Bayesian large-scale structure inference and cosmic web analysis

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How did structure appear in the Universe?

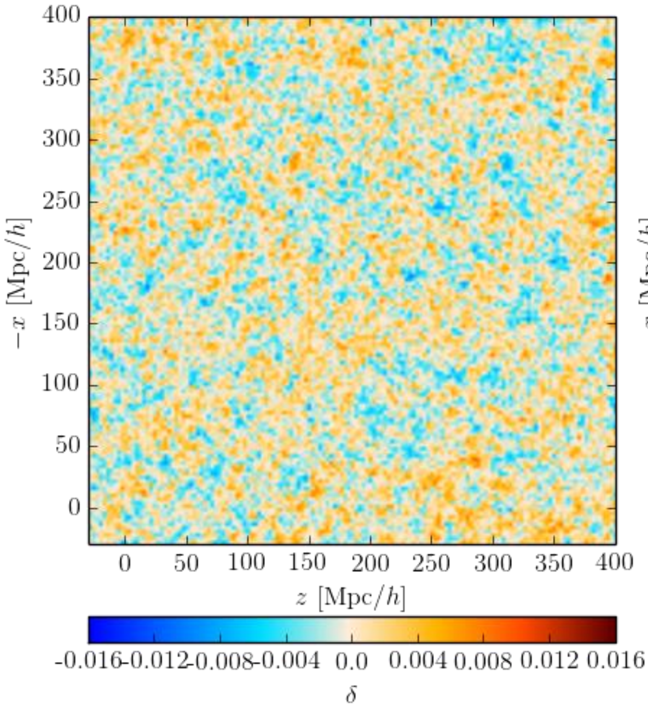
A joint problem!

- **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
  - A round trip: from theory to data, from data to theory

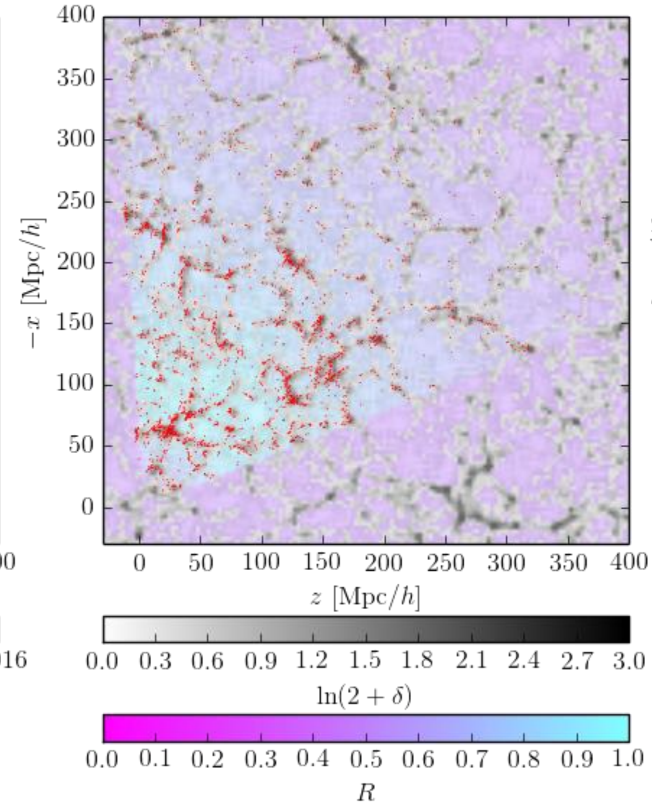
FL, Pisani & Wandelt 2014, arXiv:1403.1260

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

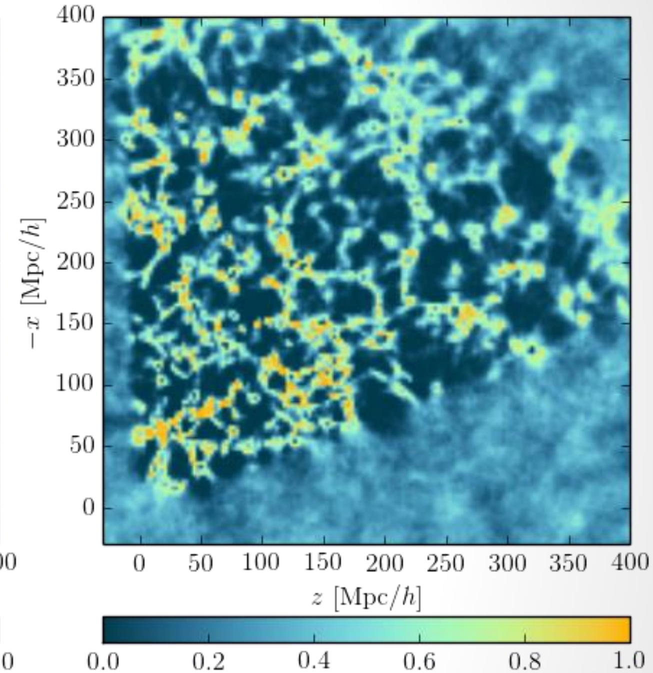
Maps of the large-scale structure



Initial conditions



Final conditions + Observations



Cosmic Web

1. Bayesian Inference

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?"

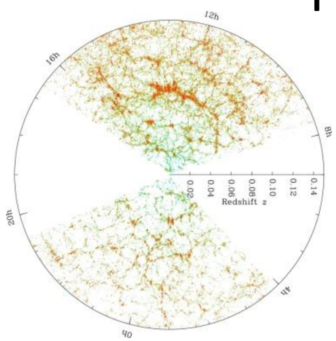
$$p(s|d)p(d) = p(d|s)p(s)$$

BORG: *Bayesian Origin Reconstruction from Galaxies*

d≈10^7

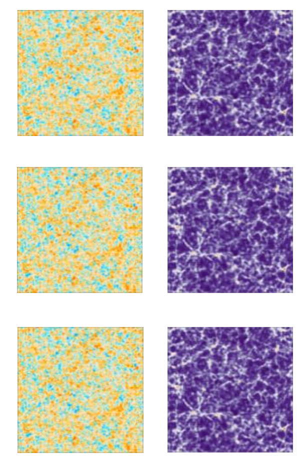
What makes the problem tractable:

