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

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in collaboration with

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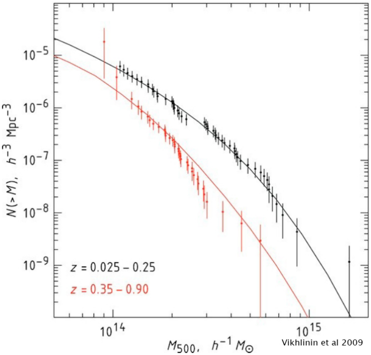
Outline

1. Cluster cosmology
   - Cosmology toolbox
   - ICM physics
   - Simulations
2. Sunyaev-Zel'dovich clusters
   - Thermal pressure
   - Scaling relations
   - Power spectrum
3. Physics in cluster outskirts
   - Gas motions
   - Gas clumping
   - Cluster anisotropy

Outline

Cluster cosmology toolbox: mass function (1)

- $N(> M)$ from N-body simulations
- Chandra X-ray measurements to determine $Y_X - M$ relation (50 clusters)
- constrain cosmological parameters

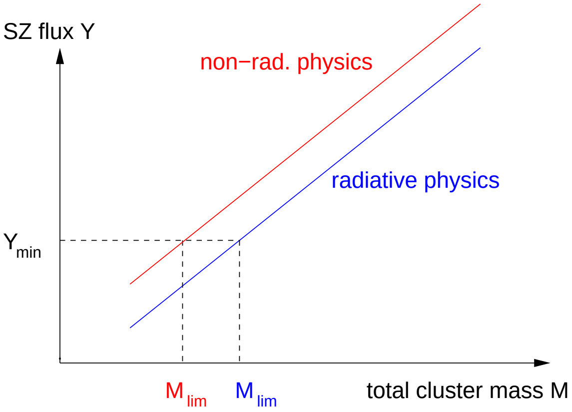


Vikhlinin et al 2009

- we do not *measure* mass → mass proxies, i.e. scaling relations:

$$L_X - T, \quad T - M, \quad L_X - M, \quad N - M, \quad Y_X - M, \quad Y - M$$

How cluster physics changes scaling relations



→ cooling and star formation depletes the gas reservoir, which decreases the SZ flux and increases the effective mass threshold for an SZ flux−limited cluster sample

Cluster cosmology toolbox (2)

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

- cluster number counts depend on scaling relations:

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

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

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- SZ power spectrum does not require mass information:

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

$\rightarrow$ depends on cluster form factor $\tilde{y}_\ell(M,z)$, i.e. Fourier transform of the thermal pressure profile
$\rightarrow$ amplitude of the SZ power spectrum $C_\ell \propto A_{\mathrm{SZ}} \propto \sigma_8^{7\ldots9}$

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 ...

SZ Simulations: e.g., Da Silva+2000, Springel+2001, Bond+2002, BBPSS 2010, BBPS 2012a,b,c,d
SZ (Semi)Analytical: e.g., Komatsu & Seljak 2001, Ostriker+2005, Bode+2009, 2012, Sehgal+2010, Shaw+2010, Trac+2011

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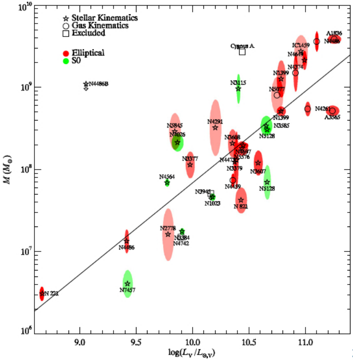
→ how does the physics impact upon various ICM observables?

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)

$$M_{\text{BH}} \propto M_{\text{star}}$$
$$E_{\text{inj}} = \varepsilon_r \dot{M}_{\text{star}} c^2 \Delta t$$



Gültekin+2009

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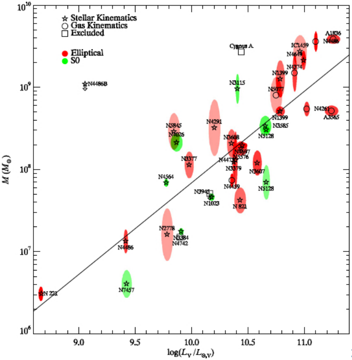
$$M_{\mathrm{BH}} \propto M_{\mathrm{star}}$$
$$E_{\mathrm{inj}} = \varepsilon_r \dot{M}_{\mathrm{star}} c^2 \Delta t$$

- find halos and inject E_{inj} within spherical region R_{AGN}
- parameters: $\Delta t, \varepsilon_r, R_{\mathrm{AGN}}$; ε_r effective radiative efficiency
- match previous AGN models

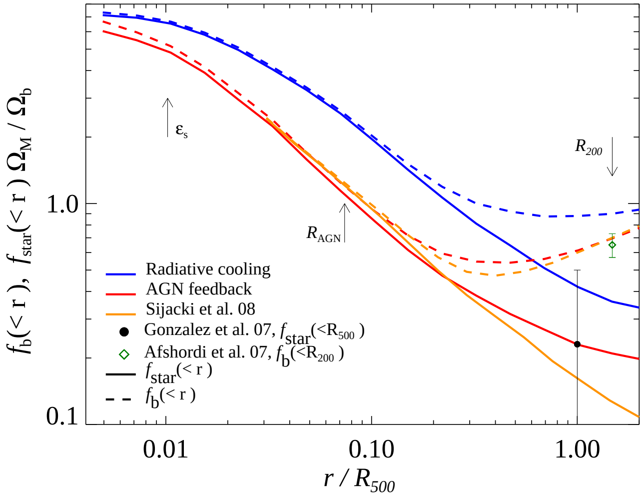
(Sijacki+2008)



