The Bullet Cluster: A Challenge to

Jounghun Lee (Seoul Nat’l Univ.)

This Lecture is based on

- J.L. & Eiichiro Komatsu (UT Austin)

  (ApJ in press, arXiv:1003.0939)

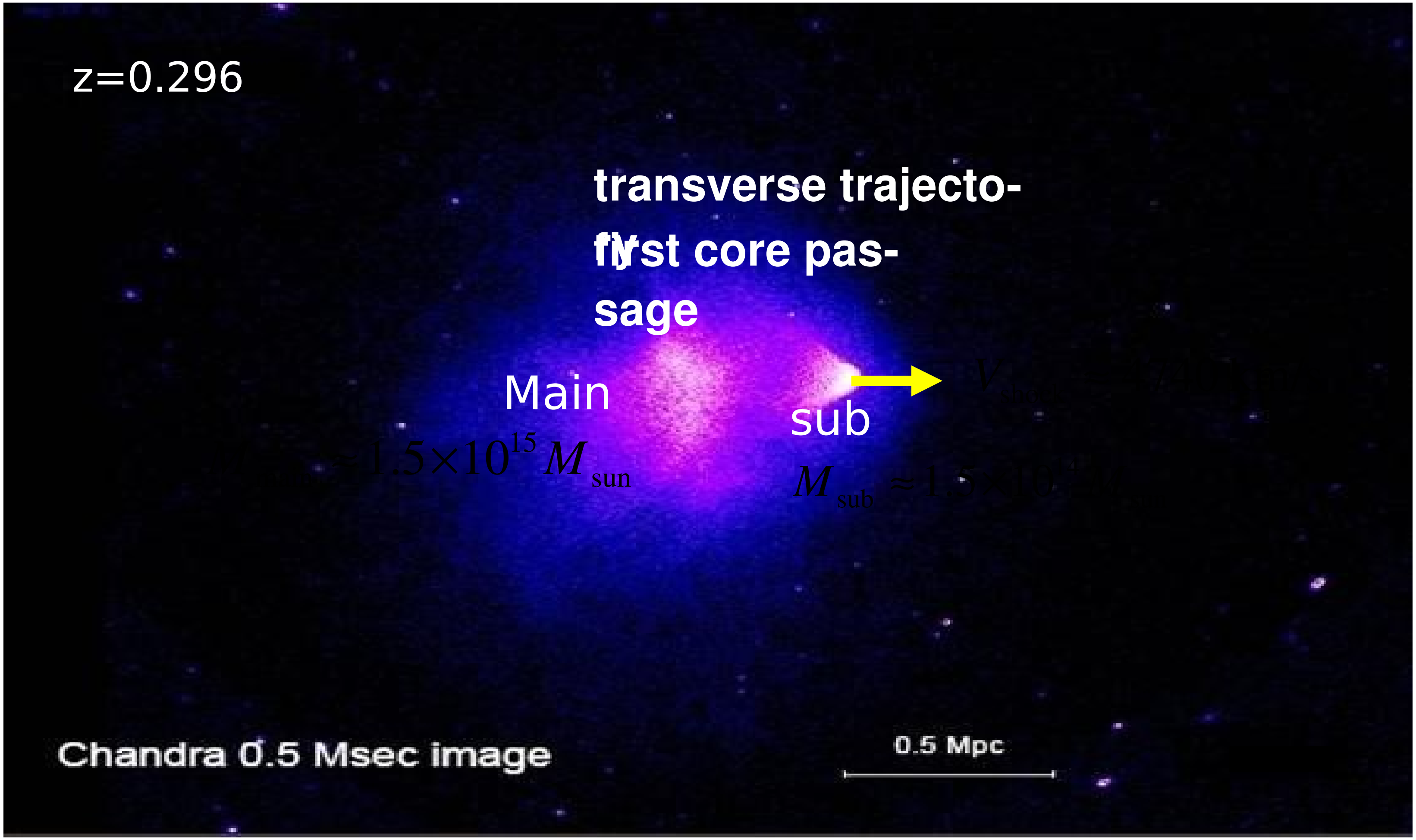
The Bullet Cluster: IE0657-56

- Discovered as a failed cluster (Tucker et al.1995):
  - a large cloud of hot-gas

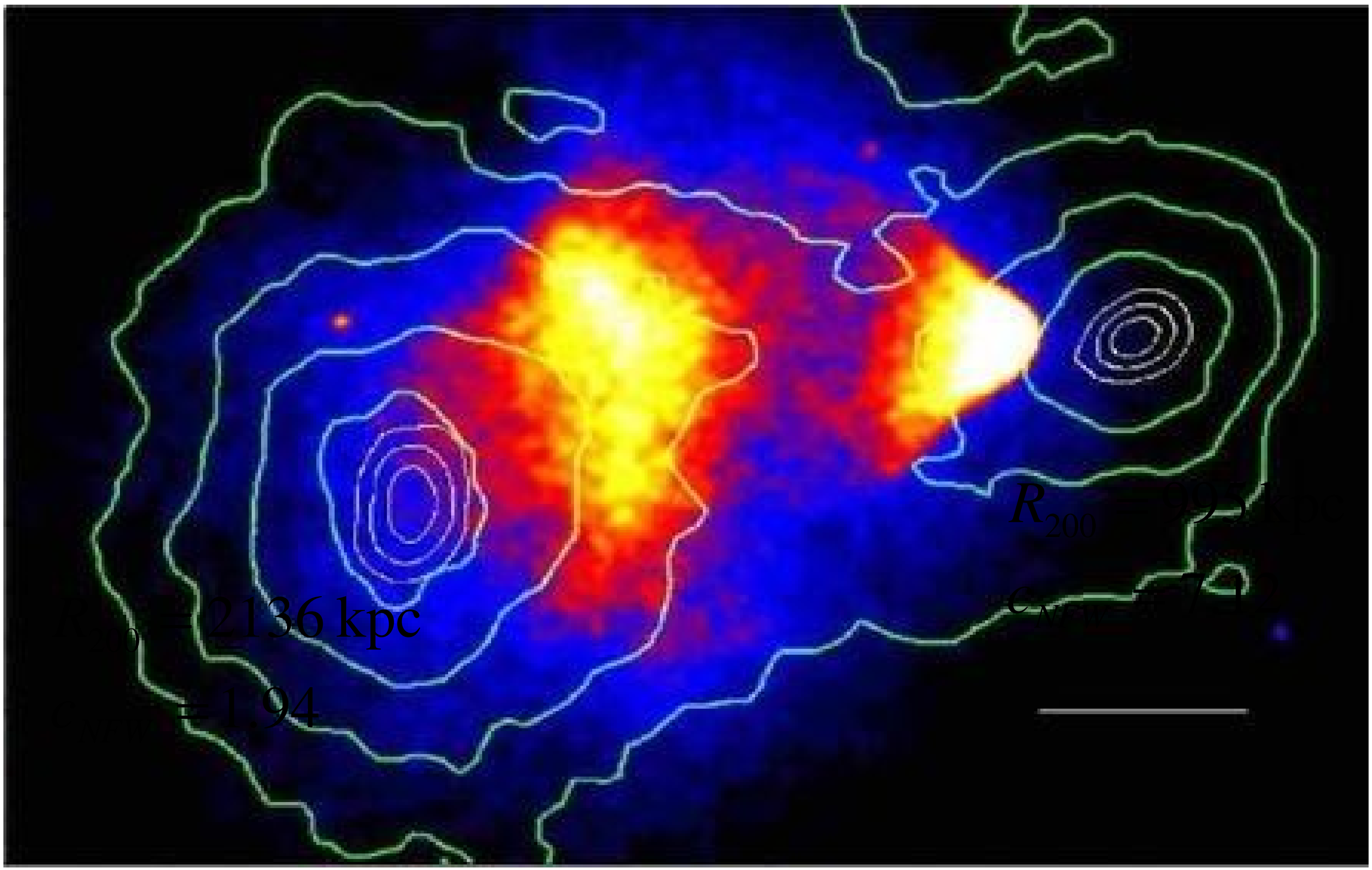
- First observed by *Chan-dra* (Markevitch et al.2002):
  - a bullet-like subclus-ter exiting its main cluster with a bow shock
  - a system of two colli-

