Two Interesting Results on Clusters of Galaxies

Eiichiro Komatsu (Texas Cosmology Center, Univ. of Texas at Austin)
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Two New Results

1. We find, *for the first time in the Sunyaev-Zel'dovich (SZ) effect*, a significant difference between relaxed and non-relaxed clusters.
   - Important when using the SZ effect of clusters of galaxies as a cosmological probe.
2. The existence of Bullet Cluster poses a challenge to the standard ΛCDM cosmology.
   - Or, a challenge to something else.

Clusters and Cosmology

- Clusters offer a powerful probe of cosmology, including the nature of dark energy and tests of General Relativity on cosmological scales.
- In order for this method to work, one must know **how the observables** (e.g., temperature, X-ray luminosity, the Sunyaev-Zel'dovich effect) **are related to the mass of clusters**.
- *Why?*

Theory gives the *mass function, dn/dM*

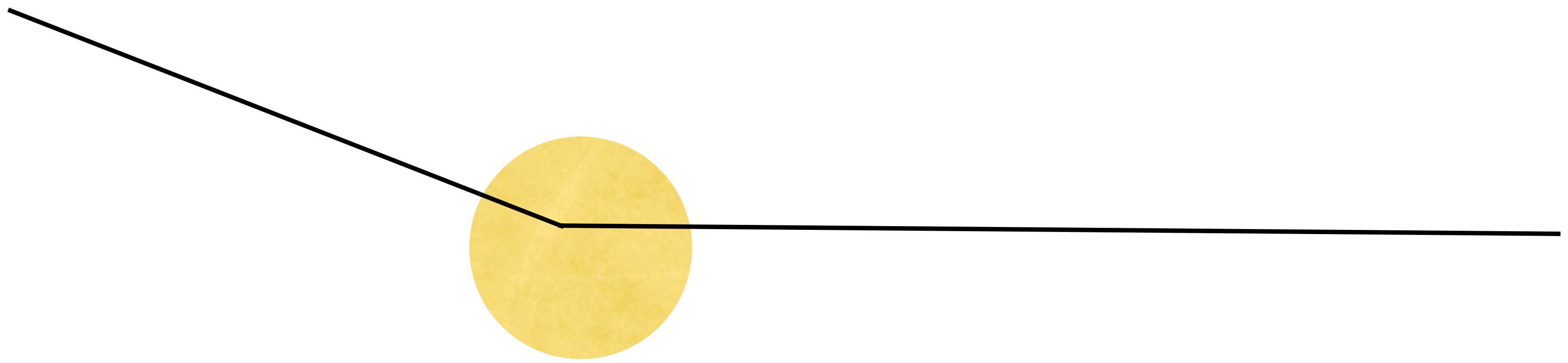
- The number of clusters as a function of redshift and mass, dn/dM, is called the mass function.
  - This function depends primarily on the amplitude (root mean square) of matter density fluctuations, σ(M,z). This quantity traces the growth of structure.
    - σ(M,z) is proportional to 1/(1+z) during the matter era.
    - σ(M,z) does not depend on z during the cosmological-constant dominated era.

Observables to dn/dM

- Therefore, we must compare the observed number of clusters to dn/dM.
  - We don't usually measure the mass of clusters directly, so we must relate the observables to the mass.
  - M–temperature; M–luminosity; M–SZ; etc
  - If this mapping is incorrect, we would infer a wrong cosmology!
- Understanding the physics of clusters themselves is very important. ***Do we understand it?***

Zel’dovich & Sunyaev (1969); Sunyaev & Zel’dovich (1972)

Sunyaev–Zel’dovich Effect



observer

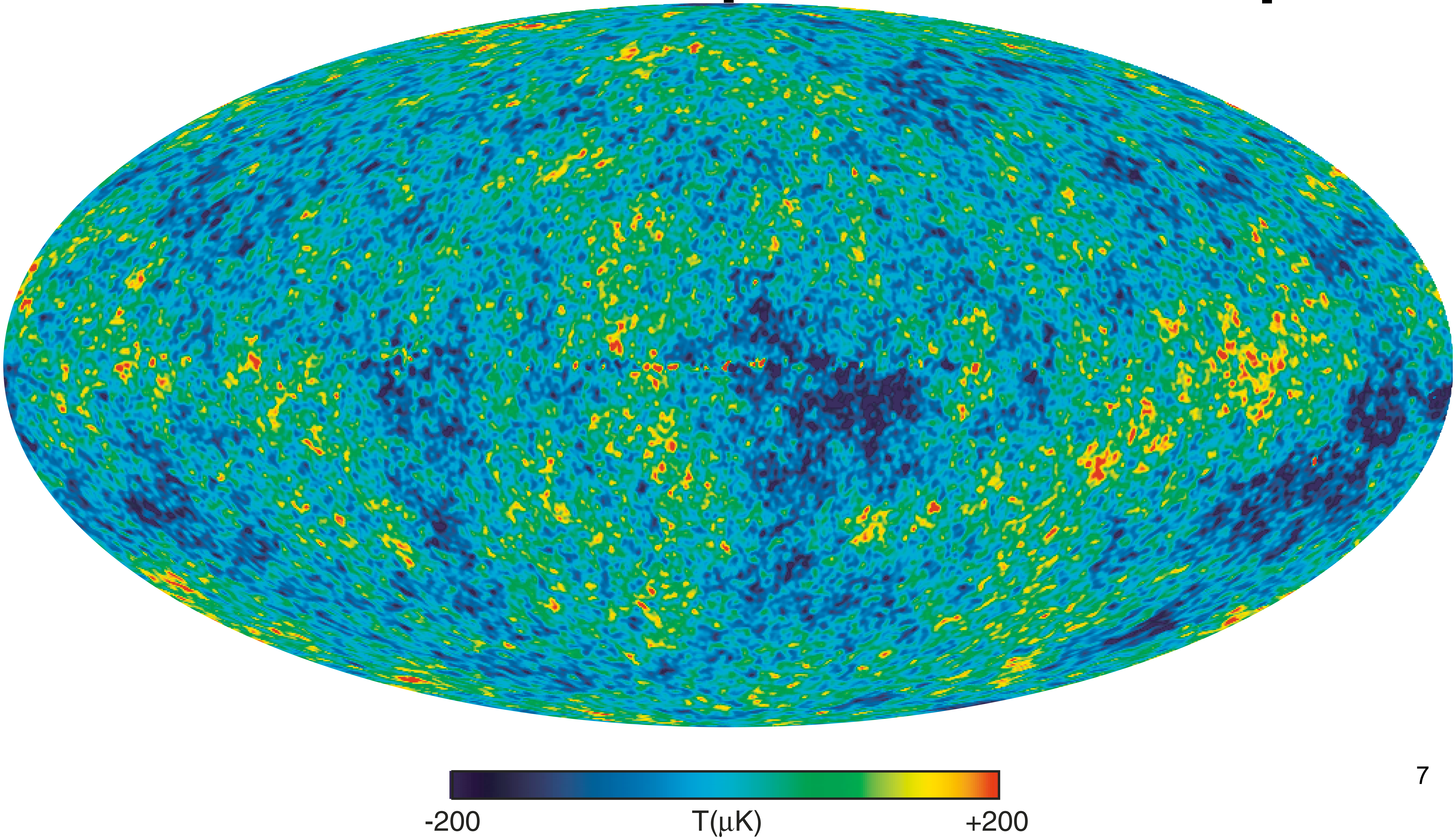
Hot gas with the
electron temperature of $T_e >> T_{cmb}$

- $\Delta T/T_{cmb} = g_\nu \mathbf{y}$

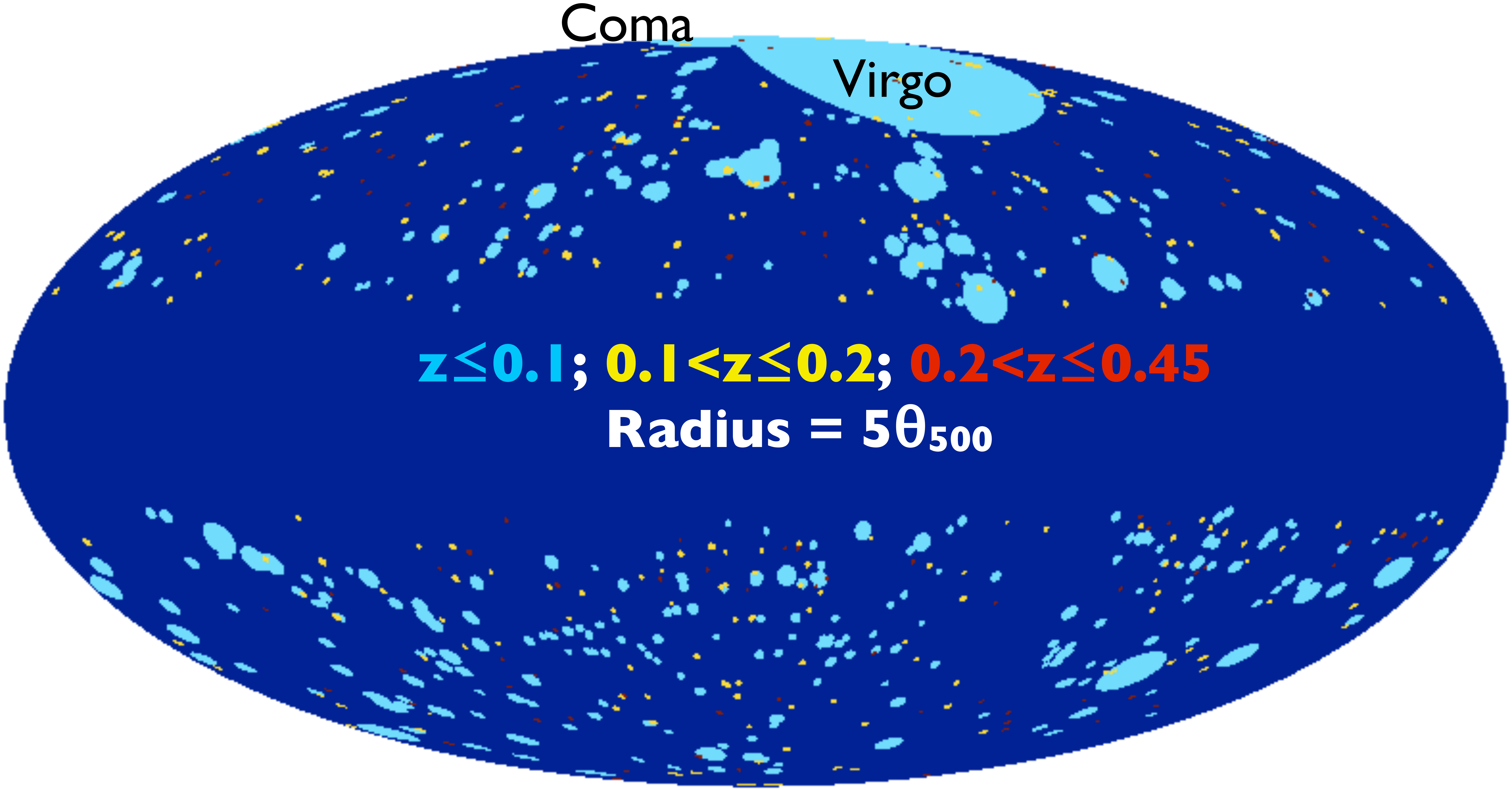
$$
\begin{aligned}
y &= (\text{optical depth of gas})\, k_B T_e/(m_e c^2) \\
&= [\sigma_T/(m_e c^2)] \int n_e k_B T_e \, d(\text{los}) \\
&= [\sigma_T/(m_e c^2)] \int (\textbf{electron pressure})\, d(\text{los})
\end{aligned}
$$

$g_\nu=-2$ ($\nu=0$); -1.91, -1.81 and -1.56 at $\nu=41$, 61 and 94 GHz

WMAP Temperature Map



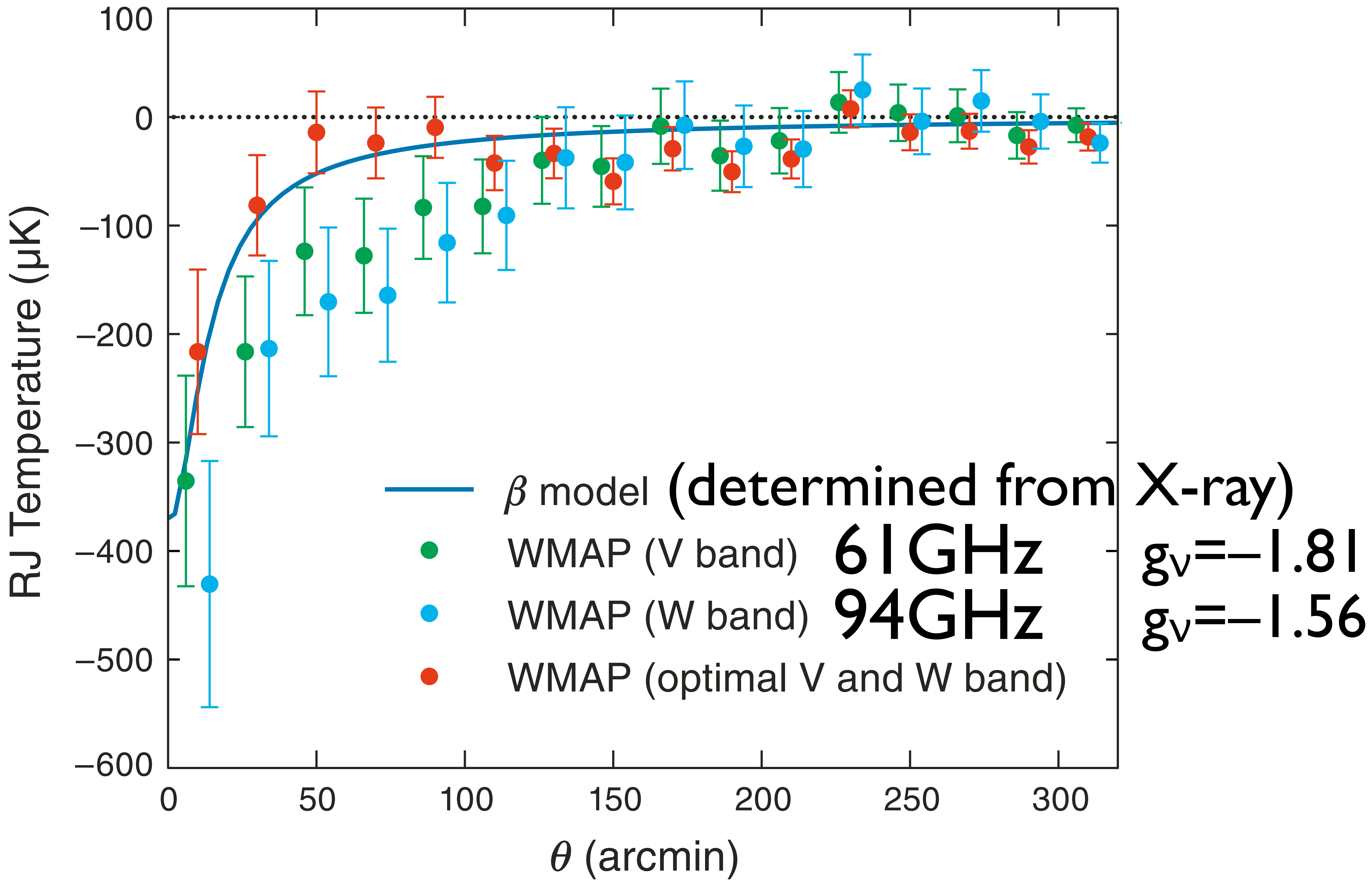
Where are clusters?



Coma Cluster (z=0.023)

We find that the CMB fluctuation in the direction of Coma is ≈ −100uK. (This is a new result!)

$y_{\mathrm{coma}}(0)=(7\pm2)\times10^{-5}$ (68%CL)



(determined from X-ray)

61GHz $g_\nu=-1.81$

94GHz $g_\nu=-1.56$

- "Optimal V and W band" analysis can separate SZ and CMB. The SZ effect toward Coma is detected at **3.6σ**.

