Impact of Cluster Physics on the Sunyaev-Zel’dovich power spectrum

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astro-ph/1006.1945: Laurie Shaw, DN, Suman Battacharya, Erwin Lau
Cosmology with Galaxy Clusters

Local ($z<0.1$) sample of 49 clusters + 37 high-$z$ clusters from the 400d X-ray selected cluster sample (http://hea-www.harvard.edu/400d/)

$\sigma_8 = 0.813(\Omega_M/0.25)^{-0.47} \pm 0.013$

$w_0 = -0.99 \pm 0.045$

$\Omega_{DE} = 0.740 \pm 0.012$

Vikhlinin et al. 2009

Mass within radius enclosing overdensity of 500 times the critical density $\rho_{\text{crit}}(z)$ derived using the low-scatter mass proxy, $Y_x$ (Kravtsov et al. 2006)

Contribution of dark energy to the energy-density of the universe in units of the critical density

H. Bohringer’s review talk
Cosmology with Sunyaev-Zel’dovich Effect

Ongoing SZE cluster surveys will produce large statistical samples, including AMI, AMiBA, APEX, SZA to ACT, Planck, and SPT

Galaxy Clusters discovered with the SPT
Staniszewski et al. 2008

W. Holzapfel and N. Segal’s talks

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Statistical detection of SZE by searching for anisotropy power at small angular scales

$$D_l = l (l+1) \frac{C_l}{2 \pi}$$
Measurements of SZ power spectrum

Amplitude of SZ power spectrum has very sensitive dependence on matter power spectrum normalization, $\sigma_8$
Tension in $\sigma_8$ measurements

Cluster Abundance

$\sigma_8 = 0.80 \pm 0.02$

Lueker et al. (2009)

SZ power spectrum

$\sigma_8 = 0.746 \pm 0.017$

In tension at 3$\sigma$ level!

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Tension in $\sigma_8$ measurements

Cluster Abundance

$\sigma_8 = 0.80 \pm 0.02$

Rozo et al. (2009)

SZ power spectrum

$Lueker et al. (2009)$

$\sigma_8 = 0.746 \pm 0.017$

I argue that the current SZ template is overpredicting the amplitude by 50-100%.

**Missing Key Physics:** Gas Motions in Outskirts of Groups and Clusters
Gastrophysical Uncertainty

- Thermal SZ power spectrum contains significant contribution from outskirts of low mass (M<3x10^{14} Msun), high-z (z>1) groups at ℓ~3000

- However, high-redshift groups are poorly studied observationally.

- Impact of star-formation, AGN, SNe, difficult to evaluate.

- Additional effects not incorporated in semi-analytic models (e.g. bulk and turbulent motions)

Better understanding of cluster physics is absolutely critical in era of precision cluster cosmology!
SZ power spectrum

Calculate SZ power spectrum by integrating the mass function over M and z, weighted by cluster signal at a given angular scale.

\[ C_l = g_\nu^2 \int_0^{z_{\text{max}}} dz \frac{dV}{dz} \int_0^{M_{\text{max}}} dM \frac{dn(M, z)}{dM} |y_l(M, z)|^2 \]

volume integral

cluster mass function
(e.g. Tinker et al 08)

electron pressure profiles

Major uncertainty lies in ICM cluster physics.
Electron pressure profiles are quantities of interest!
Predicting the Power Spectrum

• Analytic calculations

  • take ‘universal’ mass function (e.g. Tinker et al. 08)
  • assume some gas pressure profile (e.g. Komatsu and Seljak 02)
  • lack detailed cluster physics, but imperative for cosmological parameter estimation (need to vary cluster physics + cosmology)

\[ C_l = g^2_n \int_0^{z_{max}} \frac{dz}{dz} \int_0^{M_{max}} dM \frac{dn(M, z)}{dM} |y_l(M, z)|^2 \]

