# Bayesian chrono-cosmography


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September 3rd, 2014

J. Jasche, F. Leclercq, B. Wandelt, in prep.
*Bayesian chrono-cosmography with the SDSS DR7 main sample*

F. Leclercq, J. Jasche, P. M. Sutter, N. Hamaus, B. Wandelt, in prep.
*Constrained catalogs of dark matter voids in the SDSS galaxy survey*

F. Leclercq, J. Jasche, J. Chevallard, B. Wandelt, in prep.
*Bayesian identification of structure types in the SDSS and their relations with galaxies*

# How did structure appear in the Universe?

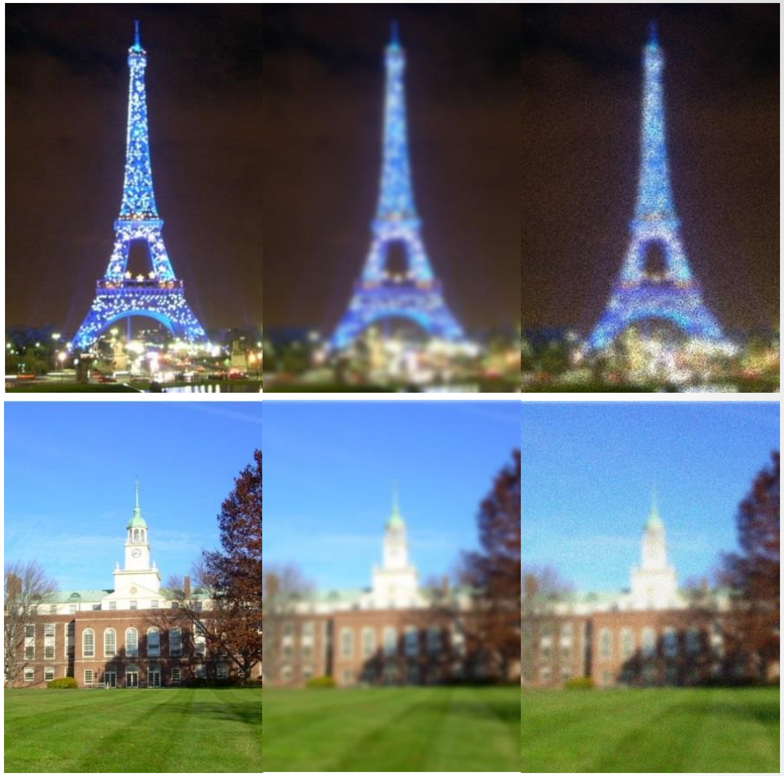
## A joint problem!

- **How did the Universe begin?**
  - What are the statistical properties of the initial conditions?
- **How did the large-scale structure take shape?**
  - What is the physics of dark matter and dark energy?
- Usually these problems are addressed in isolation.
- This talk:
  - A case for physical inference of four-dimensional dynamic states
  - A description of methodology and progress towards enriching the standard for analysis of galaxy surveys
  - From theory to data, from data to theory

FL, Pisani & Wandelt 2014, arXiv:1403.1260

(Lectures Varenna 2013 and
Paris École Doctorale for Astronomy and Astrophysics)

# 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

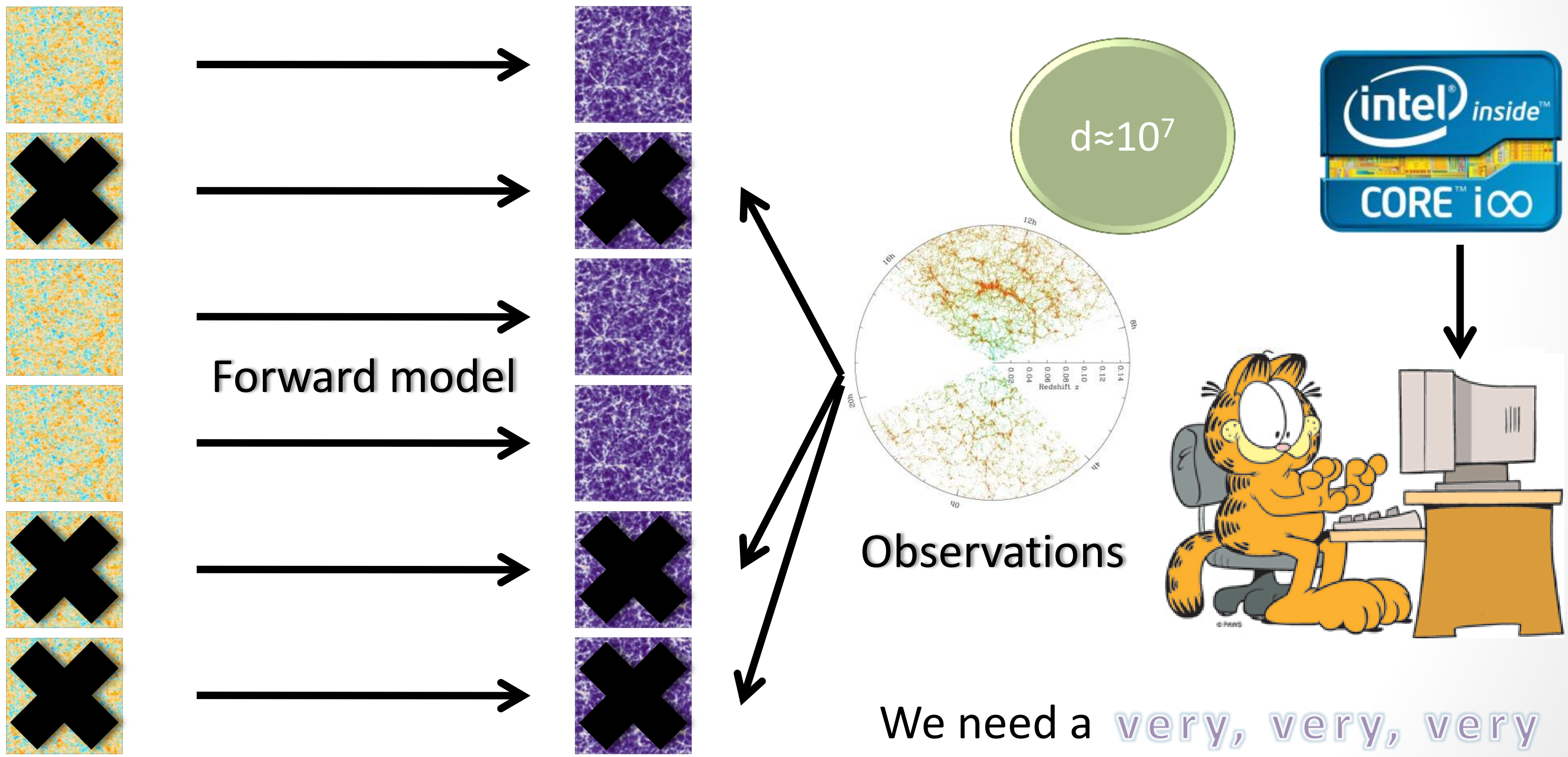
➡ **No unique recovery is possible!**

"What is the formation history of the Universe?" ➡ "What is the probability distribution of possible formation histories (signals) compatible with the observations?"

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

# Bayesian forward modeling: the ideal scenario

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



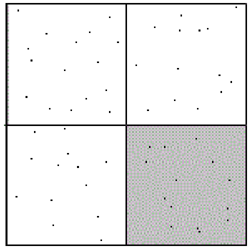

All possible ICs

All possible FCs

We need a very, very, very big computer!

