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Feedback on Large Scales

(& Cosmology)

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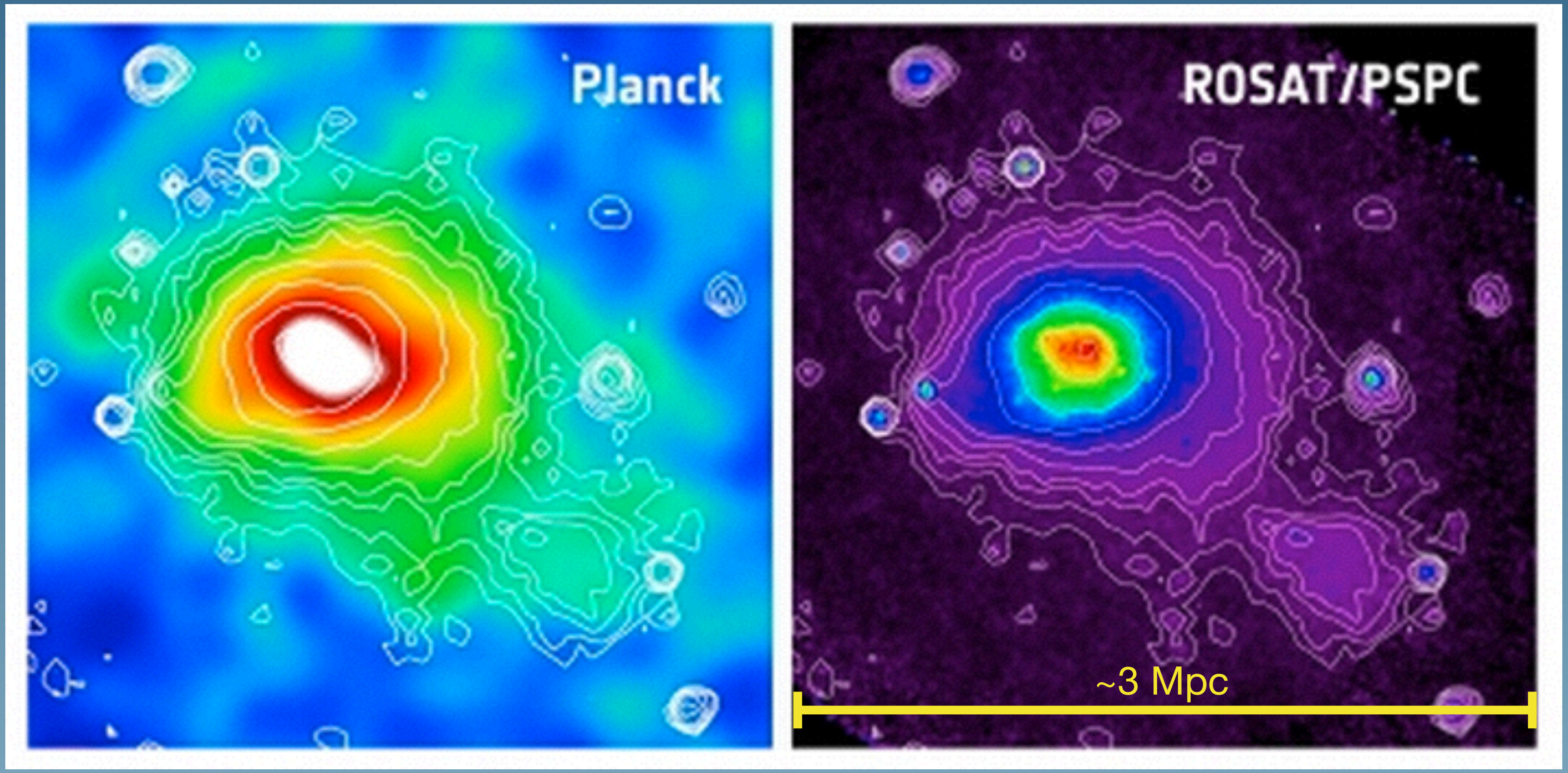
KITP
June. 17 2014

Context

Focus: Role of feedback on the Intracluster Medium (ICM)

ICM : Hot ionized plasma found in galaxy clusters

- Temperatures ~ several 10^7 K → several keV
- x-ray emission via bremsstrahlung
- CMB spectral dist. via the Sunyeav-Zeldovich effect
- Metallicity ~⅓ solar; scales ~ 1 Mpc (virial radius)



Credit: Davide De Martin (ESA/Hubble)

Context

Focus: Role of feedback on the Intracluster Medium (ICM)

Why?

Astrophysics: ICM is a unique astrophysical plasma and a laboratory for non-thermal processes

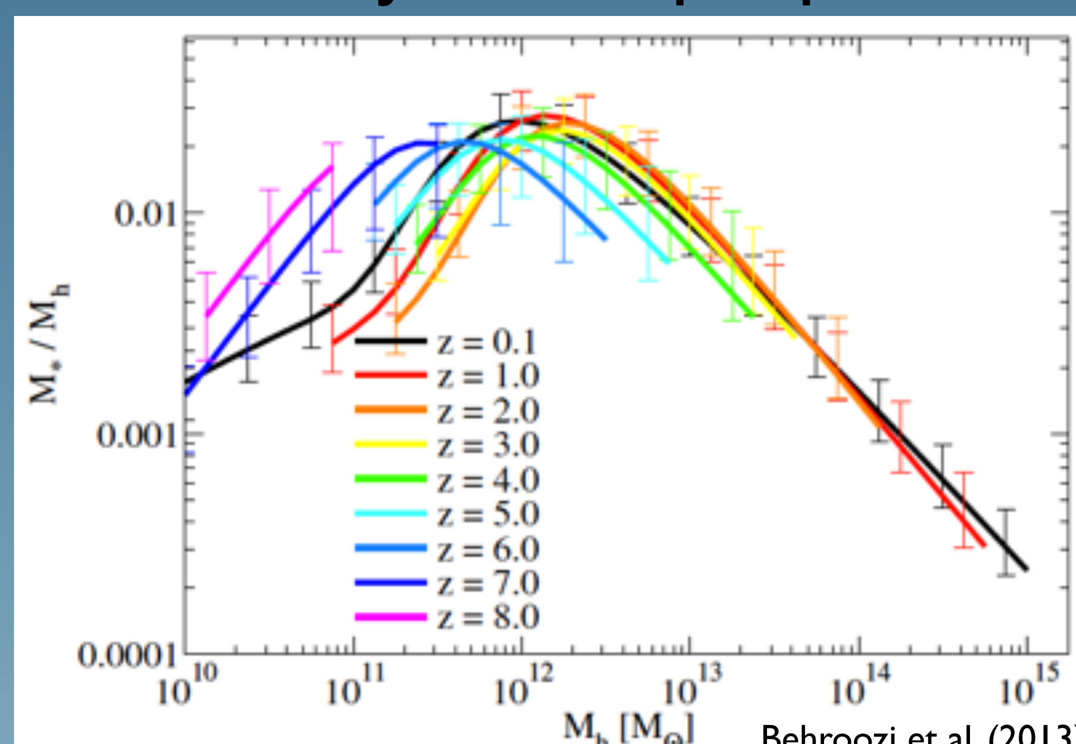
Cosmology: Galaxy clusters trace the growth of structure, sensitive to dark energy, $\sum m_\nu$, non-Gaussianity…

Largely gravitationally dominated systems

cluster mass ⇄ Thermodynamic properties (virialization)

Scaling Relations

Star Formation



Behroozi et al. (2013)

Feedback

optimizing for the problem

Simulations have limitations…

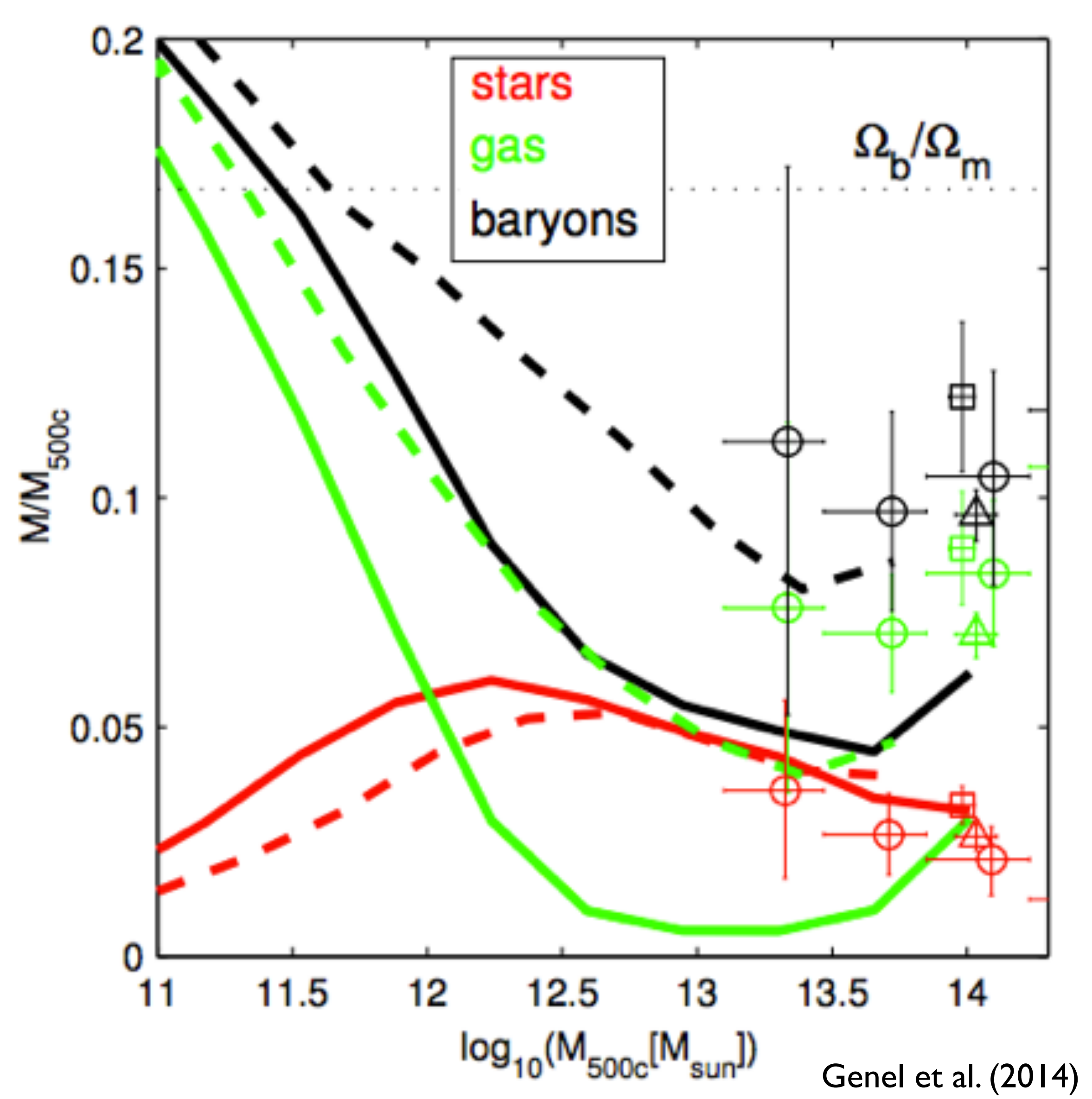
Requires tuning of the sub-grid models for SF, feedback etc.

Large scales for statistics

Coarse resolution for computational feasibility

The thermodynamic properties of the ICM is what we focused on

Dichotomy between cluster core properties require more physics



Genel et al. (2014)

All obs. that Illustris matches on galaxy scales, the cluster scale properties are discrepant with obs.

