The successes and limitations of N-body simulations in the large surveys era

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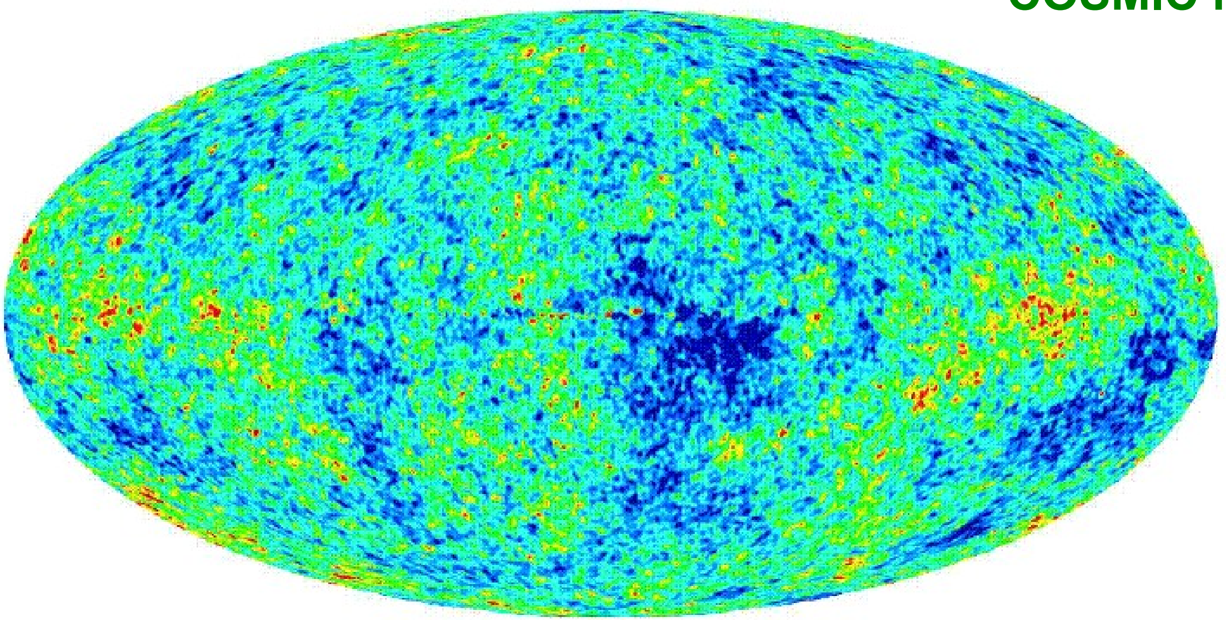
LCDM

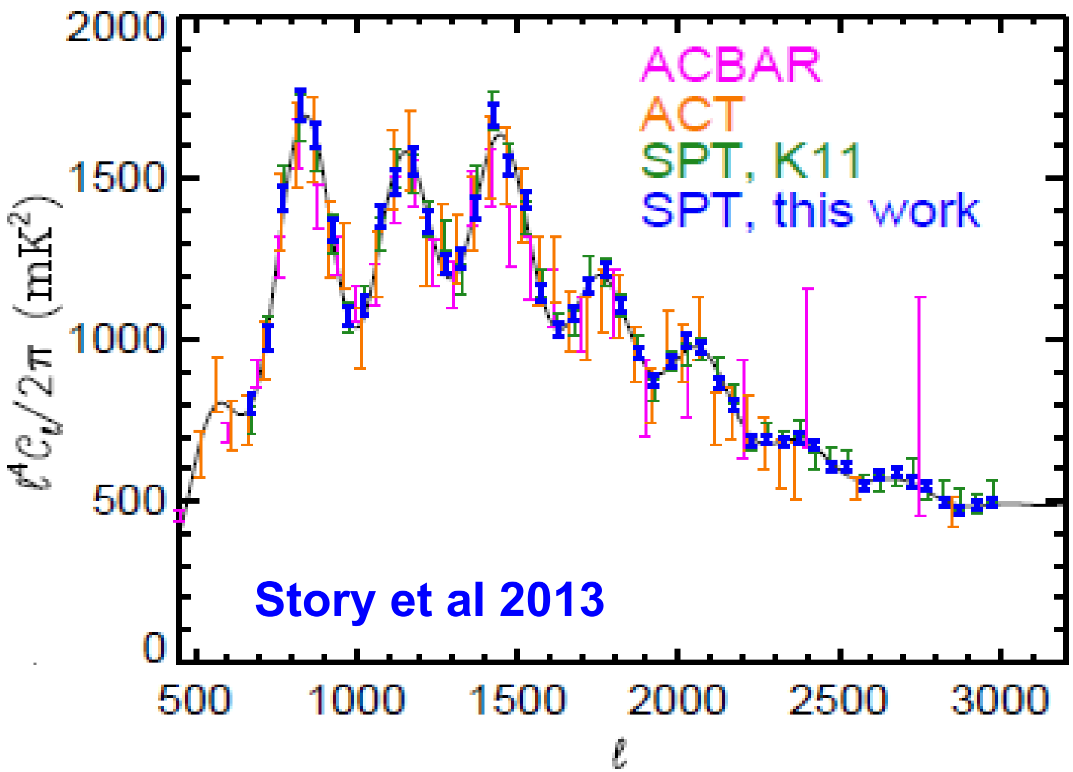
I) General Relativity
II) Dark Matter
III) Cosmological Constant
IV) Gaussian initial fluctuations

COSMIC MICROWAVE BACKGROUND

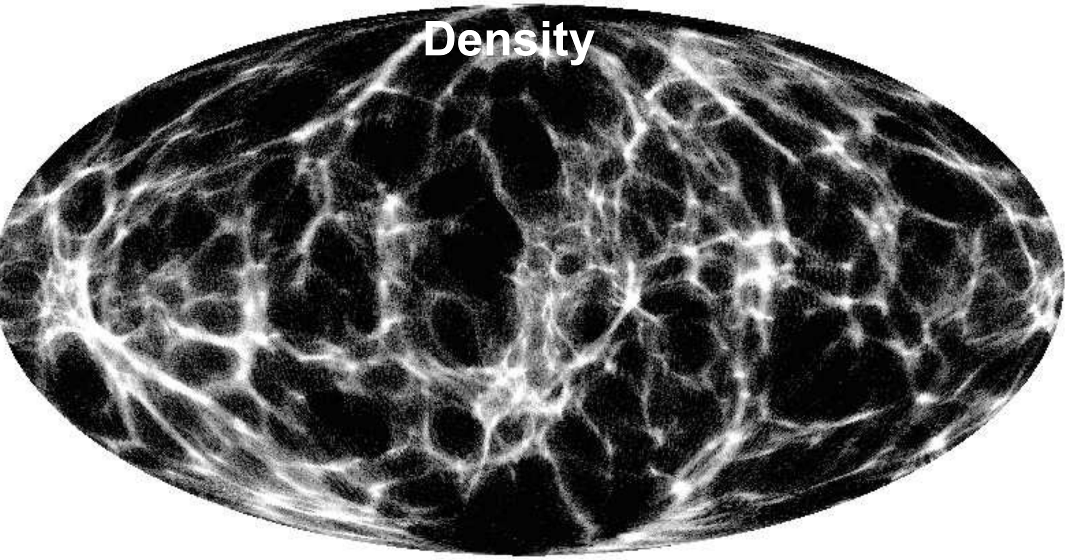


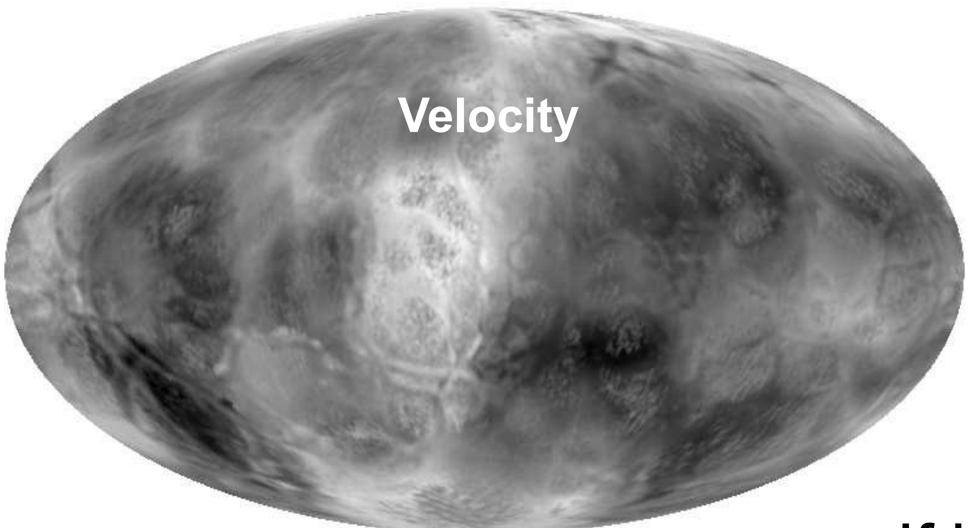
The fluctuations in the CMB “detect” DM at a 20 sigma level!

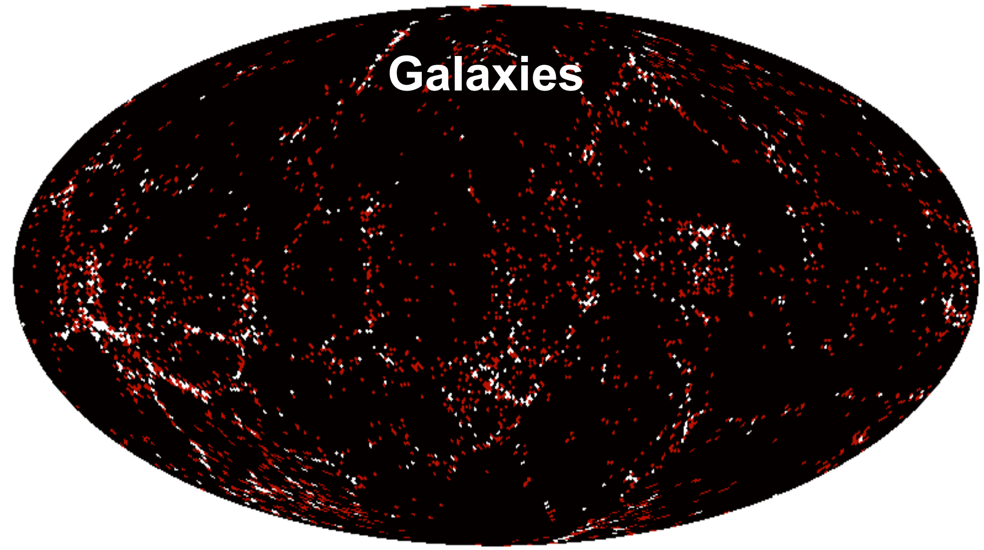
They also require:
- Flat geometry
- Lambda



THE LOCAL UNIVERSE FROM 2MASS



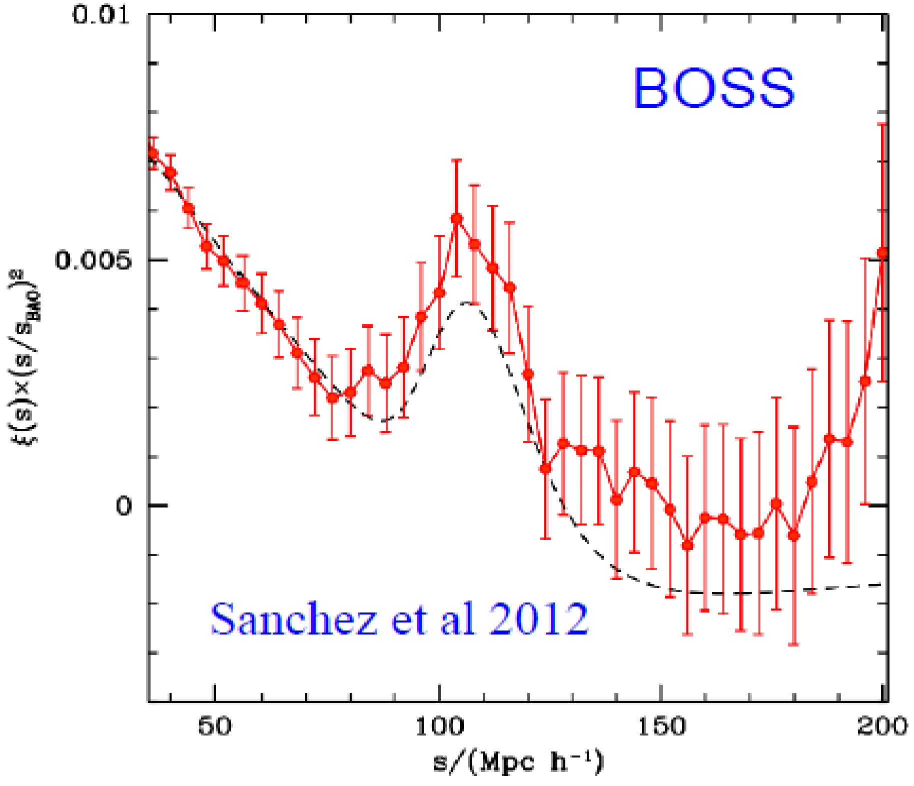


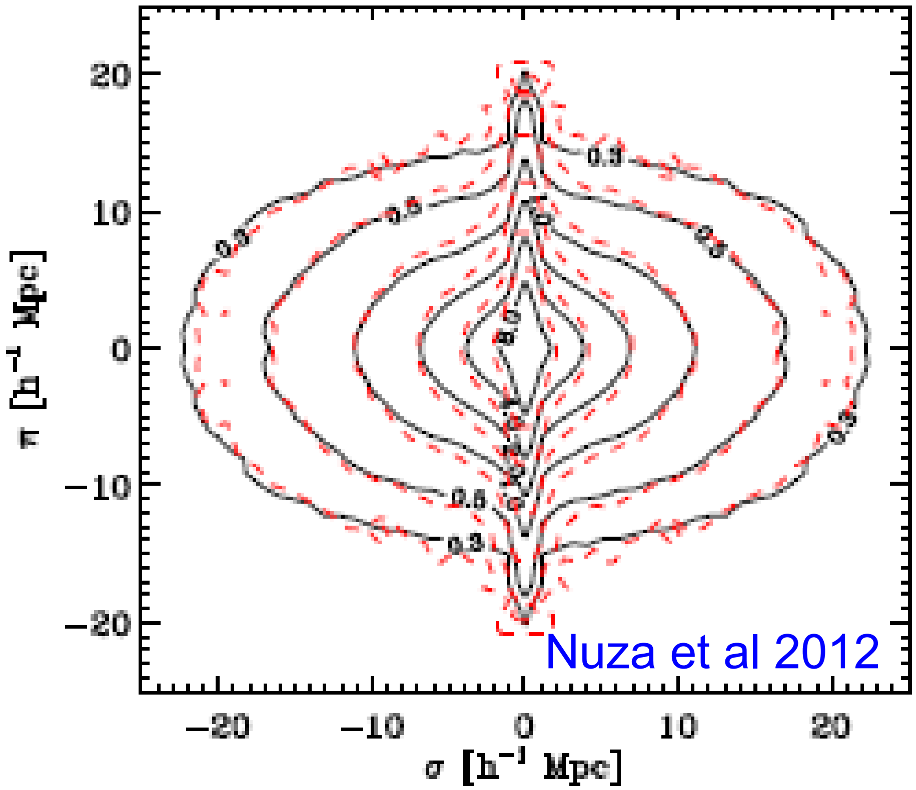


Kitaura & Angulo 2012
Kitaura, Angulo et al 2012
Kitaura et al 2012

If LCDM (GR & low-Ωm) holds at z=0, then the bulk velocity (speed and direction) of the local group matches that measured in the CMB