X-ray: Markevitch et al. (2004)
Lensing Map: Clowe et al. (2006)
Optical: Clowe et al. (2006)

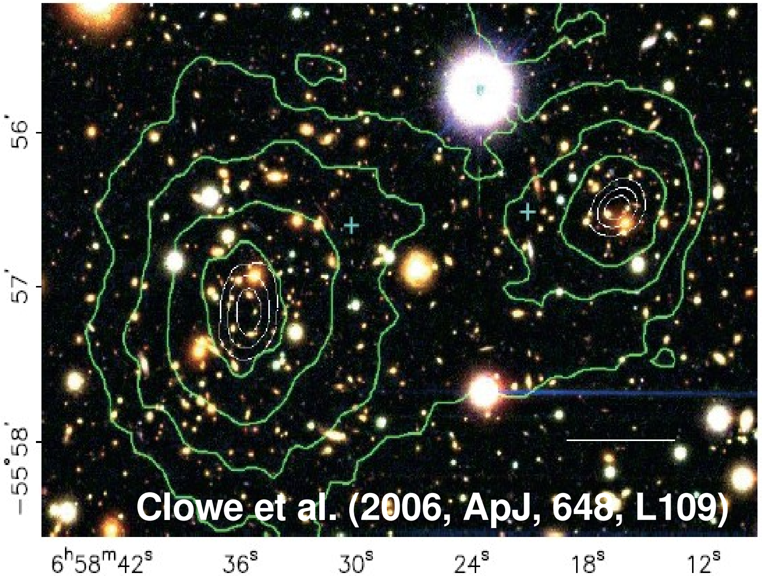
Morphology of IE0657-56



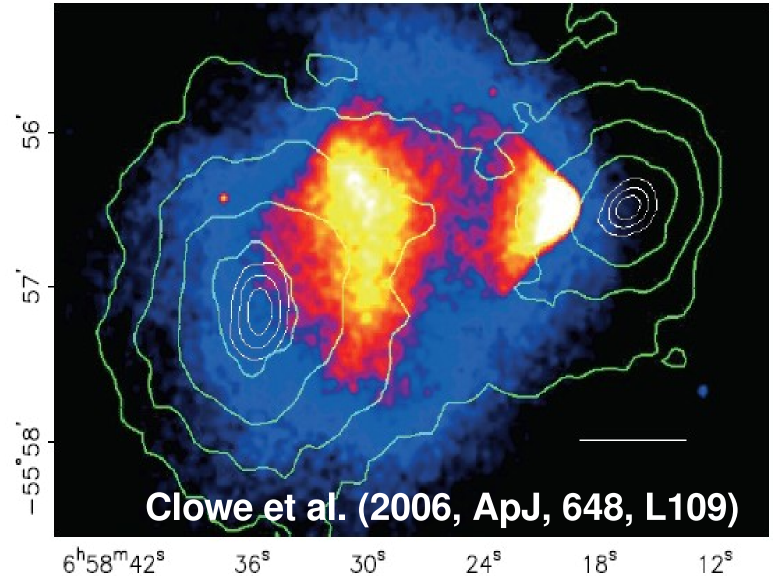
Matter Distribution of IE0657-56



Surprise 1 – Offset of CM



$$\text{center of mass} = \text{center of galaxies}$$

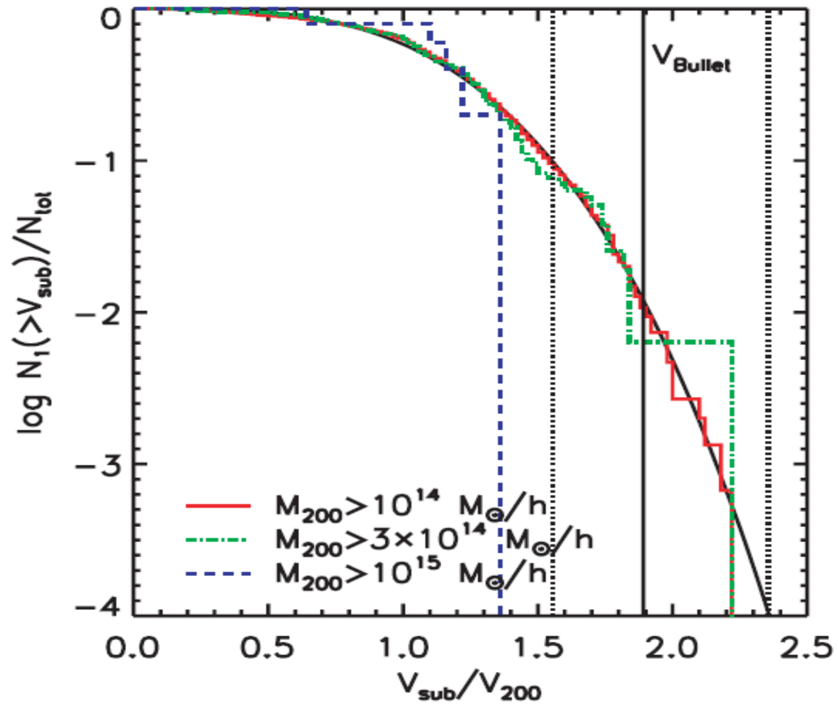


$$\text{center of mass} \neq \text{center of plasma}$$

direct proof of the existence of nonbaryonic dark matter

Likelihood of Bullet Cluster I

Hayashi & White (2006)