Overcooling

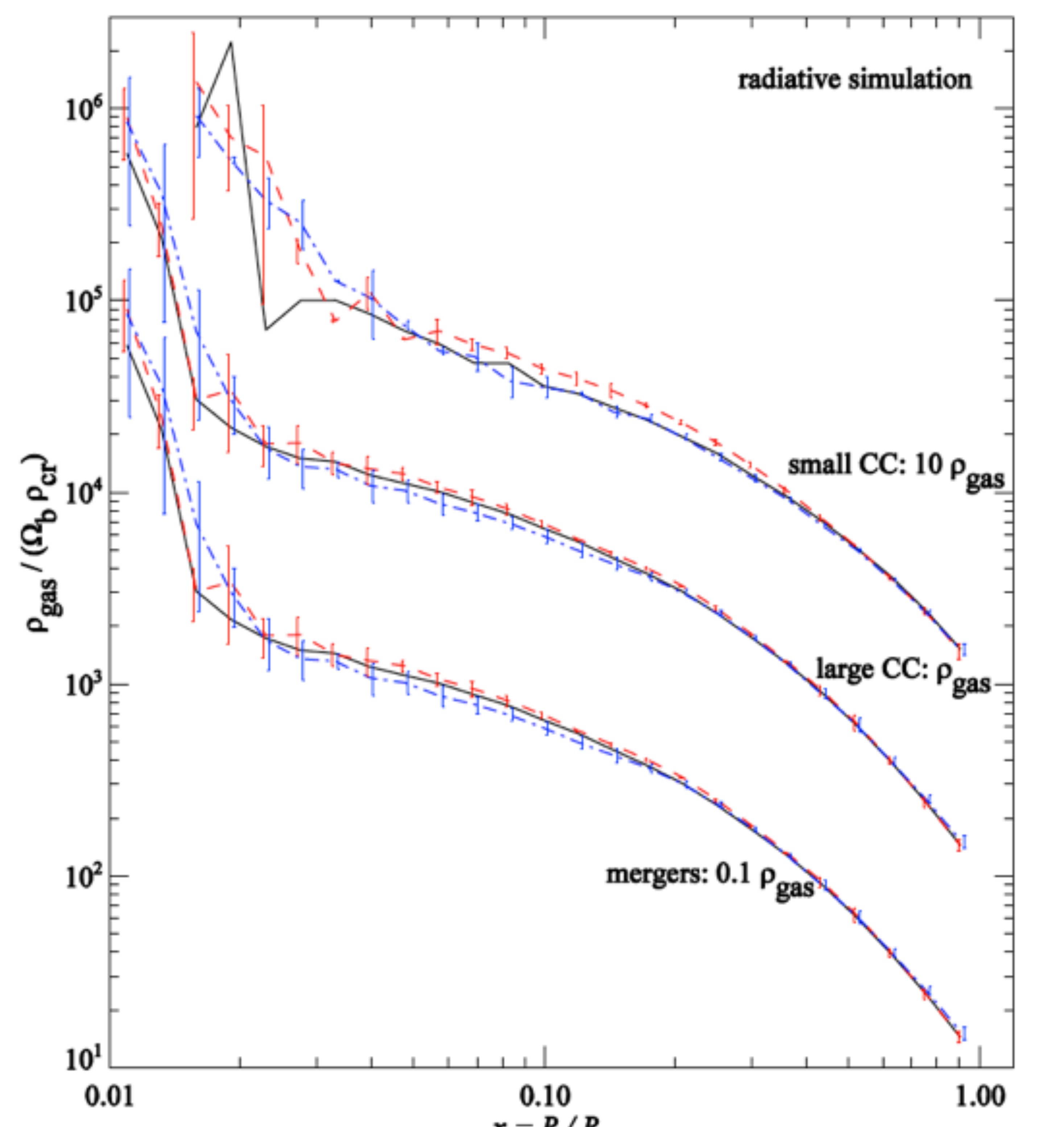
Overcooling is physical

for clusters the high densities, low entropies and cooling function, overcooling should happen, run away process

Observationally not seen

Feedback is required & necessary

- over produces stars
- modifies the ICM



Pfrommer et al. (2008)

Modeling the ICM

Simulations or (Semi)Analytical

e.g. Da Silva et al 2000, Springel 2001, Bond et al 2002, BBPSS 2010, McCarthy et al 2013

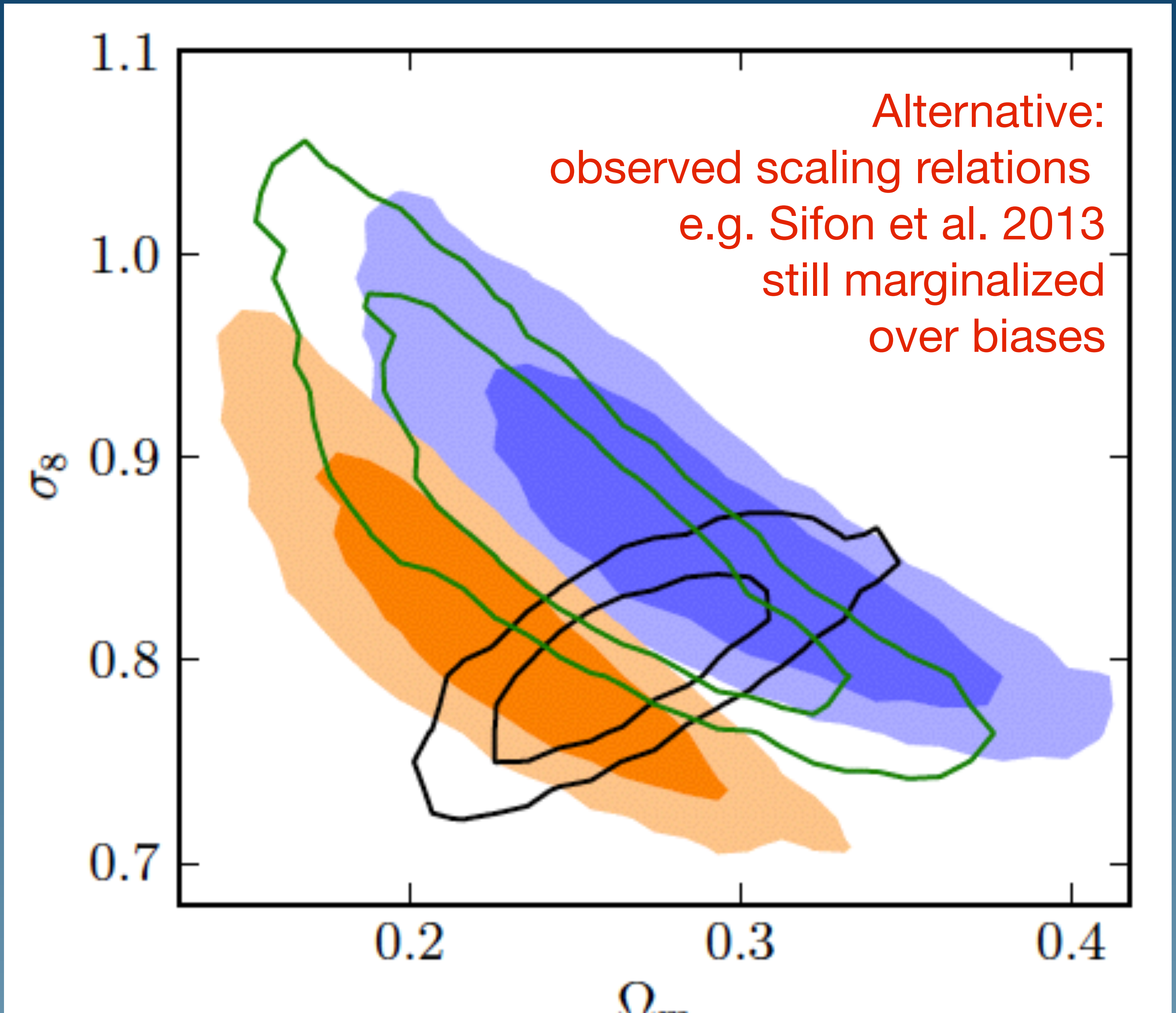
e. g. Komatsu & Seljak 2001, Ostriker et al. 2005, Bode et al 2009(12), Sehgal et al 2010, Shaw et al 2010, Trac et al 2011

Processes that need to be included (Sub-grid)

- Radiative cooling
- Star formation
- Feedback (AGN, stellar)
- Non-thermal pressure support P_{KIN}, CR, P_B …
- Asphericity and sub-structure
- Plasma processes
- etc...

The ICM is complex!

X-roads Cosmology & Astrophysics



Hasselfield et al. 2013

Latest cluster cosmology

Limited by uncertainty in the Y-M relation & Pressure profile

e.g. Benson et al 2013, Hasselfield et al 2013, Rozo et al 2013, & Planck Coll. XX 2013

Simulations are a tool for understanding and quantifying the important gastrophysics, biases, and scatter in surveys

Our Simulations

Box lengths 200-400 Mpc h^{-1}(256^3, 512^3)
Halo Mass resolution 10^{13} $M_\odot$ h^{-1}
Gadget3 (SPH) with 3 “physics” models

- Non-radiative (Adiabatic)

- Radiative cooling + SF + SNe + CR

- “AGN” feedback (coarse sub-grid)

~ 800 clusters with $M_{200} > 10^{14}$ $M_\odot$ h^{-1}

Lots of data to still be mined

A new set of simulations is coming soon

Previous Feedback models

Magorrian relation

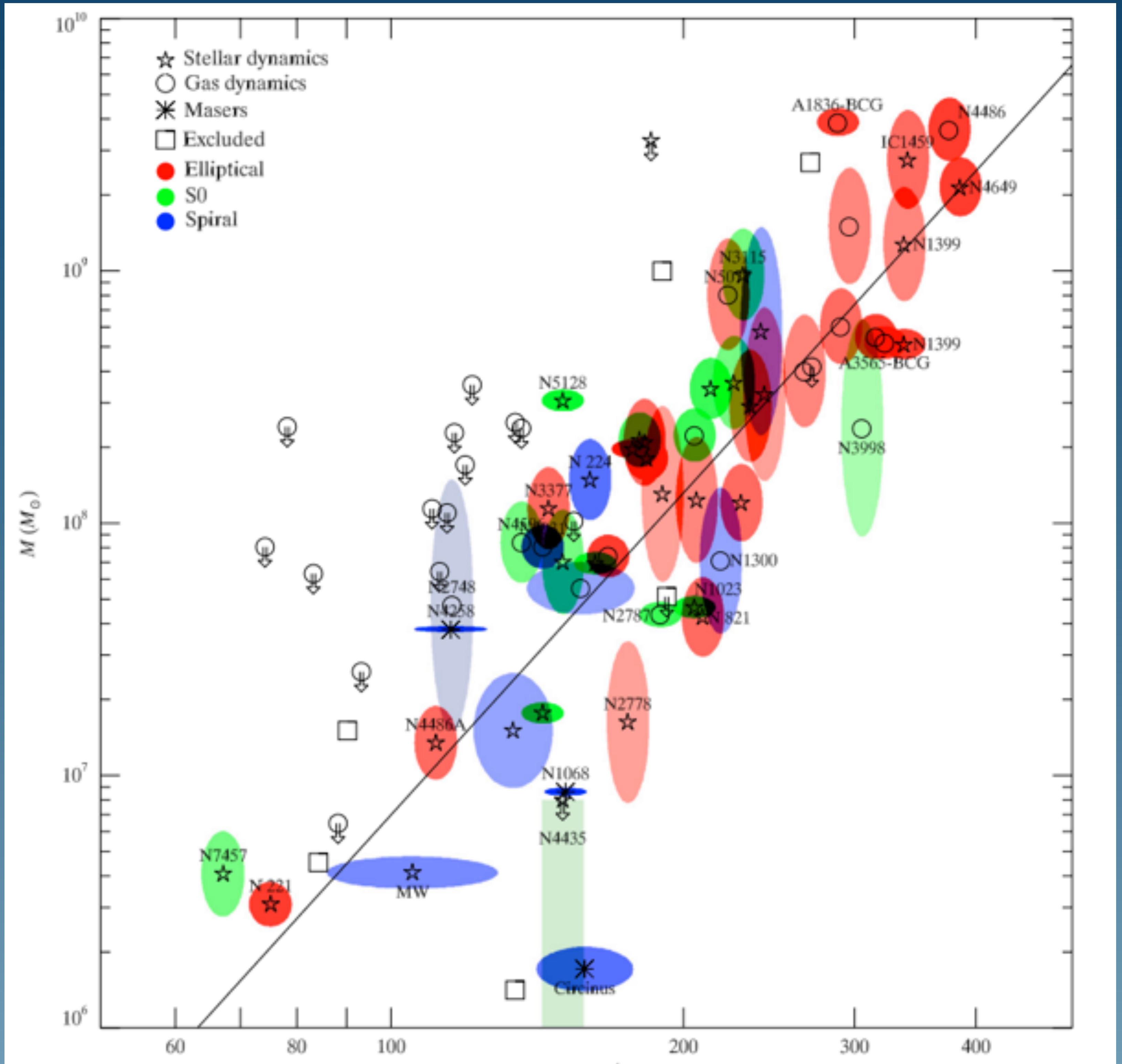
$$M_{BH} \propto \sigma^4, \dot{M}_{BH} \propto \dot{M}_{EDD}$$

- run on smaller scales
- quasars and galaxies

Estimate Bondi-Hoyle accretion

$$\dot{M}_{BH} = \frac{\alpha 4 \pi G^2 M_{BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}$$

- sink particles
- high resolution



Gultekin et al. (2009)

"AGN" feedback

Sub grid (~10^9 [OM], simulation resolution ~ 20 kpc)

Following: Thompson, Quataert & Murray 2005

$$\dot{M}_{BH} \propto \dot{M}_*$$

For typical AGN (< 1 pc):