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

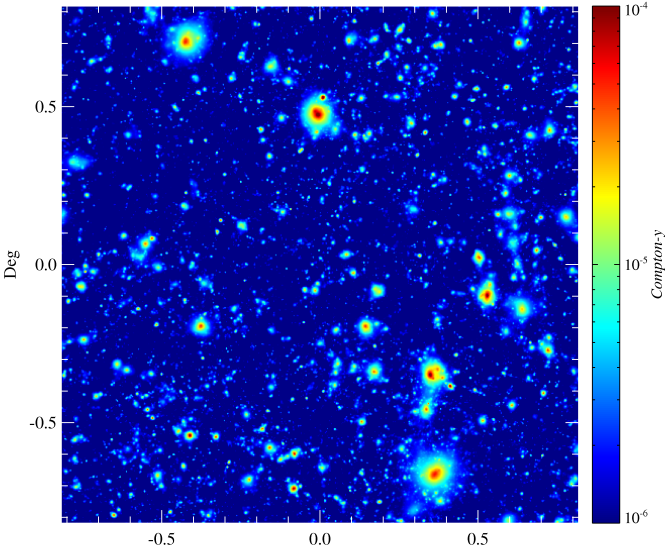
our simulations: (BBPSS 2010, BBPS 2012a,b,c,d)

- box lengths: $\{200, 400\} h^{-1}$ Mpc, $N = 2 \times \{256^3, 512^3\}$
- halo mass resolution $\sim 10^{13} h^{-1}\,\mathrm{M}_\odot$
- ~ 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

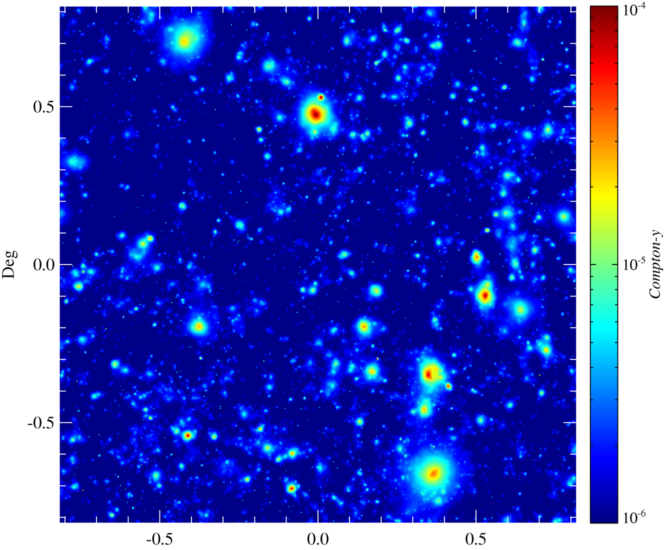
$\rightarrow$ good compromise between large volumes (SZ power spectrum) and sufficient resolution for ICM modeling (AGN feedback)

Outline

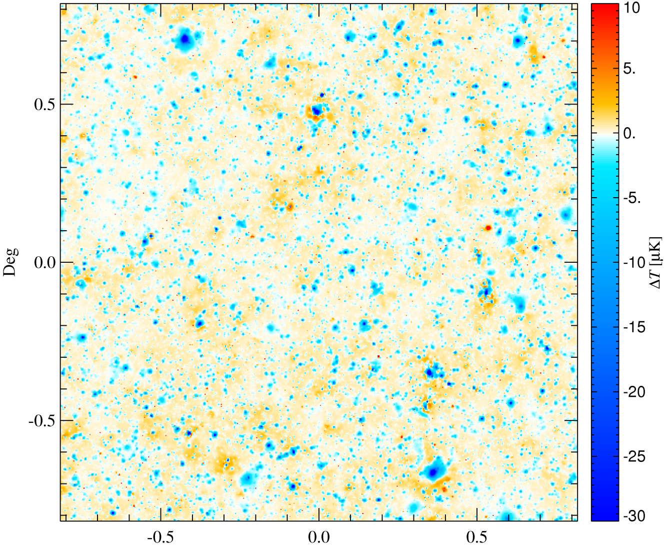
Compton-y: shock heating



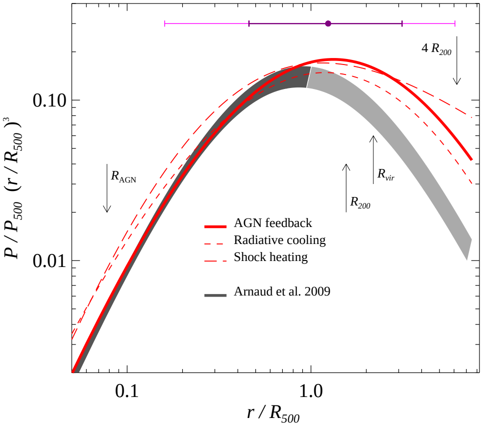
Compton-y: AGN feedback



Compton-y: shock heating - AGN feedback



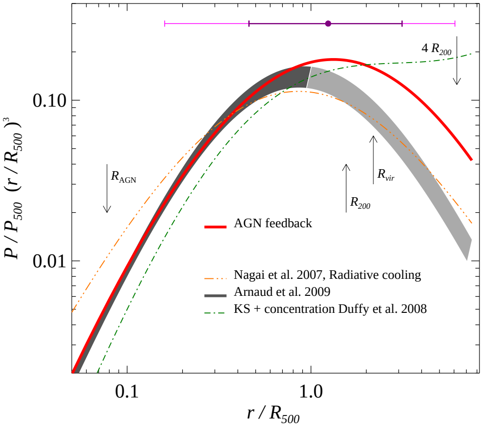
Stacked pressure profile



BBPSS 2010

- $P(r)r^3 \propto \mathrm{d}E/\mathrm{d}\log r$ peaks around virial radius with large convergence region
- AGN feedback lowers the central pressure and pushes the gas to larger radii

