Origami constraints on structure formation

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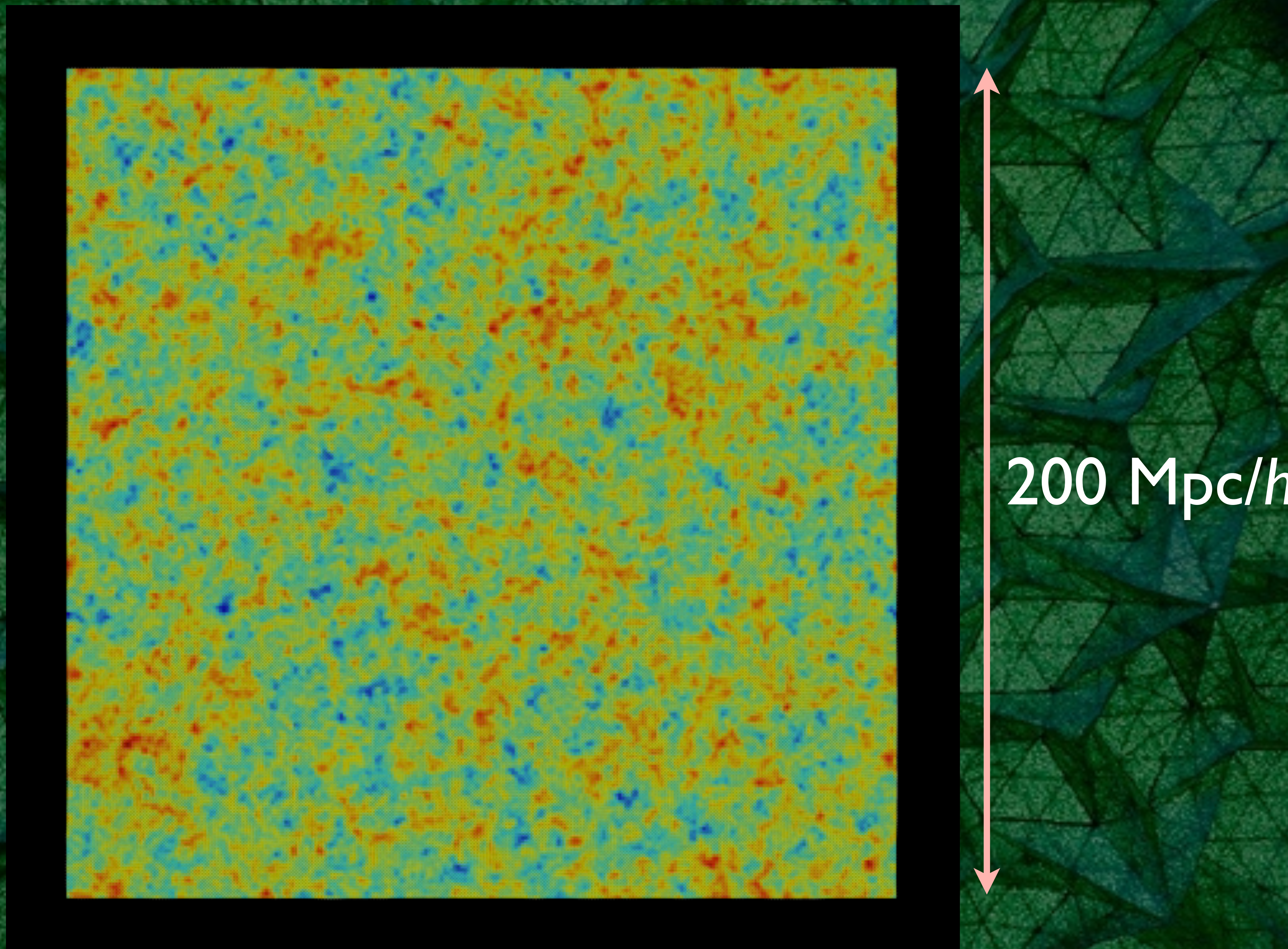
Information, printed on the spatial "sheet," tells it where to fold and form structures.



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A true Zel'dovich Universe …

Publicly available code for e.g. outreach: Google "Fold Your Own Universe"

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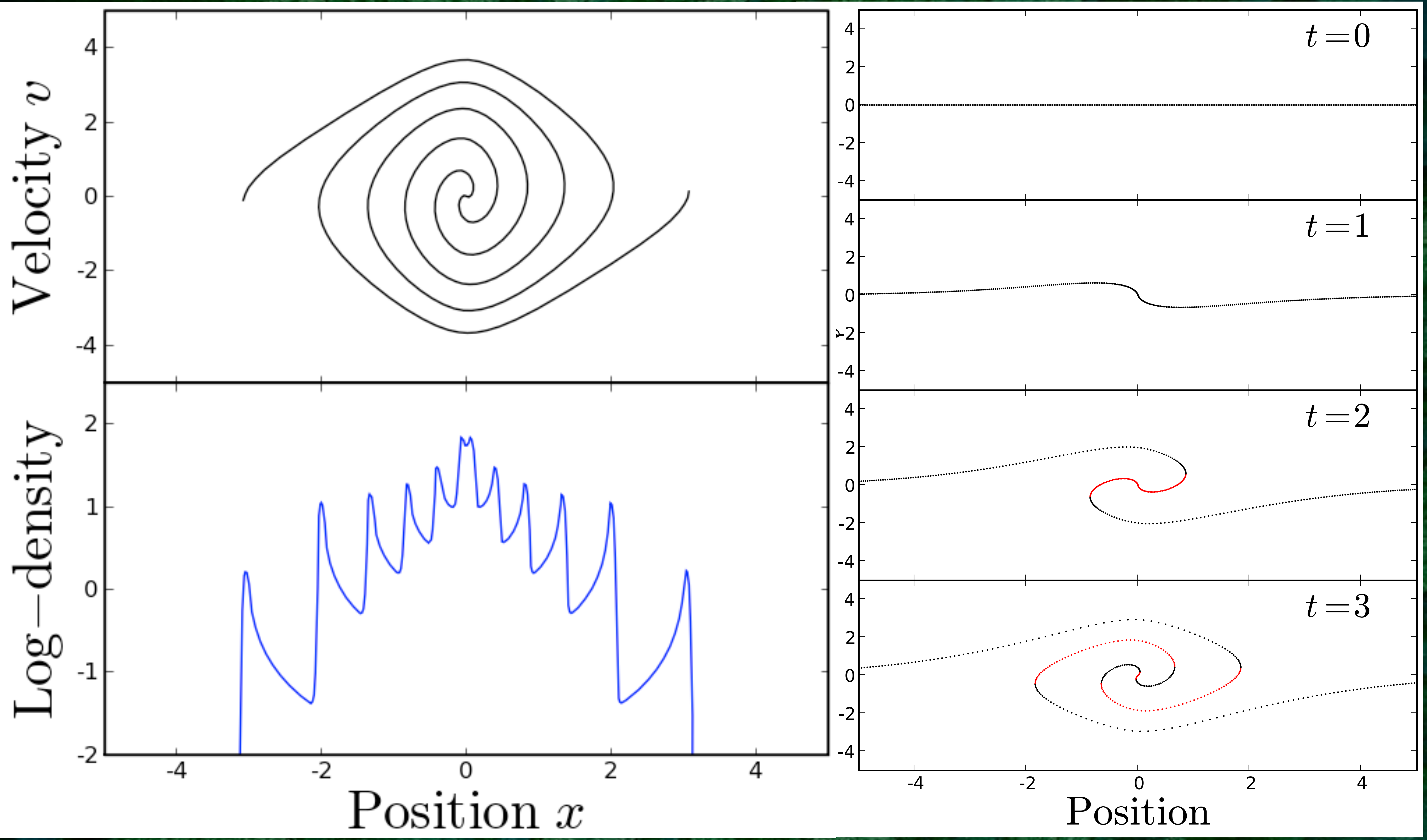
Why "folding?" In phase space ...

(e.g. analytical result in Bertschinger 1985)



