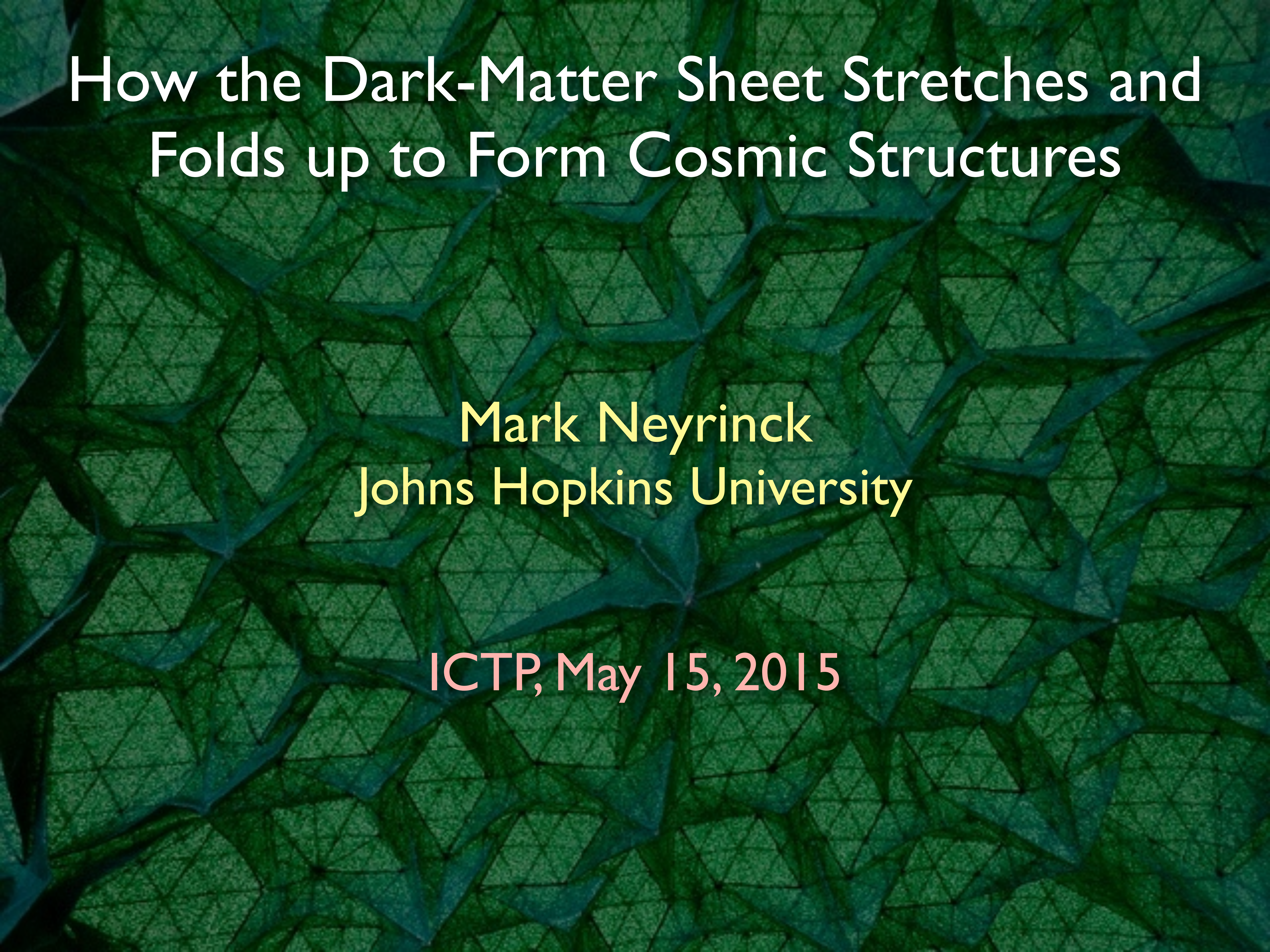
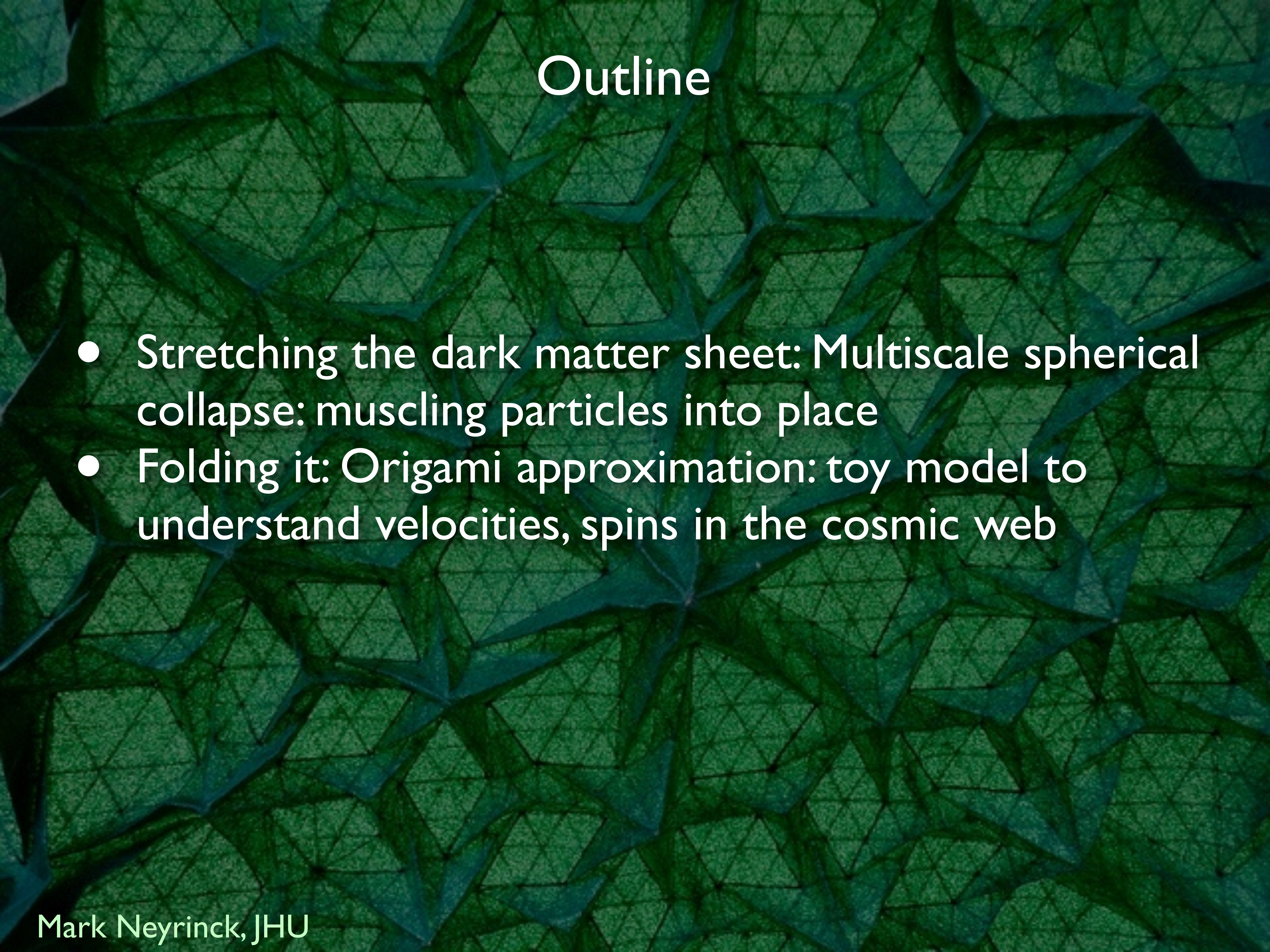


How the Dark-Matter Sheet Stretches and Folds up to Form Cosmic Structures

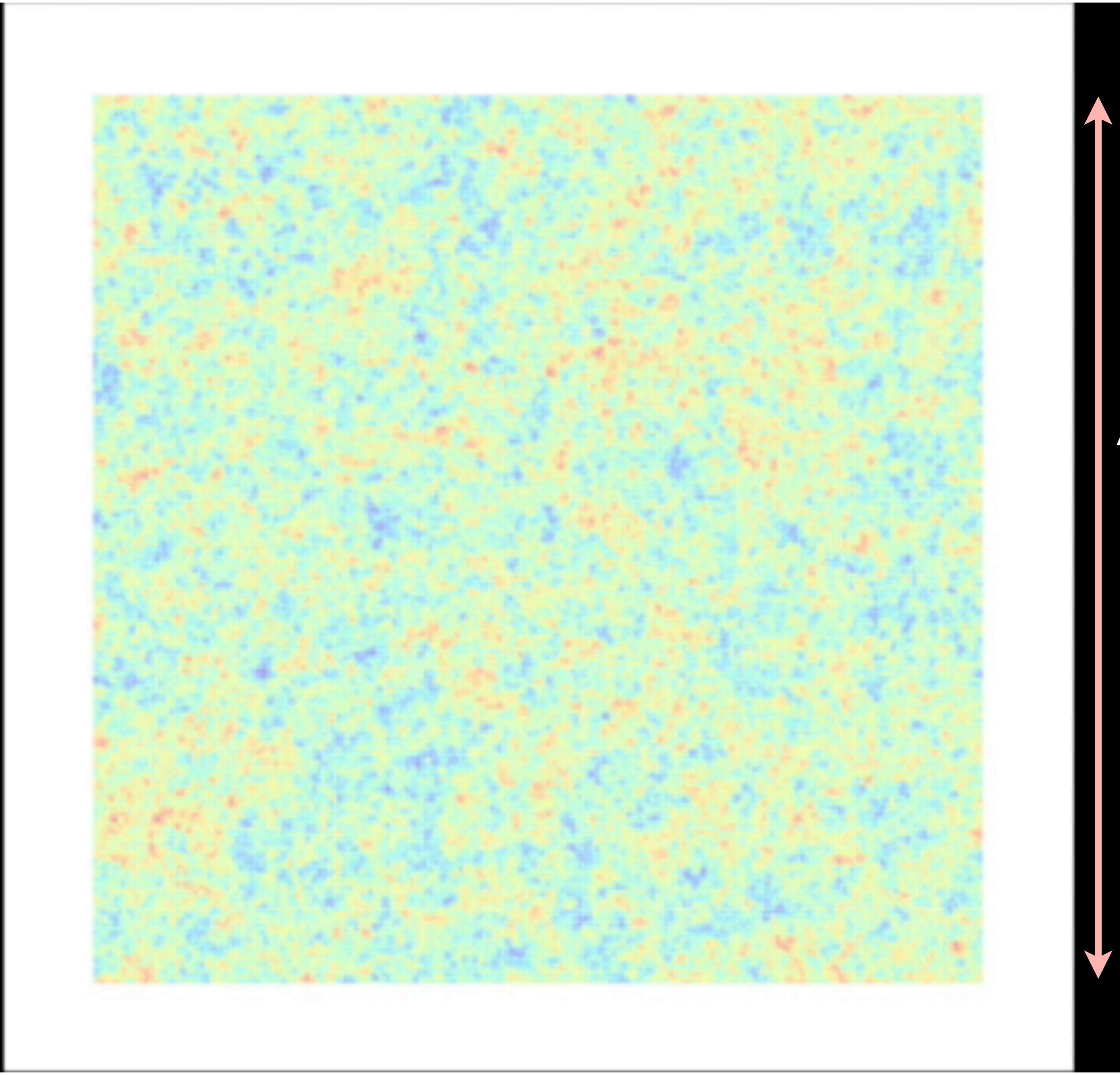
Mark Neyrinck
Johns Hopkins University

ICTP, May 15, 2015



Outline

- Stretching the dark matter sheet: Multiscale spherical collapse: muscling particles into place
- Folding it: Origami approximation: toy model to understand velocities, spins in the cosmic web



