Small scale structure in DM

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ICC
Institute for
Computational Cosmology

VIRGO

Overview

- CDM - N-body methods, halo and sub halo mass functions - structure of haloes - annihilation predictions - mass-conc relation - velocity distributions - fine phase-space structure
- WDM - differences from CDM
- Future directions

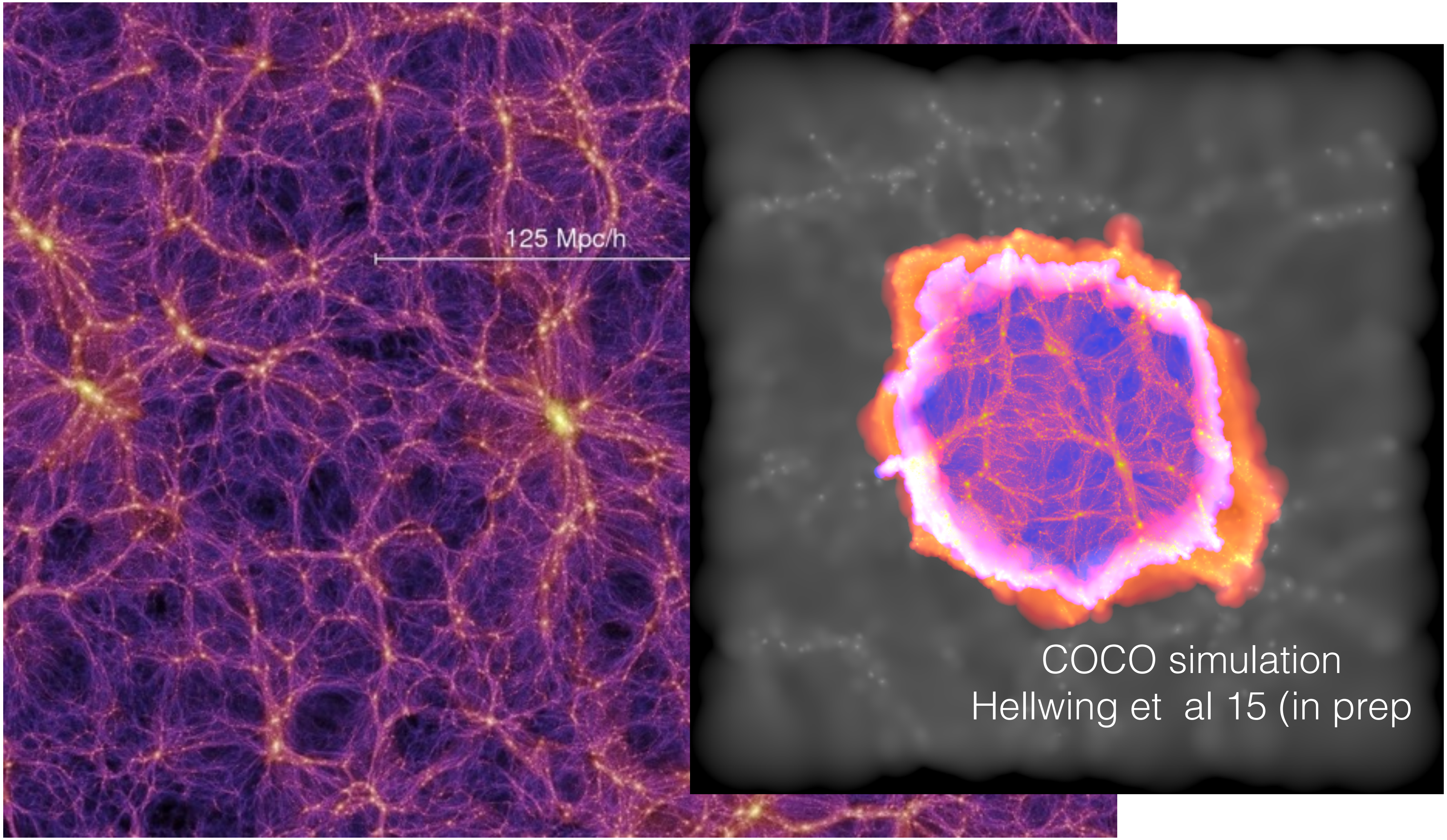
N-body methods

- Simulations of cosmological volumes - >30 years

- Huge increases in the volume surveyed, relatively modest improvements in resolution. State-of-the-art simulations ~ 1 trillion particles.

- Resimulation or zoom simulations ~20 years. Large improvements in numerical resolution. State-of-the-art calculations ~ 5-15 billion particles

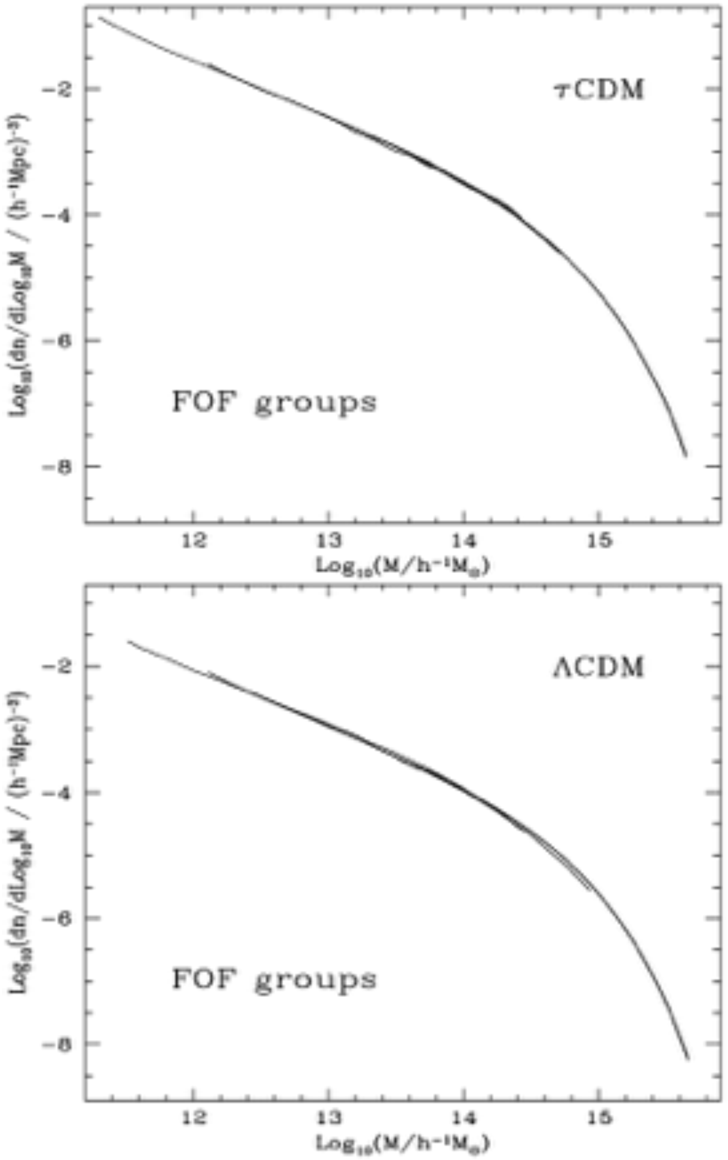
Halo mass functions



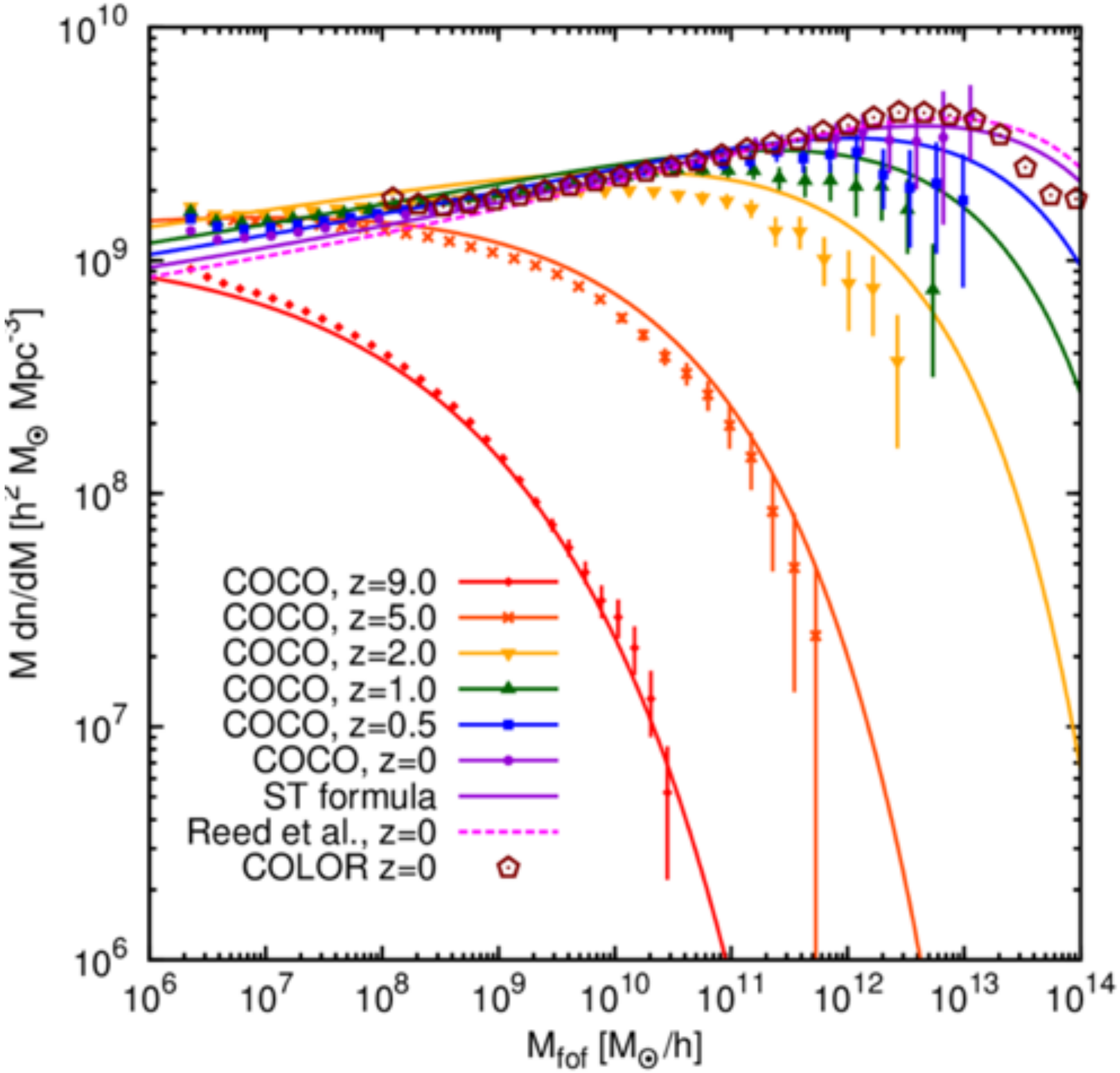
COCO simulation
Hellwing et al 15 (in prep

The halo mass function

Jenkins et al 2001

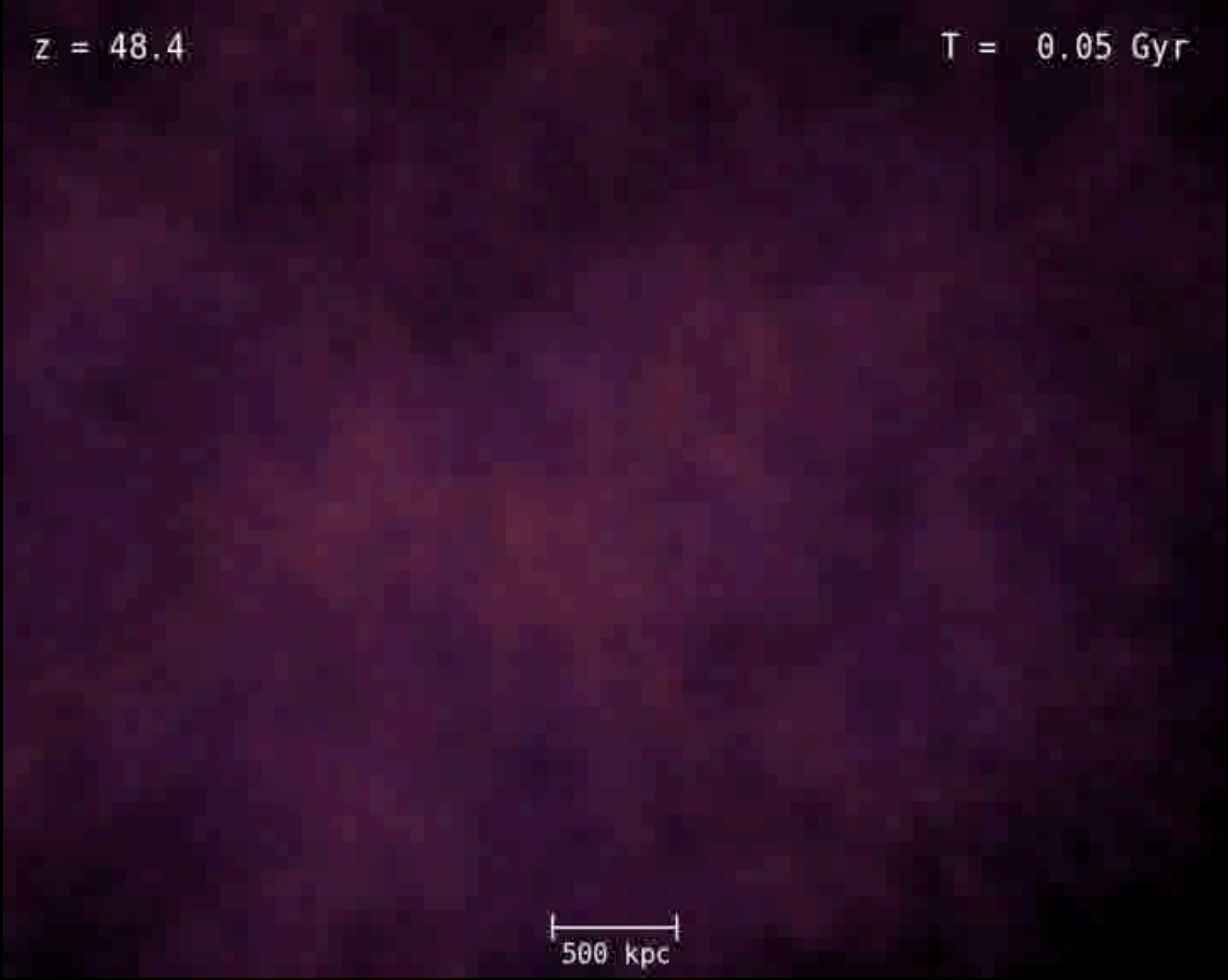


Hellwing et al 2015 (in prep)

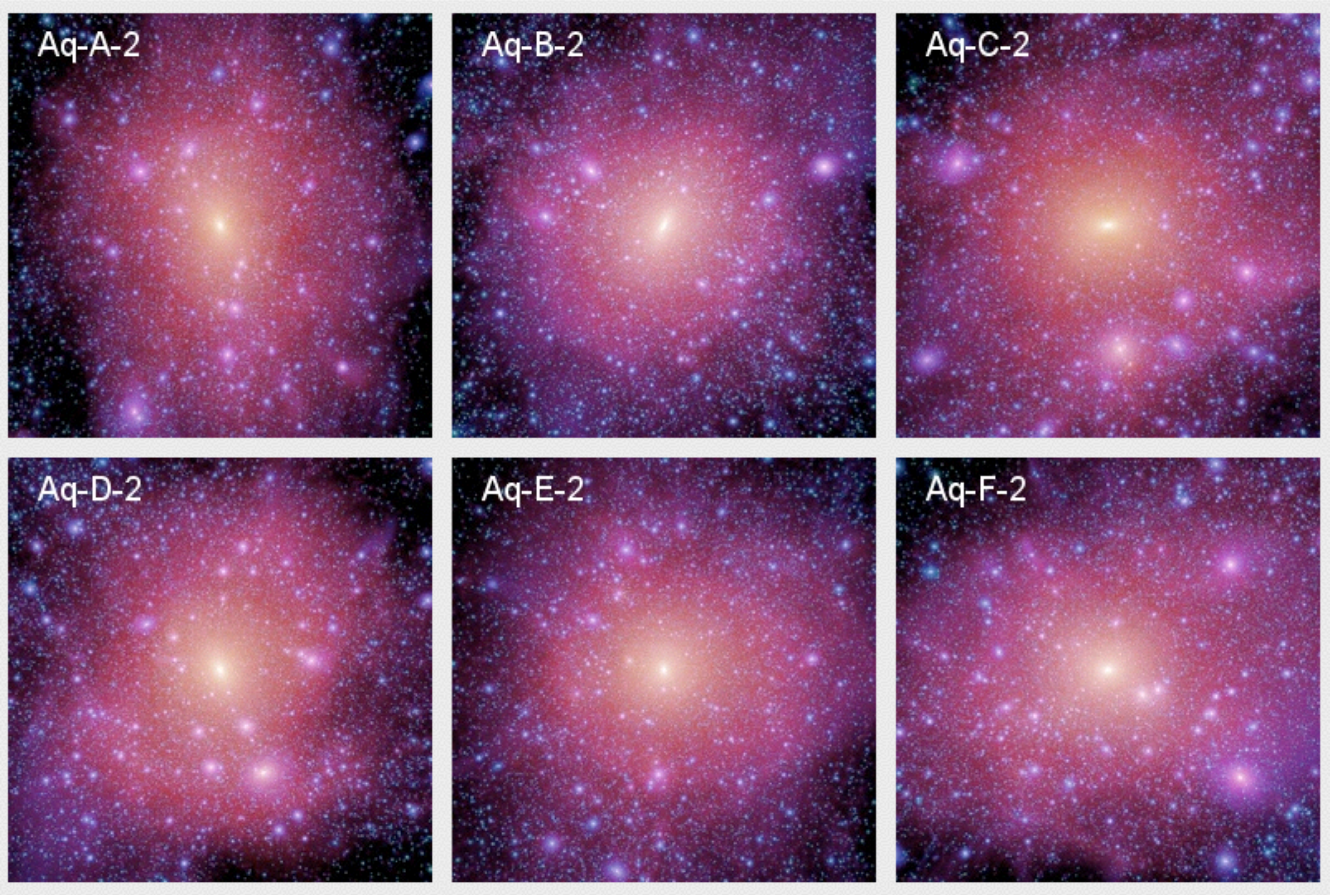


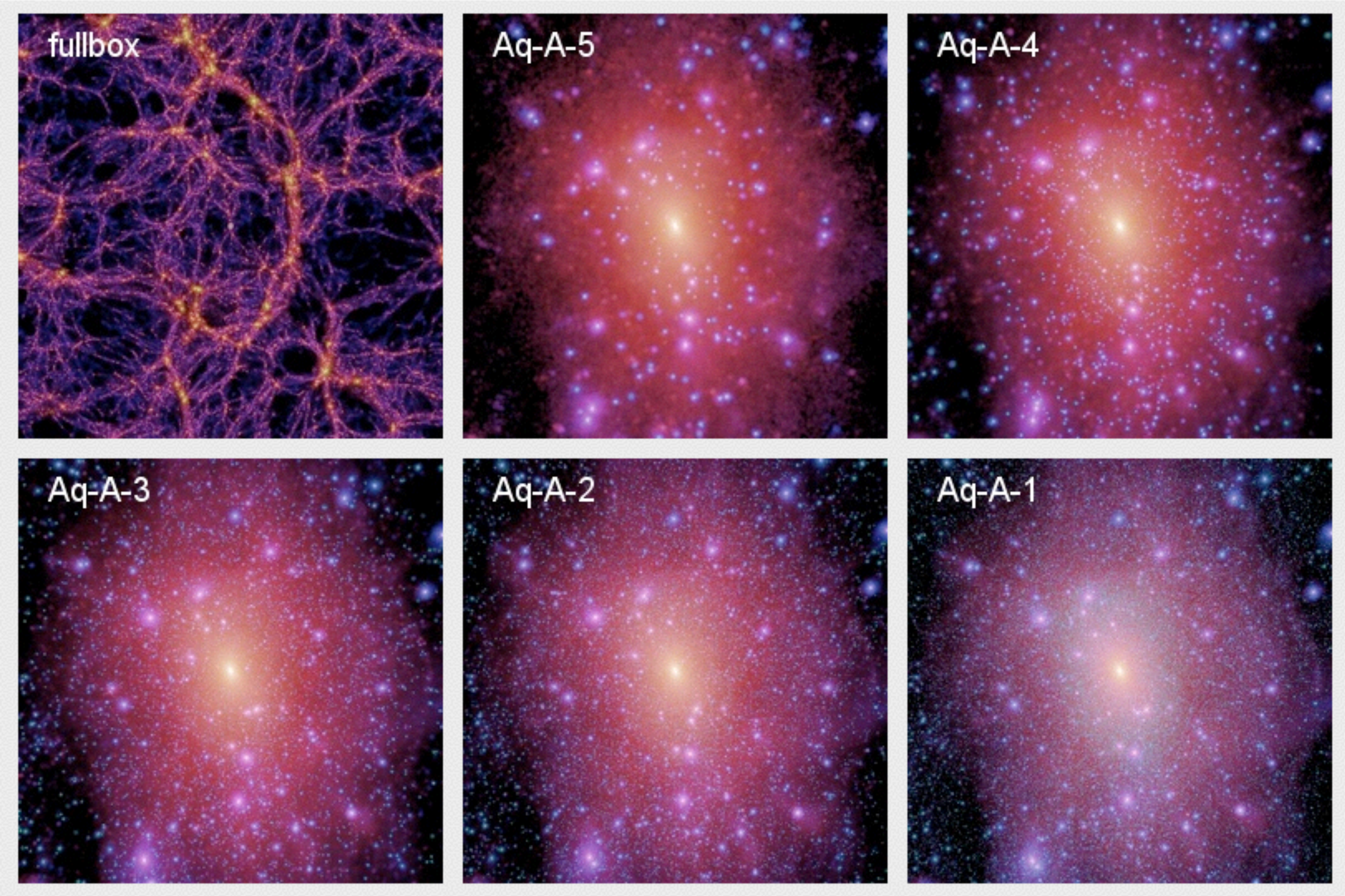
Internal halo structure

- Determined from N-body simulations of individual haloes
- e.g. Aquarius simulations - 6 `MW-mass’ haloes - Aq-A-1 with a billion particles within r200 (Springel et al 2008), GHALO (Stadel et al 2009) also billion+ particles
- Phoenix clusters haloes (9), Ph-A-1 with a billion particles within r200

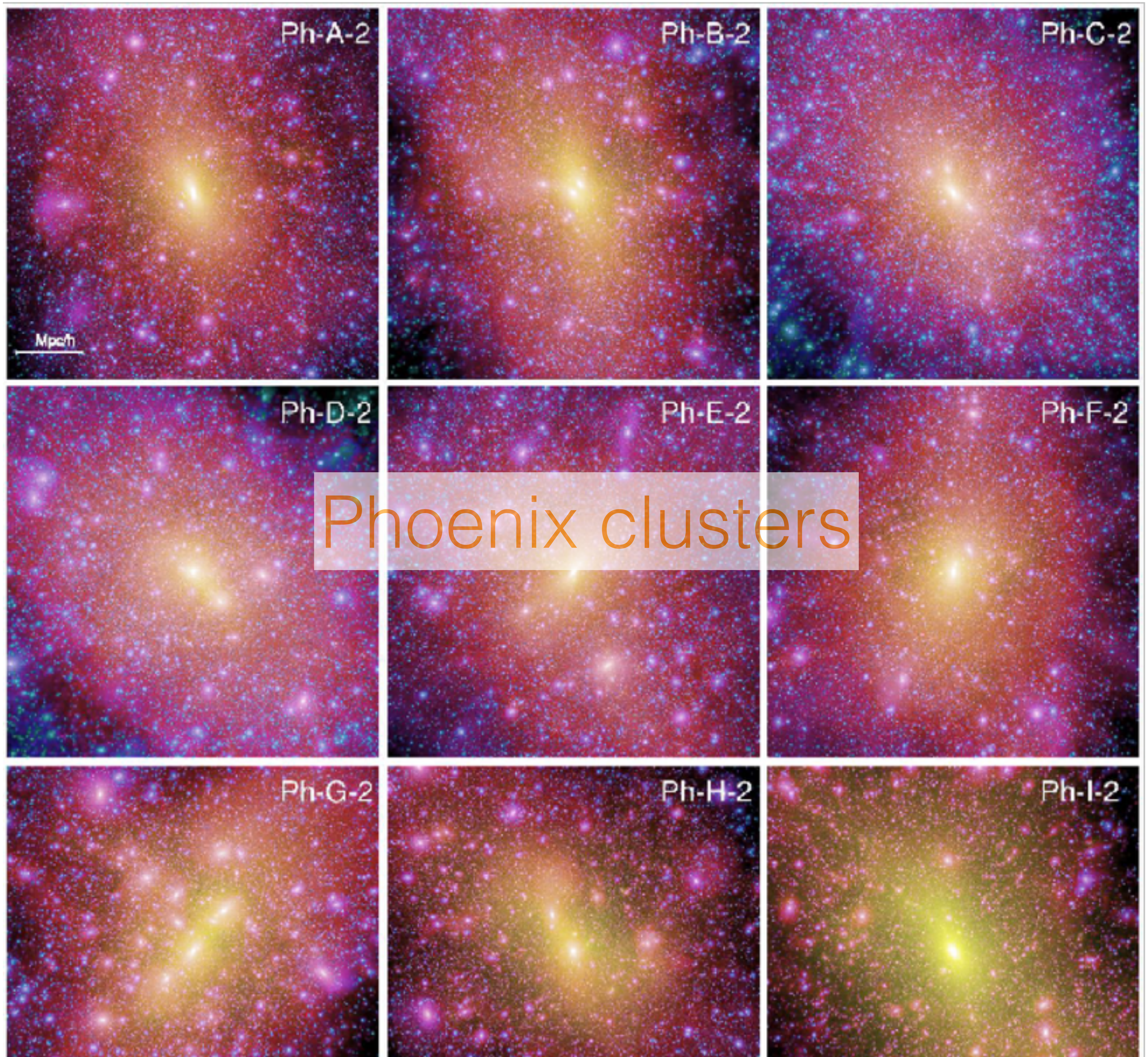

z = 48.4
T = 0.05 Gyr
500 kpc

The six aquarius halos.



