# The multi-stream local Universe


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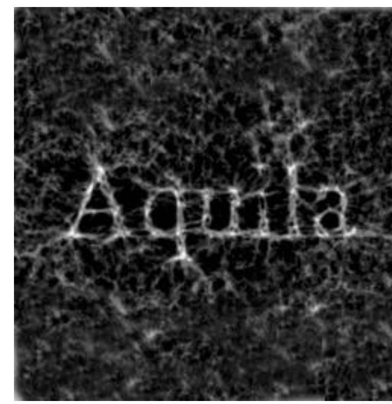
www.aquila-consortium.org


28 January 2020

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London

# The BORG inference framework

*Bayesian Origin Reconstruction from Galaxies*

- A Bayesian Hierarchical Model:

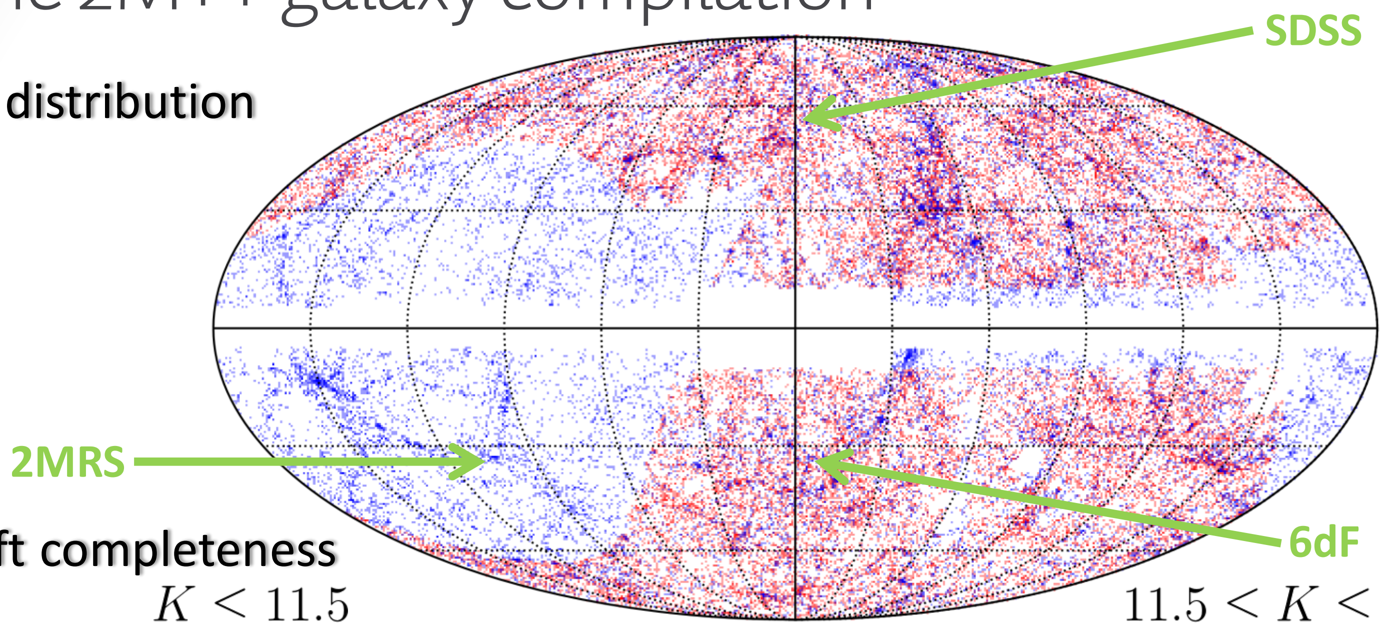
| | |
|---|---|
| $\mathcal{P}(\hat{\delta}) \propto \exp\left(-\frac{1}{2}\sum_k \frac{\lvert\hat{\delta}_k\rvert^2}{P_k}\right)$ | initial conditions |
| $\rho_\mathrm{m} = \mathcal{F}(\delta)$ | total evolved matter density |
| $\rho_\mathrm{g} = \mathcal{B}(\rho_\mathrm{m})$ | biased galaxy distribution |
| $\rho_\mathrm{g}^\mathrm{s}(\vec{x}) = S(\vec{x})\rho_\mathrm{g}(\vec{x})$ | selected sample |
| $N_\mathrm{g} \curvearrowleft \mathcal{P}(N_\mathrm{g} \lvert \rho_\mathrm{g}^\mathrm{s})$ | galaxy number count: random extraction (Poisson, Negative Binomial) |

- The multi-million dimensional posterior distribution is sampled via Hamiltonian Monte Carlo.

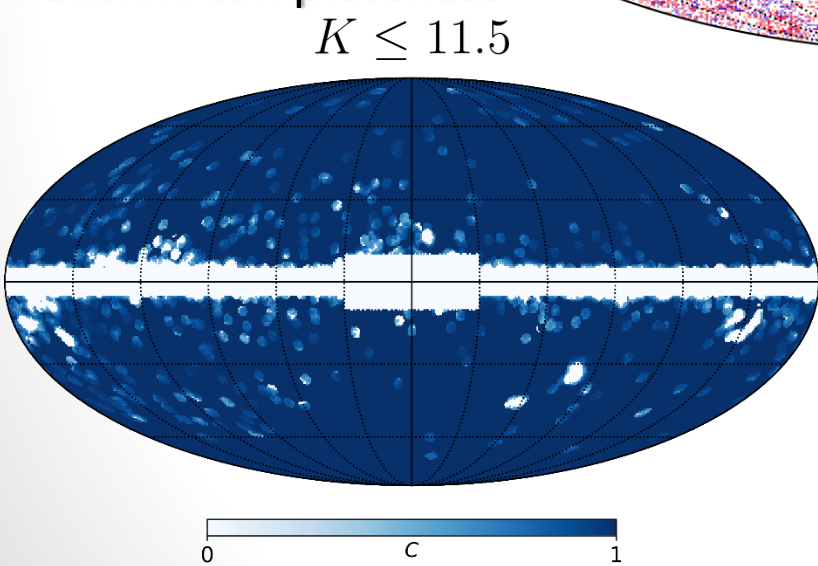
Jasche & Wandelt 2013, 1203.3639 – Jasche, FL & Wandelt 2015, 1409.6308 – Lavaux & Jasche 2016, 1509.05040 – Jasche & Lavaux 2019, 1806.11117

