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

Thermal or non-thermal origin for the observed SZE?

Thermal: relativistic Maxwellian

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

\[ \beta_{th} = \frac{m_e c^2}{kT_e} \]

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

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

Results of Abdulla+2019:

- NTE with \( p_1 \approx 1 - 10 \)
- HTG with \( kT \approx 1000 \) keV

Data do not allow to discriminate between the two cases

Note that \( f > 1 \) is unphysical in this model.
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

\[ \tau_{\text{cav}} = \sigma_T \int_{cav} n_e dl \]

- 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

(Sarazin 1999)

\[ n_{th} = 10^{-3} \text{ cm}^{-3} \]

\[ B = 1 \mu \text{G} \]

- **Coulomb losses** are basically constant with \( \gamma \) 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]:

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

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

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

\[
q = 6/5 \text{ (Sedov-like expansion)}
\]

\( B_0 \) and \( n_{th,0} \) are chosen so that values at present time are:
- \( B = 4.7 \) μG (equipartition value; Birzan et al. 2008)
- \( n_{th} = 10^{-6} - 10^{-3} \) cm\(^{-3} \)
• Bubbles approximated as homogeneous spheres with $R = 100$ kpc
• Fermi-II acceleration parameter modelled as $D_{pp} = \chi p^2 / 4$
• $\chi$ free parameter chosen to reproduce the observed steepening of the radio spectrum

Data from Birzan et al. (2008;2020)

$k_0 = 1.5 \times 10^{-3}$ cm$^{-3}$
$\chi = 3.5 \times 10^{-16}$ 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 $n_{th} = 10^{-6} - 10^{-5} - 10^{-4} - 10^{-3} \text{ cm}^{-3}$

All these spectra produce the same radio spectrum.

But we can expect they produce different non-thermal SZE spectra.
Calculating the non-thermal SZE

- Full relativistic approach [Wright 1979; Colafrancesco et al. 2003]

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

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

\[
P_1(s) = \int_{0}^{s} f_e(p)P_s(s,p)dp
\]

\[
\tau = \sigma_T \int n_e dl.
\]

<table>
<thead>
<tr>
<th>( n_{th} ) ( \text{cm}^{-3} )</th>
<th>( \tau_{nt} )</th>
<th>( P_{nt} ) ( \text{keV cm}^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{-6} )</td>
<td>( 1.81 \times 10^{-5} )</td>
<td>( 6.60 \times 10^{-2} )</td>
</tr>
<tr>
<td>( 10^{-5} )</td>
<td>( 1.34 \times 10^{-5} )</td>
<td>( 5.39 \times 10^{-2} )</td>
</tr>
<tr>
<td>( 10^{-4} )</td>
<td>( 4.01 \times 10^{-6} )</td>
<td>( 2.46 \times 10^{-2} )</td>
</tr>
<tr>
<td>( 10^{-3} )</td>
<td>( 2.63 \times 10^{-7} )</td>
<td>( 5.05 \times 10^{-3} )</td>
</tr>
</tbody>
</table>

Small \( n_{th} \)

- Reduced Coulomb losses
- Higher density of low energy electrons
- Higher \( \tau_{nt} \) 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:
  \[ n_{th} = \frac{P_{cav}}{kT} \quad (P_{cav} = 3.75 \times 10^{-2} \text{ keV cm}^{-3}; \text{Gitti et al. 2007}) \]
- For such values of the density, we calculate the spectrum of the non-thermal electrons and the thermal and non-thermal SZE

<table>
<thead>
<tr>
<th>((k_BT_e)_{th}) \text{ keV}</th>
<th>(n_{th}) \text{ cm}^{-3}</th>
<th>(\tau_{th})</th>
<th>(\tau_{nt})</th>
<th>(P_{nt}) \text{ keV cm}^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>(7.50 \times 10^{-5})</td>
<td>(3.08 \times 10^{-5})</td>
<td>(4.58 \times 10^{-6})</td>
<td>(2.57 \times 10^{-3})</td>
</tr>
<tr>
<td>1000</td>
<td>(3.75 \times 10^{-5})</td>
<td>(1.54 \times 10^{-5})</td>
<td>(7.72 \times 10^{-6})</td>
<td>(3.67 \times 10^{-2})</td>
</tr>
<tr>
<td>1500</td>
<td>(2.50 \times 10^{-5})</td>
<td>(1.03 \times 10^{-5})</td>
<td>(9.63 \times 10^{-6})</td>
<td>(4.28 \times 10^{-2})</td>
</tr>
<tr>
<td>2000</td>
<td>(1.88 \times 10^{-5})</td>
<td>(7.73 \times 10^{-6})</td>
<td>(1.09 \times 10^{-5})</td>
<td>(4.67 \times 10^{-2})</td>
</tr>
</tbody>
</table>

Higher \(T\) \quad \rightarrow \quad Smaller \(n_{th}\) \quad \rightarrow \quad Stronger non-thermal SZE
Results

For 1500 keV the two effects are quite similar

For 2000 keV the non-thermal SZE is dominant

For 1000 keV the thermal SZE is dominant
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

The thermal SZE from ICM is higher than the non-thermal one in the cavities.

Low frequencies:
Ratio 10-20% in favourable cases

Intermediate frequencies:
High ratio close to the zero frequency of the thermal effect (220 GHz)
Negative ratio until the crossover frequency of the non-thermal SZE (350-400 GHz)

High frequencies:
High ratio after 700-800 GHz
Summarizing and discussing

- Thermal and non-thermal SZE in the cavities are linked each other because of the Coulomb losses
- Higher thermal densities $\rightarrow$ weaker non-thermal SZE
- Higher temperatures $\rightarrow$ lower thermal densities $\rightarrow$ 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
  • Non-thermal electrons are definitely present in the cavity (we see the radio lobes), while the thermal component is a hypothesis (even if well motivated by simulations)
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 \( \sim 1 \) 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 jets 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!