

The phase-space structure of nearby dark matter

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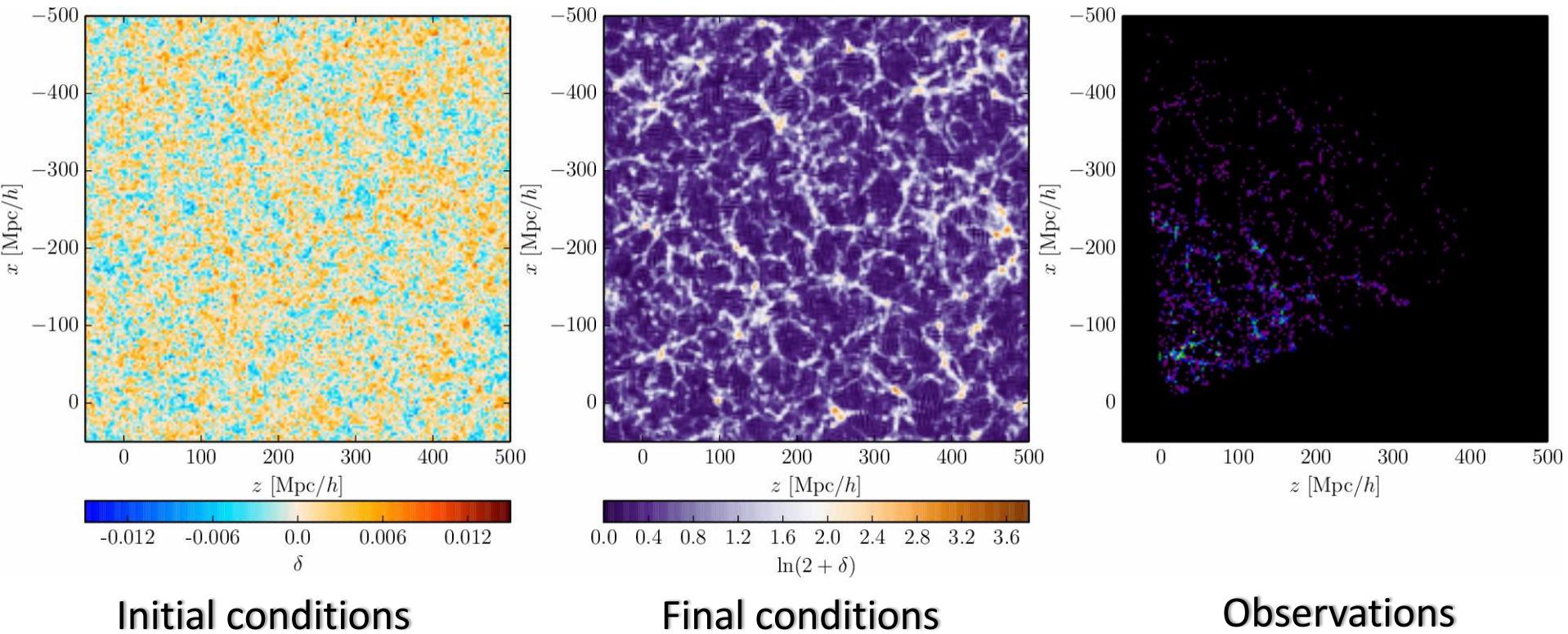


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In collaboration with:

Jens Jasche (ExC Universe, Garching), Guilhem Lavaux (IAP),
Will Percival (ICG), Benjamin Wandelt (IAP/U. Illinois)

The BORG SDSS run



Initial conditions

Final conditions

Observations

334,074 galaxies, ≈ 17 millions parameters, 3 TB of primary data products, 12,000 samples, $\approx 250,000$ data model evaluations, 10 months on 32 cores

Jasche, FL & Wandelt 2015, arXiv:1409.6308

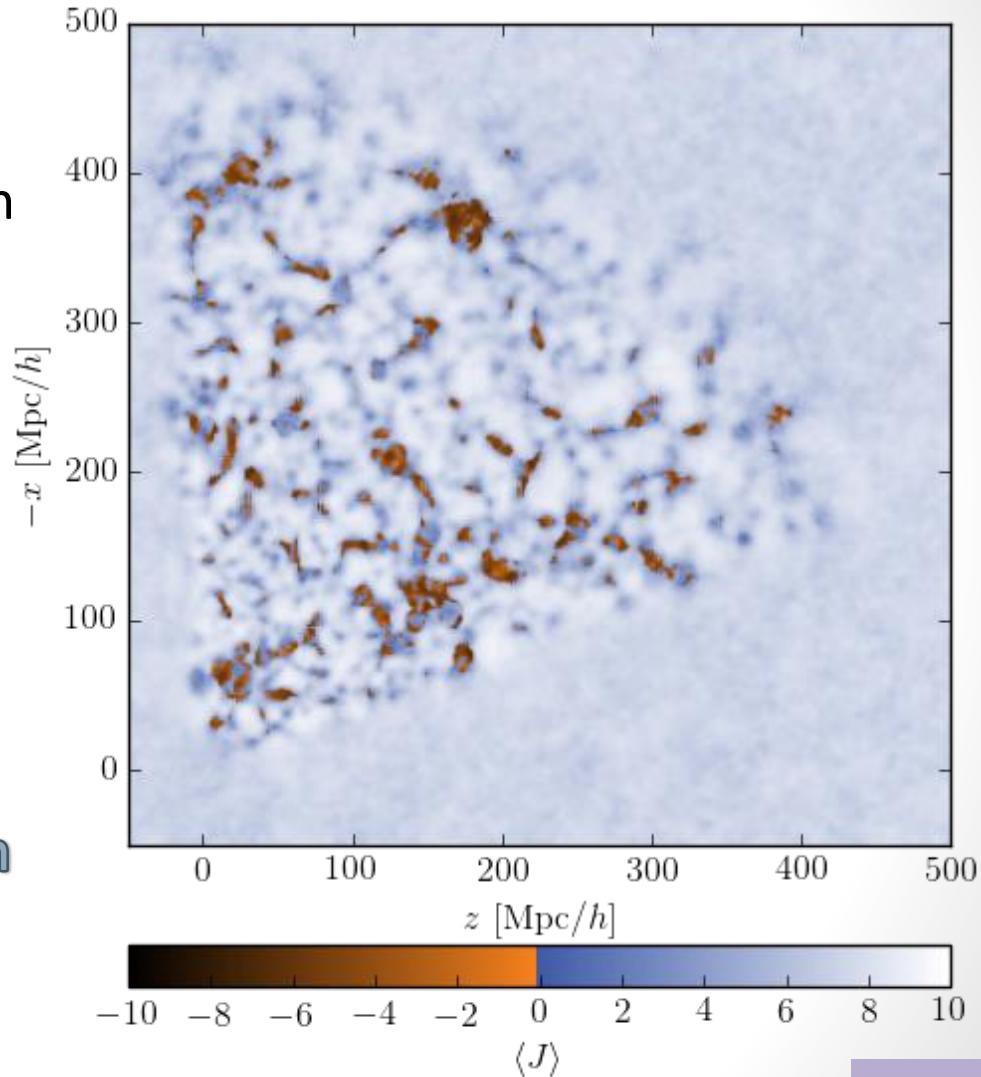
Inference of the dark matter phase-space sheet

