Axions from Strings

Ed Hardy

Based on work with
Marco Gorghetto & Giovanni Villadoro

[arXiv:1806.04677,
ongoing]

UNIVERSITY OF
LIVERPOOL

SM strong CP problem

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

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

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

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!

The QCD axion

Spontaneously broken anomalous global U(1)

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

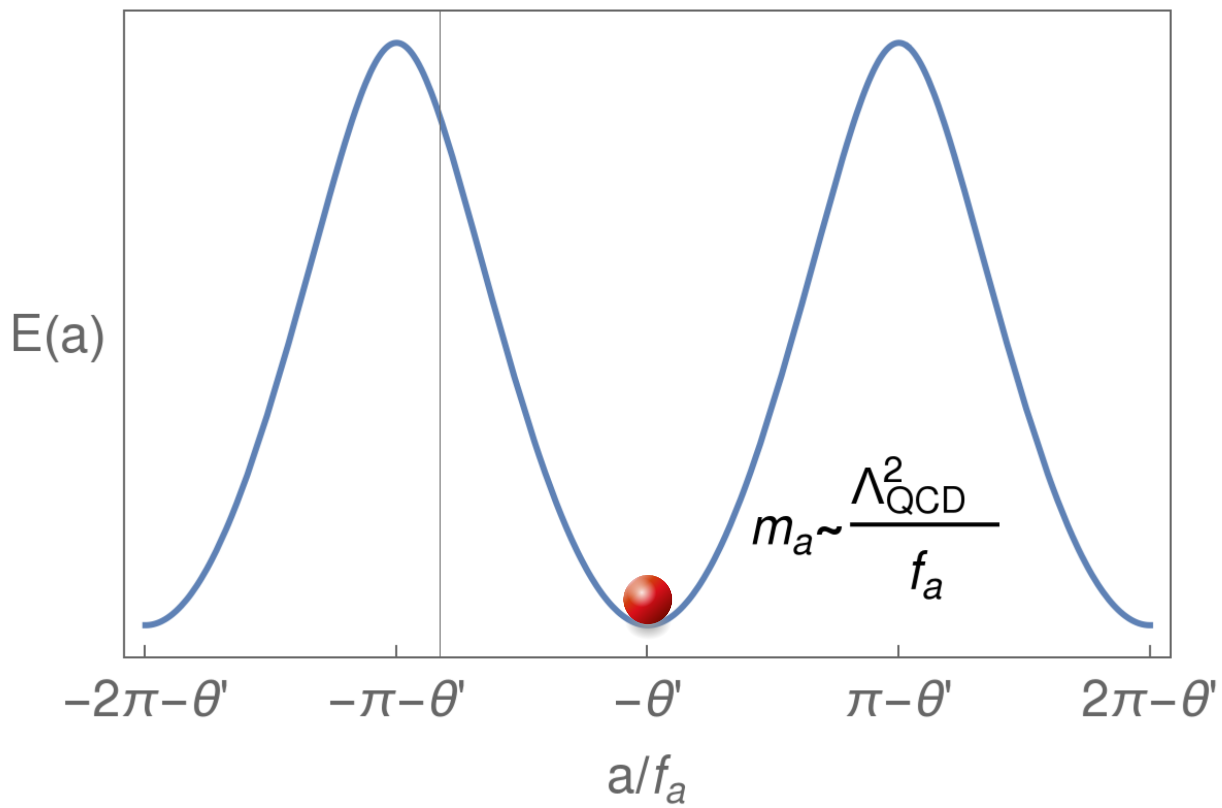
$$a \to a + \delta$$

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

QCD runs into strong coupling

→ axion potential

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



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

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

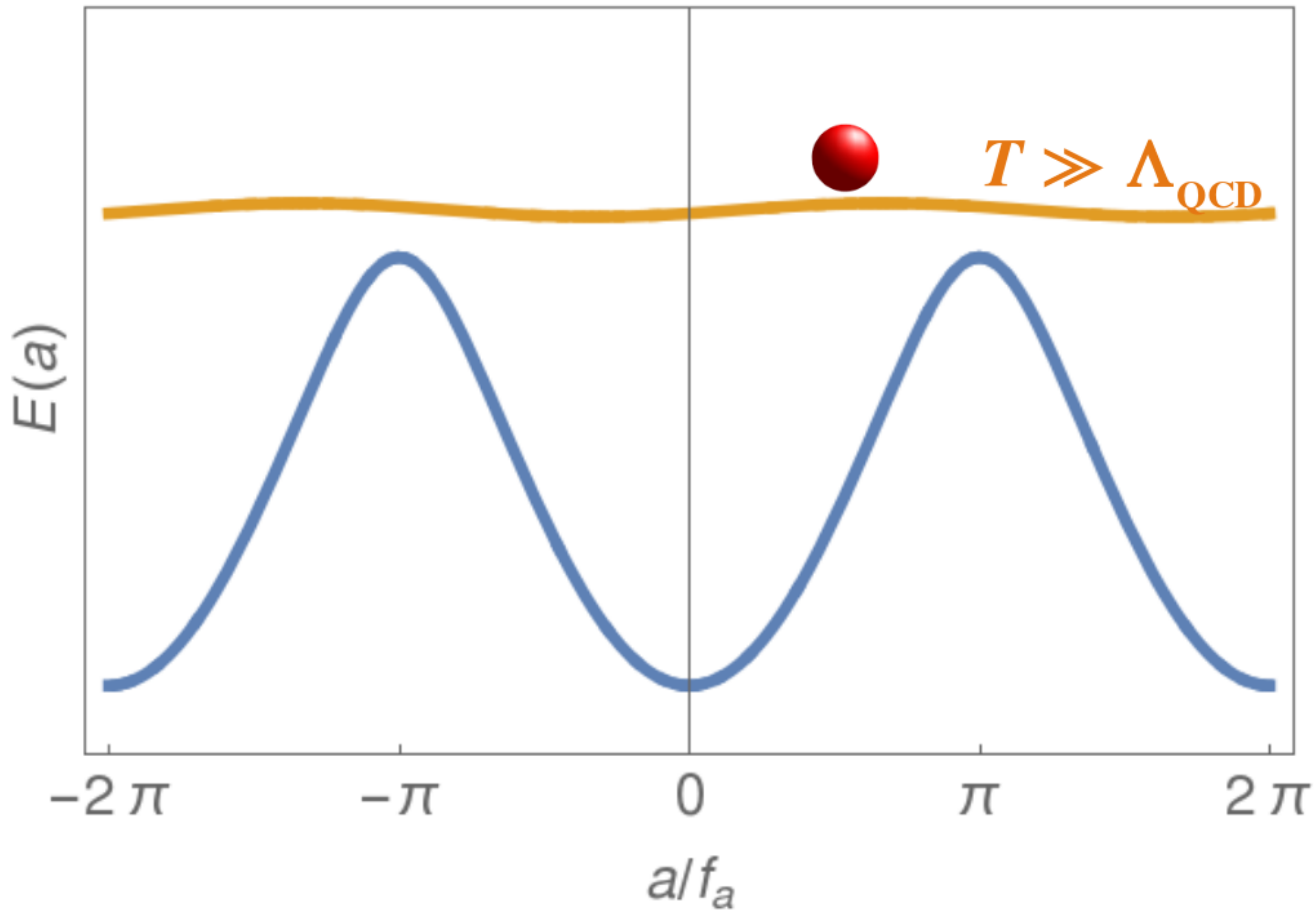
Understand physics implications of new searches

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

Dark matter

Misalignment

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



Dark matter

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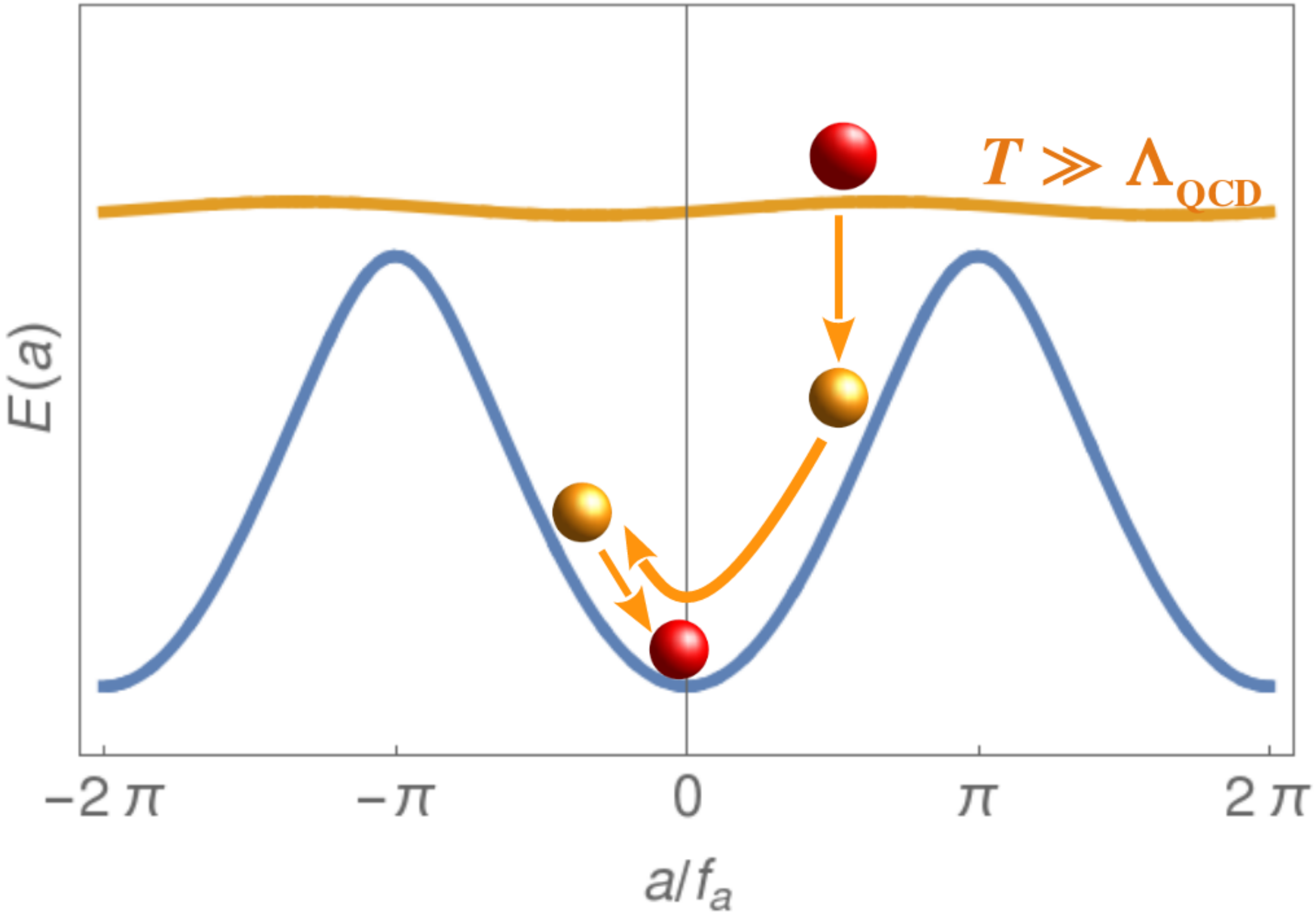
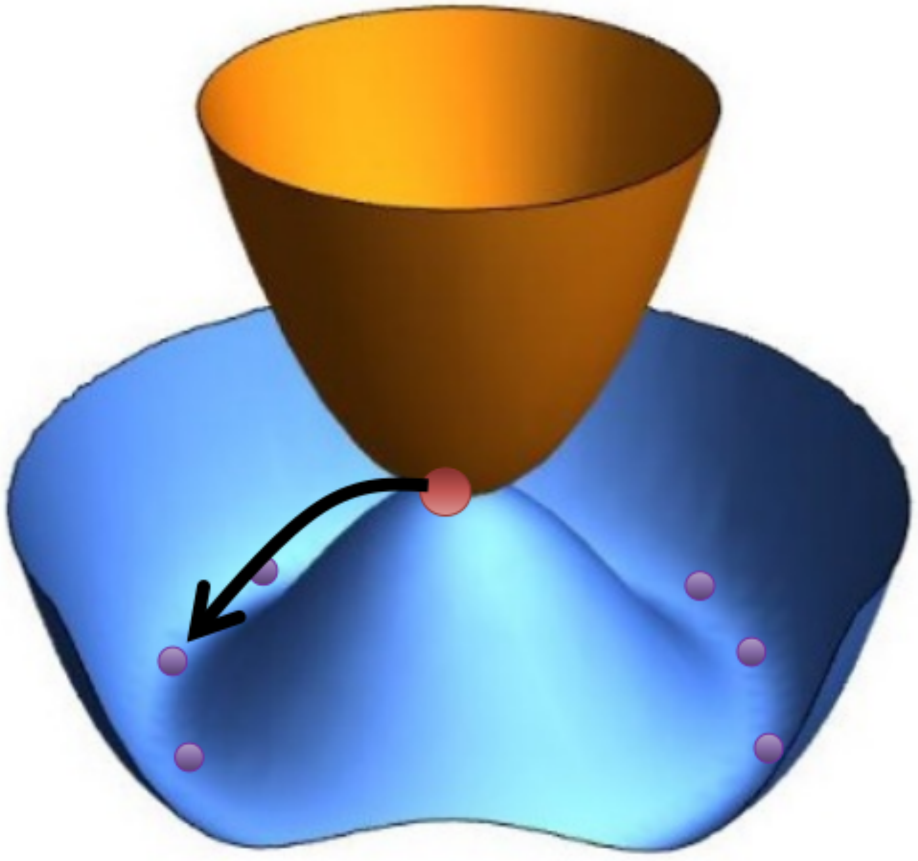


