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

Florent Leclercq

Institut d'Astrophysique de Paris & École polytechnique ParisTech

November 9th, 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)

# 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.

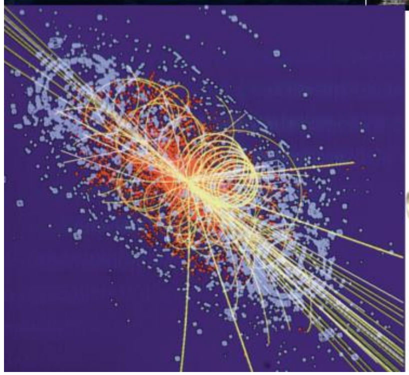
# Cosmostatistics of the initial conditions

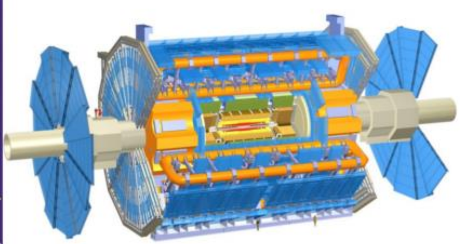
- **"Initial conditions"**: ICs for *gravitational evolution*…
  AFTER inflation
  AFTER Hot Big Bang phenomena

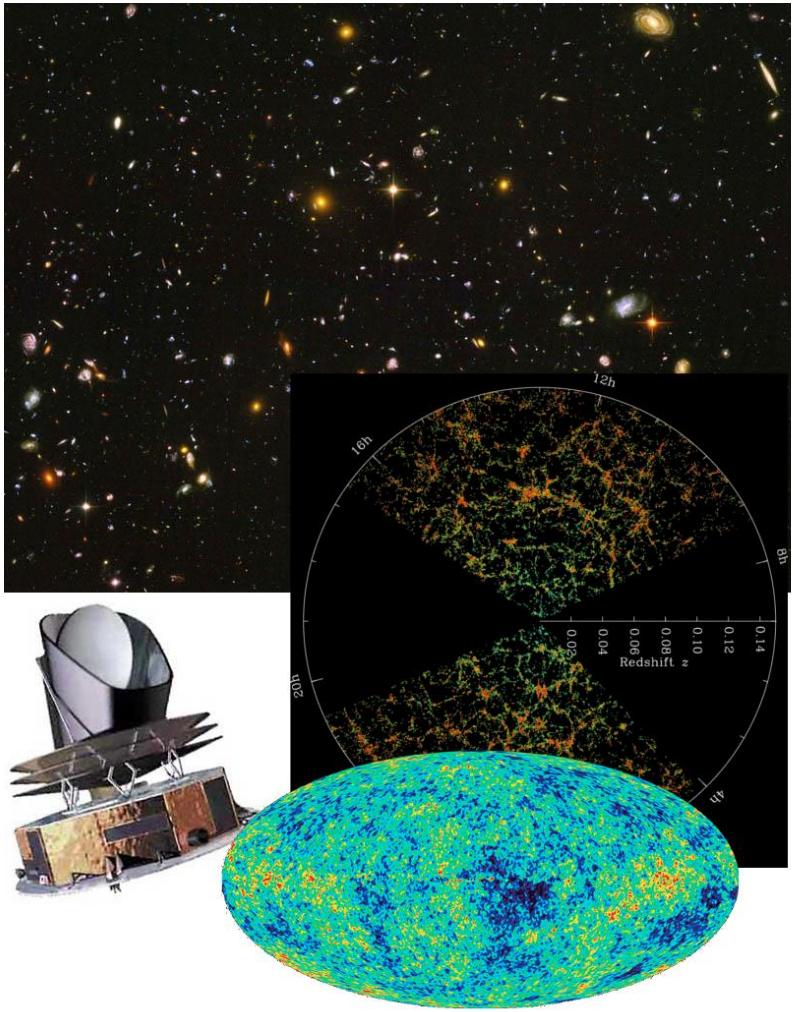
(*primordial nucleosynthesis, decoupling, recombination, free-streaming of neutrinos, acoustic oscillations of the photon-baryon plasma, transition from radiation to matter dominated universe)*

- **Cosmostatistics**: discipline 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**

