Axions from Strings

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Based on work with:

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QCD axion

Spontaneously broken anomalous global U(1)

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

$$a \to a + \delta$$

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

QCD runs into strong coupling

axion potential

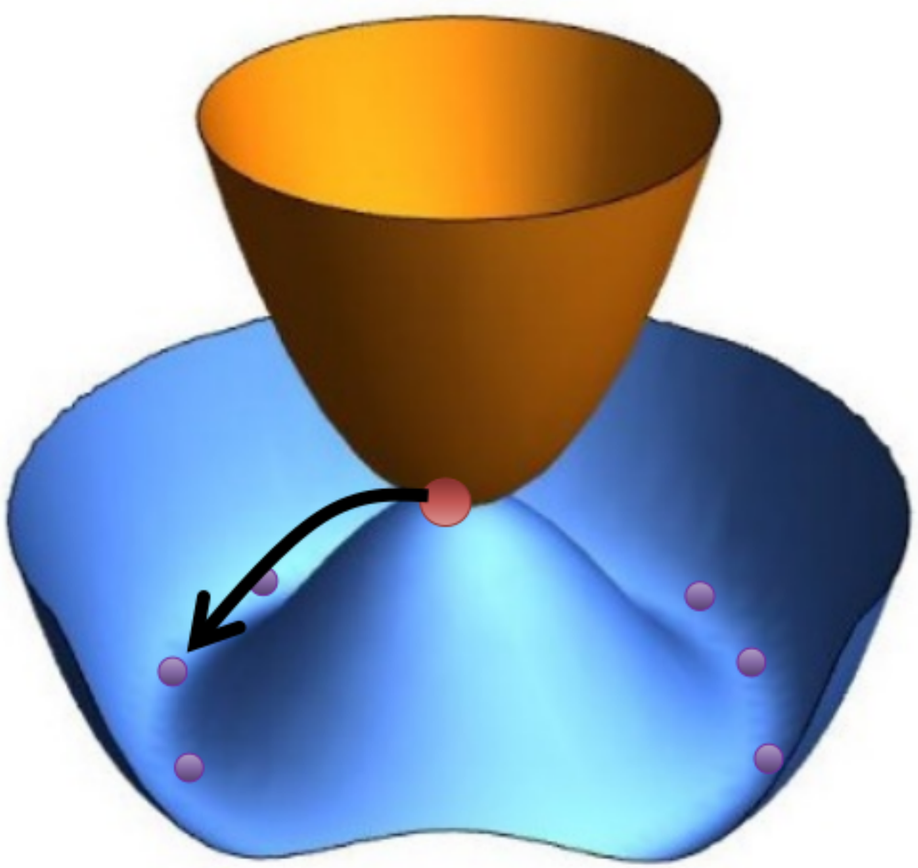
$$\theta_{\text{tot}} = \langle a \rangle + \theta' = 0$$

Dark matter

Bonus feature: a QCD axion can automatically be the dark matter

Concentrate on scenario with $\boxed{f_a < \max\left(H_I, T_{\text{eff}}\right)}$

