Connecting theory with searches for new light particles

Ed Hardy

Based on work with:

Robert Lasenby [JHEP 1702 (2017) 033]

and Marco Gorghetto & Giovanni Villadoro [JHEP 1807 (2018) 151, ongoing]

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Why new light particles?

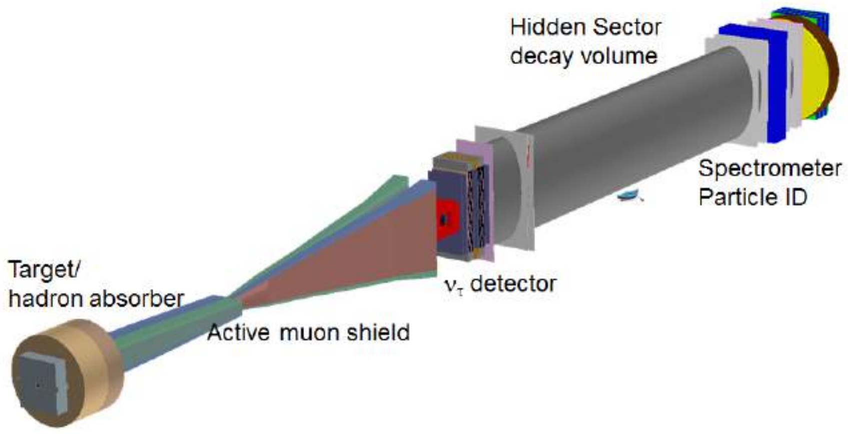
Motivated from UV and IR perspectives

- Solve problems with the SM (QCD axion)
- Dark Matter candidates or portals to dark sectors/ mediate DM self-interactions
- Plausible in typical string compactifications
- Various almost interesting experimental anomalies

Less explored than other possibilities, experimental progress likely

What can theory contribute?

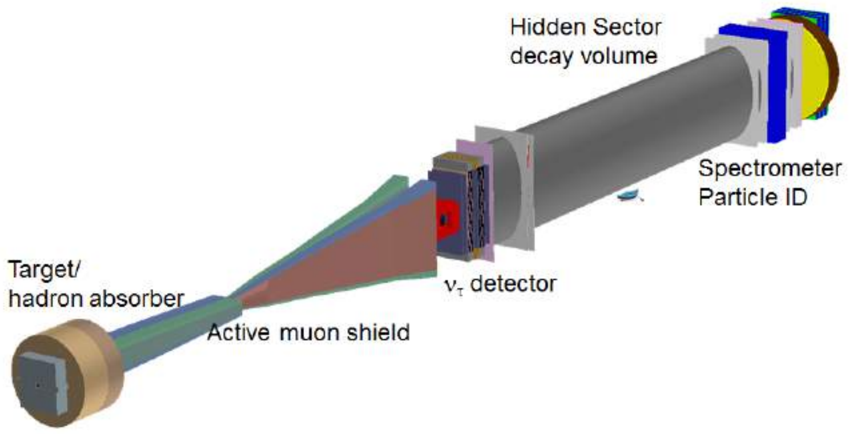
Many interesting experiments:



No sharp prediction for where to look

What can theory contribute?

Many interesting experiments:



No sharp prediction for where to look

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

This talk

Cooling Bounds

- Strong constraints on large classes of new light particles

Pinning down the QCD axion

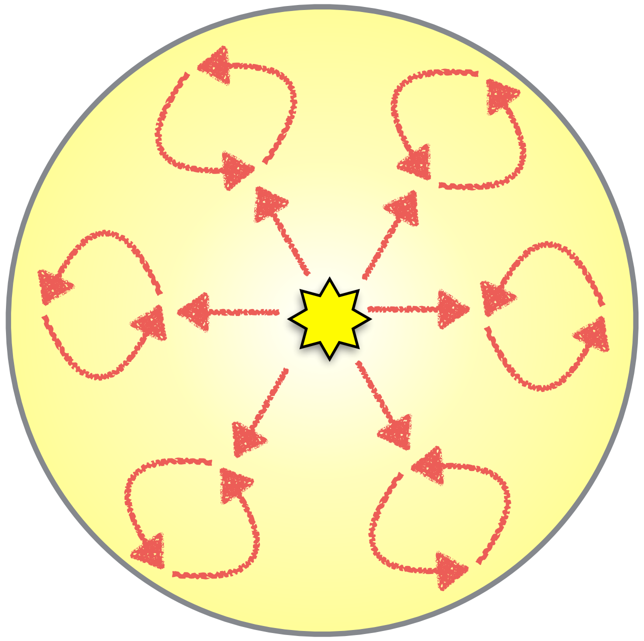
- A particularly well motivated target

Part I: Cooling bounds

A new light particle can be produced in the hot cores of stars

Leads to anomalous energy transport, often called "cooling"

Especially systems that have inefficient SM energy-loss, e.g. surface photon emission



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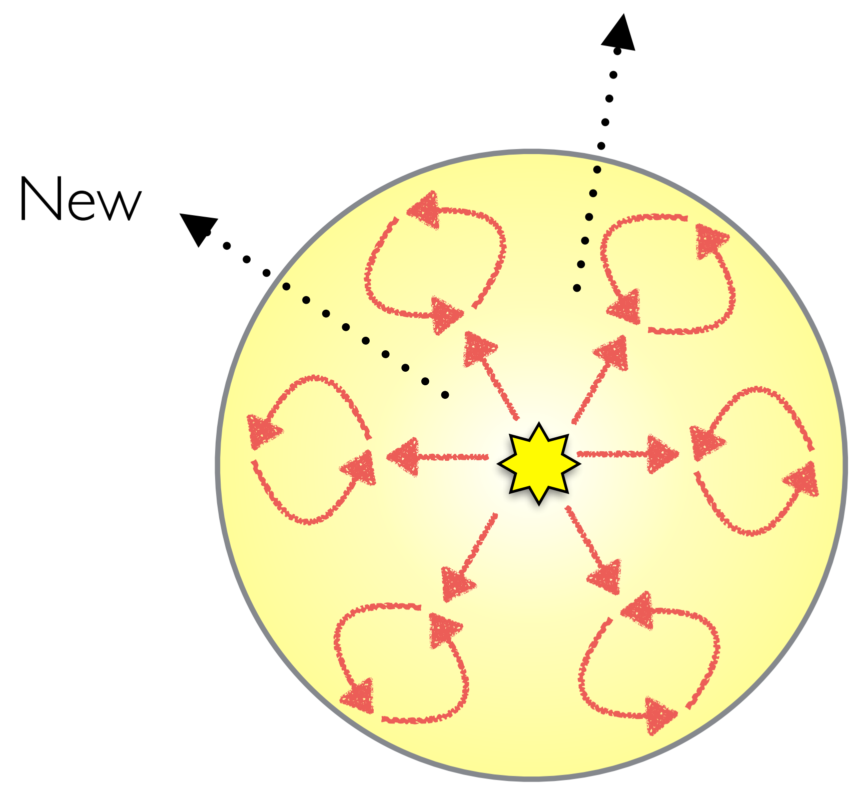
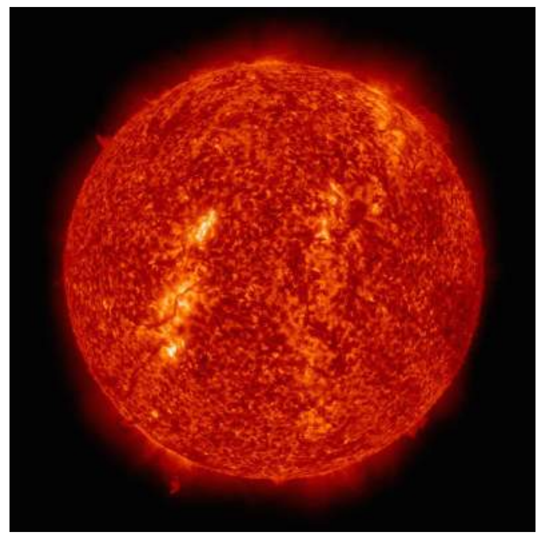


BSM volume emission

Systems to observe

	Sun	Red Giant	Horizontal Branch	Supernovae
$T_{\rm core}$	keV	10 keV	10 keV	50 MeV
$\epsilon_{\rm max}$	$0.2\ {\rm erg\ g^{-1}\ s^{-1}}$	$10\ {\rm erg\ g^{-1}\ s^{-1}}$	$10\ {\rm erg\ g^{-1}\ s^{-1}}$	$10^{19}\ {\rm erg\ g^{-1}\ s^{-1}}$

Need for plasma effects

Mass /coupling → Production rate → Energy loss → Constraints

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- Matrix elements from vacuum calculation
- Thermal abundances for SM initial and final states

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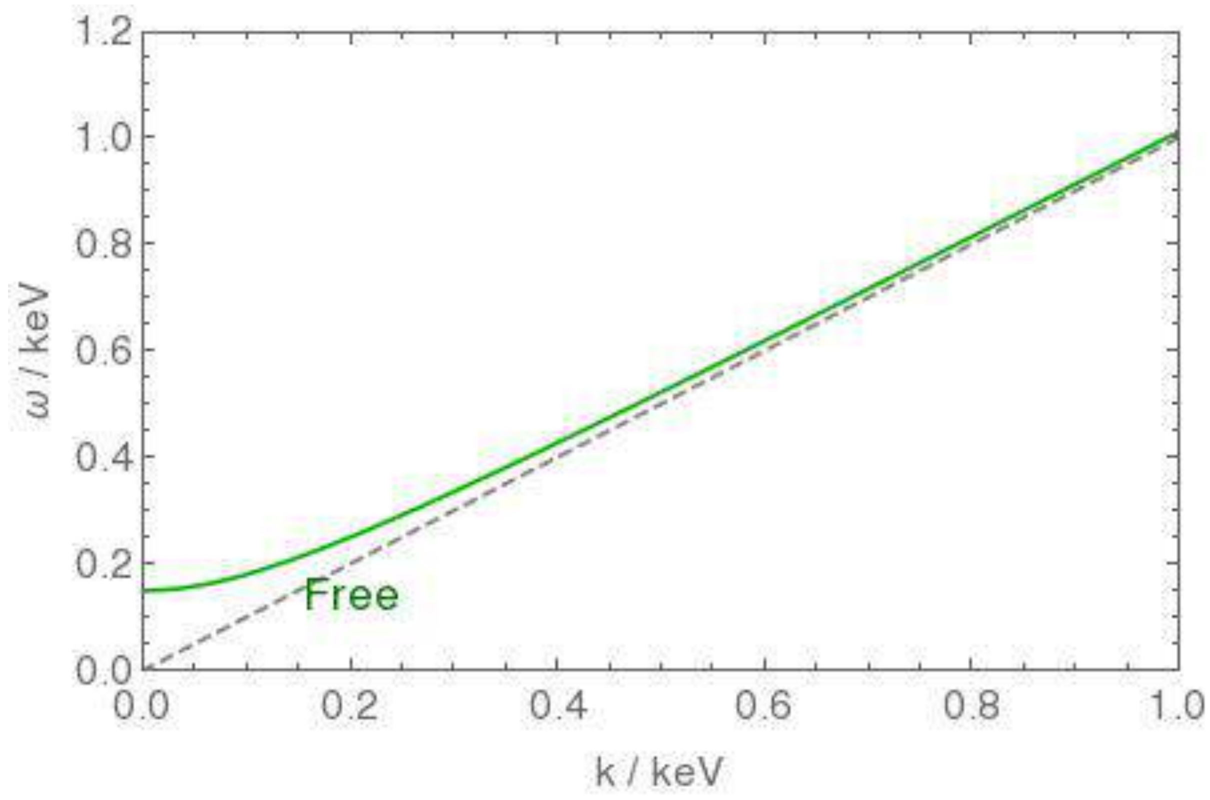