# High-energy physics experiments

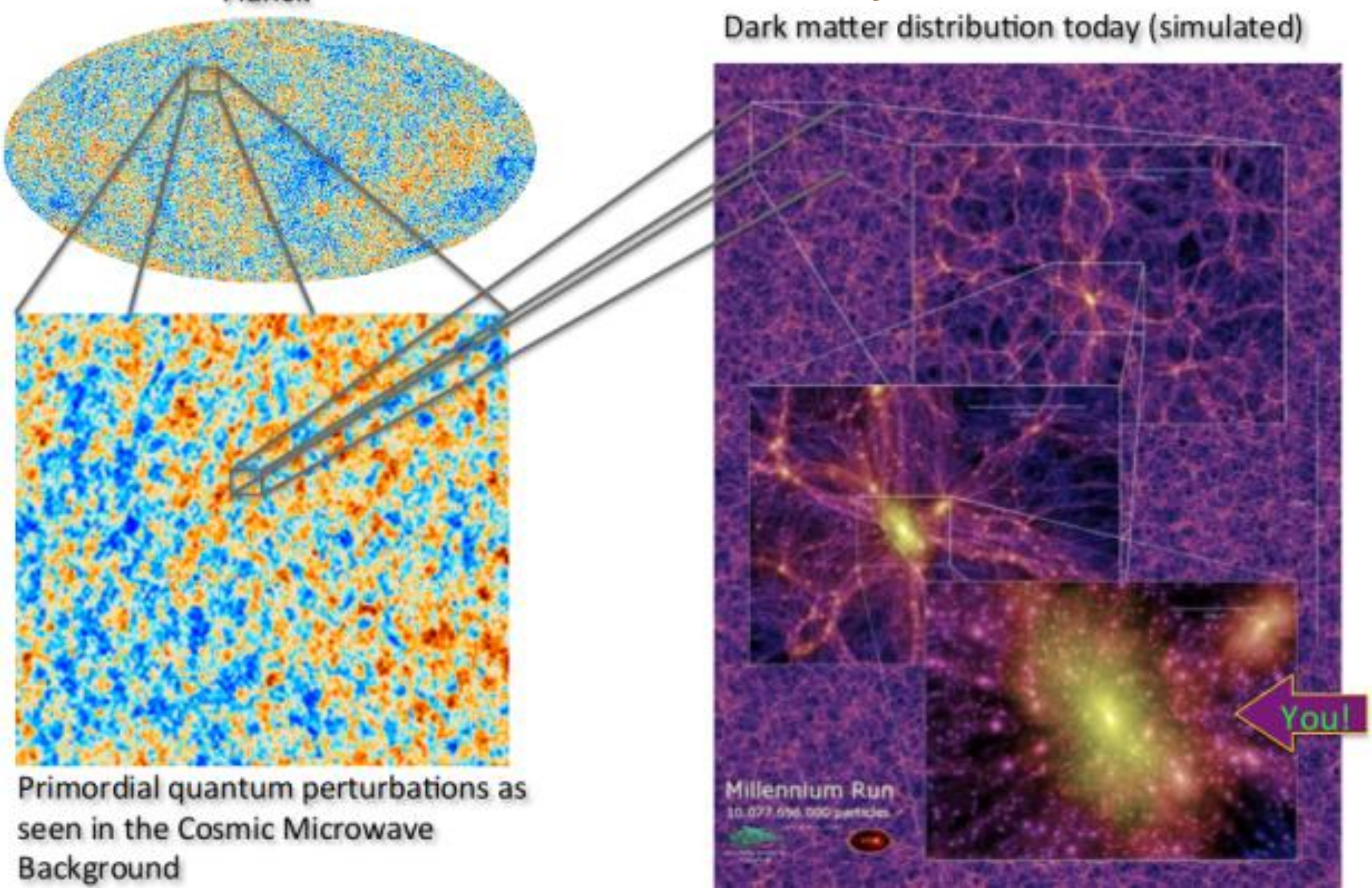




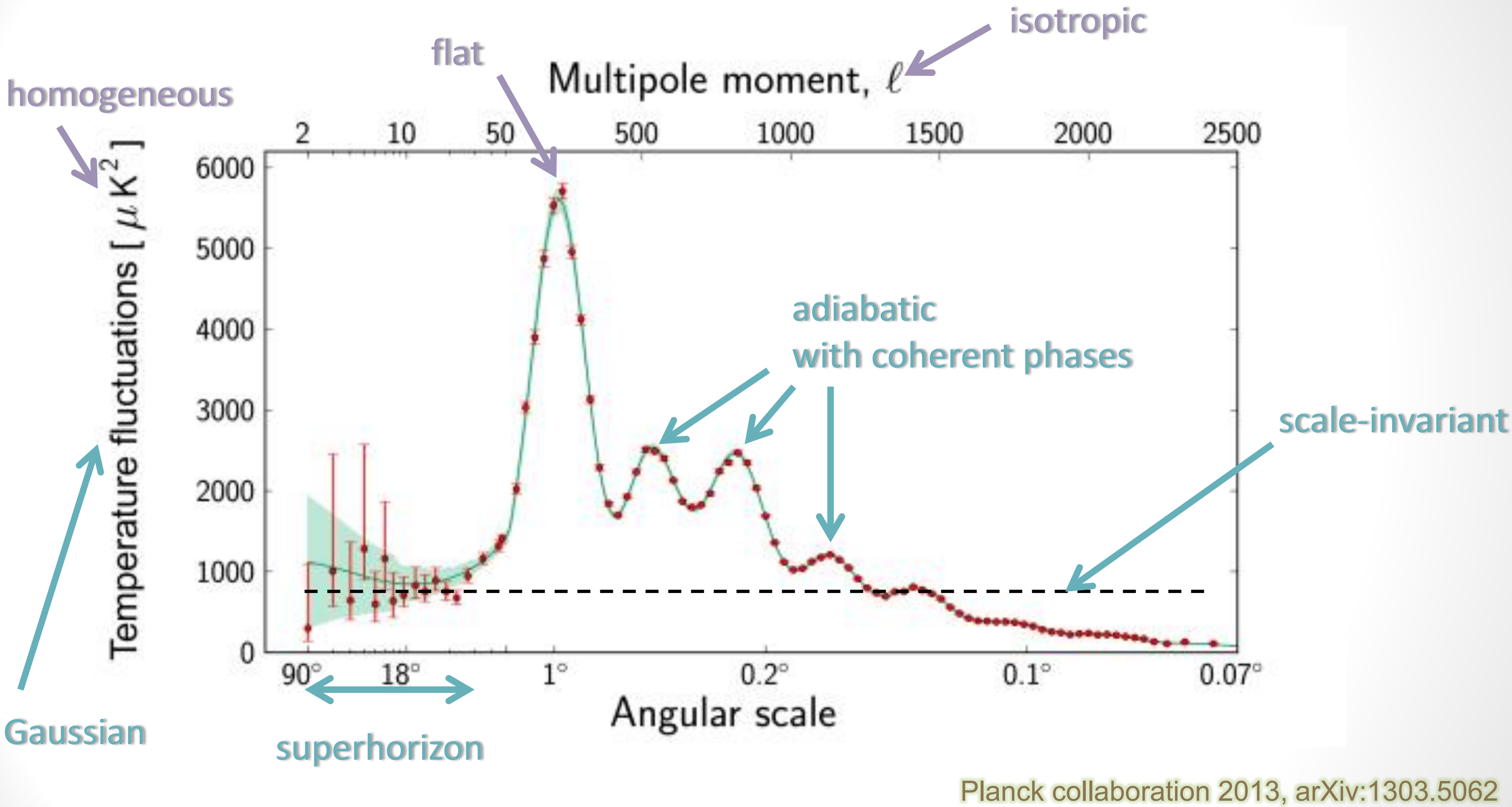
# The inhomogeneous Universe:
# the big picture

*You are here, make the best of it…*

Planck



# The most boring Universe?




- **Phenomenologically**, inflation is a great success…

# The case for physical reconstruction of the ICs

- … but what is the microphysics of inflation?

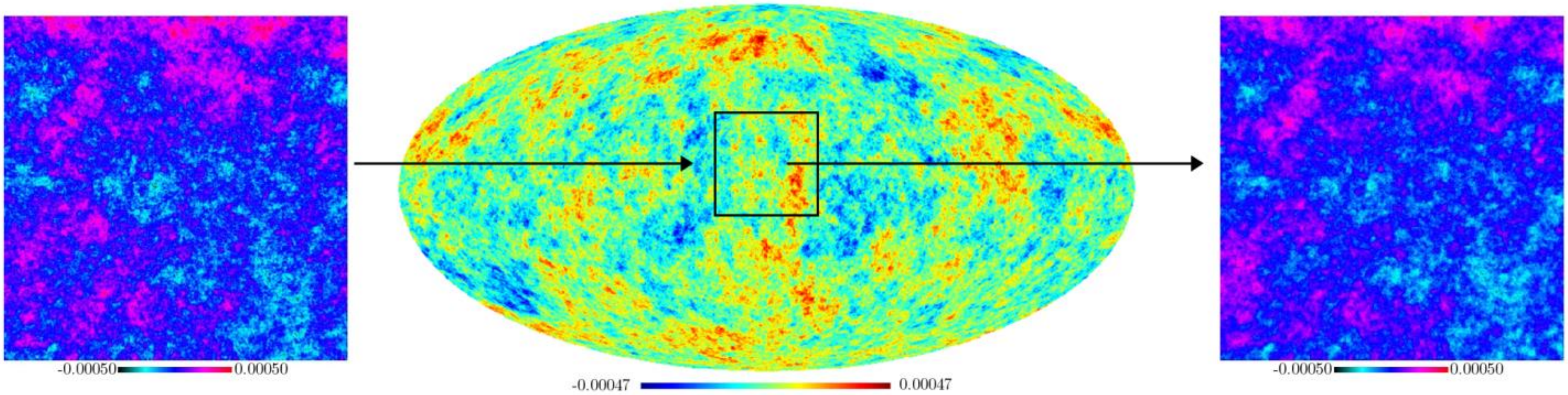
- Some challenges:
  - The eta problem: scale-invariant, superhorizon fluctuations require
    $$\eta = M_{\mathrm{Pl}}^2 \frac{V''}{V} = \frac{m_\phi^2}{3H^2} \ll 1$$
    How to achieve and stabilize this mass hierachy?
  - Large-field inflation: observational gravitational waves require
    $$r \geq 0.01 \longleftrightarrow \Delta\phi \gg M_{\mathrm{Pl}}$$
    *(Lyth bound)*

    **Astrophysics** — **Quantum gravity**

- Some open questions: *multi-field inflation? non-standard kinetic term? periods of fast-roll? non-trivial pre-inflationary state? non-Bunch-Davies vacuum?*

# The CMB time-machine

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




Input gravitational potential

CMB

Reconstruction of the gravitational potential

adapted from Elsner & Wandelt 2009, arXiv:0909.0009

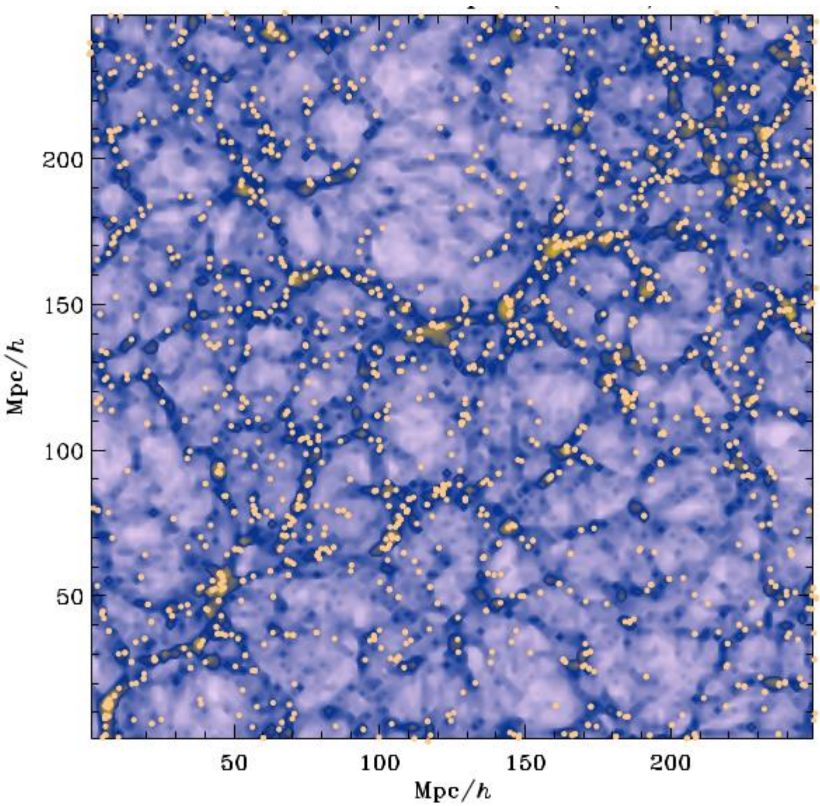
Komatsu, Spergel & Wandelt 2005, arXiv:astro-ph/0305189

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, proceedings to appear soon

# A large-scale structure in the Universe




Blue: matter distribution
Orange: dark matter halos / galaxies

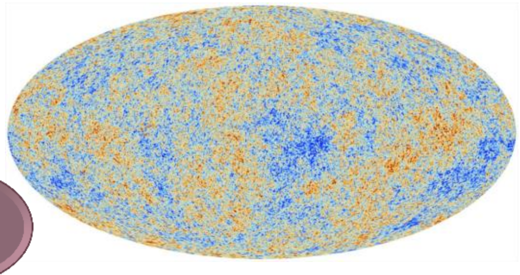
- Halos trace mass distribution (of *dark matter*).
- Halos are NOT randomly distributed: there exists a Large Scale Structure of the Universe
- How do we analyze this structure quantitatively?

Correlation functions and Fourier analysis

# Reconstruction of the initial conditions…

- … a solved problem !
- And…

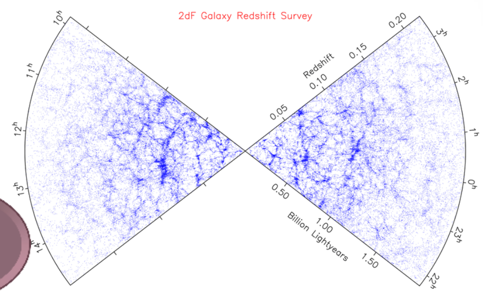
CMB:



2D

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

LSS:



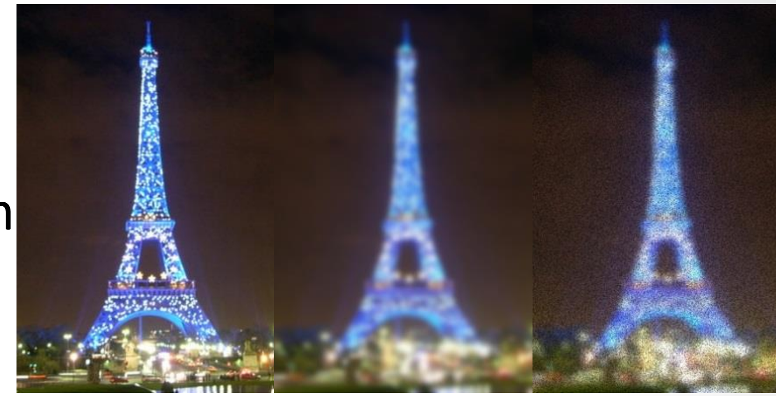

3D

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

- 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?