A billion light years

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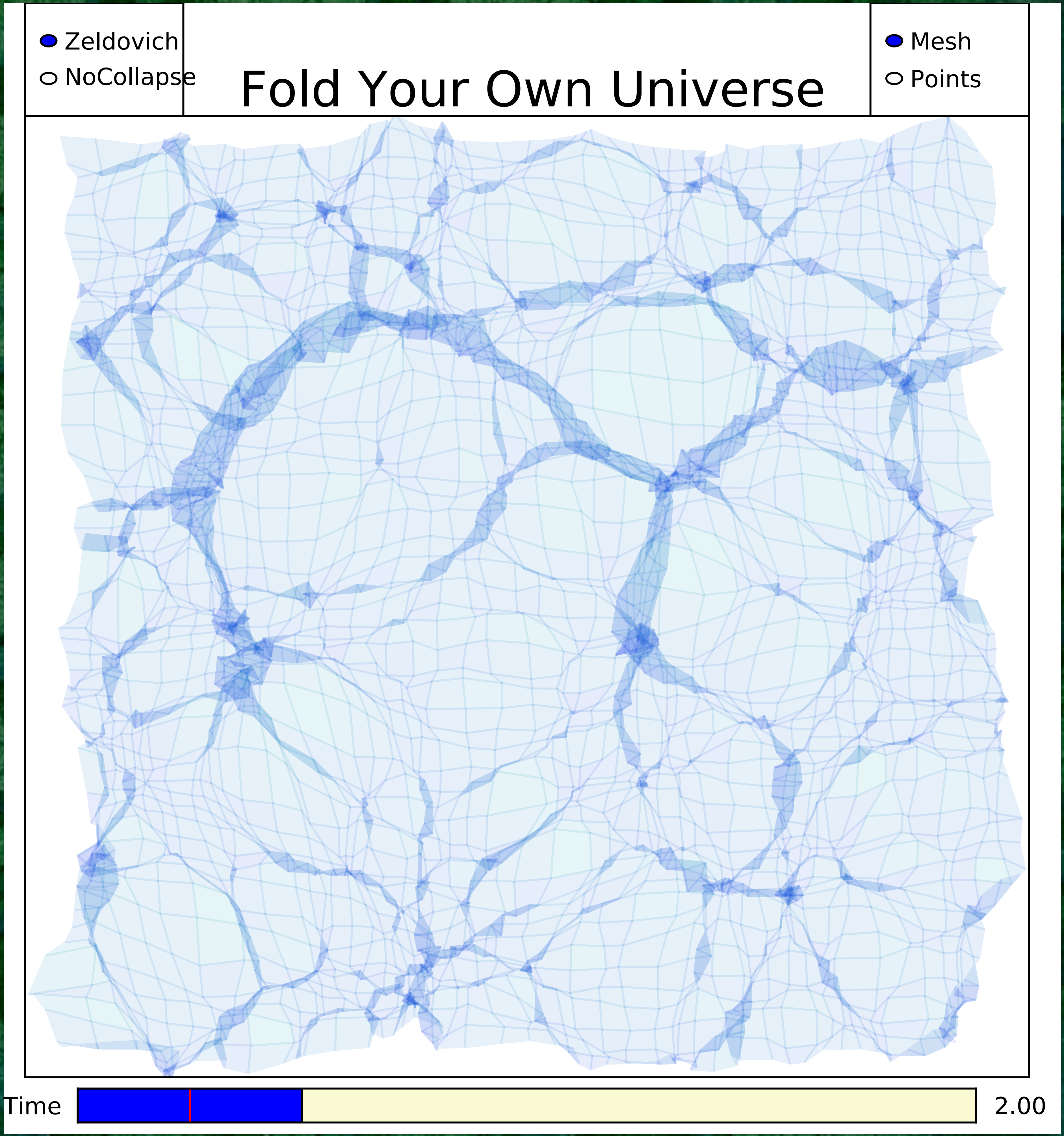
Publicly available python code for e.g. outreach: Google “Fold Your Own Universe”



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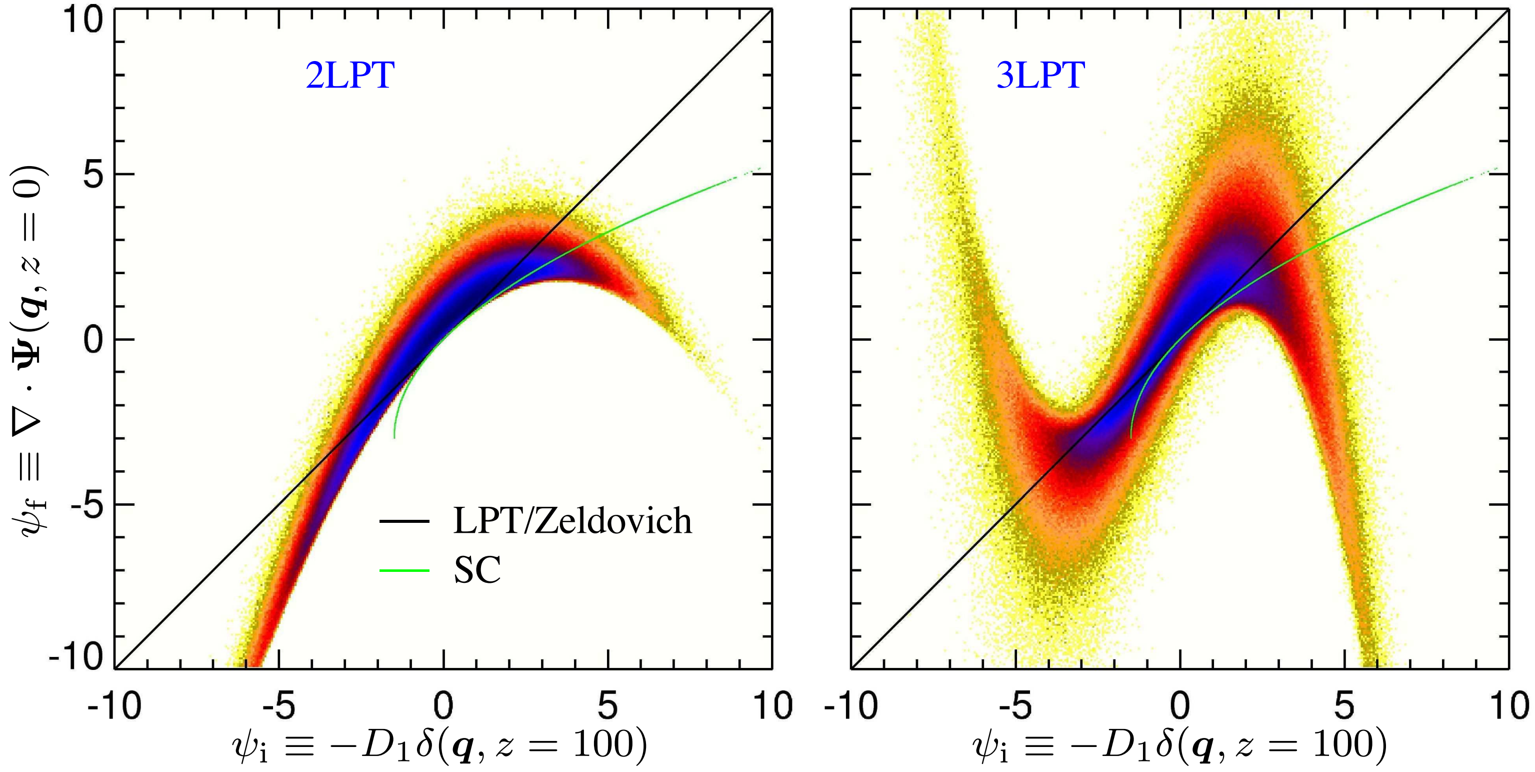
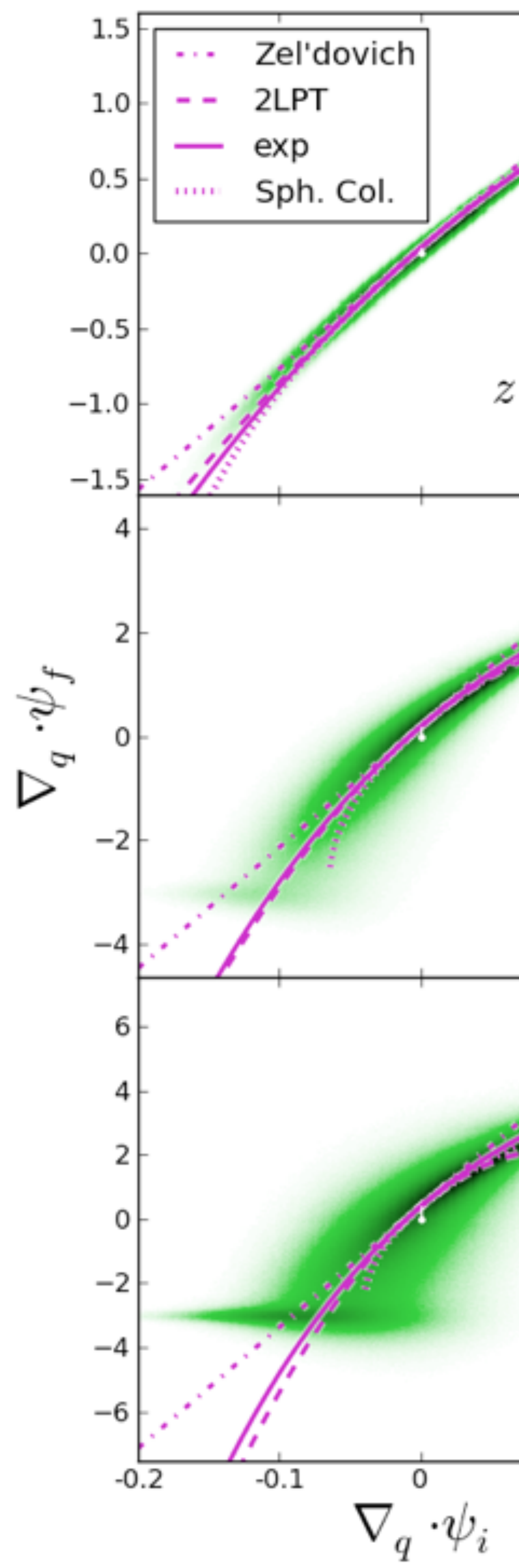
How does the dark-matter sheet really stretch?

- "stretching" $\psi \equiv \nabla_L \cdot \boldsymbol{\psi}$,
- Zel'dovich (1970): $\psi = -\delta_{\text{linear}}$.
- $\psi = -3$: halo formation, where $\boldsymbol{\nabla_L} \cdot \boldsymbol{x_f} = 0$.

- 2LPT, 3LPT:



(Kitaura & Heß 2013)



(MN 2013)

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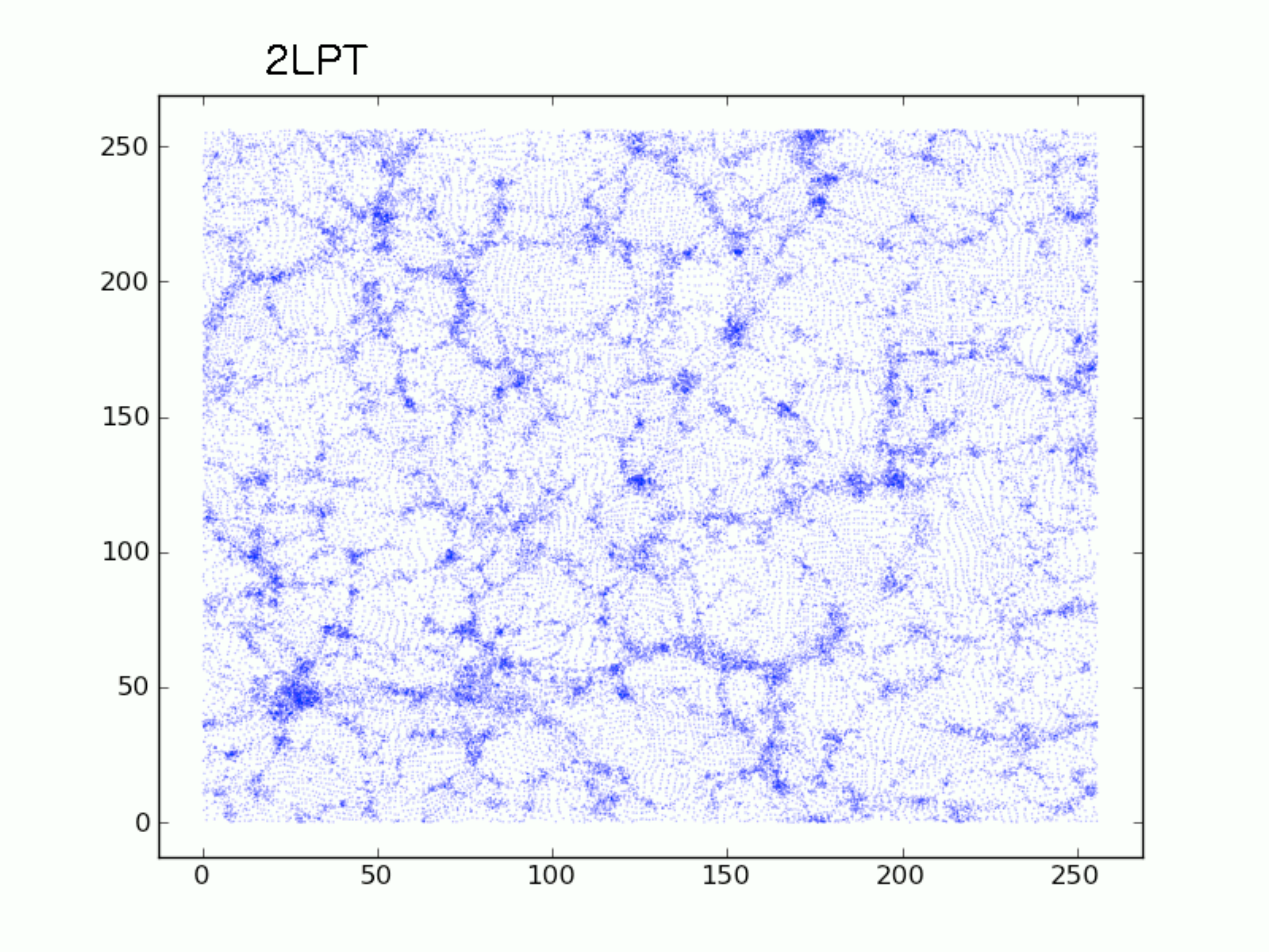
Interpolating between 2LPT and Spherical Collapse



