

Axions from Strings:

The Attractive Solution

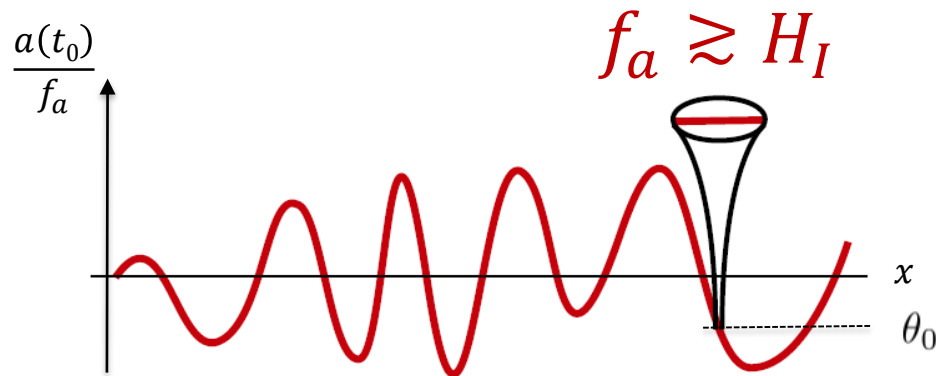
Marco Gorghetto



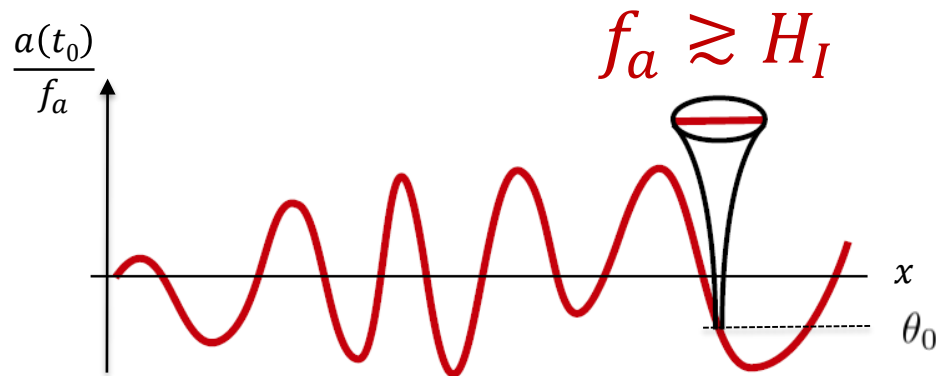
to appear with **Ed Hardy & Giovanni Villadoro**

Axion dark matter

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Axion dark matter



$$f_a \lesssim H_I$$

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



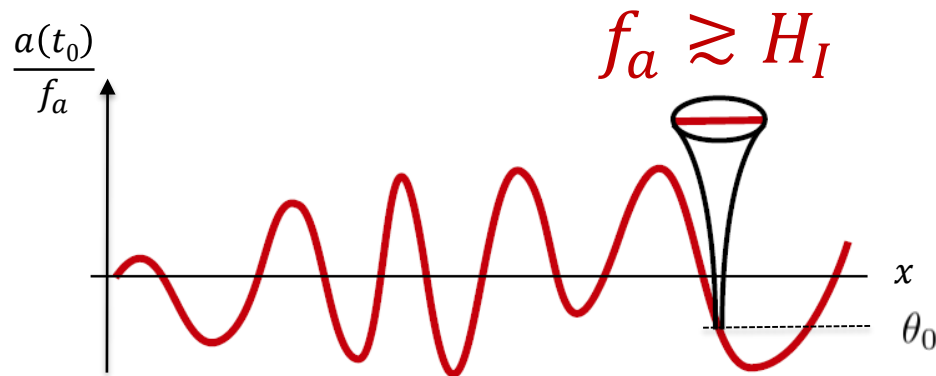
misalignment contribution fixed

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



extra axion from strings + domain walls
large uncertainties

Axion dark matter



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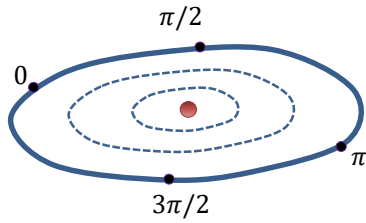
extra axion from strings + domain walls
large uncertainties

No free parameters from
initial conditions

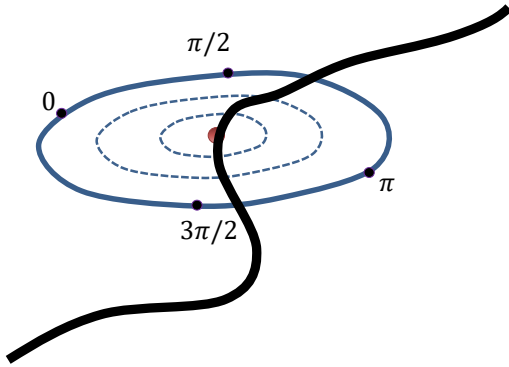
predictive!

Axion Strings

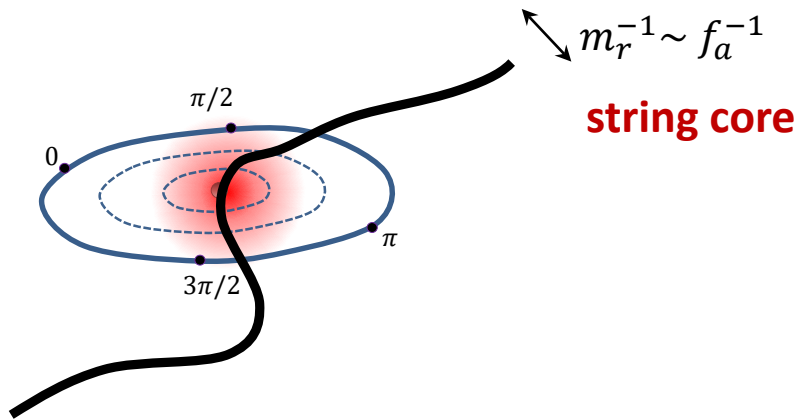
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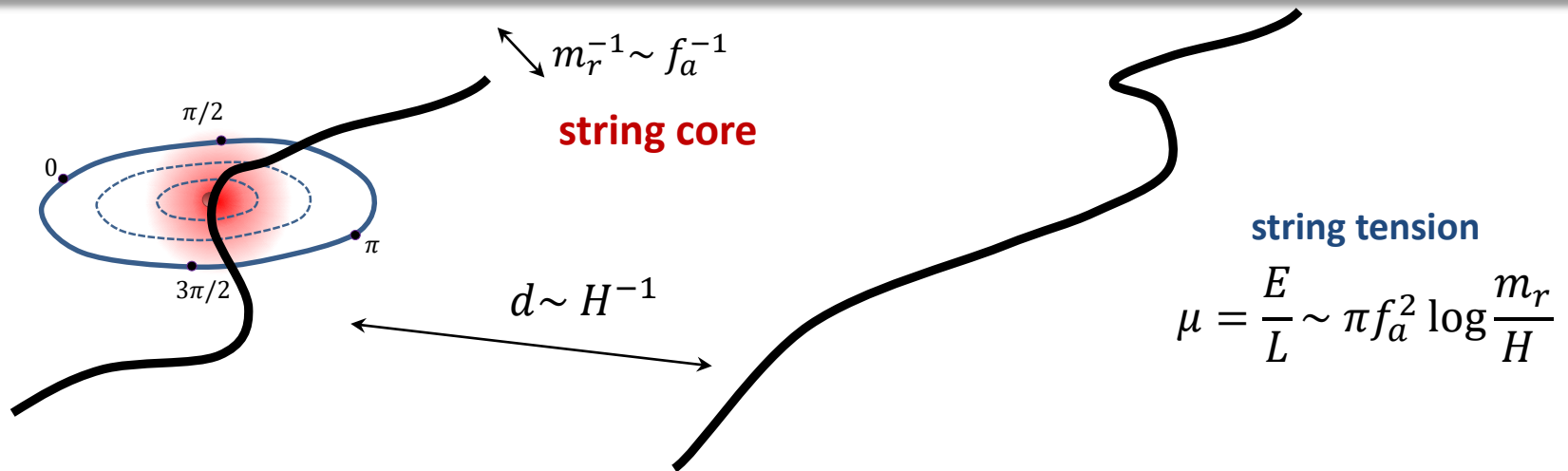
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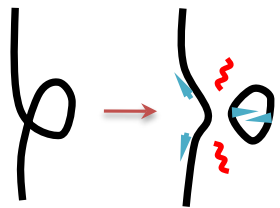
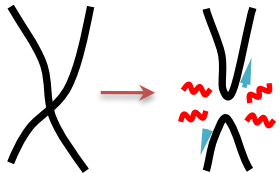
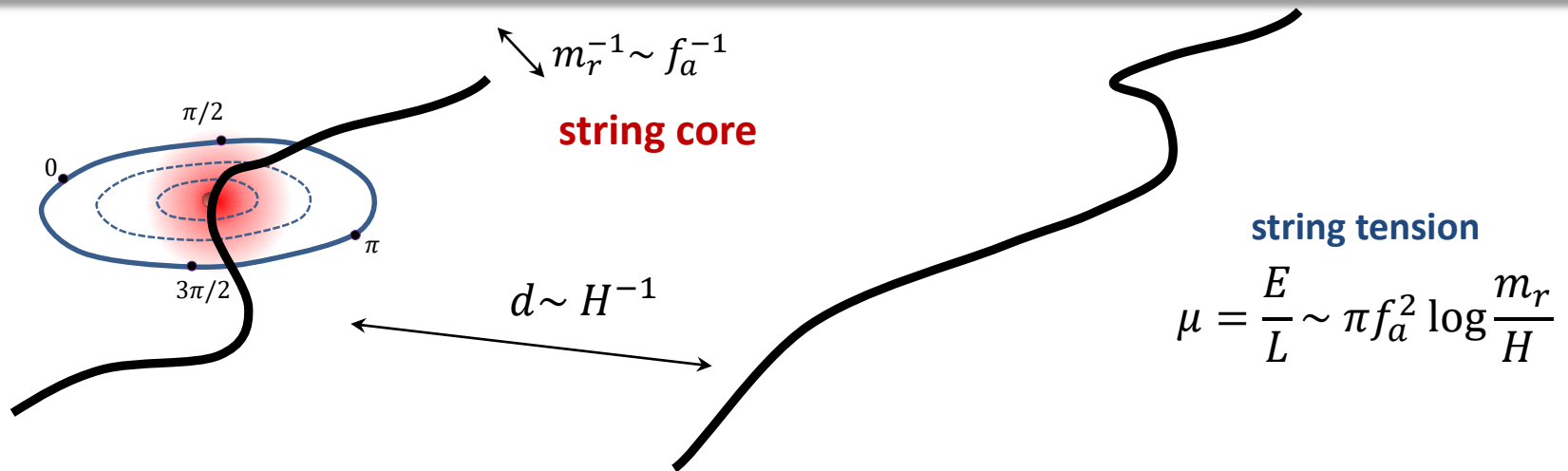
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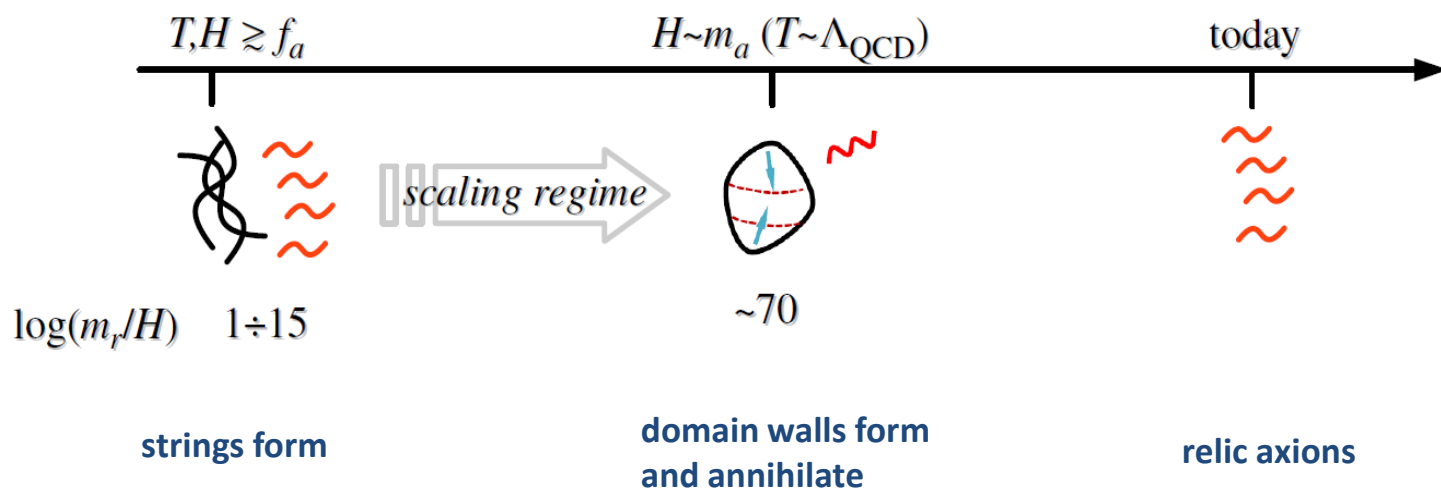
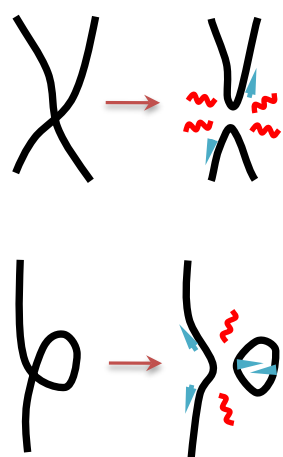
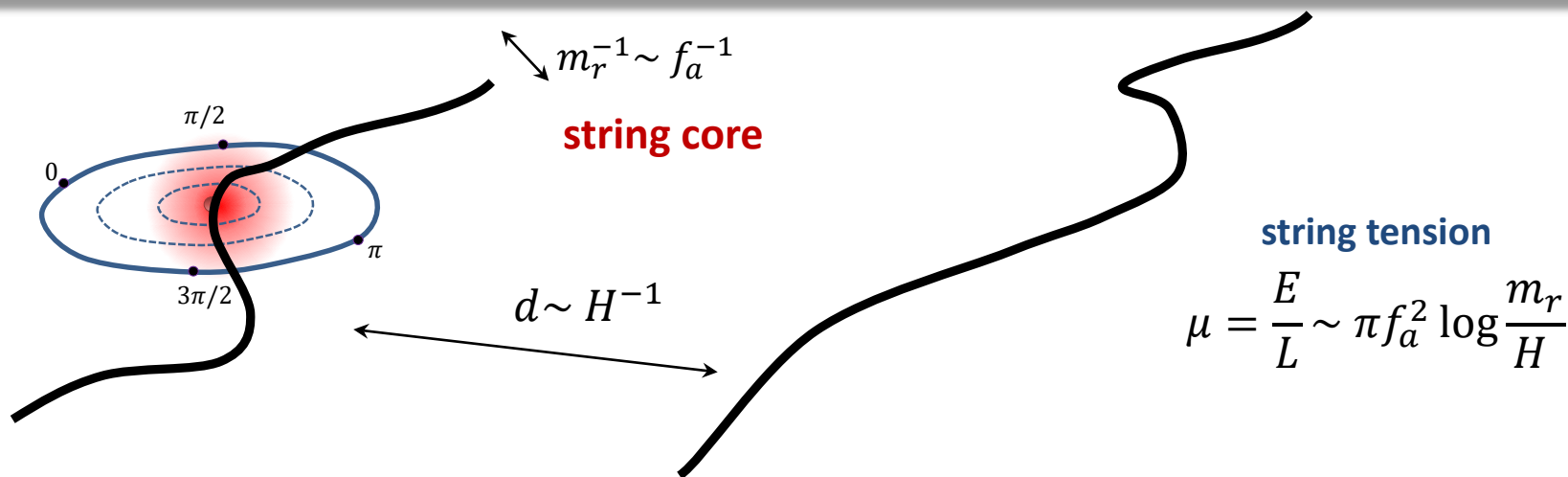
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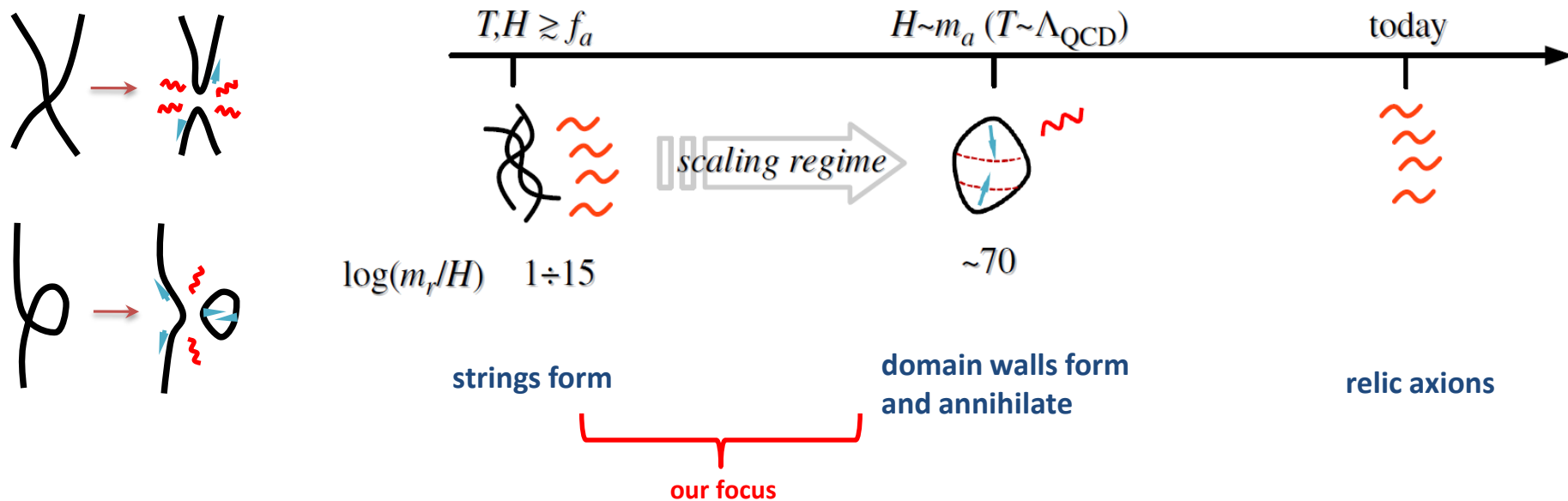
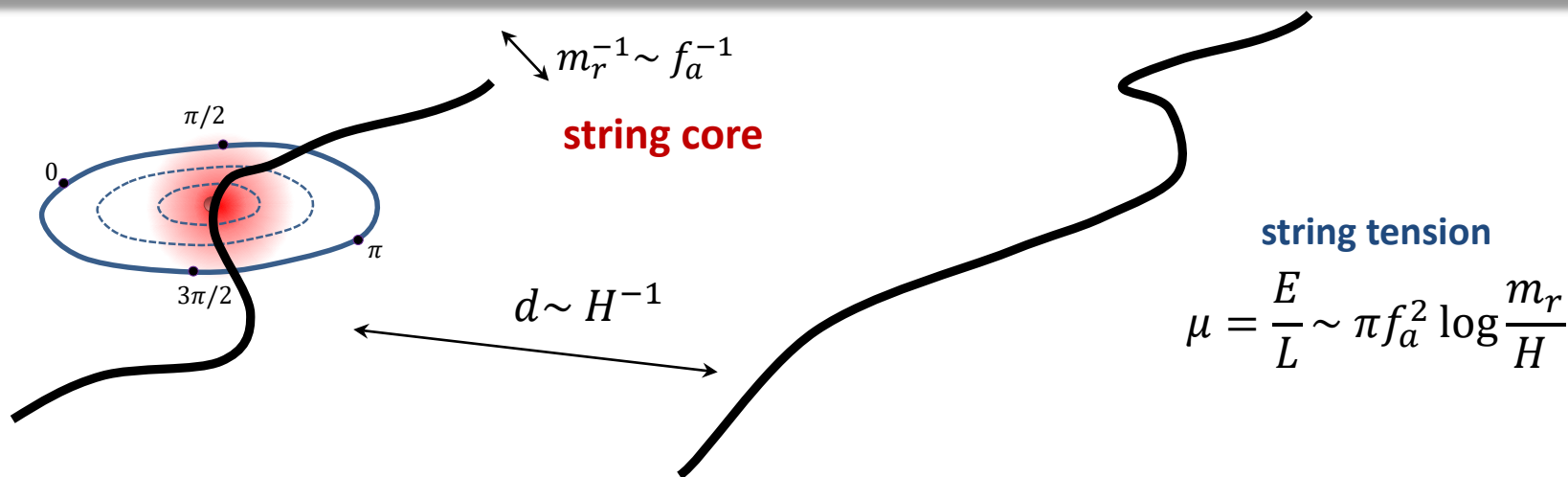
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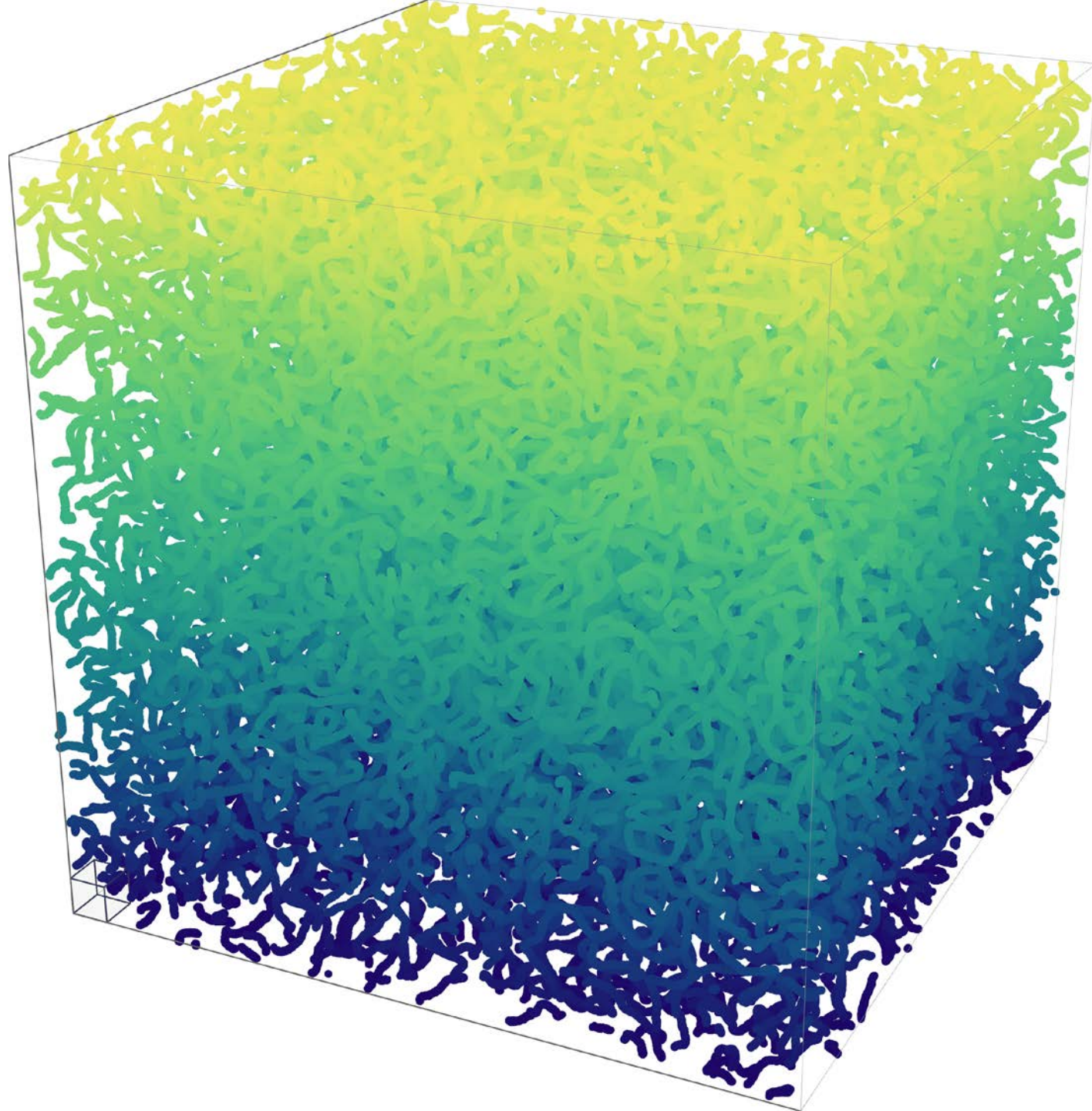


