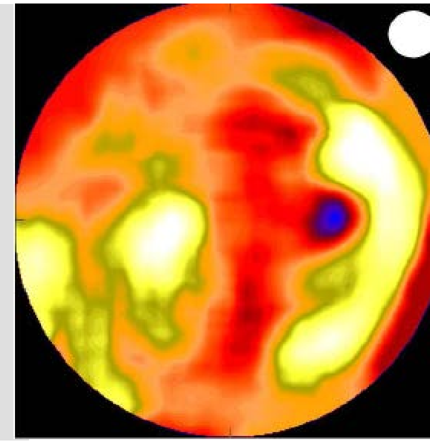
Interaction of CMB photons with Astrophysical plasma: the SZ Effect



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Outline

- Lecture 1
  - CMB photon interaction
  - LSS: plasma content
  - Spectral and spatial properties
  - Plasma – CMB photon interaction: basic mechanisms
  - ICS, Pair production, Primakov effect
- Lecture 2
  - The SZ effect: thermal, non-th, kinetic, polarization
  - General description
  - Galaxy clusters
  - RGs and other cases
  - Experimental outline
- Lecture 3
  - IC-CMB and high energy phenomena
  - X-rays
  - Gamma-rays
  - Multi-frequency studies
  - An experimental outline

The Physics of the SZ Effect

The SZ effect is a specific form of Inverse Compton Scattering

Photon fields

External

↓

CMB

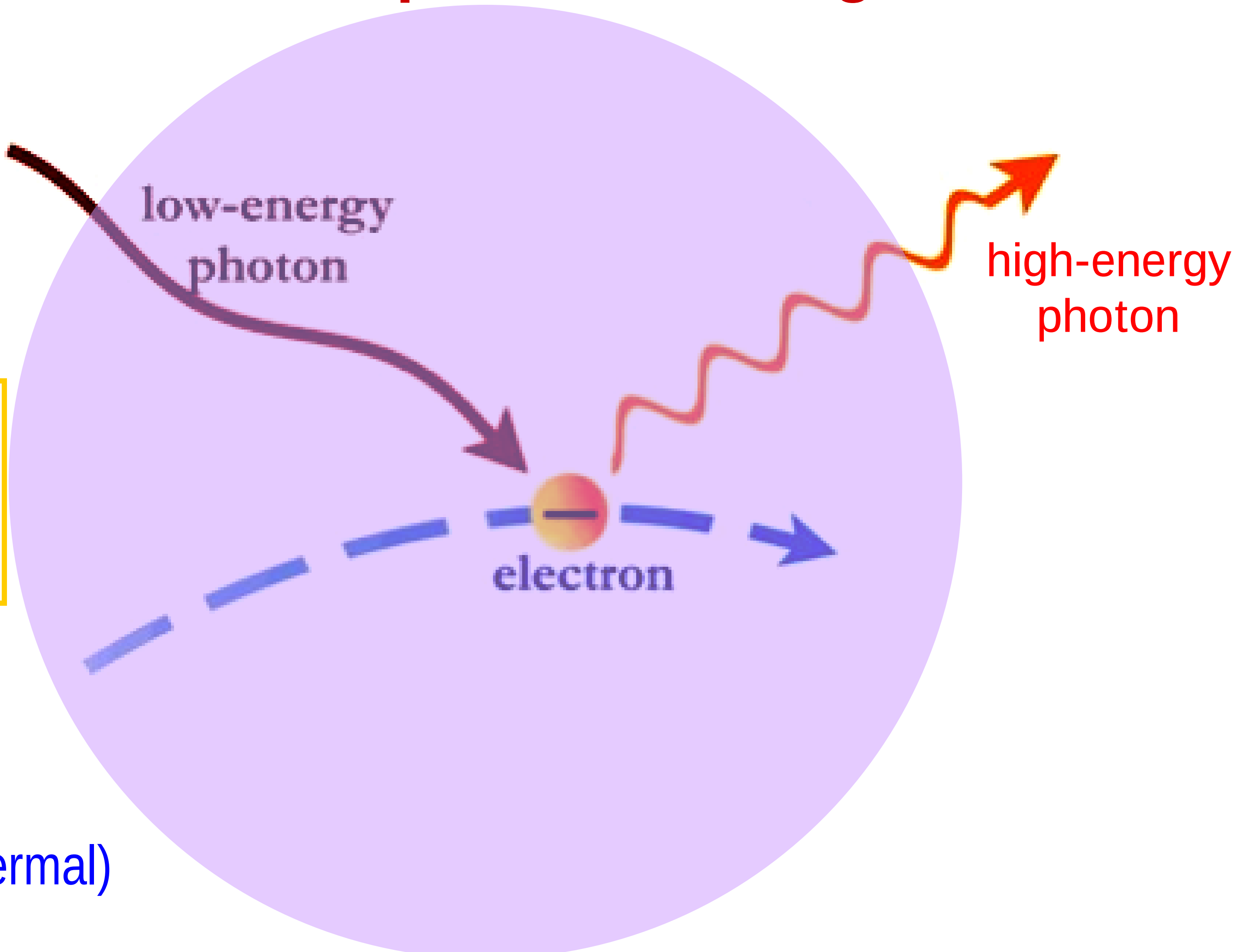
Use CMB photons to extract plasma information

↑

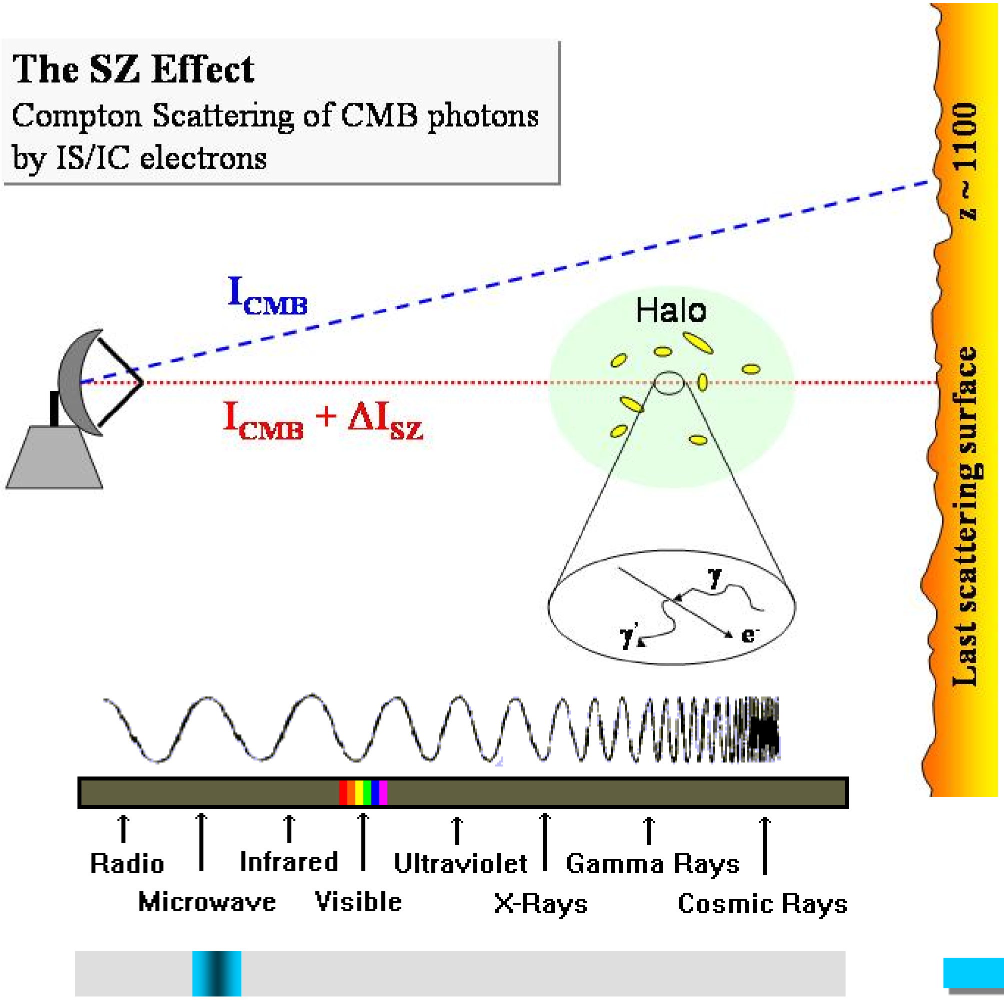
Internal

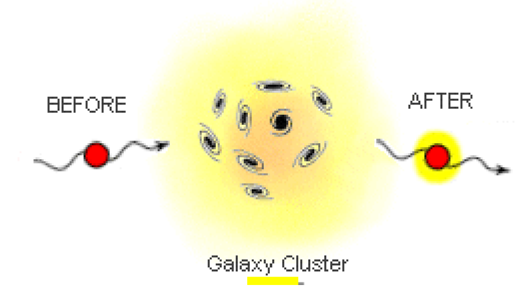
High-E electrons

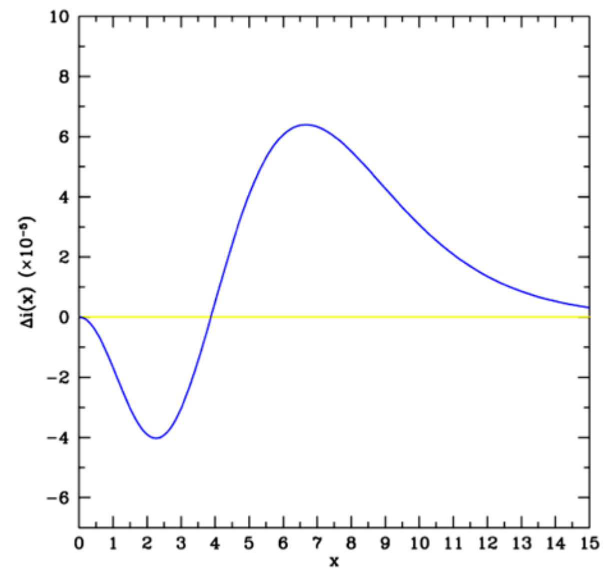
- thermal (supra-thermal)
- relativistic



SZ effect: the Standard Lore



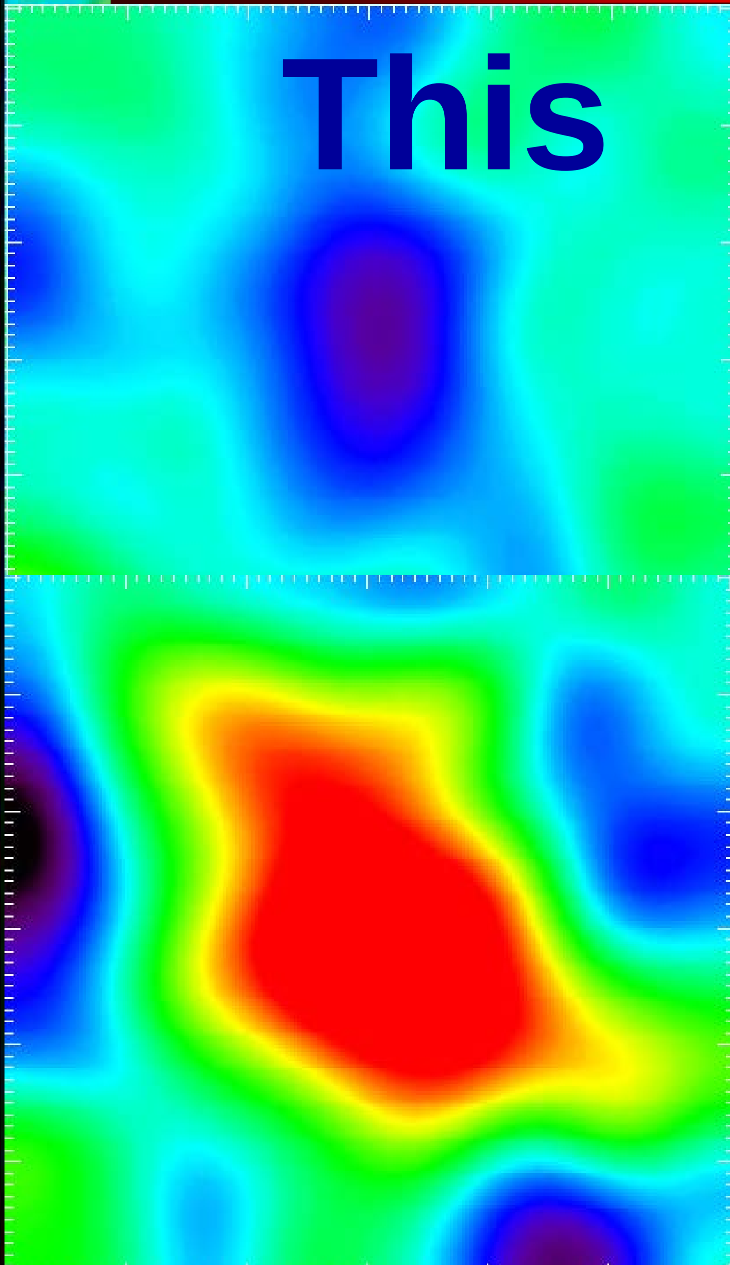




thermal NR e-

$$\frac{\Delta\nu}{\nu} \approx 4\frac{kT_e}{m_e c^2}$$

SZE: Observational fact



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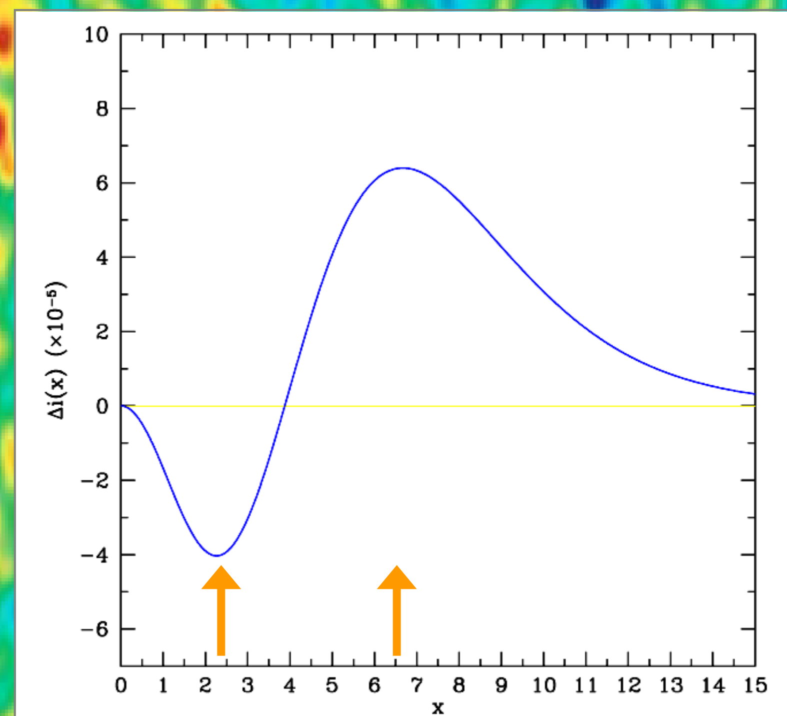


The origin of the SZ effect

Non-coherent Compton Scattering

Fall-out effect of the Cold War

1957 A.S. Kompaneets publishes his Compton scattering Fokker-Planck equation

$$\frac{\partial n}{\partial y} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(\frac{\partial n}{\partial x} + n + n^2\right)$$

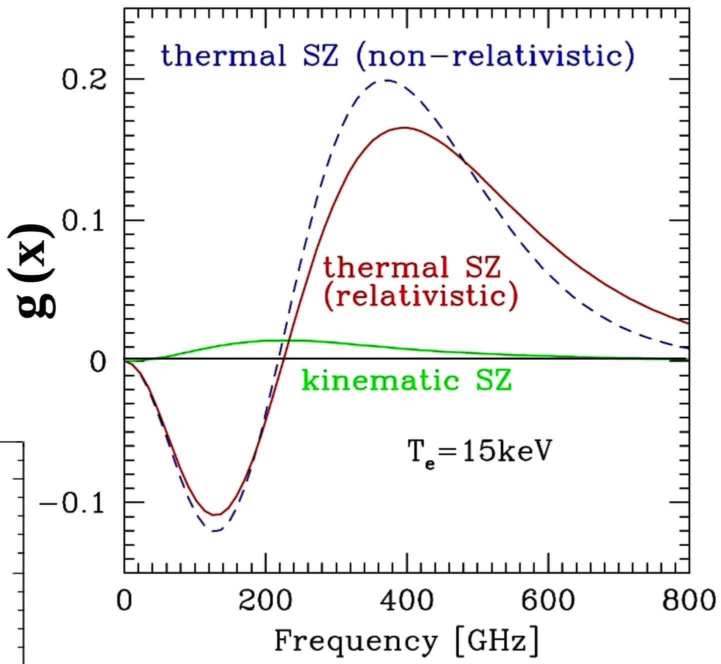
(derived by A.S. Kompaneets in Soviet Union ~ 1950 but was classified due to nuclear bomb research until 1956)

1969 Ya. B. Zel'dovich & R. Sunyaev derive the thermal SZ effect (i.e., applied the Kompaneets eq.)

SZE: working approximations

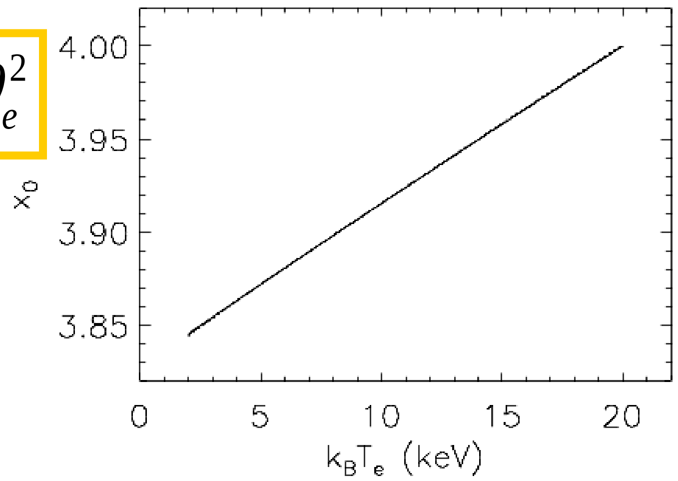
$$\Delta I_{th} = 2\frac{(kT_0)^3}{(hc)^2} y_{th} g(x)$$

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



$$X_{0,th} \approx a + b\theta_e + c\theta_e^2$$

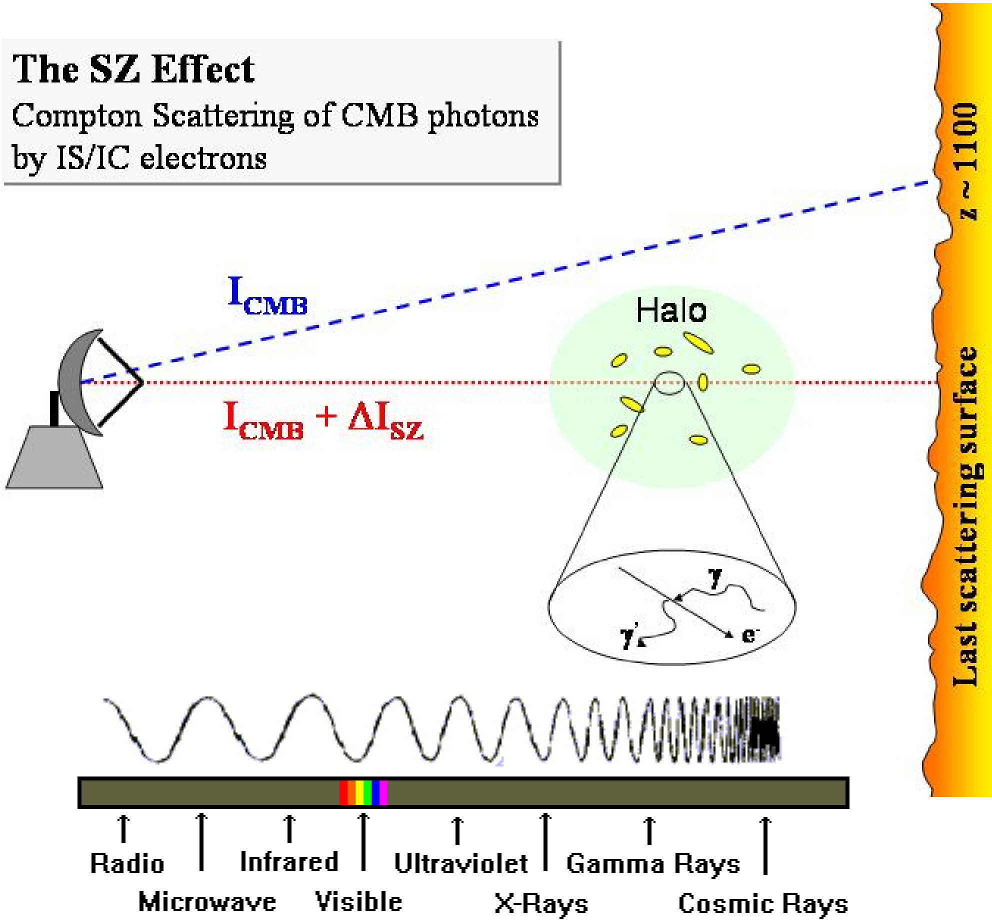
$$\theta_e \equiv \left(\frac{k_B T_e}{m_e c^2}\right)$$

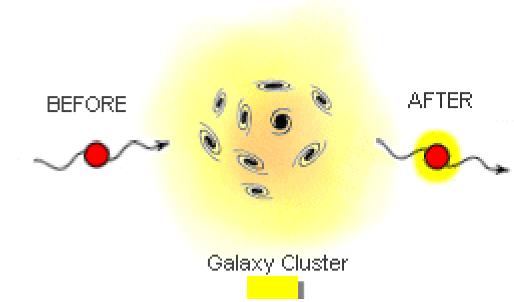


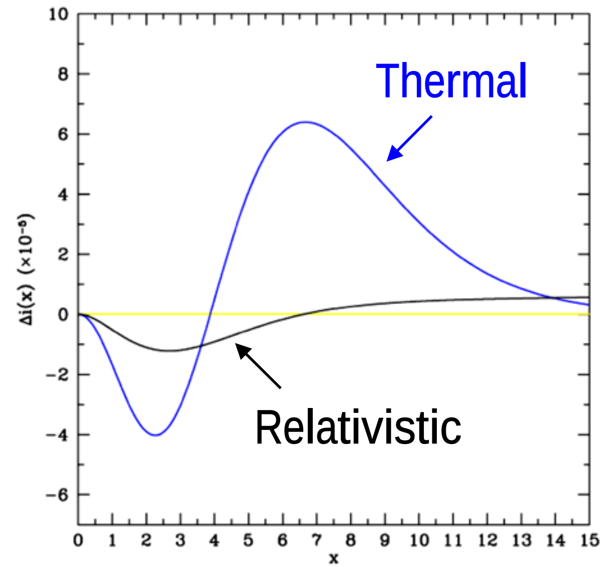
Diffusion limit → Single scattering ($\tau \ll 1$)

Single thermal population → Thermal electrons (X-ray)

SZ effect: ...more than basics







thermal NR e⁻

$$\frac{\Delta\nu}{\nu} \approx 4\frac{kT_e}{m_e c^2}$$

relativistic e⁻

$$\frac{\Delta\nu}{\nu} \approx \frac{4}{3}\gamma^2$$

SZE: general derivation

The spectrum of the Comptonized radiation is then given by

$$I(x) = \int_{-\infty}^{+\infty} \mathrm{d}s\, I_0(x\mathrm{e}^{-s}) P(s), \quad (1)$$

where

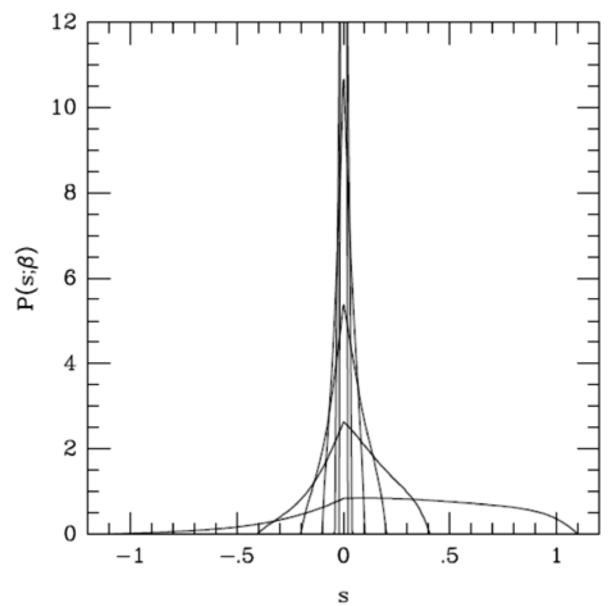
$$I_0(x) = 2\frac{(k_\mathrm{B}T_0)^3}{(hc)^2}\frac{x^3}{\mathrm{e}^x - 1} \quad (2)$$

is the incident CMB spectrum in terms of the a dimensional frequency $x = h\nu/kT_{CMB}$

The redistribution function of the CMB photons scattered once by the electrons writes in the relativistic limit as

$$P_1(s) = \int_0^{\infty} \mathrm{d}p\, f_\mathrm{e}(p) P_\mathrm{s}(s;p), \quad (3)$$

where $f_e(p)$ is the electron momentum distribution and $P_s(s;p)$ is the redistribution function for a mono-energetic electron distribution, with s=ln(t).



SZE: general derivation

Once the function P1(s) is known, it is possible to evaluate the Probability that a frequency change is produced by a numbern of repeated, multiple scattering. This is given by the repeated convol.

$$P_n(s) = \int_{-\infty}^{+\infty} \mathrm{d}s_1 \ldots \mathrm{d}s_{n-1} P_1(s_1) \ldots P_1(s_{n-1}) P_1(s - s_1 - \ldots - s_{n-1}) \equiv \underbrace{P_1(s) \otimes \ldots \otimes P_1(s)}_{n\text{times}} \quad (4)$$

The resulting total redistribution function P(s) can be written as the sum of all the functions Pn(s), each one weighted by the probability that a CMB photon can suffer n scatterings, which is assumed to be Poissonian with expected value

$$\begin{aligned} P(s) &= \sum_{n=0}^{+\infty} \frac{\mathrm{e}^{-\tau}\tau^n}{n!} P_n(s) = \mathrm{e}^{-\tau}\left[P_0(s) + \tau P_1(s) + \frac{1}{2}\tau^2 P_2(s) + \ldots\right] \\ &= \mathrm{e}^{-\tau}\left[\delta(s) + \tau P_1(s) + \frac{1}{2}\tau^2 P_1(s) \otimes P_1(s) + \ldots\right]. \end{aligned} \quad (5)$$

SZE: general derivation

The redistribution function P(s) can also be obtained in an exact form. Since the Fourier transform (FT) of a convolution product of two functions is equal to the product of the Fourier transforms of the two functions, the FT of P(s) writes as

$$\tilde{P}(k) = e^{-\tau}\left[1 + \tau\tilde{P}_1(k) + \frac{1}{2}\tau^2\tilde{P}_1^2(k) + \ldots\right] = e^{-\tau}e^{\tau\tilde{P}_1(k)} = e^{-\tau[1-\tilde{P}_1(k)]}, \qquad (6)$$

Where

$$\tilde{P}_1(k) = \int_{-\infty}^{+\infty} P_1(s)\, e^{-iks} ds \qquad (7)$$

Then the exact form of the Comptonized spectrum I(x) is then given by Eq.(1) in terms of the exact redistribution function

$$P(s) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \tilde{P}(k)\, e^{iks}\, dk \qquad (8)$$

Which is obtained as the anti Fourier transform of $\tilde{P}(k)$ in Eq.(6).