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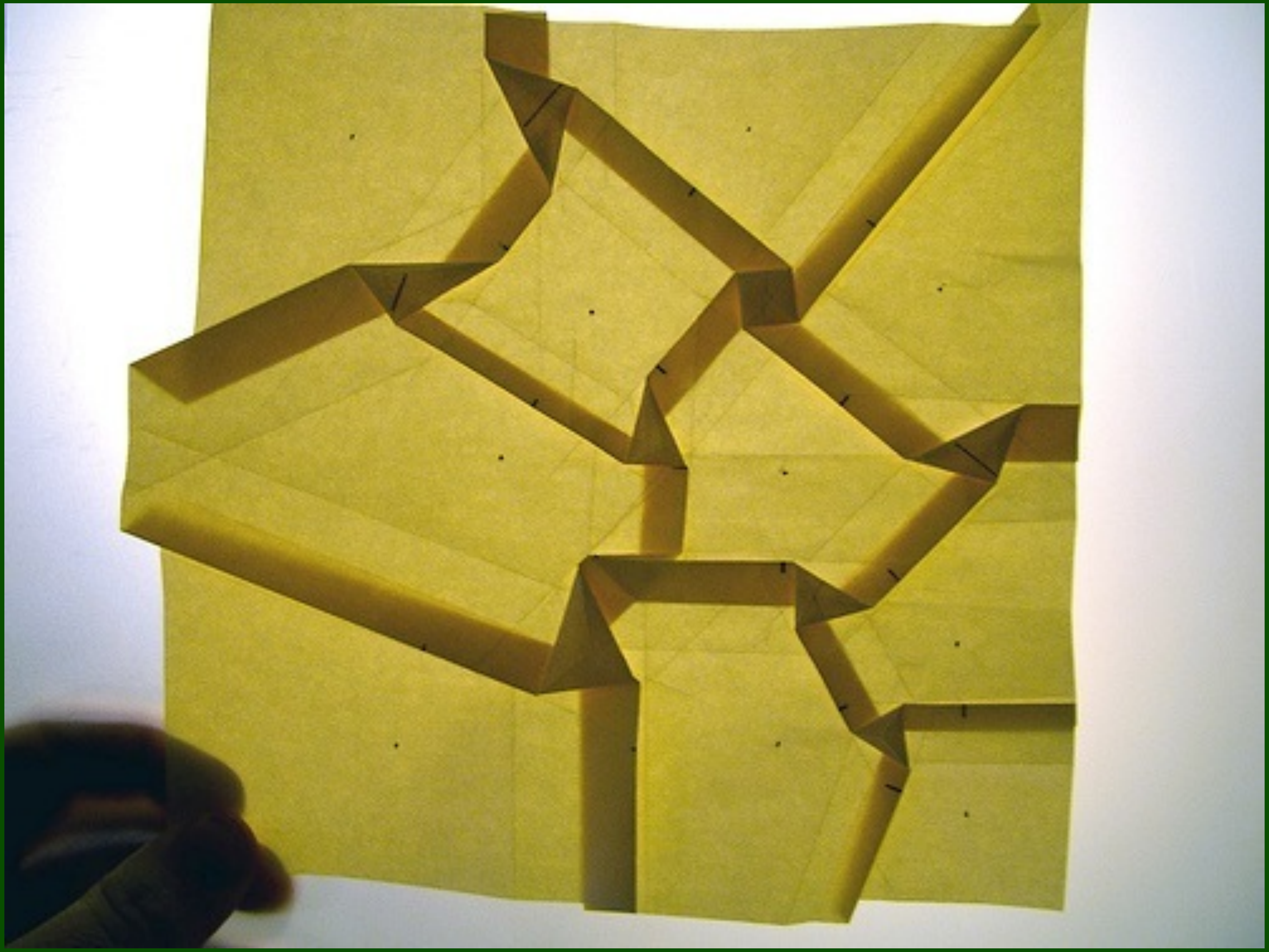
Rough analogy to origami: initially flat (vanishing bulk velocity) 3D sheet folds in 6D phase space.

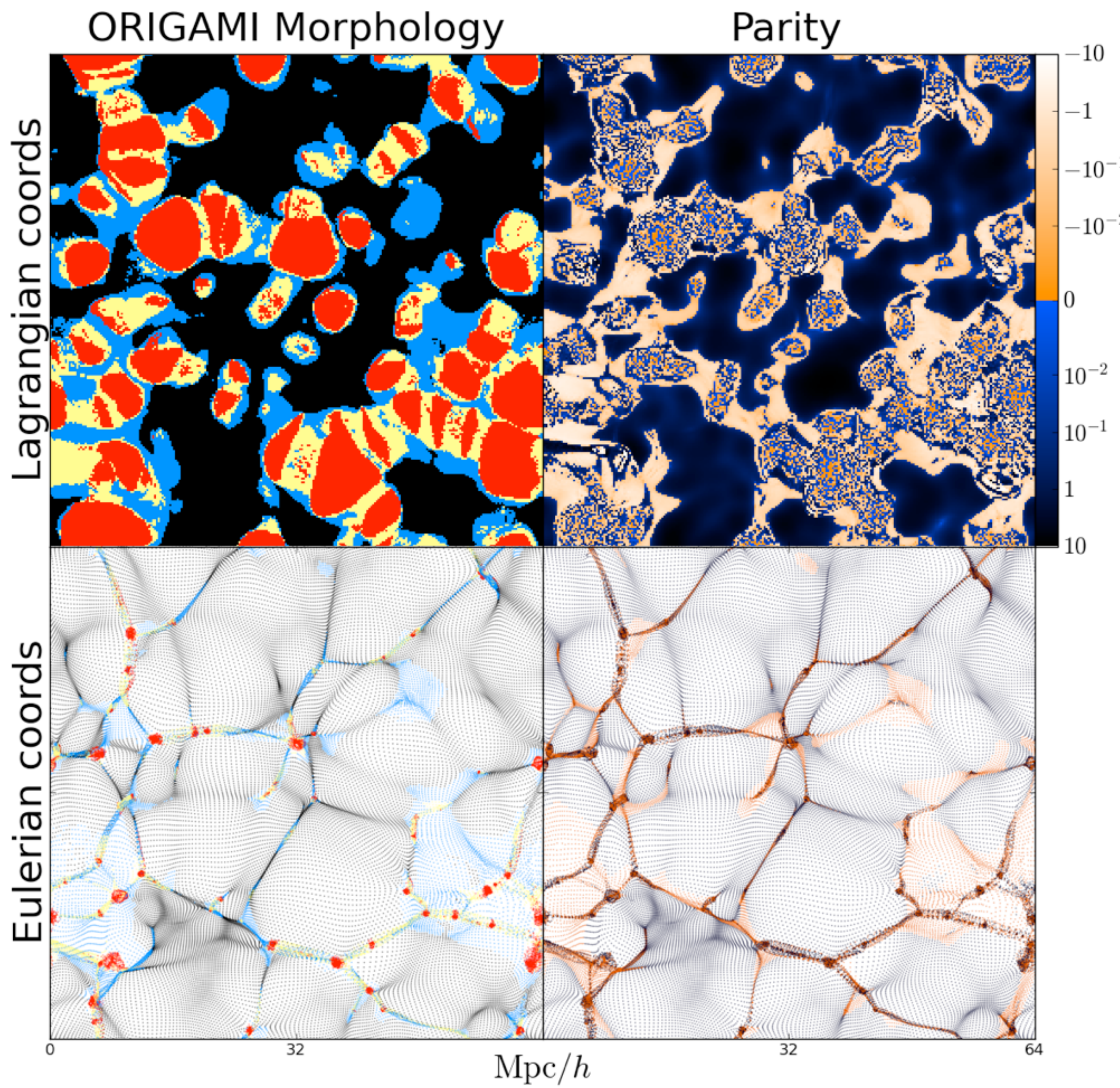
- The powerful Lagrangian picture of structure formation: follow mass elements. Particles are vertices on a moving mesh.

- Note: this is only dark matter! Baryonic matter, gas collides in filaments, nodes.



Eric Gjerde, origamitessellations.com

The Universe's crease pattern



Crease pattern before folding

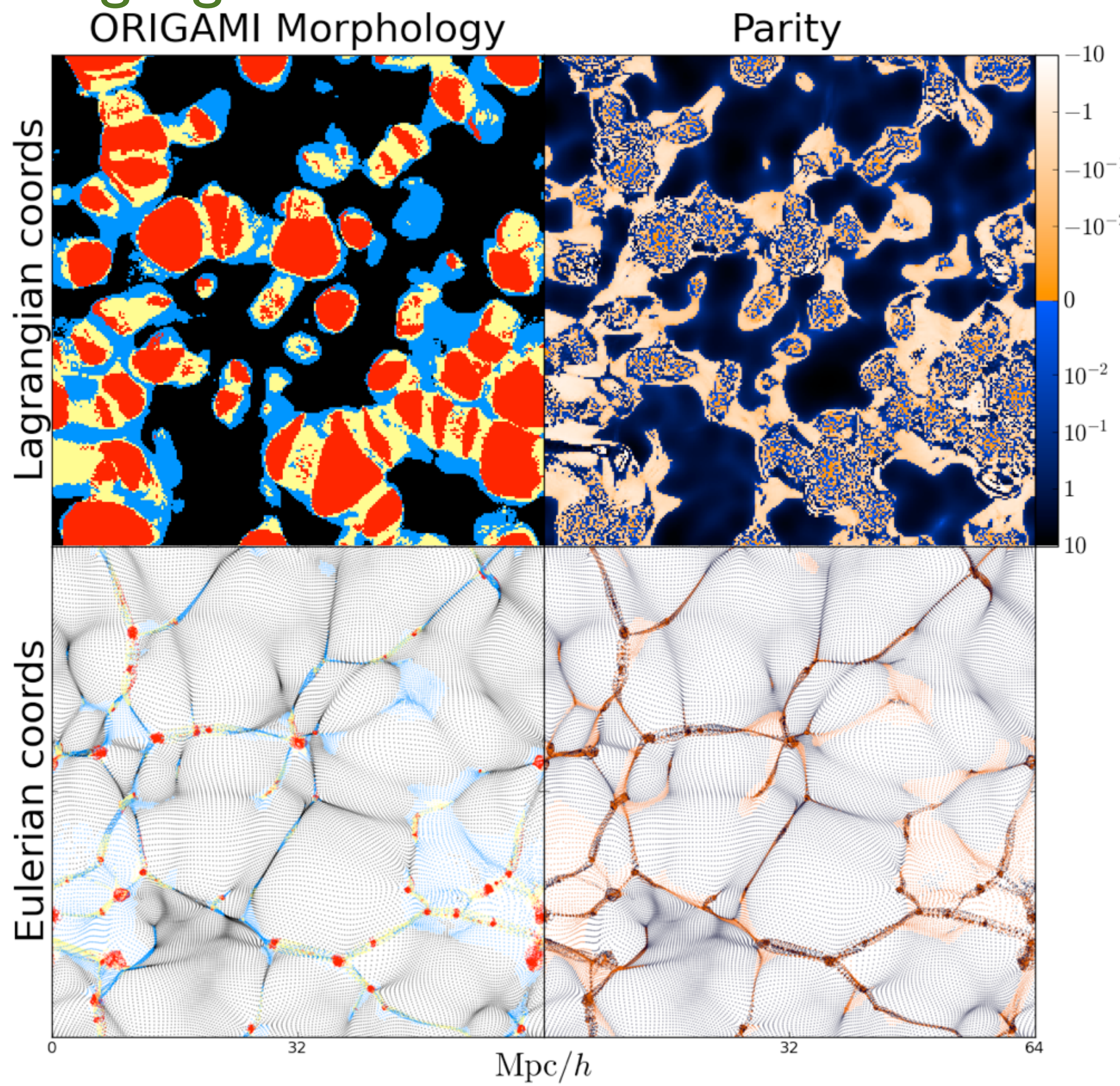
After folding

(Neyrinck 2012)

