Probabilistic cartography of the large-scale structure

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In collaboration with:

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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 the analysis of galaxy surveys (upcoming, **but also** existing)

(see talks on eBOSS by Julian Bautista, on SPHEREx by Olivier Doré, on Euclid by Martin Kunz)

BORG: *Bayesian Origin Reconstruction from Galaxies*

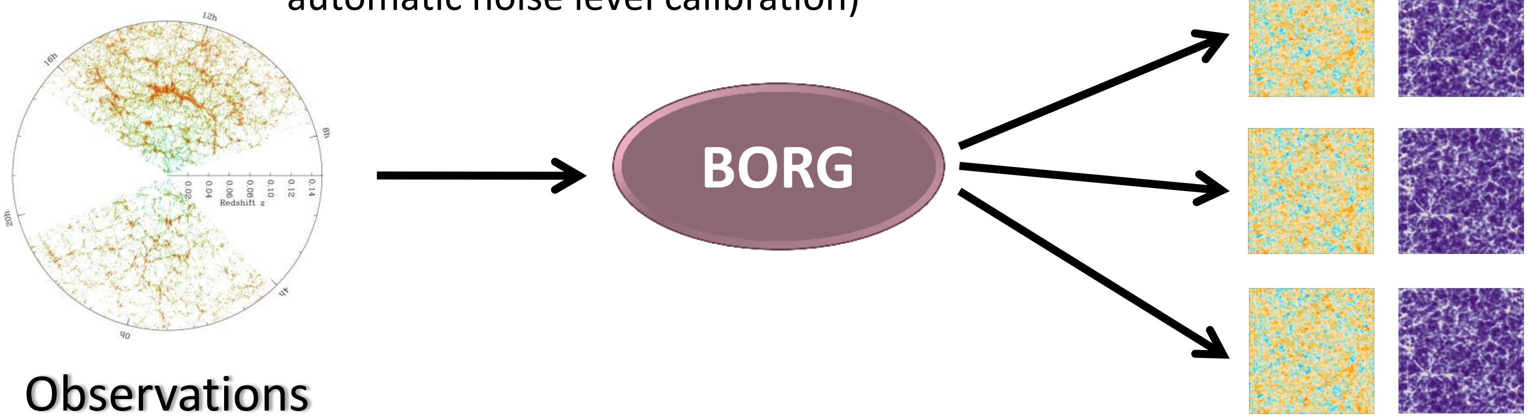
What if we could just fit the entire survey?

The challenge: $d \approx 10^7$!

What makes the problem tractable:

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

(and also: luminosity-dependent galaxy bias, automatic noise level calibration)



Observations

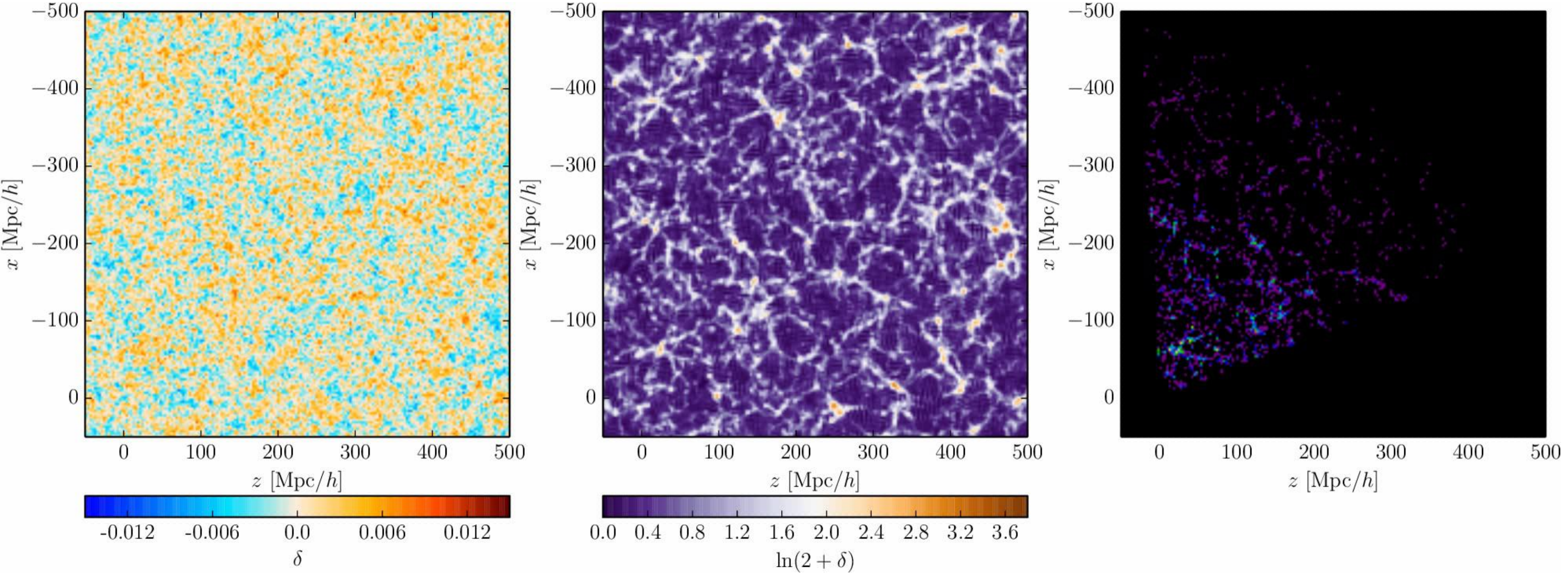
(galaxy catalog + meta-data: selection functions, completeness…)

