Large-scale structure and cosmic voids as probes of primordial physics

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Guilhem Lavaux (Perimeter Institute/U. Waterloo), Paul Sutter (U. Illinois)

1. Context in cosmology
   - The Big picture
   - The standard model of cosmology : ΛCDM
   - The inhomogeneous Universe

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

3. Cosmic voids as probes of primordial physics
   - What are cosmic voids?
   - Cosmology with void statistics

4. Perspectives and Conclusion

Why cosmology?

> "*In the beginning there was nothing, which exploded.*"
> — Terry Pratchett, *Lords and Ladies*

The big questions are:

- How did the Universe begin? (if it did!)
  $\Rightarrow$ *What happened at the initial cosmological singularity ("$t = 0$")?*
- Whence the laws of Nature?
  $\Rightarrow$ *What is the fundamental physical theory, valid at the highest energies?*

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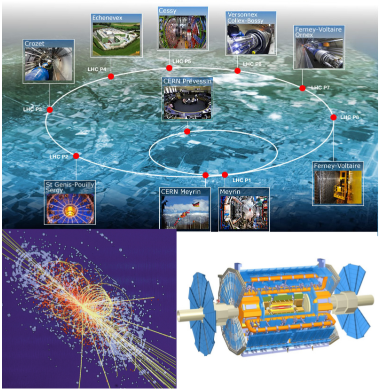
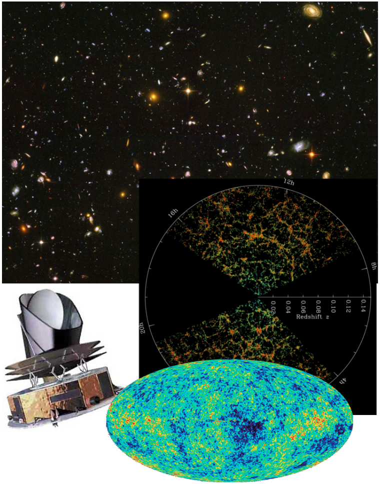
How do we study what happens at the highest energy scales?
⇒ *May I have my own Big Bang at home?*

Showdown: Particle accelerators vs cosmological observations





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- ... but trying to reach the highest energies in a particle accelerator is too ambitious
- Creating early Universe conditions in a lab is not at hand.

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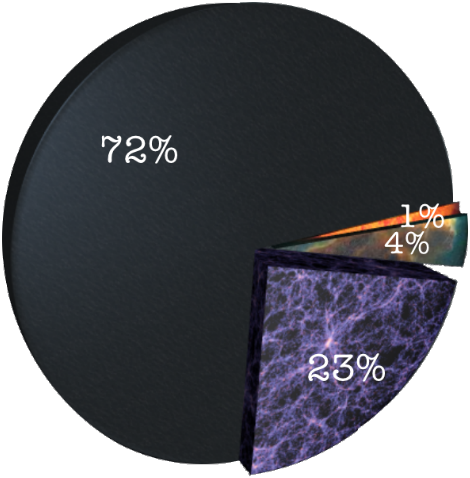
1998-2012: Observations converge... towards an unexpected Universe



"*We cannot see nine-tenths of what is real, our claims of self-reliance are pieced together by unpanned gold.*"
— Franklin D'Olier Reeve, *Coasting*, The American Poetry Review

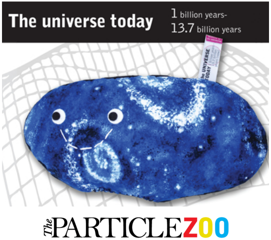
The standard model of cosmology: ΛCDM

- Dark energy (cosmological constant): $\sim 72\%$
- Dark matter: $\sim 23\%$
- Baryonic matter: $\sim 4\%$
- Radiation: $\lesssim 1\%$

Beyond the standard model of cosmology

The enigmas of the Hot Big Bang scenario:

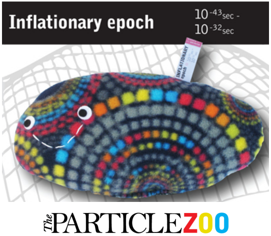
- Why homogeneity and isotropy? Horizon problem?
- Why flatness?
- Whence the seed perturbations for structure formation?



