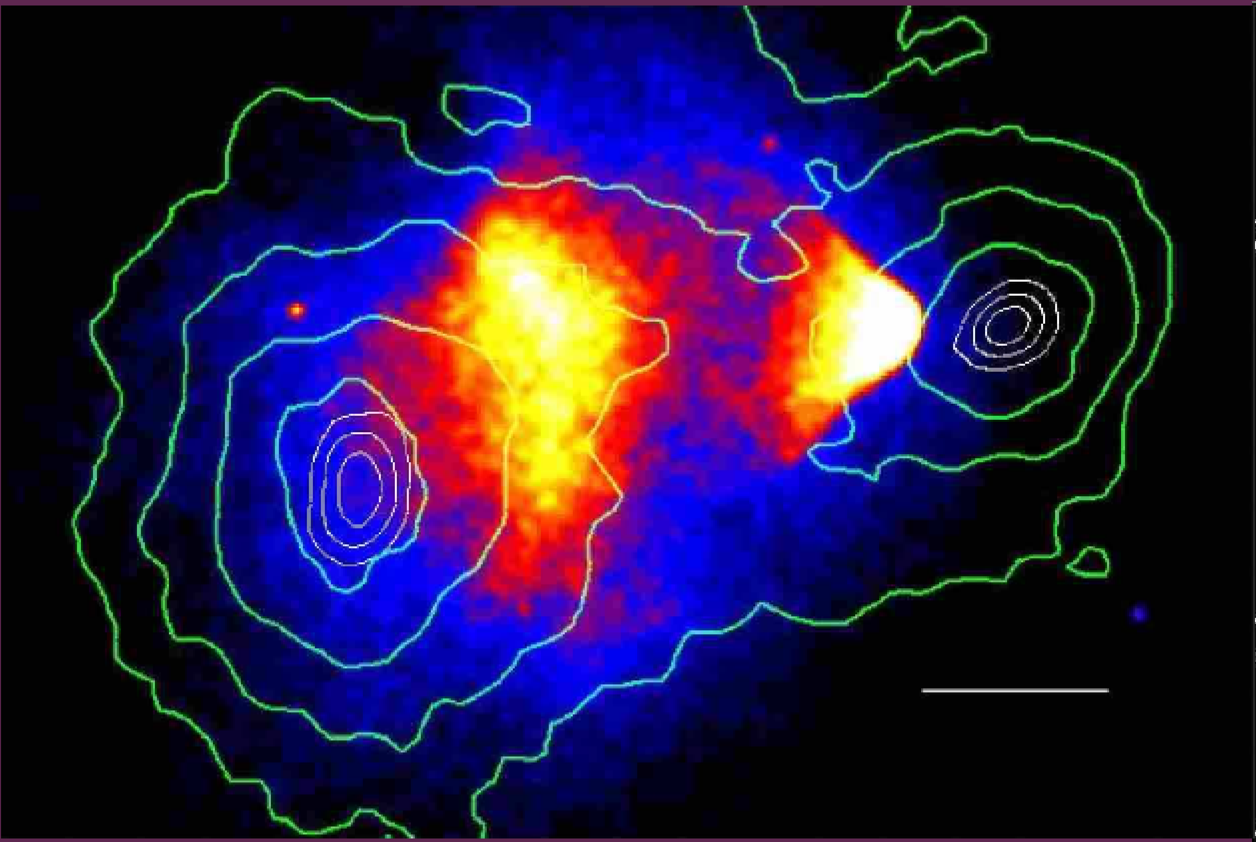
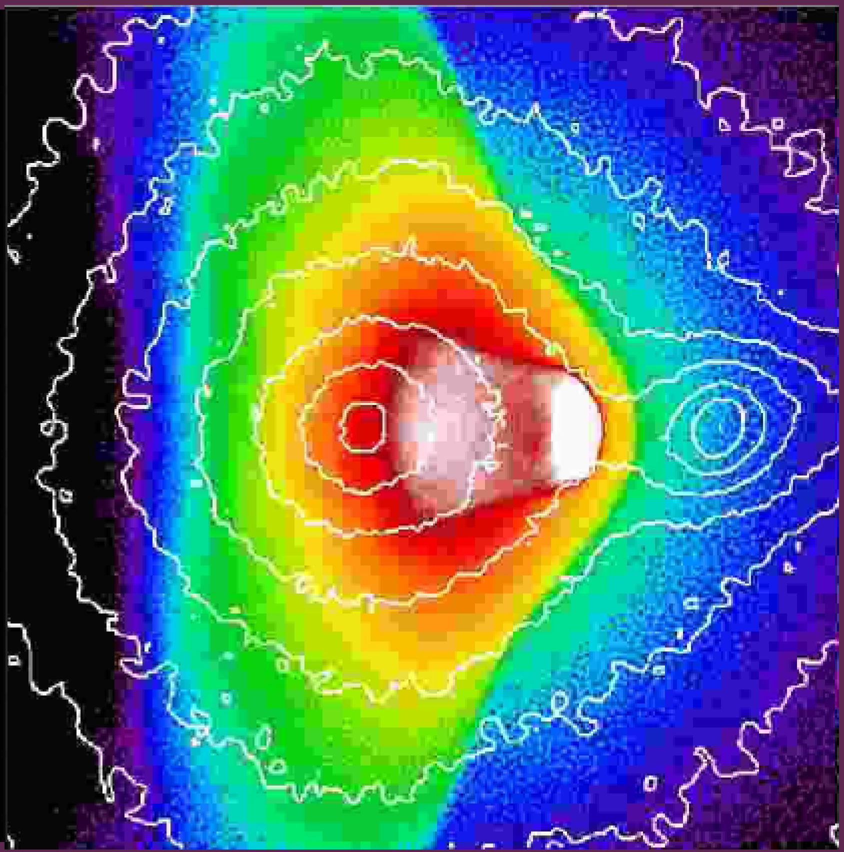
How rare is the Bullet Cluster

David Kraljic, University of Oxford
Copenhagen, August 2014





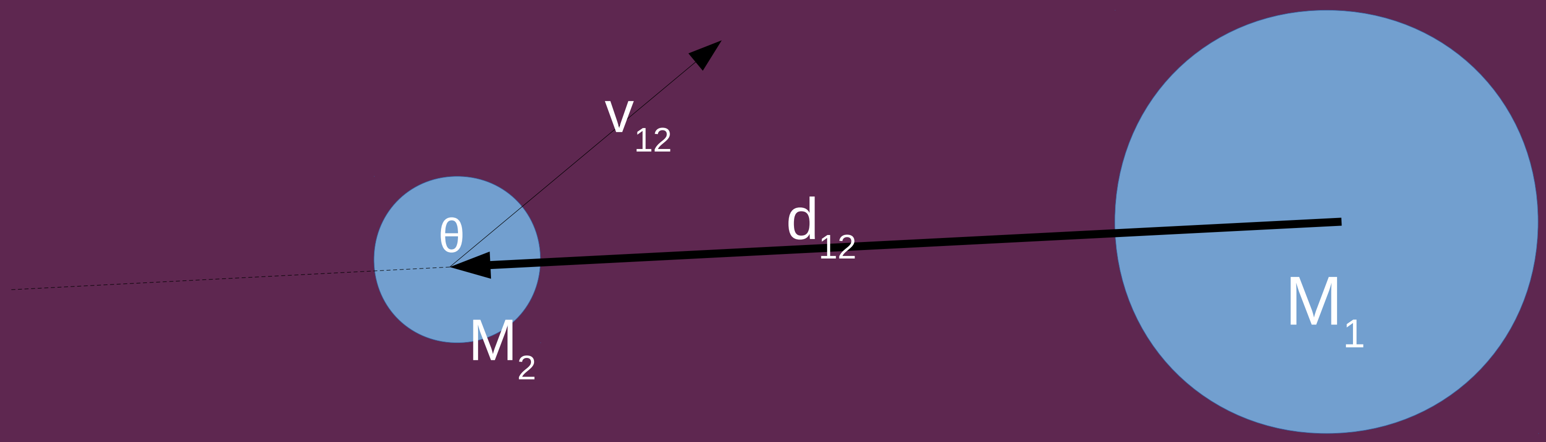
- Bullet Cluster and why it's interesting
- Review of searches in N-body simulations and their shortcomings
- Searching for Bullet-like systems in Dark Sky Simulations
- Summary

The Bullet Cluster system

- Observed at z~0.3
- Separated by 0.7 Mpc
- Masses $M_1 \sim 1.5\ 10^{15}\ M_{SUN}$ and $M_2 \sim 1.5\ 10^{14}\ M_{SUN}$
- Collision head-on and perpendicular to the line of sight
- Shock front velocity ~ 4700 km/s but relative velocity in hydrodynamical simulations smaller

- motivation = is such a system likely/consistent in LCDM
- Estimates of probabilities ranging from 10^{-11} (Lee&Komatsu 2010) to 1% (Hayashi&White 2006) !

A simple picture



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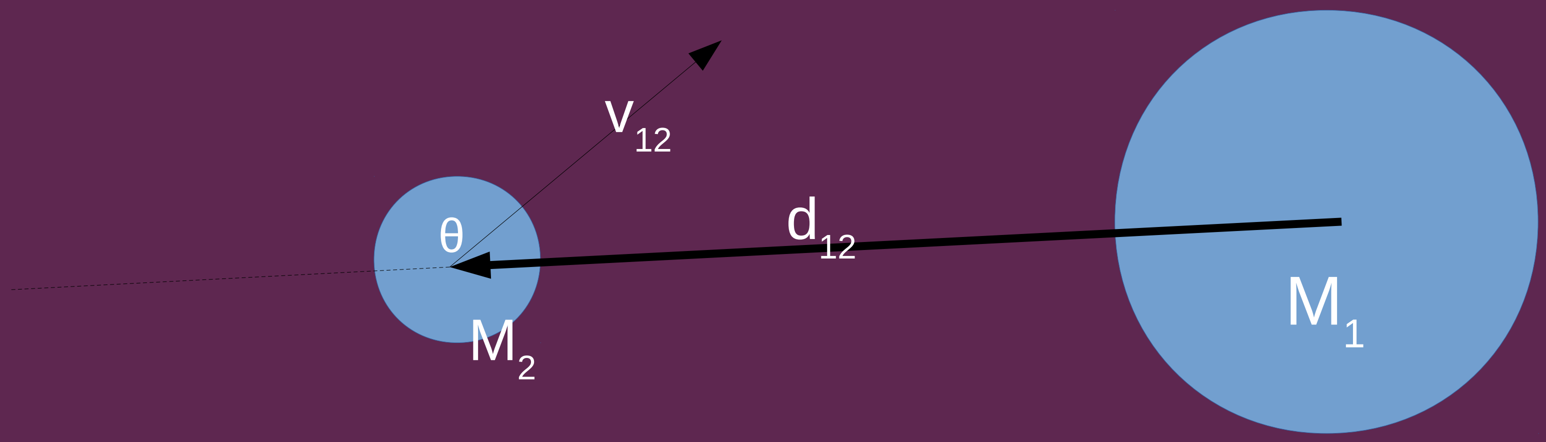

Masses frequently combined into <M>, the arithmetic mean

Velocity looked at in the comoving or real space

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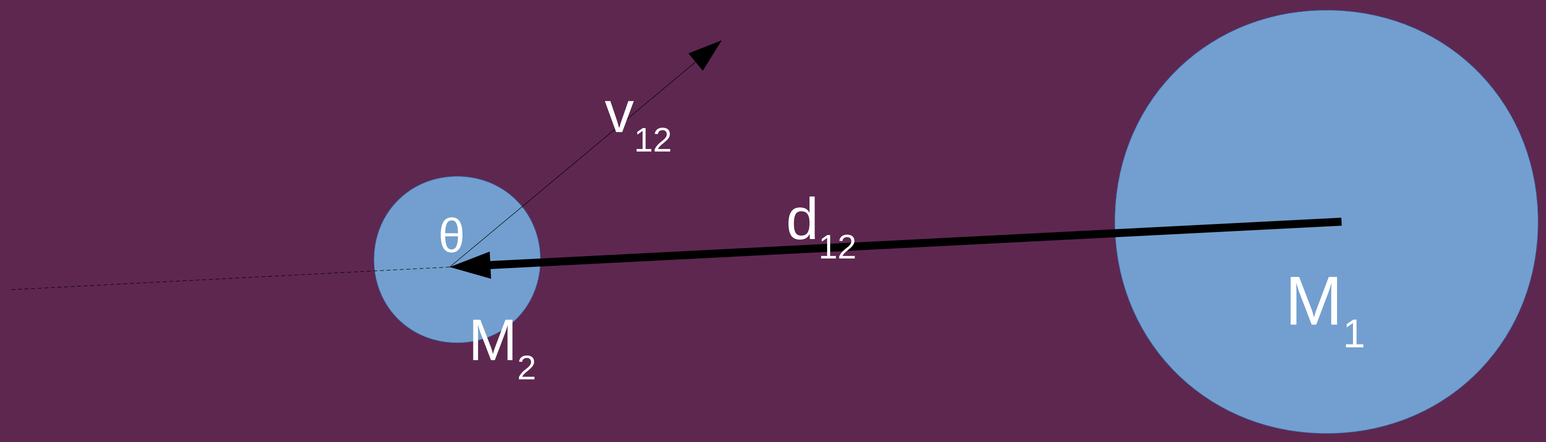

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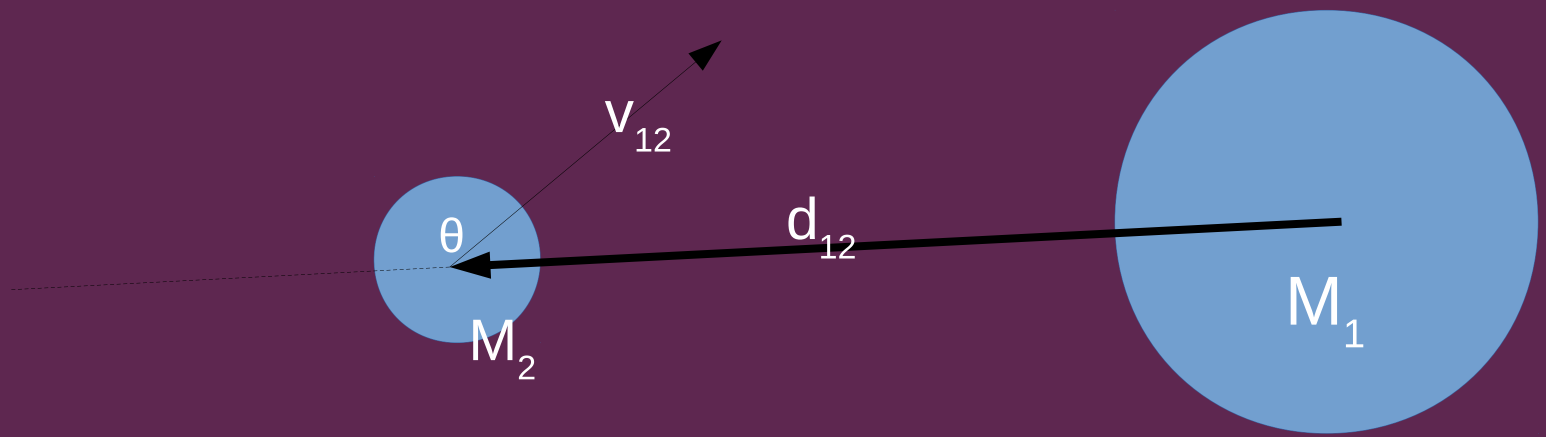

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Given certain masses, separation, angles interested in the probability that the relative velocity exceeds a certain number e.g. $P(v_{12} > 3000 km/s; \langle M \rangle > 10^{14} M_{SUN}/h; d_{12} < 10 Mpc/h; \cos(\theta) < -0.9)$

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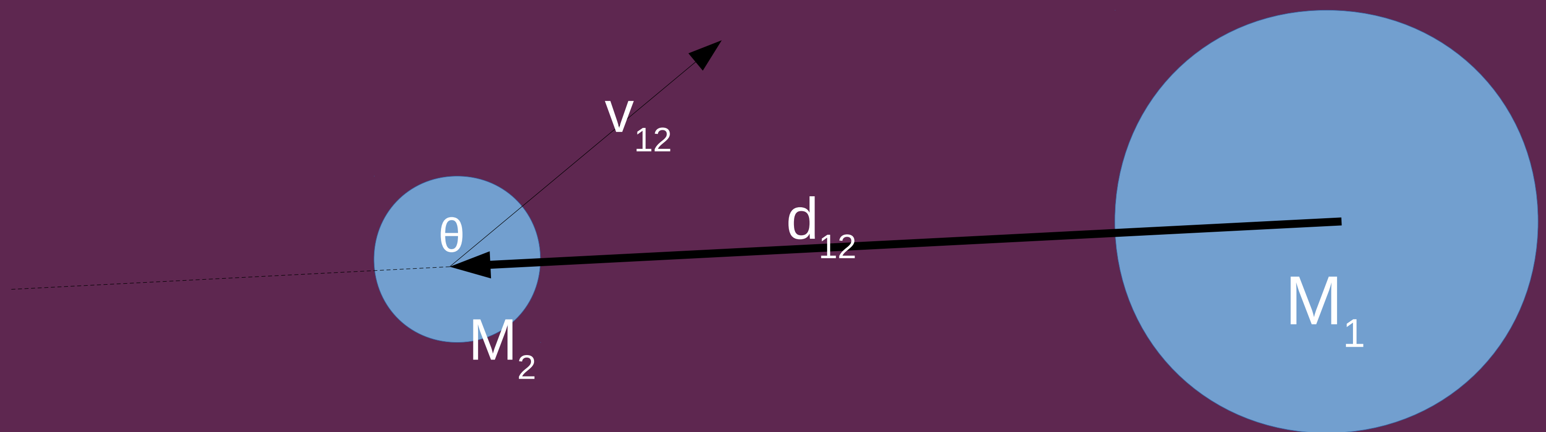

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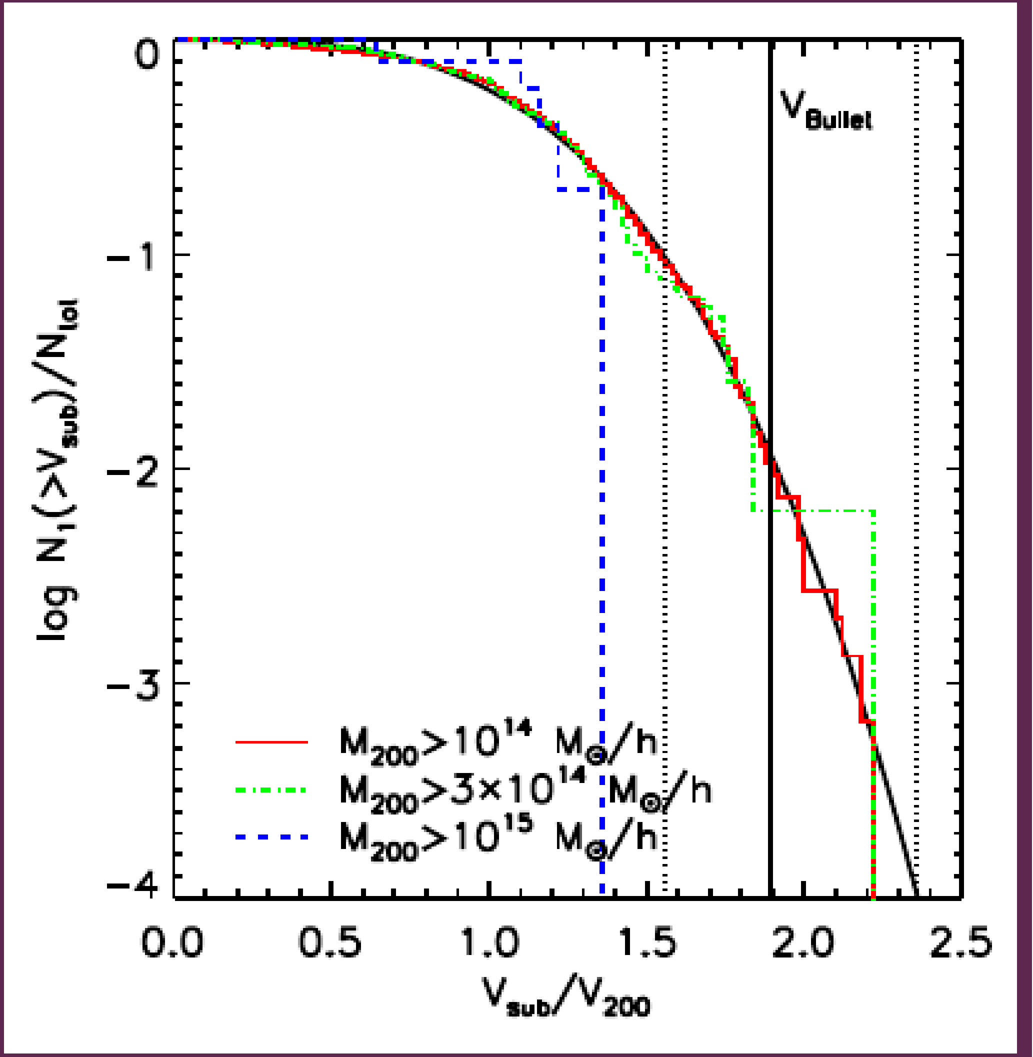
Initial conditions to reproduce the collision

