Sunyaev Zel'dovich effect in galaxy clusters cavities: thermal or non-thermal origin?

Observing the mm Universe with the NIKA2 camera
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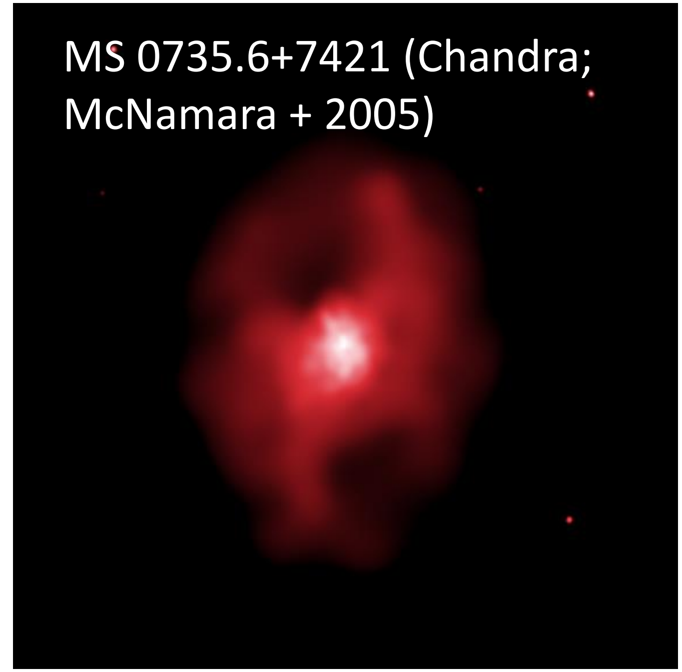
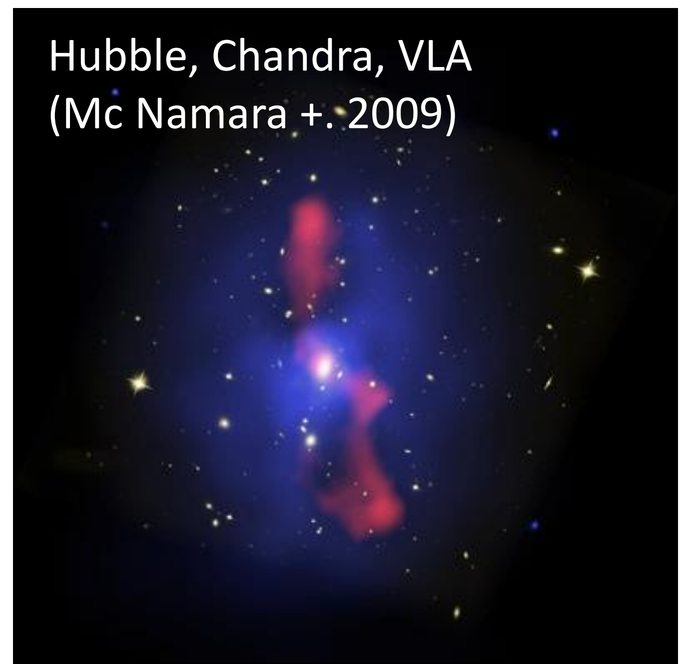
X-ray cavities in galaxy clusters

- Jets from AGNs located at the centre of relaxed clusters
- Jets can inflate lobes of relativistic plasma
- Lobes expand into the Intra Cluster Medium
- X-ray cavities in the ICM are produced

- Often cavities are filled with radio emission
- About half of known cavities (e.g. Birzan et al. 2020, MNRAS, 496, 2613)
- Synchrotron emission: relativistic electrons and magnetic fields





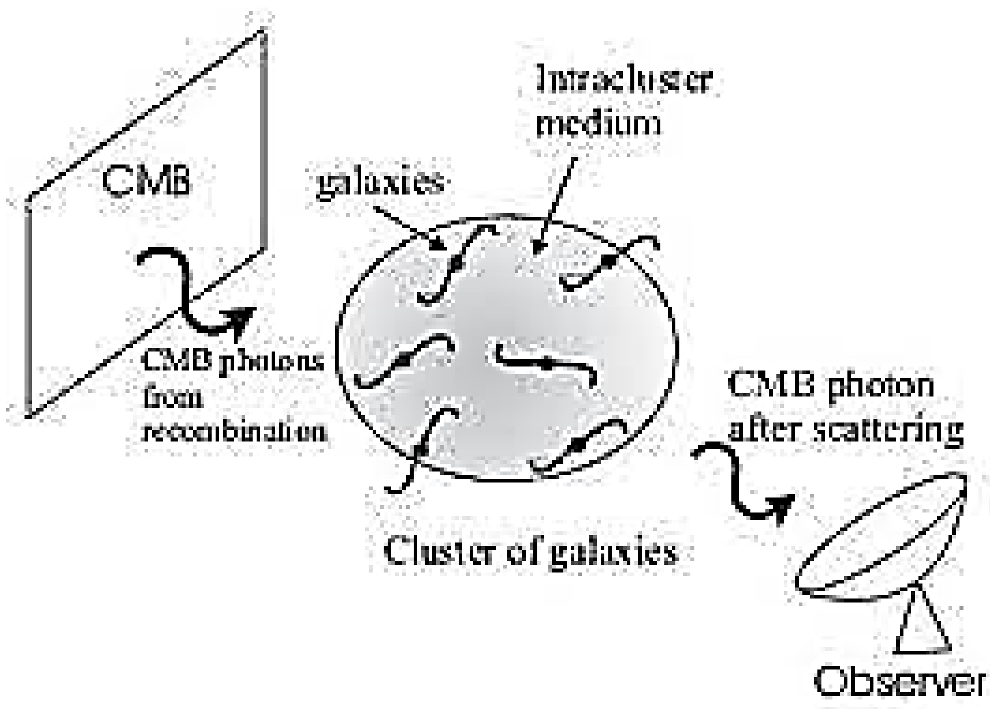
X-ray cavities: thermal or non-thermal content?

- In cavities filled with radio emission, there is definitely a population of non-thermal electrons
- Energy stored in electrons is not sufficient to inflate the lobes [Ito et al. 2008]: non-thermal protons can be present
- Hydrodynamic simulations of the lobes expansion in the ICM show that also a thermal gas with very high temperature ($T \gtrsim 100$ keV) can be present in the cavities [Sternberg & Soker 2009; Prokhorov et al. 2012]
- Given its high temperature and low density, the high temperature gas (HTG) is difficult to detect in soft X-rays

- Is the dominant component inside the cavities thermal or non-thermal?