Beyond the standard model of cosmology

Inflation: a new paradigm for the Physics of the Beginning

An accelerated phase of expansion driven by a quantum scalar field in the very early Universe.



- Solves homogeneity, isotropy, horizon and flatness problems
- Accelerated expansion can magnify vacuum quantum fluctuations into macroscopic cosmological perturbations.
- Naturally provides us with a statistically homogeneous and isotropic density field with small, very nearly Gaussian-distributed, and nearly scale-invariant density perturbations.

How do we get back to these very early times?

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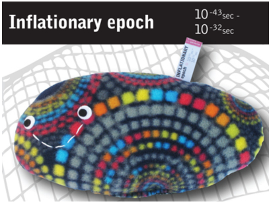

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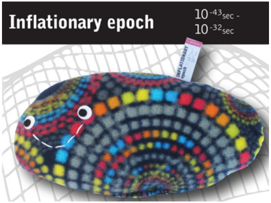

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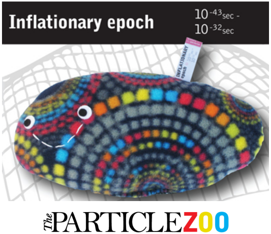

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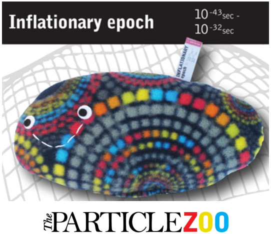

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The inhomogeneous Universe

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

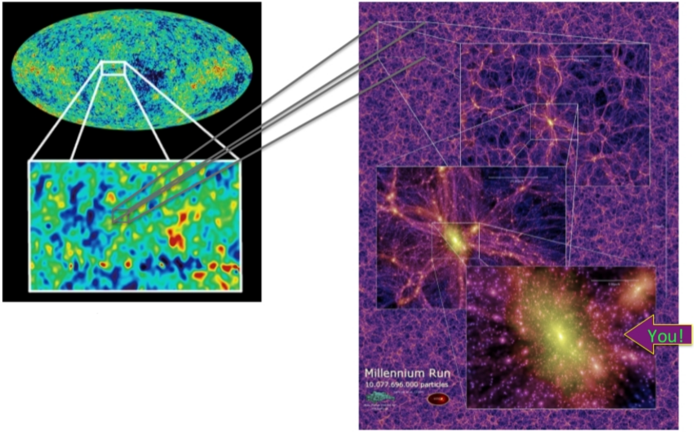

Figure: Left: Primordial perturbations as seen in the Cosmic Microwave Background anisotropies (WMAP)
Right: Dark matter distribution today (simulated)

Goals of cosmostatistics

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

The cosmological agenda for the coming decade:

- Learn about the cosmic beginning
- Learn about the content of the Universe, in particular dark matter and dark energy
- Understand cosmological evolution from cosmic seeds to presently observed structures

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Issues and methods in cosmostatistics

The data sets are huge, but there exist fundamental limits to information:

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

Cosmic variance: Large scales require careful statistical treatment to extract precious information from a relatively small number of modes.

Linear methods are suitable on intermediate scales.

The 3D cosmological revolution: The number of accessible modes in a three-dimensional galaxy survey goes like $k^3 \Rightarrow$ LSS surveys allow probing a larger number of small-scale modes in the *midly non-linear* regime.

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Fluid dynamics approach

- Standard picture of LSS formation: result of gravitational amplification of primordial fluctuations of the initial density field.
- The Vlasov-Poisson system: modeling the gravitational aggregation of cold dark matter (CDM) particles
- The Vlasov-Poisson system is *non-linear*. A common approach is to take momentum moments of the Vlasov equation ⇒ a hierarchy of equations, truncated at some point with a fluid dynamics assumption.
  - Zeroth moment: the continuity equation (conservation of mass)
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Lagrangian perturbation theory

- As in fluid mechanics, there are two ways to describe the cosmological fluid: Eulerian and Lagrangian. We focus on the 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.
  - In comoving coordinates particles just go straight in the direction set by their initial velocity.
  - *Local* approximation: does not depend on the behavior of the rest of fluid elements.
- Second-order Lagrangian perturbation theory (2LPT)
  - Remarkable improvement over the ZA in describing the global properties of density and velocity fields (the ZA fails at sufficiently non-linear stages when particles should form gravitationally bound structures instead of following straight lines)
  - *Non-local* approximation: includes corrections to the displacement due to gravitational tidal effects.