- The dark matter phase-space sheet has been studied so far in simulations

e.g. Neyrinck 2012, arXiv:1202.3364

Abel, Hahn & Kaehler 2012, arXiv:1111.3944

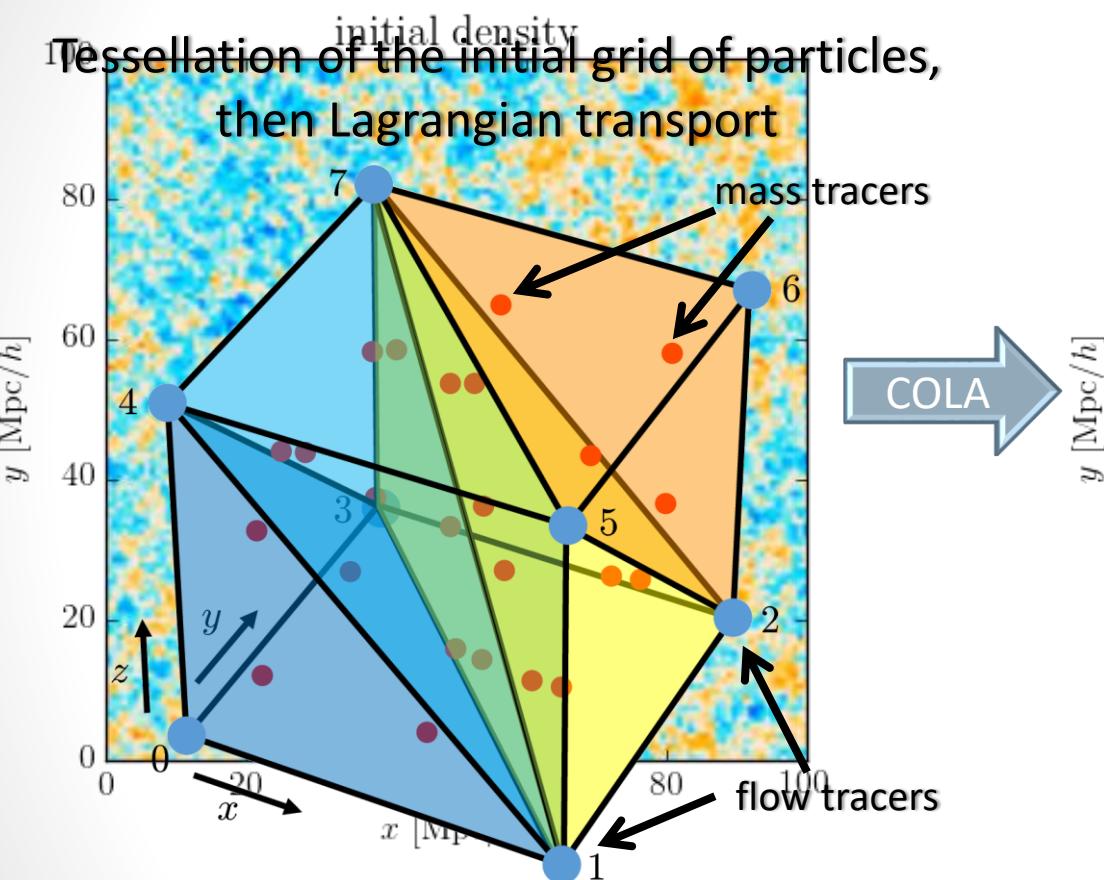
Shandarin, Habib & Heitmann 2012, arXiv:1111.2366



- BORG infers **Lagrangian dynamics** in real data
- Identified structures have a direct **physical interpretation**