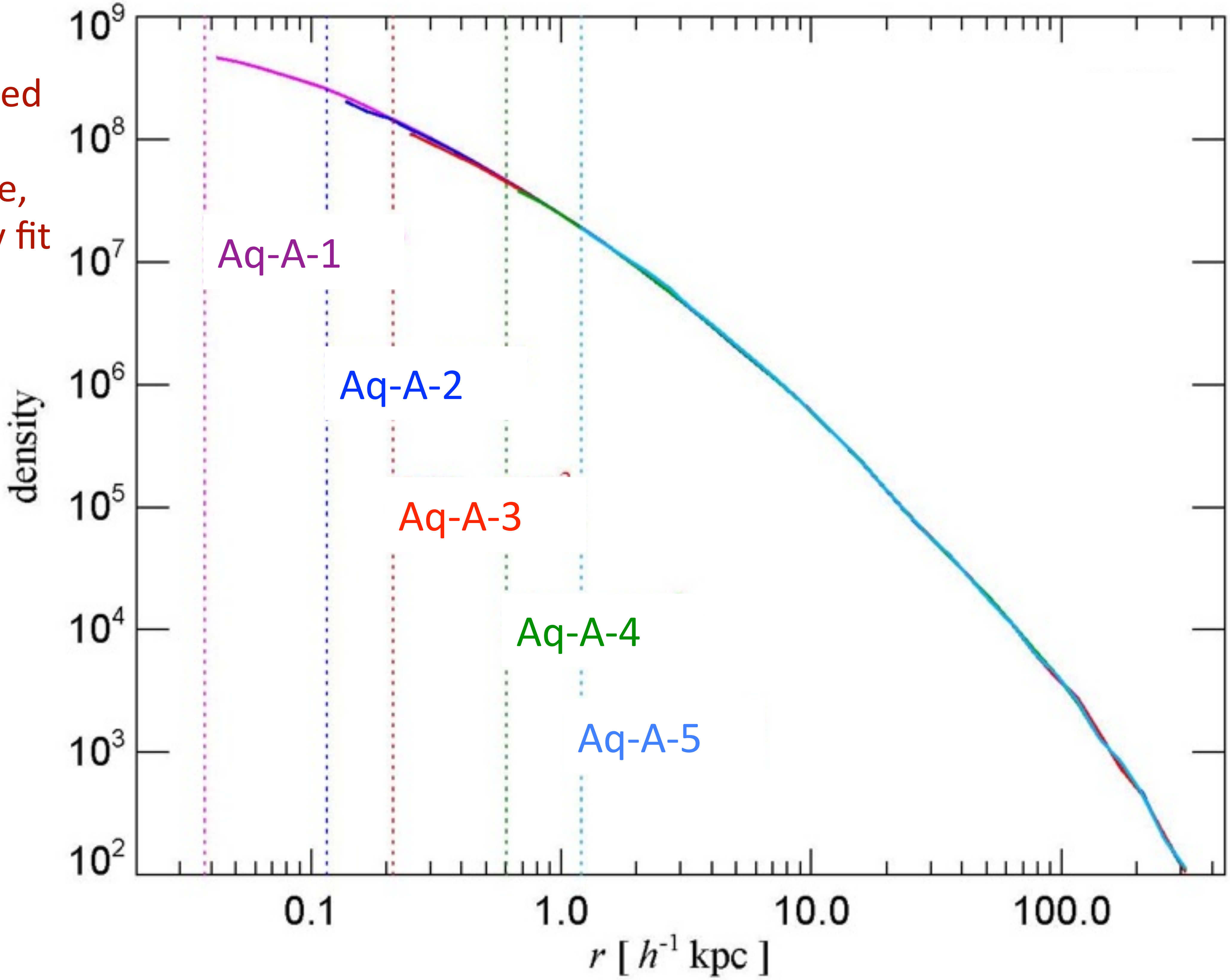

fullbox
Aq-A-5
Aq-A-4
Aq-A-3
Aq-A-2
Aq-A-1

Phoenix clusters



Density profile ρ(r): convergence test

The spherically averaged density profiles show very good convergence, and are approximately fit by a NFW profile

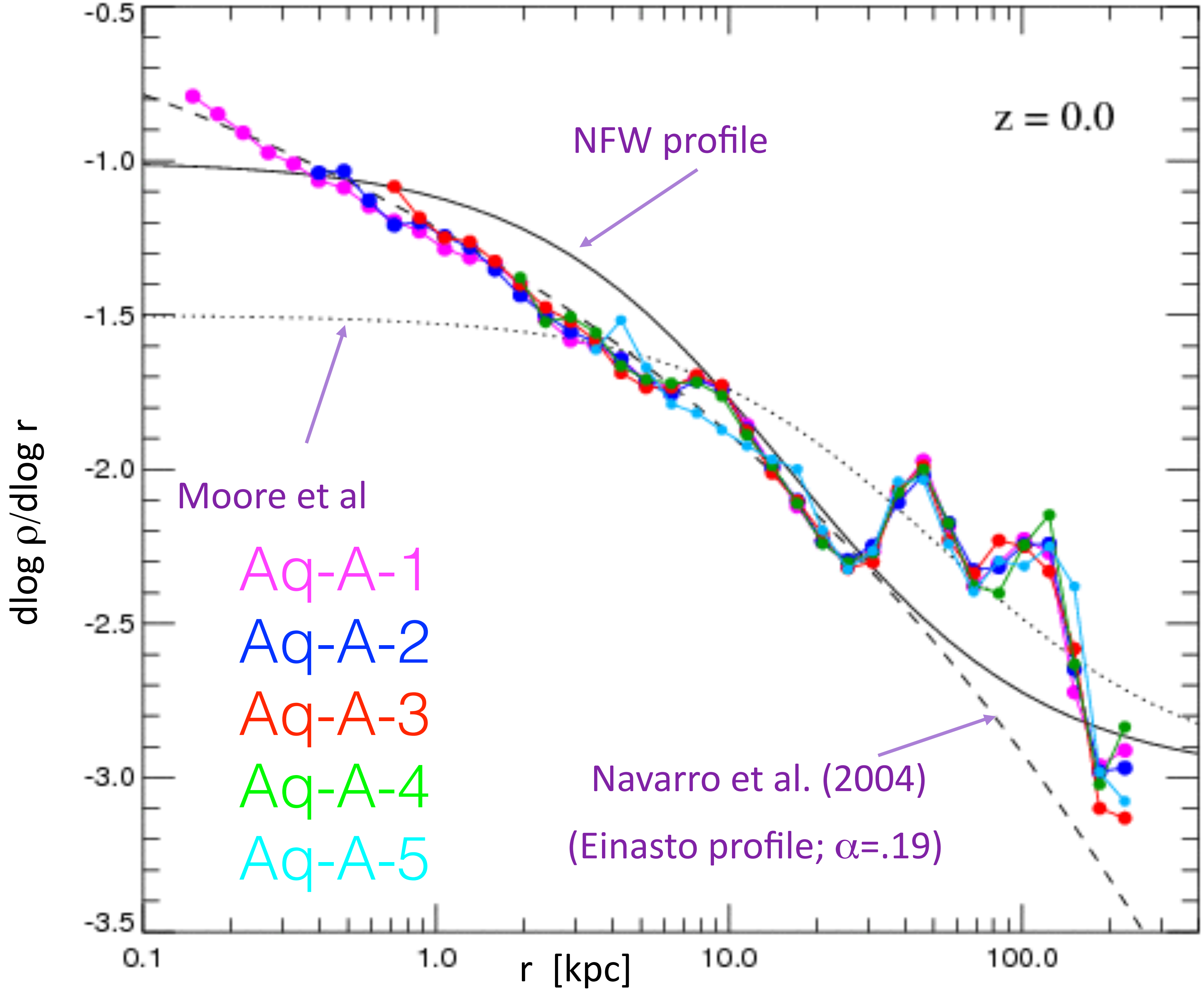


Slope of the density profile

Density profile becomes shallower towards the centre

No obvious convergence to a power law profile
Innermost slope is shallower than -1

LOGARITHMIC SLOPE OF DENSITY PROFILE AS FN OF RADIUS



NFW profile

Moore et al

Navarro et al. (2004)

(Einasto profile; α=.19)

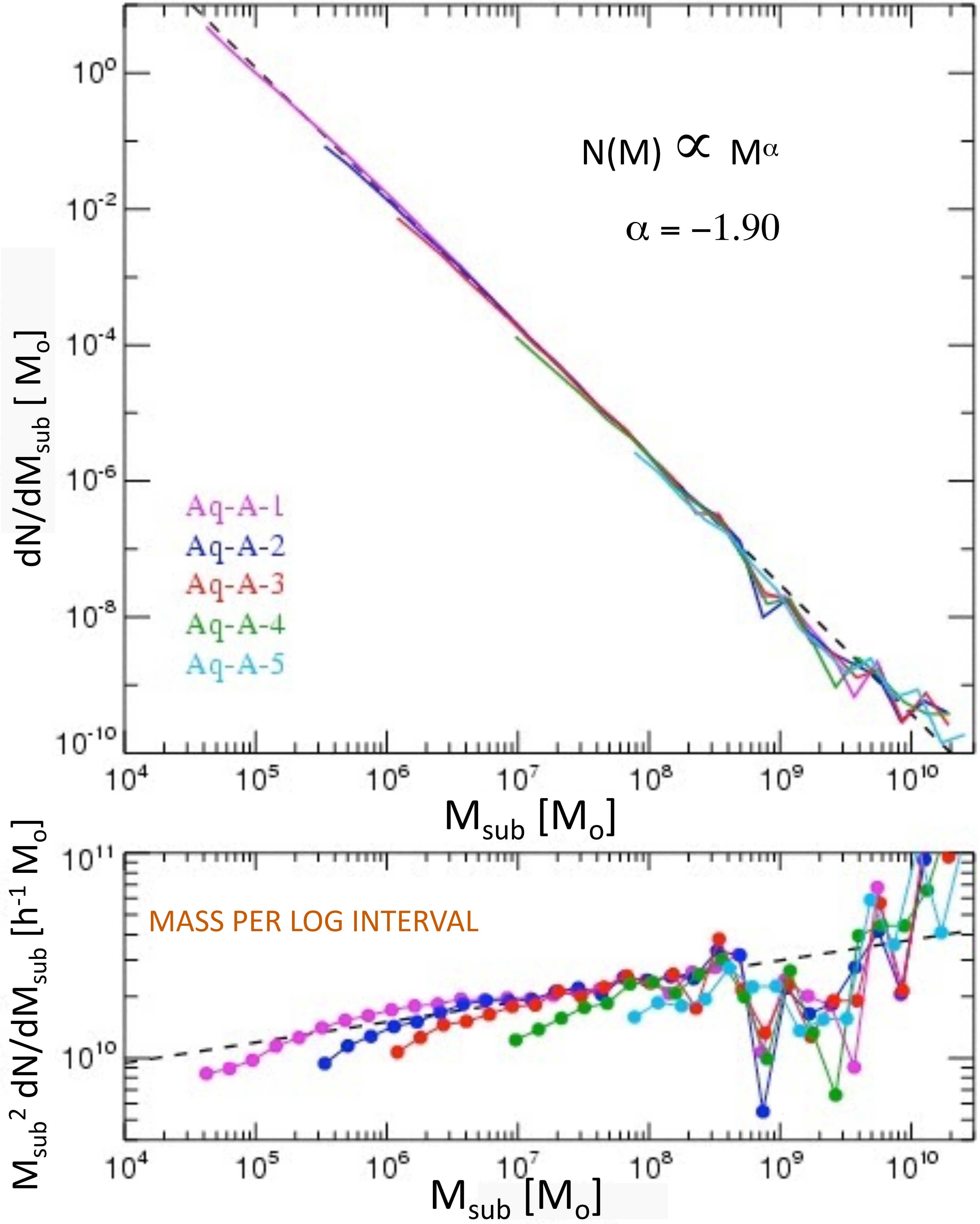
Virgo Consortium 08

The mass function of substructures

The subhalo mass function is shallower than $1/M^2$

Most of the substructure mass is in the most massive subhalos - slope is close to the critical value where each decade of subhalo mass contains the same amount of mass.

Virgo consortium
Springel et al 08

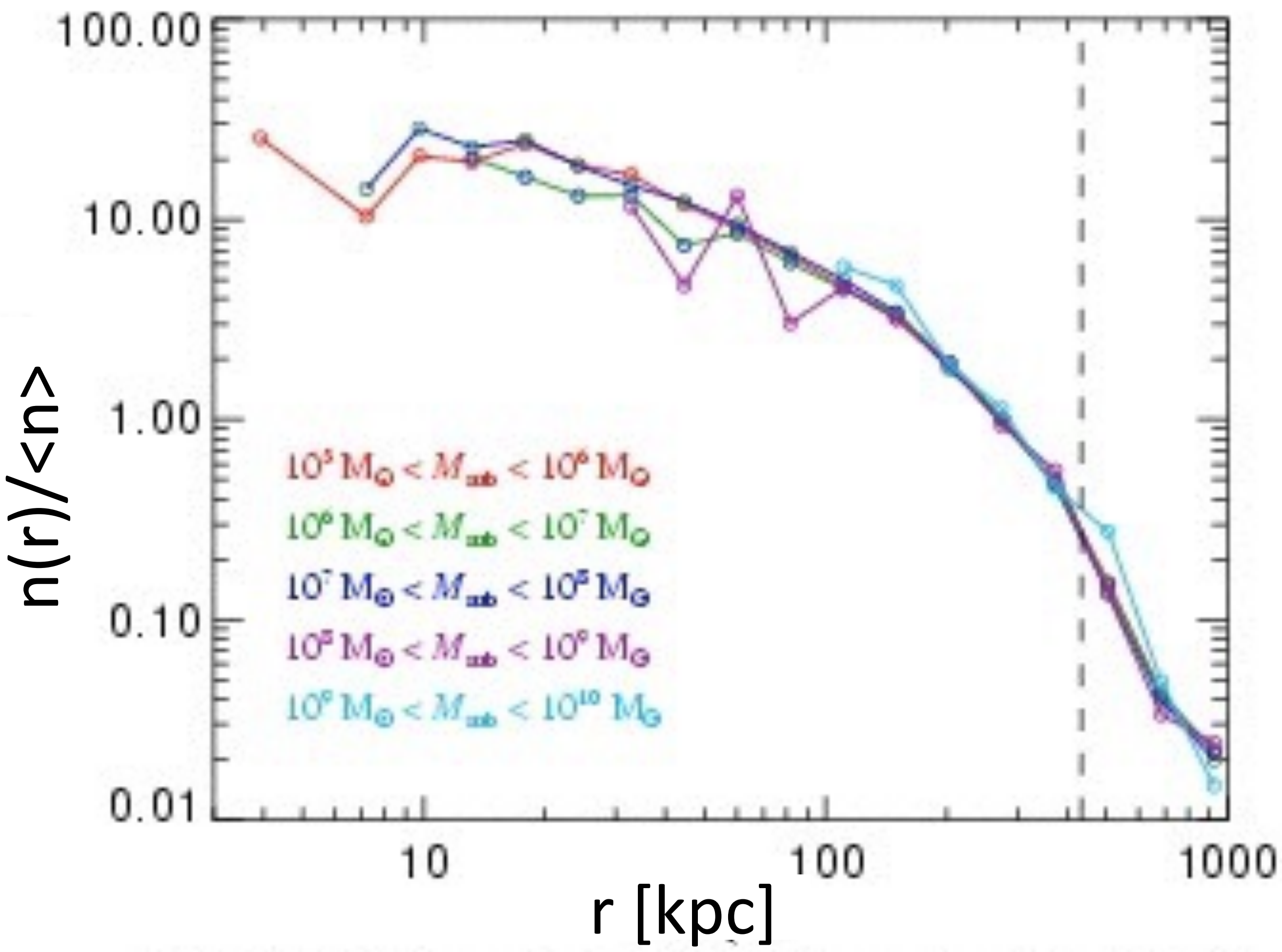

$N(M) \propto M^{\alpha}$

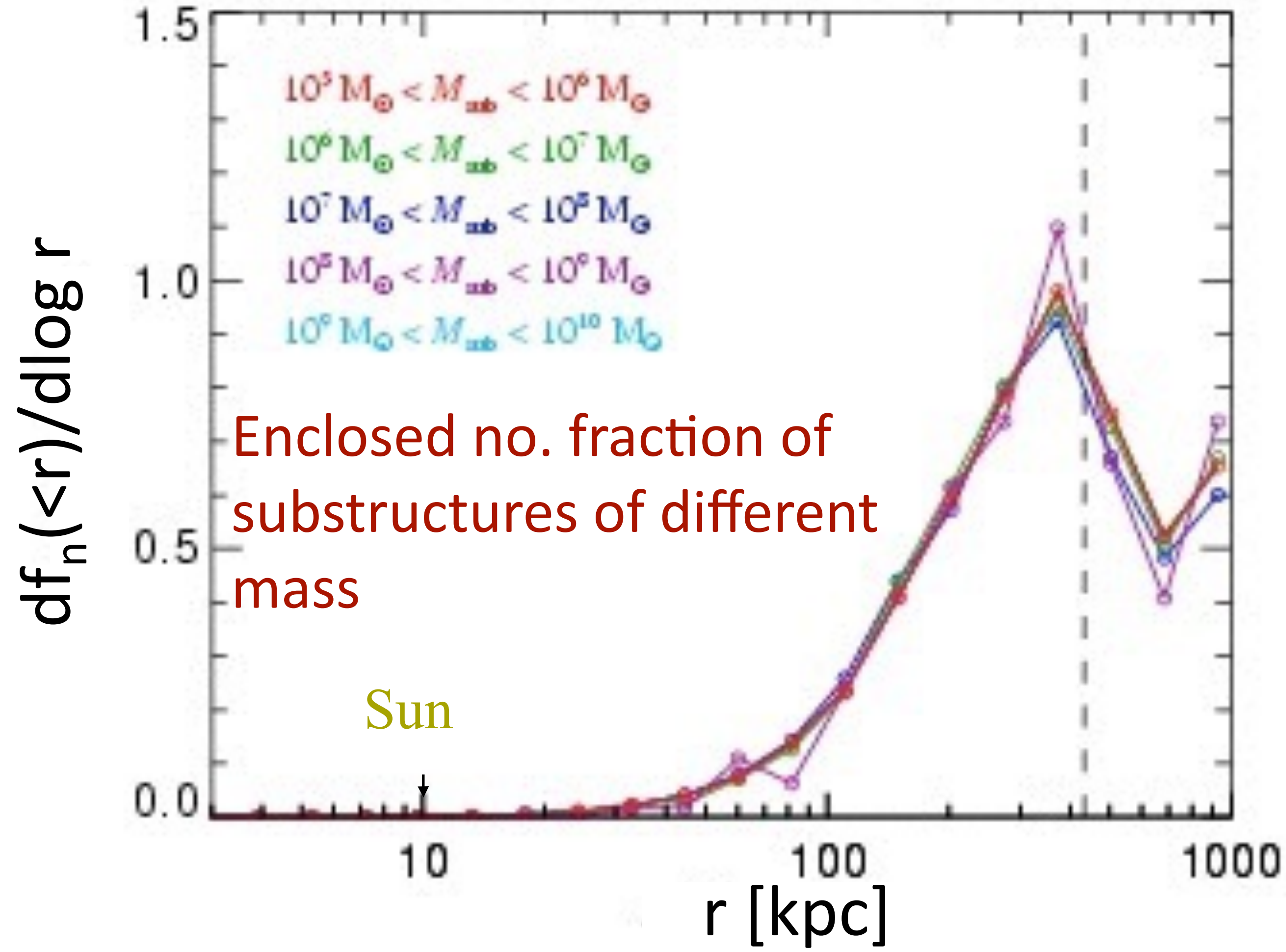
$\alpha = -1.90$

MASS PER LOG INTERVAL

The subhalo number density profile

- The spatial distribution of subhalos is independent of mass
- Most subhalos are at large radii -- subhalos are more effectively destroyed near the centre
- Most subhalos are far from the Sun – our view of the signal from our own halo is very special.



