Beyond the standard lore of the SZE

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# Clusters: more than basic

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<th>Cosmic Rays</th>
<th>Dark Matter</th>
<th>AGN jets/cavities</th>
<th>Plasma physics</th>
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</table>
| **Thermal particles**
\[ E_e \sim 0.1 - 10 \text{ keV} \] | **SZE** | **Cluster Cavities**
MS0735+7421 (Chandra) | **B-fields**
| **WIMPs**
\[ M_\chi \sim 10 - 500 \text{ GeV} \] | **1ES0657-556** | **Radio Galaxy Lobes**
3C432 (Chandra) | **Acceleration proc.**
| **Cosmic rays**
\[ E_e \sim 16 \text{ GeV} B_{\mu}^{1/2}(\nu_{GHz})^{1/2} \] | | | **Power-law**
| | | | **Maxwellian**

- **Cosmic Rays**
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- **Dark Matter**
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- **AGN jets/cavities**
  - Cluster Cavities: MS0735+7421 (Chandra)
  - Radio Galaxy Lobes: 3C432 (Chandra)

- **Plasma physics**
  - B-fields

- **Acceleration proc.**
  - Power-law
  - Maxwellian
\[ \Delta I(x) = 2\frac{(k_B T_0)^3}{(hc)^2} y \tilde{g}(x) \]

\( y(P_e, \ell) = \text{Comptonization factor} \)
\( \tilde{g}(\nu, T_0, P_e) = \text{Spectral distribution} \)

**The SZ Effect**
Compton Scattering of CMB photons by IS/IC electrons

S.Colafrancesco 2007, NewAR, 51, 394
*Beyond the Standard Lore of the SZ effect*

\[ y(P_e, \ell) = \frac{\Delta \nu}{\nu} \approx \frac{4kT_e}{m_e c^2} \]
\[ \frac{\Delta \nu}{\nu} \approx \frac{4}{3} \gamma^2 \]

**Thermal**
**Relativistic**
\[ \Delta I(x) = 2 \frac{(k_B T_0)^3}{(hc)^2} y \bar{g}(x) \]

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

**SZE amplitude:** degeneracy in physical parameters

**SZE spectra:** sensitivity to physical parameters

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

\[ P(s) = \int_0^\infty dp f_\epsilon(p) P(s; p) \]

\[ x = \frac{hv}{K T_{CMB}} \]
Polarizations arises as a natural outcome of electron-radiation scattering

\[ f(x_\nu) = \frac{e^{x_\nu}(e^{x_\nu} + 1)}{2(e^{x_\nu} - 1)^2} x_\nu^2 \]

\[ f_\perp(x_\nu) = x_\nu \frac{e^{x_\nu}}{e^{x_\nu} - 1} \left( \frac{e^{x_\nu} + 1}{e^{x_\nu} - 1} - 4 \right) \]

\[ \text{kpSZE} \]

\[ \text{tpSZE} \]

\[ \text{Kin-p} \]

\[ \text{Th} \]

\[ \text{Th-p} \]

\[ \text{Kin} \]

[Diego et al. 2007]

[Colafrancesco et al. 2010]
SZE Spectroscopy

Theoretical motivations

\[ y = \frac{\sigma_T}{m_e c^2} \int d\ell \left[ P_{e,\text{th}} + P_{e,\text{rel}} + P_{e,\text{DM}} + \ldots \right] \]
SZE spectroscopy: thermal case

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

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

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

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

The best way to measure Te are:
- SZE at high frequencies (> 300 GHz)
- spectral slope around 220 GHz

[Colafrancesco, Prokhorov, Dogiel 2009]
SZE spectroscopy will allow to derive spatially resolved T-profiles for nearby clusters out to large distances:

**Inversion Technique**

\[
\text{SZE} \rightarrow T, \tau, V_p, T_{\text{CMB}}
\]

- T profile with uncertainties similar to those of X-ray observations in the cluster cores
- T profile uniquely sampled in the outer parts of the cluster

The availability of temperature and density profiles from SZE observations will allow to estimate the total mass of the cluster, including the outer regions.

**Unbiased probes for Cosmology**

![SZE spectroscopy](image)
SZE & cavities in Clusters

MS0735.6+7421 (cavity A)

Cavity A
Cavity B

MS0735.6+7421
SZE from radio-galaxy lobes

\[ \Delta T_{\text{SZ}} \propto (kT_{\text{CMB}})^{-3} \left( \gamma \right)^{-(\alpha - 1)} \cdot E_{X \text{ min}}^{-\frac{(\alpha - 1)}{2}} \]

measure \[ T_{\text{CMB}}(z) \]

[Colafrancesco 2008]
$T_{\text{CMB}}(z)$ from SZE spectra

Four unknown

- $T_{\text{CMB}}(z)$
- $V_r$
- $\tau$
- $T_e$

Full SZE spectrum

$\sim 90-500$ GHz

$X_{th,0} \approx a(T_e) + \tau b(T_e)$

$\frac{\Delta I}{W/m^2/\text{sr}/\text{cm}^4}$

$x_{th,max} \approx 6.511(1 + 2.41\theta_e - 4.96\theta_e^2) + \tau(0.0161 + 8.16\theta_e - 35.9\theta_e^2)$

$i(x) = \frac{kT_e}{mc^2} \left[ g(x) + \frac{V_r mc^2}{c kT_e} h(x) \right]$
SZE and Dark Matter nature
1ES0657-556

Dark Matter

Hot gas
$SZ_{DM}$ from 1ES0657-556
Isolating $\text{SZ}_{\text{DM}}$ at $\sim223$ GHz

