Constrained simulations of the dynamic cosmic web

Florent Leclercq

Institut d'Astrophysique de Paris
Institut Lagrange de Paris
École polytechnique ParisTech

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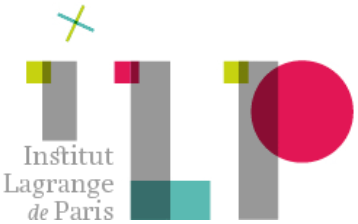
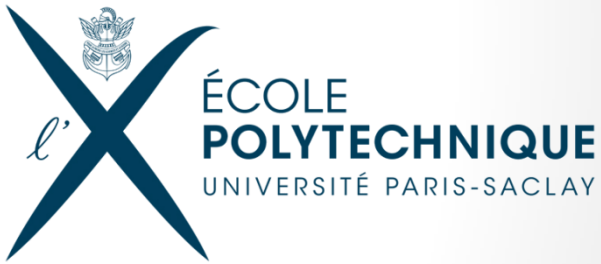




In collaboration with:

Jacopo Chevallard (U. São Paulo), Nico Hamaus (IAP),
Jens Jasche (Excellence Cluster Universe/IAP), Paul M. Sutter (Trieste/IAP/Ohio State U.),
Benjamin Wandelt (IAP/U. Illinois), Matías Zaldarriaga (IAS Princeton)

Outline

Constrained simulations of the dynamic cosmic web

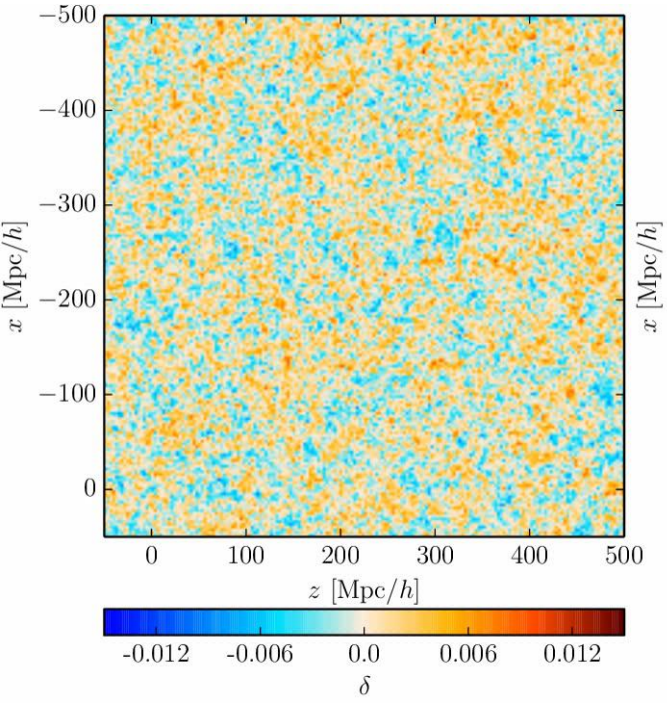
1. "Constrained": data assimilation with BORG
2. "Simulations": non-linear filtering of BORG results, COLA
3. "Cosmic web": dark matter voids and tidal shear classification

1. "CONSTRAINED"

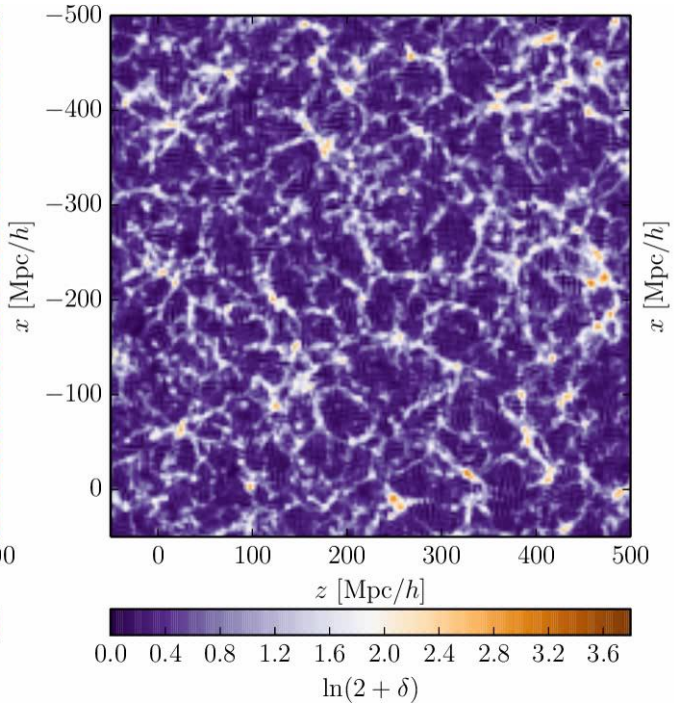
- Data assimilation with BORG
- The BORG SDSS run

J. Jasche, B. Wandelt, arXiv:1203.3639.
Bayesian physical reconstruction of initial conditions from large scale structure surveys
J. Jasche, F. Leclercq, B. Wandelt, arXiv:1409.6308.
Past and present cosmic structure in the SDSS DR7 main sample

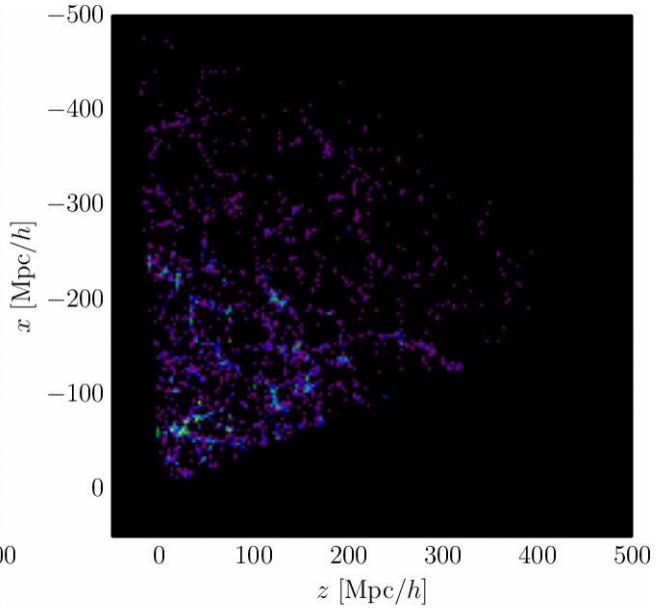
BORG at work – chronocosmography



Initial conditions



Final conditions



Observations

Jasche, FL & Wandelt 2014, arXiv:1409.6308

2. "Simulations"