FL, Jasche, Lavaux & Wandelt 2016, arXiv:1601.00093

Non-linear filtering improves density samples



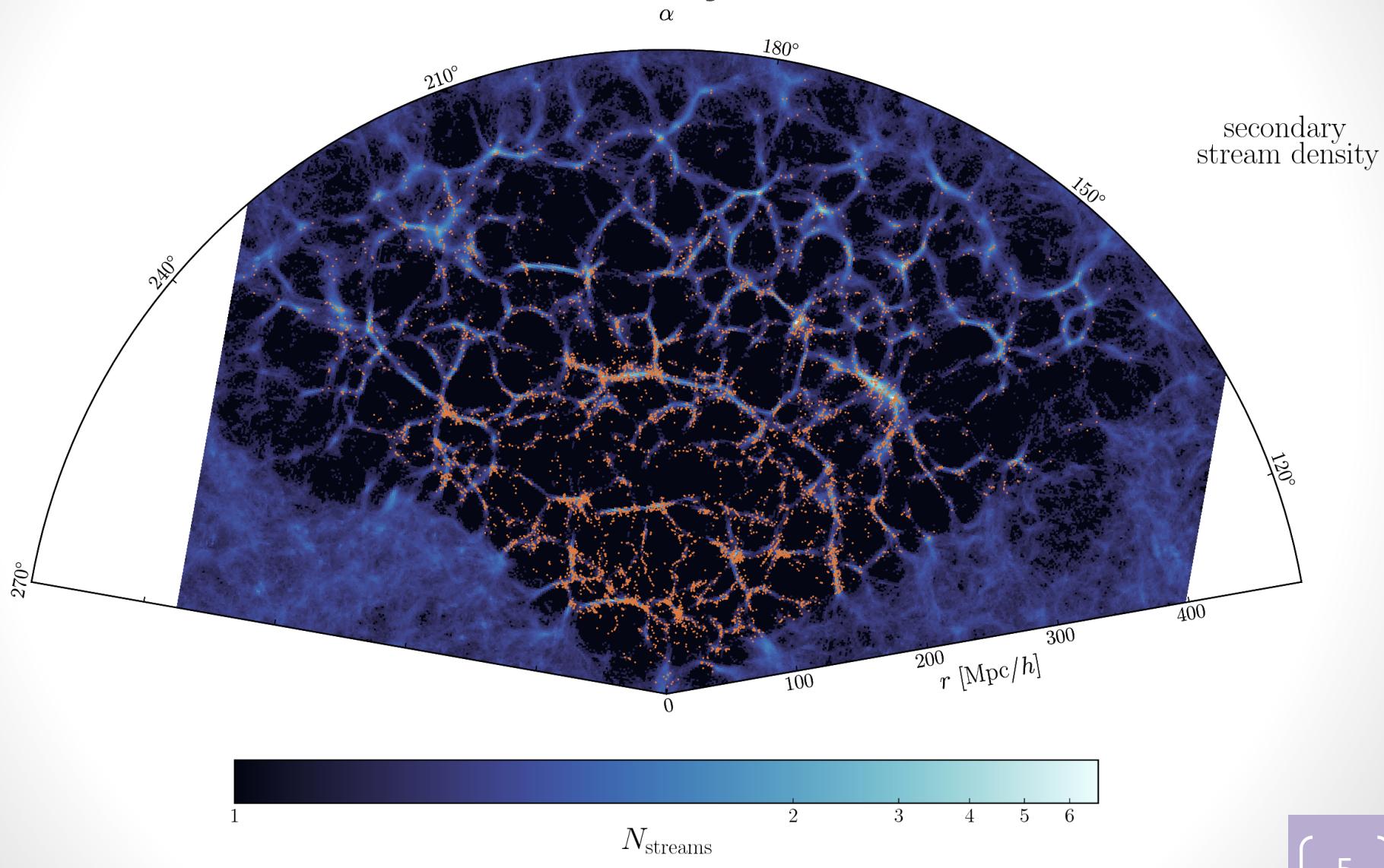
Abel, Hahn & Kaepler 2012, arXiv:1111.3944

