Axions from Strings

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Based on work with
Marco Gorghetto & Giovanni Villadoro

[arXiv:1806.04677,
ongoing]

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The QCD axion

Motivated from UV and IR perspectives

- Solves a problem with the SM
- Automatic Dark Matter candidate
- Plausible in typical string compactifications

Less explored than other possibilities, experimental progress likely

What can theory contribute?

Highlight especially well motivated parts of parameter space

Determine existing limits from e.g. astrophysical systems

Understand physics implications of new searches

In case of an anomaly or discovery interpret what has been seen

The QCD axion

Spontaneously broken anomalous global U(1)

$$\boxed{\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}}$$

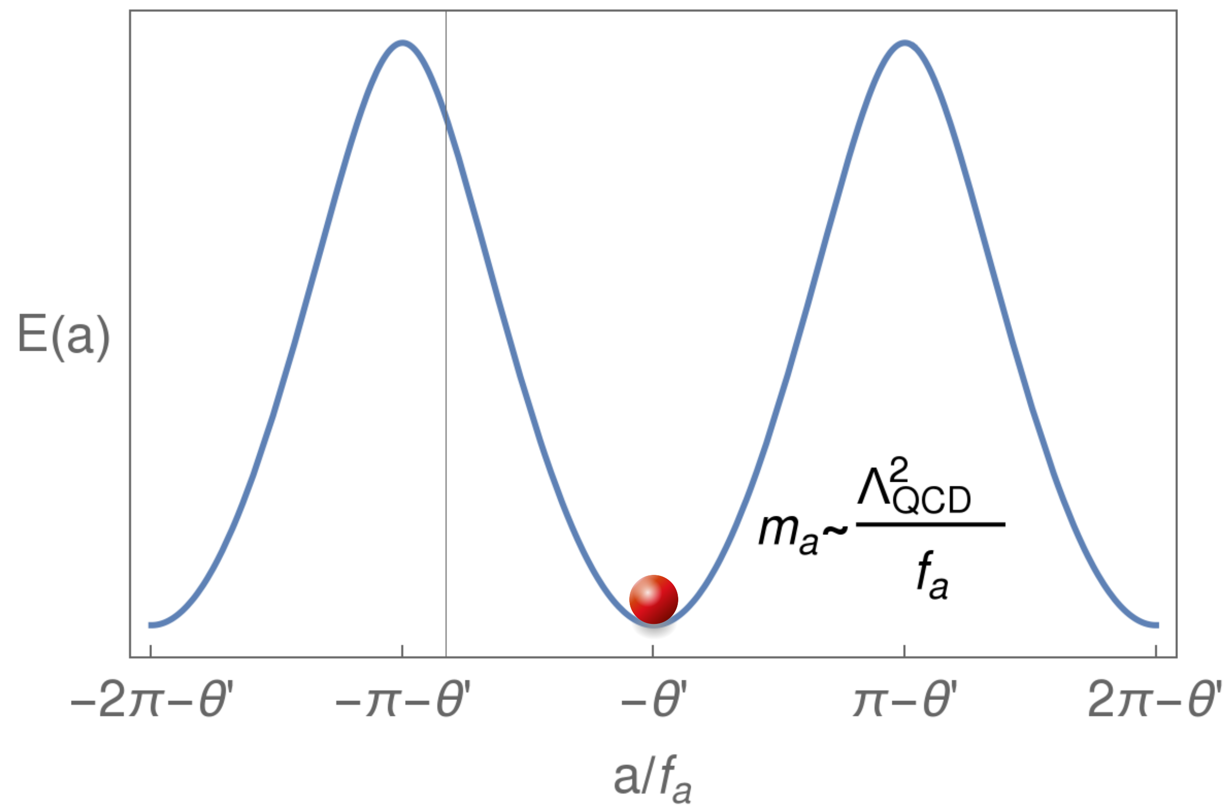
$$a \rightarrow a + \delta$$

$$f_a \gtrsim 10^8 \text{ GeV}$$

QCD runs into strong coupling

→ axion potential

$$E(a) \geq E\left(a = -\theta'\right)$$

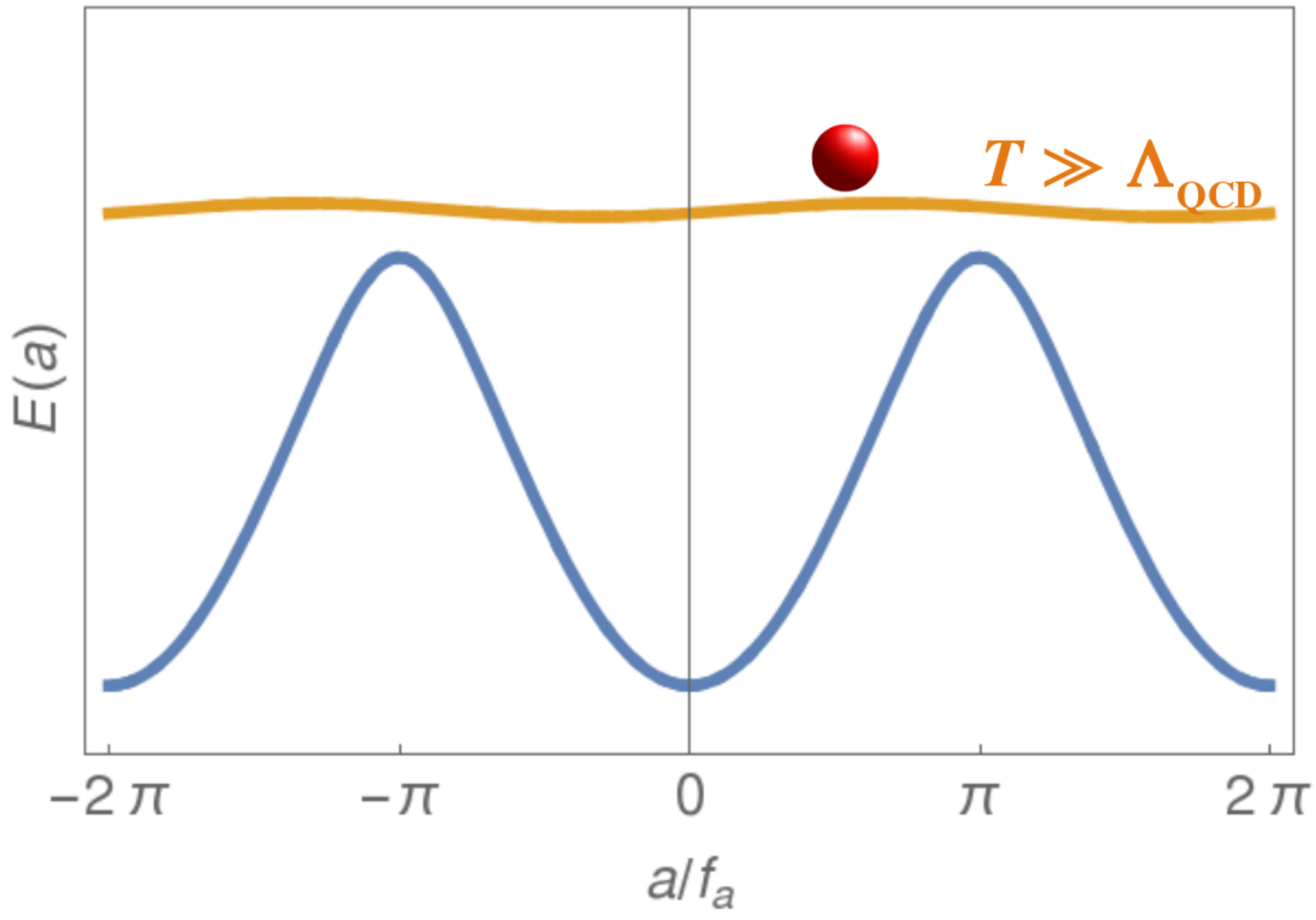


Solves the SM strong CP problem $\theta_{\text{tot}} = \langle a \rangle + \theta' = 0$

Dark matter

Misalignment

$$\ddot{a} + 3H(T)\dot{a} + m_a^2(T)\,a = 0$$



Dark matter

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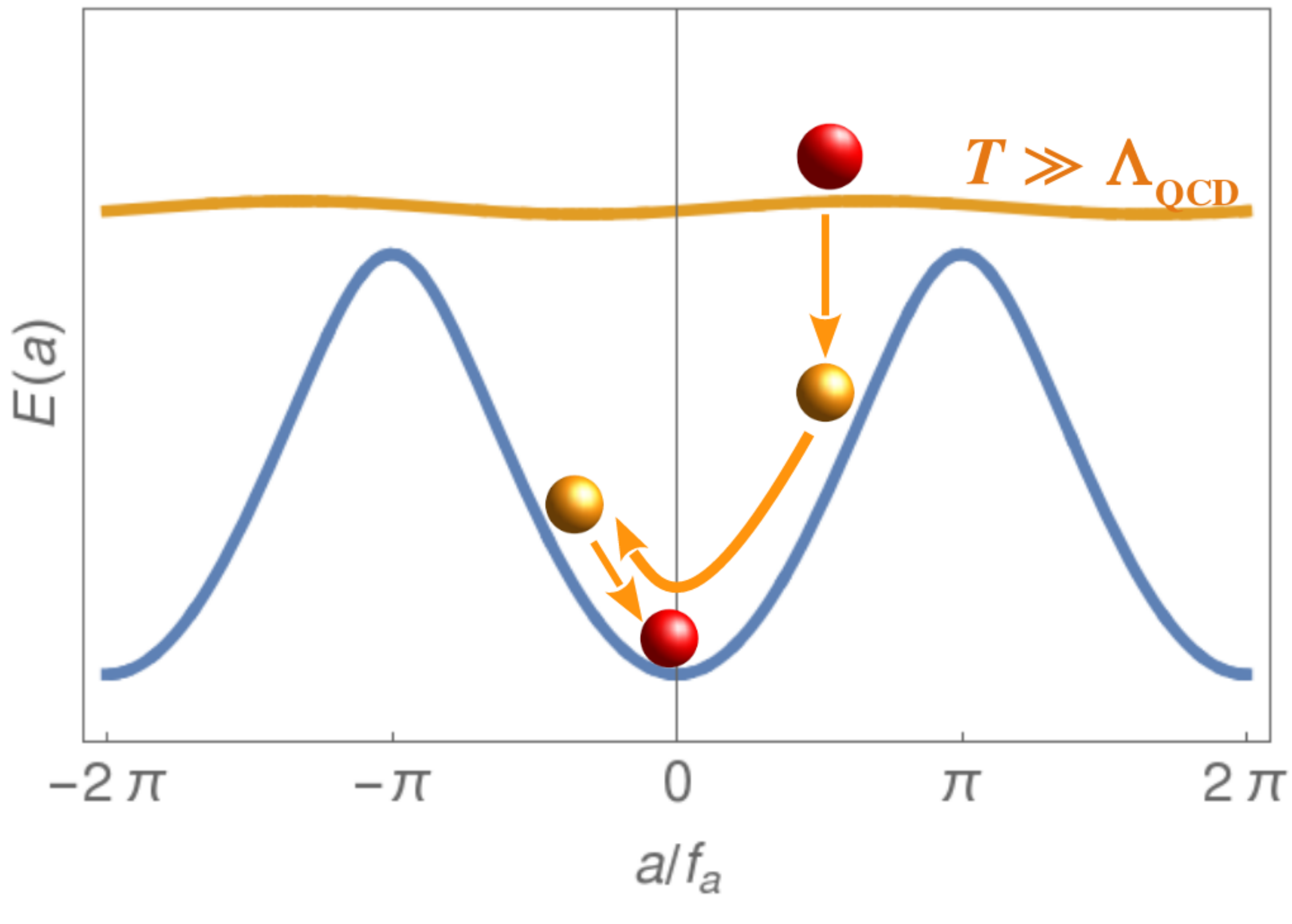
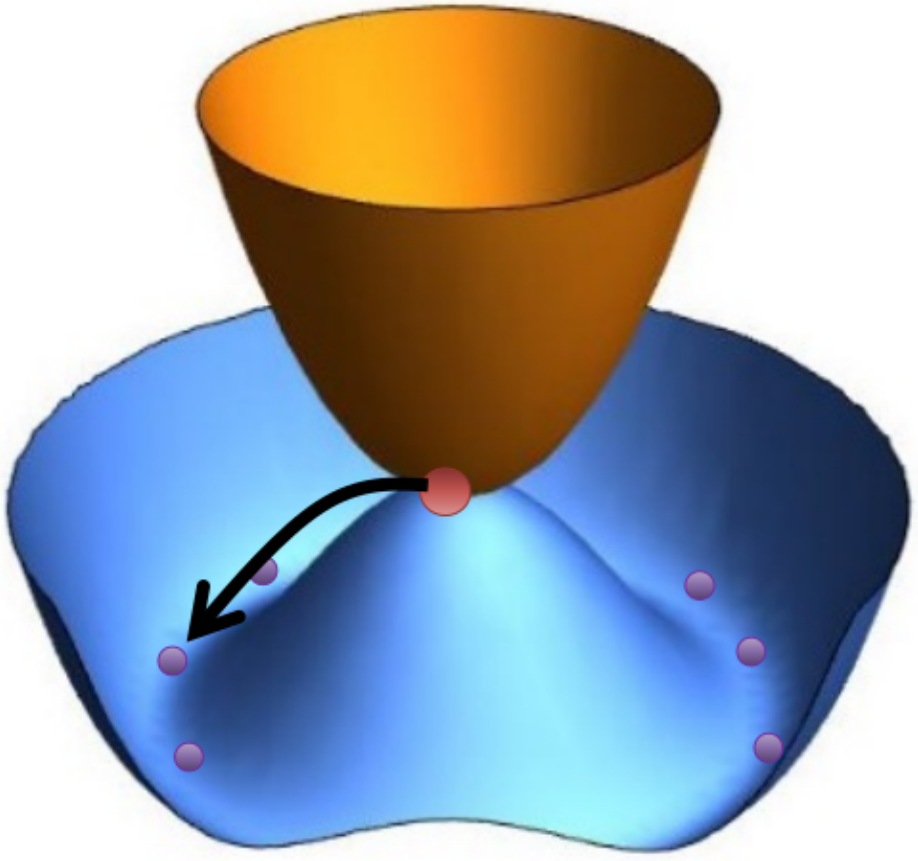


