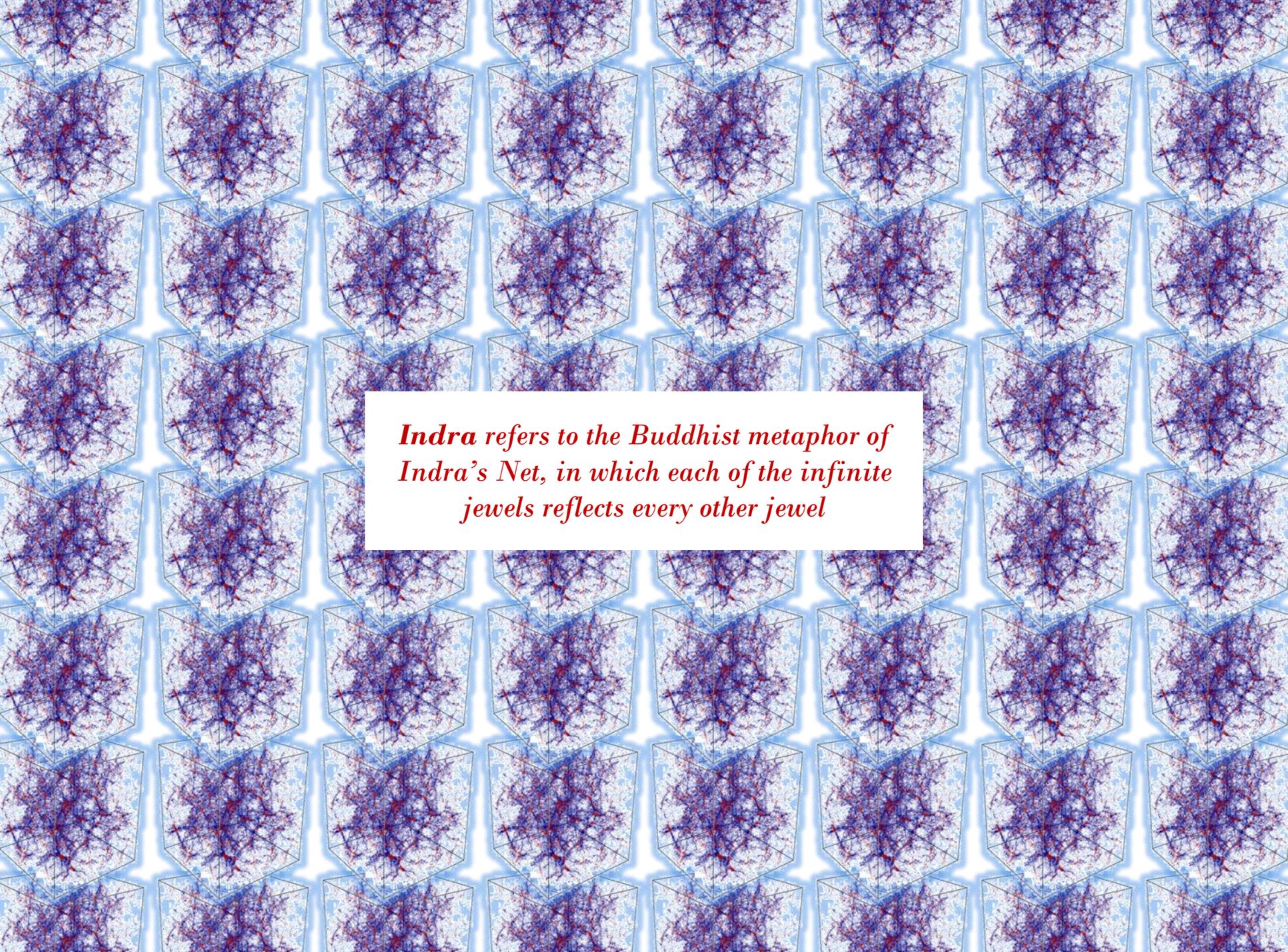


# Cosmology with the Indra Suite of $N$ -body Simulations

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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

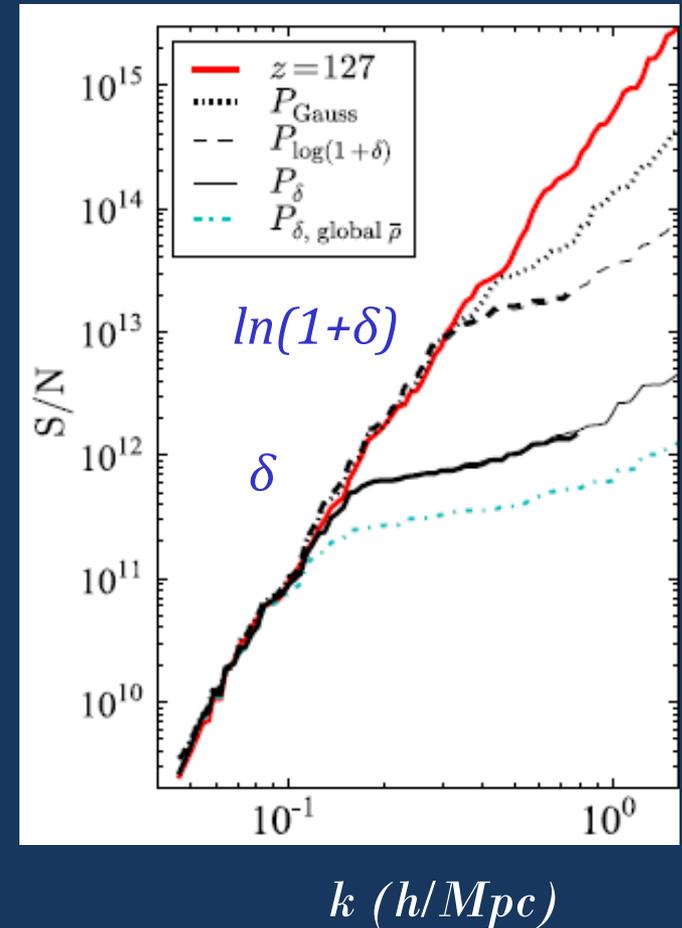
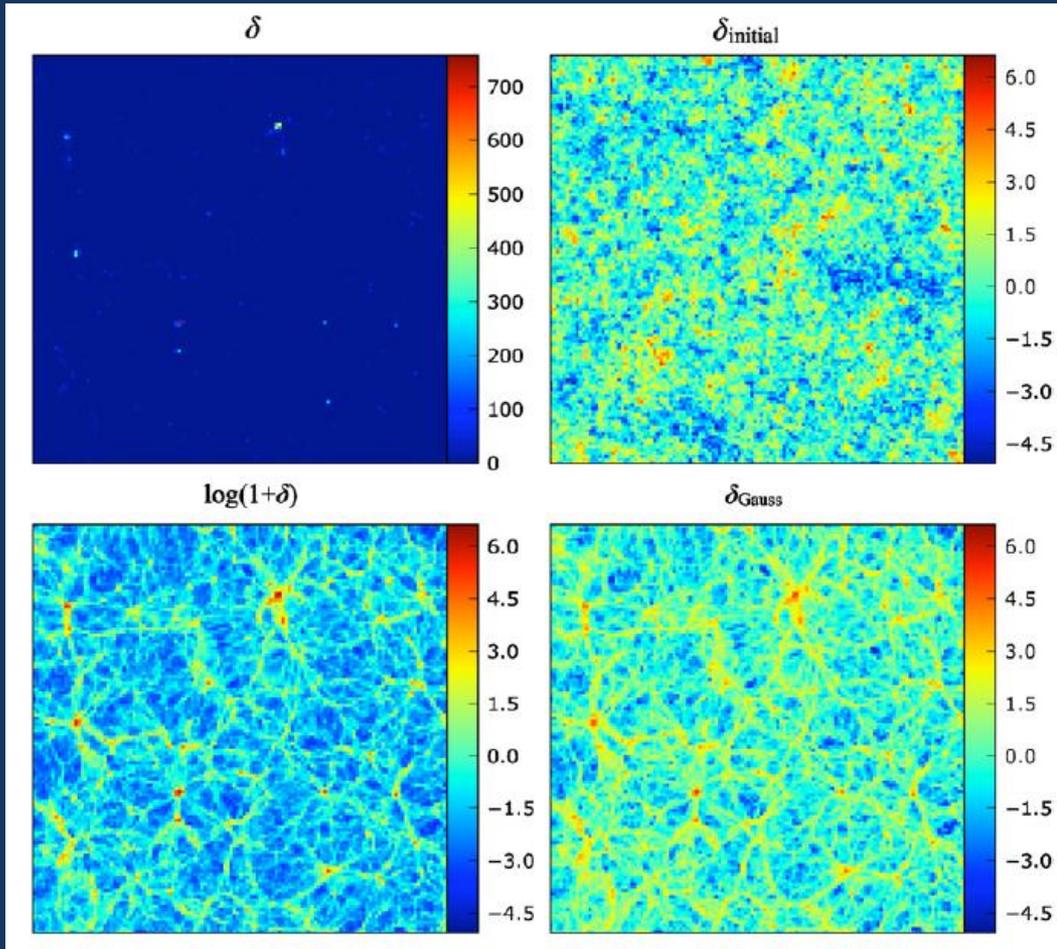
# Indra-enabled Science

- 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
- ...