Hahn, Abel & Khaeler 2013, arXiv:1210.6652

Hahn, Angulo & Abel 2015, arXiv:1404.2280

FL, Jasche, Lavaux & Wandelt 2016, arXiv:1601.00093

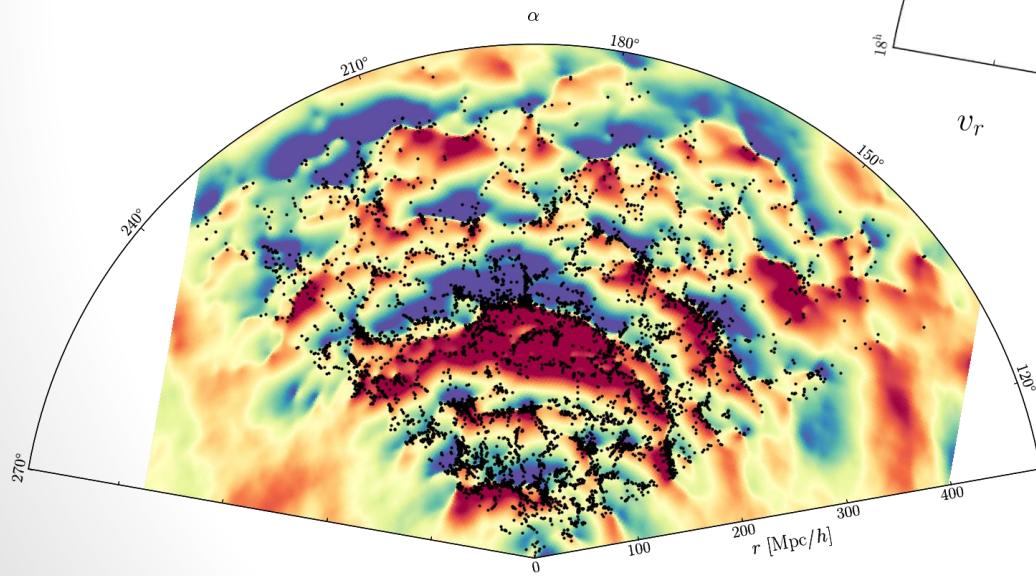
Dark matter stream density



Lagrangian transport of the velocity field

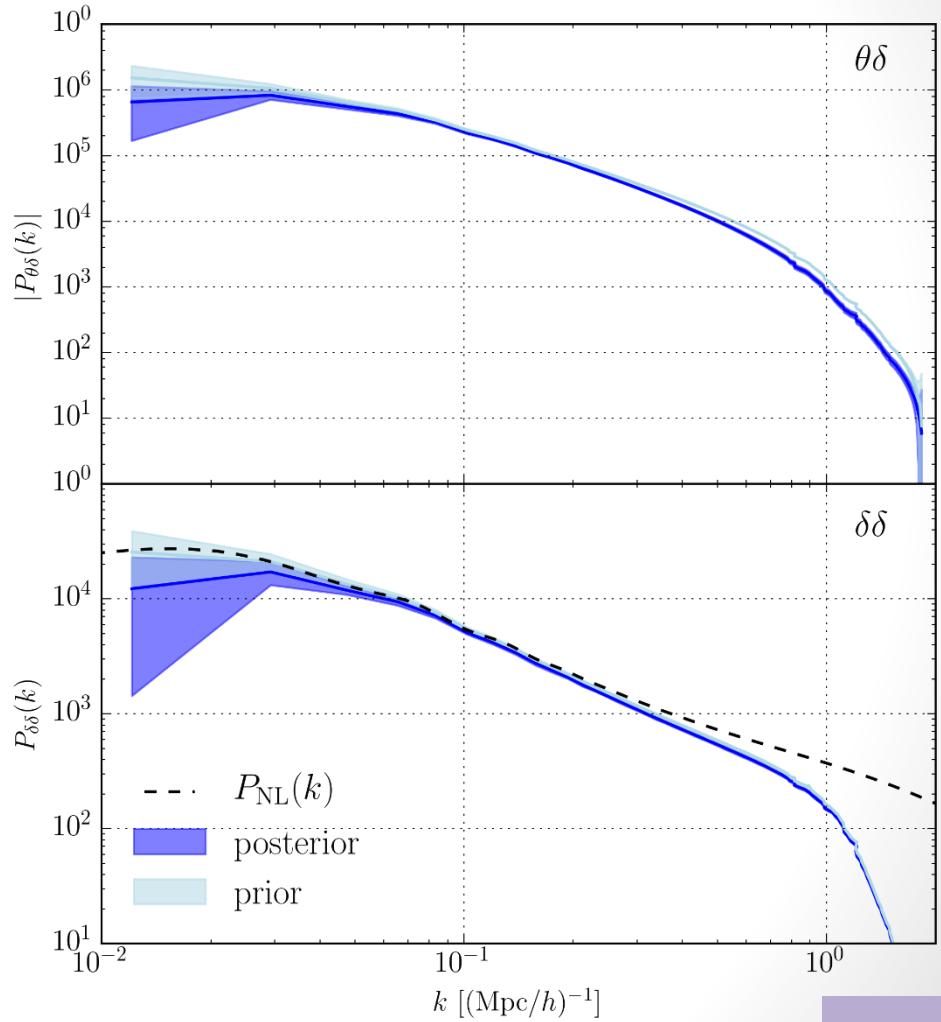
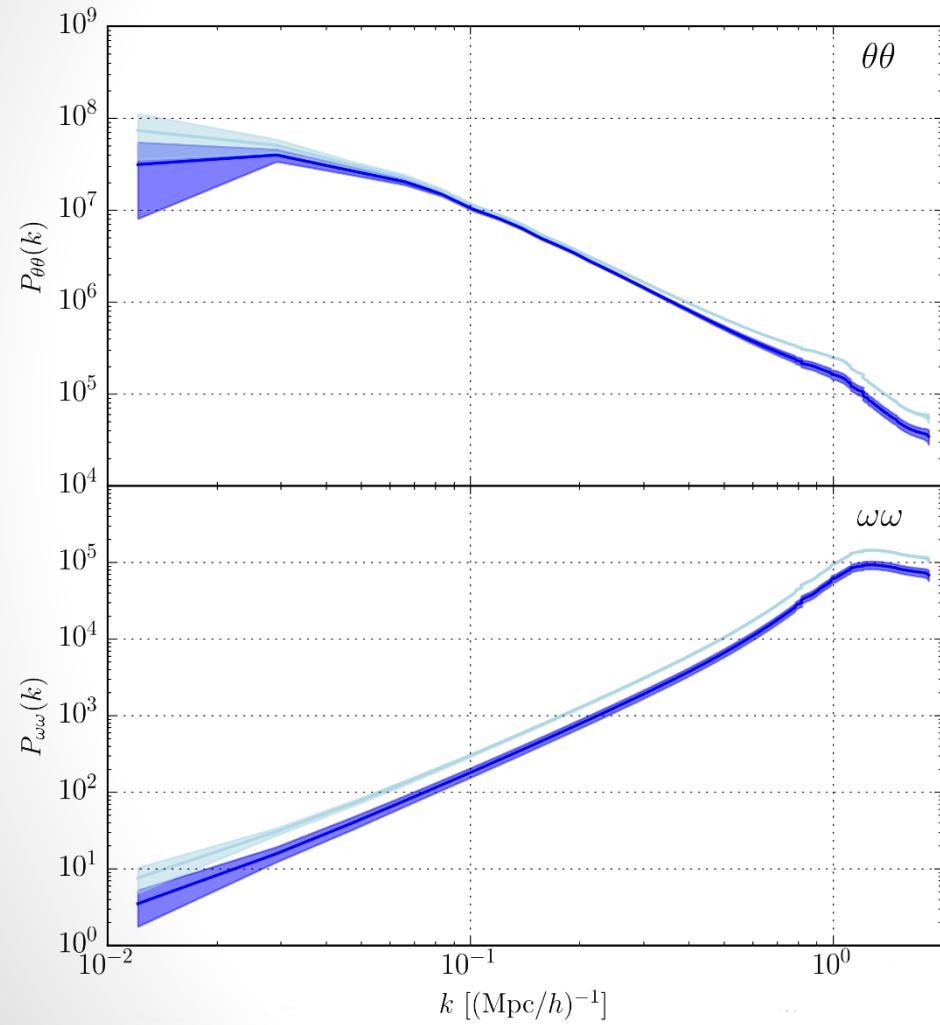
see Hahn, Angulo & Abel 2015, arXiv:1404.2280