Black hole accretion rates ~ 1 $M_\odot$ / yr

disk mass 10^6 $M_\odot$, but AGN lifetimes > 10^6 years

Mass transfer must occur from an outer to an inner disk

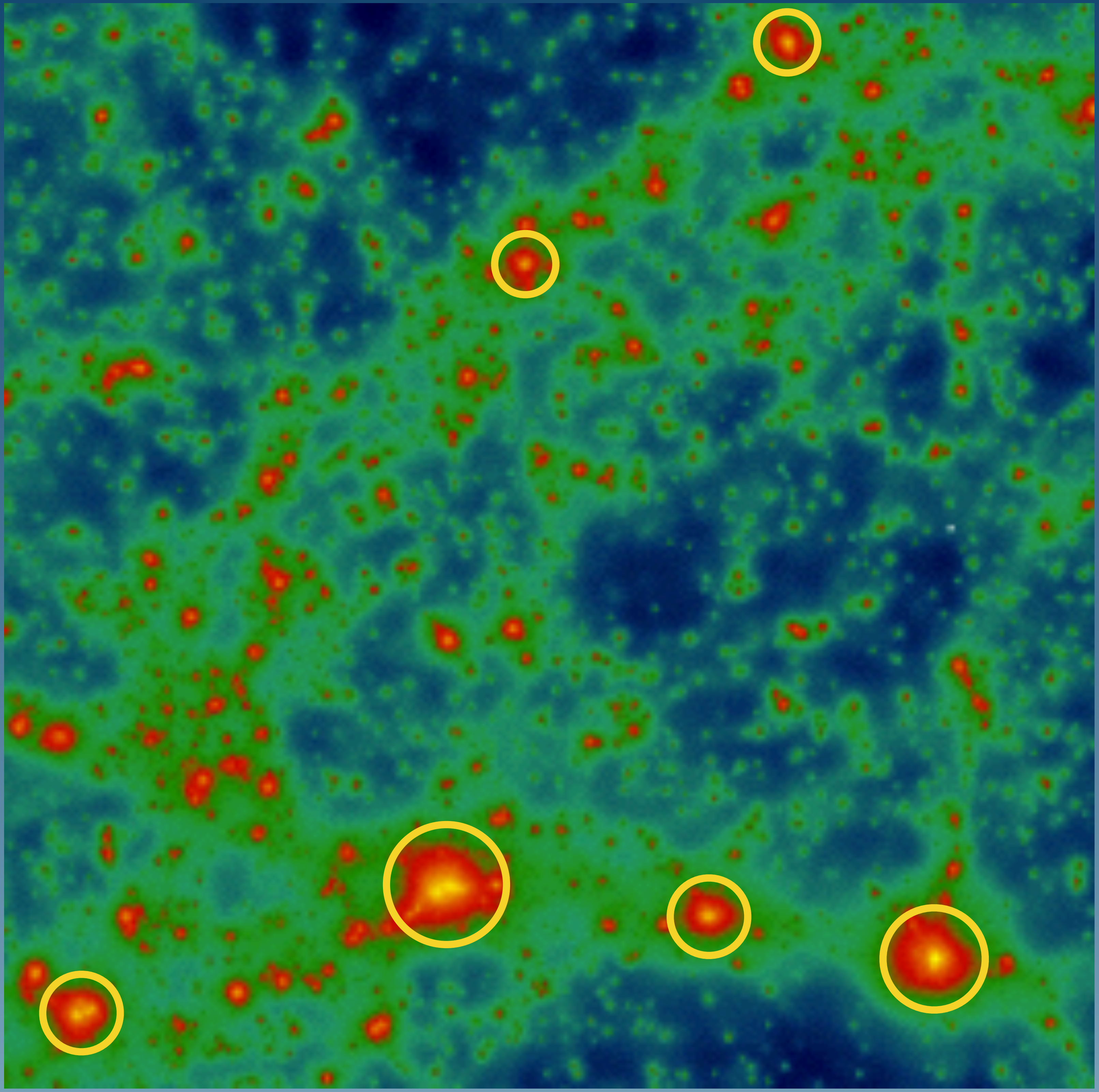
Outer disk will be unstable and forming stars

therefore, $\dot{M}_{acc}$ > SFR of the outer disk, otherwise a gap will open up, shutting off the mass transfer

$$\dot{M}_{BH} \propto \dot{M}_*$$

“AGN” feedback algorithm

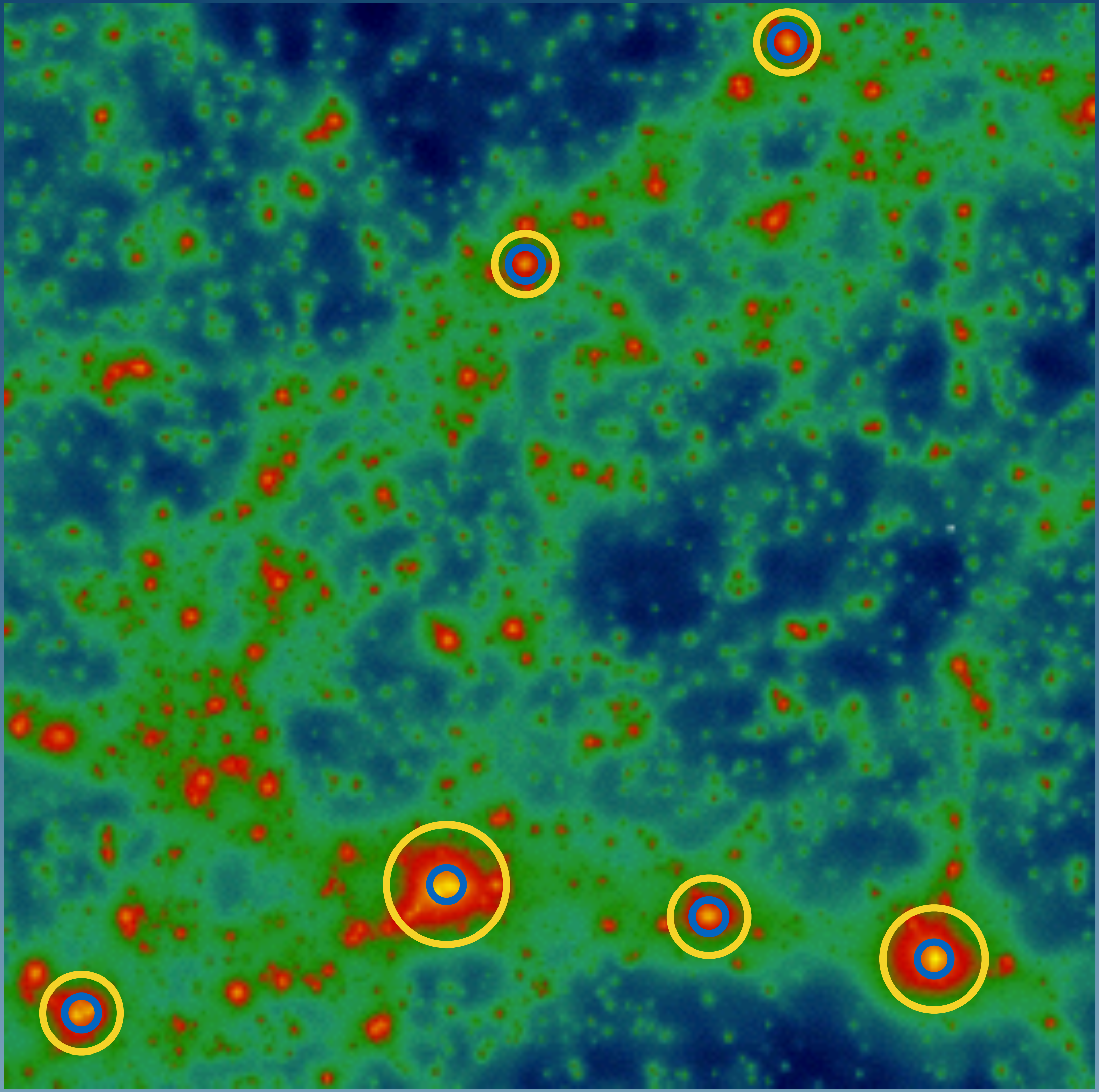
every “duty cycle” Δt
Identify halos via FOF



“AGN” feedback algorithm

every “duty cycle” Δt
Identify halos via FOF

Calculate the SFR with each R_{AGN}



"AGN" feedback algorithm

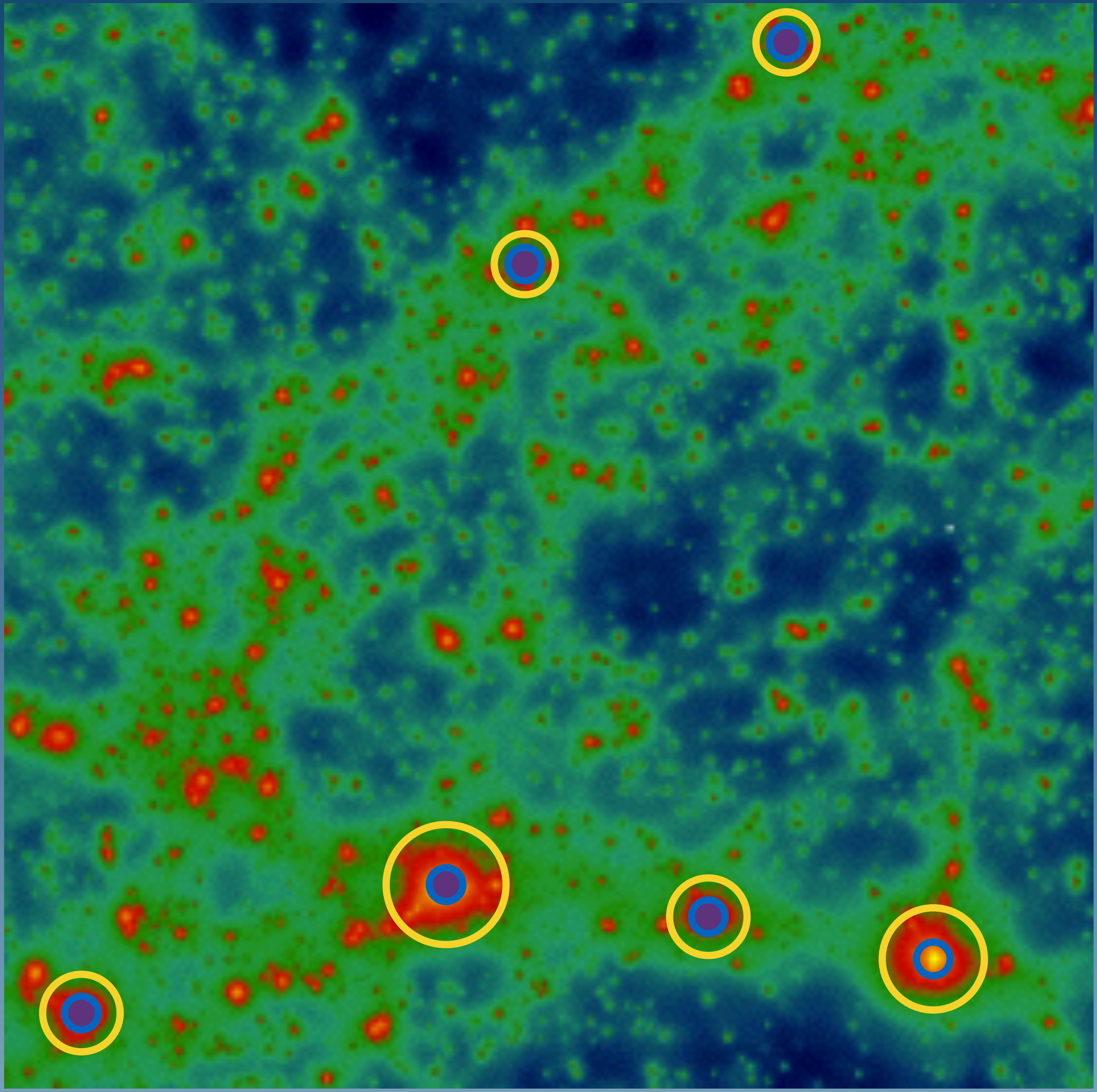
every "duty cycle" (Δt)
Identify halos via FOF

Calculate the SFR with each R_{AGN}

Inject thermal energy inside R_{AGN}, if SFR threshold is reached

$$E_{inj} = \varepsilon_r \dot{M}_* c^2 \Delta t$$

Repeat next Δt



"AGN" feedback parameters

$$f_{star}(<r) = \frac{M_{star}(<r)}{M_{TOT}(<r)}$$

Match a previous AGN model

$\Delta t = 10^8$ yr

$$R_{\rm AGN} = \max\left\{100\,h^{-1}\,{\rm kpc} \times \left[\frac{M_{\rm halo}}{10^{15}\,h^{-1}M_{\odot}\,E(z)^2}\right]^{1/3}, \frac{u_{\rm AGN}}{1+z}\right\},$$