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

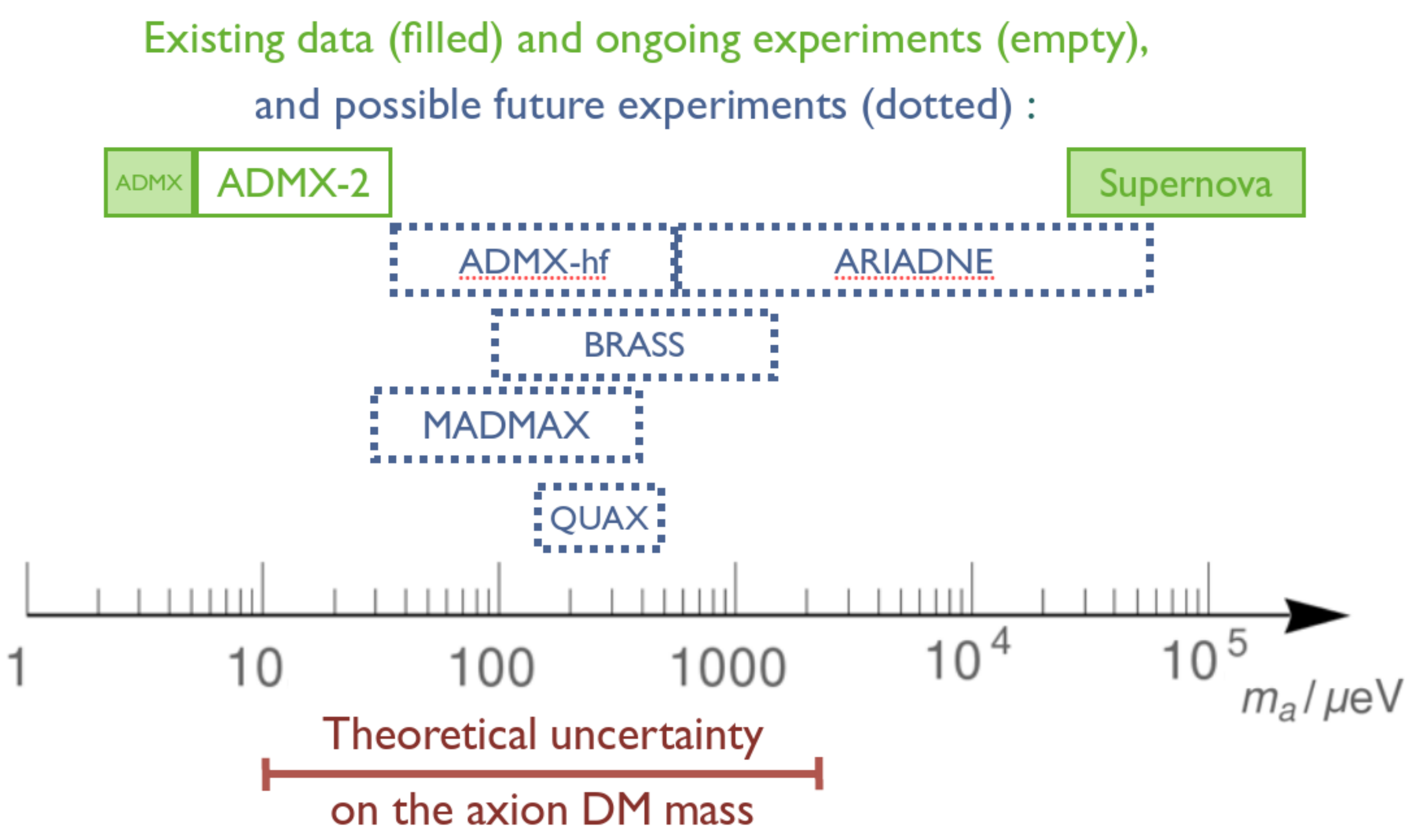


$a(t_0) = \text{random}$

U(1) breaking after inflation

In principle extremely predictive

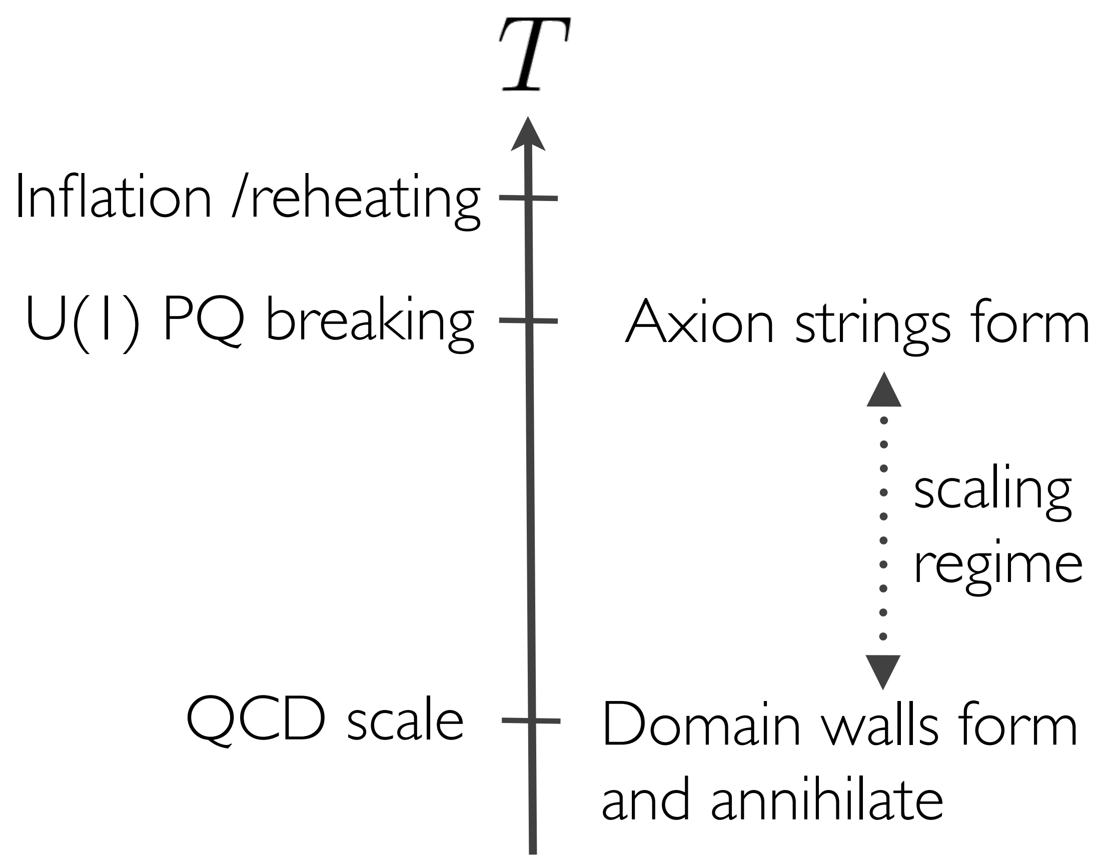
unique DM axion mass

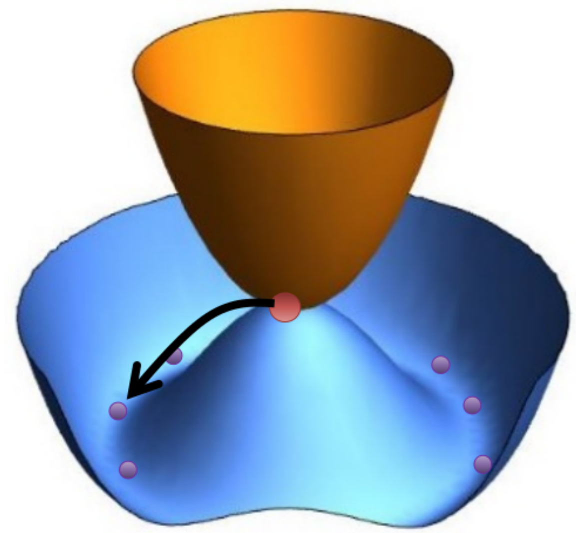


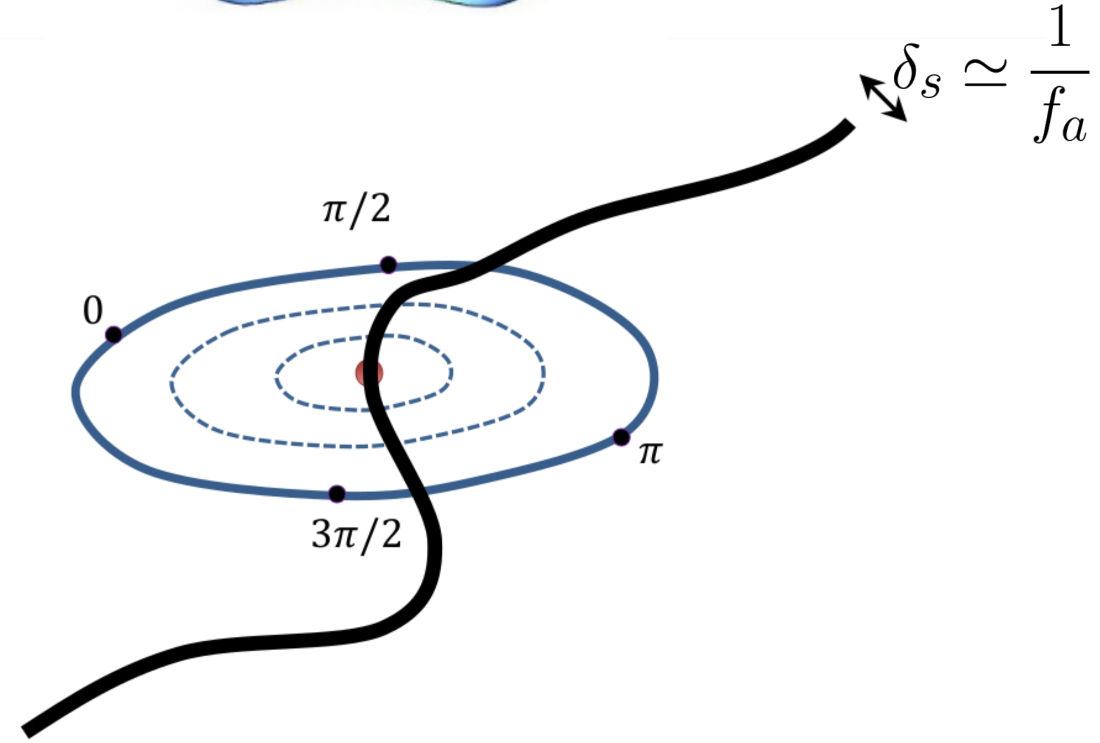
Reliable prediction: interpret ongoing experiments, design future experiments