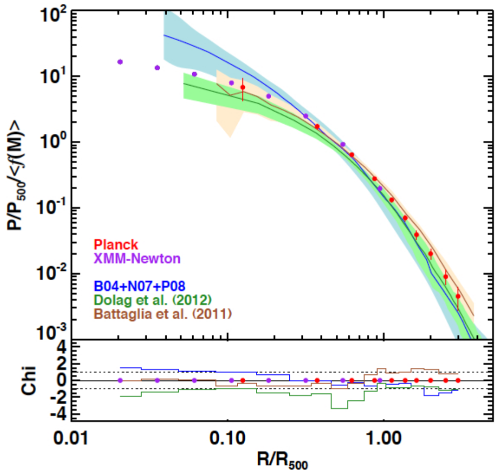
Stacked pressure profile



BBPSS 2010

- analytic models underpredict X-ray data (Komatsu & Seljak 2001)
- simulations without AGN feedback suffer from overcooling and overpredict central pressure (e.g., Nagai+2007)
- matches recent X-ray and SZ *(Planck)* results

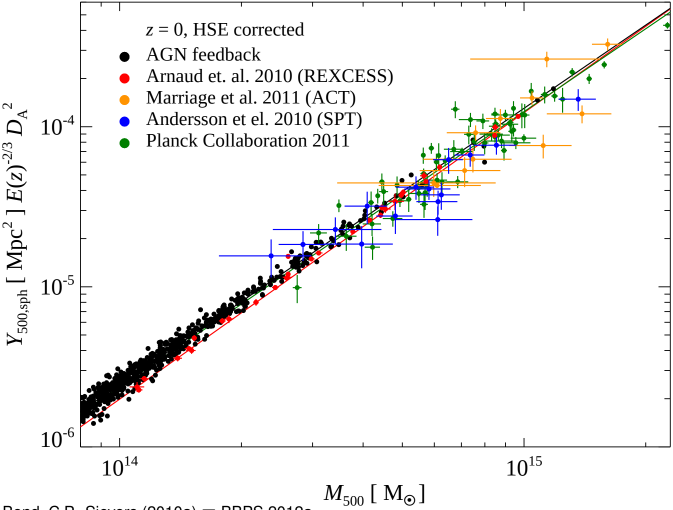
Planck stacked pressure profile



Planck Collaboration 2012

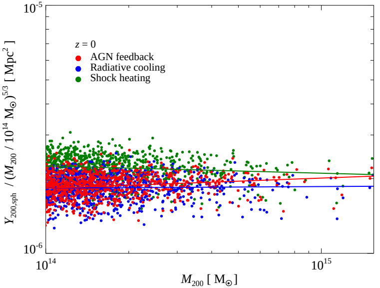
- AGN feedback lowers the central pressure and pushes the gas to larger radii
- $P(r)r^3 \propto \mathrm{d}E/\mathrm{d}\log r$ peaks around virial radius with large convergence region
- matches recent X-ray and SZ *(Planck)* results

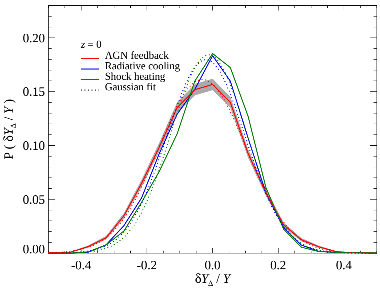
$Y - M$ relation: observations



Battaglia, Bond, C.P., Sievers (2010a) ≡ BBPS 2012a

$Y - M$ relation: comparing physics models

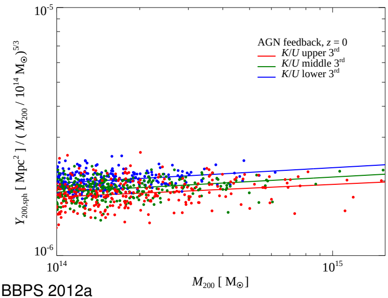




BBPS 2012a

- star formation lowers the baryon fraction and total Y
- AGN feedback steepens $Y - M$ slope because of greater impact on group scales (shallower potential wells)
- AGN feedback increases scatter (11.5% $\rightarrow$ 13.5%)

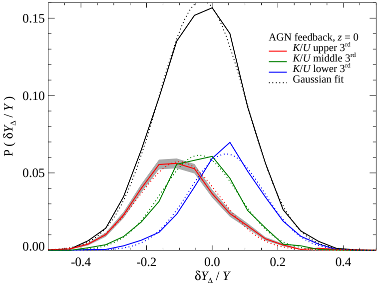
$Y - M$ relation: non-thermal pressure subsampling



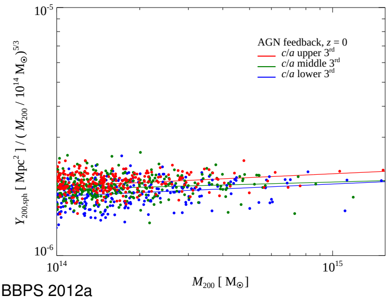
BBPS 2012a

normalization changes by $\simeq 15\%$

relaxed third $\sigma_{K/U} \simeq 11.5\%$



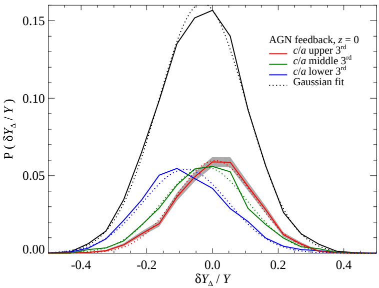
$Y - M$ relation: asphericity subsampling