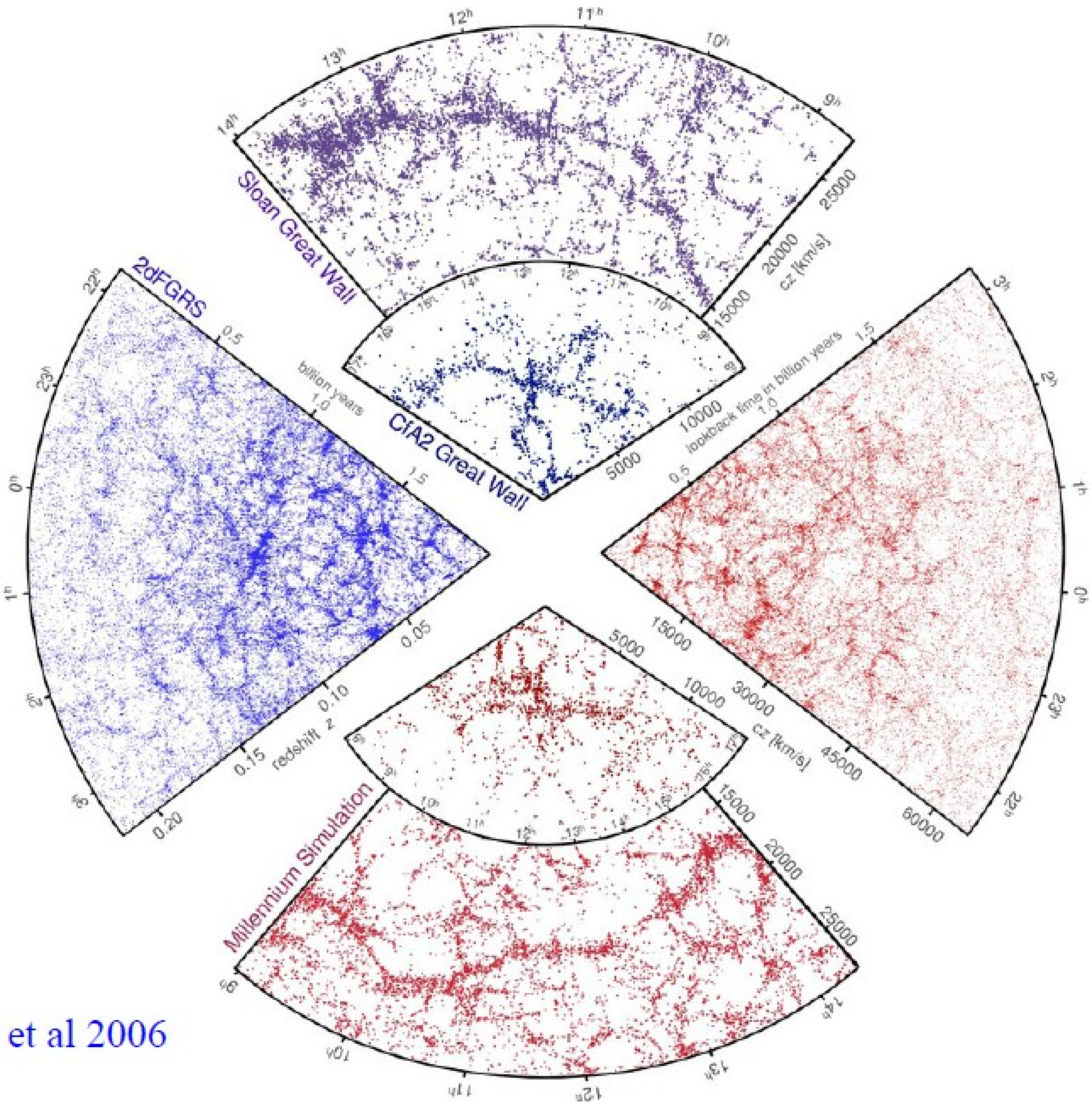
REDSHIFT SPACE DISTORTIONS AND BAO IN THE CMASS BOSS SAMPLE





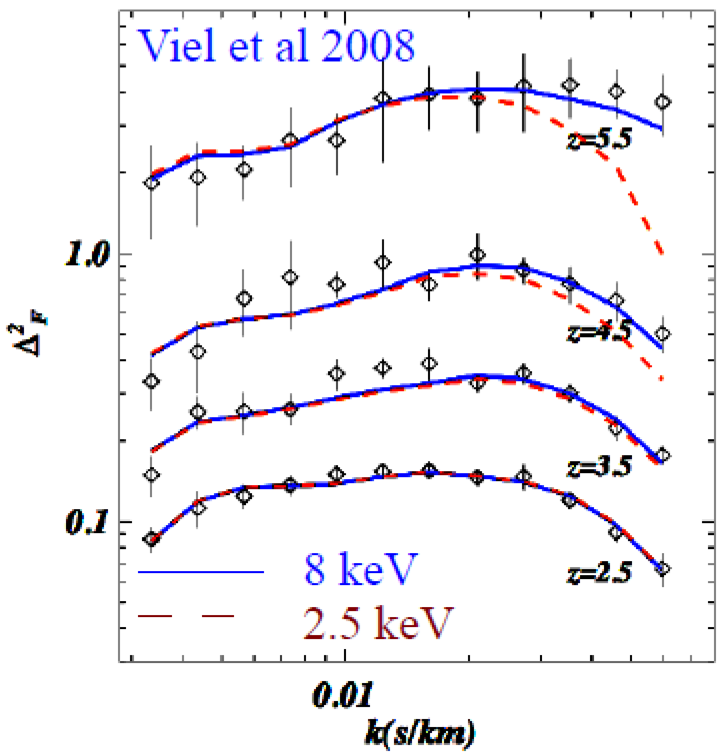
The spatial distribution of galaxies matches the expectations of a LCDM model and a simple prescription for galaxy formation

Semi-analytic models of galaxy formation and N-body simulations
Also match the topology of the large-scale structure of galaxies

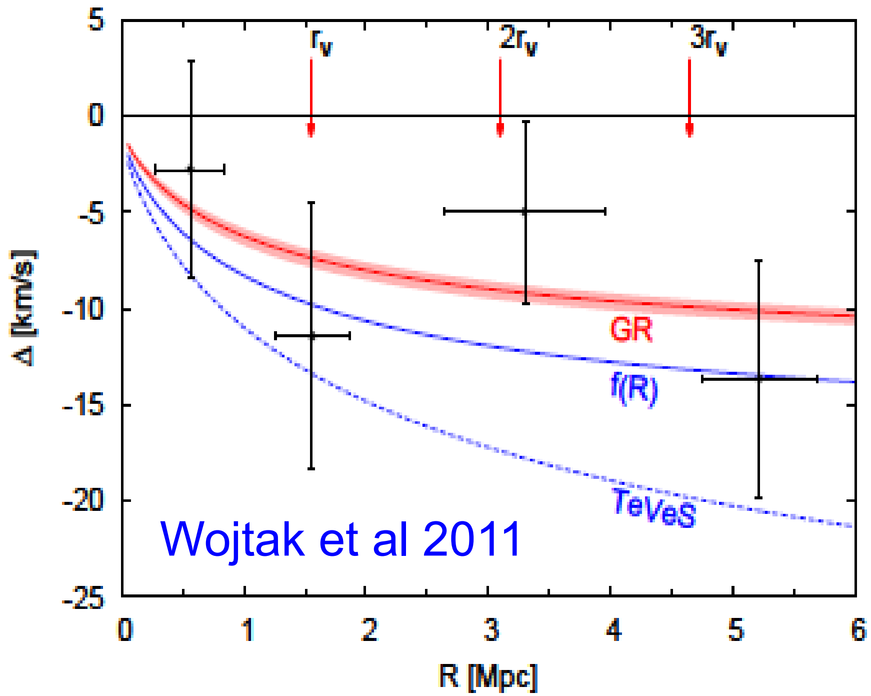


Springel et al 2006

Ly-alpha forest



Gravitational redshifts in clusters



and Weak Lensing, Galaxy clusters, ISW, etc

Numerical simulations (of different degrees of sophistication) have been essential in developing and understanding all these probes, and thus in establishing LCDM.

The unknowns of a LCDM Universe

I) Nature of Gravity

f(R) or GR?

II) Dark Matter

Cold or Warm? Free streaming scale?

III) Accelerated expansion of the Universe

Cosmological constant or w(z)?

IV) Properties of the initial fluctuations

Any primordial NonGaussianity?

Many tests can be carried out using *only* galaxies' position:

WiggleZ
BOSS
DES
HEDTEX
MS-DESI

J-PAS
EUCLID
LSST
FastSound

N-body simulations have been essential in establishing the LCDM as a viable cosmological model. In the future they will be essential too in confirming it or ruling it out

Outline

The connection between observables and cosmology:
The impact of galaxy physics in BAO measurements

Cosmological constraints:
Using N-body simulations to measure cosmology

Limitations of N-body simulations:
the Warm DM case

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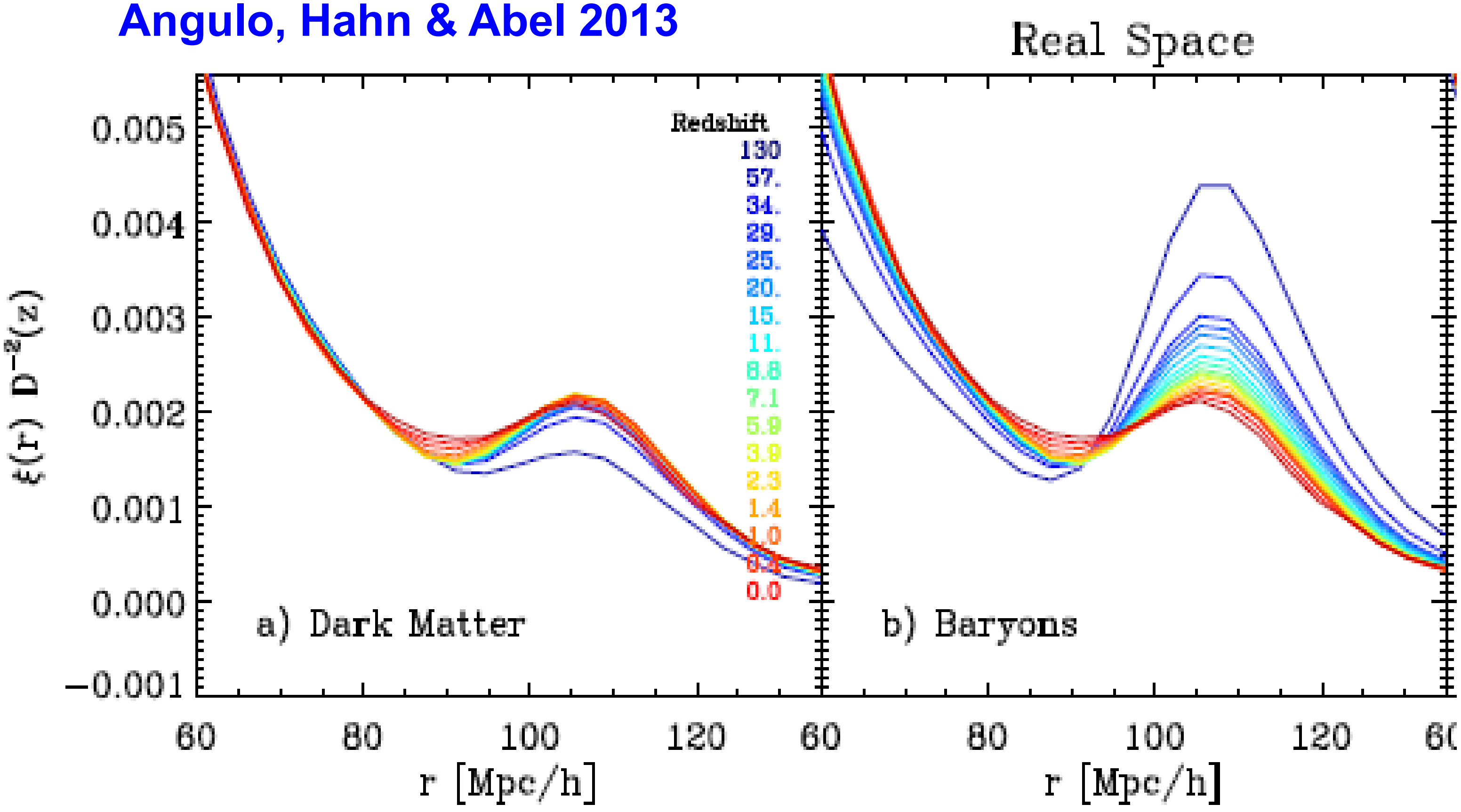
Acoustic peaks seen in the CMB are also present in the baryons, and later they will be gravitationally imprinted into the DM distribution

Angulo, Hahn & Abel 2013



High redshifts

Low redshifts

Does galaxy formation physics affect BAO measurements?

- Assembly bias (correlations with environment)
- Galaxies form in halos
- Density and tidal fields affect halo formation
- Velocity biases
- Different merger histories for satellite/central gals

Requirements

Create a "fake" experiment as realistically as possible, and more accurate than the real data!

The galaxy density field, over a larger volume and resolving all galaxies, to be observed by JPAS, EUCLID, MS-DESI, etc

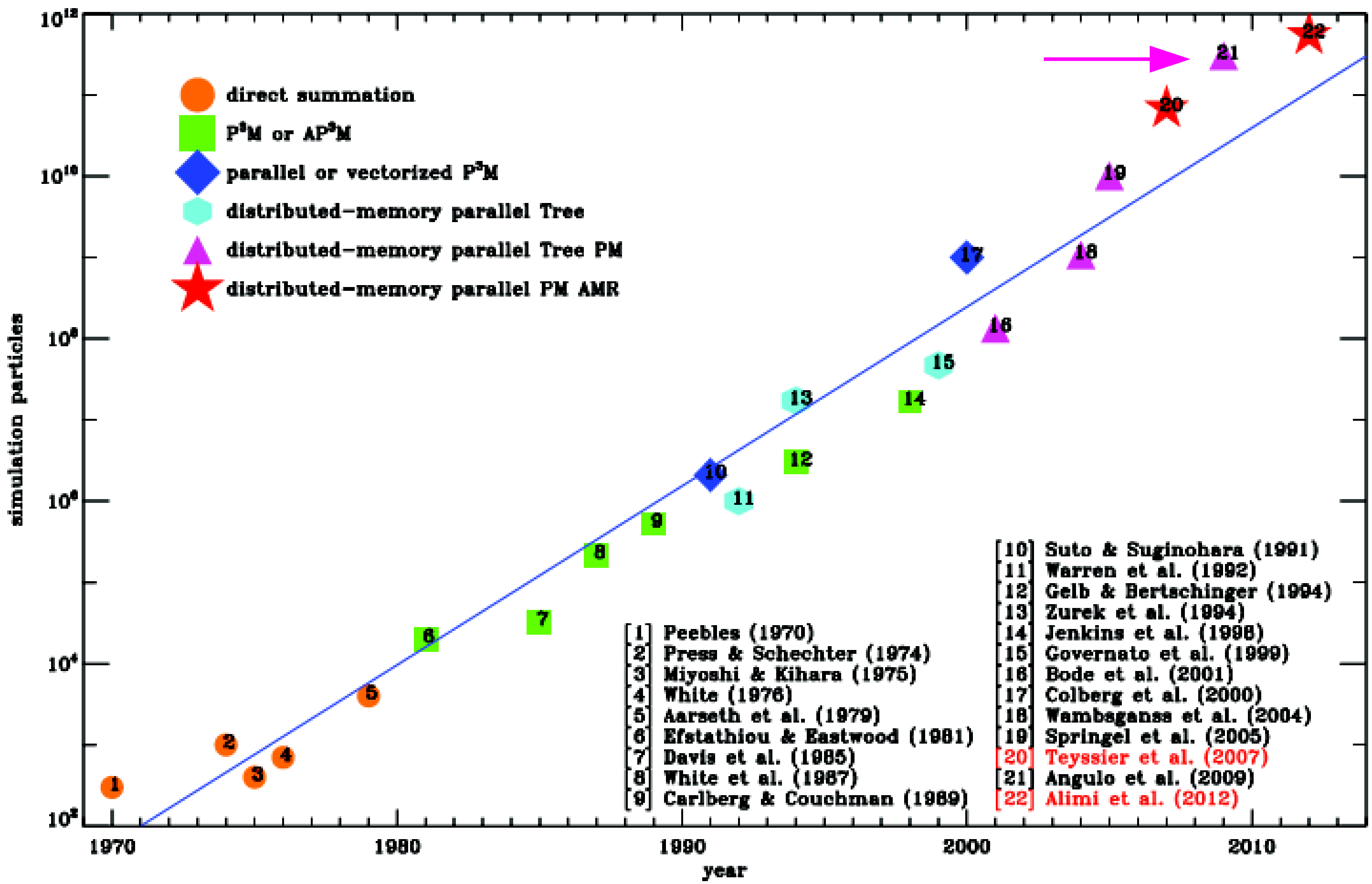
1. **Simulate the nonlinear mass density field**
2. **Follow galaxy formation and evolution.**
3. **Apply the observational setup**

Angulo et al. 2013, in prep

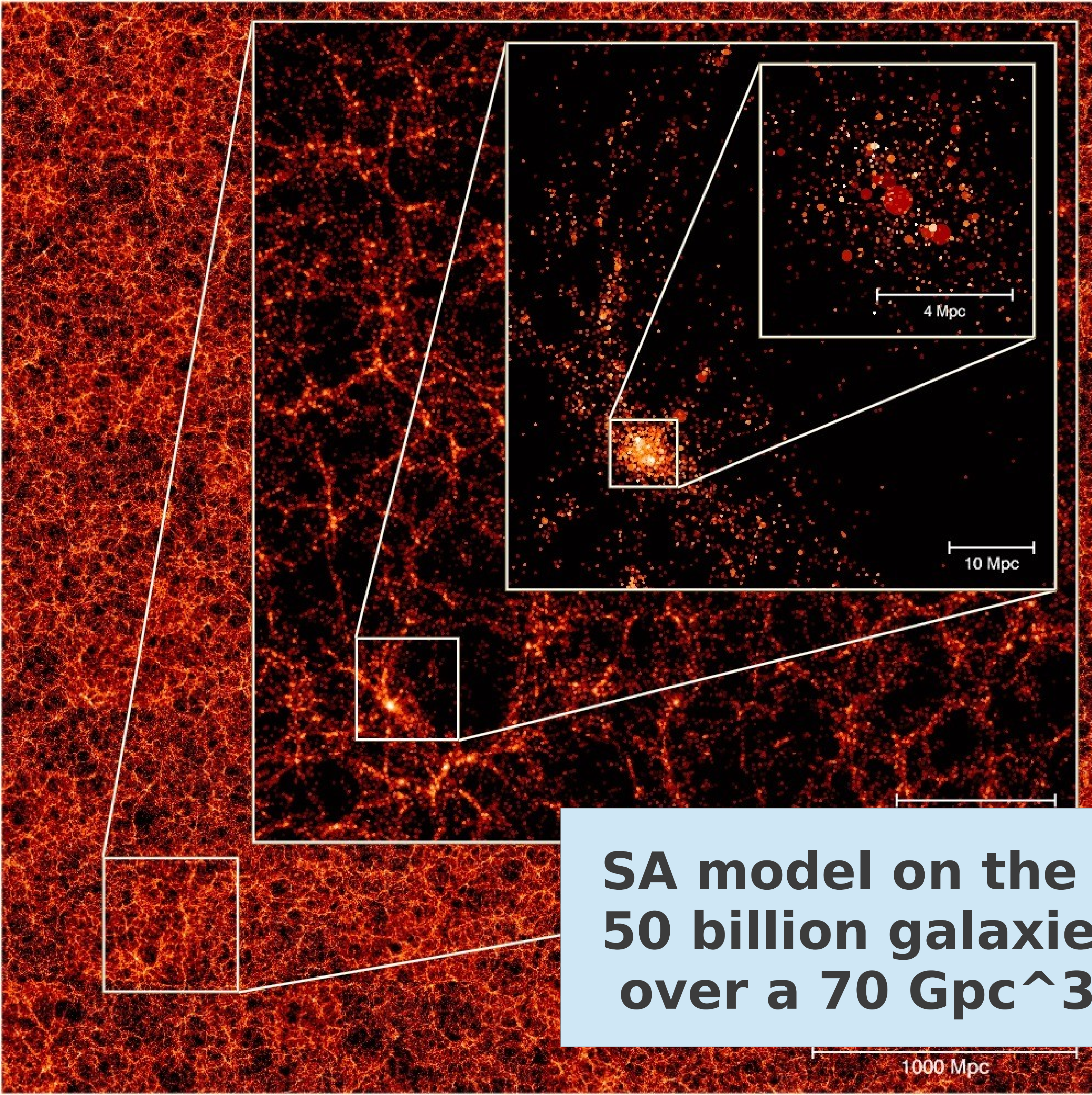
The Millennium-XXL

Volume comparable to (or larger than) LSS surveys
Mass resolution high enough to model galaxies