# (Parameter) Space: the final frontier

- The "curse of dimensionality" Bellman 1961

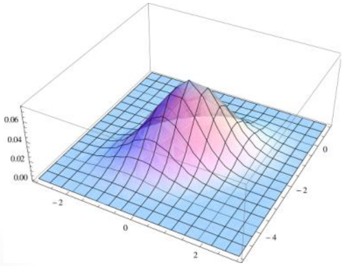


| dimension | fraction of particles in quadrant of hypercube |
|---|---|
| 1 | $2^{-1} = 0.5$ |
| 10 | $2^{-10} = 9.7 \times 10^{-4}$ |
| 100 | $2^{-100} = 7.8 \times 10^{-31}$ |
| 1000 | $2^{-1000} = 9.3 \times 10^{-302}$ |

Adding extra dimensions…

- Exponential increase of the number of particles needed for uniform sampling
- Exponential increase of sparsity given a fixed amount of particles

- High-dimensional probability distribution functions



Traditional sampling methods will fail

but gradients carry capital information

# Hamiltonian Monte Carlo

- Use classical mechanics to solve statistical problems!
  - The potential: $\psi(\mathbf{x}) \equiv -\ln(\mathcal{P}(\mathbf{x}))$
  - The Hamiltonian: $H \equiv \frac{1}{2}\mathbf{p}^T\mathbf{M}^{-1}\mathbf{p} + \psi(\mathbf{x})$

$$(\mathbf{x},\mathbf{p}) \Rightarrow \left\{ \begin{aligned} \frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} &= \frac{\partial H}{\partial \mathbf{p}} = \mathbf{M}^{-1}\mathbf{p} \\ \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} &= -\frac{\partial H}{\partial \mathbf{x}} = -\frac{\partial \psi(\mathbf{x})}{\partial \mathbf{x}} \end{aligned} \right\} \Rightarrow (\mathbf{x}',\mathbf{p}')$$

gradients

$$a(\mathbf{x}',\mathbf{x}) = \mathrm{e}^{-(H'-H)} = 1$$

acceptance ratio unity

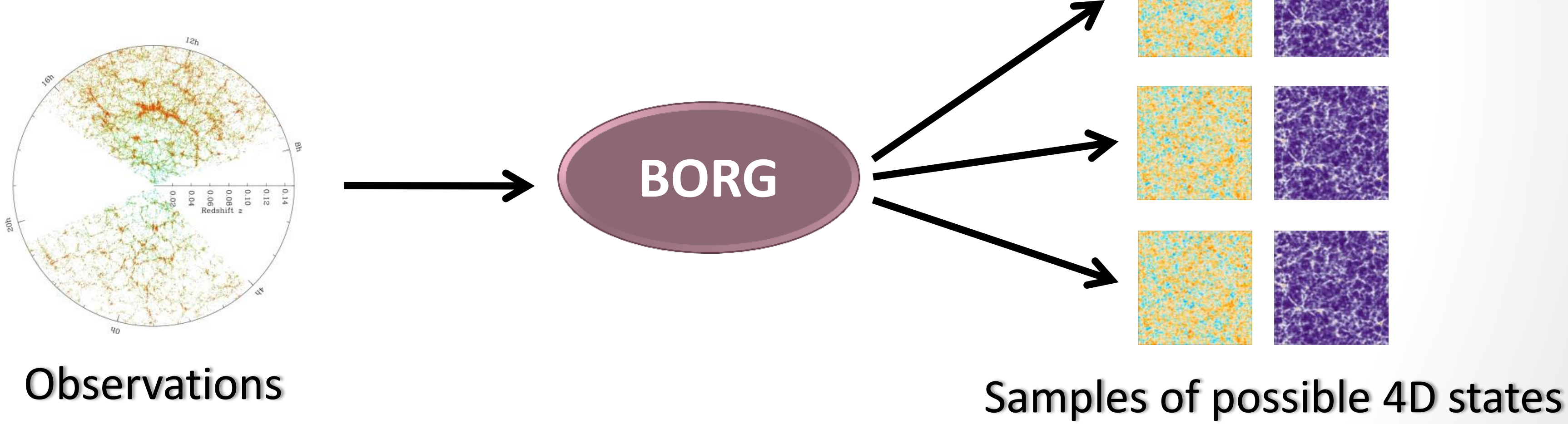
- HMC **beats the curse of dimensionality** by:
  - Exploiting gradients
  - Using conservation of Hamiltonian

Duane *et al.* 1987

# 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 2013, arXiv:1203.3639

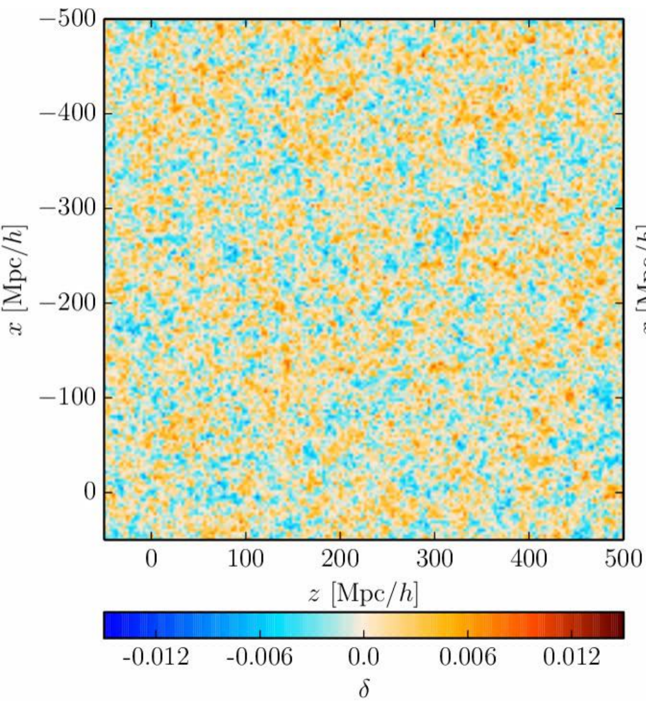
see also:
Kitaura 2013, arXiv:1203.4184
Wang, Mo, Yang & van den Bosch 2013, arXiv:1301.1348

# The BORG SDSS run

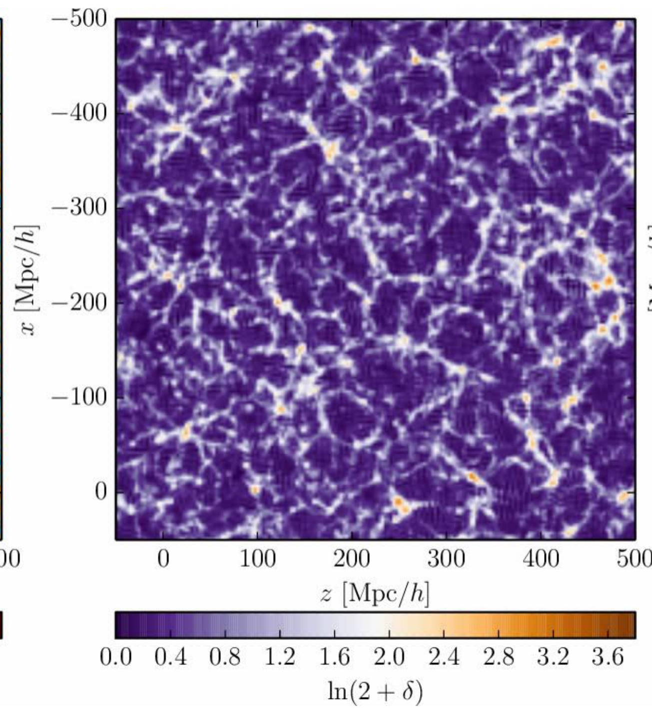
- 463,230 galaxies from the NYU-VAGC based on SDSS DR7
- Comoving cubic box of side length 750 Mpc/*h*, with periodic boundary conditions
- $256^3$ grid, resolution 3 Mpc/*h* ⇒ ≈ 17 millions parameters
- 12,000 samples, four-dimensional maps
- ≈ 3 TB disk space
- 10 months wallclock time on 16-32 cores

Jasche, FL & Wandelt, in prep.