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



Observations

BORG



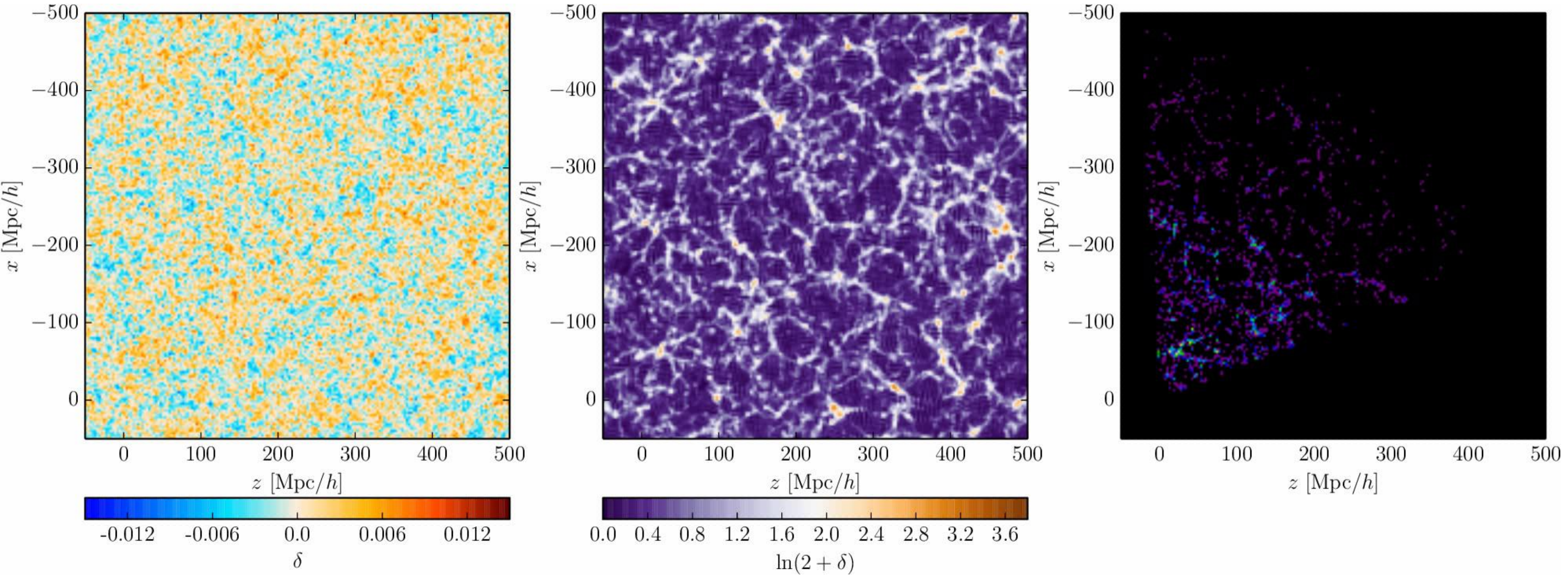
Samples of possible 4D states

Jasche & Wandelt 2013, arXiv:1203.3639

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

2. Chrono-Cosmography

BORG at work – chronocosmography



Initial conditions | Final conditions | Observations

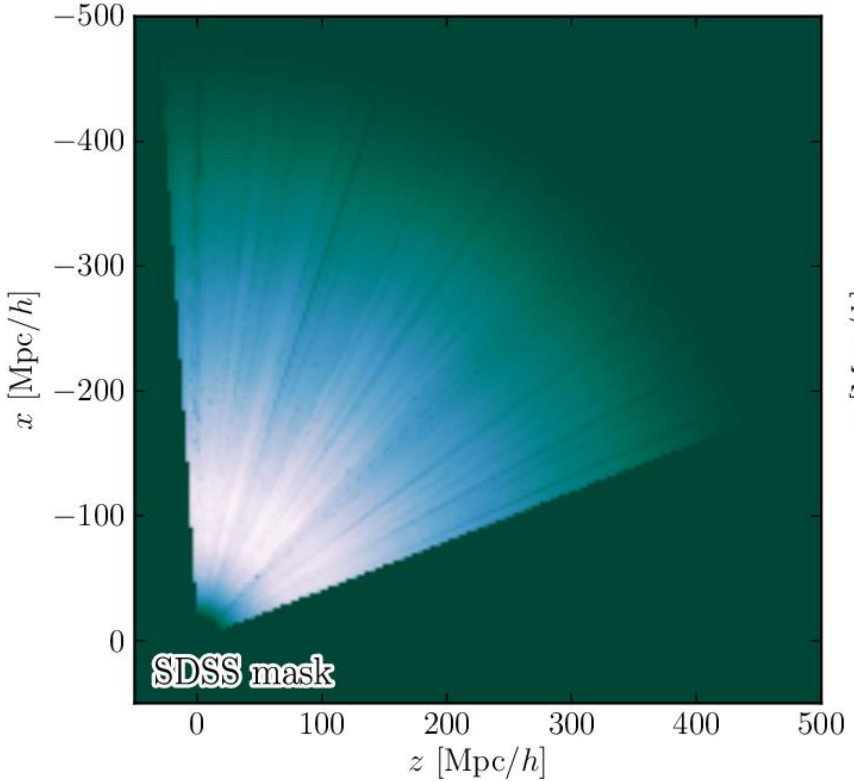
SDSS DR7:

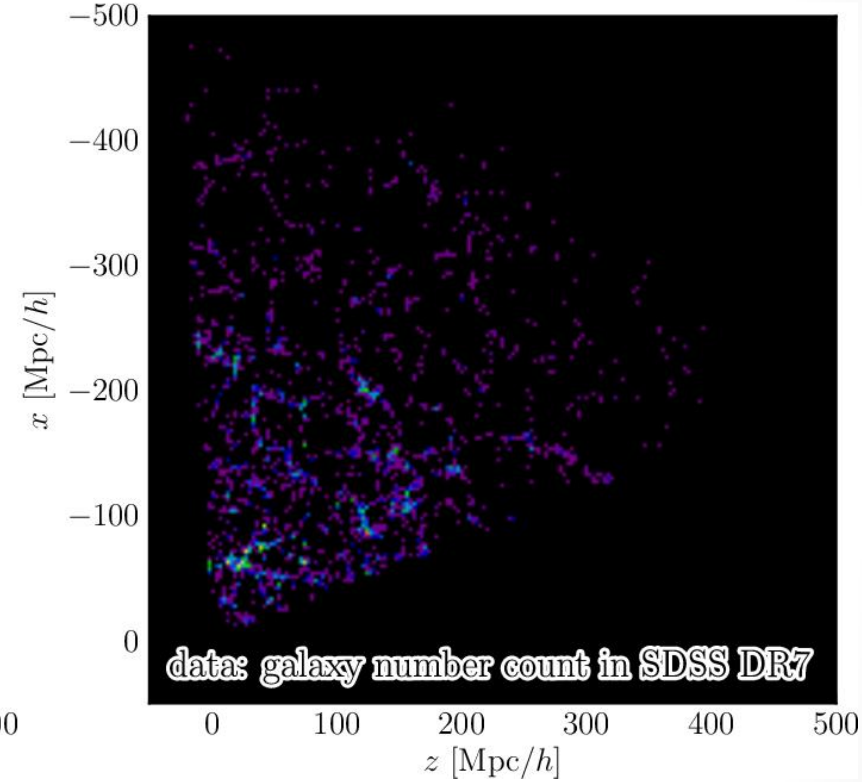
Jasche, FL & Wandelt 2014, arXiv:1409.6308

2M++ catalog:

Lavaux & Jasche 2015, submitted

Bayesian chronocosmography from SDSS DR7

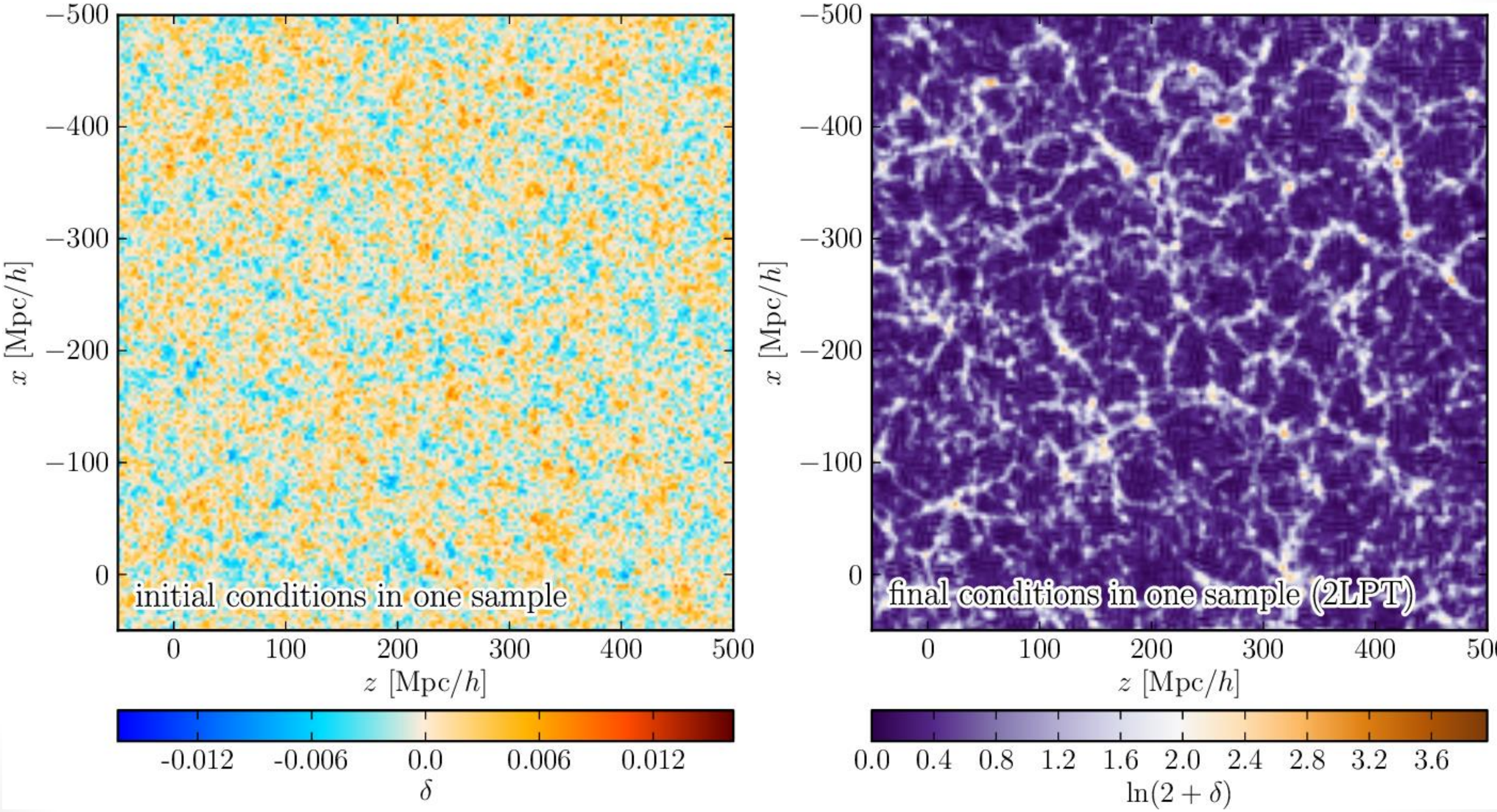




Jasche, FL & Wandelt 2014, arXiv:1409.6308

Data

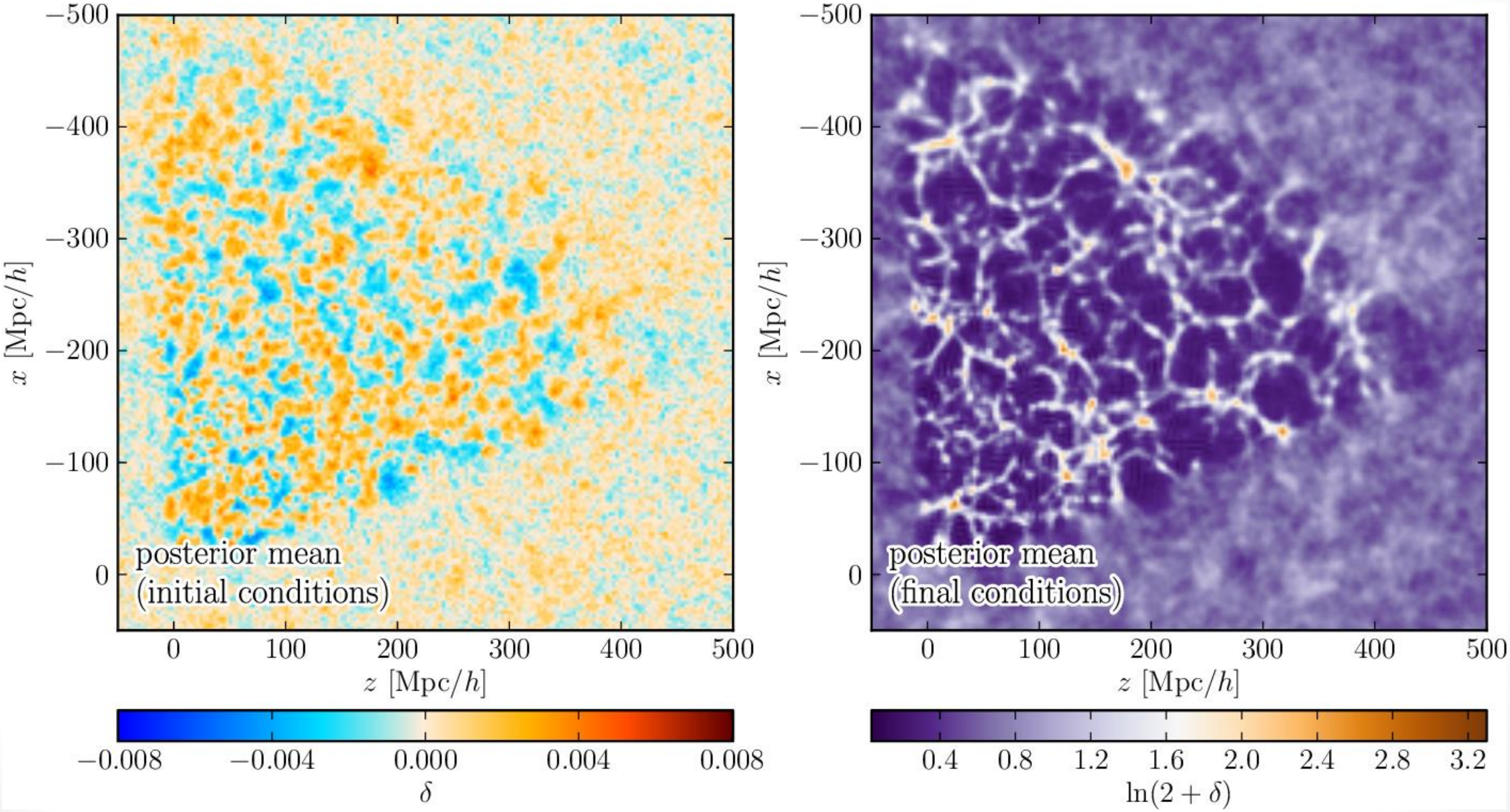
Bayesian chronocosmography from SDSS DR7