Precise agreement with an experimental discovery → minimum inflation scale

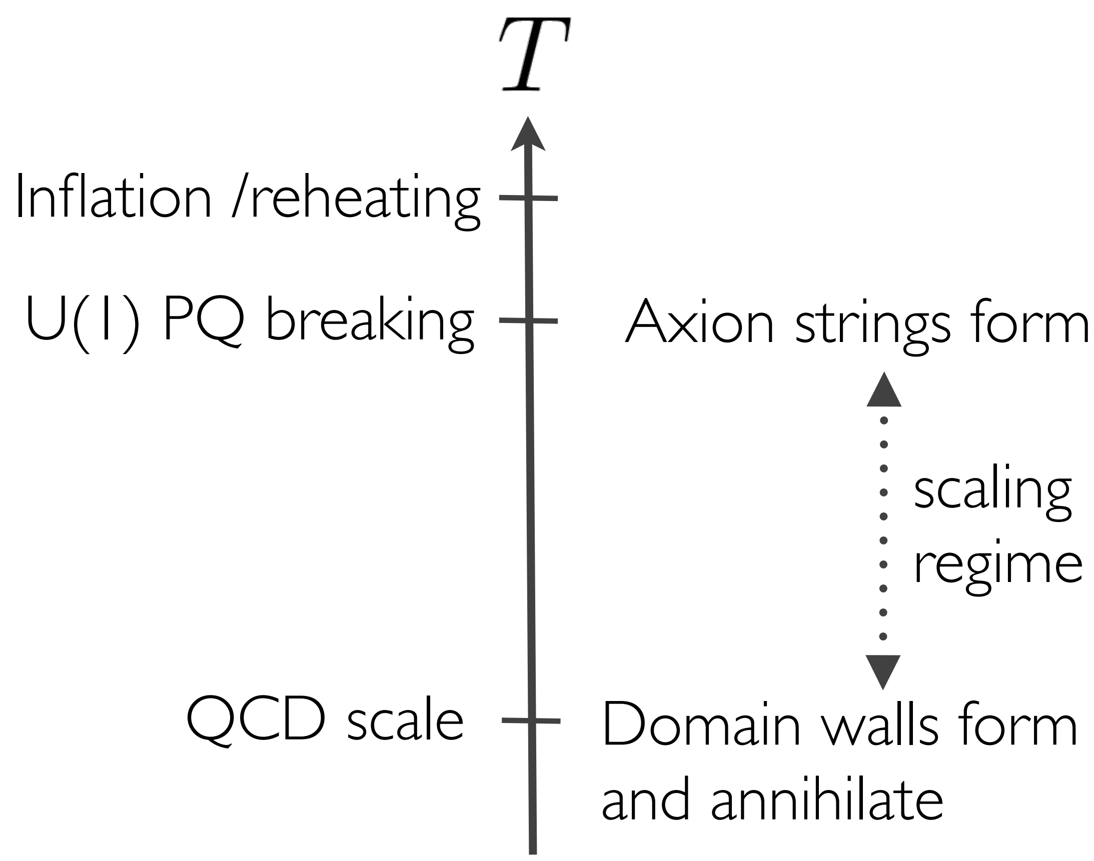
Strings and domain walls

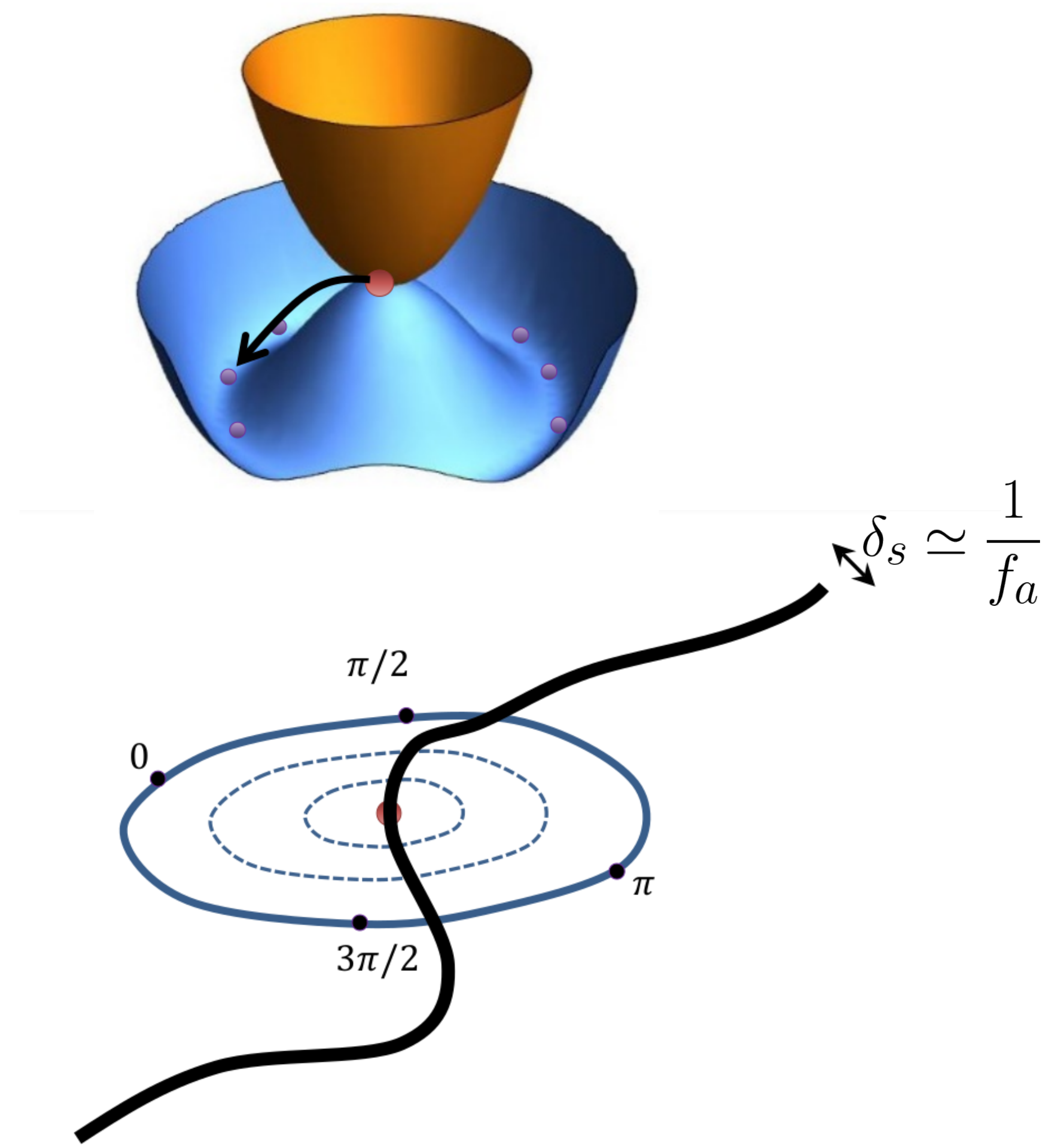






Strings and domain walls





Significant proportion of DM axions produced by strings and domain walls

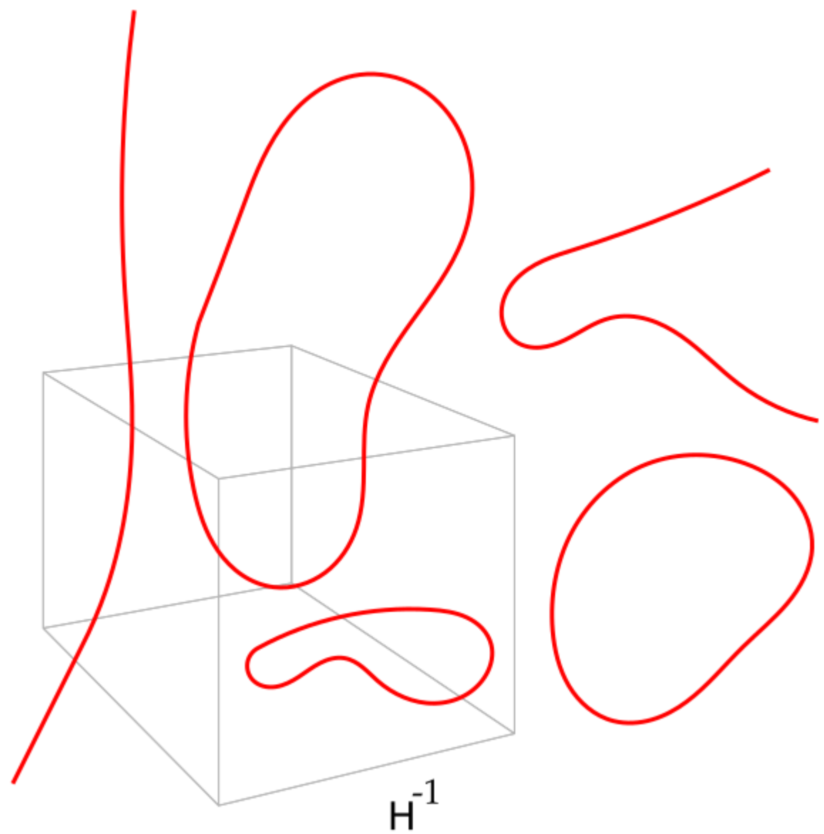
Axion emission during scaling

Parametrisation:

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

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

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



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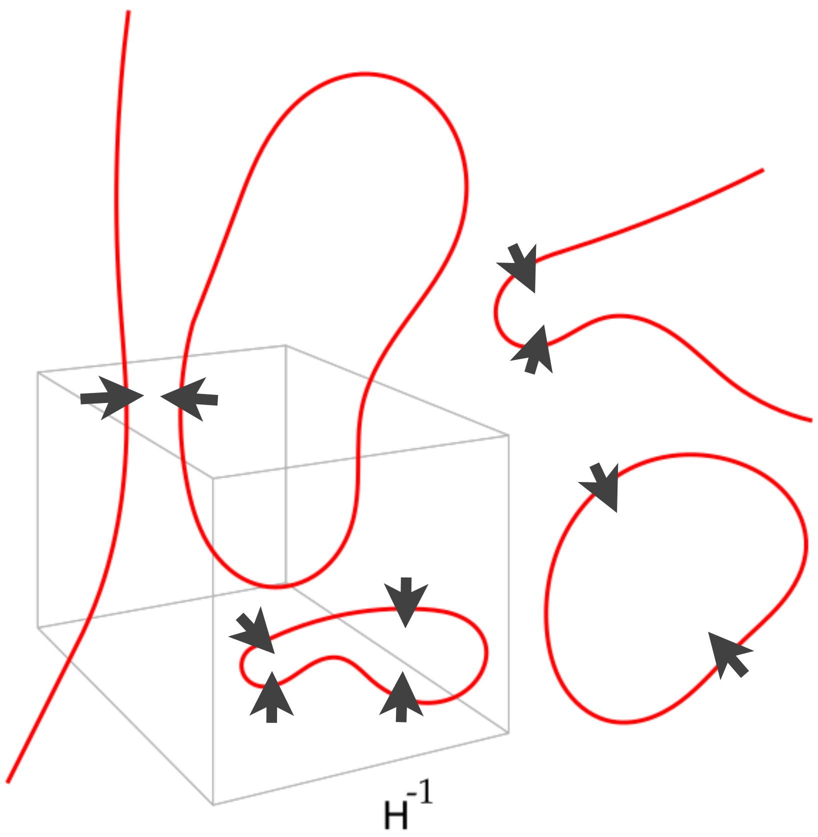

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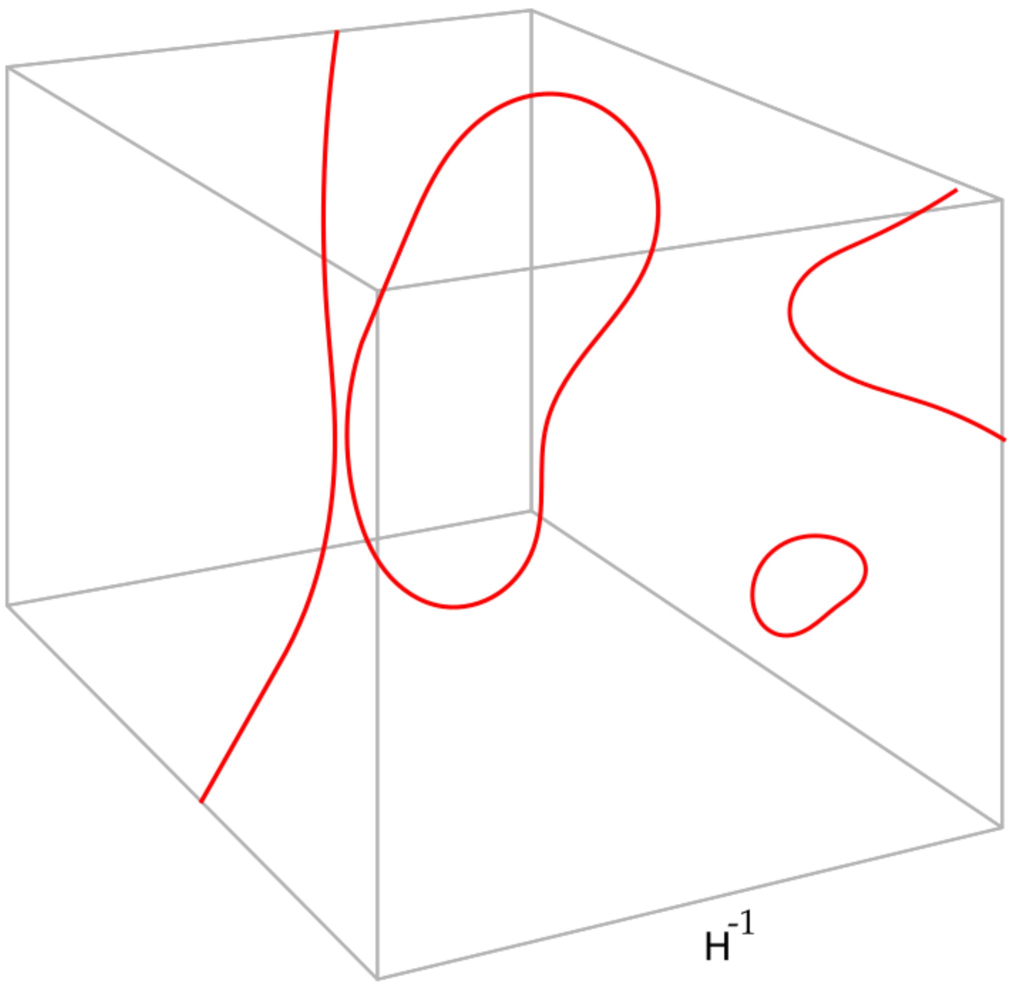


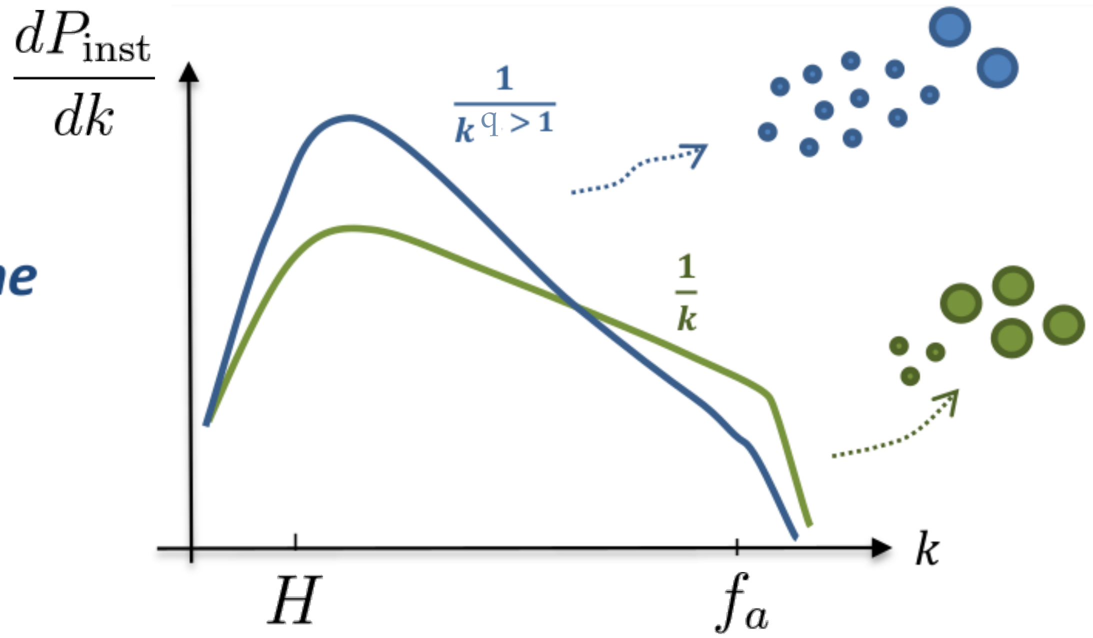
$\xi(t)$ & $\mu(t)$ approximately constant

