Bullet Cluster: A Challenge to ΛCDM Cosmology

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)

Fundamental Physics and Large-scale Structure, Perimeter Institute

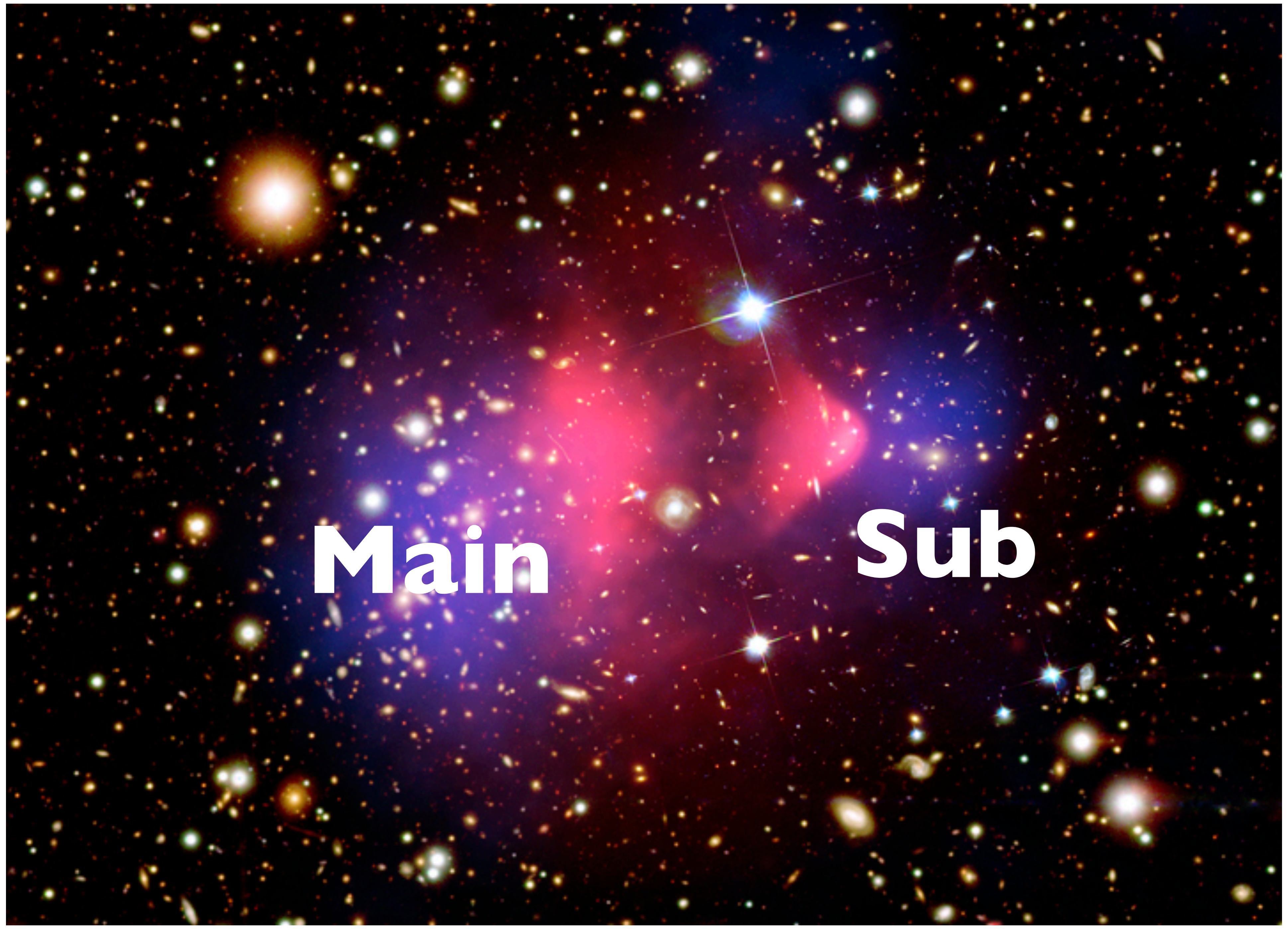
April 29, 2010

This talk is based on

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

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

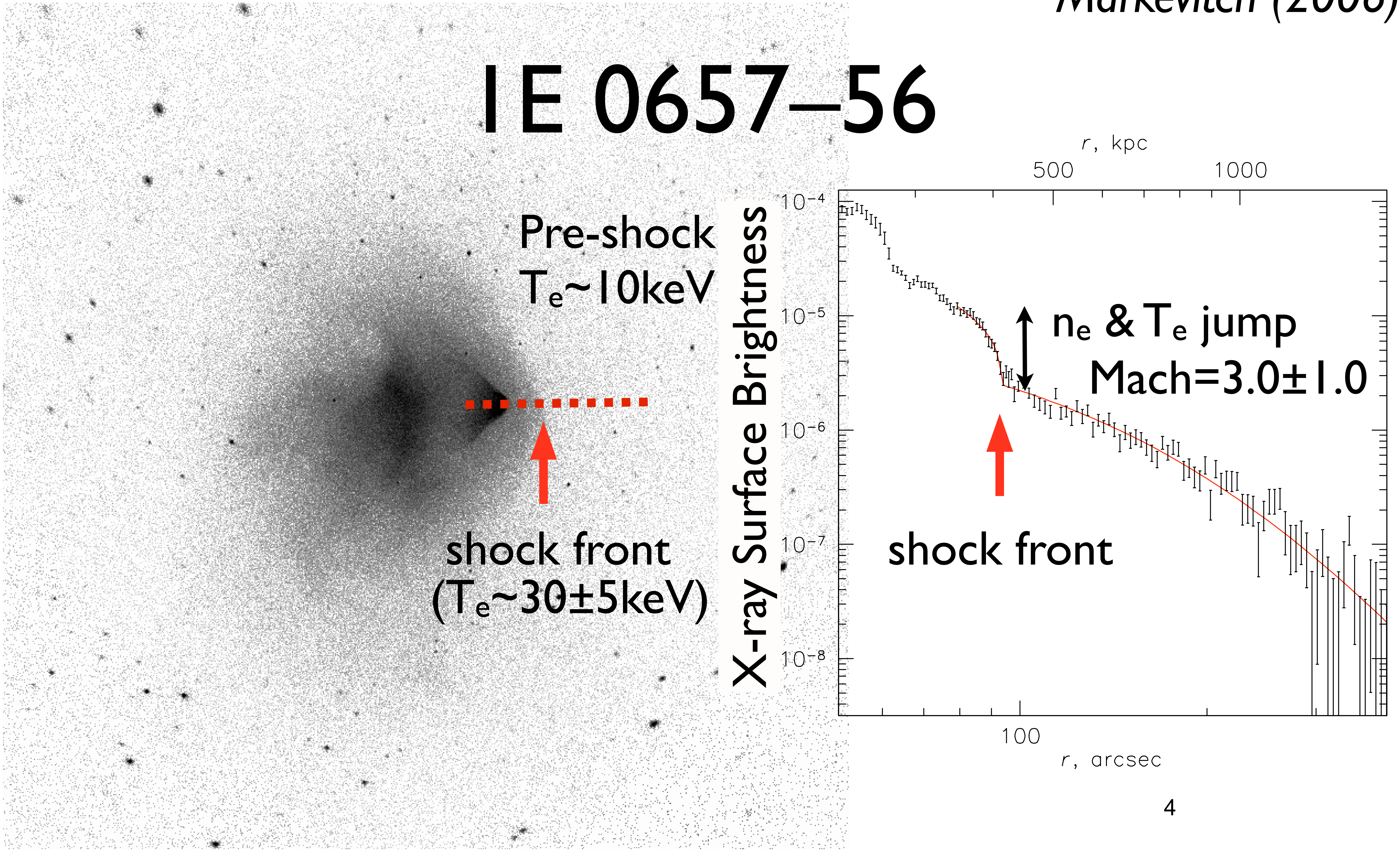
1E 0657–56



- The main-cluster mass ~ $10^{15}M_{sun}$
- The sub-cluster mass ~ $10^{14}M_{sun}$
- ~1:10 (nearly) head-on collision.