BBPS 2012a

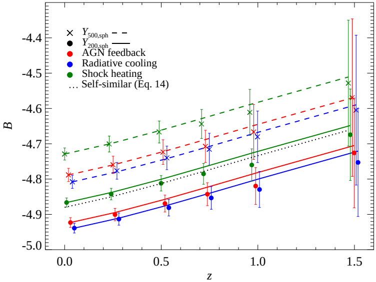
normalization changes by $\simeq 10\%$

roundest third $\sigma_{c/a} \simeq 12\%$

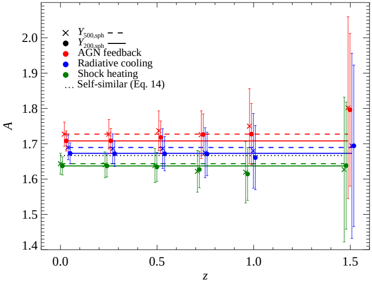


$Y - M$ relation: evolution

normalization



slope

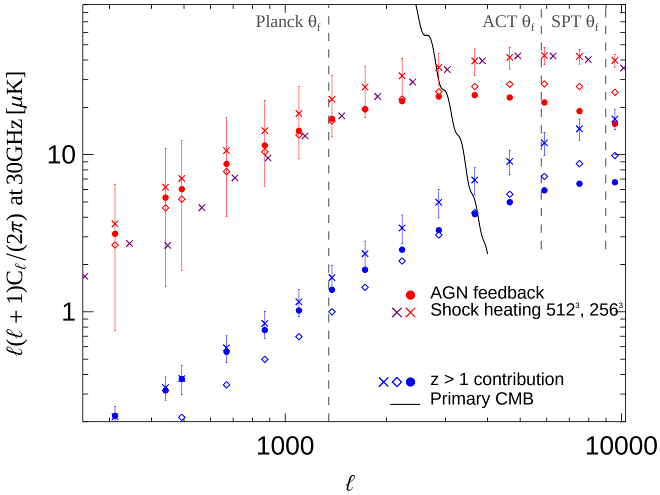


BBPS 2012a

- all physics models show self-similar evolution within the scatter
- radiative physics modifies slope

SZ power spectrum with AGN feedback

Cosmological parameters: low-ℓ part, cluster astrophysics at $z \gtrsim 0.8$: high-ℓ part



BBPSS 2010

Deconstructing the tSZ power spectrum: method

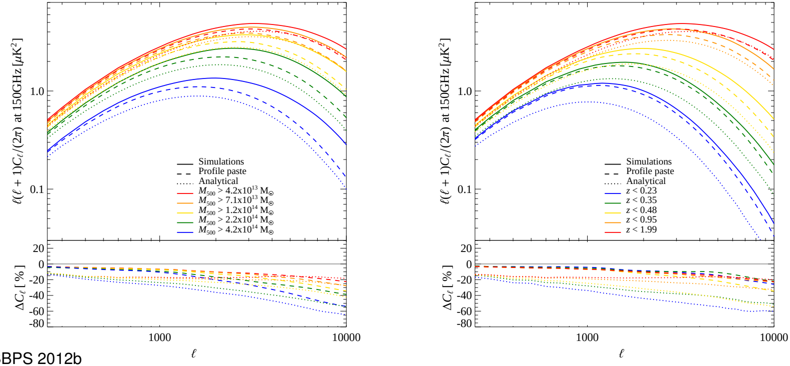
$$C_\ell = g_\nu^2 \int_0^{z_{\max}} \mathrm{d}z \, \frac{\mathrm{d}V}{\mathrm{d}z} \int_{M_{\min}(z)}^{\infty} \mathrm{d}M \, \frac{\mathrm{d}n(z,M)}{\mathrm{d}M} \, |\tilde{y}_\ell(M,z)|^2$$
$$+ \quad \text{clustering of clusters (subdominant)}$$

Compare different tSZ power spectrum methods self-consistently by using the global pressure profile from the simulations:

- analytical power spectrum for a given mass function
- paste the global pressure profile at cluster locations in the simulations
- FFT of the full simulation maps

→ understand systematic differences between methods!

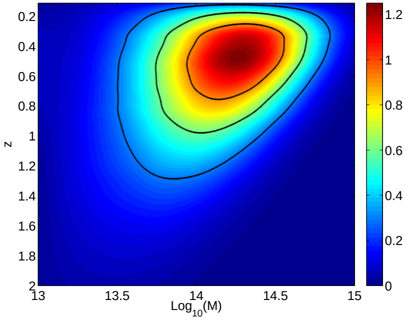
Deconstructing the tSZ power spectrum: *M* and *z*



BBPS 2012b

- cumulative tSZ power spectrum, $\mathcal{C}_\ell$, in mass *(left)* and redshift *(right)*
- simulation $\mathcal{C}_\ell$ enhanced over analytical $\mathcal{C}_\ell$ because of pressure clumping from substructures (high$-M$, high$-z$)

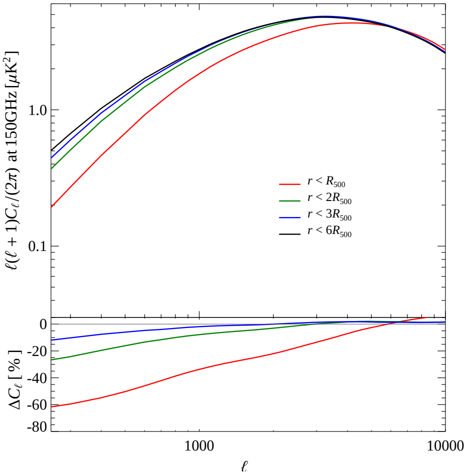
Deconstructing the tSZ power spectrum: M and z



BBPS 2012b

- fractional contribution to the tSZ power spectrum in mass and redshift at $\ell = 3000$
- 50% of the power derives from $z \in [0.2, 1]$ and $M_{200} \in [6 \times 10^{13}, 6 \times 10^{14}]\mathrm{M}_\odot$