# Indra-enabled Science

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# Log-density Power Spectrum



Log-transform reveals structure of cosmic web

Neyrinck, Szapudi, & Szalay 2009

# Density-Displacement Relation

- Continuity Equation:

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

- To linear order:

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

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

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

# Example: BAO Reconstruction

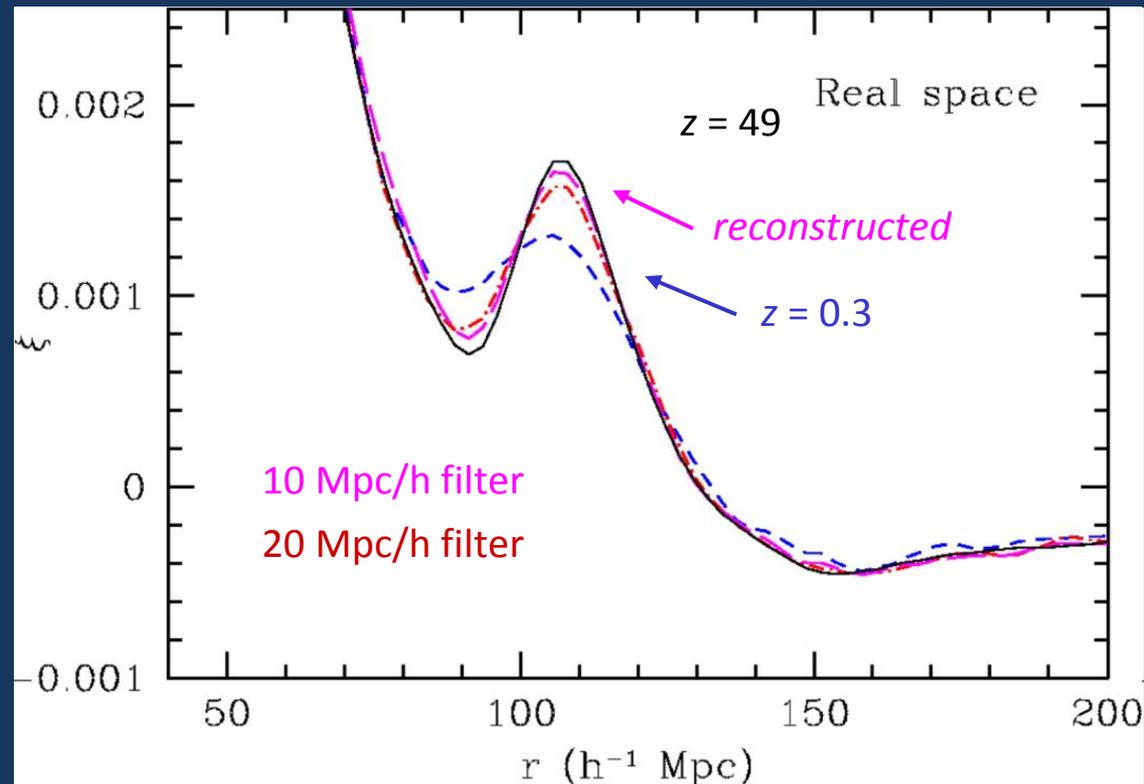
- Calculate displacement and shift galaxies back to linear-theory positions

$$\psi = x - q$$

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

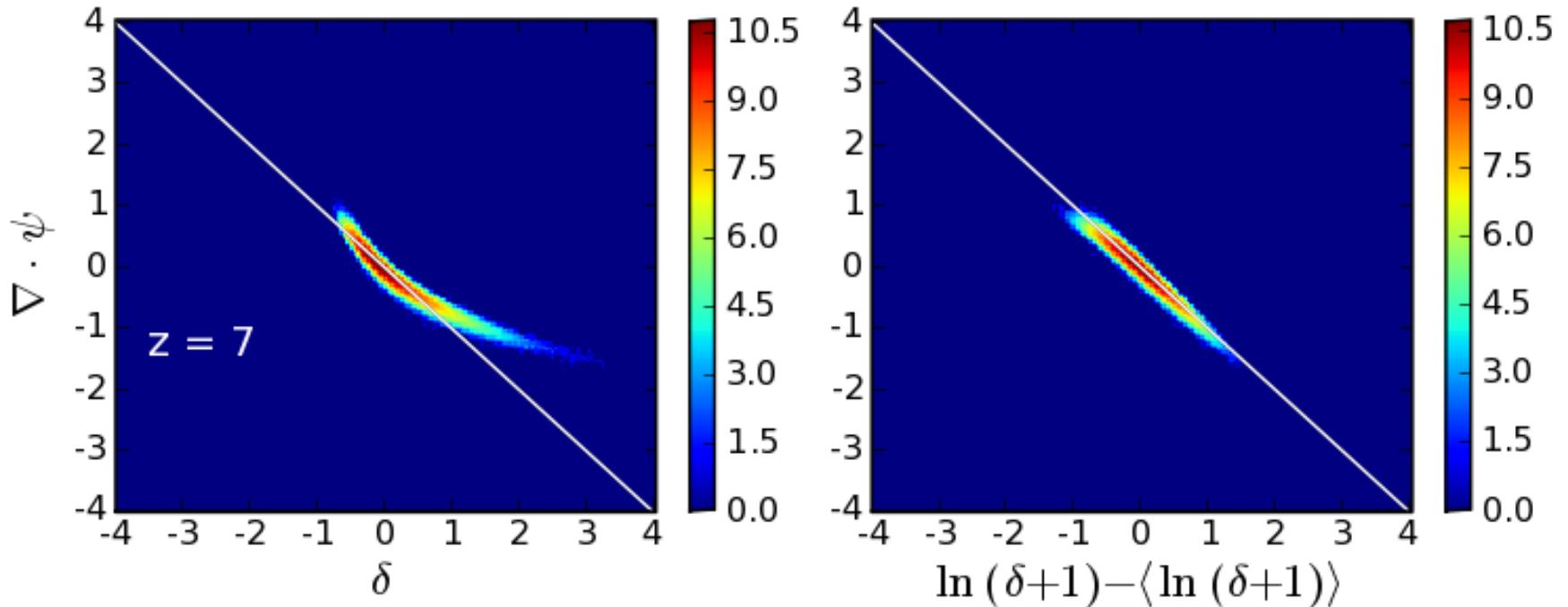
$$\nabla \cdot \psi_{linear} = -\delta$$

Reconstruction using linear displacement



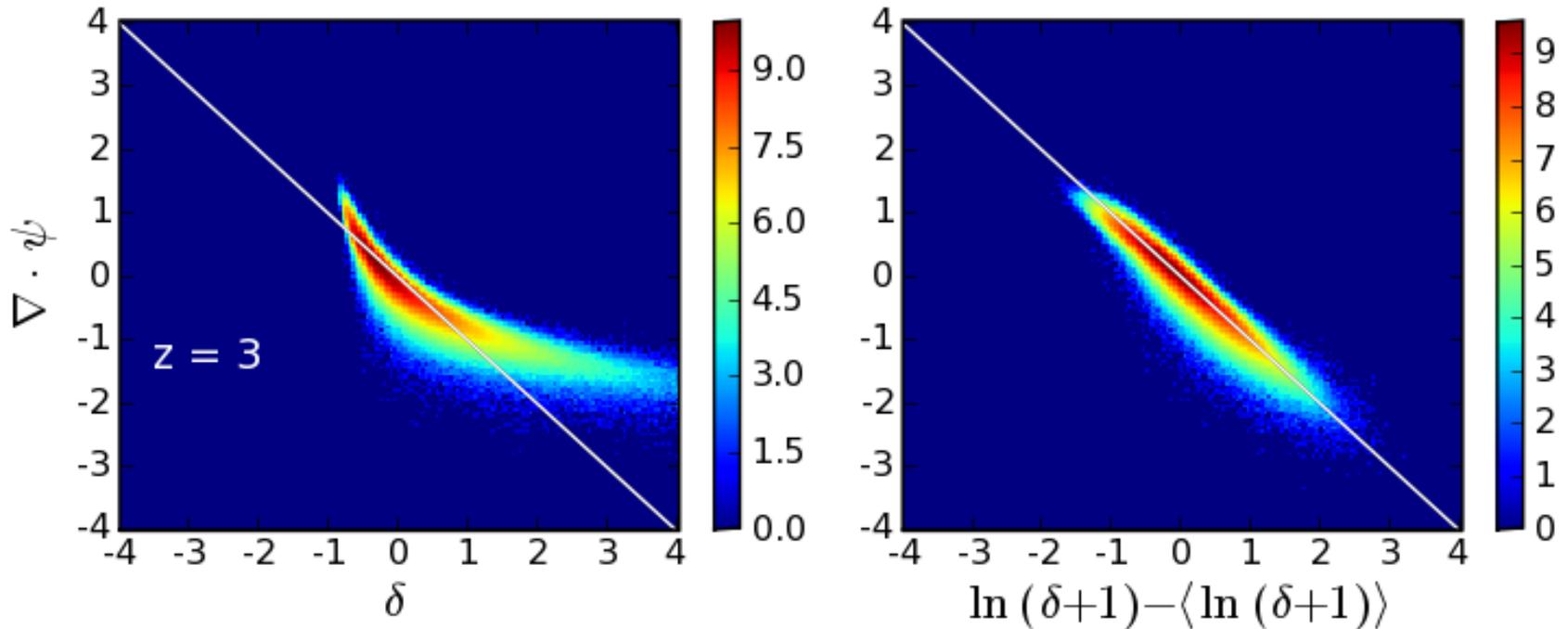
*Eisenstein, Seo, Sirko, & Spergel 2007*