~ 1/20 of R_{vir}

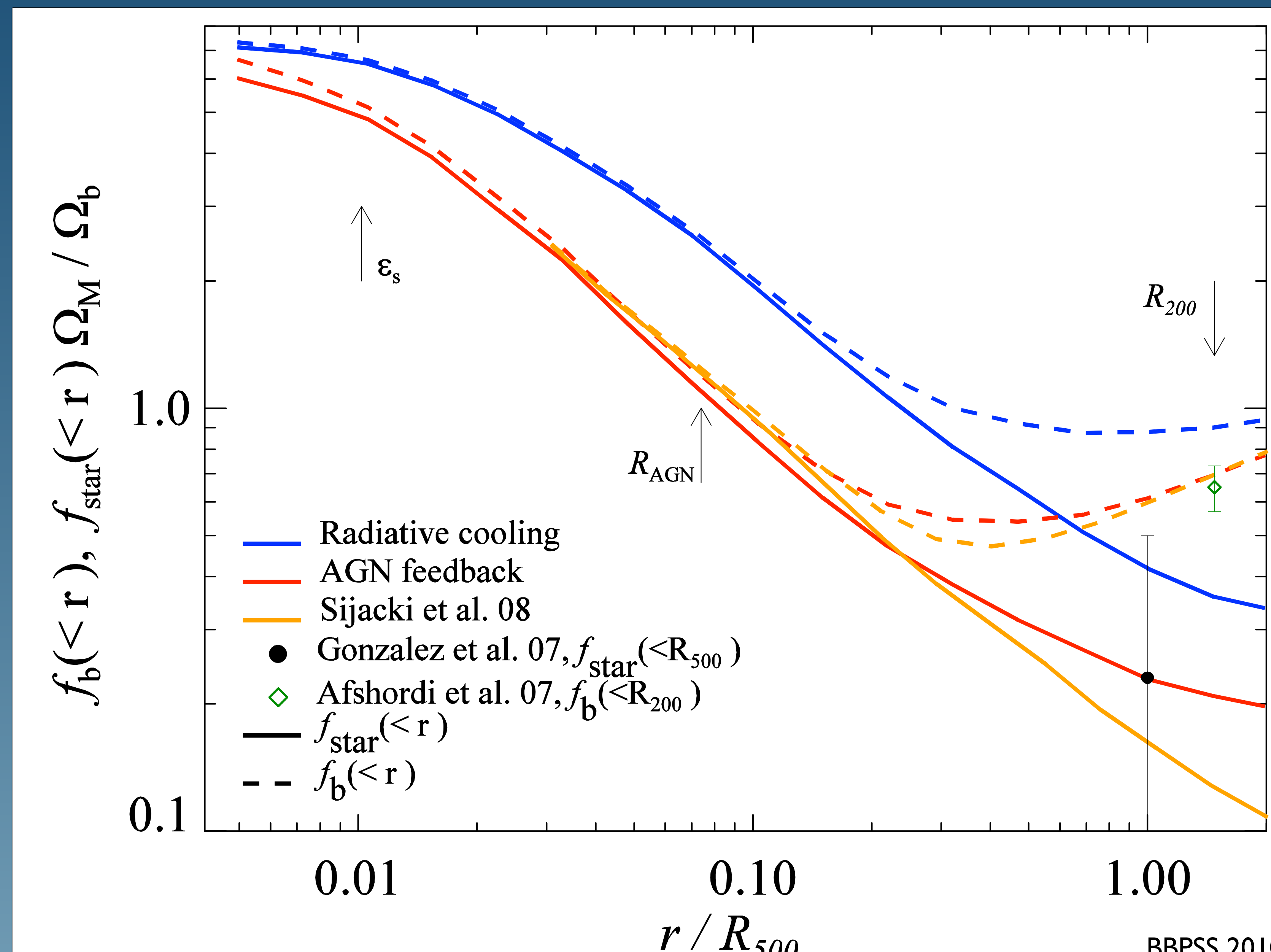
ε_r = 2 x 10-4

Many factors go into ε_r

M_{BH} to $M_\star$

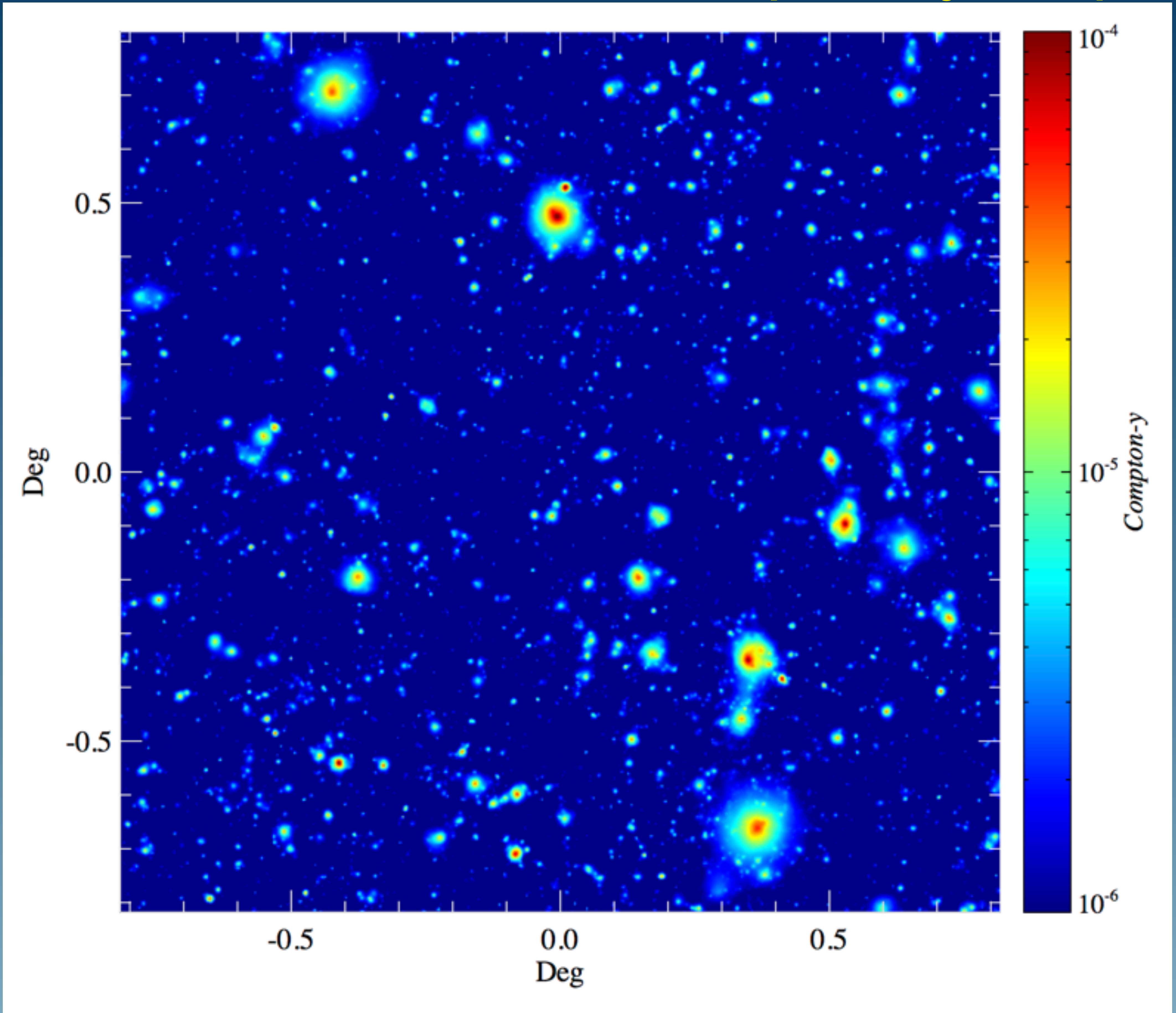
True efficiency is much lower

$\varepsilon_r = 5 \times 10^{-6}$

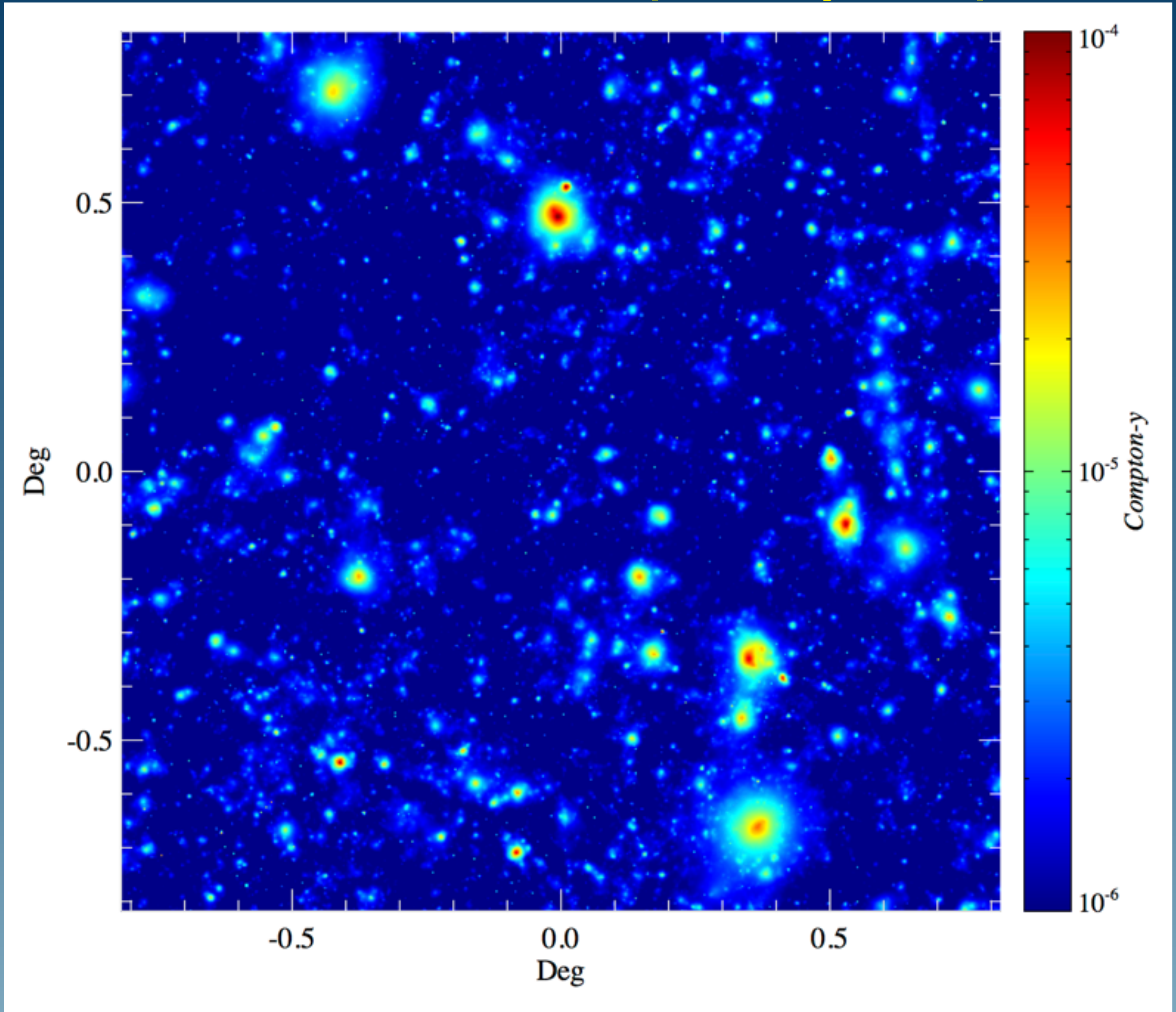


E_{inj} (z) → ~ 60% at z > 2, 20% at 2 < z < 1, and 20% at z < 1

