Axions from Strings:

The Attractive Solution

Marco Gorghetto

SISSA

with **Ed Hardy** & **Giovanni Villadoro**

based on 1806.04677

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Axion dark matter

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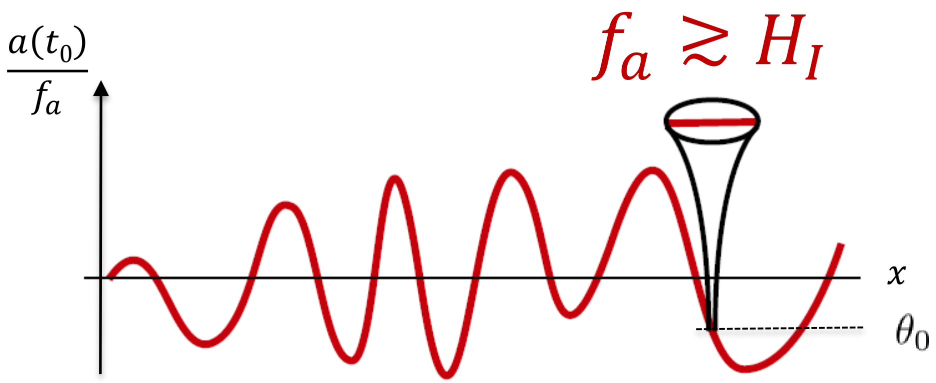

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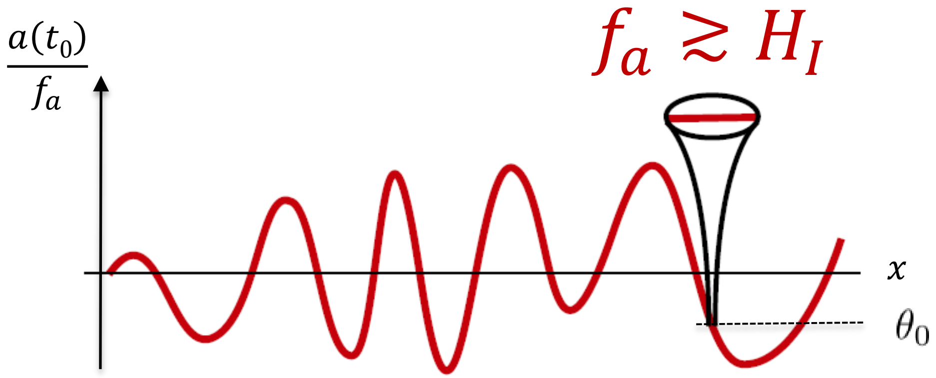

$f_a \lesssim H_I$

$$a(t_0) = \text{random}$$

misalignment contribution fixed

$$\theta_0^2 \approx \frac{\langle a^2 \rangle}{f_a^2} \approx (2.2)^2$$

extra axion from strings + domain walls
large uncertainties

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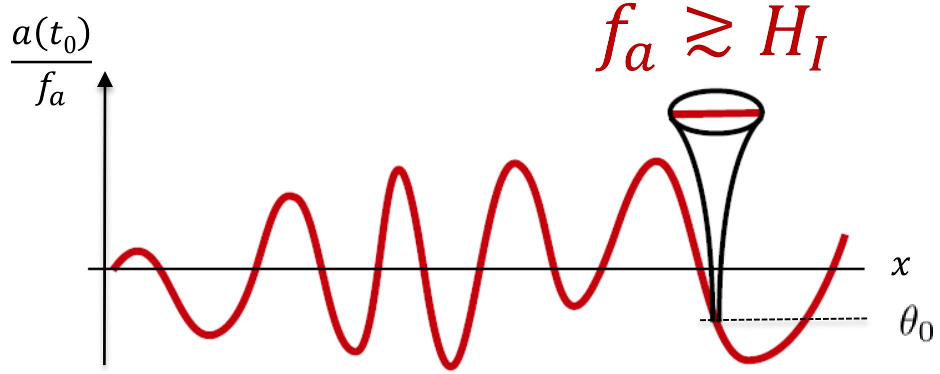

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large uncertainties

No free parameters from initial conditions

predictive!

Axion Strings

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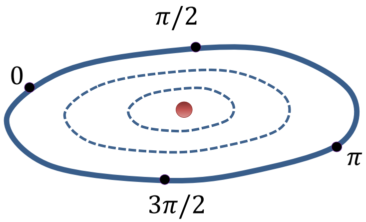

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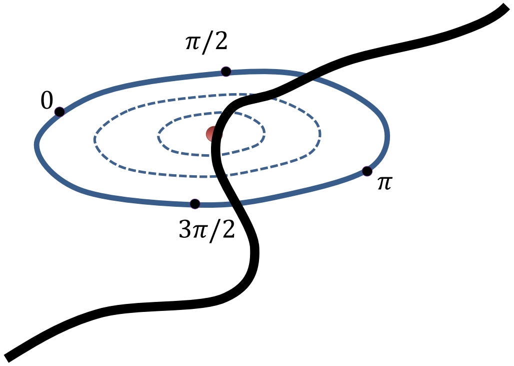

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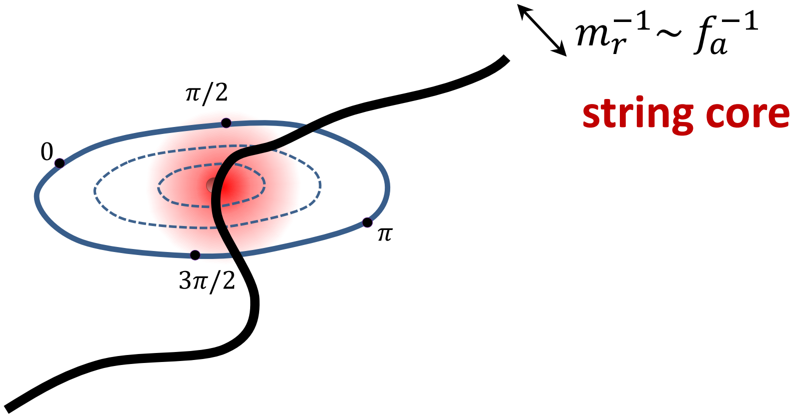

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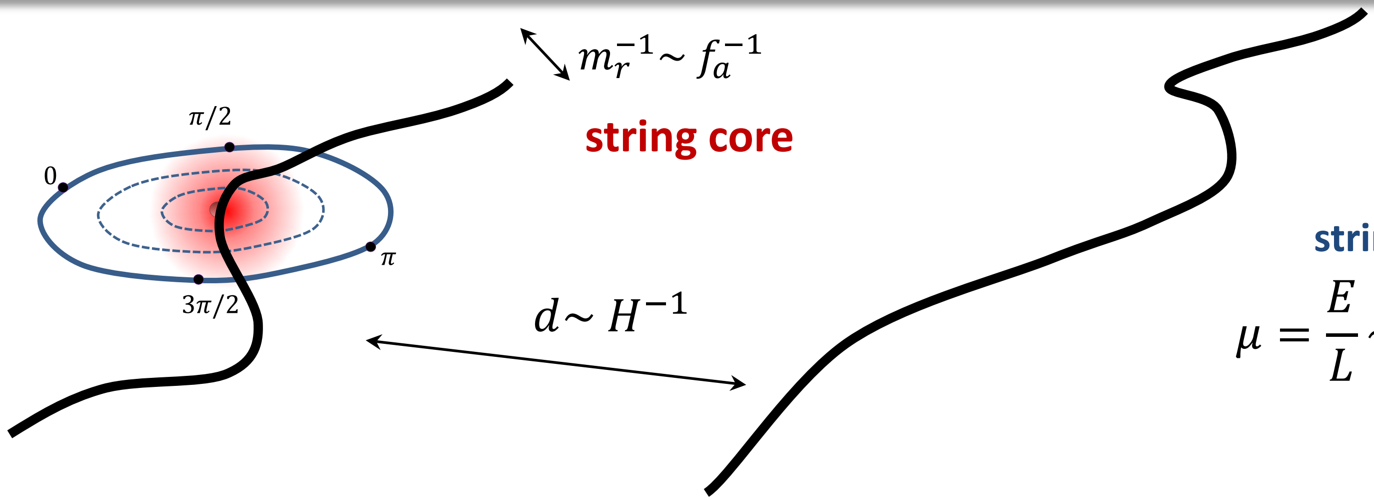

string tension

$$\mu = \frac{E}{L} \sim \pi f_a^2 \log \frac{m_r}{H}$$

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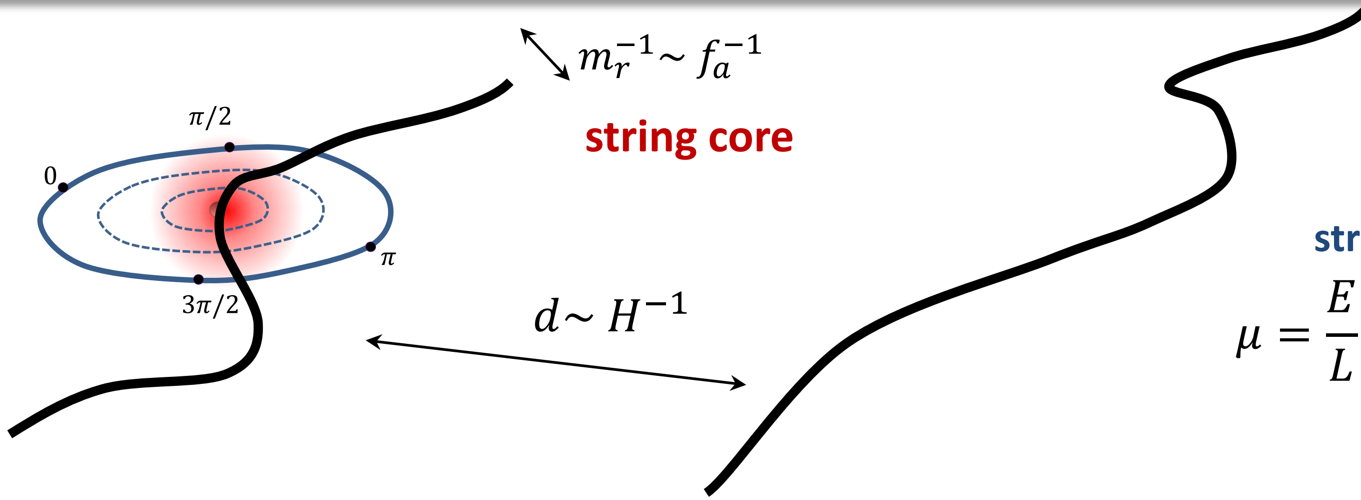

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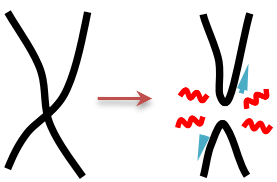

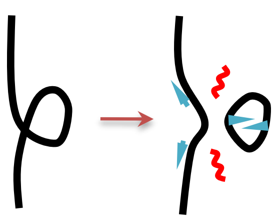

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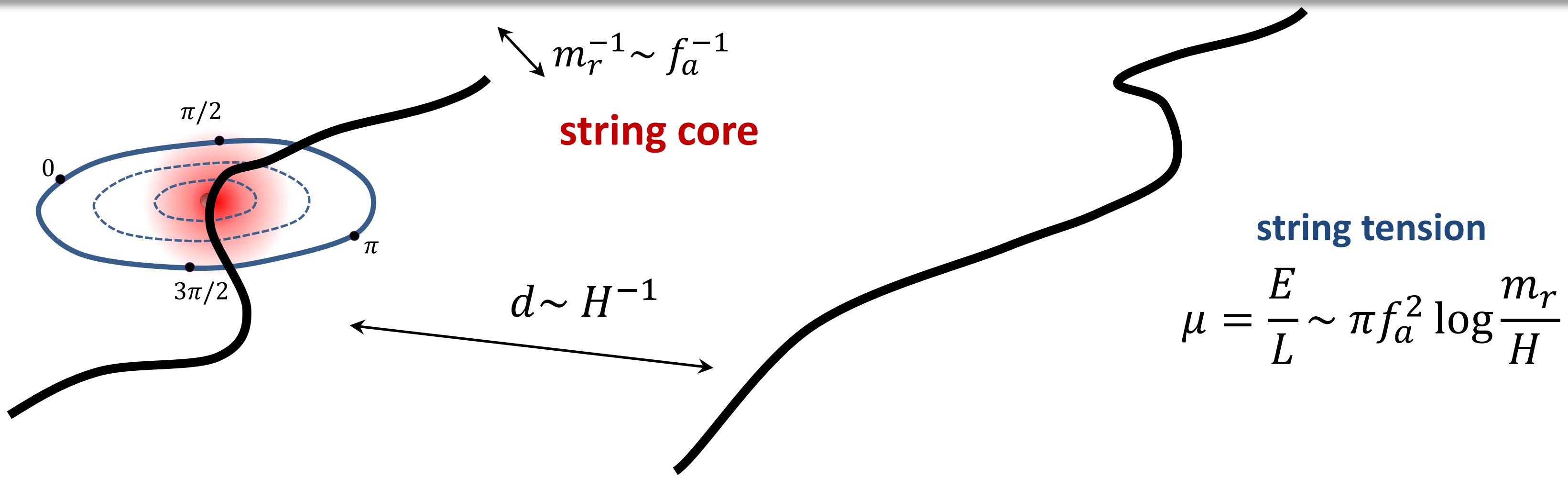

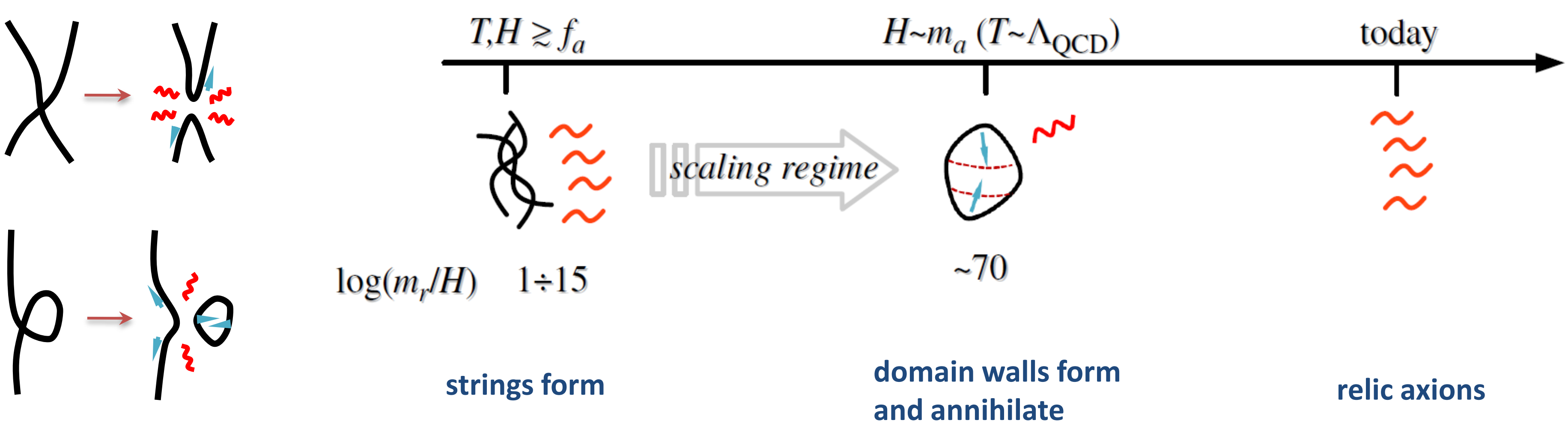

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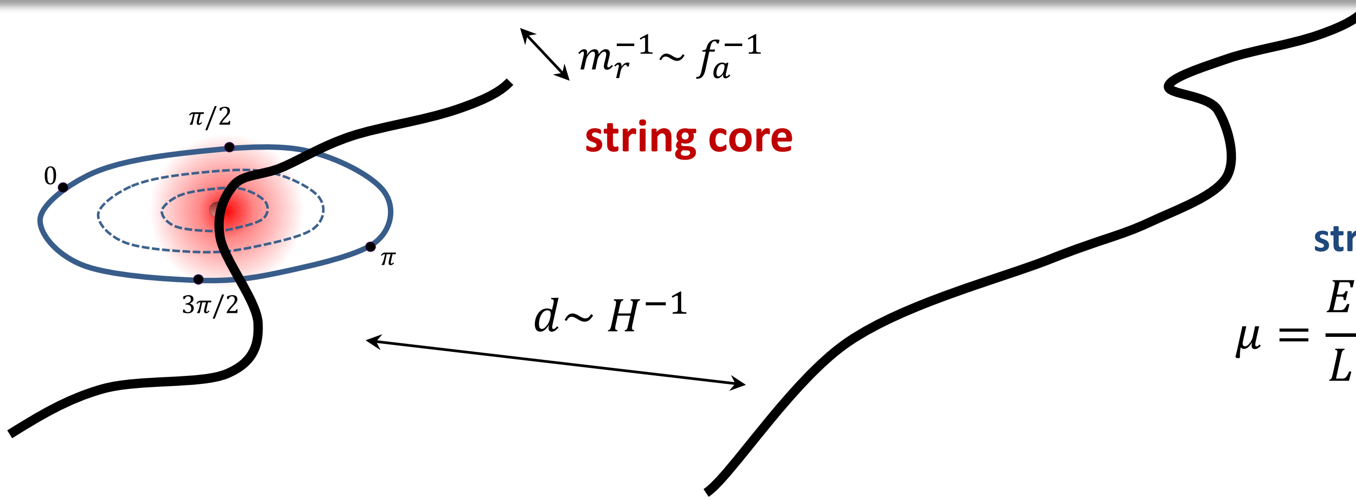

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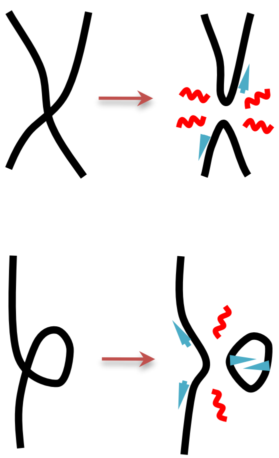
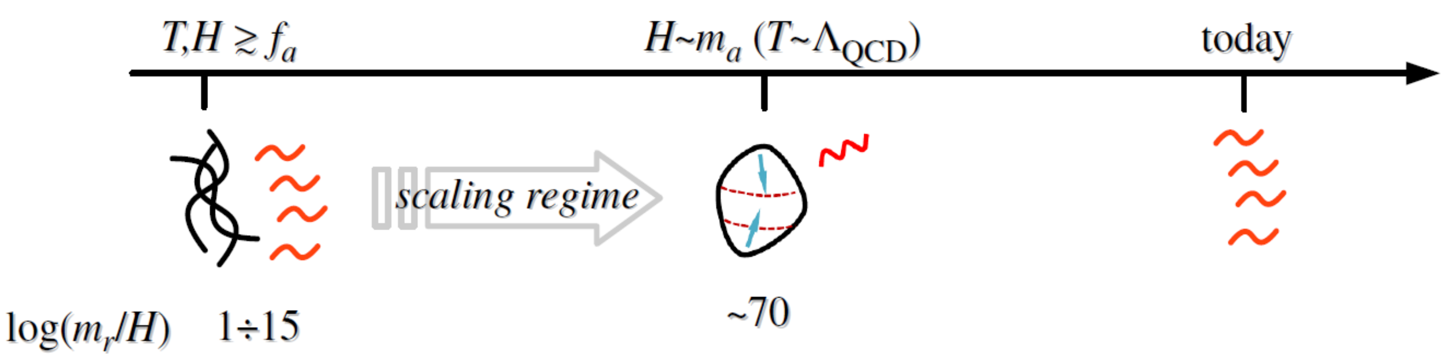


