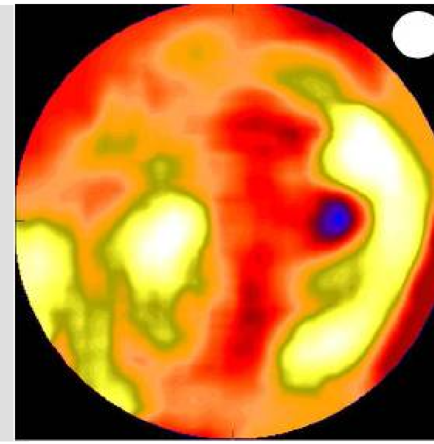
Astrophysics & Cosmology with the SZE in the Planck Era



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Cosmology with Cosmic Structures

UNIVERSE **Probes** **Tools** **Utensils**

DM-meter

DE-meter

G-meter

Jet-feedback

BHs

Baryons

B-field

Cosmic Rays

The Physics of the SZ Effect

The SZ effect is a specific form of Radiation-Matter interaction

Photon fields

~~Internal~~ External

↓ ↓

CMB

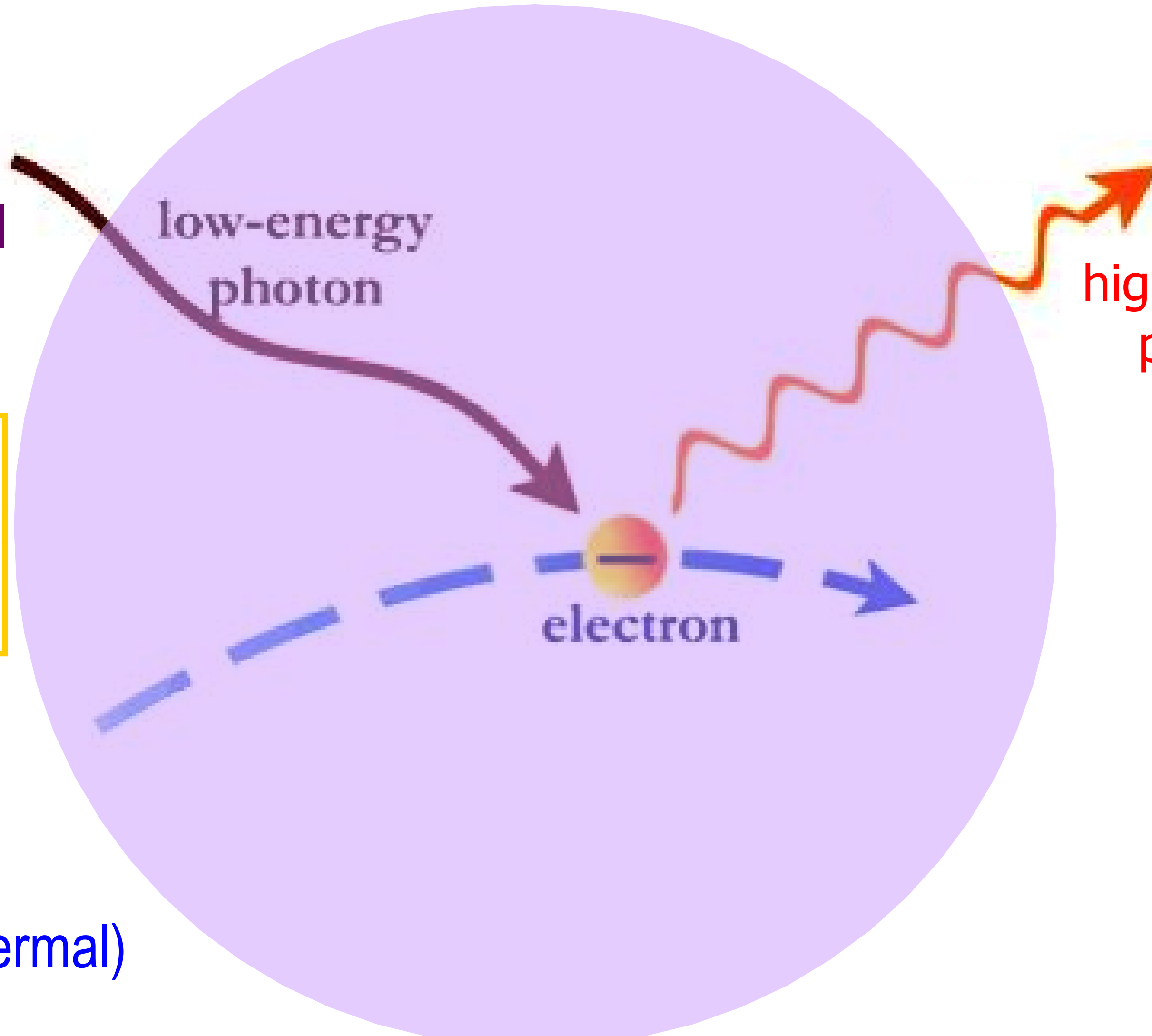
Use CMB photons to extract plasma information

↑

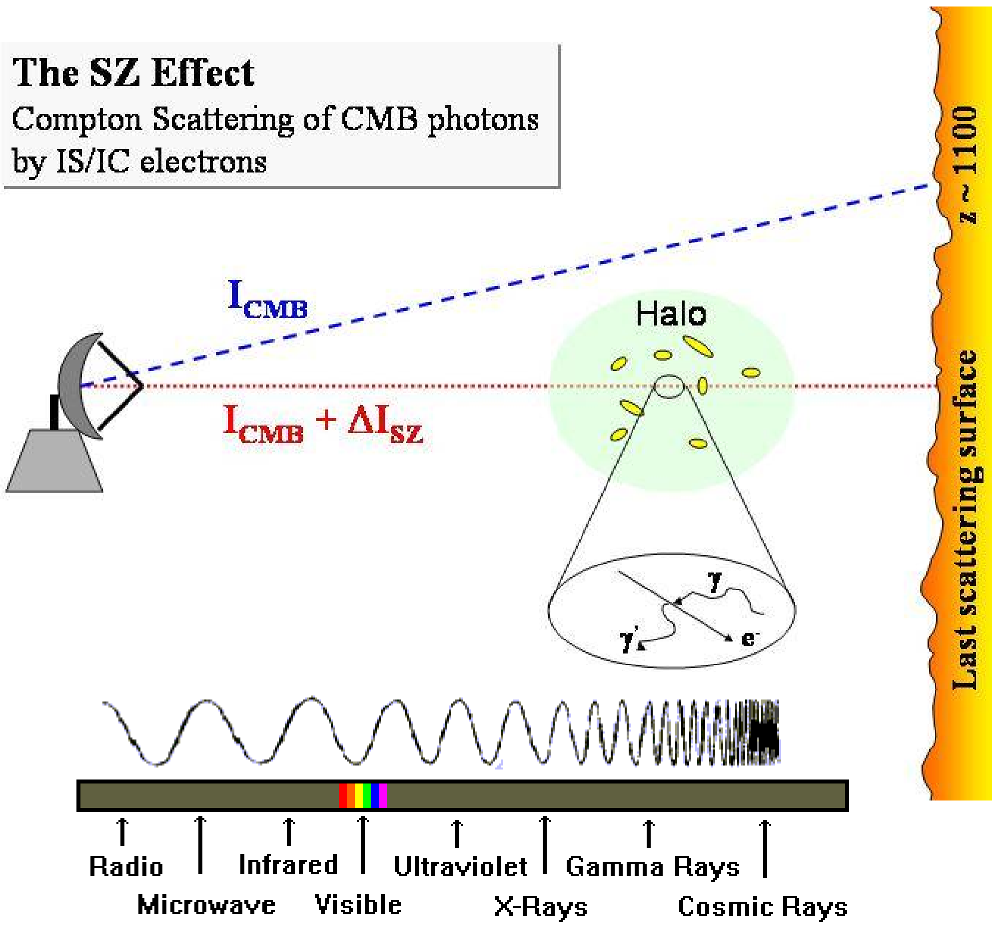
Internal

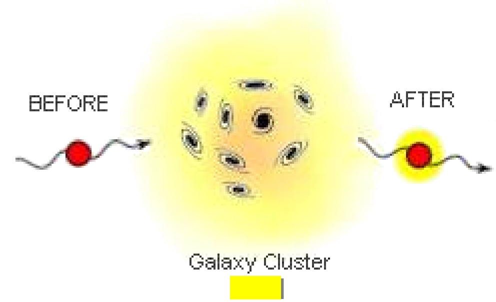
High-E electrons

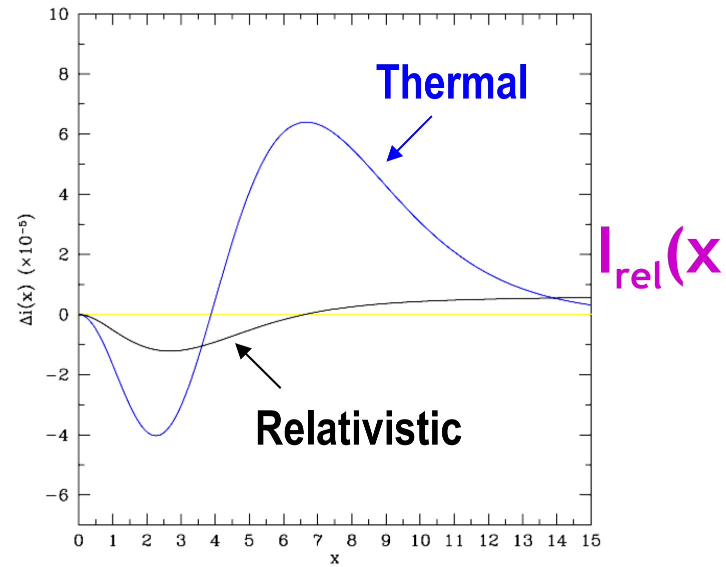
- thermal (supra-thermal)
- relativistic



SZE: general derivation







thermal NR e^- $\qquad \frac{\Delta \nu}{\nu} \approx 4 \frac{kT_e}{m_e c^2}$

relativistic e^- $\qquad \frac{\Delta \nu}{\nu} \approx \frac{4}{3} \gamma^2$

SZE: general derivation

[Colafrancesco et al. 2003, A&A, 397, 27]

Intensity change

$$\Delta I(x) = 2\frac{(k_B T_0)^3}{(hc)^2} y \bar{g}(x)$$

$$y = \frac{\sigma_T}{m_e c^2} \int P d\ell.$$

Pressure

- Thermal
- Relativistic

$$P_{th} = n_e k_B T_e$$

$$P_{rel} = n_e \int_0^{\infty} dp f_e(p) \frac{1}{3} p v(p) m_e c$$

Spectral shape

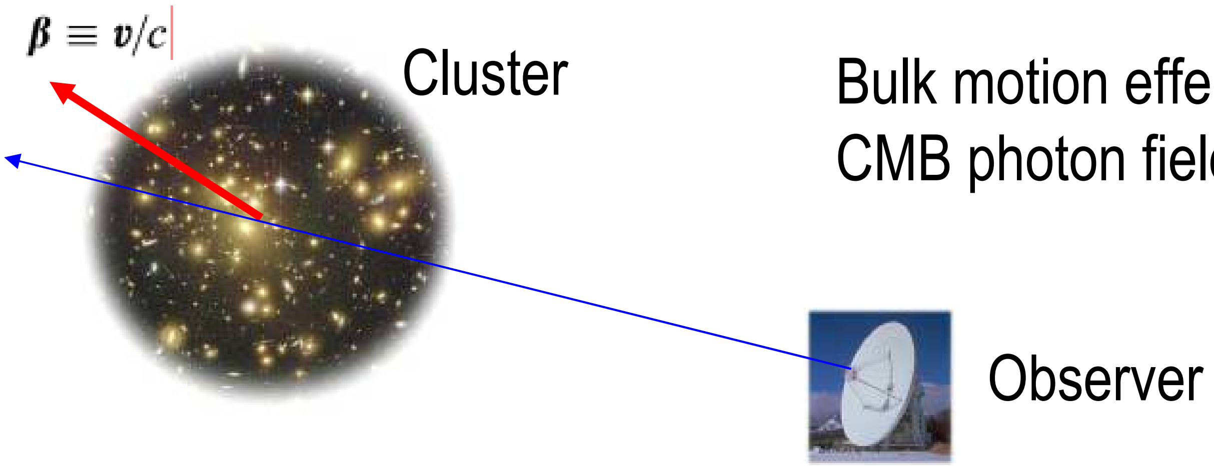
$$\bar{g}(x) = \frac{m_e c^2}{\langle k_B T_e \rangle} \left\{ \frac{1}{\tau} \left[\int_{-\infty}^{+\infty} i_0(x e^{-s}) P(s) ds - i_0(x) \right] \right\}.$$

$$\langle k_B T_e \rangle = \frac{\sigma_T}{\tau} \int P d\ell = \frac{\int P d\ell}{\int n_e d\ell}.$$

Redistribution function

$$P(s) = \int_0^{\infty} dp f_e(p) P_s(s; p)$$

SZE-kinematic: general derivation



Bulk motion effect of a gas cloud in the CMB photon field

Intensity change

$$\left.\frac{\Delta T}{T_0}\right|_{kin} = h(x) \cdot \frac{1}{m_e c} \int d\ell \sigma_T n_e p_p = h(x) \cdot \frac{p_e}{m_e c} \cdot \tau$$

Momentum

$$p_e = \gamma \cdot m_e v$$

Relativistic generalization

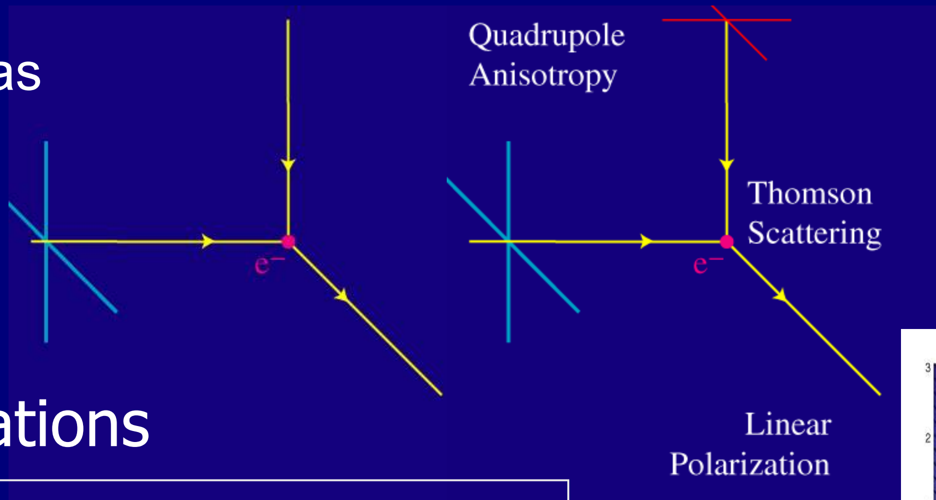
Spectral shape

$$h(x) = \frac{x^4 e^x}{\left(e^x - 1\right)^2} \left[1 + \kappa_{rel}(x)\right]$$

CMB spectrum

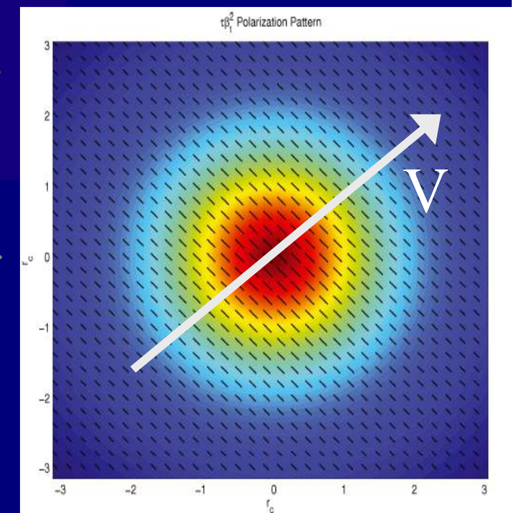
SZE: polarization

Polarizations arises as a natural outcome of γ-e scattering



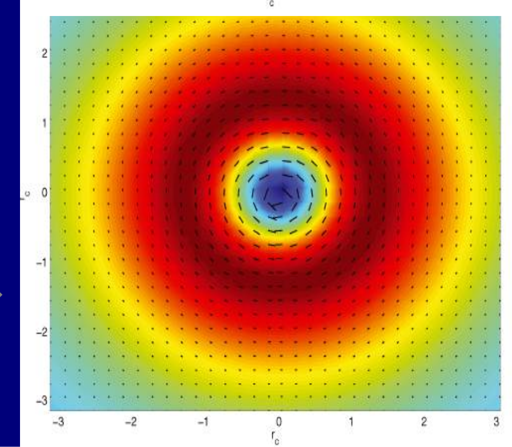
→ various polarizations

Polarization due to peculiar motion of clusters $\Pi_t \approx \beta_t^2 \tau$



Polarization due to transverse motions of plasma within the cluster $\Pi_V \approx \beta_t \tau^2$

Polarization due to multiple scattering γ-e within the cluster $\Pi_T \approx \left(\frac{kT}{m_e c^2}\right)\tau^2$



SZE polarization: general derivation

Relativistic covariant formulation [Colafrancesco & Tullio 2012]

Polarization matrix $Q_{ij} = \langle E_i E_j^* \rangle_T$

Stokes parameters

$$Q_{ij} = \begin{pmatrix} I+Q & U+iV \\ U-iV & I-Q \end{pmatrix}$$

General derivation (single scattering, Thomson limit)

$$Q'(p_1) = \frac{3}{16\pi} \int_{\hat{\mathbf{z}}} d\tau \int \frac{d^3\beta_e}{\gamma_e} f_e(\beta_e) \int d\Omega_2 \frac{n_{22} + \alpha_1 r_{12}}{(n_{12} n_{22})^2} I(\alpha_2; \vec{n}_2) \times$$
$$\times \left[\sin^2(\theta_2)\cos(2\phi_2) + 2\gamma_e \beta_e \frac{r_{12}}{n_{12}} \sin(\theta_2)\sin(\theta_e)\cos(\phi_2 + \phi_e) + \left(\gamma_e \beta_e \frac{r_{12}}{n_{12}}\right)^2 \sin^2(\theta_e)\cos(2\phi_e) \right]$$

$$U'(p_1) = \frac{3}{16\pi} \int_{\hat{\mathbf{z}}} d\tau \int \frac{d^3\beta_e}{\gamma_e} f_e(\beta_e) \int d\Omega_2 \frac{n_{22} + \alpha_1 r_{12}}{(n_{12} n_{22})^2} I(\alpha_2; \vec{n}_2) \times$$
$$\times \left[\sin^2(\theta_2)\sin(2\phi_2) + 2\gamma_e \beta_e \frac{r_{12}}{n_{12}} \sin(\theta_2)\sin(\theta_e)\sin(\phi_2 + \phi_e) + \left(\gamma_e \beta_e \frac{r_{12}}{n_{12}}\right)^2 \sin^2(\theta_e)\sin(2\phi_e) \right]$$

