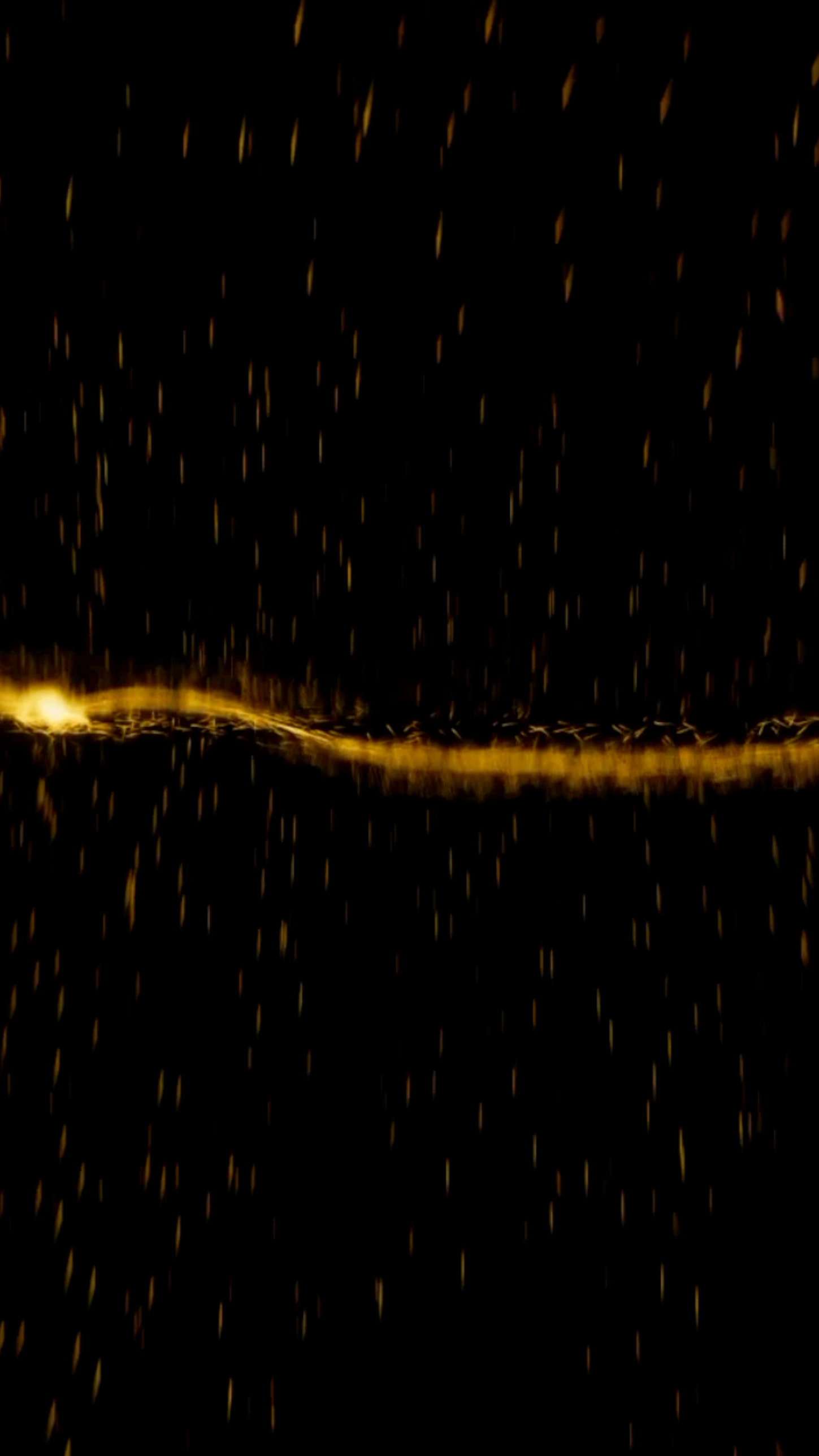
Swirls, Information and Eddies, Cosmic and Chaotic

3 02 2023

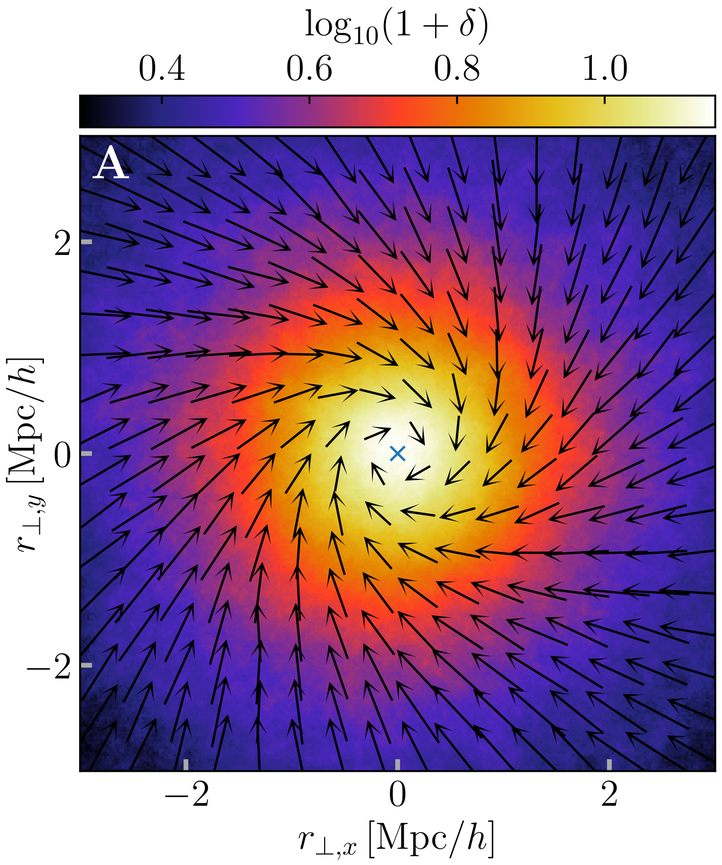
Mark Neyrinck

Visualization: Kähler Hahn & Abel

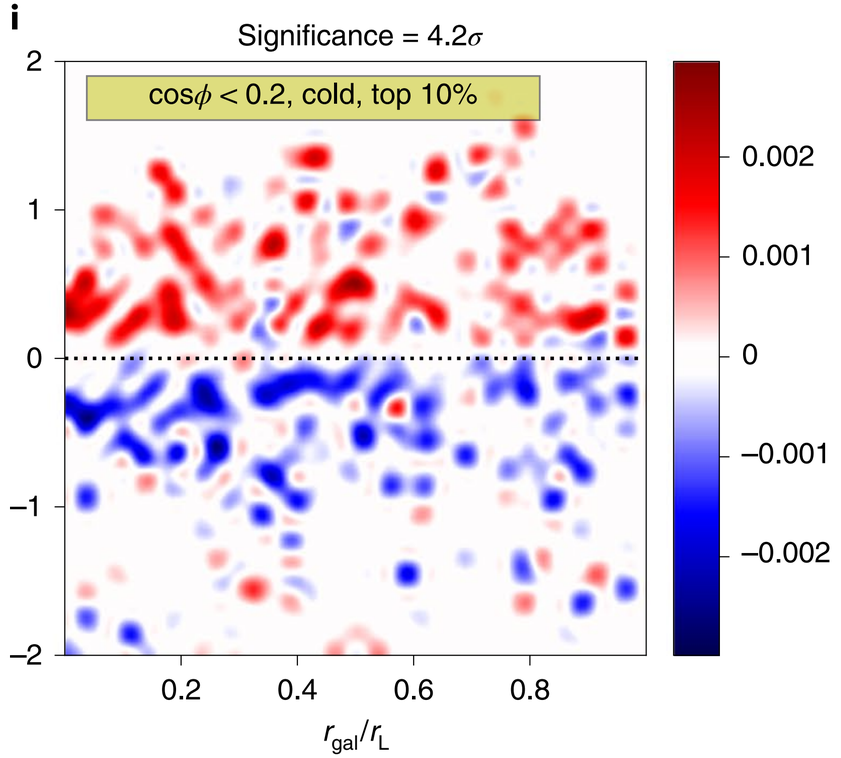

Swirls,
Information and Eddies,
Cosmic and Chaotic

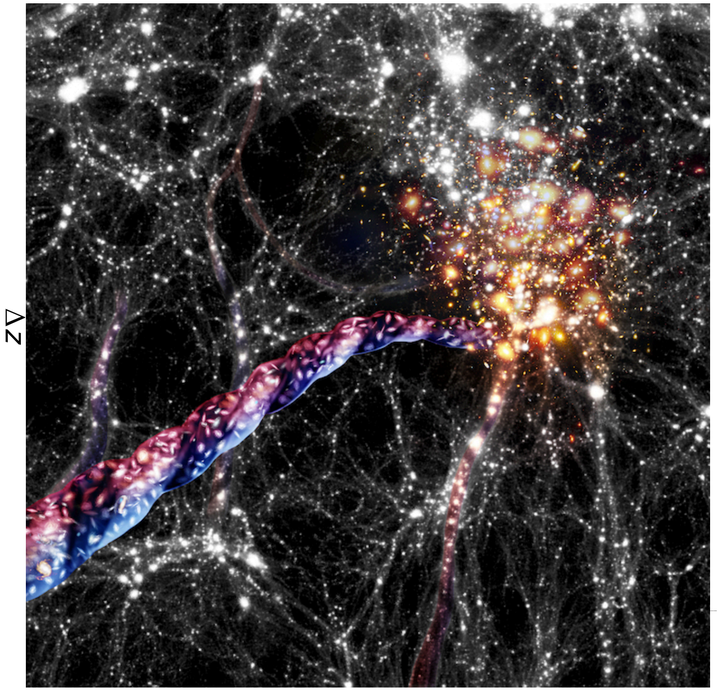


*Filaments generally spin



Xia, MN, Cai & Aragon-Calvo, arXiv:2006.02418, MNRAS (2021)

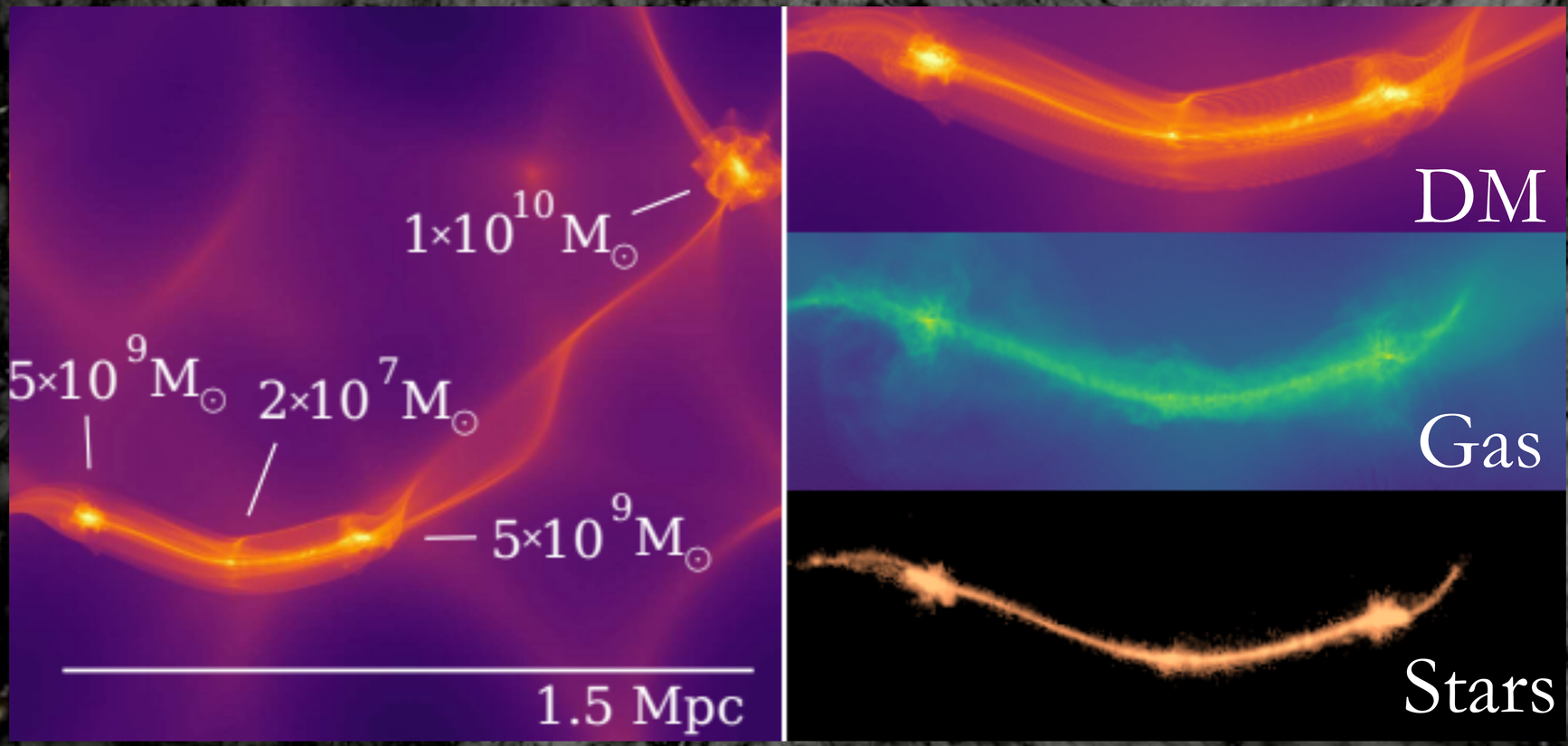




(See also Codis et al. 2012, Laigle et al. 2015, MN 2016, MN et al. 2020)