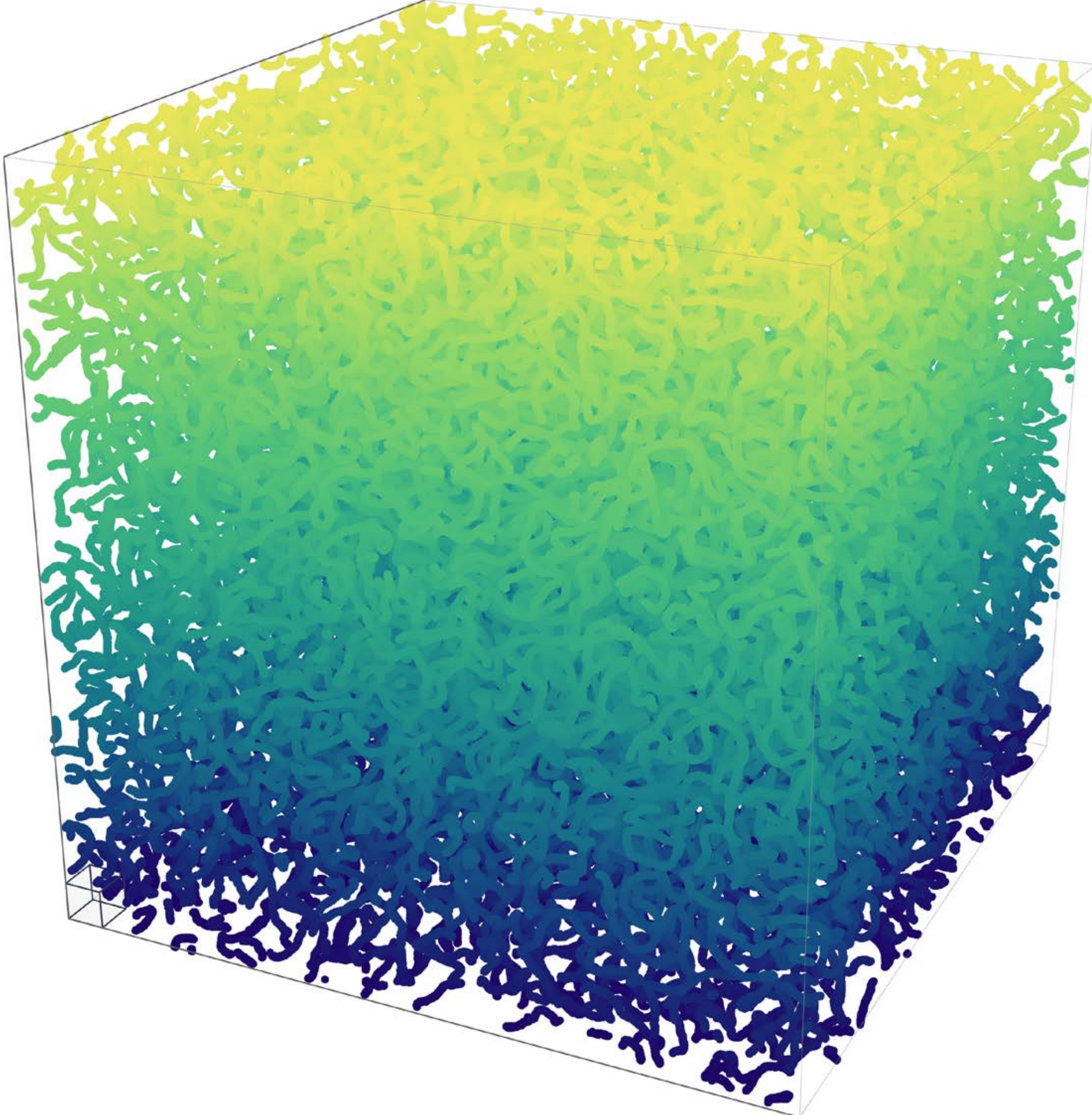


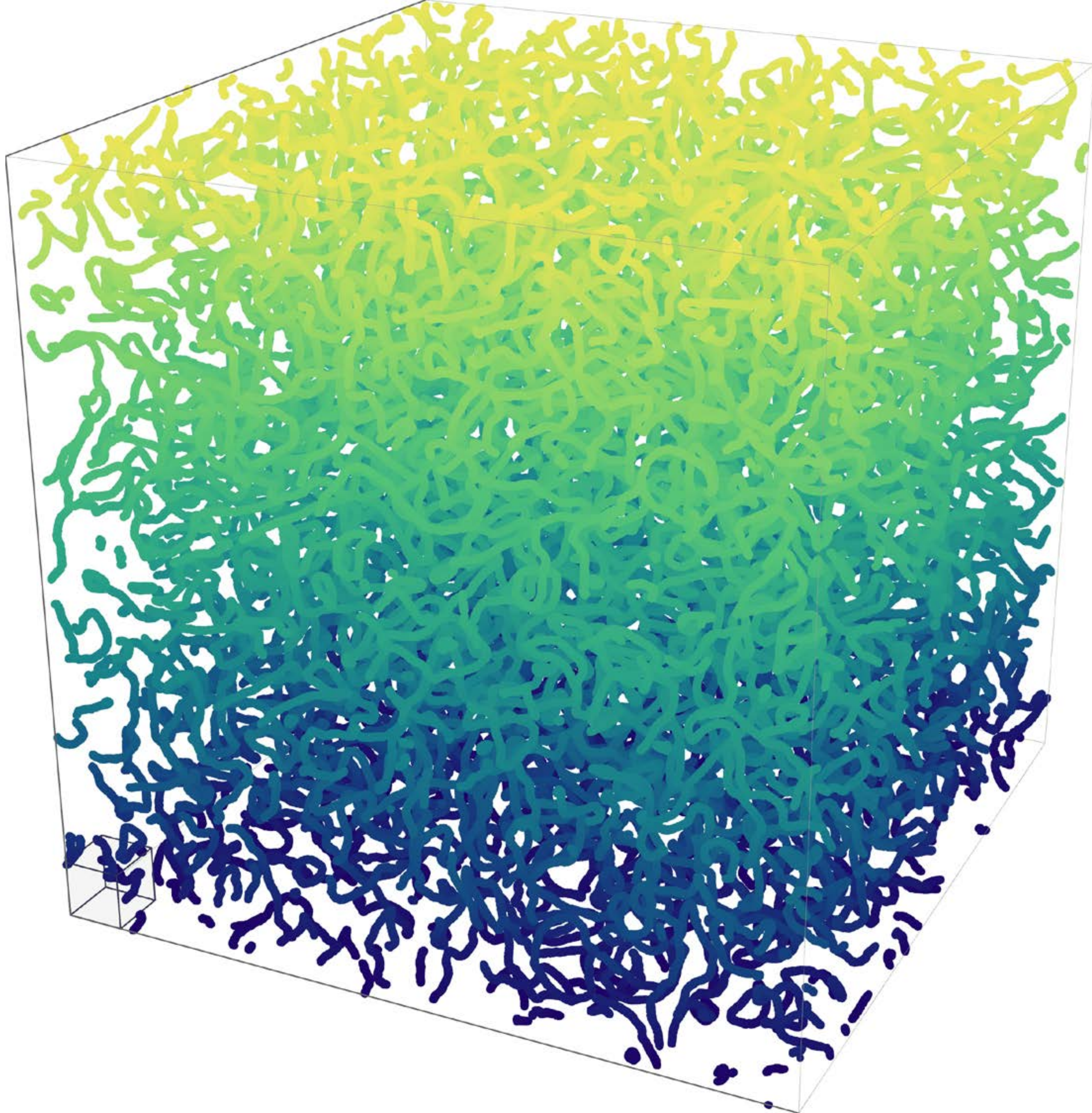
strings form

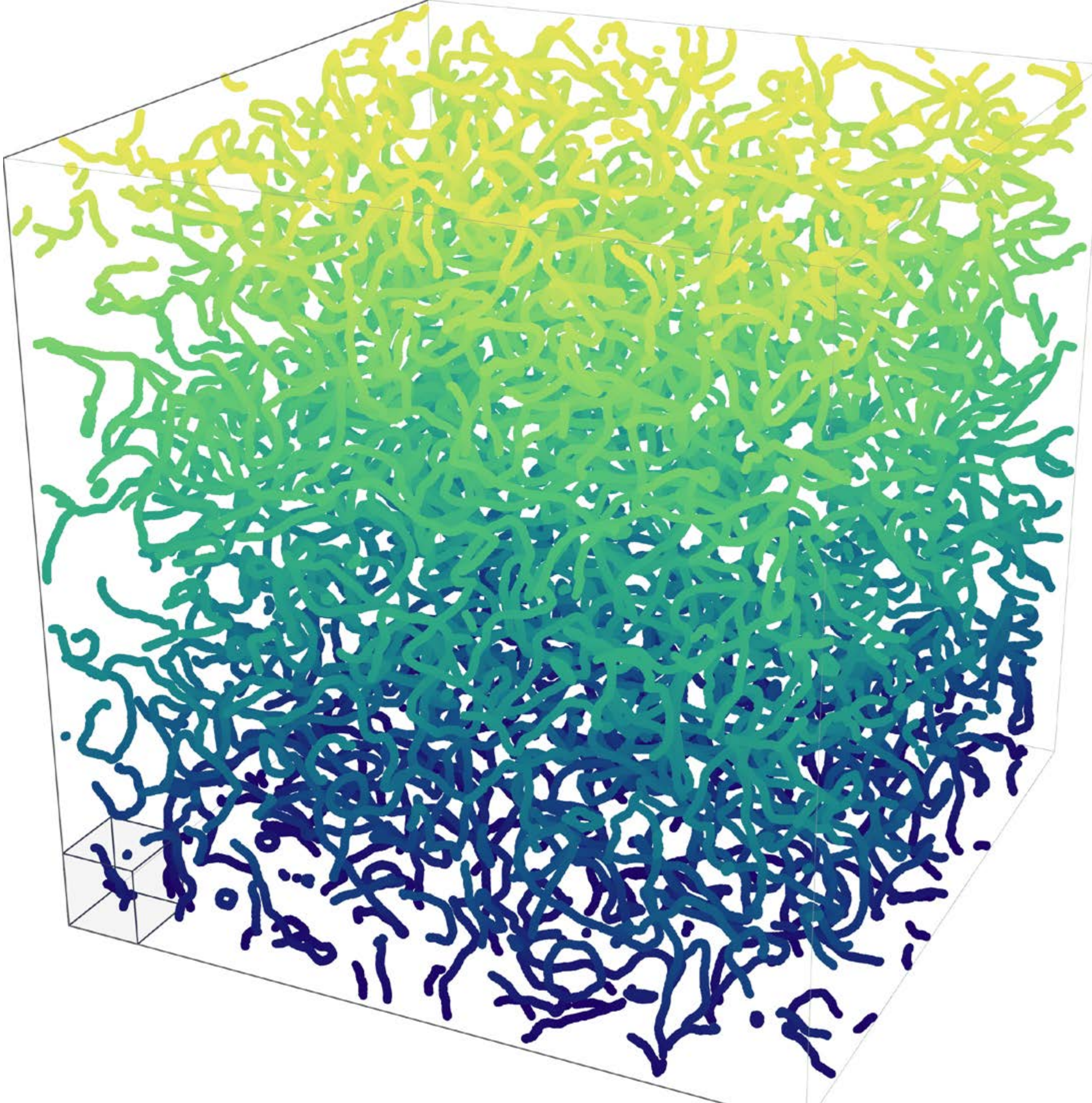
domain walls form and annihilate

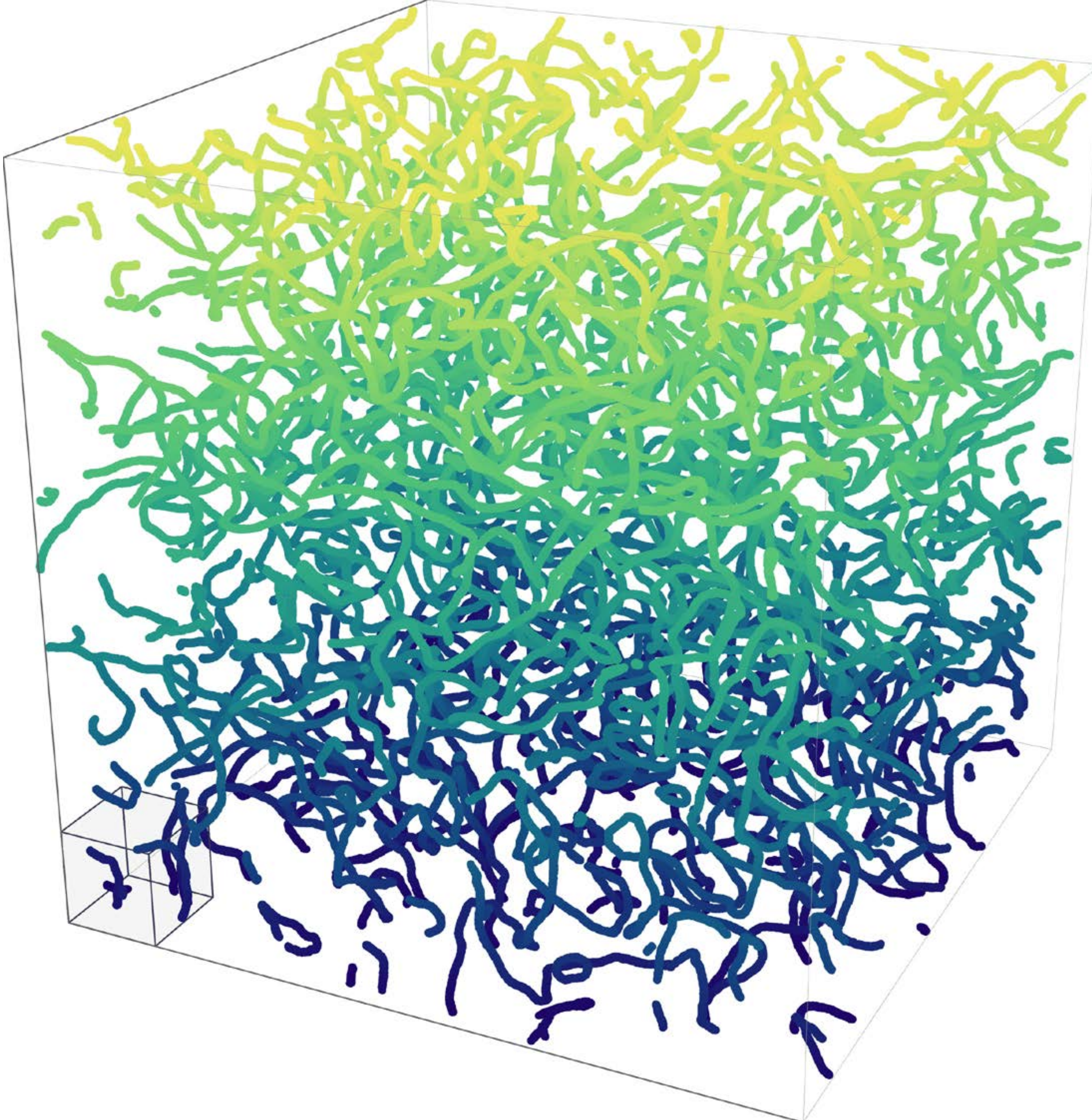
relic axions

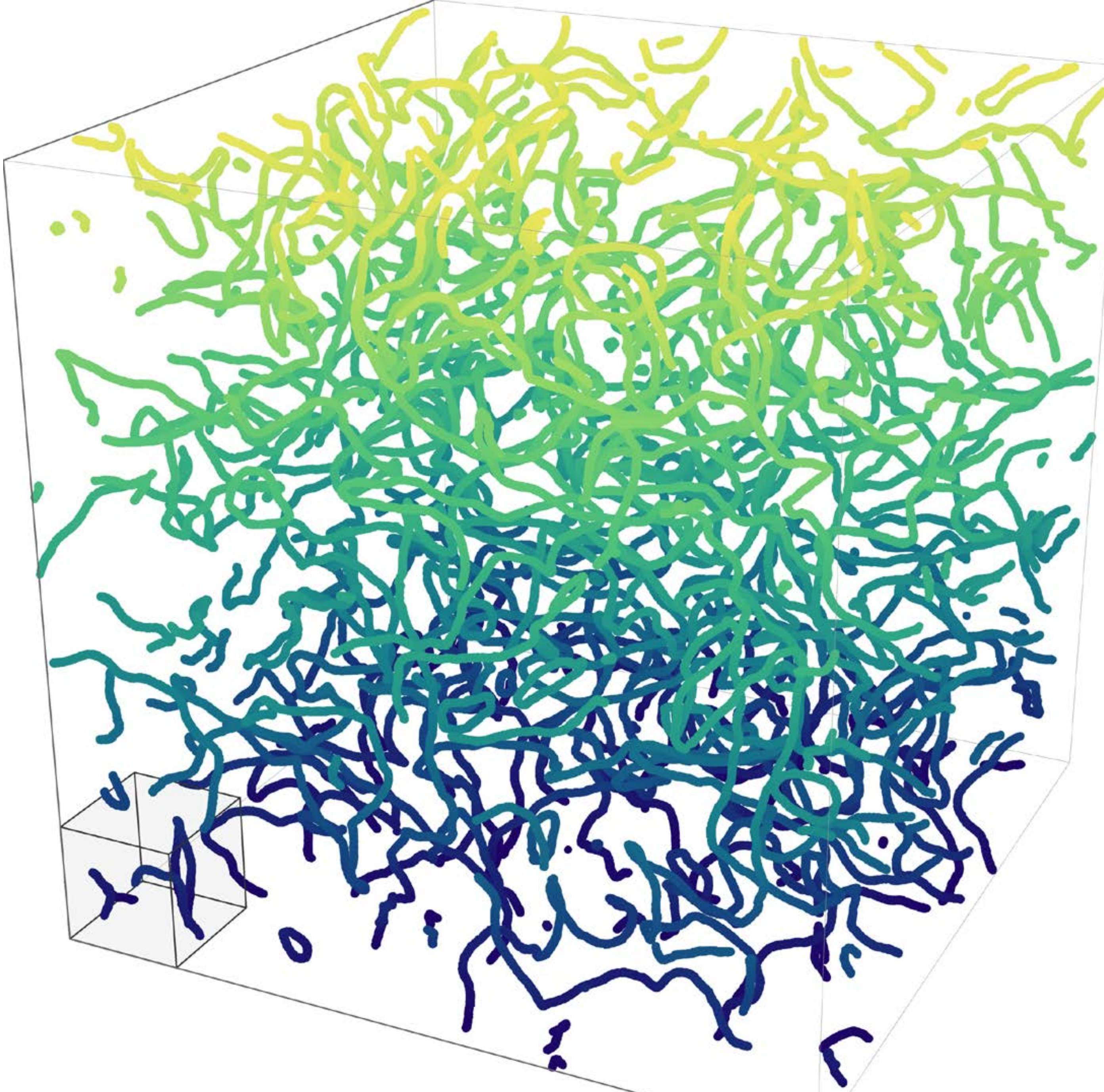
our focus

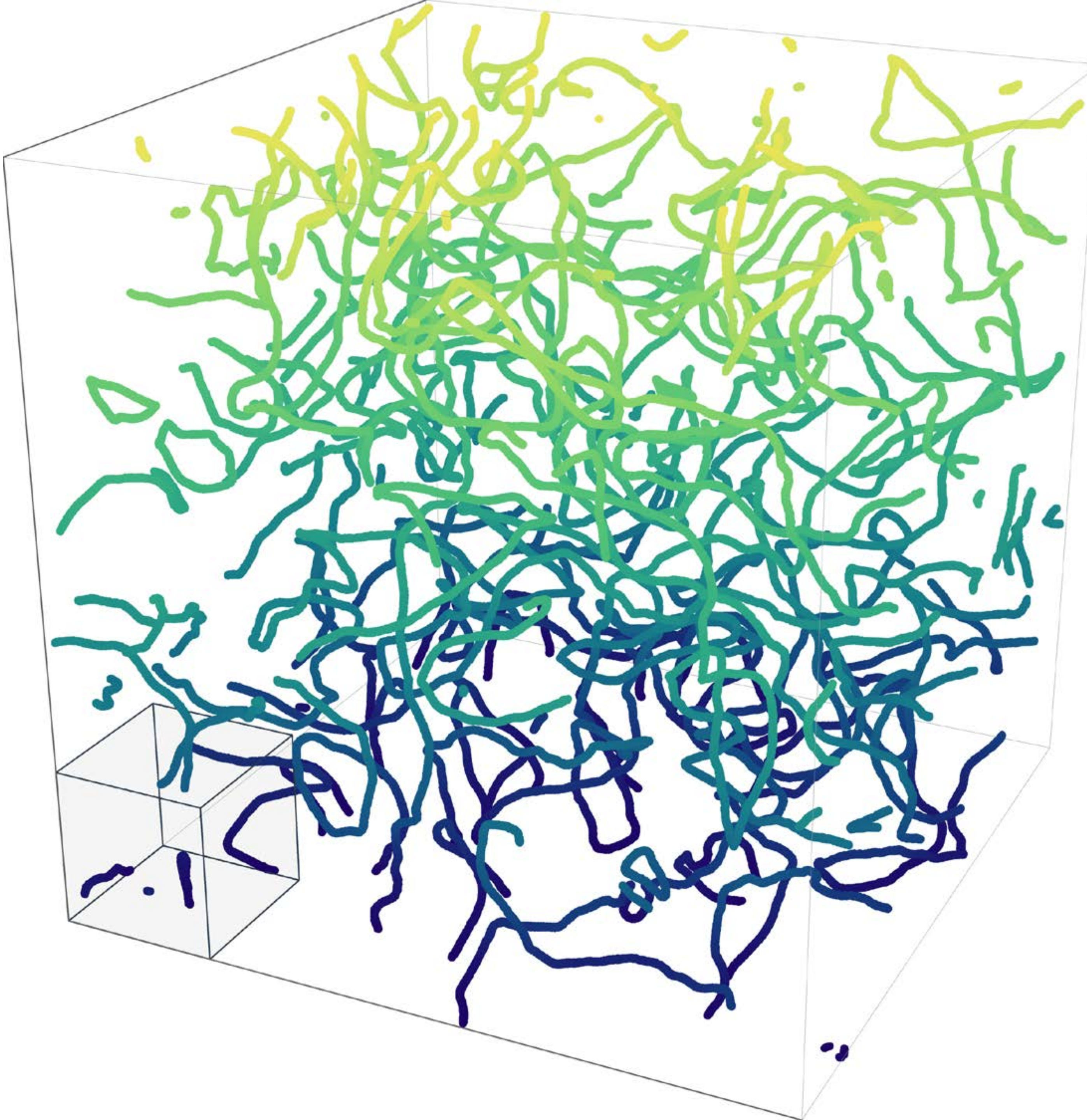


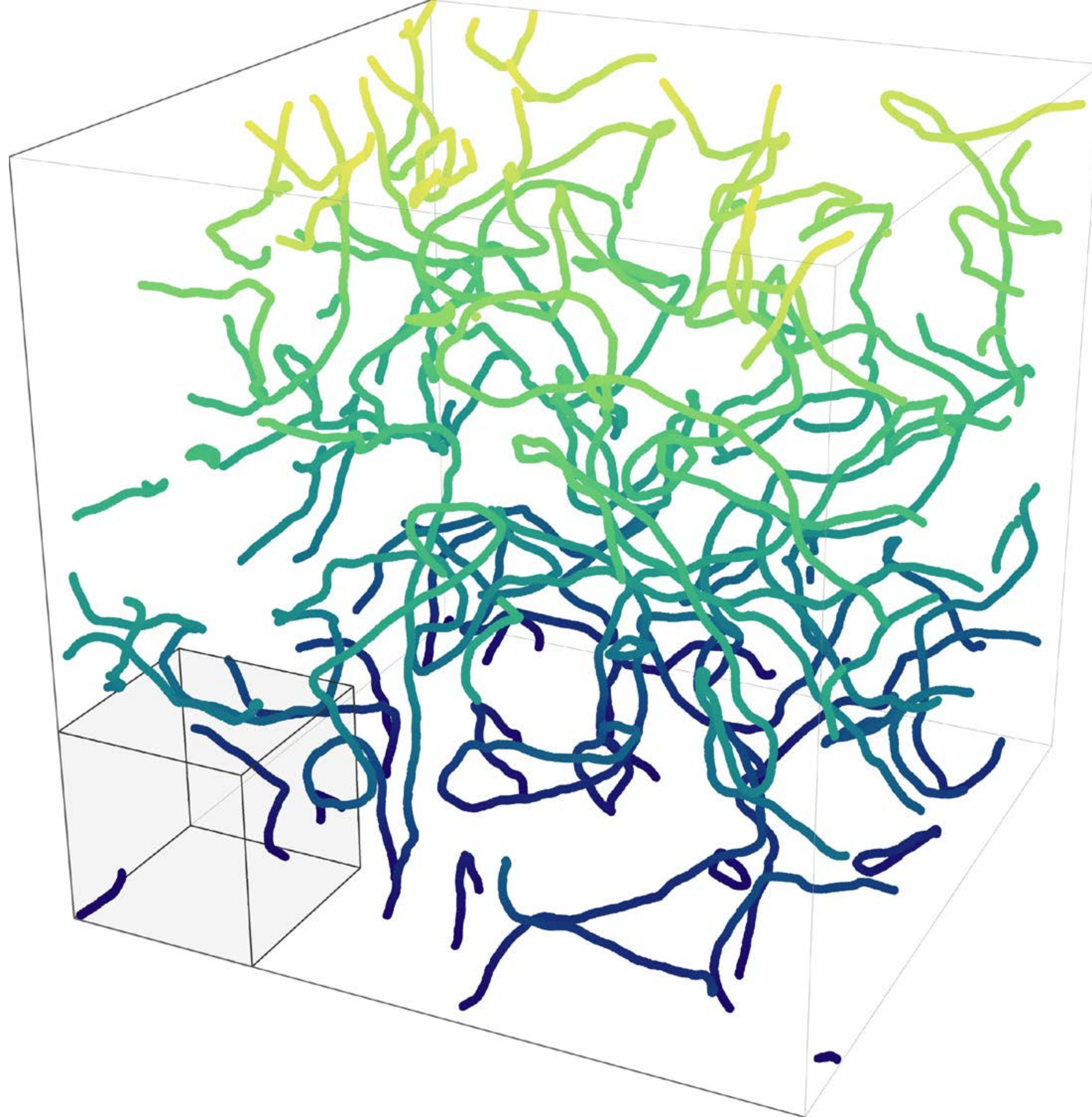


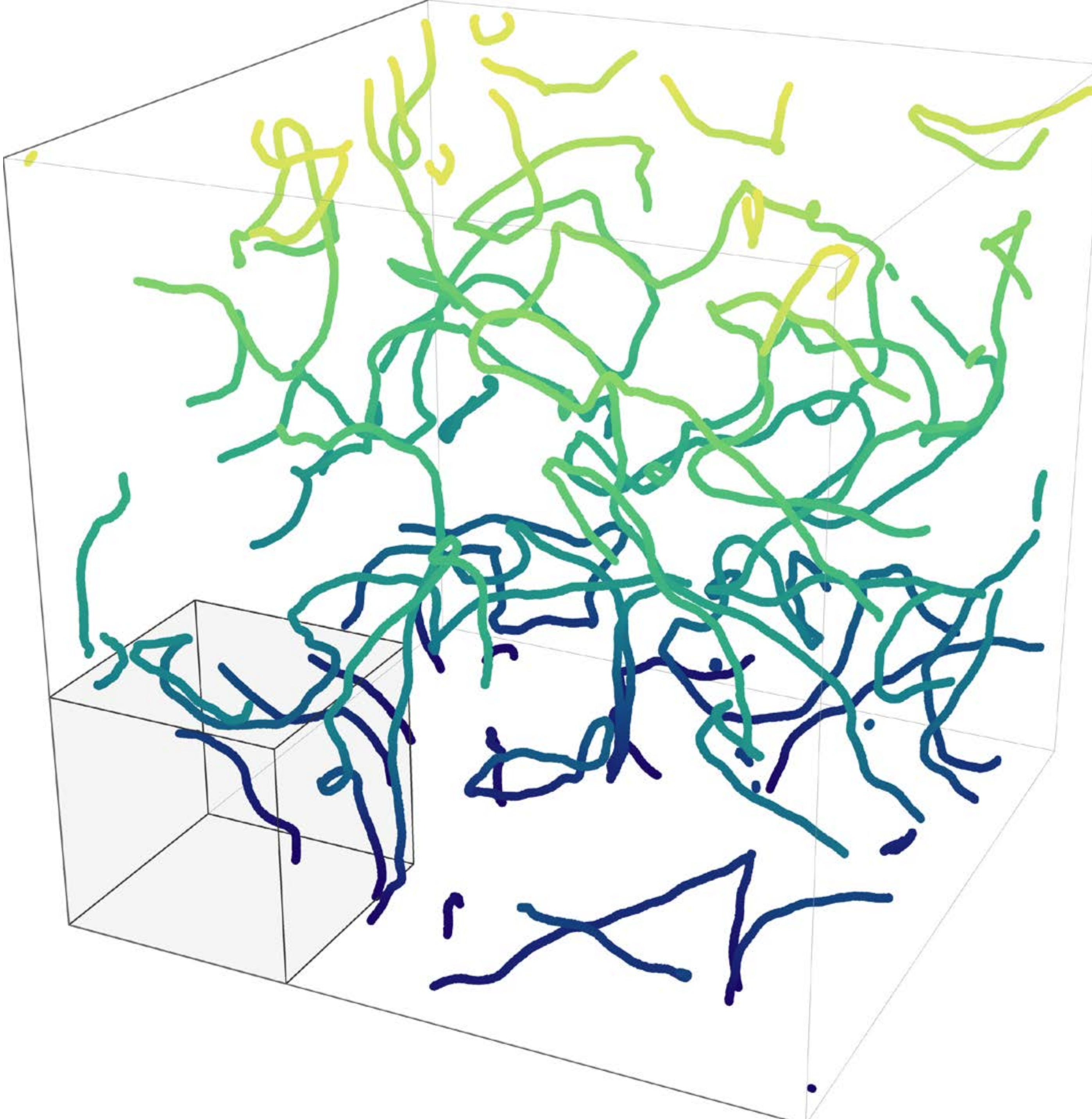


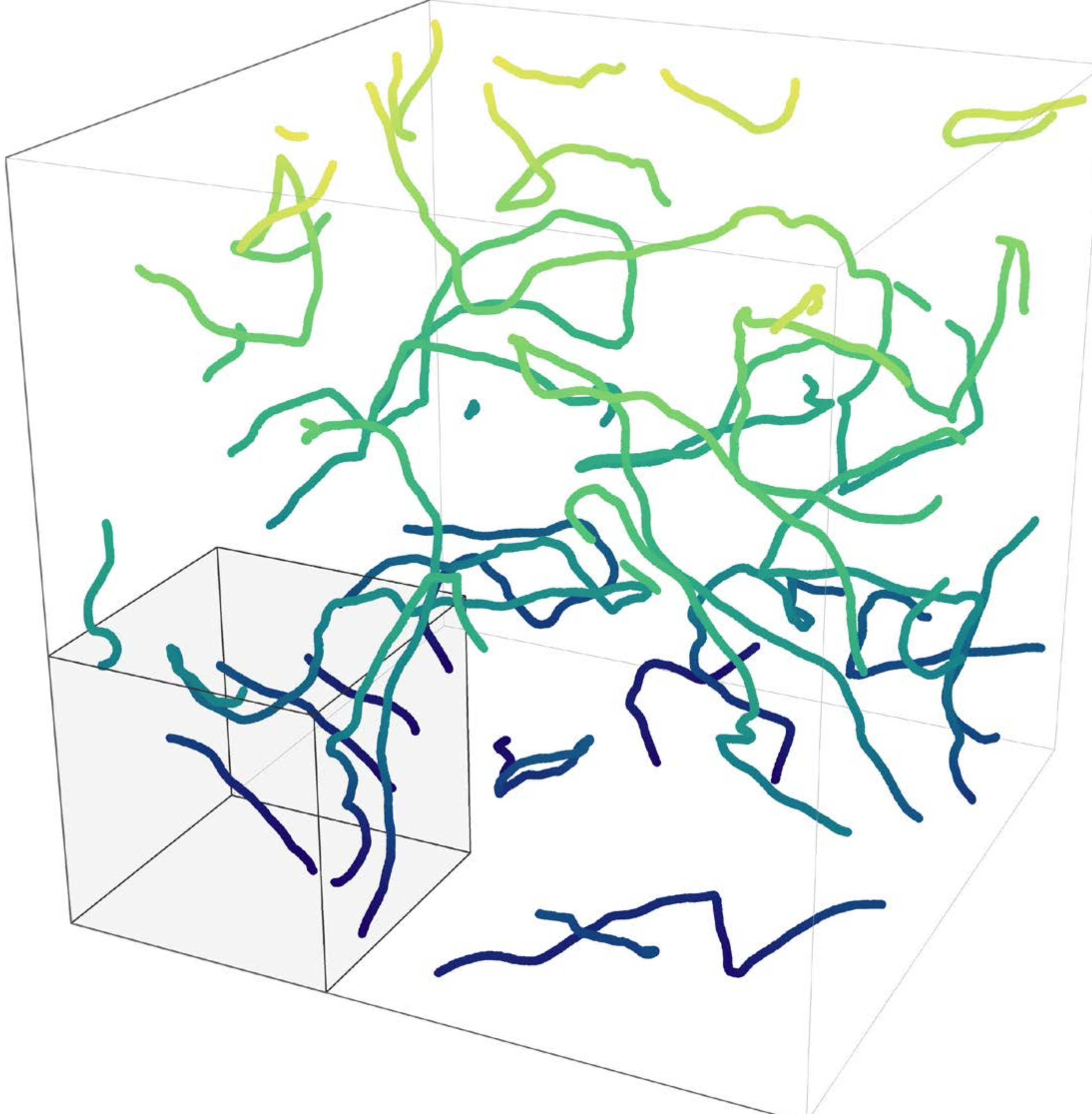


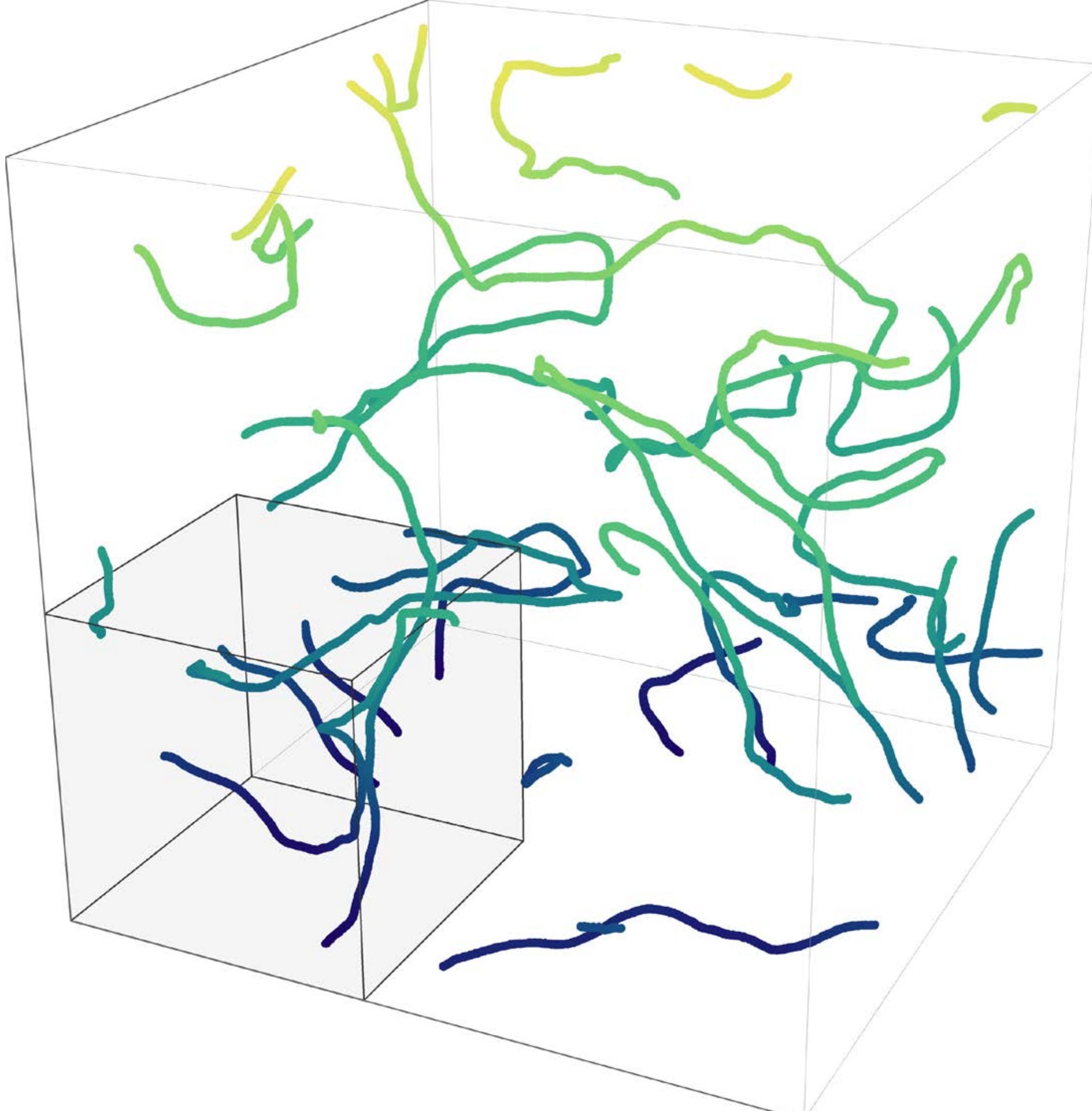


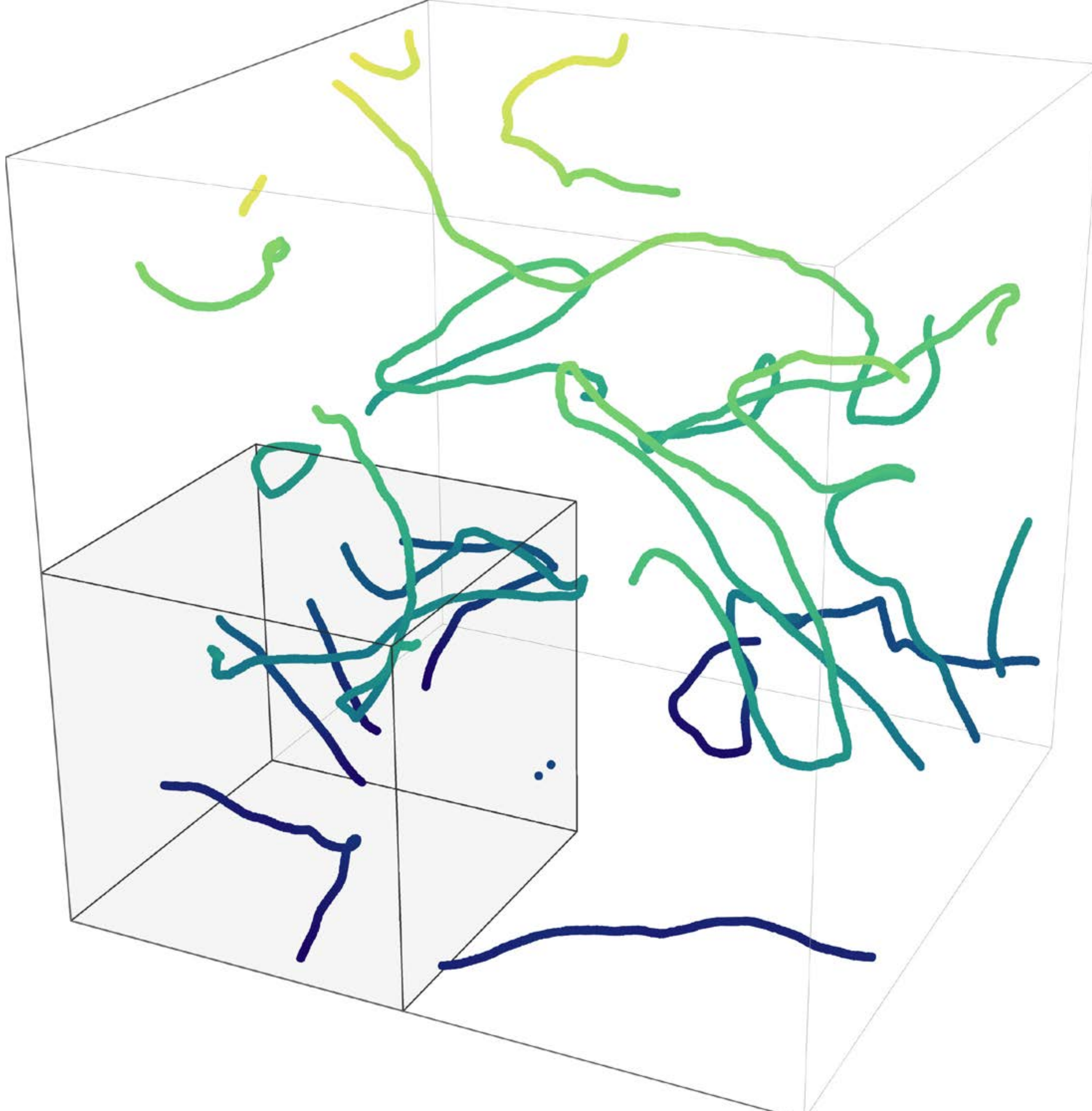