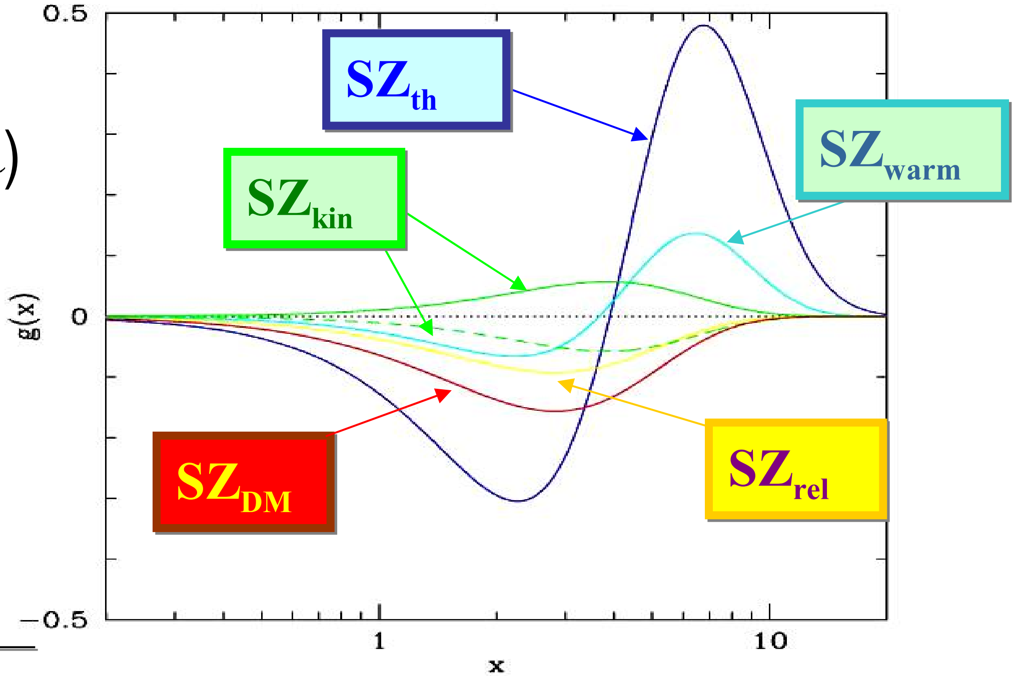
General derivation (multiple scattering, Thomson limit)

$$\tilde{I}(\vec{p}; \vec{v}_L) = I(\vec{p}; \vec{v}_L) + \int_{\hat{\mathbf{n}}} d\tau \int_{-\infty}^{\infty} P_1(s) \left[e^{3s} I_0(pe^{-s}) - I_0(p) \right] ds$$

SZE: spectro-kin. polarimetry

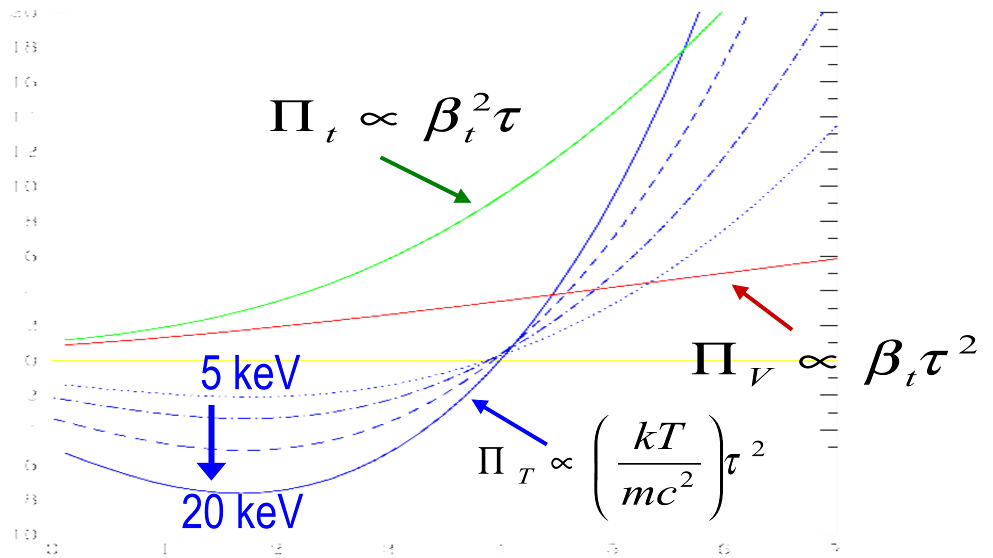
SZE Intensity:
sensitivity to projected (along the ℓ) physical parameters

τ, kT_e , P_e, E_e, M_χ, V_t



SZE polarization:
sensitivity to 3-D distribution of physical parameters

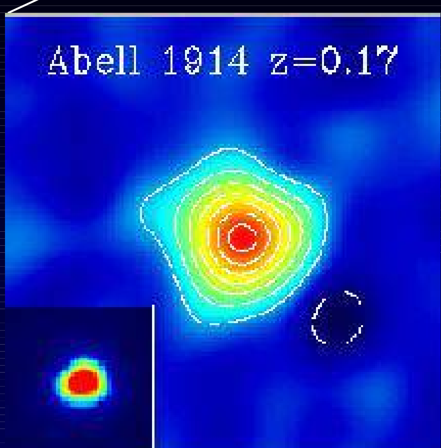
For a thermal plasma:
- Velocity sub-structure (β τ^2)
- Temperature sub-structure ($T_e\tau^2$)



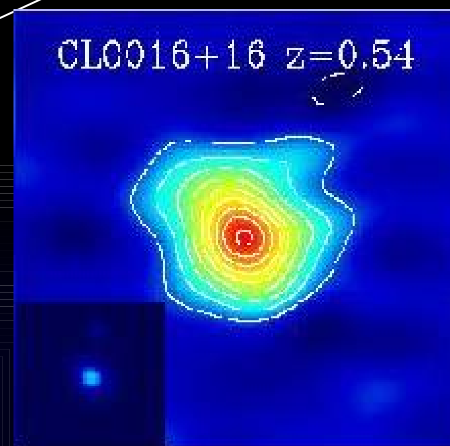
Astrophysics & Cosmology

The SZE is independent of redshift and therefore it is an optimal tool for Cosmological applications

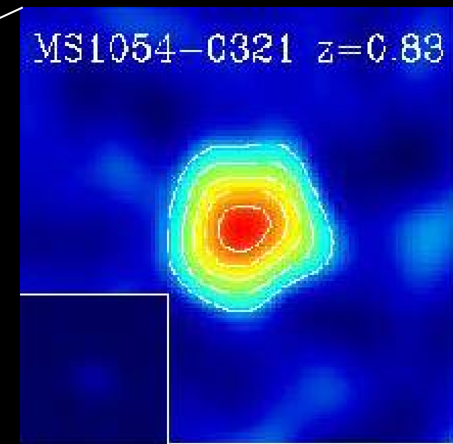
Standard-rod "physical" effect



X-rays



X-rays



X-rays

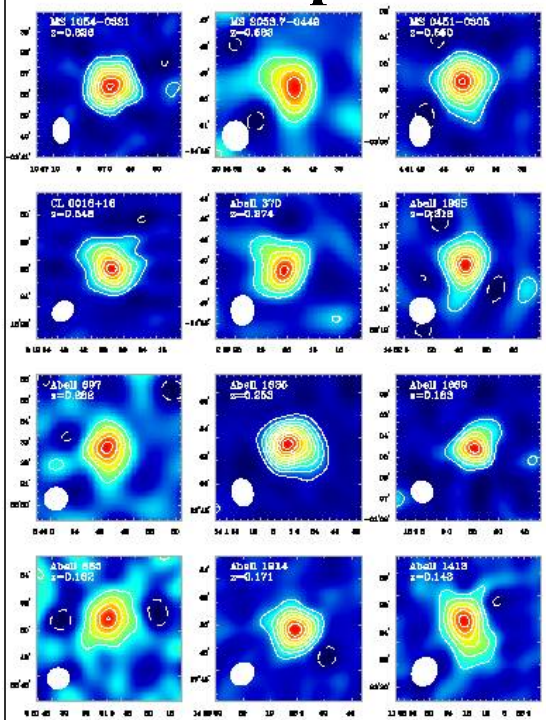
The SZE depends directly on the electron distribution in the atmospheres of cosmic structures and therefore it is an optimal tool for Astrophysical applications

Cosmic Lepto-meter, Speedo-meter

Pre-PLANCK Era

Simple Observables

Shape



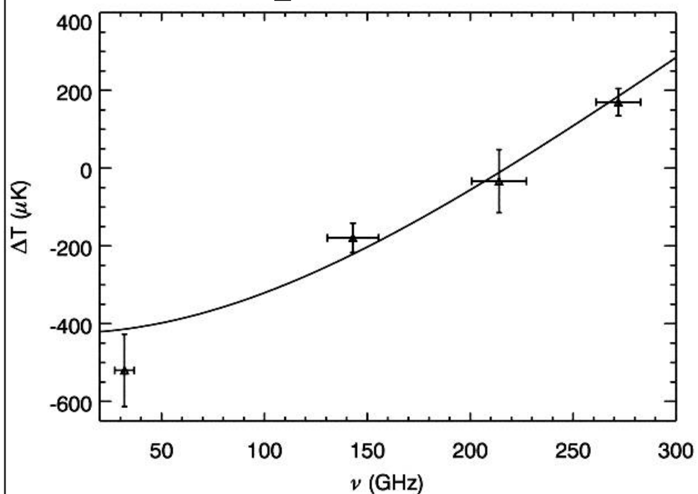
OVRO (30 GHz)

SZE has larger angular size than X-ray image

$$L_X \sim n^2(r)\ T^{1/2}$$

$$Y_{SZ} \sim n(r)\ T$$

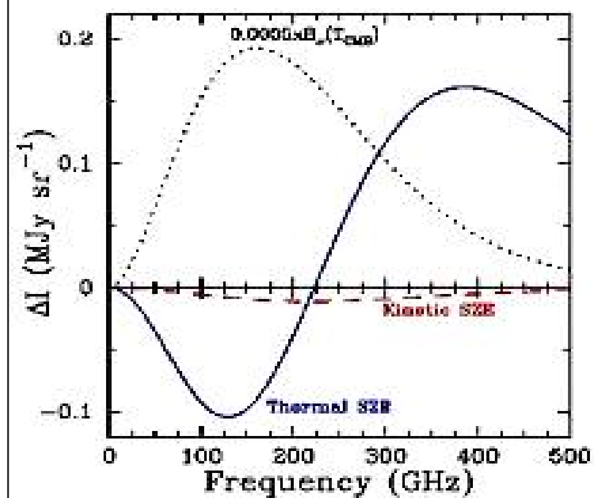
Spectrum



First SZE spectrum Coma cluster (MITO exp.) (DePetris et al. 2002)

- **Spectrum observed in a few bands (30, 150, 220, 275 GHz)**
- **The zero near the peak of CMB spectrum (~ 220 GHz)**

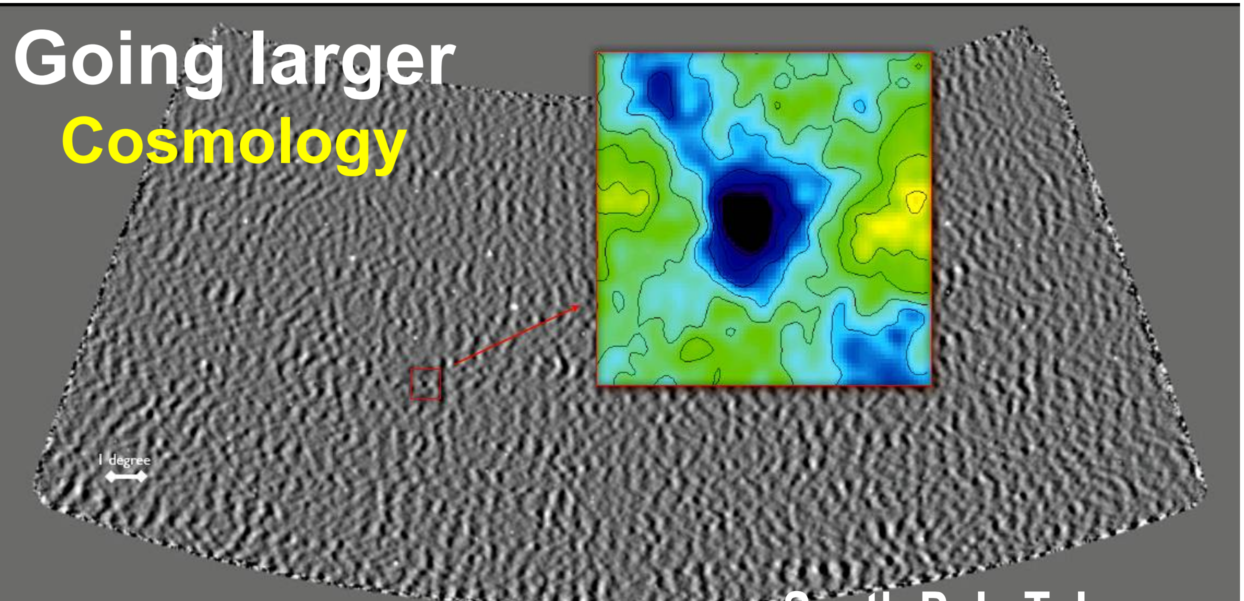
Kinematic



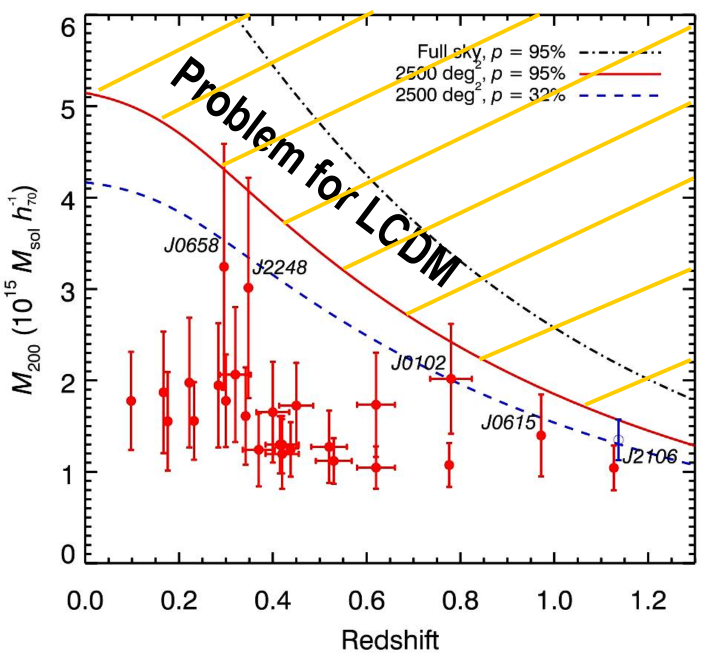
- **Small compared to thermal SZE at low ν**
- **No zero (CMB spectrum)**
- **Confused by primordial CMB structure**
- **No detection**

Pre-PLANCK Era

Going larger
Cosmology



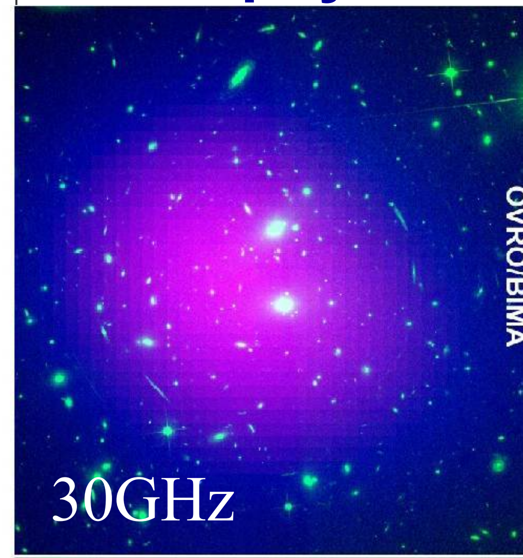
South Pole Telescope
150 GHz

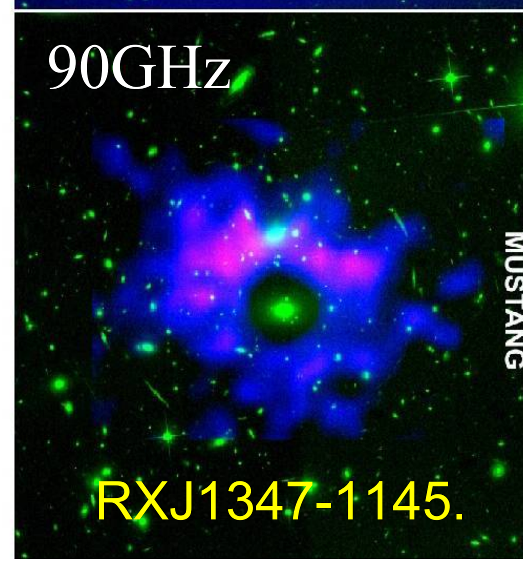


SZE-selected samples dominated by disturbed clusters

Contaminating point sources (AGN, star forming galaxies)