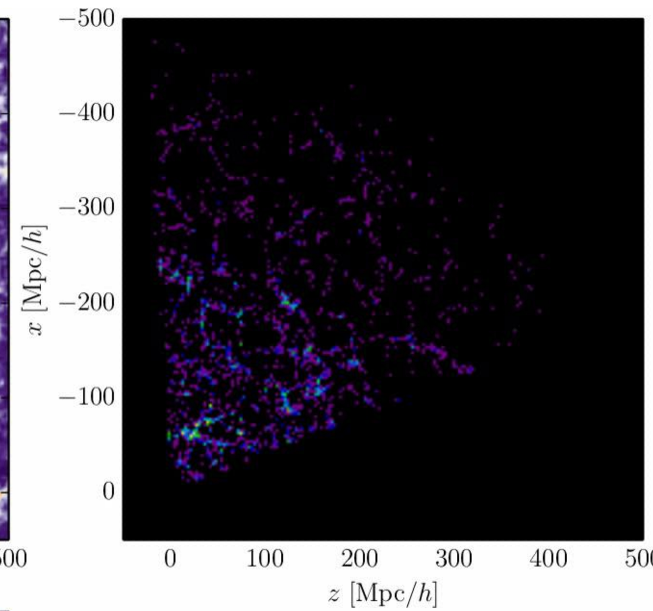
# BORG at work – chronocosmography




Initial conditions



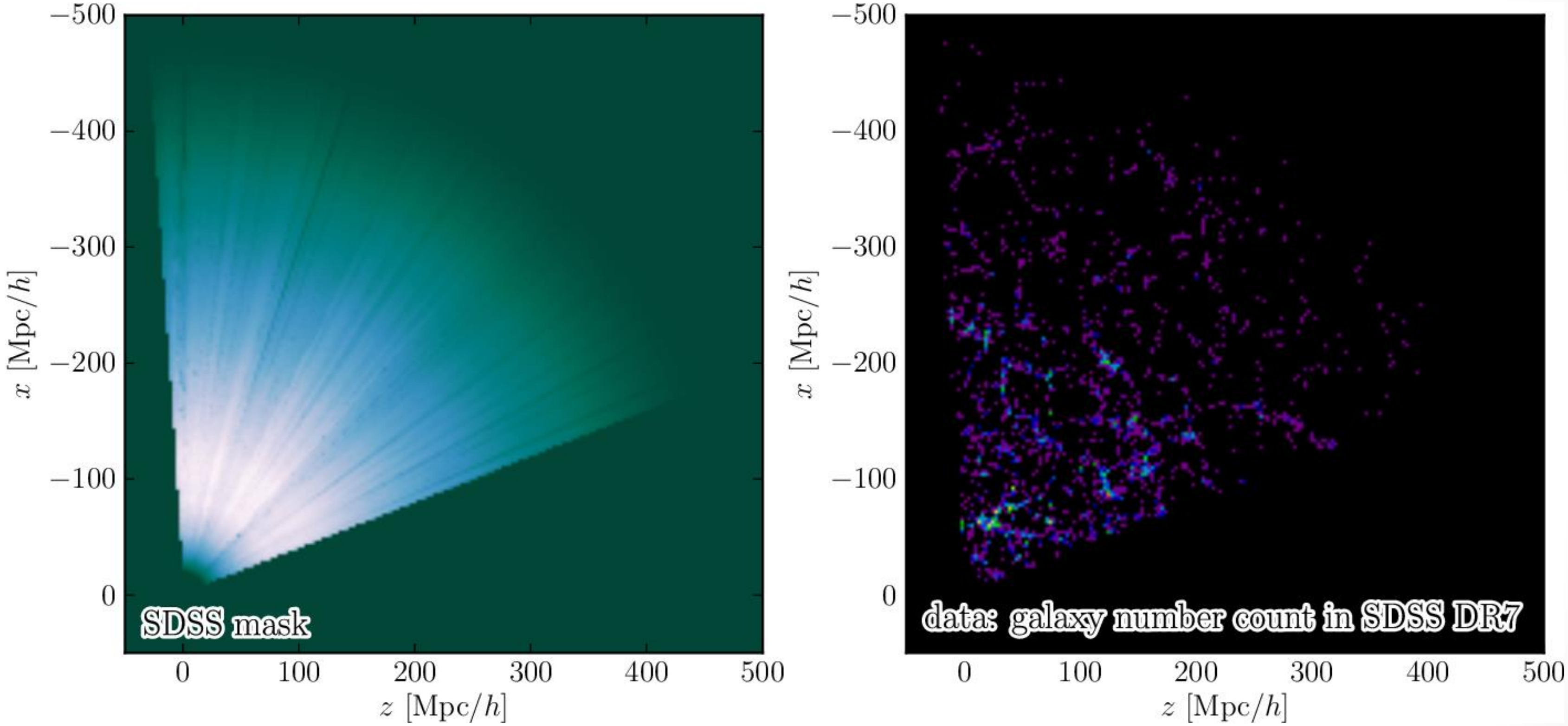

Final conditions




Observations

Jasche, FL & Wandelt, in prep.