Samples of possible 4D states

Jasche & Wandelt 2013, arXiv:1203.3639

Chrono-Cosmography

BORG at work – chronocosmography



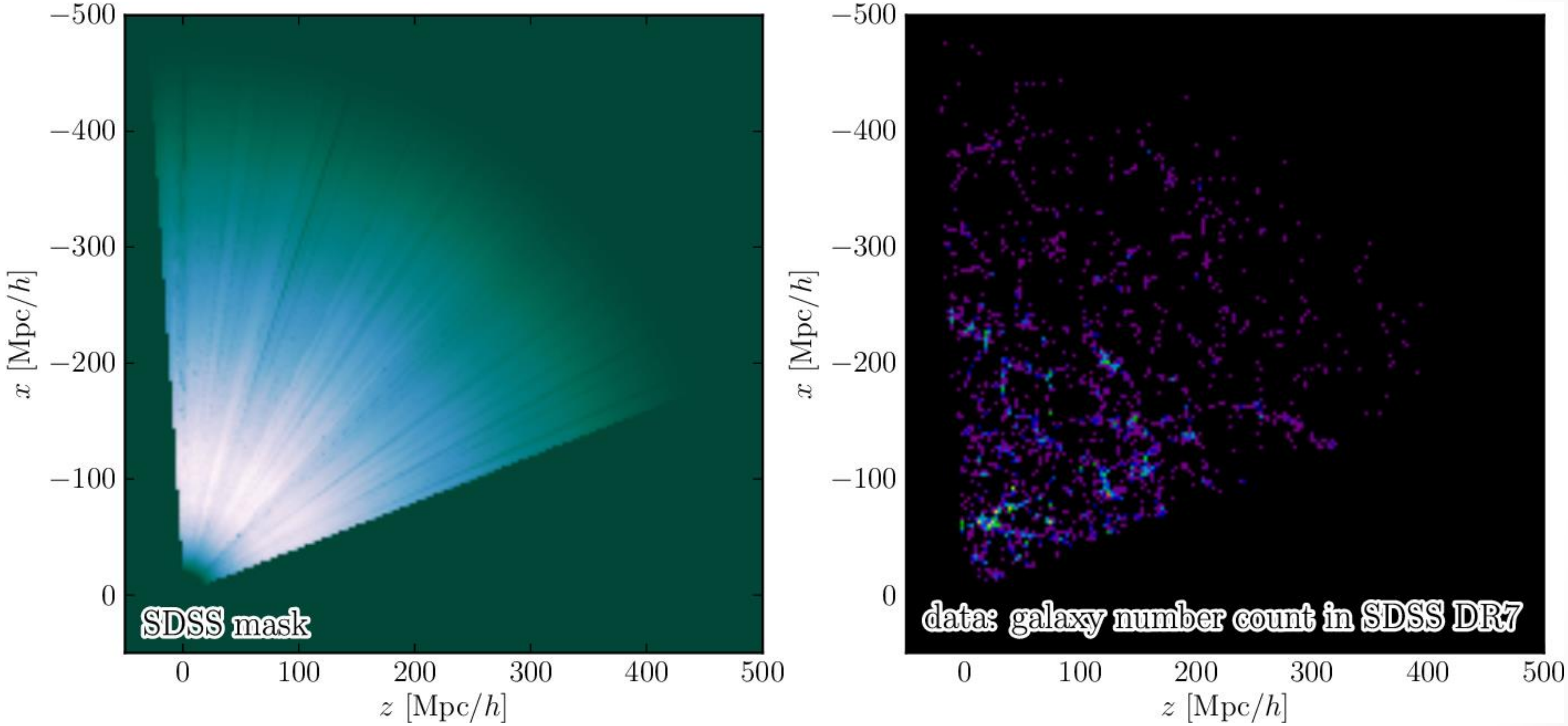
Initial conditions   Final conditions   Observations