Markevitch (2006)

1E 0657–56



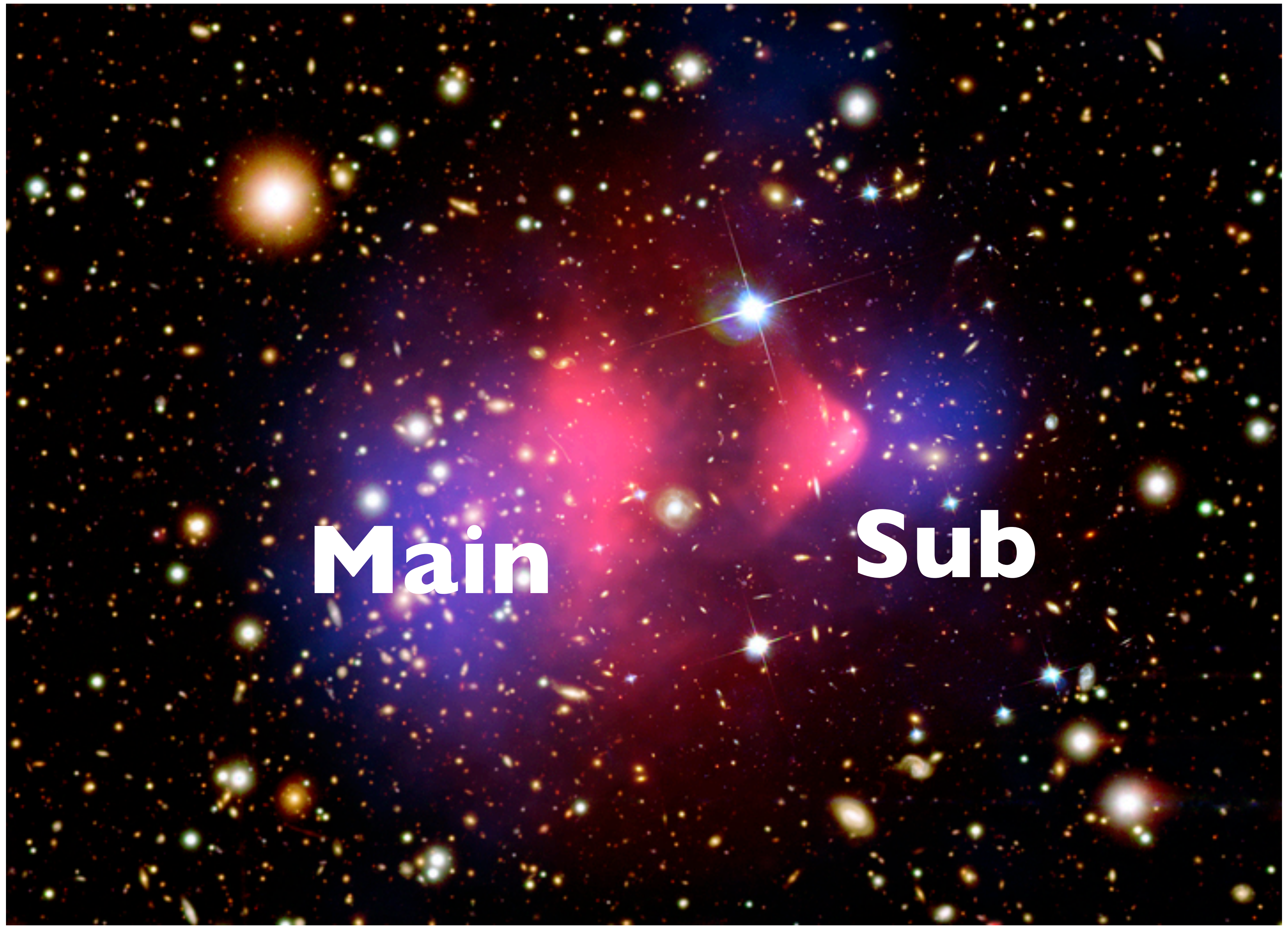
Shock Velocity vs Clump Velocity

- 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

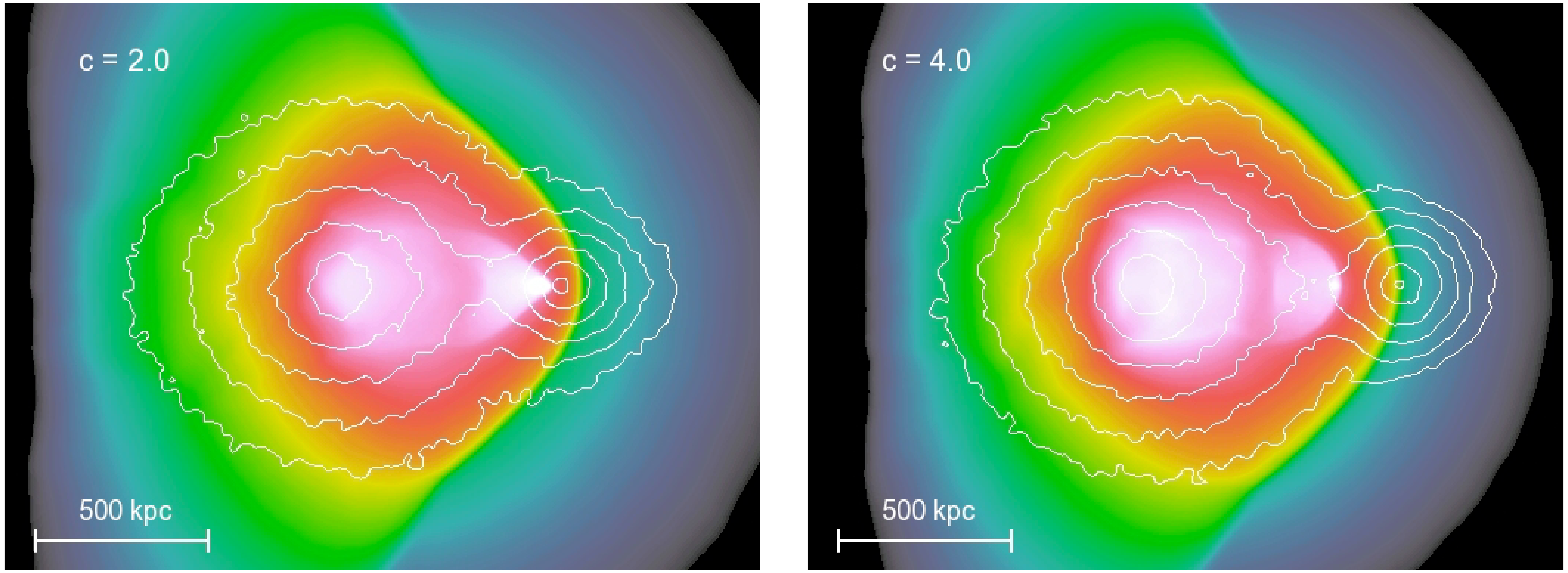
- In Hayashi & White (2006), they asked the following question: "*can we find a subclump moving at ~4500km/s somewhere in the Millennium Simulation?*"
- The answer is yes, and thus the bullet cluster does not seem anomalous at all.
  - This conclusion was later challenged by Farra & Rosen (2007), but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