Energy release:

$$P_{\text{emitted}} \simeq \frac{\xi(t)\,\mu(t)}{t^3}$$

Distribution of axion momenta

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



Theoretical expectations

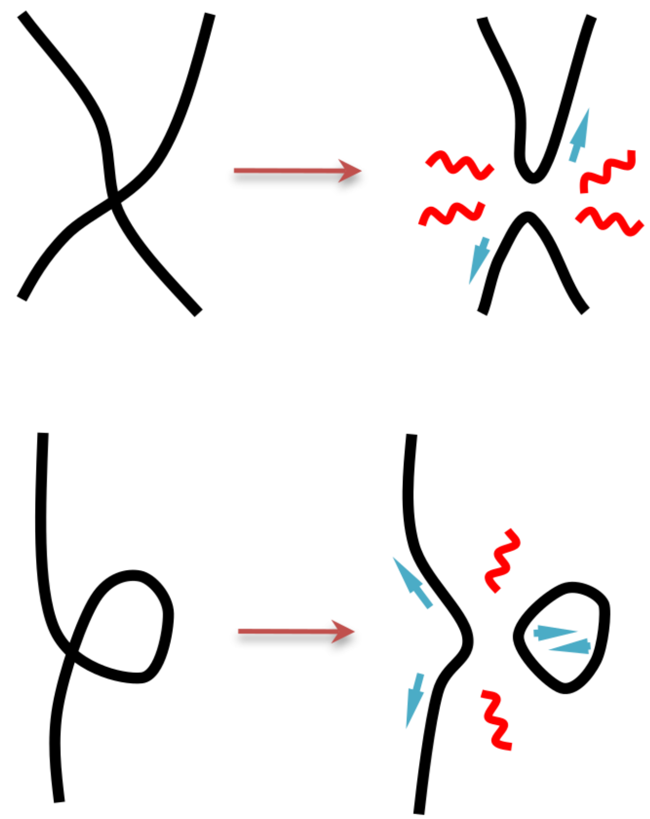
natural cut-offs at H and f_a but:

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

$q > 1$

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

String dynamics

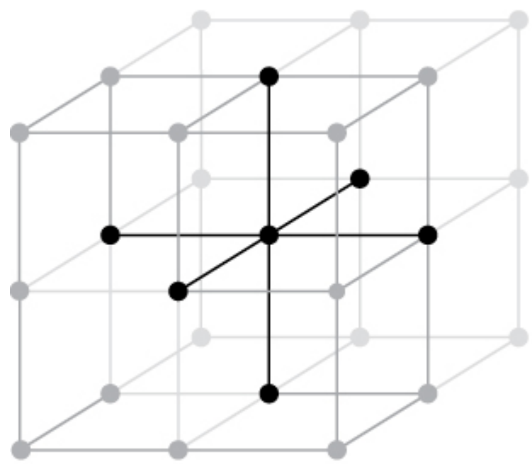


Hard to study analytically, can help with qualitative understanding, but full network has complicated interactions and dynamics

Instead resort to numerical simulations

Numerical simulation

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



Evolve using finite difference algorithm

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

 group identified lattice points

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

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

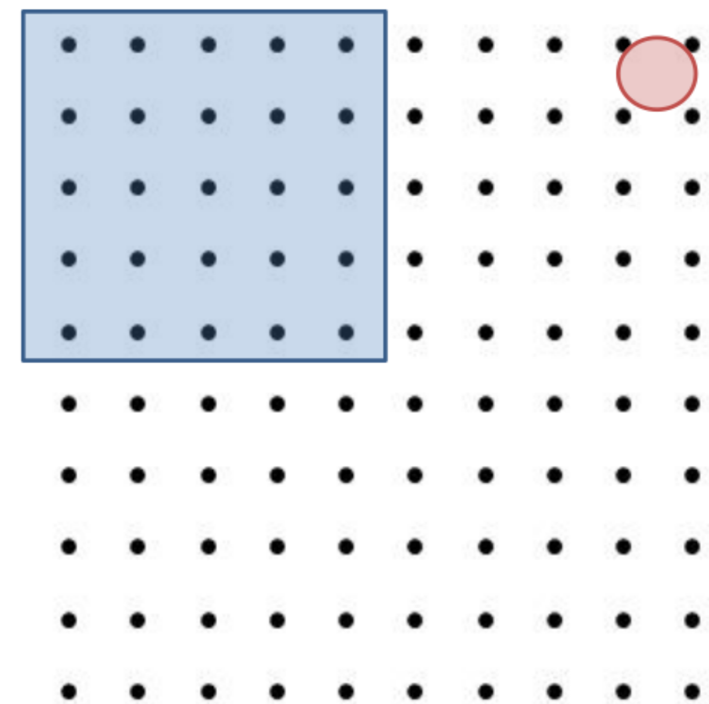
Physical scale separation $\alpha \sim 10^{30}$

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

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

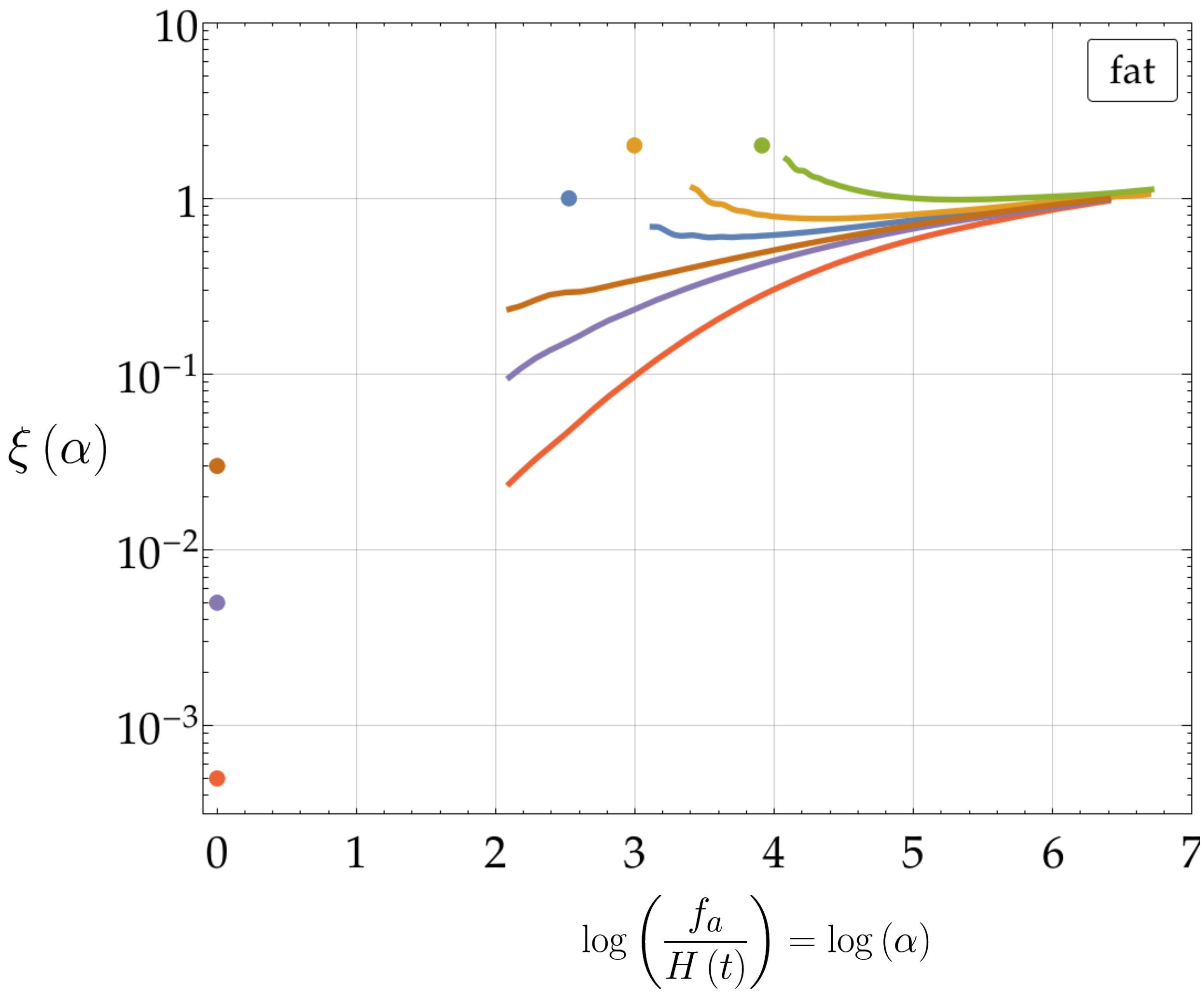
simulations: $\log \alpha \leq \log(\frac{\square}{\bigcirc}) \simeq 7$