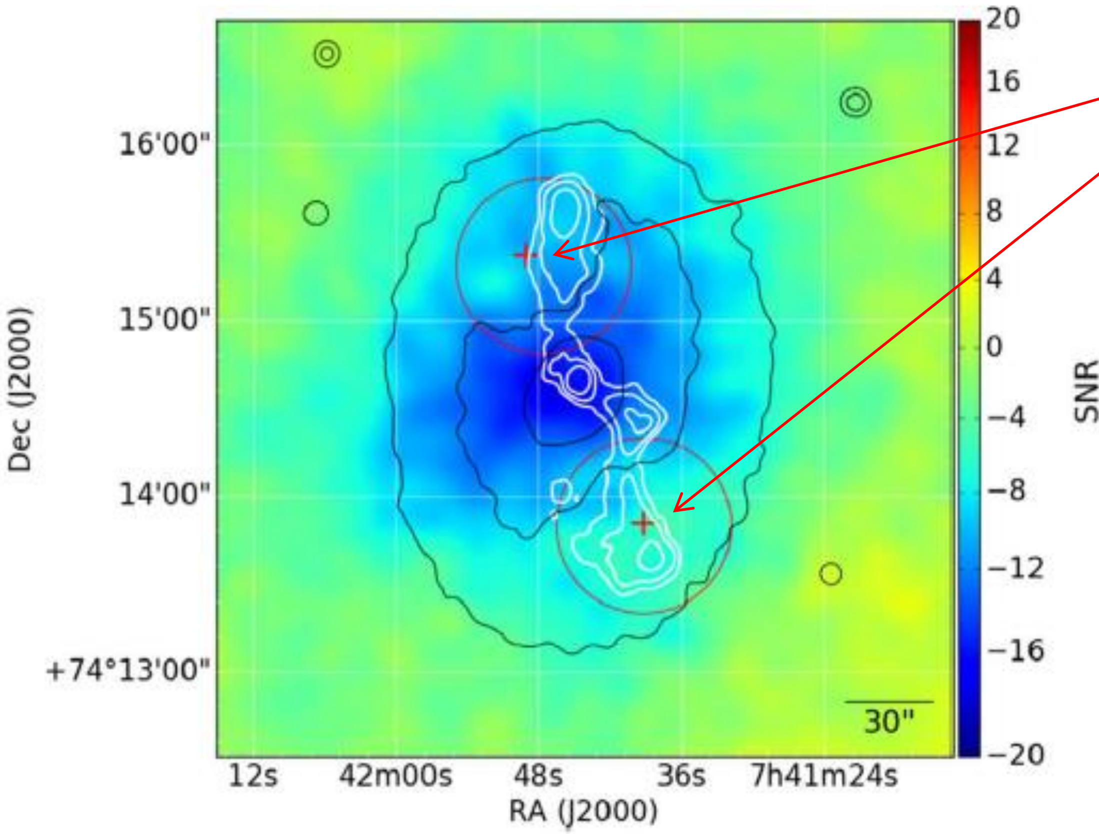
The SZ effect as a probe of the cavities content

- The SZE has been proposed as a possible probe of the cavities content (Colafrancesco 2005, Pfrommer et al. 2005)
- SZE is suitable to detect low density electrons populations
- Thermal and non-thermal SZE have different spectral shapes (Ensslin & Kaiser 2000; Colafrancesco, Marchegiani & Palladino 2003)



Detection of the SZE in the cluster cavities

- Abdulla et al. (2019): detection of the SZE in the cavities of the cluster MS 0735.6+7421
- Observation at 30 GHz with the CARMA interferometer



Deficit of SZE in correspondence of X-ray cavities

Colours: SZE map
White contours: radio
Black contours: X-rays
[Abdulla + 2019, ApJ, 871, 195]

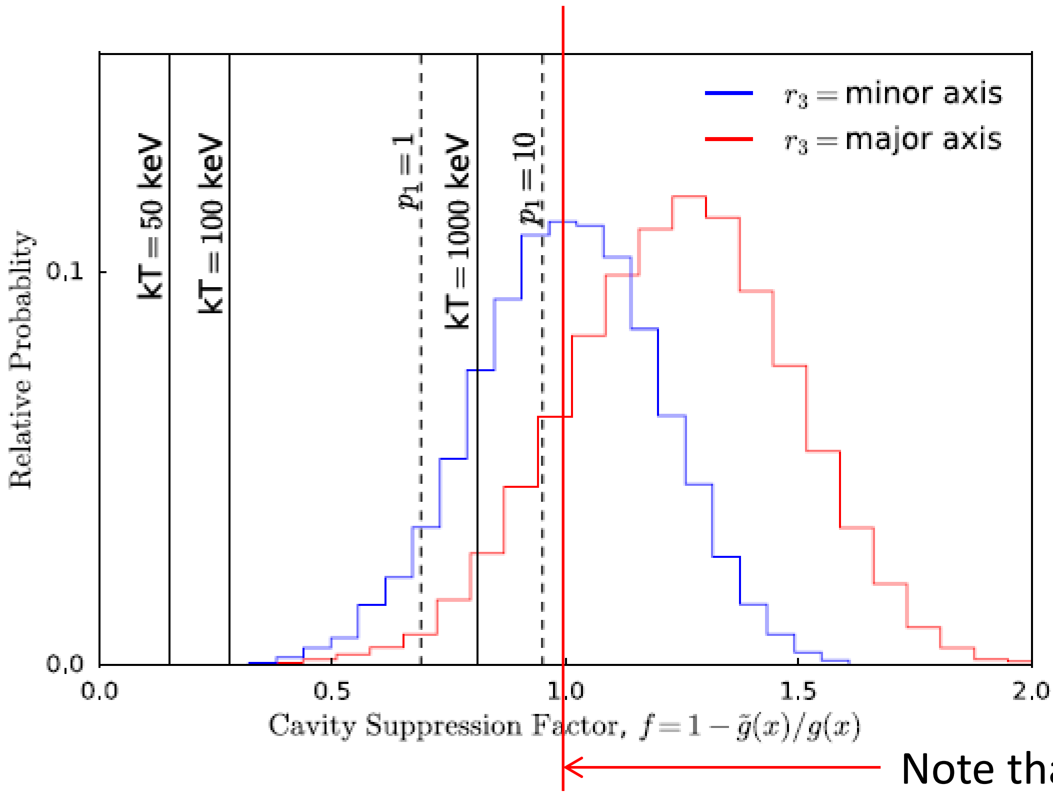
Thermal or non-thermal origin for the observed SZE?

$$f_{e,th}(p) = \frac{\beta_{th}}{K_2(\beta_{th})} p^2 \exp(-\beta_{th}\sqrt{1+p^2})$$

Thermal: relativistic Maxwellian
$\beta_{th} = m_e c^2 / kT_e$

$$f_{e,non-th}(p;\alpha,p_1,p_2) = \frac{(\alpha-1)p^{-\alpha}}{p_1^{1-\alpha} - p_2^{1-\alpha}}; p_1 < p < p_2$$

Non-thermal: power-law with minimum momentum p_1 and $\alpha = 2.48$



Note that $f > 1$ is unphysical in this model

Results of Abdulla+2019:

- NTE with $p_1 \sim 1 - 10$
- HTG with $kT \sim 1000$ keV

Data do not allow to discriminate between the two cases

Thermal and non-thermal SZE in the cavities are linked each other [Marchegiani 2021, MNRAS, 503, 4183]

- The intensity of the SZE depends on the optical depth, which depends on the electrons numerical density

$$\tau_{\rm cav} = \sigma_T \int_{\rm cav} n_e \, dl$$

- For steep power-law electrons spectra, the numerical density, and therefore the SZE, are dominated by low-energy electrons [Colafrancesco & Marchegiani 2011, A&A, 535, A108]
- For low-energy electrons, the main source of energy losses are Coulomb losses by interaction with the thermal gas
- The density of the thermal gas inside the cavity determines the shape of the non-thermal electrons spectrum at low energies, and therefore the non-thermal SZE