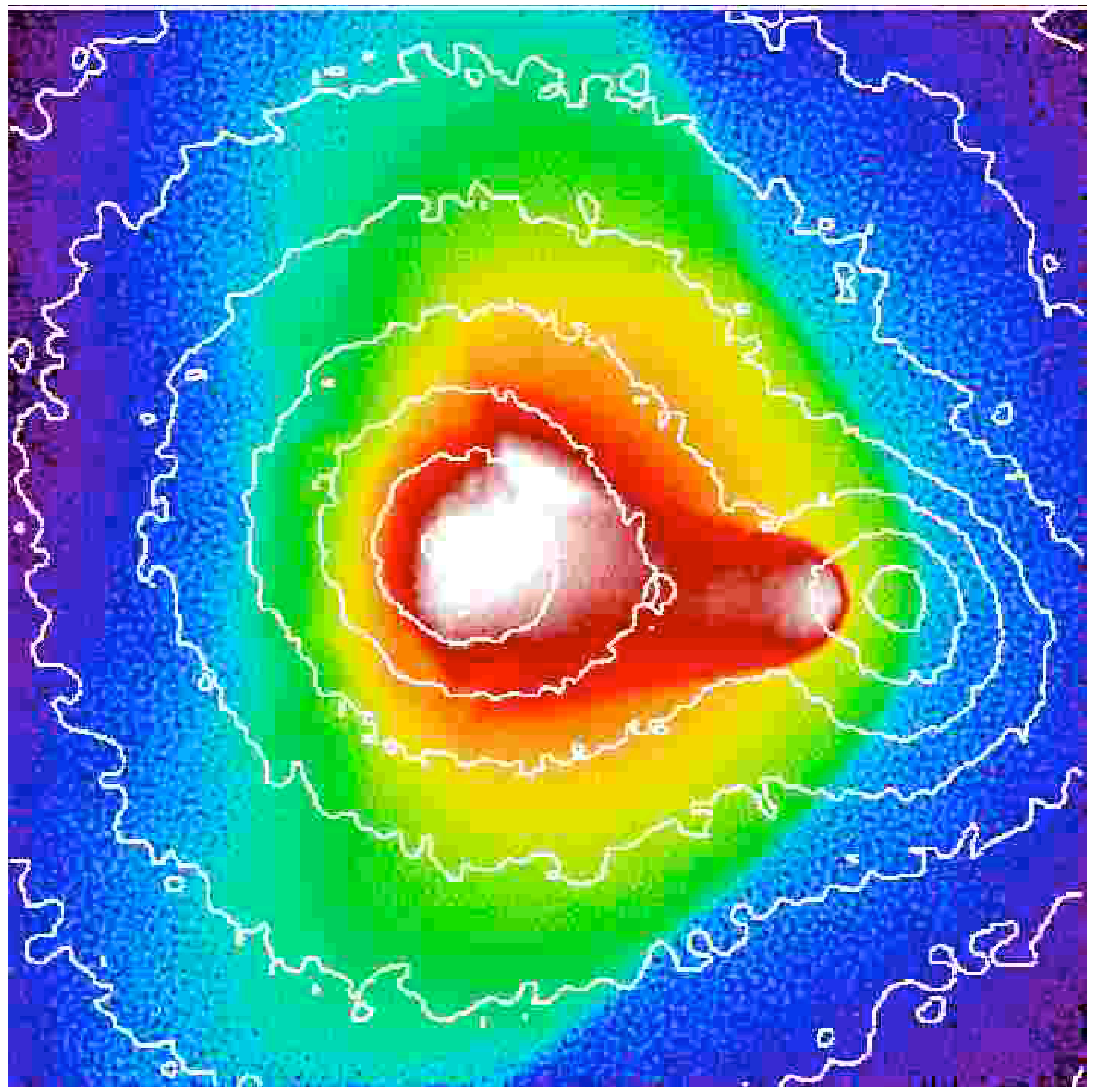
The key is the initial velocity

- 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!

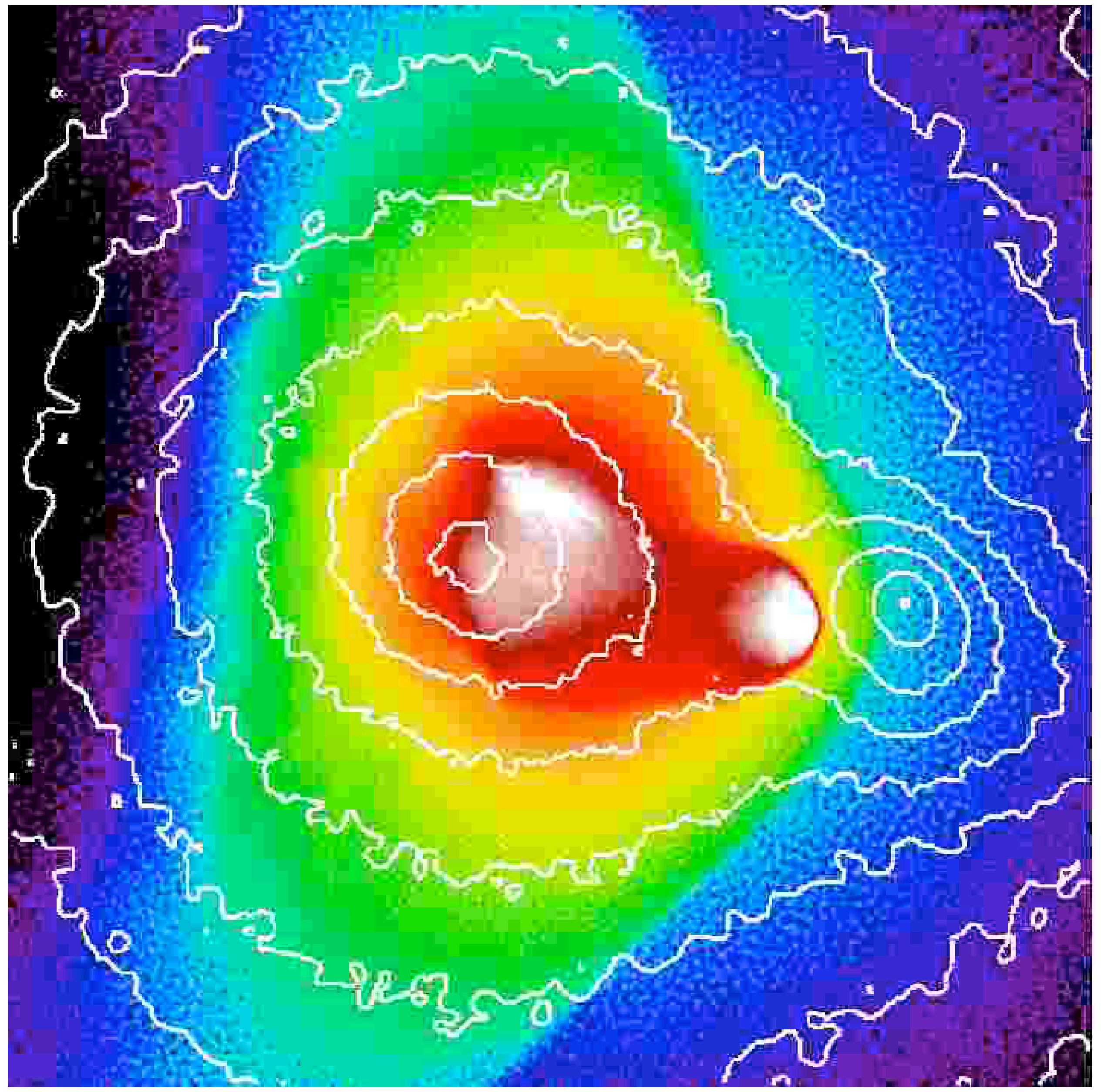
Need for parameter search

- 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.

