Collisionless Structure Formation

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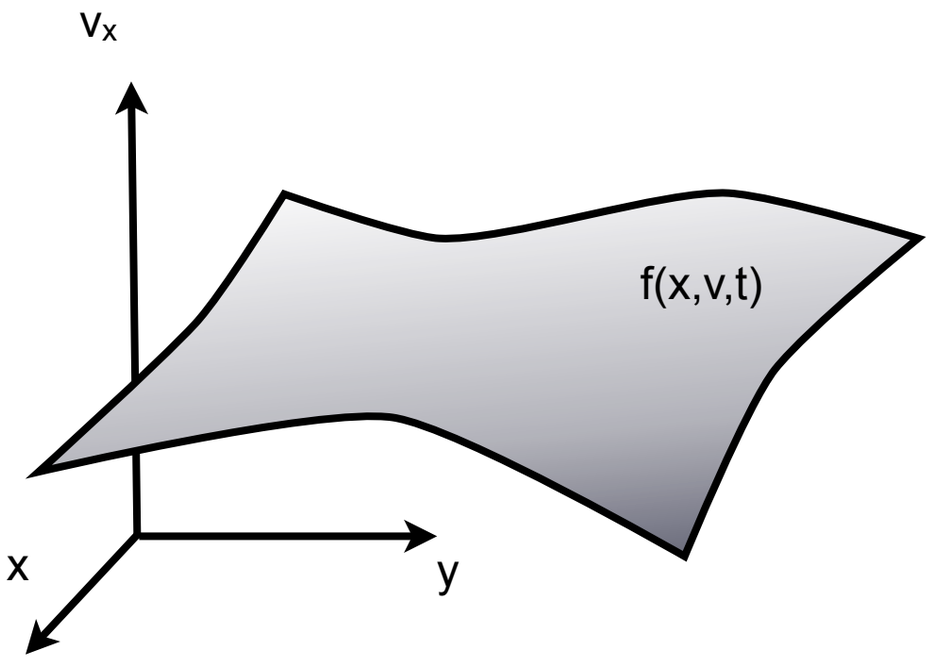
Abel, Hahn, Kaehler (2012), MNRAS
Kaehler, Hahn, Abel (2012), IEEE TVCG
Hahn, Abel, Kaehler (2013), MNRAS
Angulo, Hahn, Abel (2013), MNRAS
Hahn & Paranjape (2013) to be submitted

The CDM sheet - a new way to think of DM

WIMP (say 100 GeV) very cold (~10^{-8} km/s at z=100) i.e. no extent in vel-direction.
Almost perfectly uniformly distributed in space in the early Universe



CDM distribution function
covers a 3D submanifold of 6D phase space

- extends over all of space
- initially ‘delta’-function in velocity
- continuum limit for all practical purposes
- never tears, never self-intersects

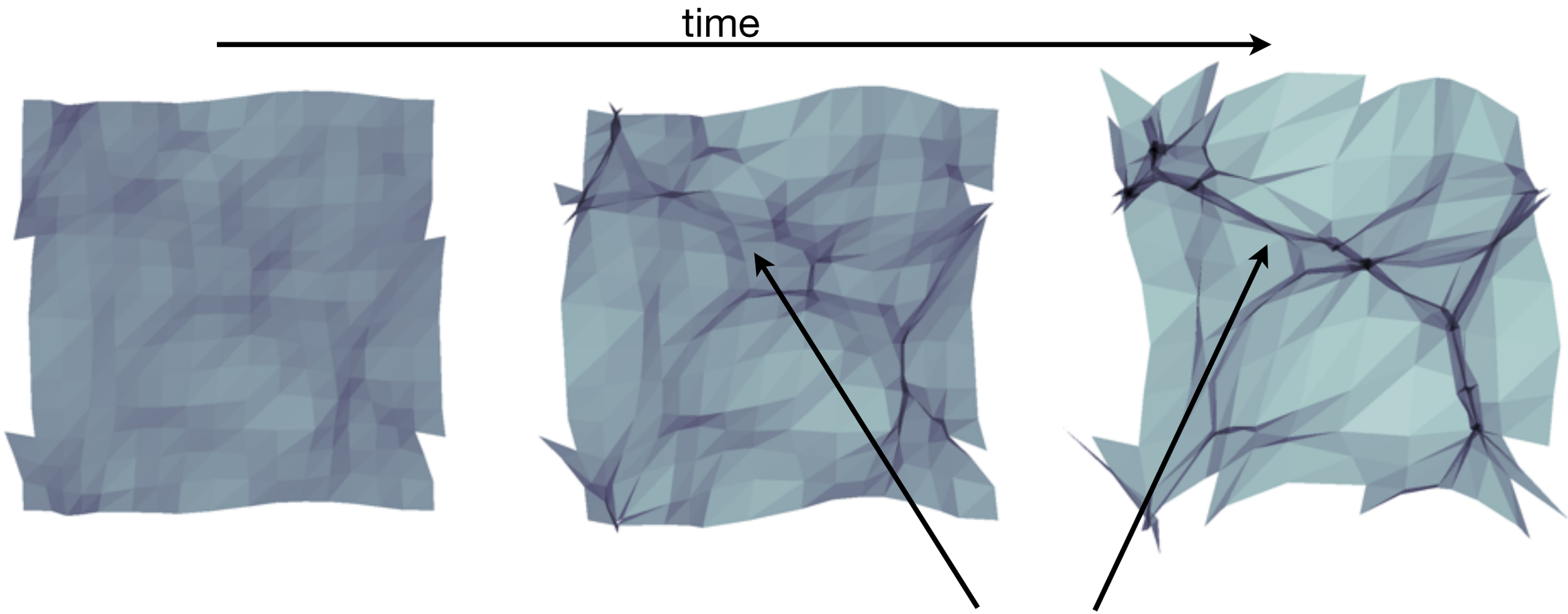
We call this 3D surface the dark matter sheet.

$$\mathbb{Q} \subset \mathbb{R}^3 \rightarrow \mathbb{R}^6 \; : \; \mathbf{q} \mapsto (\mathbf{x_q}, \mathbf{p_q})$$

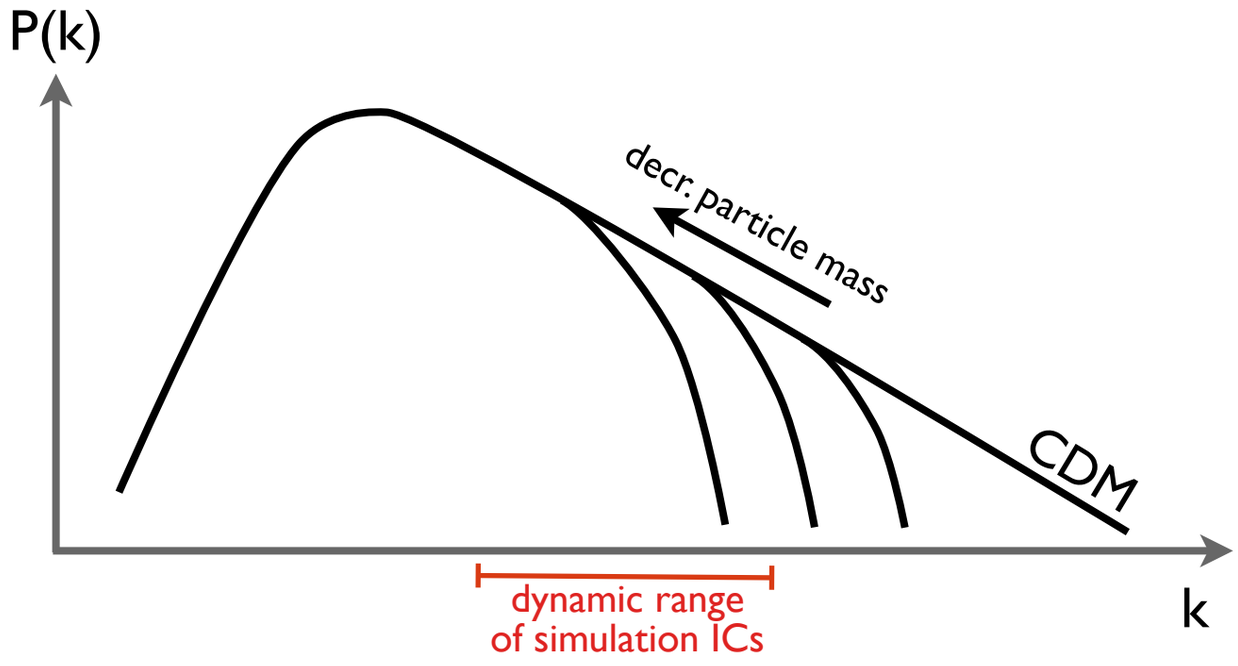
$$f(\mathbf{x}, \mathbf{p}, t) = \int \delta_D(\mathbf{x} - \mathbf{x_q}(t)) \, \delta_D(\mathbf{p} - \mathbf{p_q}(t)) \, \mathrm{d}^3 q$$

Evolution in two dimensions

- The real space density, velocity field, etc., at any given point can then be determined from **all** cells that contain that point.



