

Cosmic Order and Complexity

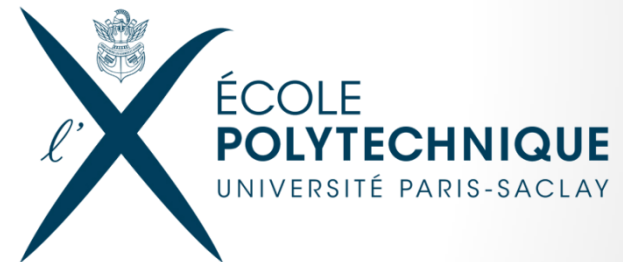
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In collaboration with:

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The Universe as seen by the Particle Zoo

The Whole Set of 12 Epochs

history of the universe

Can't decide? Get the whole set of 12 plushies illustrating the history of the universe.

Set includes:

- Planck
- Inflation
- Electroweak
- Quark-gluon plasma
- Hadron-lepton
- Nucleosynthesis
- Radiation domination
- Matter domination
- Recombination
- Dark ages
- Reionization
- The universe today

Cotton and fleece with poly-fill.

INFLATIONARY ELECTROWEAK QUARK-GLUON PLASMA HADRON LEPTON PHOTON NUCLEOSYNTHESIS MATTER DOMINATION RECOMBINATION DARK AGES REIONIZATION UNIVERSE TODAY PLANCK INFLATIONARY ELECTROWEAK QUARK-GLUON PLASMA HADRON LEPTON PHOTON NUCLEOSYNTHESIS MATTER DOMINATION RECOMBINATION DARK AGES REIONIZATION UNIVERSE TODAY PLANCK INFLATIONARY ELECTROWEAK QUARK-GLUON PLASMA HADRON LEPTON PHOTON NUCLEOSYNTHESIS MATTER DOMINATION RECOMBINATION DARK AGES REIONIZATION UNIVERSE TODAY

The PARTICLE ZOO

<http://www.particlezoo.net/>

Cosmic Order and Complexity

A joint problem!

- How did the Universe begin?
 - What are the statistical properties of the initial conditions?
- 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
- How did the large-scale structure take shape?
 - What is the physics of dark matter and dark energy?

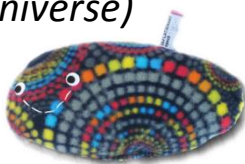
FL, Pisani & Wandelt 2014, arXiv:1403.1260