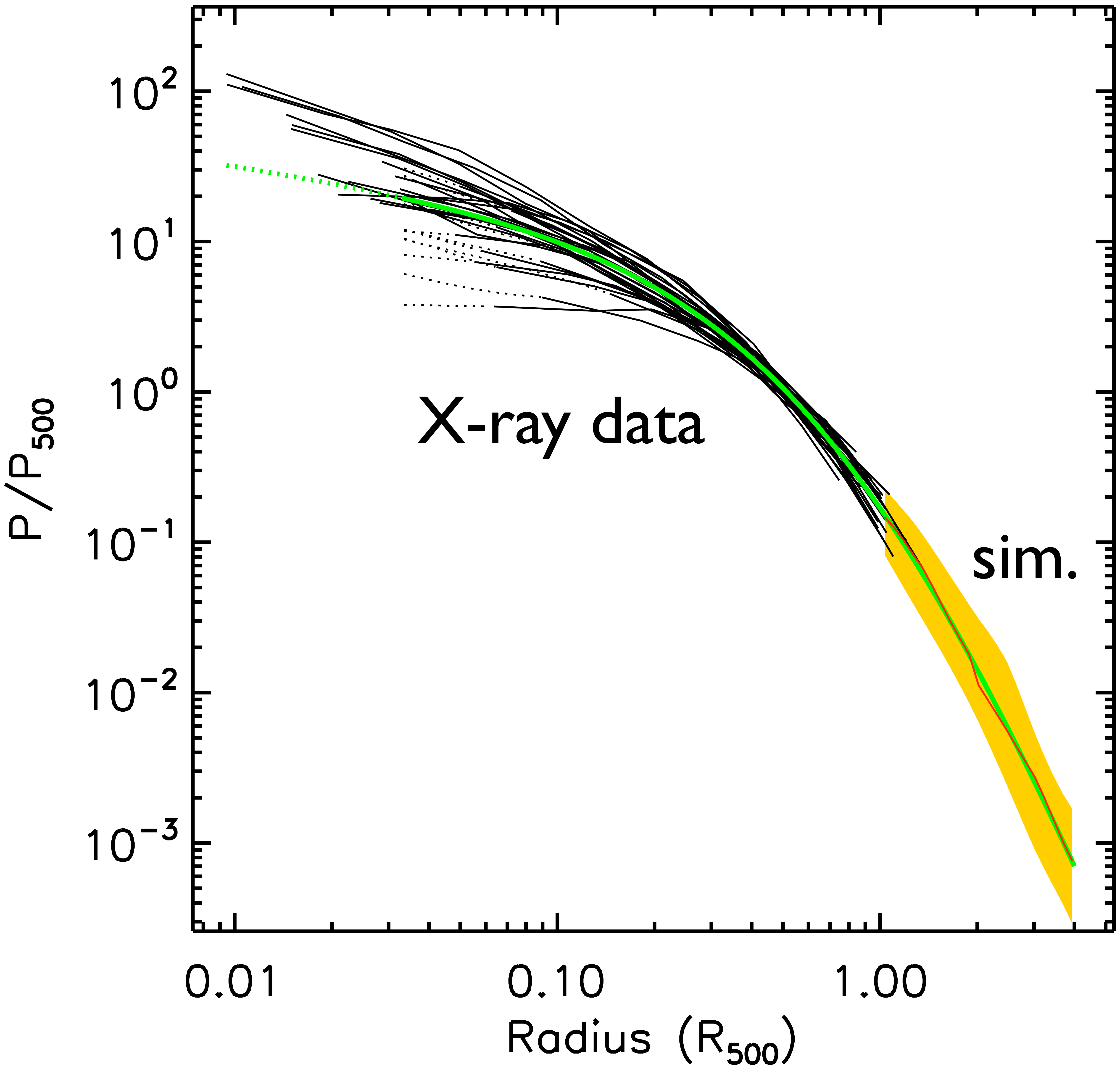
A Question

- Are we detecting the ***expected*** amount of electron pressure, P_e, in the SZ effect?
  - Expected from X-ray observations?
  - Expected from theory?

Arnaud et al. Profile

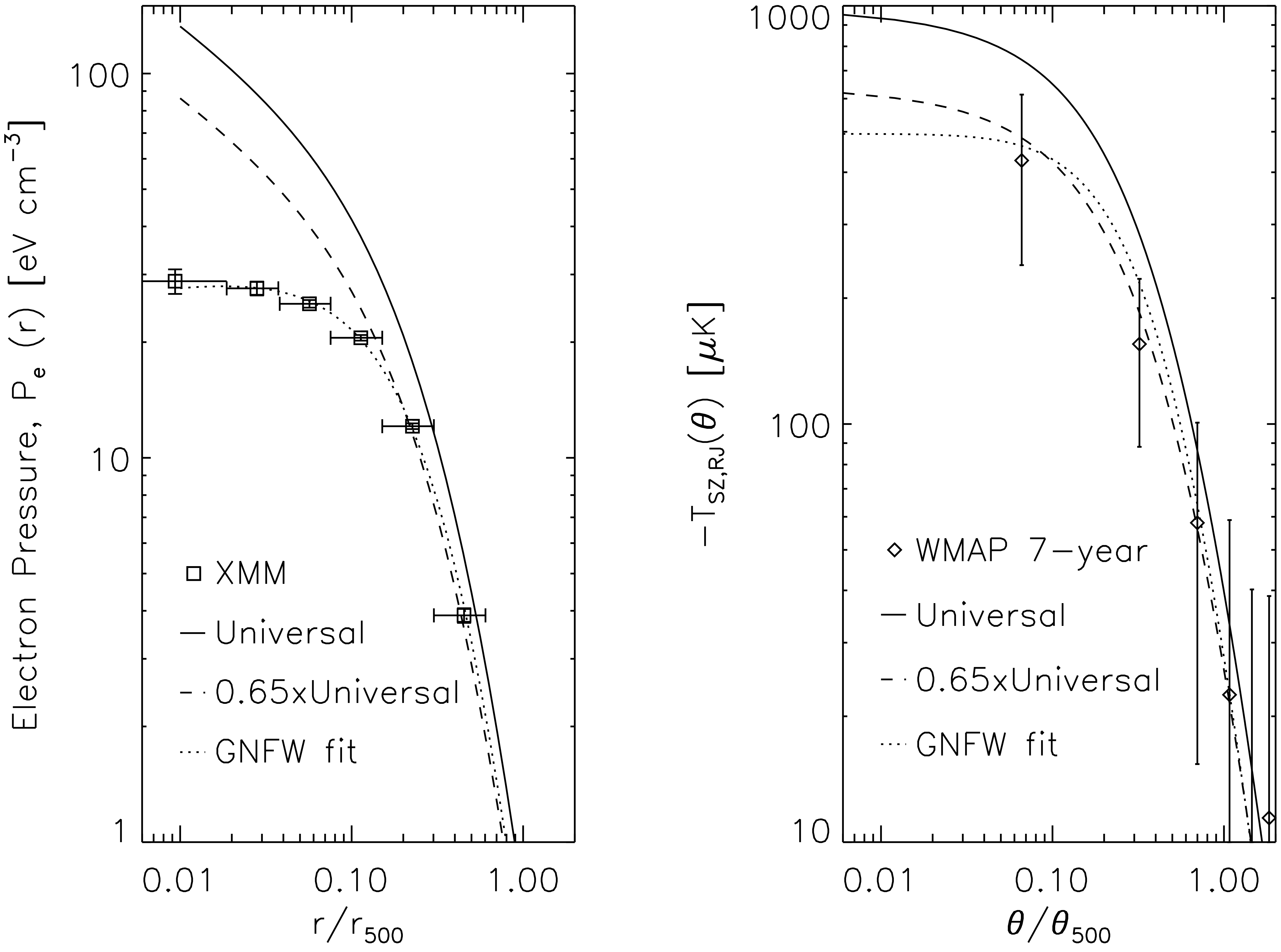
- A fitting formula for the average electron pressure profile as a function of the cluster mass (M_{500}), derived from 33 nearby ($z<0.2$) clusters.

Arnaud et al. Profile



- A significant scatter exists at $R<0.2R_{500}$, but a good convergence in the outer part.

Coma Data vs Arnaud



The X-ray data (XMM) are provided by A. Finoguenov.

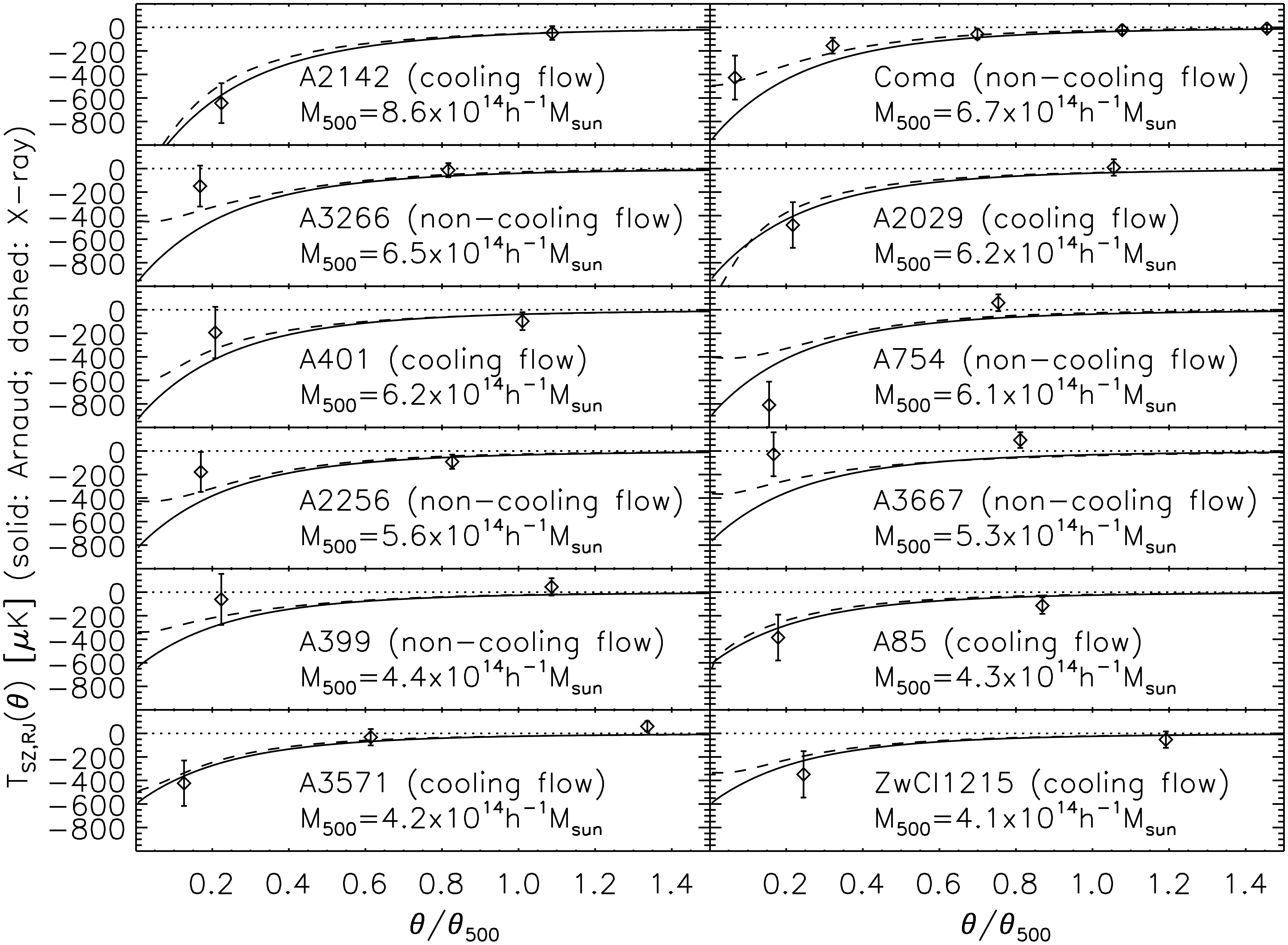
- $M_{500}=6.6\times10^{14}h^{-1}M_{sun}$ is estimated from the mass-temperature relation (Vikhlinin et al.)
  - T_X^{coma} =8.4keV.
- Arnaud et al.'s profile overestimates both the direct X-ray data and WMAP data by the same factor (0.65)!
  - To reconcile them, Tx^{coma}=6.5keV is required, but that is way too low.

Well...

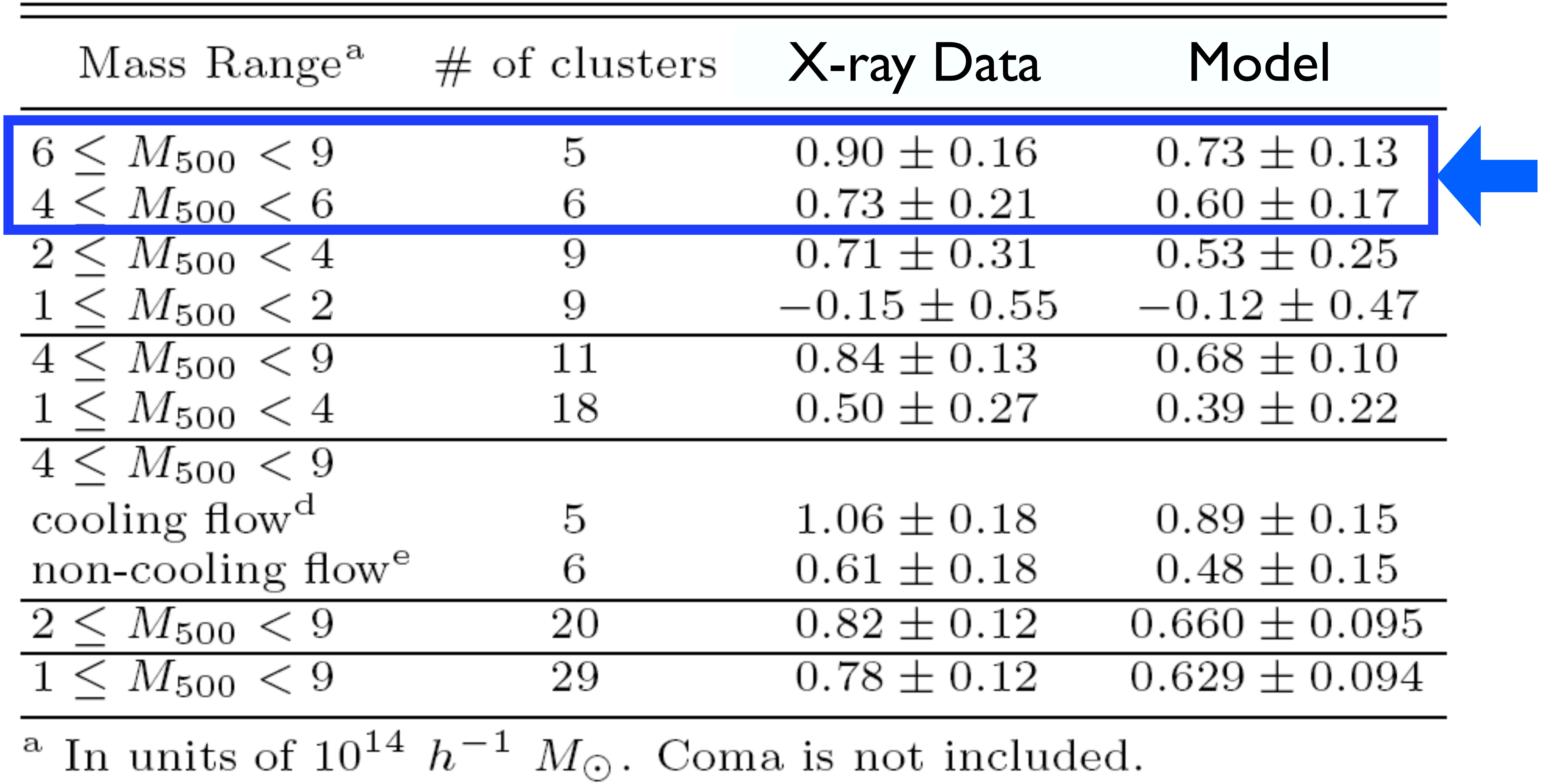
- That's just one cluster. What about the other clusters?
    - We measure the SZ effect of a sample of well-studied nearby clusters compiled by Vikhlinin et al.

WMAP 7-year Measurements!