- Volum
- # parti
- Partic



Angulo et al 2012a



SA model on the MXXL:
50 billion galaxies at z=0,
over a 70 Gpc^3 volume

The Millennium run Observatory

(Overzier, Lemson, RA, Henriquez, Marleau & White, 2012)

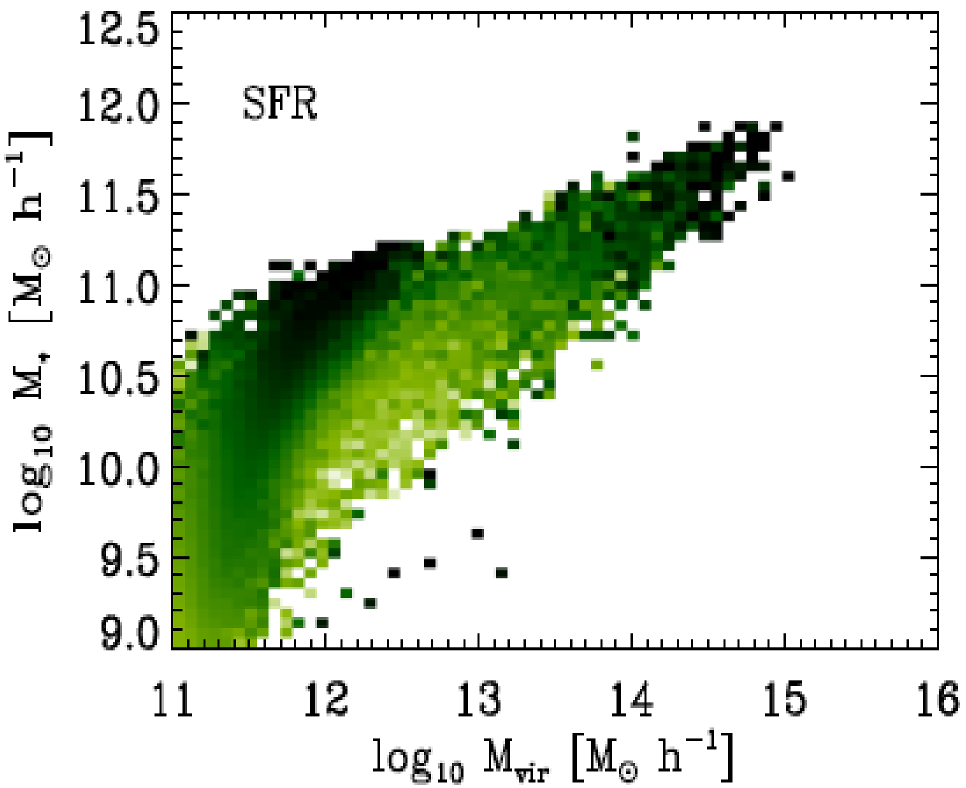
Does galaxy formation physics affects the BAO measurements?

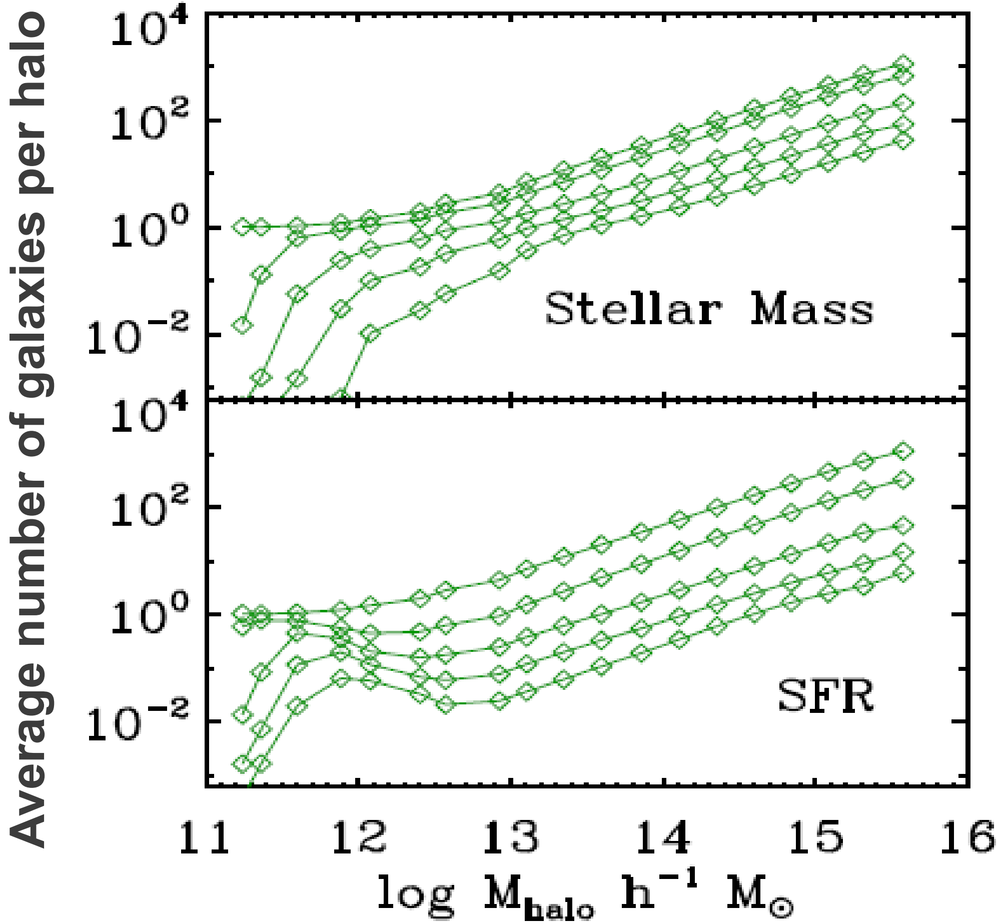
Assembly bias (correlations with environment)
Galaxies form in halos
Density and tidal fields affect halo formation
Velocity biases
Merger histories matter for satellite/central

Two catalogues
- Stellar Masses (BOSS)
- Star Formation Rates (EUCLID)