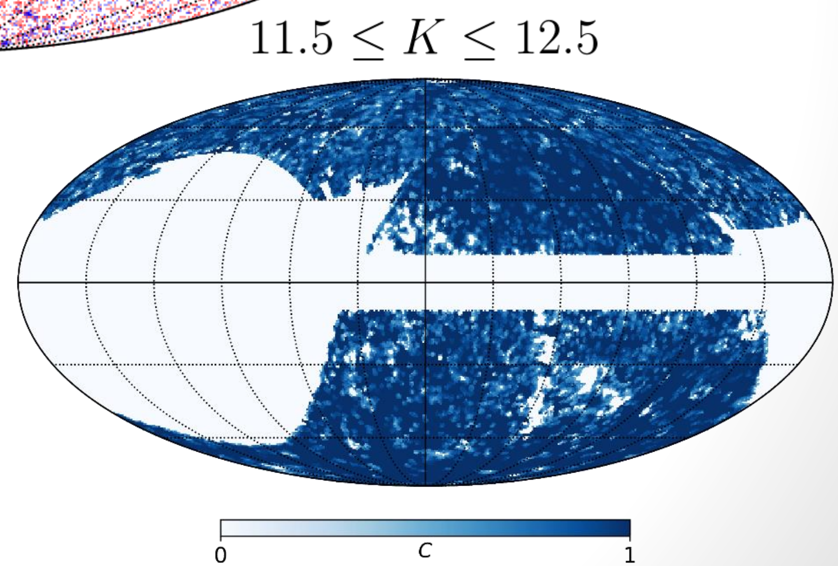
# The 2M++ galaxy compilation

**Galaxy distribution**



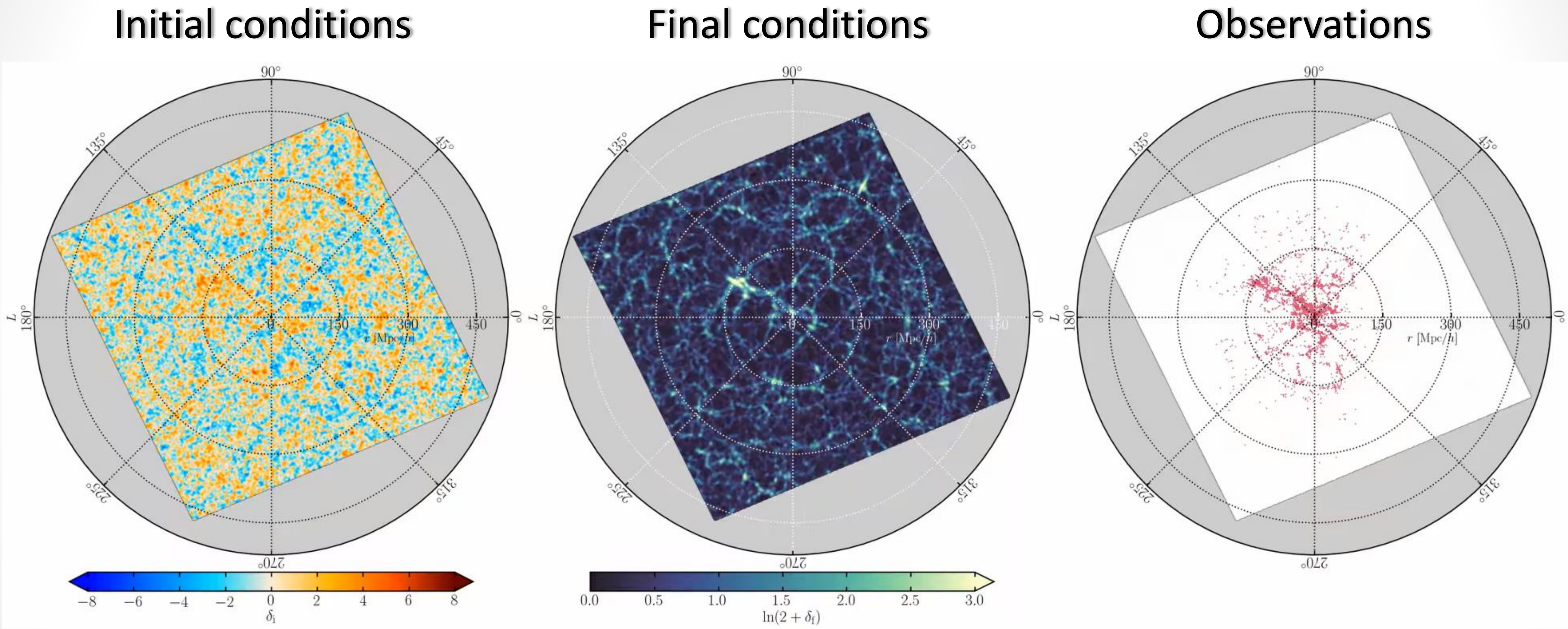

**Redshift completeness**




Lavaux & Hudson 2011, 1105.6107

# BORG at work: Bayesian chrono-cosmography

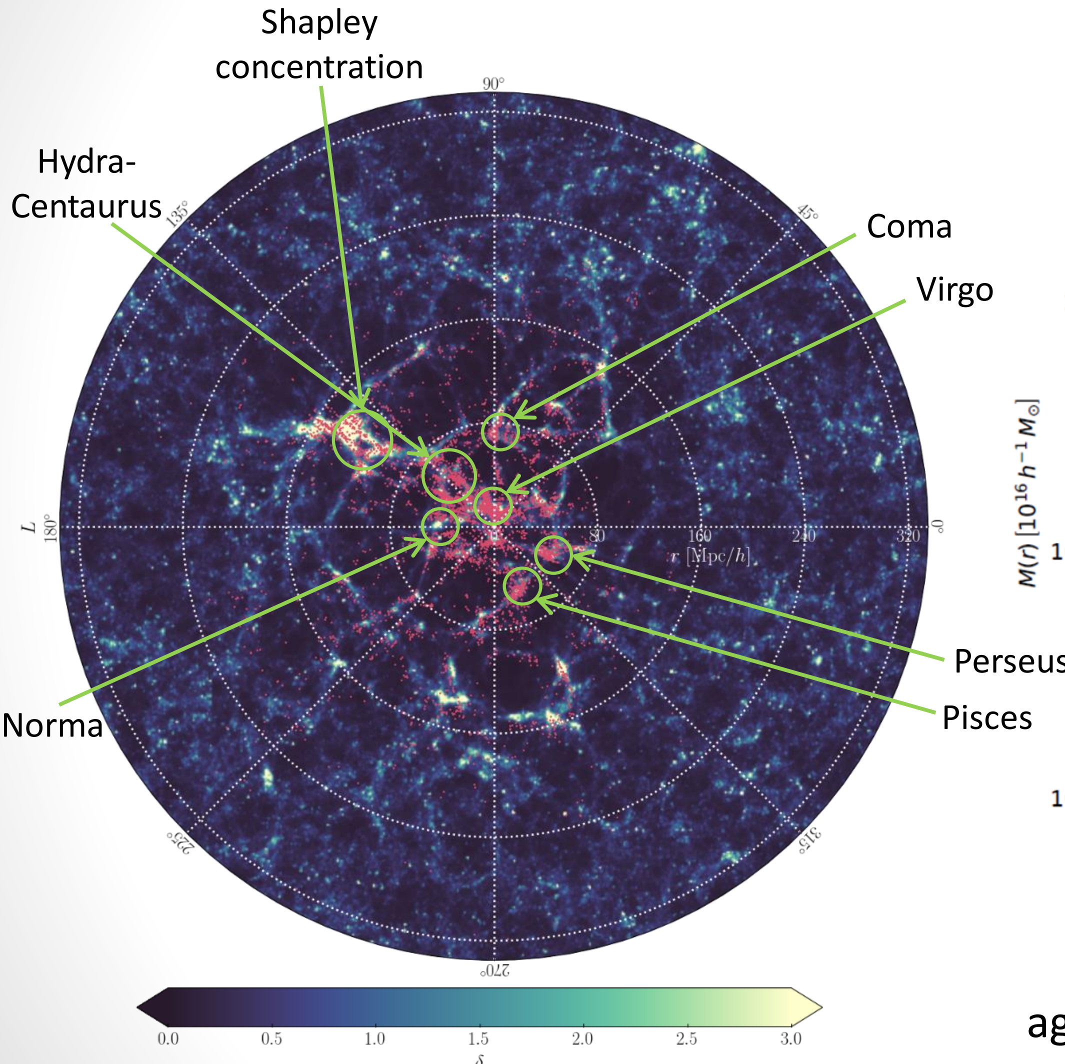


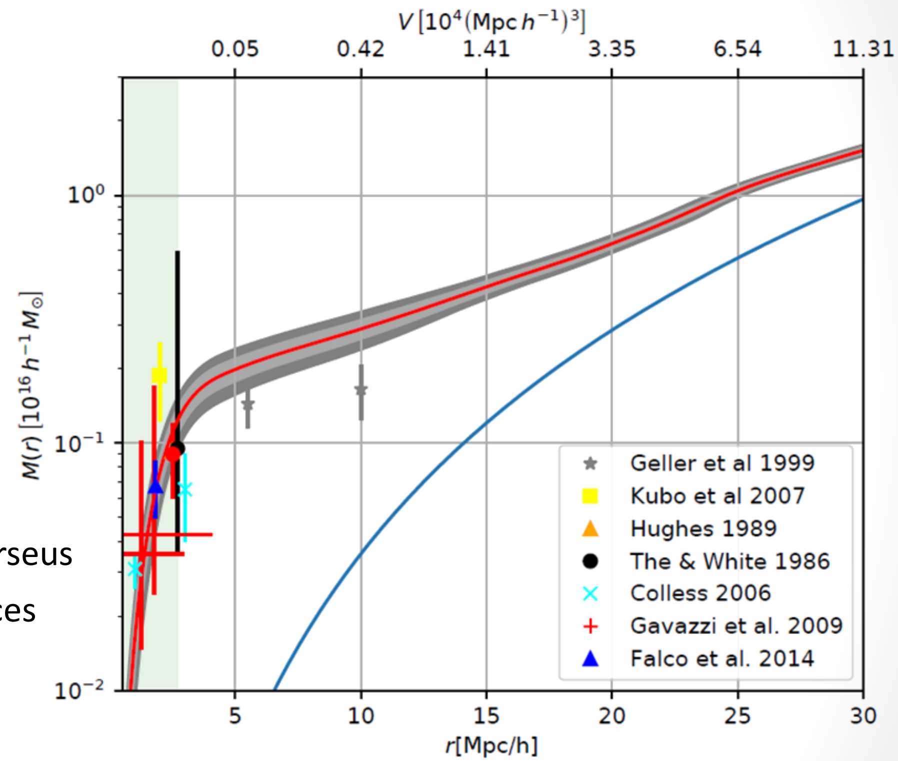

Supergalactic plane

**67,224** galaxies, ≈ **17 million** parameters, **5** TB of primary data products, **10,000** samples, ≈ **500,000** forward and adjoint data model evaluations, **1.5 million** CPU-hours

Jasche & Lavaux 2019, 1806.11117

# BORGPM density field: full non-linear dynamics



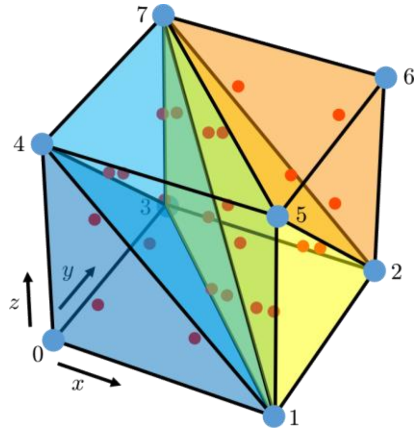



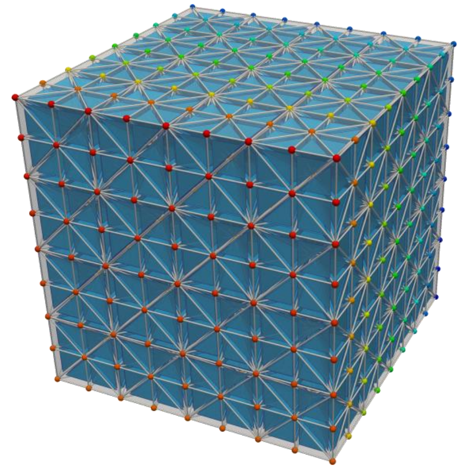

Mass profile of the Coma cluster, in agreement with gravitational lensing and X-ray observations down to a few Mpc.

