The Sunyaev-Zeldovich effect

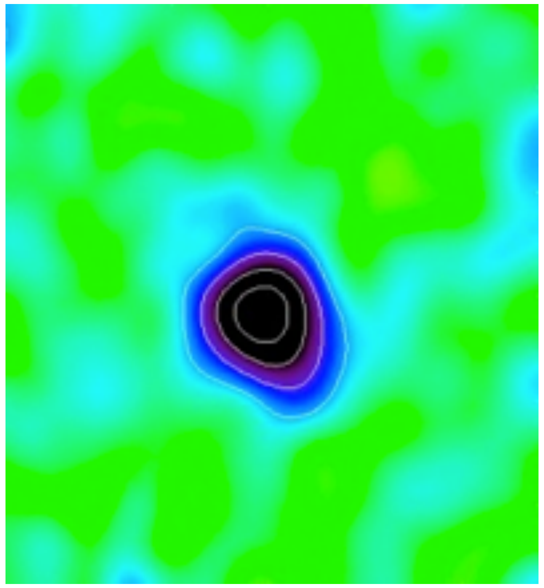
Etienne Pointecouteau

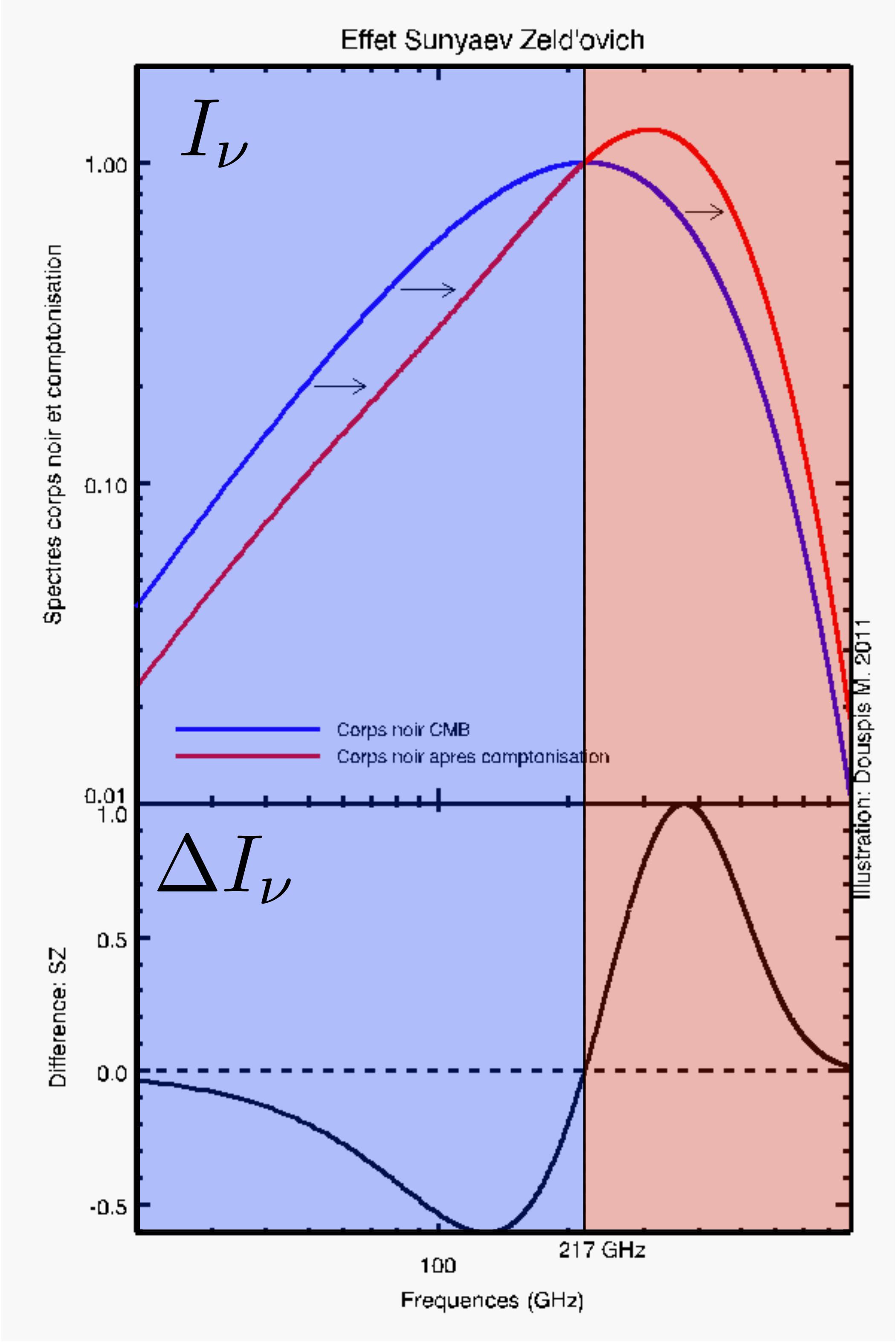
IRAP
(Toulouse, France)

The SZ effect

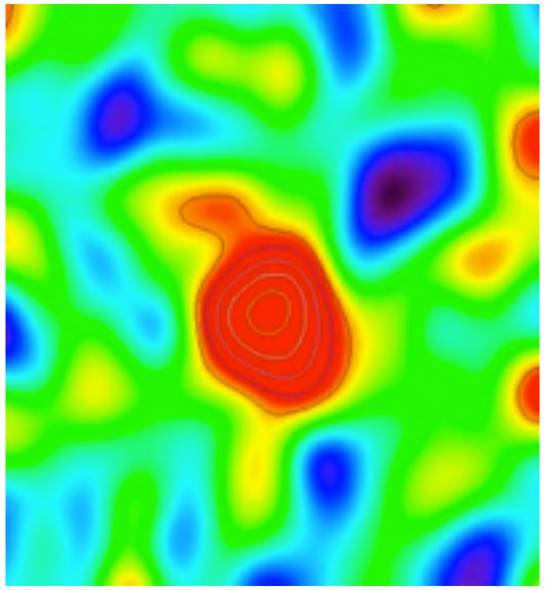
The SZ effect

"Hole in the sky"





Bump in the sky"



SZ brightness is independent from z (the SZ flux is not)

Proportional to the gas content of halos

Sunyaev & Zeldovich 1972

The SZ effect

$$\Delta I_\nu^{th} + \Delta I_\nu^{kin} + \Delta I_\nu^{rel} + \Delta I_\nu^{non-th} + \Delta I_\nu^{pol} + \Delta I_\nu^{m-scat}$$