(Wang, Libeskind, Tempel et al., Nature Astronomy, 2021)

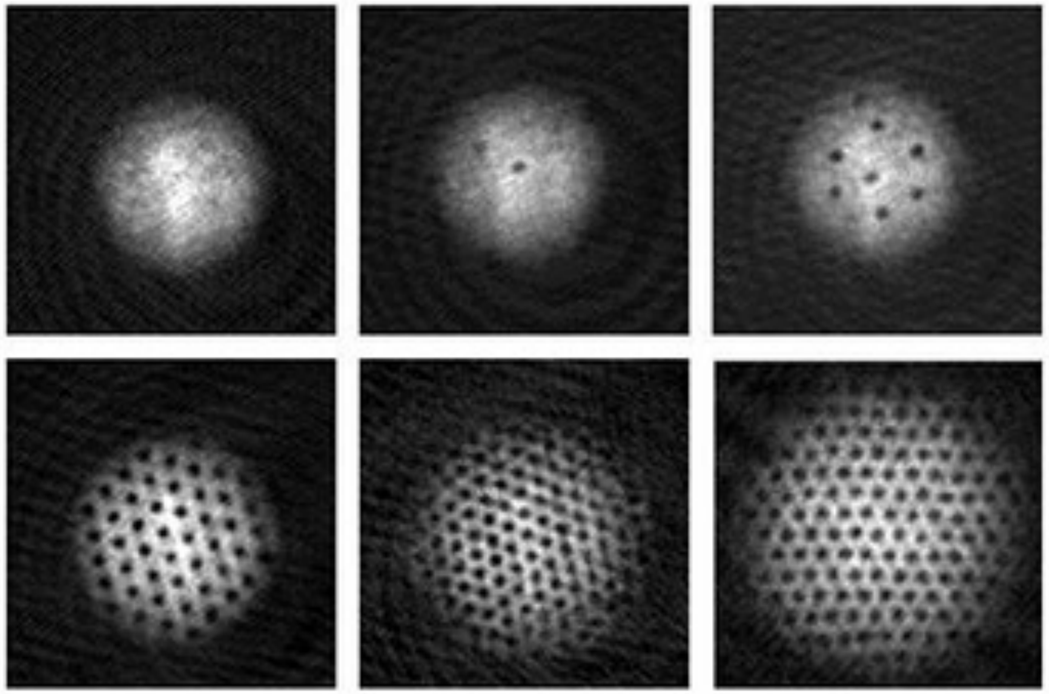
How does spin manifest in fuzzy/ultralight-axion/wave/scalar dark matter (SDM) haloes? In SDM filaments*?



Mocz et al. (2019)

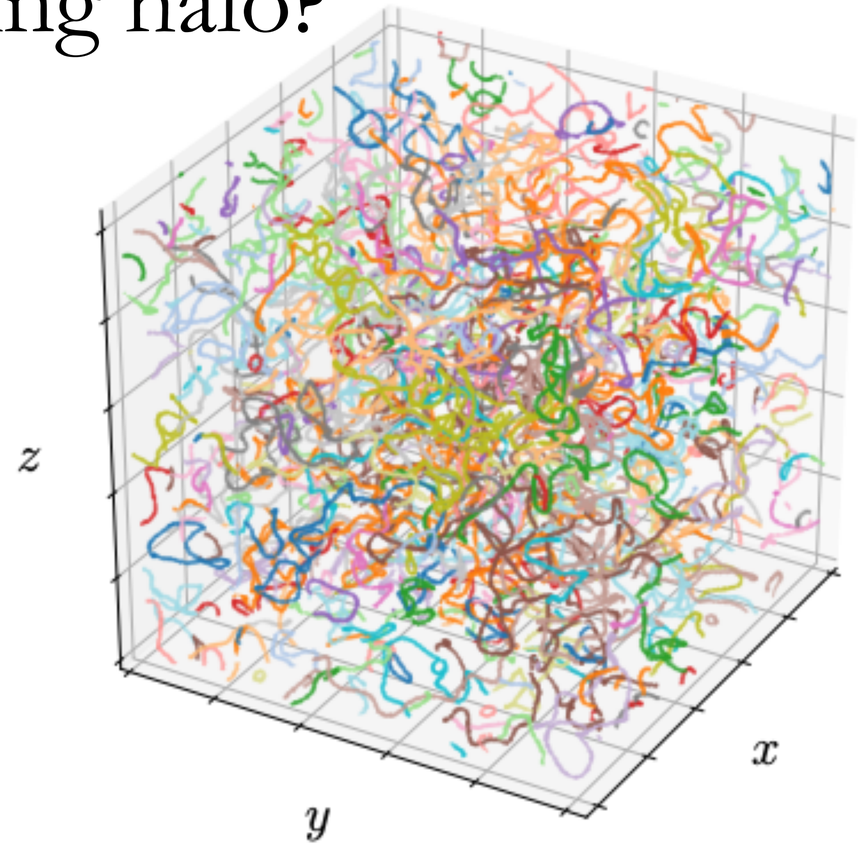
Subtle because the “velocity” field is defined in SDM via a gradient, so “vorticity” only at discrete vortices

It is a physical effect though: if you try to spin up a superfluid, the spin manifests as vortices

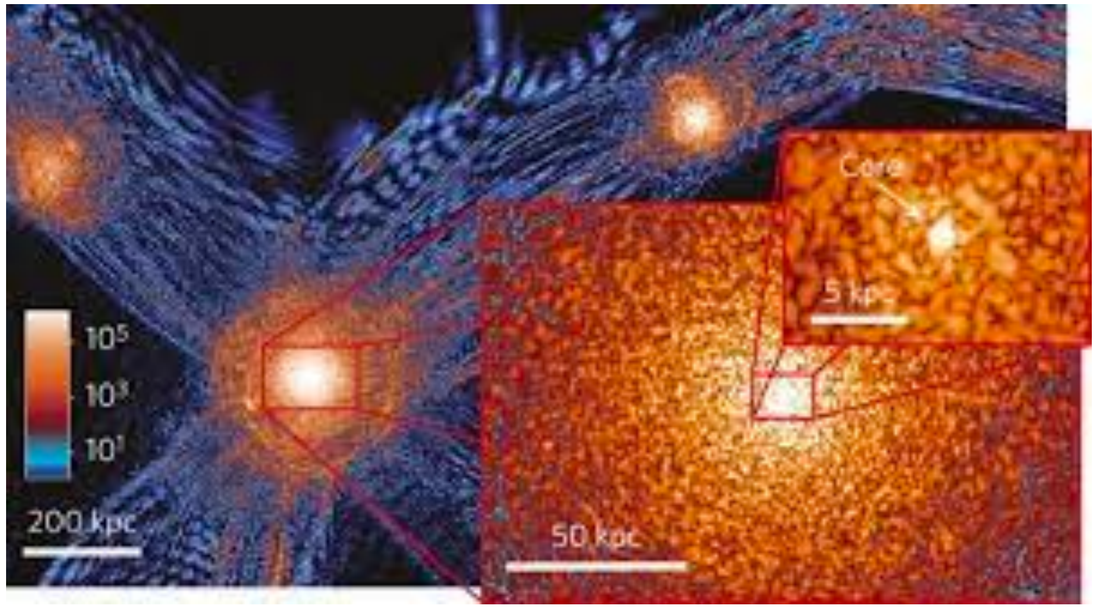


(e.g. Matthews et al. 1999)

Vortices straightforward to study in a random phase model (e.g. Hui et al. 2021). But how does this relate to a spinning halo?



Are there “spin-driven” rather than “random” vortices? Well-defined? If a vortex threaded a soliton core, it would seem spin-driven



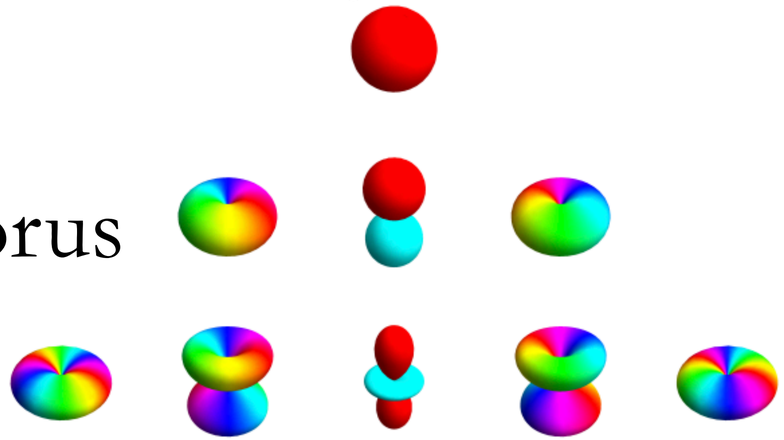
(Schive et al. 2014)

Vortex-solitons apparently absent from cosmological SDM simulations. But to get vortices in a superfluid, a confining potential is needed.

Similarly, a confining potential (e.g. from a black hole!) stabilizes a vortex-soliton

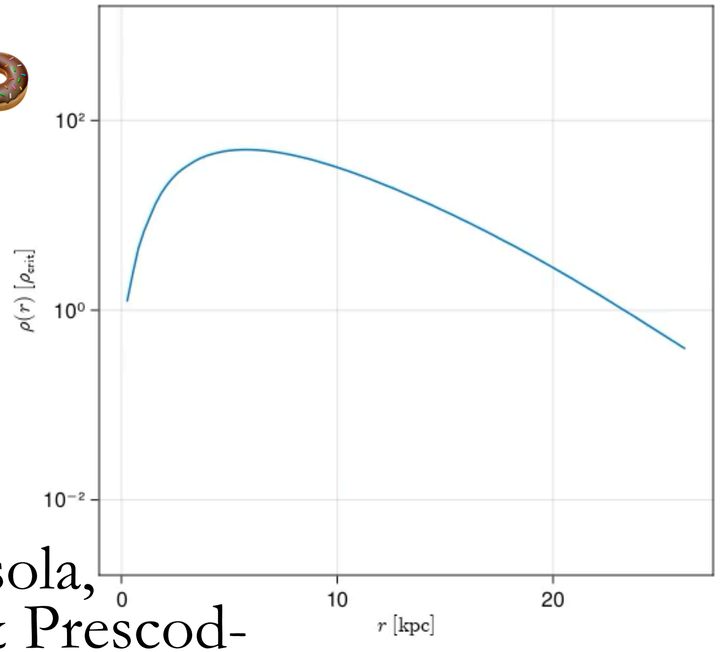
Ground state: Y_0^0: usual soliton.