Jasche & Lavaux 2019, 1806.11117 – FL, Lavaux & Jasche, in prep.

# The phase-space structure of dark matter: tools

Delaunay tessellation of elementary Lagrangian cubes (Simplex-In-Cell estimator)



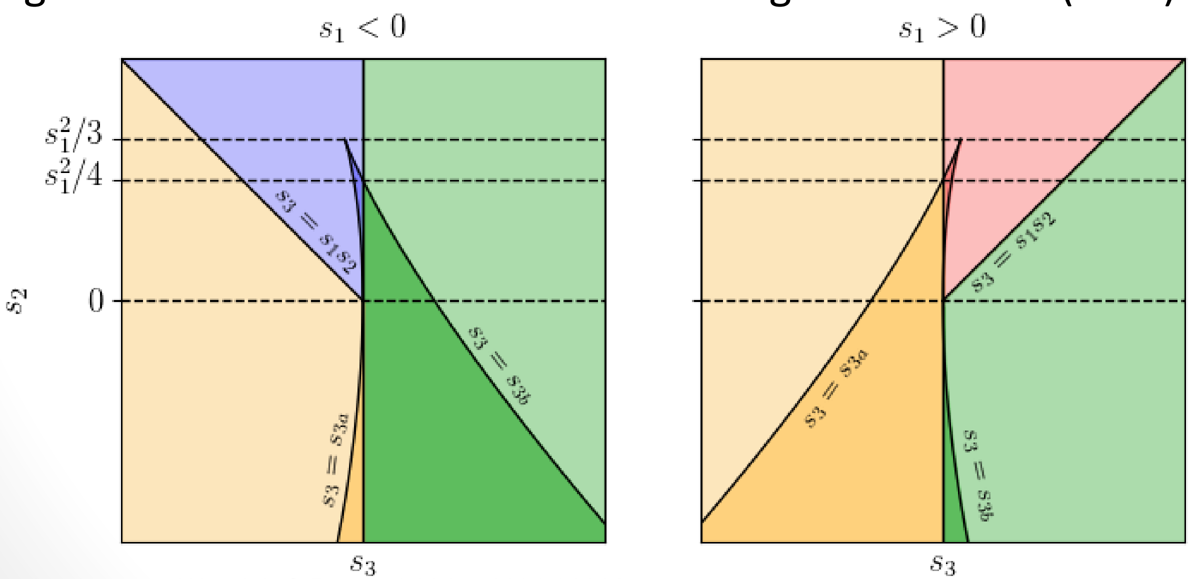



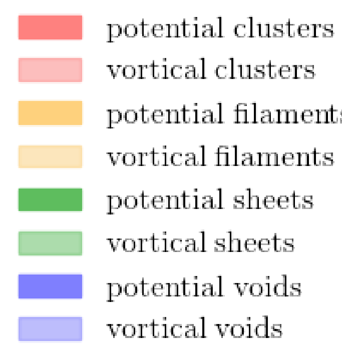
Abel, Hahn & Kaehler 2012, 1111.3944
Shandarin, Habib & Heitmann 2012, 1111.2366
Hahn, Abel & Kaehler 2013, 1210.6652
Hahn & Angulo 2016, 1501.01959
Sousbie & Colombi 2016, 1509.07720

Lagrangian Invariants Classification of Heterogeneous flows (LICH)

$$\mathcal{R}_{\ell m} \equiv \frac{\partial \Psi_\ell}{\partial \mathbf{q}_m}$$

$$\lambda^3 + \boxed{s_1}\lambda^2 + \boxed{s_2}\lambda + \boxed{s_3} = 0$$

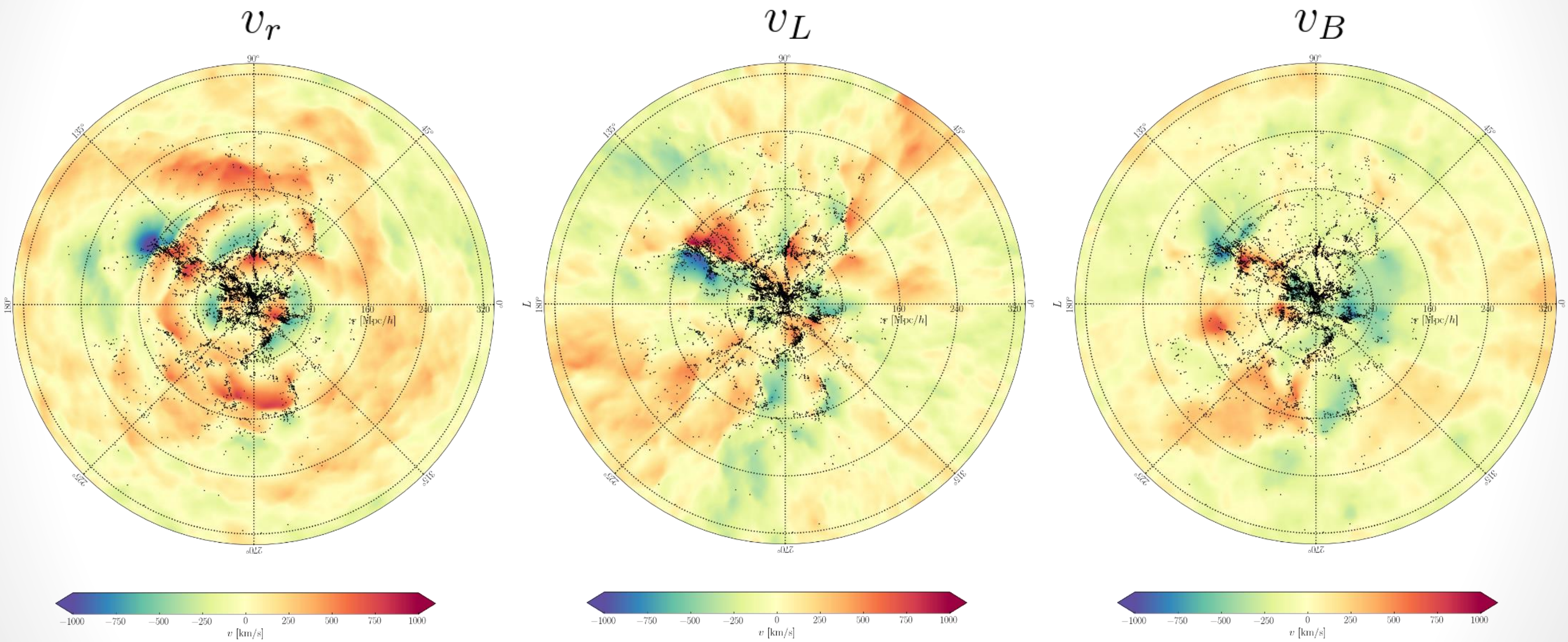



FL, Jasche, Lavaux, Wandelt & Percival 2017, 1601.00093

Generalises DIVA,
Lavaux & Wandelt 2010, 0906.4101

# Velocity field in the supergalactic plane

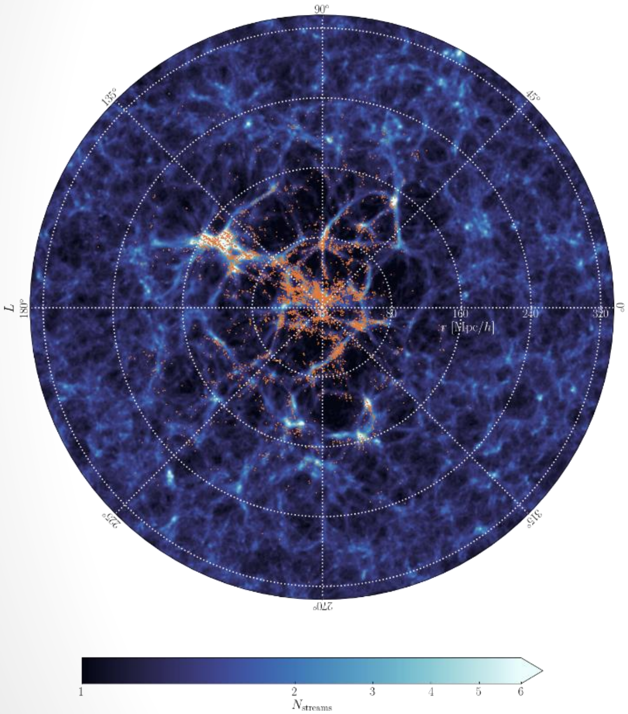



The gravitational infall of known structures can be observed.