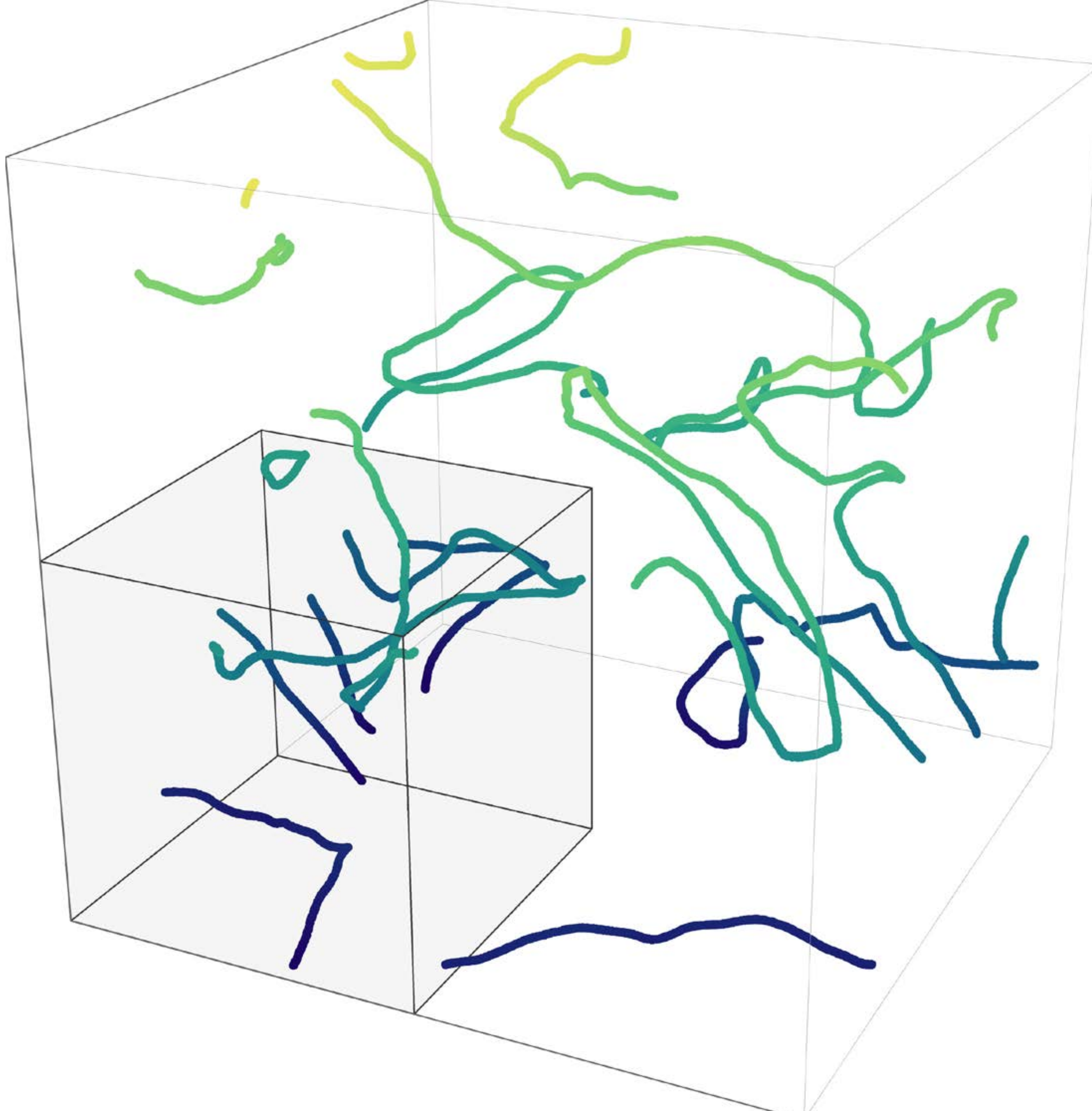










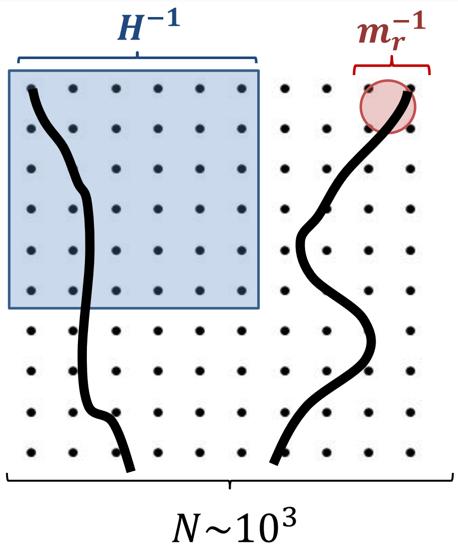


Why it’s hard

Why it's hard

- a few lattice points per string core
- a few Hubble patches

$$\log\frac{m_r}{H} \le \log\left(\frac{\square}{\bigcirc}\right) \sim 6 \ll 70$$



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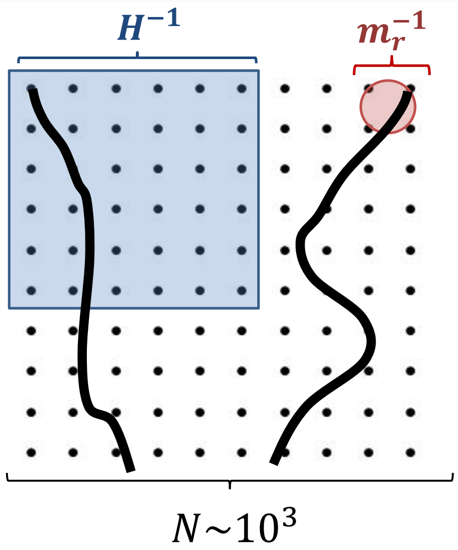
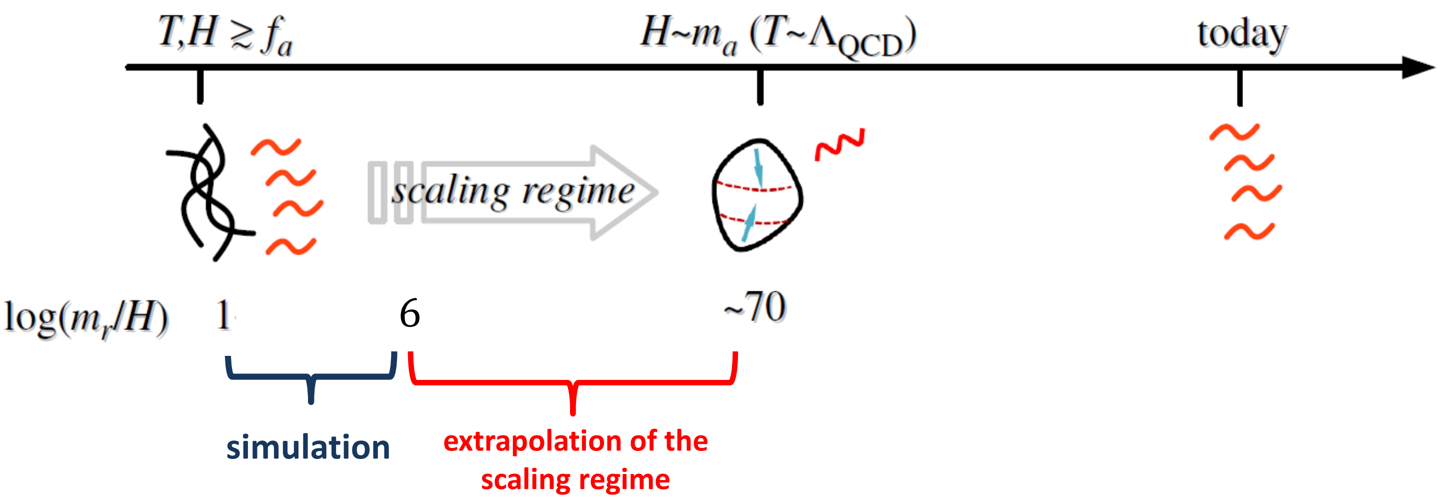


Idea: take advatage of the attractor



The Attractive Solution

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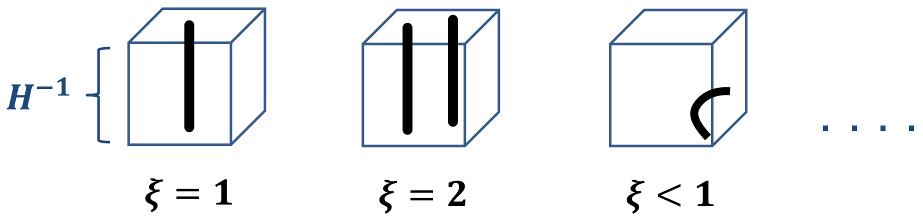
