Constraining fundamental physics and halo energetics using Sunyaev-Zel'dovich measurements

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MacNamara et al. 2009
Collaborators

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Baryons
Baryons

van Daalen et al 2011
- Pushing into the non-linear regime leads to increasing the uncertainties from baryons and potential biases in the inference of cosmological parameters.

- Or provides unique constraints on the main baryonic processes that govern the growth of structure on these scales (galaxy formation).
Lensing is Low: Cosmology, Galaxy Formation, or New Physics?

Alexie Leauthaud\textsuperscript{1,2}, Shun Saito\textsuperscript{3}, Stefan Hilbert\textsuperscript{4,5}, Alexandre Barreira\textsuperscript{3}, Surhud More\textsuperscript{2}, Martin White\textsuperscript{6}, Shadab Alam\textsuperscript{7,8}, Peter Behroozi\textsuperscript{6,9}, Kevin Bundy\textsuperscript{1,2}, Jean Coupon\textsuperscript{10},
Cosmological Simulations

The Eagle Simulations

Evolution and Assembly of Galaxies and their Environments

Illustris Collaboration

Ellipticals

Disk Galaxies

Irregular
Are the sub-grid physics models realistic?

What is the work being done on these systems?

Predictions for the energetics of (massive) halos

Impact on cosmological information?
CMB scattering sources (secondaries):SZ effect
Kinetic Sunyaev-Zel’dovich Effect
Doppler boosting of CMB photons

LOS Momentum

Credit: L. Van Speybroeck

Carlstrom et al 2002
Gallery of recent kSZ results

- Hand et al. 2012
- Planck 2016
- Schaan et al. 2015
- Soergel et al. 2016
- De Bernardis et al. 2016
What is measured?

\[ \left( \frac{\Delta T}{T} \right)_{kSZ} (x + \theta) = -\tau(\theta) \nu_r(x) \]

- Optical depth (profile)
- 'Bulk' radial velocity
- Vary \( r \) at fixed \( \theta \) \( \rightarrow \) velocity field on large scales
- Vary \( \theta \) at fixed \( x \) \( \rightarrow \) gas profile and abundance.

TWO different measurements!
We also have measurements of the pressure!
Gallery of recent tSZ results

- **Greco et al. 2015**
- **Planck Coll. Intermediate V 2013**
- **Battaglia, Hill, & Murray 2015**
- **Hojjati et al. 2015**
Combining tSZ & kSZ measurements

Previously, Knox+2004 Sehgal+2005 proposed to constrain $T$, $\tau$ & $v_{pec}$

Constraint dominant physical processes in galaxy formation
Ostriker, Bode & Babul 2005
Model for the ICM with a couple parameters
\( \gamma \) - polytropic index
\( \alpha \) - normalization of \( P_{NT} \)
\( \epsilon_{inj} \) - Eff. of energy injected

Assumptions
\[ P = K \rho^\gamma \]

Spherical Symmetry
Hydrostatic Equilibrium (\( P_{\text{tot}} \))

Conditions
\[ E_f = E_i + E_{inj} + \Delta E_P \]
\[ P_{\text{tot}} (R_f) = P_s (R_{\text{vir}}) \]

Conservation of mass

Solve for \( P_{\text{th}}(r) \) and \( \rho(r) \)
Spherical Symmetry & Polytropic Index

How do these assumptions look in simulations?

After stacking ✔

\( \gamma \) fairly constant \( \sim 2 \, R_{200} \) ✔

Battaglia et al. 2012a

Battaglia et al. 2012b
Given \( P_{\text{th}}(r) \) and \( \rho(r) \) from these measurements, can we constrain \( \gamma, \alpha \), and \( \epsilon_{\text{inj}} \)?
The improvement seen here is coming from:
Higher resolution, lower noise, and a larger sample
Combining tSZ & kSZ measurements forecast

Battaglia et al. 2017
Combining tSZ & kSZ measurements forecast

Battaglia et al. 2017
Combining tSZ & kSZ measurements forecast

DESI LRGS extremely high fidelity measurements
Can further sub-sample into other galaxy properties
Combining tSZ & kSZ measurements forecast

Can ask the same questions with Quasars
Beware of fisher forecasts

What are some of the systematics?

galaxy - gas offset

2-halo term

What is the distribution of masses in the sample?

