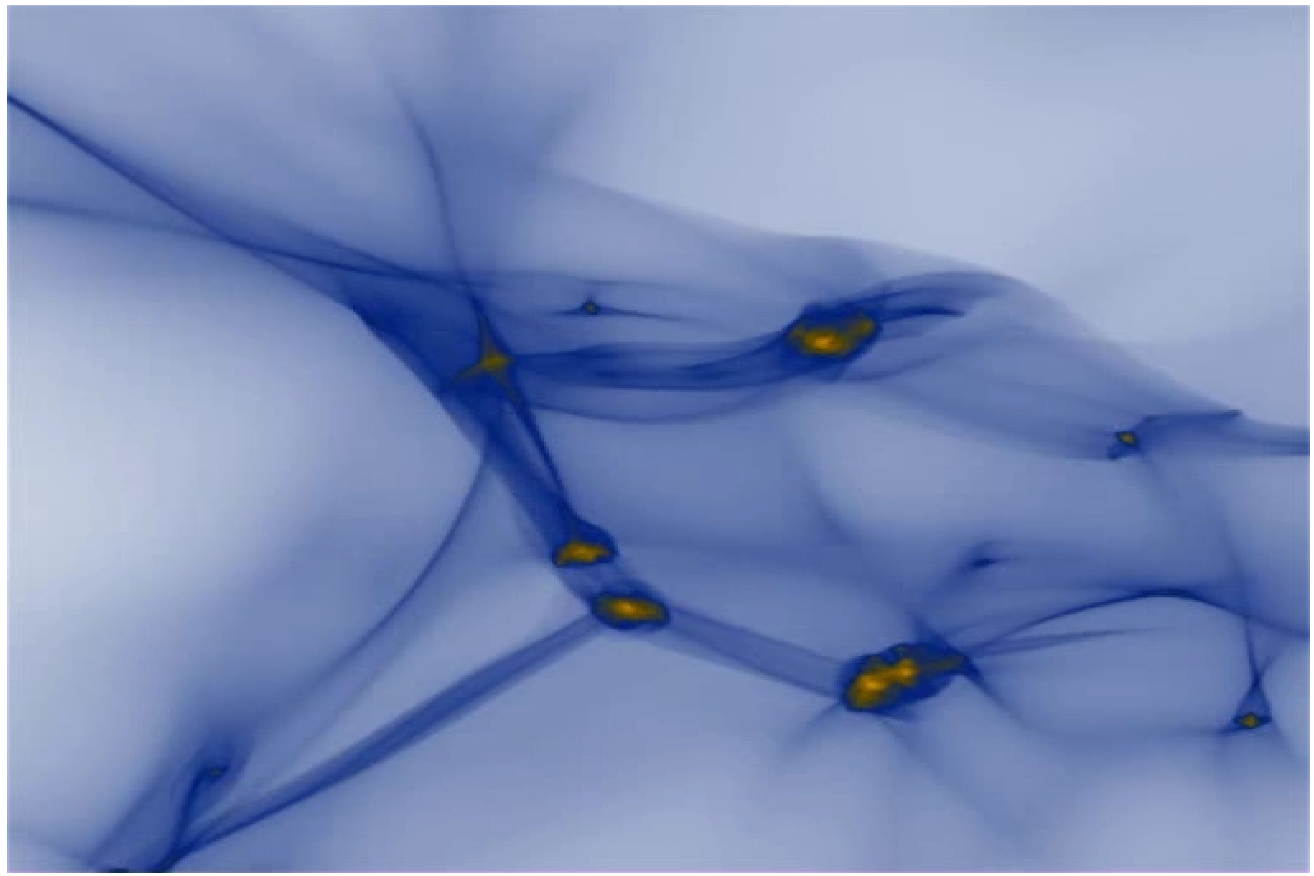
Dark Matter Simulations for the Large-Scale Structure of the Universe

Raul E. Angulo

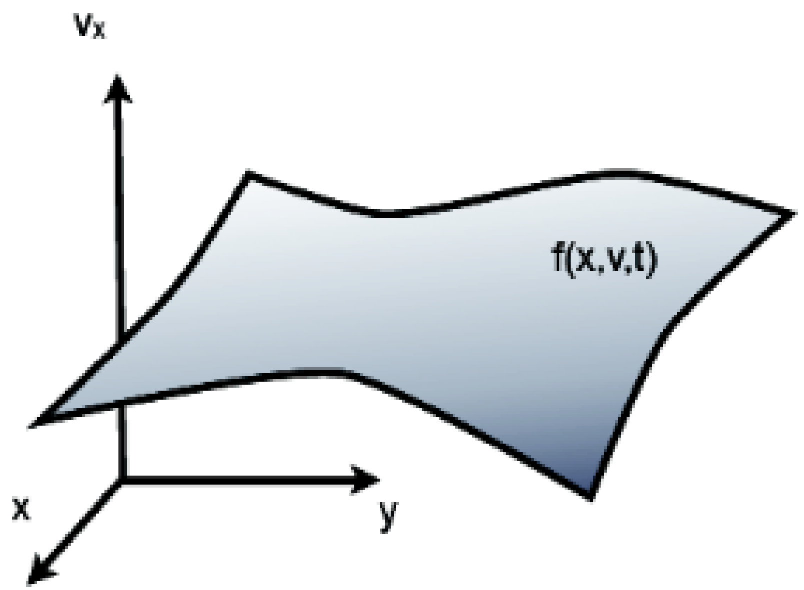


CEFCA
Centro de Estudios de Física del Cosmos de Aragón

Advanced Workshop on Cosmological Structures
ICTP, Trieste
Mayo 2015

Simulating structure formation in the Universe

Most of the mass in the Universe is in the form of an unknown elementary particle: the Cold Dark Matter



Properties of CDM

- → No thermal velocity
- → Only Gravity
- → Small primordial fluctuations

...but simulating trillions of micro-physical CDM particles is impossible

CDM forms a "sheet": A continuous 3D surface embedded in a 6D space

The Vlassov-Poisson Equation

$$0 = \frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\mathbf{v}}{a^2} \cdot \frac{\partial f}{\partial \mathbf{v}} - \frac{\partial f}{\partial \mathbf{x}} \frac{\partial \Phi}{\partial \mathbf{x}}$$

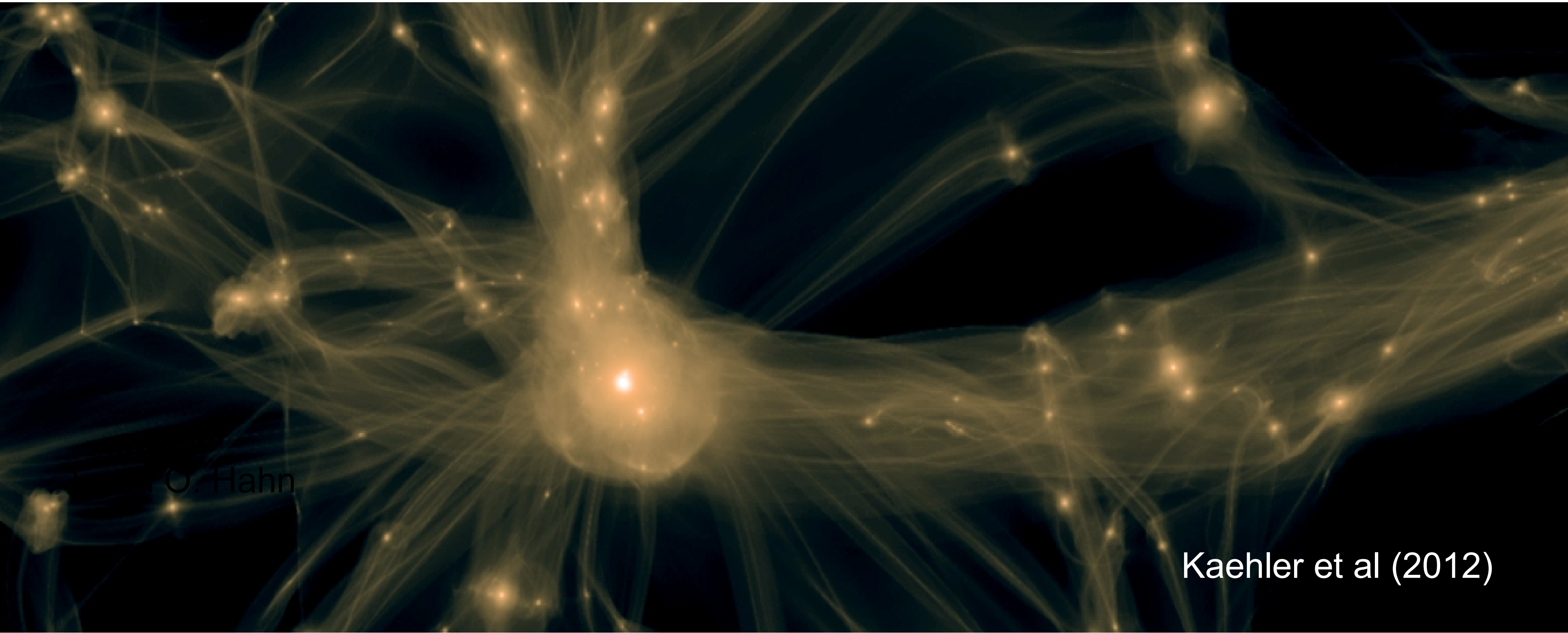
$$\nabla^2 \Phi = \frac{4\pi G}{a} \int f \mathrm{d}^3 v$$

CDM Sheet Properties

→ phase-space is conserved along characteristics

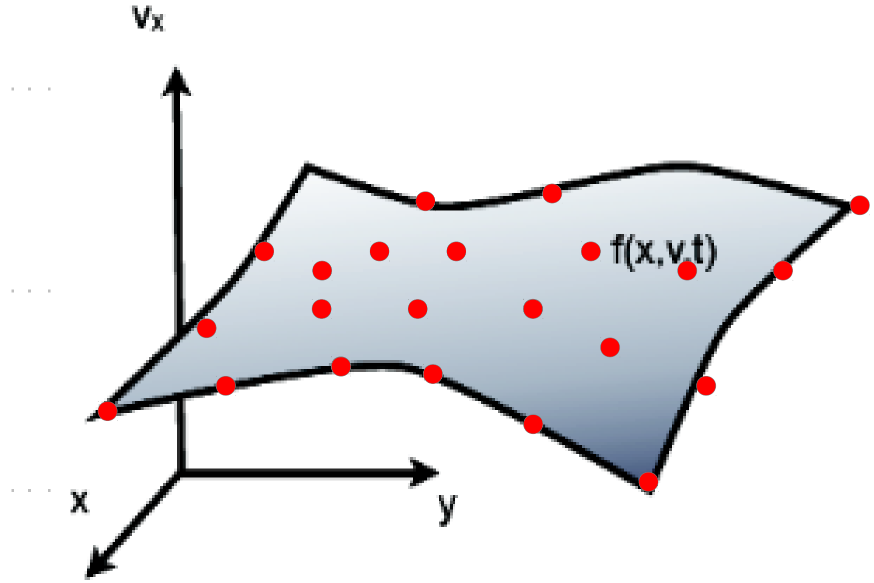
→ It can never tear

→ It can never intersect



Standard approach to solving the VP equation:

Montecarlo Sampling and coarse graining the CDM distribution function

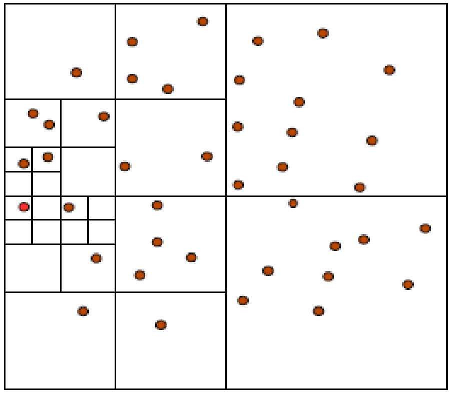


$$\frac{d^2\mathbf{x}_i}{d^2t} = \nabla_i \Phi(\mathbf{x}_i),$$

$$\Phi(\mathbf{x}) = -G \sum_i \frac{m_i}{[(\mathbf{x}_i - \mathbf{x})^2 + \varepsilon^2]}$$

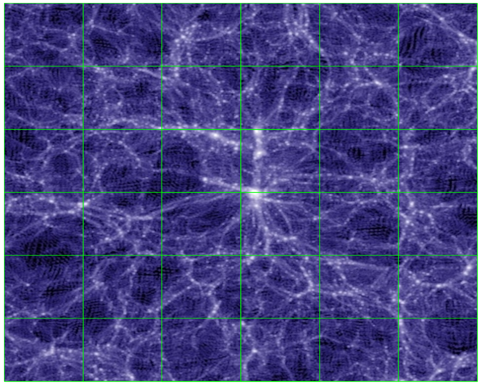
Tree Algorithms

Multipole decomposition



Particle-Mesh

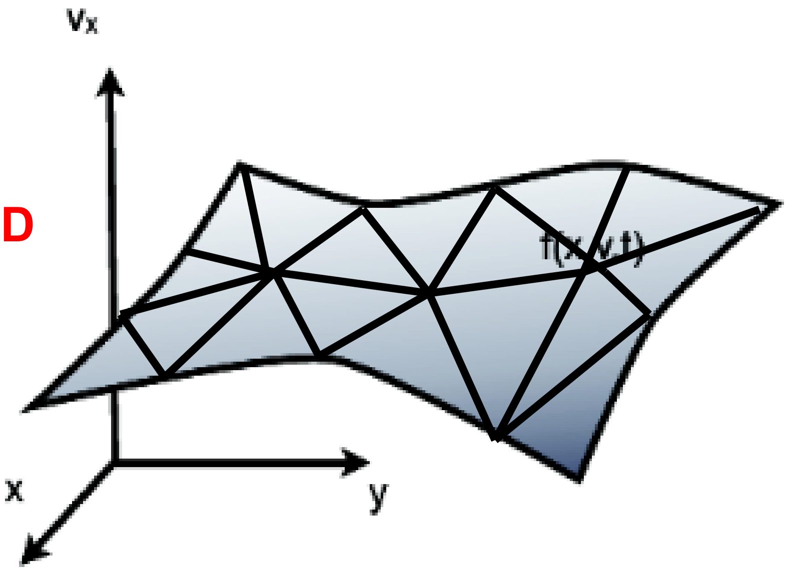
Poisson equation



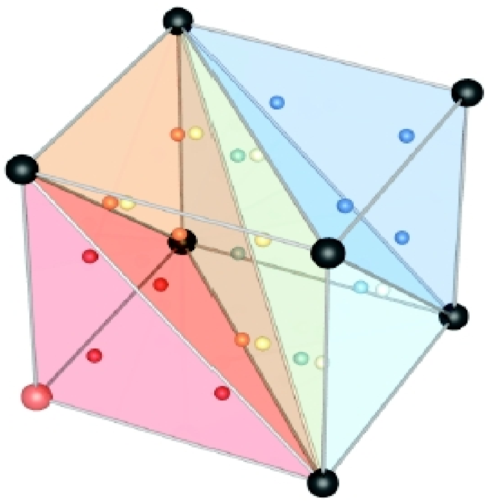
An alternative approach:

Discretization of the DM fluid using phase-space element methods

2+1D



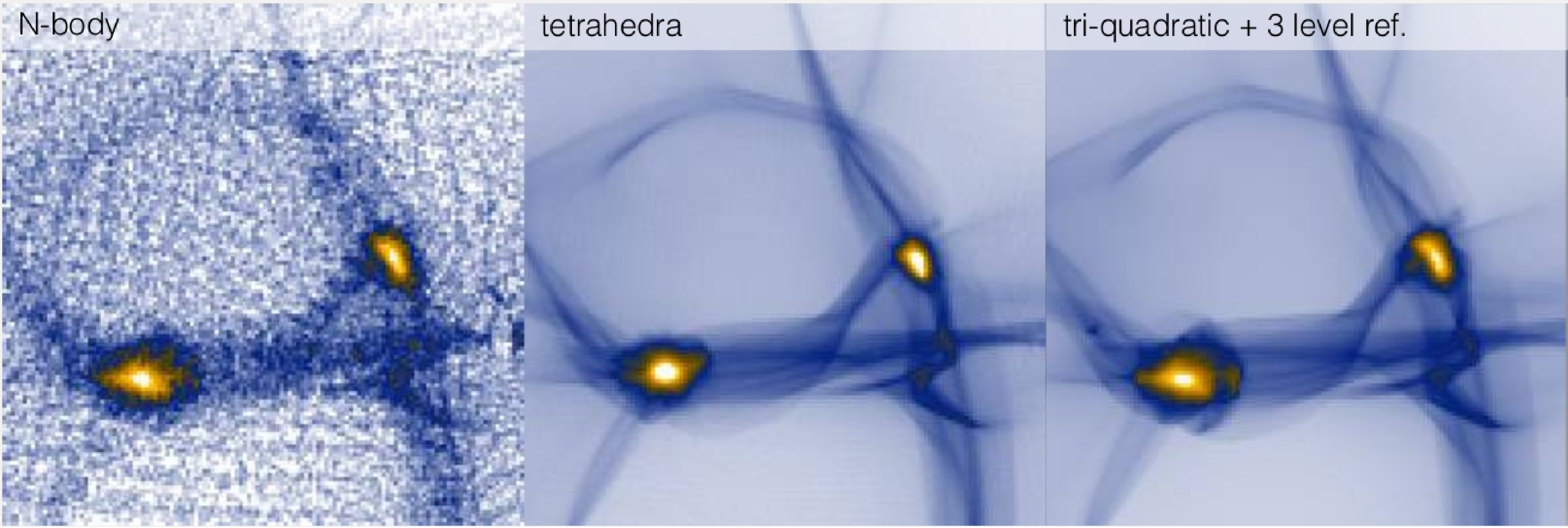
3D



A tessellation of a finite number of mesh-generating points in Lagrangian space allows to continuously map the deformation of the dark matter sheet

(Abel+ 2012, Shandarin+ 2012, Kaehler+ 2013, Hahn+ 2013, Angulo+ 2013, Hahn & Angulo 2015)

Simulations of the same region of the Universe

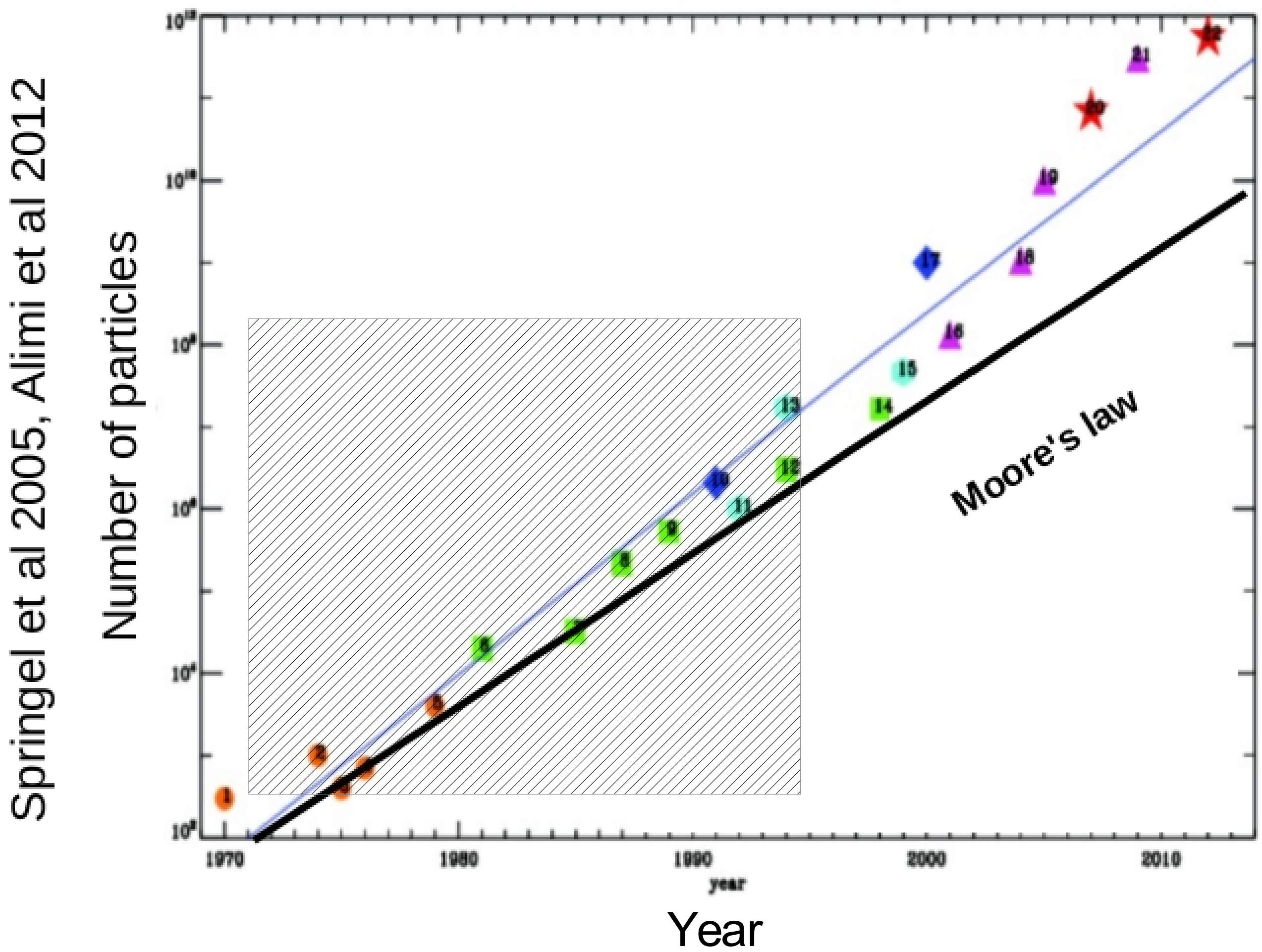


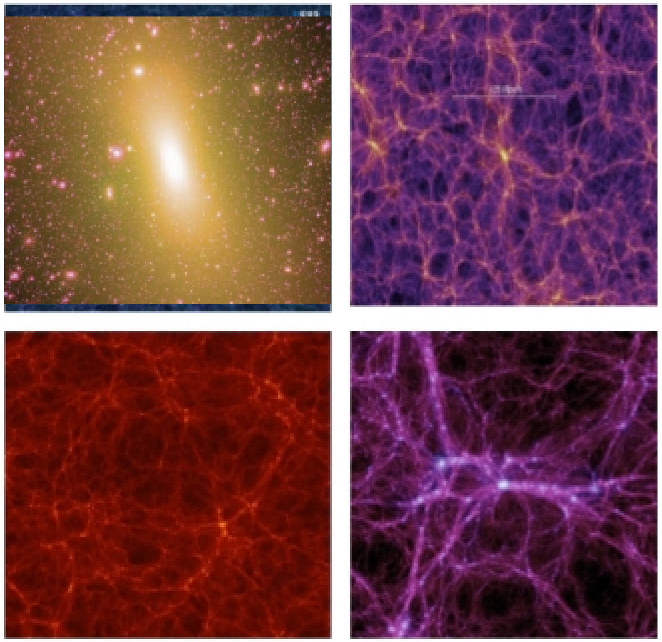
Hahn & Angulo 2015

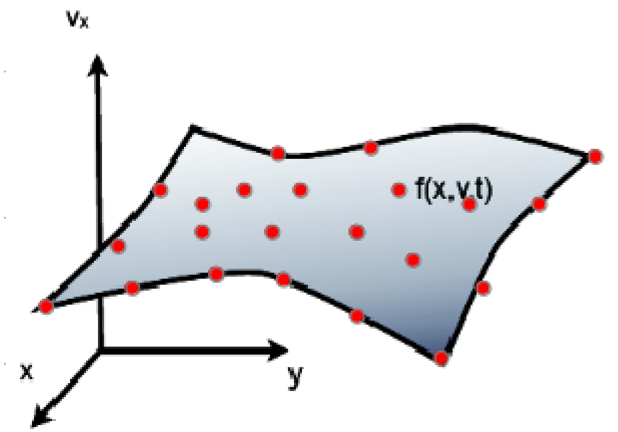
See O. Hahn's talk

Exponential growth of computing power over 40 years

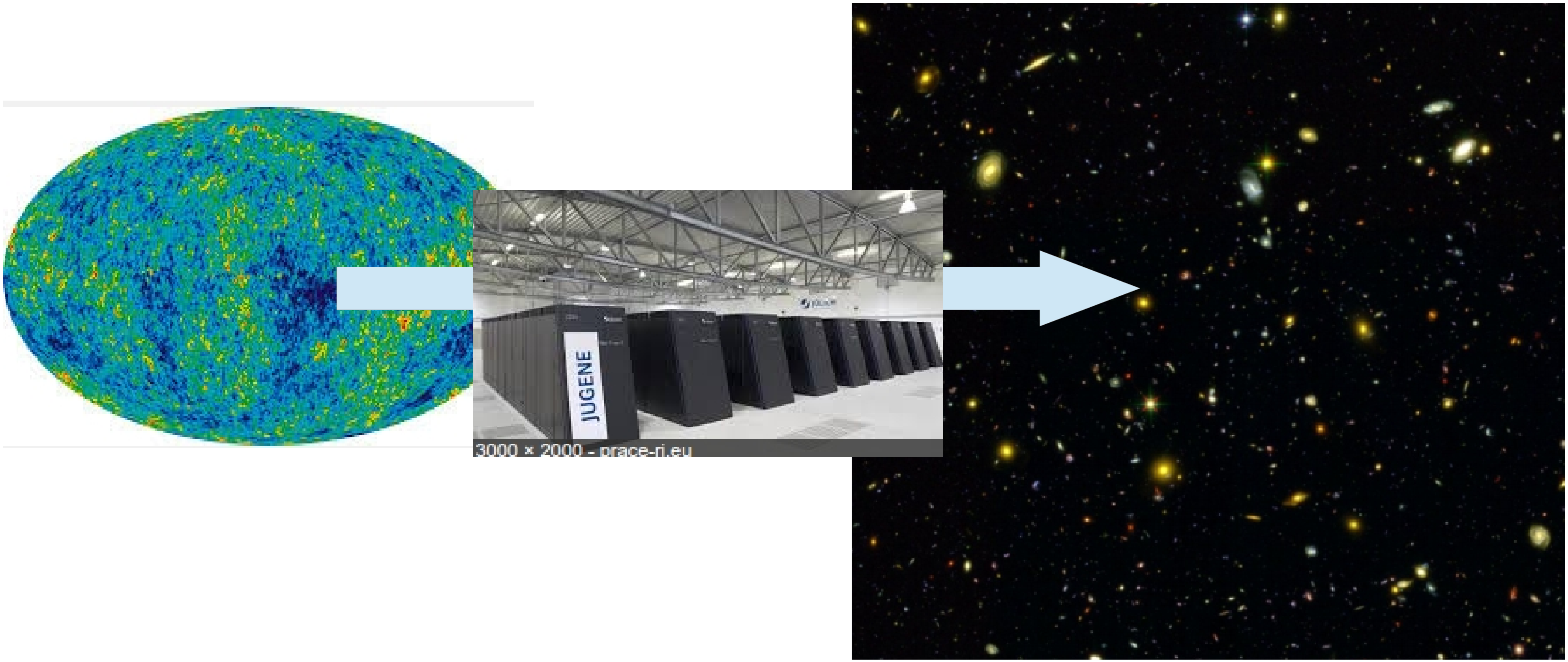
10 trillion particle N-body simulations are expected by 2020





