Constraining the gas mass fraction of galaxy clusters from the Sunyaev-Zel’dovich power spectrum

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PhD Project

Study the intra-cluster gas of galaxy clusters.

Two parts:

• Development of source detection algorithms for eROSITA.
  • Launch in 2014.

• Study the gas mass fraction of galaxy clusters from the thermal Sunyaev-Zel’dovich power spectrum.
Galaxy Clusters

• Galaxy clusters are the most massive, gravitational bound entities of the Universe.

• Components:
  • Dark matter (~ 80%)
  • Hot intra-cluster gas (~ 16%)
  • Galaxies (~ 4%)

• How to study galaxy clusters?
  • Optical
  • Lensing
  • X-ray
  • Sunyaev-Zel’dovich effect
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  - Optical
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  - X-ray
  - Sunyaev-Zel’dovich effect
CMB photons are inverse Compton scattered by free electrons in the intra-cluster gas.
Thermal Sunyaev-Zel’’dovich (tSZ) effect

\[ \Delta T_{SZ} \propto f_\nu(x) \sigma_T \int n_e T_e ds \]

Electron temperature

Electron density

Hot gas

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CMB power spectrum

Angular scale

Temperature fluctuations from average

$T - T_{\text{average}}$ ~ 30 $\mu$K - 70 K

$D_{l}$ ($\mu$K$^2$)

$\mu$K$^2$

150 GHz

Multipole $= \ell$

Shirokoff et al. 2011
CMB power spectrum

South Pole Telescope

Angular scale

Temperature fluctuations from average

150 GHz

Multipole = $l$

Shirokoff et al. 2011
At $l > 2500$ the microwave sky is composed of:

1. Lensed CMB,
2. Infrared galaxies: a. Clustered, b. Poisson,
3. Radio galaxies,
4. Thermal SZ signal.
At $l > 2500$ the microwave sky is composed of:

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Secondary anisotropies

Reichardt et al. 2012
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Reichardt et al. 2012
SPT measurements: microwave sky

- Multifrequency observations of the microwave sky:
  - Different contribution at different frequencies.
  - Yields important constraints on the components.

![Graph showing multifrequency observations of the microwave sky](image-url)
SPT measurements: microwave sky

- Multifrequency observations of the microwave sky:
  - Different contribution at different frequencies.
  - Yields important constraints on the components.

- Current tSZ constraints are significant lower than predicted.
Predicting the tSZ Power Spectrum

The distribution of temperature fluctuations on the sky induced by a population of clusters:

\[ D_l \propto f_\nu^2(x) \int_0^{z_{\text{max}}} dz \frac{dV}{dz} \int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dn(M, z)}{dM} |\tilde{y}_l(M, z)|^2 \]
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Compton \( y \)-parameter

\[ y = \frac{\sigma_T}{m_e c^2} \int_{-\infty}^{\infty} P_e ds \]
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Halo mass function

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- Co-moving volume
- Halo mass function
- Compton y-parameter

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The distribution of temperature fluctuations on the sky induced by a population of clusters:

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- **Spectral function**
- **Co-moving volume**
- **Halo mass function**
- **Compton \( y \)-parameter**

\[ y = \frac{\sigma_T}{m_e c^2} \int_{-\infty}^{\infty} P_{ed} ds \]
Self-similar model

- Physics of the ICM: only **gravity determines** the properties of the hot diffuse gas.

- Gravity has no preferred scale: 
  → **Galaxy clusters of different size/mass are scaled version of each other.**

- Use the relation between observables to study galaxy clusters: **scaling relations.**
Observed Pressure profile

Arnaud et al. (2010): electron pressure profile,

- 33 local clusters: $z < 0.2$
- High mass clusters: $7 \times 10^{13} \lesssim M_{500}/h^{-1} M_\odot \lesssim 6 \times 10^{14}$

$$P_e(r) = 3.4 \, h^2 \text{eV cm}^{-3} \, E^8(z) \left( \frac{M_{500}}{(2 \times 10^{14}/h) M_\odot} \right)^{\frac{2}{3} + 0.12} p(r/r_{500}),$$

Arnaud et al. 2010
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Sun et al. (2012) agreement with galaxy groups.
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P_e(r) = 3.4 \ h^2 \text{eV cm}^{-3} \ E^{8/3}(z) \left[ \frac{M_{500}}{(2 \times 10^{14}/h) \ M_\odot} \right]^{2/3+0.12} p(r/r_{500}),
\]

→ Excellent agreement out to \( r_{500} \)
→ Simulations to extrapolate at larger radii.
At $l > 2500$ the microwave sky is composed of:

1. Lensed CMB
2. Thermal SZ signal
3. Infrared galaxies:
   a. Clustered
   b. Poisson
4. Radio galaxies
tSZ power spectrum given by empirical pressure profile **significantly exceeds** the SPT constraints.
tSZ power spectrum given by empirical pressure profile significantly exceeds the SPT constraints.

