Non-linear cosmological structure formation

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- **The (very) big picture**
- **Recent research @LPNHE**
- **Perspectives**

The field in perspective

The paradigm of Modern Cosmology

Phase 1: The (homogeneous and isotropic) Big Bang

Theory: 1915→1960

Observation (key dates): 1929, 1965, 1998.

(exp, cmb, accel)

Phase 2: The perturbed FRW Universe

Theory: 1960→1980

Observation (key dates): 1992, 1998, 2005

(δ-cmb, ao- cmb, bao)

Phase 3: The non-linear Universe

Theory: 1970s onward

Observation (key dates): ??

Non-linear structure formation

Open boundary with astrophysics (e.g. star formation, gravitational waves)

What is the problem of (non-linear) cosmological structure formation?

To account for the organisation of matter (visible and dark) at scales sufficiently large that gravity dominates

(Very roughly: galaxy scales upwards, 0.1-10 Mpc)

Very rich observations (e.g. galaxy clustering, lensing...), but no key confirming observation

A very coherent and elaborate theoretical framework has emerged, but theory lags behind observation !

Non-linear cosmological structure formation

Practical goal: to calculate predictions for observables

Complexity of non-linear physics -> **Centrality of numerical simulation**

What is role of (non-numerical) theory?

- help **understand the physical processes**
- provide **control on numerical simulation**
- build **model for observables** using numerical simulations

Recent research @ LPNHE

Theory@LPNHE

Subgroup of **“équipe cosmologie energie noire”** @LPNHE (11 permanents)

Theory:

1 permanent (MJ) + (currently) 2 Ph.D. students

+ french (non-in2p3) and international collaborations:

Main current external collaboration (since 2017)

D. Eisenstein (Center for Astrophysics, Harvard)
L. Garrison (Flatiron Institute, New York)
B. Diemer (University of Maryland)

Focus : “Problem 0” of non-linear SF

Clustering of matter in standard cosmological models in the

- **non-relativistic**
- **dissipationless (i.e. “gravity only”)**

limit

The matter distribution obtained in this limit is still a cornerstone for building predictions for observables
(e.g. lensing, galaxy correlation via “HOD”)

Dissipationless cosmological SF

Solve **Vlasov-Poisson equations** for the phase space density of dark matter

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

$$\nabla^2\Phi(\mathbf{x}) = \frac{4\pi G}{a^3} \int (f - f_0)\, d\mathbf{v}$$

given

- cosmological **initial conditions** (initial fluctuations→ power spectrum)
- **cosmology** a(t)

(specified fully by **cosmological parameters**)

Numerical simulation of cosmological SF

Use **"N-body" method**: simulate **particles** evolving under their self-gravity

Particles are **not physical particles!**

→ **Unphysical IR/UV cut-offs**: box size, initial grid scale, "force softening"

Physical results must be independent of these cut-offs!