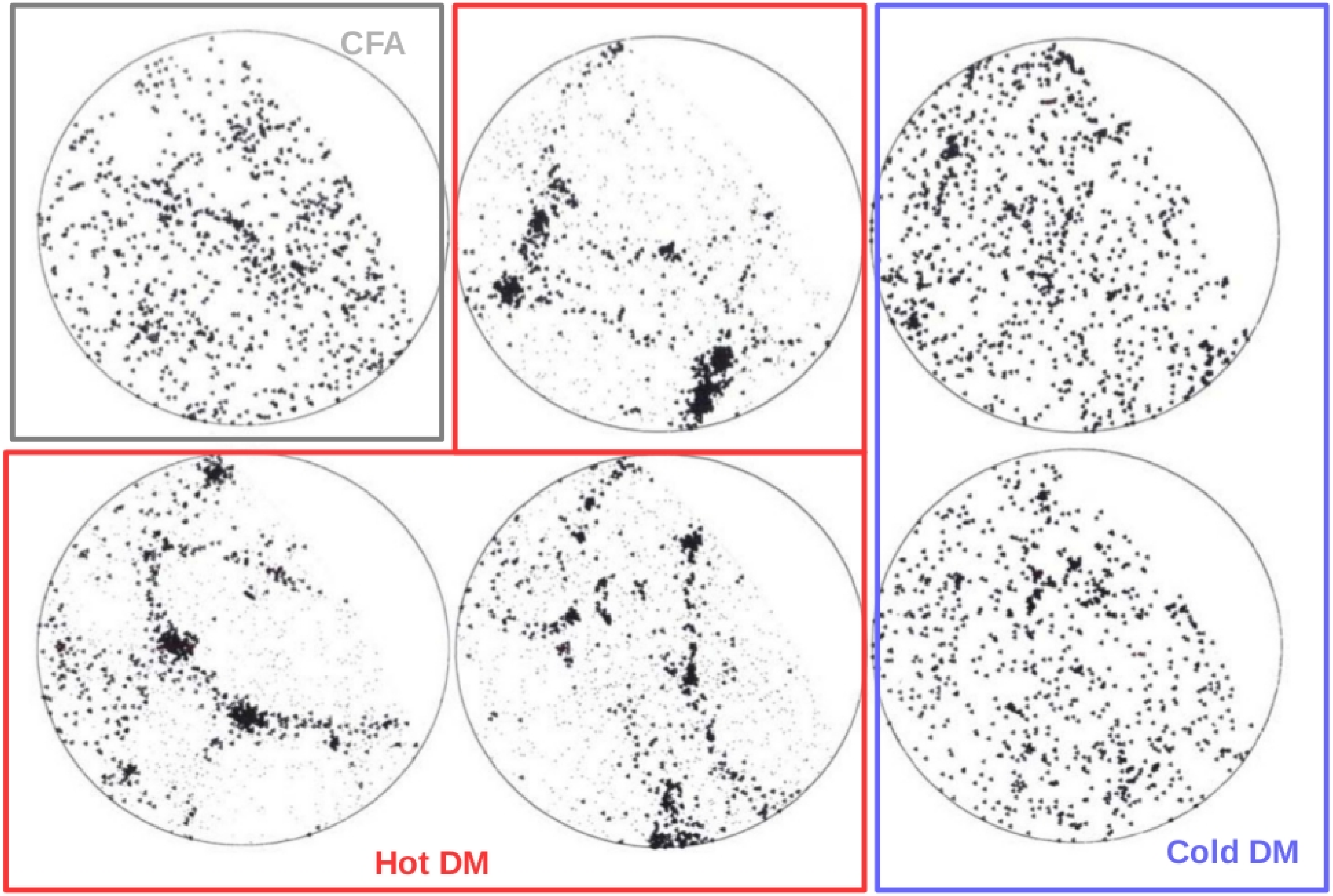


Numerical simulations have been essential in the establishment of the "cosmology standard model"



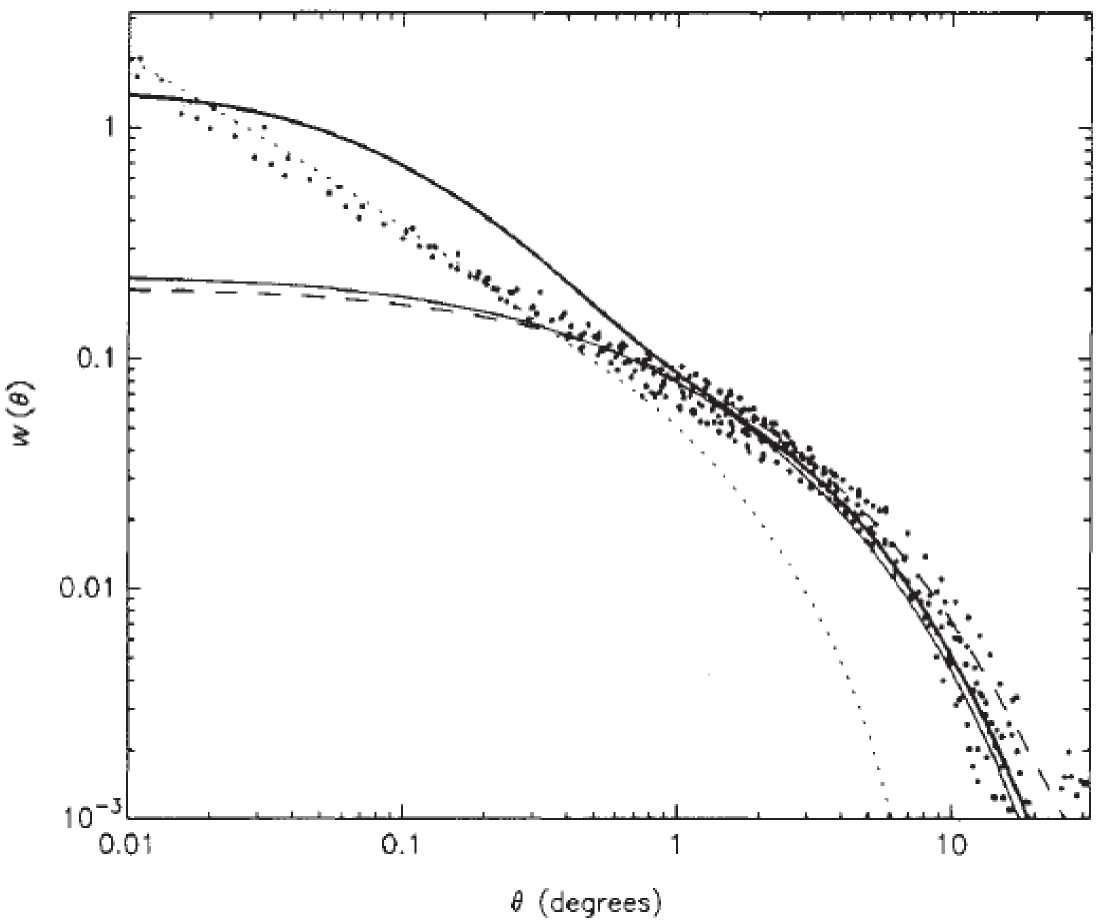
They aim to bridge 13.6 billion years of nonlinear evolution

1985: The CDM model plus gravitational instability can explain qualitatively the observed universe



Davis, Efstathiou, Frenk & White 1985

1990: A cosmological constant is needed to explain the observed clustering of galaxies



Data: APM Survey
Theory: Dotted Omega_m = 1
Solid Omega_m = 0.2
Omega_lambda = 0.8

Efsthathiou, Sutherland & Maddox (1990)

"We argue that the successes of the CDM Theory can be retained and the new Observation accommodated in a spatially Flat cosmology in which as much as 80% Of the critical density is provided by a Positive cosmological constant..."

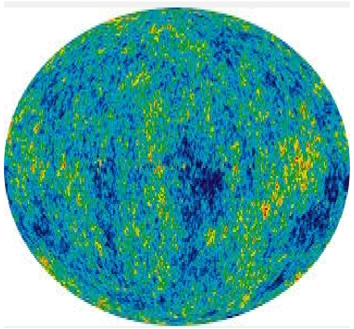
Our current understanding of structure formation in the Universe stands on four key ideas:

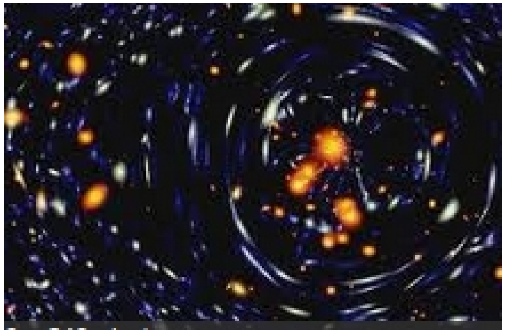
General Relativity

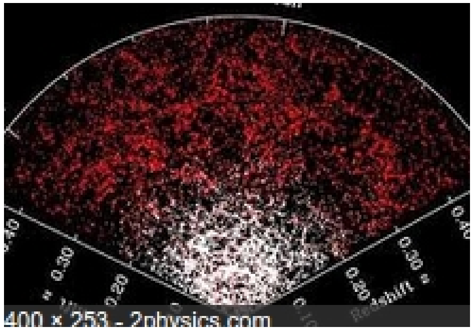
Dark Matter

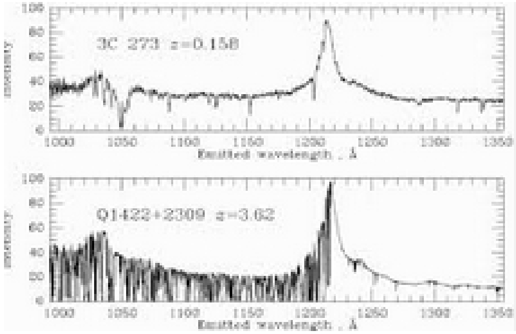
Dark Energy

Inflation









There are fundamental open questions about each of its pillars.

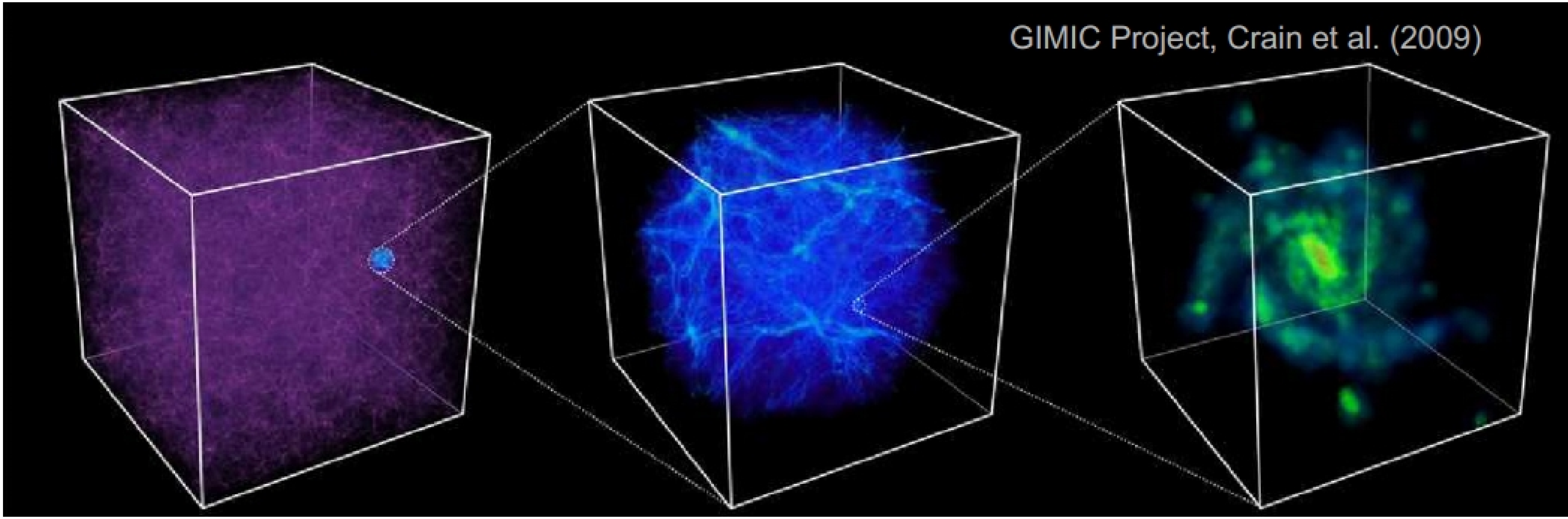
General Relativity **Galileon, f(R)?**	**Dark Matter** **Warm or Cold?**
Dark Energy **w(z) or Lambda?**	**Inflation** **Single/multi field?**

These enigmas have driven multi-million dollar experiments.

The signature of departures from ΛCDM depend sensitively on:

- → the detailed distribution of dark matter
- → the precise impact of dark energy on cosmic structure
- → the physics of galaxy formation

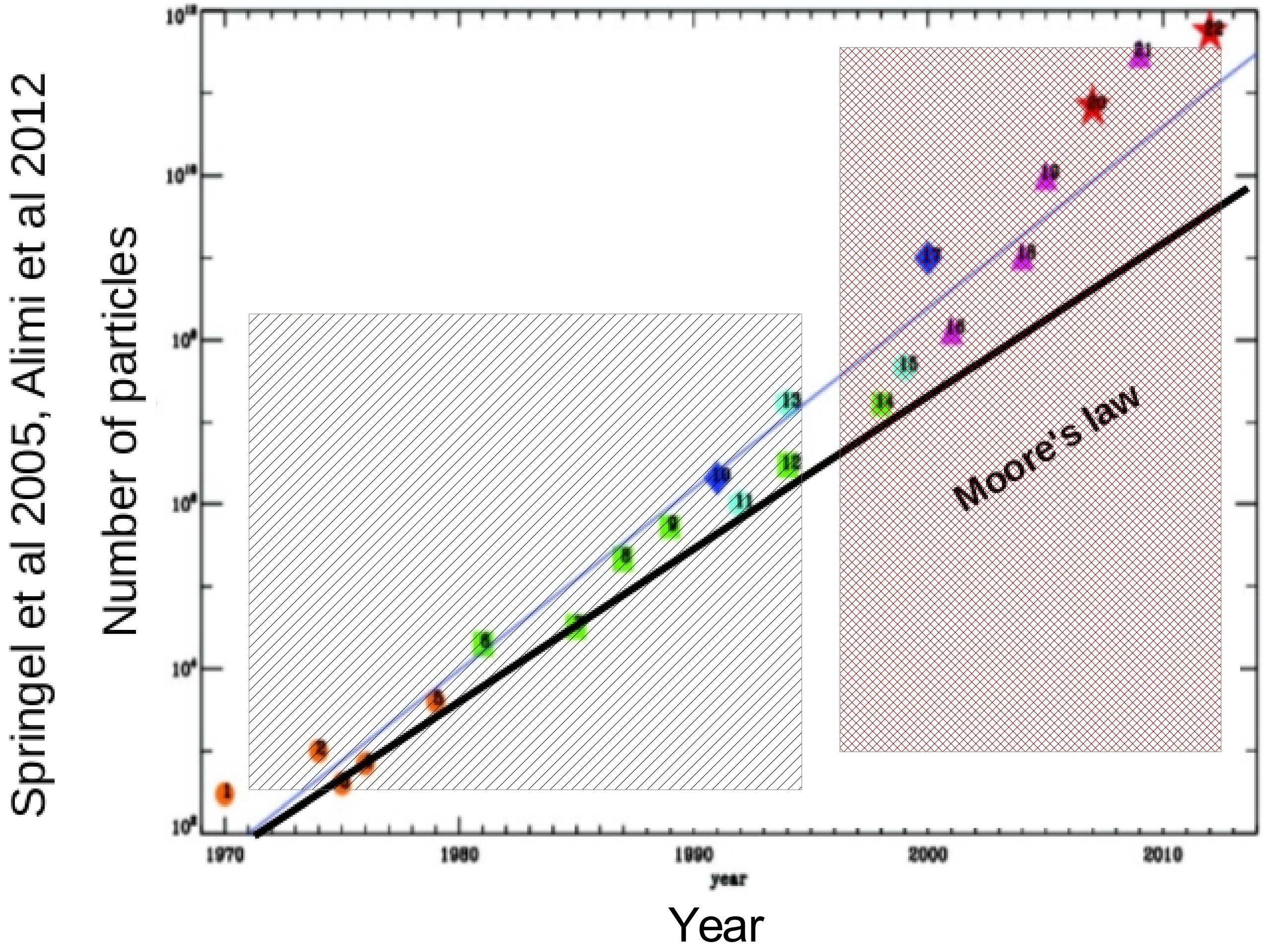
All this from gigaparsecs down to subgalactic scales