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

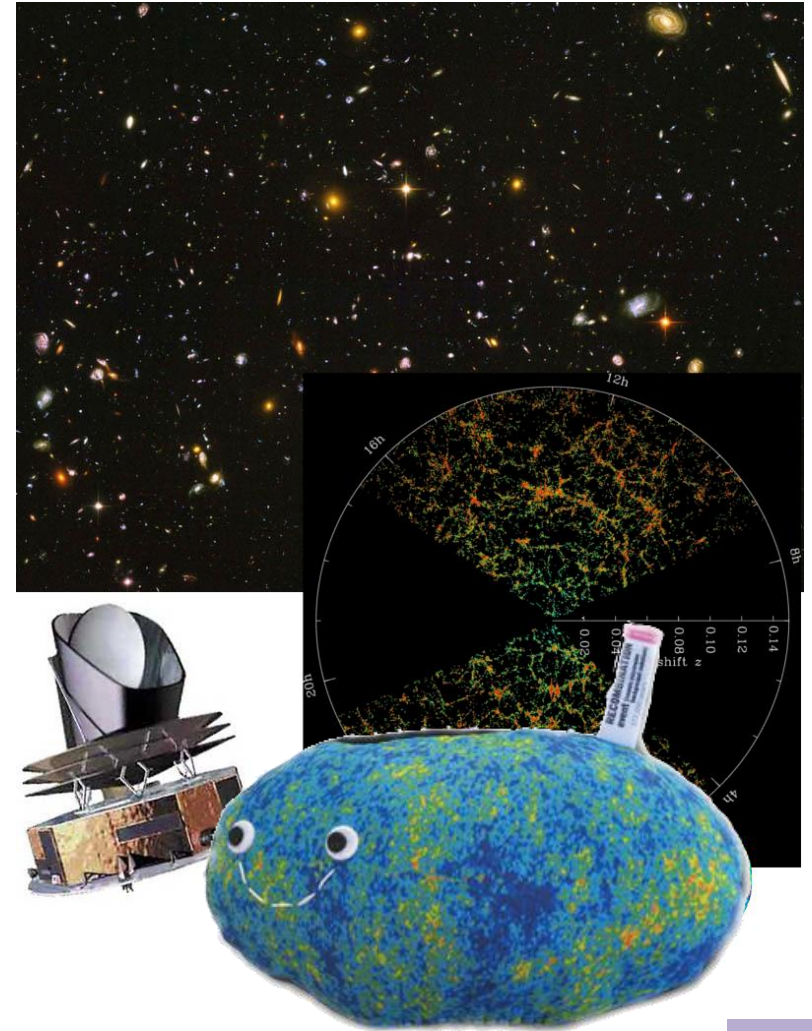
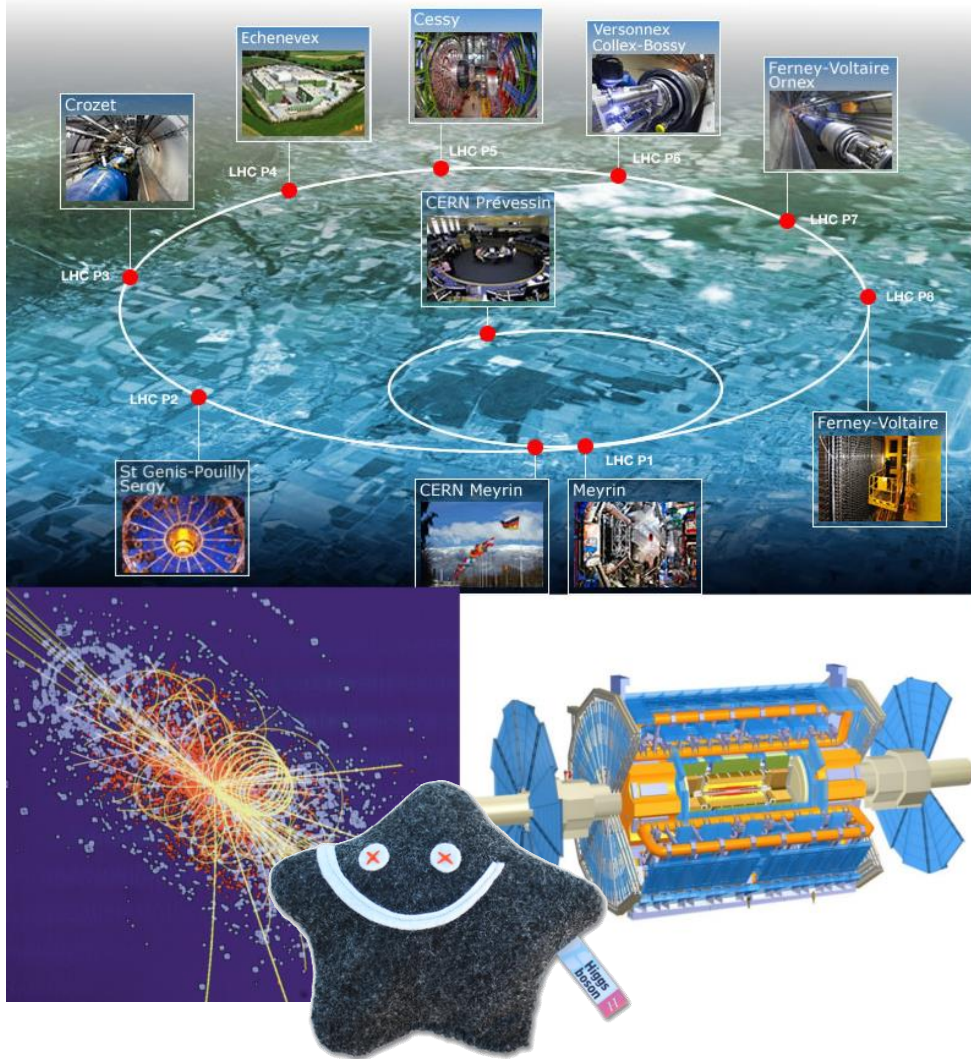
Cosmostatistics of the initial conditions

- **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)
- **“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)