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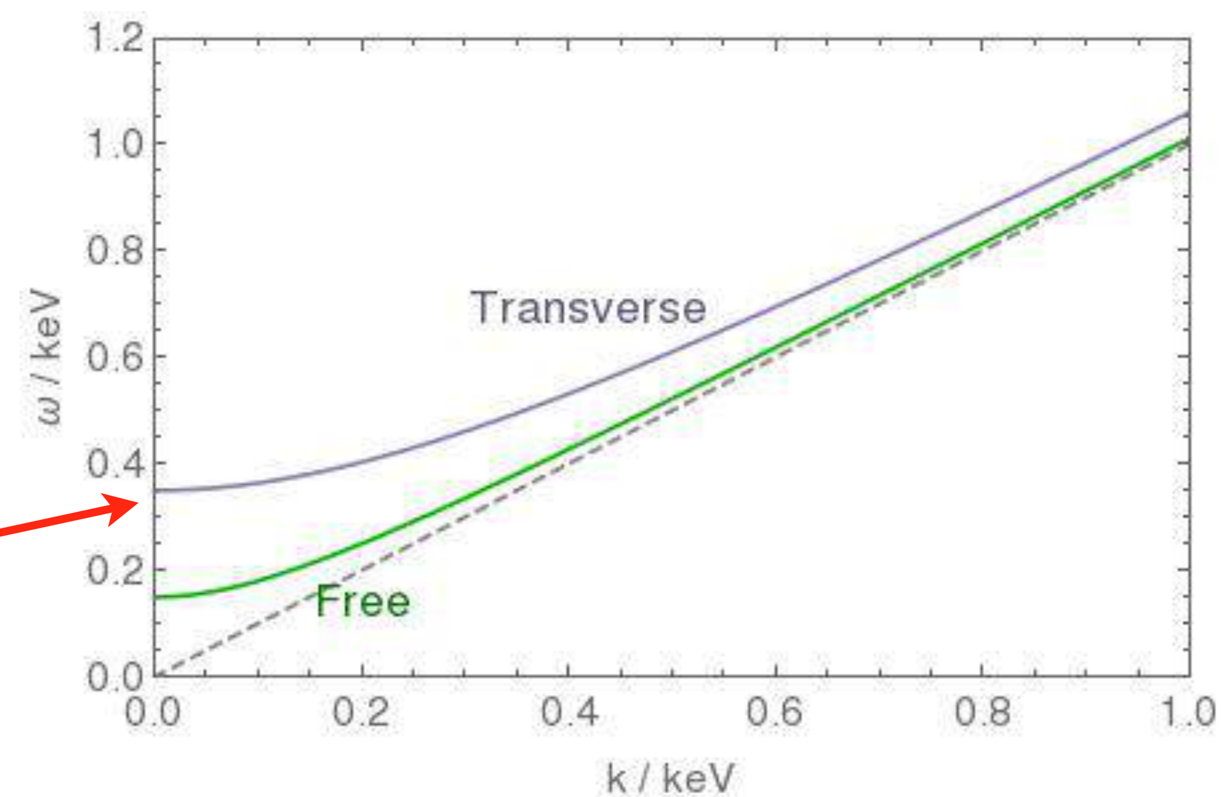

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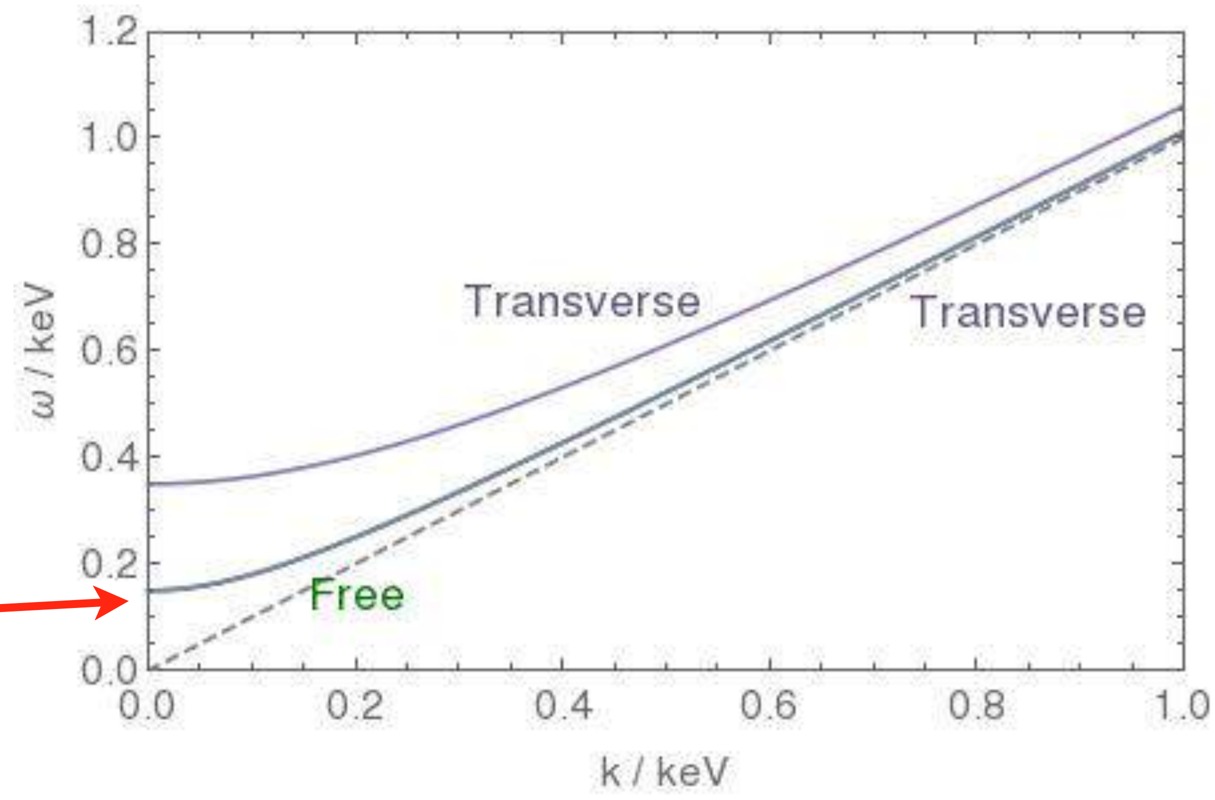

Plasma frequency at a different location

Need for plasma effects

Mass /coupling → Production rate → Energy loss → Constraints

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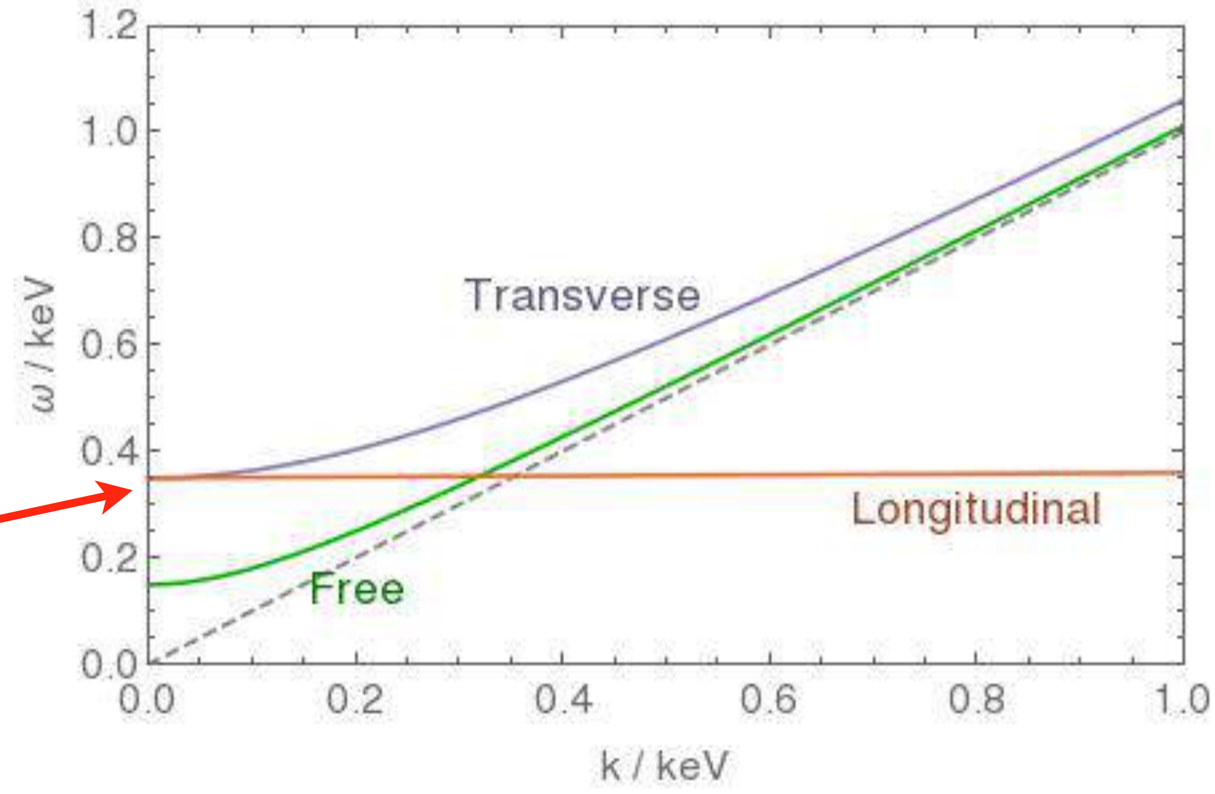
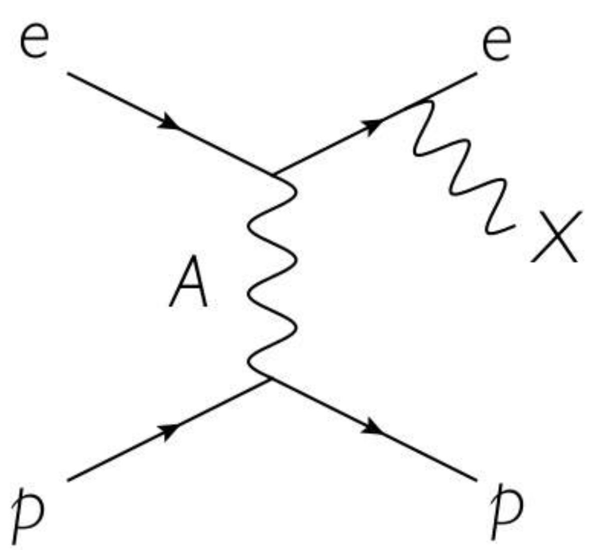
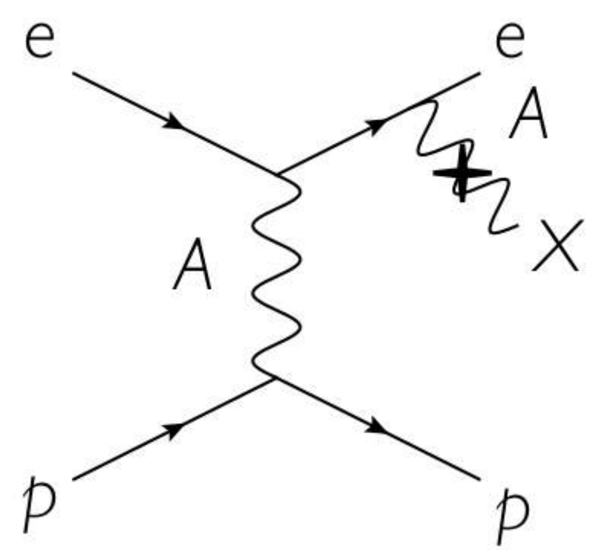
Plasma frequency at a location



Production rate

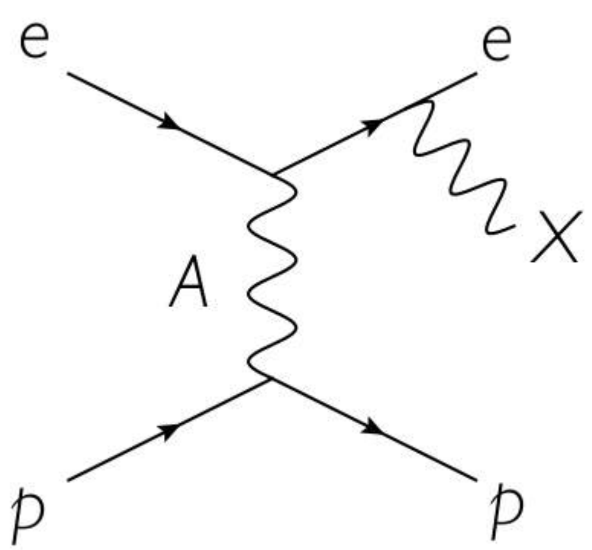




"Naive"
production rate

If X not a propagation eigenstate, have mixing contributions

Production rate



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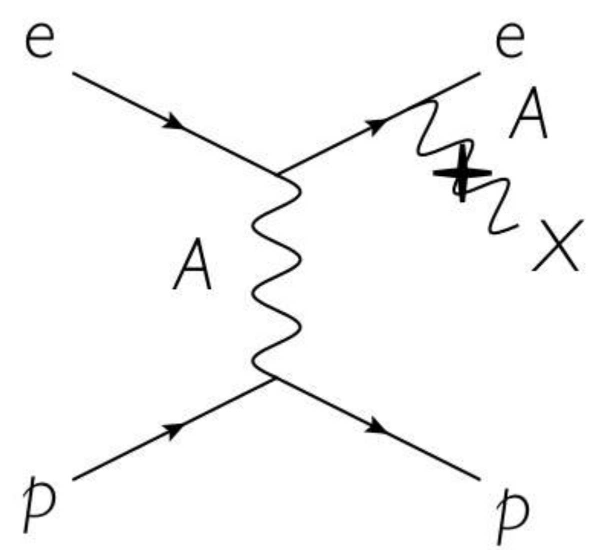

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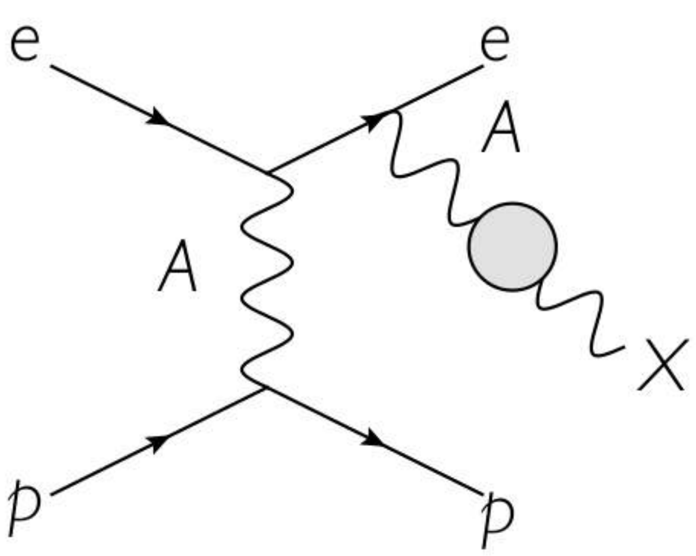