Going deeper
Astrophysics





Pre-PLANCK Era

$$\Delta I_{th} = 2\frac{(kT_0)^3}{(hc)^2} y_{th} g(x)$$

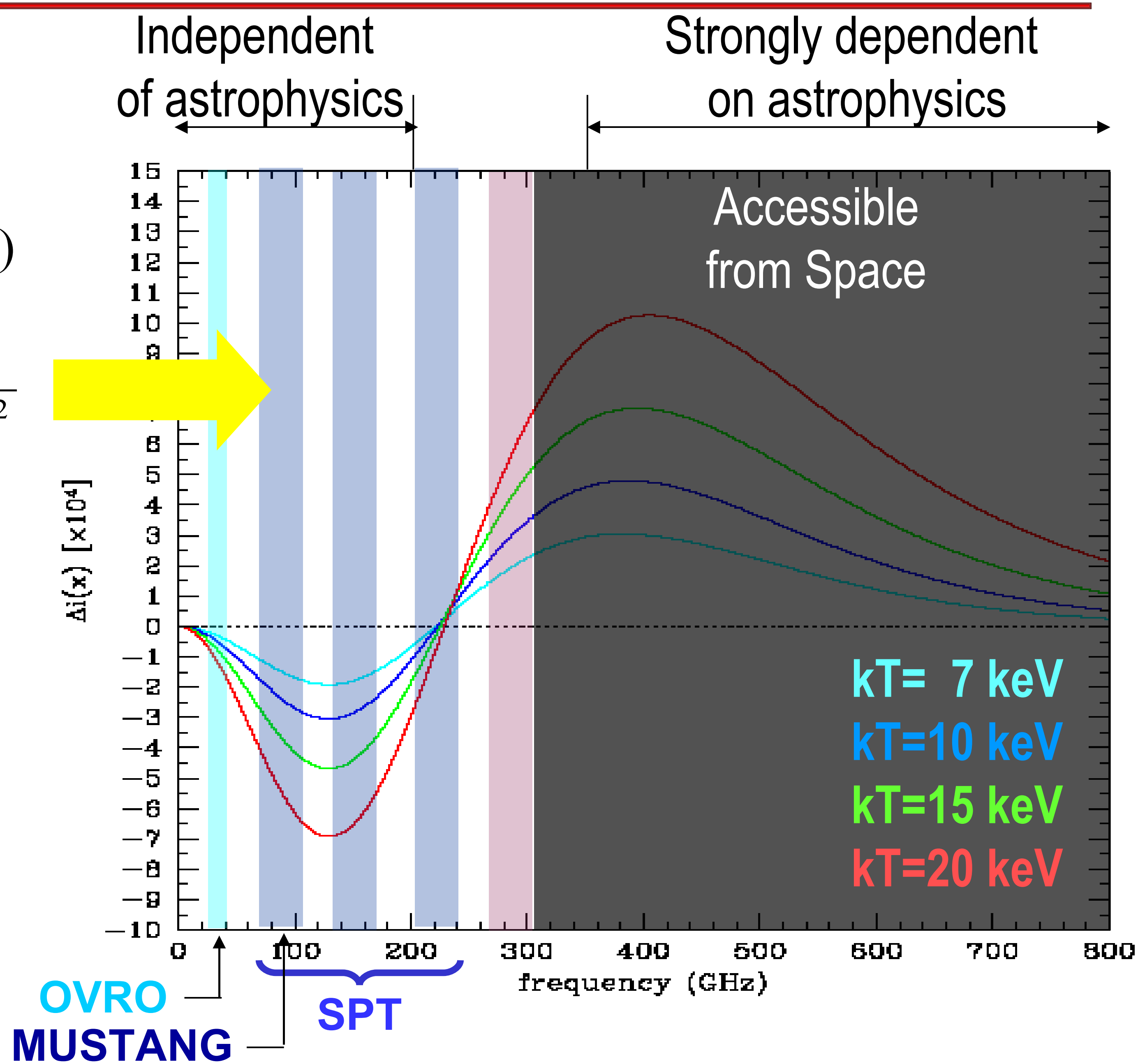
$$y_{th} = \sigma_T \int d\ell n_e \frac{kT_e}{m_e c^2}$$

Need external priors

- X-ray □ kT
- WL □ M
- O □ z

for a proper use in

- Cosmology
- Astrophysics



PLANCK-Era

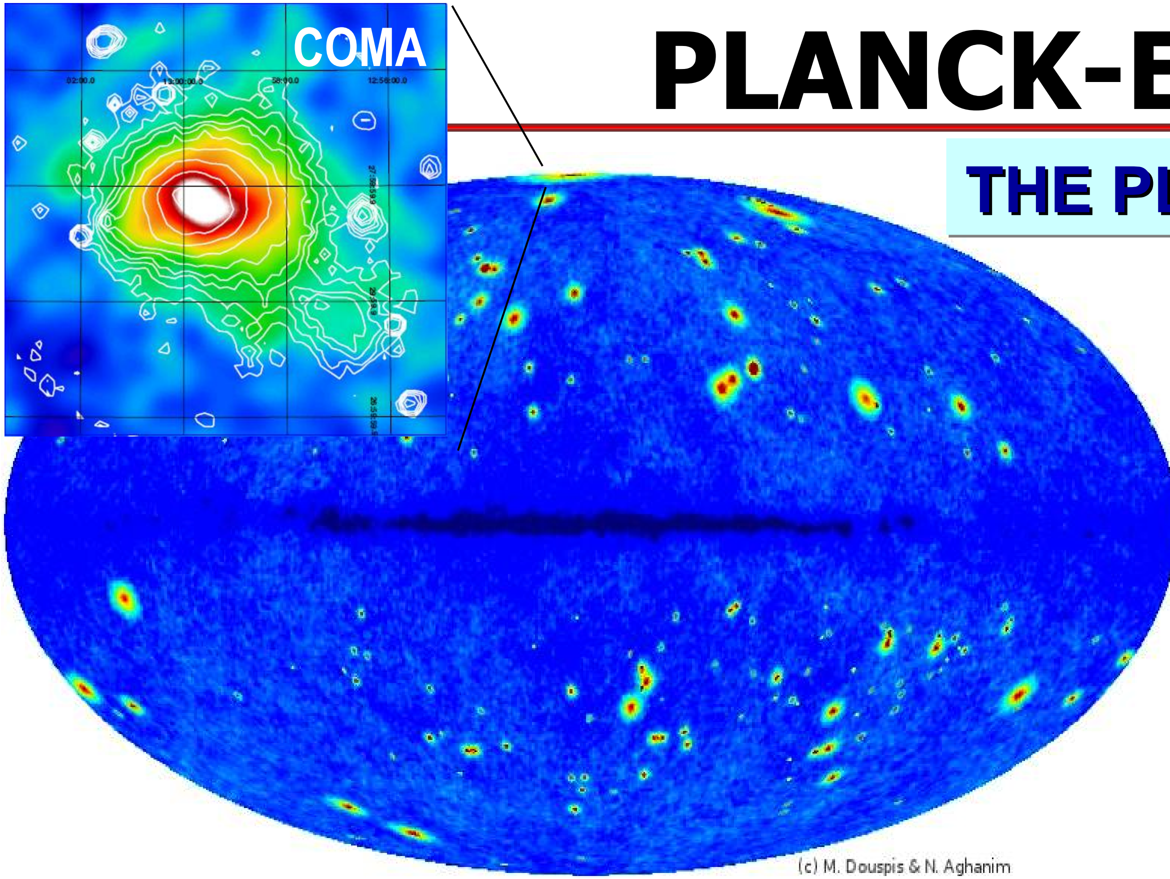
THE PLANCK MISSION

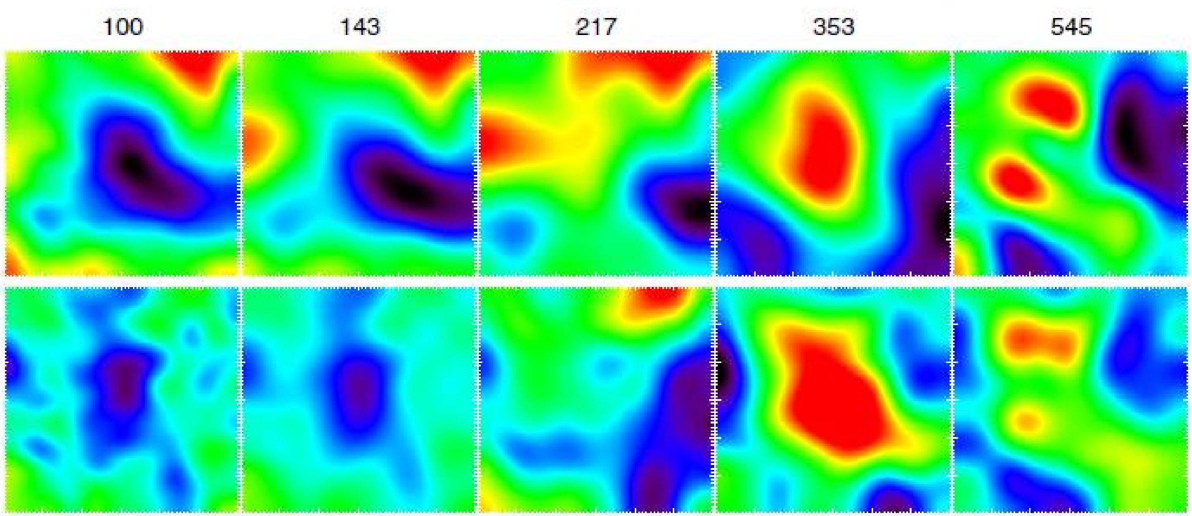
- Launch in May 2009 ; L2 orbit
- 1.5 m gregorian telescope
- 9 frequency bands 30-857GHz
- $\sim$ 5-30 arcmin resolution
- LFI 22 radiometers, 3 frequencies
- HFI 72 bolometers+thermometers cooled down to 0.1 K, 6 frequencies
- nominal mission = 2 full sky surveys
- extended mission = 4 surveys+

THE HERSCHEL MISSION

- 3.5 m telescope
- HIFI: high-resolution spectrometer
- PACS Camera & Spectrometer
- SPIRE: FTS spectro-photometer

PLANCK-Era





Coma, S/N=21.93

THE PLANCK EARLY SZ SKY

189 SZ sources (S/N > 6)

- First SZE measure for ~ 80% of known clusters
- 37 new clusters

Detection of SZ clusters

- Multi-matched filter
- Internal validation
- Ancillary data
- Follow-ups
  - X-rays (XMM-Newton)
  - SZ (AMI)
  - Optical (ESO, NOAO,...)
  - Confirmation
  - Redshift estimation
  - Global physical parameters

PLANCK-Era

NEW DETECTED CLUSTERS

8 unconfirmed ESZ candidates

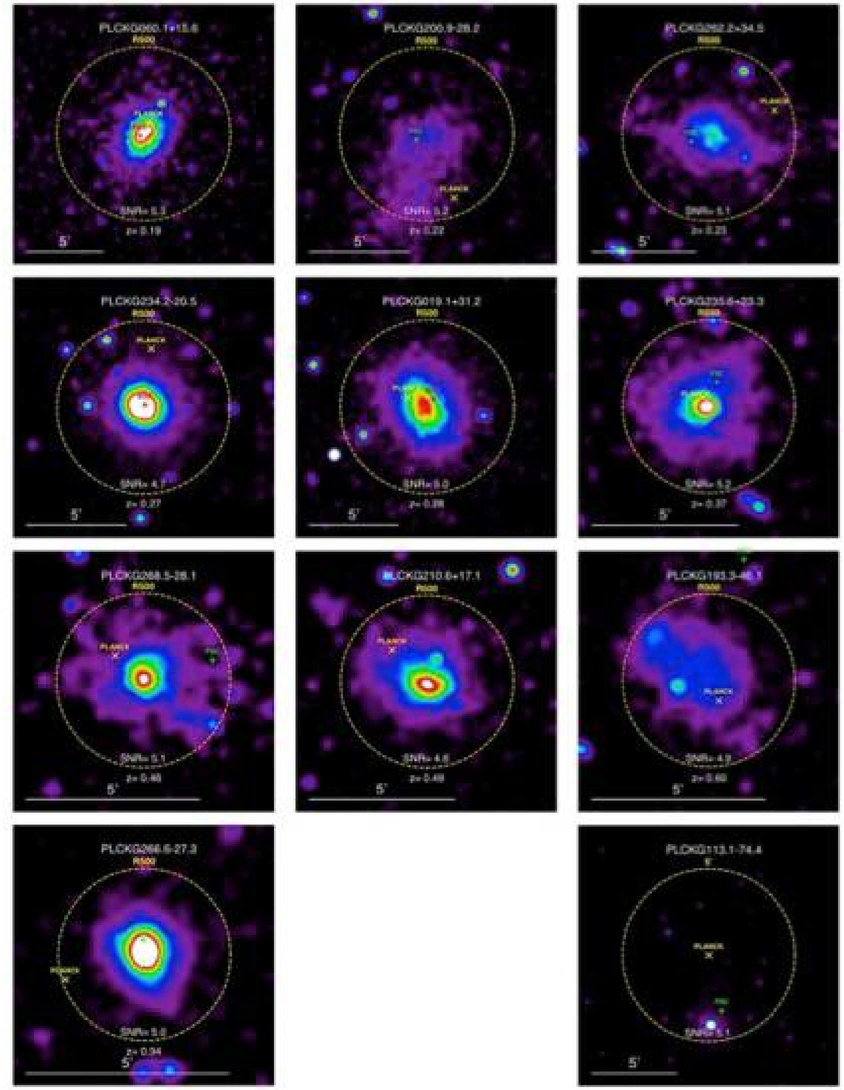
- 7 confirmed by third party (SPT, AMI)

XMM-Newton DDT program

- maximize the synergy between the two ESA missions
- short snapshot exposures (10ksec)
- high success rate (>85%)
- 27 single clusters
- 2 double systems
- 2 triple systems

- 37 new clusters with XMM-Newton

+ 15 SZ targets for validation run 4



(Validation run 3)
[Pointecouteau 2012]

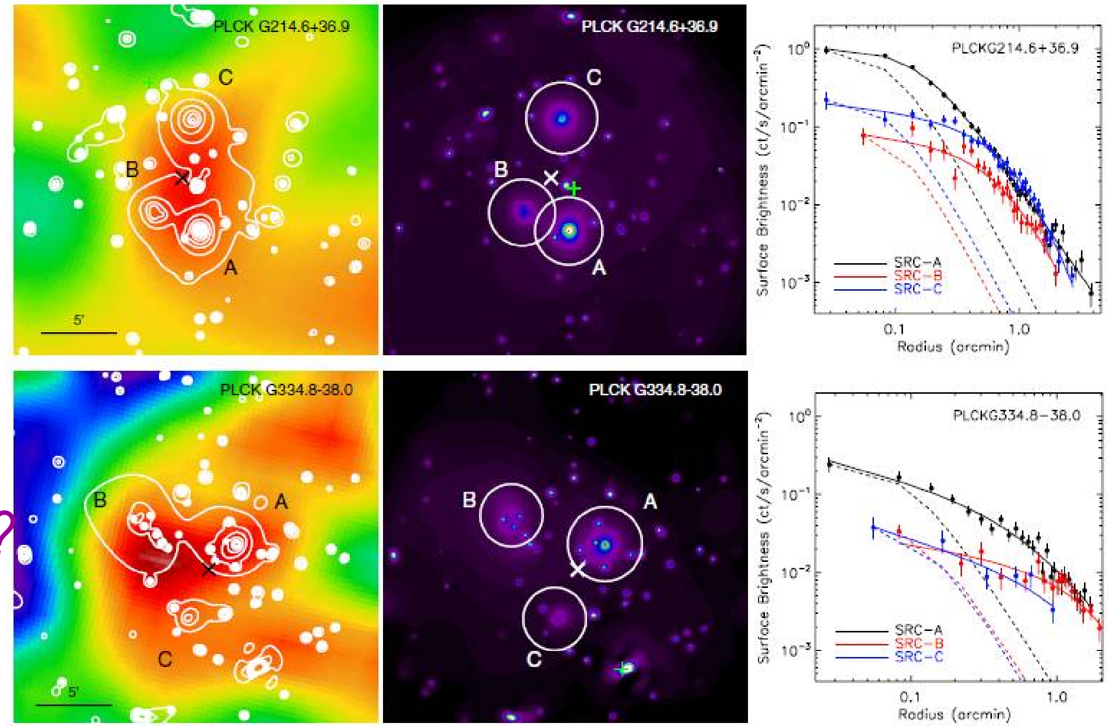
PLANCK-Era

Multiple SZE systems

SZE-selected samples are dominated by disturbed clusters

Question:

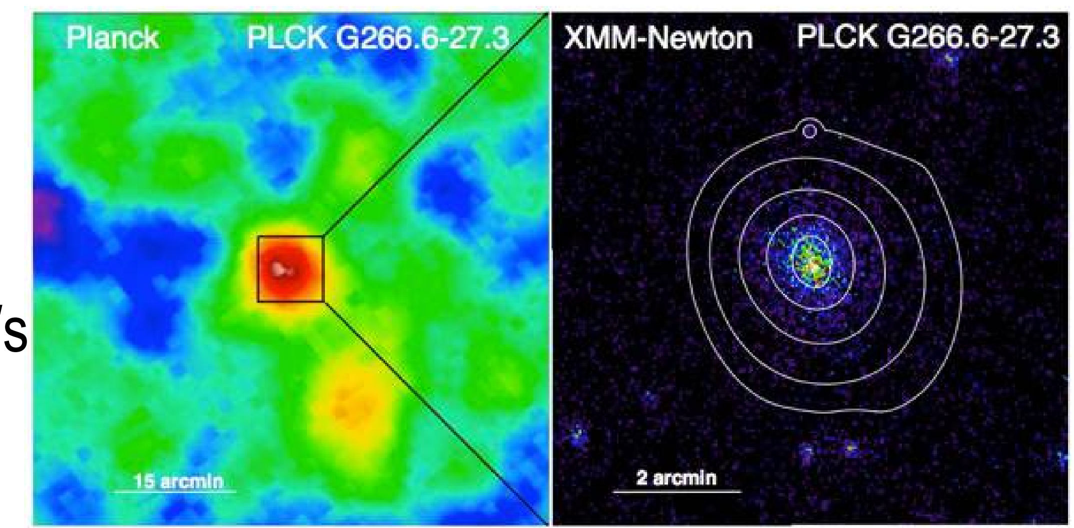
How much does merger activity bias (scatter) the SZE cluster samples, as a function of M & z ? i.e. affects Cosmological use?