The BORG SDSS run:

463,230 galaxies, ≈ 17 millions parameters, 12,000 samples, 3 TB, 10 months on 32 cores

Jasche, FL & Wandelt 2015, arXiv:1409.6308

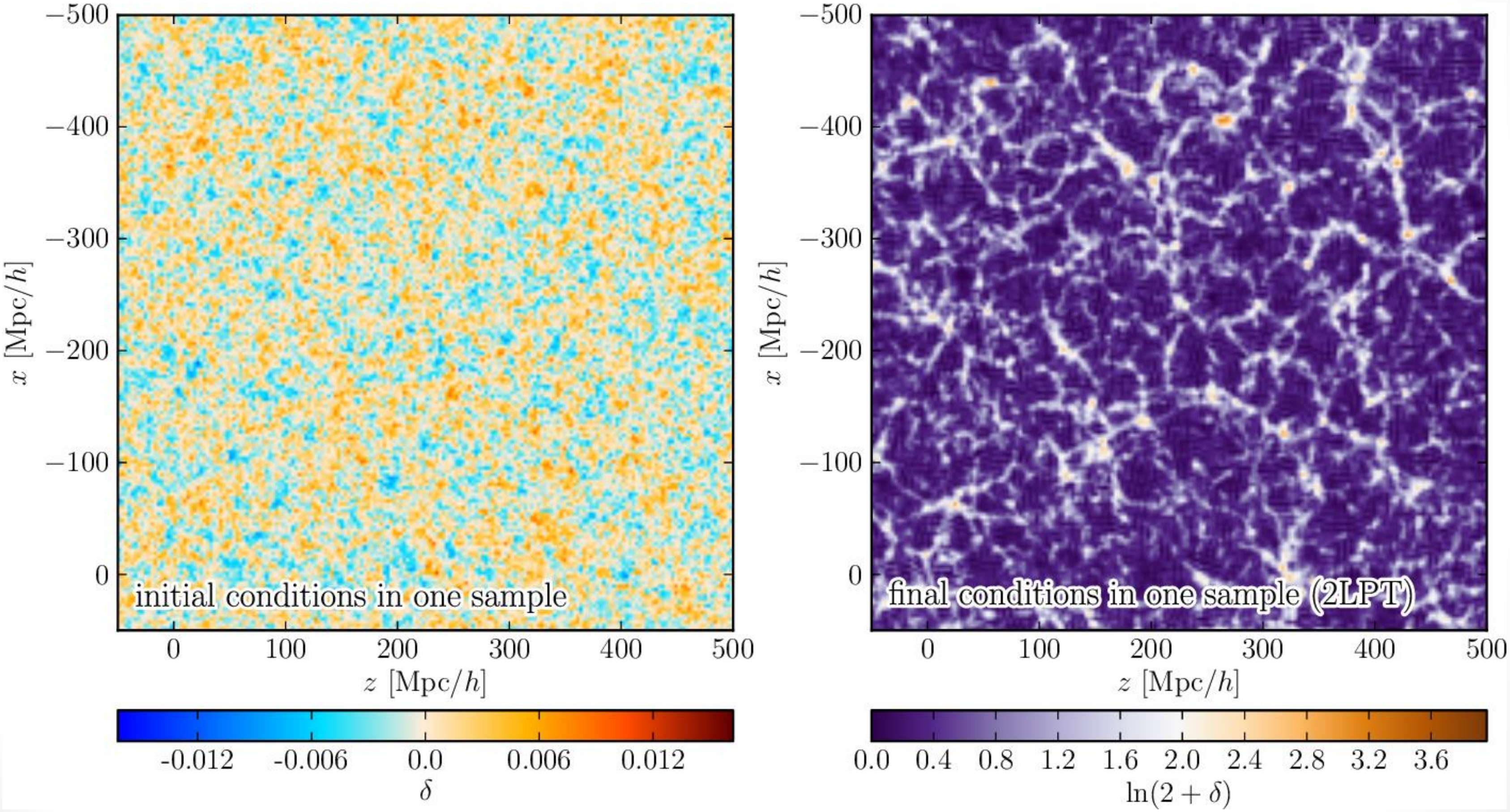
Bayesian chronocosmography from SDSS DR7



