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

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in collaboration with

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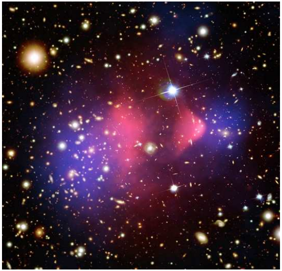
Outline

1. Cluster cosmology
   - Introduction
   - Cosmology toolbox
   - Modeling the ICM physics
2. Describing cluster outskirts
   - Gas motions
   - Gas clumping
   - Cluster anisotropy
3. Understanding the clumping physics
   - Inhomogeneities in shells
   - Clumping power spectra
   - Conclusions

Clusters in the era of "precision cosmology"

why bothering about clusters?

- complementarity of cosmological parameter estimates
- sensitive to growth of structure (Ω_m, σ_8)
- extreme objects can probe early Universe physics, e.g., primordial non-Gaussianity



1E 0657-56: "Bullet cluster"

$\rightarrow$ clusters are assembling today:
"every cluster is a bullet cluster – or a miniature version of it!"

Clusters in the era of “precision cosmology”

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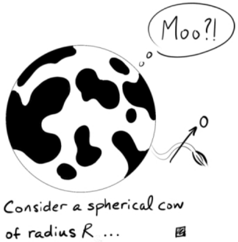

→ clusters are assembling today:
“every cluster is a bullet cluster – or a miniature version of it!”
→ need to go beyond the spherical-cow approximation; necessarily with a heavy computational component!

Cluster cosmology toolbox

Number counts and Sunyaev-Zel'dovich (SZ) power spectrum

- cluster number counts depend on scaling relations:

$$N = \int_0^{z_{\max}} \mathrm{d}z \, \frac{\mathrm{d}V}{\mathrm{d}z} \int_{M_{\min}(z)}^{\infty} \mathrm{d}M \, \frac{\mathrm{d}n(z,M)}{\mathrm{d}M(Y,T,L_X)}$$

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

- SZ power spectrum does not require mass information:

$$C_\ell = g_\nu^2 \int_0^{z_{\max}} \mathrm{d}z \, \frac{\mathrm{d}V}{\mathrm{d}z} \int_0^{\infty} \mathrm{d}M \, \frac{\mathrm{d}n(z,M)}{\mathrm{d}M} \, |\tilde{y}_\ell(M,z)|^2$$

  → 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 $C_\ell \propto A_{SZ} \propto \sigma_8^{7\ldots9}$

HITS

Modeling the ICM

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_{kin}, P_{CR}, P_B . . .
- plasma processes
- etc . . .

Modeling the ICM

processes that need to be included:

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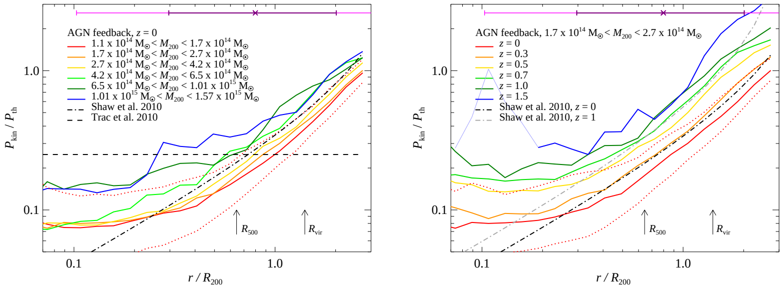
- non-thermal pressure support $P_{\rm kin}$, $P_{\rm CR}$, P_B ...
- plasma processes
- etc ...