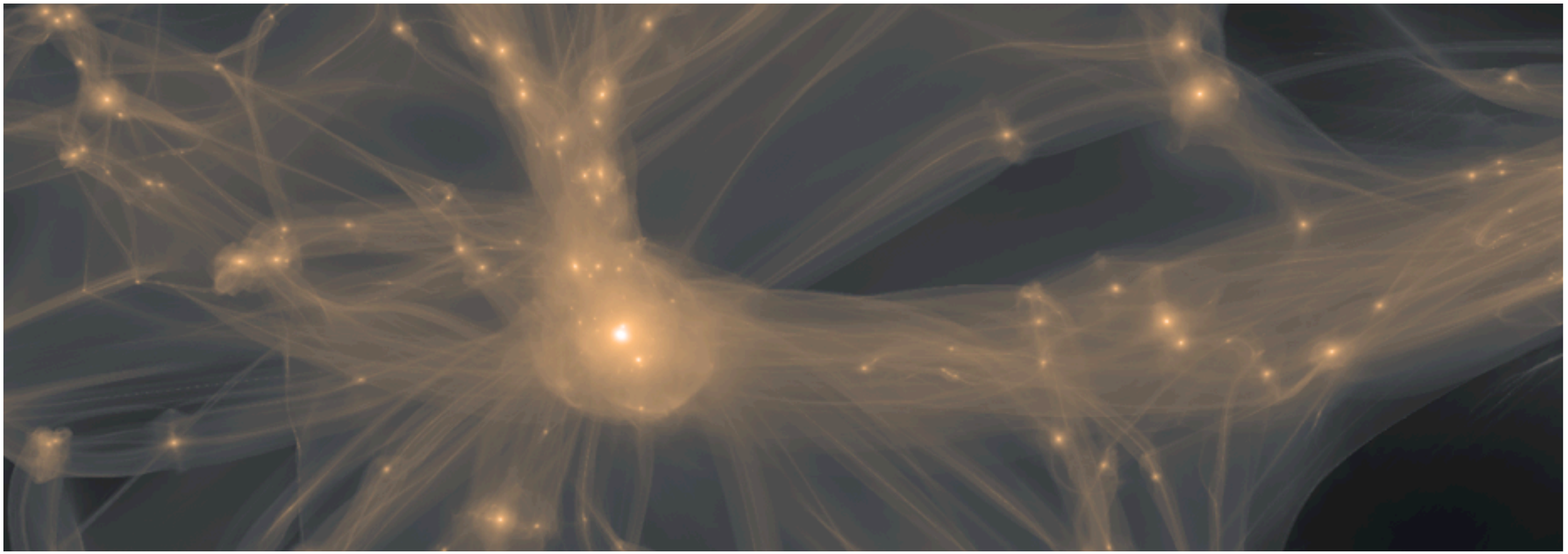
Warm/Hot DM



CDM has perturbations on all scales
CDM is inherently unresolvable

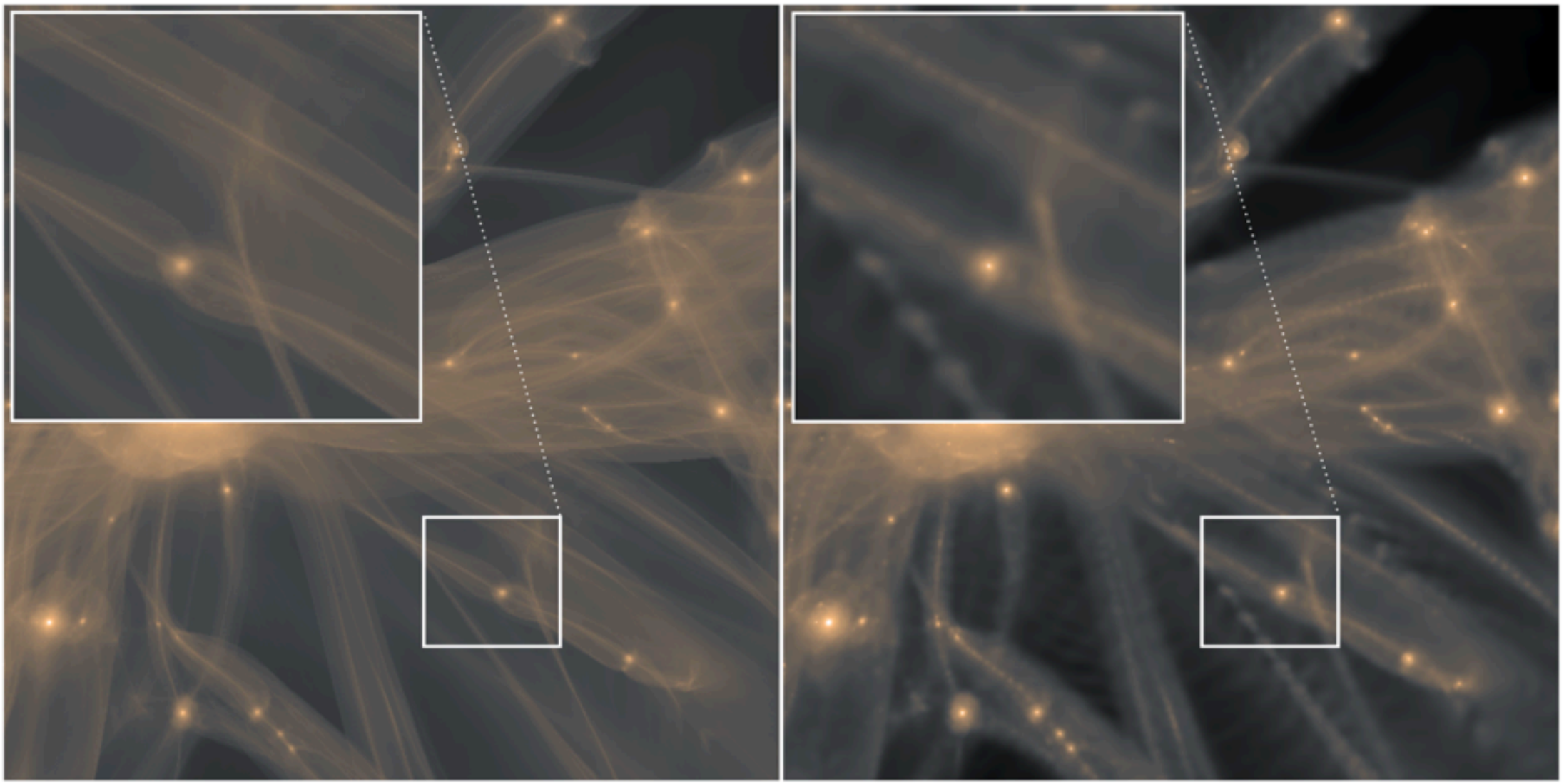
WDM viable option (satellite problems)
Possible to resolve all perturbations!
-> Well defined numerical problem

Neglect thermal component (Small compared to velocities from structure formation) -> WDM in cold limit



Use DM sheet to get distribution function

Renderings of same WDM simulation data



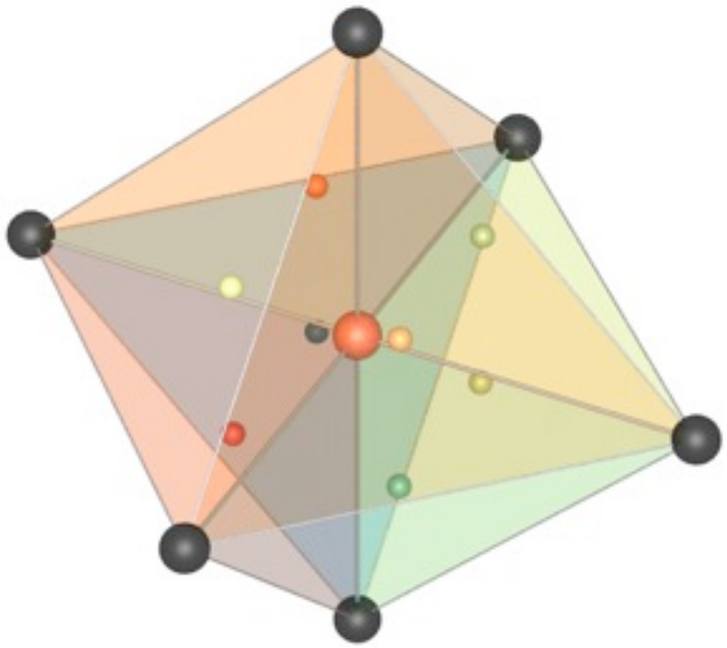
Kaehler et al. 2012 full tet rendering

Adaptive kernel filtered

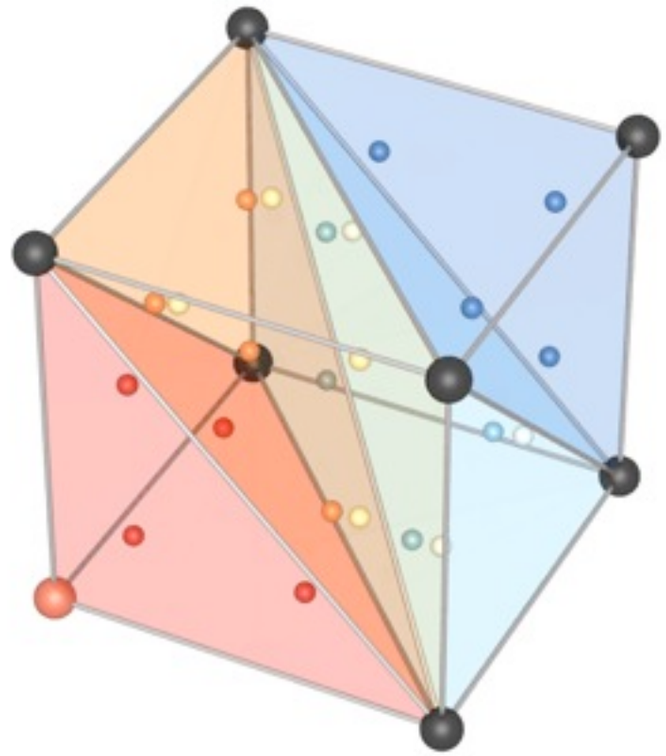
Mass is spread out ⇒ fragmentation reduced

Compute the force due to tetrahedra

- Expensive! -> use pseudo-particle approximation to tets



Monopole approximation



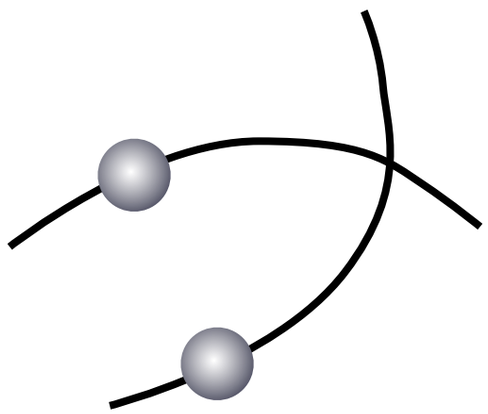
Quadrupole approximation

- use pseudo-particles for mass deposit
- -> mass tracer vs. flow tracer particles