Number of strings per Hubble

$$\xi \equiv \frac{N_{strings}}{H^{-3}}$$



string length in one Hubble volume in units of H^{-1}

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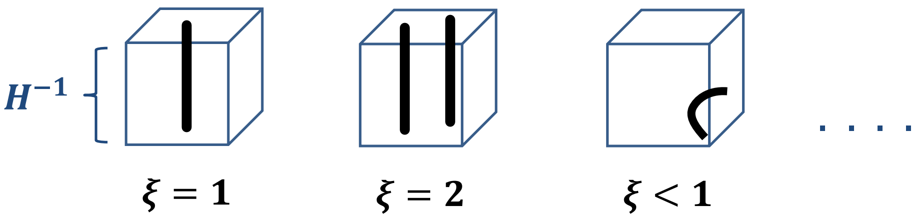

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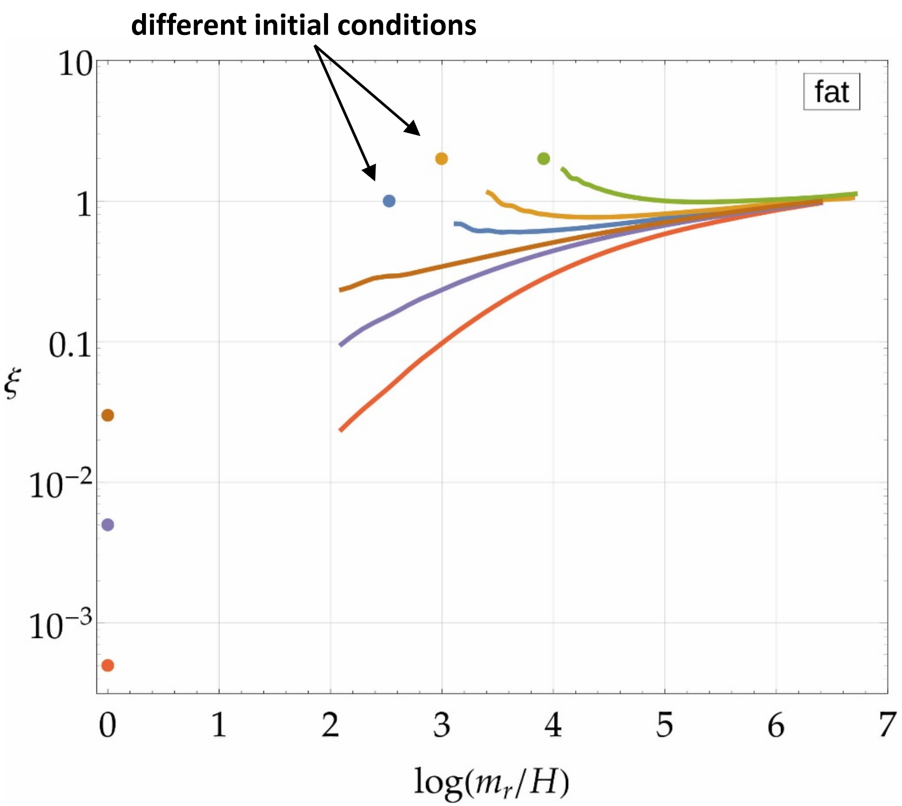

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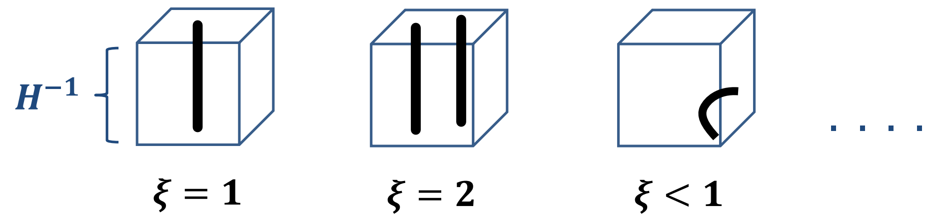

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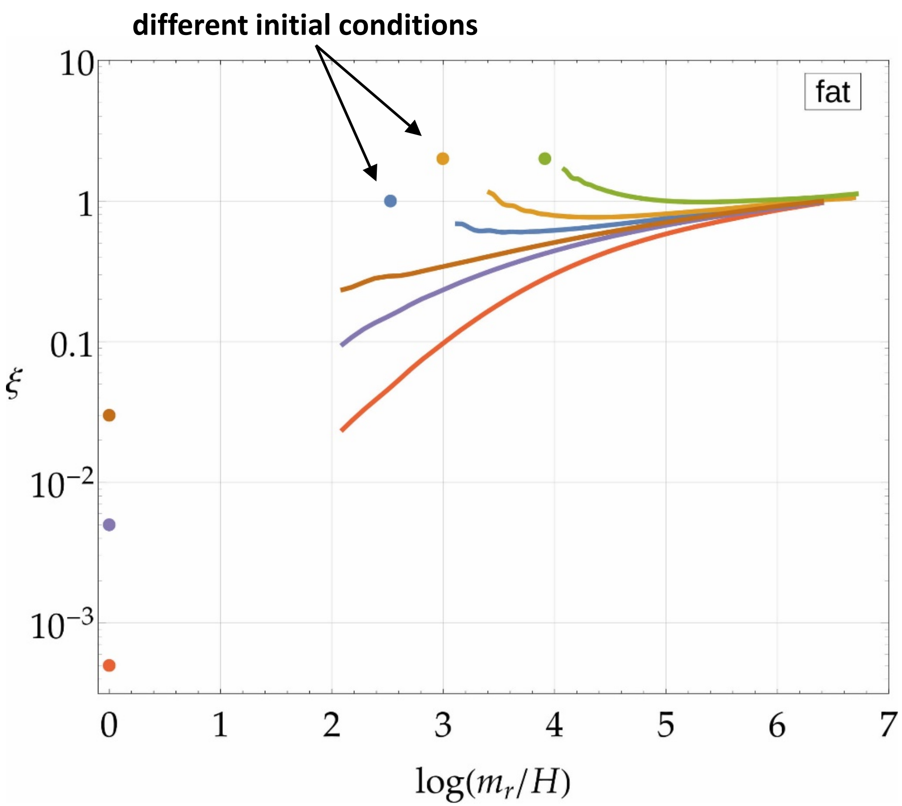