Thermal

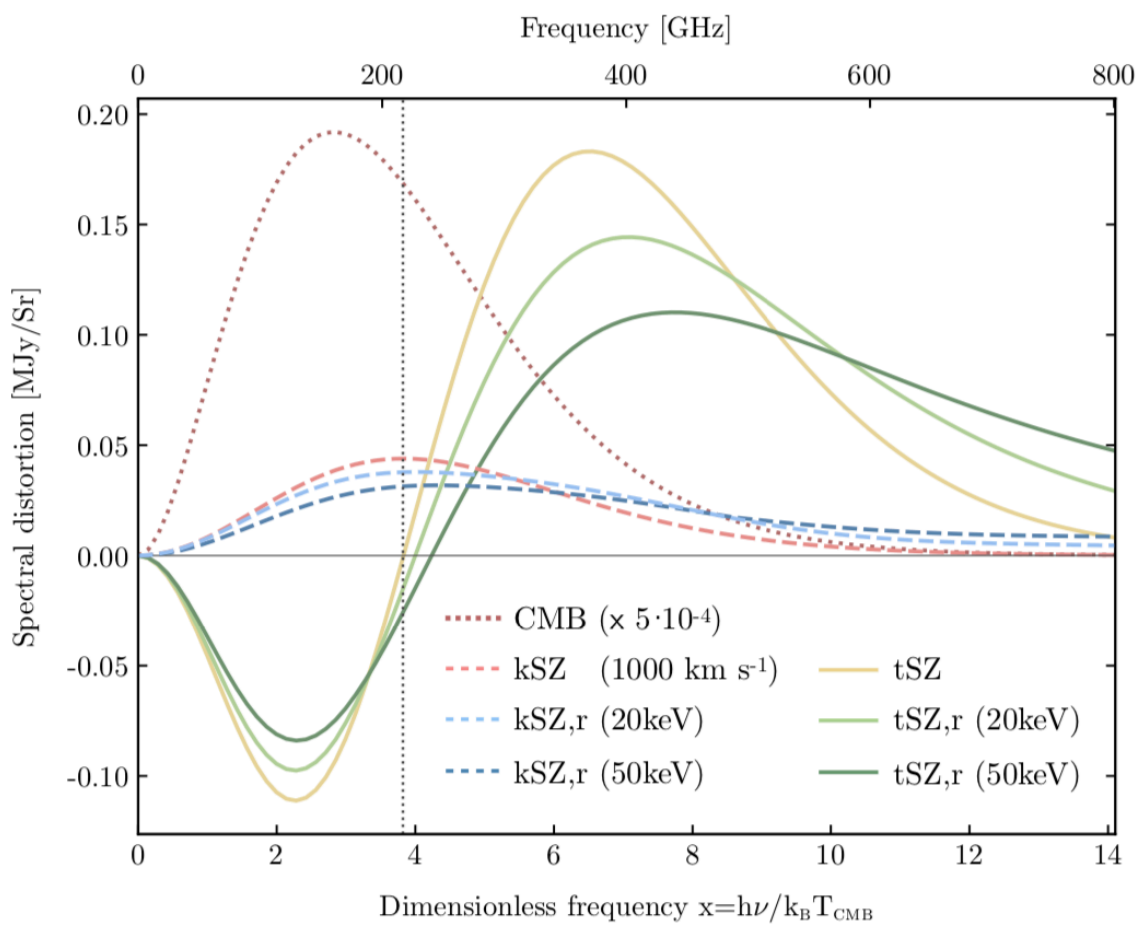
Kinetic

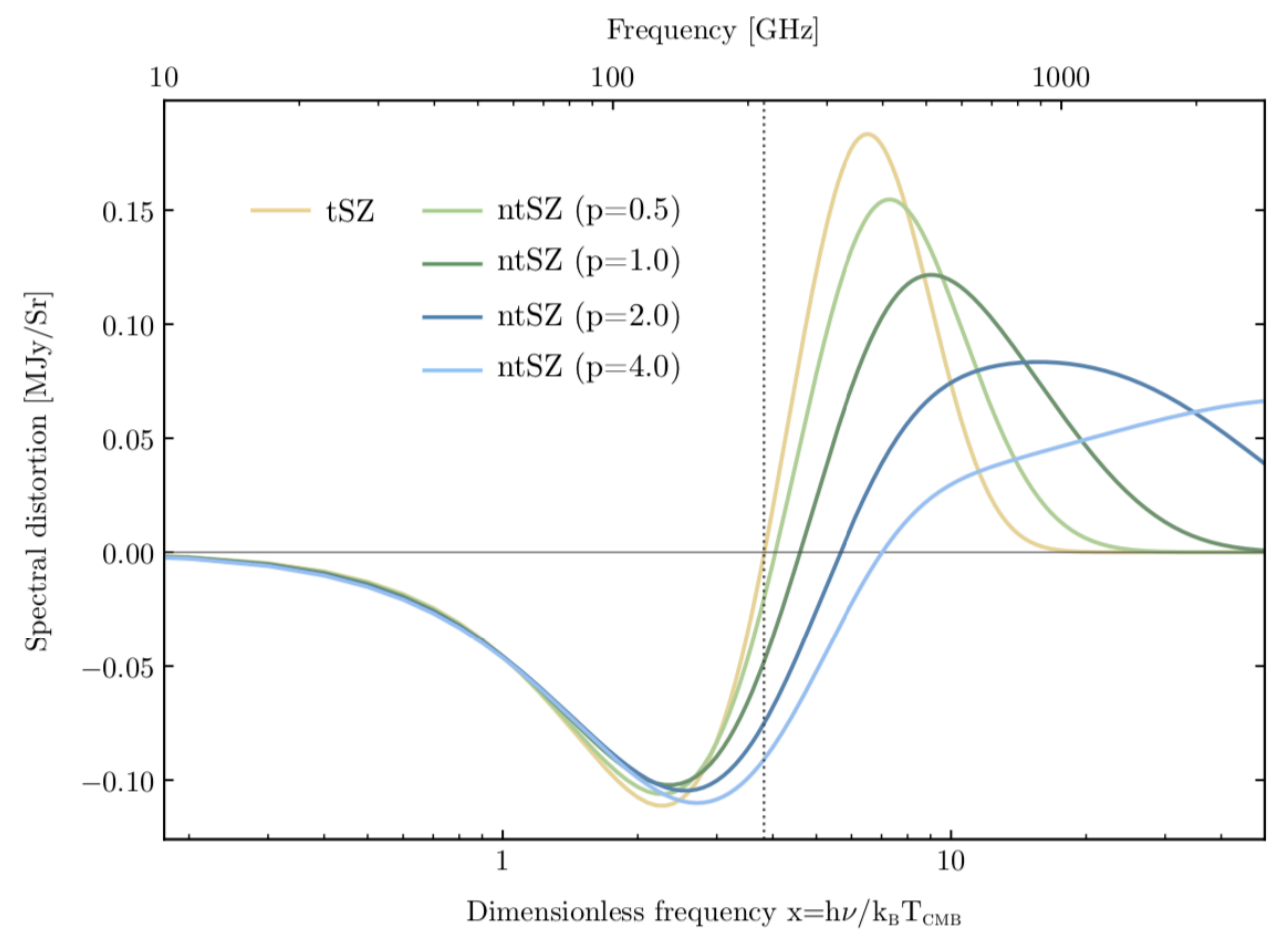
Relativistic corrections

Non-thermal

Polarised

Multiple Scattering



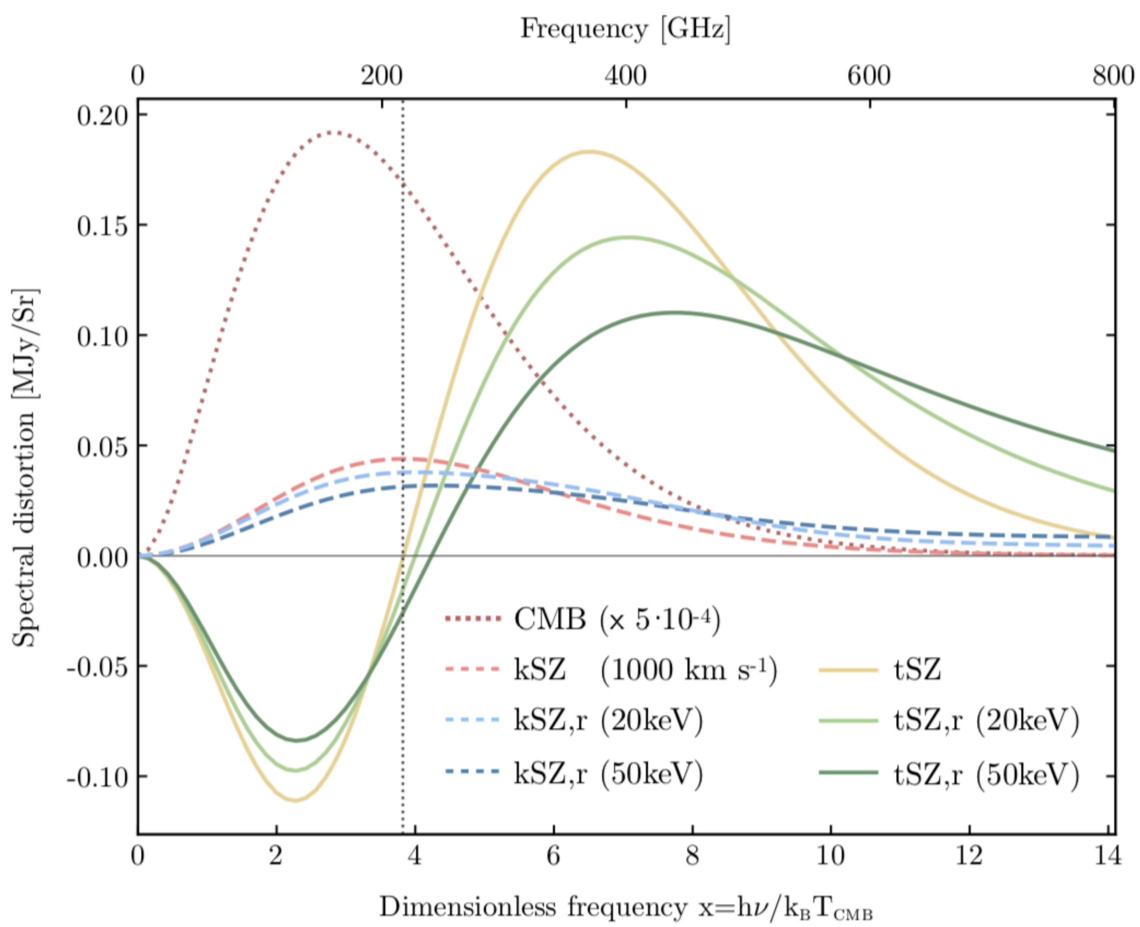


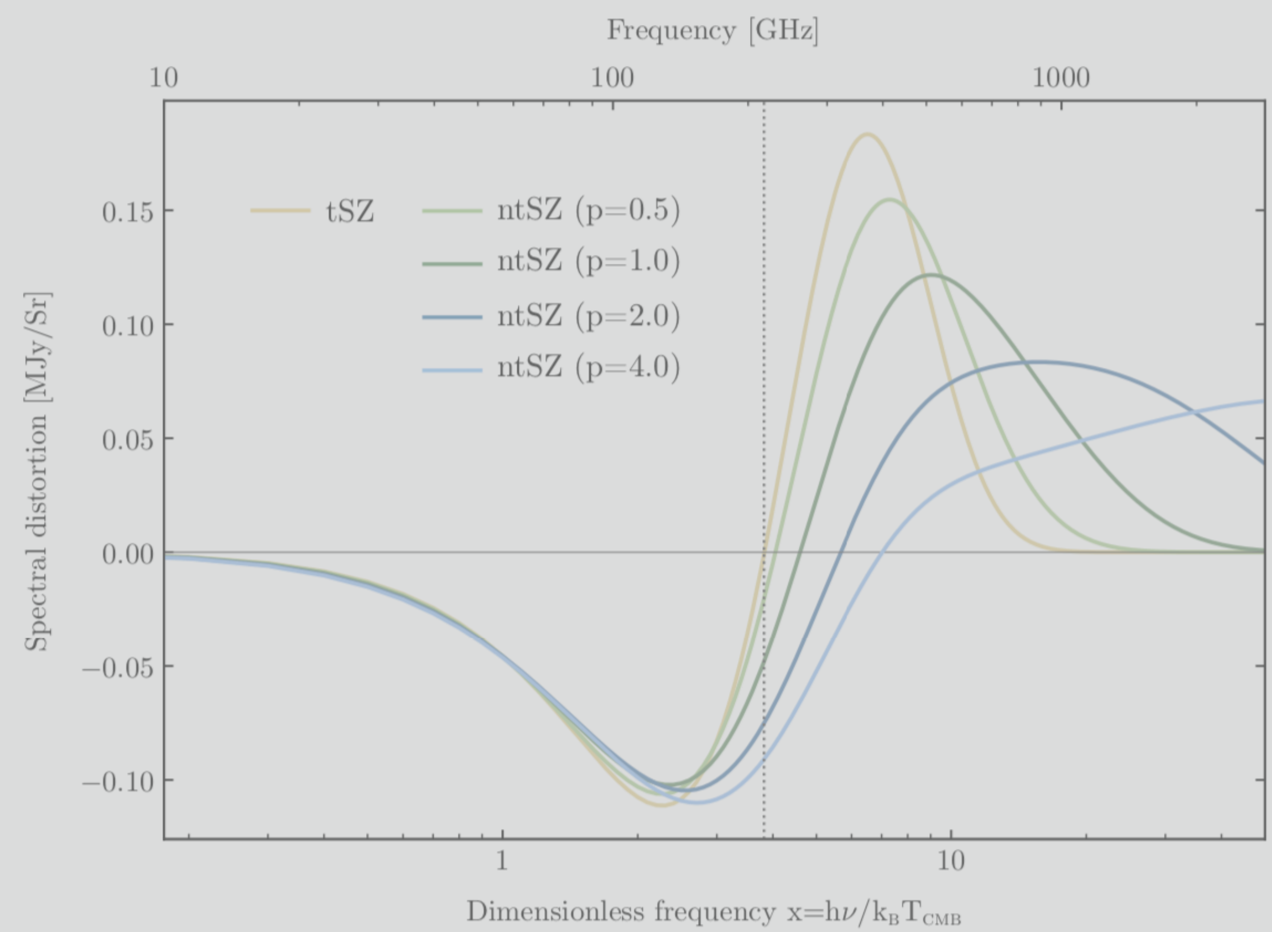
Mroczkowski+2019

The SZ effect

$$\Delta I_\nu^{th} + \Delta I_\nu^{kin} + \Delta I_\nu^{rel} + \Delta I_\nu^{non-th} + \Delta I_\nu^{pol} + \Delta I_\nu^{m-scat}$$

Thermal | Kinetic | Relativistic corrections | Non-thermal | Polarised | Multiple Scattering





Mroczkowski+2019

The SZ effect

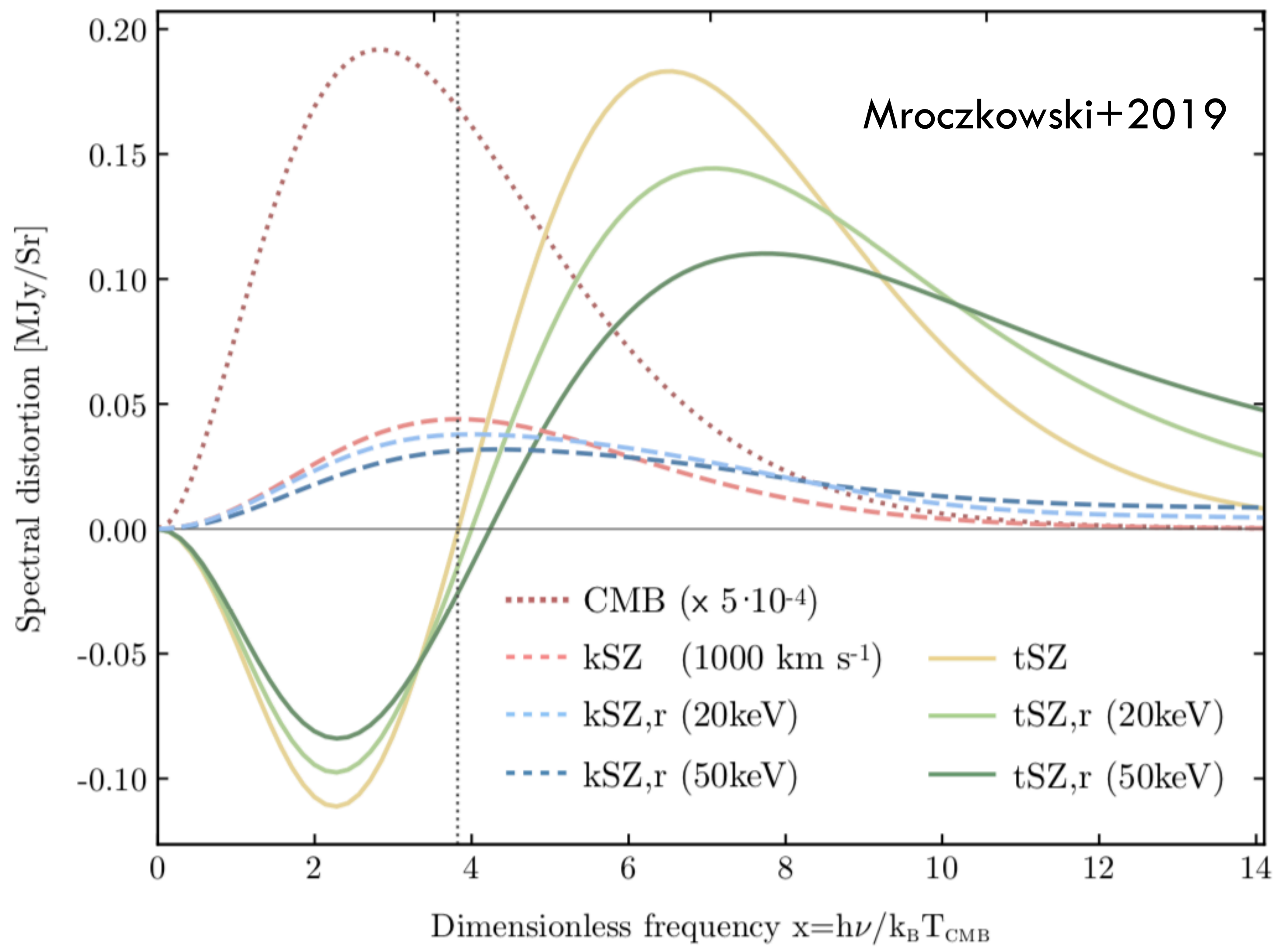
$$\frac{\Delta I_\nu}{I_0} = f(x, T_e)\, y_{tSZ} + f(x, v_z, T_e)\, y_{kSZ}$$

