How is the cosmic web woven? – A Bayesian approach

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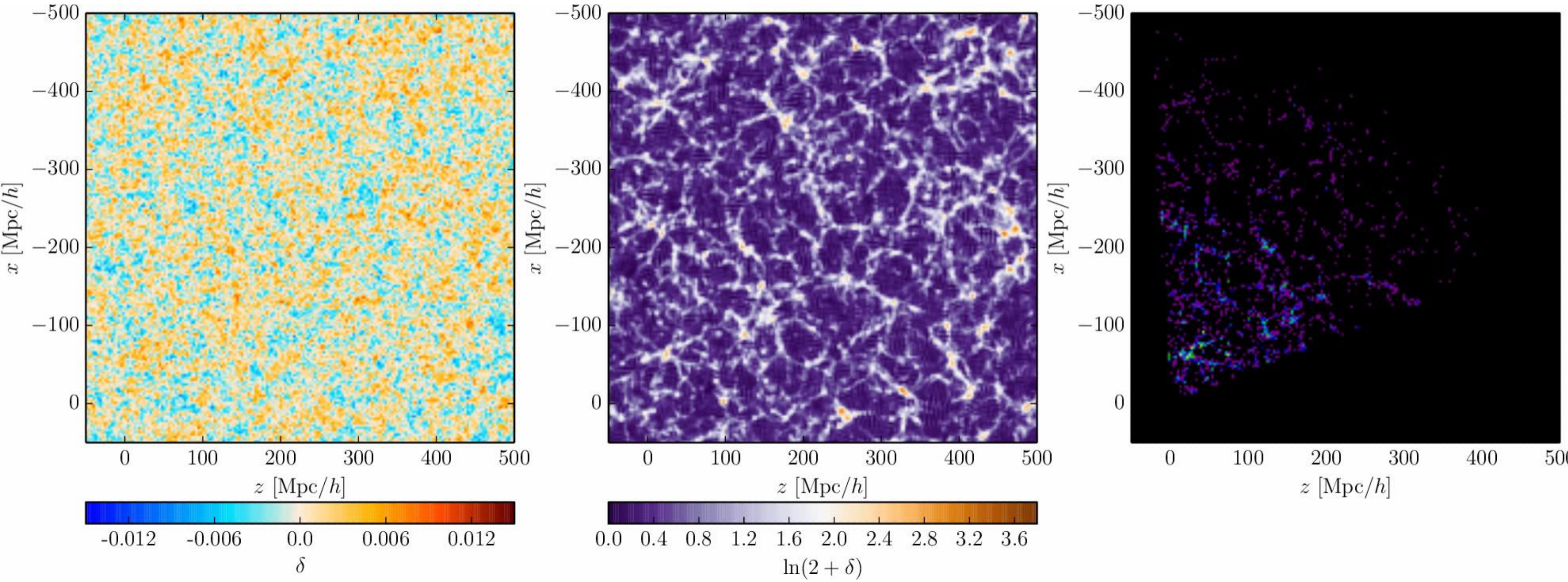
BORG at work – chronocosmography