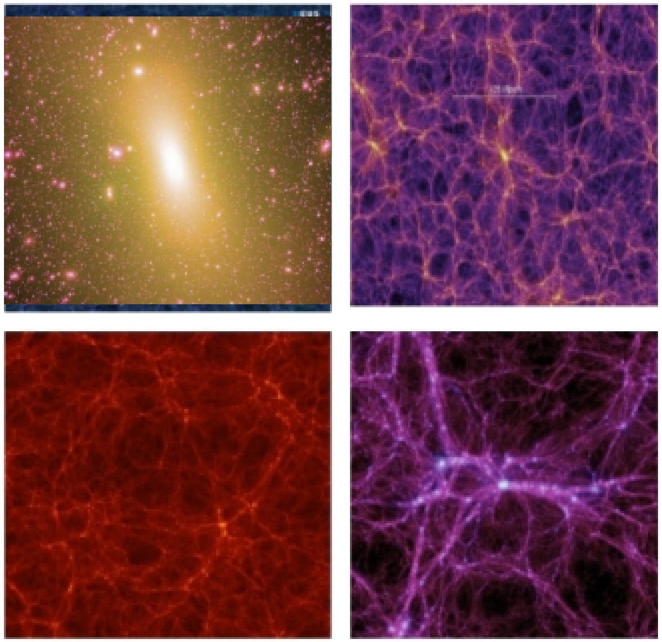


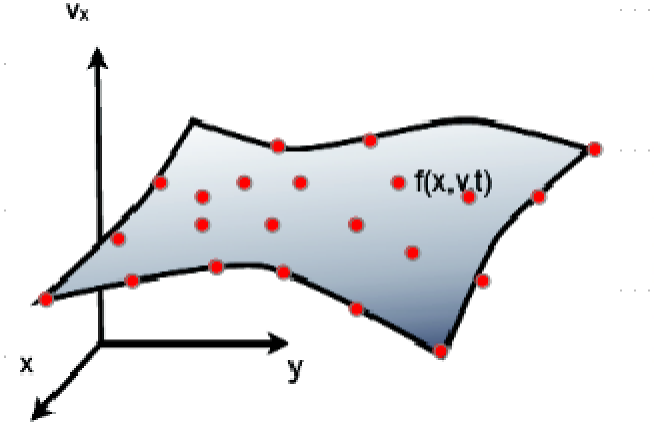
Modern simulations face new challenges in terms of their accuracy and predictive power.

Exponential growth of computing power over 40 years

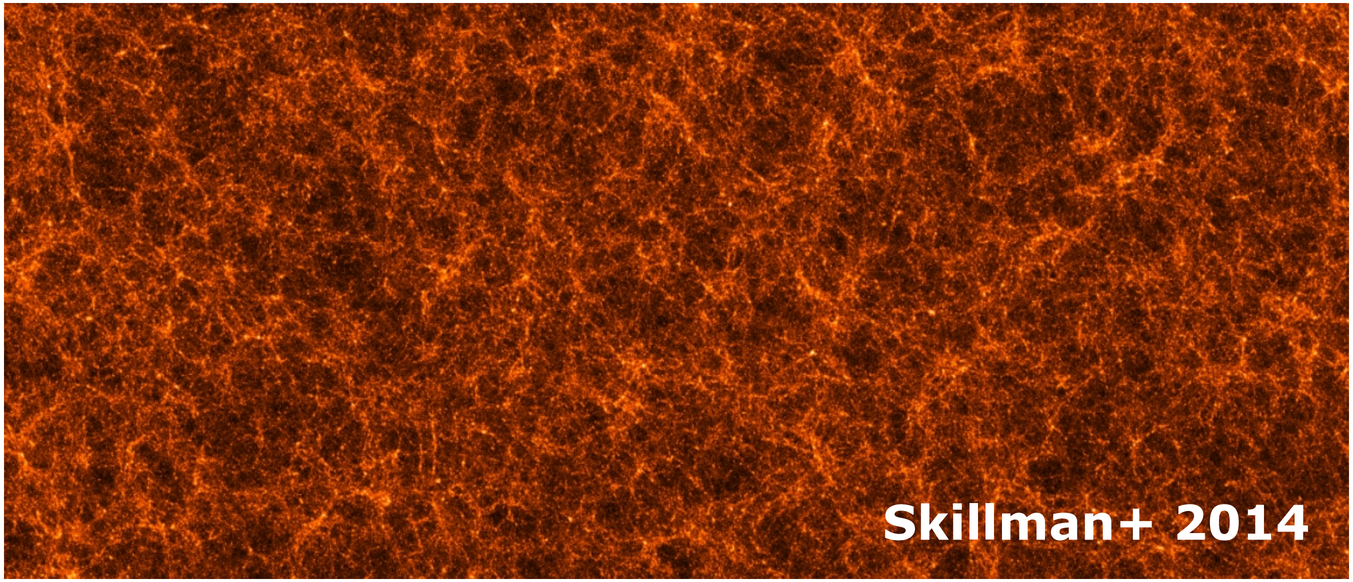
10 trillion particle N-body simulations are expected by 2020







The record holder: DarkSky simulations



→ 1 trillion particles

→ 10 Gpc box

→ 200,000 CPUs

→ 70 Tb RAM

Large-scale N-body simulations aim to predict:

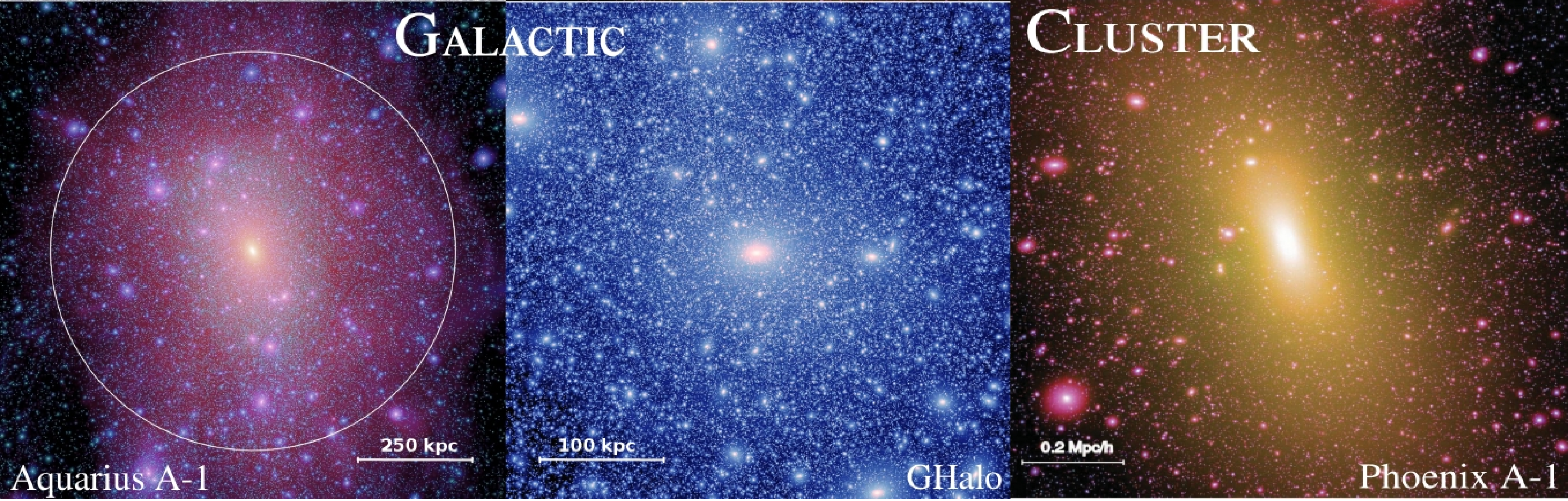
→ The nonlinear state of mass

→ The velocity field

→ Abundance and properties of collapsed DM structures

→ The places of galaxy formation

BAO & Galaxy Clustering
Abundance of Clsters
Weak Gravitational Lensing
Redshift-Space Distortions



Springle+ 2008 Stadel+ 2009 Gao+ 2012

Zoom-In N-body simulations aim to predict:

- → Halo density and velocity profiles
- → Substructure mass function
- → Substructure spatial distribution

Direct Detection
Indirect Detection
Astrophysical Probes

Dark Matter simulations are robust and provide testable results

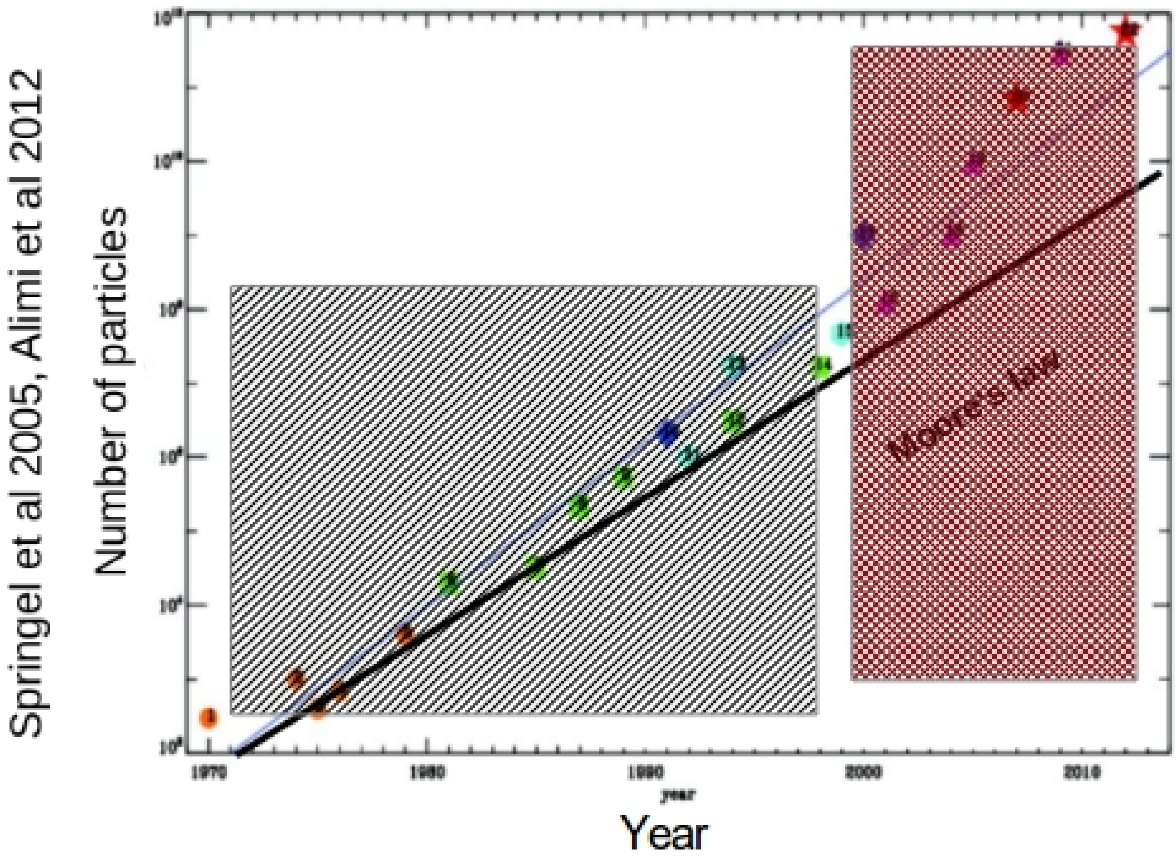
- Haloes are triaxial and rotate slowly.

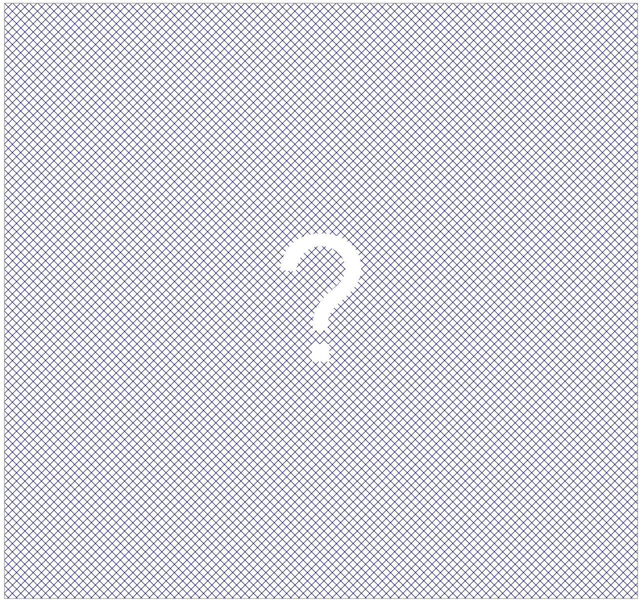
- Halos density profile is described by an universal functional form

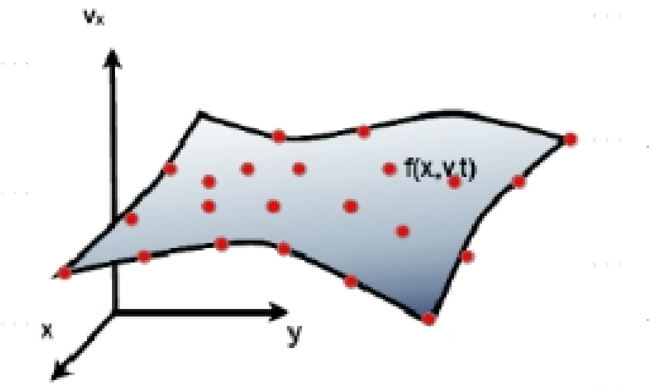
Accurate characterization of:
- Mass function
- clustering
- subbhalo population
- cosmic web