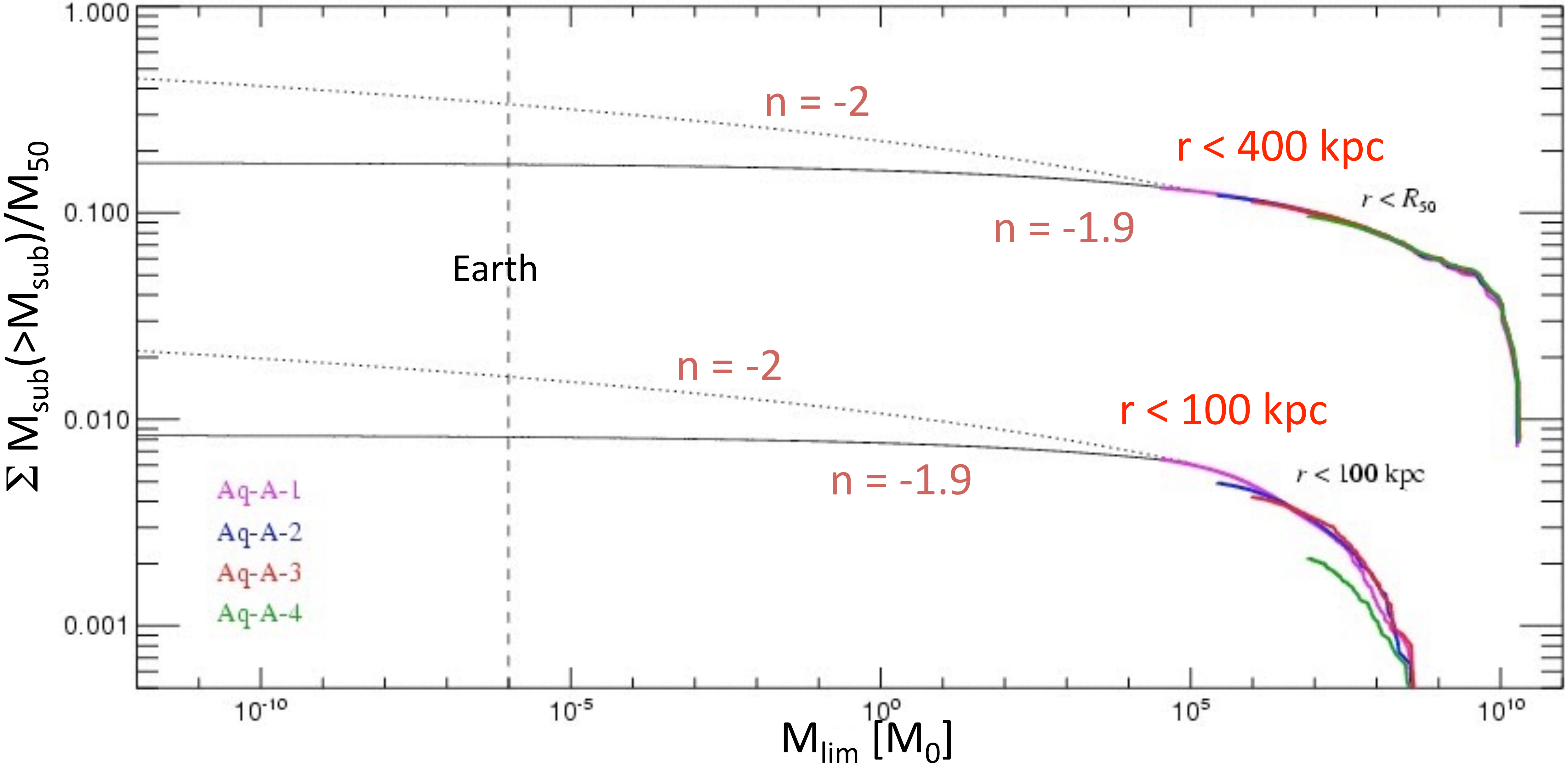


Enclosed no. fraction of substructures of different mass

How lumpy is the MW halo?

Mass fraction in subhalos as a function of the cutoff mass in CDM PS

The Milky Way halo is expected to be quite smooth!



n = -2

r < 400 kpc

n = -1.9

n = -2

r < 100 kpc

n = -1.9

Substructure mass fraction within R_{sun} < 0.1%

Annihilation in CDM

- What annihilation signal is predicted for a given annihilation cross-section?

A blueprint for detecting halo CDM

Supersymmetric particles annihilate and lead to production of γ-rays which may be observable by FERMI

The production of annihilation radiation at ***x*** depends on:

$$\int \rho^2(\boldsymbol{x}) \quad \langle \sigma v \rangle \, dV$$

halo density at ***x*** cross-section

⟹ Theoretical expectation requires knowing $\rho(\boldsymbol{x})$

⟹ Accurate high resolution N-body simulations of halo formation from CDM initial conditions

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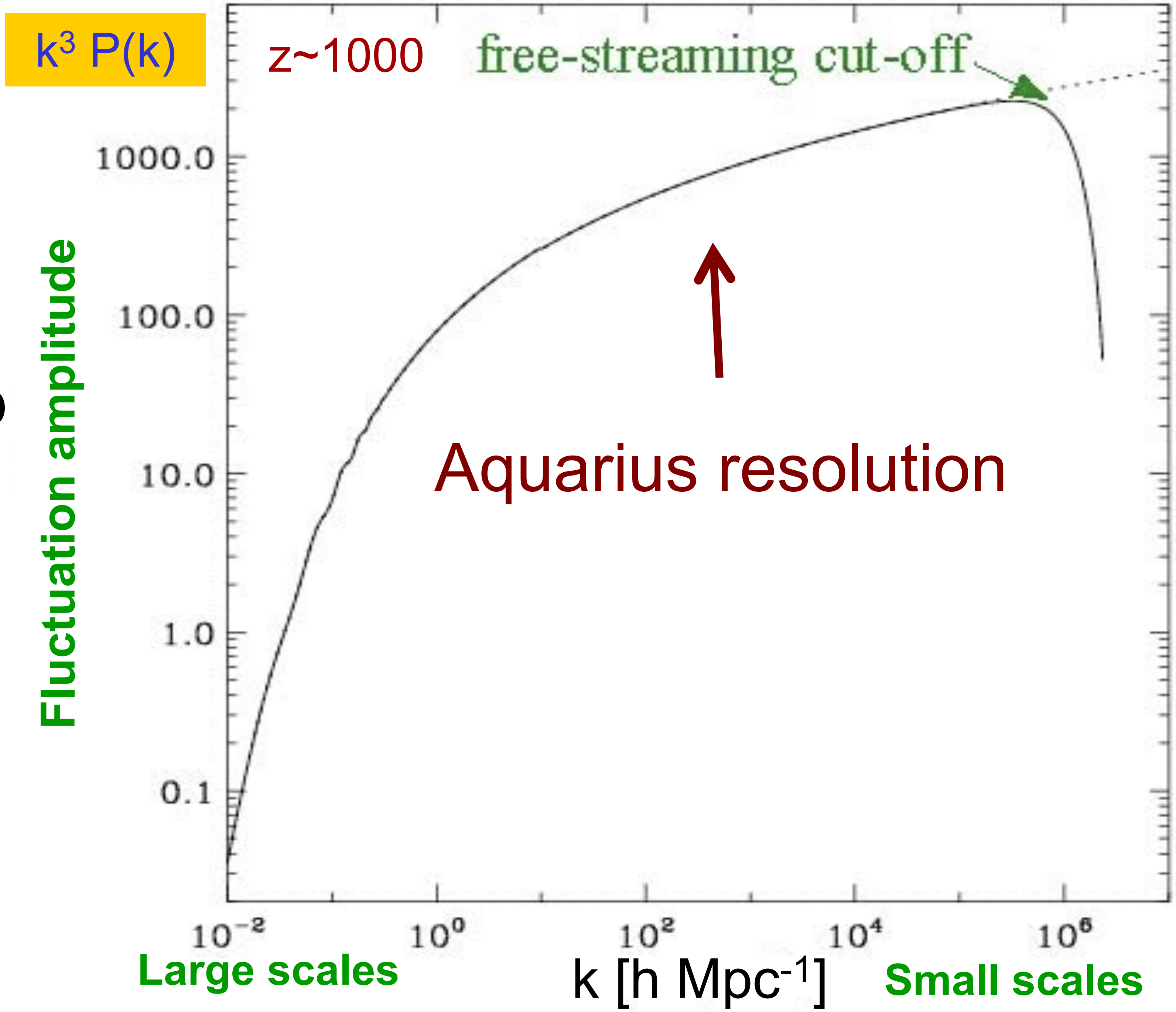
The cold dark matter power spectrum

The linear power spectrum
("power per octave")

Assumes a 100GeV wimp
Green et al '04



Institute for Computational Cosmology

A blueprint for detecting halo CDM

Supersymmetric particles annihilate and lead to production of γ-rays which may be observable by Fermi

Intensity of annihilation radiation at ***x*** depends on:

$$L \propto \int \rho^2(\boldsymbol{x}) \langle \sigma v \rangle \, dV$$

halo density at ***x***

cross-section

Converges for $\rho(r)$ with slope shallower than -1.5

For NFW:

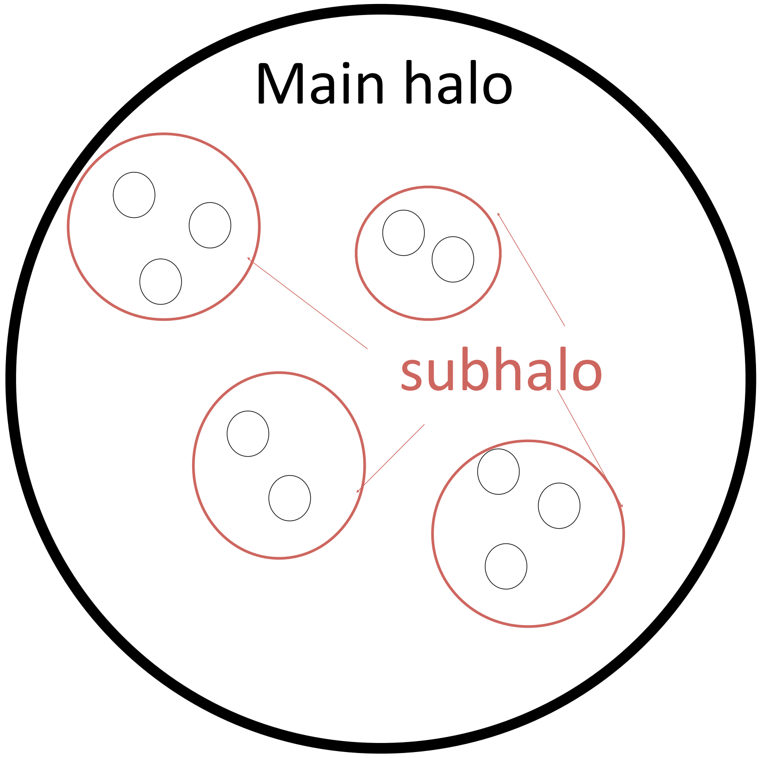
- 95% of L from $r_{\max}$
- 50% of L from $0.1r_{\max}$

For a smooth halo:

$$L \propto \frac{V^4_{\max}}{r_{\max}}$$

A blueprint for detecting halo CDM

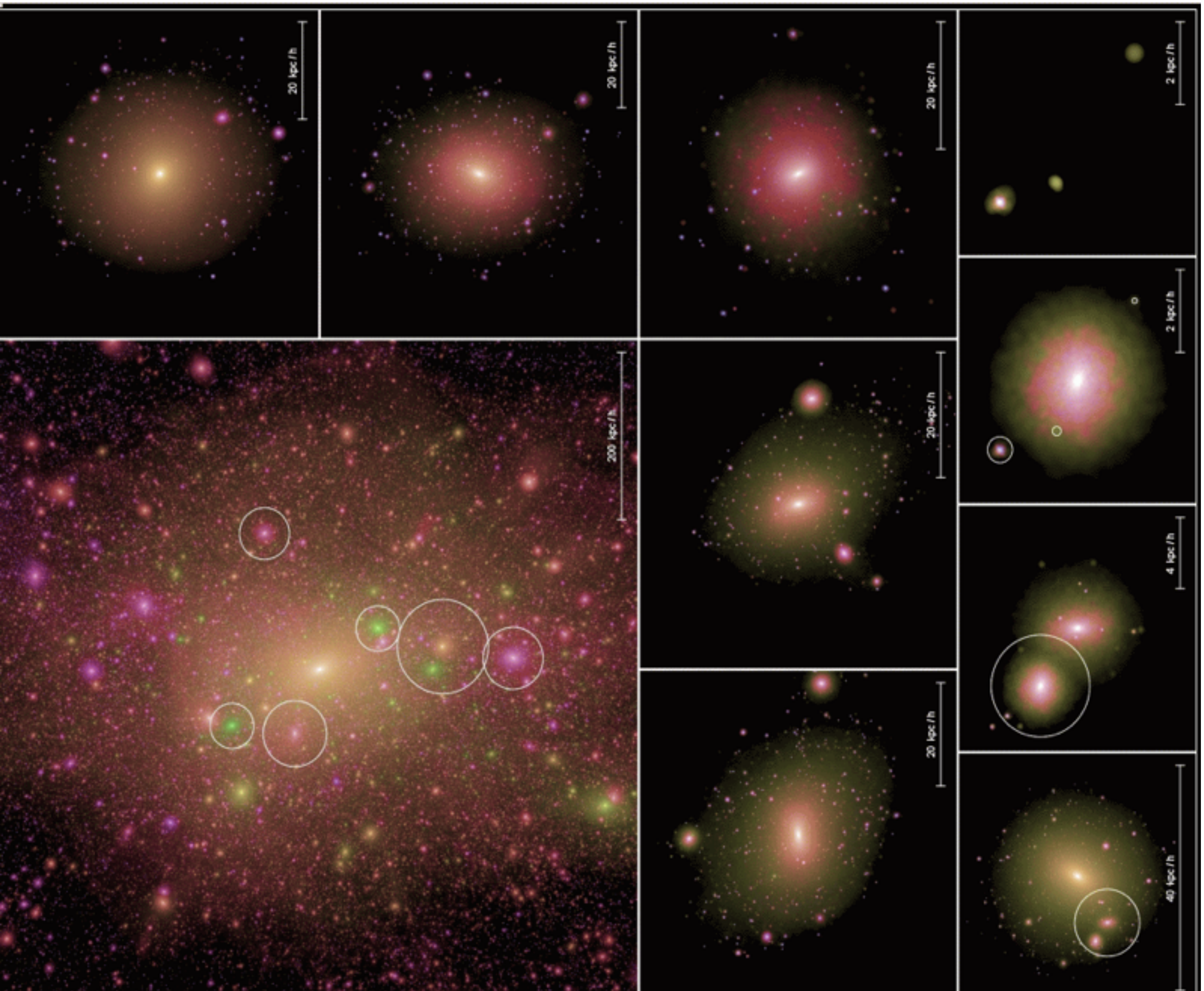
To calculate annihilation luminosity need contribution from 4 components:



1. Smooth emission from main halo
2. Smooth emission from resolved subhalos
3. Emission from unresolved subhalos in main halo
4. Emission from substructure of subhalos

Springel et al 2008

Substructures within substructures



There are substructures embedded within other structures. We detect 4 generations

The hierarchy is NOT self-similar and is heavily dependent on the degree of tidal stripping of subhalos.

More on substructure convergence

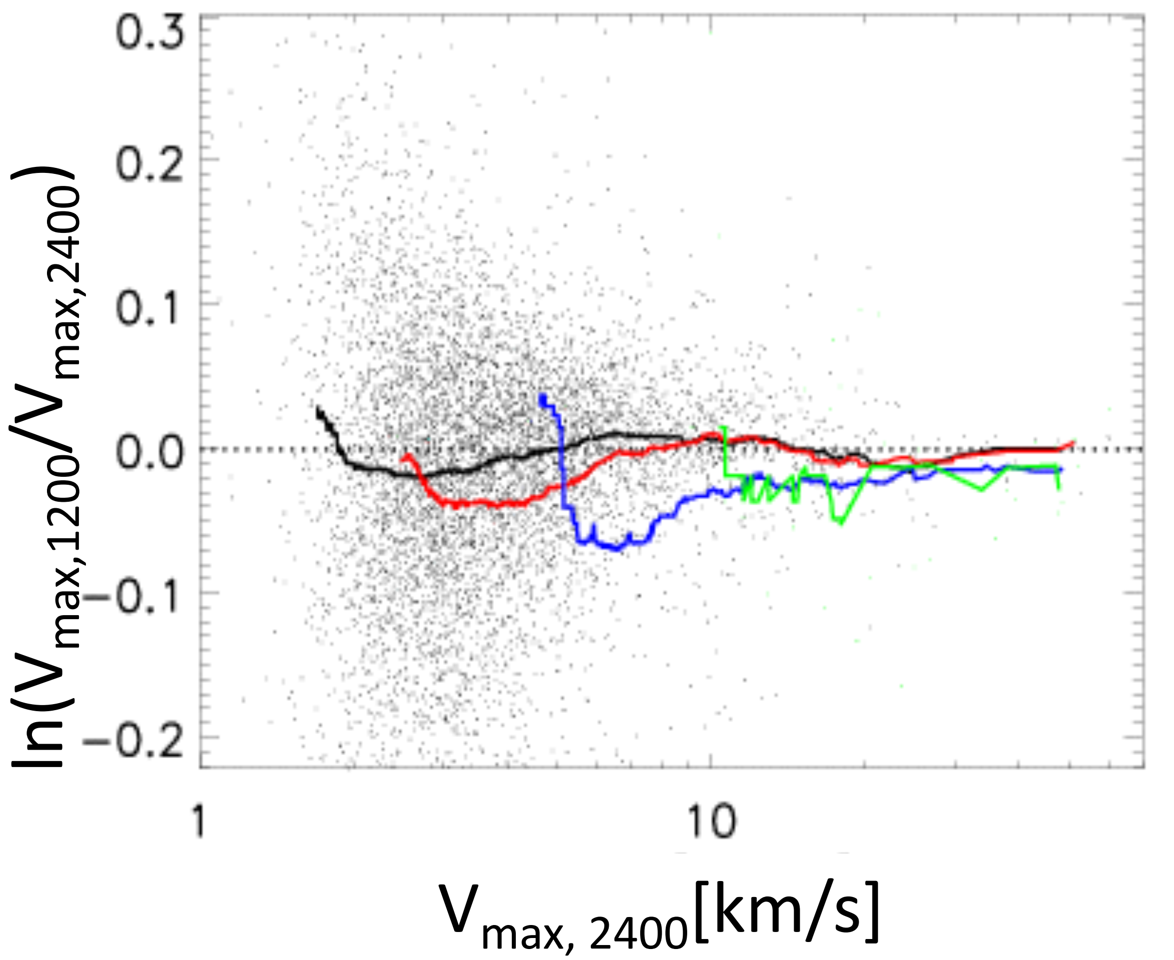
Convergence in the size and maximum circular velocity for individual subhalos cross-matched between simulation pairs.

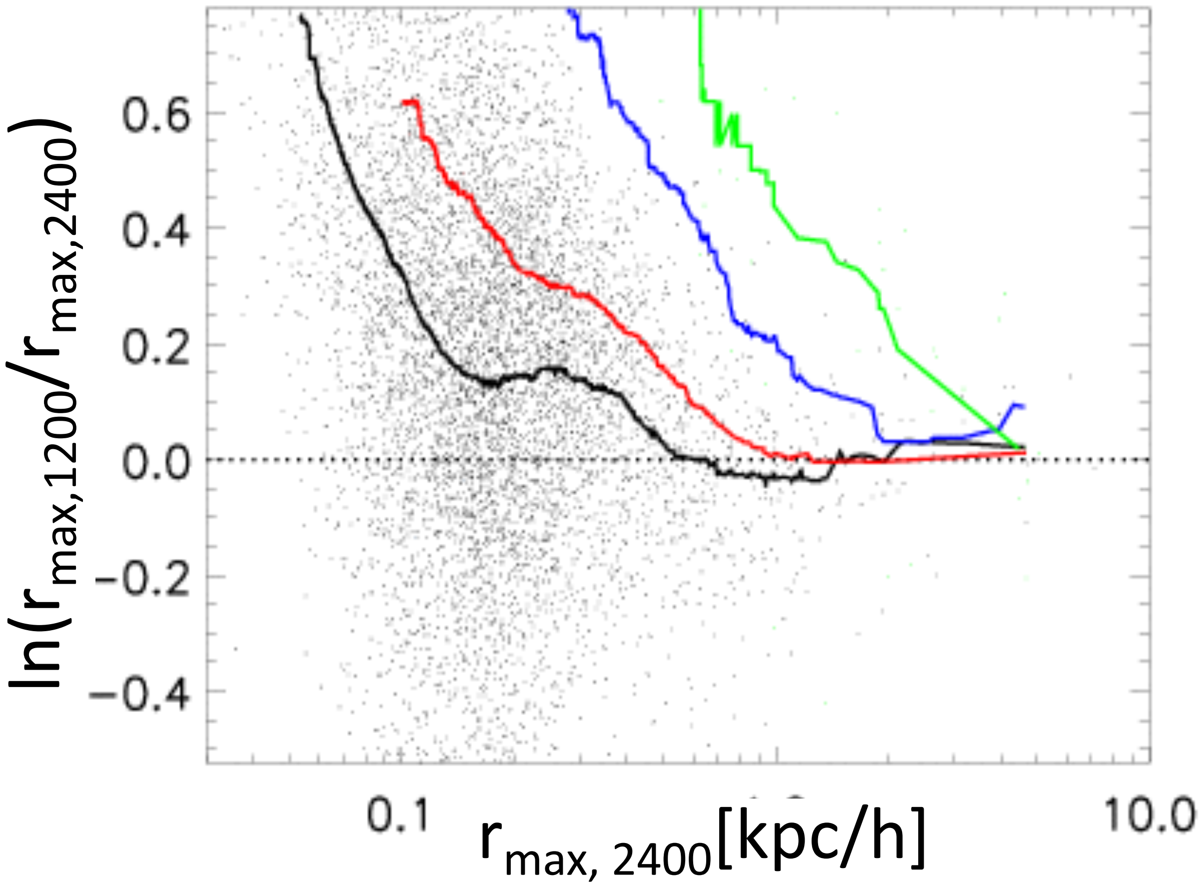
Biggest simulation gives convergent results for

$V_{max} > 1.5$ km/s
$r_{max} > 165$ pc

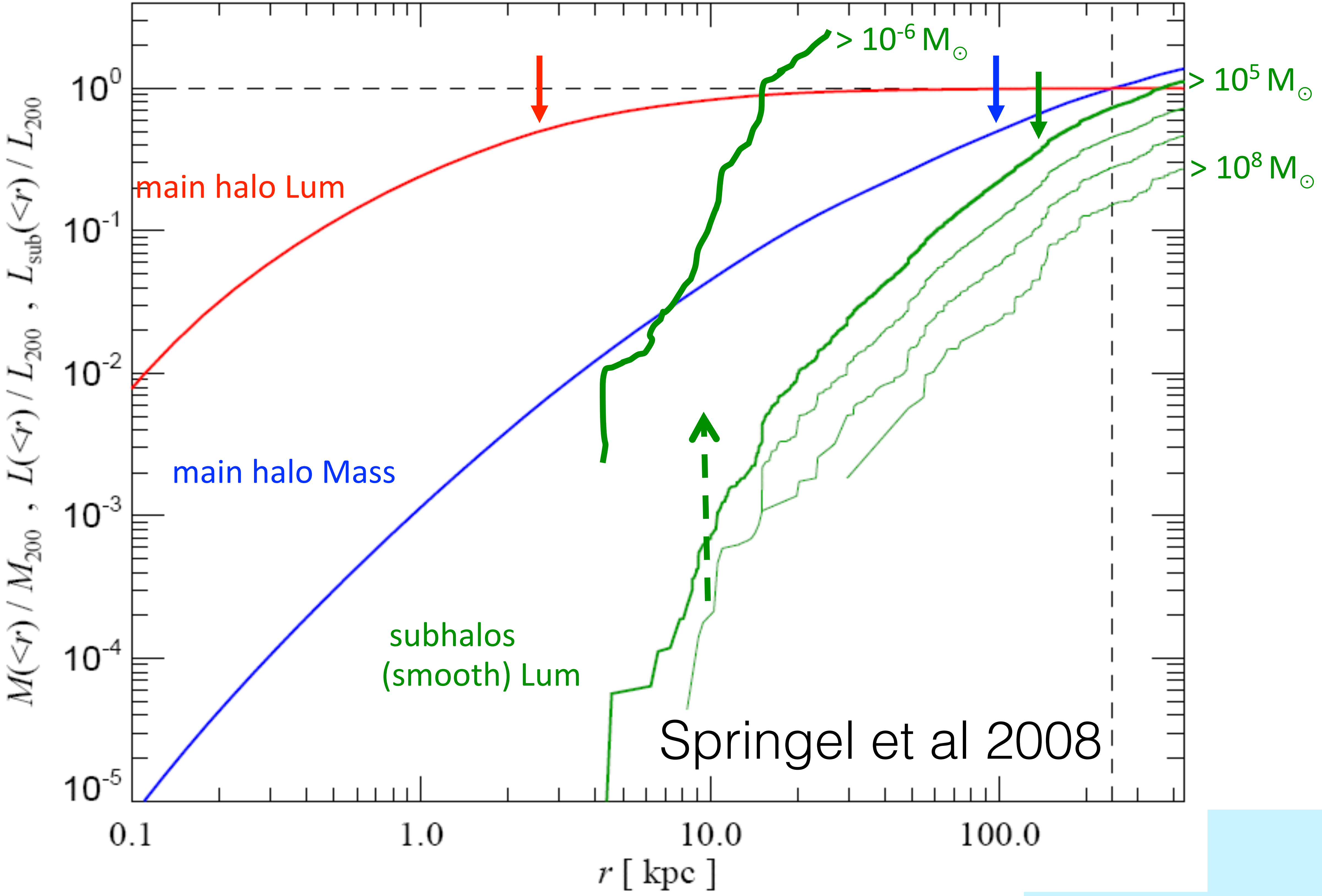
Much smaller than the halos inferred for even the faintest dwarf galaxies