• Numerical simulations

  • don’t need to ‘assume profiles’
  • follow detailed hydrodynamical evolution of gas in clusters (+ star-formation, AGN, bulk+turbulent gas motions...)
  • need both large big simulation boxes and high-resolution to resolve relevant sub-grid cluster physics. **Prohibitively expensive!!**
Requirements for modeling the SZ power spectrum

• Model must be able to reproduce existing observations (largely low-z, massive clusters)
  • Scaling relations (e.g., $f_{\text{gas}}$-$M$, $T_x$-$M$, $Y_x$-$M$ etc.)
  • radial electron pressure profiles (e.g., Arnaud et al. 2009)
• Extend model to higher redshifts
• Vary input physics and evaluate effect on power spectrum and explore degeneracy with cosmological parameters
Toward more realistic cluster gas model

• Dark Matter Halos - NFW density profiles

\[ c(M, z) = 7.85A_C \left( \frac{M_{\text{vir}}}{2 \times 10^{12} h^{-1} M_\odot} \right)^{-0.081} (1+z)^{-0.71} \]

• Gas resides in hydrostatic equilibrium in dark matter halos

\[ \frac{dP_{\text{tot}}(r)}{dr} = -\rho_g(r) \frac{d\Phi(r)}{dr} \]

• Polytropic equation of state for the ICM: \( P_{\text{tot}} = P_0 \left( \frac{\rho_{\text{gas}}}{\rho_0} \right)^\Gamma \) with \( \Gamma = 1.2 \) and \( P_{\text{tot}}(r) = P_{\text{therm}}(r) + P_{\text{nt}}(r) \)

• Assume that some fraction of the gas has radiatively cooled and formed stars. Adopt the stellar mass fraction by Gonzalez et al. 2007 (see A. Gonzalez’s talk).

\[ c.f., \text{Ostriker et al. 2005; Bode & Ostriker et al. 2007} \]
Cluster Astrophysics

\[ E_{g,f} = E_{g,i} + \varepsilon_{\text{DM}} |E_{DM}| + \varepsilon_f M_* c^2 + \Delta E_p \]

- Energy feedback from Supernovae/AGN: \( \varepsilon_f \sim 10^{-6}-10^{-5} \)
- Dynamical heating by mergers: \( \varepsilon_{\text{DM}} \sim 0.05 \)
- Non-thermal pressure due to gas motions in galaxy clusters

Gas motions (bulk+turbulent) are ubiquitous in \( \Lambda \)CDM clusters
Cluster Astrophysics

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- Energy feedback from Supernovae/AGN: \( \varepsilon_f \sim 10^{-6} - 10^{-5} \)
- Dynamical heating by mergers: \( \varepsilon_{\text{DM}} \sim 0.05 \)
- Non-thermal pressure support: \( \alpha_0, \beta, n_{nt} \)

\[ \frac{P_{nt}}{P_{tot}} (z) = \alpha(z) \left( \frac{r}{R_{500}} \right)^{n_{nt}} \]

where \( \alpha(z) = \alpha_0 (1+z)^\beta \)

Calibrate with hydro simulations:
- \( \alpha_0 = 0.18, \beta = 0.5, n_{nt} = 0.8 \)
- Enhanced at high-z
- Enhanced toward outskirts

18% at \( R_{500} \) at \( z=0 \)

Graph: AMR simulations of 16 groups and clusters by Lau, Kravtsov, Nagai 2009

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fiducial</th>
<th>Min.</th>
<th>Max.</th>
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<td>energy feedback ($\varepsilon_f$)</td>
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<td>dynamical heating ($\varepsilon_{DM}$)</td>
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<tr>
<td>non-thermal z-evolution ($\beta$)</td>
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<td>1</td>
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<td>$c_{DM}-M$ relation ($A_C$)</td>
<td>1.0</td>
<td>0.8</td>
<td>1.2</td>
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</tbody>
</table>

Duffy et al. 2008
Matching to $f_{\text{gas}}$-$M$ observations

$$f_{\text{gas}} \equiv M_{\text{gas}}/M_{\text{tot}}$$

No feedback model with $\varepsilon_f = \varepsilon_{\text{DM}} = 0$

Miximal feedback model with $\varepsilon_f = 10^{-5}$ and $\varepsilon_{\text{DM}} = 0.1$

$\varepsilon_f = 10^{-7}, 10^{-6}, 5 \times 10^{-6}, 10^{-5}$
Impact of Energy Feedback on Pressure Profiles

Energy feedback does NOT significantly modify the electron pressure profiles of massive clusters.