Dark matter

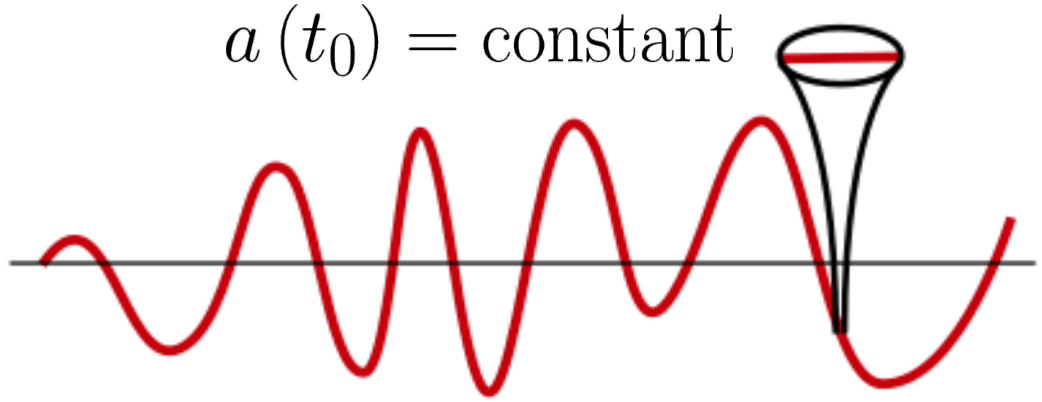
Immediately after U(1) breaking, the axion field is random over the universe:



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)

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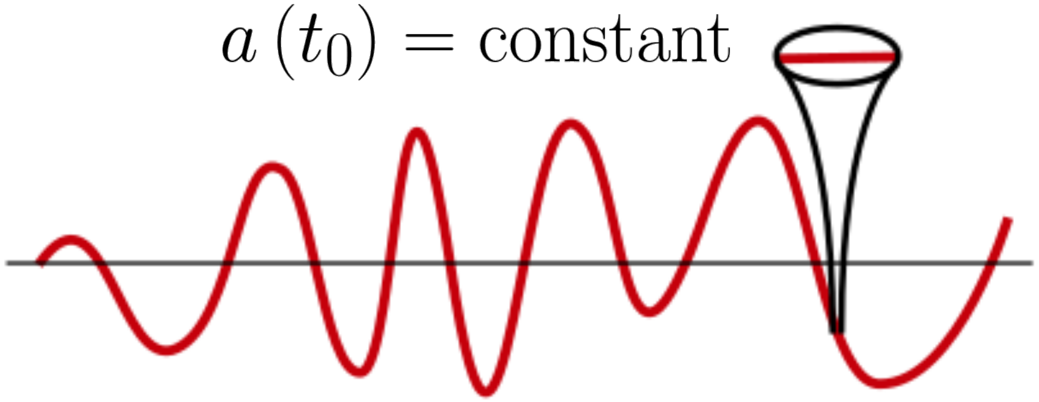

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$\theta_0 < \pi \quad \Leftrightarrow \quad f_a \gtrsim 10^{12}\ \text{GeV}$

PQ symmetry unbroken during inflation or subsequently restored

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

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

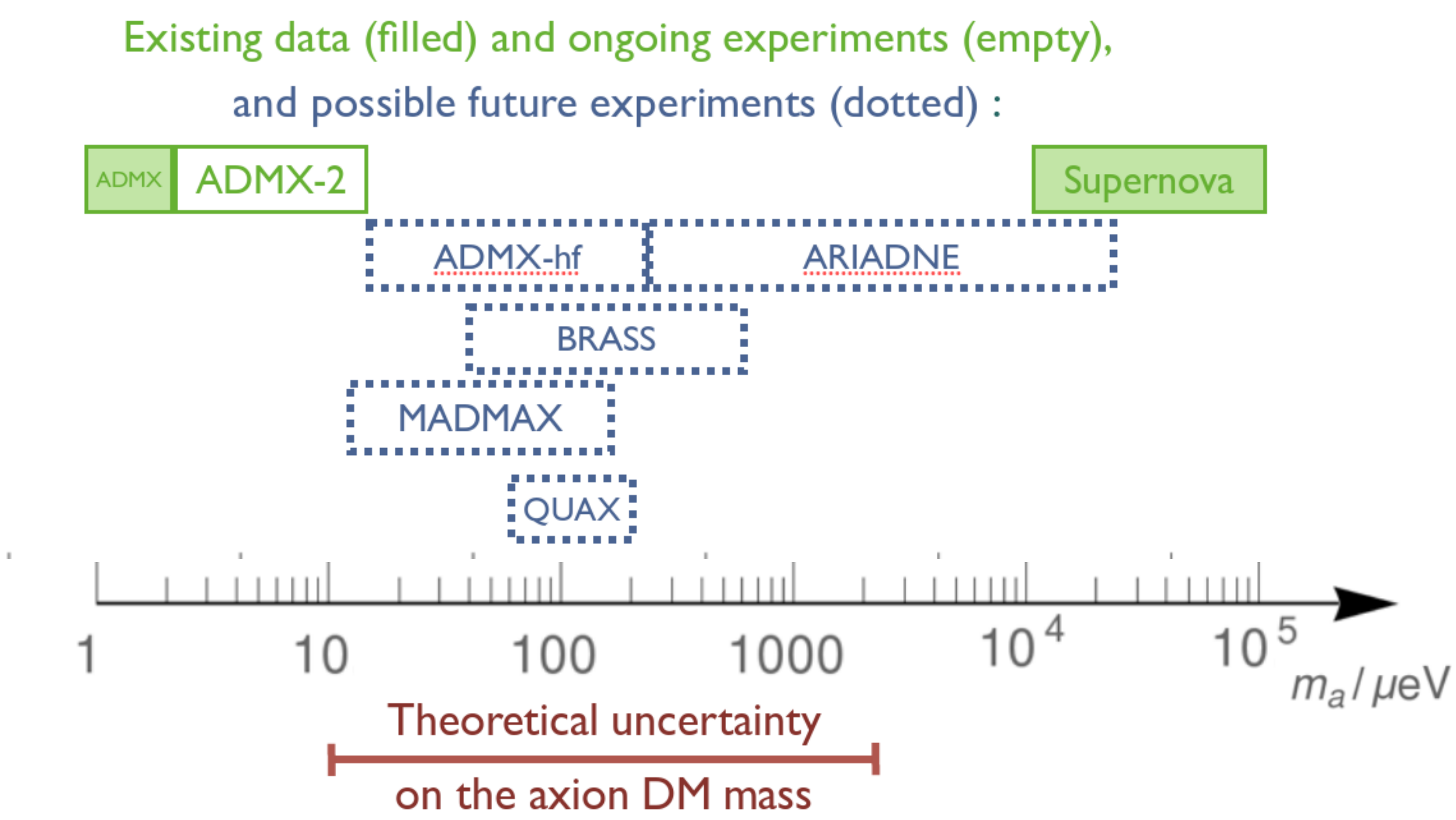
$\Omega_a > \Omega_a^{mis} \quad \Leftrightarrow \quad f_a < f_a^{mis} \sim 10^{12}\ \text{GeV}$