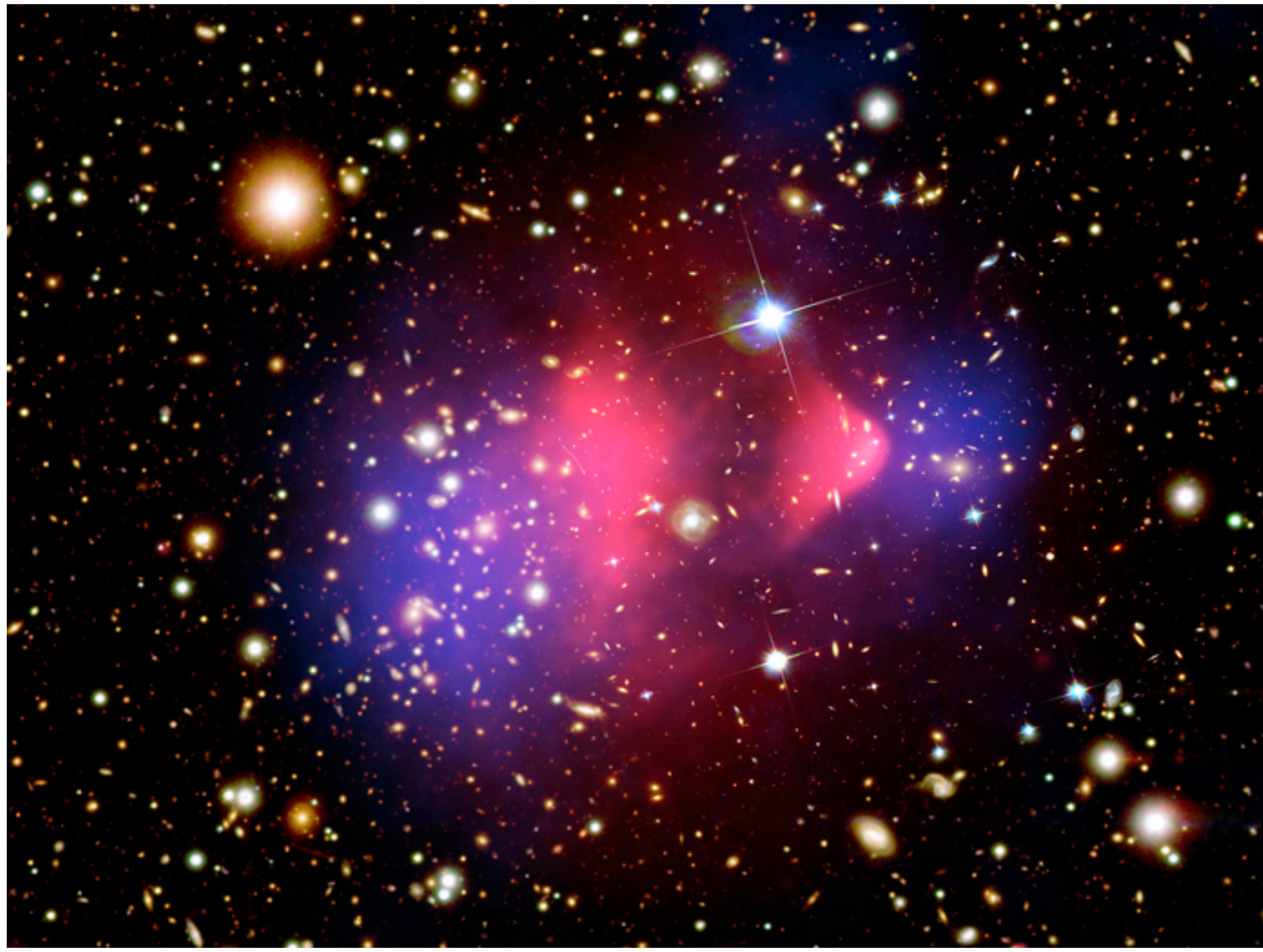
~3000 km/s is required



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 ~2R_{200}?*"
- To do this, we need a very large cosmological simulation because we need many ~$10^{15}M_{sun}$ halos for good statistics.

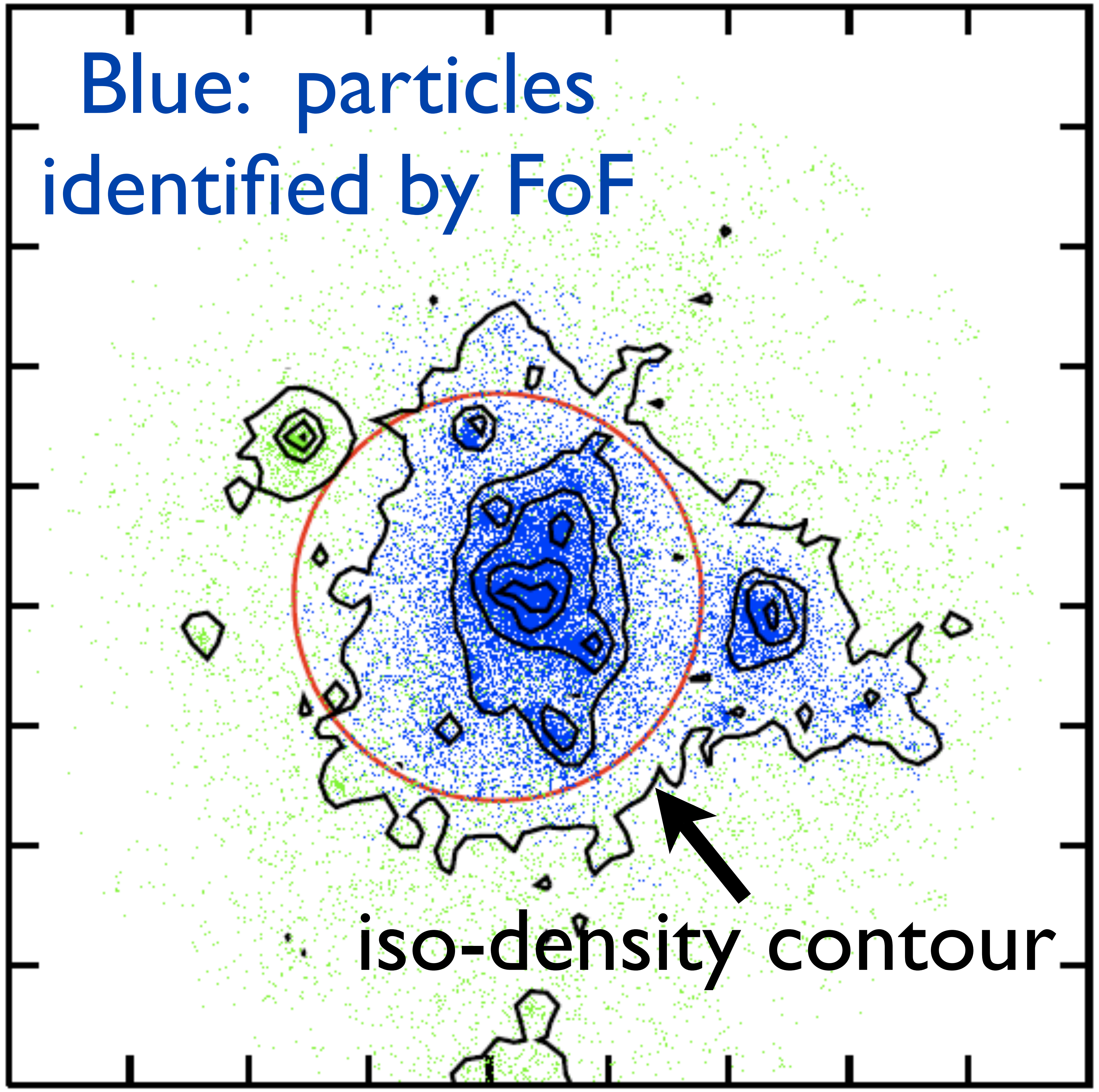
MICE Simulation

- 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 = $2\times10^{11}h^{-1}M_{sun}$.
    - Perfect for our purpose because we only need to resolve $>10^{14}h^{-1}M_{sun}$. Many particles per halo.

Finding 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.