Model for the non-thermal electrons evolution

$$\frac{\partial N_e(p)}{\partial t} = \frac{\partial}{\partial p}\left[\left(-\frac{2}{p}D_{pp} + \sum_i b_i(p)\right)N_e(p) + D_{pp}\frac{\partial N_e(p)}{\partial p}\right]$$

p: normalized electrons momentum ($p = \beta\gamma$)

$N_e(p)$: electrons spectrum

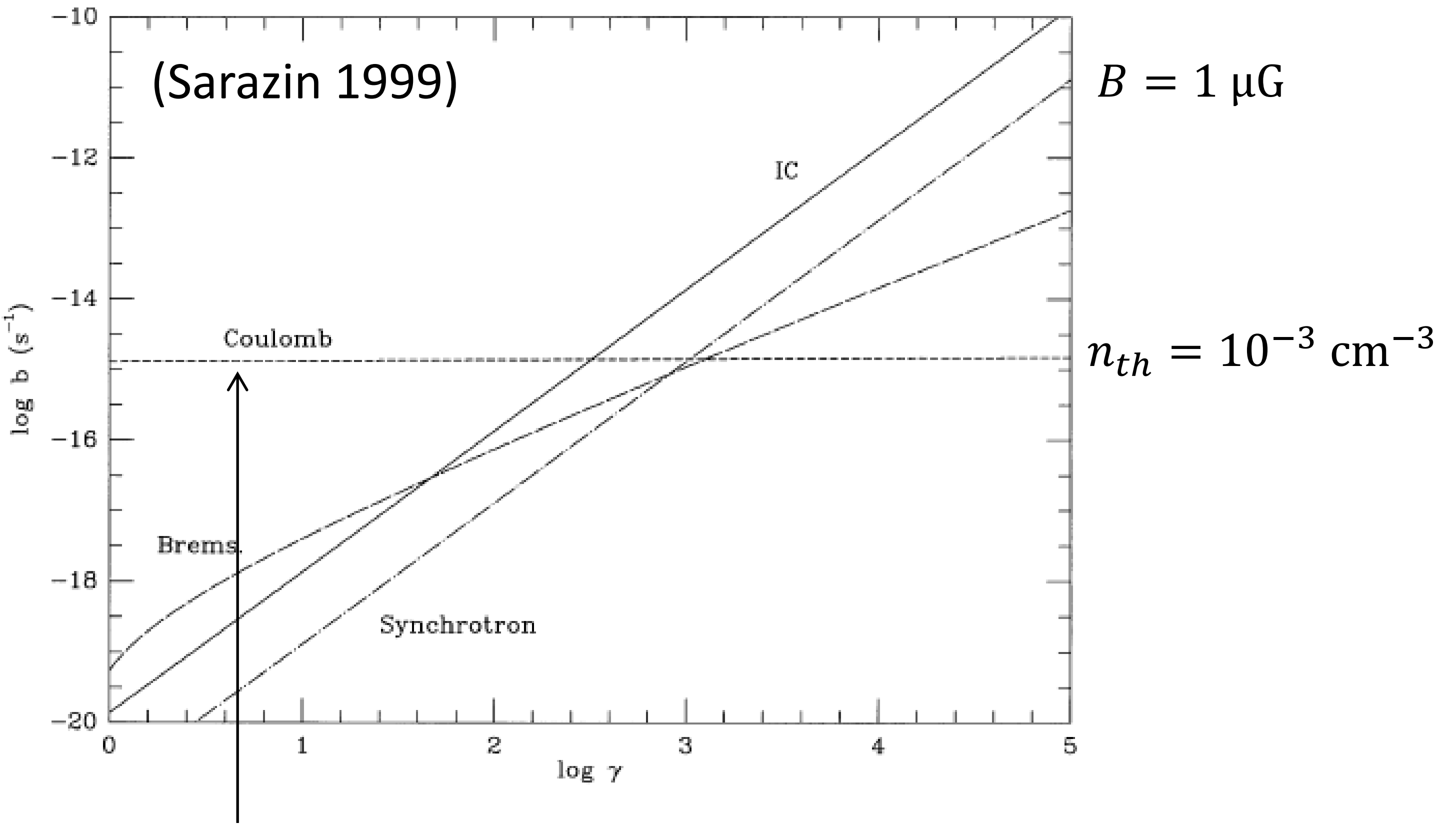
$b_i(p)$: energy loss term by different processes:

- Inverse Compton Scattering with CMB photons
- Synchrotron losses with magnetic field
- Coulomb losses with the thermal gas
- Non-thermal bremsstrahlung with the thermal gas
- Adiabatic expansion

D_{pp}: diffusion term in momentum space (Fermi-II acceleration)

After the initial injection, no subsequent injection is assumed (no source term)

Energy losses



- Coulomb losses are basically constant with γ at low energies (apart from a $1/\beta$ dependence at very low energies)
- They depend linearly on the thermal density value
- They dominate at low energies, also for values of the thermal density of the order of $10^{-6}\ \text{cm}^{-3}$

Method

- Electrons are initially injected with $N_e(p, t_0) = k_0 p^{-s}$
  - k_0 normalization factor (free parameter)
  - $s = 2.7$ from the spectrum of the radio emission in the lobe
- Electrons evolve for a time of 160 Myr (bubbles age estimated from X-ray observations [Vantyghem et al. 2014] and MHD simulations [Ehlert et al. 2019])
- Evolution is subject to energy losses and adiabatic expansion losses [Ensslin & Gopal-Krishna 2001]:

$$V(t) = V_0 \left(\frac{t}{t_0}\right)^q$$

$q = 6/5$ (Sedov-like expansion)

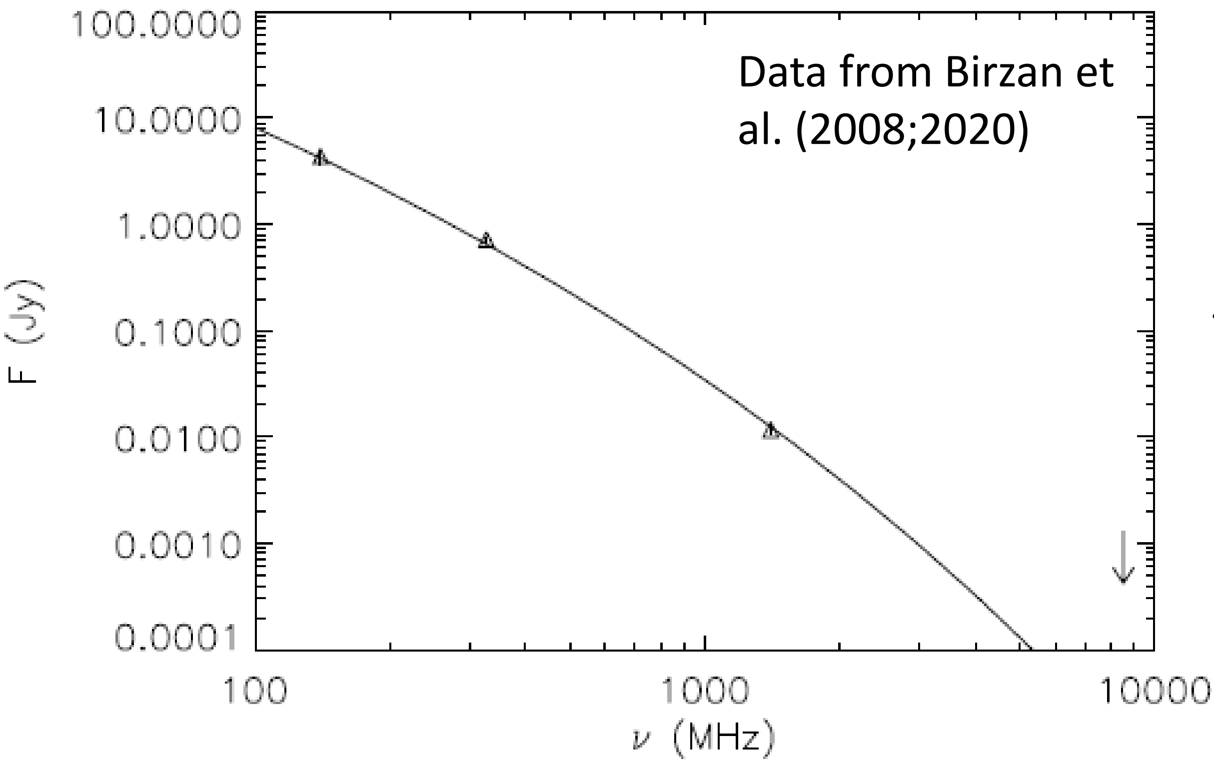
$$B(t) = B_0 \left(\frac{t}{t_0}\right)^{-\frac{2}{3}q}$$