# Bayesian inference of the ICs

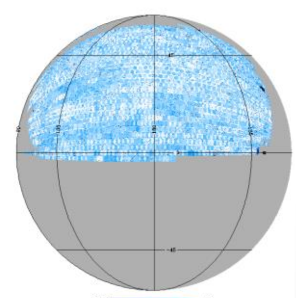


- Why do we need Bayesian inference?

  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?"



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

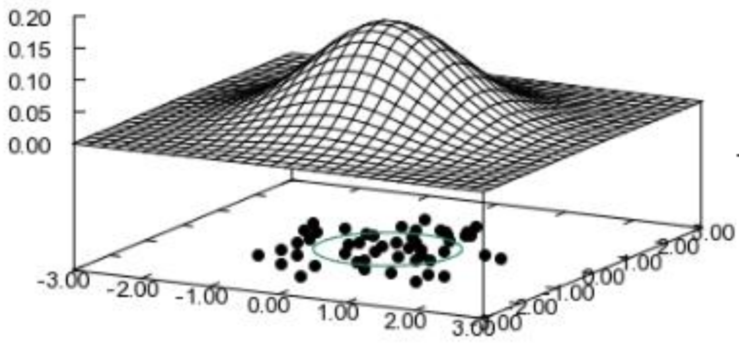
from J. Jasche

# Bayesian inference of the ICs

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

➡ No reduction of the problem size is possible!

  - Complex posterior distribution
- Numerical approximation: for dim > 4: sampling the posterior distribution



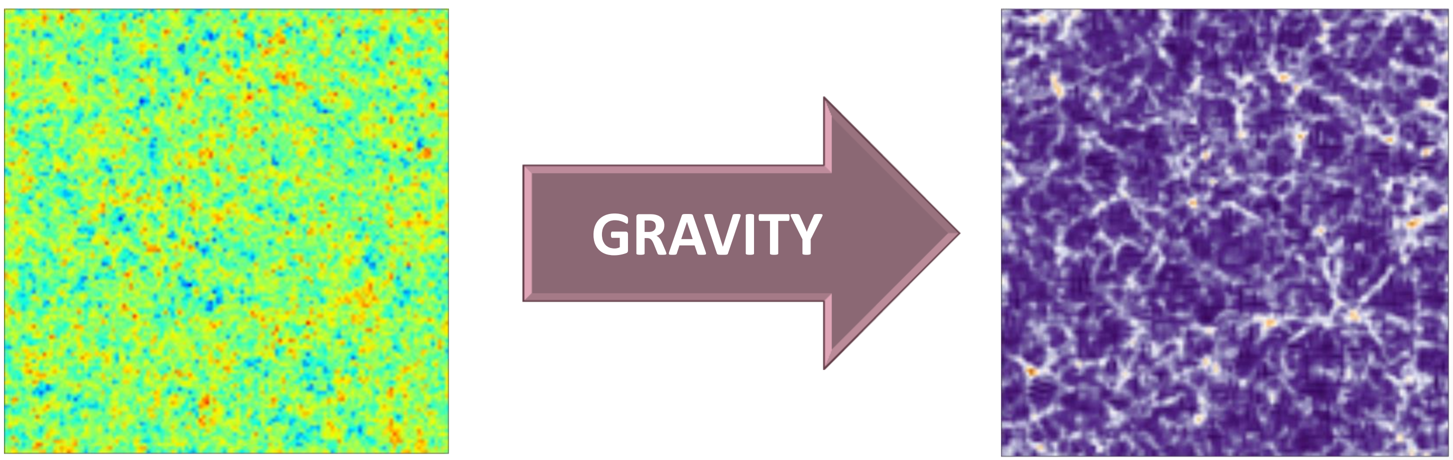

$$p(s|d) \rightarrow p_N(s|d) = \frac{1}{N}\sum_{i=1}^{N} \delta_{\mathrm{D}}(s - s_i)$$

- But how to "get the dots" ?

from J. Jasche

# 4D 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

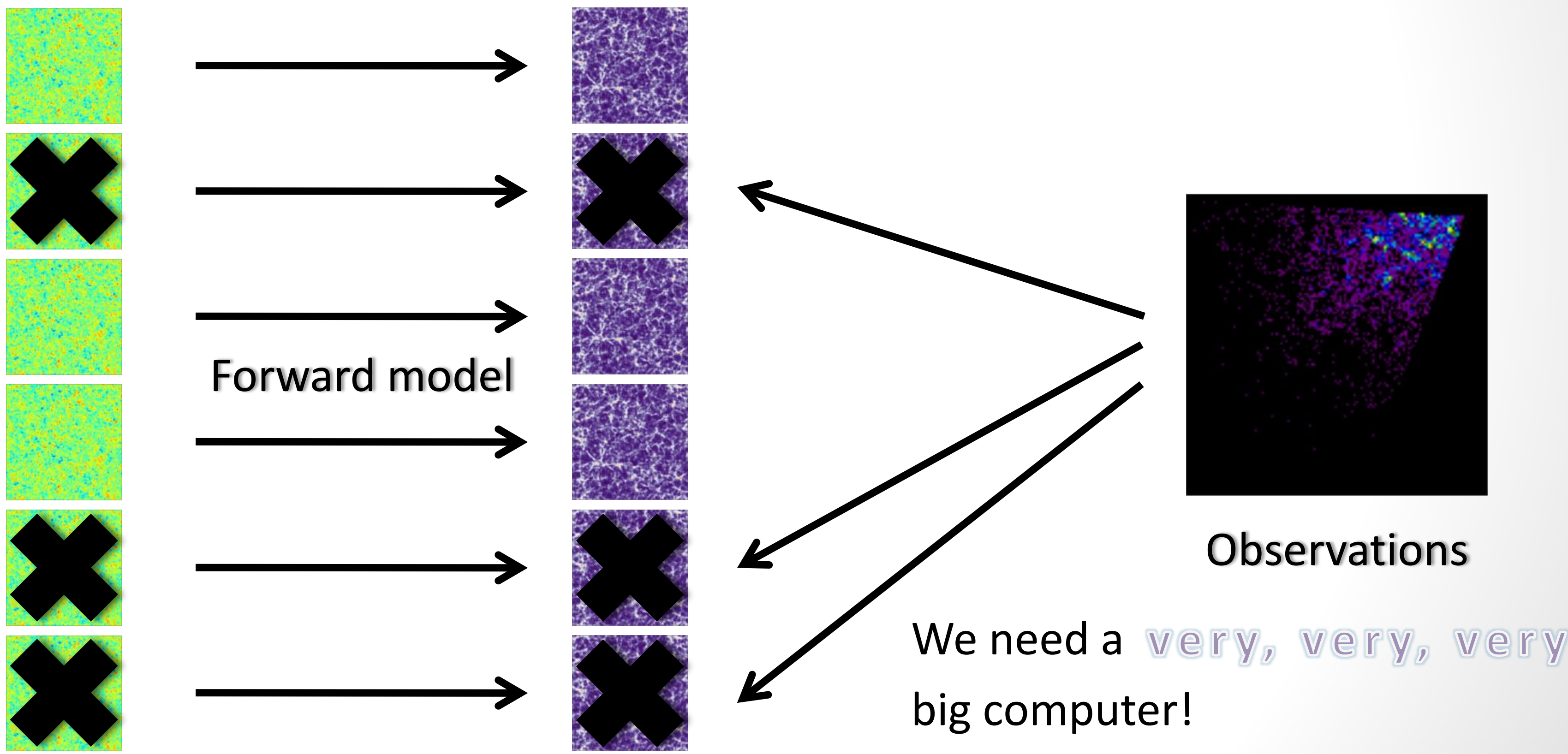
Final state

from J. Jasche

# 4D physical inference of the ICs

- The ideal scenario:

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




Every possible ICs

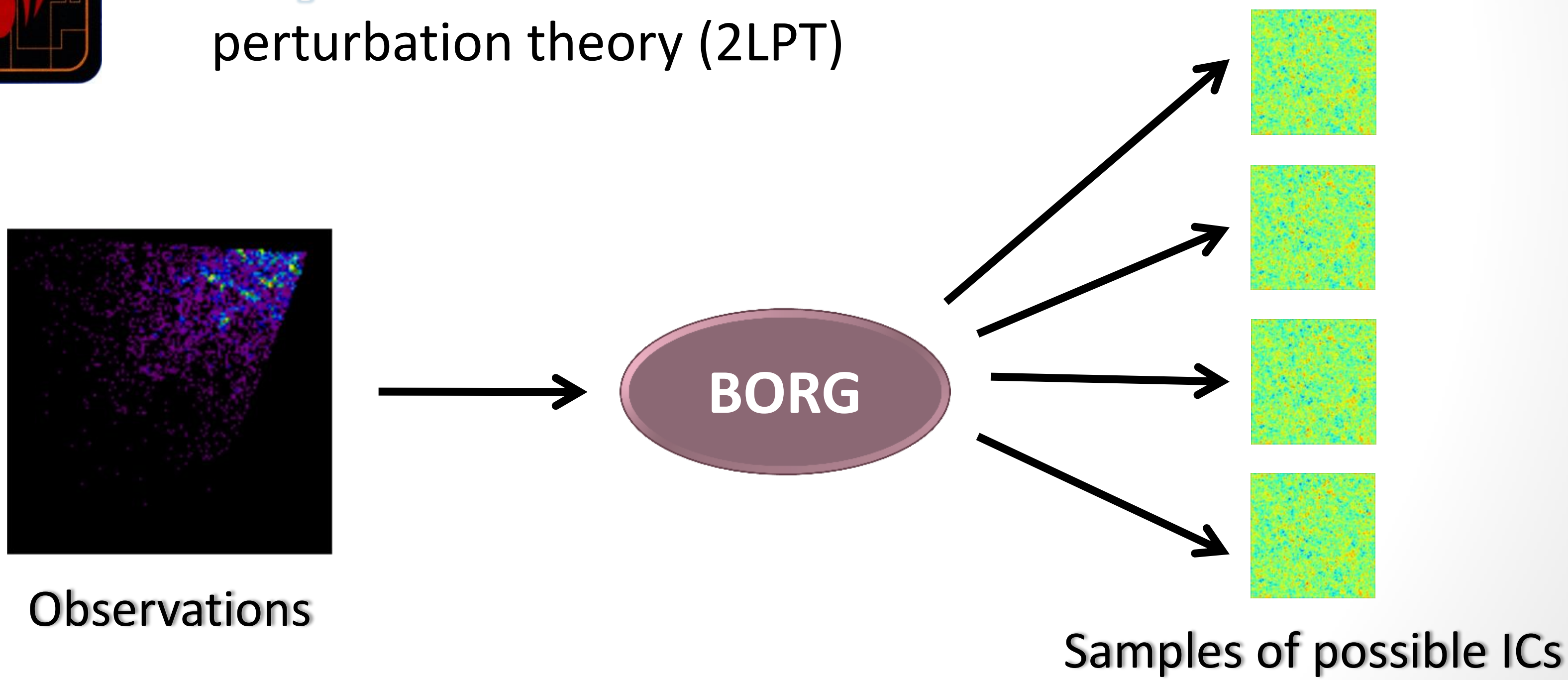
Every possible FCs

from J. Jasche

# BORG: *Bayesian Origin Reconstruction from Galaxies*

What makes the problem tractable:

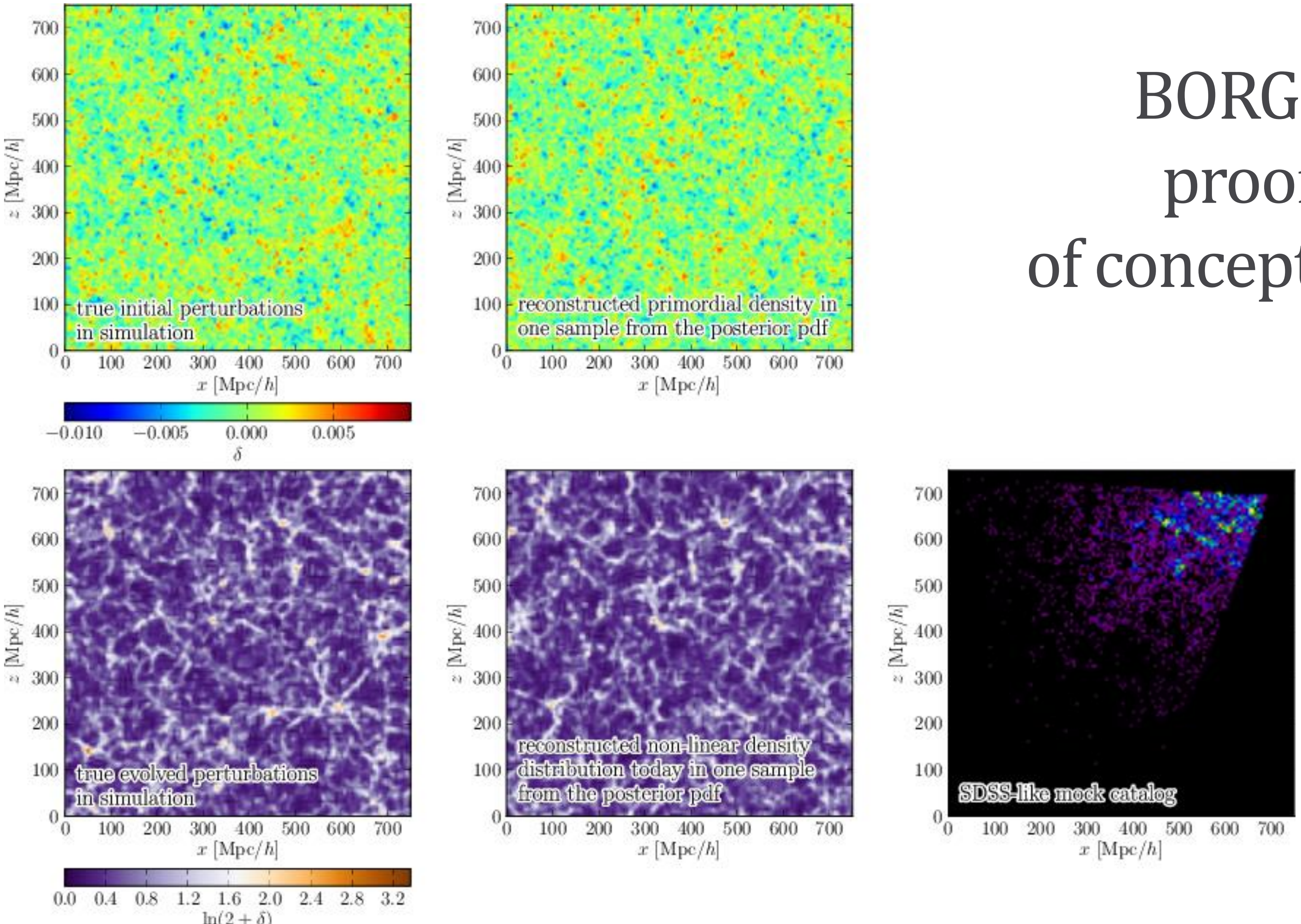
- **Sampler**: Hamiltonian Markov Chain Monte Carlo method
- **Physical model**: Second-order Lagrangian perturbation theory (2LPT)




Jasche & Wandelt 2012, arXiv:1203.3639

from J. Jasche

# BORG: proof of concept




adapted from Jasche & Wandelt 2012, arXiv:1203.3639

# Samples of the posterior density

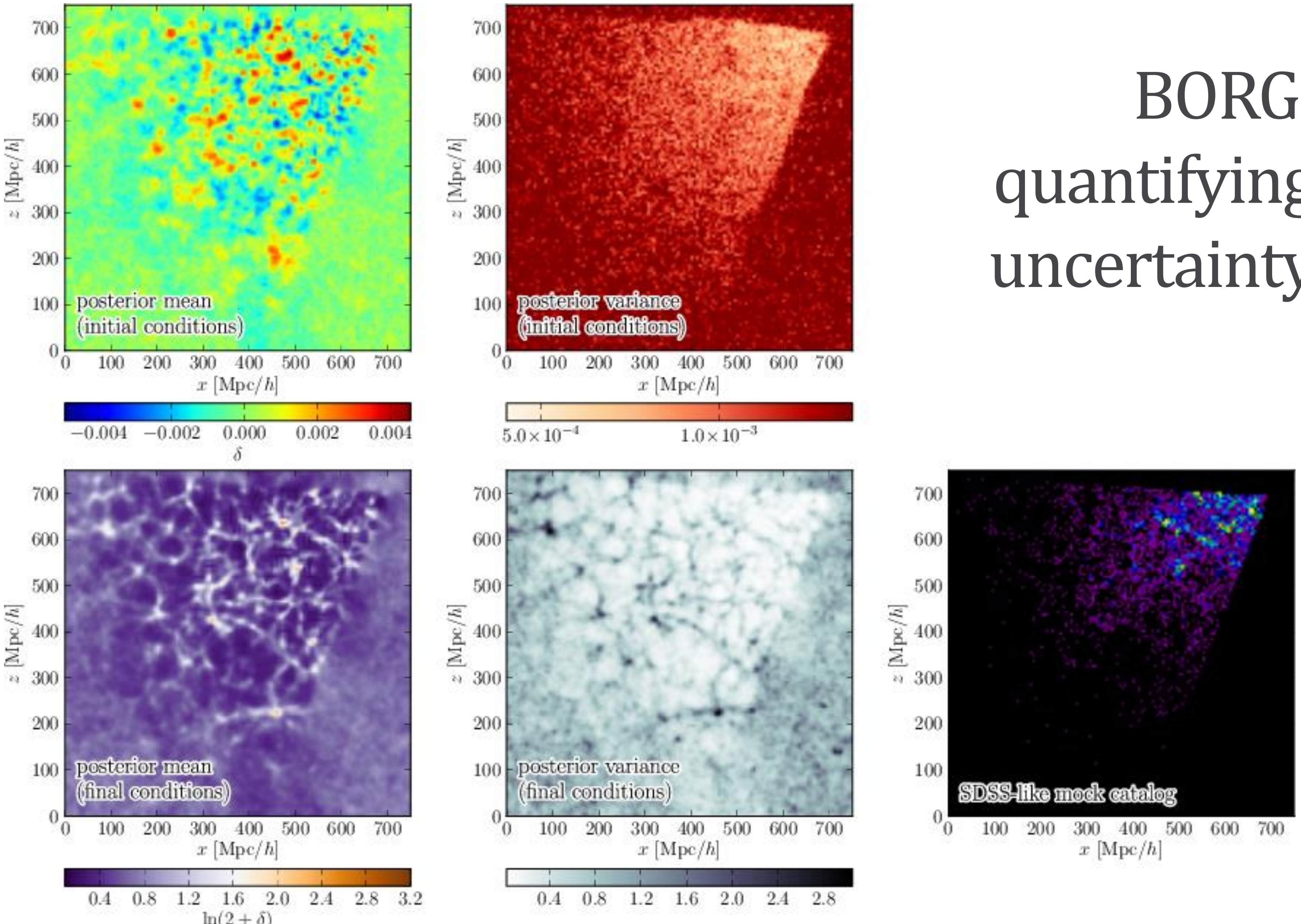
- Each sample: a **possible version of the truth**