Virgo Consortium 2008





Mass and annihilation radiation profiles of a MW halo




Ph-A-1

University of Durham

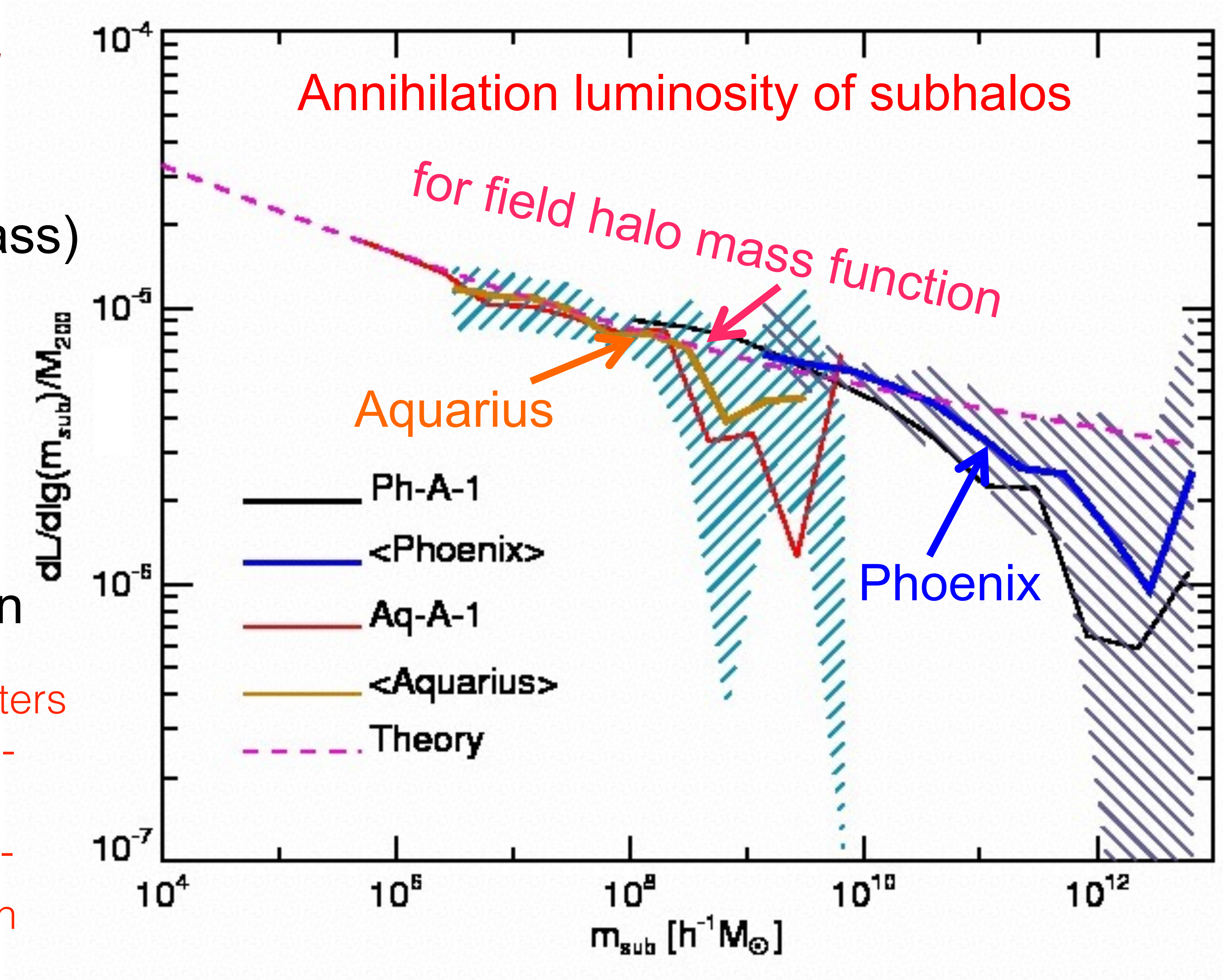
Extrapolation to Earth mass

Annihilation luminosity of subs. per unit mass

Subhalo L (per halo mass) similar to L of field halo mass fn.

Extrapolate using halo mass function (x1.5) + mass-concentration reln

Factors ~1000 boost for clusters due to substructures if mass - concentration relation is extrapolated as a power-law - but is a very **big** assumption



Gao, Frenk, Jenkins, Springel & White ‘12

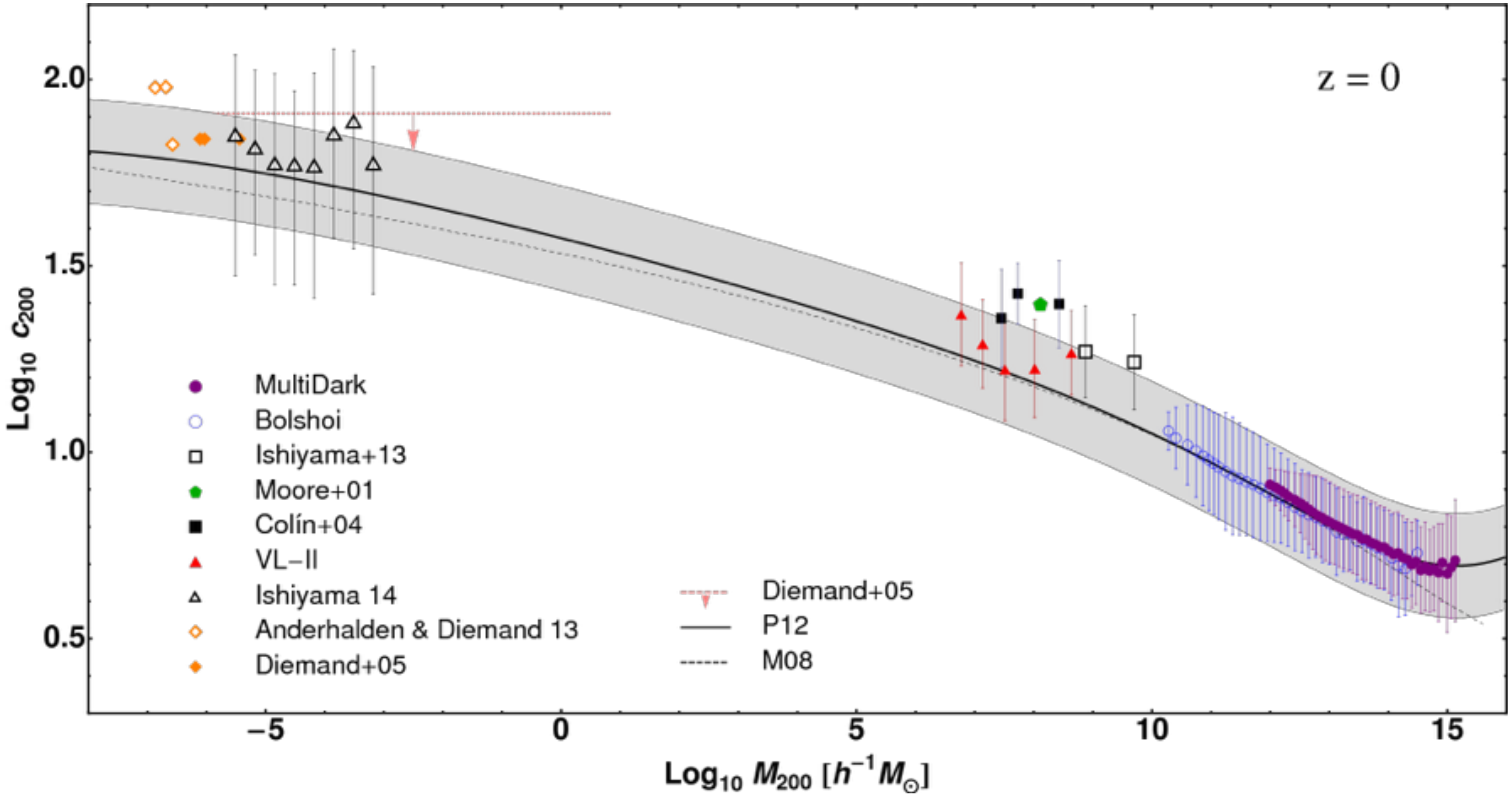
Mass-concentration relation

- Crucial for predicting the annihilation rate from the smallest substructures

$$c_{200} = \frac{r_{200}}{r_{-2}}$$

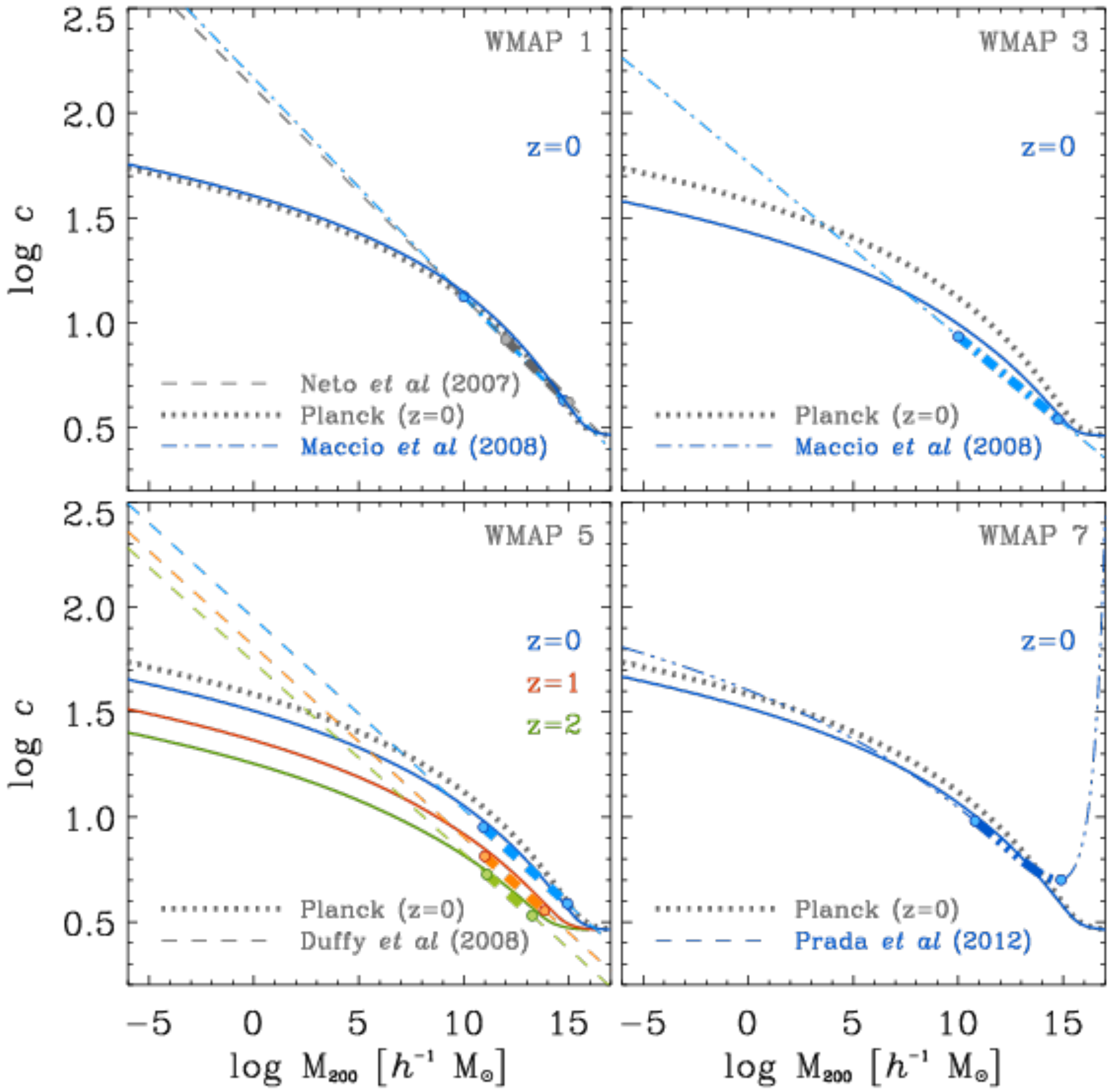
$$\frac{\mathrm{d}\ln\rho(r)}{\mathrm{d}\ln r} = -2$$

Mass - concentration relation

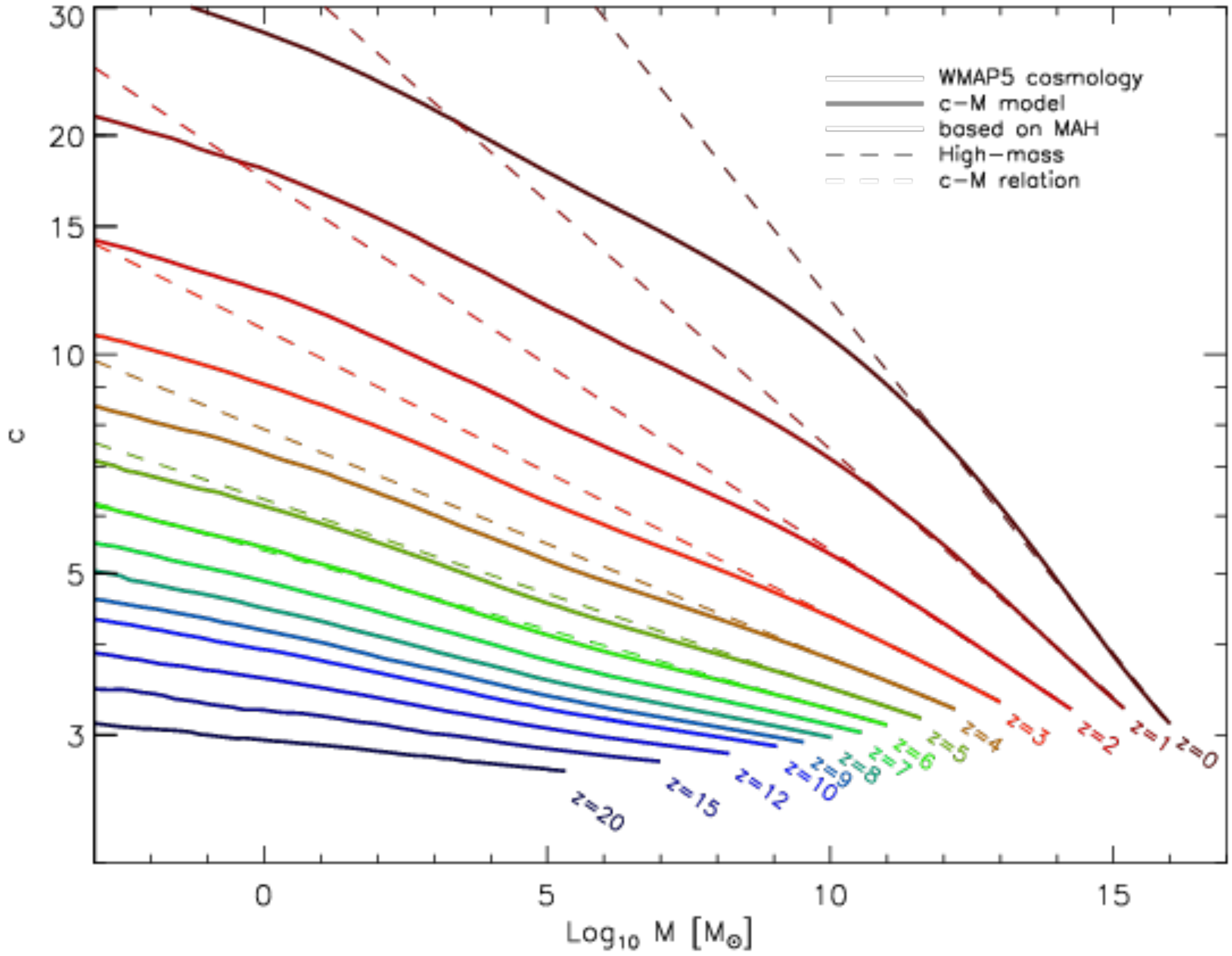


Sanchez-Conde & Prada 2014

Mass - concentration relation



Ludlow et al 2014



Semi-analytic model - Correa et al 2015
Ludlow et al 2014

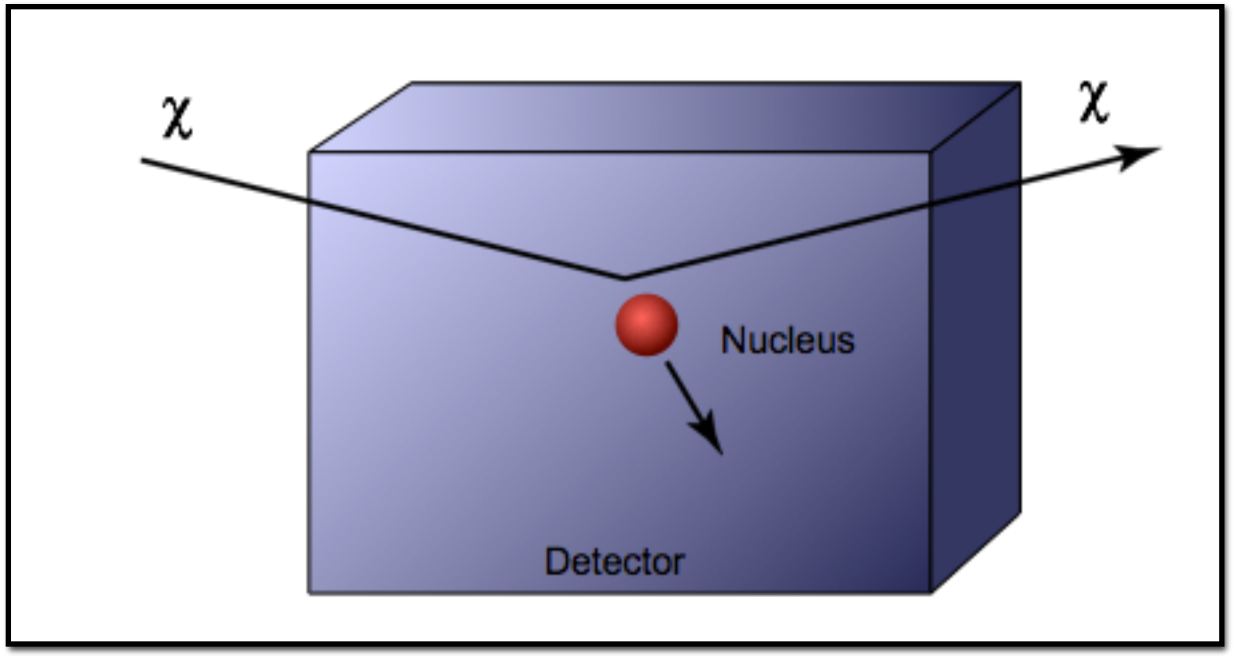
Summary of annihilation

- N-body simulations of DM haloes alone are insufficient to predict the total annihilation rate
- Large extrapolations are required as substructure is very important
- The mass-concentration relation for substructures deduced from simulations of MW-mass and cluster haloes gives large boost factors due to the substructure
- Recent work suggest the mass- concentration relation flattens at smaller masses, reducing the boost, but significant extrapolations are still required to estimate the mass - concentration relation at the free streaming scale.
- Further numerical work needed to reliably determine the mass-concentration relation at redshift zero for the smallest haloes/substructures

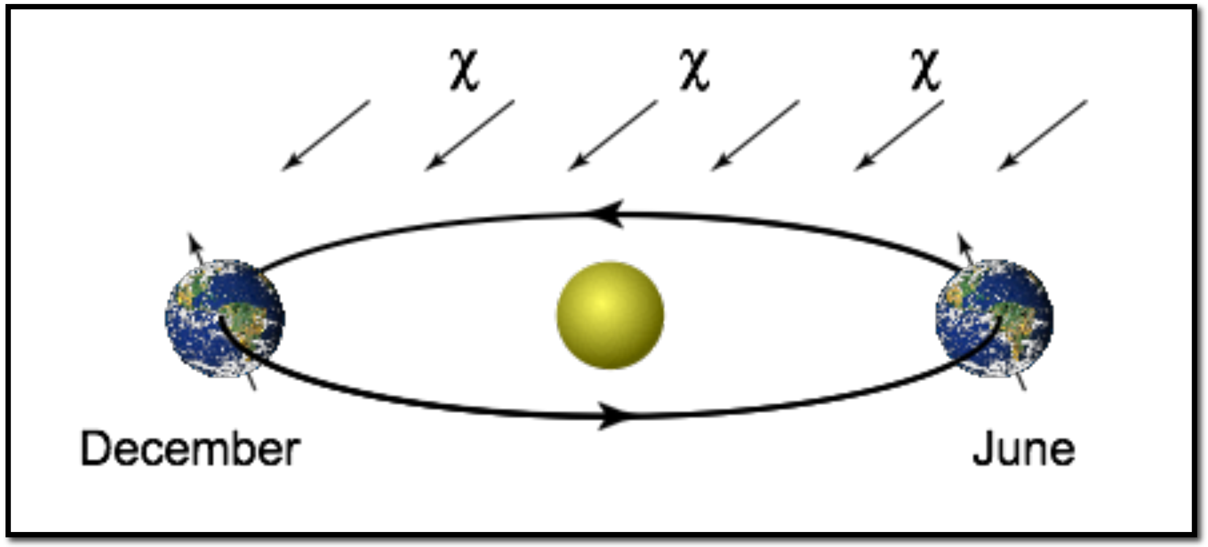
Velocity distributions of particles within haloes

- What signal should a direct detection experiment expect?
- How lumpy is the halo at the solar radius?

Direct detection of WIMPS



- WIMP + nucleus → WIMP + nucleus
- Measure recoil energy (~10KeV)
- Suppress background enough to be sensitive to a signal, or...