- From non-cosmological hydrodynamical simulations
  - Springel & Farrar (2007) d_{12} ~ 3.4Mpc and v_{12}~2060km/s
  - Mastropietro & Burkert (2008) d_{12} ~ 5Mpc and v_{12}~3000km/s at z~0.5
- Ideal for N-body simulations because the clusters are well separated (configuration space based halofinders have difficulties resolving the 'actual' collision at z=0.3)

Millenium Run: Hayashi&White (2006)

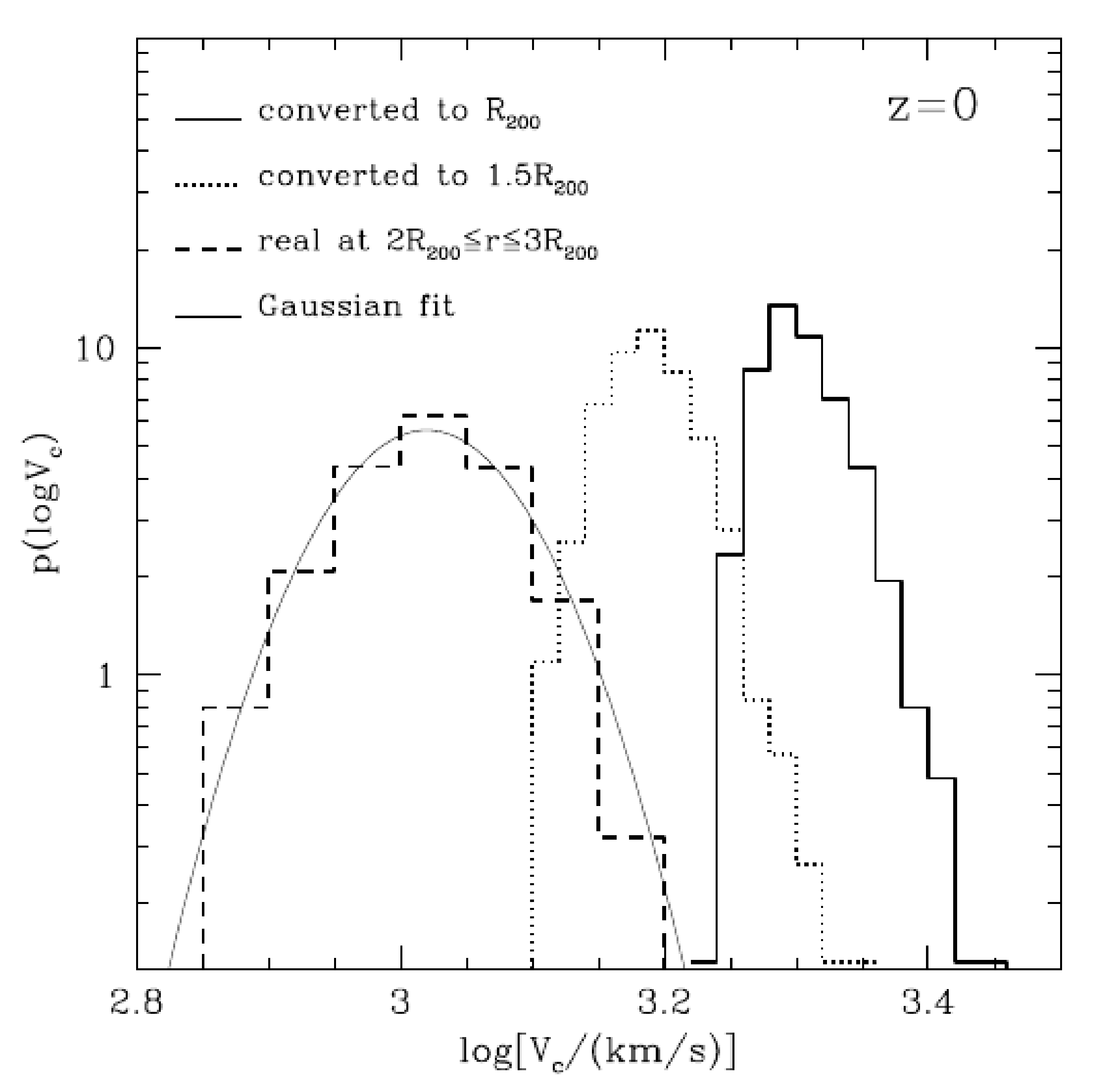
- MR: 500Mpc/h box
  - Not many extreme objects in terms of mass
- Looked for a subcluster moving away with at least 4500km/s (shock front velocity) separated by at least 0.7Mpc at z~0.3
- Had to extrapolate to get pdf-s for host halo mass > 10^{14} M_{SUN} / h
- Probable within LCDM (1%) but uncertain to 2 orders of magnitude dependent on the velocity cut



Lee & Komatsu (2010)

- Used MICE (3Gpc/h box with 2048^3 particles)
- Reapplied FoF to clusters to find subclusters
- Probability of finding M&B(2008) initial conditions at z=0 is

  ~10^{-11} determined by Gaussian interpolation => Improbable in LCDM



Thompson & Nagamine (2012)

- Examined the effect of the box size and resolution in N-body sims. on the pairwise velocity distribution of DM halos
- Better resolution and bigger box extend the tail of the pairwise velocity pdf

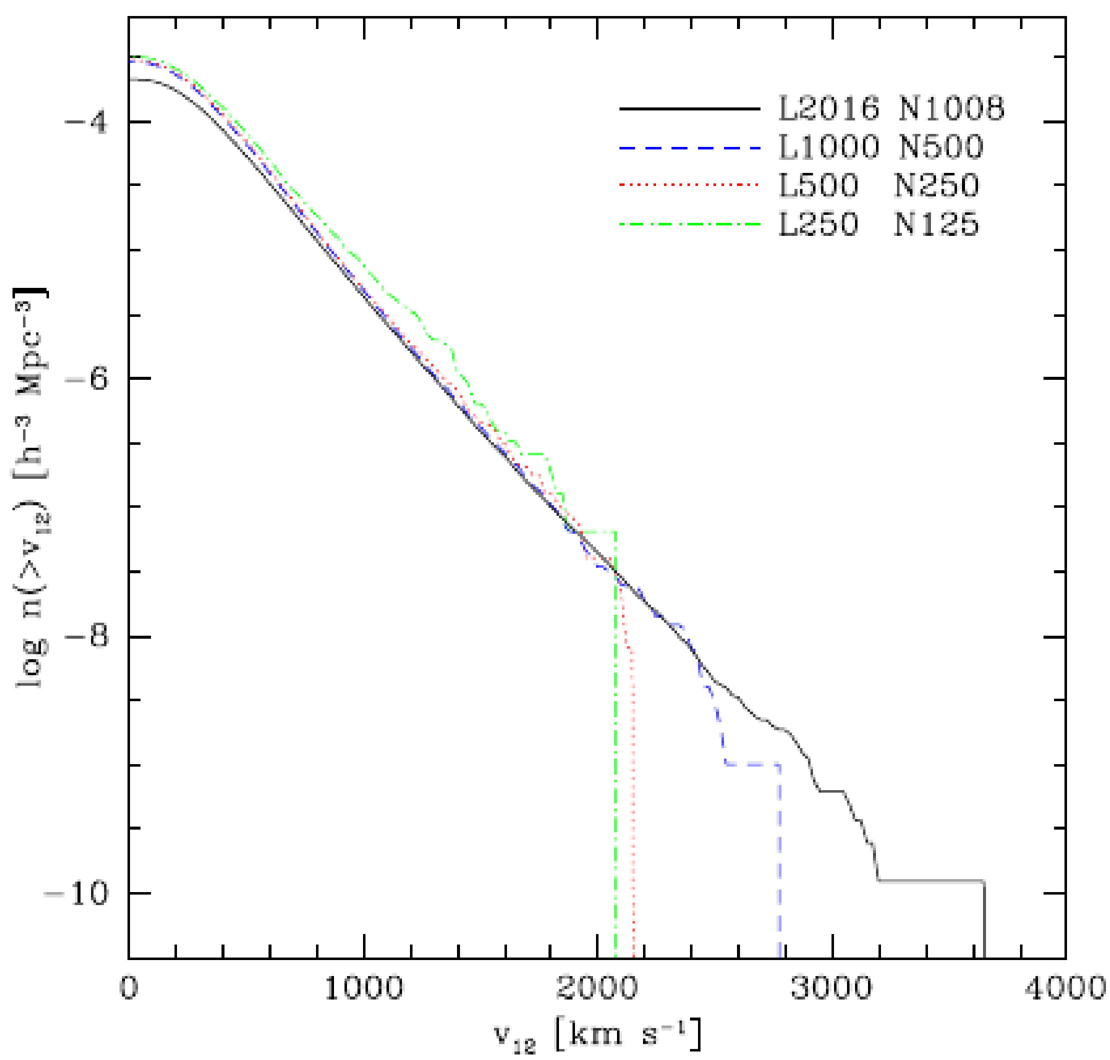


Figure 7. Cumulative v_{12} function of DM halos at z=0. This figure shows how increasing the box size increases the number of high-v_{12} pairs, extending the tail of the distribution.

Thompson & Nagamine (2012)

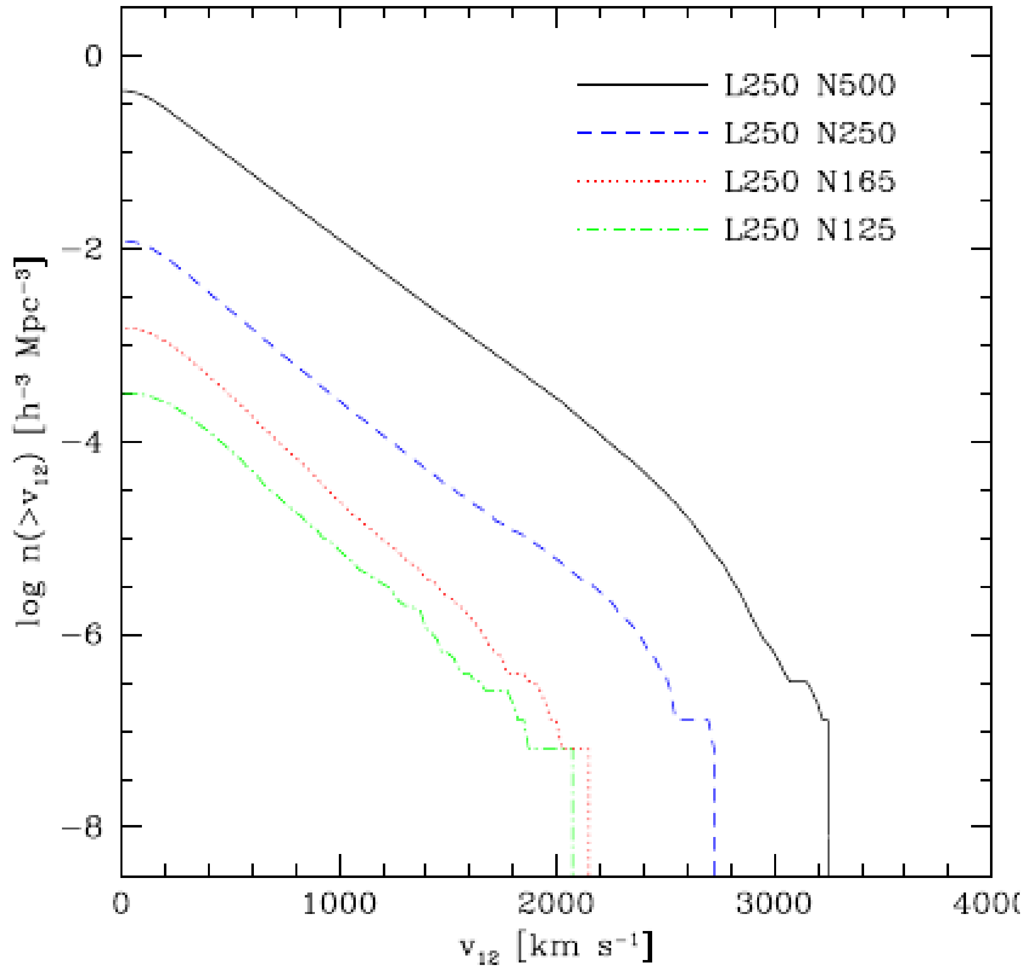
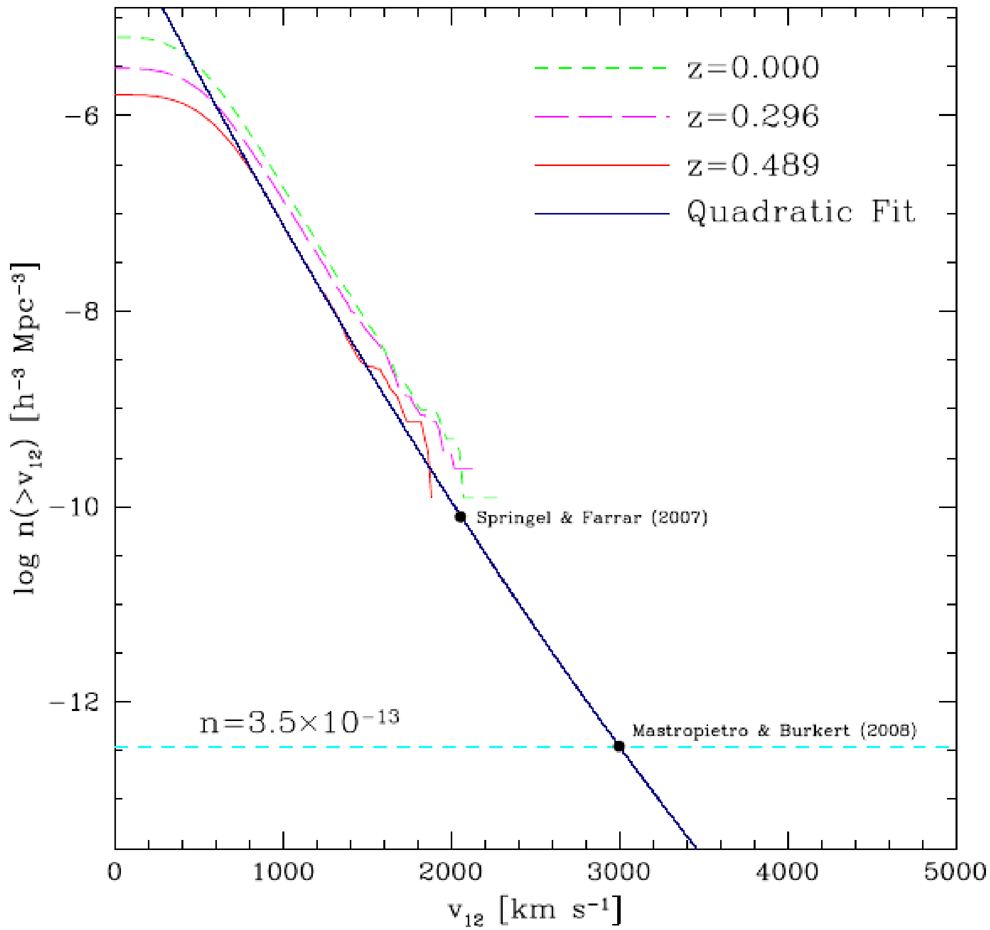


Figure 8. Cumulative v_{12} function of DM halos at z=0. This figure shows the resolution effect. As the resolution increases, the normalization of the distribution increases due to a larger number of lower mass halos with higher velocities.