SZE: general derivation

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

Intensity change

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

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

Pressure

Thermal

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

Relativistic

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

Spectral shape

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

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

Redistribution function

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

SZE: general derivation

Thermal population

$$f_{e,th} \propto p^2 \exp(-\eta\sqrt{1+p^2})$$

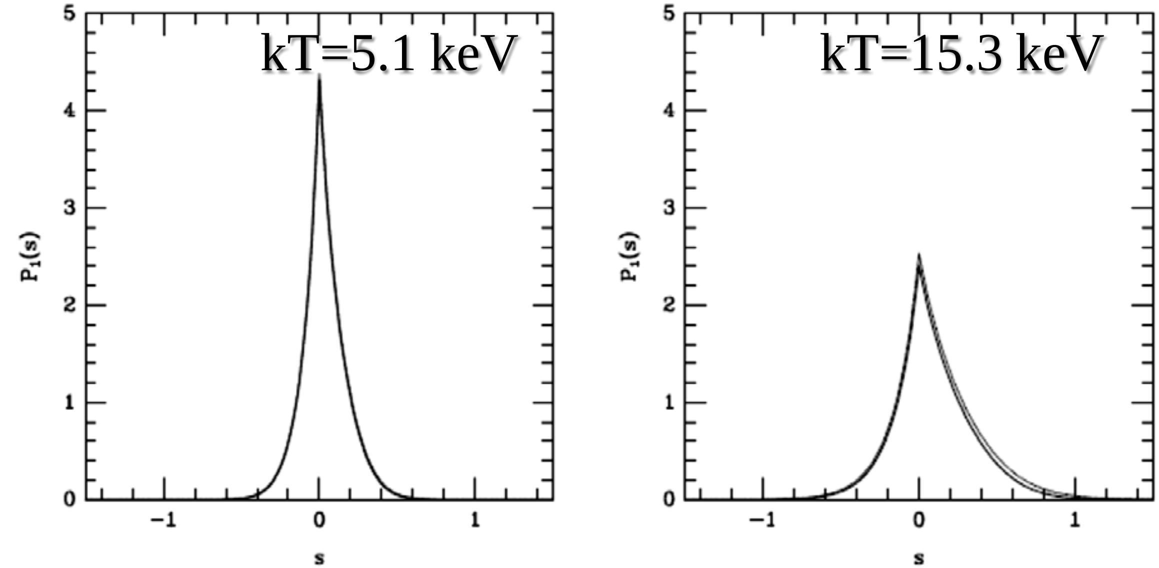
$$\eta = m_e c^2 / k_B T_e,$$

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

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

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

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



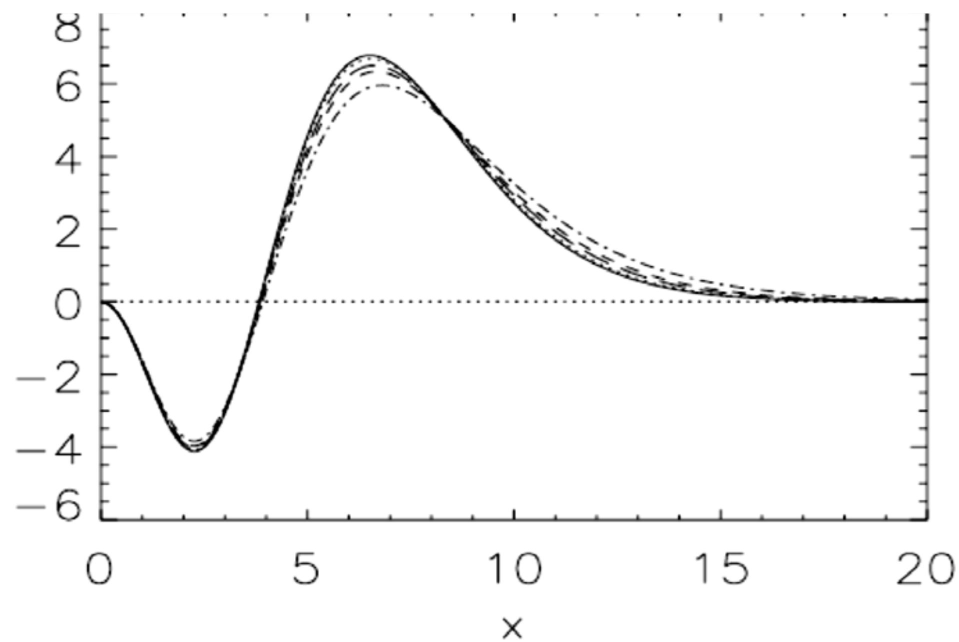


Fig. The function g(x) (solidline) is compared with the function ˜g(x) for thermal electron populations with kBTe=10 (dot-dashed), 5(dashes), 3(longdashes) and 1(dotted) keV

SZE: general derivation

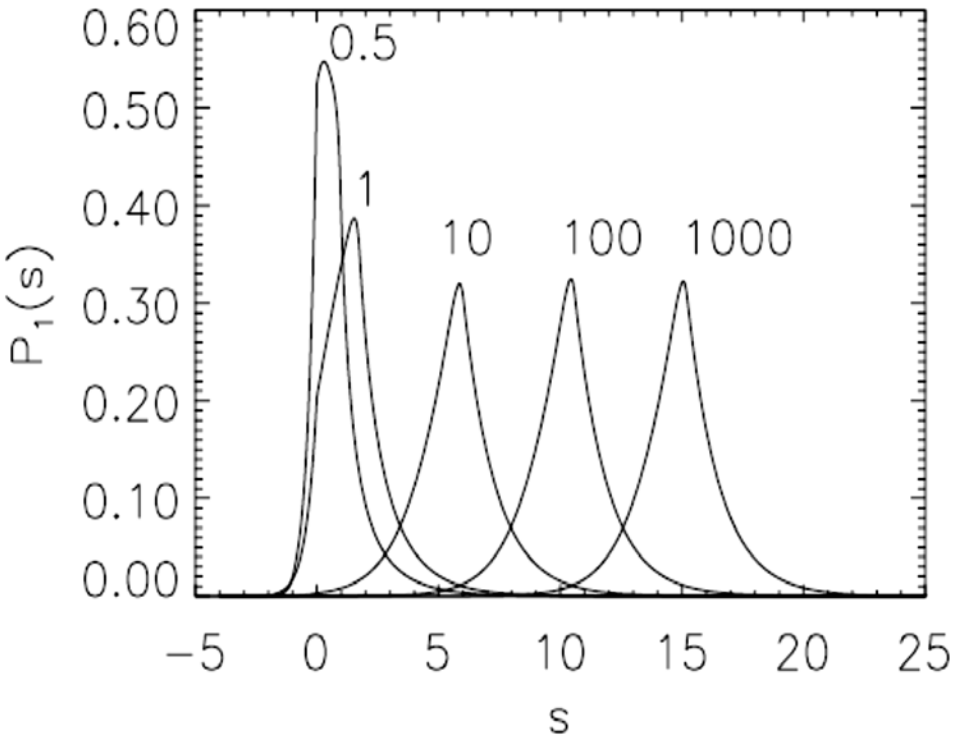
Non-Thermal population

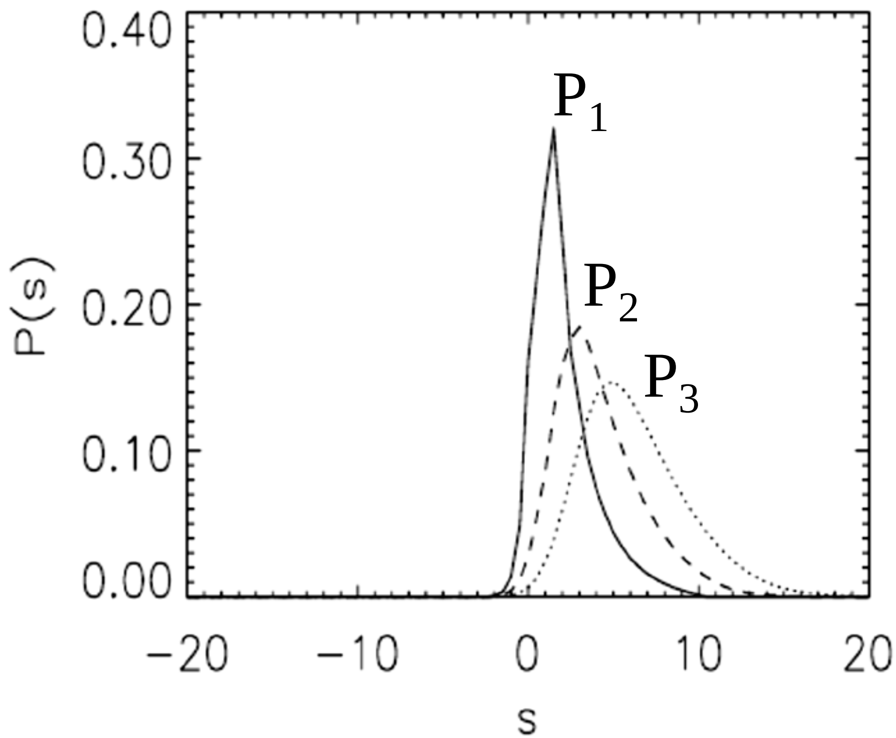
$$f_{\mathrm{e,rel}}(p; p_1, p_2, \alpha) = A(p_1, p_2, \alpha) p^{-\alpha} \; ; \qquad p_1 \le p \le p_2$$

$$A(p_1, p_2, \alpha) = \frac{(\alpha - 1)}{p_1^{1-\alpha} - p_2^{1-\alpha}}$$

$$P_{\mathrm{rel}} = n_{\mathrm{e}} \int_0^{\infty} \mathrm{d}p \, f_{\mathrm{e}}(p) \frac{1}{3} p v(p) m_{\mathrm{e}} c$$

$$= \frac{n_{\mathrm{e}} m_{\mathrm{e}} c^2 (\alpha - 1)}{6 [p^{1-\alpha}]_{p_2}^{p_1}} \left[B_{\frac{1}{1+p^2}} \left(\frac{\alpha - 2}{2}, \frac{3 - \alpha}{2} \right) \right]_{p_2}^{p_1}$$





SZE: general derivation

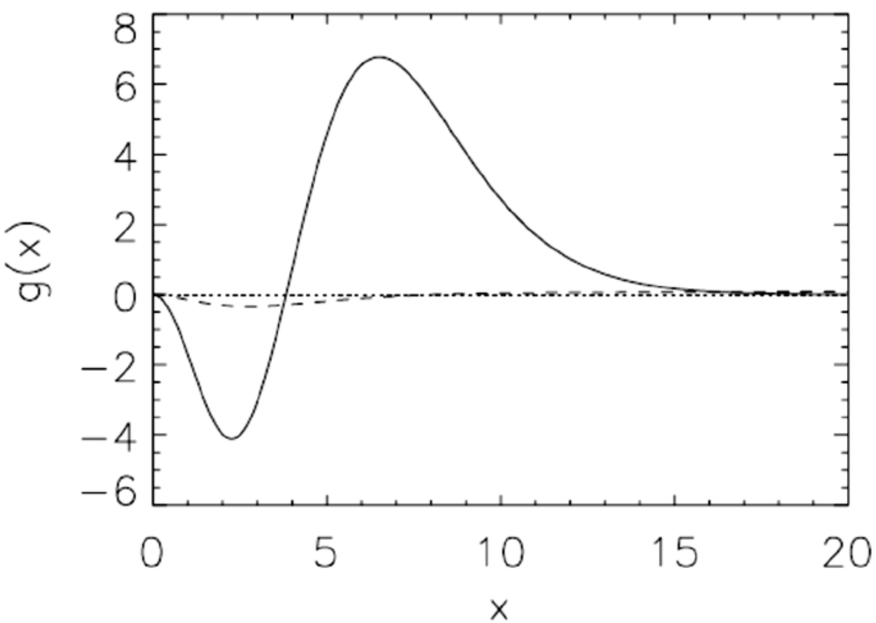
Also for a non-thermal electron population it is possible to write the spectral distortion in a general form

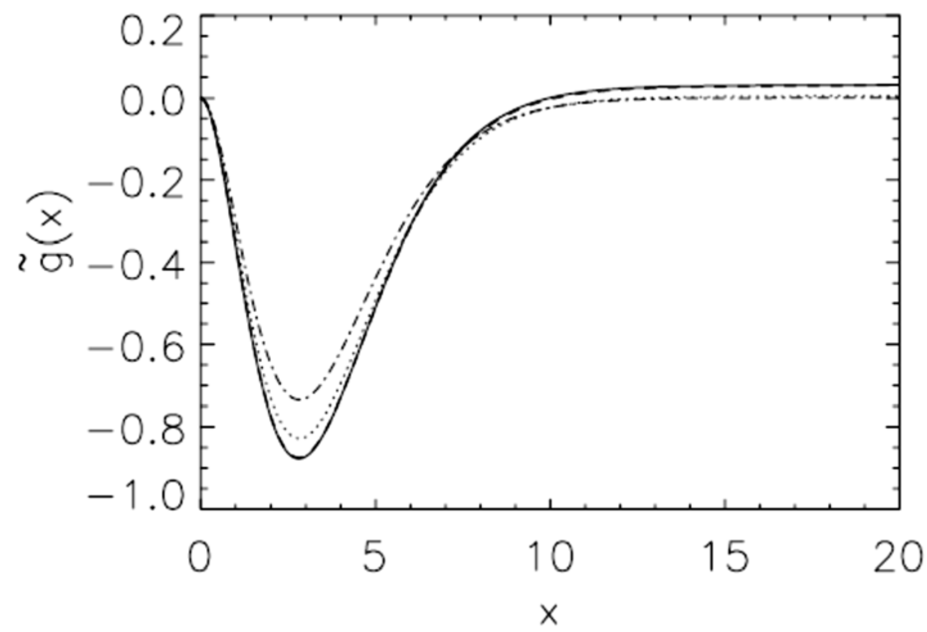
$$\Delta I_{\rm non-th}(x) = 2\frac{(k_{\rm B}T_0)^3}{(hc)^2} y_{\rm non-th}\,\tilde{g}(x),$$

$$y_{\rm non-th} = \frac{\sigma_{\rm T}}{m_{\rm e}c^2}\int P_{\rm rel}\,{\rm d}\ell,$$

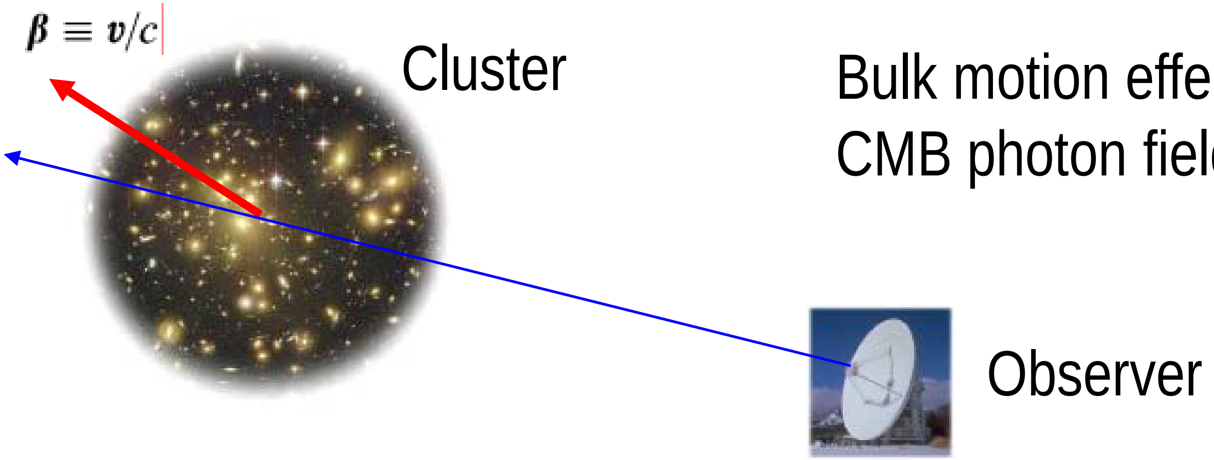
$$\tilde{g}(x) = \frac{m_{\rm e}c^2}{\langle k_{\rm B}T_{\rm e}\rangle}\left\{\frac{1}{\tau}\left[\int_{-\infty}^{+\infty} i_0(x{\rm e}^{-s})P(s)\,{\rm d}s - i_0(x)\right]\right\}.$$

$$\langle k_{\rm B}T_{\rm e}\rangle \equiv \frac{\sigma_{\rm T}}{\tau}\int P\,{\rm d}\ell$$





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

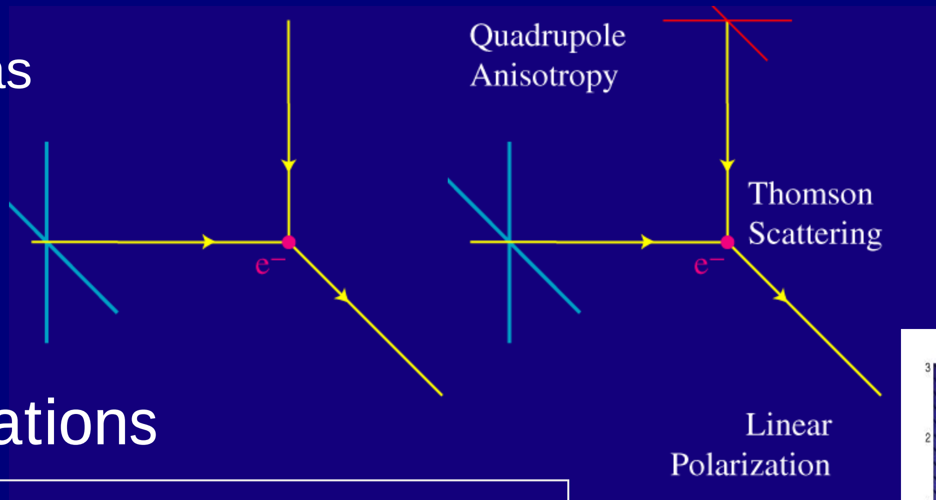
Spectral shape

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

CMB spectrum

SZE: polarization

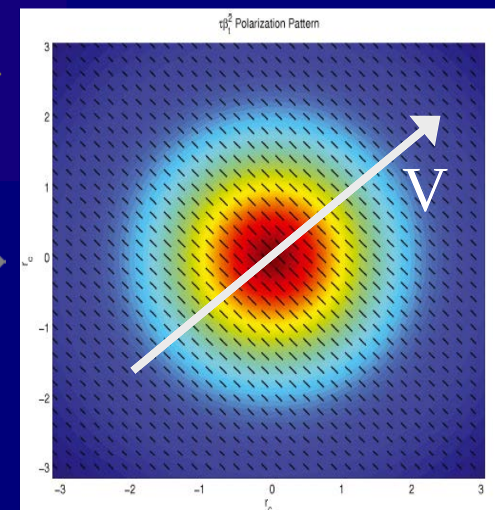
Polarizations arises as a natural outcome of γ-e scattering



→ various polarizations

Polarization due to peculiar motion of clusters

$$\Pi_t \approx \beta_t^2 \tau$$

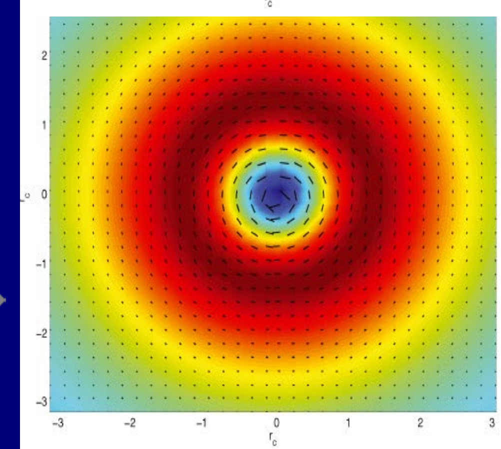


Polarization due to transverse motions of plasma within the cluster

$$\Pi_V \approx \beta_t \tau^2$$

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 formalism

Relativistic covariant formulation

[Colafrancesco et al. 2011-12]

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)

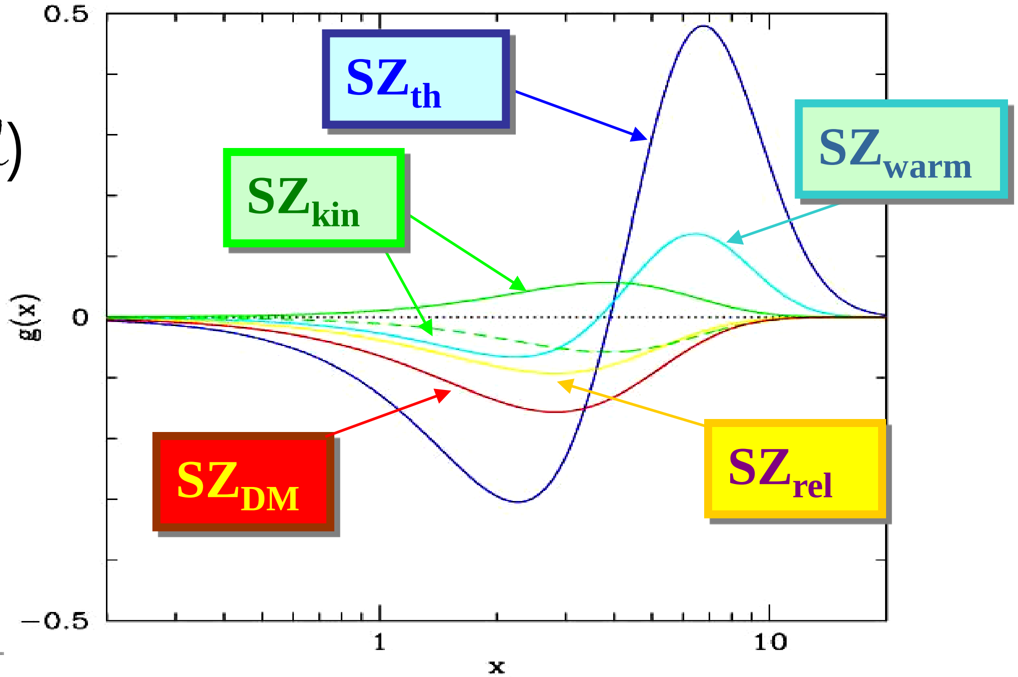
$$\tilde{I}(\vec{p}; \vec{v}_L) = I(\vec{p}; \vec{v}_L) + \int_{\hat{\mathbf{n}}} d\tau \int_{-\infty}^{\infty} P_1(s) \left[e^{3s} I_0(pe^{-s}) - I_0(p) \right] ds$$

SZE spectro-polarimetry

SZE Intensity:

sensitivity to projected (along the ℓ) physical parameters

τ, kT_e, P_e, E_e, M_χ, V_t

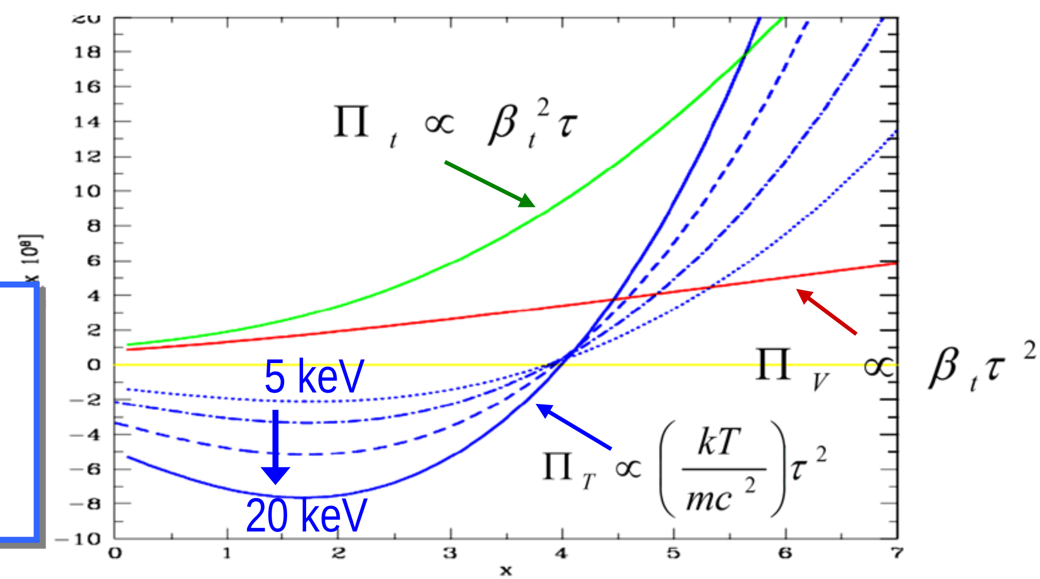


SZE polarization:

sensitivity to m-D distribution of physical parameters

For a thermal plasma:

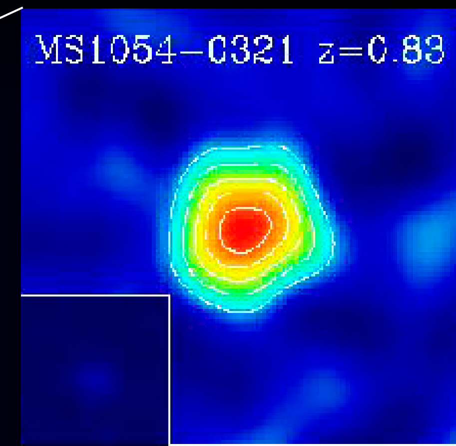
- Velocity sub-structure ($\beta \tau^2$)
- Temperature sub-structure ($T_e \tau^2$)



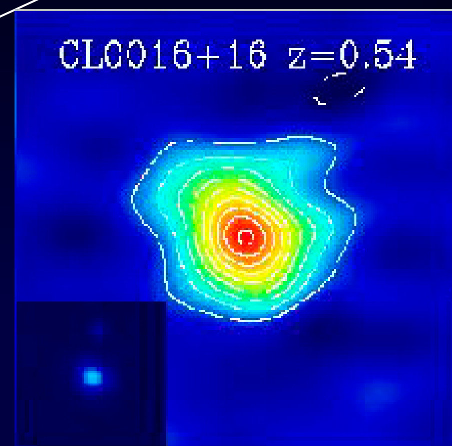
Astrophysics & Cosmology

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

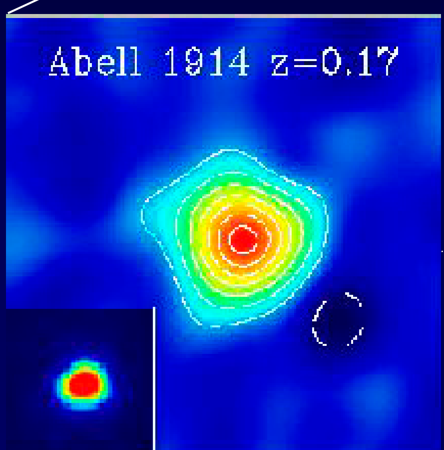
Standard-rod "physical" effect



X-rays



X-rays



X-rays

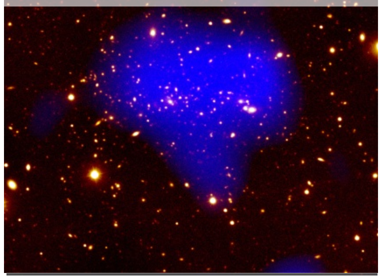
The SZE depends directly on the electron distribution in the atmospheres of cosmic structures and therefore it is an optimal tool for Astrophysical applications

Cosmic Lepto-meter, speedo-meter

Astrophysical relevance

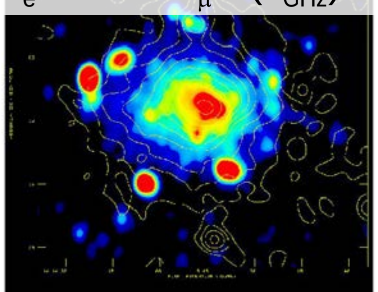
Galaxy clusters

Thermal particles
$E_e \sim 0.1 - 10$ keV



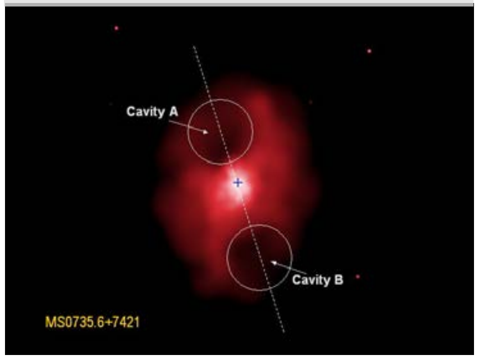
WIMPs
$M_\chi \sim 10–500$ GeV

Cosmic rays
$E_e \sim 16 GeV\ B_\mu^{1/2} (\nu_{GHz})^{1/2}$

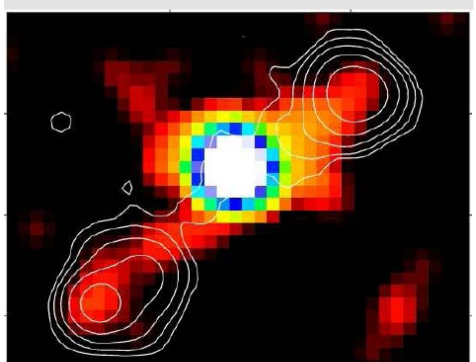


AGN jets/cavities

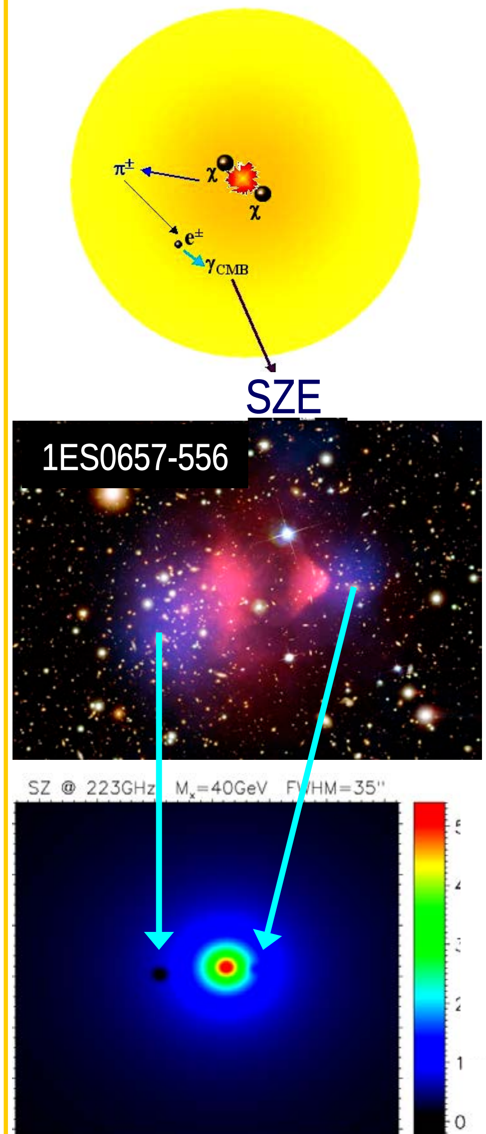
Cluster Cavities
MS0735+7421 (Chandra)



Radio Galaxy Lobes
3C432 (Chandra)

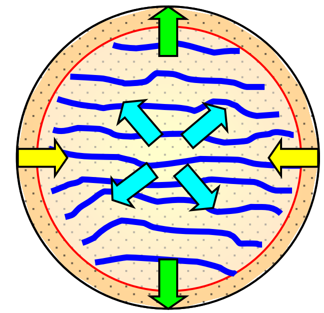


DM nature

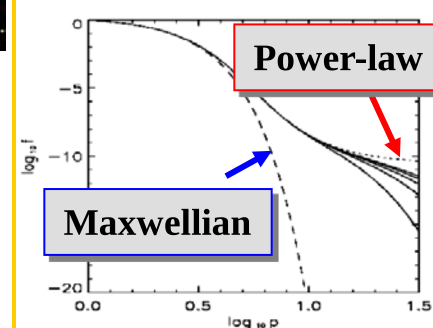


Plasma physics

B-fields



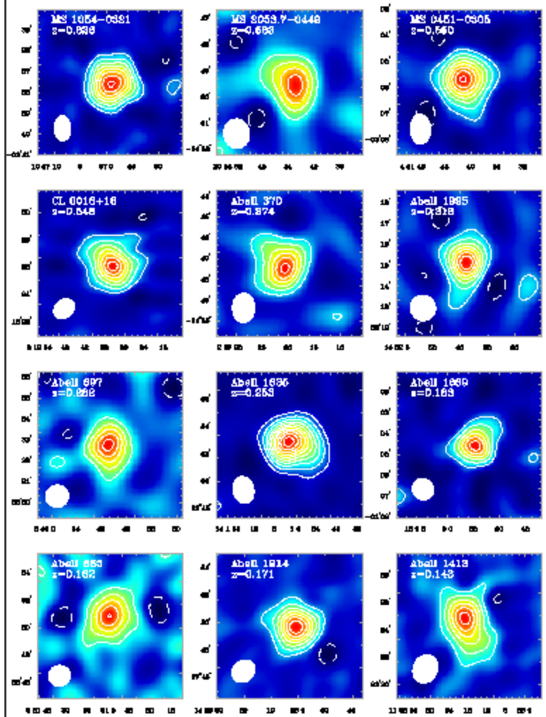
Acceleration proc.