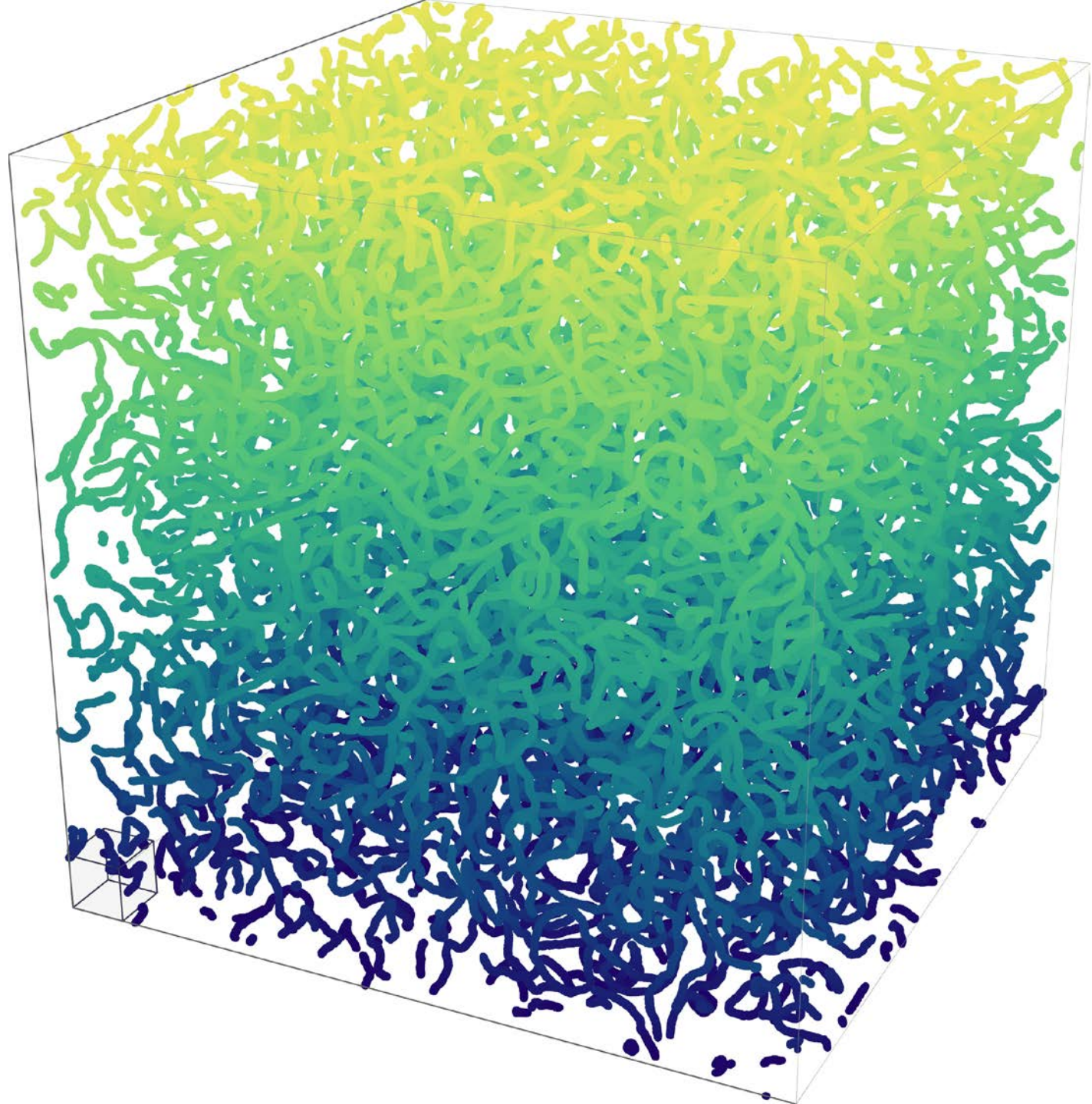
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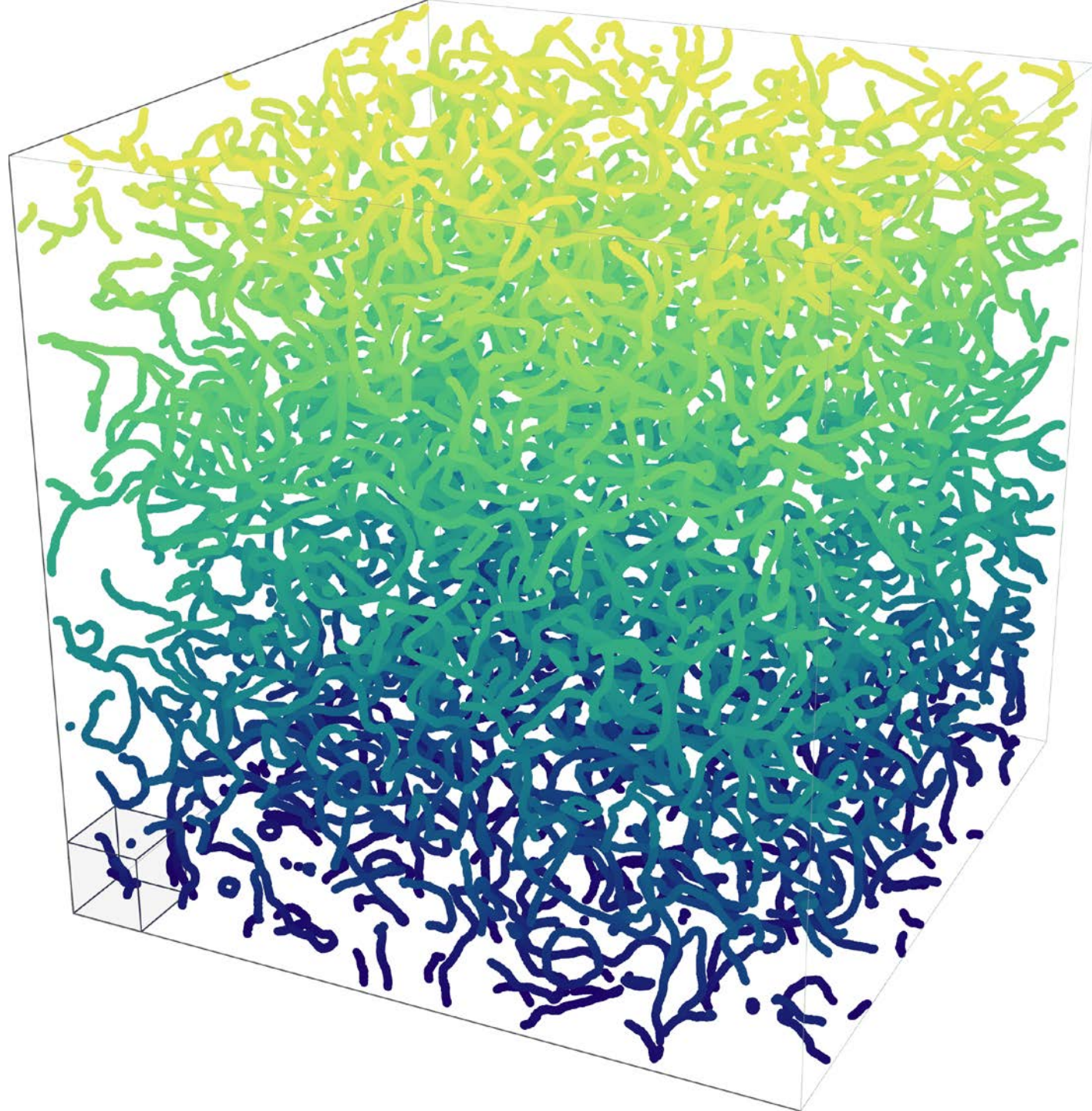


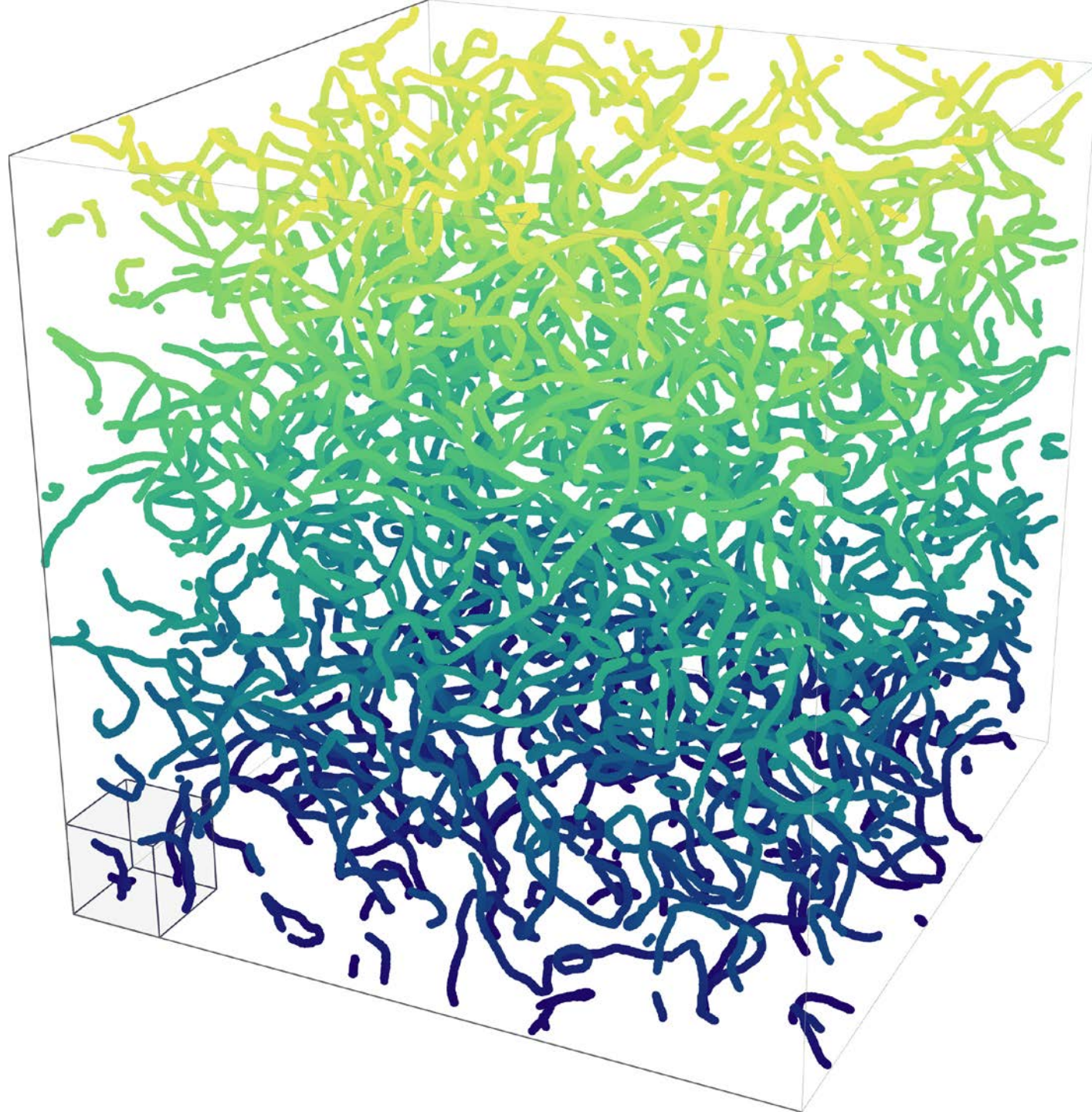
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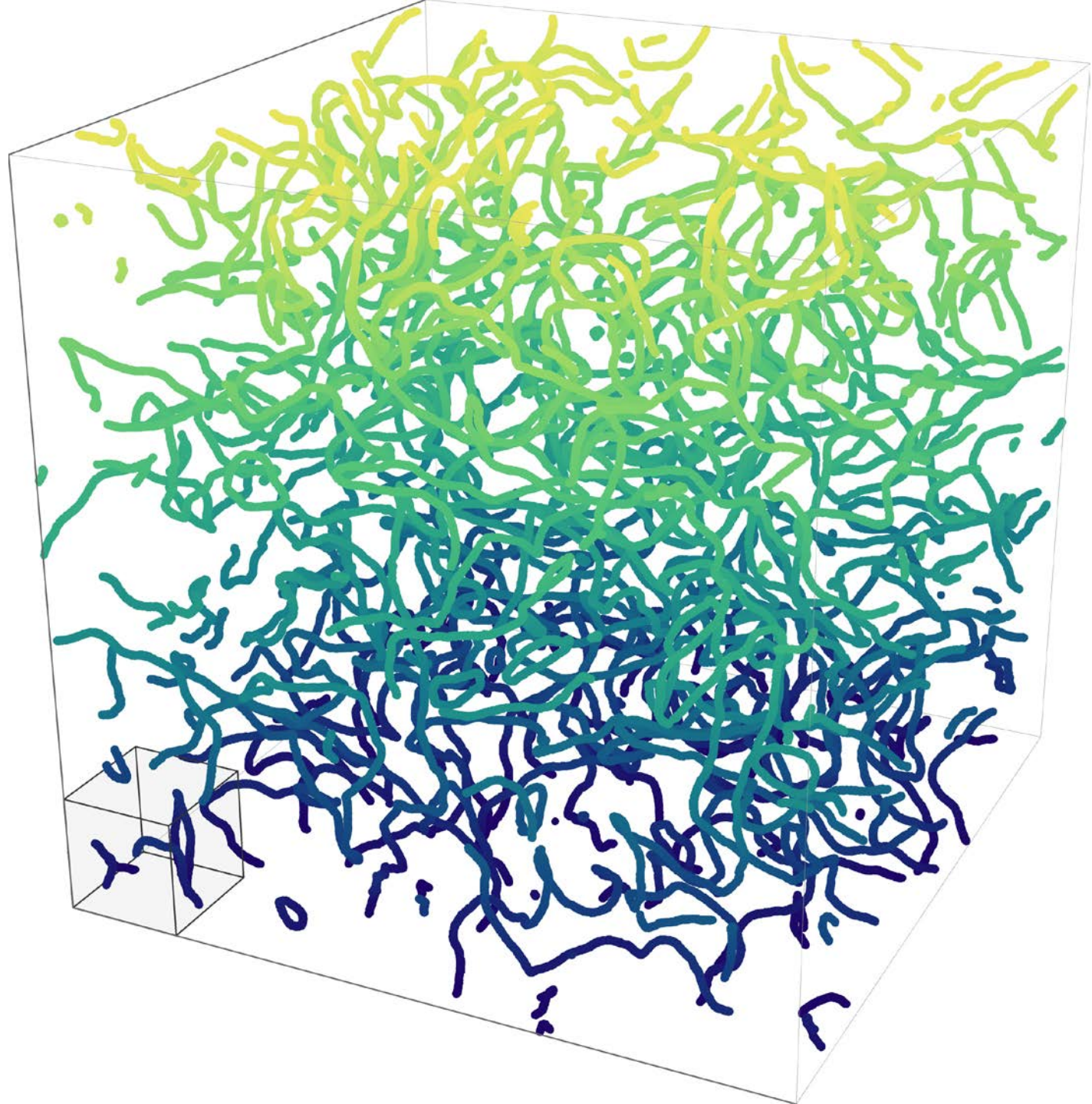