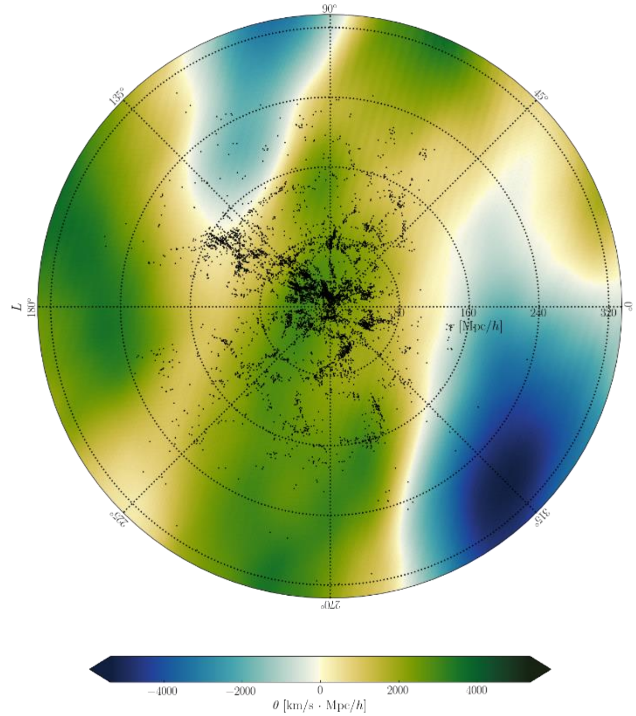
Prideaux-Ghee, FL, Heavens, Lavaux & Jasche, in prep.

# Number of streams and vorticity

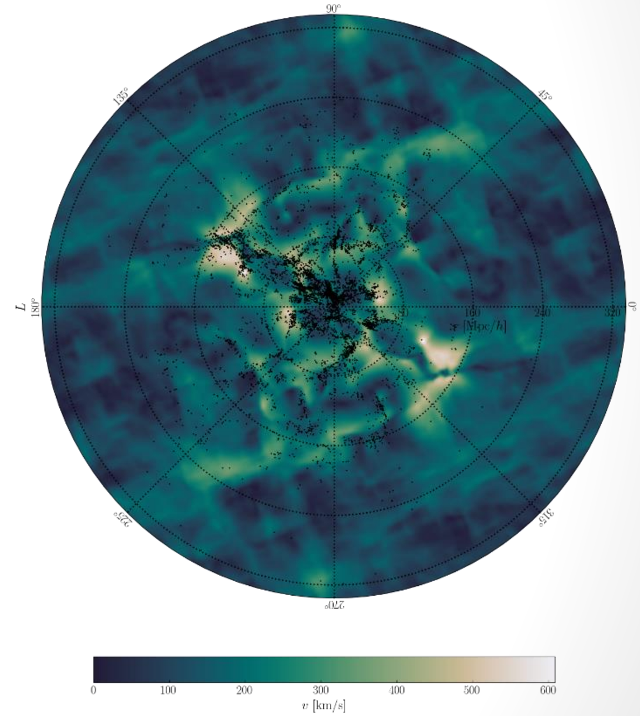
Number of streams



Velocity potential



Norm of vorticity

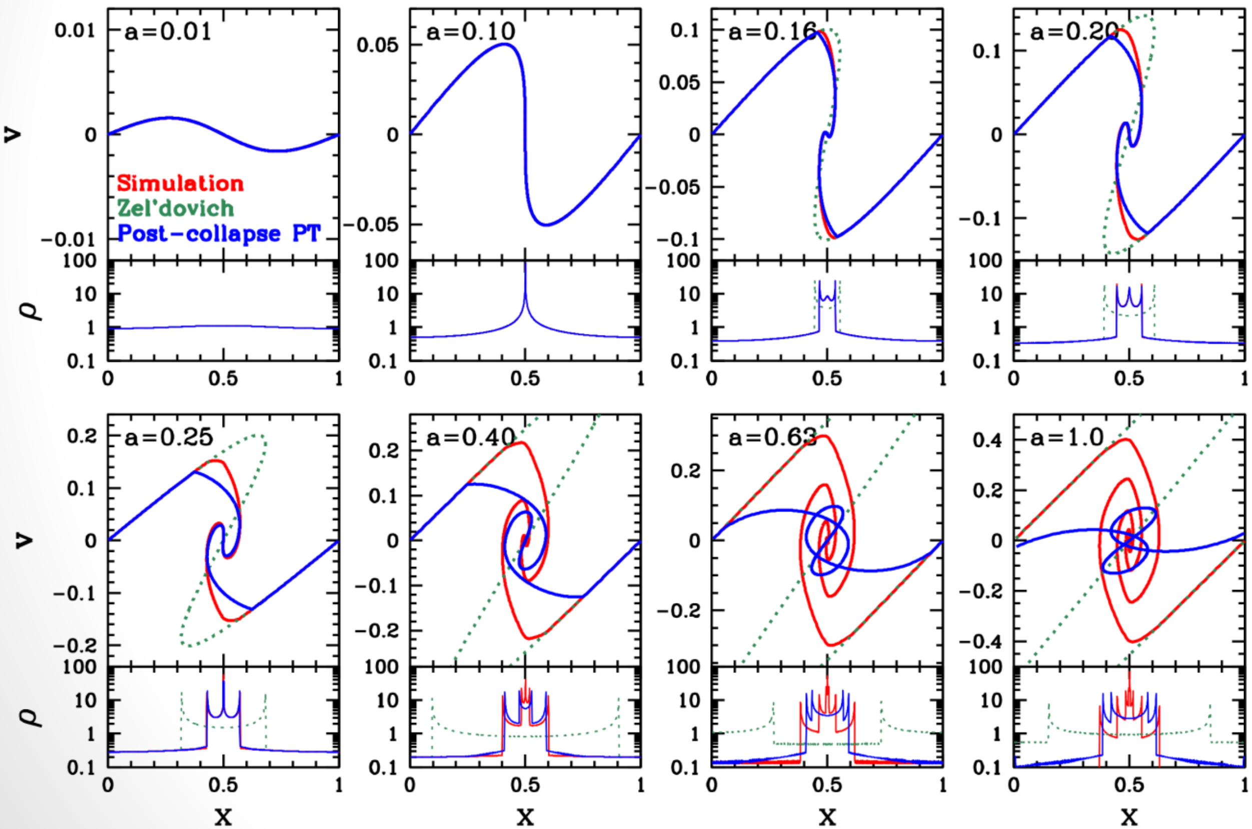


In earlier work ( FL, Jasche, Lavaux, Wandelt & Percival 2017, arXiv:1601.00093 ),
these were postdictions. Thanks to BORGPM (full non-linear dynamics),
we have now actual measurements - with uncertainties.

Prideaux-Ghee, FL, Heavens, Lavaux & Jasche, in prep.

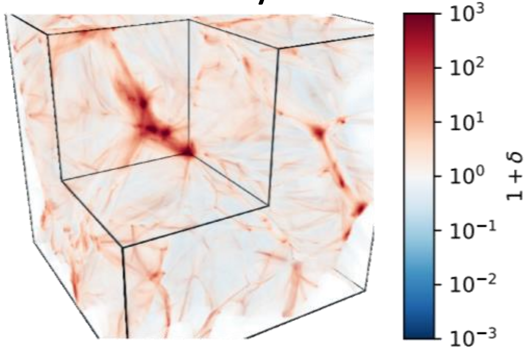
# The multi-stream regime and velocity dispersion

- The breakdown of $\sigma_{ij} \approx 0$, describing the generation of velocity dispersion or anisotropic stress due to the multiple-stream regime, is generically known as shell-crossing.