Pre-PLANCK Era

Simple Observables

Shape



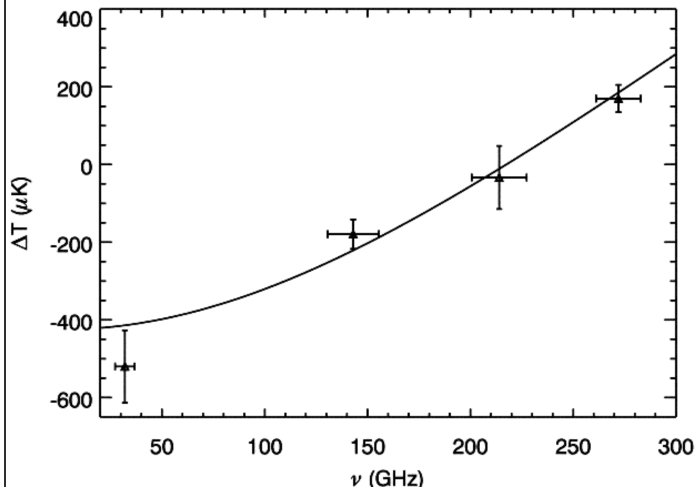
OVRO (30 GHz)

SZE has larger angular size than X-ray image

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

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

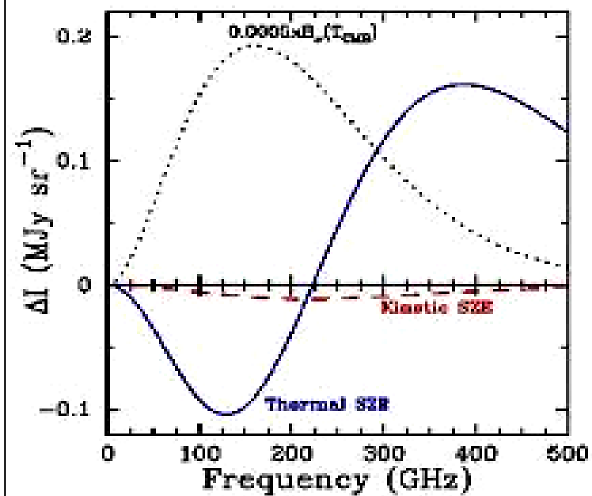
Spectrum



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

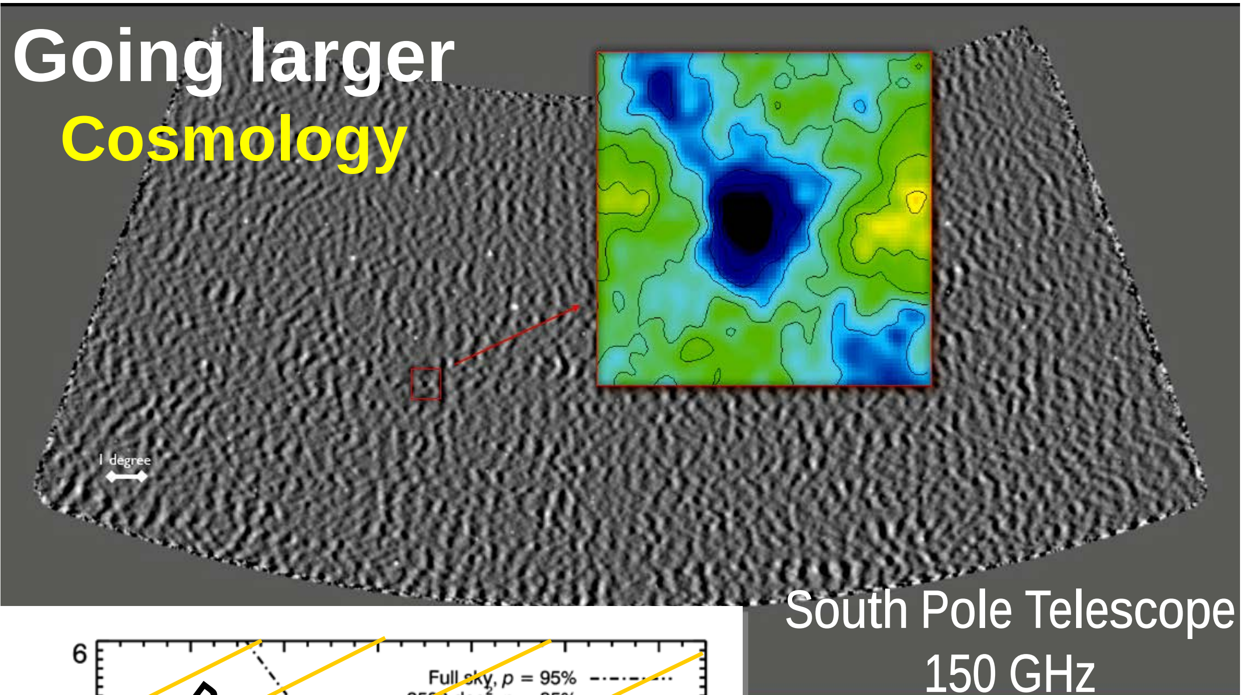
- Spectrum observed in a few bands (30, 150, 220, 275 GHz)
- The zero near the peak of CMB spectrum (~ 220 GHz)

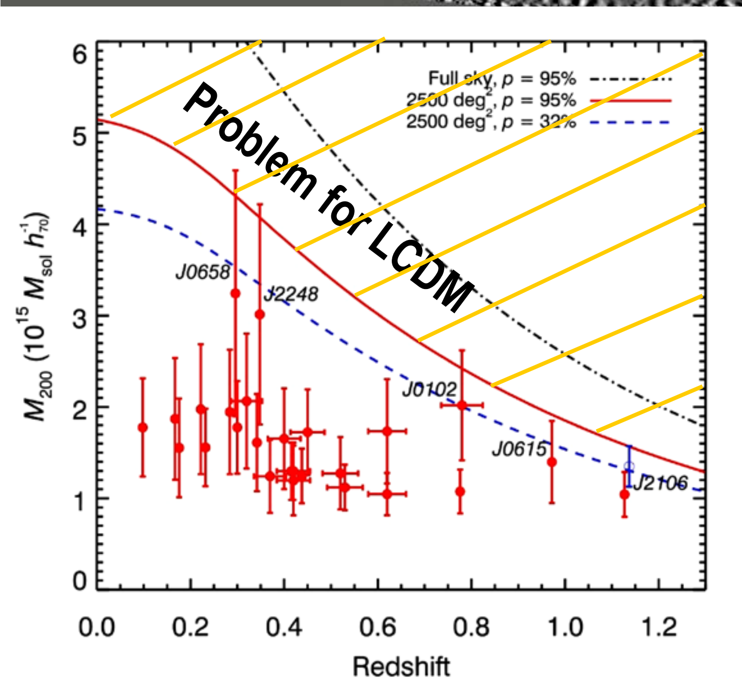
Kinematic



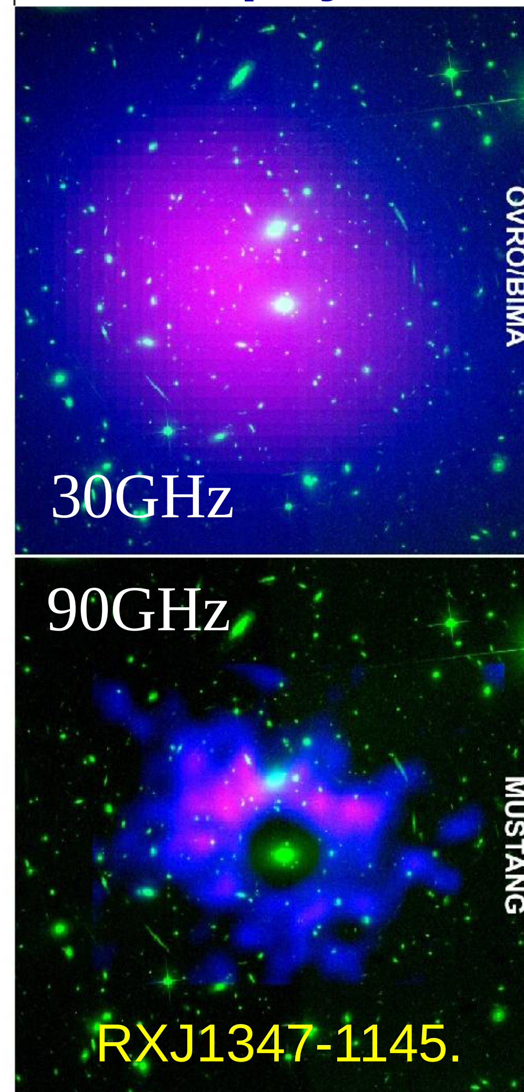
- Small compared to thermal SZE at low ν
- No zero (CMB spectrum)
- Confused by primordial CMB structure
- No detection

Pre-PLANCK Era





Going deeper
Astrophysics



SZE-selected samples dominated by disturbed clusters

Contaminating point sources (AGN, star forming galaxies)

Pre-PLANCK Era

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

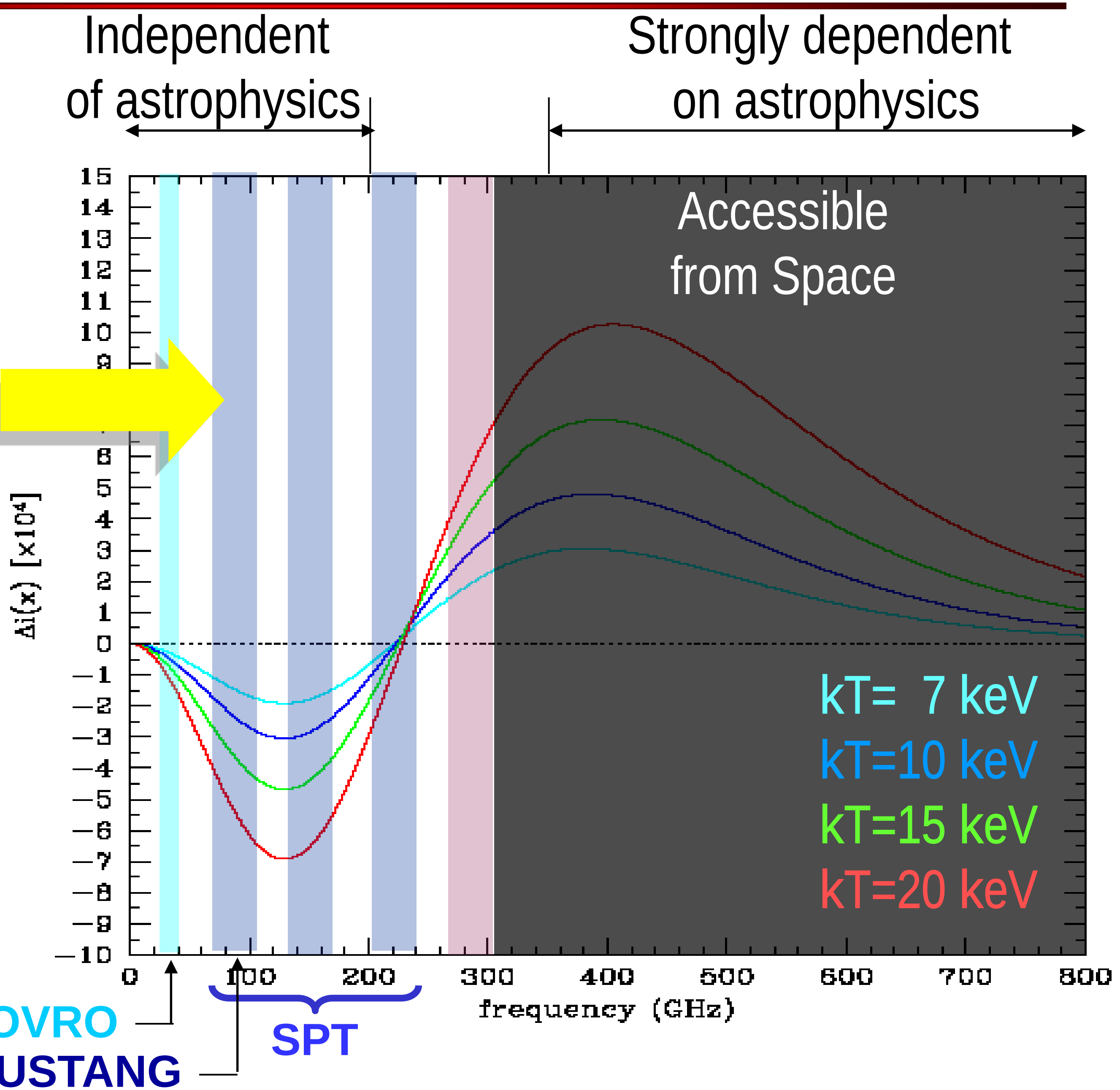
$$y_{th} = \sigma_T \int d\ell n_e \frac{kT_e}{m_e c^2}$$

Need external priors

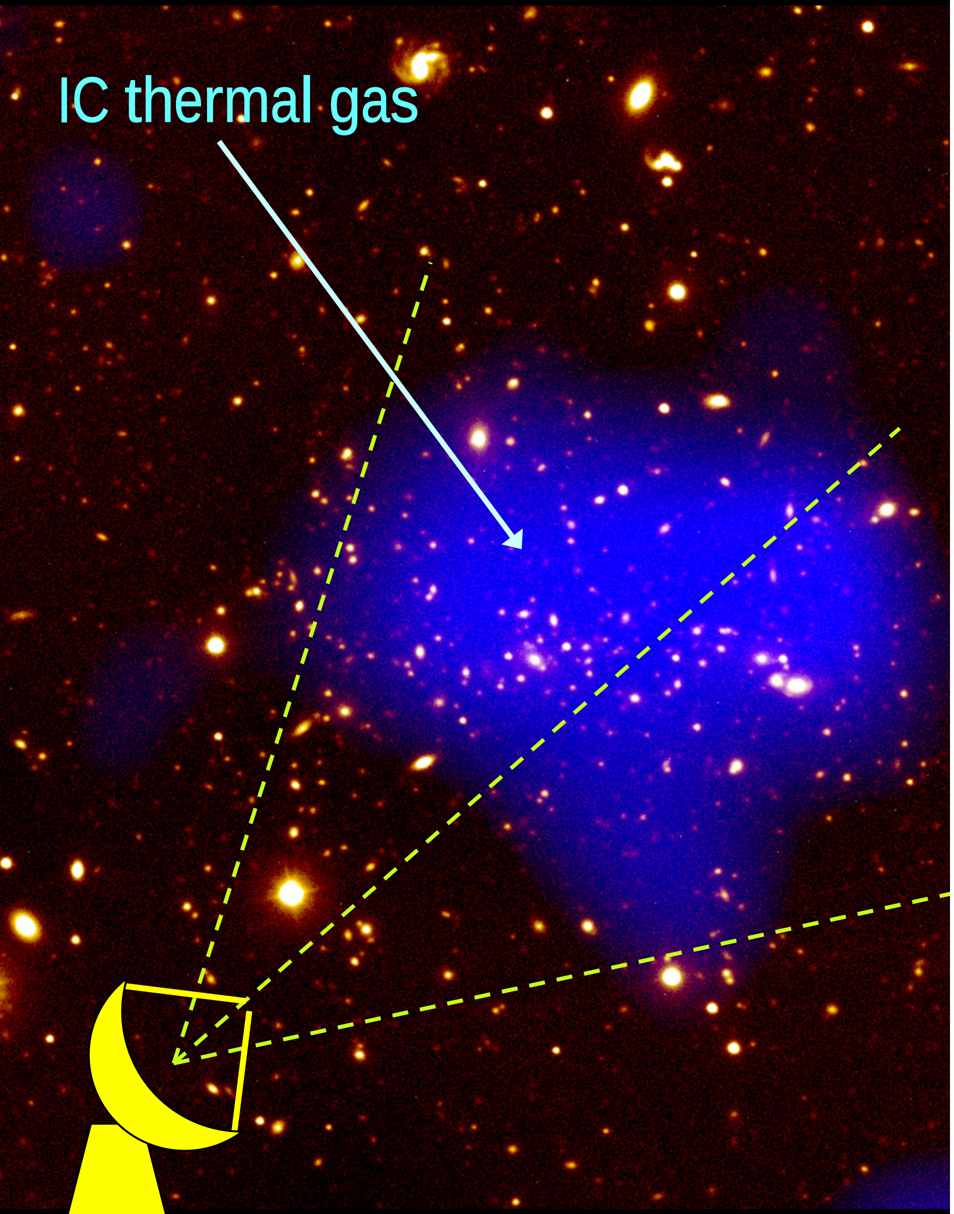
- X-ray ⇨ kT
- WL ⇨ M
- O ⇨ z

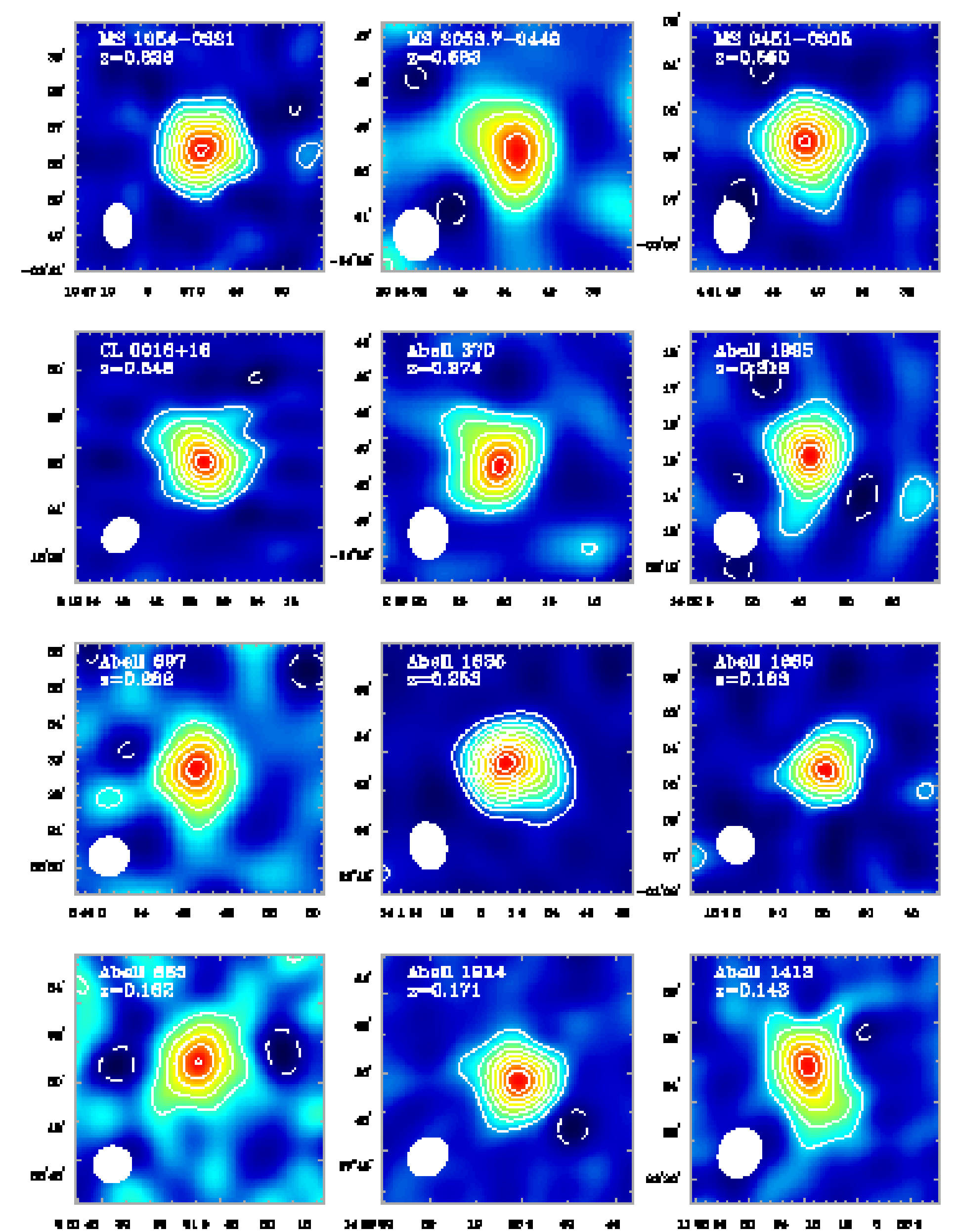
for a proper use in

- Cosmology
- Astrophysics



Pre-PLANCK Era Blob-ology



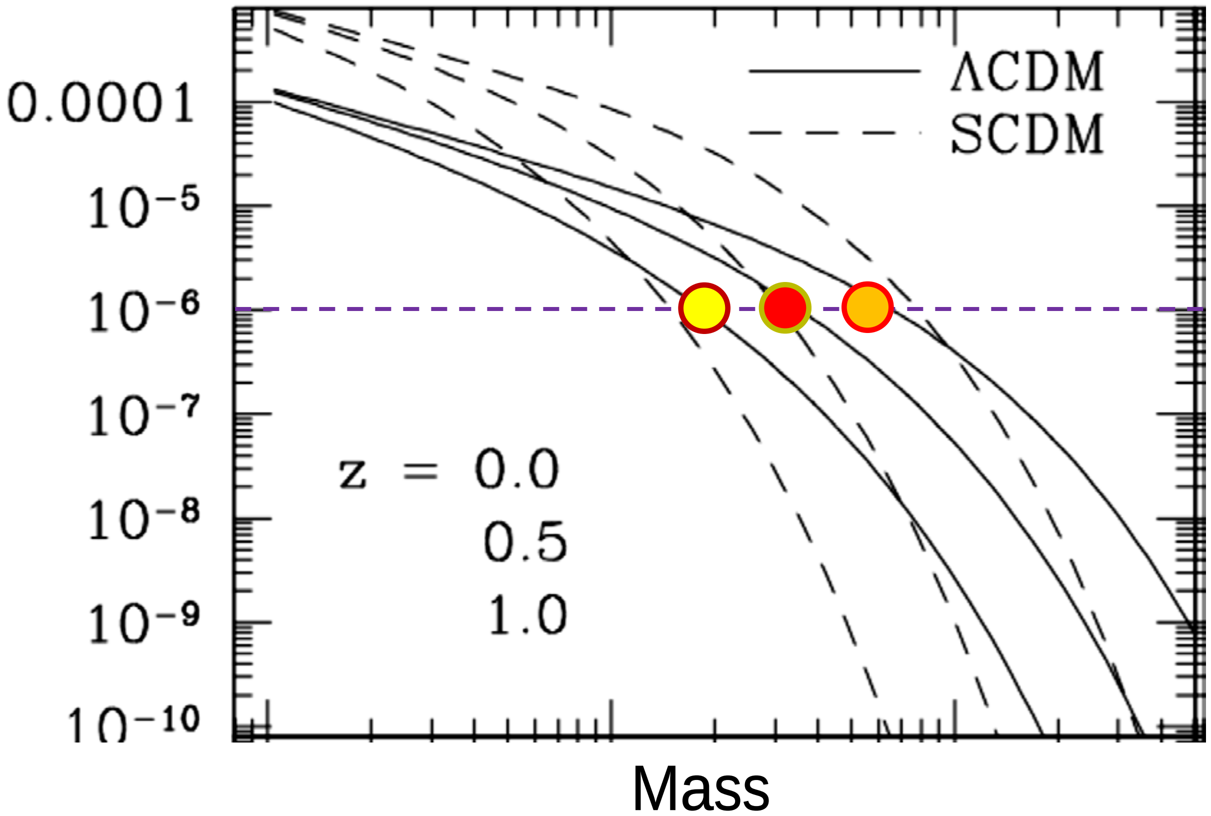


Pre-PLANCK Era

Use SZE cluster counts to probe Cosmology

- Reliable blob counting method for pre-Planck instruments
- Uncertain Mass reconstruction (need external proxy: X-ray, GL)

$$M(r) = -\frac{1}{G\rho(r)} r^2 \frac{d}{dr}\left[P_{tot}\right]$$ (Hydrostatc Equilibrium)



PLANCK-Era

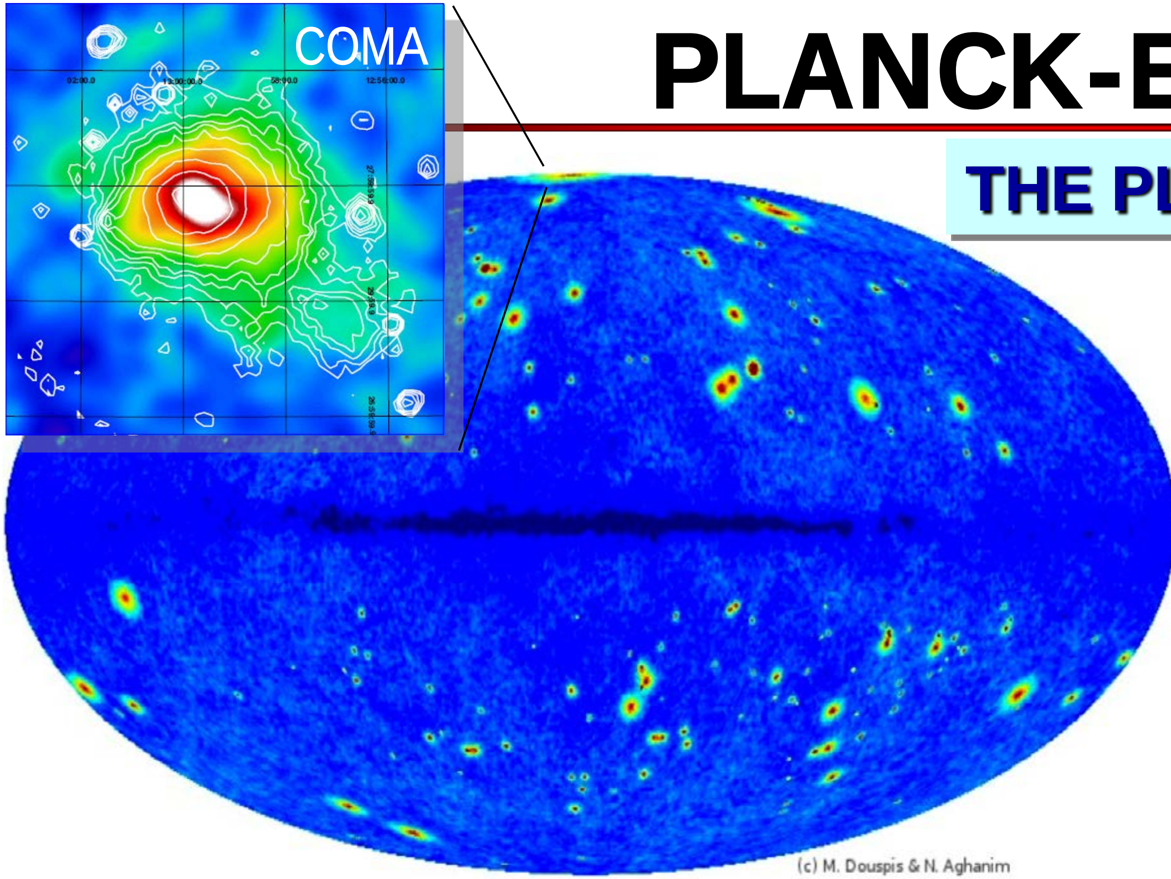
THE PLANCK MISSION

- Launch in May 2009 ; L2 orbit
- 1.5 m gregorian telescope
- 9 frequency bands 30-857GHz
- ~ 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