- Thermal effect

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

- Kinetic effect

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

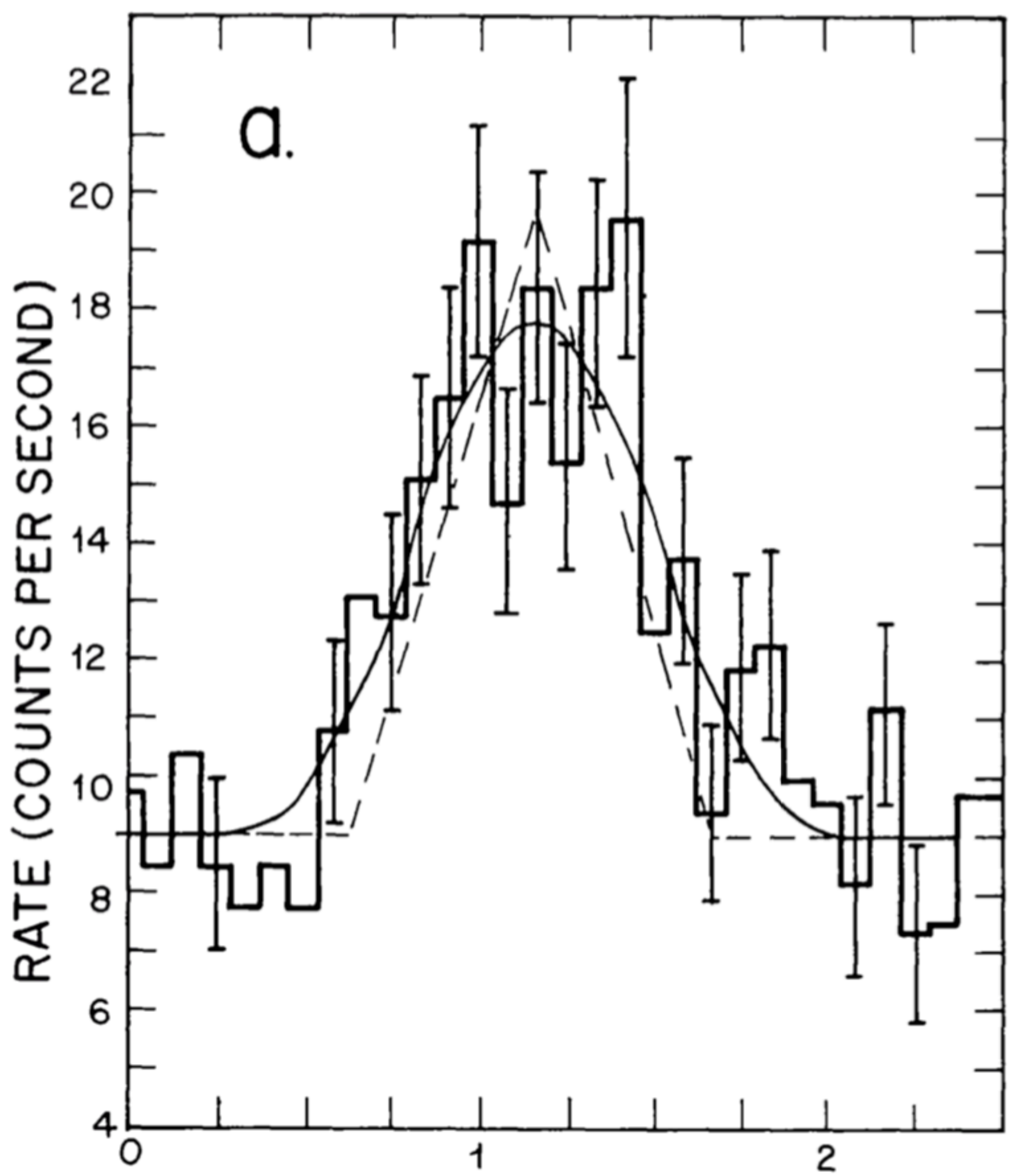


- Reflect the state of the gas in the potential well
- High-z Universe

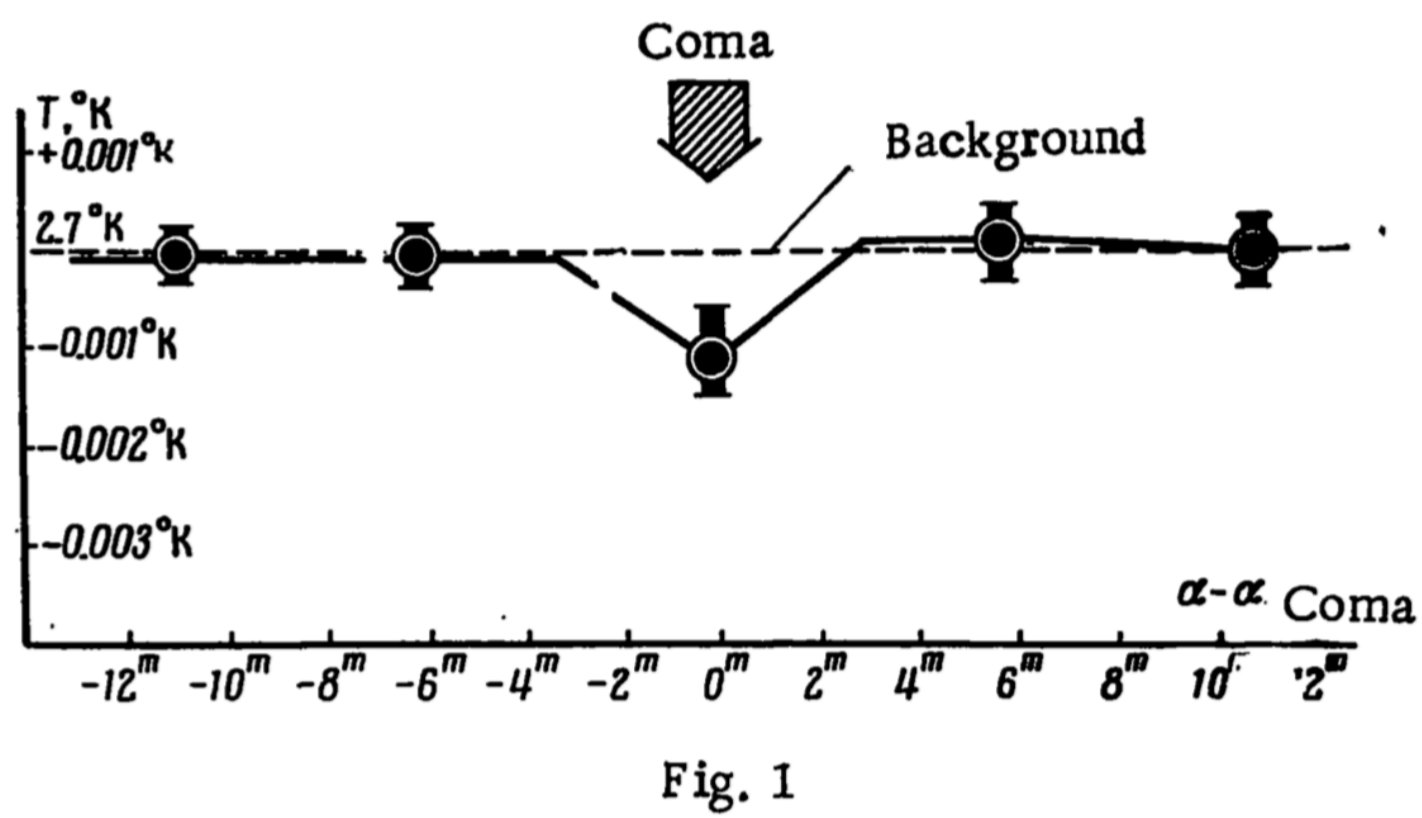
The SZ and X-ray synergy

Hot gas in clusters

- First detection of the Coma cluster in X-ray and SZ



Gurski 1971

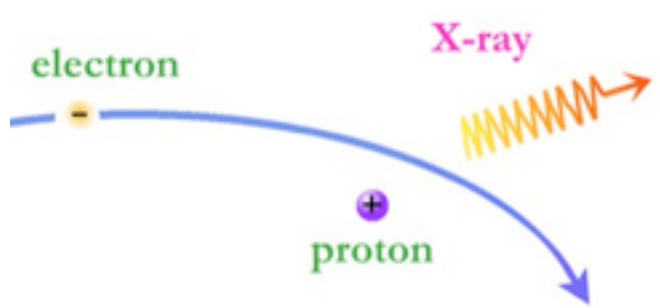


Pariiskii 1973

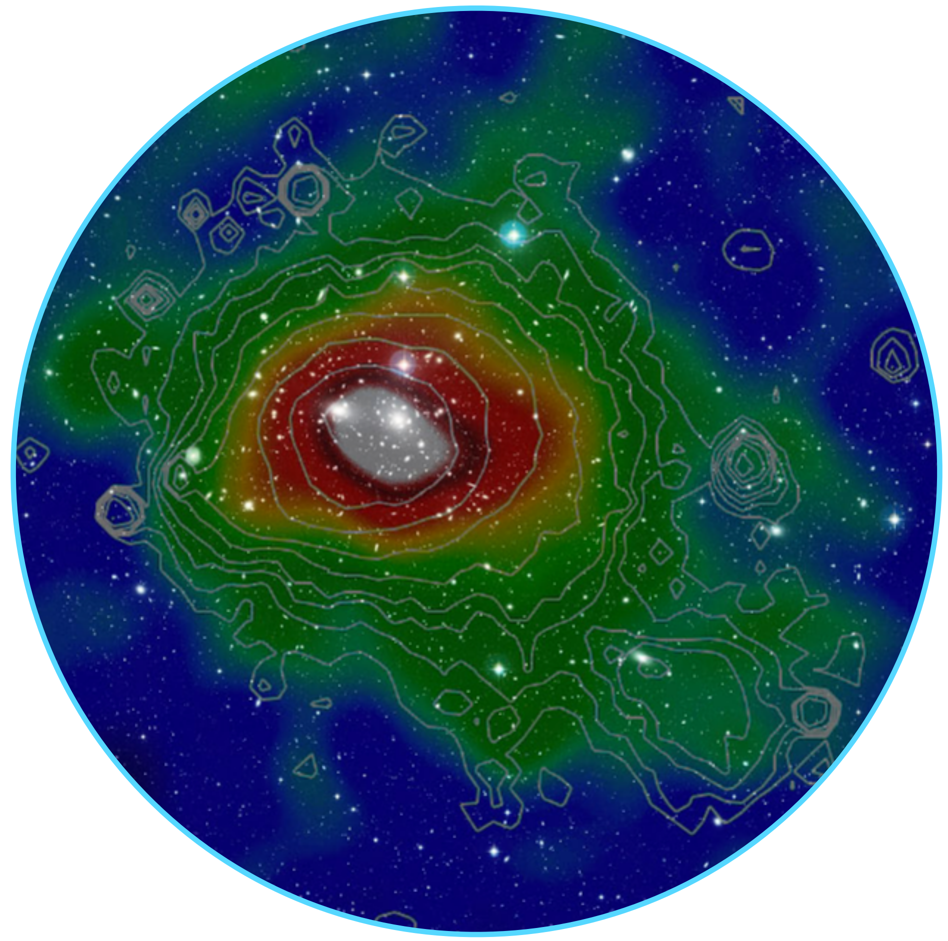
Hot gas in clusters

- $10^{7\text{-}8}$ K, $n_e \sim 10^{-3}$ cm^{-3} ($\tau_e \sim 0.01$), ~10–1000 galaxies
- M_{tot} = (0.85 DM + 0.12 gas + 0.03 galaxies) $10^{14\text{-}15}$ $M_\odot$

Bremsstrahlung

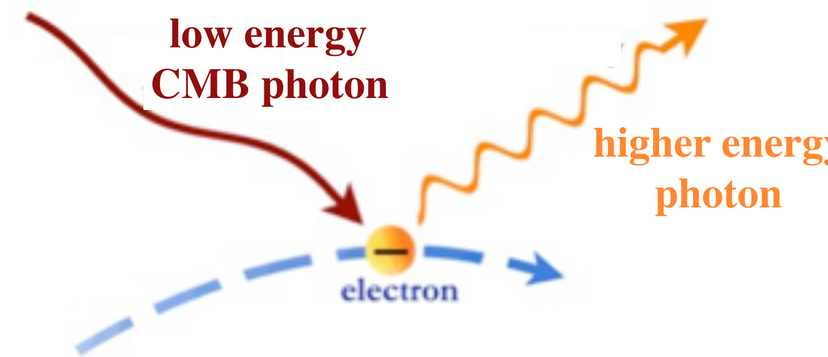


$$E_X \propto \int_V n_e^2 \Lambda(T) dV$$



Coma cluster seen by Planck, ROSAT, DSS
(Planck Collaboration 2013)

Inverse Compton



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

- Two independent probes of the same physical component

see talk by E. Ettori

SZ and X-ray combination

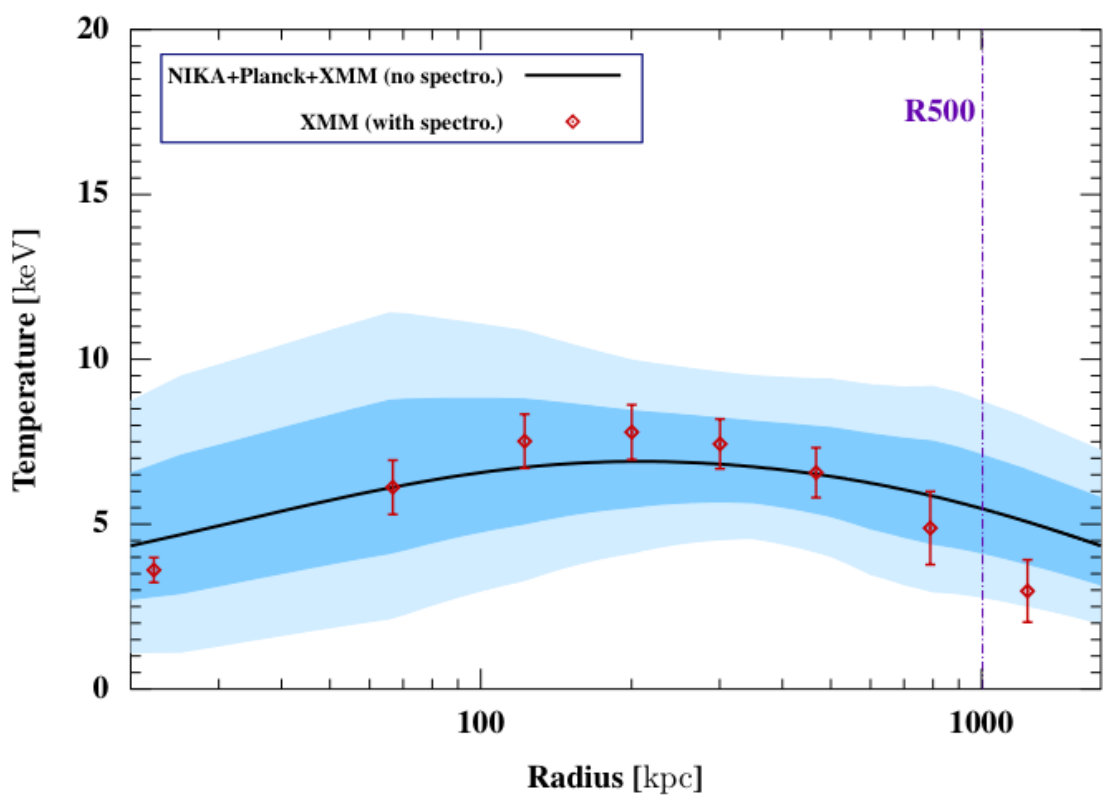
- Joint SZ and X-ray imaging
  - bypass X-ray spectroscopy

$$y_{tSZ} \equiv f(T_e)\int P_e \, dl$$

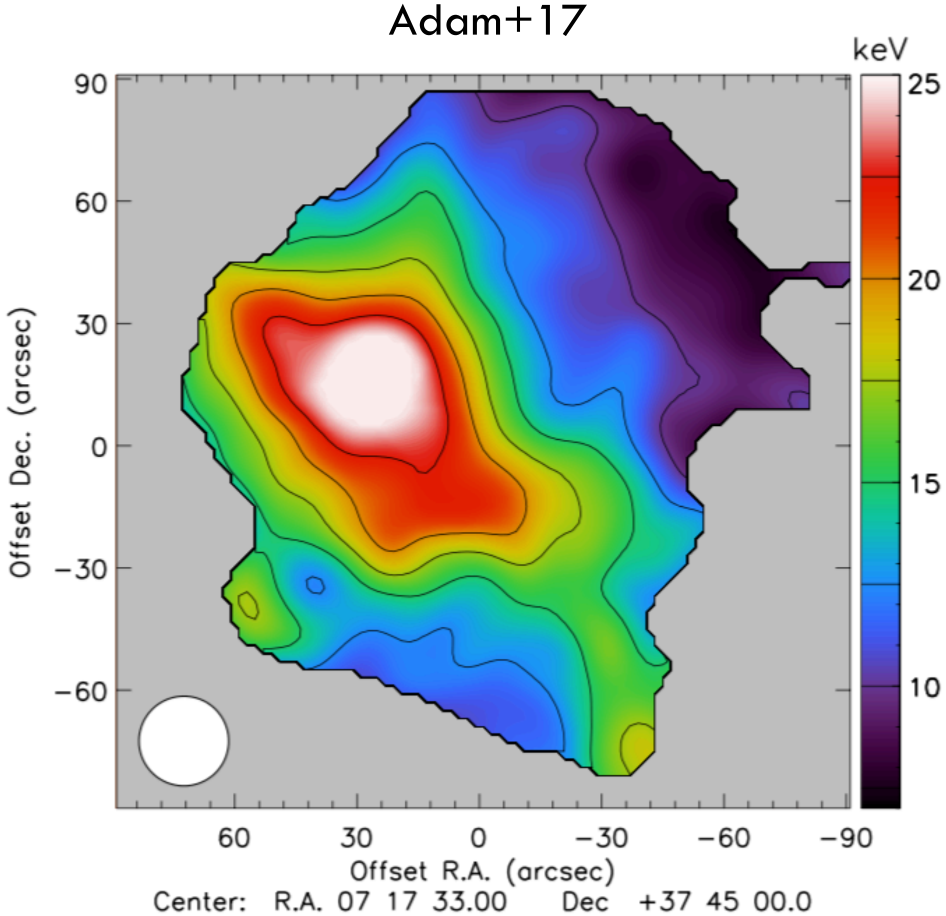
$$S_X \equiv \int n_e^2 \Lambda(T_e)\, dl$$