Dark matter

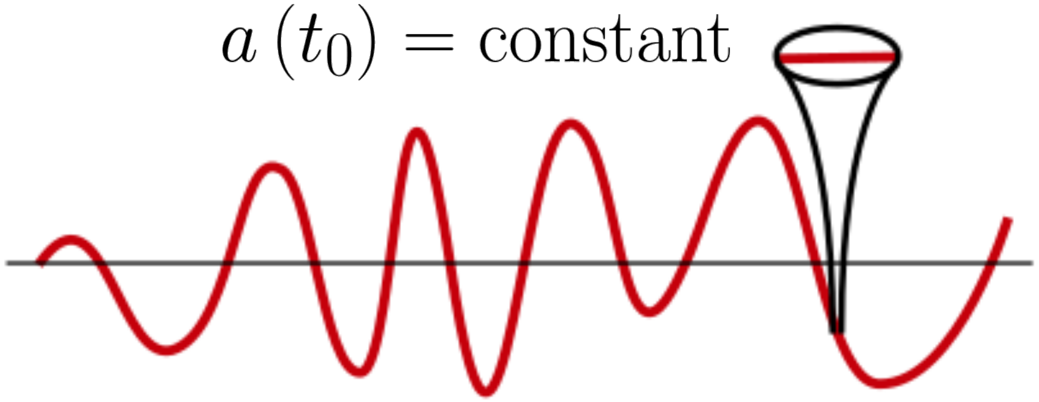
Immediately after U(1) breaking, the axion field is random over the universe:



Dark matter scenarios

PQ symmetry broken during inflation
and not subsequently restored

$a\,(t_0) = \text{constant}$



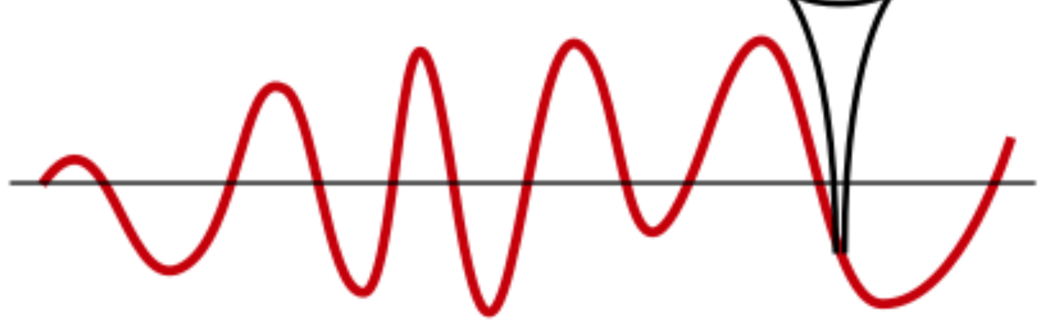
only contribution from misalignment
but not calculable

$\theta_0 < \pi \quad \Leftrightarrow \quad f_a \gtrsim 10^{12}\ \text{GeV}$

(For smaller f_a , i.e. larger masses, the axion still solves the Strong CP problem, but is not DM)

Dark matter scenarios

PQ symmetry broken during inflation and not subsequently restored	PQ symmetry unbroken during inflation or subsequently restored
$a\,(t_0) = \text{constant}$	$a\,(t_0) = \text{random}$



only contribution from misalignment
but not calculable

$$\theta_0 < \pi \quad \Leftrightarrow \quad f_a \gtrsim 10^{12}\ \text{GeV}$$

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

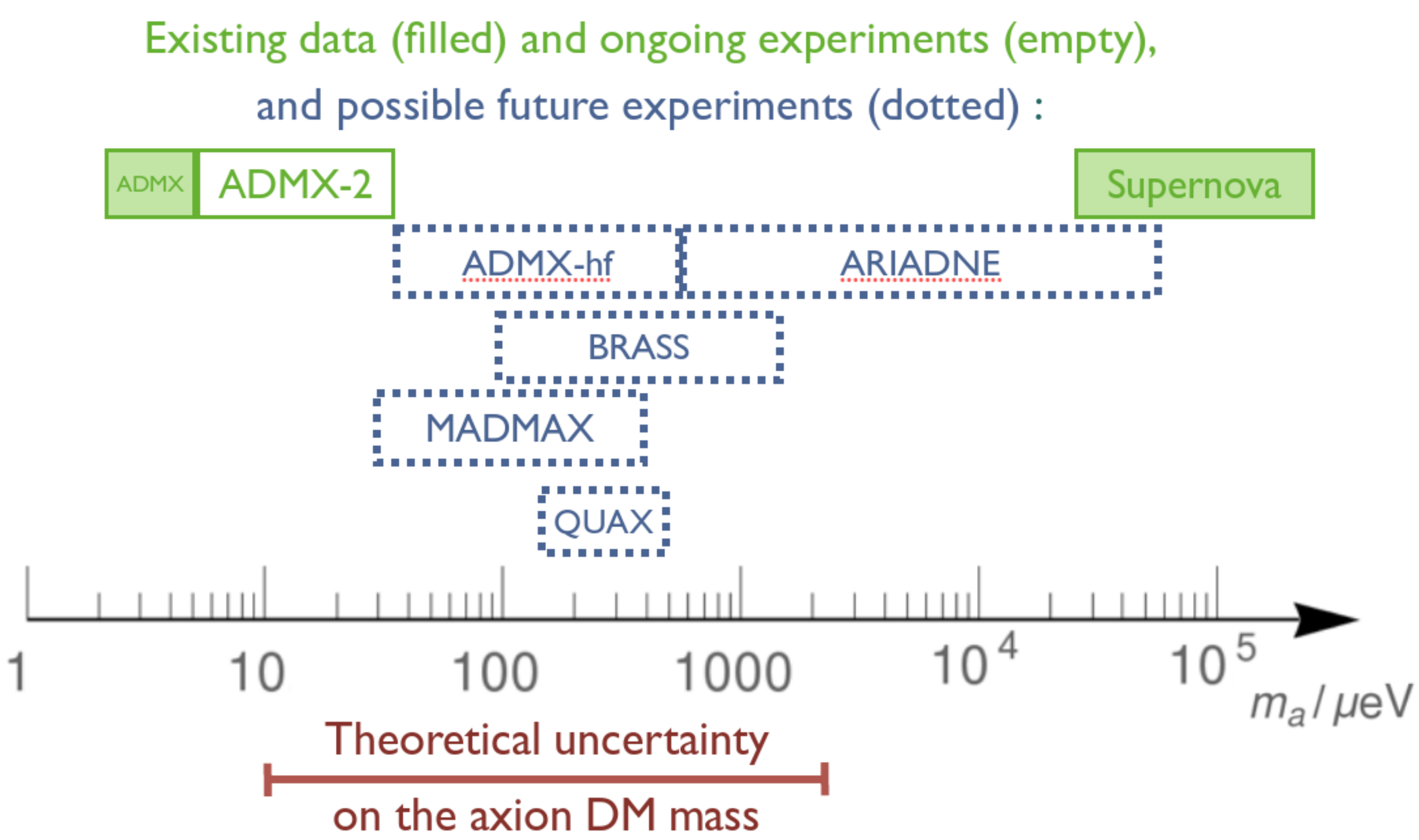
$$\Omega_a > \Omega_a^{mis} \quad \Leftrightarrow \quad f_a < f_a^{mis} \sim 10^{12}\ \text{GeV}$$

(For smaller f_a , i.e. larger masses, the axion still solves the Strong CP problem, but is not DM)