(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

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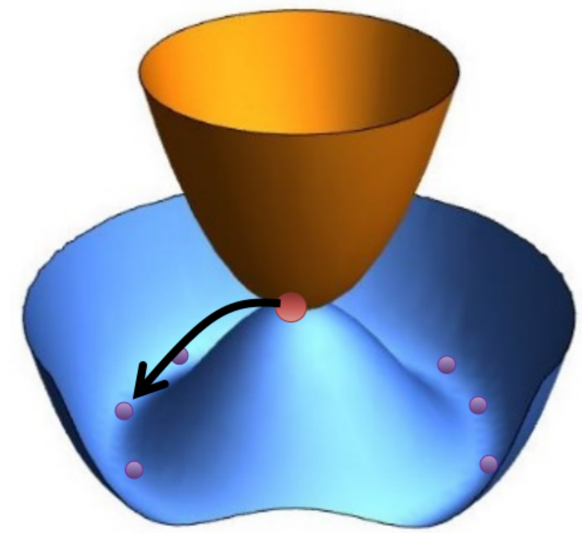
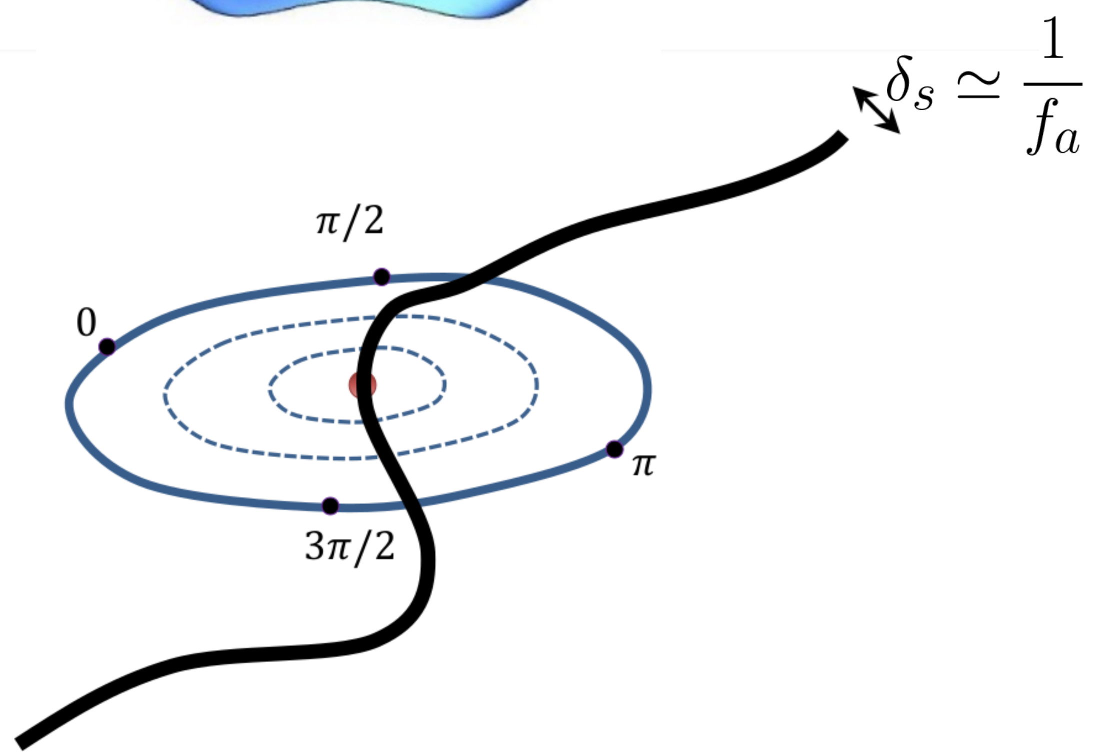
Inflation /reheating

U(1) PQ breaking — Axion strings form

scaling regime

QCD scale — Domain walls form and annihilate





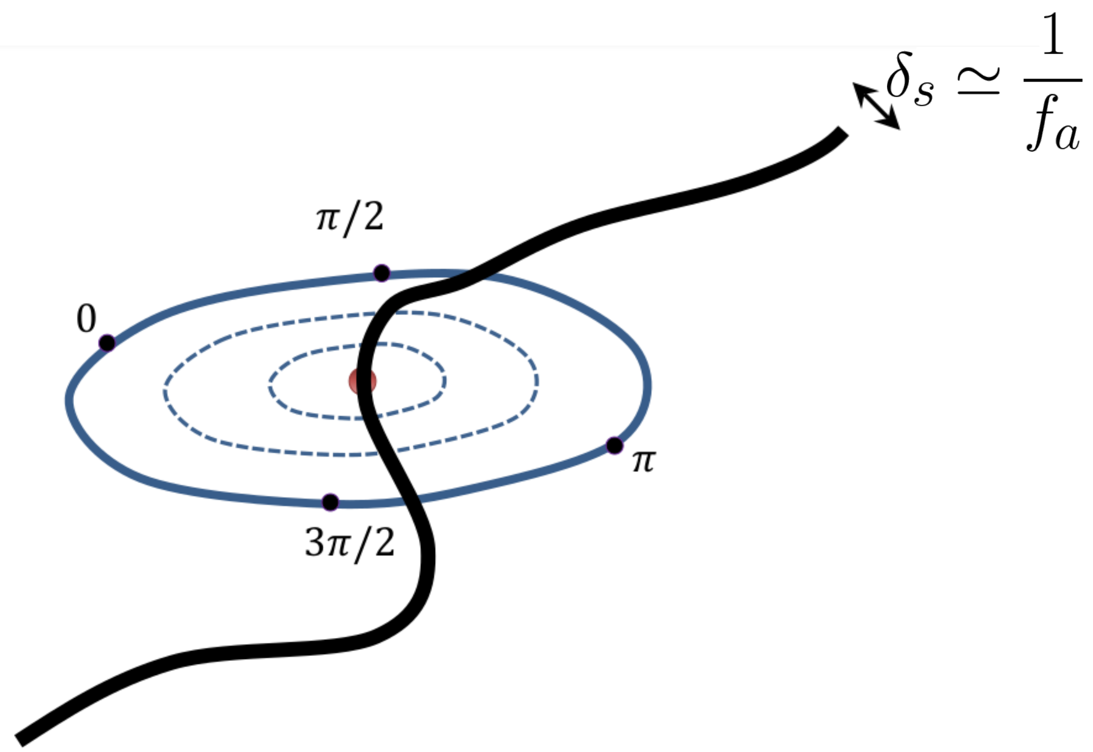
Significant proportion of DM axions produced by strings and domain walls

Scaling regime

- Loops with radius < Hubble collapse
- Strings within a Hubble distance can annihilate

Neglecting size of string cores, no other relevant scales

Reach a balance between strings re-entering each others horizons and string length being destroyed



Axion emission during scaling

In the scaling regime

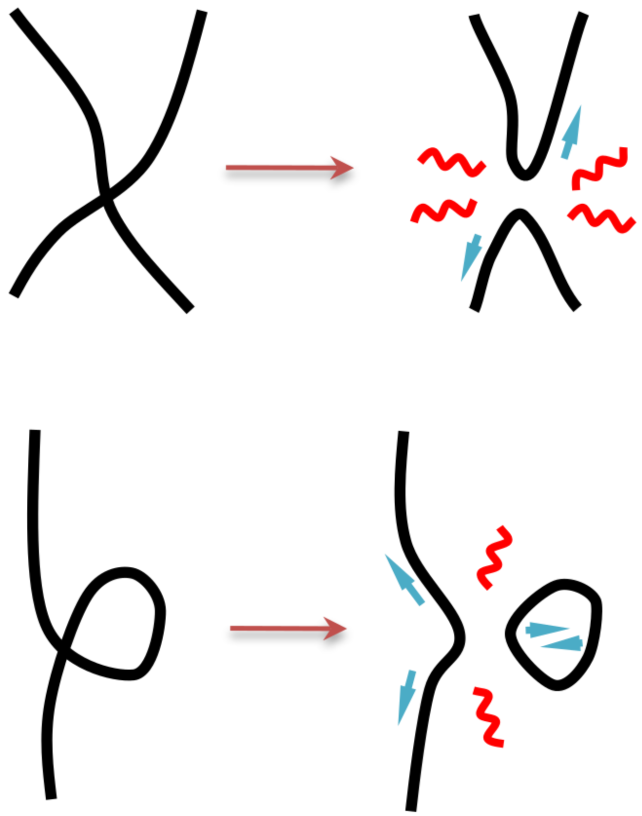
$\xi\,(t)$ = Length of string per Hubble volume

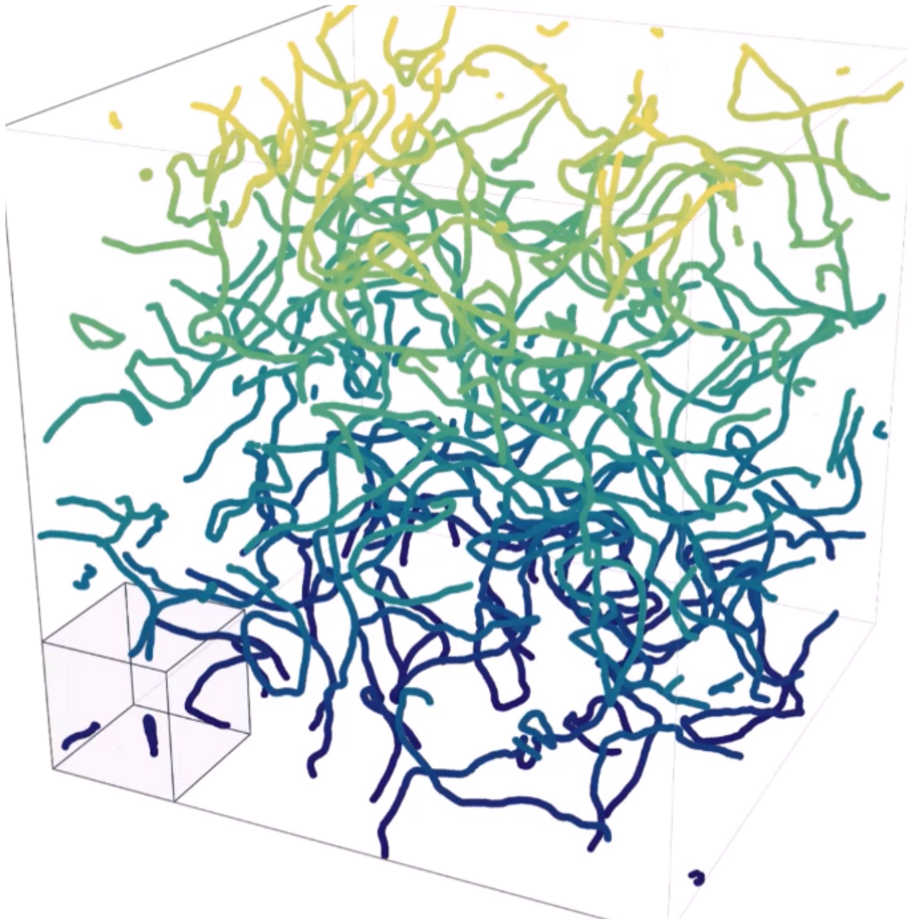
$\mu\,(t)$ = string tension = energy per length

constant + log corrections

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

String dynamics



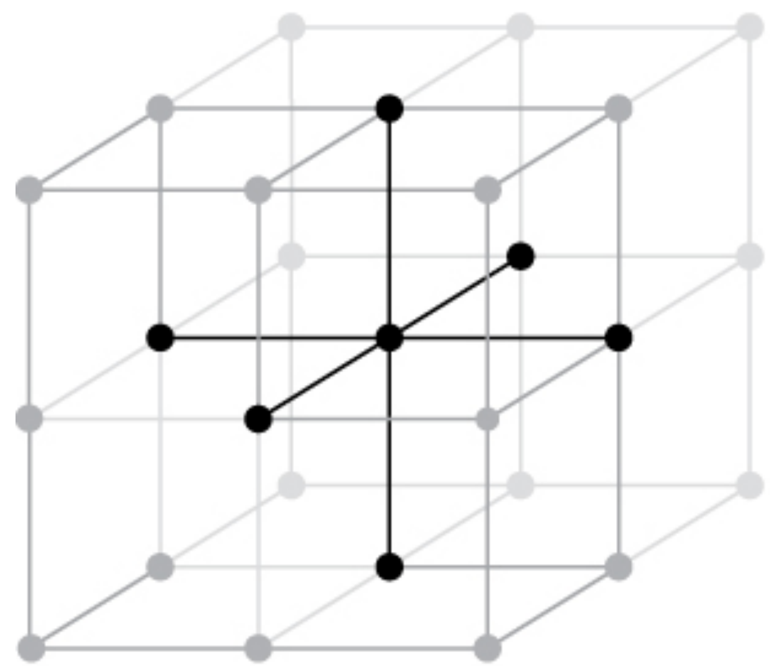


Hard to study analytically, can help with qualitative understanding, but full network has complicated interactions and dynamics