→ 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

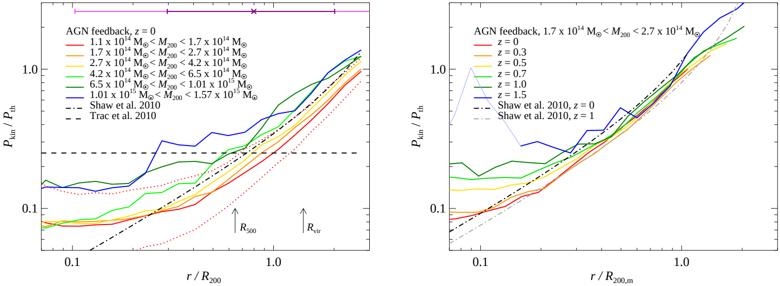
Kinetic pressure support



BBPS 2012a

- $P_{\mathrm{kin}}/P_{\mathrm{th}}$ increases with mass and redshift due to hierarchical formation history

Kinetic pressure support

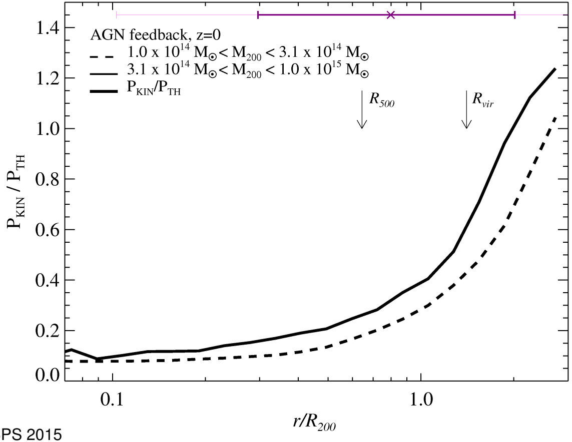


BBPS 2012a

- $P_{\rm kin}/P_{\rm th}$ almost insensitive to z when scaled to $R_{200,\rm mean}$!

Outskirts of galaxy clusters

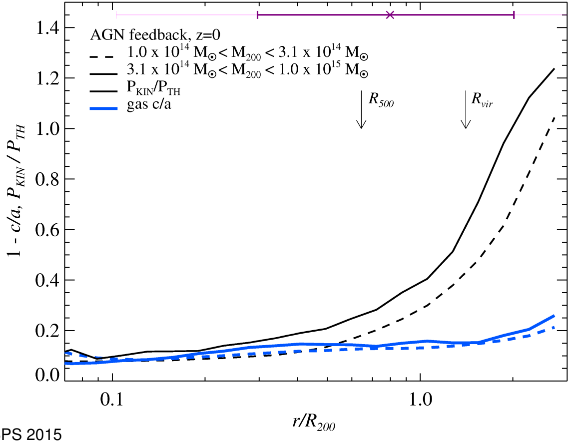
$P_{\rm kin}/P_{\rm th}$ increases with radius: dissipating formation shocks



BBPS 2015

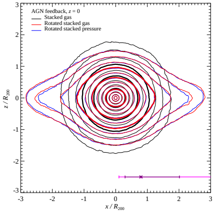
Outskirts of galaxy clusters

Rotate-stacked gas ellipticities



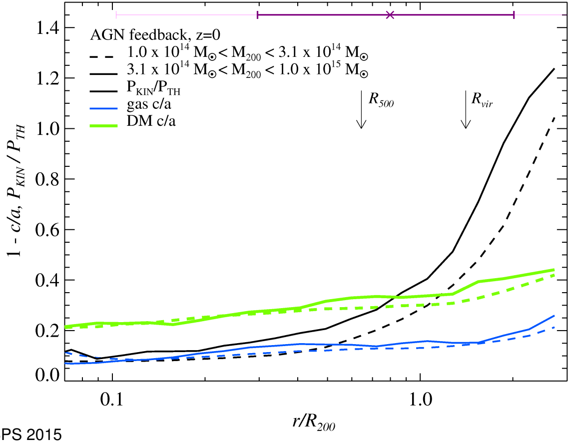
BBPS 2015

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

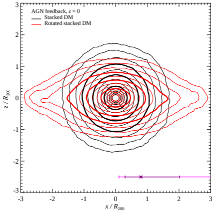


Outskirts of galaxy clusters

Rotate-stacked DM ellipticities



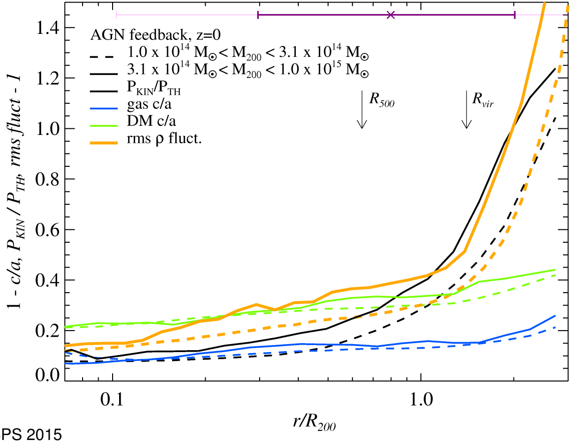
compute **DM** moment-of-inertia tensor, rotate and stack