- 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…)

- By the way… Bayesian probability theory deals with uncertainty **independently of its origin**

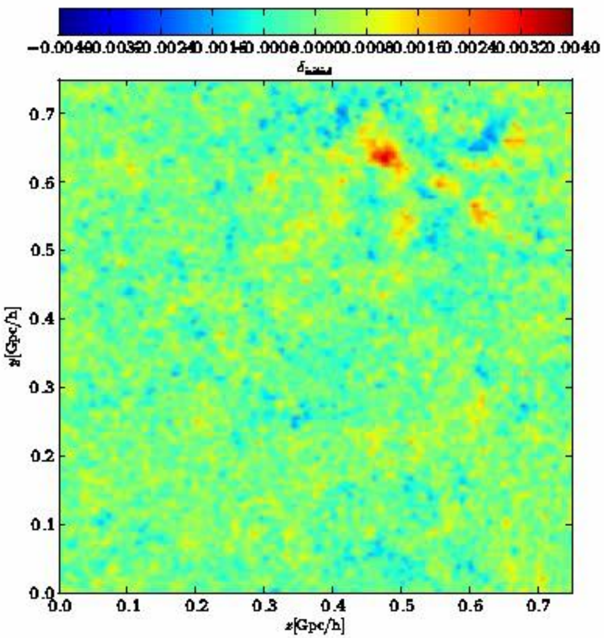
see also FL, Pisani & Wandelt, proceedings to appear soon

# BORG: quantifying uncertainty

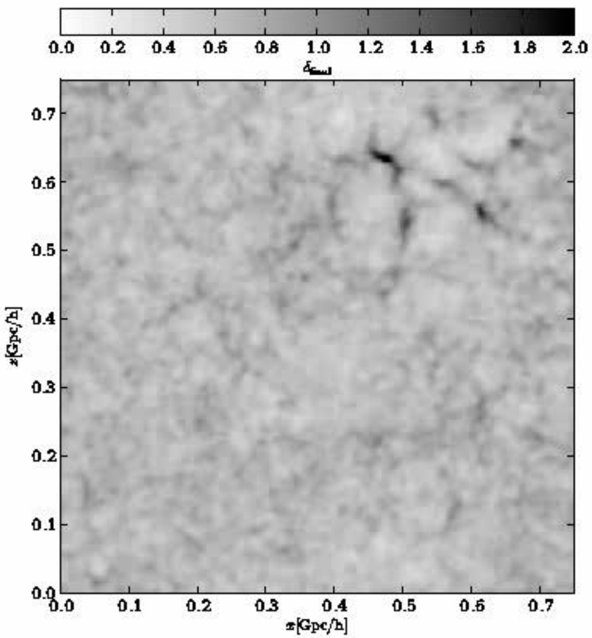



adapted from Jasche & Wandelt 2012, arXiv:1203.3639

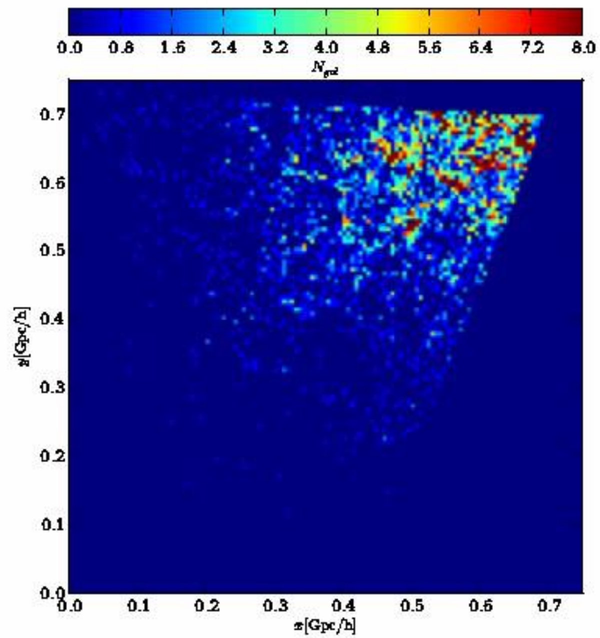
# BORG at work




Initial conditions




Final conditions




Observations

Jasche & Wandelt 2012, arXiv:1203.3639

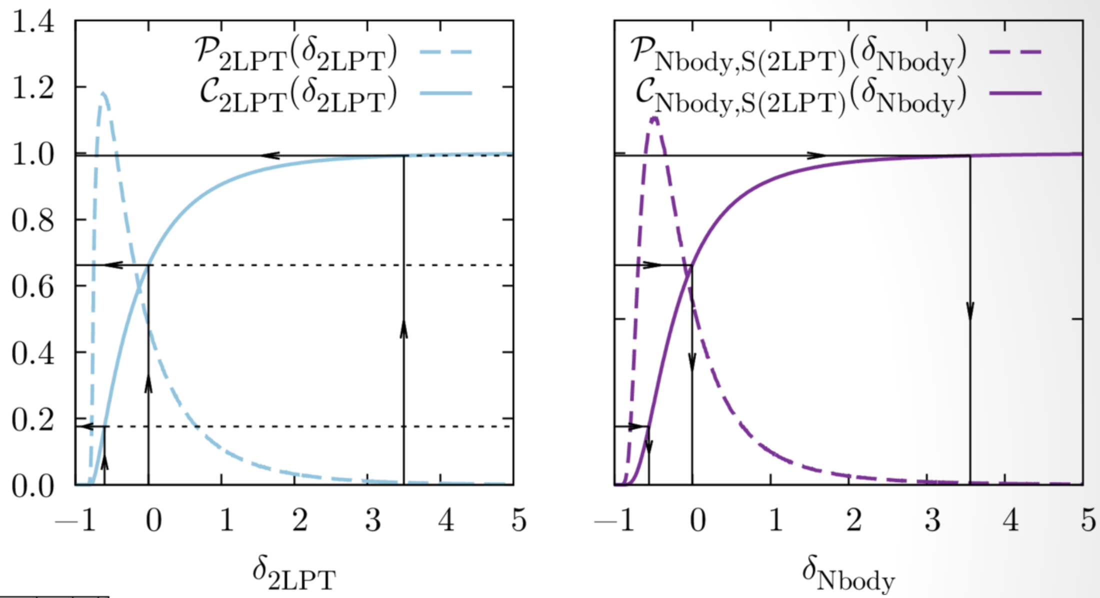
# Aside: beyond 2LPT?

- 2LPT breaks down at small scales.
- Recall the number of usable modes goes like $k^3$.
- Even small improvements yield a wealth of yet unexploited cosmological information (in existing surveys!).
- We need numerically efficient and flexible tools to model cosmic structure formation in the non-linear regime.

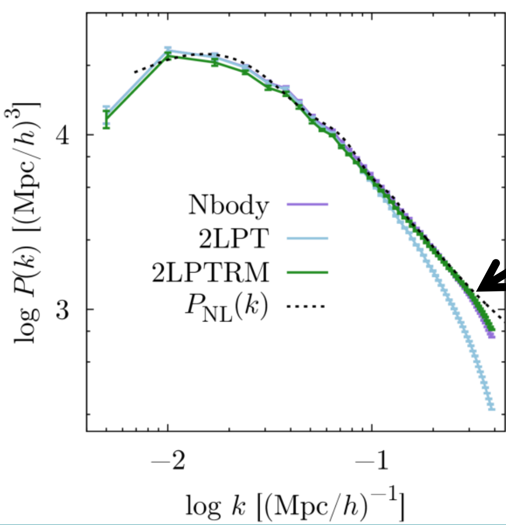
# Remapping 2LPT in the mildly non-linear regime

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

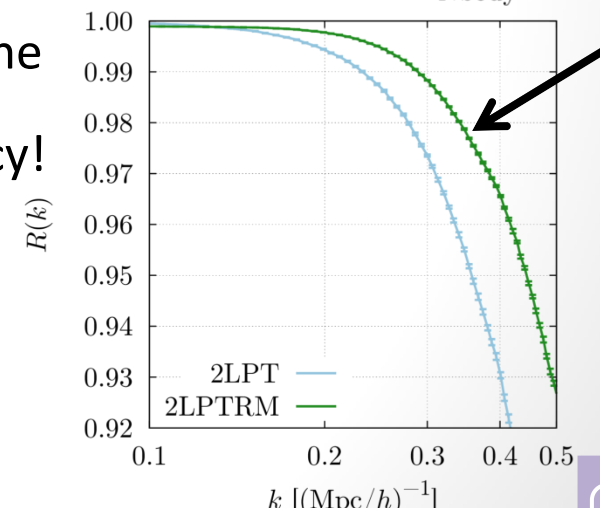
- Replacing the one-point distribution of 2LPT by one which accounts for the full non-linear system…




- …also improves the higher-order correlators…




- …and the phase accuracy!