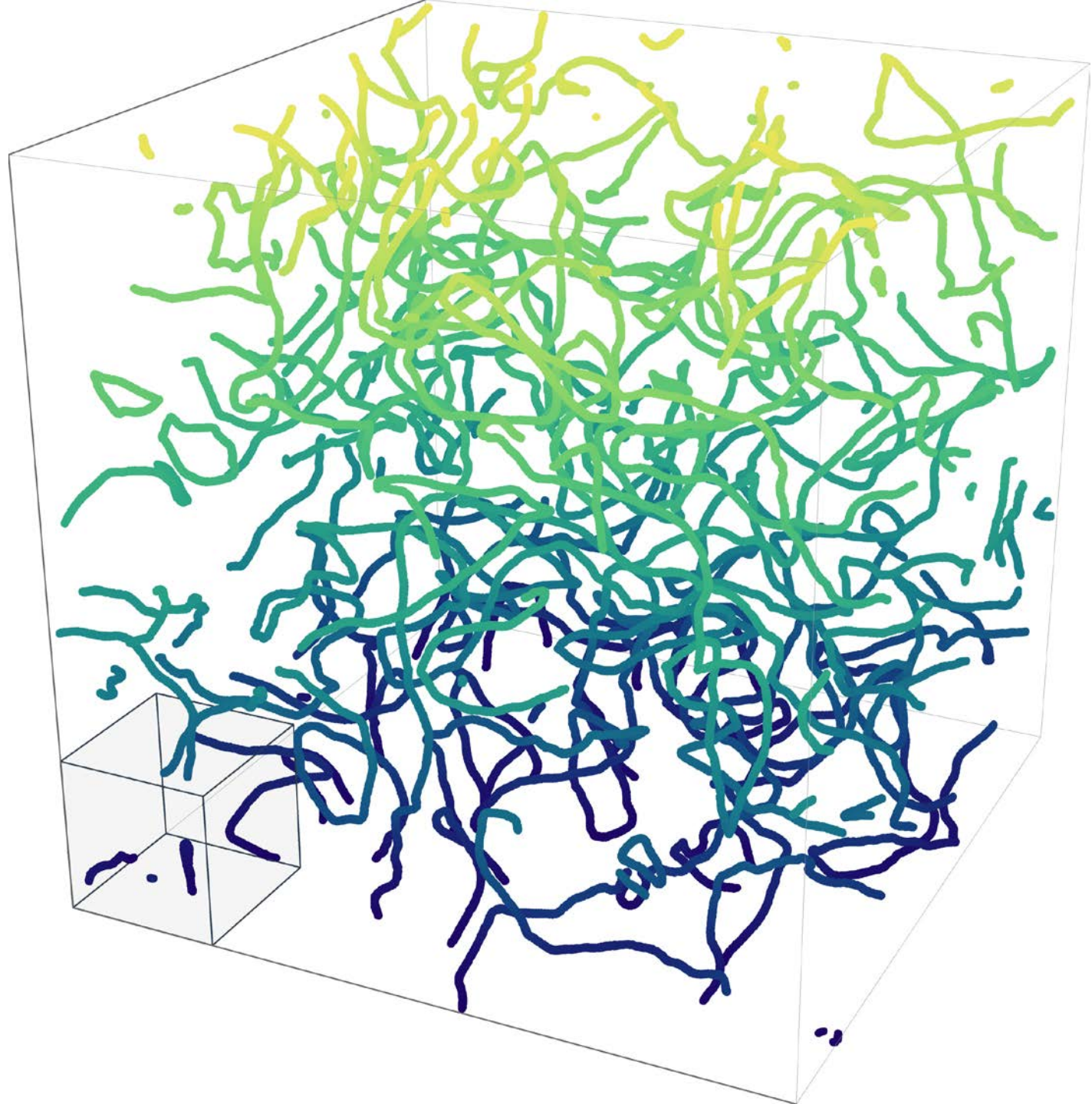


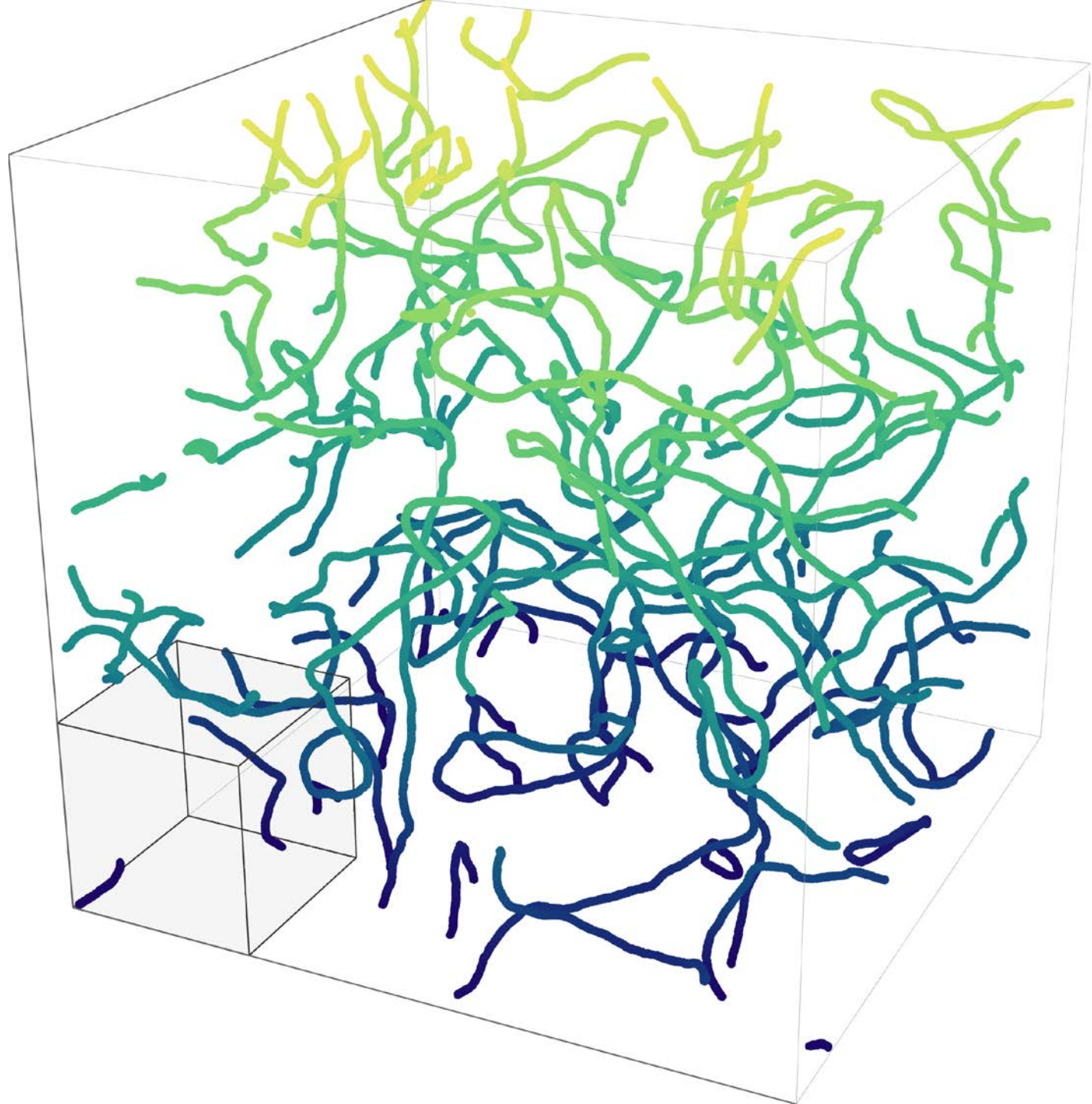


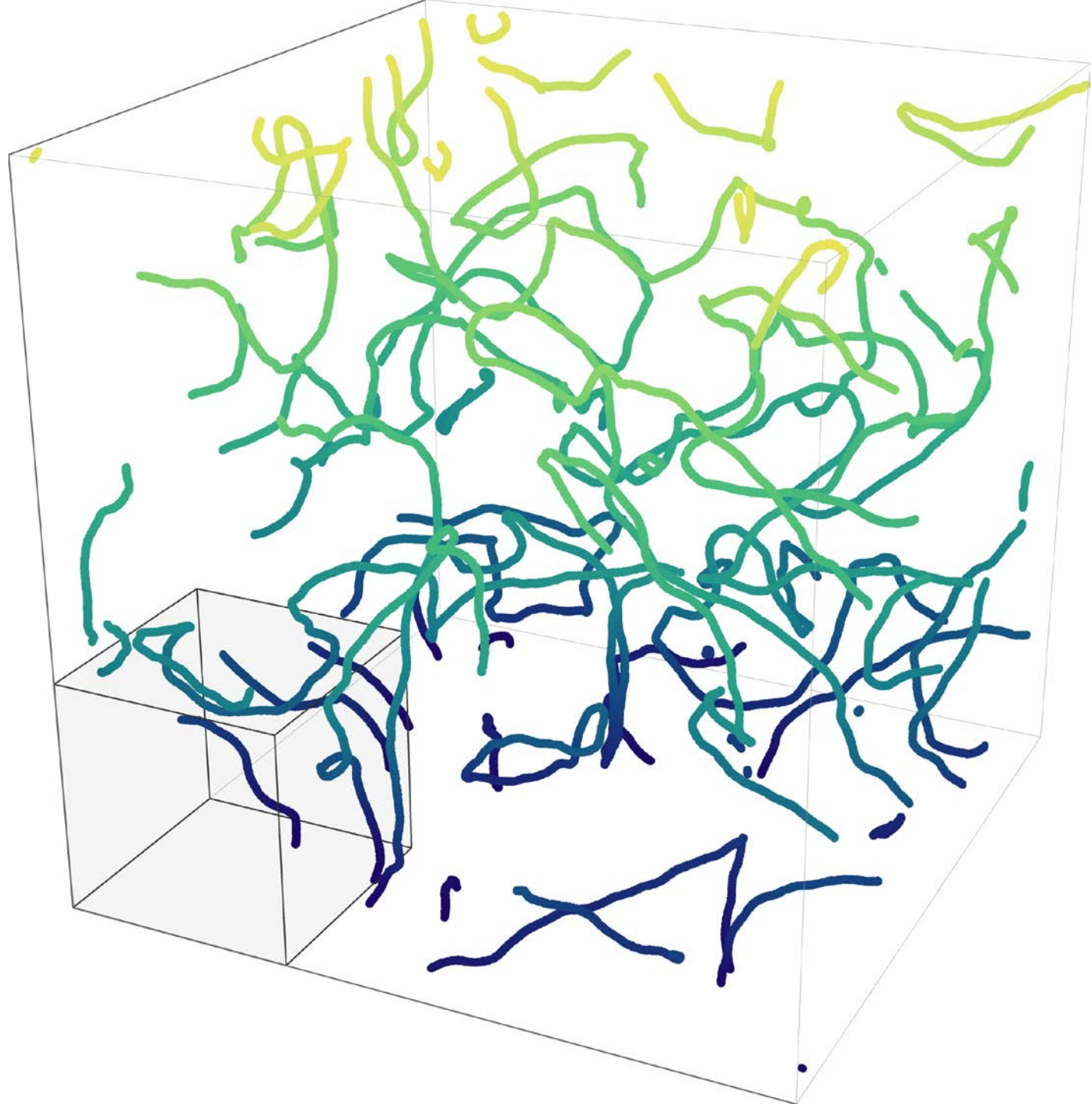


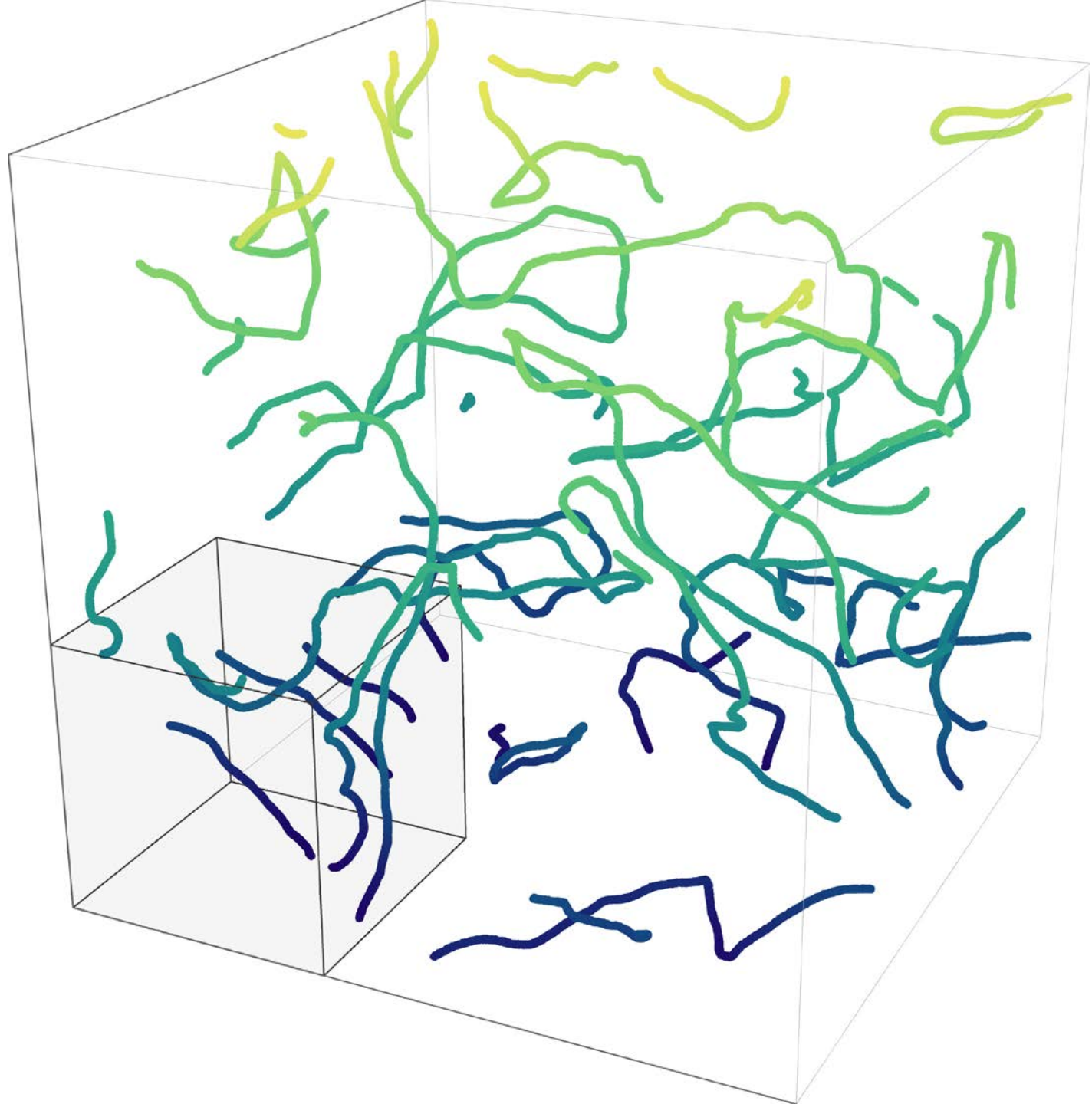


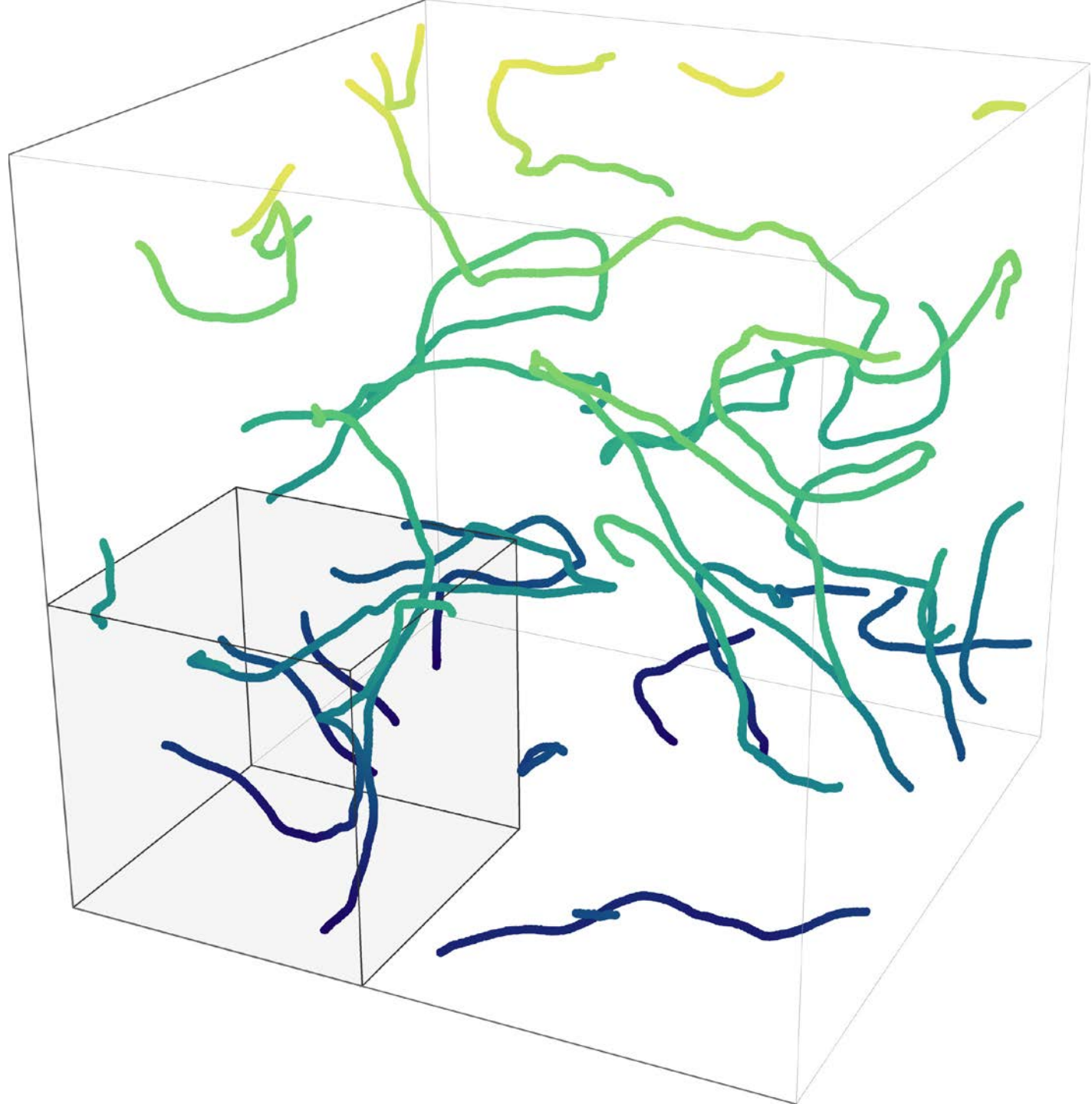


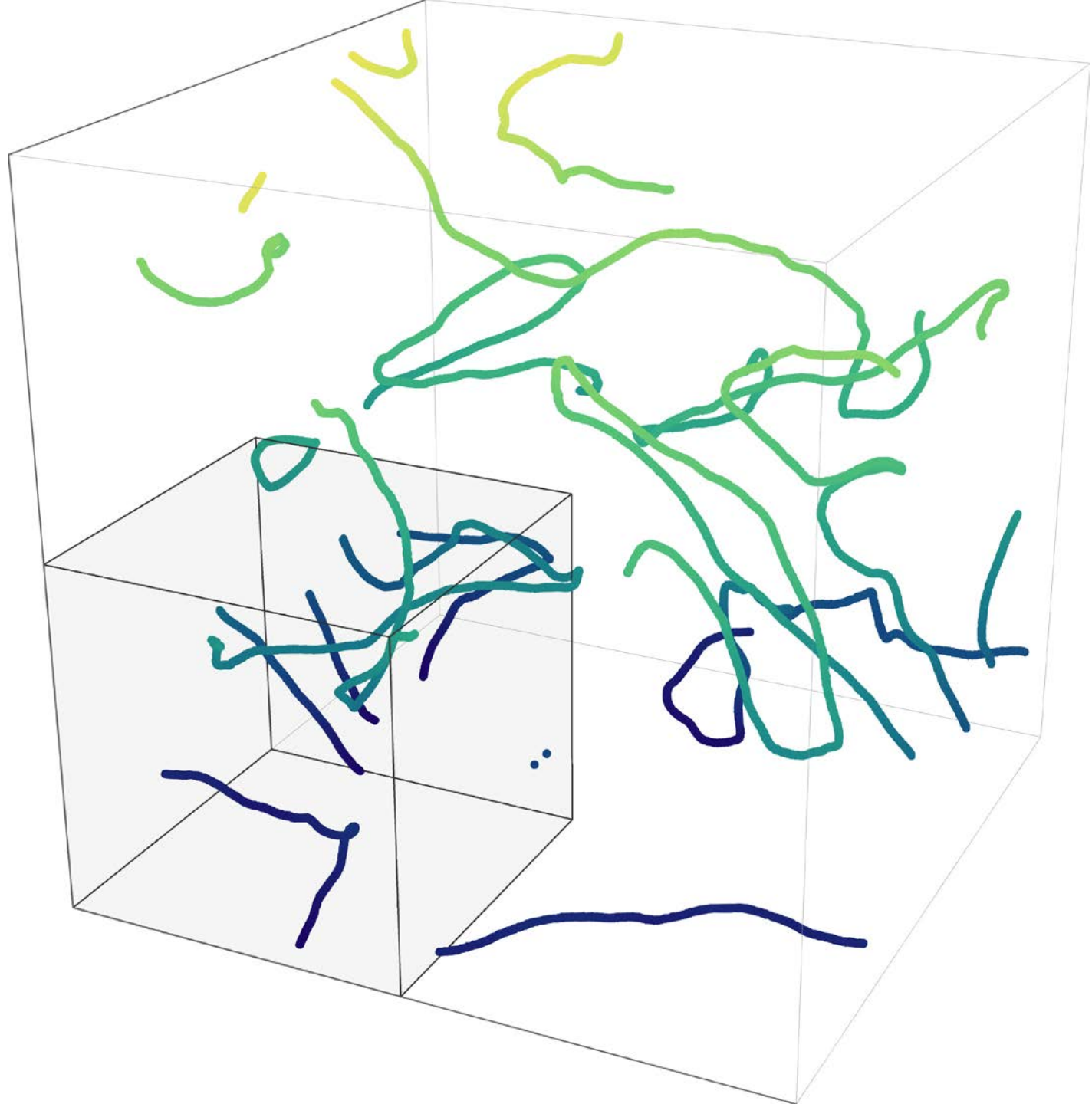


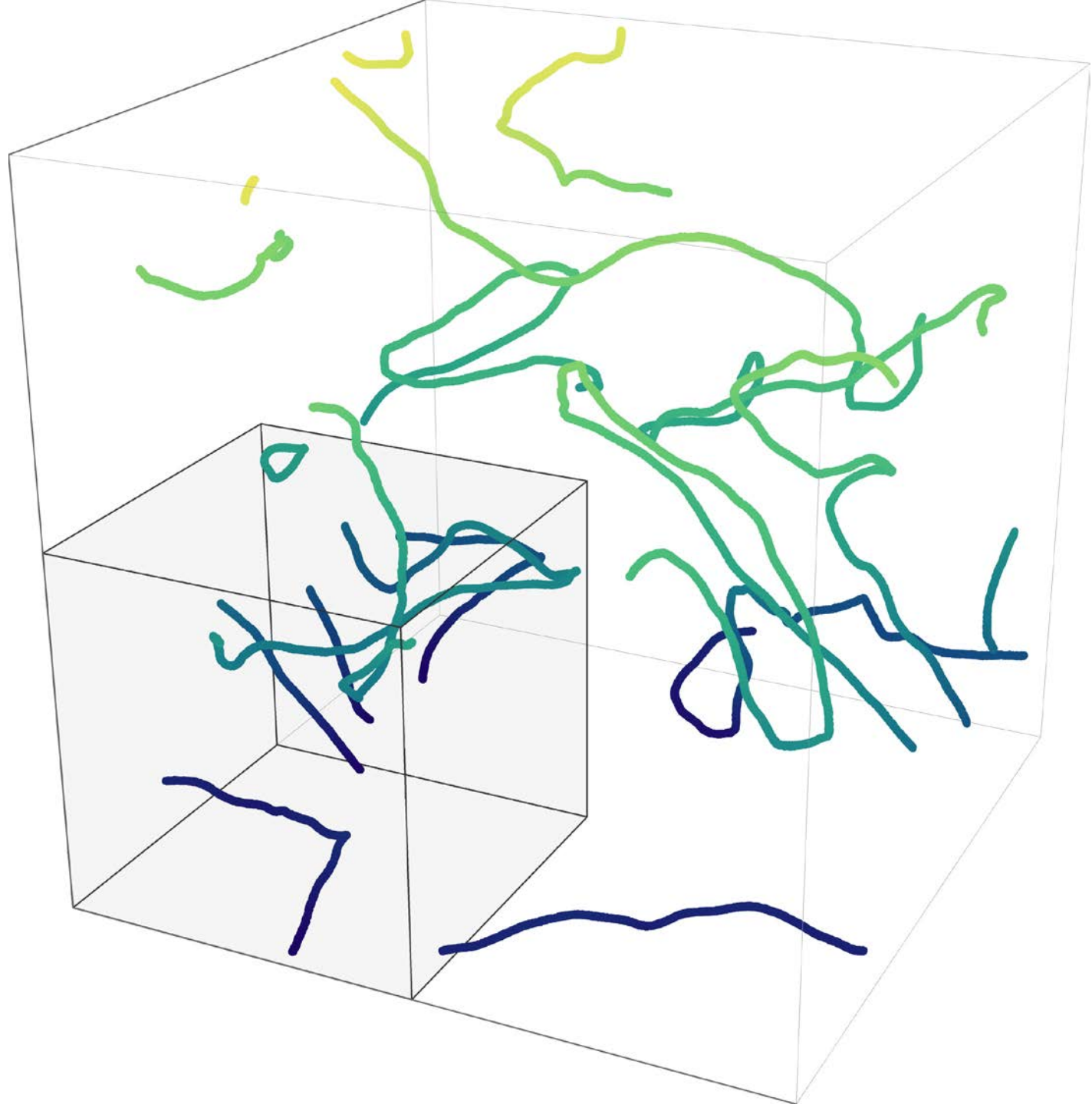










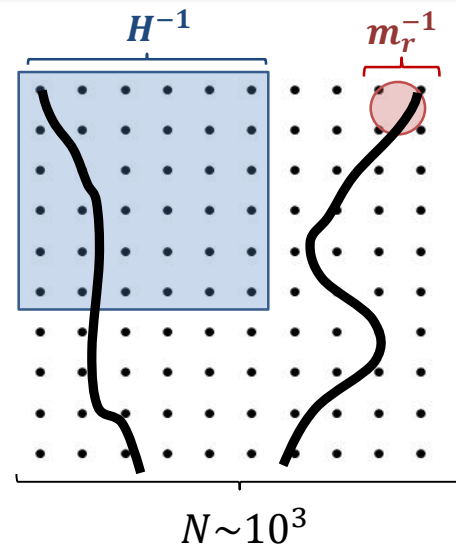


Why it's hard

Why it's hard

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

