Cosmic Order and Complexity

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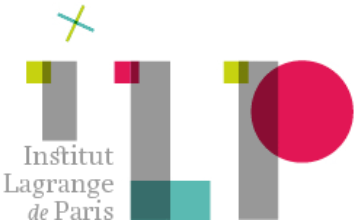
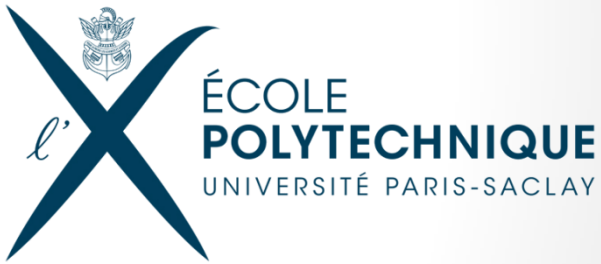
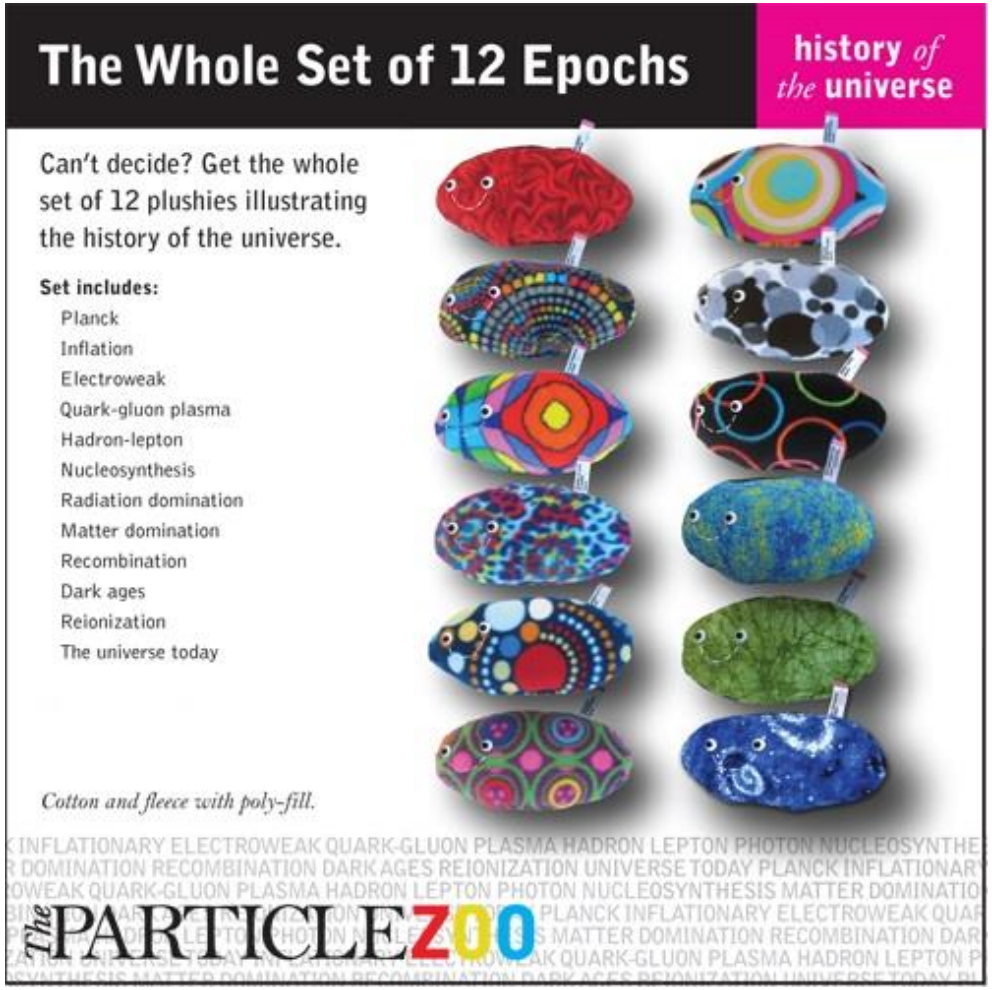




In collaboration with:
Jens Jasche (Excellence Cluster Universe, Garching), Alice Pisani (LAM/IAP),
Nico Hamaus (IAP), Paul Sutter (Trieste/Ohio State U./IAP),
Benjamin Wandelt (IAP/U. Illinois)

The Universe as seen by the Particle Zoo



http://www.particlezoo.net/

Some specificities of cosmology

- **Unicity**. The experience is unique and irreproducible by physical experimentation. There is no exteriority nor anteriority. The properties of the Universe cannot be determined statistically on a set.
- **Energy**. The energy scales at stake in the early Universe are orders of magnitude higher than anything we can reach on Earth.
- **Arrow of time**. Reasoning in cosmology is "bottom-up". The final state is known and the initial state has to be inferred.

⇨ The **initial conditions** of the Universe have a **particular status**.

Cosmostatistics of the initial conditions

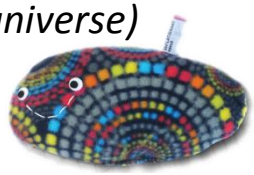
- **Cosmostatistics**: discipline dealing with stochastic quantities as seeds of structure in the Universe
  - prediction of cosmological observables from random inputs

    (from theory to data)
  - use of the departures from homogeneity in astronomical surveys to distinguish between cosmological models

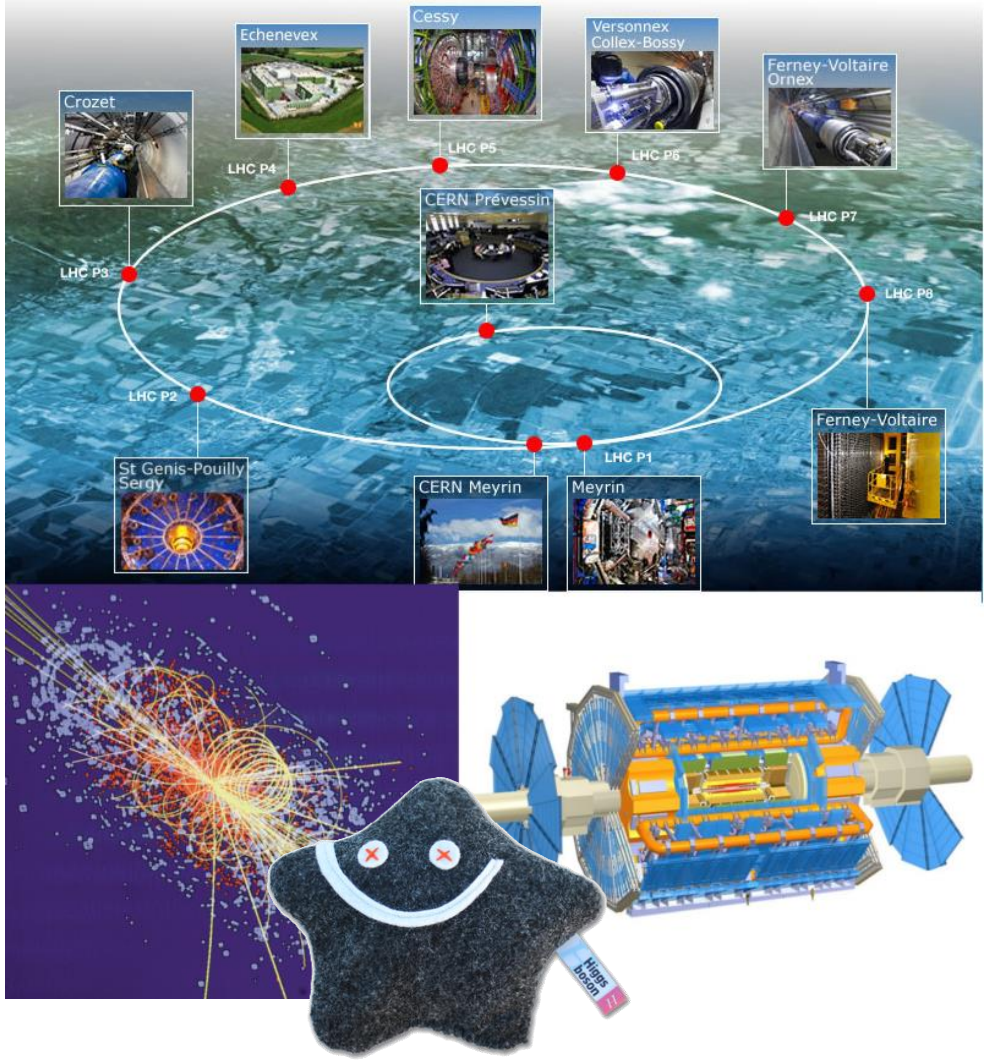
    (from data to theory)

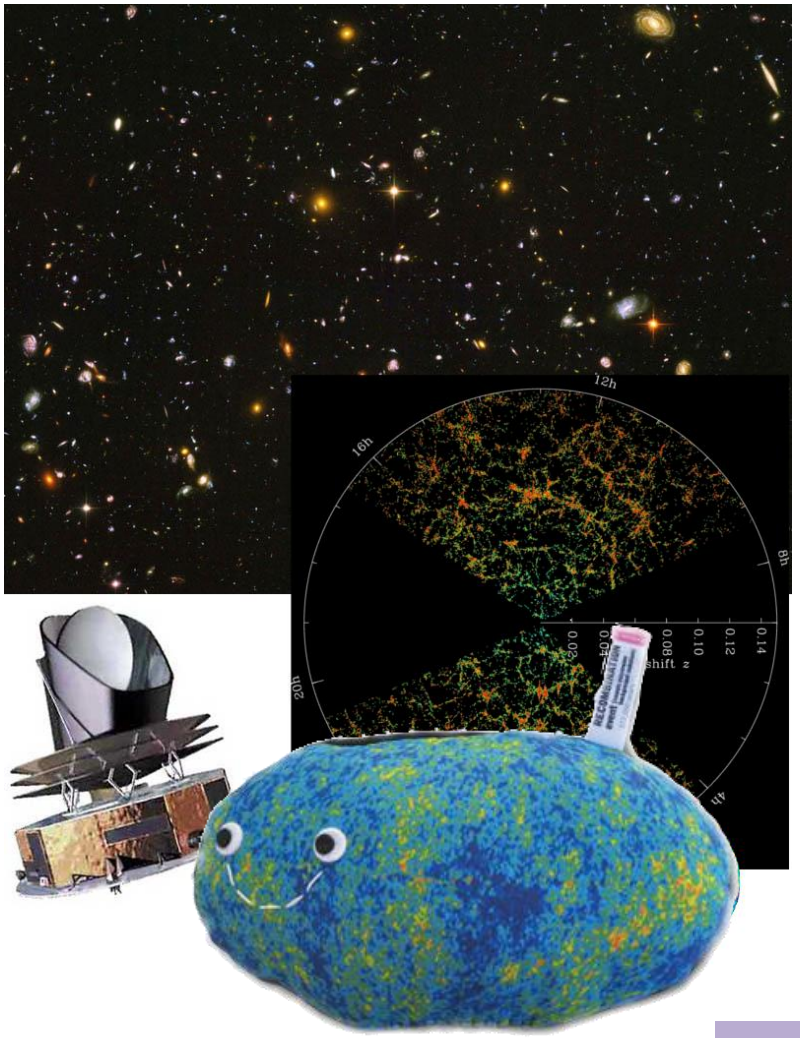
    FL, Pisani & Wandelt 2014, arXiv:1403.1260
- **"Initial conditions"**: ICs for *gravitational evolution*…
  - AFTER inflation
  - AFTER Hot Big Bang phenomena

(*primordial nucleosynthesis, decoupling, recombination, free-streaming of neutrinos, acoustic oscillations of the photon-baryon plasma, transition from radiation to matter dominated universe)*