Possible explanation:
- Assumption of self-similar evolution.
Modifying the electron pressure profile

Redshift evolution:

\[ P_e(r) \propto E^{8/3 - \epsilon(z)} M_{500}^{2/3 + 0.12} \]

Unmodified pressure profile at low redshift.

Lower pressure profile amplitude at high redshift.
Modifying the electron pressure profile

Redshift evolution:

\[ P_e(r) \propto E^{\frac{8}{3} - \varepsilon(z)} M_{500}^{\frac{2}{3} + 0.12} \]

\[ \varepsilon = 0.90 \pm 0.24 \]

Unmodified pressure profile at low redshift.

Lower pressure profile amplitude at high redshift.
Modifying the electron pressure profile

Lower the tSZ power spectrum and reach the SPT constraints.

No observational counterpart for cross-checking our results.
Non-self similar evolution from $f_{\text{gas}}$

- Pressure profile:
  \[ P \propto f_{\text{gas}} M^{\frac{2}{3}} E^{\frac{8}{3}}(z) \]
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- Empirical pressure profile:
  \[ P \propto M^{\frac{2}{3}+0.12} E^{\frac{8}{3}}(z) \]

→ Non-self similar evolution due **gas mass fraction**:

\[ f_{\text{gas}} \propto M^{0.12} \]
Non-self similar evolution from $f_{\text{gas}}$

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  → Non-self similar evolution due **gas mass fraction**:

  $$f_{\text{gas}} \propto M^{0.12}$$

→ Observations show that $f_{\text{gas}}$ has a mass dependence.

→ Non-gravitational processes
  
  - AGN feedback.
  - Star formation.
Non-self similar evolution from $f_{\text{gas}}$

- **Pressure profile:**
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- **Empirical pressure profile:**
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  \( \rightarrow \) Non-self similar evolution due **gas mass fraction**:
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- **Our model:**
  \[ P \propto M^{\frac{2}{3} + 0.12} E^{\frac{8}{3} - (0.90 \pm 0.24)} (z) \]
  \( \rightarrow \) Gas mass fraction relation:
  \[ f_{\text{gas}} \propto M^{0.12} E^{-(0.90 \pm 0.24)} (z) \]
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Luminosity-Temperature (L-T) relation:
\[ L_{\text{bol}} \propto f_{\text{gas}}^{2} T^{2} E(z) \]

Reichert et al. 2011
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- Luminosity-Temperature (L-T) relation:
  \[ L_{\text{bol}} \propto f_{\text{gas}}^2 T^2 E (z) \]

Hilton et al. (2012)

\[ L_{\text{bol}} \propto T^{3.18} E^{-1.2 \pm 0.5} (z) \]
Non-self similar evolution from \( f_{\text{gas}} \)

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Hilton et al. (2012)

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Combining results:

\[
L_{\text{bol}} \propto T^{2.36} E^{-1.04\pm0.48} (z)
\]
Summary and Perspectives

- To match current observational constraint we must modify the self-similar evolution in the electron pressure.

- Try a different parametrization of the redshift evolution.

- Study the outer slope of the electron pressure profile and its effects on the tSZ power spectrum.

- Forecast tSZ power spectrum constraints for future experiments: CCAT.
Summary and Perspectives

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• Try a different parametrization of the redshift evolution.

• Study the outer slope of the electron pressure profile and its effects on the tSZ power spectrum.

• Forecast tSZ power spectrum constraints for future experiments: CCAT.

Thank you for your attention.
Perspective

• Develop tools to study galaxy clusters:
  • X-rays:
    • With XXL survey as test bed for eROSITA.
  • tSZ power spectrum:
    • Have the tools to study future results
CMB power spectrum

Temperature fluctuations from average

Angular scale

$\sim 18^\circ \rightarrow \sim 3' \rightarrow \sim 2'$

Multipole

$\sim 10' \rightarrow \sim 3' \rightarrow \sim 18^\circ \rightarrow \sim 2'$

$D_{l}$ ($\mu$K$^2$)

150 GHz

$\sim 70 \mu$K

$\sim 30 \mu$K

WMAP 7-year
ACBAR
QUaD
ACT
SPT

Shirokoff et al. 2011
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