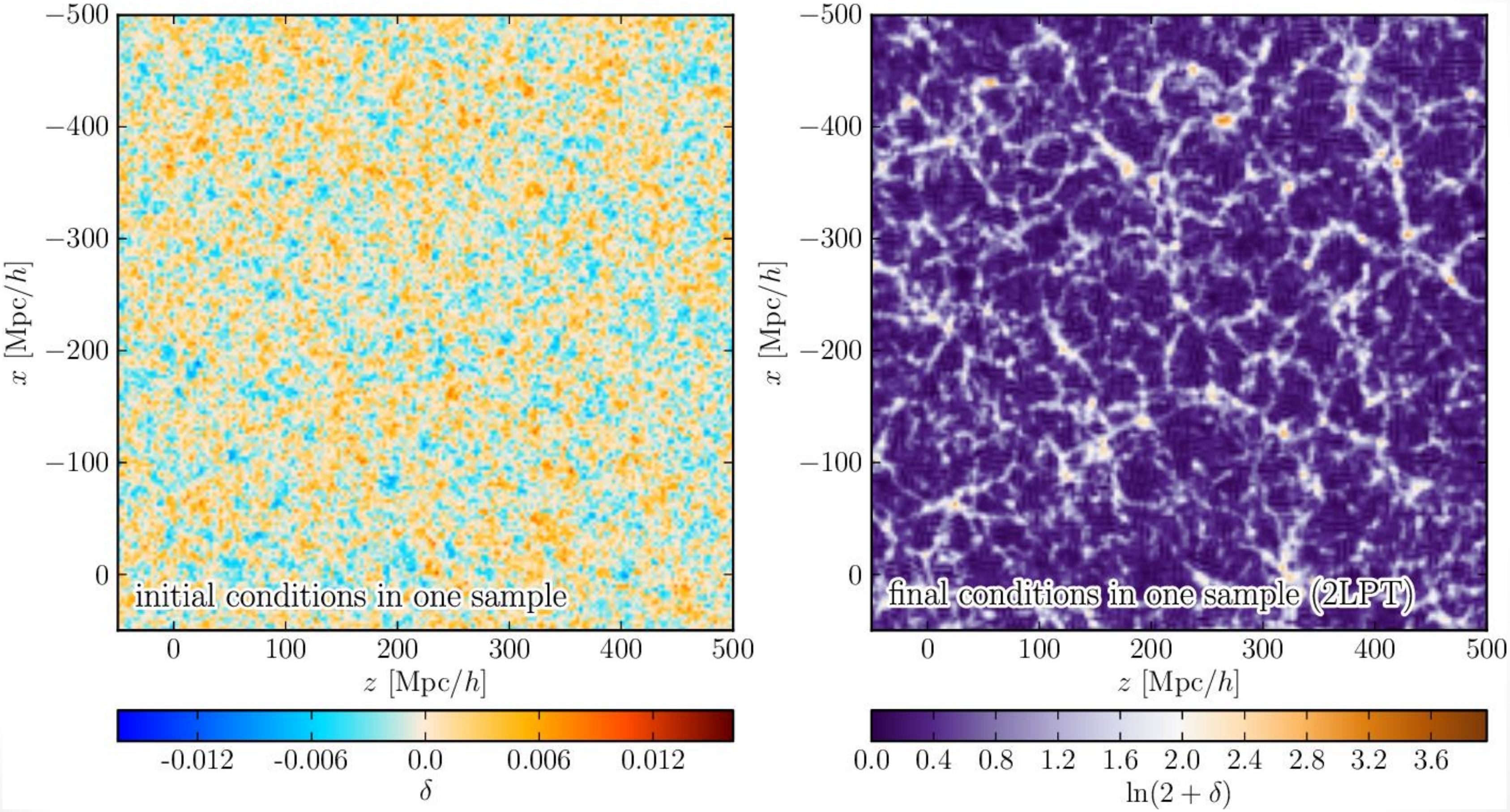
Initial conditions

Final conditions

Observations

Jasche, FL & Wandelt 2015, arXiv:1409.6308

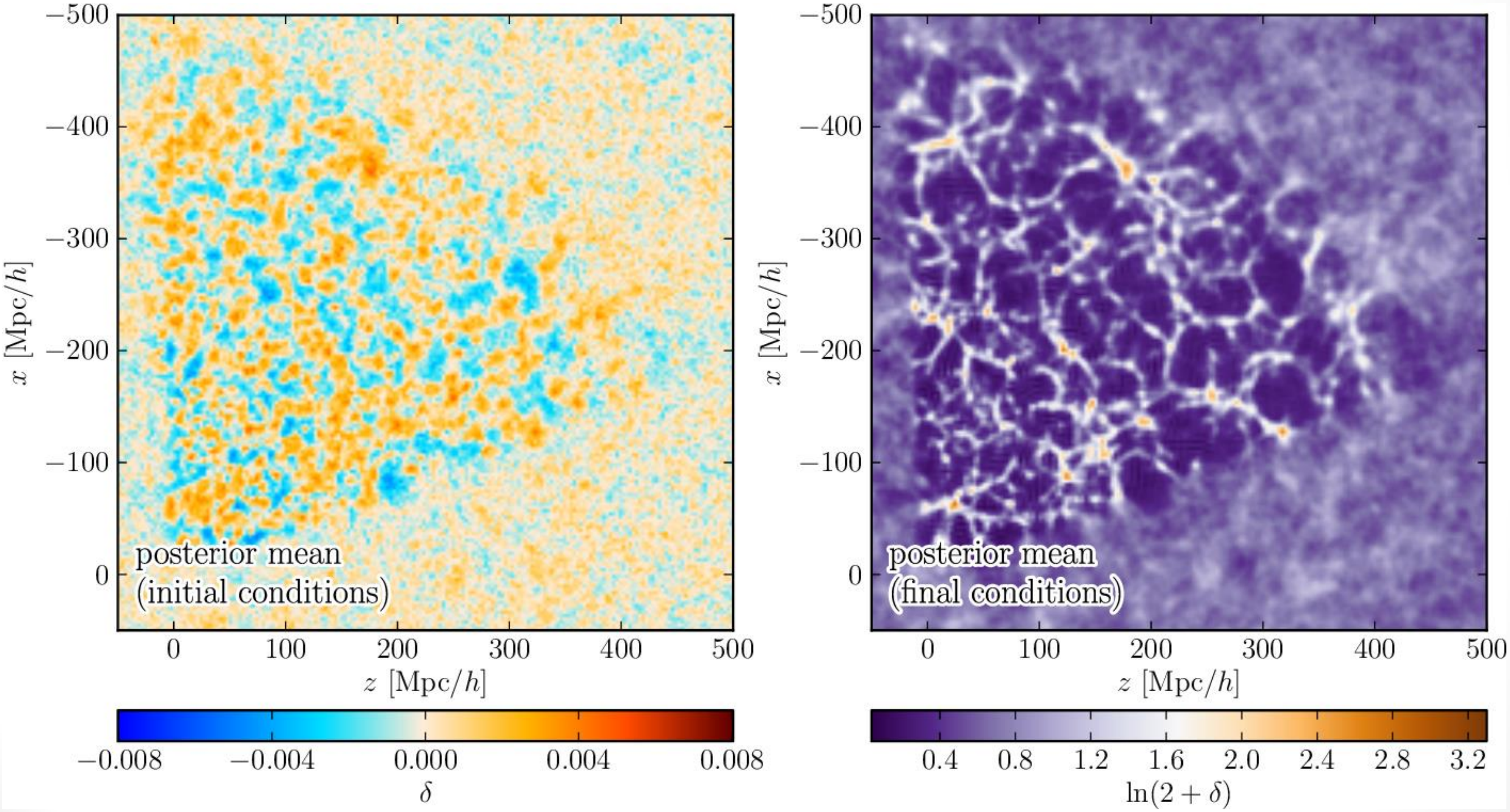
Bayesian chronocosmography from SDSS DR7



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

- Each sample: a "possible version of the truth"
- In Bayesian large-scale structure inference, the variation between samples quantifies the uncertainty that results from having, e.g.
  - incomplete observations (mask, finite volume and number of galaxies, selection effects)
  - an imperfect experiment (noise, biases, photometric redshifts…)
  - only one Universe (a more precise version of "cosmic variance")

Uncertainty quantification

- Uncertainty quantification is **crucial**!
- Can we **propagate uncertainties** to structure type classification?

