On the Cluster Physics of Sunyaev-Zel’dovich and X-ray Surveys

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Clustering cosmology
Describing cluster outskirts
Understanding the clumping physics

Introduction
Cosmology toolbox
Modeling the ICM physics

Clusters in the era of “precision cosmology”

why bothering about clusters?

- **complementarity** of cosmological parameter estimates
- sensitive to growth of structure \((\Omega_m, \sigma_8)\)
- **extreme objects** can probe early Universe physics, e.g., primordial non-Gaussianity

→ clusters are assembling today:
“every cluster is a bullet cluster – or a miniature version of it!”

1E 0657-56: “Bullet cluster”
Clusters in the era of “precision cosmology”

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→ clusters are assembling today:

“every cluster is a bullet cluster – or a miniature version of it!”

→ need to go beyond the spherical-cow approximation; necessarily with a heavy computational component!
Cluster cosmology toolbox
Number counts and Sunyaev-Zel’dovich (SZ) power spectrum

- Cluster number counts depend on scaling relations:

\[
N = \int_0^{z_{\text{max}}} dz \frac{dV}{dz} \int_{M_{\text{min}}(z)}^{\infty} dM \frac{dn(z, M)}{dM(Y, T, L_X)}
\]

→ depends on space-time geometry, growth of structure, and cluster physics (selection function, scaling relation)

- SZ power spectrum does not require mass information:

\[
C_\ell = g^2_\nu \int_0^{z_{\text{max}}} dz \frac{dV}{dz} \int_0^{\infty} dM \frac{dn(z, M)}{dM} |\tilde{y}_\ell(M, z)|^2
\]

→ depends on cluster form factor \( \tilde{y}_\ell(M, z) \), i.e. Fourier transform of the thermal pressure profile

→ amplitude of the SZ power spectrum \( C_\ell \propto A_{\text{SZ}} \propto \sigma_8^{7\ldots9} \)
processes that need to be included:

- cosmological cluster growth: asphericity and substructure
- radiative cooling and star formation
- energy feedback (AGN, SN)
- non-thermal pressure support \( P_{\text{kin}}, P_{\text{CR}}, P_{B} \ldots \)
- plasma processes
- etc \ldots
Modeling the ICM

processes that need to be included:

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- etc \ldots

→ how does the physics impact upon various ICM observables?
→ run large simulations: good compromise between large volumes (SZ power spectrum) and sufficient resolution for ICM modeling
$P_{\text{kin}}/P_{\text{th}}$ increases with mass and redshift due to hierarchical formation history
Kinetic pressure support

\[ \frac{P_{\text{kin}}}{P_{\text{th}}} \text{ almost insensitive to } z \text{ when scaled to } R_{200,\text{mean}}! \]
Outskirts of galaxy clusters

$P_{\text{kin}} / P_{\text{th}}$ increases with radius: dissipating formation shocks

AGN feedback, $z=0$

- $1.0 \times 10^{14} \, M_\odot < M_{200} < 3.1 \times 10^{14} \, M_\odot$

- $3.1 \times 10^{14} \, M_\odot < M_{200} < 1.0 \times 10^{15} \, M_\odot$

$P_{\text{kin}} / P_{\text{th}}$

$R_{500}$

$R_{\text{vir}}$

BBPS 2015
Outskirts of galaxy clusters

Rotate-stacked gas ellipticities

compute gas moment-of-inertia tensor, rotate and stack

BBPS 2015
Outskirts of galaxy clusters
Rotate-stacked DM ellipticities

compute DM moment-of-inertia tensor, rotate and stack

BBPS 2015
Outskirts of galaxy clusters
Density clumping ($T > 10^6$ K) biases $f_{\text{gas}}$ measurements

Density/pressure clumping:

$$C_\rho = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$$

$$C_P = \frac{\langle P^2 \rangle}{\langle P \rangle^2}$$
Outskirts of galaxy clusters
Pressure clumping adds small-scale power to tSZ power spectrum

Density/pressure clumping:

\[ C_\rho = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \]

\[ C_P = \frac{\langle P^2 \rangle}{\langle P \rangle^2} \]
Pressure inhomogeneities, $z \approx 0$