$Y_1^{\pm 1}$: torus

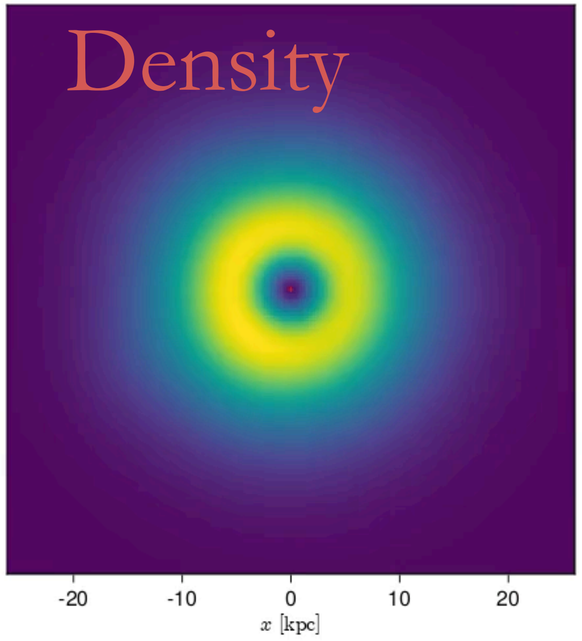


(Schmeder 2010)

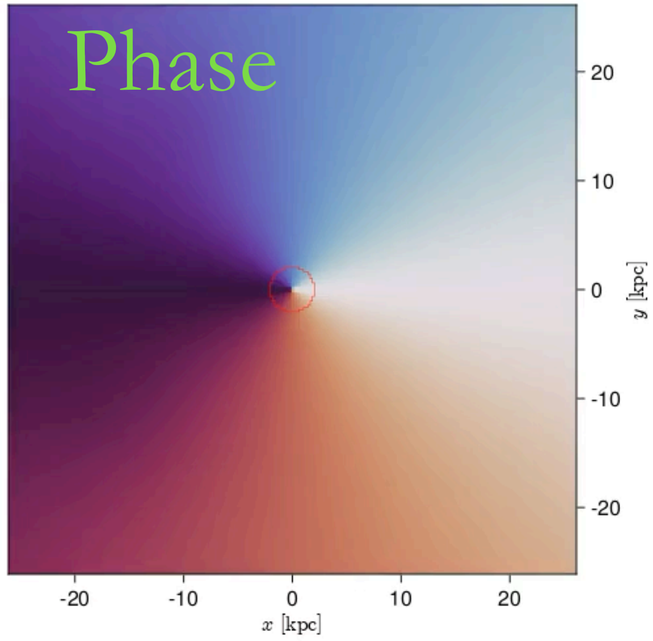
$M_{\bullet}=2M_{\odot}$



Density

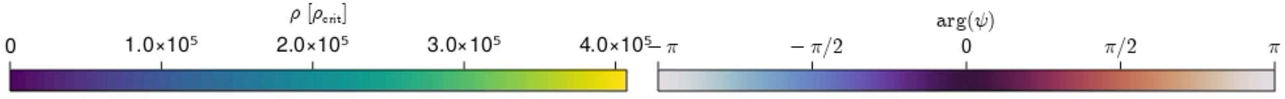


Phase

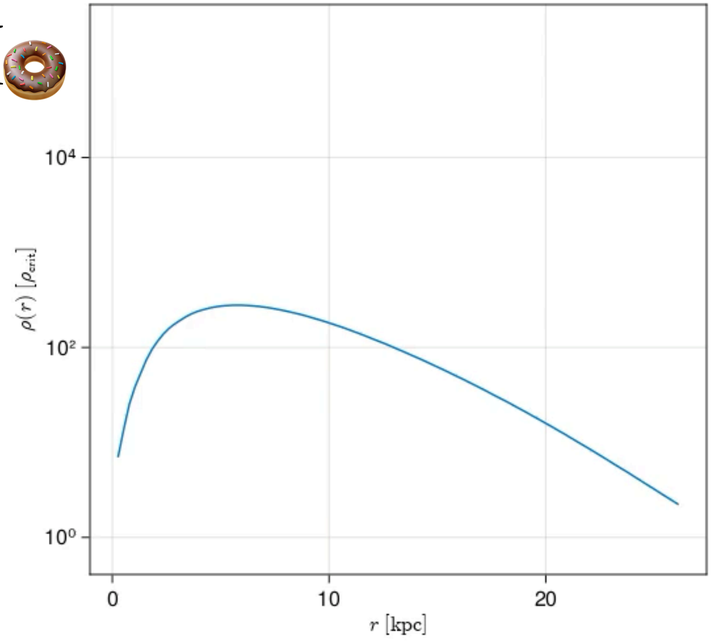


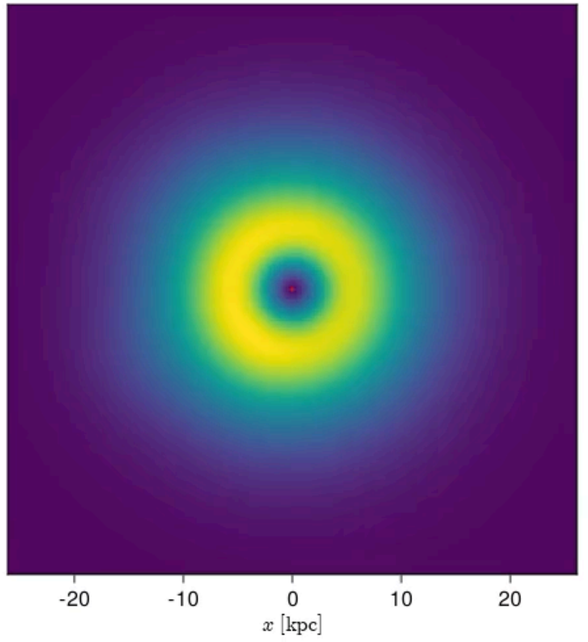
Glennon, Mirasola, Musoke, MN & Prescod-Weinstein 2023
arXiv: 2301.13220

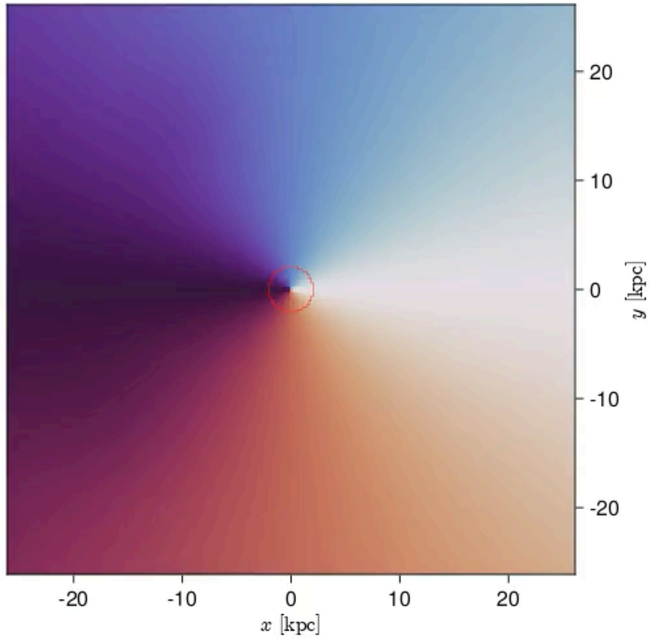
$t = 0.0$ [Gyr]



$M_{\bullet}=⅓M_{\odot}$

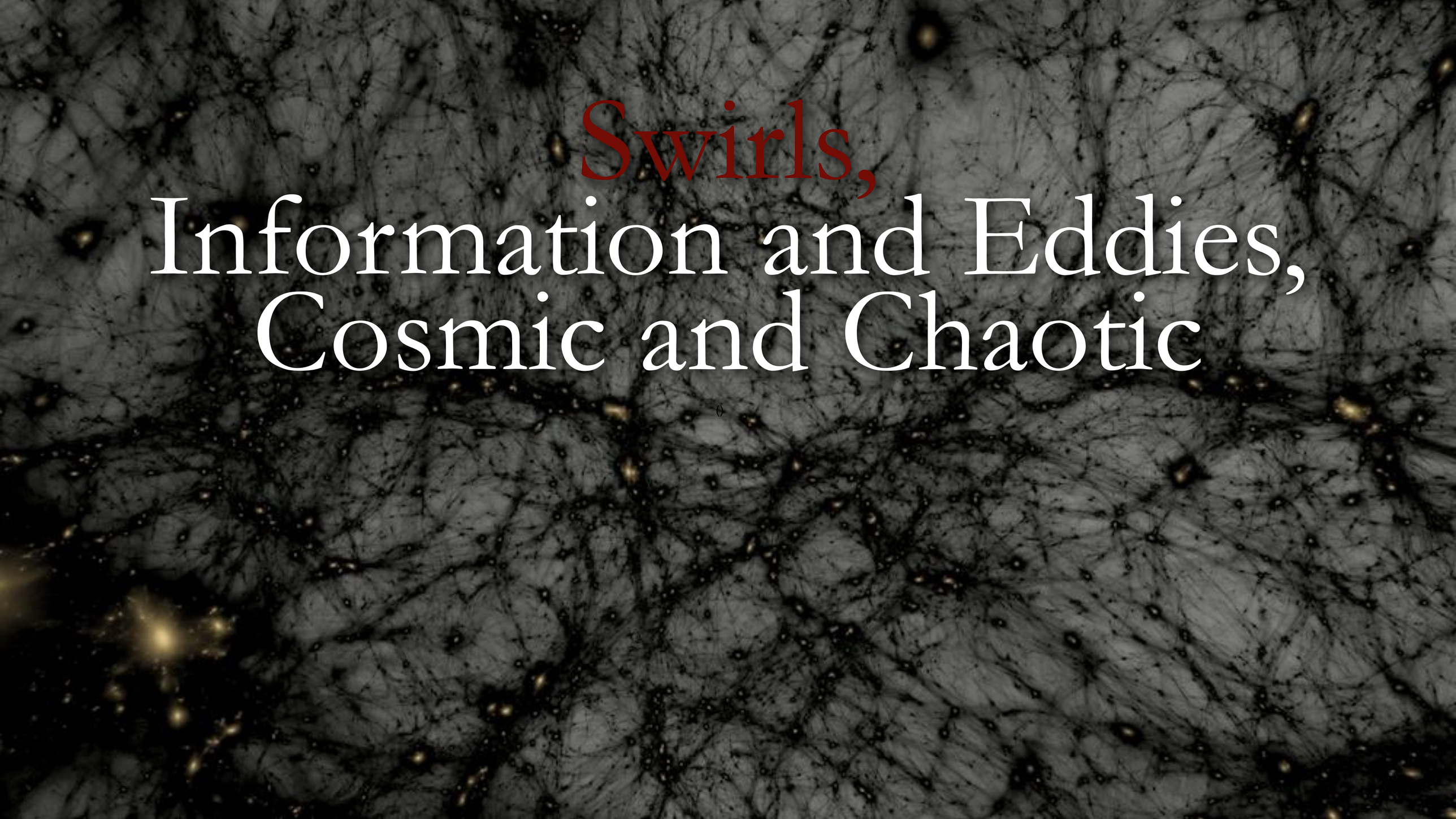






Astrophysically relevant? Maybe: largest cluster galaxies with particularly massive black holes? (Probably not Sag A*, but M87*?)
(Non-ultra)light axions?

