Cosmostatistics: the initial conditions and the large-scale structure of the Universe

Florent Leclercq

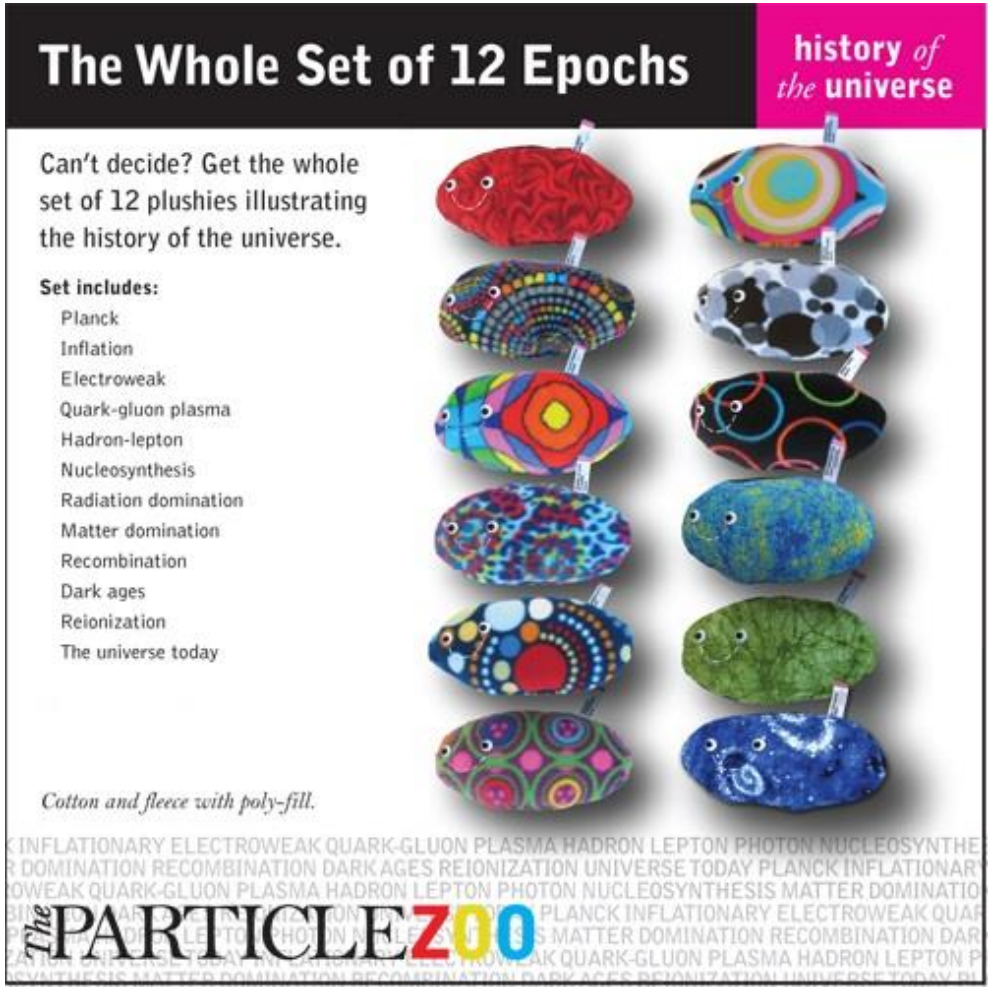
Institut d'Astrophysique de Paris & École polytechnique ParisTech

November 27th, 2013

In collaboration with:

Héctor Gil-Marín (U. Portsmouth/U. Barcelona), Jens Jasche (IAP), Emilio Romano-Díaz (U. Bonn), Svetlin Tassev (U. Princeton), Benjamin Wandelt (IAP/U. Illinois), Matías Zaldarriaga (IAS Princeton)

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 infered.

⇨ The **initial conditions** of the Universe have a **particular status** with respect to other physical phenomena.