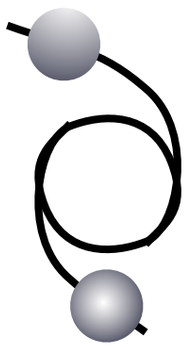
Problems of the N-body method

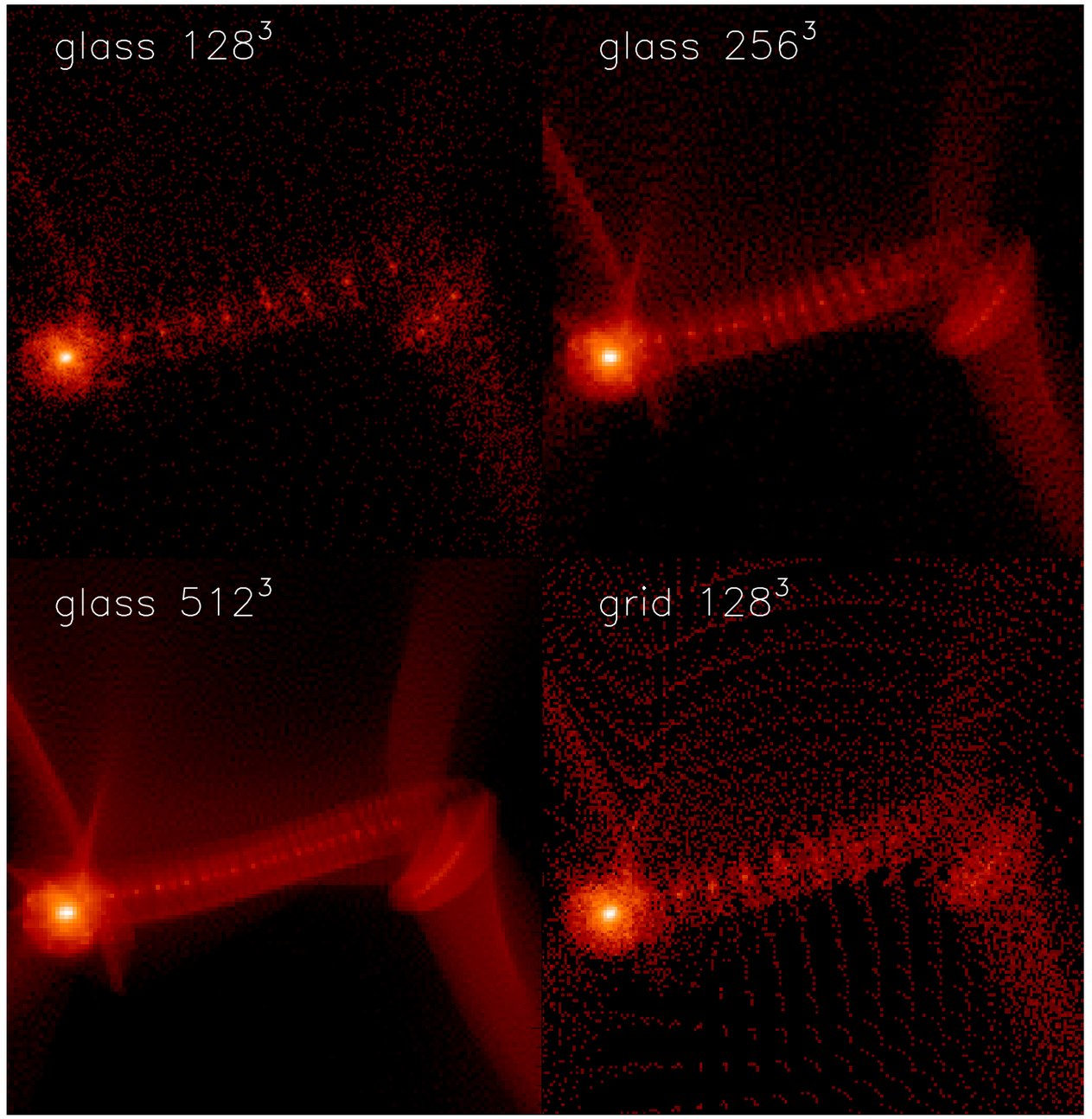
Main Problem: two-body effects, directly related to force softening

Scattering



Clumping/
Fragmentation



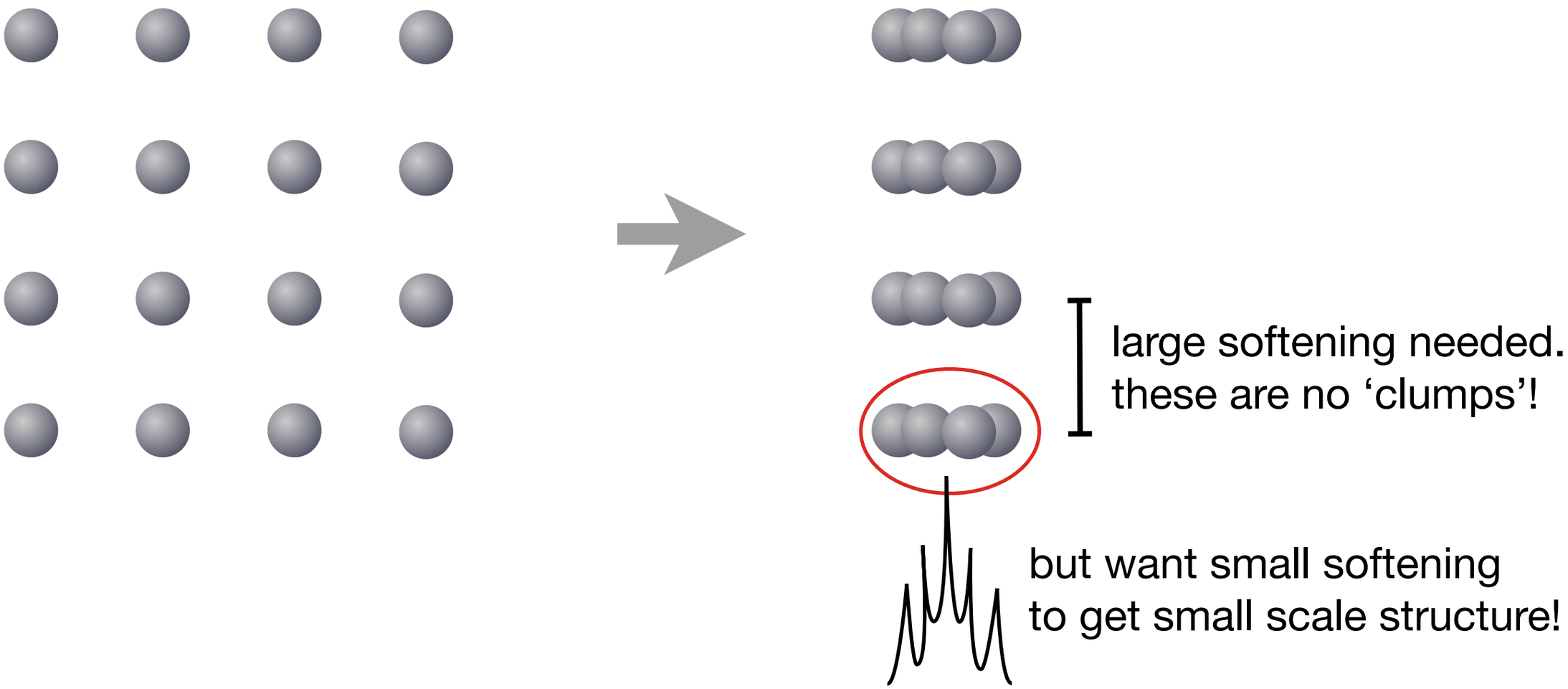


Most problematic for non-CDM simulations!

(e.g. Centrella&Melott 1983, Melott&Shandarin 1989, Wang&White 2007)

Why is this so hard?

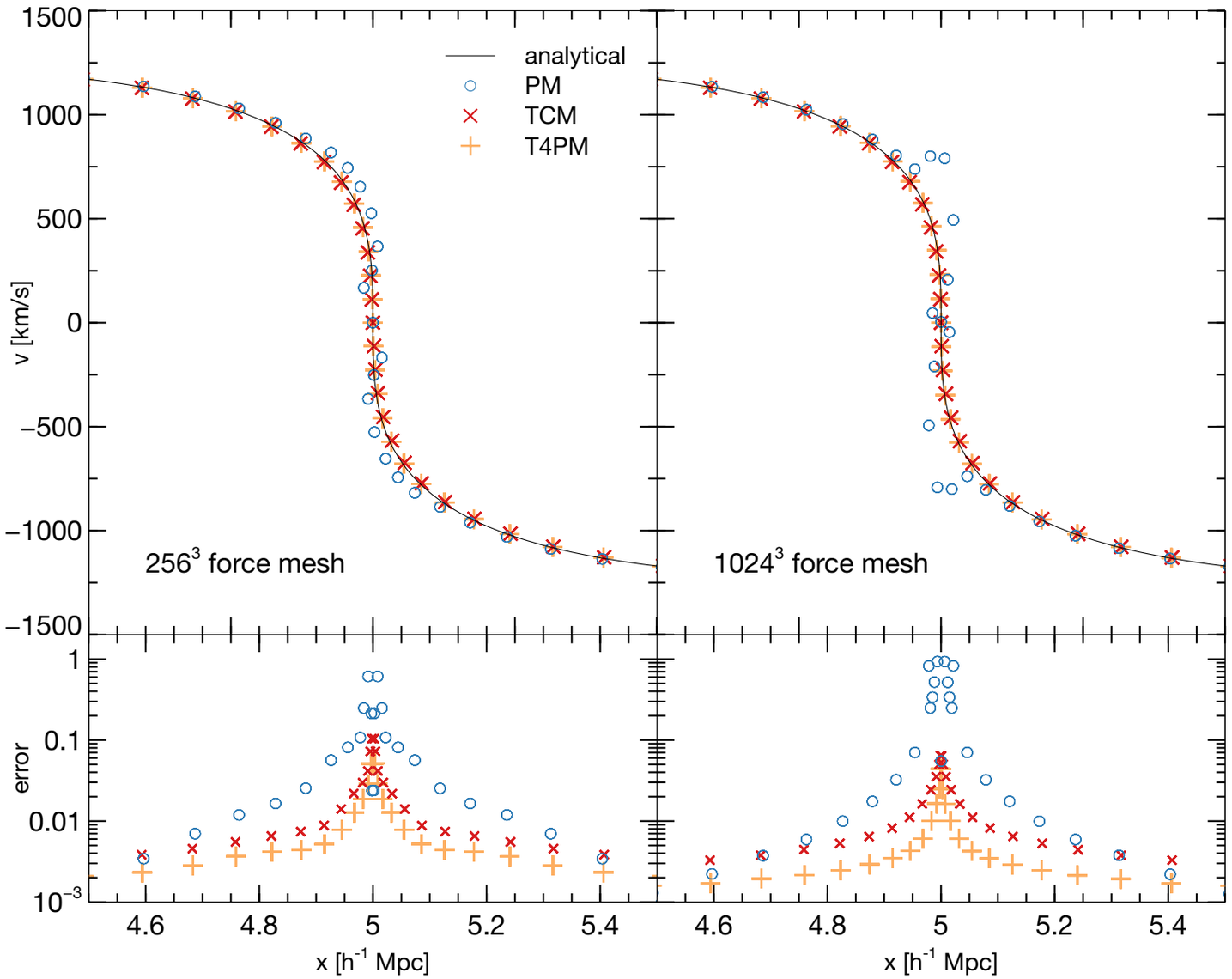
Anisotropic Compression in triaxial collapse