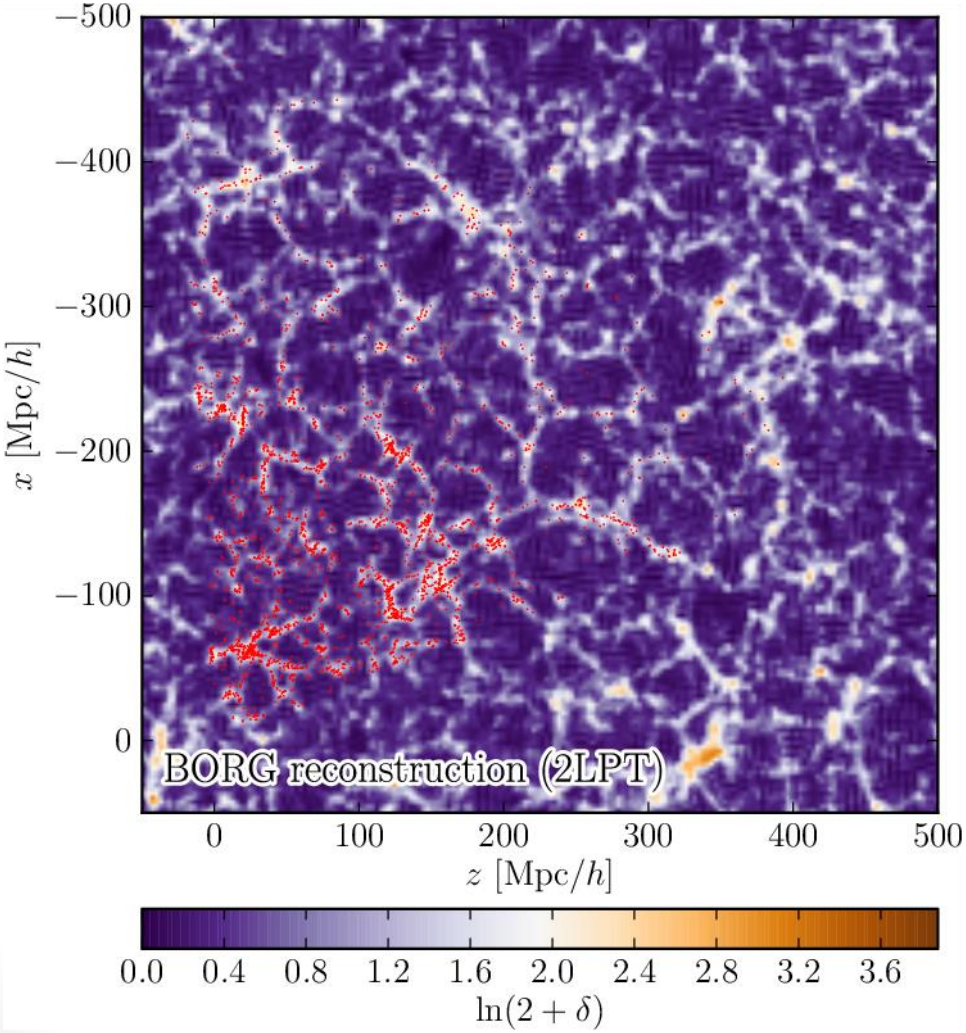
- Non-linear filtering of BORG results
- The COLA method

F. Leclercq, J. Jasche, P. M. Sutter, N. Hamaus, B. Wandelt, arXiv:1410.0355.
Dark matter voids in the SDSS galaxy survey

S. Tassev, M. Zaldarriaga, D. Eisenstein, arXiv:1301.0322.
Bayesian analysis of the dynamic cosmic web in the SDSS galaxy survey

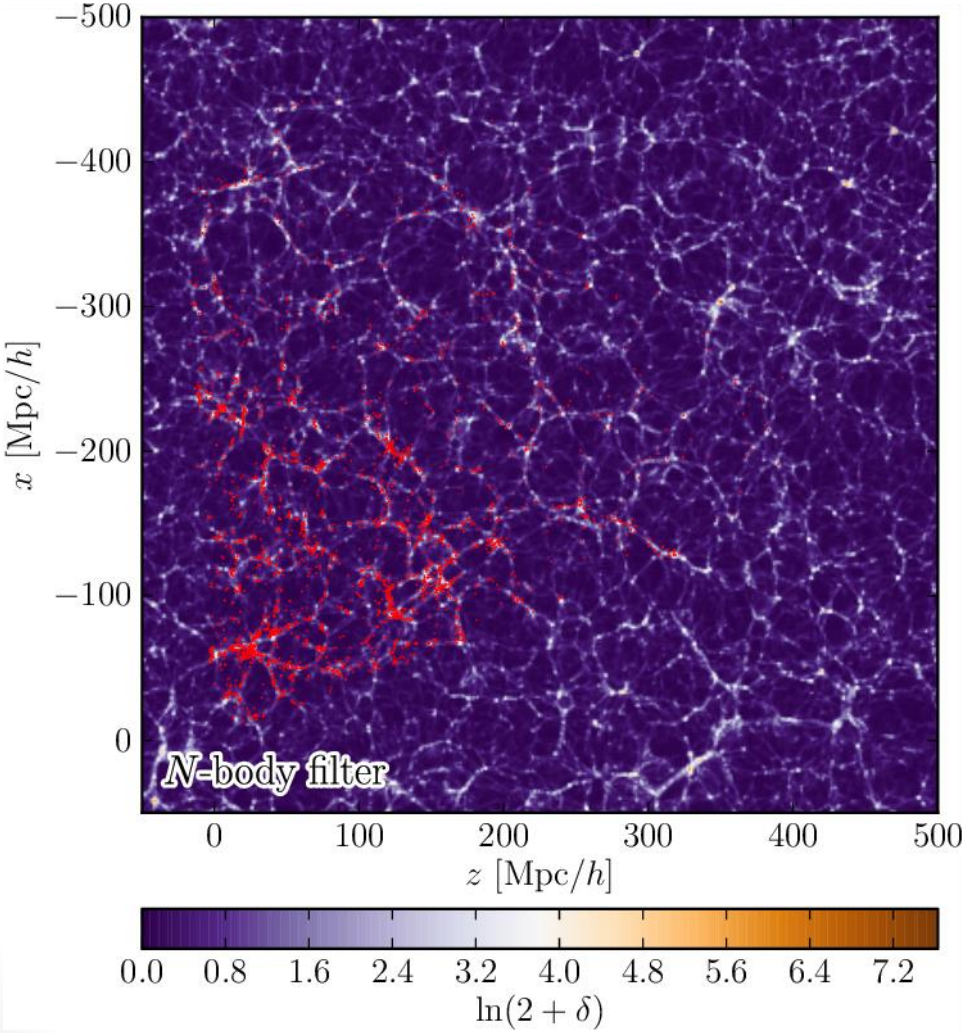
S. Tassev, D. Eisenstein, B. Wandelt, M. Zaldarriaga, in prep. + F. Leclercq, B. Wandelt, *et al.*, in prep.
Extending the N-body Comoving Lagrangian Acceleration Method to the Spatial Domain