The relationship between haloes and galaxies

STELLAR MASS TRACES HOST HALO MASS, BUT SFR CORRELATES MORE STRONLY WITH THE CENTRAL BLACK HOLE MASS

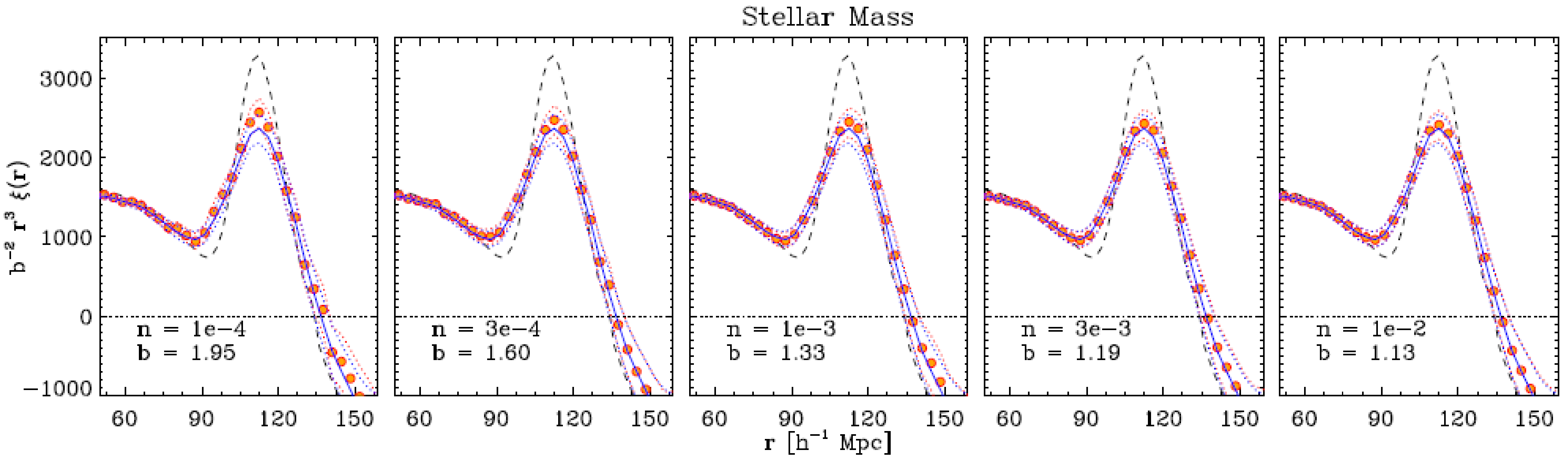




Angulo et al 2013

The BAO peak in the galaxy field

CORRELATION FUNCTION OF SAMPLES IN THE MXXL SIMULATION



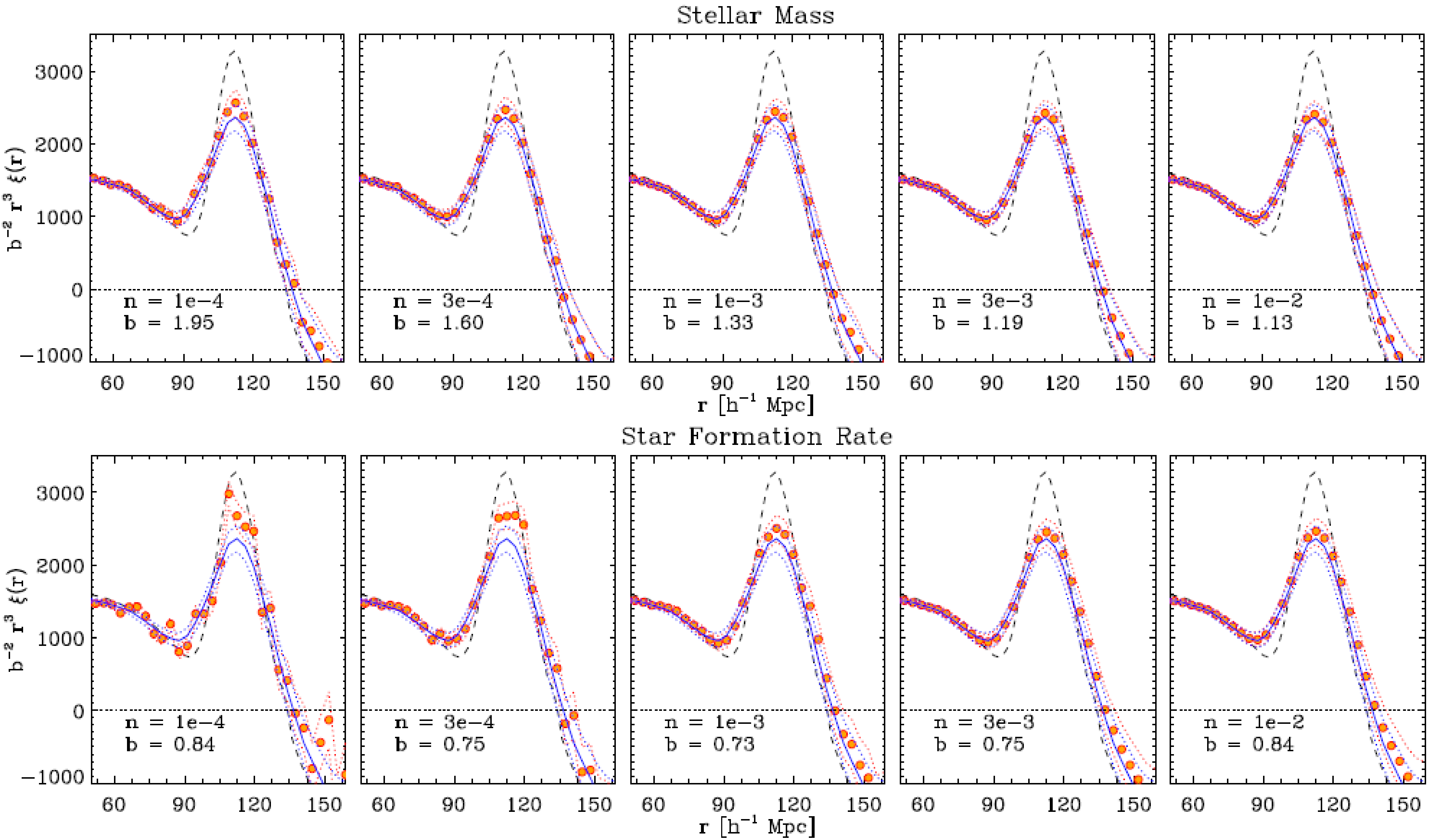
Dashed: Linear Theory

Blue: Dark Matter

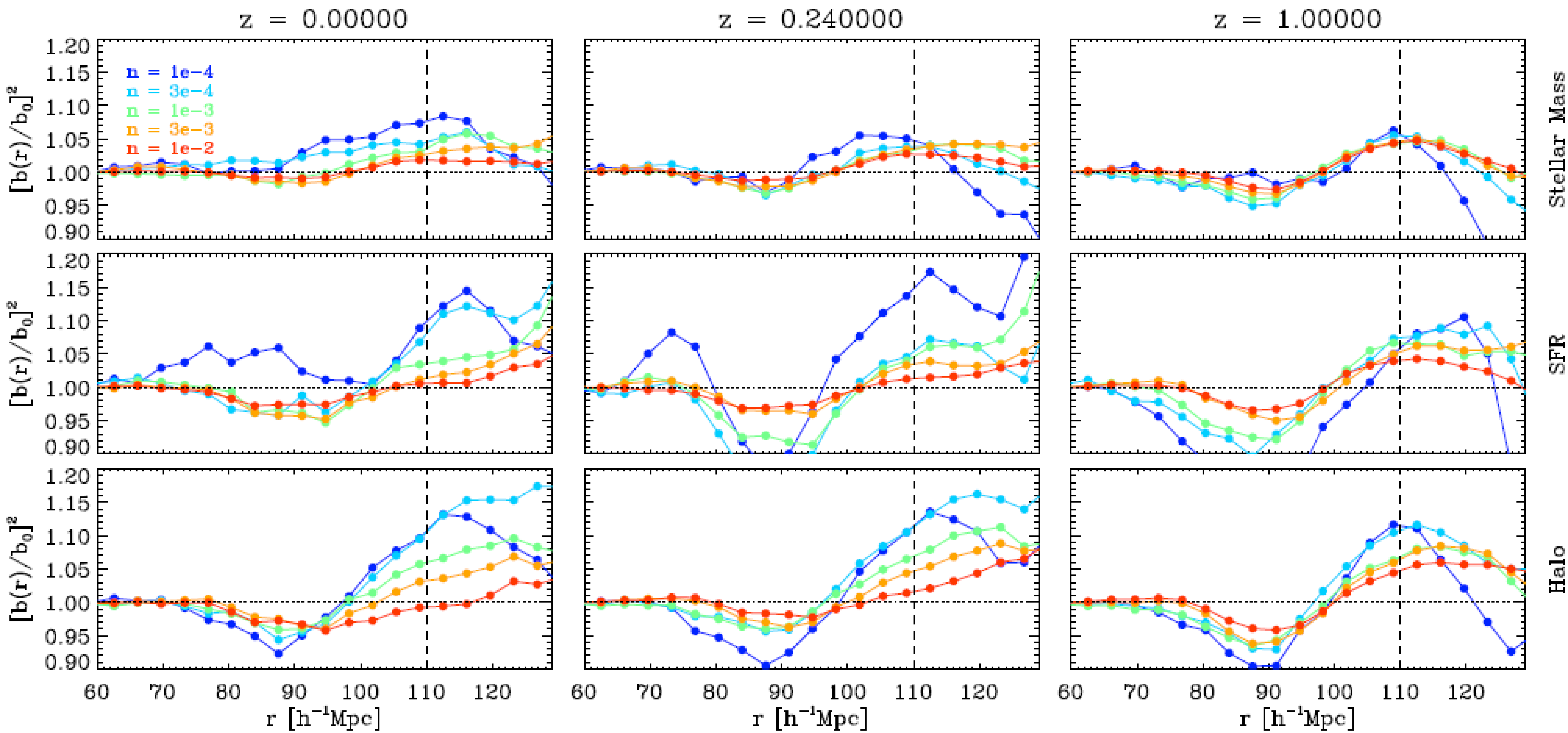
Circles: Galaxies

The BAO peak in the galaxy field

CORRELATION FUNCTION OF SAMPLES IN THE MXXL SIMULATION



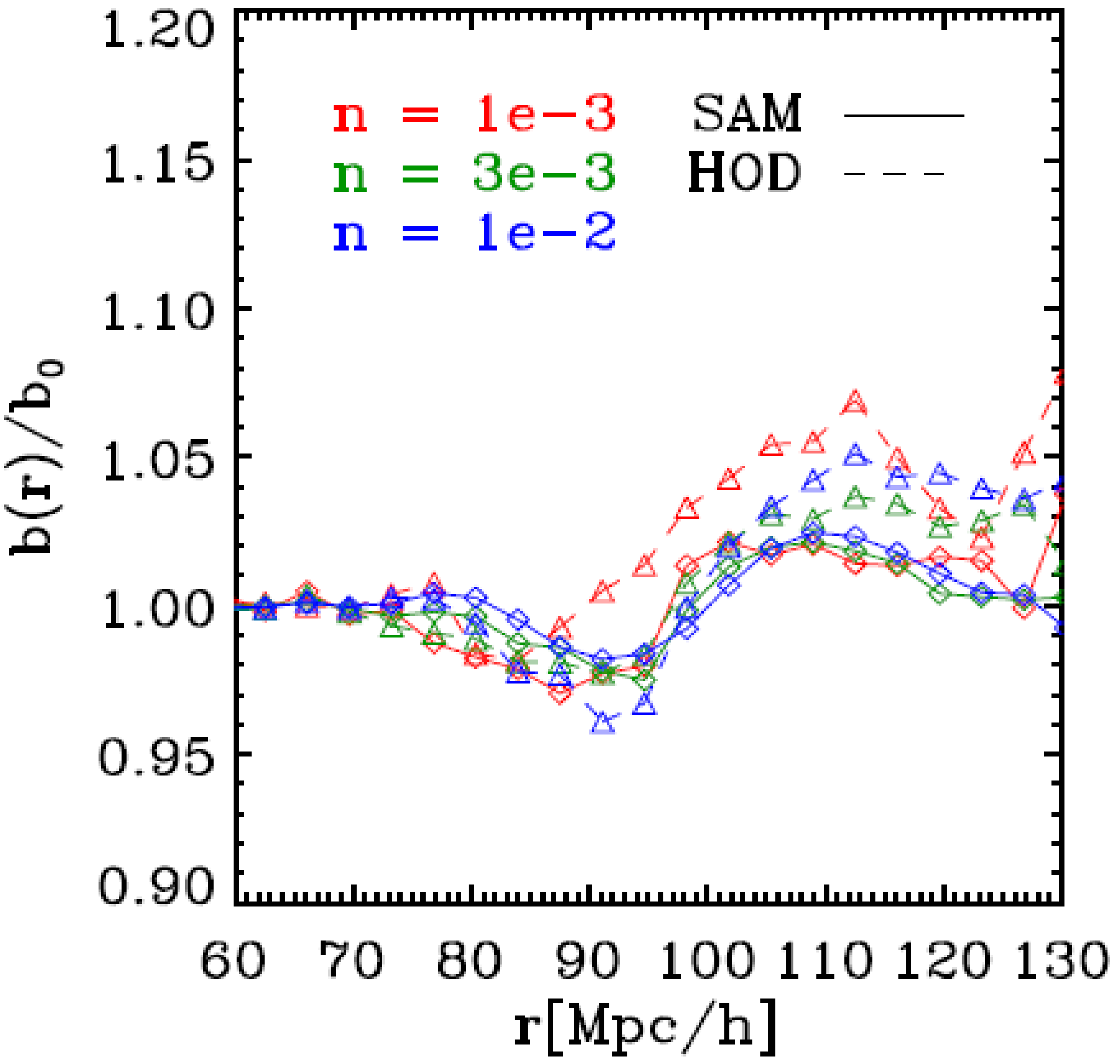
Deviations from the standard model: Linear bias + nonlinear dark matter



b/b0 = 1 → galaxies are exactly a scaled version of the underlying DM field.

Deviations can be explained qualitatively by distortions at the halo level

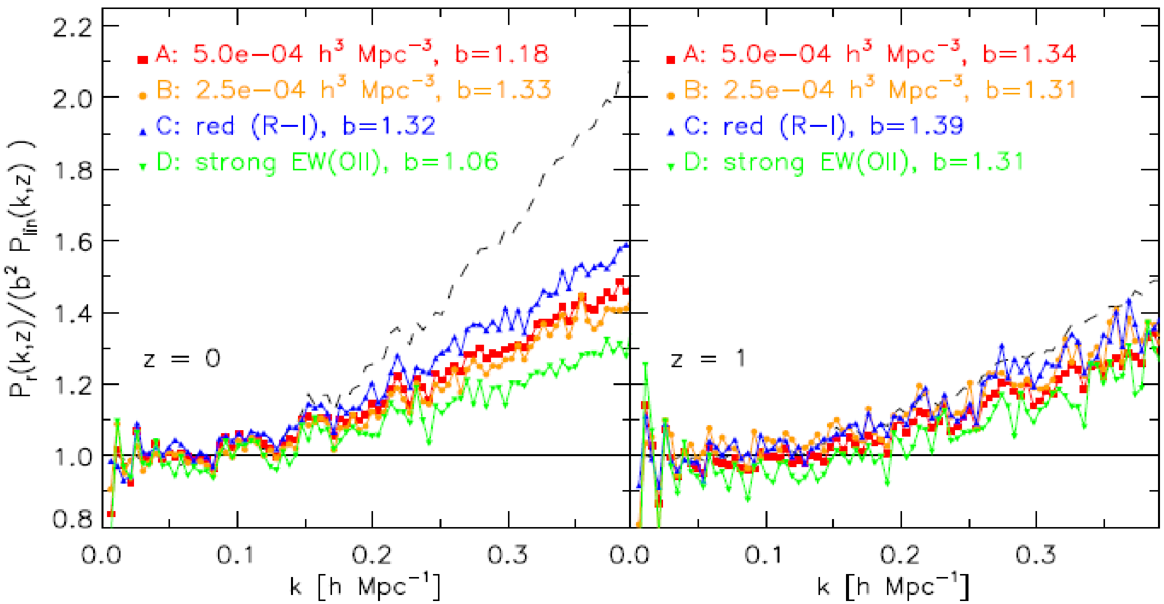
RATIO RELATIVE TO A LINEAR BIAS ON TOP OF THE NONLINEAR DARK MATTER



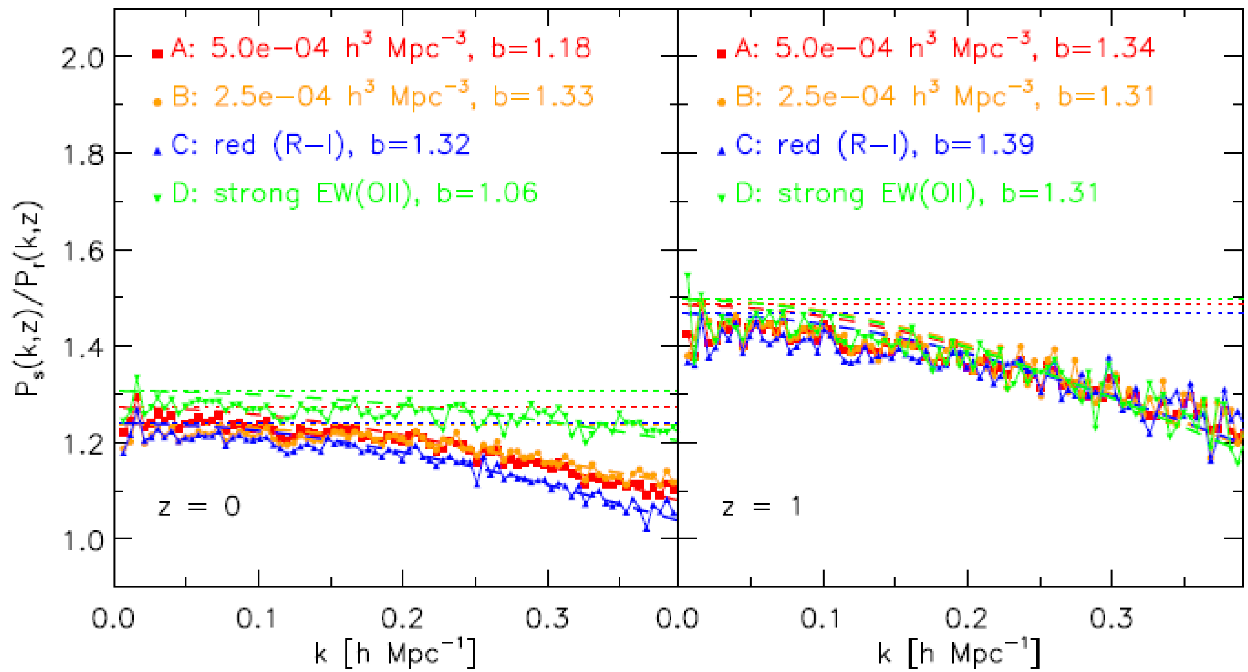
Good News:
Galaxy formation does not seem to introduce artifacts large enough to affect stage IV experiments

Scale-dependent galaxy bias

Configuration Space



Redshift Space



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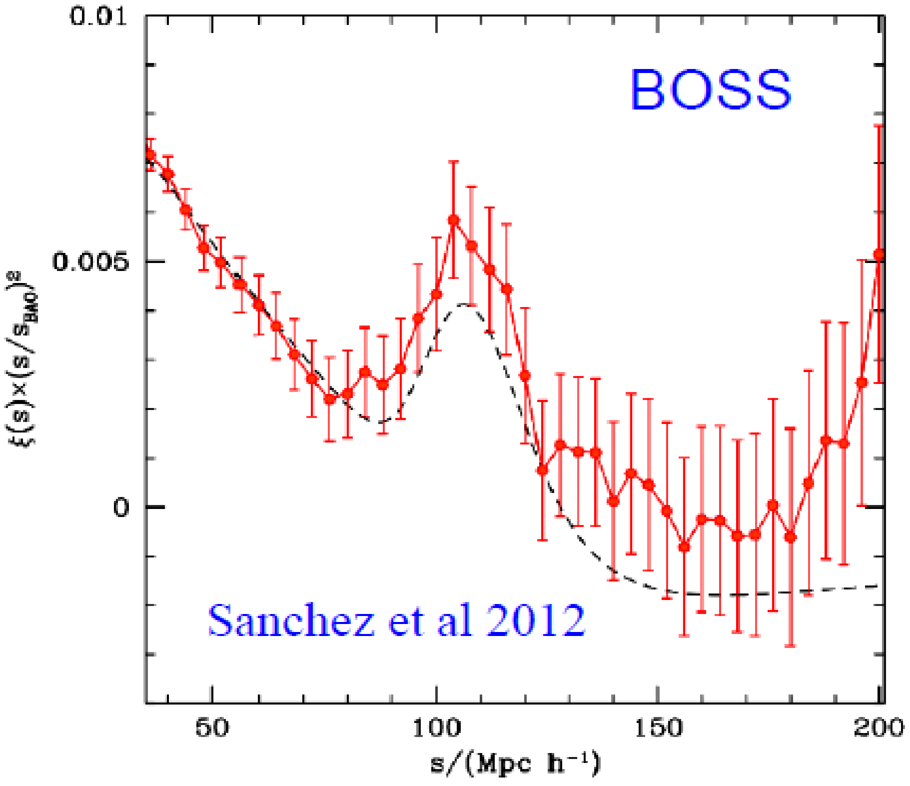
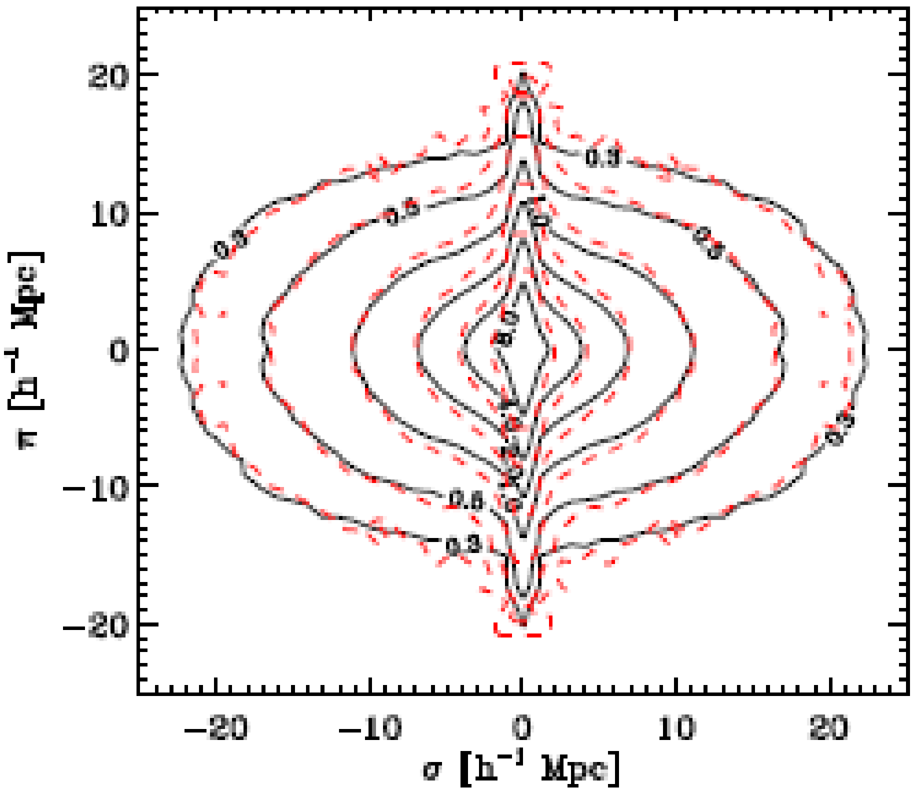
Limitations of N-body simulations:
the Warm DM case

Cosmological parameter constraints for the next generation of surveys

CURRENT MODELS: FITTING FORMULAE AND/OR SIMPLIFICATED TREATMENTS OF STRUCTURE FORMATION: THIS LIMITS THE POWER OF FUTURE DATA!!

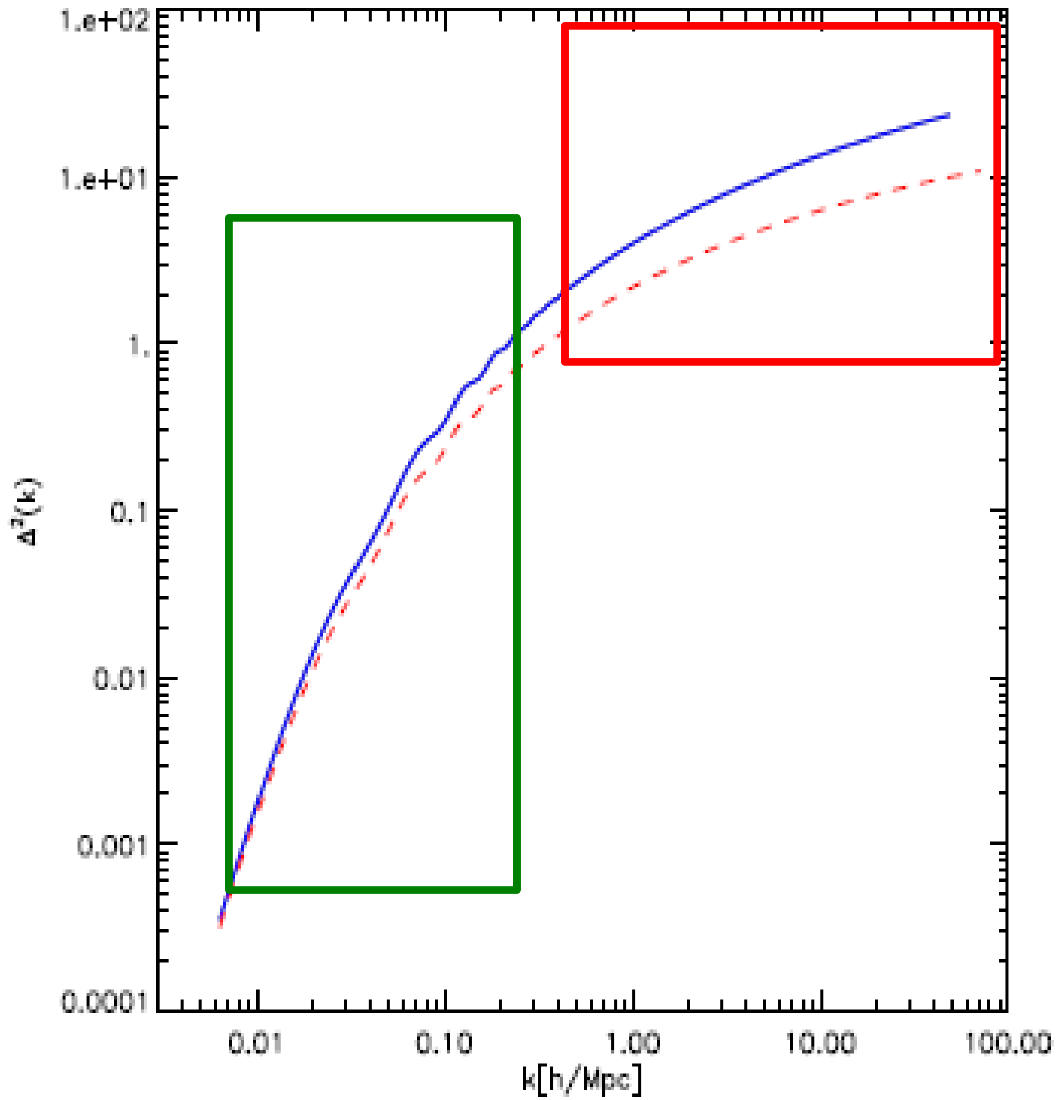




N-BODY SIMULATIONS CAN MAKE REALIABLE PREDICTIONS OVER A WIDE RANGE OF SCALES, BUT THEY ARE COMPUTATIONALLY EXPENSIVE.