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 $\alpha \sim 10^{30}$

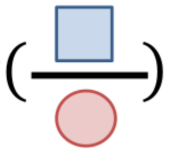
→ $\log\alpha \simeq 70$

Why it's hard

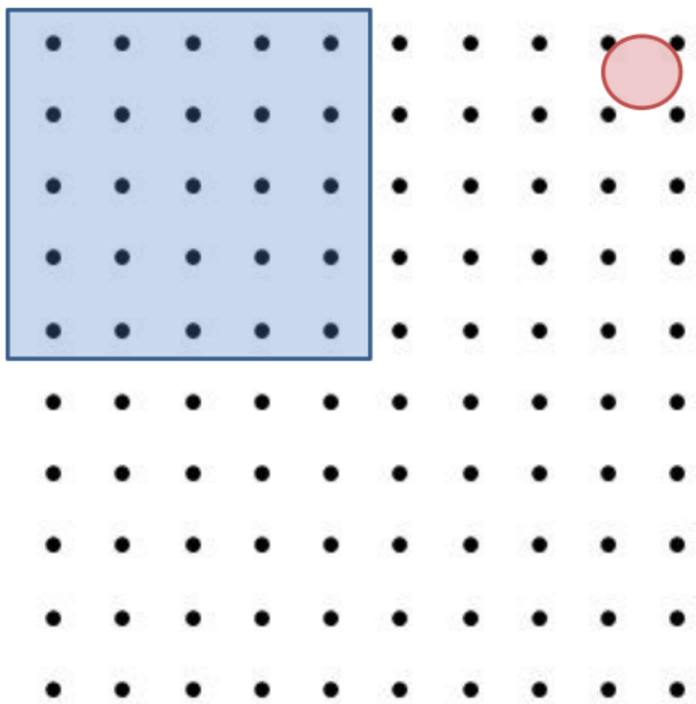
Numerical simulations need

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

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

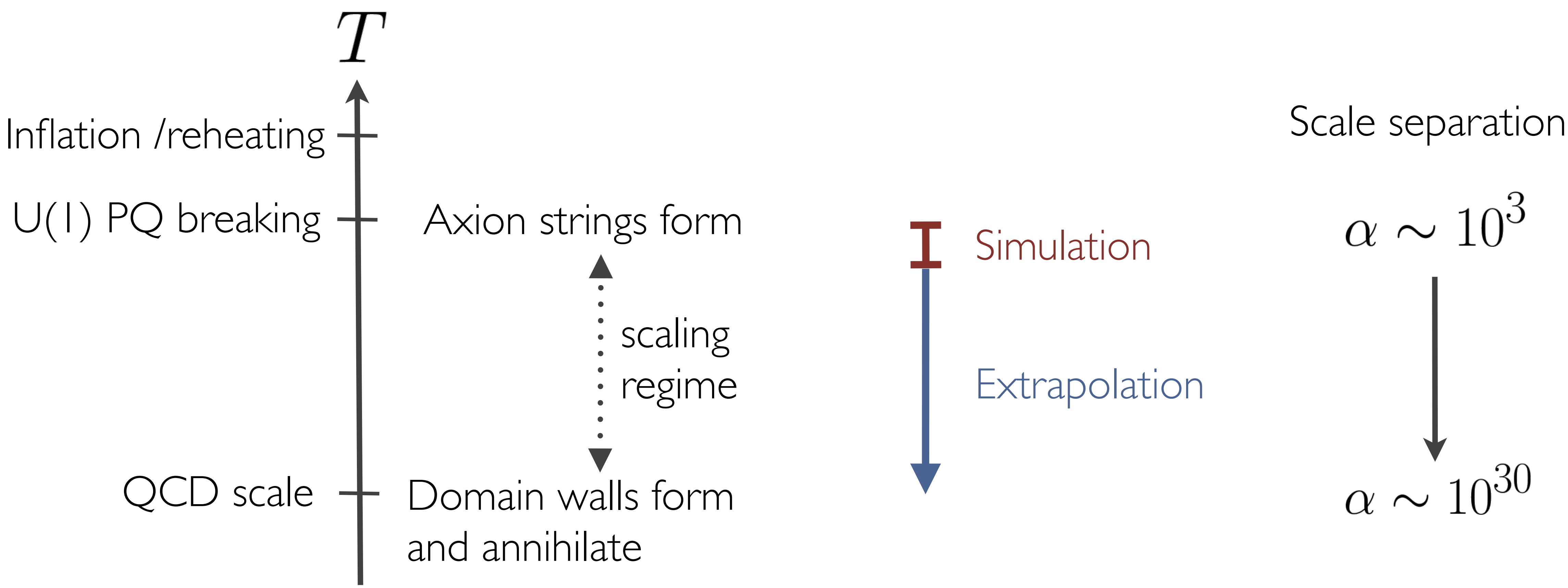
simulations: $\log \alpha \leq \log($  $) \sim 7$