U(1) breaking after inflation

In principle extremely predictive

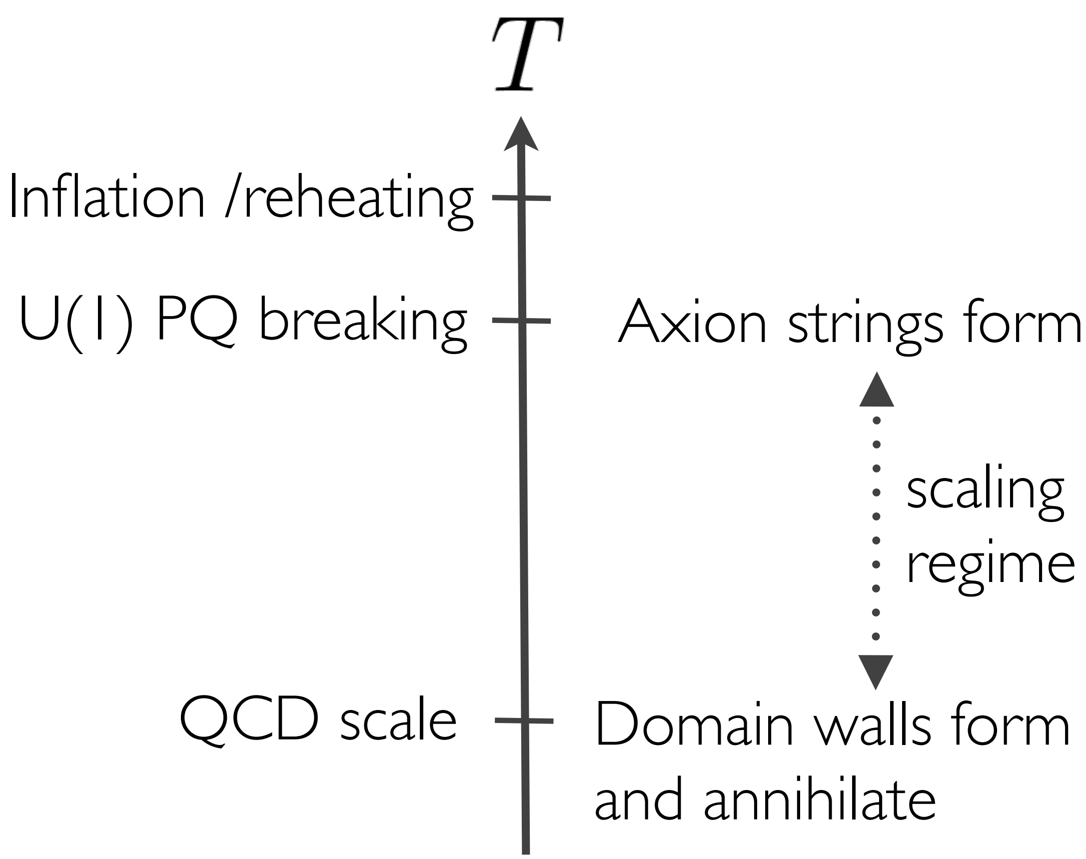
unique DM axion mass

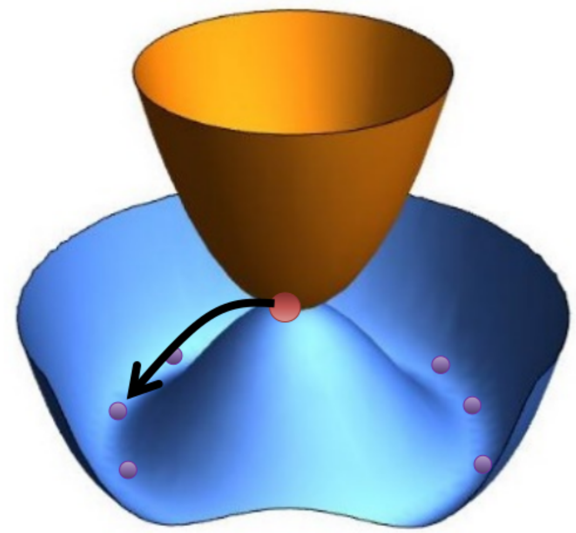


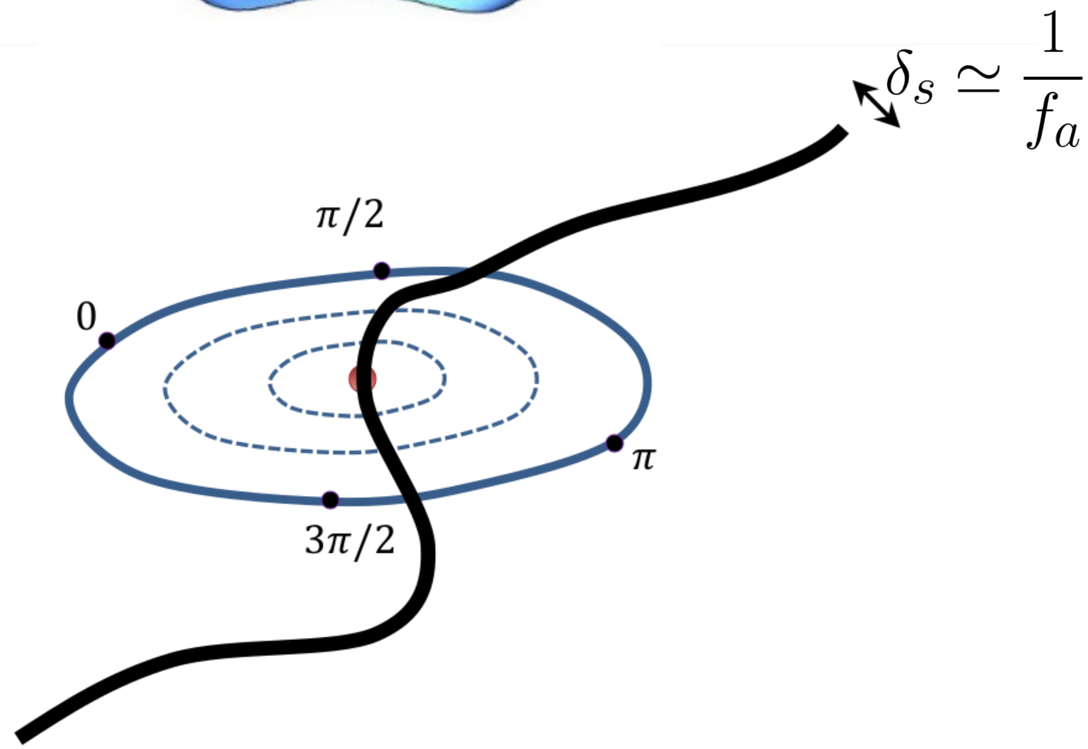
Reliable prediction: interpret ongoing experiments, design future experiments

Precise agreement with an experimental discovery → minimum inflation scale

Strings and domain walls







Significant proportion of DM axions
produced by strings and domain walls

Axion emission during scaling

Energy in the scaling regime:

$$\rho_{\text{scaling}} = \frac{\xi(t)\,\mu(t)}{t^2}$$

$\xi(t)$ = Length of string per Hubble volume

$\mu(t)$ = string tension = energy per length

Axion emission during scaling

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Rate of energy release per volume $\quad P_{\text{emitted}} \simeq \dfrac{\xi(t)\,\mu(t)}{t^3}$

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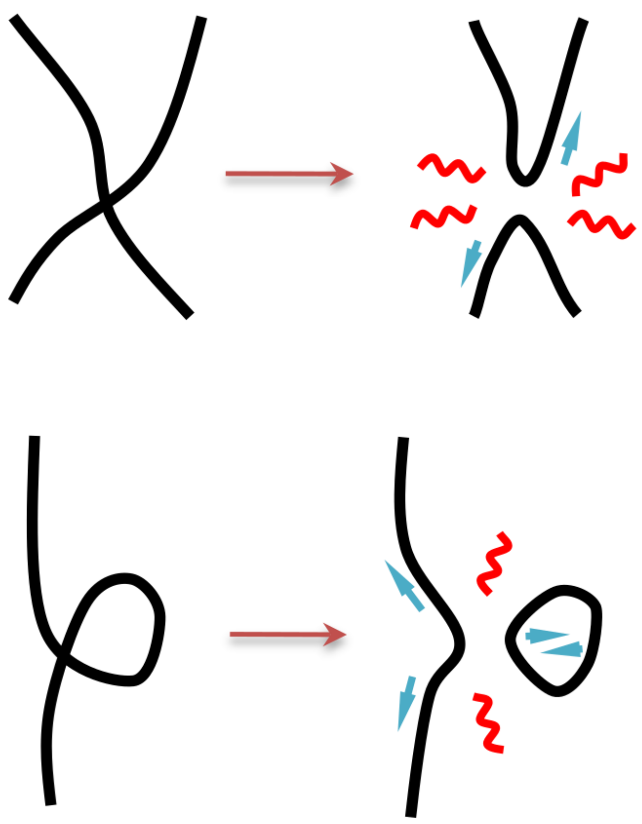
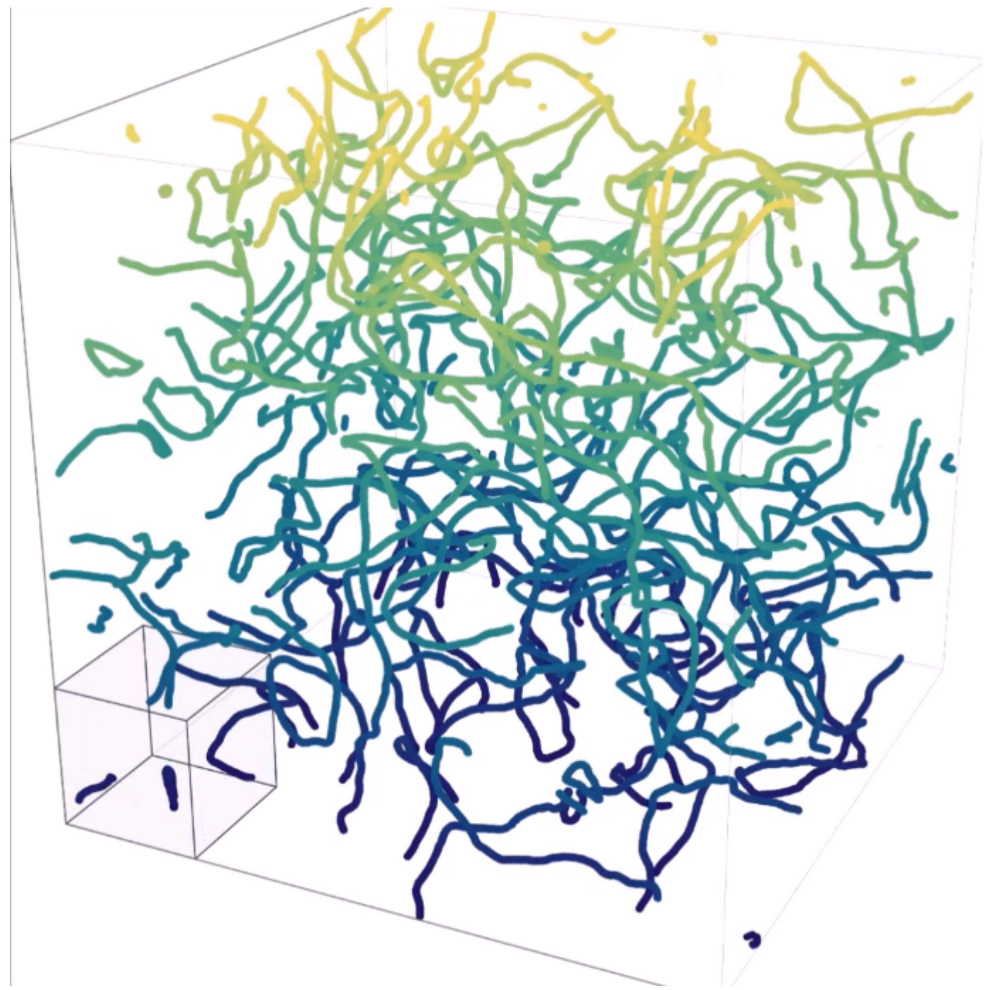
Analysis of the scaling regime alone gives a lower bound on the DM axion mass

Also crucial to set the correct initial conditions for string network at axion mass turn on