$$n_{th}(t) = n_{th,0} \left(\frac{t}{t_0}\right)^{-q}$$

B_0 and $n_{th,0}$ are chosen so that values <u>at present time</u> are:

- $B = 4.7$ μG (equipartition value; Birzan et al. 2008)
- $n_{th} = 10^{-6} - 10^{-3}\ \mathrm{cm}^{-3}$

- Bubbles approximated as homogeneous spheres with $R = 100$ kpc
- Fermi-II acceleration parameter modelled as $D_{pp} = \chi p^2/4$
- χ free parameter chosen to reproduce the observed steepening of the radio spectrum

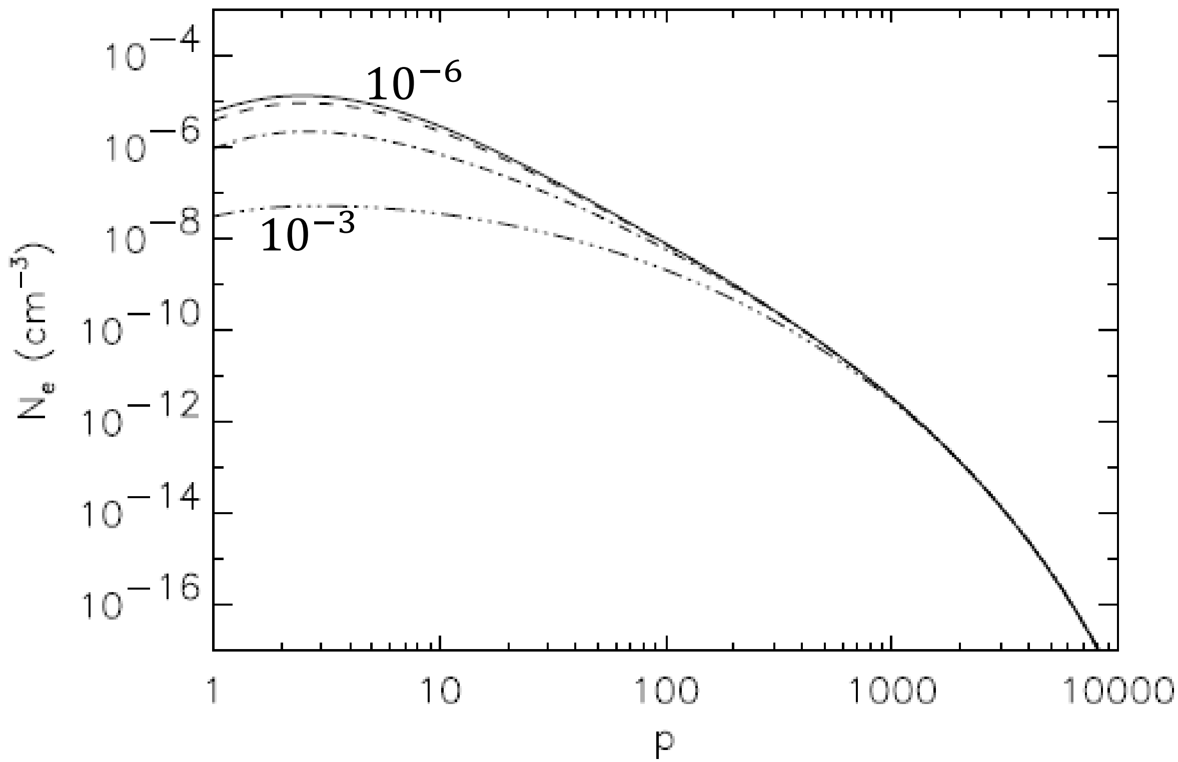


$$k_0 = 1.5 \times 10^{-3}\ \mathrm{cm}^{-3}$$
$$\chi = 3.5 \times 10^{-16}\ \mathrm{s}^{-1}$$

This is the spectrum for the sum of the two lobes (divide k_0 by two to obtain an approximation for a single lobe)

- Radio spectrum is produced by high energy electrons ($\gamma > 10^3$)
- It is not sensible to the value of the thermal density

Electrons spectra



- Electrons spectra for $n_{th} = 10^{-6} - 10^{-5} - 10^{-4} - 10^{-3}\ \mathrm{cm}^{-3}$
- All these spectra produce the <u>same radio spectrum</u>
- But we can expect they produce <u>different non-thermal SZE spectra</u>

Calculating the non-thermal SZE

- <u>Full relativistic approach</u> [Wright 1979; Colafrancesco et al. 2003]

$$\Delta I(x) = \tau[J_1(x) - I_0(x)]$$

$$J_1(x) = \int_{-\infty}^{+\infty} I_0(xe^{-s}) P_1(s) ds$$

$$P_1(s) = \int_0^{\infty} f_e(p) P_s(s,p) dp$$

$$\tau = \sigma_T \int n_e d\ell$$

n_{th} cm^{-3}	τ_{nt}	P_{nt} keV cm^{-3}
10^{-6}	1.81×10^{-5}	6.60×10^{-2}
10^{-5}	1.34×10^{-5}	5.39×10^{-2}
10^{-4}	4.01×10^{-6}	2.46×10^{-2}
10^{-3}	2.63×10^{-7}	5.05×10^{-3}