Propagation eigenstates in medium not the same as those in vacuum

Production rate

Propagating states are the null eigenvectors of:

$$\begin{pmatrix} \omega_c^2 - k^2 - \Pi^{AA} & -\Pi^{AX} \\ -\Pi^{XA} & \omega_c^2 - k^2 - m^2 - \Pi^{XX} \end{pmatrix}$$

corresponding frequencies

$$\omega_c^2 = k^2 + m^2 + \left(\Pi^{XX} - \frac{(\Pi^{AX})^2}{\Pi^{AA} - m^2} \right)$$

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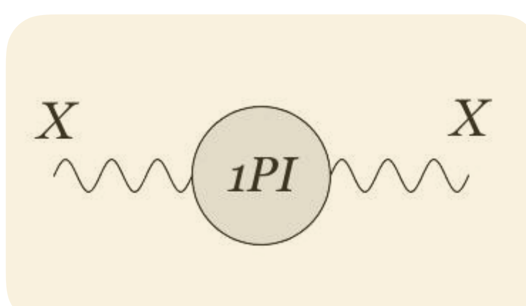
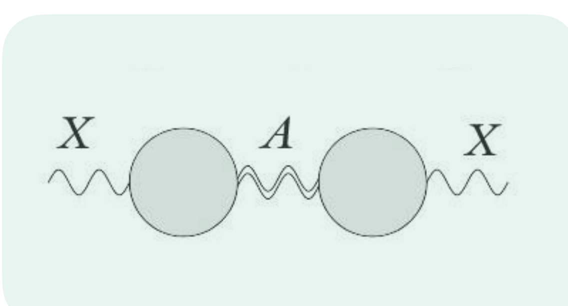
Production rate ~ Imaginary part of thermal field theory self energy

$$\frac{dN_{\rm prod}}{dV\,dt} = \int \frac{d^3k}{(2\pi)^3} \Gamma_{\rm prod} = -\int \frac{d^3k}{(2\pi)^3} \frac{f_B(\omega)}{\omega} \,\mathrm{Im} \left(\Pi^{XX} - \frac{(\Pi^{AX})^2}{\Pi^{AA} - m^2} \right)$$

1PI diagrams





E.g. Dark photon

Extra U(1): $SU(3) \times SU(2) \times U(1) \times U(1)'$

$$\boxed{\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{1}{4}F'^2 + \frac{1}{2}m^2X^2 + J_{\rm EM}\left(A + \epsilon X\right)}$$

(same as $-\frac{1}{2}\epsilon F F'$)

previously done correctly for stars but not SN
[An, Pospelov, Pradler]

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Simple relation between the self-energies $\Pi^{XX} = \epsilon^2 \Pi^{AA},\ \Pi^{AX} = \epsilon \Pi^{AA}$

$$-\,\mathrm{Im}(\omega_c^2) = \mathrm{Im}\left(\Pi^{XX} - \frac{(\Pi^{AX})^2}{\Pi^{AA} - m^2}\right)$$

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$$\Pi^{AA} \equiv \Pi$$

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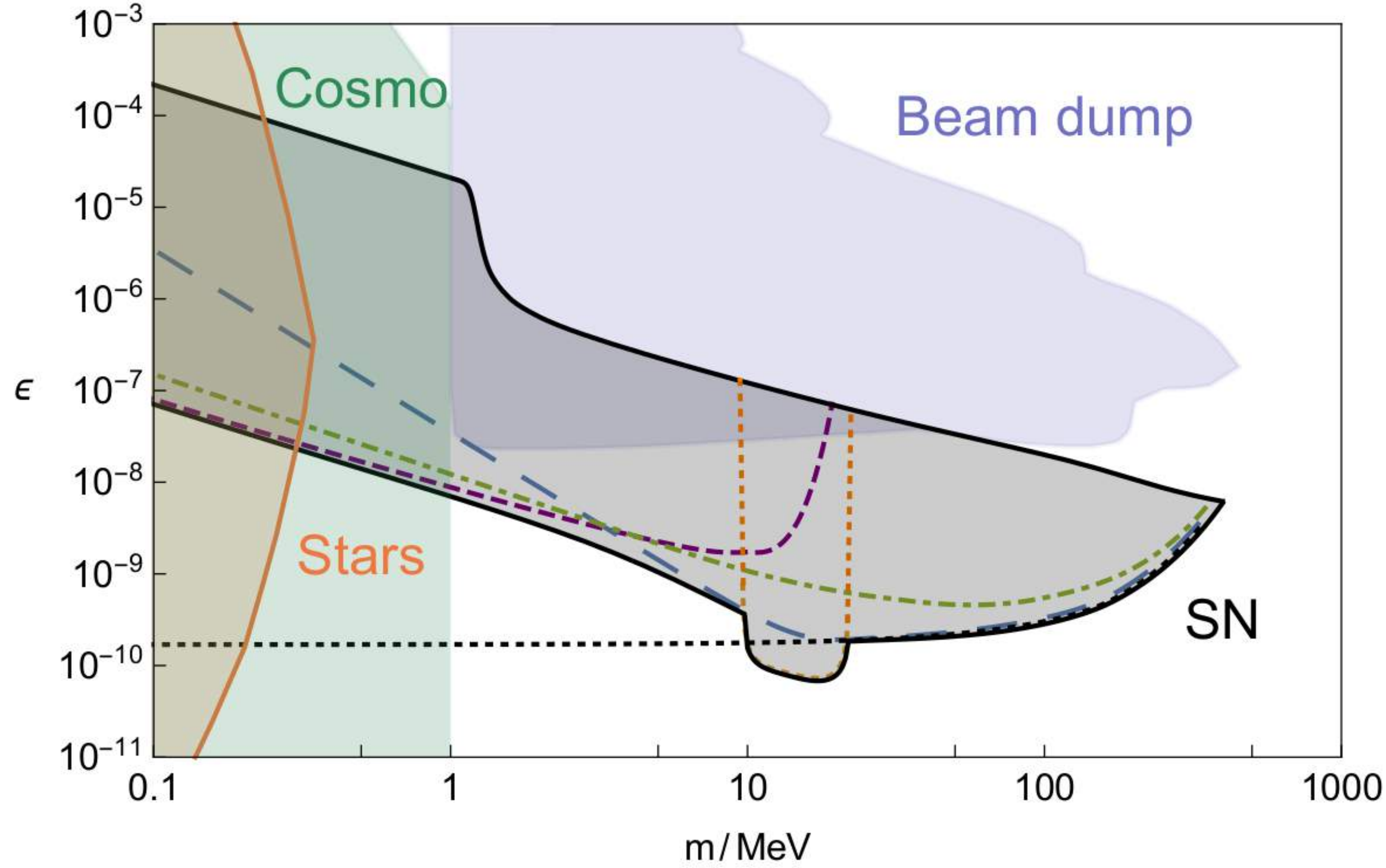
$$\boxed{= \epsilon^2 \frac{m^4(-\Pi_i)}{\Pi_i^2 + (\Pi_r - m^2)^2} + \mathcal{O}(\epsilon^4)}$$

$$\Pi^{AA} \equiv \Pi = \Pi_r + i\Pi_i$$

Dark photon from supernova



Higgs portal scalar

$$V \supset m^2\phi^2 + \frac{1}{4}\lambda_{h\phi}\phi^2 H^\dagger H$$

couplings to fermions $\sum_f (m_f/v)\sin\theta\phi\bar{f}f$

$$\sin\theta \sim \lambda_{h\phi}\frac{\langle\phi\rangle}{\langle H\rangle}$$

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$\Rightarrow$ couplings to fermions $\sum_f \underbrace{(m_f/v)\sin\theta}_{\equiv g}\phi\bar{f}f$ $\quad \sin\theta \sim \lambda_{h\phi}\frac{\langle\phi\rangle}{\langle H\rangle}$

No scalar states in low energy SM, so no mixing in vacuum

But plasma rest frame breaks Lorentz: mixing with longitudinal photon mode

Allows resonant production when $m \lesssim$ plasma frequency

Self energies

Non-relativistic fermion: $\Pi^{\phi A}_{\mu} \simeq \frac{g}{eQ_f}\Pi^{AA}_{0\mu}$

$$\omega\,\Gamma_{\rm prod} = -\Pi_i^{\phi\phi} - \frac{\Pi_i^{AA}((\Pi_r^{A\phi})^2 - (\Pi_i^{A\phi})^2) - 2(\Pi_r^{AA} - m^2)\Pi_r^{A\phi}\Pi_i^{A\phi}}{(\Pi_i^{AA})^2 + (\Pi_r^{AA} - m^2)^2}$$

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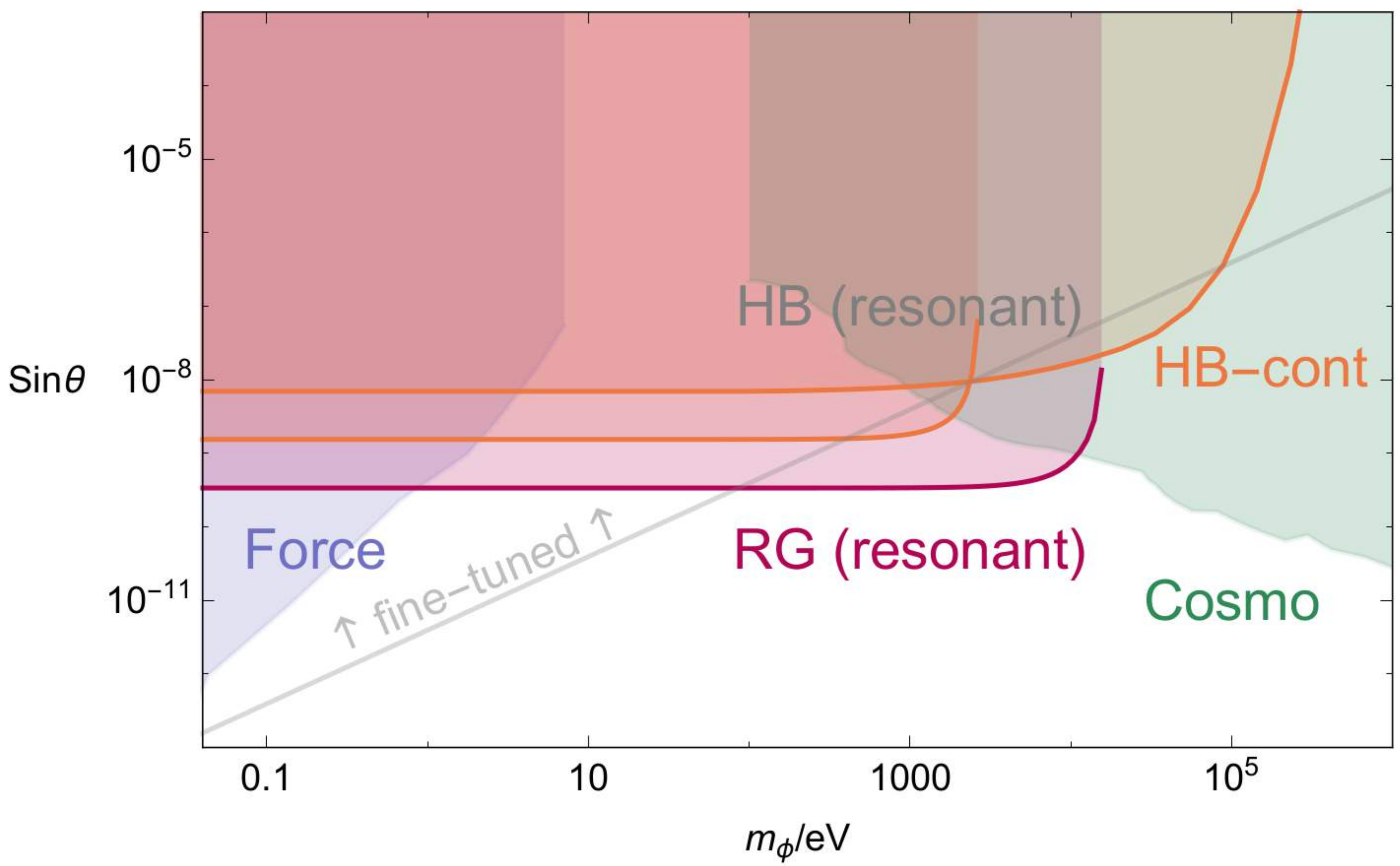
$$\Gamma_{\rm prod} \simeq \frac{g^2}{e^2}k^2\omega\frac{\omega\sigma_L}{(\omega\sigma_L)^2 + (\omega^2 - \omega_p^2)^2}$$

σ_L ~ production rate of long. photon

$$\frac{Q_{\rm res}}{Q_{\rm Comp}} \simeq \frac{\pi^2}{2}\frac{n_e}{T^3} \quad , \quad \frac{Q_{\rm res}}{Q_{\rm brem}} \simeq \frac{4\pi}{3\alpha Z_i}\sqrt{\frac{T}{m_e}}$$

Higgs portal scalar

$$g_{\phi\bar{e}e}/g_{\phi\bar{N}N} \simeq 2 \times 10^{-3} > m_e/m_N \simeq 5 \times 10^{-4}$$



Future work

- Past: cases where we knew there would be a parametric effect
- Future: extend analysis to a wider range of particles
- Concentrate on masses and couplings that are relevant to proposed experiments, reliable limits
- Also particularly motivated candidates for new physics, e.g. explanations of muon g-2

Possible effects in cosmology?