Deconstructing the tSZ power spectrum: radius

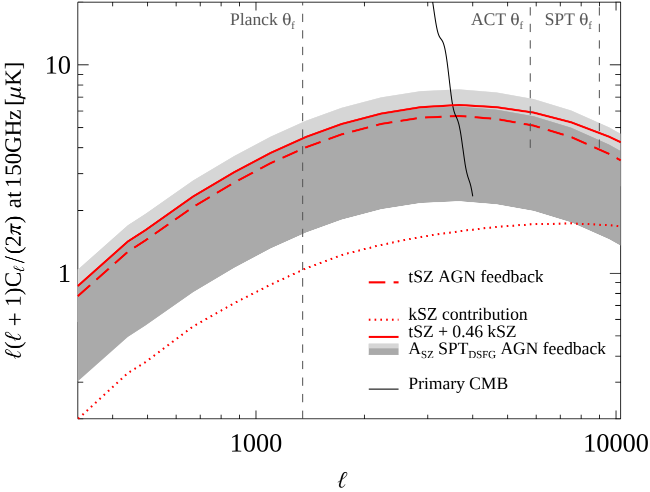


BBPS 2012b

- apply radial 3D taper to each cluster with multiple of R_{500} (real space)
- cumulative tSZ power spectrum, $\mathcal{C}_\ell$, in cluster radius
- cluster outskirts especially important at low-ℓ *(Planck!)*

SZ power spectrum: cosmological constraints

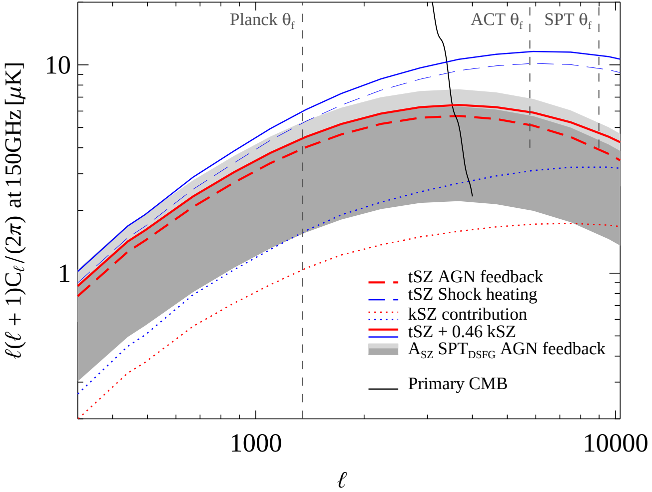
SPT data with WMAP $\sigma_8 = 0.8$ consistent with our AGN models



BBPSS 2010

SZ power spectrum: cosmological constraints

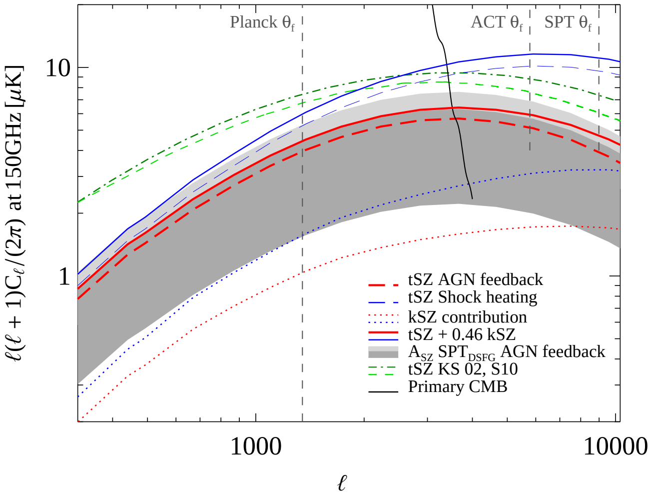
SPT data with WMAP $\sigma_8 = 0.8$ inconsistent with simple non-radiative models



BBPSS 2010

SZ power spectrum: cosmological constraints

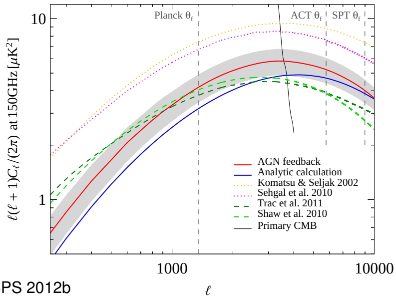
SPT data with WMAP $\sigma_8 = 0.8$ inconsistent with (semi-)analytic models



BBPSS 2010

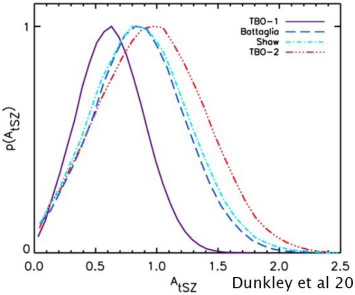
SZ power spectrum: latest cosmological constraints

models



BBPS 2012b

data

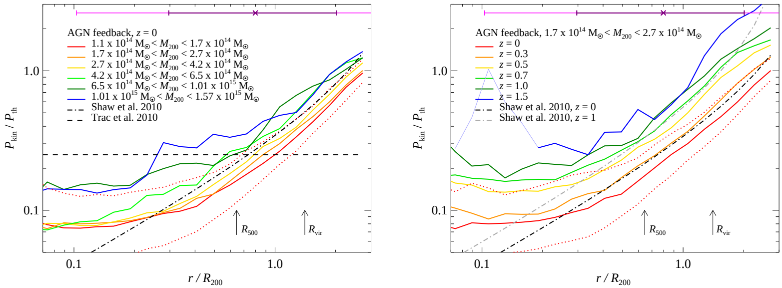


Dunkley et al 2010

- current SZ power spectrum models are consistent with $A_{\rm SZ} = 1$ $\rightarrow \sigma_8$ values are consistent with CMB
- importance of unvirialized motions/turbulence and AGN feedback to reduce power at $\ell \simeq 3000$