Order-Reversing Gravity Apprehended Mangling Indices

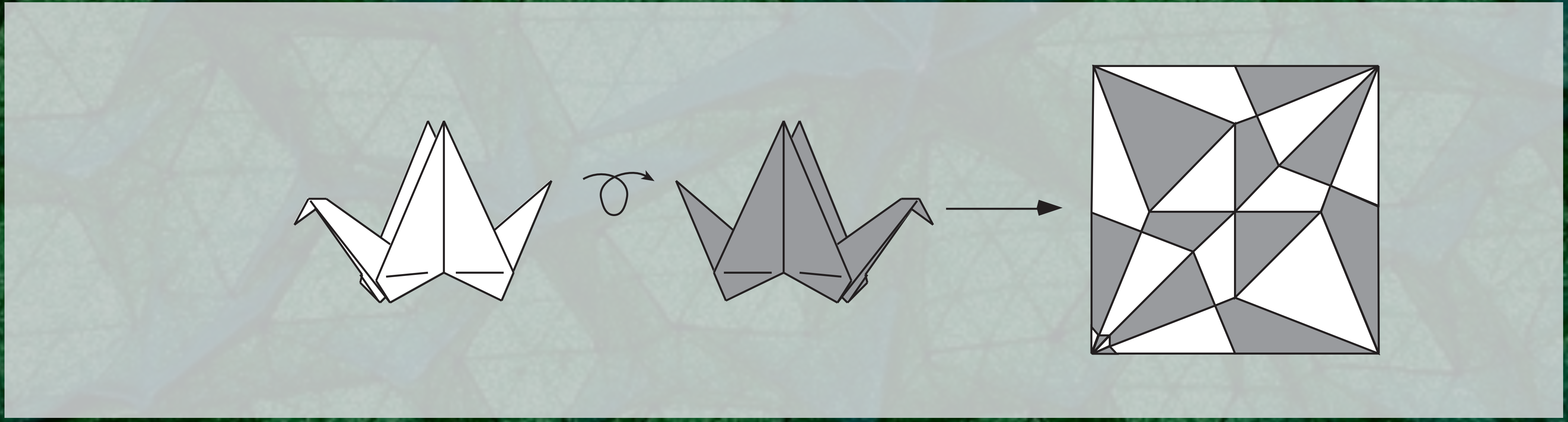
(Falck, Neyrinck & Szalay 2012)

Red=node crossing along 3 axes
Yellow=filament, 2 axes
Blue = wall, 1 axis
Black = void, 0 axes



Mathematical definition of a flat-origami design

- Restrictions on 2D crease-pattern vertices (e.g. Demaine & O'Rourke 2007)
  - Polygons on crease pattern two-colorable
  - Sums of all odd angles, and all even angles, = 180°
  - # mountain, valley folds differ by 2
  - No paper crossing, tearing
  - *No inhomogeneous stretching of the paper
    - All creases straight



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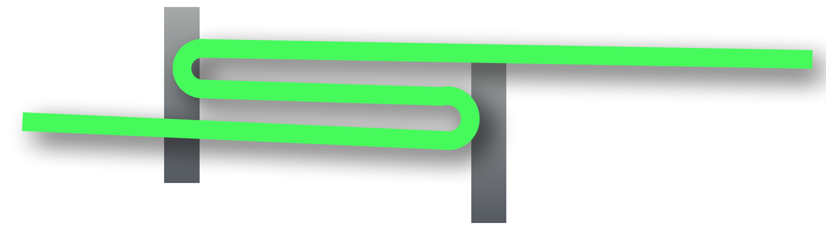
Cosmological Origami

- Streams two-colorable
- Sums of all odd angles, and all even angles, = 180°
- # mountain, valley folds differ by 2
- No paper crossing, tearing
- *No inhomogeneous stretching of the paper
  - Caustics straight in Lagrangian space
  - — not true, e.g. spherical collapse, simplest singularities

Cosmological Origami

- Caustics = reflections
- 1D: easy. A squashed pile of string in 2D



- 2D
  - Lagrangian → Eulerian mapping $x(q)$ is a piecewise-continuous isometry — can be encoded as a set of reflections
  - Basic element: filaments (segments of parallel reflections)
  - Restrict vorticity = 0 in single-stream regions
- Filaments don't just stop in a cusp — this would violate origami rules
- A full idealized cosmic web with polygonal (3D: polyhedral) voids

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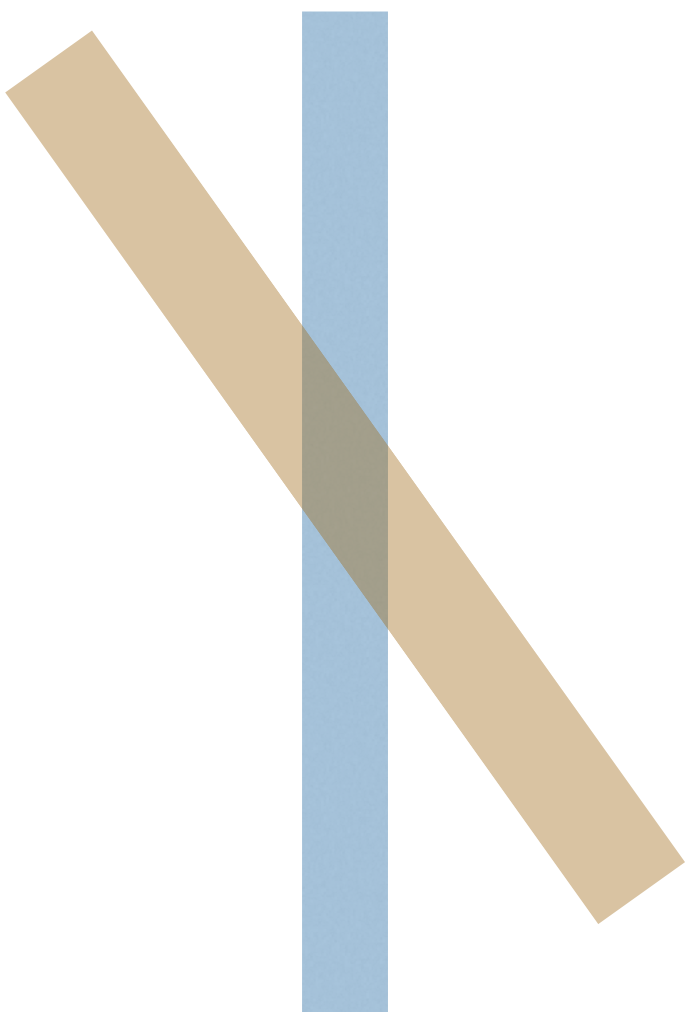
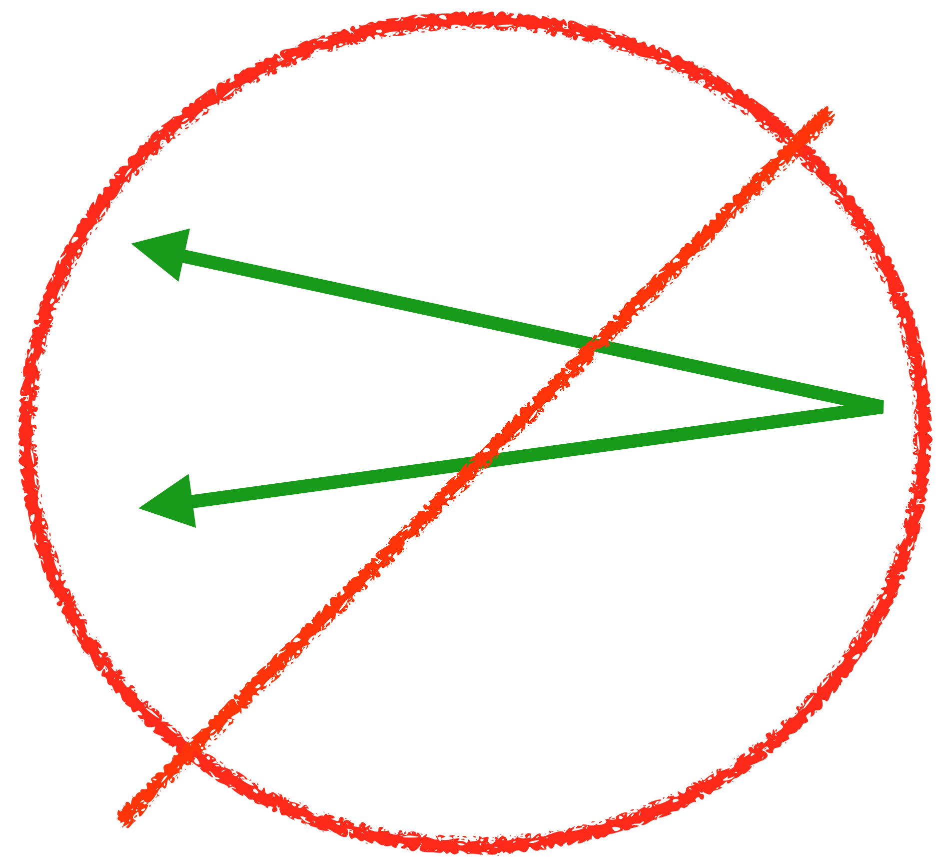
Cosmological Origami

- Two types of filament intersections:
  1. Superposition of filaments that form sequentially
  2. Anything else?