Future work: turn the axion mass on

String dynamics



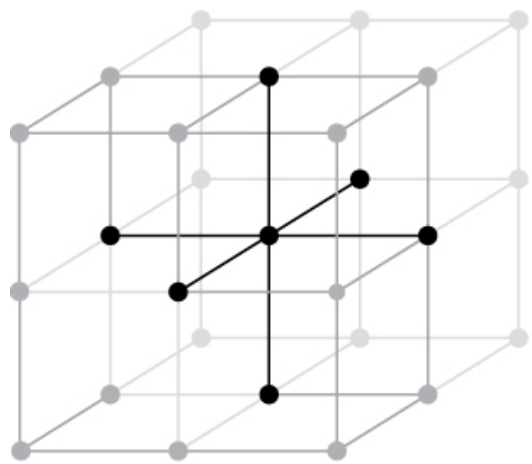


Hard to study analytically, can help with qualitative understanding, but full network has complicated interactions and dynamics

Instead resort to numerical simulations

Numerical simulation

Simulate full complex scalar field on a lattice (no benefit to simulating just the axion field)



Evolve forward in time

Identify strings by looking at field change around loops in different 2D planes

→ group identified lattice points and form strings

Why it's hard

Large separation of scale

- String core is very thin $\delta_s \simeq \frac{1}{f_a}$
- Hubble distance is much larger $H^{-1} \simeq \frac{M_{\rm pl}}{T^2} \simeq \frac{M_{\rm pl}}{\Lambda_{\rm QCD}^2}$

String tension depends on the ratio of string core size and Hubble scale

$$\mu(t) \simeq \pi f_a^2 \log\left(\frac{H(t)^{-1}}{\delta_s}\right) =: \pi f_a^2 \log(\alpha(t))$$

Physical scale separation $\alpha \sim 10^{30}$

$\Rightarrow$ $\log \alpha \simeq 70$

Why it's hard

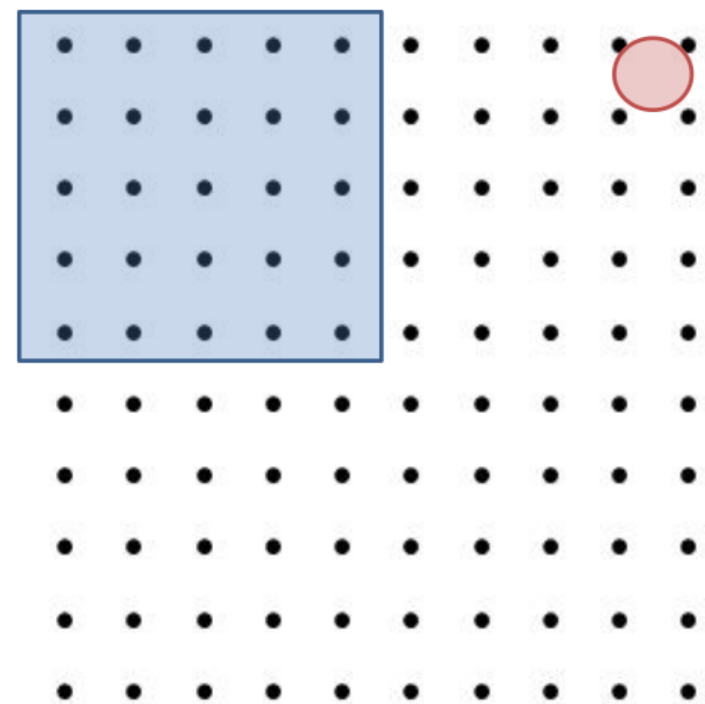
Numerical simulations need

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

Can only simulate grids with $\sim 5000^3$ points

simulations: $\log\alpha \le \log\left(\frac{\square}{\bigcirc}\right) \sim 6$

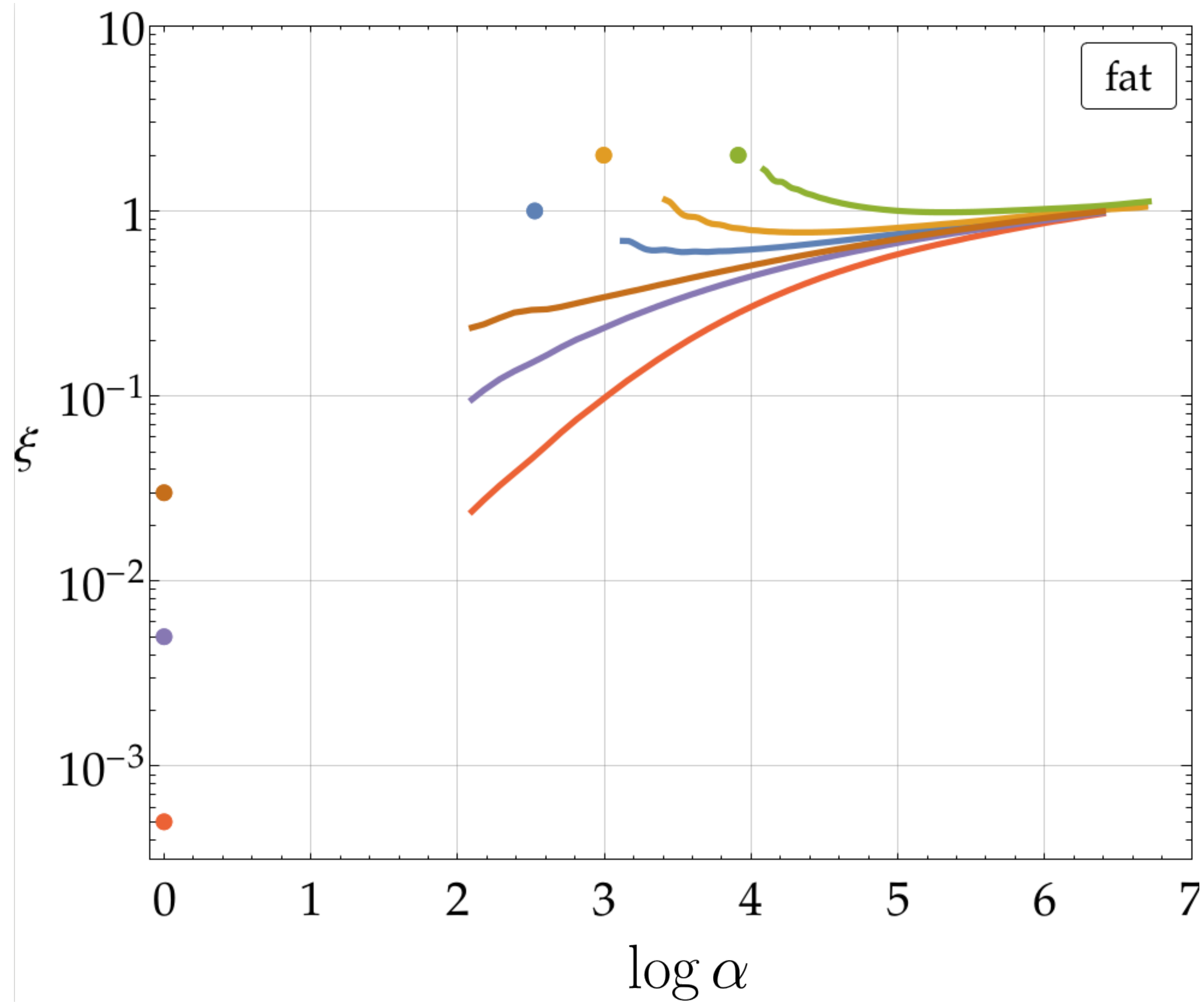
physical: $\log\alpha \sim 70$



Current literature just gives results at small scale separation

The attractor solution

Start with overdense/ underdense, at different times, also with random field initial conditions

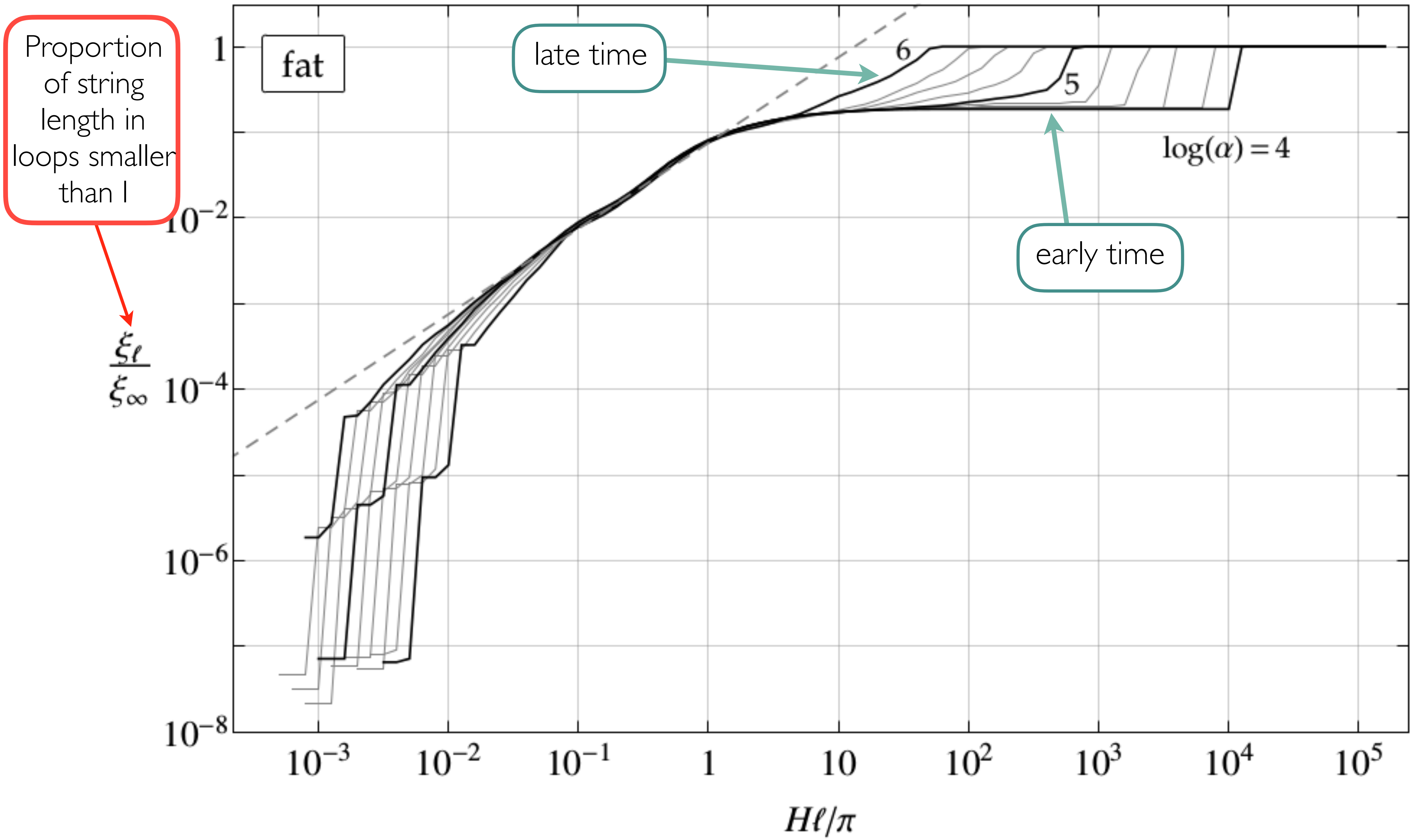


Solution is approximately scale invariant:

- Neglecting the core size, only scale is H
- E.g. ξ constant

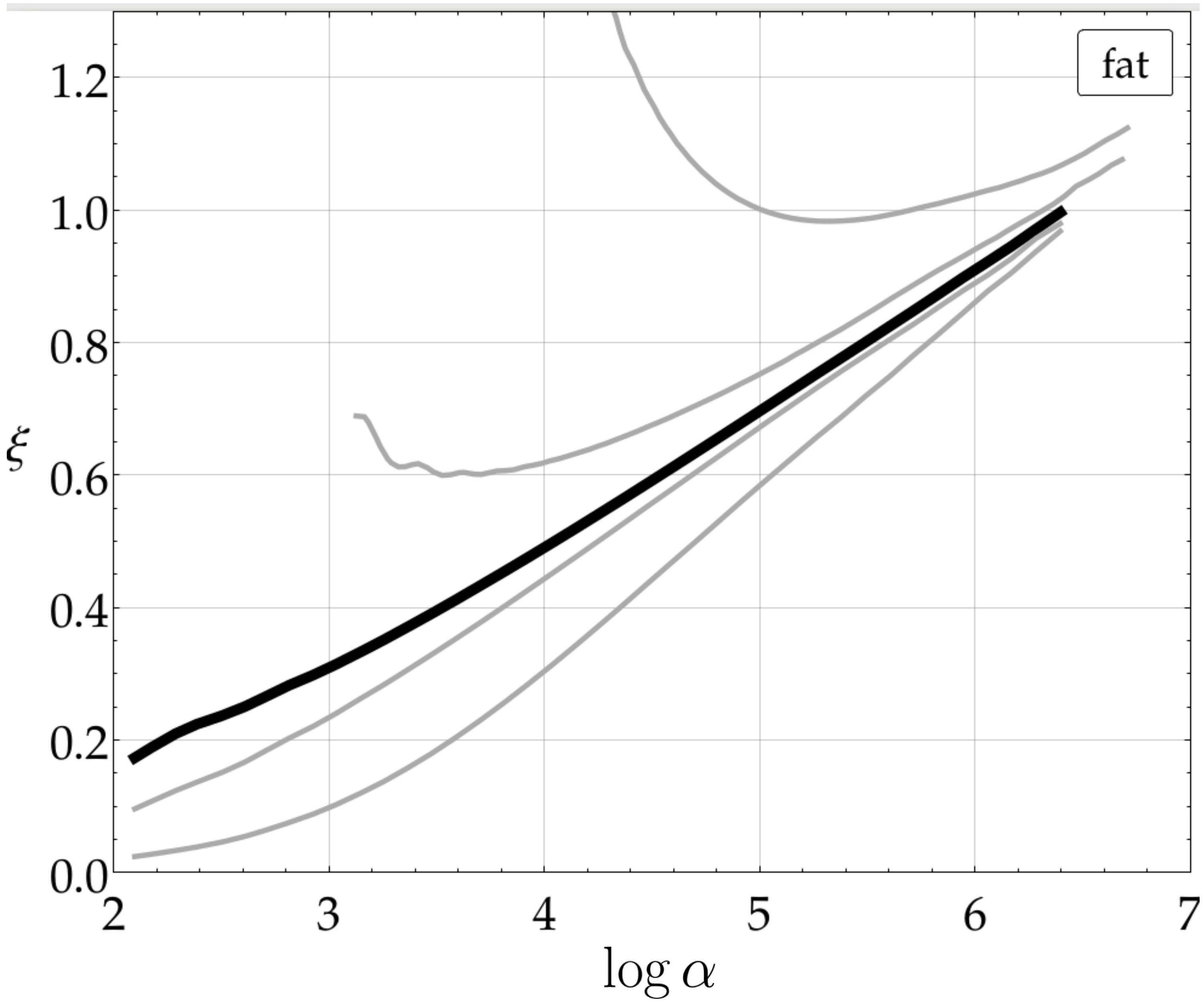
Final result is not dependent on the details of the phase transition

Distribution of loop length



Scaling violations

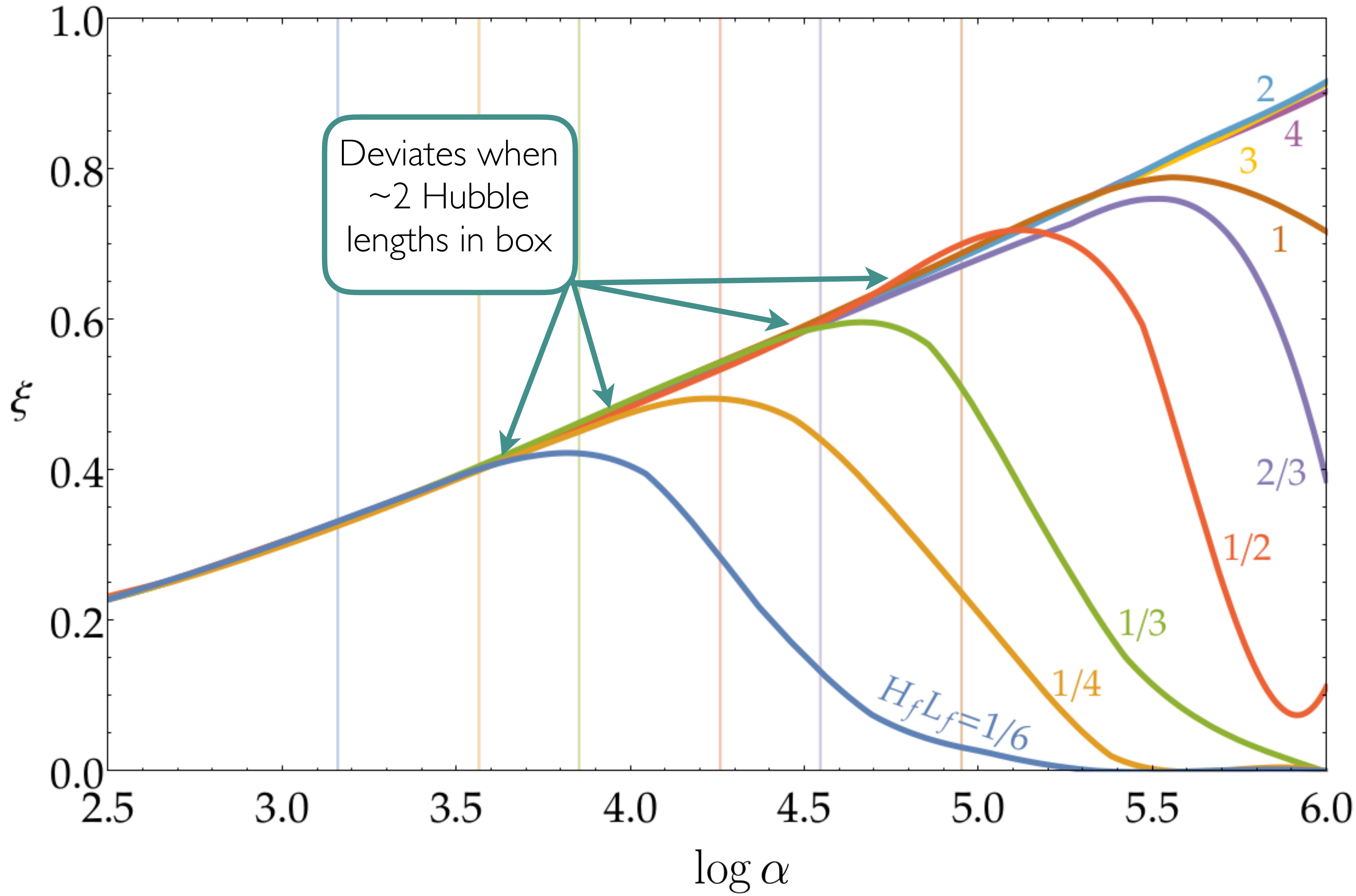
Find a log increase, theoretically plausible since the tension is increasing



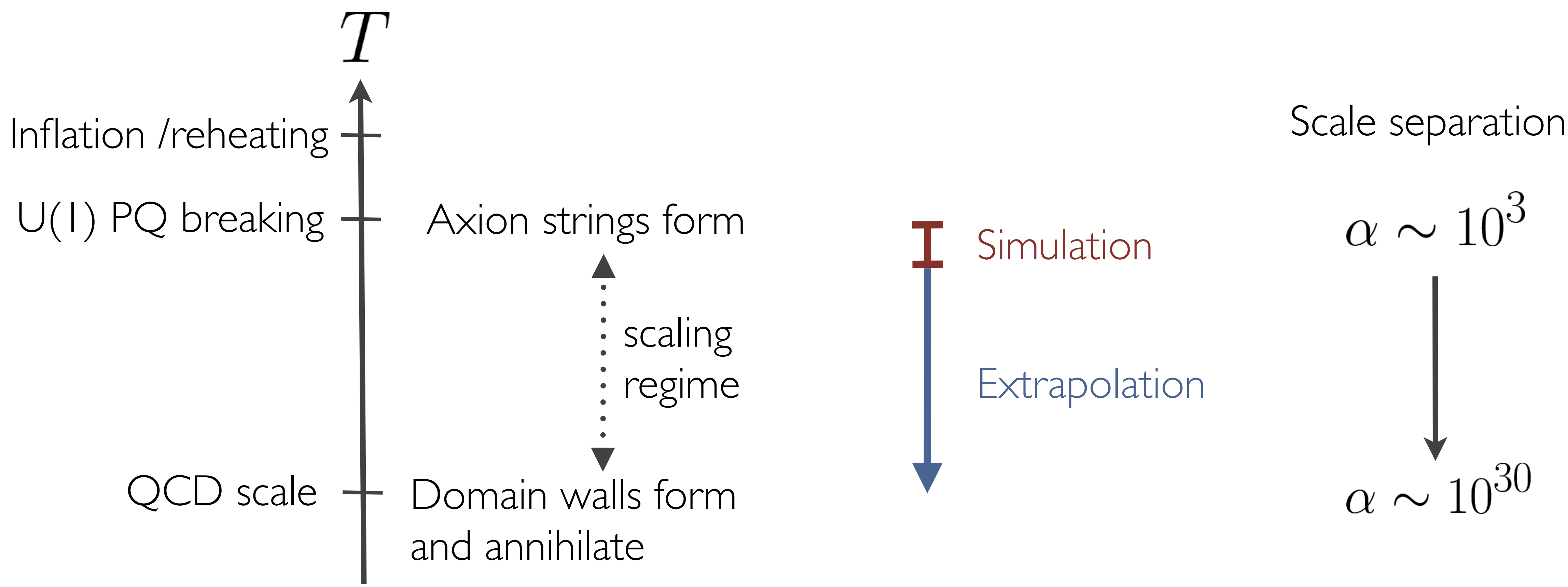
If extrapolation is valid, grows to ~10 at QCD scale