One sample

Jasche, FL & Wandelt 2014, arXiv:1409.6308

Bayesian chronocosmography from SDSS DR7

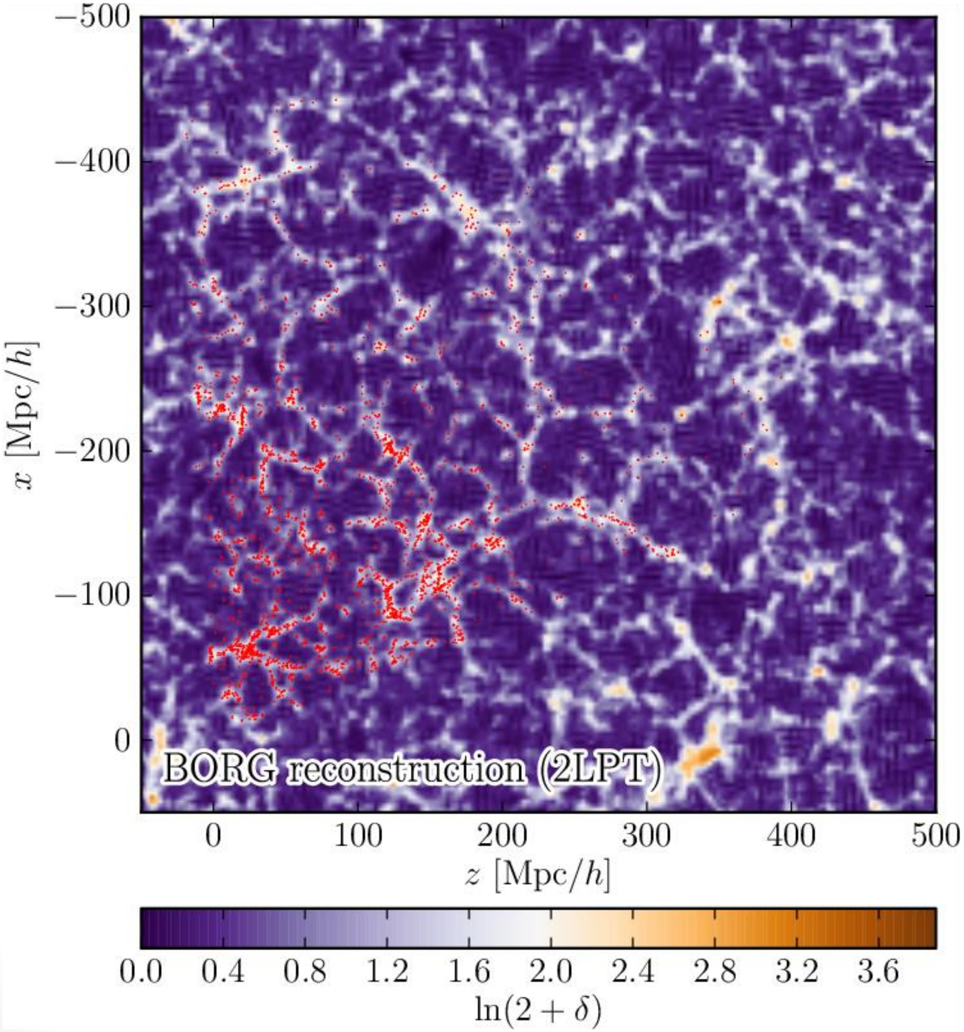


Posterior mean

Jasche, FL & Wandelt 2014, arXiv:1409.6308

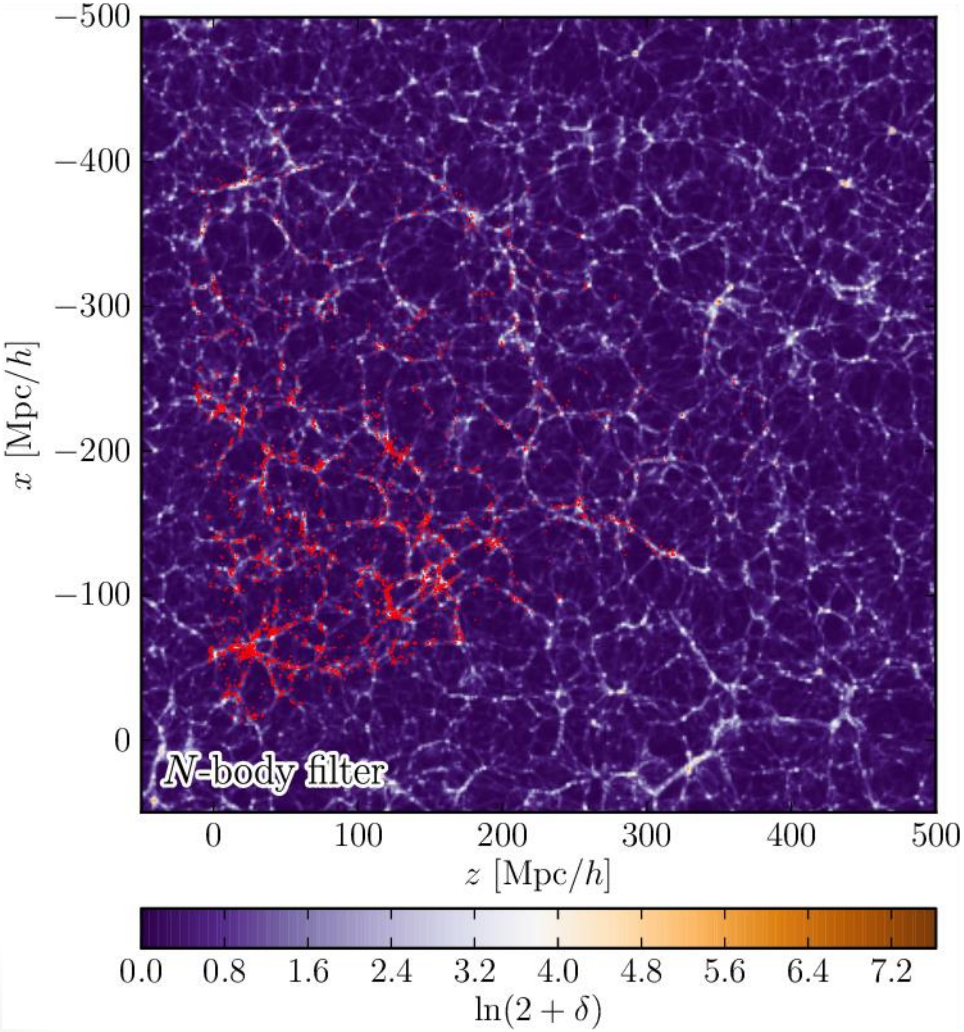
3. The Non-Linear Regime of Structure Formation