# Density-Displacement Relation



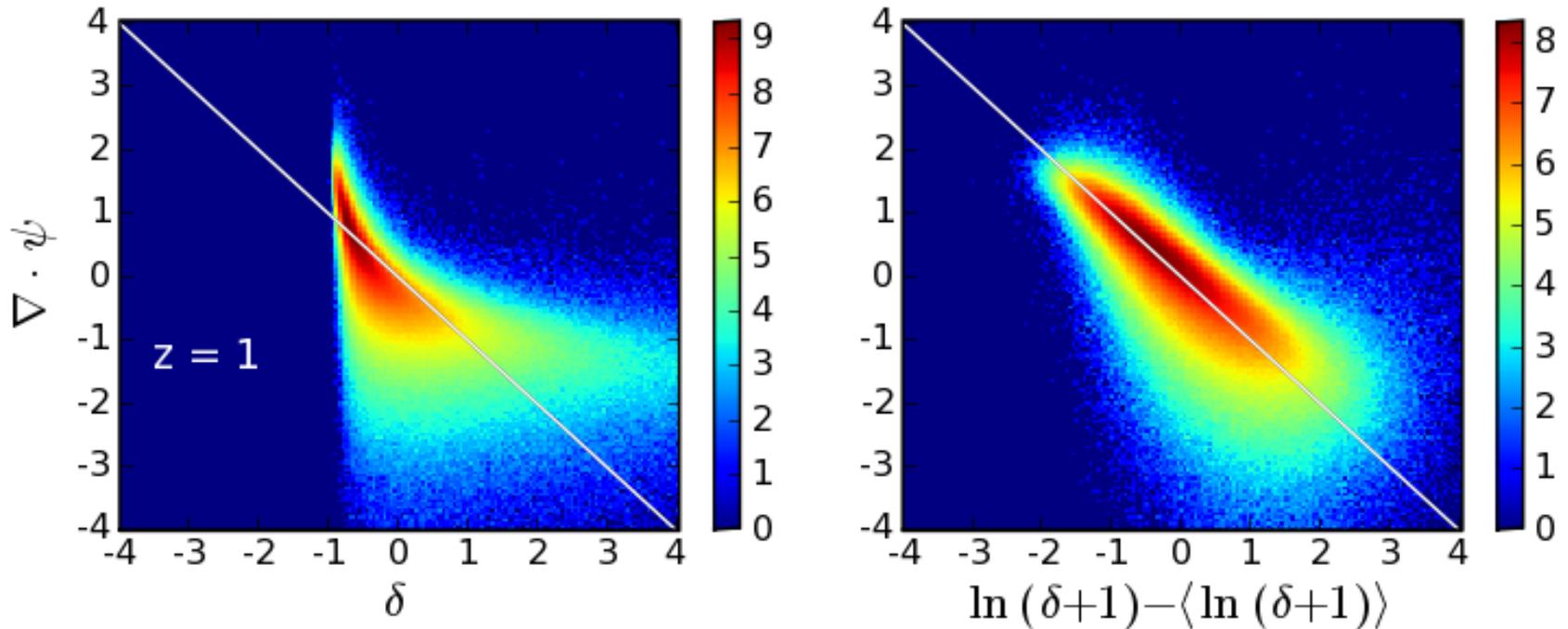
$z = 7$ ,  $1.6 h^{-1} \text{Mpc}$  cells:  
both linear and log do well

# Density-Displacement Relation



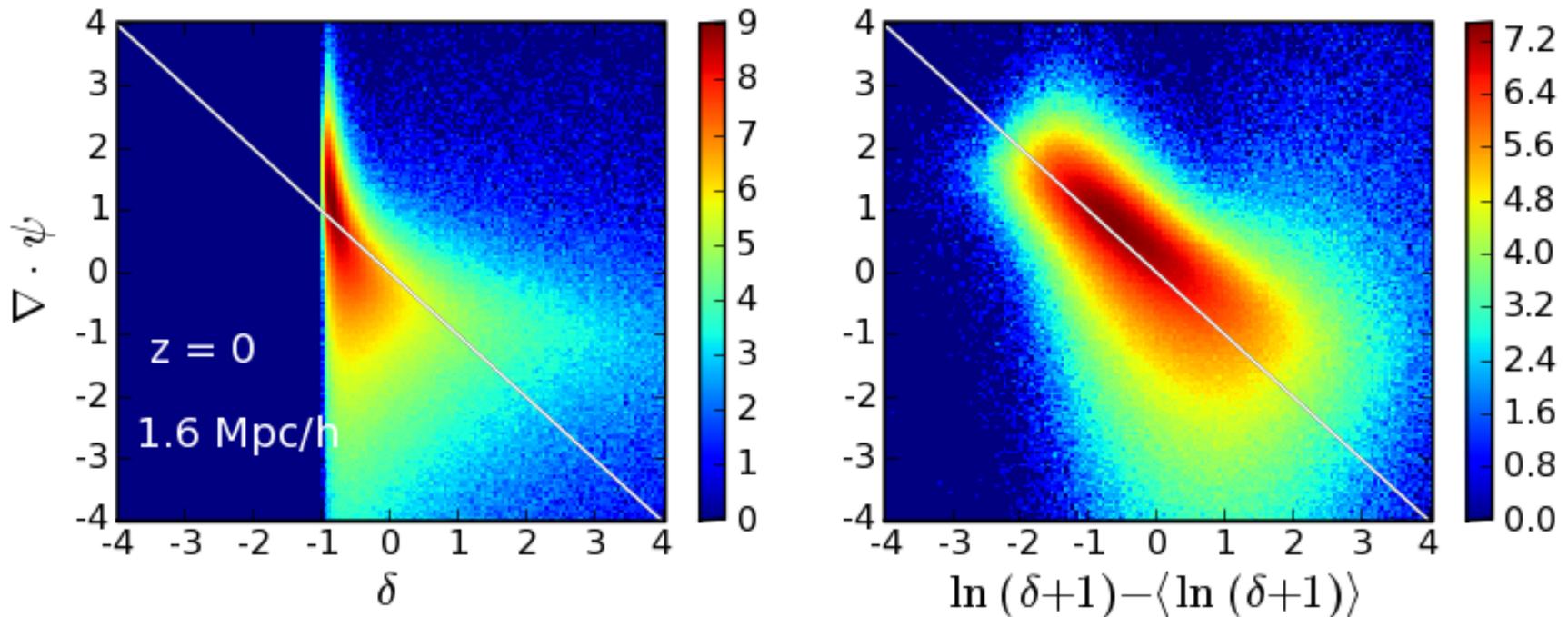
$z = 3, 1.6 h^{-1} \text{Mpc cells}:$   
both linear and log do well