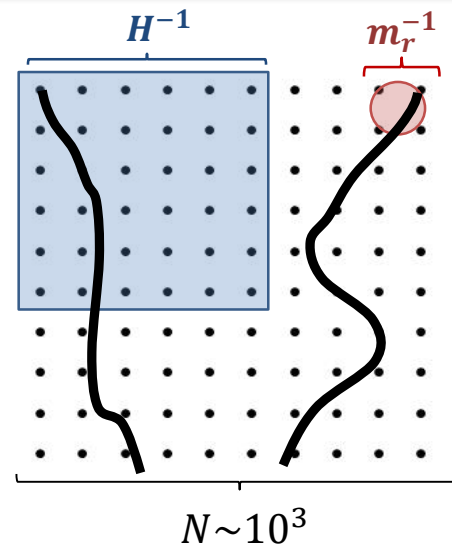
$$\log \frac{m_r}{H} \leq \log\left(\frac{\text{blue square}}{\text{red circle}}\right) \sim 6 \ll 70$$



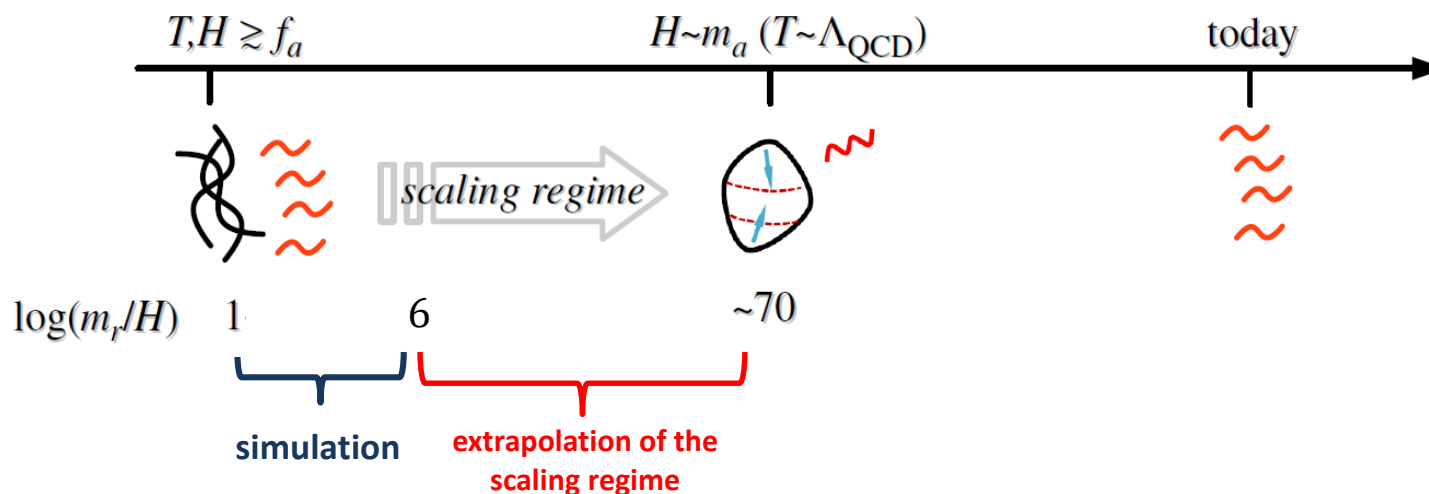
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Idea: take advantage of the attractor

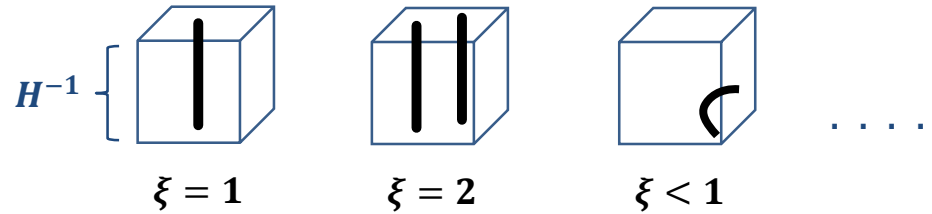


The Attractive Solution

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Number of strings per Hubble