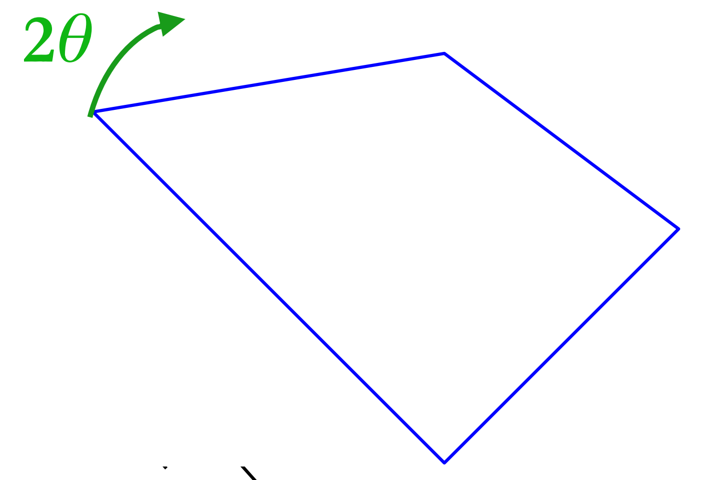
1.

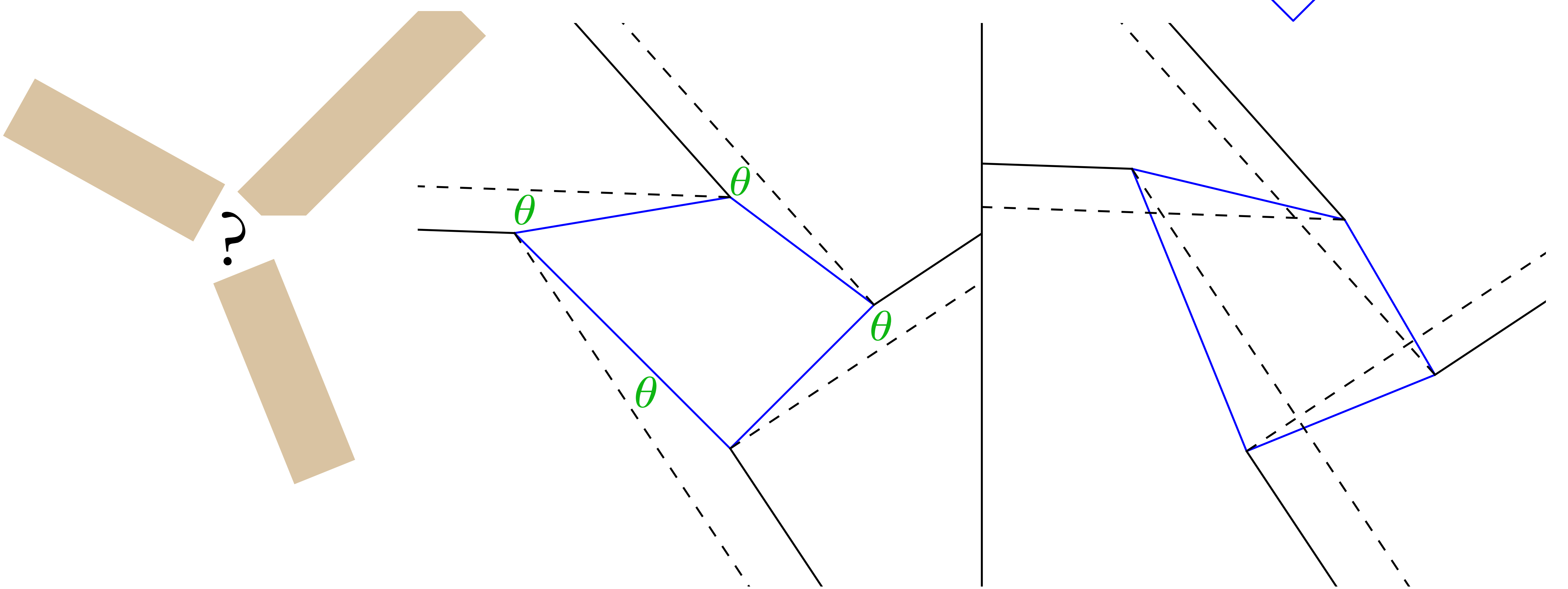




Cosmological Origami

- Two types of filament intersections:
  1. Superposition of filaments that form sequentially — filaments stay parallel
  2. Filaments that form together
     - In (?), >1 reflection → *rotation*
     - Called a "twist fold" by origamists





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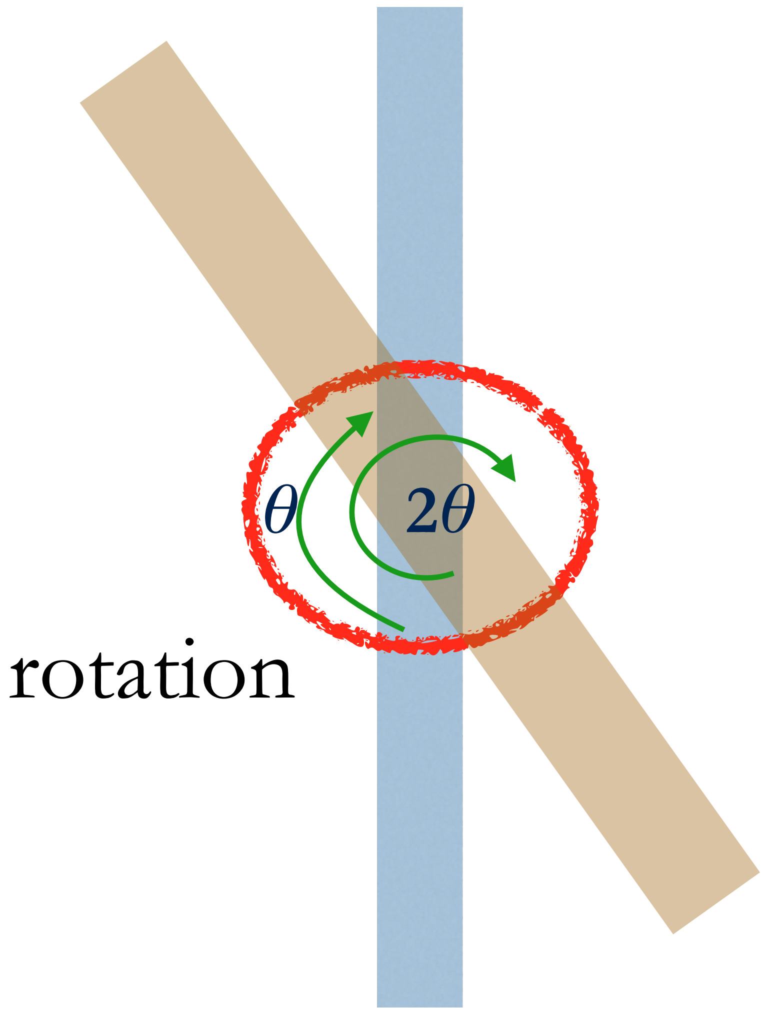
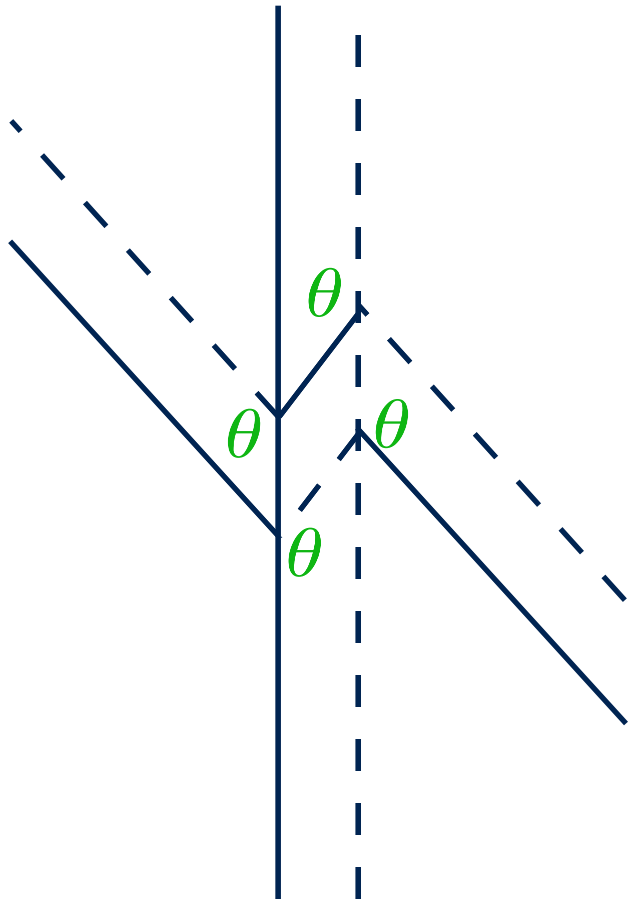
BTW The 2-filament intersection also rotates