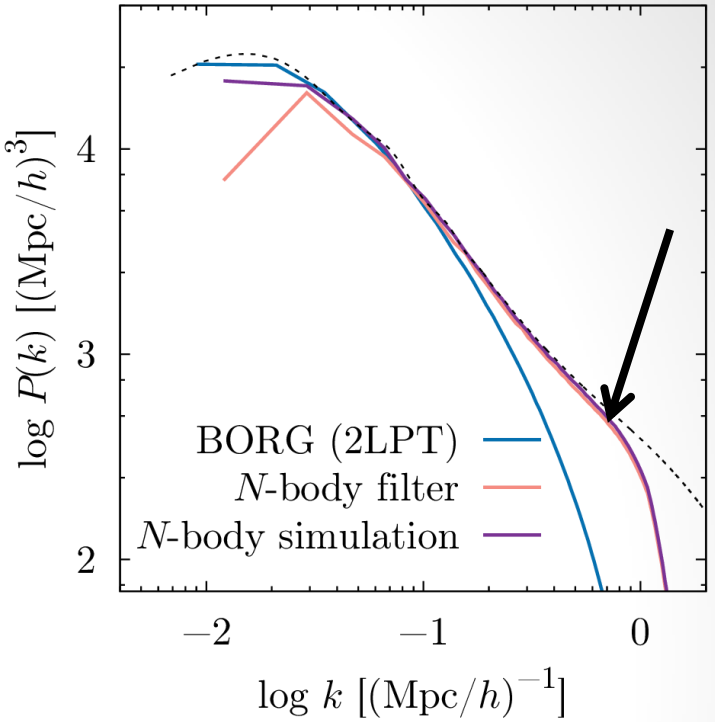
Non-linear filtering



FL, Jasche, Sutter, Hamaus & Wandelt 2014, arXiv:1410.0355 + Jasche, FL, Romano-Diaz & Wandelt, in prep.

Non-linear filtering





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 2014, arXiv:1410.0355 + Jasche, FL, Romano-Diaz & Wandelt, in prep.

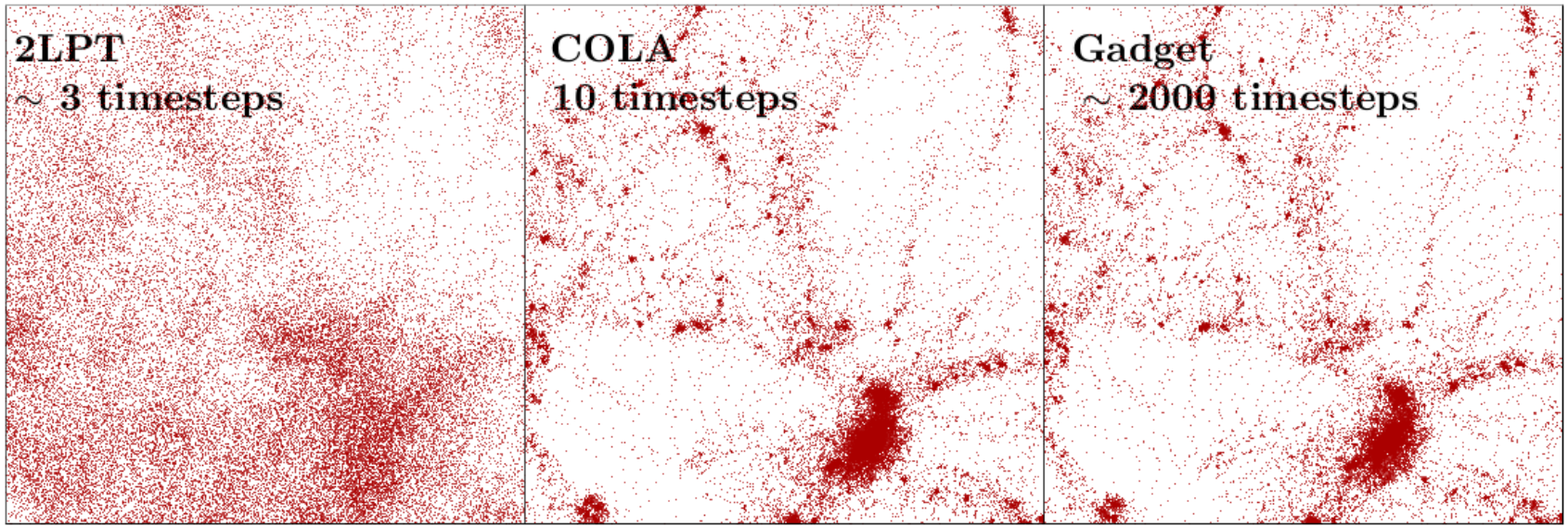
COLA: *COmoving Lagrangian Acceleration*

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

Tassev & Zaldarriaga 2012, arXiv:1203.5785

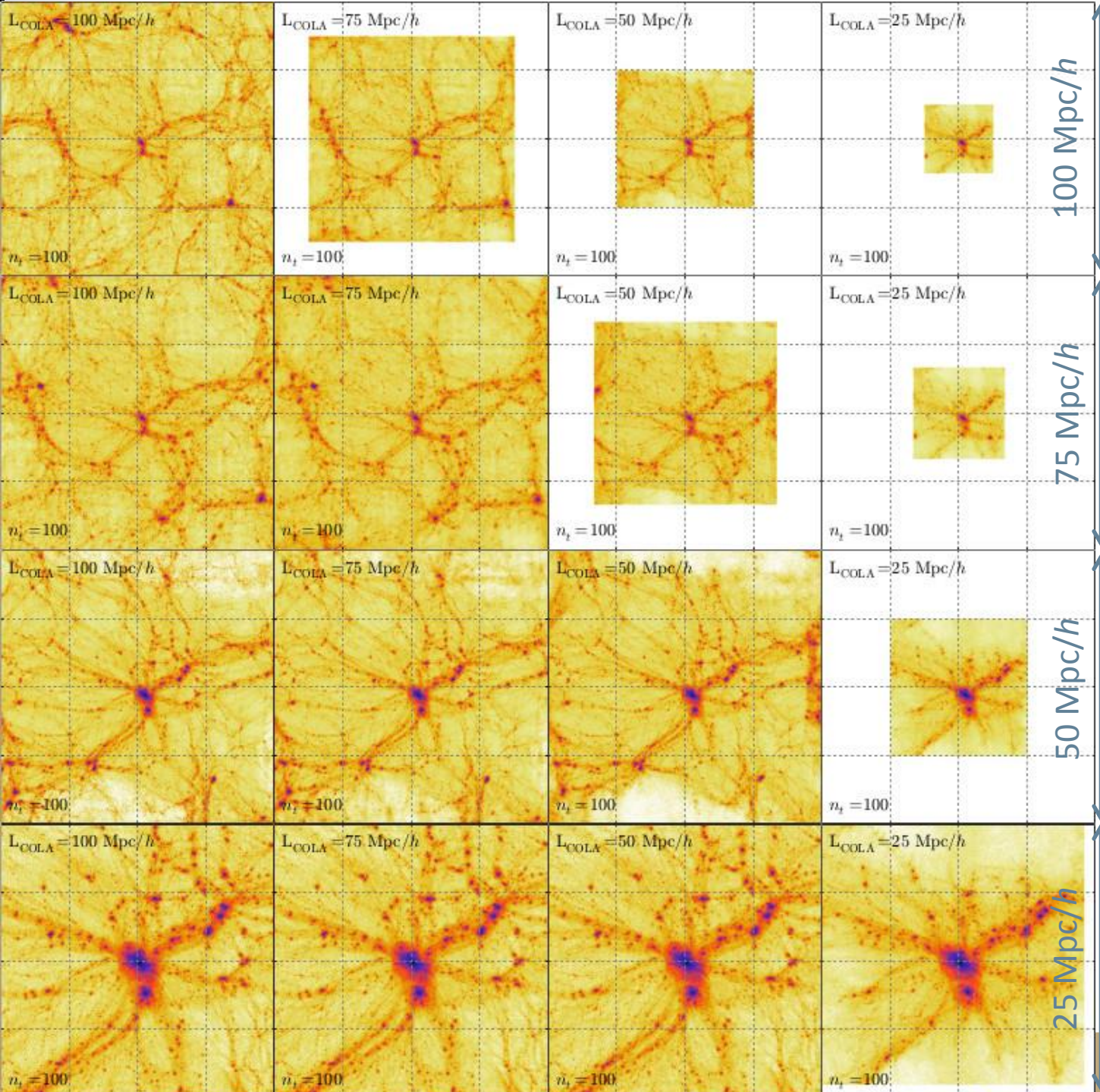
- Time-stepping (omitted constants and Hubble expansion):