Numerical checks

E.g. number of Hubble patches at end of simulation



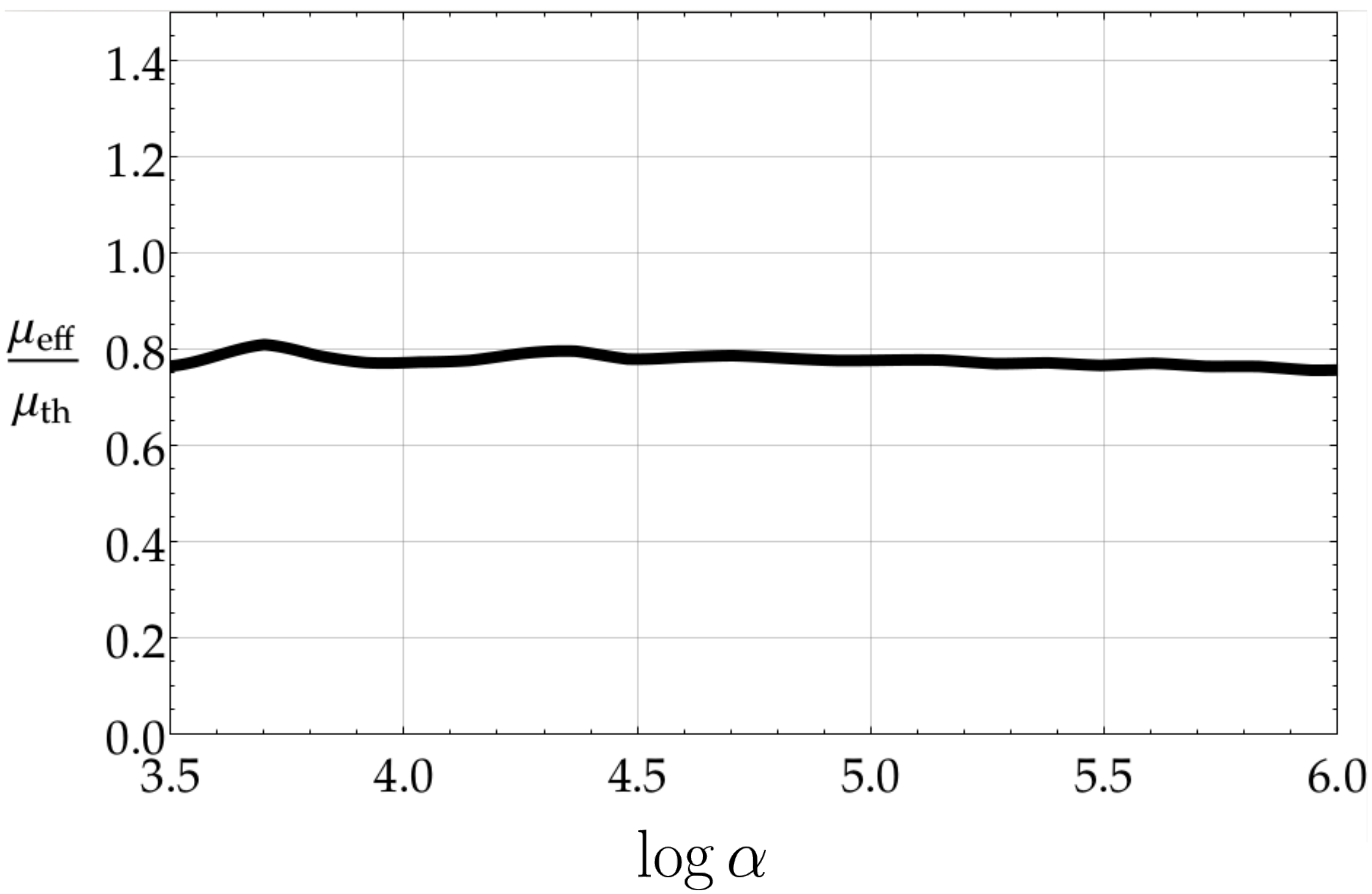
Extrapolation



Understanding the dependence of the physics on the scale separation is crucial

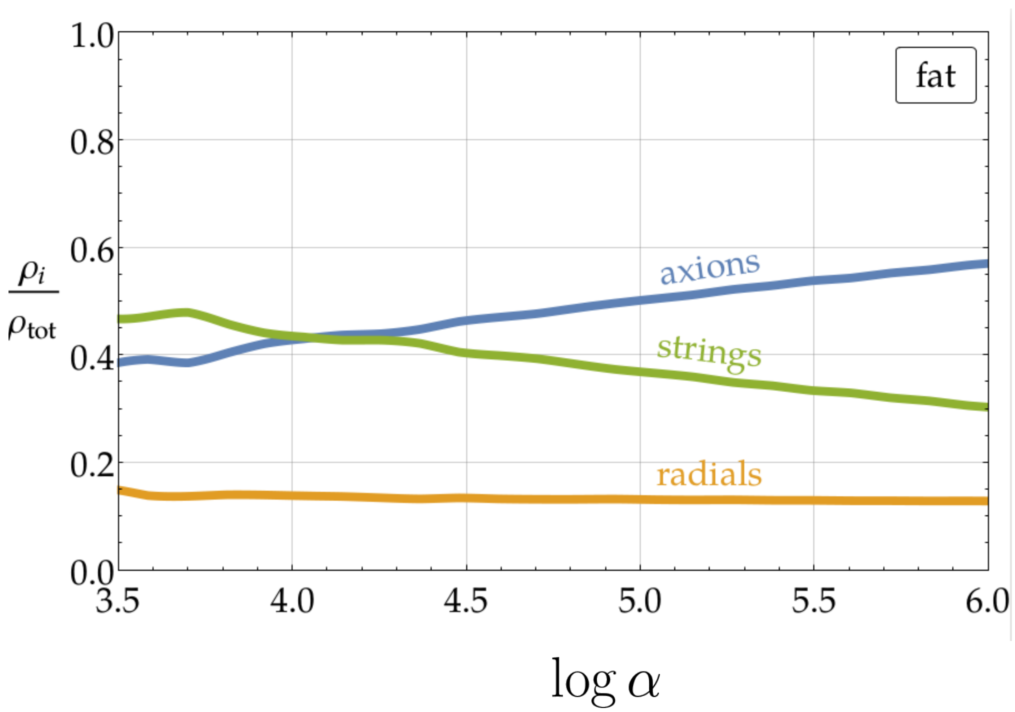
Energy stored in strings

Calculate the effective string tension in simulations from string energy and $\xi(t)$



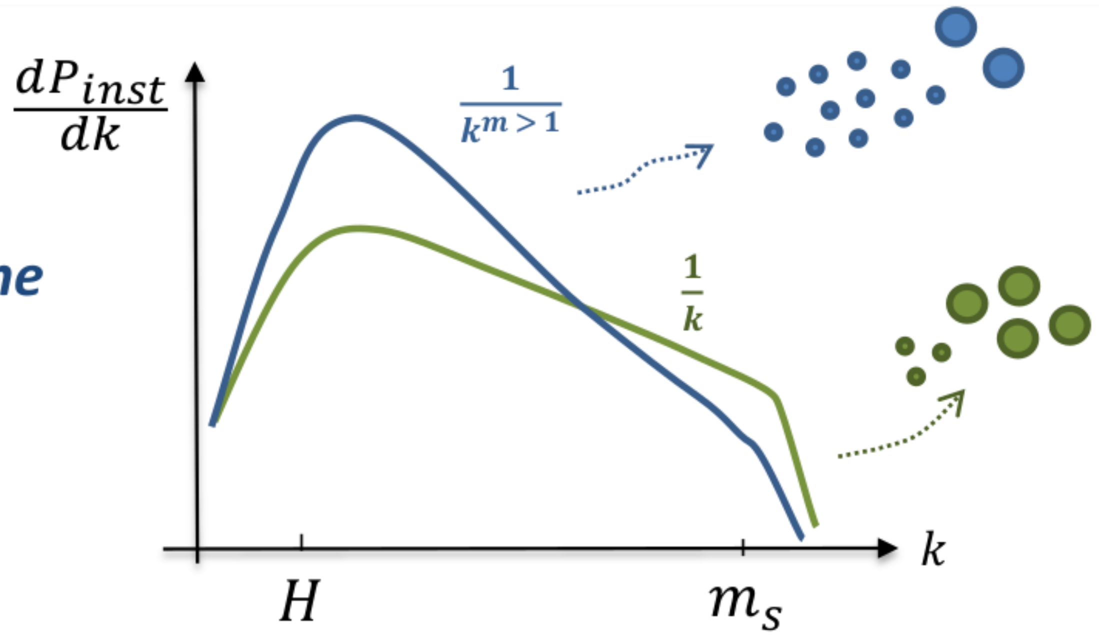
Agrees well with theoretically expected form:

$$\mu_{\rm th}(t) \simeq \pi f_a^2 \log\left(c\frac{H^{-1}}{\delta_s}\right)$$



Distribution of axion momenta

$\frac{dP_{inst}}{dk}$ $\equiv$ ***spectrum of axions radiated per unit time***



Theoretical expectations

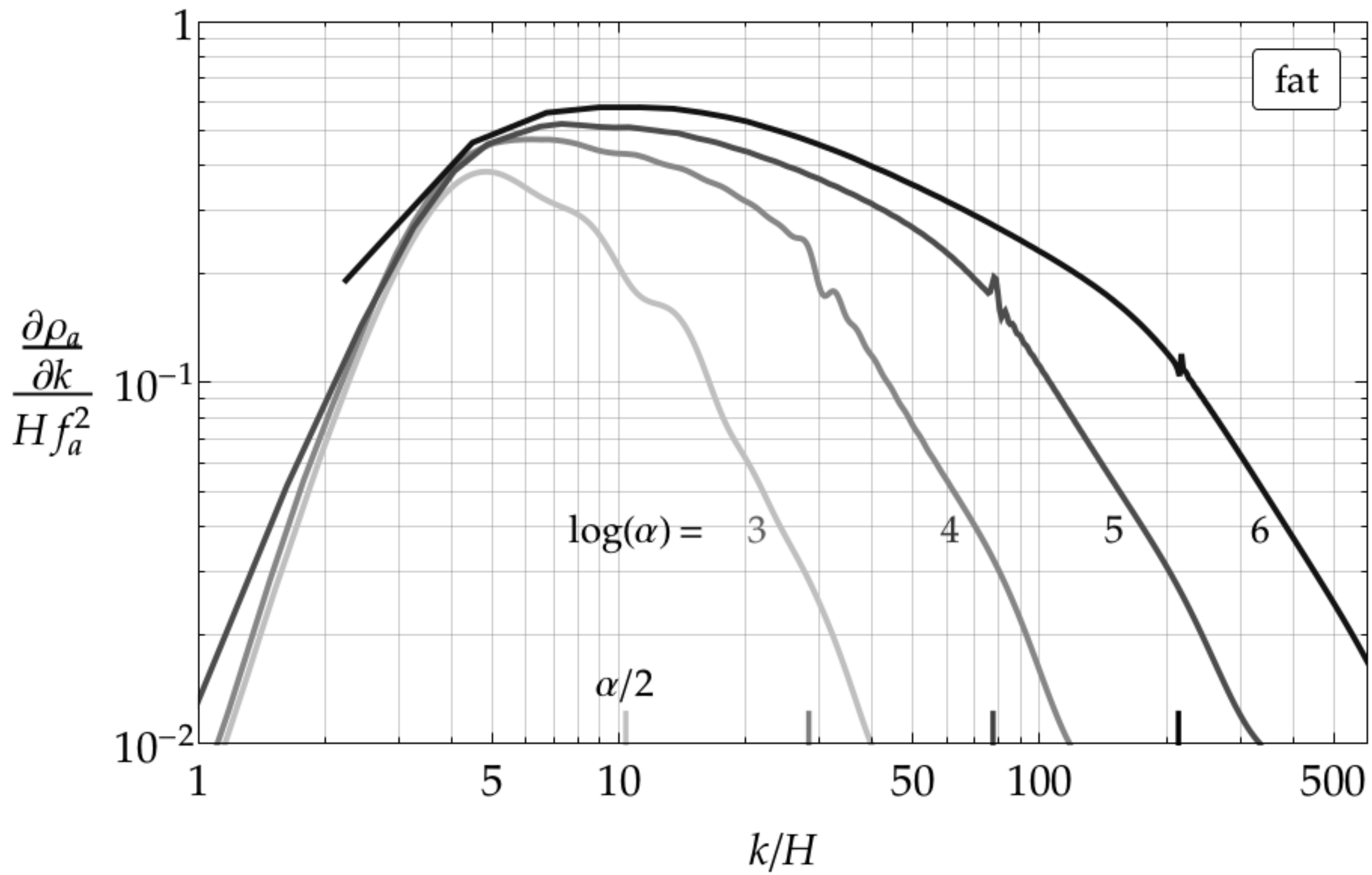
natural cut-offs at H and m_s but:

(1) $\frac{dP_{inst}}{dk} \sim \frac{1}{k^m}$ "soft" spectrum with $\langle k^{-1} \rangle \propto H^{-1}$

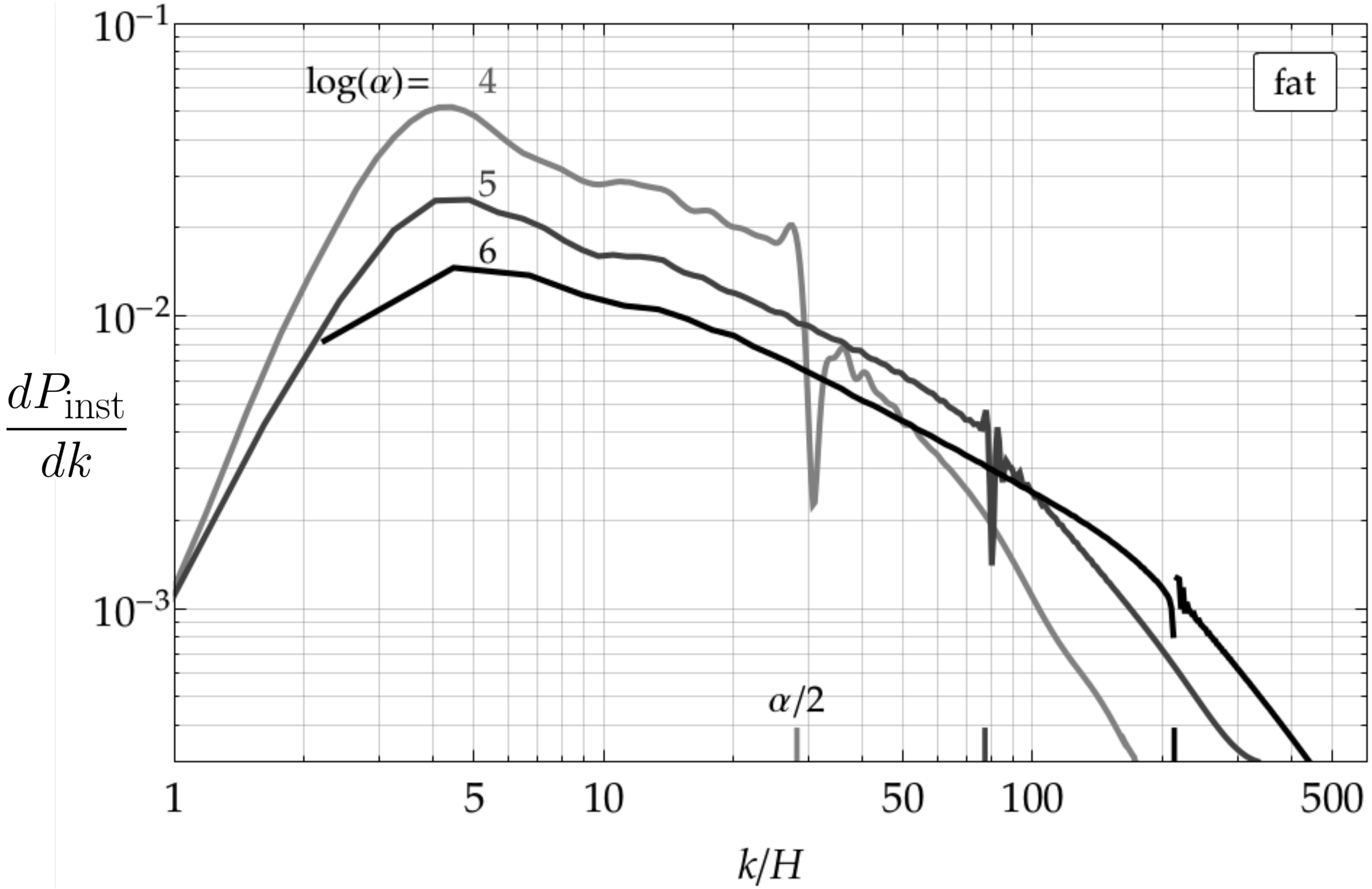
$\boldsymbol{m > 1}$

(2) $\frac{dP_{inst}}{dk} \sim \frac{1}{k}$ "hard" spectrum with $\langle k^{-1} \rangle \propto \frac{H^{-1}}{\log \alpha}$

Total spectrum



Instantaneous emission



Power law between IR and UV cutoffs

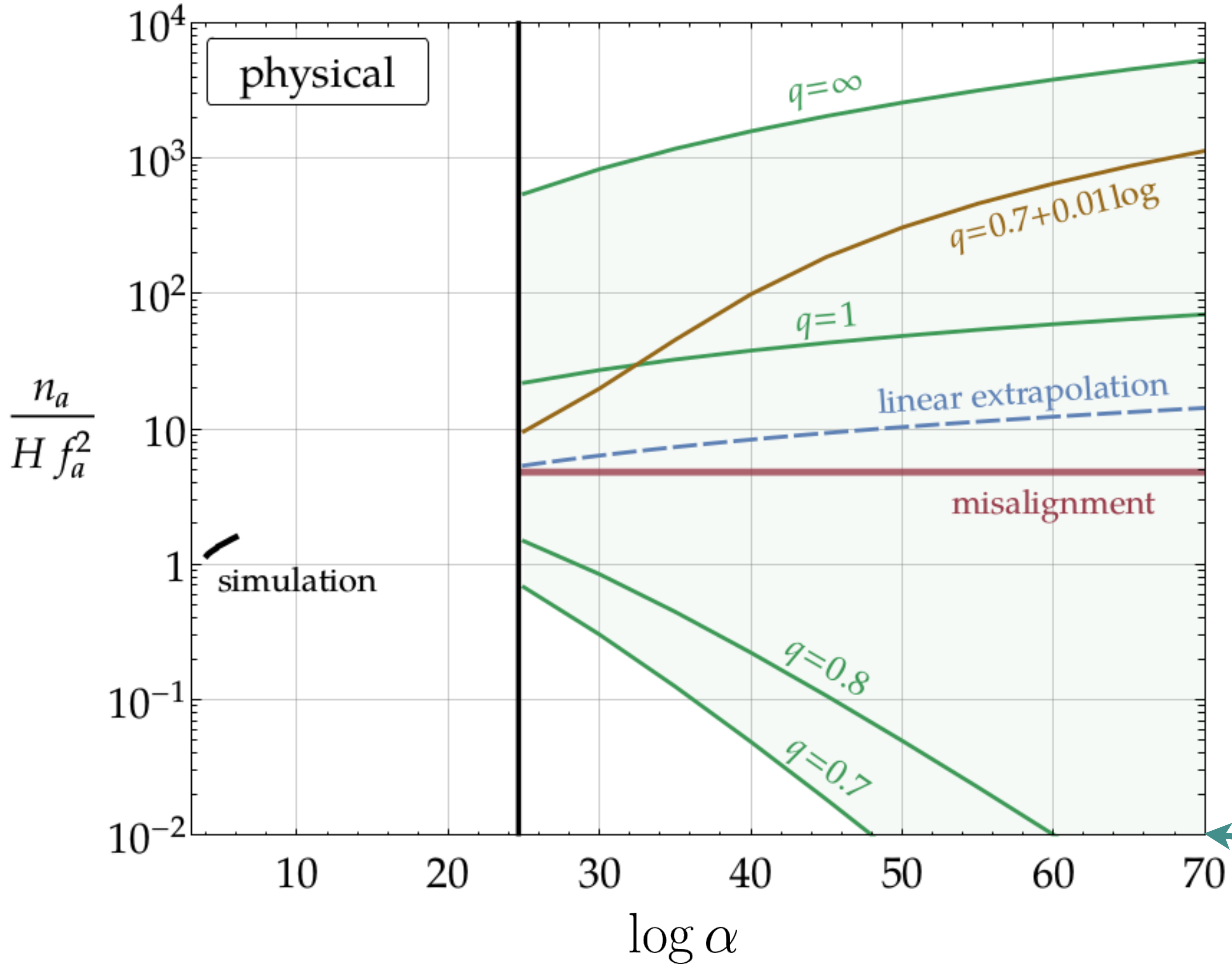
$$\frac{dP_{\text{inst}}}{dk} \sim \frac{1}{k^q}$$

with:

$$q < 1$$

Impact on the relic abundance

- Extrapolation of $\xi(t) \sim \log\left(\frac{f_a}{H(t)}\right)$ is plausible
- Axion spectrum from simulations does not match expectation at large scale separation



A small scaling violation in shape of spectrum would have a dramatic effect

physically relevant scale separation for typical models

Conclusions

- Unique, experimentally important, axion DM mass prediction in this scenario
- Cannot directly study physically relevant regime
- Our approach is to carry out simulations at small scale separation and extrapolate
- Attractor solution makes this viable
- Log increase in the string number density, leads to a corresponding change in relic density
- Next step: determine if the spectrum changes

Thanks

SM strong CP problem

$$\mathcal{L} \supset \theta_0 \frac{\alpha_S}{8\pi} G\tilde{G}$$

Neutron EDM  $d_n < 2.9 \cdot 10^{-26}\, e\, cm$

$$\theta' = \theta_0 + \arg\left(\mathrm{Det} M_q\right) \lesssim 10^{-10}$$

Strong CP Problem

Other phases in Yukawa matrices order 1

Non-decoupling contributions from new CP violating physics

Effects on large distance physics irrelevant

Begs for a dynamical explanation!