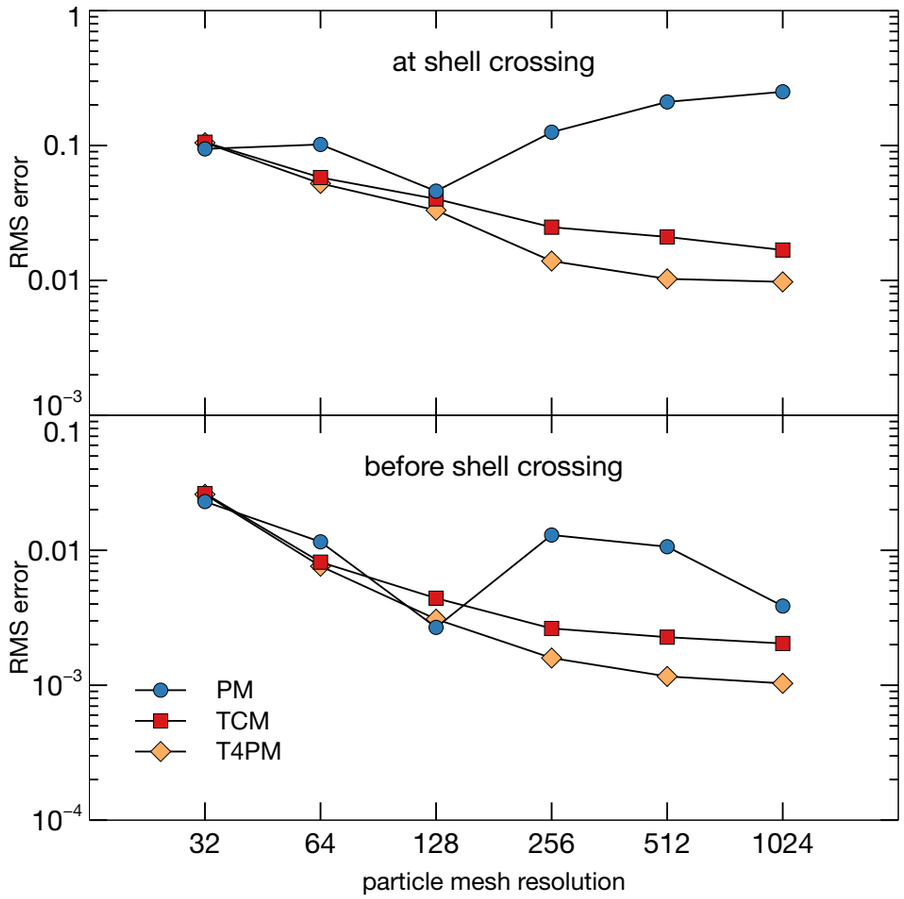
cannot have both -> only linear improvement!
but tets take this into account!

Plane wave collapse I

Plane wave at shell-crossing

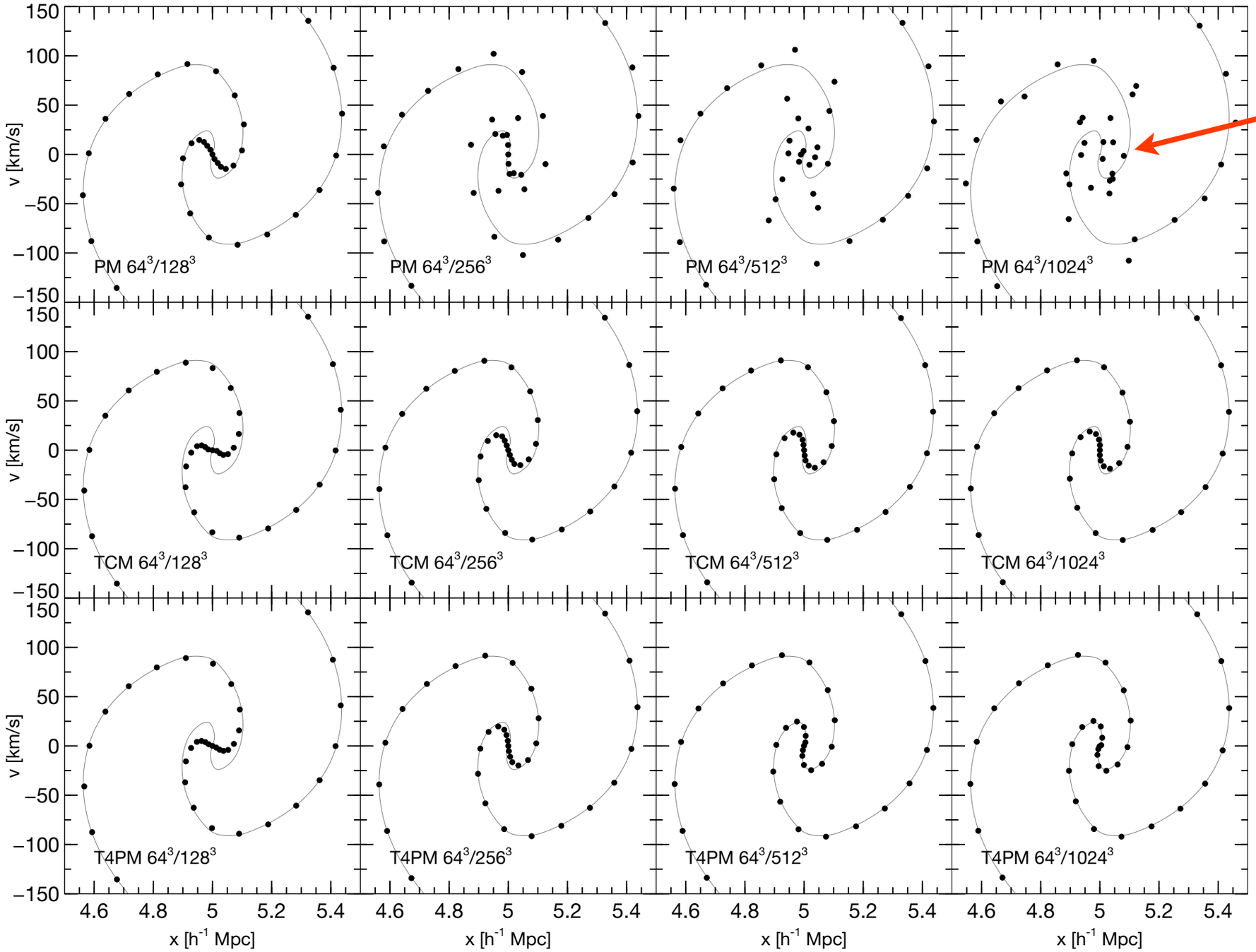


Convergence?