High-energy physics experiments

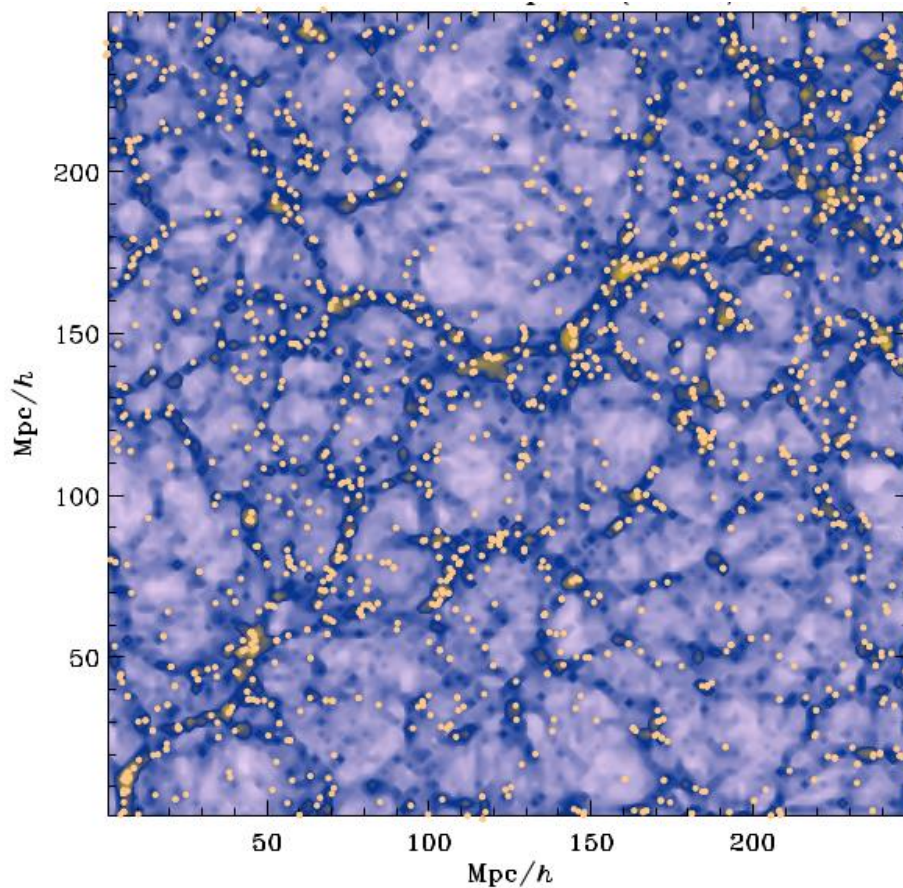


Order in the Universe: the large-scale structure



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

Complexity in the Universe:

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?”