# COLA: *COmoving Lagrangian Acceleration*

- Write the displacement vector as: $\mathbf{s} = \mathbf{s}_{\mathrm{LPT}} + \mathbf{s}_{\mathrm{MC}}$

Tassev & Zaldarriaga 2012, arXiv:1203.5785

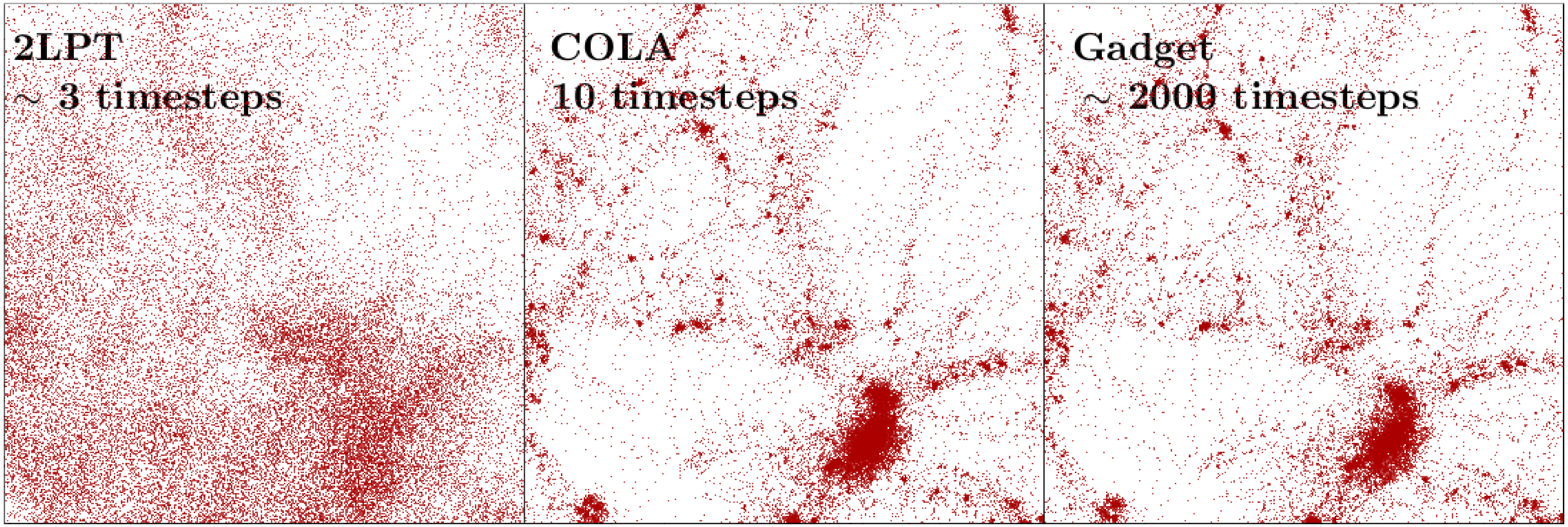
- Time-stepping (omitted constants and Hubble expansion):

Standard:

$$\partial_\tau^2 \mathbf{s} = -\nabla\Phi$$

Modified:

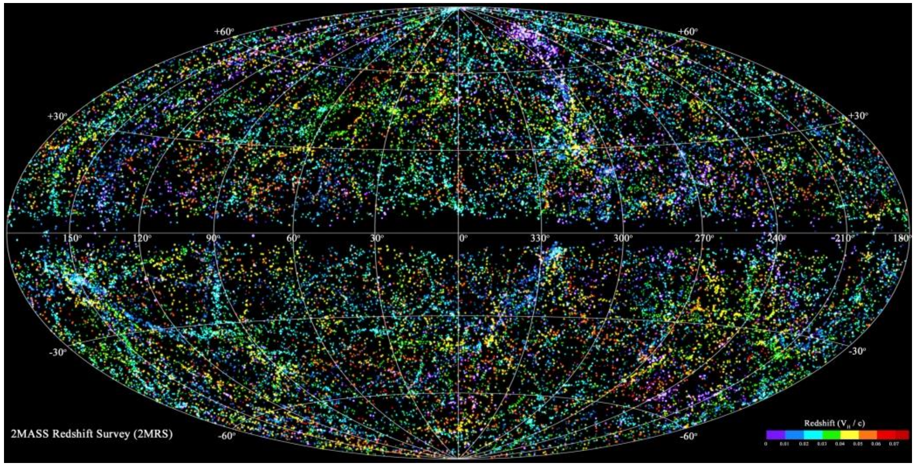
$$\partial_\tau^2 \mathbf{s}_{\mathrm{MC}} = \partial_\tau^2(\mathbf{s} - \mathbf{s}_{\mathrm{LPT}}) = -\nabla\Phi - \partial_\tau^2 \mathbf{s}_{\mathrm{LPT}}$$




Tassev, Zaldarriaga & Einsenstein 2013, arXiv:1301.0322

# Back to BORG

- What about the real Universe?




  - Reconstruction of the initial conditions from SDSS DR7

    Jasche, FL & Wandelt, in prep.

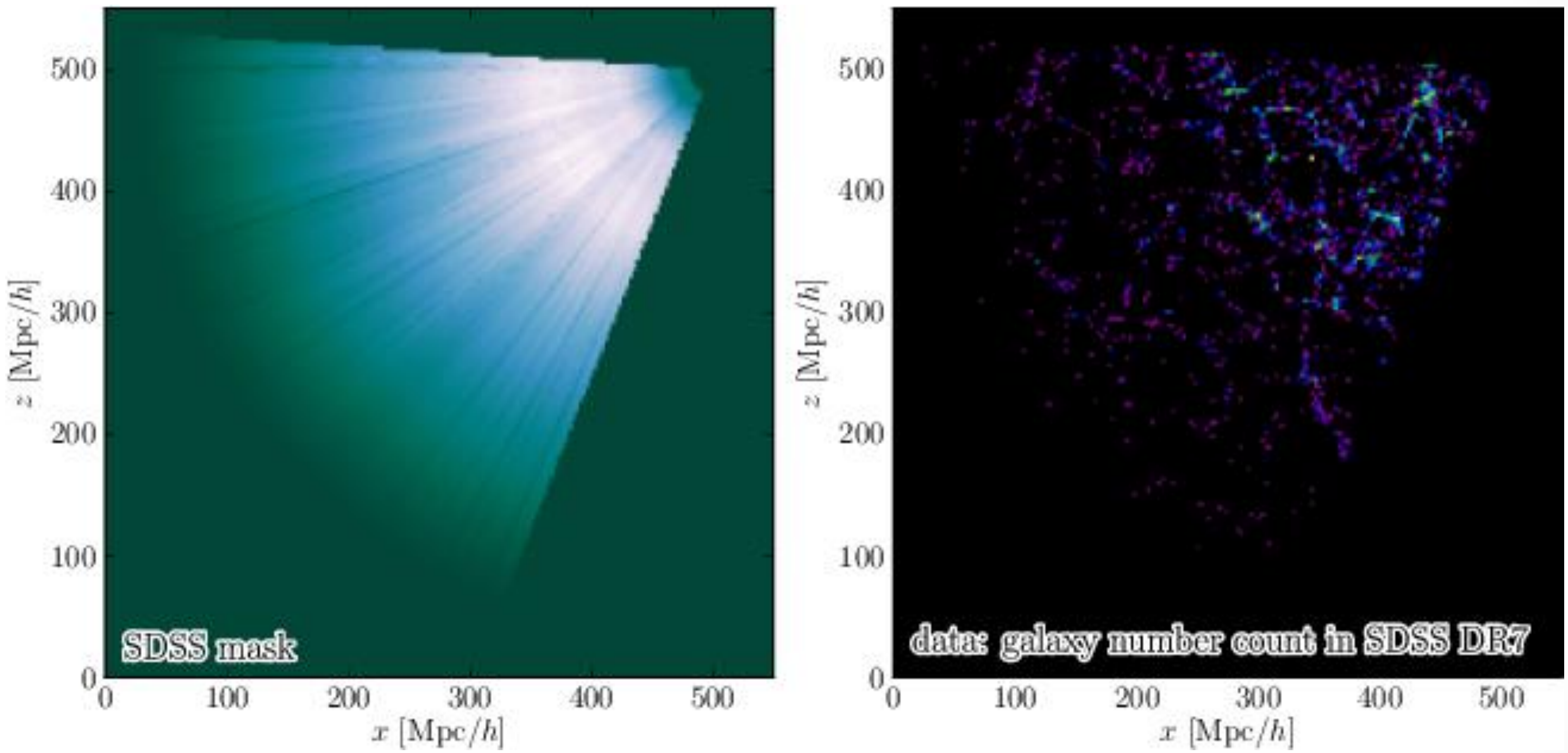
  - Resimulation of the late-time Universe from these ICs

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

  - Optimizing an ensemble of constrained simulations to probe the non-linear regime

    FL, Jasche & Wandelt, in prep.