Plane wave collapse II

Plane wave long after first shell-crossing

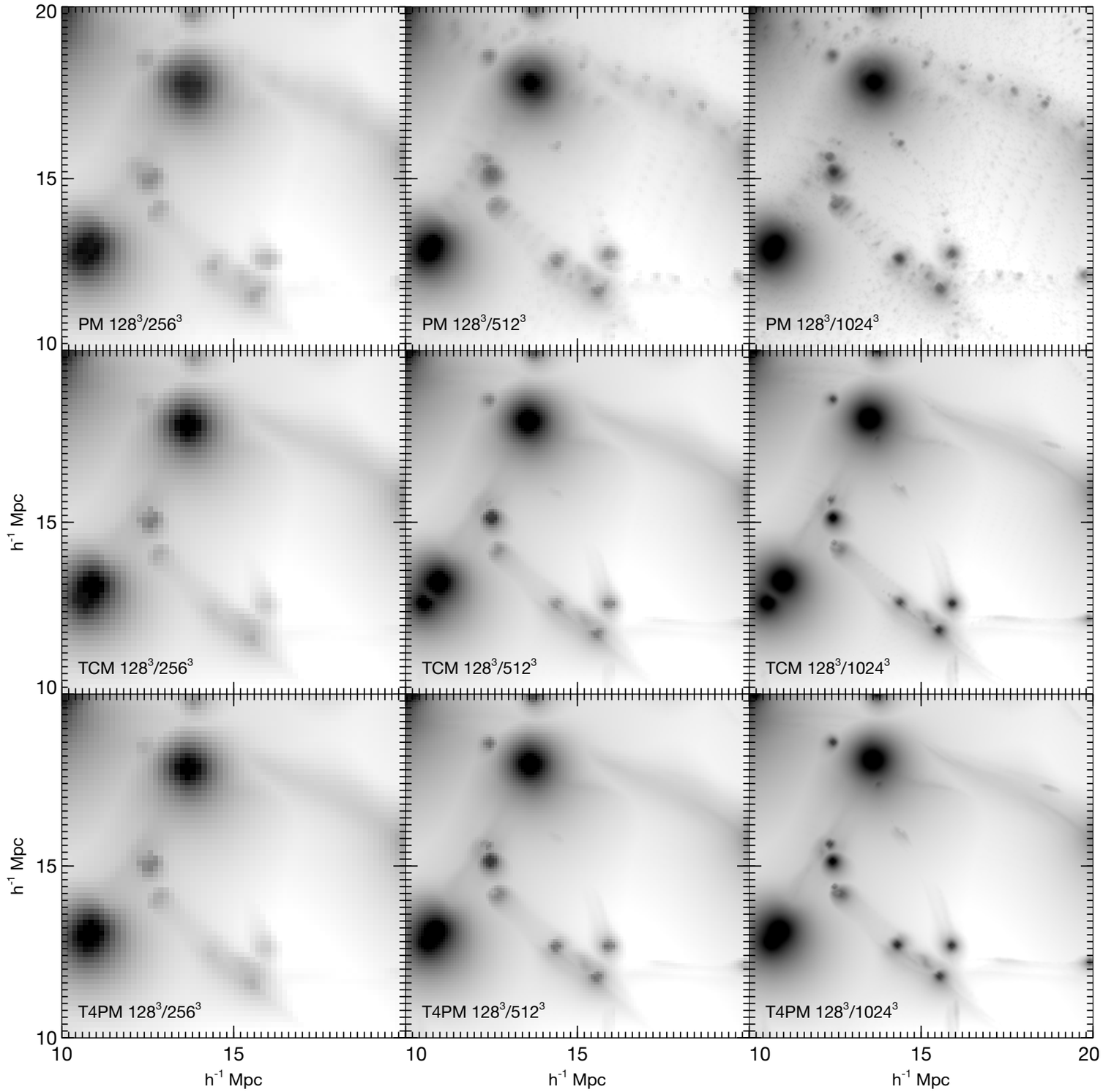


two-body effects

force res ≈ 16x mass res

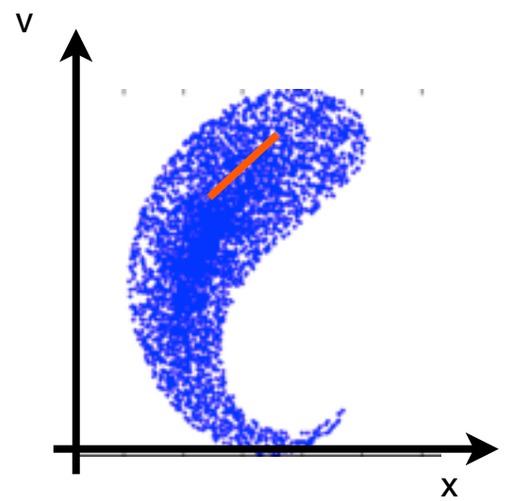
300eV toy problem

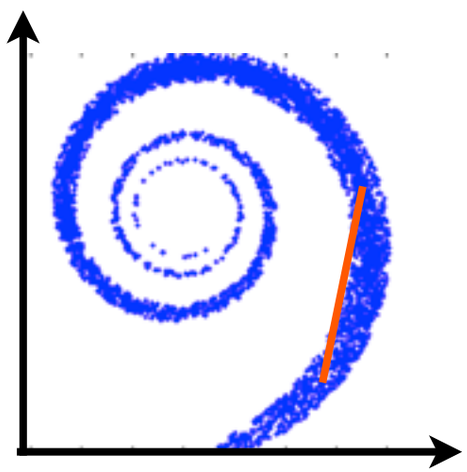
fixed mass, varying force resolution:



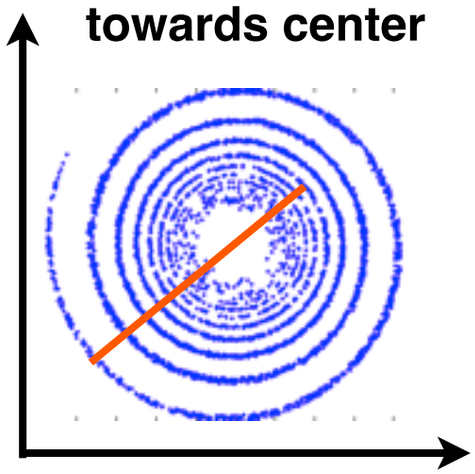
Current Limitations

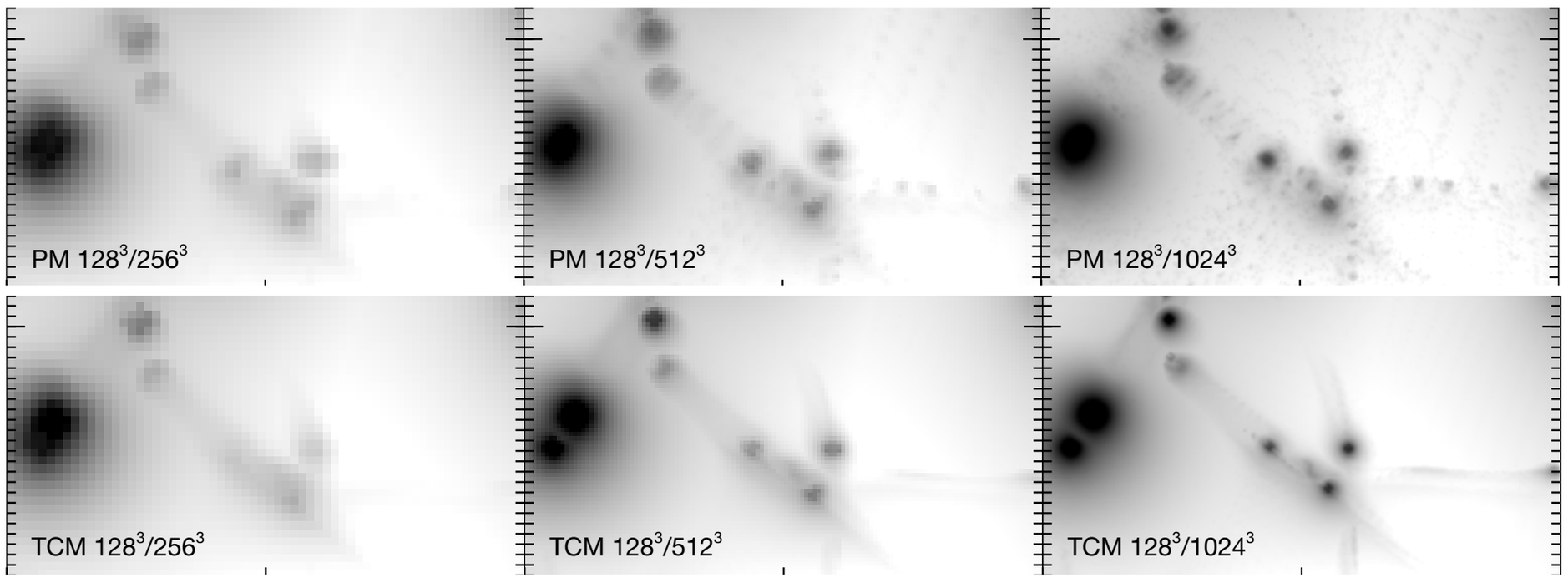
Mixing
need increasingly larger number of elements to trace the sheet surface





otherwise bias density estimate towards center





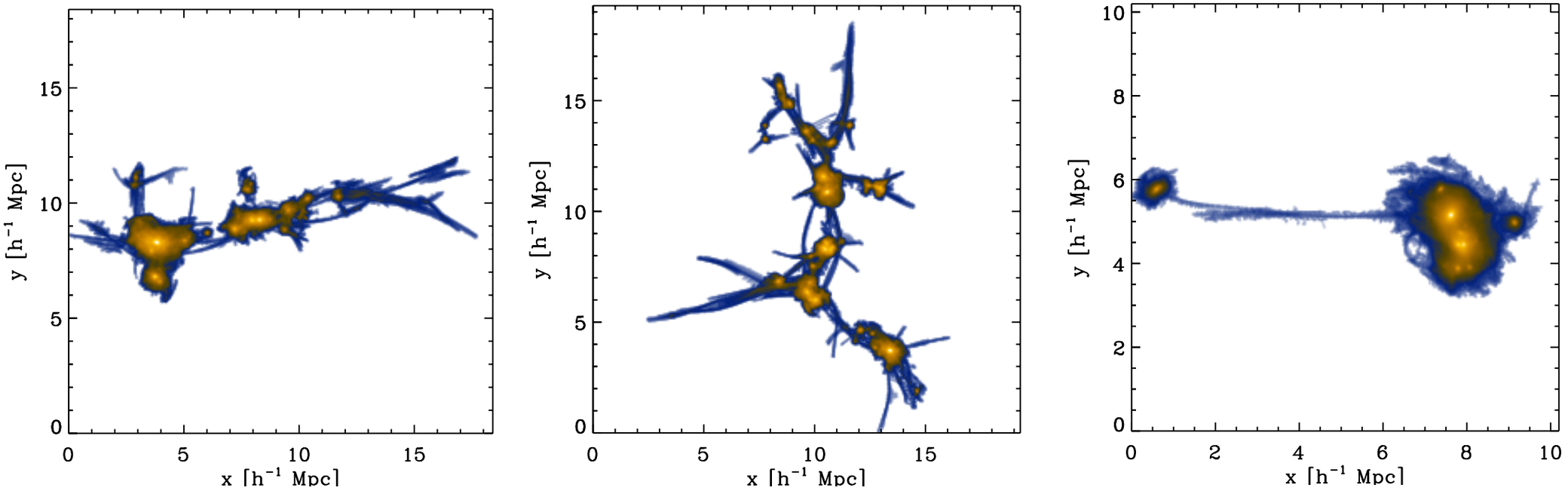
halos too concentrated

Lagrangian motion insufficient to track growth of distribution function

refinement!

No Fragmentation -> Halo finding becomes challenging...

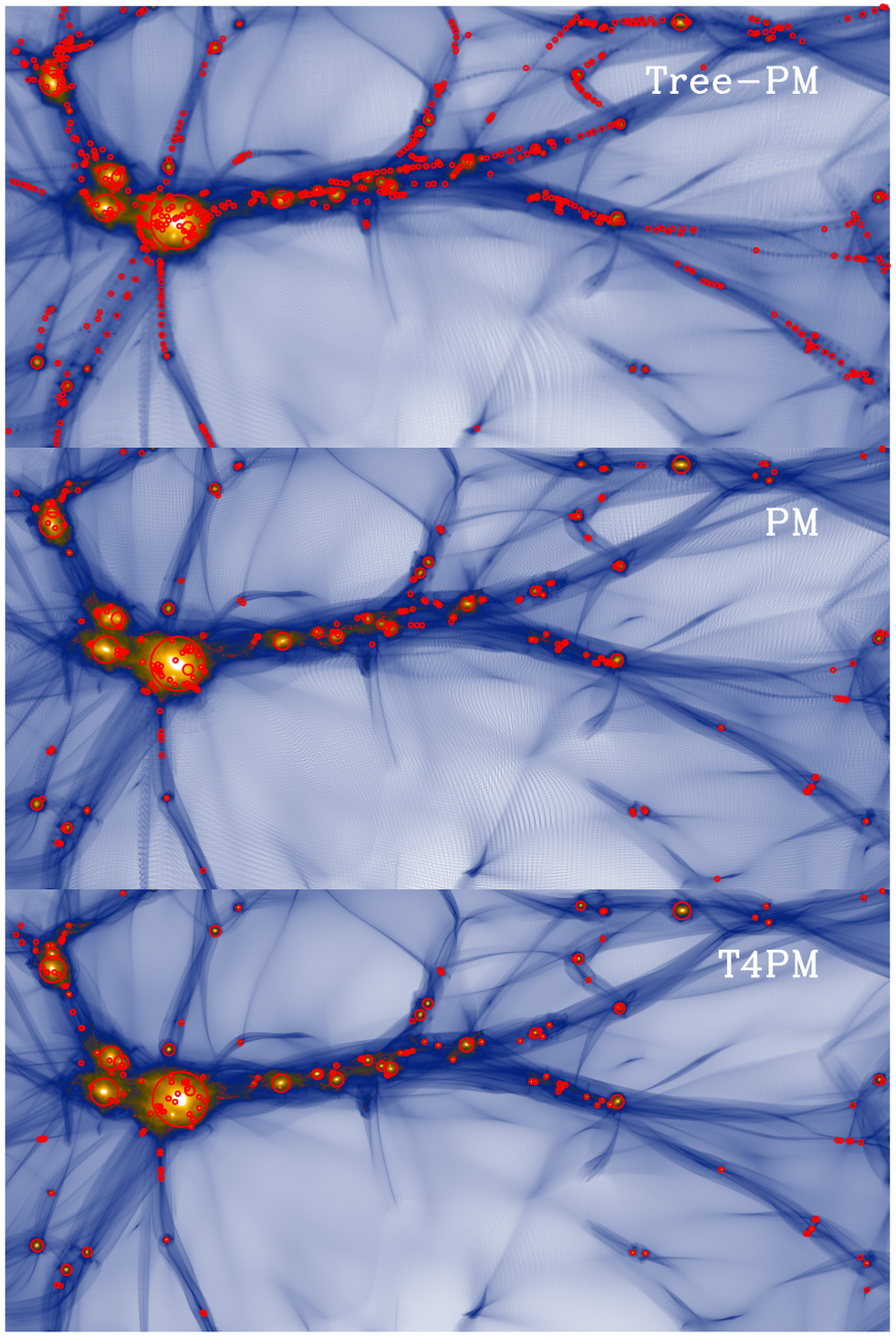
FoF groups start to percolate due to non-fragmenting filaments