Compton-$y$ of simulated cluster

$z = 0.05, M_{200} = 1.4 \times 10^{15} M_\odot$

spherical fit to simulations
Pressure inhomogeneities, $z \approx 0$

Compton-$y$ of simulated cluster

$z = 0.05, M_{200} = 1.4 \times 10^{15} M_\odot$

$\delta y \rightarrow$ projected pressure clumps
Pressure inhomogeneities, $z \simeq 0.5$

Compton-$\gamma$ of simulated cluster

$z = 0.48, M_{200} = 2.2 \times 10^{14} M_{\odot}$
Pressure inhomogeneities, $z \simeq 0.5$

Compton-$y$ of simulated cluster

$z = 0.48, M_{200} = 2.2 \times 10^{14} \, M_\odot$

$\delta y \rightarrow$ projected pressure clumps
tSZ power spectrum with pressure inhomogeneities

Sub-structure contribution!

Implications for tSZ power spectrum:
- high-mass halos: 25% at $\ell \sim 3000$
- all masses: 15% at $\ell \sim 3000$

→ pressure clumping crucial for analytical tSZ power spectrum calculations!
Understanding the outskirts of galaxy clusters

Simionescu+2011, Science
Understanding the outskirts of galaxy clusters

- density clumping needed by data $C \sim 10 – 20$?
- density clumping in simulations $C \sim 1.1 – 1.3$
- other important effects: large non-thermal pressure, pressure clumping, anisotropy

Simionescu+2011, Science
Biases of X-ray-inferred gas mass fractions

measurement biases of $f_{\text{gas}}$:

- $M_{\text{HSE}}$ bias:
  20% at $R_{200}$

- density clumping bias:
  10 – 20% at $R_{200}$
  (mass dependent)
measurement biases of $f_{\text{gas}}$:

- $M_{\text{HSE}}$ bias: 20% at $R_{200}$
- density clumping bias: 10 – 20% at $R_{200}$ (mass dependent)
- cluster-to-cluster variance: 5% for true $f_{\text{gas}}$ but 20% for $f_{\text{gas,HSE+clump}}$
clusters are anisotropic:

- large angular variations of mass profiles: cosmic filaments seed anisotropic substructure distribution
- large offsets of DM and gas → cannot use DM as a gas proxy!
Variance of mass profiles in cluster-centered cones

\[ \sigma_{M_{\text{gas}}}(r): \]

\[ \sigma_{M_{\text{DM+gas+stars}}}(r): \]

\[ \sigma_{f_{\text{gas}}}(r): \]

Clusters are anisotropic:

- Mean of the angular variance of \( f_{\text{gas}} \) across all clusters:
  \[ \sigma_{f_{\text{gas}}} \simeq 30 - 35\% \]

- Collisionless DM more anisotropic than gas (shock physics)
Cluster-centered shells of $\delta P$ and $\delta \rho$ (1)
Cluster-centered shells of $\delta P$ and $\delta \rho$ (2)

BBPS 2015
Cluster-centered shells of $\delta T$ and $\delta j_X$

$M_{200} \approx 1.15 \times 10^{15} M_\odot$

$\delta T_X$

$0.44 < R/R_{200} < 0.55$

$1.33 < R/R_{200} < 1.66$

$3.21 < R/R_{200} < 4.00$

$M_{200} \approx 6.5 \times 10^{14} M_\odot$

$\delta j_X$

$0.44 < R/R_{200} < 0.55$

$1.33 < R/R_{200} < 1.66$

$3.21 < R/R_{200} < 4.00$

BBPS 2015
define filaments as the 4 cones with the largest $M_{\text{gas}}(r < R_{200})$ (dotted) and $M_{\text{gas}}(r < 4R_{200})$ (solid)

filaments only account for $\sim 8.3\%$ of the volume

they contribute $\sim 30\% (R_{200})$ and $\sim 80\% (4R_{200})$ to the total density clumping factor
Understanding clumping: power spectra $C_\ell(\ell)$

- Scaled angular power spectra show apparent evolution of the spectral shape from a bump (at $R_{200}/2$) to an almost flat distribution (at $4R_{200}$).
Power spectra $C_\ell(k_\perp)$ of shells quantify super-clumping

- which part of this evolution is driven by the decrease in angular scale when moving an object of fixed physical scale toward larger radii?

