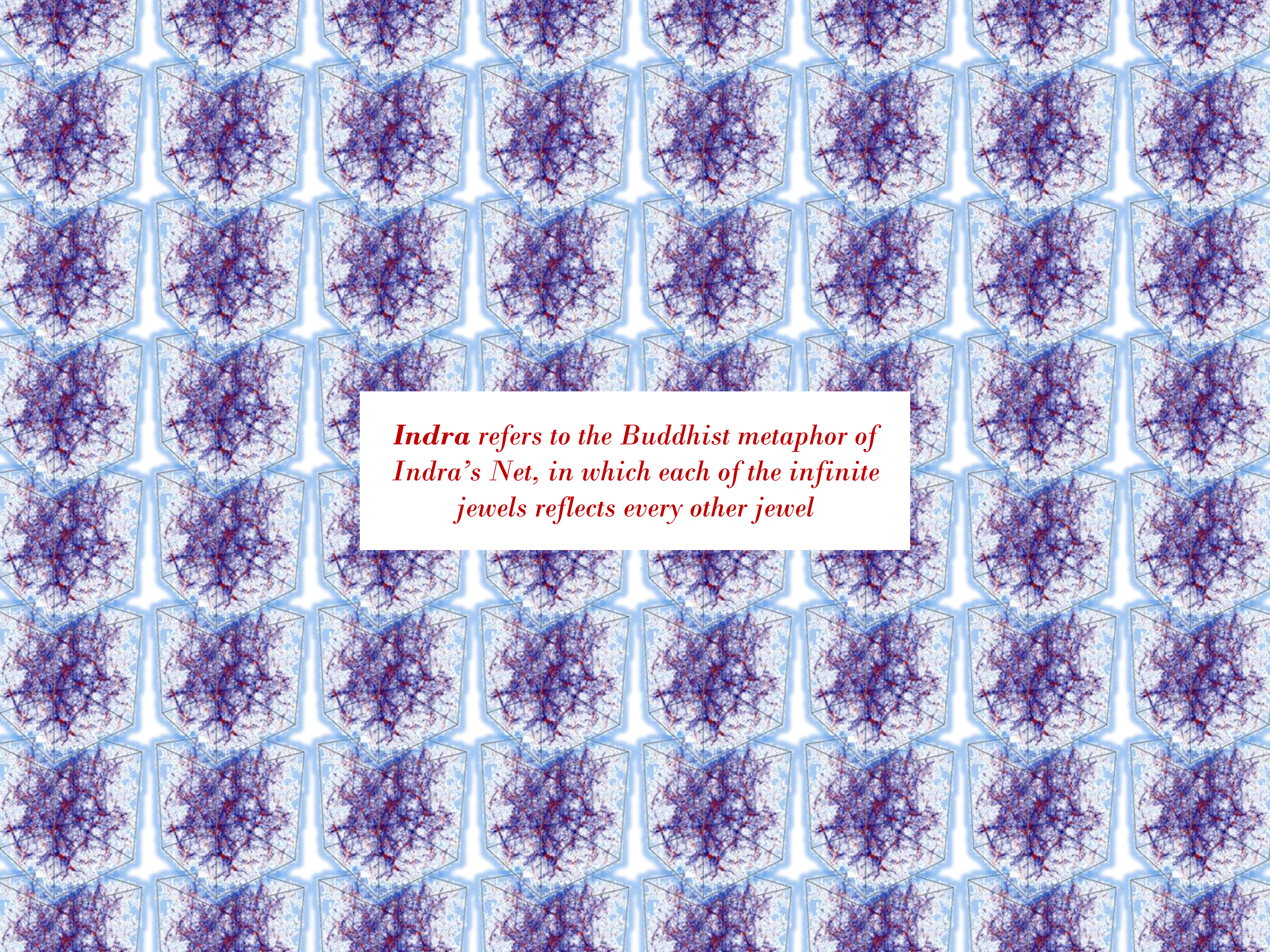
Cosmology with the Indra Suite of *N*-body Simulations

Bridget Falck (Johns Hopkins University)

with Tamás Budavári (JHU), Shaun Cole (Durham), Daniel Crankshaw (JHU), László Dobos (Eötvös), Adrian Jenkins (Durham), Gerard Lemson (MPA), Mark Neyrinck (JHU), Alex Szalay (JHU), and Jie Wang (Durham)



***Indra** refers to the Buddhist metaphor of Indra's Net, in which each of the infinite jewels reflects every other jewel*

The Indra Simulations

- Suite of dark matter *N*-body simulations
  - 512 different random instances, WMAP7 cosmology
  - each 1 Gpc/h-sided box
  - 1024^3 particles per simulation
  - About 1 PB of data!
  - All data loaded into a SQL database
  - Available to the public

- Particle data:
  - All particle positions and velocities for all 64 snapshots of each simulation run
- Halo catalogs:
  - Standard Friends-Of-Friends (and others), linked to particles
- Fourier modes:
  - Density grid for 512 time steps of each run

Indra-enabled Science

- Covariance of the matter power spectrum
- Baryon Acoustic Oscillations in real and redshift space
- Cluster and void statistics
- Large-scale structure morphology
- Galaxy formation and evolution with halo catalogs and merger trees
- Mock galaxy catalogs
- Logarithmic density variable
- …

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- **Large-scale structure morphology**
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- **Logarithmic density variable**
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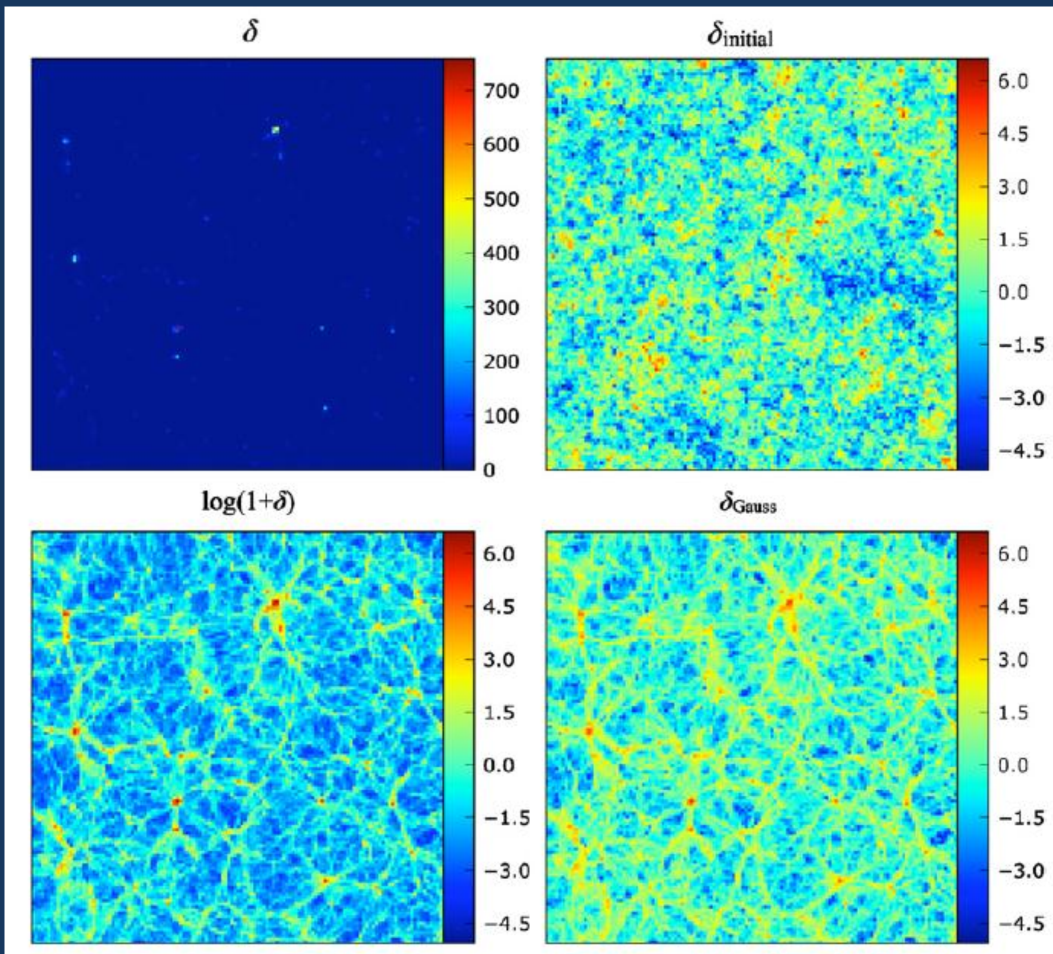
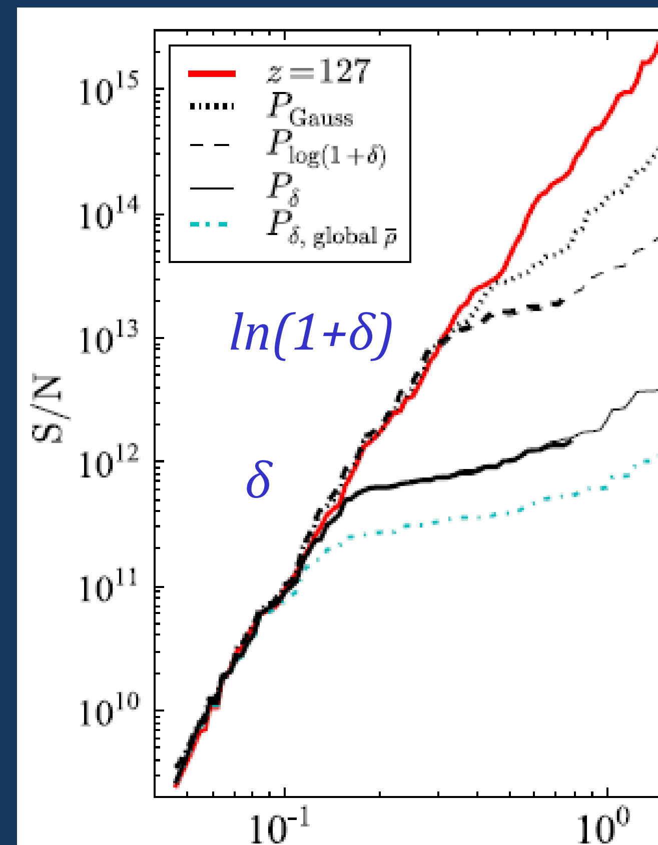
Log-density Power Spectrum