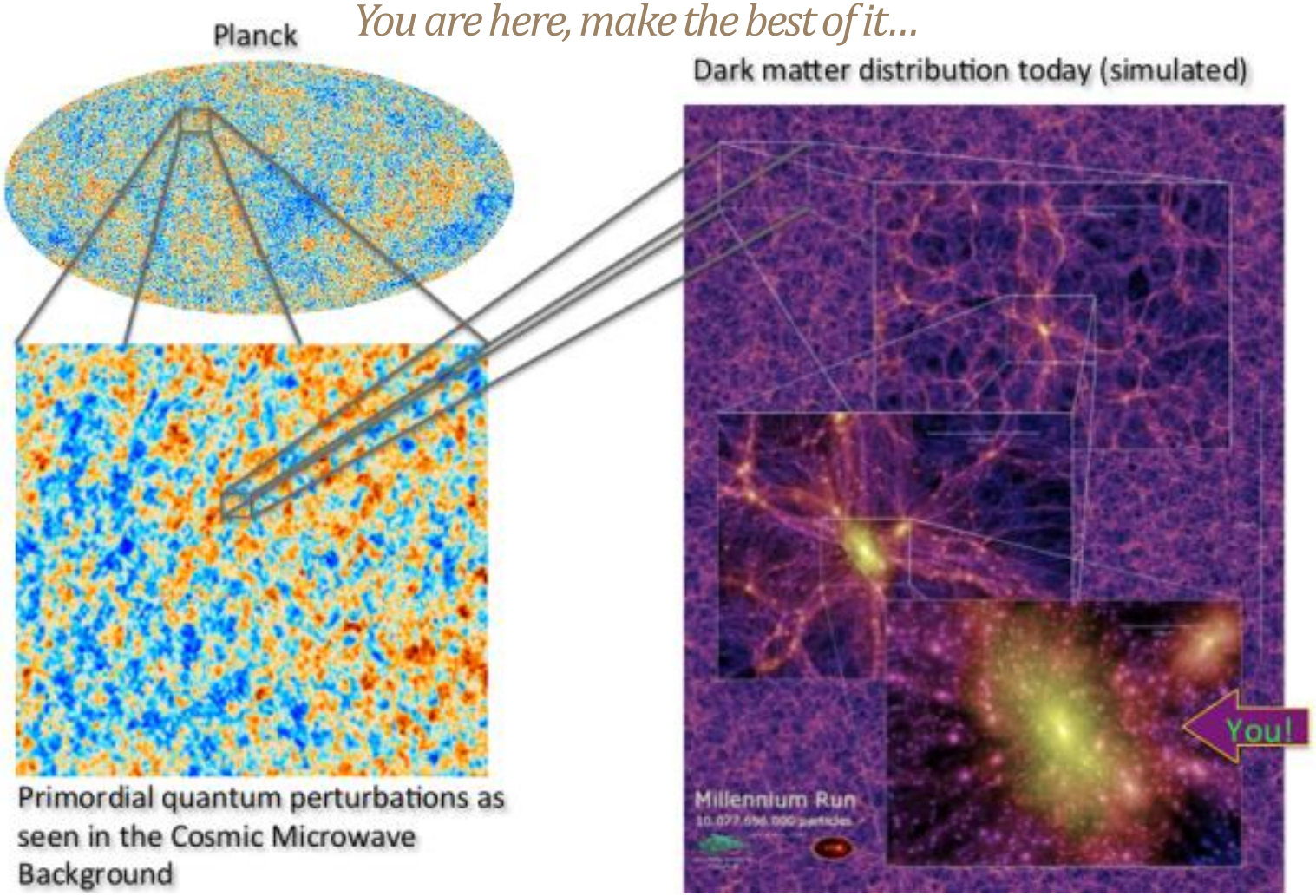
High-energy physics experiments





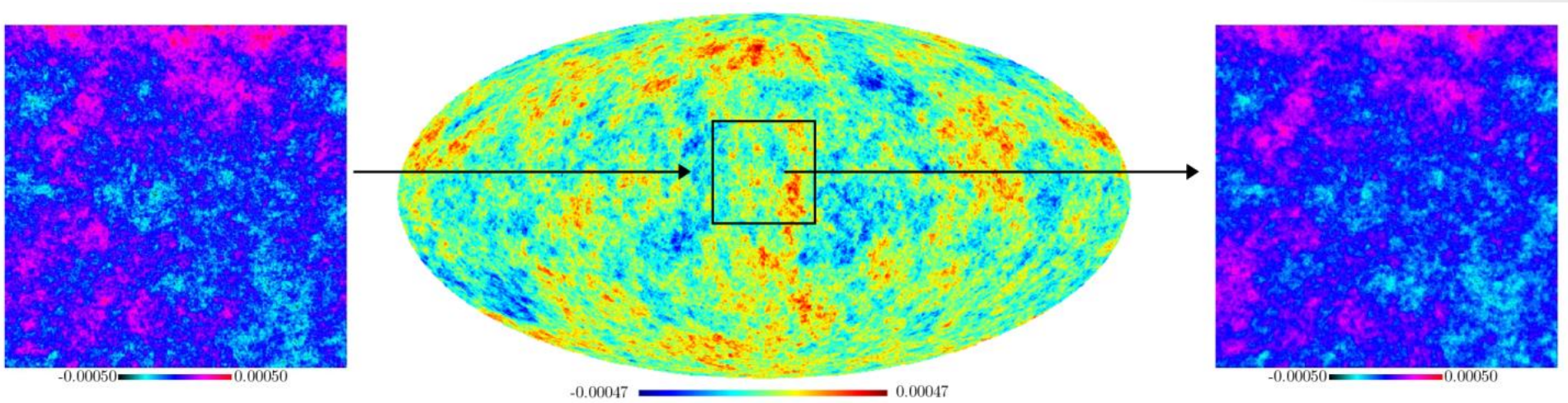
The inhomogeneous Universe: the big picture

You are here, make the best of it…



The CMB time-machine

- A time-machine (380,000 yrs ⇨ 10^{-35} s): linear perturbation theory



Input gravitational potential

adapted from Elsner & Wandelt 2009, arXiv:0909.0009

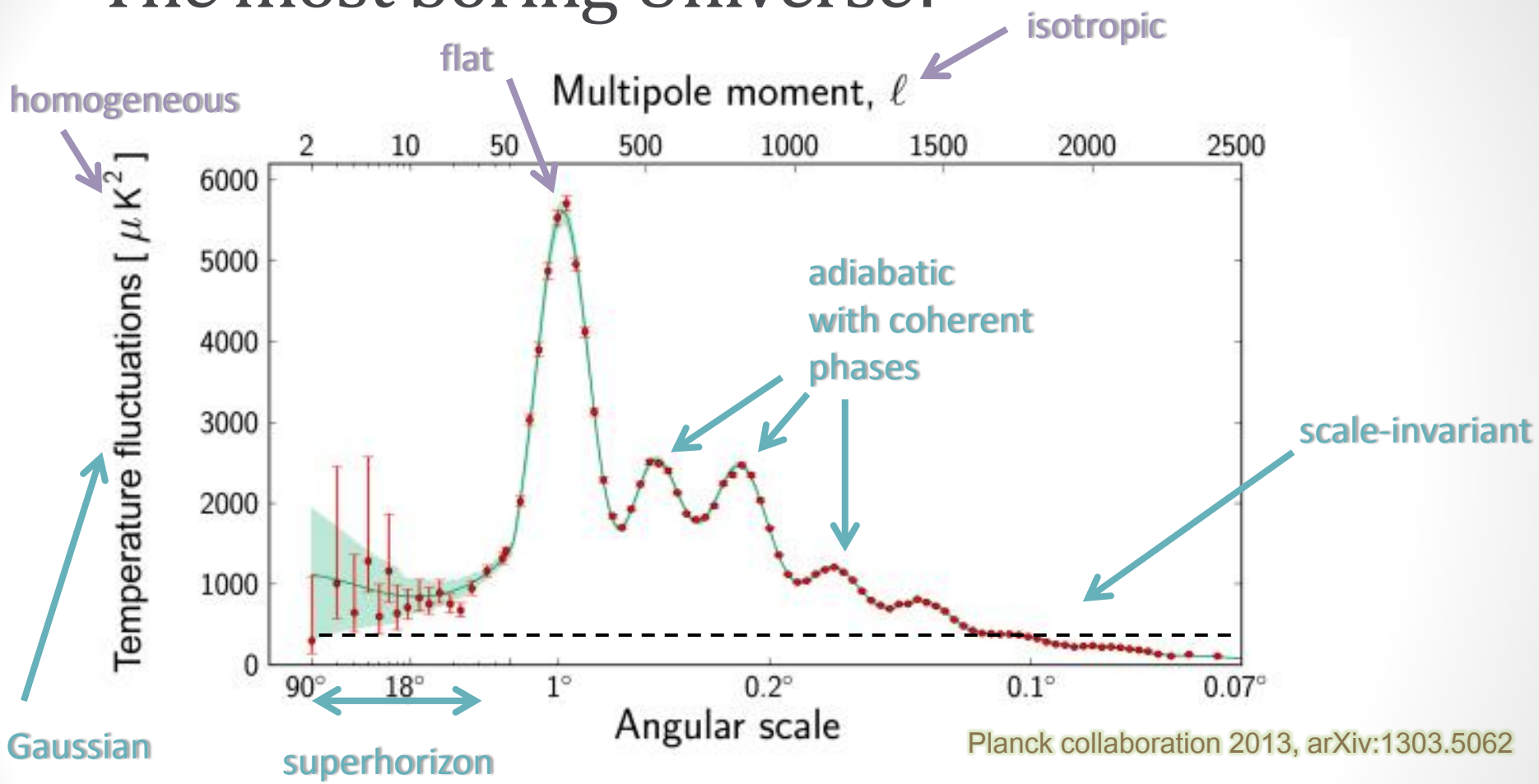
Reconstruction of the gravitational potential

Komatsu, Spergel & Wandelt 2005, arXiv:astro-ph/0305189
Yadav & Wandelt 2005, arXiv:astro-ph/0505386

- Relies on:
  - Gaussian random fields
  - Linear transfer
  - Optimal inference of a GRF from a GRF: Wiener filtering

see also FL, Pisani & Wandelt 2014, arXiv:1403.1260

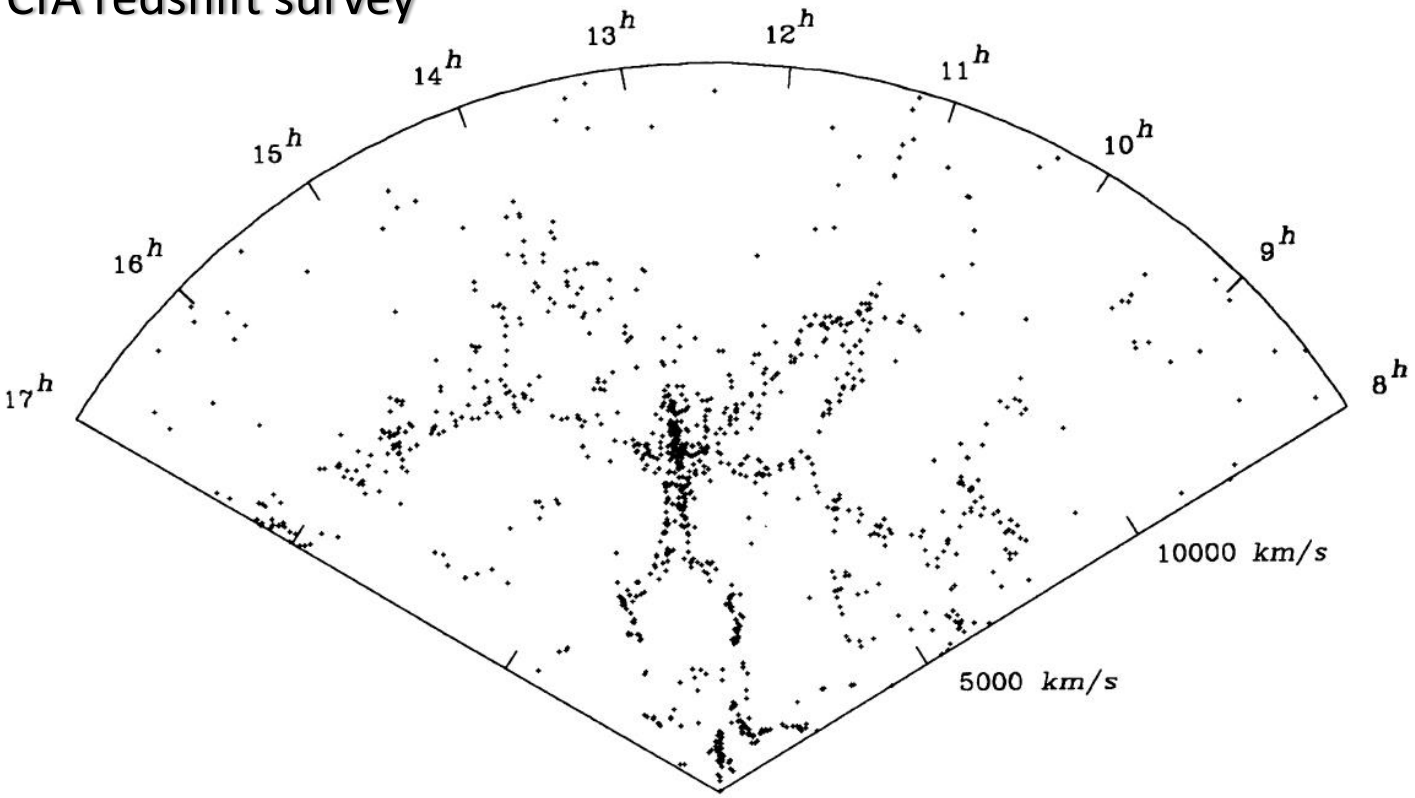
The most boring Universe?



- Phenomenologically, inflation is a great success…
- … but what is the microphysics of inflation?

Order in the Universe: the large-scale structure

CfA redshift survey



de Lapparent, Geller & Huchra 1986

Order in the Universe: the large-scale structure

A SLICE OF THE UNIVERSE[1]

VALÉRIE DE LAPPARENT,[2,3] MARGARET J. GELLER,[2] AND JOHN P. HUCHRA[2]

Received 1985 November 12; accepted 1985 December 5

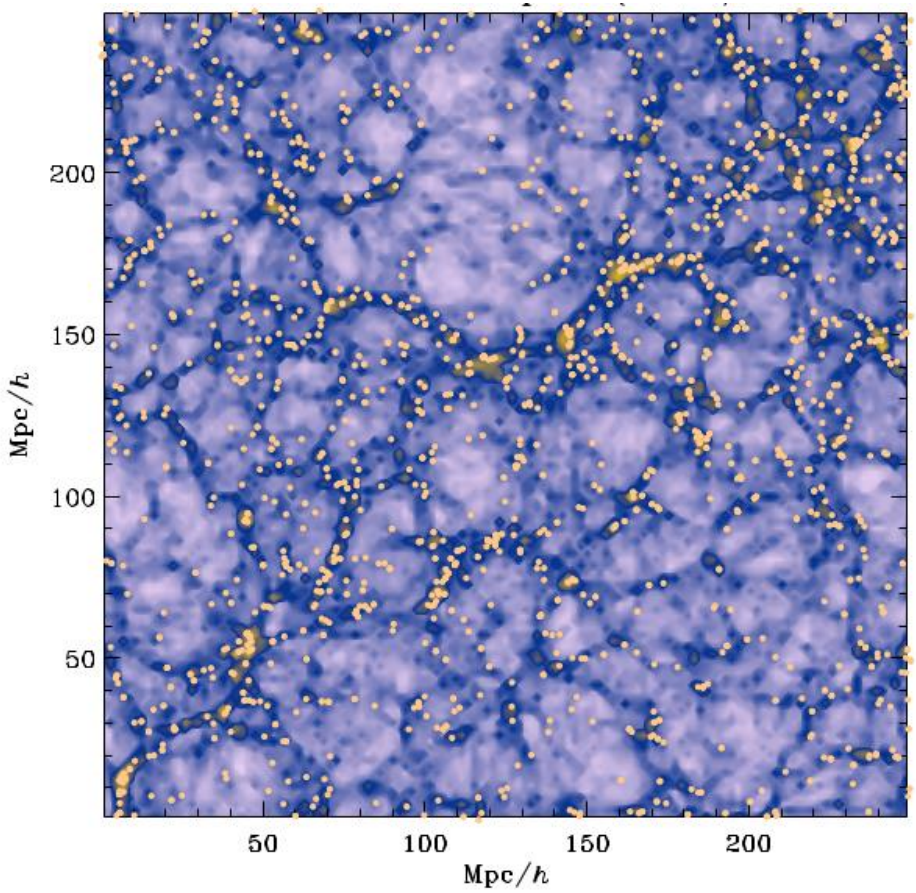
ABSTRACT

We describe recent results obtained as part of the extension of the Center for Astrophysics redshift survey to $m_B = 15.5$. The new sample contains 1100 galaxies (we measured 584 new redshifts) in a $6° \times 117°$ strip going through the Coma cluster. Several features of the data are striking. The galaxies appear to be on the surfaces of bubble-like structures. The bubbles have a typical diameter of $\sim 25h^{-1}$ Mpc. The largest bubble in the survey has a diameter of $\sim 50h^{-1}$ Mpc, comparable with the most recent estimates of the diameter of the void in Bootes. The galaxy density in the region of the largest void contained in the survey is only 0.20 of the mean. The edge of the largest void in the survey is remarkably sharp.

All of these features pose serious challenges for current models for the formation of large-scale structure. The best available model for generating these structures is the explosive galaxy formation theory of Ostriker and Cowie, published in 1981. These new data might be the basis for a new picture of the galaxy and cluster distributions.

Subject headings: cosmology — galaxies: clustering — galaxies: formation

Order in the Universe: the large-scale structure



Blue: matter distribution
Orange: dark matter halos / galaxies

- Halos trace mass distribution (of *dark matter*).
- Halos are NOT randomly distributed: there exists a Large Scale Structure of the Universe
- How do we analyze this structure quantitatively?