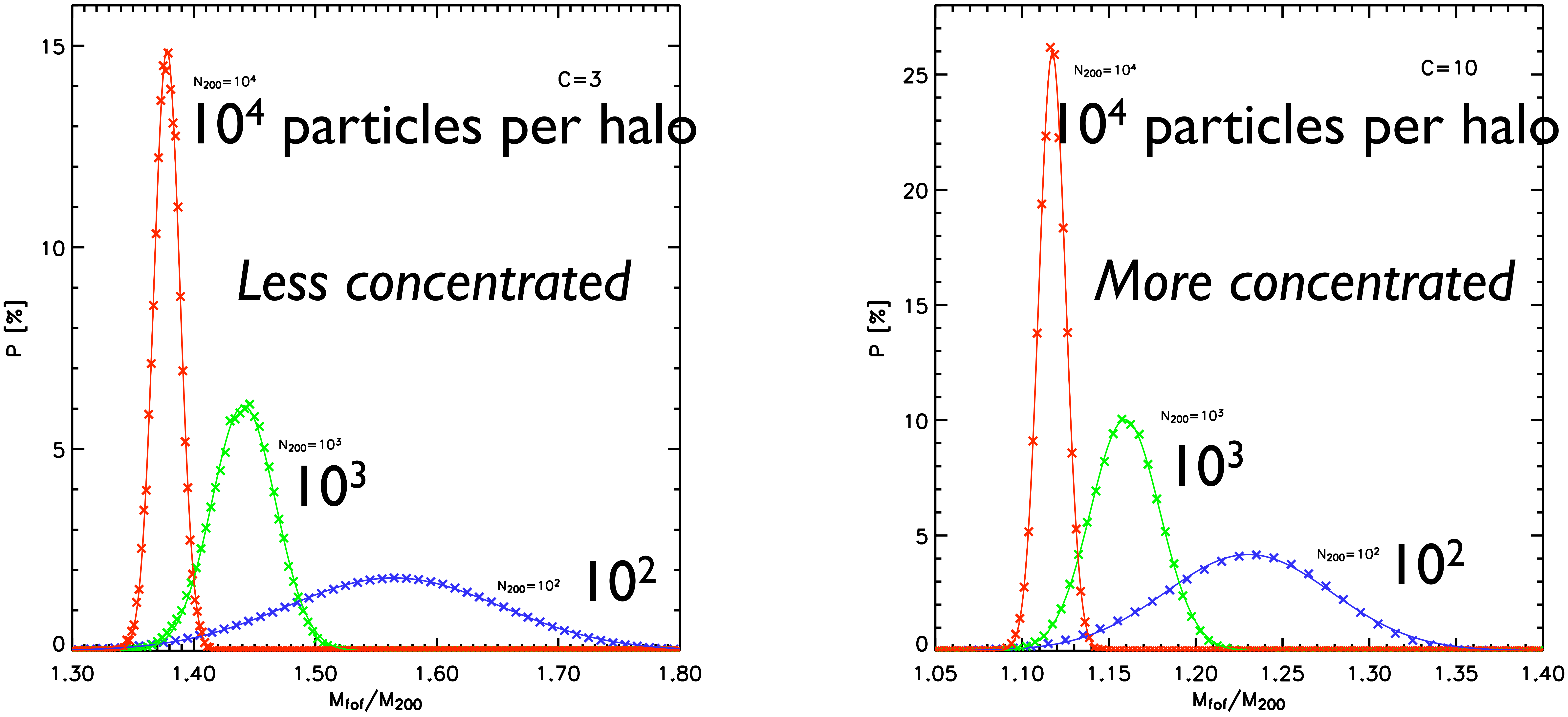
FoF Mass



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}



10^4 particles per halo

Less concentrated

10^3

10^2

10^4 particles per halo

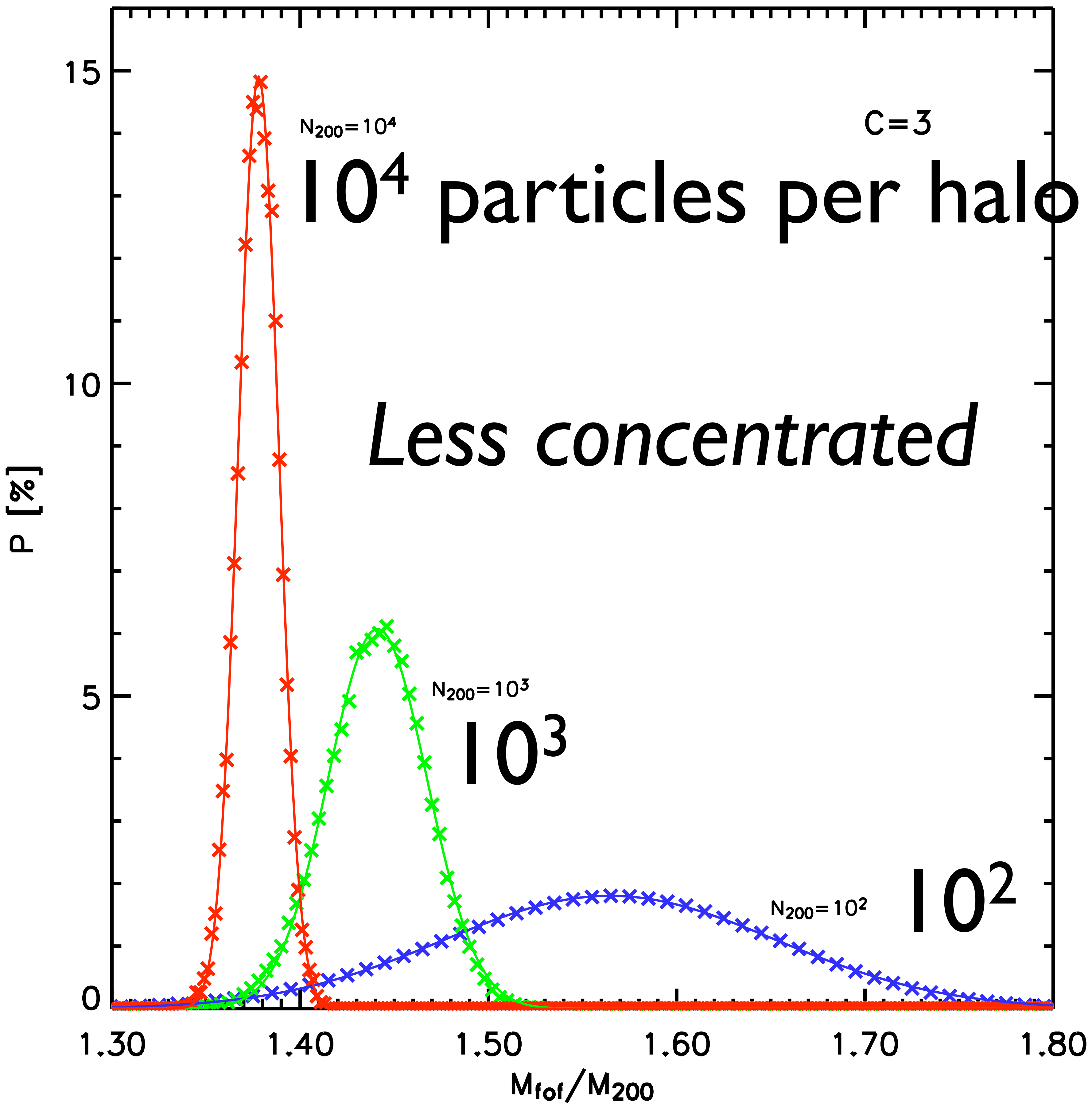
More concentrated

10^3

10^2

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

FoF Mass vs M_{200}

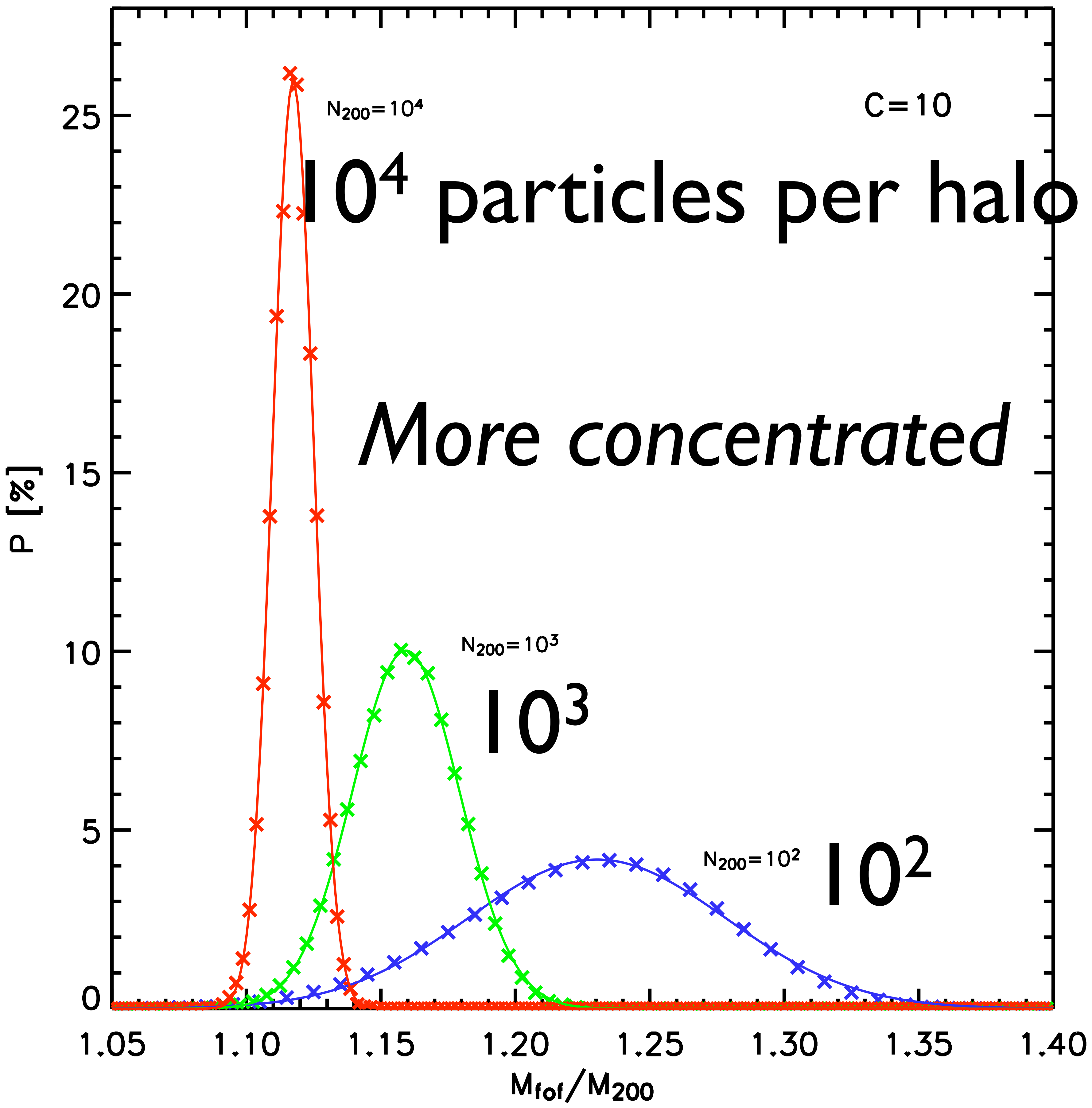