How does cosmology affect structure formation?

Responsible for nonlinear structures



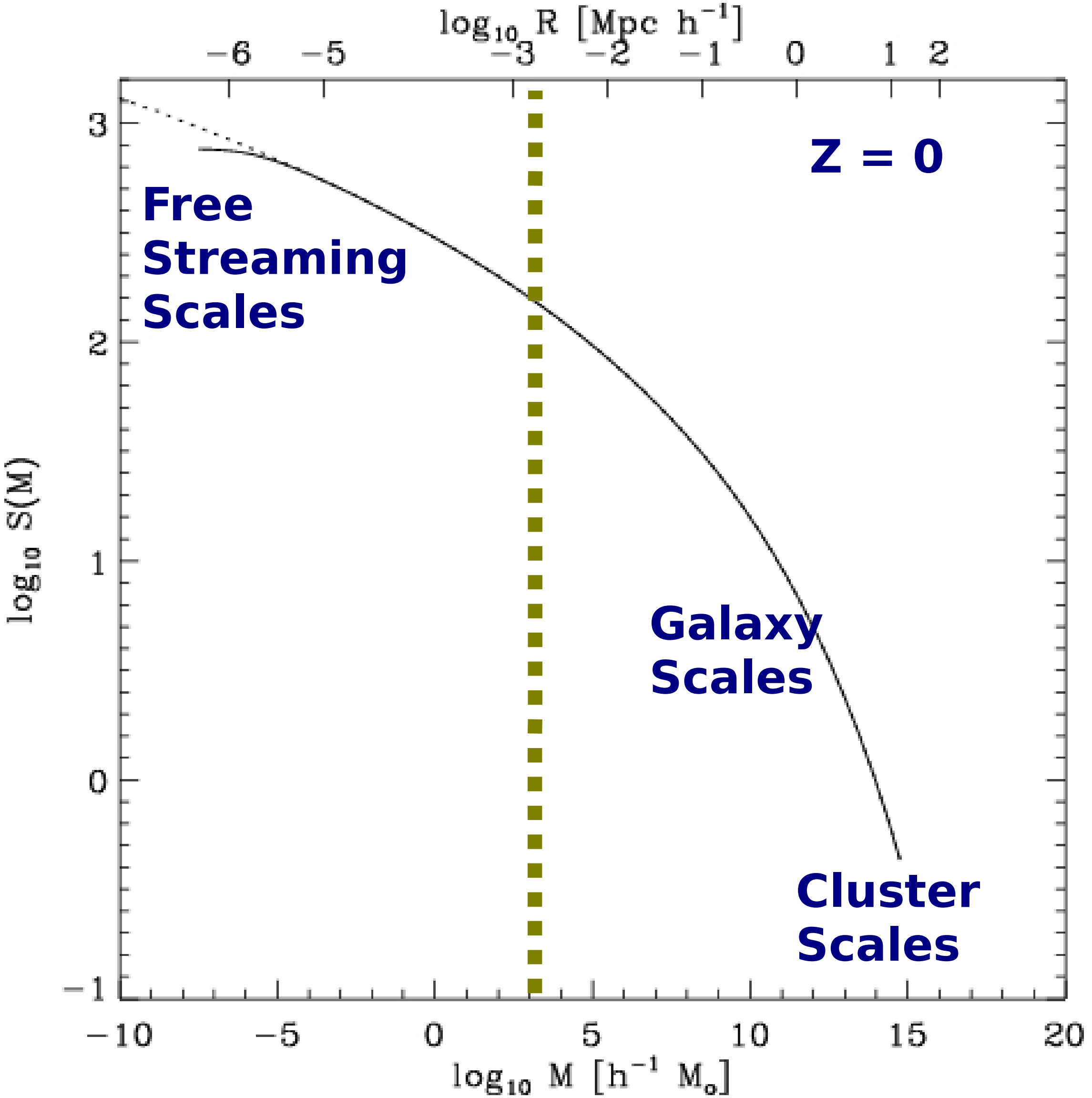
Information about early physics and cosmology

Can we mimic structure formation on different cosmologies?

In EPS, the variance of the linear field as a function of scale determines all the properties of nonlinear objects

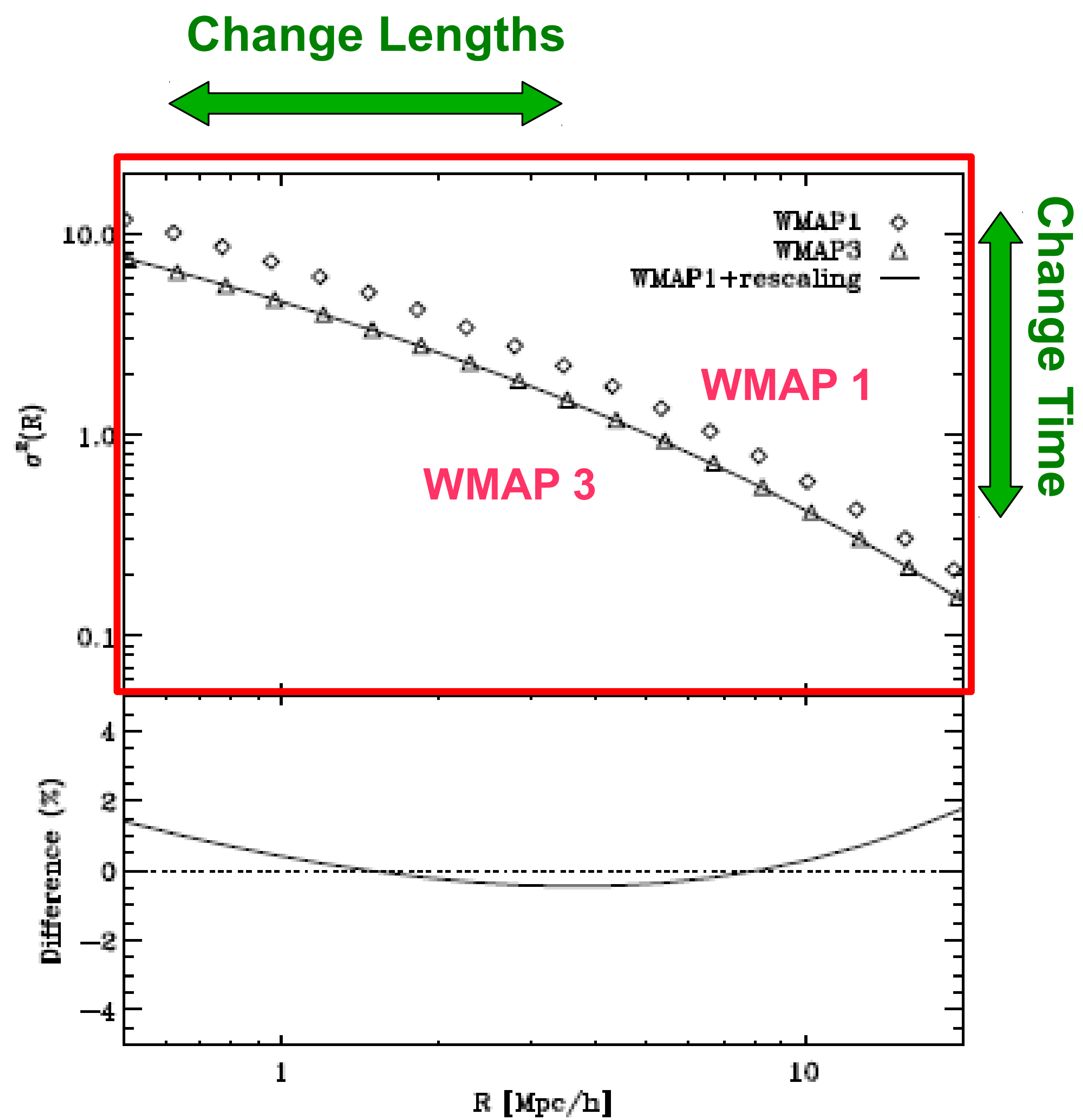
- mass function
- merger history
- bias

This is also true in simulations. Main halo properties depend mainly on the associated peak height.



One Simulation to Fit them All

(Angulo & White 2010)



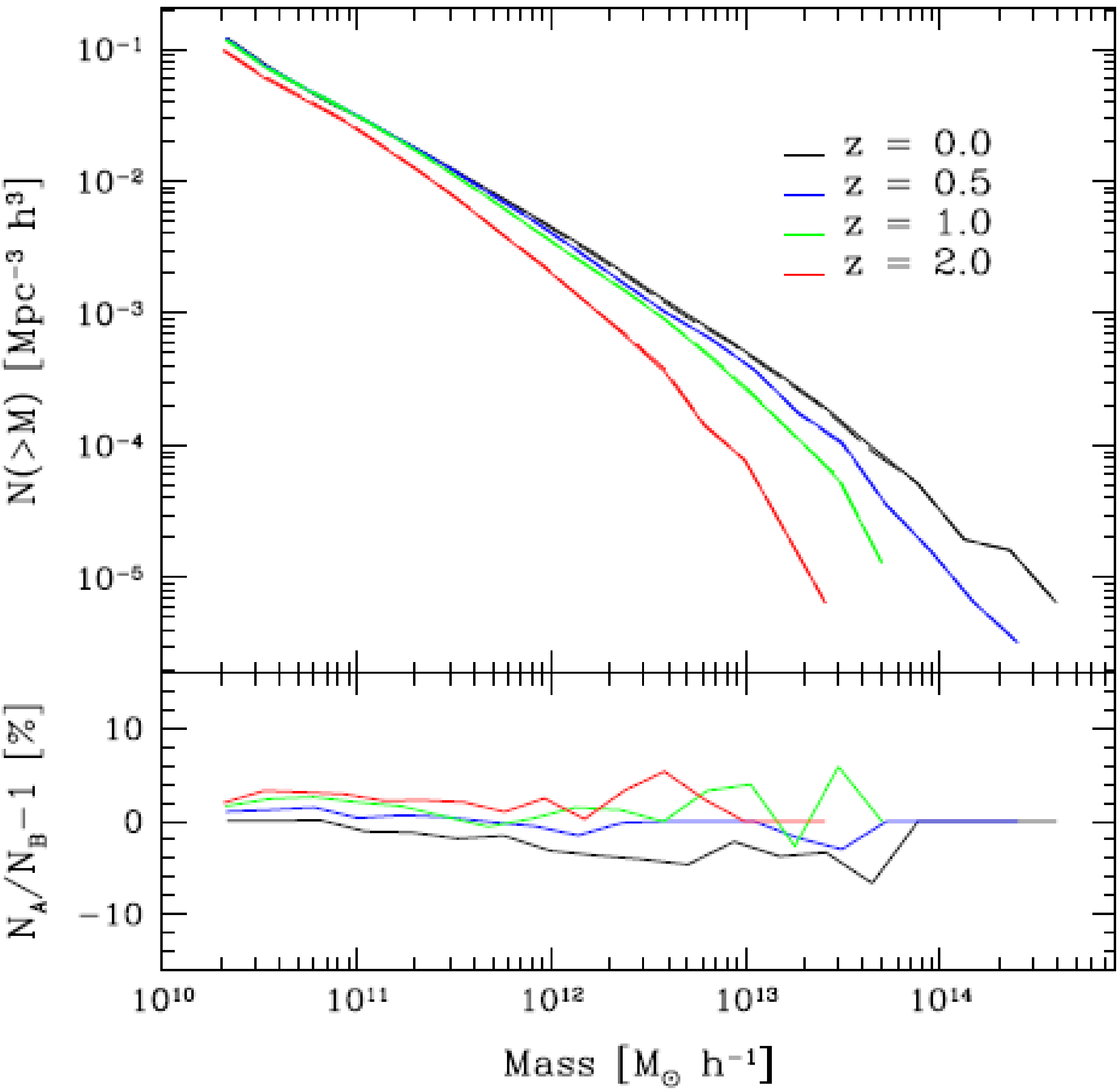
Linear and quasi linear scales can be modelled in the ZA

$$x(q, z) = q - D(z)S(q).$$

$$a\dot{x} \equiv v(q, z) = -\frac{\dot{D}(z)}{1+z}S(q)$$

How well can we scale the mass function?

(Ruiz et al 2011)

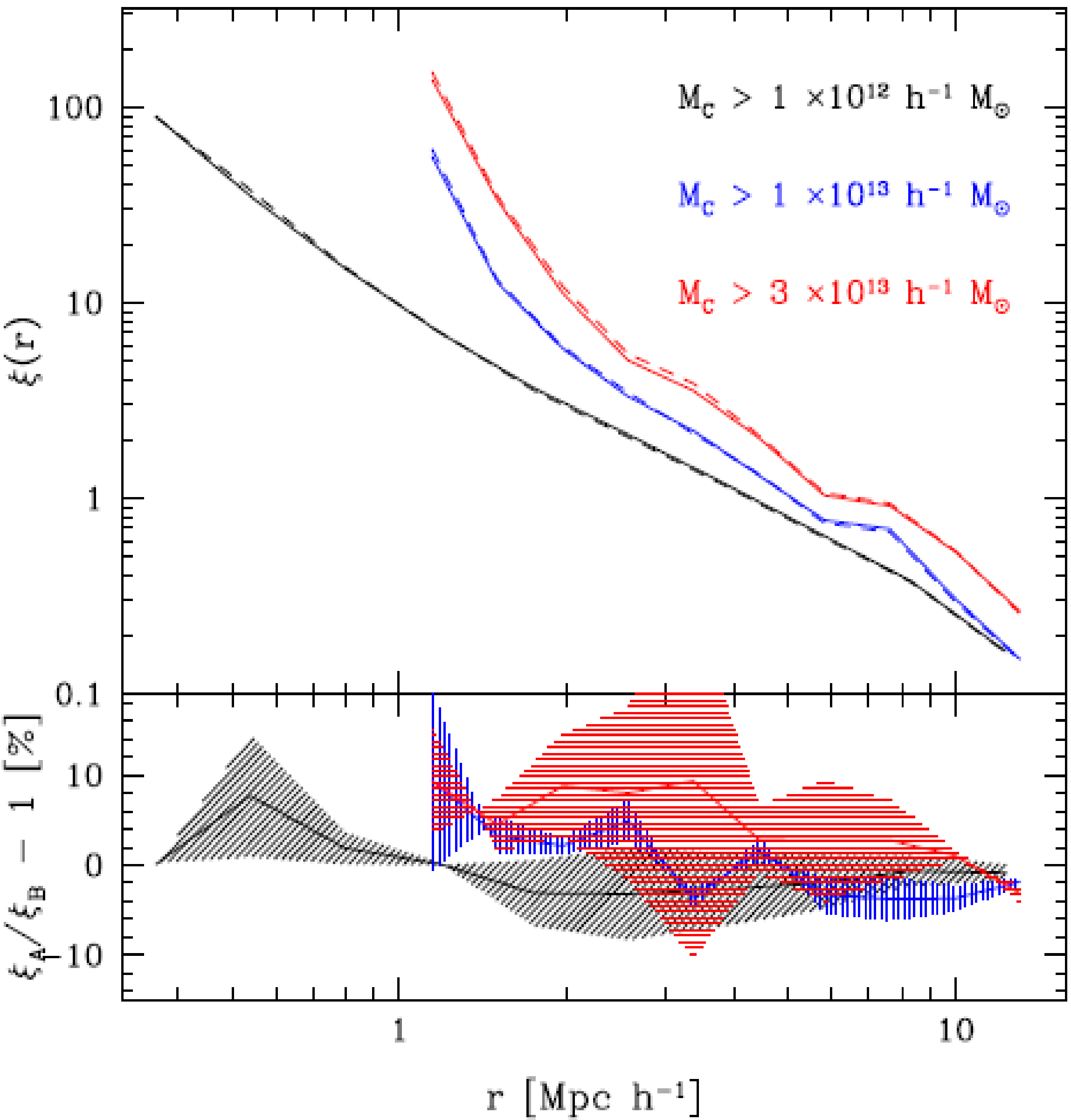


Dashed:
WMAP 1 scaled to WMAP5

Solid:
WMAP 5

How well can we scale the clustering?