Cosmostatistics of the initial conditions

- **"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)*

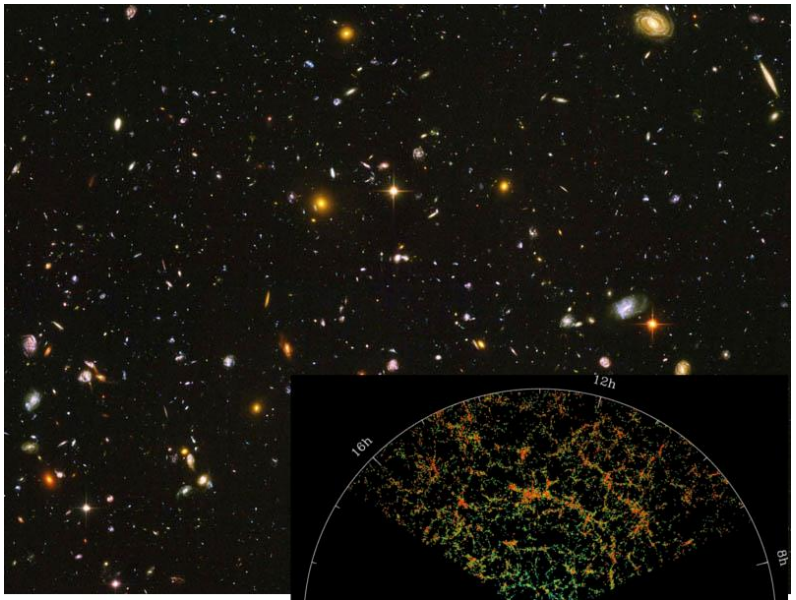
- **Cosmostatistics**: discipline dealing with stochastic quantities as seeds of structure in the Universe
  - prediction of cosmological observables from random inputs

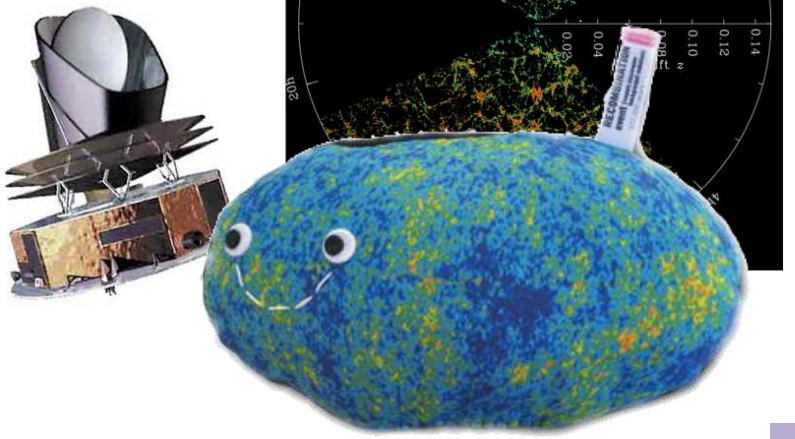
(from theory to data)

  - use of the departures from homogeneity in astronomical surveys to distinguish between cosmological models

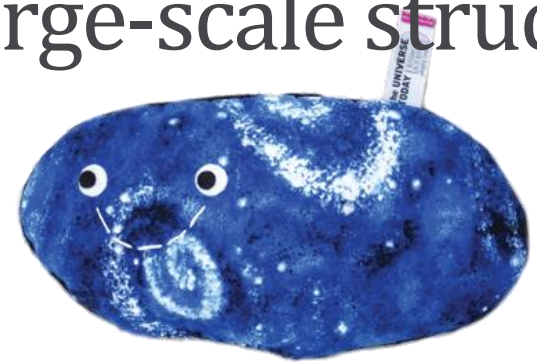
(from data to theory)