$\longrightarrow$ $P_e(r)$, $n_e(r)$

Ruppin+17

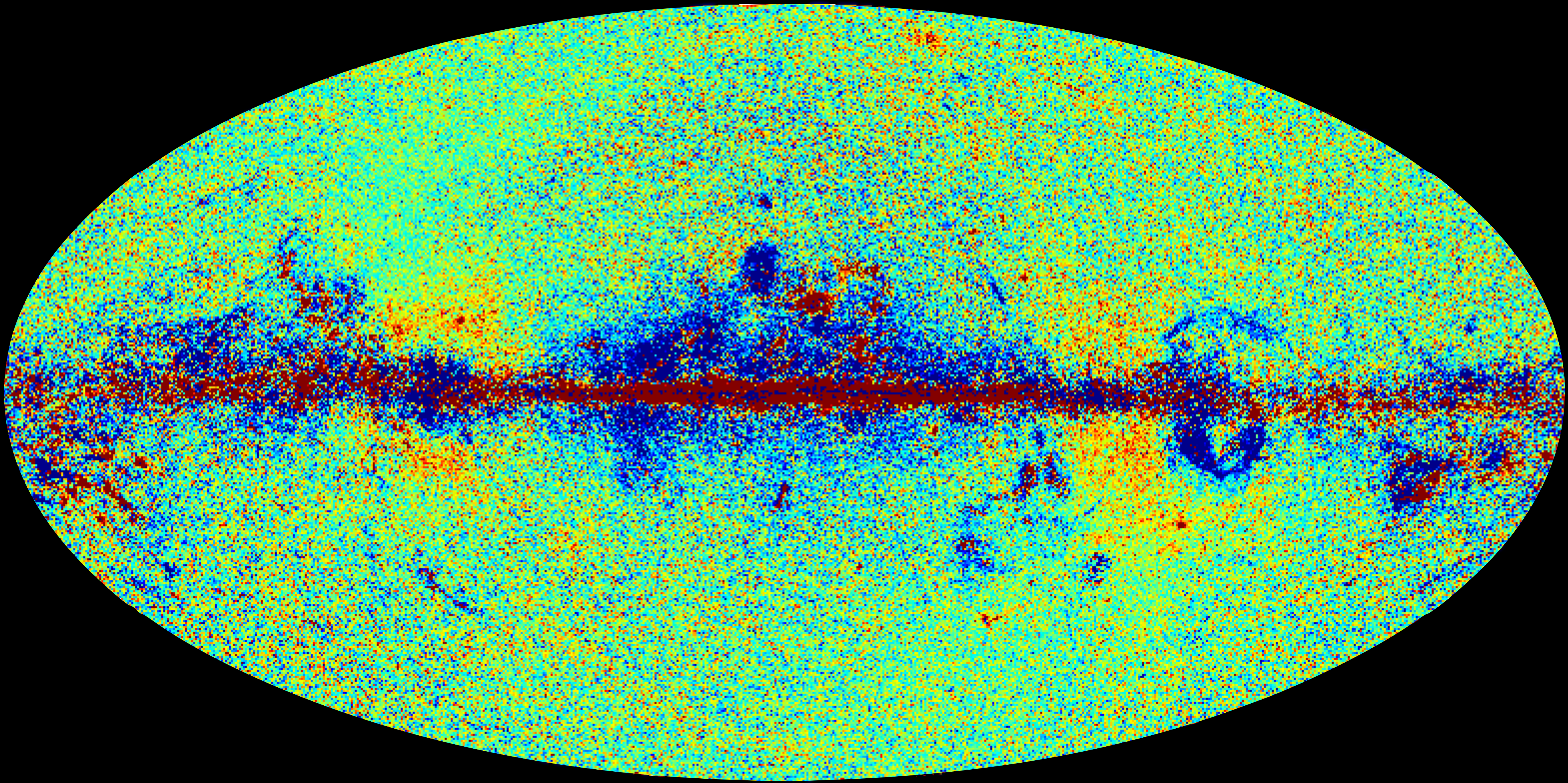


Adam+17

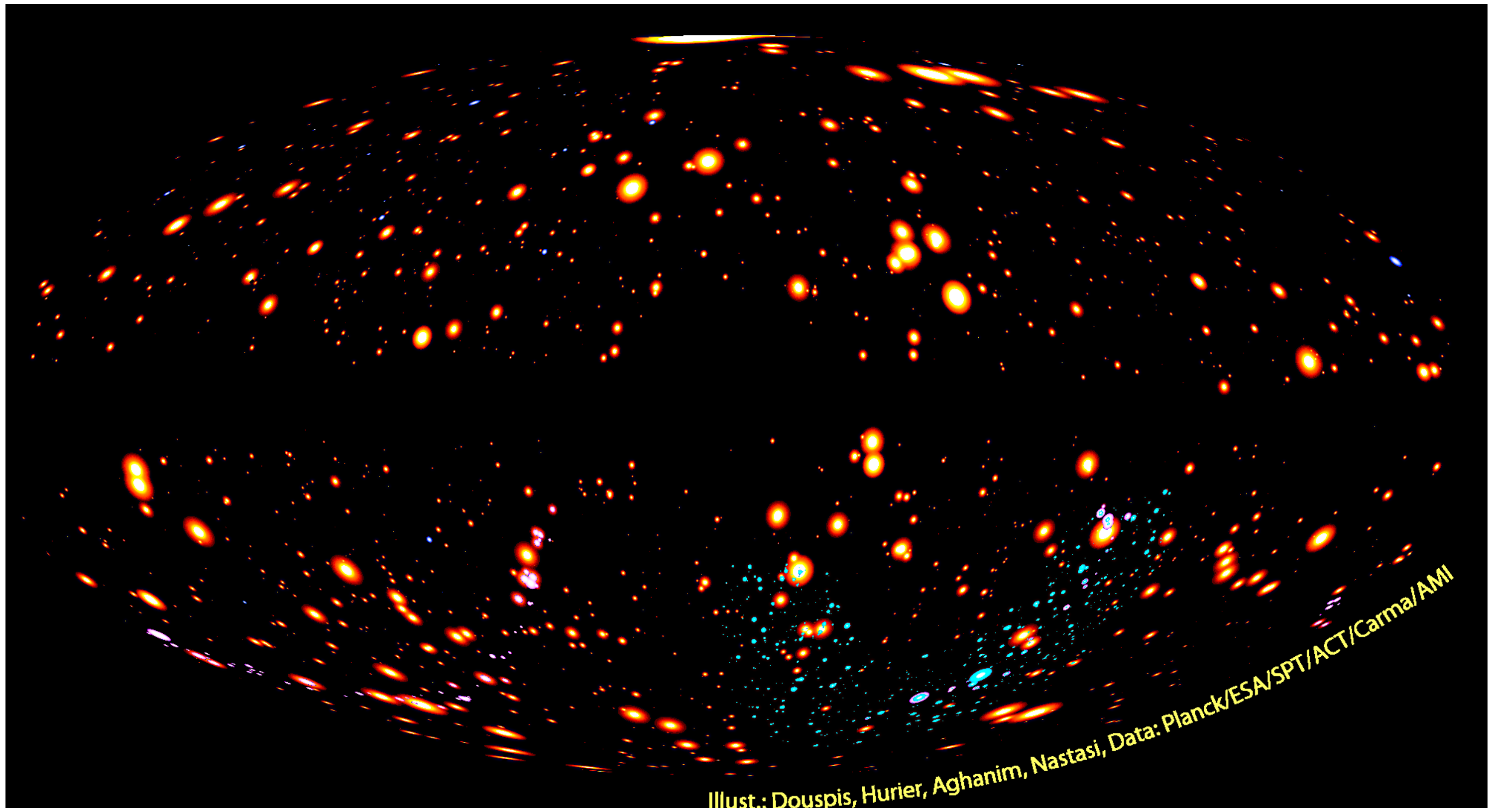


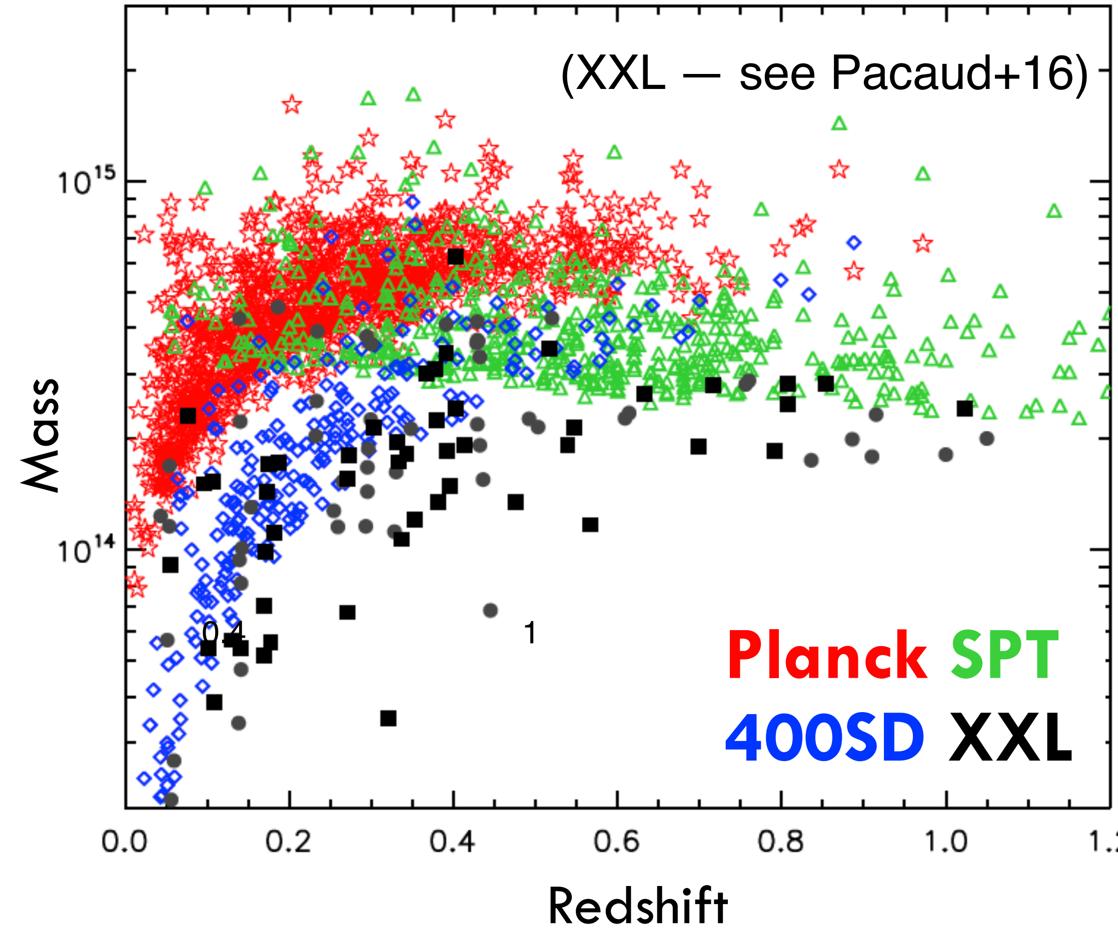
Why we care ?

SZ surveys



SZ surveys



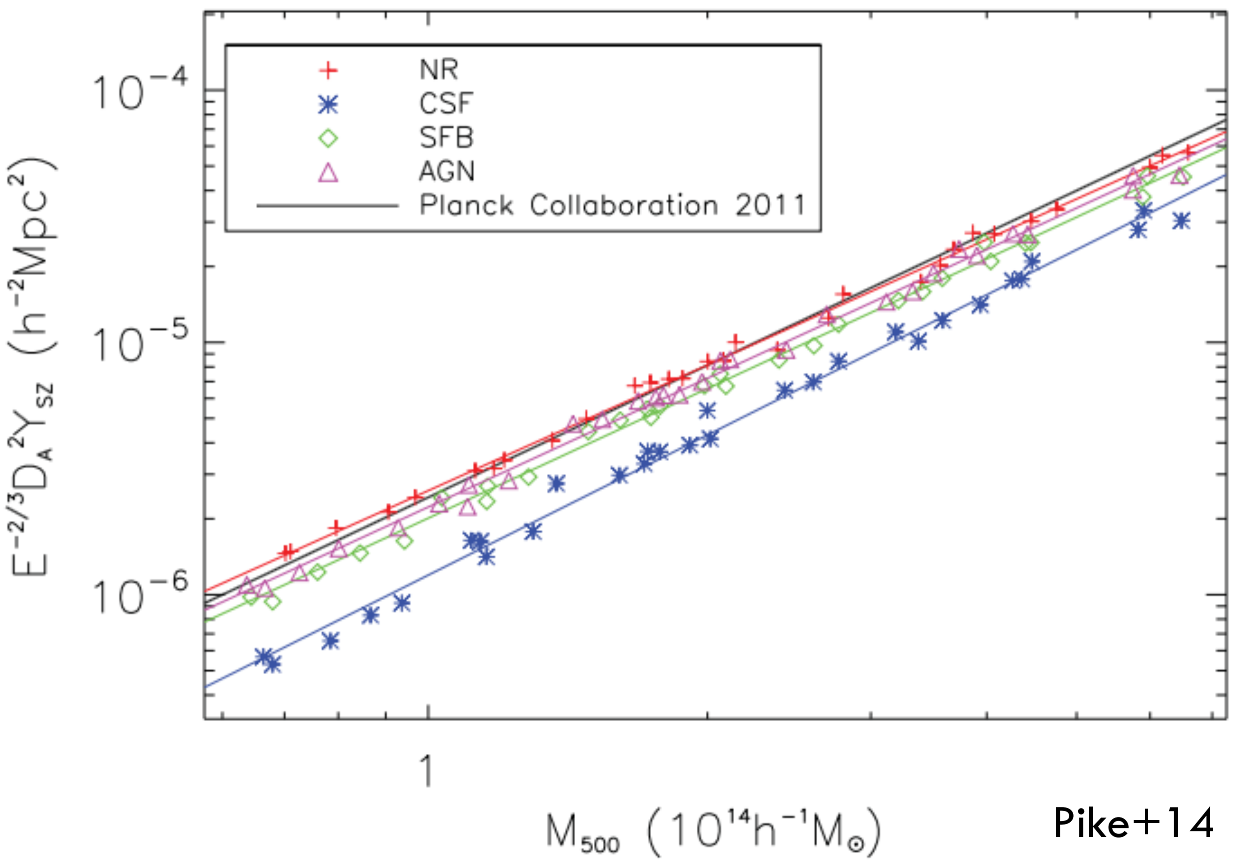


ACT	PLANCK	SPT
1,5’	4.5-10’	1.6’
91	1963	747
Hasselfield+13	Planck Coll.+11+13+15	Bleem+15

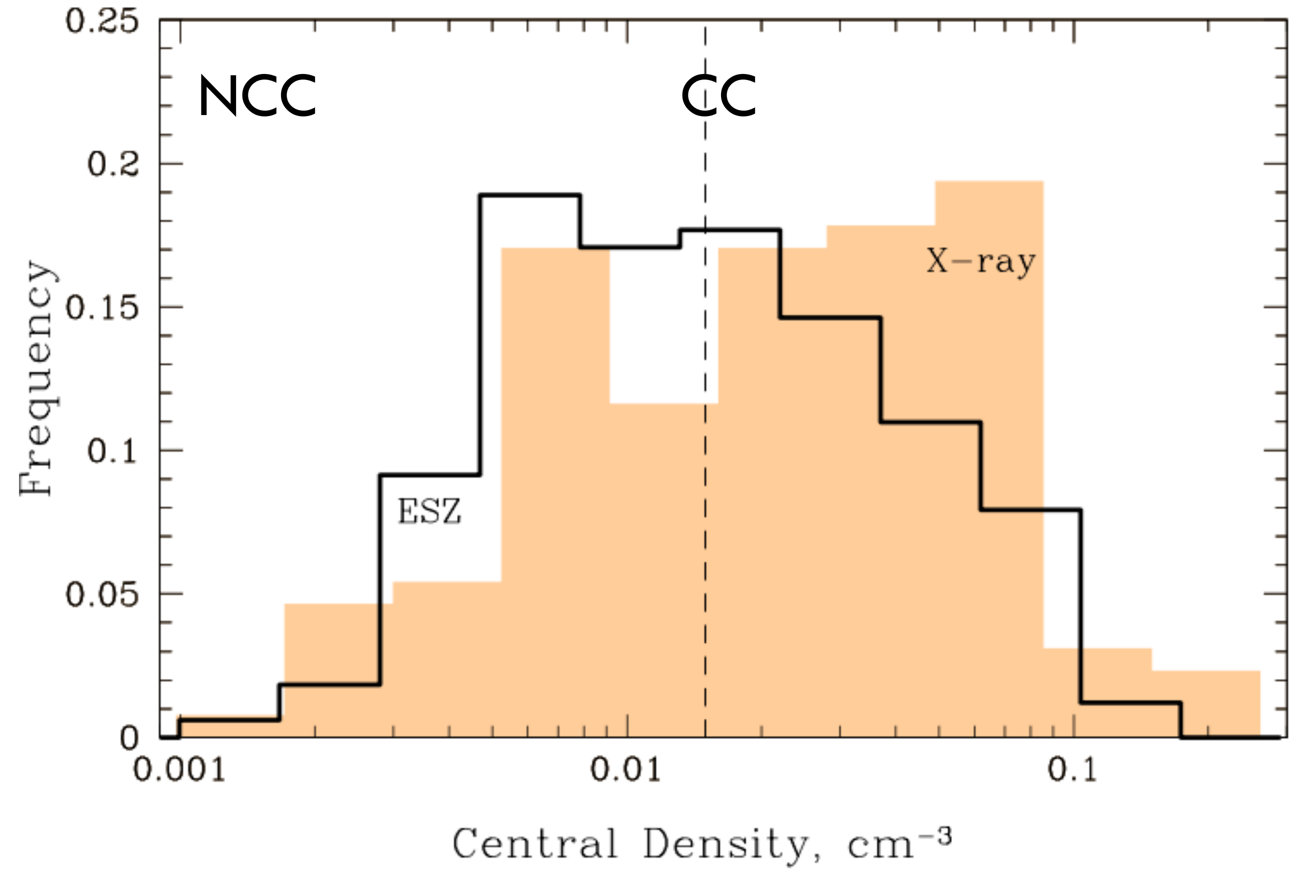
see talk by J. Macias-Perez

- (All sky) catalogues of clusters
- Mass limited surveys up to high z

The cluster population



Pike+14



Andrade-Santos+17

Weak dependence on non-grav. physics (low scatter Y - M relation)