(Komatsu et al. 2010)



Low-SZ is seen in the WMAP



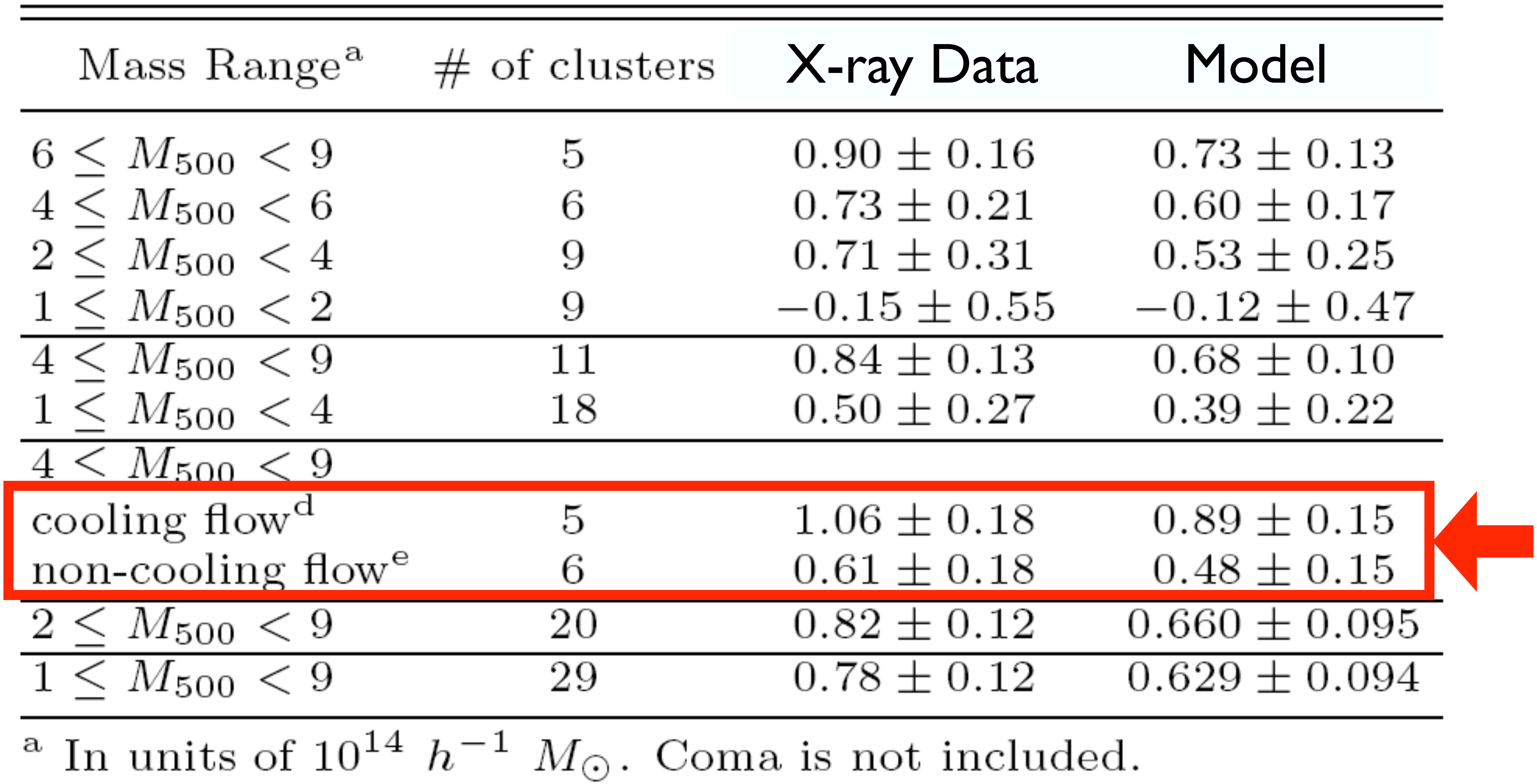
Mass Range[a]	# of clusters	X-ray Data	Model
$6 \leq M_{500} < 9$	5	0.90 ± 0.16	0.73 ± 0.13
$4 \leq M_{500} < 6$	6	0.73 ± 0.21	0.60 ± 0.17
$2 \leq M_{500} < 4$	9	0.71 ± 0.31	0.53 ± 0.25
$1 \leq M_{500} < 2$	9	-0.15 ± 0.55	-0.12 ± 0.47
$4 \leq M_{500} < 9$	11	0.84 ± 0.13	0.68 ± 0.10
$1 \leq M_{500} < 4$	18	0.50 ± 0.27	0.39 ± 0.22
$4 \leq M_{500} < 9$			
cooling flow[d]	5	1.06 ± 0.18	0.89 ± 0.15
non-cooling flow[e]	6	0.61 ± 0.18	0.48 ± 0.15
$2 \leq M_{500} < 9$	20	0.82 ± 0.12	0.660 ± 0.095
$1 \leq M_{500} < 9$	29	0.78 ± 0.12	0.629 ± 0.094

[a] In units of $10^{14}\ h^{-1}\ M_{\odot}$. Coma is not included.

d: ALL of "cooling flow clusters" are relaxed clusters.

e: ALL of "non-cooling flow clusters" are non-relaxed clusters.

Low-SZ: Signature of mergers?



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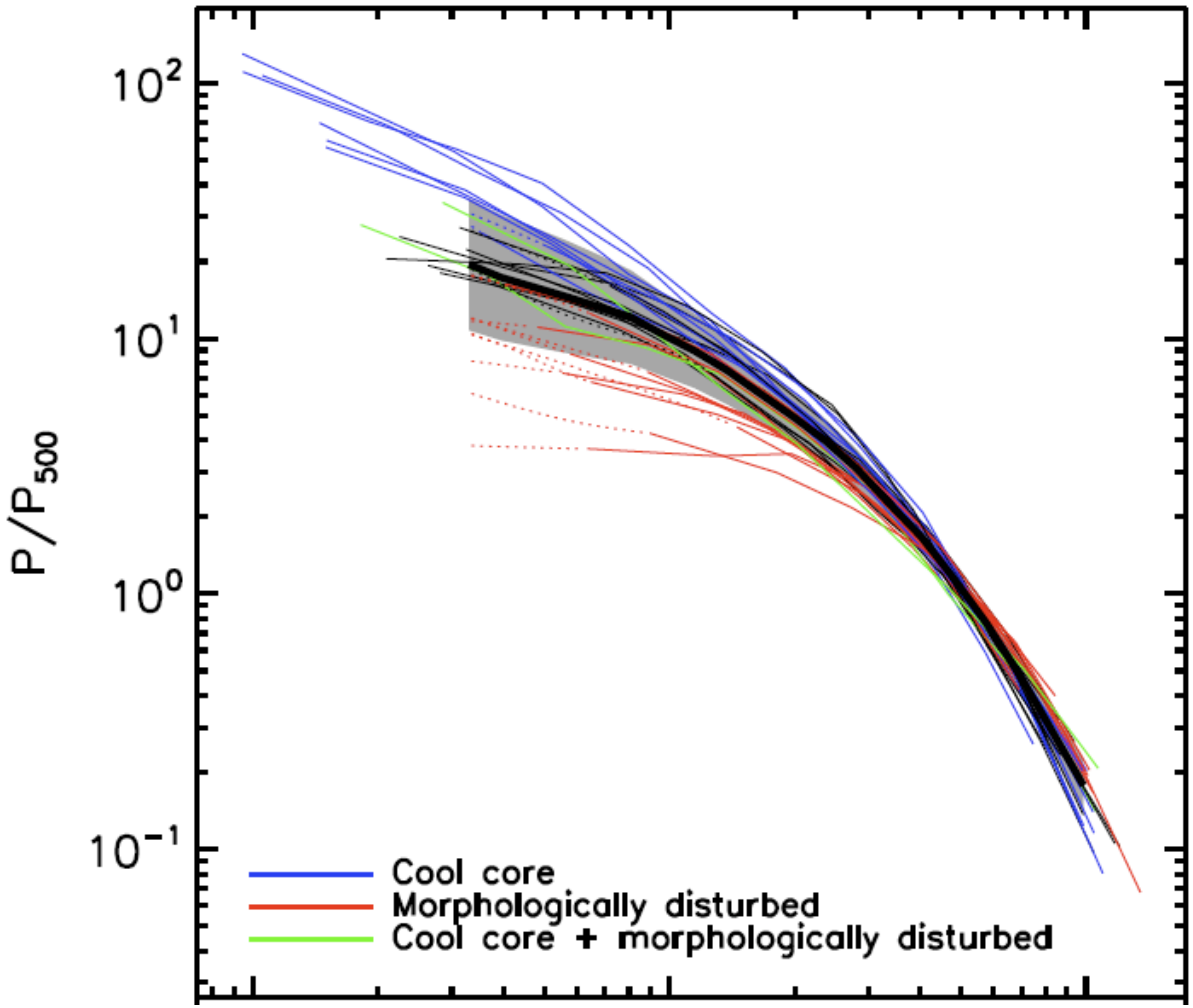
SZ: Main Results

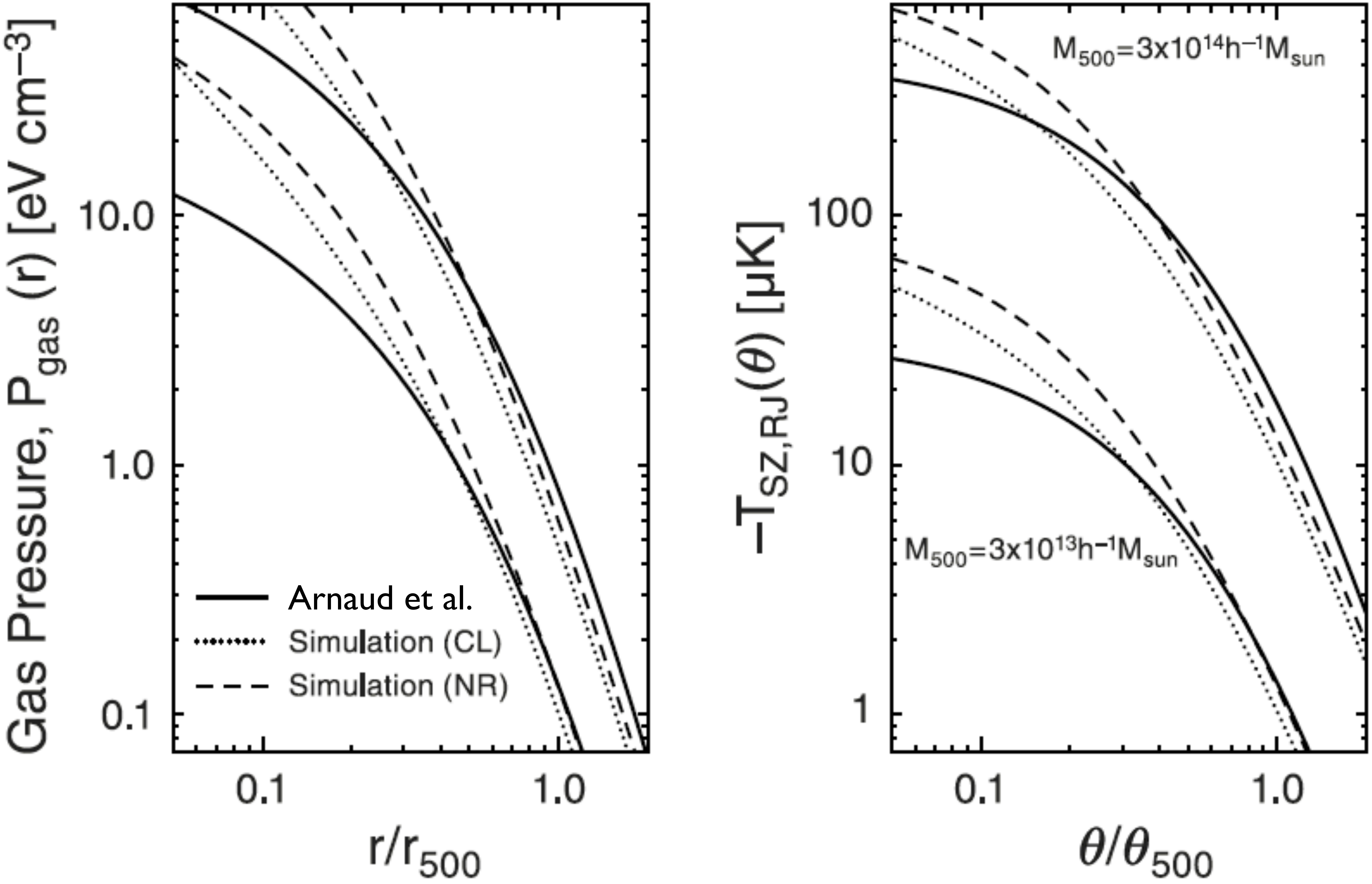
- Arnaud et al. profile systematically overestimates the electron pressure! (Arnaud et al. profile is ruled out at 3.2σ).
- But, the X-ray data on the *individual* clusters agree well with the SZ measured by WMAP.
- Reason: Arnaud et al. did not distinguish between relaxed (CF) and non-relaxed (non-CF) clusters.
  - This will be important for the proper interpretation of the SZ effect when doing cosmology with it.

Cooling Flow vs Non-CF

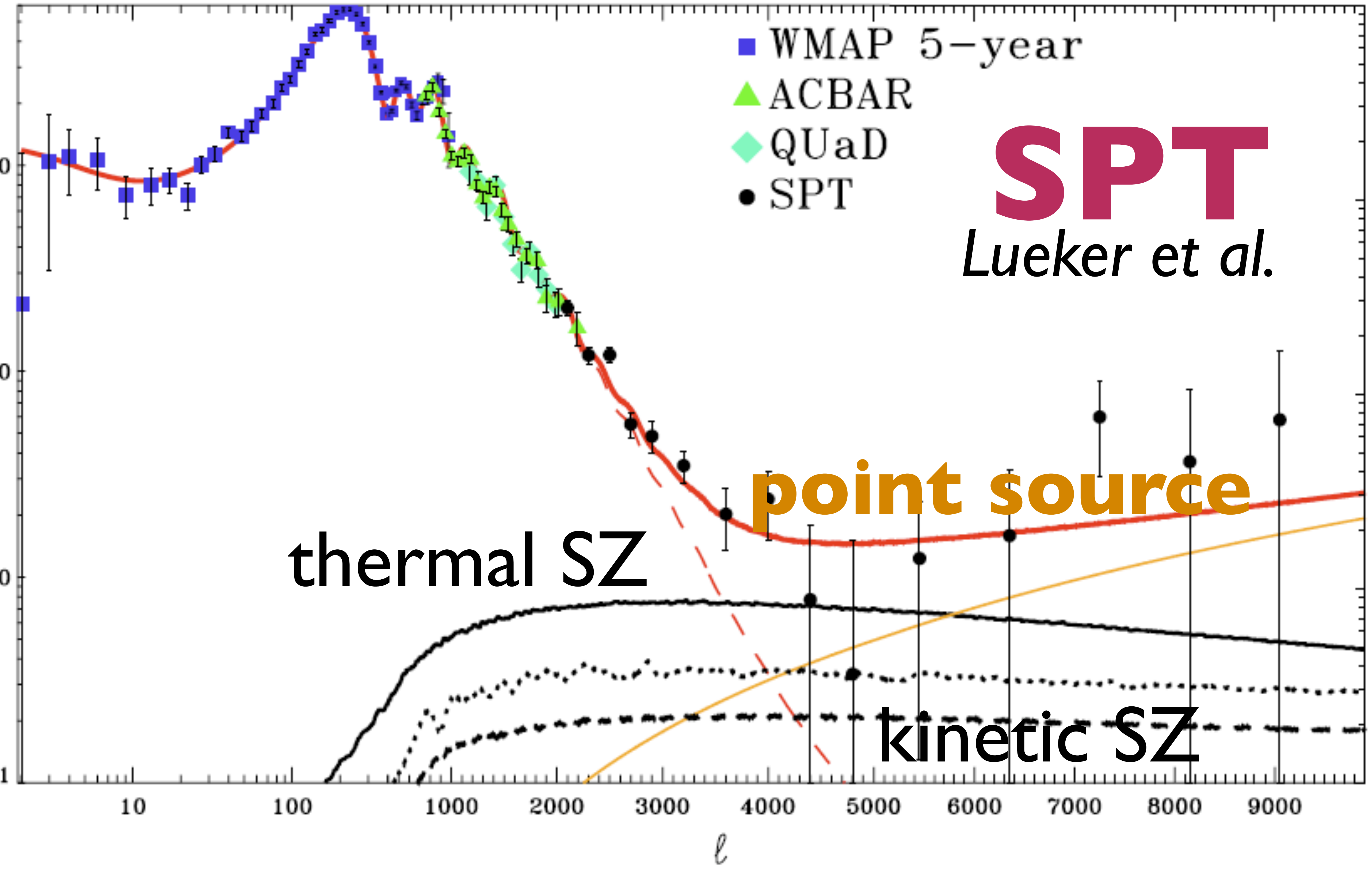


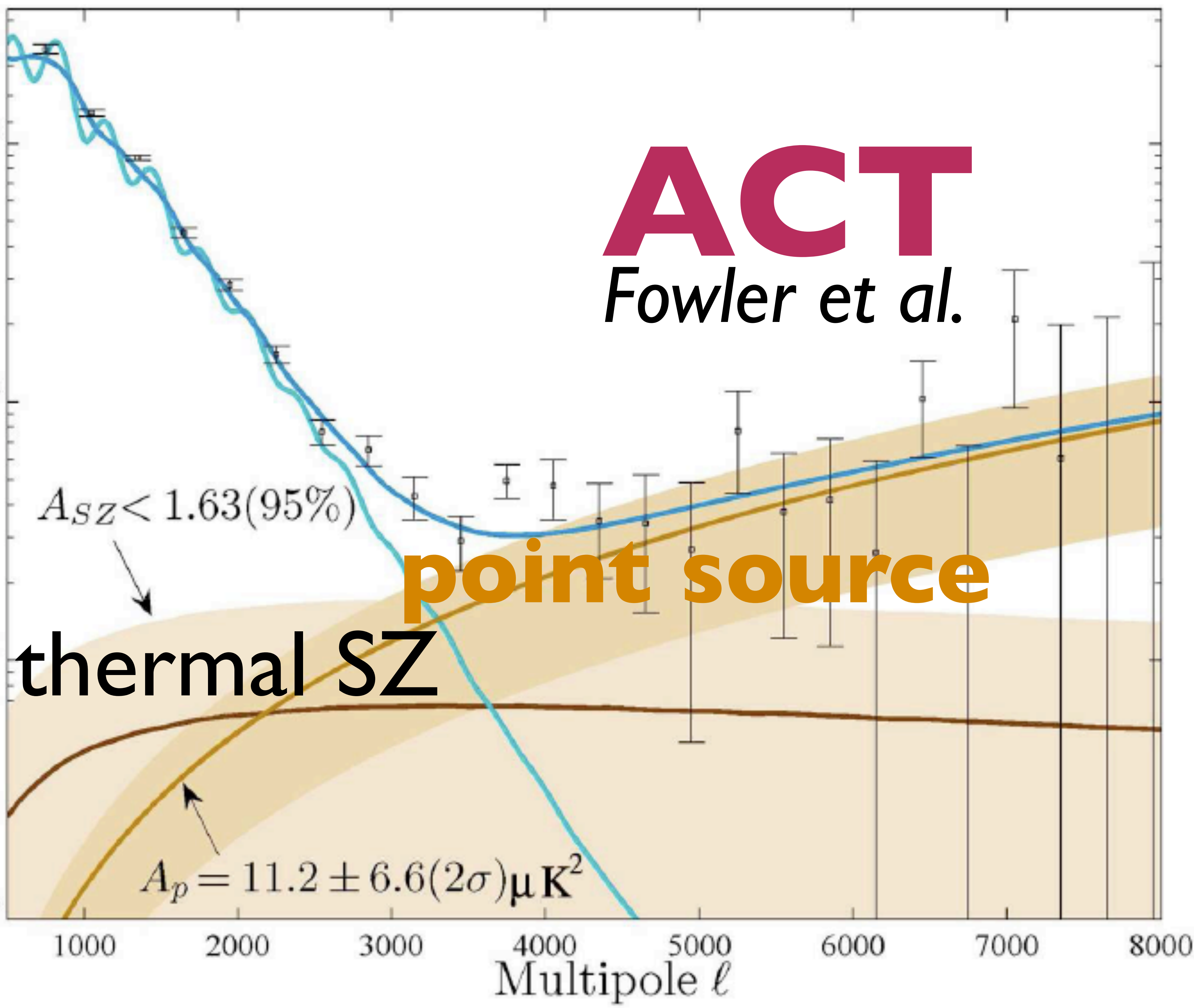
- In Arnaud et al., they reported that the cooling flow clusters have much steeper pressure profiles in the inner part.
- Taking a simple median gave a biased "universal" profile.