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

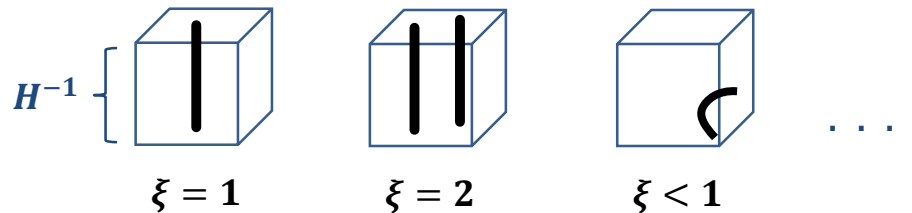


string length in one Hubble volume in units of H^{-1}

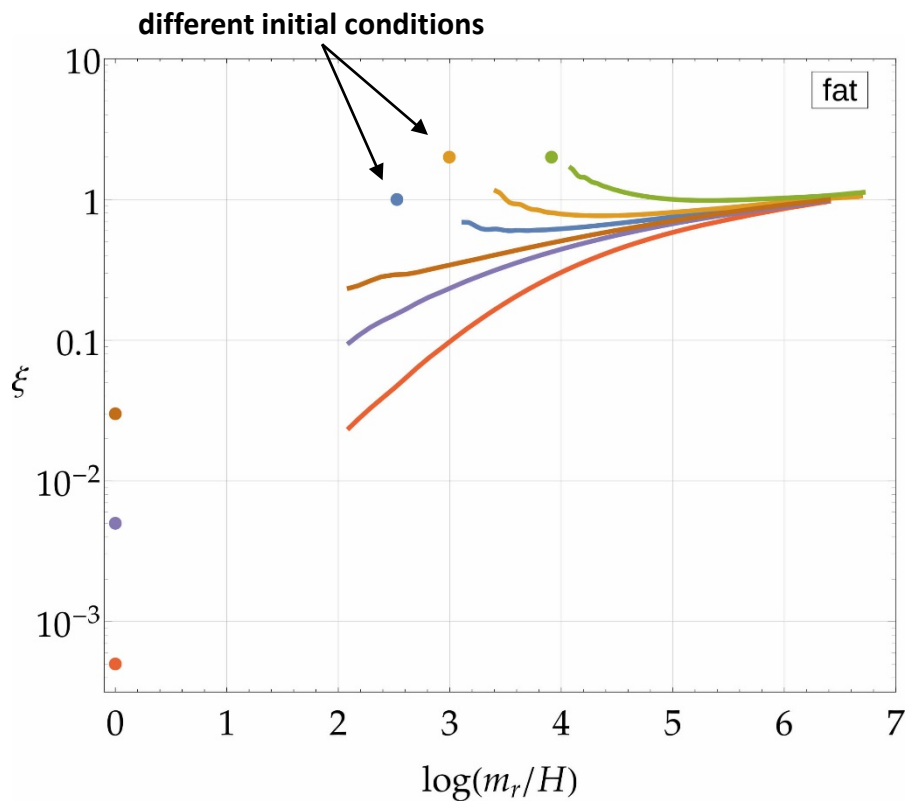
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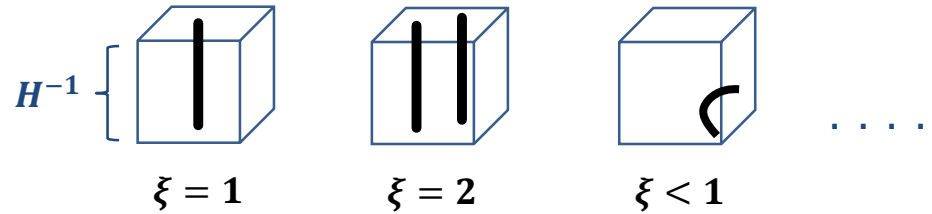
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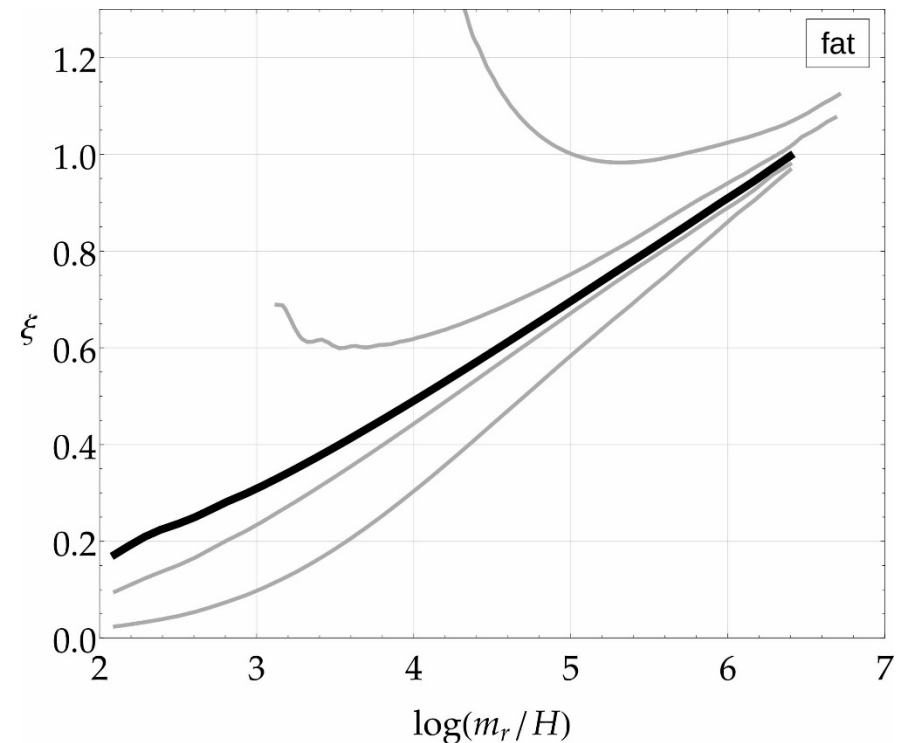
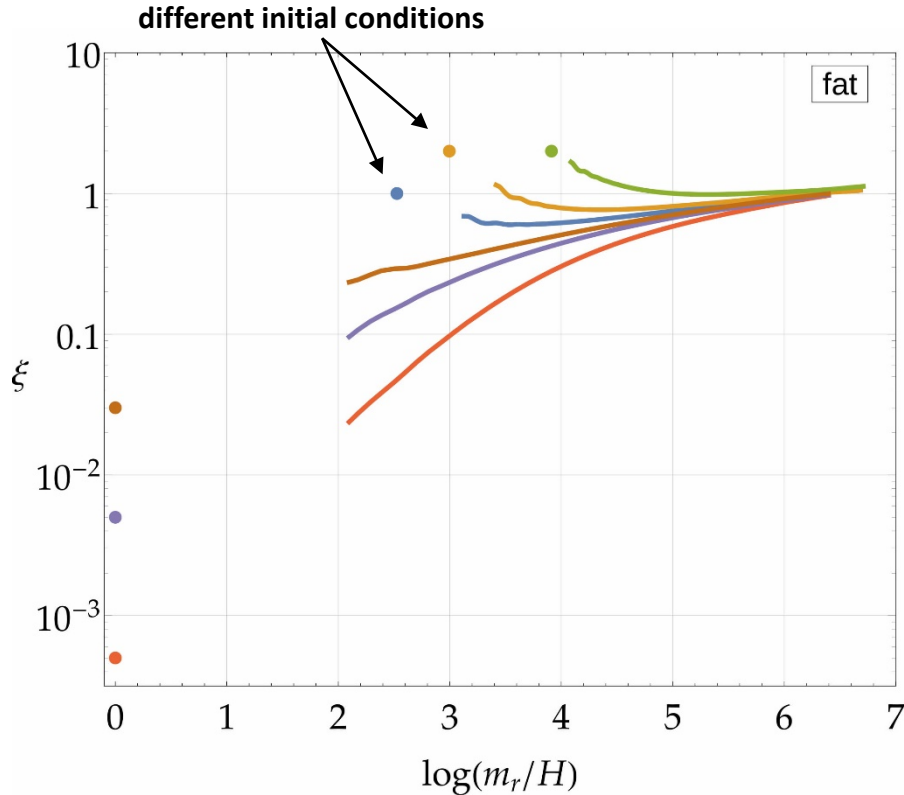
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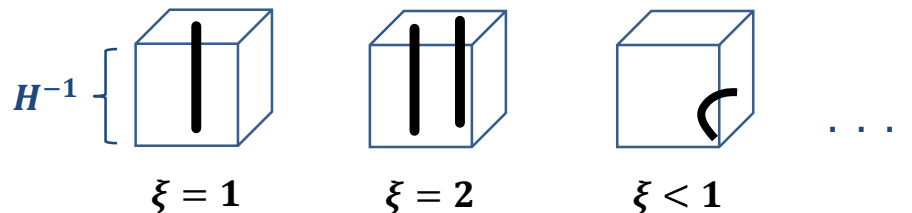
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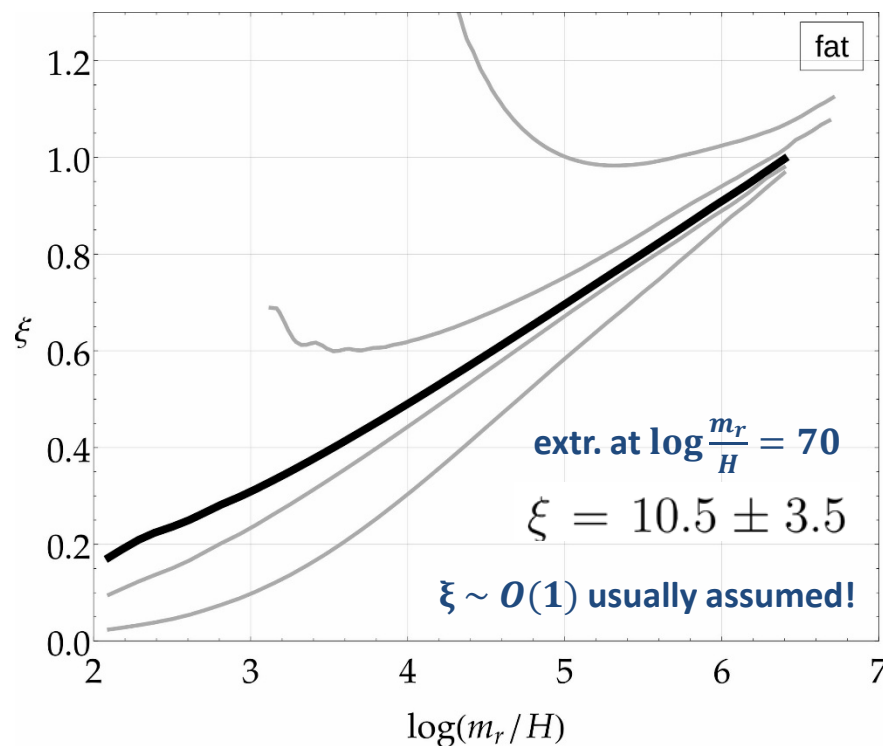
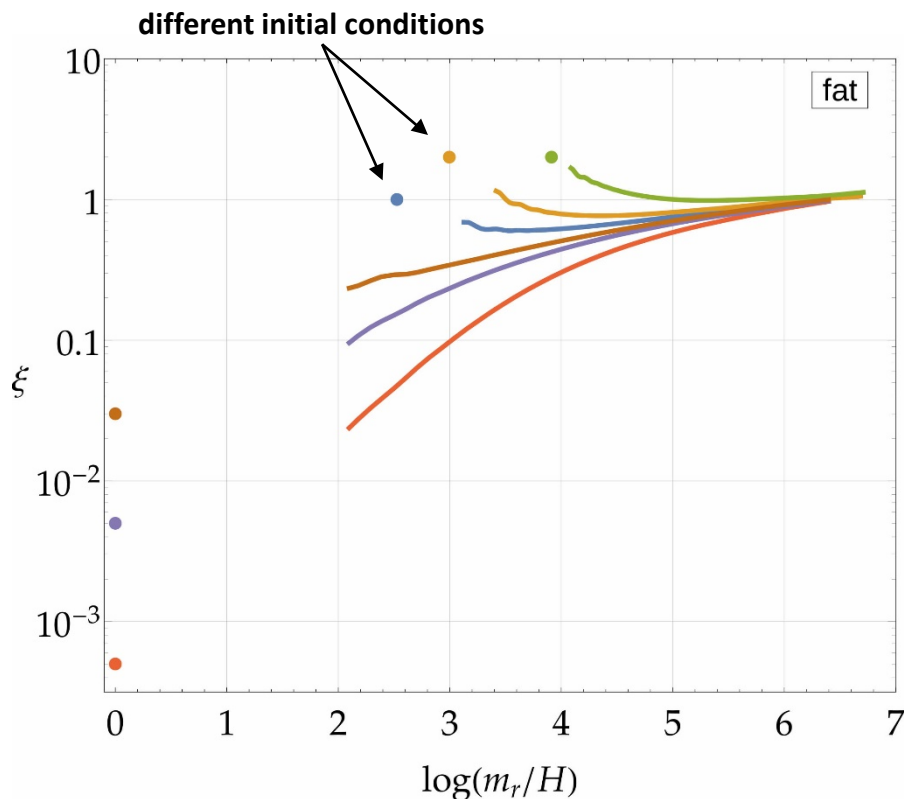
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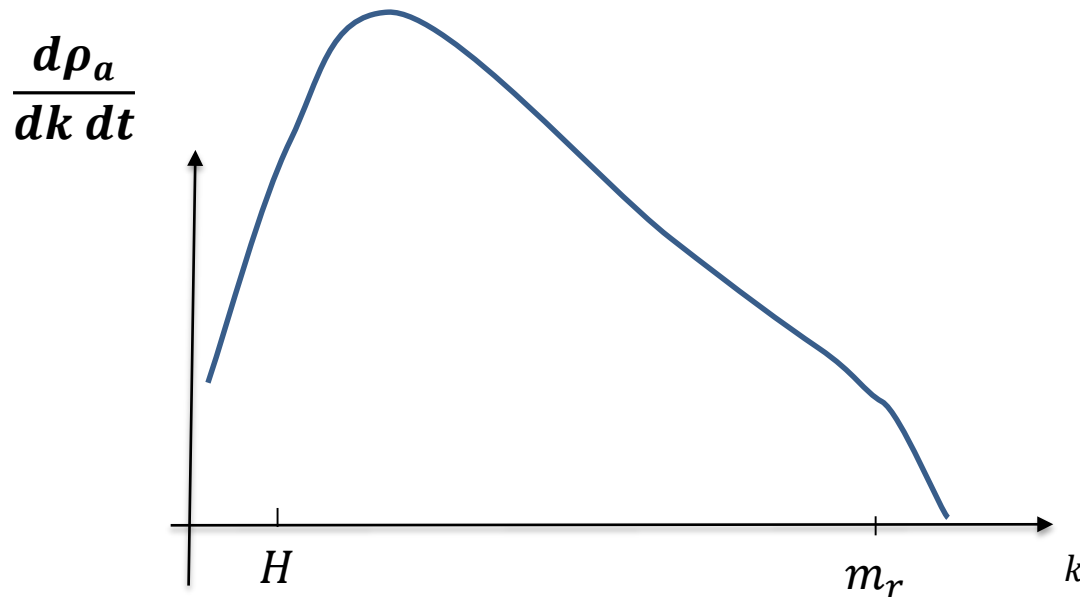
Theoretical expectation

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Theoretical expectation

- area fixed by energy conservation
- natural cut-offs at H and m_r
- peak at H because strings have curvature of $O(H)$
- in between an approximate power law $\frac{d\rho_a}{dk dt} \sim \frac{1}{k^q}$

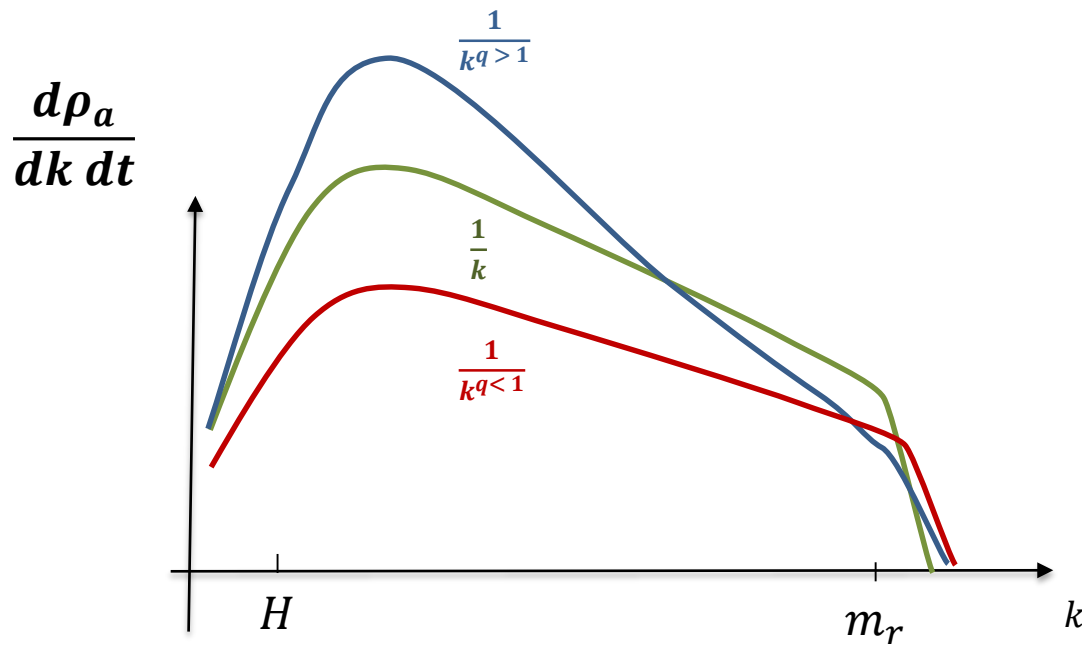


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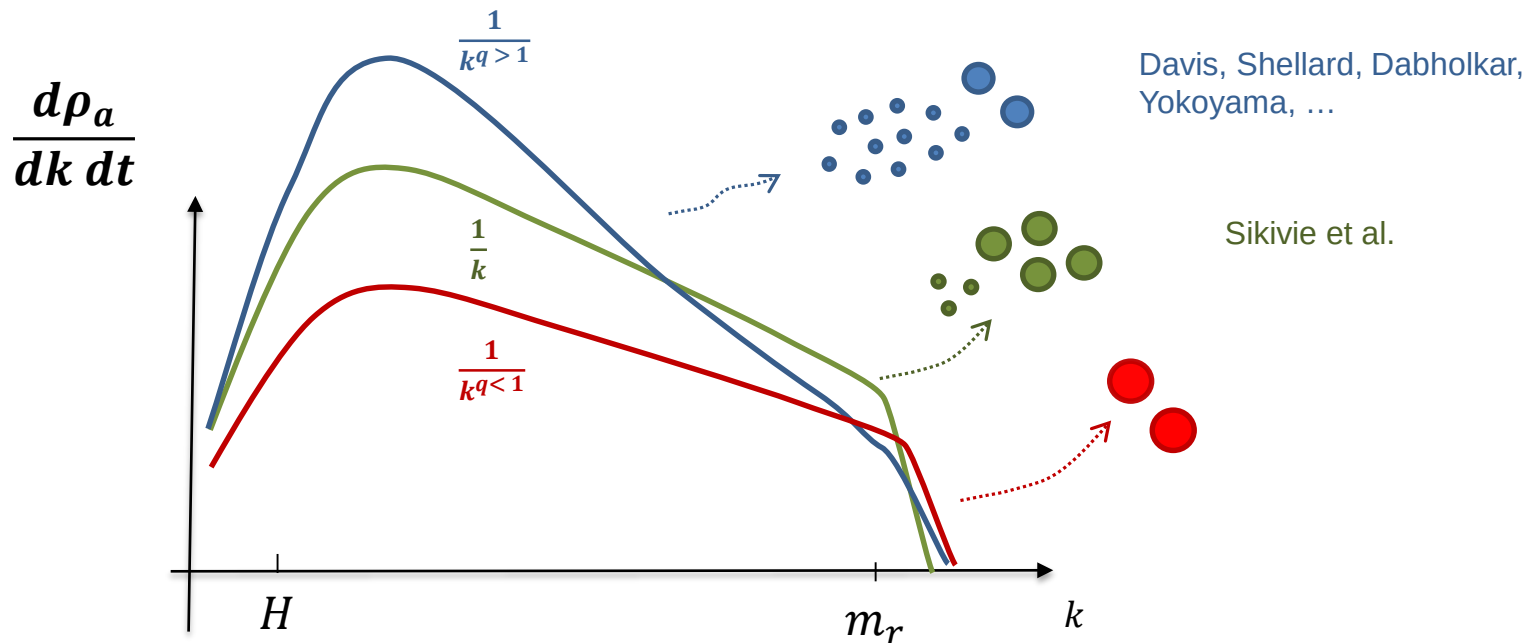