# Density-Displacement Relation



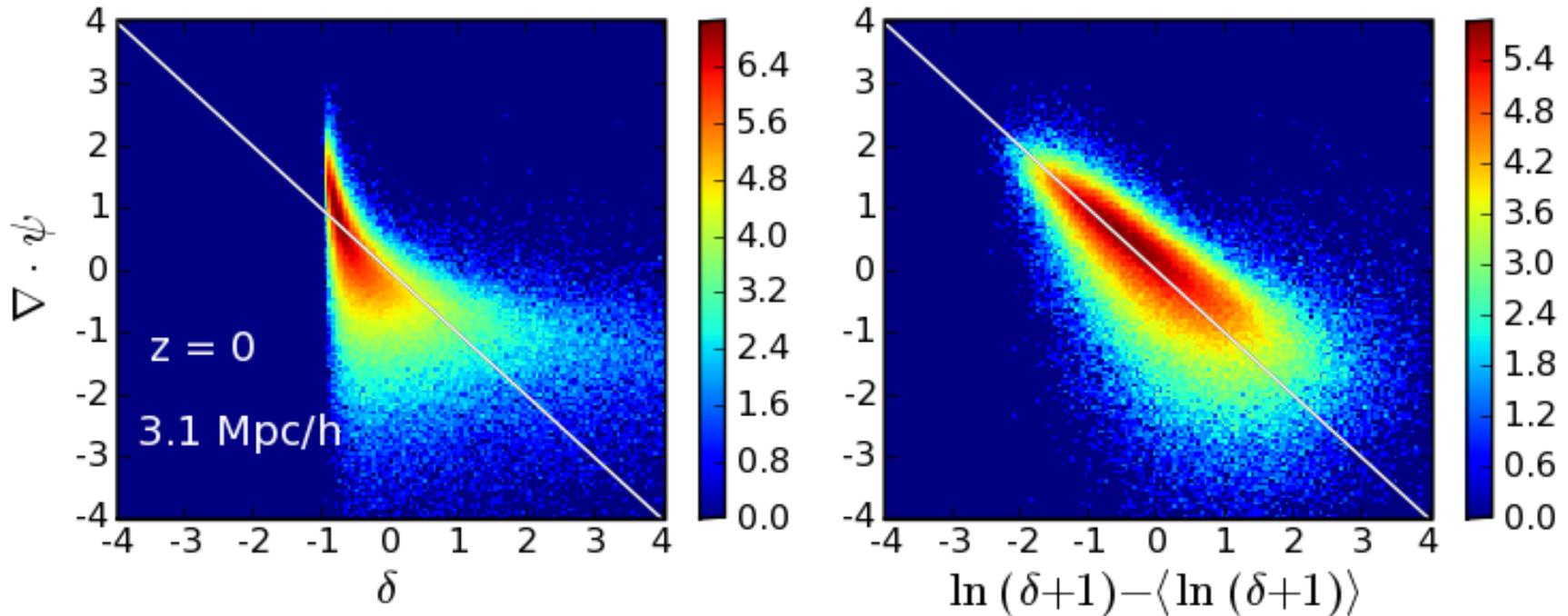
$z = 1, 1.6 h^{-1} \text{Mpc cells}$ :  
log does much better

# Density-Displacement Relation



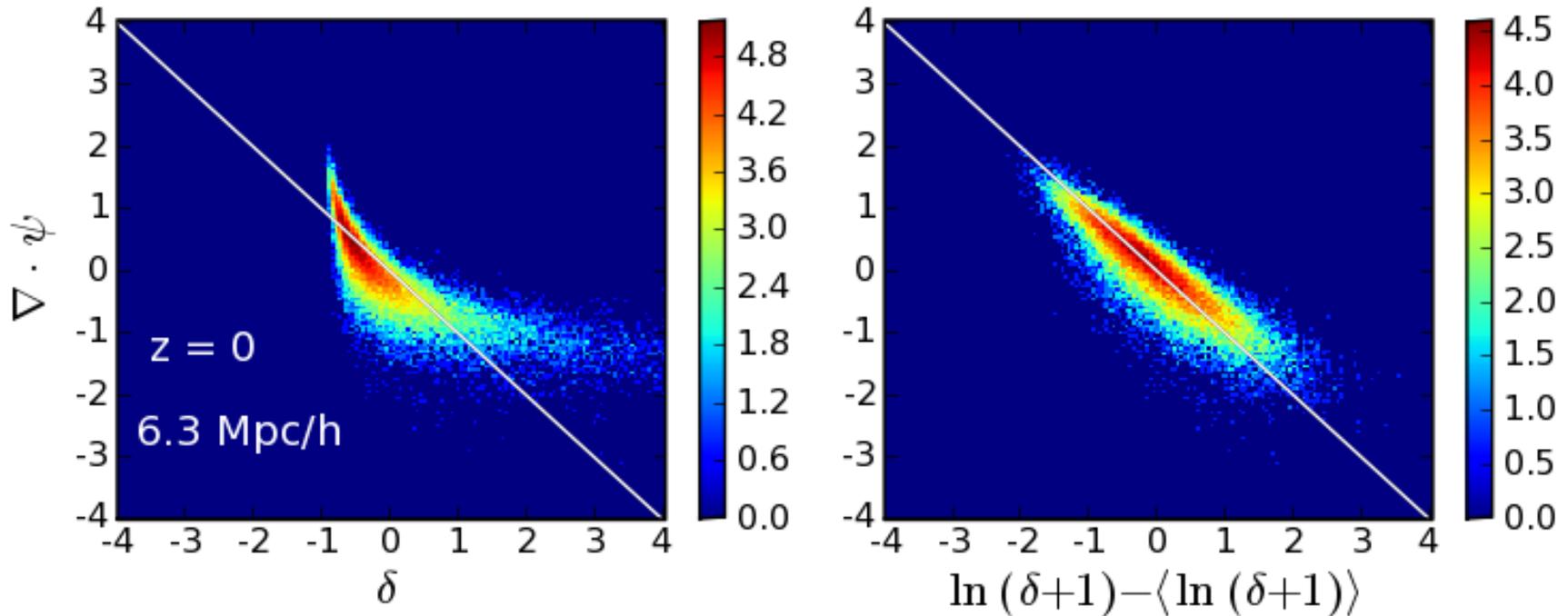
$z = 0, 1.6 \text{ h}^{-1} \text{ Mpc cells:}$   
log does much better

# Density-Displacement Relation



$z = 0, 3.1 \text{ h}^{-1} \text{ Mpc cells:}$   
both improve with larger cells

# Density-Displacement Relation



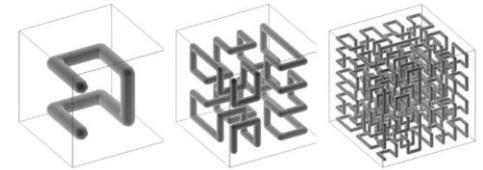
$z = 0, 6.3 \text{ h}^{-1} \text{ Mpc cells:}$   
both improve with larger cells

# Future Directions

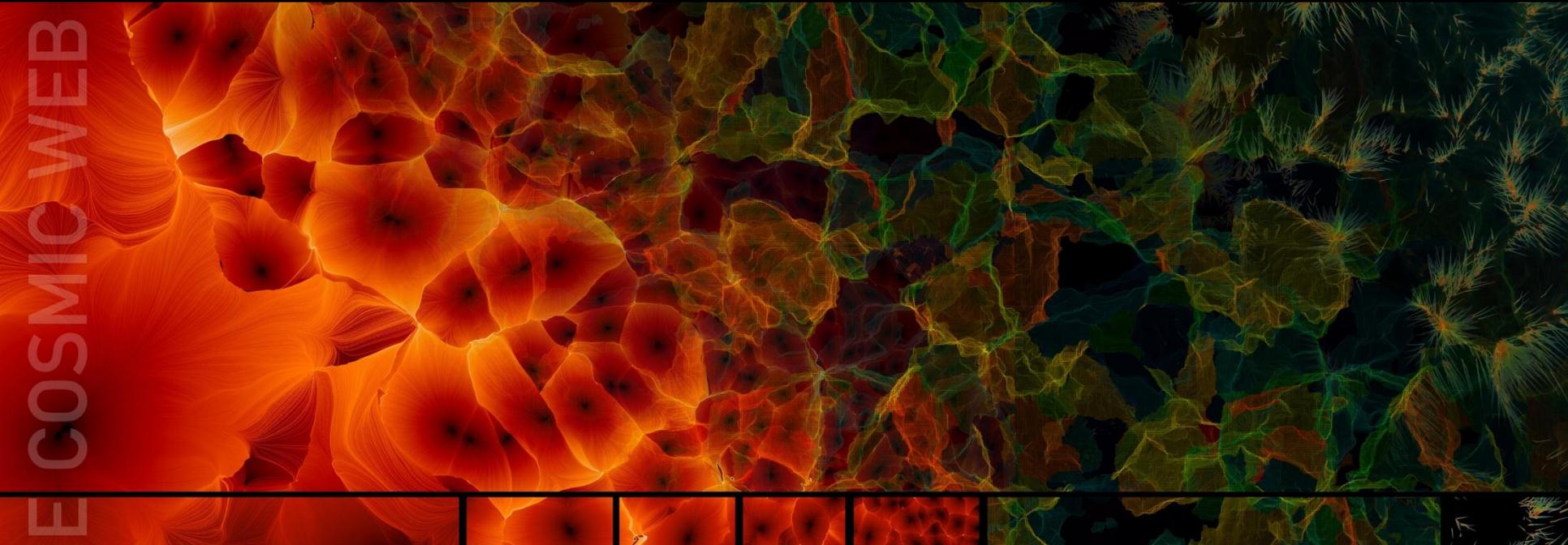
- The log-density could provide quick and efficient improvement to linear reconstruction methods (for example BAO reconstruction), allowing smoothing on smaller scales
- We also plan to test simulation results by measuring statistics of log-density of SDSS galaxies
- **Further studies of log-density 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



This cosmological pure dark matter simulation spans 240 million light years in vertical scale. From left to right the simulation's periodic boundary conditions are exploited to visualize different representations of the Cosmic Web.