BBPS 2015

Outskirts of galaxy clusters

Density clumping ($T > 10^6$ K) biases $f_{\rm gas}$ measurements



BBPS 2015

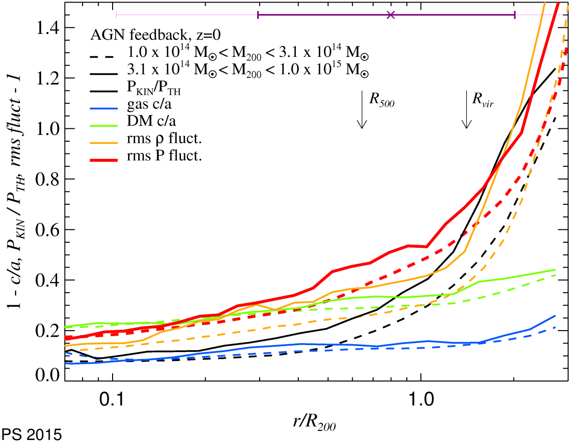
density/pressure clumping:

$$\mathcal{C}_\rho = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$$

$$\mathcal{C}_P = \frac{\langle P^2 \rangle}{\langle P \rangle^2}$$

Outskirts of galaxy clusters

Pressure clumping adds small-scale power to tSZ power spectrum



BBPS 2015

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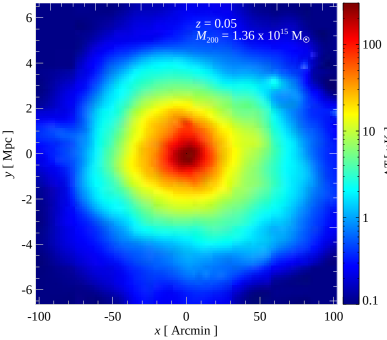
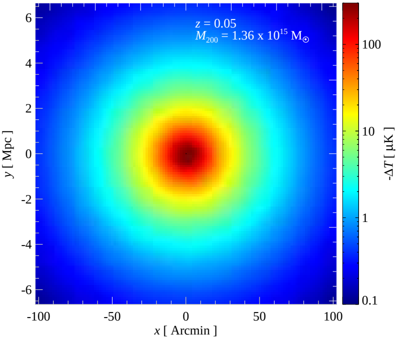
Pressure inhomogeneities, $z \simeq 0$