physical: $\log \alpha \sim 70$



Many previous papers just use results at small scale separation

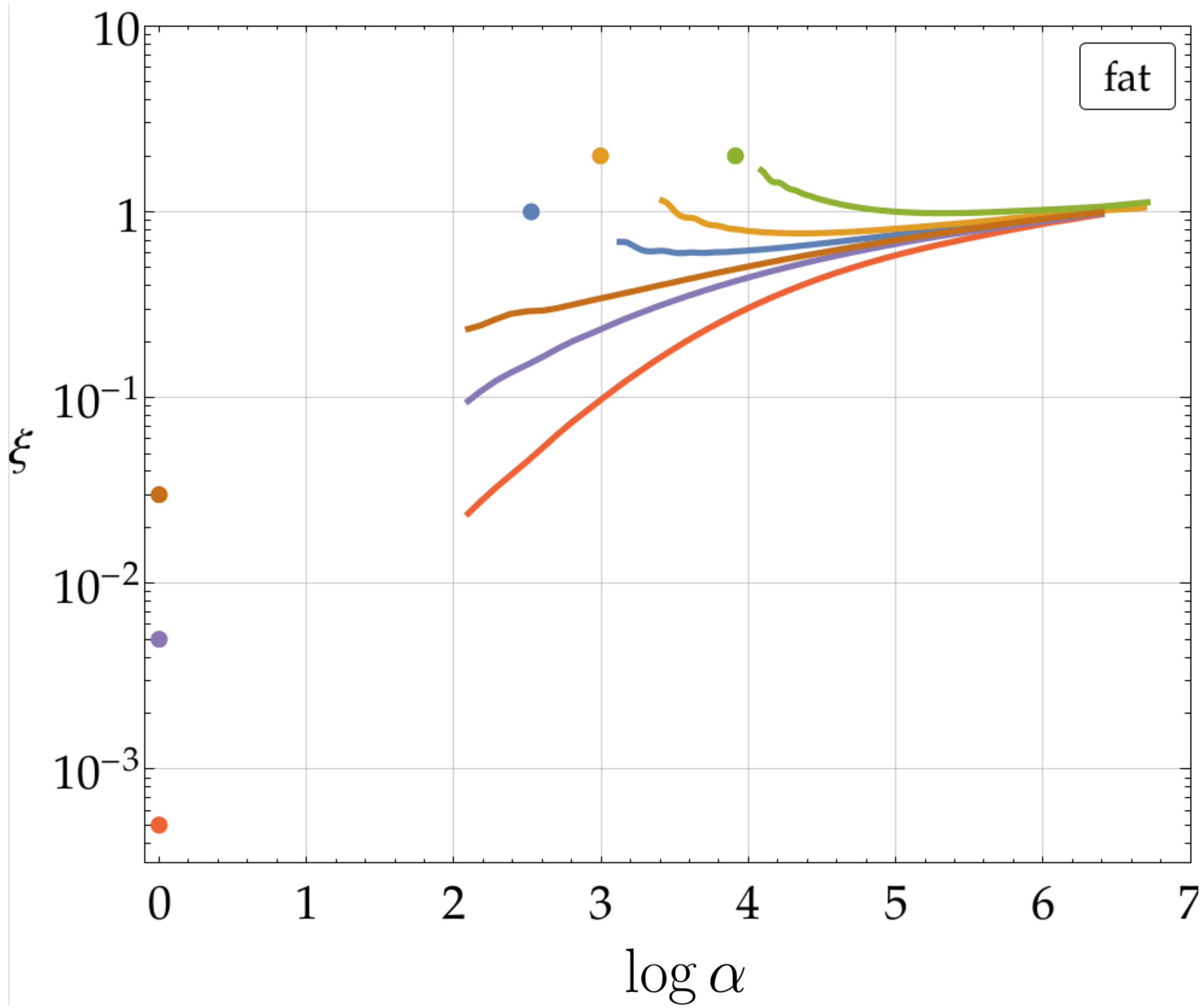
Extrapolation



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

The attractor solution

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

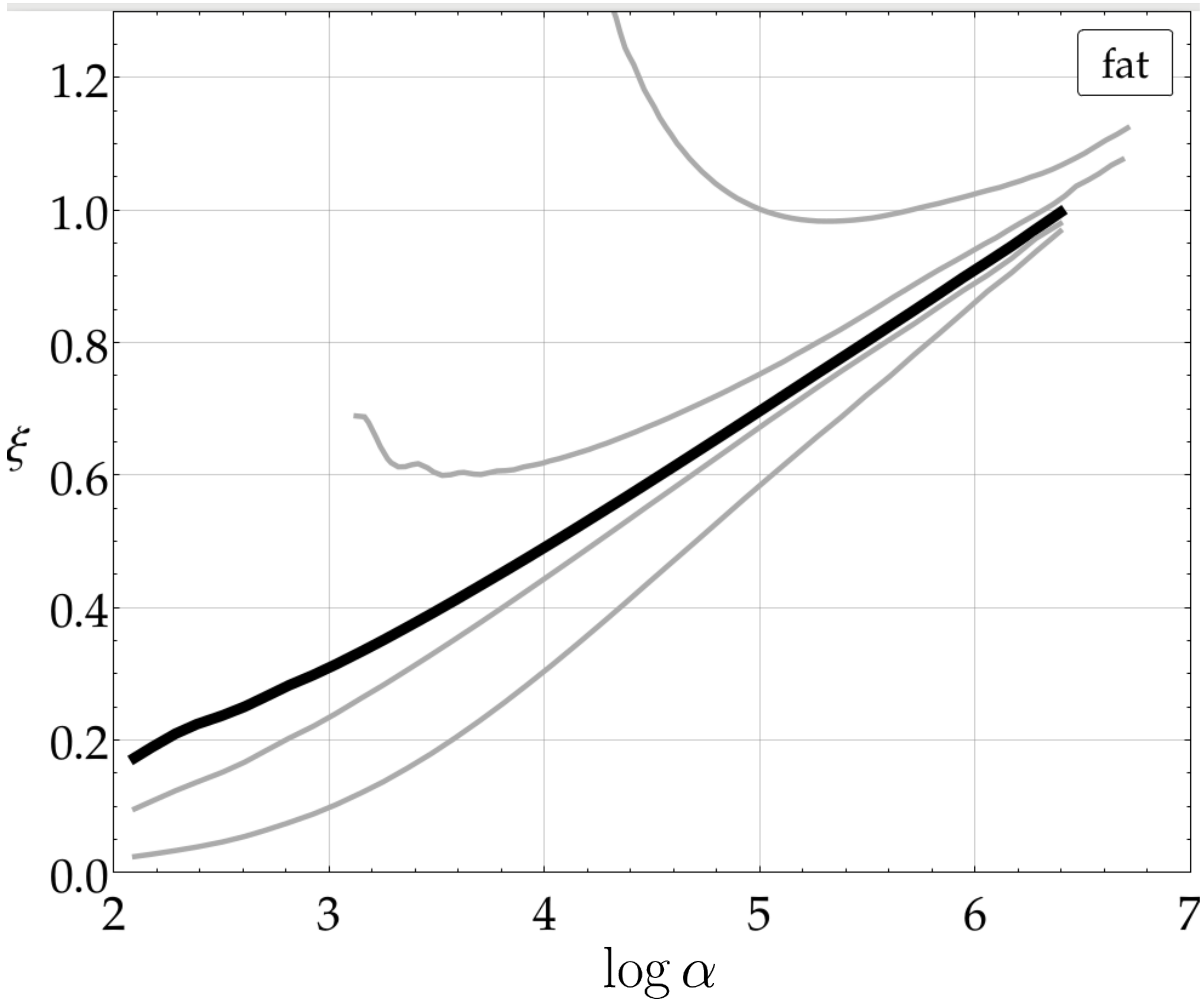


Solution is approximately scale invariant

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

Scaling violations

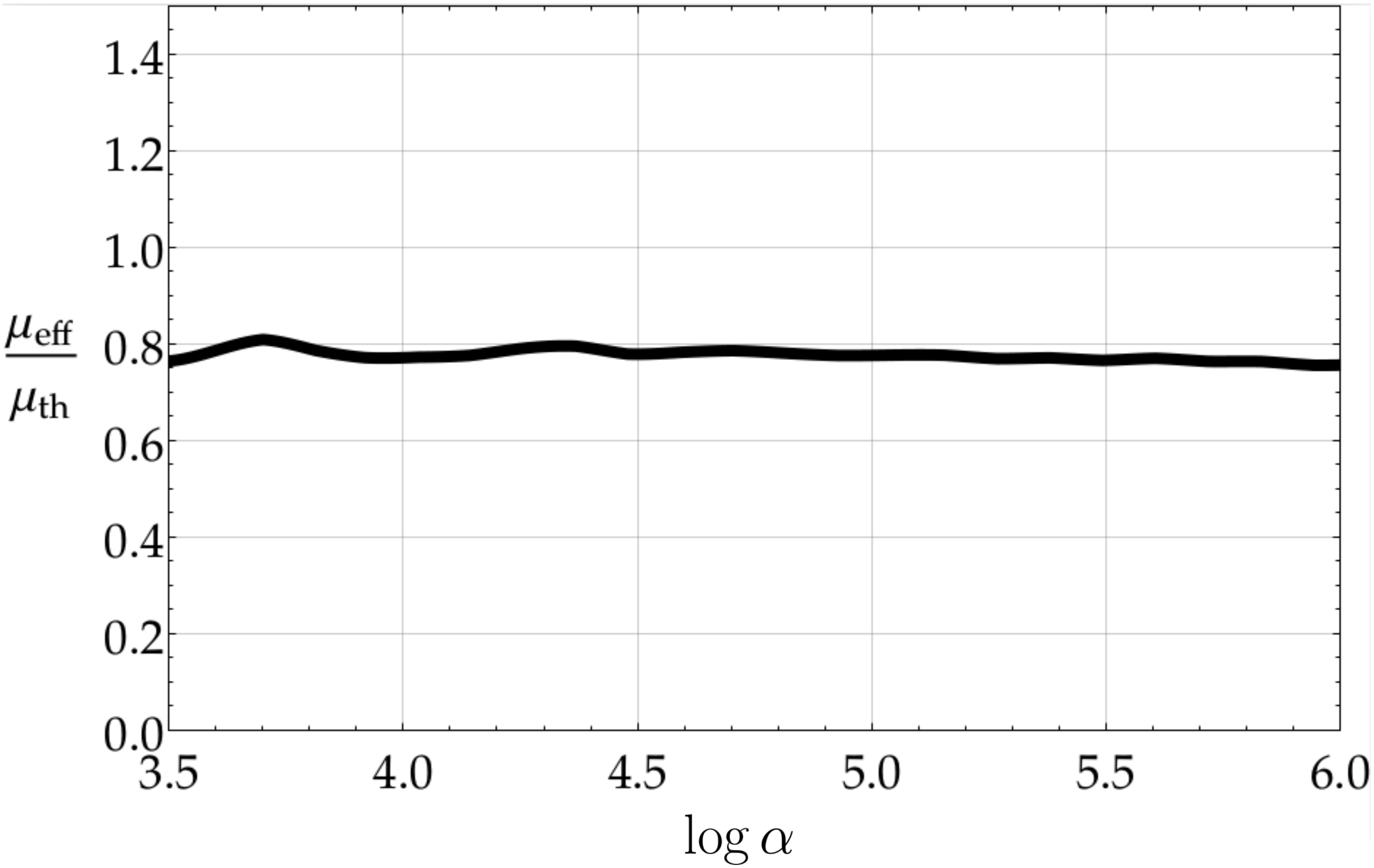
Find a log increase, theoretically plausible since the tension is increasing



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

Energy stored in strings

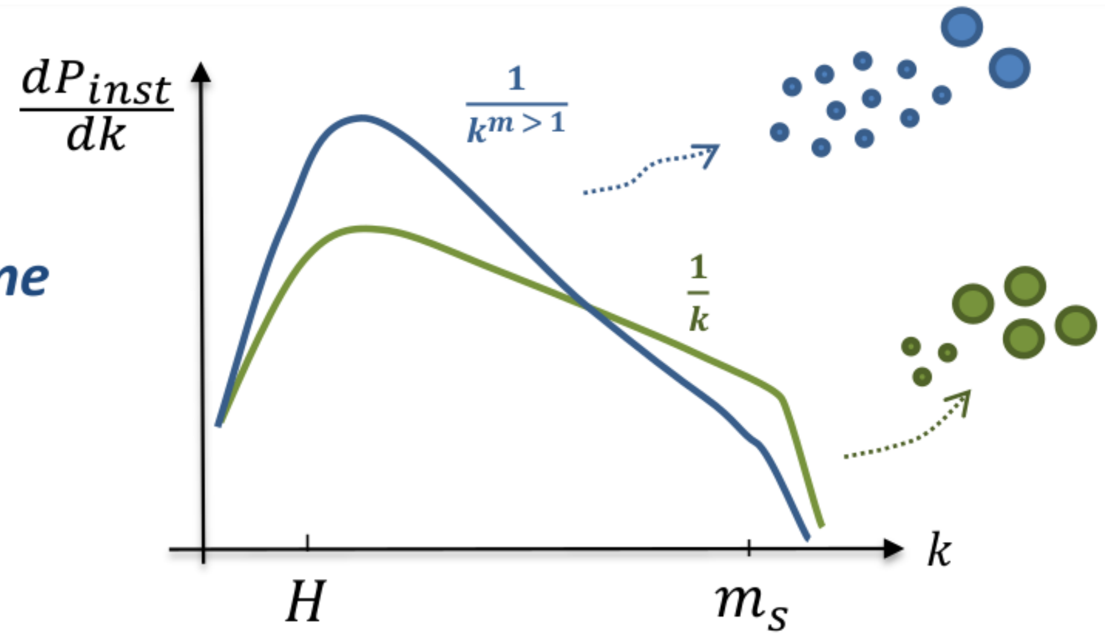
Calculate the effective string tension in simulations from string energy and $\xi(t)$