Small n_{th}

↓

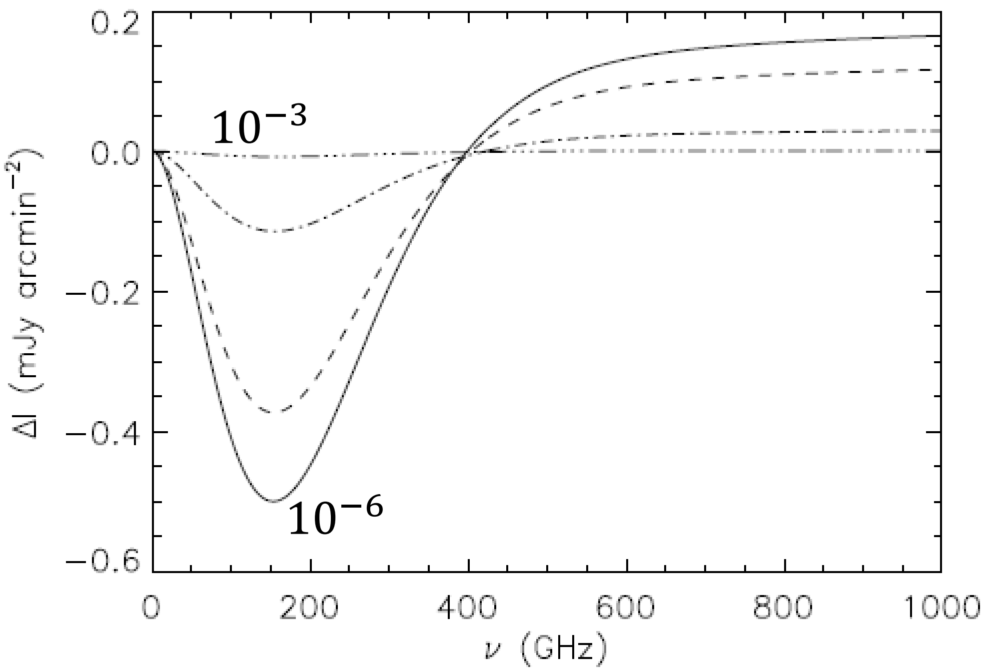
Reduced Coulomb losses

↓

Higher density of low energy electrons

↓

Higher τ_{nt} and stronger SZE



Thermal vs. non-thermal SZE in the cavities

- Density and temperature of the High Temperature Gas in the cavities are unknown
- We assume several values of the temperature (500 – 2000 keV)
- We assume the maximum values of the thermal density to not exceed the pressure of the external ICM:

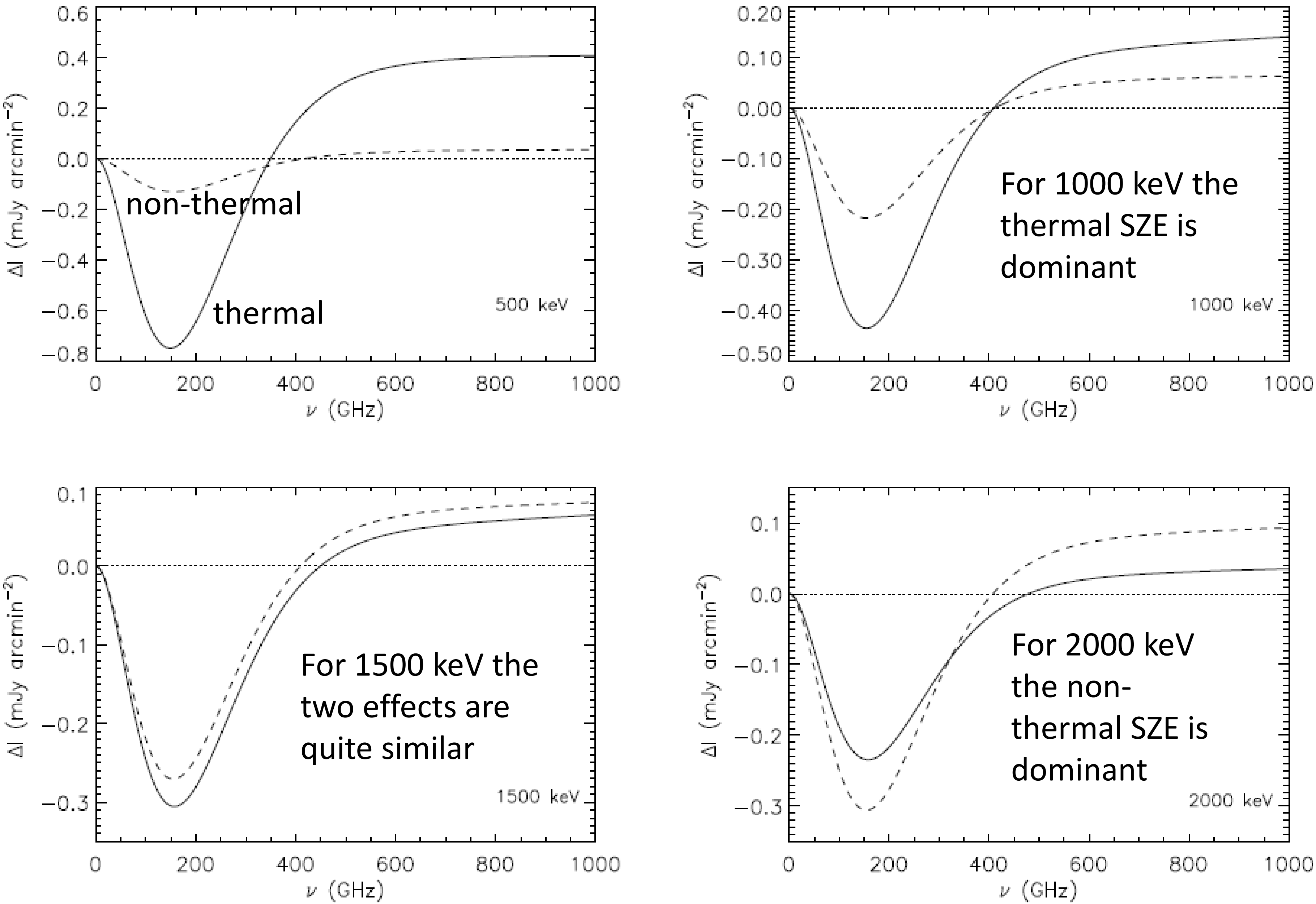
$n_{th} = P_{cav}/kT$ ($P_{cav} = 3.75 \times 10^{-2}$ keV cm^{-3}; Gitti et al. 2007)

- For such values of the density, we calculate the spectrum of the non-thermal electrons and the thermal and non-thermal SZE

$(k_B T_e)_{th}$ keV	n_{th} cm^{-3}	τ_{th}	τ_{nt}	P_{nt} keV cm^{-3}
500	7.50×10^{-5}	3.08×10^{-5}	4.58×10^{-6}	2.57×10^{-3}
1000	3.75×10^{-5}	1.54×10^{-5}	7.72×10^{-6}	3.67×10^{-2}
1500	2.50×10^{-5}	1.03×10^{-5}	9.63×10^{-6}	4.28×10^{-2}
2000	1.88×10^{-5}	7.73×10^{-6}	1.09×10^{-5}	4.67×10^{-2}

Higher T → Smaller n_{th} → Stronger non-thermal SZE

Results



ΔI (mJy arcmin⁻²)
ν (GHz)
non-thermal
thermal
500 keV
For 1000 keV the thermal SZE is dominant
1000 keV
For 1500 keV the two effects are quite similar
1500 keV
For 2000 keV the non-thermal SZE is dominant
2000 keV