Theoretical Models



“World” Power Spectrum





- The SPT measured the secondary anisotropy from (possibly) SZ. **The power spectrum amplitude is A_{SZ}=0.4–0.6 times the expectations.** Why?

Lower ASZ: **Two** Possibilities

$$C_l = g_\nu^2 \int_0^{z_{\rm max}} dz \frac{dV}{dz} \int_{M_{\rm min}}^{M_{\rm max}} dM \boxed{\frac{dn(M,z)}{dM}} |\tilde{y}_l(M,z)|^2$$

- **[1] The number of clusters is less than expected.**
  - In cosmology, this is parameterized by the so-called “σ_8” parameter.

➡ $\frac{l(l+1)C_l}{2\pi} \simeq 330\,\mu{\rm K}^2 \boxed{\sigma_8^7} \left(\frac{\Omega_{\rm b} h}{0.035}\right)^2$ x [gas pressure]^2

- σ_8 is 0.77 (rather than 0.81): $\sum m_\nu \sim 0.2$eV?

Lower A_{SZ}: **Two** Possibilities

$$C_l = g_\nu^2 \int_0^{z_{\max}} dz \frac{dV}{dz} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} \boxed{|\tilde{y}_l(M,z)|^2}$$

- **[2] Gas pressure per cluster is less than expected.**
  - The power spectrum is [gas pressure]^2.
  - A_{SZ}=0.4–0.6 means that the gas pressure is less than expected by ~0.6–0.7.
- *And, our measurement shows that this is what is going on!*

A Puzzle

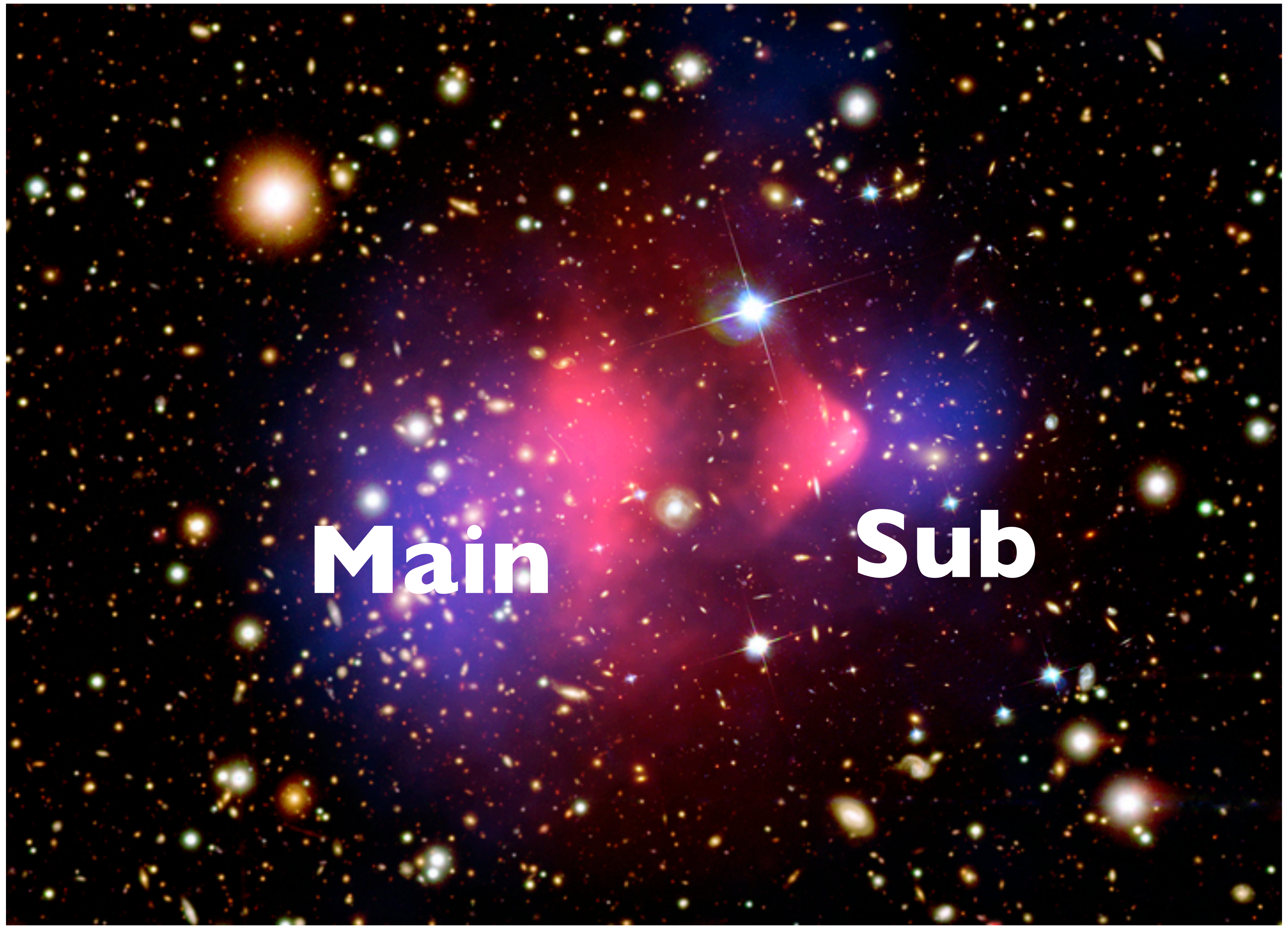
- SZ effect: Coma's radial profile is measured, several massive clusters are detected, and the statistical detection reaches 6.5σ.
  - Evidence for lower-than-theoretically-expected gas pressure.
  - The X-ray data are fine: we need to revise the existing models of the intracluster medium.
    - Distinguishing relaxed and non-relaxed clusters is very important!

Bullet Cluster: A Challenge to ΛCDM Cosmology

- Jounghun Lee (Seoul National) and EK, arXiv:1003.0939

Markevitch et al. (2002); Clowe et al. (2004, 2006)

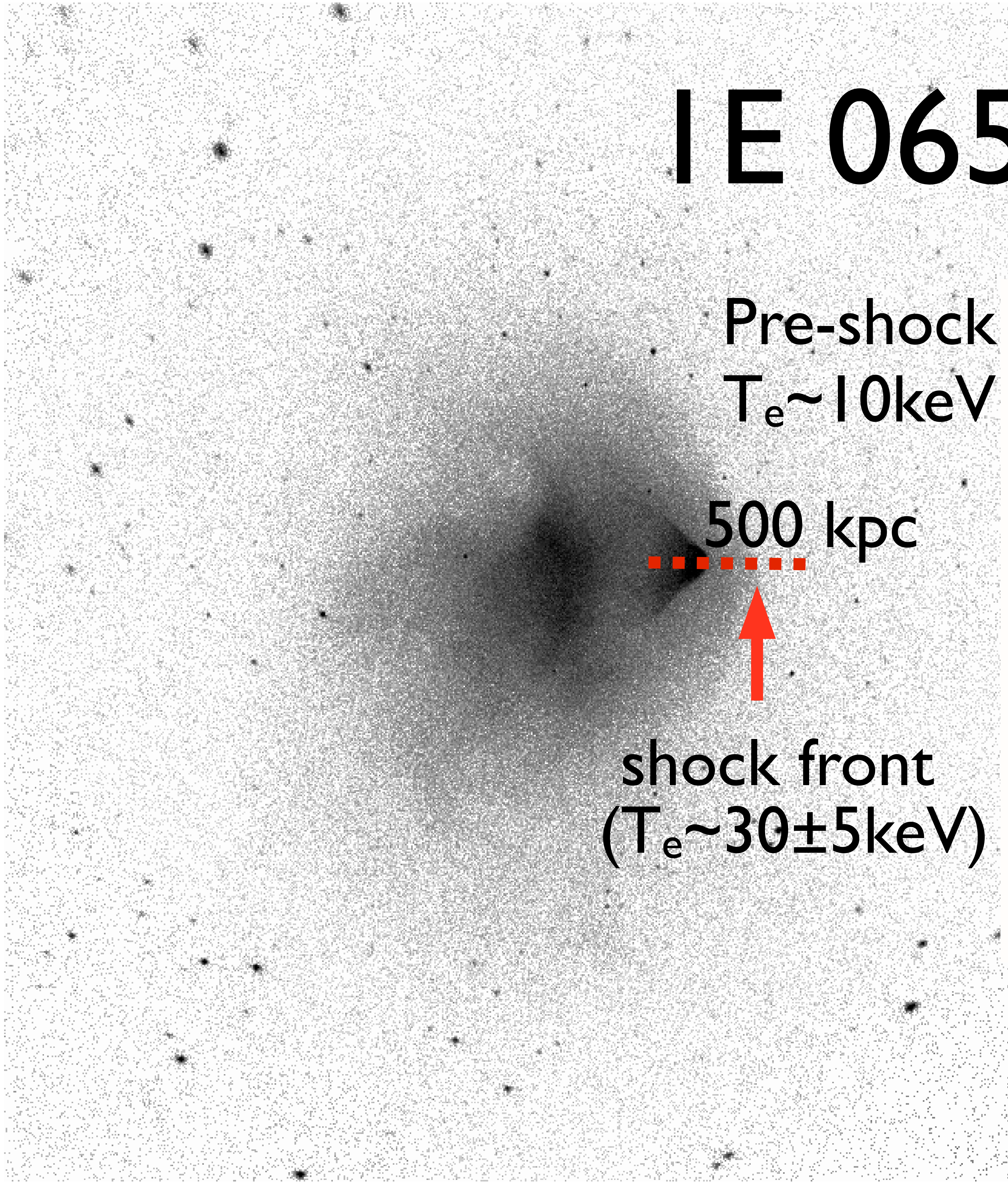
1E 0657–56



- The main-cluster mass ~ $10^{15}M_{sun}$
  - The virial radius is~2Mpc
- The sub-cluster mass ~ $10^{14}M_{sun}$
- ~1:10 to 1:6 (nearly) head-on collision.

Markevitch (2006)

1E 0657–56



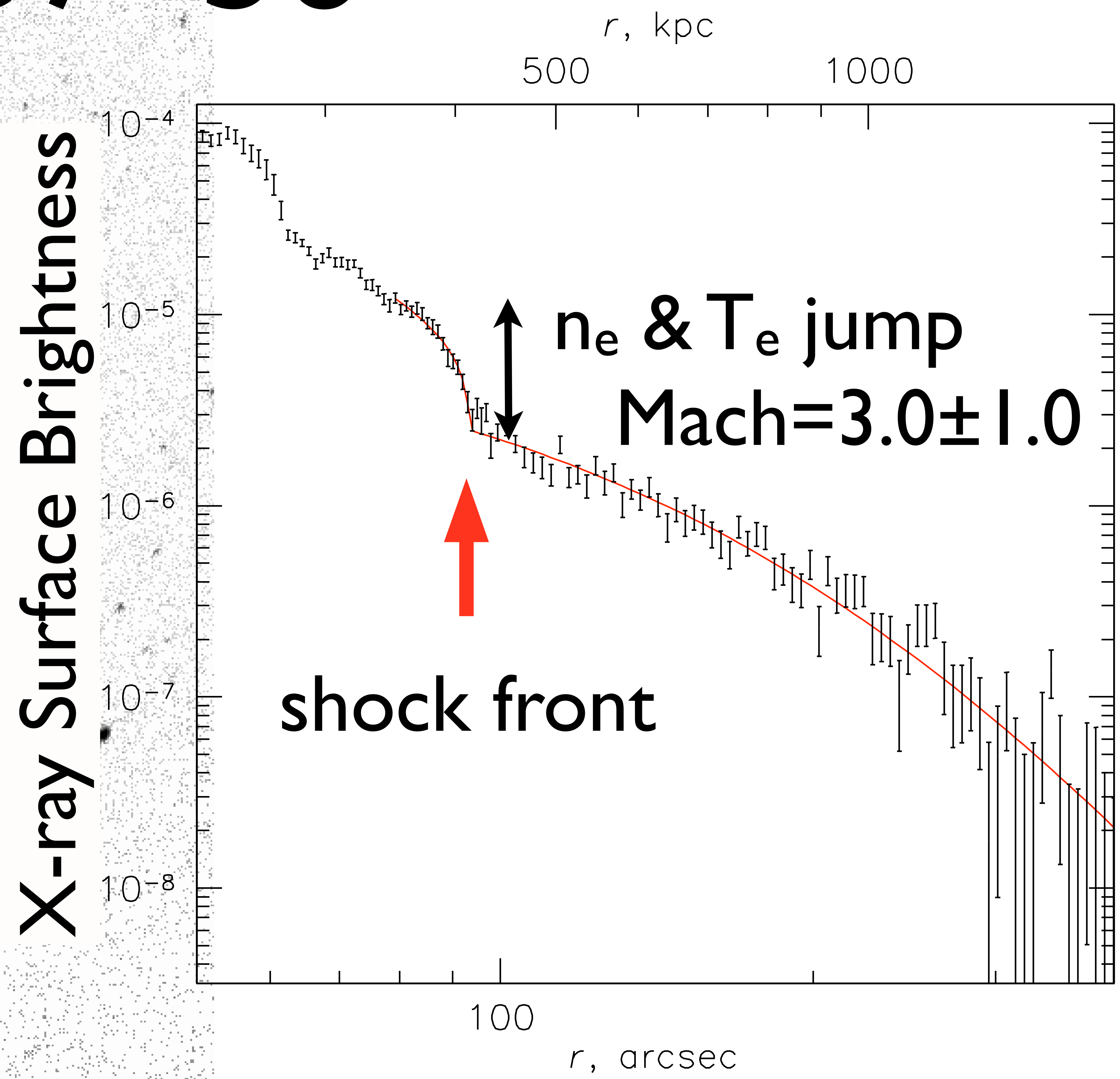
Pre-shock

T_e~10keV

500 kpc

shock front

(T_e~30±5keV)