Part II: QCD axion

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

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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!

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 axion

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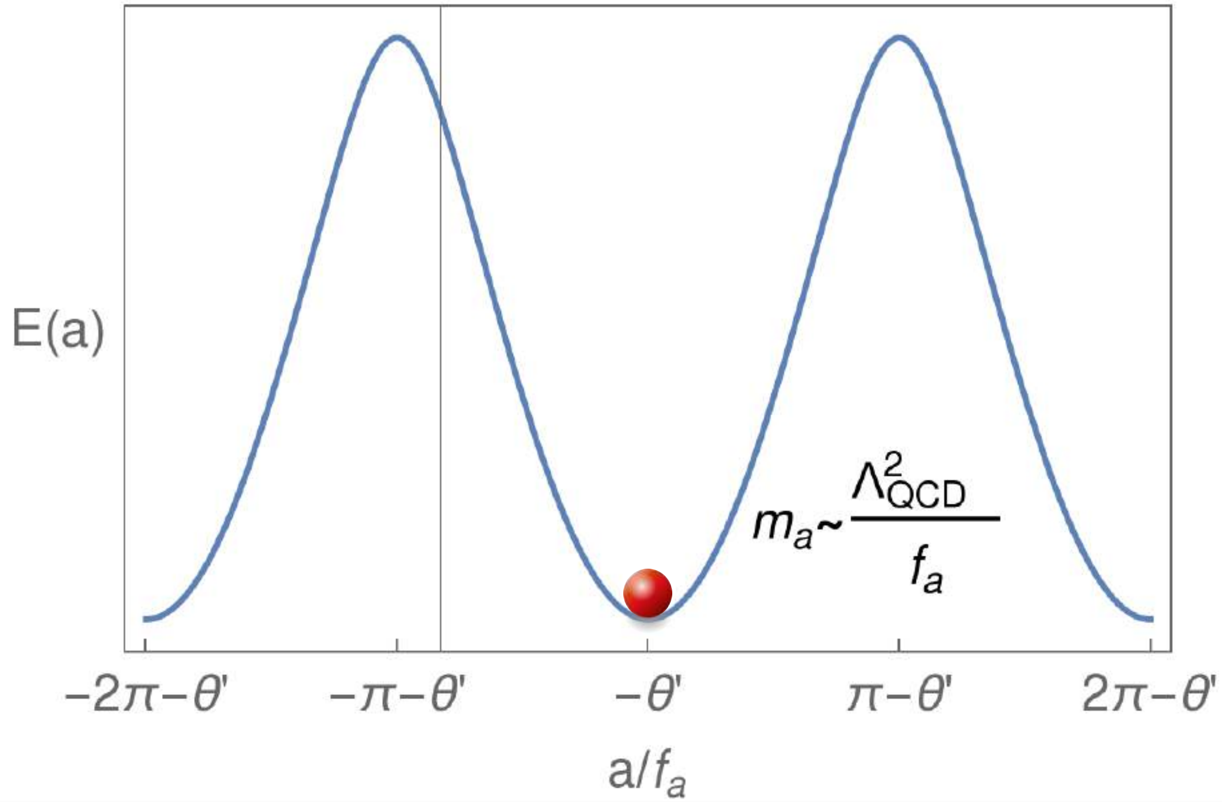
QCD runs into strong coupling

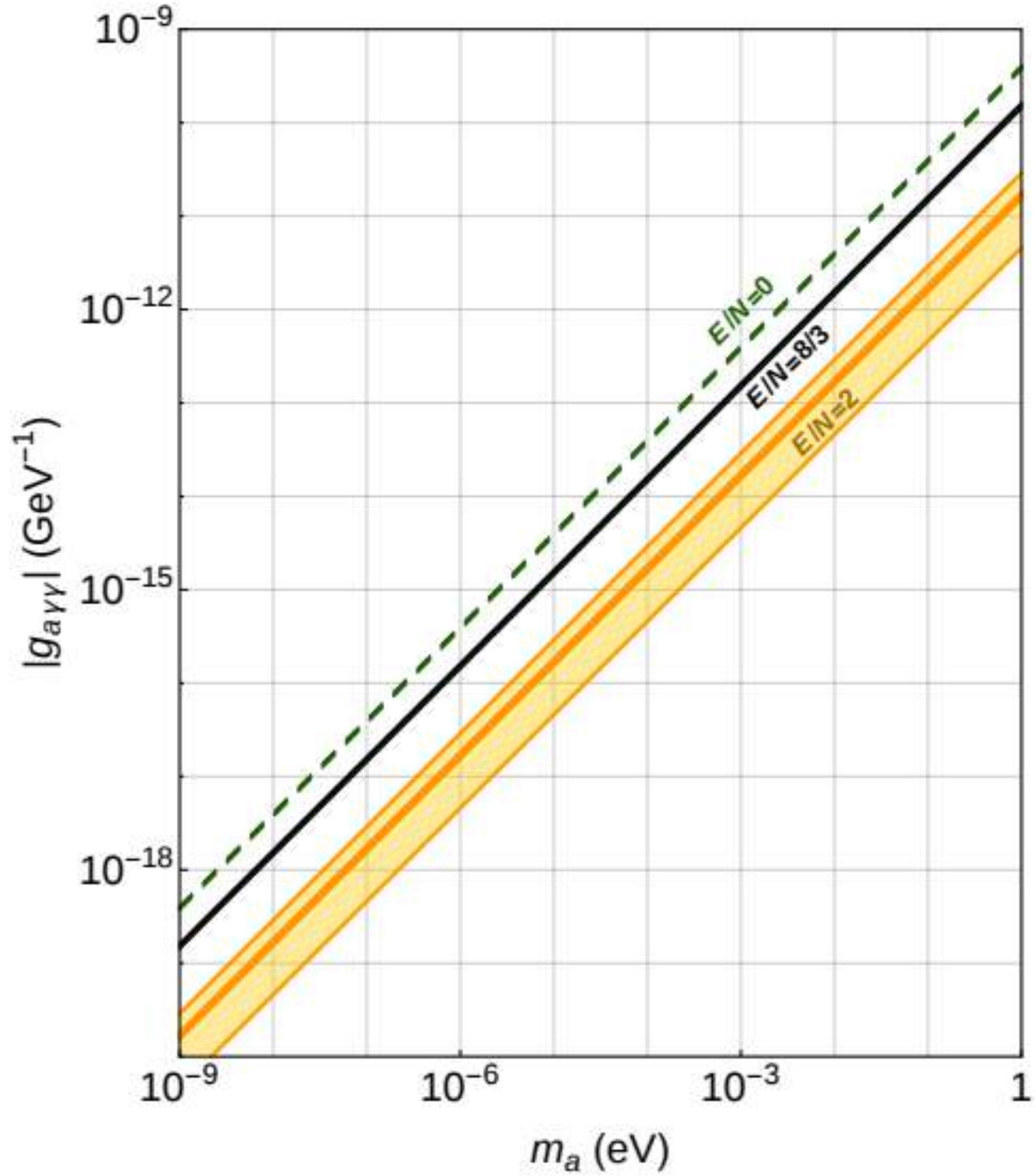
→ axion potential



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

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

Properties at zero temperature



$$g_{a\gamma\gamma} = \left[0.203(3)\frac{E}{N} - 0.39(1)\right] \frac{m_a}{\mathrm{GeV}^2}$$

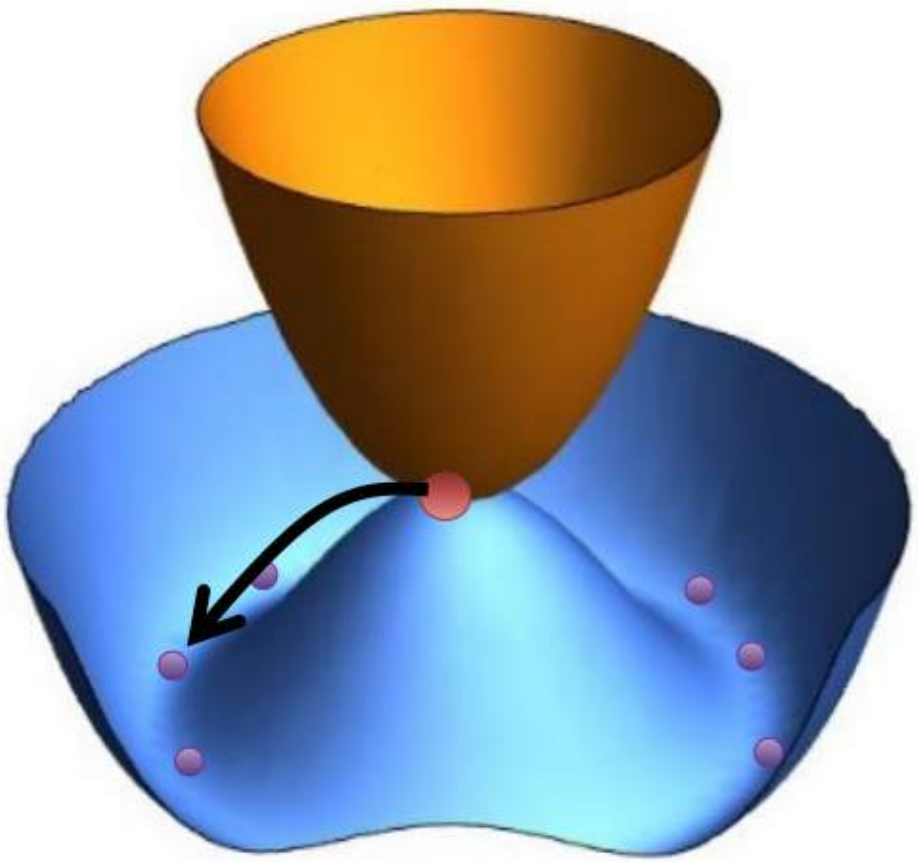
[Grilli di Cortona, EH, Vega, Villadoro, JHEP 1601 (2016) 034]