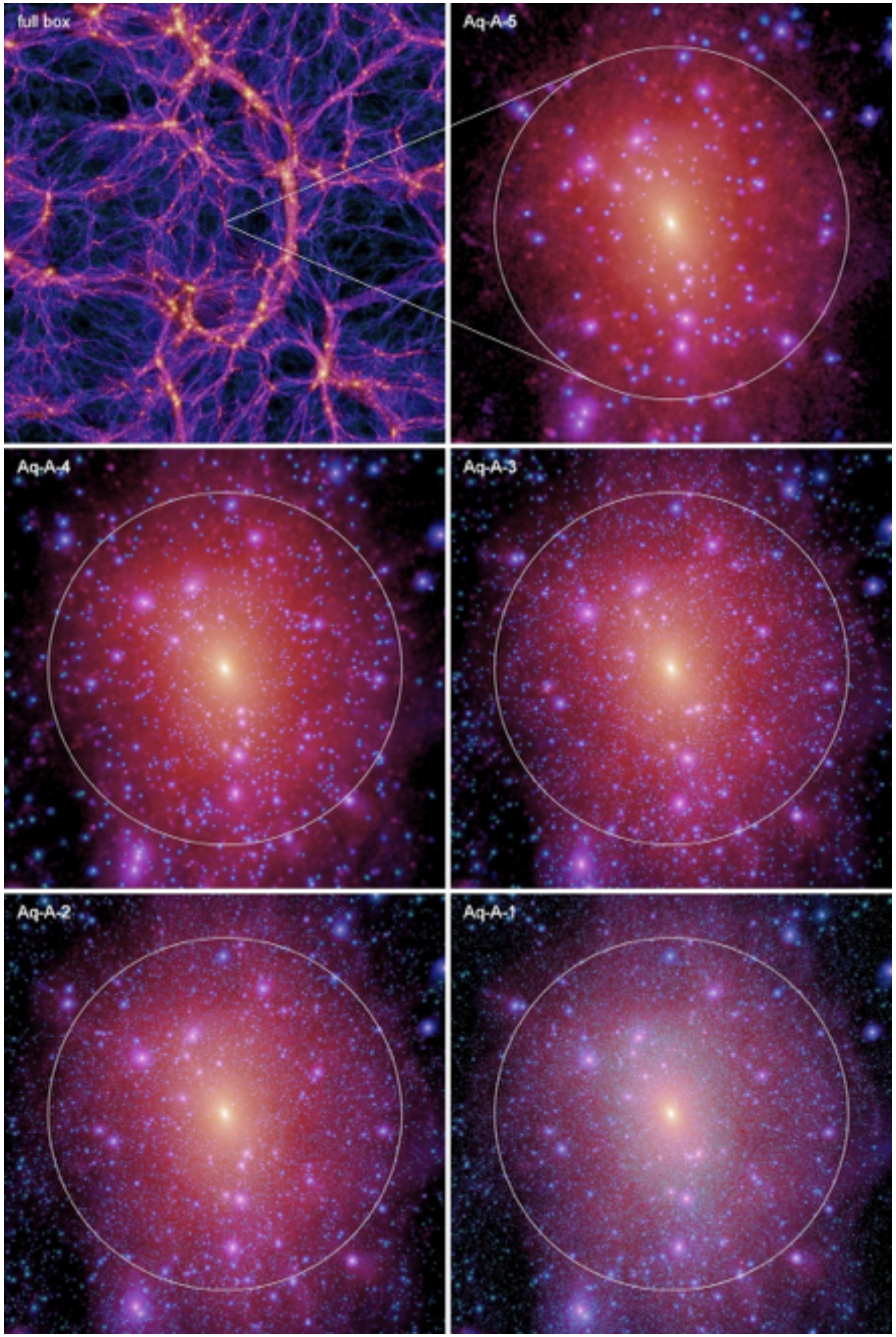
- Search for an annual modulation due to the Earth's motion in the halo

Adapted from Joachim Edsjo

Aquarius Project

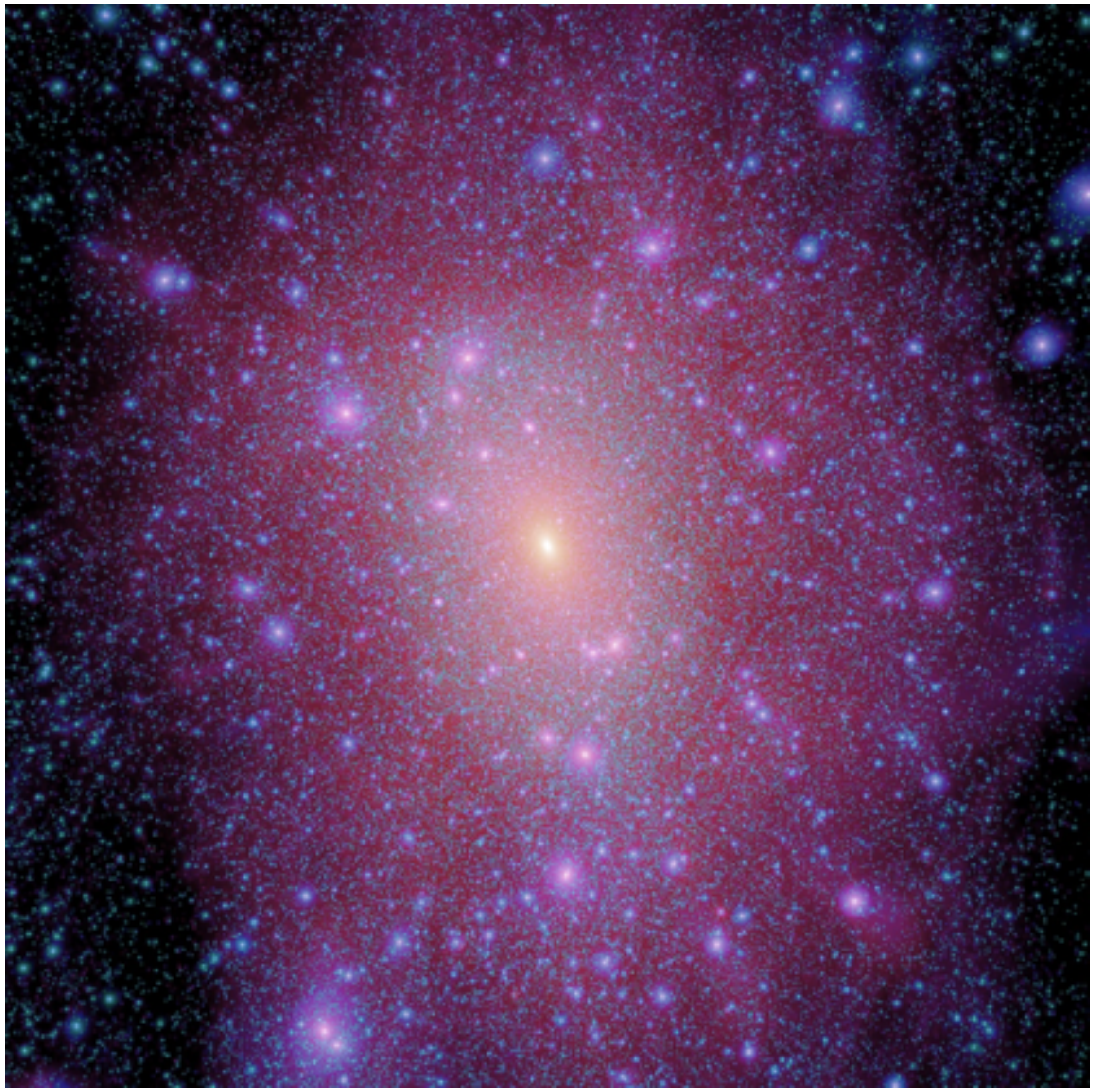
1 Mpc^3

-six Milky Way-like Haloes-



Springel et al (2008)

m_p [$M_\odot$]	ϵ [pc]	N_{hr}
1.712×10^3	20.5	4,252,607,000

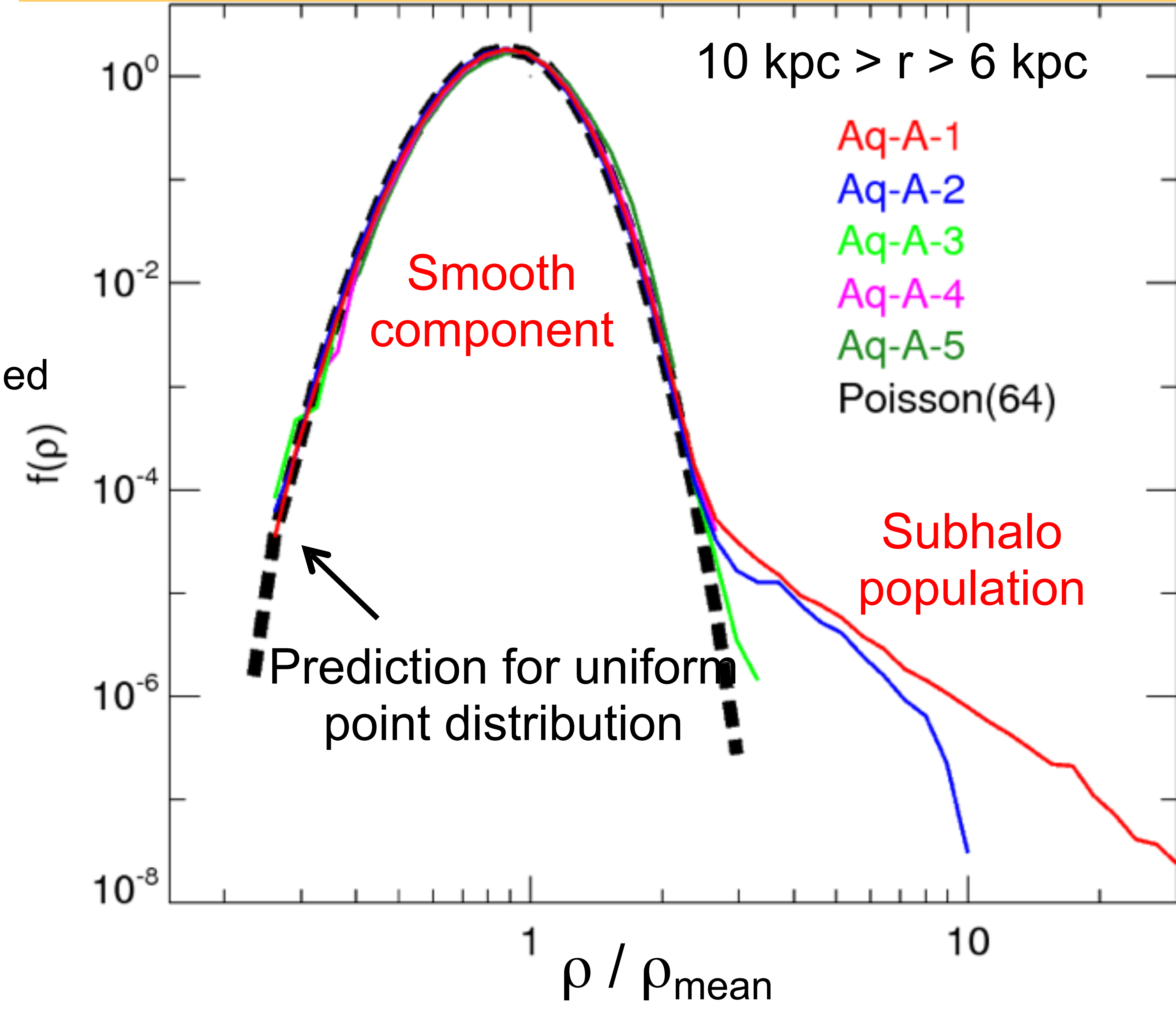


Probing DM near the Sun!

CDM distribution around the Sun

Density prob distribution fn around solar circle

- Estimate ρ at a point by adaptive smoothing with 64 nearest particles
- Fit to smooth ρ profile stratified on ellipsoids



Vogelsberger et al '09

University of Durham

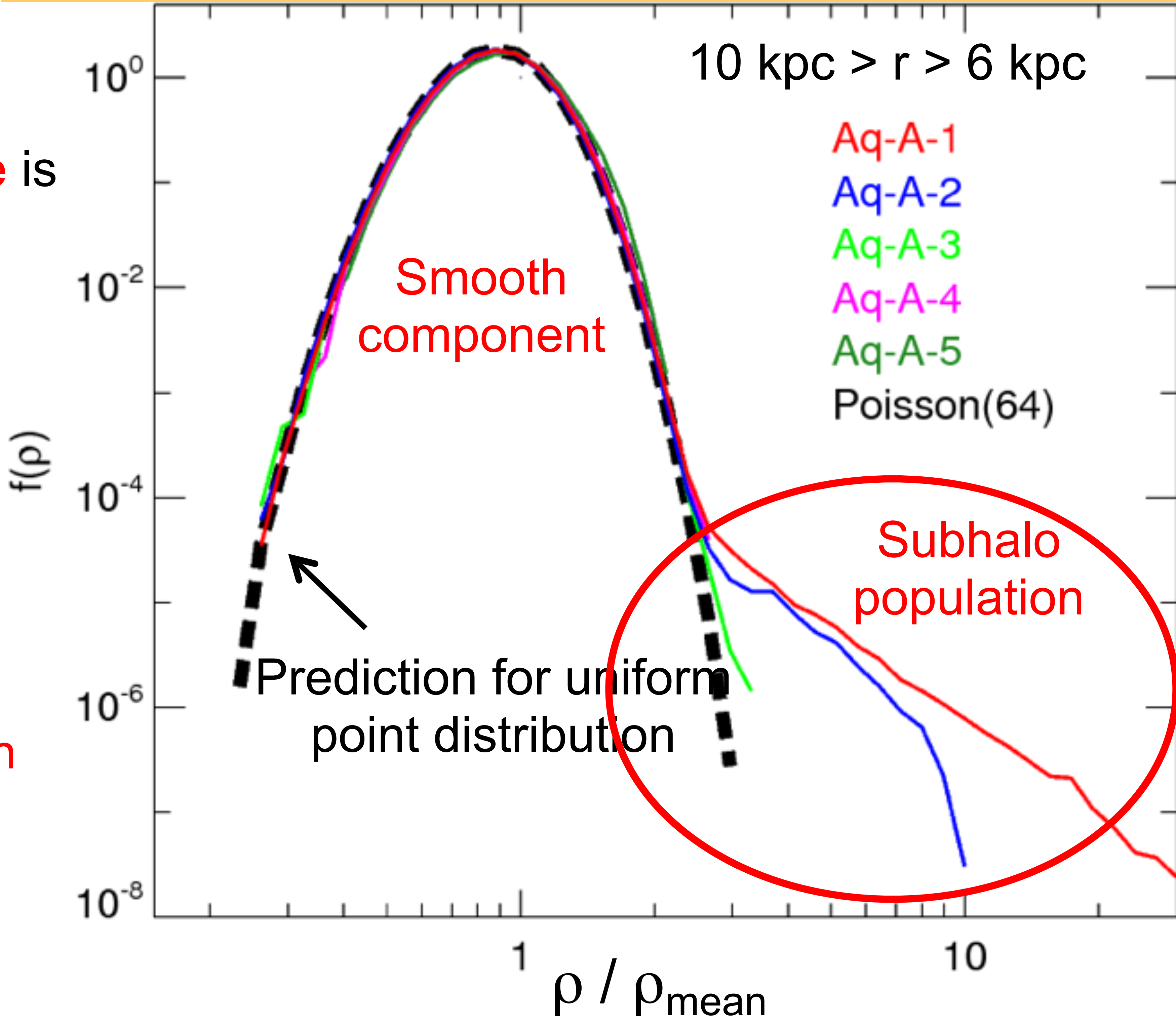
CDM distribution around the Sun

- The chance of a random point lying in a substructure is $< 10^{-4}$

- The *rms* scatter about smooth model for the remaining points is ~4%

- With >99.9% confidence, the DM density near the Sun differs from smooth mean value by < 15%

Density prob distribution fn around solar circle

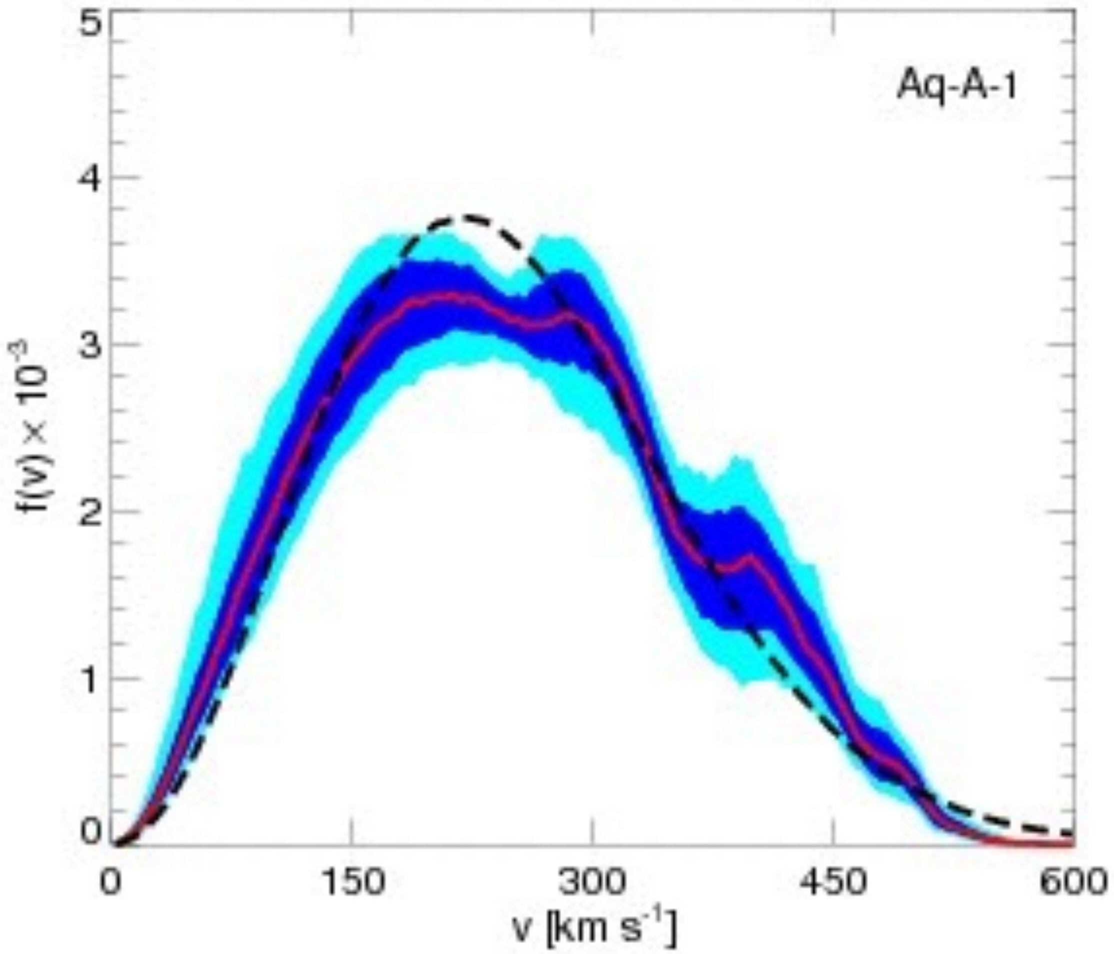


Vogelsberger et al ‘09

Direct detection: halo velocity distribution

Aquarius simulation

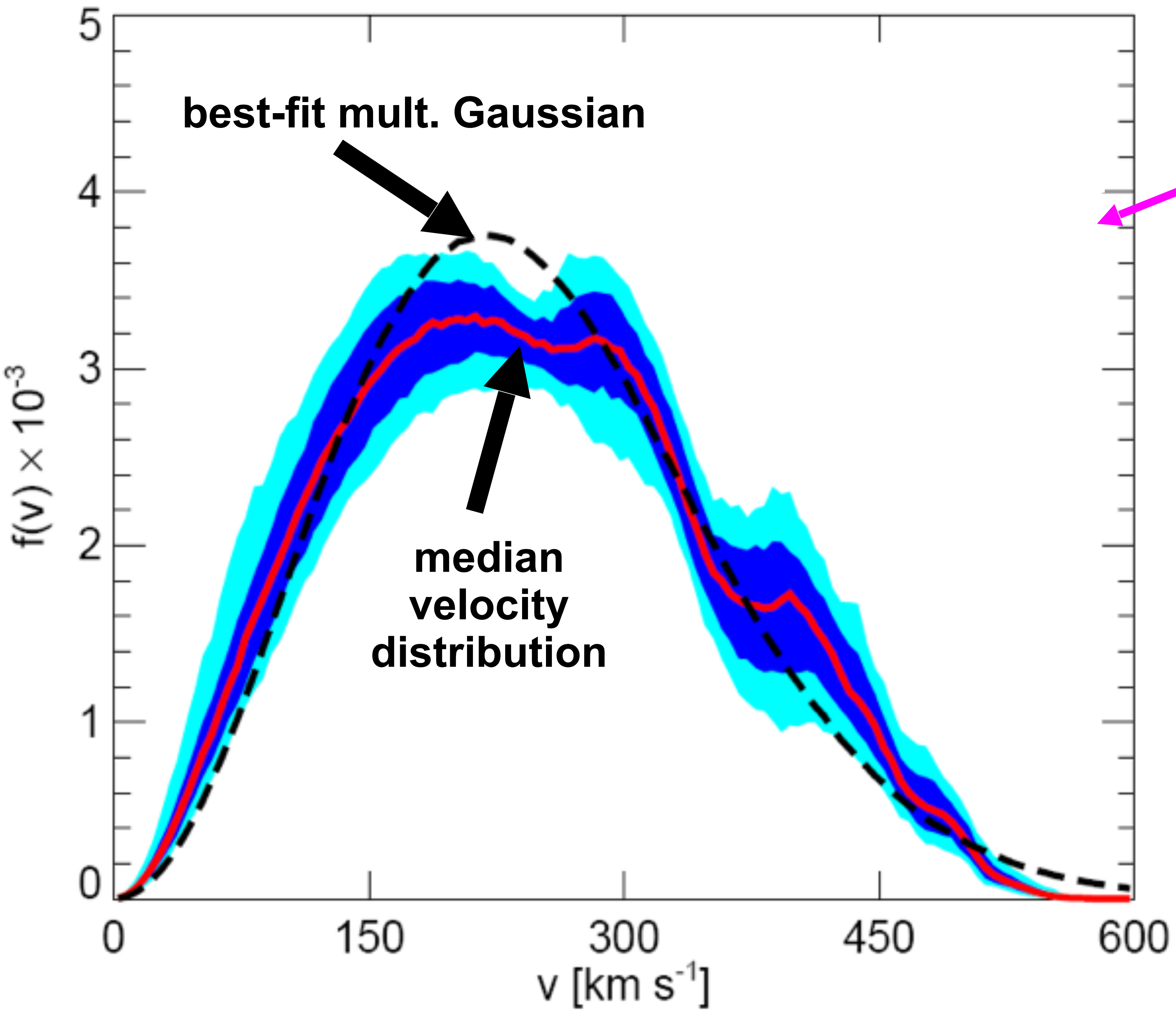
Vogelsberger et al ‘09



Experiments assume “standard halo modeL” → Gaussian vel distr

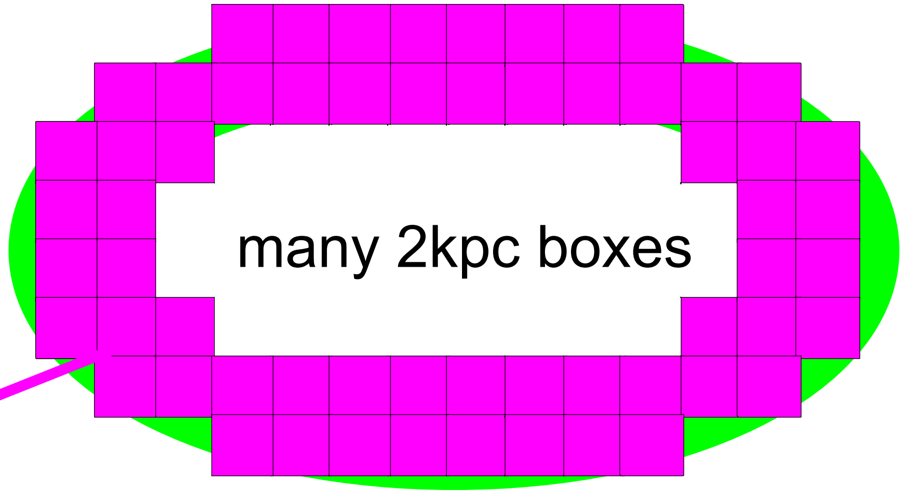
Simulations → fewer particles in tail of distribution; smooth fall off to escape vel.

… at Solar Circle



best-fit mult. Gaussian

median velocity distribution



Bumps in velocity modulus at the same velocity

Not Maxwellian

Not Gaussian

Fine-scale phase space structure

- Detectors on ~1m scale - how smooth is the velocity distribution of particles on this scale?

