The large-scale structure of the Universe as a probe of primordial physics

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1 The context: high energy physics, cosmology and cosmostatistics
- The Big picture
- The inhomogeneous Universe

2 Fundamental physics with cosmic voids
- Cosmic voids: expectations
- Cosmology with void statistics

3 The mildly non-linear regime of cosmic structure formation
- Dynamics of gravitational instability
- Remapping Lagrangian perturbation theory

4 Perspectives and Conclusion

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Why cosmology to probe high energy physics?

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— Terry Pratchett, *Lords and Ladies*

How do we study what happens at the highest energy scales?
$\Rightarrow$ *May I have my own Big Bang at home?*

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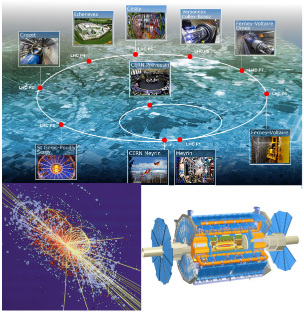
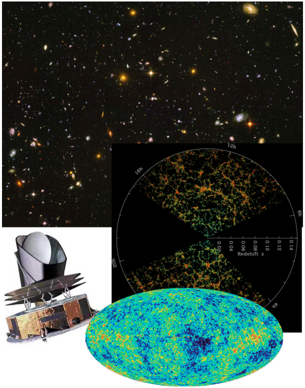
Showdown: Particle accelerators vs cosmological observations





The inhomogeneous Universe

You are here, make the best of it...

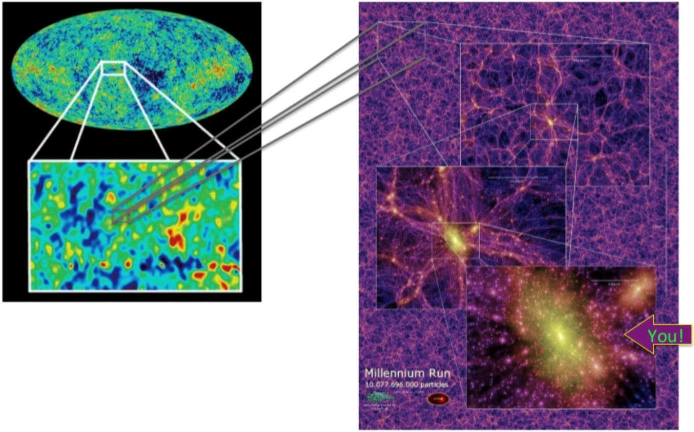


Figure: Left: Primordial perturbations as seen in the Cosmic Microwave Background anisotropies (WMAP)
Right: Dark matter distribution today (simulated)

Issues and methods in cosmostatistics

Cosmostatistics: discipline of **using the departures from homogeneity** observed in astronomical surveys to **distinguish between cosmological models**.

Huge data sets, but fundamental limits to information:

- on large scales: causality
- on small scales: non-linearity

Large scales: careful statistical treatment required (cosmic variance).

Intermediate scales: linear methods are suitable.

Small scales: number of accessible modes in a 3D galaxy survey $\propto k^3$
$\Rightarrow$ LSS surveys allow probing a larger number of small-scale modes in the *midly non-linear* regime (the 3D "cosmological revolution").

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The cosmic web

What is the large-scale structure of the Universe made of?

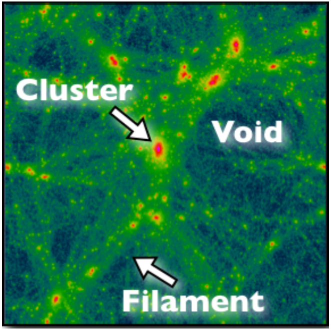

Figure: Courtesy of P. M. Sutter

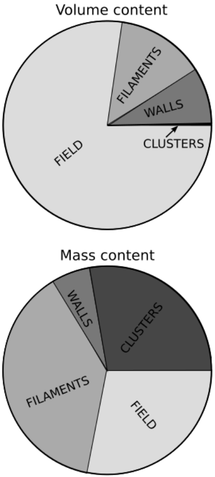

Figure: Aragón-Calvo, van de Weygaert & Jones, 2010

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Cosmic voids in the large-scale structure of the Universe

What do we expect of voids?

- Number count:
  - cluster masses determination
  - void size determination
- Dynamics:
  - clusters are gravitationally collapsed objects, highly non-linear
  - voids can be found in the linear or mildy non-linear regime

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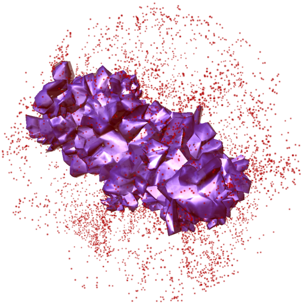
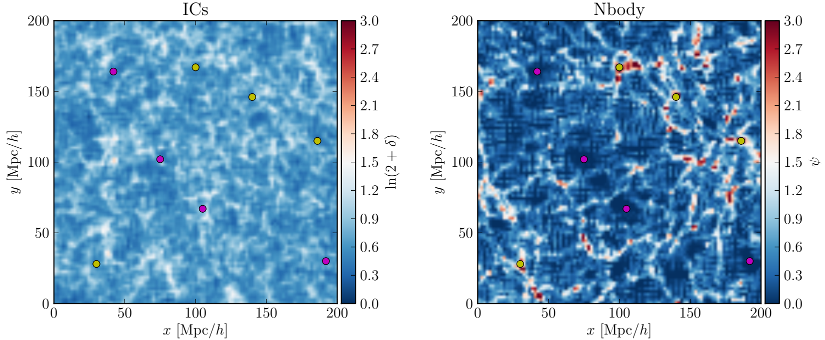
An efficient identification of voids is now possible thanks to numerical methods.
A public void catalog from the Sloan Digital Sky Survey DR7:



Sutter, Lavaux, Wandelt & Weinberg, 2012
http://www.cosmicvoids.net/

Dynamics of cosmic voids



Fundamental physics with cosmic voids

Some possible questions to be addressed with voids:

- relationship with the statistical properties of the ICs of the Universe
- relationship with the DM field and luminous tracers (the "bias" problem)
- tests of the standard GR picture of structure formation, discrimination among modified gravity models

First steps towards a systematic study of void statistics:

- The void one-point function (number count): provides constraints on the dark energy equation of state (Alizadeh, Biswas, Lavaux, Sutter, FL & Wandelt, in prep.)
- The void-void two-point correlation function: addresses the bias problem, the extraction of primordial non-Gaussianity (FL & Wandelt, in prep., Hamaus *et al.*, in prep.)

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Lagrangian perturbation theory

- Limited analytic understanding the Vlasov-Poisson system, modeling the gravitational amplification of primordial fluctuations
- Two ways to describe the cosmological fluid: Eulerian and Lagrangian. Lagrangian approach:

$$\mathbf{x}(\tau) = \mathbf{q} + \Psi(\mathbf{q}, \tau)$$

$\mathbf{q}$: initial position, $\mathbf{x}$: final position, Ψ: displacement field

- The Zel'dovich approximation (ZA) = first order Lagrangian perturbation theory.
  - *Local* approximation: does not depend on the behavior of the rest of fluid elements.
- Second-order Lagrangian perturbation theory (2LPT)
  - *Non-local* approximation: includes corrections to the displacement due to gravitational tidal effects.

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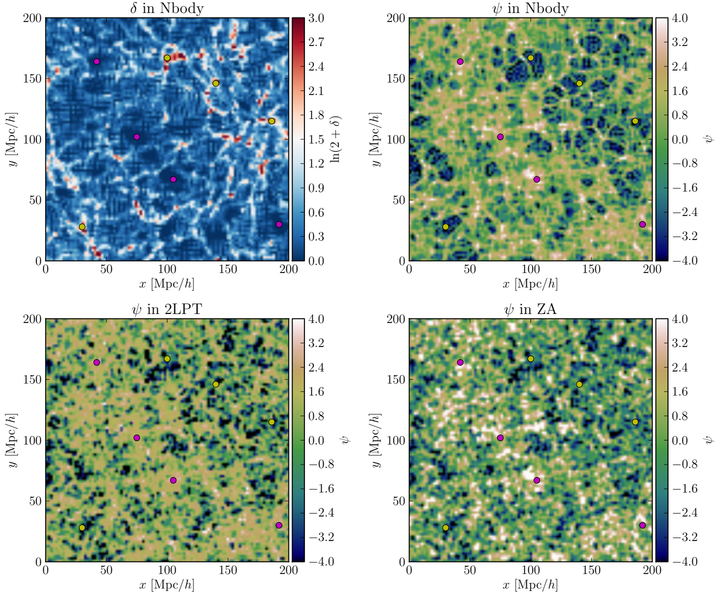
Displacement field and dynamics of large-scale structure



Remapping Lagrangian perturbation theory

FL, Jasche, Gil-Marín & Wandelt, in prep.

- Goal: Improve the correspondence between LPT-approximate models and full numerical N-body simulations.
- Even non-linear evolution tends to preserve the *rank order* of the pixels, sorted by density.
- In LPT, the divergence of the displacement field ψ plays a similar role as the Eulerian density contrast δ and is a more natural object.

$\Rightarrow$ Remapping algorithm:

- keep positions of under- and over-densities predicted by LPT
- point-by-point update of ψ_{LPT} using the corresponding value of ψ_{Nbody}

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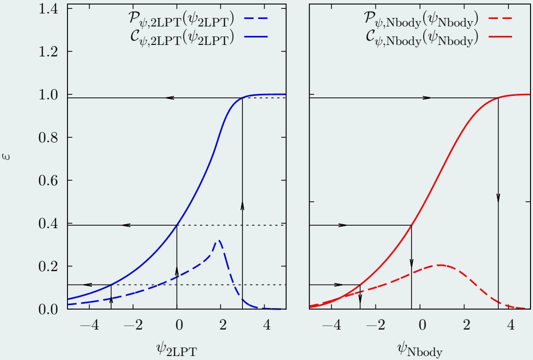
The remapping procedure

FL, Jasche, Gil-Marín & Wandelt, in prep.

$$\mathcal{C}_{\psi,\mathrm{LPT}}(\psi_{\mathrm{LPT}}) = \mathcal{C}_{\psi,\mathrm{Nbody}}(\psi_{\mathrm{Nbody}})$$



$\mathcal{P}_{\mathrm{LPT}}$, $\mathcal{P}_{\mathrm{Nbody}}$: PDFs for the divergence of the displacement field.
$\mathcal{C}_{\mathrm{LPT}}$, $\mathcal{C}_{\mathrm{Nbody}}$: the corresponding CDFs (their integrals).

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Cosmic voids instead of galaxy clusters:

- simpler number count
- less affected by non-linearity
- earlier affected by dark energy

The remapping procedure: a fast way of producing mock galaxy distribution:

- A substantial improvement with respect to existing methods (NL affect even large scales: BAO: ~ 125 Mpc$/h$).
- Non-linear cosmological inference of the initial conditions of the Universe becomes feasible.

Outlook

- Constraints on primordial non-Gaussianities (f_{NL}) and therefore on inflationary models (multi-field inflation? non-standard kinetic term? periods of fast-roll? non-trivial pre-inflationary state? non-Bunch-Davies vacuum?).
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