Distant clusters via SZE

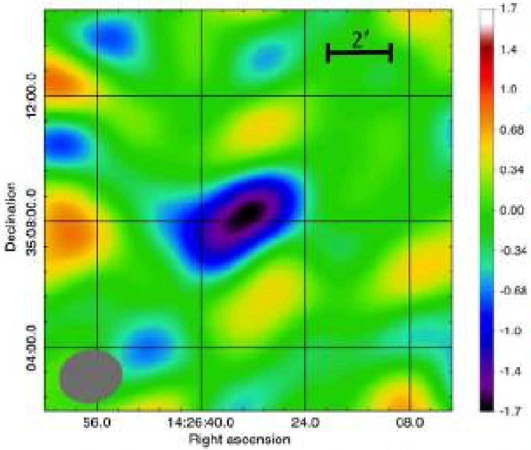
PLCK G266.6-27.3

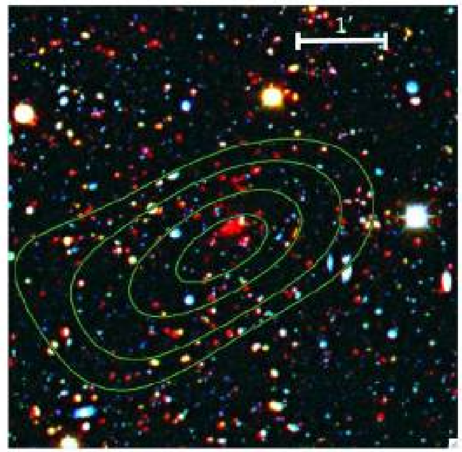
- SNR = 5
- z_{FeK}=0.94
- L_X[0.5-2keV]=(1.4±0.5)×10^{45} erg/s
- M_{500}=(7.8±0.8)×10^{14} $M_\odot$
- Highly relaxed

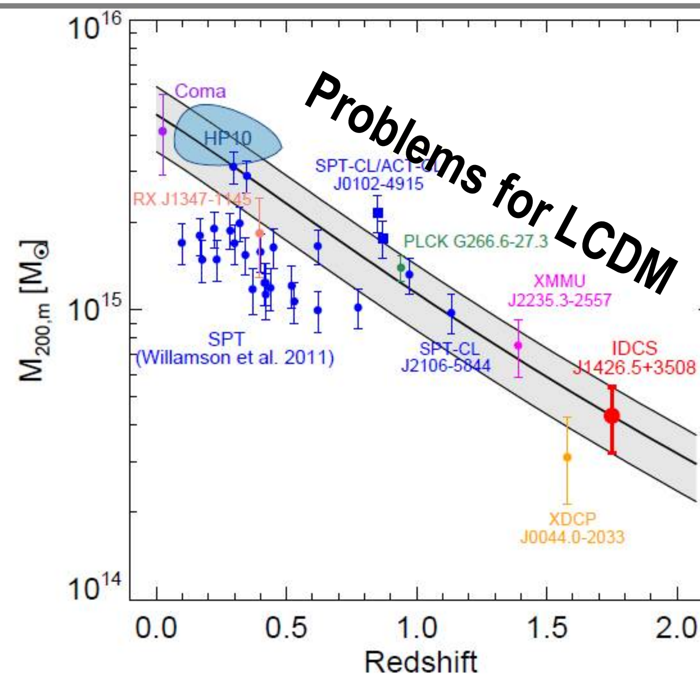


SZE: other results in the PLANCK-Era

Very distant clusters with CARMA (31 GHz)
IDCSJ1426.5+3508 (z=1.75)

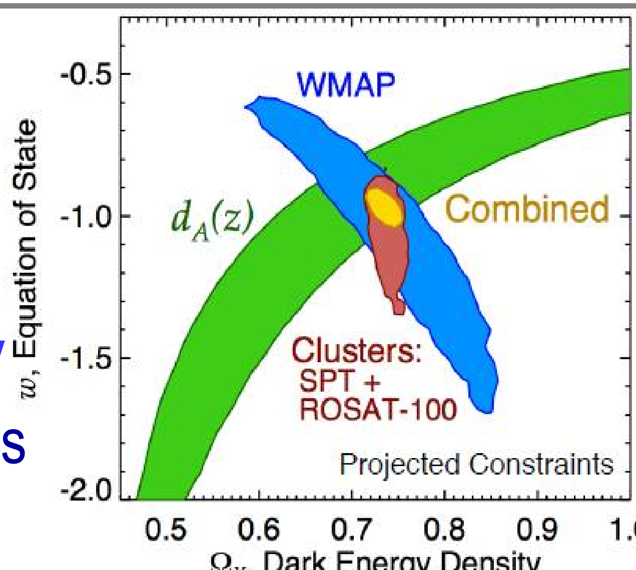


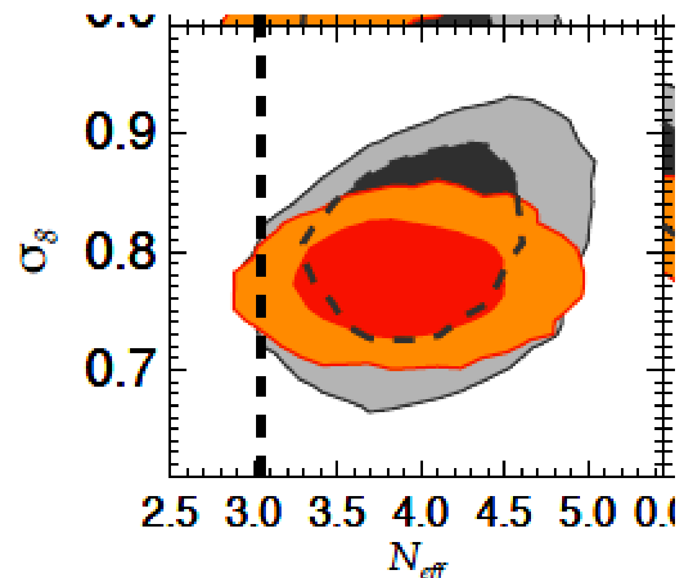




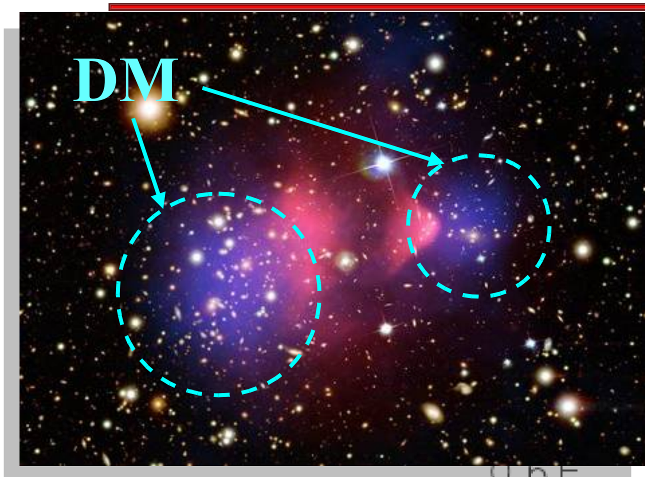
SPT: 450 clusters

- Δw ~ 5%
- 2-σ preference for non-zero mν
  $\sum$m=0.34 +/-0.17 eV
  and an extra ν species
  Neff=3.91+/-0.42