Estimate $P(v_{12}>3000\text{km/s}) \sim 10^{-8}$

To find Bullet-like system need L=4.5Gpc/h with 500^3 particles per $(\text{Gpc/h})^3$

Watson et al. (2013/14) using Jubilee

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- v2: “we find that ... Bullet cluster exists in the far-tail in the distribution ”
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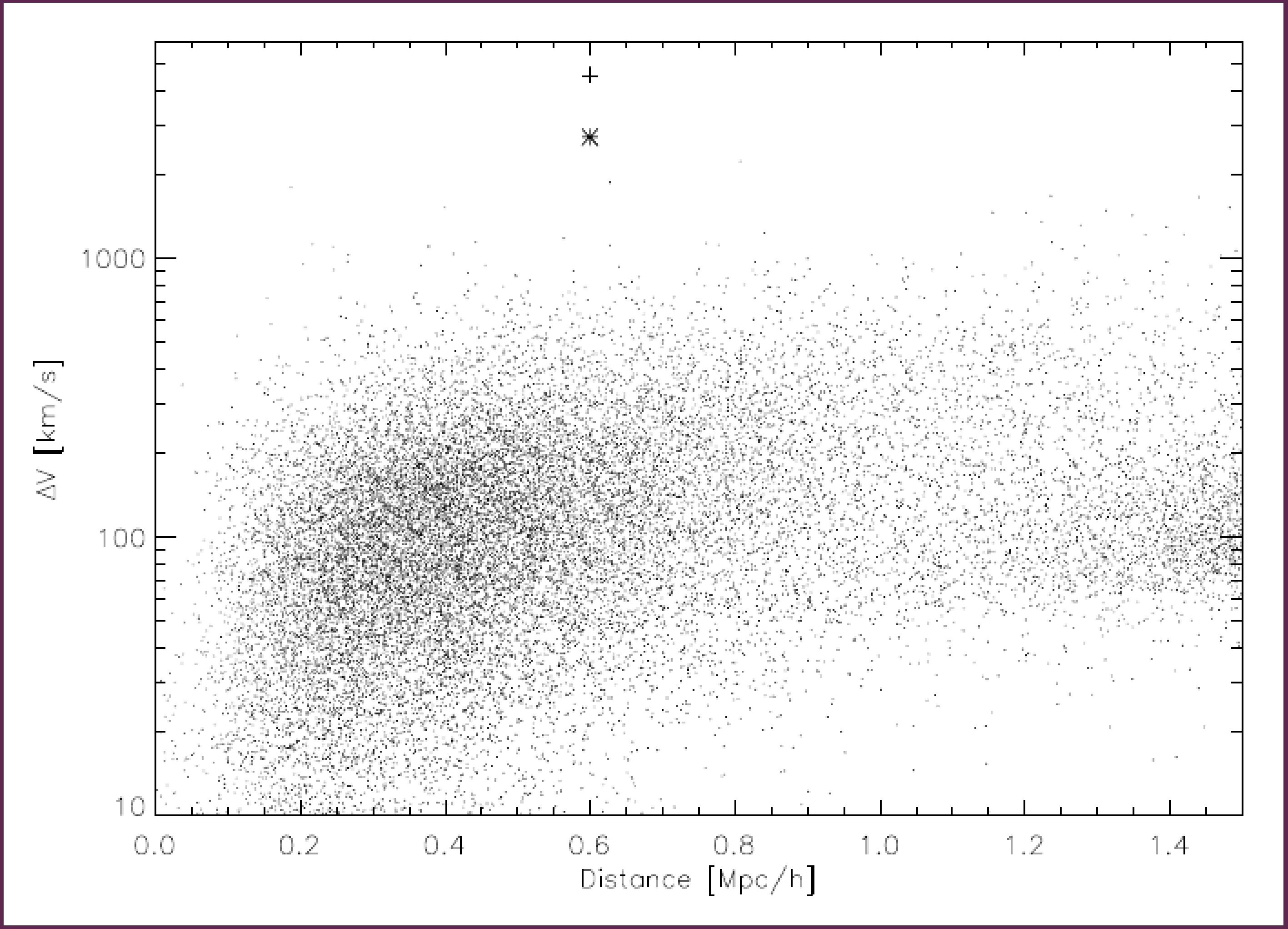

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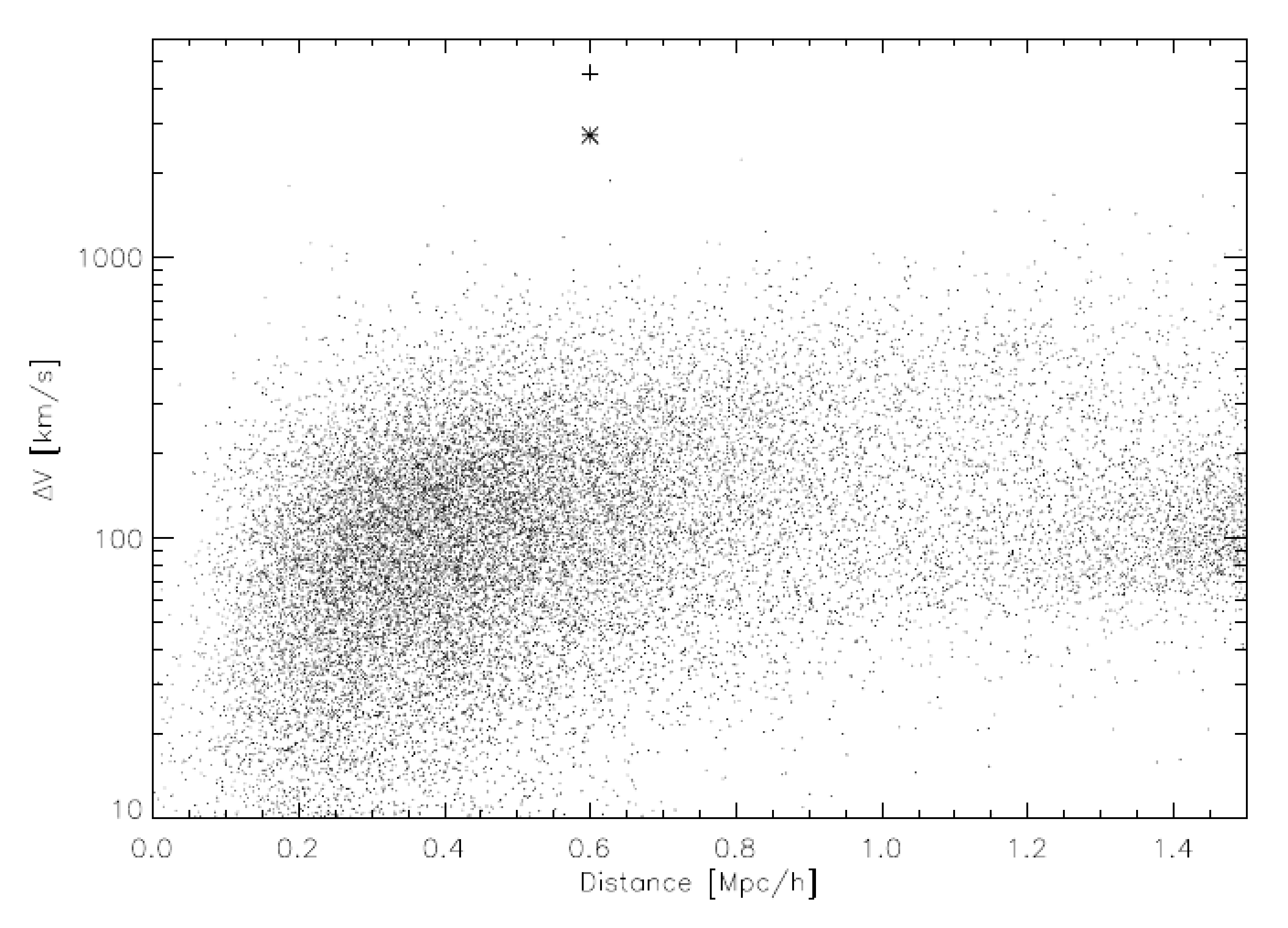

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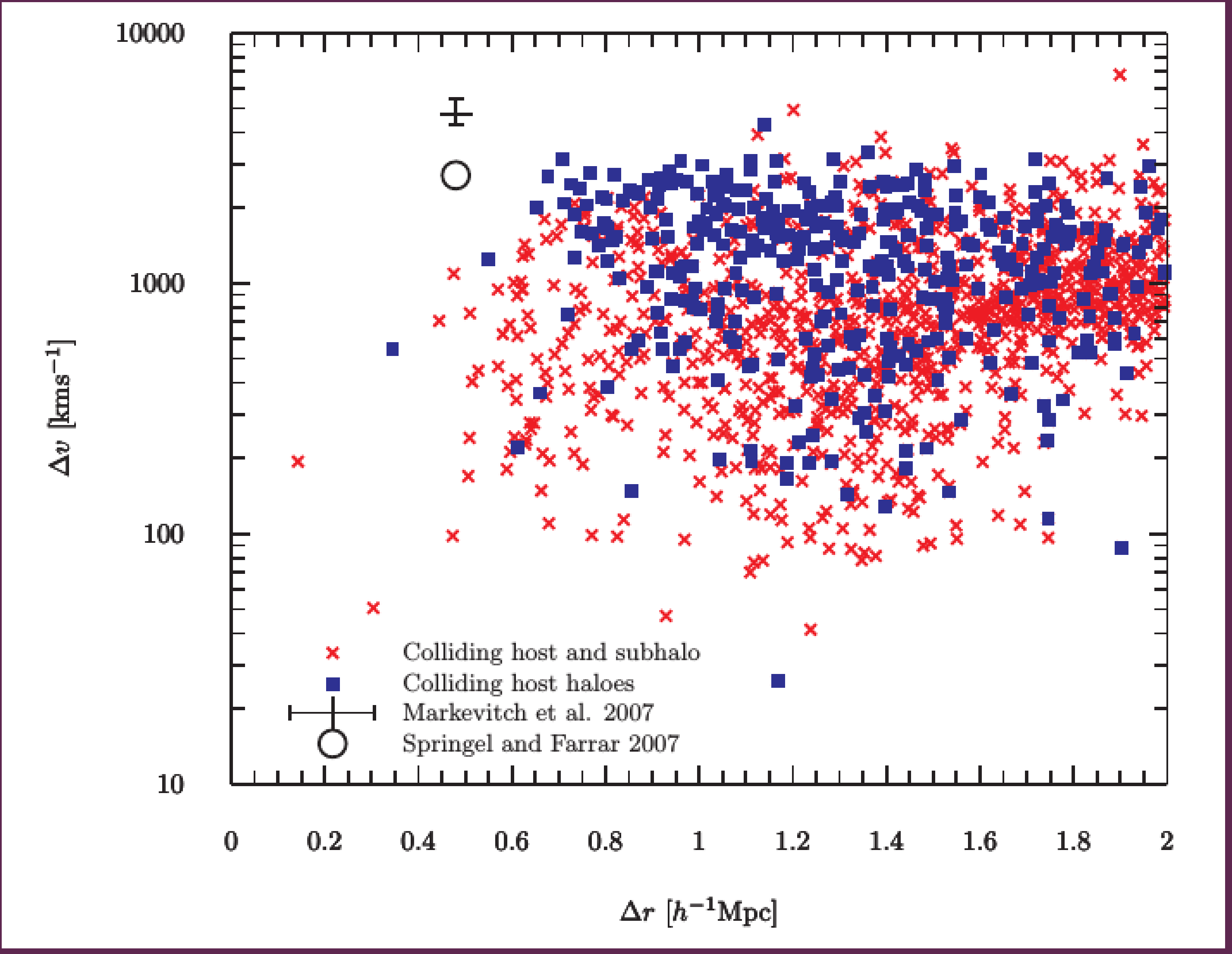

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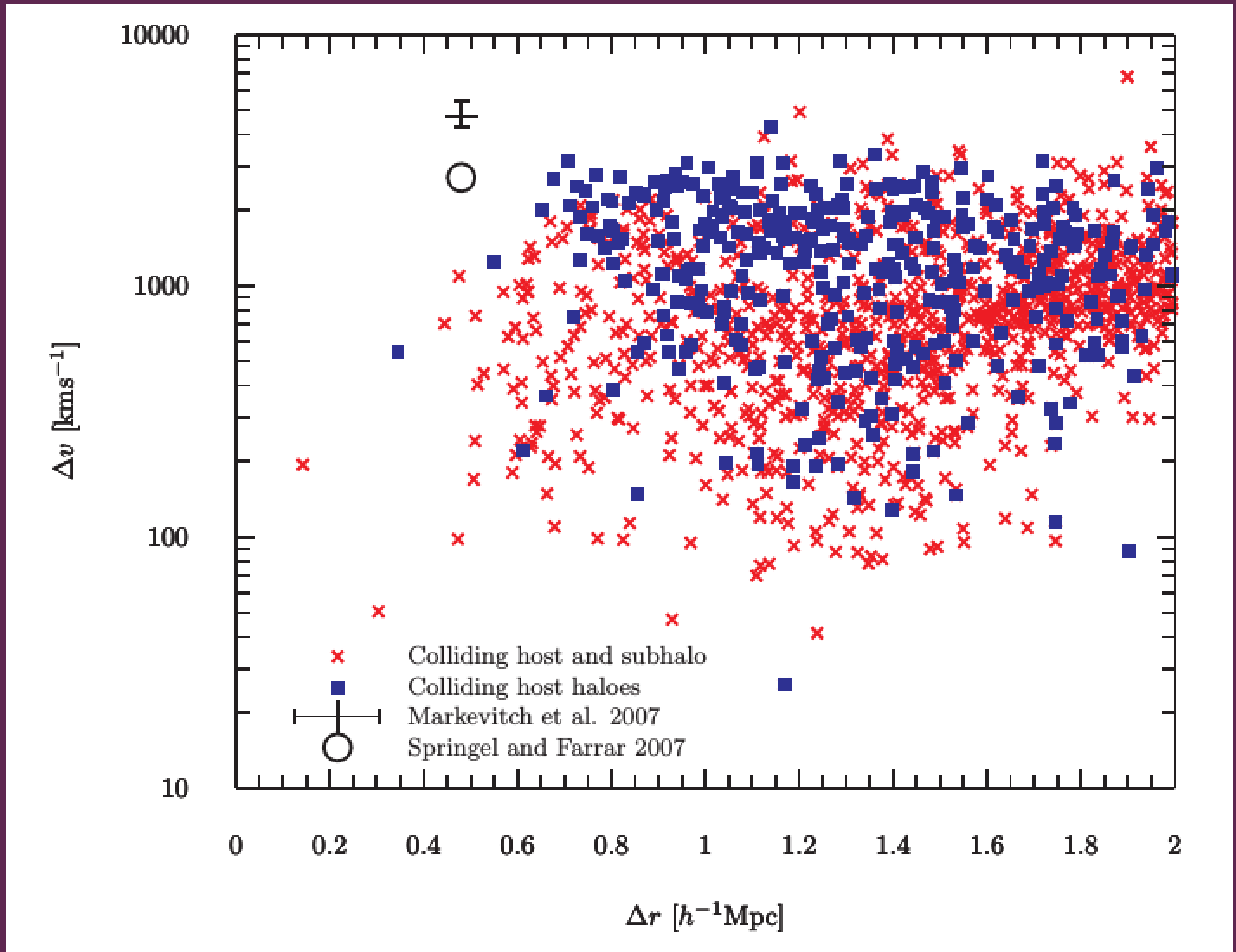

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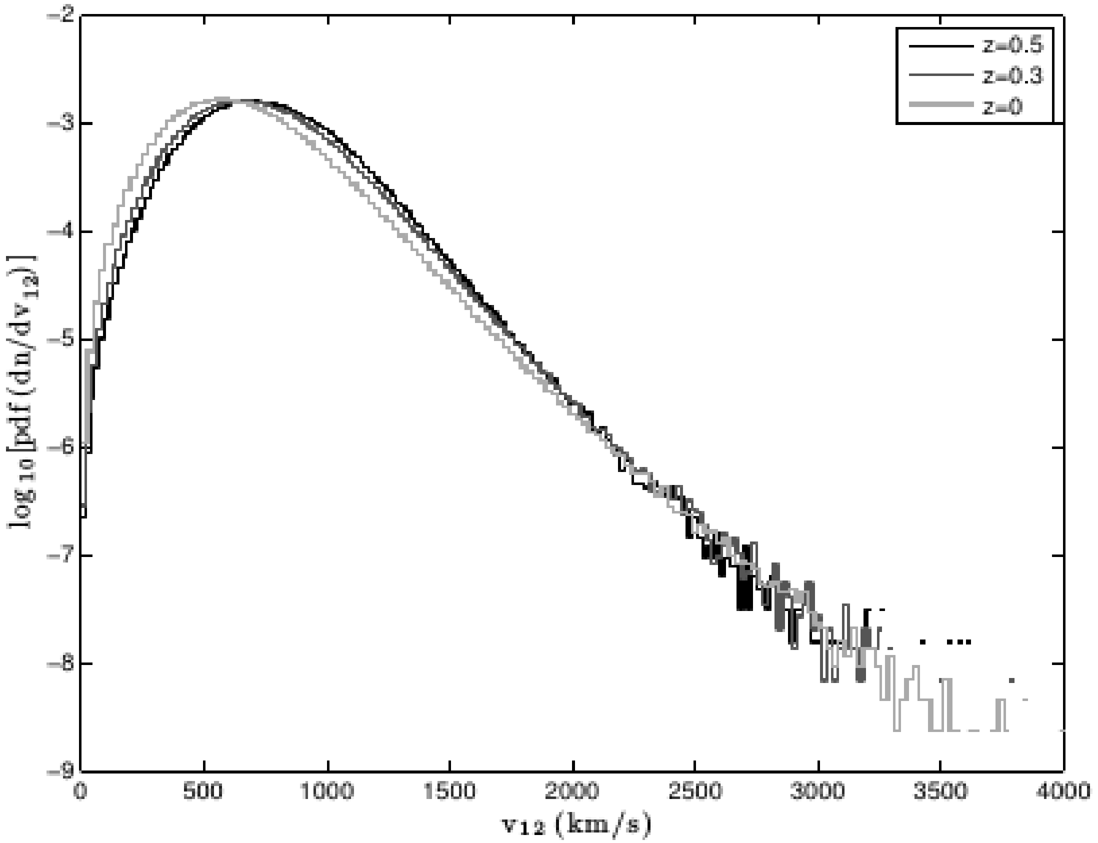

Figure 4. Redshift evolution of the probability density function of the pairwise velocity for FoF(b=0.15) halo pairs from the DEUS-FUR ΛCDM-W7 simulation with distance separation $d_{12} < 10\,\mathrm{h}^{-1}$ Mpc at $z = 0.5$ (black), $z = 0.3$ (grey) and $z = 0$ (light grey) respectively.

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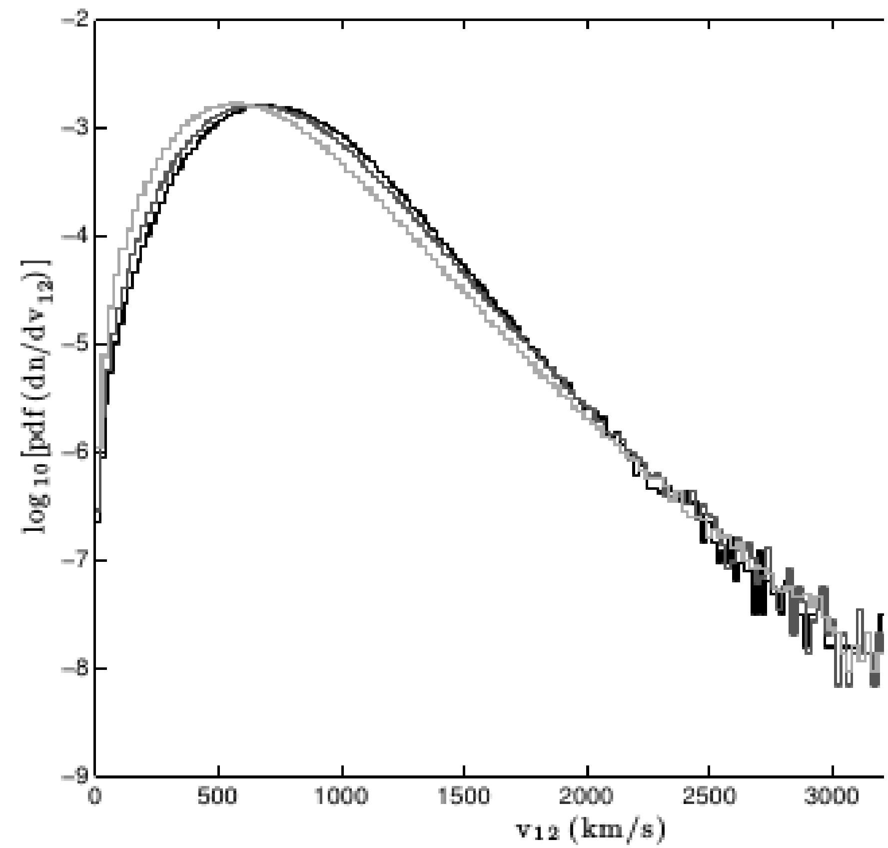

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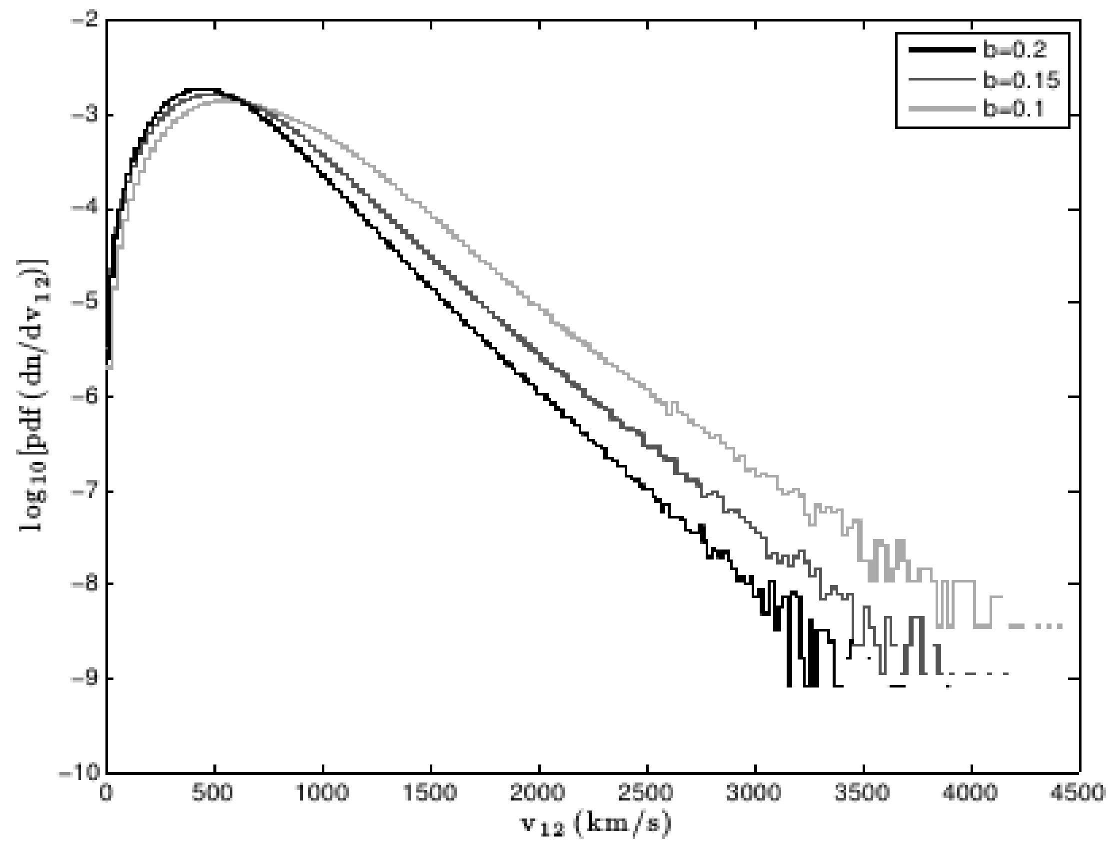

Figure 2. Probability density function of the pairwise velocity from the DEUS-FUR ΛCDM-W7 simulation at $z = 0$ for pairs with separation $d_{12} < 15\ \mathrm{h}^{-1}$ Mpc detected assuming linking-length values $b = 0.1$ (light grey), $b = 0.15$ (grey) and $b = 0.2$ (black) respectively.