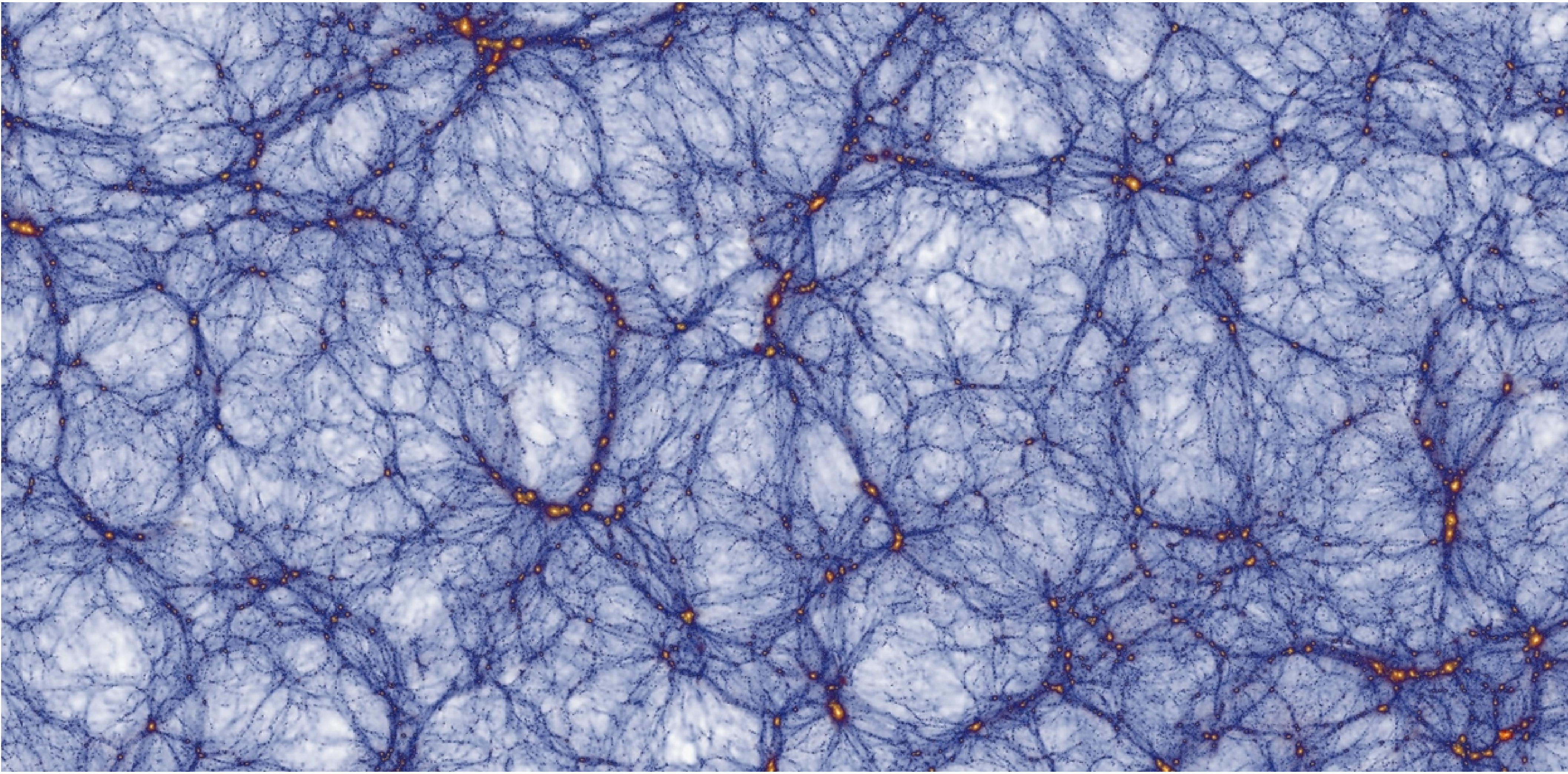
...as a function of cosmological Ingredients.

Is there anything left for Dark Matter simulations after 40 years of development?









MXXL, Angulo+ 2012

How can we optimally extract all the cosmological information encoded in the clustering of galaxies?

The challenge

→ (Nonlinear) density field
→ (Nonlinear) velocity field
→ (Nonlinear, stochastic, non-local) Galaxy bias
→ Higher order correlation functions
→ Precise accounts of observational setups

The reward

→More accurate and robusts constrains on
- Inflation, Gravity, Dark Energy, Dark Matter
- Galaxy Formation physics

→ (*Higher order, Tree loop, Renormalized, Lagrangian, Eulerian, Effective Field Theory of LSS, augmented, integrated)* Perturbation theories; Halo Model; Halo Fit

N-body simulations can and should be used to directly to constraint cosmological parameters

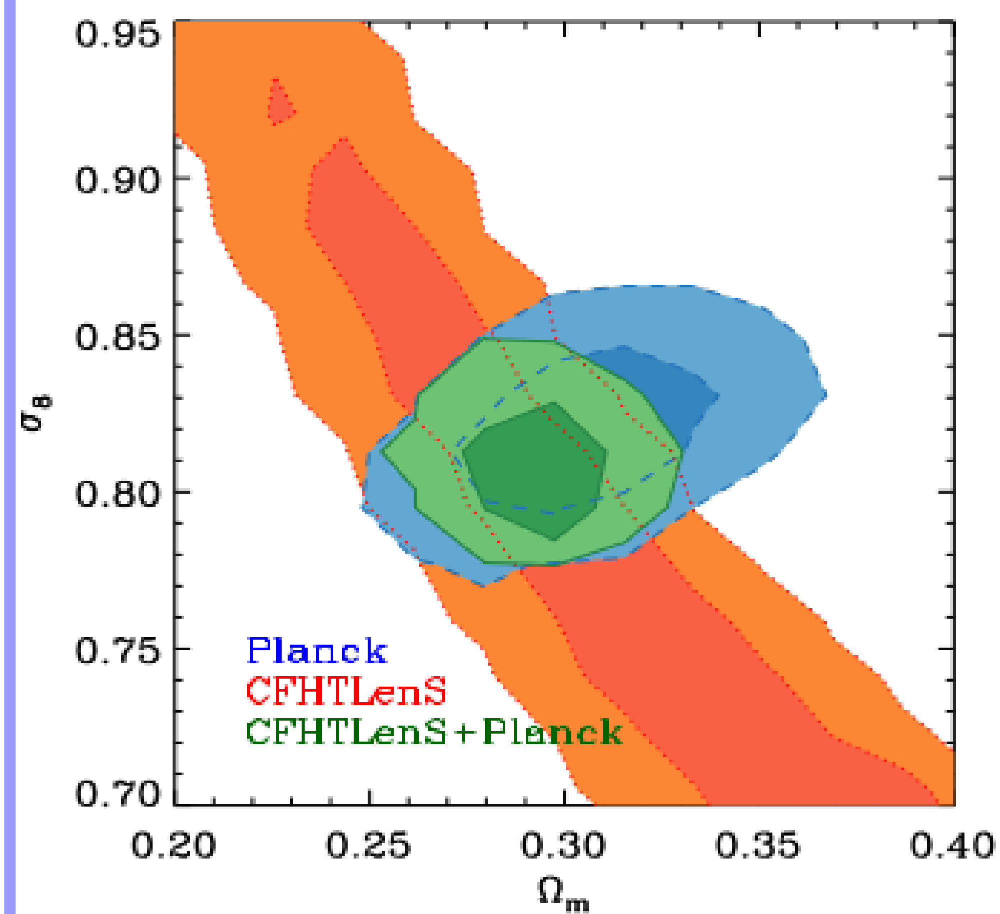
The dark matter as a function of cosmology

→ A grid of DMO simulations
→ Emulators
→ **Cosmology scaling**

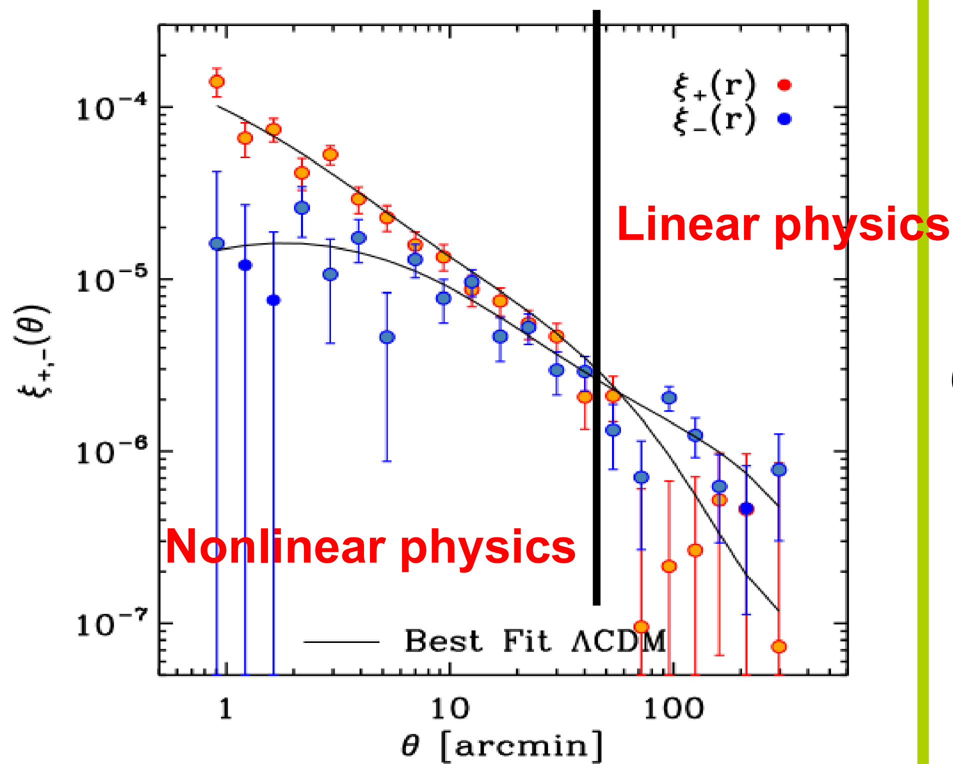
The galaxy population

N-body simulations can nowadays be used to directly constraint cosmological parameters

$$\Omega_m = 0.29 \pm 0.01$$
$$\sigma_8 = 0.81 \pm 0.01$$

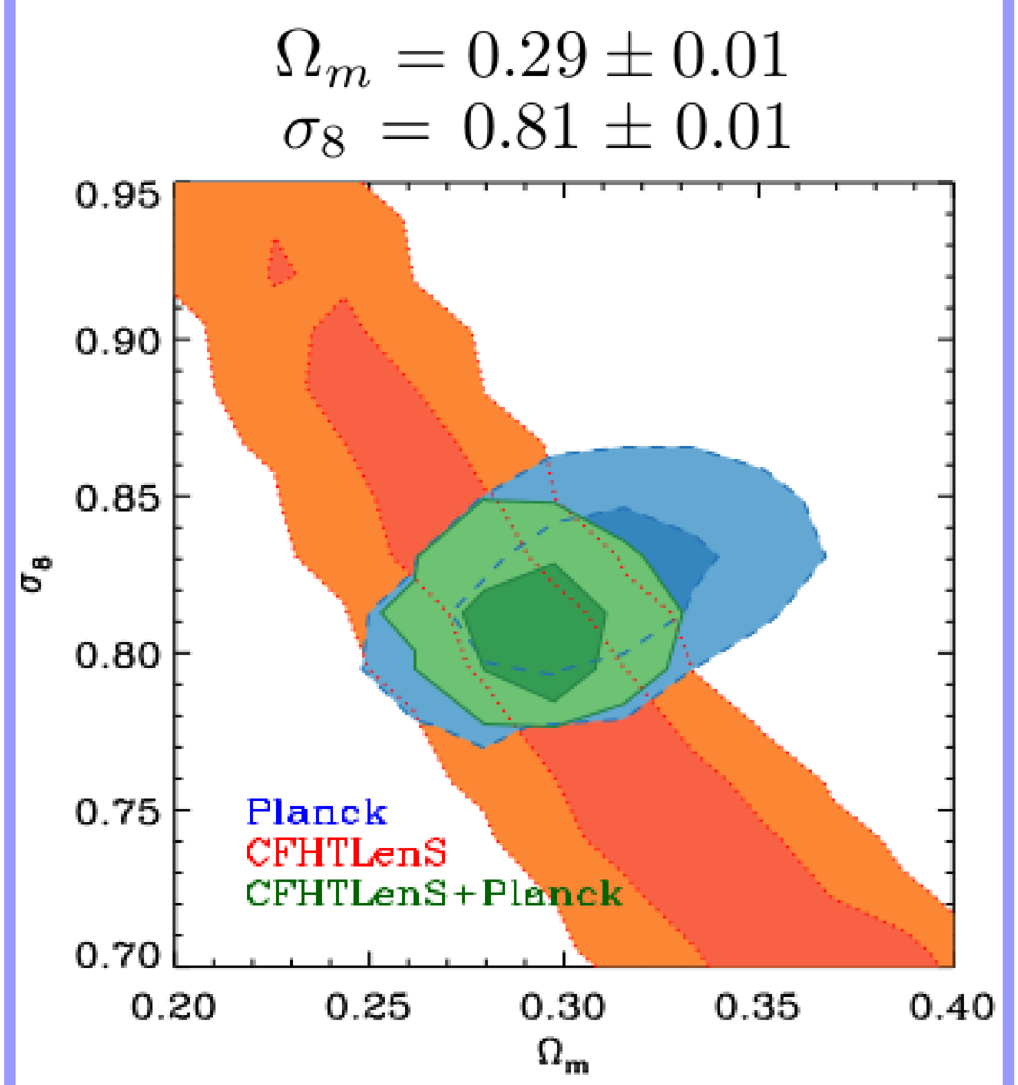


Shear Correlation measurements

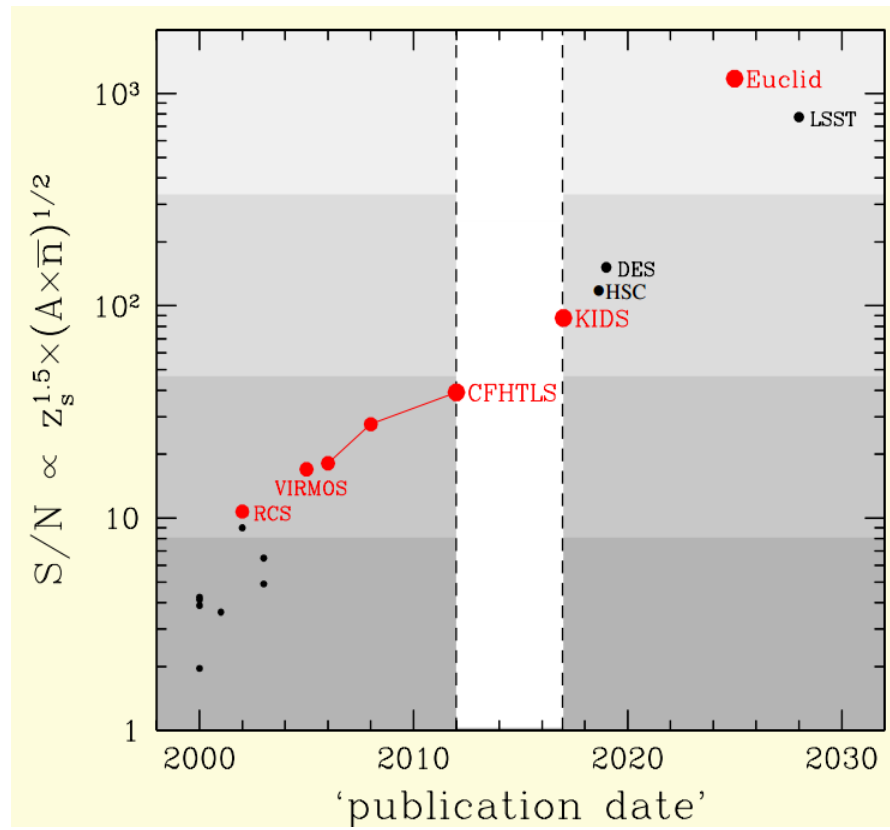


Angulo & Hilbert 2014

N-body simulations can nowadays be used to directly constraint cosmological parameters