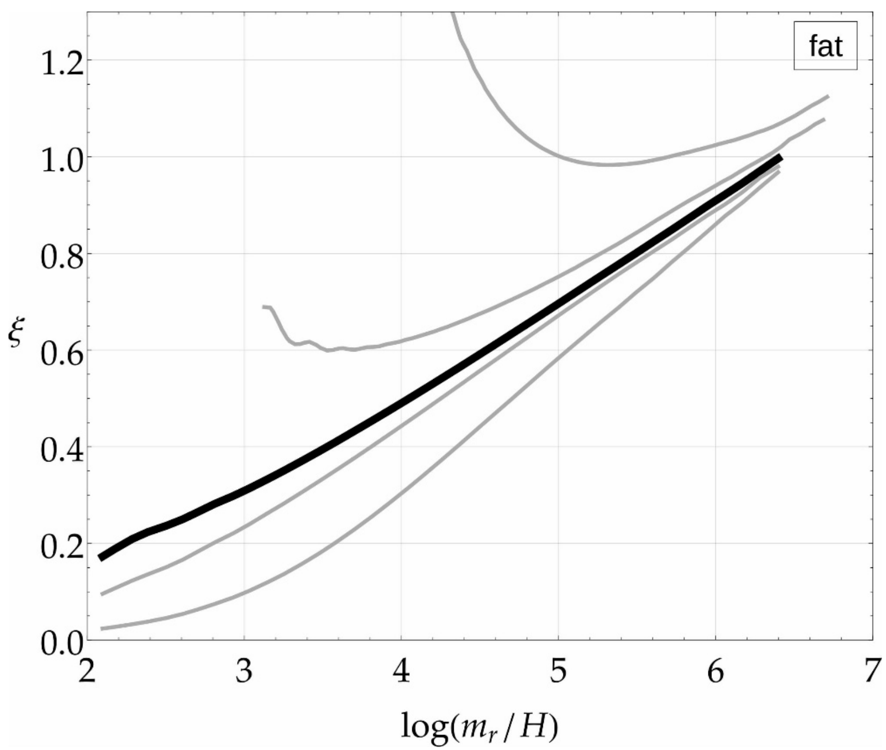

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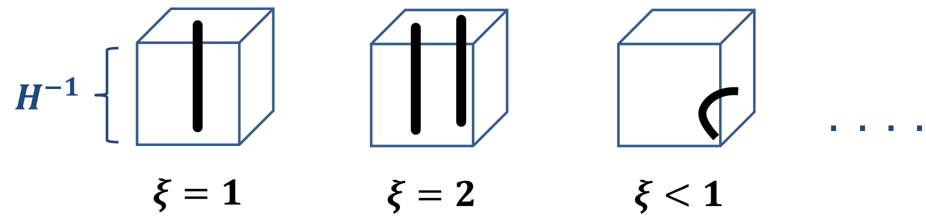

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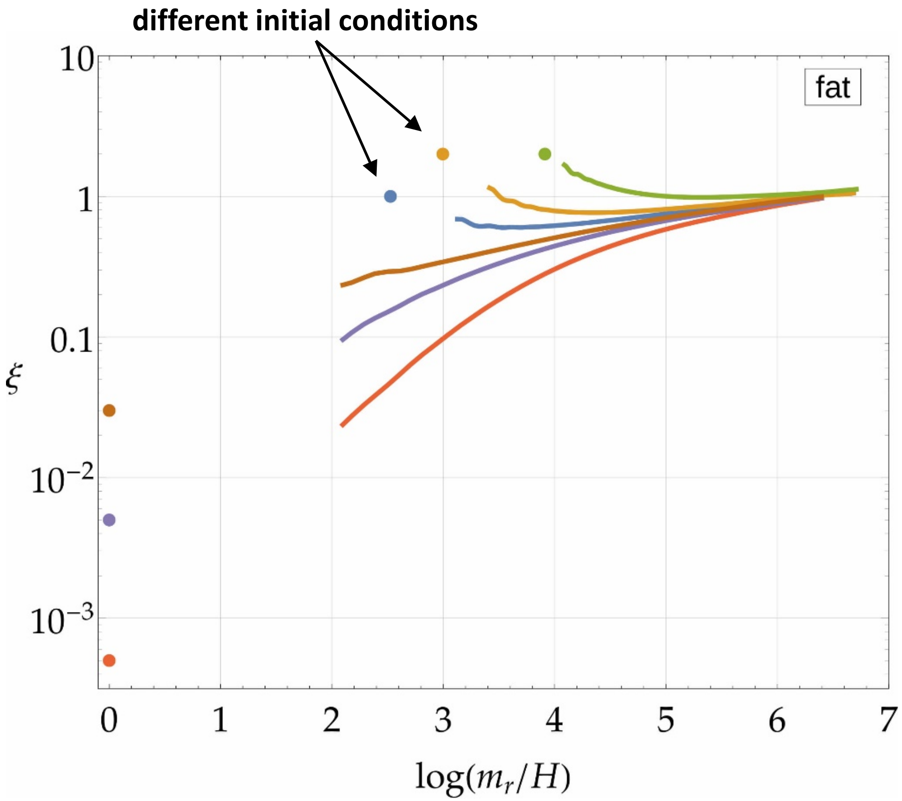

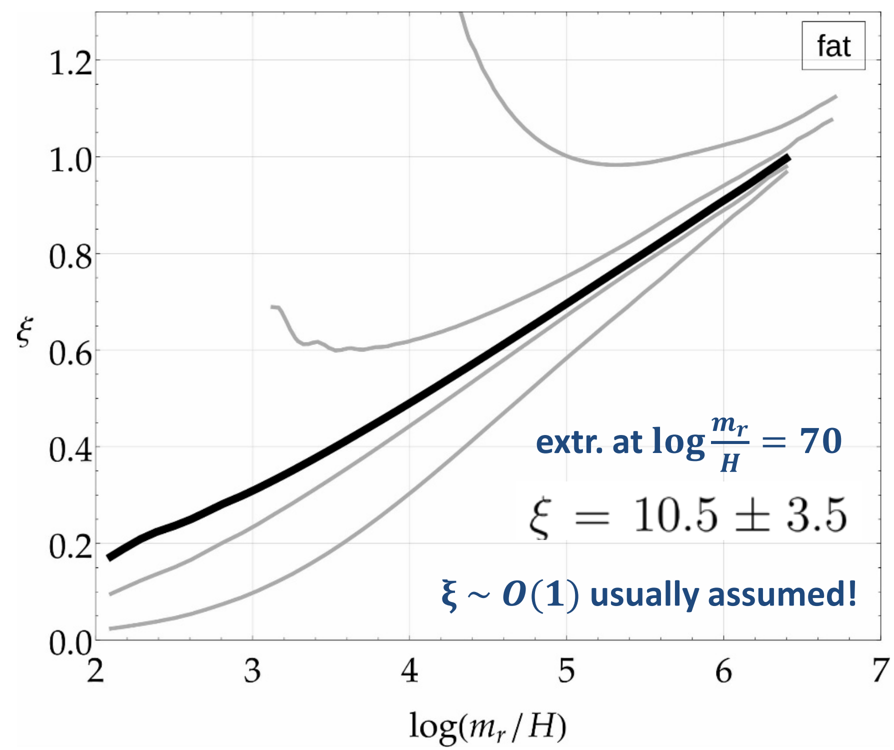

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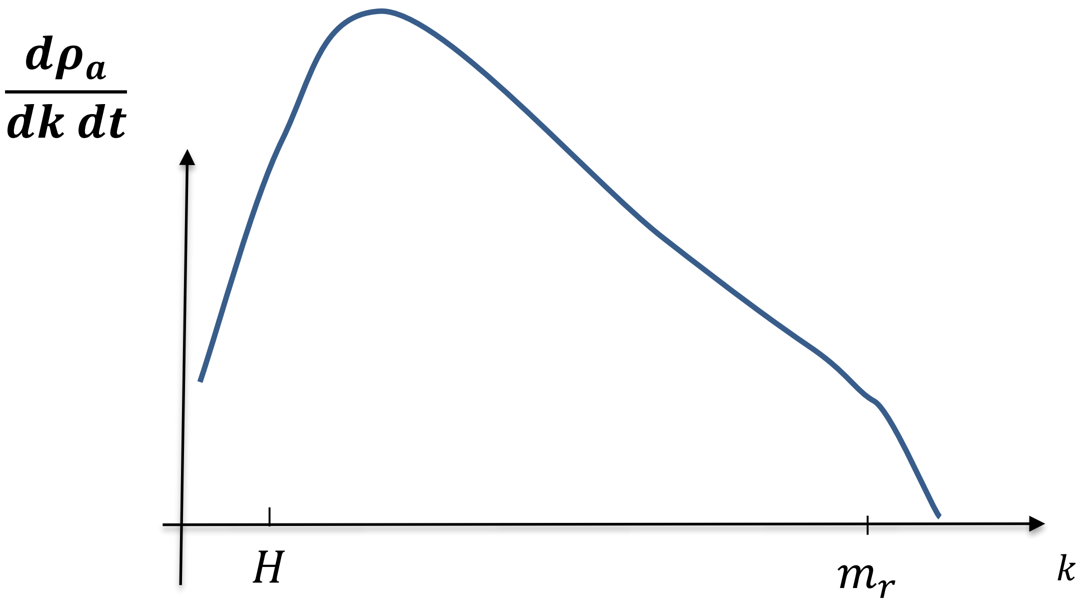
- in between an approximate power law $\frac{d\rho_a}{dk\,dt} \sim \frac{1}{k^q}$



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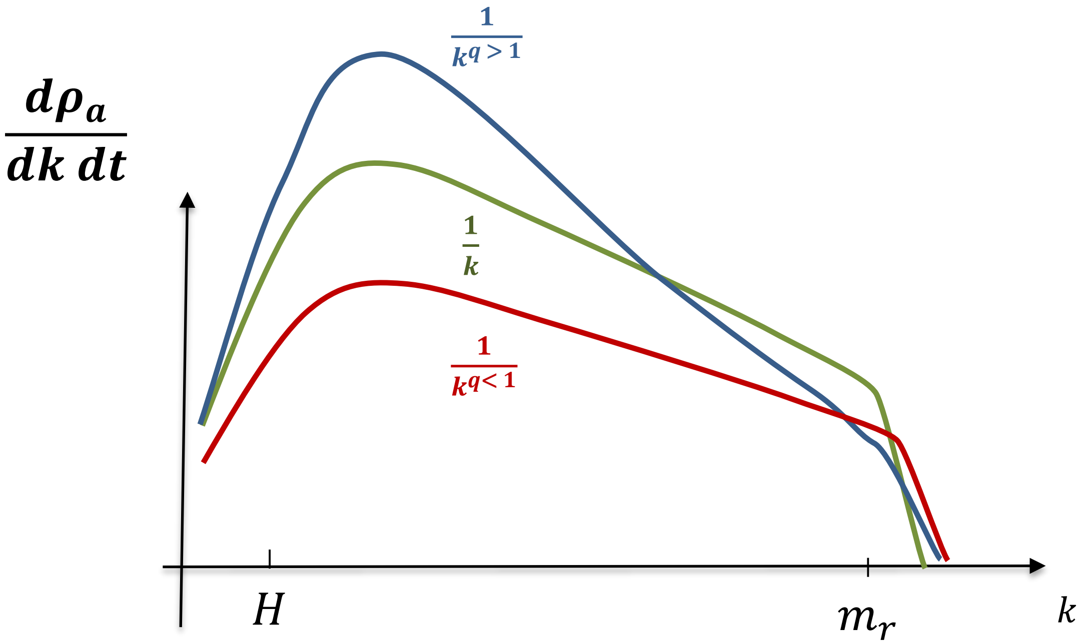

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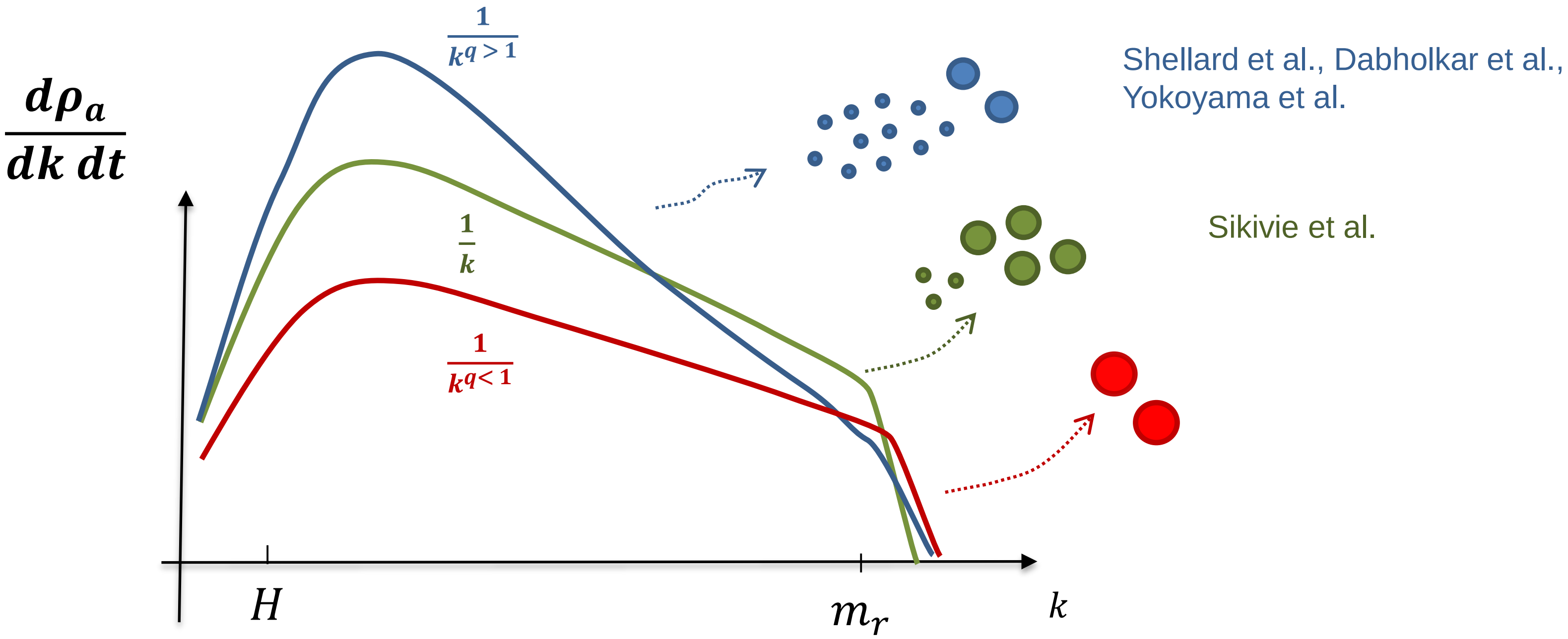

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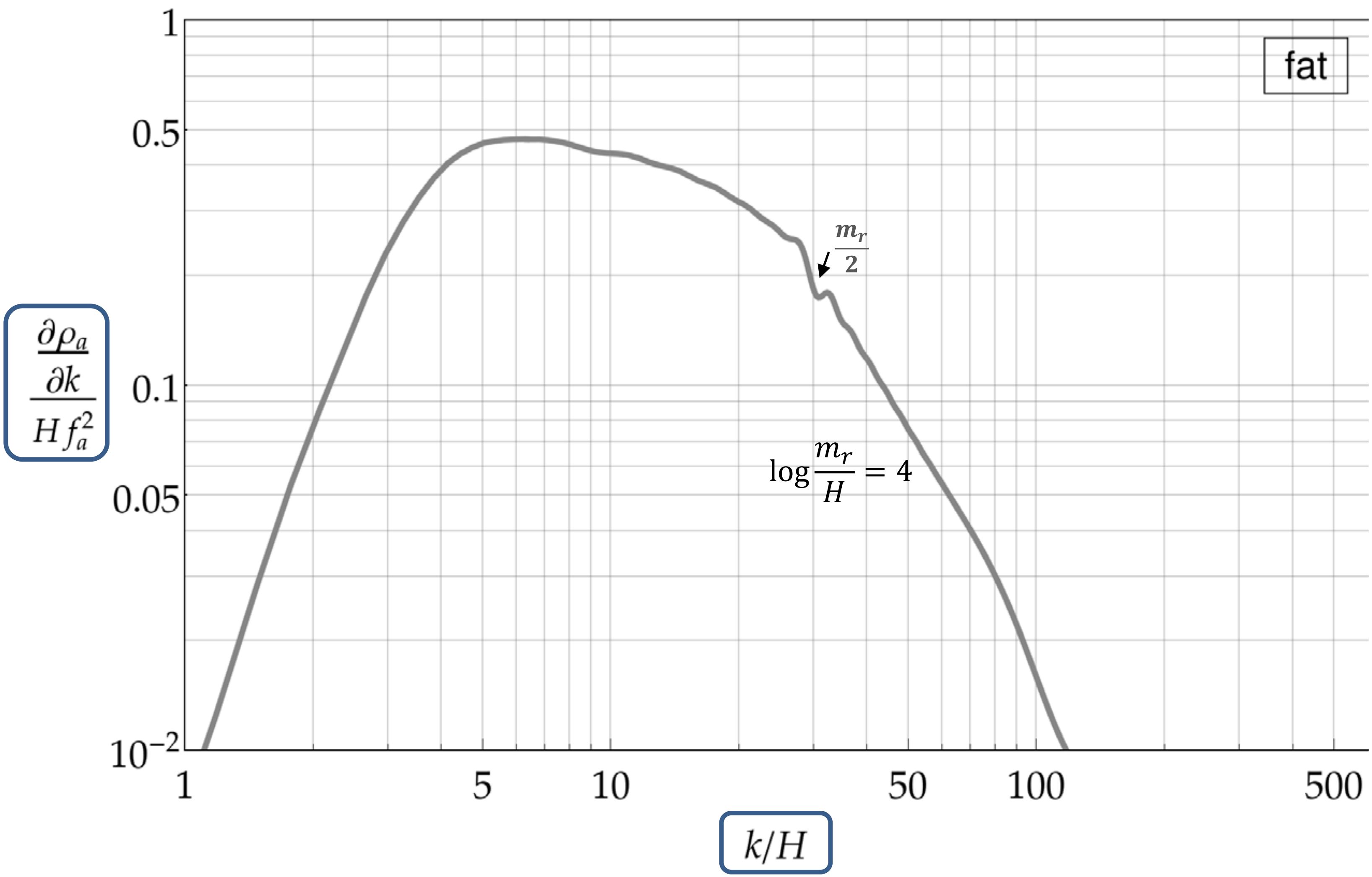