Axion solar system halo?
(Possibly detectable? Eg. Banerjee et al. 2020, Tsai et al. 2022)
This work suggests that such a halo may be rotating 😇


Swirls,
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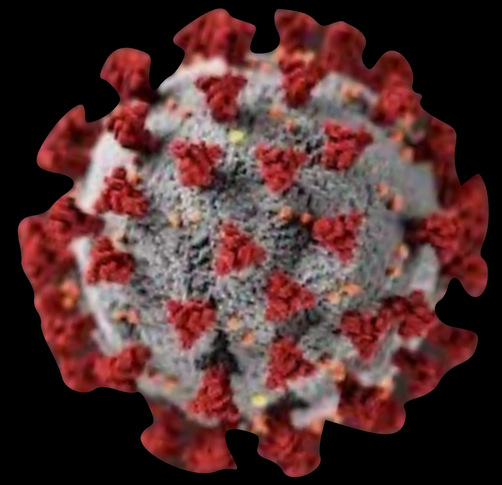
What was encoded in the initial conditions of the Universe?

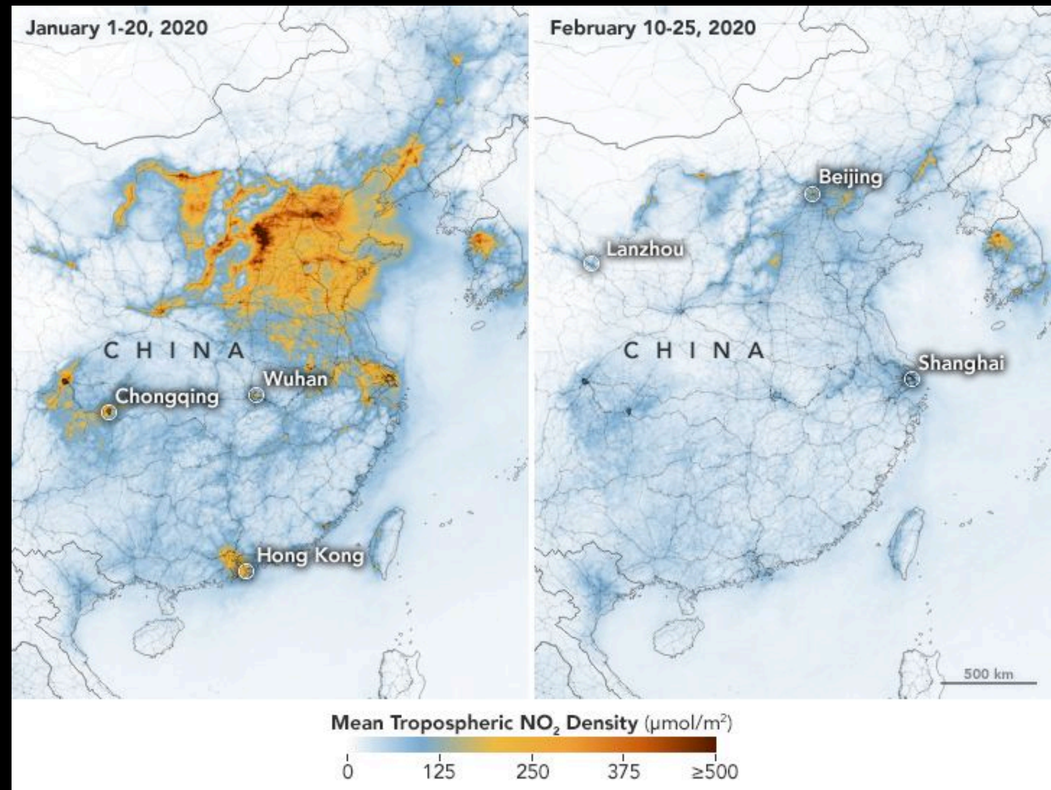
Was life?

Was this presentation?

Example: covid pandemic! Some small probability of a pandemic each year. But genuinely random events* likely led to this particular one, which obviously had global impact, not just for humans

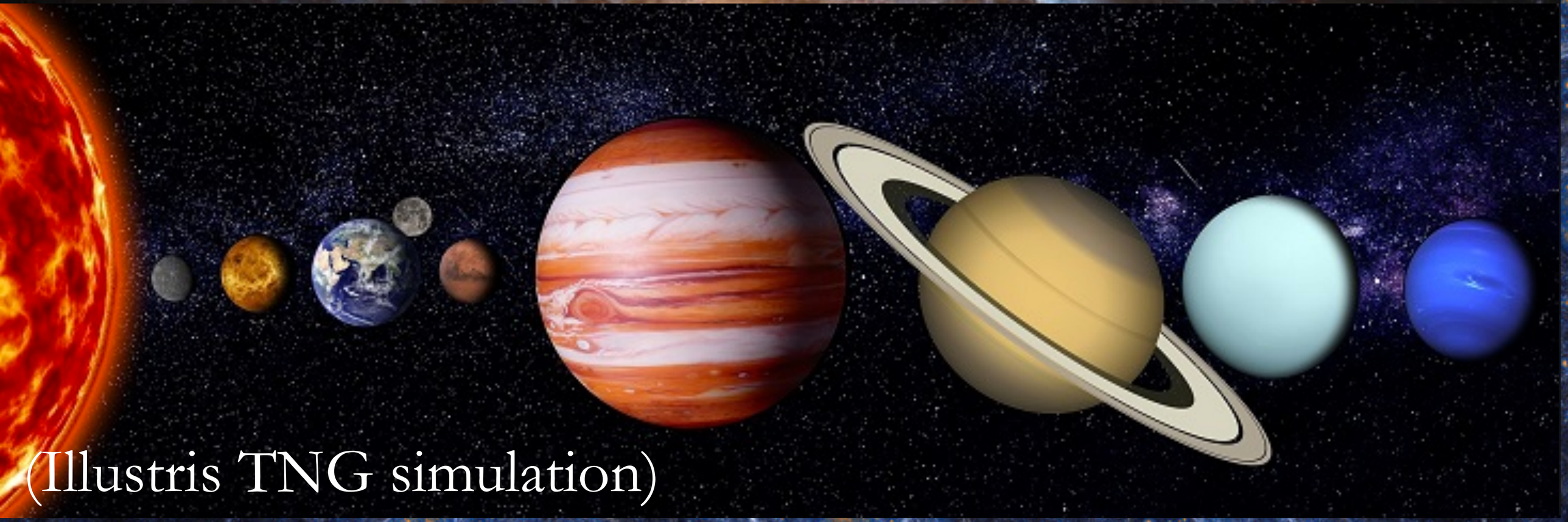


* mutation from cosmic rays?
* indeterminism in animal decisions?
* chaos/indeterminacy in atmospheric fluid dynamics?
* cosmic rays may even seed clouds!



What about extragalactic scales?

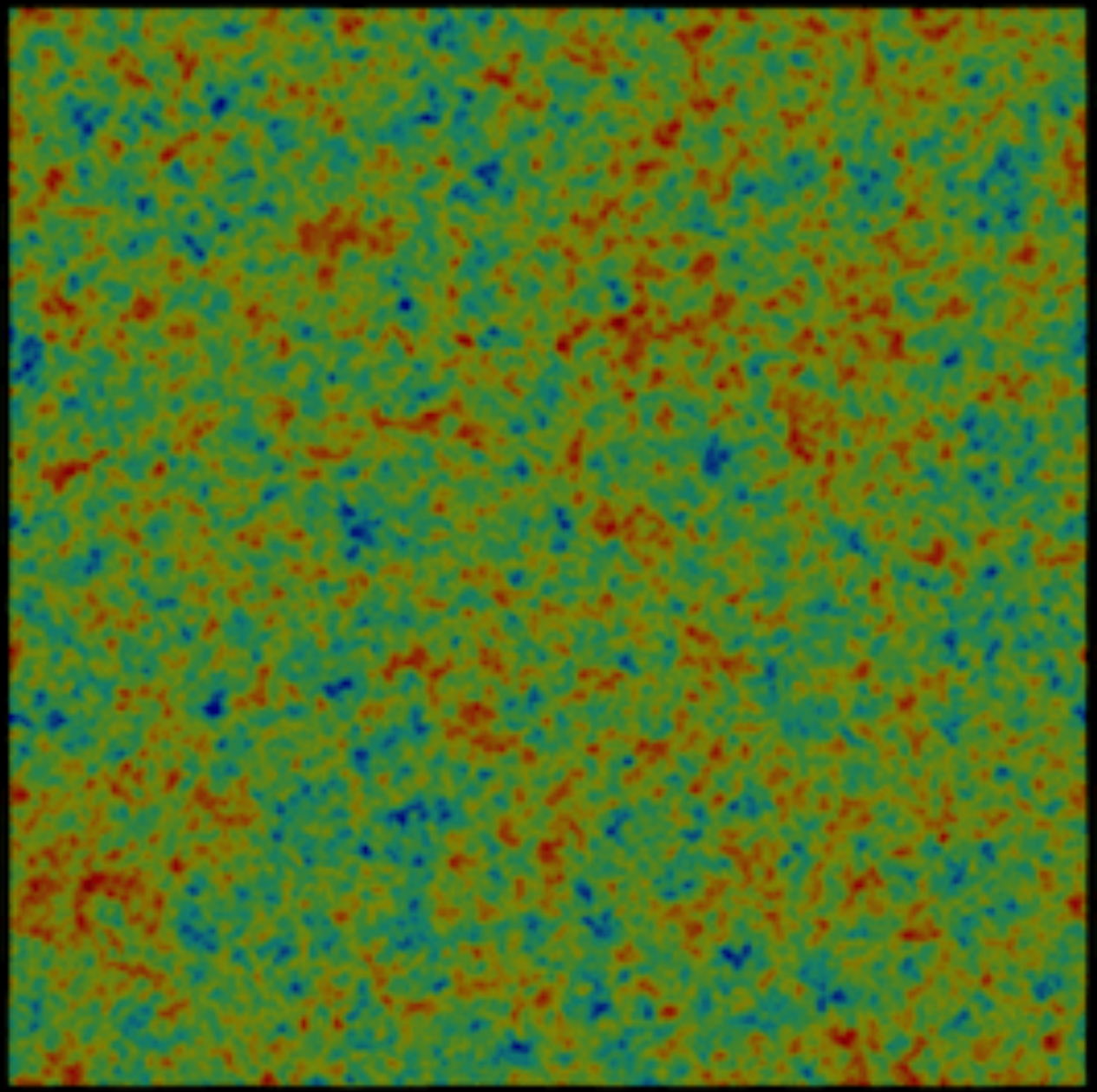
Was the Solar System prescribed in the primordial universe?