From H. Hoekstra



Angulo & Hilbert 2014

N-body simulations can and should be used to directly to constraint cosmological parameters

The dark matter as a function of cosmology

→ A grid of DMO simulations
→ Emulators
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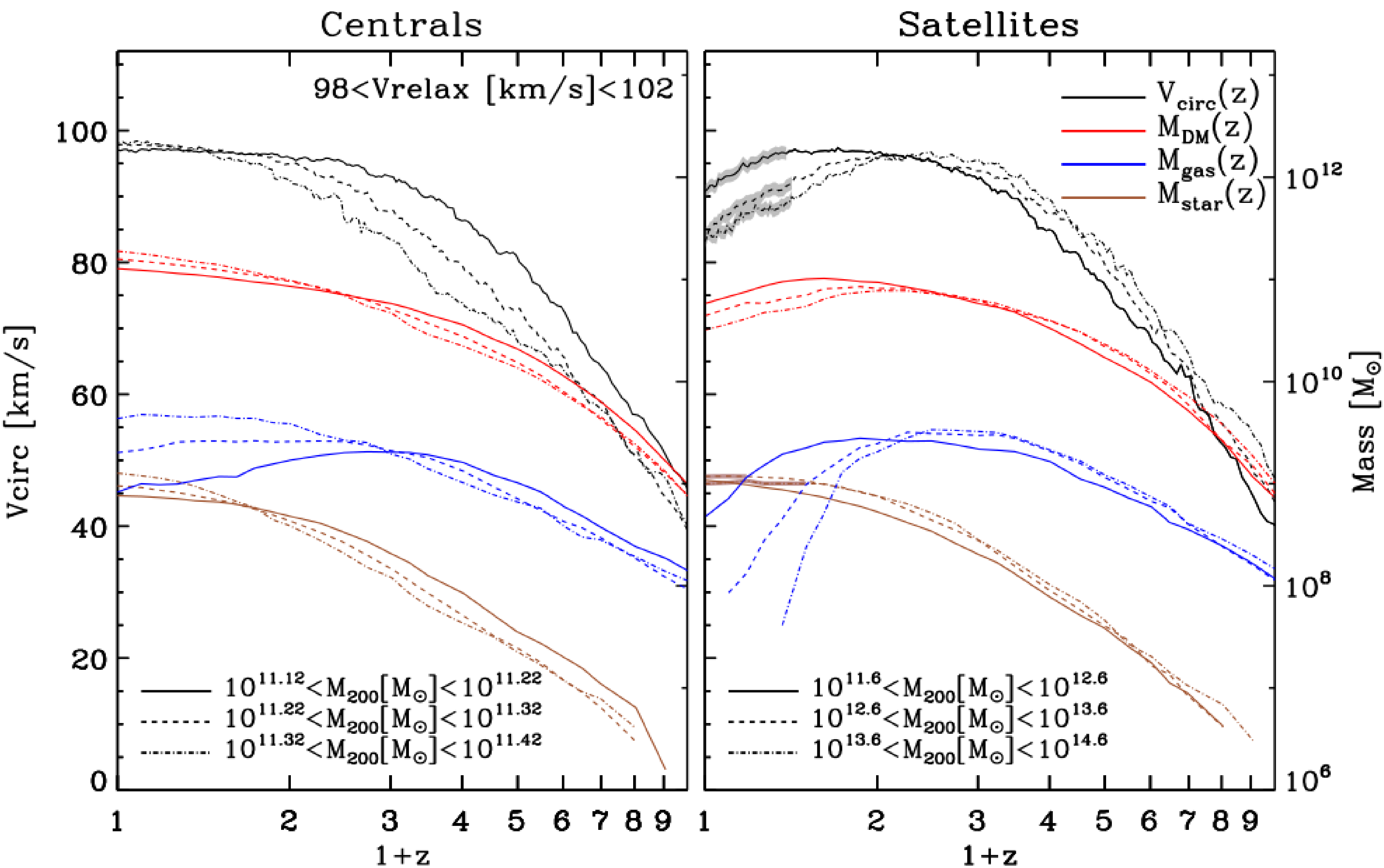
The galaxy population

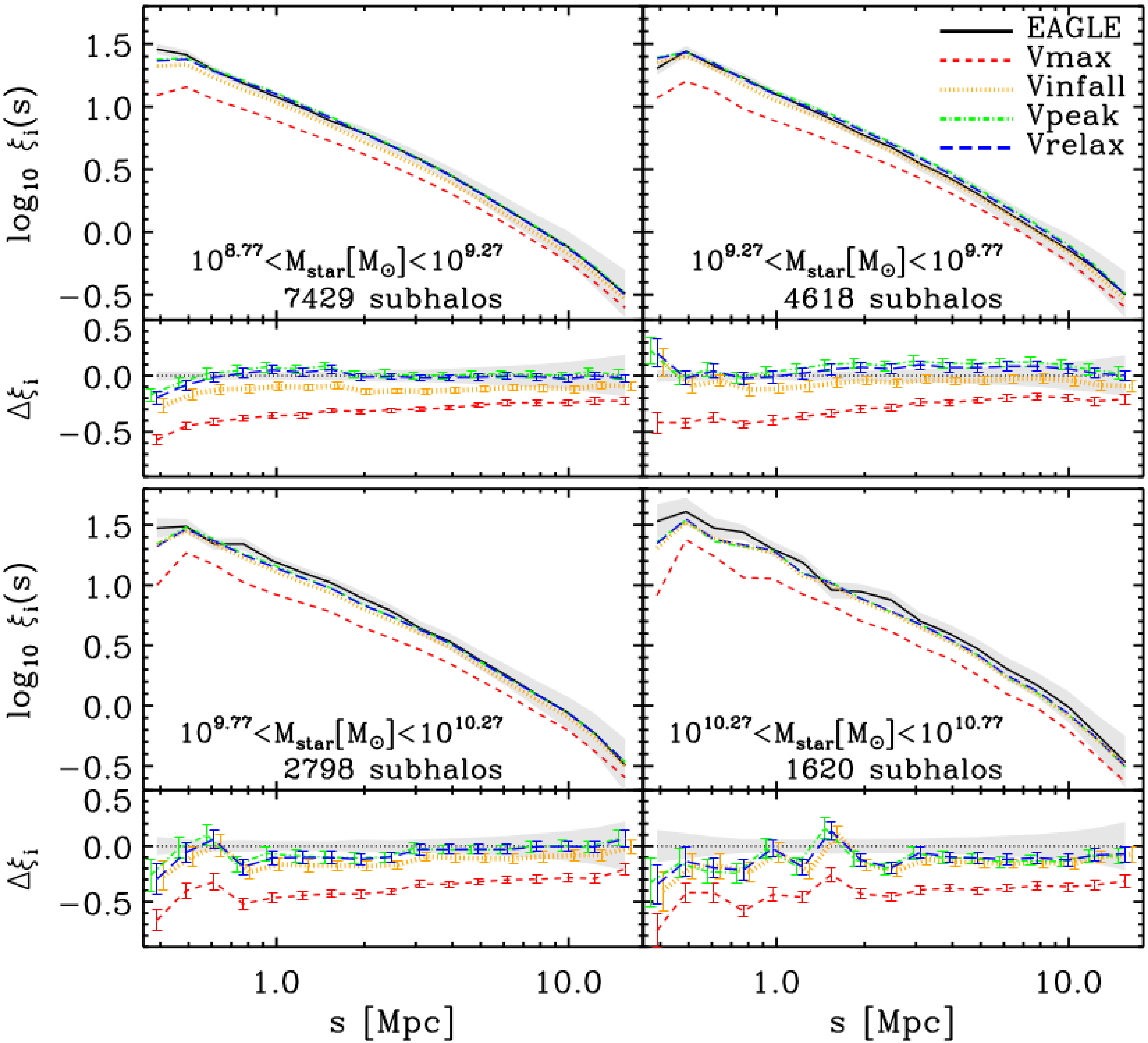
→ Hydrodynamical simulations
→ Semi-analytics models
→ Halo Ocupation distribution
→ **Subhalo Abundance matching**

Testing SHAM in hydrodynamical simulations



Chavez, Angulo + EAGLE team (2015, in prep)

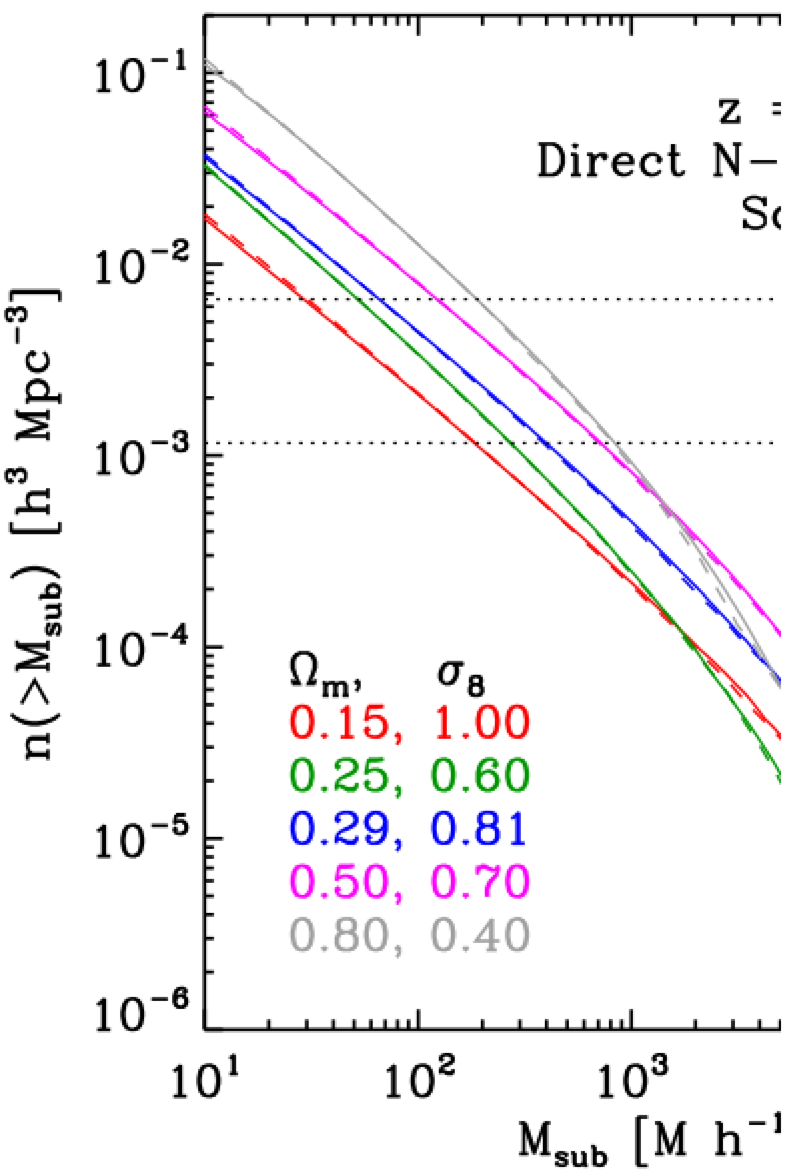
Redshift space clustering

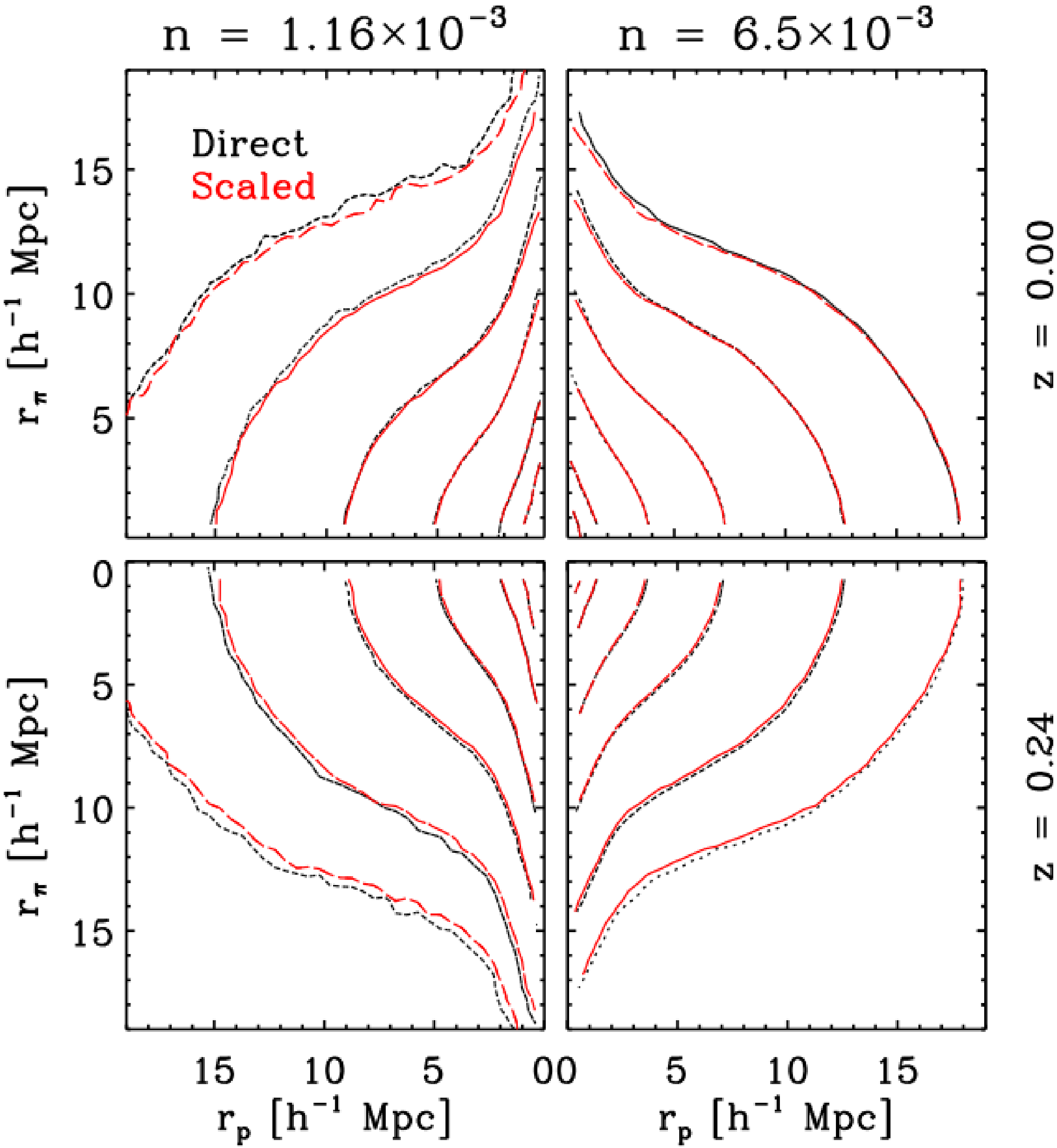


Can we put these two ingredients together?