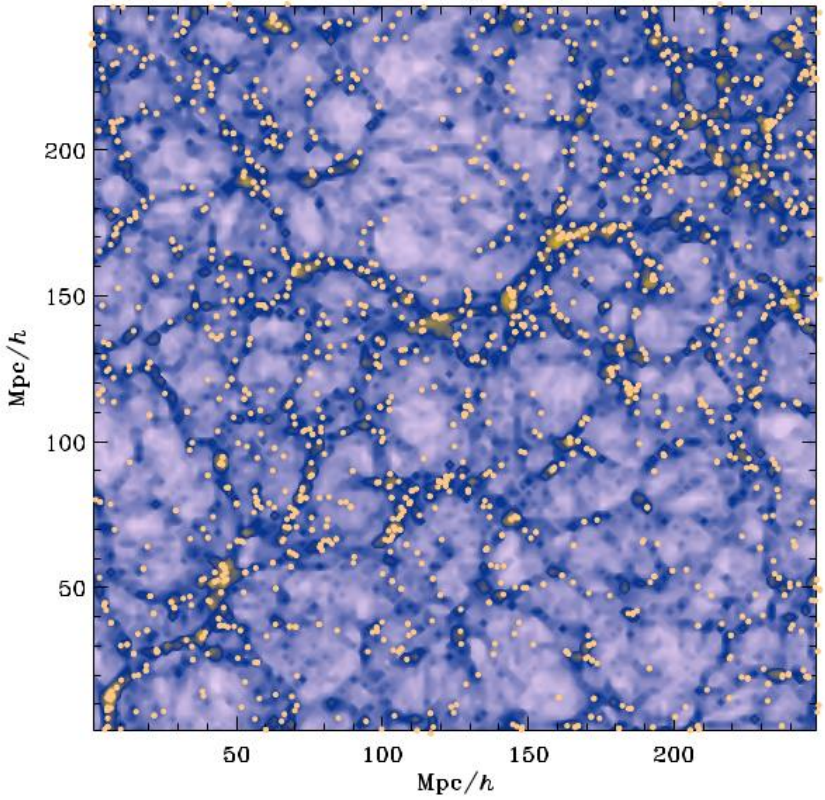
High-energy physics experiments





A large-scale structure in the Universe





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**

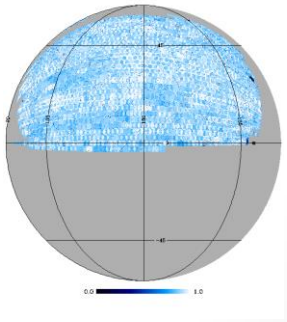
Bayesian inference of the ICs

- Why do we need Bayesian inference?

  Inference of signals = ill-posed problem
  - Noise
  - Incomplete observations: survey geometry, selection effects
  - Systematic uncertainties, biases
  - Cosmic variance

No unique recovery is possible!

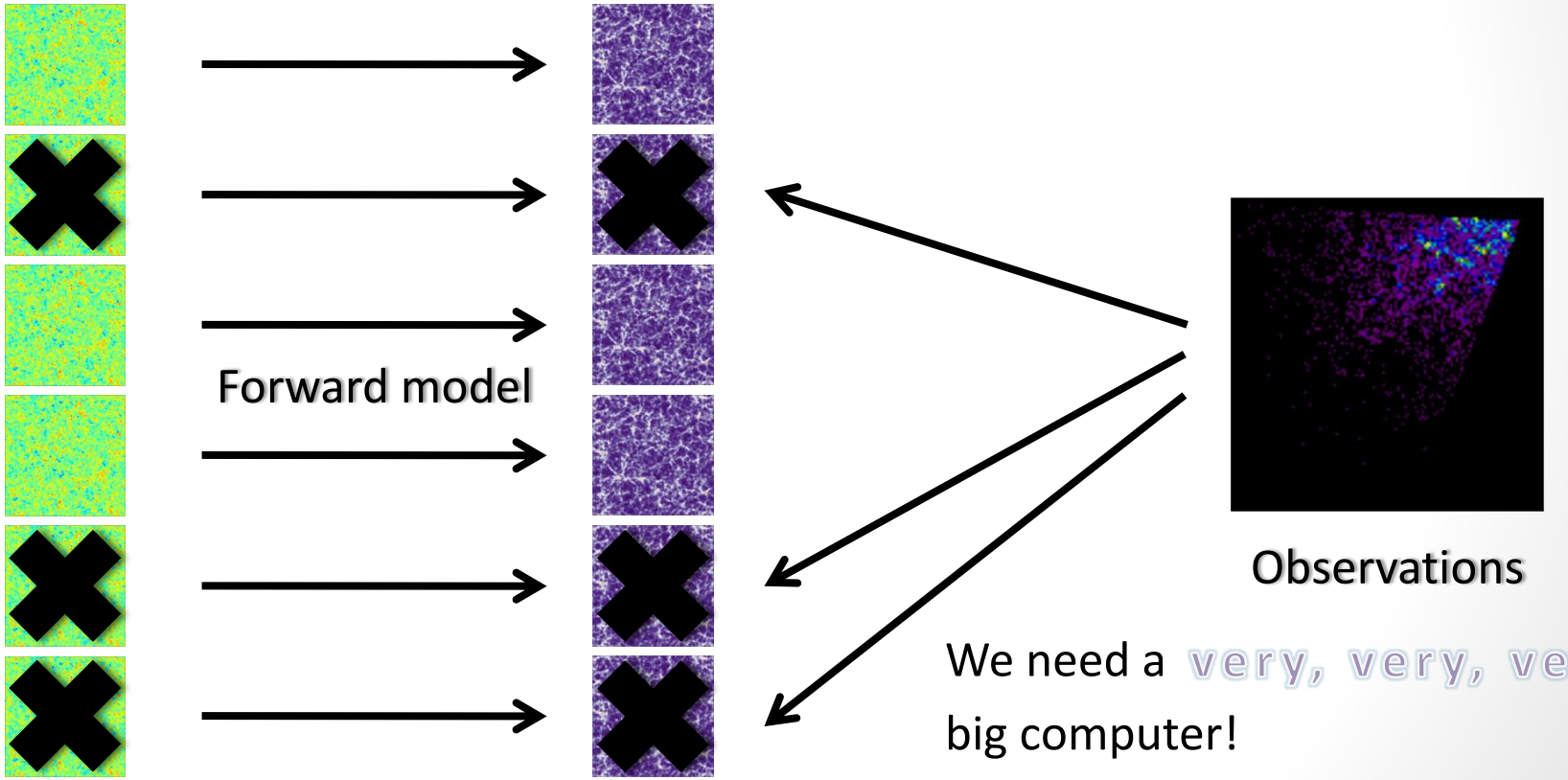
- A good question: “What is the probability distribution of possible signals compatible with the observations?”