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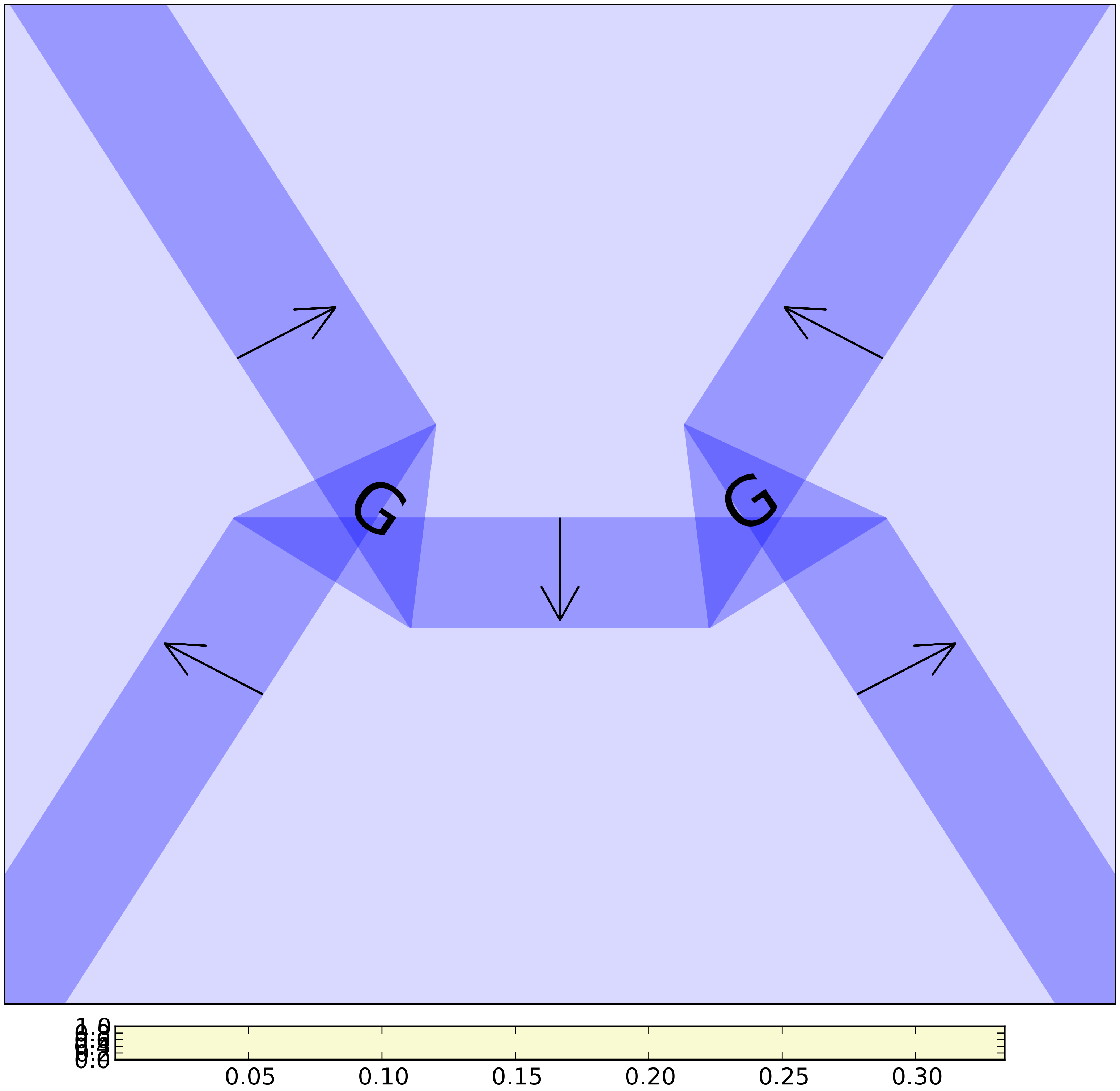
That was a static model; dynamical?



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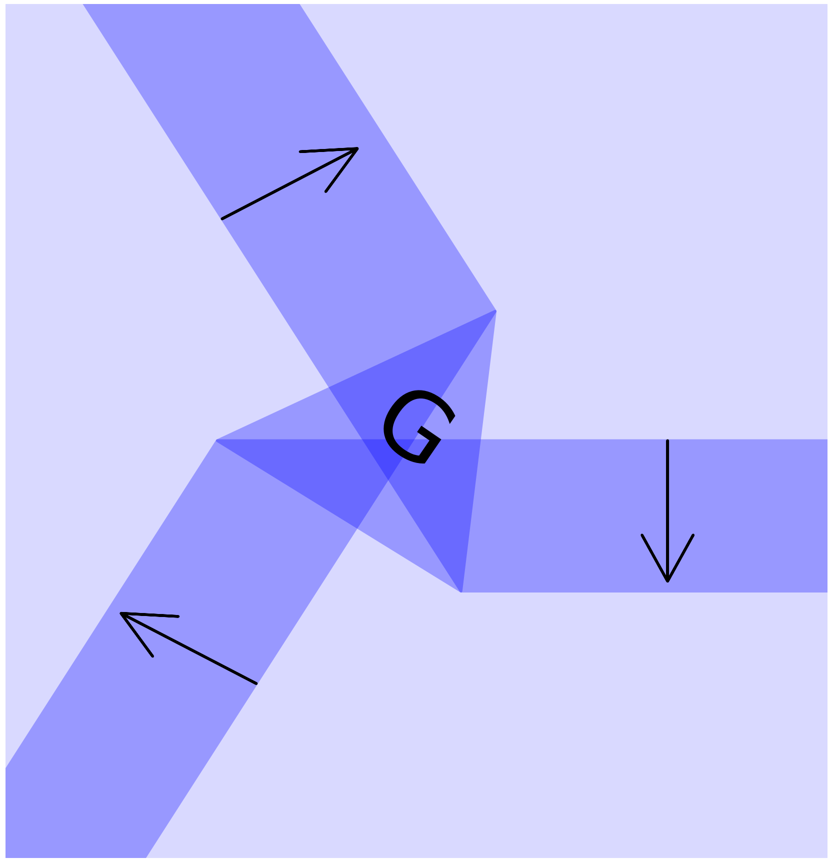
What about 3D?

- Still working on theorems constraining 3D origami!
- Progress still possible by making the mapping as before:
  - voids from 2D universe → voids
  - filaments from 2D universe → walls
  - galaxies from 2D universe → filaments
  - → galaxies



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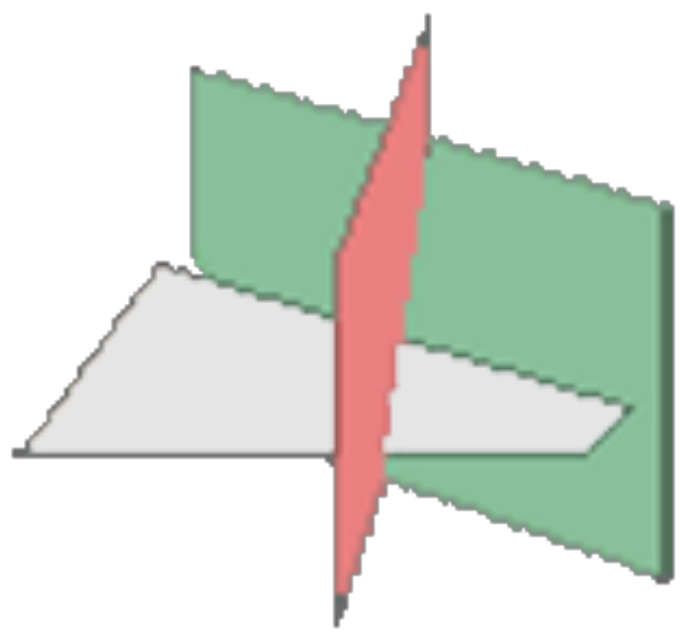
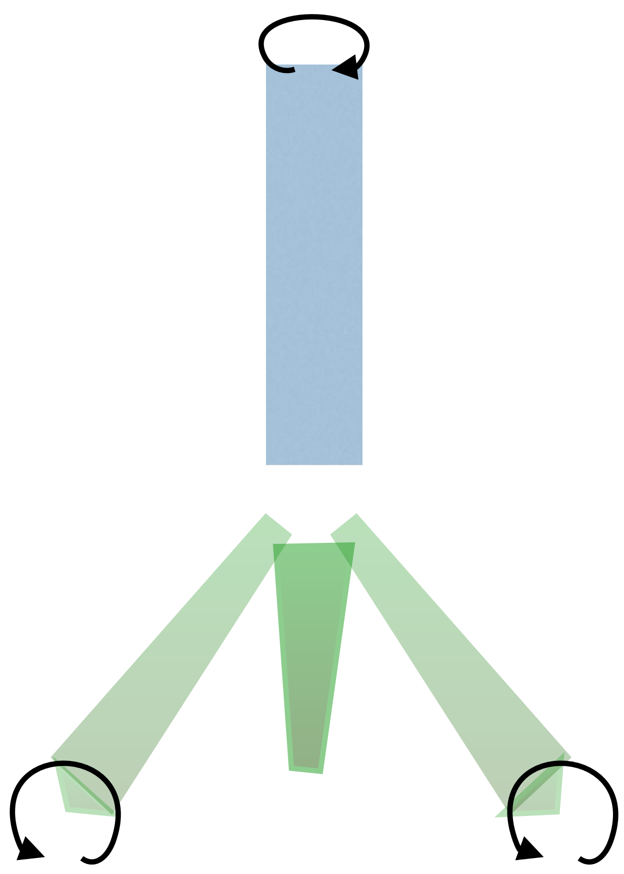
What about 3D?