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

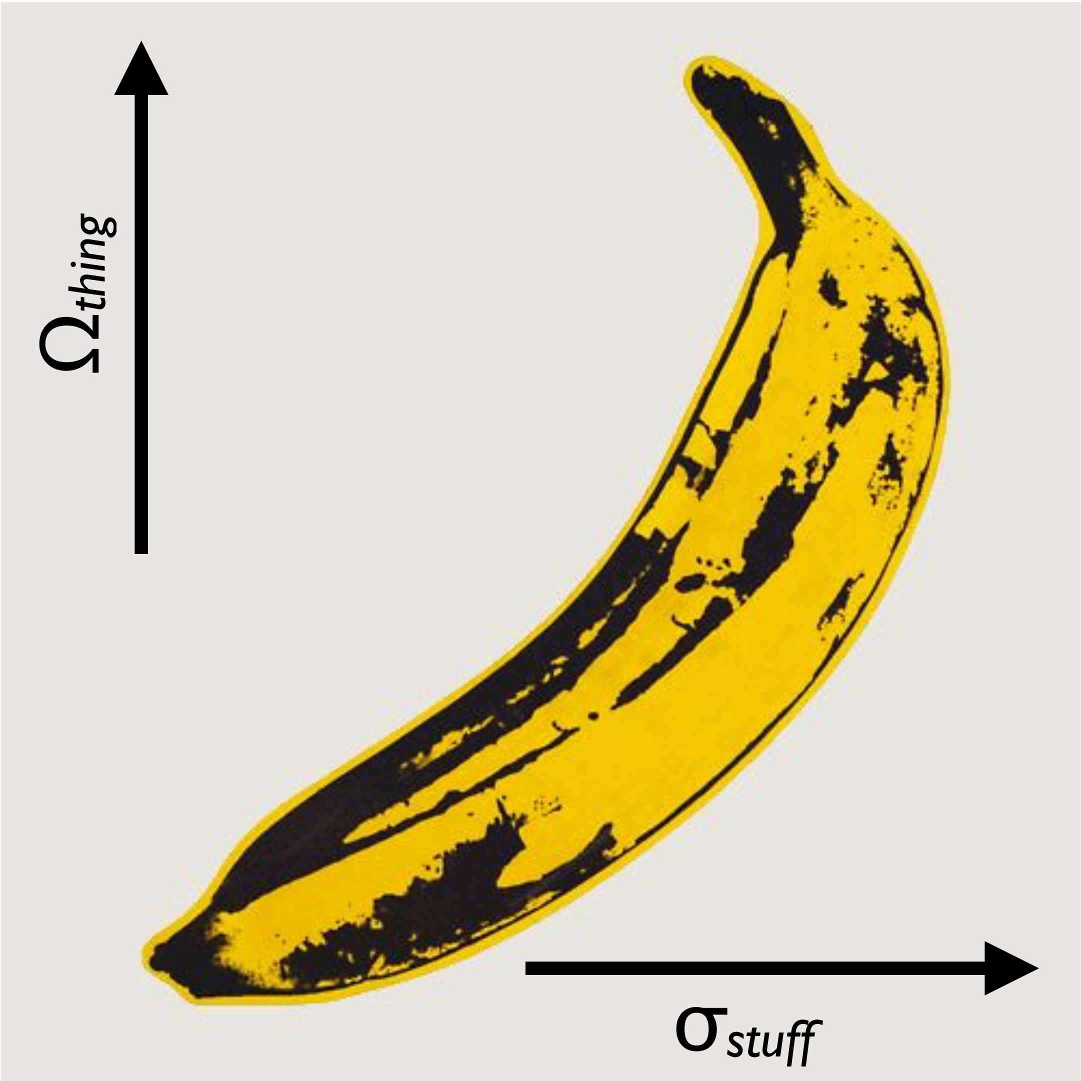
⇒ **cluster formation and evolution**

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

see talks by
M. Rossetti
A. Ferragamo

Cosmology with the SZ clusters

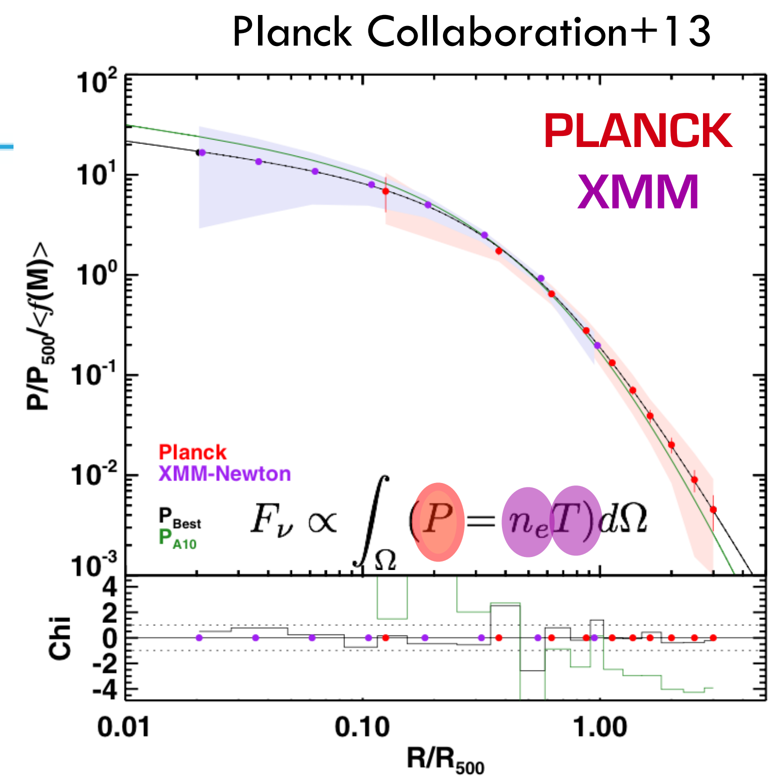
- N(M,z) extremely sensitive to the geometry and matter content of the universe.
  - a powerful cosmological probe

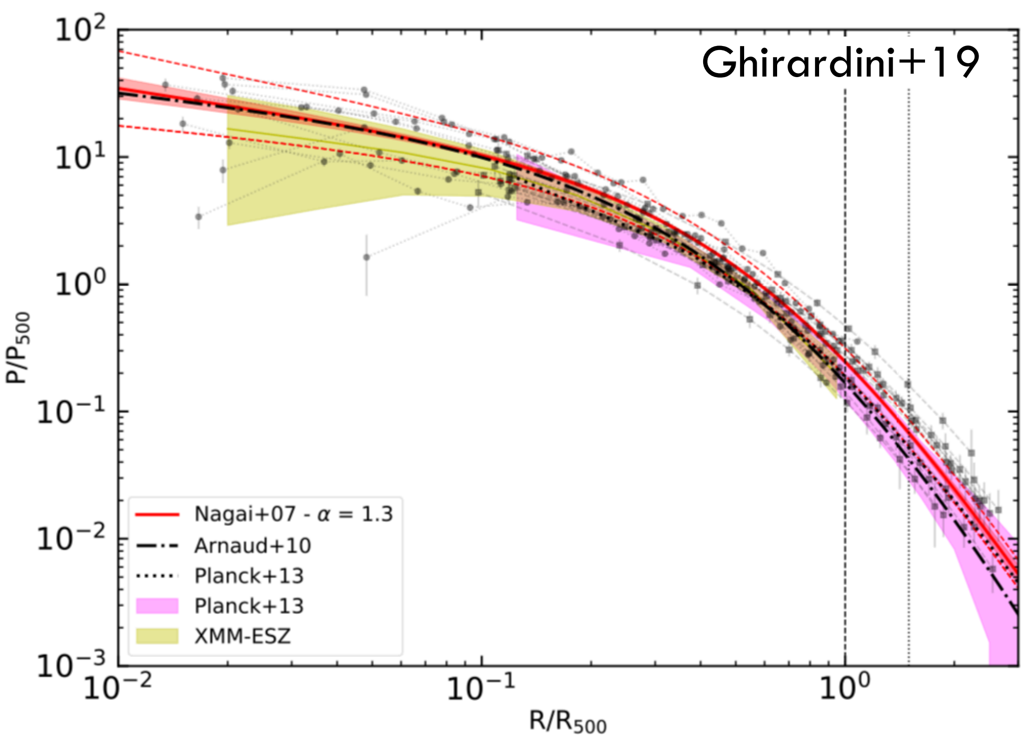


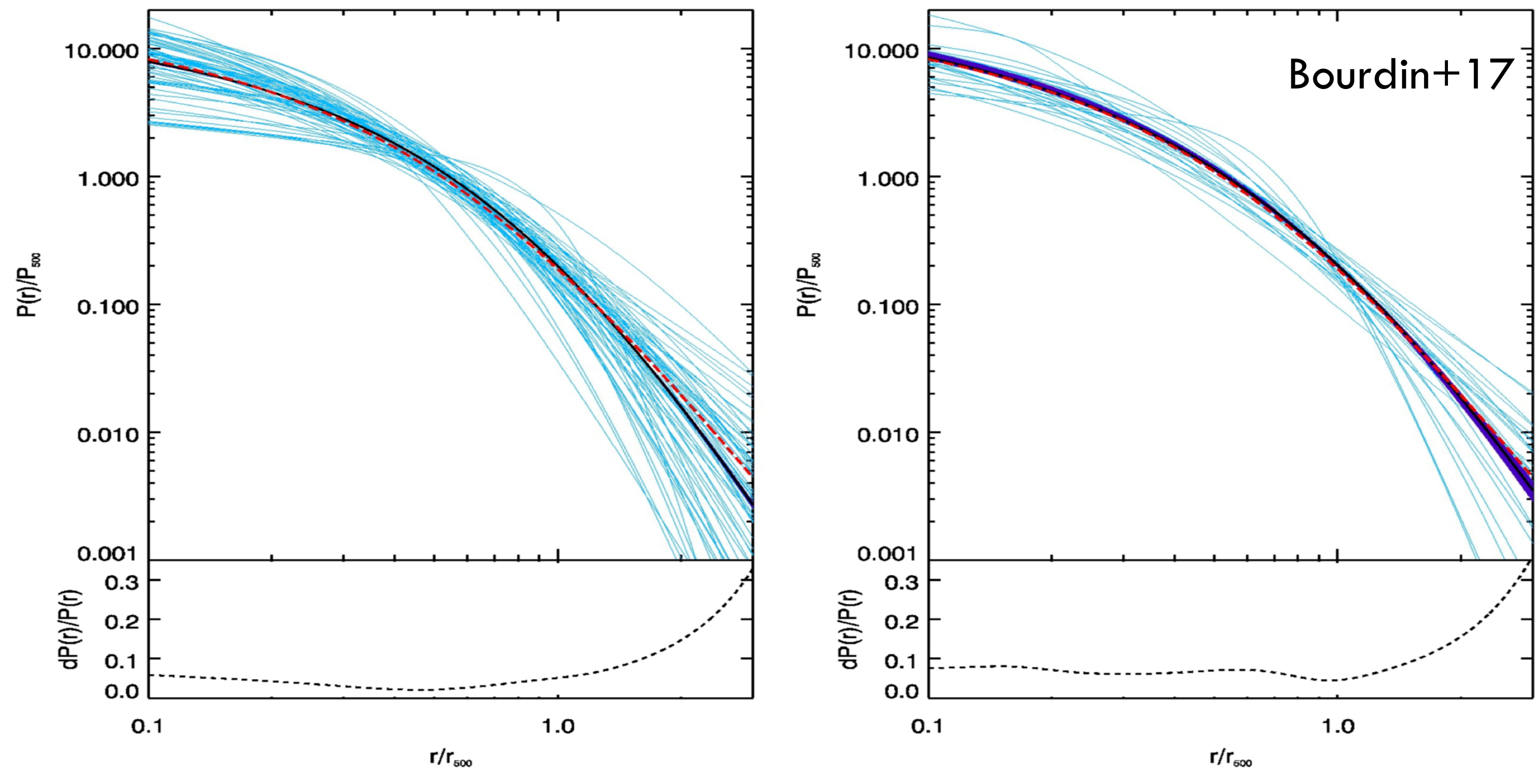
see talk by F. Mayet

Pressure of the gas

- Consistent thermal pressure distribution for the ICM gas through the various samples, methods and numerical simulations





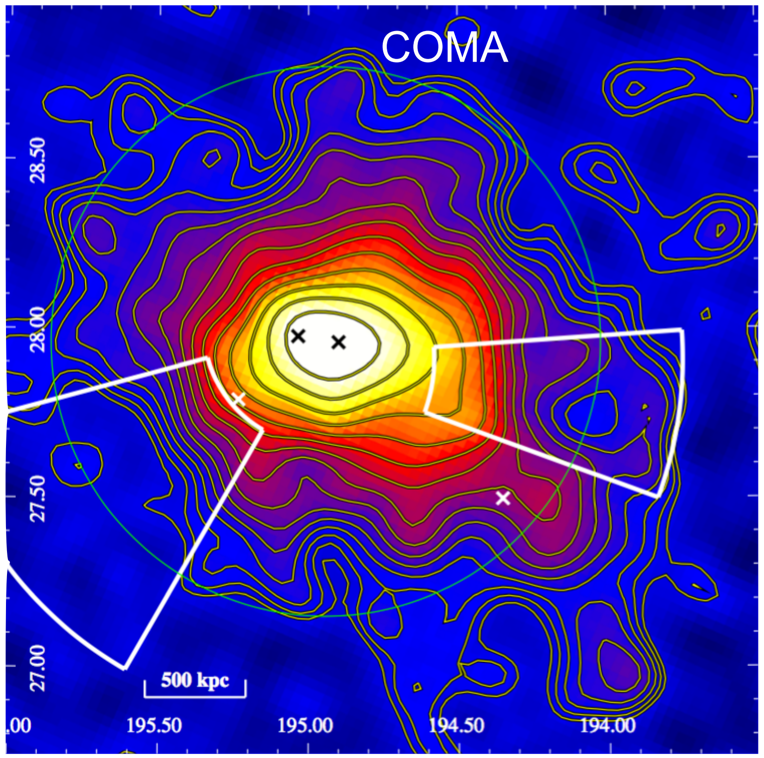


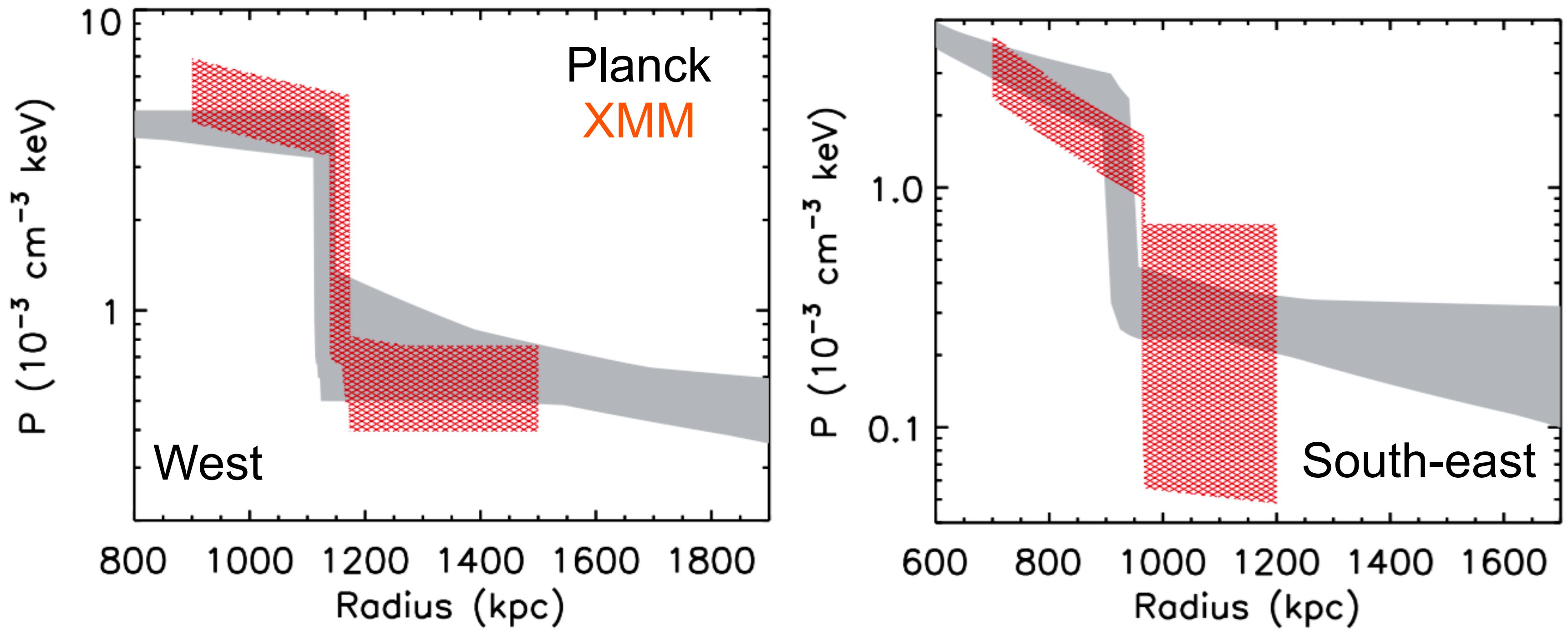
see also Kay+12, Bataglia+12, Eckert+13,Adam+15+16, Dolag+16, Sayers+16, Romero+17, Ruppin+17+18 Shitanishi+17
see also talk by N. Battaglia, poster by A.-R. Pop

see talk by A. Baldi

Dynamics of clusters

Planck Int. Result X, 2013





Mach number:

Mw = 2.03 [+0.09,−0.04]

MSE = 2.05 [+0.25,-0.02]