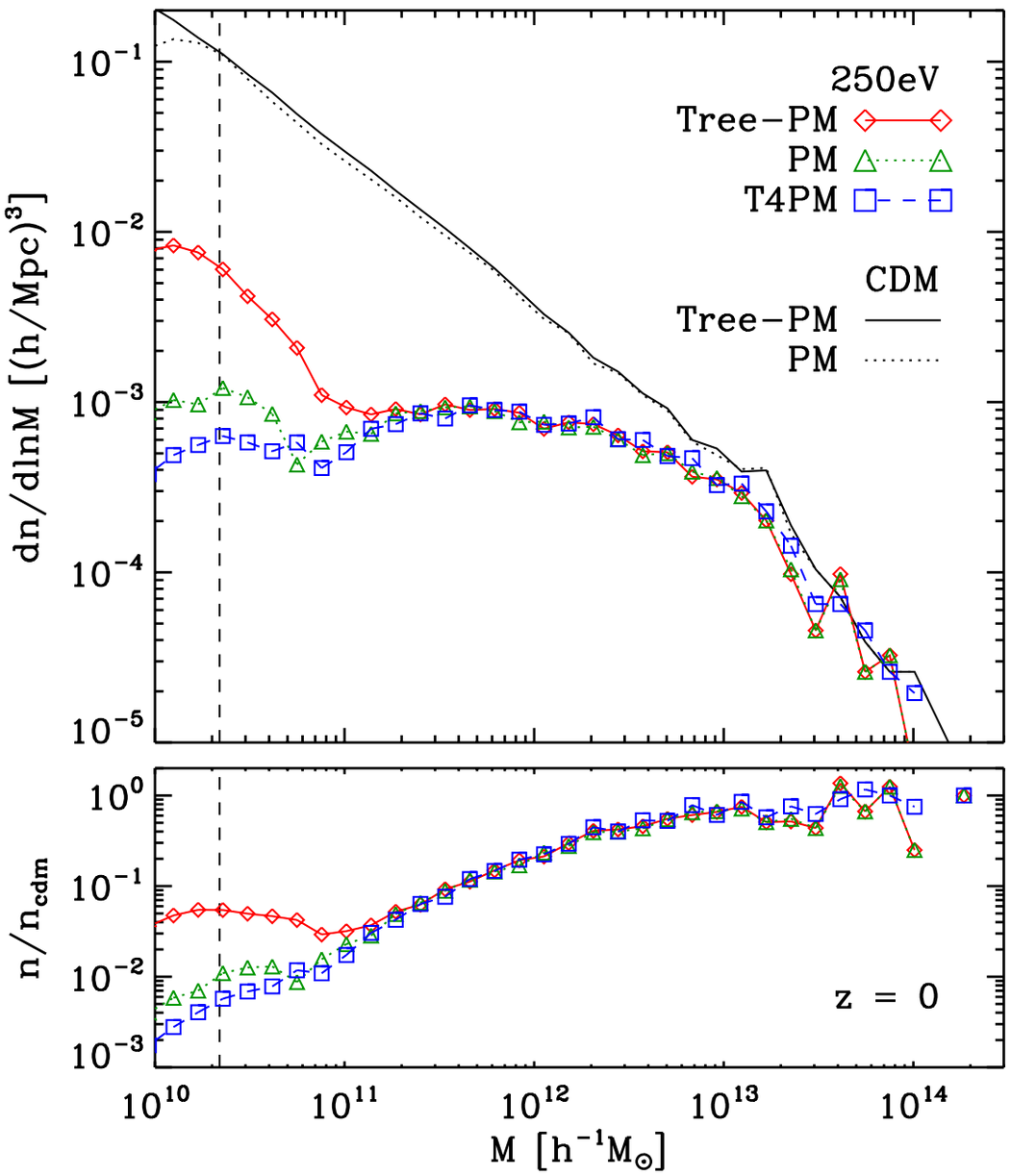


More work has to be one w.r.t. identification of bound structures

Angulo, Hahn & Abel 2013

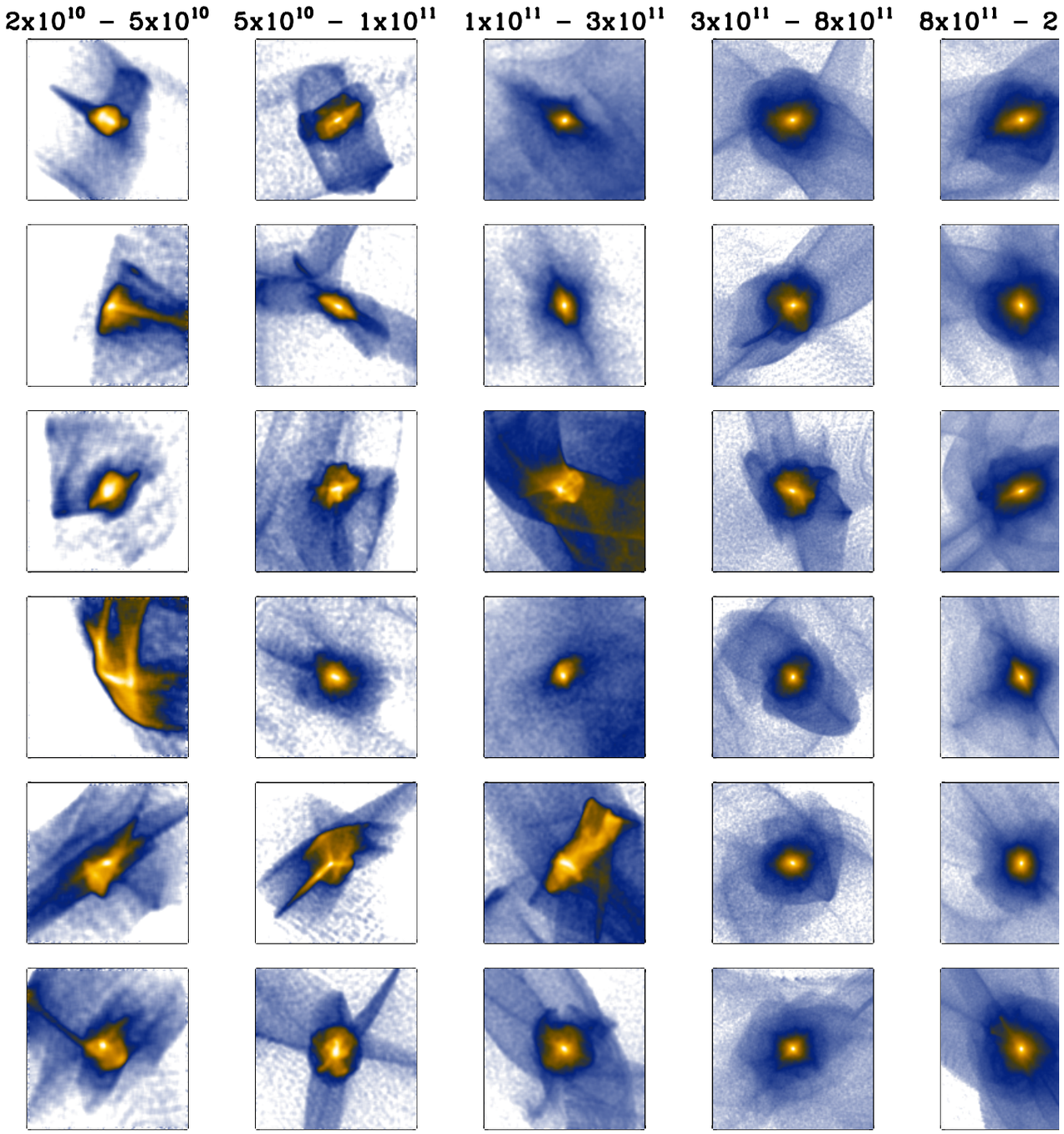
New simulation code based on sheet: Curing WDM fragmentation