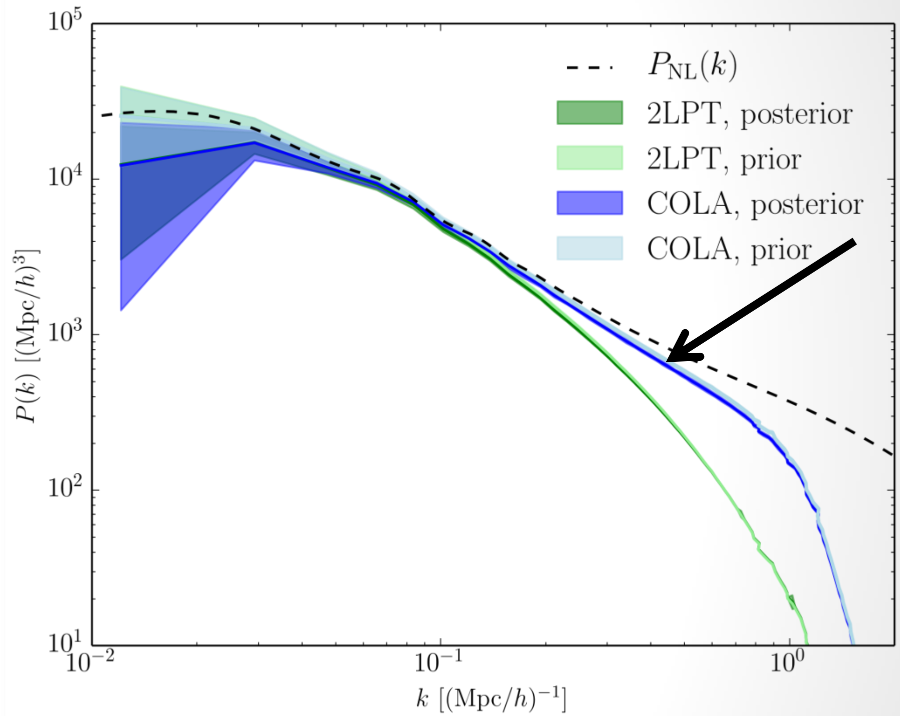
Non-linear filtering



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

Non-linear filtering





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

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

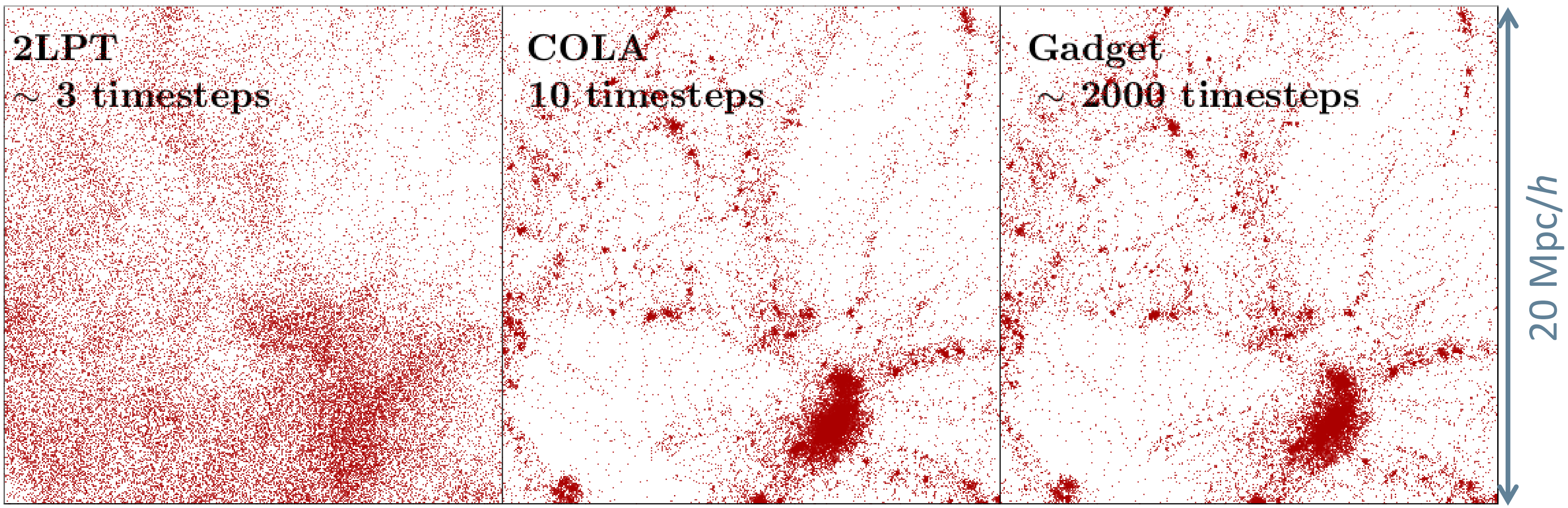
- Time-stepping (omitted constants and Hubble expansion):

Standard:

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

Modified:

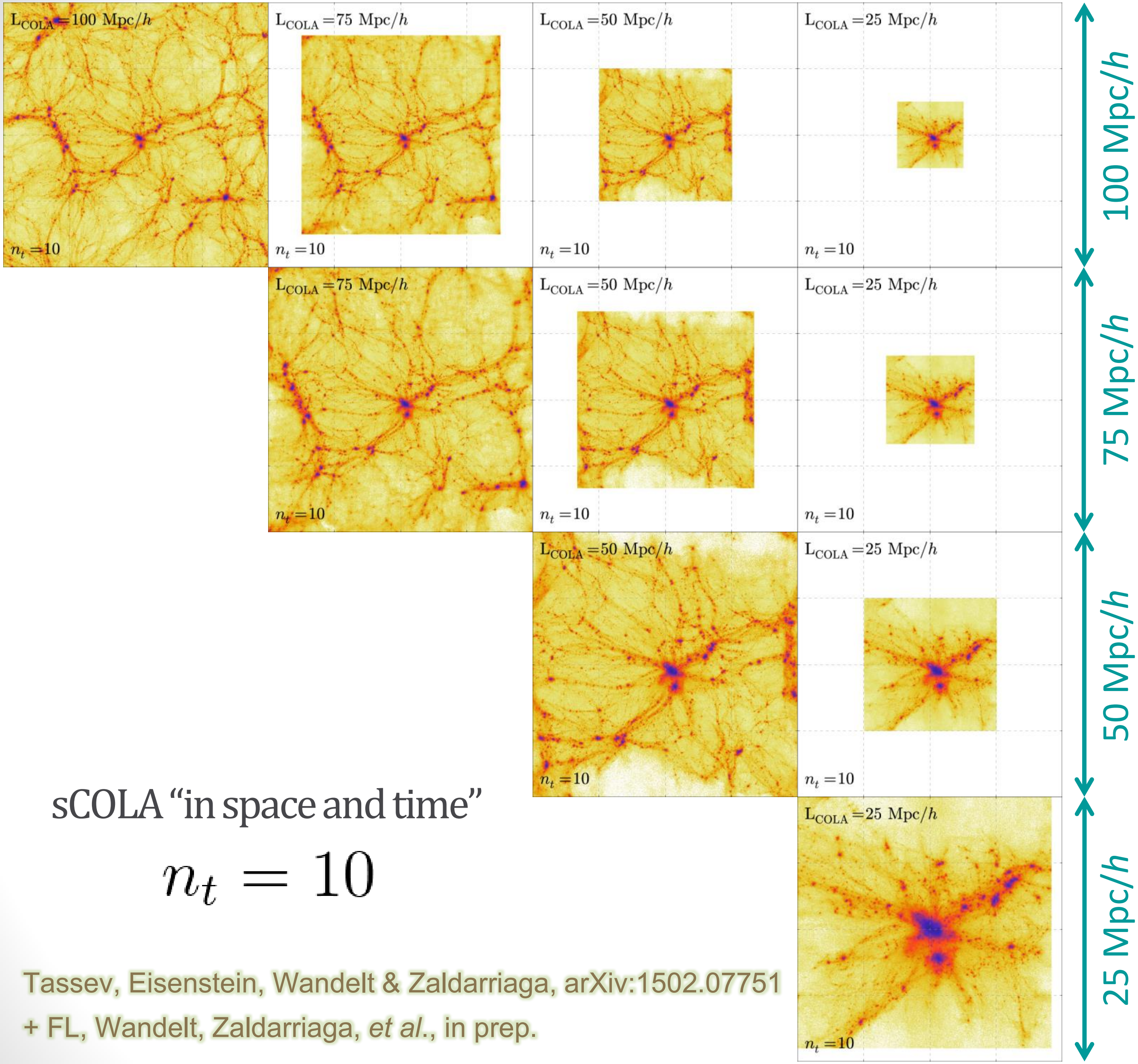
$$\partial_\tau^2 \mathbf{s}_{\mathrm{MC}} = \partial_\tau^2 (\mathbf{s} - \mathbf{s}_{\mathrm{LPT}}) = -\nabla\Phi - \partial_\tau^2 \mathbf{s}_{\mathrm{LPT}}$$