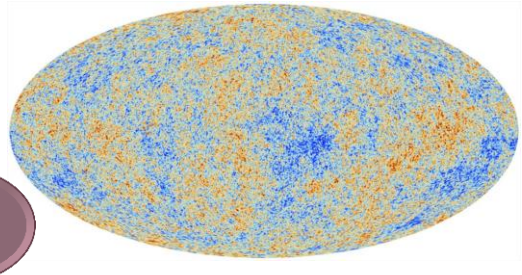
Correlation functions and Fourier analysis

Reconstruction of the initial conditions…

- … a solved problem!
- And…

CMB:

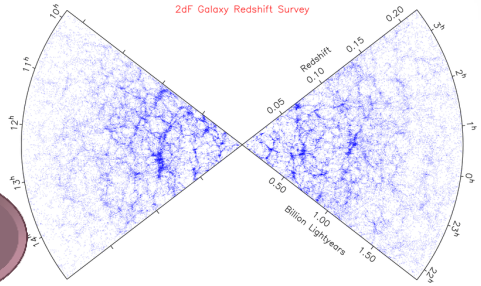
2D



$$N_{\rm mode}^{\rm CMB} \propto l_{\rm max}^2$$

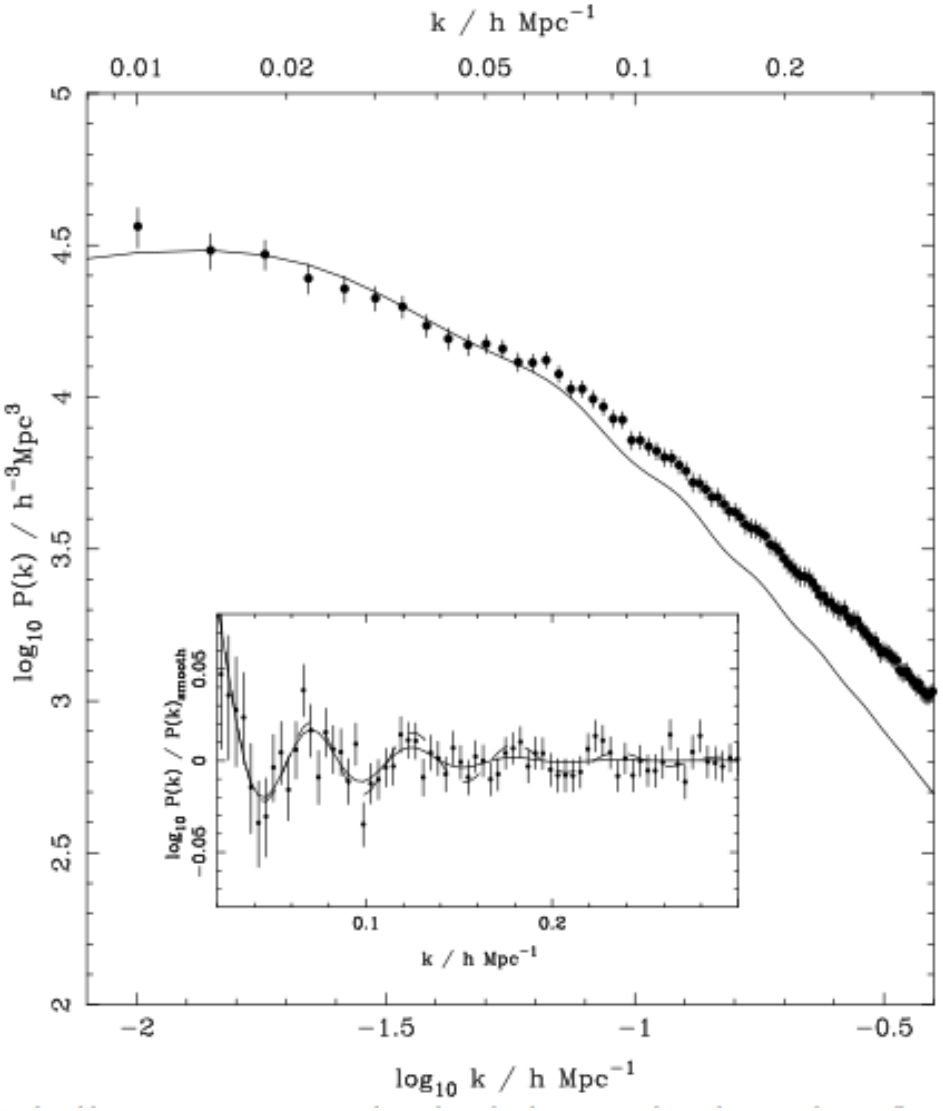
LSS:

3D



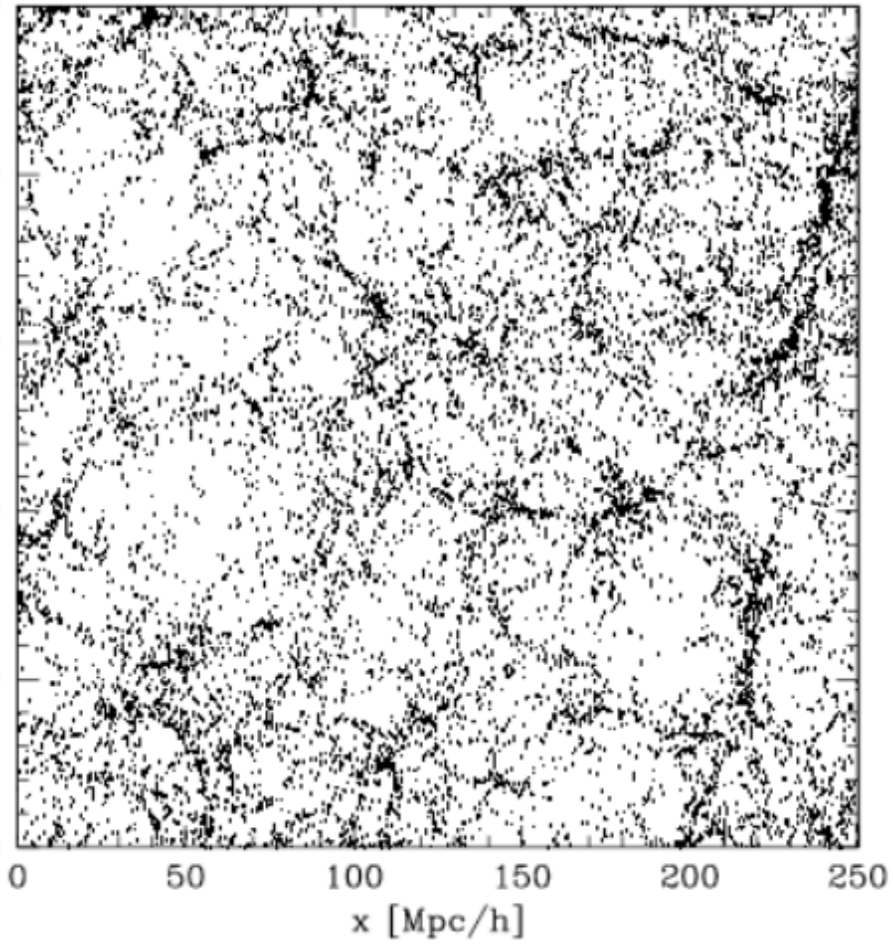
$$N_{\rm mode}^{\rm LSS} \propto k_{\rm max}^3$$

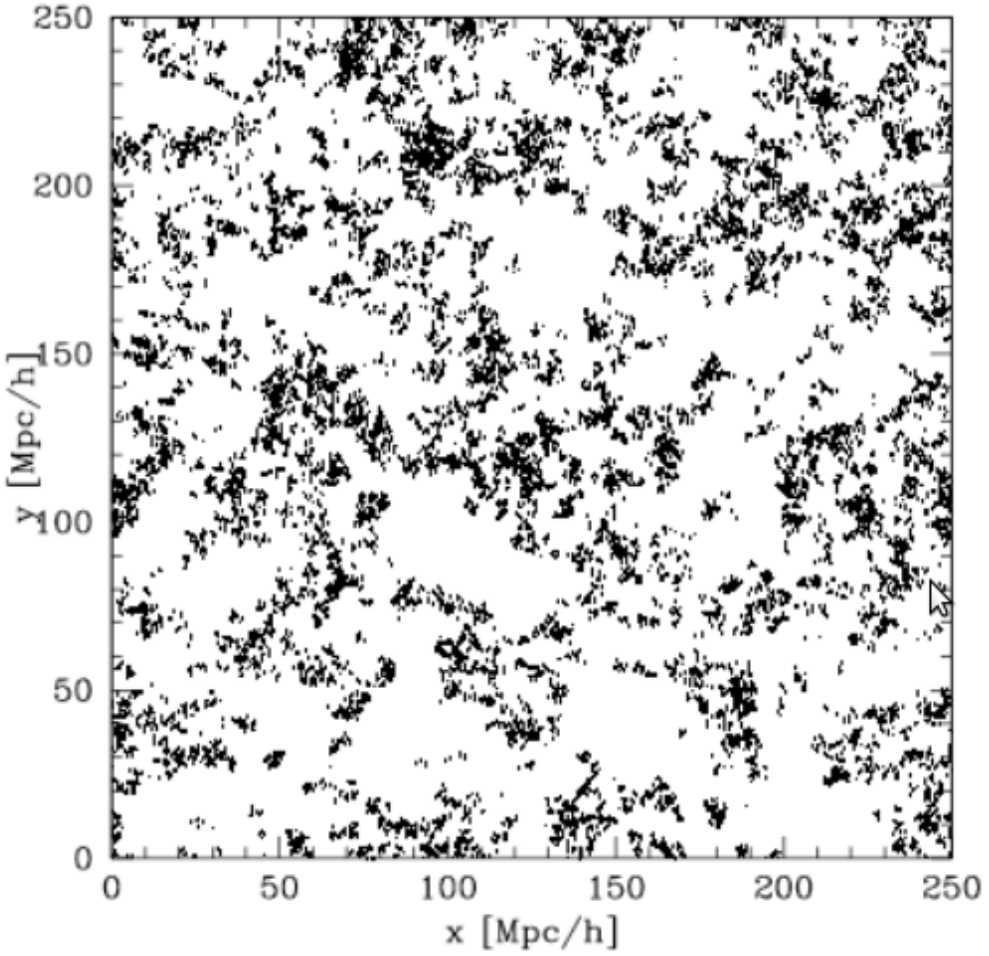
Where the Universe becomes non-Gaussian…



Percival *et al*. 2006, arXiv:astro-ph/0608636

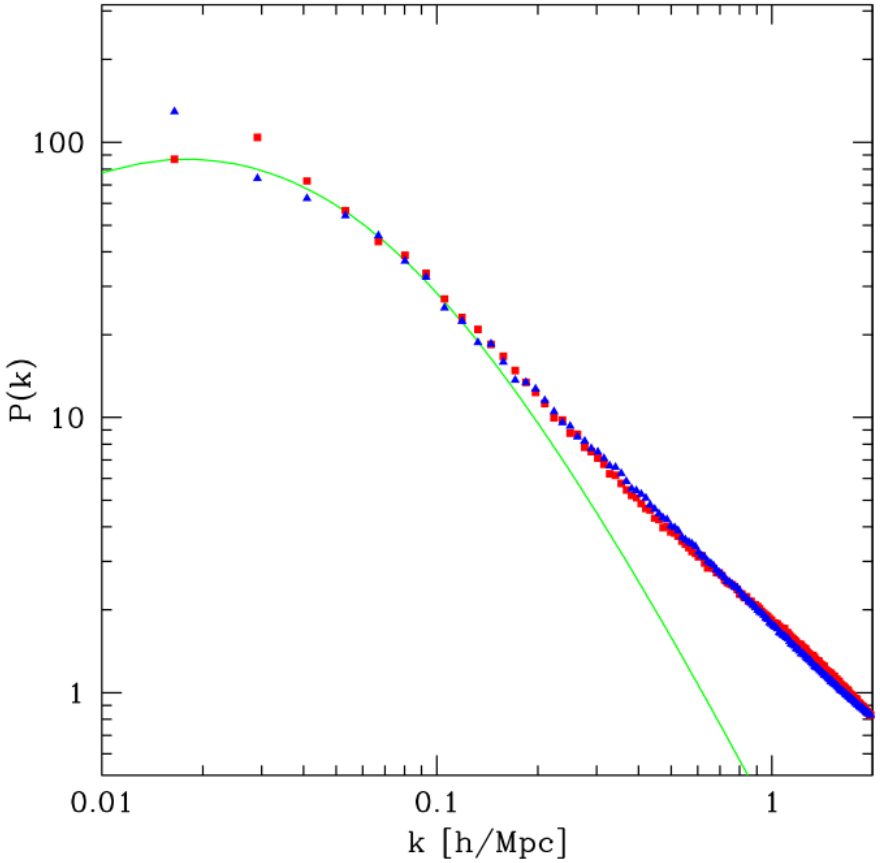
Gaussian vs non-Gaussian information



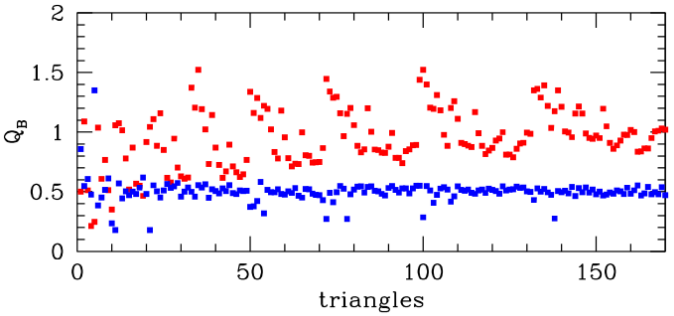


from R. Scoccimarro

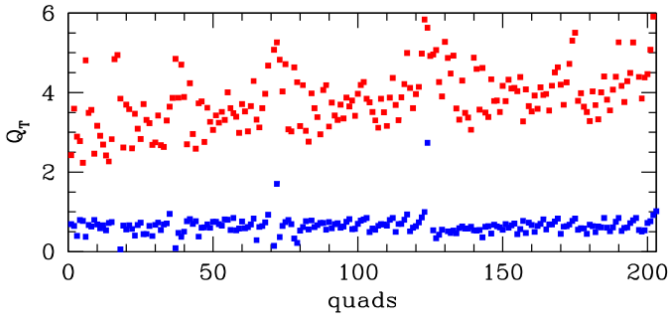
Gaussian vs non-Gaussian information



The two distributions have about the same power spectrum!



bispectrum



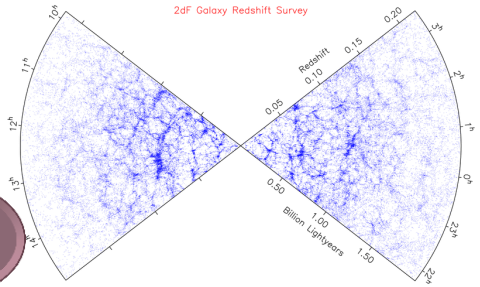
trispectrum

from R. Scoccimarro

Reconstruction of the initial conditions…

LSS:

3D



$$N_{\mathrm{mode}}^{\mathrm{LSS}} \propto k_{\mathrm{max}}^{3}$$

- The challenges : non-linearity and non-Gaussianity
  - Non-linear transfer functions in the Hot Big Bang phenomena
  - Gravitational evolution
  - Primordial non-Gaussianity (…?)
  - Data imperfection and systematics…

Can we go from the linear to the non-linear problem?

Complexity in the Universe: Why Bayesian inference?