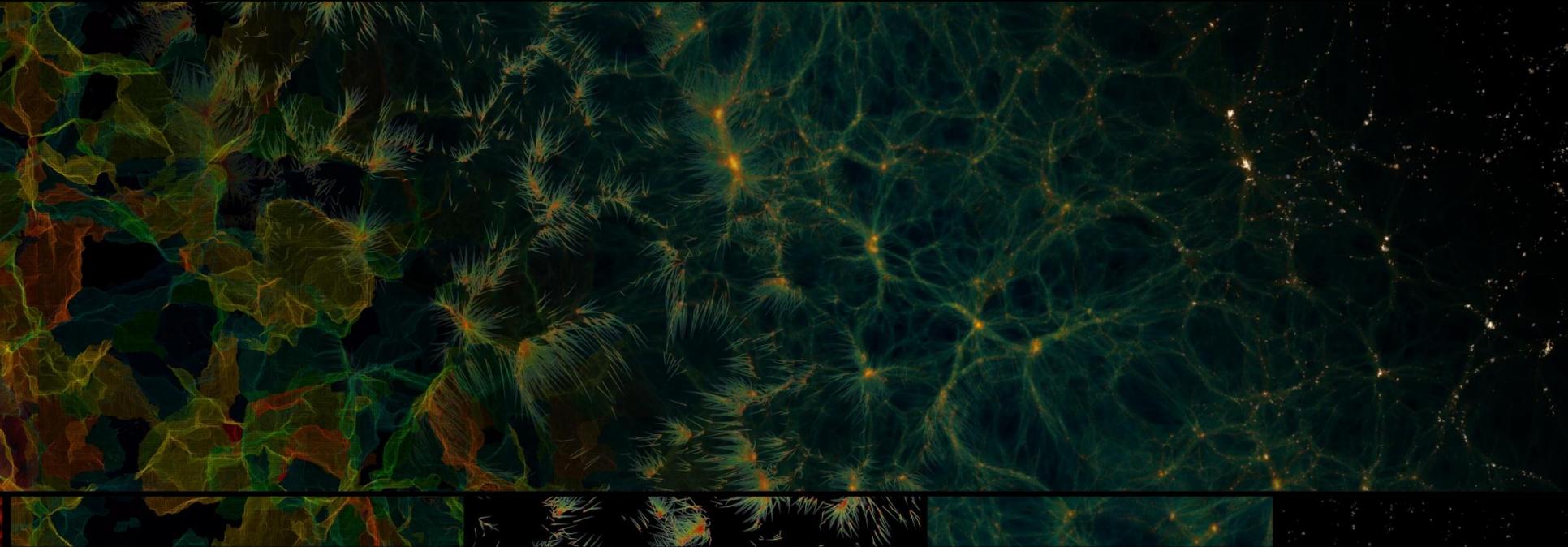
**COSMIC TIDES:** In the Universe, gravity is the motor that sets matter in motion. The streams in this figure illustrate the close relation between the geometry and the dynamics of the Cosmic Web as matter moves from underdense voids onto increasingly dense walls, filaments and clusters. Five versions of the velocity field are presented. From left to right, each visualization progressively filters out more of the large-scale flows, highlighting the local dynamics on scales from superclusters down to galaxies.

**VOID NETWORK:** The structure of the Universe at large scales is dominated by vast empty regions known as voids. Most of the matter in the Universe (including galaxies) is located in a complex network of walls, filaments and clusters. Here we see the individual voids as membranes, each designated with a different color.

**MATTER TRAILS:** The early universe most linear motion. Together, the dynamic tions, and the trails go

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



motor that sets mat-  
rate the close rela-  
of the Cosmic Web  
increasingly dense  
velocity field are  
progressively fill-  
ing the local dy-  
xies.

**VOID NETWORK:** The structure of the Universe at large scales is dominated by vast empty regions known as voids. Most of the matter in the Universe (including galaxies) is located in a complex network of walls, filaments and clusters. Here we see the individual voids as membranes, each designated with a different color.

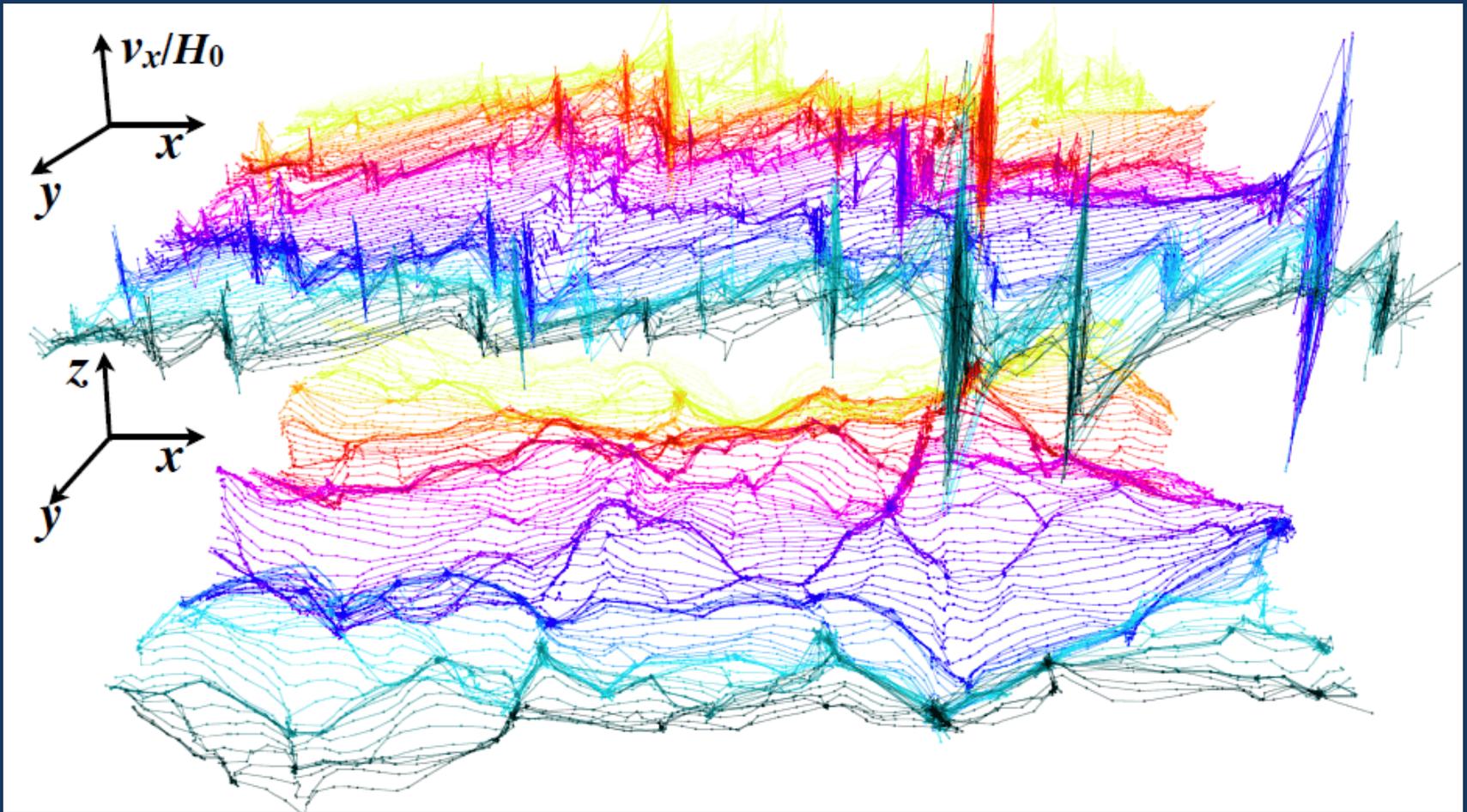
**MATTER TRAILS:** This image shows individual trails of matter from the early universe up until today (red). Everything starts with almost linear motion. As time goes by and gravity pulls matter together, the dynamics become dominated by small-scale interactions, and the trails grow more and more complex.