physical: $\log \alpha \sim 70$

We simulate at small scale separation then extrapolate

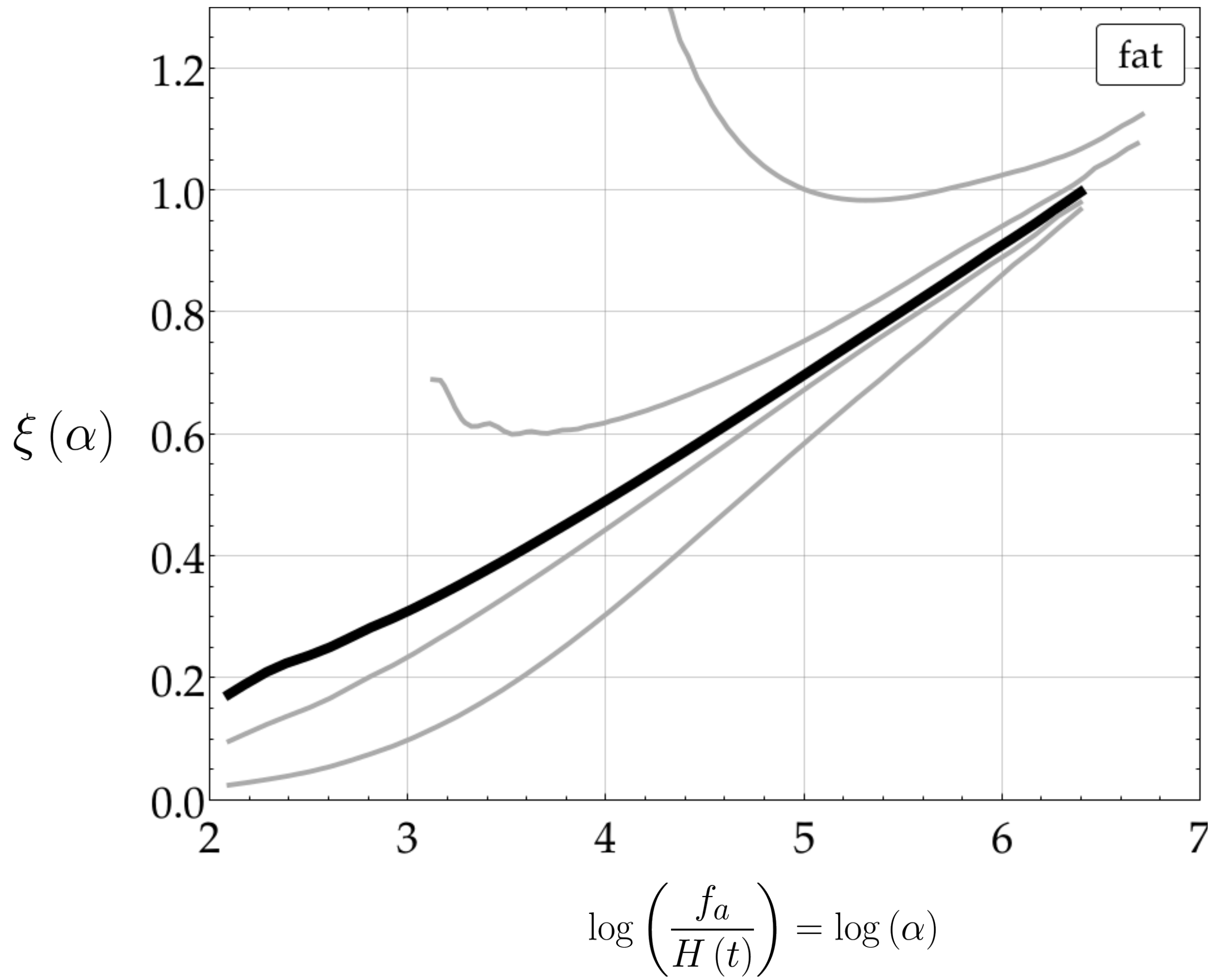
Crucial to extrapolate the correct quantities (not the number density)

String length per Hubble volume



Attractor solution, independent of initial conditions

String length per Hubble volume

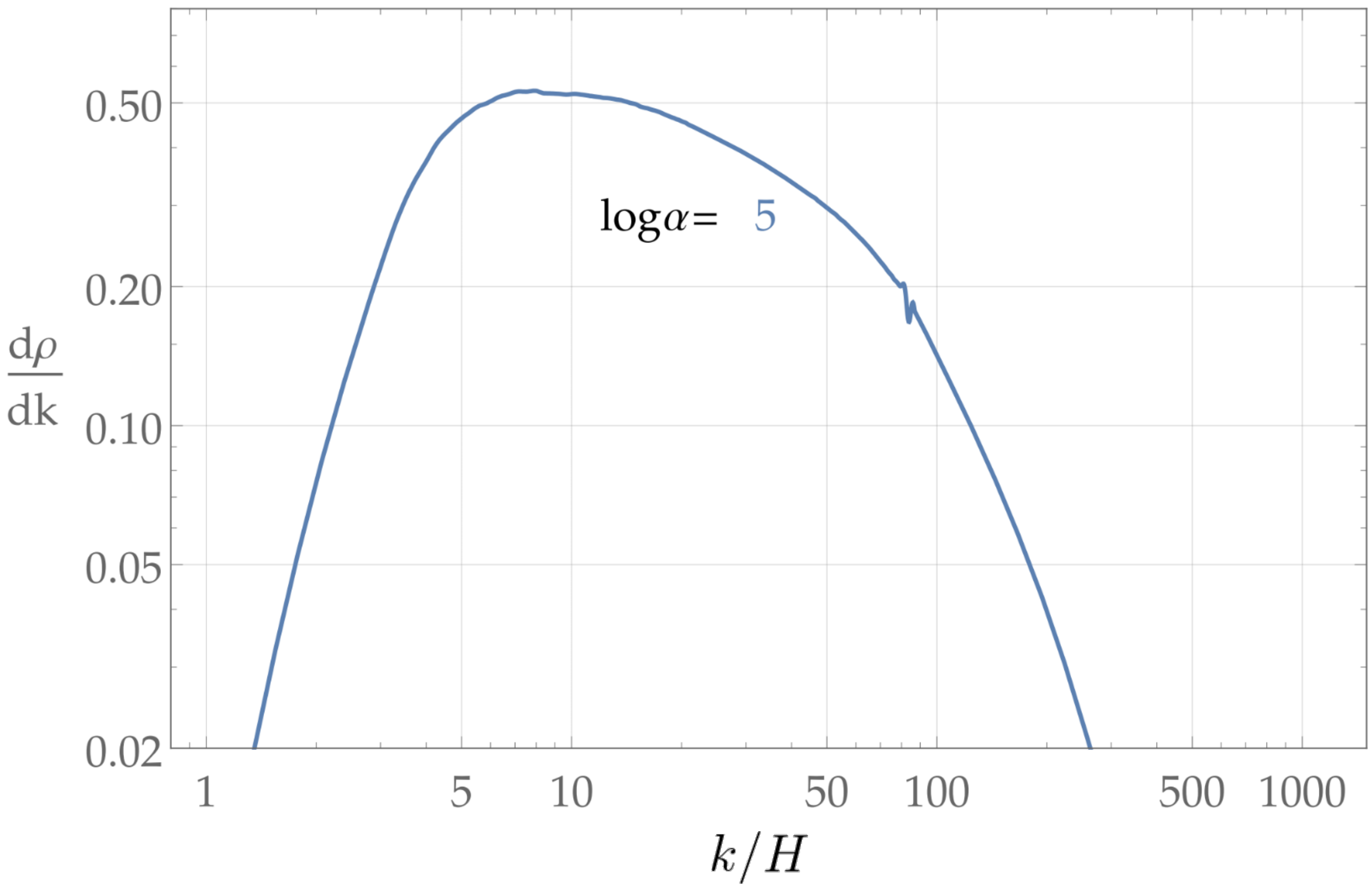


Find a log increase,

theoretically plausible: tension is increasing

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

Total spectrum



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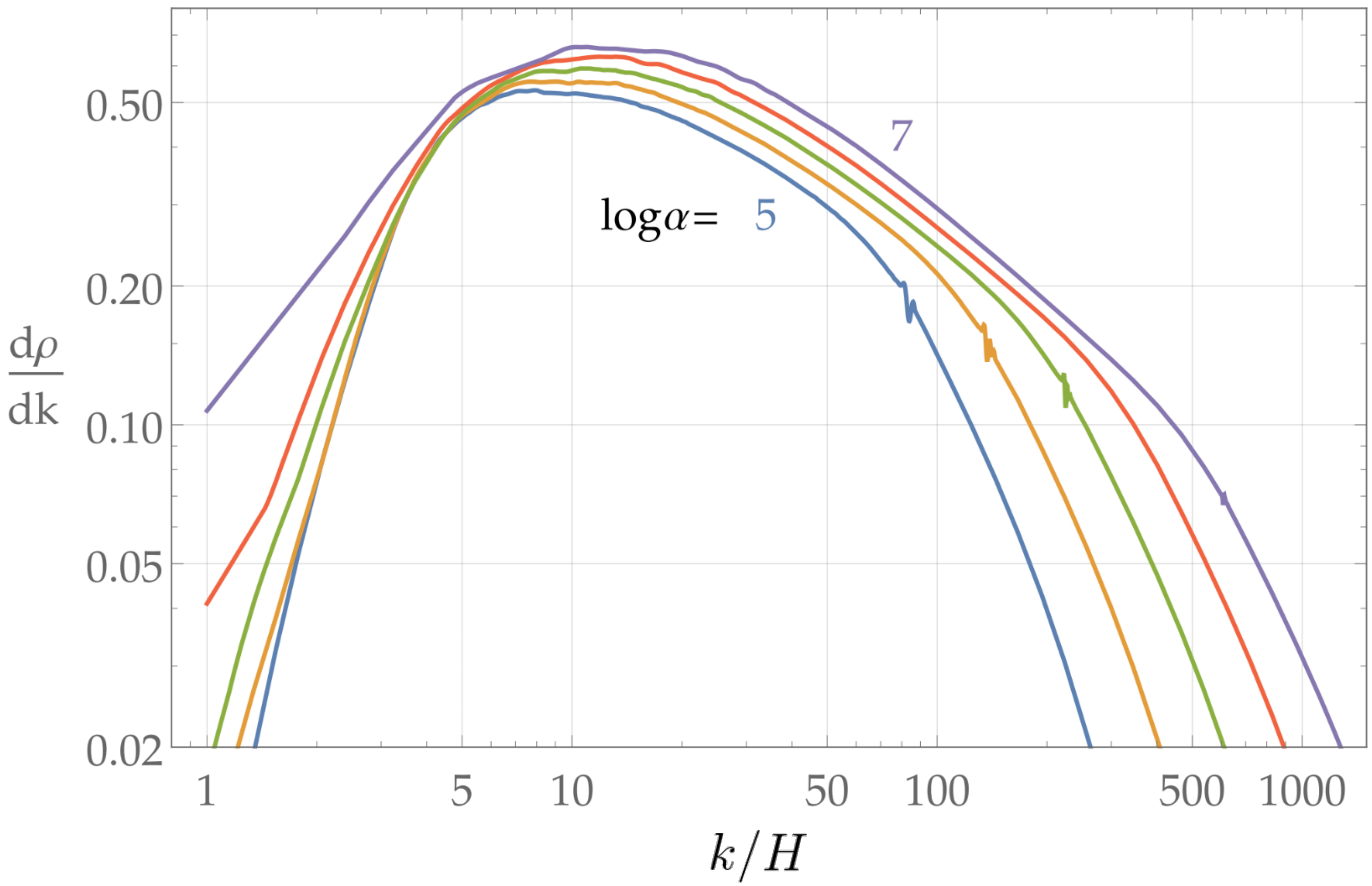
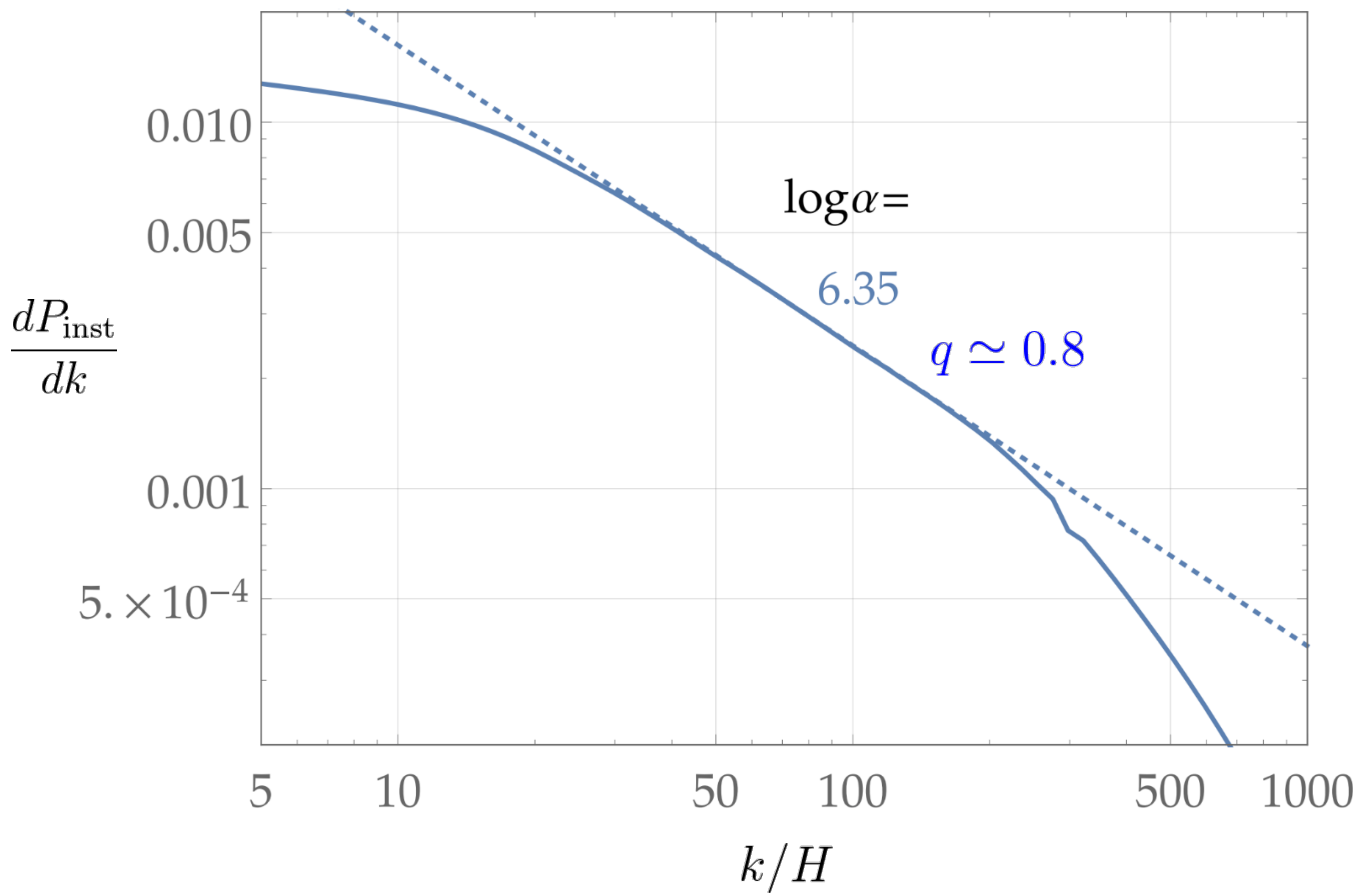