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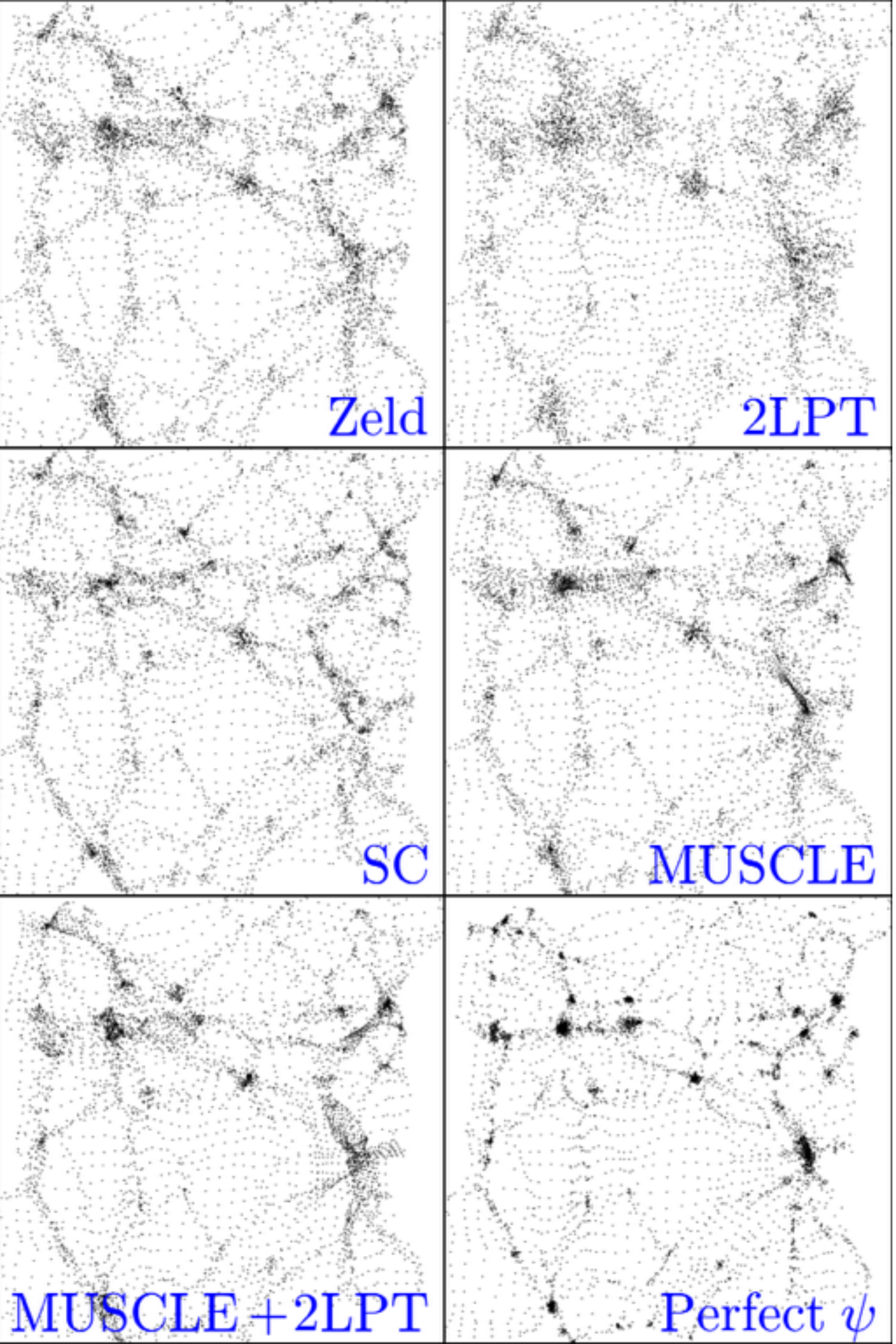
Multiscale Spherical Collapse

Alternative solution: apply spherical collapse on many scales. Gaussian*-smooth the field at scales $2^n c$, where c = cell size, where $n < \sim 5$

If $\delta_{\mathrm{lin}} > 3/2$ at any scale, set $\psi = -3$.
Apply spherical collapse formula at c, otherwise.

*- Top-hat smoothing didn't work as well. Other multiscale prescriptions possible.



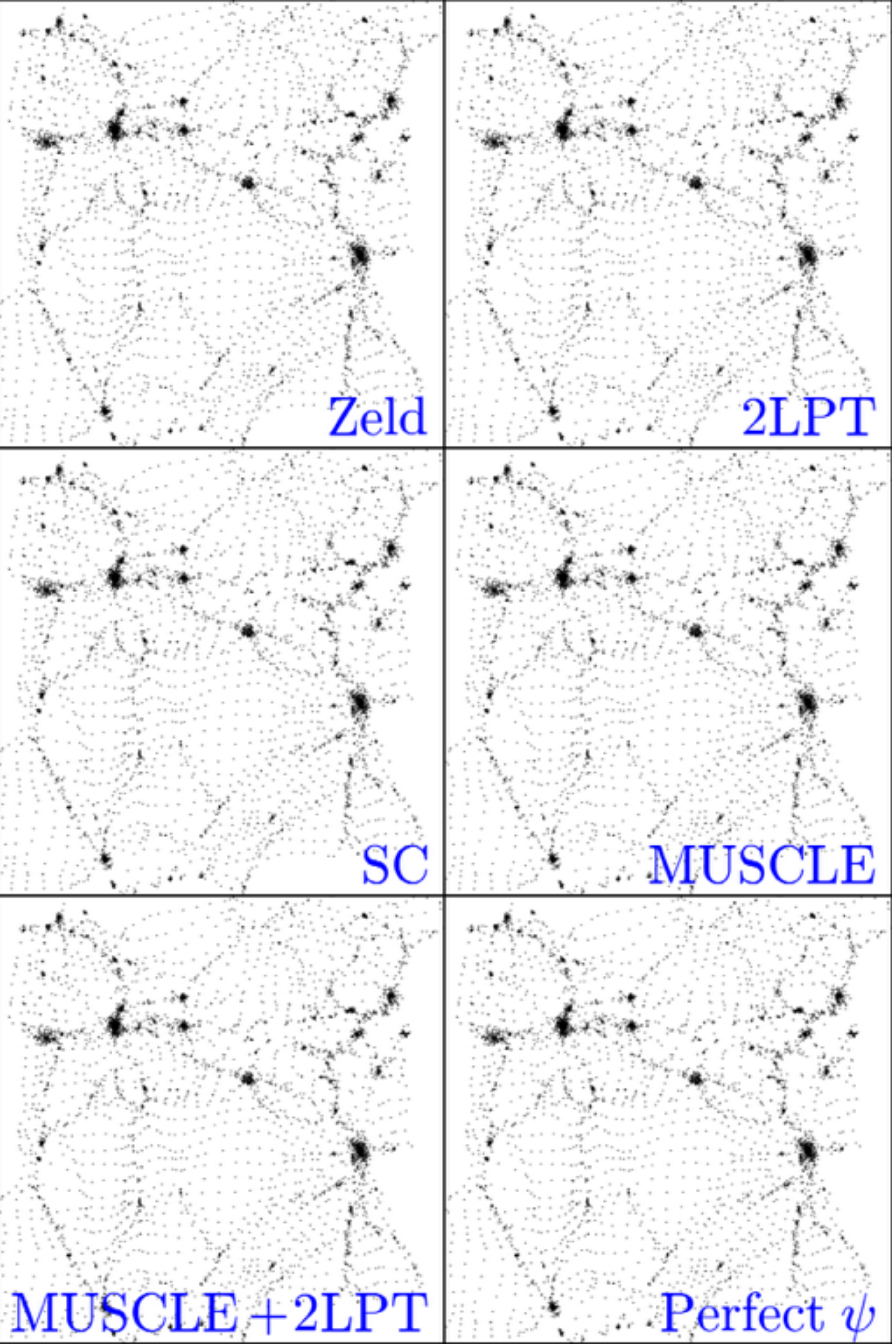
How does the dark-matter sheet really stretch?

← perturbative

← Non-perturbative: **MU**ltiscale **S**pherical **C**ol**L**apse **E**volution

- Approaches based on the "stretch parameter" $\psi \equiv \nabla_L \cdot \boldsymbol{\psi}$ directly from initial conditions (Lagrangian divergence of the displacement field)

How does the dark-matter sheet really stretch?



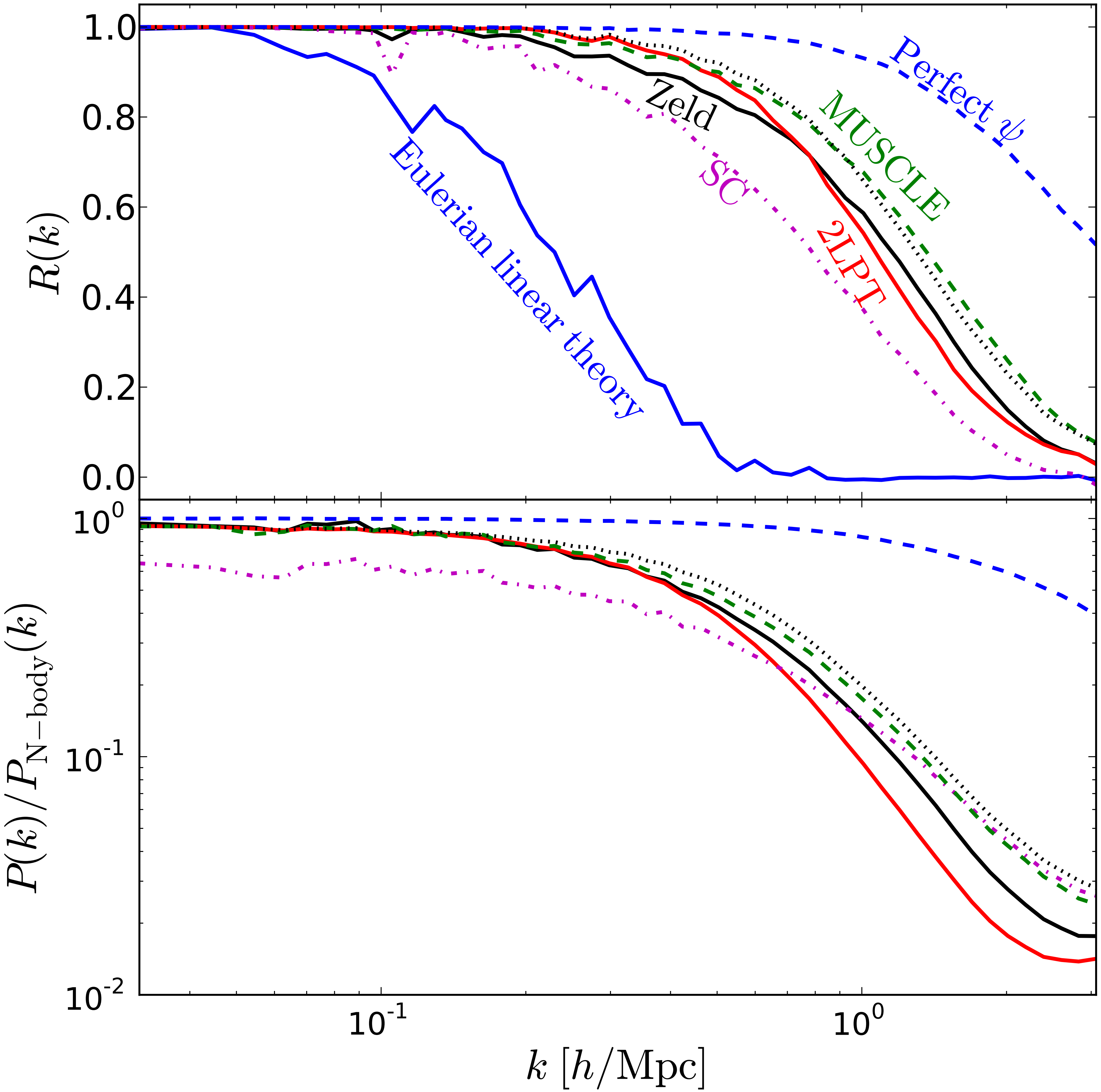
← perturbative

(*N*-body)

← Non-perturbative: **MU**ltiscale **S**pherical **C**ol**L**apse **E**volution

- Large scale structure simpler than often imagined on quasilinear scales!