Data

Jasche, FL & Wandelt 2015, arXiv:1409.6308

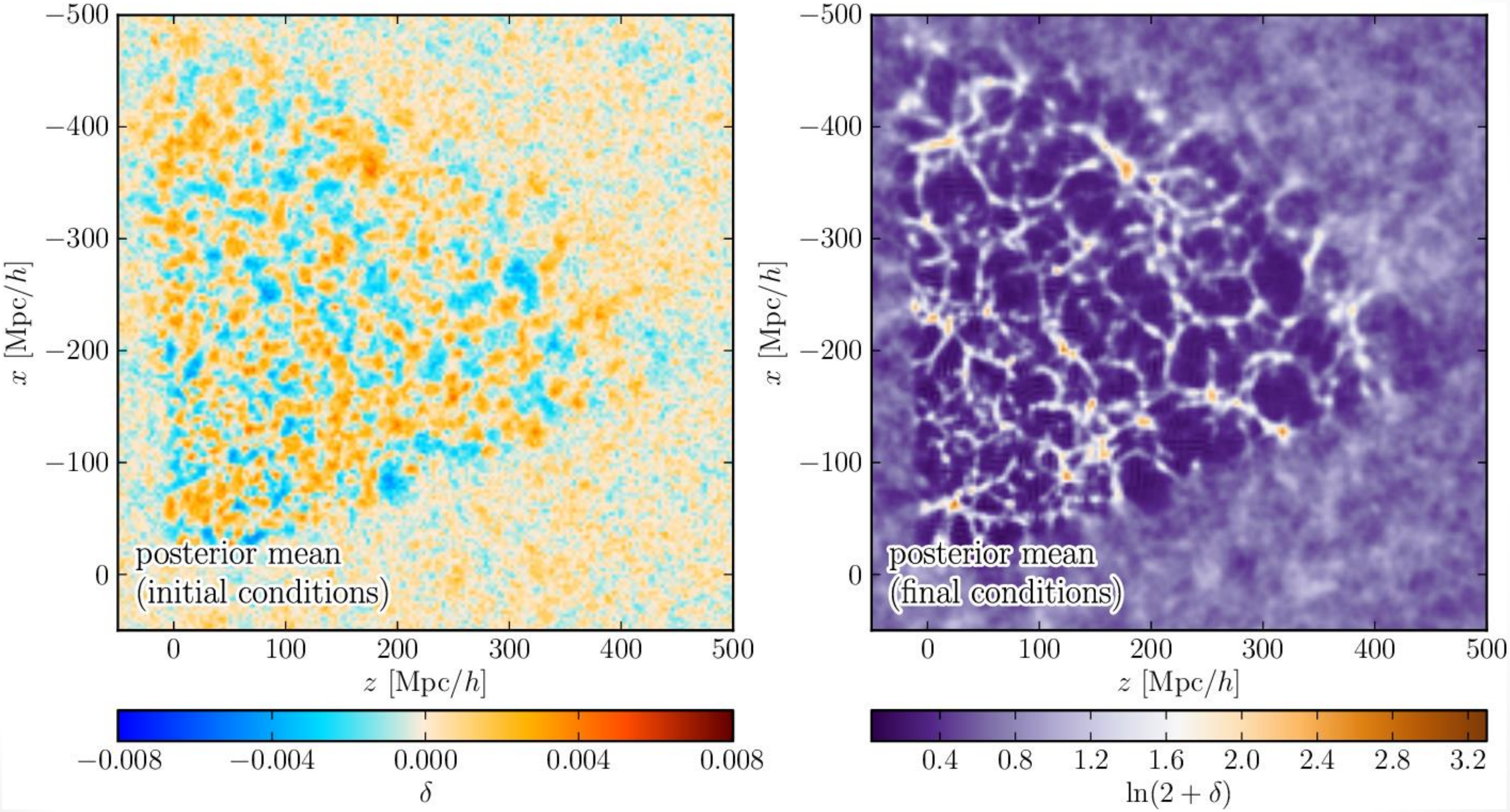
Bayesian chronocosmography from SDSS DR7



One sample

Jasche, FL & Wandelt 2015, arXiv:1409.6308

Bayesian chronocosmography from SDSS DR7



Posterior mean

Jasche, FL & Wandelt 2015, arXiv:1409.6308

Uncertainty quantification

- Uncertainty quantification is **crucial**!
- Can we **propagate uncertainties** to other physical quantities or observables?

Two examples: cosmic web classification and CMB secondary effects

How is the Cosmic Web Woven?

Cosmic web classification procedures

void, sheet, filament, cluster?