Instantaneous emission spectrum

This is the physically relevant thing to extrapolate



UV dominated!

Instantaneous emission spectrum

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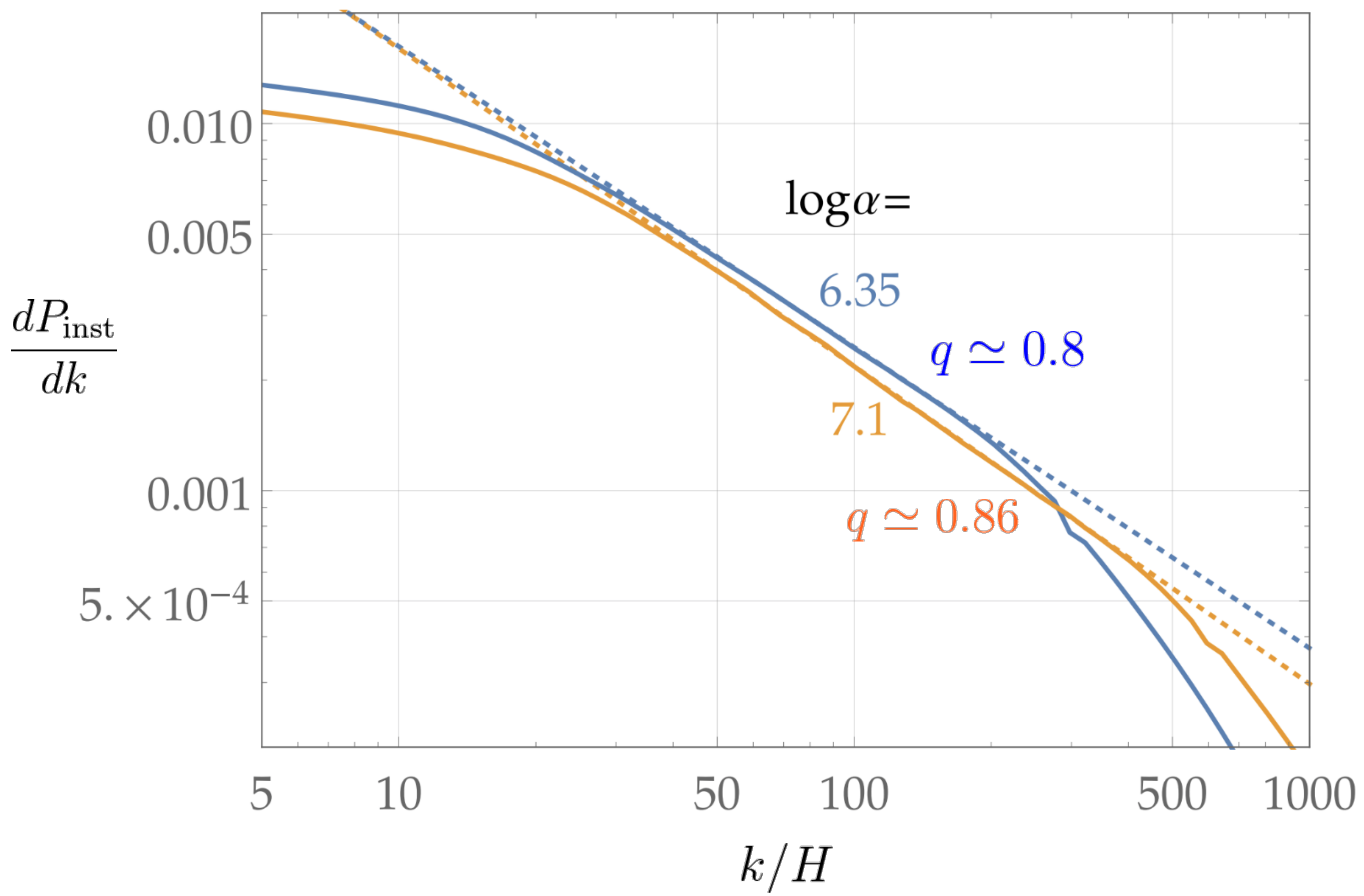
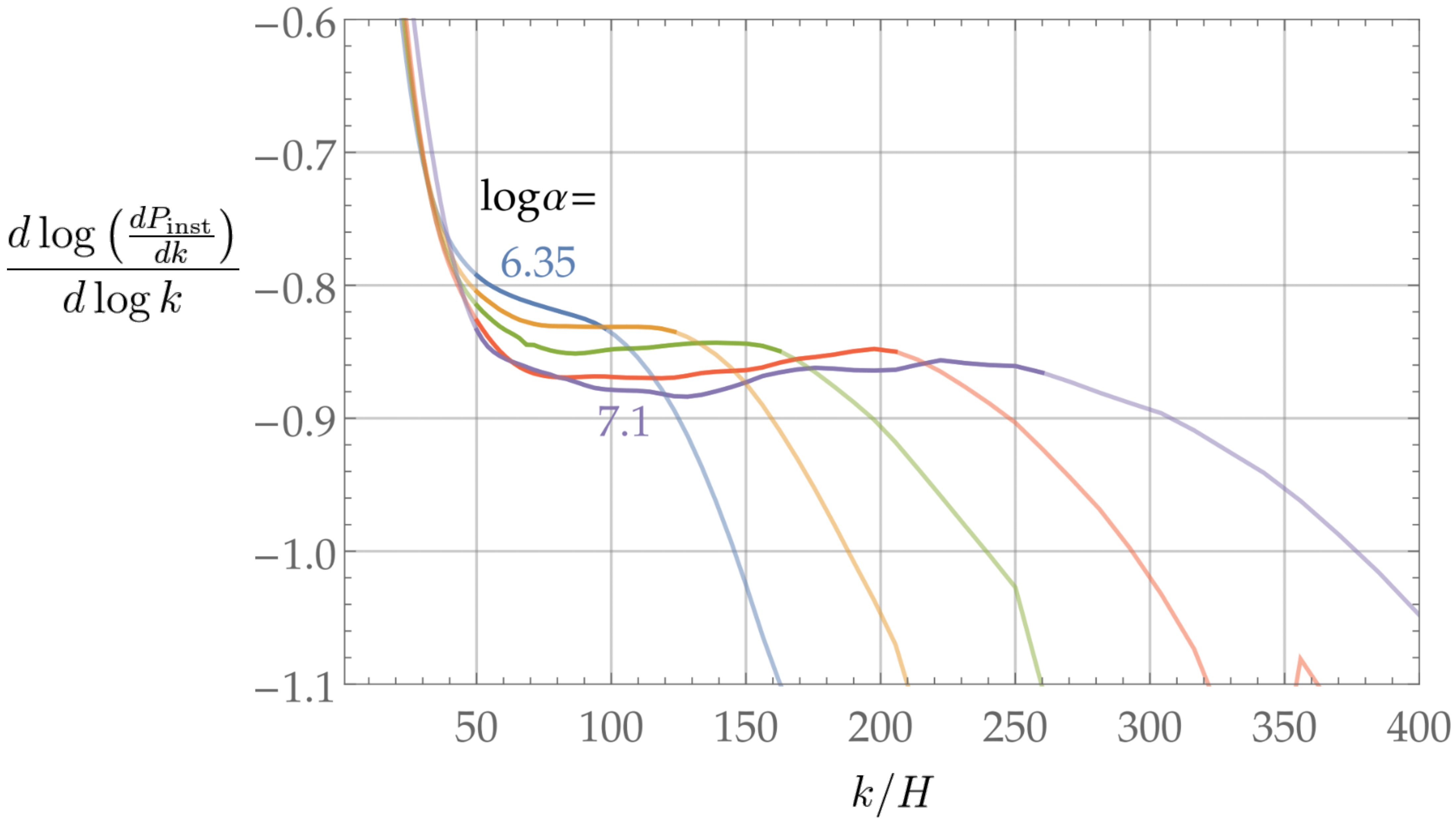