- Vogelsberger & White 2011 - using Aquarius haloes

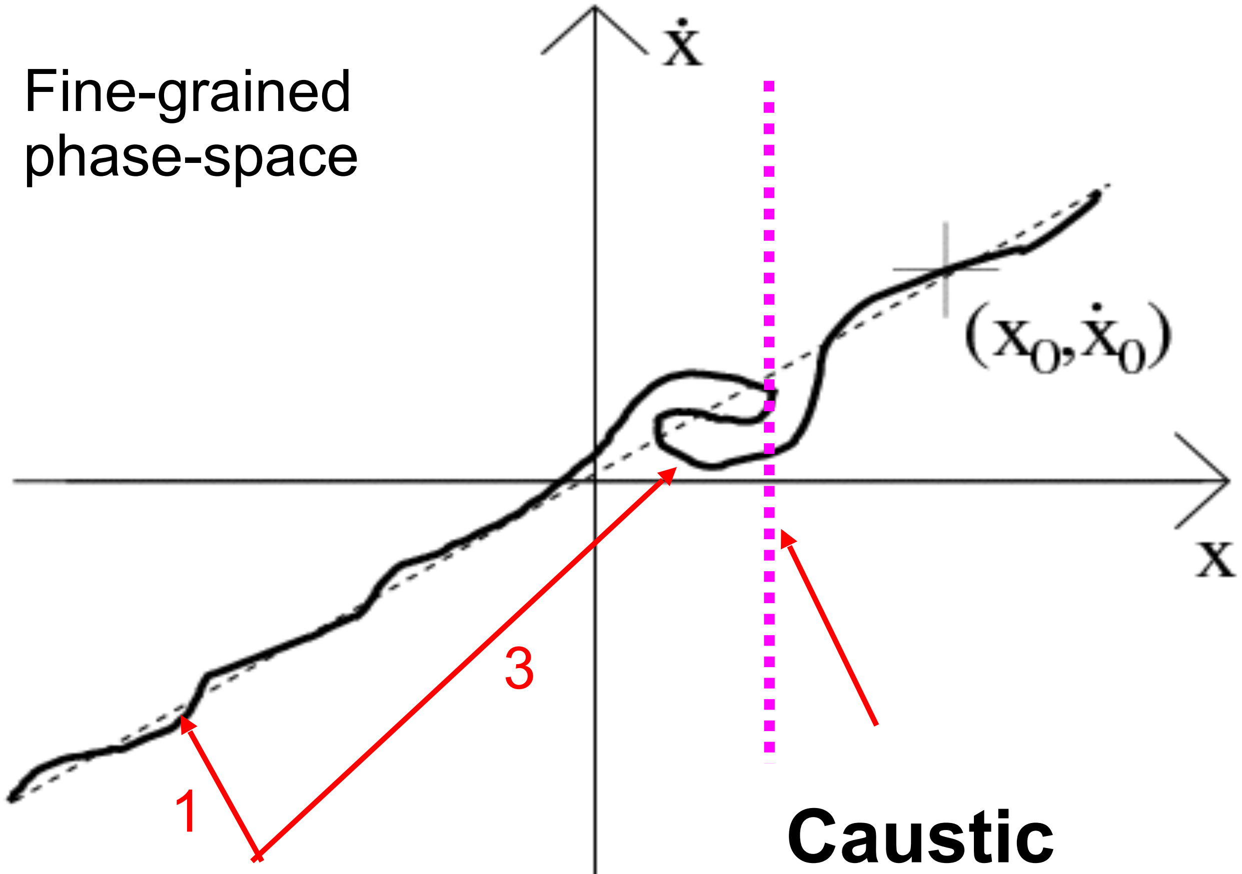
CDM – very small scales

CDM is **cold** and **collisionless**

→

CDM lies on 3D hypersurface in 6D phase-space

Fine-grained phase-space



streams

Caustic
(catastrophe)

Thickness of line:
primordial velocity dispersion

Amplitude of wiggles:
velocity due to density perturbations

Wind-up:
growth of an overdensity

Phase space sheet:

regions of **very high CDM density**

Vogelsberger & White 2011

SELF-SIMILAR GRAVITATIONAL COLLAPSE IN AN EXPANDING UNIVERSE[1]

James A. Fillmore and Peter Goldreich
California Institute of Technology

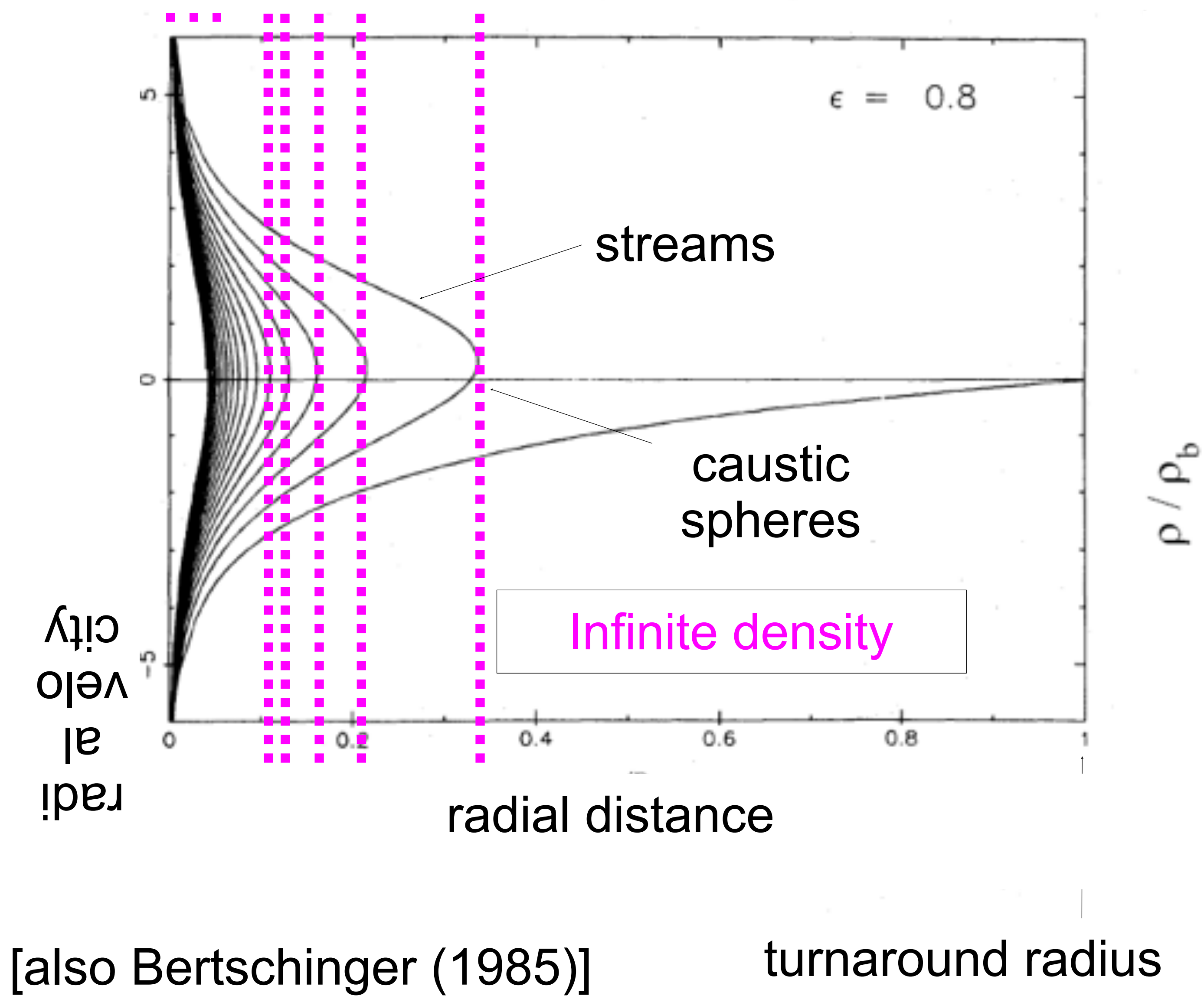
Received 1983 October 10; accepted 1983 December 5

Starting point
Analytic 1D model

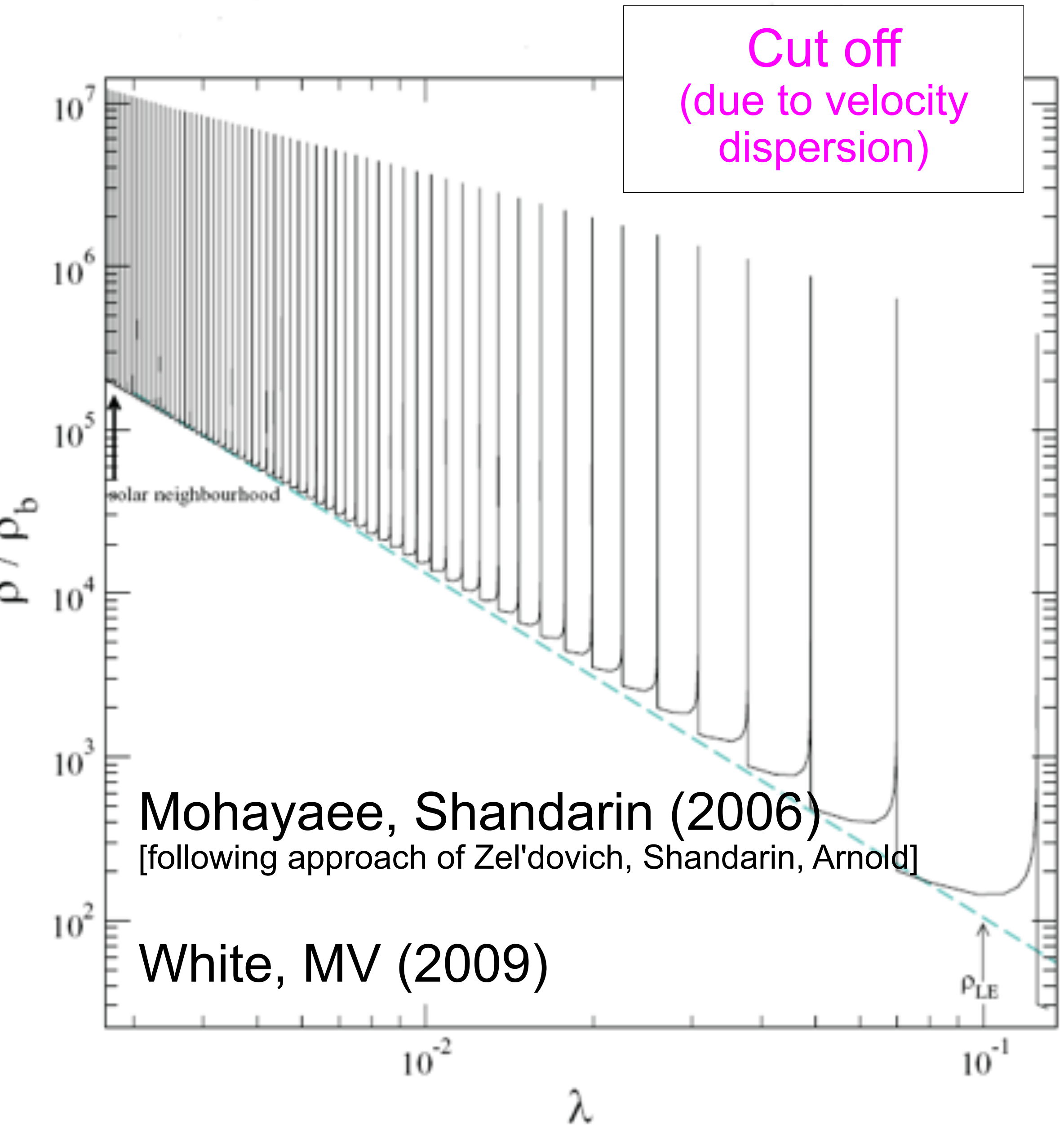
ABSTRACT

We derive similarity solutions which describe the collapse of cold, collisionless matter in a perturbed Einstein–de Sitter universe. We obtain three classes of solutions, one each with planar, cylindrical, and spherical symmetry. Our solutions can be computed to arbitrary accuracy, and they follow the development of structure in both the linear and nonlinear regimes.

Subject headings: cosmology — relativity



[also Bertschinger (1985)]

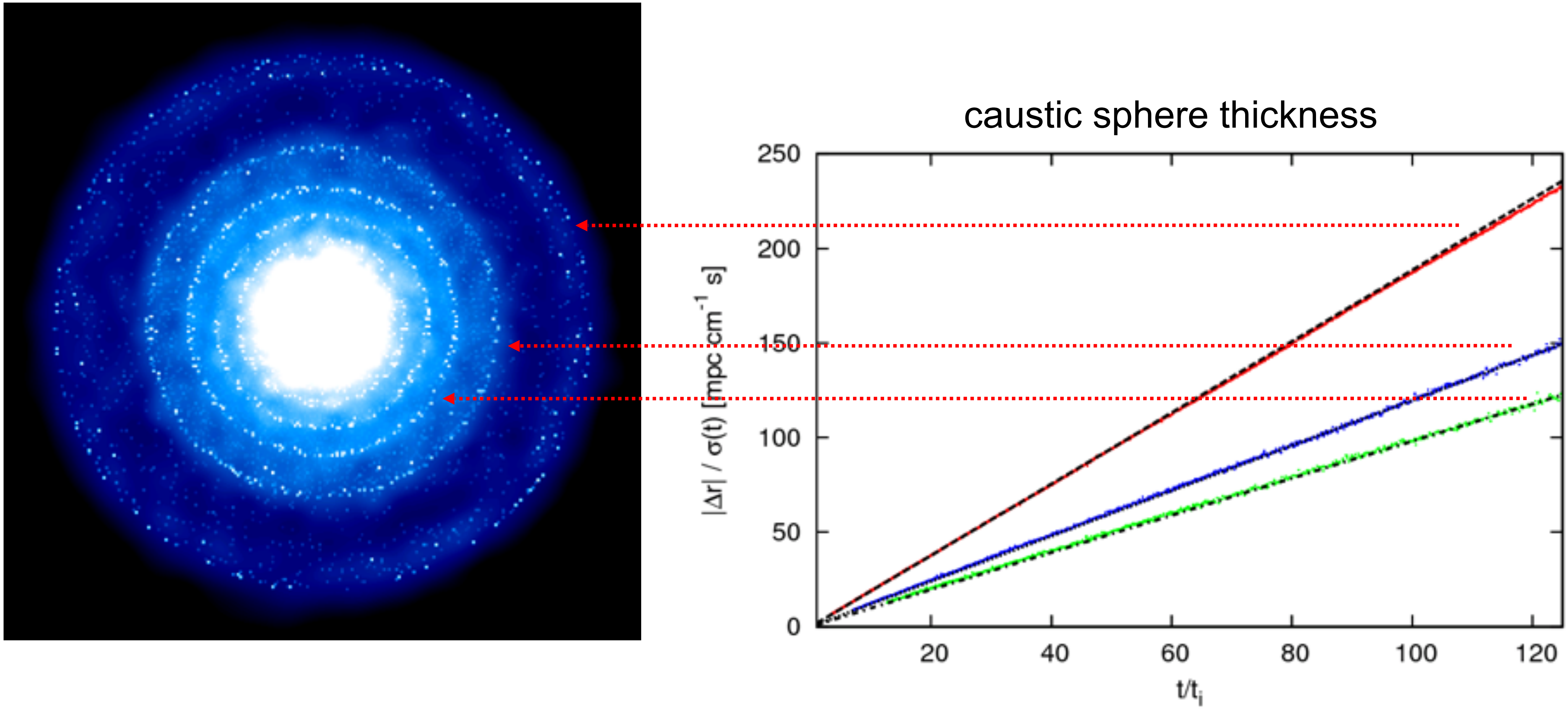


Mohayaee, Shandarin (2006)
[following approach of Zel'dovich, Shandarin, Arnold]

White, MV (2009)

Caustic Annihilation radiation
- 1D gravity -

1 AU^3



caustic spheres on top of smooth annihilation signal

Caustic spheres at the solar position have a thickness of the order of **Astronomical Units!**

Resolving fine-grained caustics with N-body simulations

Problem: N-body simulations have too coarse phase-space sampling
(→ missing many orders of magnitude in mass resolution/particle number)

Solution: Follow the local phase-space evolution for each particle
(→ with a phase-space geodesic deviation equation)

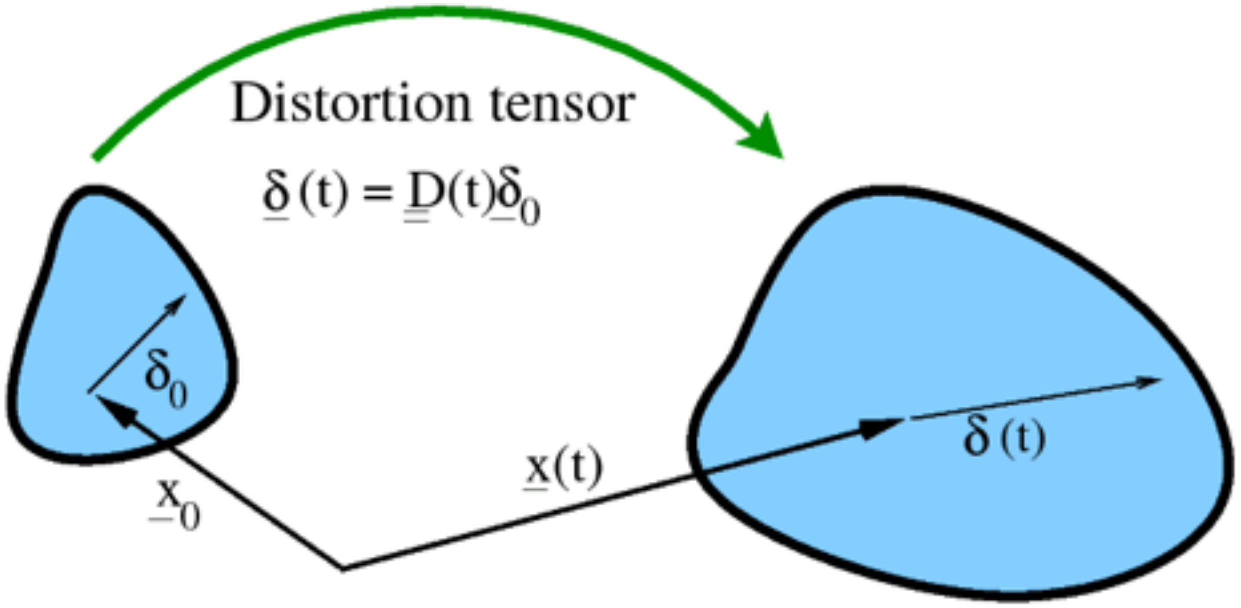
- **calculation of stream density**
- **identification of caustics**
- **Monte-Carlo estimate for intra-stream annihilation**

→ allows caustic annihilation calculation

gaining resolution *without* using larger computers

$$\frac{\mathrm{d}\mathcal{A}_{s,i}}{\mathrm{d}t} = \frac{<\sigma v>_\chi}{m_\chi^2} m_i \rho_{s,i}$$

[Implementation in GADGET-3]



MV et al (2008)

Vogelsberger & White 2009

Caustics and streams

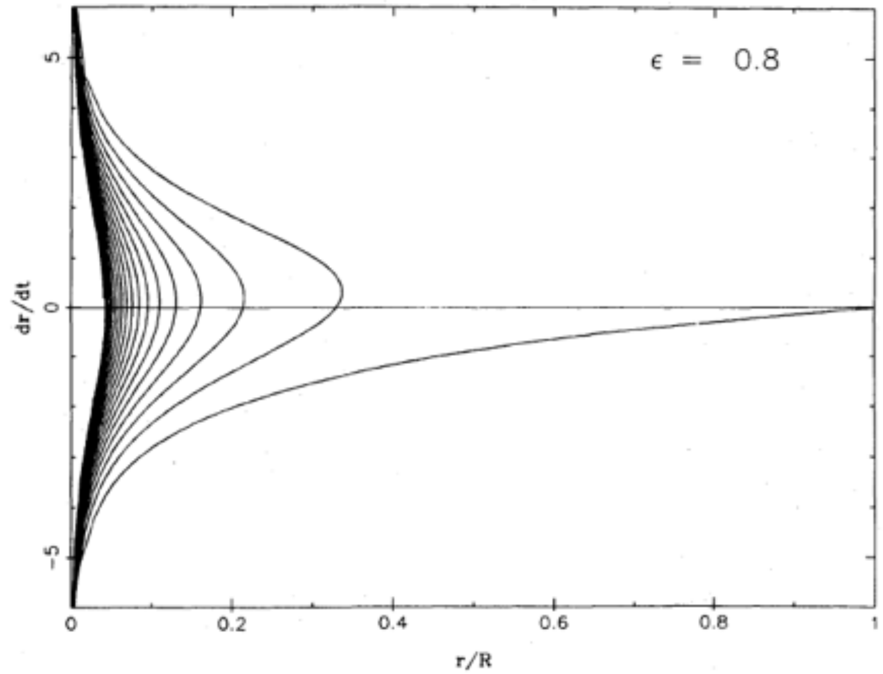
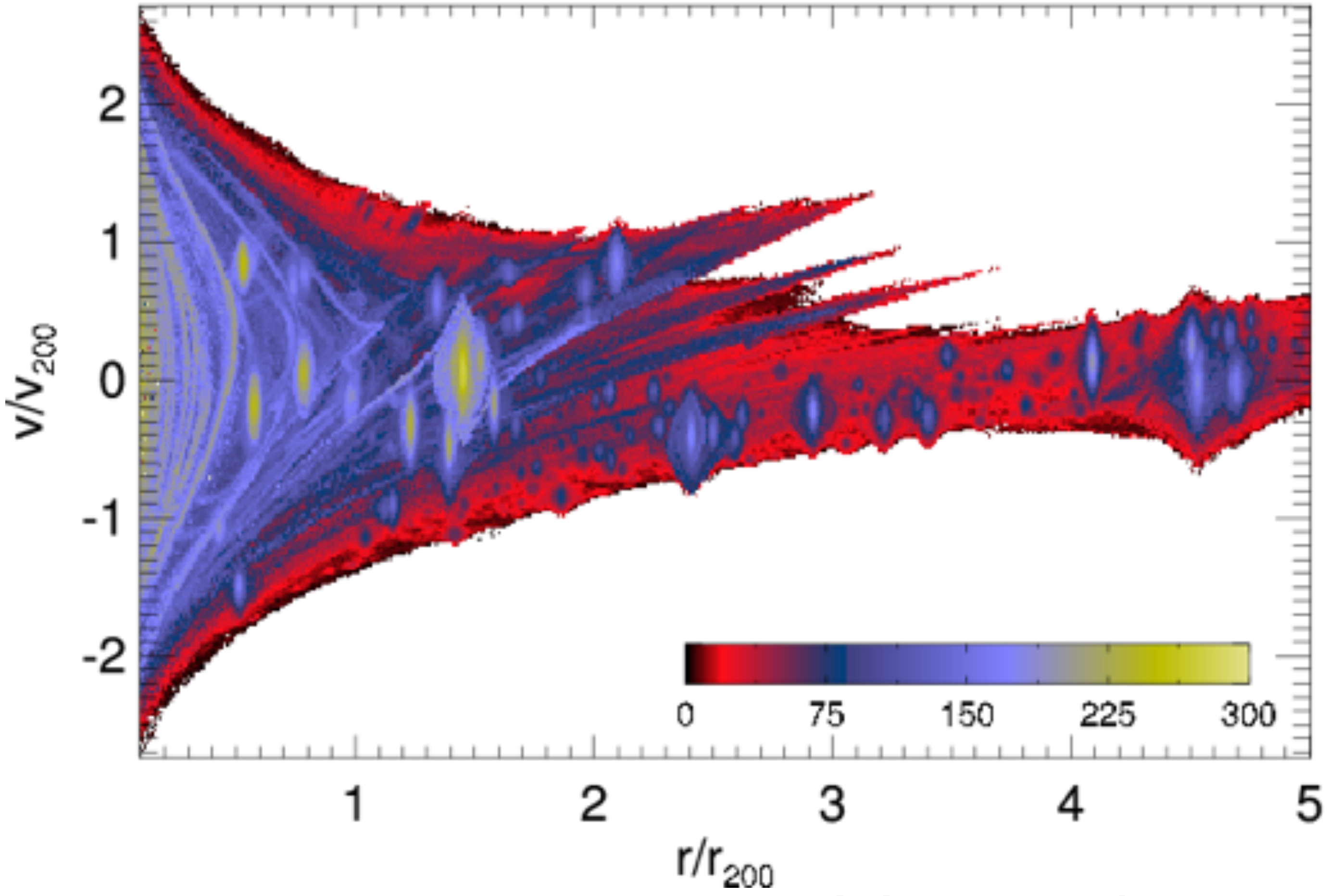
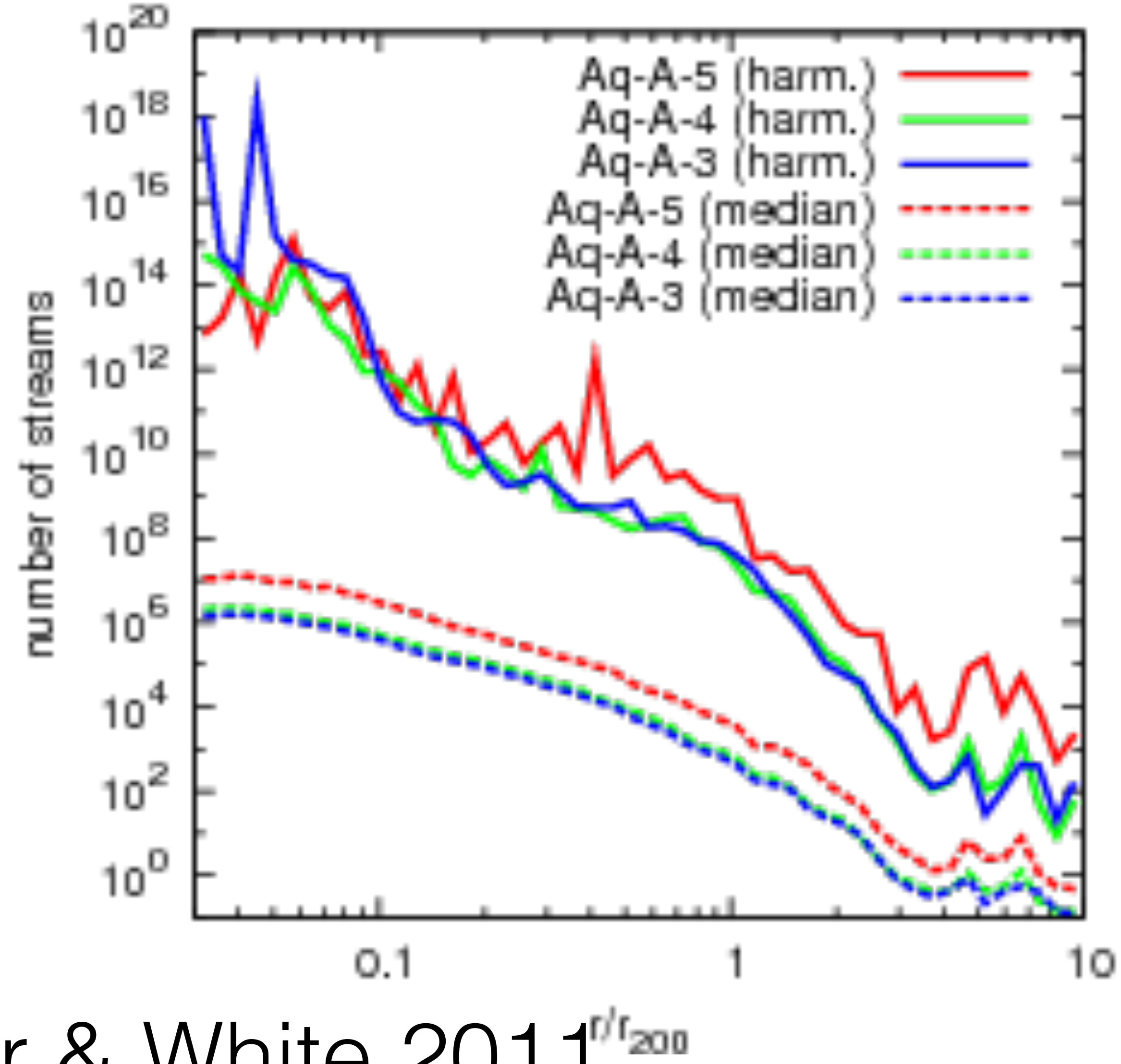