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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 of gravitational large-scale structure formation.
- Due to mode coupling, positive and negative fluctuations grow at different rates in the non-linear regime, but even non-linear evolution tends to preserve the *rank order* of the pixels, sorted by density.
- In Lagrangian description of cosmological large-scale structure, 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
- at pixel of rank order ψ_{LPT}, assign a new divergence of the displacement field, ψ_{Nbody}
- reconstruct the curl-free displacement field from its remapped divergence, and evolve the particles accordingly

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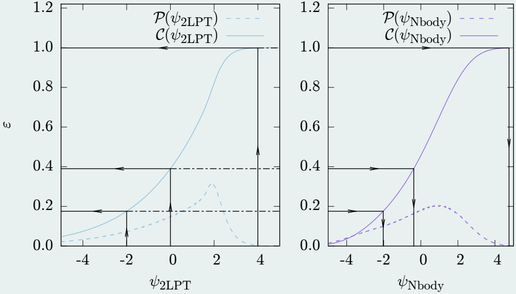
The remapping procedure

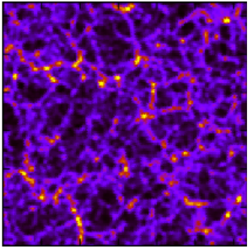
FL, Jasche, Gil-Marín & Wandelt, in prep.

$$\mathcal{C}_{\mathsf{LPT}}(\psi_{\mathsf{LPT}}) = \mathcal{C}_{\mathsf{Nbody}}(\psi_{\mathsf{Nbody}})$$

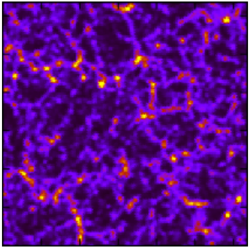


$\mathcal{P}_{\mathsf{LPT}}$, $\mathcal{P}_{\mathsf{Nbody}}$: PDFs for the divergence of the displacement field.
$\mathcal{C}_{\mathsf{LPT}}$, $\mathcal{C}_{\mathsf{Nbody}}$: the corresponding CDFs (their integrals).

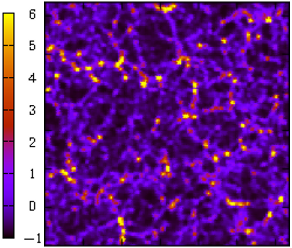
Location of particles



ZA

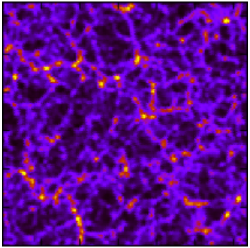


2LPT

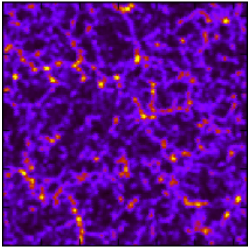


Nbody

Redshift $z = 0$, mesh size
4 Mpc/h



ZA-RM



2LPT-RM

Two-point statistics

How does remapping affect the higher-order correlators?

- we expect the higher-order correlations to be respected by the remapping procedure;
- possible improvements could be exploited in data analysis or artificial galaxy survey applications.

Power spectrum:

$$\langle \delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\rangle = \delta_\mathrm{D}(\mathbf{k}_1+\mathbf{k}_2)\,P(k)$$

- simplest statistic of interest beyond one-point function
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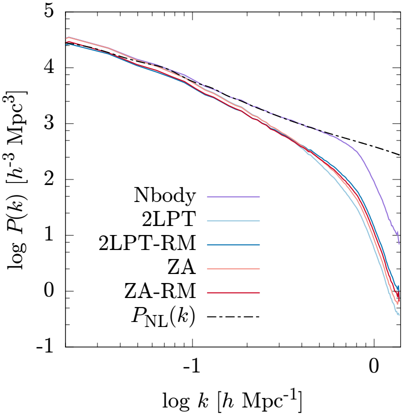

Redshift $z = 0$, mesh size 4 Mpc/h.