- Why do we need Bayesian inference?

Inference of signals = ill-posed problem

- Incomplete observations: survey geometry, selection effects
- Noise, biases, systematic effects
- Cosmic variance

No unique recovery is possible!

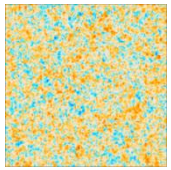
"What are the initial conditions of the Universe?"

"What is the probability distribution of possible initial conditions (signals) compatible with the observations?"

$$p(s|d)p(d) = p(d|s)p(s)$$

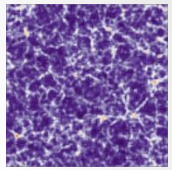
Bayesian physical inference of the ICs

- Physical motivation:
  - Complex final state, simple initial state
  - A "forward only" problem
    (we have a generative model for the final state)



Initial state

GRAVITY



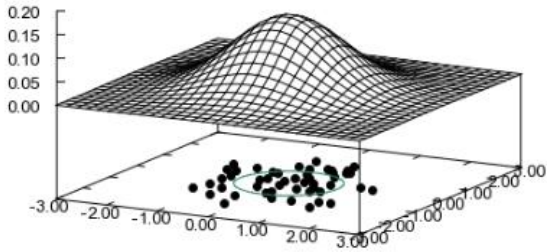
Final state

- Problems:
  - Highly dimensional inference (10^7 parameters)
  - A large number of correlated parameters

→ No reduction of the problem size is possible!

  - Potentially complex posterior distribution

- Numerical approximation: sampling the posterior

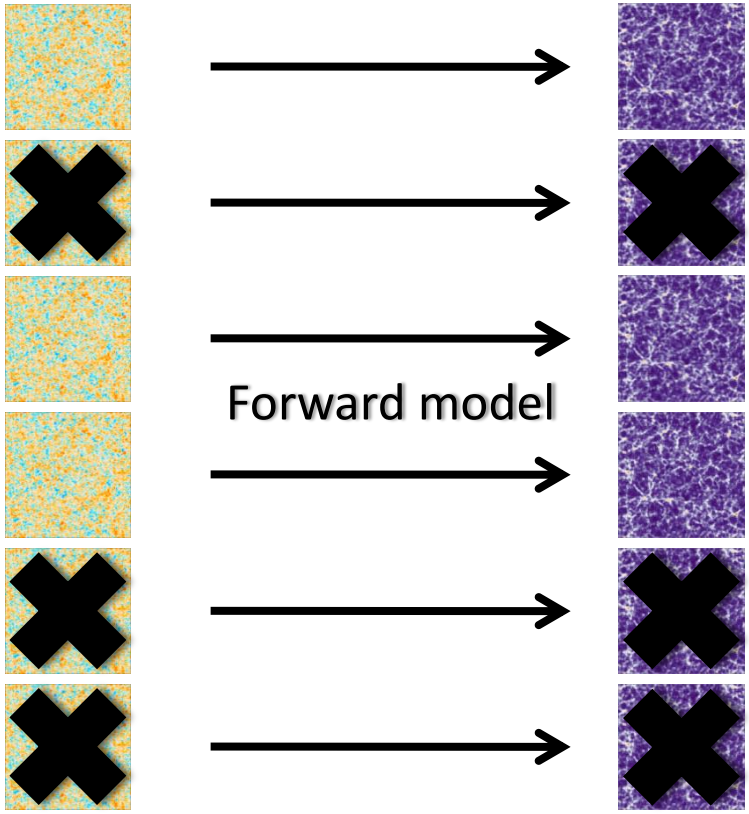


$$p(s|d) \rightarrow p_N(s|d) = \frac{1}{N}\sum_{i=1}^{N}\delta_{\mathrm{D}}(s - s_i)$$

- But how to "get the dots" ?

Bayesian forward modeling: the ideal scenario

Forward model = N-body simulation + Halo occupation +
Galaxy formation + Feedback + …

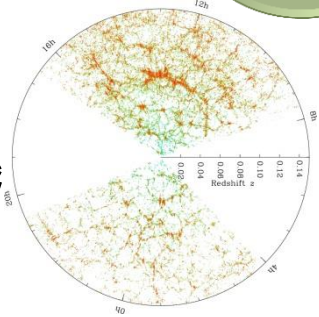


Forward model

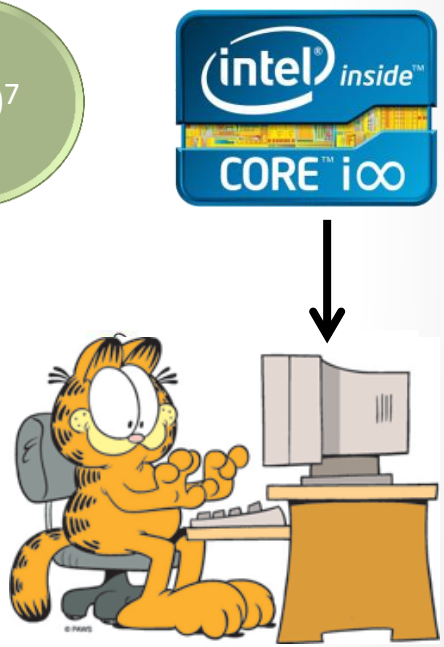
All possible ICs

All possible FCs

$d \approx 10^7$



Observations

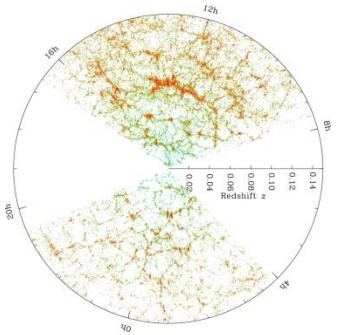


We need a very, very, very big computer!

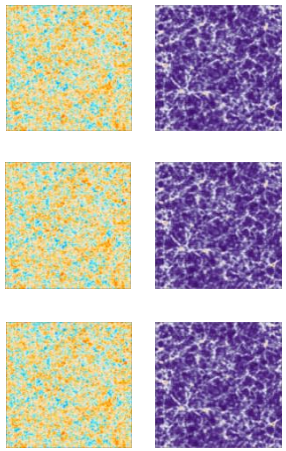
BORG: *Bayesian Origin Reconstruction from Galaxies*

What makes the problem tractable:

- **Sampler**: Hamiltonian Markov Chain Monte Carlo method
- **Physical model**: Second-order Lagrangian perturbation theory (2LPT)



Observations

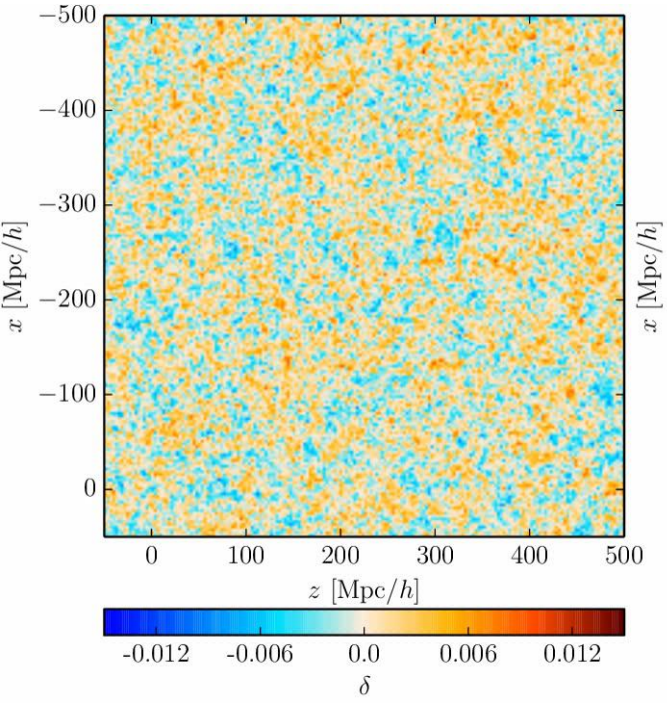


Samples of possible 4D states

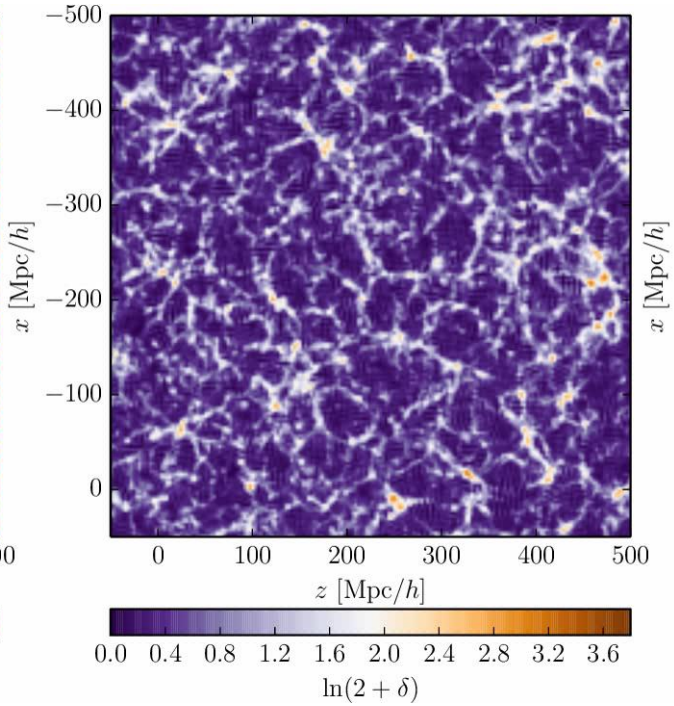
Jasche & Wandelt 2013, arXiv:1203.3639
Jasche, FL & Wandelt 2014, arXiv:1409.6308

see also:
Kitaura 2013, arXiv:1203.4184
Wang, Mo, Yang & van den Bosch 2013, arXiv:1301.1348

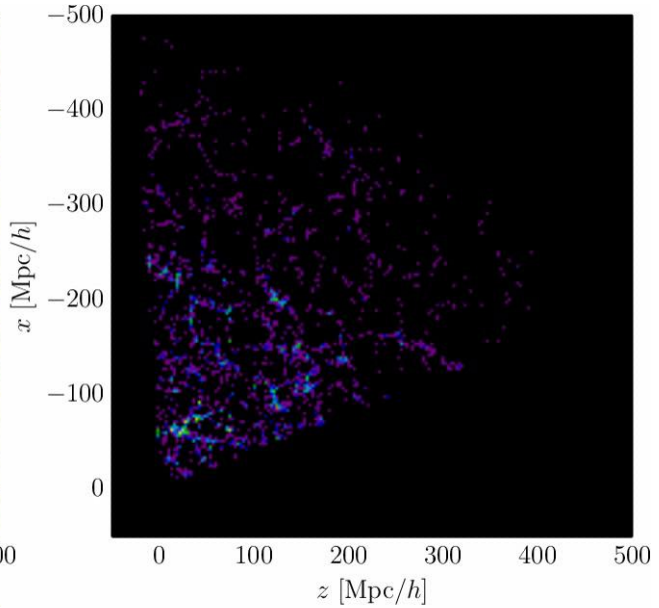
BORG at work – chronocosmography



Initial conditions



Final conditions



Observations

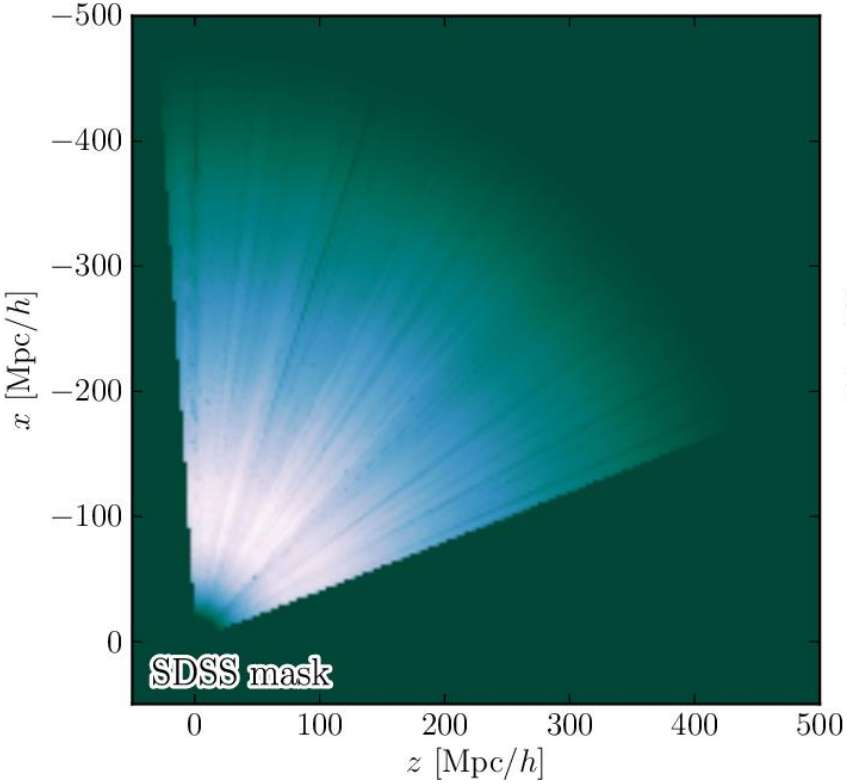
Jasche, FL & Wandelt 2014, arXiv:1409.6308