Dark matter

Extra bonus feature: a QCD axion can automatically be the dark matter

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

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

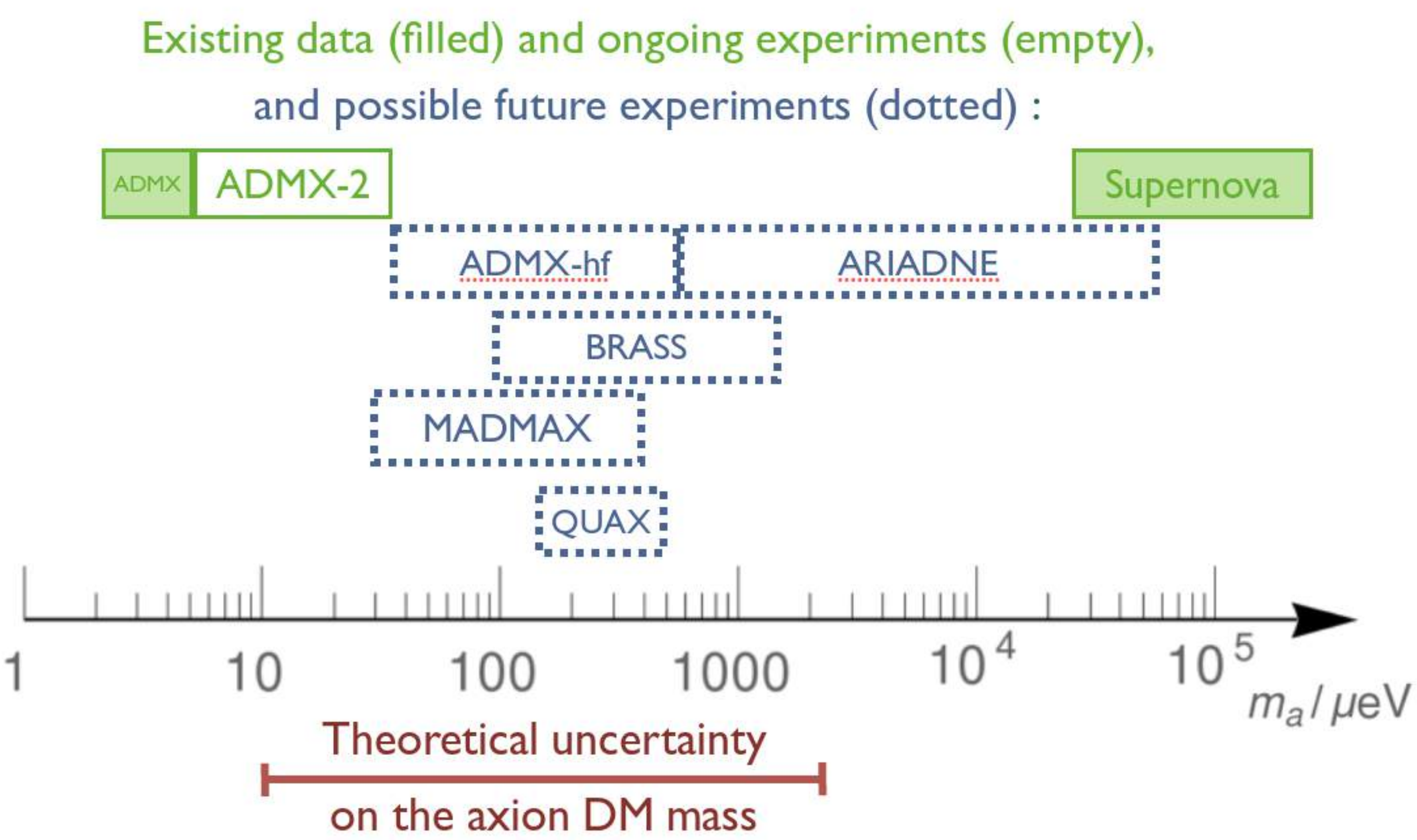


$a(t_0) = \mathrm{random}$

U(1) breaking after inflation

In principle extremely predictive

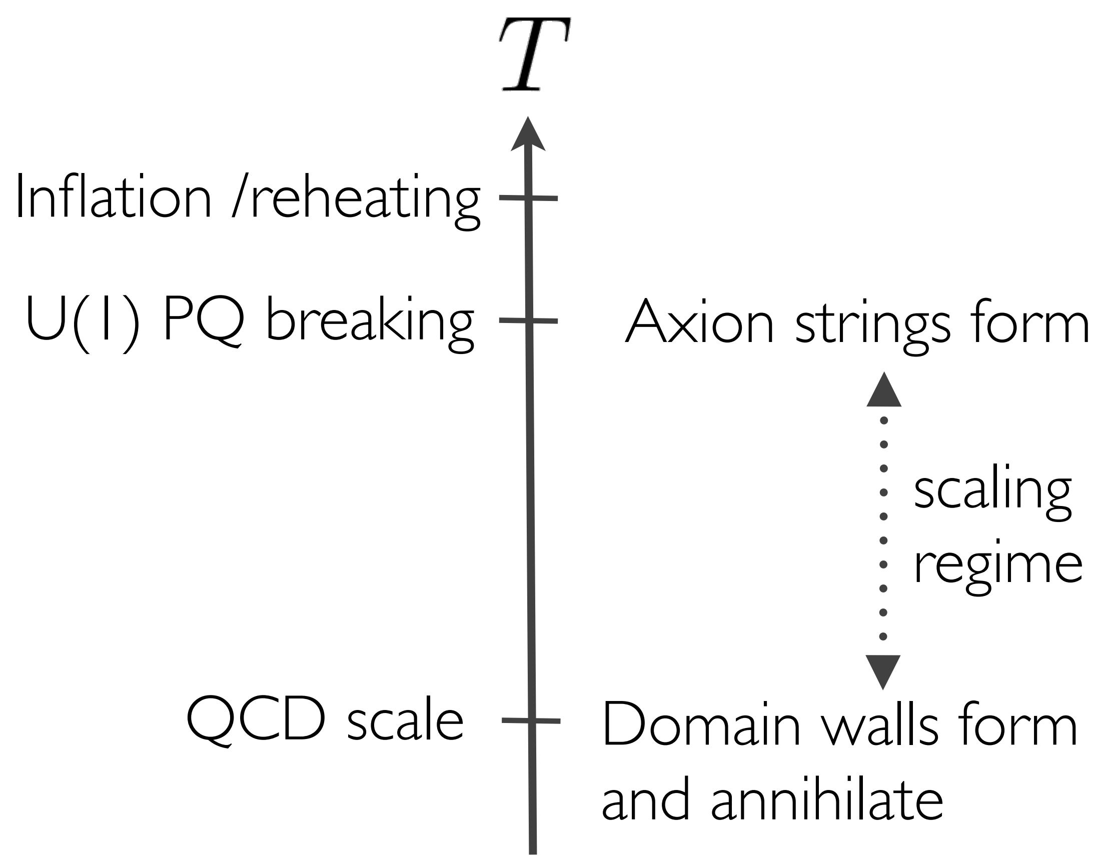
unique DM axion mass

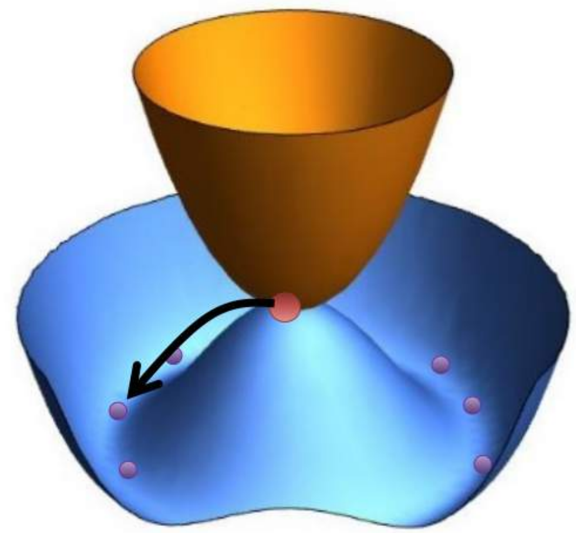


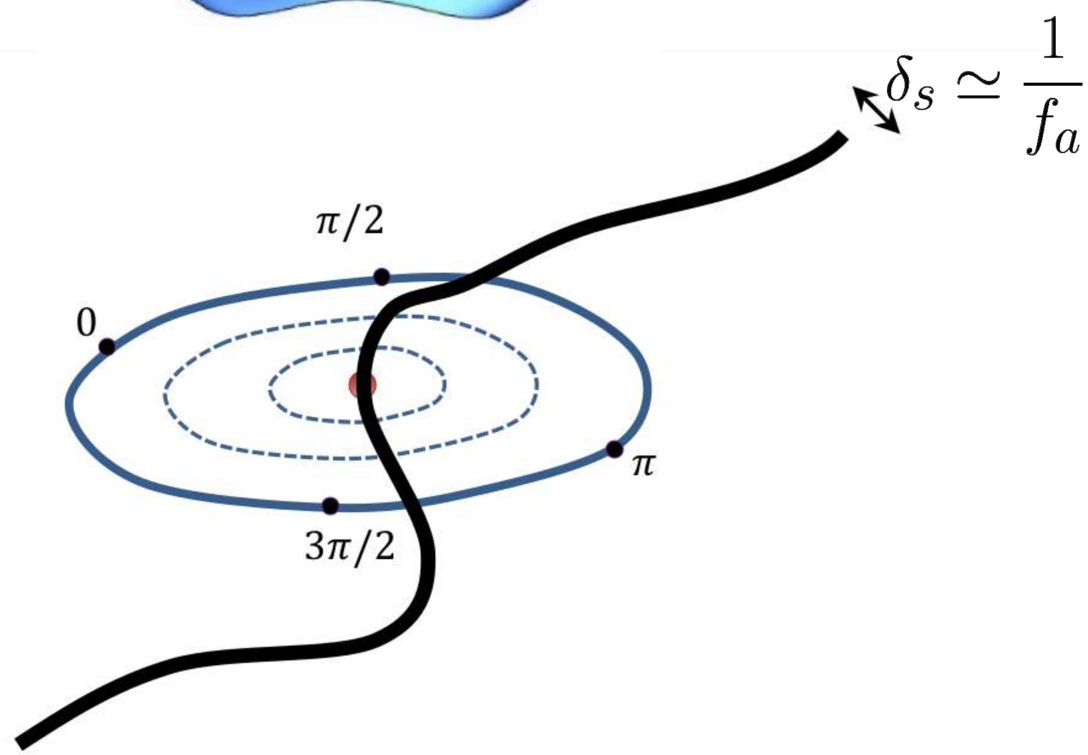
Reliable prediction: interpret ongoing experiments, design future experiments

Precise agreement with an experimental discovery → minimum inflation scale

Strings and domain walls







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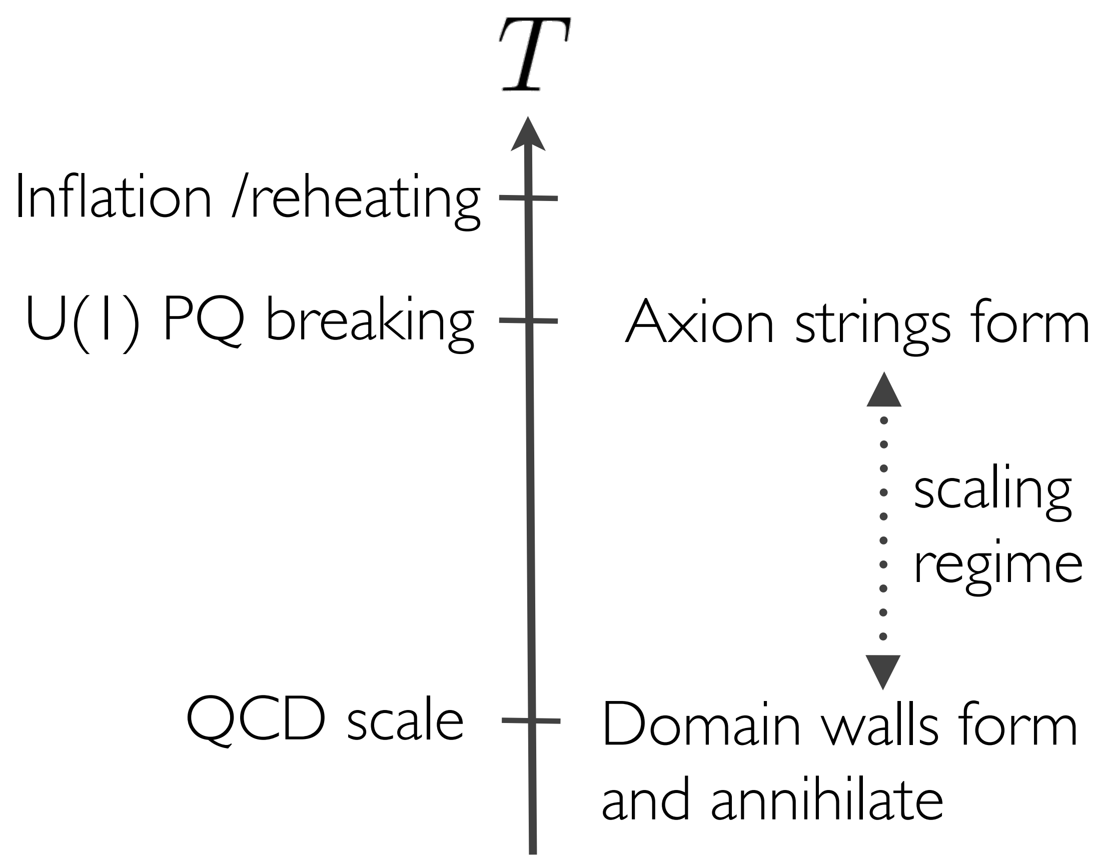
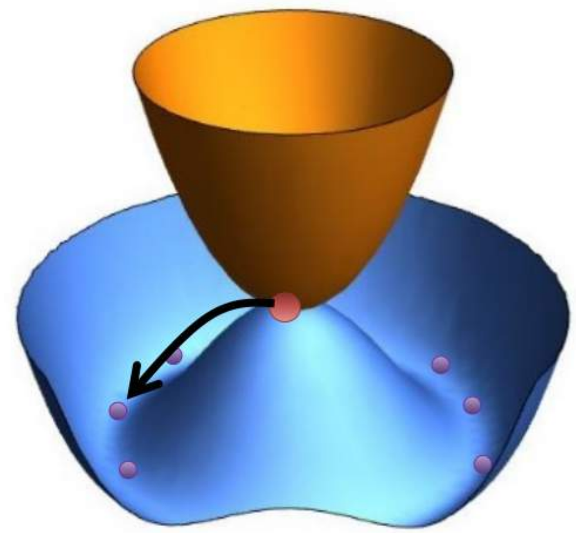
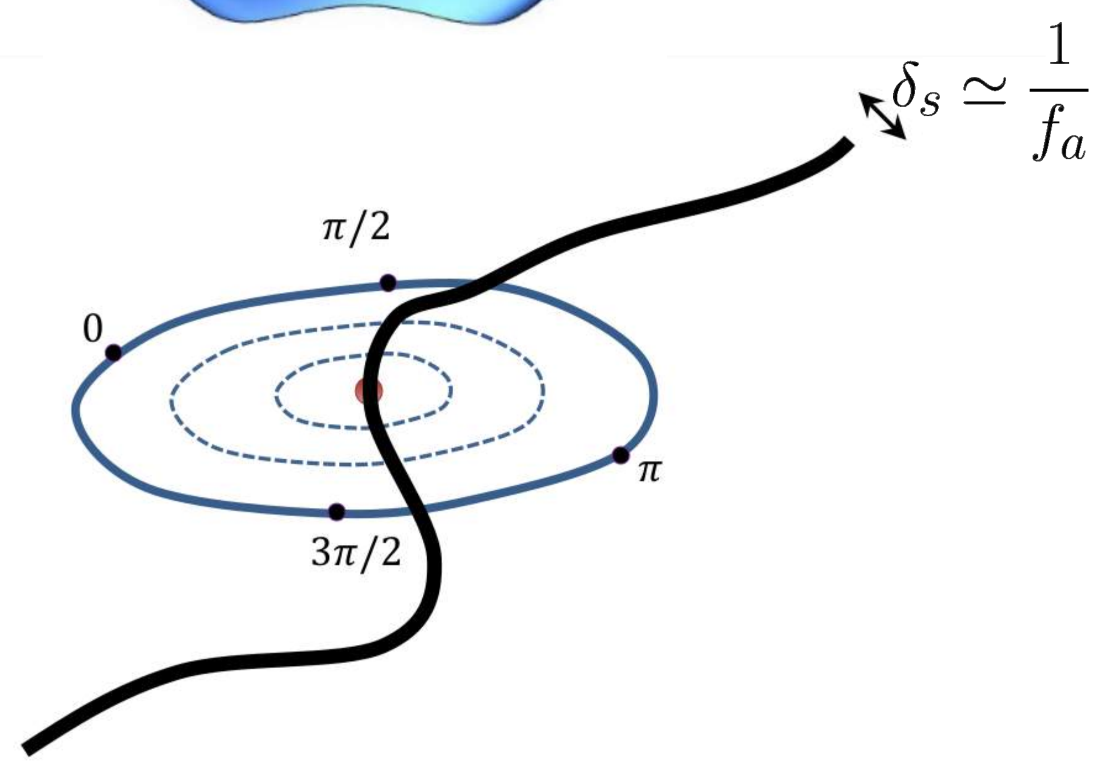