4D physical inference of the ICs

- The ideal scenario:

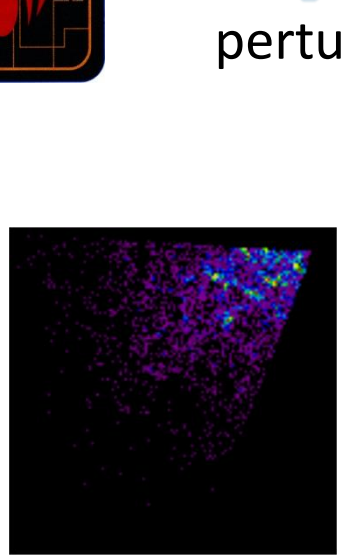
Forward model = N-body simulation + Halo occupation + Galaxy formation + Feedback + …



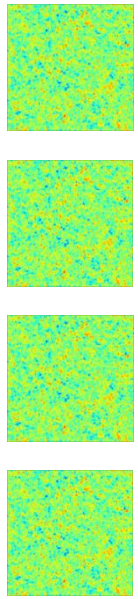
BORG: *Bayesian Origin Reconstruction from Galaxies*

What makes the problem tractable:

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



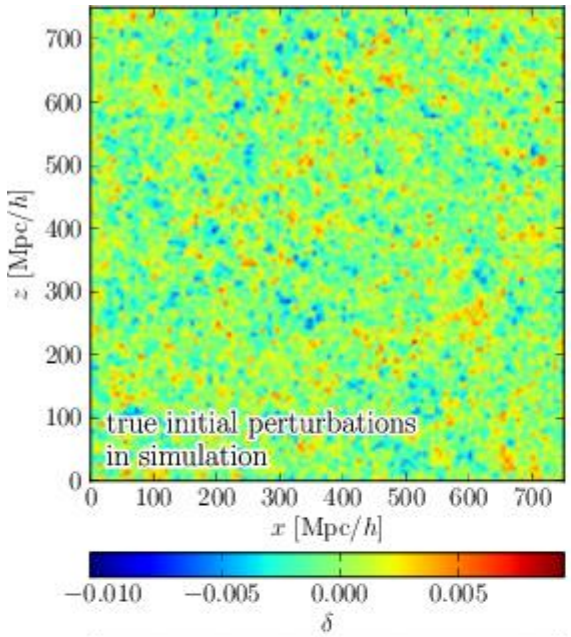
Observations

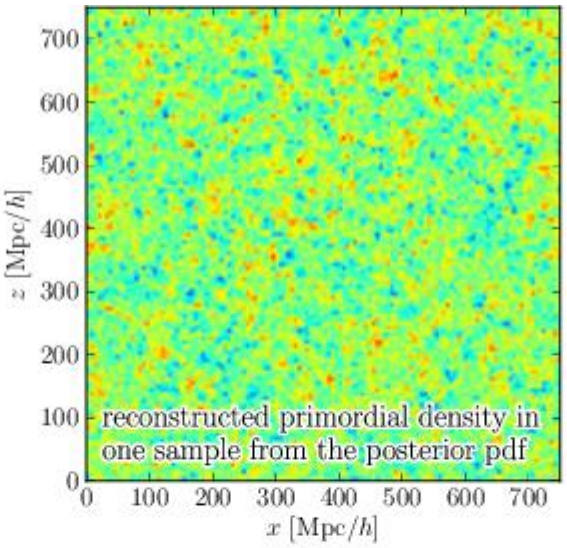


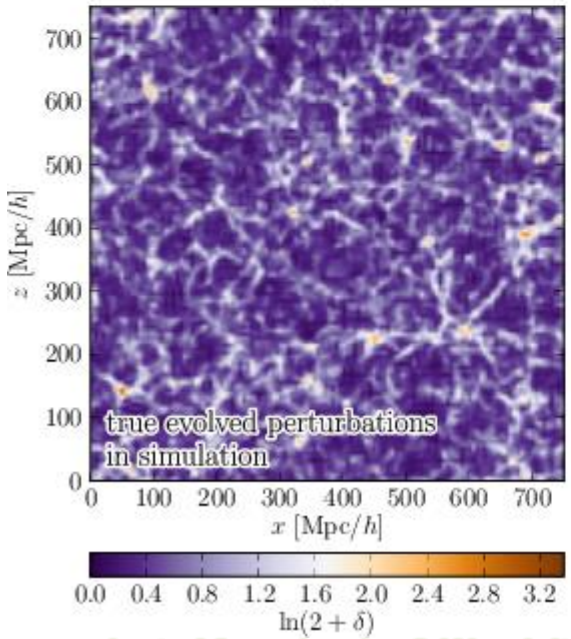
