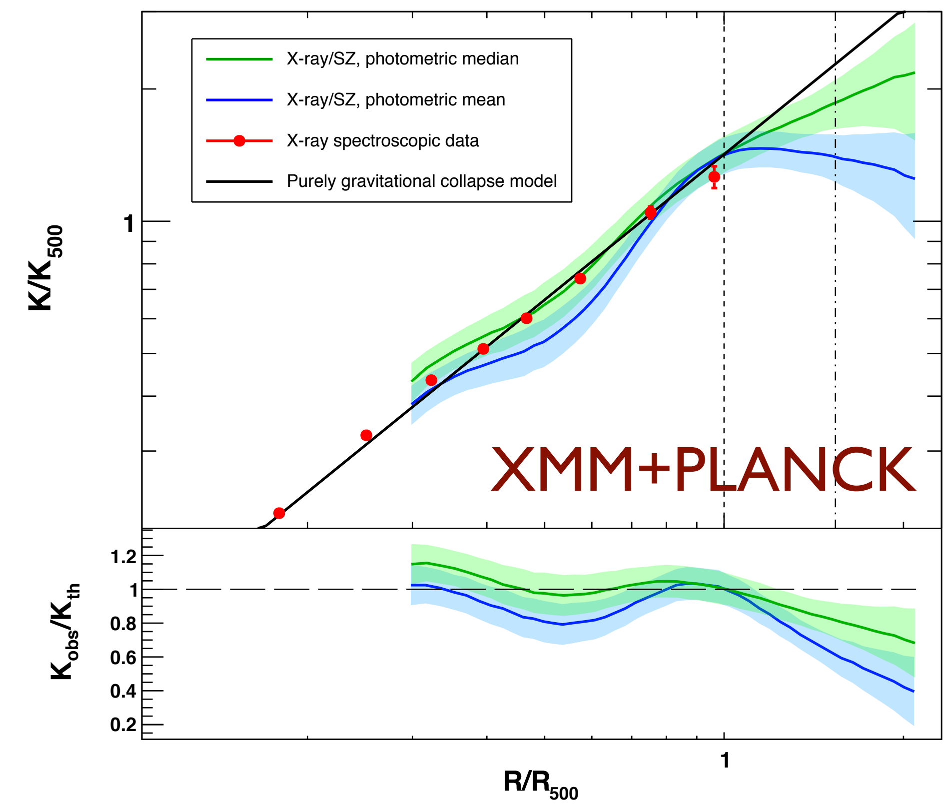
- Require X-rays and SZ with similar spatial resolution
- Direct probe of T_{mw}
- Comparison with T_X: clumpiness, ellipticity, T_{sl} effects