The number fraction of bul-
let-like
subclusters in a LCDM uni-
verse.

$$f = \exp\left[-\left(\frac{V_{\rm sub}/V_c}{1.55}\right)^{3.3}\right] \approx \frac{1}{500}$$

- large uncertainty due to the small sample size
- using inaccurate old data of the bullet cluster

$$V_{shock} = 4500\ \mathrm{km/s}$$

$$V_{main} = 2380\ \mathrm{km/s}$$

Likelihood of Bullet Cluster II

- Farra & Rosen (2007) reestimated the likelihood of bullets, using the updated data:

$$V_{shock} = 4500\,\mathrm{km/s} \qquad \Rightarrow \qquad V_{shock} = 4740\,\mathrm{km/s}$$

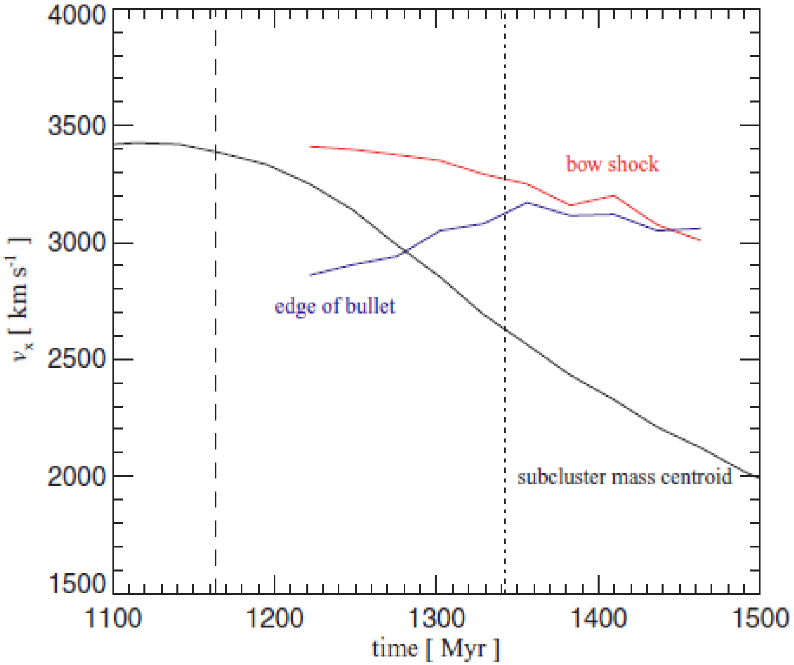
$$V_{main} = 2380\,\mathrm{km/s} \qquad \Rightarrow \qquad V_{main} = 1770\,\mathrm{km/s}$$

$$f \approx 10^{-7}$$

- The bullet cluster seems to be quite unusual in LCDM…

Likelihood of Bullet Cluster III

- Hydrodynamic simulations by Springel & Farra (2007)



$$V_{shock} \neq V_{sub}$$

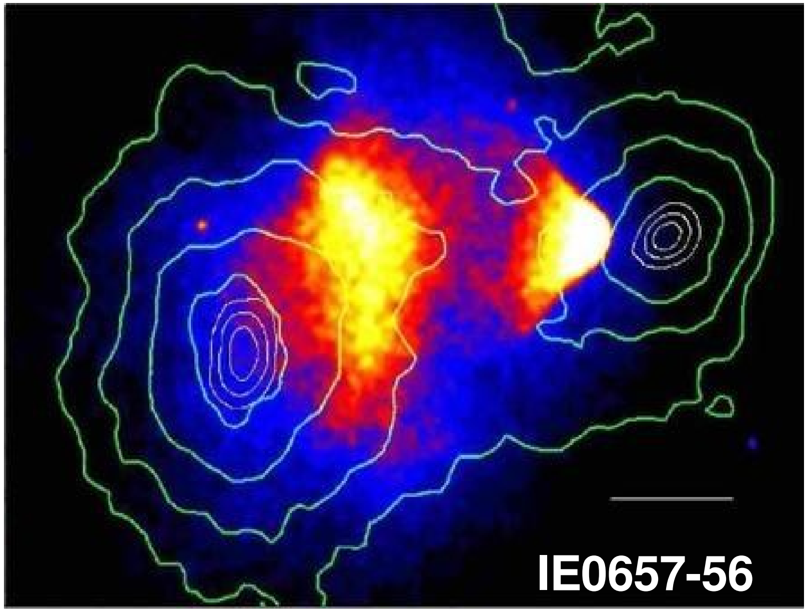
$$V_{shock} = 4500 \text{ km/s}$$

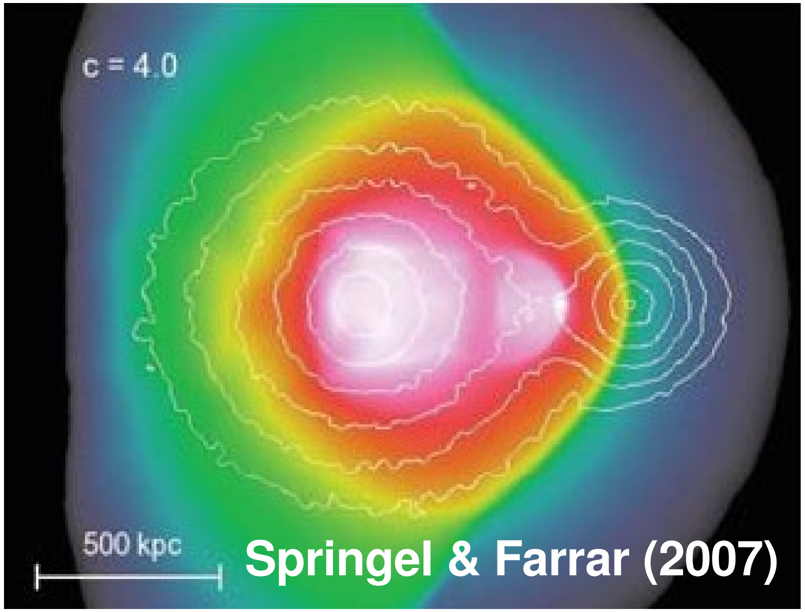
$$\Rightarrow V_{sub} = 2700 \text{ km/s}$$

$$\Rightarrow f \approx 0.07$$

The bullet cluster systems are not so rare in LCDM.