- Still working on origami vertex constraints in 3D.
- Most naive example: intersection of three walls



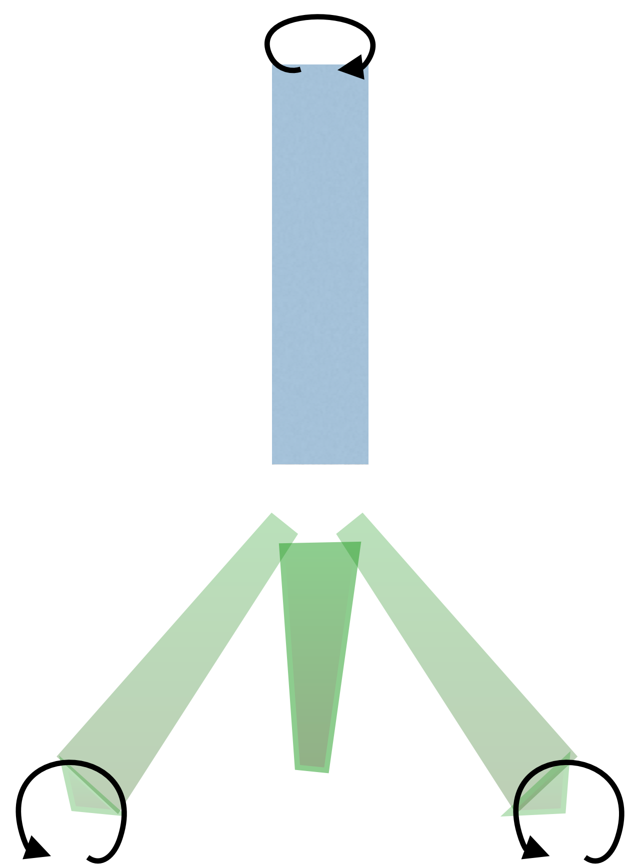
What about 3D?

- Tetrahedral "twist fold"
- Filaments: triangular tubes (2D "galaxies")
- Most naive, regular tetrahedron: no perfectly symmetric twist folds.
- Sum of angular momenta in filaments, $\Sigma\lambda_i\theta_i = 0$
- e.g. 1 big filament that spins one way, 3 smaller filaments that spin oppositely



What about 3D?

- Future work: possible to predict galaxy/filament spins by assigning masses to filaments in a network?



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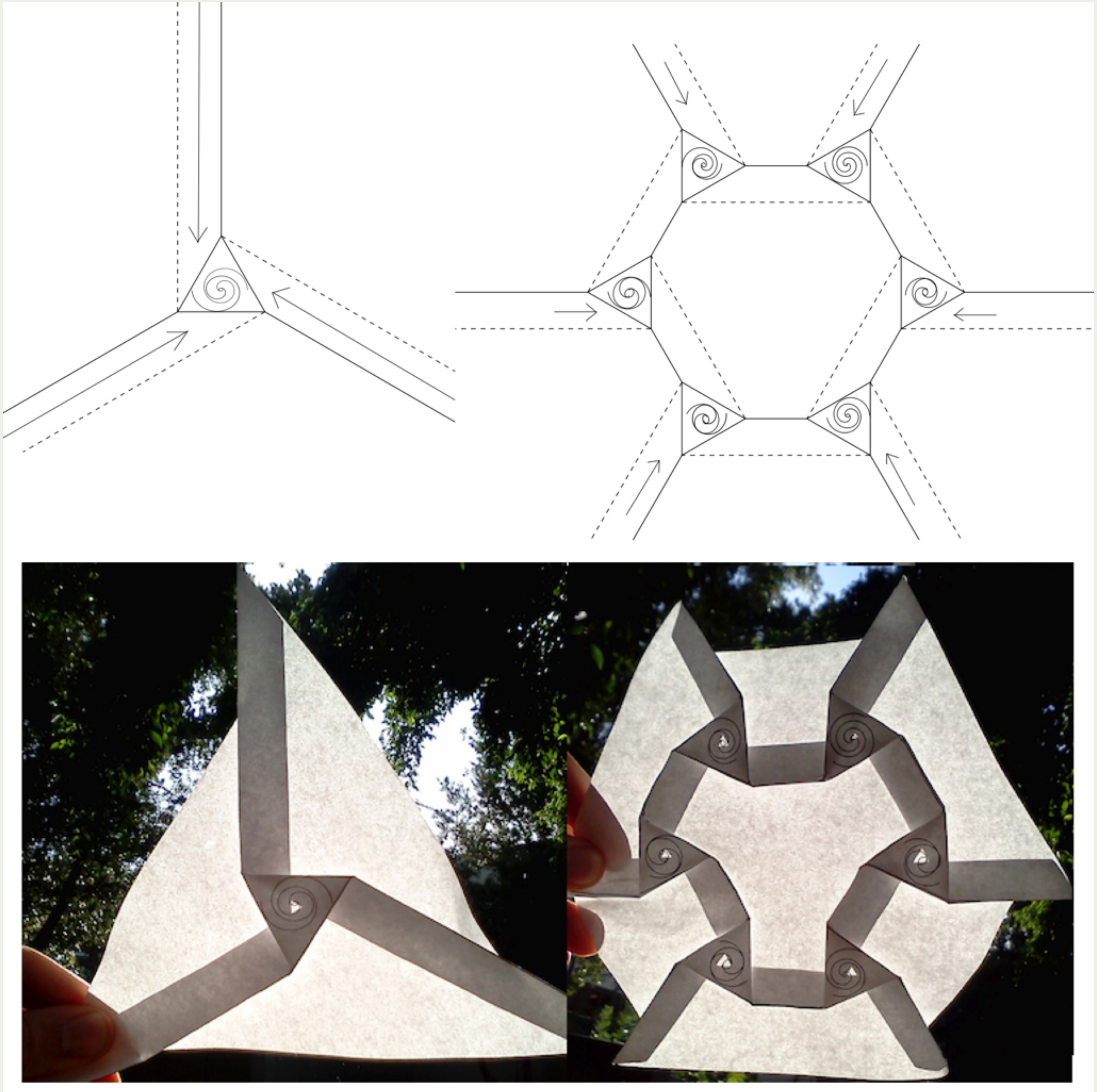
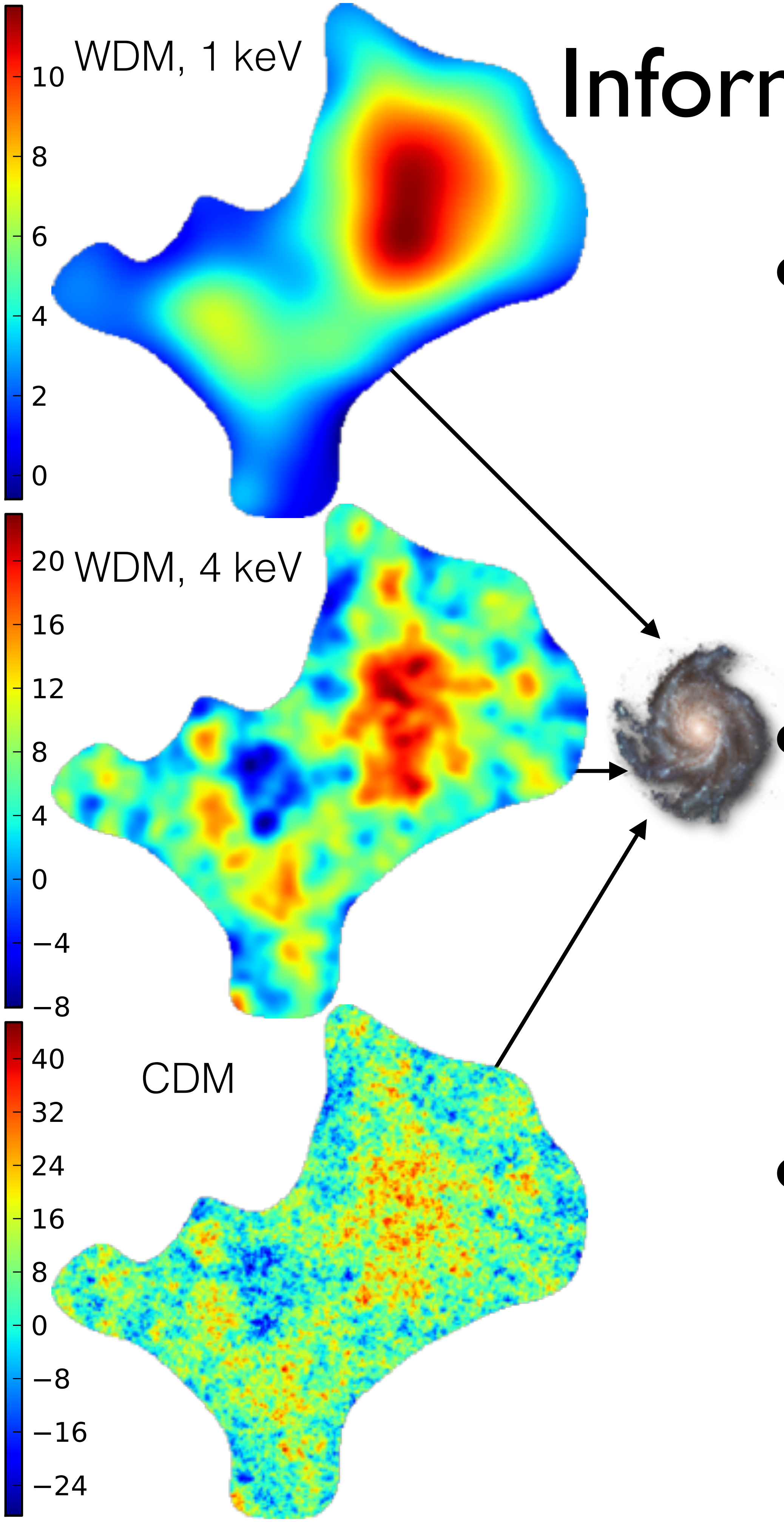
Crease patterns available at
http://skysrv.pha.jhu.edu/~neyrinck/origalaxies.html