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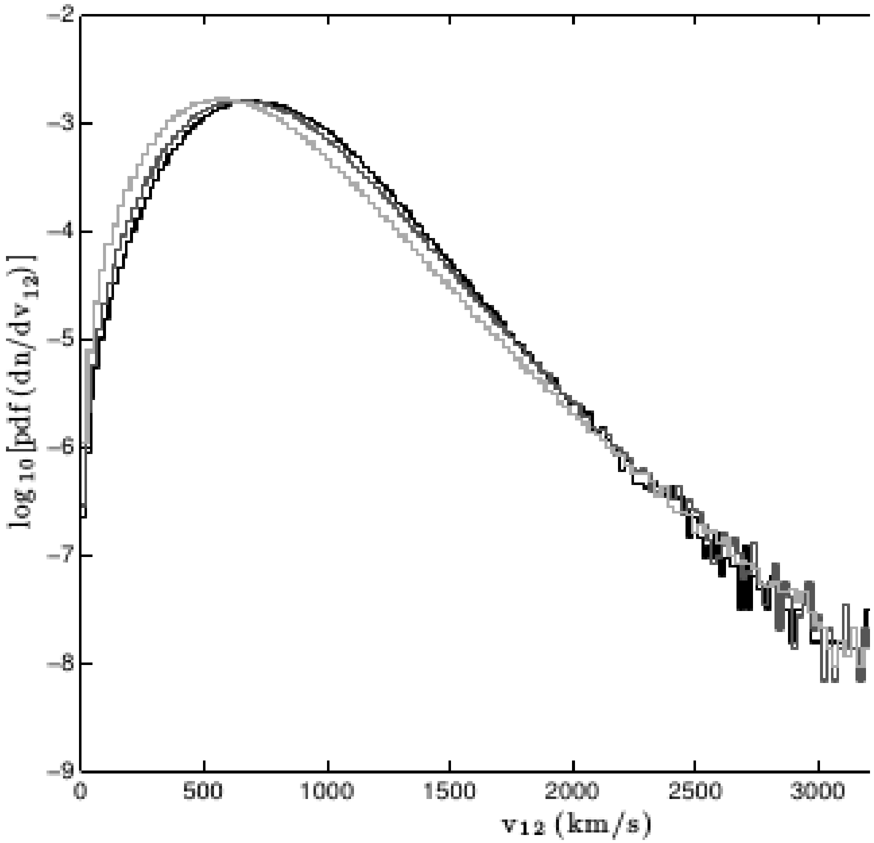

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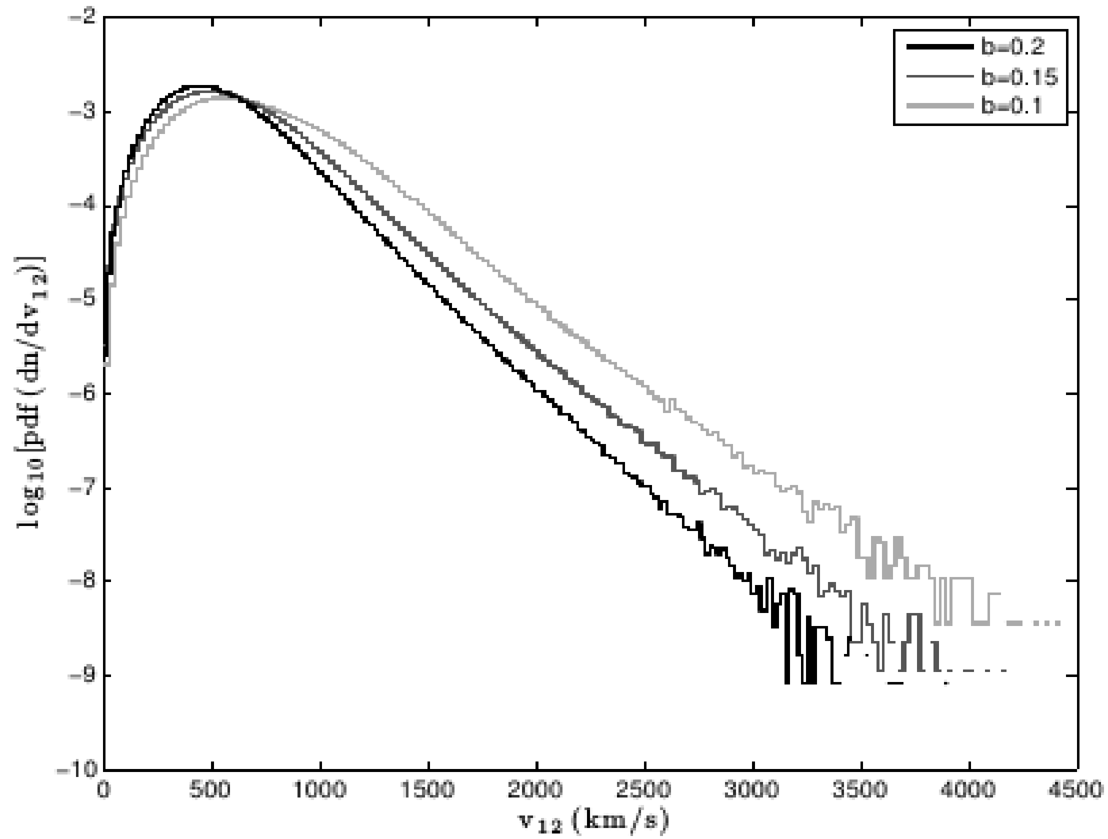

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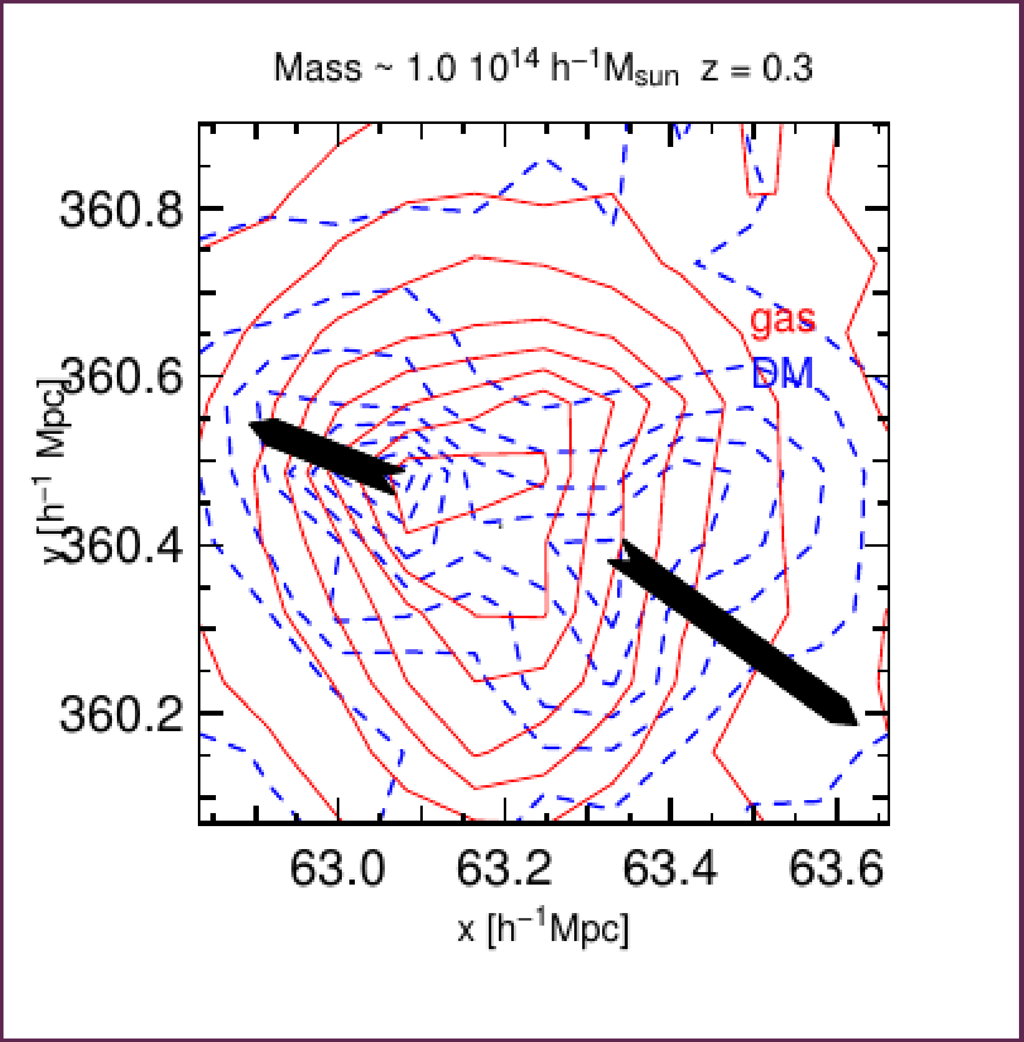
Estimate $P(v_{12}$>3000km/s) ~ $6*10^{-6}$ in LCDM (using b=0.15)

Other approaches

- Forero-Romero et al. (2010) looking at 2D projected displacement between DM and gas in MareNostrum simulations → find Bullet-like configurations in 1-2% of cases



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  - Compare with Jubilee (L=6 Gpc/h with 1000^3 particles per $(Gpc/h)^3$), MICE (L=3 Gpc/h with 666^3 particles per $(Gpc/h)^3$), Thom.&Nag.(2008) (L=2 Gpc/h with 1000^3 particles per $(Gpc/h)^3$)
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For a gravitationally bound system expect the scaling to be $v_{12} \sim M^{1/2}$

Prelim.

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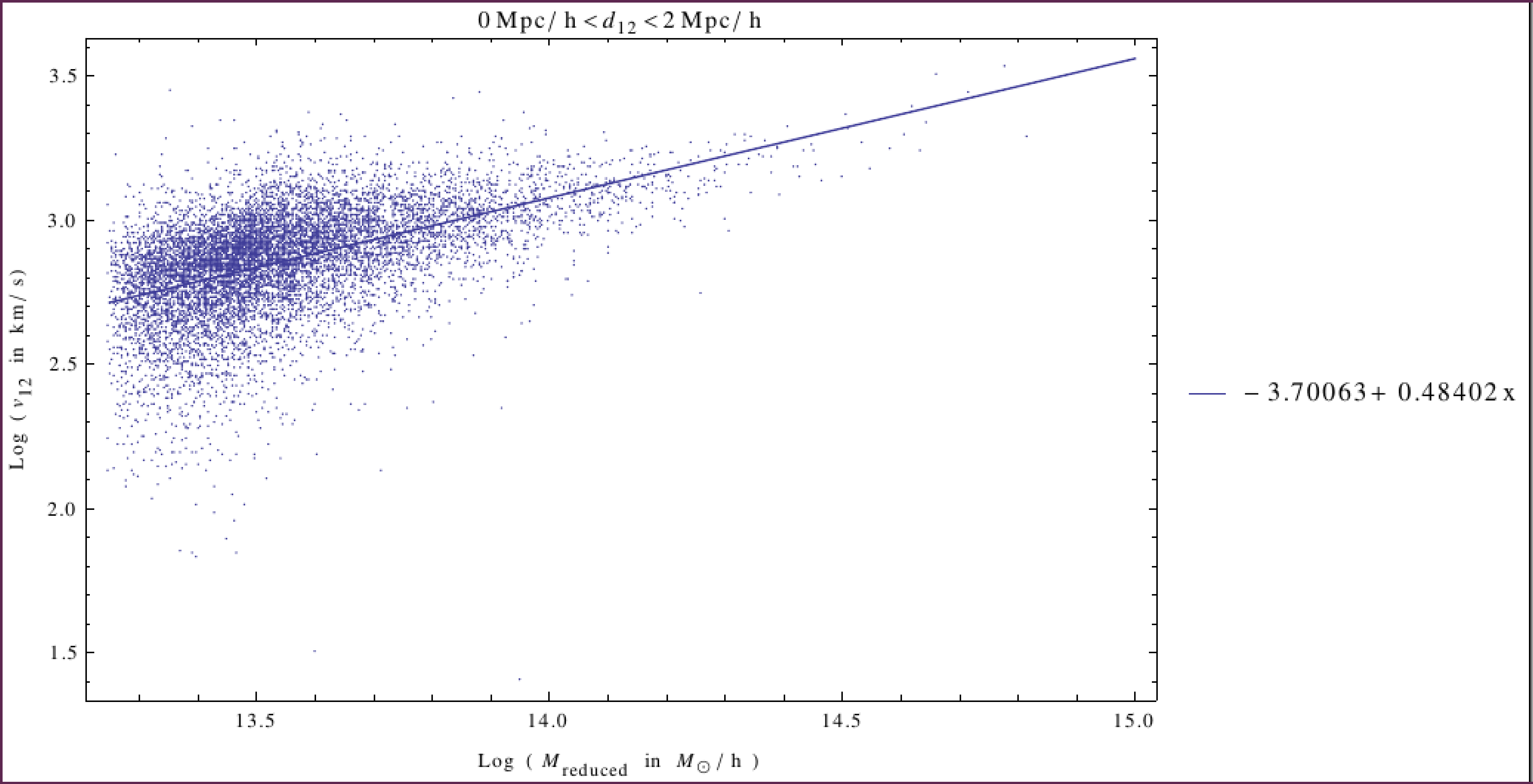

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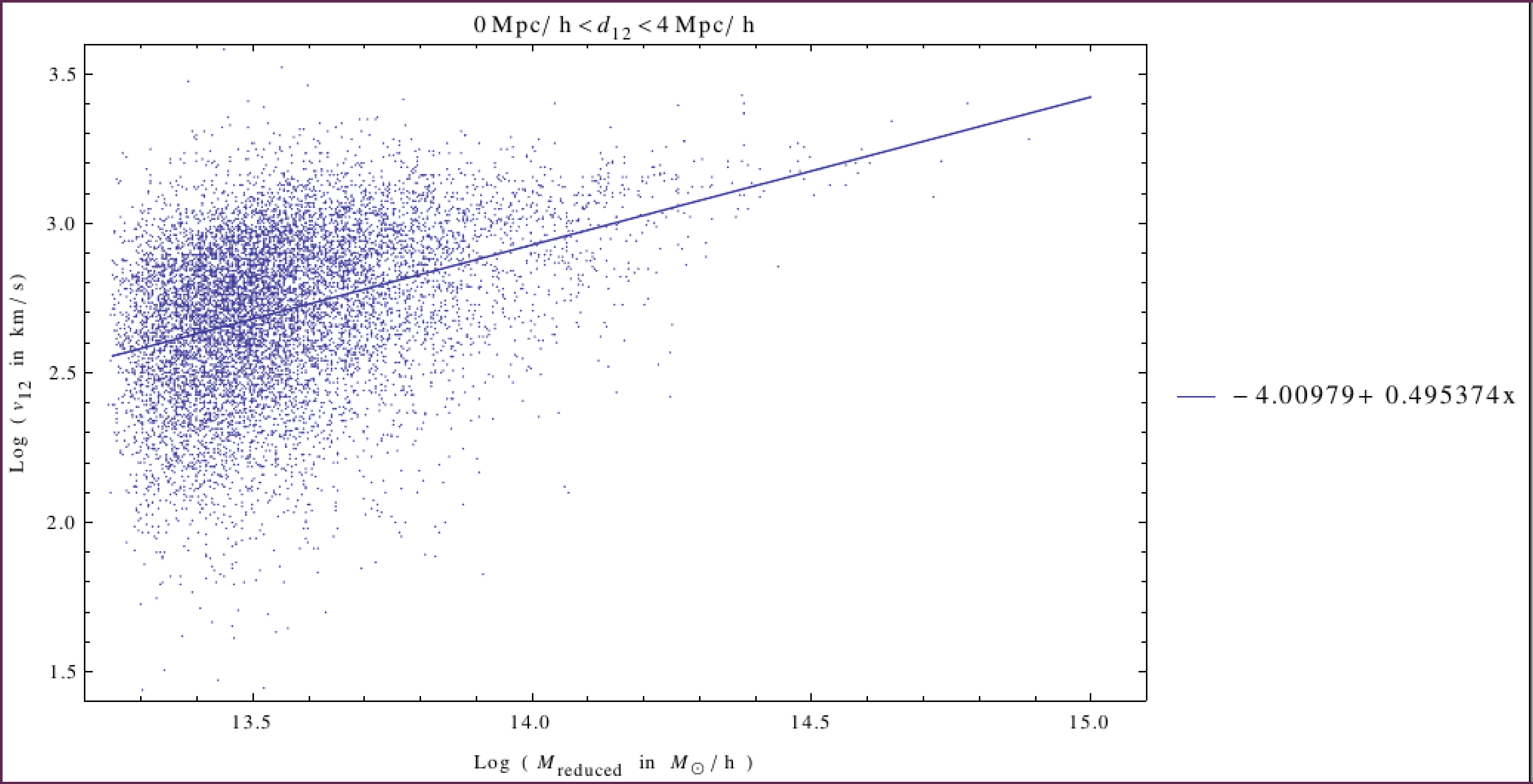