Velocity field: 2014 vs 2016

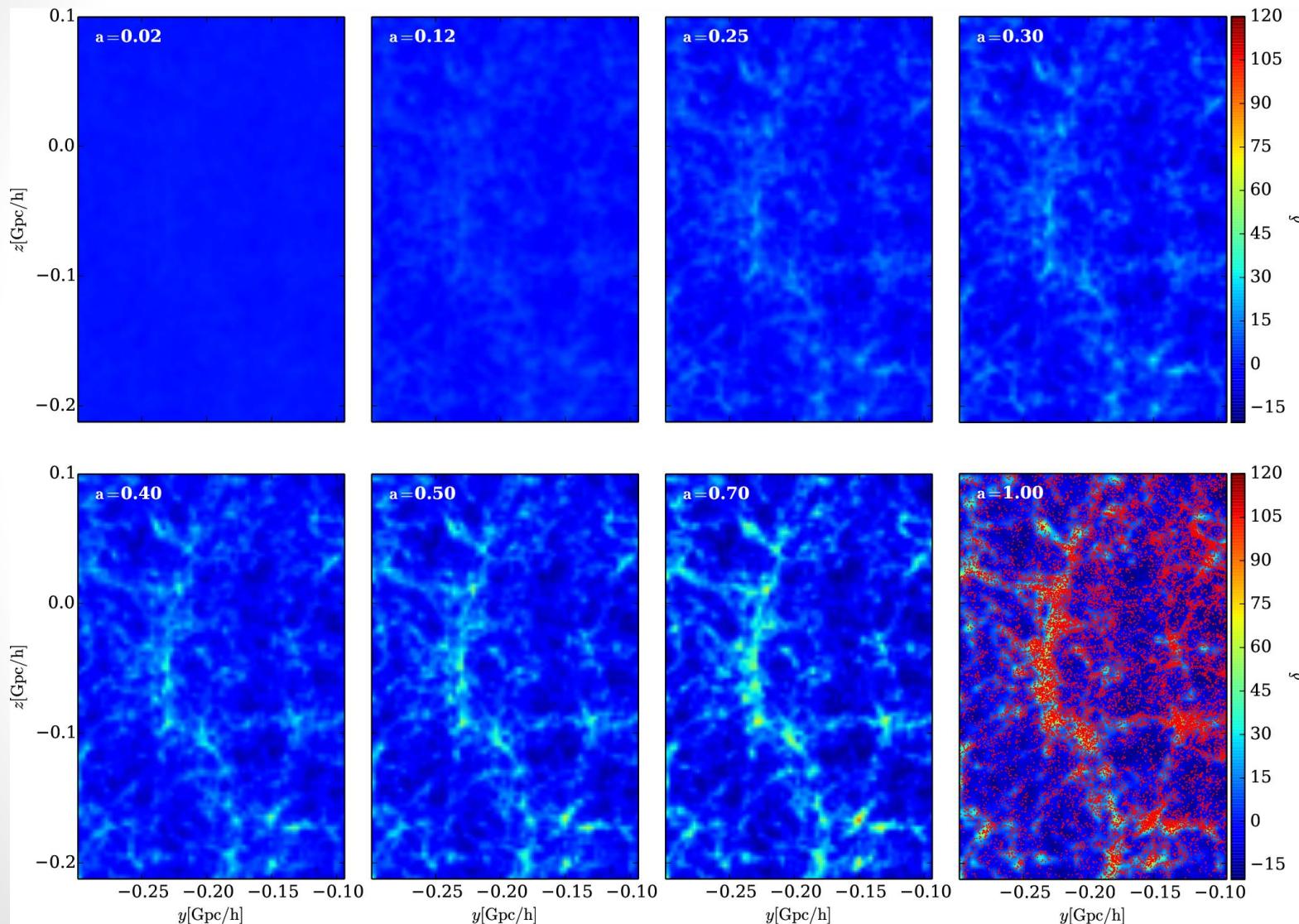


FL, Jasche, Lavaux & Wandelt 2016, arXiv:1601.00093

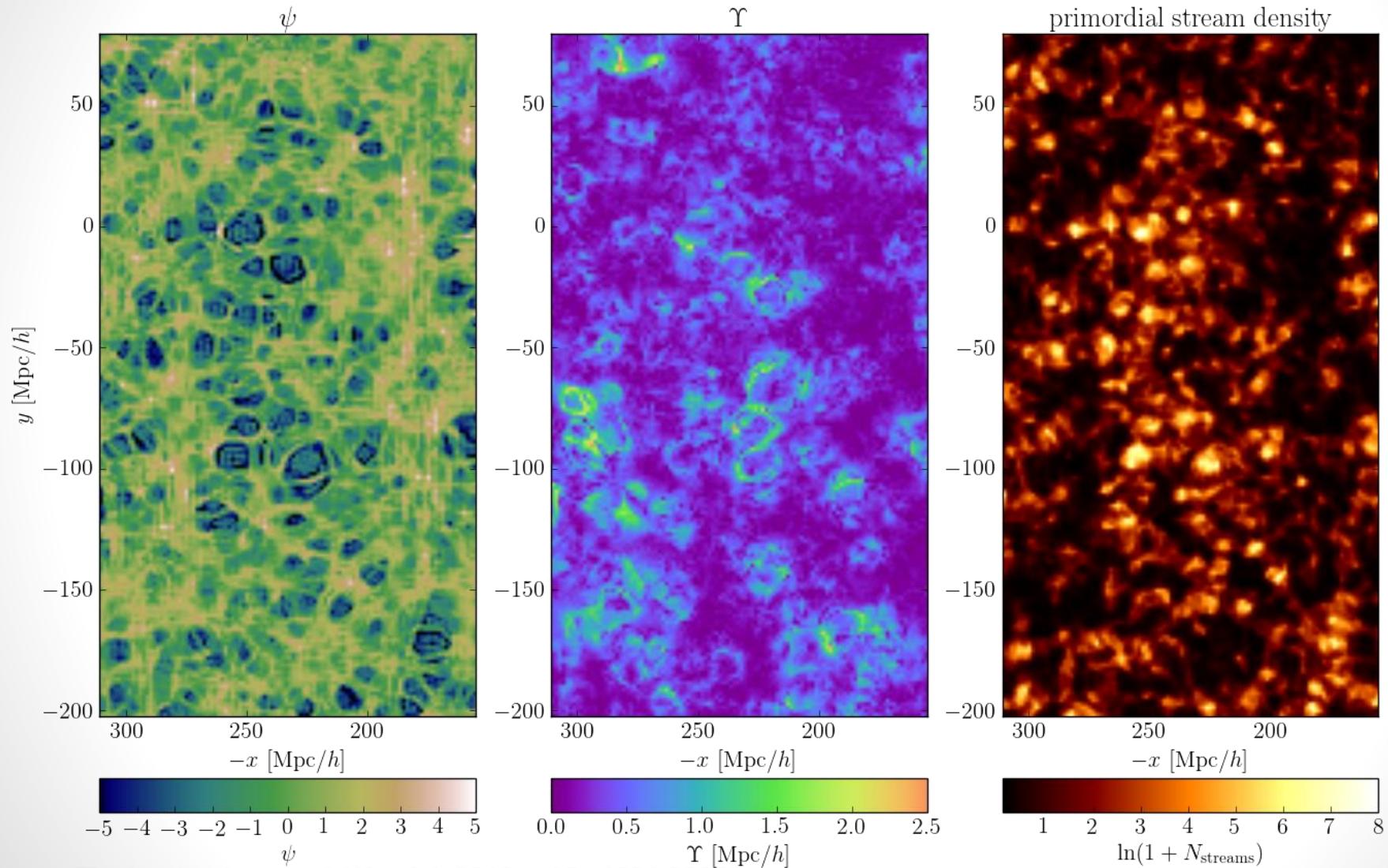
Inferred velocity fields are accurate in spite of the approximate inference model