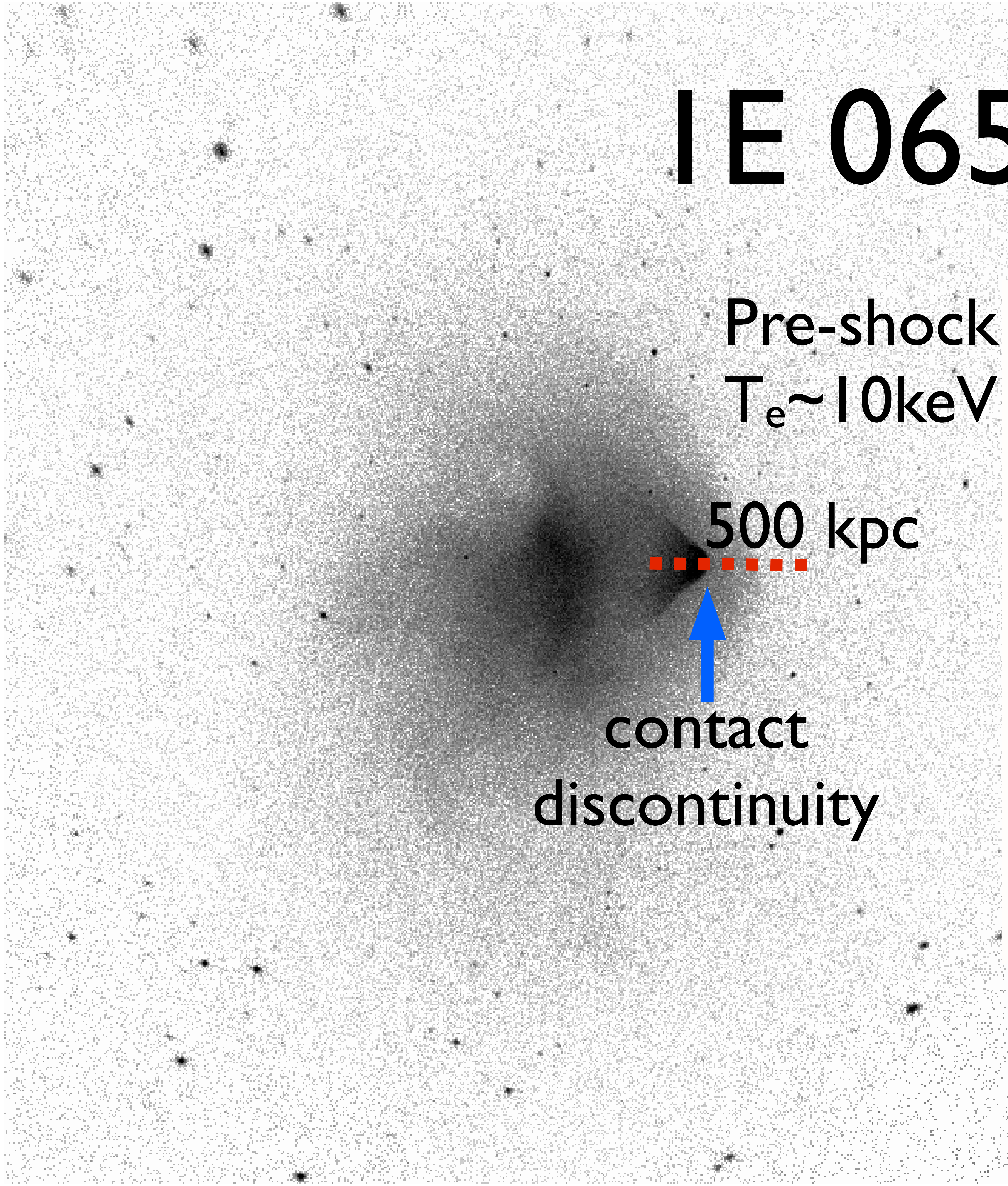
n_e & T_e jump

Mach=3.0±1.0

shock front

Markevitch (2006)

1E 0657–56

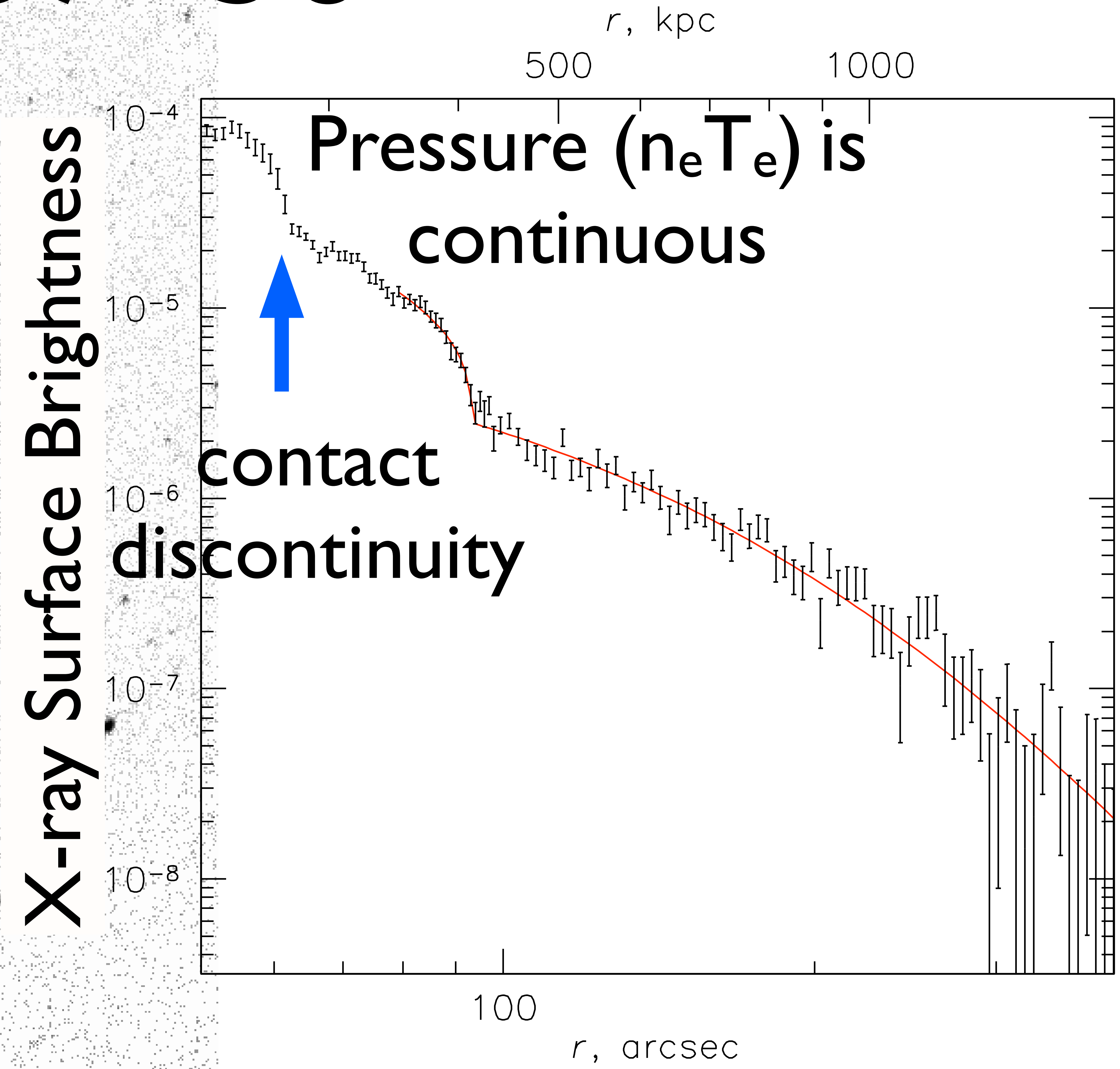


Pre-shock

T_e~10keV

500 kpc

contact discontinuity



Pressure (n_eT_e) is continuous

contact discontinuity

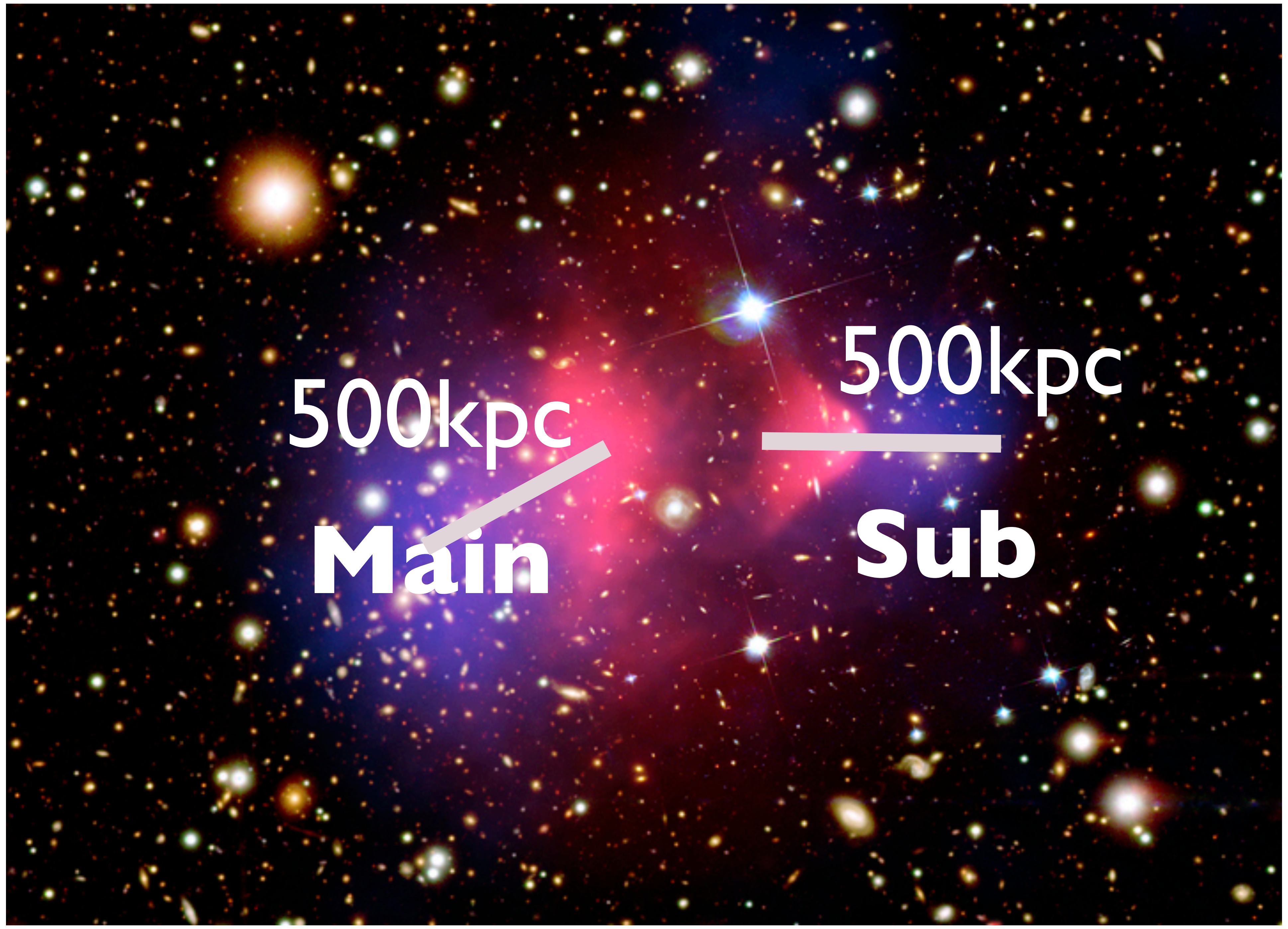
Shock Velocity vs Clump Velocity

- The Mach number derived from the X-ray data at the shock implies a very high shock velocity (i.e., the velocity of the shock front) of 4700 km/s.
  - This, however, does not mean that the **dark matter clump** is moving at this velocity.
  - The clump can slow down significantly by gravitational friction, etc., relative to the shock. (Milosavljevic et al.; Springel & Farrar; Mastropietro & Burkert).
  - The clump velocity can be ~3000 km/s.

A question asked by White

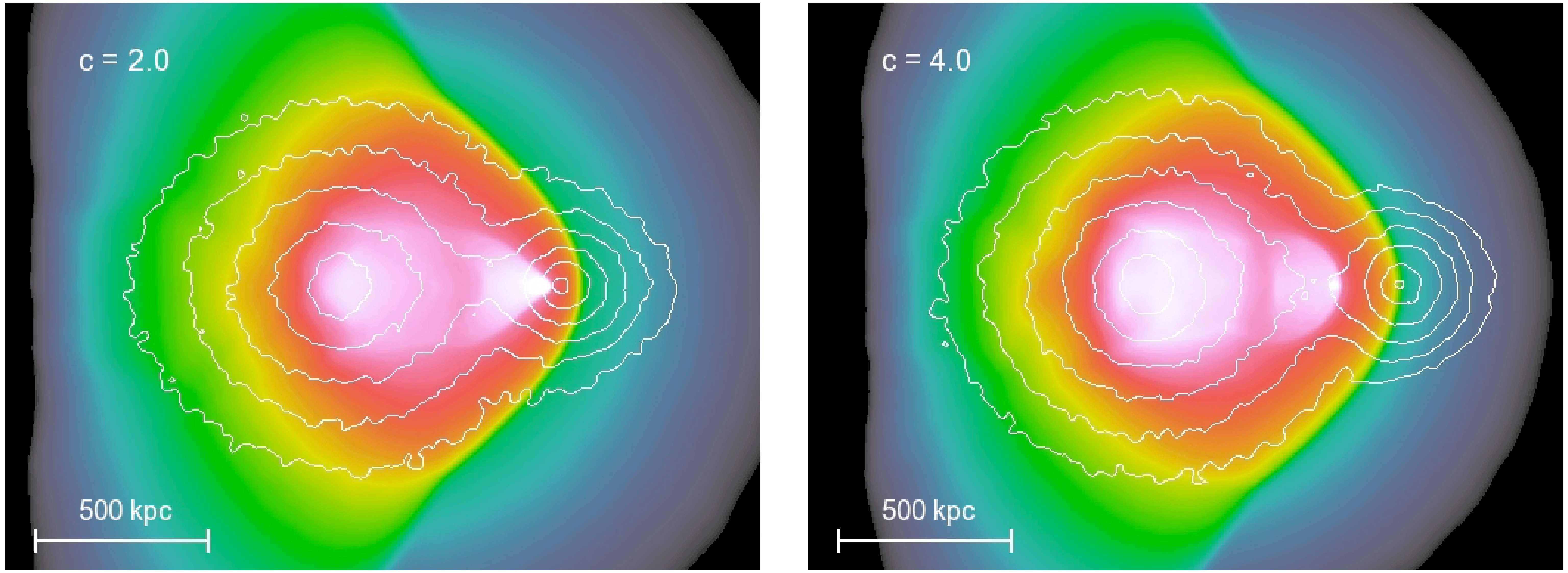
- In Hayashi & White (2006), they asked the following question: "*can we find a subclump moving at ~4500km/s somewhere in the Millennium Simulation?*"
- The answer is yes, and thus the bullet cluster does not seem anomalous at all.
  - This conclusion was later challenged by Farra & Rosen (2007), but the recent finding that the subclump can be as slow as ~3000 km/s makes the velocity of the subclump consistent with ΛCDM. **However...**

1E 0657–56 is more than just the shock velocity!



- The stunning observational fact is that the gas of the **main** cluster (remember this thing is $10^{15}M_{sun}$) is ripped off the gravitational potential.
- How did that happen?

A 3D Hydrodynamical Simulation by Springel



X-ray surface brightness maps with different concentration parameters

- The bullet seems reproduced well, but look at the main cluster: the gas couldn’t escape from the main cluster.