**DARK MATTER:** Most of the matter in the Universe is dark. We only notice its effects through gravity. Here we see the distribution of dark matter as it would look if it emitted light. A rich system of structures appear: massive clusters connected by long threads of matter form an interconnected network that permeate space. The nodes of this cosmic network are places where dark matter accumulates and galaxies form.

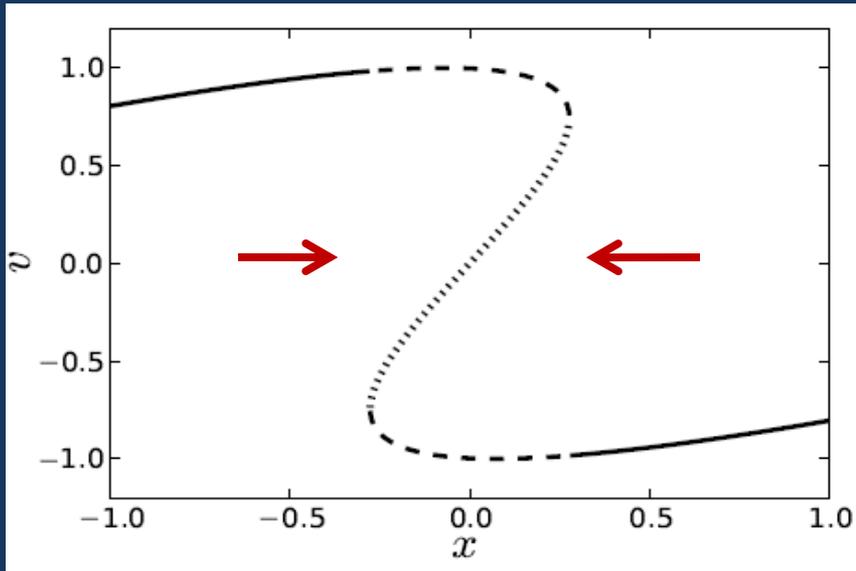
**GALAXIES:** This visualization shows the galaxy field we would expect to observe given the underlying dark matter distribution. Different galaxy types are assigned to dark matter haloes according to their density; red ellipticals are characteristic of the large dense clusters but can be also found in low density regions, while blue spirals tend to avoid dense environments.