(Ruiz et al 2011)



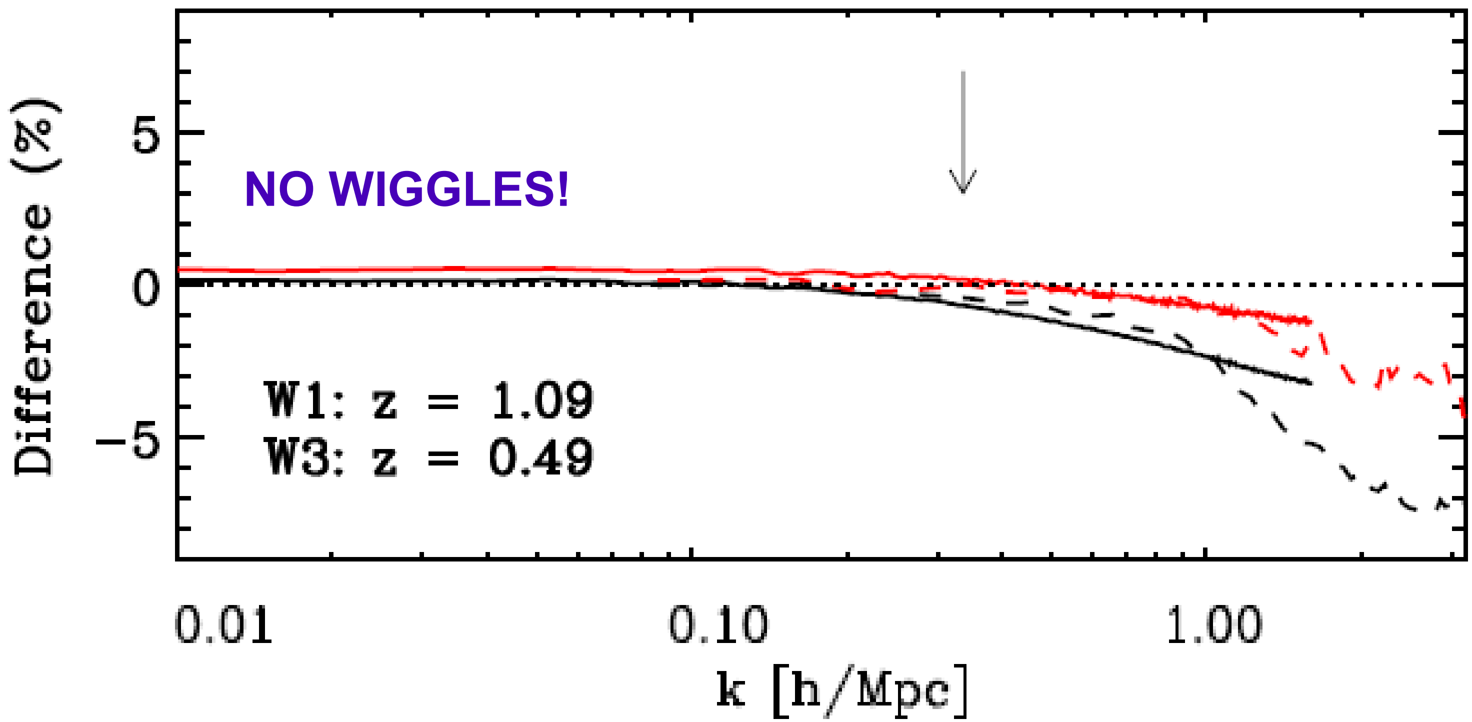
Dashed:
WMAP 1 scaled to WMAP5

Solid:
WMAP 5

One Simulation to fit them all!

(Angulo & White 2010)

Difference between the dark matter power spectra in of direct and scaled WMAP3 simulations

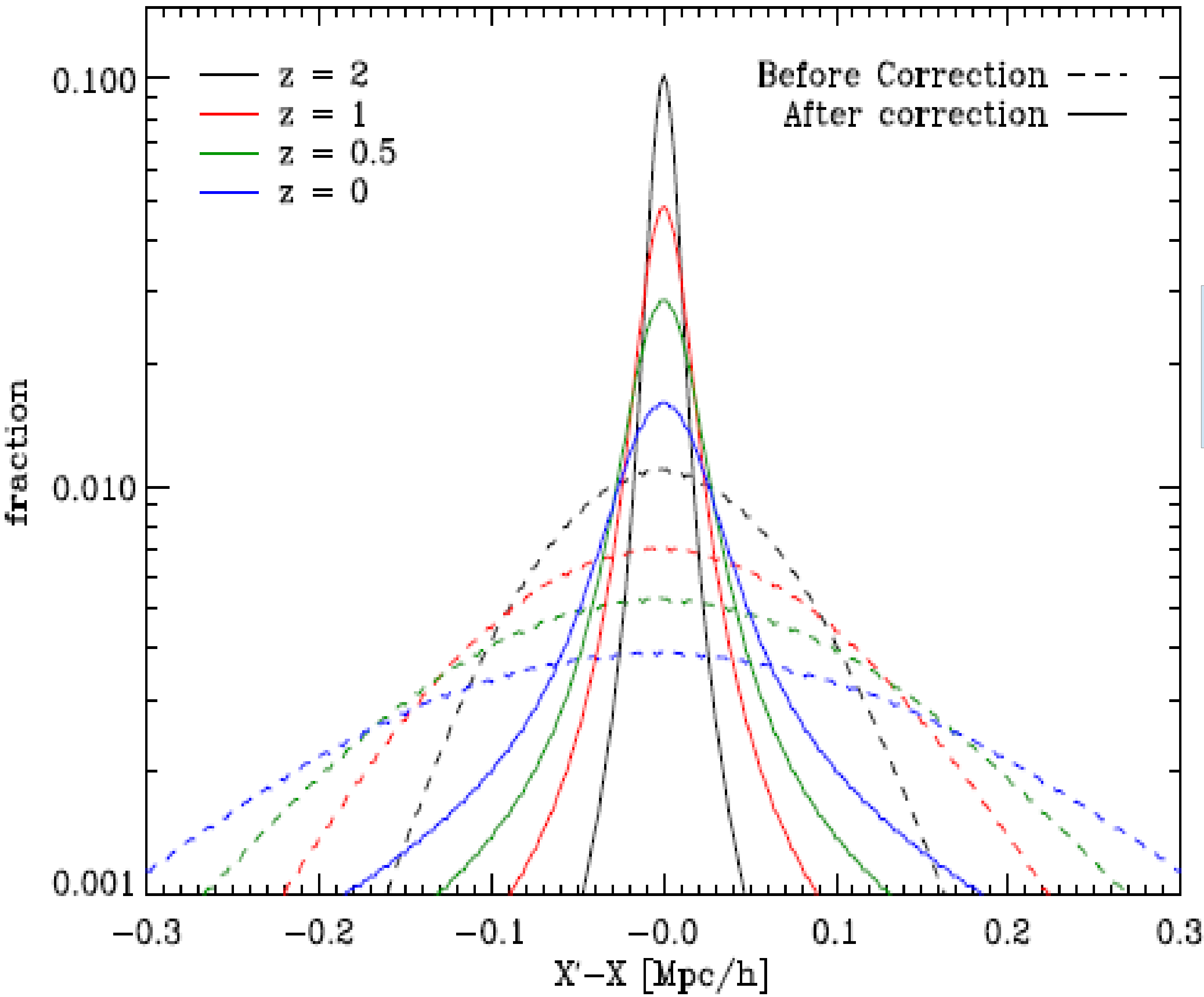


Differences are below 1% for k > 2 h/Mpc

One Simulation to fit them all!

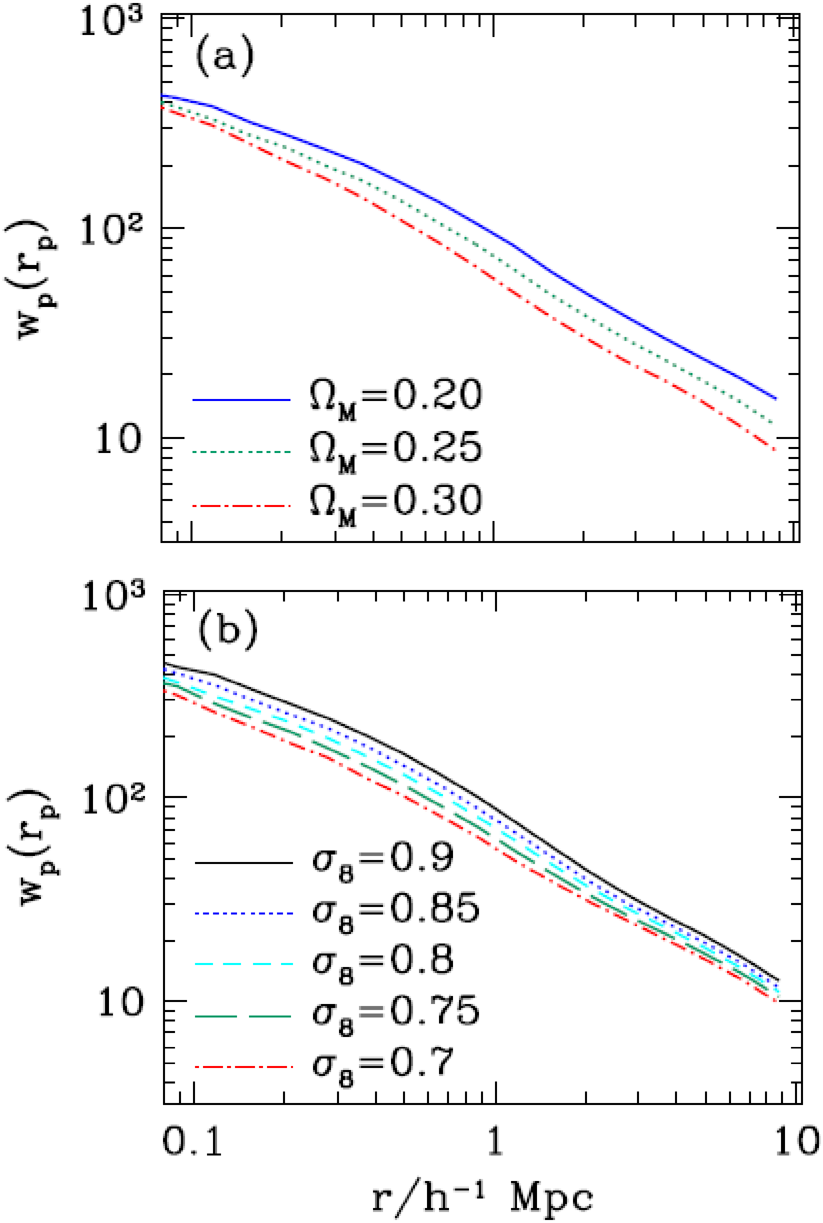
(Angulo & White 2010)

Distribution of "error" in the position of particles

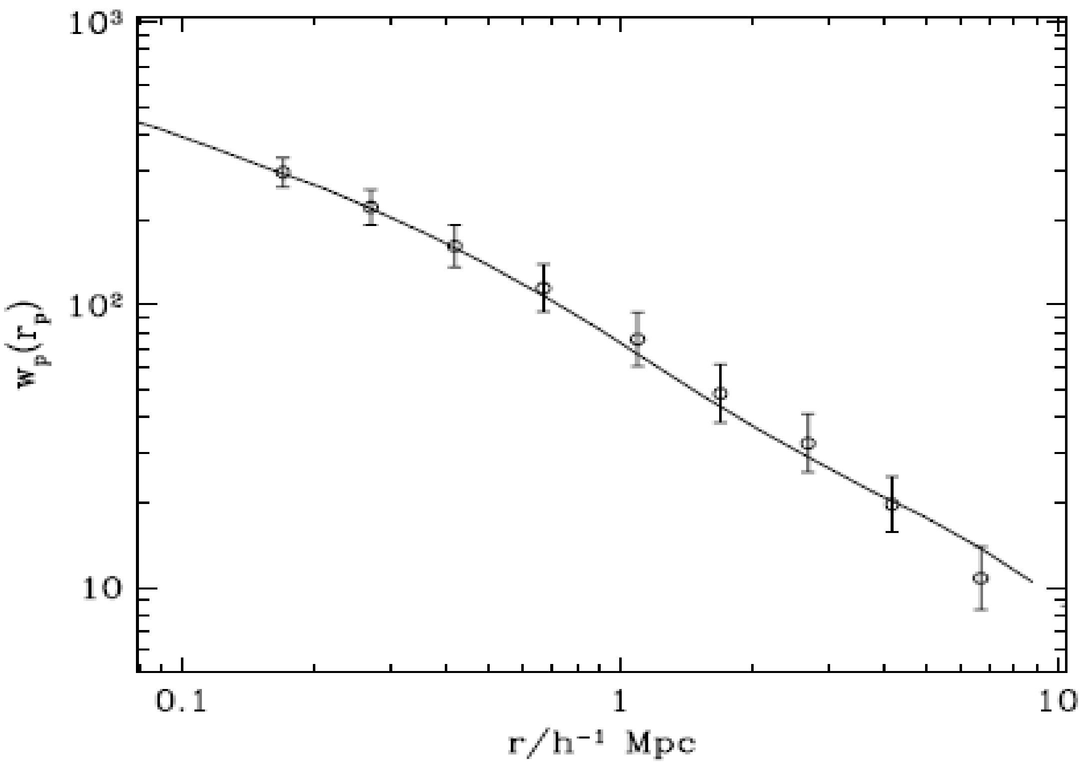


Particles are predicted with a 30 kpc/h rms at z=1

Simulations can be used to constrain cosmological parameters using the nonlinear regime

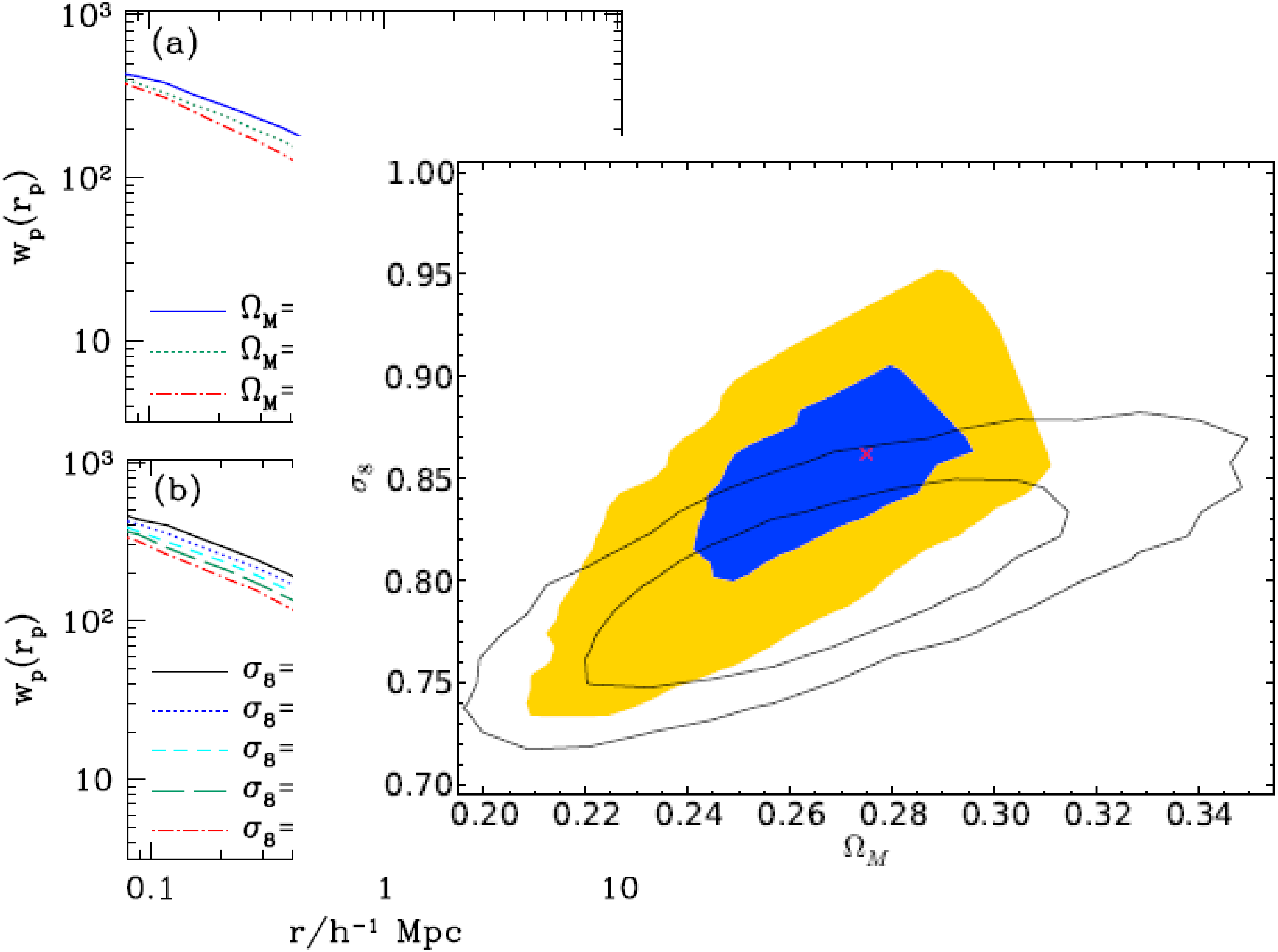


The projected correlation function Of SDSS main galaxies (Mr = -18)



Simha & Cole 2013
Angulo & Marin, 2013 in prep

Simulations can be used to constrain cosmological parameters on the nonlinear regime



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Simulation Dynamics

The Collisionless Boltzmann Equation

$f = f(\mathbf{x}, \mathbf{v}, t)$ **number density of particles in phase-space (x,v)**

Vlasov equation

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \mathbf{v} + \frac{\partial f}{\partial \mathbf{v}} \cdot \left(-\frac{\partial \Phi}{\partial \mathbf{x}} \right) = 0$$

The gravitational potential is related to the mass density via the Poisson equation:

$$\nabla^2 \Phi(\mathbf{x}, t) = 4\pi G \int f(\mathbf{x}, \mathbf{v}, t)\, \mathrm{d}\mathbf{v}$$

CBE implies that phase-space density around a given particle remains constant

Directly solving this system of differential equations is, in practice, impossible! …. We need to solve for the evolution Of a coarse-grained phase-space distribution.