Standard: $\partial_\tau^2 \mathbf{s} = -\nabla\Phi$ ⇒ Modified: $\partial_\tau^2 \mathbf{s}_{\rm MC} = \partial_\tau^2(\mathbf{s} - \mathbf{s}_{\rm LPT}) = -\nabla\Phi - \partial_\tau^2 \mathbf{s}_{\rm LPT}$



Original COLA "in time"

Tassev, Zaldarriaga & Einsenstein 2013, arXiv:1301.0322

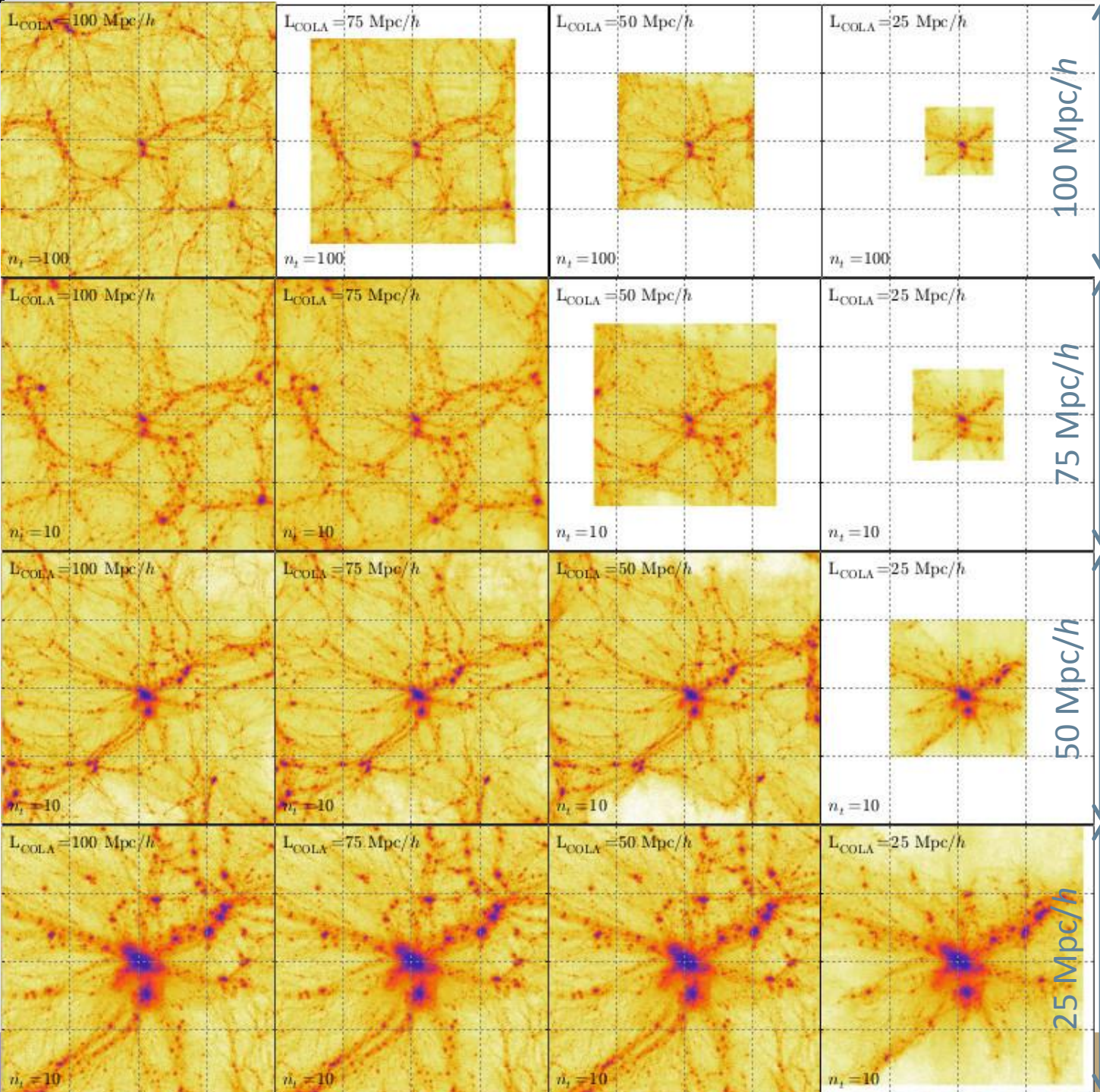


Extending COLA

New COLA "in space"

Tassev, Eisenstein, Wandelt & Zaldarriaga, in prep.

+ FL, Wandelt, *et al.*, in prep.



Extending COLA

New COLA "in space and time"

Tassev, Eisenstein, Wandelt & Zaldarriaga, in prep.

+ FL, Wandelt, *et al.*, in prep.