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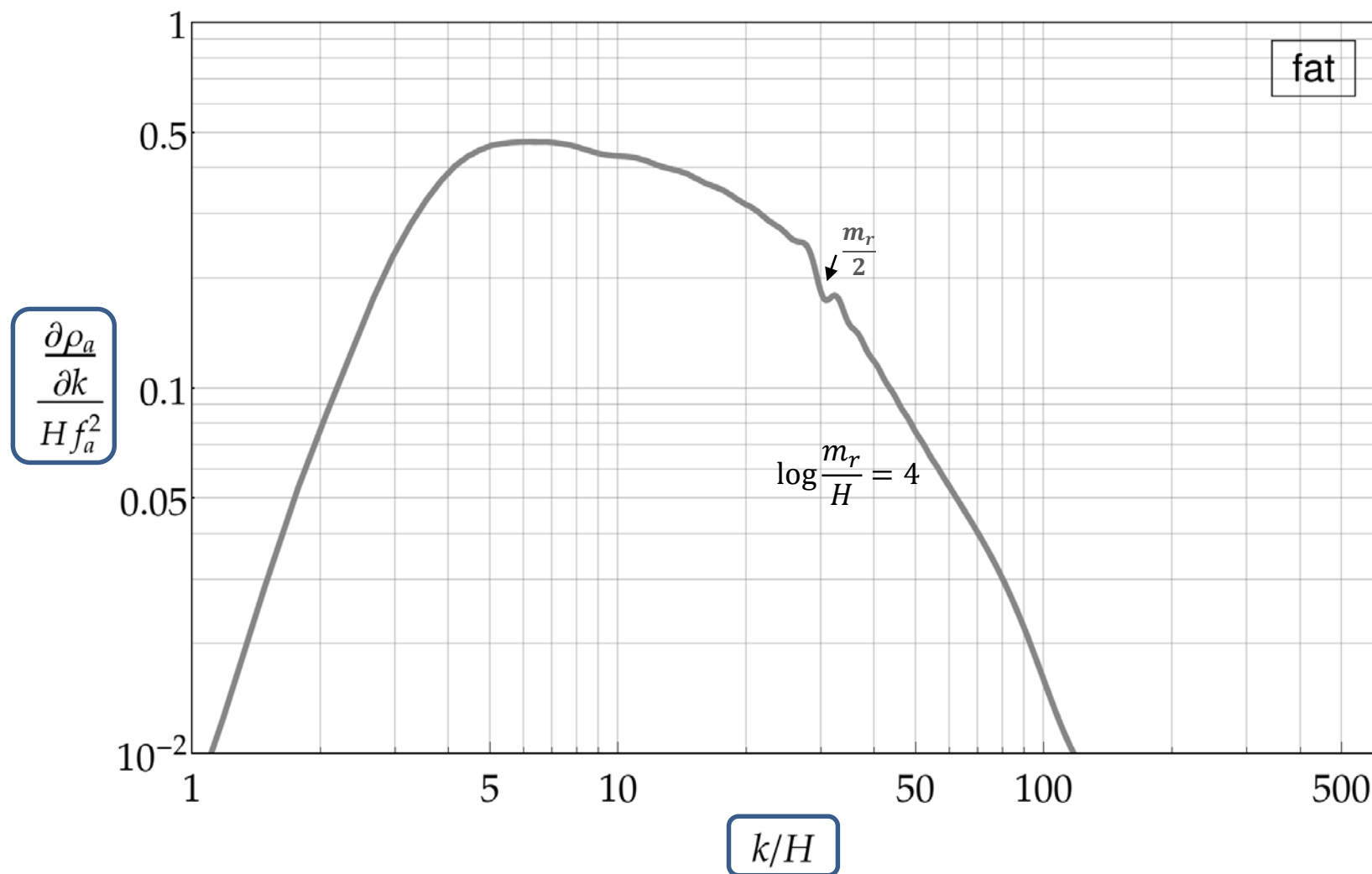
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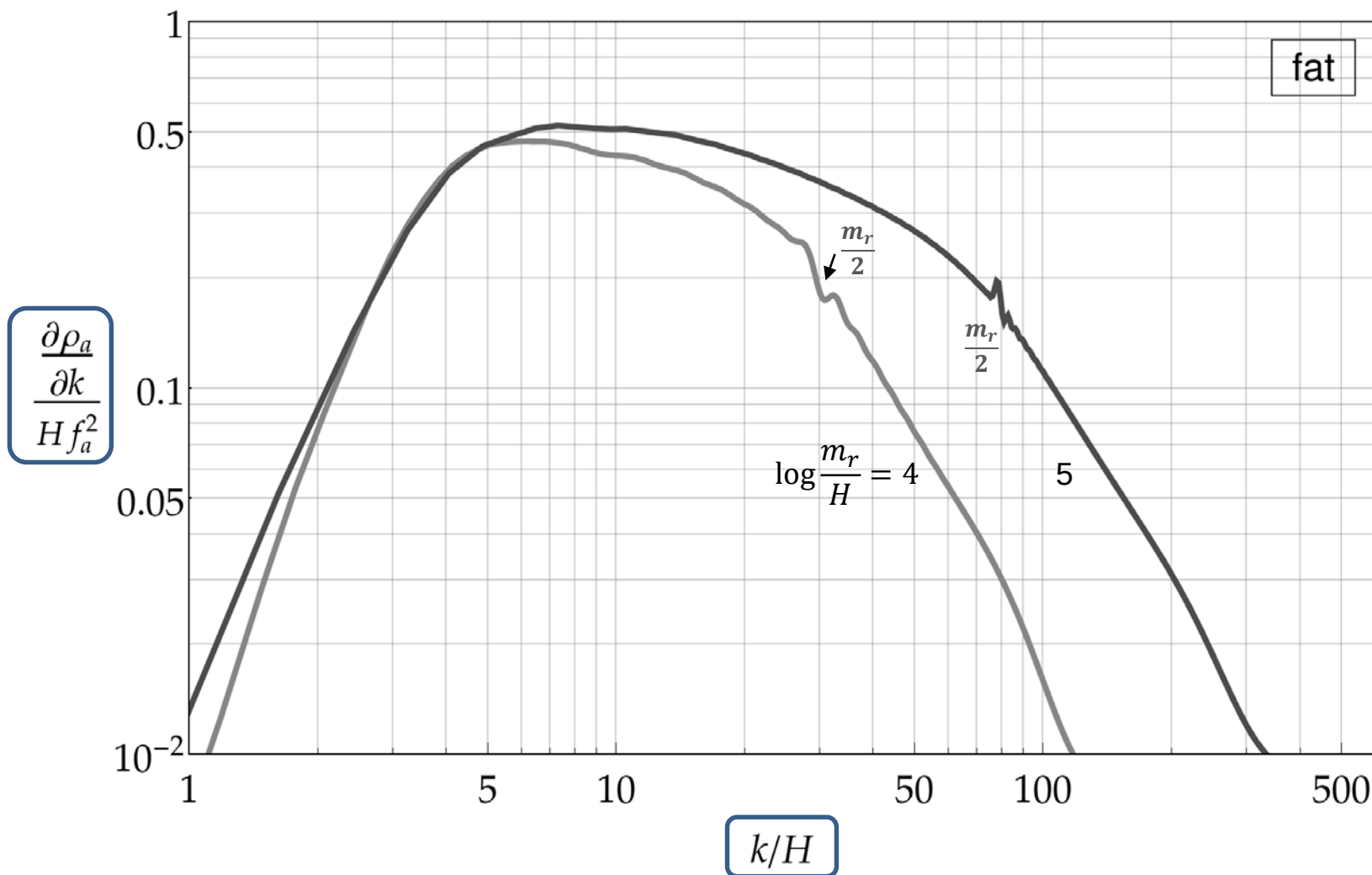


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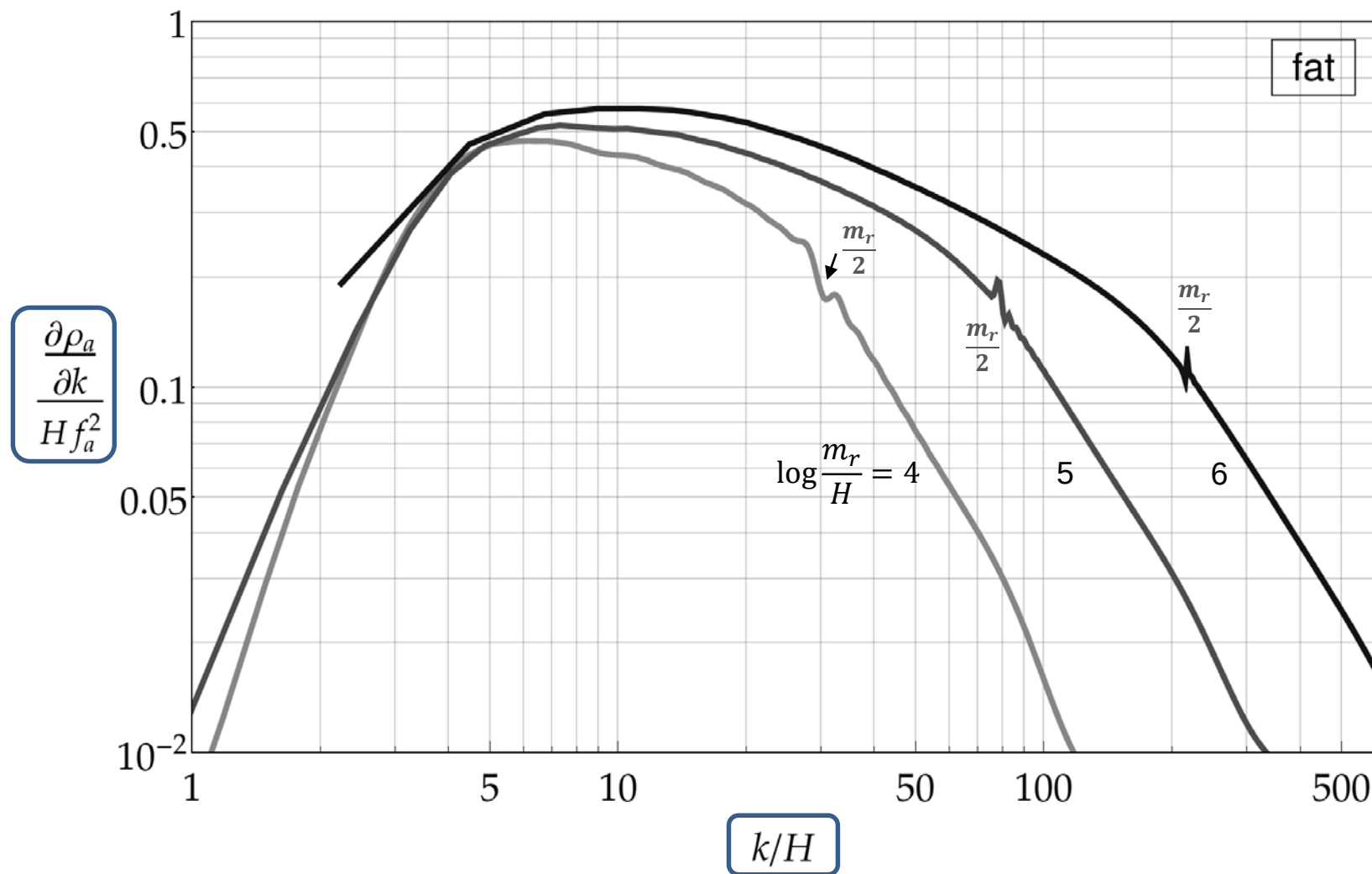
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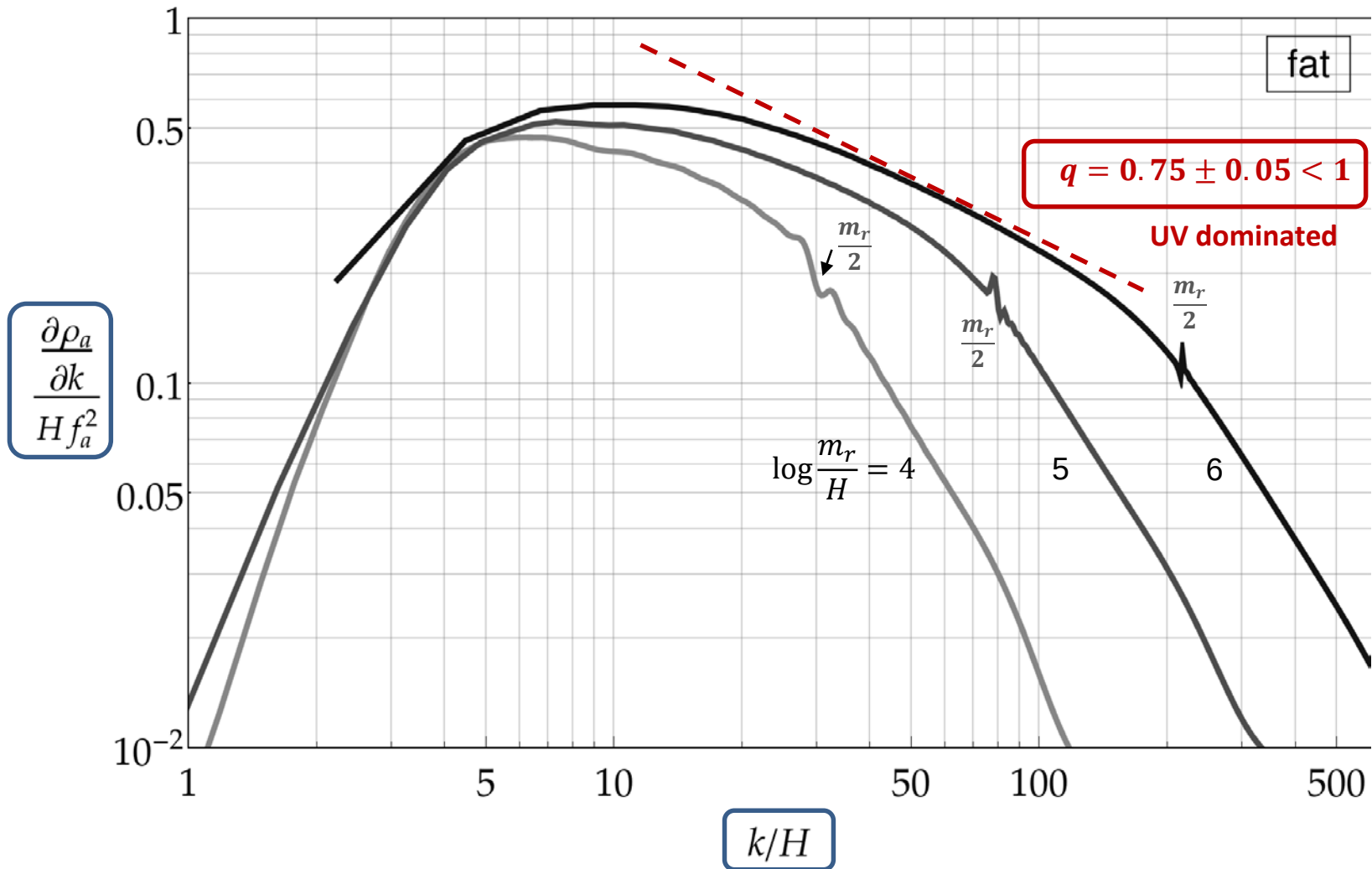
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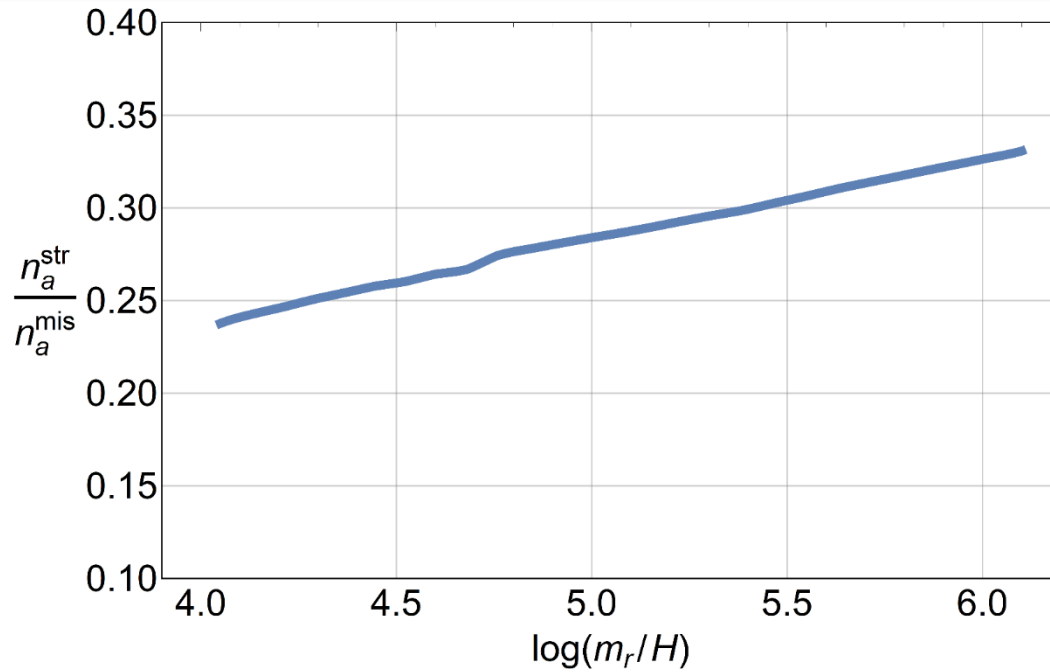