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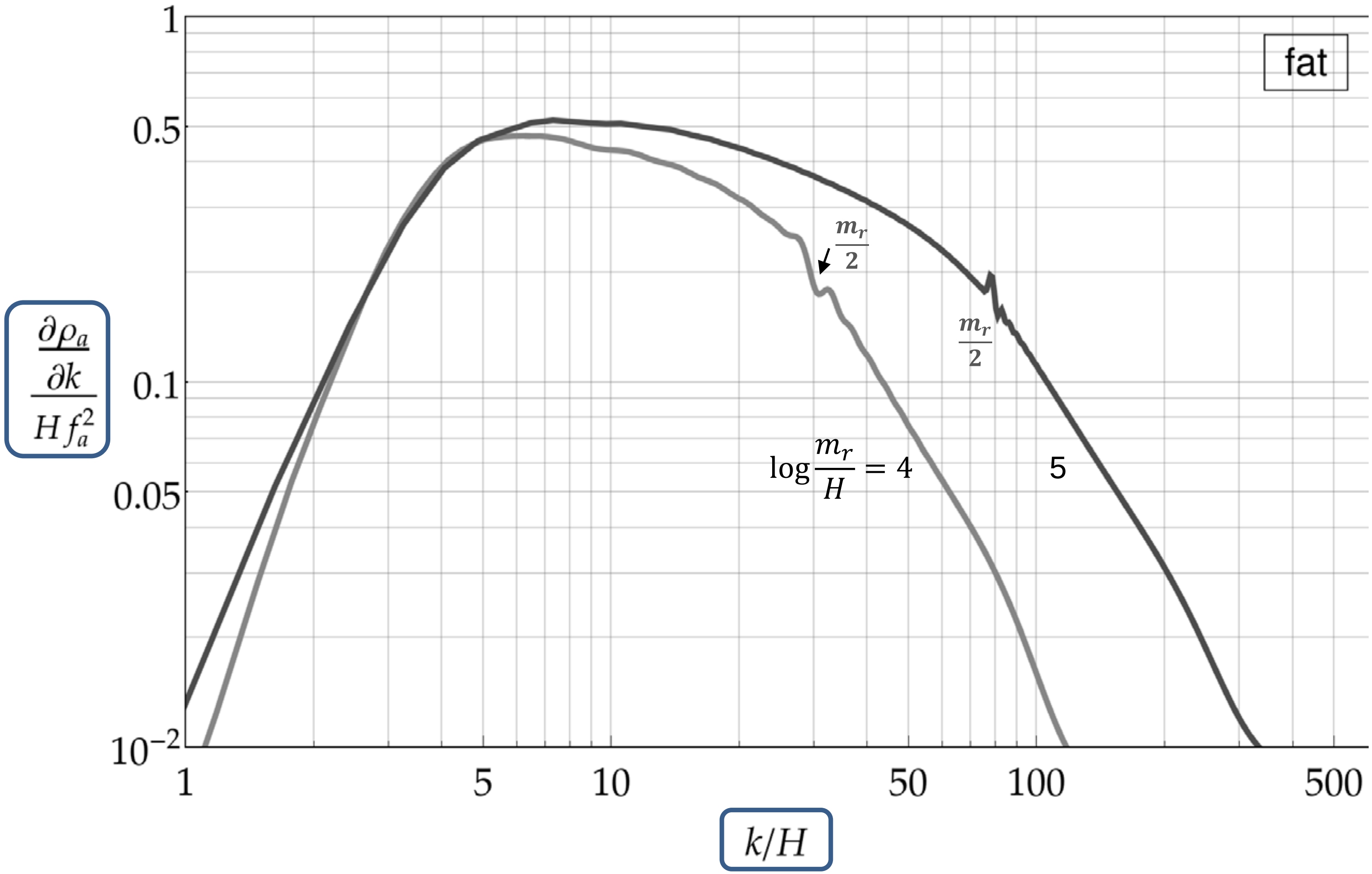

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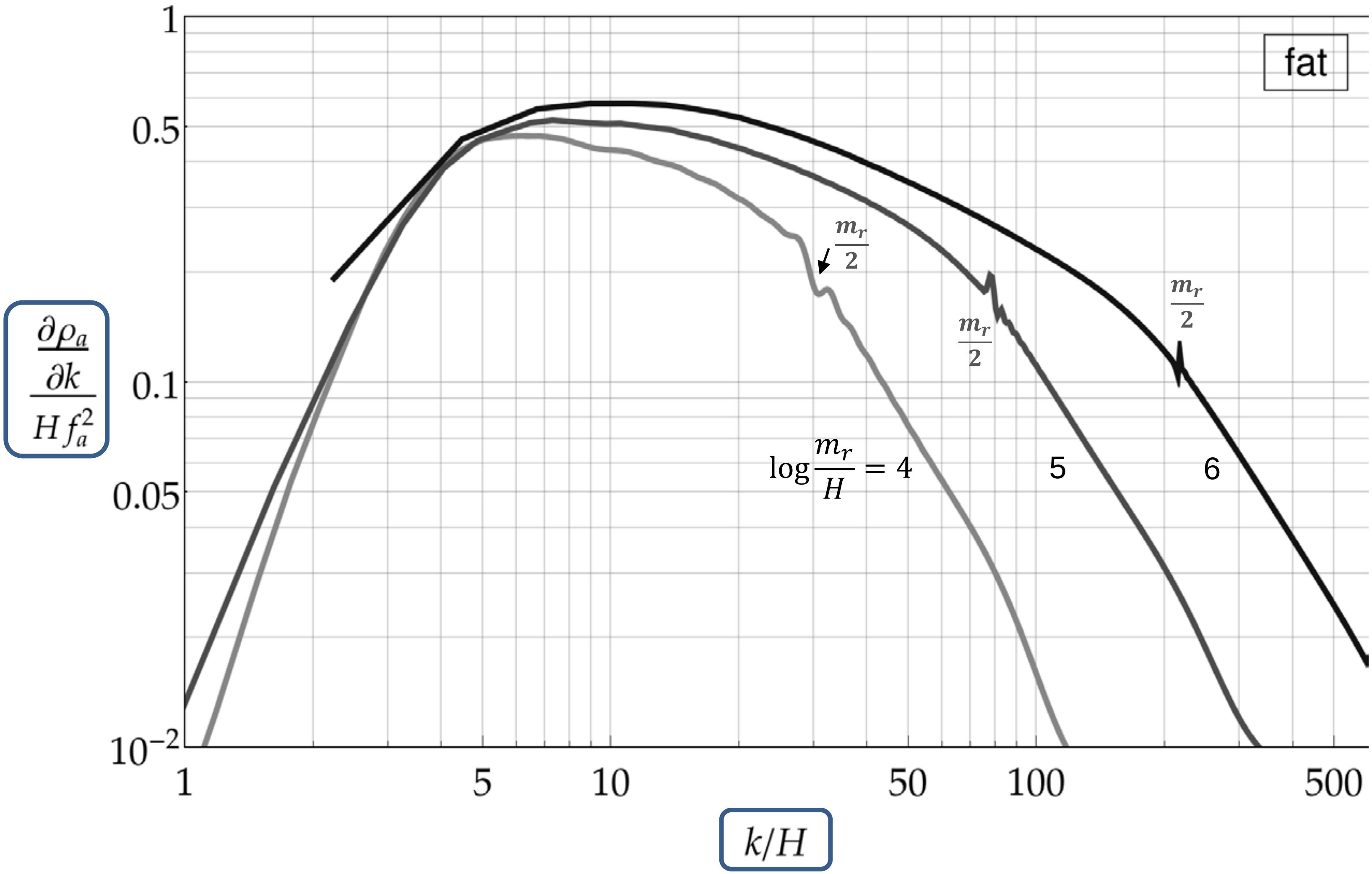

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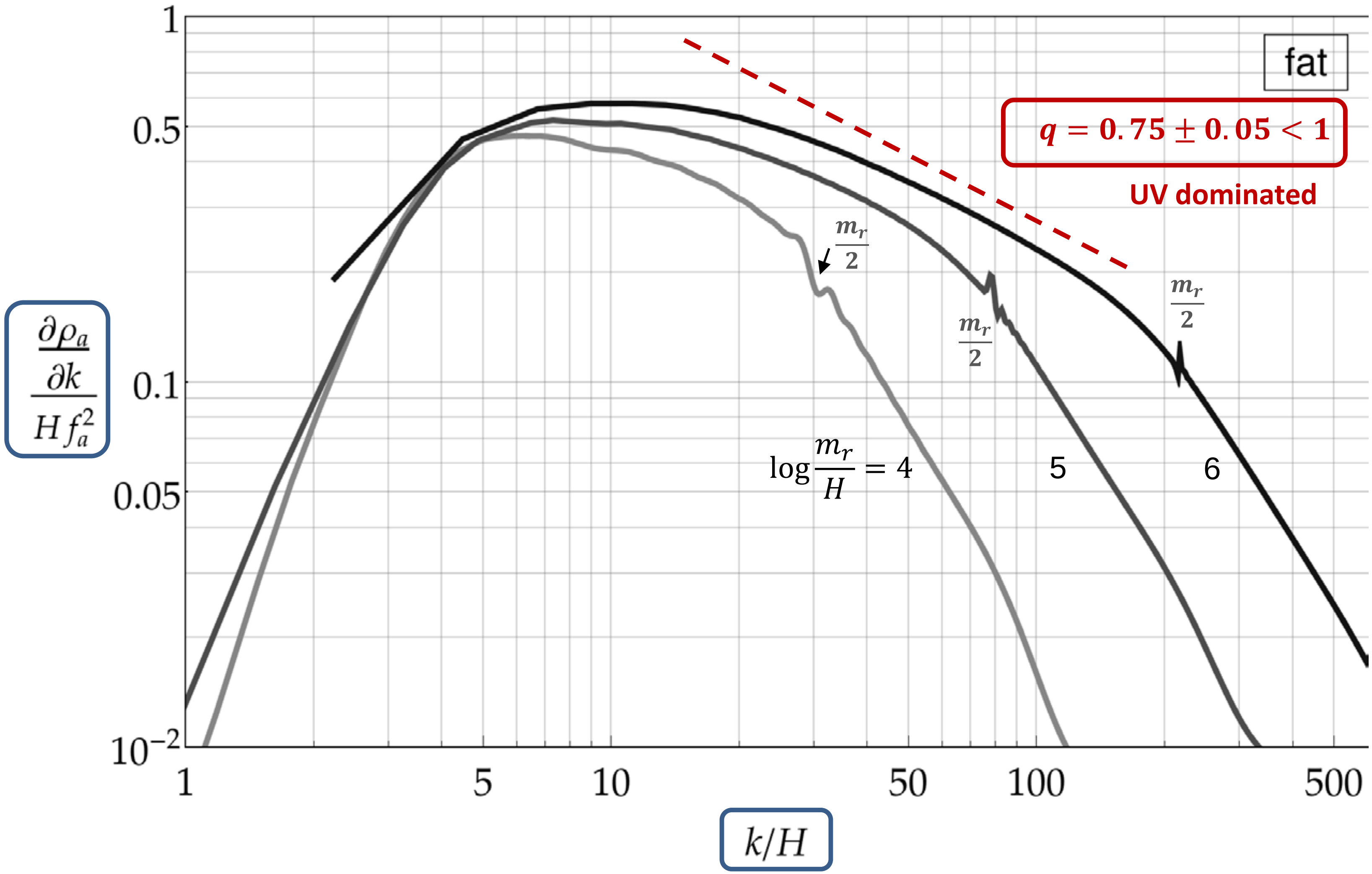

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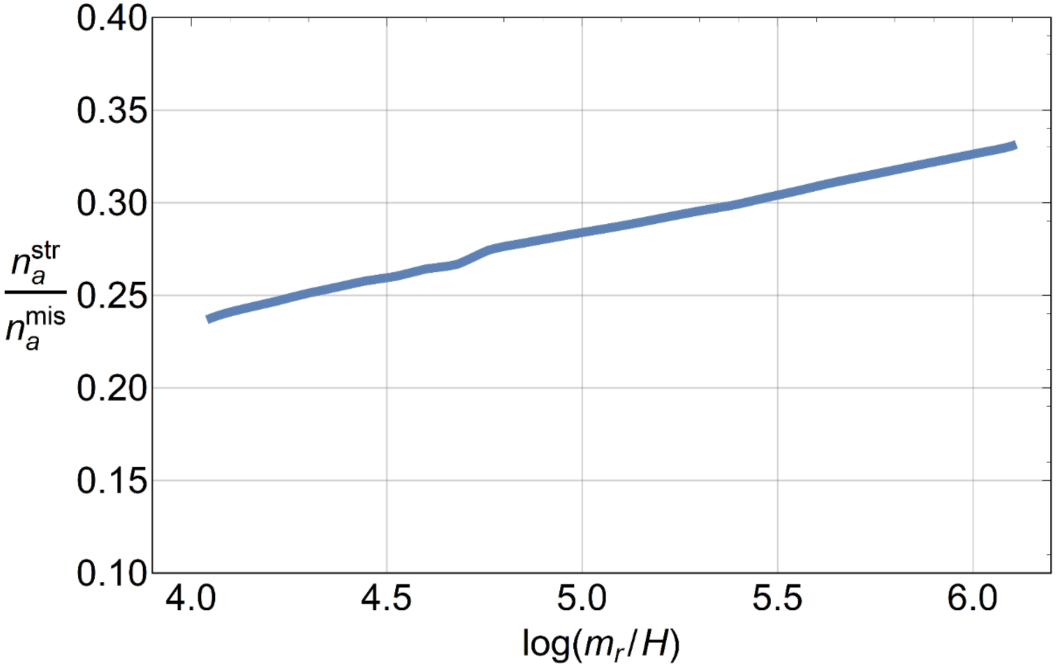

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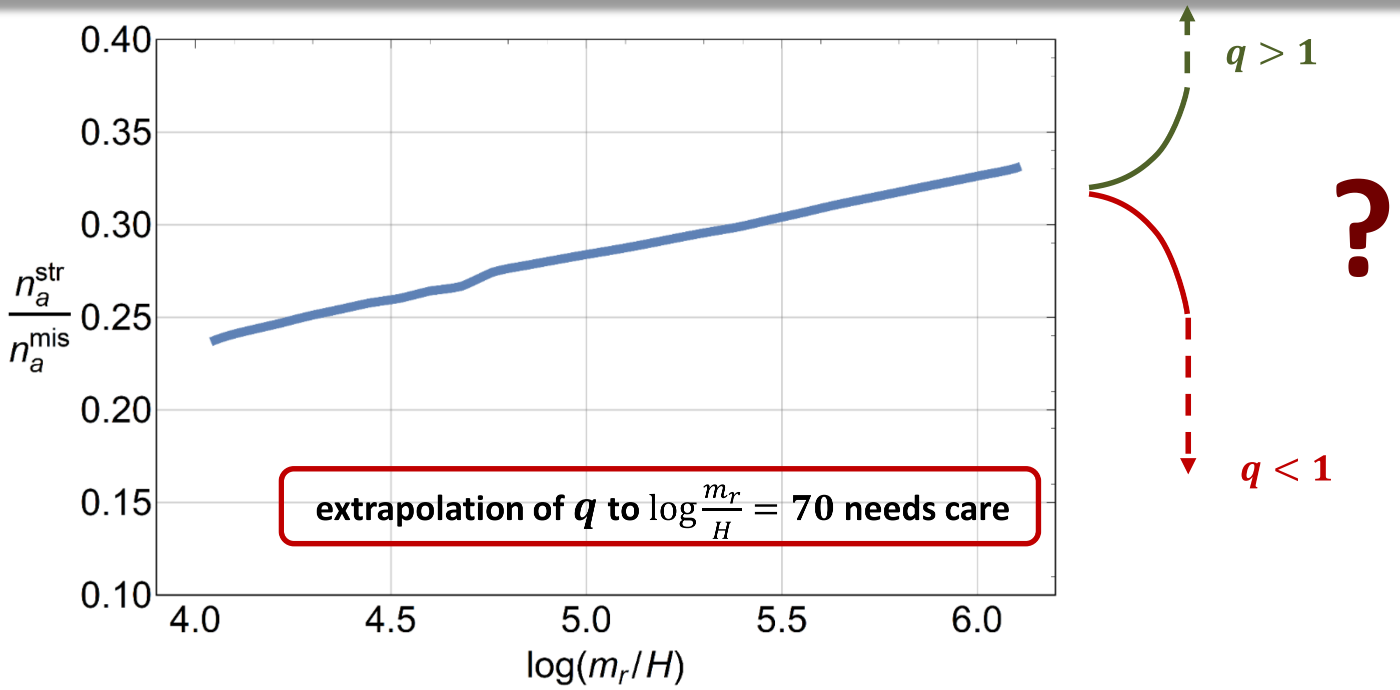