- The **T-web**:

uses the sign of μ_1, μ_2, μ_3: eigenvalues of the tidal field tensor, Hessian of the gravitational potential: $T_{ij}(\mathbf{x}) = \partial_i \partial_j \Phi(\mathbf{x})$

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

- **DIVA**:

uses the sign of $\lambda_1, \lambda_2, \lambda_3$: eigenvalues of the shear of the Lagrangian displacement field: $R_{\ell m}(\mathbf{q}) = \partial_m \Psi_\ell(\mathbf{q})$

Lavaux & Wandelt 2010, arXiv:0906.4101

- **ORIGAMI**:

uses the dark matter "phase-space sheet" (number of orthogonal axes along which there is shell-crossing)

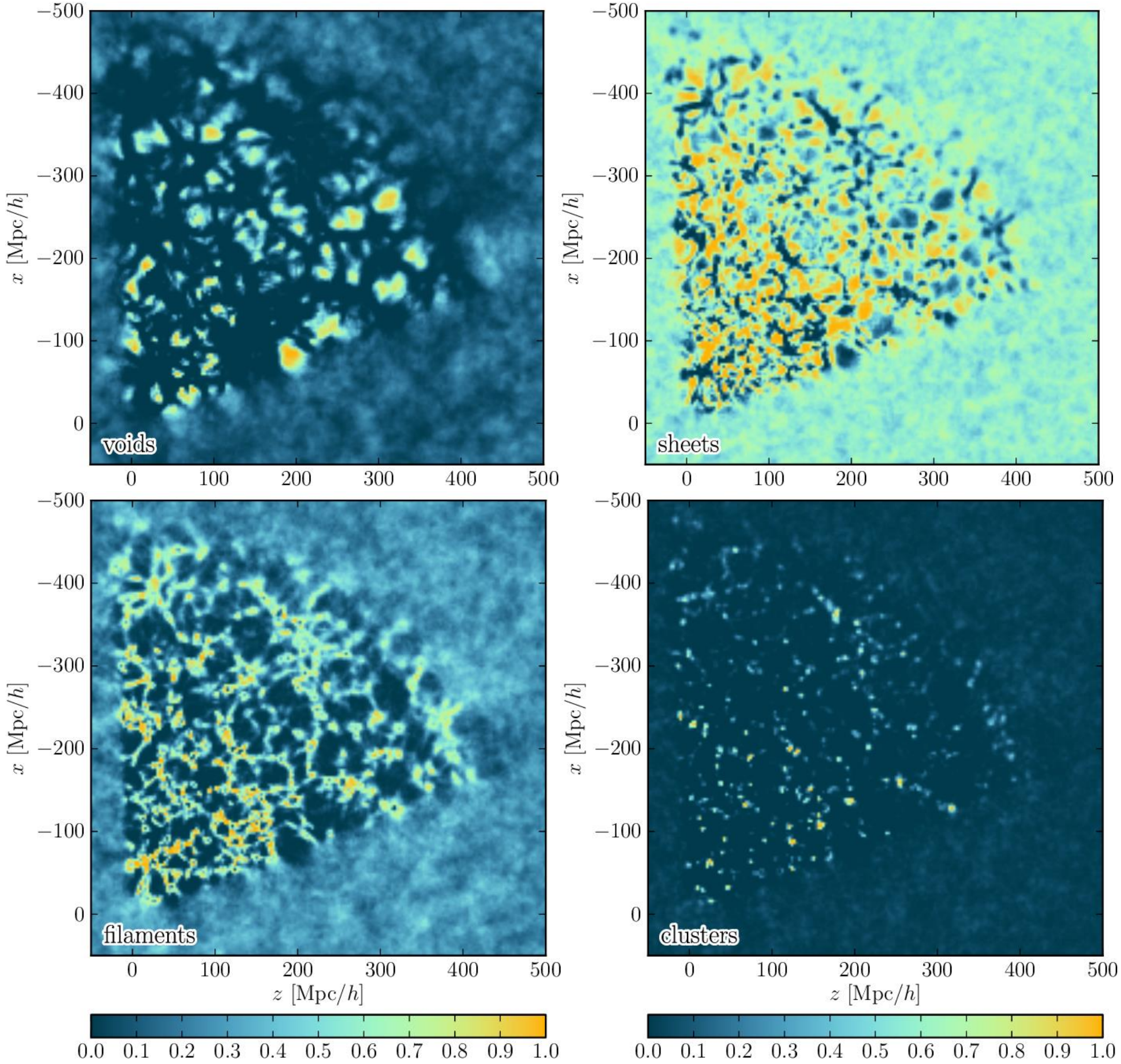
Falck, Neyrinck & Szalay 2012, arXiv:1201.2353

Lagrangian classifiers

now usable in real data!