The Axion Spectrum

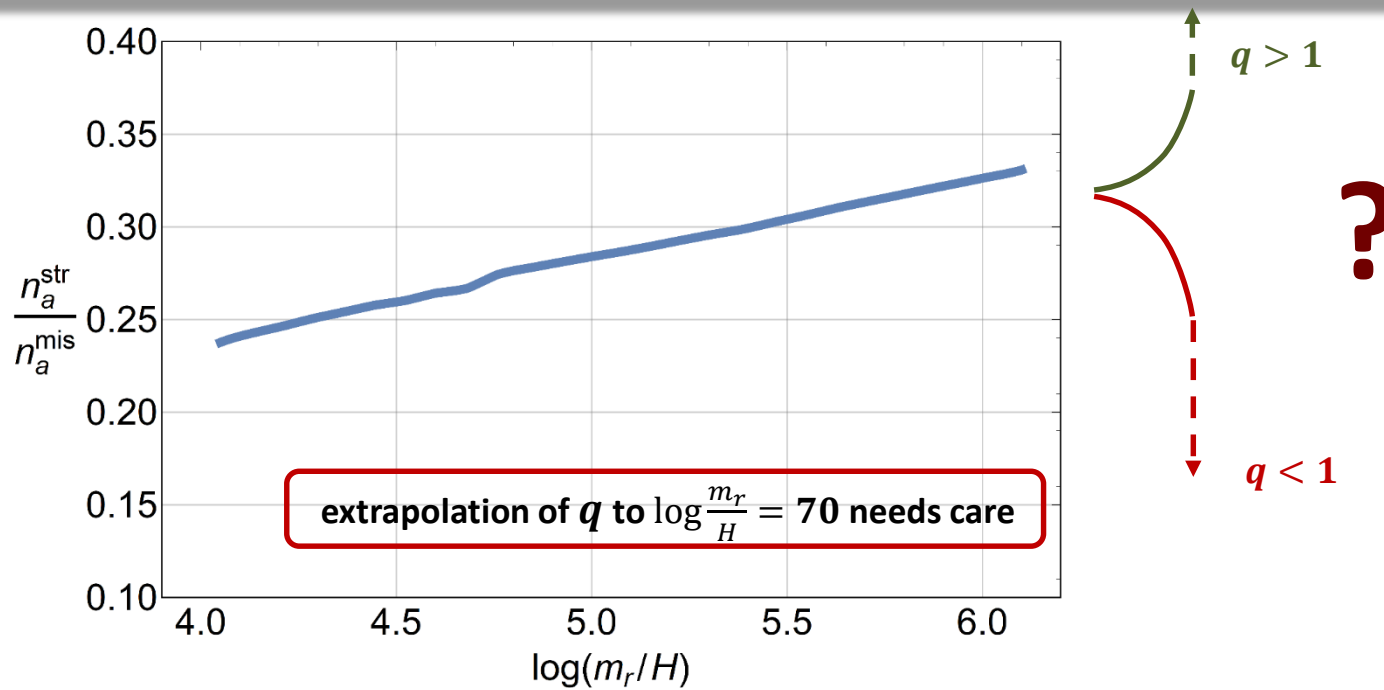


The Axion Number density

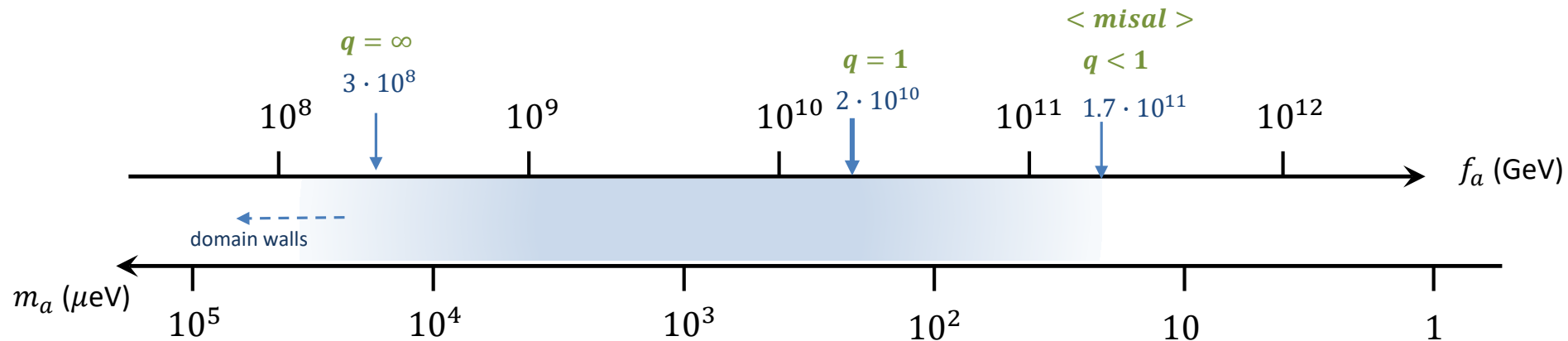
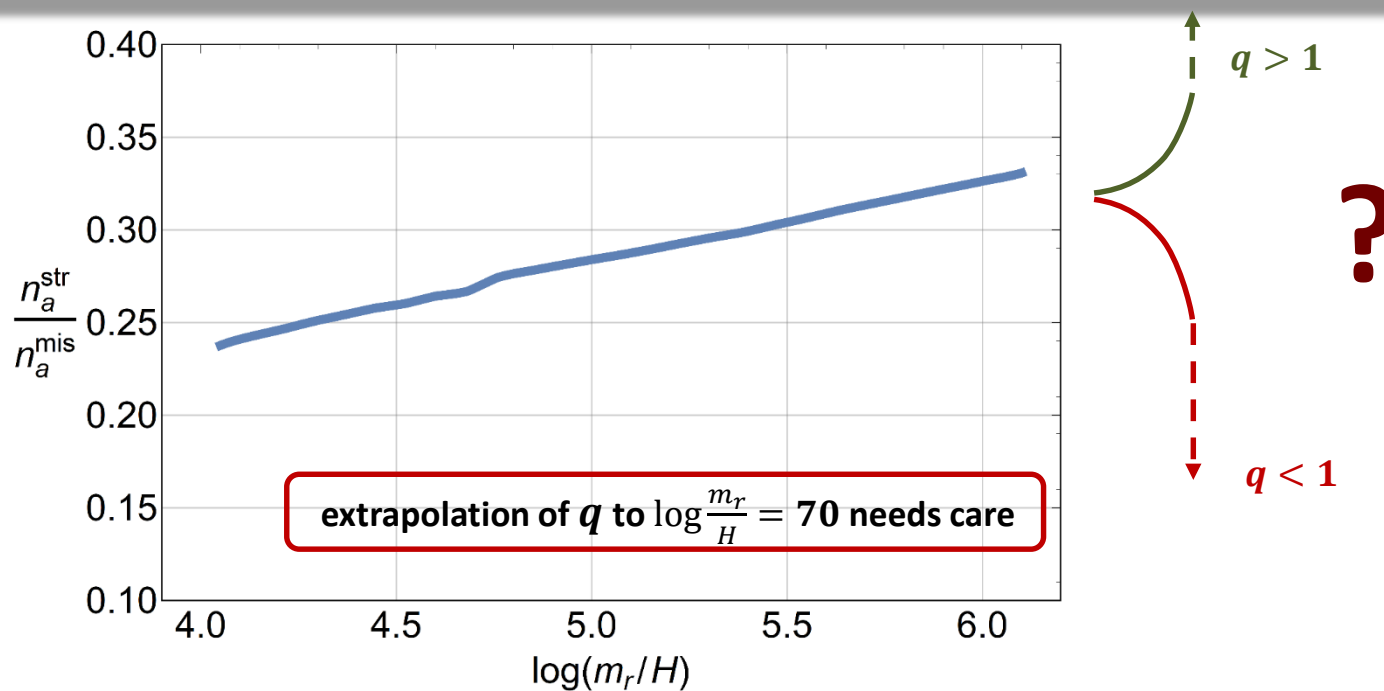
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The Axion Number density



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 $\log \frac{m_r}{H}$

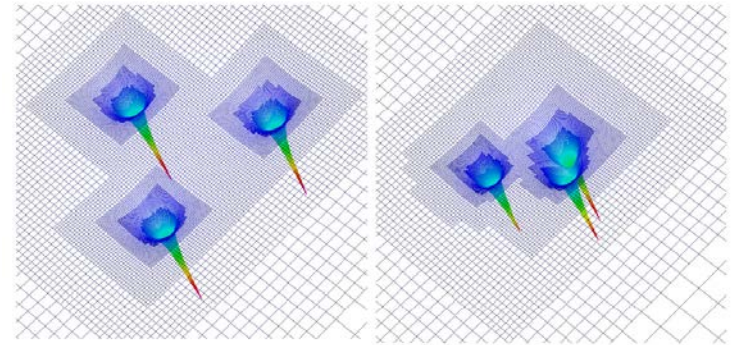
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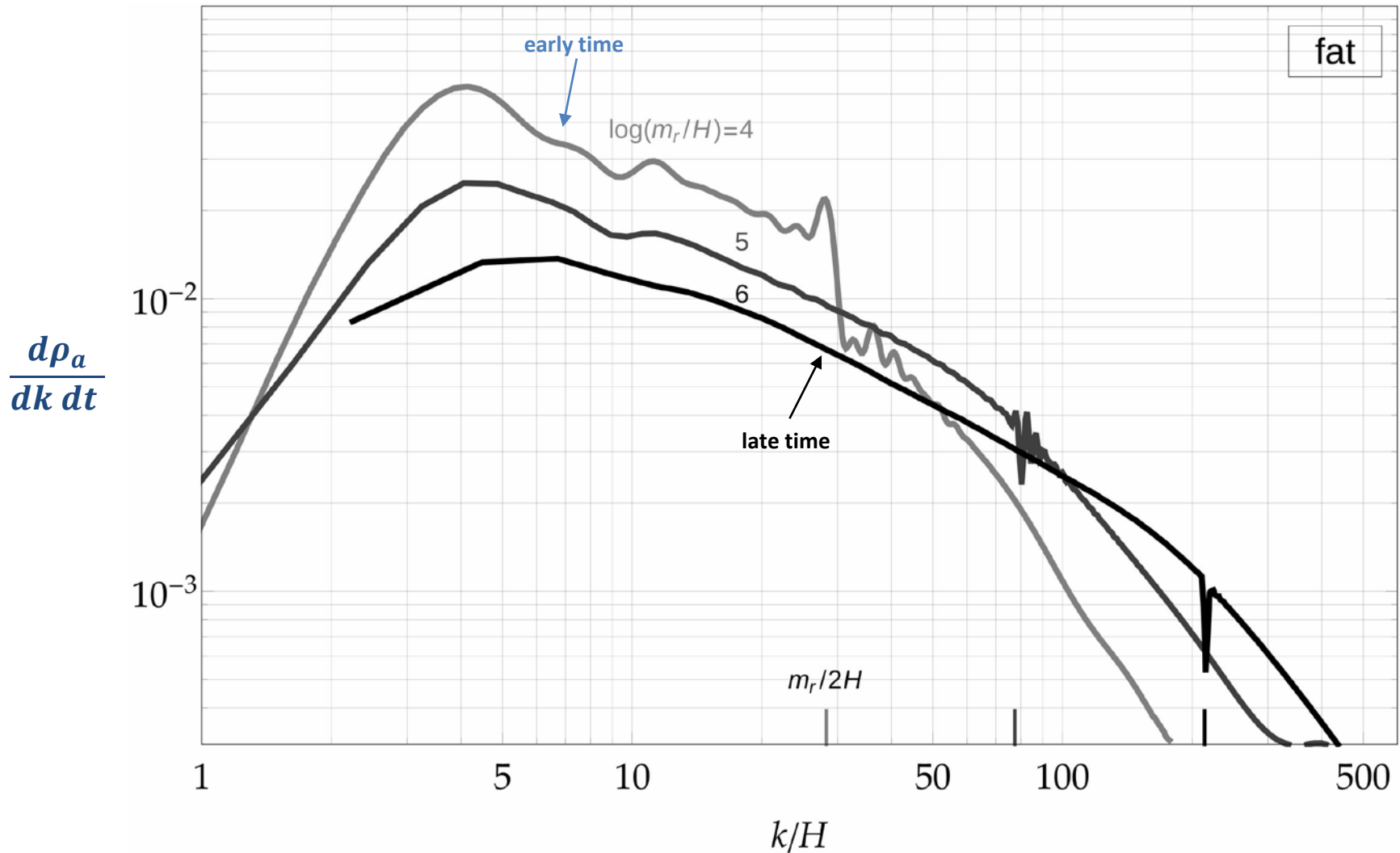
- Adaptive mesh, win factor of 10?



Instantaneous axion spectrum

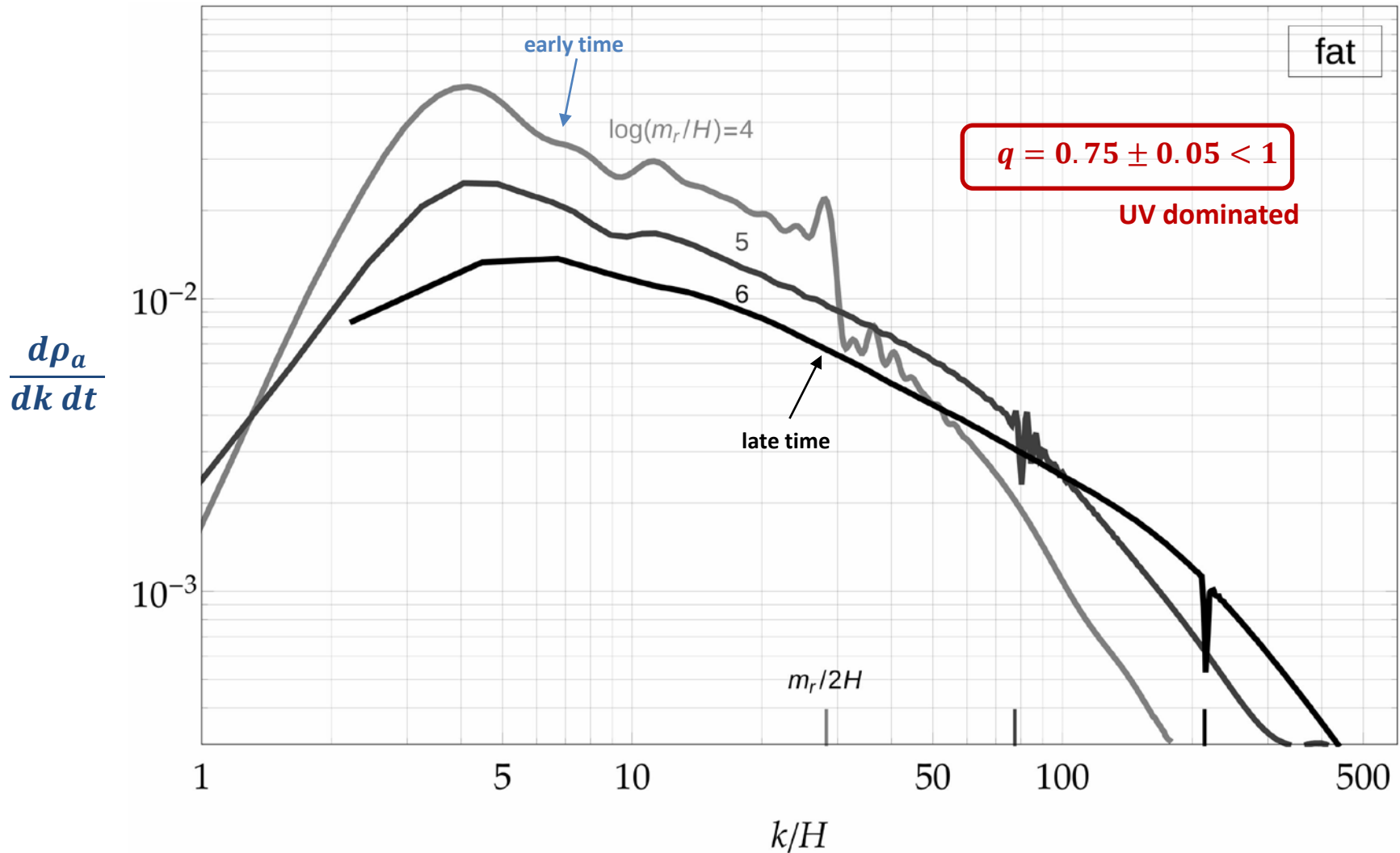
Instantaneous axion spectrum

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



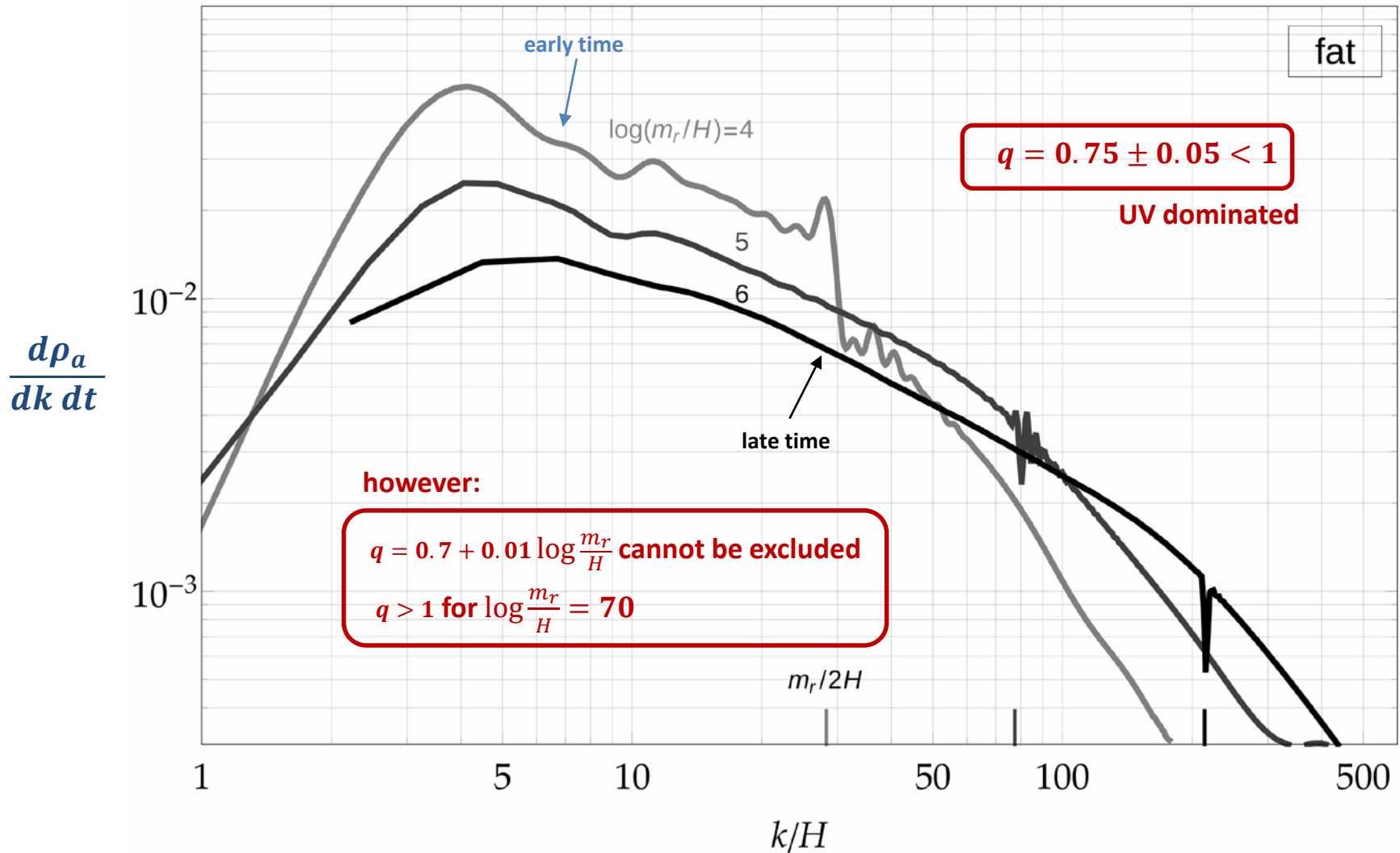
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Previous literature

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 $m \gg 1$ (which might be physically correct but not justified from their analysis)
- 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, but not physically reliable