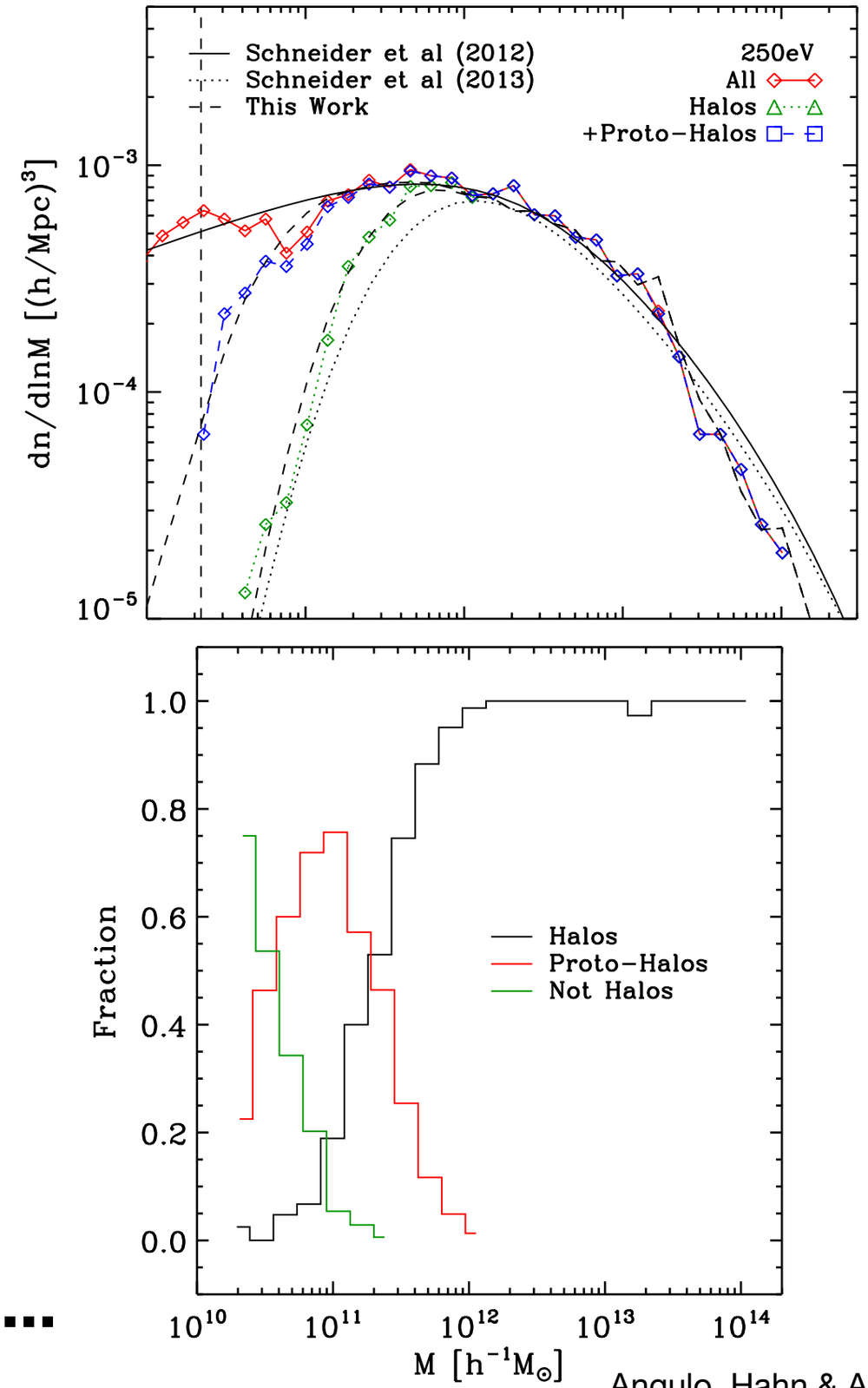




Angulo, Hahn & Abel 2013

WDM structures at different masses...



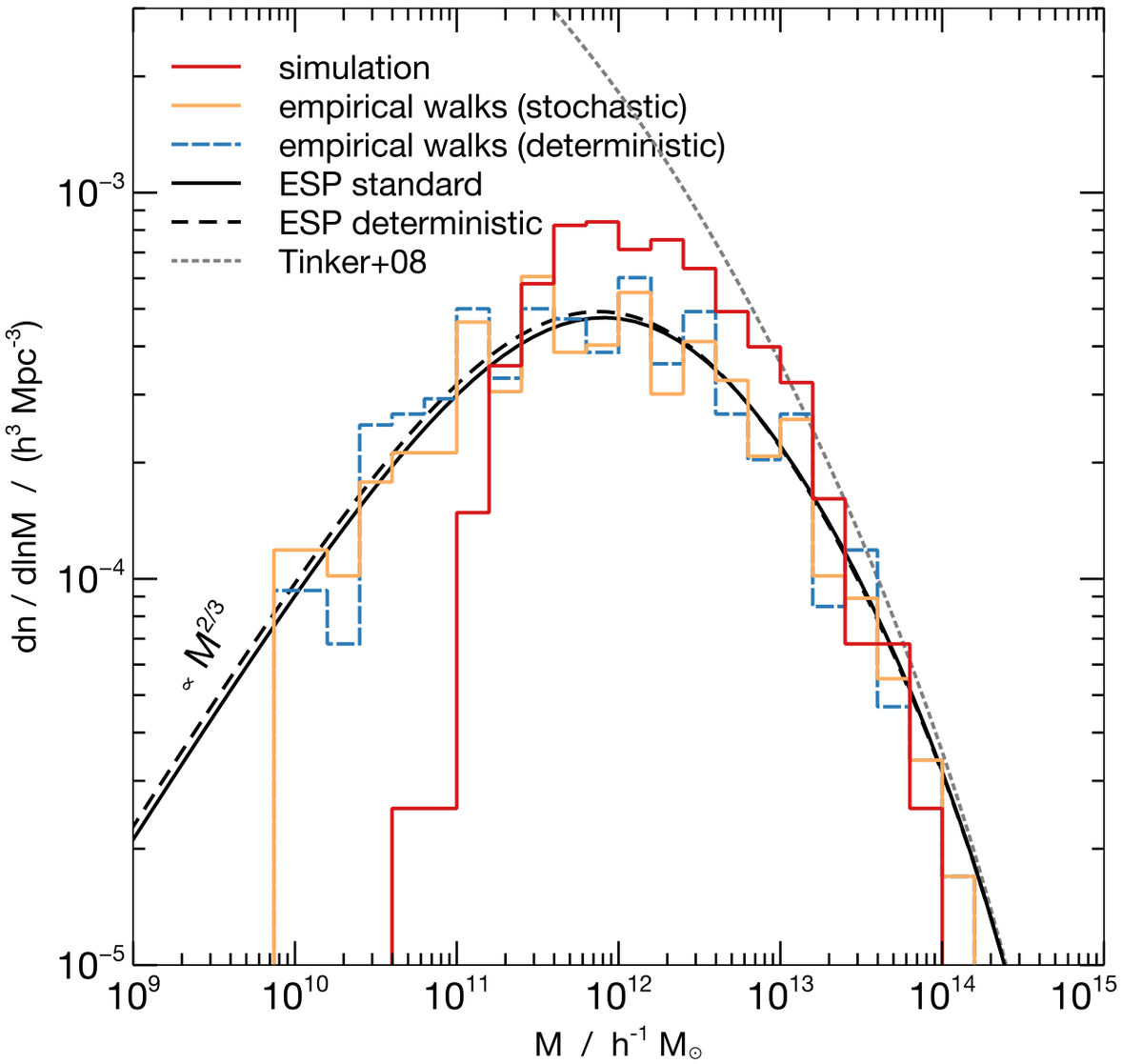


Are at different stages of formation...

Angulo, Hahn & Abel 2013

What's the analytical status?

- Standard EPS with correlated steps completely fails for WDM
- EPS with sharp-k filtering, works, but what does it mean?
- Excursion set peaks is very interesting! sort of works!



Excursion Set Peaks formalism:
Paranjape&Sheth 2012

- Count peaks as function of smoothing scale
- Ensure peak height matches "collapse barrier" (use approximate ellipsoidal dynamics)
- Ensure "first crossing"; i.e., (approximately) solve cloud-in-cloud problem

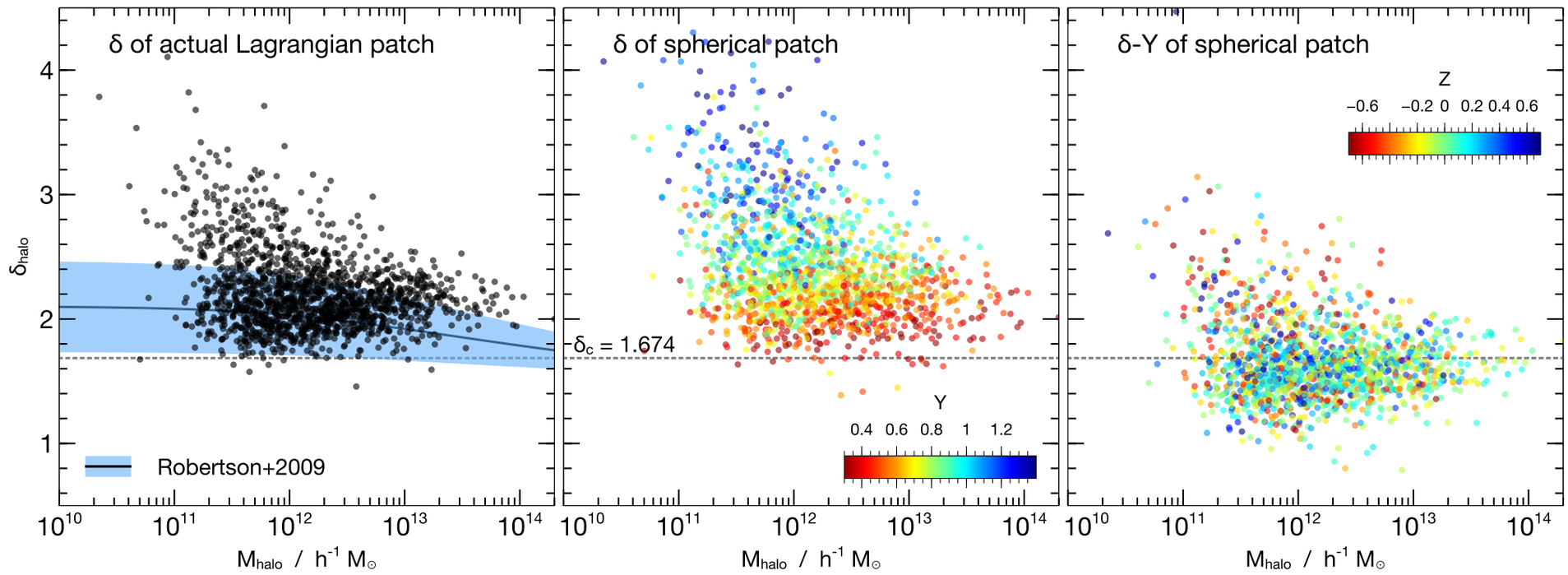
Produces turn-over!