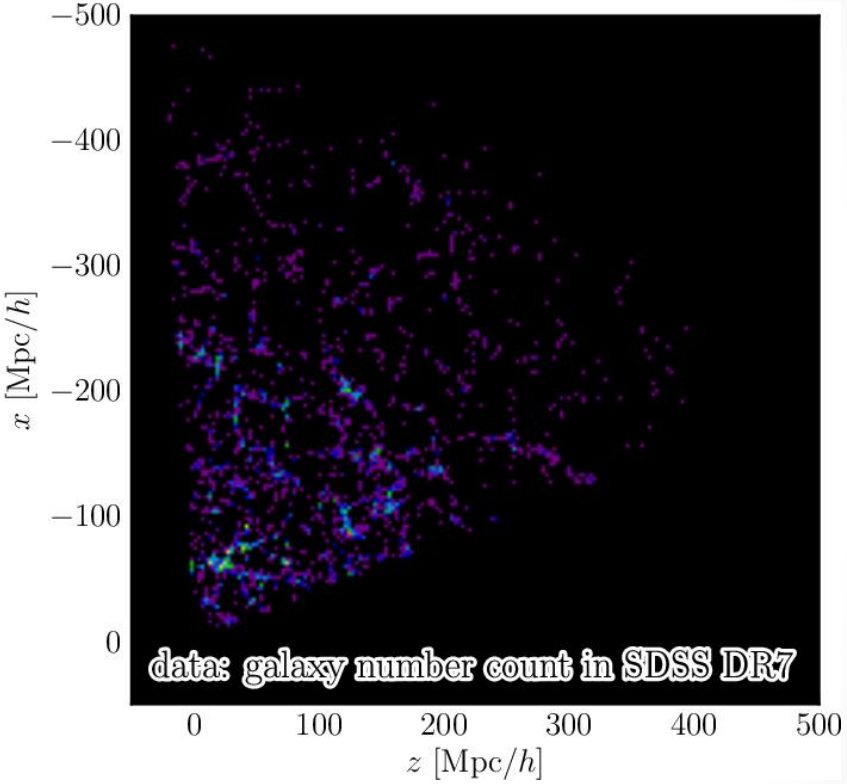
Samples of the posterior density

- Each sample: a possible "version of the truth"
- The variation between samples quantifies the uncertainty that results from having
  - only one Universe (a more precise version of "cosmic variance")
  - incomplete observations (mask, finite volume and number of galaxies, selection effects)
  - imperfect data (noise, biases…)

see also FL, Pisani & Wandelt, arXiv:1403.1260

Bayesian chronocosmography from SDSS DR7

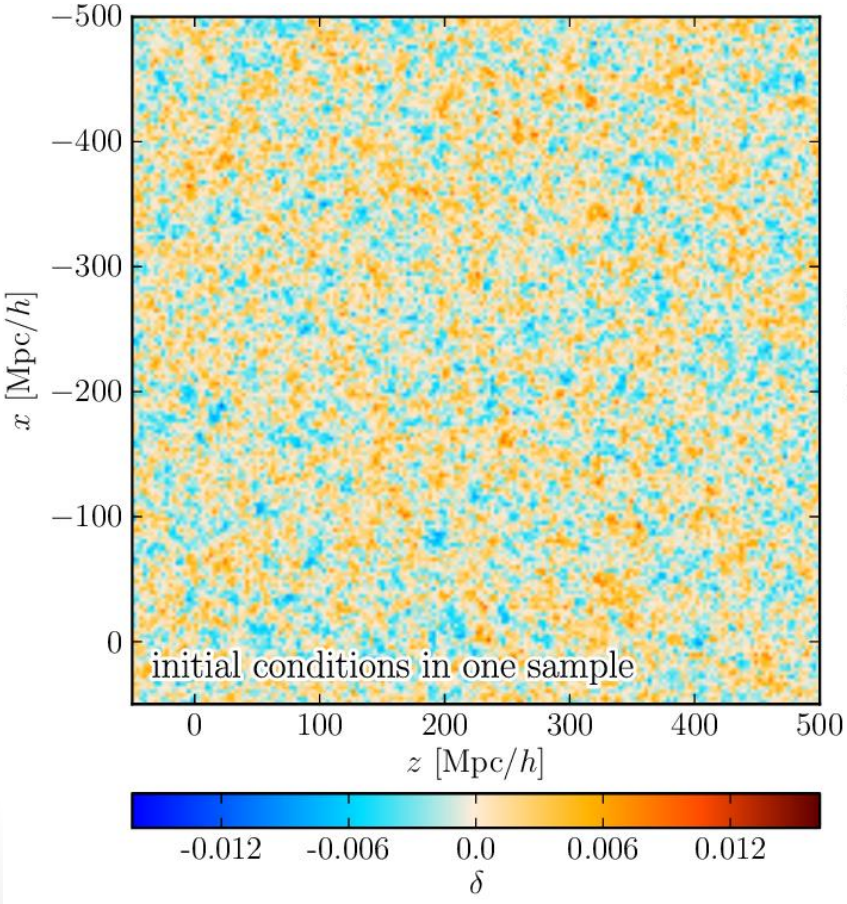


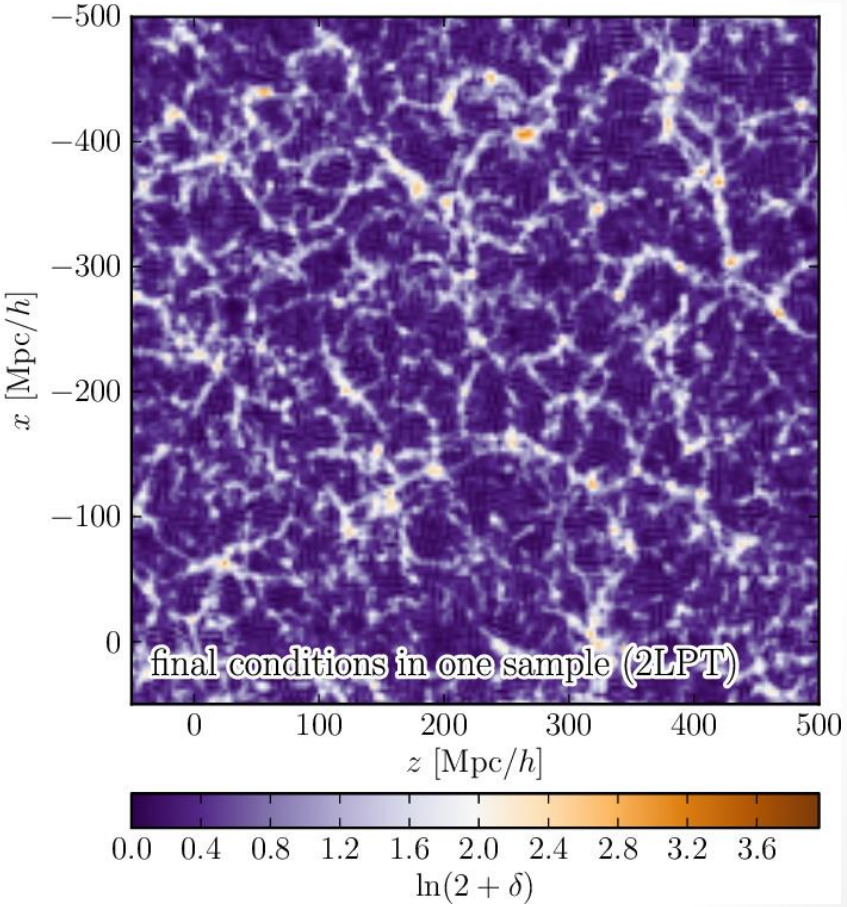


Data

Jasche, FL & Wandelt 2014, arXiv:1409.6308

Bayesian chronocosmography from SDSS DR7

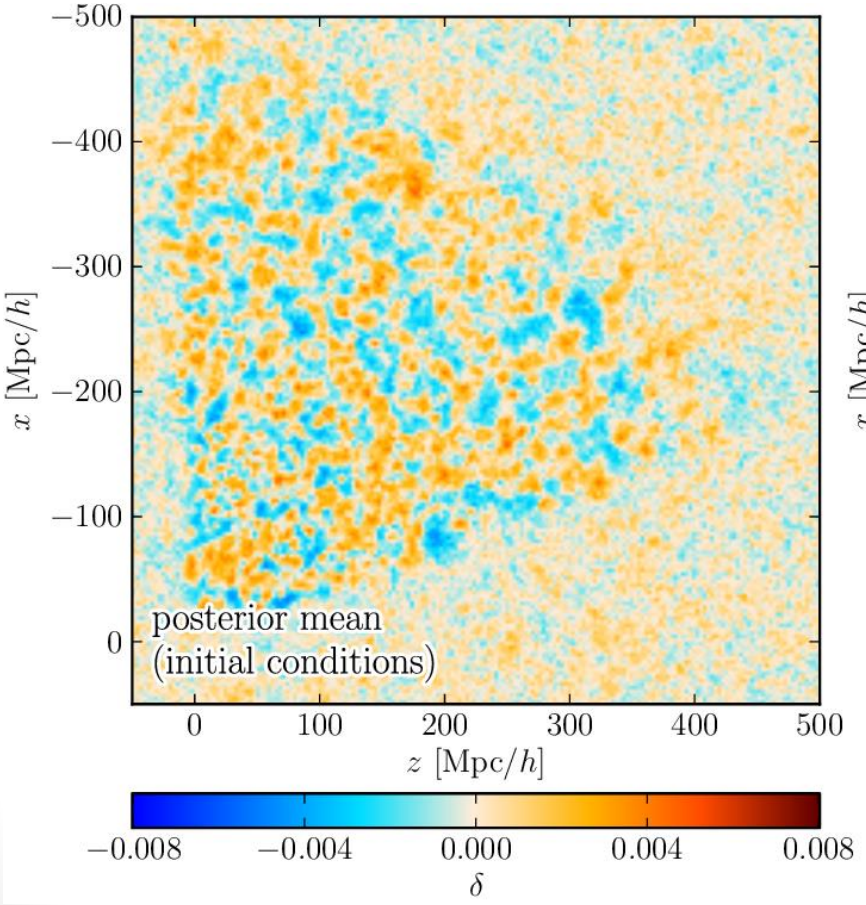


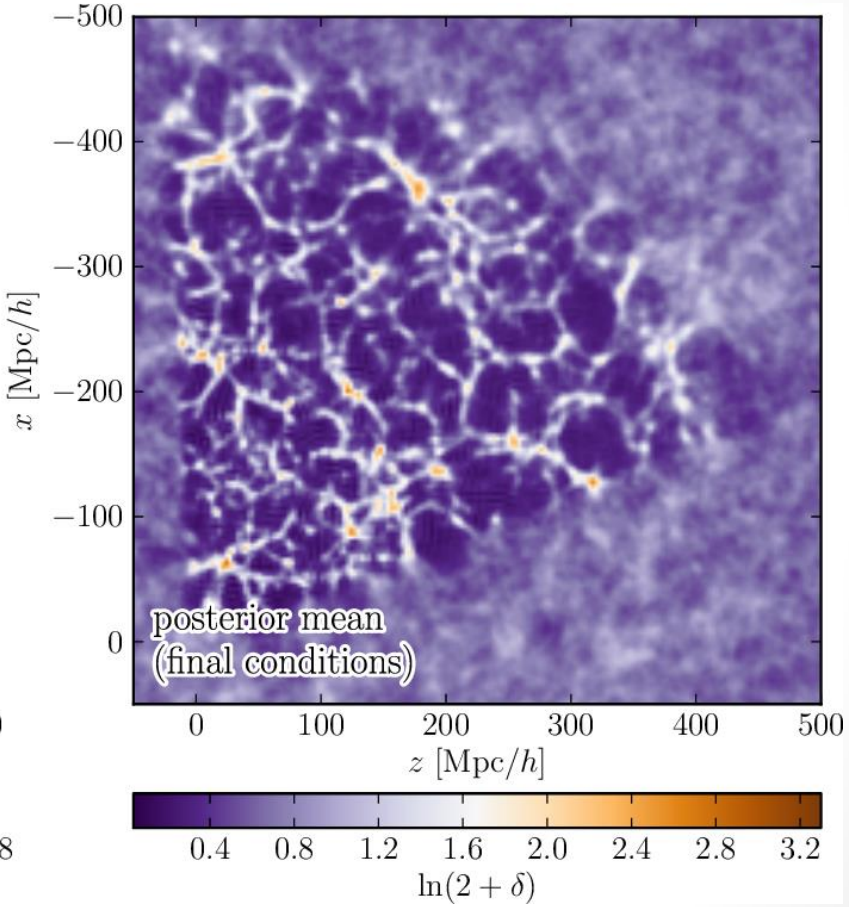


One sample

Jasche, FL & Wandelt 2014, arXiv:1409.6308

Bayesian chronocosmography from SDSS DR7

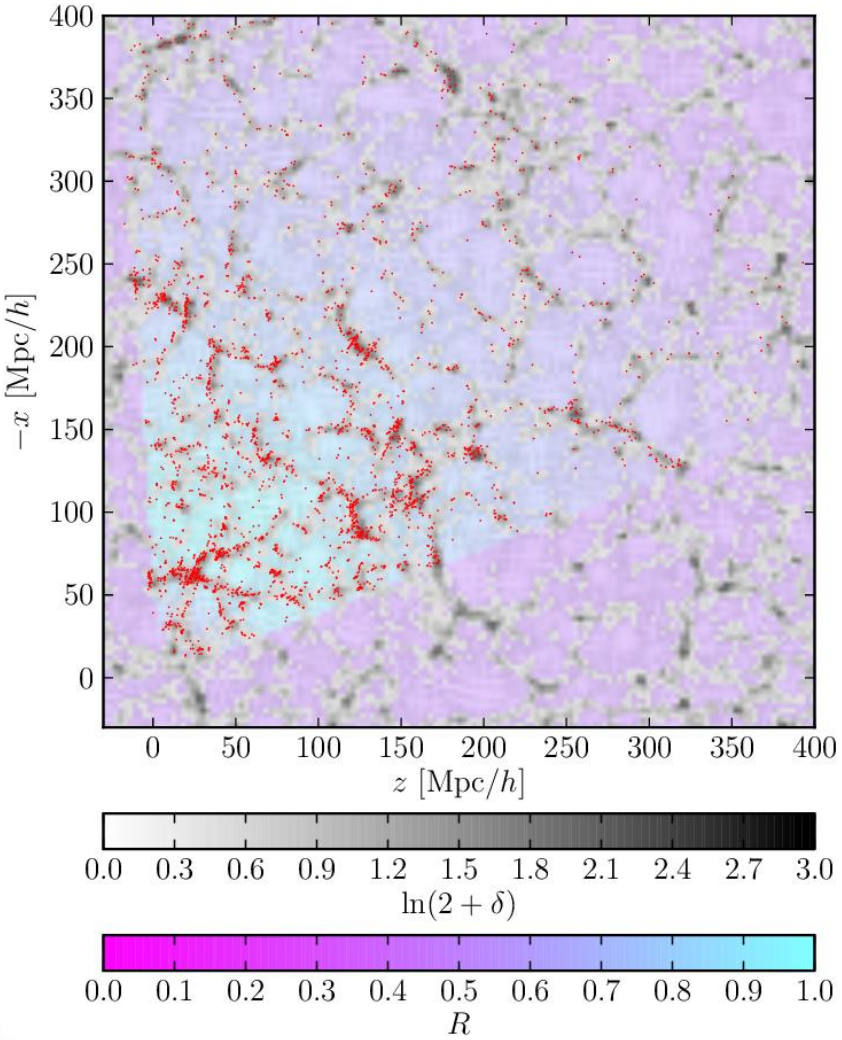




Posterior mean

Jasche, FL & Wandelt 2014, arXiv:1409.6308

Dark matter voids in the SDSS



FL, Jasche, Sutter, Hamaus & Wandelt 2014, arXiv:1410.0355

- Why?

Sparsity & Bias

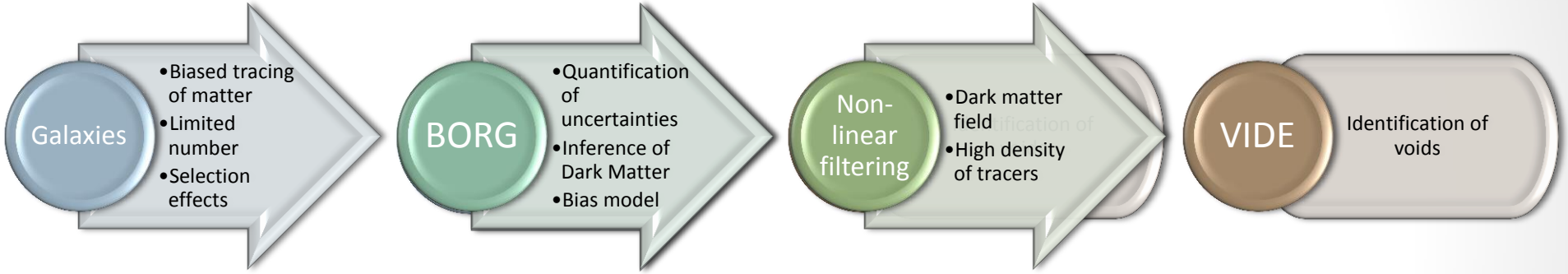
Sutter *et al*. 2013, arXiv:1309.5087
Sutter *et al*. 2013, arXiv:1311.3301

- How?