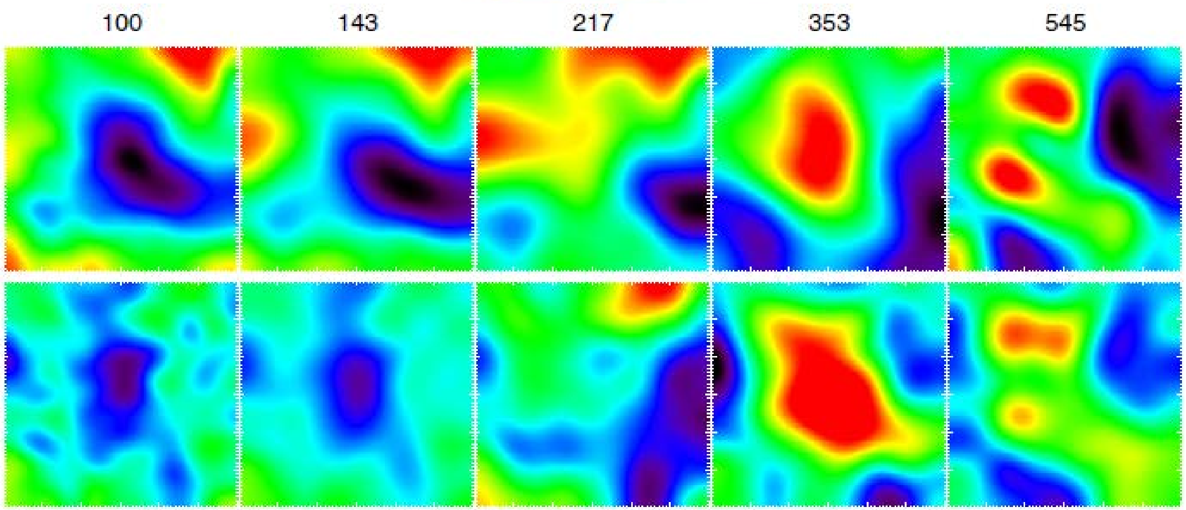
THE PLANCK EARLY SZ SKY

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



Coma. S/N=21.93

PLANCK-Era

NEW DETECTED CLUSTERS

8 unconfirmed ESZ candidates

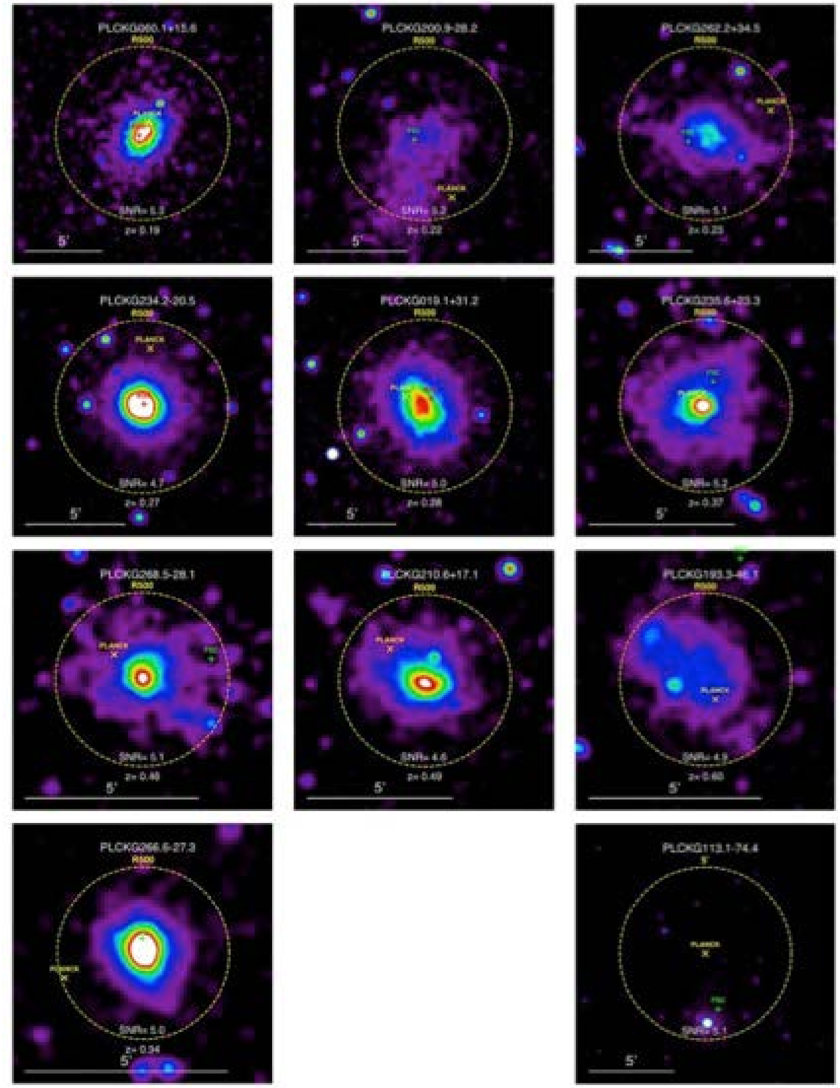
- 7 confirmed by third party (SPT, AMI)

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]

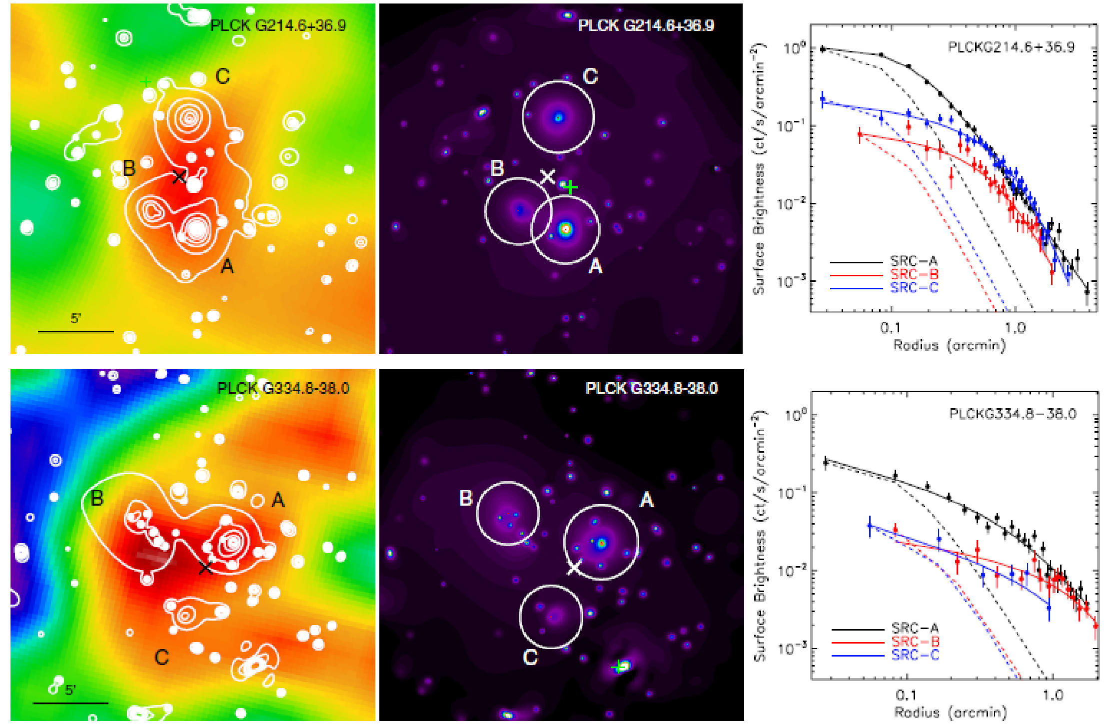
PLANCK-Era

Multiple SZE systems

SZE-selected samples are dominated by disturbed clusters

Question:

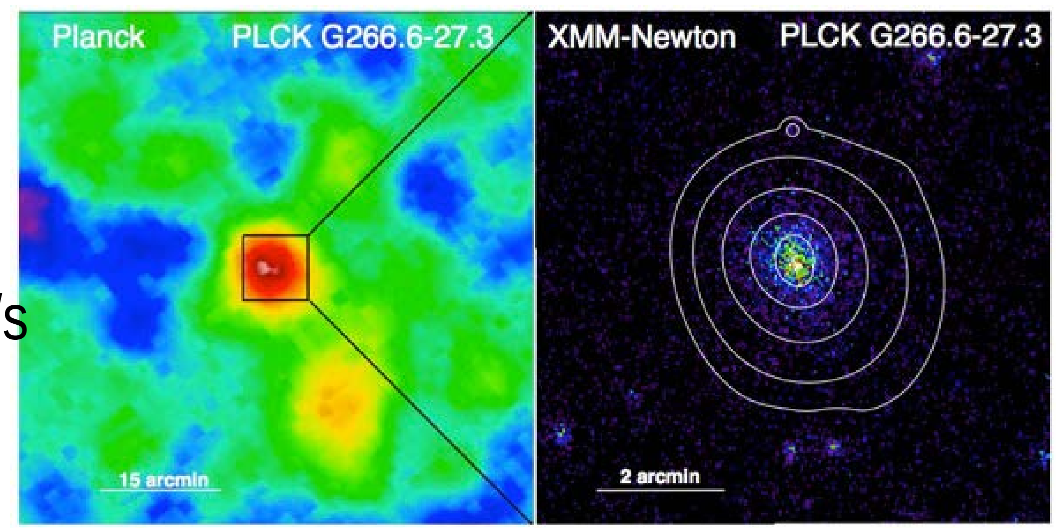
How much does merger activity bias (scatter) the SZE cluster samples, as a function of M , z ? i.e. affects Cosmological use?



Distant clusters via SZE

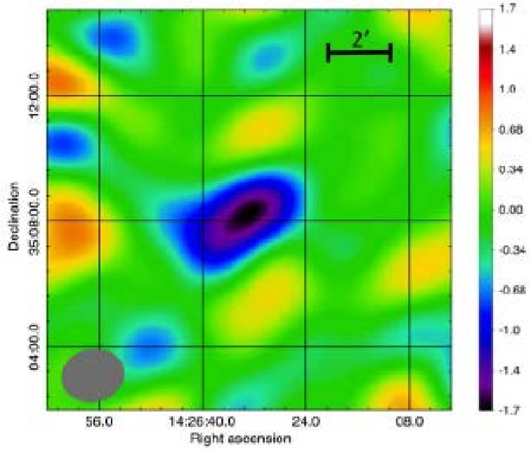
PLCK G266.6-27.3

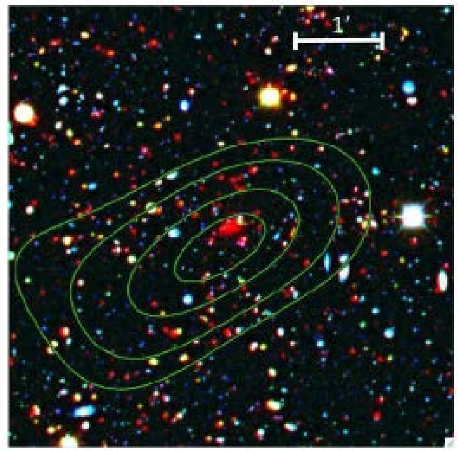
- SNR = 5
- z_{FeK}=0.94
- L_X[0.5-2keV]=(1.4±0.5)×10^{45} erg/s
- M_{500}=(7.8±0.8)×10^{14} $M_\odot$
- Highly relaxed

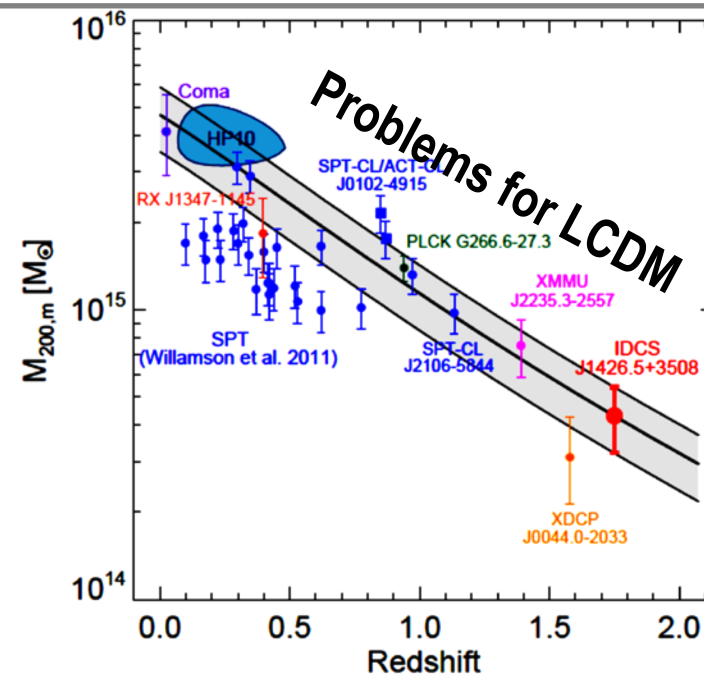


SZE: other results in the PLANCK-Era

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

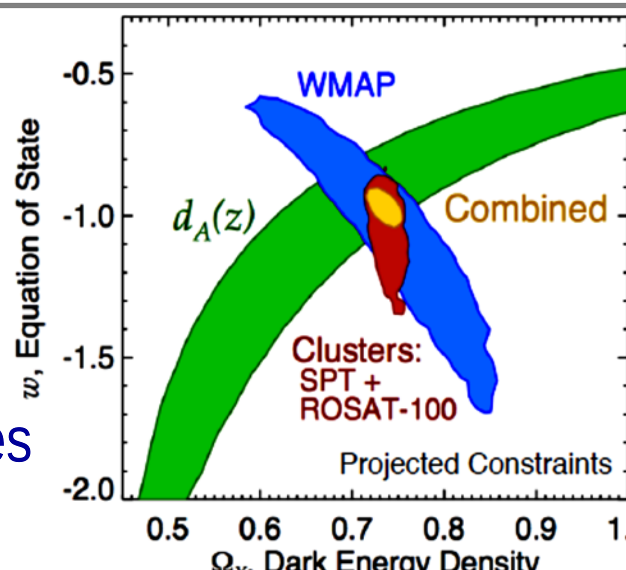


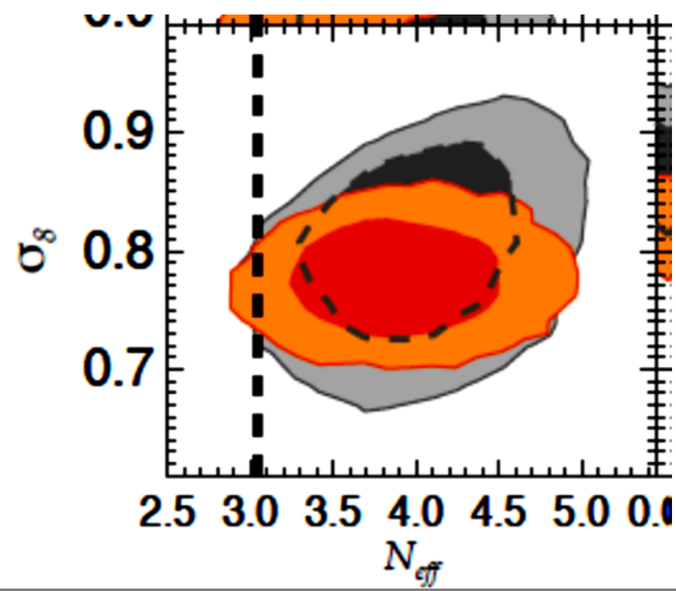




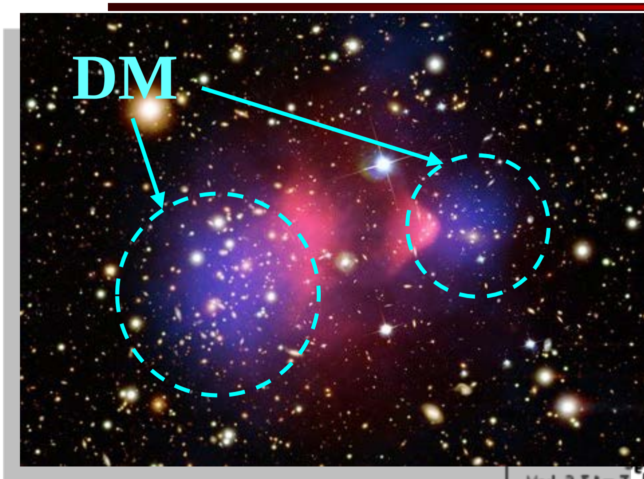
SPT: 450 clusters

- $\Delta w \sim 5\%$
- 2-σ preference for non-zero m_ν
  $\Sigma m = 0.34 \pm 0.17$eV
  and an extra ν species
  Neff=3.91±0.42

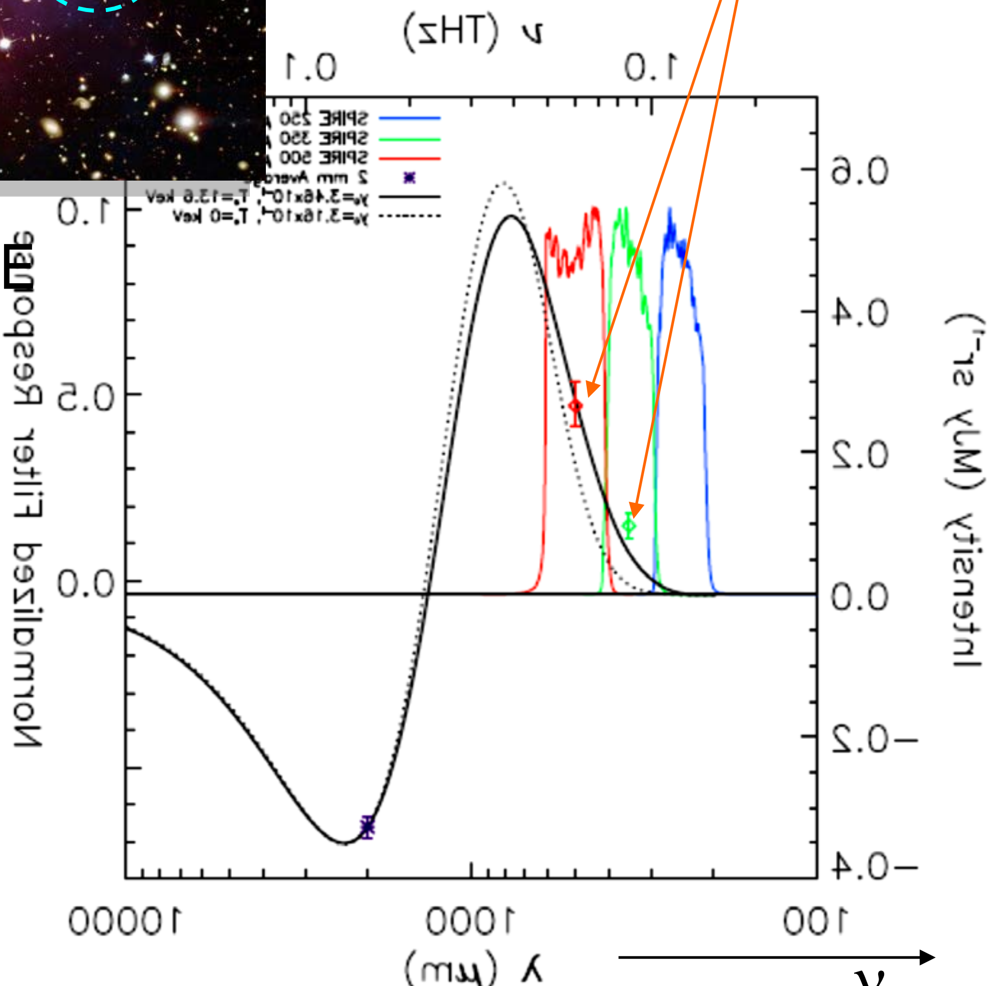


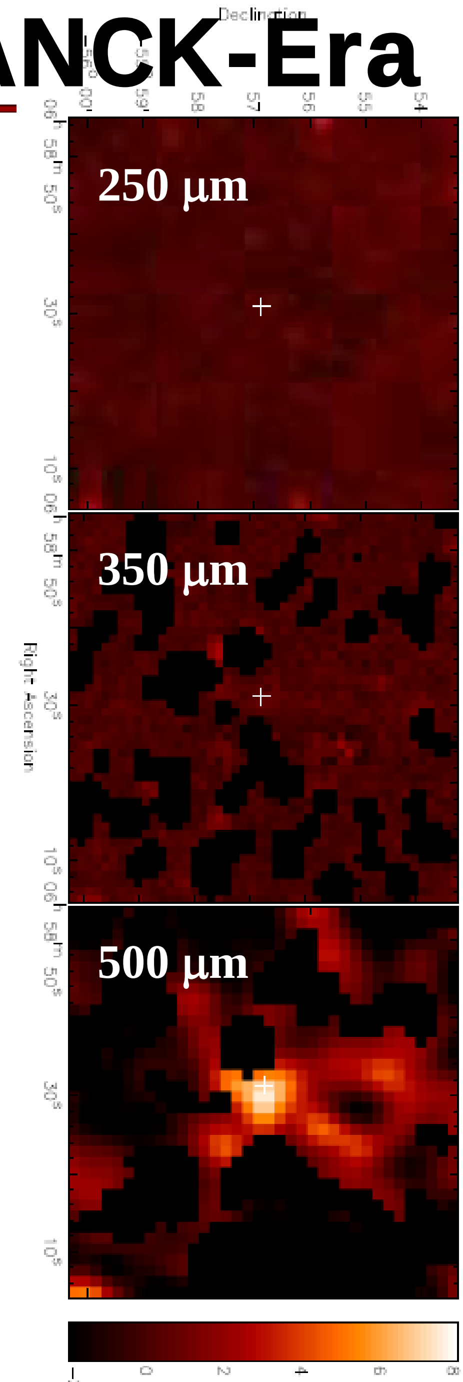


SZE: other results in the PLANCK-Era



First evidence of relativistic / non-thermal effects





Herschel SPIRE view of the Bullet cluster

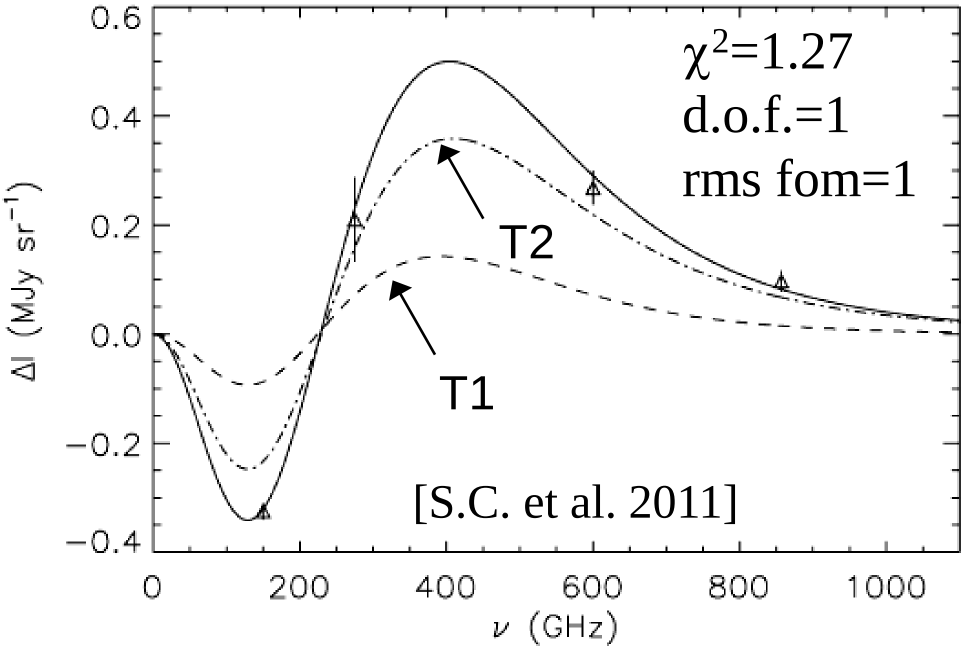
SZE: probes of astrophysics

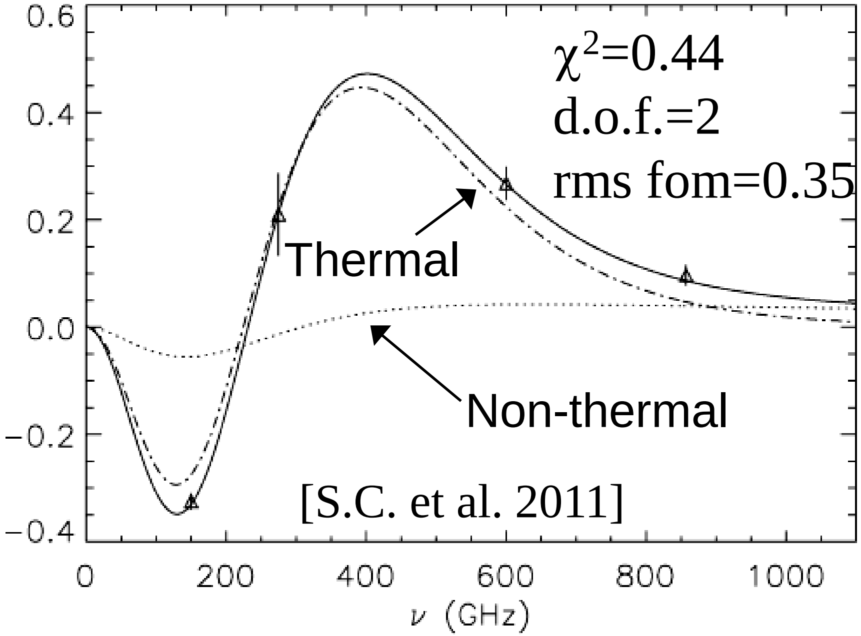
Multi - Temperature

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

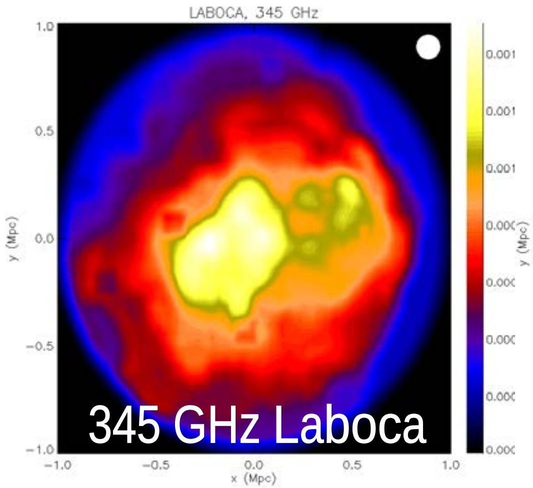
Shock acceleration or MHD acceleration

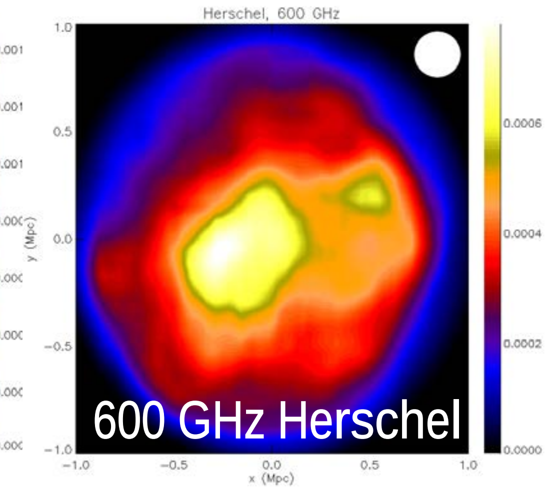
Stochastic electron acceleration

Continuous hadron acceleration

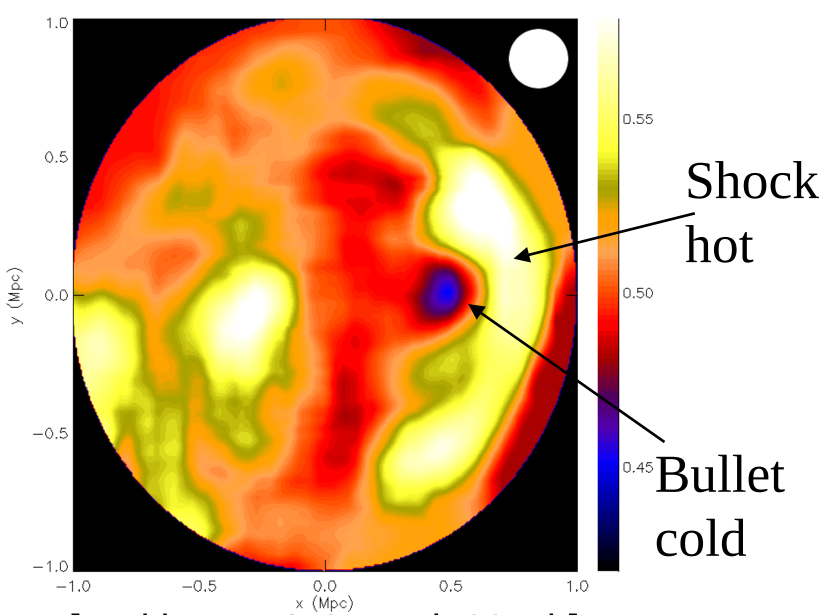
SZE: 3-d tomography

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

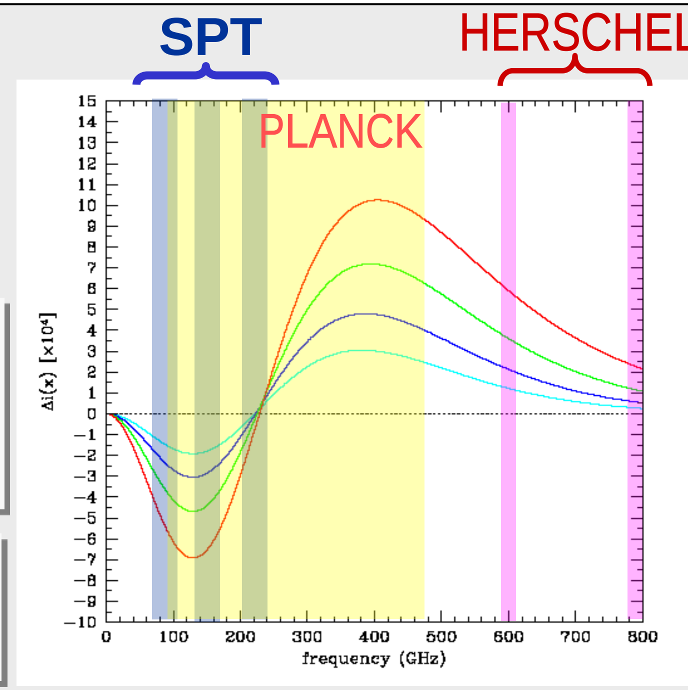
- Measure of the temperature stratification in clusters
- Measure of plasma in-homogeneity along the line-of-sight