Robustly predicts power-law at small masses

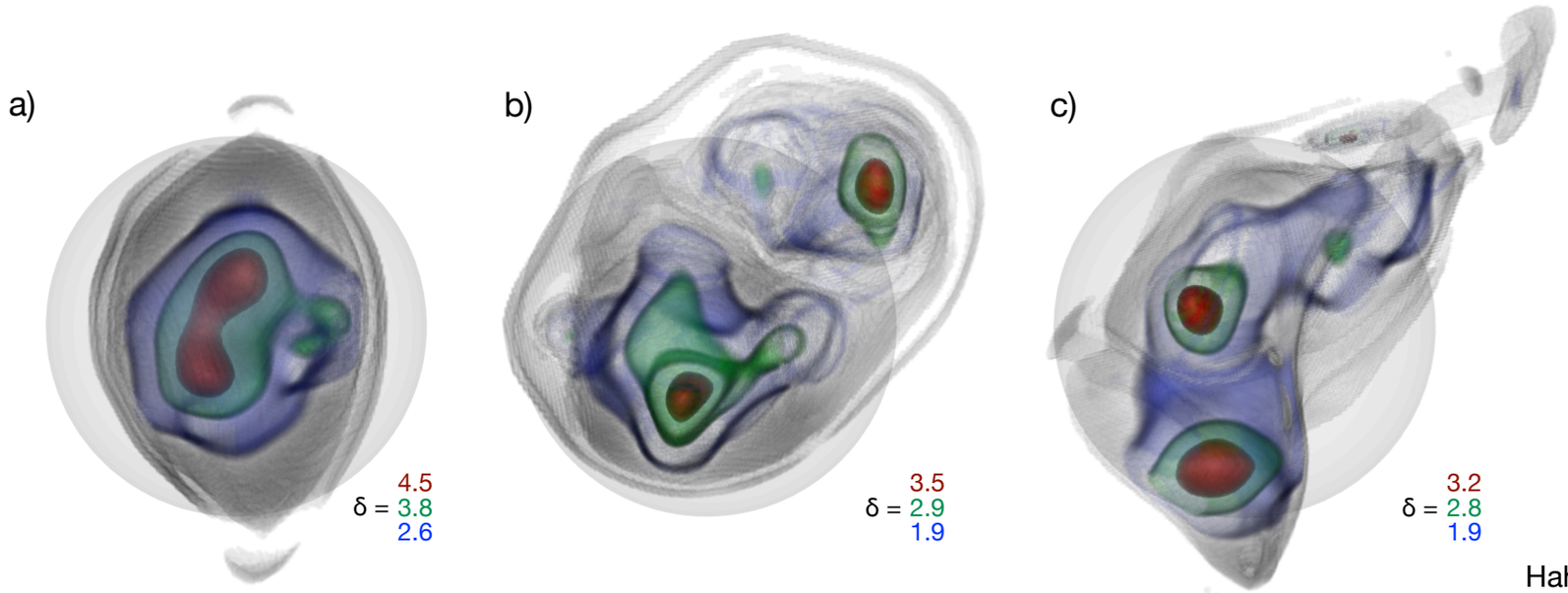
Hahn & Paranjape 2013 (in prep)

Do WDM haloes form differently?

We find that simpler barrier works as good as Sheth, Mo & Tormen (2001) here

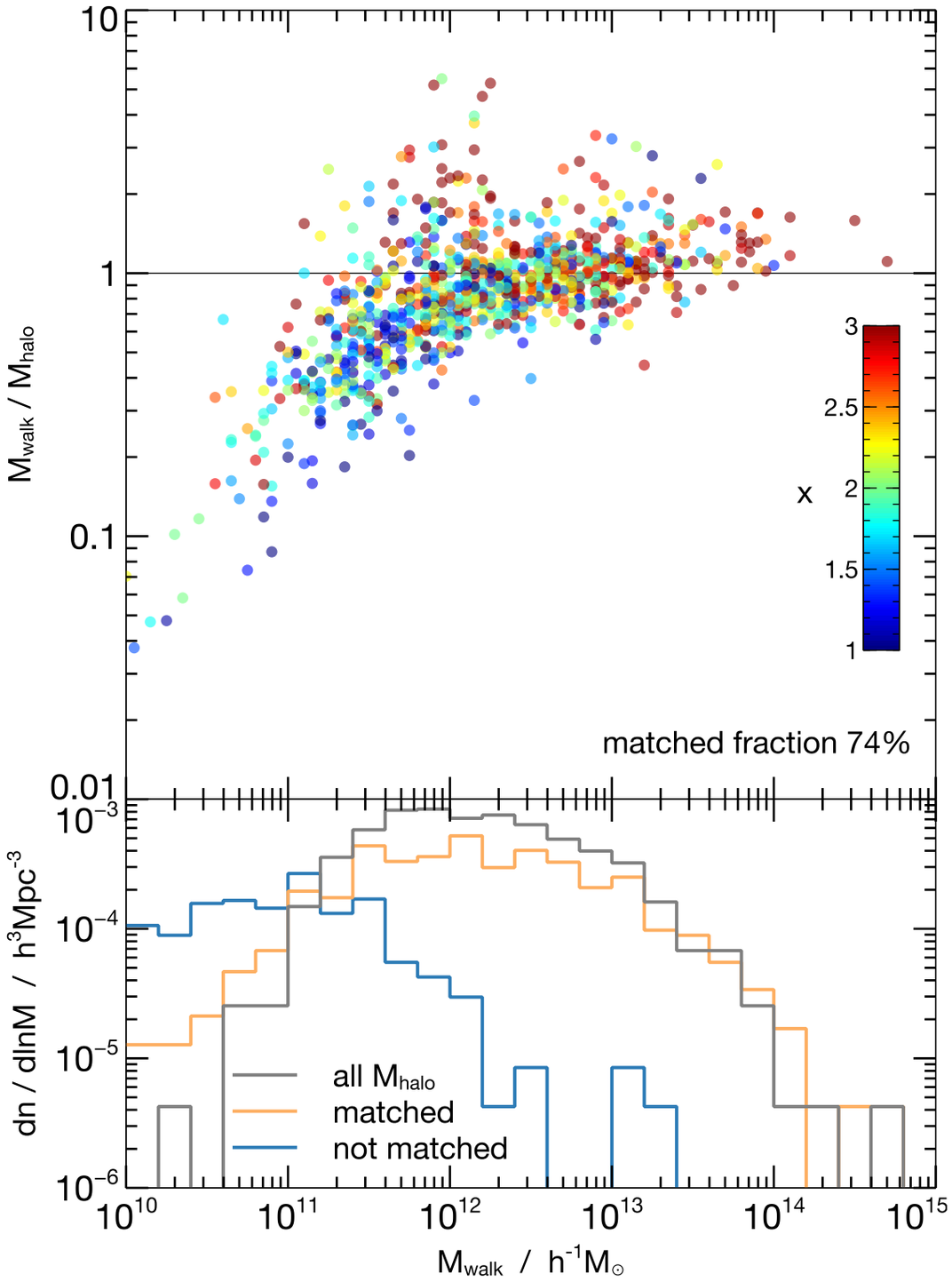


Proto-haloes consistent with peaks, not more complicated catastrophes, e.g.



Hahn & Paranjape 2013 (in prep)

What's going wrong?

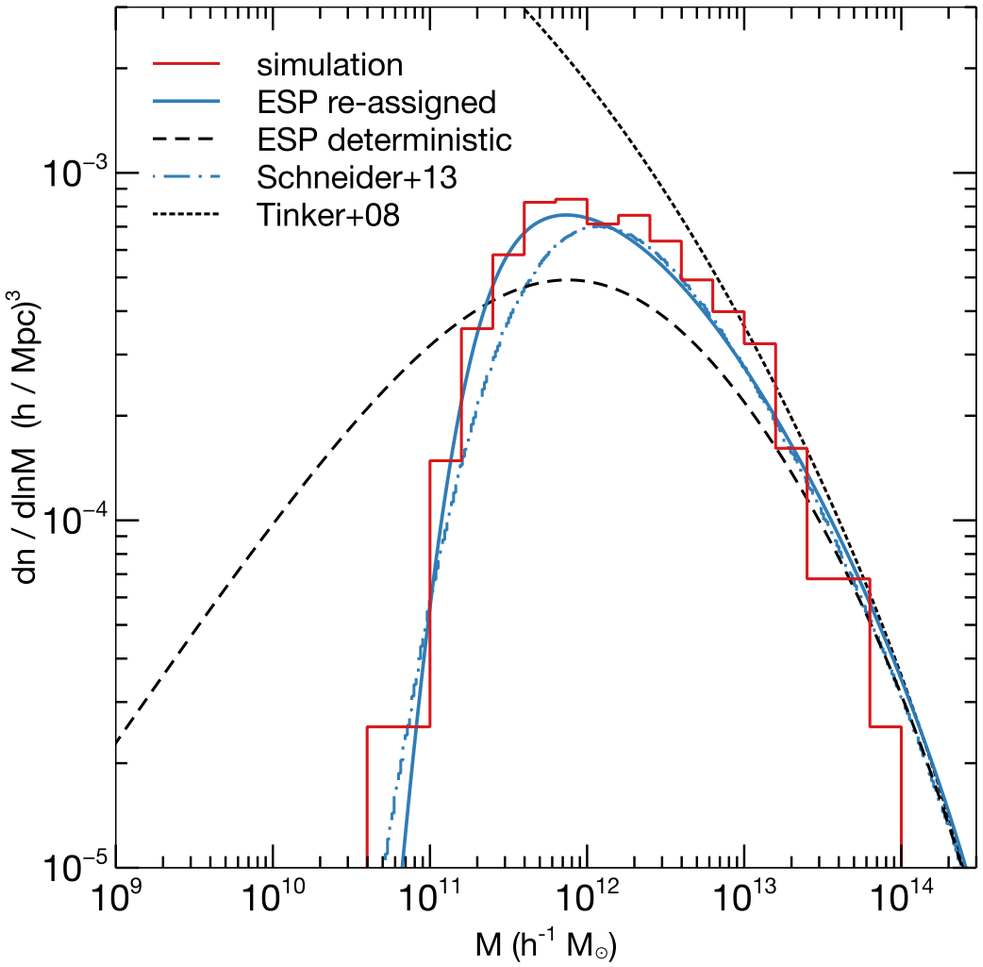


Hahn & Paranjape 2013 (in prep)

All proto-halo locations consistent with peaks, but

- mass bias in matched objects
- not matched objects are all low mass
- mismatch correlates with peak curvature.

Do we get collapse time wrong? Can fix:



but maybe also assembly-bias like effects

Formation of a WDM halo

Summary

- Dark Matter (in cold limit) occupies 3D sheet in 6D phase space
- Can build new kind of collisionless fluid solver with much reduced fragmentation/collisionality
- Currently of limited usability due to fast growth of distribution function due to mixing, but allowed new insights:

WDM structure formation without fragments

- First ‘direct’ measurement of mass function below cut-off in WDM
- Tricky for halo finding - not every dense structure is virialised
- Tricky for analytical predictions - hard to predict final mass