FIG. 10.—Spherical symmetry: instantaneous location of all particles in phase space for $\epsilon = 0.8$.





Vogelsberger & White 2011

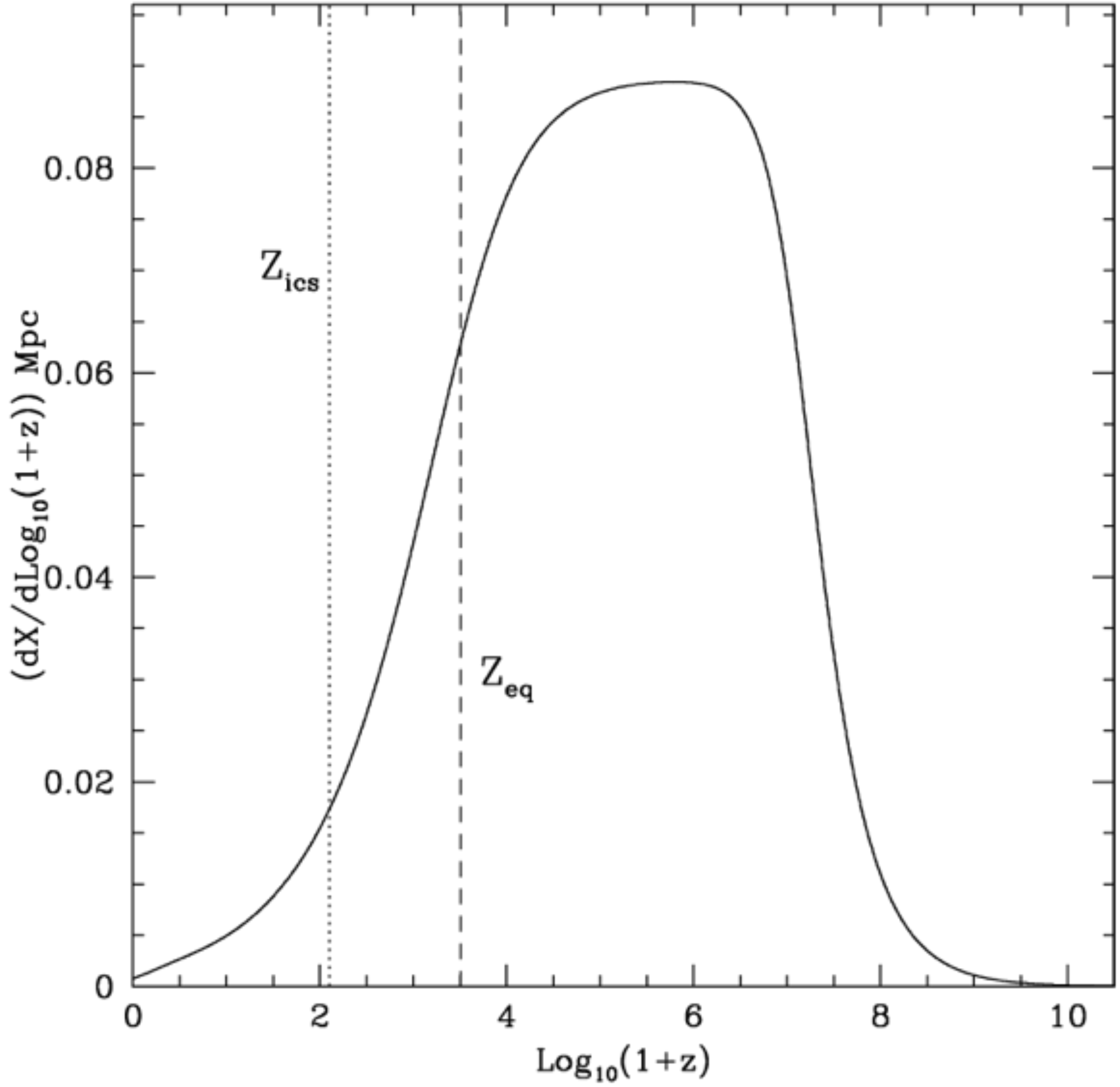
Summary density/velocity distributions

- Dark matter haloes smooth density at the solar radius
- Very small probability the Earth is within a substructure
- Velocity distributions close to Gaussian, but with interesting features at 10% level
- At least a million streams contributing to 50% of the dark matter flux, none more important than ~0.1% of the total flux
- Simulations probably weakly converging - if anything haloes will be even smoother

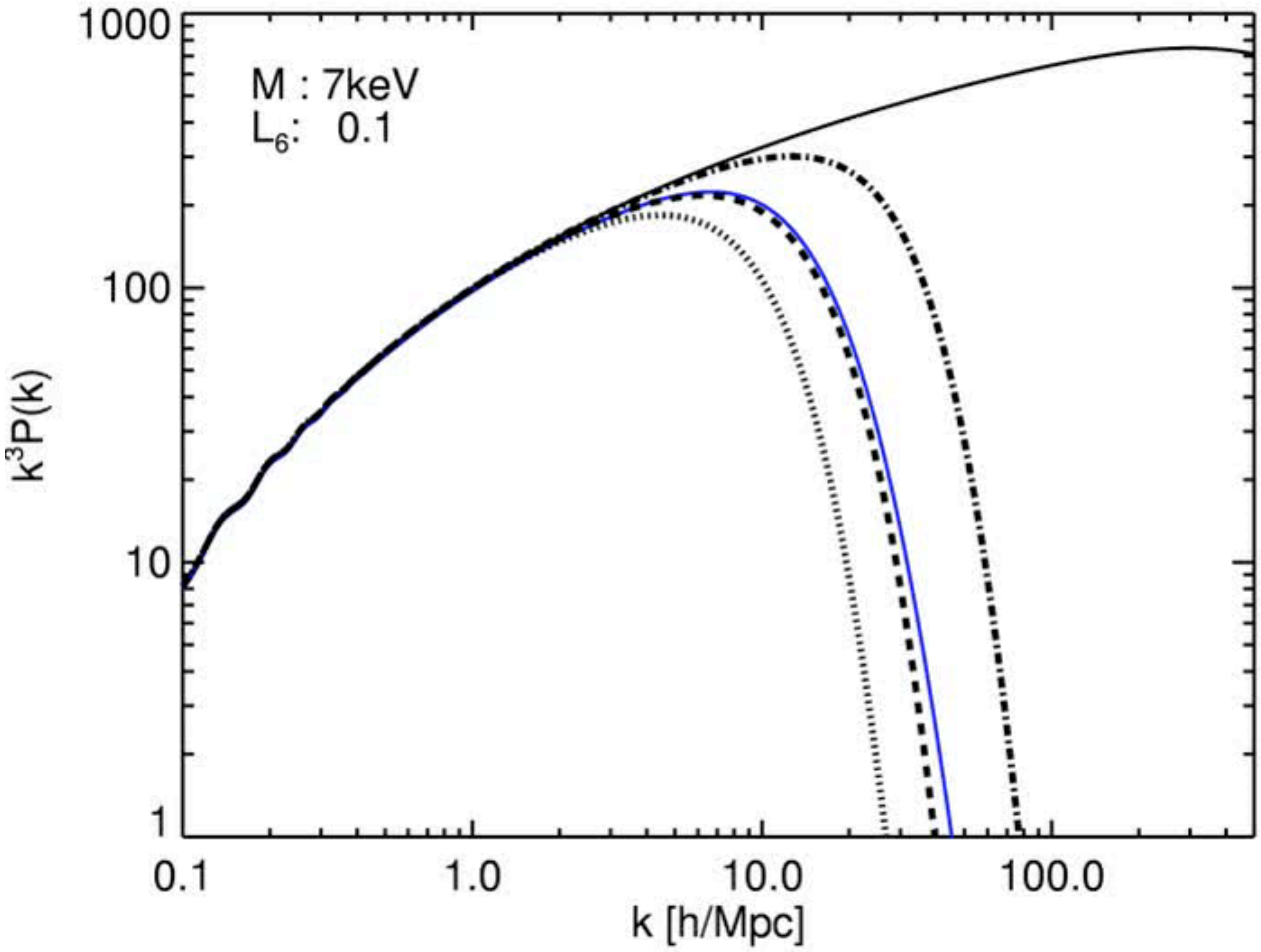
Warm Dark Matter

- Potential candidates for the dark matter e.g. sterile neutrinos (Dodelson & Widrow 1994)

