The SZ Effect in the PLANCK & HERSCHEL Era

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The Cosmic History

Gravity
GR

Dark Matter

Dark Energy

Afterglow Light Pattern
400,000 yrs.

Inflation

Quantum Fluctuations

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion

1st Stars about 400 million yrs.

Big Bang Expansion
13.7 billion years
Cosmology with Cosmic Structures

**UNIVERSE**

- **DM**
- **DE**
- **GR**

**Tools**

- DM-meter
- DE-meter
- G-meter

**Probes**

**Utensils**

- Jet-feedback
- BHs
- Baryons
- B-field
- Cosmic Rays

DM halos
Large-Scale Structures
(Galaxy Clusters)

More than basics
LSS and Dark Matter
Dark Matter nature

[Colafrancesco 2006, 2007]
LSS shock waves

$\rho_{\text{gas}}$

$T_{\text{gas}}$

Shocks

$M$

[Pfrommer et al. 2006]
LSS shock waves

\[ \rho_{\text{gas}} \]

Shocks

\[ T_{\text{gas}} \]

\[ \pi^{0,\pm} \rightarrow X + \gamma \gamma + e^{\pm} \]

\[ P_{\text{th}} \]

\[ P_{\text{cr}} \]

\[ e^{-}_{\text{cr}} \]

[\( \gamma_{\text{ICS}}, \gamma_{\text{br}} \)]

Heating

Cooling

UV/X-rays

[\( \rho_{\text{gas}} \rightarrow (1 + \beta_{\text{gas}}) \rho_{\text{gas}} \)]

\[ p_{\text{th}}, p_{\text{cr}} \]

\[ \gamma_0, \gamma_1 \]

M

[Pfrommer et al. 2006]
Magnetic fields in LSS

**Origin**
- Primordial
- Post-recombination

**G + MHD** → \( B(\delta \rho, z; P_k) \)

[Sigl et al. 2005]
B-field in clusters: evidence

Synchrotron radiation

Radio Halos
\[ B \approx 0.1 - 5 \mu G \]

Radio Relics
\[ B \approx 0.2 - 8 \mu G \]

Faraday Rotation
\[ B \approx 1 - 50 \mu G \]
BHs in galaxy clusters: evidence

Virgo

A4059

A262

Perseus
BHs in galaxy clusters: ejecta

Relativistic plasma
AGN core
Cavities

MS0735.6+7421

RG lobe emission
Blazar-like emission
RG lobe emission
Cooling or not cooling?

$A2052$

$\frac{E}{dE/dt} = \frac{E}{L} \approx \frac{nkT}{n^2 \sqrt{kT}} = \frac{\sqrt{kT}}{n}$

$3kn(r) \frac{dT(r,t)}{dt} = -\left(\frac{dE}{dt}\right)_{cooling}$

[Blanton et al. 2005]
Cluster cool cores

[S.C. Dar & DeRujula (2004)]
[S.C. (2005)]
[S.C. & Marchegiani (2008)]
Clusters: crossroads of cosmic physics

- Dark Matter
- Cosmic rays
- AGNs
- B field
- Thermal plasma
Challenge

Multi-D tomography
(disentangle cluster atmospheres)

Multi-technique single-purpouse
(Radio to TeV)

Multi telescopes
Multi techniques

Single-technique multi-purpouse
(SZE)

Single telescope
Single technique

radio µwave-mm X-ray γ-ray TeV µwave-mm
A single-technique approach: SZE

- A single-technique and powerful tool for multi-D tomography
  - Particle-AstroPhysics
  - Cosmology

Opportunities
- PLANCK
- HERSCHEL
- ALMA
- SKA
- Wide-band Spectro-Polarimetry @ μwave – mm
  offering a complete approach to study SZE in cosmic structures
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**

- **High-E electrons**
  - thermal (supra-thermal)
  - relativistic
The SZ Effect
Compton Scattering of CMB photons by IS/IC electrons