Quantitatively:



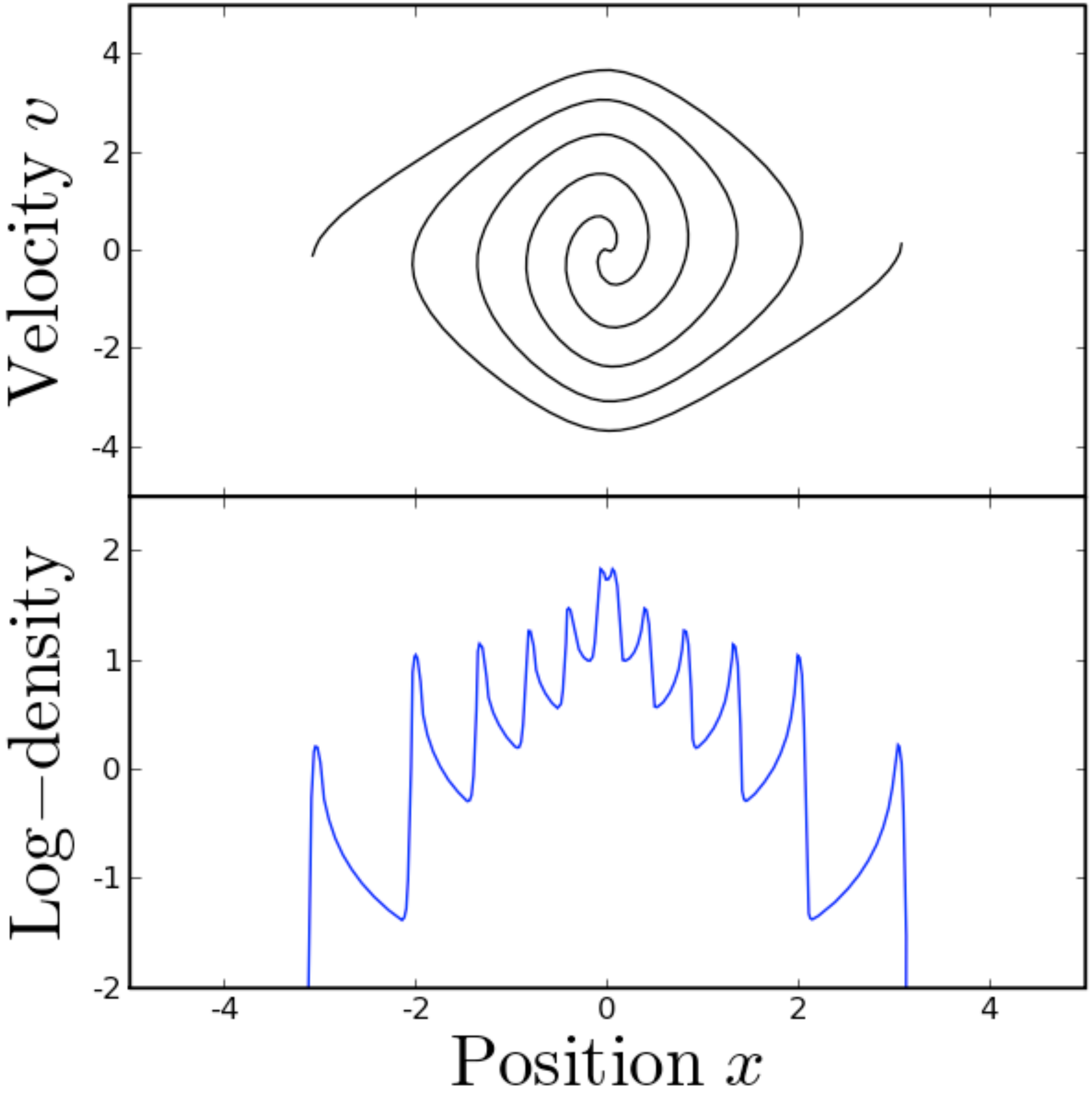
Simple Python Code for quick N-body realizations & IC's at

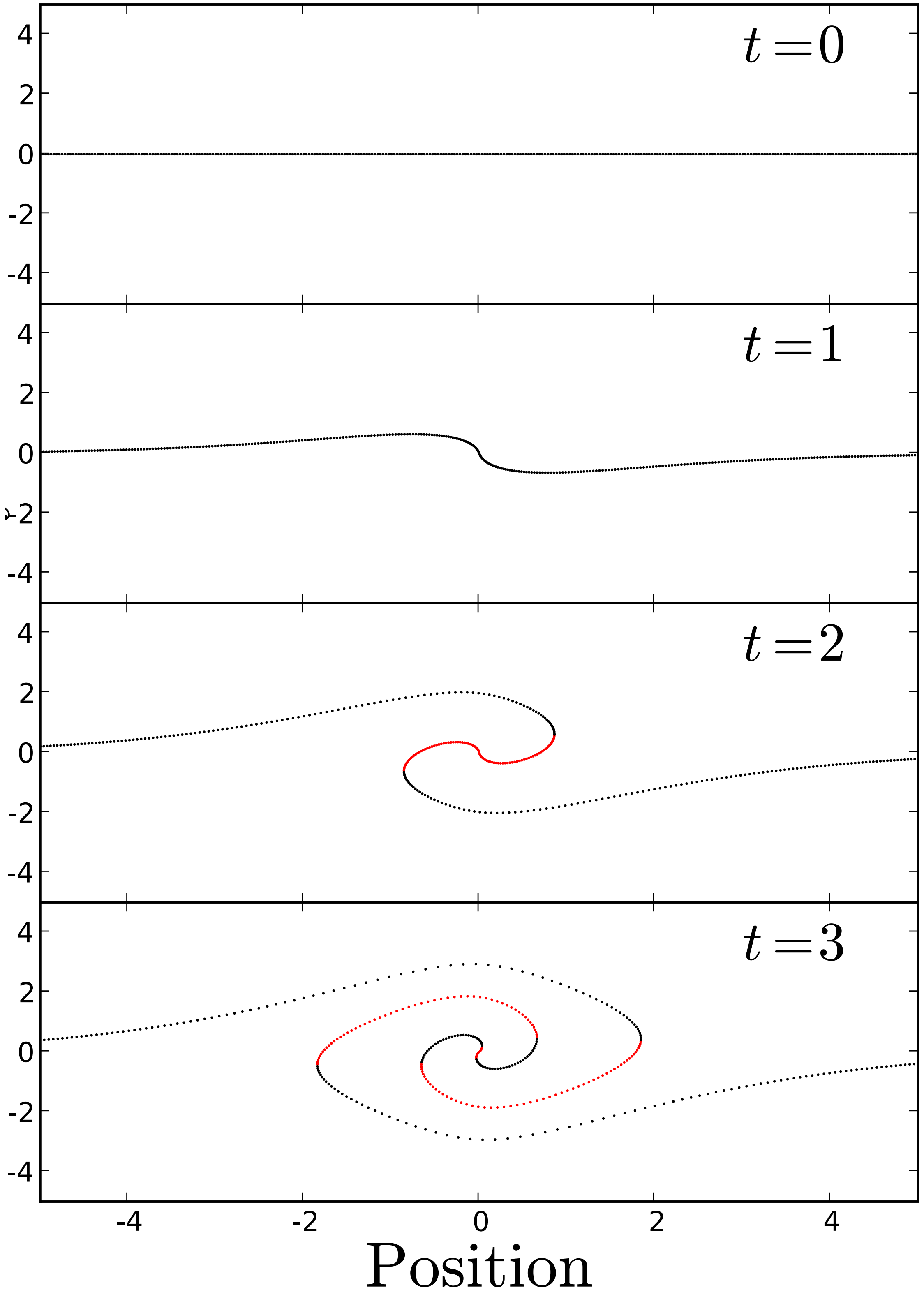
http://skysrv.pha.jhu.edu/~neyrinck/muscle

How does it fold?