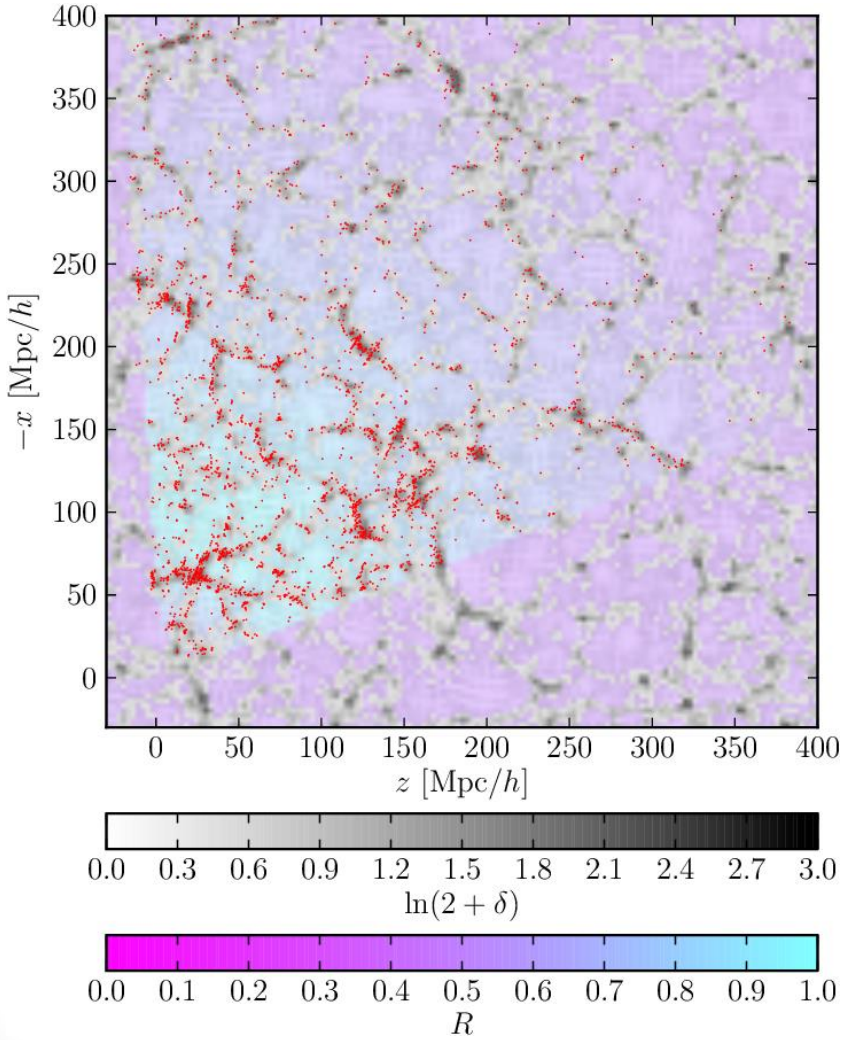
3. "Cosmic Web"

- Dark matter voids in the SDSS
- Tidal shear analysis in the SDSS, dynamic structure type classification

F. Leclercq, J. Jasche, P. M. Sutter, N. Hamaus, B. Wandelt, arXiv:1410.0355.
Dark matter voids in the SDSS galaxy survey

F. Leclercq, J. Jasche, B. Wandelt, in prep.
Bayesian analysis of the dynamic cosmic web in the SDSS galaxy survey

Dark matter voids in the SDSS



- How?

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

based on ZOBOV: Neyrinck 2007, arXiv:0712.3049

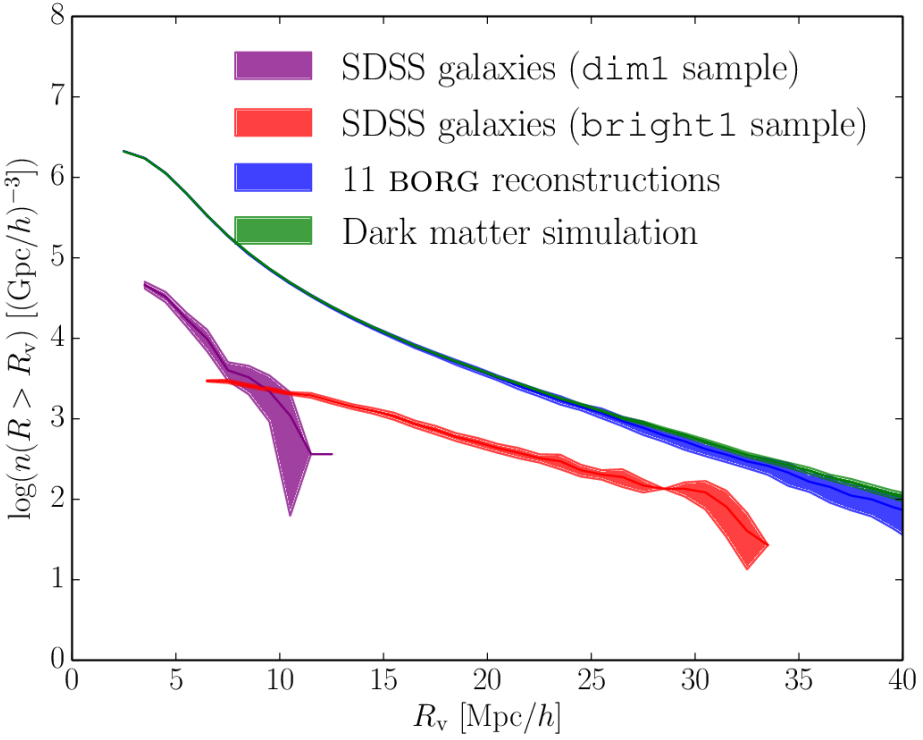
- Why?

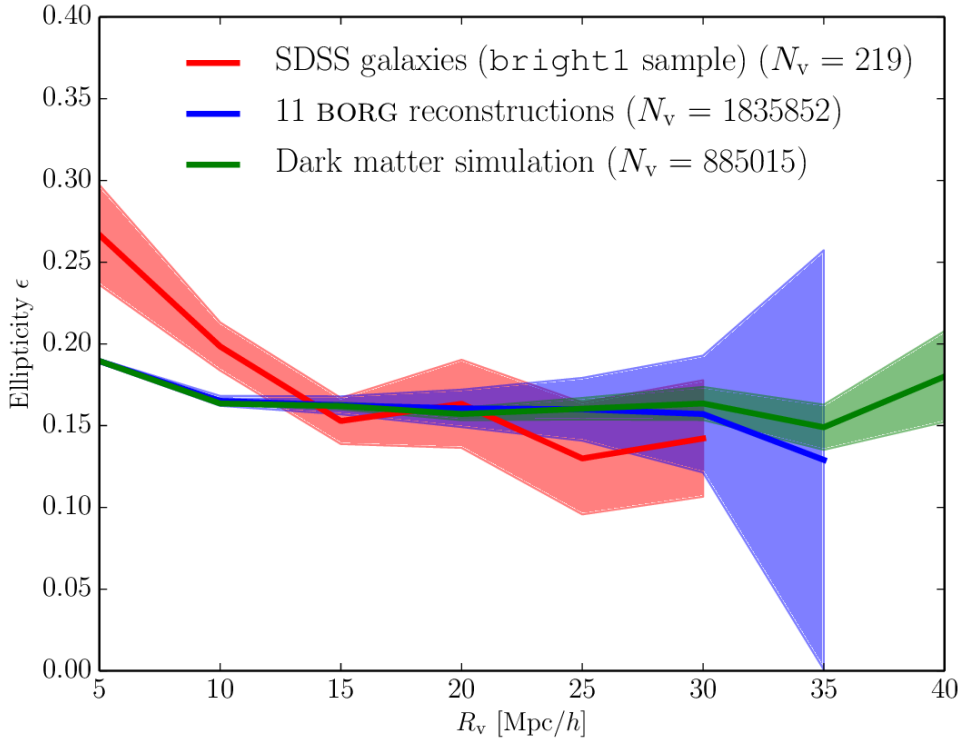
Sparsity & Bias

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

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

Dark matter void properties





All catalogs will be made publicly available at

www.cosmicvoids.net (and they are already ready for the workshop)