Surprise 2 – Escape of Gas



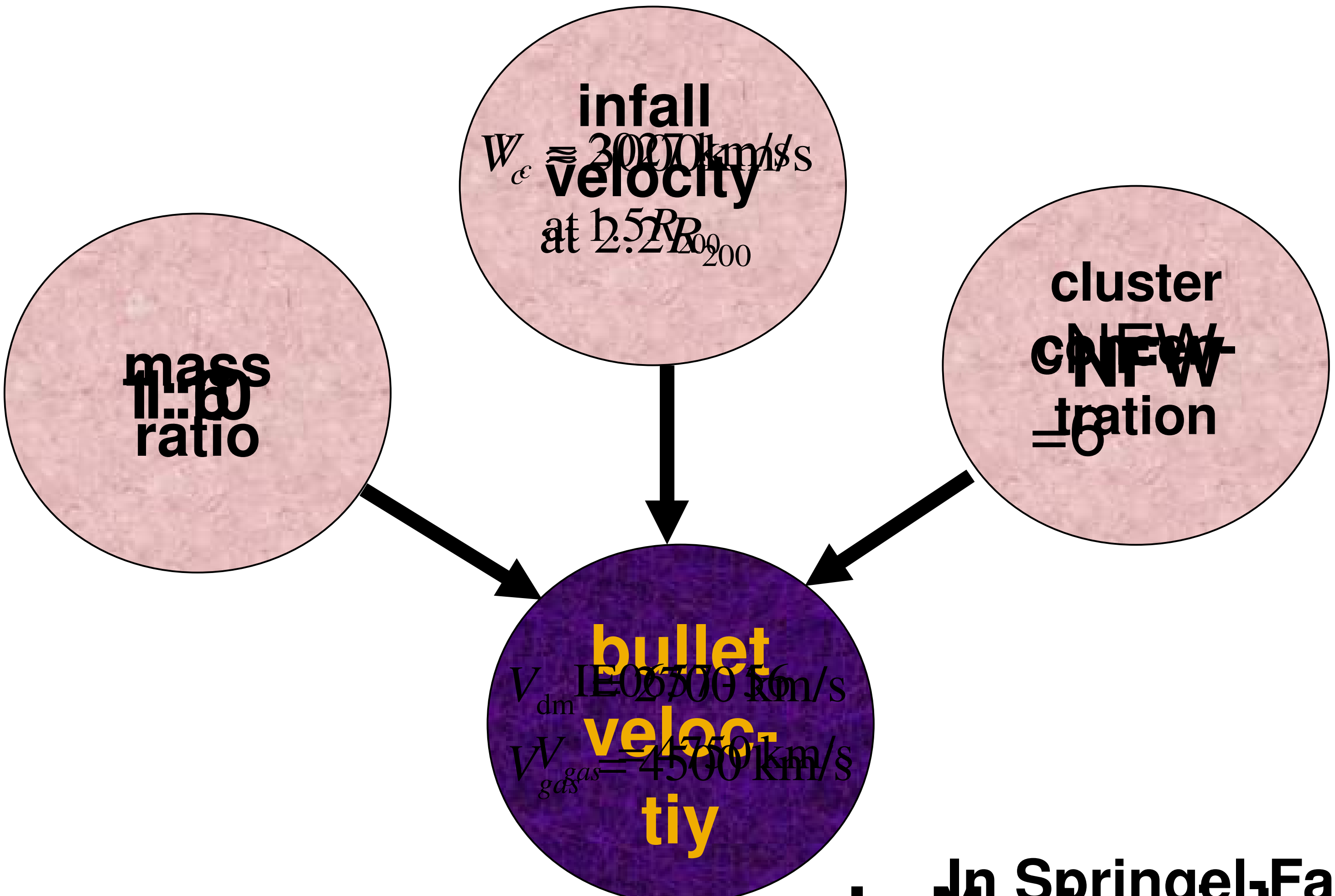


Gas of the main cluster escape the gravitational potential.

Gas of the main cluster could not escape the gravitational potential.

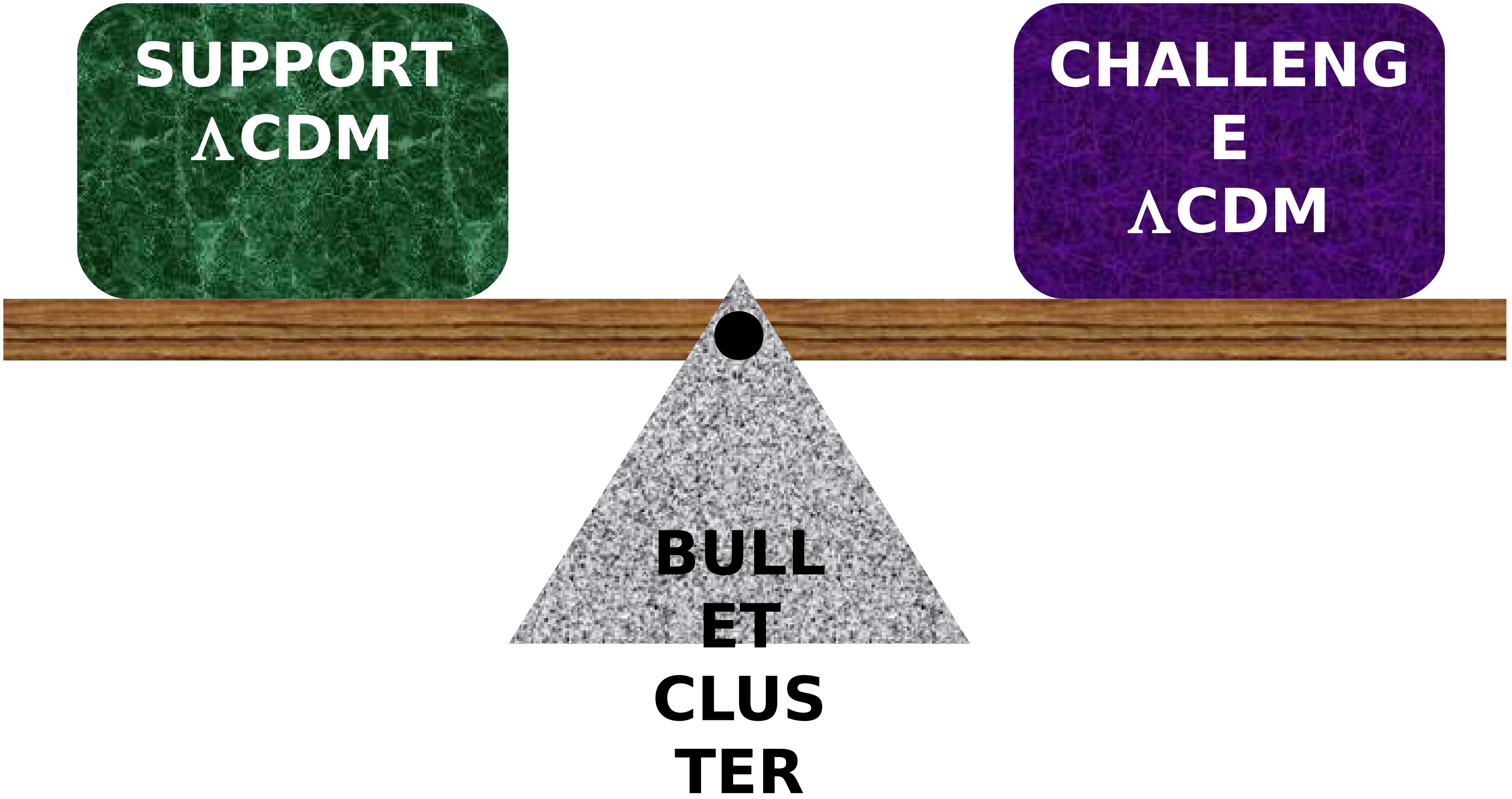
The velocity of the bullet cluster is not fast enough!