Free streaming



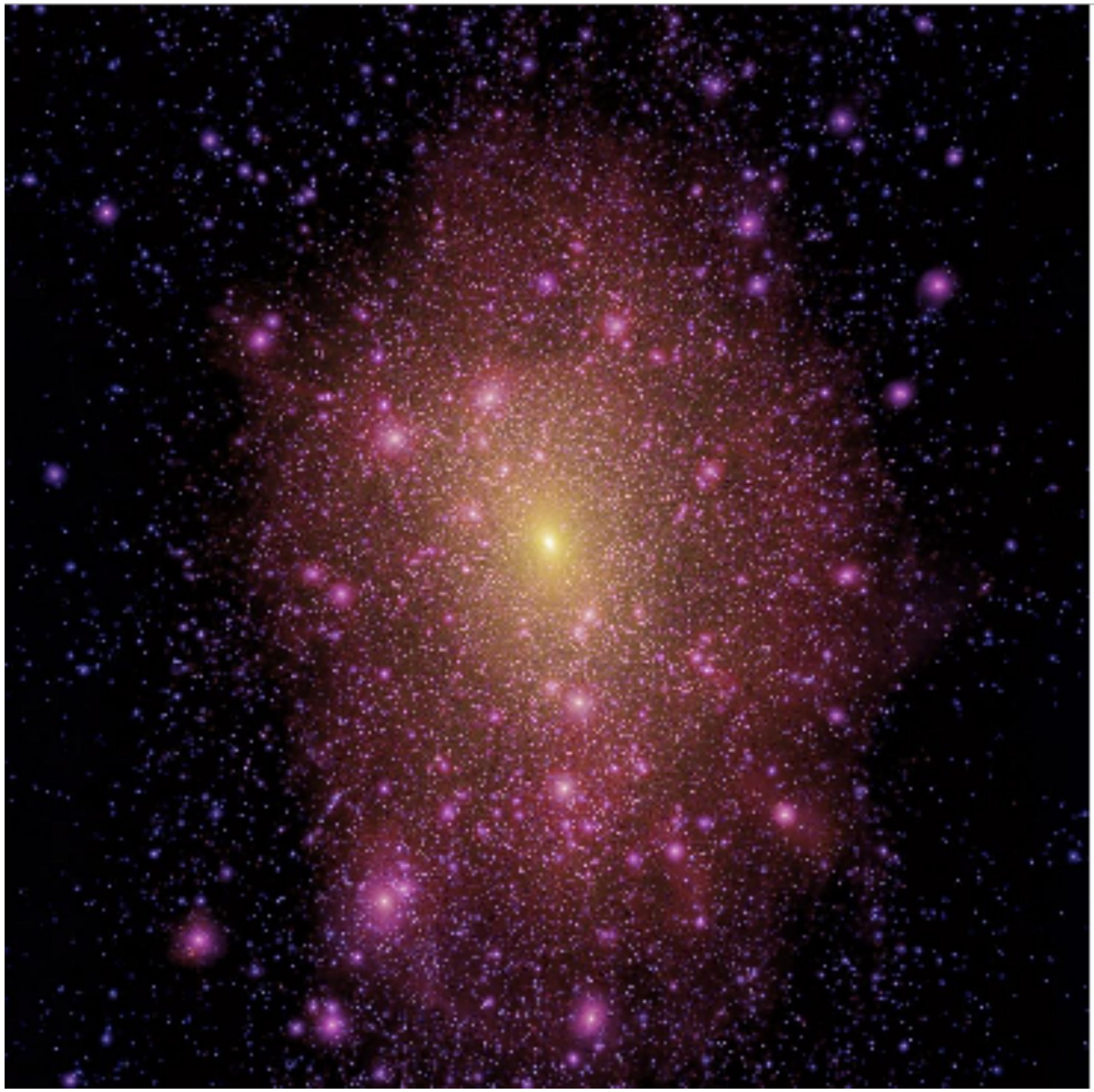
Lovell et al 2012



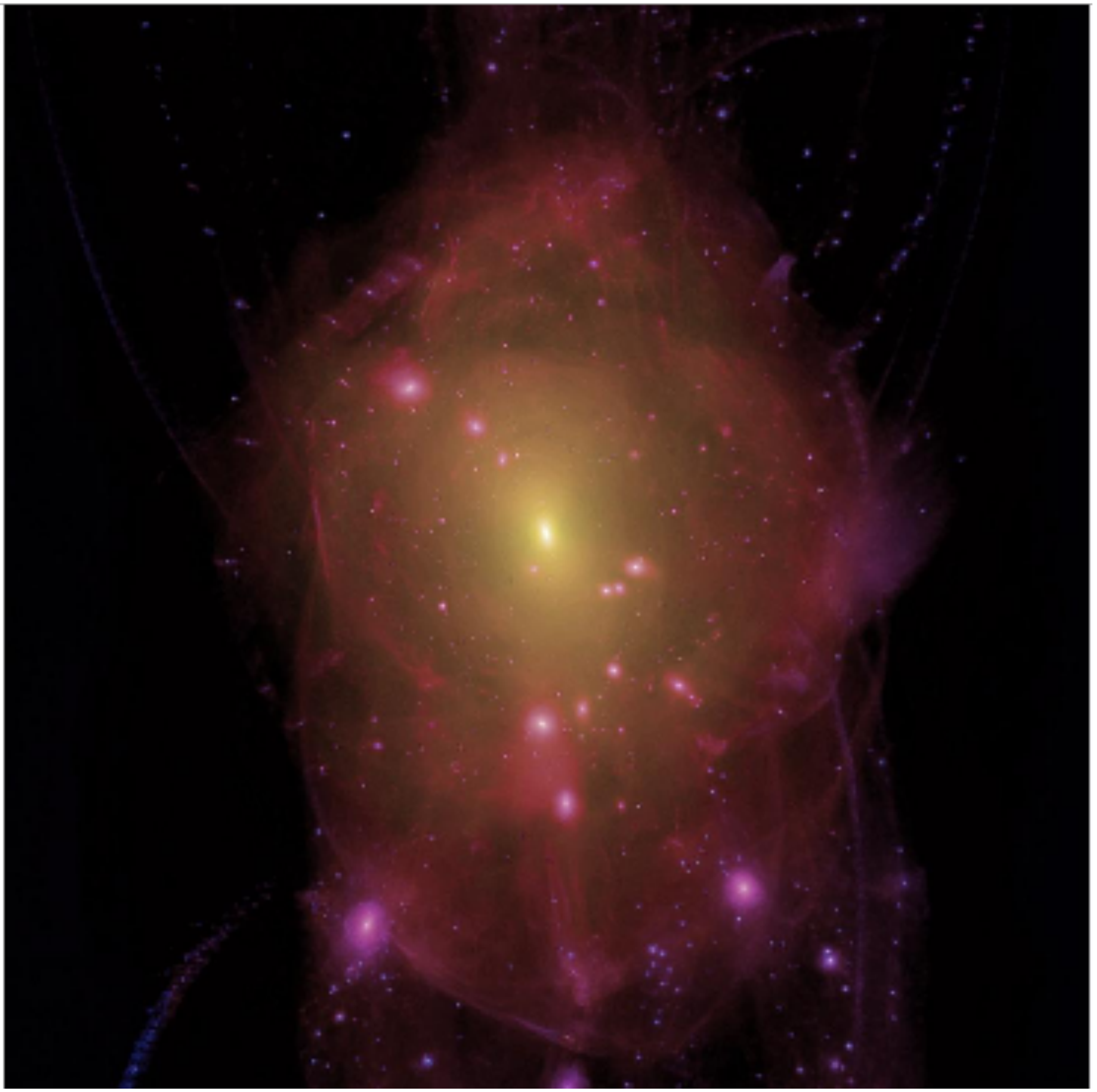
Example: nuMSM power spectra

Source: Lovell, Boyarski, Ruchayskiy

CDM

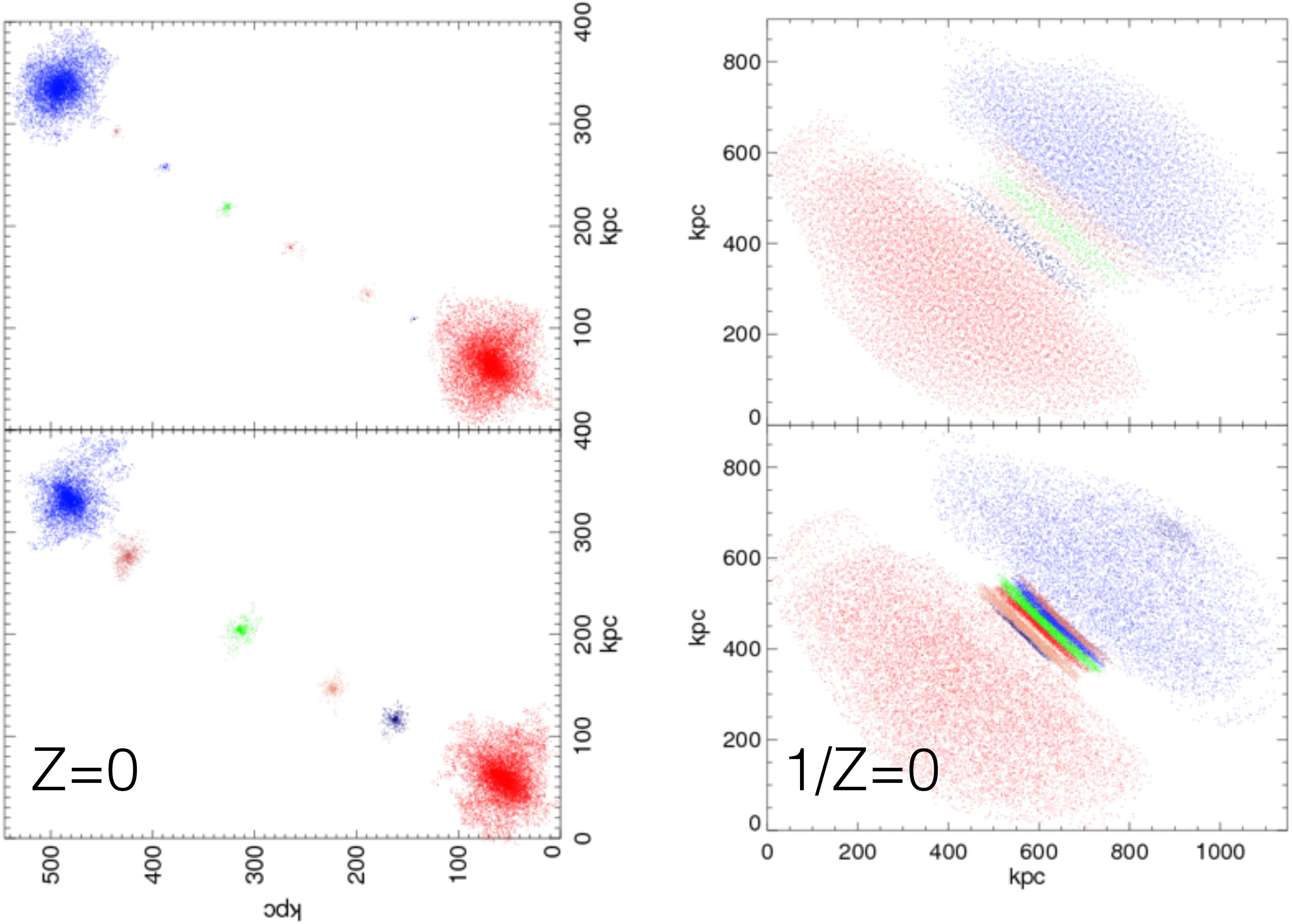


WDM



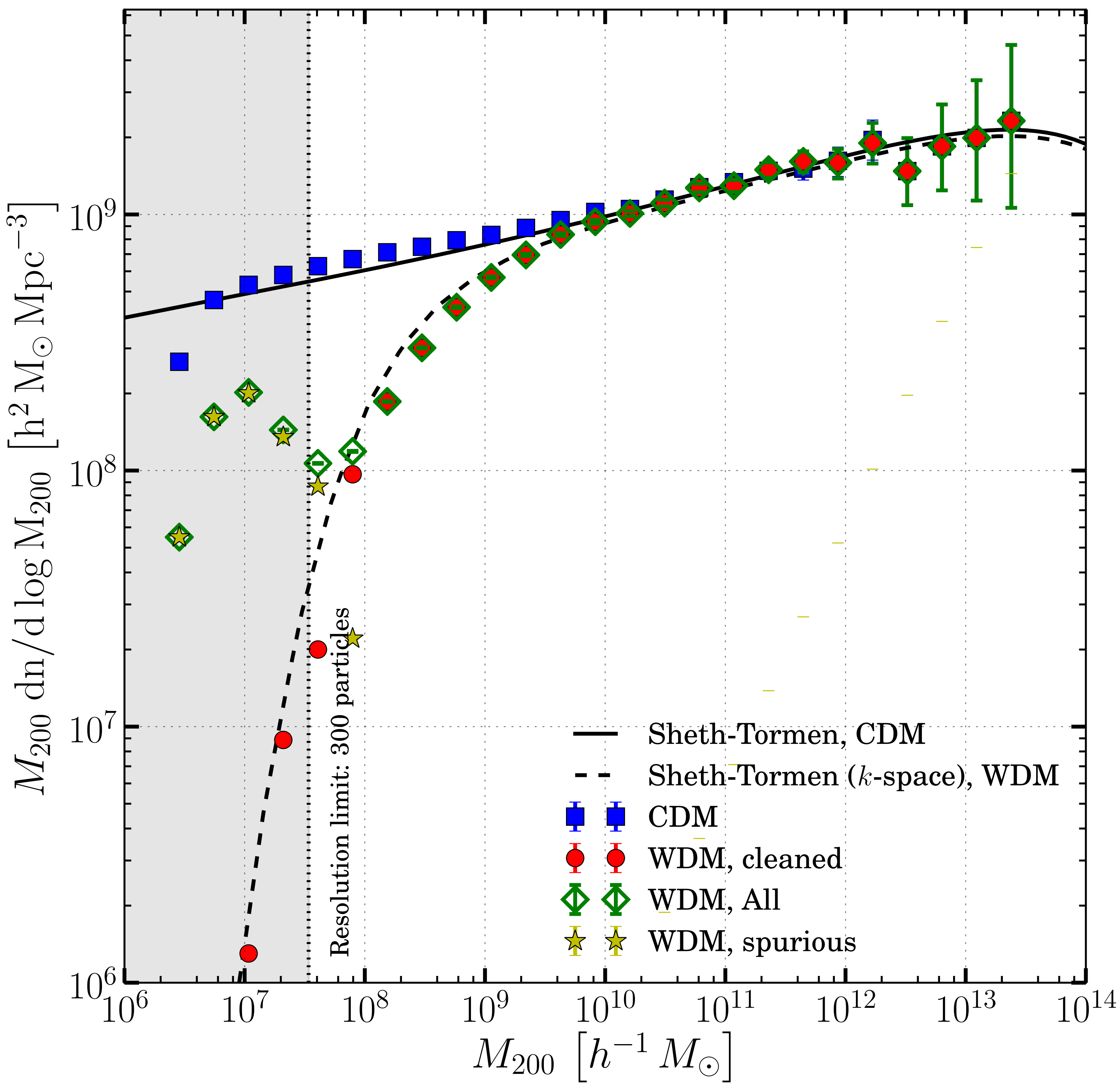
Lovell et al 2012

Spurious structure in WDM



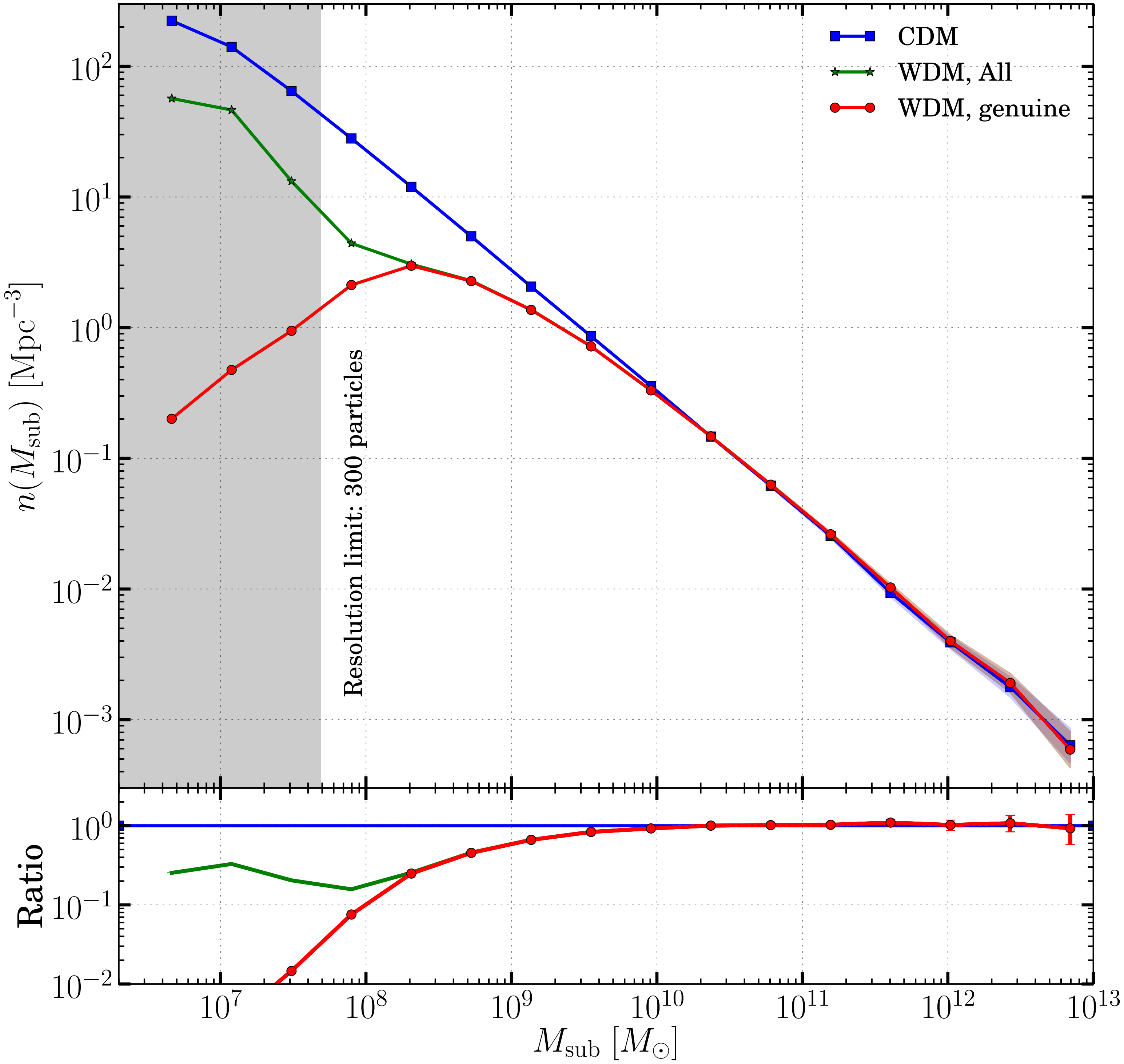
Lovell et al 2014

Halo mass function in WDM



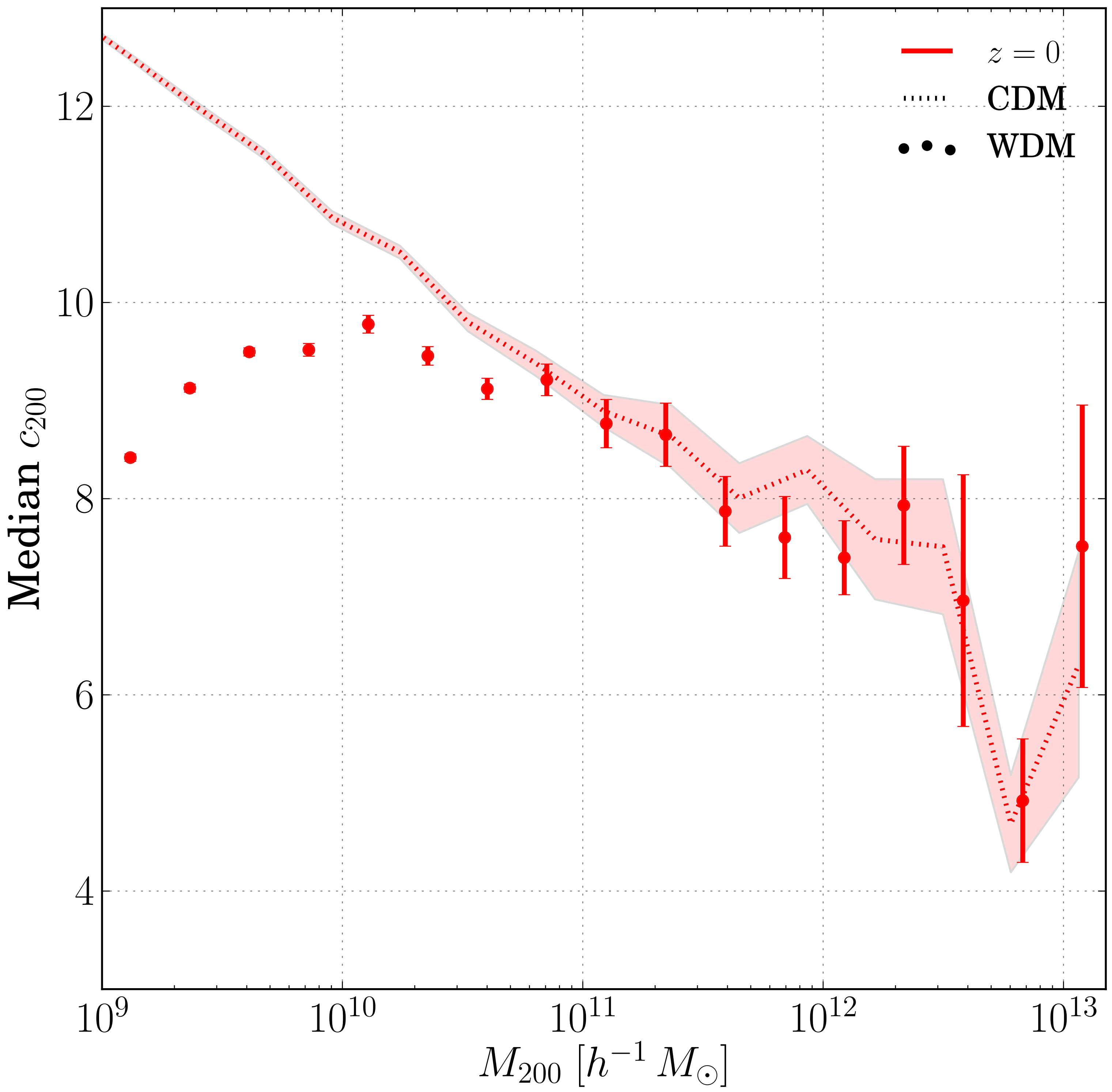
Bose et al 2015 (in prep)

Subhalo mass function in WDM



Bose et al 2015 (in prep)

Mass - Concentration relation



Bose et al 2015 (in prep)

WDM cores

- WDM haloes should have cores
- But core sizes are predicted to be very small (Maccio et al 2012, Shao et al 2013)
- Simulating cores for WDM candidates, which have not been ruled out, is very challenging

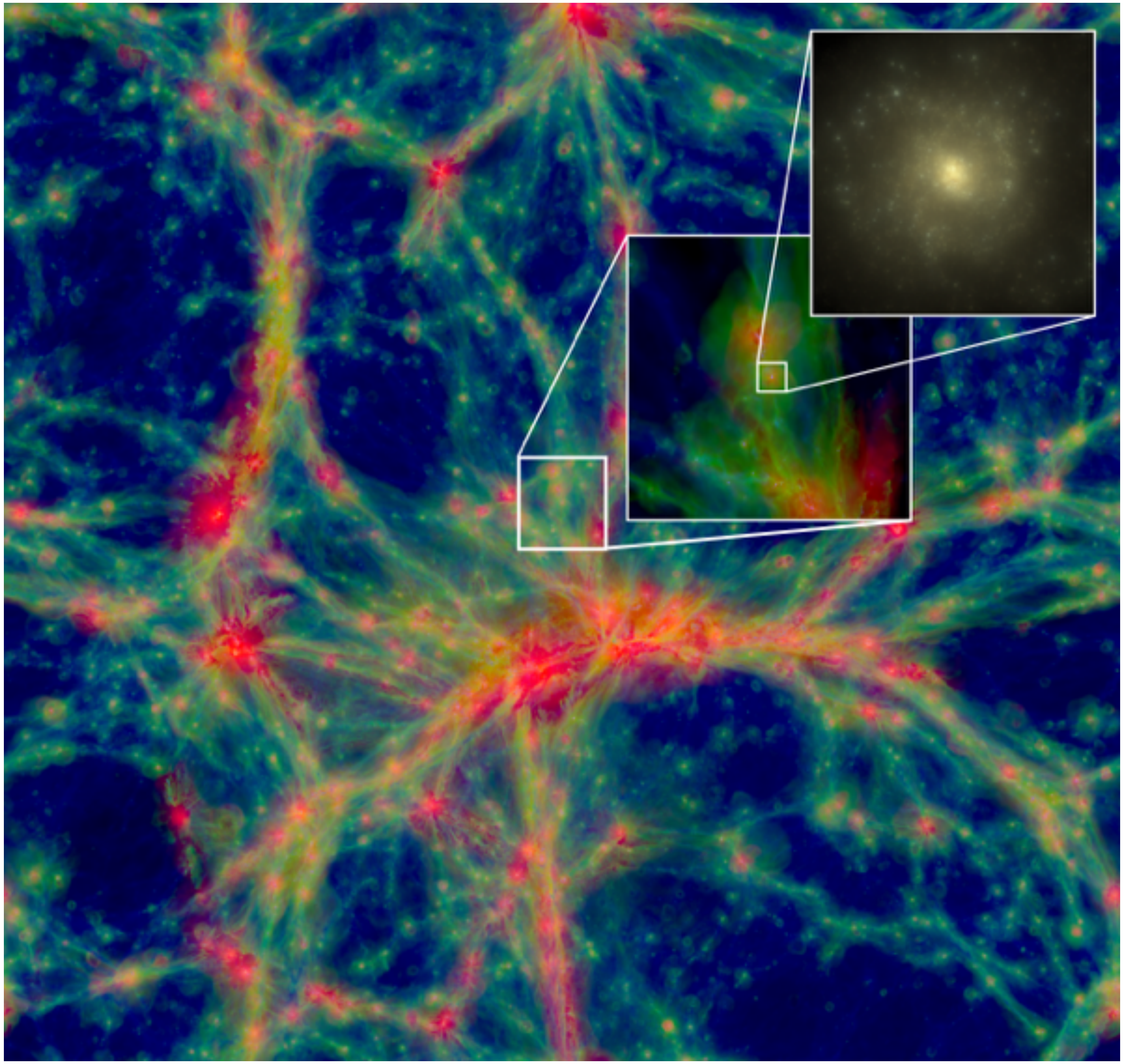
Summary WDM

- Simulating substructure more challenging to model due to fragmentation

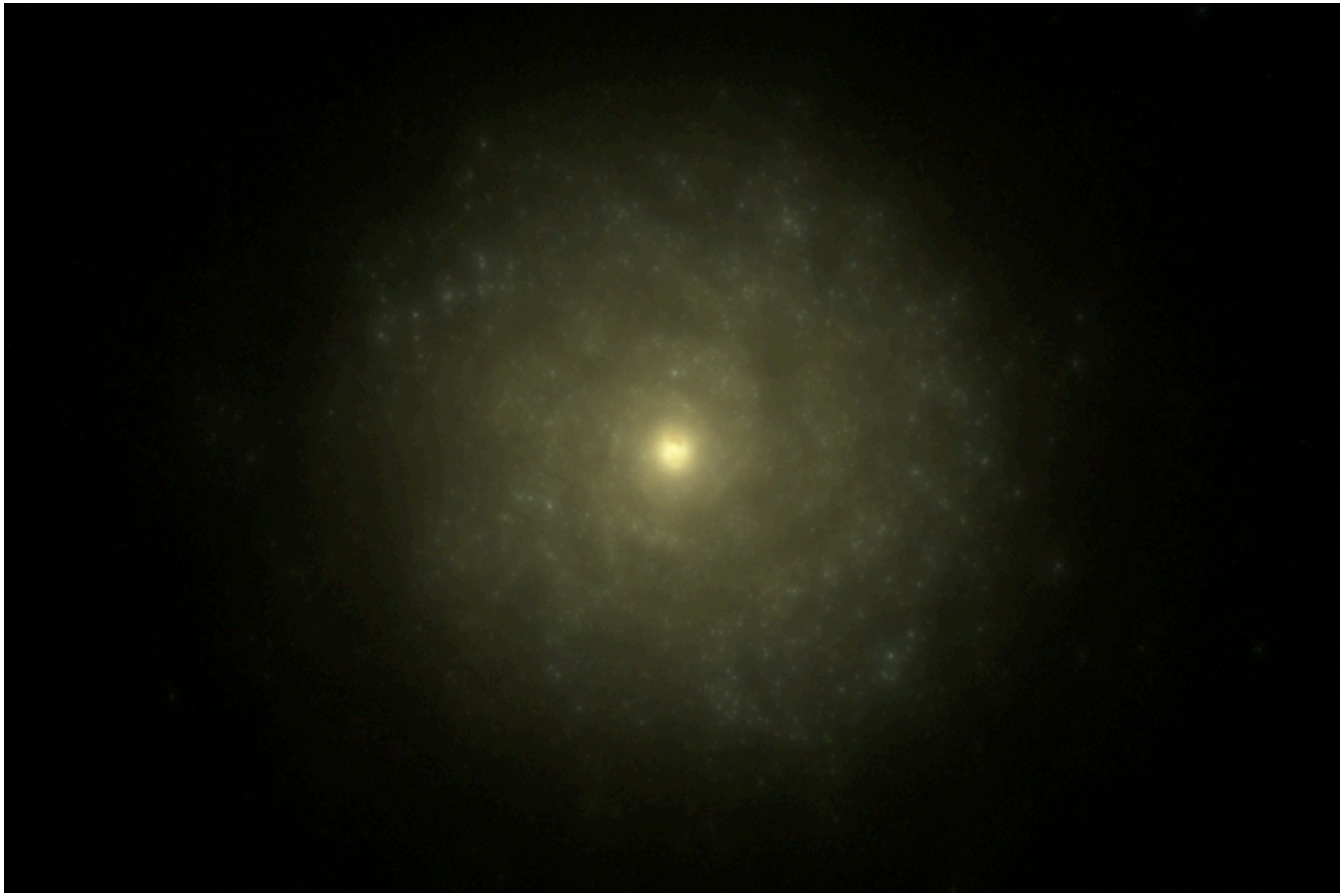
- However substructure is less interesting - not important for predicting decay radiation

- Mass-concentration relation flattens - the central regions of WDM haloes of a given mass form later

Including baryonic physics …



Eagle simulation:
Schaye et al 2015



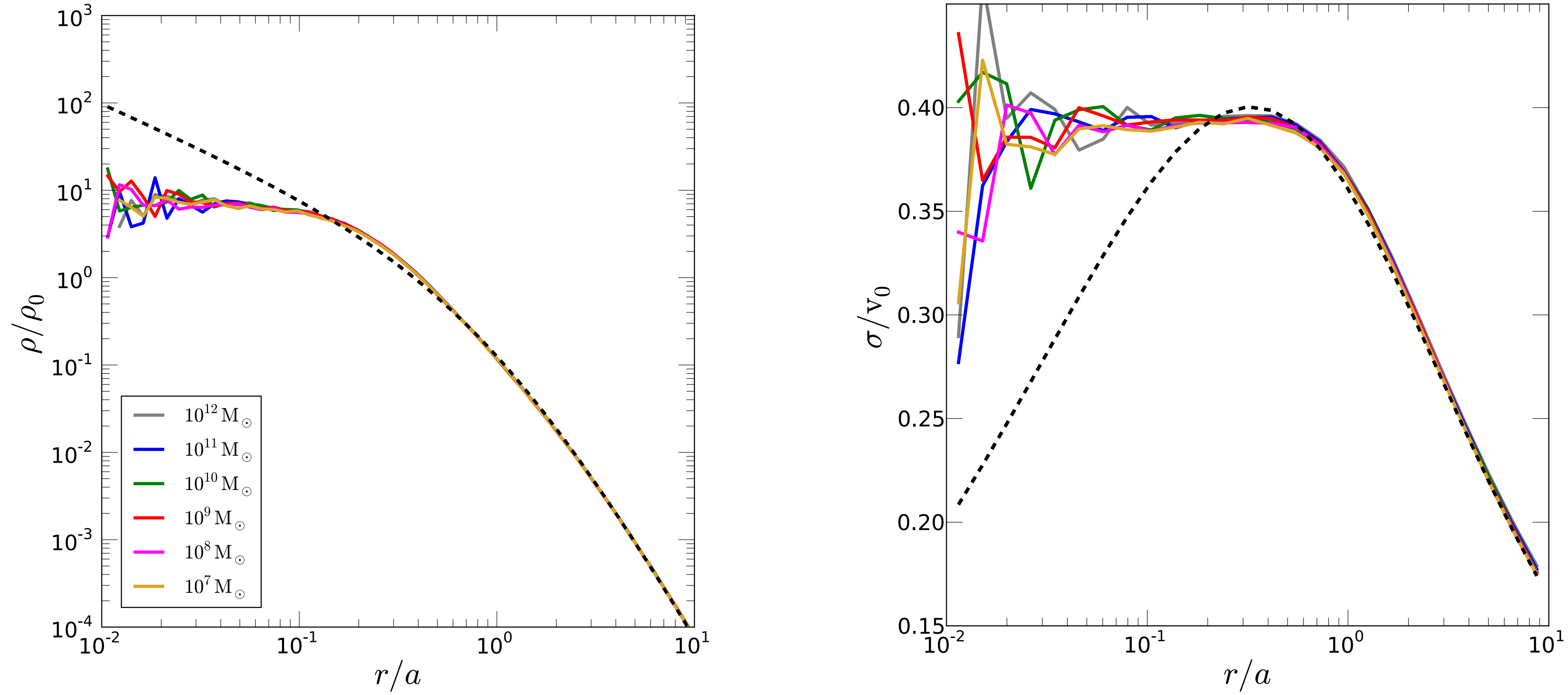
More complicated DM

- Smallest DM structures known are associated with dwarf galaxies

- If CDM correct, galaxy formation is complex - only a proportion of dark matter haloes of a given mass occupied by galaxies, and galaxy formation may affect the structure of these haloes - e.g. changing cusps to cores

- Alternatively DM may be more complex - e.g. Self-Interacting Dark matter, Psi-CDM

S.I.D.M.



Vogelsberger, Zavala, Loeb 2012

Summary

- N-body methods crucial to understanding the structure of dark matter on small scale
- CDM - extremely rich structure. At the solar circle DM expected to appear smooth and near Gaussian velocity distributions
- CDM - substructure important for annihilation radiation predictions - but still significant uncertainty in predictions
- WDM - substructure hard to model accurately for numerical reasons.
- Modelling baryonic processes may be essential for making accurate predictions for haloes around galaxies

Future directions for N-body modelling of structure

- CDM: Mass-concentration relation and density profiles of the smallest haloes in CDM over the whole mass range is not well determined. More work is needed …

- WDM: Properties of substructures not that well determined - new methods may be required - e.g. T4PM (Hahn & Angulo arXiv:1501.01959)

- This field would be revitalised if dark matter is detected …

THE END

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