Markevitch et al 2006

Hill et al 2017
Cosmological Implications

LSST $L_{\text{max}} = 5000$ at $z = 0.3, 0.5, 1.0$

“cumulative density profile”

NFW (dark matter only)

GAS

BOSS CMASS galaxies + ACTPol CMB data
$z \sim 0.6, M \sim 2 \times 10^{13} M_{\odot}$

Schaan, Ferraro, ++ (ACTPol) 2015
Cosmological impact of feedback

Alternatively:
Use small scale information to constrain feedback
Foreman+2016
kSZ with LSST - projected fields approach

Hill, Ferraro, Battaglia et al. 2016
kSZ with LSST - projected fields approach

\[ \text{S/N} \sim 3.8-4.5 \]

- Case A
- Fiducial

\[ \langle \text{planck}^2 \times \text{WISE} \rangle \]

Future experiments

\[ r(\ell) = \frac{C_{\ell}^{\text{kSZ}}}{(C_{\ell}^{\text{kSZ}} + C_{\ell}^{TT})^{1/2}} \]

\[ \ell \]

\begin{tabular}{|l|c|c|}
\hline
CMB experiment & beam FWHM & effective noise \[\Delta_T \text{[\mu K-arcmin]}\] \\
\hline
Planck (2015 LGMCA map) & 5 & 47 \\
Advanced ACTPol & 1.4 & 10 \\
CMB-S4 (case 1) & 3 & 3 \\
CMB-S4 (case 2) & 1 & 3 \\
CMB-S4 (case 3) & 3 & 1 \\
CMB-S4 (case 4) & 1 & 1 \\
\hline
\end{tabular}

\begin{itemize}
\item \textbf{LSST} 26 gal/arcmin\(^2\) (preliminary)
\item \textbf{x AdvACT} 326
\item \textbf{x CMB-S4 (case 1)} 402
\item \textbf{x CMB-S4 (case 2)} 1032
\item \textbf{x CMB-S4 (case 3)} 1006
\item \textbf{x CMB-S4 (case 4)} 1230
\end{itemize}

\textbf{BUT CAREFUL with SYSTEMATICS (foregrounds!)}

Hill, Ferraro, Battaglia et al. 2016
Ferraro, Hill, Battaglia et al. 2016

Slide credit S. Ferraro
AdvACT + LSST

Funded, large area, multiple frequency bands
Potential for kSZ cross correlations is large
Further ahead there will be Simons Obs. & CMB S4
The Simons Observatory

http://simonsobservatory.org

• A five year, $45M+ program to pursue key Cosmic Microwave Background science targets, and advance technology and infrastructure in preparation for CMB-S4.

• Merger of the ACT and POLARBEAR/Simons Array teams.

• Tentative plans include:
  • Major site infrastructure
  • Technology development (detectors, optics, cameras)
  • Demonstration of new high throughput telescopes.
  • CMB-S4 class receivers with partially filled focal planes.
  • Data analysis

http://simonsobservatory.org
Baryons

Summary and Outlook

SZ cross-correlations are going to be a new window into thermodynamic process within halos.

High S/N kSZ on coming soon

Learn about the physical processes. Constrain sub-grid energetics models.

Push future cosmological probes into non-linear regime.

Thank You!
Extras
What is measured?

\[
\left( \frac{\Delta T}{T} \right)_{kSZ} (x + \theta) = -\tau(\theta) \, v_r(x) \quad (+\text{2-halo})
\]

- Vary $r$ at fixed $\theta$ → velocity field on large scales
- Vary $\theta$ at fixed $x$ → gas profile and abundance.

Two different measurements!
Velocity field on large-scales

\[ v \approx f_g \left( \frac{aH}{k^2} \right) \delta \]

\[ f_g = \frac{d \ln \delta}{d \ln a} \approx \left[ \Omega_m(z) \right]^\gamma \]

\[ f_g(z, k) \approx \mu(k) \Omega_m^\gamma(z) \]

\[ \gamma = 0.55 + 0.05(1 + w) \]
Pair-wise velocity statistic & measurements

\[ \langle \frac{\Delta T}{T}(x) \nu_r^{\text{rec}}(y) \rangle = -\bar{\tau} \langle \nu_r^{\text{true}}(x) \nu_r^{\text{rec}}(y) \rangle \]

Also see Planck Coll. 2016 & SPT Soergel et al. 2016
Motivation - kSZ cosmology forecasts

Pair-wise velocity estimator

Huge potential to constrain fundamental physical parameters and extensions to the concordance cosmological model
For a halo of a given mass, what is the optical depth?
Uncertainties on $\tau$ will soon be a leading systematic uncertainty in the cosmological parameters obtained from kSZ measurements.

How does one measure $\tau$ since it is not a “direct” observable?
Not surprisingly there is a relation between $\tau - y$
At fixed gas mass temperature fluctuations are small found in simulations but this appears to independent of SG-model at the $< 10\%$ level