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

thermal NR e⁻
SZE: Observational fact

This — This
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

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

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

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

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

Diffusion limit  \quad \rightarrow \quad \text{Single scattering} \quad (\tau \ll 1)

Single thermal population  \quad \rightarrow \quad \text{Thermal electrons (X-ray)}
Blob-ology

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

\[ I_{\text{CMB}} + \Delta I_{\text{SZ}} \]

 Thermal
Relativistic

\[ \Delta v \approx 4 \frac{kT_e}{m_e c^2} \]
\[ \Delta v \approx \frac{4}{3} \gamma^2 \]
**SZE: general derivation**

**Intensity change**

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

**Pressure**

- Thermal
  \[ P_{th} = n_e k_B T_e \]

- Relativistic
  \[ P_{rel} = n_e \int_0^\infty dp f_e(p) \frac{1}{3} pv(p) m_e c \]

**Spectral shape**

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

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

**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
\[ \frac{\Delta T}{T_0} \bigg|_{\text{kin}} = h(x) \cdot \frac{1}{m_e c} \int d\ell \sigma_T n_e p_p = h(x) \cdot \frac{p_e}{m_e c} \cdot \tau \]

Momentum
\[ p_e = \gamma \cdot m_e v \]
Relativistic generalization

Spectral shape
\[ h(x) = \frac{x^4 e^x}{(e^x - 1)^2} \left[ 1 + \kappa_{\text{rel}}(x) \right] \]
CMB spectrum
SZE: polarization

Polarizations arise as a natural outcome of $\gamma$-e scattering → various polarizations

Polarization due to peculiar motion of clusters

\[ \Pi_i \approx \beta_i^2 \tau \]

Polarization due to transverse motions of plasma within the cluster

\[ \Pi_V \approx \beta_i \tau^2 \]

Polarization due to multiple scattering $\gamma$-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 & Tullio 2010-11]

Polarization matrix

\[ Q_{ij} = \langle E_i E^*_j \rangle_T \]

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

Stokes parameters

General derivation (single scattering, Thomson limit)

\[
Q'(p_1) = \frac{3}{16\pi} \int_2 d\tau \int \frac{d^3 \beta_e}{\gamma_e} f_e(\beta_e) \int d\Omega_2 \frac{n_{22} + \alpha_1 r_{12}}{(n_{12} n_{22})^2} I(\alpha_2; \vec{n}_2) \times \\
\times \left[ \sin^2(\theta_2) \cos(2\phi_2) + 2\gamma_e \beta e \frac{r_{12}}{n_{12}} \sin(\theta_2) \sin(\theta_e) \cos(\phi_2 + \phi_e) + \left( \gamma_e \beta e \frac{r_{12}}{n_{12}} \right)^2 \sin^2(\theta_e) \cos(2\phi_e) \right]
\]

\[
U'(p_1) = \frac{3}{16\pi} \int_2 d\tau \int \frac{d^3 \beta_e}{\gamma_e} f_e(\beta_e) \int d\Omega_2 \frac{n_{22} + \alpha_1 r_{12}}{(n_{12} n_{22})^2} I(\alpha_2; \vec{n}_2) \times \\
\times \left[ \sin^2(\theta_2) \sin(2\phi_2) + 2\gamma_e \beta e \frac{r_{12}}{n_{12}} \sin(\theta_2) \sin(\theta_e) \sin(\phi_2 + \phi_e) + \left( \gamma_e \beta e \frac{r_{12}}{n_{12}} \right)^2 \sin^2(\theta_e) \sin(2\phi_e) \right]
\]

General derivation (multiple scattering, Thomson limit)

\[
\bar{I}(\vec{p}; \vec{v}_L) = I(\vec{p}; \vec{v}_L) + \int_{-\infty}^{\infty} d\tau \int_{-\infty}^{\infty} P_1(s) \left[ e^{3s} I_0(p e^{-s}) - I_0(p) \right] ds
\]
SZE spectro-polarimetry

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

\[ \tau, kT_e, P_e, E_e, M_\chi, V_t \]

**SZE polarization:**
sensitivity to m-D distribution of physical parameters

For a thermal plasma:
- Velocity sub-structure \((\beta \tau^2)\)
- Temperature sub-structure \((T_e \tau^2)\)
The SZE is independent of redshift and therefore it is an optimal tool for Cosmological applications.