Log-transform reveals structure of cosmic web



k (h/Mpc)

Neyrinck, Szapudi, & Szalay 2009

Density-Displacement Relation

- Continuity Equation:

$$\frac{\partial(1+\delta)}{\partial t}+\frac{1}{a}\nabla\cdot(1+\delta)\mathbf{v}=0, \quad \text{with} \quad \mathbf{v}=a\dot{\psi}$$

- To linear order:

$$\frac{\partial\delta}{\partial t}+\frac{1}{a}\nabla\cdot\mathbf{v}=0 \quad \rightarrow \quad \nabla\cdot\psi_{linear}=-\delta$$

- Retain some higher-order terms to get logarithmic derivative:

$$\frac{1}{(1+\delta)}\frac{\partial(1+\delta)}{\partial t}+\frac{1}{a}\nabla\cdot\mathbf{v}=0 \quad \rightarrow \quad \nabla\cdot\psi_{\log}=-\ln(1+\delta)$$

Example: BAO Reconstruction

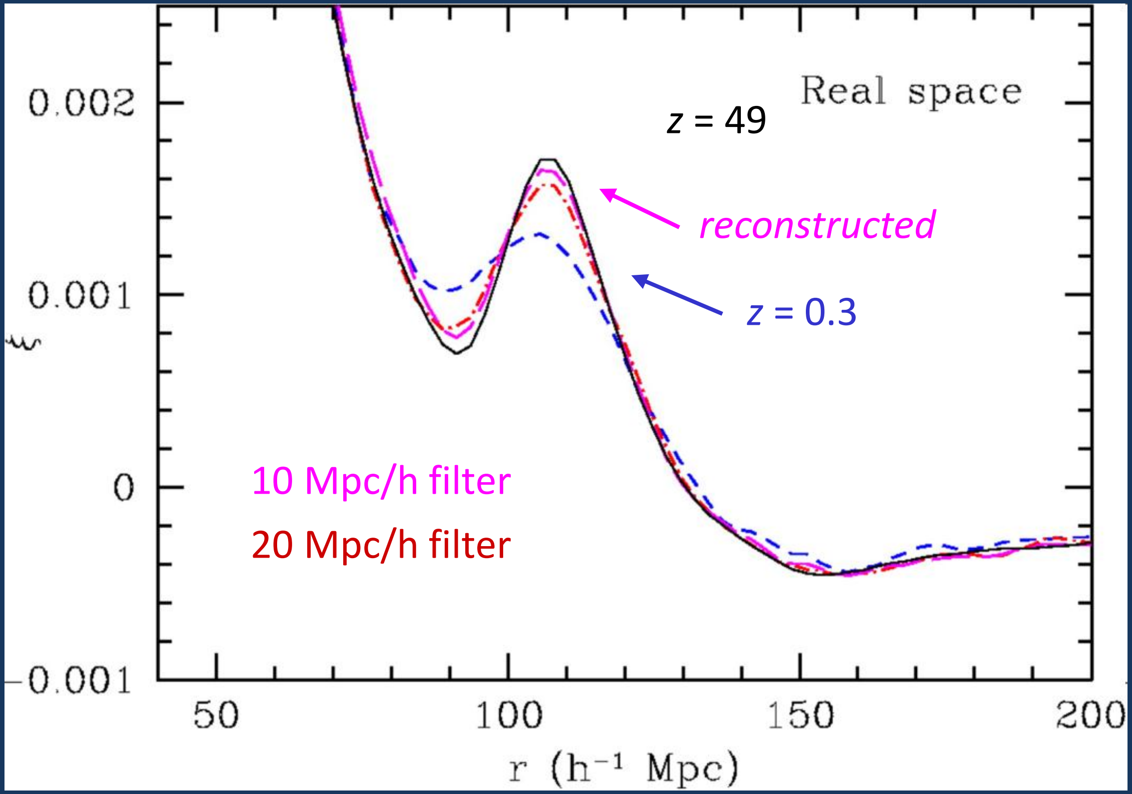
- Calculate displacement and shift galaxies back to linear-theory positions

$$\psi = x - q$$

- Linear Zel'dovich displacement effective, but need to smooth the density field on 10-20 Mpc/h scales

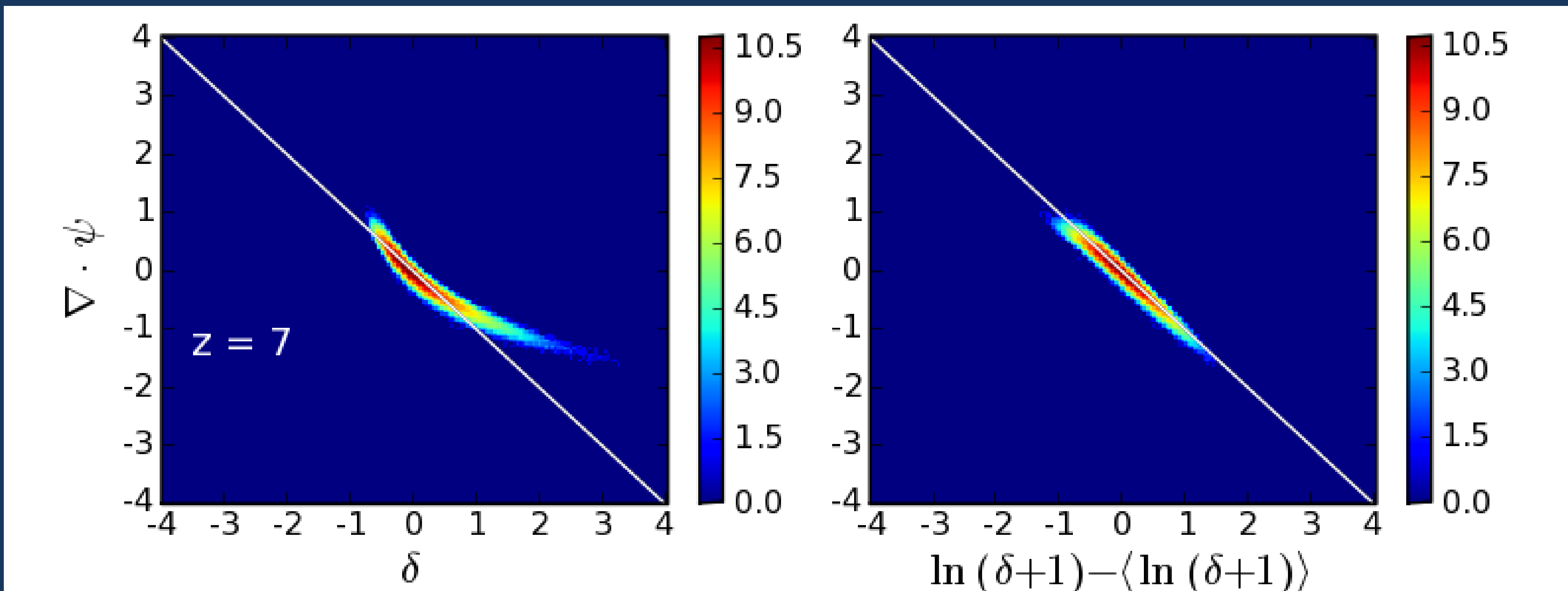
$$\nabla \cdot \psi_{linear} = -\delta$$