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

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: $\lambda_1 > 0$ and $\lambda_2, \lambda_3 < 0$
  - Filaments: $\lambda_1, \lambda_2 > 0$ and $\lambda_3 < 0$
  - Clusters: $\lambda_1, \lambda_2, \lambda_3 > 0$

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

see also:

- Extensions:

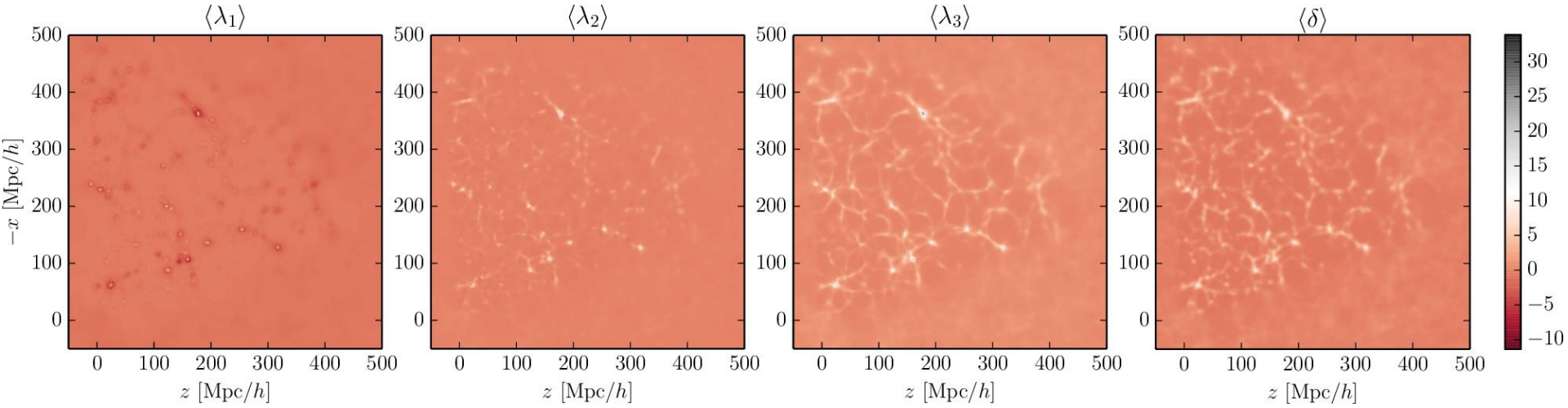
Forero-Romero *et al*. 2008, arXiv:0809.4135
Hoffman *et al*. 2012, arXiv:1201.3367

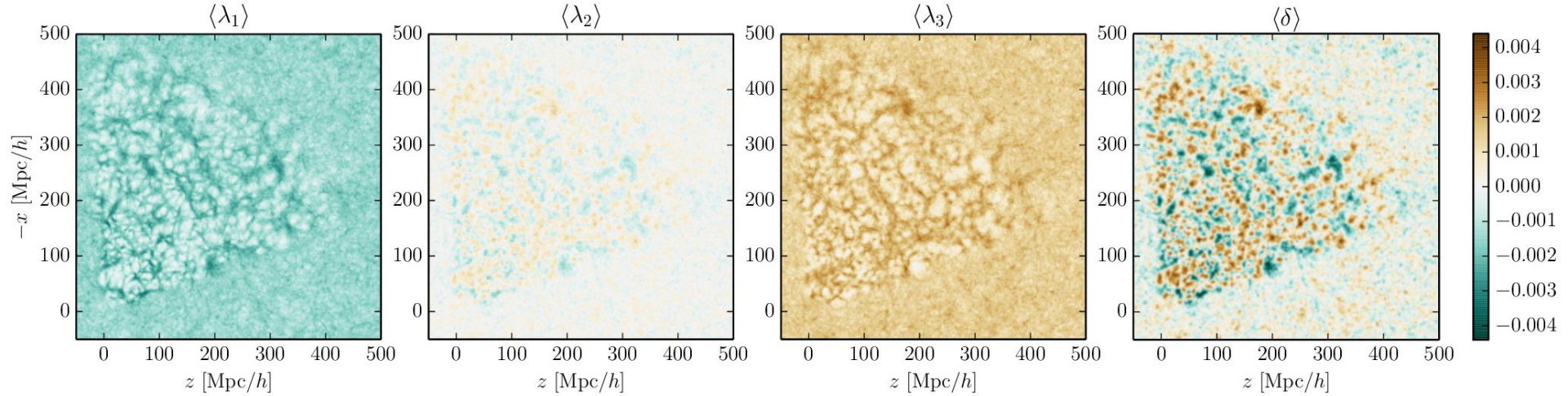
- Similar web classifiers:

DIVA, Lavaux & Wandelt 2010, arXiv:0906.4101
ORIGAMI, Falck, Neyrinck & Szalay 2012, arXiv:1201.2353