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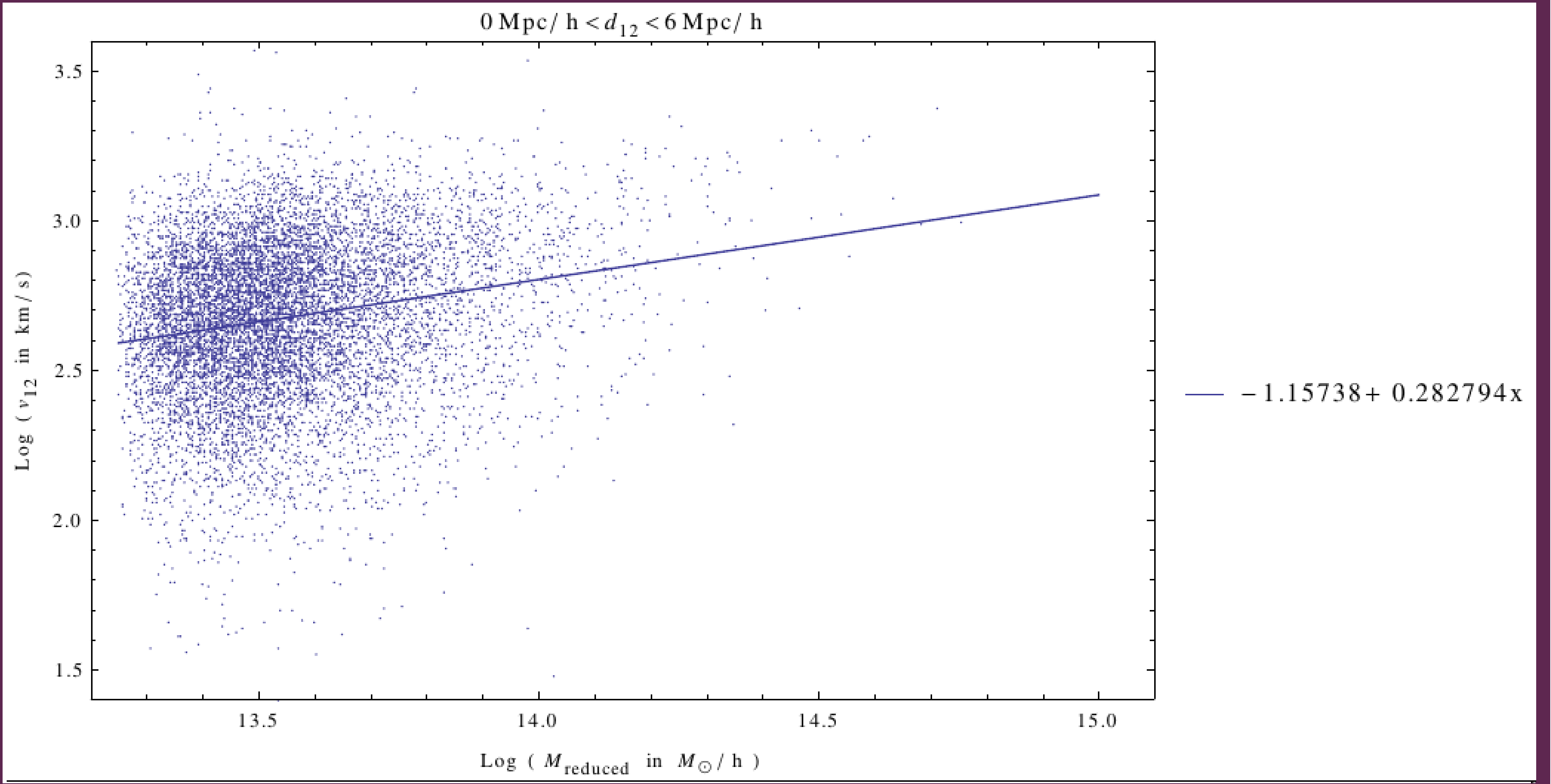

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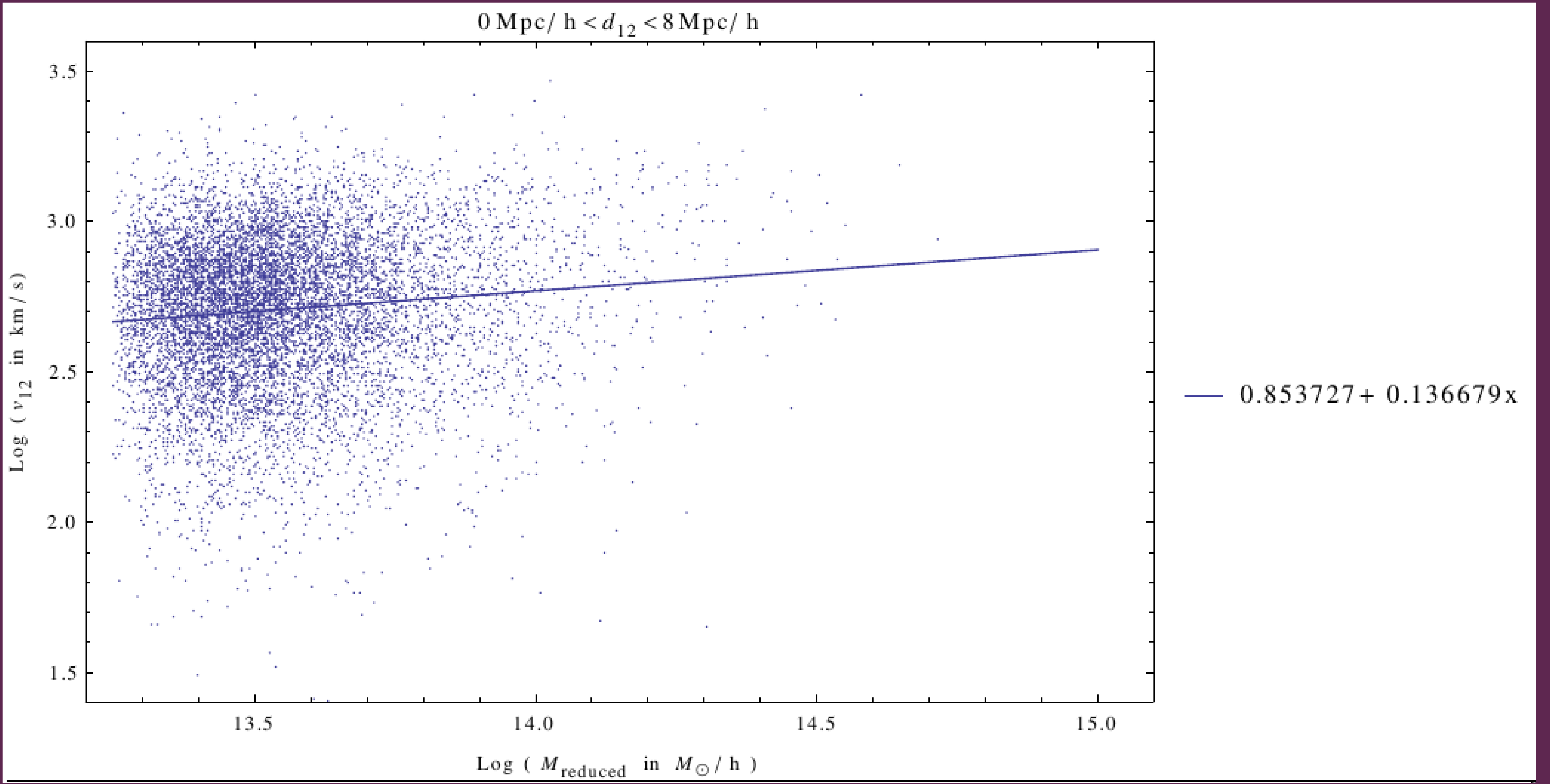

Collisional angle dependence on distance

For smaller distances we expect the halos to deviate from the Hubble flow (0°) and become more likely to be in a head-on collision (180°)

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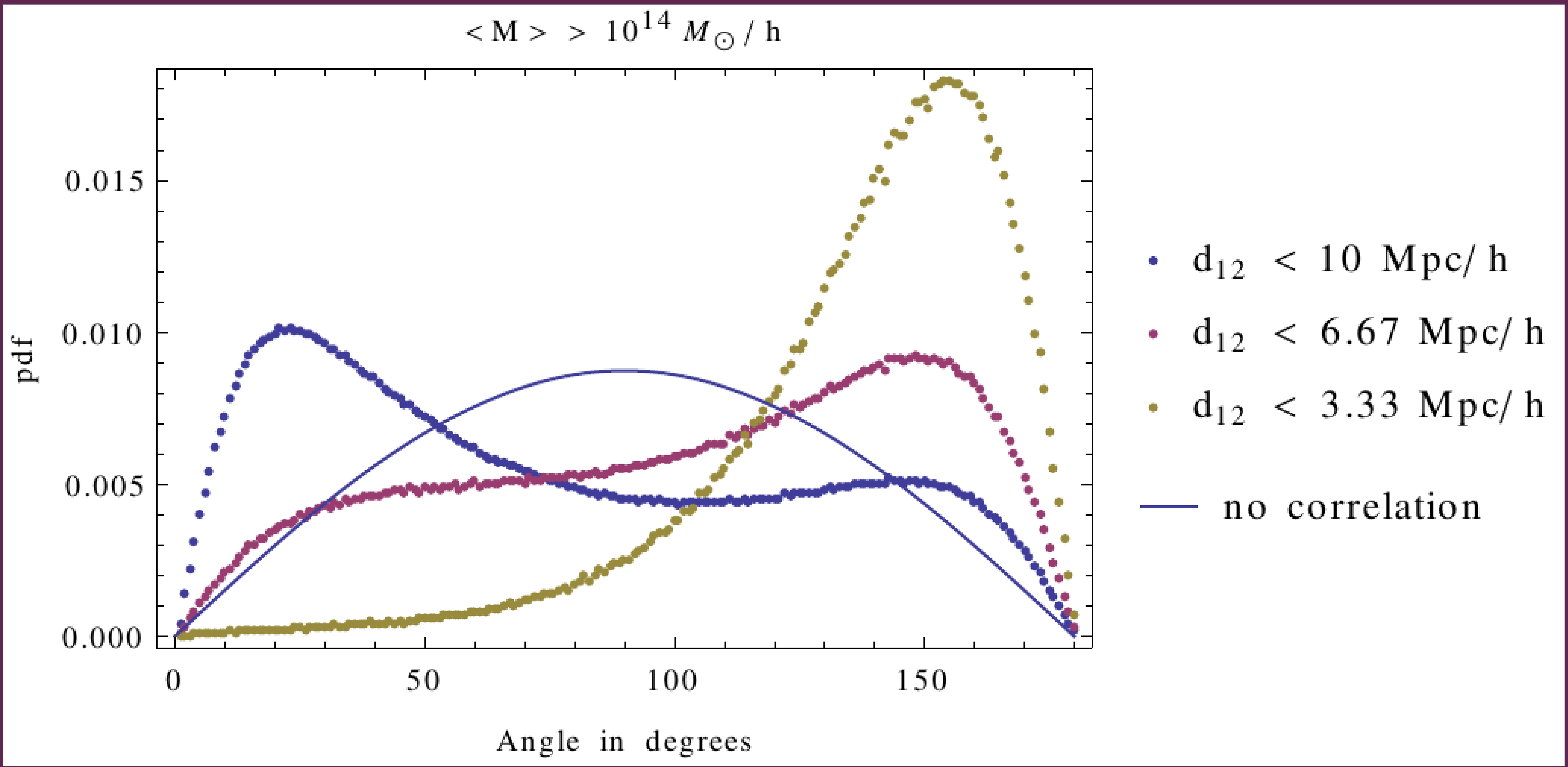

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Collisional angle dependence on pairwise velocity

High pairwise relative velocities are not from the Hubble flow and originate from the attractive force and are expected to be more head-on

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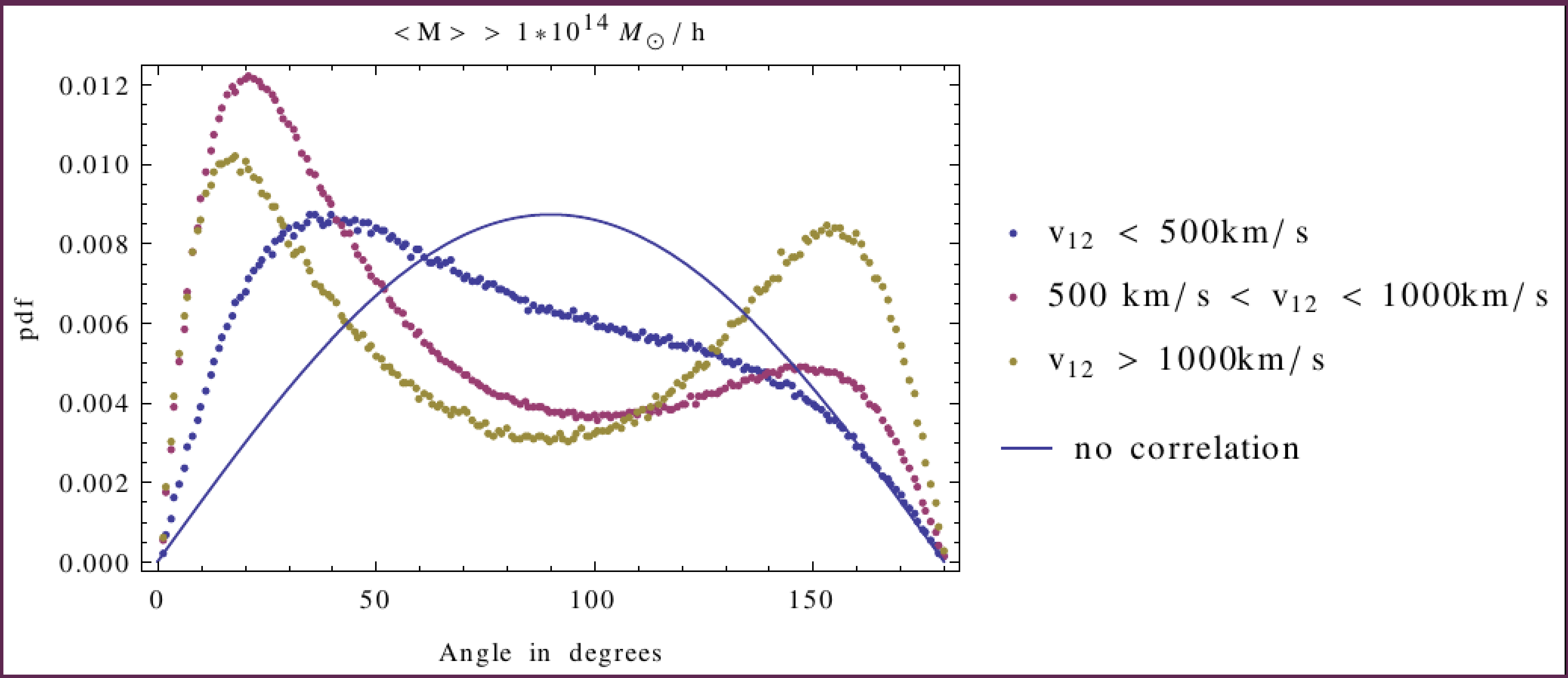

Collisional angle dependence on mass

For a fixed distance we expect the more massive halos to attract gravitationally more and therefore have a larger probability for a head-on collision

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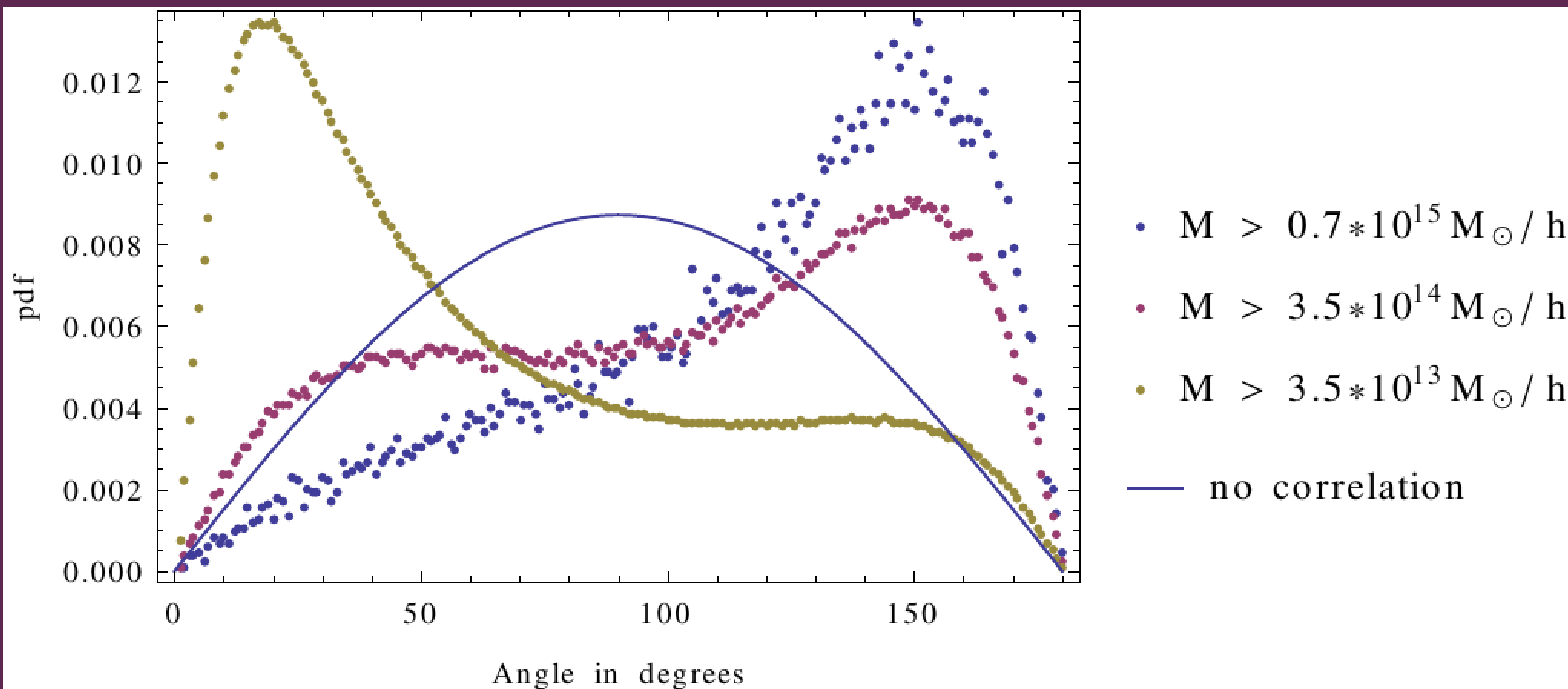

Mass vs pairwise velocity

Pairs of halos consist of two populations with different M vs v_{12} distribution determined by the relative distance d_{12}

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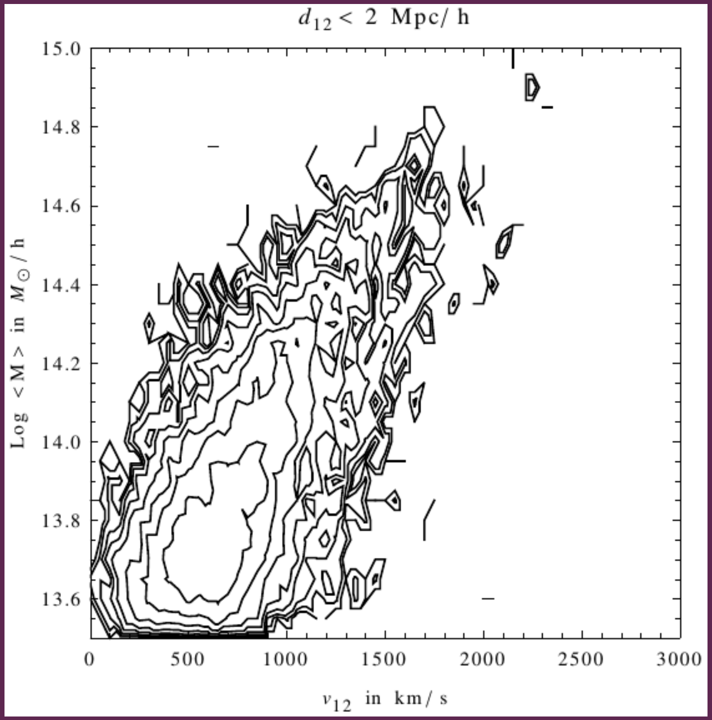