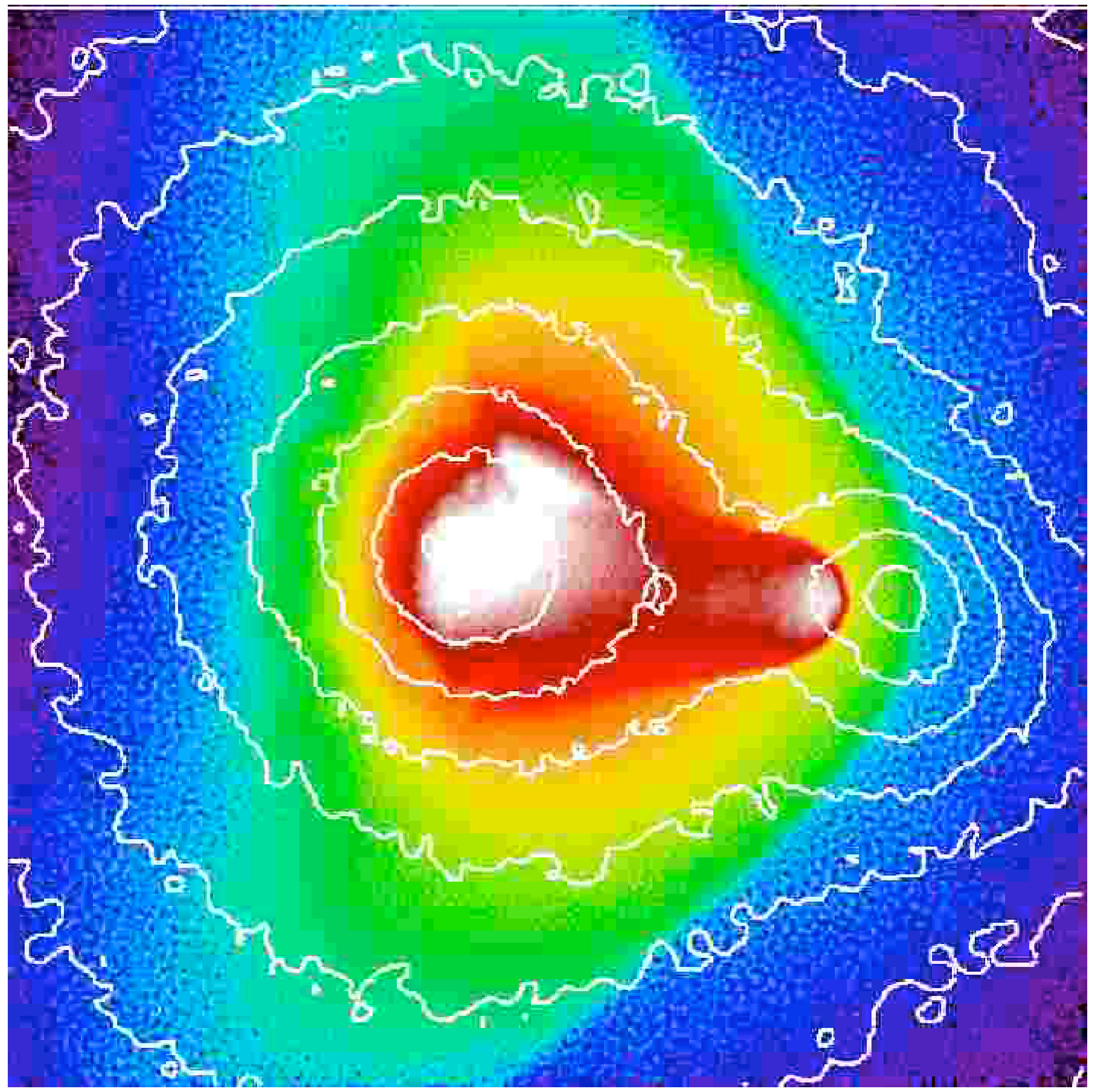
The key is the initial velocity

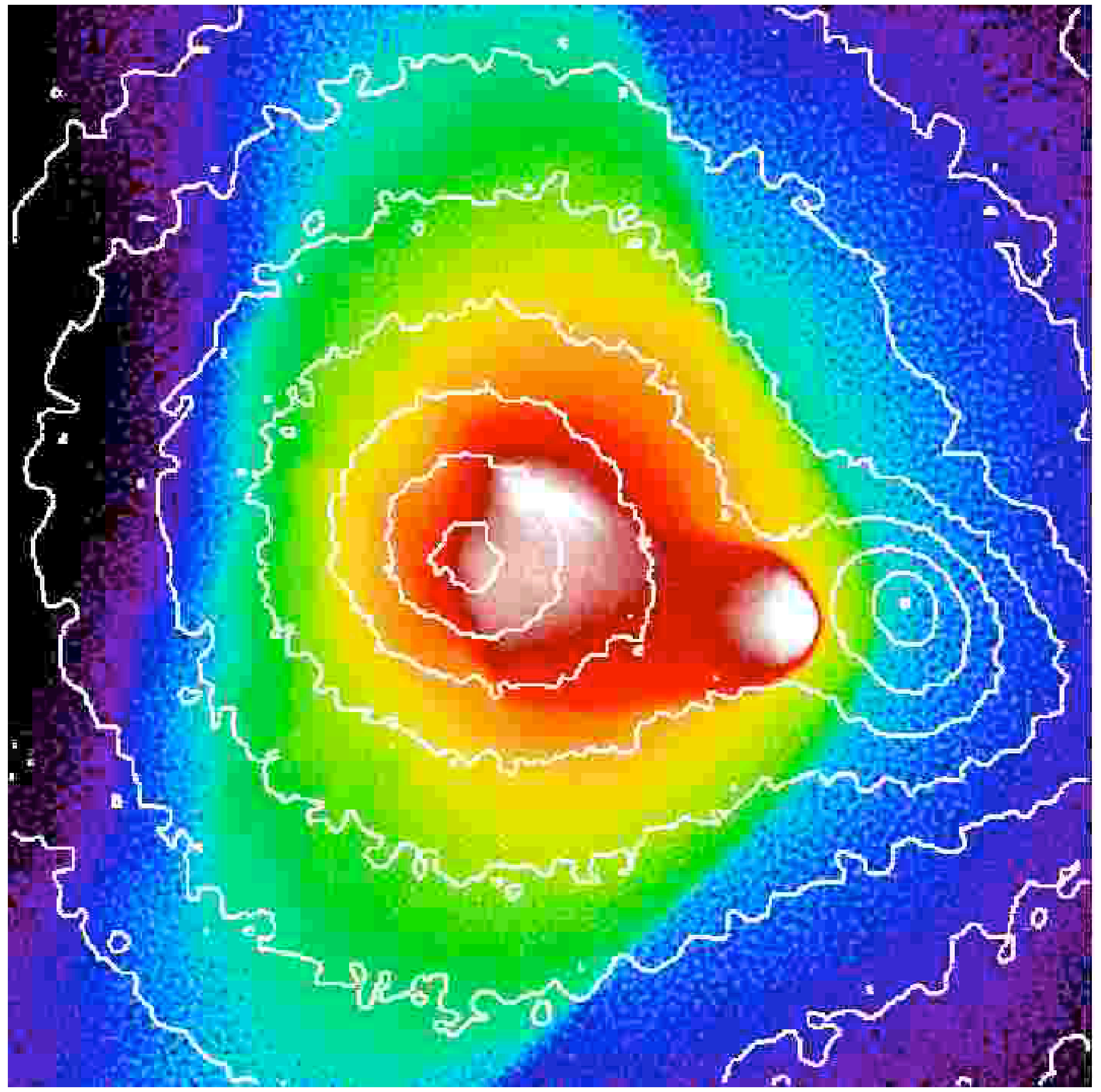
- In Springel’s simulation, two clusters (1:10 mass ratio) were given zero relative velocities at infinity.
- The bullet picks up the velocity of 2057 km/s at 3.37 Mpc, which is about 1.5 R_{200} of the main cluster.
- This velocity was not sufficient!

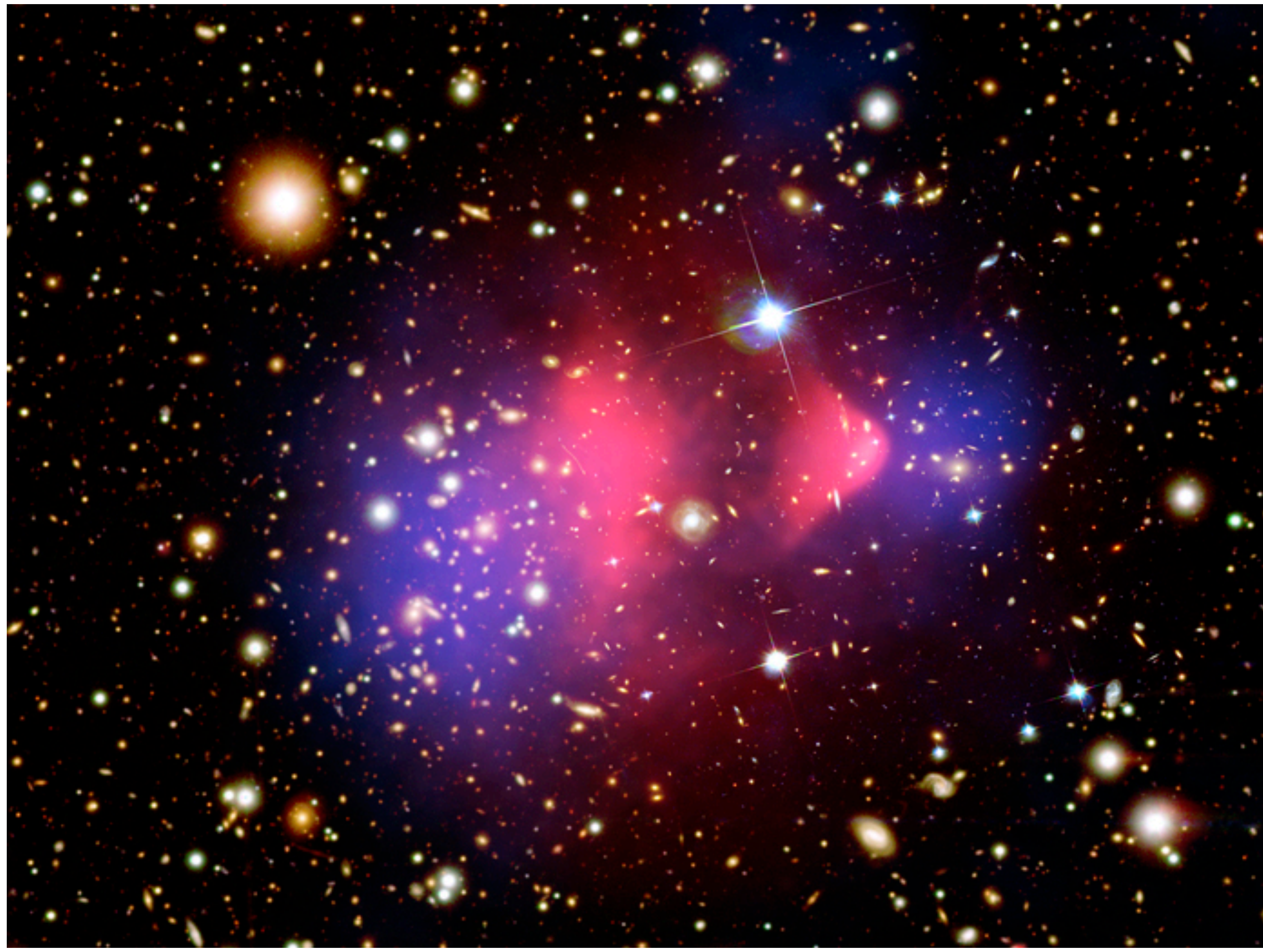
Need for parameter search

- In order to find the best parameters that can reproduce the details of the bullet cluster, Mastropietro & Burkert (2008) have run a number of simulations with different parameters.
  - Mass ratios (1:6 seems better than 1:10)
  - Initial velocities (2000 to 5000 km/s at 2.2 R_{200})
  - Concentration parameters
- Note that these are *non-cosmological* simulations.

~3000 km/s is required


2000 km/s at 2.2 R_{200}


3000 km/s at 2.2 R_{200}



- The initial velocity of ~3000 km/s can (barely) reproduce the gas distribution. ~2000 km/s cannot.
- Why? The escape velocity of the main cluster is 2000 km/s!

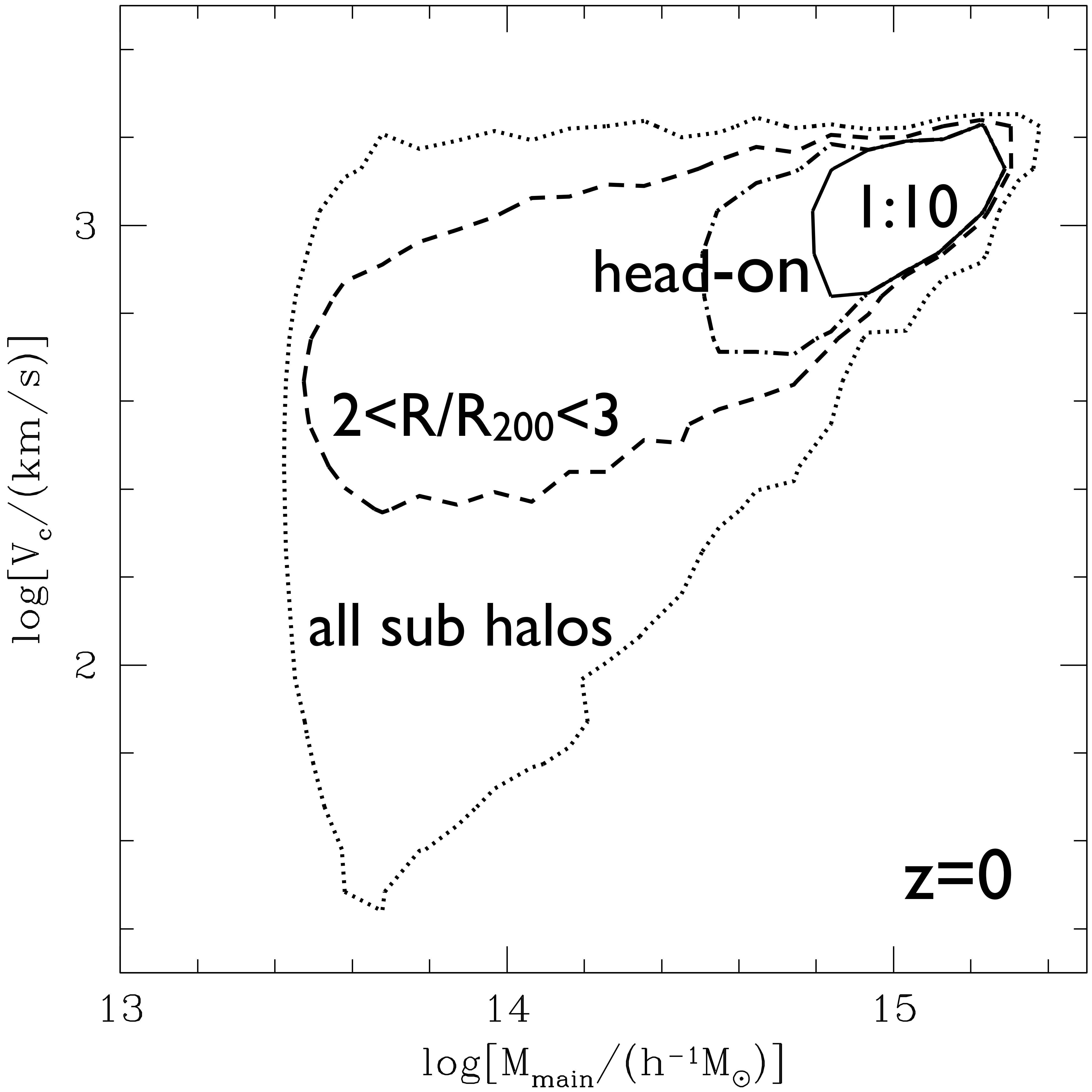
The real question

- So, the real question that should have been asked is, "*can we find sub clusters that are entering the main cluster at the initial velocity of ~3000 km/s at ~2*R_{200}*?*"
- To do this, we need a very large cosmological simulation because we need many ~$10^{15}M_{sun}$ halos for good statistics.

MICE Simulation

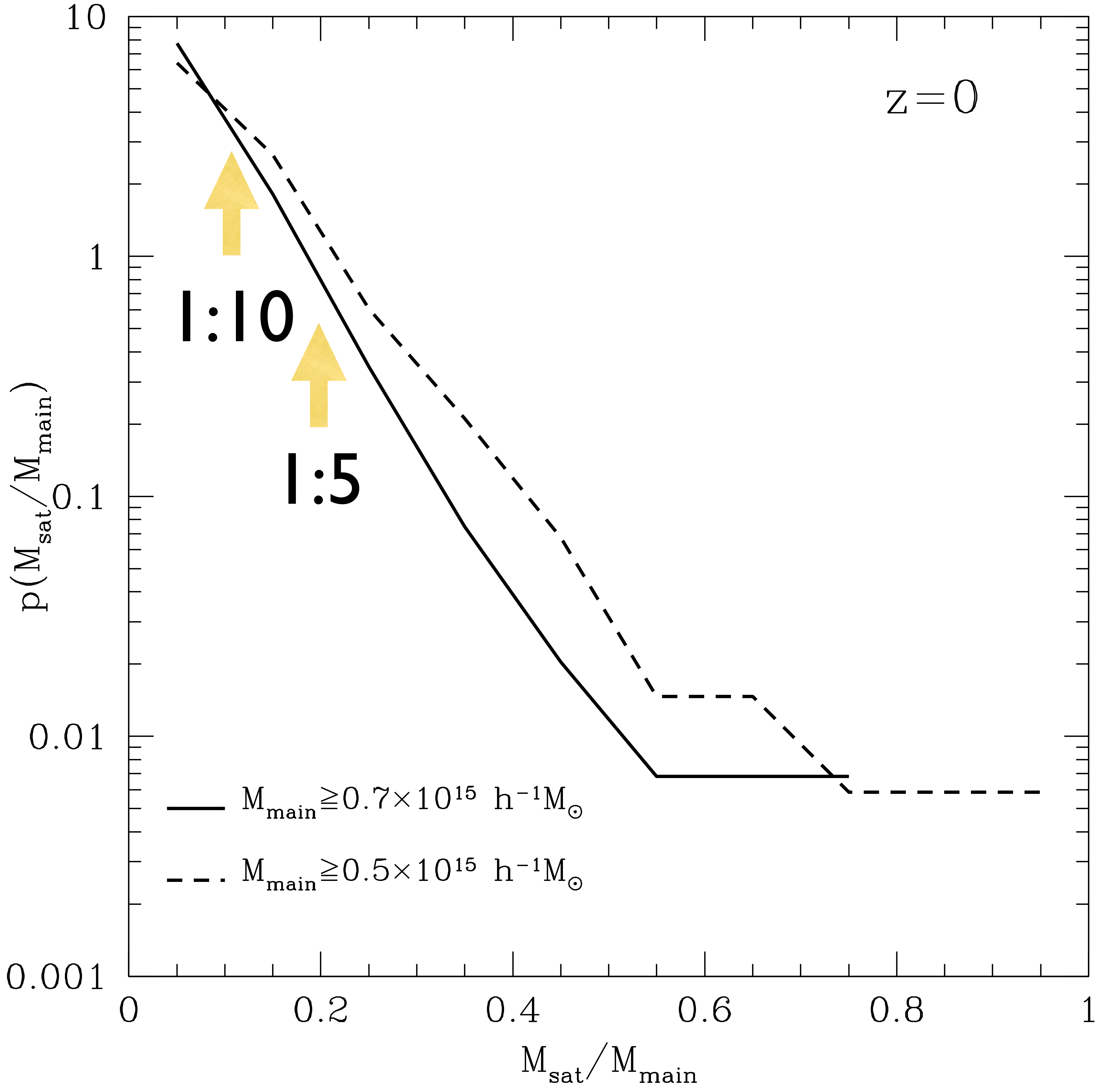
- Such a simulation is conveniently publicly available!
- MICE Simulation (Fosalba et al. 2008; Crocce et al. 2010)
  - Flat ΛCDM with Ω_m=0.25, h=0.7, n_s=0.95, σ_8=0.8
  - Box size = 3 h^{-1} Gpc (huge!)
  - # of particles = 2048^3
  - The particle mass = $2\text{x}10^{11}h^{-1}M_{sun}$.
    - Perfect for our purpose because we only need to resolve $>10^{14}h^{-1}M_{sun}$. Many particles per halo.