1. Context in cosmology
   - The Big picture
   - The standard model of cosmology : ΛCDM
   - The inhomogeneous Universe

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

3. Cosmic voids as probes of primordial physics
   - What are cosmic voids?
   - Cosmology with void statistics

4. Perspectives and Conclusion

The cosmic web

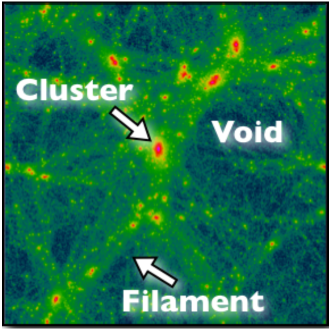

Figure: Courtesy of P. M. Sutter

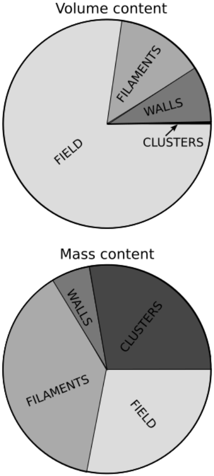

Figure: Aragón-Calvo, van de Weygaert & Jones, 2010

Cosmic voids

What do we expect of voids?

- Number count: the issue of cluster masses determination is replaced by void size determination.
- Dynamics: clusters are gravitationally collapsed objects and thus highly nonlinear, voids can be found in the linear or mildy non-linear regime.

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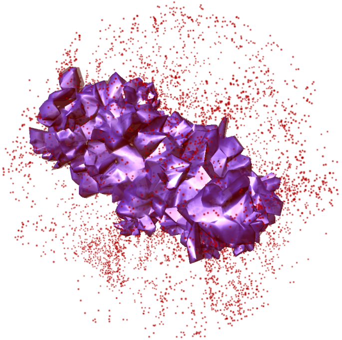
An efficient identification of voids is now possible thanks to numerical methods.

A public void catalog from the Sloan Digital Sky Survey DR7:



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

Fundamental physics with cosmic voids

Some possible questions to be addressed:

- the relationship between the presently observed void distribution and the statistical properties of the initial conditions of the Universe
- how voids relate to luminous tracers which are the actual directly available information in galaxy surveys (the "bias" problem)
- how voids could test the standard general relativistic picture of structure formation and help discriminate 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.)
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FL & Wandelt, in prep.

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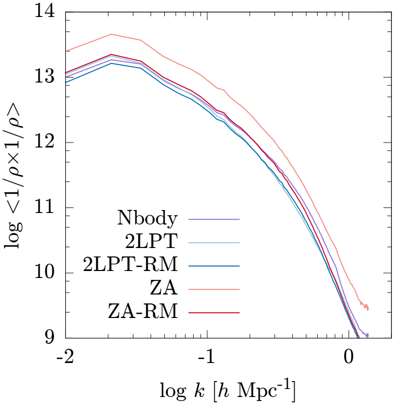

Figure: FL & Wandelt, preliminary

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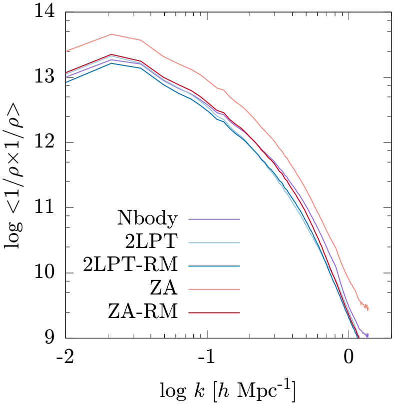

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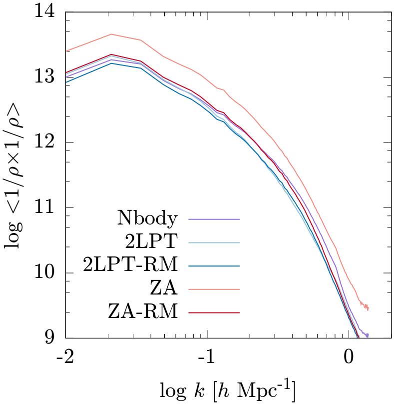

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Concluding thoughts

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

- A substantial improvement with respect to existing methods, since non-linearities begin to affect even large-scale cosmographic measurements such as the determination of the baryon acoustic oscillations scale (~ 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?).
- Focus on cosmic voids instead of clusters: objects less affected by non-linearity, more affected by dark energy. ⇒ the inference of the initial conditions and of the properties of dark energy should be easier!

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