COLA: *COmoving Lagrangian Acceleration*

$$\mathbf{s} = \mathbf{s}_{\mathrm{LPT}} + \mathbf{s}_{\mathrm{MC}}$$

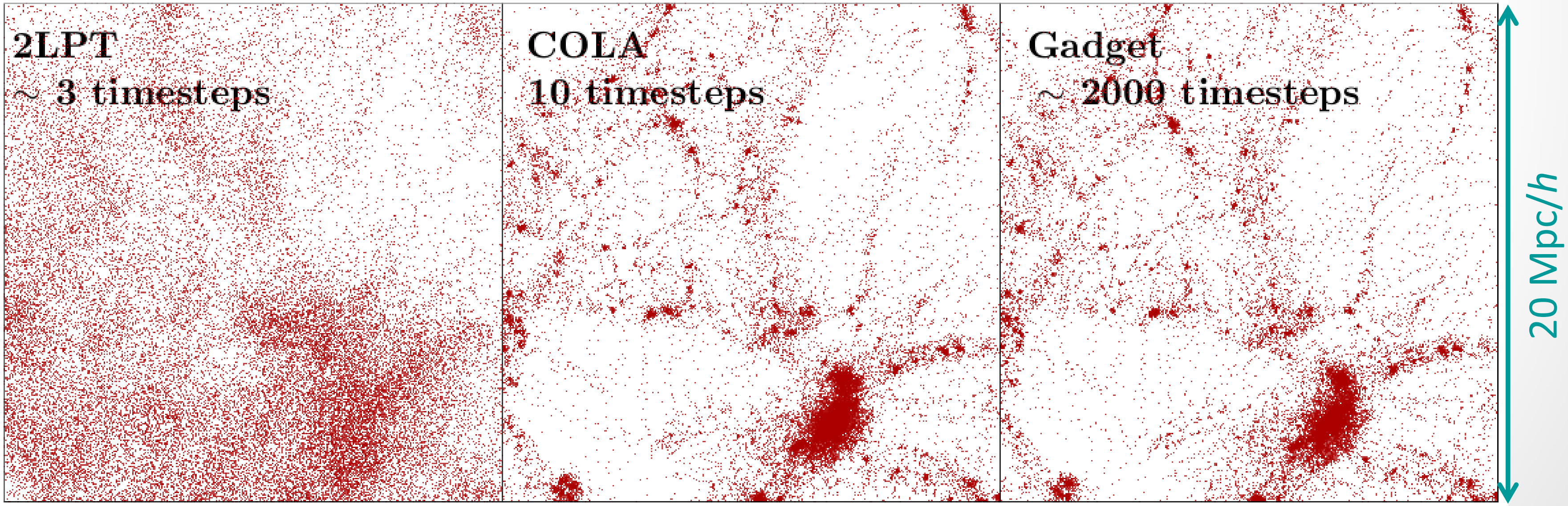
- Write the displacement vector as: Tassev & Zaldarriaga 2012, arXiv:1203.5785
- Time-stepping (omitted constants and Hubble expansion):

Standard:

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

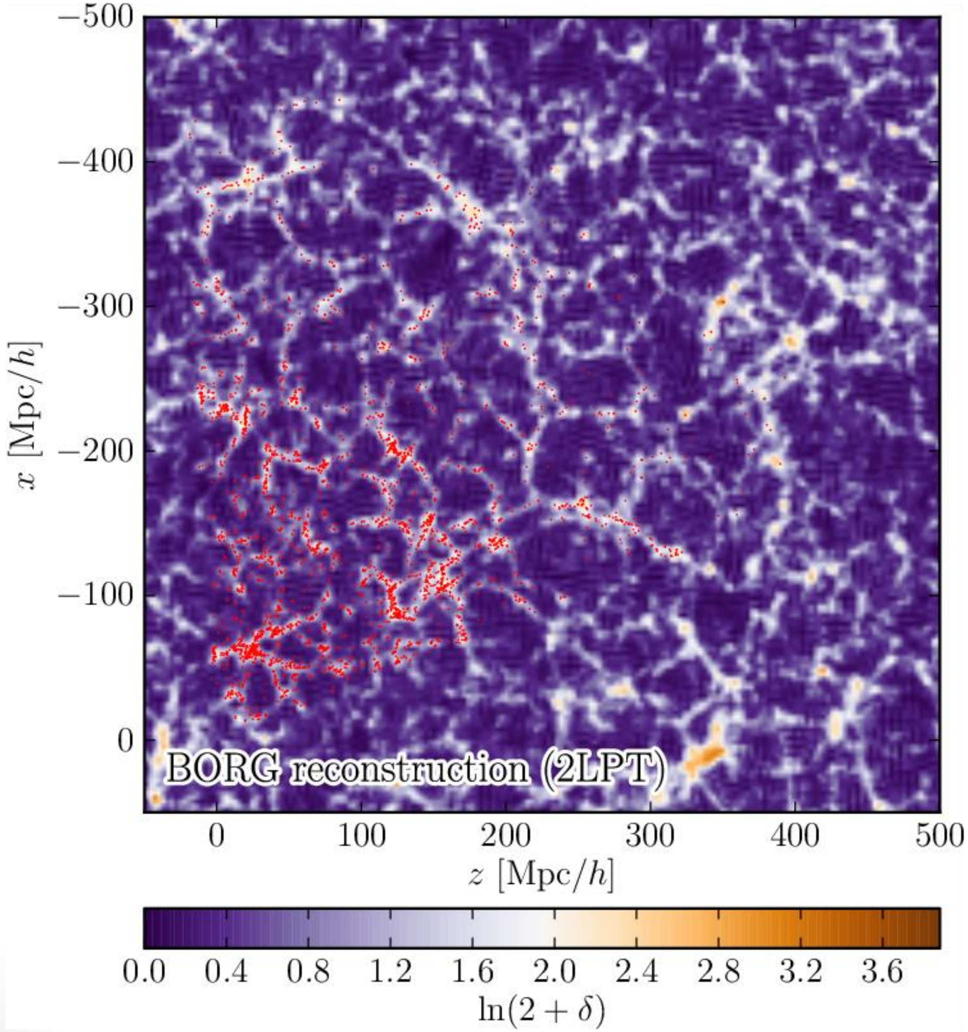
Modified:

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



Tassev, Zaldarriaga & Einsenstein 2013, arXiv:1301.0322

Non-linear filtering of BORG samples



= Fast constrained simulations of the Nearby Universe

FL, Jasche, Sutter, Hamaus & Wandelt 2015, arXiv:1410.0355

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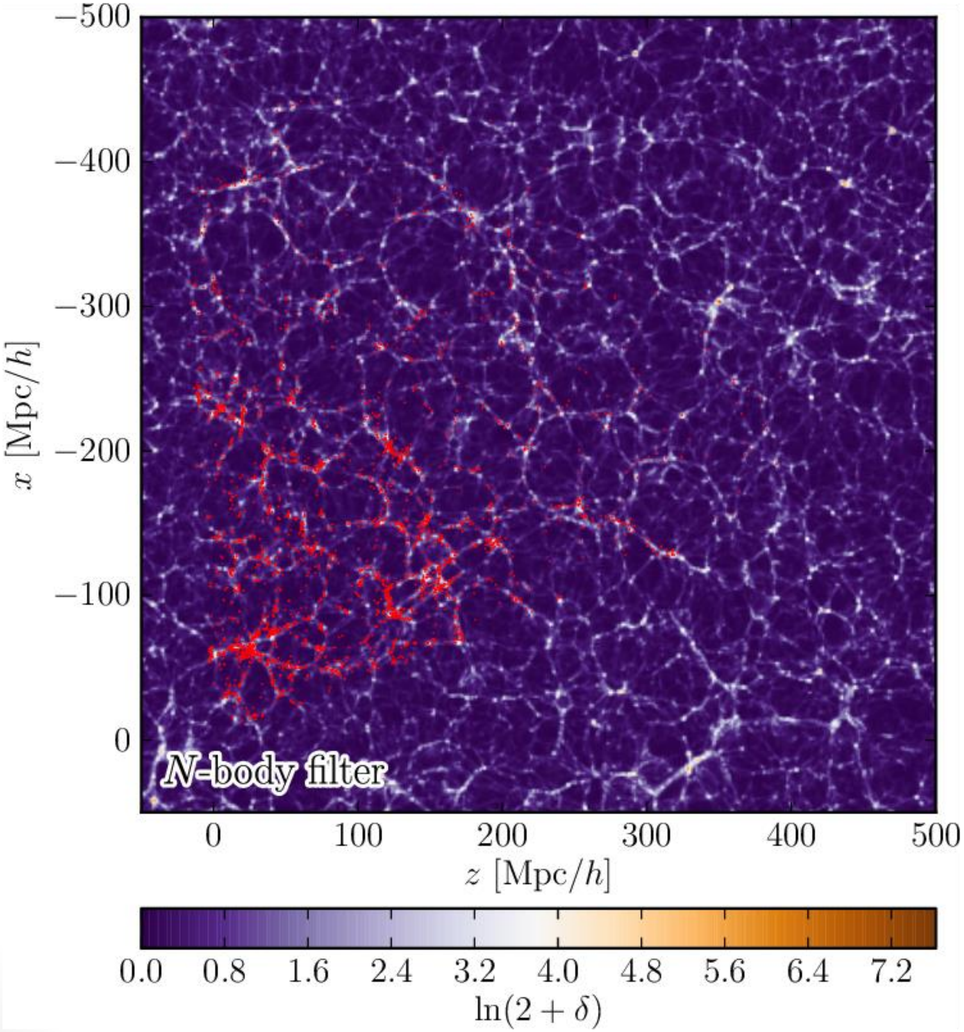

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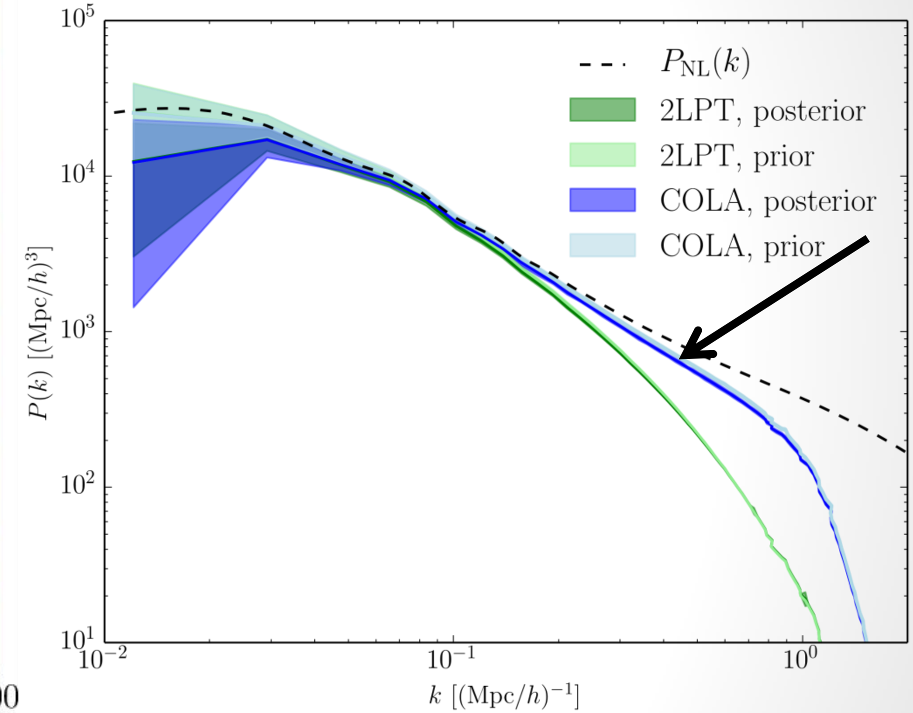