Significant proportion of DM axions produced by strings and domain walls

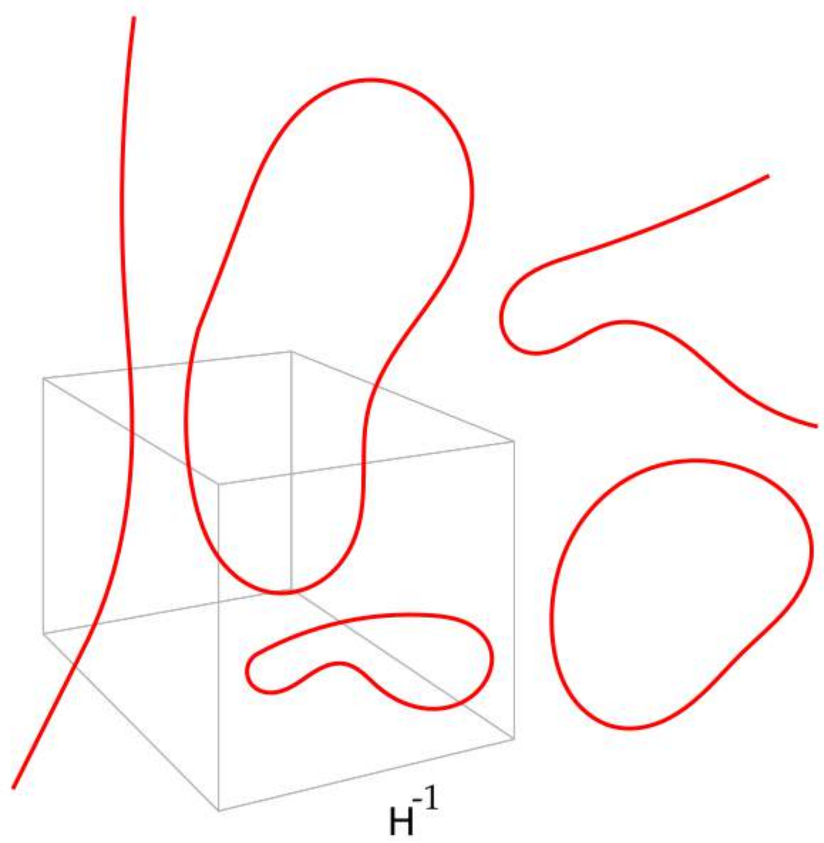
Axion emission during scaling

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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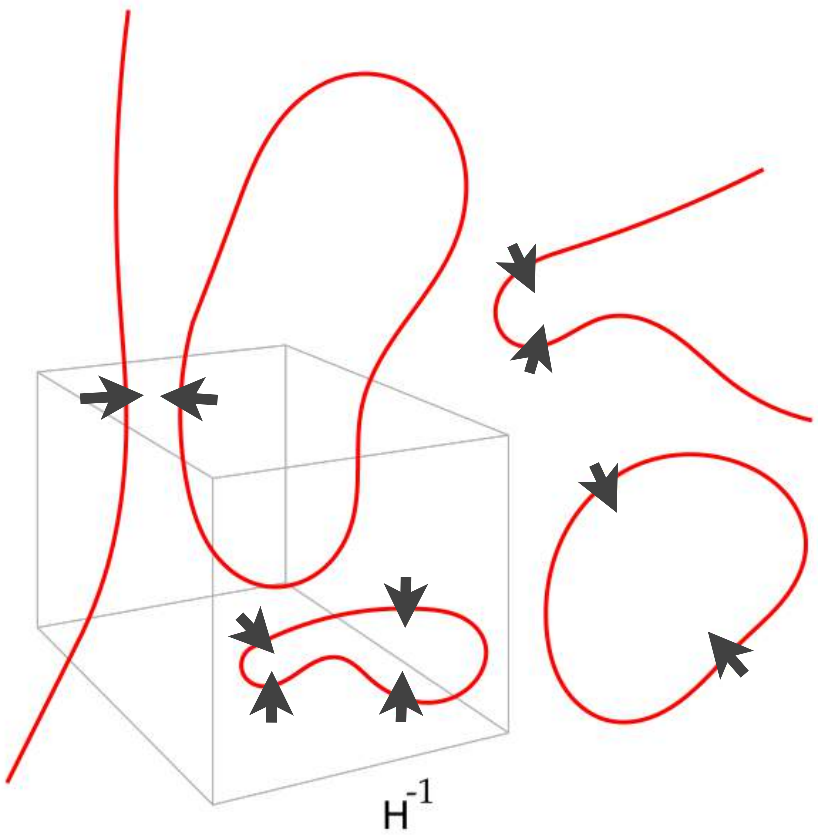

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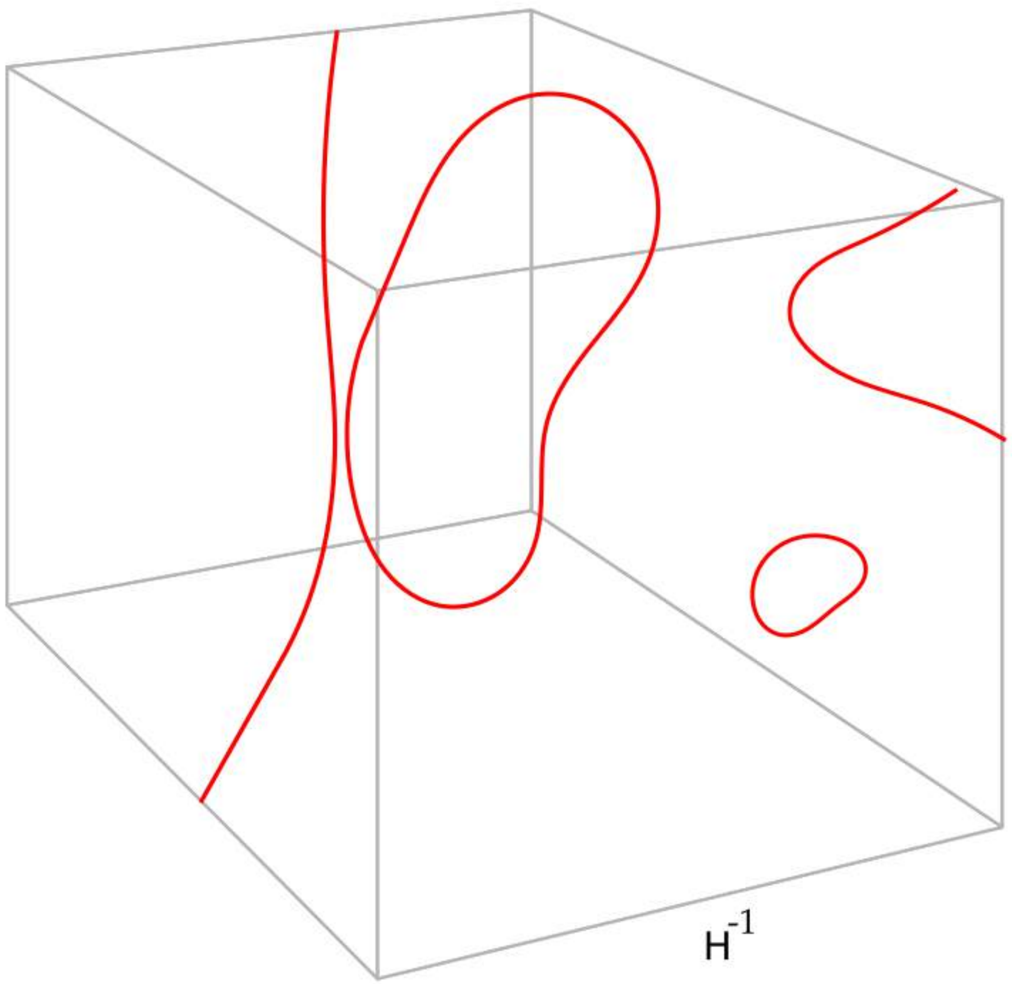


$\xi(t)$ = Length of string per Hubble volume

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

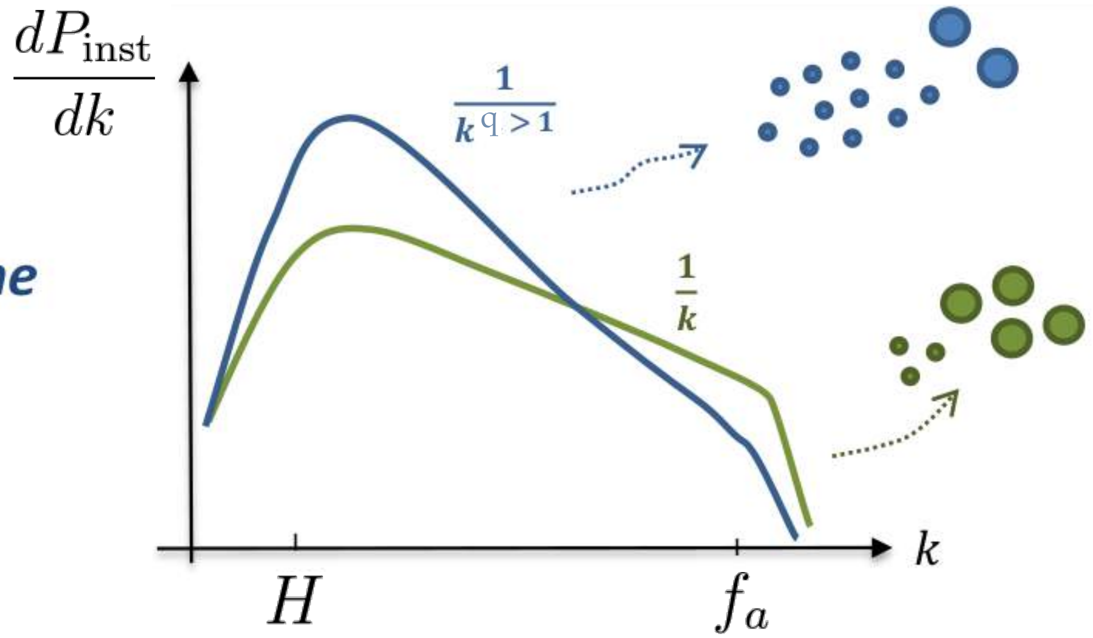
$\xi(t)$ & $\mu(t)$ approximately constant

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

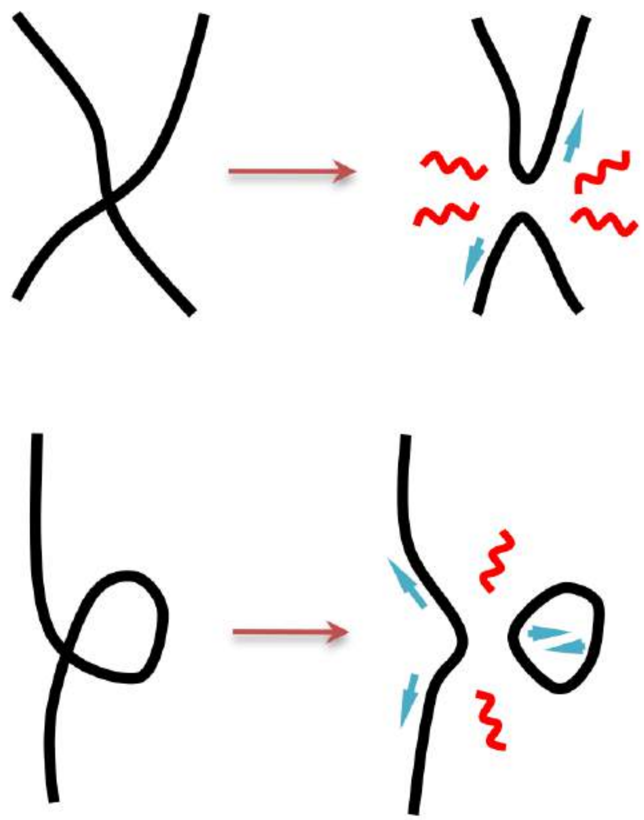
natural cut-offs at H and f_a but:

(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 $\langle k^{-1} \rangle \sim \frac{H^{-1}}{\log\left(f_a/H\right)}$

String dynamics

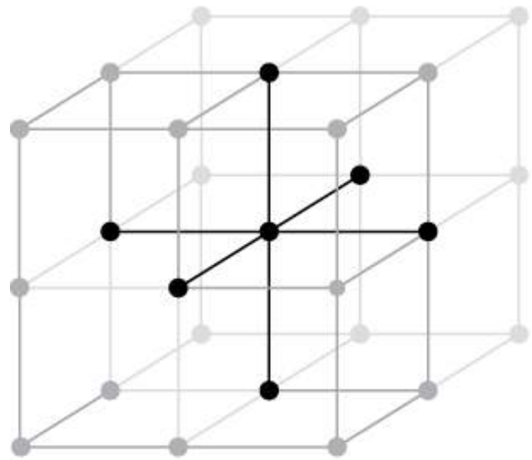


Hard to study analytically, can help with qualitative understanding, but full network has complicated interactions and dynamics

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

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

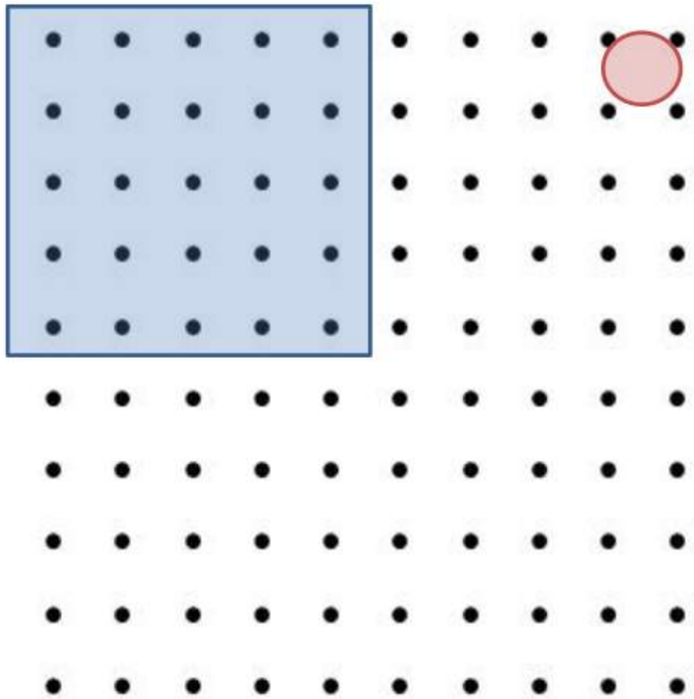
Physical scale separation $\alpha \sim 10^{30}$

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

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

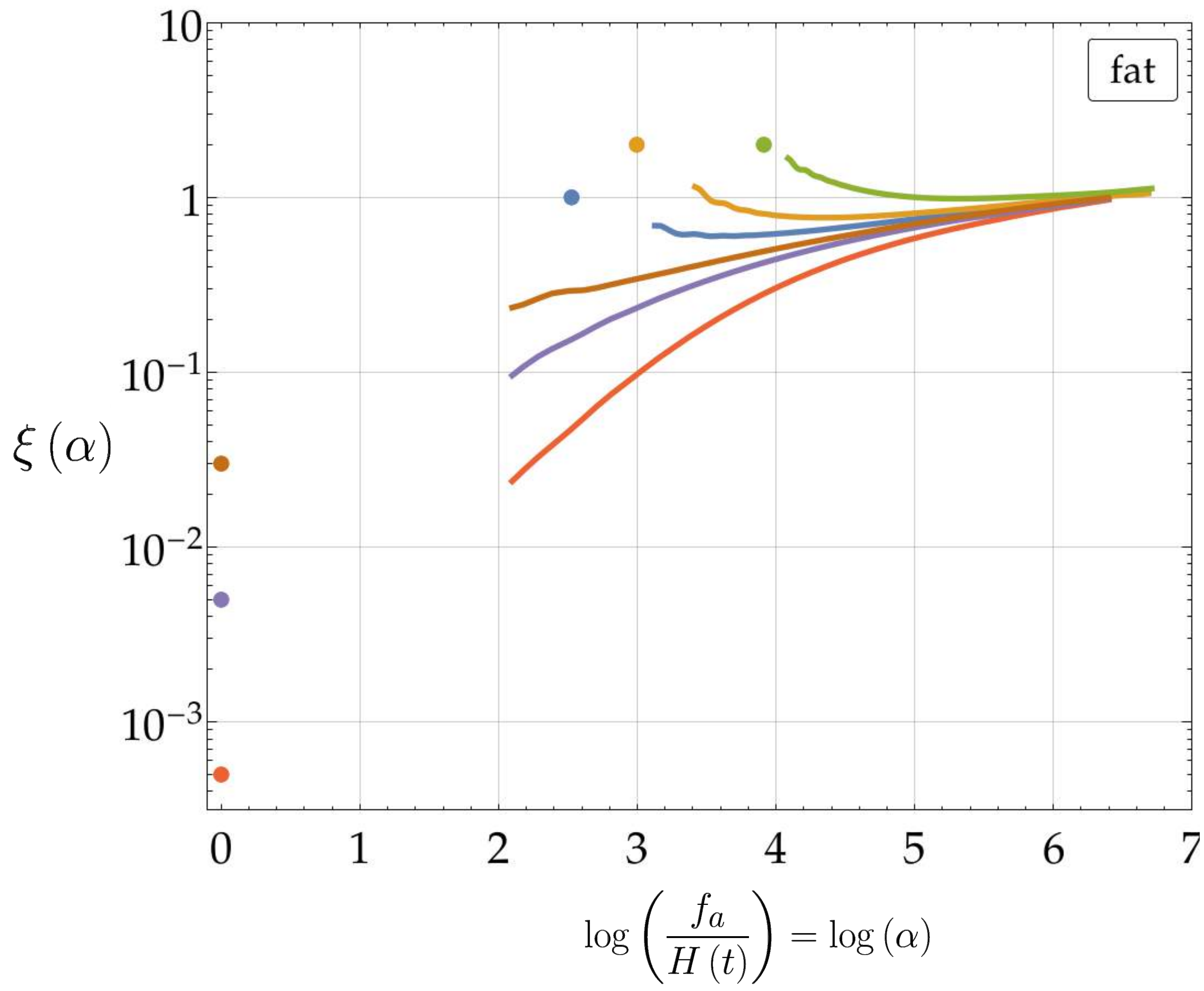
simulations: $\log \alpha \leq \log(\frac{\square}{\bigcirc}) \simeq 7$

physical: $\log \alpha \sim 70$

We simulate at small scale separation then extrapolate

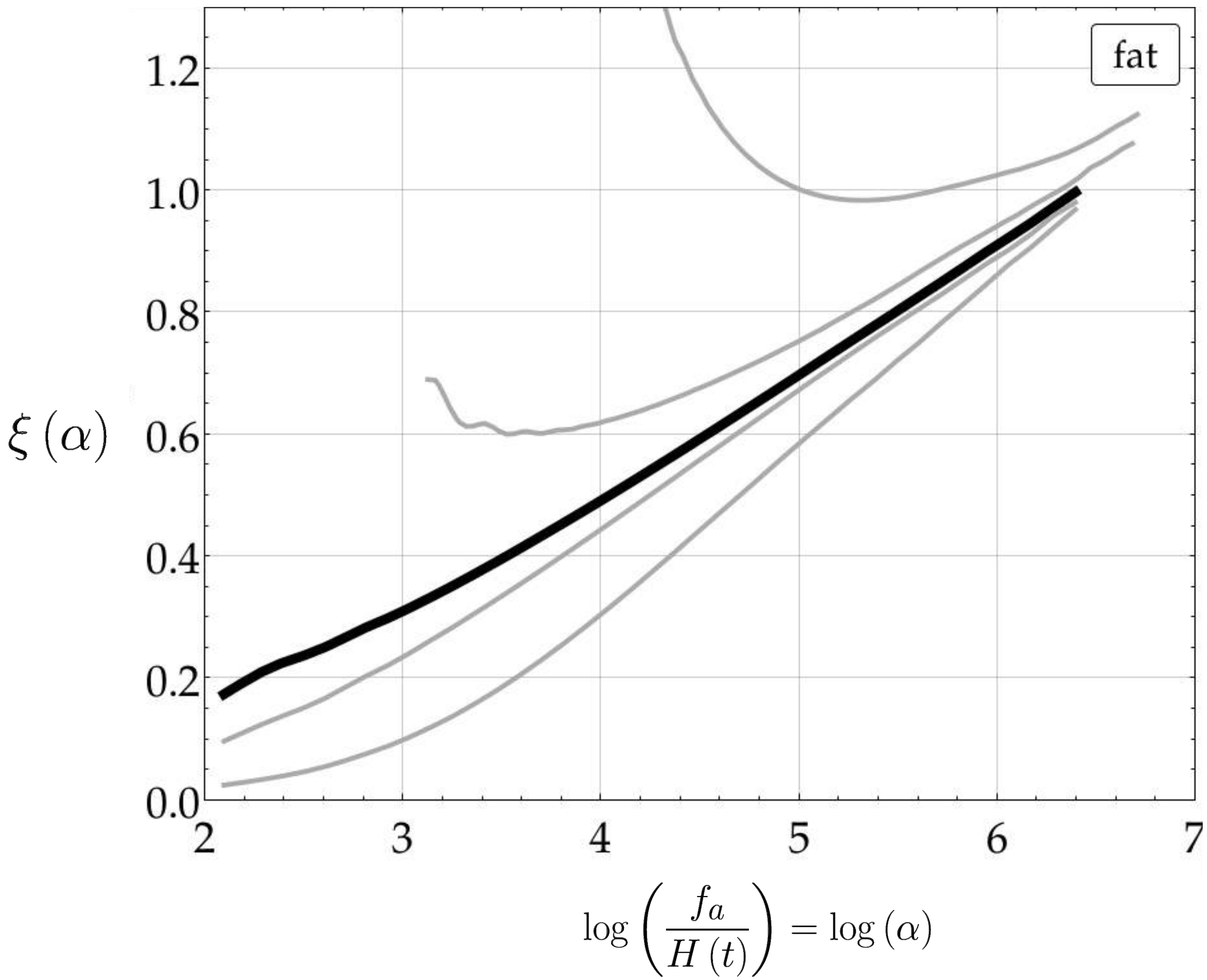
Crucial to extrapolate the correct quantities (not the number density)