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

<table>
<thead>
<tr>
<th>Galaxy clusters</th>
<th>AGN jets/cavities</th>
<th>DM nature</th>
<th>Plasma physics</th>
</tr>
</thead>
</table>
| **Thermal particles**  
\( E_e \sim 0.1 \text{–} 10 \text{ keV} \) | **Cluster Cavities**  
MS0735+7421 (Chandra) | **SZE**  
1ES0657-556 | **B-fields** |
| **WIMPs**  
\( m_\chi \sim 10 \text{–} 500 \text{ GeV} \) | | | |
| **Cosmic rays**  
\( E_e \sim 16 \text{GeV} \)  
\( B_{\parallel}^{1/2}(\nu_{\text{GHz}})^{1/2} \) | **Radio Galaxy Lobes**  
3C432 (Chandra) | | **Acceleration proc.** |

- **Power-law**
- **Maxwellian**
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 \( \nu \)
- No zero (CMB spectrum)
- Confused by primordial CMB structure
- No detection
Pre-PLANCK Era

Going larger
Cosmology

South Pole Telescope
150 GHz

Going deeper
Astrophysics

SZE-selected samples dominated by disturbed clusters

Contaminating point sources (AGN, star forming galaxies)
Pre-PLANCK Era

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

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

Need external priors
- X-ray \( kT \)
- WL \( M \)
- O \( z \)

for a proper use in
- Cosmology
- Astrophysics

Accessible from Space

Independent of astrophysics

Strongly dependent on astrophysics

kT = 7 keV
kT = 10 keV
kT = 15 keV
kT = 20 keV

OVRO

MUSTANG

SPT
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
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
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]
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
- $z_{\text{FeK}}=0.94$
- $L_{X}[0.5-2\text{keV}]=\left(1.4\pm0.5\right)\times10^{45}\text{ erg/s}$
- $M_{500}=\left(7.8\pm0.8\right)\times10^{14}\text{ M}_\odot$
- 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-$\sigma$ preference for non-zero $m_\nu$
  \[ \Sigma m = 0.34 \pm 0.17 \text{eV} \]
  and an extra $\nu$ species
  $\text{Neff}=3.91 \pm 0.42$
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, $\tau = 3.5 \times 10^{-3}$
- $kT_2 = 25$ keV, $\tau = 5.5 \times 10^{-3}$

**Thermal + non-thermal**

- $kT = 13.9$ keV, $\tau = 1.1 \times 10^{-2}$
- $n_e \sim E^{-2.7}$, $p_1 = 1$, $\tau = 2.4 \times 10^{-4}$

**Evidence of non-gravitational activity in the cluster merging**

- Shock acceleration or MHD acceleration
- Stochastic electron acceleration
- Continuous hadron acceleration

**Graphs**

- Left: $\chi^2 = 1.27$, d.o.f. = 1, rms fom = 1
- Right: $\chi^2 = 0.44$, d.o.f. = 2, rms fom = 0.35

[S.C. et al. 2011]
SZE: 3-d tomography

Morphological SZE

345 GHz Laboca

600 GHz Herschel

T standard deviation

First measurement of the temperature standard deviation in galaxy clusters: using the SZE

[Prokhorov & Colafrancesco 2012]

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

Bullet Cluster

$$\langle T \rangle \sim 13.9 \text{ keV}$$

$$\sigma = 10.6 \pm 3.8 \text{ keV}$$

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

[Prokhorov, S.C. et al. 2011b]
From PLANCK onward

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

- SZ + LABOCA
  150-215 345 GHz
- No spectroscopy
- Different instruments

<p>|</p>
<table>
<thead>
<tr>
<th><strong>PLANCK</strong></th>
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</thead>
<tbody>
<tr>
<td>Full sky, but shallow survey</td>
</tr>
<tr>
<td>A few thousand clusters with low-moderate S/N ratio.</td>
</tr>
<tr>
<td>Low-moderate spatial resolution &amp; spectroscopy in</td>
</tr>
<tr>
<td>bands</td>
</tr>
</tbody>
</table>