10^4 particles per halo

Less concentrated

10^3

10^2



10^4 particles per halo

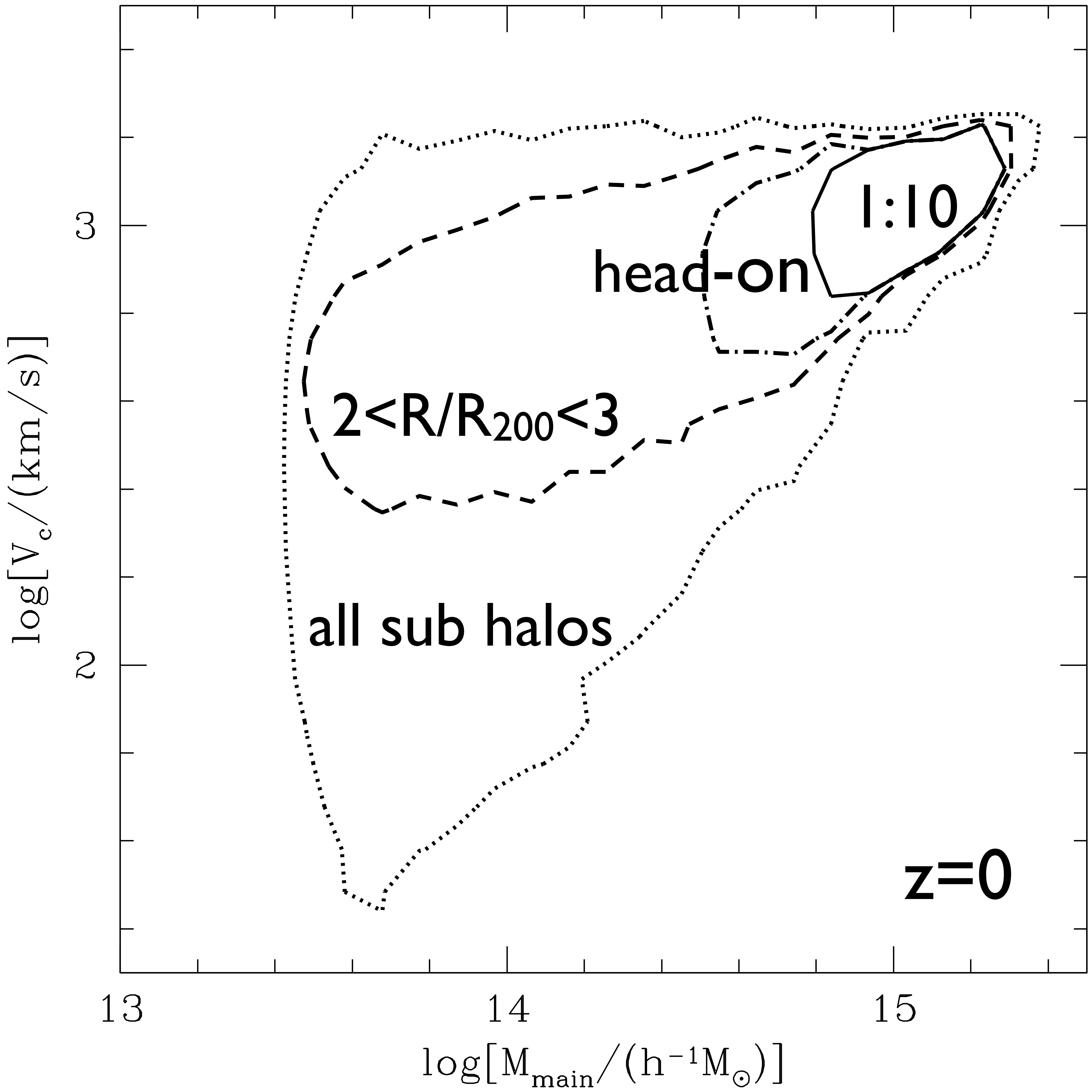
More concentrated

10^3

10^2

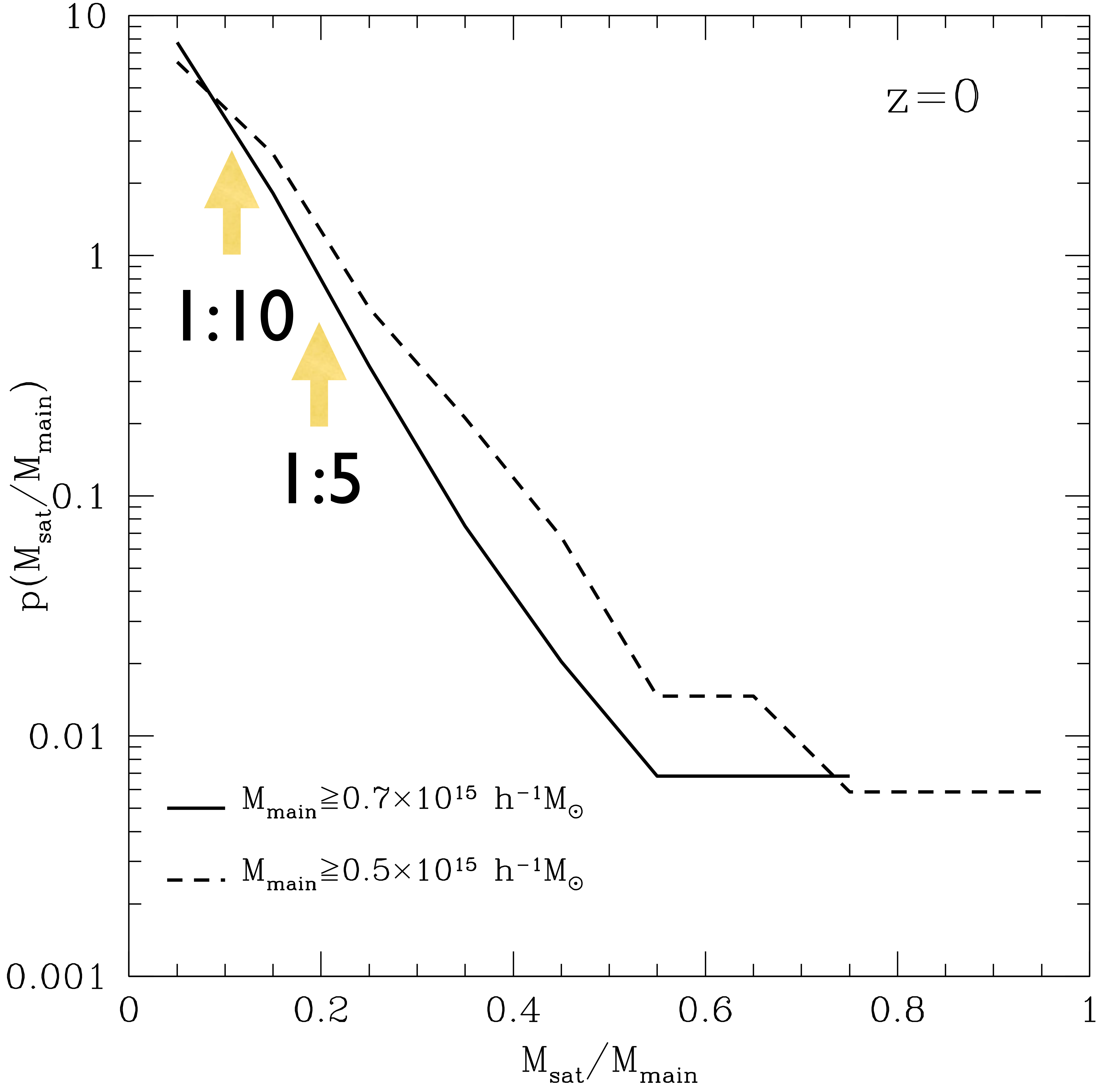
- The average of N_{200} is ~3000 for $M>0.5\times10^{15}h^{-1}M_{sun}$
- M_{fof}/M_{200}~1.3, giving R_{fof}/R_{200}~1.1. I.e., **not important.**