The number of modes usable for cosmology scales like k^3!

FL, Jasche, Sutter, Hamaus & Wandelt 2015, arXiv:1410.0355

Tidal shear analysis

- $\lambda_1, \lambda_2, \lambda_3$: eigenvalues of the tidal field tensor, the Hessian of the gravitational potential: $T_{ij} = \partial_i \partial_j \Phi$ $\lambda_1 + \lambda_2 + \lambda_3 = \delta$
  - 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*. 2007, arXiv:astro-ph/0610280

see also:

- Extensions:

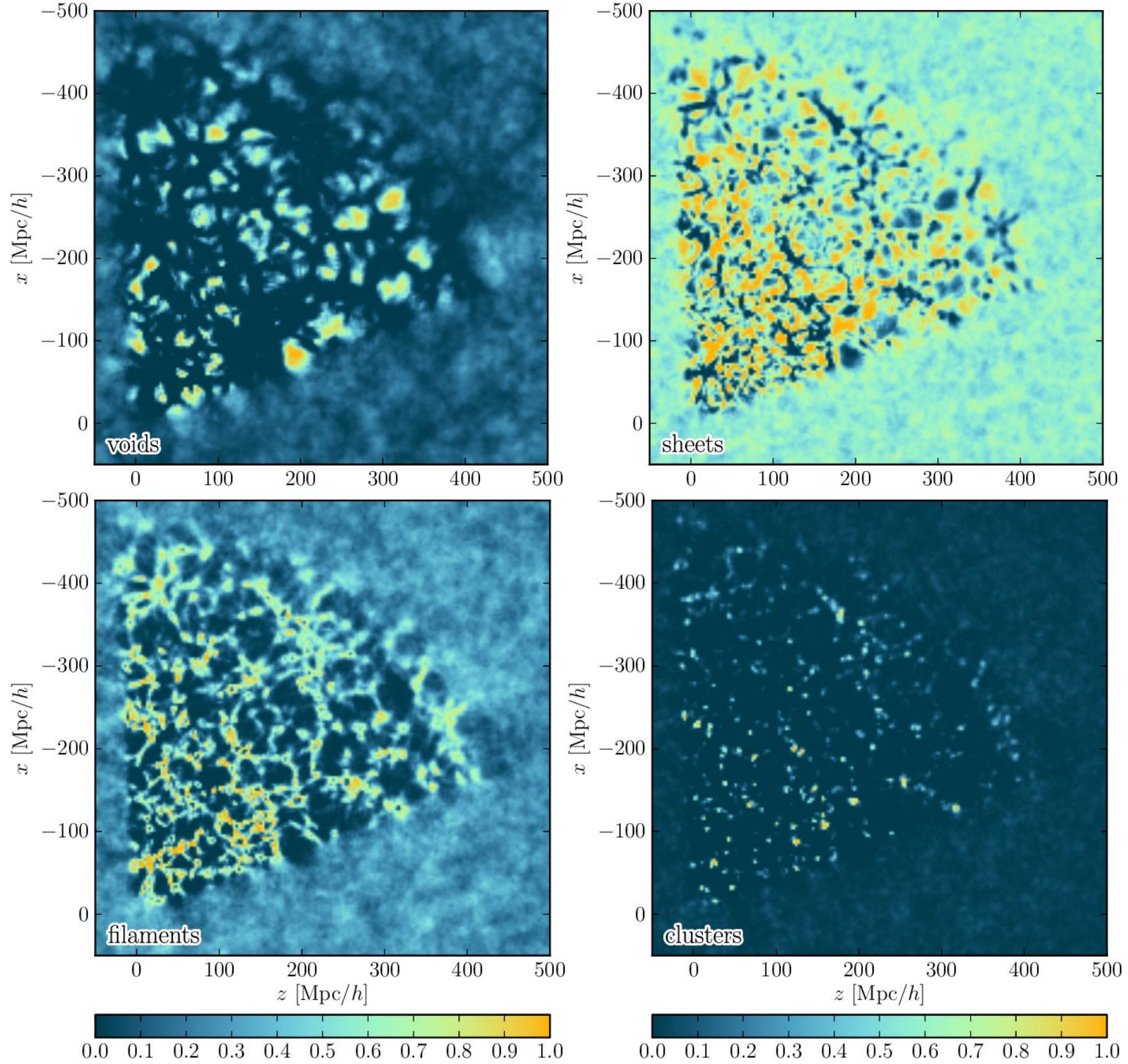
Forero-Romero *et al*. 2009, arXiv:0809.4135
Hoffman *et al*. 2012, arXiv:1201.3367

- Similar web classifiers:

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

Dynamic structures inferred by BORG

Final conditions



FL, Jasche & Wandelt 2015, arXiv:1502.02690

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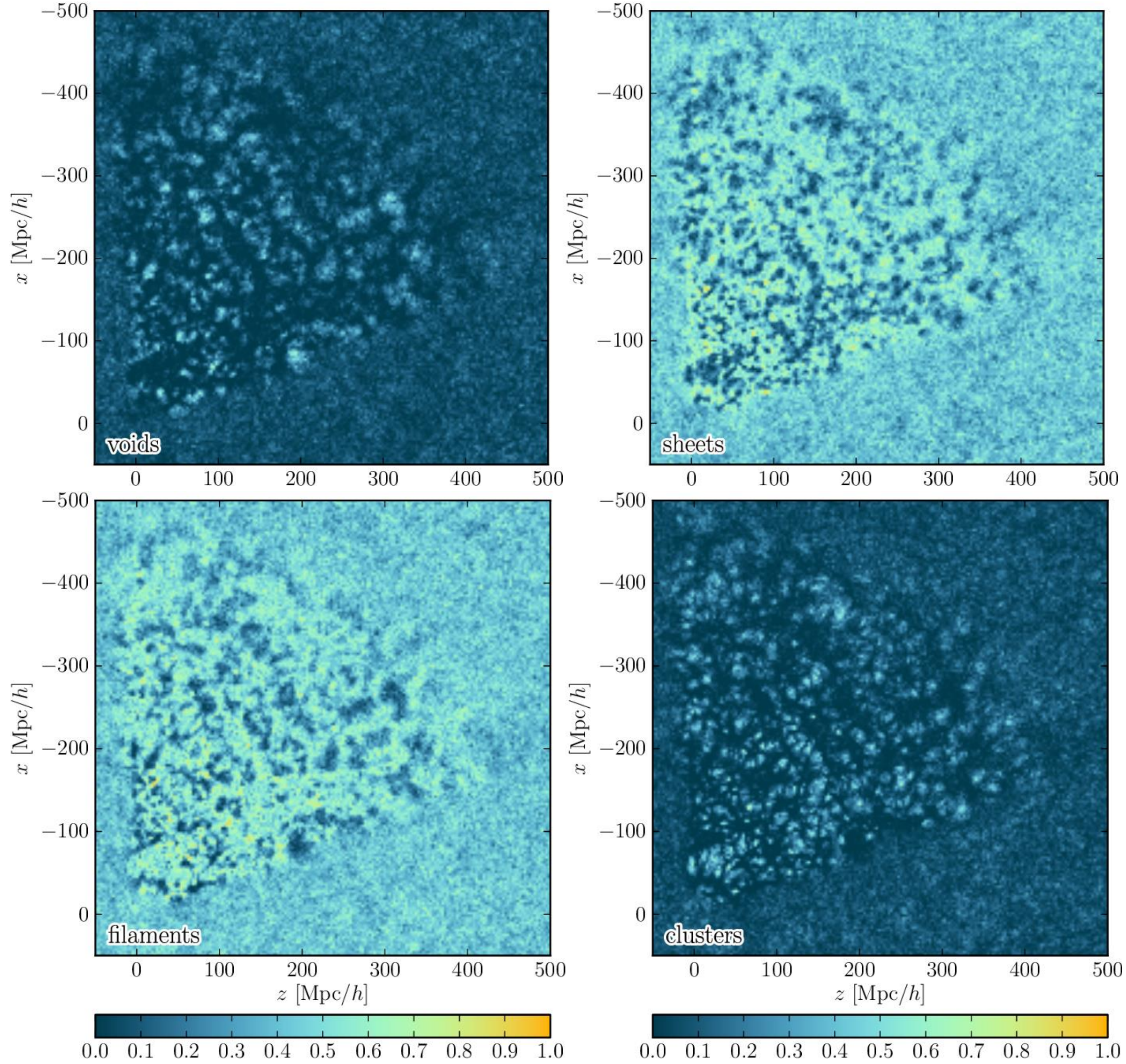

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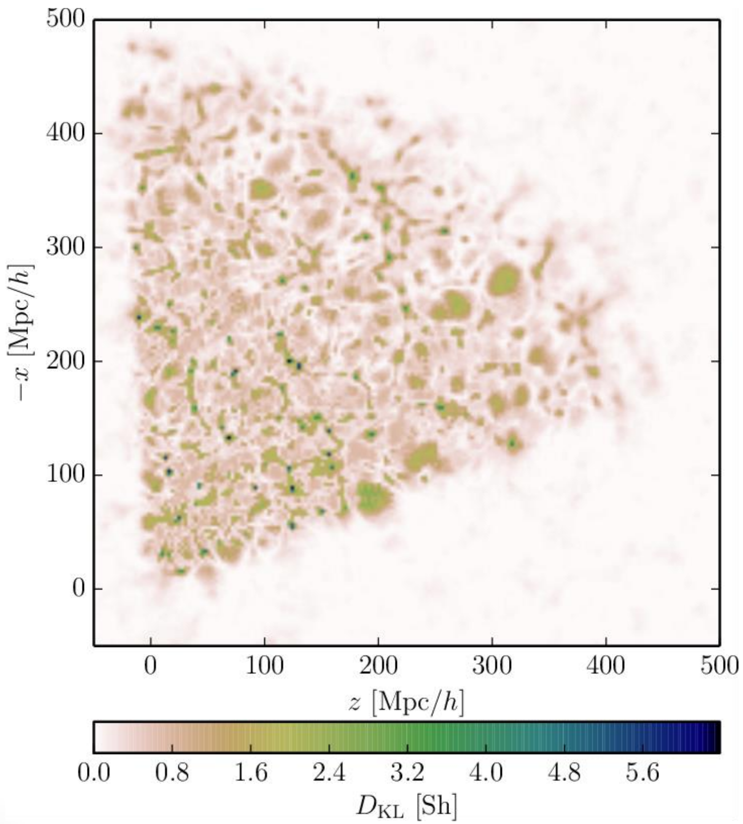
Kullback-Leibler divergence posterior/prior