But evidence for a log dependence

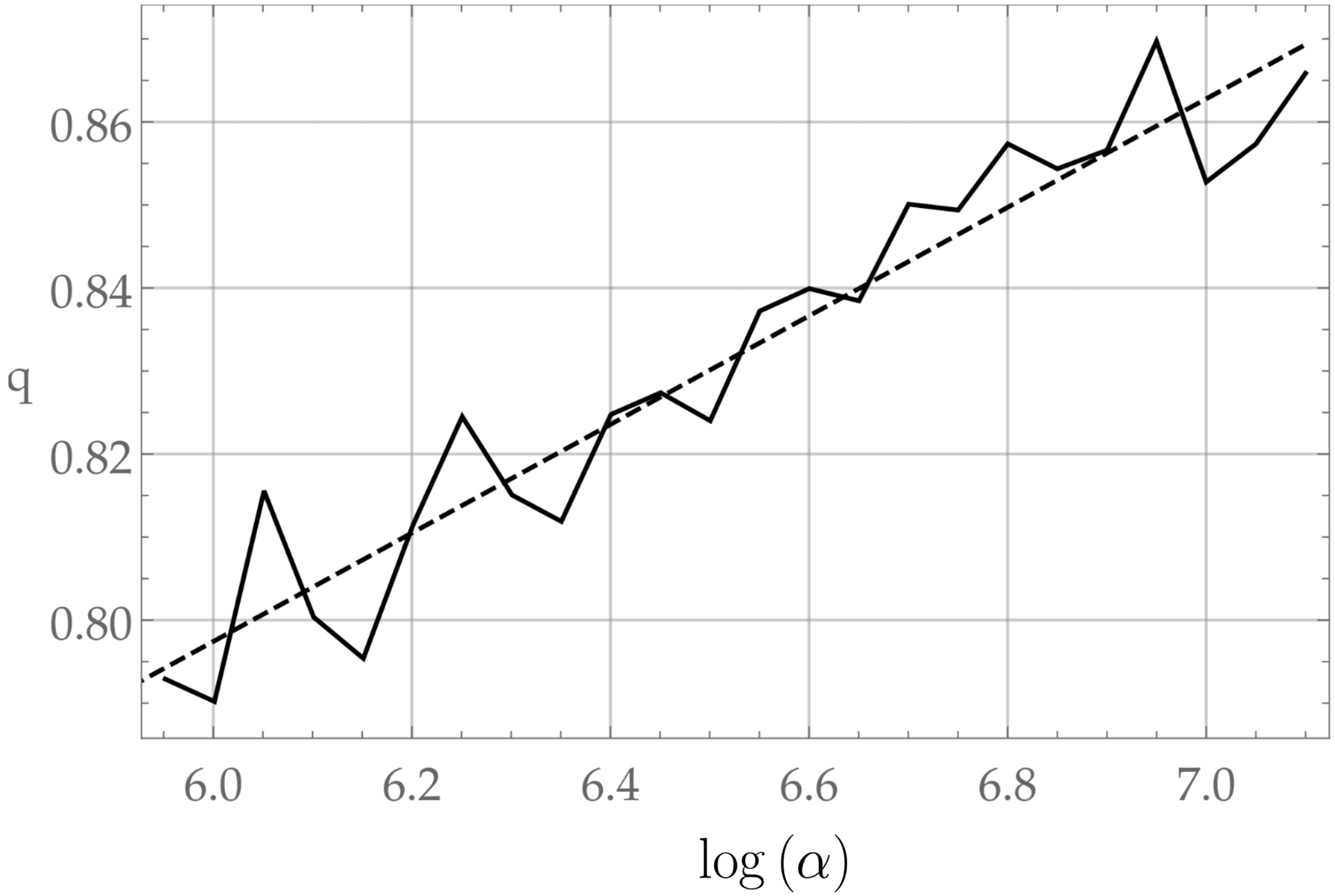
Fitting the power law



Slope of the instantaneous spectrum

Spectrum

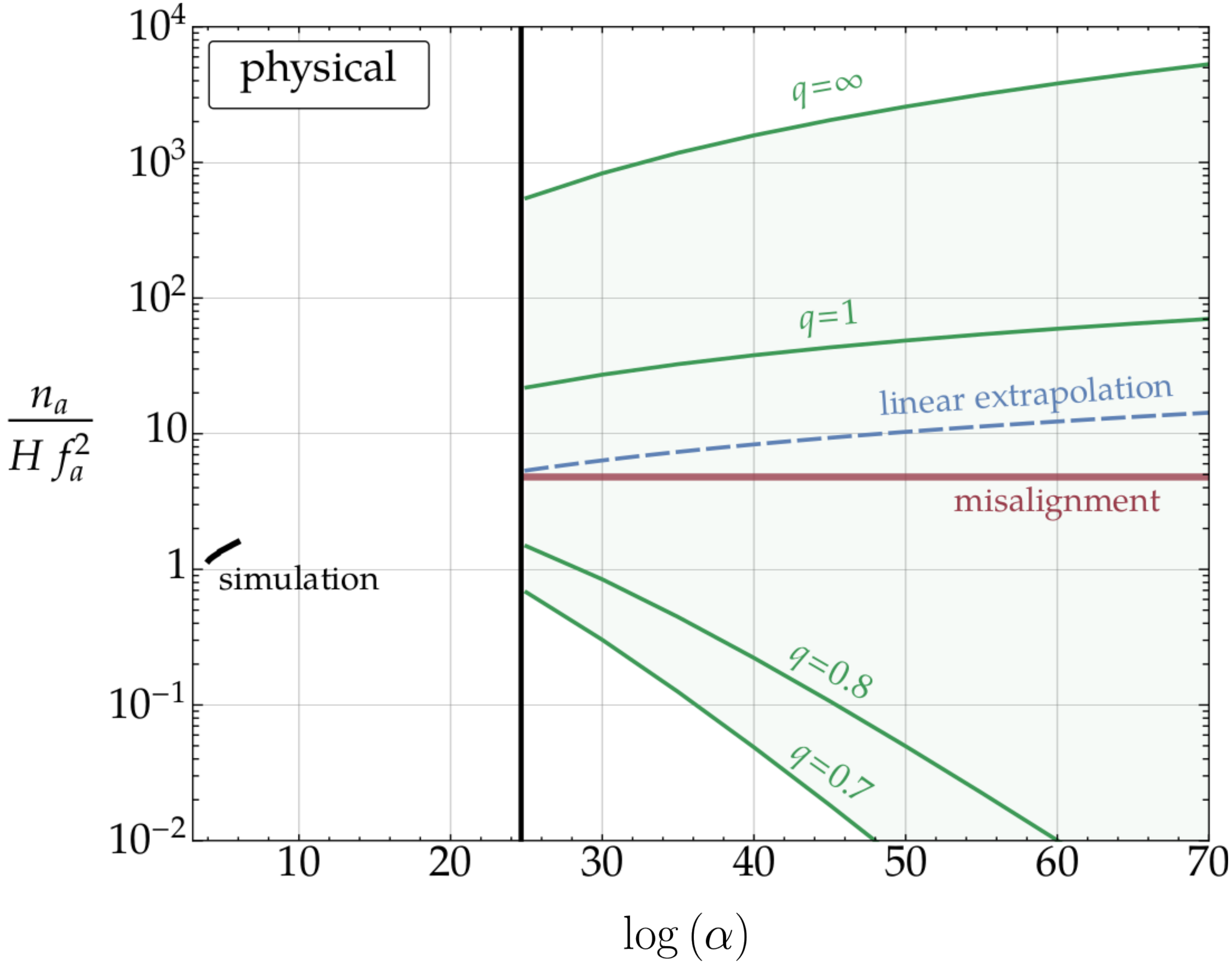
Best fit over the constant slope region:



Also seems to have a log dependence

Axion number density

Extrapolate all the way to large logs



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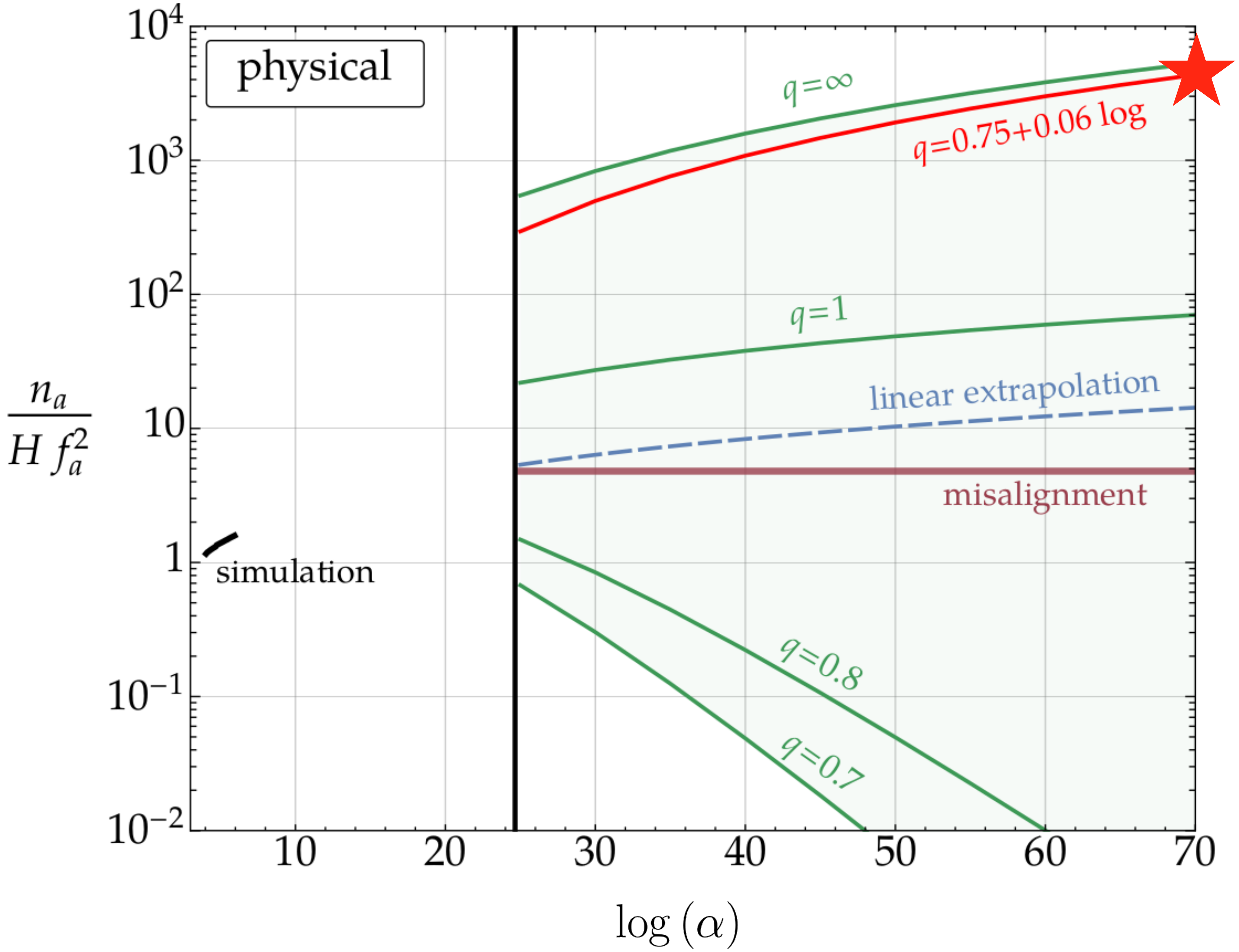
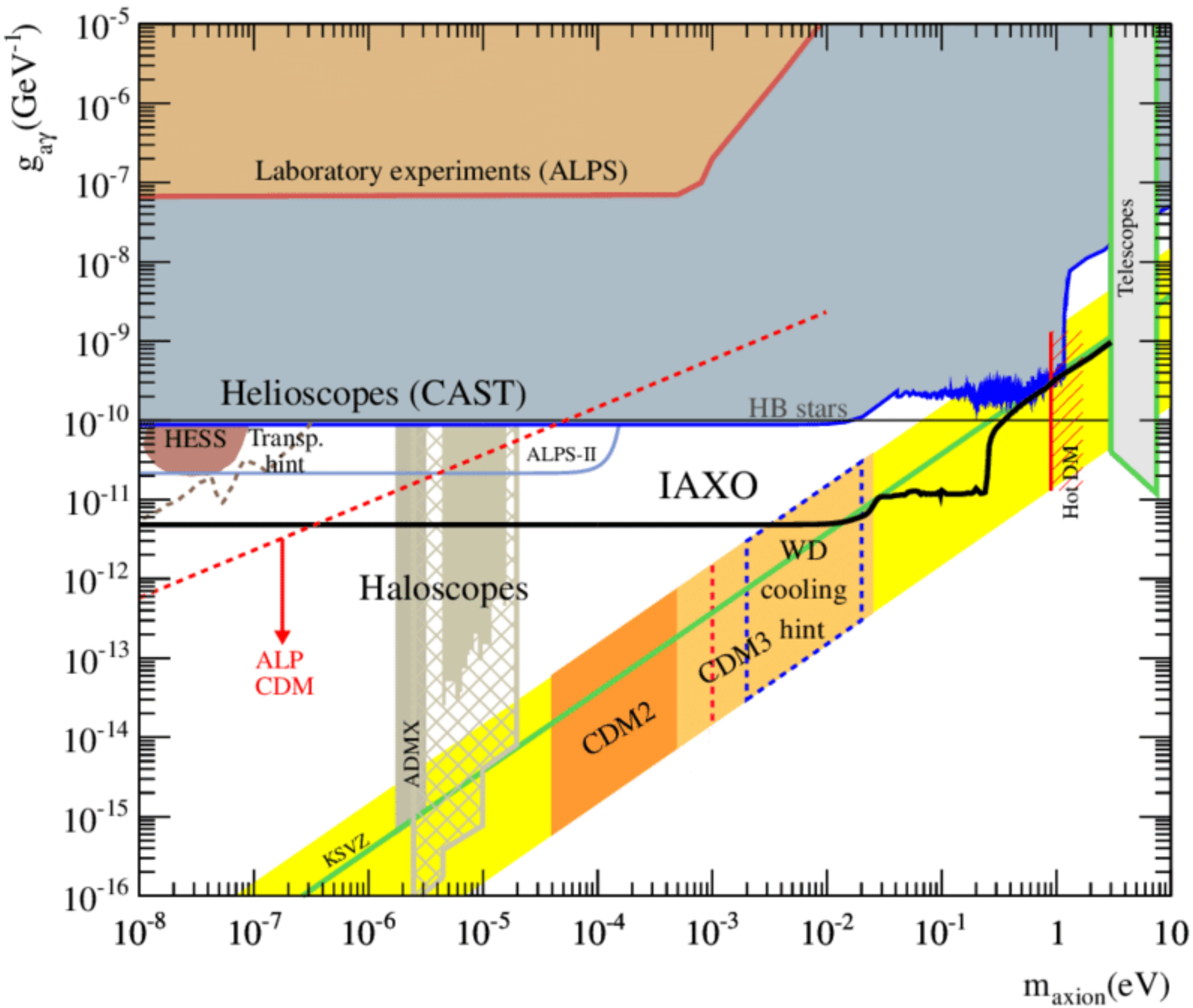


Impact on the relic abundance



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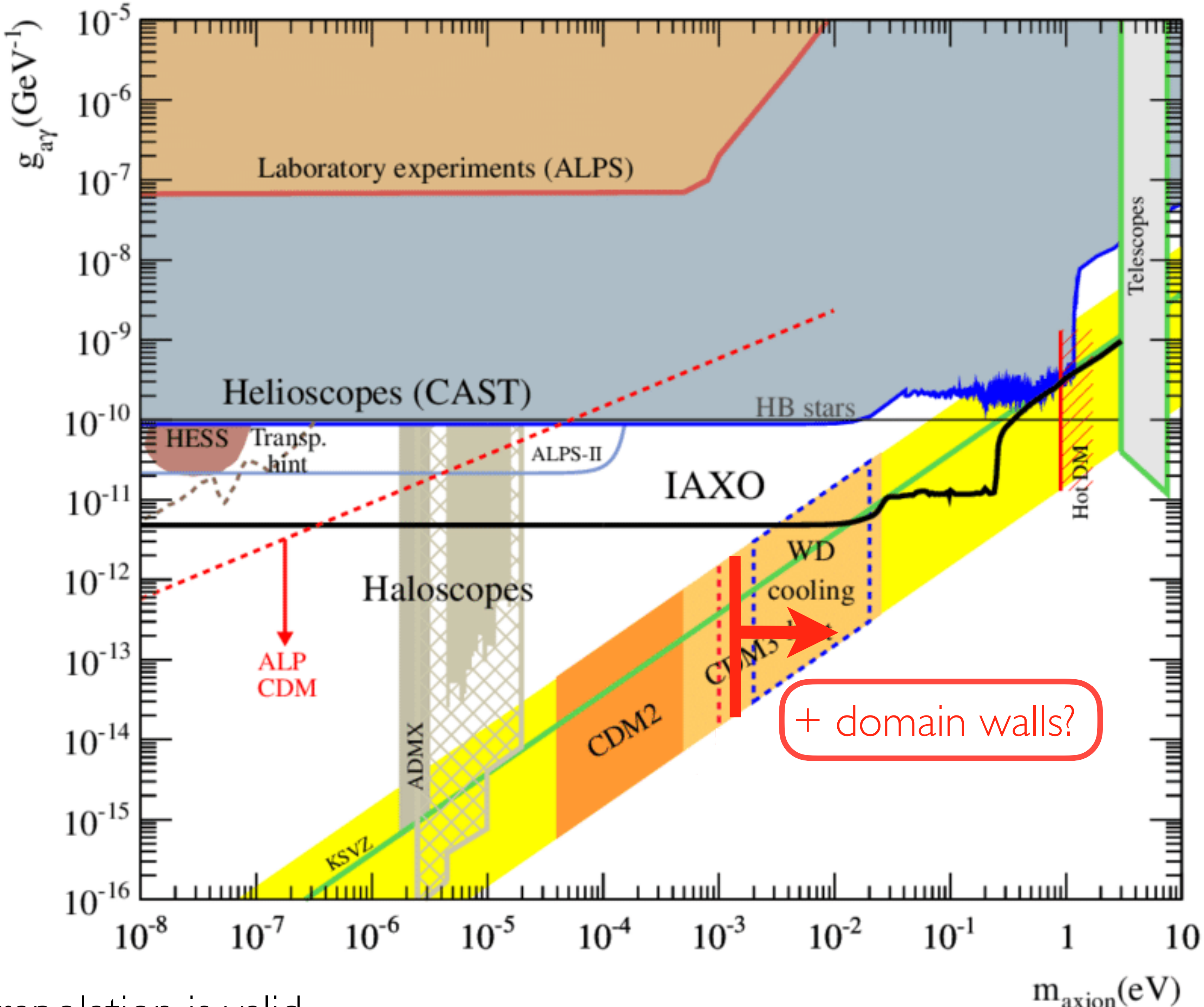

Assuming extrapolation is valid

Conclusions

- QCD axion particularly well motivated
- PQ symmetry breaks after inflation in large classes of models
- In principle leads unique prediction for the axion dark matter mass
- Simulations are far from the physically relevant regime
- Essential to extrapolate, and be aware of the uncertainties

Thanks