To fully exploit the SZE info. we would need

- Spectroscopic capabilities
- Wider & continuous frequency coverage (no multi-band, no atmosphere)
- Better calibration
- Better knowledge of foregrounds
- Deep integrations on selected targets/fields

**HERSCHEL**

**SPT**
Expectations: spectra

Different spectroscopic configurations for studying the SZE in cosmic structures

[DeBernardis, Colafrrancesco et al. 2011]
Requirements

EC2

EC3

EC5
(cold spectrometer satellite in L2 actively cooled (4K) telescope)
SZE in Space: a future outline

MILLIMETRON ~2020
12m dish
Active cooling (4 K)
\( \Theta < 0.1-1.0 \) arcmin
Noise < 0.1 mJy/\( \sqrt{\text{Hz}} \)
FTS spectroscopy
Polarimetry
Super VLBI

MILLIMETRON 12m

SAGACE 3m
3 m dish
Passive cooling (50 K)
\( \Theta = 0.7-4.2 \) arcmin
Noise = 18 mJy/\( \sqrt{\text{Hz}} \)
FTS spectroscopy

Large-survey mode
Pointed mode

Observatory mode
Small-survey mode
SZE spectroscopy: precision

**COMA in SZE: Current data**

- MILLIMETRON (3m)
  - 10 min. exposure
  - $R=20$

- MILLIMETRON (12m)
  - 10 min. exposure
  - $R=100$

[Colafrancesco 2004-2010]
SZE: resolving cluster atmospheres

X-ray

MS0735

3 m. 12 m.

150 GHz 150 GHz

350 GHz 350 GHz

R = 100

Millimetron

$A_1 \left( \frac{W \cdot m^2}{sr \cdot cm^{-2}} \right)$

center
cavity total
cavity with only
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 $\geq 4$ 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** $\text{SZE} \rightarrow T, \tau, V_p, T_{\text{CMB}}$

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

**T profile uniquely sampled in the outer parts of the cluster**

[Colafrancesco & Marchegiani 2010]
SZE spectro-polarimetry: 6-d

SZE intensity spectrum allow to measure the plasma temperature $kT$

Polarization due to finite optical depth $\tau$ allow to measure the density and velocity distribution of the electron plasma $\rightarrow$ 6-d phase-space

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

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

Measure $\tau$ independently of cluster parameters $(T, V_t)$

Measure $\beta_t$ given $kT$ and $\tau$

BB spectrum

5 keV
8 keV
13 keV
20 keV
Particle acceleration

$E_e \sim$ a few GeV

$E \approx 16.6 GeV \sqrt{\nu_{GHz} B_\mu}$

CREDIT: R.J. van Weeren, Leiden Observatory
SZE: high-E particles (CRs)

Power-law

Maxwellian

Turbulent acceleration

Shock acceleration: relativistic covariant formulation

\[ t_{eq} \geq t_{acc} \]

\[ t_{eq} \ll t_{acc} \]

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

[Wolfe & Melia 2006]

SZE Quasi-Thermal

8.2 keV

SZE Thermal

8.2 keV

13 keV

20 keV
SZE and cluster cavities
Cavities are isolated from the surrounding cluster atmosphere at
- $\nu \sim 220$ GHz
- $\nu > 800$ GHz

$\Delta I \sim \int dl \cdot U_{e,\text{tot}}$: advantage w.r.t. X-rays
SZE and radio-galaxy lobes
SZE: radio-galaxy lobes

X-rays

3C294

IC emission from lobes
SZE

AGN central source

3C432

IC emission from lobes
SZE

AGN central source

Total leptonic spectrum of RG lobes

B-field structure in RG lobes

\[ \frac{F_{\text{radio}}}{F_{\text{ICS}}} = \frac{P_{\text{tot}}; E_{\text{min}}}{U_B} \]