The formation history of the Sloan Great Wall



Lagrangian picture of the Sloan Great Wall



FL, Jasche, Lavaux & Wandelt 2016, arXiv:1601.00093

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

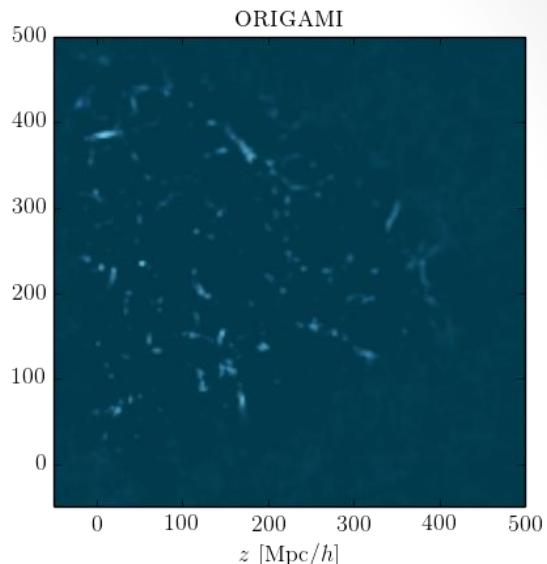
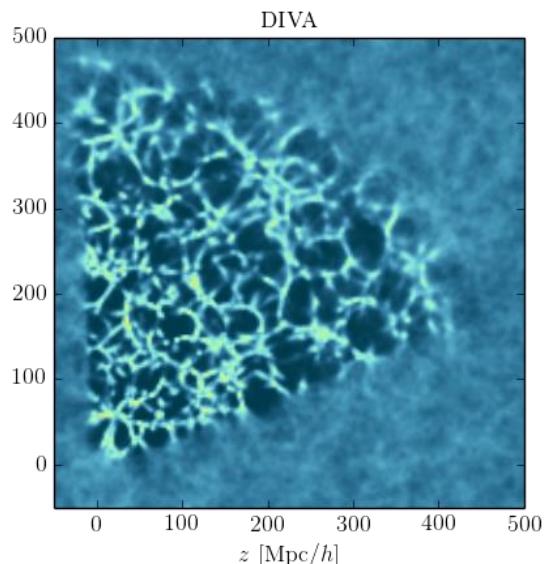
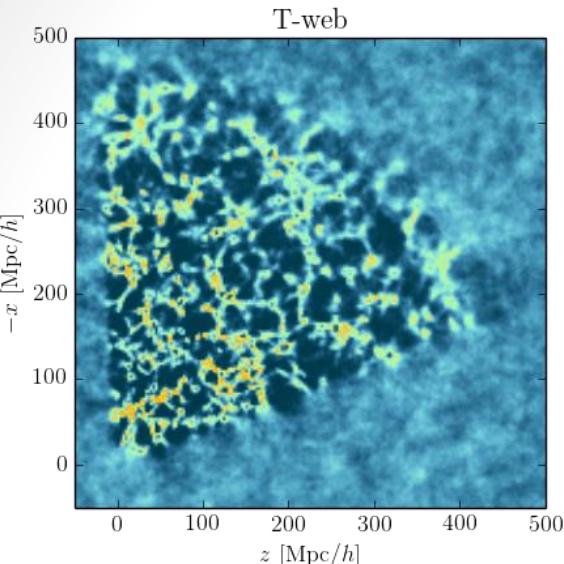
and many others...

Lagrangian
classifiers

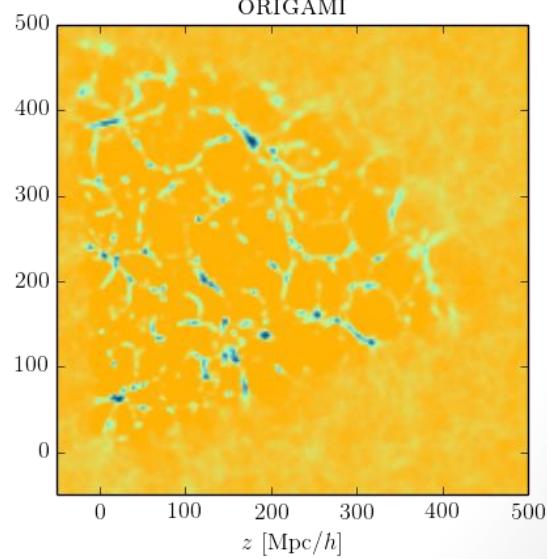
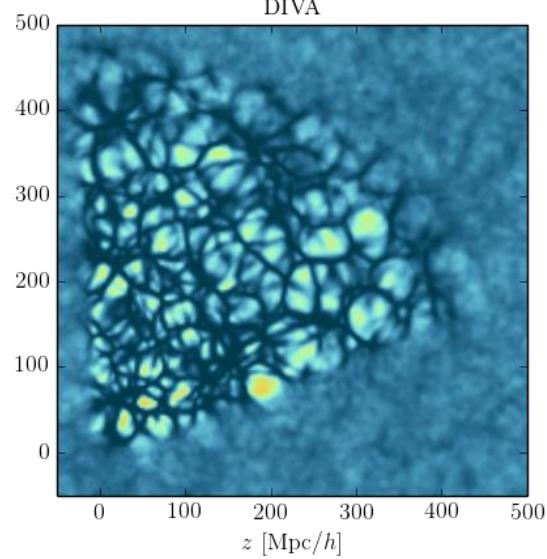
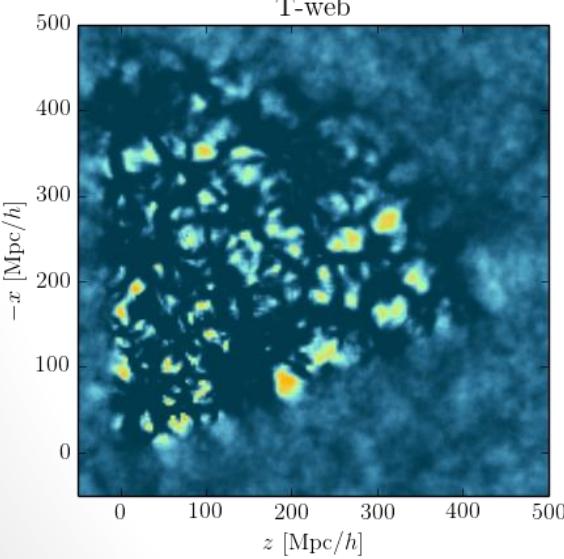
now usable
in real data!