"Monte-Carlo" Approach to Collisionless Dynamics

The N-body method samples the underlying distribution function with particles

$$\ddot{\mathbf{x}}_i = -\nabla_i \, \Phi(\mathbf{x}_i)$$

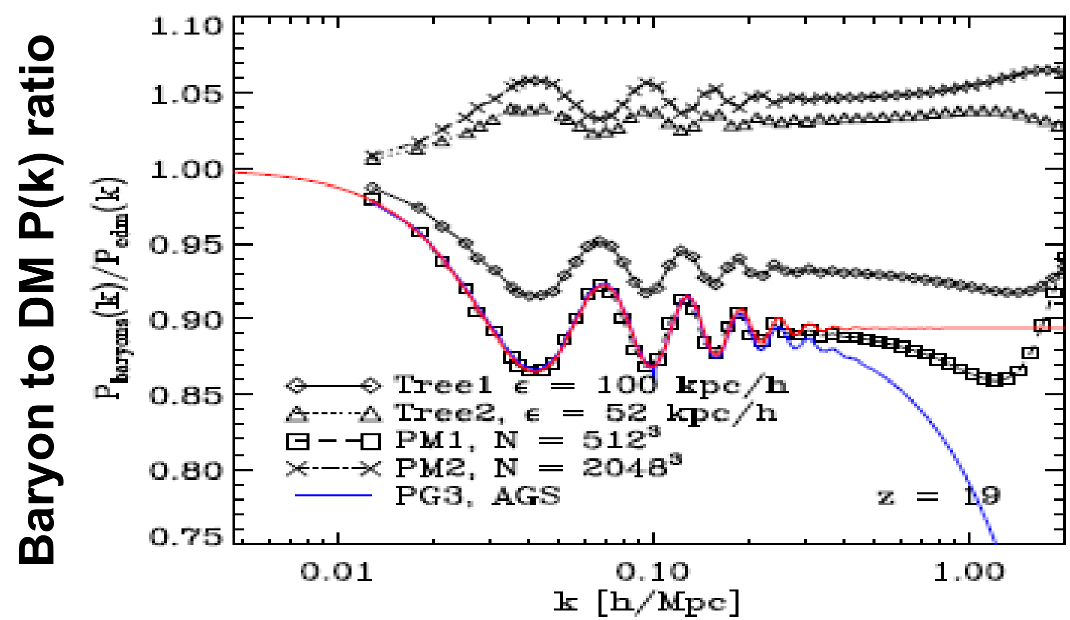
$$\Phi(\mathbf{x}) = -G \sum_{j=1}^{N} \frac{m_j}{[(\mathbf{x} - \mathbf{x}_j)^2 + \epsilon^2]}$$

Softening length prevent forces to diverge, which would lead to unrealistic large-angle scattering events.

Collisionless Relaxation

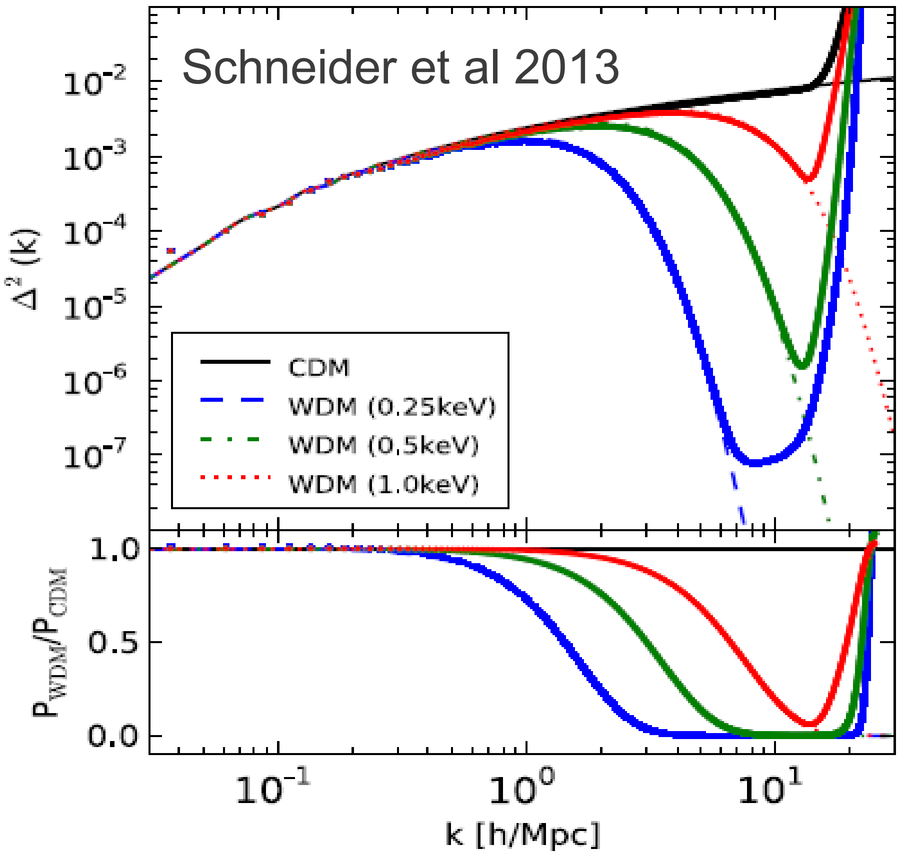
Phase Mixing
Chaotic Mixing
Violent Relaxation
Landau Damping

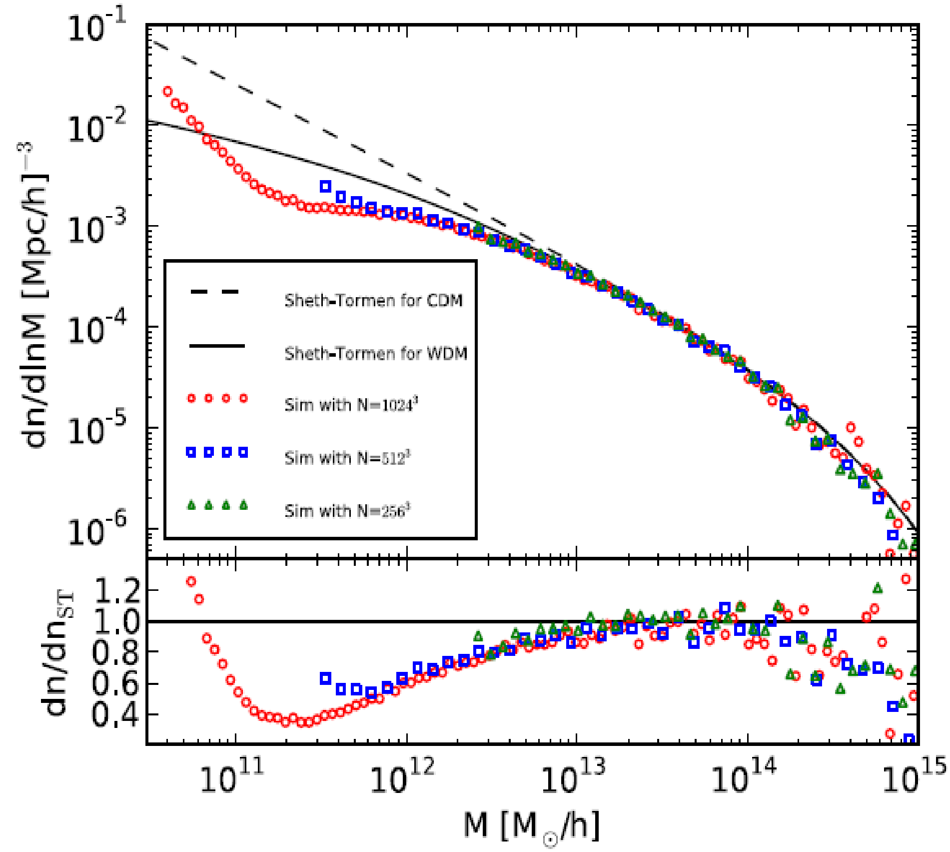
Angulo, Hahn, Abel 2013



Warm DM Cosmological Simulations

FREE-STREAMING OF PARTICLES WASHES OUT SMALL-SCALE PERTURBATIONS

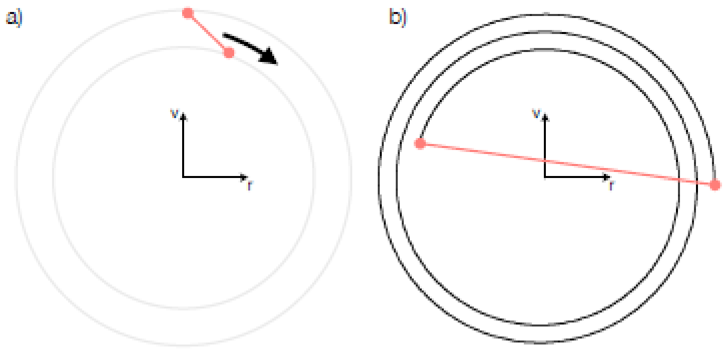




N-BODY SIMULATIONS FAIL DUE TO ARTIFITIAL(NUMERICAL) FRAGMENTATION OF FILAMENTS. THIS PROBLEM HAS EXISTED FOR DECADES!

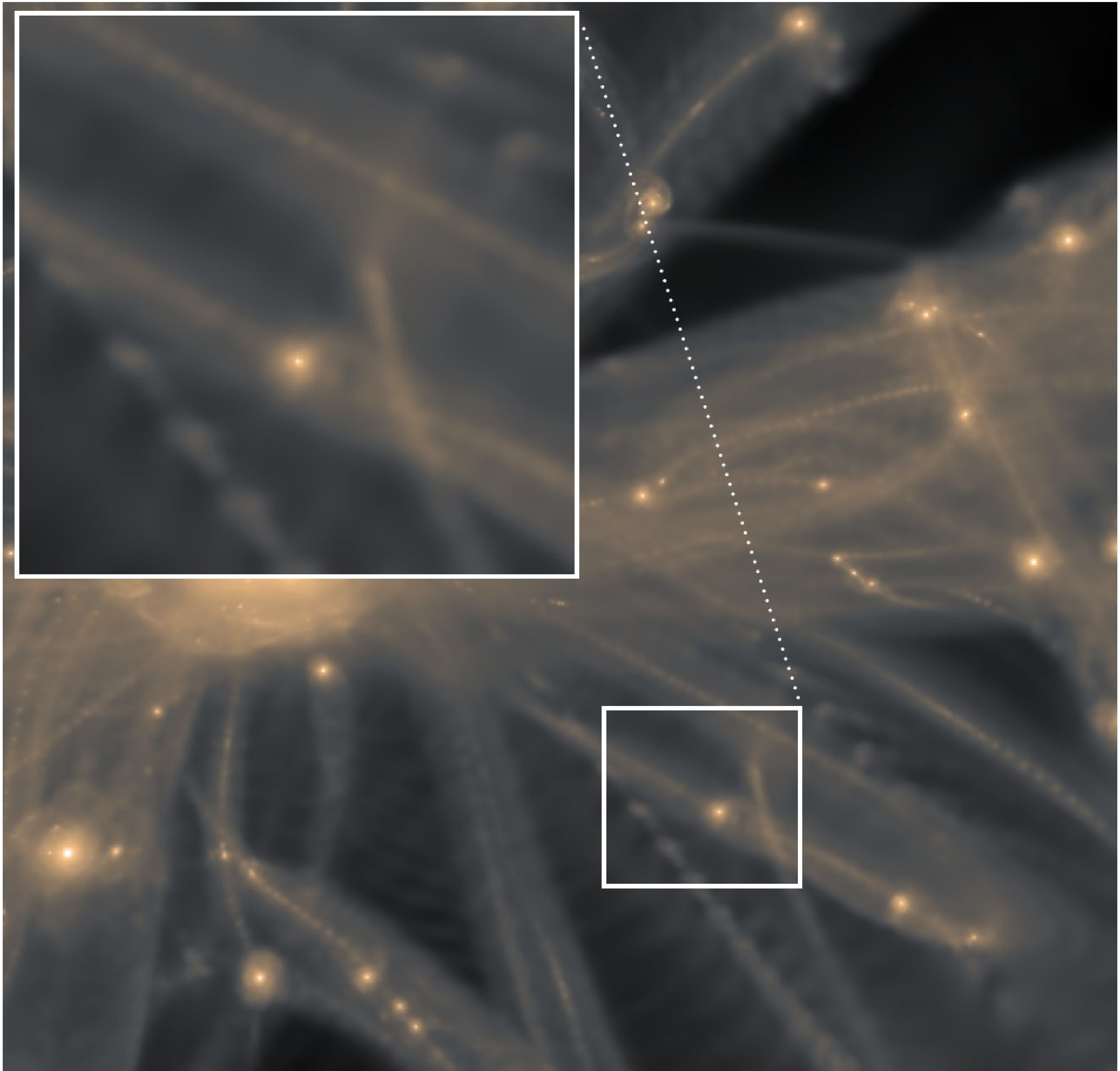
A new Approach to Collisionless Dynamics

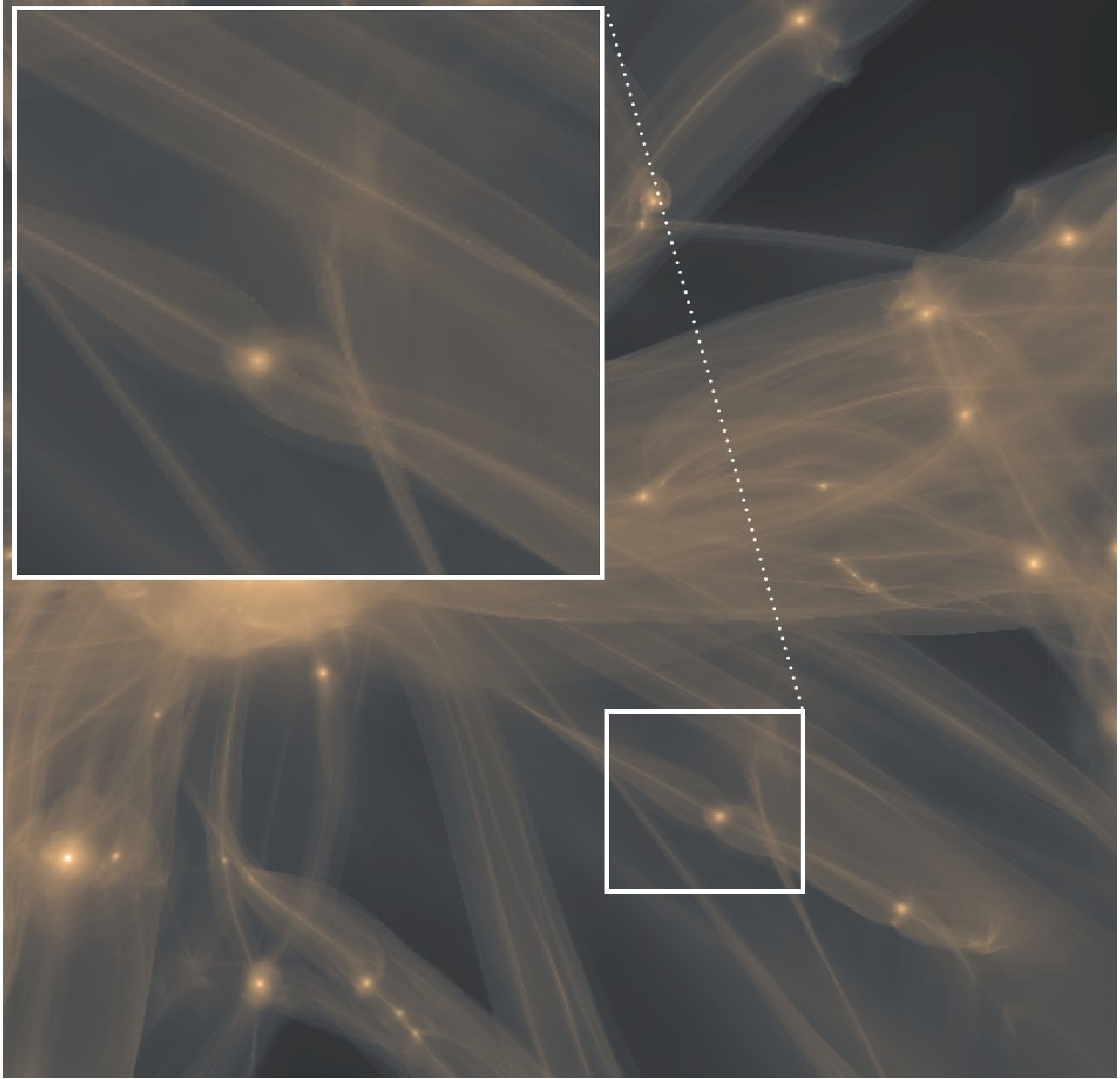
Hahn, Abel & Kaehler 2013; Kaehler, Hahn & Abel 2013



Standard Approach:
The state of the system at any time is described by the positions and velocities of all particles.