Conditions for Bullet



In Springel-Farrar07

In Mastropietro-Burkert08


SUPPORT
ΛCDM
CHALLENG
E
ΛCDM
BULL
ET
CLUS
TER

A Key to the Puzzle

V_c at $r = R_{200}$

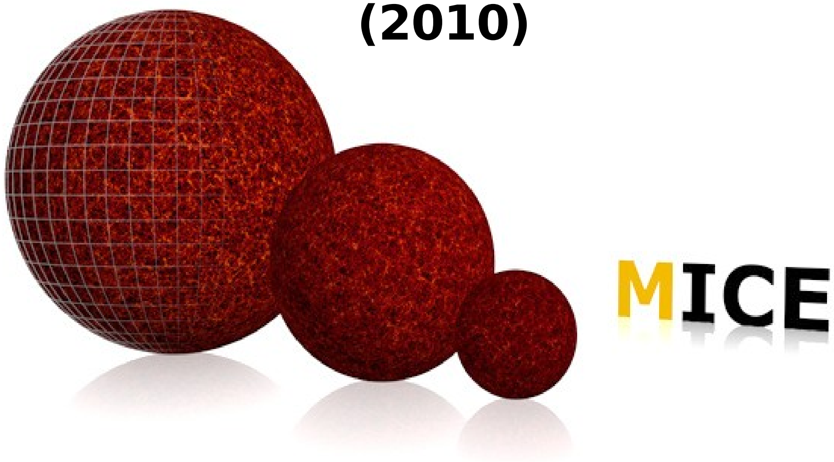
V_c at $r \approx 2R_{200}$

The Strategy

MICE Simulation

- A flat LCDM with
  - Wm=0.25, h=0.7
  - ns=0.95, s8=0.8

Crocce et al. (2010)



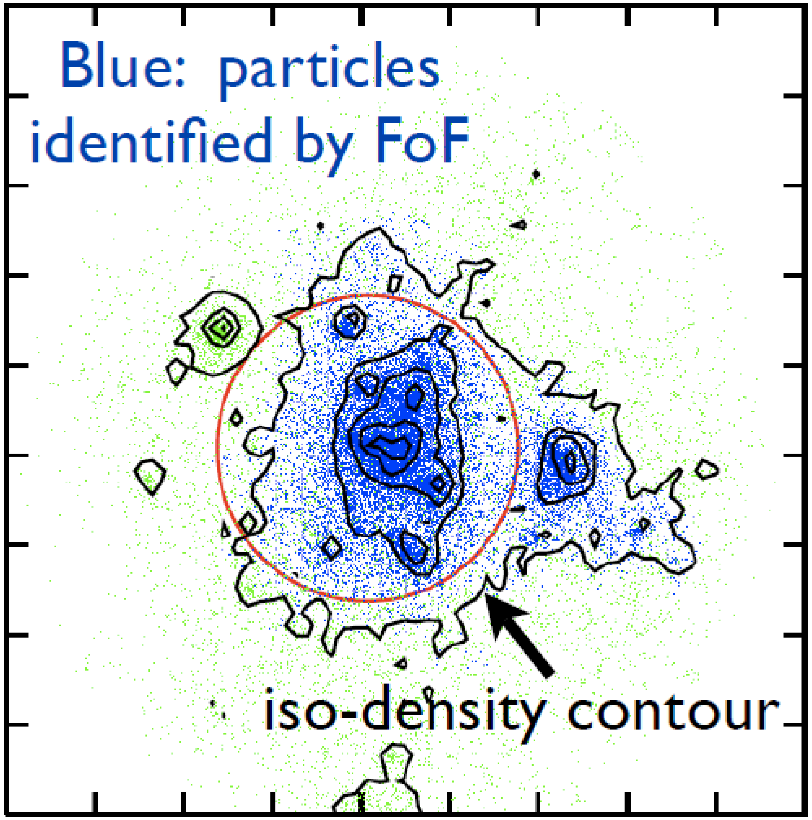
- Lbox = 3h-1Gpc: largest ever!
- # of particles = 2048
- Mpar=2x1011 h-1M-sun