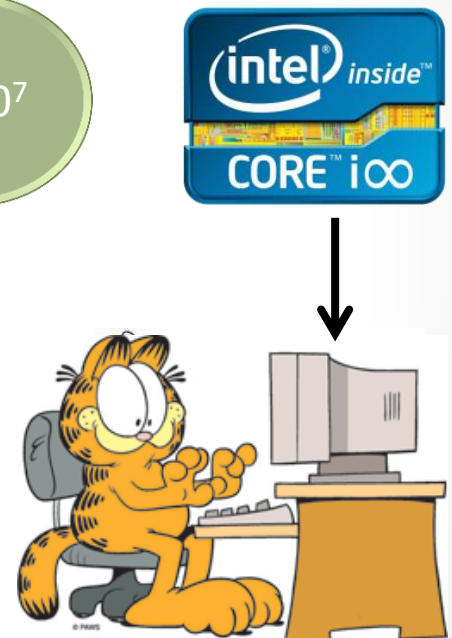
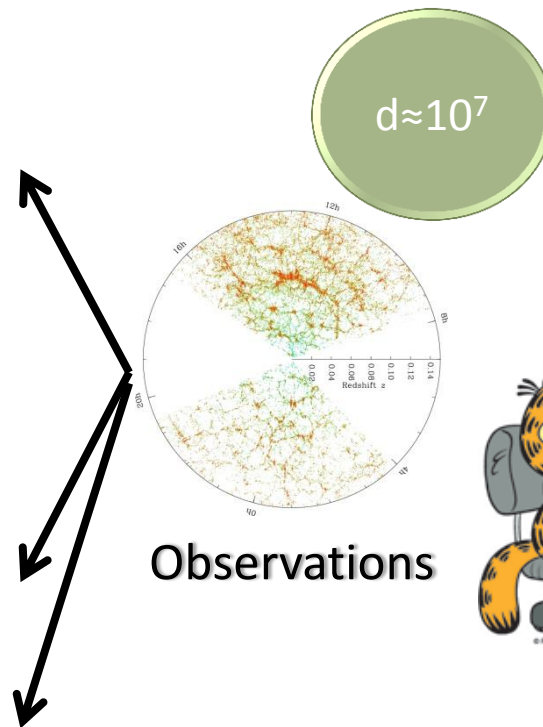
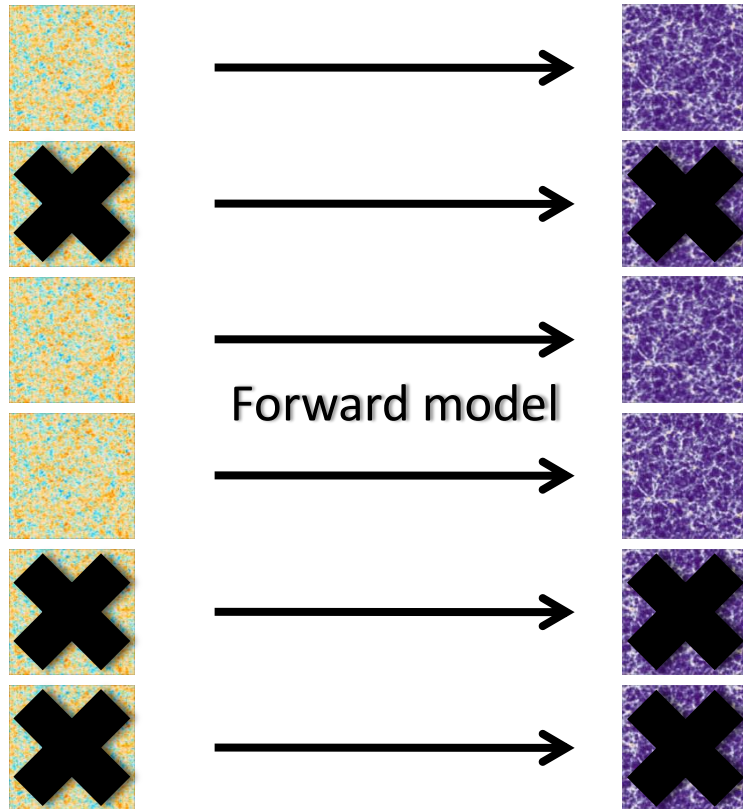


“What is the probability distribution of possible formation histories (signals) compatible with the observations?”

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

Bayesian forward modeling: the ideal scenario

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



We need a *very, very, very*
big computer!

All possible ICs

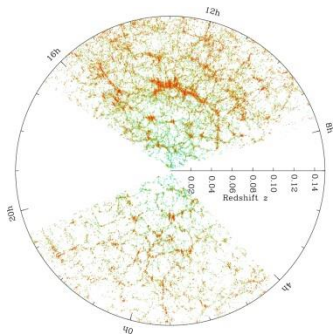
All possible FCs

BORG: *Bayesian Origin Reconstruction from Galaxies*

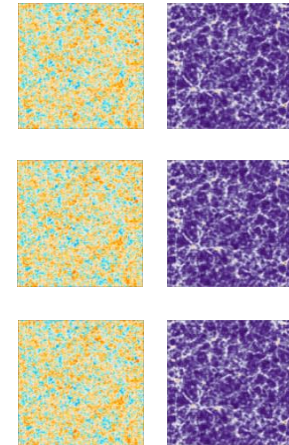


What makes the problem tractable:

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



Observations

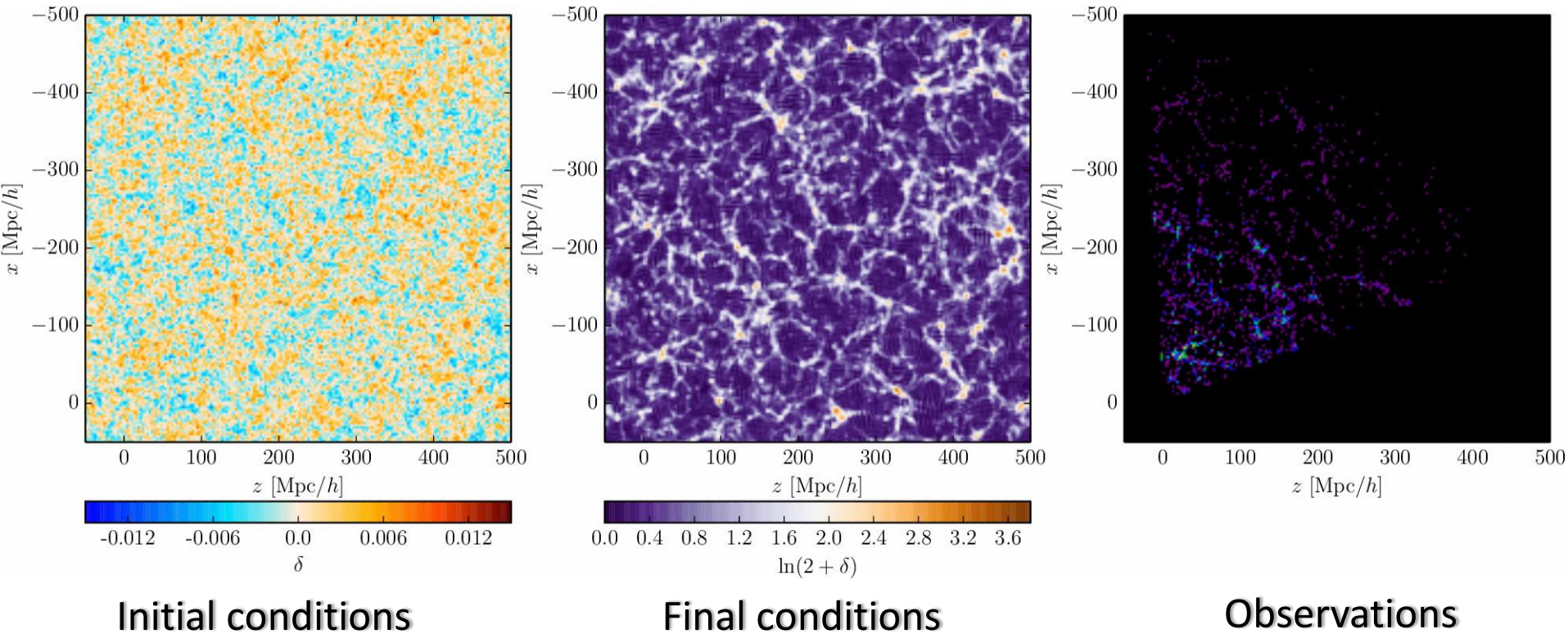


Samples of possible 4D states

Jasche & Wandelt 2013, arXiv:1203.3639
Jasche, FL & Wandelt 2014, arXiv:1409.6308