From PLANCK onward

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

- SZ + LABOCA
150-215 345 GHz

- No spectroscopy
- Different instruments



PLANCK

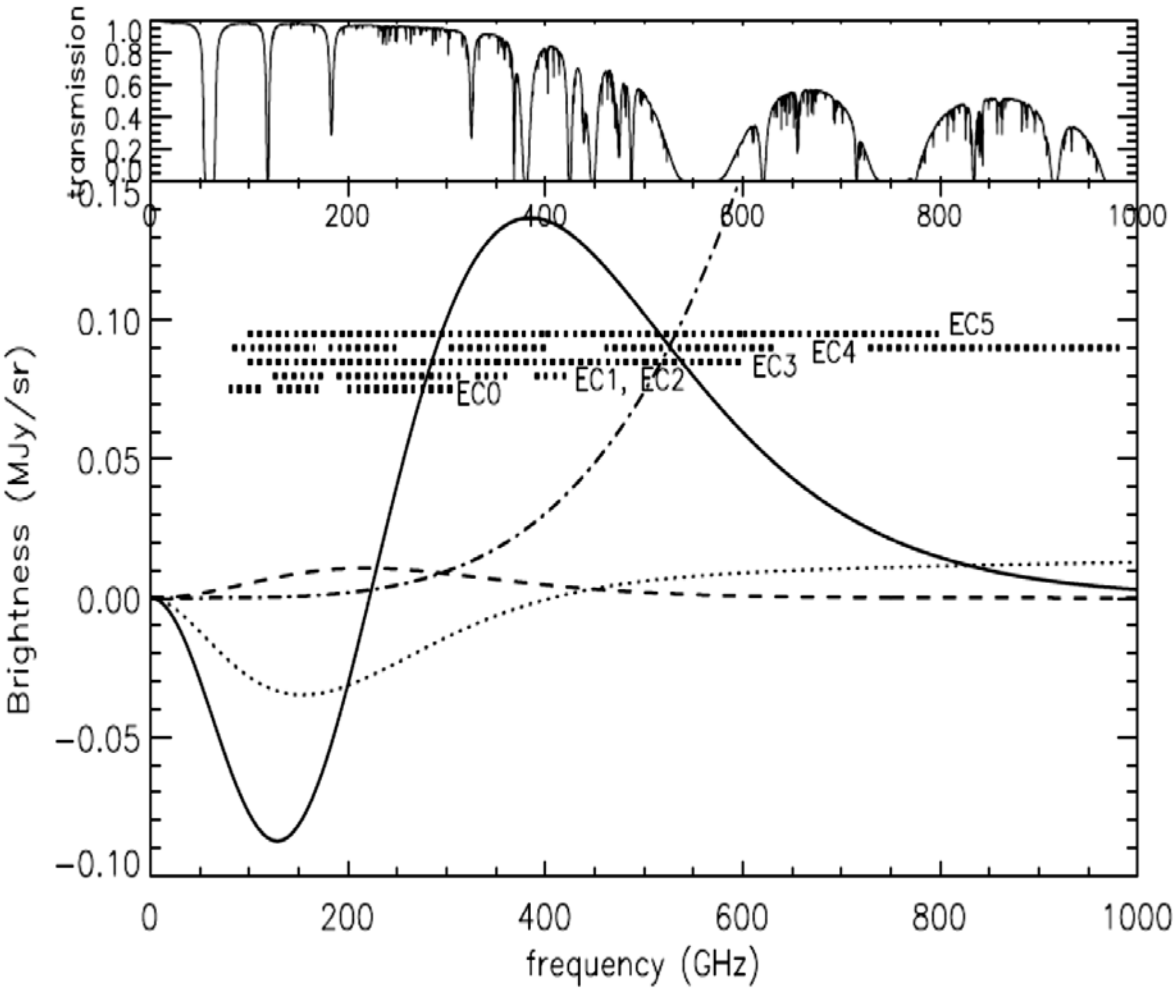
Full sky, but shallow survey
A few thousand clusters with low-moderate S/N ratio.
Low-moderate spatial resolution & spectroscopy in bands

To fully exploit the SZE info. we would need

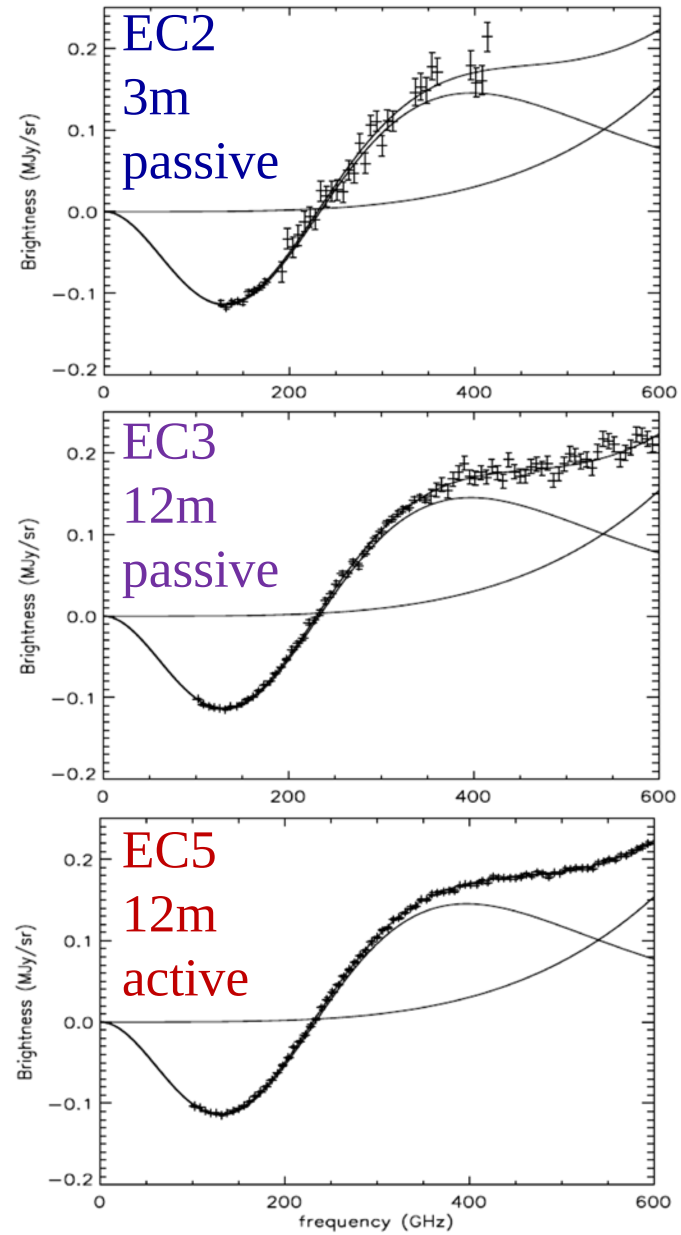
- Spectroscopic capabilities — wide-band
- Wider & continuous frequency coverage — FTS-like
- Better calibration — (no multi-band, no atmosphere)
- Better knowledge of foregrounds — PS separation
- Deep integrations on selected targets/fields — Astro+Cosmo

Requirements

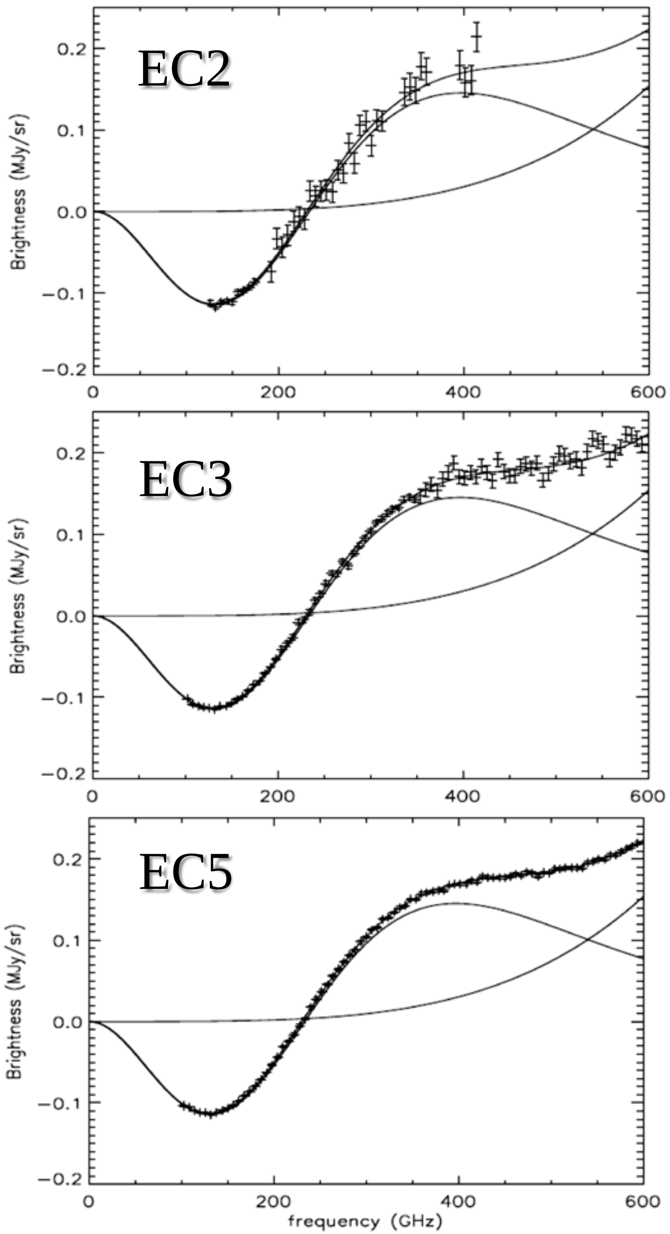
Different spectroscopic configurations
for studying the SZE in cosmic structures

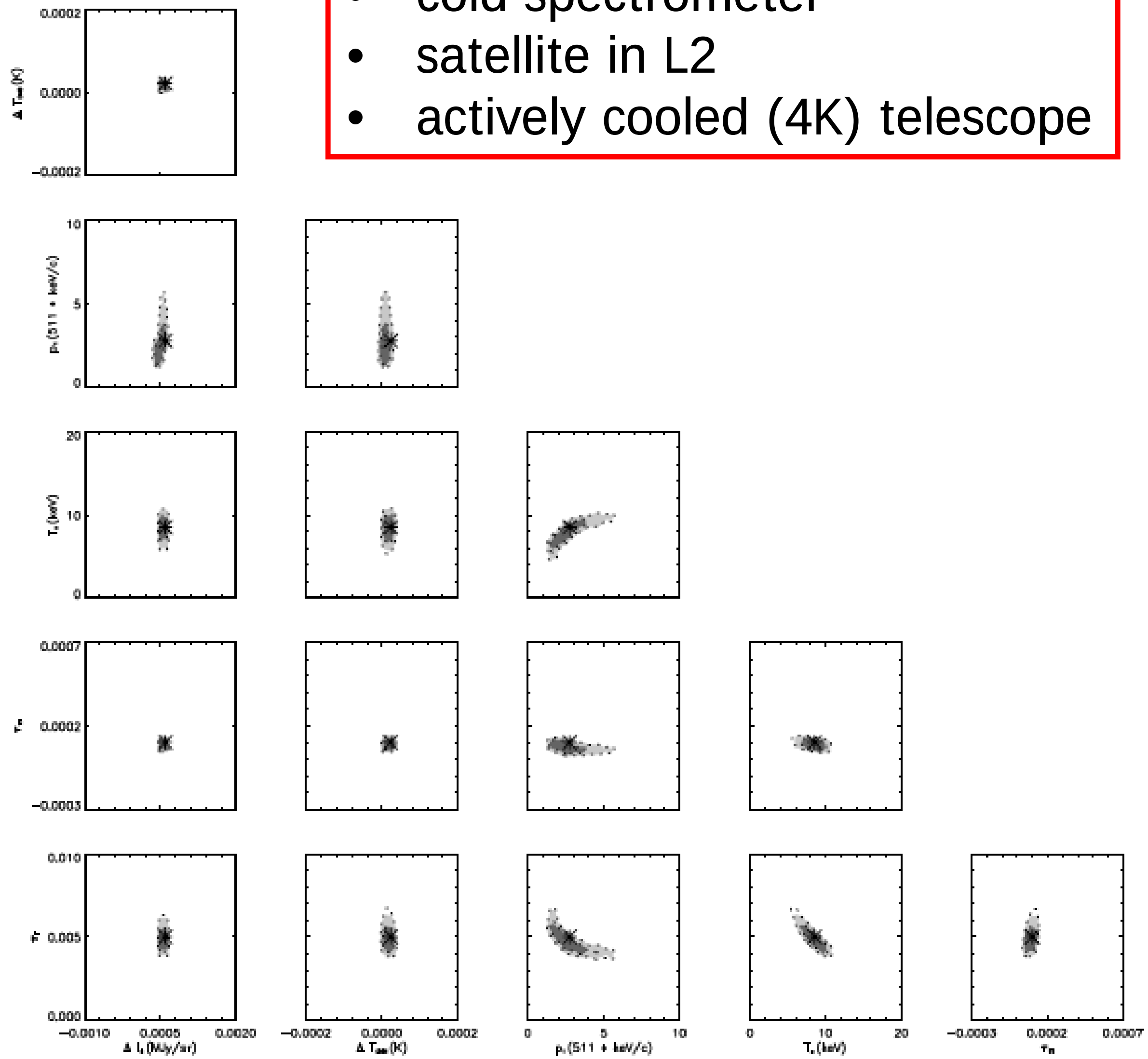


[DeBernardis, Colafrancesco et al. 2011]



Requirements

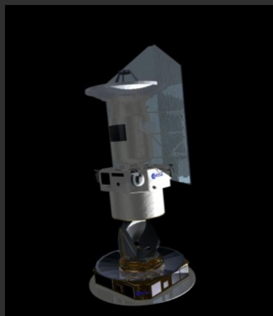




EC5
- cold spectrometer
- satellite in L2
- actively cooled (4K) telescope

SZE in Space: a future outline

2012

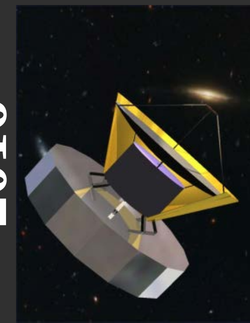


PLANCK HERSCHEL

~2013

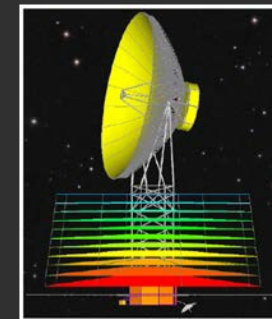
OLIMPO

~2016



SAGACE

~2020

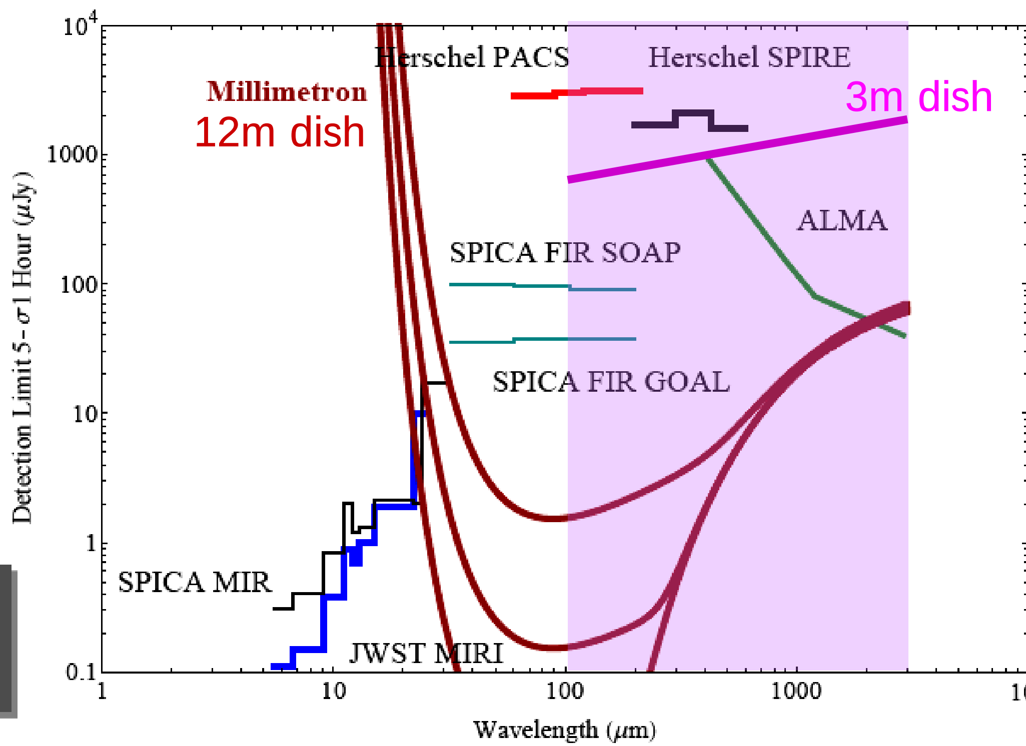


MILLIMETRON

SAGACE 3m

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

Large-survey mode
Pointed mode



MILLIMETRON 12m

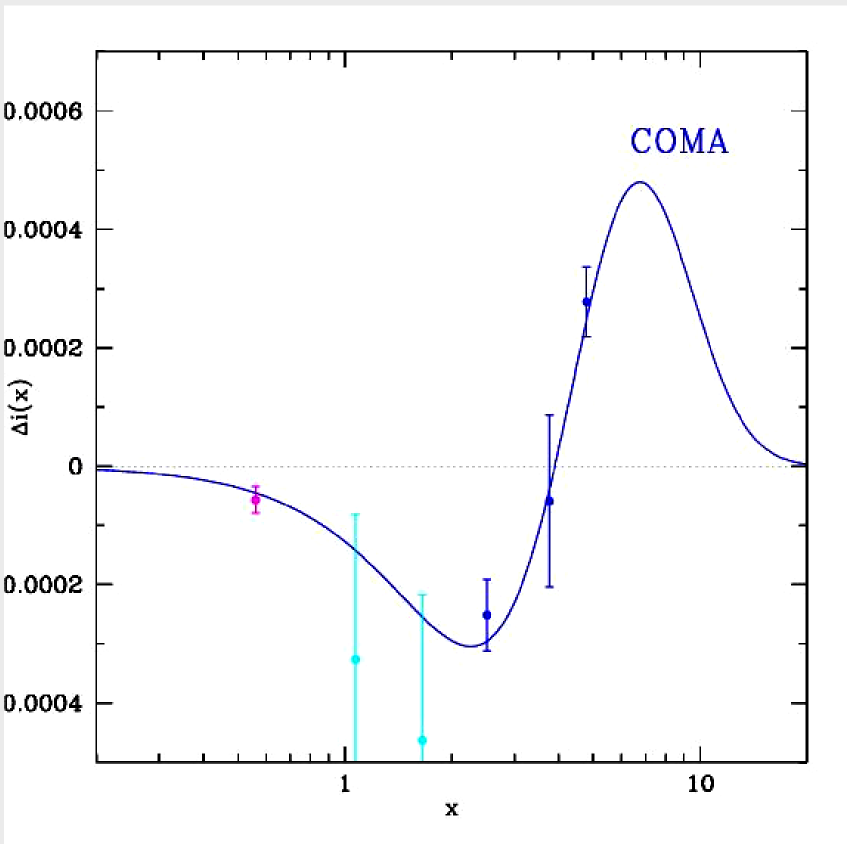
- 12 m dish
- Active cooling
- (4 K)
- Θ< 0.1-1.0 arcmin
- Noise<**0.1 mJy/√Hz**
- FTS spectroscopy
- Polarimetry
- Super VLBI

Observatory mode
Small-survey mode

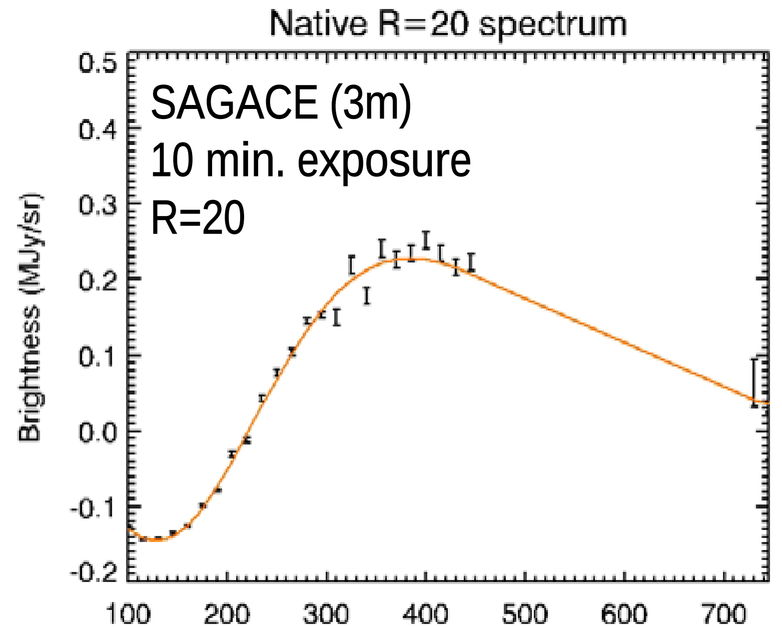
SZE spectroscopy: precision

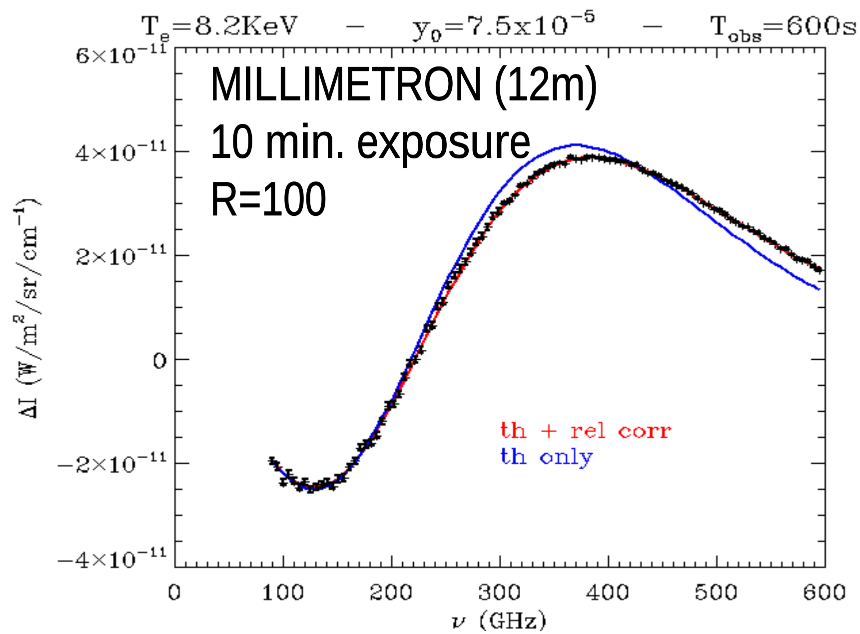
COMA in SZE: Current data

(Battistelli et al. 2003, ApJ 598, L75)

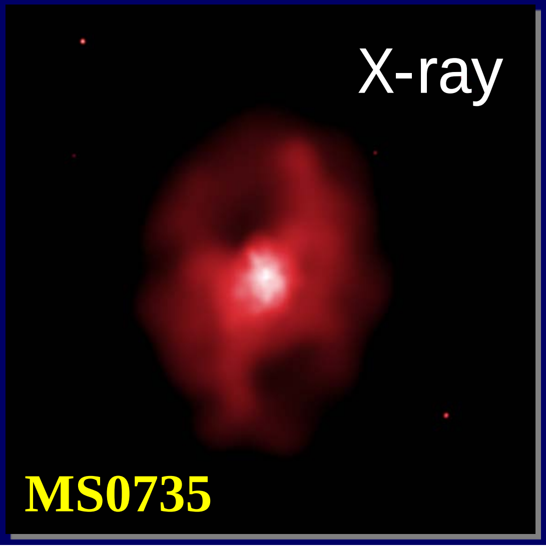


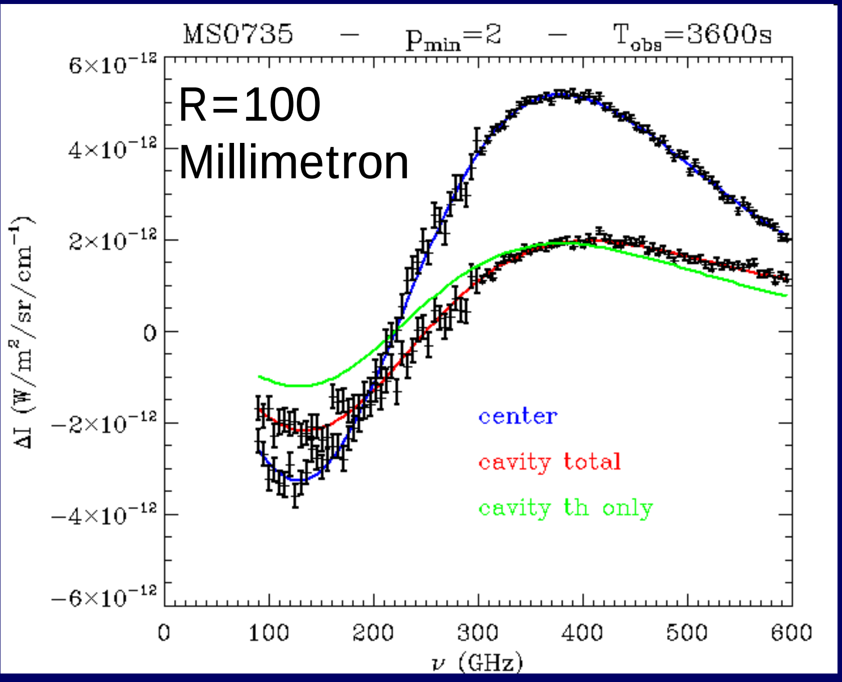
[Colafrancesco 2004-2010]

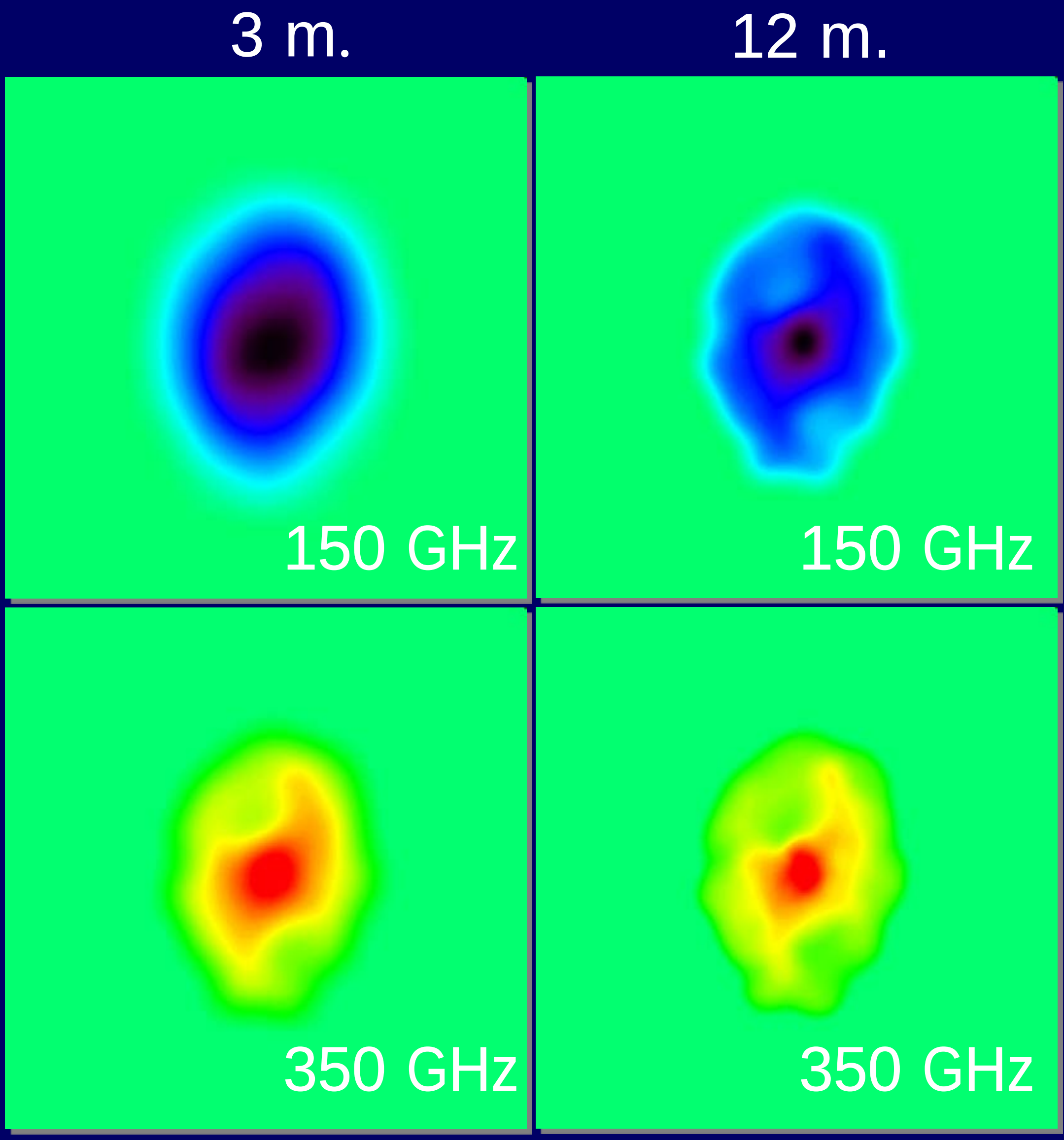




SZE: resolving cluster atmospheres

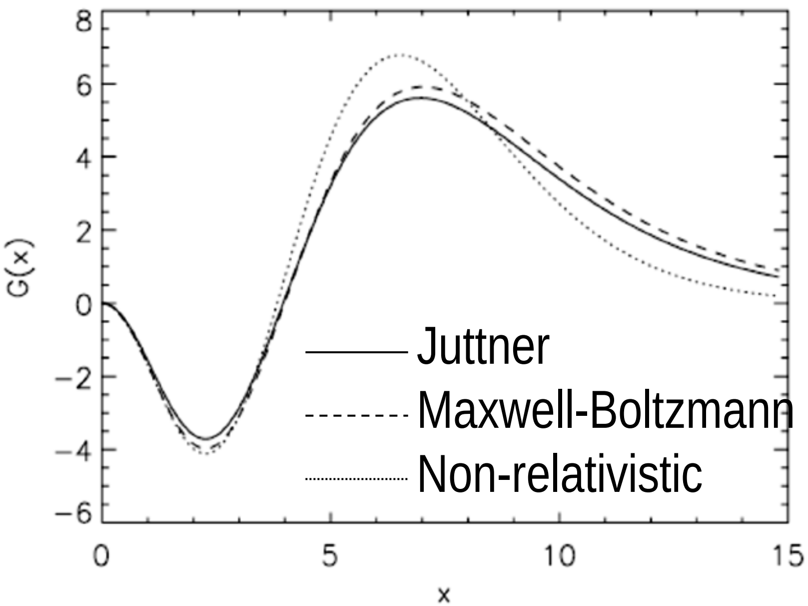






SZE and thermal plasma

SZE spectroscopy: thermal plasma



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

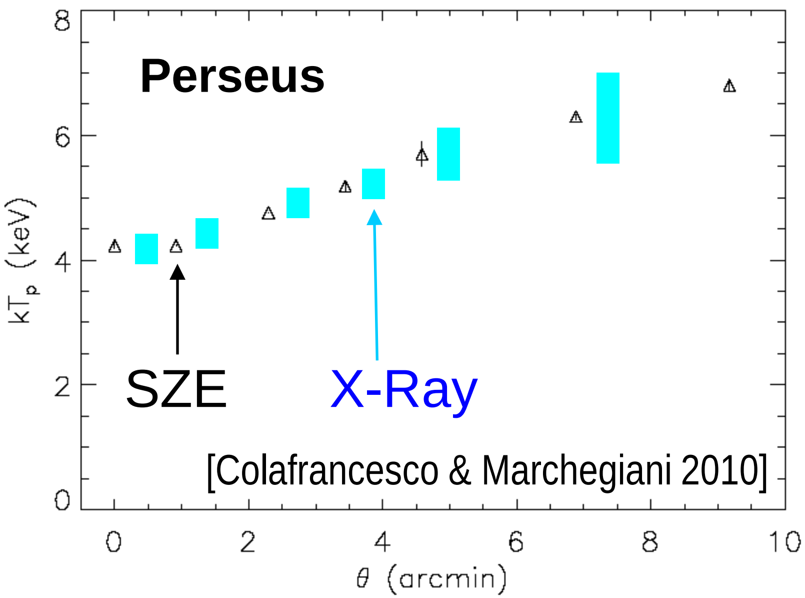
A method based on Fourier analysis to derive the velocity DF of electrons by using SZE observations at ≥ 4 frequencies.
[Prokhorov, Colafrancesco, et al. 20011a]