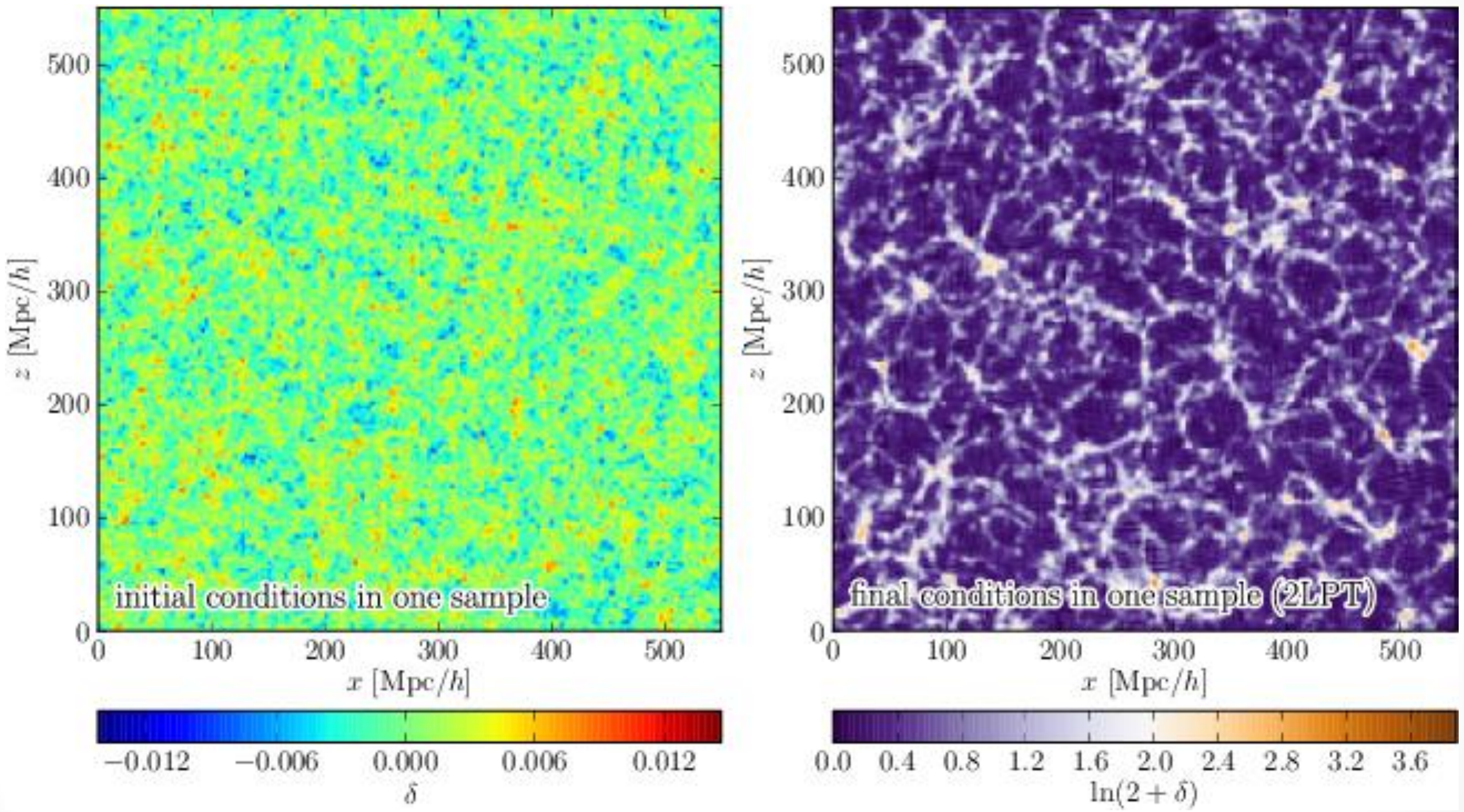
# BORG: reconstructions from SDSS DR7




Data

Jasche, FL & Wandelt, in prep.

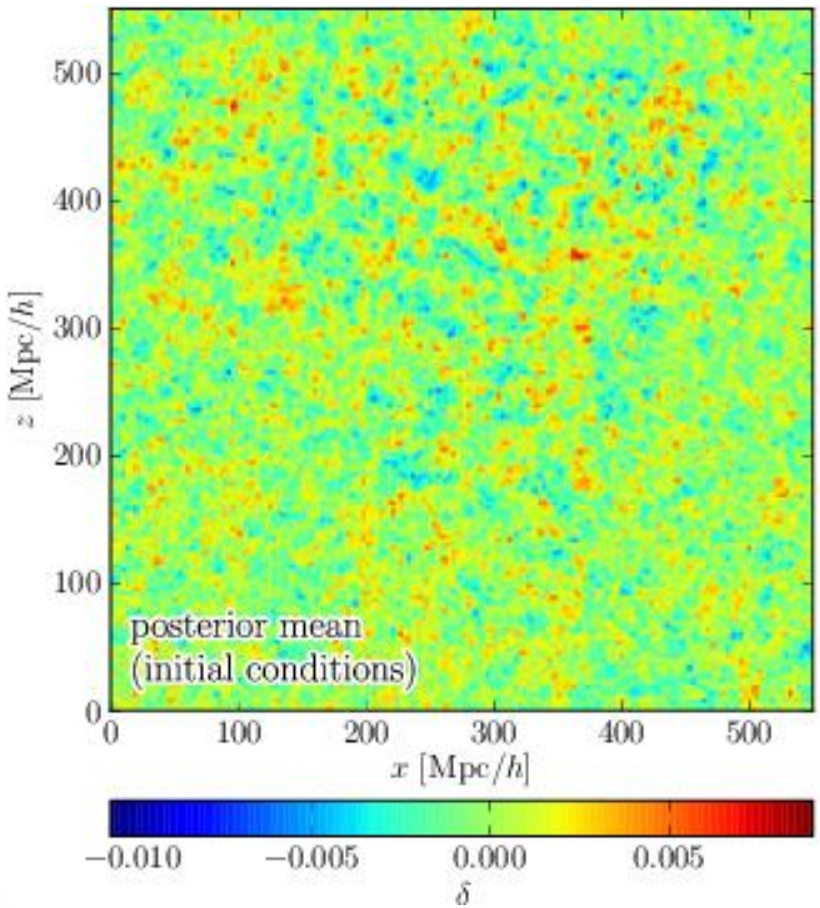
# BORG: reconstructions from SDSS DR7

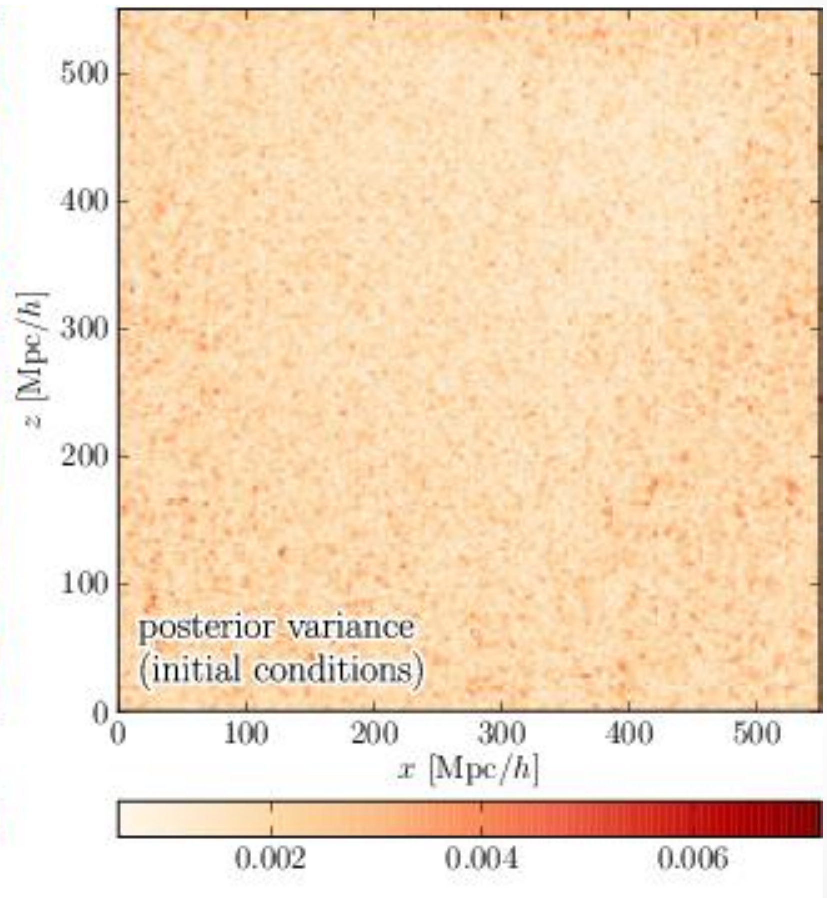



One sample

Jasche, FL & Wandelt, in prep.