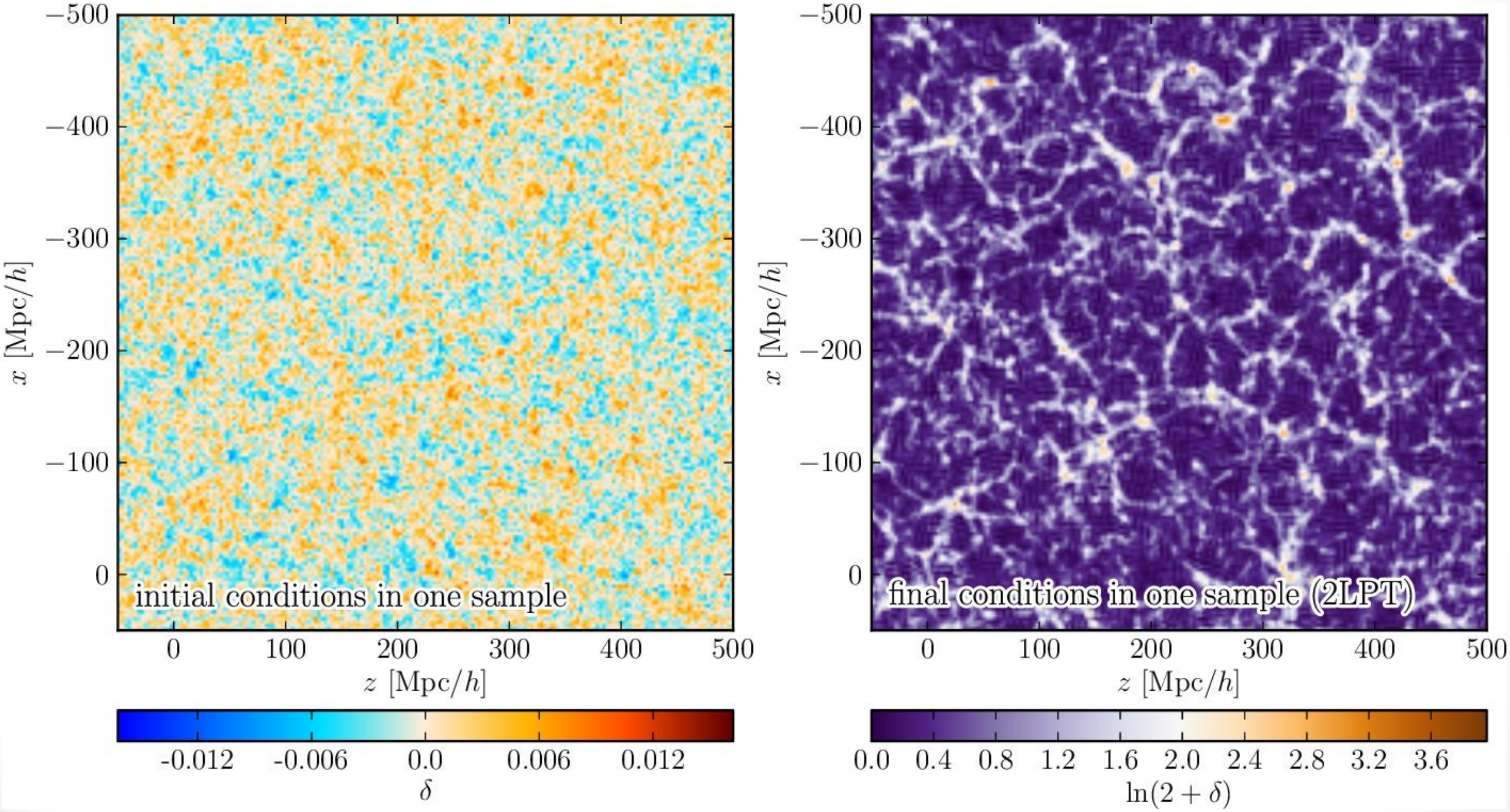
# Bayesian chronocosmography from SDSS DR7




Data

Jasche, FL & Wandelt, in prep.

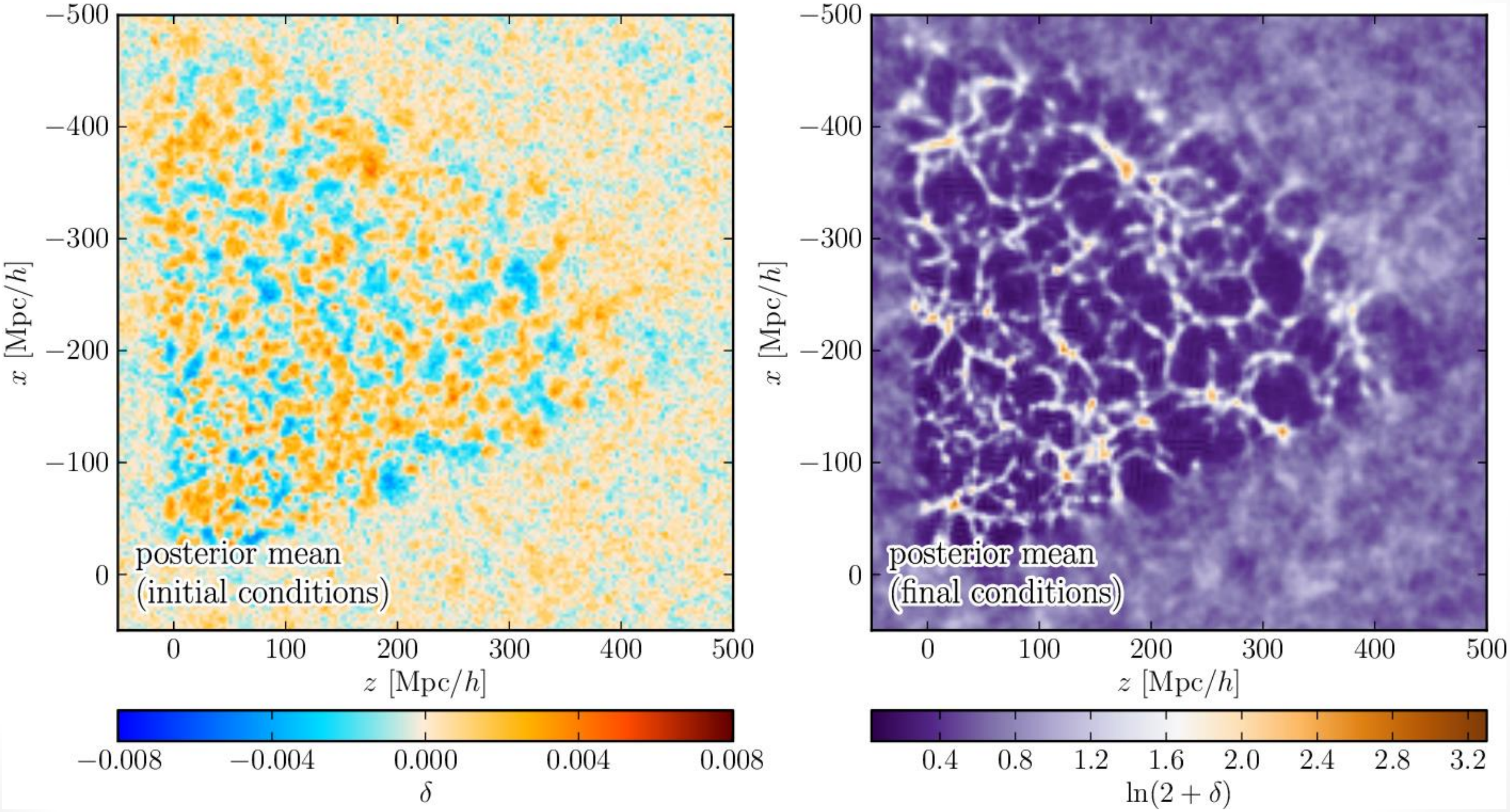
# Bayesian chronocosmography from SDSS DR7




One sample

Jasche, FL & Wandelt, in prep.