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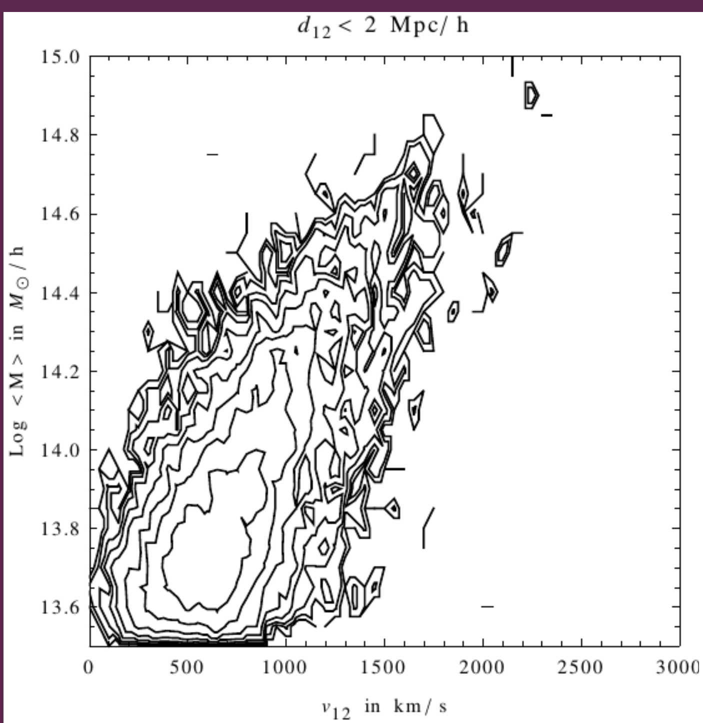

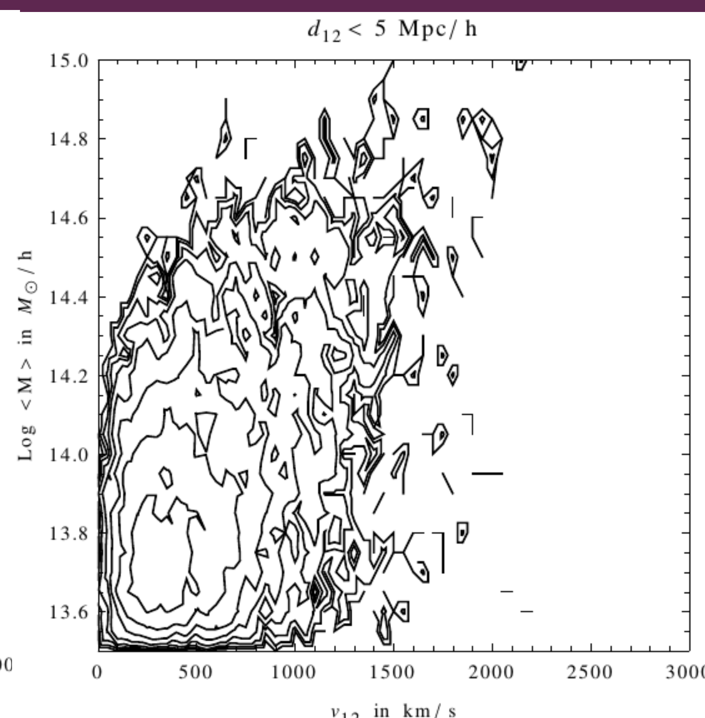

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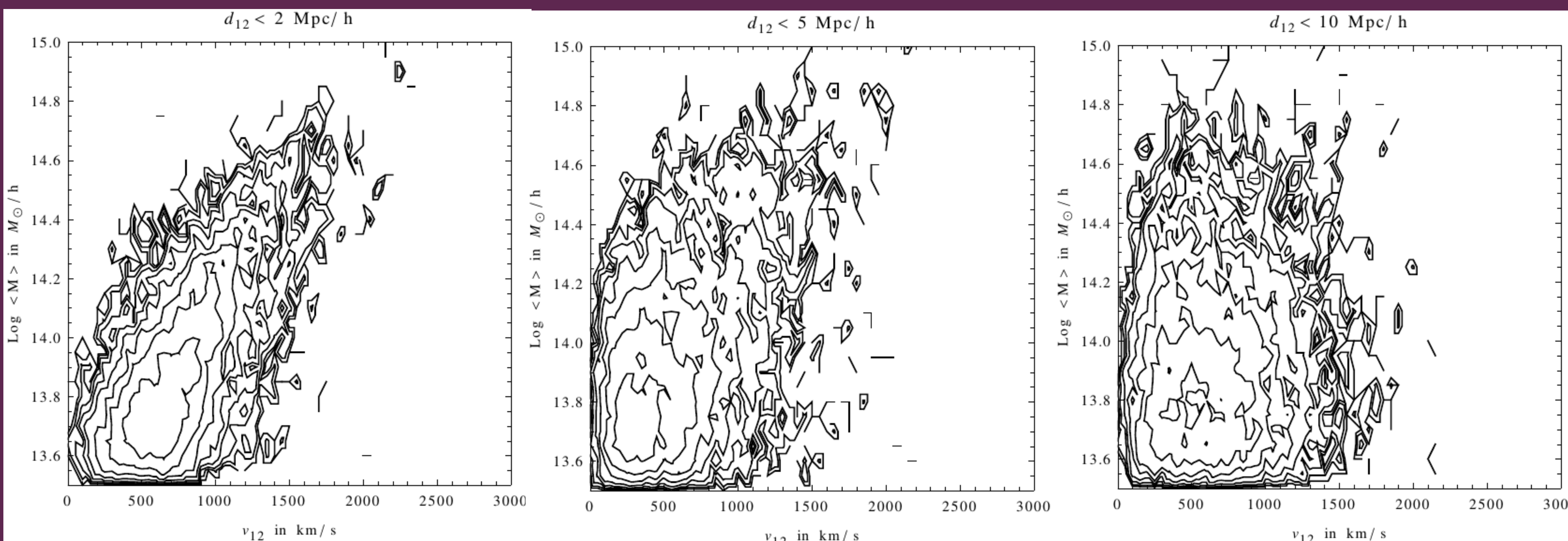

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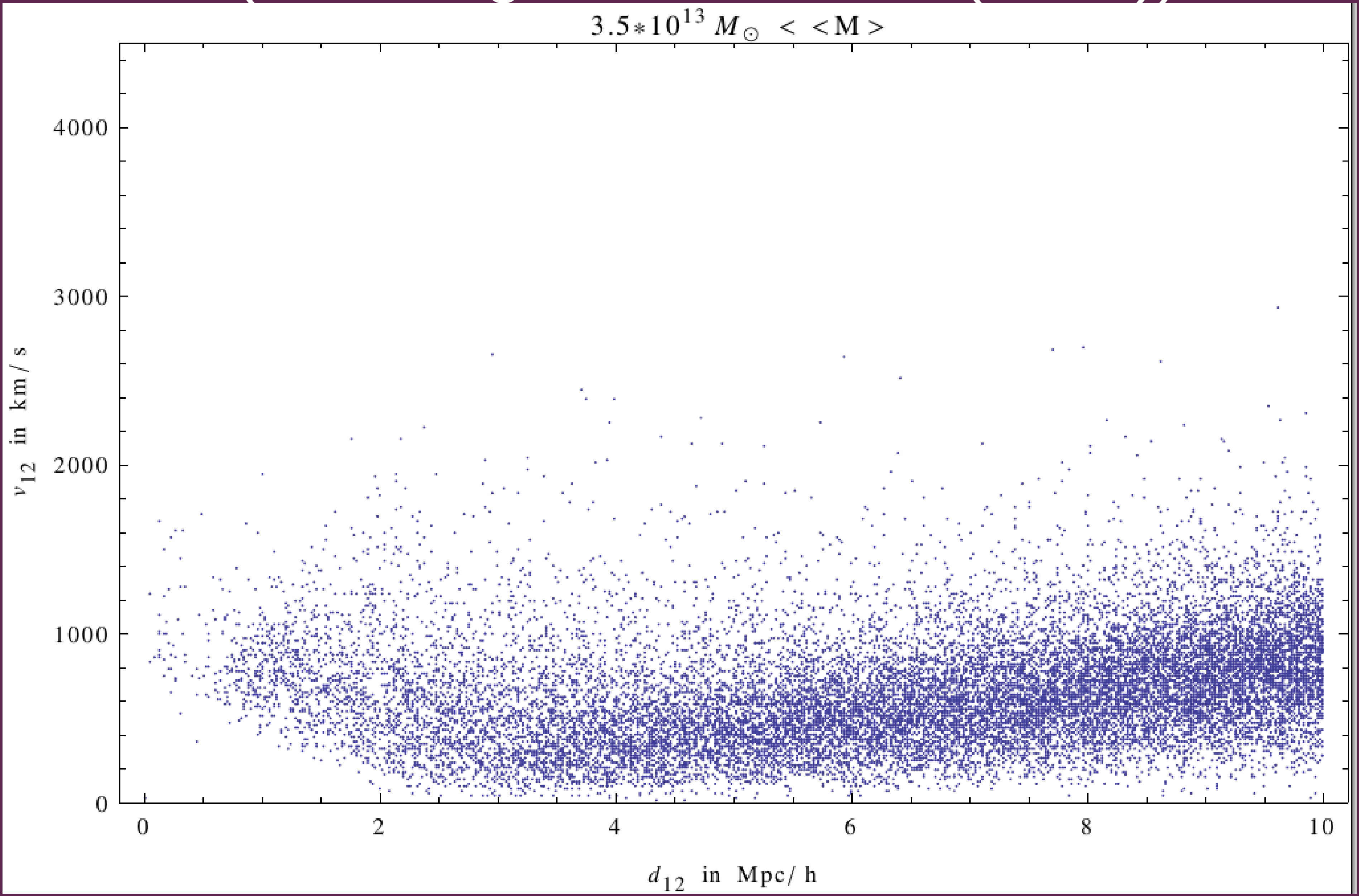

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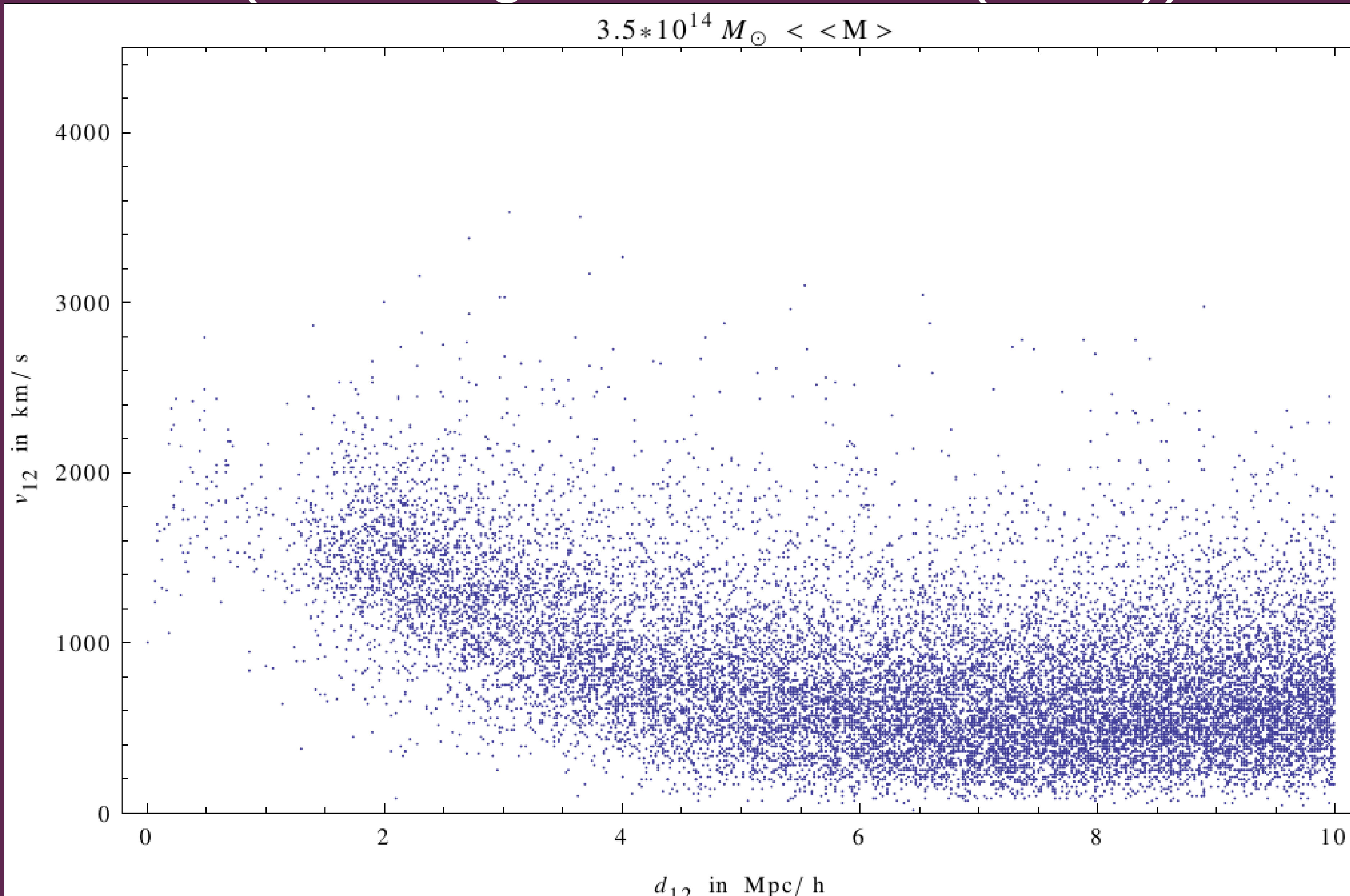

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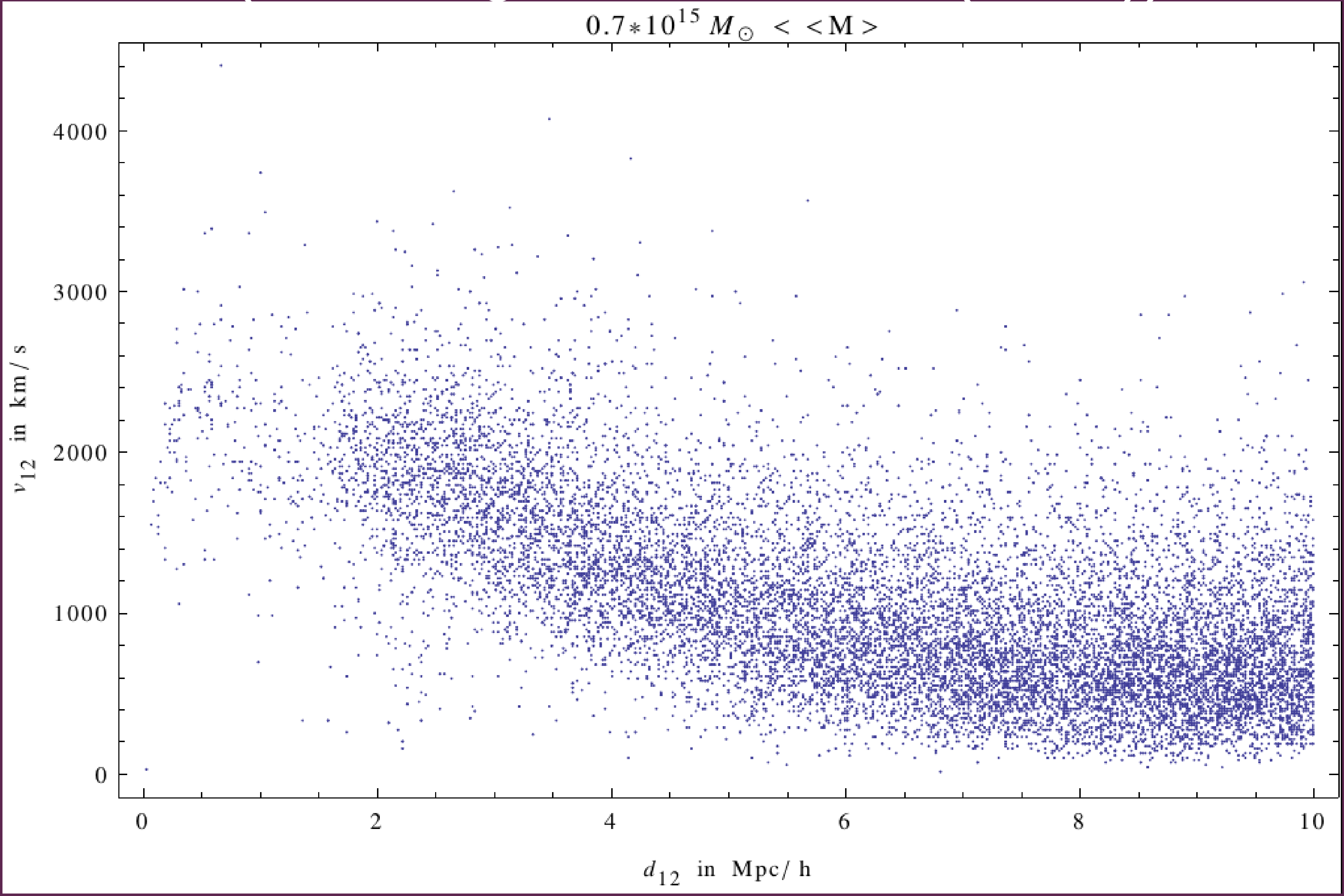

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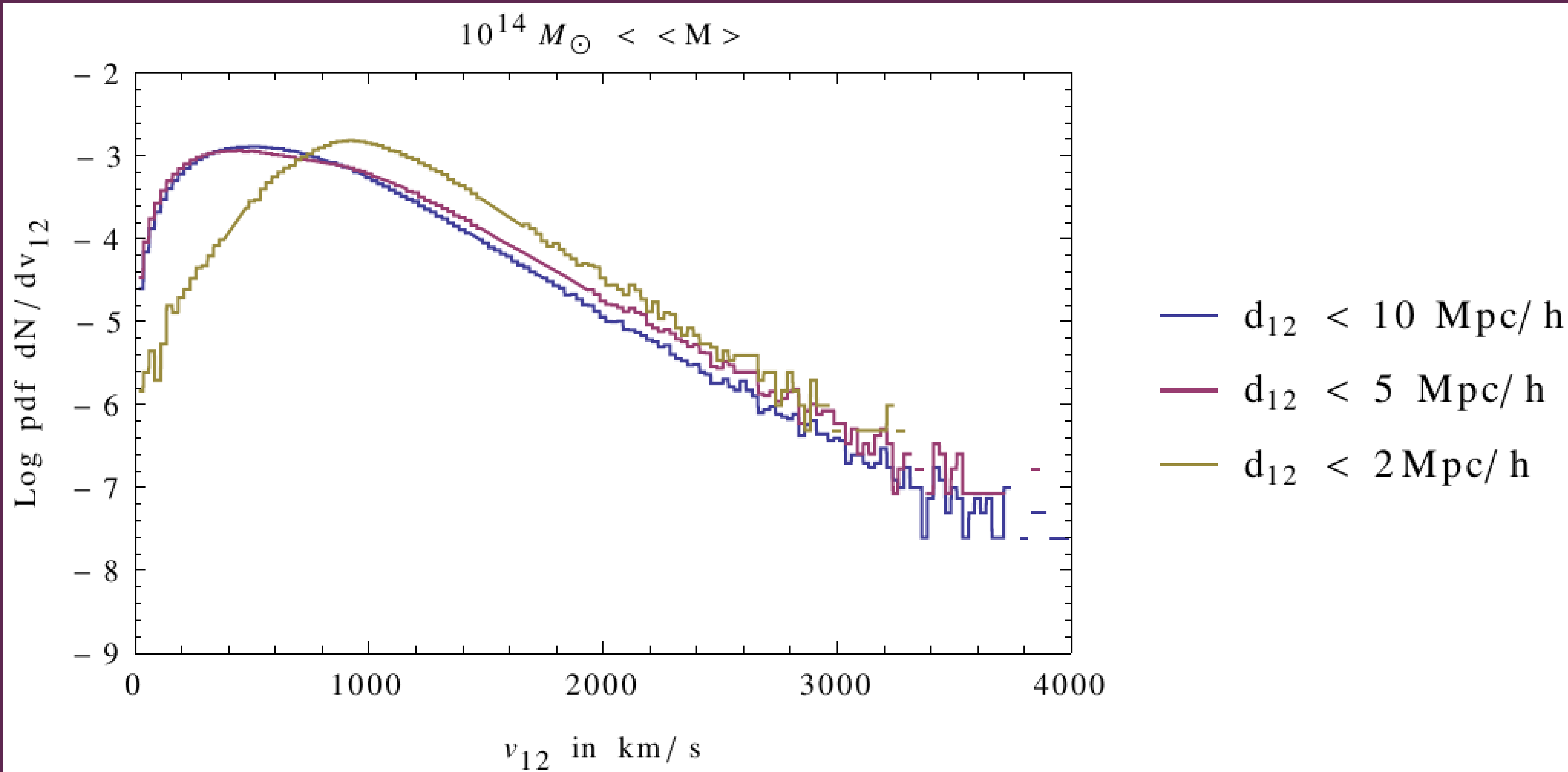