Reconstruction using linear displacement



Eisenstein, Seo, Sirko, & Spergel 2007

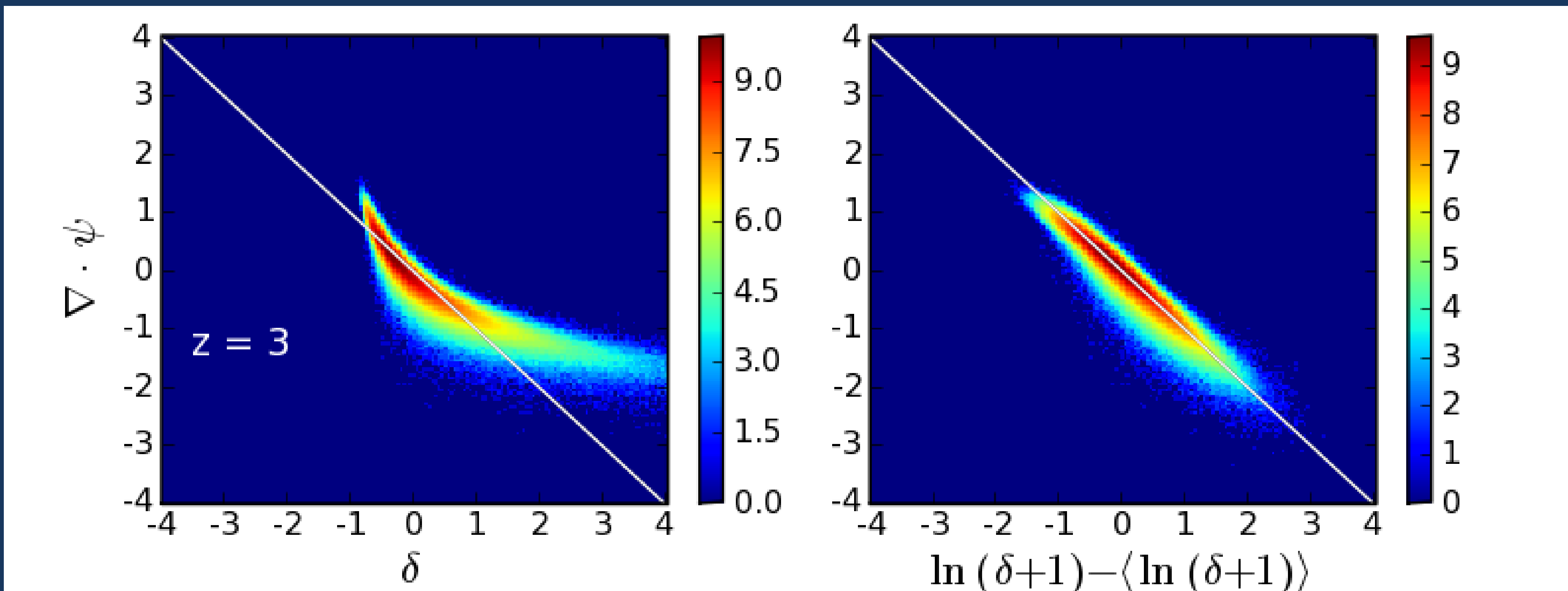
Density-Displacement Relation



z= 7, 1.6 h^{-1}Mpc cells:

both linear and log do well

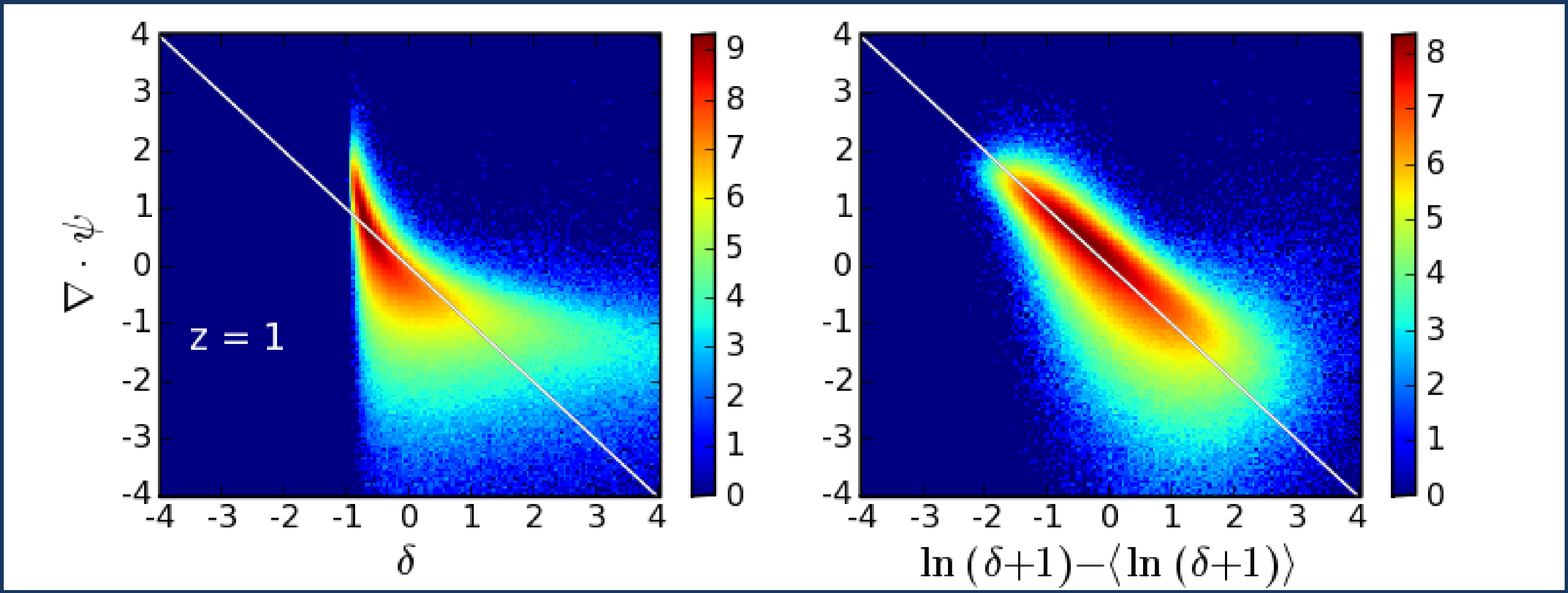
Density-Displacement Relation



z= 3, 1.6 h^{-1}Mpc cells:

both linear and log do well

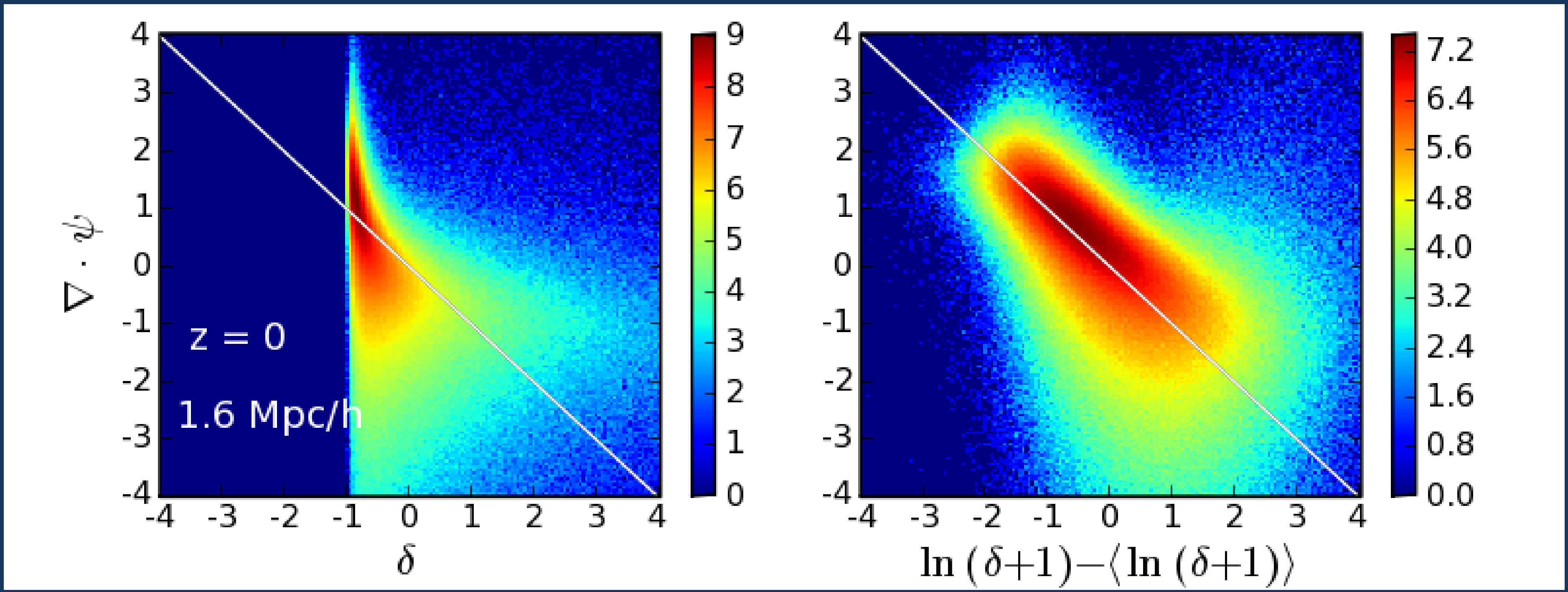
Density-Displacement Relation



z= 1, 1.6 h^{-1}Mpc cells:

log does much better

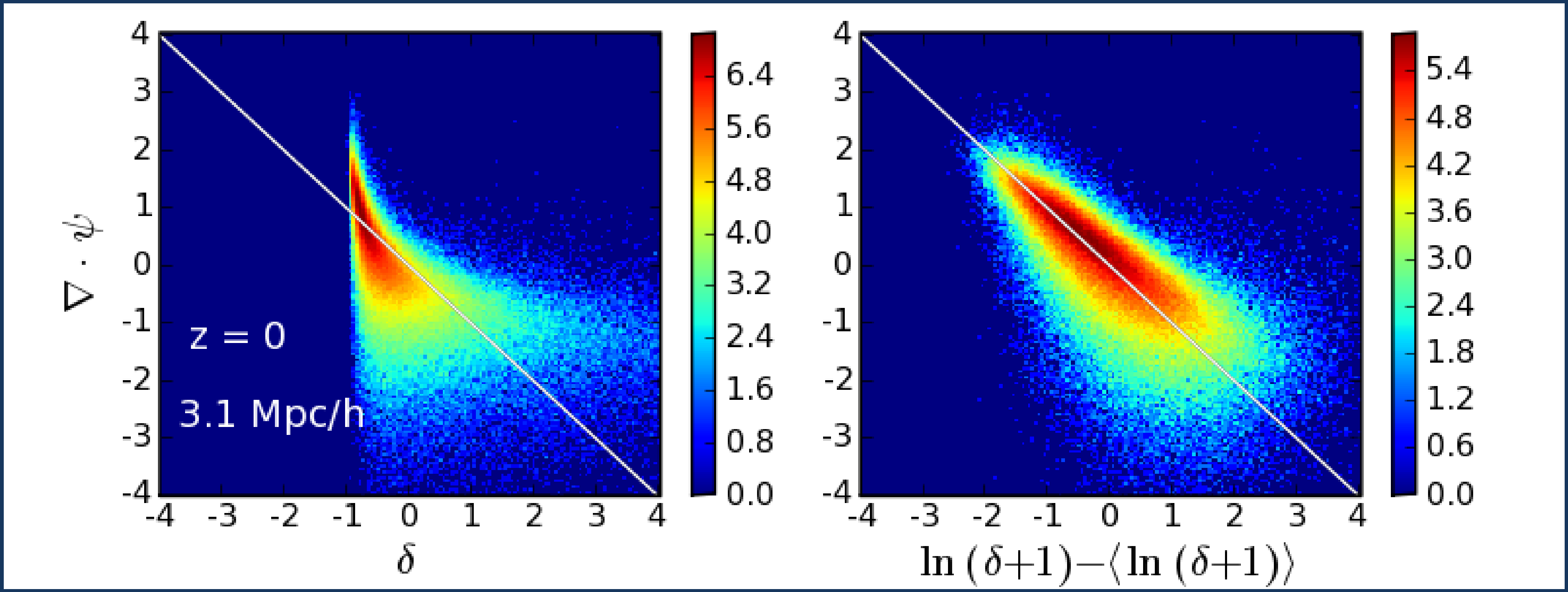
Density-Displacement Relation



z= 0, 1.6 h^{-1}Mpc cells:

log does much better

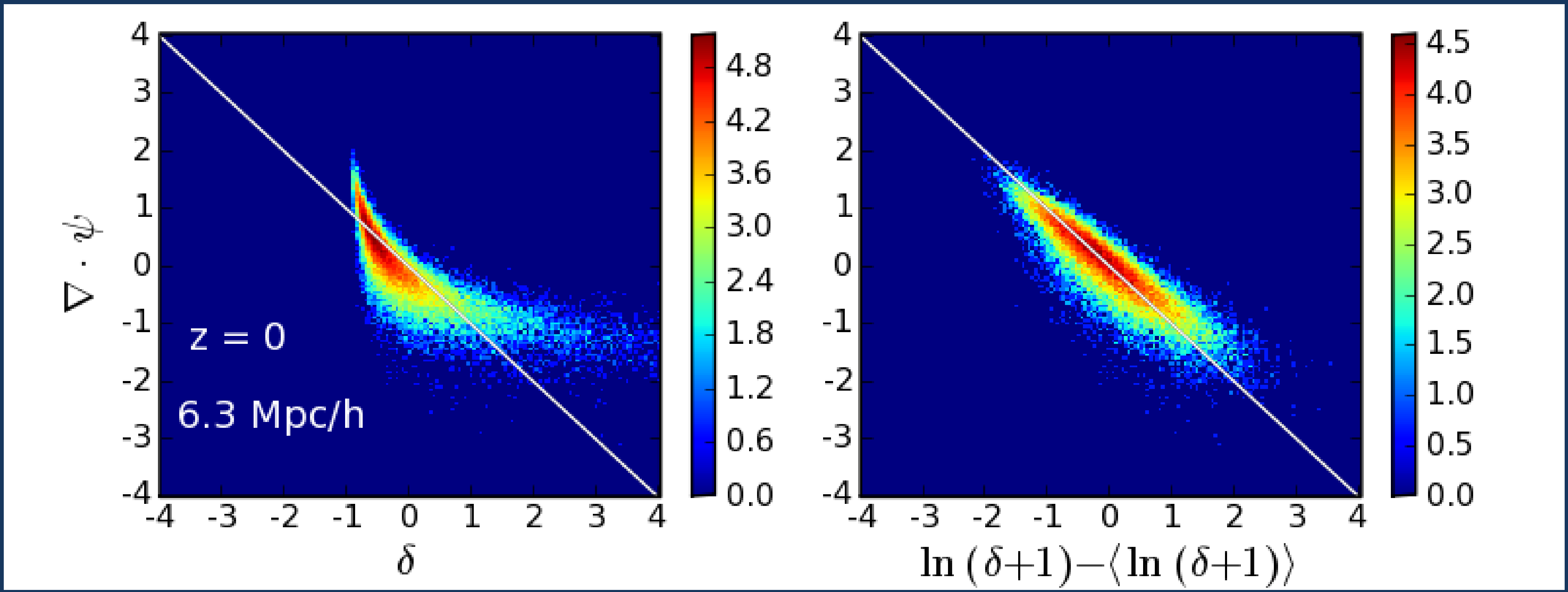
Density-Displacement Relation



z= 0, 3.1 h^{-1}Mpc cells:

both improve with larger cells

Density-Displacement Relation



z= 0, 6.3 h^{-1}Mpc cells:

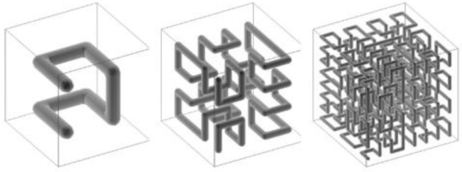
both improve with larger cells

Future Directions

- The log-density could provide quick and efficient improvement to linear reconstruction methods (for example BAO reconstruction), allowing smoothing on smaller scales
- We also plan to test simulation results by measuring statistics of log-density of SDSS galaxies
- **Further studies of log-density would be benefitted by large volume of mock surveys from the Indra simulations**

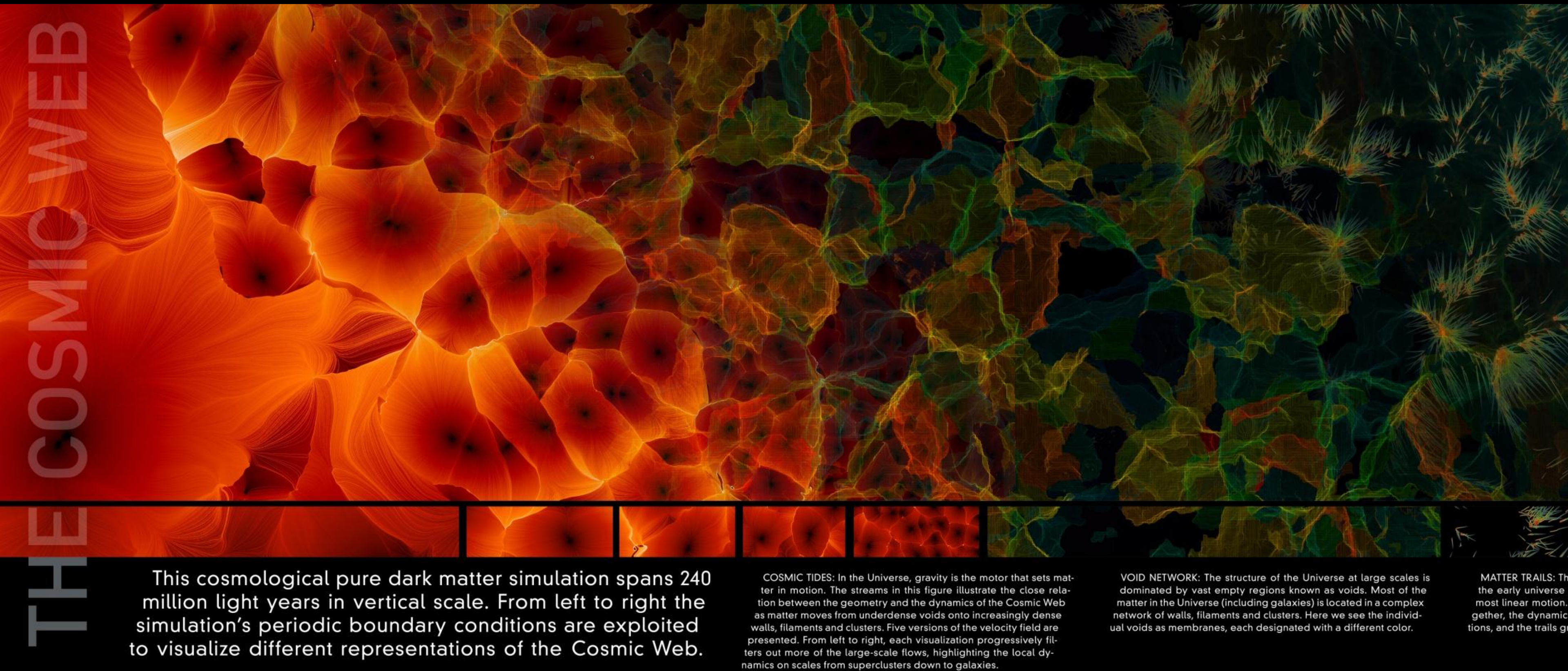
Mock Catalogs with Indra

- Large volume for mock surveys
- 512 simulations for many many mocks
- Spatial indexing in the database enables very fast on-the-fly light cones



- Standard FOF catalog will be loaded (like Millennium DB), but new halo catalogs can be created from particle positions and velocities
- Halo catalogs linked to particle tables

The Cosmic Web

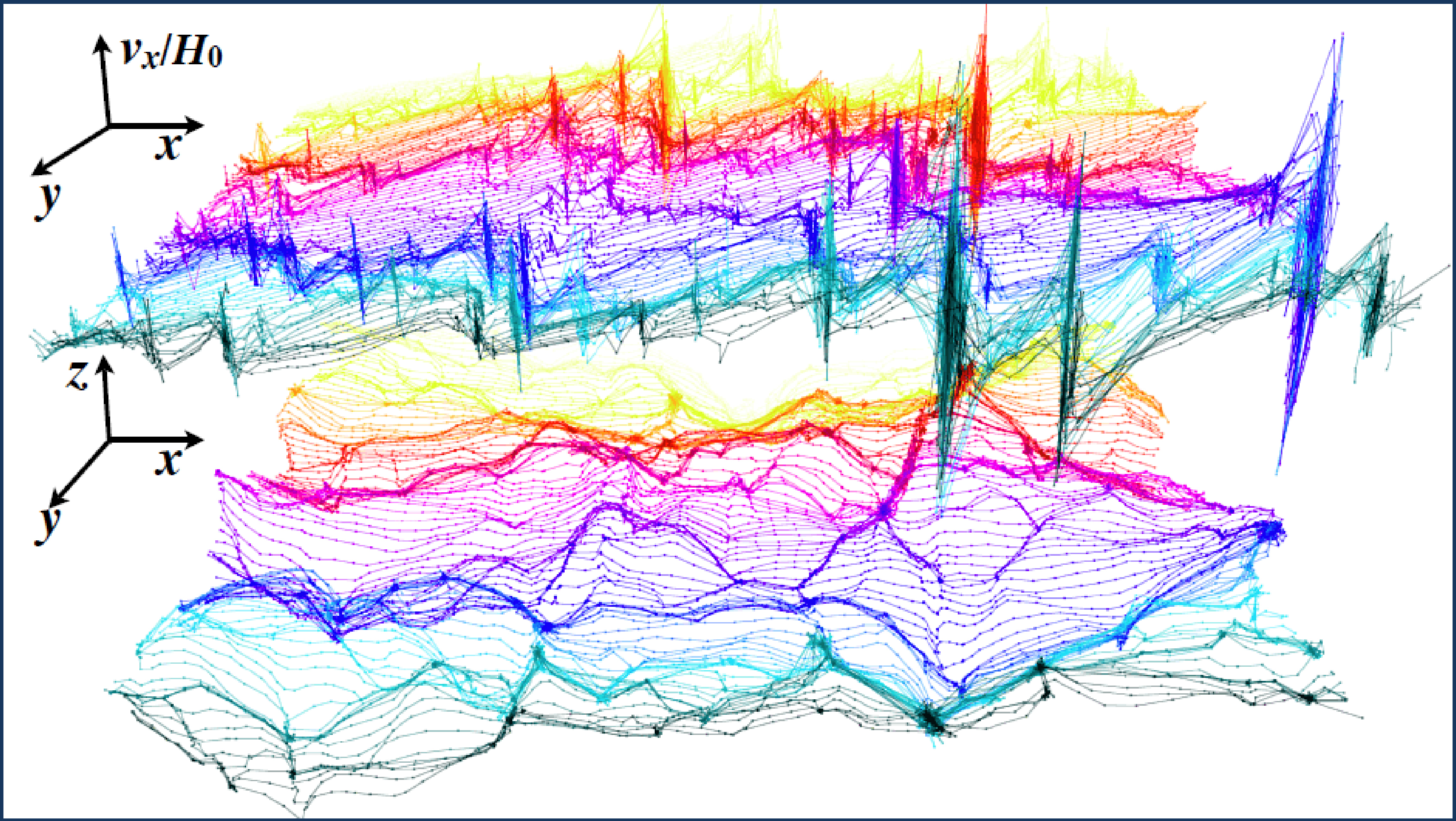


Miguel Aragon-Calvo's winning visualization (and February cover of Science magazine) shows different aspects of the cosmic web, starting with the large scale voids on the left…