Outline

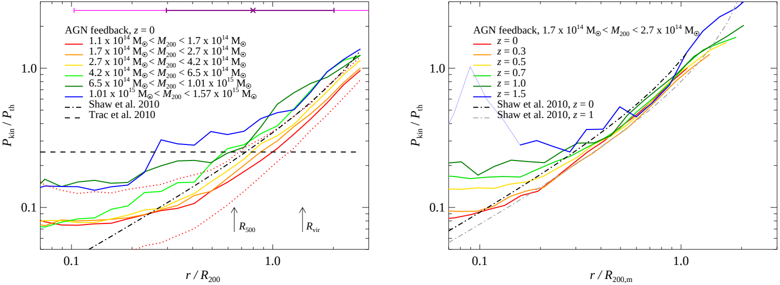
Kinetic pressure support



BBPS 2012a

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

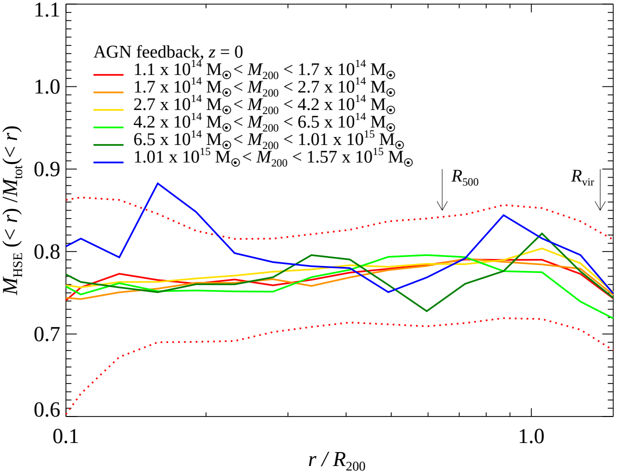
Kinetic pressure support



BBPS 2012a

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

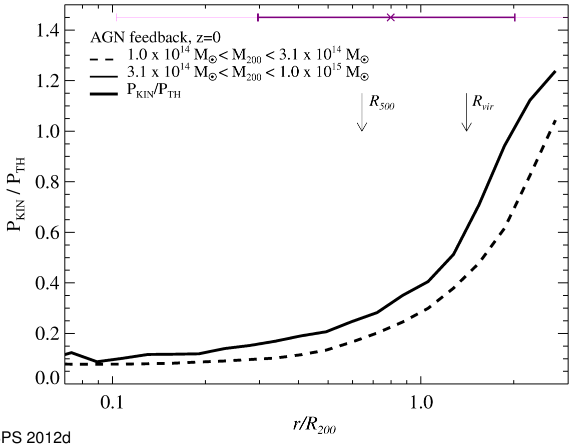
Hydrostatic mass bias



BBPS 2012a

Outskirts of galaxy clusters

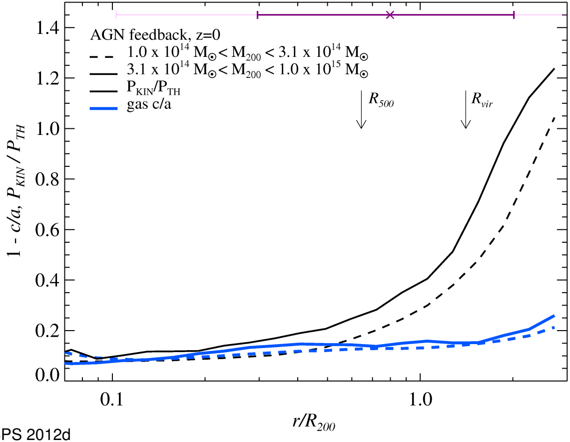
$P_{\rm kin}/P_{\rm th}$ increases with radius: dissipating formation shocks



BBPS 2012d

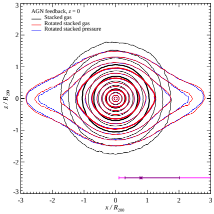
Outskirts of galaxy clusters

Rotate-stacked gas ellipticities

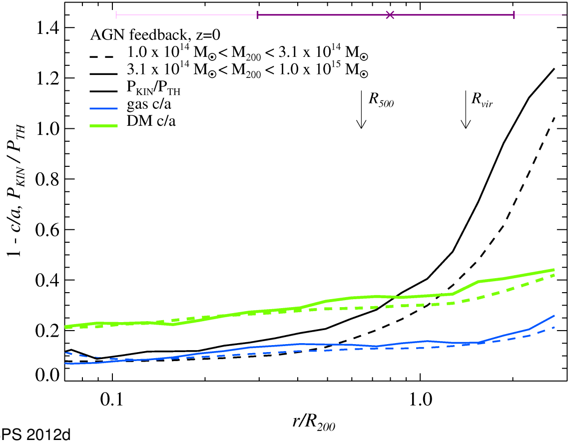


BBPS 2012d

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

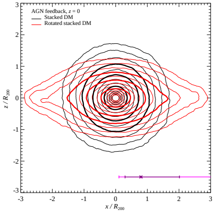


Outskirts of galaxy clusters
Rotate-stacked DM ellipticities



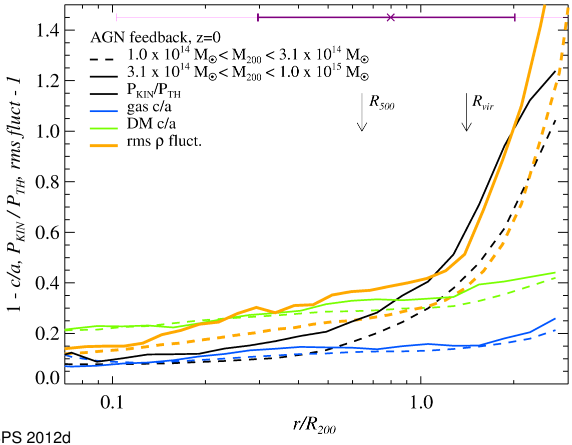
BBPS 2012d

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



Outskirts of galaxy clusters

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



BBPS 2012d

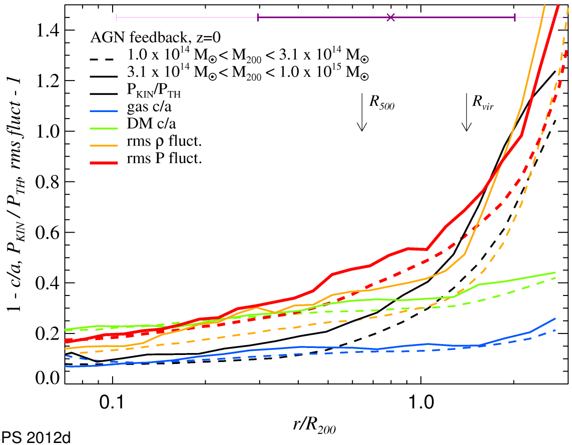
density/pressure clumping:

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

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

Outskirts of galaxy clusters

Pressure clumping adds small-scale power to tSZ power spectrum



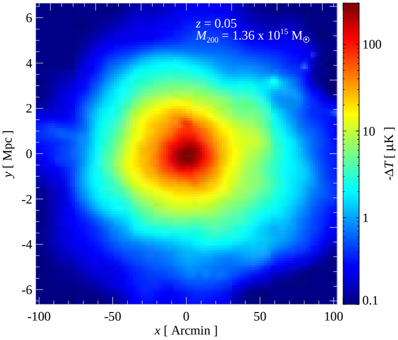
BBPS 2012d

density/pressure clumping:

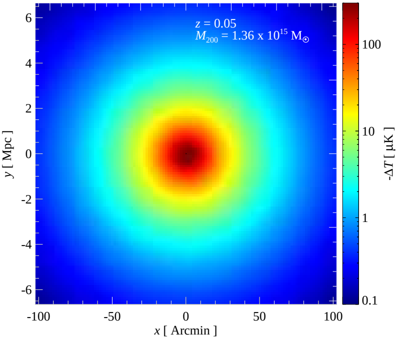
$$\mathcal{C}_\rho = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$$

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

Pressure inhomogeneities, $z \simeq 0$



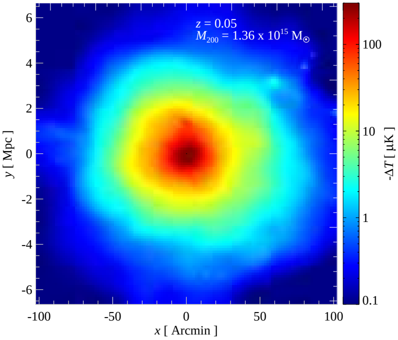
Compton-y of simulated cluster

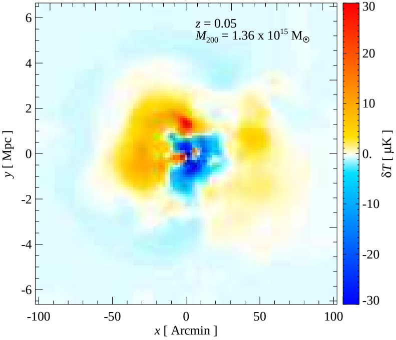


spherical fit to simulations

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

Pressure inhomogeneities, $z \simeq 0$



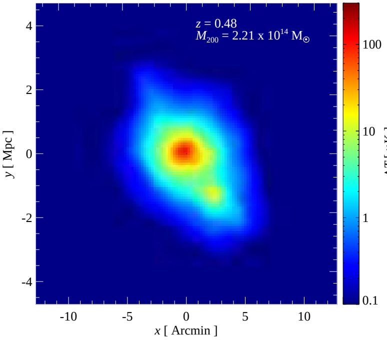


Compton-y of simulated cluster

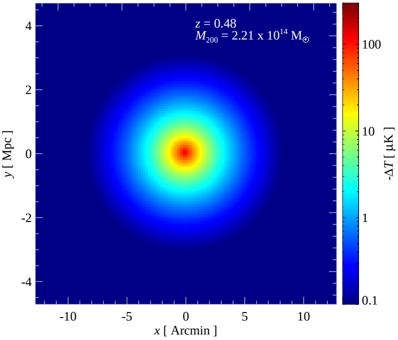
$\delta y \rightarrow$ projected pressure clumps