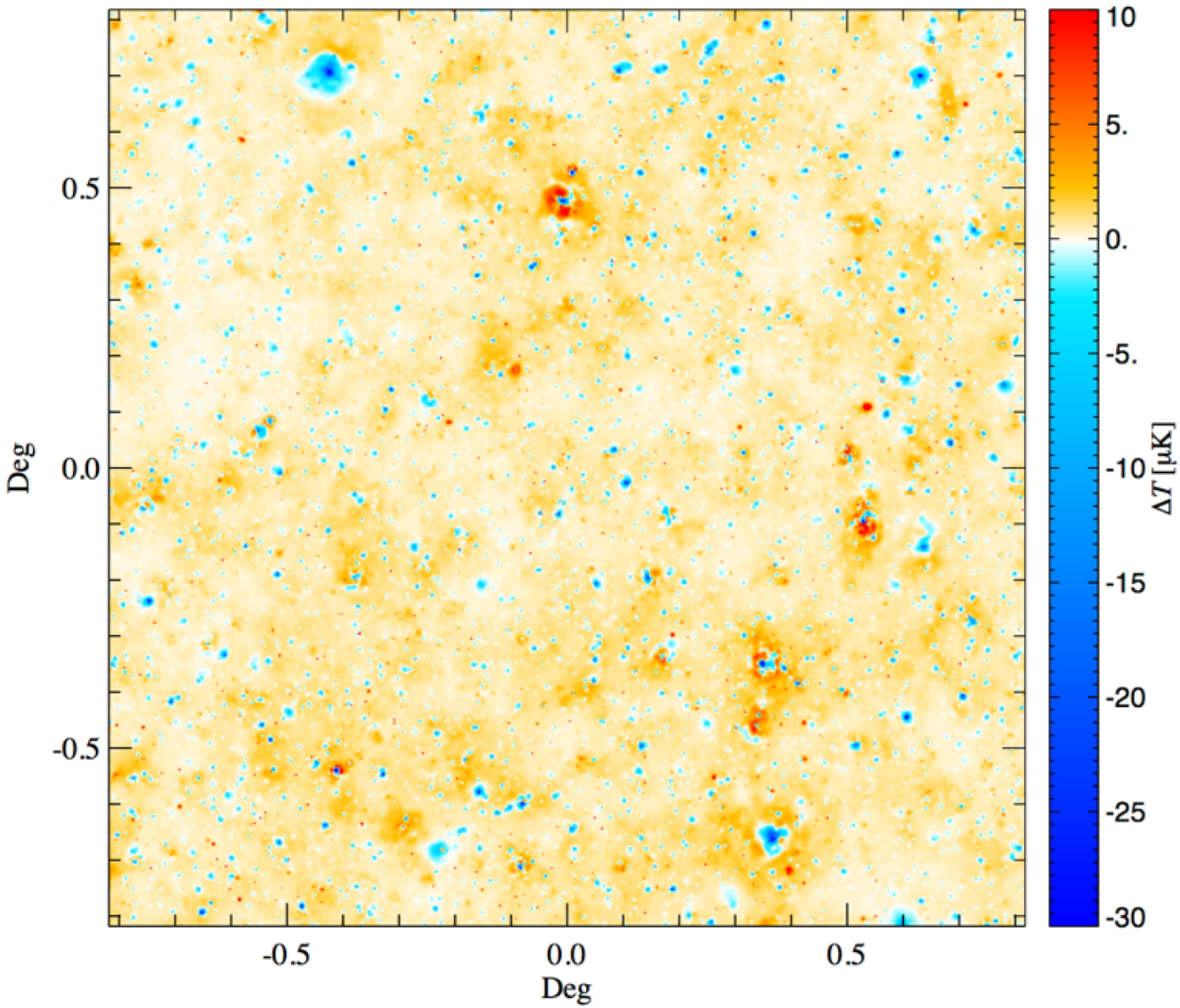
c+sf+w+SNe+CR Compton-y map



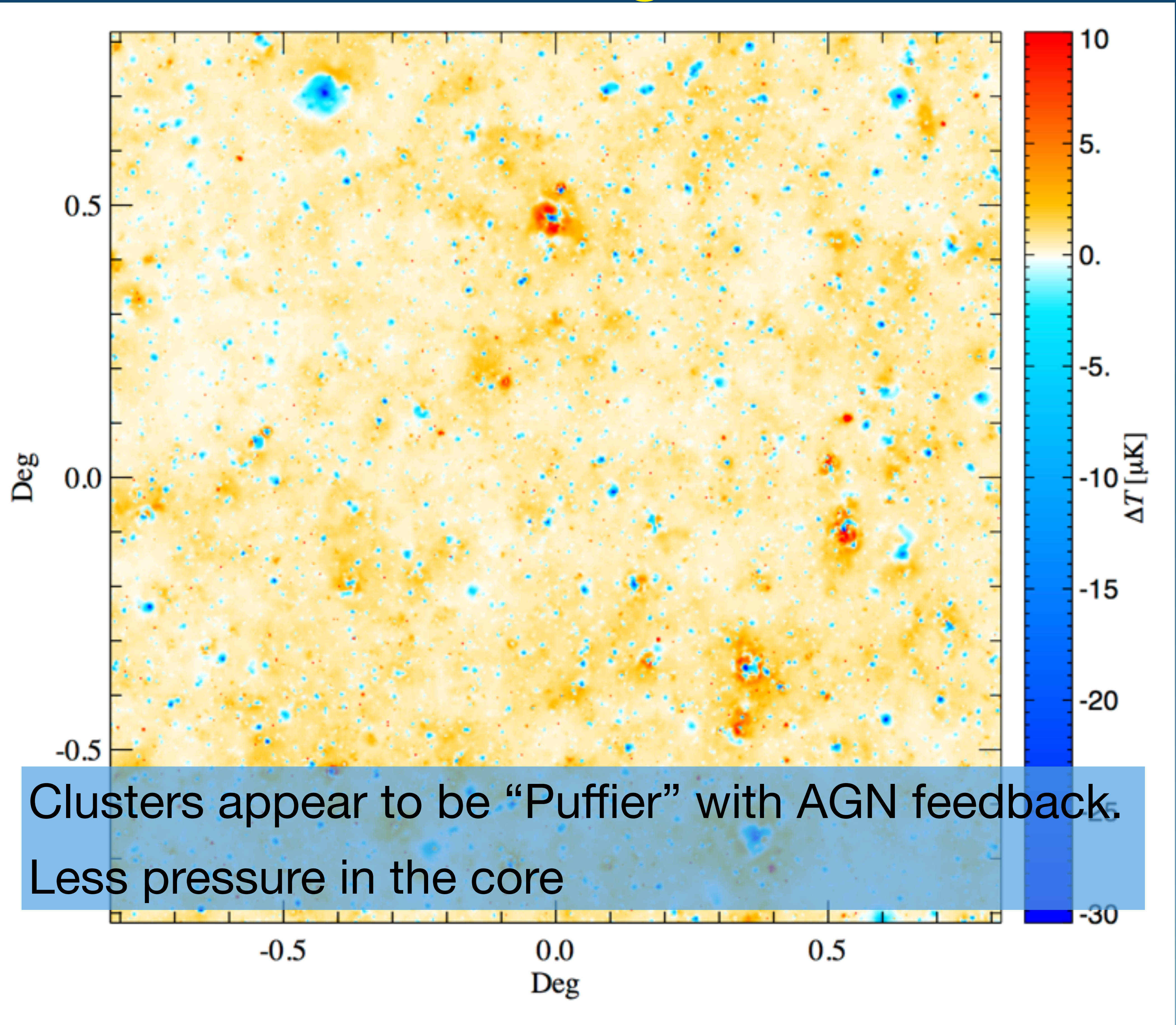
Feedback Compton-y map



Radiative cooling - Feedback



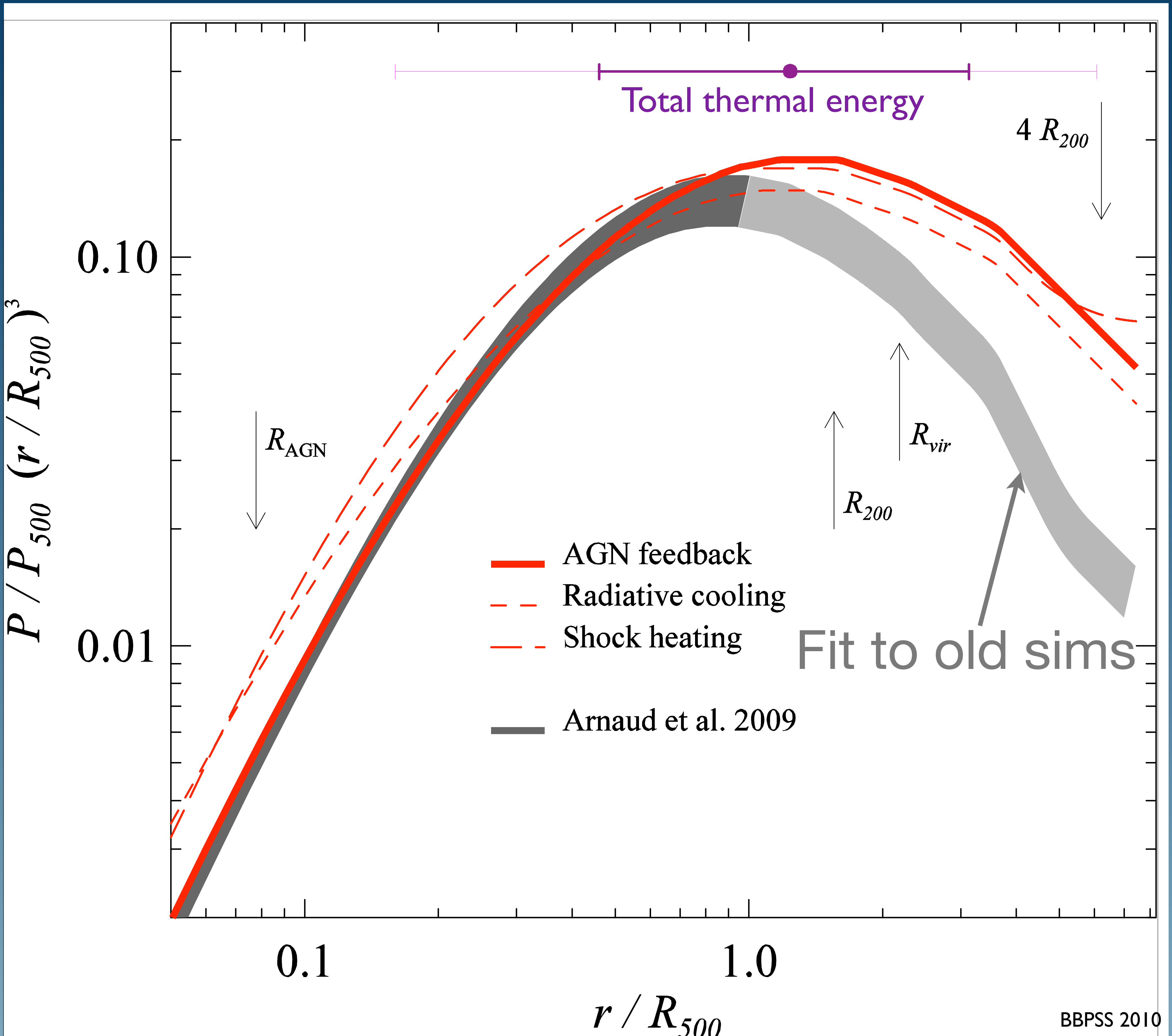
Radiative cooling - Feedback



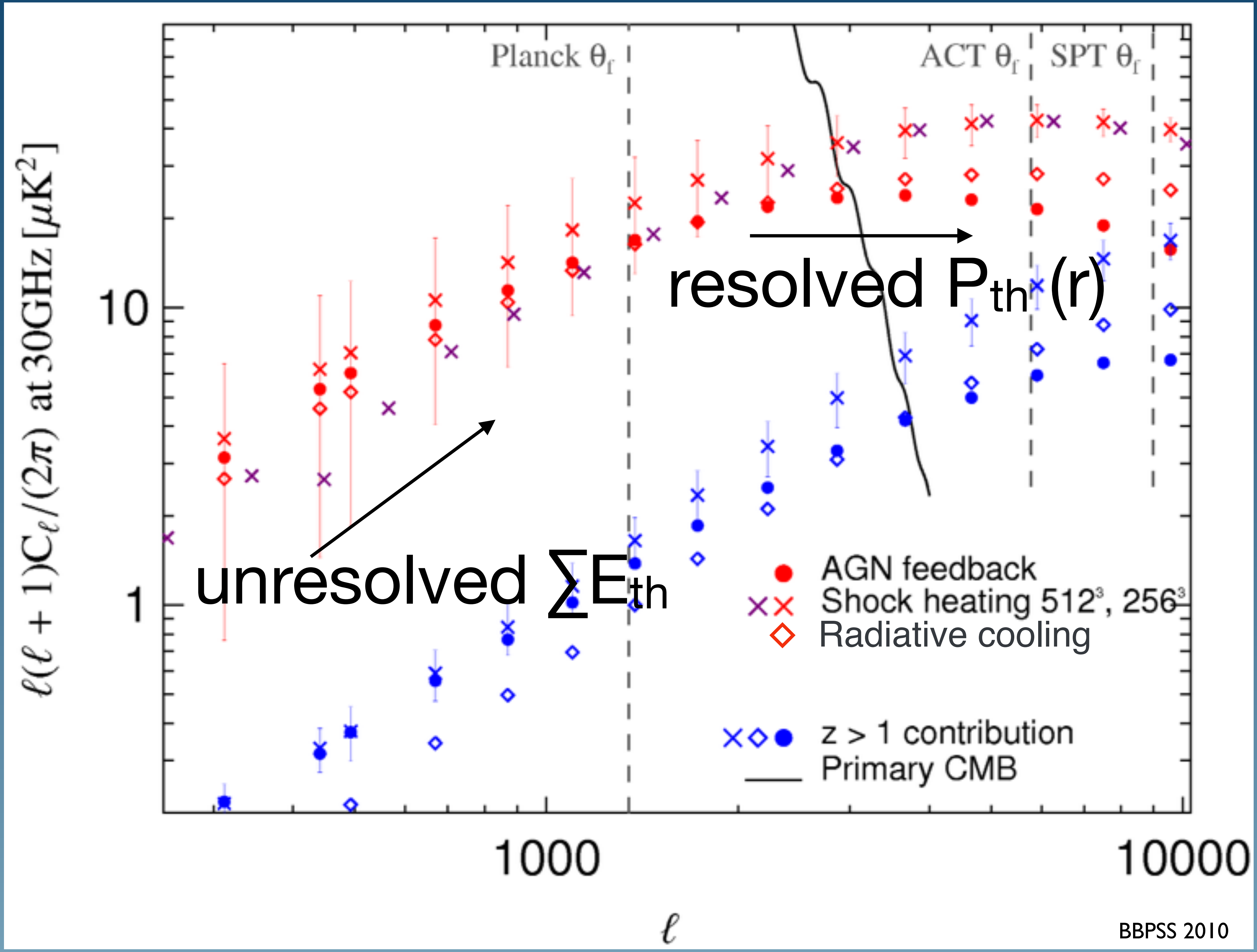
Clusters appear to be "Puffier" with AGN feedback.