Finding Bullet-like Systems



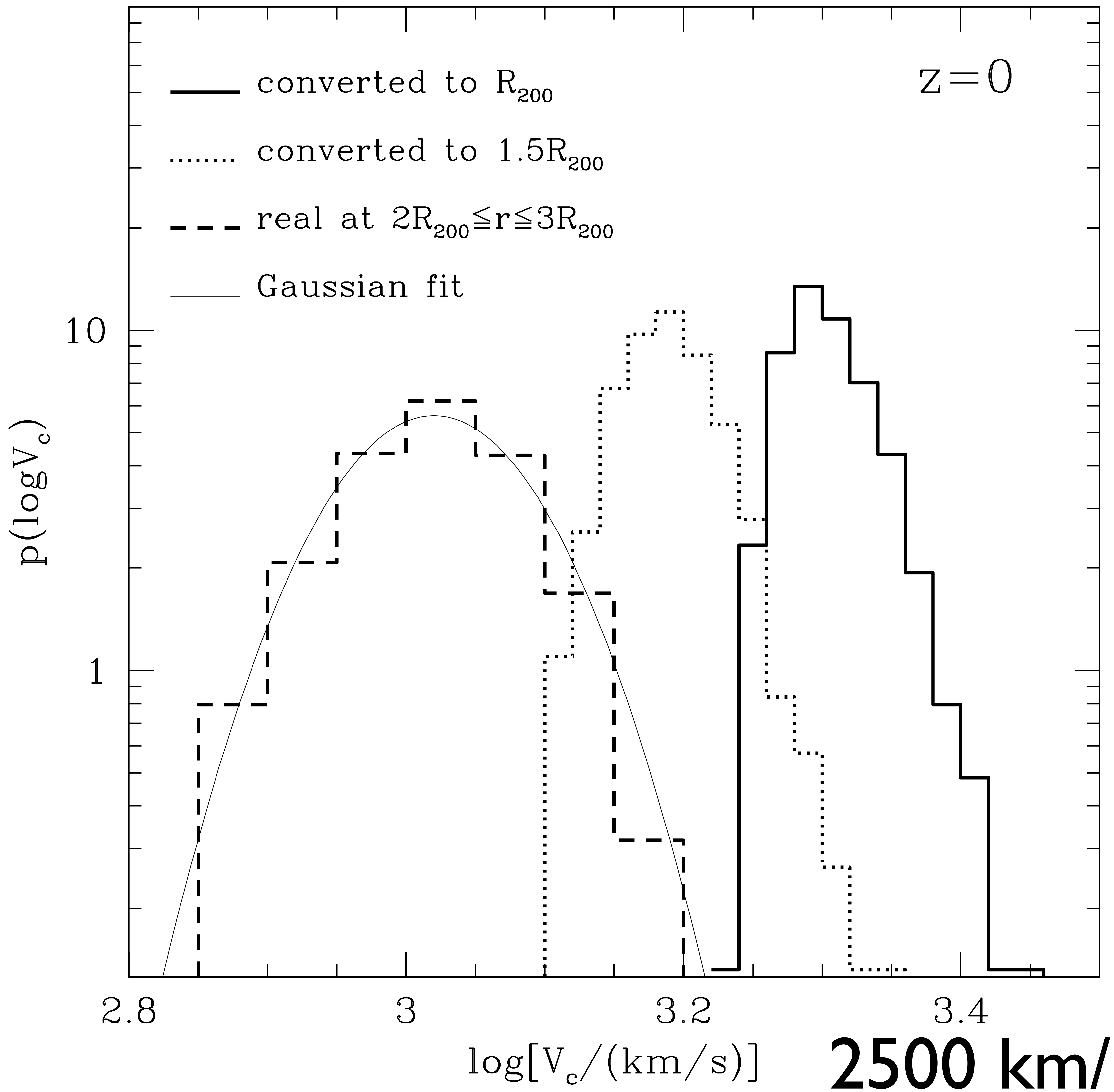
- Select the “bullet-like systems” by choosing:
- the sub halos near the main cluster ($2<R/R_{200}<3$)
- Nearly head-on collision
- Mass ratio of $M_{sub}/M_{main}<0.1$, where $M_{main}>10^{15}M_{sun}$
- **We have ~1000 systems that satisfy all the above conditions.**

Mass Ratio Distribution



- We will assume that the mass ratio of 1E0657–56 is 1:10.
  - Mastropietro & Burkert argue that 1:6 reproduces the observation better.
  - Then, this system would be even rarer than what we find (which is already quite rare).

Result: Velocity Distribution



2500 km/s

- Just focus on the dashed histogram, which is the distribution of velocities in $2<R/R_{200}<3$, measured from the simulation.
- Easy to understand: a body freely-falling into the $M_{200}=10^{15}M_{sun}$ cluster would pick up the velocity of **1200–1400 km/s in $3>R/R_{200}>2$**.

And...

- 3000 km/s is way, way off.
  - By approximating the velocity distribution as a log-normal distribution (which is a good fit), we find p(V>3000 km/s) = 3.3×10^{-11}, at $z=0$.
- 1E0657–56 is at $z=0.3$.
  - Using the MICE simulation output at $z=0.5$, we find p(V>3000 km/s) = 3.6×10^{-9}.
- There are less fast-moving bullets at z=0 because Λ slows down the structure formation.

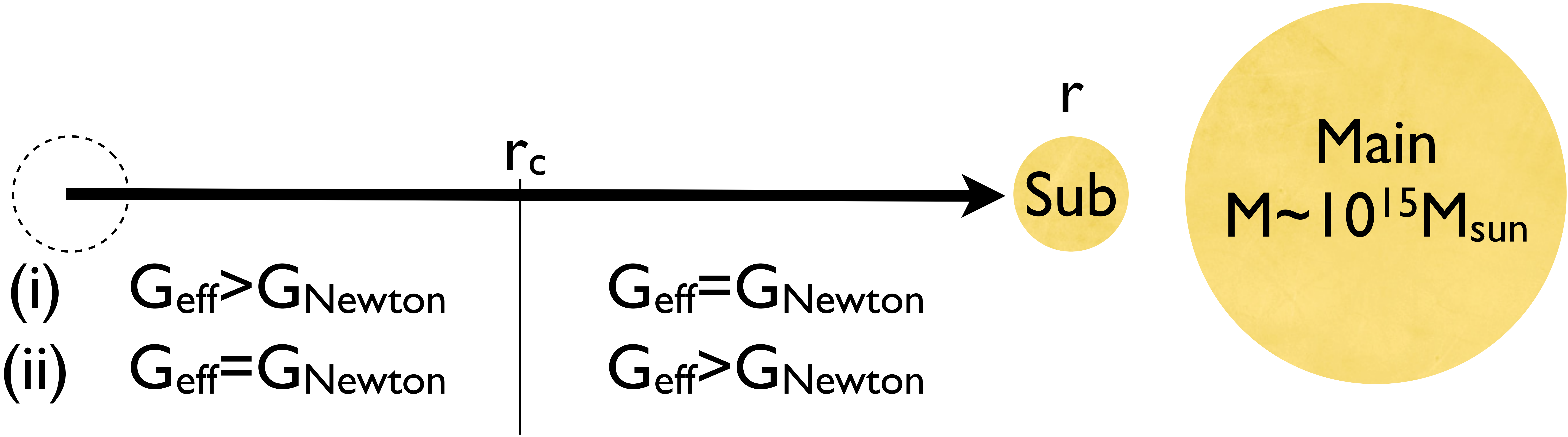
Statement

- ΛCDM does not predict the existence of 3000 km/s sub-halos falling into $10^{15}M_{sun}$ clusters.

Two Implications

1. The existence of 1E0657–56 rules out ΛCDM.
   - Modified gravity? (*Wyman & Khoury*, 1004.2046; *Moffat & Toth*, 1005.2685)
2. We haven't exhausted all the parameter space in the hydro simulations.
   - Can the initial velocity of V<1800 km/s reproduce the observation?

One way to think about this



r_c

r

Sub

Main

$M \sim 10^{15} M_{sun}$

(i) $G_{eff} > G_{Newton}$ $G_{eff} = G_{Newton}$

(ii) $G_{eff} = G_{Newton}$ $G_{eff} > G_{Newton}$

- $V^2 = GM_{main}/R$. So, you can get a higher velocity by somehow increasing G.

(i) $V^2 = 2M_{main} * [G_{eff}/r_c + (G_N/r - G_N/r_c)]$

(ii) $V^2 = 2M_{main} * [G_N/r_c + (G_{eff}/r - G_{eff}/r_c)]$

Conclusion

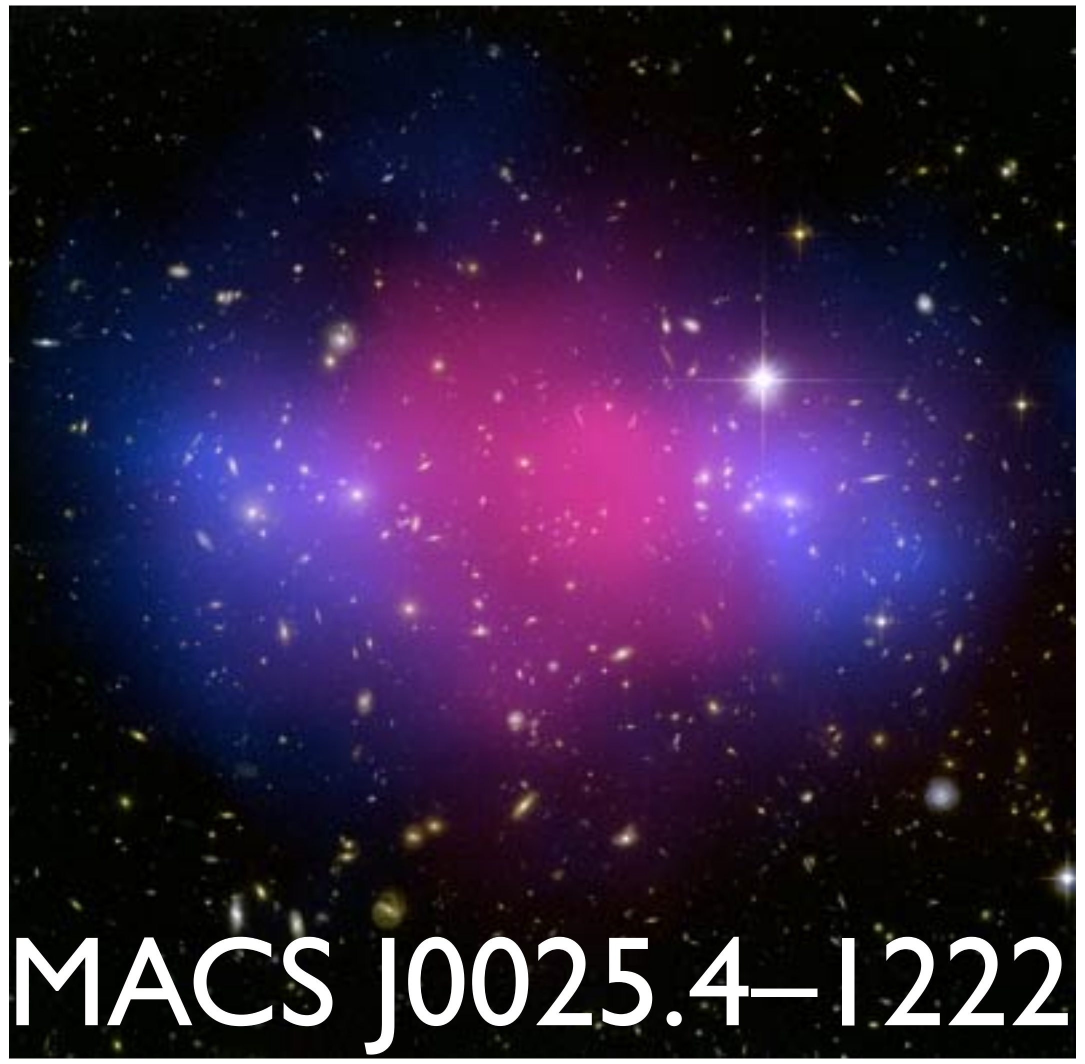
- The observed morphology of 1E0657–56 calls for a high-velocity initial condition, ~3000 km/s, at ~$2R_{200}$.
- This is not possible in a ΛCDM universe.
- Either (i) we haven't tried hard enough to find a lower velocity solution for 1E0657–56, or (ii) ΛCDM is ruled out.
- **A pink elephant?**

A Pink Elephant (a remark by Neta Bahcall)

1E0657–56 may not be the only one.

- RXJ1347–1145 (Komatsu et al. 2001; Mason et al. 2009)
  - The combined analysis of the SZ and X-ray gave the shock velocity of 3900 km/s. (Kitayama et al. 2004)
  - Confirmed by Suzaku (Ota et al. 2008)
- MACS J0025.4–1222 (Bradac et al. 2008)

  - These clusters may provide equally serious challenges to ΛCDM!



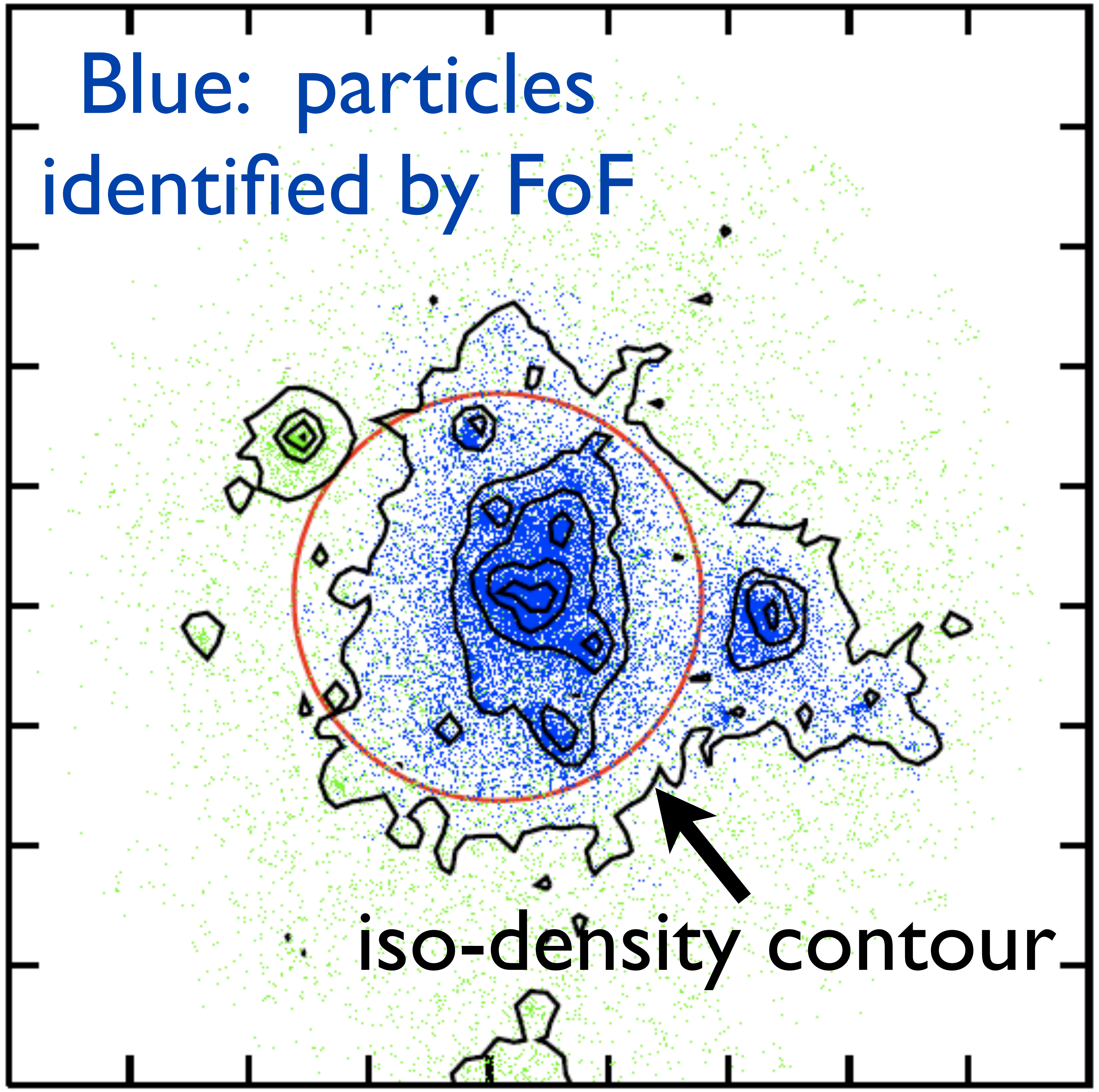
Summary

1. We have found a significant difference between relaxed and non-relaxed clusters.
   - Important when using the SZ effect of clusters of galaxies as a cosmological probe.
2. The existence of Bullet Cluster poses a challenge to the standard ΛCDM cosmology.
   - Or, a challenge to something else: how do we move the gas out of the gravitational potential of $10^{15}M_{sun}$ object?