Samples of possible ICs

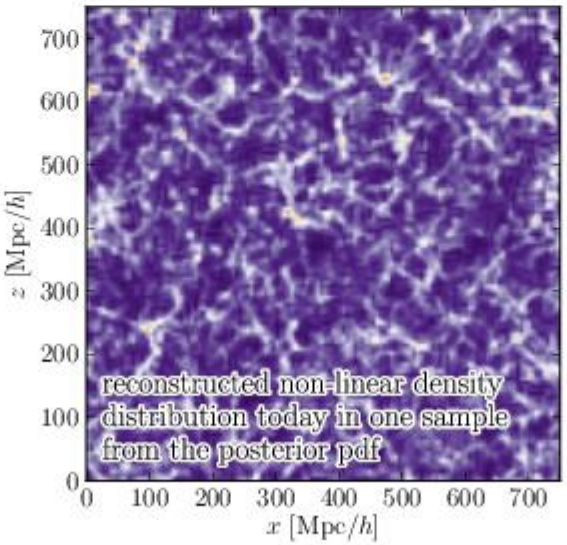
Jasche & Wandelt 2012, arXiv:1203.3639

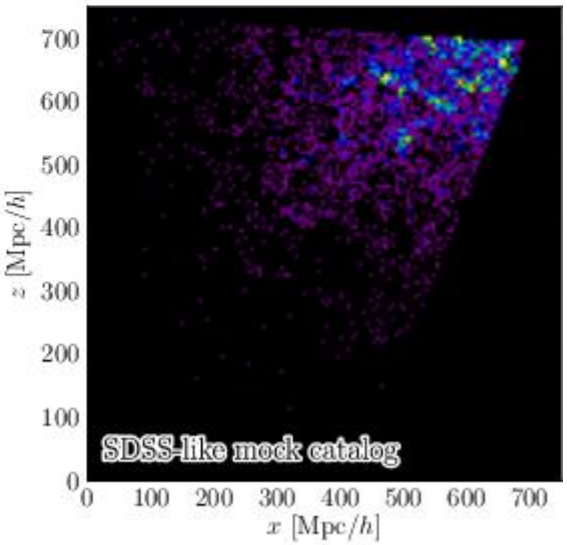
BORG: proof of concept











adapted from Jasche & Wandelt 2012, arXiv:1203.3639

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, photometric redshifts…)

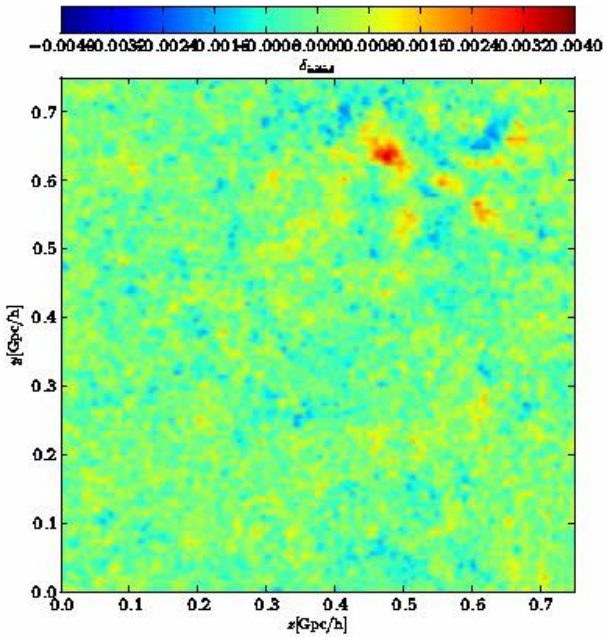
see also FL, Pisani & Wandelt, proceedings to appear soon

- On the importance of **efficient tools to model cosmic structure formation** in the non-linear regime…