http://skysrv.pha.jhu.edu/~neyrinck/muscle

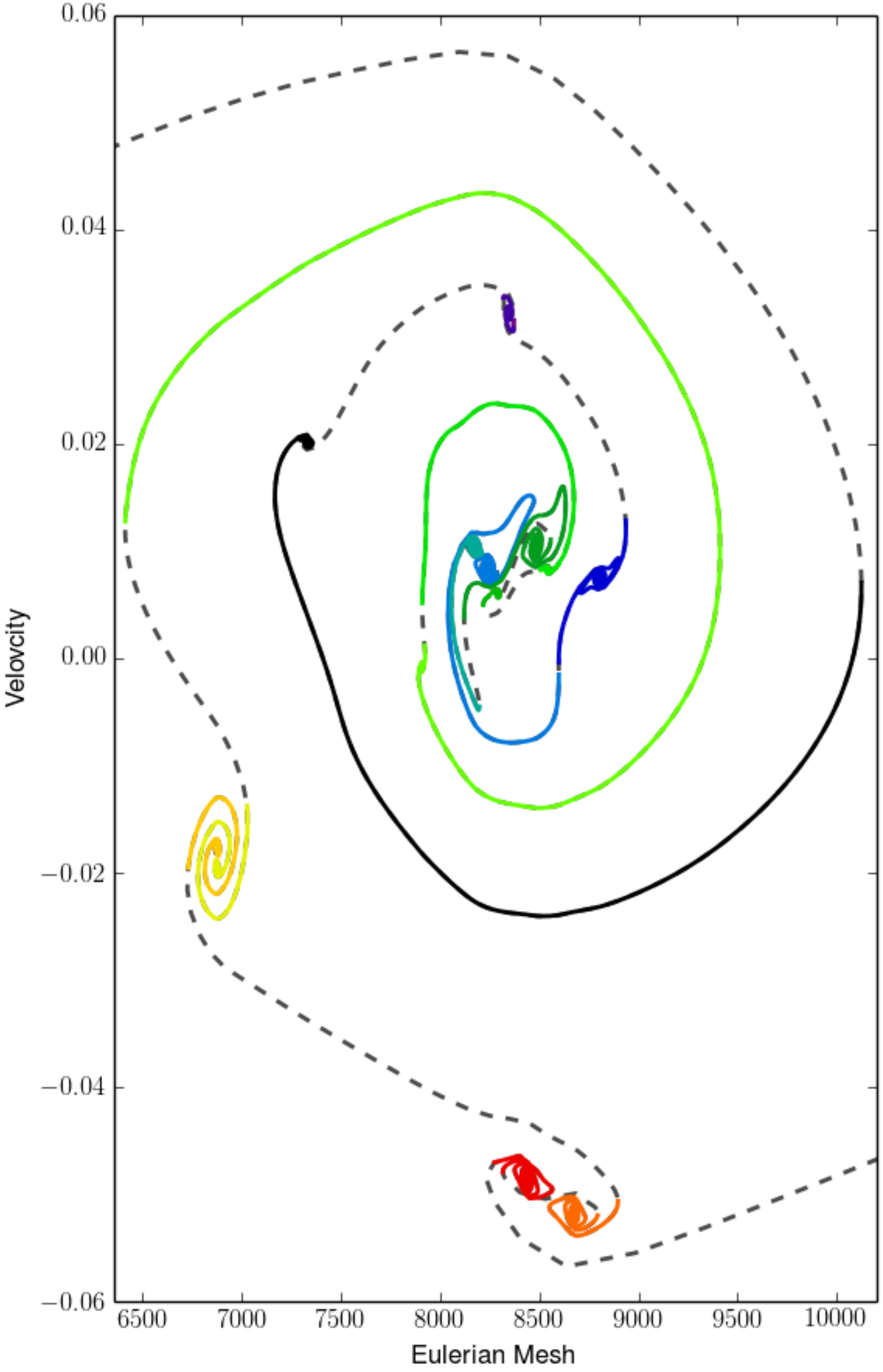
Folding in a 1D universe





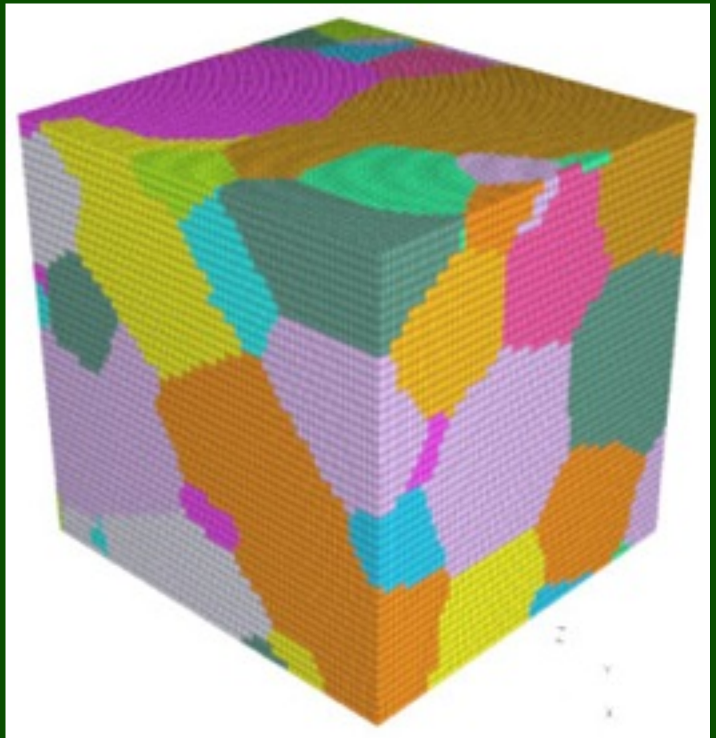
- Tools needed to understand phase-space geometry of haloes and subhaloes necessary — difficult to distinguish substructures in crowded environments

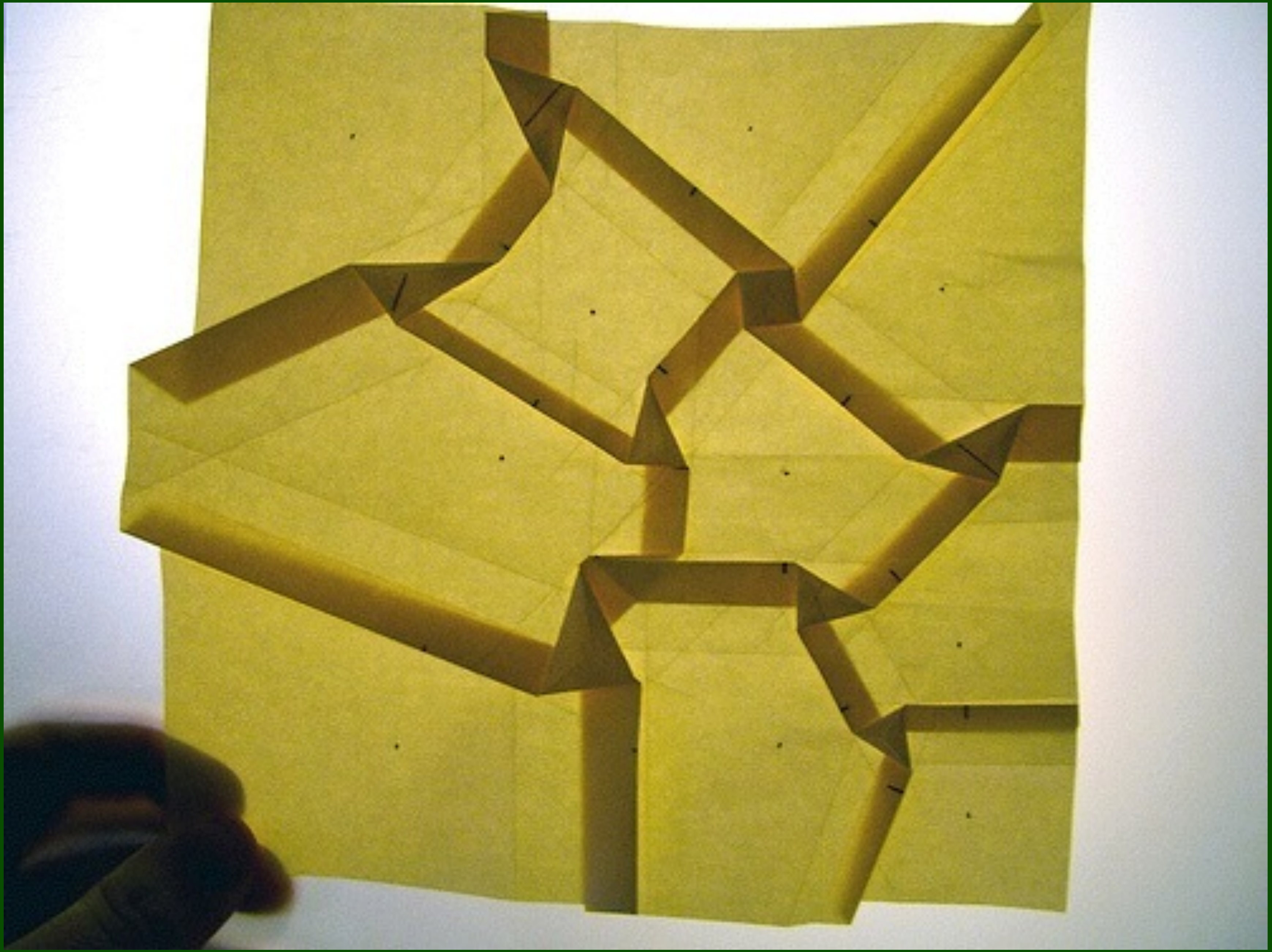
- Easy to visualize in 1D, but 2D? 3D?



(Shandarin & Medvedev 2014)

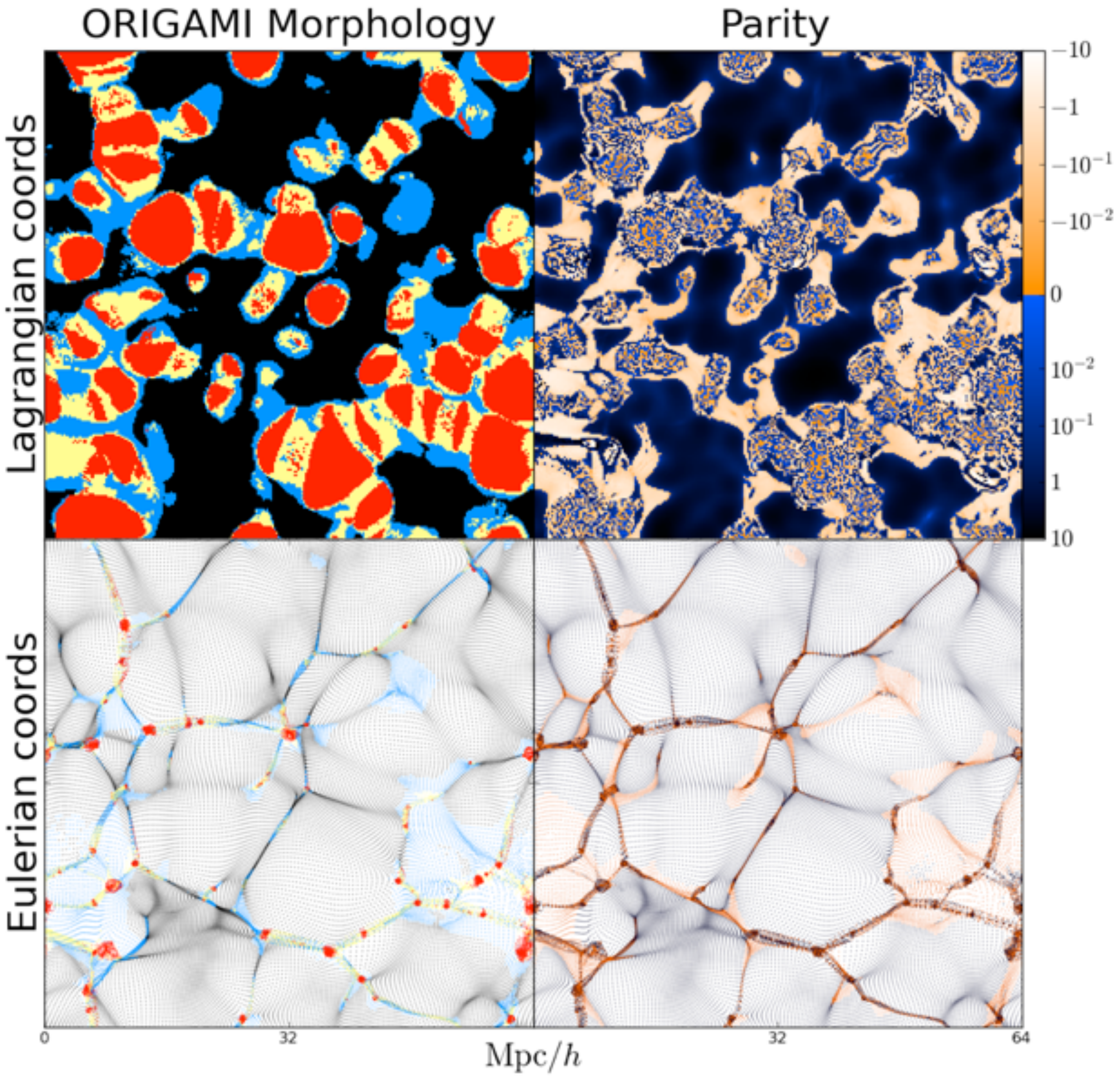
Rough analogy to origami: initially flat (vanishing bulk velocity) 3D sheet folds in 6D phase space.