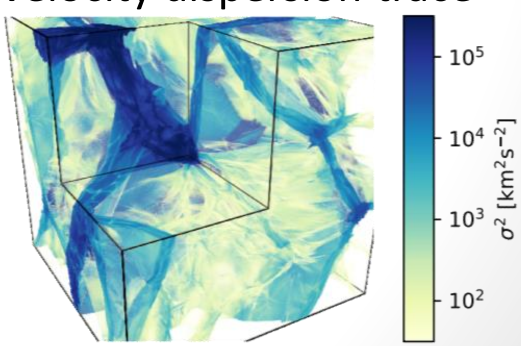



Taruya & Colombi 2017, 1701.09088

Density



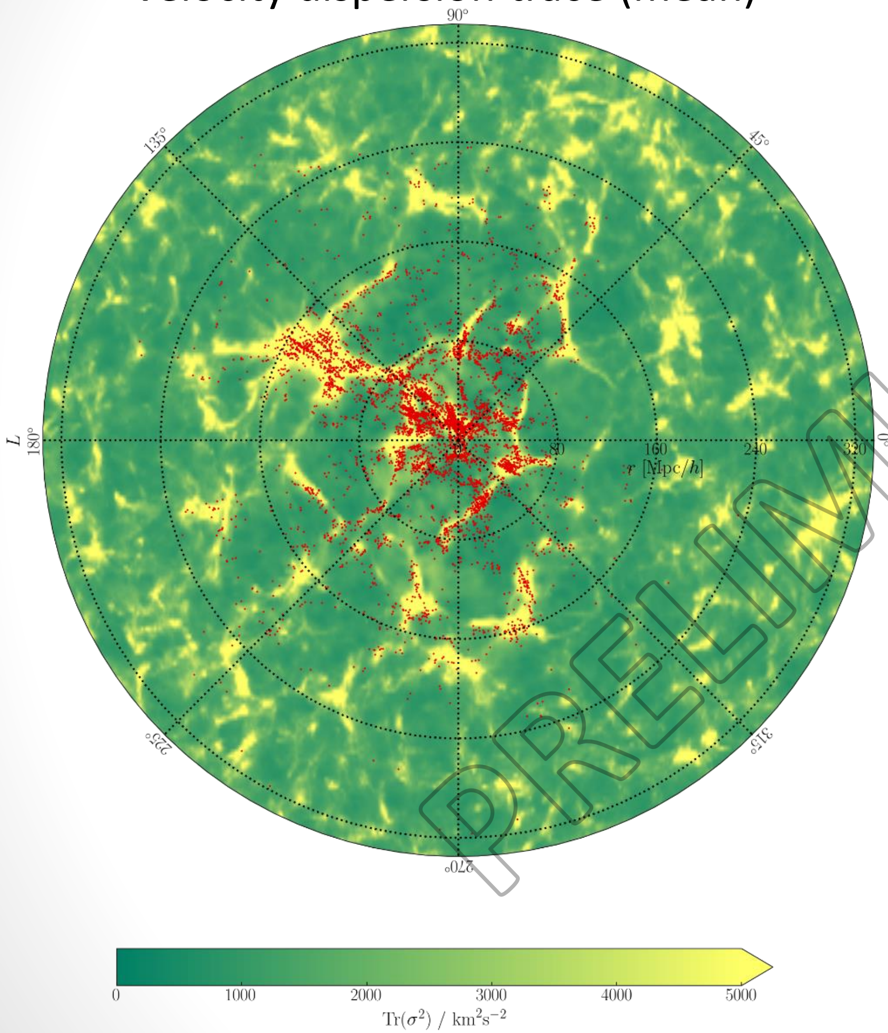

Velocity dispersion trace



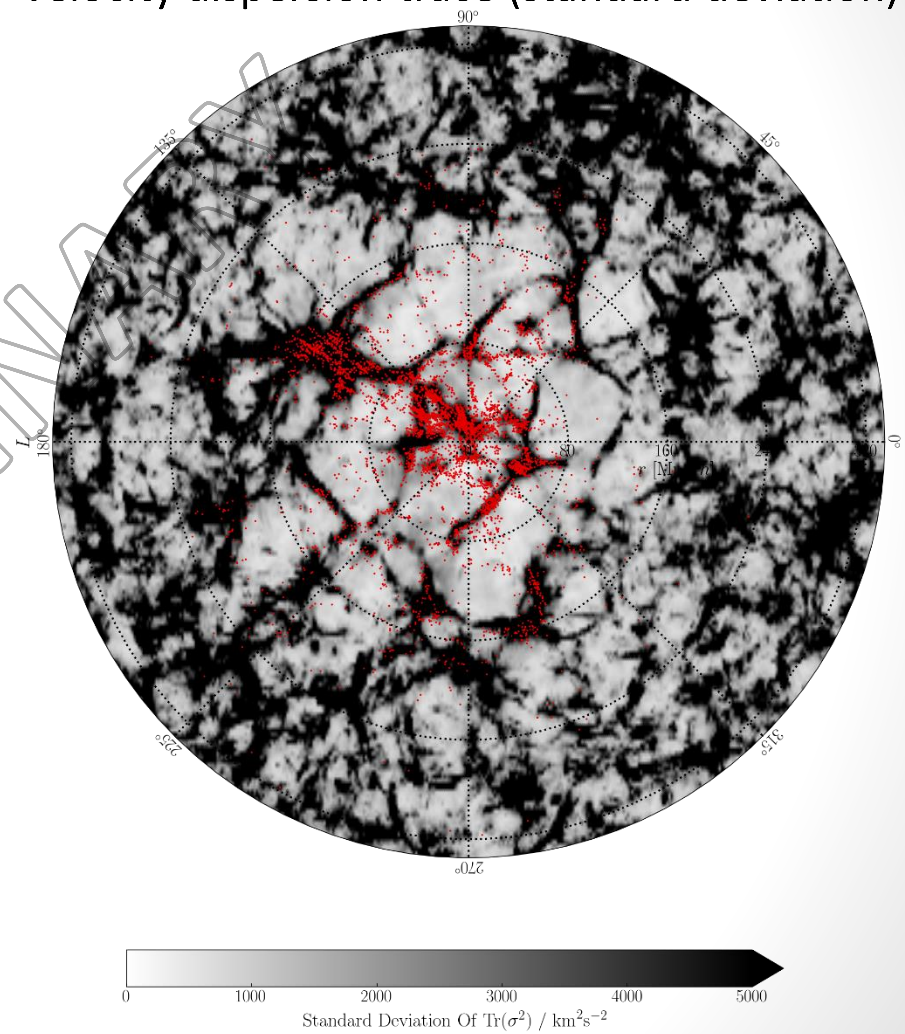

Buehlmann & Hahn 2019, 1812.07489

# Velocity dispersion in the local Universe

Velocity dispersion trace (mean)

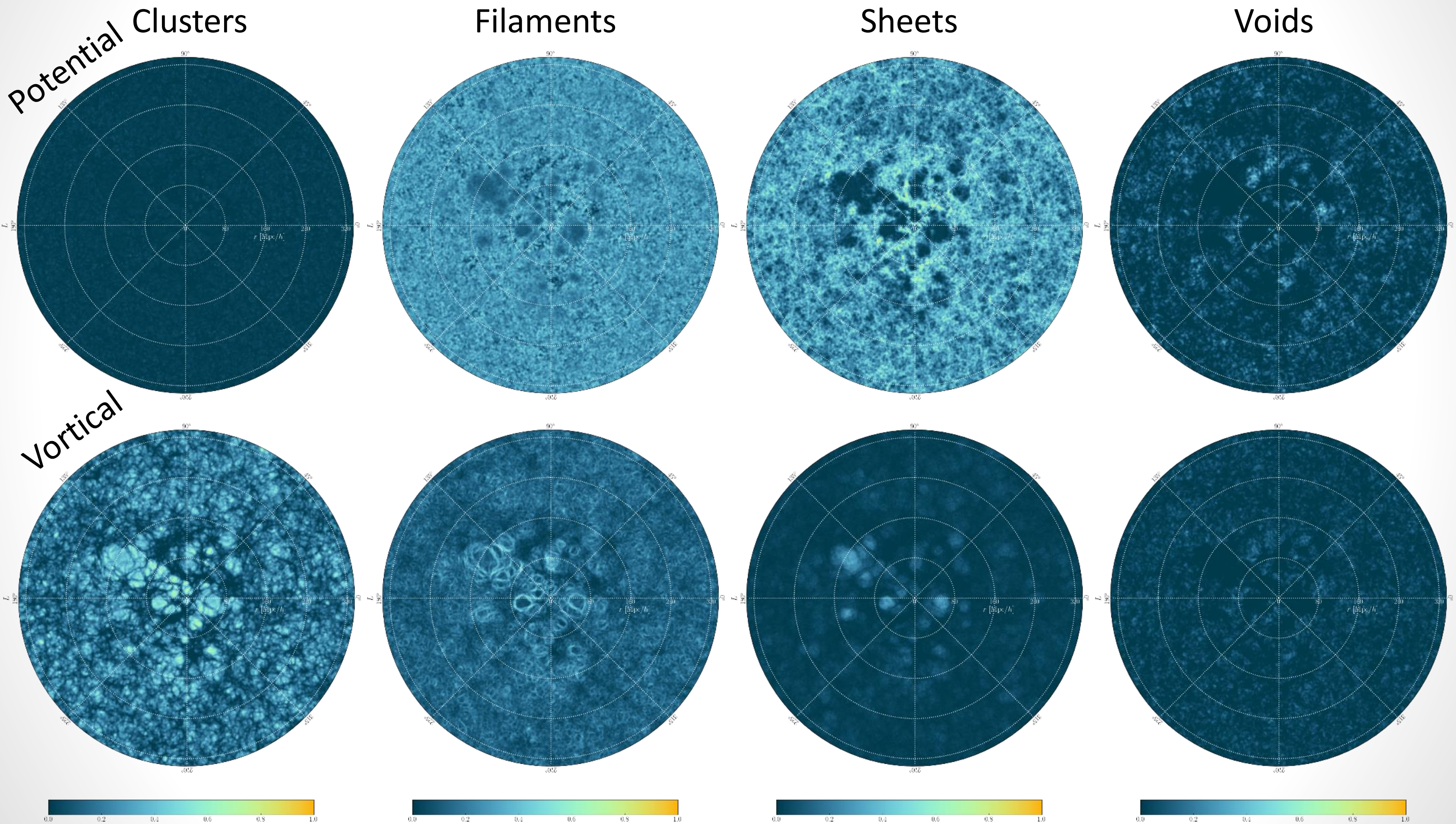



Velocity dispersion trace (standard deviation)