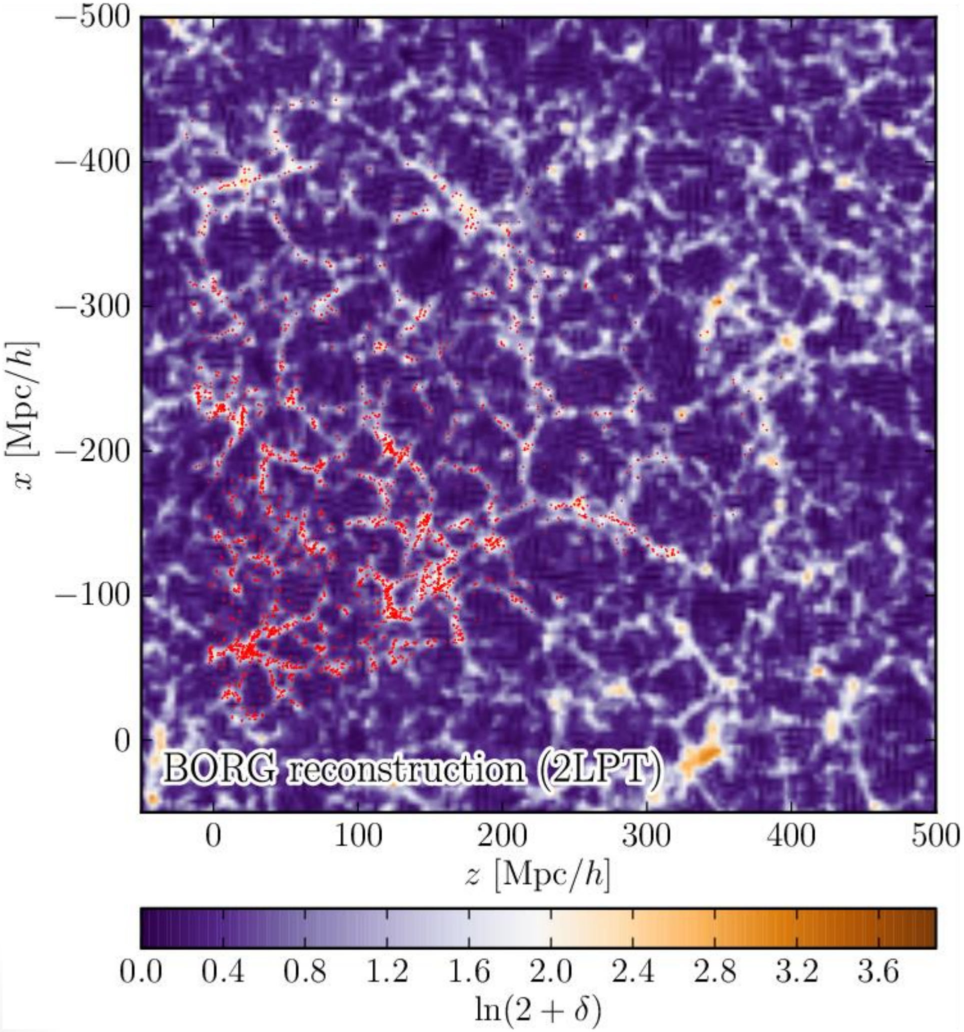
# Bayesian chronocosmography from SDSS DR7




Posterior mean

Jasche, FL & Wandelt, in prep.

# Non-linear filtering




FL, Jasche, Sutter, Hamaus & Wandelt, in prep. + Jasche, FL, Romano-Diaz & Wandelt, in prep.

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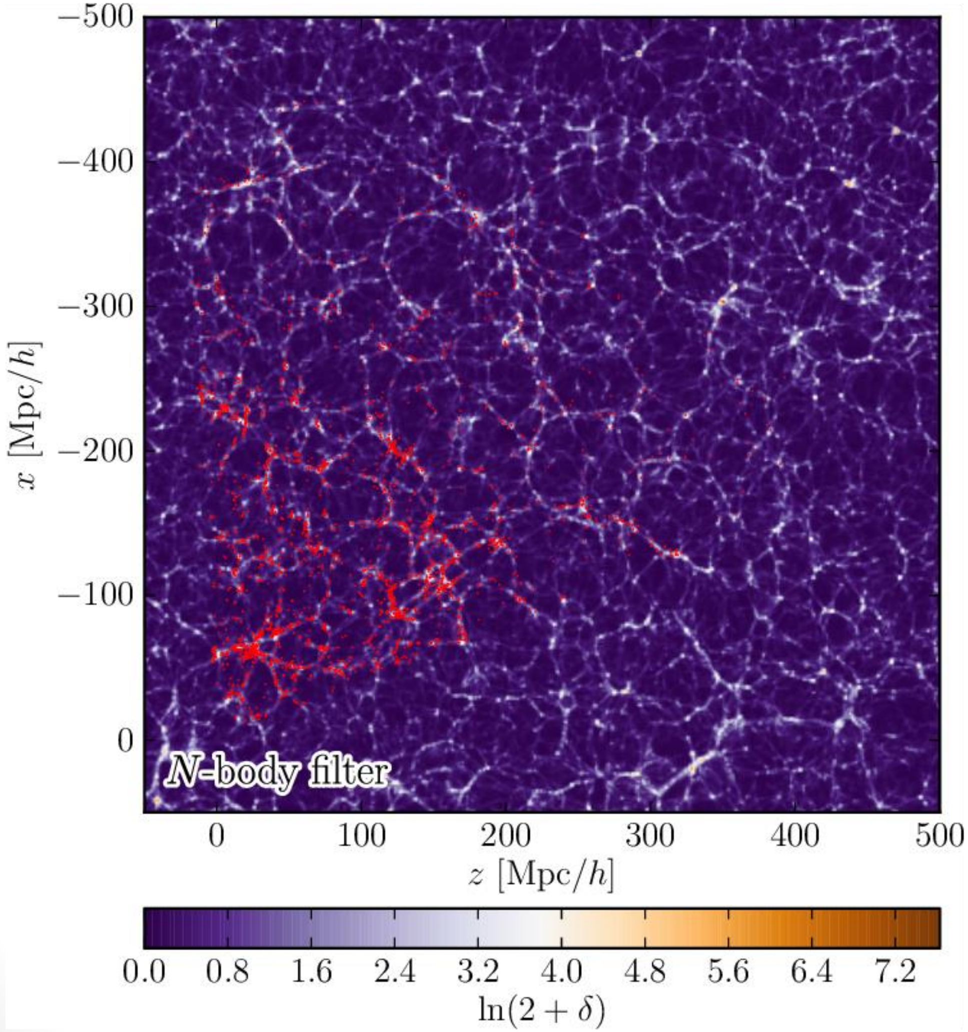
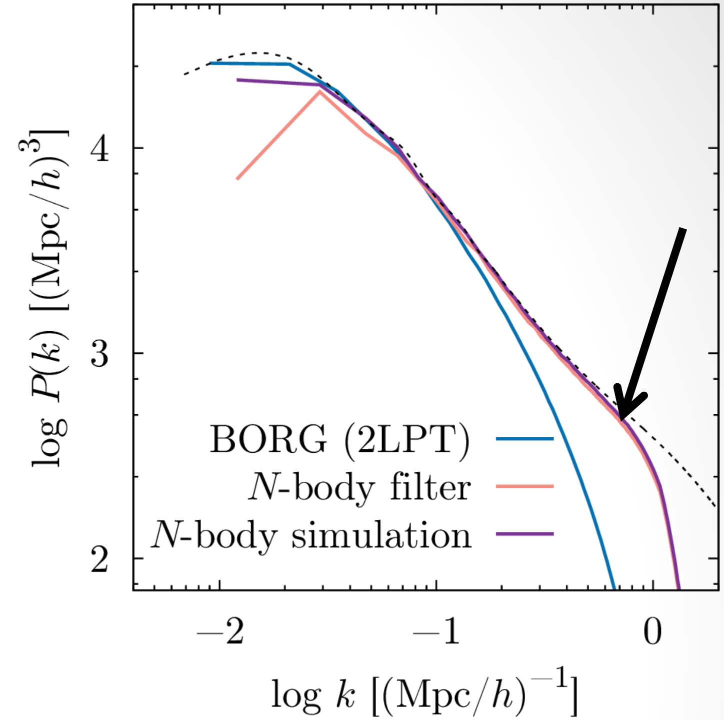



More on non-linear/non-Gaussian data models:

- Remapping LPT

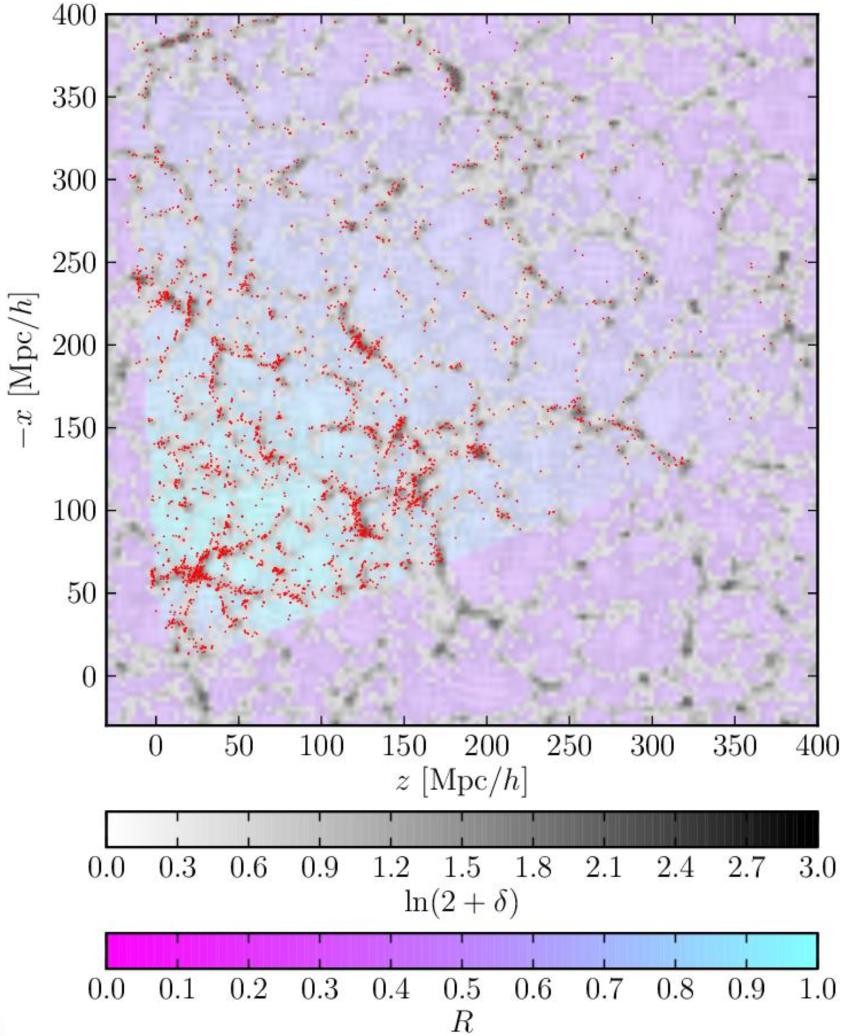
FL, Jasche, Gil-Marín & Wandelt 2013, arXiv:1305.4642

- COLA

Tassev, Zaldarriaga, Eisenstein 2013, arXiv:1301.0322

FL, Jasche, Sutter, Hamaus & Wandelt, in prep. + Jasche, FL, Romano-Diaz & Wandelt, in prep.

# Dark matter voids in the SDSS




FL, Jasche, Sutter, Hamaus & Wandelt, in prep.

- How?

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

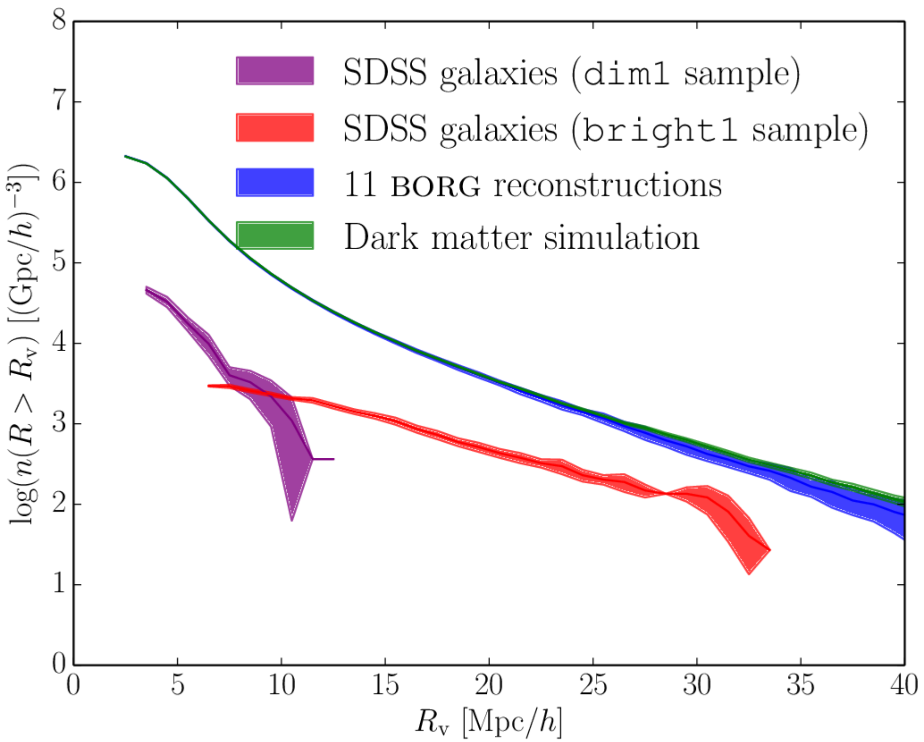
based on ZOBOV: Neyrinck 2007, arXiv:0712.3049

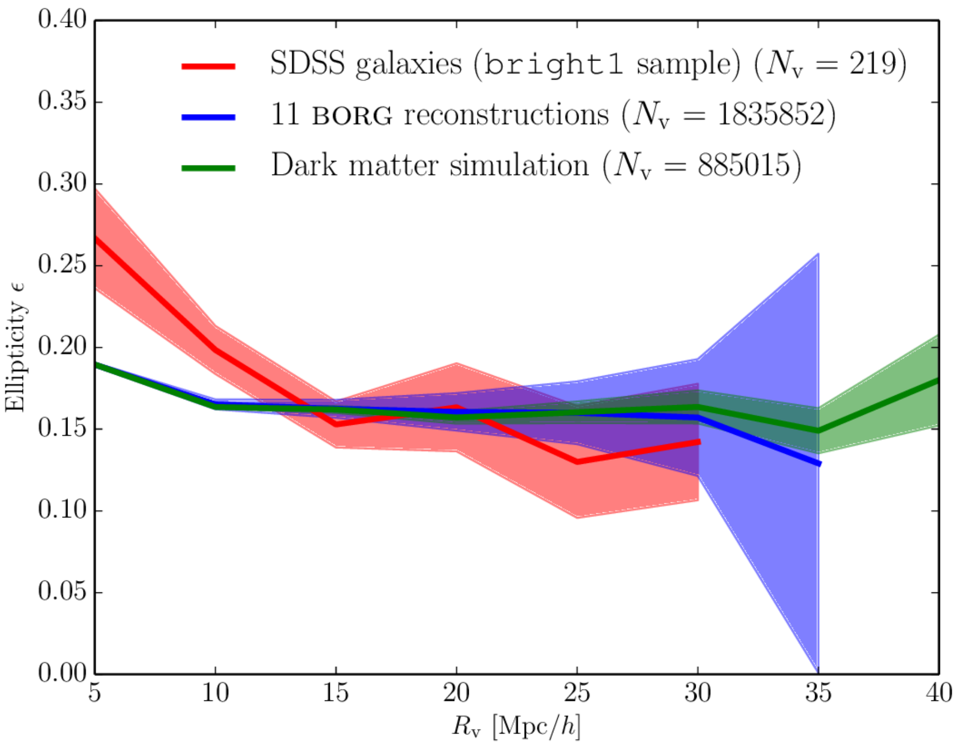
- Why?