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

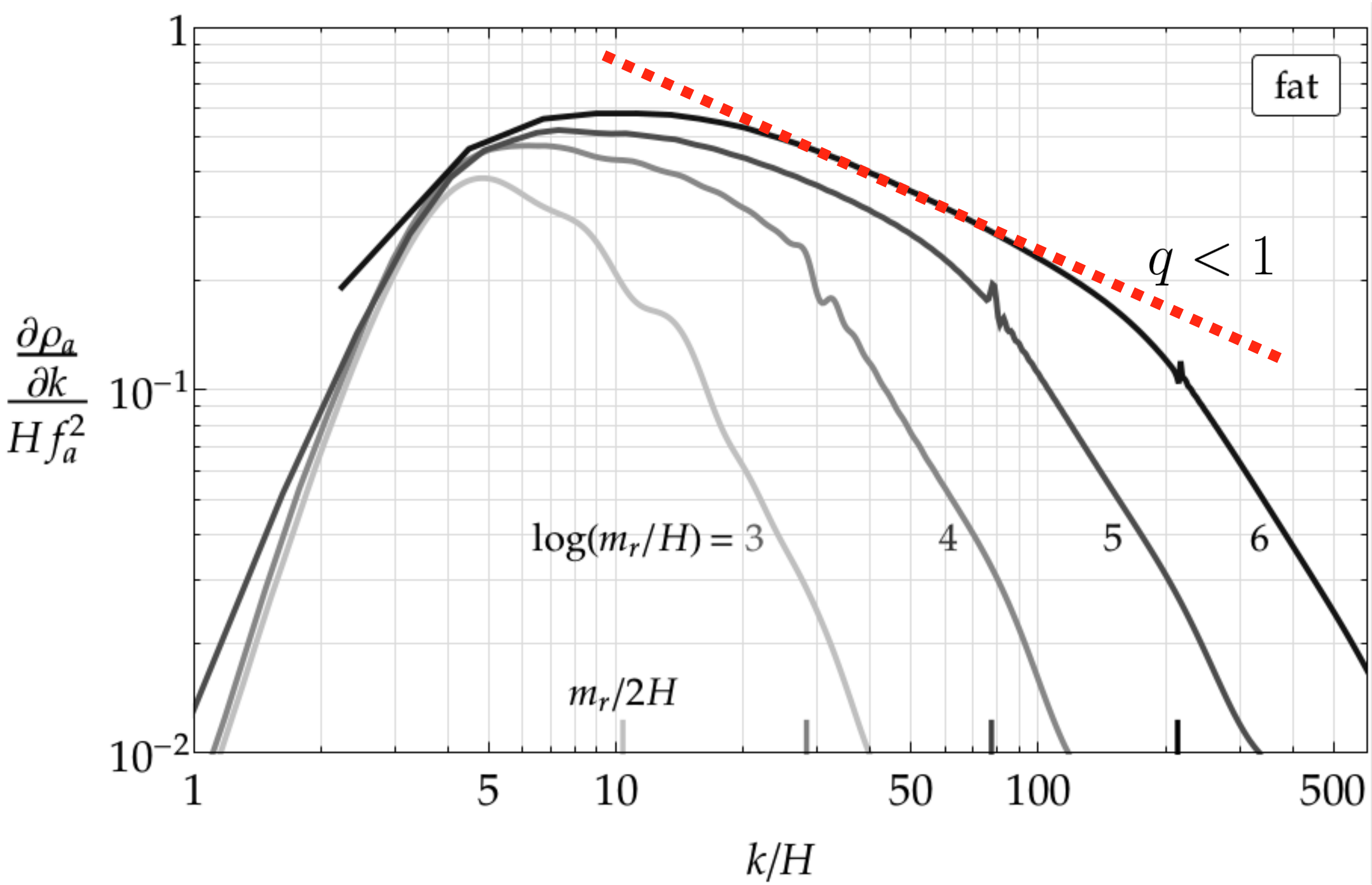
natural cut-offs at H and m_s but:

(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 $\langle k^{-1} \rangle \propto \frac{H^{-1}}{\log \alpha}$