Eric Gjerde,
origamitessellations.com

The Universe's crease pattern

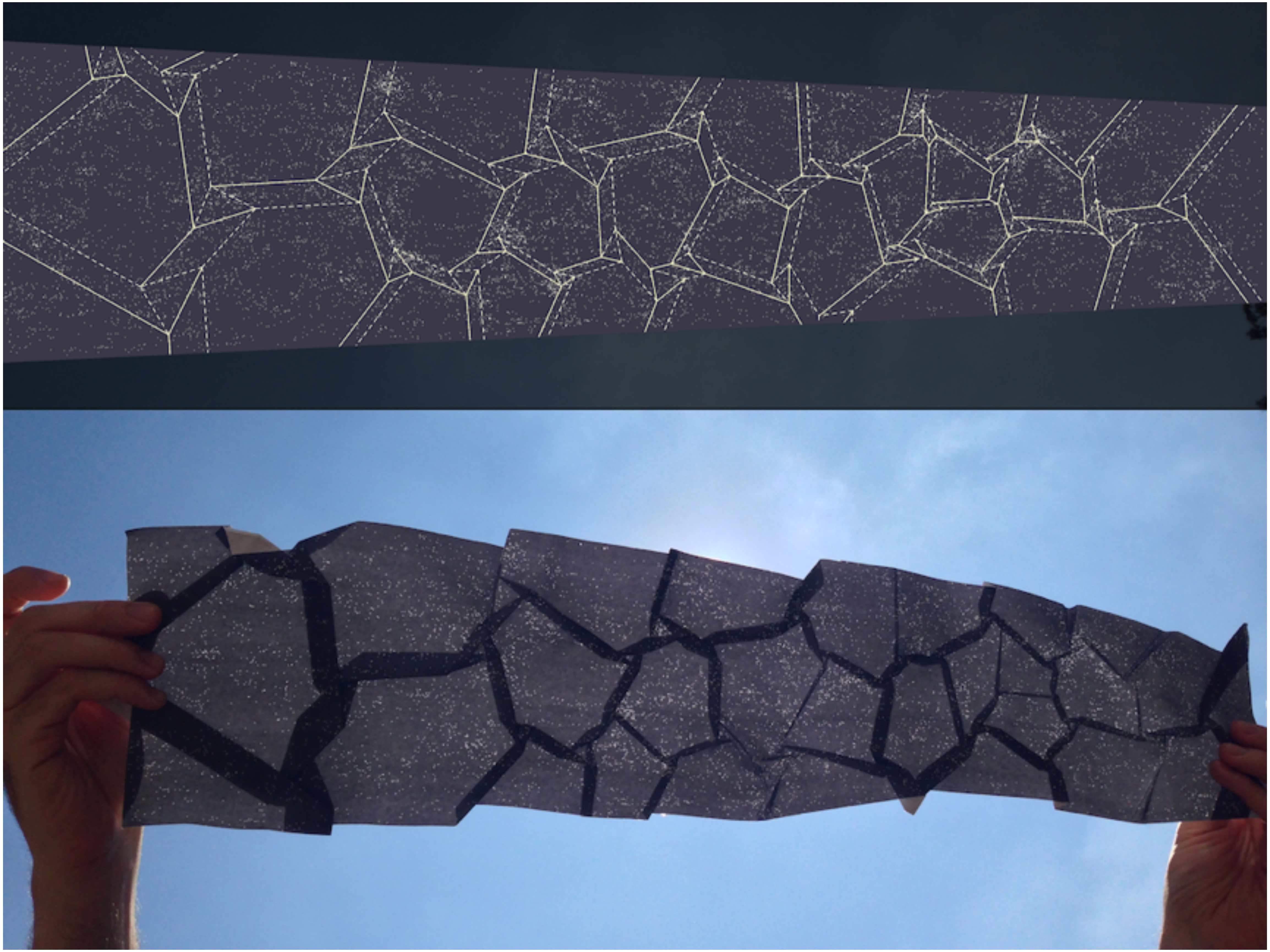


Crease pattern before folding

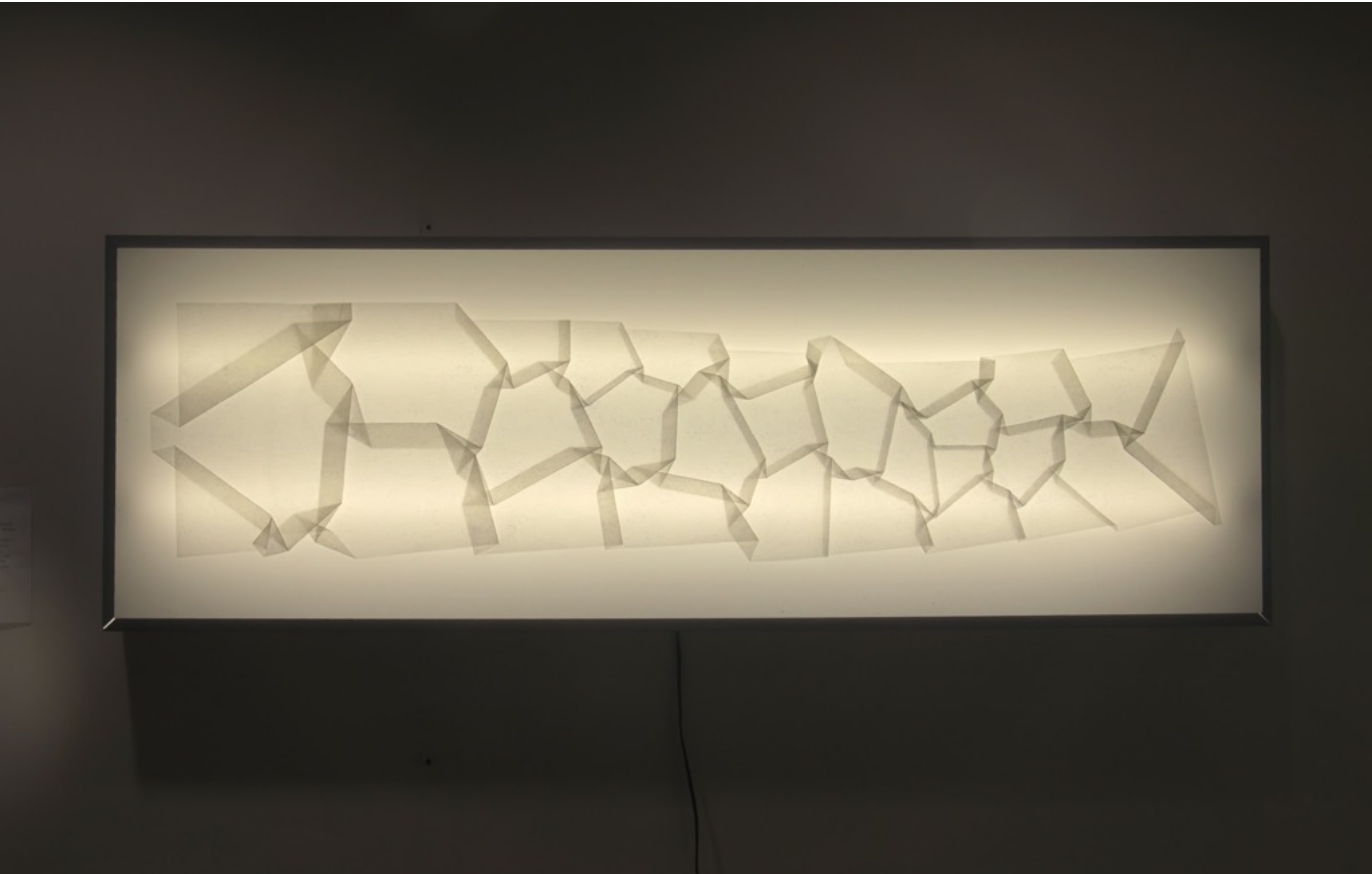
After folding

(Neyrinck 2012)

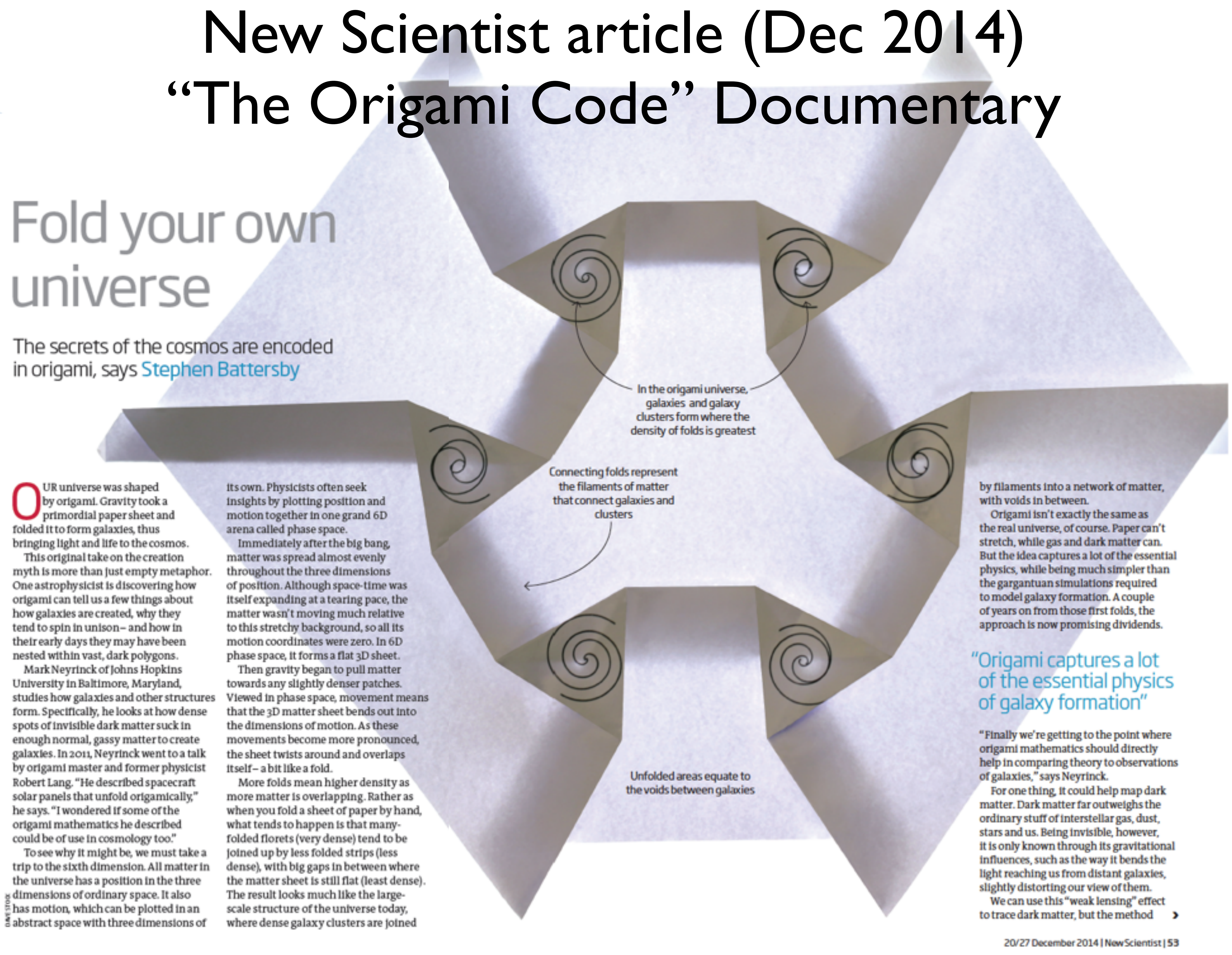
Schematic, based on the VIPERS survey



Currently on display in the JHU physics dept:



New Scientist article (Dec 2014)
“The Origami Code” Documentary



Fold your own universe

The secrets of the cosmos are encoded in origami, says Stephen Battersby

OUR universe was shaped by origami. Gravity took a primordial paper sheet and folded it to form galaxies, thus bringing light and life to the cosmos.

This original take on the creation myth is more than just empty metaphor. One astrophysicist is discovering how origami can tell us a few things about how galaxies are created, why they tend to spin in unison – and how in their early days they may have been nested within vast, dark polygons.

Mark Neyrinck of Johns Hopkins University in Baltimore, Maryland, studies how galaxies and other structures form. Specifically, he looks at how dense spots of invisible dark matter suck in enough normal, gassy matter to create galaxies. In 2011, Neyrinck went to a talk by origami master and former physicist Robert Lang. “He described spacecraft solar panels that unfold origamically,” he says. “I wondered if some of the origami mathematics he described could be of use in cosmology too.”

To see why it might be, we must take a trip to the sixth dimension. All matter in the universe has a position in the three dimensions of ordinary space. It also has motion, which can be plotted in an abstract space with three dimensions of its own. Physicists often seek insights by plotting position and motion together in one grand 6D arena called phase space.

Immediately after the big bang, matter was spread almost evenly throughout the three dimensions of position. Although space-time was itself expanding at a tearing pace, the matter wasn’t moving much relative to this stretchy background, so all its motion coordinates were zero. In 6D phase space, it forms a flat 3D sheet.

Then gravity began to pull matter towards any slightly denser patches. Viewed in phase space, movement means that the 3D matter sheet bends out into the dimensions of motion. As these movements become more pronounced, the sheet twists around and overlaps itself – a bit like a fold.

More folds mean higher density as more matter is overlapping. Rather as when you fold a sheet of paper by hand, what tends to happen is that many-folded florets (very dense) tend to be joined up by less folded strips (less dense), with big gaps in between where the matter sheet is still flat (least dense). The result looks much like the large-scale structure of the universe today, where dense galaxy clusters are joined by filaments into a network of matter, with voids in between.