... 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

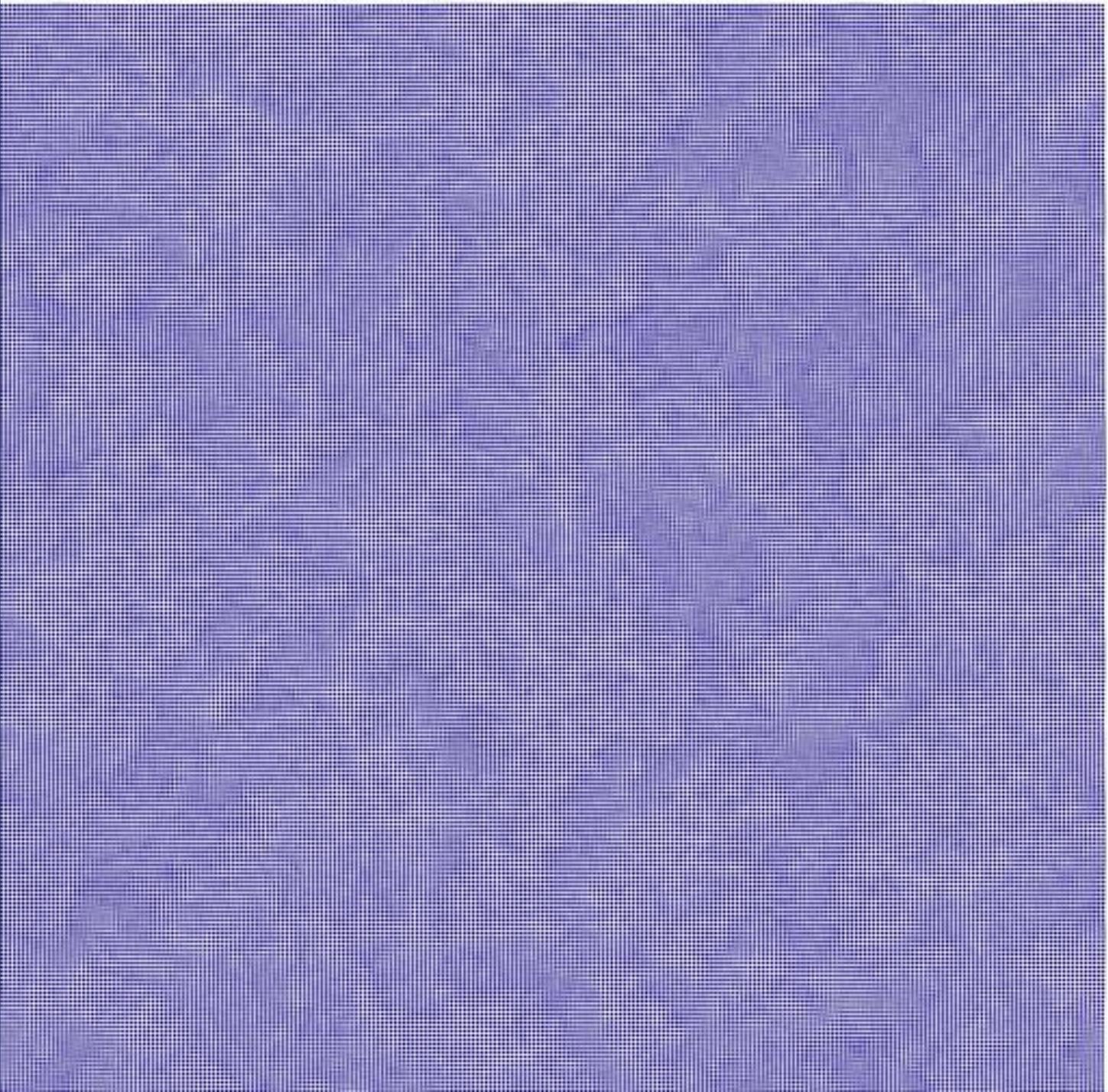


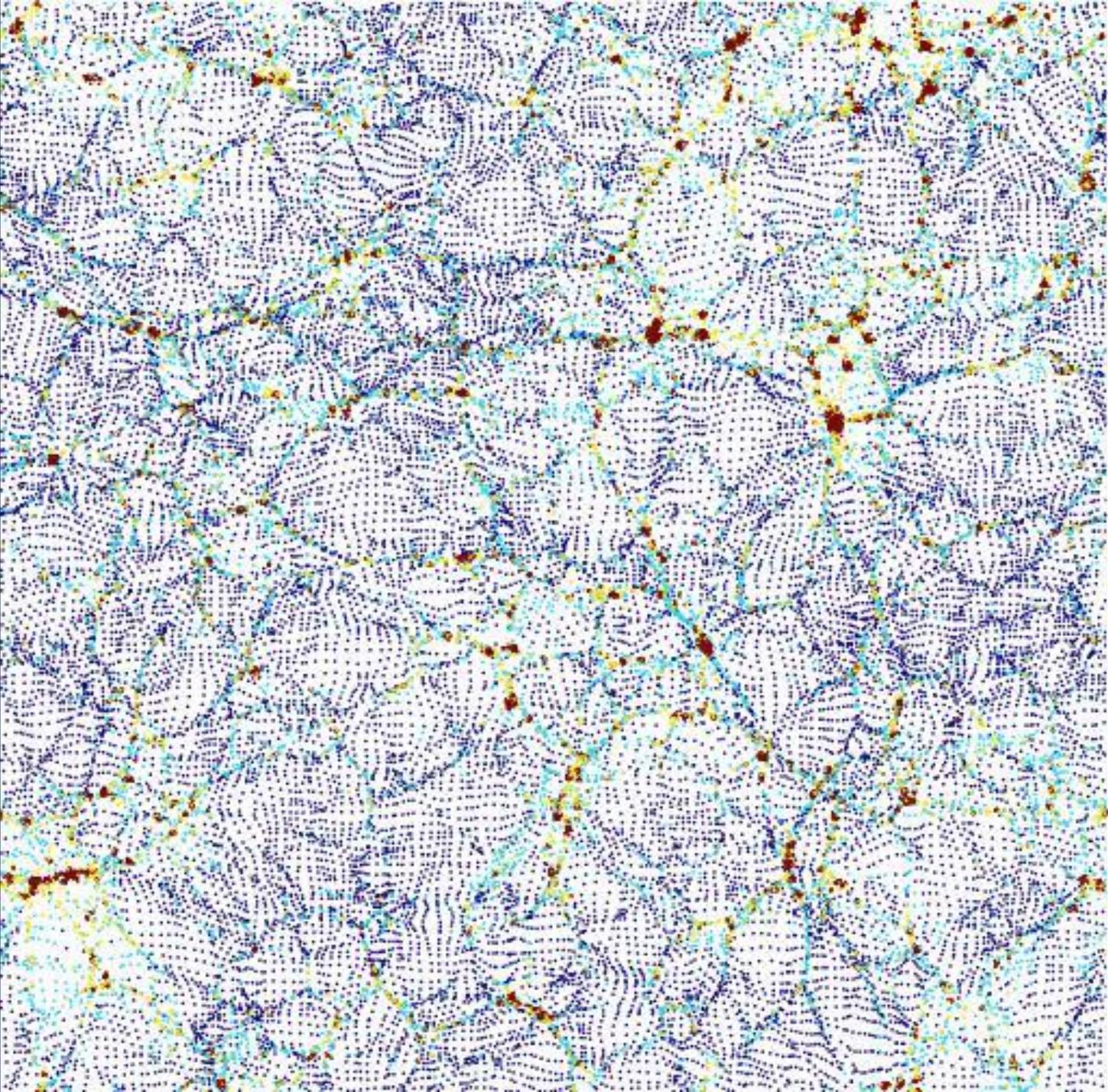
# The ORIGAMI method

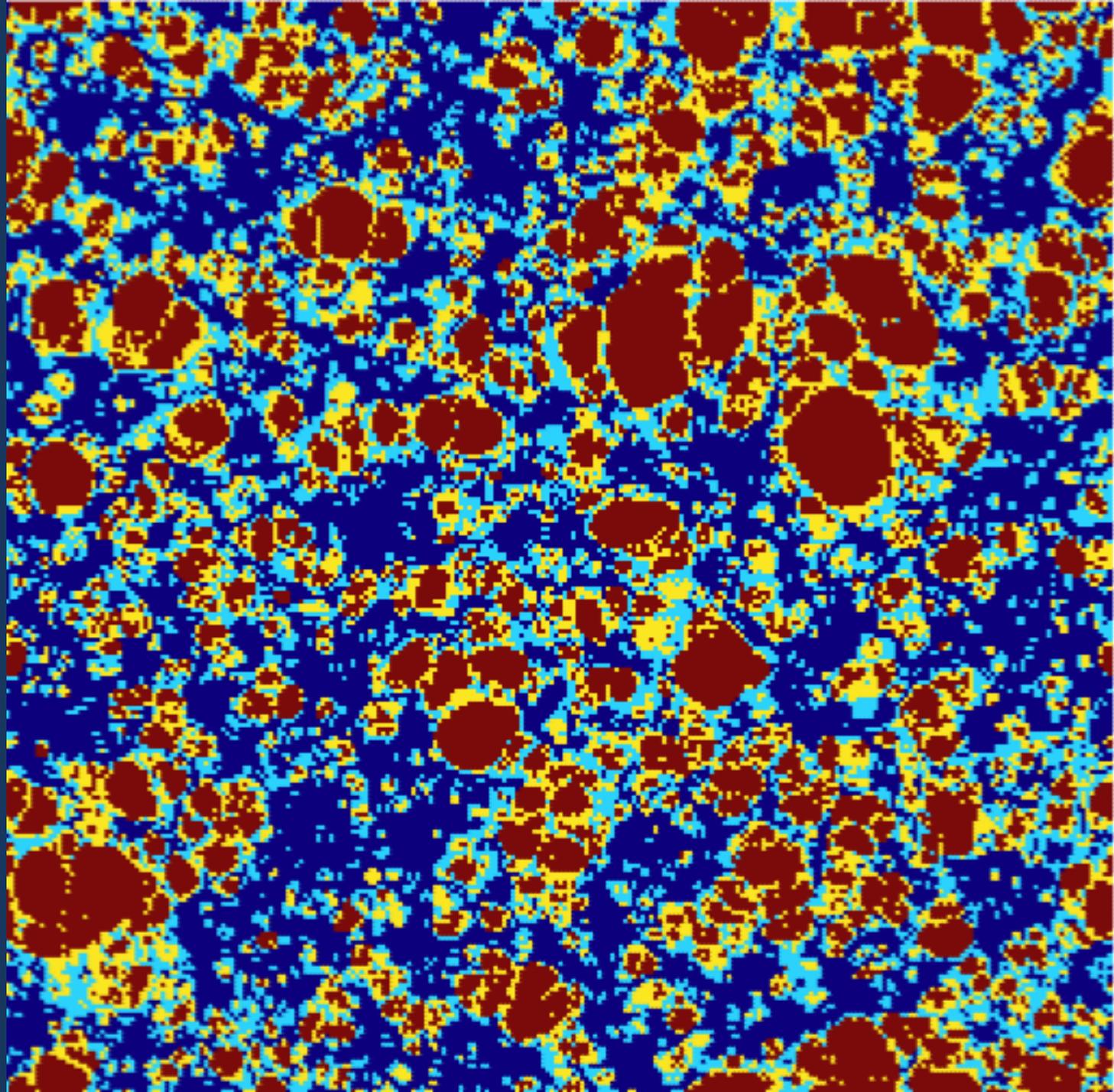


In this 1D example, particles flow toward an initial overdensity at the origin, eventually creating a fold in phase-space

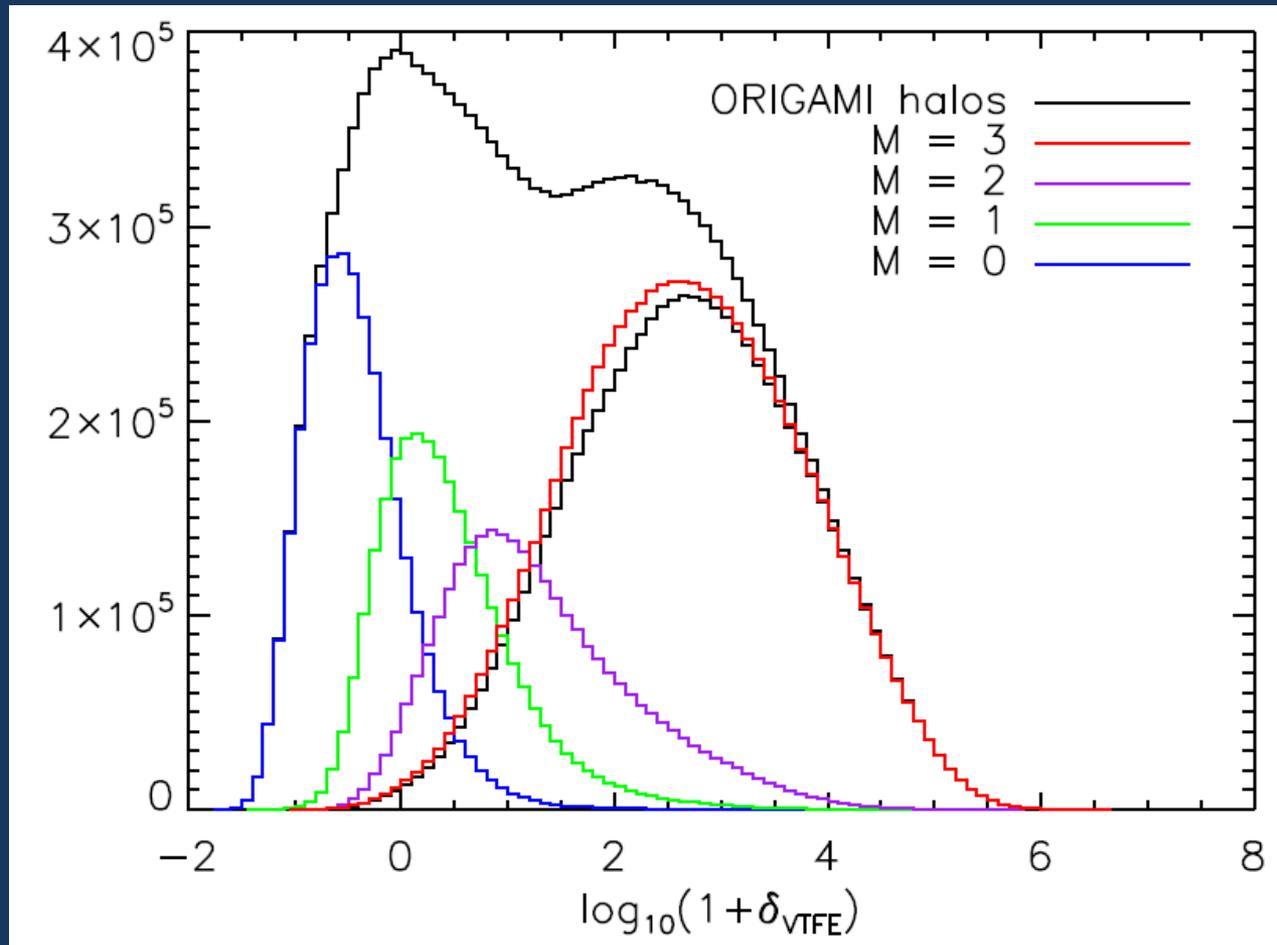
- ORIGAMI finds shell-crossing by looking for particles out of order with respect to their original configuration
- Halo particles have undergone shell-crossing along 3 orthogonal axes, filaments along 2, walls 1, and voids 0