VIDE toolkit: Sutter *et al*. 2014, arXiv:1406.1191
www.cosmicvoids.net

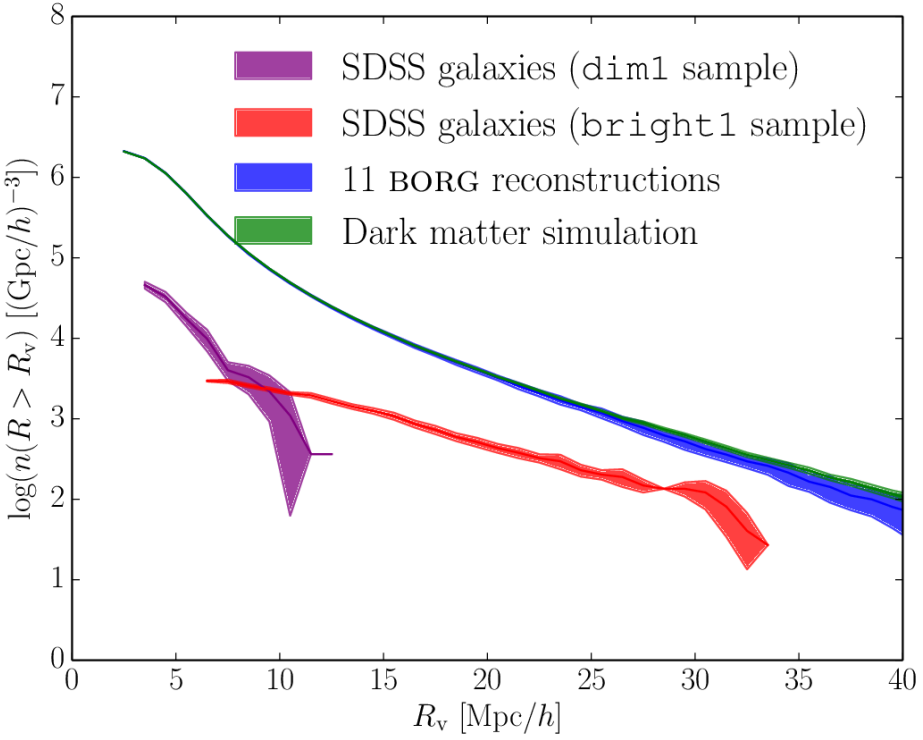
based on ZOBOV: Neyrinck 2007, arXiv:0712.3049

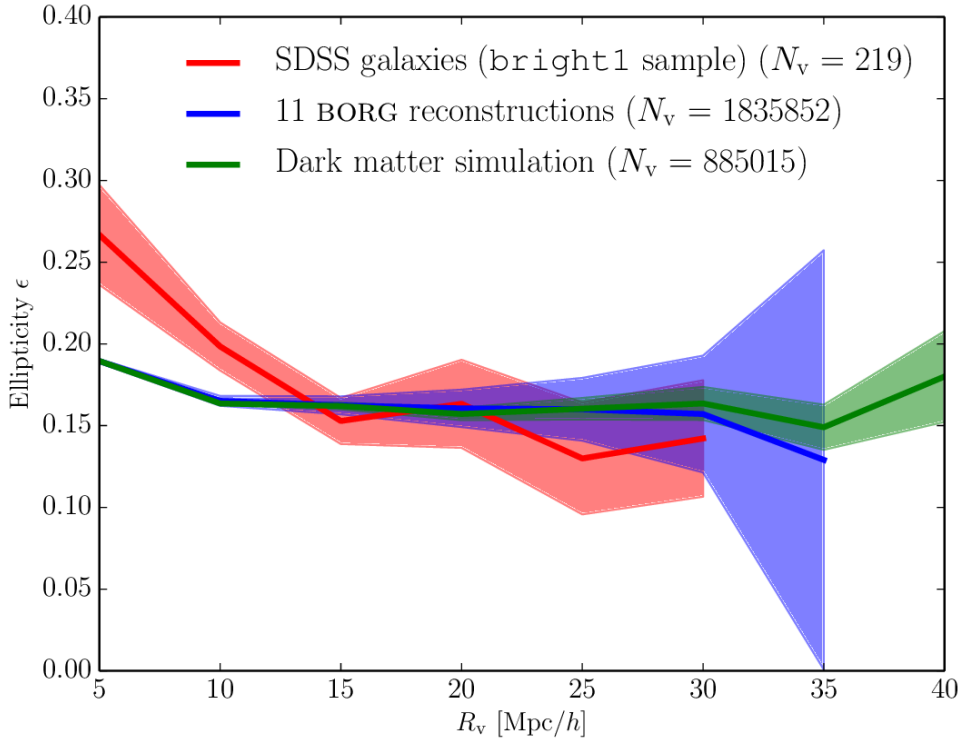
Dark matter voids: pipeline



FL, Jasche, Sutter, Hamaus & Wandelt 2014, arXiv:1410.0355

Dark matter void properties





All catalogs will be made publicly available at
www.cosmicvoids.net

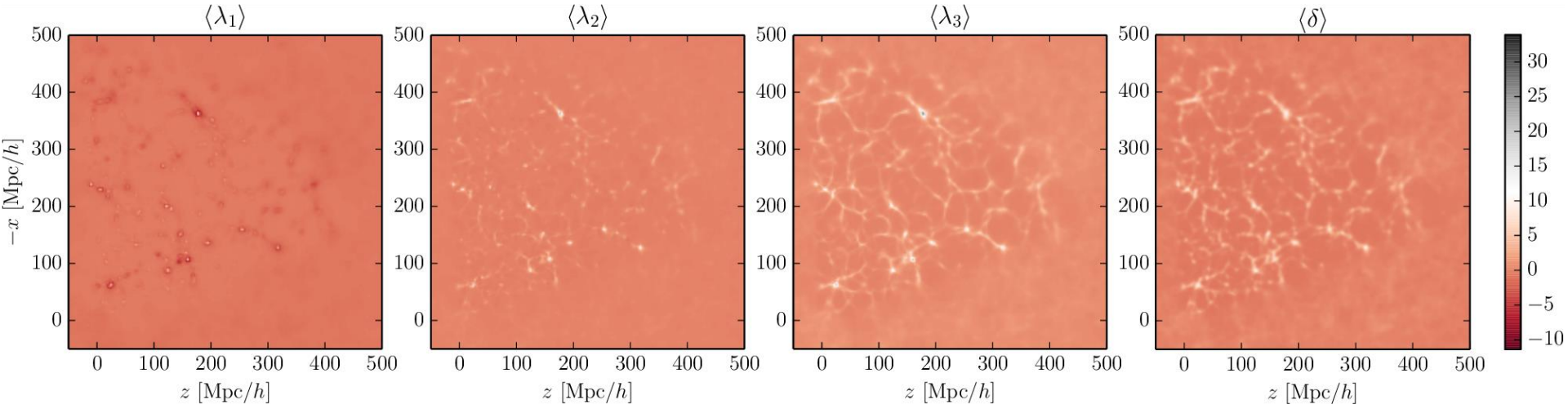
FL, Jasche, Sutter, Hamaus & Wandelt 2014, arXiv:1410.0355