Comparing classifiers

Filaments



Voids



FL, Jasche & Wandelt 2015a, arXiv:1502.02690

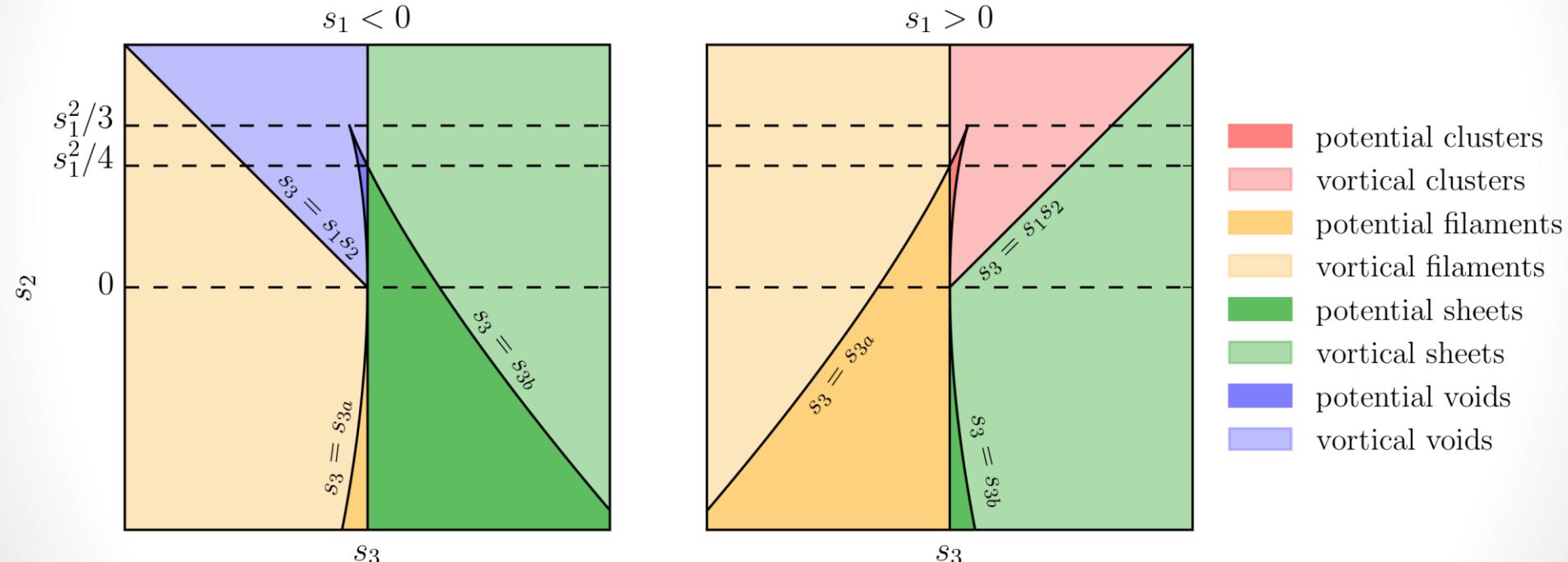
FL, Jasche, Lavaux & Wandelt 2016, arXiv:1601.00093

Introducing LICH

(Lagrangian Invariants Classification of Heterogeneous flows)

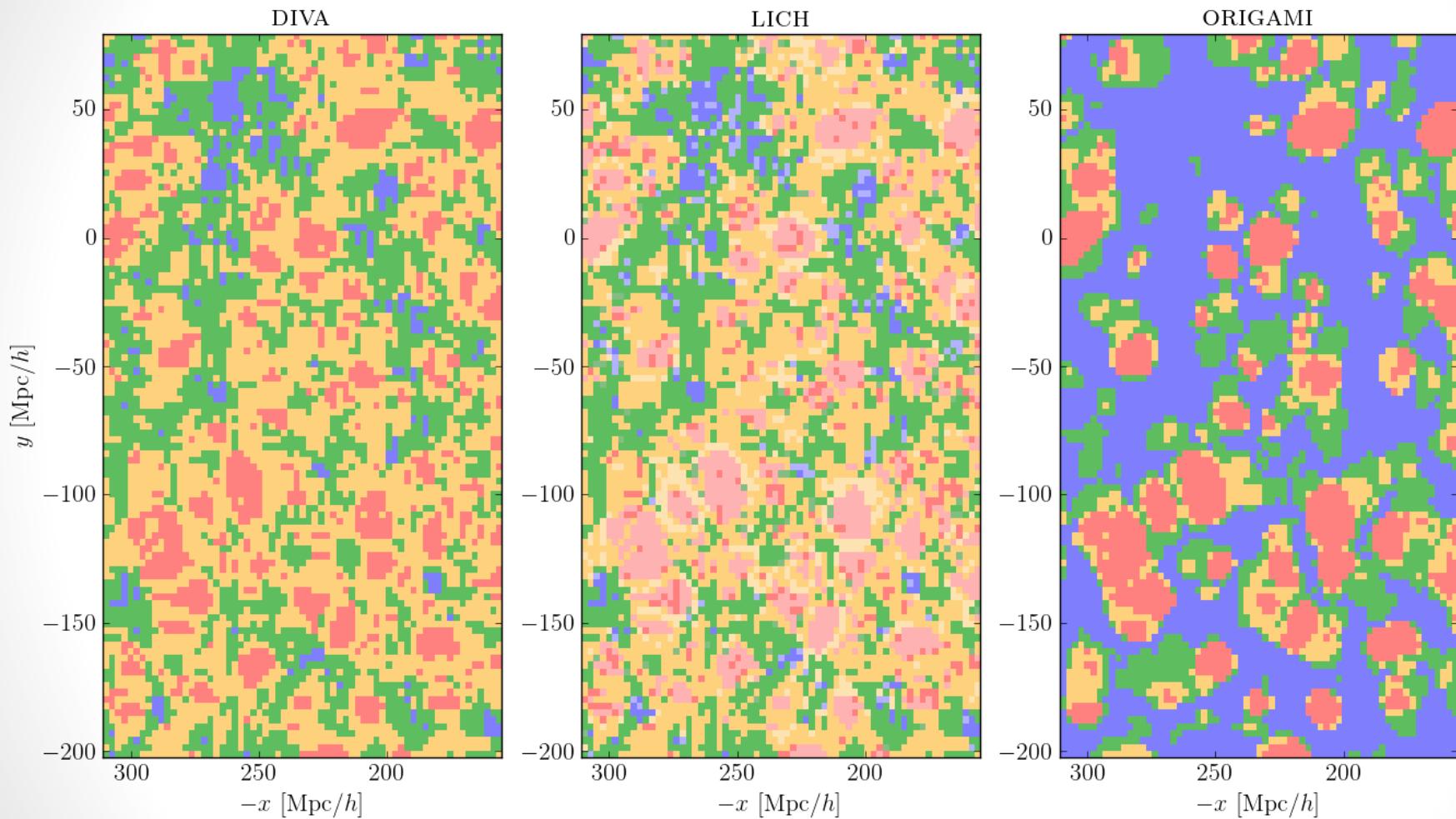
- **Characteristic equation** for the shear of the displacement:

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

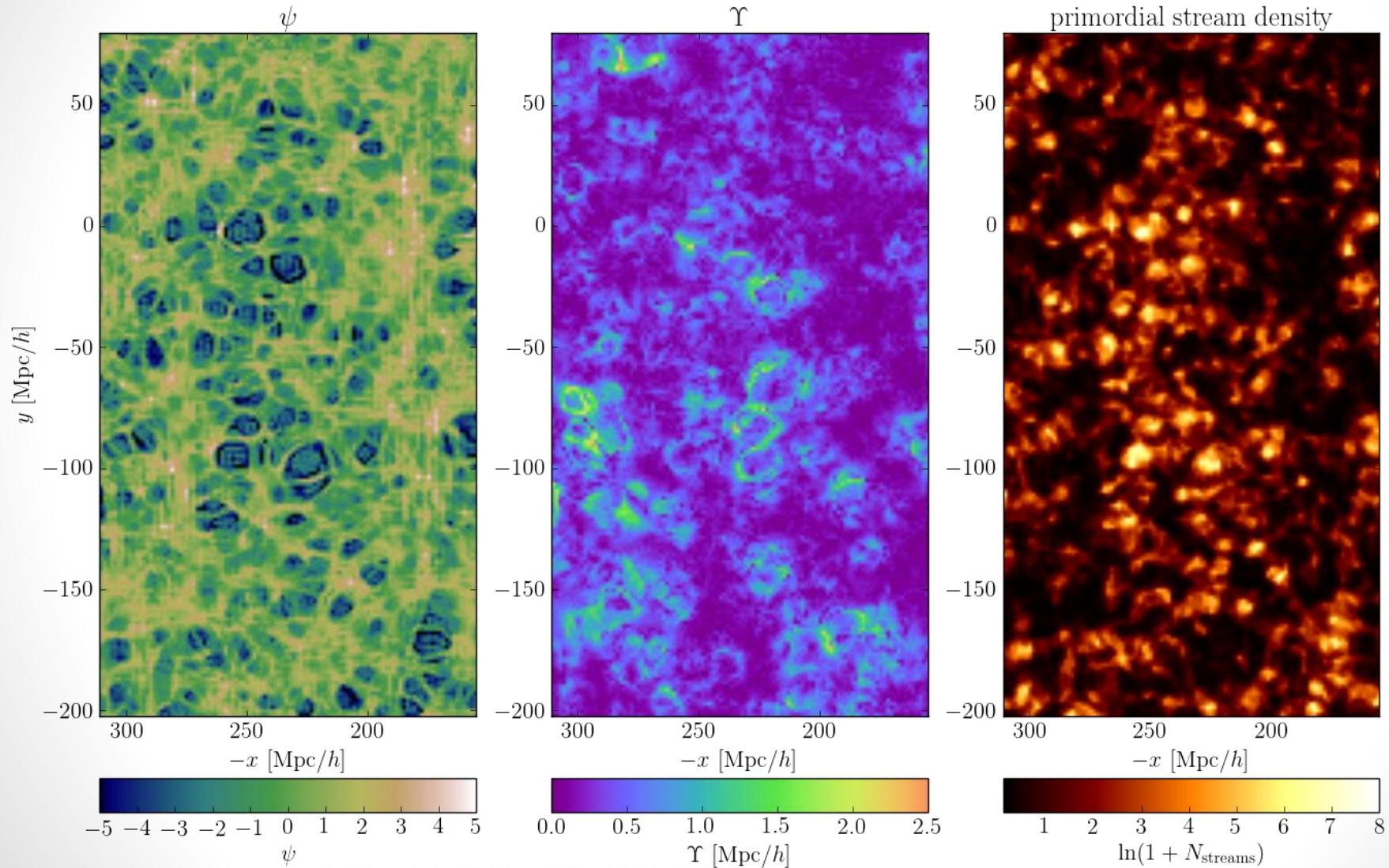


- **LICH** is a generalization of **DIVA** to the case of heterogeneous (potential and vortical) flows

Lagrangian structures in the Sloan Great Wall



Lagrangian picture of the Sloan Great Wall



FL, Jasche, Lavaux & Wandelt 2016, arXiv:1601.00093

Summary & Conclusions

- Thanks to **BORG**, we now have a **phase-space description of nearby dark matter**
- **Lagrangian transport** allows an enhanced description of density field, velocity field, stream density...
- We have introduced a new structure classifier, based on the Lagrangian invariants: **LICH**
- The **cosmic web** can be described using various classifiers, Eulerian (T-web...) or Lagrangian (DIVA, ORIGAMI, LICH...)
- Potential **applications**: dark matter indirect searches, supernovae cosmology, kinetic Sunyaev-Zel'dovich effect, intrinsic alignments for weak lensing and CMB lensing...

All maps, catalogs & scripts are publicly available at <http://icg.port.ac.uk/~leclercq/>