(Illustris TNG simulation)

Easier question: chaos

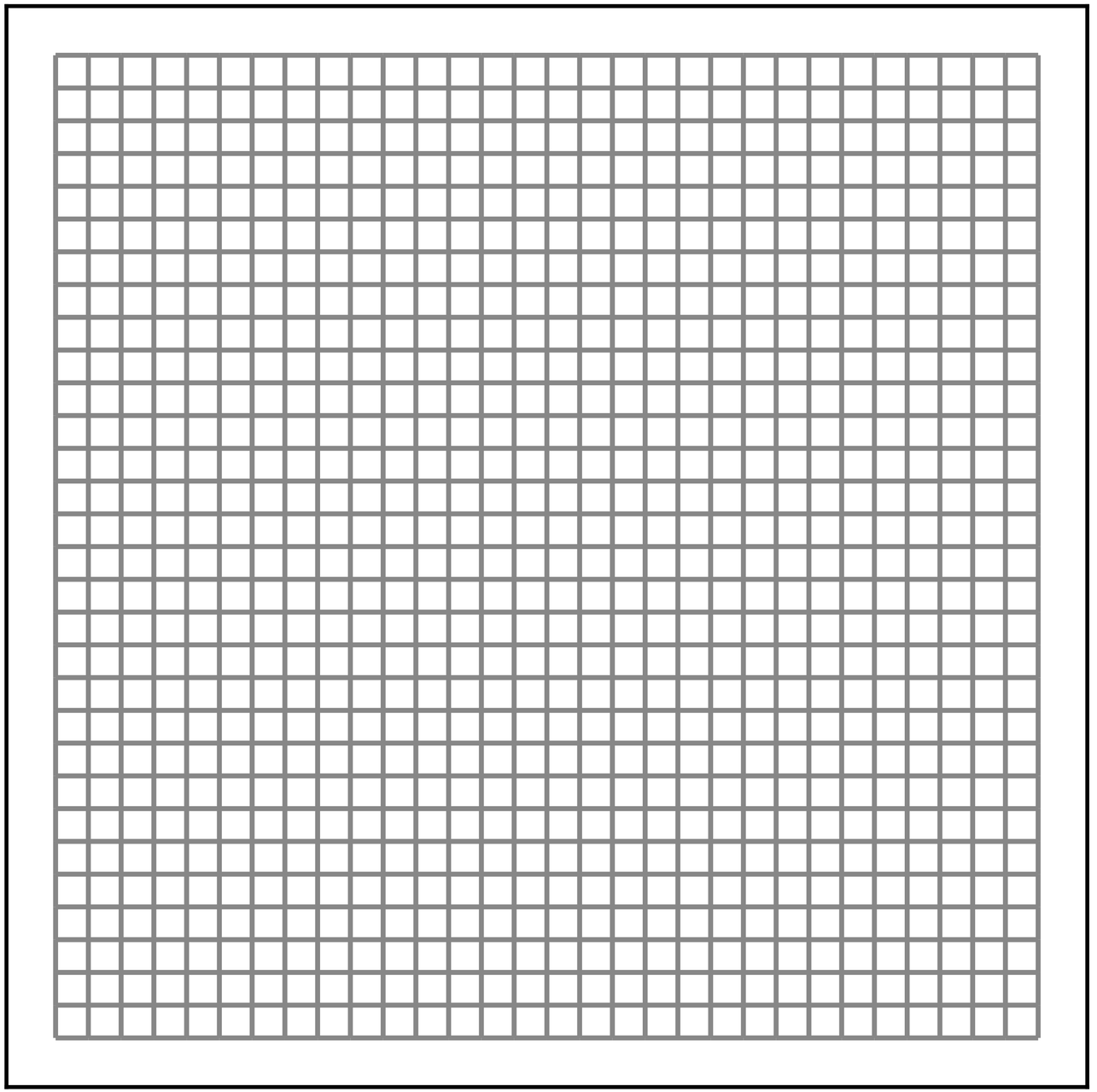
"Primordial randomness": blueprint for the structure in the Universe

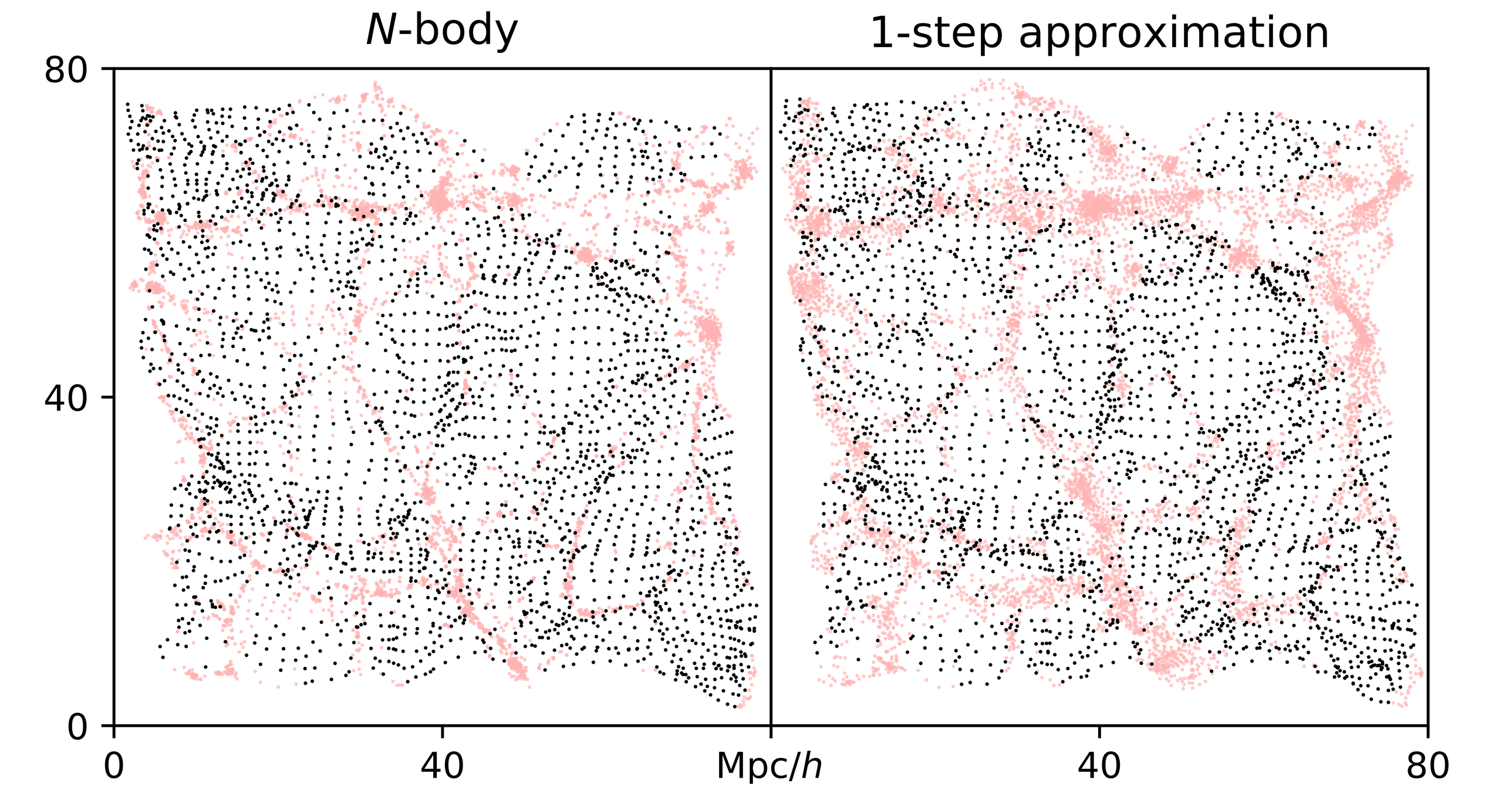


Separate Universe Approximation

Accurate approximation, that before patches of matter collide, each cell develops like a separate universe (Dai et al. 2015)

Completely deterministic adhesion (Gurbatov 1984, Vergassola et al. 1994, Hidding et al. 2012, 2016; Neyrinck et al. 2018)
https://github.com/jhidding/adhesion-example



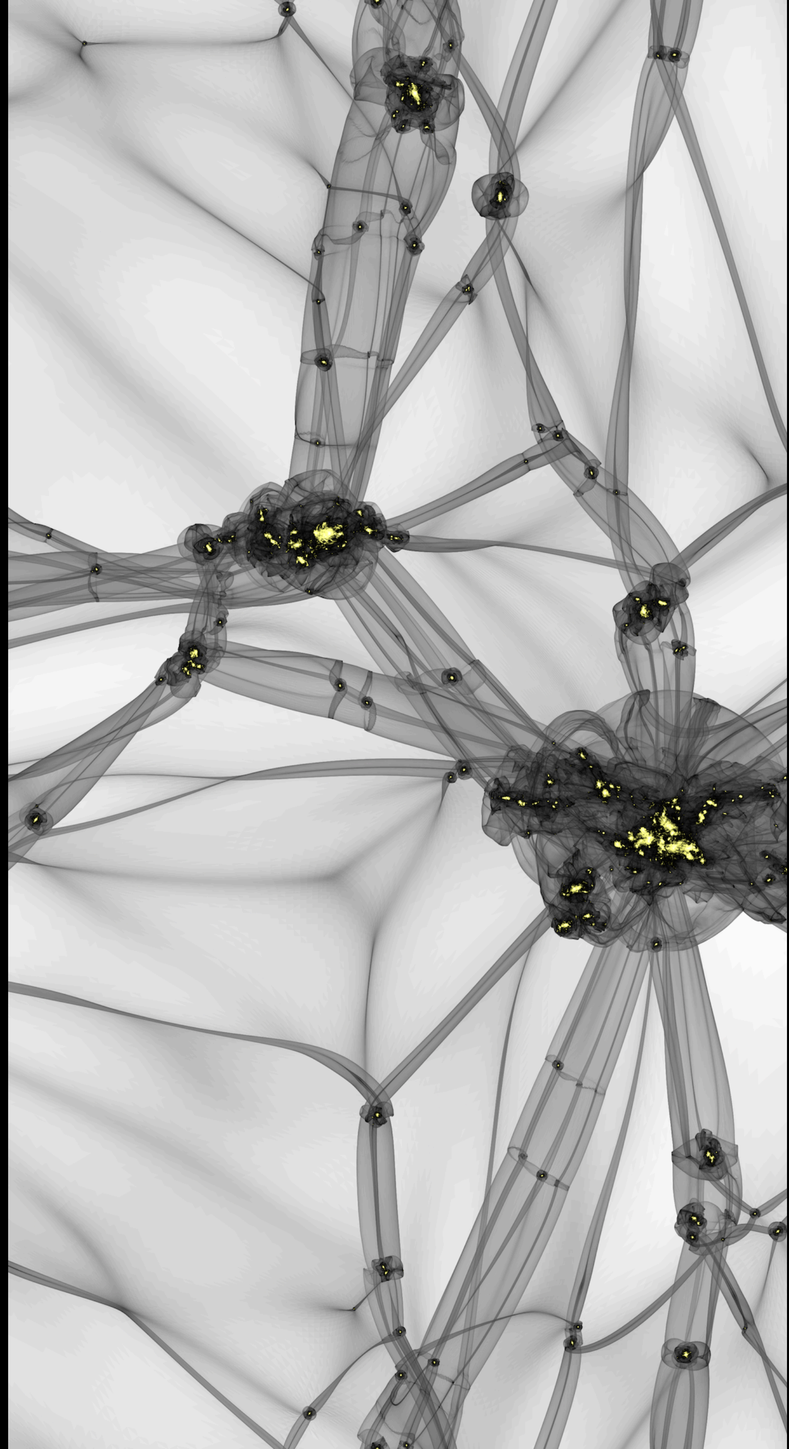


MUSCLE (Neyrinck 2016; Tosone, Neyrinck et al. 2021)

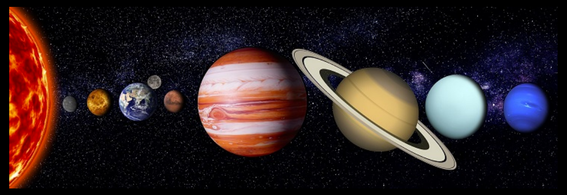
Why so simple?