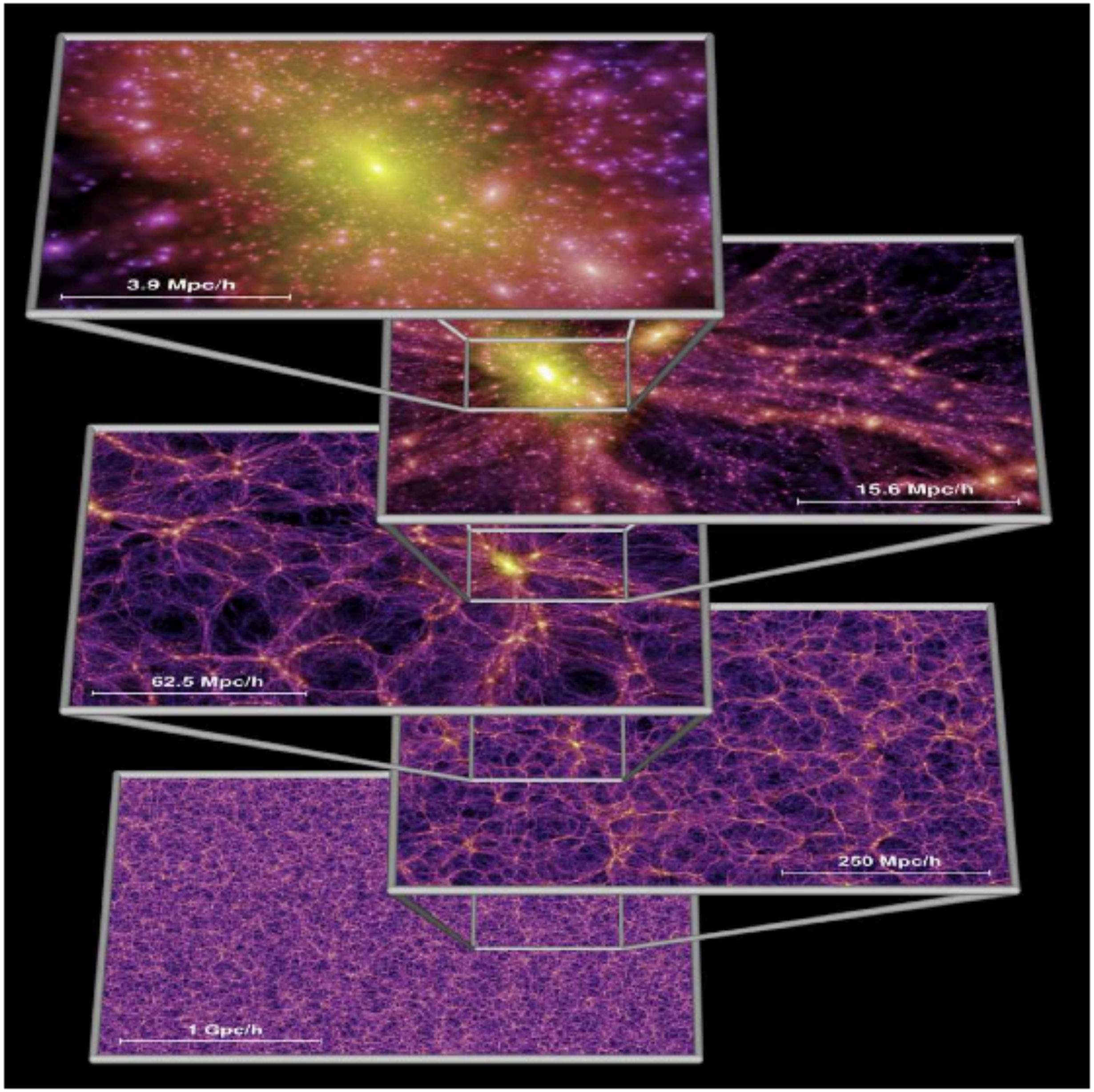


Figure 1: The dark matter density field on various scales. Each individual image shows the projected dark matter density field in a slab of thickness $15\,h^{-1}$Mpc (sliced from the periodic simulation volume at an angle chosen to avoid replicating structures in the lower two images), colour-coded by density and local dark matter velocity dispersion. The zoom sequence displays consecutive enlargements by factors of four, centred on one of the many galaxy cluster halos present in the simulation.

Current focus: scale-free models as a tool

"Scale-free" cosmological models

Power law initial fluctuations in a **matter dominated (EdS) universe**

$$P(k) \propto k^n$$

$$a(t) \propto t^{2/3}$$

Why scale-free cosmologies are useful (1)

Evolution of clustering is self-similar (if independent of UV/IR cut-offs):