**Sparsity** & **Bias**

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

# Dark matter void properties

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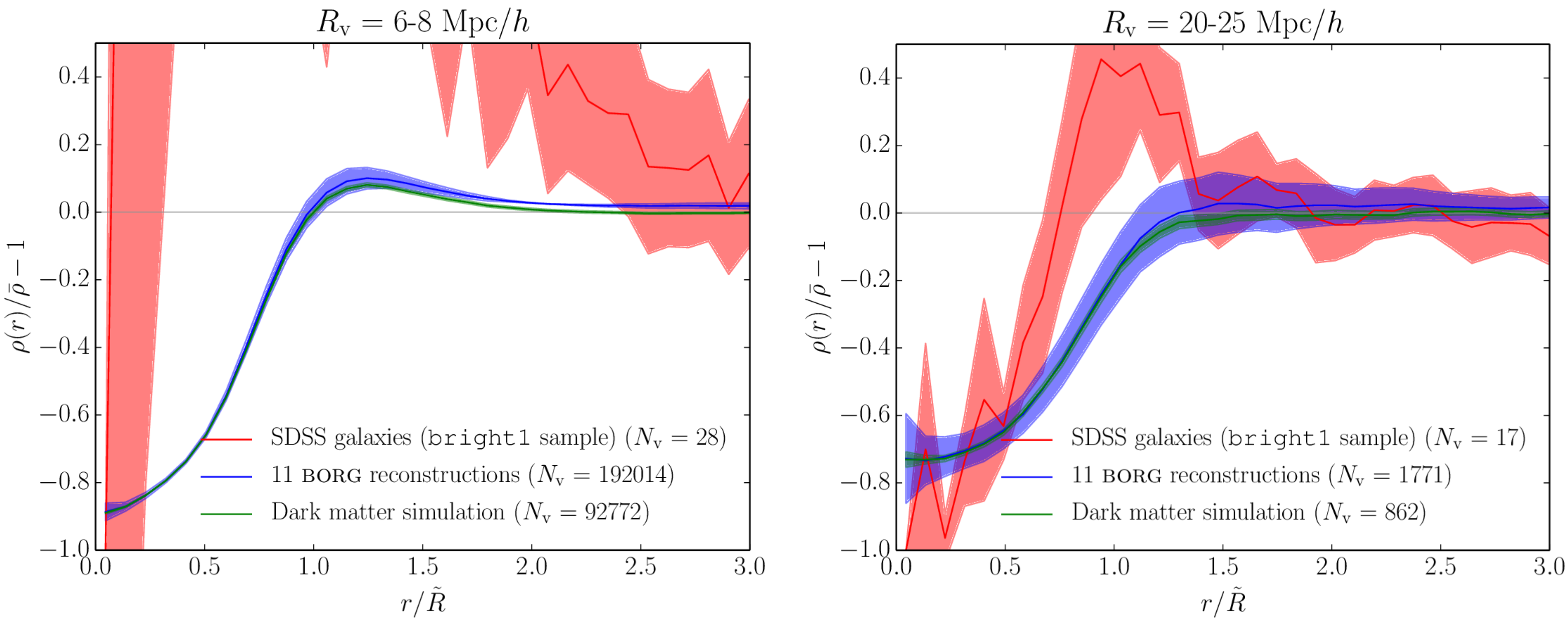


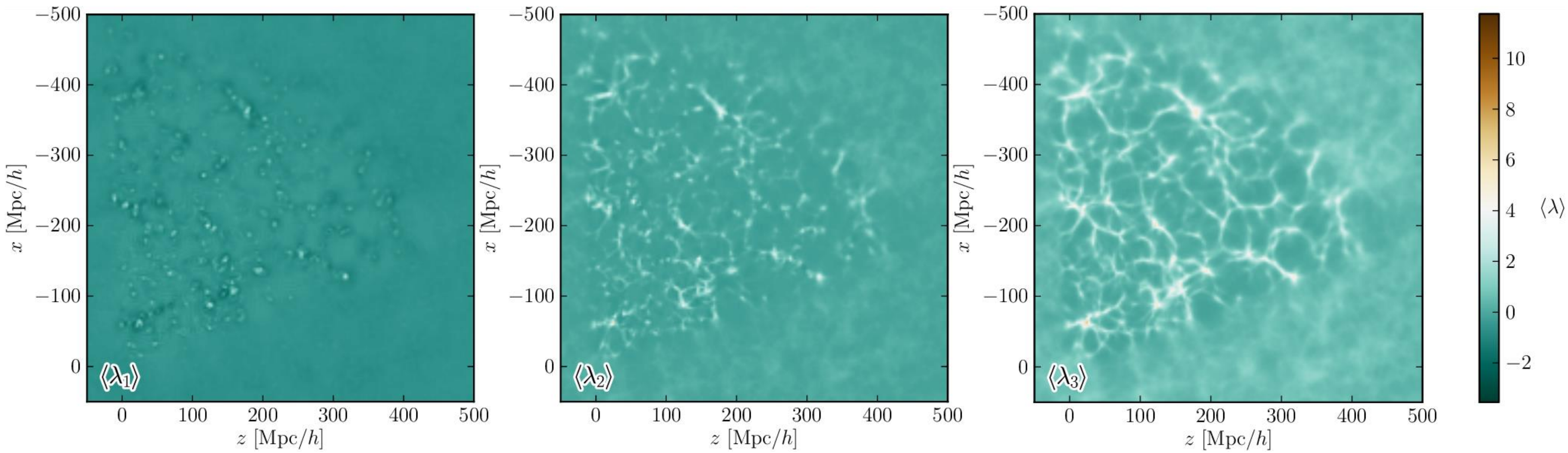

All catalogs will be made publicly available at
www.cosmicvoids.net

FL, Jasche, Sutter, Hamaus & Wandelt, in prep.

# Tidal shear analysis

- $\lambda_1, \lambda_2, \lambda_3$ : eigenvalues of the tidal field tensor, the Hessian of the gravitational potential: $T_{ij} = \partial_i \partial_j \Phi$
  - Voids: $\lambda_1, \lambda_2, \lambda_3 < 0$
  - Sheets: $\lambda_1 > 0 \text{ and } \lambda_2, \lambda_3 < 0$
  - Filaments: $\lambda_1, \lambda_2 > 0 \text{ and } \lambda_3 < 0$
  - Clusters: $\lambda_1, \lambda_2, \lambda_3 > 0$