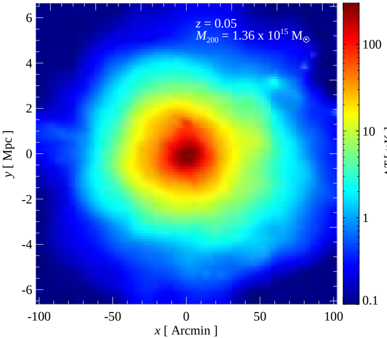


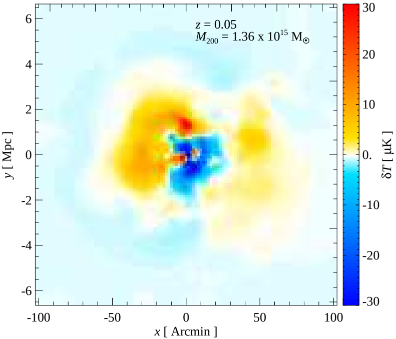
Compton-y of simulated cluster

spherical fit to simulations

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

Pressure inhomogeneities, $z \simeq 0$



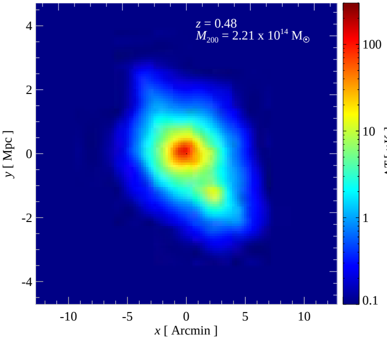


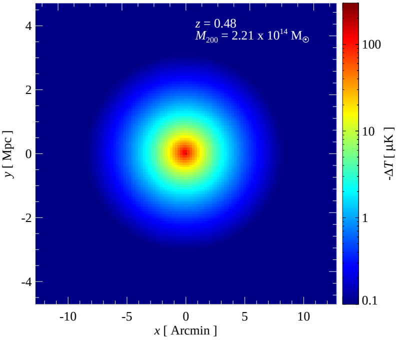
Compton-y of simulated cluster

$\delta y \rightarrow$ projected pressure clumps

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

Pressure inhomogeneities, $z \simeq 0.5$



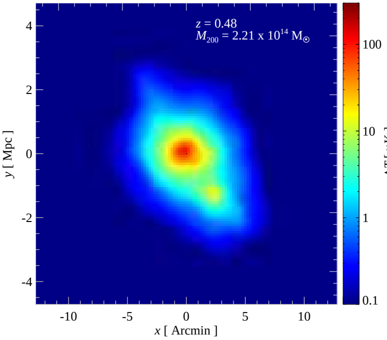


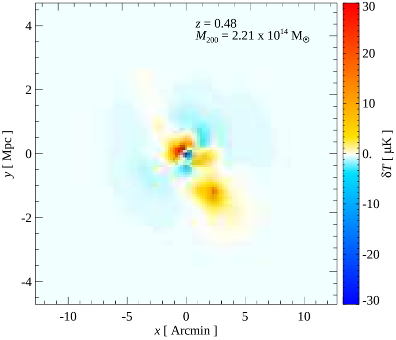
Compton-y of simulated cluster

spherical fit to simulations

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

Pressure inhomogeneities, $z \simeq 0.5$





Compton-y of simulated cluster

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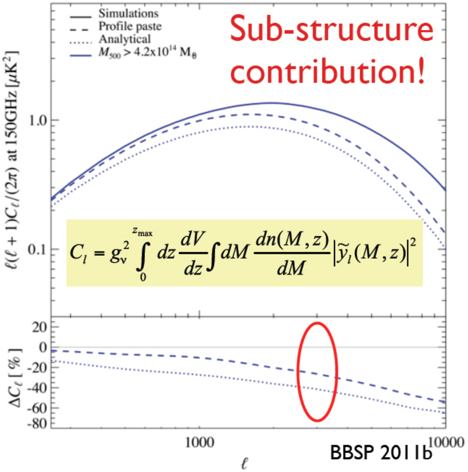
tSZ power spectrum with pressure inhomogeneities

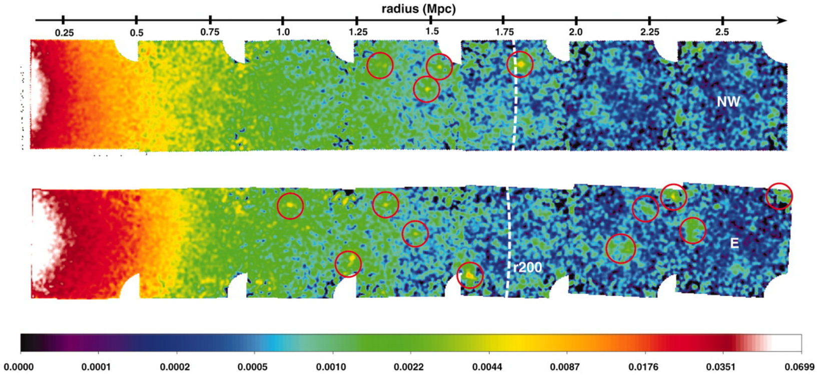


implications for tSZ power spectrum:

- high-mass halos: 25% at $\ell \sim 3000$
- all masses: 15% at $\ell \sim 3000$

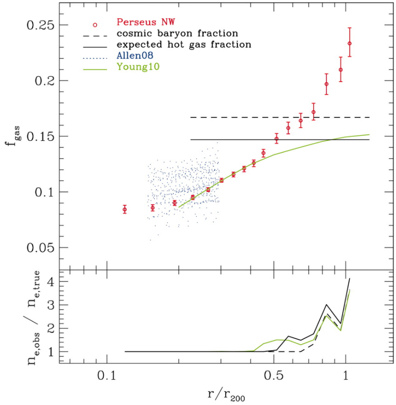
$\rightarrow$ pressure clumping crucial for analytical tSZ power spectrum calculations!