“Single-stream region” = not overlapping in phase space; no patch of dark matter has run into another. Stretching; no crumpling

No crossing time. In CDM: ~1% of dark matter (by mass) will *never* cross. By volume, much more

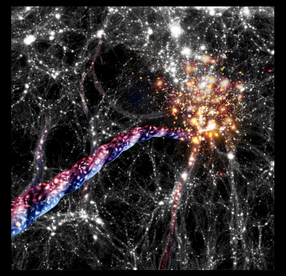


Solar system: dynamical time ~years —
still “cosmic” (orderly) on human timescales



Galaxy: rotation: ~230 million years rotation. Some shorter dynamical times

Intergalactic filament: period of order a Hubble time (with some a factor of several faster)



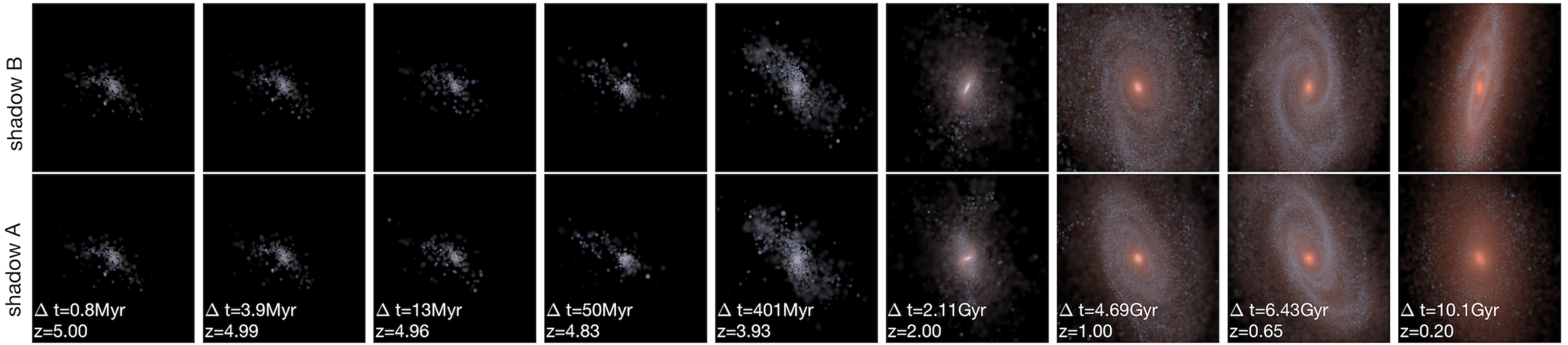
Wall: also Hubble-timescale?

Void: crossing time undefined!

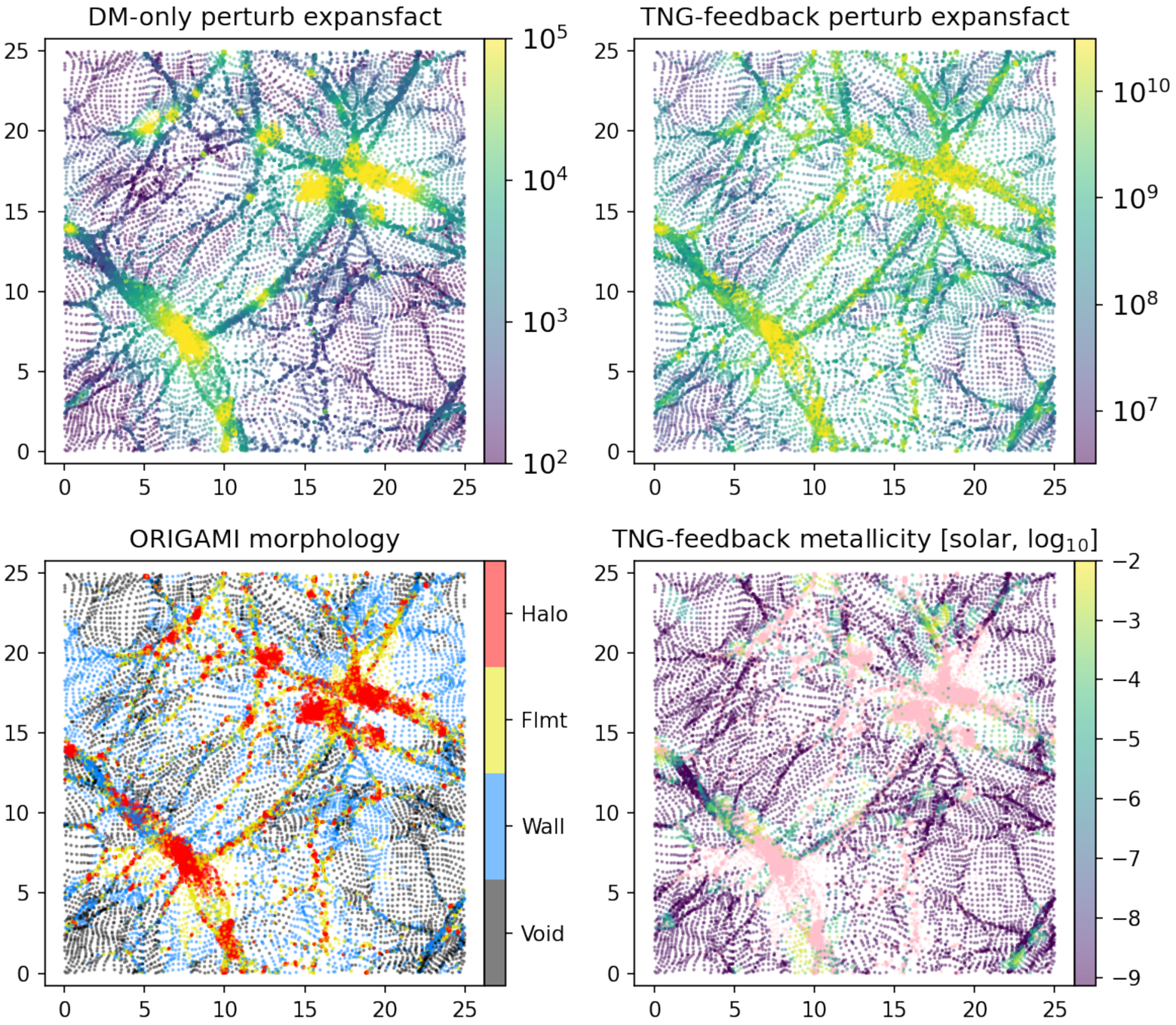
But what about the collapsed regions?

Machine-precision (μpc/h(!) ~ 1 part in 10^{15}) perturbations in particle positions, in first frame

Galaxies experience severe chaos in the simulation, up to scales of the galaxy! But not yet clear how much of that is *physical*

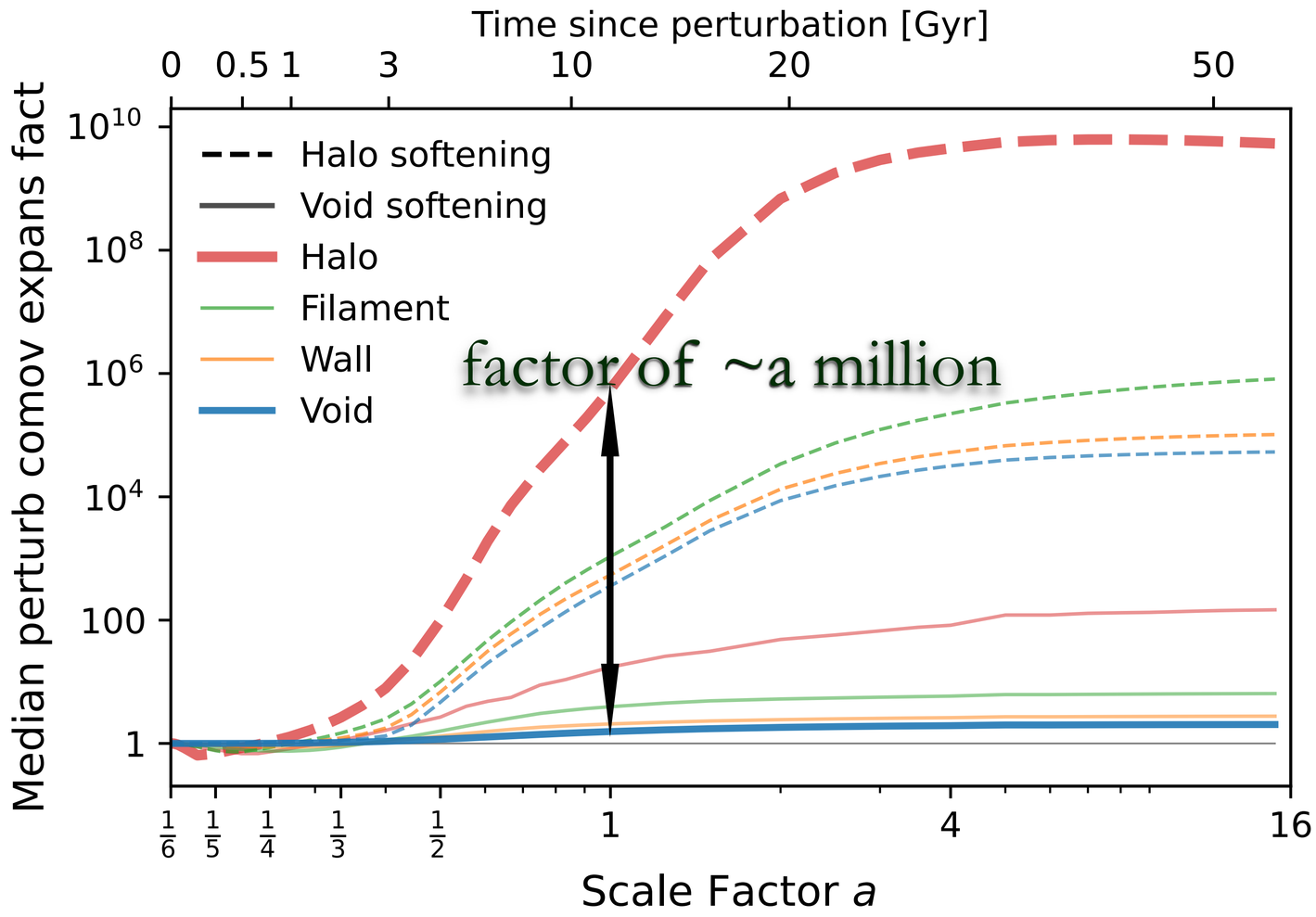


(Genel et al., 2019)



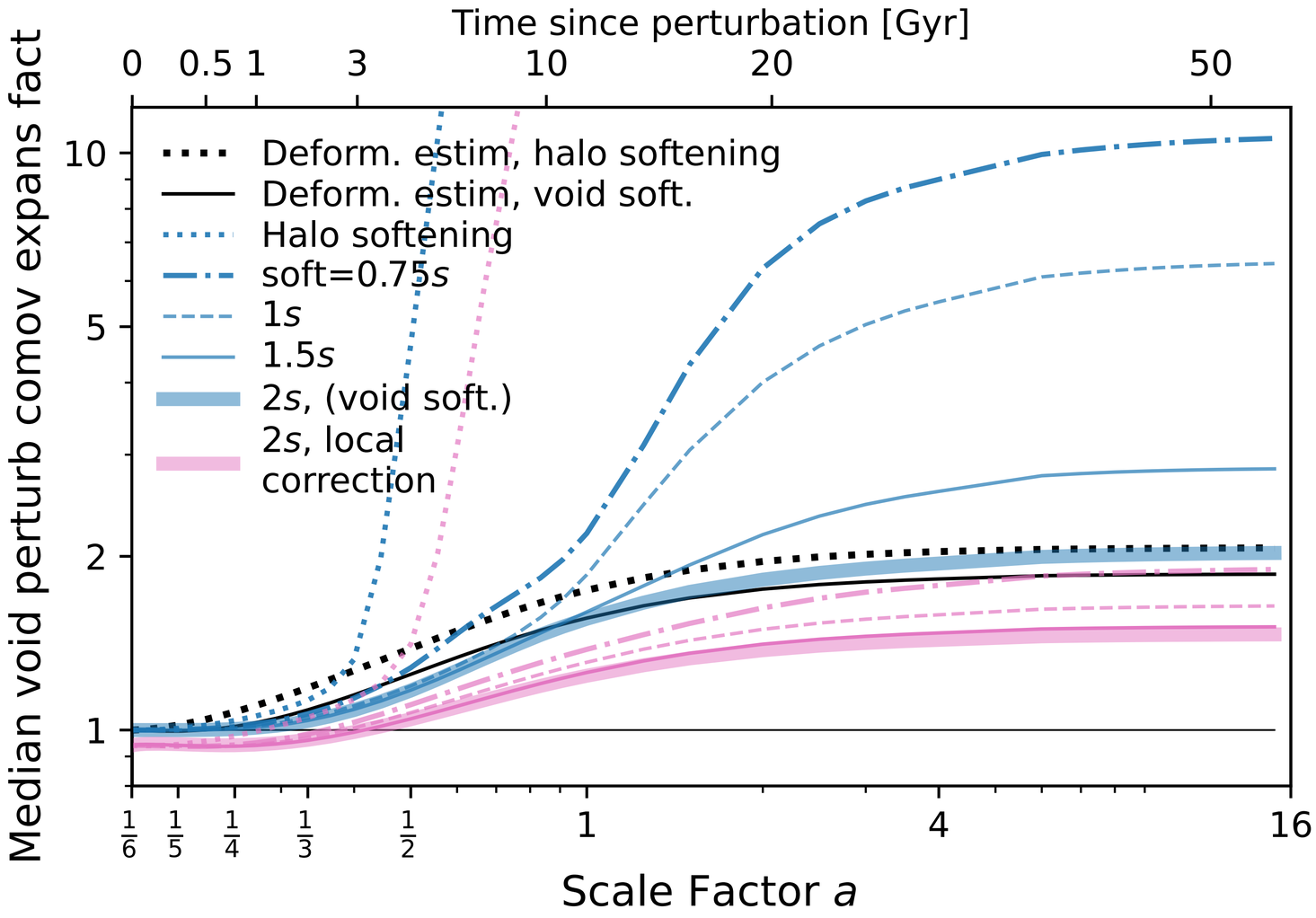
- Dark-matter chaos high in haloes … low/nonexistent in voids. Filaments and walls: modest chaos
- Even AGN outflows don't provoke chaos in voids
- Void spherical-density-evolution *sub-linear*