  $\rightarrow$ plot $C_\ell(k_\perp)$, where $k_\perp = (\ell + 1/2)/x$ in the small-angle limit

- super-clumping: density and pressure clumping is dominated by comparably large (sub-)structures with scales $L_\perp \gtrsim \pi R_{\text{200}}/k_\perp \sim R_{\text{200}}/5$
Conclusions

describing cluster outskirts:

- kinetic pressure contribution increasing with radius
- density and pressure clumping increasing with radius:
  biases $f_{\text{gas}}$ and adds power to $C_\ell$ for $\ell \gtrsim 3000$
- large anisotropies within clusters of $M_{\text{gas}}$, $M_{\text{DM}}$, and $f_{\text{gas}}$ due to infalling substructures along filaments

towards an understanding of clumping in cluster outskirts:

- clumping is dominated by gravitationally-driven, large substructures $\rightarrow$ “super-clumping”
- these inhomogeneities are sourced by cosmic filaments that are channeling baryonic and dark matter onto clusters and maintain contact down to radii of order $R_{200}/3$
- such large-scale, radial overdense “super clumps” resemble structures in the deep Chandra observation of Abell 133
Literature for the talk

additional slides
Hydrostatic mass bias

AGN feedback, $z = 0$

- $1.1 \times 10^{14} M_\odot < M_{200} < 1.7 \times 10^{14} M_\odot$
- $1.7 \times 10^{14} M_\odot < M_{200} < 2.7 \times 10^{14} M_\odot$
- $2.7 \times 10^{14} M_\odot < M_{200} < 4.2 \times 10^{14} M_\odot$
- $4.2 \times 10^{14} M_\odot < M_{200} < 6.5 \times 10^{14} M_\odot$
- $6.5 \times 10^{14} M_\odot < M_{200} < 1.01 \times 10^{15} M_\odot$
- $1.01 \times 10^{15} M_\odot < M_{200} < 1.57 \times 10^{15} M_\odot$

$R_{500}$ and $R_{\text{vir}}$
AGN feedback

- sub-resolution approach: \( r_{\text{softening}} \sim 10^8 r_{\text{Schwarzschild}} \)
- tying feedback to virial properties not successful, \( E_{\text{inj}} \propto M_{200} c^2 \)
- self-regulated feedback (Thompson+05)
  \[
  M_{\text{BH}} \propto M_{\text{star}} \\
  E_{\text{inj}} = \varepsilon_r \dot{M}_{\text{star}} c^2 \Delta t 
  \]
- find halos and inject \( E_{\text{inj}} \) within spherical region \( R_{\text{AGN}} \)
- parameters: \( \Delta t, \varepsilon_r, R_{\text{AGN}} \); \( \varepsilon_r \) effective radiative efficiency
- match previous AGN models (Sijacki+2008)
Baryon and stellar mass fraction

\[ f_{\text{star}}(< r) = \frac{M_{\text{star}}(< r)}{M_{\text{tot}}(< r)} \] is reduced by AGN feedback to observed values

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Radiative cooling
AGN feedback
Sijacki et al. 08
Gonzalez et al. 07, \( f_{\text{star}}(< R_{500}) \)
Afshordi et al. 07, \( f_{\text{b}}(< R_{200}) \)
Sijacki et al. 08

Battaglia, Bond, C.P., Sievers, Sijacki (2010) \( \equiv \) BBPSS 2010
Simulations

our simulations: (BBPSS 2010, BBPS 2012a,b,c,d)

- box lengths: $\{200, 400\} h^{-1}$ Mpc, $N = 2 \times \{256^3, 512^3\}$
- halo mass resolution $\sim 10^{13} h^{-1} M_\odot$
- $\sim 800$ clusters with $M_{200} > 10^{14} h^{-1} M_\odot$
- Gadget2+ (SPH) with three different physics models:
  - shock heating (non-radiative)
  - radiative cooling + star formation + SNe + CR
  - additionally ‘AGN’ feedback

→ good compromise between large volumes (SZ power spectrum) and sufficient resolution for ICM modeling (AGN feedback)