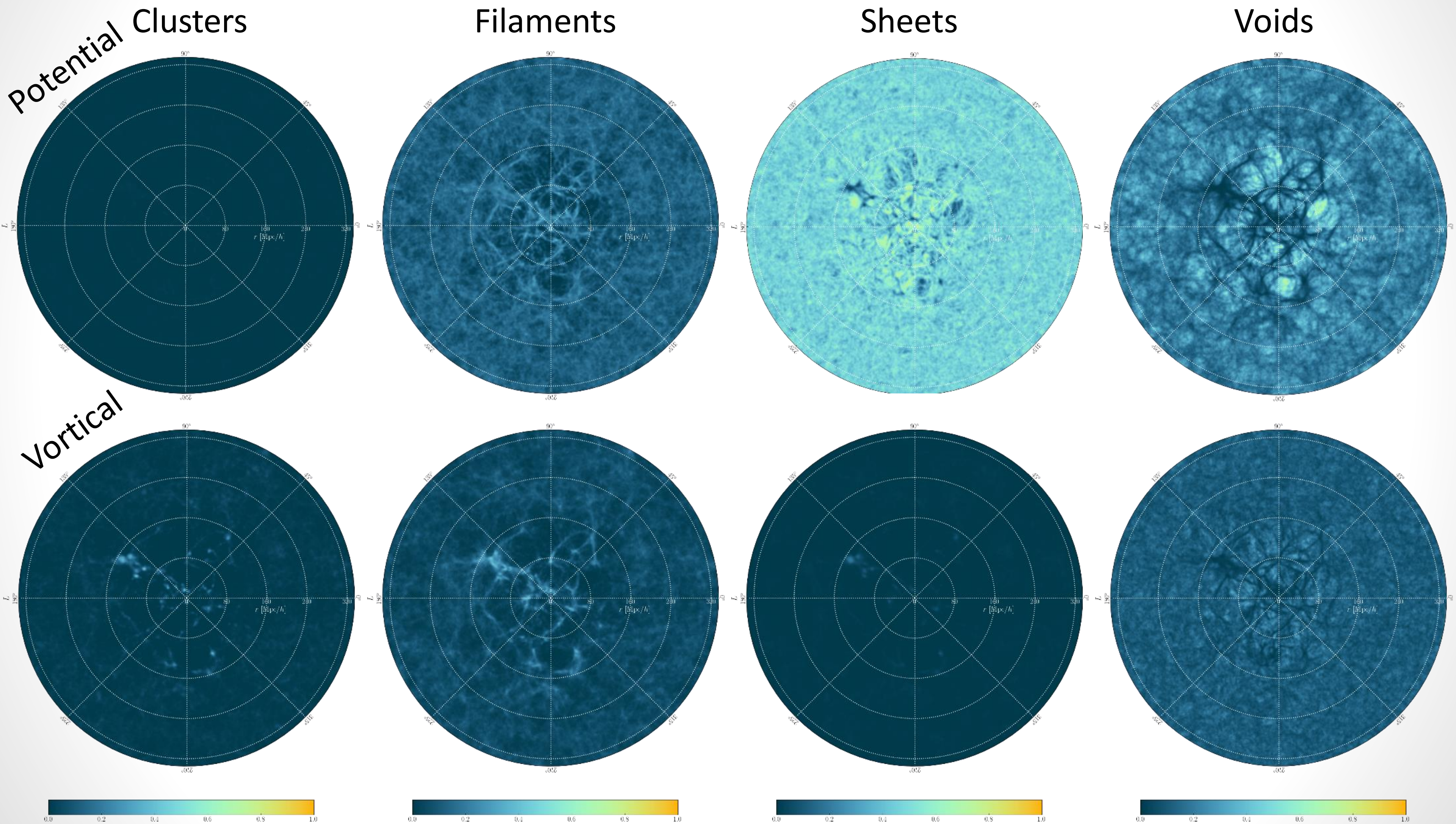

Prideaux-Ghee, FL, Heavens, Lavaux & Jasche, in prep.

# LICH initial structures inferred by BORG




Prideaux-Ghee, FL, Heavens, Lavaux & Jasche, in prep.

# LICH final structures inferred by BORG




Prideaux-Ghee, FL, Heavens, Lavaux & Jasche, in prep.

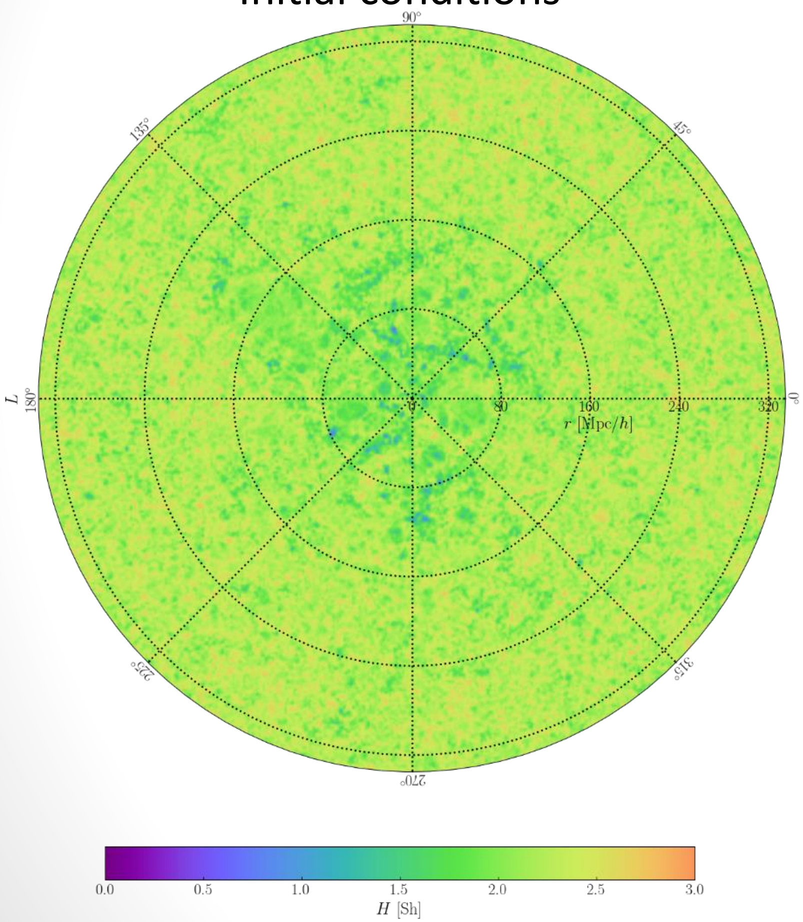
# How is information propagated?

Shannon entropy:

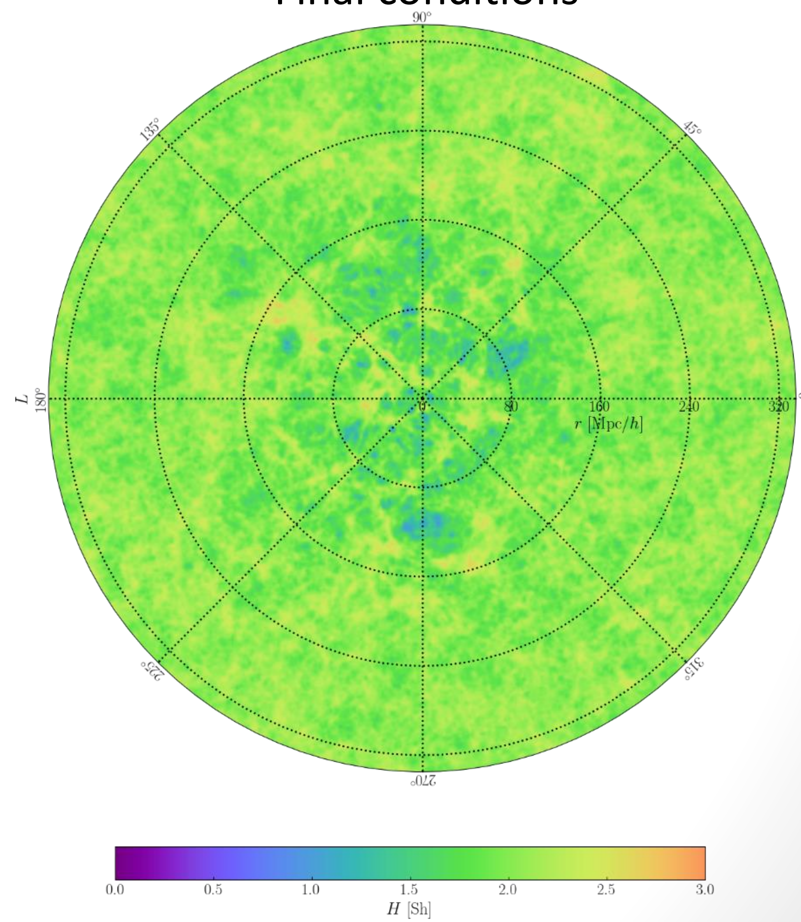
$$H[\mathcal{P}(\mathrm{T}(\vec{x})|d)] \equiv -\sum_{i=0}^{7} \mathcal{P}(\mathrm{T}_i(\vec{x})|d)\ \log_2(\mathcal{P}(\mathrm{T}_i(\vec{x})|d))$$

in shannons (Sh)