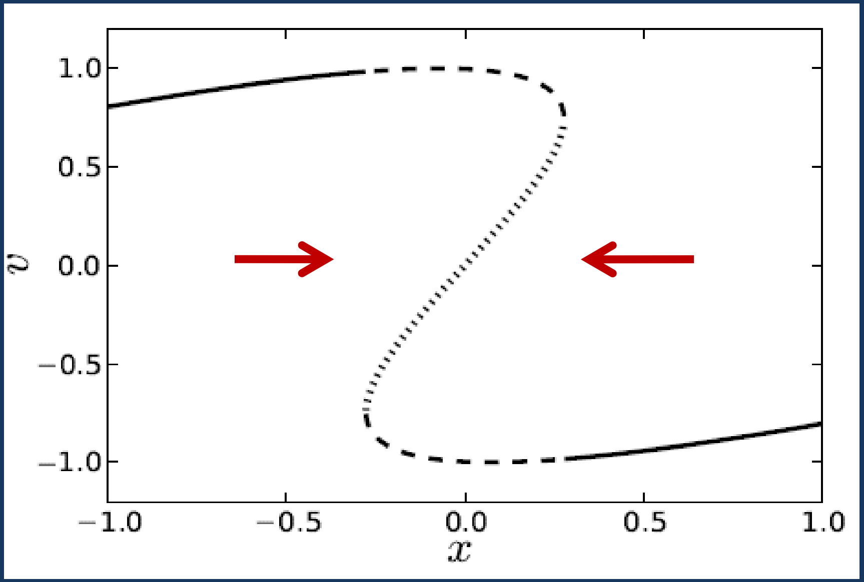
The Cosmic Web

… to dark matter halos populated with galaxies on the right.
Identifying structures in simulations remains a key challenge to understanding the formation and evolution of structures in the Universe.