Original COLA "in time"

Tassev, Zaldarriaga & Einsenstein 2013, arXiv:1301.0322

Extending COLA



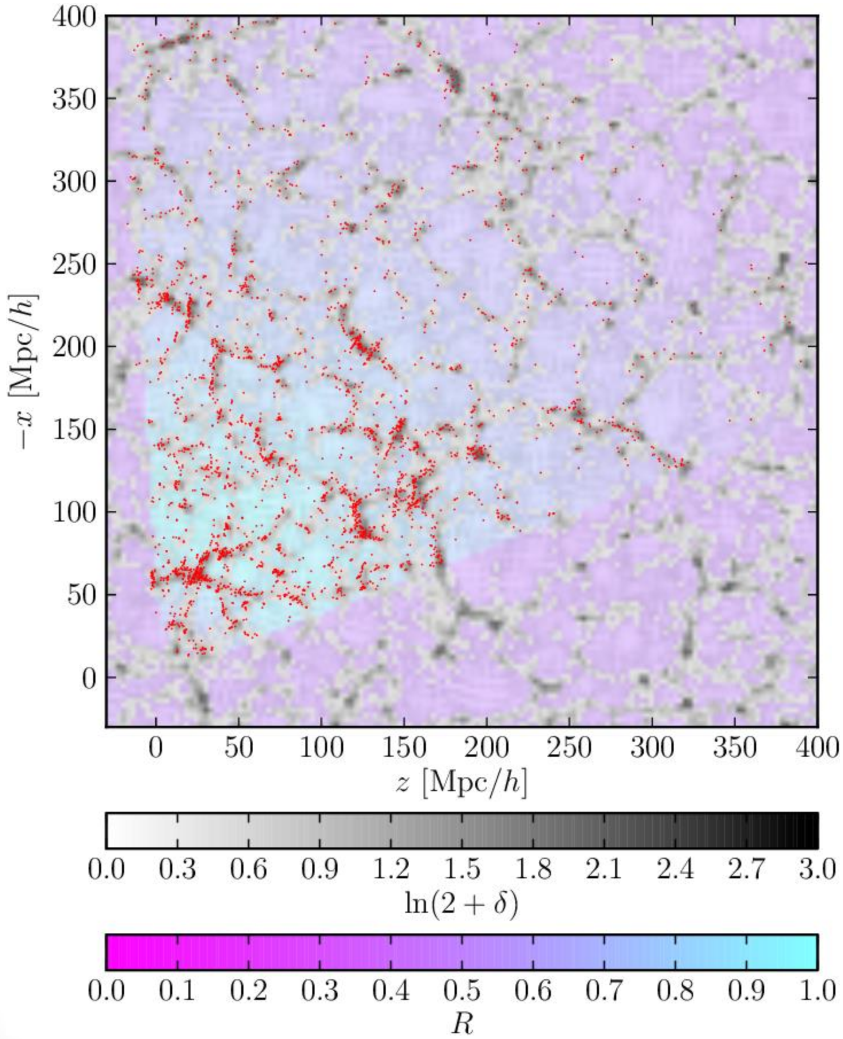
sCOLA "in space and time"

$$n_t = 10$$

Tassev, Eisenstein, Wandelt & Zaldarriaga, arXiv:1502.07751
+ FL, Wandelt, Zaldarriaga, *et al.*, in prep.