Boundary between regimes

Depends on the details of reheating

(e.g. for quadratic inflation $m^2\phi^2 + g^2 m\phi\chi^2$, $\Gamma \simeq \frac{g^4}{8\pi}m$)

In the PQ breaking after inflation regime if any of following are larger than f_a

Hubble scale during inflation	H_I
Reheating temperature when radiation domination begins	$T_{\rm RH} = \sqrt{\Gamma M_{\rm Pl}}$
Maximum temperature during perturbative inflaton decay	$T_{\rm max} \simeq \left(M_{\rm Pl}^2 H_I \Gamma\right)$
Effective temperature during preheating (if this occurs)	$T_{\rm pre} \simeq \sqrt{M_{\rm Pl} H_I}$

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

Domain walls

Axion mass becomes cosmologically relevant when

$$m_a\left(T_0\right) \simeq H\left(T_0\right)$$

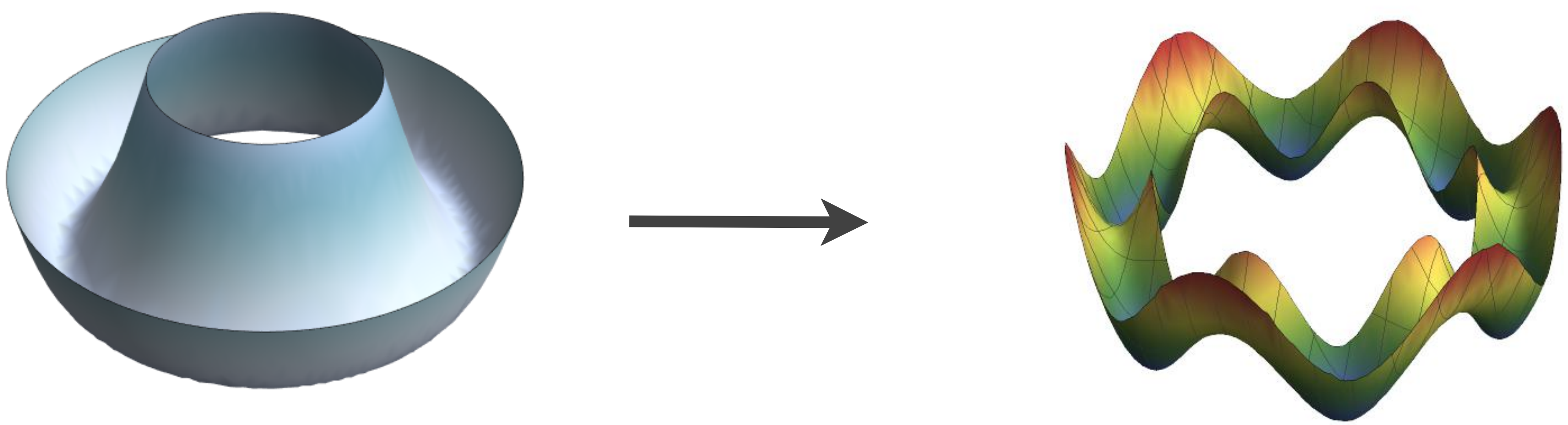
Subsequently it increases fast, and quickly $m_a\left(T\right) \gg H\left(T_0\right)$

But typical size of domain walls still $\sim 1/H\left(T_0\right)$, momentum of lowest harmonics $\sim H\left(T_0\right)$
emission at higher harmonics strongly suppressed

Could this delay the destruction of the domain wall network? Potentially a big effect on the relic abundance?

Domain walls

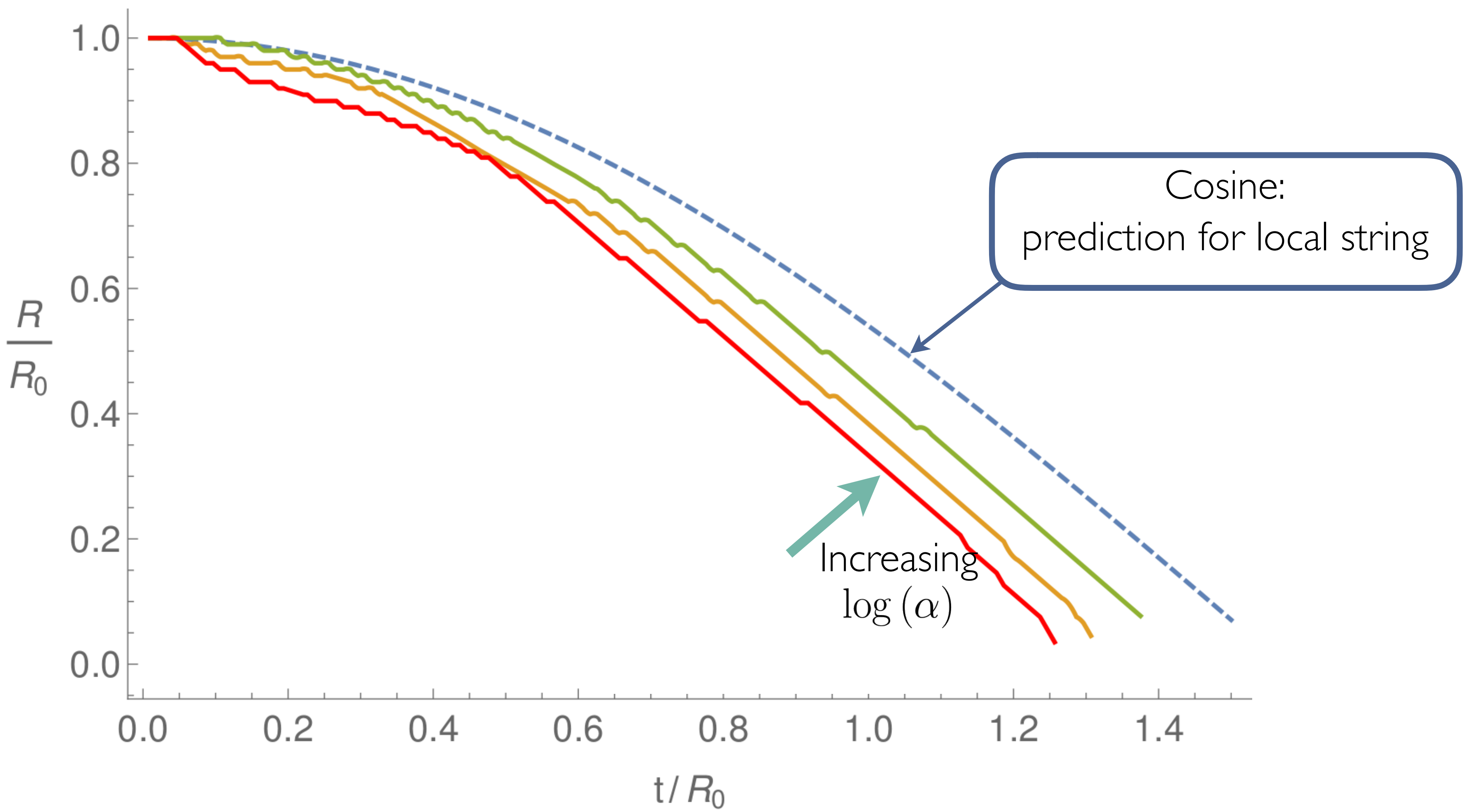
To get a final result, also need to study the dynamics of domain walls



Depends on the anomaly coefficient:

- $N = 1$, unstable, automatically decay
- $N > 1$, stable in the absence of extra PQ breaking, current simulations seems marginally ruled out unless fine-tuned

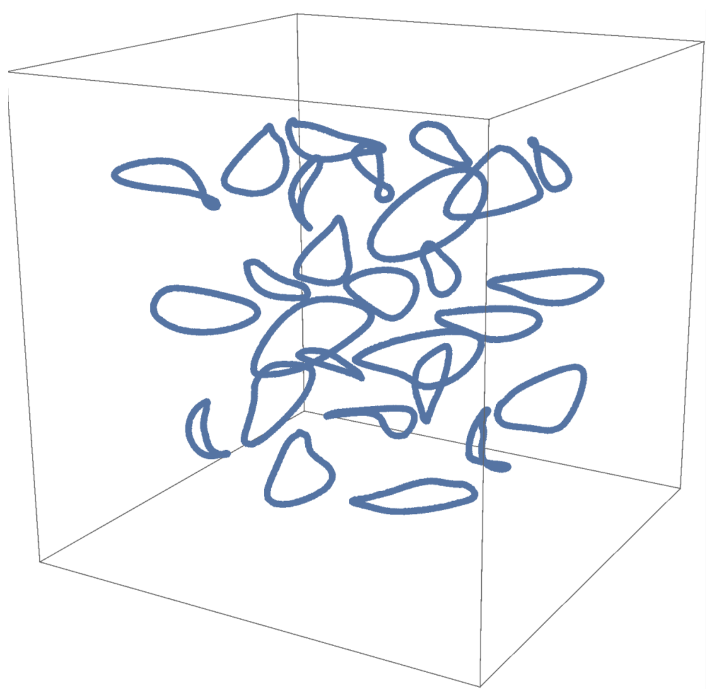
Dynamics for different log



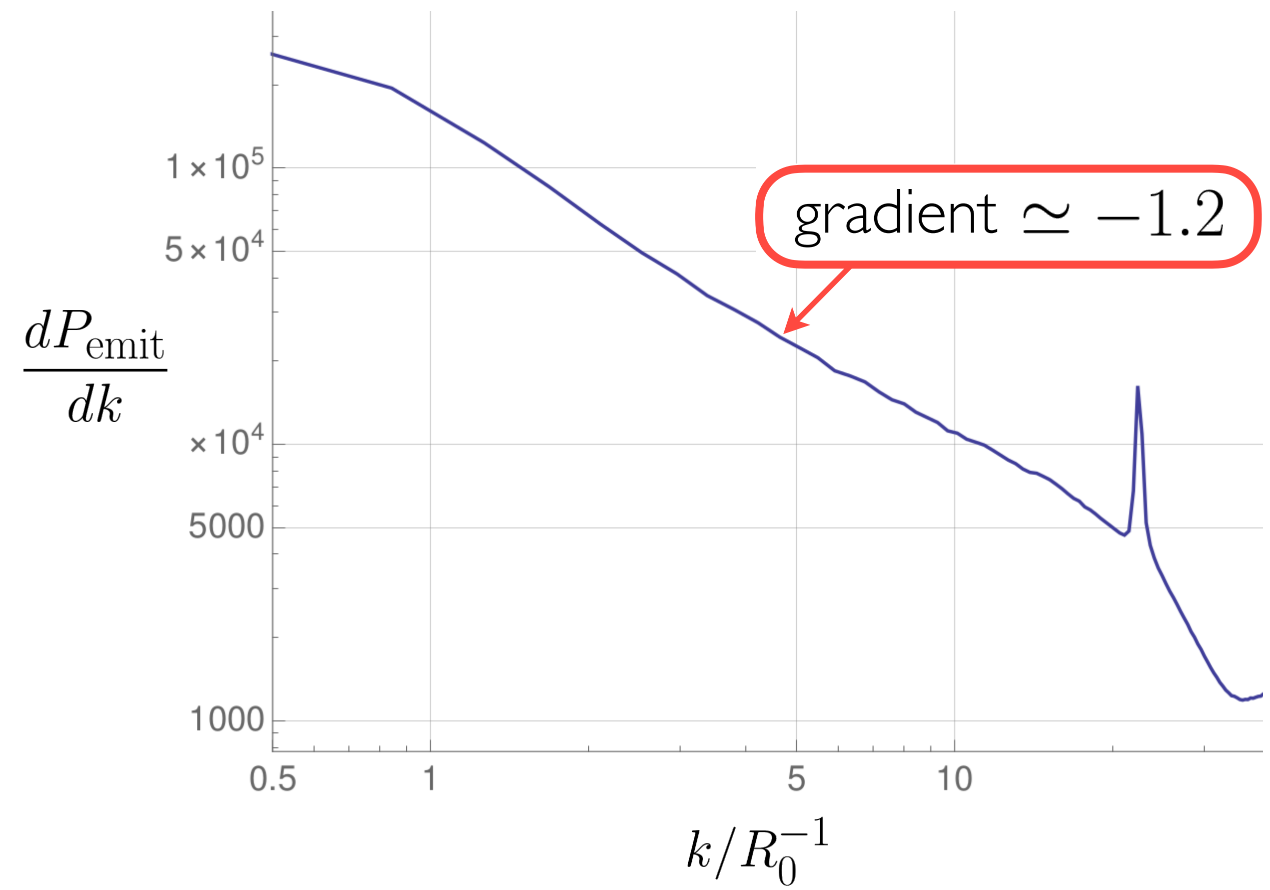
Convergence towards the local string cosine prediction

Collapsing loops

Ensemble of non-circular loops



Spectrum emitted



Power law with $m > 1$ so predicts emission dominantly at $k \sim H$