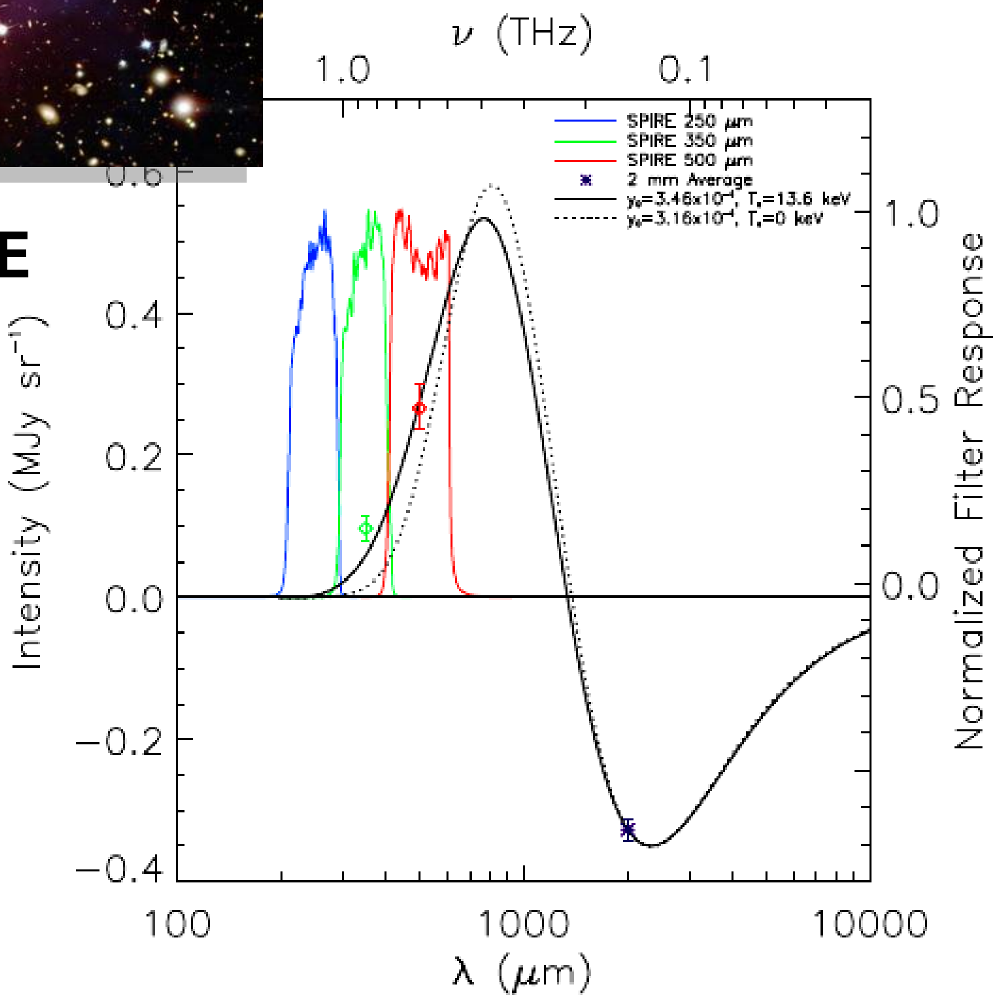


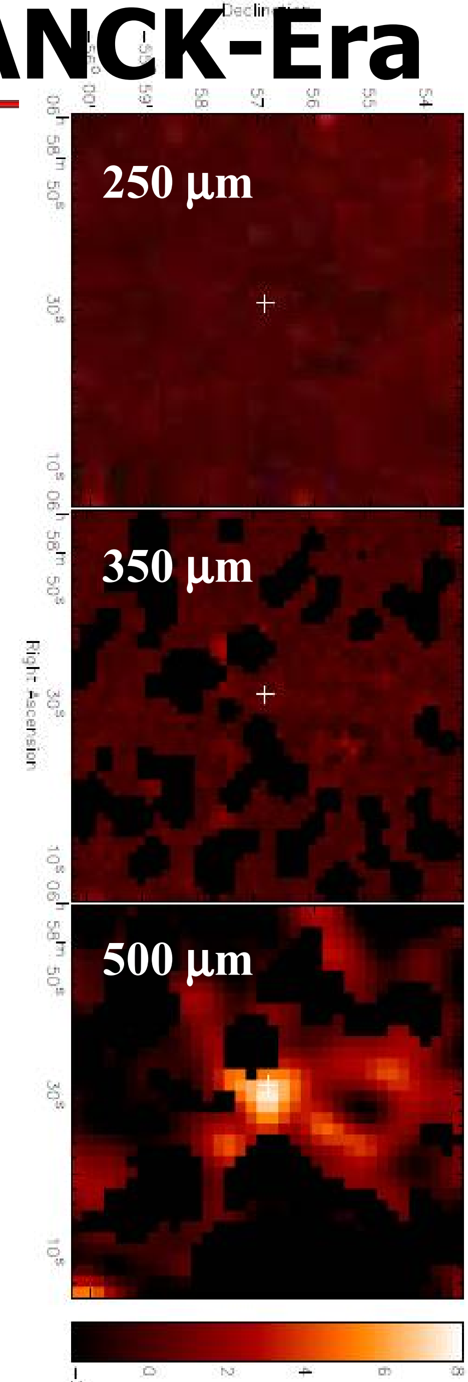


SZE: other results in the PLANCK-Era

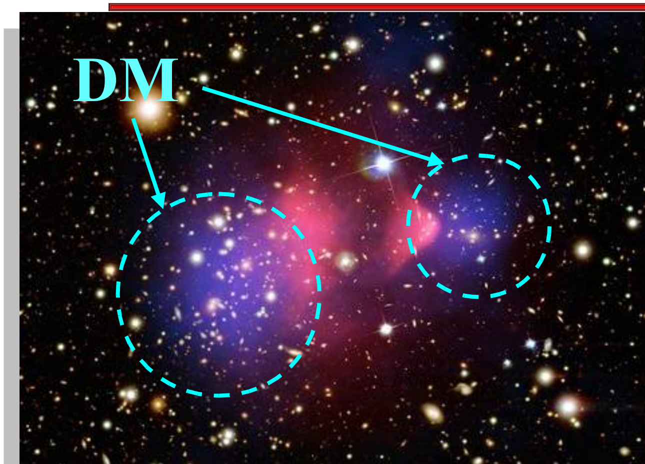


Herschel SPIRE view of the Bullet cluster

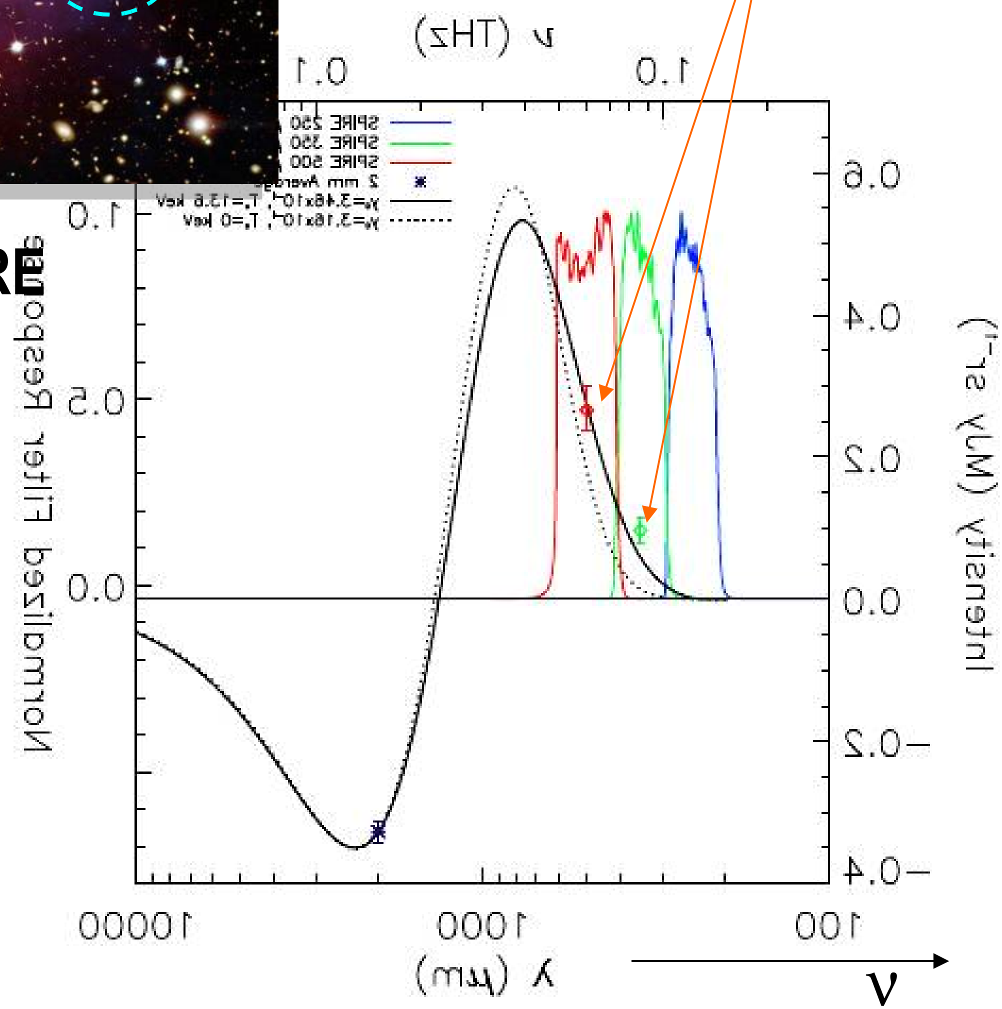




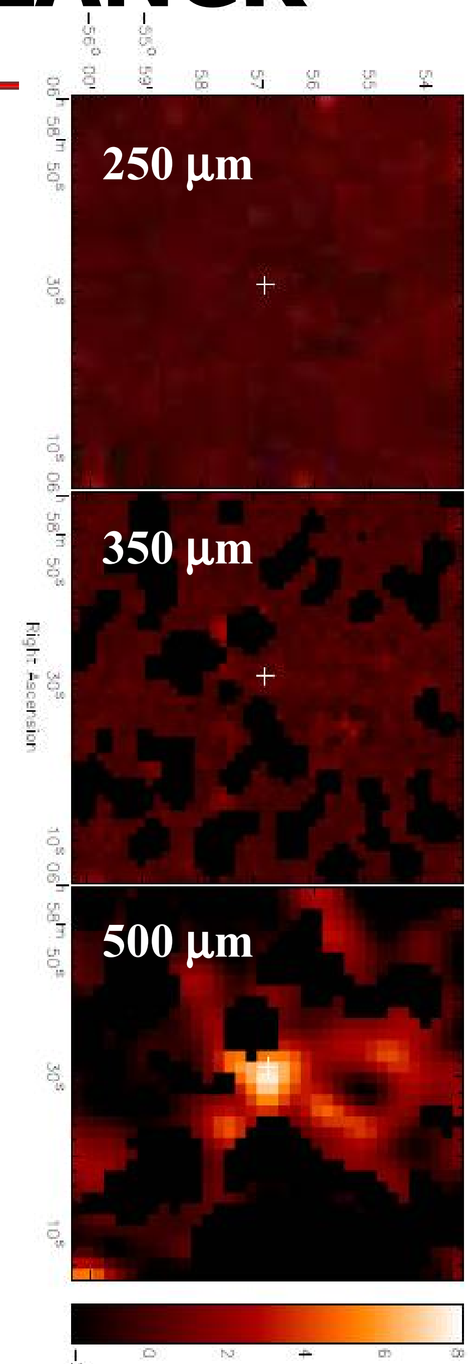
SZE: other results in the PLANCK-Era



First evidence of relativistic / non-thermal effects



Herschel SPIRE view of the Bullet cluster



SZE: probes of astrophysics

Multi - Temperature

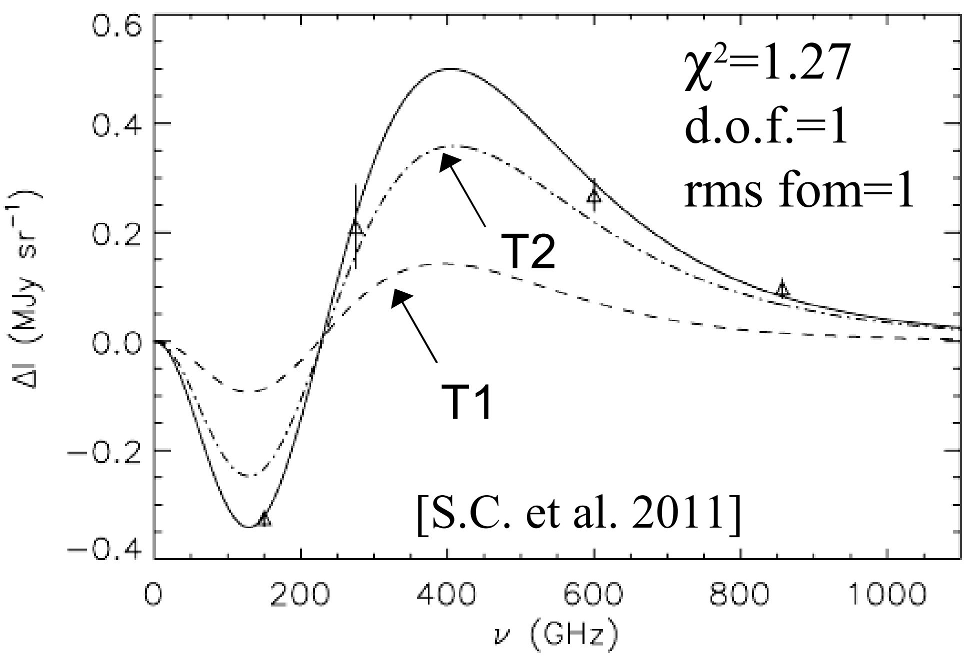
kT_1= 13.9 keV τ=3.5e-3

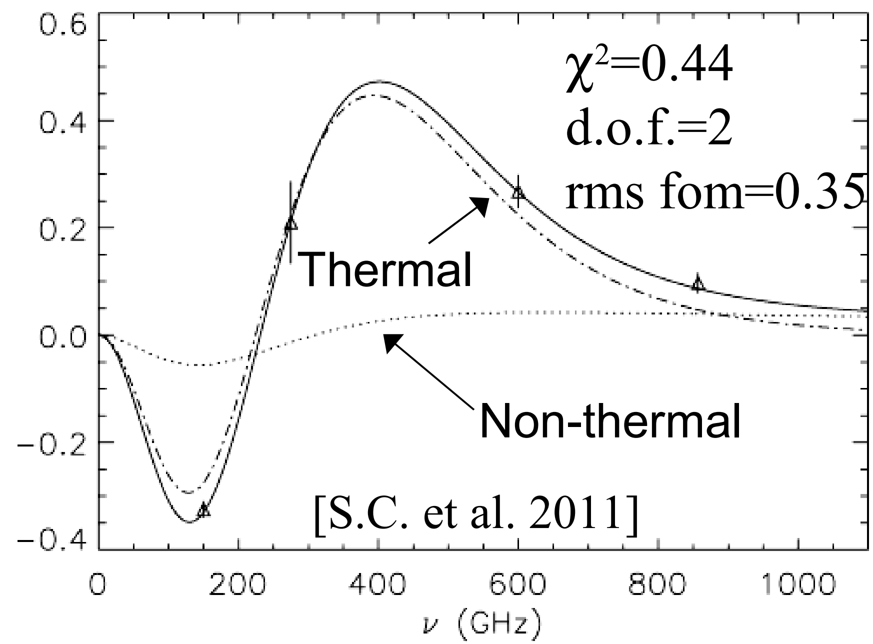
kT_2= 25 keV, τ=5.5e-3

Thermal + non-thermal

kT = 13.9 keV τ=1.1e-2

$n_e \sim E^{-2.7}$, p_1=1, τ=2.4e-4





Evidence of non-gravitational activity in the cluster merging

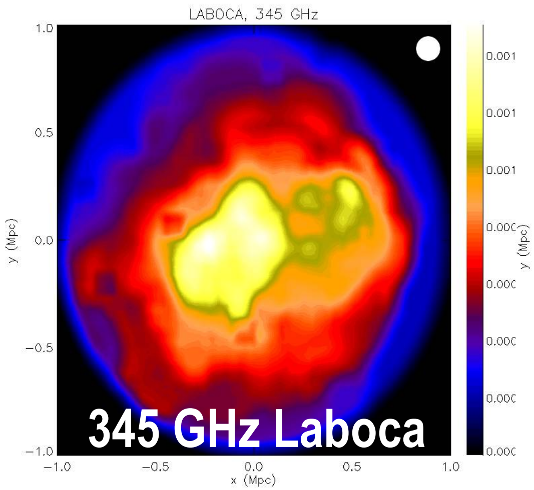
Shock acceleration or MHD acceleration

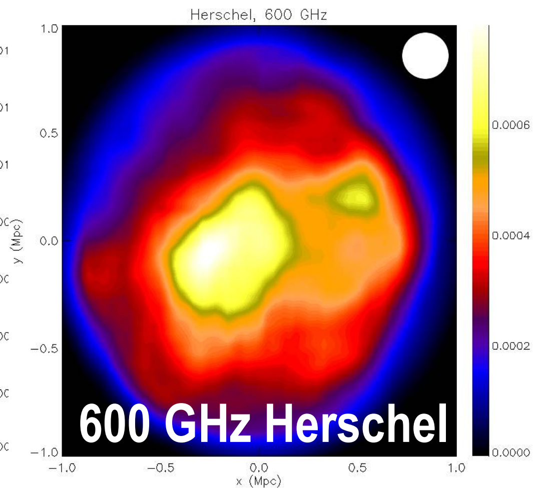
Stochastic electron acceleration

Continuous hadron acceleration

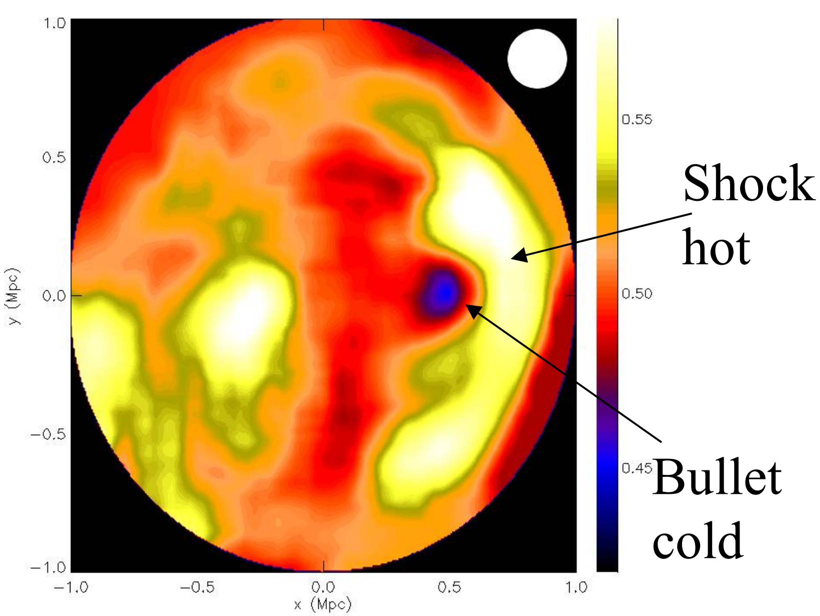
SZE: 3-d tomography

Morphological SZE





$$\frac{\Delta I_{600GHz}}{\Delta I_{345GHz}}$$



[Prokhorov, S.C. et al. 2011b]

T standard deviation

First measurement of the temperature standard deviation in galaxy clusters: using the SZE [Prokhorov & Colafrancesco 2012]

$$\sigma = \sqrt{\langle (k_b T_e)^2 \rangle - (\langle k_b T_e \rangle)^2}$$

Bullet Cluster

<T> ~ 13.9 keV

σ = 10.6 ± 3.8 keV

- Measure of the temperature stratification in clusters
- Measure of plasma in-homogeneity along the line-of-sight

From PLANCK onward

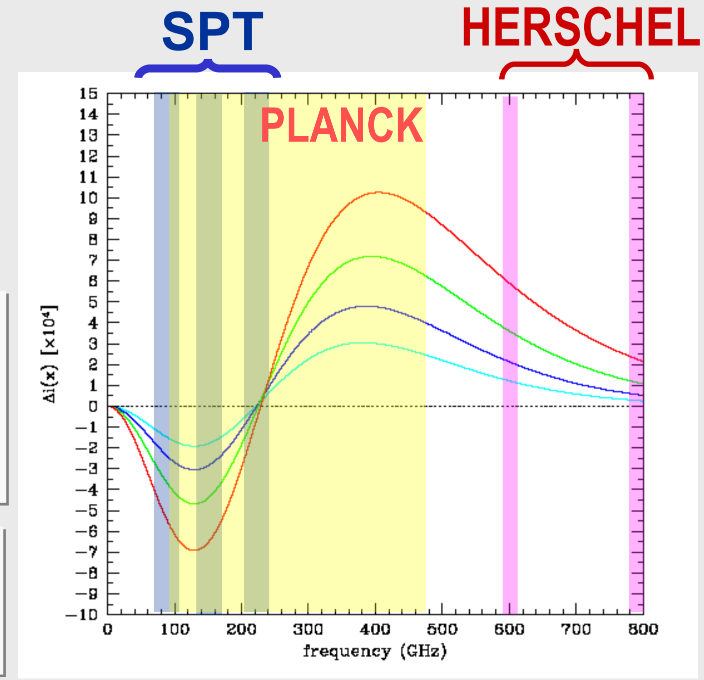
SOUTH POLE TELESCOPE
will help scientists reveal new details regarding a mysterious phenomenon called Dark Energy

ACT Atacama Cosmology Telescope Project
Observing the birth and evolution of the universe.....

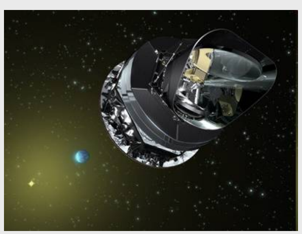
Deep integrations, high resolution, ~10^3 deg^2 survey.
- No access to positive peak of SZE (ν>300 GHz)
- No spectroscopy.

APEX - SZ + LABOCA
150-215 345 GHz

- No spectroscopy
- Different instruments



PLANCK



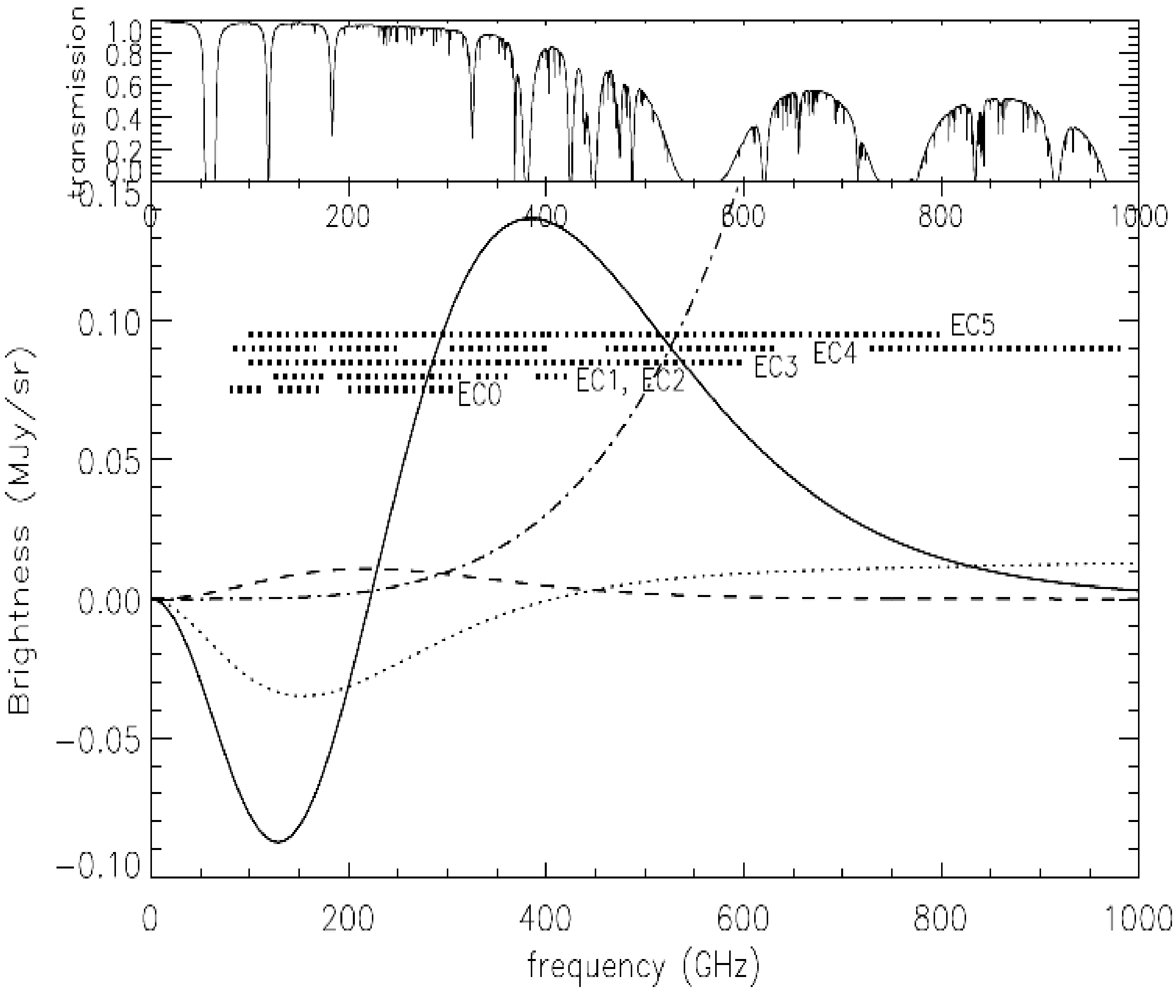
Full sky, but shallow survey
A few thousand clusters with low-moderate S/N ratio.
Low-moderate spatial resolution & spectroscopy in bands

To fully exploit the SZE info. we would need

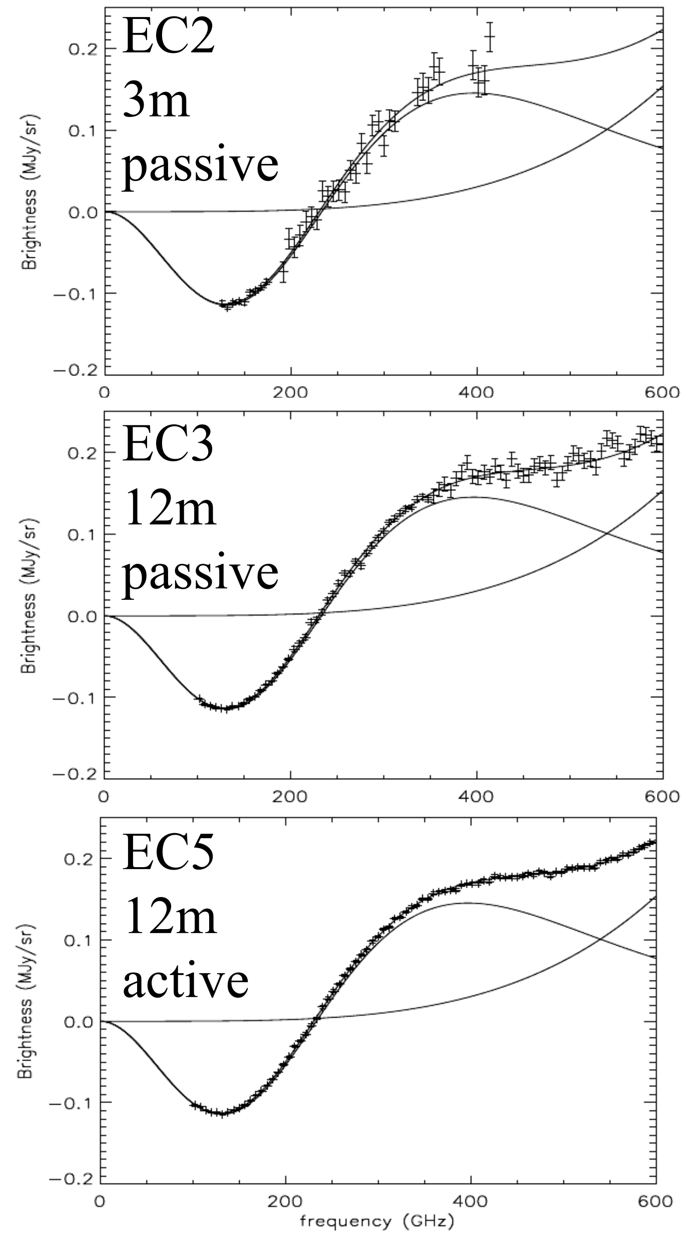
- **Spectroscopic capabilities** — **wide-band**
- **Wider & continuous frequency coverage** — **FTS-like**
- **Better calibration** — **(no multi-band, no atmosphere)**
- **Better knowledge of foregrounds** — **PS separation**