$$D_{\mathrm{KL}}(\mathcal{P}(\mathrm{T}(\vec{x_k})|d)||\mathcal{P}(\mathrm{T})) \equiv \sum_i \mathcal{P}(\mathrm{T}_i(\vec{x_k})|d) \log_2 \left(\frac{\mathcal{P}(\mathrm{T}_i(\vec{x_k})|d)}{\mathcal{P}(\mathrm{T}_i)} \right)$$ in Sh

Final conditions



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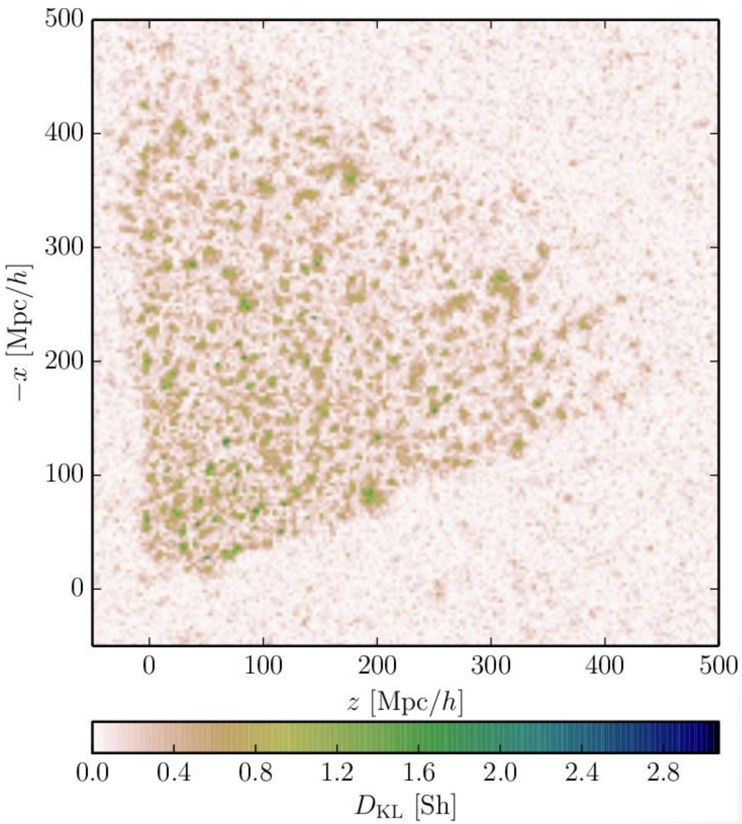

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A decision rule for structure classification

- 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 that maximizes the expected 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 2015, arXiv:1503.00730

Gambling with the Universe

- One proposal:

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

"Winning"
"Loosing"
"Not playing"

- Without data, the expected utility is

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

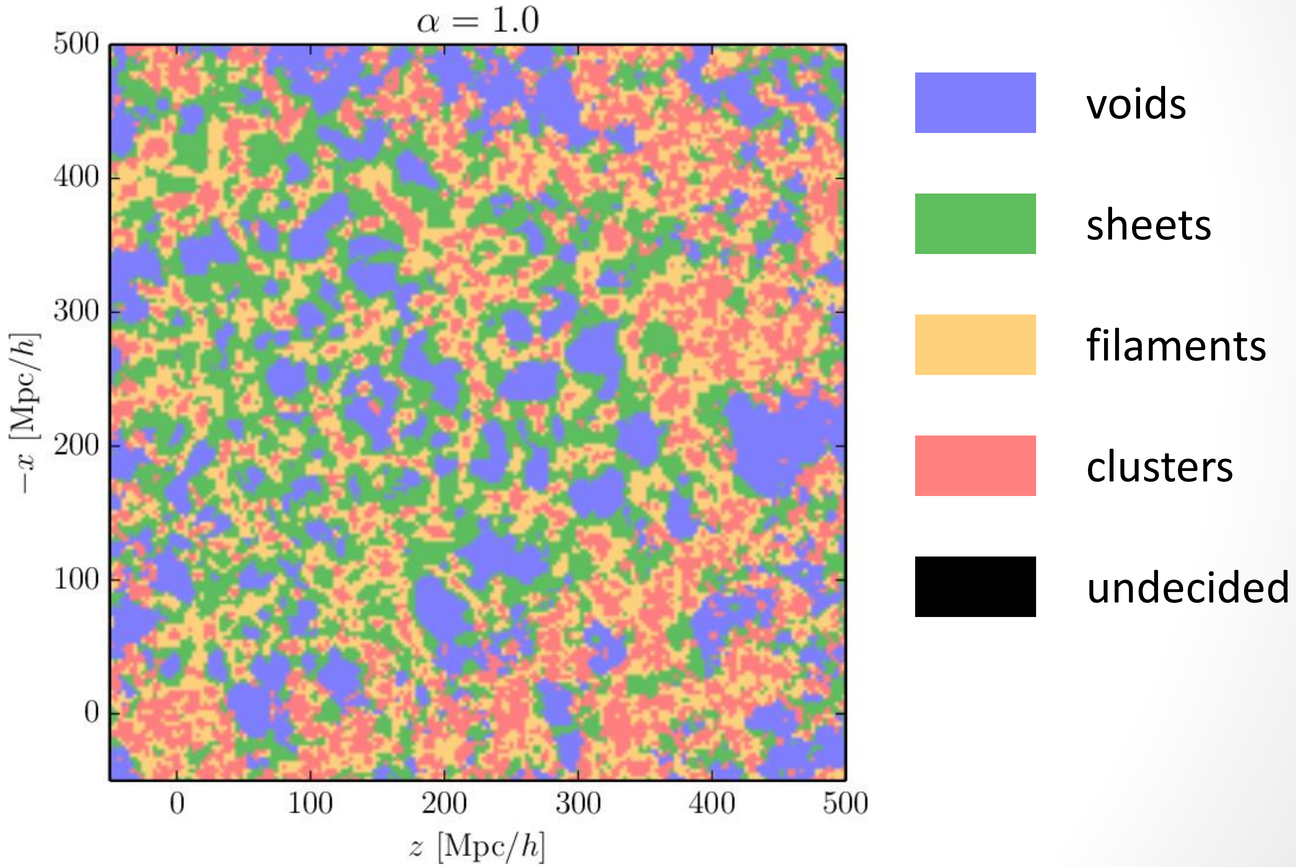
$$U(a_{-1}) = 0$$ "Not playing the game"