Initial conditions




Final conditions



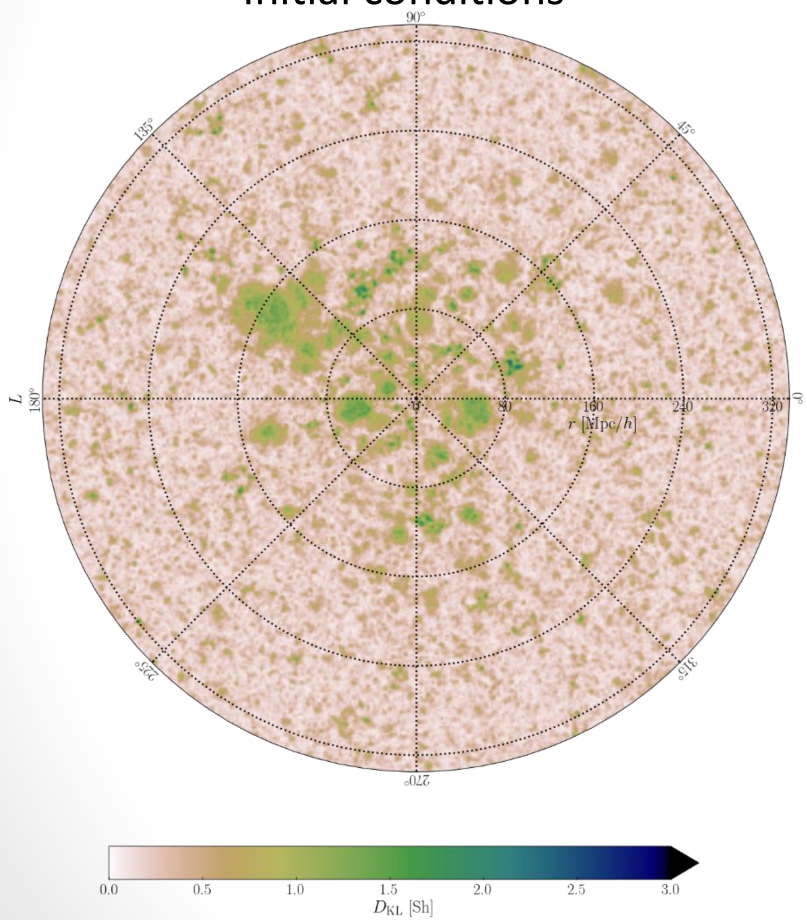

FL, Lavaux & Jasche, in prep.

# How much did the data surprise us?

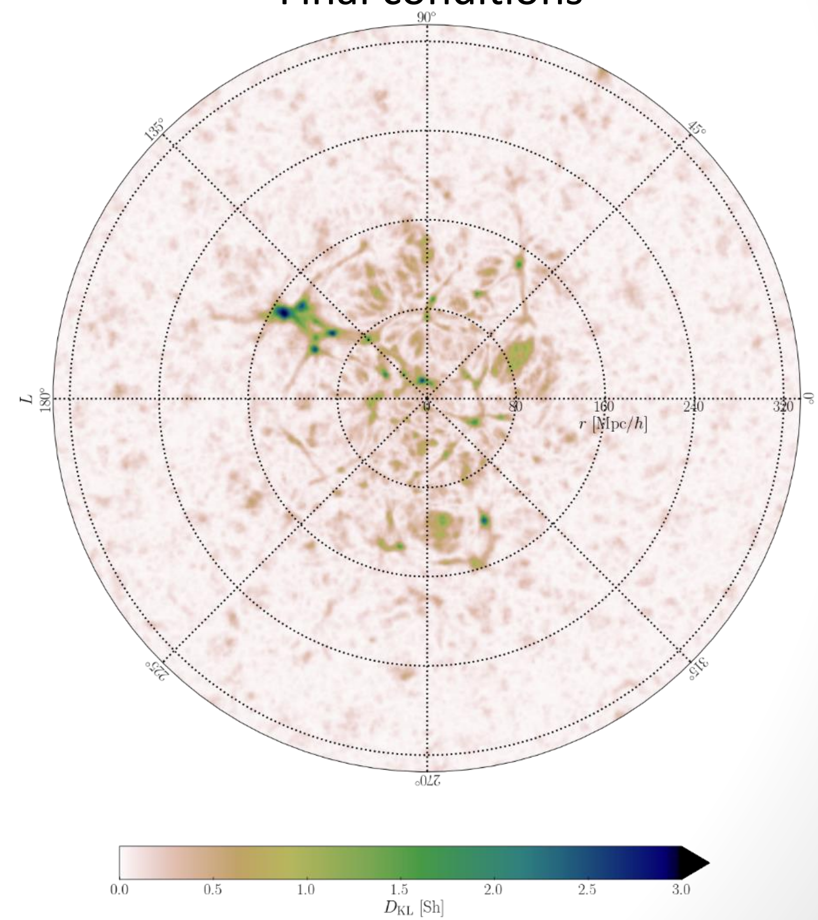
Information gain:

$$D_{\mathrm{KL}}[\mathcal{P}(\mathrm{T}(\vec{x})|d)||\mathcal{P}(\mathrm{T})] \equiv -\sum_{i=0}^{7} \mathcal{P}(\mathrm{T}_i(\vec{x})|d)\ \log_2\left(\frac{\mathcal{P}(\mathrm{T}_i(\vec{x})|d)}{\mathcal{P}(\mathrm{T}_i)}\right)$$ in shannons (Sh)

Initial conditions




Final conditions




FL, Lavaux & Jasche, in prep.

# A decision rule to build catalogues of objects

- Space of 8 "input features":

$$\{\mathrm{T}_0 = \text{potential void}, \mathrm{T}_1 = \text{potential sheet}, \mathrm{T}_2 = \text{potential filament}, \\ \mathrm{T}_3 = \text{potential cluster}, \mathrm{T}_4 = \text{vortical void}, \mathrm{T}_5 = \text{vortical sheet}, \\ \mathrm{T}_6 = \text{vortical filament}, \mathrm{T}_7 = \text{vortical cluster}\}$$

- Space of 9 "actions":

$$\{a_j = \text{``decide structure } \mathrm{T}_j\text{'' for } 0 \leq j \leq 7, \\ a_{-1} = \text{``remain undecided''}\}$$

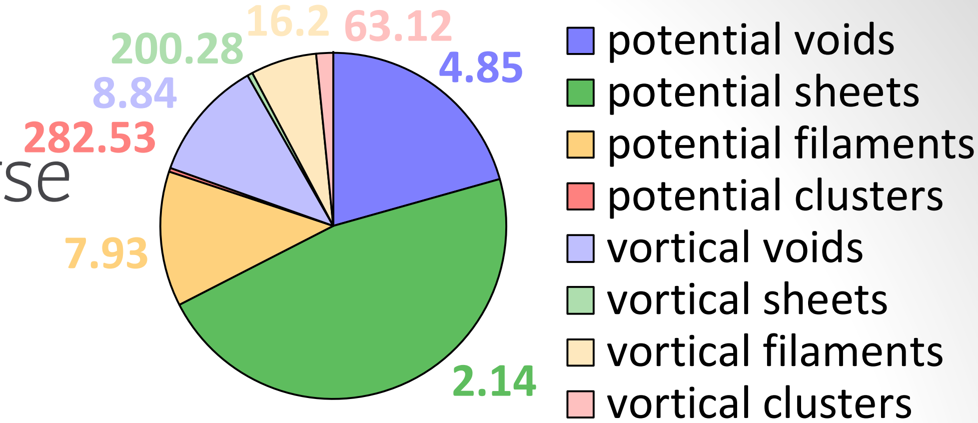
➡ A problem of Bayesian decision theory:
one should take the action that maximises the utility

$$U(a_j(\vec{x})|d) = \sum_{i=0}^{7} G(a_j|\mathrm{T}_i)\, \mathcal{P}(\mathrm{T}_i(\vec{x})|d)$$

- How to write down the gain functions?