Expectations: spectra

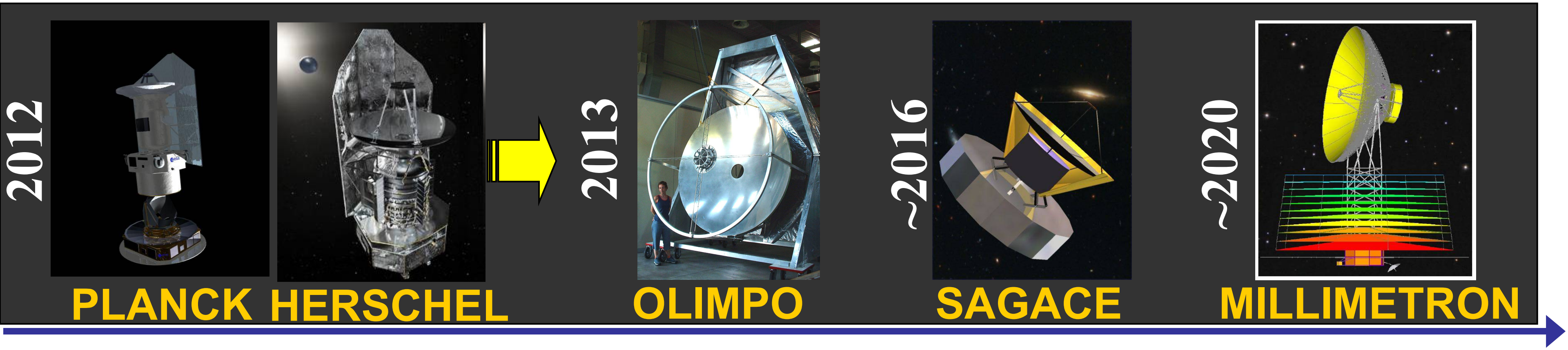
Different spectroscopic configurations for studying the SZE in cosmic structures



[DeBernardis, Colafrancesco et al. 2011]



SZE in Space: a future outline

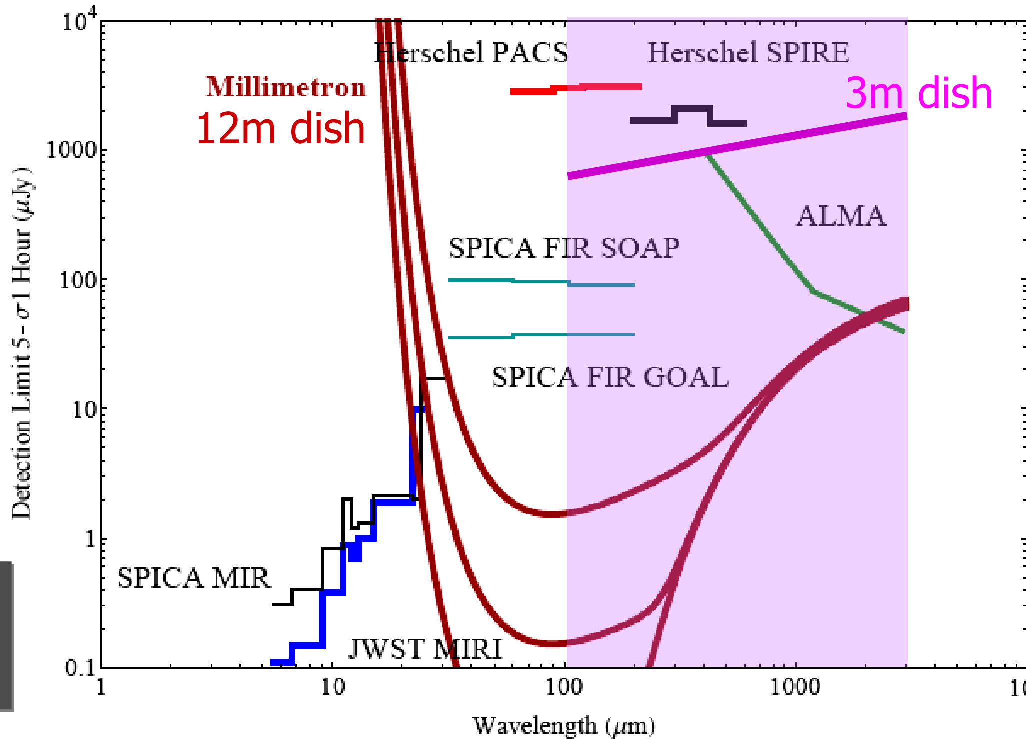


SAGACE 3m

MILLIMETRON 12m

3 m dish
Passive cooling
(50 K)
Θ= 0.7-4.2 arcmin
Noise=18 mJy/√Hz
FTS spectroscopy

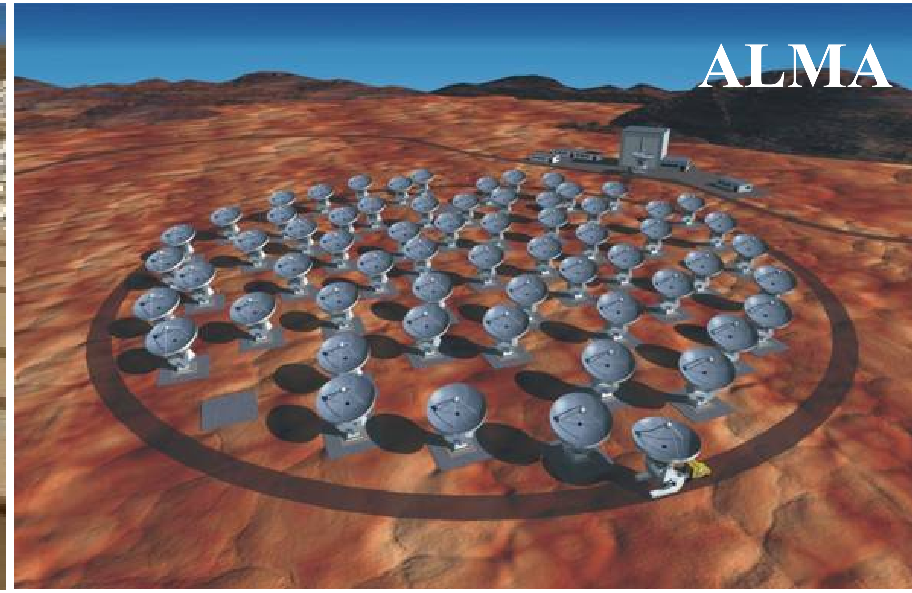
Large-survey mode
Pointed mode



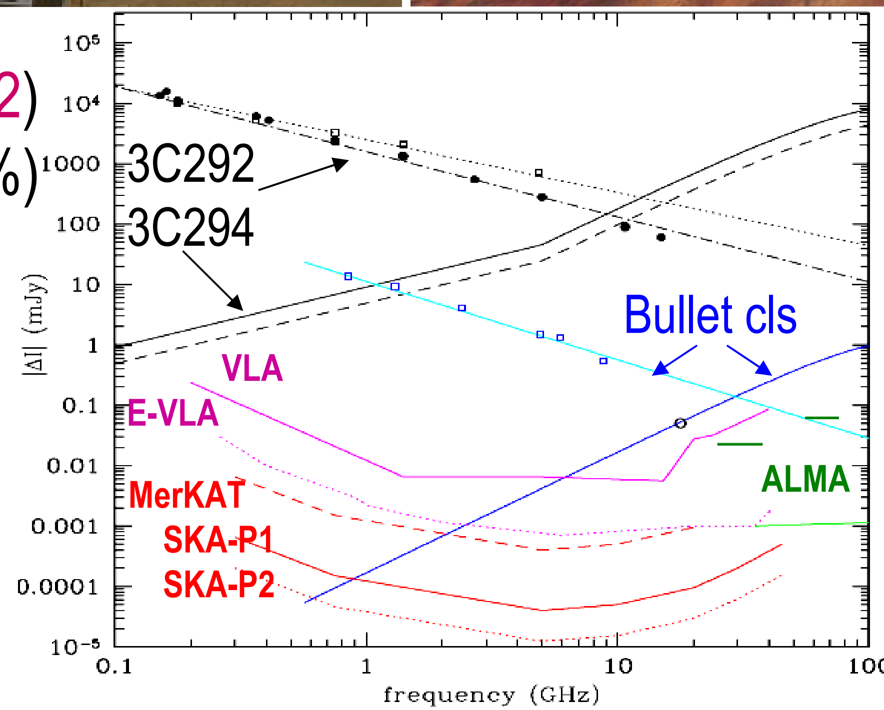
12 m dish
Active cooling
(4 K)
Θ< 0.1-1.0 arcmin
Noise<0.1 mJy/√Hz
FTS spectroscopy
Polarimetry
Super VLBI

Observatory mode
Small-survey mode

Synergy with ground-based exps.

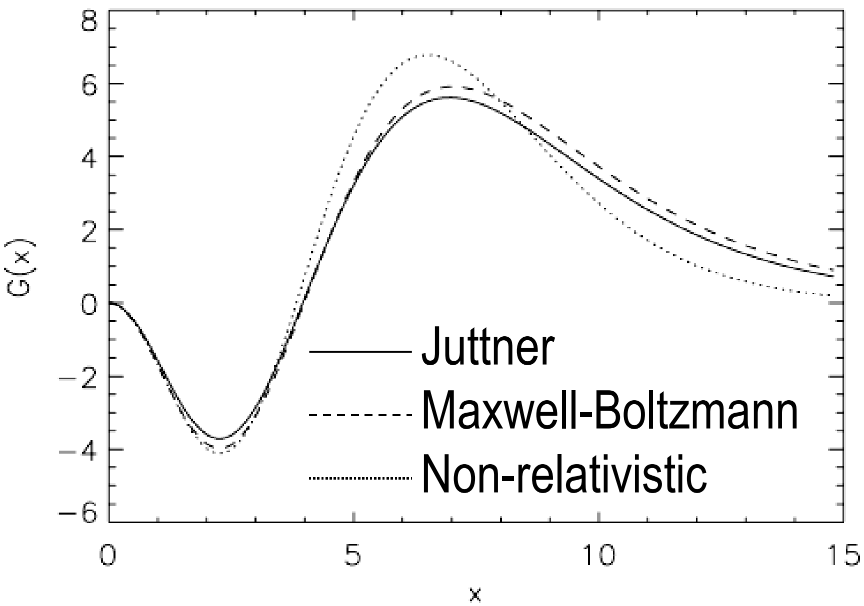


- Approved (25/5/2012)
- SA (70%) & Au (30%)
  SA: 0.7-15 GHz
  Au: low-ν + ASKAP
- Wide FOV
- Multi-beaming
- High survey speed
- Polarization



- Operating
- ESO
  84 - 950 GHz
  3.6" - 0.43"
- Small FOV
- Mosaicing mode
- Polarization

SZE spectroscopy: thermal plasma



The relativistic kinetic theory (DF derivation) of astrophysical plasma is still unknown !

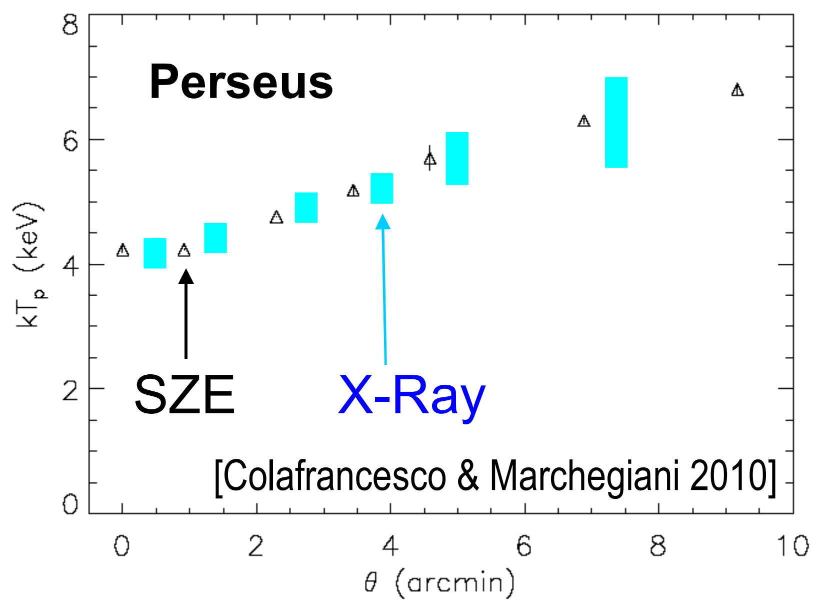
A method based on Fourier analysis to derive the velocity DF of electrons by using SZE observations at ≥ 4 frequencies.
[Prokhorov, Colafrancesco, et al. 20011a]

SZE spectroscopy will allow to derive spatially resolved T-profiles for nearby clusters out to large radii:

Inversion Technique SZE → T, τ, V_p, T_{CMB}

T profile with uncertainties similar to those of X-ray observations

T profile uniquely sampled in the outer parts of the cluster



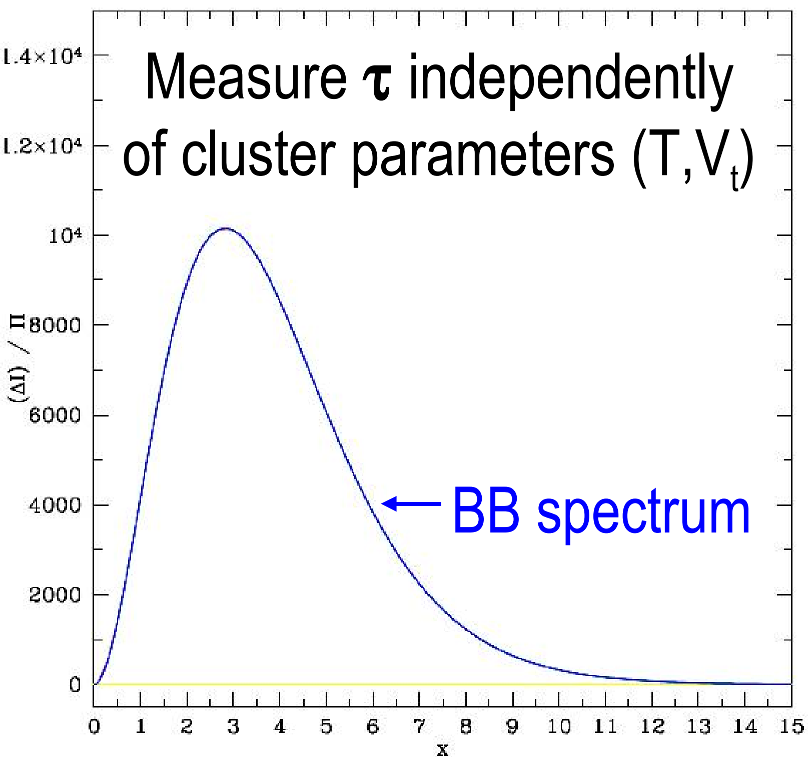
SZE spectro-polarimetry: 6-d

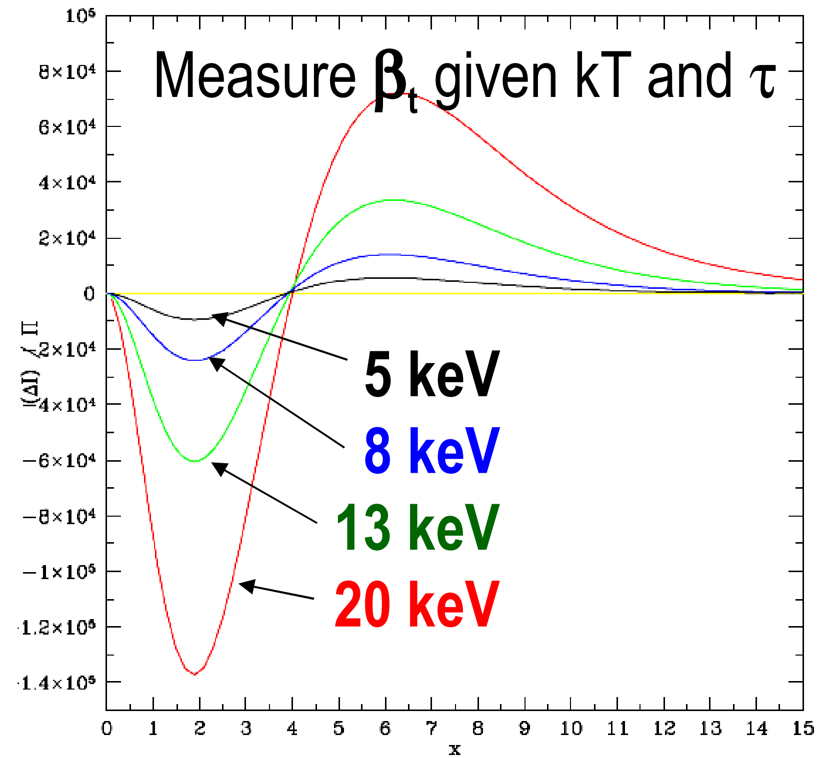
SZE intensity spectrum allow to measure the plasma temperature kT

Polarization due to finite optical depth **τ** allow to measure the density and velocity distribution of the electron plasma → 6-d phase-space