Less pressure in the core

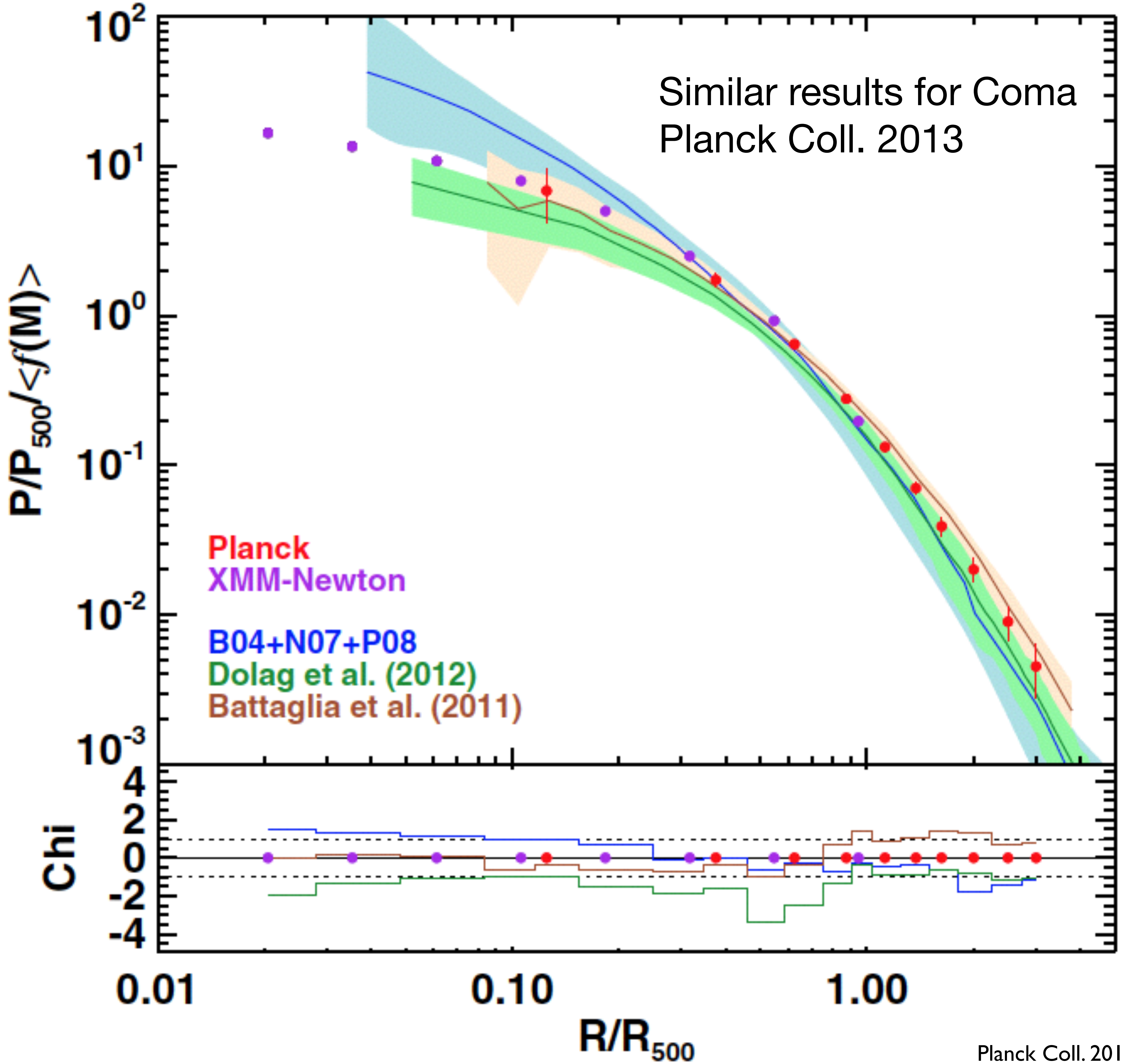
Simulation P_{th} Profile



tSZ PS

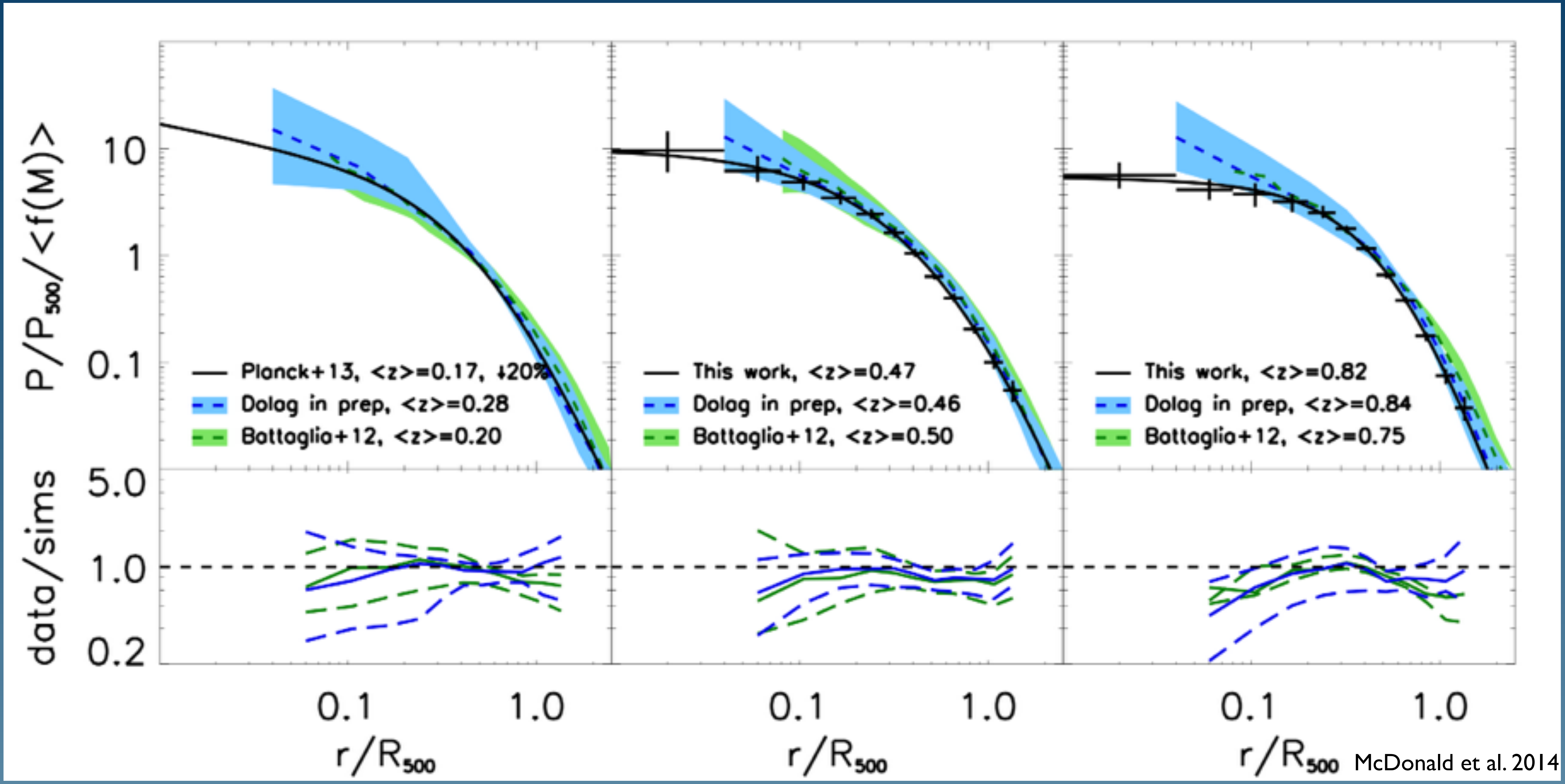

Planck θf
ACT θf
SPT θf
resolved $P_{th}(r)$
unresolved $\sum E_{th}$
AGN feedback
Shock heating 512³, 256³
Radiative cooling
z > 1 contribution
Primary CMB
10
1
1000
10000
$\ell(\ell+1)C_\ell/(2\pi)$ at 30GHz [μK^2]
ℓ
BBPSS 2010