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

Planck

OLIMPO

HERSCHEL

---

**WMAP**

Planck

OLIMPO

HERSCHEL

---

**Expectation**

Planck

OLIMPO

HERSCHEL

---

**Multi-ν constraints**

[Multi-ν constraints plot]

[Planck, OLIMPO, HERSCHEL plots]

[S.C., Marchegiani, DeBernardis, Masi 2011]
SZE: RG lobe energetics revisited

\[ U_e = \int_{p_1}^{\infty} dpN(p)(\sqrt{1 + p^2} - 1)m_e c^2 \]

**X-ray** rough misleading measure of \( U_e \)

**SZE** reliable unbiased measure of \( U_e \)

**SKA, MeerKAT, E-VLA**

\( \Delta \nu = 0.1 - 45 \text{ GHz} \)

Separate Synchrotron & SZE
SZE: galaxy winds and SF

Combine MILLIMETRON and SKA to study the wind composition & energetic

Thermal wind

Non-thermal wind

[Colafrancesco et al 2012]

[Colafrancesco et al 2012]
## Cosmological relevance

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<tr>
<td><strong>Hubble constant</strong></td>
<td><strong>$T_{CMB}(z)$</strong></td>
<td><strong>SUSY DM</strong></td>
<td><strong>Baryon fraction</strong></td>
</tr>
<tr>
<td>[Graph showing $D_L$ vs $z$ (redshift)]</td>
<td>[Image of 3C432 with Excluded by SZE in Coma]</td>
<td>[Excluded by WMAP]</td>
<td>[Graph showing $\Omega_\text{DM}/\Omega_\text{DE}$ vs $M_{500,\text{c}}$ (M$_\odot$)]</td>
</tr>
<tr>
<td><strong>Dark Energy - ModG</strong></td>
<td></td>
<td></td>
<td><strong>CR history</strong></td>
</tr>
<tr>
<td>[Graph showing $\Omega_\text{DM}$ and $\Omega_\text{DE}$ vs redshift]</td>
<td></td>
<td></td>
<td>[Graph showing CR history over time]</td>
</tr>
<tr>
<td><strong>Cosmological Principle</strong></td>
<td></td>
<td></td>
<td><strong>B-field</strong></td>
</tr>
<tr>
<td>[Diagram showing Earth's location in the cosmic microwave background frame]</td>
<td></td>
<td></td>
<td>[Graph showing $\mathcal{M}(\mathcal{M}<em>{\odot})$ vs $\mathcal{M}$ (M$</em>{\odot}$)]</td>
</tr>
</tbody>
</table>

\[
\frac{\Delta T}{F_{IC}} \propto (kT_{CMB})^{-3} \times \gamma_{\text{min}}^{-(\alpha-1)} \cdot E_X^{-(\alpha-1)/2} \]

---

Excluded by SZE in Coma
Excluded by WMAP
Excluded by BBN
SZE: clusters cosmology

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

\[ N(M) = \frac{\rho}{M} f(v) \frac{dv}{dM} \]

DE models

[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

\[ P_p \propto D_M^2(t) \cdot k^n \]

\[ P(k, t) = P_p(k, t) + P_M(k, t) \]

Primordial-B density fluctuations

\[ P_M \propto D_M^2(t) \cdot I_k^2 \]

[Tashiro et al. 2010; S.C. et al. 2011]
SZE and Dark Matter nature

ICS on CMB
$S\bar{Z}_{DM}$ from 1ES0657-556
SZE and Dark Matter

SZE

DM

Neutralino mass ($\nu = 223$ GHz)

Frequency ($M_\chi = 20$ GeV)
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]

Last scattering surface
CMB Intensity & Polarization

Large (non-perturbative) th. or kin. SZE

non-FLRW universe

Large (non-perturbative) SZE polarization

non-FLRW universe

Nearby cluster
THANKS

for your attention