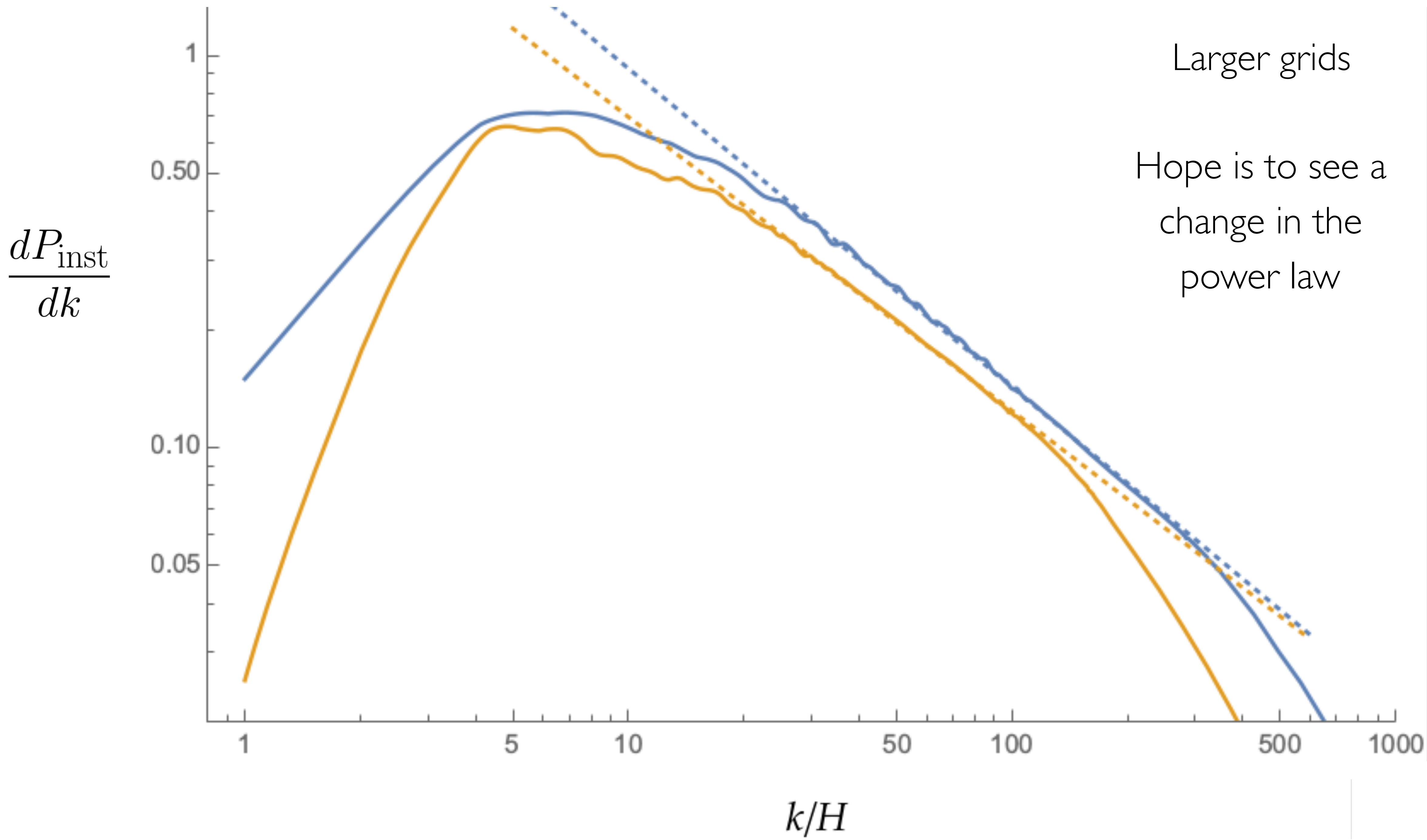
Spectrum



Power law between IR and UV cutoffs

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

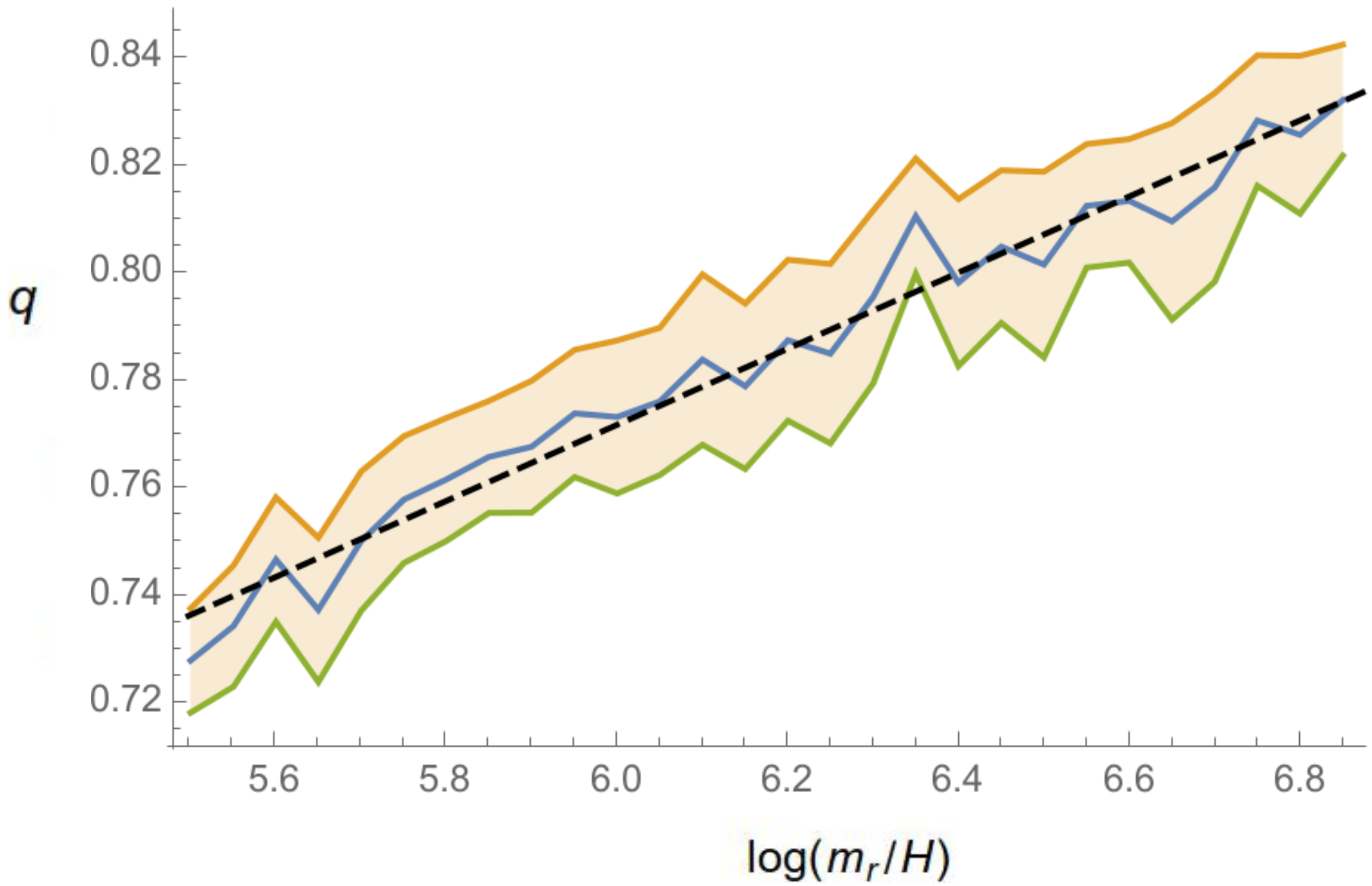
New Data



Larger grids

Hope is to see a change in the power law

New data



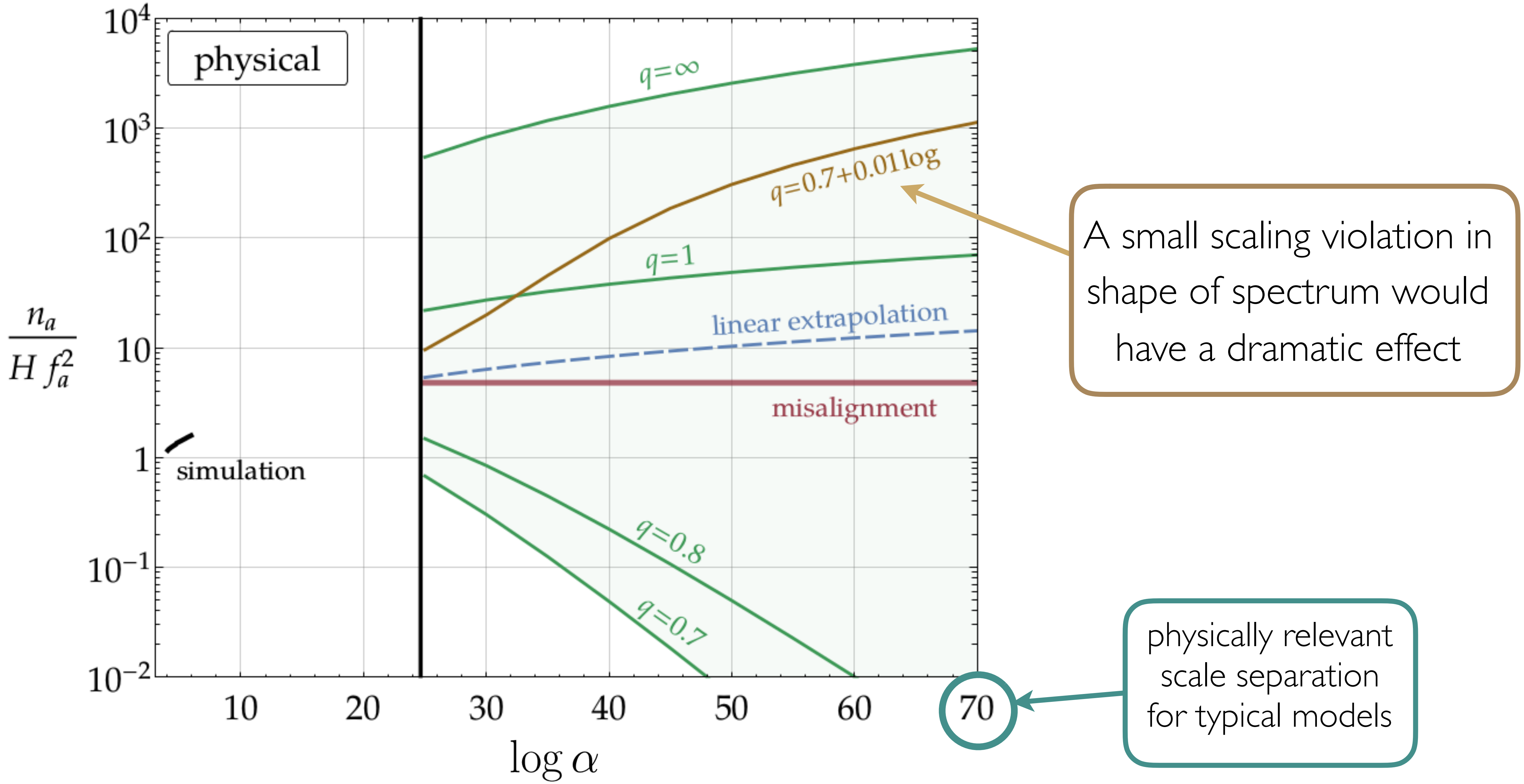
$$\frac{dP_{\rm inst}}{dk} \sim \frac{1}{k^q}$$

Possible log dependence in the power law of the spectrum

Warning: systematic uncertainties not yet fully studied

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



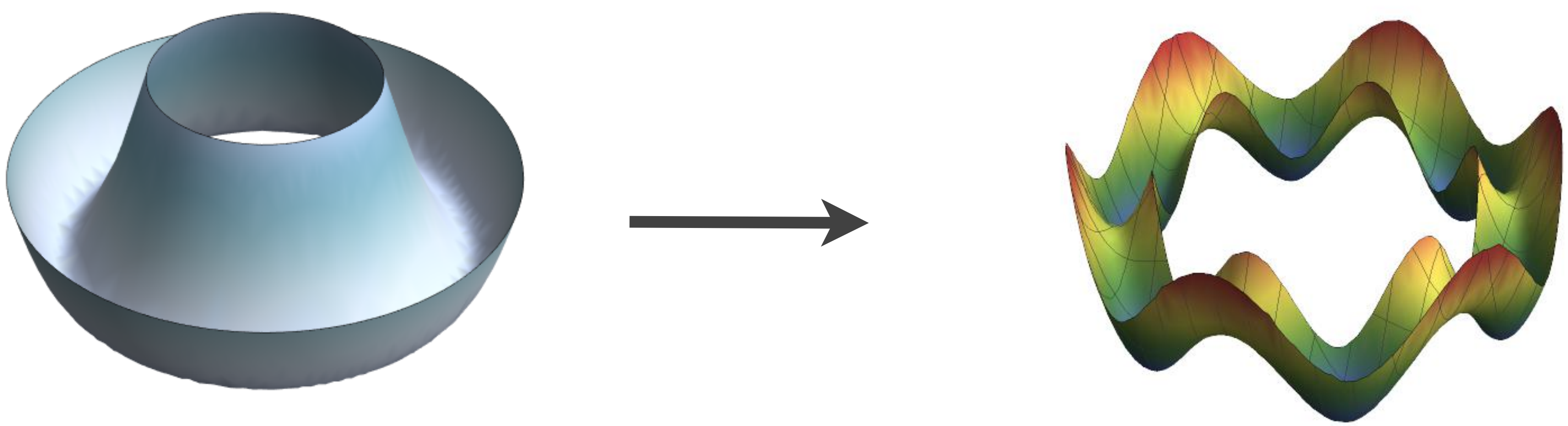
Conclusions

- 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
- After that: domain walls

Thanks

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

Domain walls

Axion mass becomes cosmologically relevant when

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

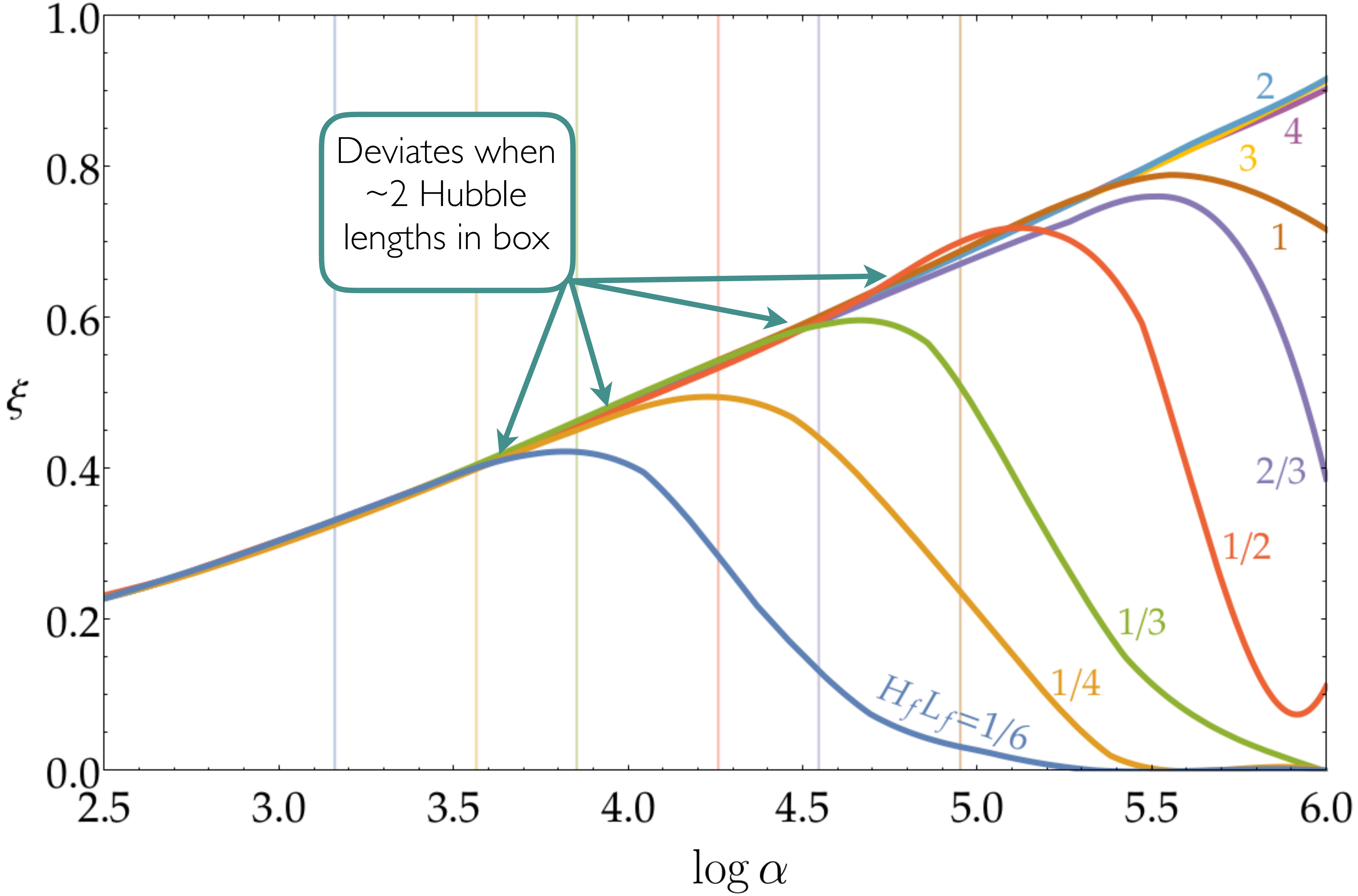
Subsequently it increases fast, and quickly $m_a(T) \gg H(T_0)$