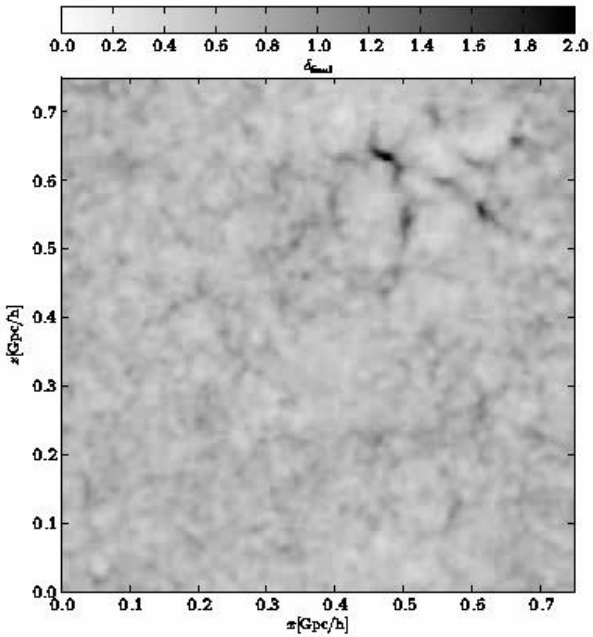
FL, Jasche, Gil-Marín & Wandelt 2013, arXiv:1305.4642