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

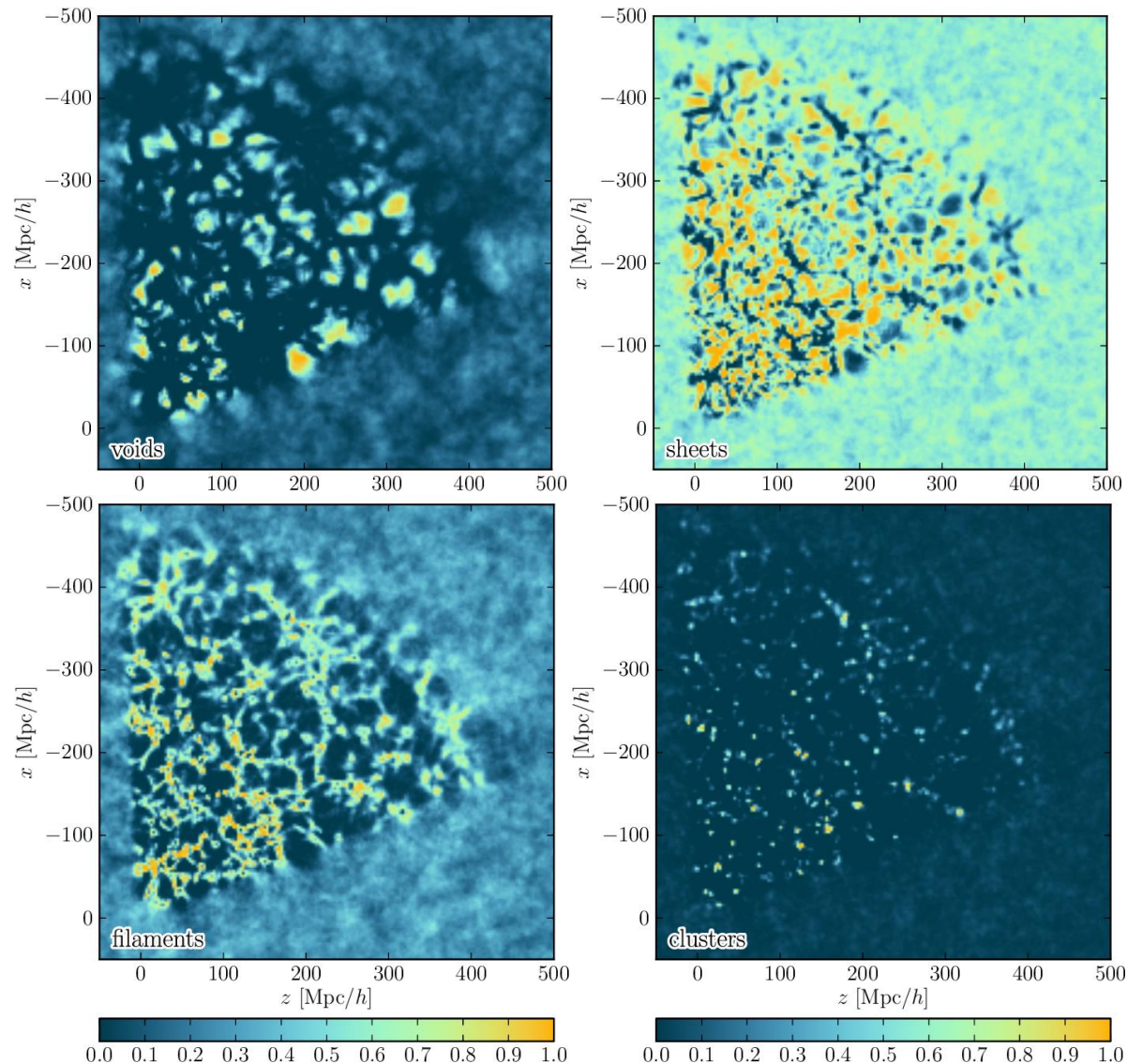
BORG at work – chronocosmography



Jasche, FL & Wandelt 2014, arXiv:1409.6308