Finding Halos

- The MICE simulation gives us a halo catalog, found by the standard Friends-of-Friends method with a linking length of $0.2(L_{box}/\#\text{ of particles})=0.3h^{-1}$Mpc.
- This “linking length of 0.2” is known to (magically) produce the results that closely match the virial theorem.

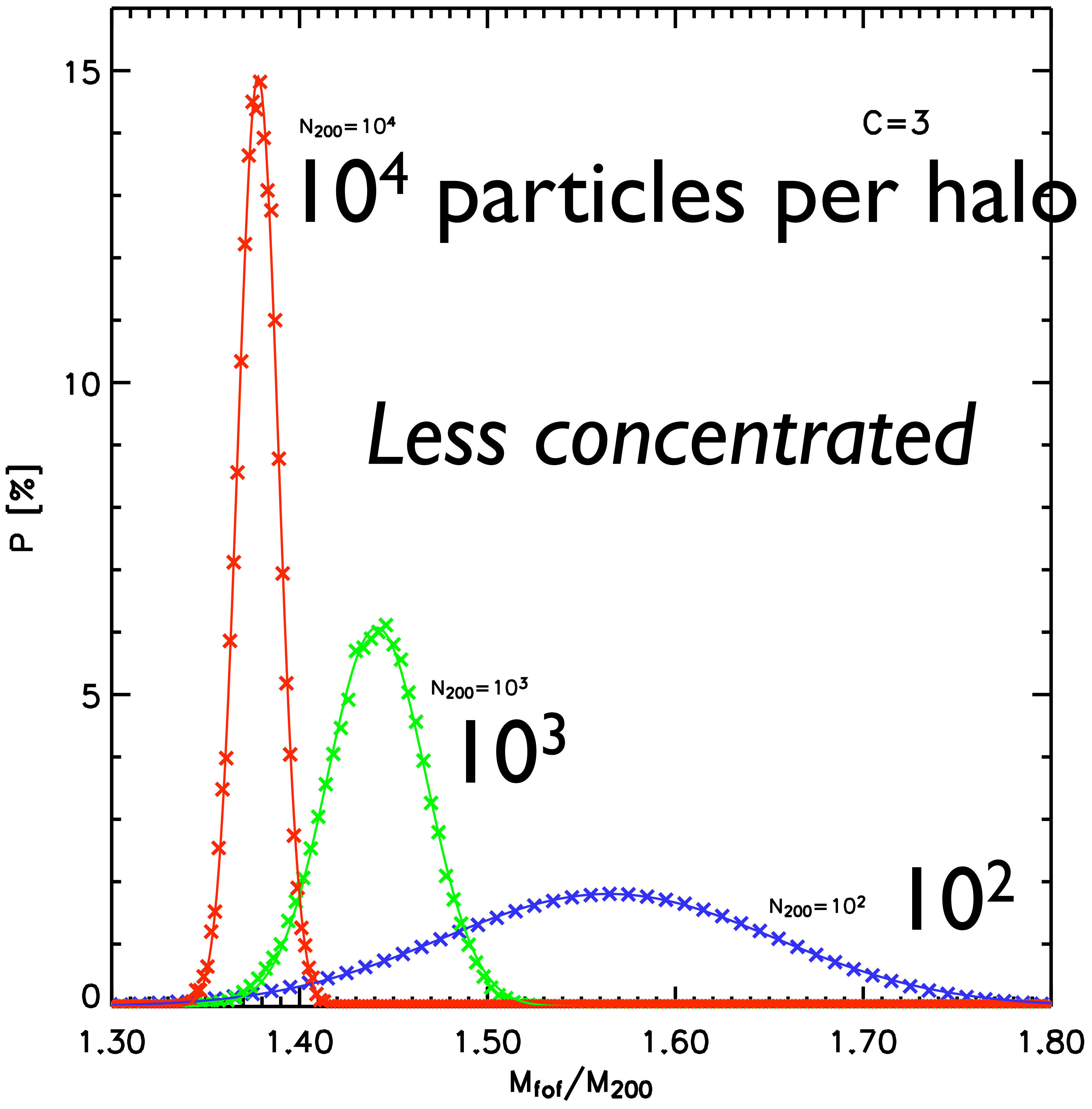
FoF Mass

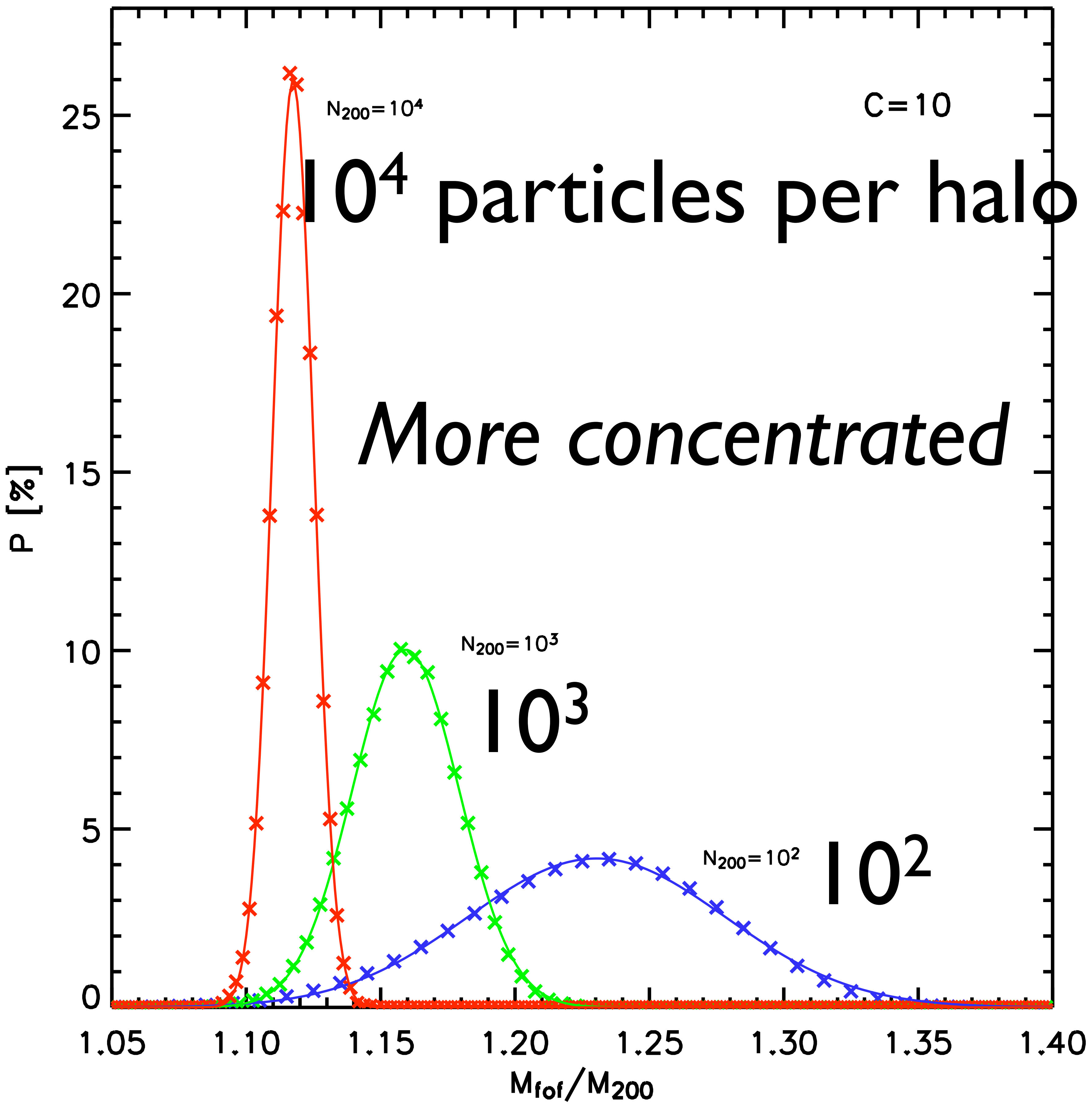


Lukic et al. (2008)

- The particles identified by the FoF method reflect the iso-density contour.
- A good way to identify real halos, which are not at all spherical.
- But, how is the total mass of this halo identified by the FoF compared to M_{200} that people normally use?

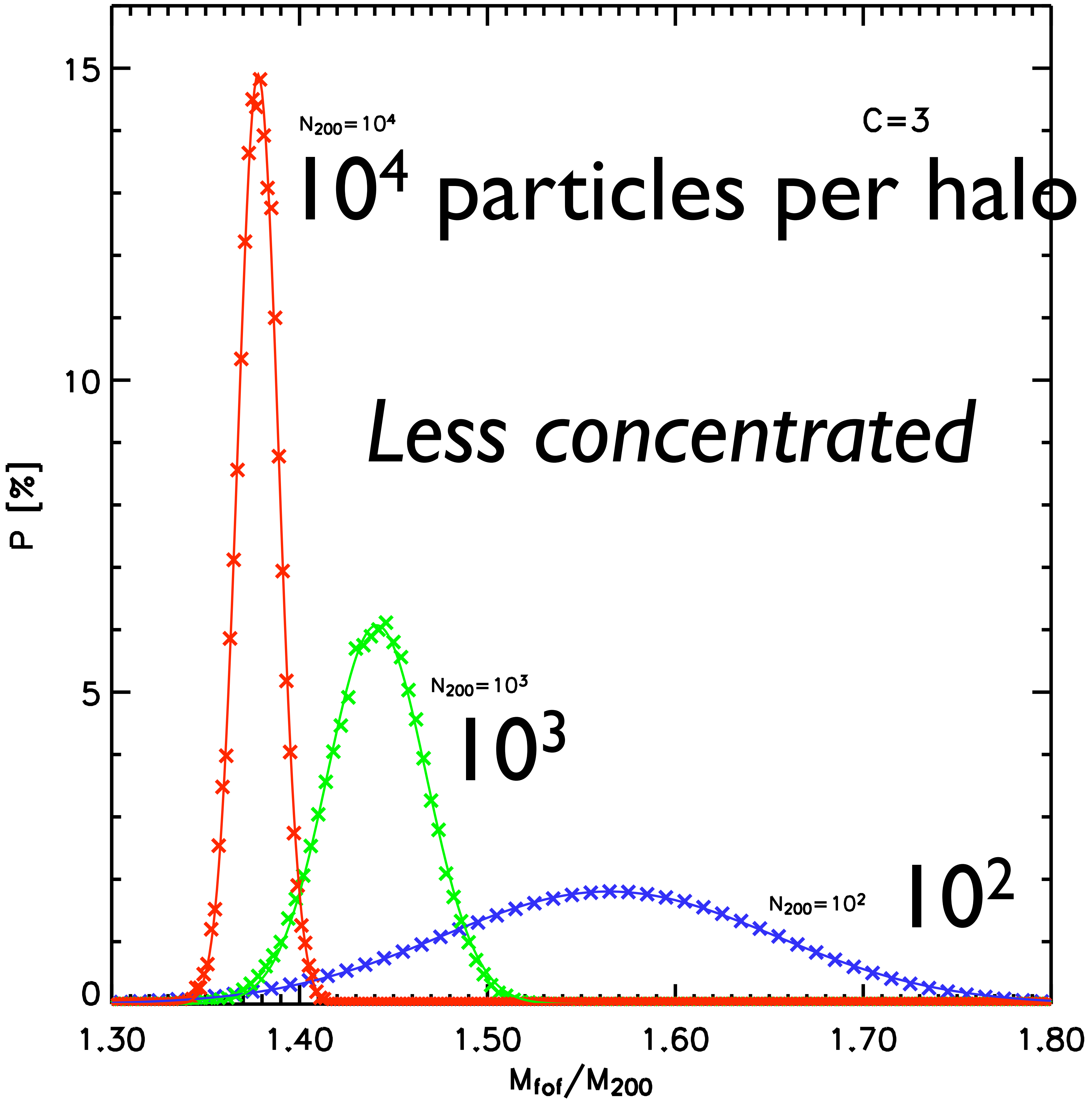
FoF Mass vs M_{200}

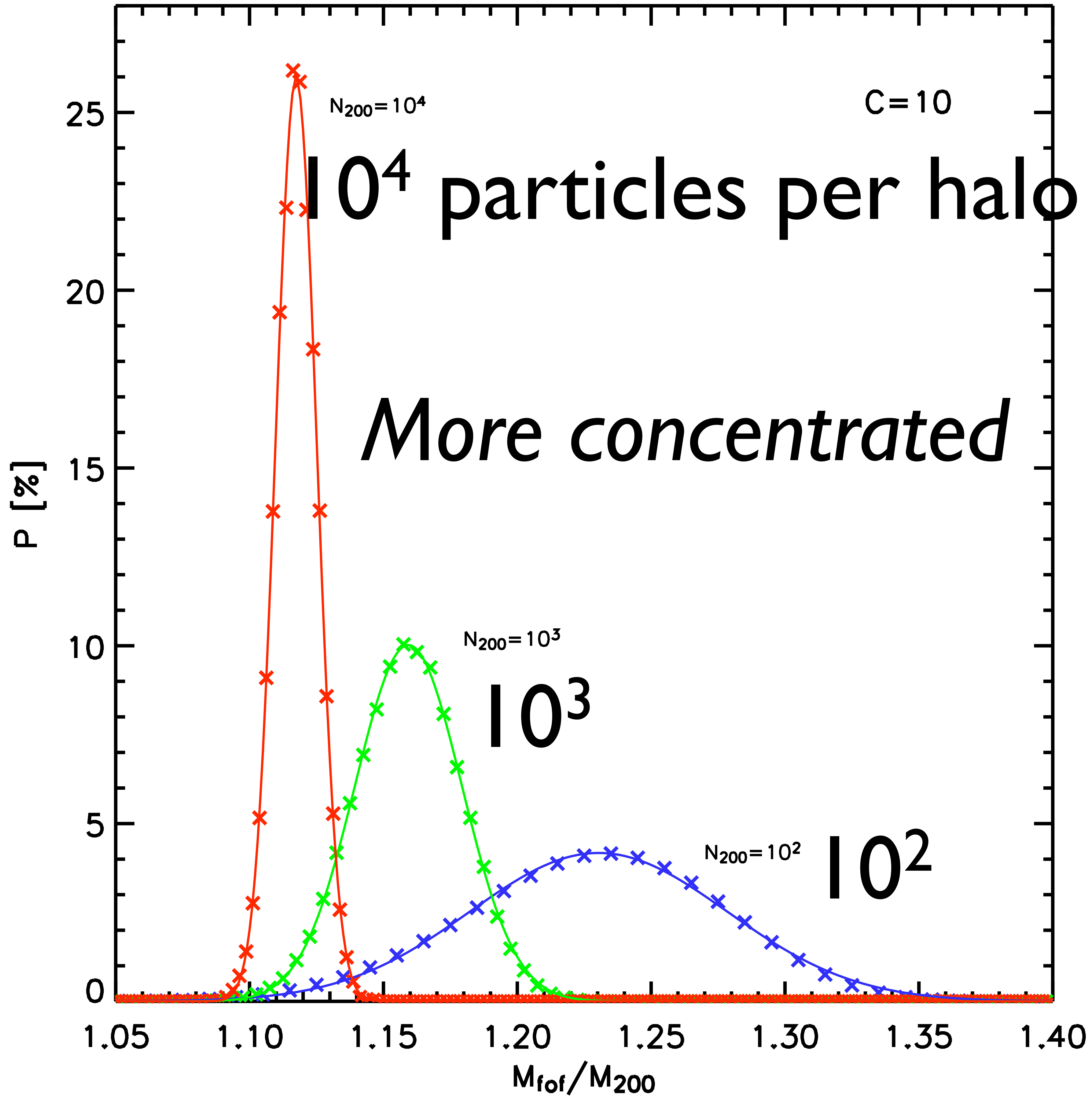




- It depends on the number of particles per halo and how halos are concentrated.

FoF Mass vs M_{200}





- The average of N_{200} is ~3000 for $M>0.5\times10^{15}h^{-1}M_{\rm sun}$
- $M_{\rm fof}/M_{200}\sim1.3$, giving $R_{\rm fof}/R_{200}\sim1.1$. I.e., **not important.**