Joint X-ray and SZ profiles





Ruppin+17



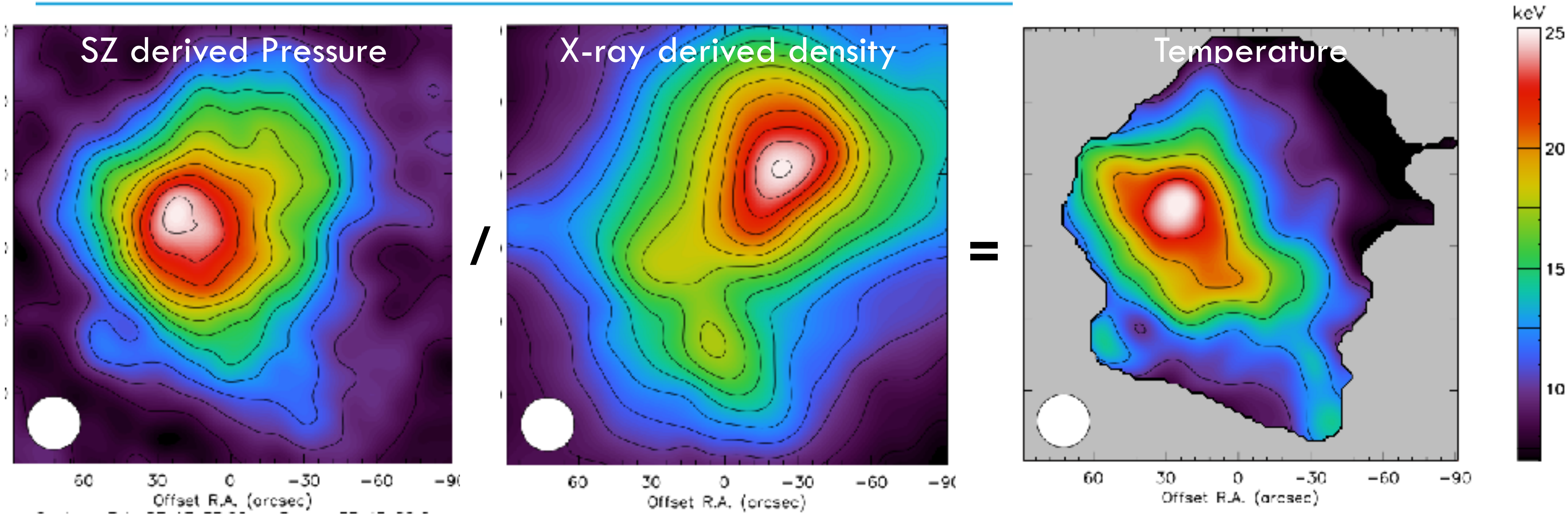
Tchernin+16

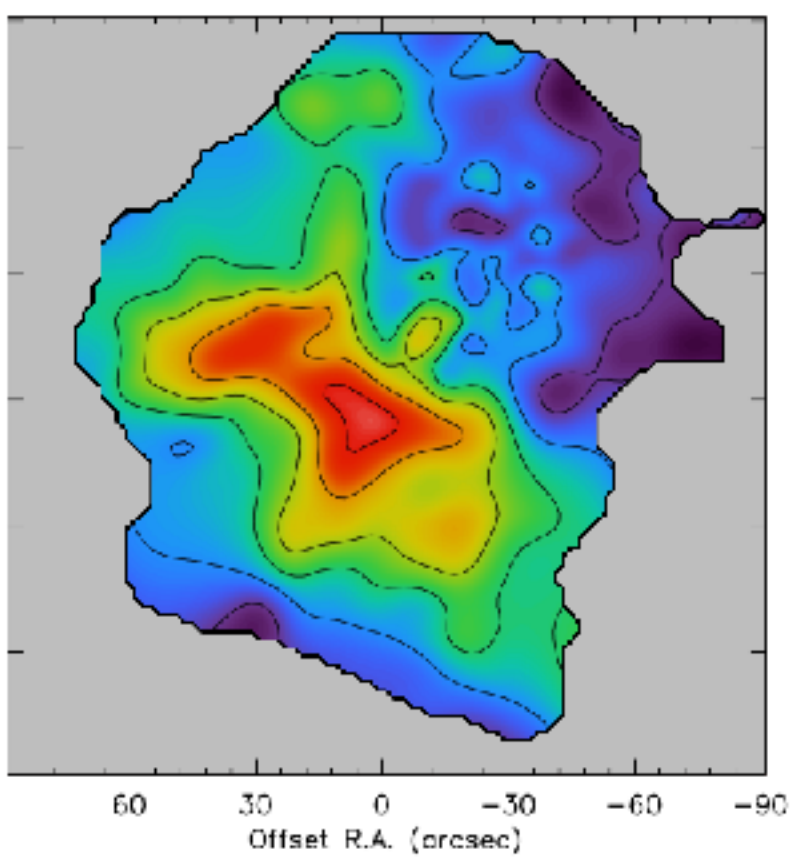
Entropy follows gravitational model

Probe of accretion physics
in outskirts

[Cheaper] thermodynamical profiles at high z

Joint X-ray and SZ imaging





Adam+17, subm.

MACS J0717.5+3745 at z=0.55

$$T_{gmw} \equiv \frac{y_{tSZ}}{\sqrt{S_X l_{eff}}} \qquad l_{eff} = \frac{\left(\int n_e \, dl\right)^2}{\int n_e^2 \, dl}$$

First kT map from SZ and X-ray imaging

Take home messages

- The SZ effect reflect the physical state of the hot gas and is a good probe of gravitational physics (shock, turbulence,…)
  - direct measurement of the gas pressure and (with enough sensitivity) of the gas velocity (also expected from X-ray line shift in a near future)

- As compared to X-ray
  - Better mass proxy → unbiased catalogs
  - No z dimming → high z clusters
  - Proportional to n_e (rather than n_e^2) → outskirts

- Joint X-ray/SZ imaging
  - Cheaper than X-ray spectroscopy at high z and high radii
  - Probe of T_{mw}

- Excellent match between the new generation SZ telescope and XMM/Chandra