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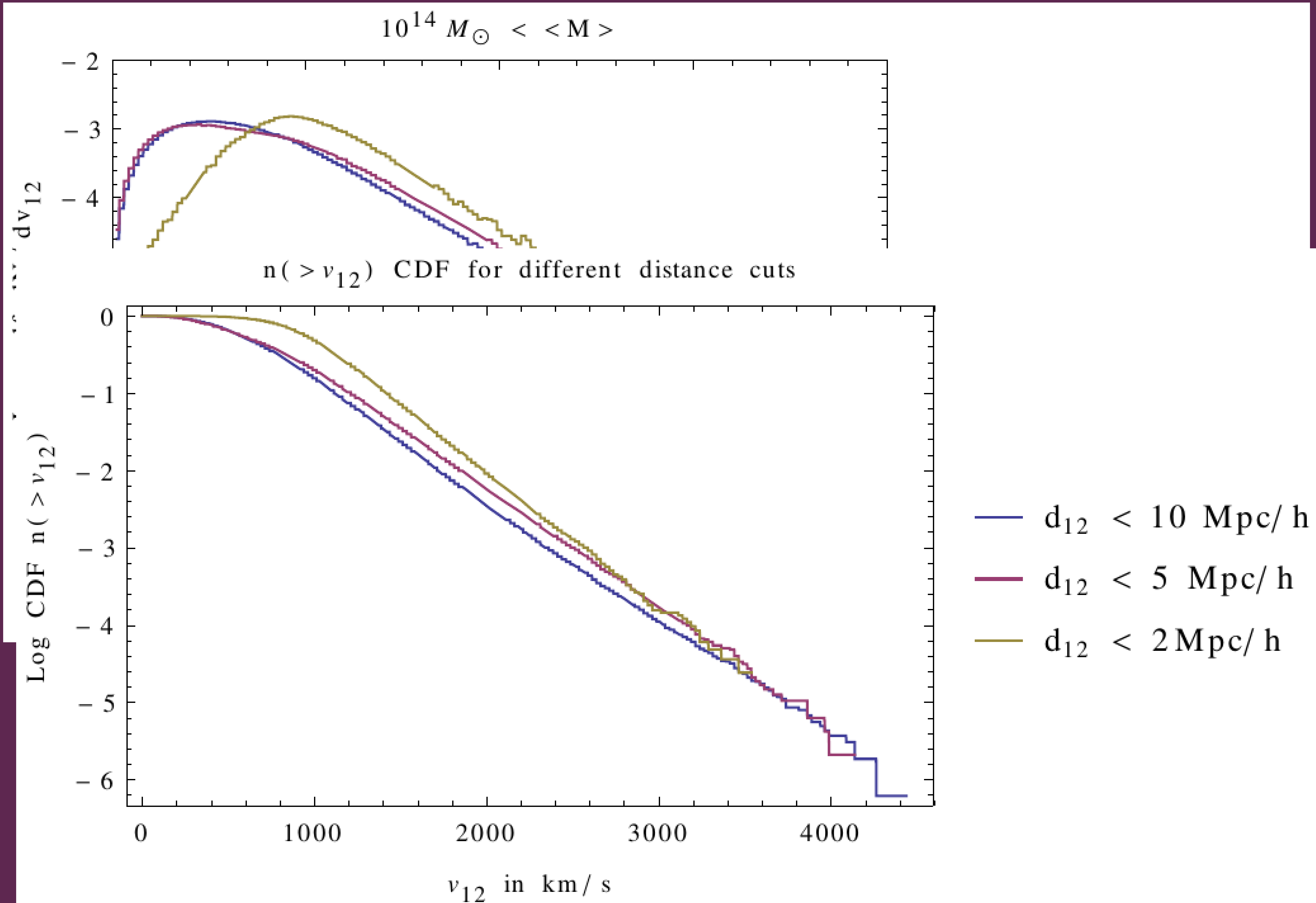

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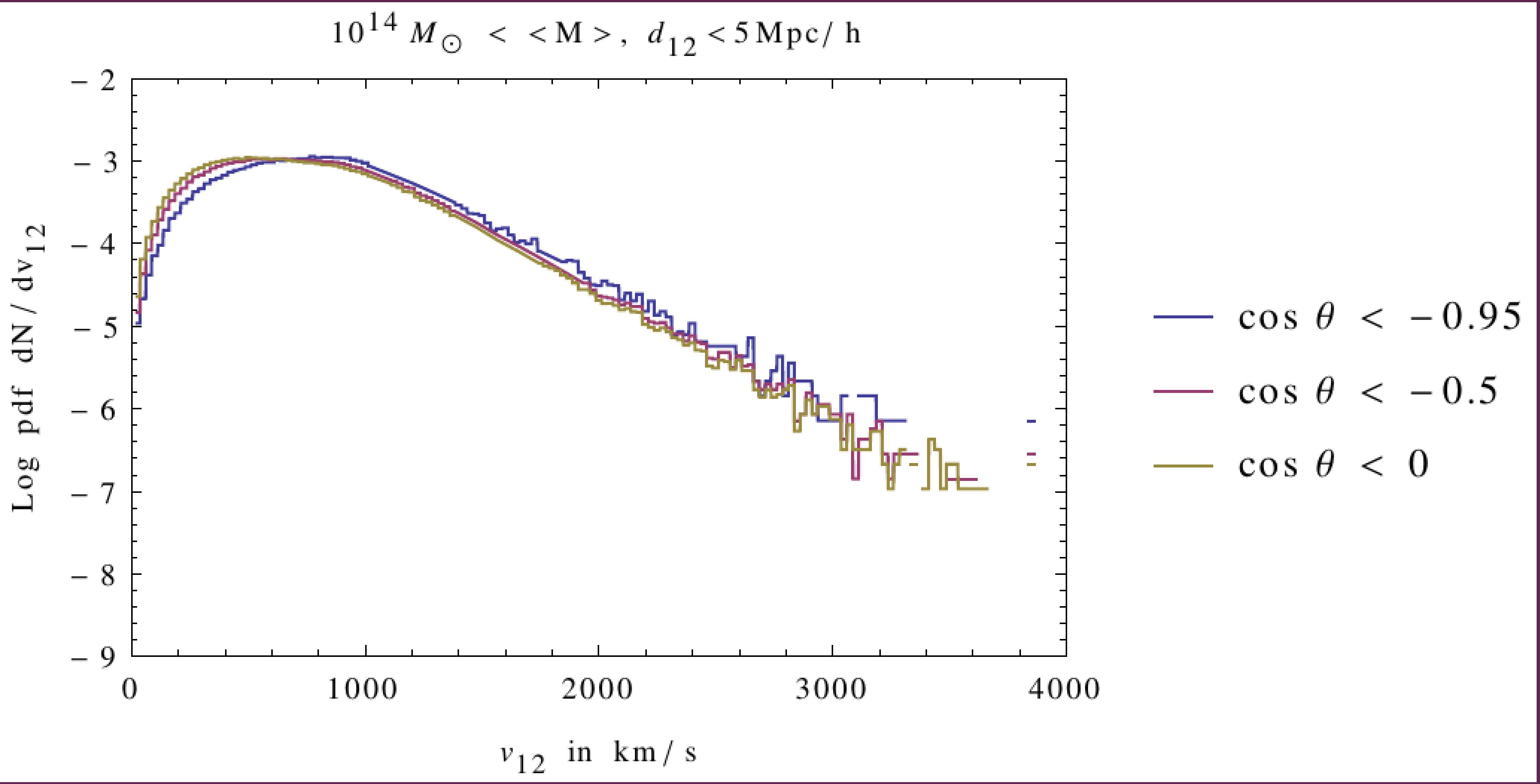

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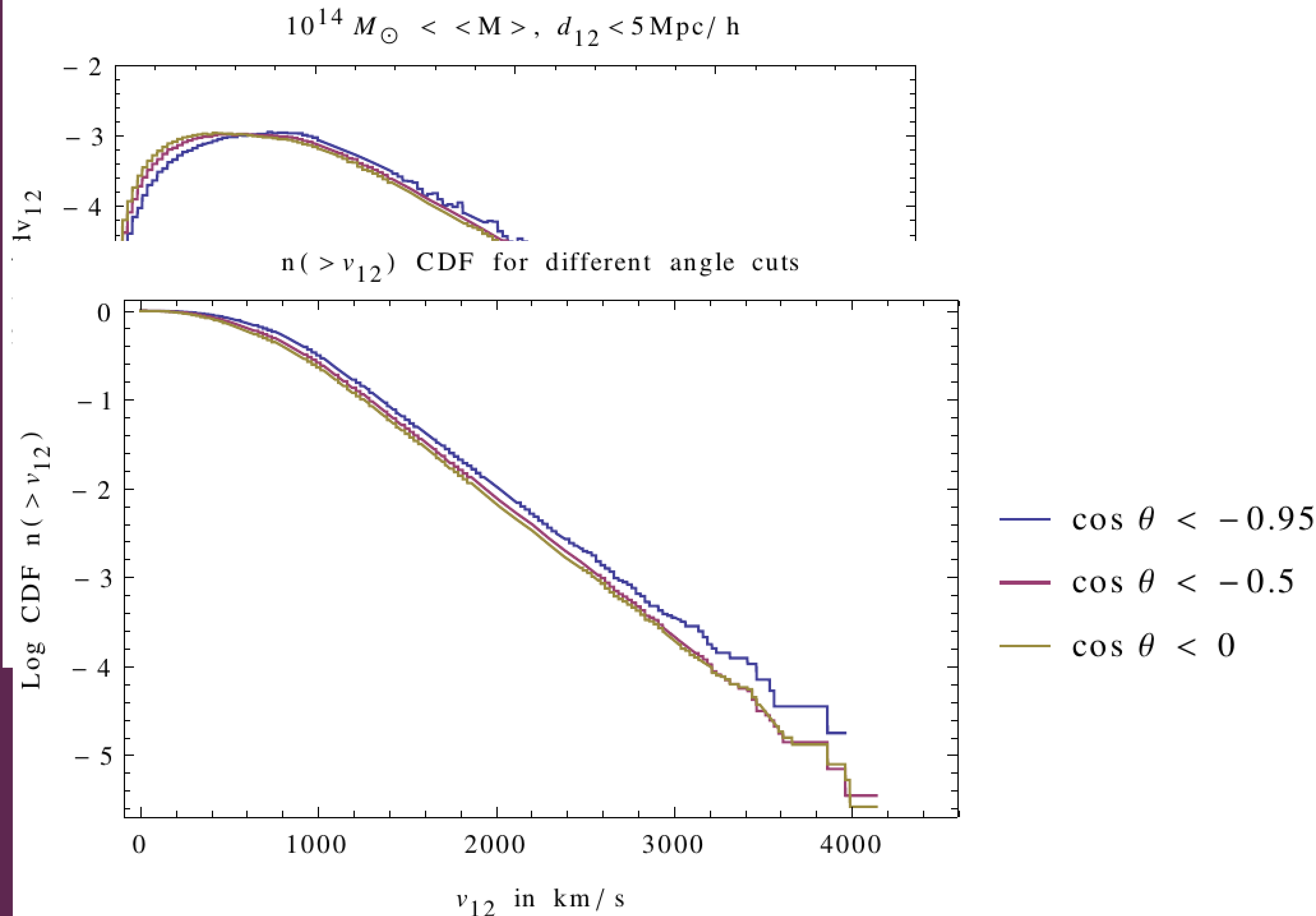

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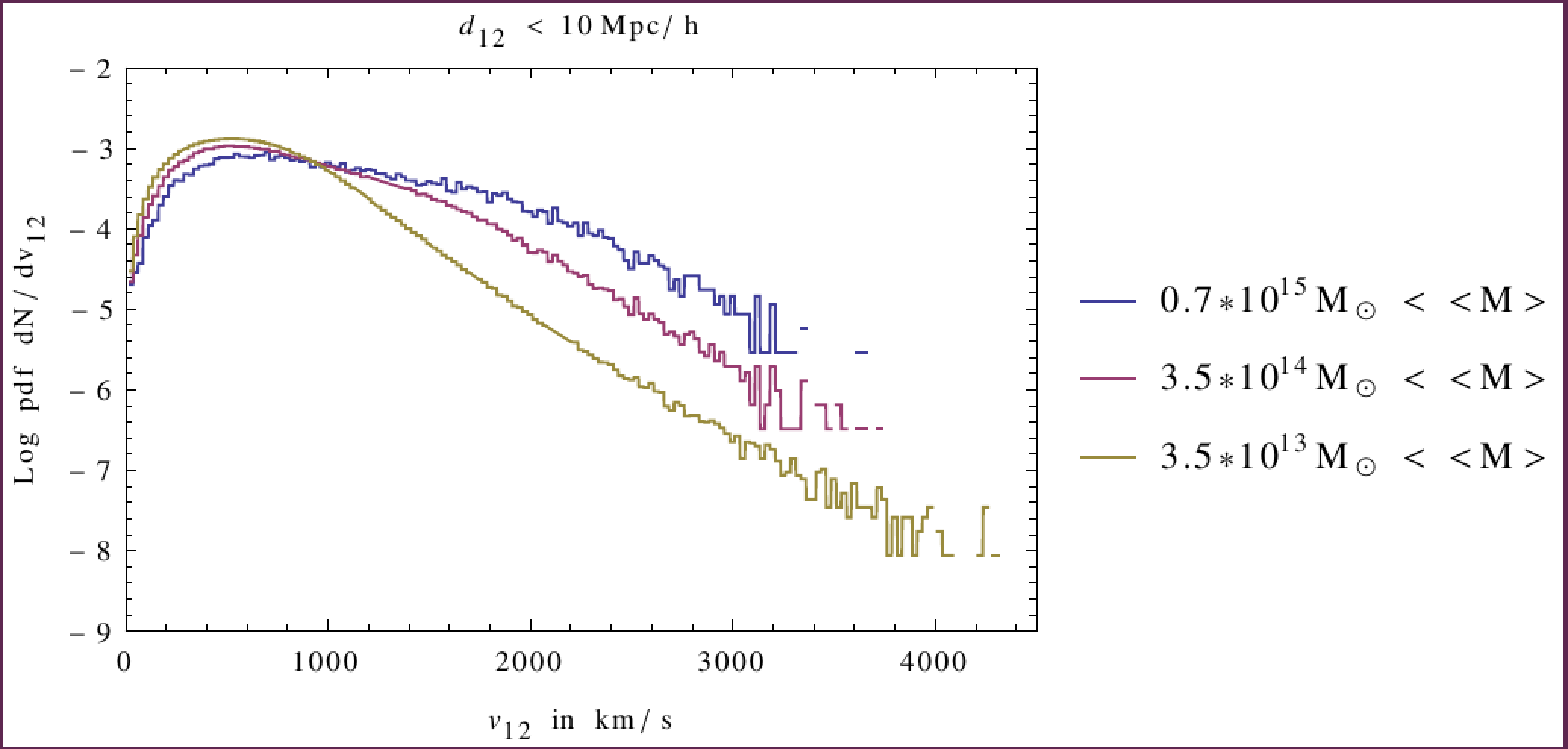

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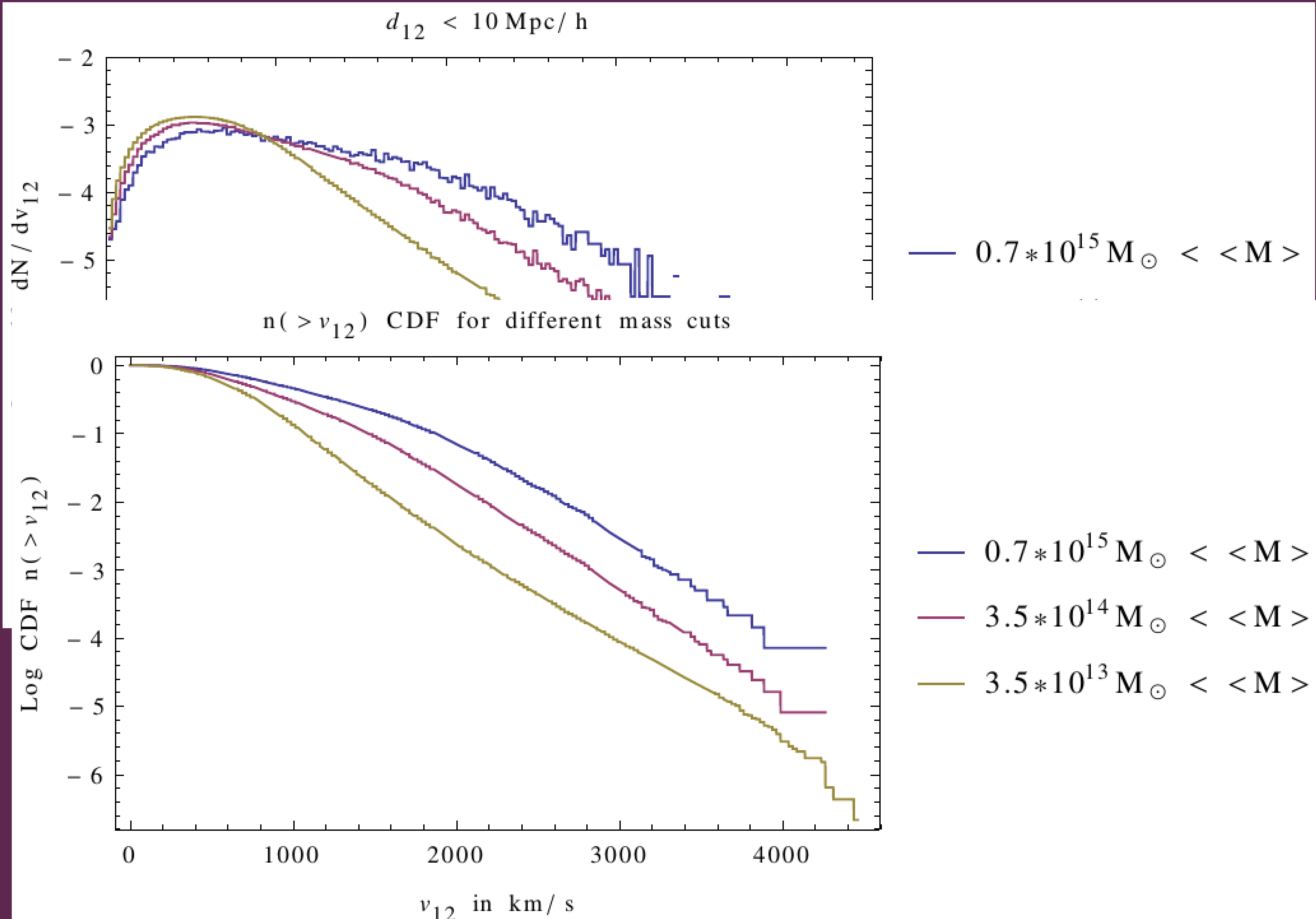

