How “sub-grid” physics affects the Sunyaev-Zel’dovich effect power spectrum

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Over the past ~10 years X-ray observations and theory have converged on a general physical picture for the hot gas in groups & clusters (ICM). Gravity dominates thermodynamics at large radii, whereas its AGN vs. cooling in the central regions. Both theory and observations suggest AGN did most of their work at high-z. Relative importance of radio vs. QSO modes remains poorly known.
Hot gas in groups and clusters: the X-ray view

But, as with all types of observations, biases will be present. Both in the detection/selection and in the deduced properties of detected systems.

Selection biases may be severe at low masses and high redshift. Are X-ray groups special? What do we really know about the evolution of X-ray groups and clusters?

As for detected systems, how robust are our measurements of thermodynamic properties and system masses?

These biases can potentially change our qualitative picture of groups/clusters.

Can get a handle on these things with:

• Self-consistent cosmological hydro simulations
• Sunyaev-Zeldovich effect (SZE) observations
A spectral distortion in the CMB caused by inverse Compton up-scattering off hot electrons in the ICM.

\[
\frac{\Delta T_{SZE}}{T_{CMB}} = f(x) y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T d\ell,
\]
The “resolved” SZE

Now have catalogs with several hundreds clusters detected through the SZE with the SPT, ACT, SZA, Planck, and others. Many are blind detections (first SZ-selected clusters).
The “unresolved” SZE

Compton y maps from Planck. Can analyse statistical properties of the map. Signal is very sensitive to cosmological parameters that control structure growth rate.
First SZE power spectrum results revealed models had too much power on intermediate scales. Due mainly to inefficient (or absent) feedback.

Simulations/models that invoke AGN feedback (e.g., Shaw et al. 2010, Battaglia et al. 2010) do better.

Simulations of Battaglia (adopting WMAP7 cosmology) were only marginally consistent with SPT/ACT data. Better data shows larger discrepancy.

SPT/ACT constrain power spectrum at $l \sim 3000$
OverWhelmingly Large Simulations

Systematic exploration of the importance of “sub-grid” processes on galaxy formation (Schaye et al. 2010).

AGN feedback model successfully reproduces many of the X-ray and optical properties at $z=0$ (IGM et al. 2010, 2011).

SZ power spectrum?

Optical-X-ray luminosity relation

Hot gas mass fractions

Luminosity-temperature relation

Stott et al. 2012

IGM et al. 2010
New simulations: “cosmo-OWLS”

Method: SPH - Gadget-3 (OWLS version)

Sub-grid physics:
- Metal-dependent radiative cooling (Wiersma et al. 2008)
- Chemodynamics & stellar evolution (Wiersma et al. 2009)
- Star formation (Schaye & Dalla Vecchia 2008)
- Kinetic supernova feedback (Dalla Vecchia & Schaye 2008)
- AGN feedback (Booth & Schaye 2009)

Cosmology: WMAP-7

Box size: 400 h⁻¹ Mpc

Number of particles: 2x10²⁴³

Gravitational softening: 4 h⁻¹ kpc

VARY SUB-GRID PHYSICS
(particularly AGN)

Produce lightcone maps
Black hole (BH) seeds placed at the centre of haloes that exceed some threshold mass. Given some seed mass.

BHs grow by mergers with other BHs and by accretion of neighbouring gas.

Gas accretion rate is the smaller of (scaled) Bondi and Eddington rates:

$$\dot{m}_{\text{accr}} = \alpha \frac{4\pi G^2 m_{\text{BH}}^2 \rho}{(c_s^2 + v^2)^{3/2}}$$

$$\dot{m}_{\text{Edd}} = \frac{4\pi G m_{\text{BH}} m_p}{\epsilon_r \sigma_T \epsilon_c}$$

A certain fraction of rest mass energy of accreted gas is assumed to heat local gas thermally:

$$E_{\text{feed}} = \epsilon_f \epsilon_r \dot{m}_{\text{BH}} c^2 \Delta t$$

To ensure AGN feedback is efficient (not immediately radiated away), BHs store energy until they are able to heat nearby gas to a pre-defined minimum temperature. \(\Delta T_{\text{heat}} \gg T_{\text{vir}}\) for heating to be efficient (avoid significant radiative losses).

See also Sijacki et al. (2007)
Sz power spectrum: feedback dependence

Curves are mean power spectrum constructed from 10 lightcone realizations.

It is possible to hit Planck and SPT/ACT data by adjusting the AGN feedback $\Delta T_{\text{heat}}$.

But are these models reasonable? (Energetically speaking they are, but do they reproduce the observed X-ray universe?)
Hot gas content and resolved SZE:
feedback dependence

AGN feedback models with minimum heating temperature of $10^8 - 10^{8.5}$ K work reasonably well. Important to do mock X-ray observations (HSE bias & clumping). Caveat: mock SZE analysis not (yet) performed here (matched filter etc.)
At presently accessible scales, power spectrum probes pretty massive haloes ($\log M_{500} > \sim 14.5$) at relatively large radii ($\sim r_{500}$).
Low to intermediate redshifts (0 < z < 1, roughly)

Decent overlap with X-ray samples in mass and redshift. Radial range slightly different.
Just one problem: Planck CMB cosmology
Just one problem: Planck CMB cosmology

Using scalings of Millea et al. 2012 to scale power spectrum amplitude as a function of cosmological parameters.

For Planck maximum-likelihood cosmology.
Sample Planck MCMC to assess impact of uncertainties on cosmological parameters.

Non-negligible.

Best model consistent with Planck PS data at ~2 sigma level. But trouble remains at intermediate scales....
When Planck consortium analyses WMAP9 data

Something is fundamentally different between Planck and WMAP9 data.

(Inferred cosmology consistent with number counts results)
Conclusions and possibilities

It is difficult to construct a model that can simultaneously match low-redshift X-ray properties and SZ power spectrum (particularly SPT/ACT data) assuming a Planck cosmology.

Possible resolutions:

i) Planck primary CMB cosmology is “wrong”. WMAP9 works better (not totally out of the question, as Planck cluster number counts are much lower than expected).

ii) Low-z X-ray samples are highly biased (i.e., missing systems with low $f_{\text{gas}}$). Quite likely for groups. But power spectrum is dominated by massive guys.

iii) Models are not correctly capturing outskirts of clusters, where X-ray observations do not typically probe but which is important for the SZ PS. Different hydro solvers agree here but maybe there is missing physics (e.g. maybe kinetic theory should really apply here).
p.s. Just to confuse the matter more

Stacked SZ signal indicates close to self-similar scaling!!

Seems inconsistent with the need for huge feedback to match SZ power spectrum and X-ray properties of groups. What biases are present?