Understanding the outskirts of galaxy clusters



Simionescu+2011, Science

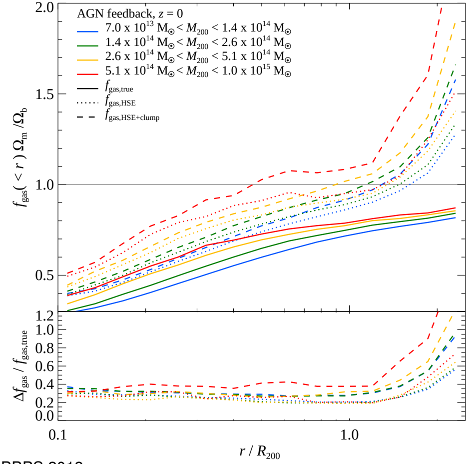
Understanding the outskirts of galaxy clusters



Simionescu+2011, Science

- 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

Biases of X-ray-inferred gas mass fractions

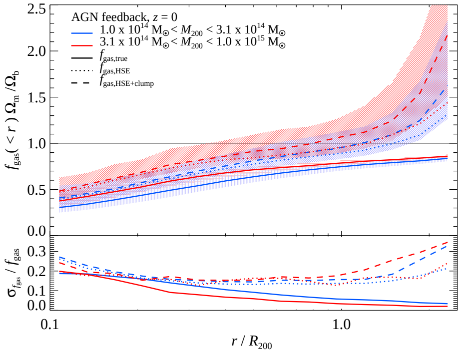


BBPS 2013

measurement biases of f_{gas}:

- M_{HSE} bias:
  20% at R_{200}
- density clumping bias:
  10 – 20% at R_{200}
  (mass dependent)

Biases of X-ray-inferred gas mass fractions



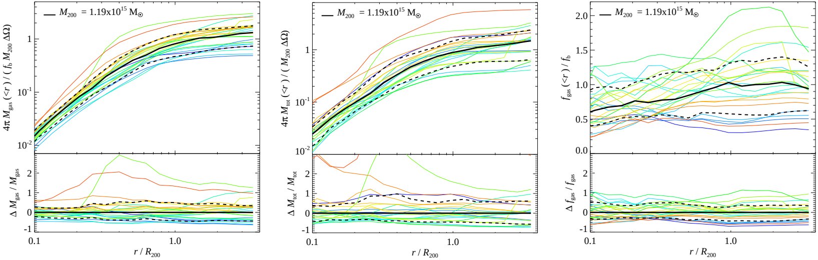
BBPS 2013

measurement biases of f_{gas}:

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

Mass profiles in cluster-centered cones

$M_{\rm gas}(r)$: $M_{\rm DM+gas+stars}(r)$: $f_{\rm gas}(r)$:



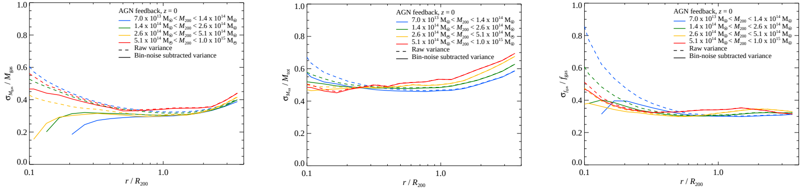
BBPS 2013

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

$\sigma_{M_{\rm gas}}(r)$: $\sigma_{M_{\rm DM+gas+stars}}(r)$: $\sigma_{f_{\rm gas}}(r)$:

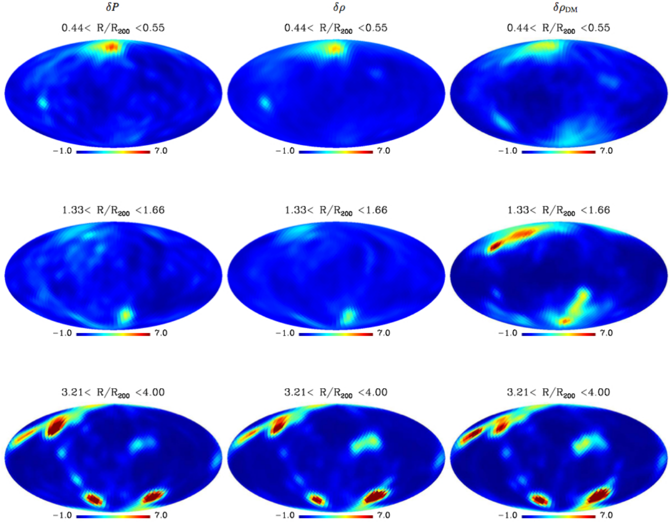


BBPS 2013

clusters are anisotropic:

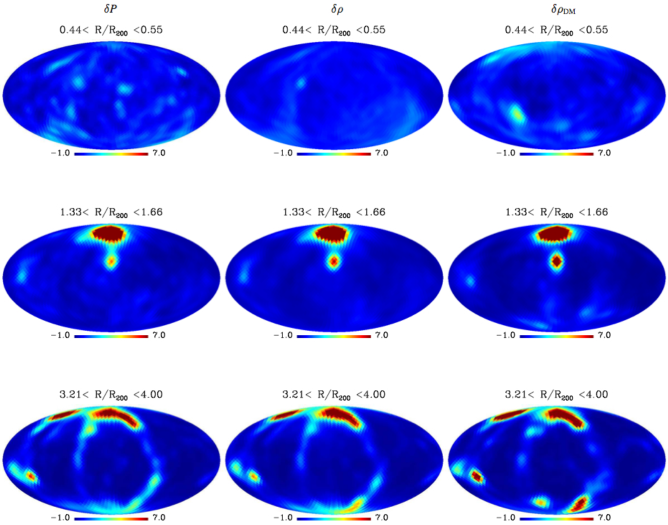
- mean of the angular variance of $f_{\rm gas}$ across all clusters: $\sigma_{f_{\rm gas}} \simeq 30 - 35\%$
- collisionless DM more anisotropic than gas (shock physics)

Cluster-centered shells of δP and $\delta \rho$ (1)



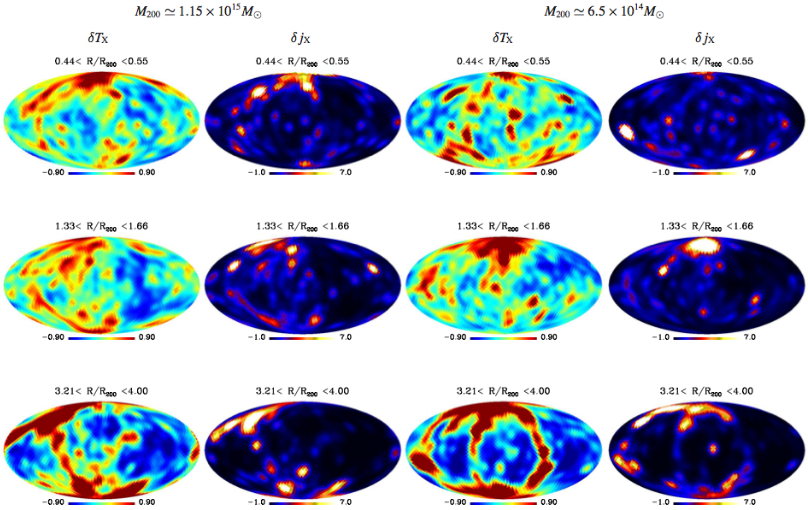
BBPS 2015

Cluster-centered shells of δP and $\delta \rho$ (2)