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



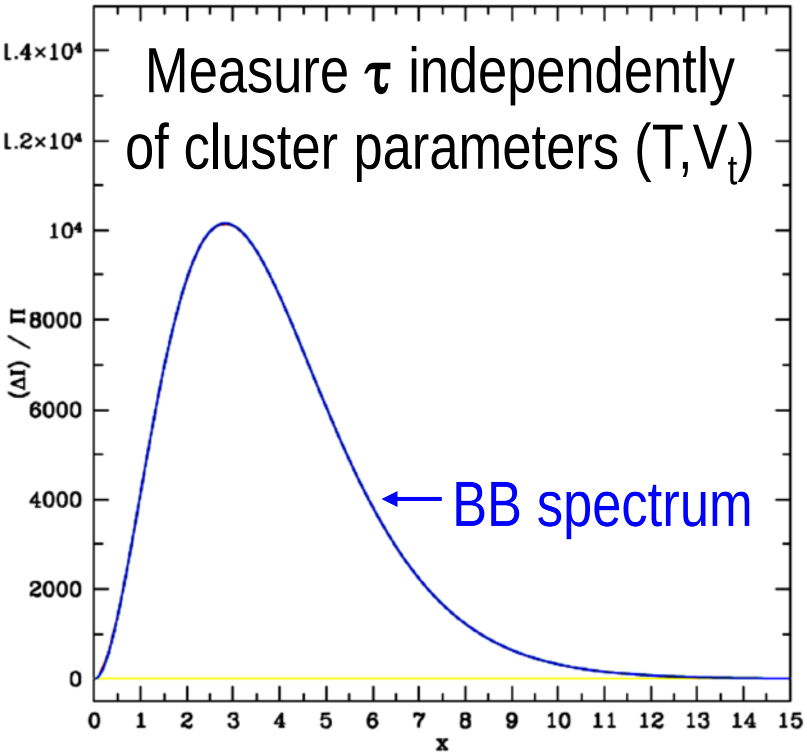
SZE spectro-polarimetry: 6-d

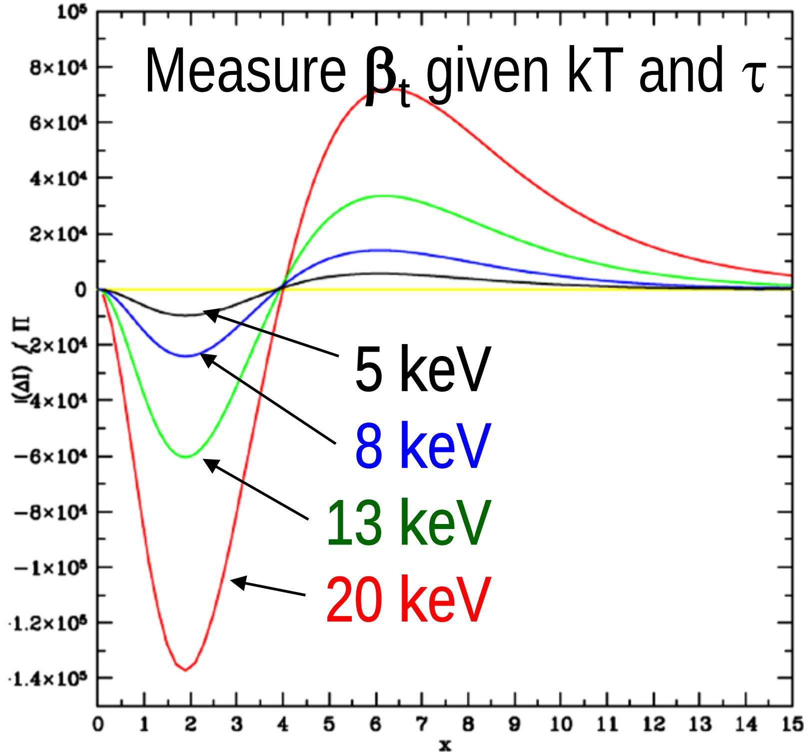
SZE intensity spectrum allow to measure the plasma temperature kT

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

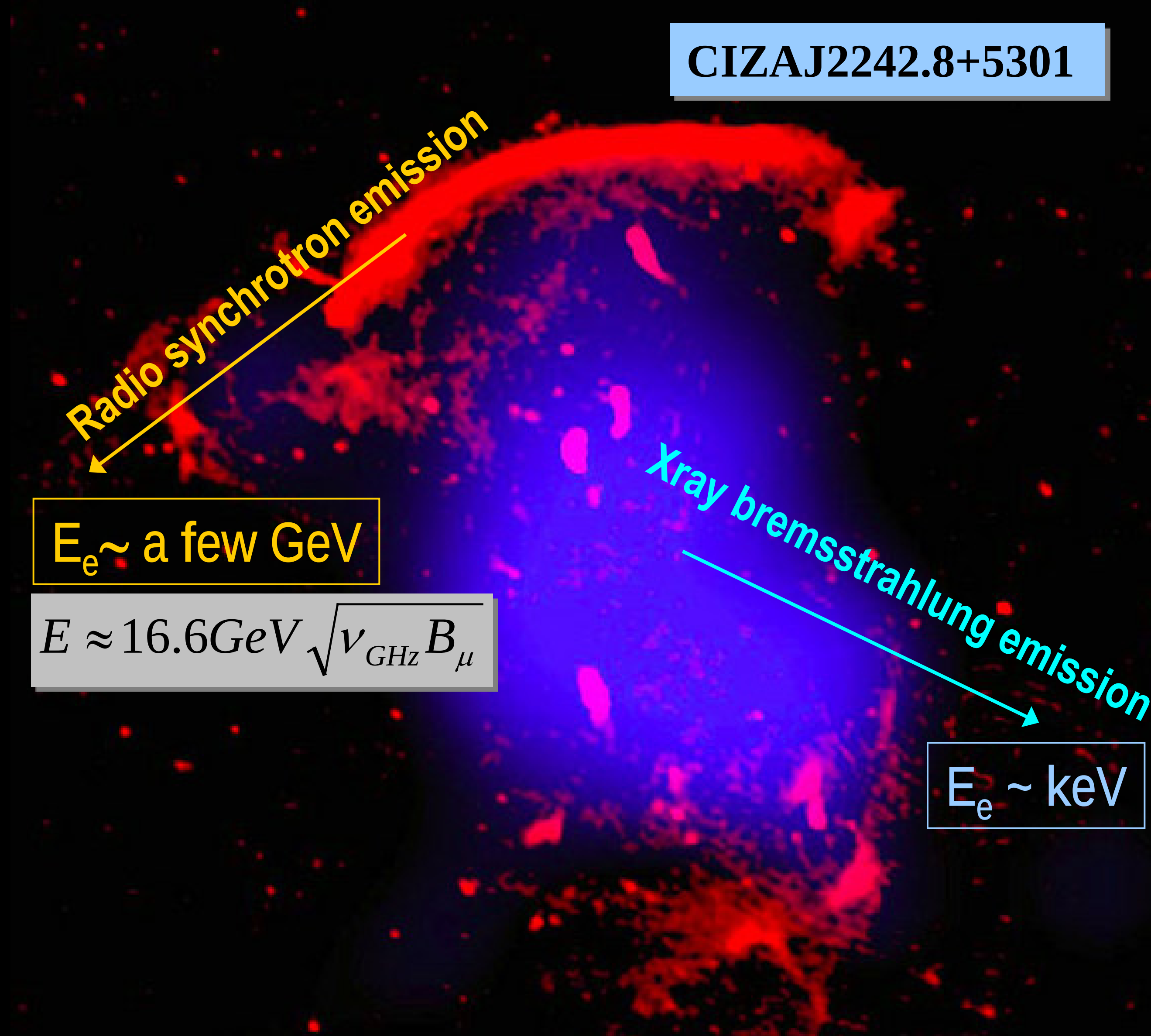
$$\frac{\Delta I}{\Pi_T} = 71.43 \frac{g(x)}{f_T(x)} \frac{1}{\tau}$$

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



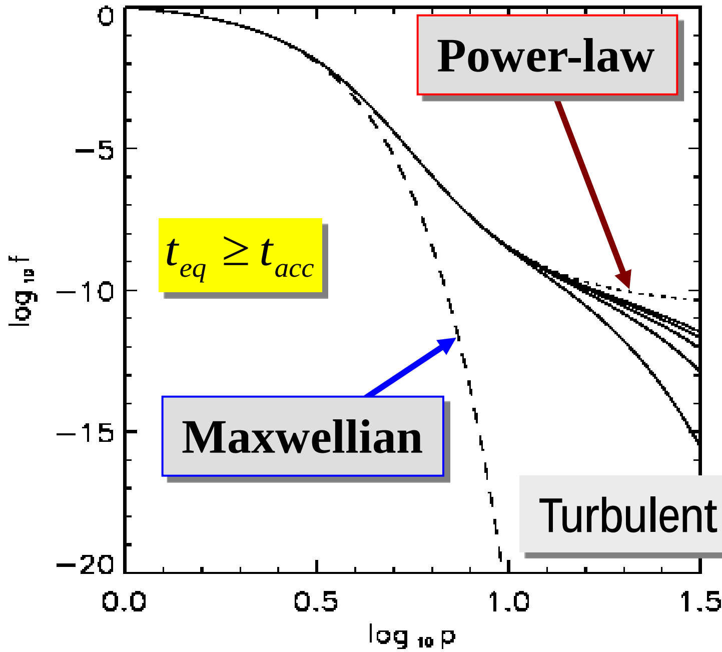


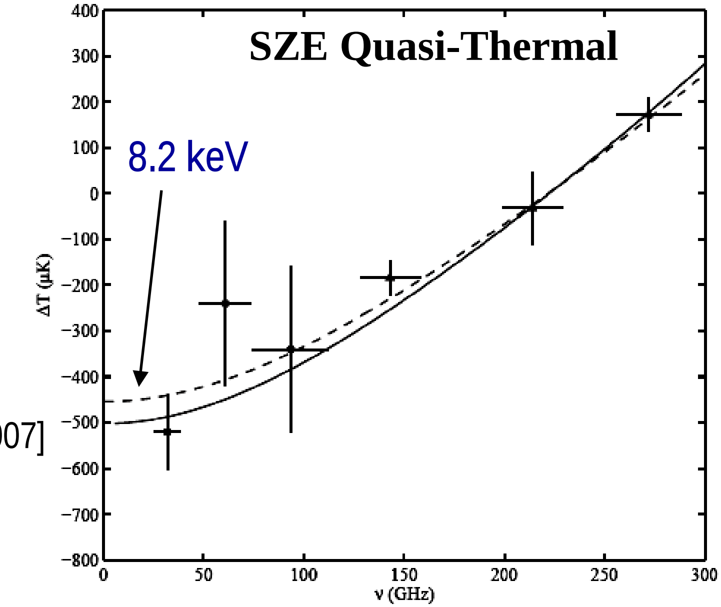
Particle acceleration



CREDIT: R.J. van Weeren, Leiden Observatory

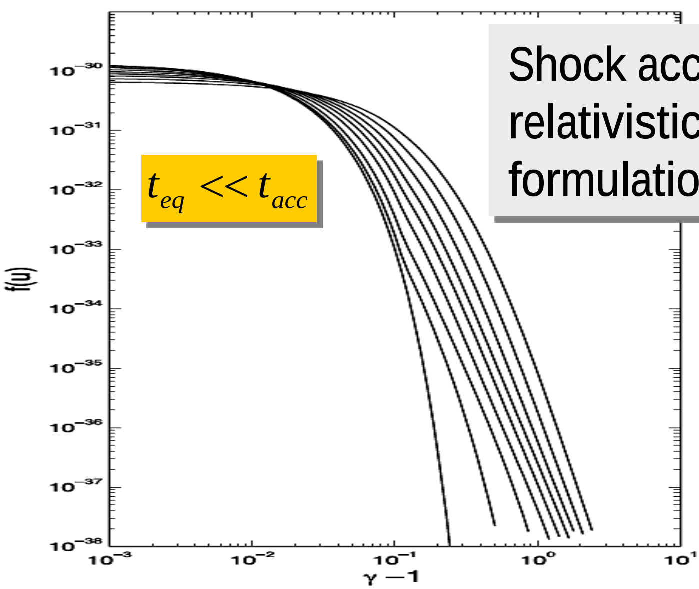
SZE: high-E particles (CRs)



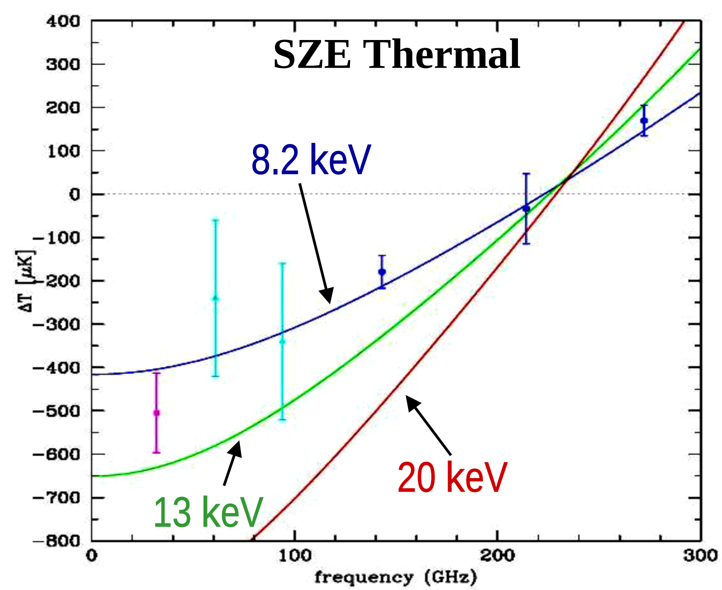


[Dogiel, S.C., et al. 2007]

Turbulent acceleration

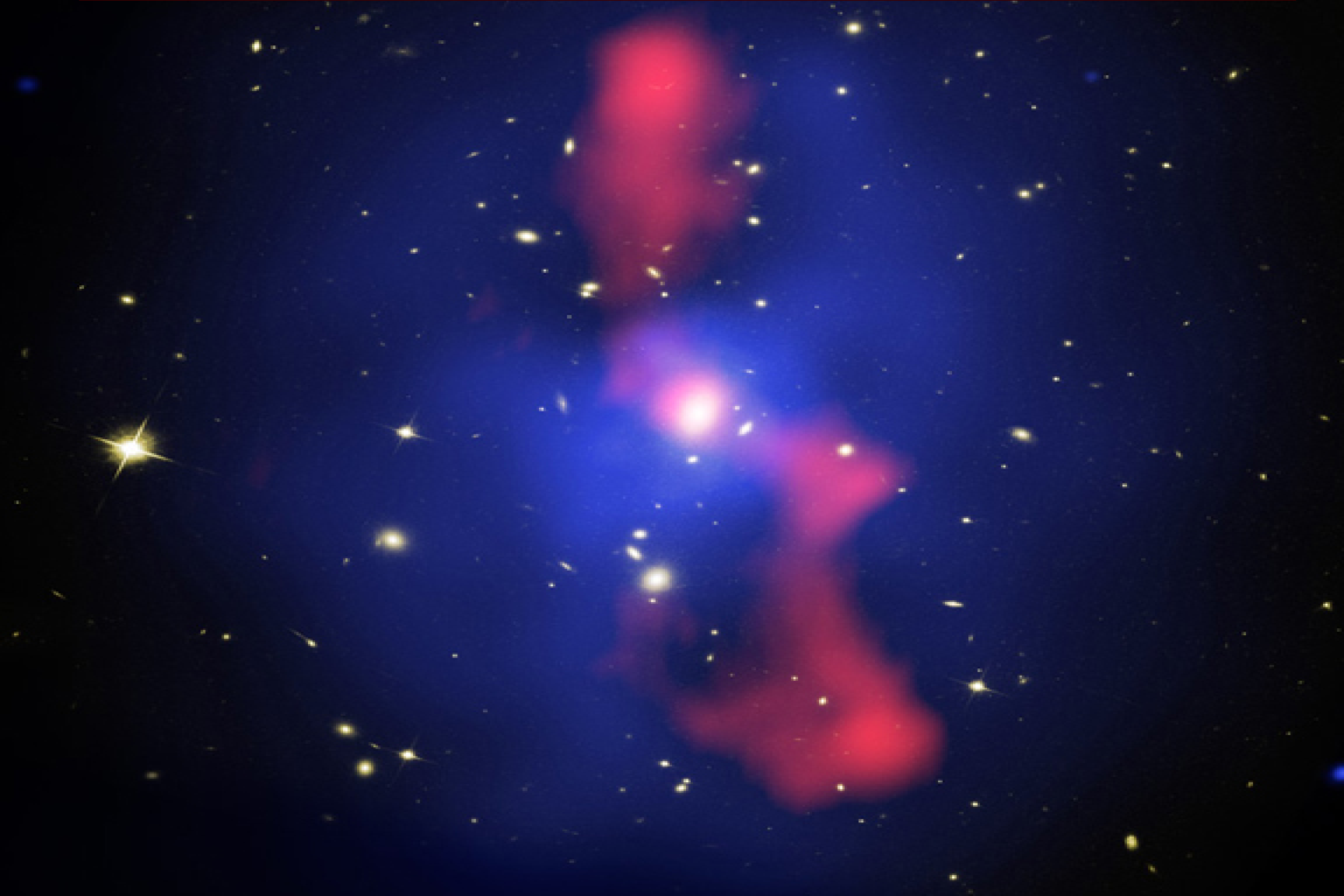


Shock acceleration: relativistic covariant formulation



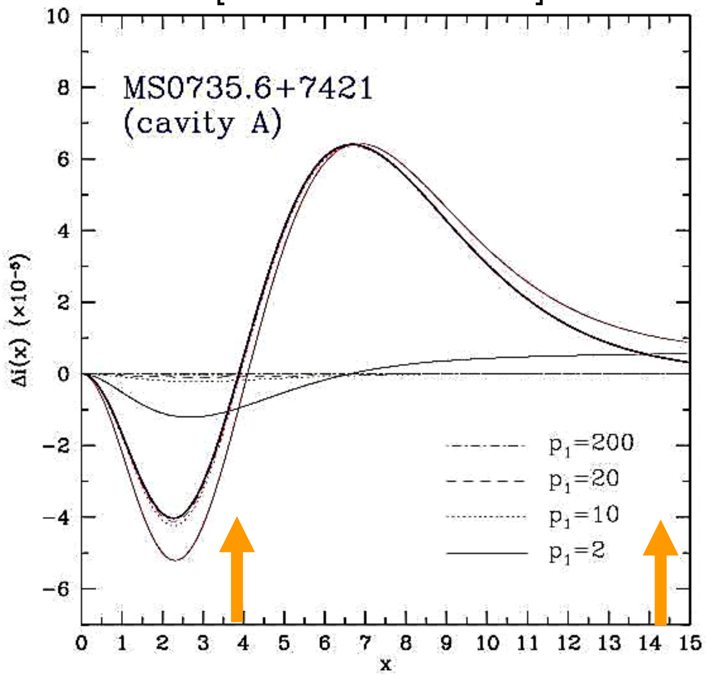
[Wolfe & Melia 2006]

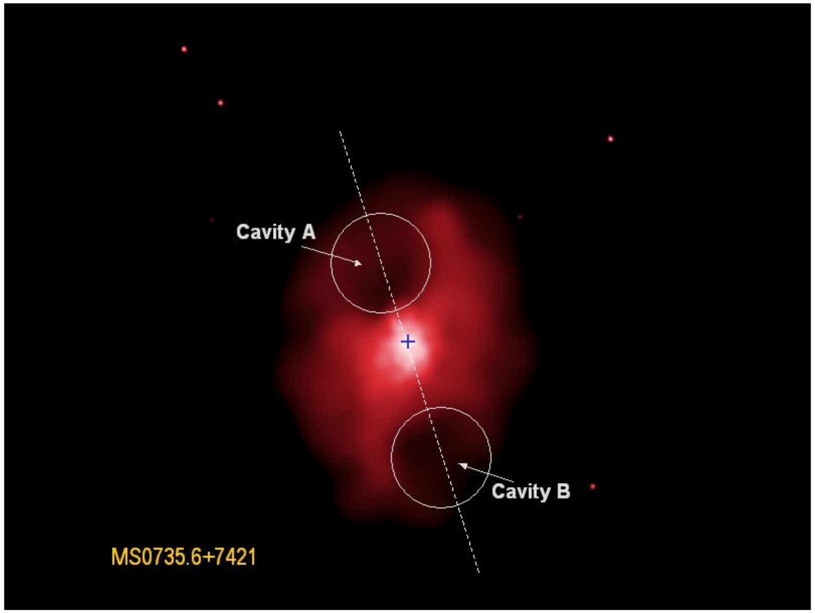
SZE and cluster cavities

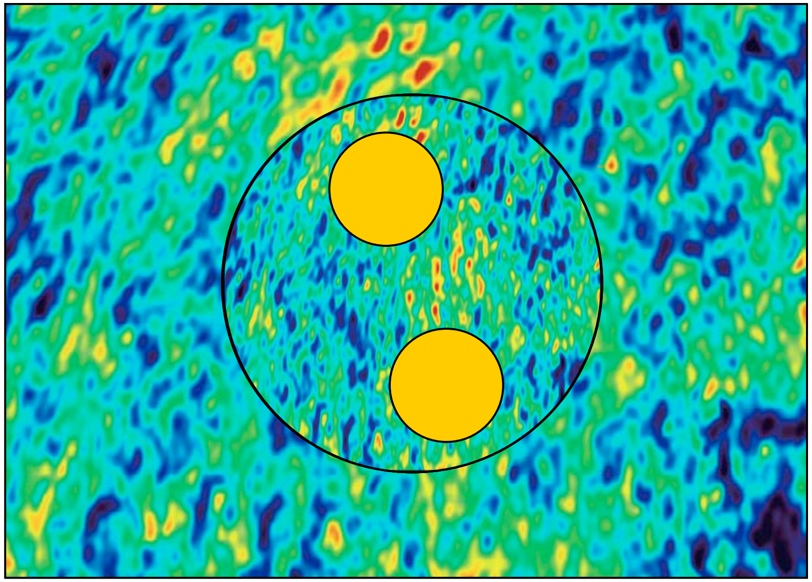


SZE: cavities in Clusters

[Colafrancesco 2005]







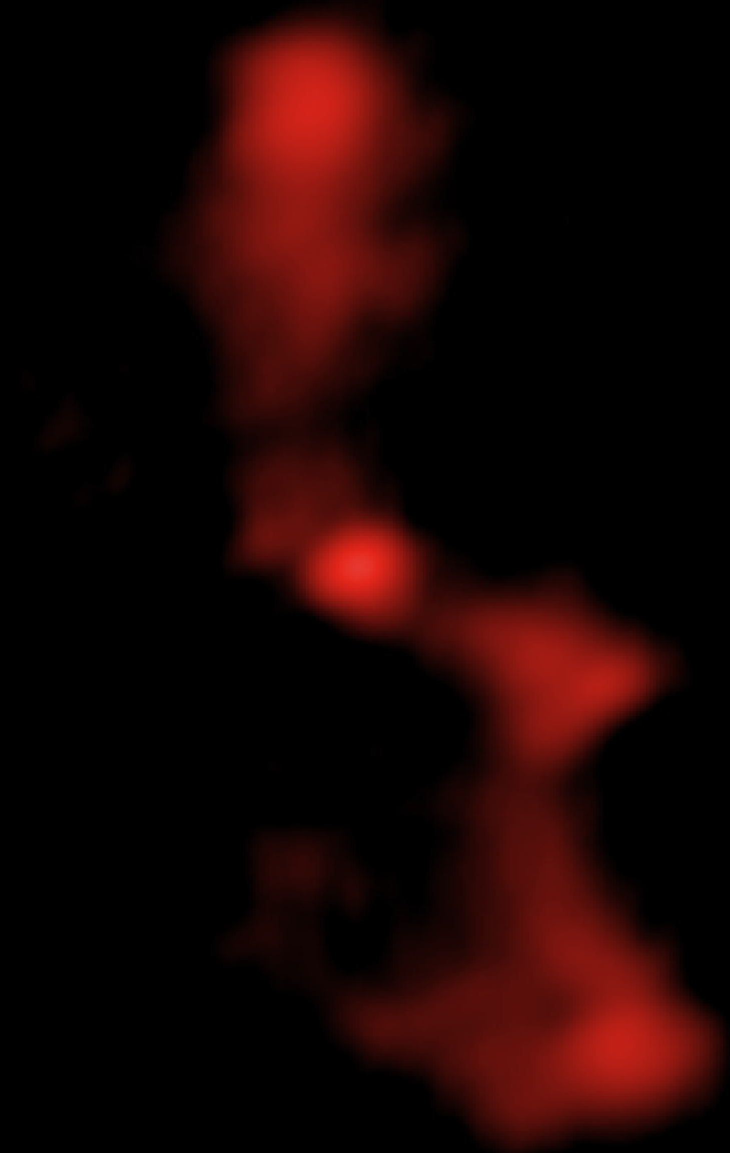
Cavities are isolated from the surrounding cluster atmosphere at

– ν ~ 220 GHz

– ν > 800 GHz

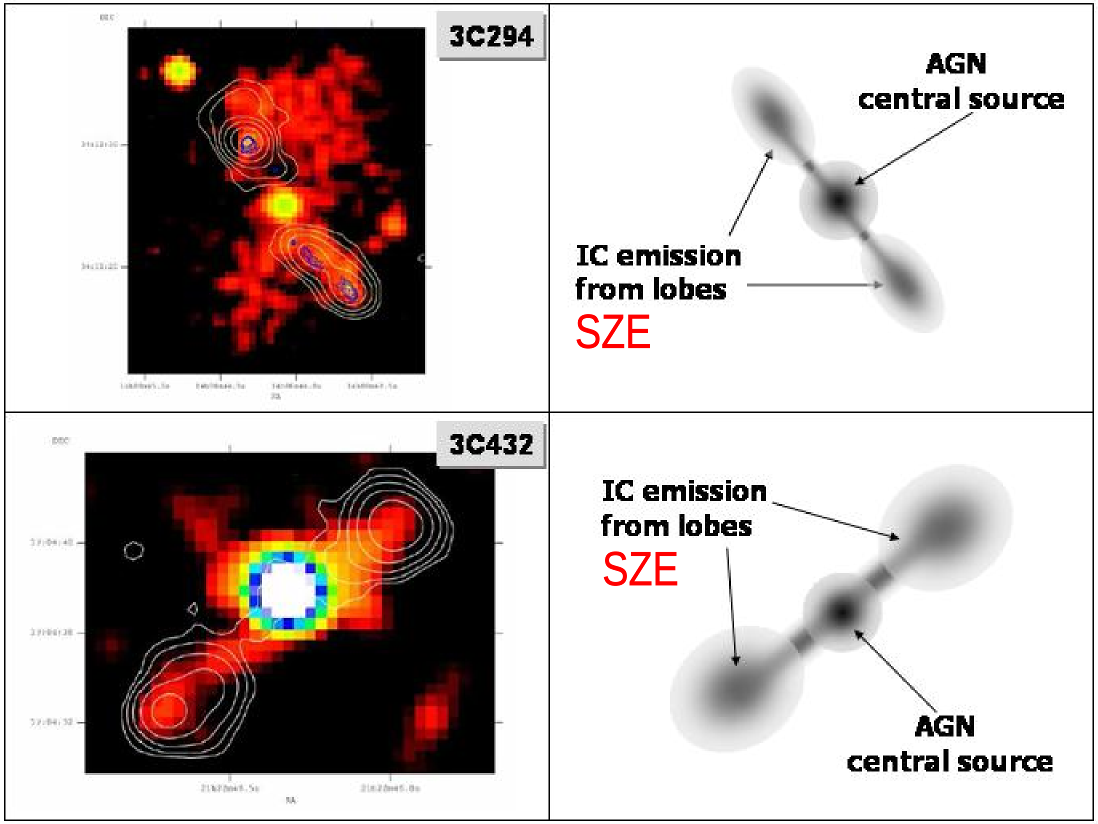
$\Delta I \sim \int dl \cdot U_{e,tot}$: advantage w.r.t. X-rays