Planck P_{th} Profile



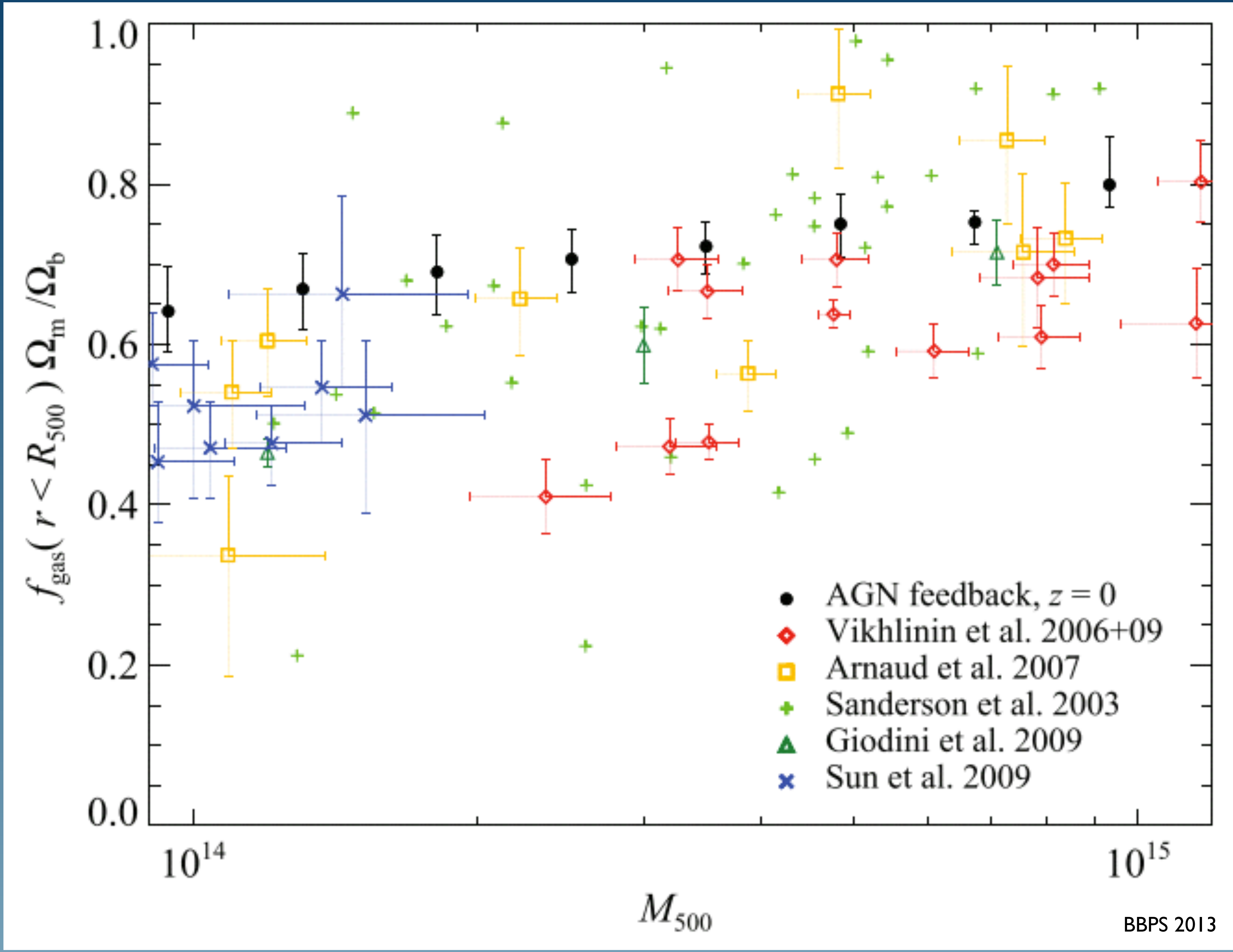
Planck Coll. 2013

SPT P_{th} Profile z > 0.3

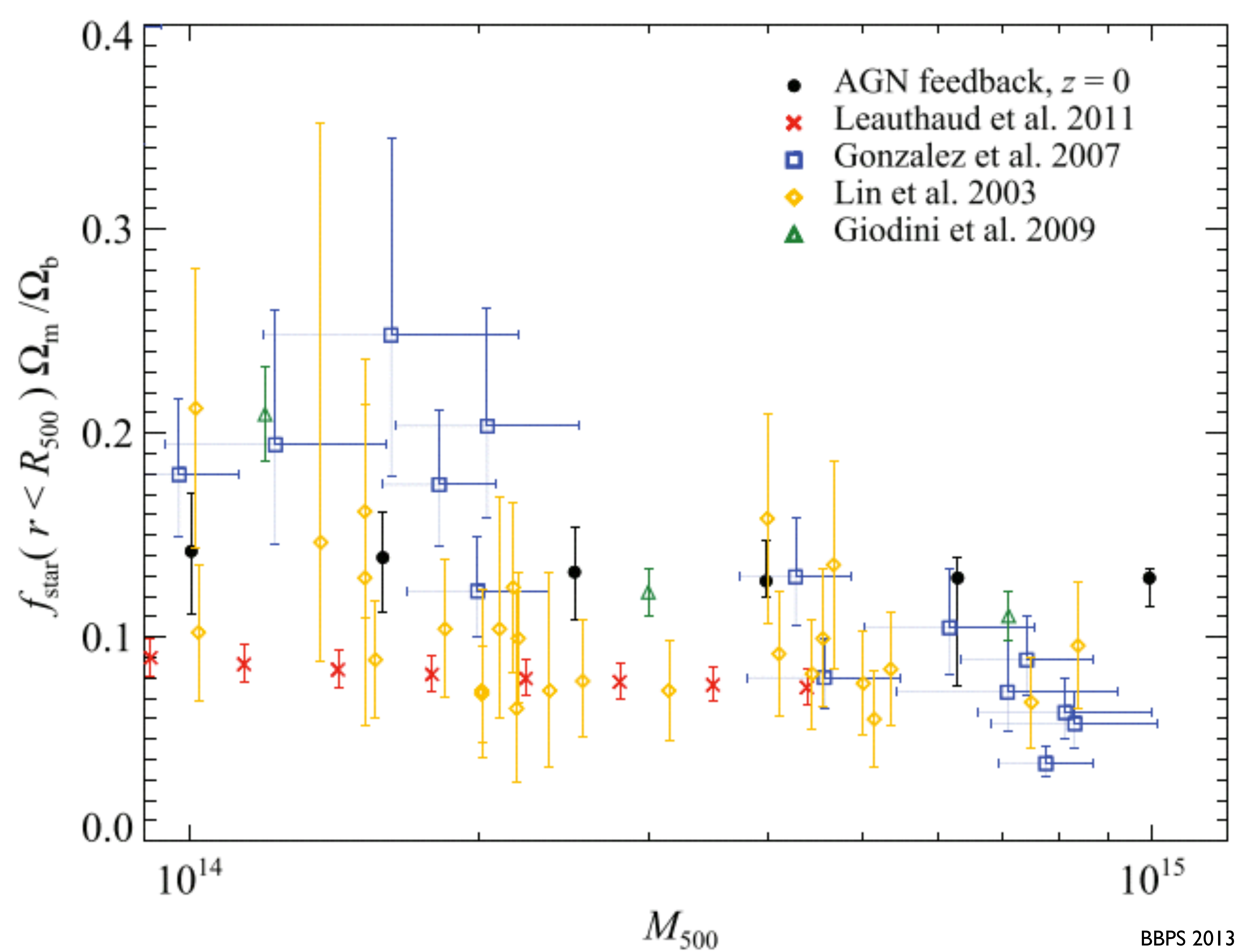


Simulations do well to match the observed pressure profile at higher redshifts too