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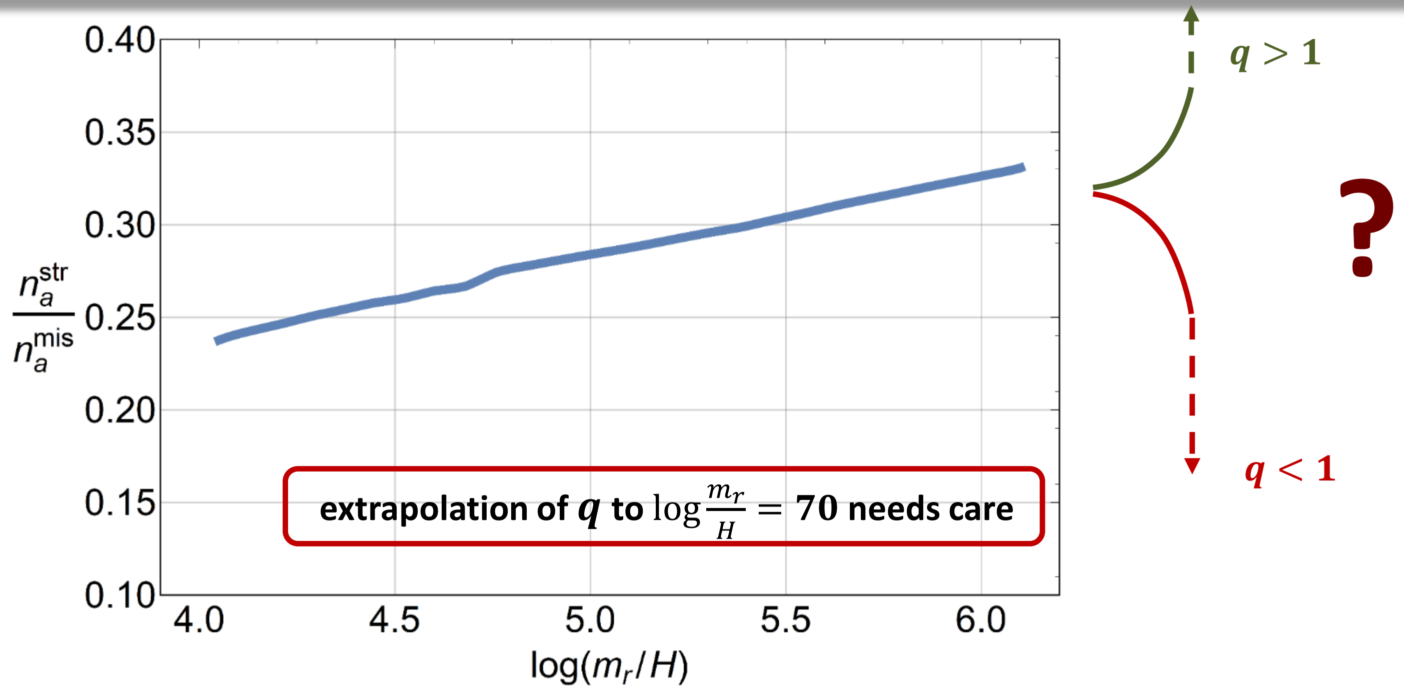

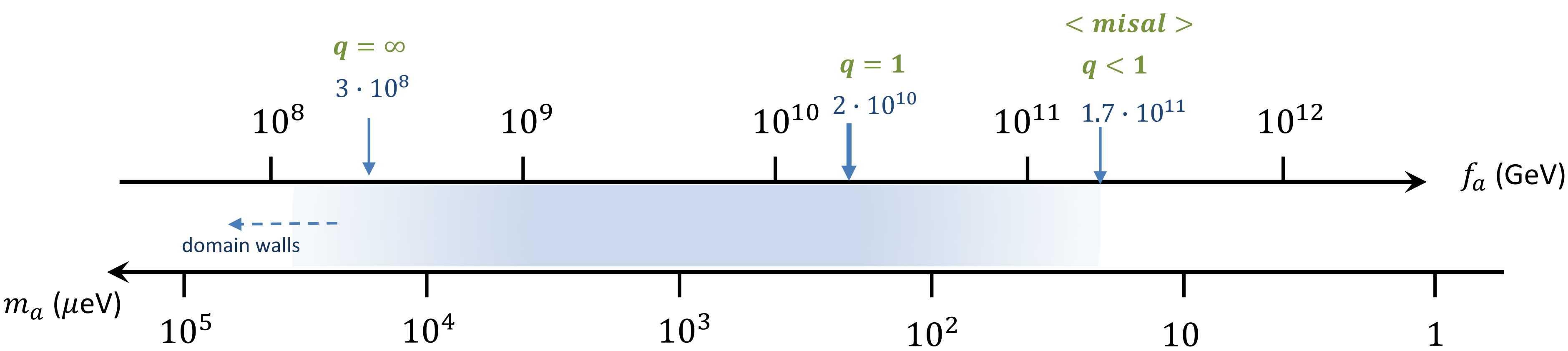

Summary

- **String networks are driven towards an Attractor Solution**
  - **string density** $\propto \log\frac{m_r}{H}$
  - **for** $\log\frac{m_r}{H} \leq 6:$
    - **UV dominated spectrum difficult to extrapolate**
    - **Knowing the precise dependence of q on time is of extreme importance**

Depending on the extrapolation, more than 1 order of magnitude change w.r.t. previous estimates

Thanks!

Backup

Future possibilities

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- **Bigger grids give only a small improvement in** $\log \frac{m_r}{H}$

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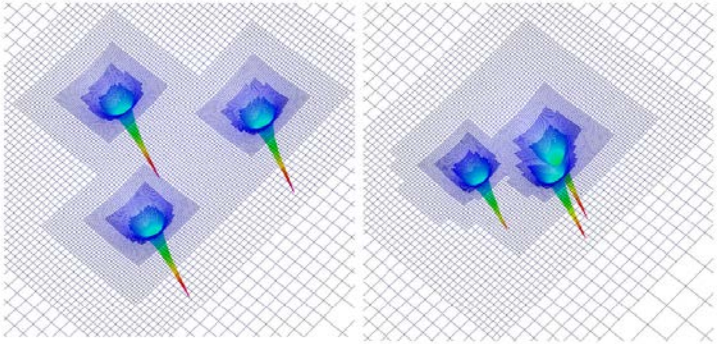
- **Adaptive mesh, win factor of 10?**



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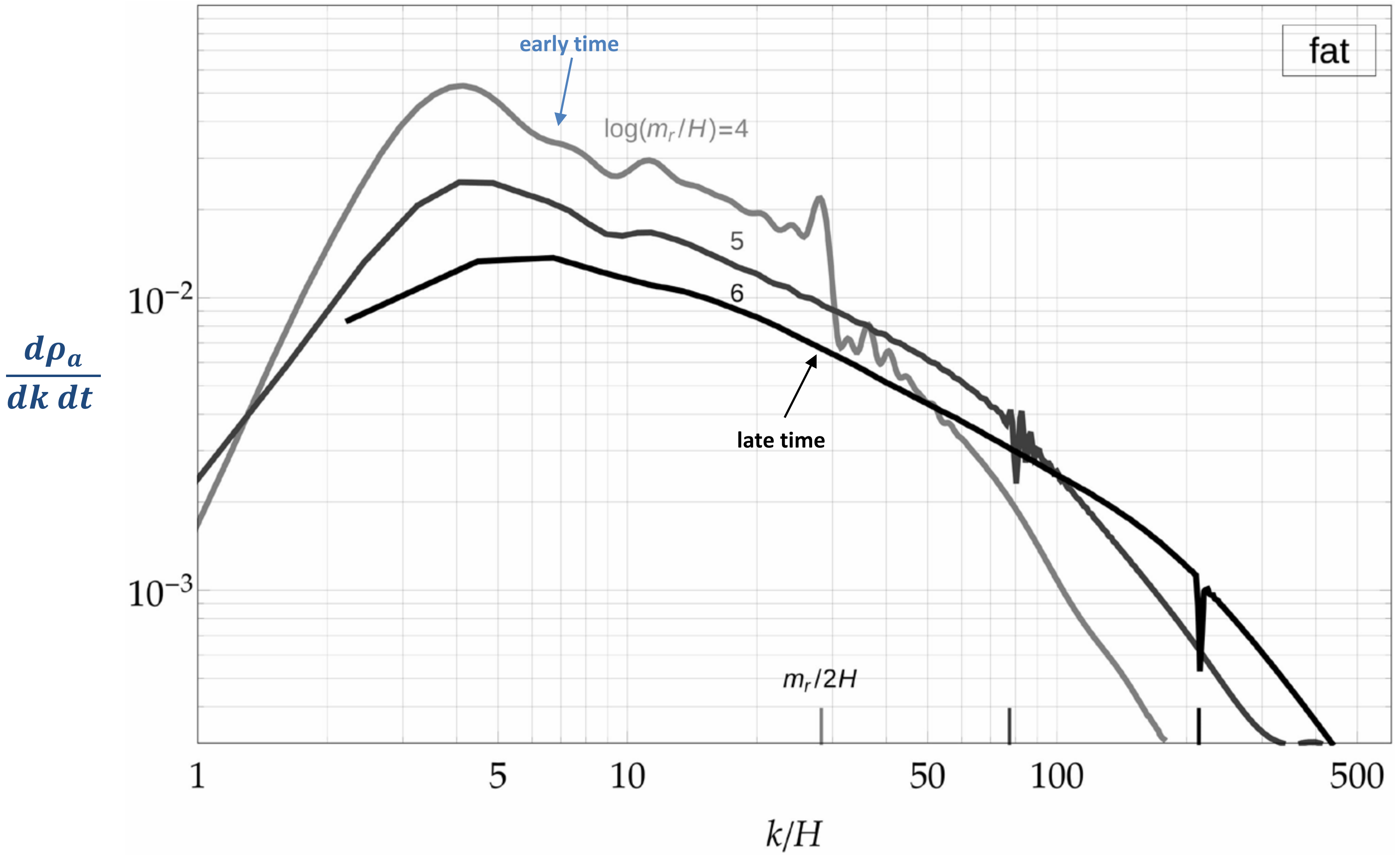
From differences of the total spectrum one obtains the instantaneous axion spectrum $\frac{d\rho_a}{dk\,dt}$



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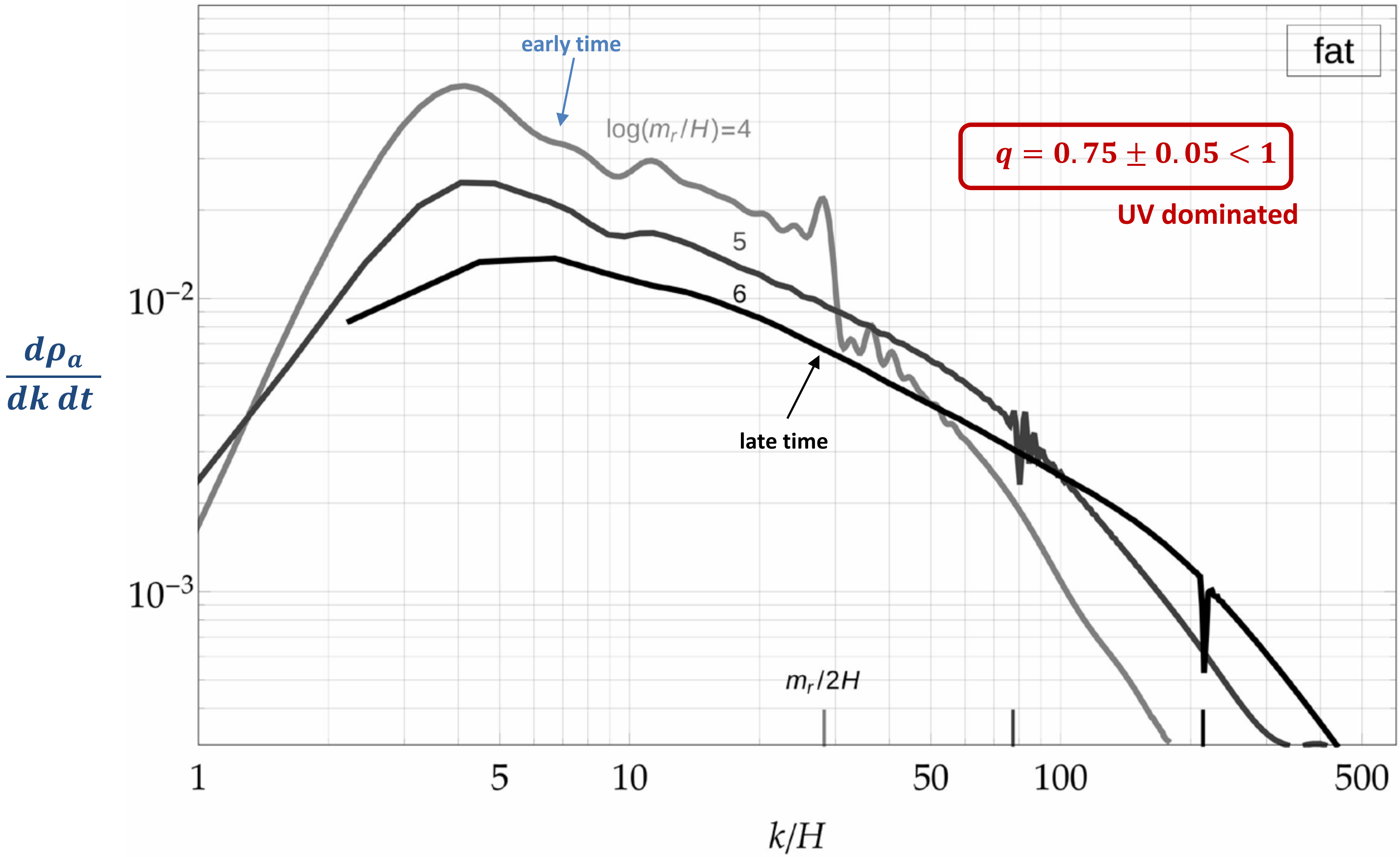

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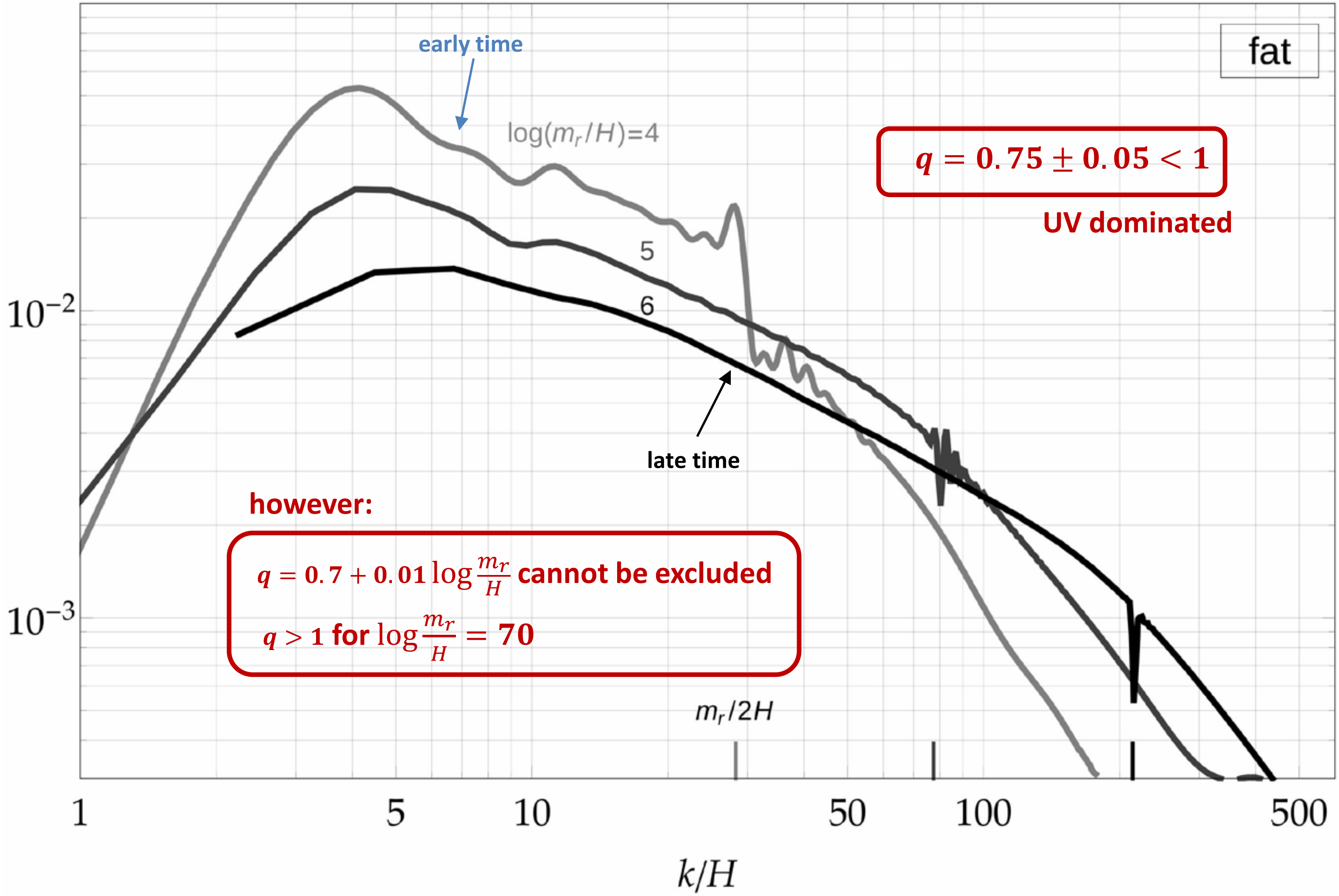


$q = 0.75 \pm 0.05 < 1$

UV dominated

however:

$q = 0.7 + 0.01 \log\frac{m_r}{H}$ **cannot be excluded**

$q > 1$ **for** $\log\frac{m_r}{H} = 70$

Previous literature

Hiramatsu, Kawasaki, Saikawa, Toyokazu Sekiguchi , e.g. arXiv:1202.5851

- Extract the spectrum at small scale separation
- But are looking at the region to the right of the string core peak
- Find m >> 1
- Find $\xi(t) \sim 1$ (since at small scale separation)
- Use this to compute relic abundance

Moore, arxiv:1509.00026

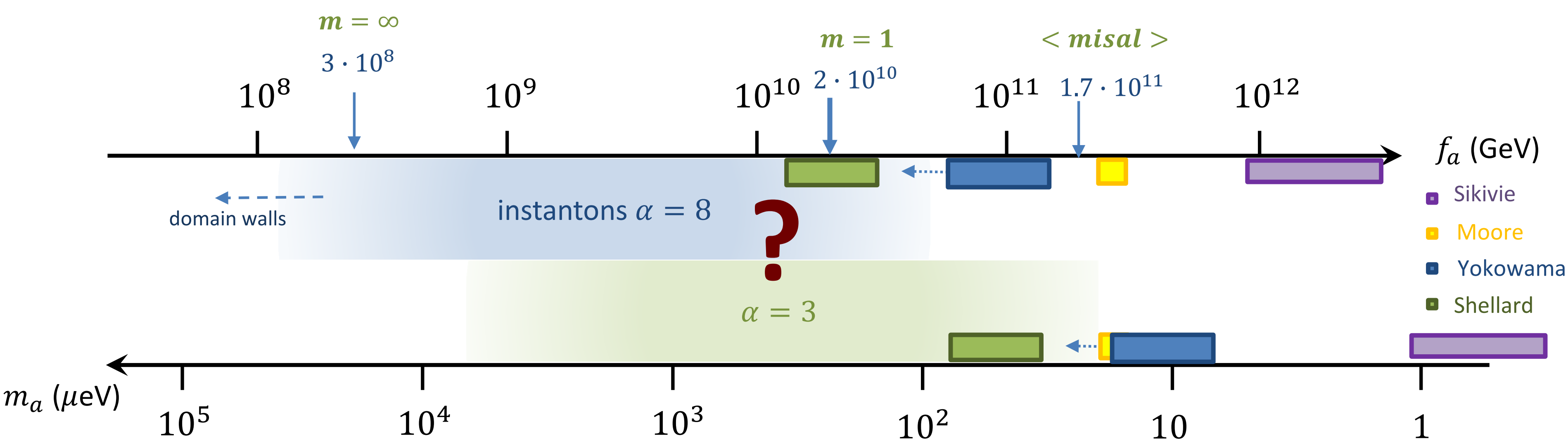
- Simulation at small tension and extracts axion number density directly
- No extrapolation
- Results are compatible with our measurements of $\xi(t)$ and spectrum