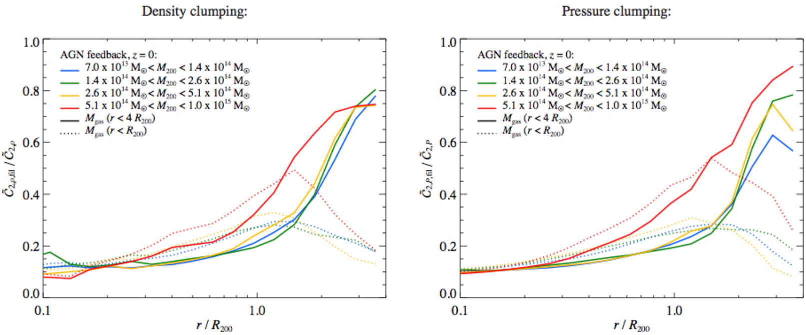
BBPS 2015

Cluster-centered shells of δT and δj_X



BBPS 2015

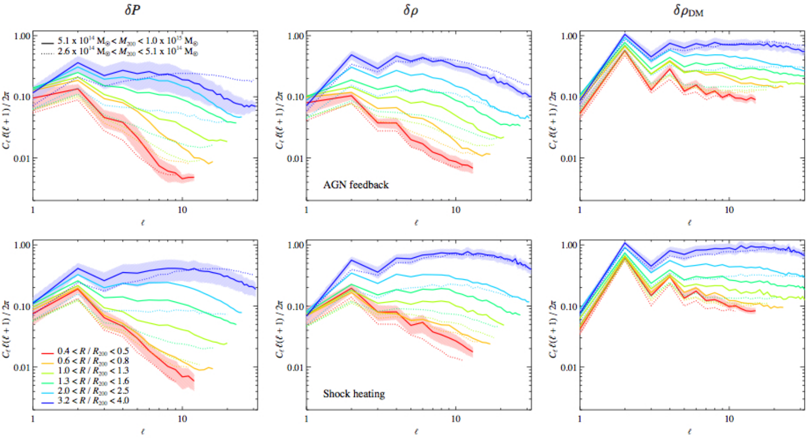
Contribution of cosmic filaments to clumping



BBPS 2015

- define filaments as the 4 cones with the largest $M_{\mathrm{gas}}(r < R_{200})$ (dotted) and $M_{\mathrm{gas}}(r < 4R_{200})$ (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

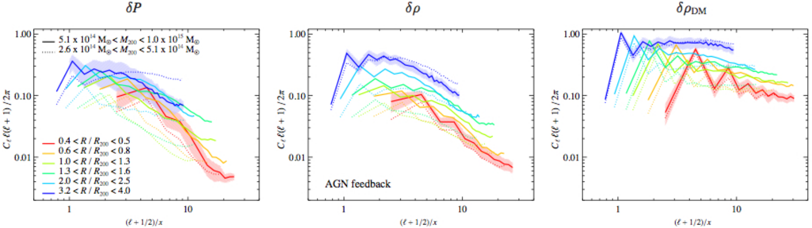
Understanding clumping: power spectra $C_\ell(\ell)$



BBPS 2015

- scaled angular power spectra show apparent evolution of the spectral shape from a bump (at $R_{200}/2$) to an almost flat distribution (at 4 R_{200})

Power spectra $\mathcal{C}_\ell(k_\perp)$ of shells quantify super-clumping



BBPS 2015

- 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 $\mathcal{C}_\ell(k_\perp)$, 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 $L_\perp \gtrsim \pi R_{200}/k_\perp \sim R_{200}/5$

Conclusions

describing cluster outskirts:

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

towards an understanding of clumping in cluster outskirts:

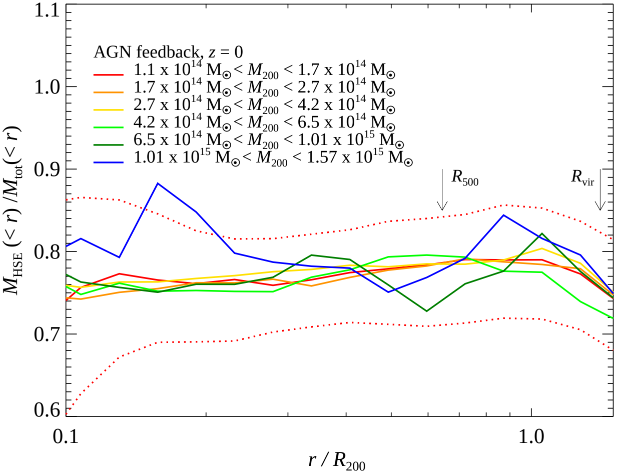
- clumping is dominated by gravitationally-driven, large substructures $\rightarrow$ **"super-clumping"**
- these inhomogeneities are sourced by cosmic filaments that are channeling baryonic and dark matter onto clusters and maintain contact down to radii of order $R_{200}/3$
- such large-scale, radial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