# BORG: reconstructions from SDSS DR7

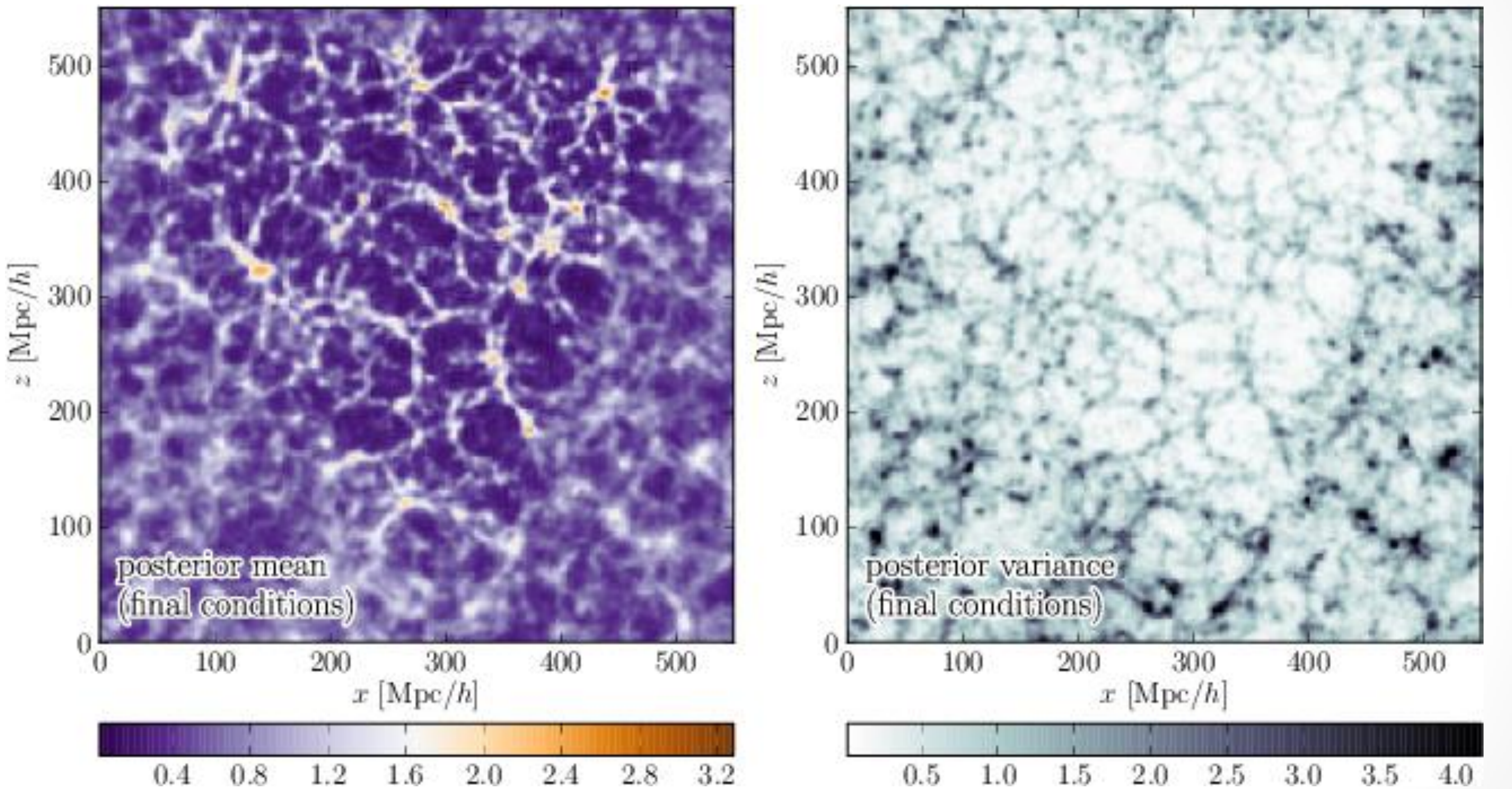



Quantifying uncertainty in the ICs

Jasche, FL & Wandelt, in prep.

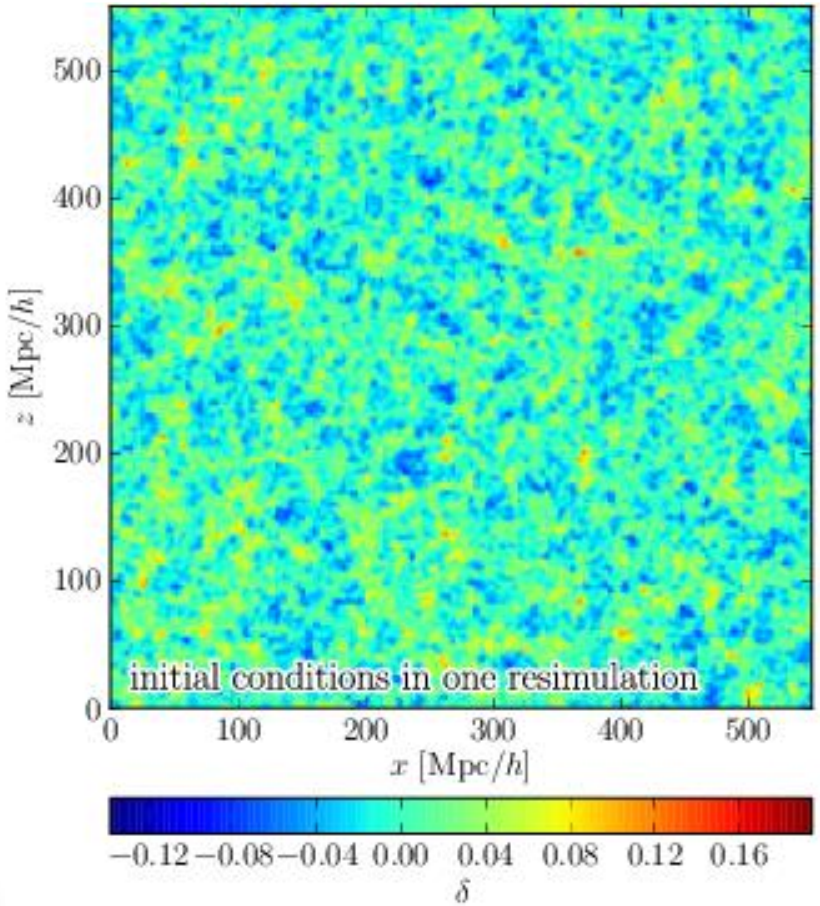
# BORG: reconstructions from SDSS DR7

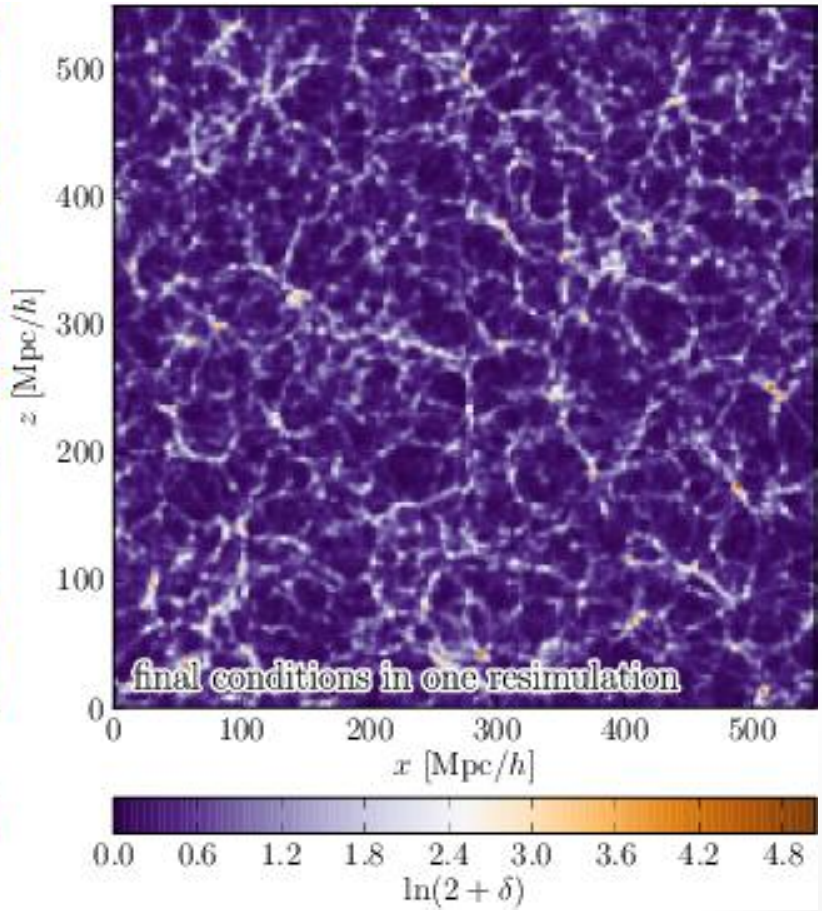



Quantifying uncertainty in the FCs

Jasche, FL & Wandelt, in prep.

# BORG: resimulating the Universe




Resimulation of one sample

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

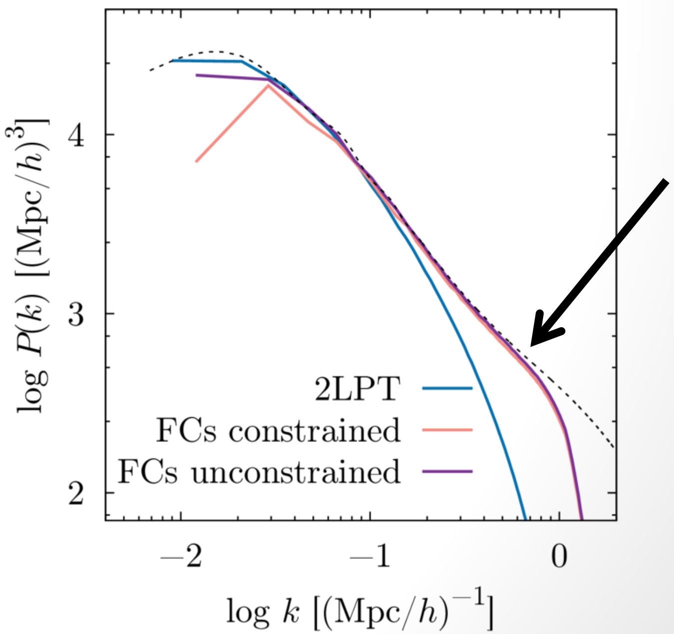
# BORG: resimulating the Universe

- A dynamic physical model naturally introduces some correlations between the constrained and unconstrained parts
- Constrained resimulations act as hypothesis generating machines, whose predictions can be tested with complementary observations in the actual sky.

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

- With a full N-body simulation, we address the non-linear regime of structure formation!

more on non-linear reconstruction of the ICs in FL, Jasche & Wandelt, in prep.




see also:

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

Tassev, Zaldarriaga & Einsenstein 2013, arXiv:1301.0322

# Concluding thoughts

- BORG: A **non-linear time machine** using Bayesian posterior exploration to infer primordial quantities from late-time observations
- Need for **efficient tools to model cosmic structure formation** the non-linear regime
- Cosmological **physical reconstruction of the initial conditions** of the Universe is becoming feasible. Great science is waiting behind the door:
  - Baryon acoustic oscillations, clusters, voids
  - Non-Gaussianity
  - Isocurvature perturbations
  - Gravitational waves in the large-scale structure…

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