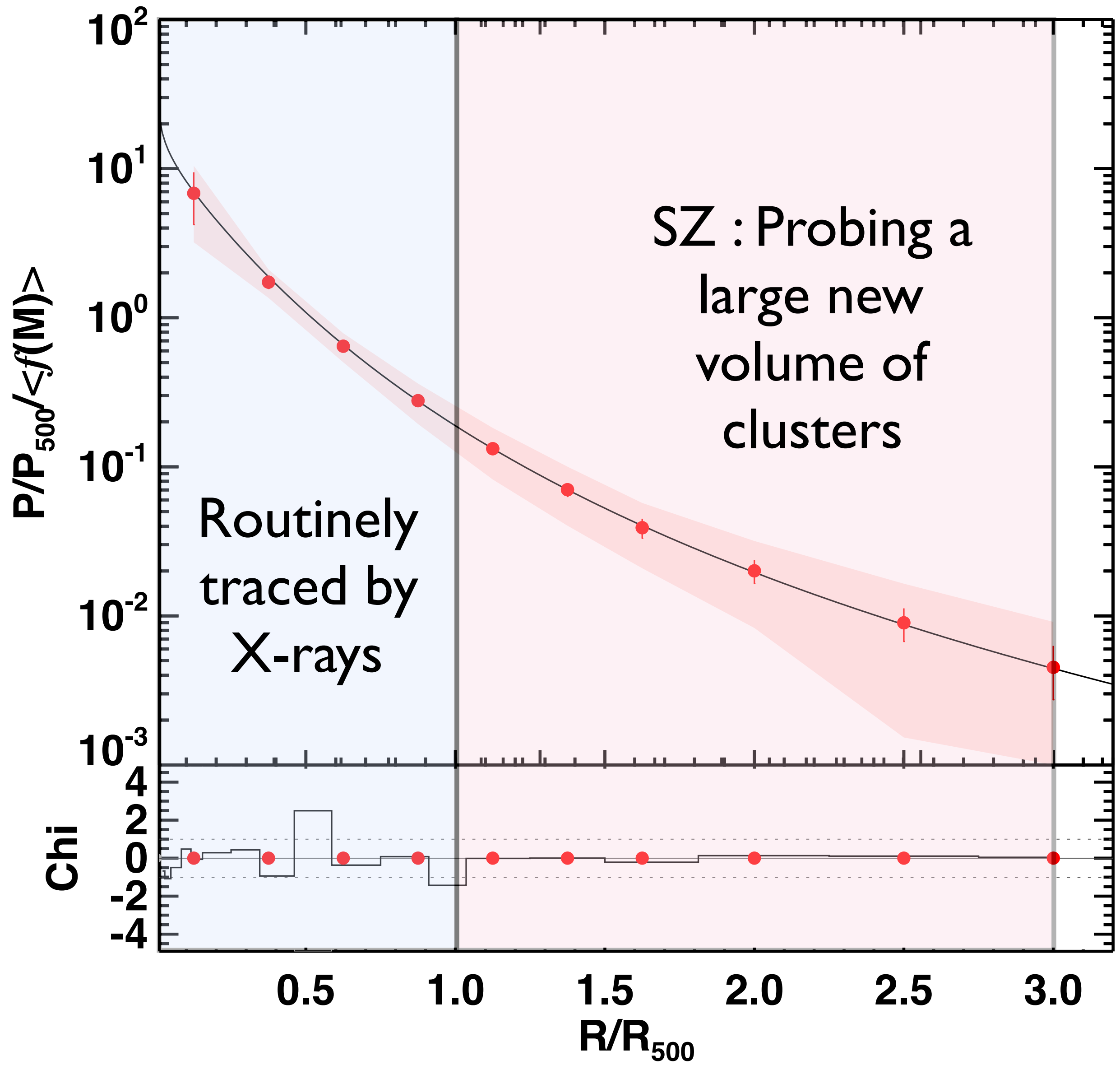
- Pressure jumps sign the presence of shocks

see talk by H. Bourdin

Outskirts of clusters

- Assembly of structures
  - Virialising regions of massive halos
  - Accretion from the cosmic web
  - Physics of the hot gas out to the virial radius

see talks by
D. Eckert
D. Nagai

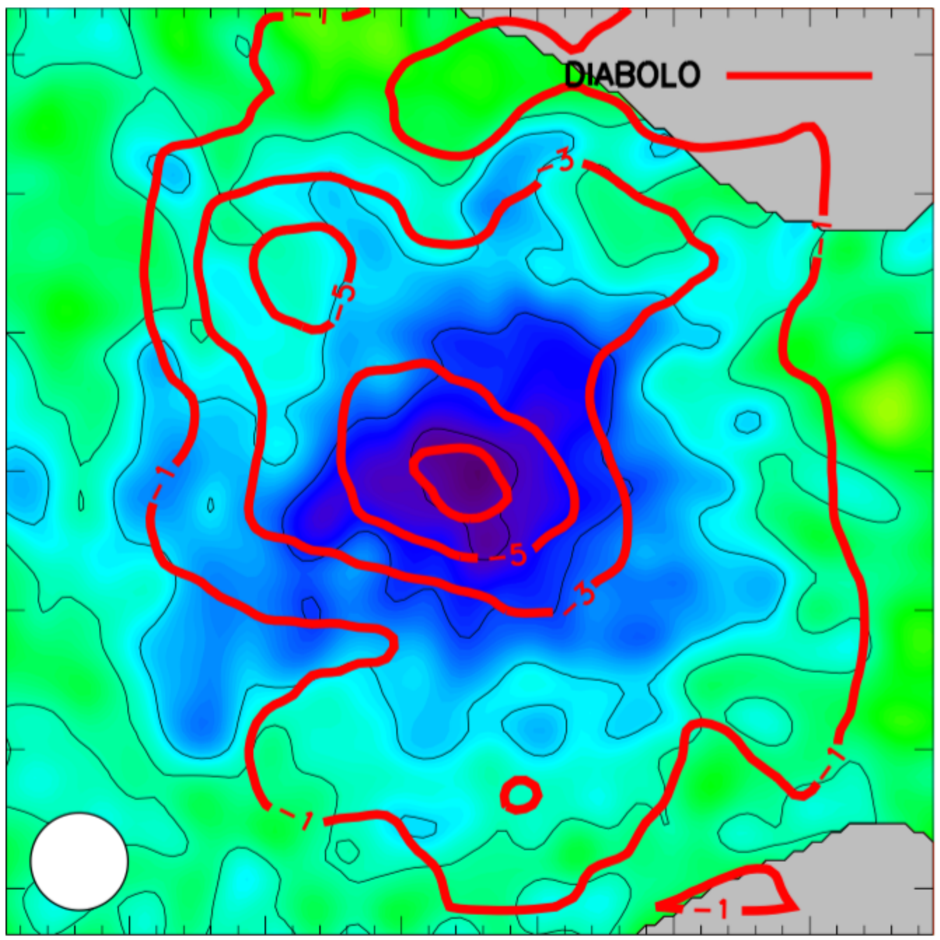


Towards high spatial resolution

The new era of high spatial resolution

The benchmark cluster — RXJ1347-1145 (z=0.45)

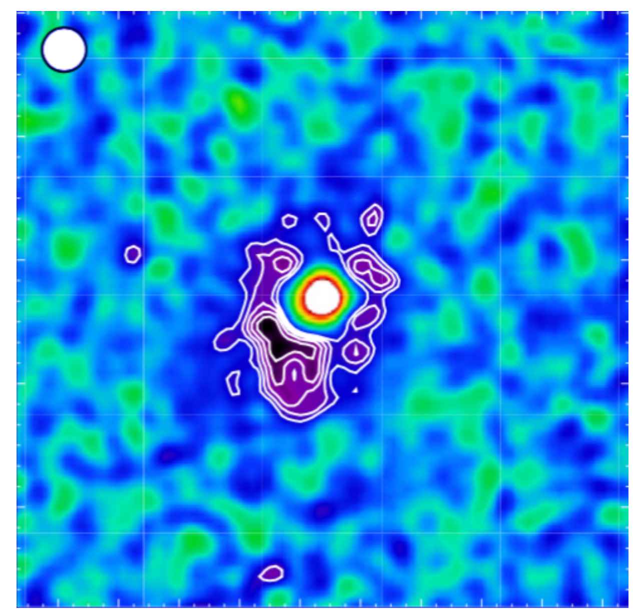
3.5 arcmin



Adam+2014

NIKA-1 @ IRAM 30m
150 GHz, 18” FWHM

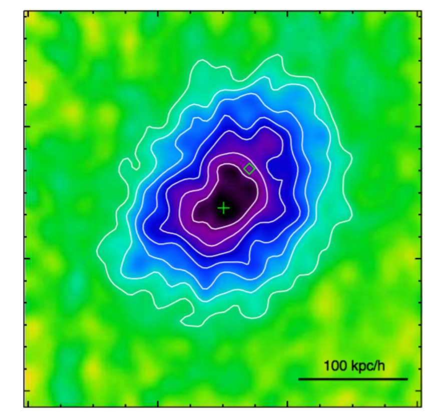
2.3 arcmin



Mason+10, Korngut+11

MUSTANG-1 @ GBT 100m
90 GHz, 9” FWHM

1.5 arcmin



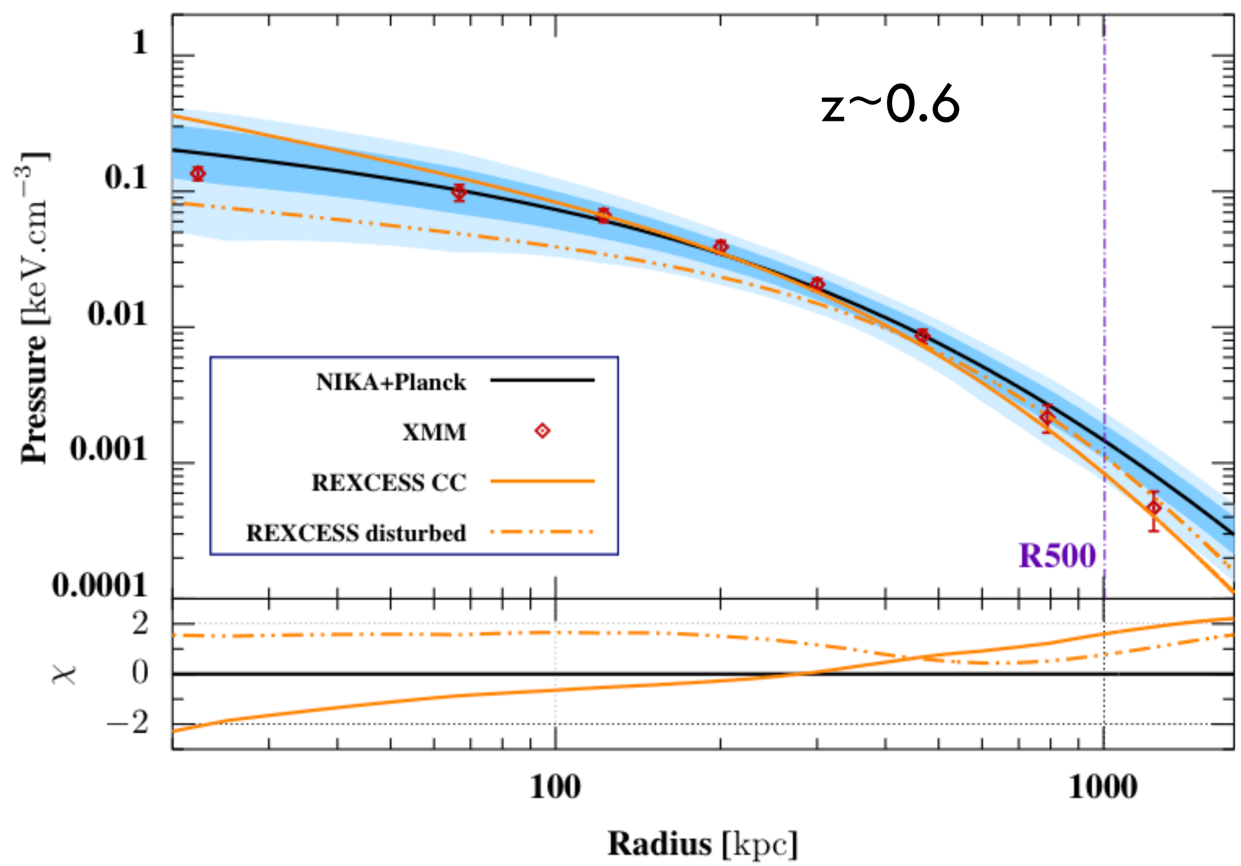
Kitayama+16

ALMA
90 GHz, 5” FWHM

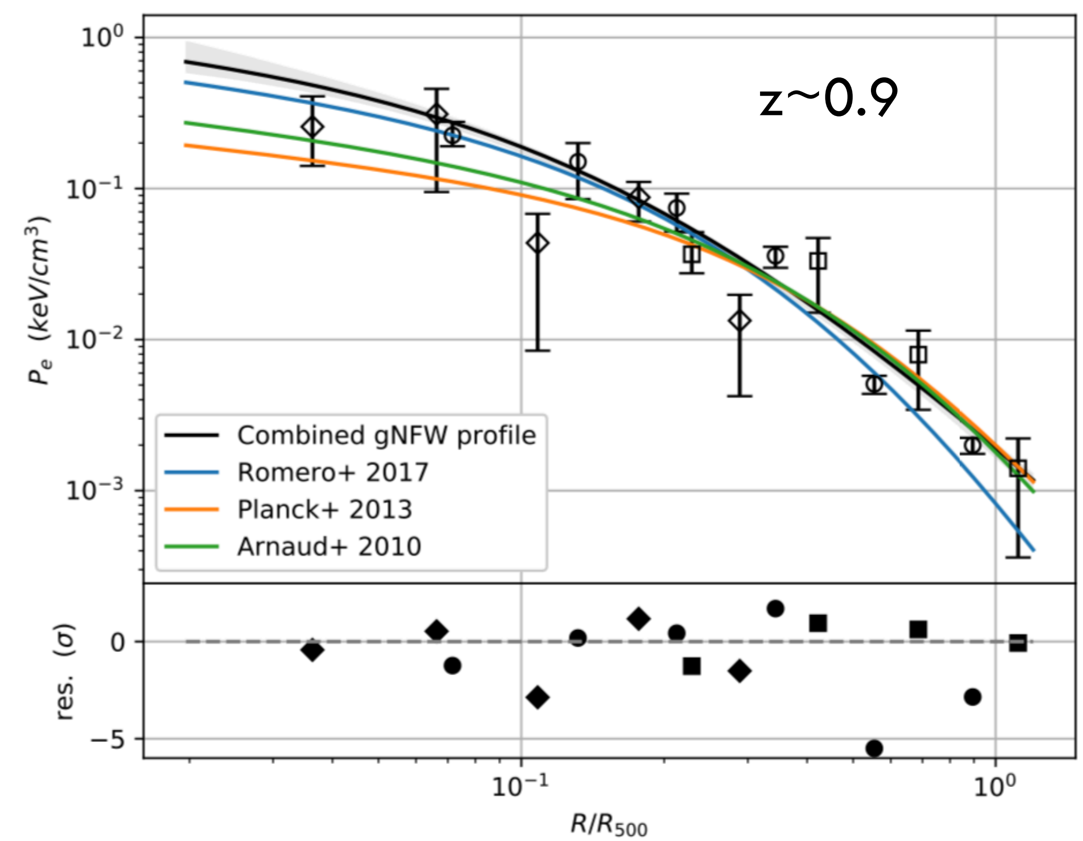
Pressure profile at high z

- SZ is competitive with X-ray observations
  - Sensitivity
  - Spatial resolution