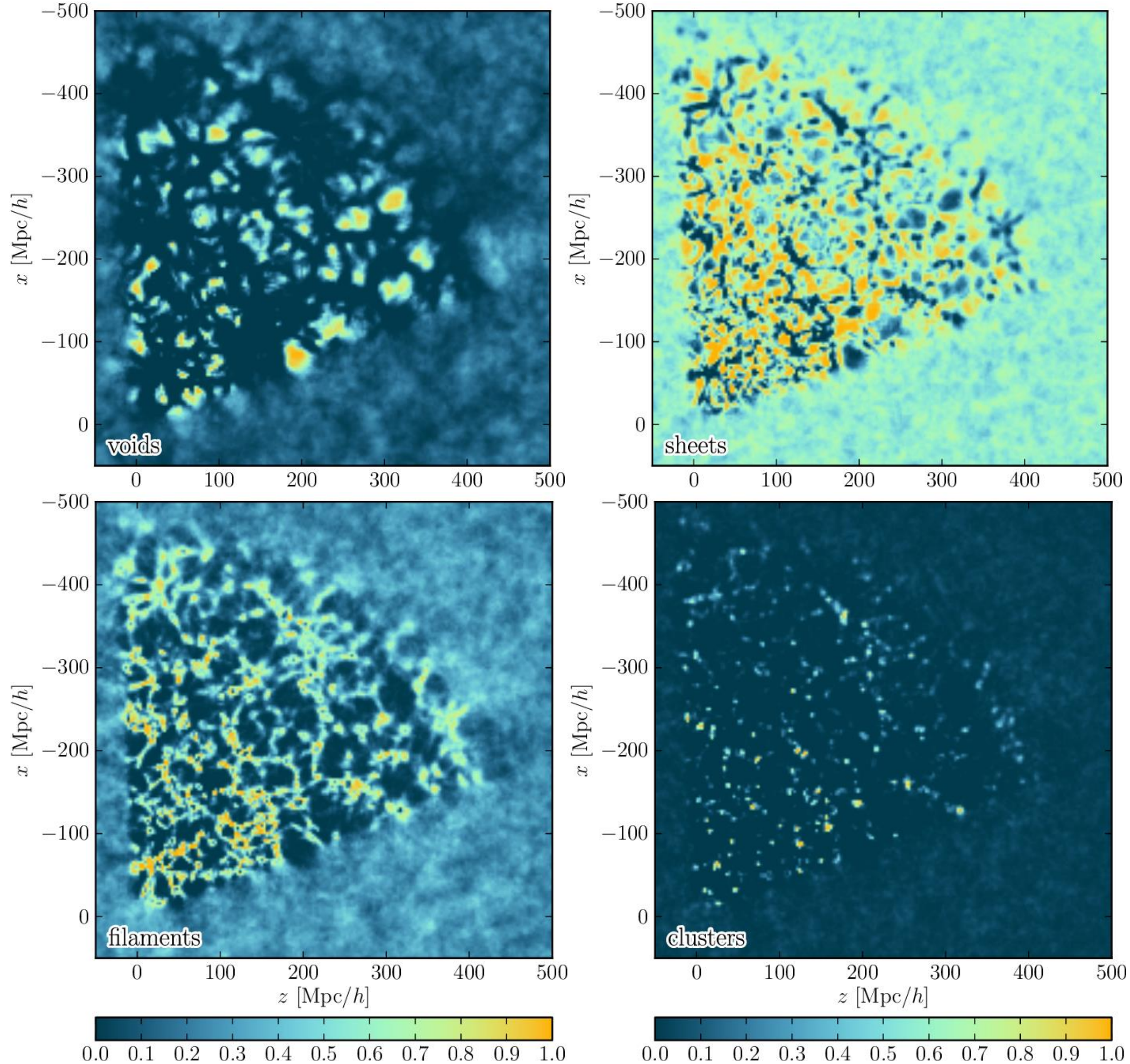
Hahn *et al*. 2006, arXiv:astro-ph/0610280
see also:
Forero-Romero *et al*. 2008, arXiv:0809.4135
Hoffman *et al*. 2012, arXiv:1201.3367




FL, Jasche, Chevallard & Wandelt, in prep.

# Dynamic structures inferred by BORG

Final conditions

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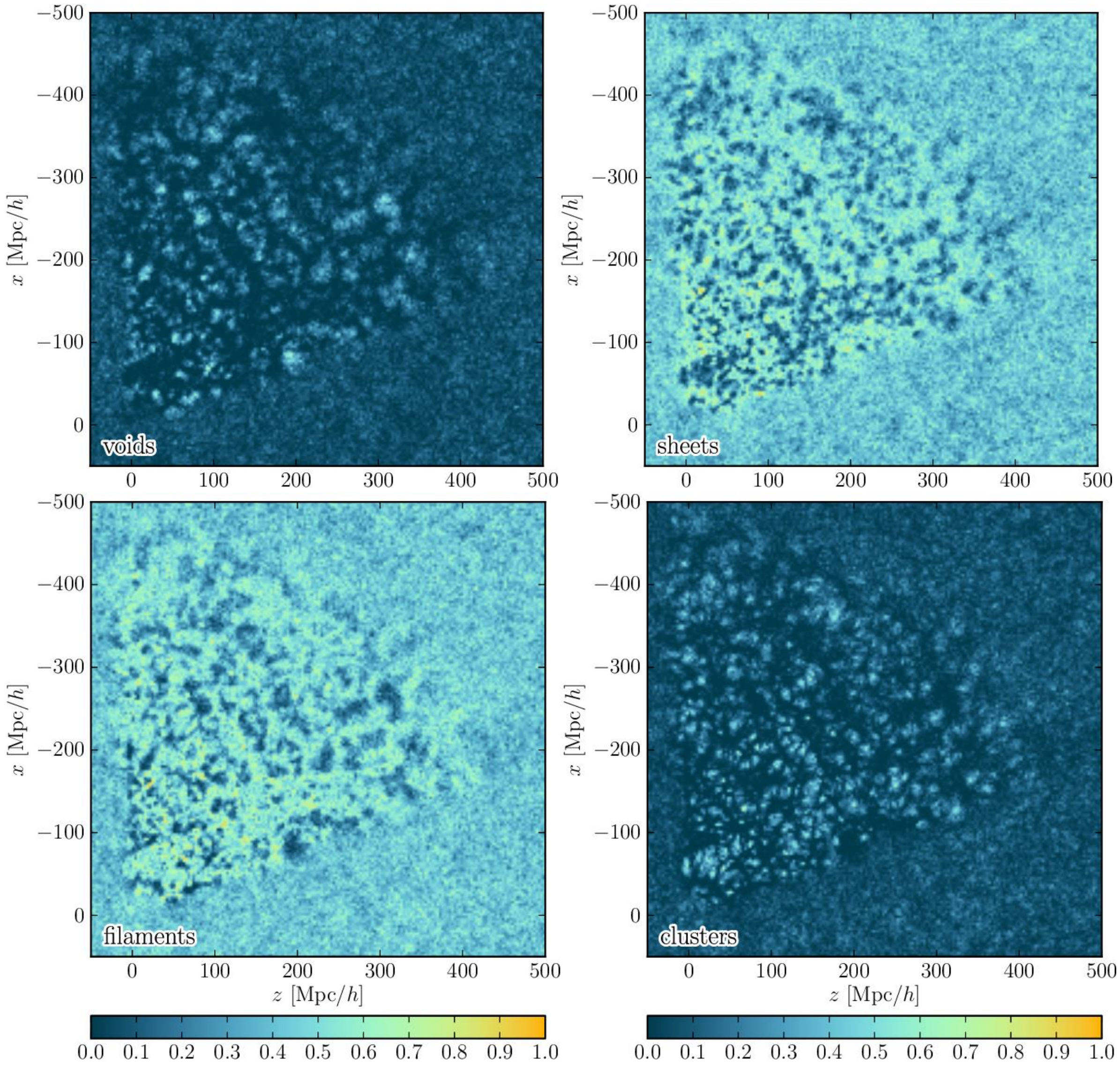
Initial conditions




FL, Jasche, Chevallard & Wandelt, in prep.

# Summary & Conclusions

- **Bayesian large-scale structure inference** in 10 millions dimensions is possible!
  - Non-linear and non-Gaussian inference
  - Uncertainty quantification (noise, survey geometry, selection effects and biases)
- Application to data: four-dimensional **chronocosmography**
  - Simultaneous analysis of the morphology and formation history of the large-scale structure
  - Physical reconstruction of the initial conditions
  - Inference of cosmic voids at the level of the dark matter distribution
  - Characterization of the dynamic cosmic web underlying galaxies