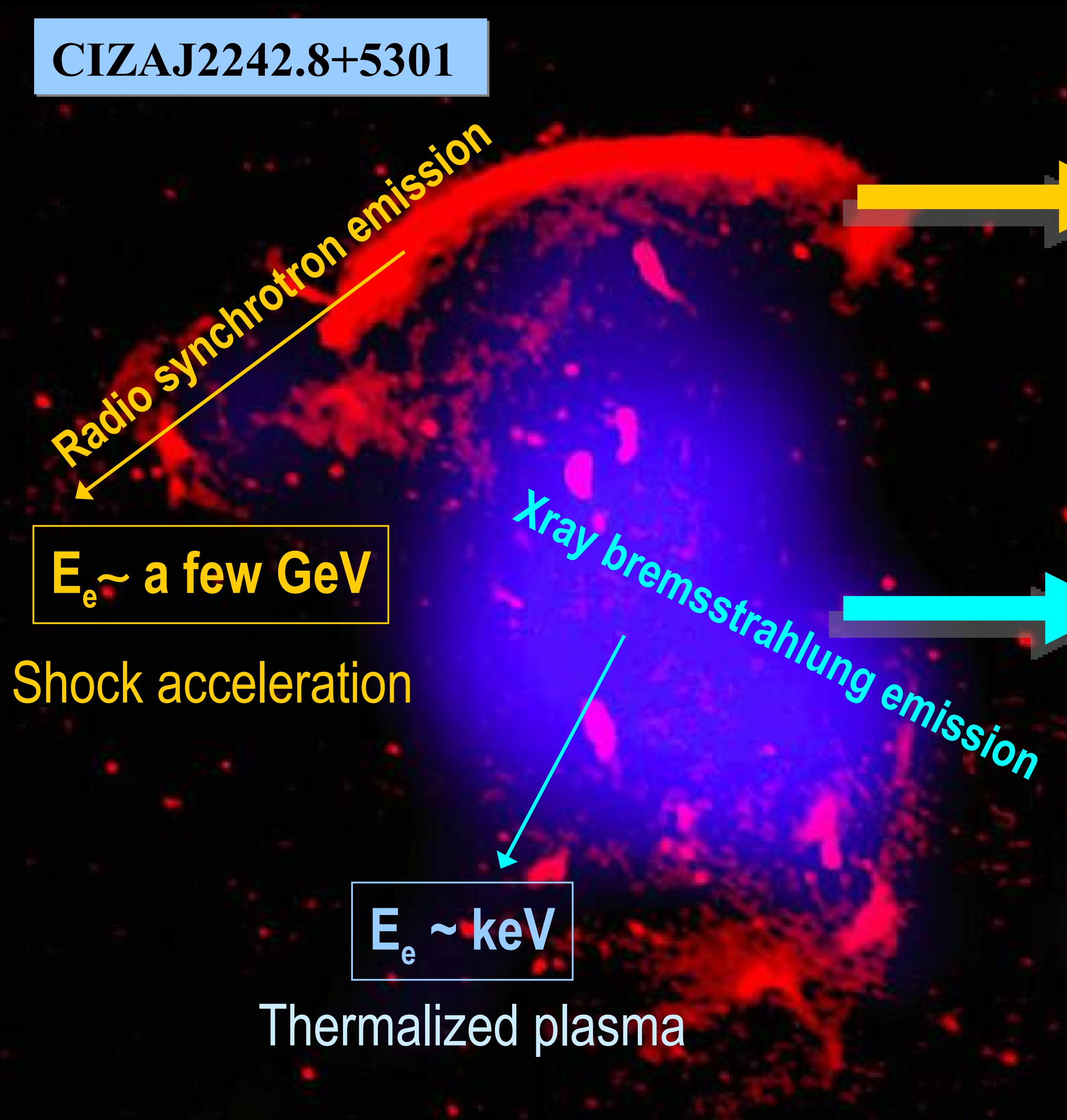
$$\frac{\Delta I}{\Pi_T} = 71.43 \frac{g(x)}{f_T(x)} \frac{1}{\tau}$$

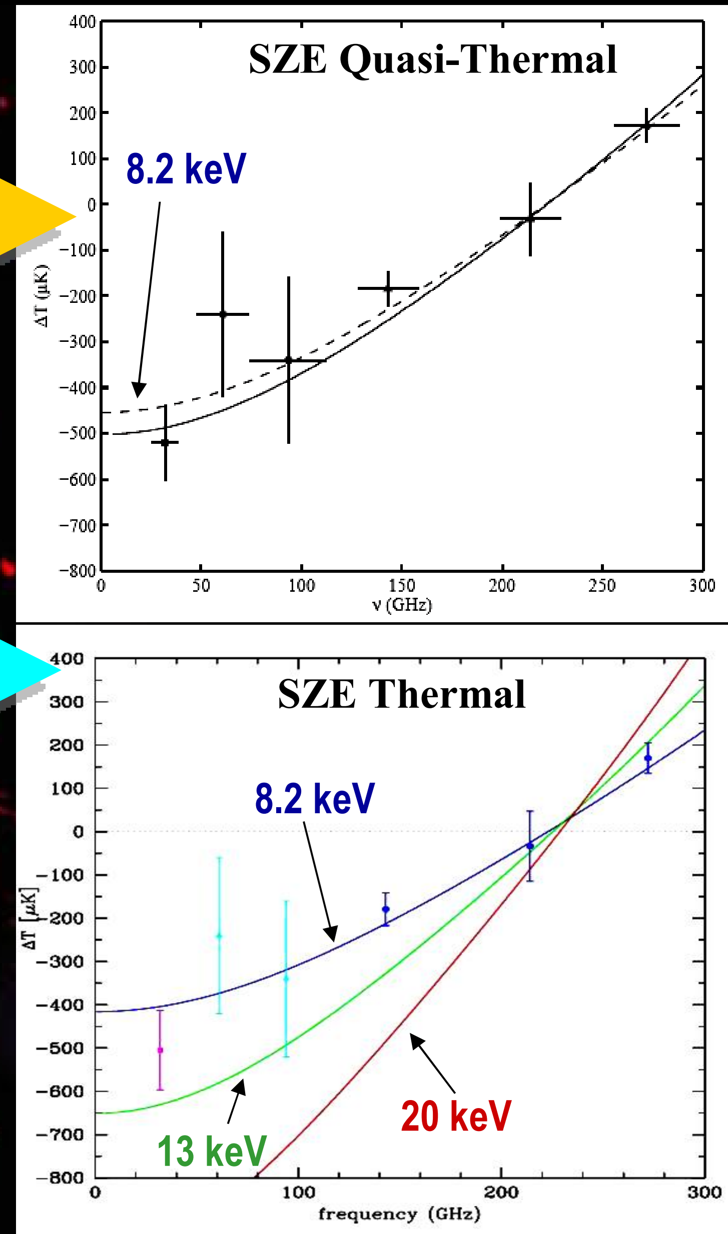
$$\frac{\Delta I}{\Pi_V} = 40 \frac{g(x)}{f(x)} \frac{1}{\tau} \frac{1}{\beta_t} \frac{kT}{m_e c^2}$$





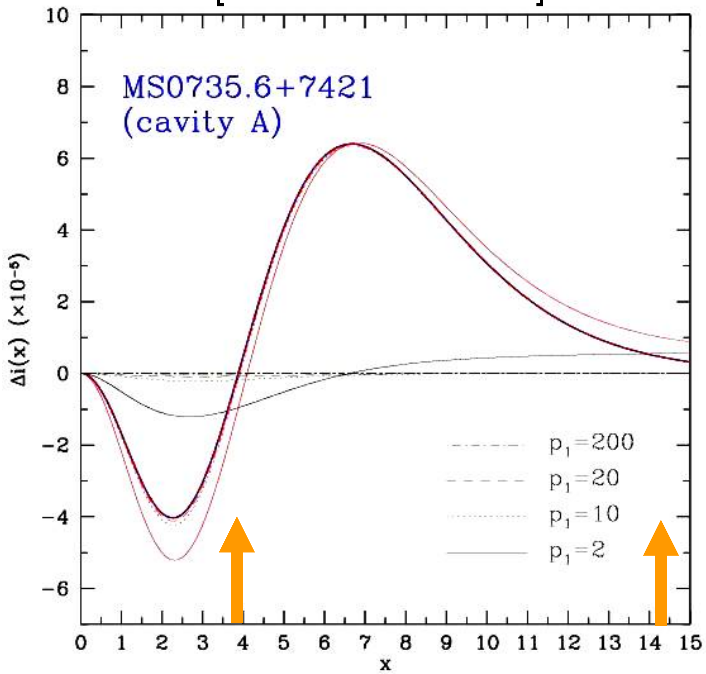
SZE: particle acceleration

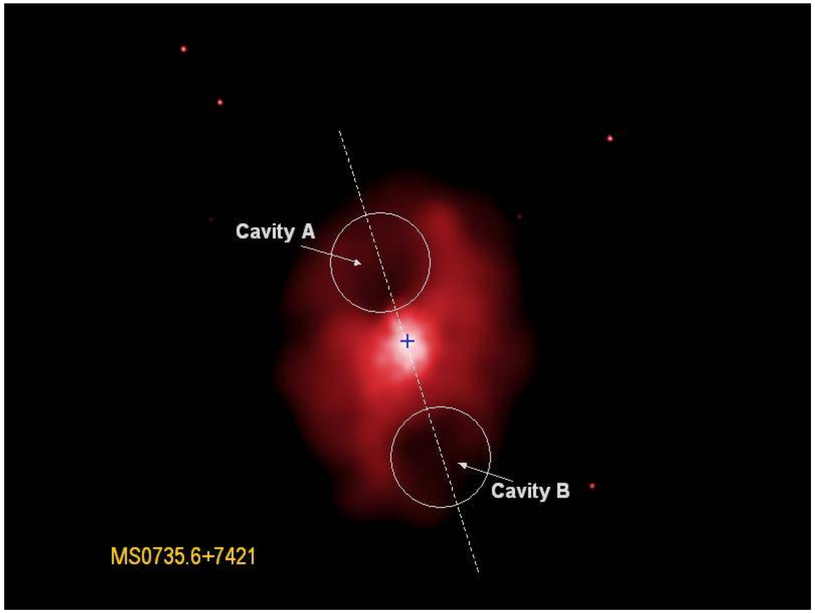


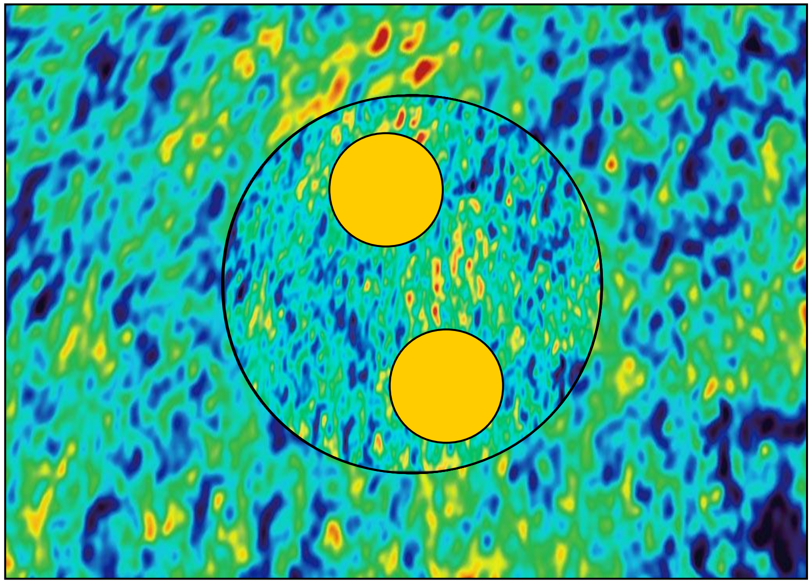


SZE: cavities in Clusters

[Colafrancesco 2005]







Cavities are isolated from the surrounding cluster atmosphere at

- **$\nu \sim 220$ GHz**
- **$\nu > 800$ GHz**

$\Delta I \sim \int dl \cdot U_{e,tot}$: advantage w.r.t. X-rays

SZE: radio-galaxy lobes

Total leptonic spectrum

$P_{tot}; E_{min}$

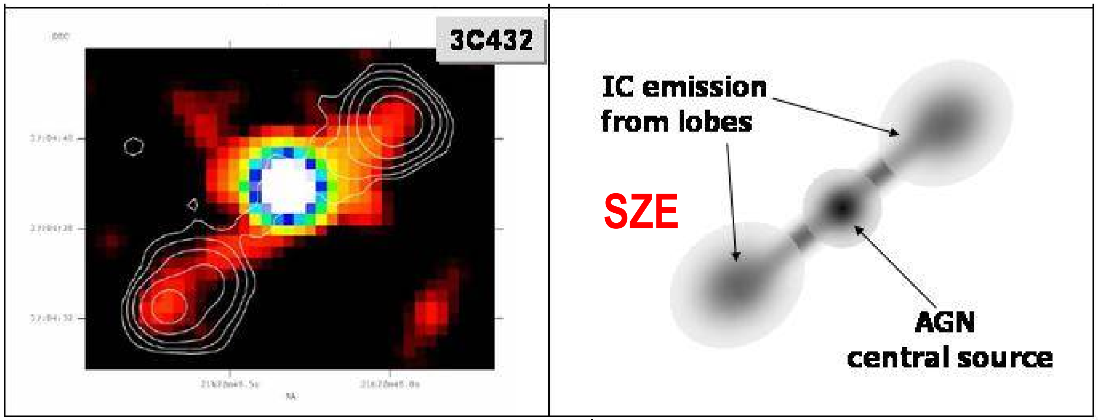
B-field structure

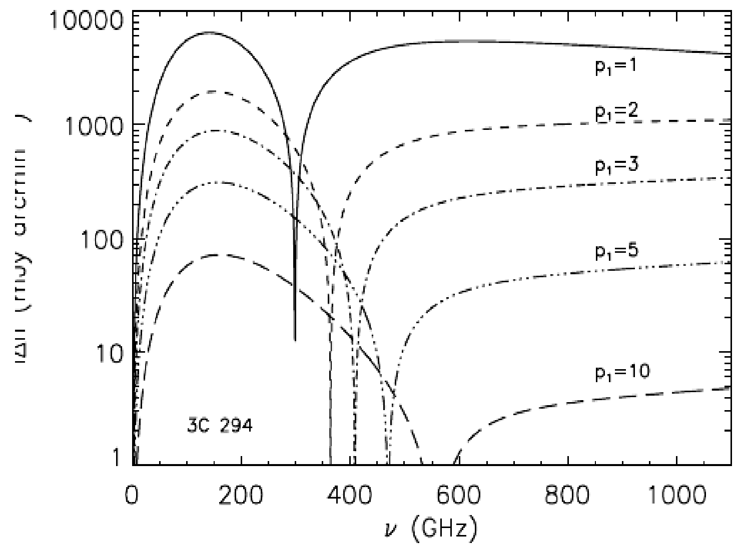
$$\frac{F_{radio}}{F_{ICS}} = \frac{U_B}{U_{rad}}$$

$T_{CMB}(z)$

$$\frac{\Delta T_{SZ}}{F_{IC}} \propto (kT_{CMB})^{-3} \times f(\gamma_{min}, E_{X\,min})$$

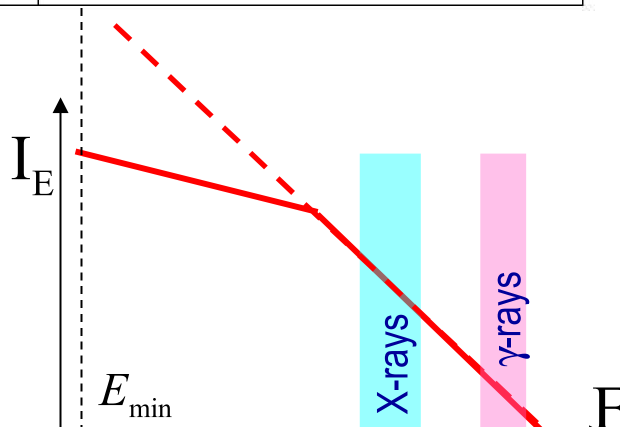
$$\Delta I(x) \propto g(x) \cdot \int d\ell \cdot U_{e,rel}$$