T-web structures inferred by BORG

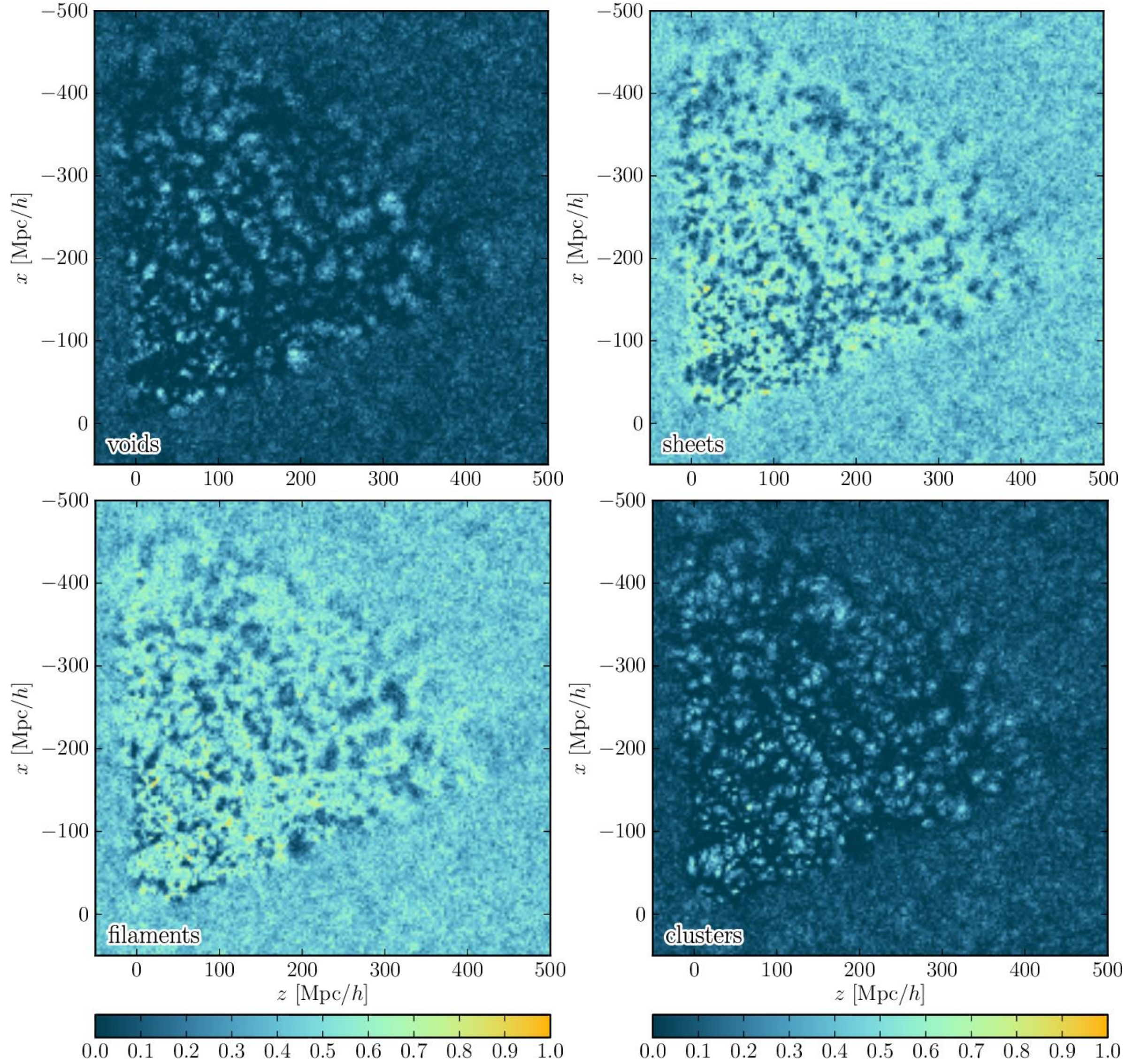
Final conditions



FL, Jasche & Wandelt 2015, arXiv:1502.02690

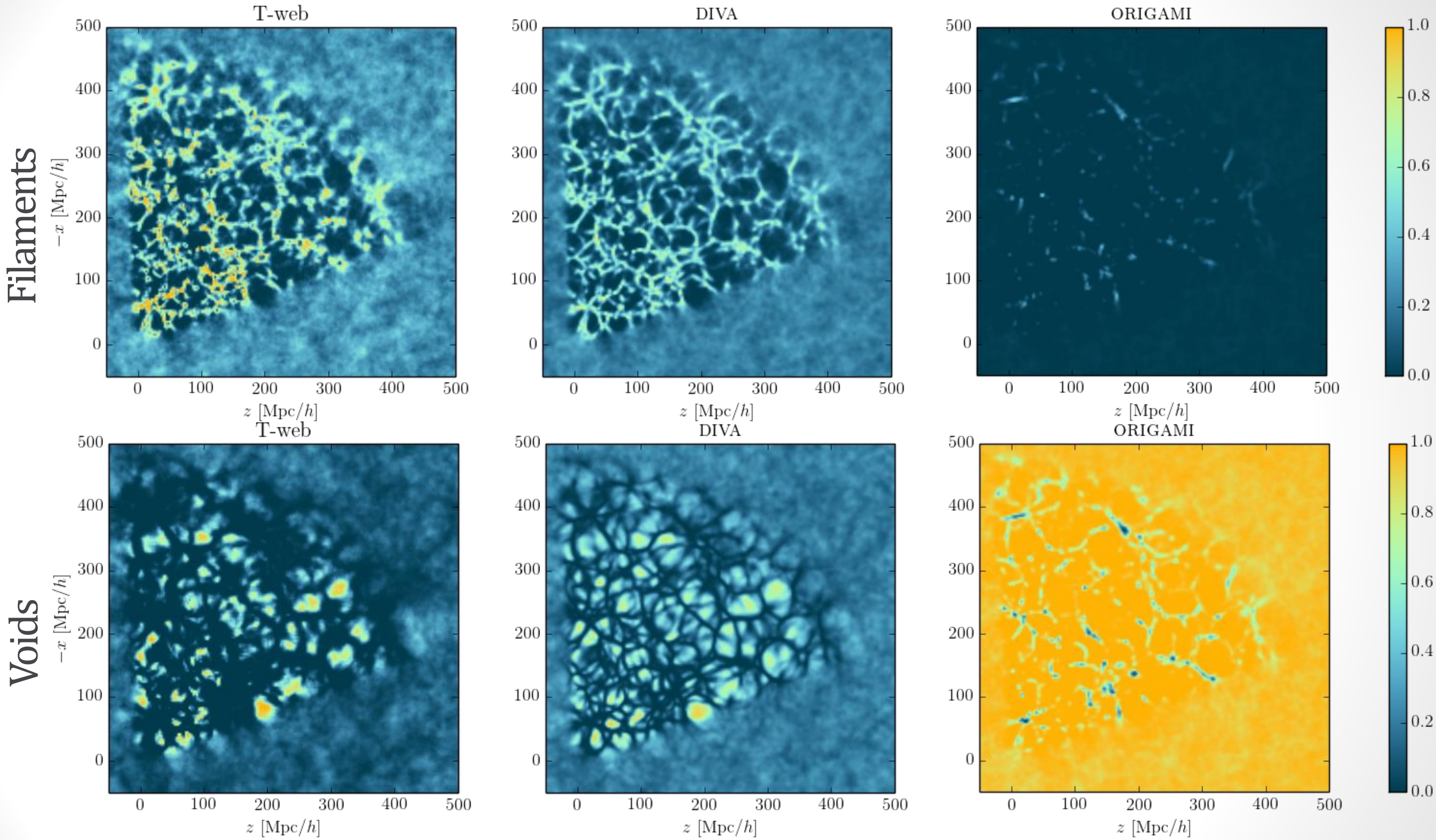
T-web structures inferred by BORG

Initial conditions



FL, Jasche & Wandelt 2015, arXiv:1502.02690

Comparing classifiers and making a decision



FL, Jasche, Lavaux & Wandelt, in prep. (comparing classifiers, with quantitative arguments using information gain)

FL, Jasche & Wandelt 2015, arXiv:1503.00730 (selecting structures via Bayesian decision theory)

Templates for CMB Secondary Effects

Producing LSS-CMB observables