Tidal shear analysis

Final conditions



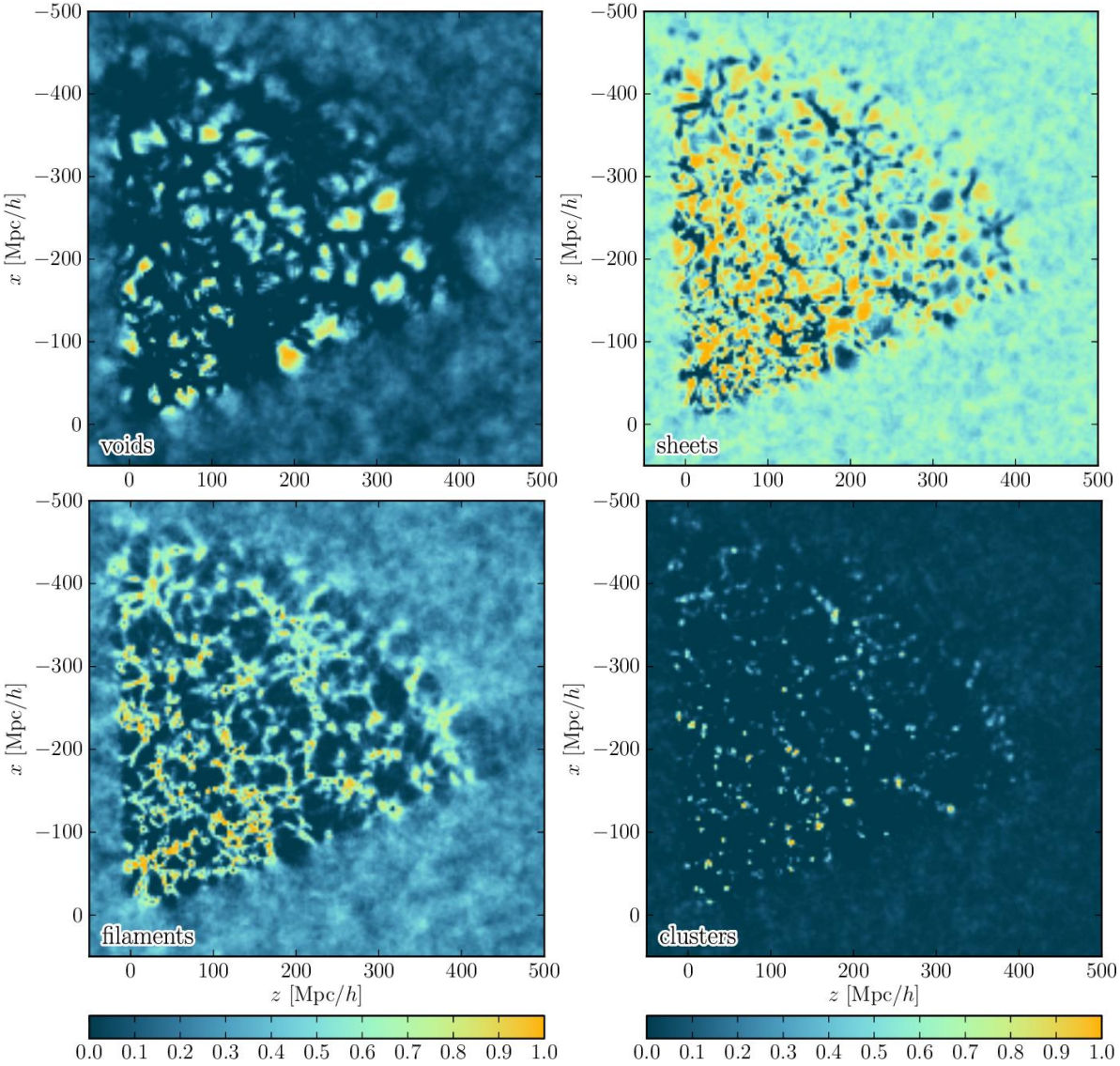


FL, Jasche & Wandelt, in prep.

Initial conditions

Dynamic structures inferred by BORG

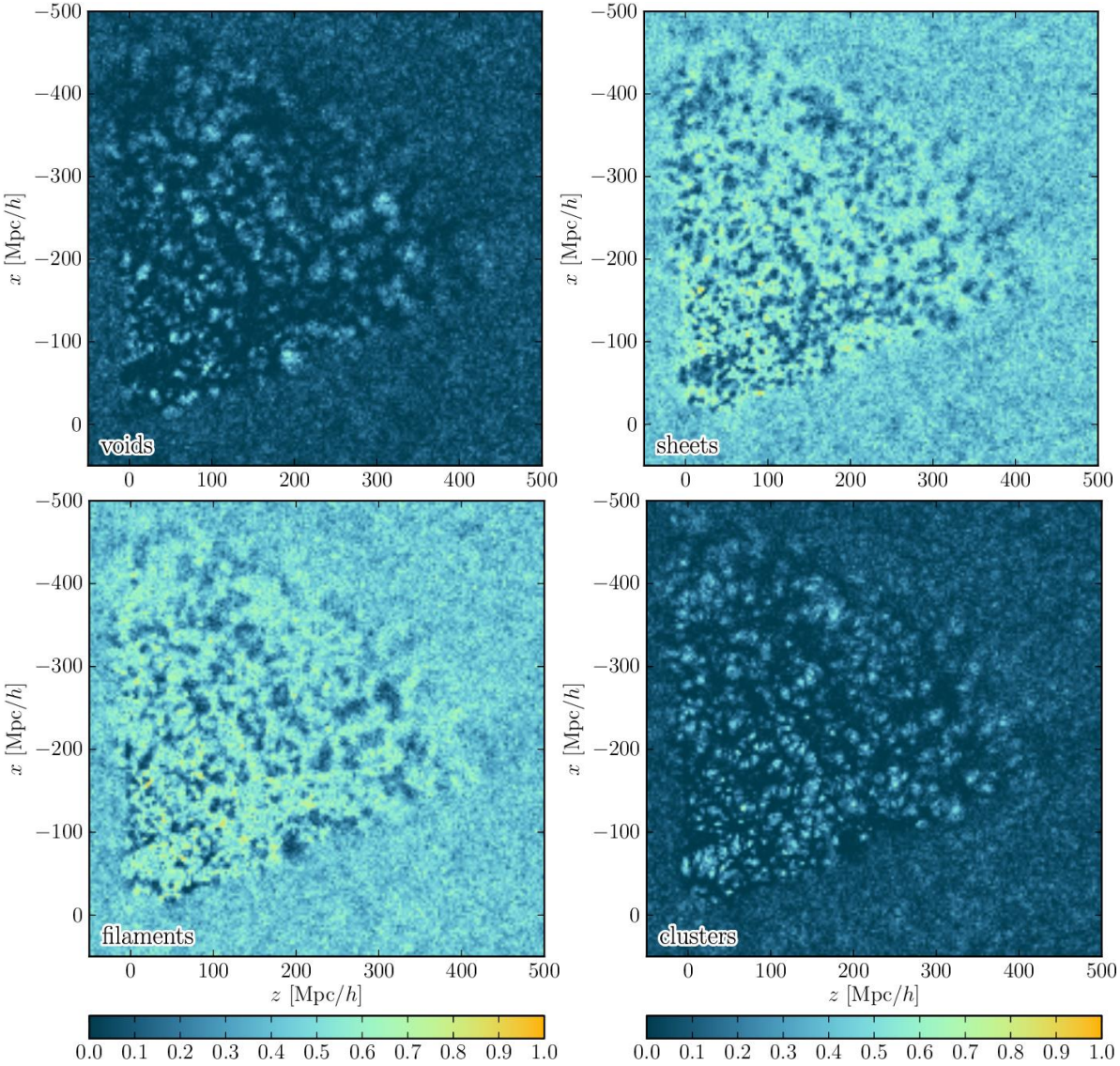
Final conditions



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.