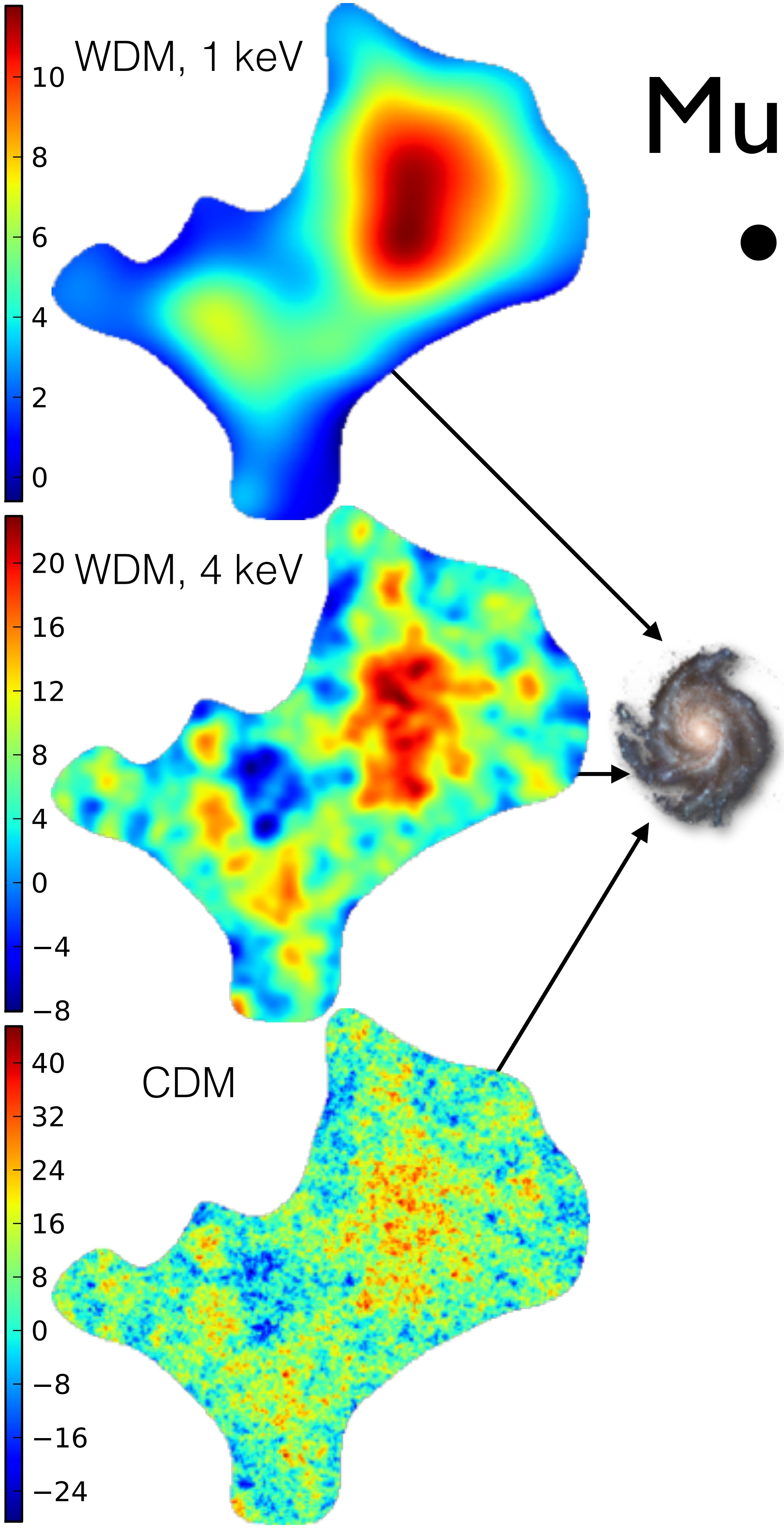
Information and warm dark matter



- Suppose the dark matter were warm (WDM). Then the smallest fluctuations would have been smoothed at a scale α by free-streaming, from thermal motions.
- Reduces primordial (Kolmogorov) information content in the universe, by a huge factor. This goes into "entropy"

$$I_{WDM}/I_{CDM} \sim (\alpha_{WDM}/\alpha_{CDM})^{-3} \sim 10^{18}$$

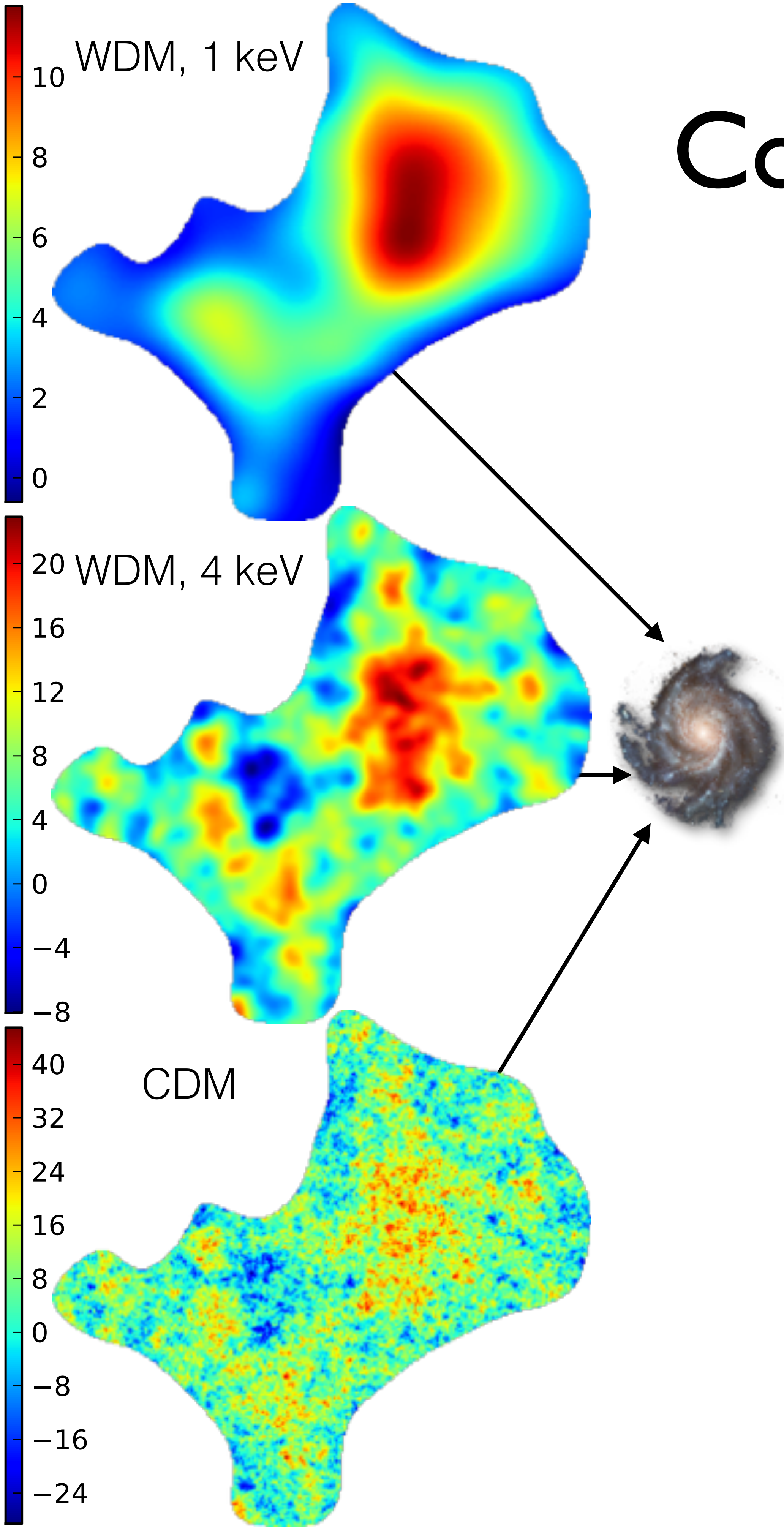
- 1 keV ⇒ only ~ 2000^3 "pixels" in the Milky Way



Much more structure in CDM

- In a WDM scenario, how could the intricate structure in the Milky Way arise?
  - Possibility 1: fragmentation, star formation, etc., determined in a complicated way by initial conditions, like an apparently complex fractal with underlying simplicity
  - Possibility 2: non-primordial information: jets from black hole accretion disks?