FL, Jasche & Wandelt 2015, 1503.00730

# Gambling with the Universe




- One proposal:

$$G(a_j|\mathrm{T}_i) = \begin{cases} \frac{1}{\mathcal{P}(\mathrm{T}_i)} - \alpha & \text{if } j \in [\![0,7]\!] \text{ and } i = j \\ -\alpha & \text{if } j \in [\![0,7]\!] \text{ and } i \neq j \\ 0 & \text{if } j = -1. \end{cases}$$

"Winning"
"Losing"
"Not playing"

- Without data, the expected utility is

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

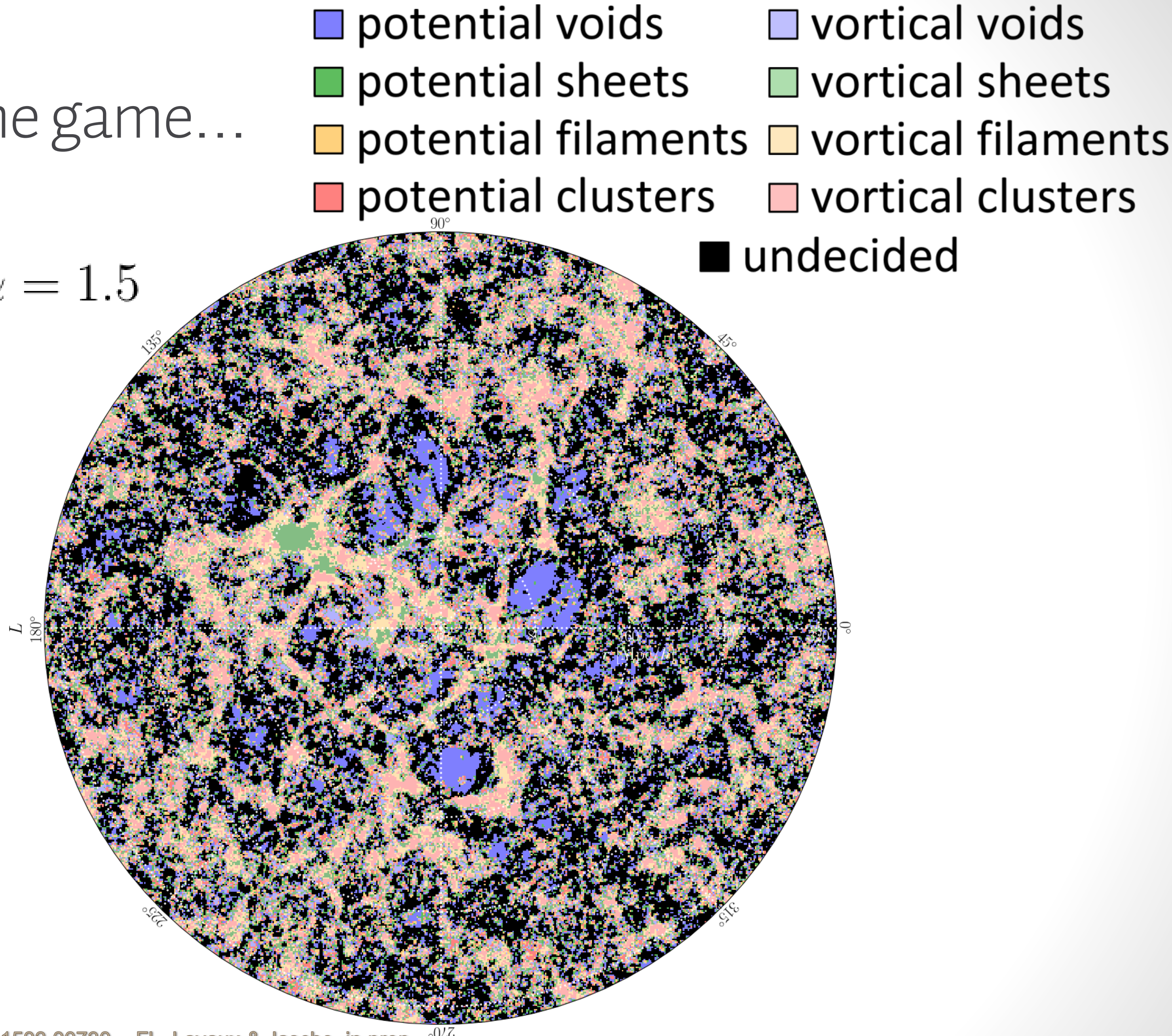
$$U(a_{-1}) = 0$$ "Not playing the game"

- 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, 1503.00730

# Playing the game…

$\alpha = 1.5$




FL, Jasche & Wandelt 2015, 1503.00730 – FL, Lavaux & Jasche, in prep.

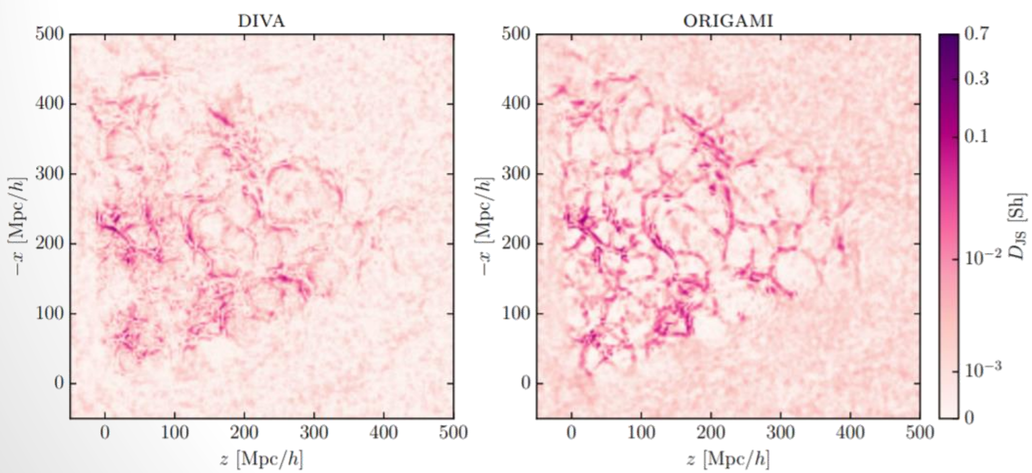
# Comparing cosmic web classifiers

- The decision problem can further extended to the space of classifiers, with a utility function depending on the desired application:

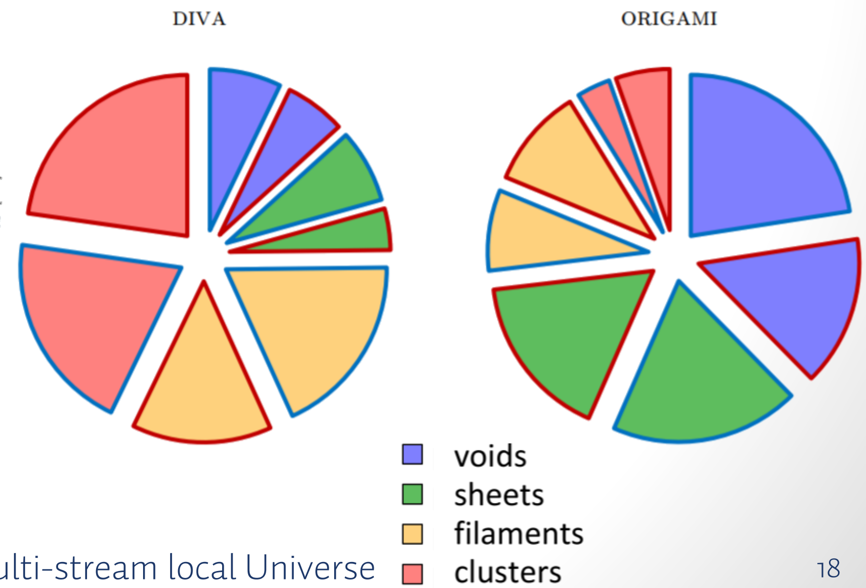
$$\underset{\text{classifier}}{U(\xi)} = \int U(\xi, d)p(d|\xi)\,\mathrm{d}\underset{\text{data}}{d}$$

- Examples:

Comparing dark energy models




Classifying blue/red galaxies as a function of their environment




FL, Lavaux, Jasche & Wandelt 2016, 1606.06758

# Conclusions

- BORG is a Bayesian inference engine allowing the analysis of the large-scale structure and its formation history.
- Thanks to BORGPM, it is possible to map the multi-stream local Universe, including the velocity dispersion tensor.
- The cosmic web can be physically described using LICH, a classifier distinguishing potential and vortical flows.
- A probabilistic analysis of the cosmic web yields a data-supported connection between cosmology and information theory.
- Decision theory offers a framework to classify structures in the presence of data constraints and uncertainty.