Origami isn’t exactly the same as the real universe, of course. Paper can’t stretch, while gas and dark matter can. But the idea captures a lot of the essential physics, while being much simpler than the gargantuan simulations required to model galaxy formation. A couple of years on from those first folds, the approach is now promising dividends.

> “Origami captures a lot of the essential physics of galaxy formation”

“Finally we’re getting to the point where origami mathematics should directly help in comparing theory to observations of galaxies,” says Neyrinck.

For one thing, it could help map dark matter. Dark matter far outweighs the ordinary stuff of interstellar gas, dust, stars and us. Being invisible, however, it is only known through its gravitational influences, such as the way it bends the light reaching us from distant galaxies, slightly distorting our view of them.

We can use this “weak lensing” effect to trace dark matter, but the method ›

In the origami universe, galaxies and galaxy clusters form where the density of folds is greatest

Connecting folds represent the filaments of matter that connect galaxies and clusters

Unfolded areas equate to the voids between galaxies

DAVE STOCK

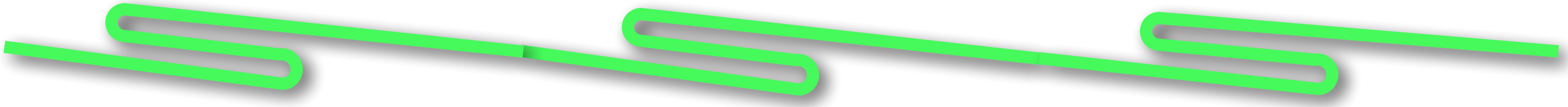
Origami mathematics:
Helps in art, engineering, biology.
Can it help to understand structure formation?
Let's see …

Dr. Robert J. Lang

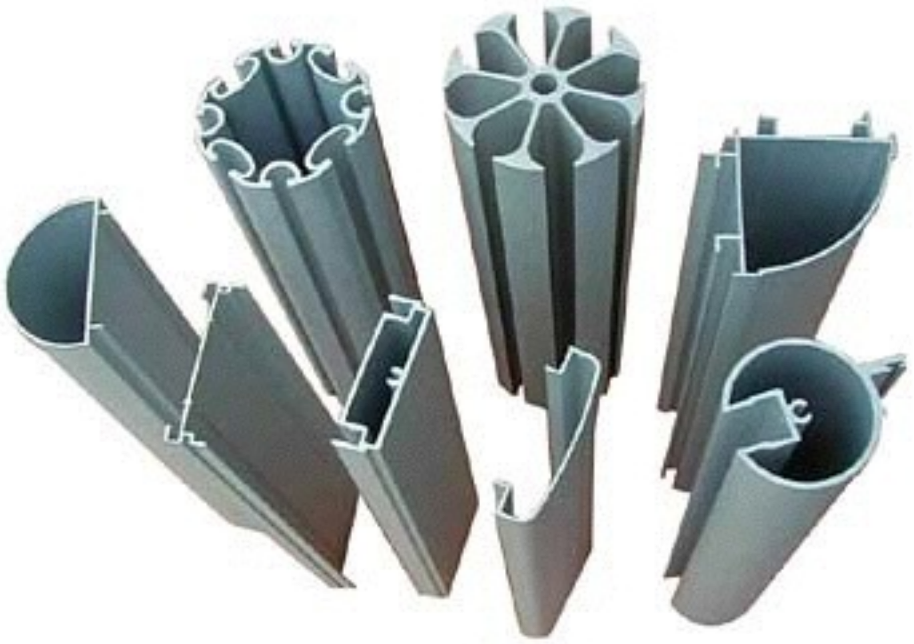
Mark Neyrinck, JHU

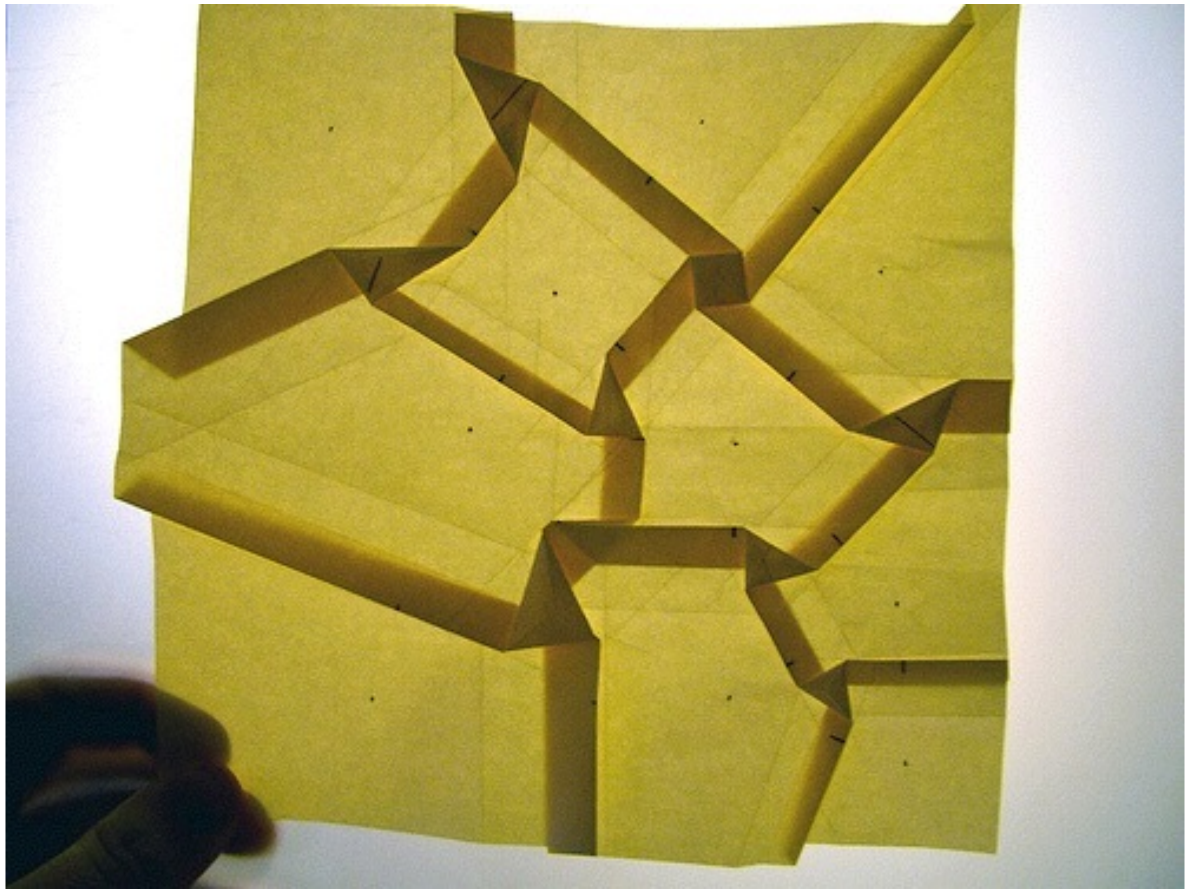
Origami approximation to large-scale structure

- 1D cosmic web:



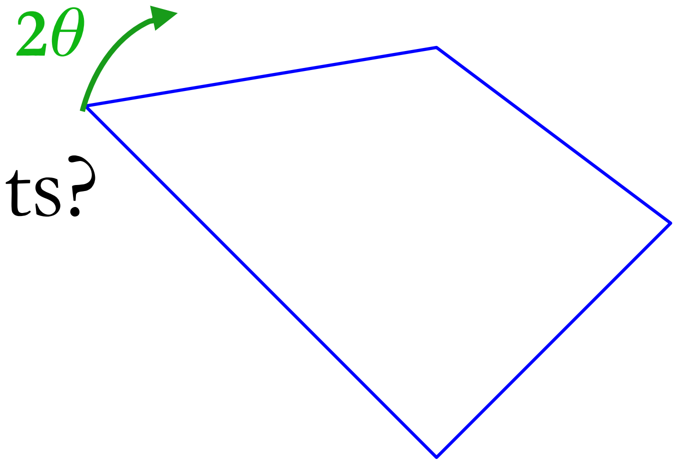
- creases = reflections
- 1D: Nodes form between "void centers." Squashed pile of string
- 2D: Extrude — make sure single-stream/layer regions don't rotate
  - 2D voids from 1D voids
  - 2D filaments from 1D nodes
  - 2D nodes new (can twist!)

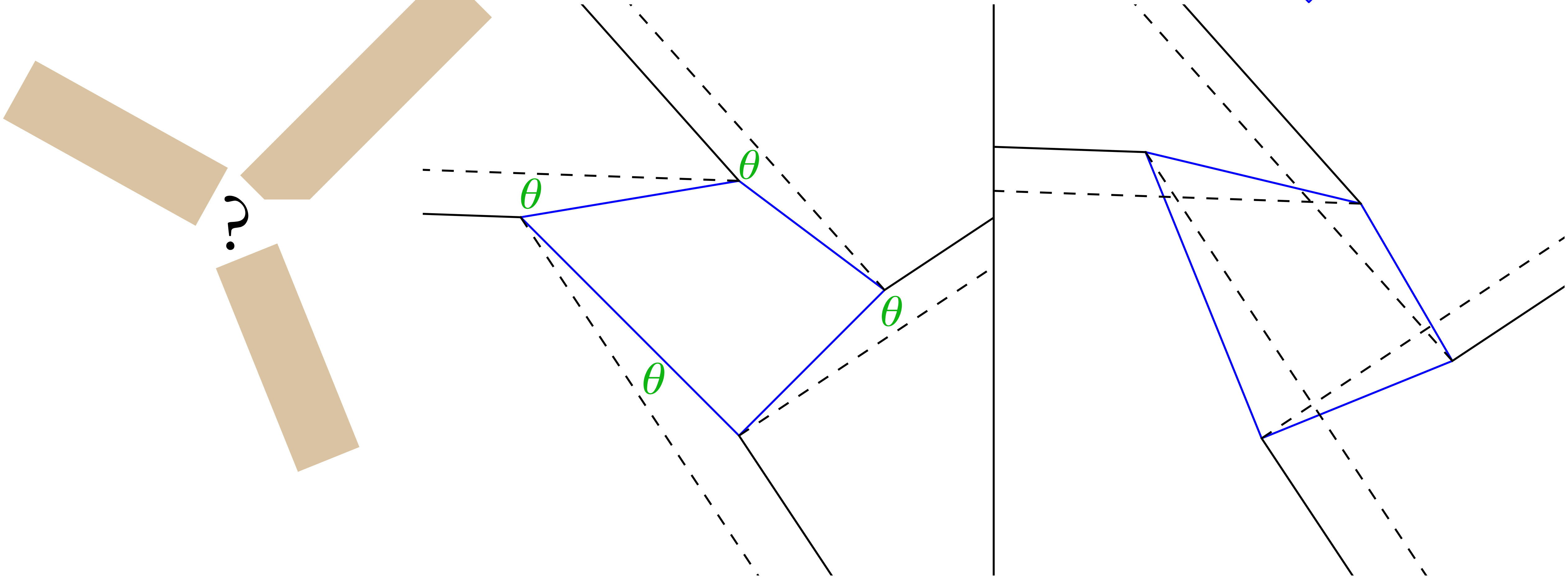




Cosmological Origami

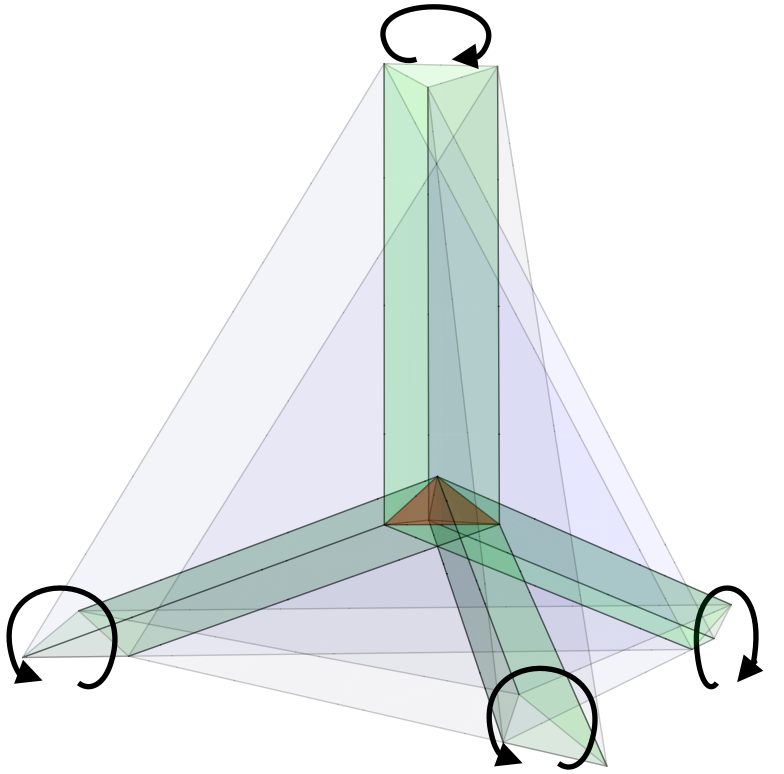
- Filaments that form together
  - In (?), >1 reflection → *rotation*
  - Called a “twist fold” by origamists
  - “Triangular collapse” by cosmologists?