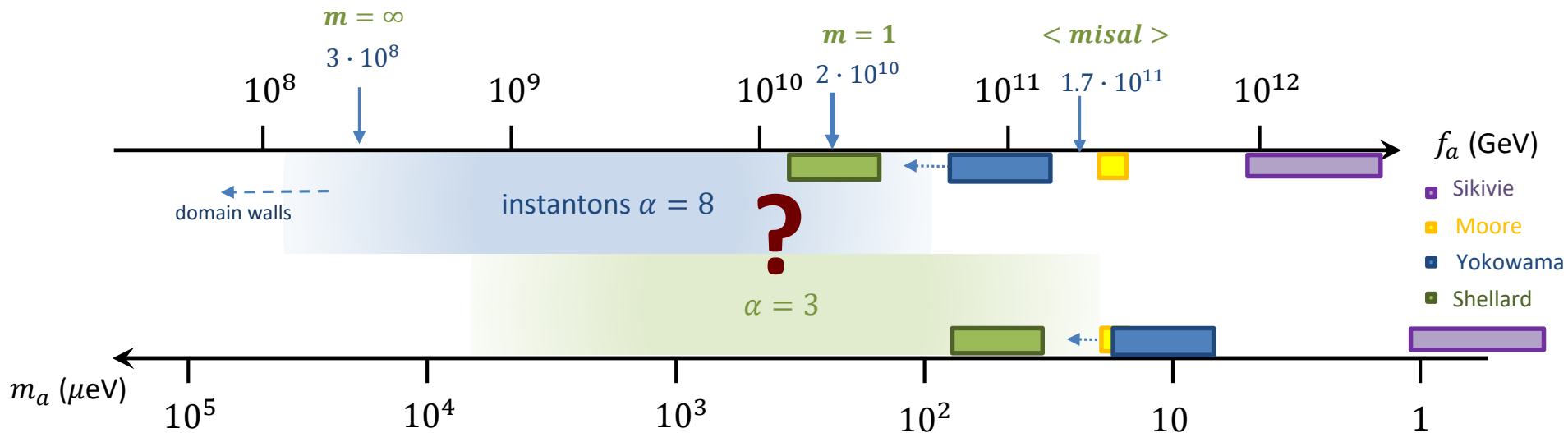
Consequence of axion mass

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

$\uparrow$
 ~ 10

$$F(m = 1) = 1$$

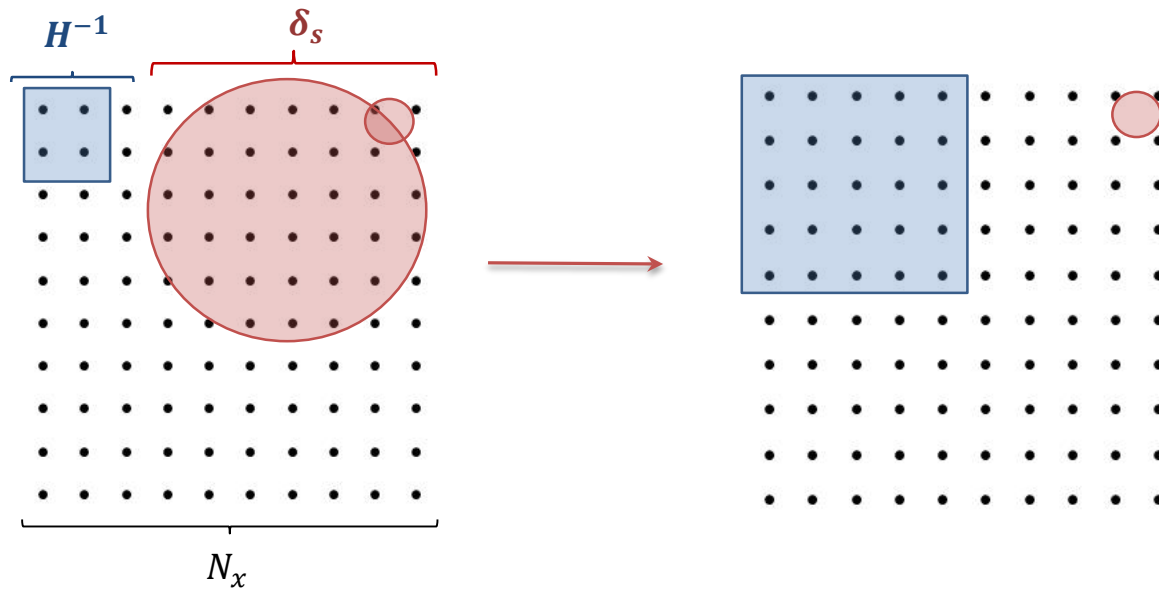
$$F(m \rightarrow \infty) = \log \alpha \sim 70$$



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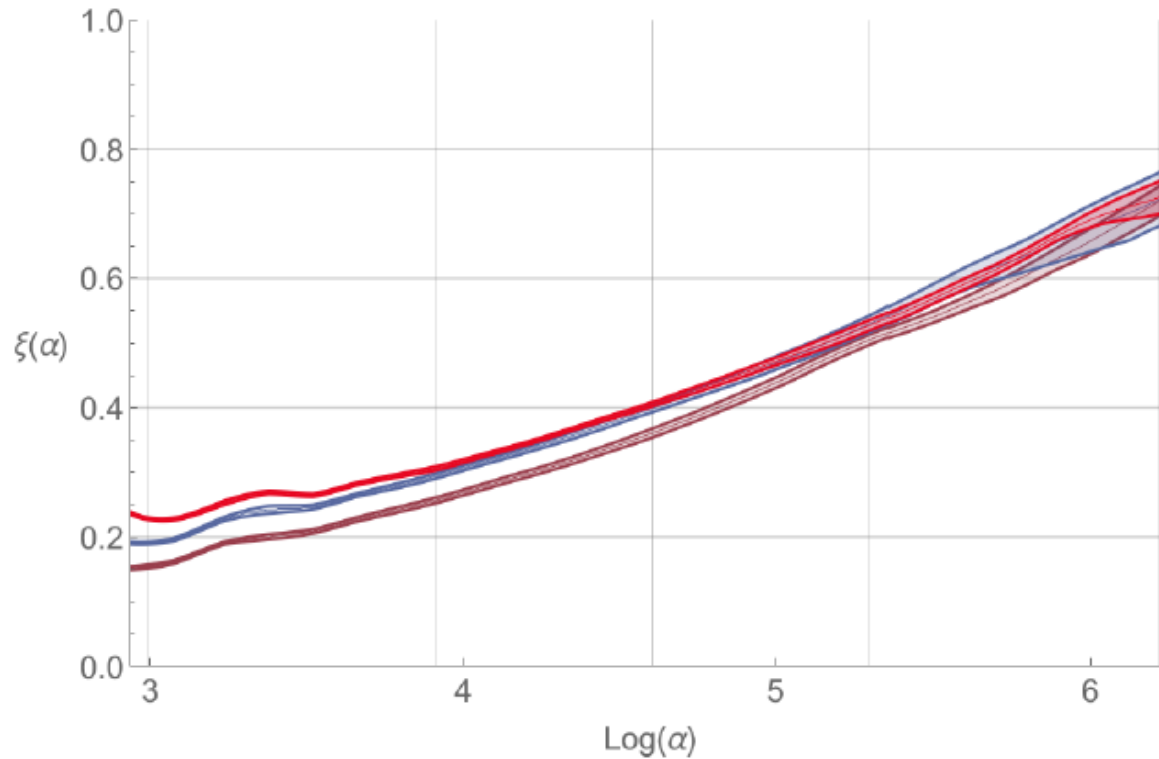


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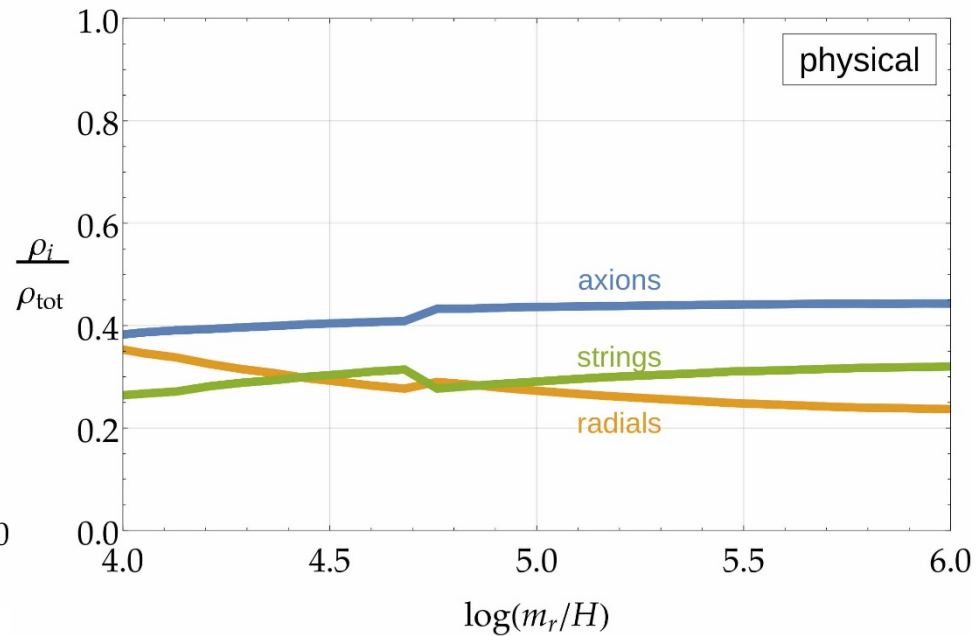
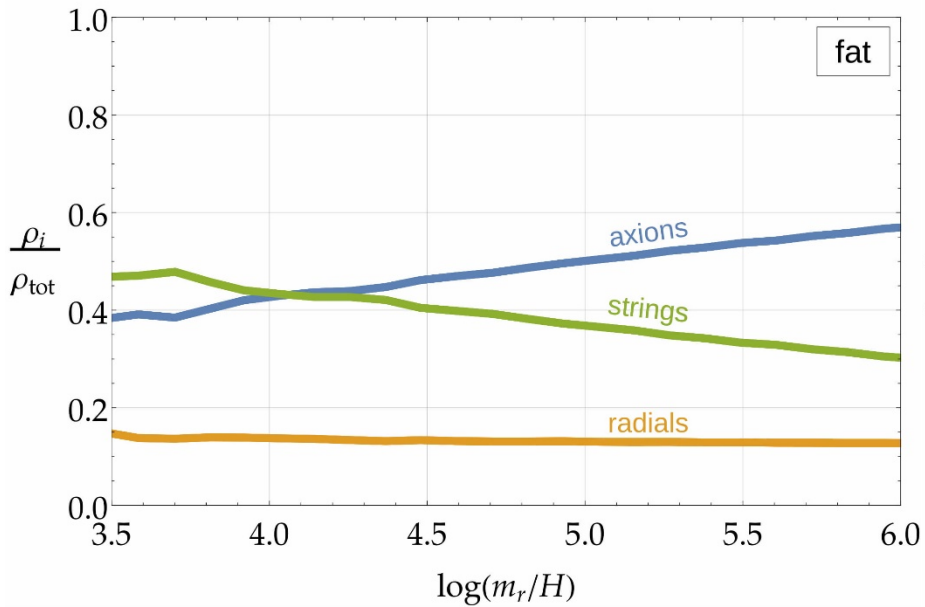
Local Strings



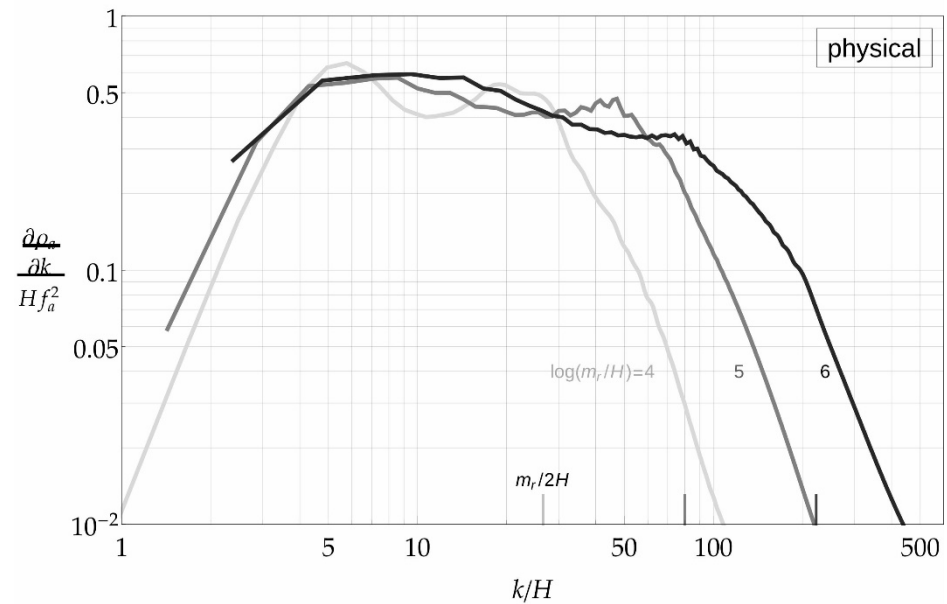
These also seem to have a log increase in $\xi(t)$ even though tension is constant

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

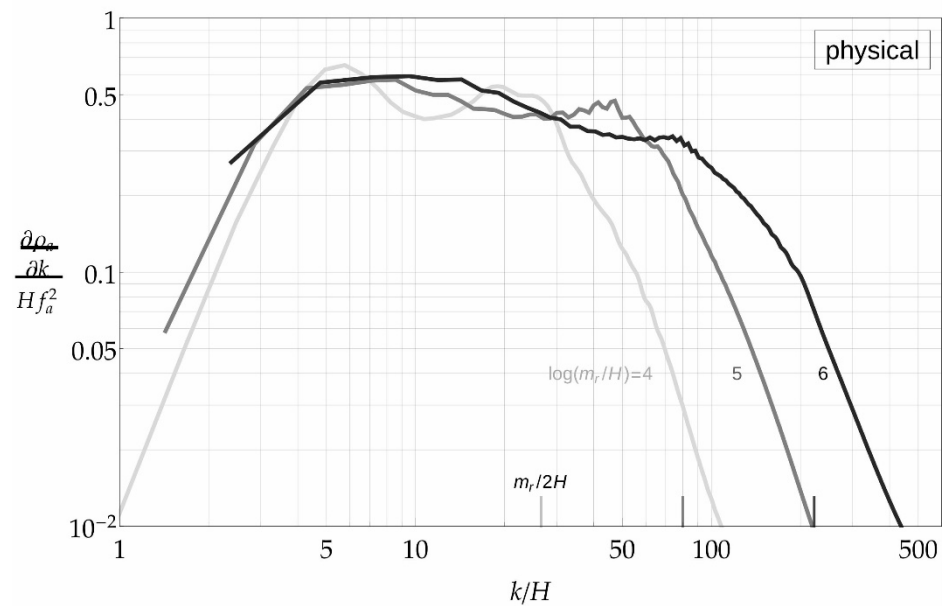
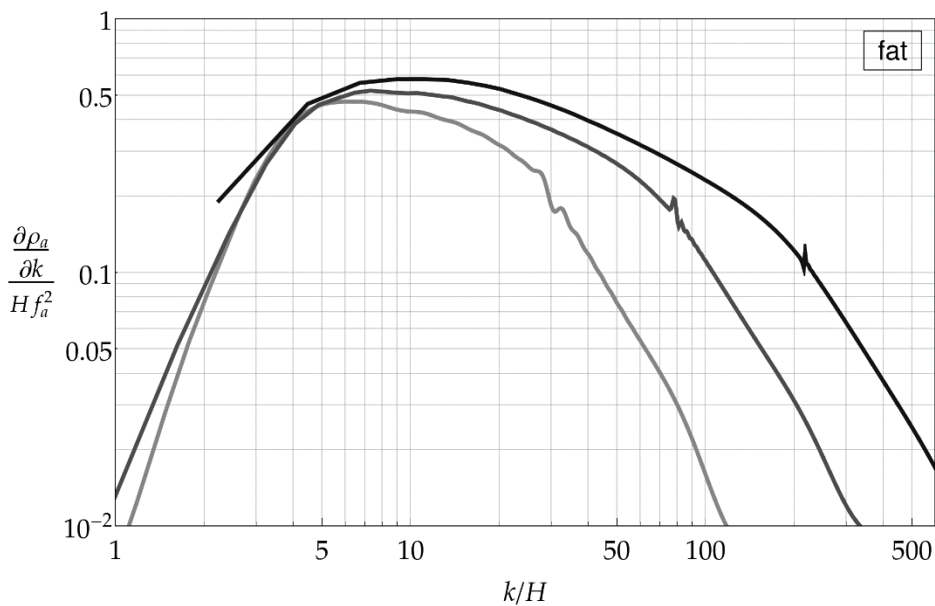
Energy budget



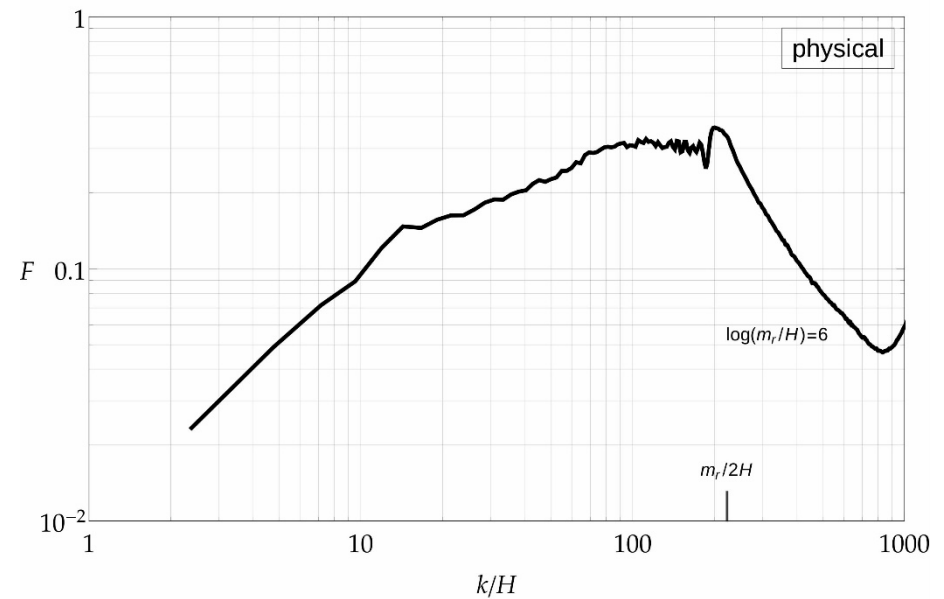
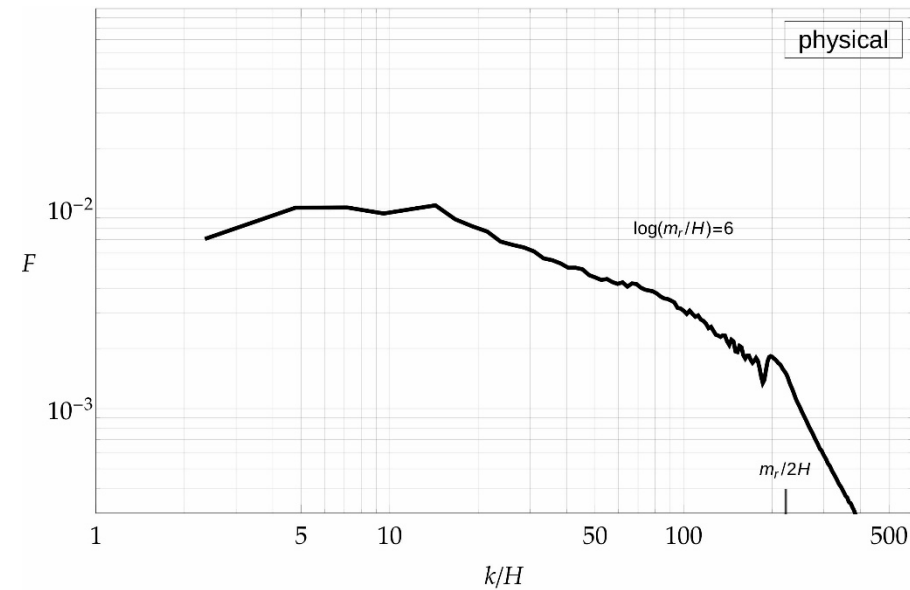
Physical total spectrum



Physical total spectrum



Physical instantaneous spectrum



Finite volume dependence