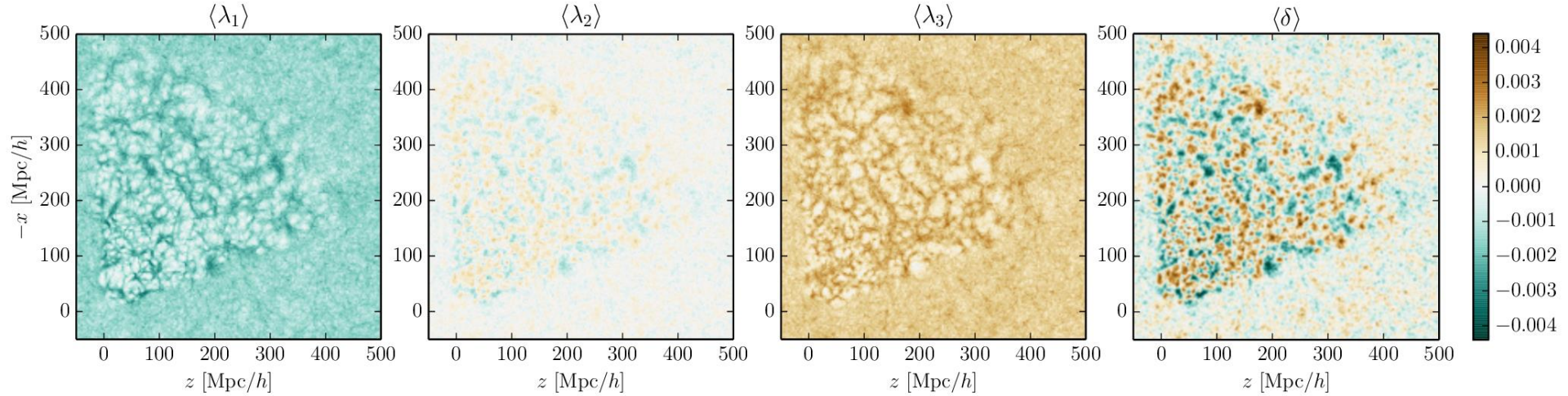
Tidal shear analysis

$$T_{ij} = \partial_i \partial_j \Phi$$

Hahn *et al.* 2007, arXiv:astro-ph/0610280

Final conditions



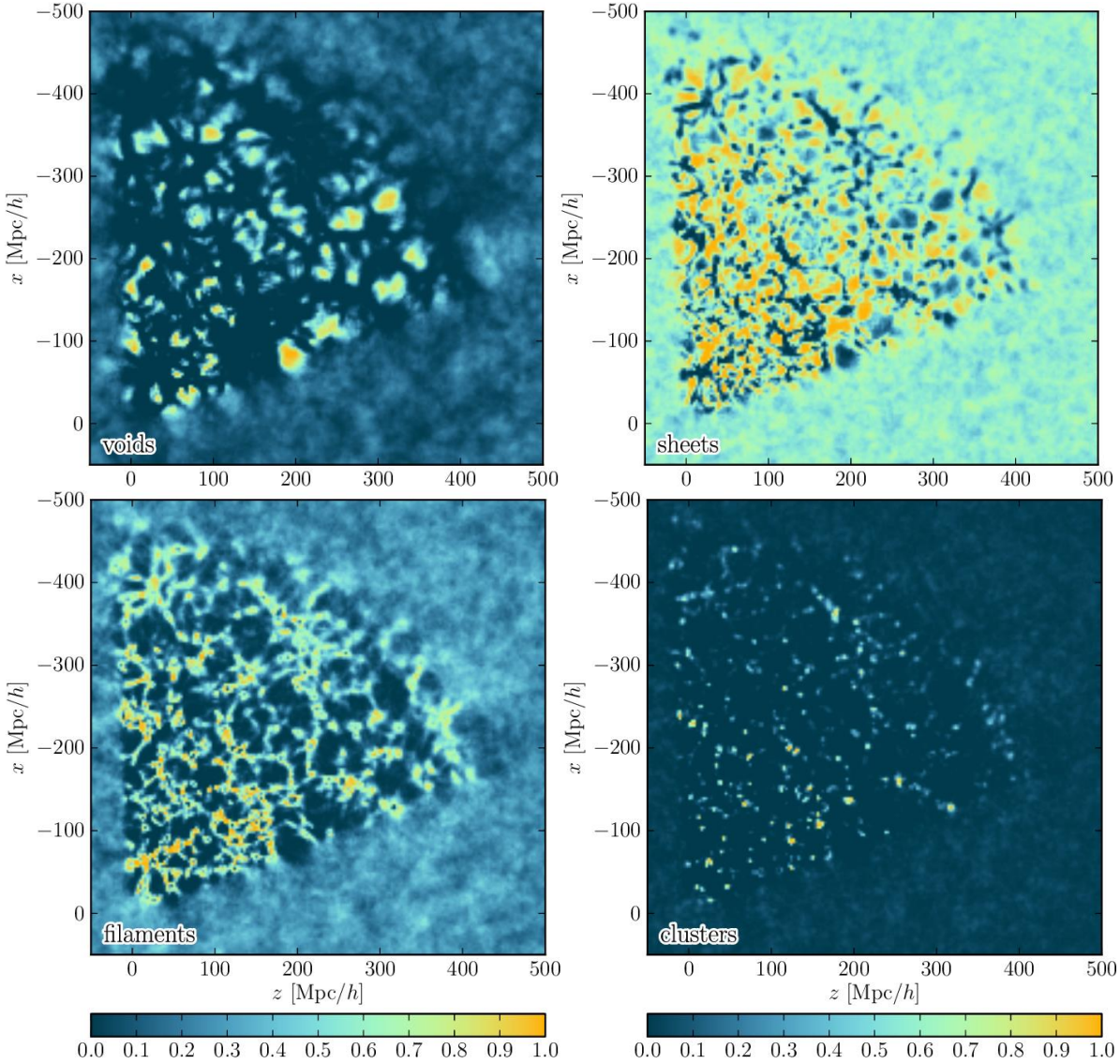


FL, Jasche & Wandelt 2015, arXiv:1502.02690

Initial conditions

Dynamic structures inferred by BORG

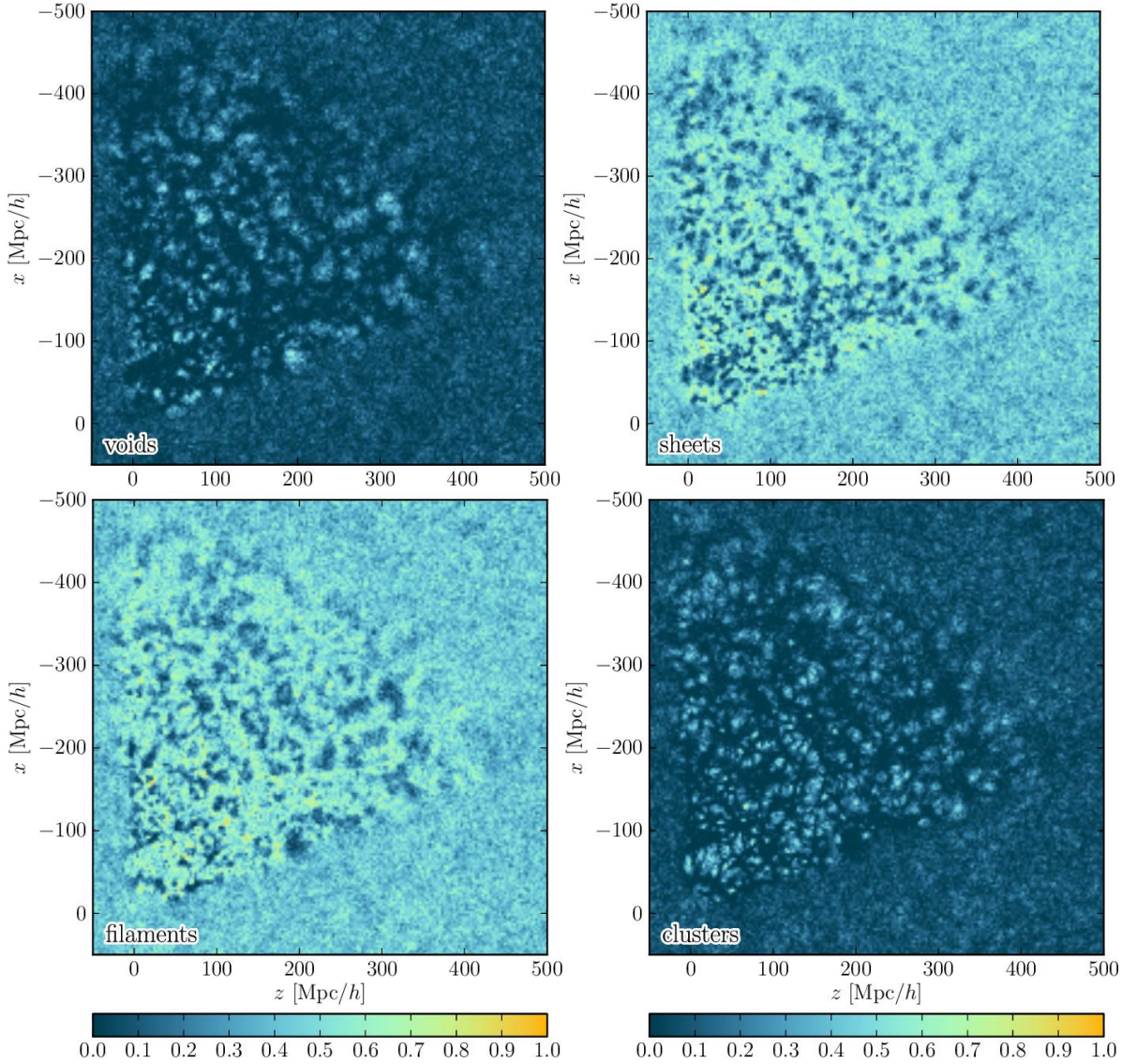
Final conditions



FL, Jasche & Wandelt 2015, arXiv:1502.02690

Dynamic structures inferred by BORG

Initial conditions

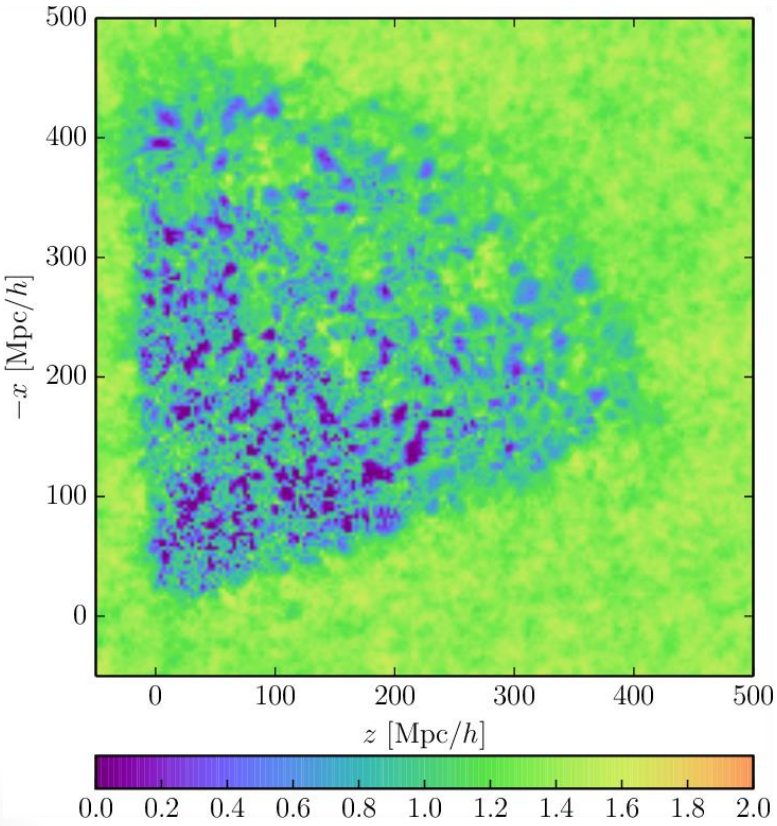


FL, Jasche & Wandelt 2015, arXiv:1502.02690

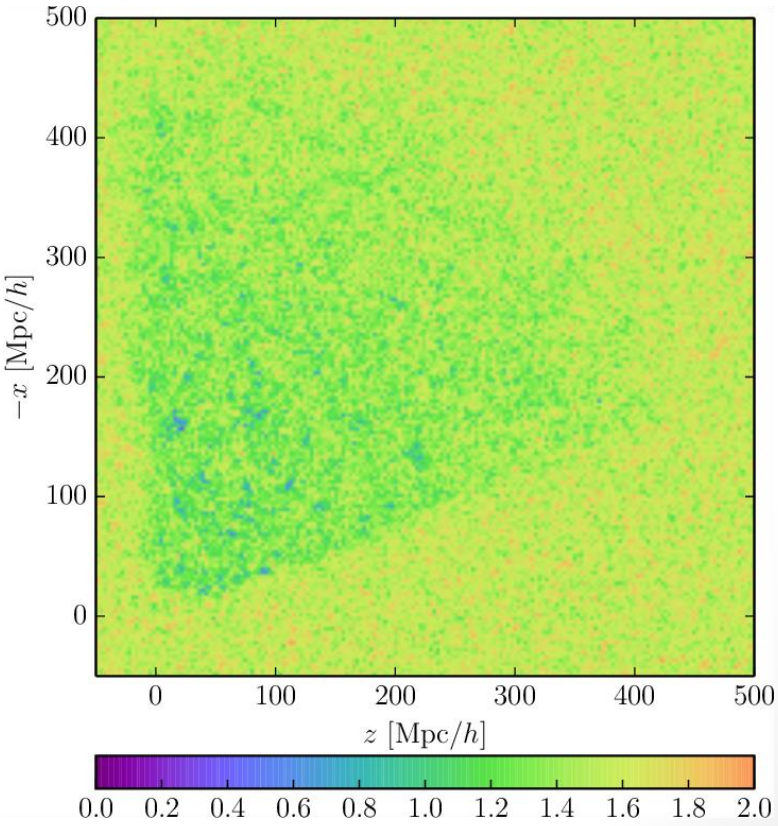
Entropy of the structure types pdf

$$H\left[\mathcal{P}(\mathrm{T}(\vec{x}_k)|d)\right] \equiv -\sum_{i=0}^{3} \mathcal{P}(\mathrm{T}_i(\vec{x}_k)|d)\log_2(\mathcal{P}(\mathrm{T}_i(\vec{x}_k)|d))$$ in shannons (Sh)

Final conditions



Initial conditions

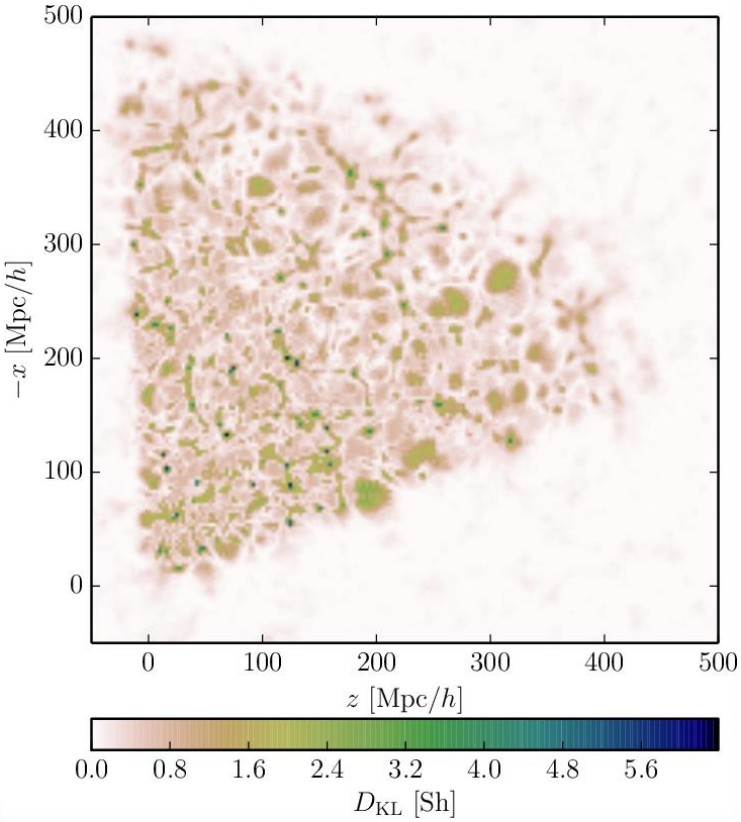


FL, Jasche & Wandelt 2015, arXiv:1502.02690

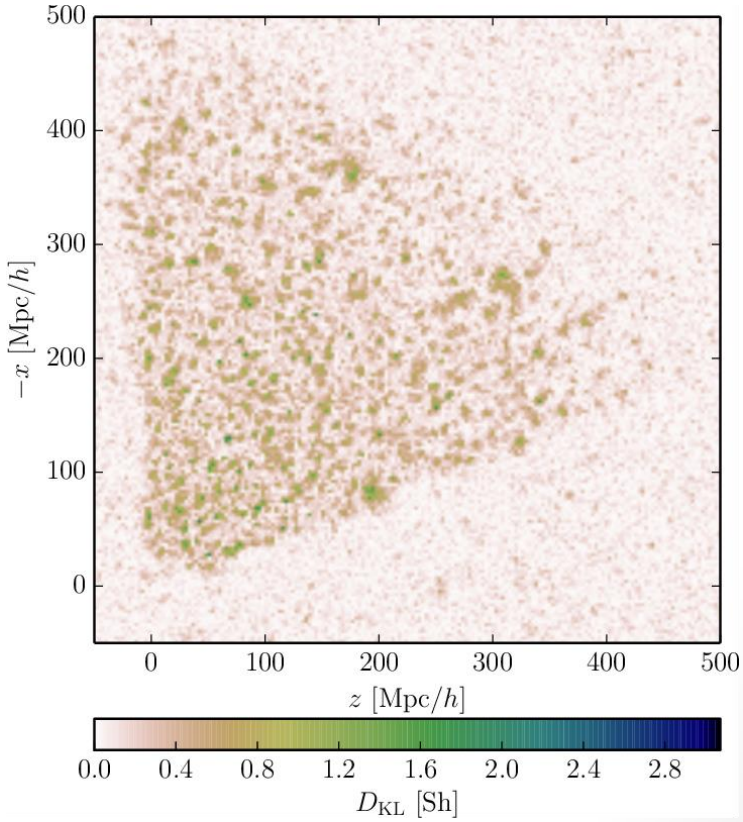
Kullback-Leibler divergence posterior/prior

$$D_{\mathrm{KL}}(\mathcal{P}(\mathrm{T}(\vec{x_k})|d)||\mathcal{P}(\mathrm{T})) \equiv \sum_i \mathcal{P}(\mathrm{T}_i(\vec{x_k})|d) \log_2 \left(\frac{\mathcal{P}(\mathrm{T}_i(\vec{x_k})|d)}{\mathcal{P}(\mathrm{T}_i)} \right)$$ in Sh

Final conditions

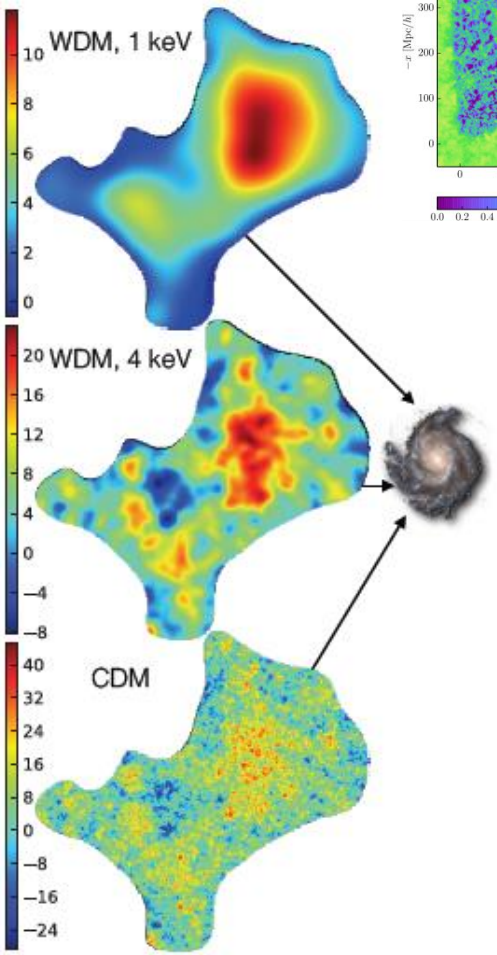


Initial conditions

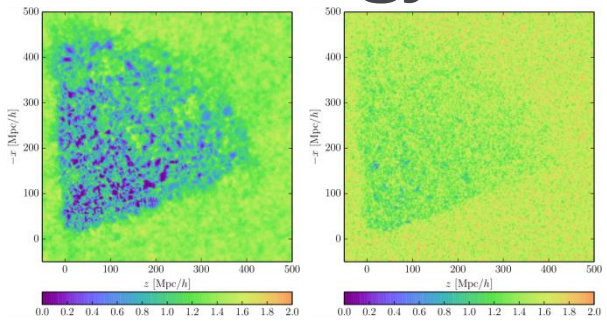


FL, Jasche & Wandelt 2015, arXiv:1502.02690

The future: cosmology and information theory



Neyrinck 2014, arXiv:1409.0057



$$H\left[\mathcal{S}\right] = -\sum_i p_i \log_2 p_i$$

FL, Jasche & Wandelt 2015, arXiv:1502.02690

- Quantification of the information content of Lagrangian patches that collapse to form structures
- Link between information-theoretic and physical entropy?
- Cosmological evolution of the gravitational entropy of the LSS

  Marozzi, Uzan, Umeh, Clarkson, arXiv:1501.04906
- Complexity vs. entropy

  Aaronson, Carroll, Ouellette 2014, arXiv:1405.6903
- Scale-dependent test of the degree of determinism in structure formation in link with a Lagrangian EFT of LSS

  Porto, Senatore & Zaldarriaga 2013, arXiv:1311.2168

A decision rule for structure classification

- Space of "input features":

$$\{\mathrm{T}_0 = \text{void}, \mathrm{T}_1 = \text{sheet}, \mathrm{T}_2 = \text{filament}, \mathrm{T}_3 = \text{cluster}\}$$

- Space of "actions":

$$\{a_0 = \text{“decide void”}, a_1 = \text{“decide sheet”}, a_2 = \text{“decide filament”}, a_3 = \text{“decide cluster”}, a_{-1} = \text{“do not decide”}\}$$

⇨ A problem of **Bayesian decision theory**:
one should take the action which maximizes the utility

$$U(a_j(\vec{x}_k)|d) = \sum_{i=0}^{3} G(a_j|\mathrm{T}_i)\,\mathcal{P}(\mathrm{T}_i(\vec{x}_k)|d)$$

- How to write down the gain functions?