Cluster baryons observations z ~ 0

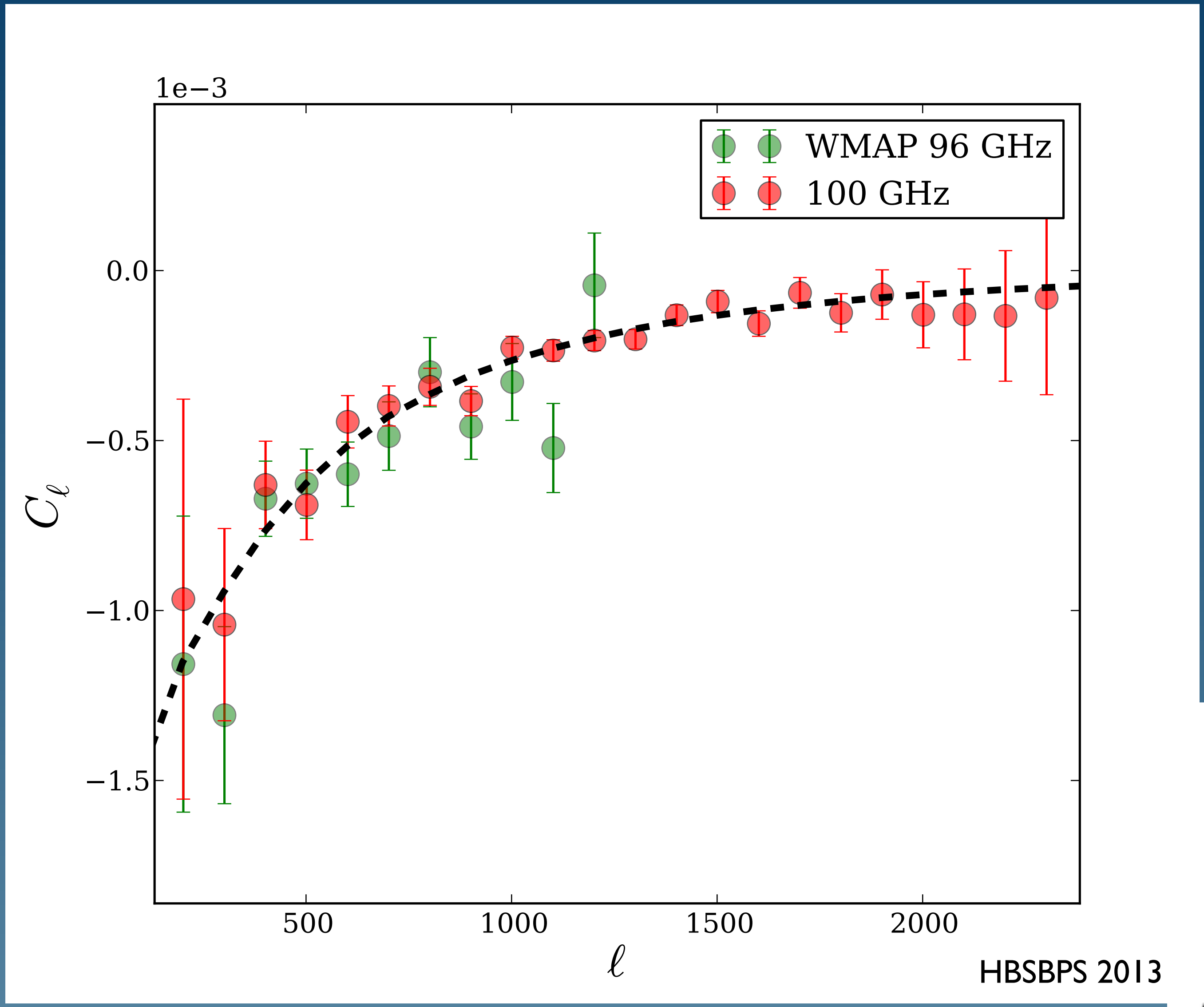


Cluster baryons observations z ~ 0



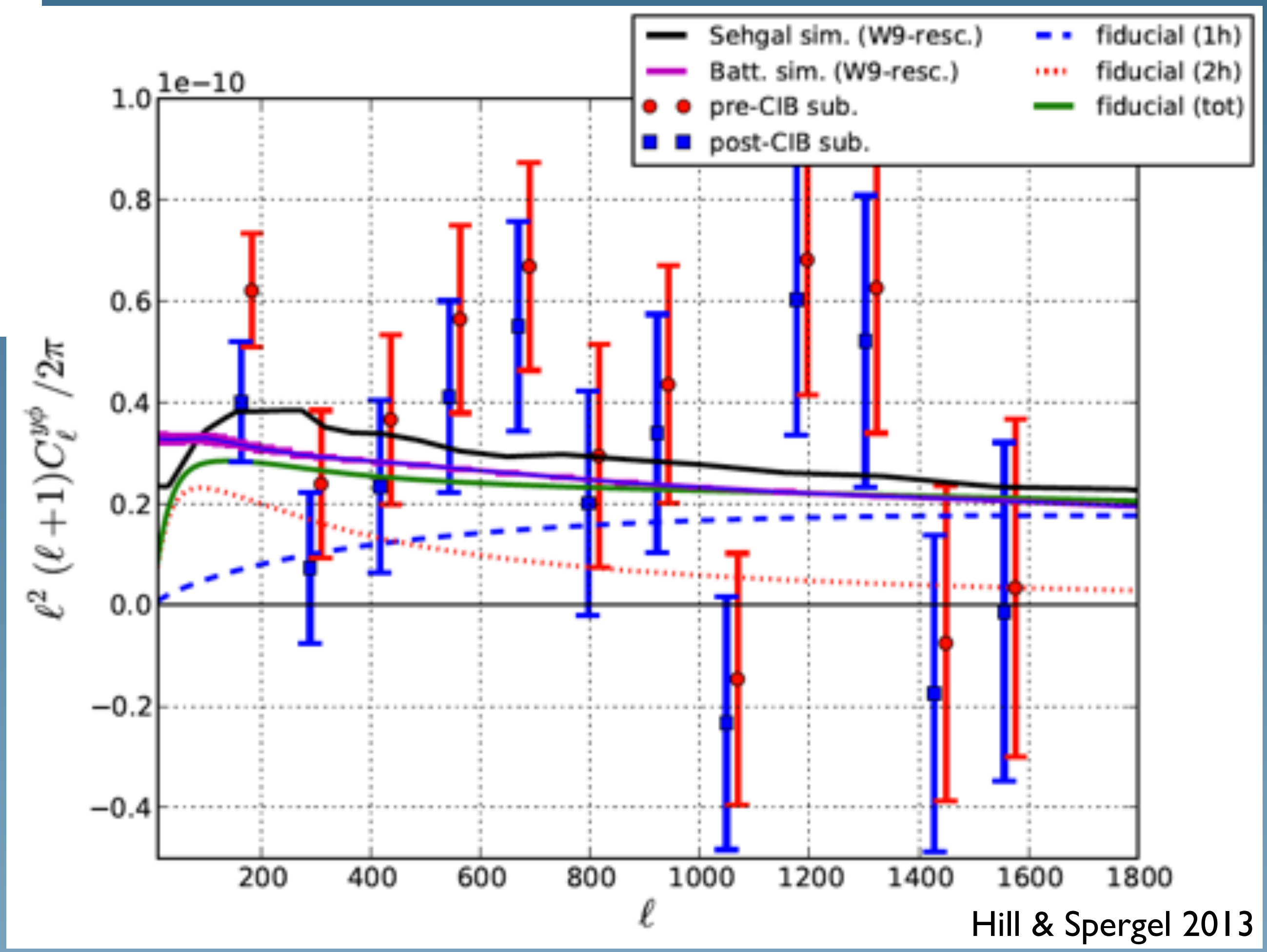
BBPS 2013

Other cross-correlations

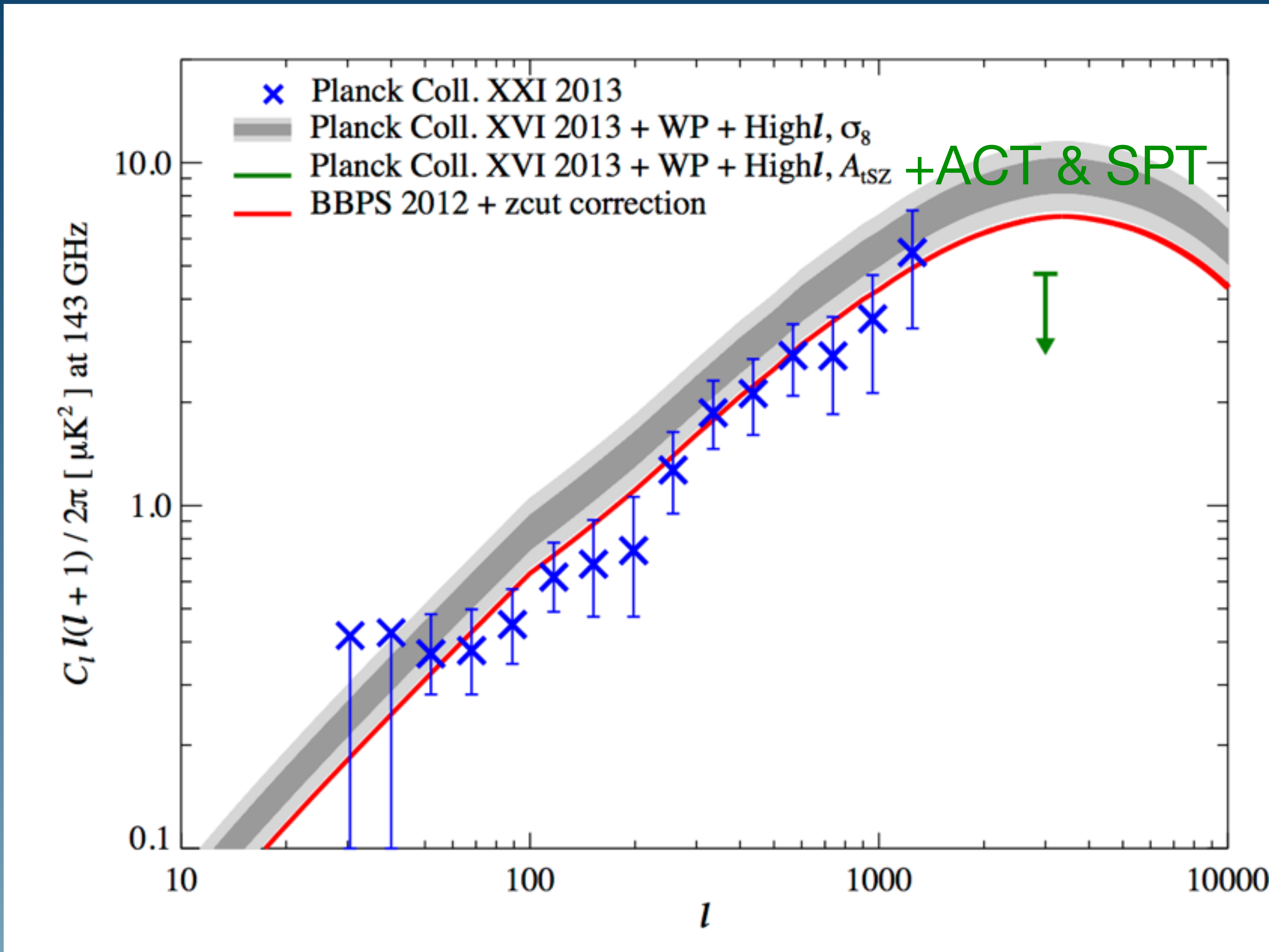


x-ray cluster locations cross-correlated with CMB matched by sims
Lower redshift
Higher halo mass

CMB lensing potential cross-correlated with y matched by sims
- Higher redshift
- Lower halo mass



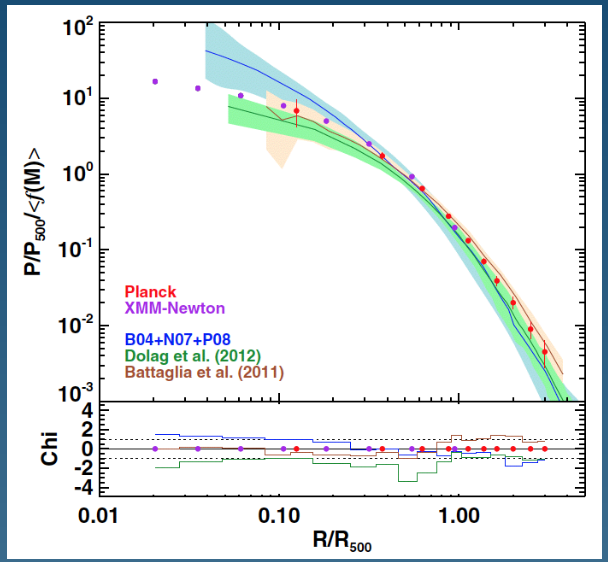
Caution…



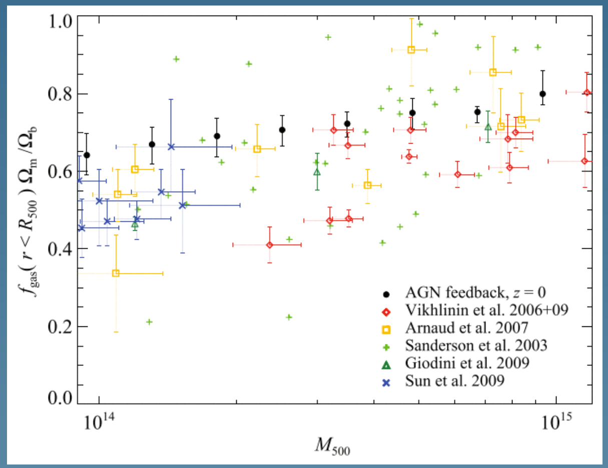
Planck Coll. XXI 2013
Planck Coll. XVI 2013 + WP + High$l$, σ_8
Planck Coll. XVI 2013 + WP + High$l$, A_{tSZ}
BBPS 2012 + zcut correction
+ACT & SPT
10.0
1.0
0.1
10
100
1000
10000
l
$C_l\, l(l+1) / 2\pi$ [μK^2] at 143 GHz

Final thoughts

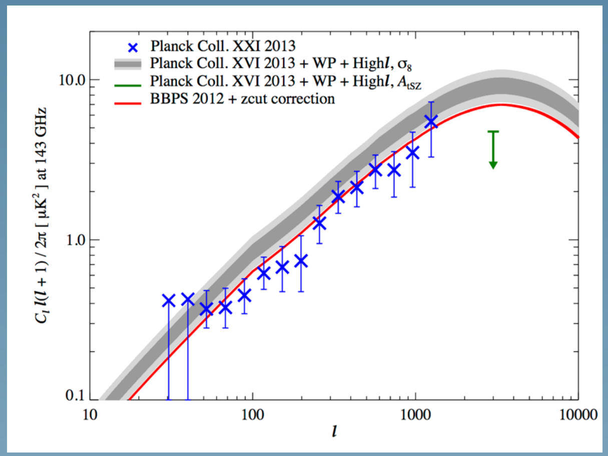
This coarse grid “AGN” feedback model compares well against the current ICM observables (not tuned that way…)



However ICM modeling is not finished there are still open issues



In the pipeline - new simulations modified feedback models

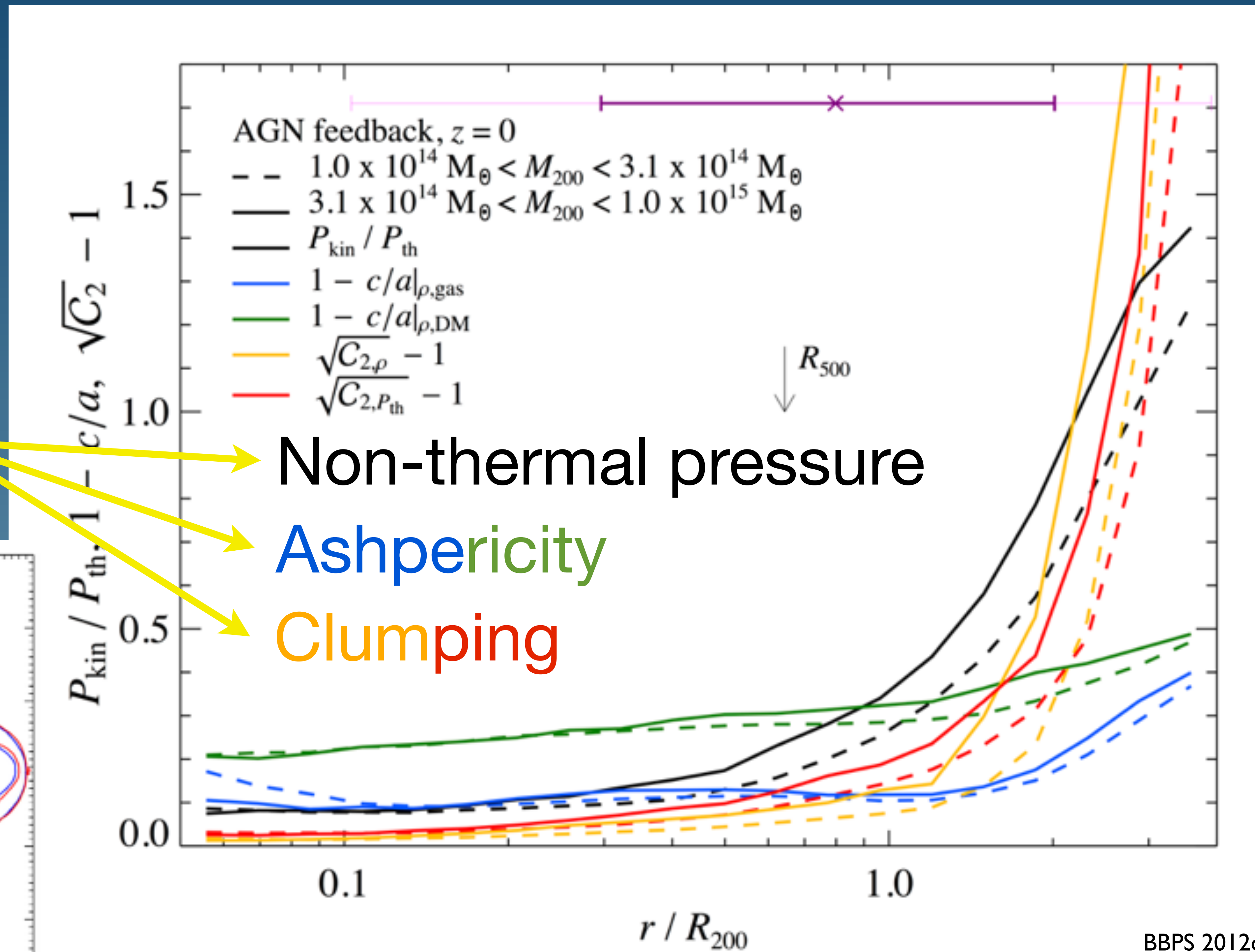


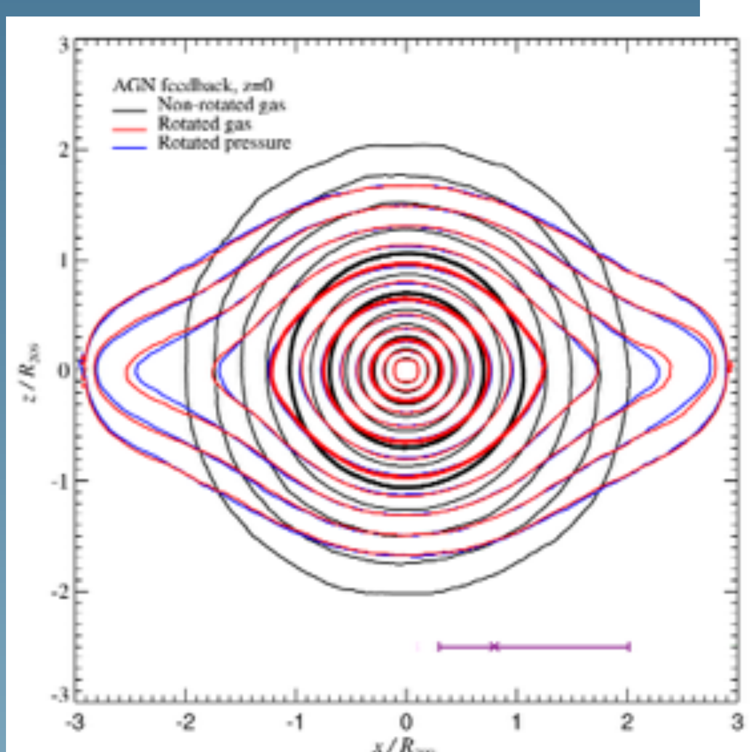
Data driving the theory...

Thank you!

Into the ICM Outskirts

Beyond R_{200}:
- Not currently constrained by observations.
- Increases in





Mass proxies & form-factors

Cluster counts

Selection function & Mass proxy

$$N = \int_0^{z_{\max}} dz \frac{dV}{dz} \int dM \frac{dn(M,z)}{dM}$$

Gastrophysics

tSZ power spectrum $A_{tSZ} \propto \sigma_8^{8}$

$$C_l = g_\nu^2 \int_0^{z_{\max}} dz \frac{dV}{dz} \int dM \frac{dn(M,z)}{dM} \left|\tilde{y}_l(M,z)\right|^2$$

+ Clustering of clusters (Sub-dominant)