New Approach:
The mass is assumed to be uniformly distributed between The particles that define a Phase-space unit in Lagrangian coordinates

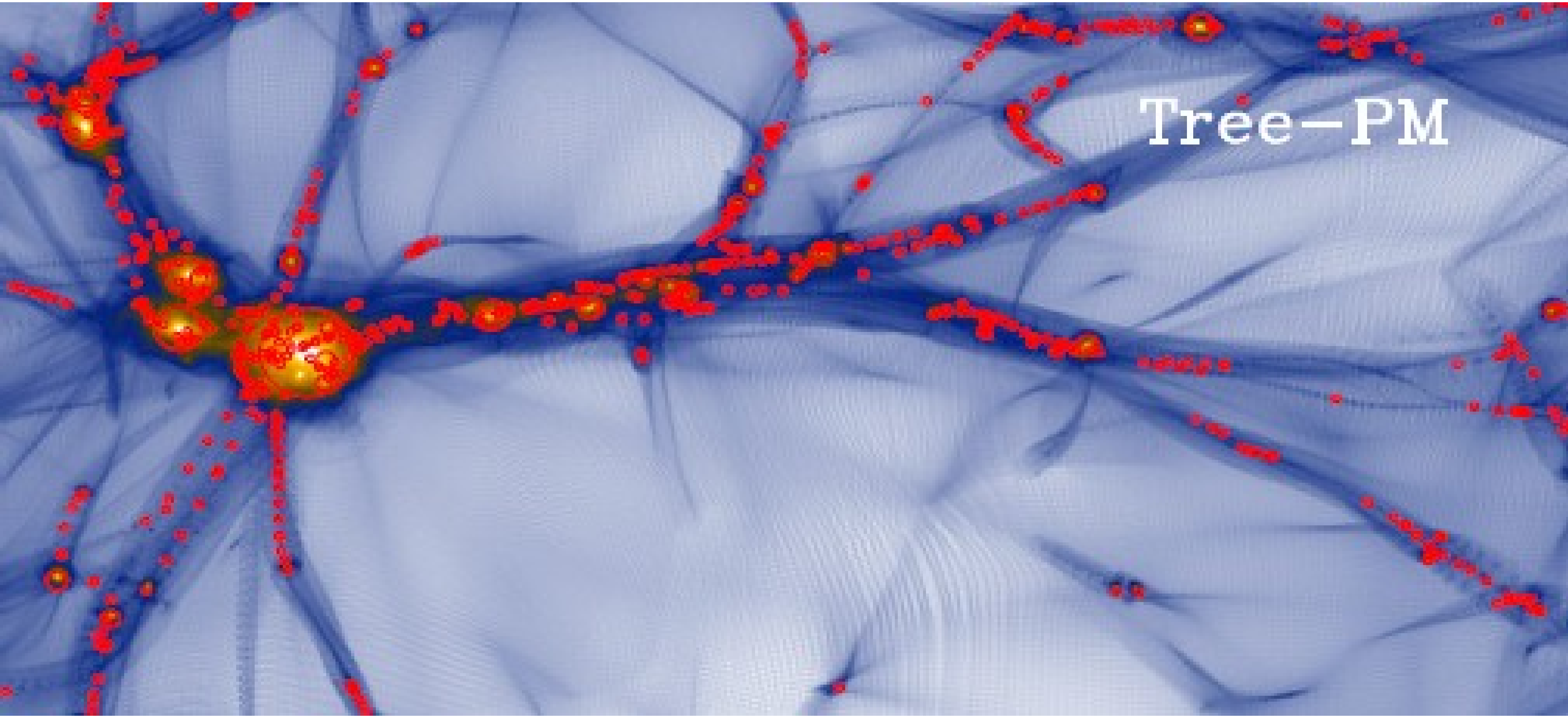




The WDM halo mass function below the cutoff scale

Angulo, Hahn, Abel 2013, in prep

L = 80 Mpc/h, Mp = 3.6e7 Msun/h



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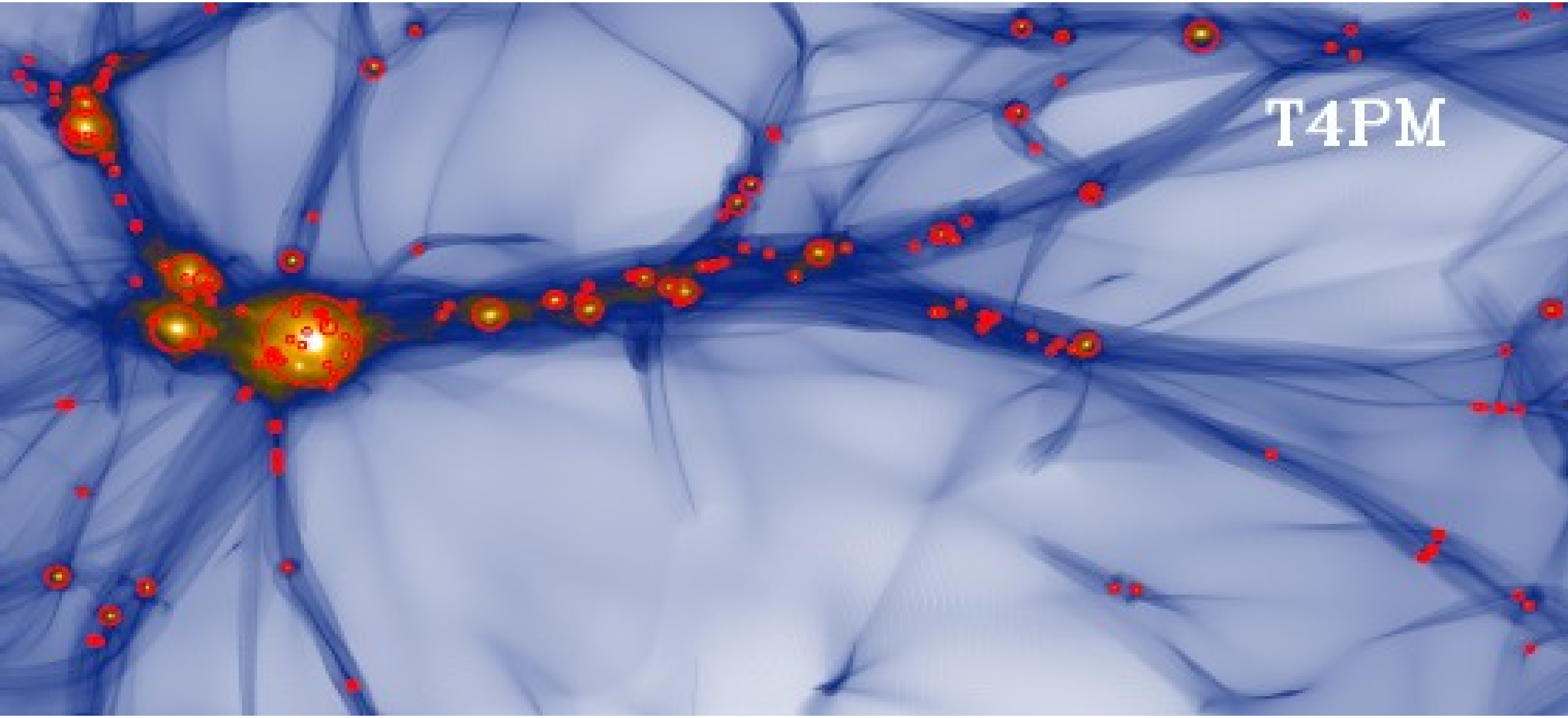
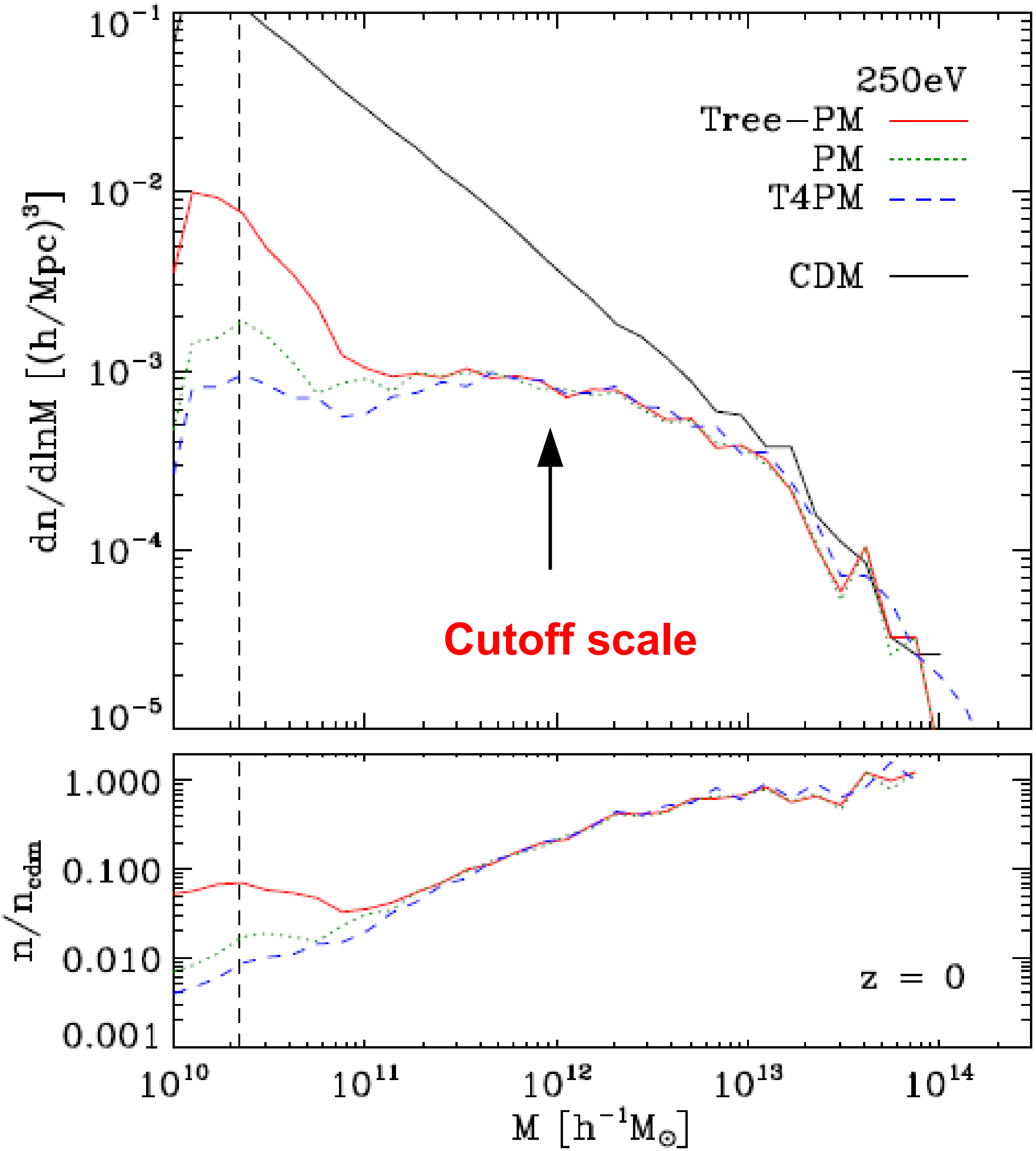


New force calculation implemented in L-Gadget3

The WDM halo mass function below the cutoff scale

Angulo, Hahn, Abel 2013, in prep



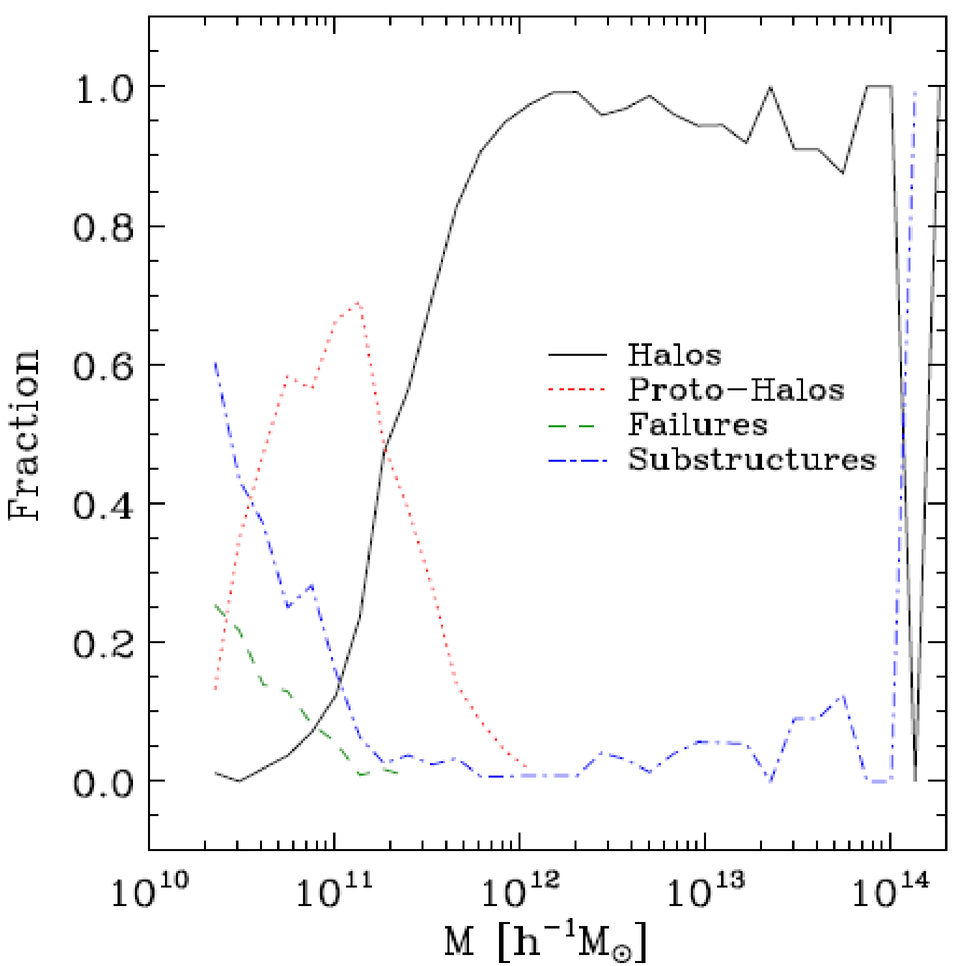
The WDM halo mass function below the cutoff scale

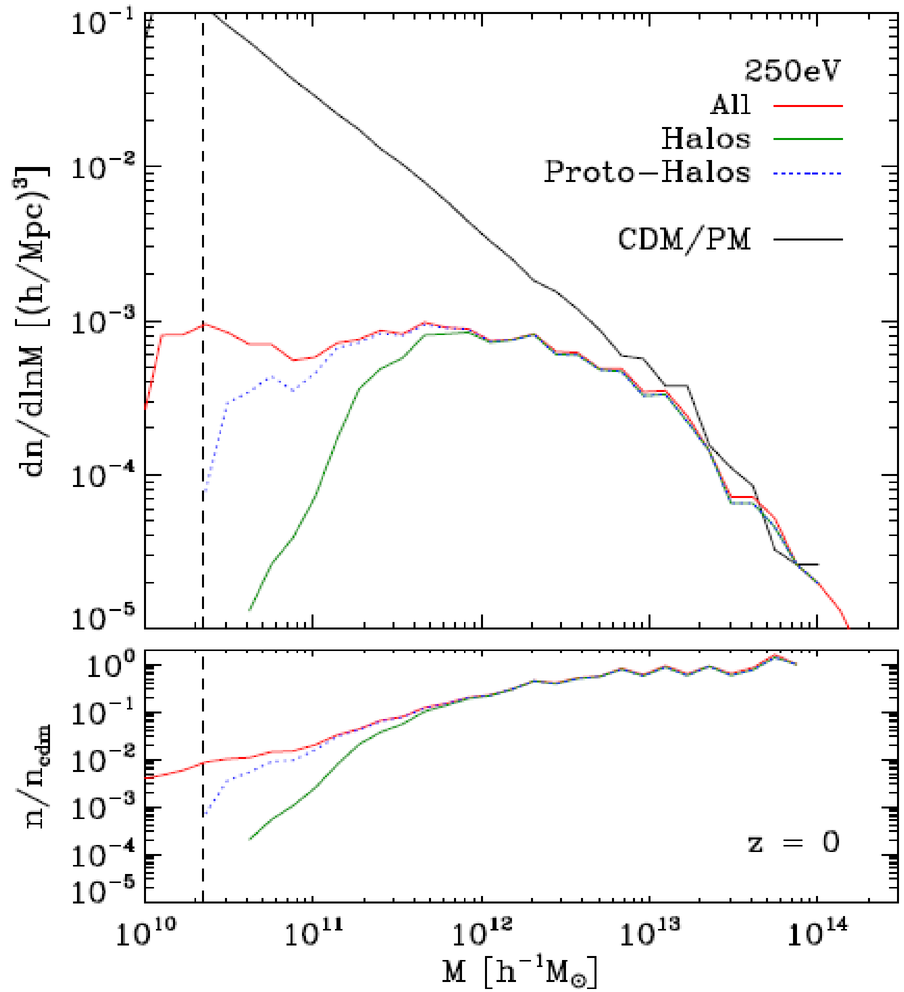
Angulo, Hahn, Abel 2013, in prep

Zoom In simulation, Mp = 1e5 Msun/h

The WDM halo mass function below the cutoff scale

Objects below the cut-off scale correspond to proto-halos, filaments and outer caustics.





DOES THESE NUMERICAL ARTIFACTS CAUSE ANY EFFECT IN THE PROPERTIES OF HALOES, I.E. DENSITY PROFILE, ELLIPTICITY ETC?

Summary

The connection between observables and cosmology:
The impact of galaxy physics in BAO measurements

The galaxy clustering is not simply a scaled version of the DM. However, The distortions are unlikely to affect strongly the results of stage IV surveys

Cosmological constraints:
Using N-body simulations to measure cosmology

There is now the remarkable possibility of make constrain cosmological parameters directly using cosmological N-body simulations

Limitations of N-body simulations:
The Warm DM case

Discretisation in the N-body problem creates an artificial population of low mass halos. Using a new method, we have resolved the mass Function below the cut-off mass scale in a WDM cosmology.