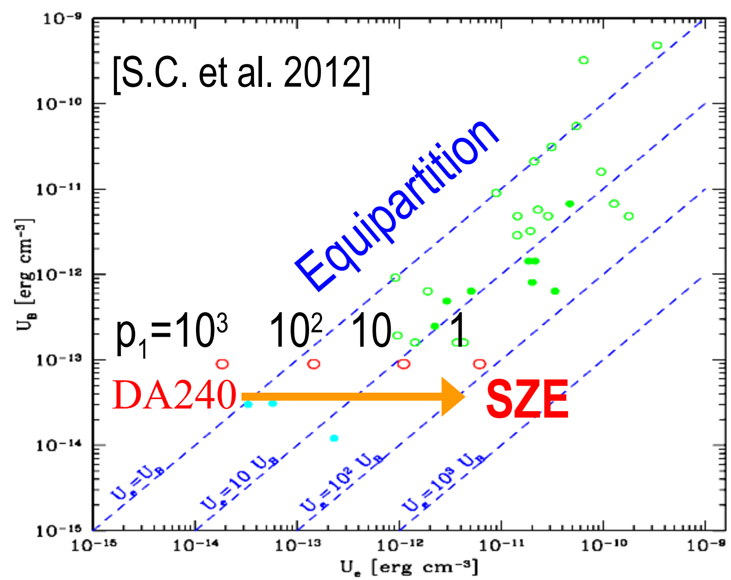




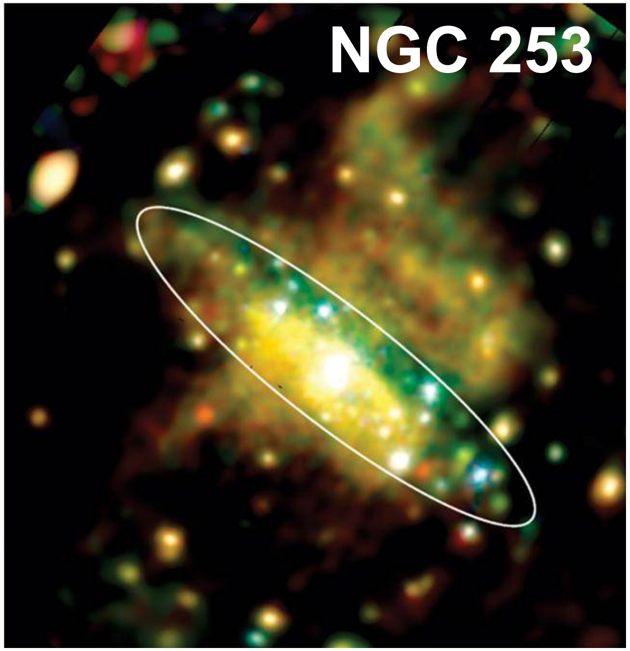
X-ray: rough misleading measure of Ue

SZE: reliable unbiased measure of Ue

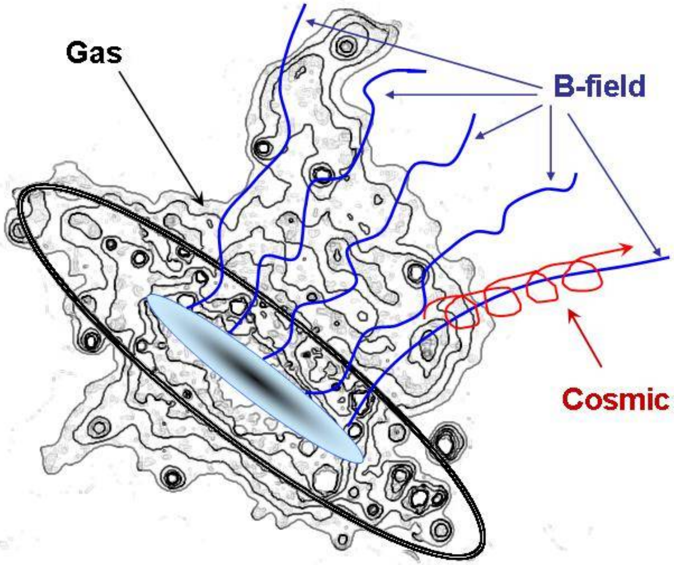




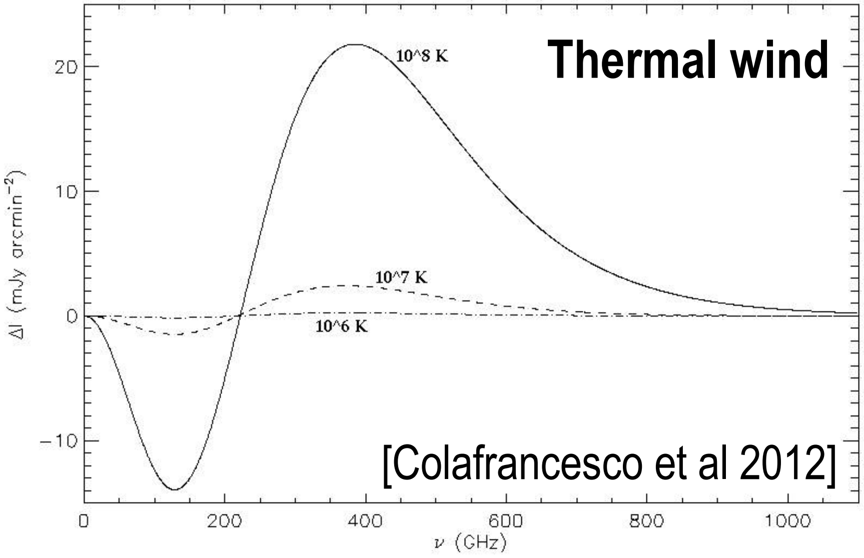
SZE: galaxy winds and SF

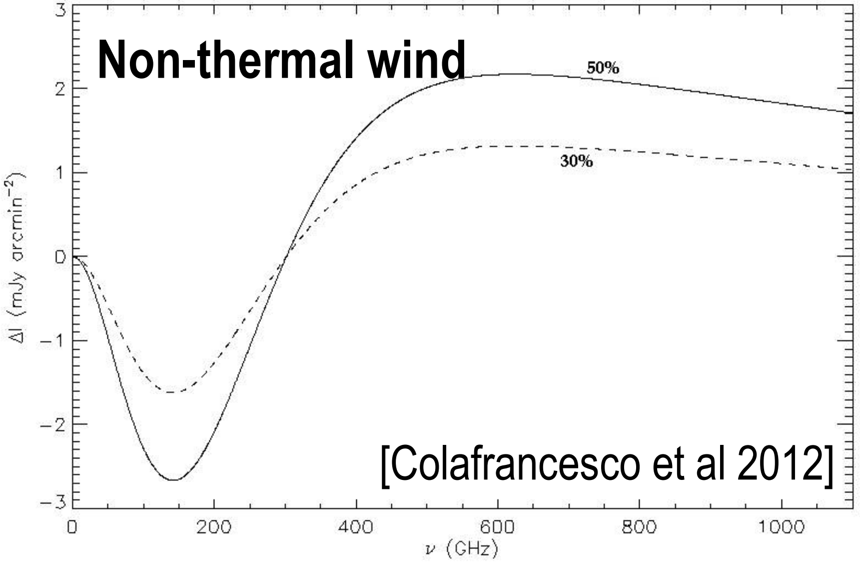


Combine MILLIMETRON and SKA



to study the wind composition & energetic

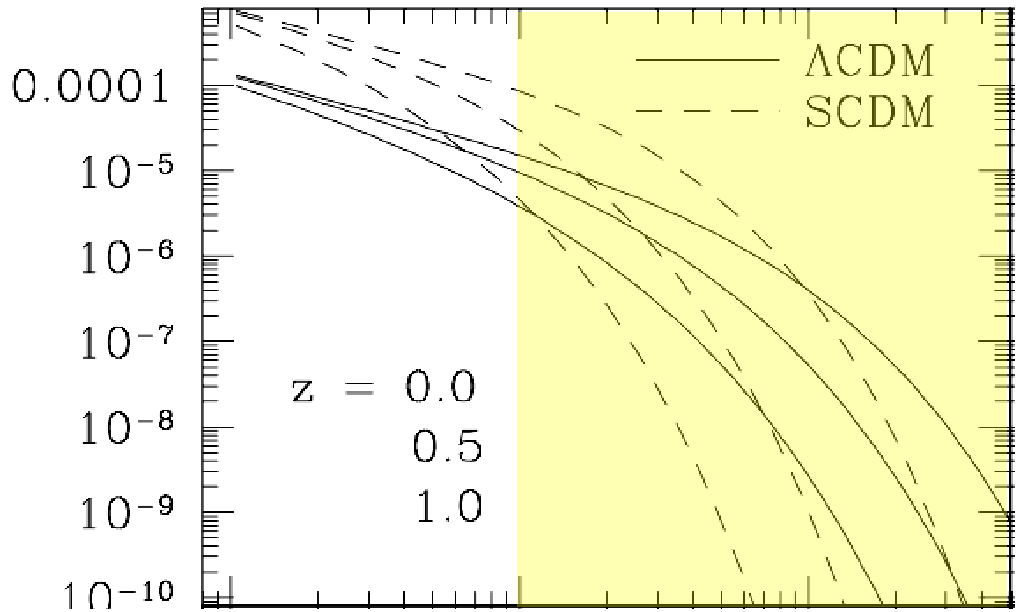




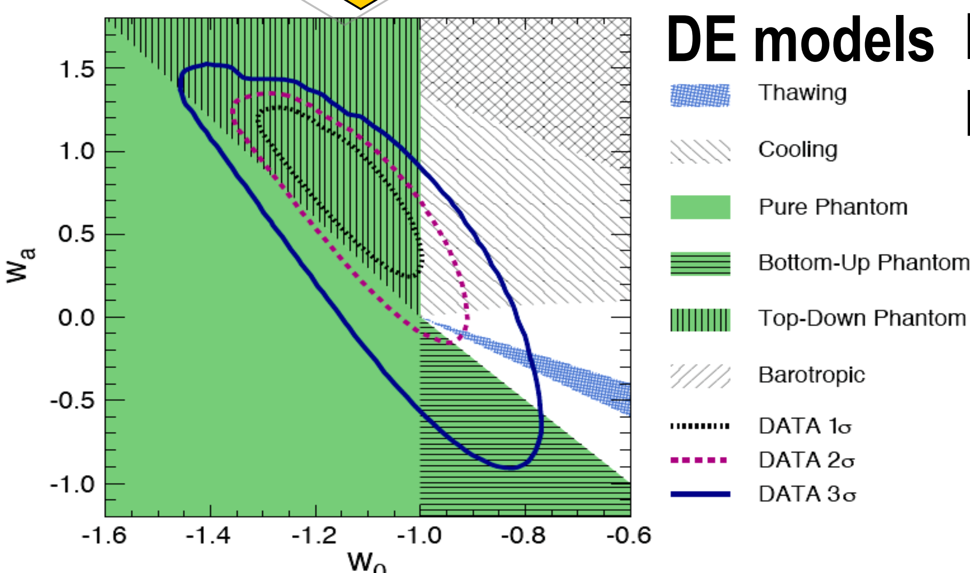
SZE: clusters cosmology

SZE will allow to derive an unbiased measure of cluster DM mass

$$N(M) = \frac{\rho}{M} f(\nu) \frac{d\nu}{dM}$$

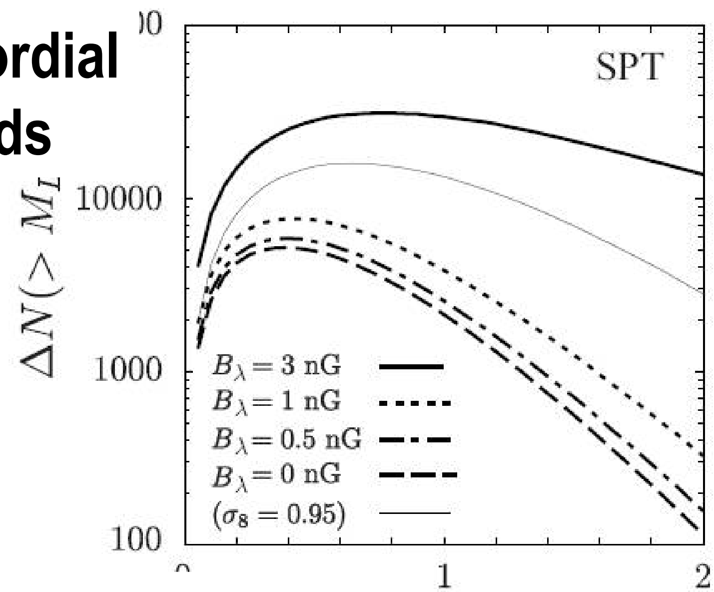


DE models



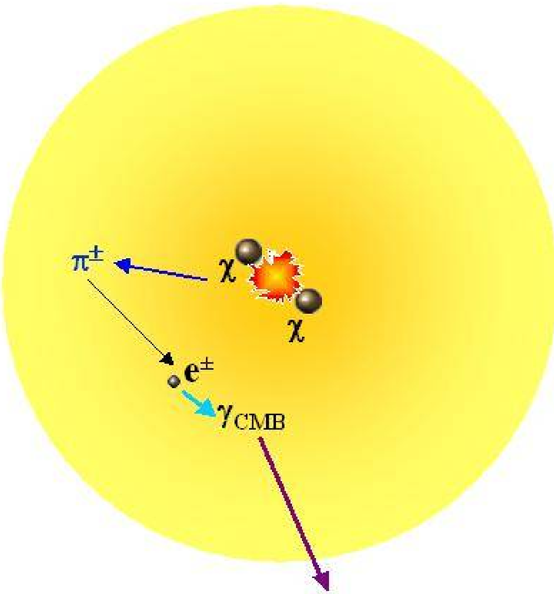
[Campanelli et al. 2011]

Primordial B-fields

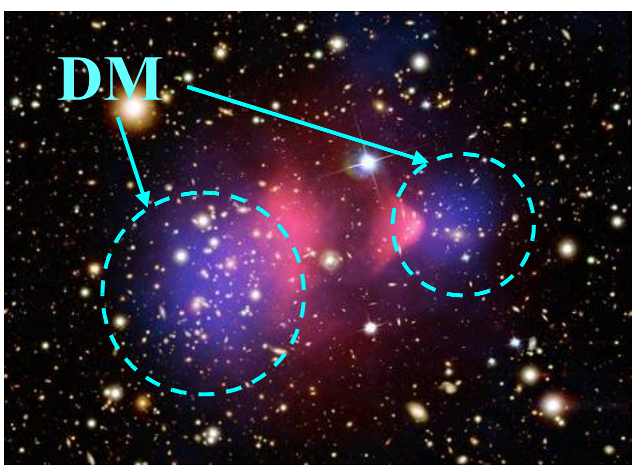


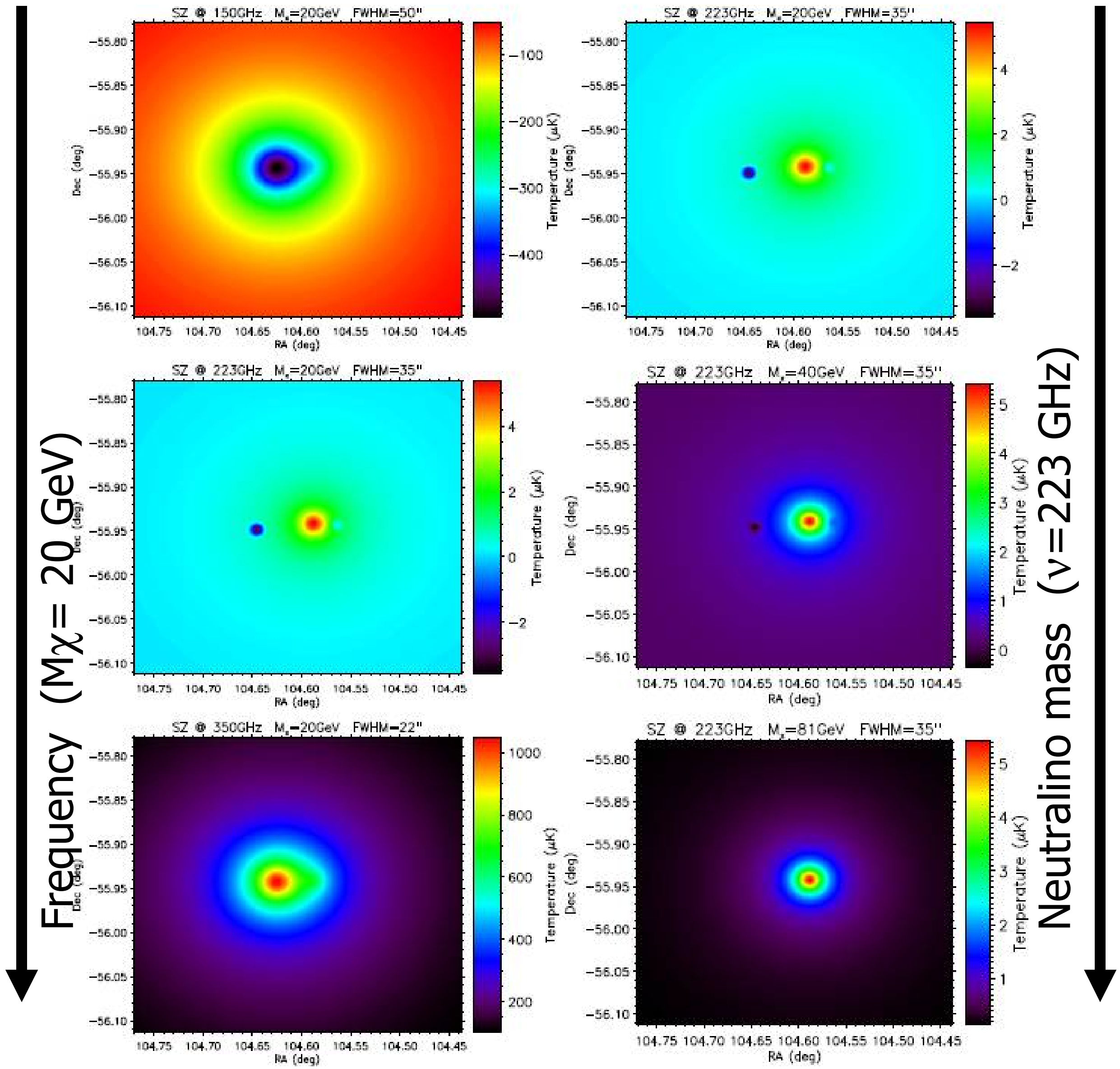
[Tashiro et al. 2010]

SZE: the nature of Dark Matter



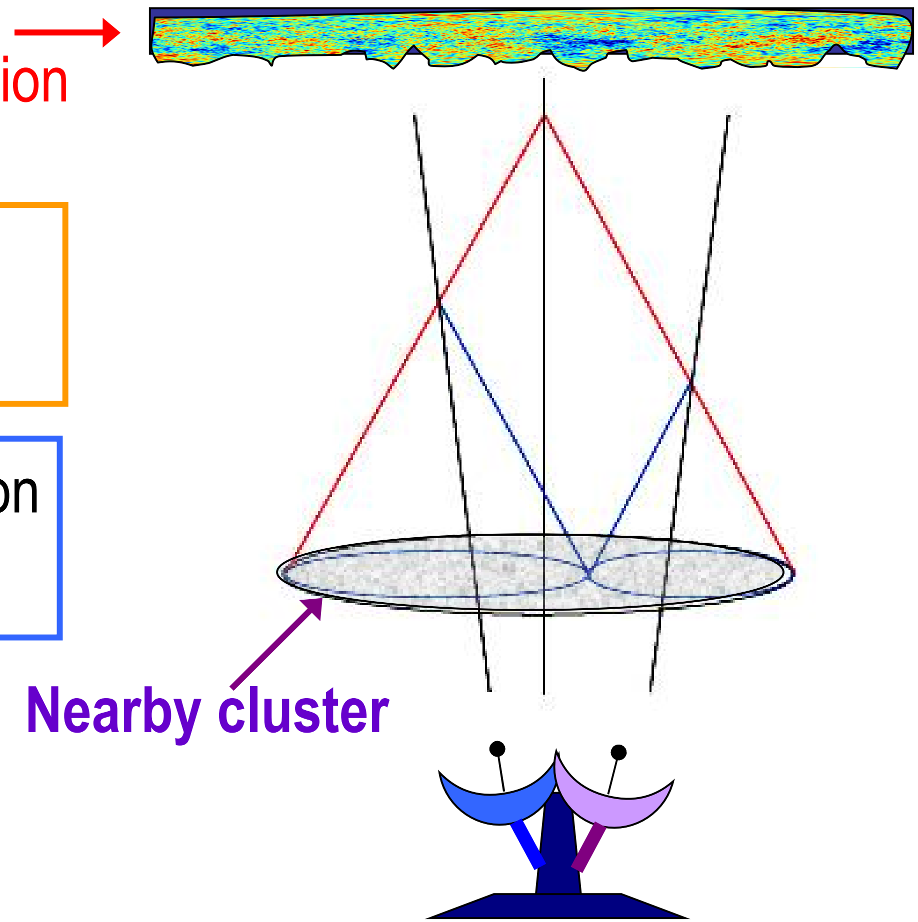
SZE





SZE: the Cosmological Principle

Although we cannot directly observe Homogeneity, we can test the **Cosmological Principle** at the foundation of **Homogeneity**, using observations that carry information from inside our past lightcone.
[R. Marteens 2011]



Large (non-perturbative) th. or kin. SZE
□ non-FLRW universe

Large (non-perturbative) SZE polarization
□ non-FLRW universe

THANKS

for your attention