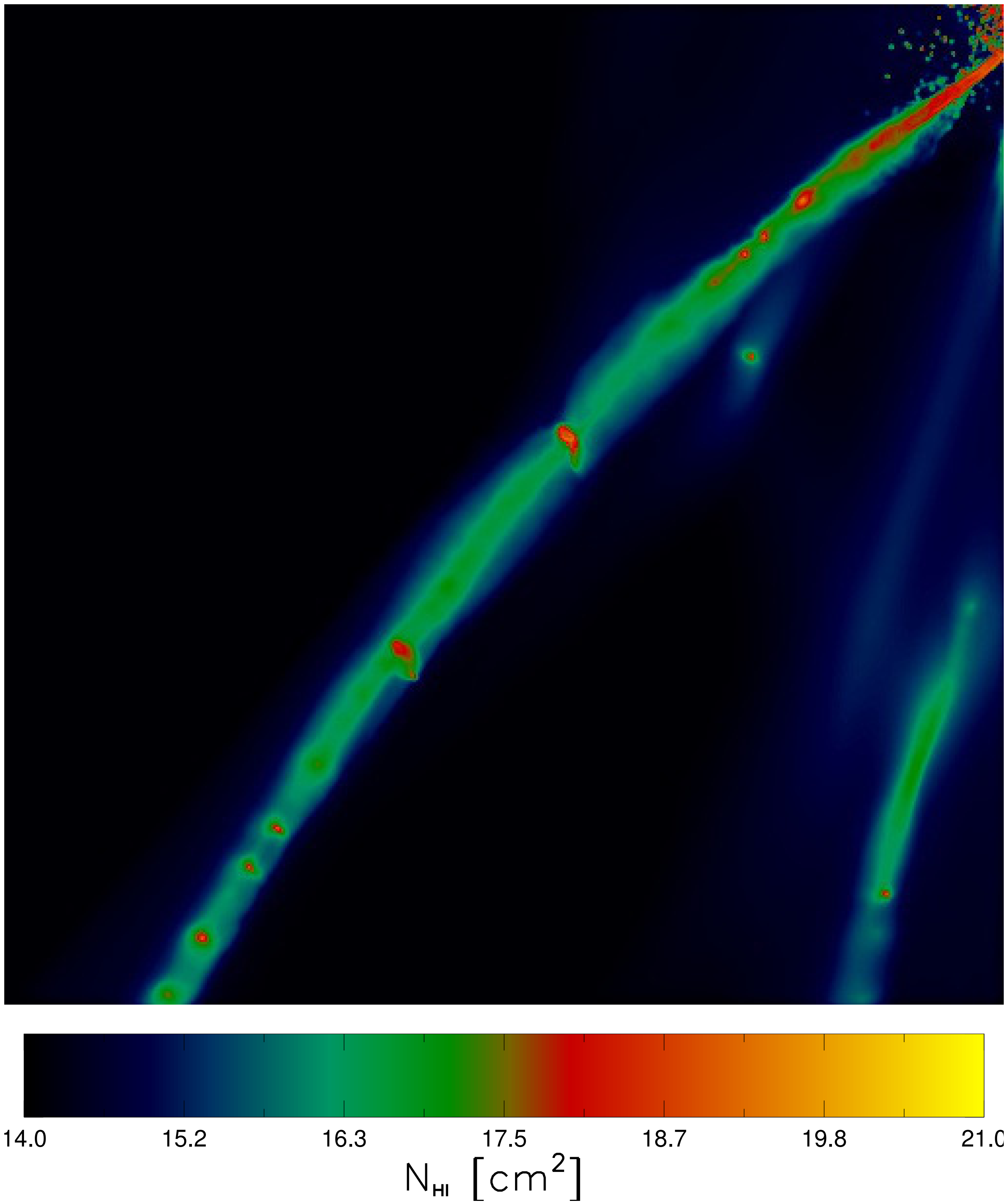
Consequences if WDM were proven:



- Possibility 1 (deterministic galaxy formation) smaller set of possible Milky Ways than usually thought? (still $2^{\# \text{ bits}}$, very large)
- Possibility 2: the Galaxy is not as deterministic as many of us assume

Milky Way in hydrodynamic simulations

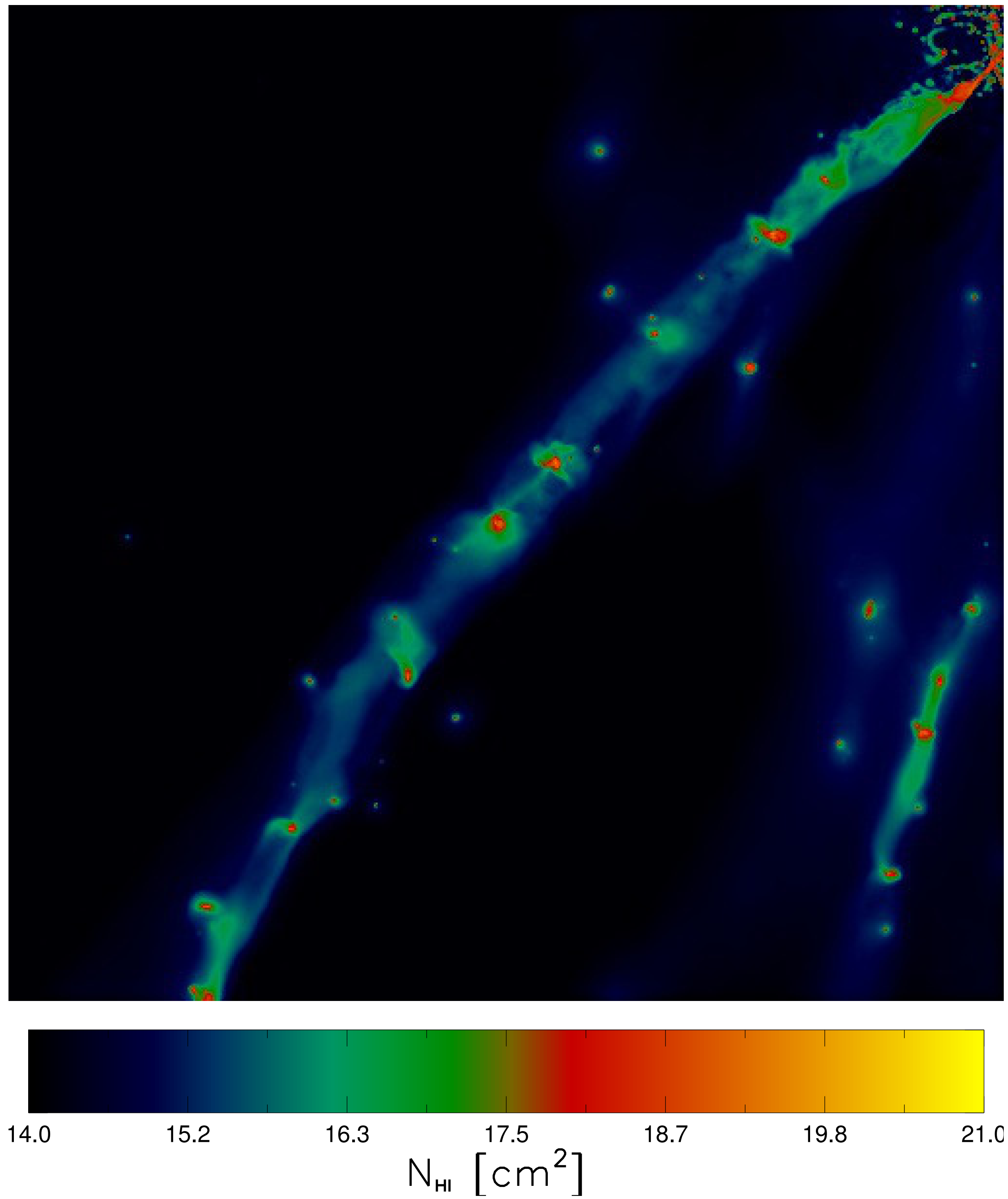
z = 2.5
WDM



(Gao, Theuns & Springel 2014)

Milky Way in hydrodynamic simulations

z = 2.5
CDM



(Gao, Theuns & Springel 2014)

Summary

- An incompressible, collisionless origami approximation gives some constraints on structure formation — remains to test against simulations
- Goal: clarify connection between filament, galaxy rotation and cosmic web

- Low primordial information in WDM scenario