Finding Bullet-like Systems



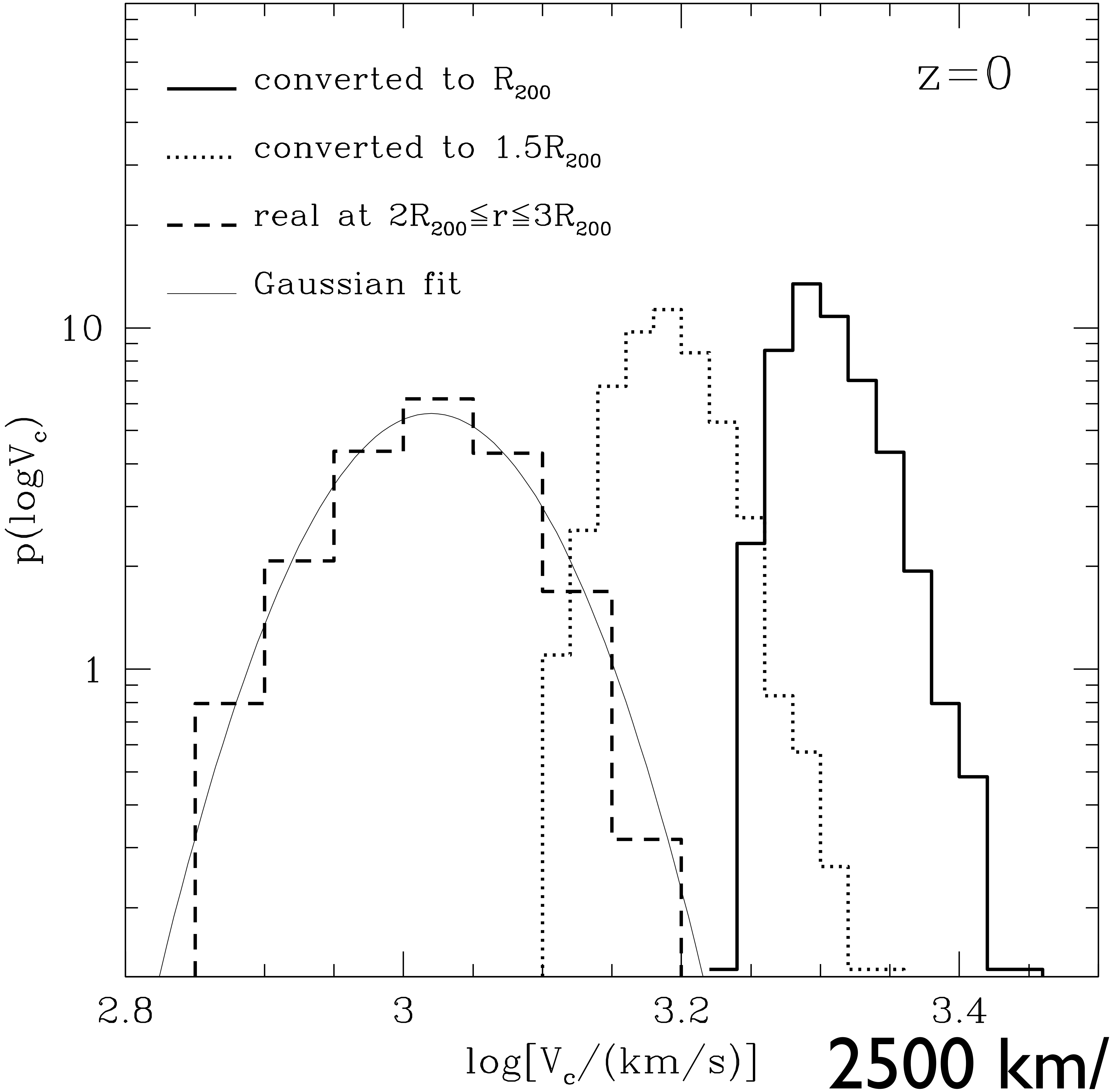
- Select the "bullet-like systems" by choosing:
- the sub halos near the main cluster ($2<R/R_{200}<3$)
- Nearly head-on collision
- Mass ratio of $M_{sub}/M_{main}<0.1$, where $M_{main}>10^{15}M_{sun}$
- **We have ~1000 systems that satisfy all the above conditions.**

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.

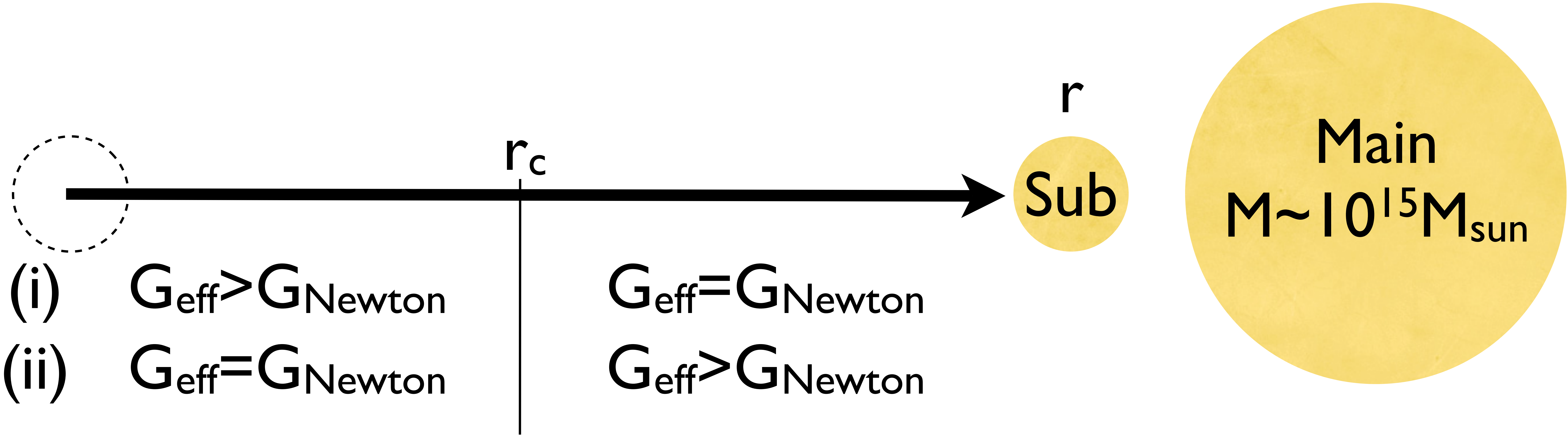
Statement

- 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)
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) $G_{eff} = G_{Newton}$ $G_{eff} > G_{Newton}$