The dark matter as a function of cosmology

The galaxy population

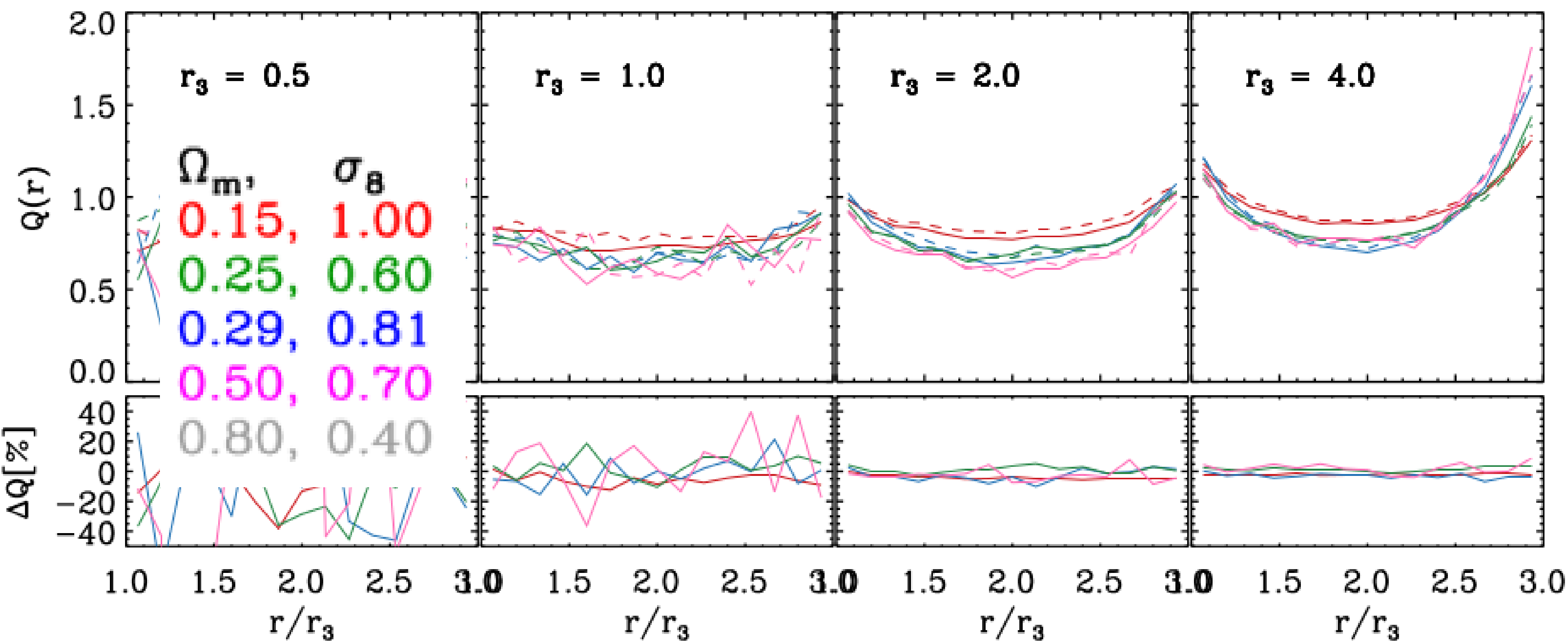




Can we push this further?
3pt correlation functions in *redshift* space

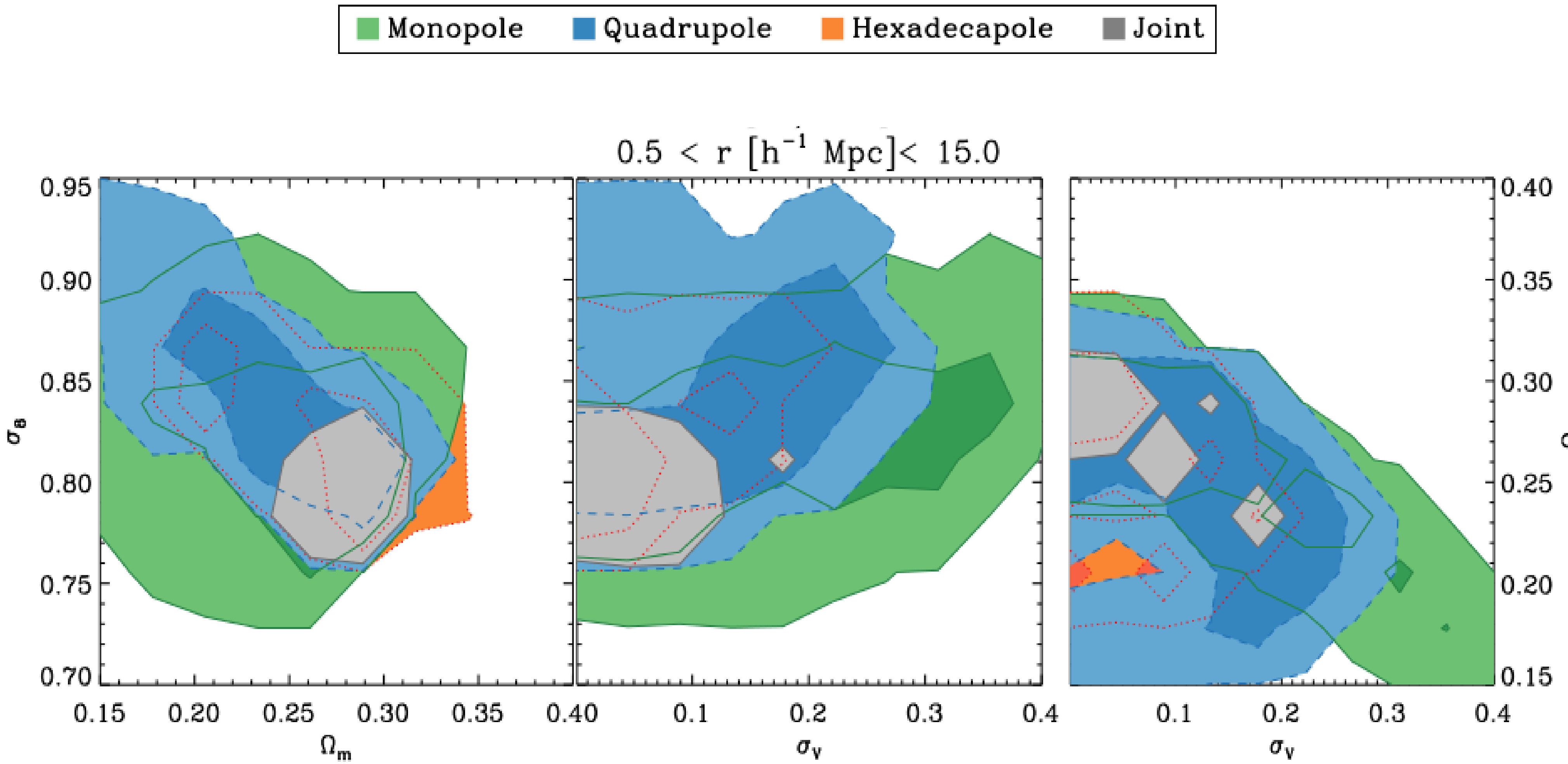
Different triangular configurations can be predicted to the same accuracy

$$Q(s,u,\theta) \equiv \frac{\zeta(s,u,\theta)}{\xi(r_1)\xi(r_2)+\xi(r_2)\xi(r_3)+\xi(r_3)\xi(r_1)}$$



Application: Main SDSS sample

Angulo, Marin & White, in prep



After BAO and RSD, future surveys will extract information from the largest cosmological scales

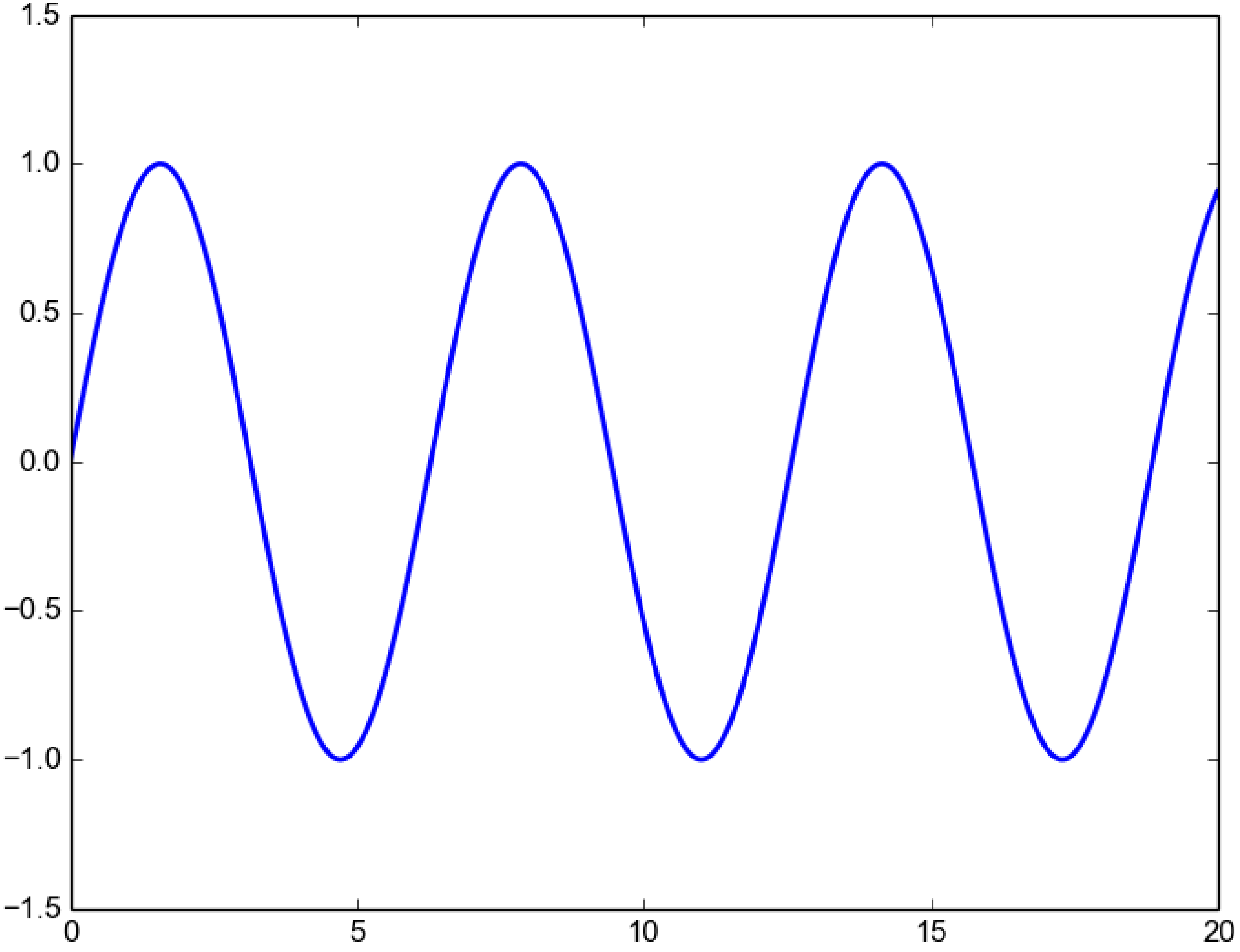
→ Non-Gaussianities

→ General Relativity effects

→ Neutrino Masses

A forward modelling would also make simpler to model complex observational setups

How do we optimally measure those scales?