Ruppin+17



Romero+17



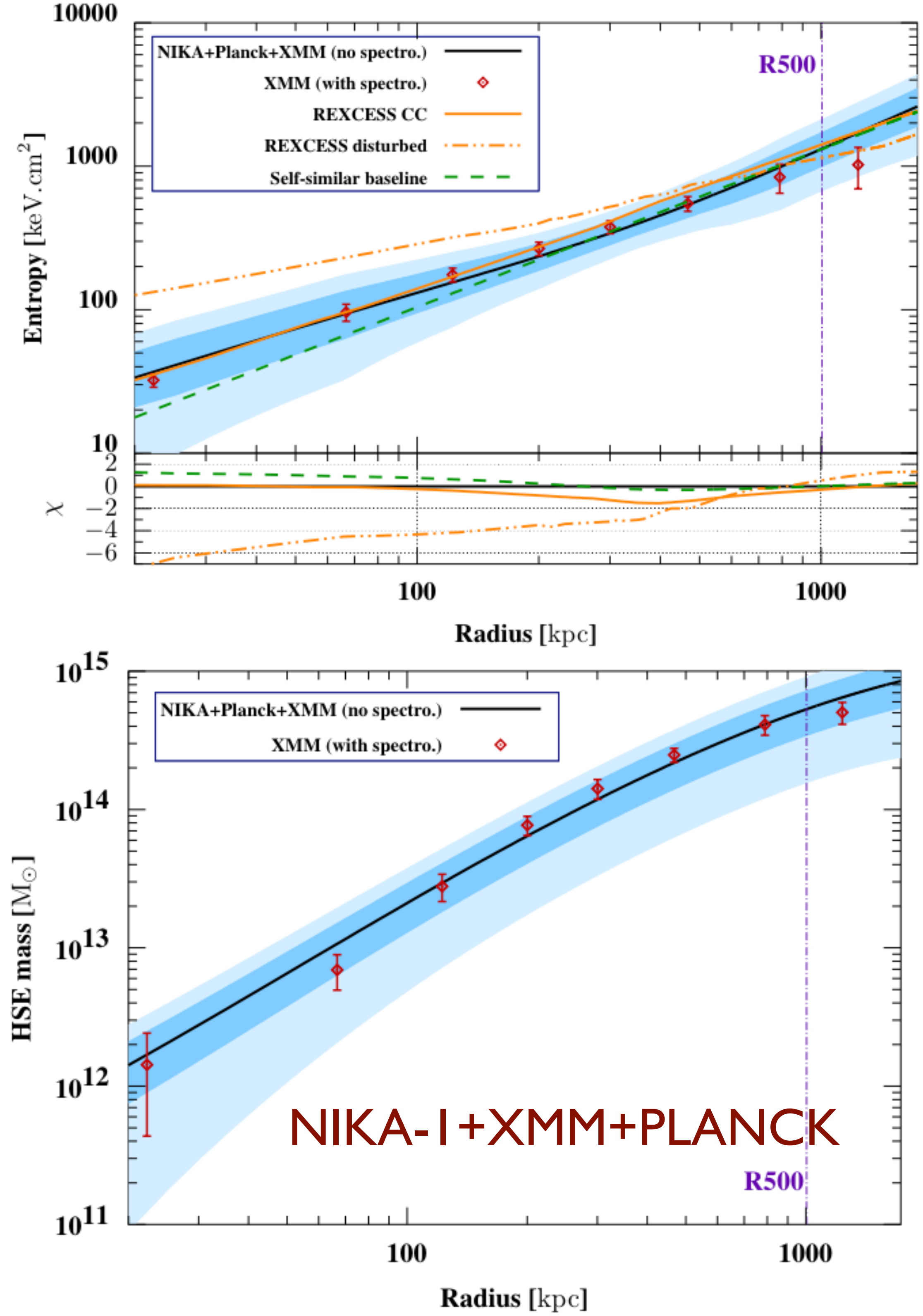
- NIKA-1 @ IRAM 30m
- 150 GHz, 18” FWHM

Gas thermodynamics at high z

- SZ+X-ray imaging
  - Pressure from SZ
  - Density from X-rays
- Derive all thermodynamical quantities:
  - Temperature (mass weighted), HE mass, Entropy, …

see talks by
F. Ruppin
F. Kéruzoré
I. Bartalucci

Ruppin+17



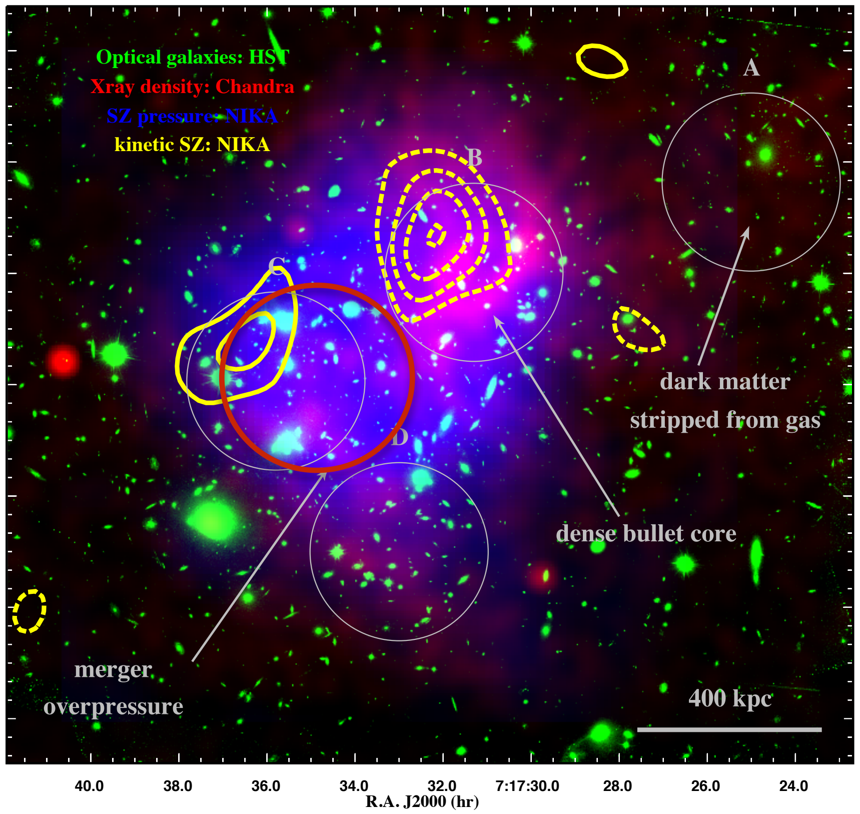
irap astrophysique & planétologie

Dynamics of clusters at high z

- MACS J0717.5+3745 at z=0.55
- A triple merger system with a complex dynamics

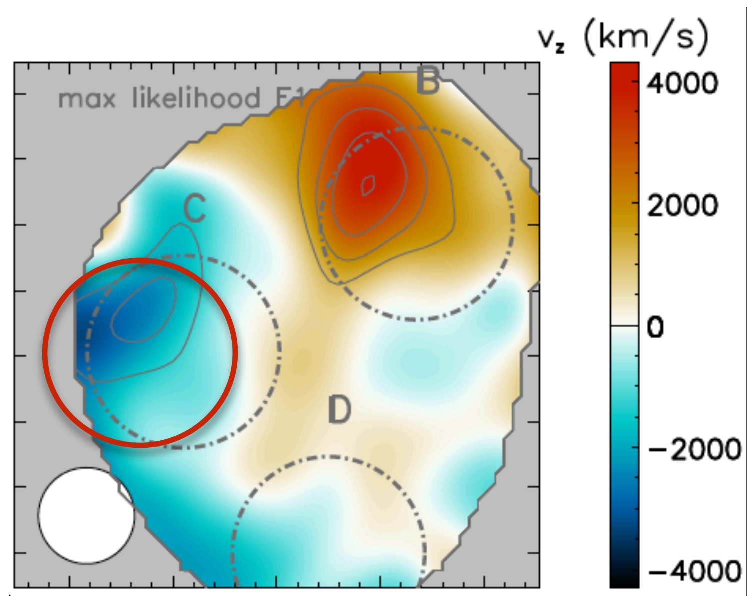
MUSTANG-1 @ GBT

Mroczkowski+2012

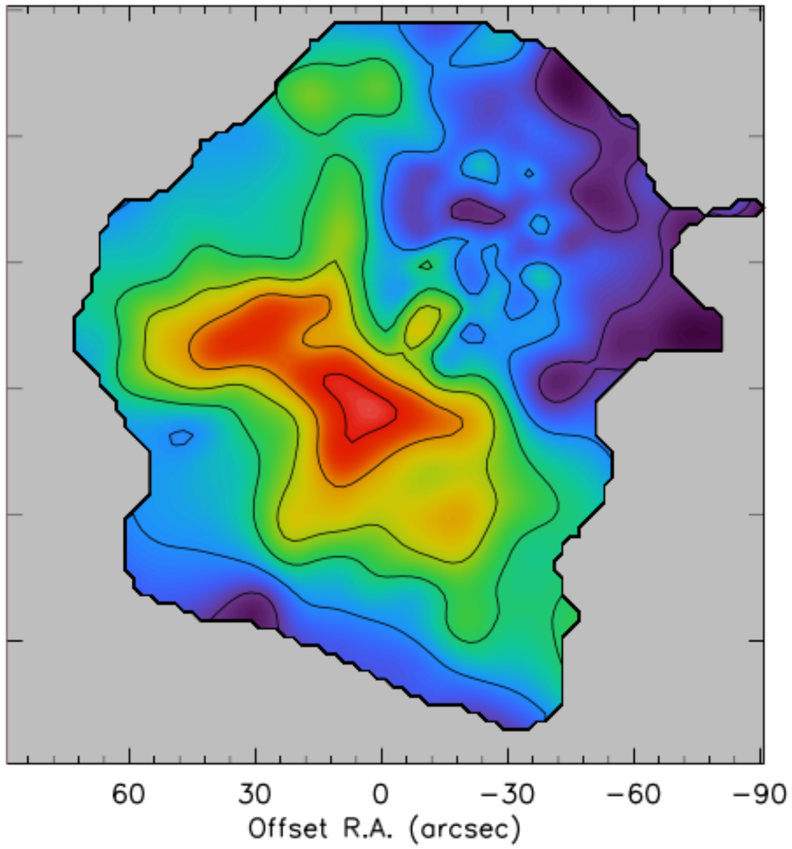


NIKA-1 @ IRAM 30m

Adam+2016



Adam+2017



Separate kSZ and tSZ with 2 bands

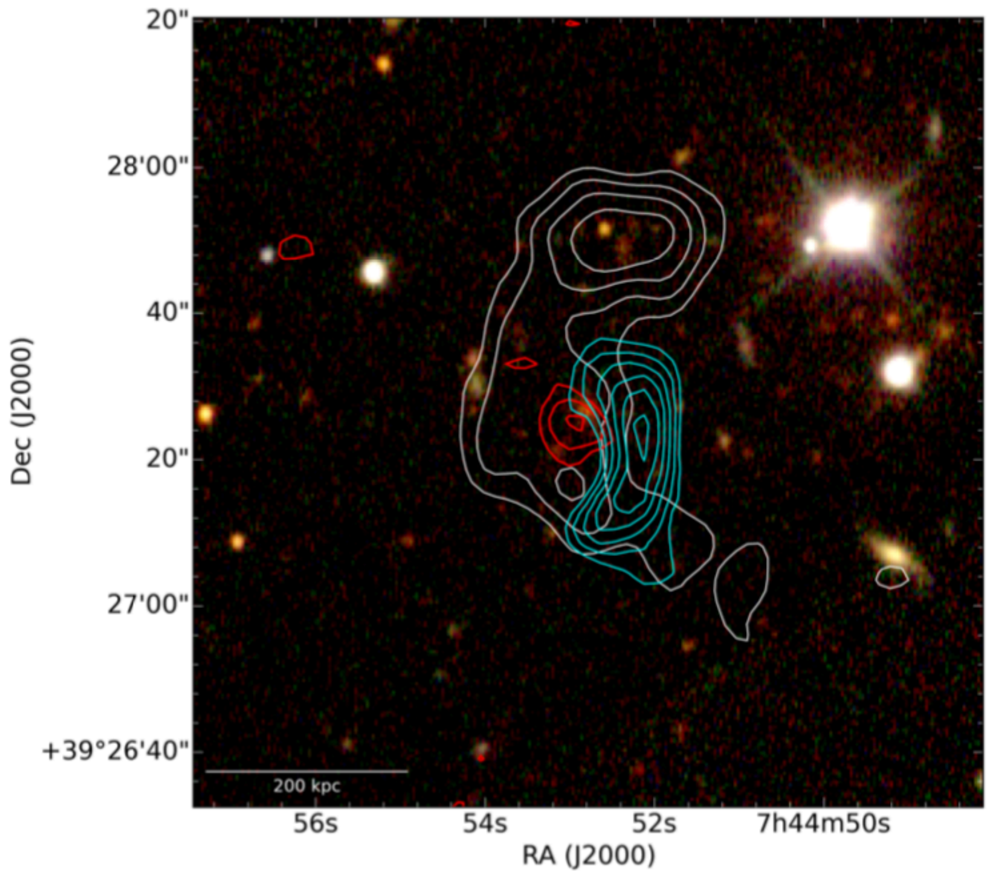
Map the bulk motions distribution

First temperature map

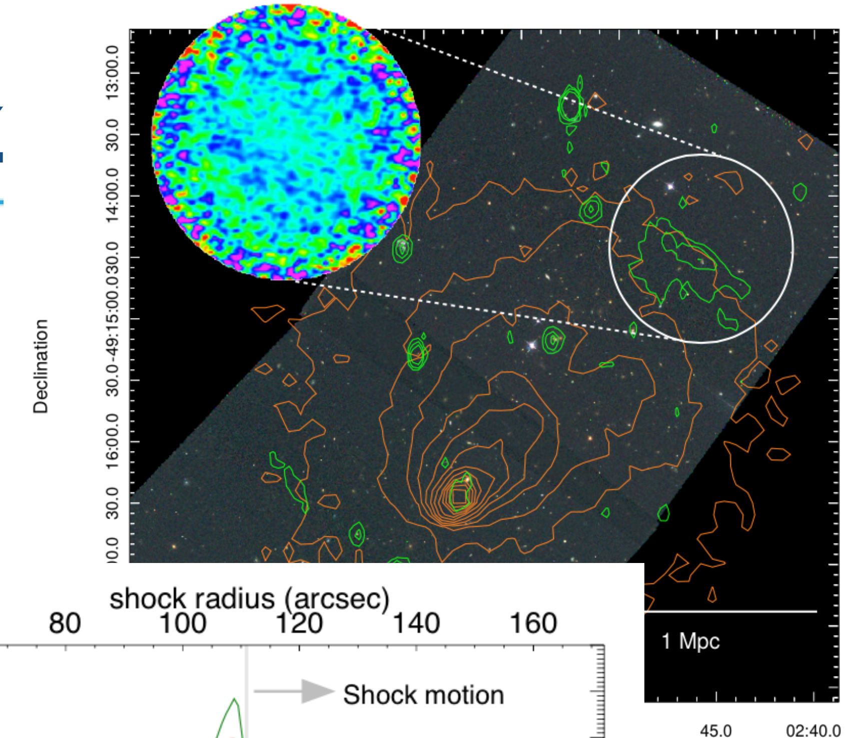
$$T_{gmw} \equiv \frac{y_{tSZ}}{\sqrt{S_X l_{eff}}}$$