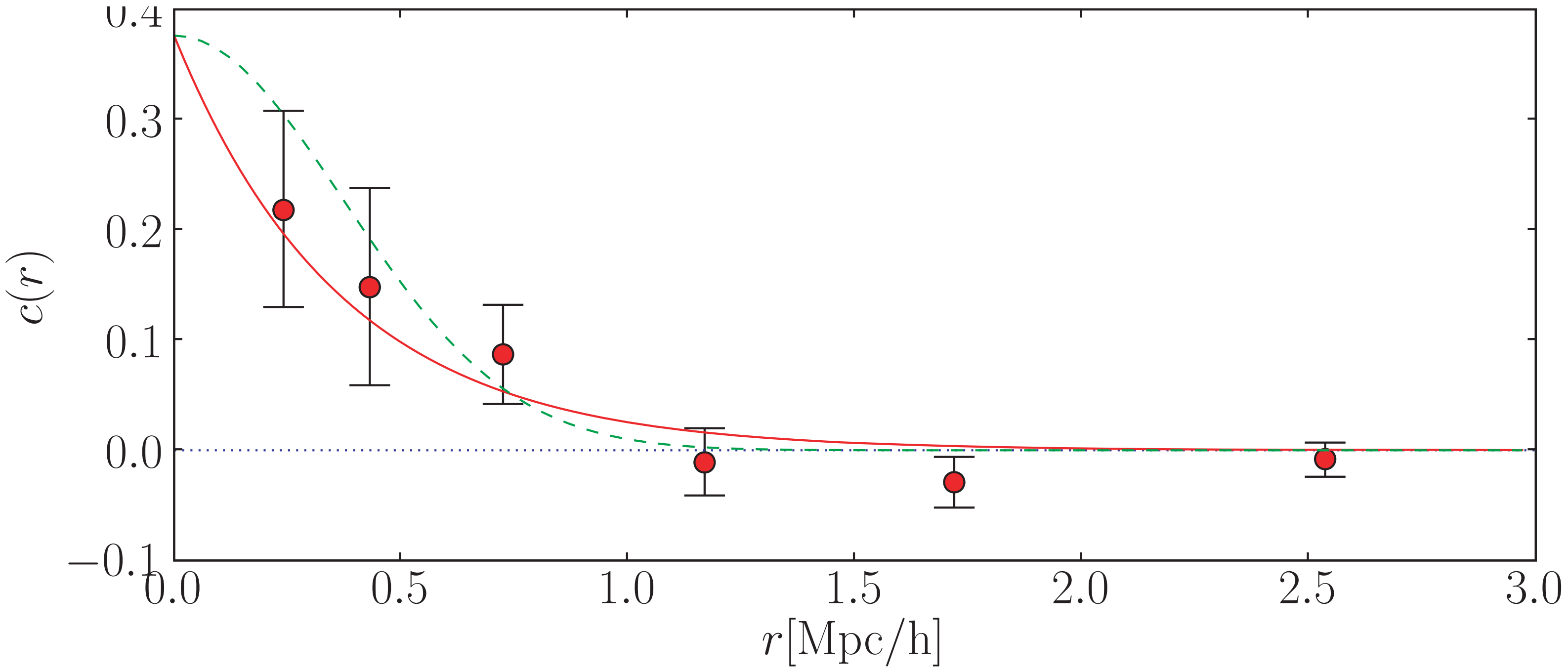


Mark Neyrinck, JHU

Tetrahedral Twist Folds/Tetrahedral collapse

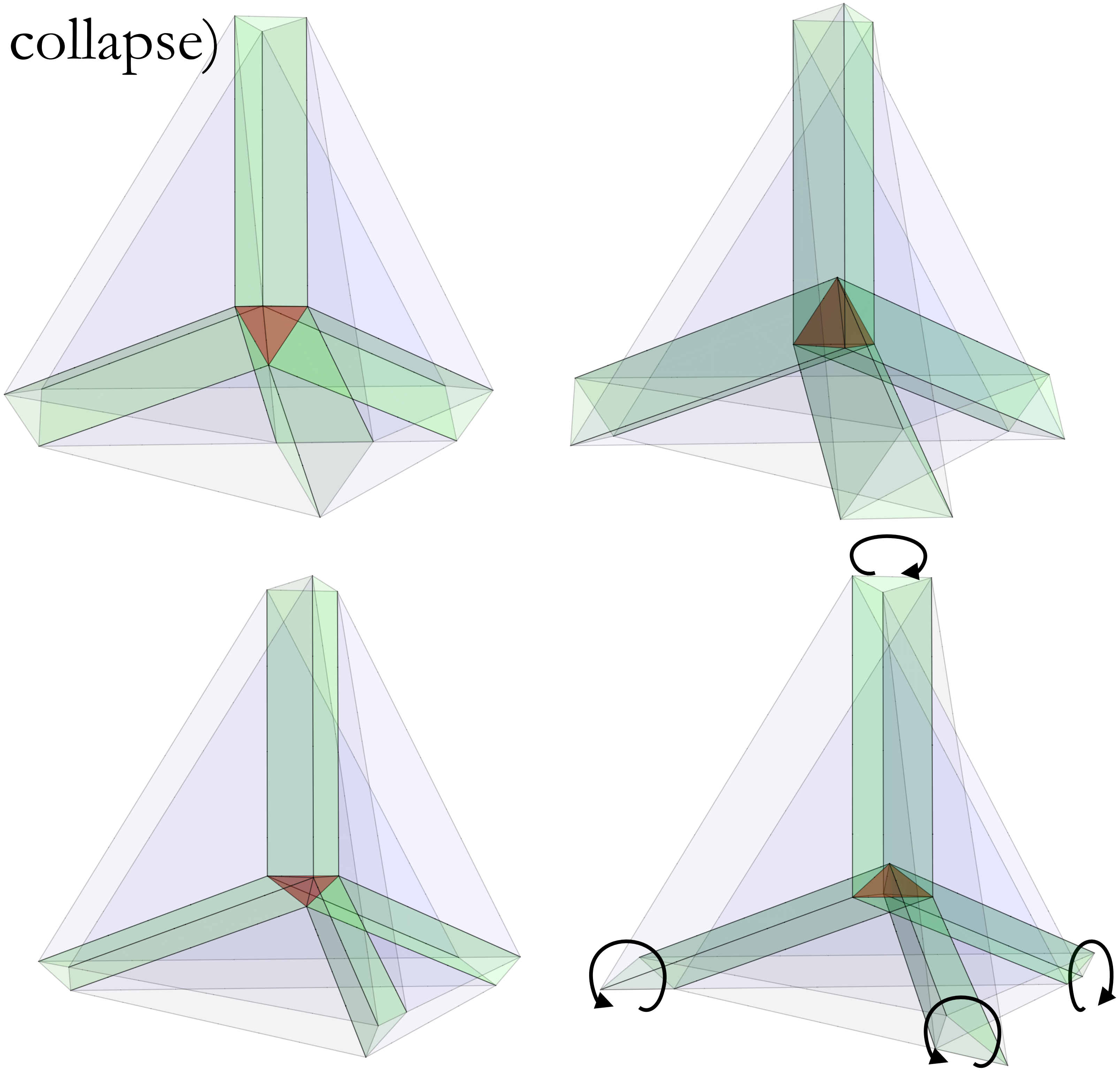


Unless the central node has no rotation, filaments will twist, giving a correlation between adjacent halo spins



Chirality correlation observed in SDSS (Slosar et al. 2008)

Tetrahedral Twist Fold



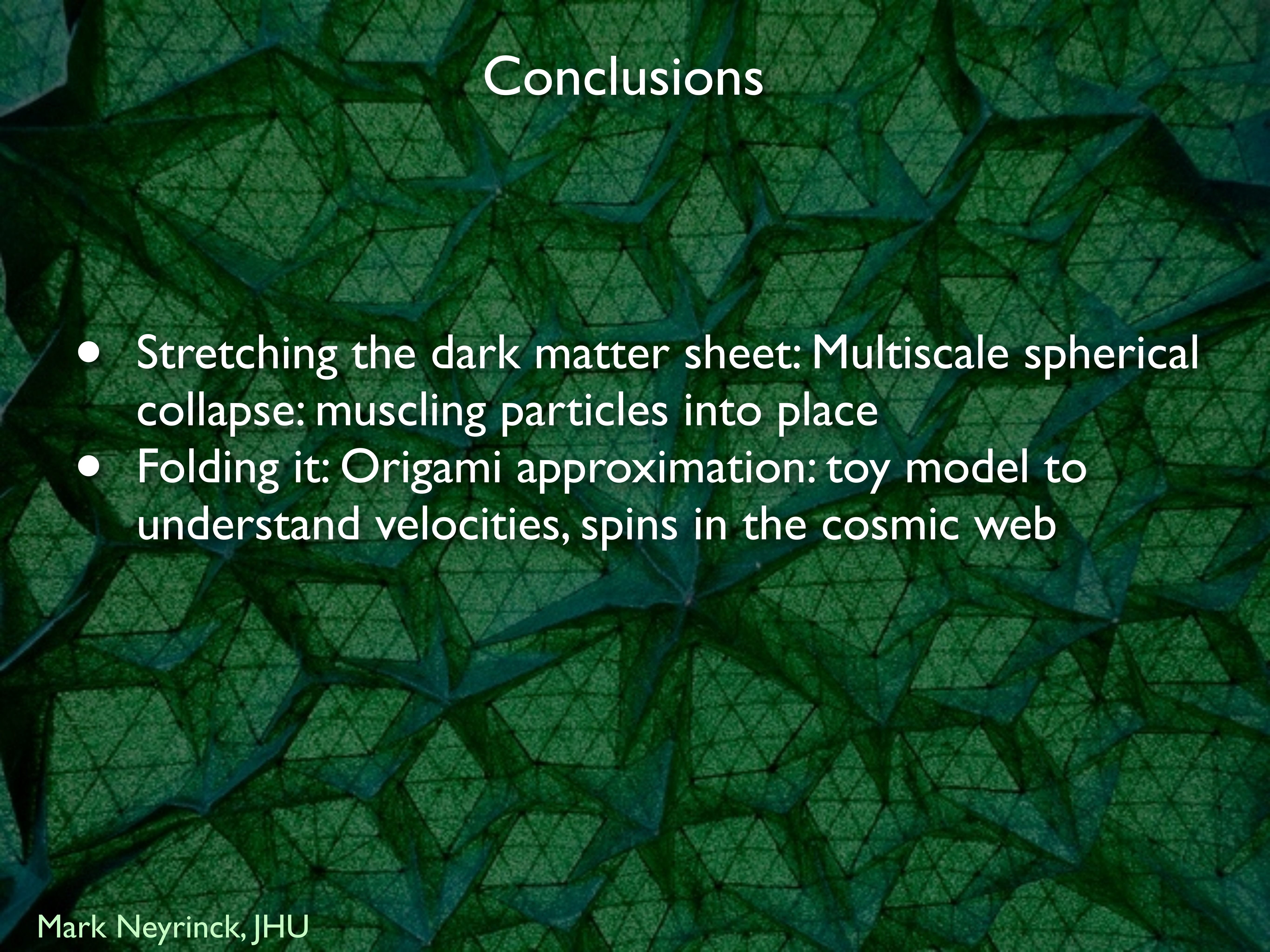
Irrotational (~ spherical collapse)

Rotational

Before folding

After folding

Conclusions



- Stretching the dark matter sheet: Multiscale spherical collapse: muscling particles into place
- Folding it: Origami approximation: toy model to understand velocities, spins in the cosmic web