FL, Jasche & Wandelt, in prep.

Gambling with the Universe

- One proposal:

$$G(a_j|\mathrm{T}_i) = \begin{cases} \dfrac{1}{\mathcal{P}(\mathrm{T}_i)} - \alpha & \text{if } j \in [\![0,3]\!] \text{ and } i = j \\ -\alpha & \text{if } j \in [\![0,3]\!] \text{ and } i \neq j \\ 0 & \text{if } j = -1. \end{cases}$$

"Winning"

"Loosing"

"Not playing"

- Without data, the expected utility is

$$U(a_j) = 1 - \alpha \quad \text{if } j \neq 1$$

"Playing the game"

$$U(a_{-1}) = 0$$

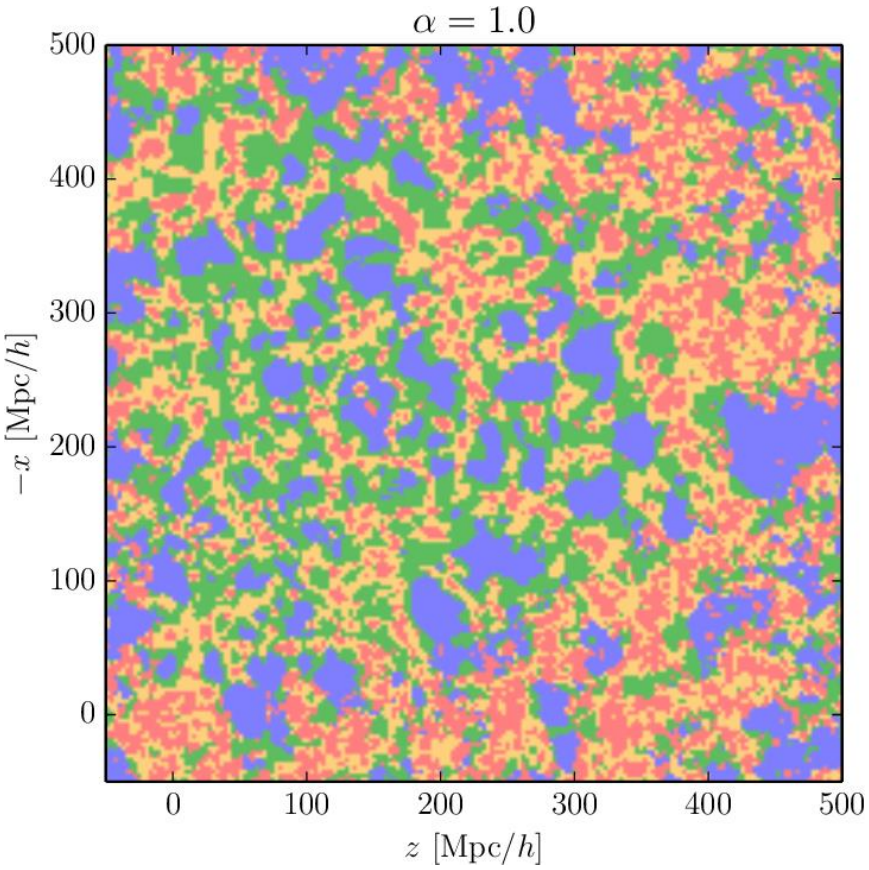
"Not playing the game"

- With $\alpha = 1$, it's a *fair game* ⇒ always play ⇒ "speculative map" of the LSS
- Values $\alpha > 1$ represent an *aversion for risk* ⇒ increasingly "conservative maps" of the LSS

FL, Jasche & Wandelt, in prep.

Playing the game…

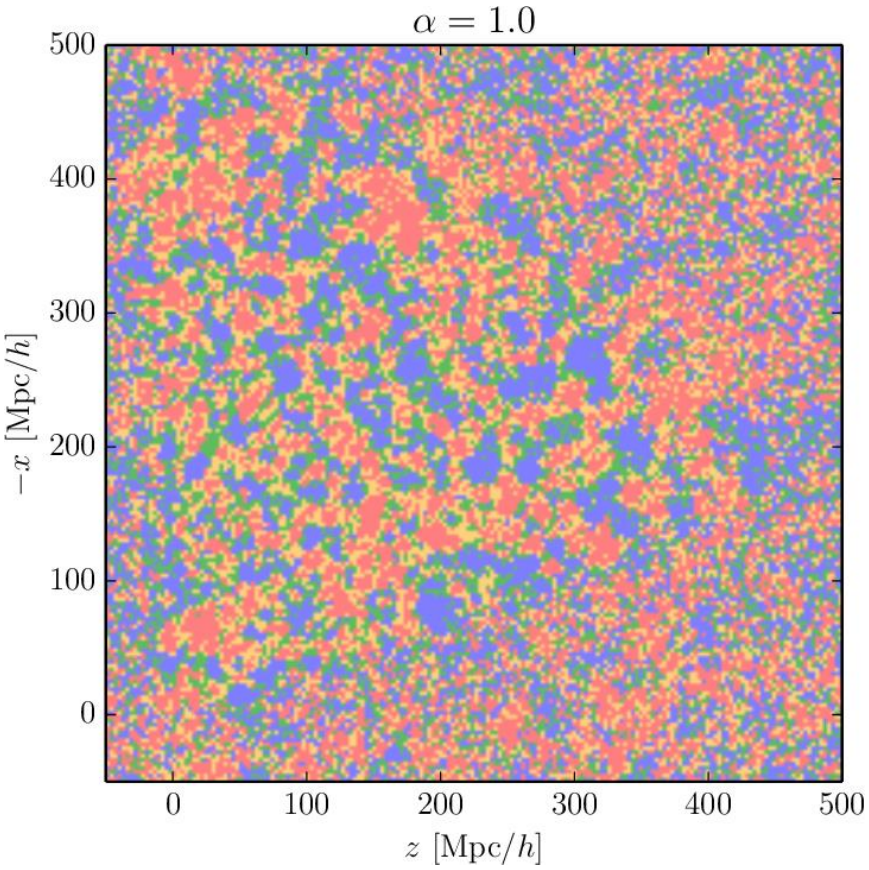
Final conditions



FL, Jasche & Wandelt, in prep.

Playing the game…

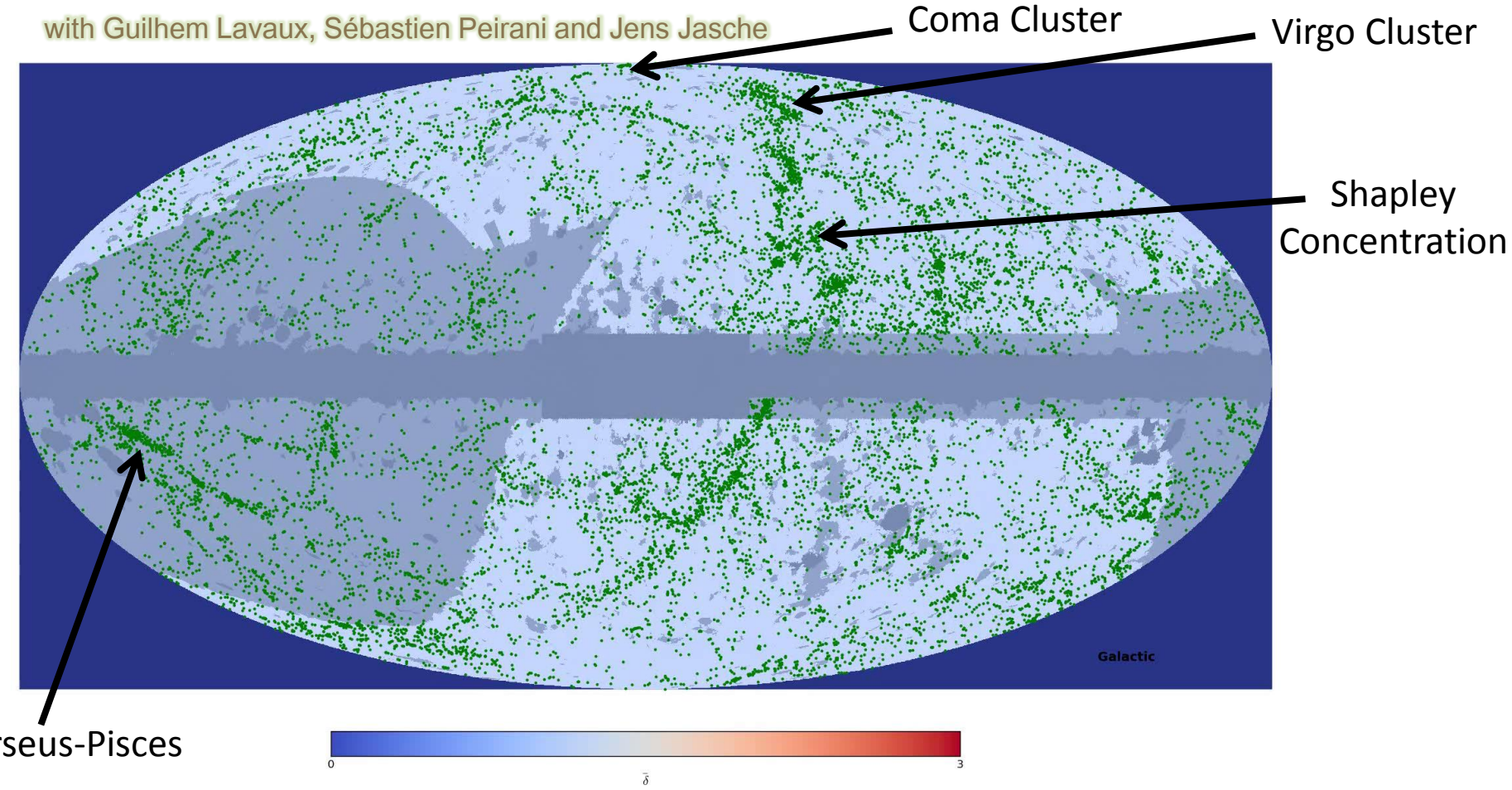
Initial conditions



FL, Jasche & Wandelt, in prep.

Ongoing project: PLUS: *the Paris Local Universe Simulation*

with Guilhem Lavaux, Sébastien Peirani and Jens Jasche



600 Mpc/*h* box, 60 Mpc/*h* projection, 512^3 dark matter particles

2M++ catalog: Lavaux & Hudson 2011, arXiv:1105.6107 (compiled 2MASS, 6dF, SDSS DR7)

Ongoing project: PLUS: *the Paris Local Universe Simulation*

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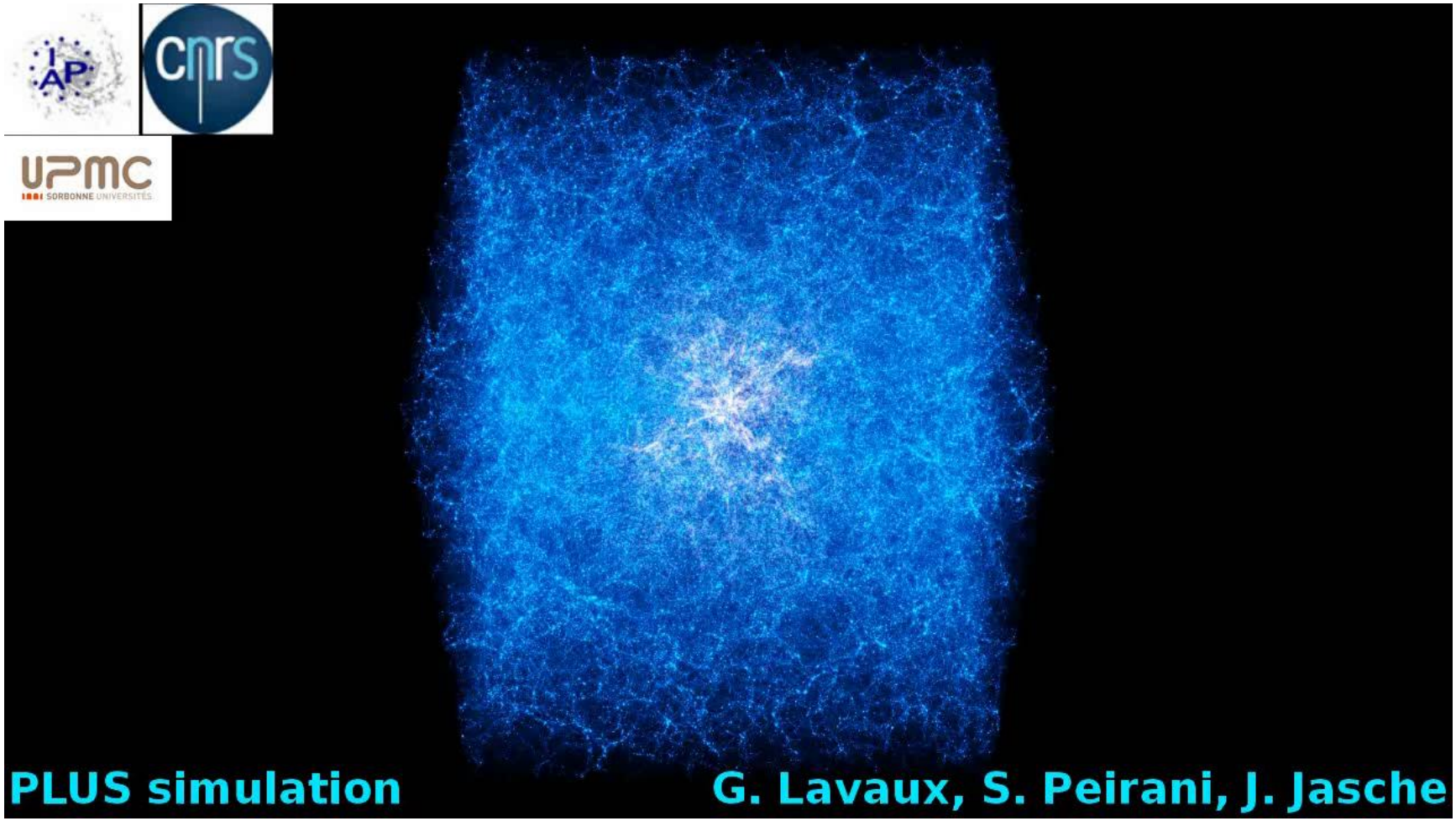

Mapping the Universe: epilogue?

Concluding thoughts

- Cosmological **physical reconstruction of the initial conditions** of the Universe is becoming feasible.
- It allows high-precision **cosmic web** analysis
  - A new, enhanced **dark matter voids** catalog.
  - Probabilistic maps of the **dynamic structures**
- More on methods and perspectives on Monday (March 2)!
- Additional **great science** is waiting behind the door.
  - Baryon acoustic oscillations, clusters, galaxies
  - Non-Gaussianity
  - Isocurvature perturbations
  - Gravitational waves in the large-scale structure…