ORIGAMI: Finding folds in phase-space

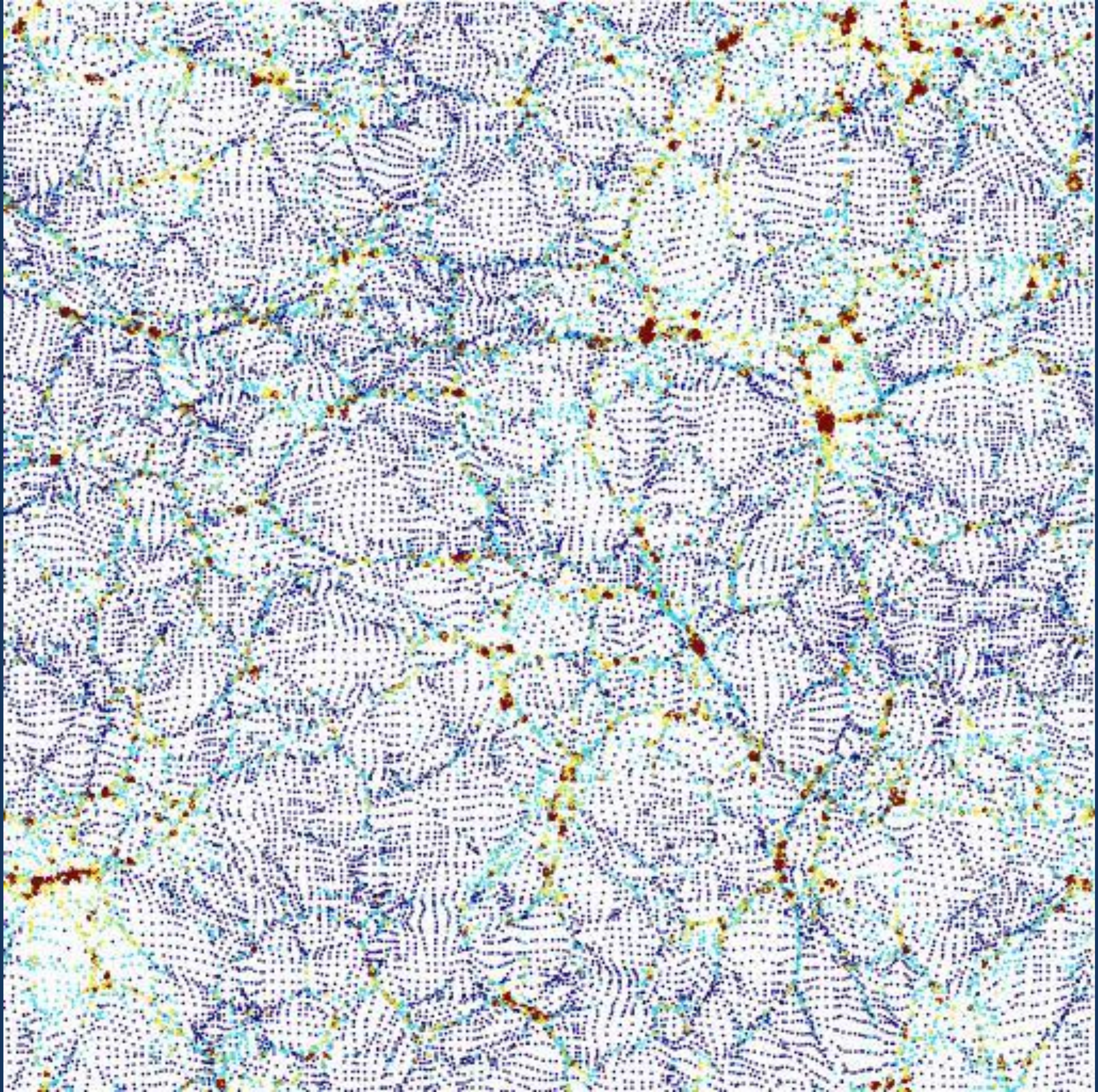


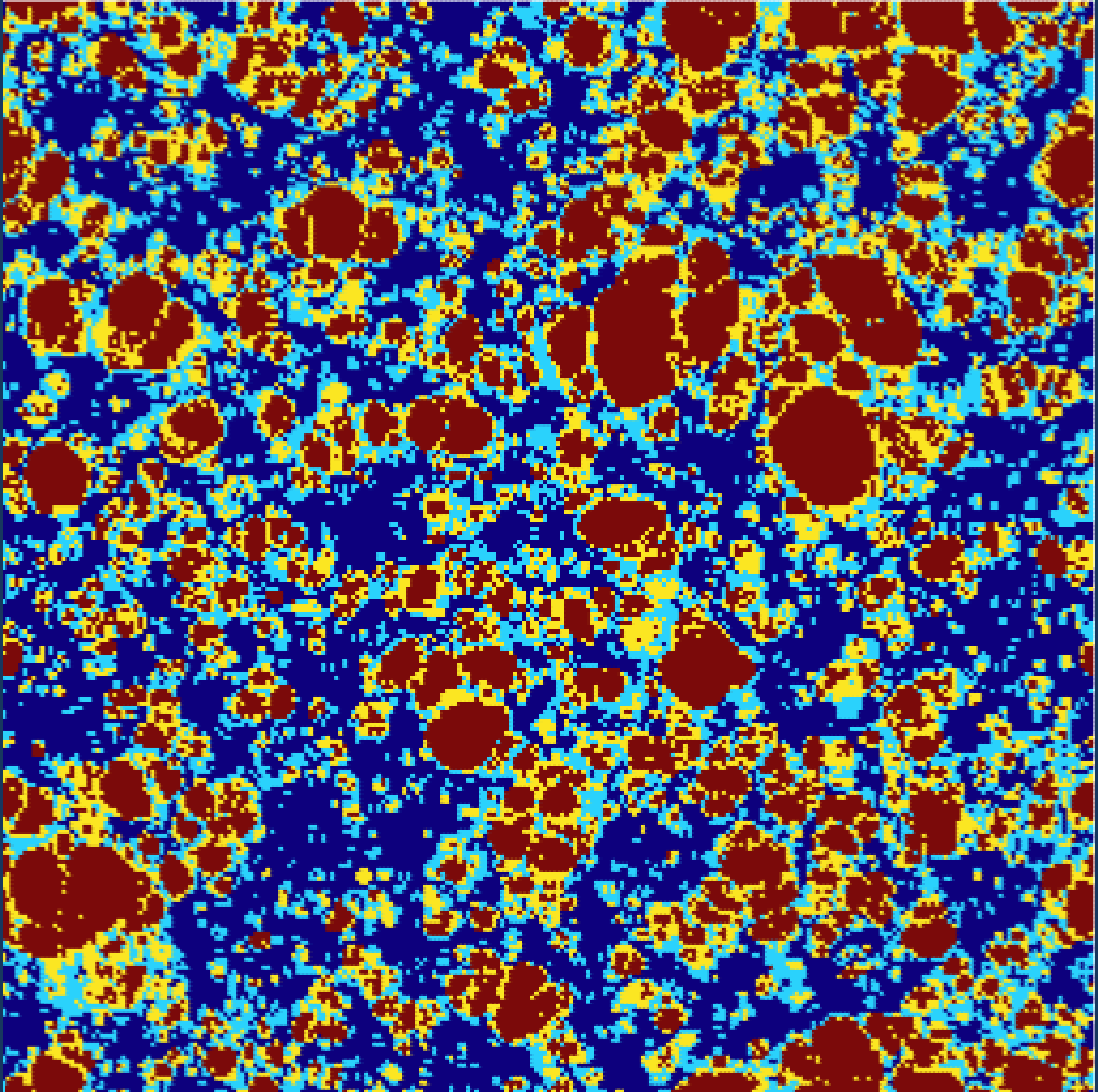
The ORIGAMI method



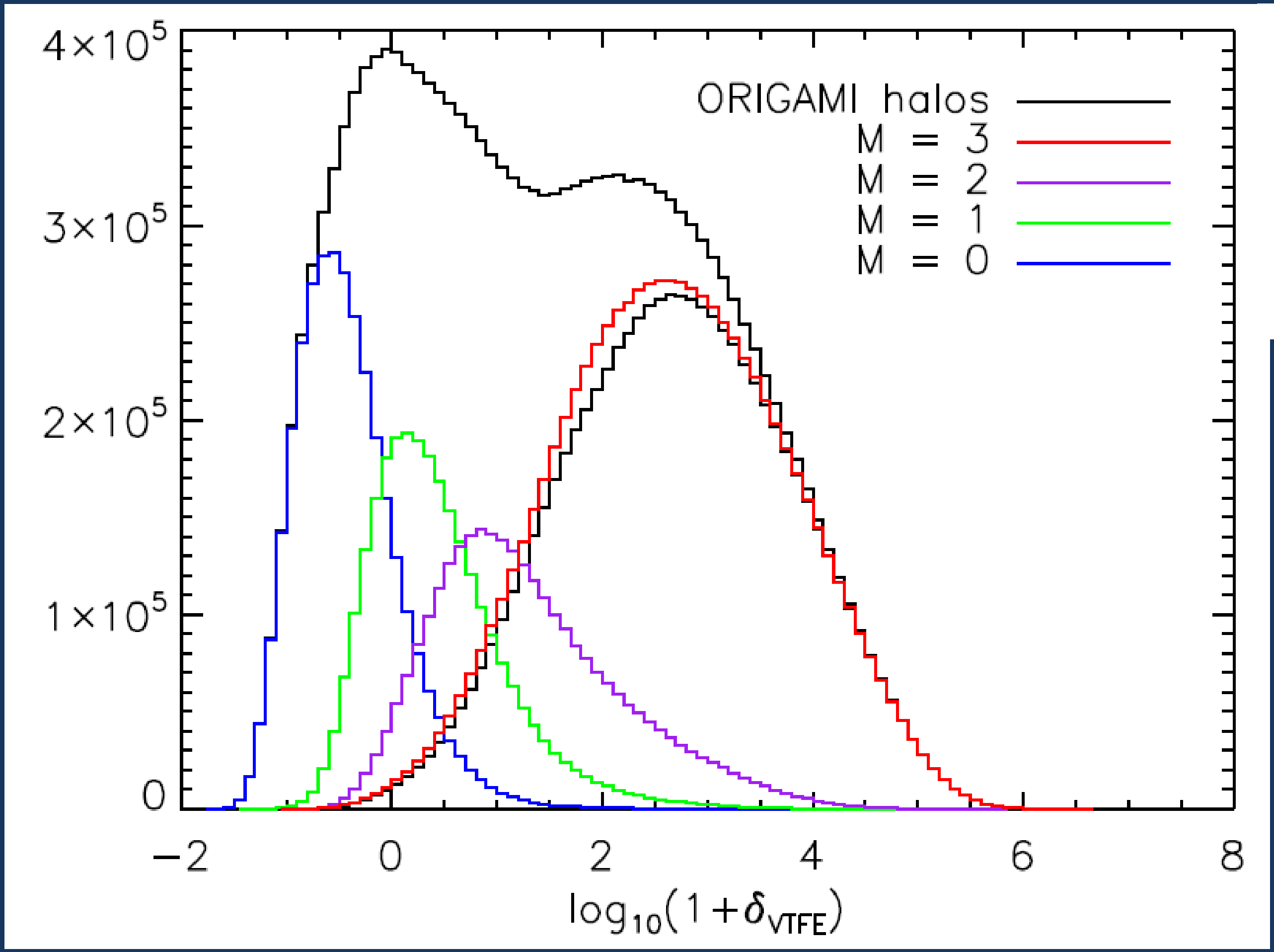
In this 1D example, particles flow toward an initial overdensity at the origin, eventually creating a fold in phase-space

- ORIGAMI finds shell-crossing by looking for particles out of order with respect to their original configuration
- Halo particles have undergone shell-crossing along 3 orthogonal axes, filaments along 2, walls 1, and voids 0