4. Cosmic Web Classification

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

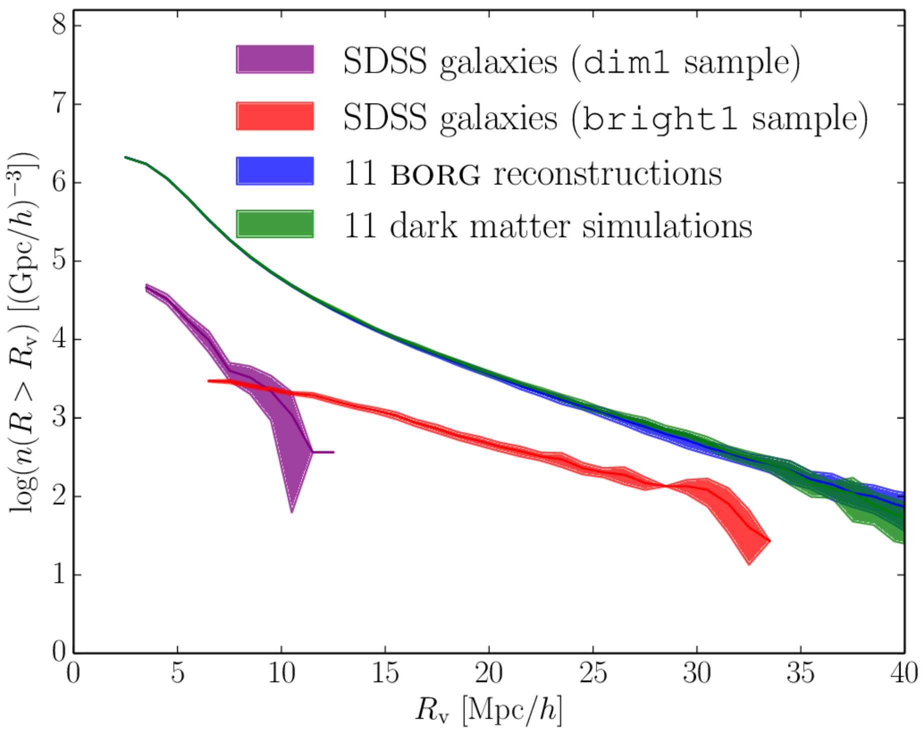
Sutter *et al.* 2013, arXiv:1311.3301

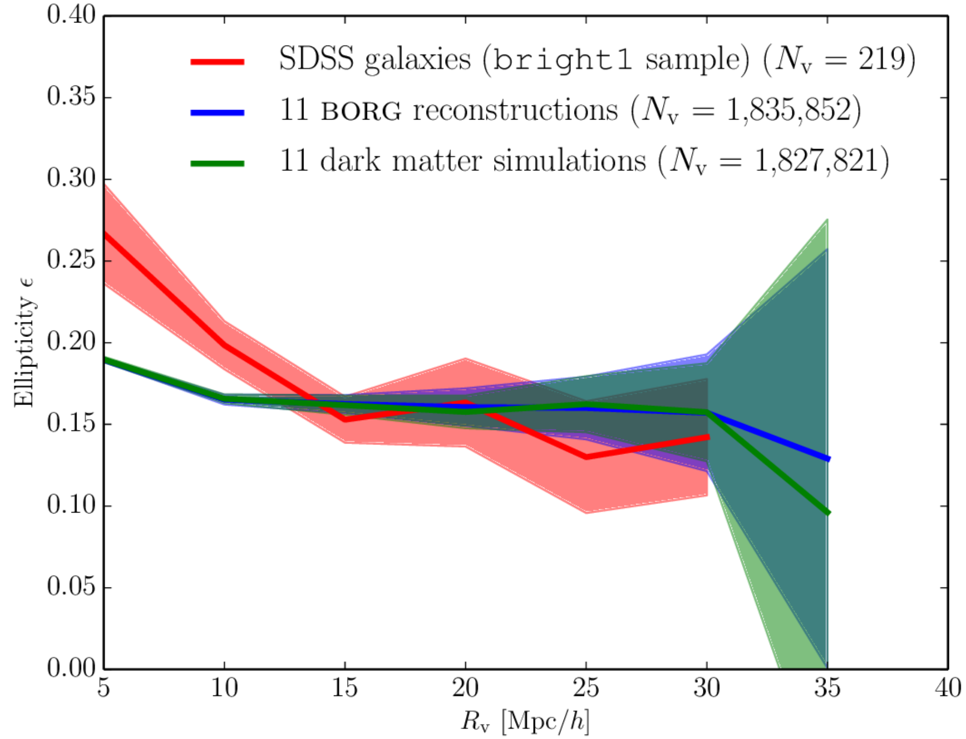
- How?

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

based on ZOBOV: Neyrinck 2007, arXiv:0712.3049

Dark matter void properties





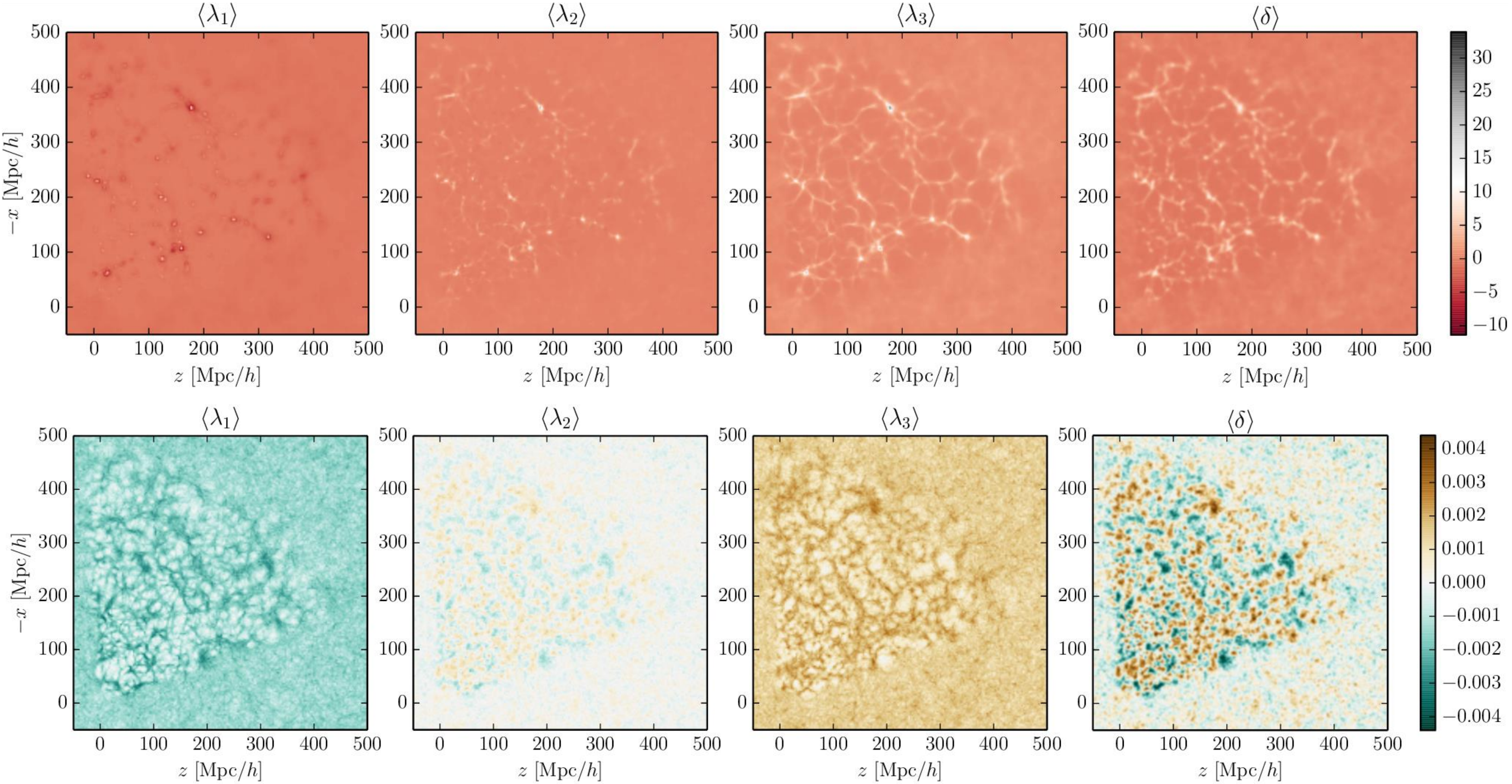
FL, Jasche, Sutter, Hamaus & Wandelt 2014, arXiv:1410.0355

$$T_{ij} = \partial_i \partial_j \Phi \qquad \lambda_1 + \lambda_2 + \lambda_3 = \delta$$