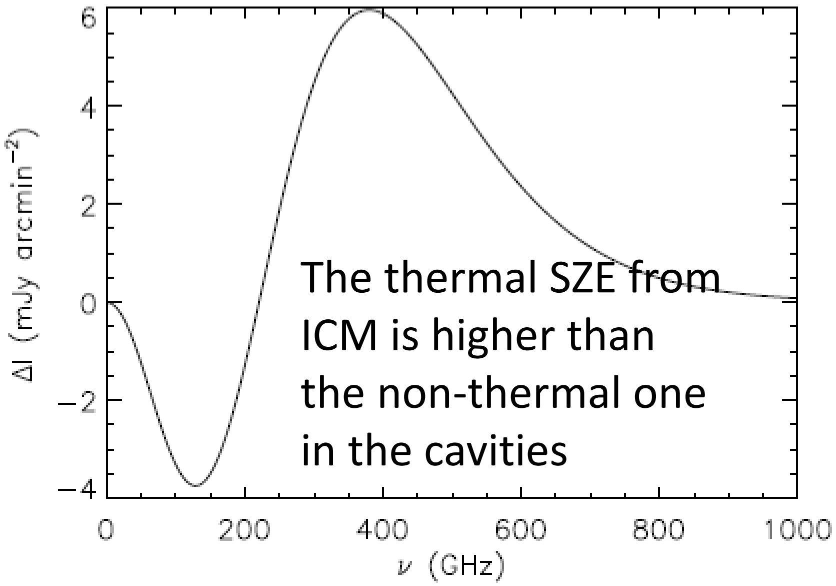
Comparison with the SZE from the external ICM

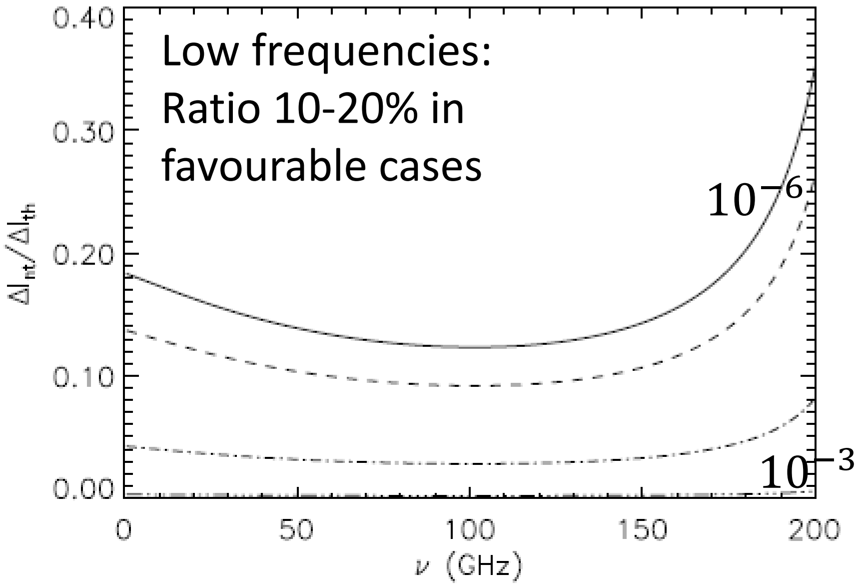
- The ICM is modelled as an unperturbed gas distribution with a hole in correspondence of the cavity [Pfrommer et al. 2005]
- Double beta model fitted to X-ray data [Vantyghem et al. 2014]:

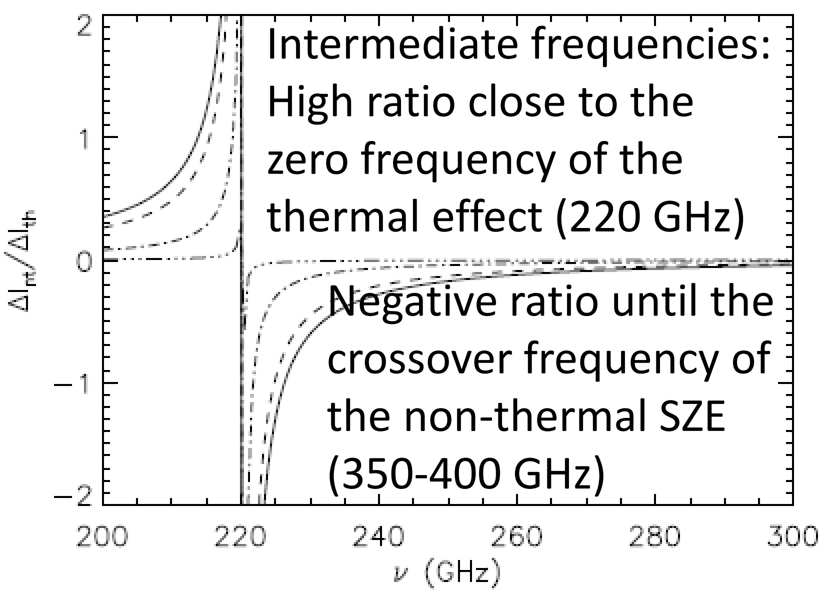
$$n_e(r) = n_{e1}\left[1+\left(\frac{r}{r_{c1}}\right)^2\right]^{-\frac{3}{2}\beta_1} + n_{e2}\left[1+\left(\frac{r}{r_{c2}}\right)^2\right]^{-\frac{3}{2}\beta_2}$$

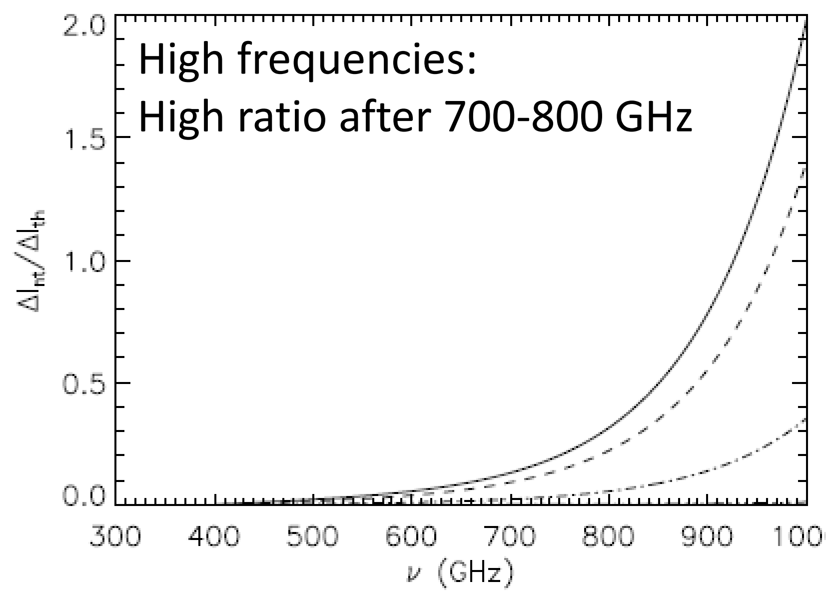
- Temperature of 5.5 keV (outside of the cool core)
- Cavities modelled as spheres with a radius of 100 kpc located at a distance of 150 kpc from the cluster center
- Density integrated until $4R_{vir}$ [Battaglia et al. 2010] with $R_{vir} = 2.23$ Mpc [Gitti et al. 2007]
- The resulting optical depth in the direction of the cavity center is $\tau_{ICM} = 4.0 \times 10^{-3}$
- We compare this thermal SZE with the non-thermal SZE calculated for four values of the thermal density inside the cavity