Particle Density by ORIGAMI Morphology



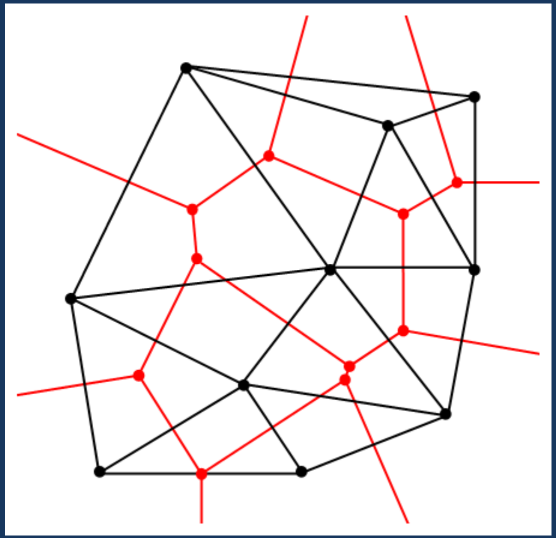
halo
filament
wall
void

Grouping Particles into Halos

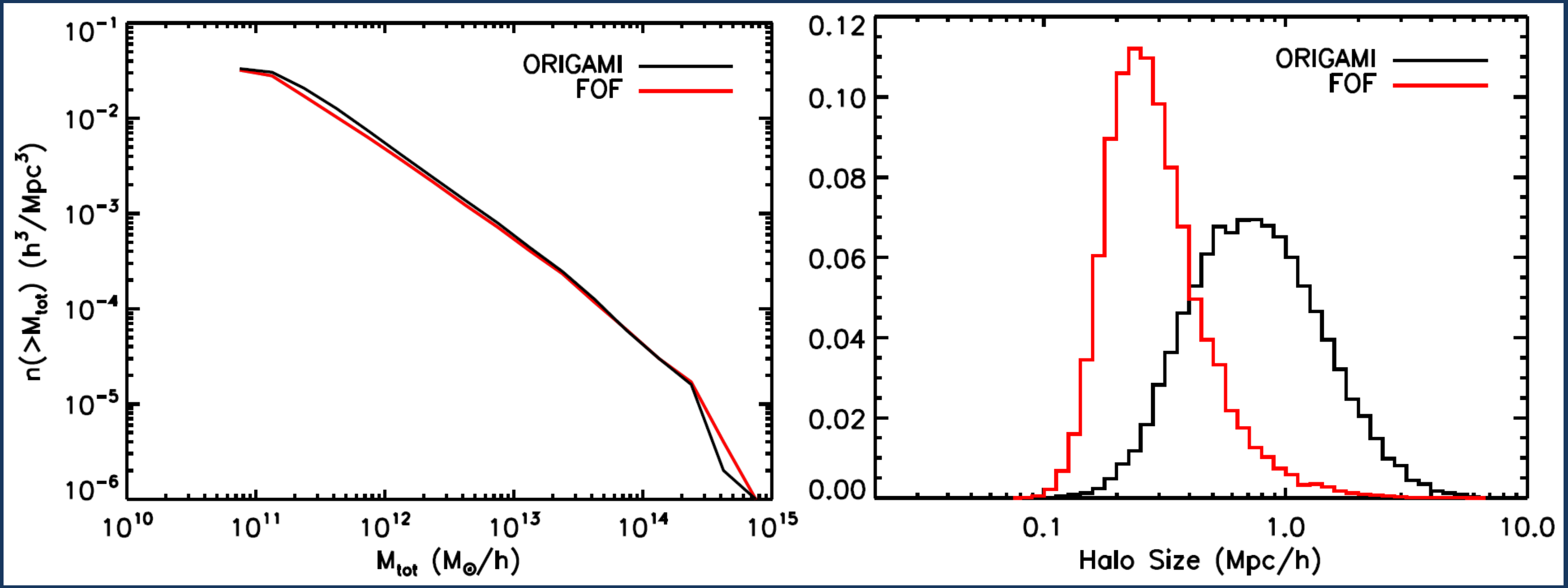
- ORIGAMI is primarily a morphology classification algorithm, but useful to group particles into individual structures

- We group halo particles that are connected on a Delaunay tessellation, which provides a set of nearby neighbors for every particle

- Alternatively, could feed ORIGAMI-identified particles into other substructure code

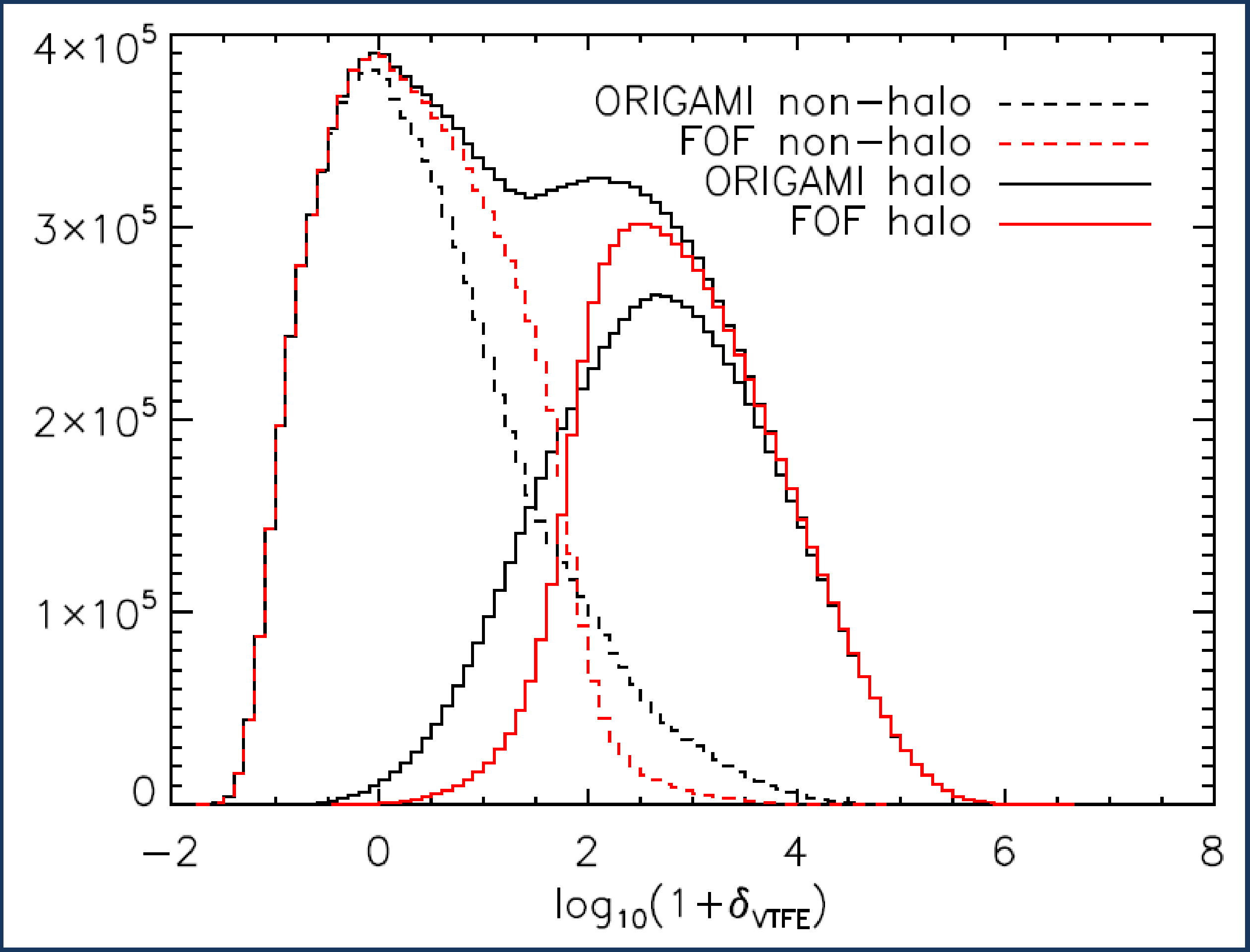


Halo Comparison to FOF



- Mass functions similar; ORIGAMI halos larger
- Size difference due to definition of halo edge
- FOF may miss some collapsed particles (Anderhalden & Diemand 2011)
- (See also Knebe et al. 2011: Halo-Finder Comparison Project)

ORIGAMI vs. FOF Particle Density



ORIGAMI Summary and Future Work

- ORIGAMI identifies halo, filament, wall, and void particles by detecting shell-crossing
  - This gives a dynamical, geometric definition of the outer edge of a halo
  - Halos are larger and more diffuse than FOF halos but with similar total masses

- Future comparison with other structure-finders
  - Can particle-based morphology improve other algorithms?
  - Will use of velocity enable detection of sub-structure?

- **ORIGAMI morphology can easily be added to Indra**

Current Status of Indra

- Initial Conditions for all simulations generated and first runs completed
  - Will be able to re-simulate a few boxes with higher resolution (Jenkins 2010 IC code)
- Database design being optimized
  - Efficient storage with SQL Arrays, and fast searches with spatial indexing and partitioning the data on the disk
- Developing common queries, analysis functions, on-the-fly visualization, and data-handling tools (1PB is a lot!)

Summary

- The log-density reveals cosmic structures on nonlinear scales
  (Falck, et al. 2012, ApJ, 745, 17, arXiv:1111.4466)

- ORIGAMI identifies structures by detecting folds in phase-space
  (Falck, Neyrinck, & Szalay 2012, arXiv:1201.2353)

- The Indra ensemble of Gpc/h simulations will produce ~ 1 PB of N-body data for precision cosmology