Frequency ($M_\chi = 20$ GeV)

Neutralino mass ($\nu = 223$ GHz)

[S.C. et al. 2007]
Observational Strategy
$x_0 = x_0(P_e)$

Degenerate w.r.t. $V_p, E_{CR}, M_{DM}, P_{WHICM}$

Slope $= \frac{\Delta i(x)}{\Delta x}$

Unbiased probe at $\sim x_0$

Continuous spectroscopy

Wide $\nu$-band spectroscopy

High-$\nu$ spectroscopy

[Colafrancesco, Prokhorov, Dogiel 2009]
Observational requirements

1) A low-$\nu$ band to determine the overall amplitude of the SZE that is proportional to $y = \int dl \, n \cdot T$ (mainly depending on $\tau = \sigma_T \int dl \, n$ → insensitive to $T$)

3) A high-$\nu$ band to determine the electron temperature $T$ from the shape of the SZ spectrum (→ highly sensitive to $T$)

2) A medium-$\nu$ band to determine the crossover of the spectrum that allows to obtain information on
   - electron pressure $P_e$
   - $T_{\text{CMB}}(z)$
   - $V_{\text{pec}}$

4) Very high-$\nu$ band to monitor the foregrounds (Galaxy, Point-like Sources)
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Thermal SZE spectra

B$_{\text{atm}} > 10$K

Bands: 1 2 3 4
From SAGACE to Millimetron

SAGACE
- 3 m dish
- Passive cooling (50 K)
- $\Theta = 0.7-4.2$ arcmin
- Noise = 18 mJy/\(\sqrt{Hz}\)
- FTS spectroscopy
- Elliptical orbit
- Large-survey mode
- Pointed mode

Millimetron
- 12 m dish
- Active cooling (4 K)
- $\Theta < 0.1-1.0$ arcmin
- Noise < 0.1 mJy/\(\sqrt{Hz}\)
- FTS spectroscopy
- Polarimetry
- L2
- Observatory mode
- Small-survey mode
SZE spectroscopy: precision

COMA in SZE: Current data

[Colafrancesco 2004]
SZE spectroscopy: physics

Low-resolution space spectrometer vs. ground based multiband (3-BP)

Spectroscopic capabilities will allow to separate the cluster parameters:

\[ n_e \quad T_e \quad V_p \quad T_{CMB} \]

- the main physical quantities of the cluster thermal plasma (density \( n_e \), temperature \( T_e \))
- the cluster peculiar velocity \( V_p \)
- the value of the CMB temperature \( T_{CMB}(z) \) at the cluster redshift \( z \)

All with good precision (independent derivation !)
FTS-SP: resolving cluster atmospheres

X-ray

MS0735

4 m.

150 GHz

12 m.

150 GHz

350 GHz

350 GHz
Differential-Martin Puplett Imaging Interferometer. [DeBernardis et al. 2009]
Each detector measures the difference of spectra from two sky regions.
The Martin-Puplett imaging interferometer can be modified to become sensitive to polarized radiation: if the input polarizer is removed, only the polarized component of the signal will produce a modulated output.

However, this configuration is sensitive to polarization oriented at 45° from the beamsplitter wires.

Add a polarization modulator, so that the system is sensitive to any polarization orientation and a small polarized fraction can be extracted. [DeBernardis et al. 2009]
FTS and detector coupling

TES

Concept, prototype design and tests already available

KID

Typical geometry of the resonator

[Tc = 305 mK]

[Sensitivity ~ 10^-100 nK]

[Romai I Univ., Genova Univ., ASI]

[Romai I Univ. + ASI + SRON (Utrecht)]
Observation plan: SAGACE (3m)

SAGACE allows to carry out the first spectroscopic SZE survey

≥ 100 known clusters from pointed observations

> 2000 clusters from blind surveys

Differential Spectroscopy

The SAGACE telescope has a FOV 50 times larger than Herschel SPIRE spectrometer. An FTS with photon noise limited detectors can be 30 times more sensitive.
Observation plan: Millimetron (12m)

<table>
<thead>
<tr>
<th>Millimetron will provide the first spectro-polarimetric SZE obs.</th>
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<tbody>
<tr>
<td>all known clusters</td>
</tr>
<tr>
<td>from pointed/blind obs.</td>
</tr>
<tr>
<td>&gt; 1000 clusters</td>
</tr>
<tr>
<td>from small deep surveys</td>
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**Differential Spectro-Polarimetry**

The **Millimetron** telescope can have a FOV 20-50 times larger than Herschel SPIRE spectrometer. An FTS-SP with photon noise limited detectors can be 1,000-10,000 times more sensitive.

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Spectro-polarimetry @ mm

Probe the 3D structure of Large Scale Structures
- Galaxy clusters
- LSS and CMB
- Galaxies (RG, AGNs, Starbursts)

We developed a mid-term program with a strong technological effort which is directed towards high sensitivity ($\sim 10\,\text{nK} - \mu\text{K level}$) and high spatial resolution (arcsec-arcmin level) together with a wide-band continuum spectral coverage obtainable from space experiments. This goal is at the frontier of the present technology but will be at hand for SAGACE and MILLIMETRON. These experiments will be able to open the door to the full exploration of the SZE as a single-technique multi-disciplinary probe: the nature of DM, DE, mod-G scenarios, the origin of cosmic rays and B-fields, the BH feedback in large-scale structures and other relevant questions which are on the discussion table of modern cosmology.
THANKS for your attention

MILLIMETRON (approved)  
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INFN  
INAF  

Netherlands  
SRON  

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