Neyrinck, Genel & Stücker 2022
arXiv:2206.10666


Time since perturbation [Gyr]
0
0.5
1
3
10
20
50
Median perturb comov expans fact
10^{10}
10^{8}
10^{6}
10^{4}
100
1
Halo softening
Void softening
Halo
Filament
Wall
Void
factor of ~a million
$\frac{1}{6}$
$\frac{1}{5}$
$\frac{1}{4}$
$\frac{1}{3}$
$\frac{1}{2}$
1
4
16
Scale Factor *a*

Softening prescription makes a big difference

A reason to use an adaptive dark-matter-sheet code for dark-matter simulations



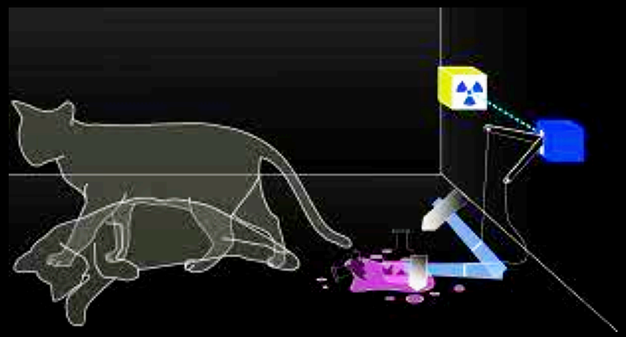
How much physical stochasticity is there? Some?

(but how much, and on what scales?)

Does God play dice?

If so, how big are they?

- Quantum randomness



- Randomness in turbulent systems? Spontaneous stochasticity, the “real” butterfly effect

How much physical stochasticity?

- Richardson (1926 — quantum times!) “anomalous” diffusion in turbulent flows
- Weather balloon RMS distances $\langle r(r_0, t)^2 \rangle^{1/2} = A(r_0) t^{3/2}$
- Surprisingly, $A(r_0 \to 0) = A_0 > 0$. So two balloons would end up in different places even if released at the same place and time!

Lorenz (1969)
("The real 🦋 effect,"
Palmer et al. 2014)

Weather seems to be in class 3: fundamental couple-of-week limit on predictability

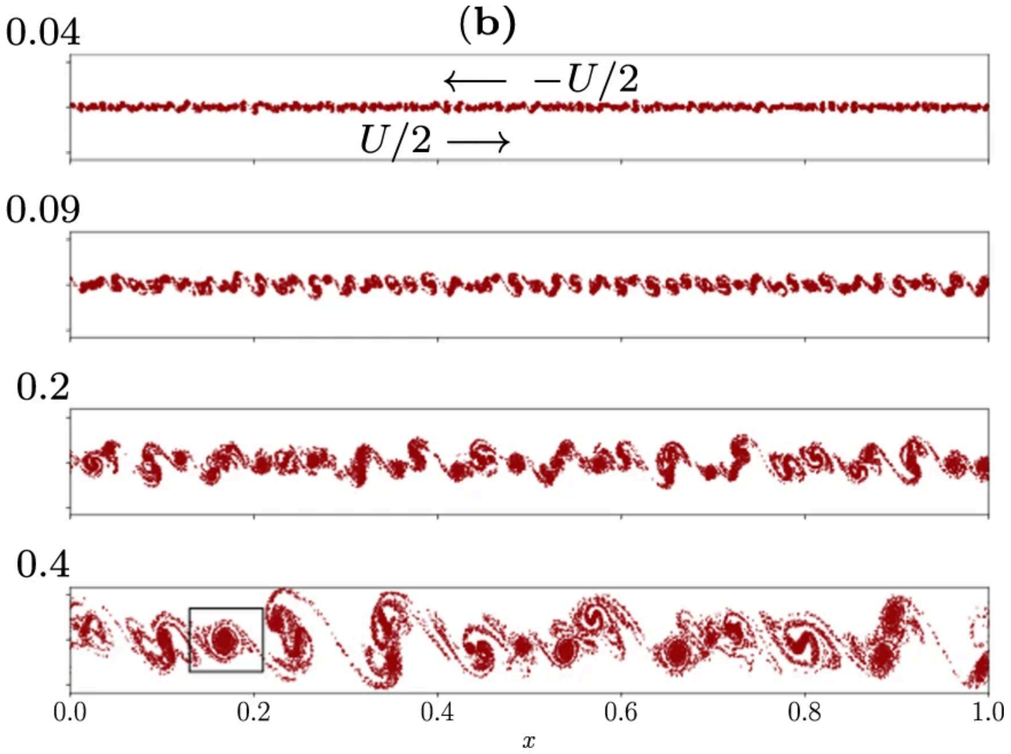
The predictability of a flow which possesses many scales of motion

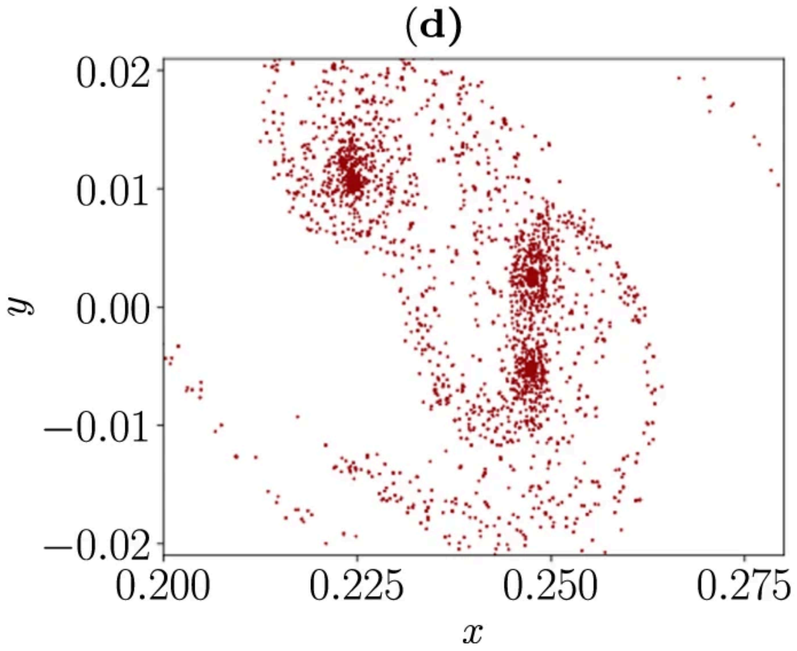
If at some initial time an error is in some sense small, it may subsequently follow one of several courses. We shall classify the systems under consideration into three categories, according to the general behavior of initially small errors.

1. At all future times the error remains comparable to or smaller than the initial error. The error may be kept arbitrarily small by making the initial error sufficiently small.

2. The error eventually becomes much larger than the initial error. At any particular future time the error may be made arbitrarily small by making the initial error sufficiently small, but, no matter how small the initial error (if not zero), the error becomes large in the sufficiently distant future.

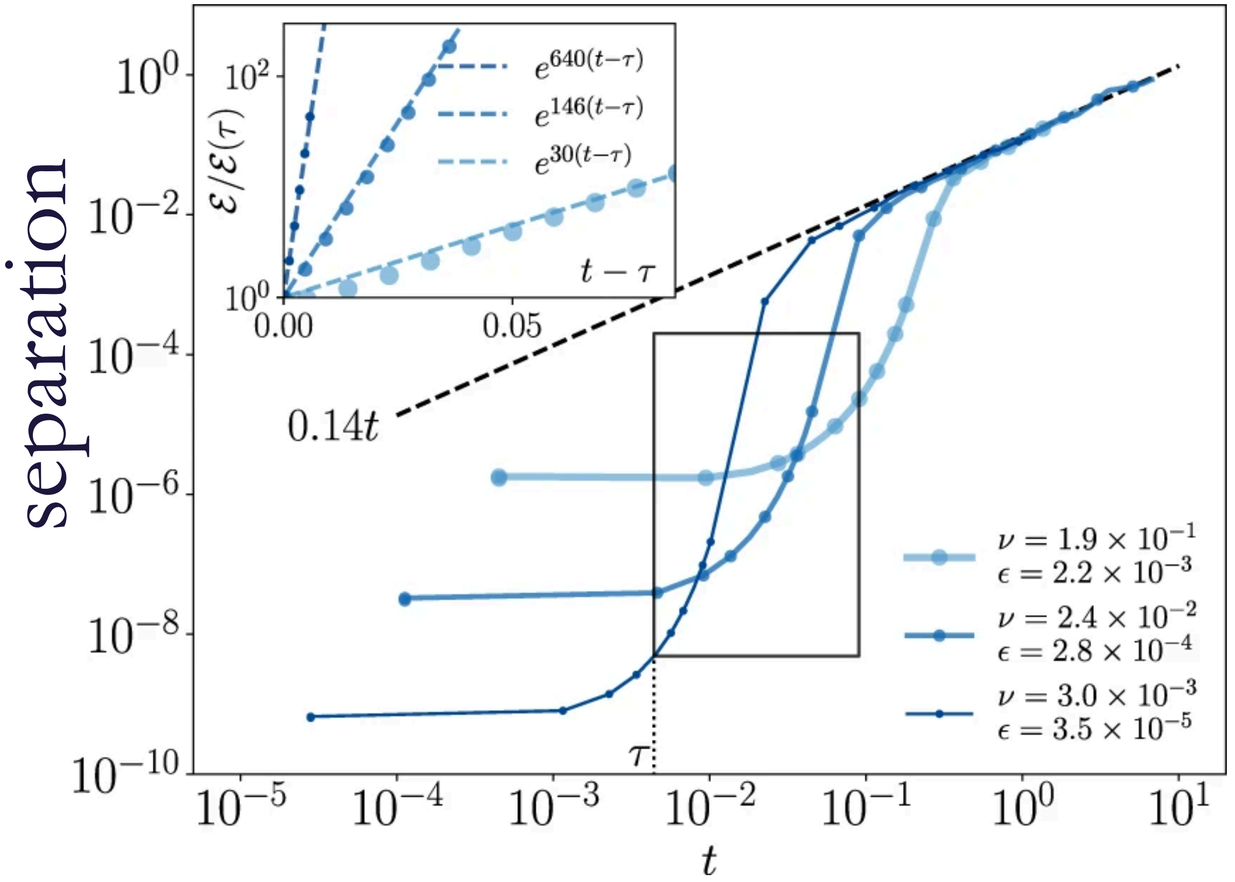
3. The error eventually becomes much larger than the initial error. For any particular future time there is a limit below which the error cannot be reduced, no matter how small the initial error (if not zero) is made.