Literature for the talk

- **BBPSS 2010:** Battaglia, Bond, Pfrommer, Sievers, Sijacki, *Simulations of the Sunyaev-Zel'dovich Power Spectrum with AGN Feedback*, ApJ, 725, 91 (2010).
- **BBPS 2012a:** Battaglia, Bond, Pfrommer, Sievers, *On the Cluster Physics of Sunyaev-Zel'dovich and X-ray Surveys I: the Influence of Feedback, Non-thermal Pressure and Cluster Shapes on $Y-M$ Scaling Relations*, ApJ, 758, 74 (2012).
- **BBPS 2012b:** Battaglia, Bond, Pfrommer, Sievers, *On the Cluster Physics of Sunyaev-Zel'dovich and X-ray Surveys II: Deconstructing the Thermal SZ Power Spectrum*, ApJ, 758, 75 (2012).
- **BBPS 2013:** Battaglia, Bond, Pfrommer, Sievers, *On the Cluster Physics of Sunyaev-Zel'dovich and X-ray Surveys III: Measurement Biases and Cosmological Evolution of Gas and Stellar Mass Fractions*, ApJ, 777, 123, (2013).
- **BBPS 2015:** Battaglia, Bond, Pfrommer, Sievers, *On the Cluster Physics of Sunyaev-Zel'dovich and X-ray Surveys IV: Density and Pressure Clumping due to Infalling Substructures*, ApJ, 806, 43 (2015).

additional slides

Hydrostatic mass bias



BBPS 2012a

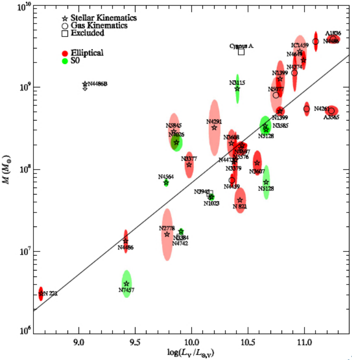
AGN feedback

- 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_{inj} within spherical region R_{AGN}
- parameters: $\Delta t, \varepsilon_r, R_{\text{AGN}}$; ε_r effective radiative efficiency
- match previous AGN models

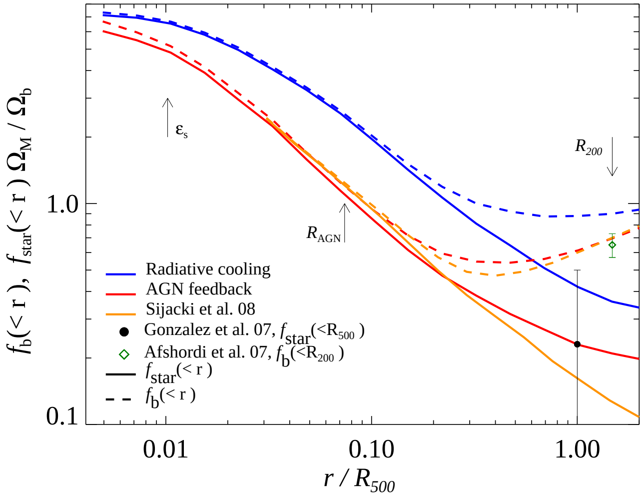
(Sijacki+2008)



Gültekin+2009

Baryon and stellar mass fraction

$f_{\rm star}(<r) = M_{\rm star}(<r)/M_{\rm tot}(<r)$ is reduced by AGN feedback to observed values



Battaglia, Bond, C.P., Sievers, Sijacki (2010) ≡ 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 $\sim 10^{13} h^{-1}\,\mathrm{M}_\odot$
- $\sim$ 800 clusters with $M_{200} > 10^{14} h^{-1}\,\mathrm{M}_\odot$
- 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)