SZE and radio-galaxy lobes

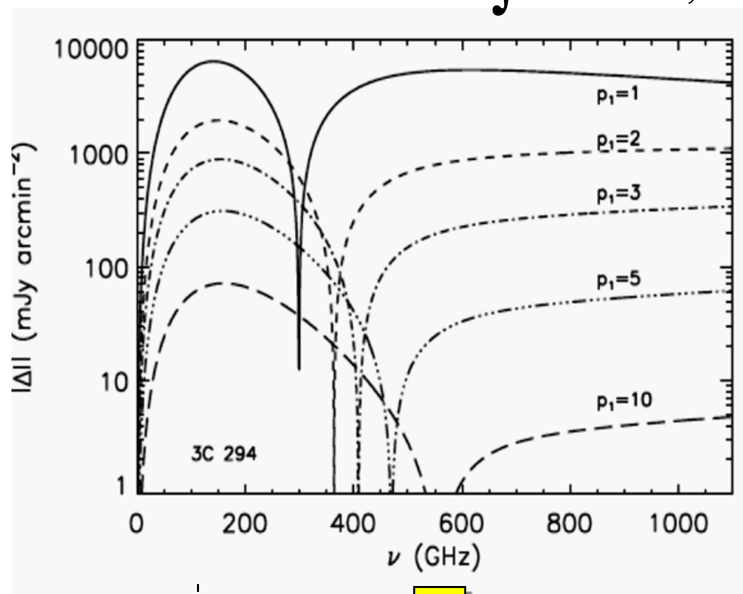


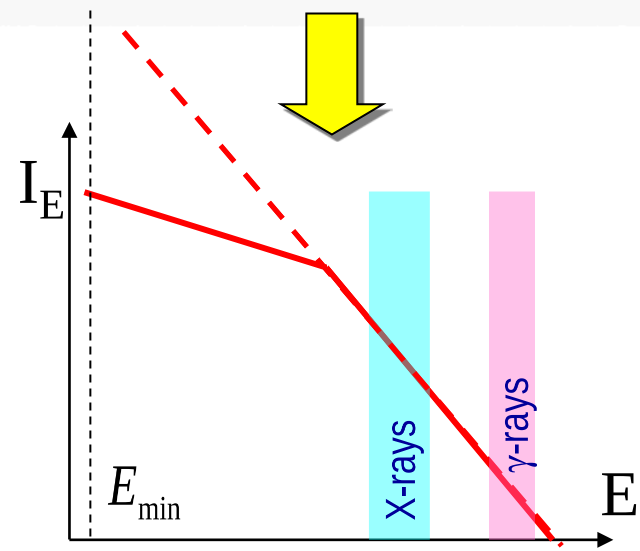
SZE: radio-galaxy lobes

X-rays **SZE**



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



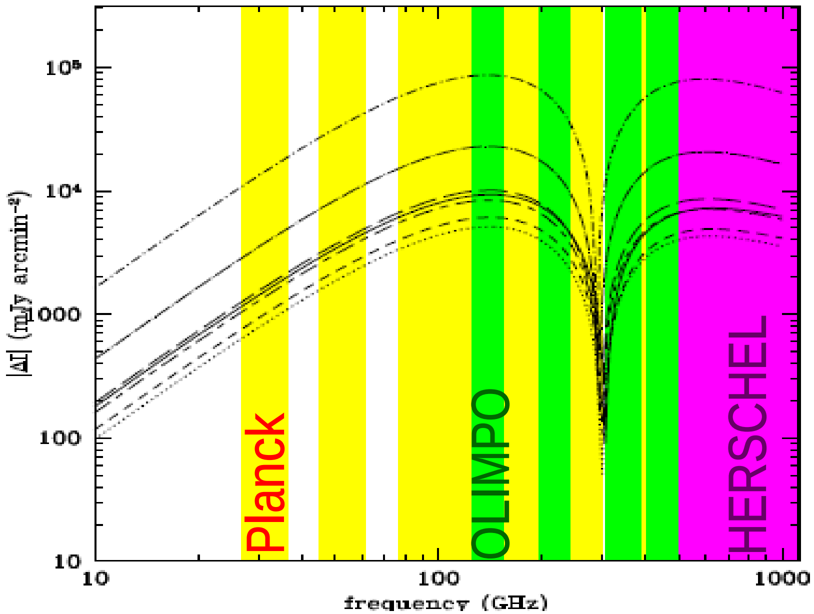


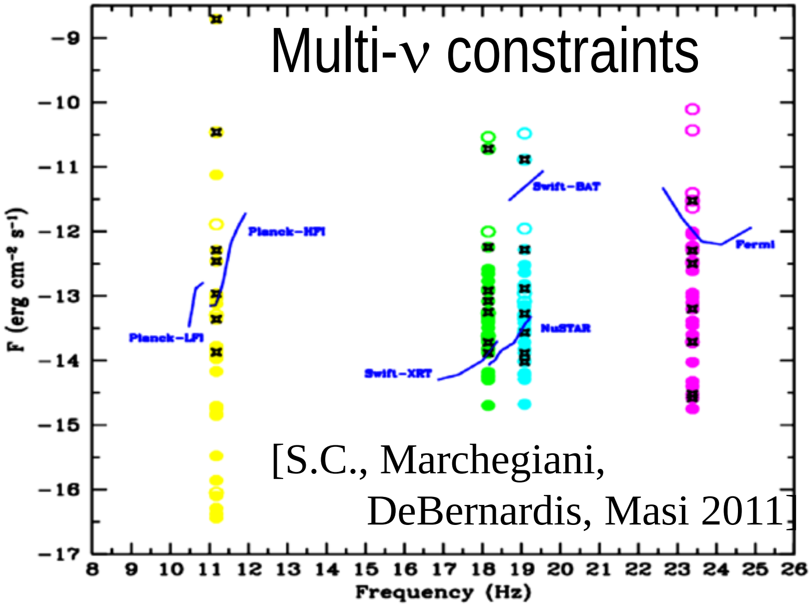
Total leptonic spectrum of RG lobes $P_{tot}; E_{\min}$

B-field structure in RG lobes $\frac{F_{radio}}{F_{ICS}} = \frac{U_B}{U_{rad}}$

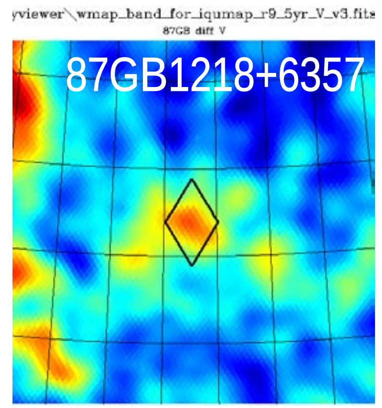
$T_{CMB}(z)$ $\frac{\Delta T_{SZ}}{F_{IC}} \propto (kT_{CMB})^{-3} \times f(\gamma_{\min}, E_{X\,\min})$

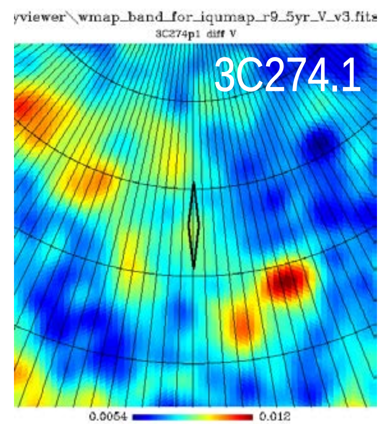
Theory

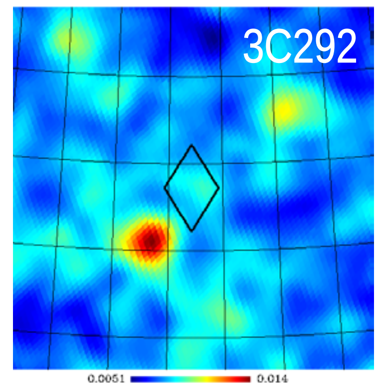




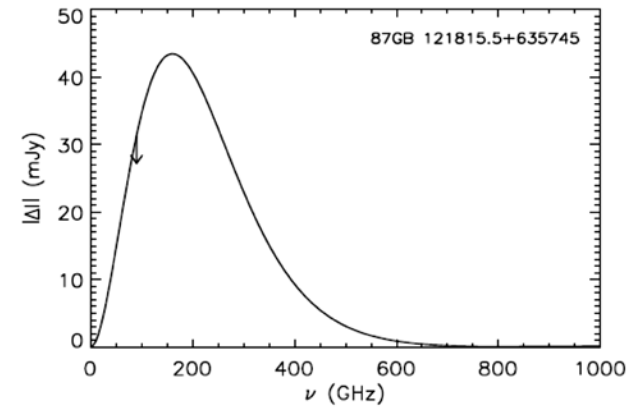
WMAP

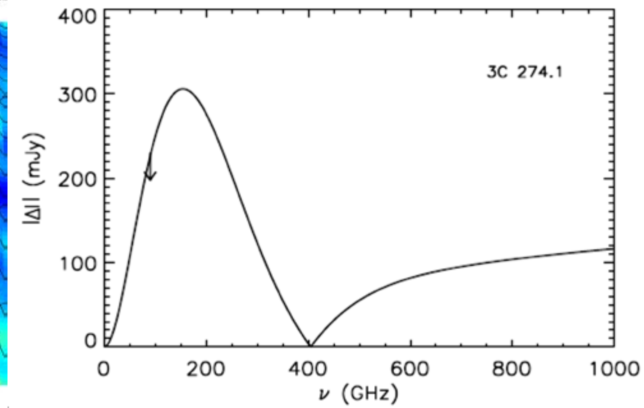


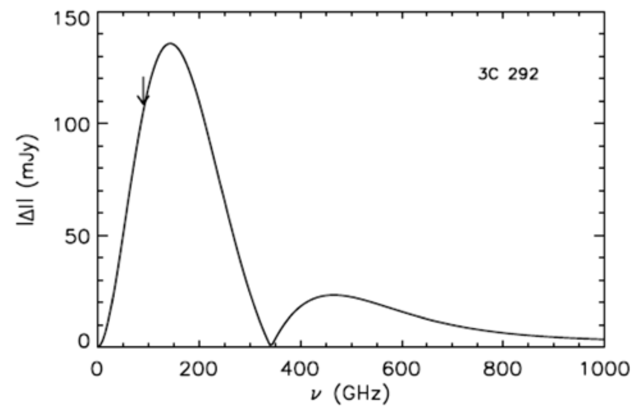




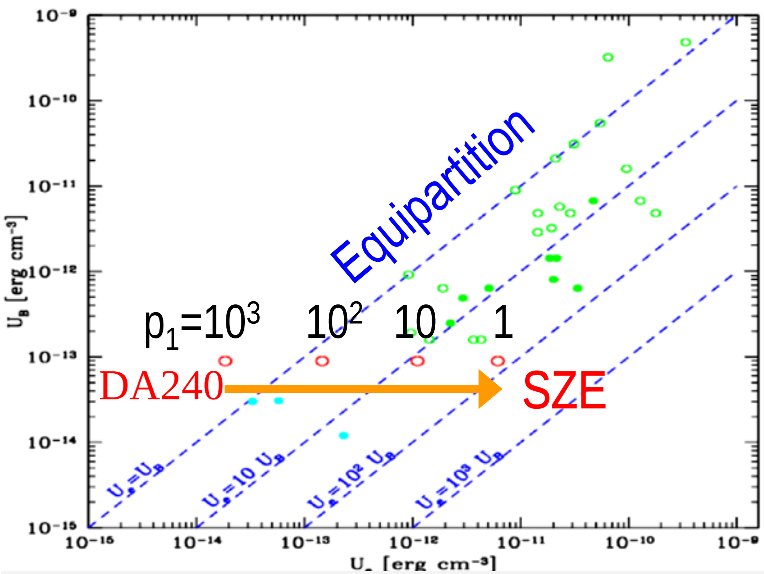
Expectation







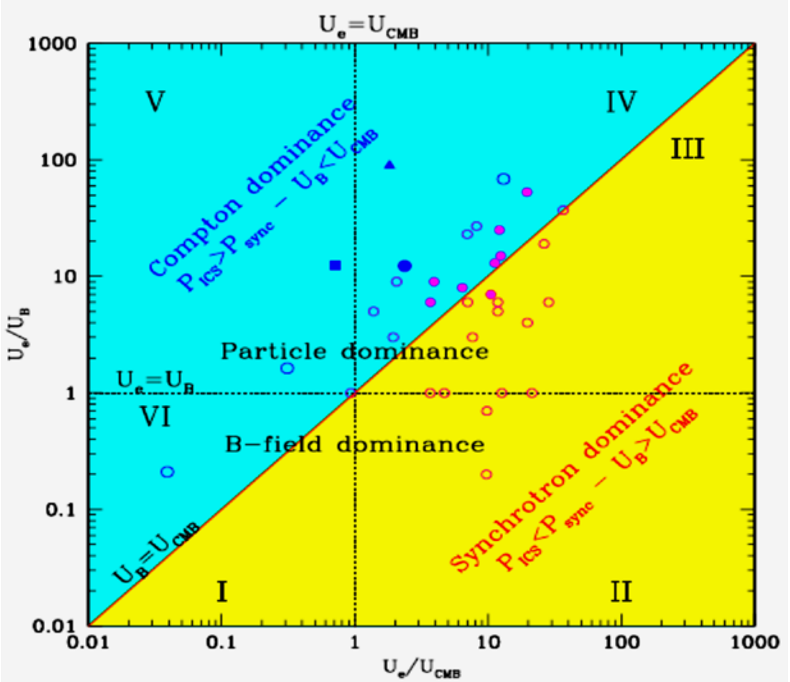
SZE: RG lobe energetics revisited



$$U_e = \int_{p_1}^{\infty} dp N(p)(\sqrt{1+p^2}-1) m_e c^2$$

X-ray → rough misleading measure of Ue

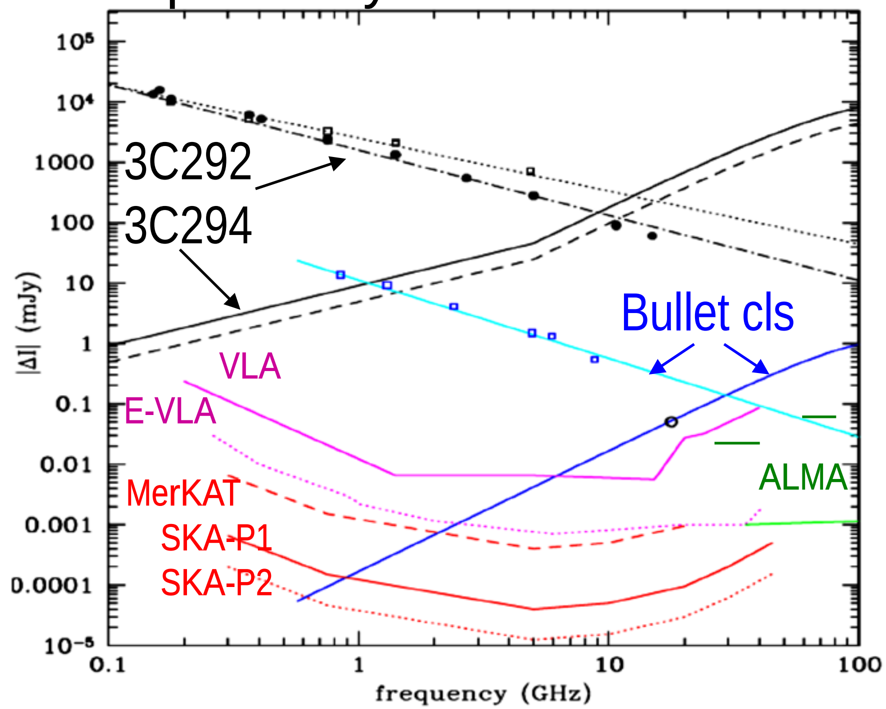
SZE → reliable unbiased measure of Ue



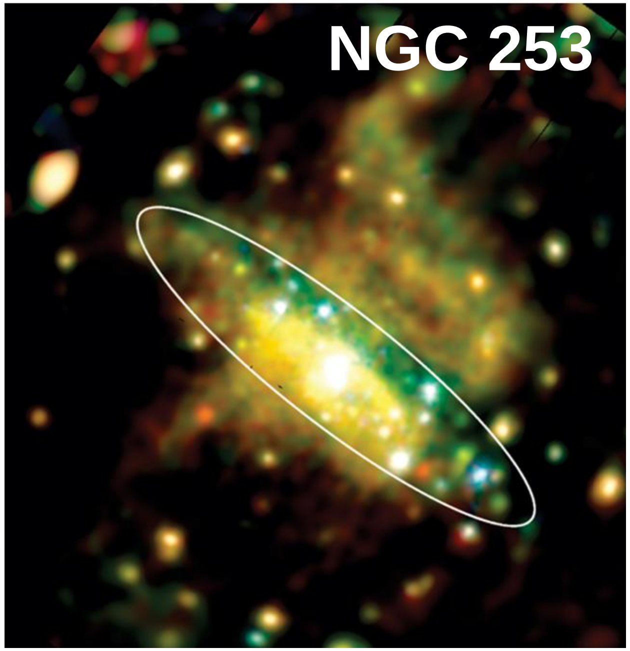
SKA, MeerKAT, E-VLA

$\Delta\nu$ = 0.1 - 45 GHz

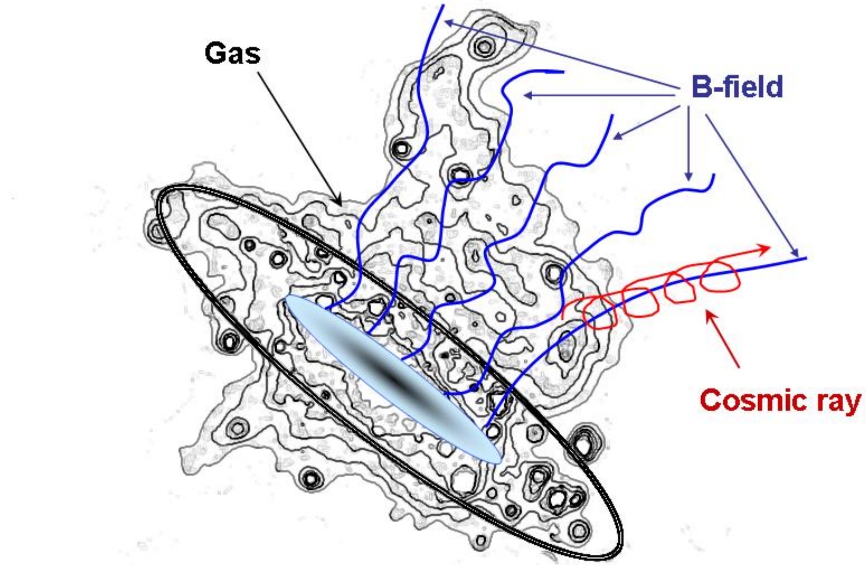
Separate Synchrotron & SZE



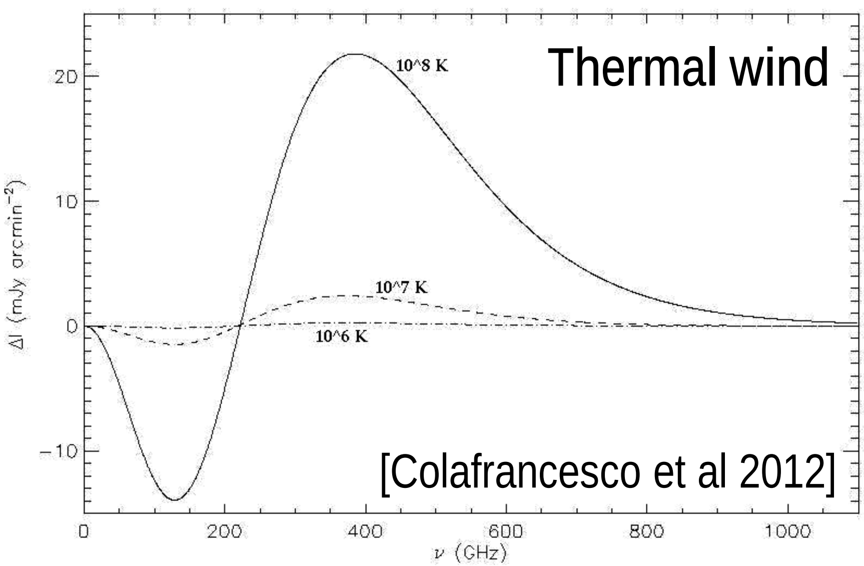
SZE: galaxy winds and SF

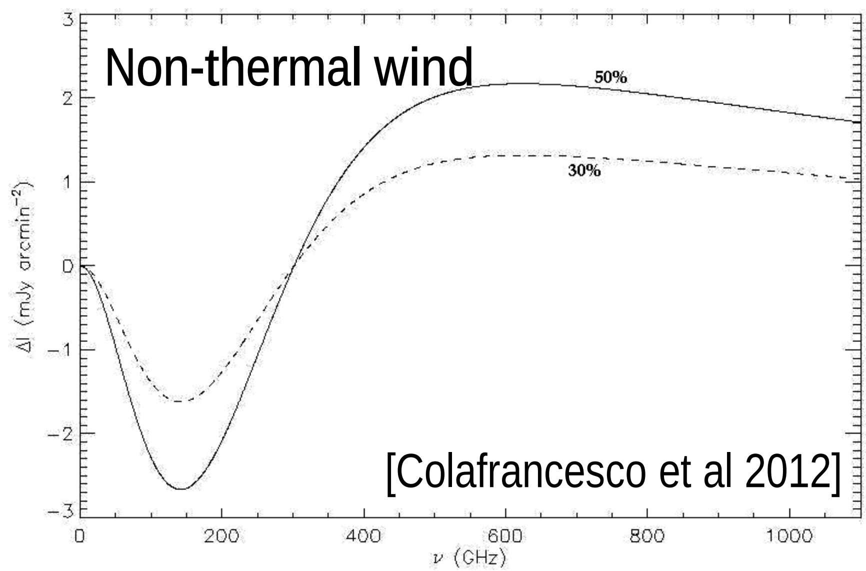


Combine MILLIMETRON and SKA



to study the wind composition & energetic

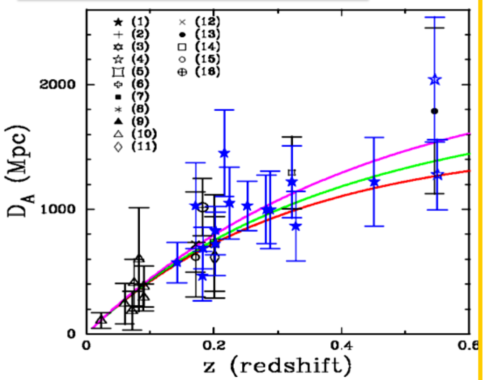




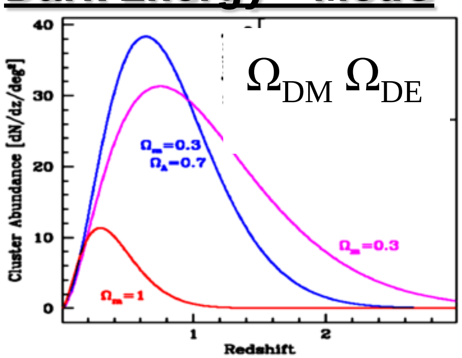
Cosmological relevance

Galaxy clusters	AGN jets/cavities	DM nature	Plasma physics

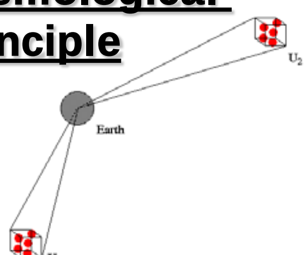
Hubble constant



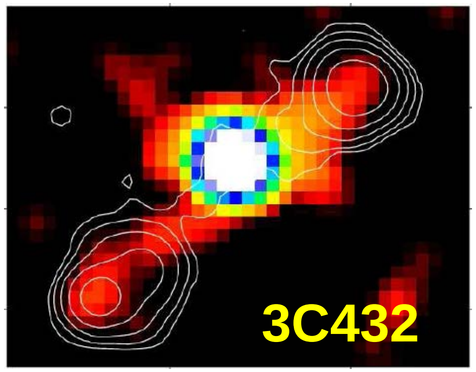
Dark Energy - ModG



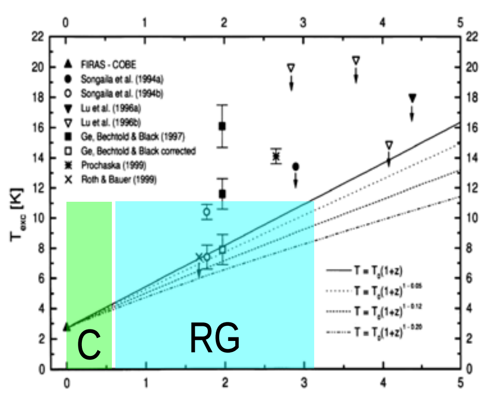
Cosmological Principle



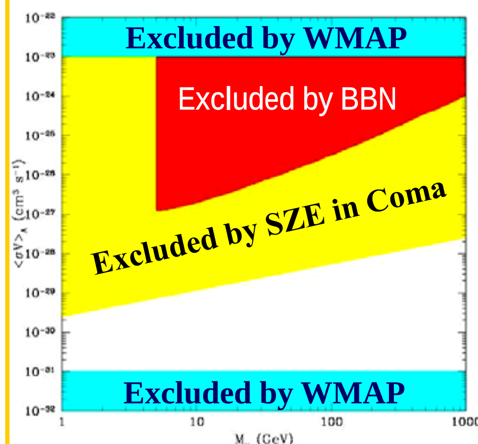
$T_{CMB}(z)$



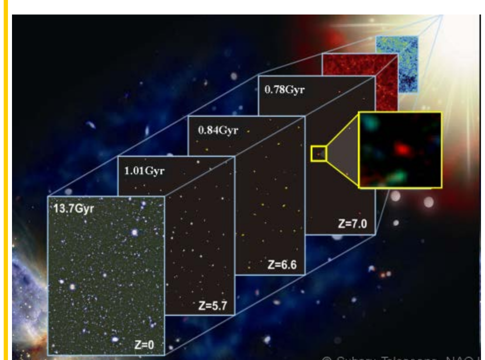
$$\frac{\Delta T}{F_{IC}} \propto (kT_{CMB})^{-3} \times \gamma_{\min}^{-(\alpha-1)} \cdot E_{X\,\min}^{-(\alpha-1)/2}$$