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

Pressure inhomogeneities, $z \simeq 0.5$



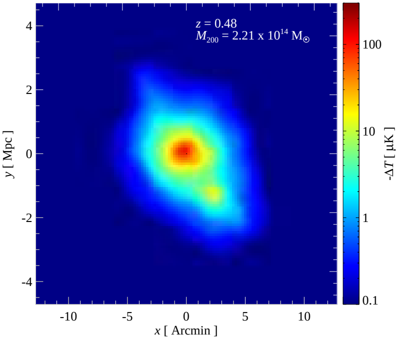
Compton-y of simulated cluster

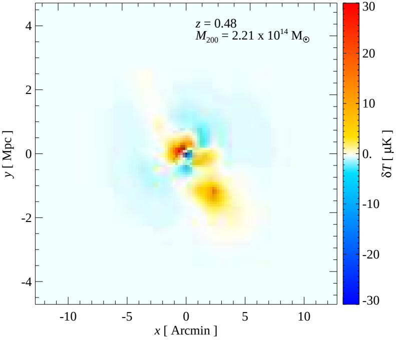


spherical fit to simulations

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

Pressure inhomogeneities, $z \simeq 0.5$



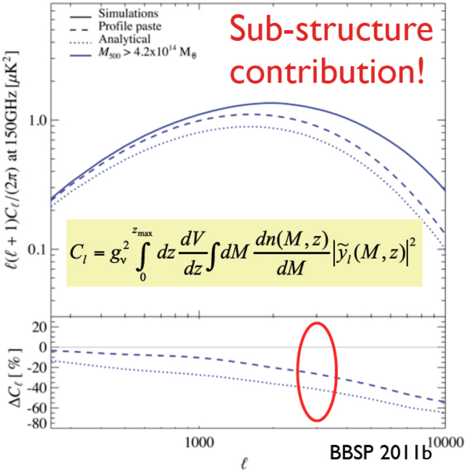


Compton-y of simulated cluster

$\delta y \rightarrow$ projected pressure clumps

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

tSZ power spectrum with pressure inhomogeneities

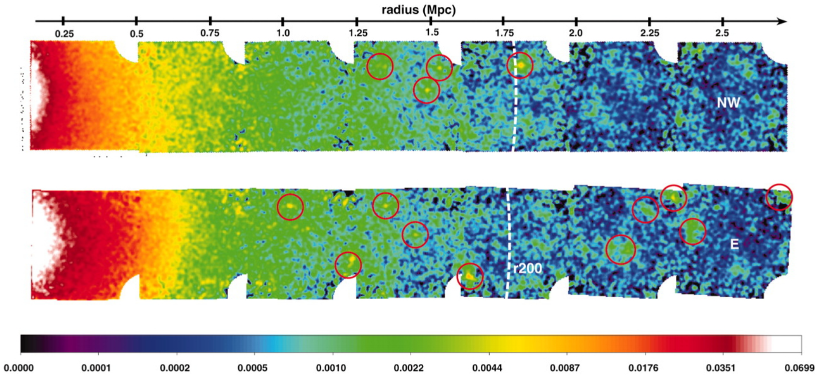


implications for tSZ power spectrum:

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

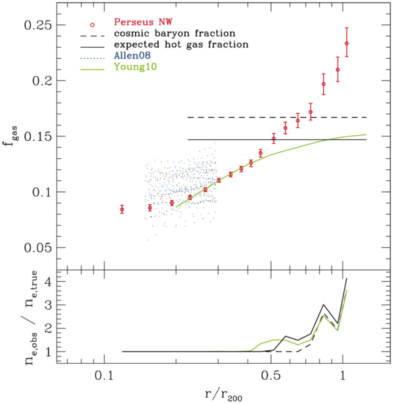
→ pressure clumping crucial for analytical tSZ power spectrum calculations!

Understanding the outskirts of galaxy clusters



Simionescu+2011, Science

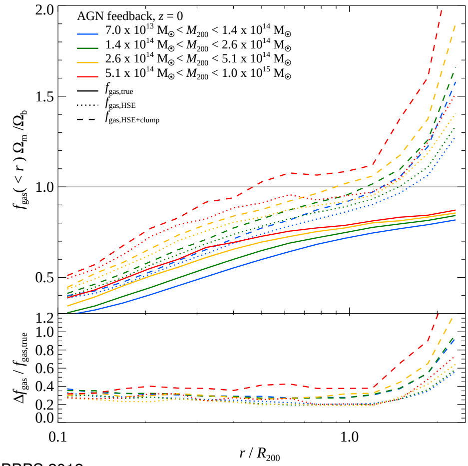
Understanding the outskirts of galaxy clusters



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

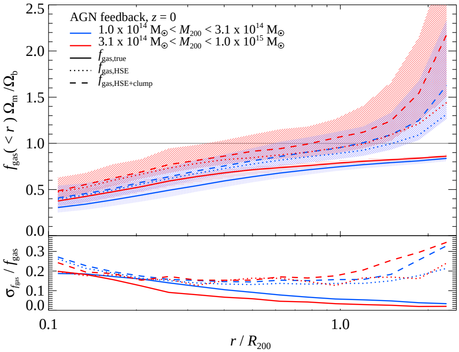


BBPS 2012c

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



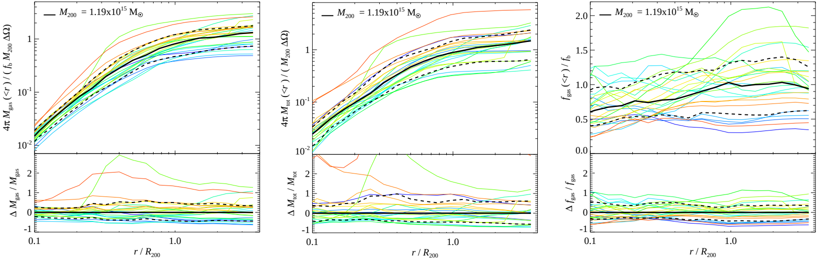
BBPS 2012c

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 $f_{\mathrm{gas,HSE+clump}}$

Mass profiles in cluster-centered cones

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



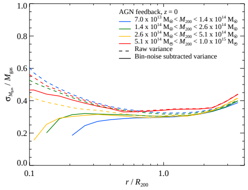
BBPS 2012c

clusters are anisotropic:

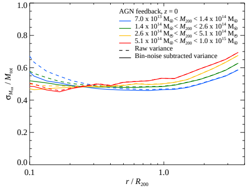
- large angular variations of mass profiles: cosmic filaments seed anisotropic substructure distribution
- large offsets of DM and gas → cannot use DM as a gas proxy!

Variance of mass profiles in cluster-centered cones

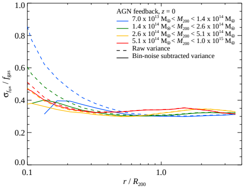
$\sigma_{M_{\rm gas}}(r)$:



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



$\sigma_{f_{\rm gas}}(r)$:



BBPS 2012c

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)

Conclusions

key cluster physics for $Y - M$ and tSZ power spectrum:

- kinetic pressure contribution ($\rightarrow$ scatter in $Y - M$)
- locking baryons up into stars
- AGN feedback:
  - smoothes central pressure: lowers $\mathcal{C}_\ell$ at $\ell \sim 3000$
  - pushed gas beyond R_{500} and increases peripheral pressure
  - lowers Y and steepens $Y - M$ (compared to self-similar)

Conclusions

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physics in 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

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 2012c:** 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*, submitted, arXiv:1209.4082.
- **BBPS 2012d:** 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*, in prep.