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

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

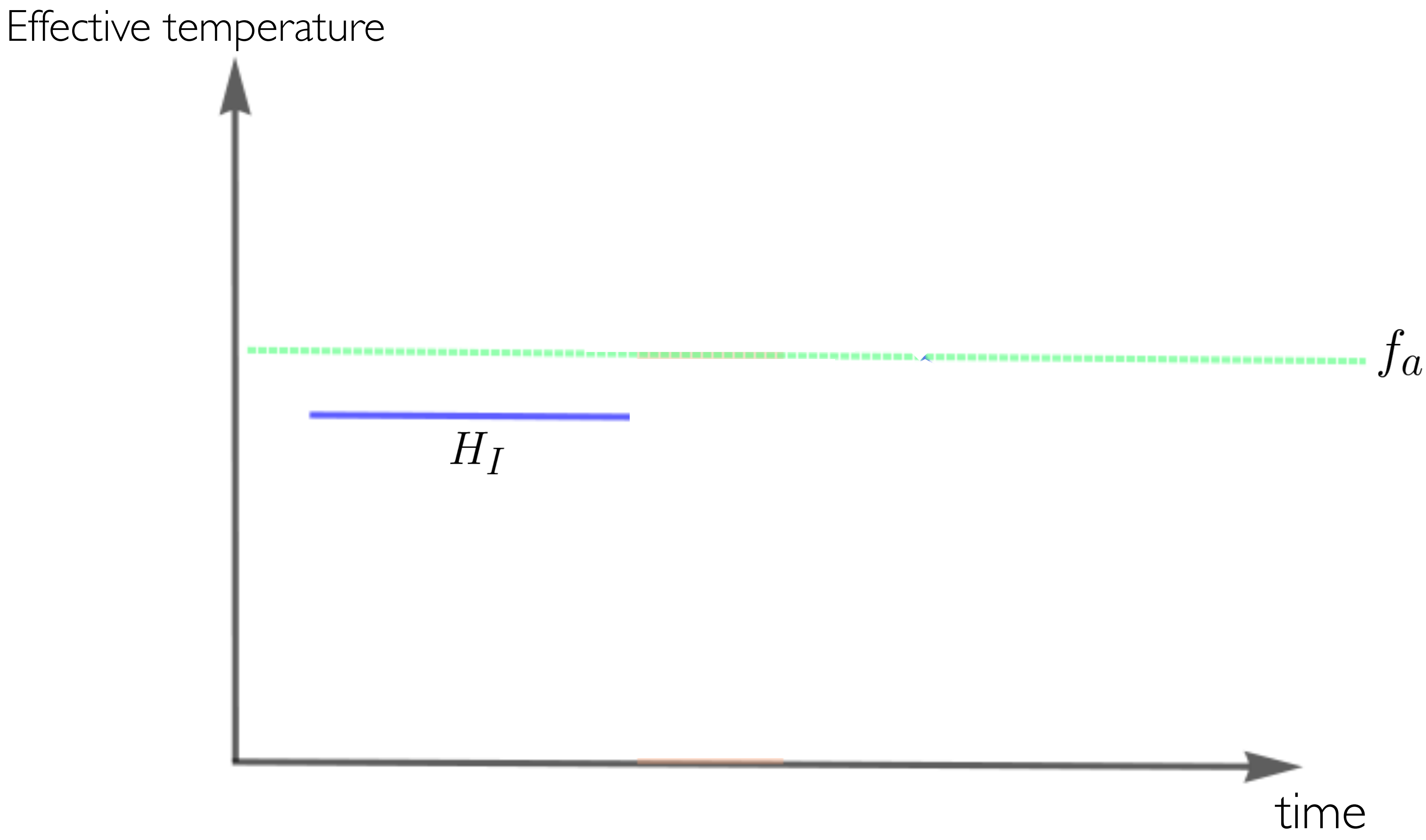
Numerical checks

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



Boundary between regimes

Depends on the details of reheating, e.g. with inflaton decay rate Γ



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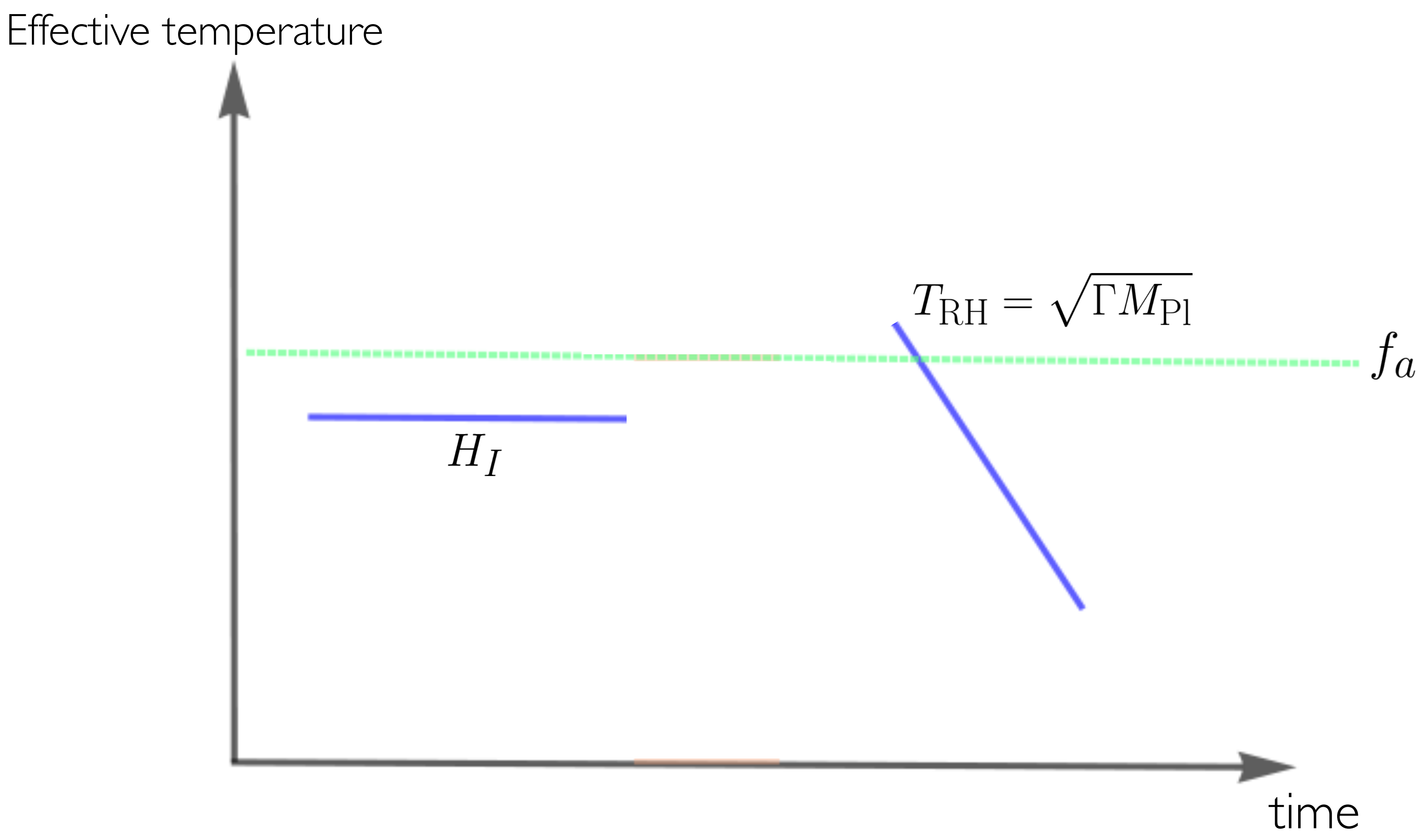

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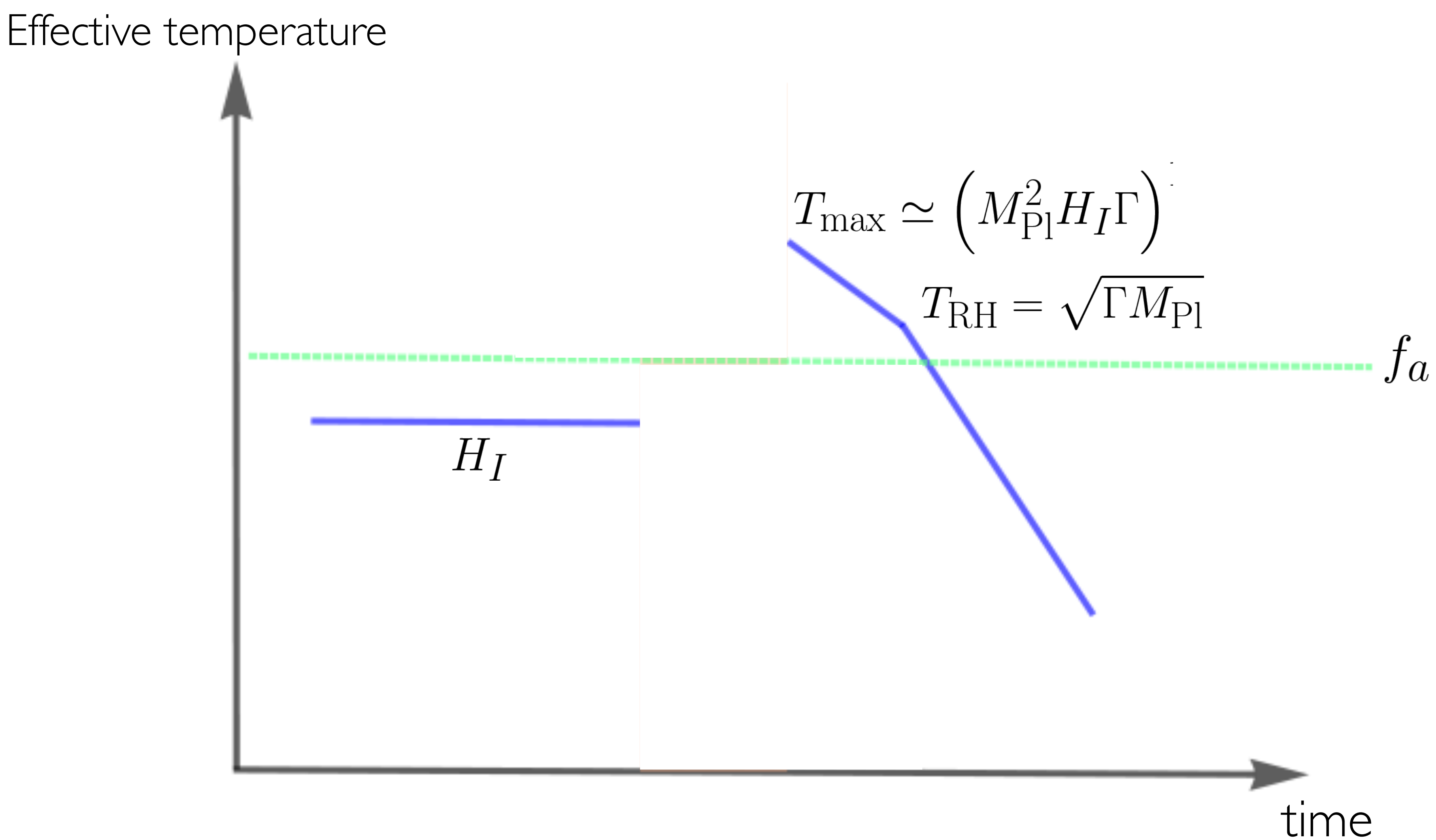

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