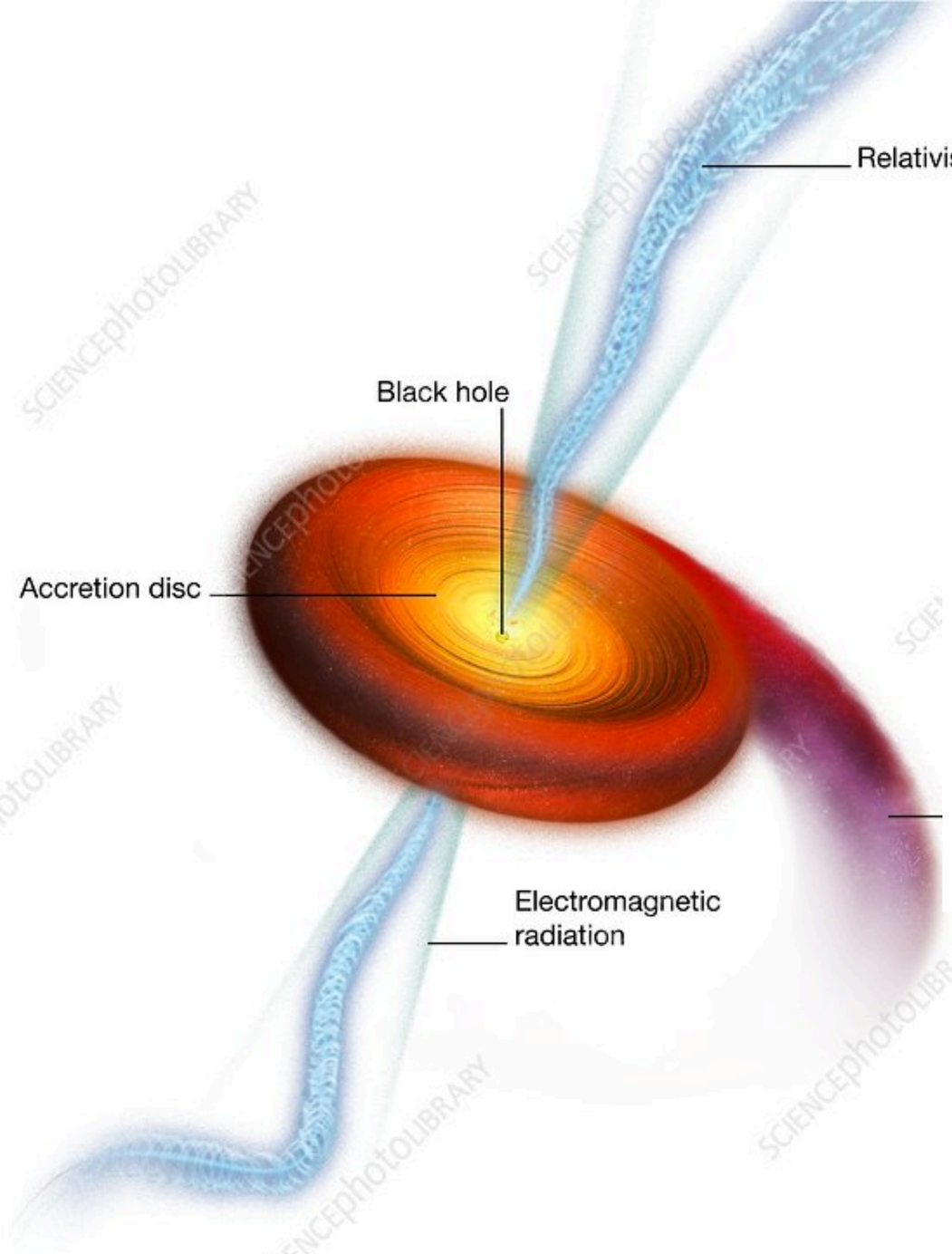




In Kelvin-Helmholtz simulations, final separations → (const > 0) when initial separations → 0

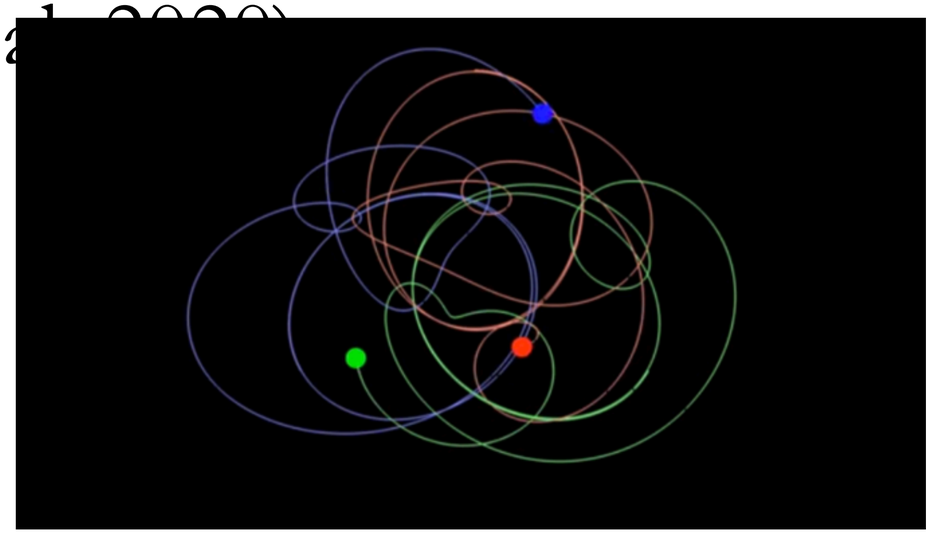
(Thalabard et al. 2020, Nature Comms)





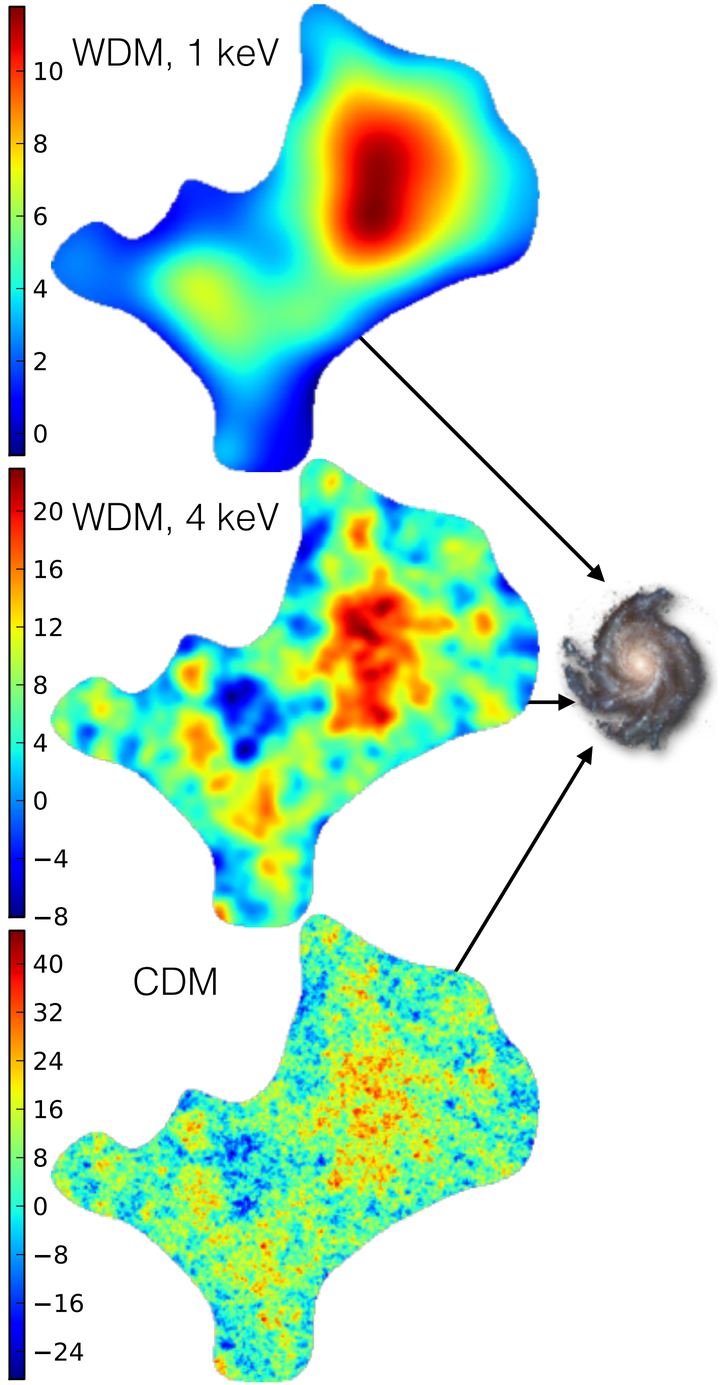
Processes could broadcast small-scale (non-astronomical-scale) non-primordial information eventually to the scale of a galaxy:

- Jets, supernovae
- Black-hole triples and other chaos (Boekholt et a

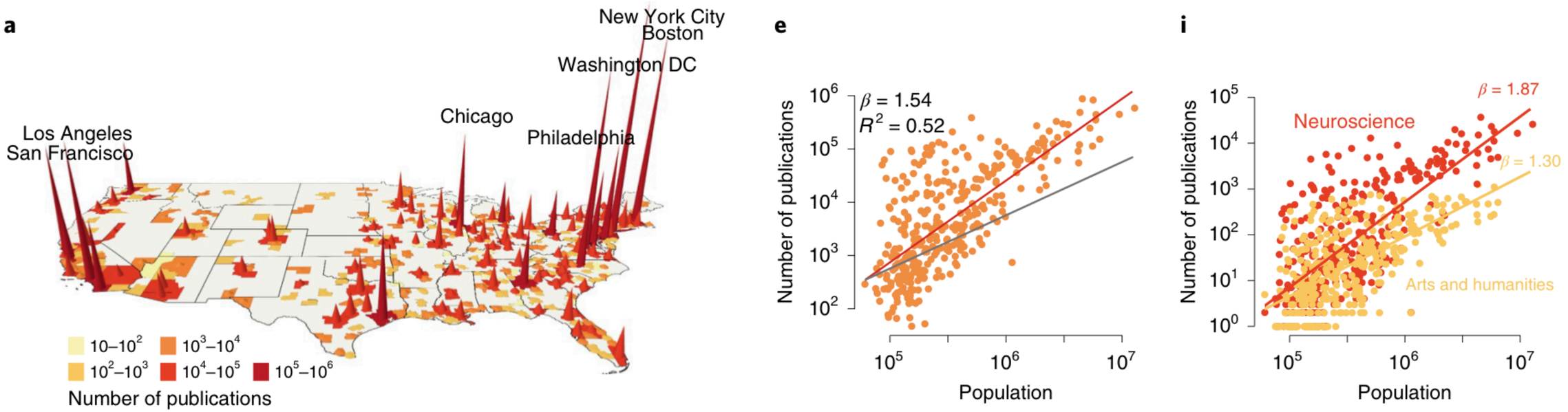


Speculation on cosmic (Kolmogorov) information …

- In a wave/fuzzy/ultralight-axion or warmDM scenario, the MW's primordial patch was very smooth — where did all the info come from? (Neyrinck 2015)
- 1 keV warmDM: ~30 Gb
- 4 keV warmDM: ~4 Tb
- Fiducial CDM (0.012 pc cutoff): ~10^{25} bytes
- 1 bit per Planck mass (Lagrangian Planck volume): ~10^{80} bits … a lot, but still less than the #bits in/on Sag A*, ~10^{90}



Galaxies as information breeding grounds



(Balland et al. 2020 — see also Bettencourt 2013)

So, where is the cosmos stochastic/chaotic/deterministic?
Depends on scale, but roughly …

Galaxies: highly chaotic.
Indeterminism?

Filaments: slight chaos.
Indeterminism?

Voids: deterministic dark matter; some stochasticity in gas from outflows?