Consequence of axion mass

$$\frac{n_{strings}}{n_{misal}} = \frac{8\,\pi\, f_a^2\, \langle k^{-1}\rangle\, H_*^2\, \xi(H_*)\, F(m)}{\langle \theta_0^2\rangle\, f_a^2 H_*} \sim\; 0.8\;\xi(H_*)\,F(m)$$

$\xi(H_*) \sim 10$

$$\boldsymbol{F(m=1) = 1}$$
$$\boldsymbol{F(m\to\infty) = \log\alpha \sim 70}$$



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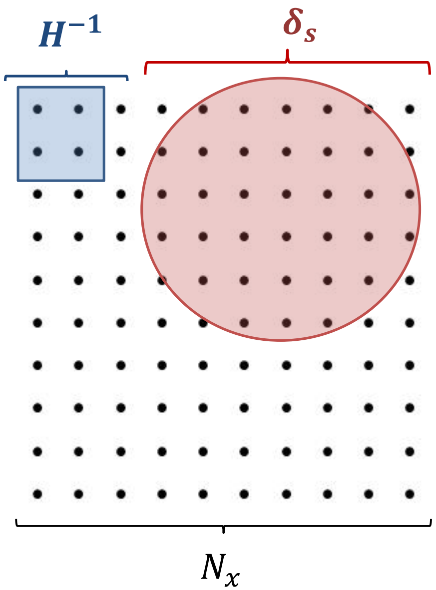
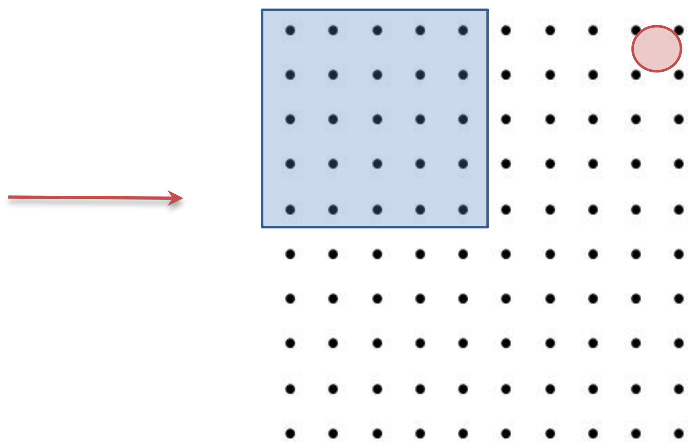
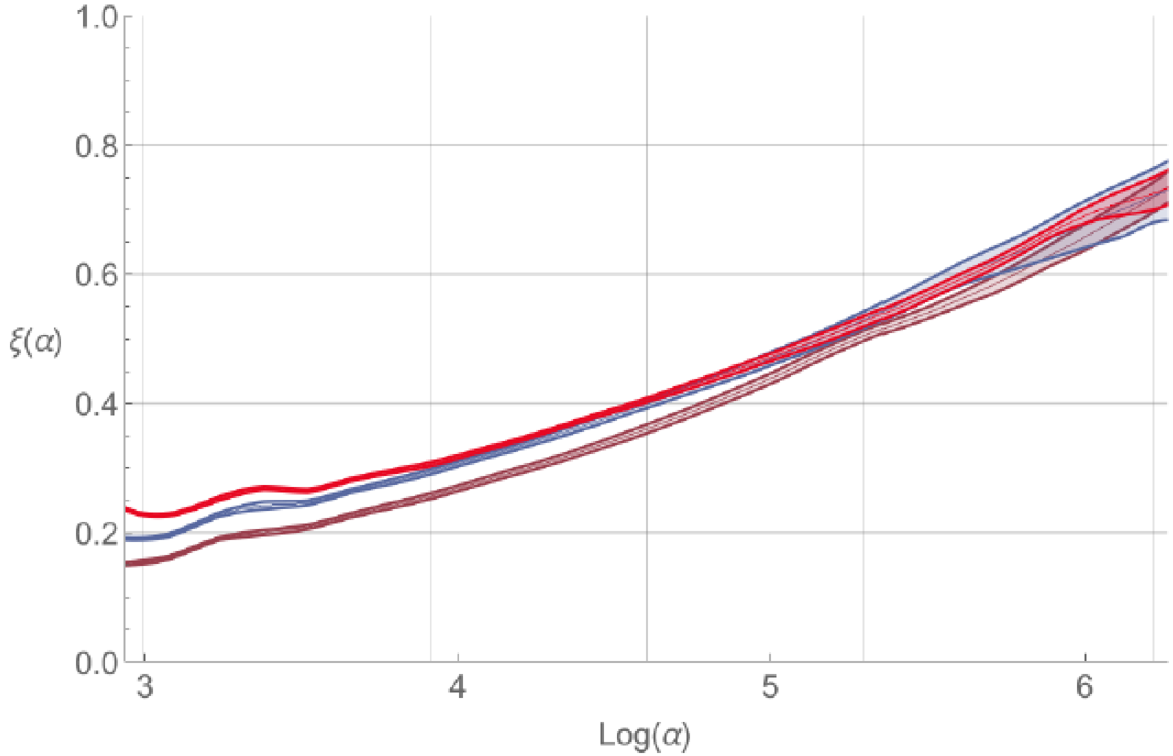




$$\log\frac{m_r}{H} \leq \log\left(\frac{\square}{\bigcirc}\right) \sim 6$$

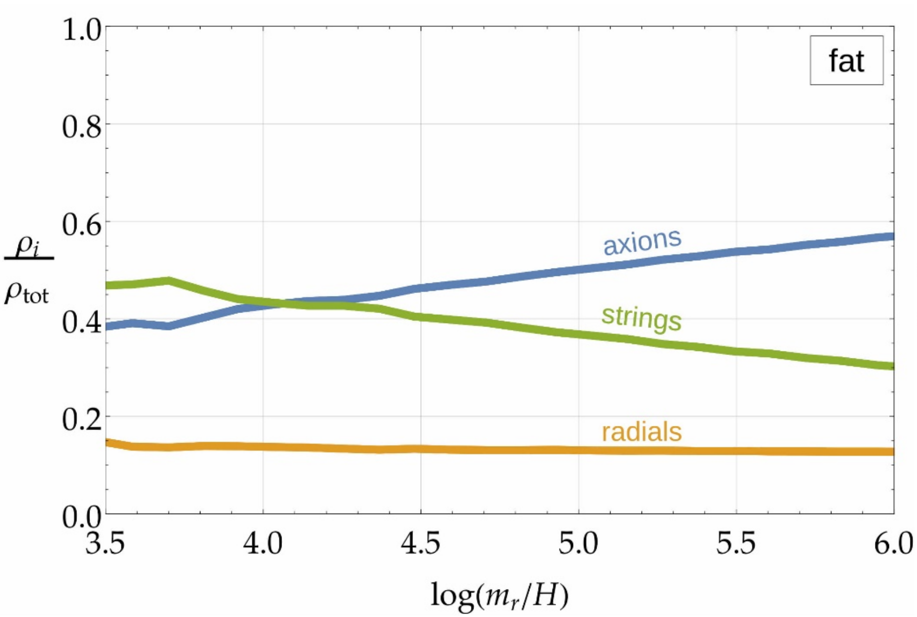
Local Strings

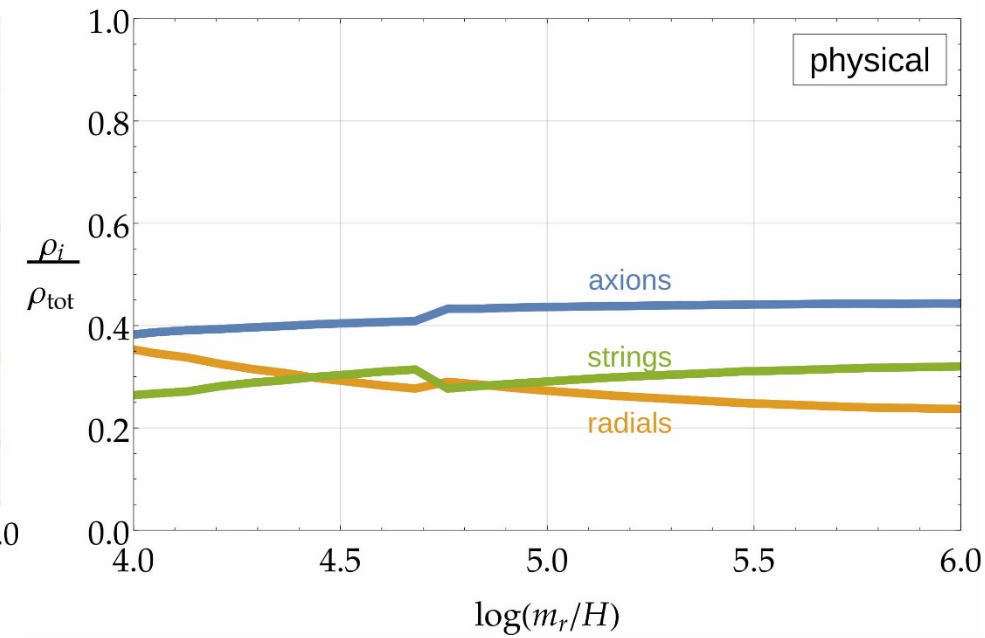


These also seem to have a log increase in $\xi(t)$ even though tension is constant

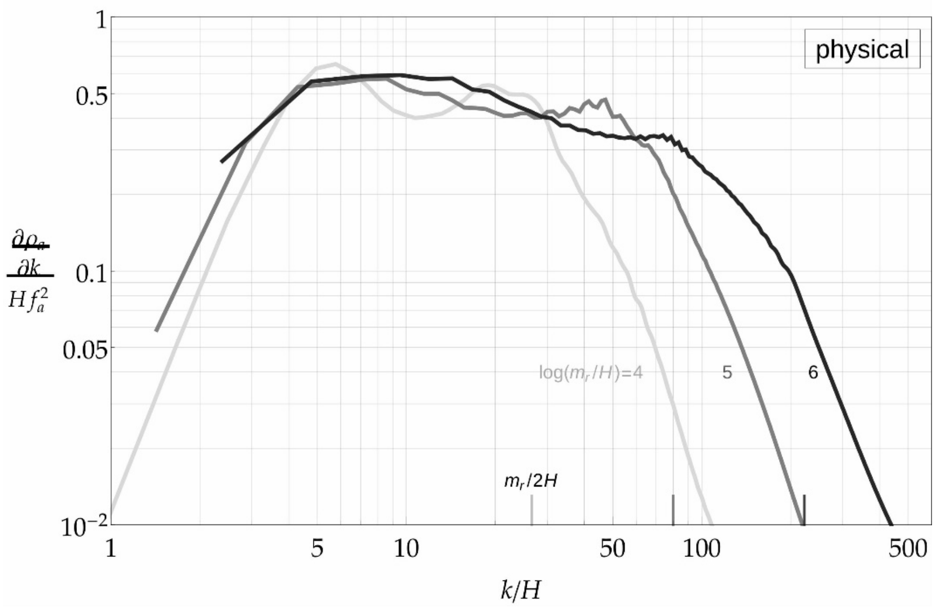
Emission to heavy modes not so suppressed, but mysterious where log is coming from?!

Energy budget

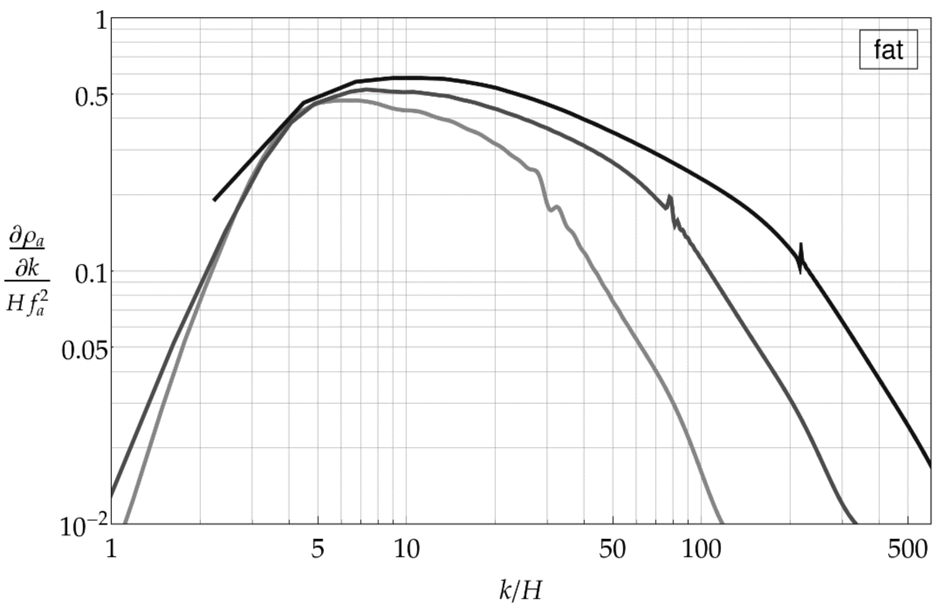


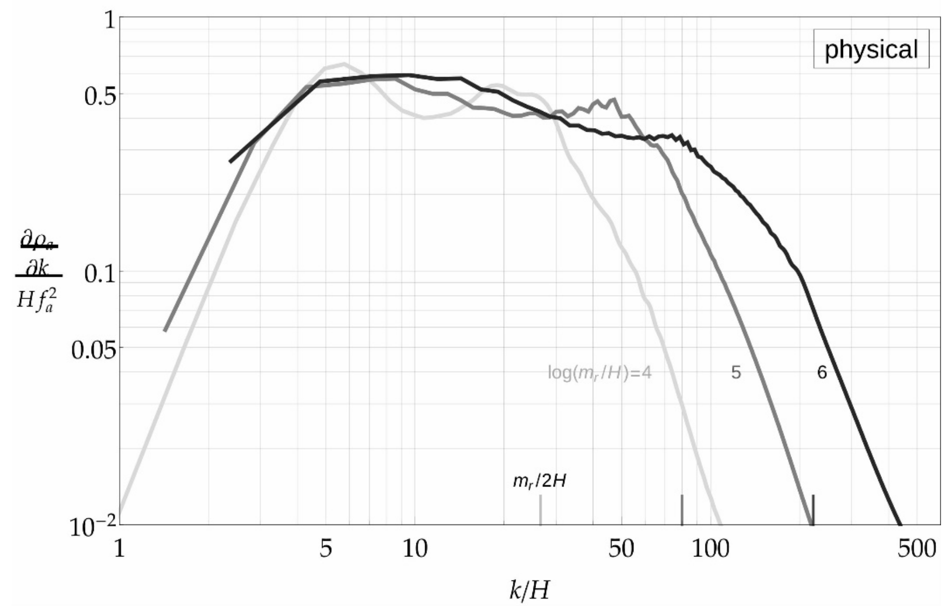


Physical total spectrum

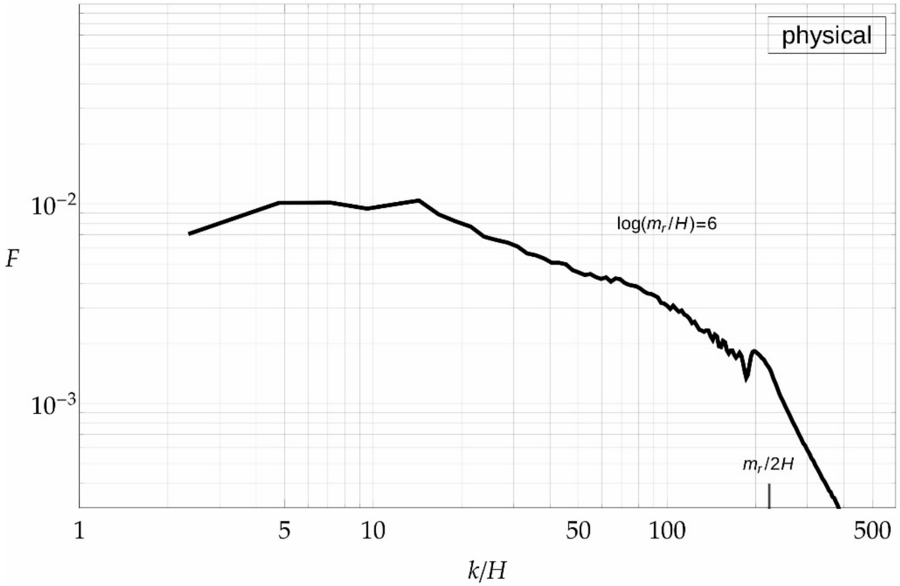


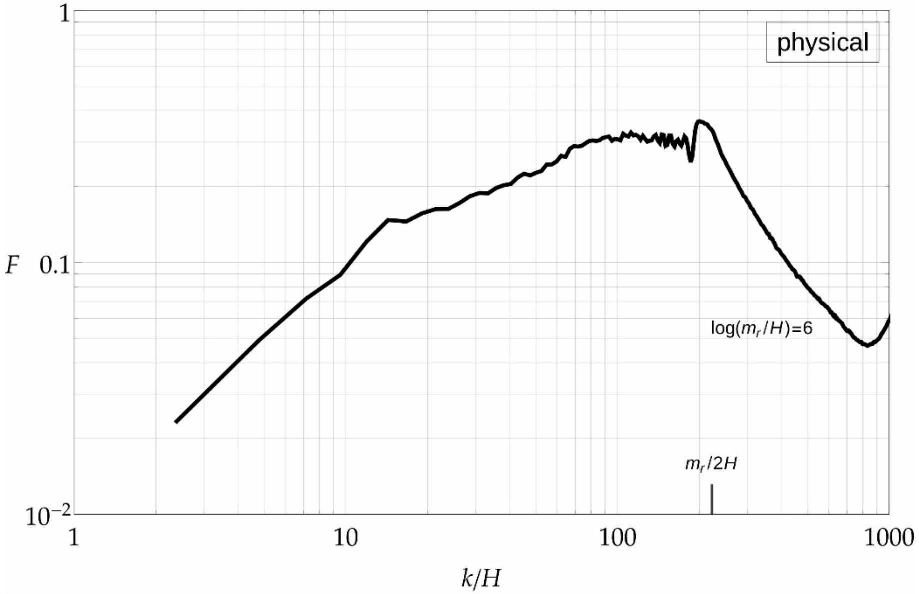
Physical total spectrum





Physical instantaneous spectrum





Finite volume dependence