Universal electron pressure profile (Arnaud et al. 2009)

\[ \frac{P_e}{P_{500}} \left(\frac{r}{R_{500}}\right)^3 \]

\[ \varepsilon_f = 10^{-7}, 10^{-6}, 5 \times 10^{-6}, 10^{-5} \]

Black: \( M = 3 \times 10^{14} \ h^{-1} \text{ Msun} \)

20% scatter
Impact of Energy Feedback on Pressure Profiles

\( \varepsilon_f = 10^{-7}, 10^{-6}, 5 \times 10^{-6}, 10^{-5} \)

Black: \( M = 3 \times 10^{14} \; h^{-1} \; \text{Msun} \)
Red: \( M = 3 \times 10^{13} \; h^{-1} \; \text{Msun} \)

But, significant impact on groups!
Impact of Gas Motions on Pressure Profiles

Non-thermal pressure due to gas motions suppress electron pressure in outskirts of both groups and clusters.
Redshift Evolution of Pressure Profile

At high-z, electron pressure is lower primarily due to enhanced non-thermal pressure.
Impact of Cluster Physics on the SZ Power Spectrum

$D_{\ell} [\mu K^2]$ vs $\ell$

- **No feedback model**
- **Miximal feedback model**

$\varepsilon_f: 10^{-7} \Rightarrow 10^{-6} \Rightarrow 10^{-5}$

Non-thermal pressure
$0 \Rightarrow 0.18 \Rightarrow 0.3$

$z$-evolution
$-1 \Rightarrow 0.5 \Rightarrow 1$

Red: Fiducial model

$0.8 \Rightarrow 1.0 \Rightarrow 1.2$

Enhanced gas motions toward high-$z$
Our fiducial model

KS02 model predicts larger power by roughly a factor of 2 at all scales, compared to our model. The differences are due to lack of star formation, feedback, and non-thermal pressure in the KS model.
Comparison to the universal pressure profile model by Arnaud et al. (2009)

The predicted power spectra match at large scales, but our model is below that of the A09 profile at small scales due to enhanced non-thermal pressure at high-z.

Calibrated based on X-ray observations of massive, low-z clusters. Assumes self-similar evolution.
Comparison to non-radiative hydrodynamical simulations

The overall amplitude is in reasonable agreement, but our model predicts less power at small scales ($l > 4000$) compared to the simulation.
Comparison to Sehgal et al. SZ template

Non-thermal pressure causes reduction of power by 50-60% at all scales.
A model with $\varepsilon_f = 5 \times 10^{-6} + \text{non-thermal pressure}$ predicts the lower SZ power by a factor of 2 (100%) at $l \sim 3000-5000$, compared to the Seghal et al. template. This physically plausible model can completely remove the tension in $\sigma_8$ measurements from cluster abundance and SZ power spectrum.
Future Prospects

✦ Measurements of the shape of the power spectrum can reveal useful information on important physical processes in groups and clusters, especially at high-redshift where there exists little observational data.

✦ Many exciting activities in cluster cosmology and astrophysics are underway!!

– Next generation of experiments:
  • X-ray (e.g., eROSITA, Astro-H)
  • SZE (e.g., ACT, SPT, Planck)
  • Optical/IR (e.g., DES, LSST)

– More sophisticated computational modeling of galaxy clusters with AGN feedback and plasma physics are underway (see S. Borgani and D. Rudd’s talks)