A decision rule for structure classification

- Space of "input features":

$$\{\mathrm{T}_0 = \text{void}, \mathrm{T}_1 = \text{sheet}, \mathrm{T}_2 = \text{filament}, \mathrm{T}_3 = \text{cluster}\}$$

- Space of "actions":

$$\{a_0 = \text{“decide void”}, a_1 = \text{“decide sheet”}, a_2 = \text{“decide filament”}, a_3 = \text{“decide cluster”}, a_{-1} = \text{“do not decide”}\}$$

⇨ A problem of **Bayesian decision theory**:
one should take the action which maximizes the utility

$$U(a_j(\vec{x}_k)|d) = \sum_{i=0}^{3} G(a_j|\mathrm{T}_i)\,\mathcal{P}(\mathrm{T}_i(\vec{x}_k)|d)$$

- How to write down the gain functions?

FL, Jasche & Wandelt, in prep.

Gambling with the Universe

- One proposal:

$$G(a_j|\mathrm{T}_i) = \begin{cases} \dfrac{1}{\mathcal{P}(\mathrm{T}_i)} - \alpha & \text{if } j \in [\![0,3]\!] \text{ and } i = j \\ -\alpha & \text{if } j \in [\![0,3]\!] \text{ and } i \neq j \\ 0 & \text{if } j = -1. \end{cases}$$

"Winning"

"Loosing"

"Not playing"

- Without data, the expected utility is

$$U(a_j) = 1 - \alpha \quad \text{if } j \neq 1$$

"Playing the game"

$$U(a_{-1}) = 0$$

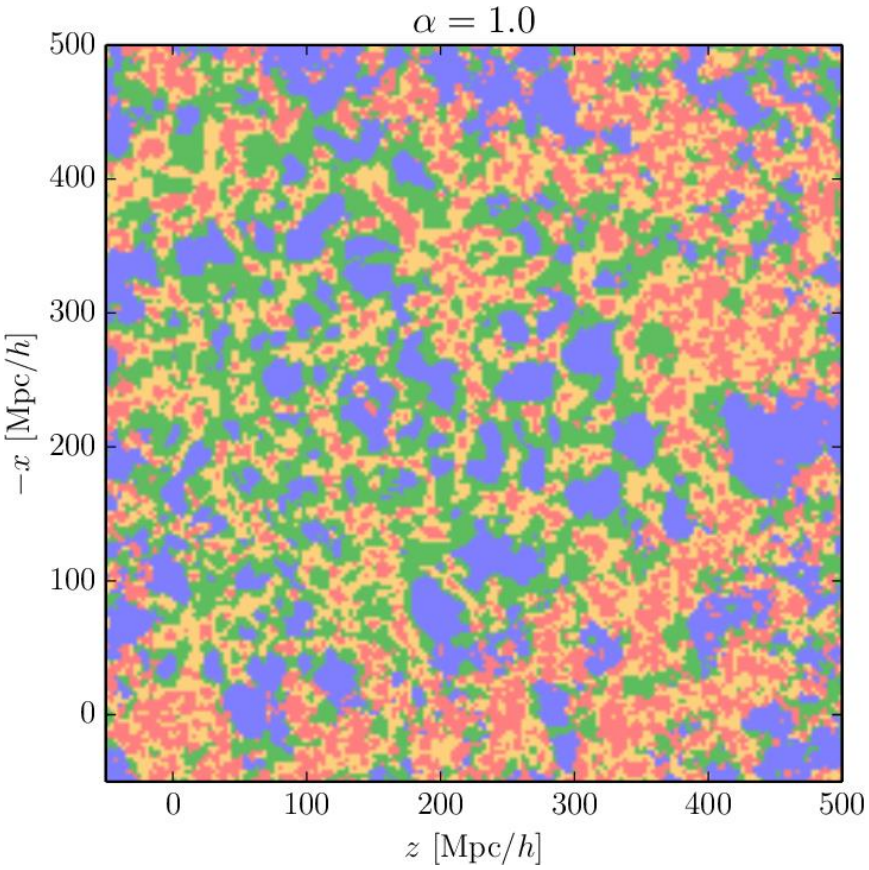
"Not playing the game"

- With $\alpha = 1$, it's a *fair game* ⇒ always play ⇒ "speculative map" of the LSS
- Values $\alpha > 1$ represent an *aversion for risk* ⇒ increasingly "conservative maps" of the LSS

FL, Jasche & Wandelt, in prep.

Playing the game…

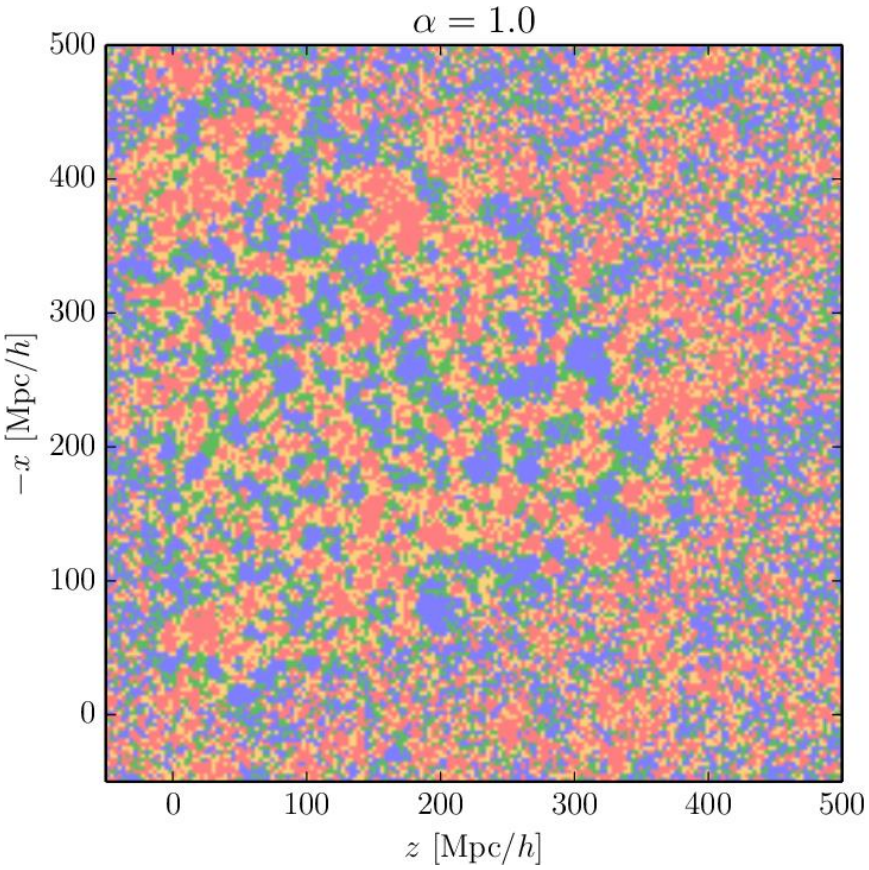
Final conditions



FL, Jasche & Wandelt, in prep.

Playing the game…

Initial conditions



FL, Jasche & Wandelt, in prep.

Summary & Conclusions

- **Bayesian large-scale structure inference** 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