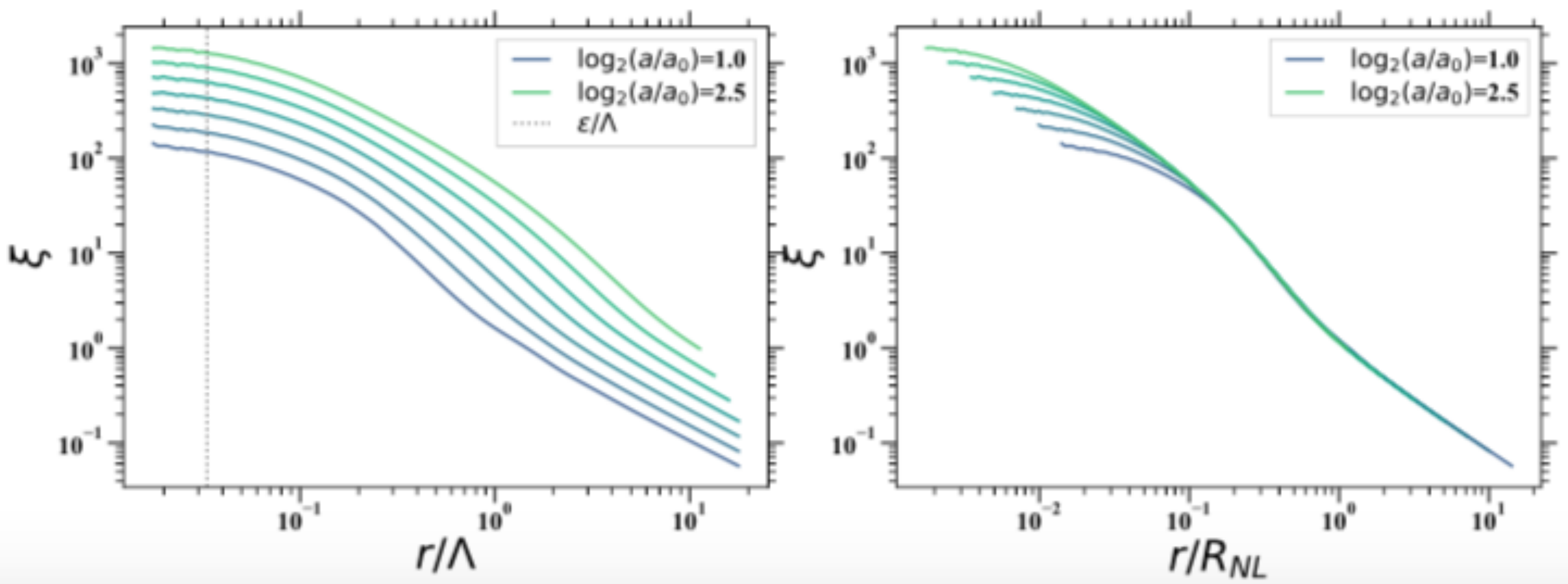
Temporal evolution = Spatial rescaling

→ Tool for controlling accuracy of N-body simulation

Quantifying resolution in N-body simulations using self-similarity

M. Joyce , L. Garrison and D. Eisenstein,

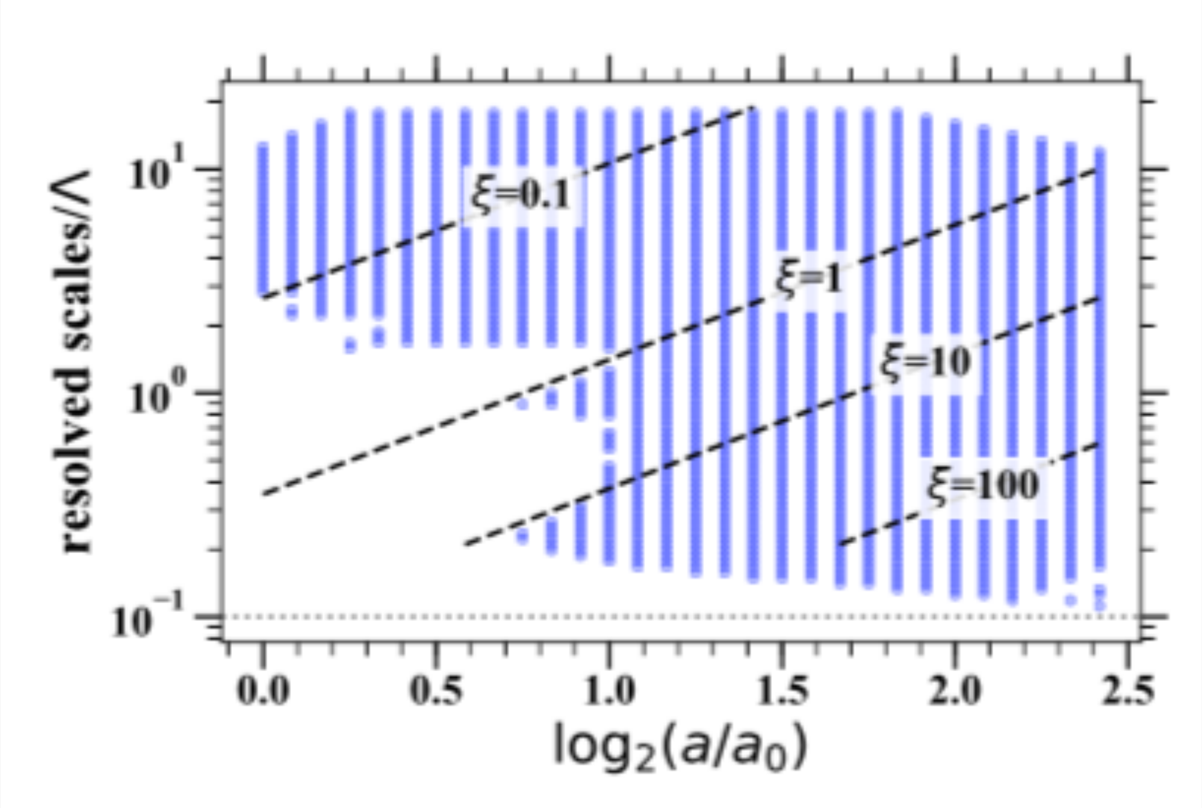
Mon. Not. R. Astron., 501, 5064 (2021)



Spatial resolution of N-body simulations

M. Joyce , L. Garrison and D. Eisenstein,

Mon. Not. R. Astron., 501, 5064 (2021)



A tool with many uses..

M. Leroy, L. Garrison , D. Eisenstein, MJ and S. Maleubre
"Testing **dark matter halo properties** using self-similarity"
Mon. Not. R. Astron., 501, 5064 (2021)

L. Garrison, MJ and D. Eisenstein,
"Good and proper: Self-similarity of N-body simulations with proper **force softening**"
Mon. Not. R. Astron., 501, 5064 (2021)

S. Maleubre, D. Eisenstein, L. Garrison and MJ,
"**Accuracy of power spectrum measurements** in dissipationless cosmological simulations"
in preparation

Why scale-free cosmologies are useful (2)

Standard cosmologies ~ interpolation of scale-free models

→ Models for cosmological parameter dependence of statistics

B. Diemer and MJ,
"An accurate physical model for halo concentrations",
Astrophys. J. 871, 168 (2019)

+ work in progress for 2 point statistics and more..

Perspectives

Perspectives (1)

Immediate future (next 2-3 years):

Likely continued focus on scale-free models

1) as a "control tool " of accuracy
2) as a tool for model building

Progression (and link to observations!): Dark matter → Halo → Galaxies

Other remarks:

For galaxy stats, possible local collaboration (P. Zarrouk LPNHE/DESI)

Aim to develop use of l(ocal/national) numerical resources for GPU optimized "ABACUS" code

Perspectives(2)

Longer term (> 2-3 years)

Possible focuses:

- structure formation **with dissipation**
- simplified approaches to the **Vlasov-Poisson system**

→ Possibility of fruitful collaboration with statistical physics?

Role of theory will remain important in ever more numerically driven field