Dynamic structures inferred by BORG

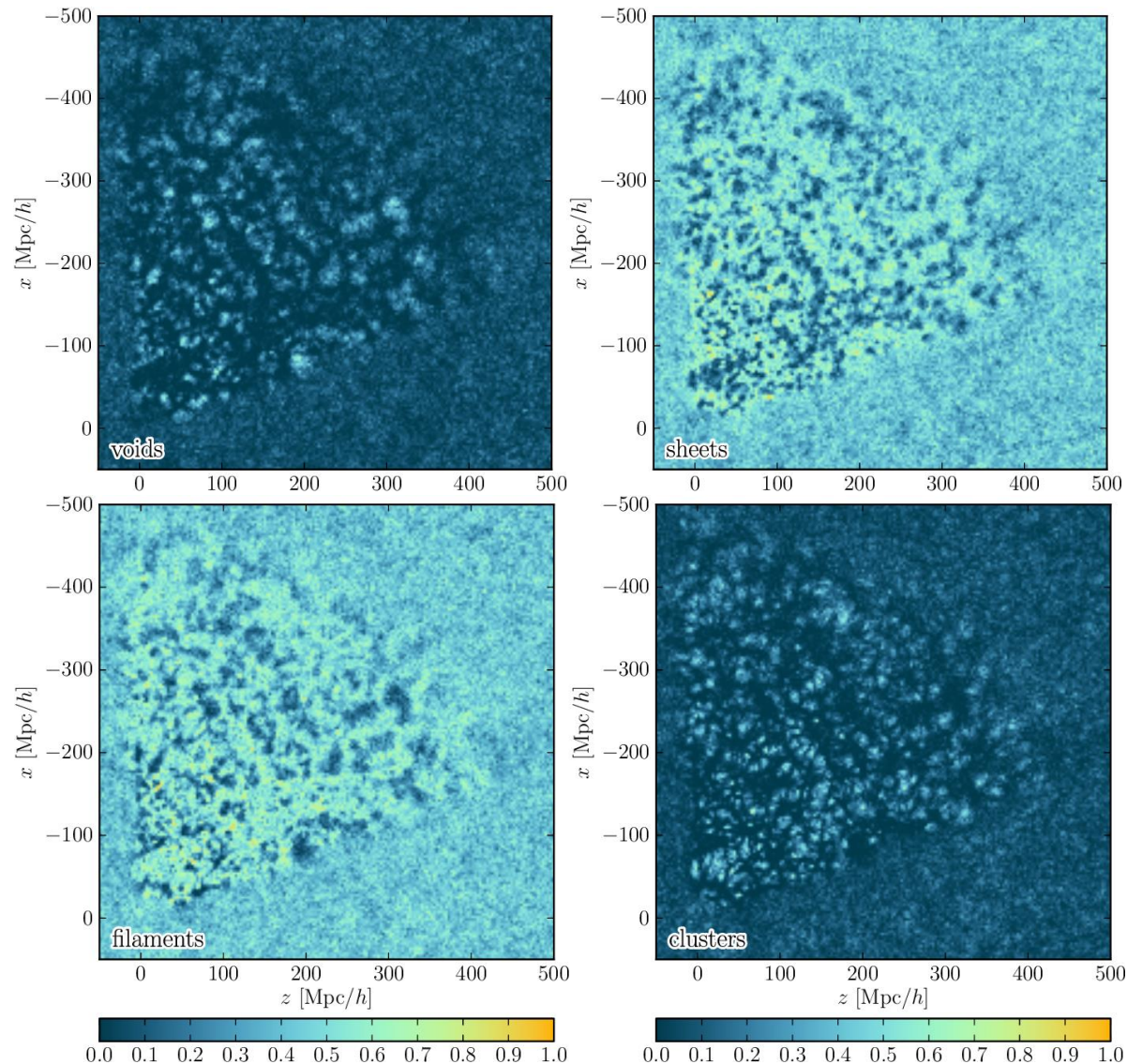
Final conditions



FL, Jasche & Wandelt, in prep. + Chevallard, FL, Jasche & Wandelt, in prep.