Probability of finding a bullet-like system in DS

(cuts from Thompson&Nagamine(2012) and Buillot et al. (2014) ~ M&B(2008) initial conditions)

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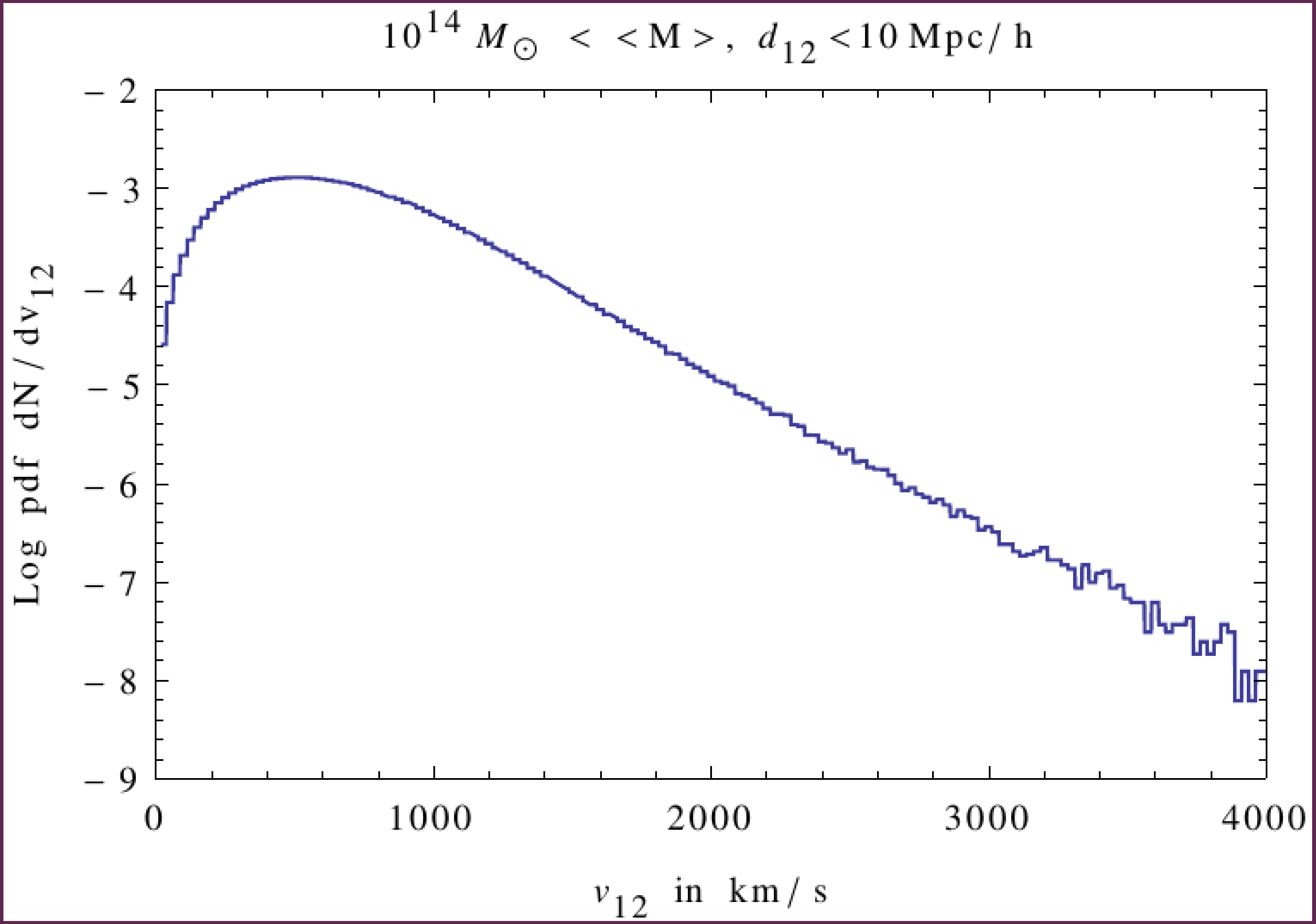

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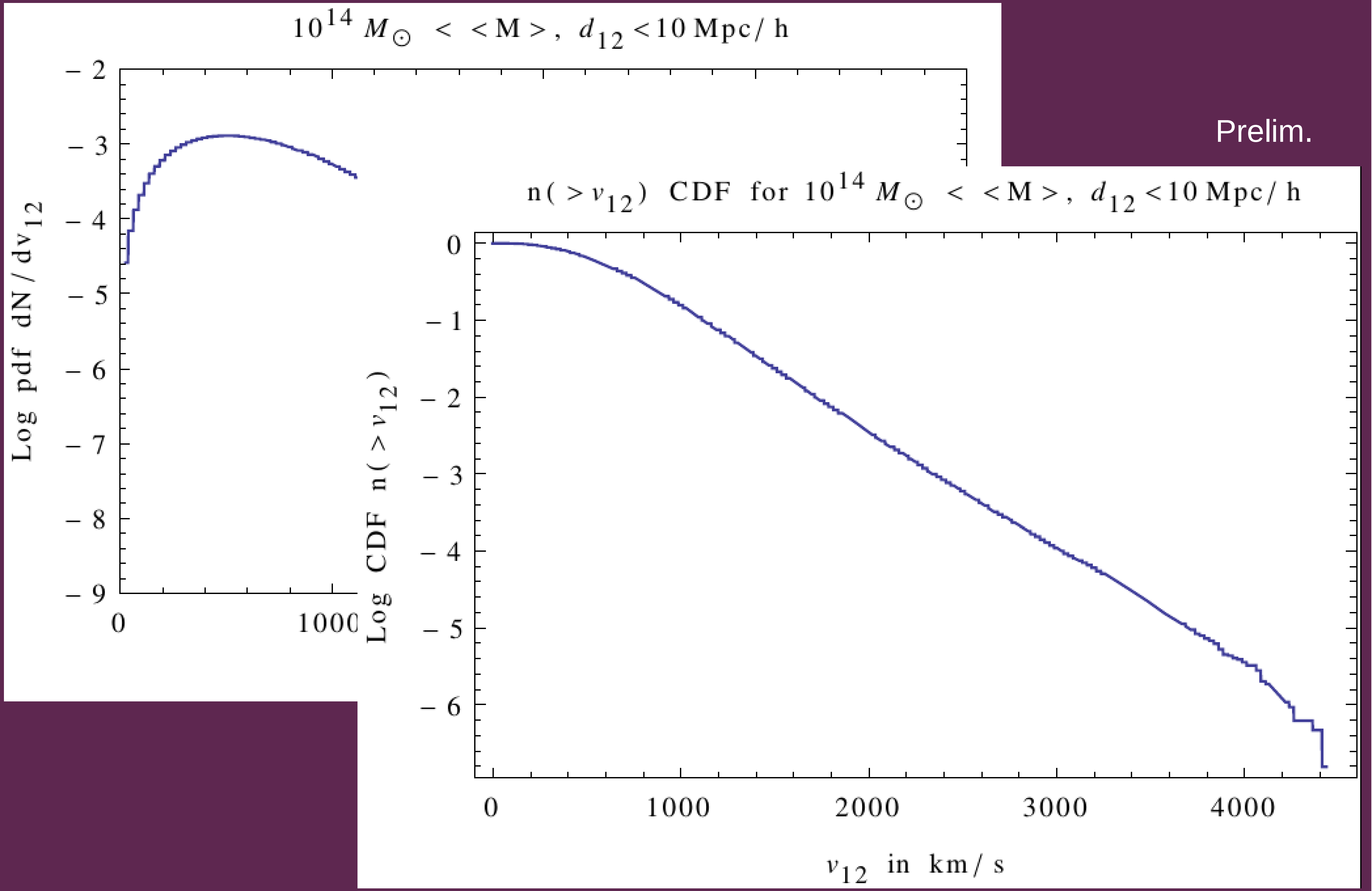
(cuts from Thompson&Nagamine(2012) and Buillot et al. (2014) ~ M&B(2008) initial conditions)

Prelim.



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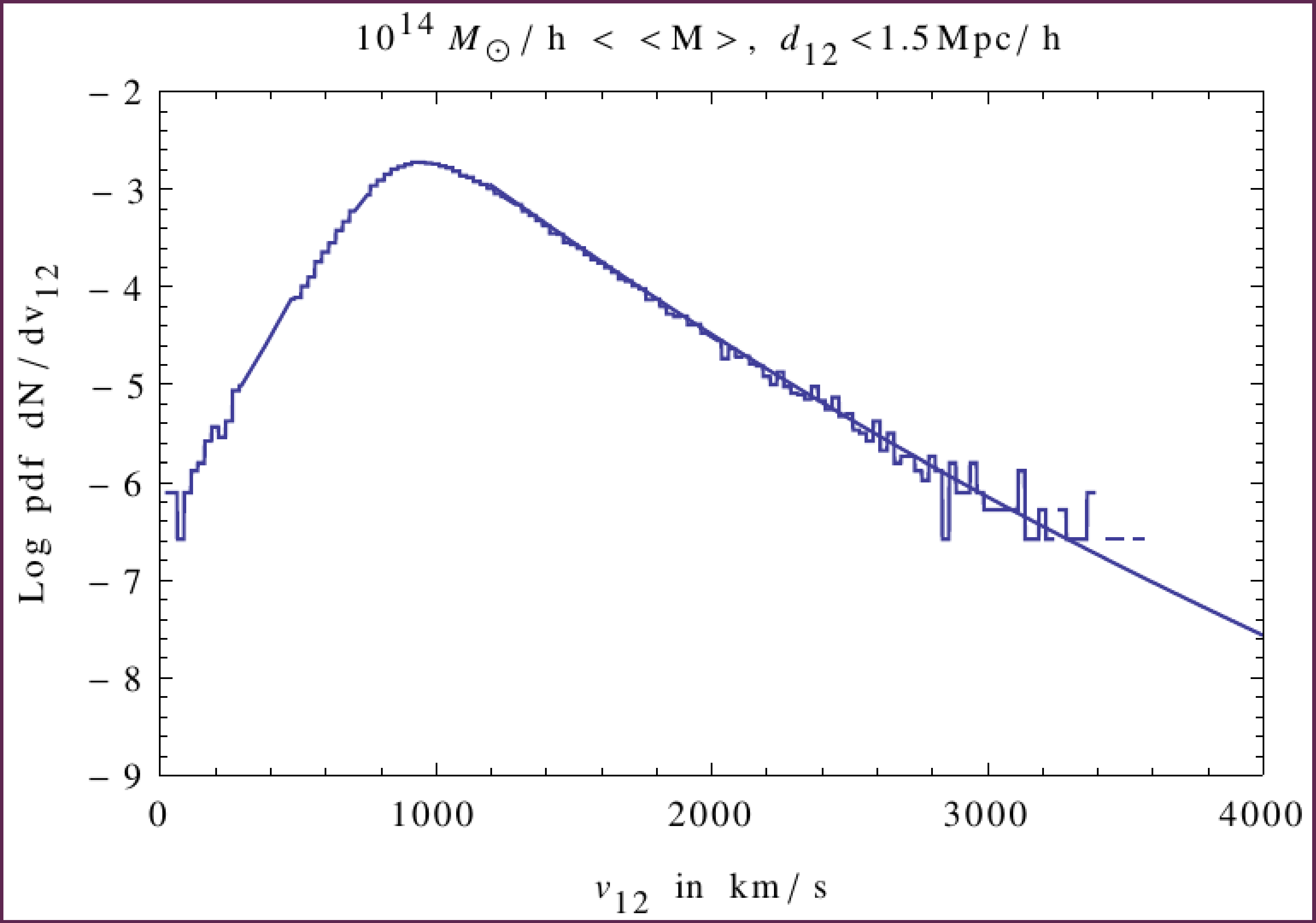

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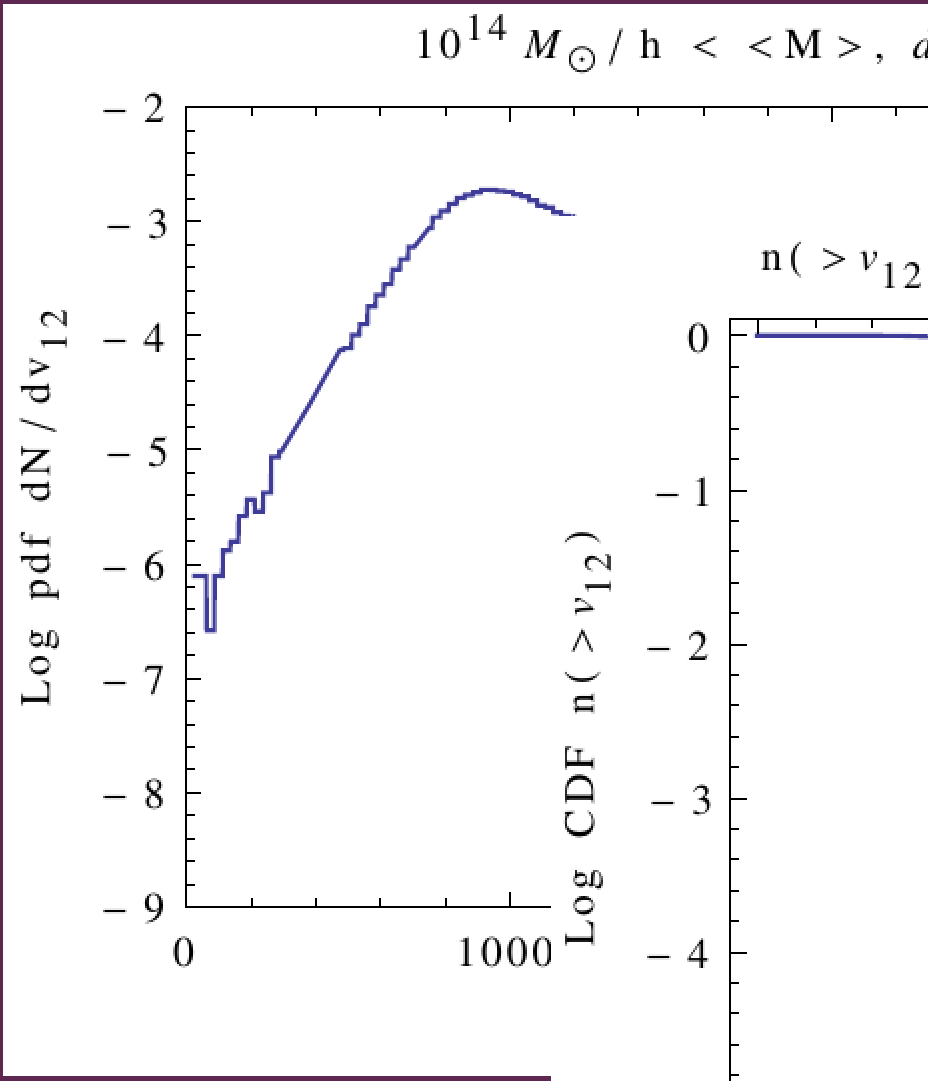

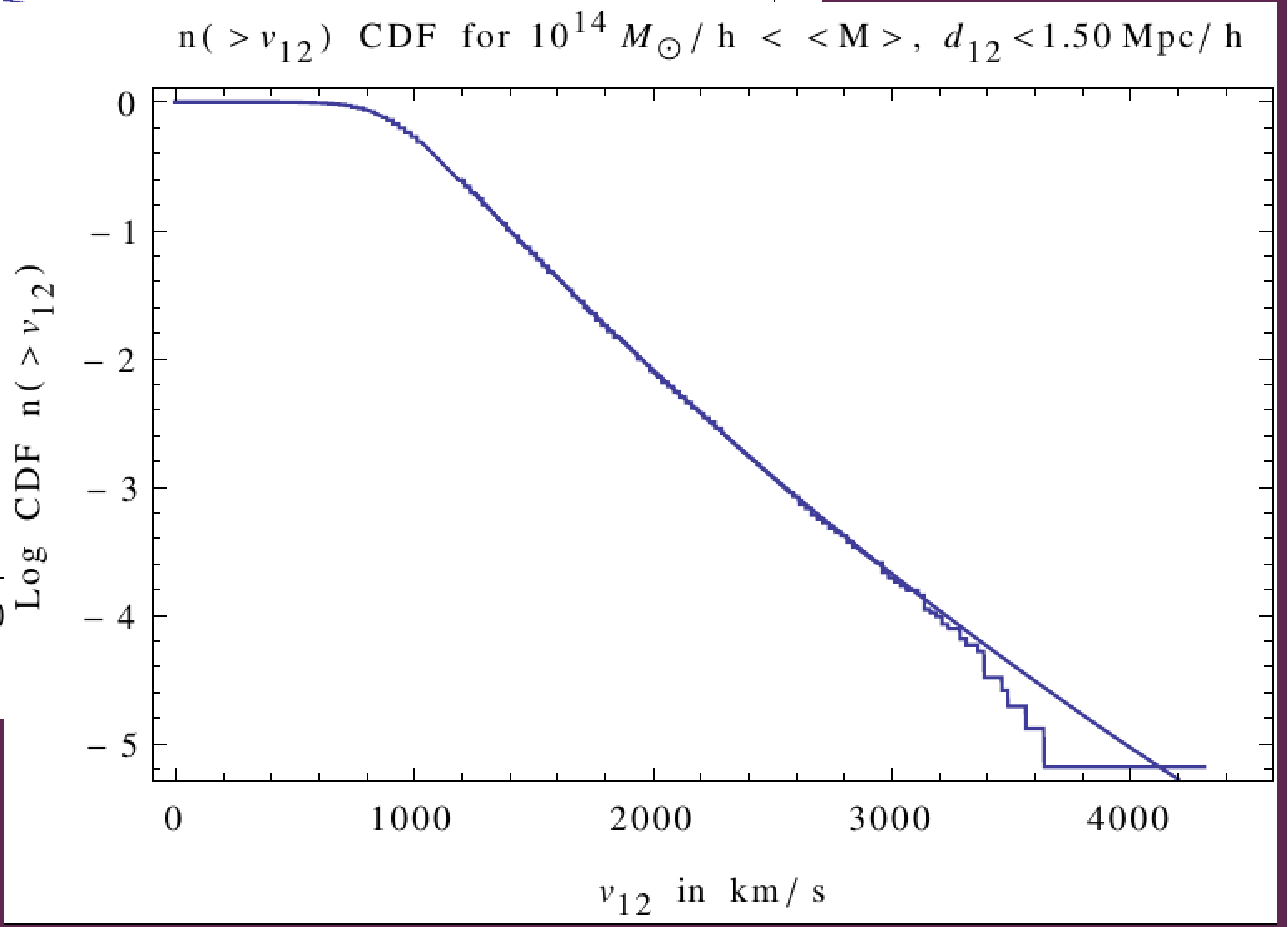

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