- 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 2015, arXiv:1503.00730

Playing the game…

Final conditions



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Playing the game…

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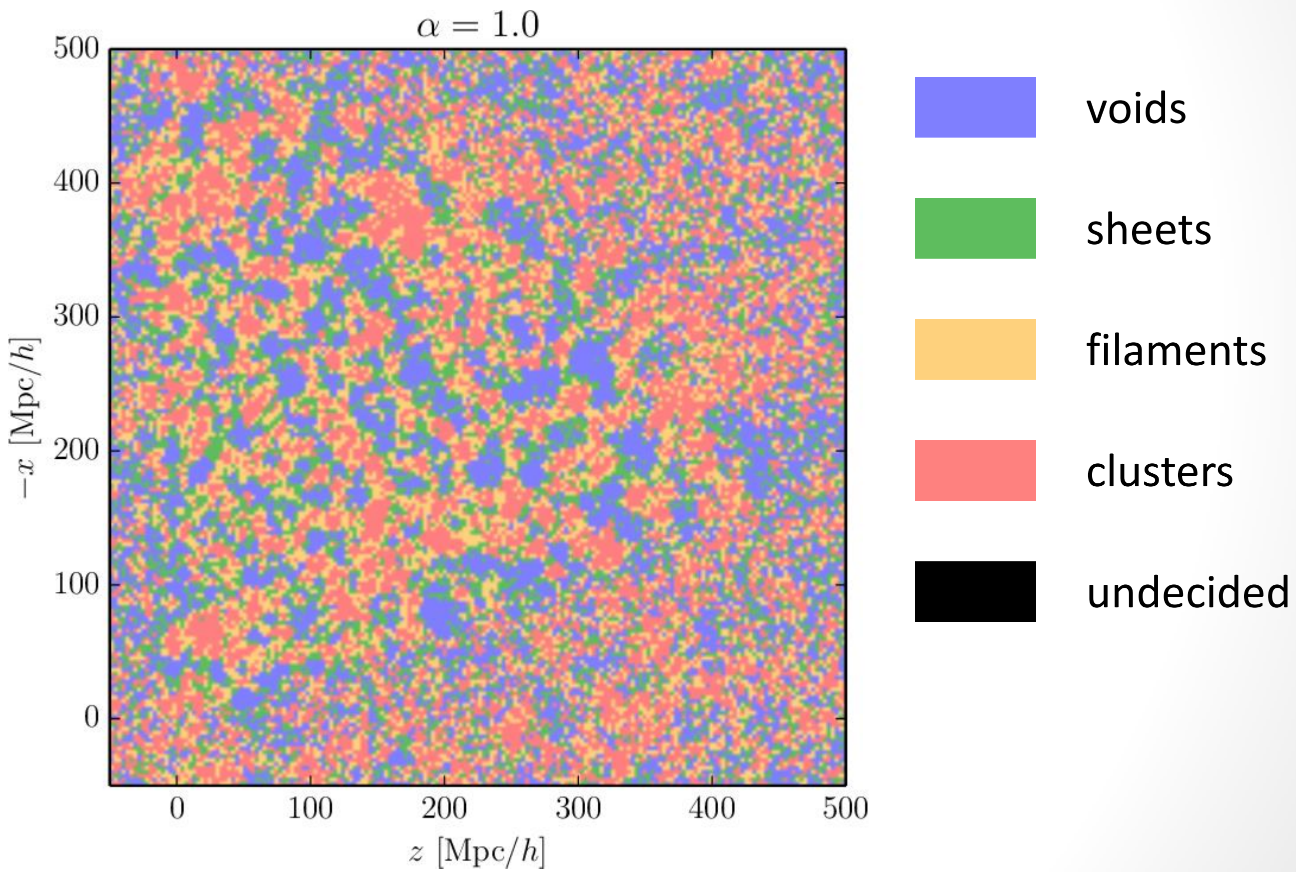

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Summary & Conclusions

- (More) **Bayesian large-scale structure inference**
  - Uncertainty quantification (noise, survey geometry, selection effects and biases)
  - A non-linear and non-Gaussian inference with improving techniques

- (More) **Chronocosmography**
  - Simultaneous analysis of the morphology and formation history of the cosmic web
  - Characterization of dynamic structures underlying galaxies
  - A new framework for problems of classification in the presence of uncertainty