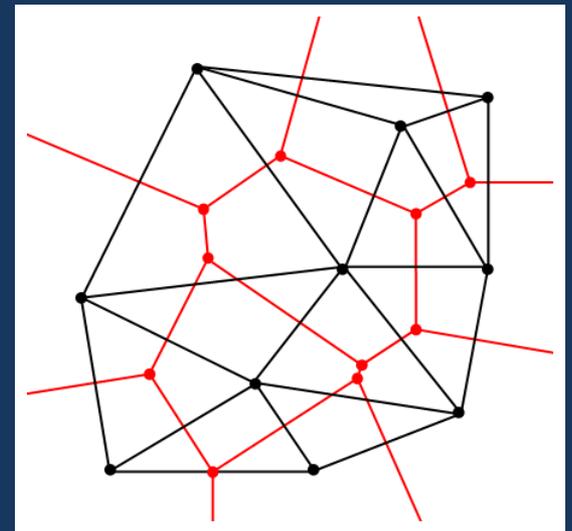
# Particle Density by ORIGAMI Morphology



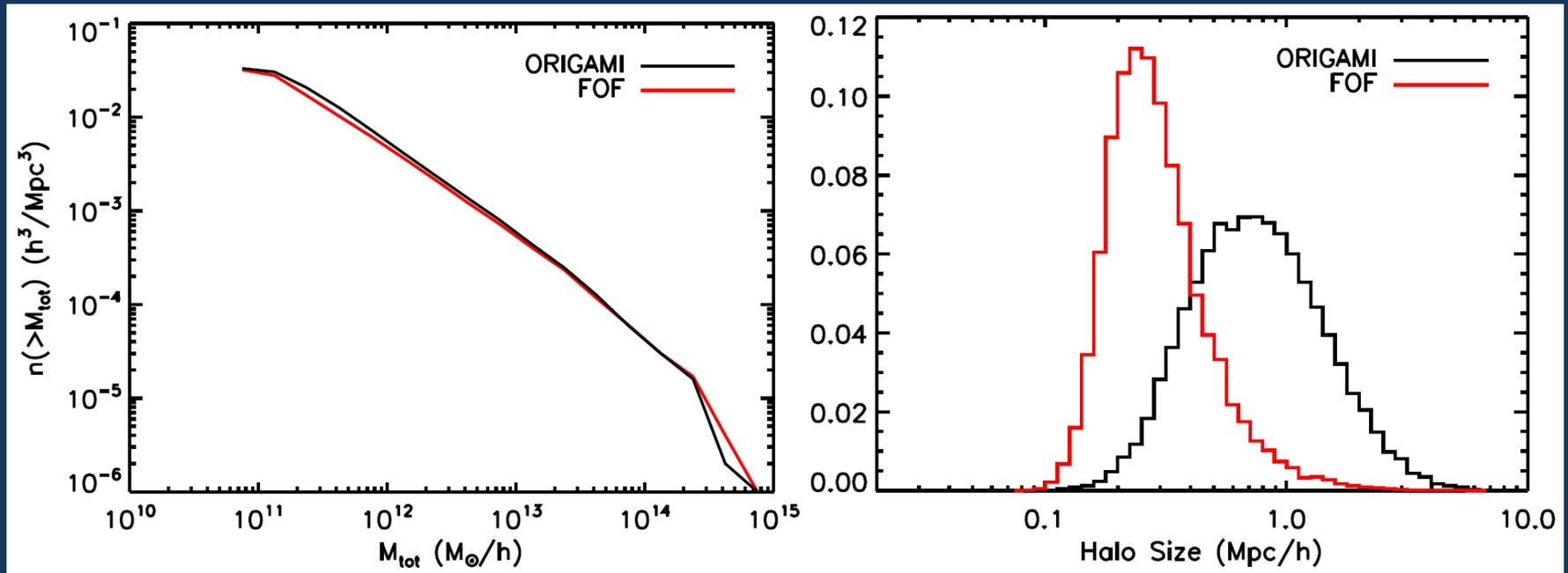
halo  
filament  
wall  
void

# 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

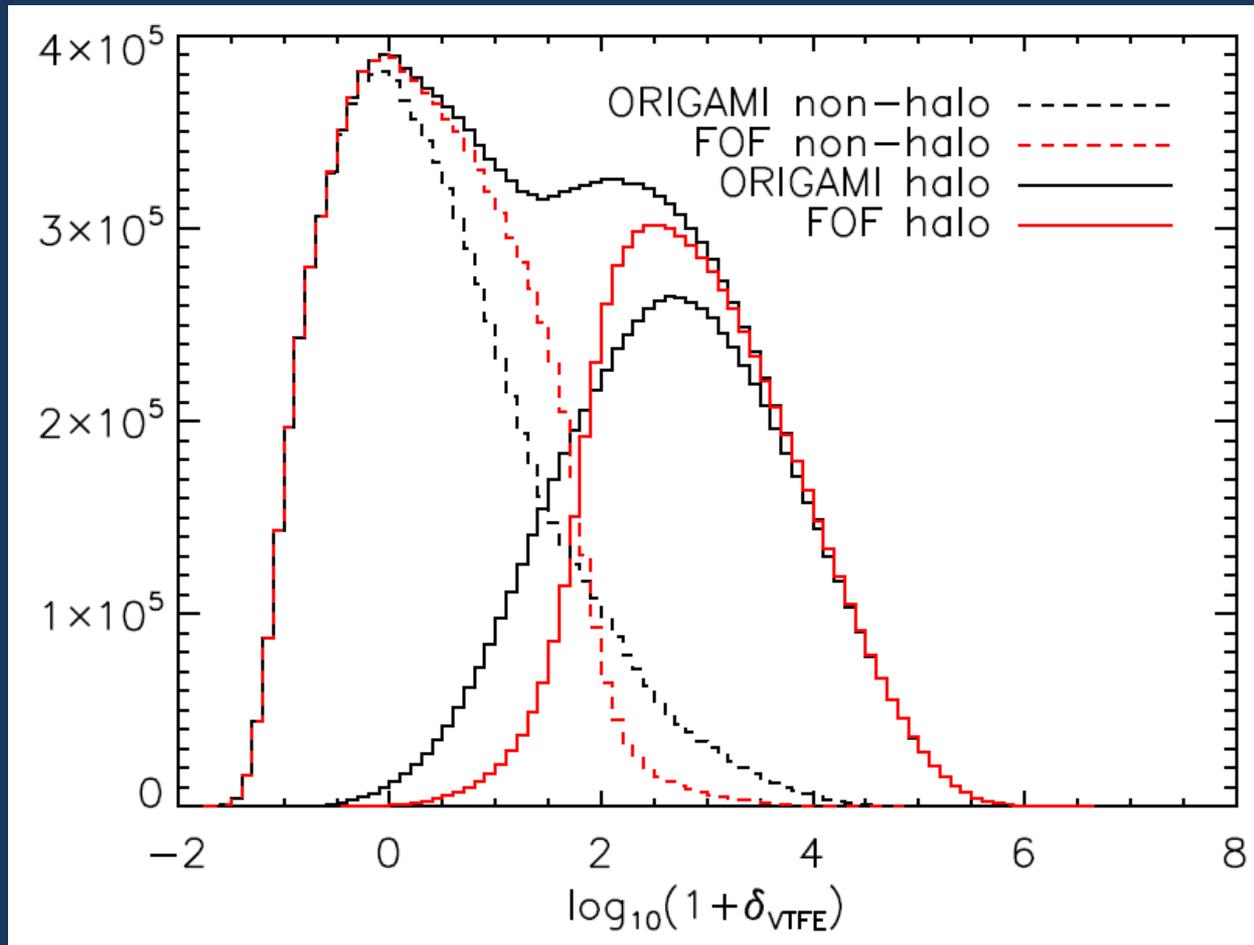


# Halo Comparison to FOF



- 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  $\sim 1$  PB of  $N$ -body data for precision cosmology