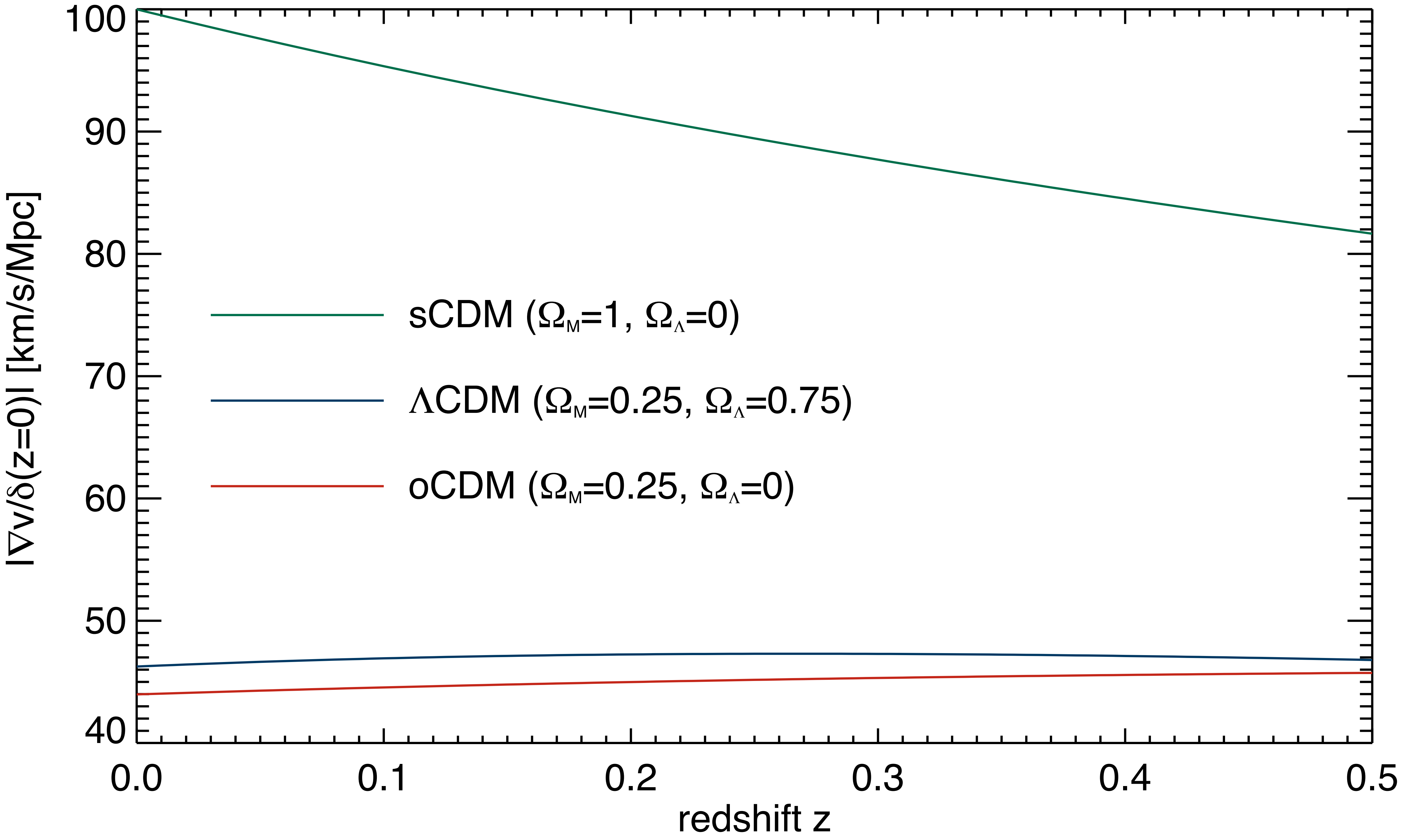
- $V^2 = GM_{main}/R$. So, you can get a higher velocity by somehow increasing G.

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

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

An Amusing Thought

- What if the acceleration is due to the modification of gravity at very large distances, and the space around clusters is Ω_m=1 (*which must be ruled out already*)?



Then you get a large boost in the velocity.

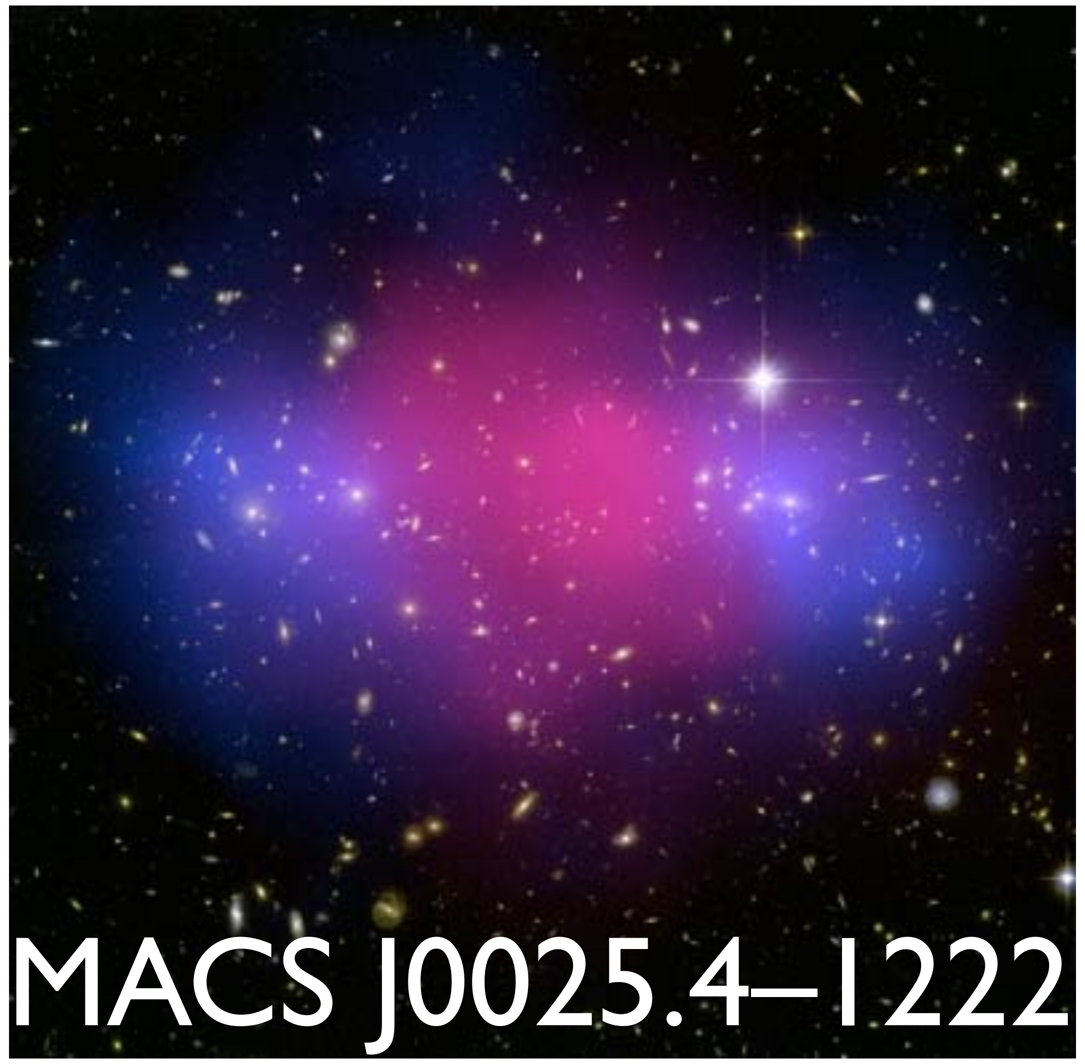
Conclusion

- 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?**

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 4600 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!


MACS J0025.4–1222