http://segre.ieec.uab.es/fosalba/MICE/

MICE Catalog of Cluster Halos

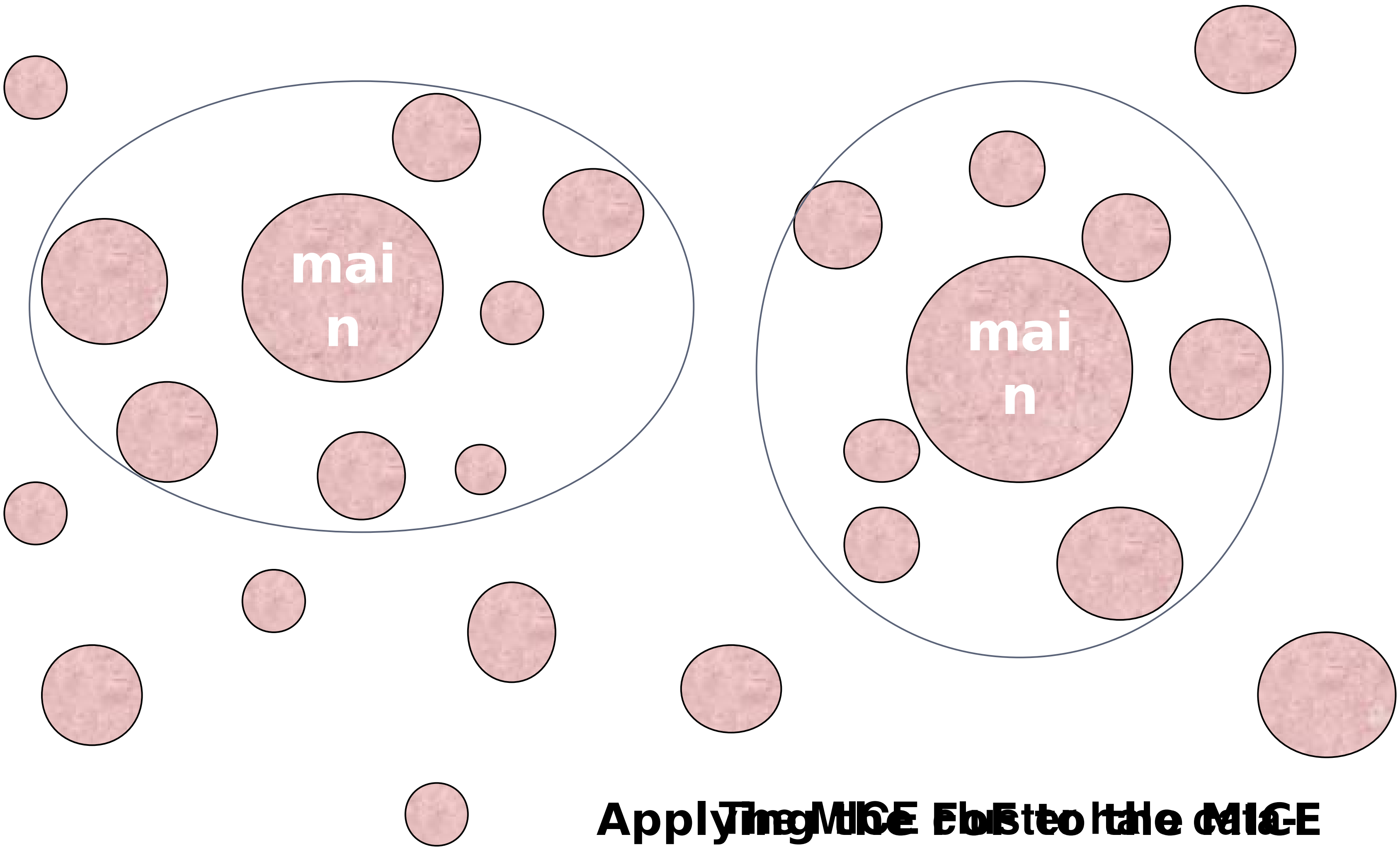
- Identified by the friends-of-friends algorithm with a linkage parameter

z	the number of clusters
0	2.8 million
0.5	1.7 million



Lukic et al. (2008)

Clusters of Clusters



Applying the FoF to the MICE catalog

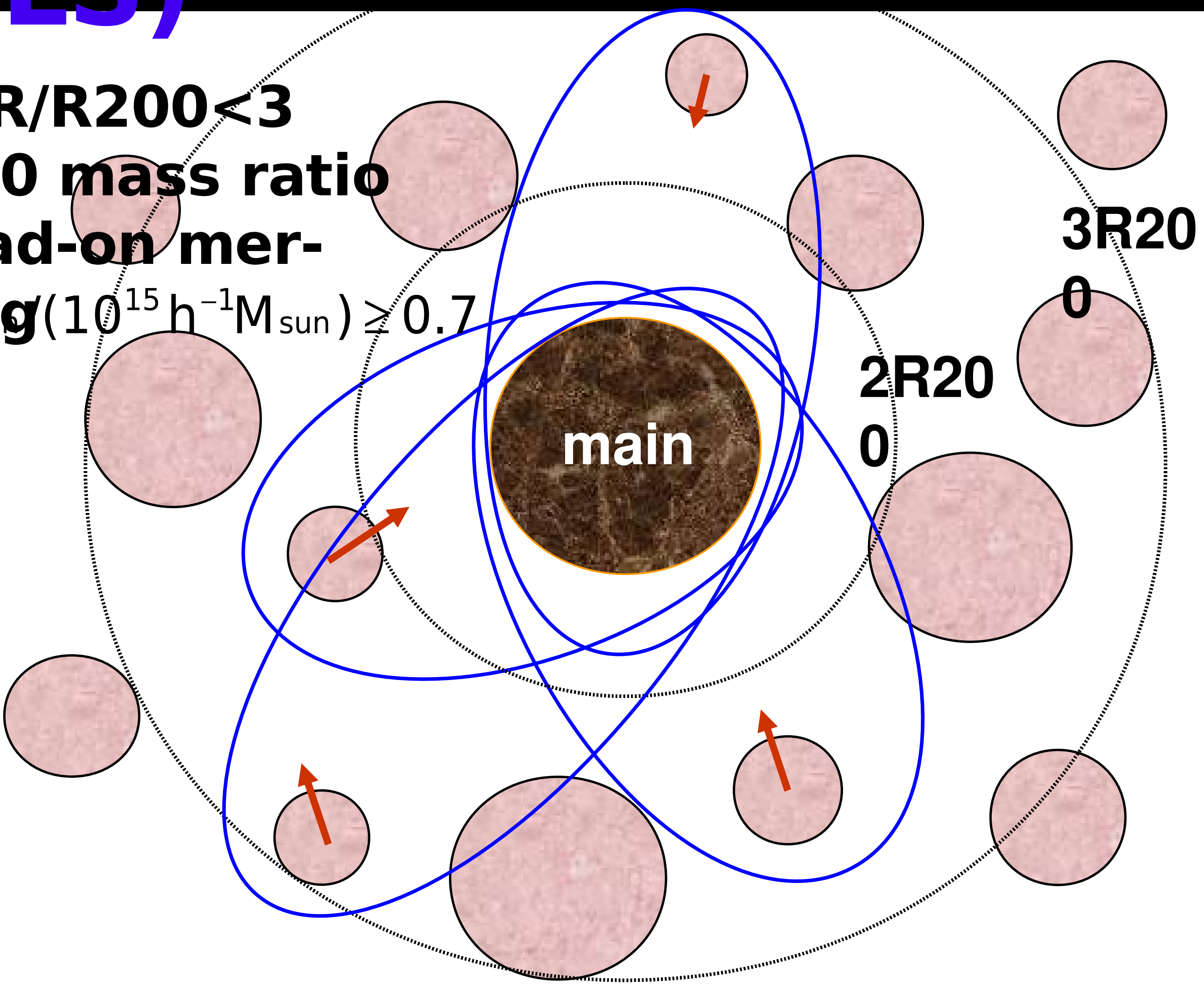
The MICE cluster cata-log

z	the number of clusters	the number of clusters of clusters[a]	the mean mass of main clusters
0	2.8 million	0.29 million	$1.3 \times 10^{14}\ h^{-1}\ M_\odot$
0.5	1.7 million	0.20 million	$1.1 \times 10^{14}\ h^{-1}\ M_\odot$