2M++ catalog — Lavaux & Hudson 2011, arXiv:1105.6107, Lavaux & Jasche 2015, submitted

Initial conditions from BORG

↓ **Resimulations with COLA**

Tassev, Zaldarriaga & Eisenstein, arXiv:1301.0322

Constrained realizations with hard-to-compute non-linear dynamics

Gravitational potential	Momentum field	Gas profiles in clusters
↓	↓	↓
Integrated Sachs-Wolfe (iSW) and Rees-Sciama (RS) effects	kinetic Sunyaev-Zel'dovich (kSZ) effect	thermal Sunyaev-Zel'dovich (tSZ) effect

Raytracing algorithm

Cai *et al*. 2010, arXiv:1003.0974

kSZ/tSZ model

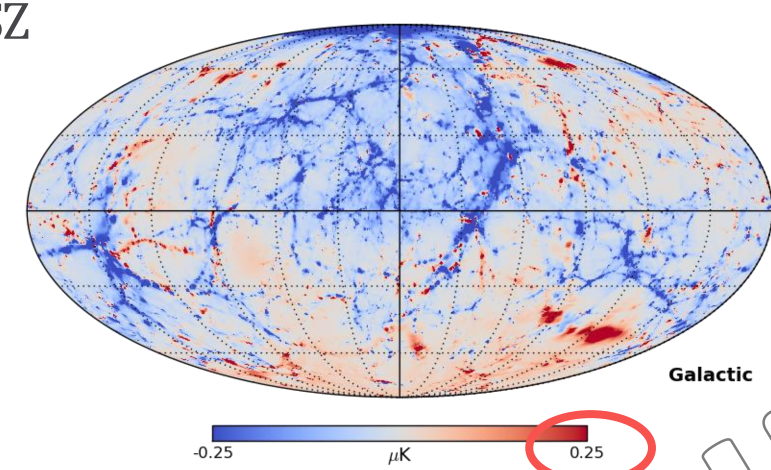
Lavaux, Afshordi & Hudson 2012, arXiv:1207.1721