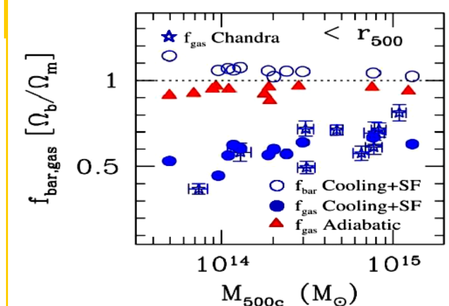
SUSY DM



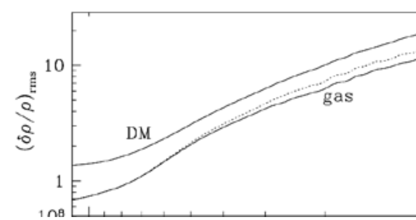
Early DM-galaxies



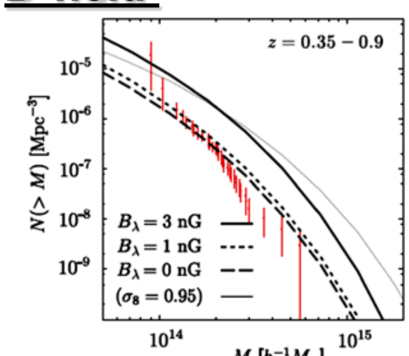
Baryon fraction



CR history



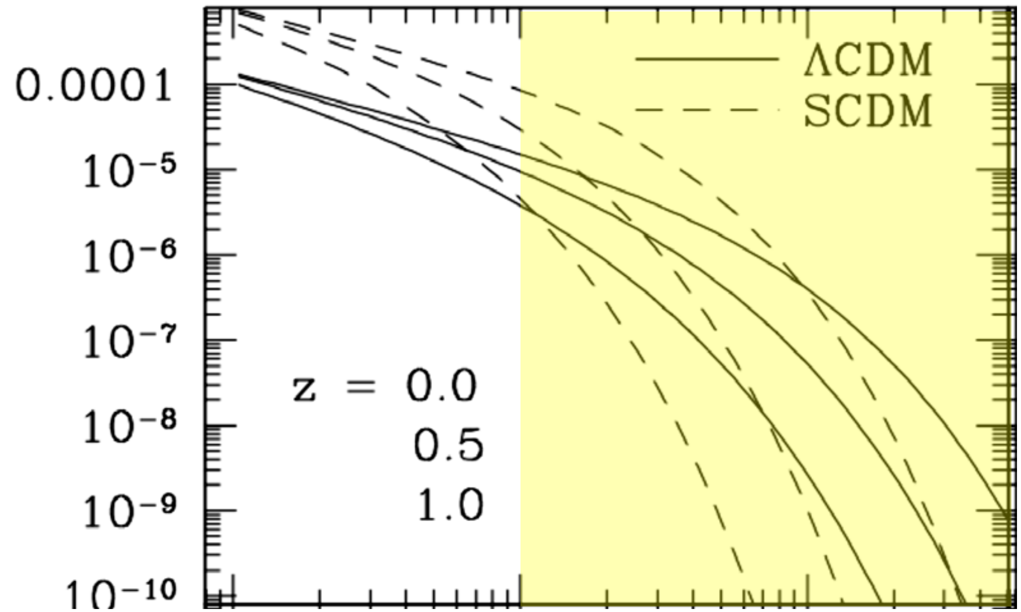
B-field

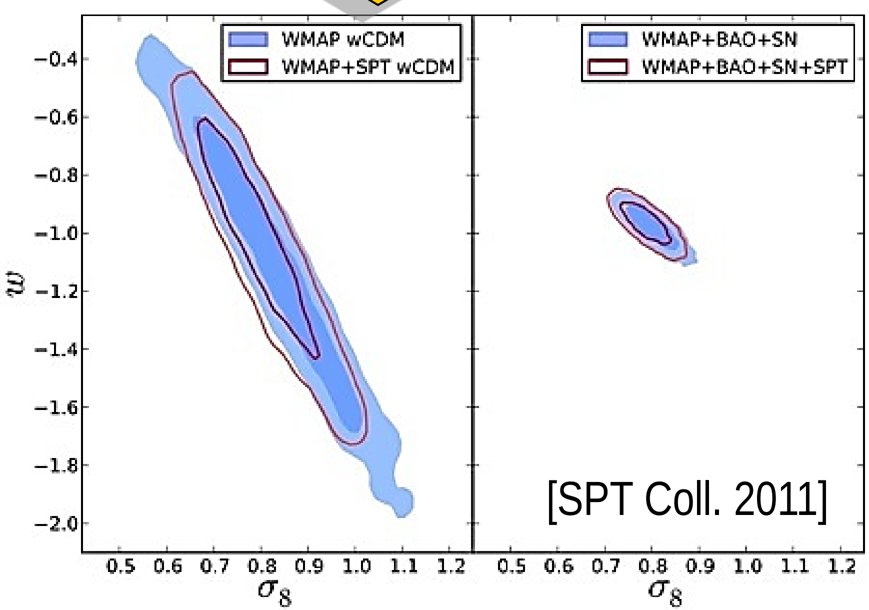


SZE: clusters cosmology

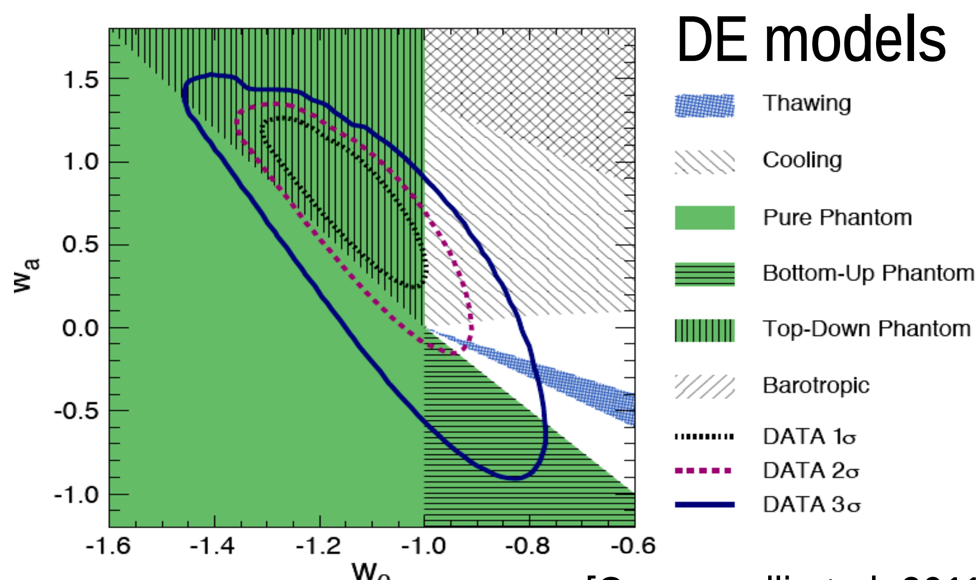
SZE will allow to derive an unbiased measure of cluster DM mass

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





[SPT Coll. 2011]



[Campanelli et al. 2011]

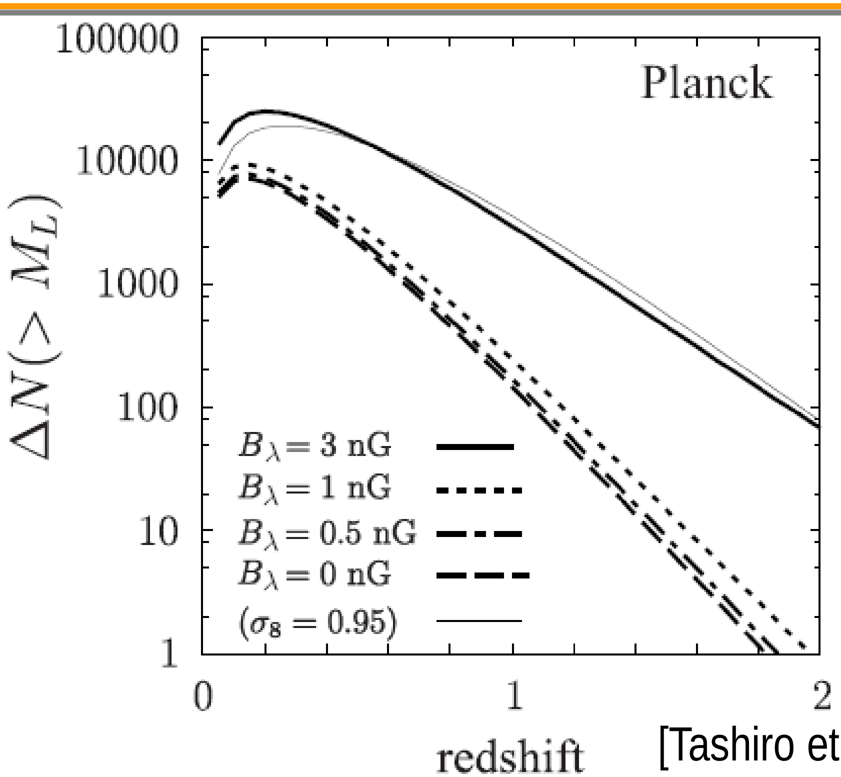
SZE and primordial B-field

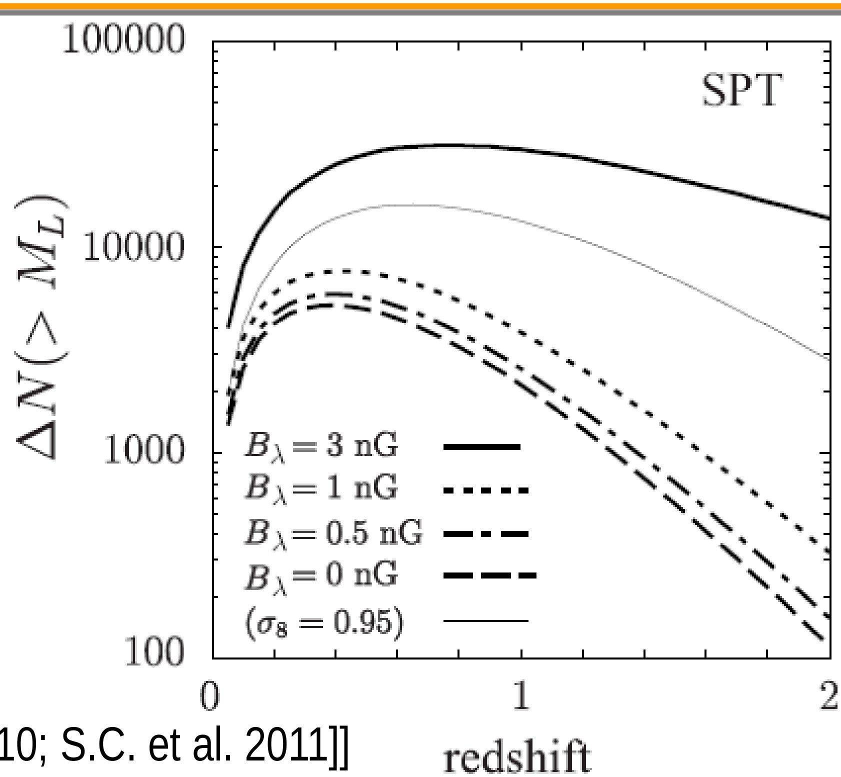
After the epoch of recombination, a primordial B-field generates additional density fluctuations forming additional cosmic structures. Such density fluctuations enhance the number of galaxy clusters.

Primordial density fluctuations → P_P ; Primordial-B density fluctuations → P_M

$$P(k,t) = P_{\rm P}(k,t) + P_{\rm M}(k,t)$$

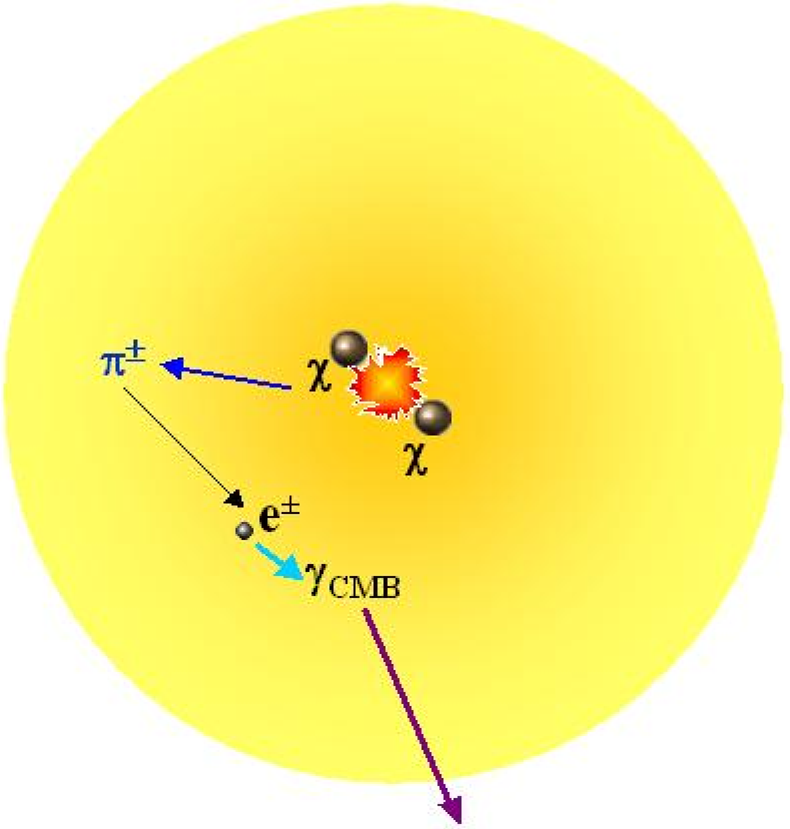
$$P_P \propto D_M^2(t) \cdot k^n \qquad P_M \propto D_M^2(t) \cdot I_k^2$$





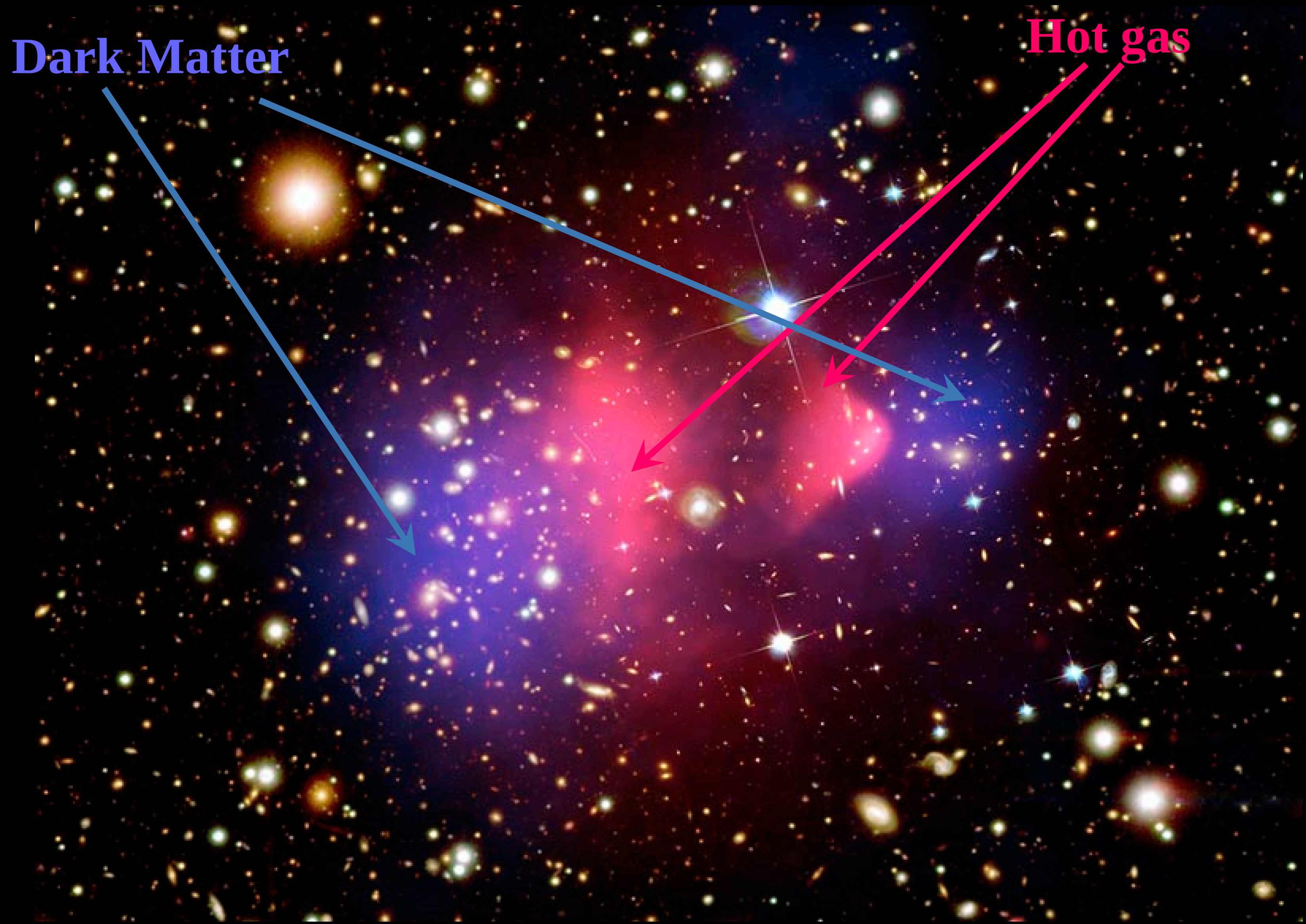
[Tashiro et al. 2010; S.C. et al. 2011]]

SZE and Dark Matter nature

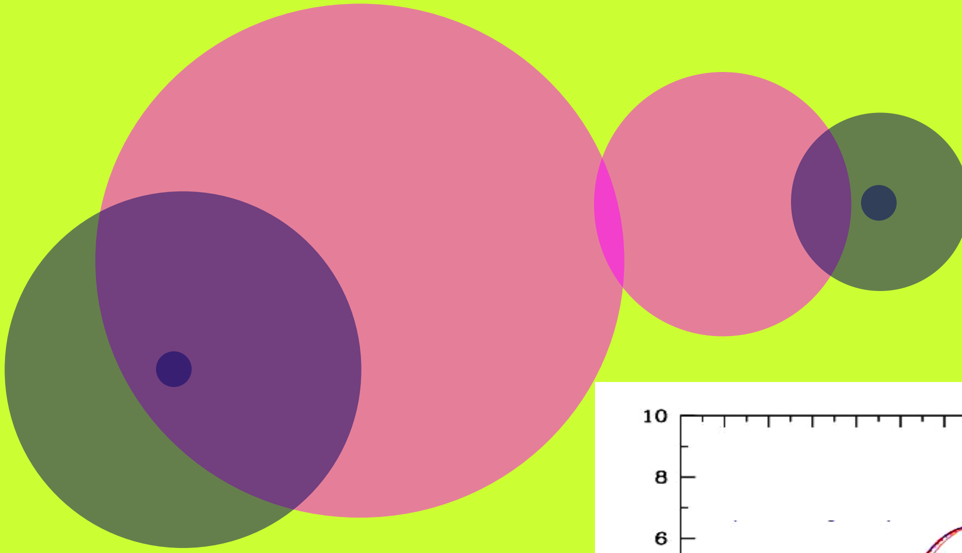


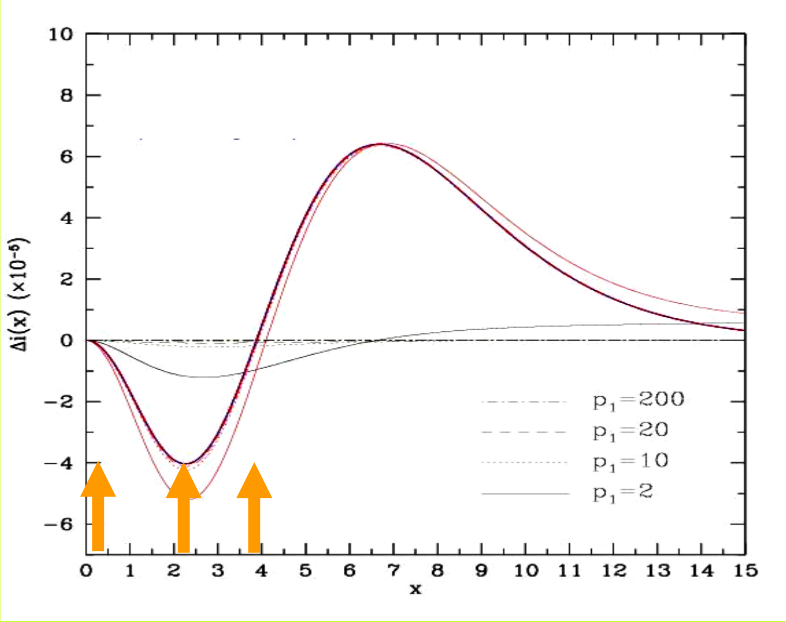
SZE
ICS on CMB

1ES0657-556

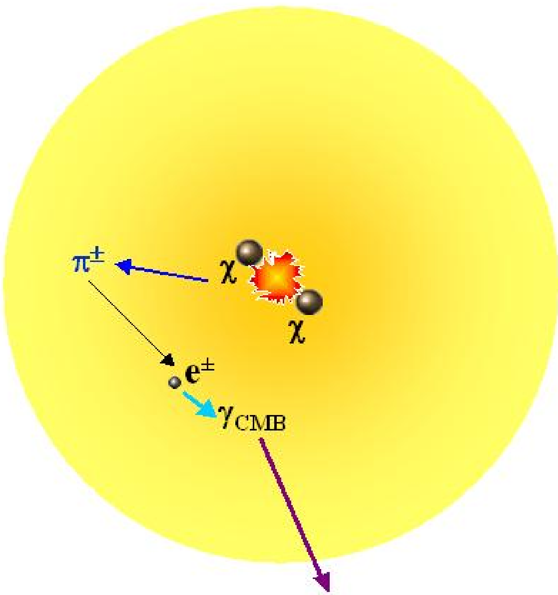


SZ_{DM} from 1ES0657-556

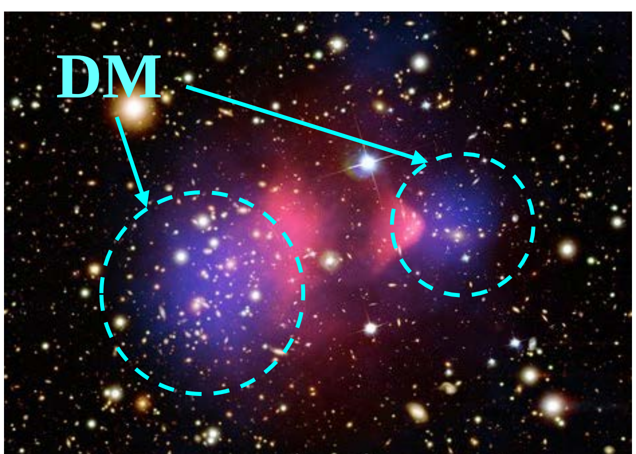


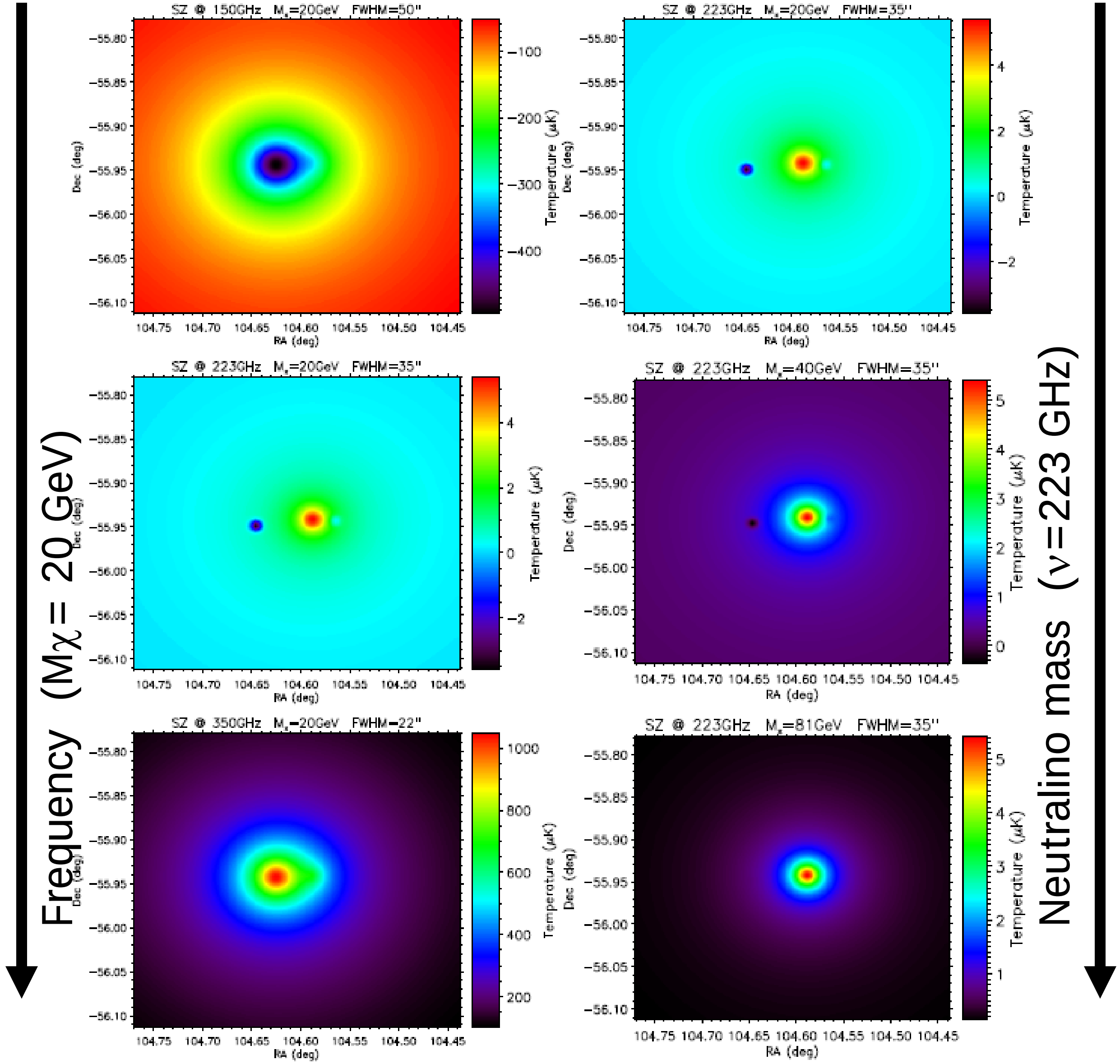


SZE and Dark Matter



SZE

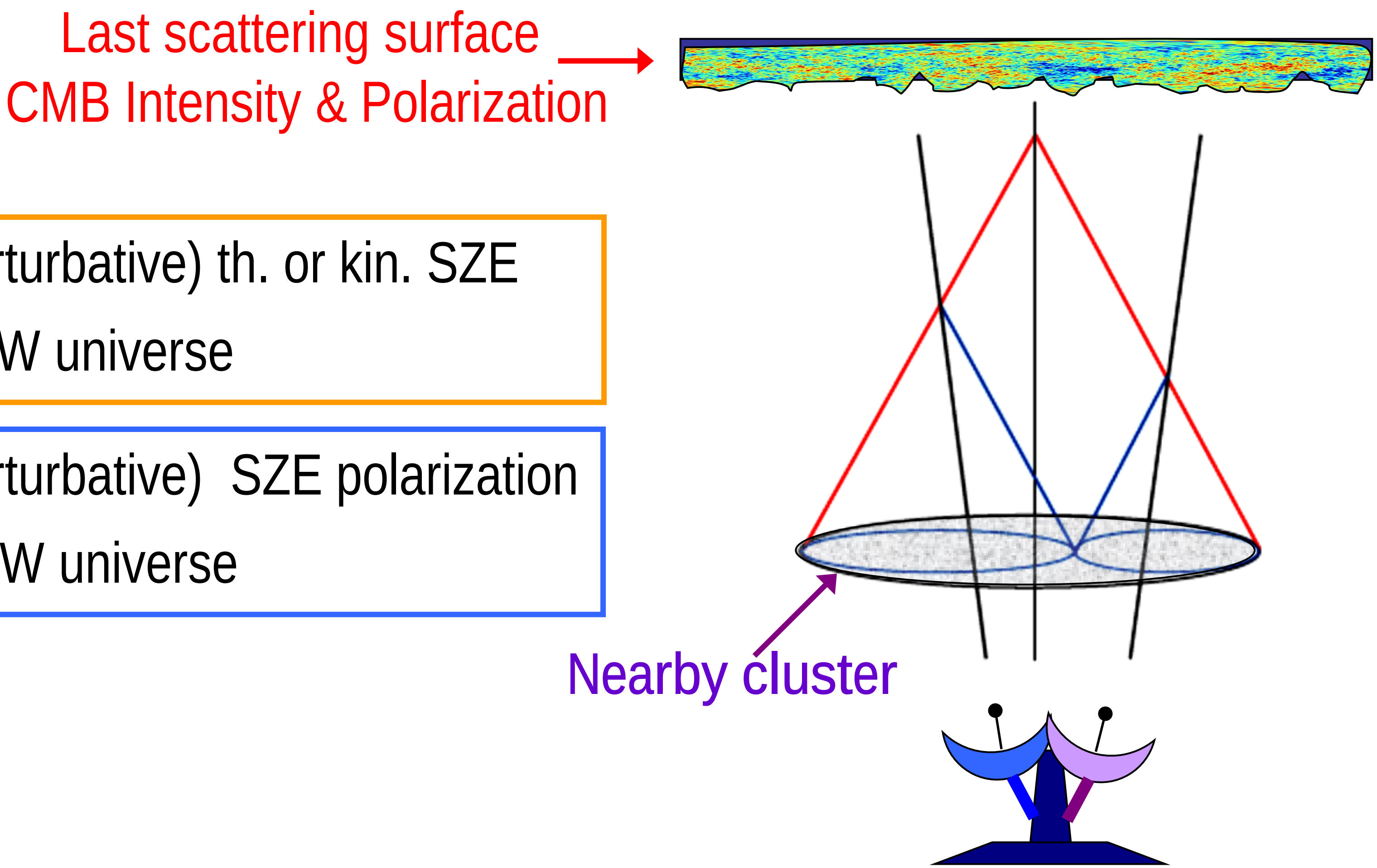




SZE: the Cosmological Principle

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

Challenge

Multi-D tomography
(disentangle cluster atmospheres)

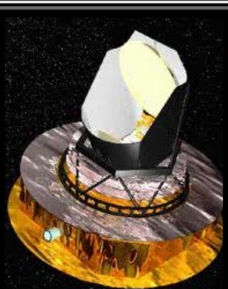
Multi-technique single-purpouse (Radio to TeV)

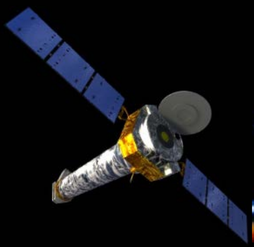
Single-technique multi-purpouse (SZE)

Multi telescopes
Multi techniques

Single telescope
Single technique

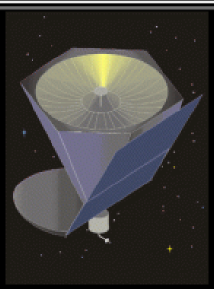

radio


μwave-mm


X-ray


γ-ray


TeV


μwave-mm

Further readings

Colafrancesco et al.: A&A 397, 27–52 (2003)
: 2011A&A...527L...1C
: 2010A&A...520A..31C
: 2008MNRAS.385.2041C
: 2007NewAR..51..394C
: 2004A&A...422L..23C
Birkinshaw, M. 1999, Phys. Rep., 310, 97
Sunyaev, R. A., & Zel'dovich, Ya. B. 1980, ARA&A, 18, 537
Planck Collaboration: 2010-2012 (more than 30 papers)
SPT Collaboration: http://pole.uchicago.edu/public/publications.html
ACT Collaboration: http://www.physics.princeton.edu/act/papers.html
deBernardis,, Colafrancesco et al.: 2012A&A...538A..86D
Millimetron: ask Sergio Colafrancesco