Tassev, Zaldarriaga & Einsenstein 2013, arXiv:1301.0322

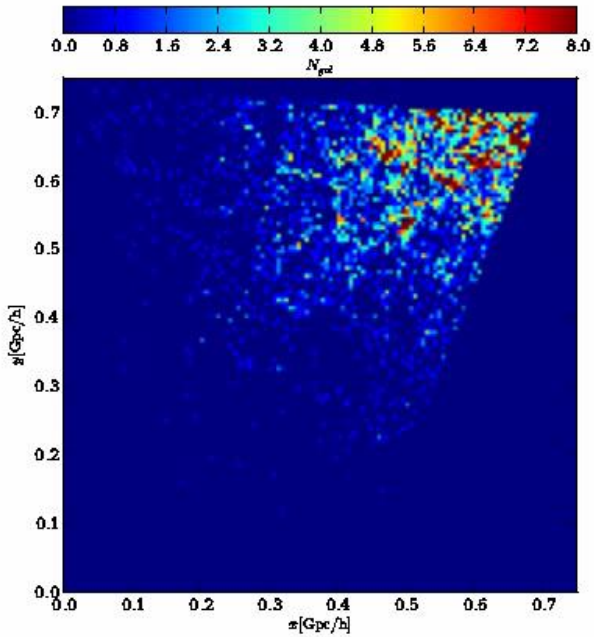
BORG at work



Initial conditions



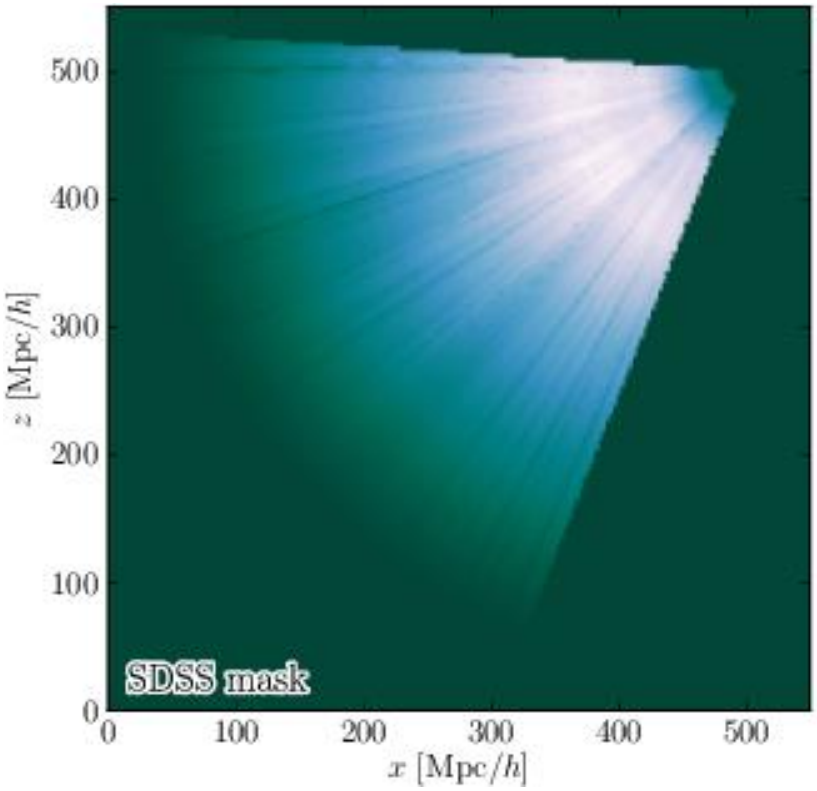
Final conditions

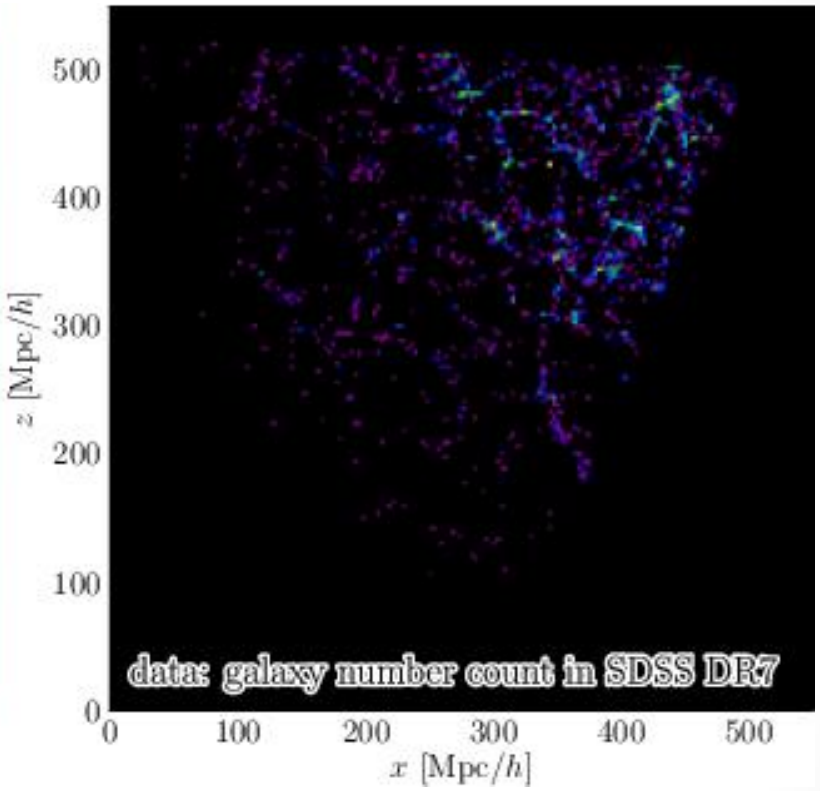


Observations

Jasche & Wandelt 2012, arXiv:1203.3639

BORG: reconstructions from SDSS DR7





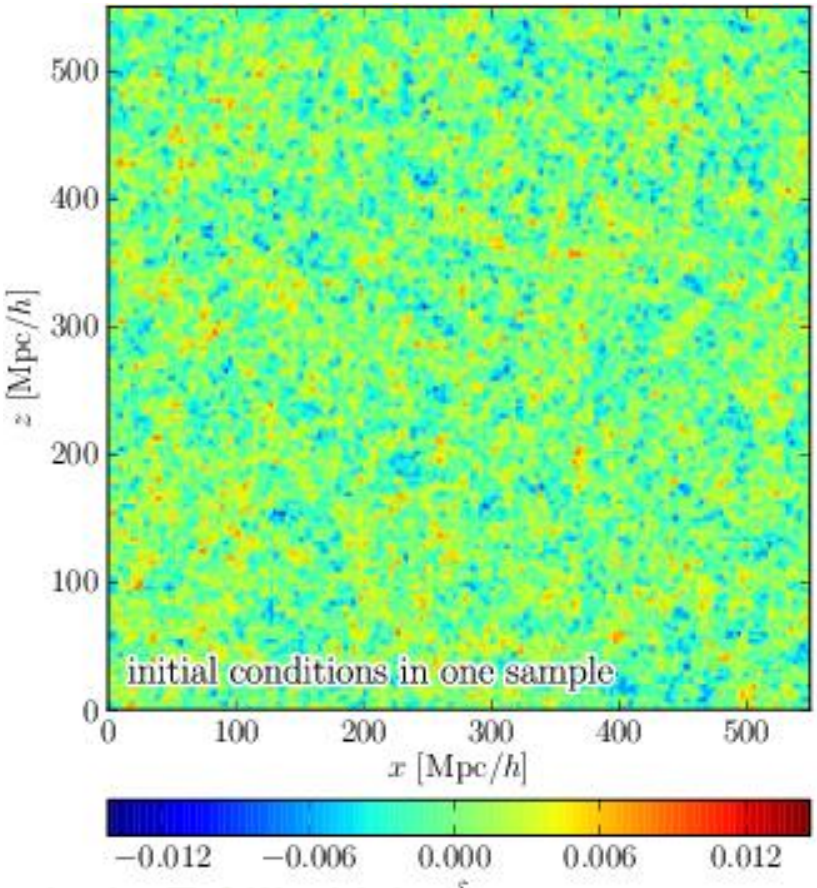
Jasche, FL & Wandelt, in prep.