Thermal SZE and non-thermal/thermal ratio in three bands



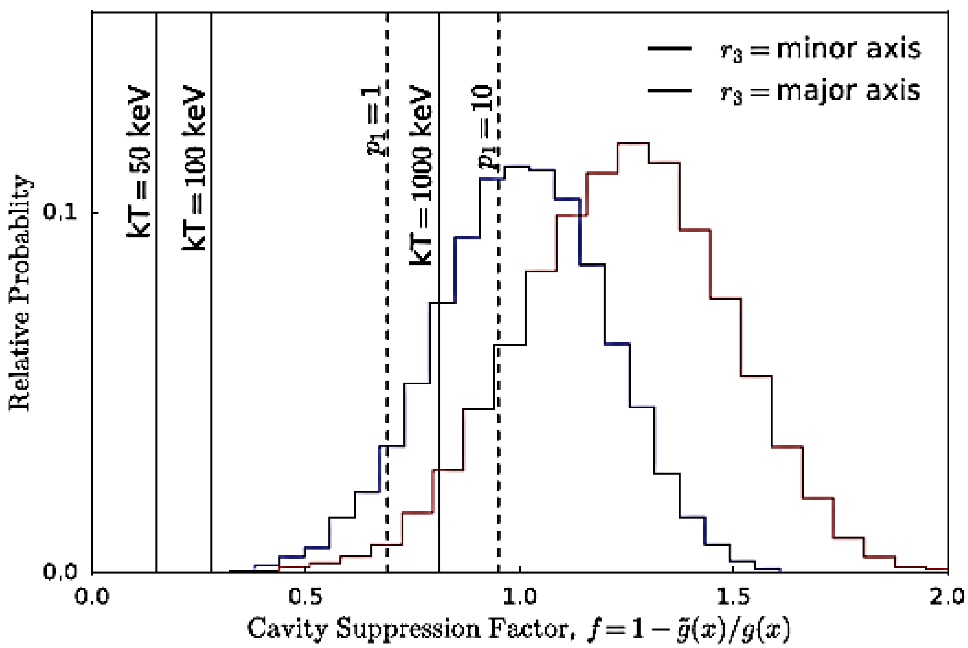






Summarizing and discussing

- Thermal and non-thermal SZE in the cavities are linked each other because of the Coulomb losses
- Higher thermal densities → weaker non-thermal SZE
- Higher temperatures → lower thermal densities → stronger non-thermal SZE

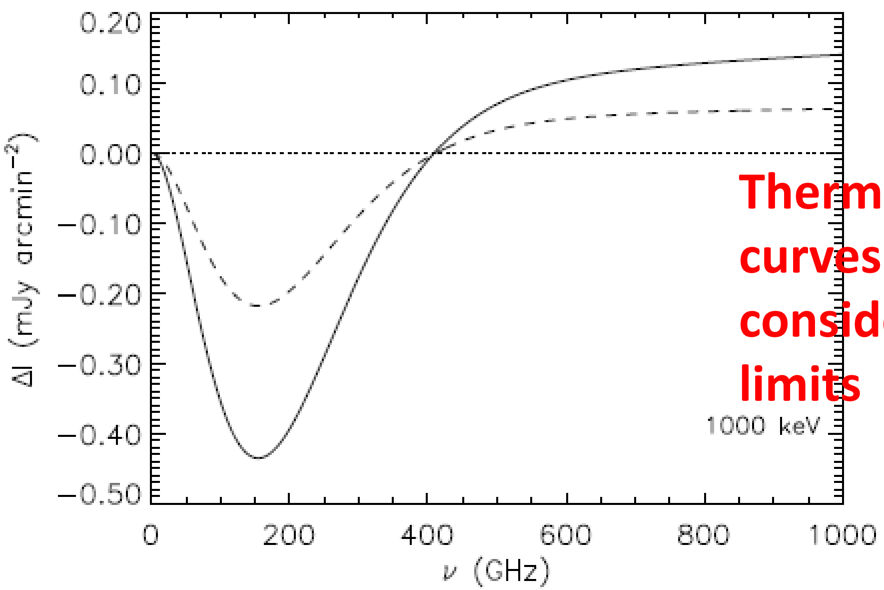


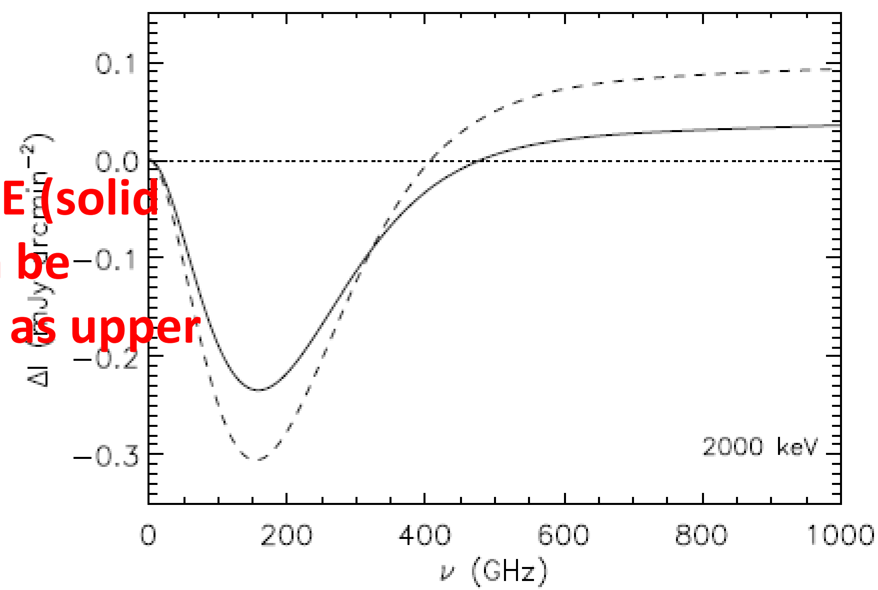
- Abdulla results points to $kT > 1000$ keV

We have found that:

- $kT < 1500$ keV $SZ_{TH} > SZ_{NT}$
- $kT > 1500$ keV $SZ_{TH} < SZ_{NT}$

- Can we say if the observed SZE inside the cavities is thermal or non-thermal?
    - With present data it is not possible to establish it, but:
    - Density in the cavity should be quite low ($f \lesssim 1$)
    - This should enhance the non-thermal component
    - <u>Non-thermal electrons are definitely present in the cavity</u> (we see the radio lobes), while <u>the thermal component is a hypothesis</u> (even if well motivated by simulations)





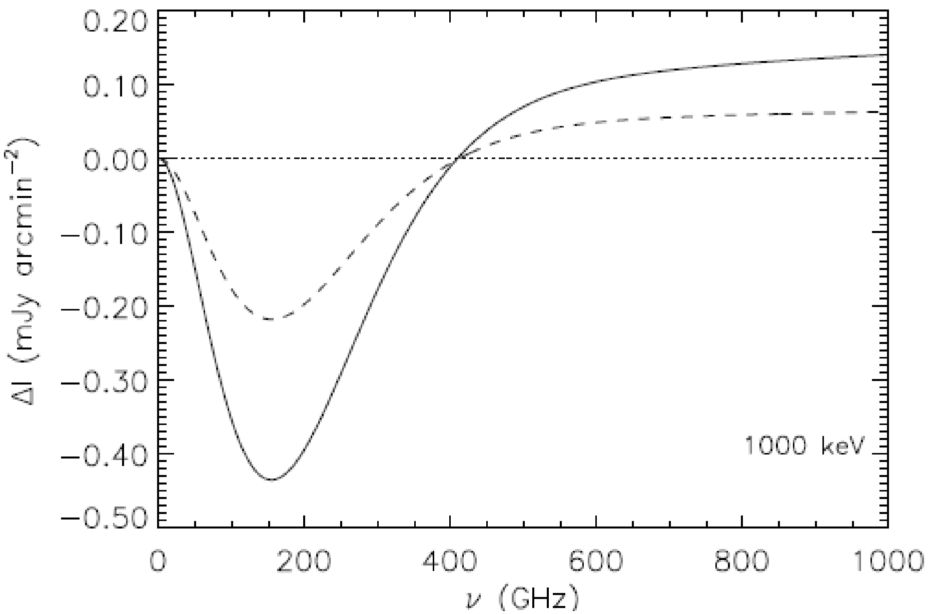
Thermal SZE (solid curves) can be considered as upper limits