Better modeling yields higher Signal/Noise ratio

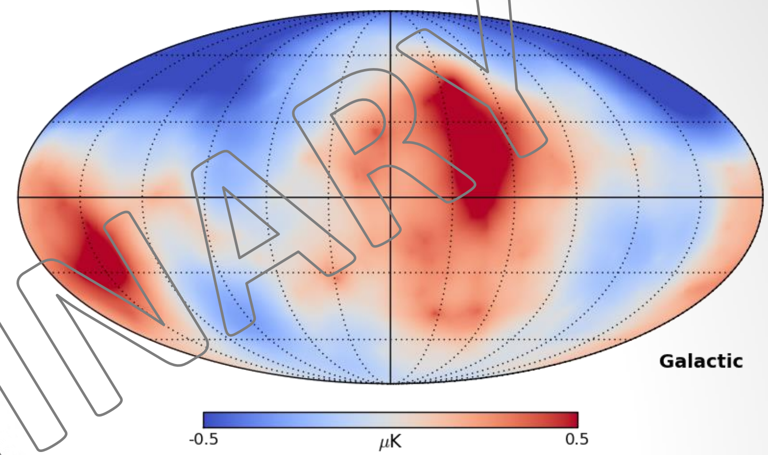
Templates for secondary effects in the CMB

with G. Lavaux, J. Jasche, B. Wandelt

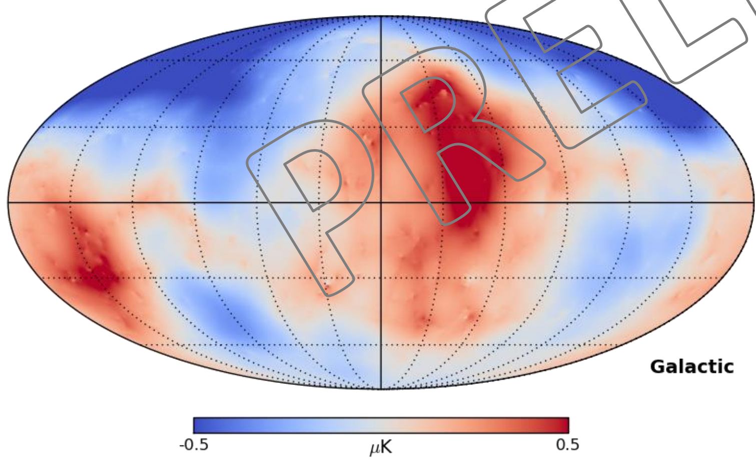
kSZ



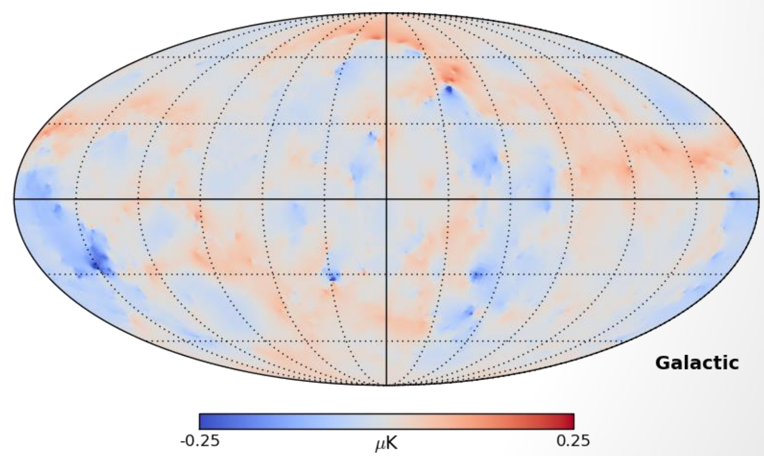
iSW



iSWRS



Only non-linear effects (iSWRS – iSW)



- Simulations in **ONE** BORG sample, raytraced from 0 to 100 Mpc/*h*
- The full posterior is available for Hierarchichal Bayesian analysis

Summary & Conclusions

- A new method for the analysis of galaxy surveys: **Bayesian large-scale structure inference**
  - 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
  - Characterization of the dynamic cosmic web underlying galaxies
  - Cross-correlation of galaxy surveys and CMB data through kSZ/iSW/RS effects

PhD defense on Thursday, September 24th in the IAP amphitheater –
Much more about all these ideas – There will be champagne – Everybody is welcome!