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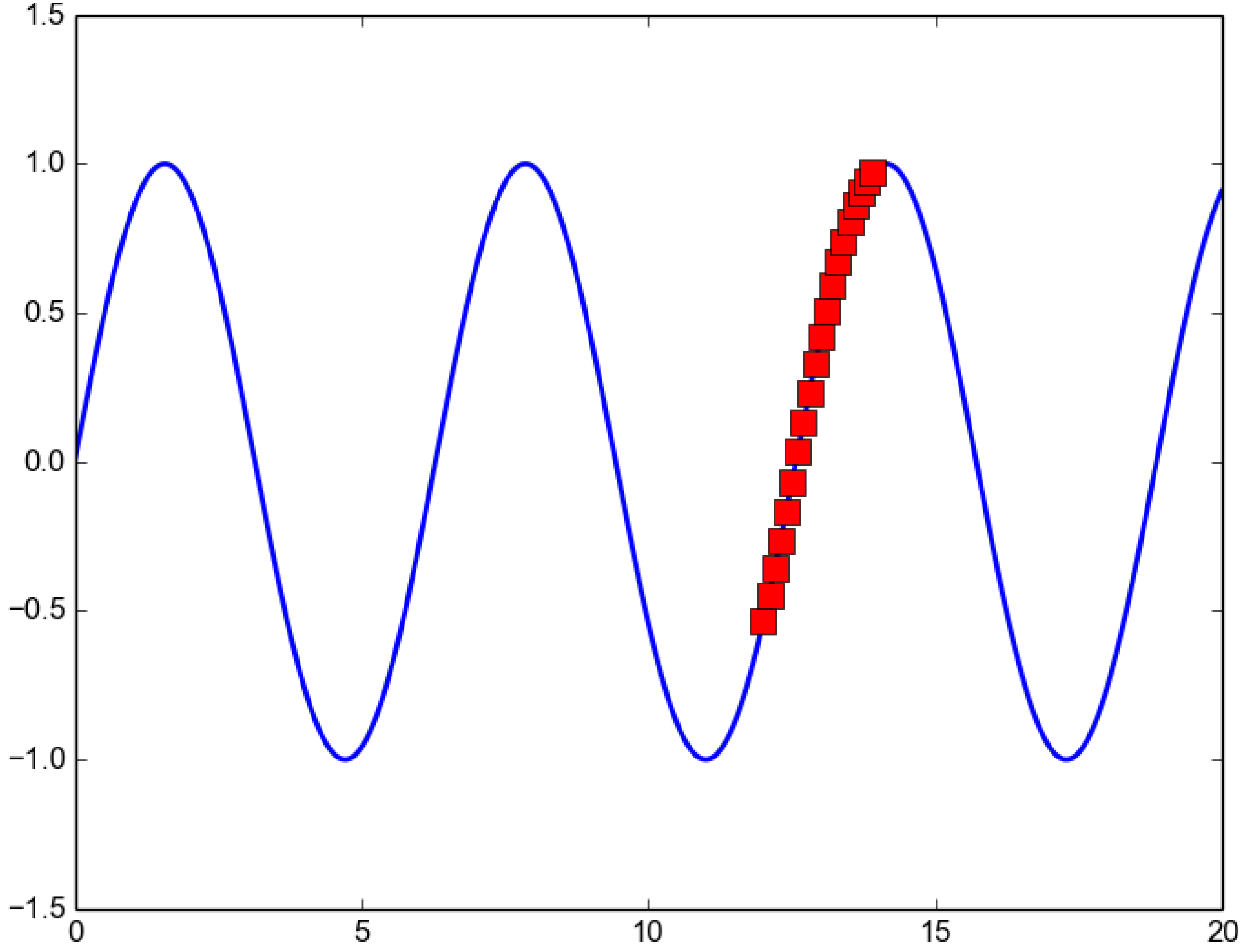

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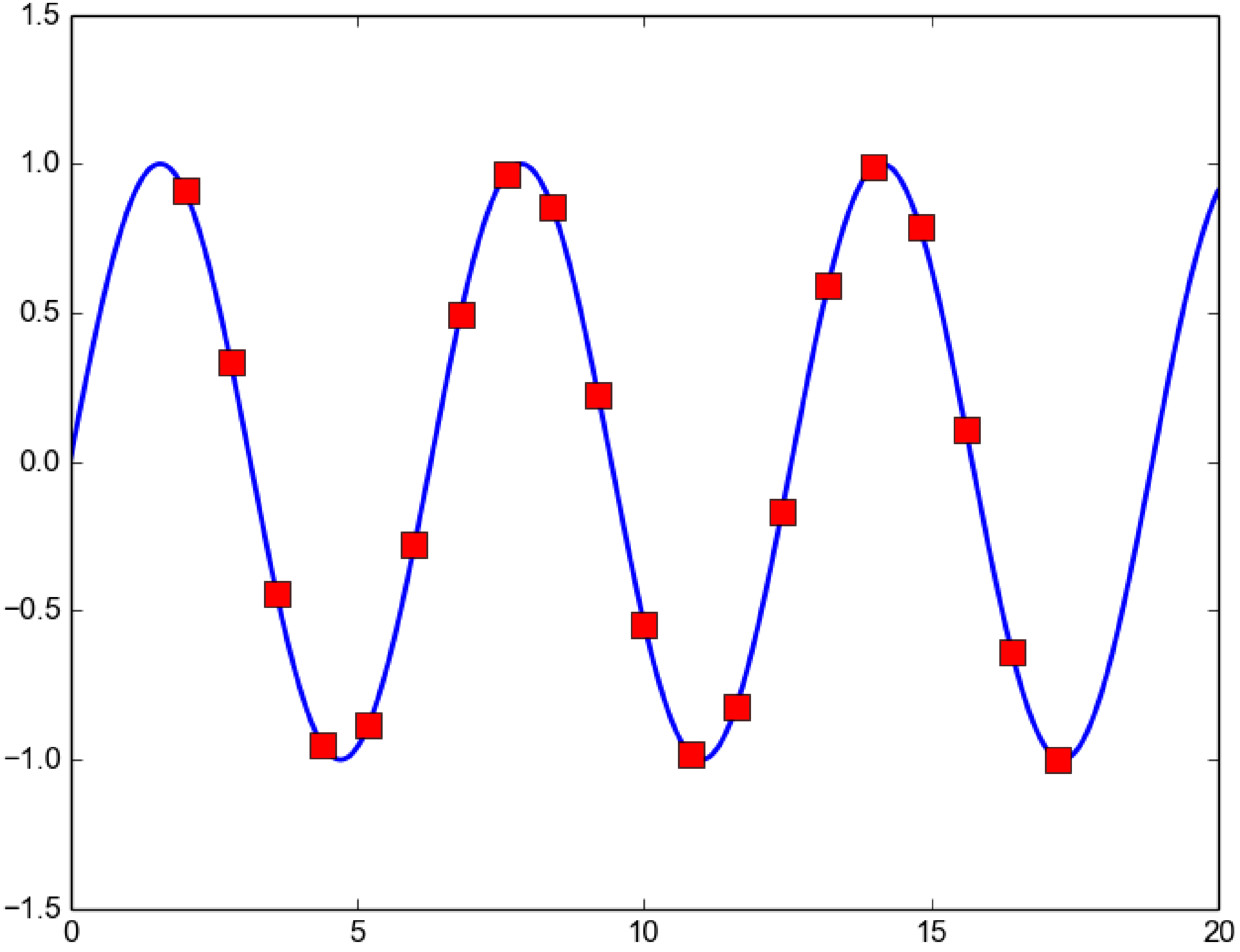
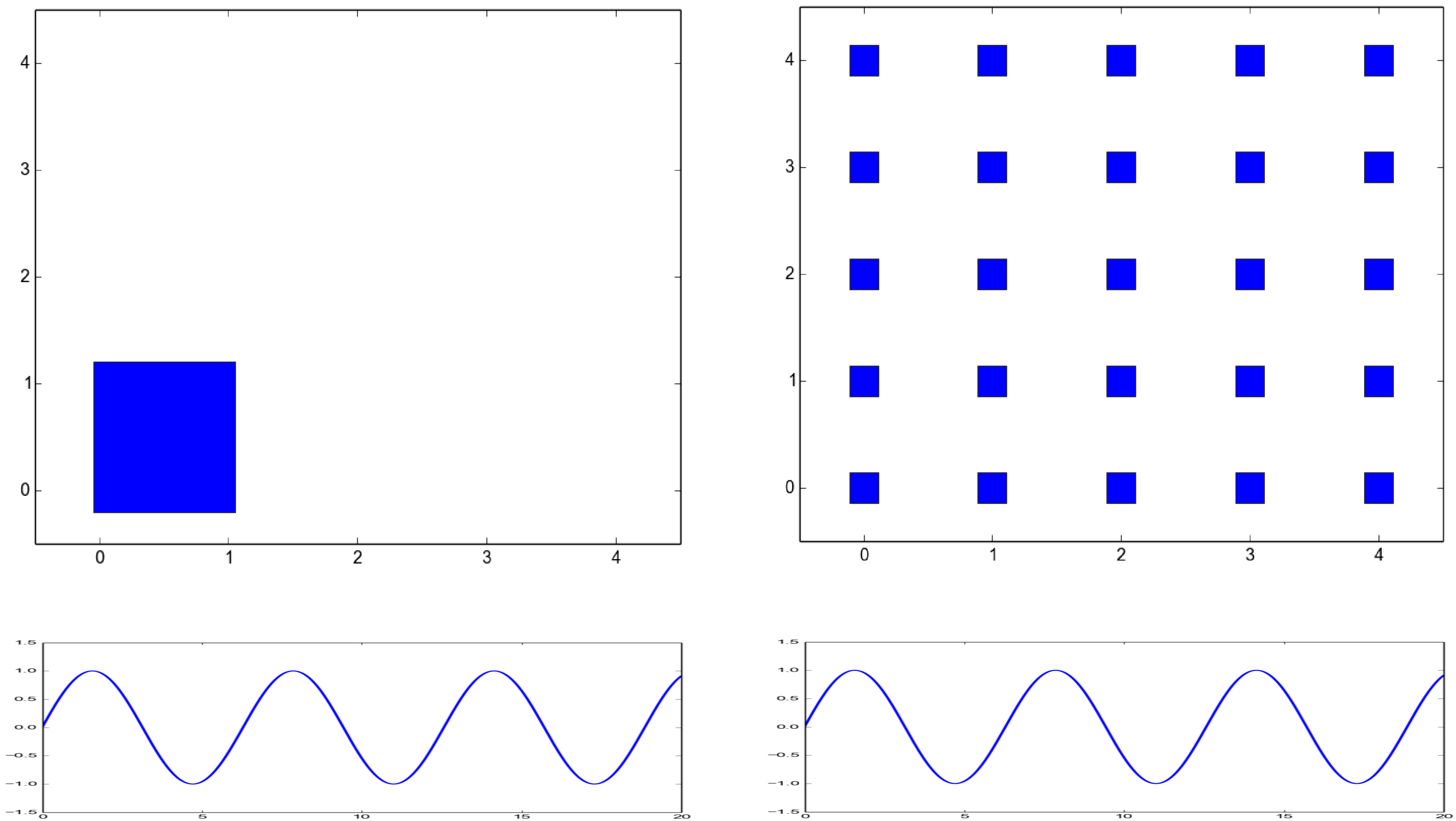
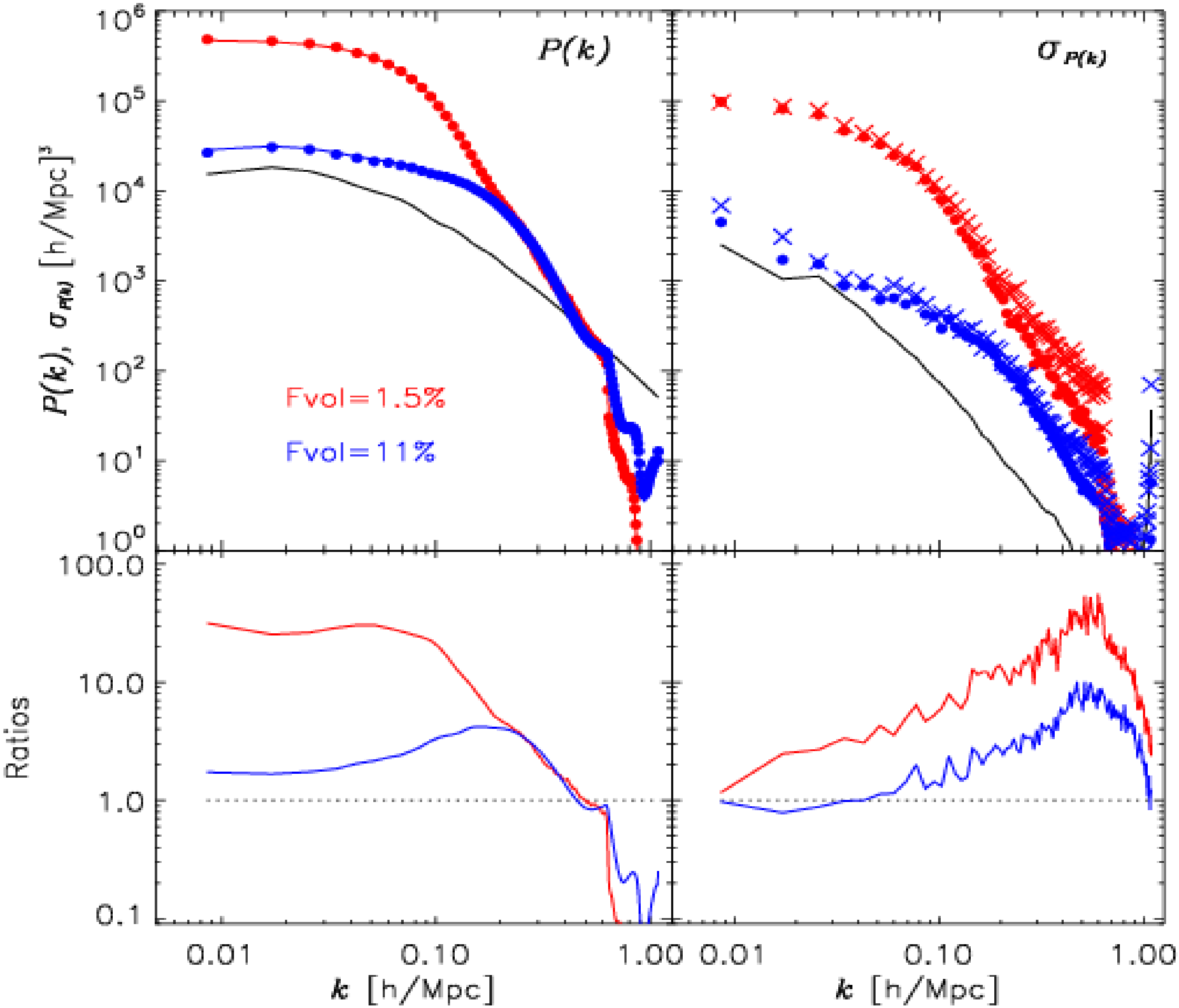


Continuous v/s sparse sampling

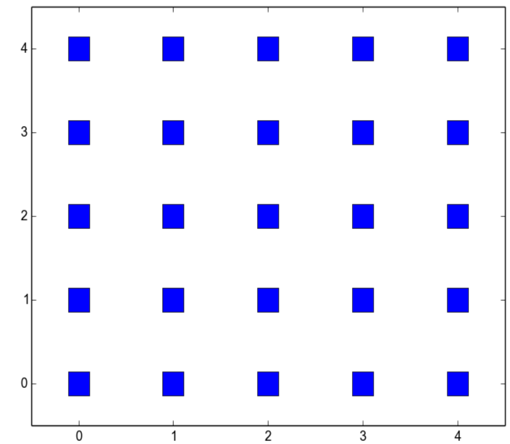


k < 0.1 h/Mpc scales can be measured in 10% of the time

k < 0.01 h/Mpc scales can be measured in 1% of the time



dx = 5Mpc/h



L = 1200 Mpc/h

Hernandez-Monteagudo & Angulo (2015, in prep)

Summary

→ Modern N-body simulations are essential to address current and future challenges in cosmology. The exaflop limit and 10 trillion particle runs are expected by 2020

→ In a formative era, simulations were essential to probe that the Universe we observed can be explained by simple initial conditions and the laws of physics

→ In a consolidation era, simulations have provided us for very accurate predictions for the properties of structure

→ In the next era, N-body results could be used directly in cosmological analyses