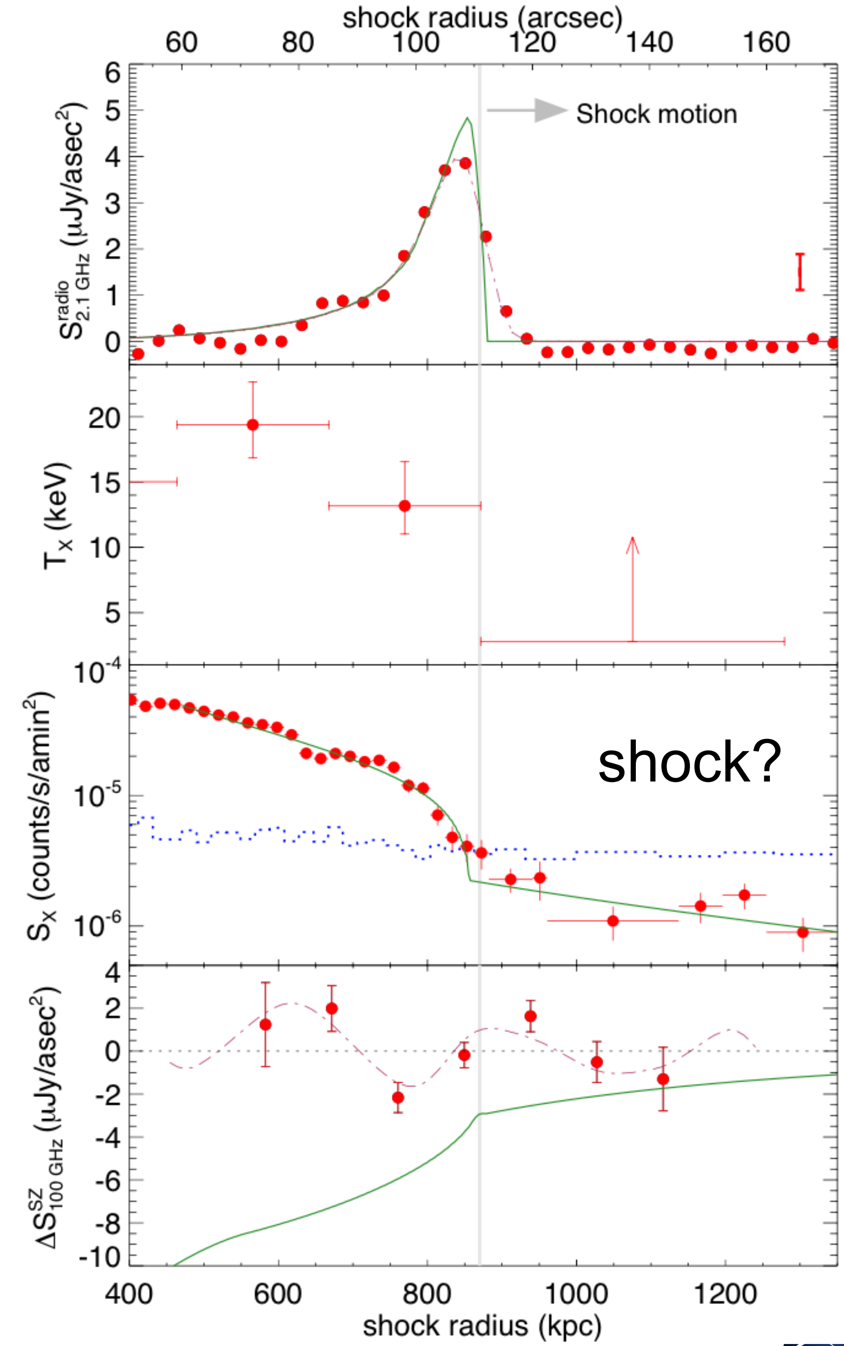
Dynamics of clusters at high z

- Shock detection in SZ+radio
  - MACS J0744.9+3927 (z~0.7)
  - Wilber+19, Korngut+11



Basu+16





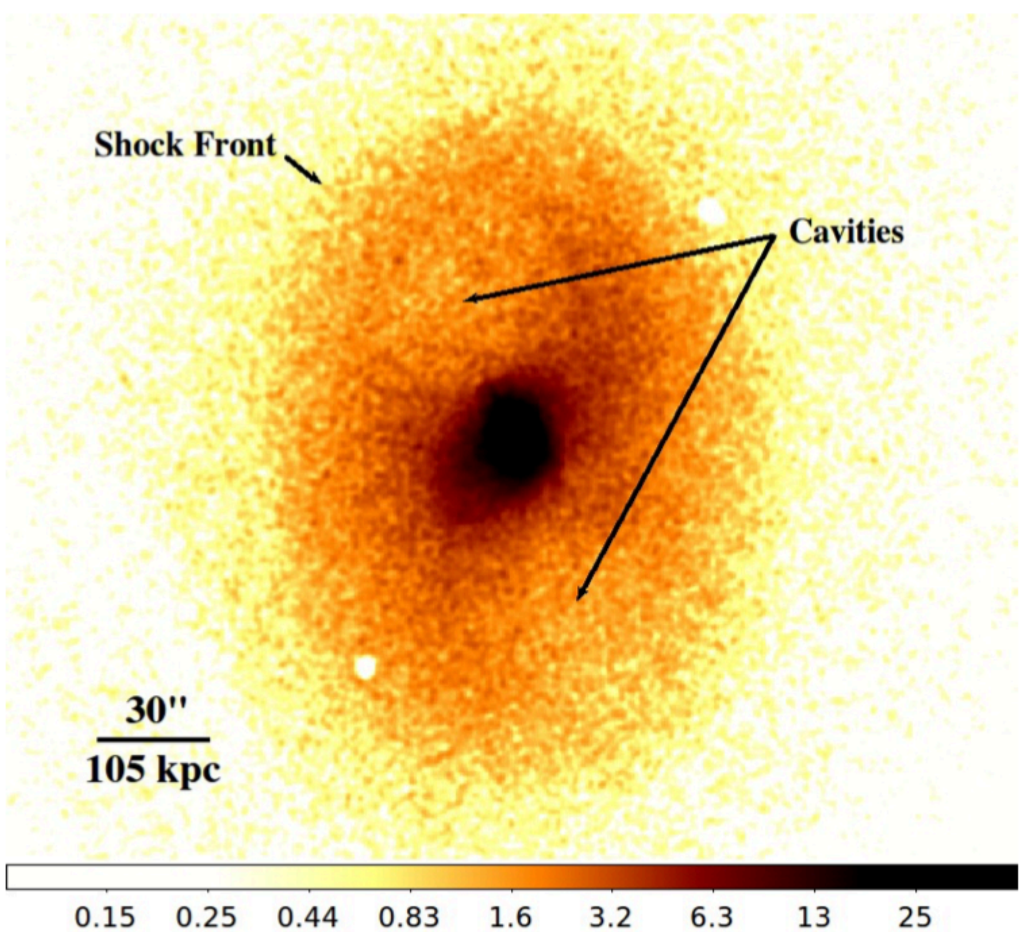
- Unambiguous detection of P jump at z~0.9 (El Gordo)
- Correlated to radio emission ⇒ B field

irap

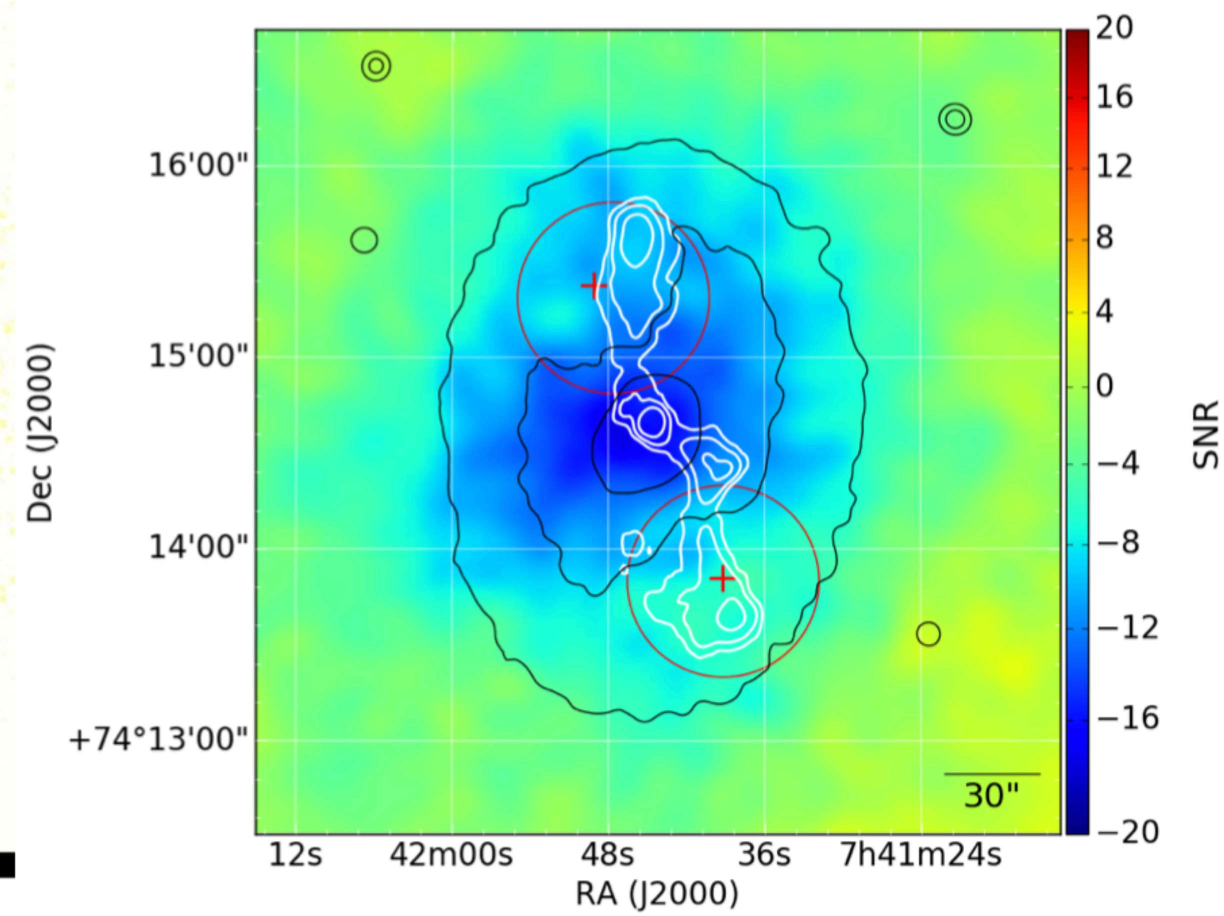
AGN feedback in clusters

- SZ can discriminate between thermal, non-thermal, and other sources of pressure support
- MS 0735.6+7421 @ z=0.216
-

Vantyghem+14



Abdulla+18



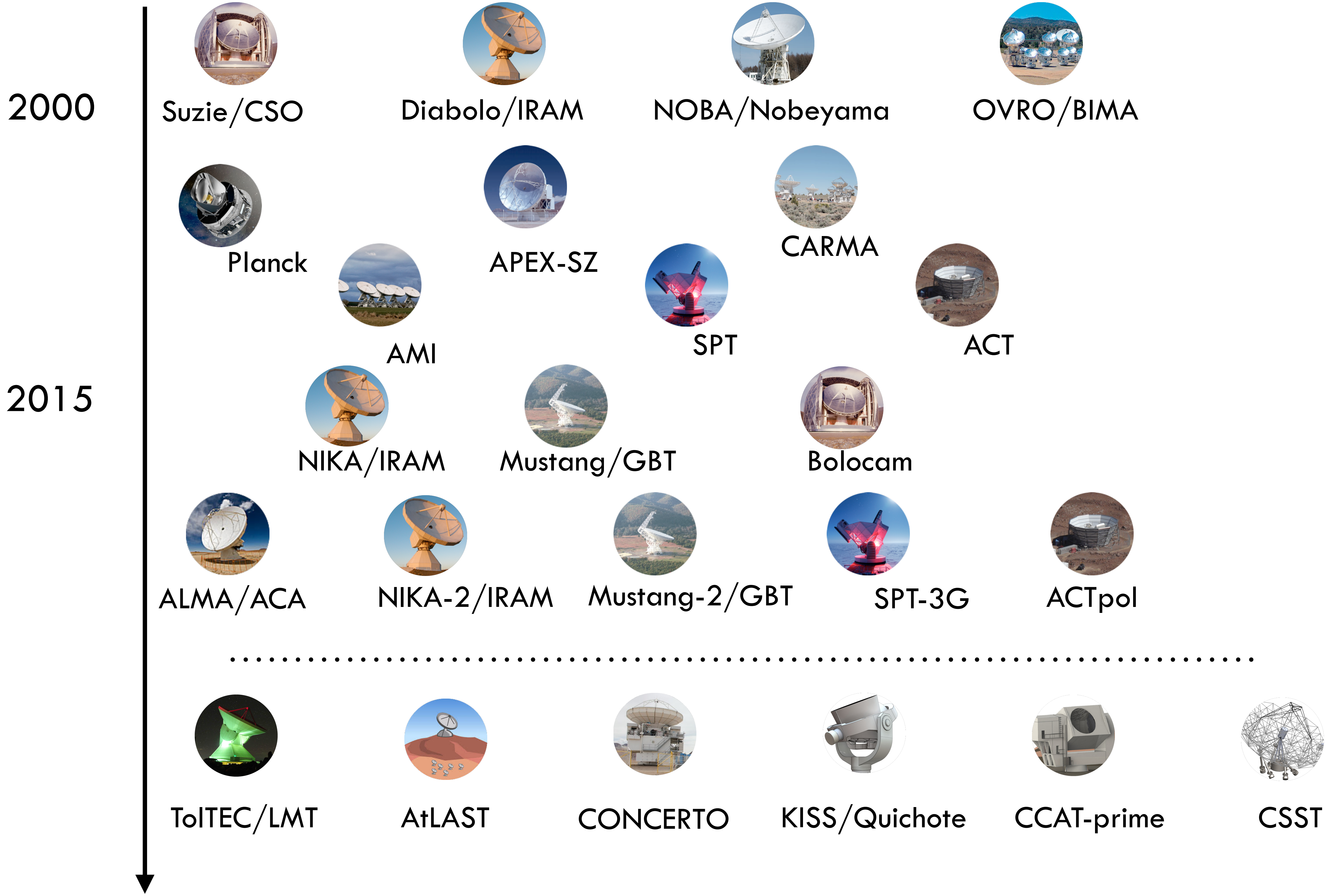
Take home messages

- The SZ effect reflect the physical state of the hot gas and is a good probe of gravitational physics
  - direct access to the gas pressure and velocity
- Joint X-ray/SZ imaging
  - Cheaper than X-ray spectroscopy at high z and high radii
  - Hot gaz thermodynamics
  - Assembly of structure
    - bulk motion (kSZ)
    - turbulence (brightness fluctuations)
  - Energetic of the AGN feedback
- Excellent match between the new generation SZ machines and XMM/ Chandra

The Sunyaev-Zeldovich effect from clusters of galaxies	*Dr. Etienne POINTECOUTEAU*	09:00 - 09:30
Planck SZ	*Dr. Juan Francisco MACIAS-PEREZ*	09:30 - 10:00
Cluster cosmology with the NIKA2 SZ Large program	*Prof. Frédéric MAYET*	10:00 - 10:30
Cartography of the ICM properties of the on-going merger MOO J1142+1527 at z = 1.2 from a joint analysis of NIKA2 and Chandra data	*Dr. Florian RUPPIN*	11:00 - 11:30
TBD	*Mr. Florian KÉRUZORÉ*	11:30 - 11:55
Extracting the thermal SZ signal from heterogeneous millimeter data sets	*Mr. Herve BOURDIN*	11:55 - 12:25
X-ray, SZ and dark matter in galaxy clusters	*Dr. Stefano ETTORI*	13:30 - 14:00
The X-COP project: Galaxy cluster reconstruction with joint X-ray and SZ data	*Dr. Dominique ECKERT*	14:00 - 14:30
Spectral imaging and pressure profiles of the X-COP galaxy clusters with the Sunyaev-Zel'dovich effect	*Anna Silvia BALDI*	14:30 - 15:00
The galaxy cluster mass scale	*Dr. Gabriel PRATT*	15:00 - 15:30
The MUSIC of Galaxy Clusters: A database of synthetic clusters from cosmological hydrodynamical simulations	*Prof. Gustavo YEPES*	16:00 - 16:30
Confirmation of NIKA2 investigation of the Sunyaev-Zel'dovich effect by using synthetic clusters of galaxies	*Prof. Marco DE PETRIS*	16:30 - 17:00
Exploiting the Plank legacy: properties of SZ-selected galaxy clusters at high-z and high-mass	*Dr. Mariachiara ROSSETTI*	17:00 - 17:30
Physics of Galaxy Cluster Outskirts	*Prof. Daisuke NAGAI*	17:30 - 18:00

- Review on the SZ effect: Mroczkowski et al. 2019 (arXiv:1811.02310)

SZ machines


2000
Suzie/CSO
Diabolo/IRAM
NOBA/Nobeyama
OVRO/BIMA
Planck
APEX-SZ
CARMA
AMI
SPT
ACT
2015
NIKA/IRAM
Mustang/GBT
Bolocam
ALMA/ACA
NIKA-2/IRAM
Mustang-2/GBT
SPT-3G
ACTpol
TolTEC/LMT
AtLAST
CONCERTO
KISS/Quichote
CCAT-prime
CSST