Dynamic structures inferred by BORG

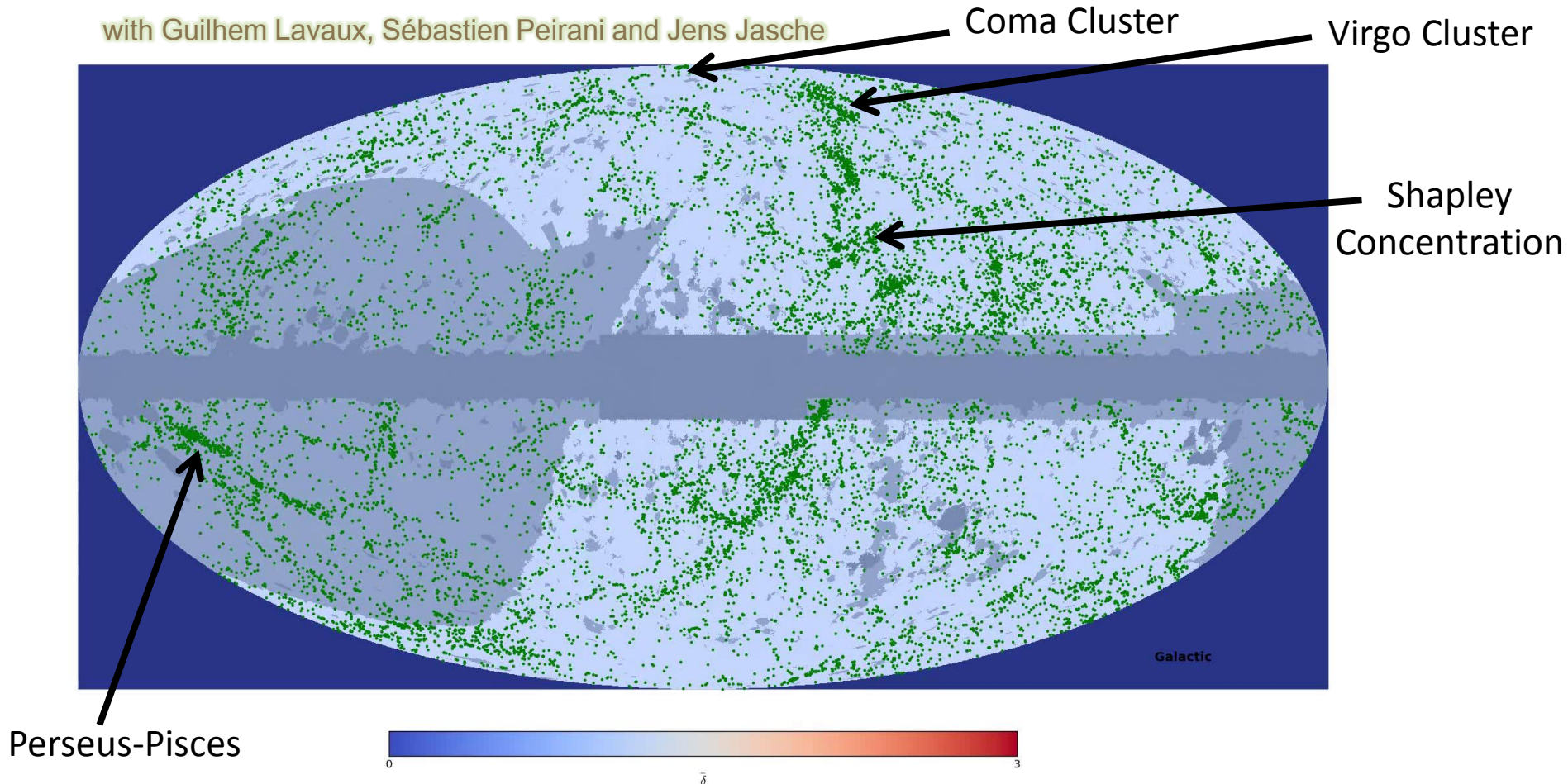
Initial conditions



FL, Jasche & Wandelt, in prep. + Chevallard, FL, Jasche & Wandelt, in prep.

Ongoing project: PLUS: *the Paris Local Universe Simulation*

with Guilhem Lavaux, Sébastien Peirani and Jens Jasche

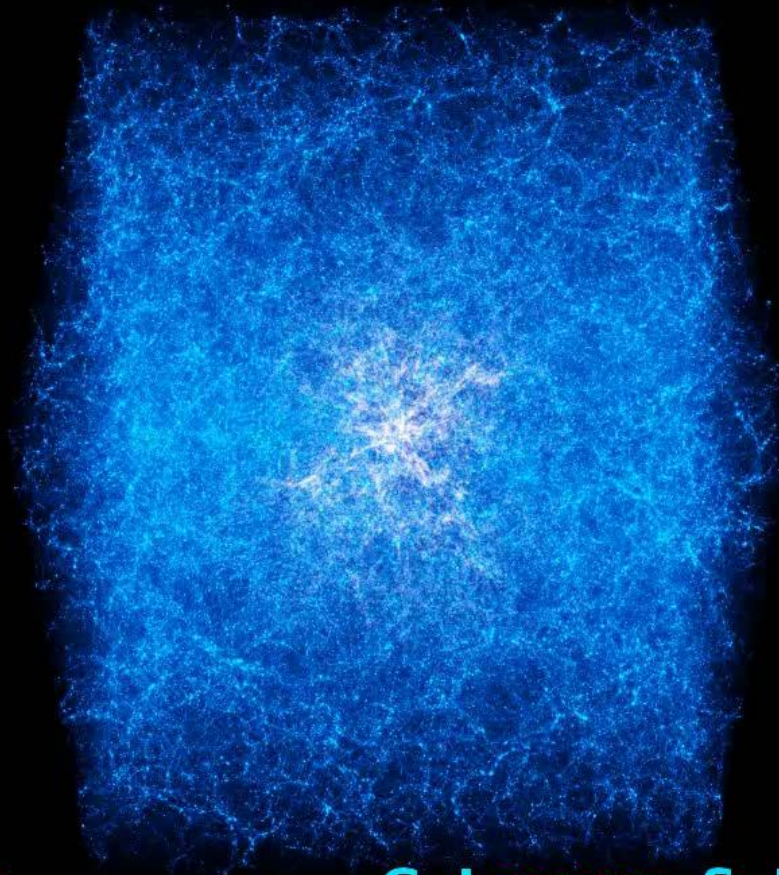


600 Mpc/ h box, 60 Mpc/ h projection, 512^3 dark matter particles

2M++ catalog: Lavaux & Hudson 2011, arXiv:1105.6107 (compiled 2MASS, 6dF, SDSS DR7)

Ongoing project: PLUS: *the Paris Local Universe Simulation*

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PLUS simulation

G. Lavaux, S. Peirani, J. Jasche

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
- Cosmological physical reconstructions of the Universe is becoming feasible. Great science is waiting behind the door:
 - Galaxy environment
 - Baryon acoustic oscillations, structures
 - Primordial non-Gaussianity
 - Isocurvature perturbations
 - Gravitational waves in the large-scale structure...