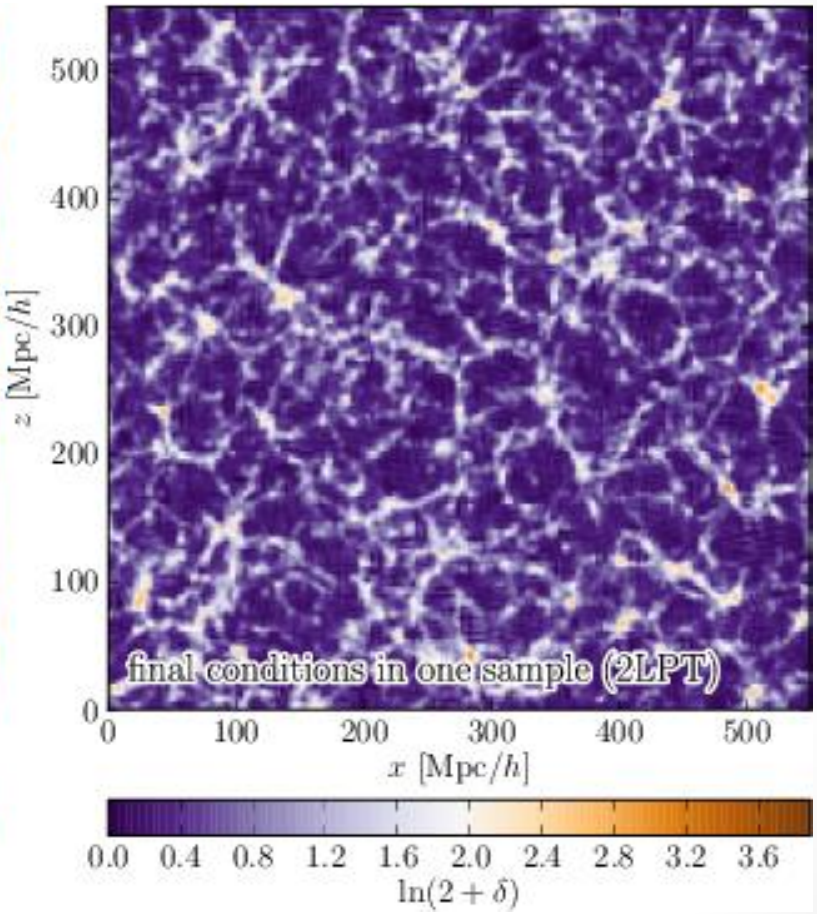
Jasche, Romano-Díaz, FL & Wandelt, in prep.

FL, Jasche & Wandelt, in prep.

Data

BORG: reconstructions from SDSS DR7





Jasche, FL & Wandelt, in prep.

Jasche, Romano-Díaz, FL & Wandelt, in prep.

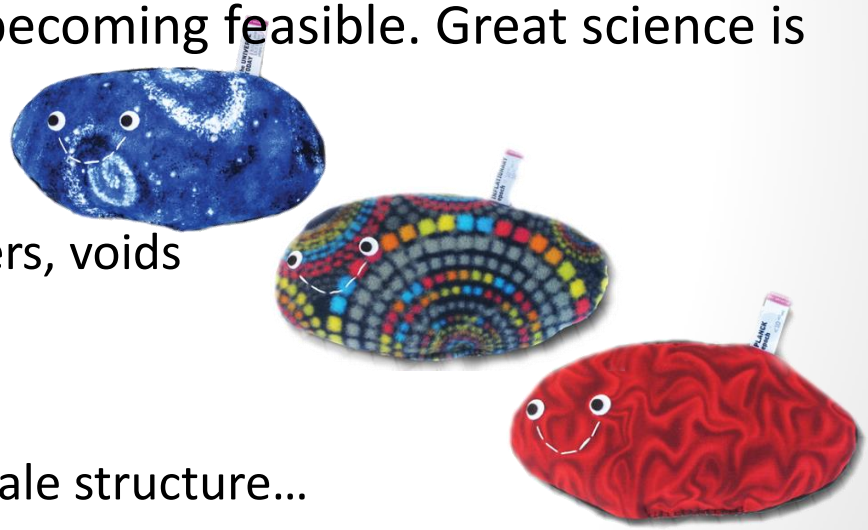
FL, Jasche & Wandelt, in prep.

One sample

Concluding thoughts

- BORG: A **non-linear time machine** using Bayesian exploration to infer primordial quantities from late-time observations

- Cosmological **physical reconstruction of the initial conditions** of the Universe is becoming feasible. Great science is waiting behind the door:
  - Galaxy environment
  - Baryon acoustic oscillations, clusters, voids
  - Primordial non-Gaussianity
  - Isocurvature perturbations
  - Gravitational waves in the large-scale structure…



Don't fight non-linearity to get cosmological information – embrace it!