Bullet-Like Systems (BLS)

2<R/R200<3
1:10 mass ratio
head-on merging

$M_{main}/(10^{15}\,h^{-1}M_{sun}) \geq 0.7$

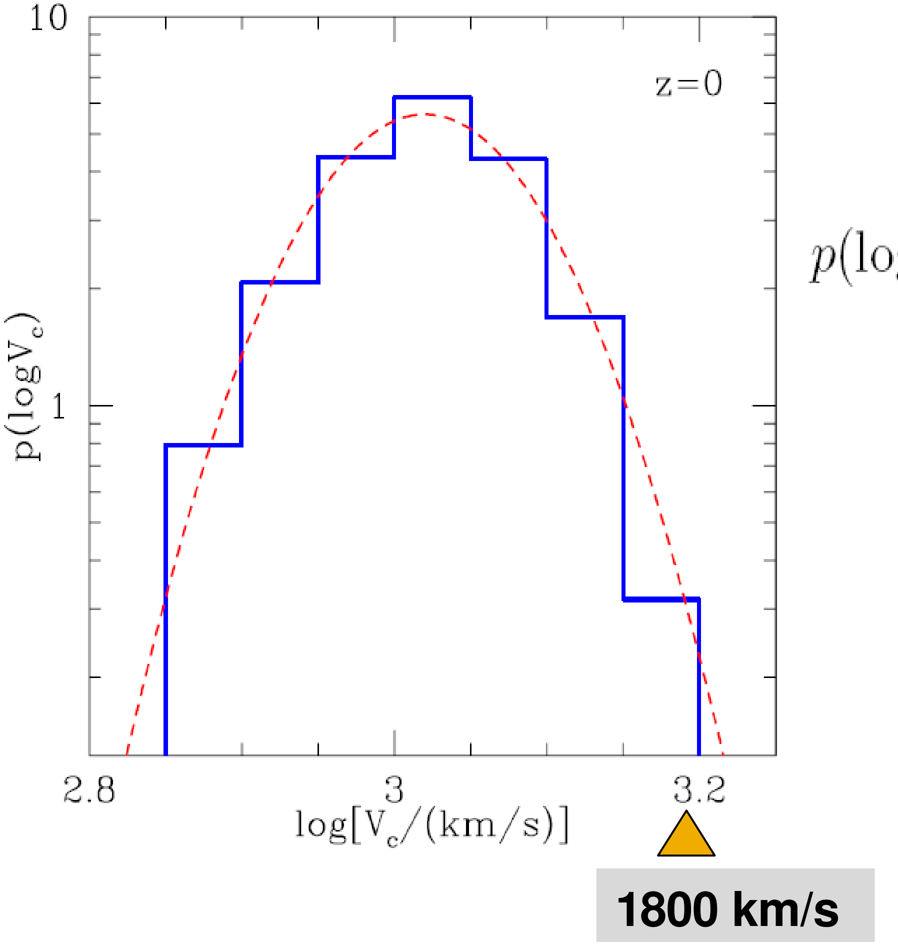


M_{main} $[10^{15}h^{-1}M_{\odot}]$	the number of clusters of clusters at $z=0$	the number of bullet-like systems at $z=0$
≥ 0.5	8523	2189
≥ 0.7	3135	1135
≥ 1	911	351

[redacted]

$M_{\rm main}$ $[10^{15}h^{-1}M_\odot]$	the number of clusters of clusters at $z = 0.5$	the number of bullet-like systems at $z = 0.5$
≥ 0.5	3108	186
≥ 0.7	800	78
≥ 1	138	27

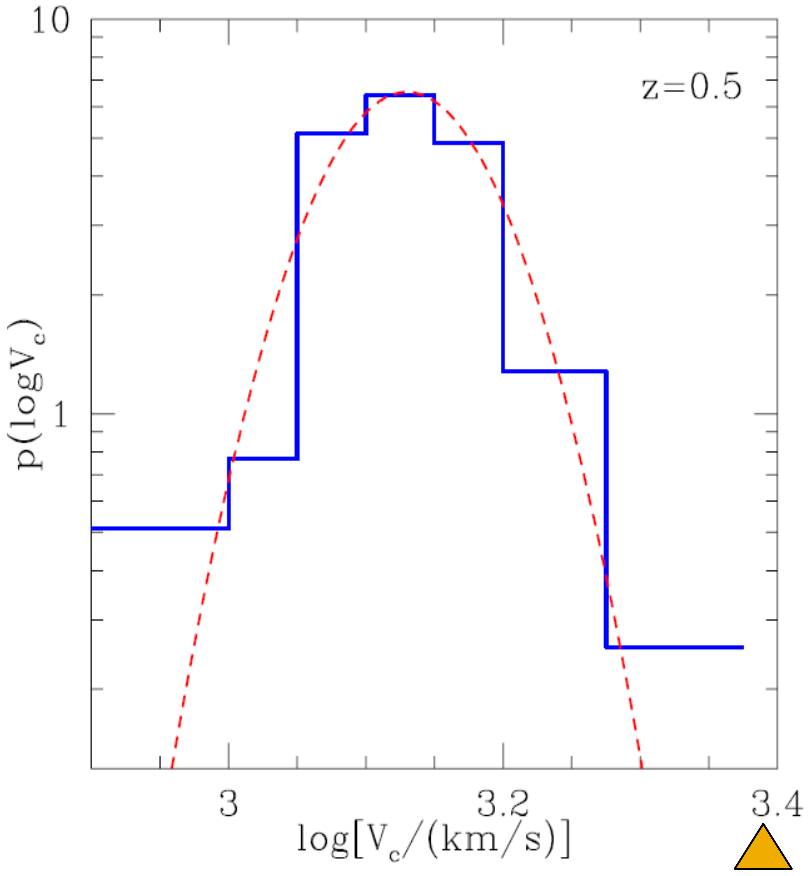
Infall Velocity Distribution at z=0



$$p(\log V_c) = \frac{1}{\sqrt{2\pi\sigma_\nu^2}} \exp\left[-\frac{(\log V_c - \nu)^2}{2\sigma_\nu^2}\right]$$

$$P(V_c \geq 3000\ \mathrm{km/s}) \approx 3.3\times 10^{-11} \text{ at } z = 0$$

Infall Velocity Distribution at z=0.5



2500 km/s

$P(V_c \geq 3000\ \mathrm{km/s}) \approx 3.6 \times 10^{-9}$

at $z = 0.5$

Λ **slows down the structure formation.**

Surprise 3 – Infall Velocity

- IE0657-56 requires *Vc~3000* km/s at *2R200* (Masptropietro & Burkert 2008).