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

Tidal shear analysis

Final conditions

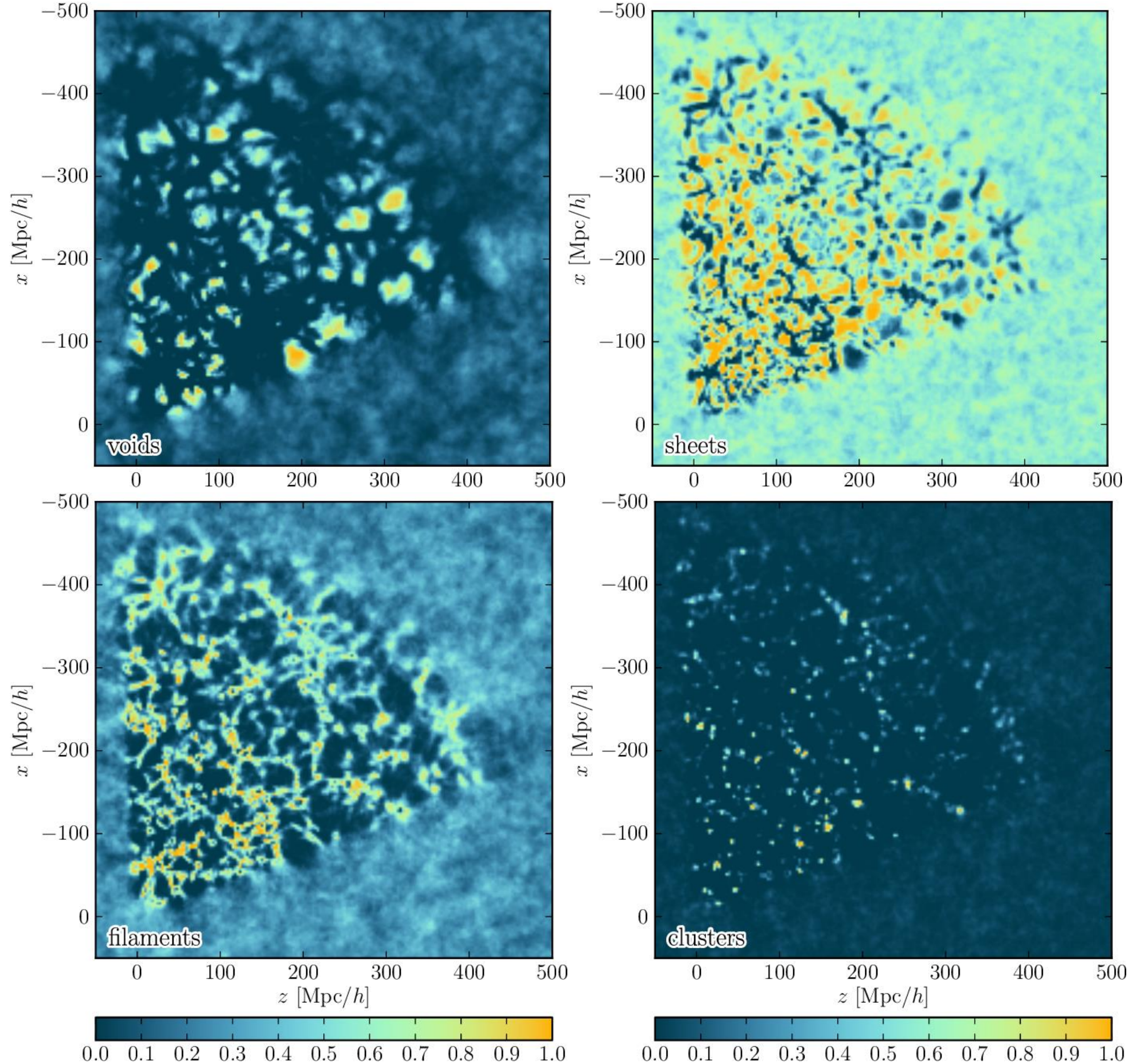


FL, Jasche & Wandelt 2015, arXiv:1502.02690

Initial conditions

Dynamic structures inferred by BORG

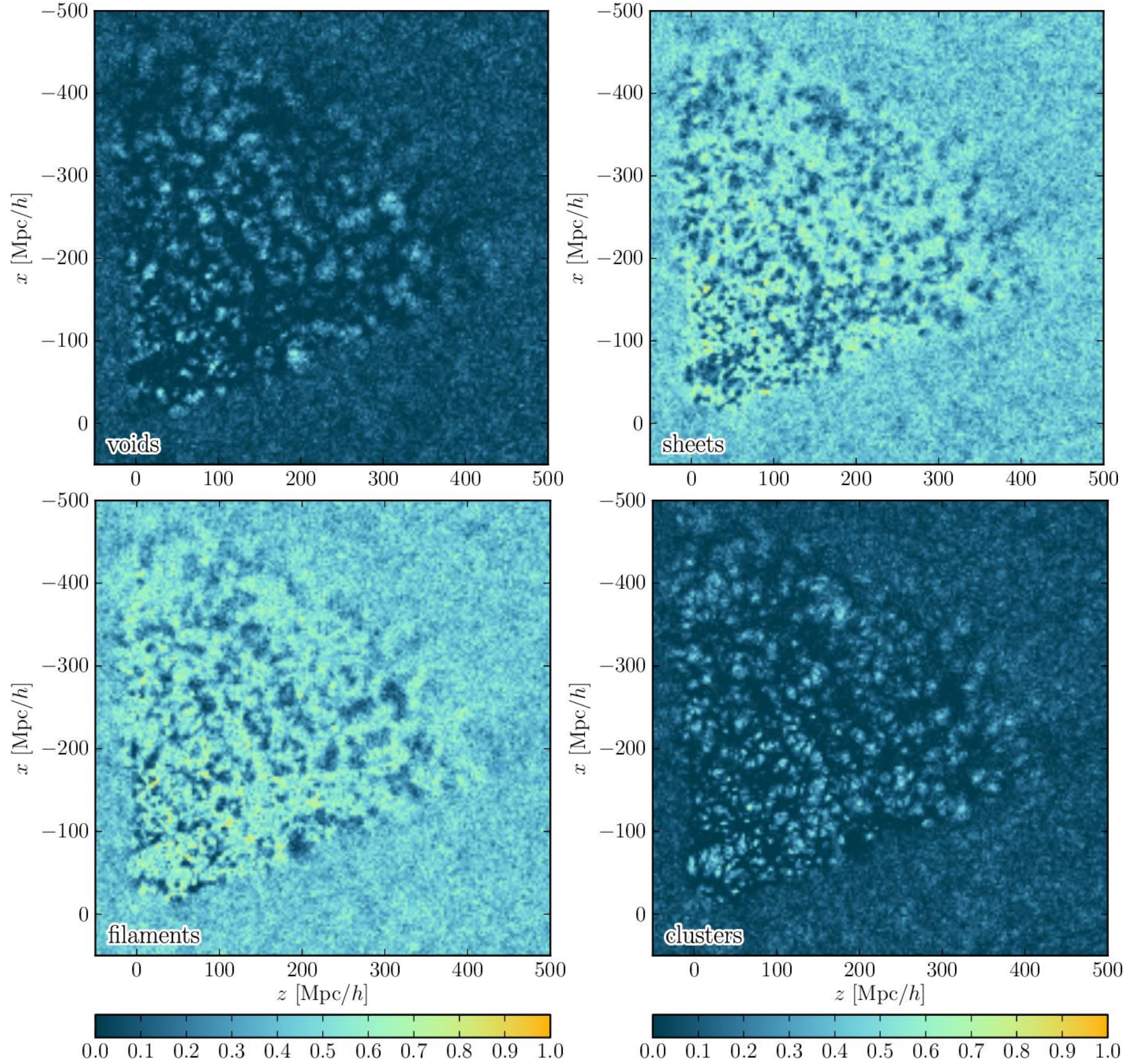
Final conditions



FL, Jasche & Wandelt 2015, arXiv:1502.02690

Dynamic structures inferred by BORG

Initial conditions



FL, Jasche & Wandelt 2015, arXiv:1502.02690

Concluding thoughts

- Bayesian large-scale structure inference in 10 millions dimensions is possible!
  - Uncertainty quantification (noise, survey geometry, selection effects and biases)
  - Non-linear and non-Gaussian inference with improving techniques
- 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

Mapping the Universe: epilogue?