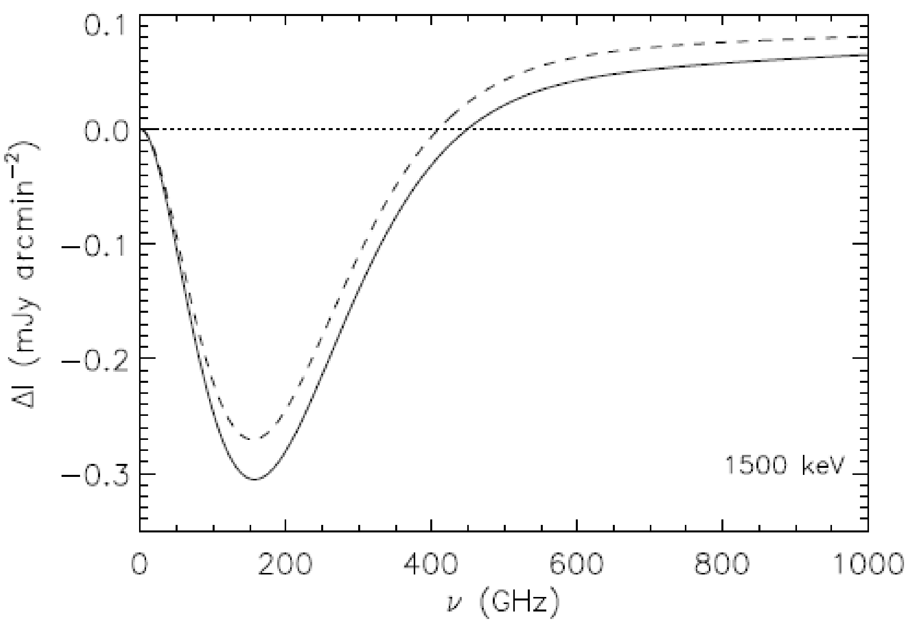
- Which observations can help to answer the question?
    - CARMA observations are done at 30 GHz
    - Multi-frequency observations can help to better constrain the spectral shape of the SZE
    - In MS 0735.6+7421 the diameter of the cavities is ∼1 arcmin
    - Instruments with sensitivities of the order of 10 arcsec are appropriate to detect the SZE in the cavities
    - Combination of **Nika2** (150 and 260 GHz) with measures at 90 GHz (**Mustang-2** at GBT; **Mistral** at SRT) can help to constrain the spectral shape of the SZE
    - Note that for both very high temperature gas and non-thermal electrons the SZE is negative until 300 – 400 GHz
    - Higher frequencies would be useful to complete the frequency sampling: **Millimetron**

Possible problems

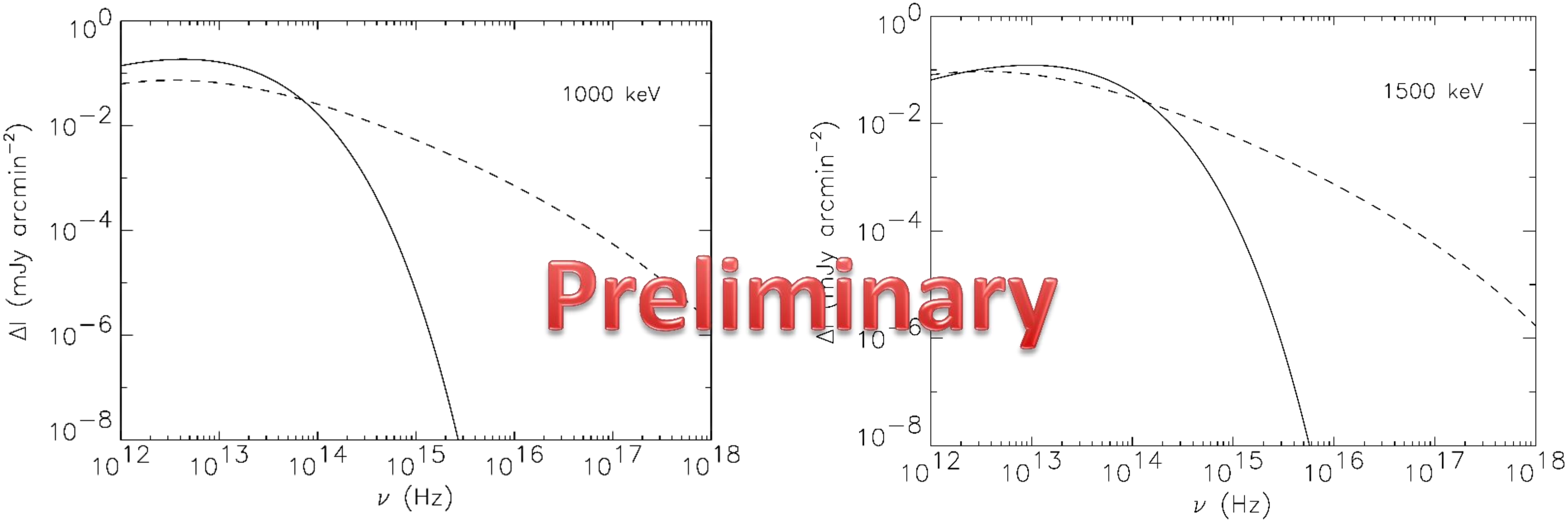
- Kinetic SZ effect
  - from the whole cluster [Pfrommer et al. 2005]
    - It should be present also in cluster regions far from cavities
    - It is important to observe with high-angular instruments also the rest of the cluster
  - from the cavities [Ehlert et al. 2019]
    - It is reduced if the jets are almost perpendicular to the line of sight
    - Taking an average of the two cavities, the kinematic component should be reduced if jest have opposite directions
  - Observing at $\nu > 600$ GHz this contribution should be small
- Infrared contaminants at high frequencies
  - Galactic dust
  - Dust in the cluster
  - Background galaxies

A further problem: the spectral shapes of NTE and HTG





- For $kT \sim 1000 - 1500$ keV, the spectral shapes of thermal and non-thermal SZE are quite similar
- This means that, even if we could measure the SZE along the whole spectral range, it might be difficult to establish if the SZE is thermal or non-thermal
- How would it be possible to discriminate between the two cases?
- Possible solution: observing the ICS emission in high-energy bands



- Thermal SZE should fall at optical/UV frequencies
- Non-thermal SZE should arrive at Hard X-rays
- Work in progress:
    - Check the effect of the Klein-Nishina cross section
    - Add bremsstrahlung of the high temperature gas
    - Compare with the emission from the cluster
    - Check which instruments can be used
- Hopefully these results will be ready for the proceedings!

Thank you!