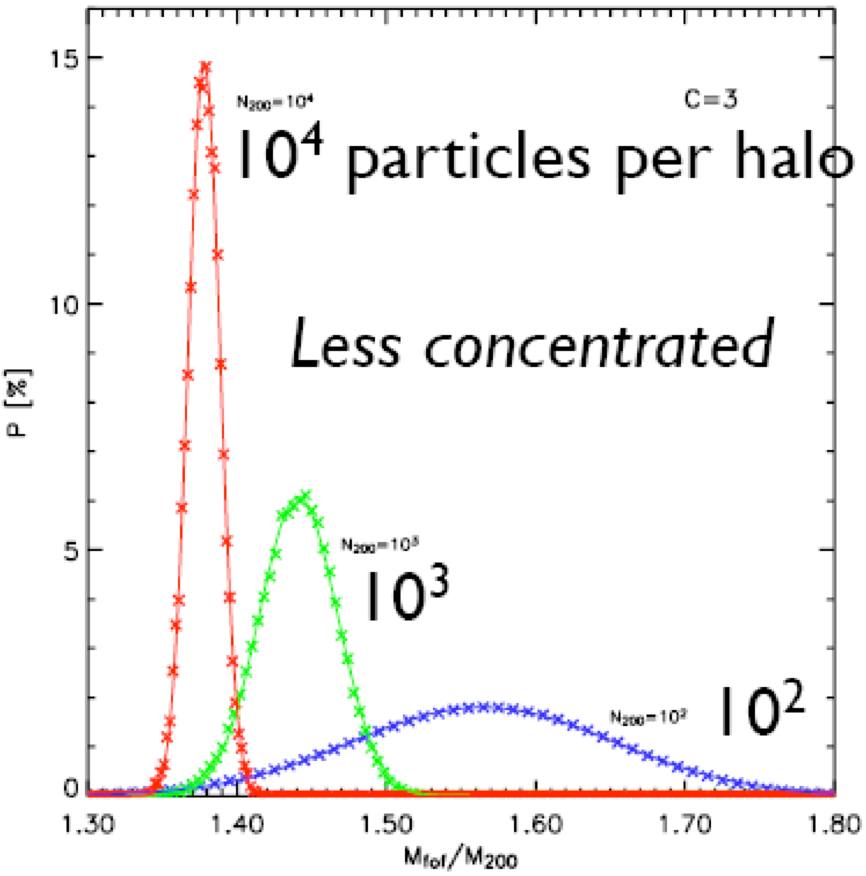
- While LCDM predicts

$$P(V_c \geq 3000\ \mathrm{km/s}) \approx 3.3\times10^{-11}\ \ \text{at } z=0,$$

$$P(V_c \geq 3000\ \mathrm{km/s}) \approx 3.6\times10^{-9}\ \ \text{at } z=0.5.$$

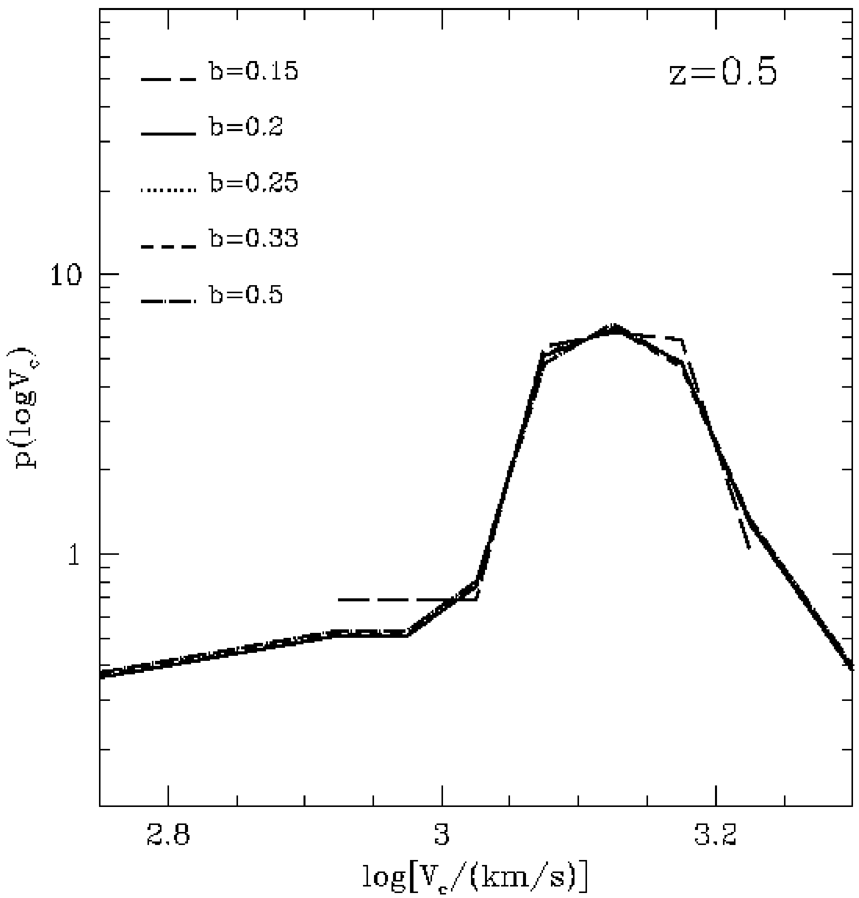
Discussion on Uncer-tainty I

- How accurate is our estimate of R200 ?
  - It depends on the halo concentration and the number of particles.
  - Rfof/R200 ~ 1.1.
  - Good enough!



Discussion on Uncer-tainty II

- How does the final result depend on the linking length, *b,* used to identify clusters of clusters?
  - Almost no change as the value of *b* changes.
  - Statistically robust.



The Other Candidates

(Komatsu et al.2001)
Vshock~ 3900 km/s

(Bradac et al.2008)

Conclusions

- The observed property of IE0657-56 calls for a high infall velocity: 3000 km/s at 2R200.