String length per Hubble volume



Attractor solution, independent of initial conditions

String length per Hubble volume

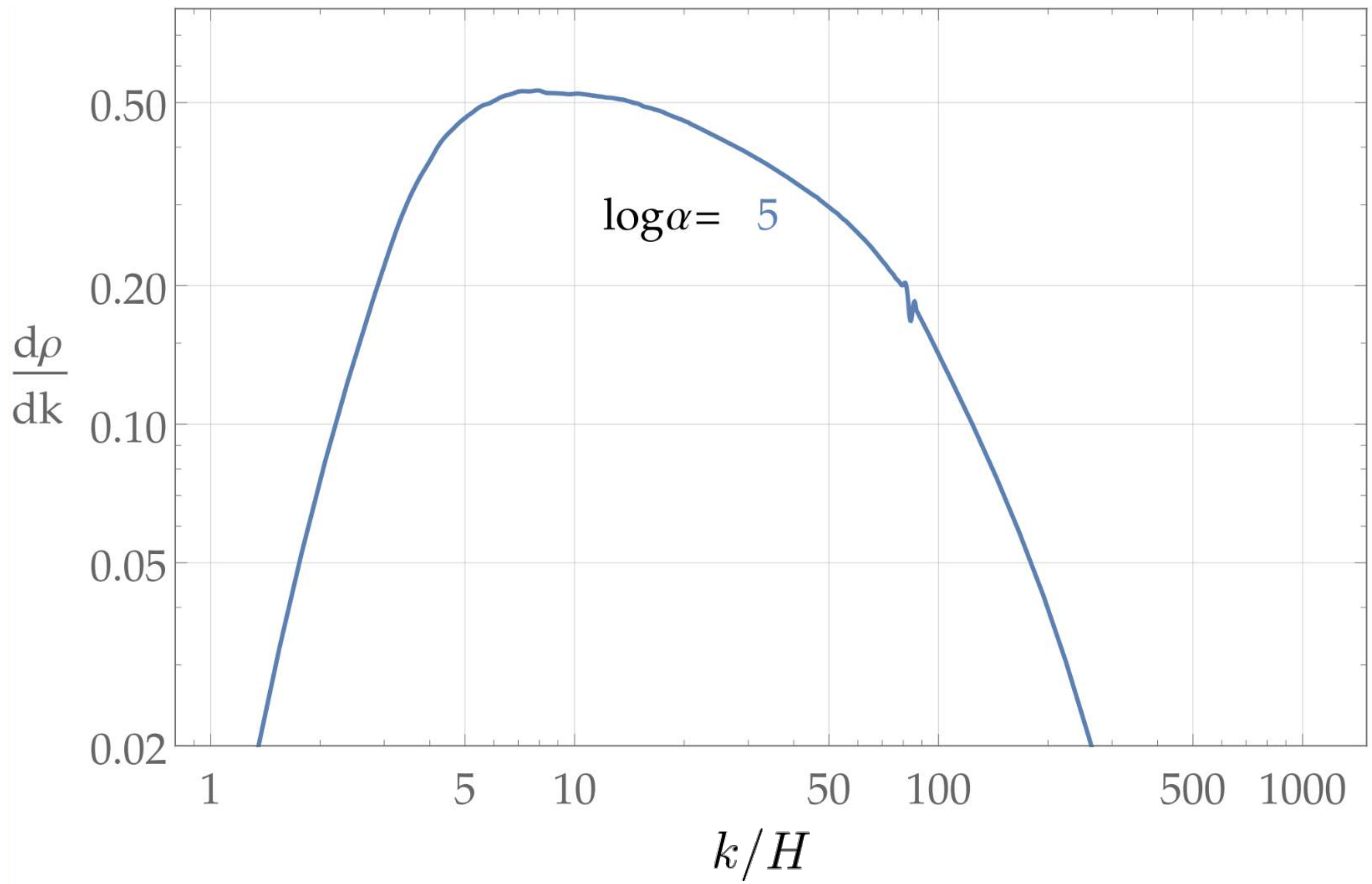


Find a log increase,

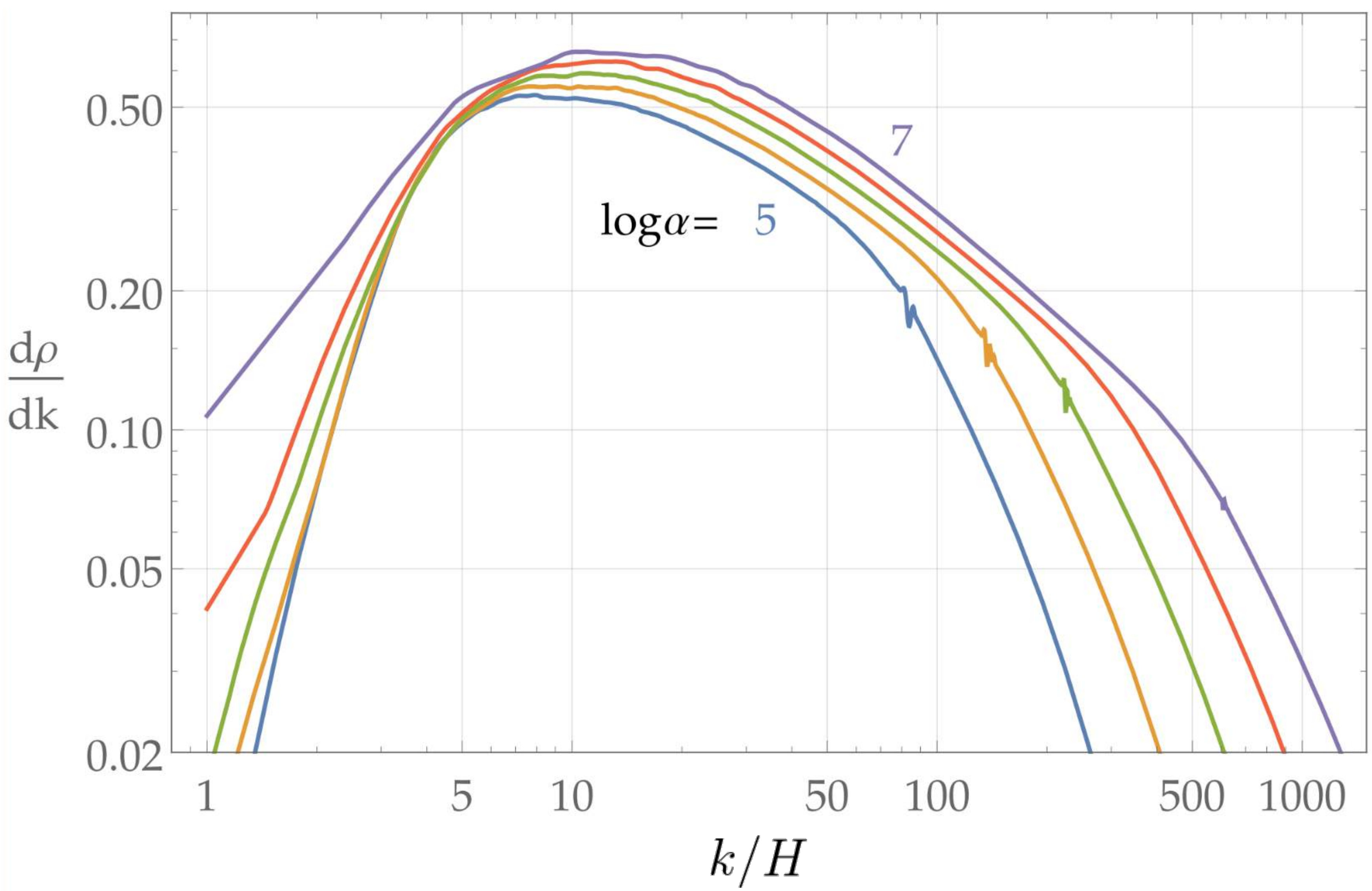
theoretically plausible: tension is increasing

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

Total spectrum

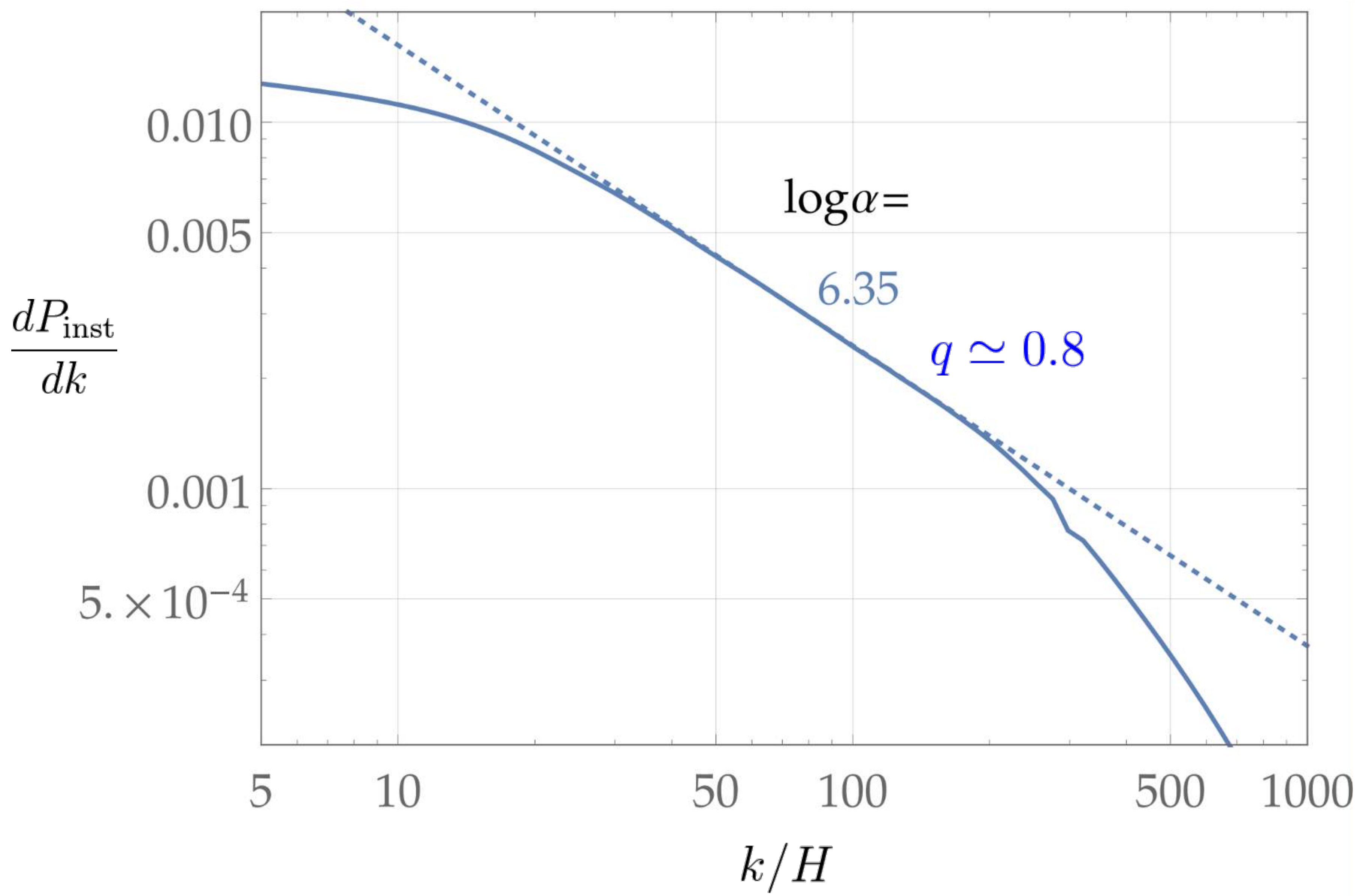


Total spectrum



Instantaneous emission spectrum

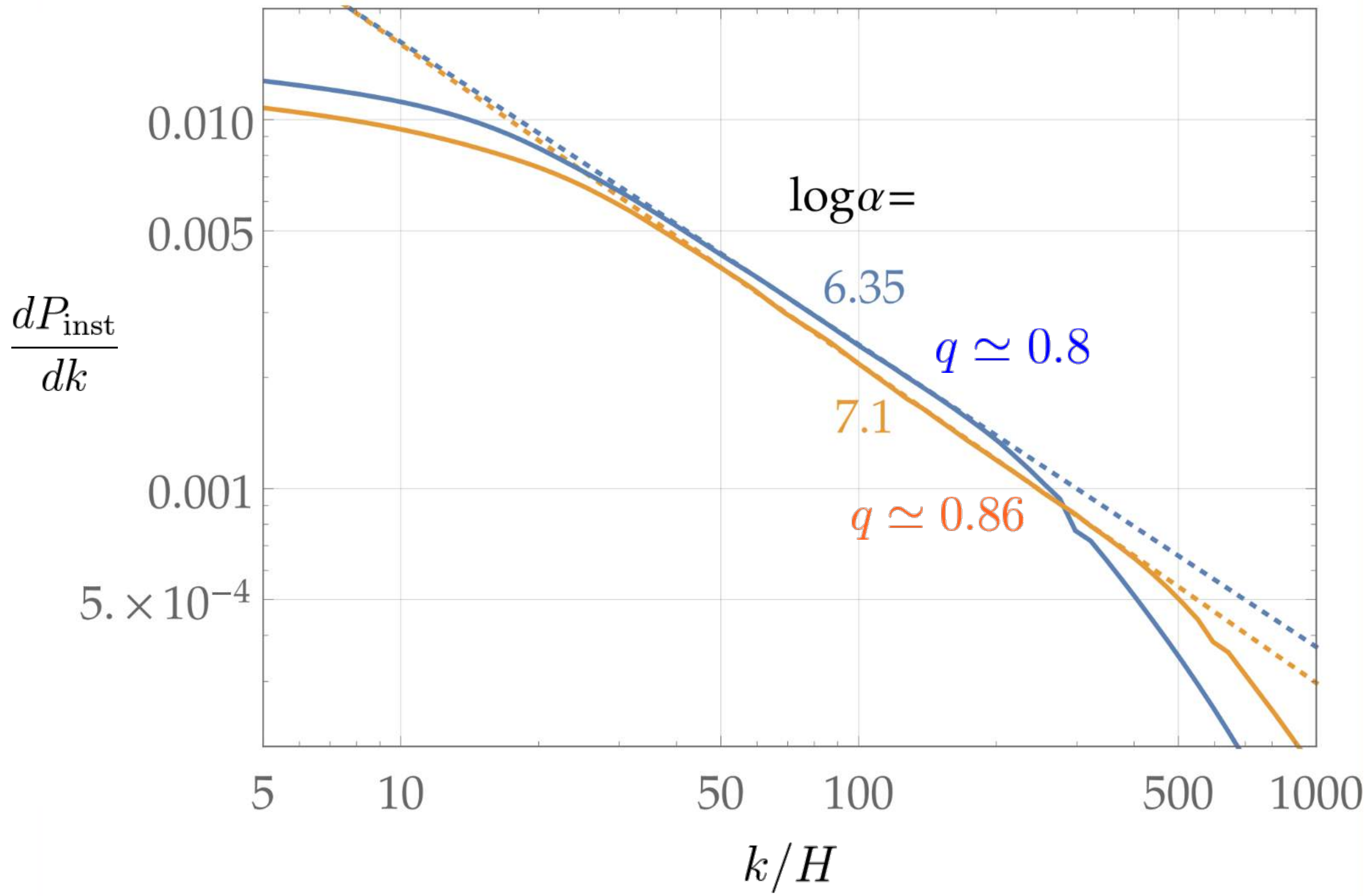
This is the physically relevant thing to extrapolate



UV dominated!

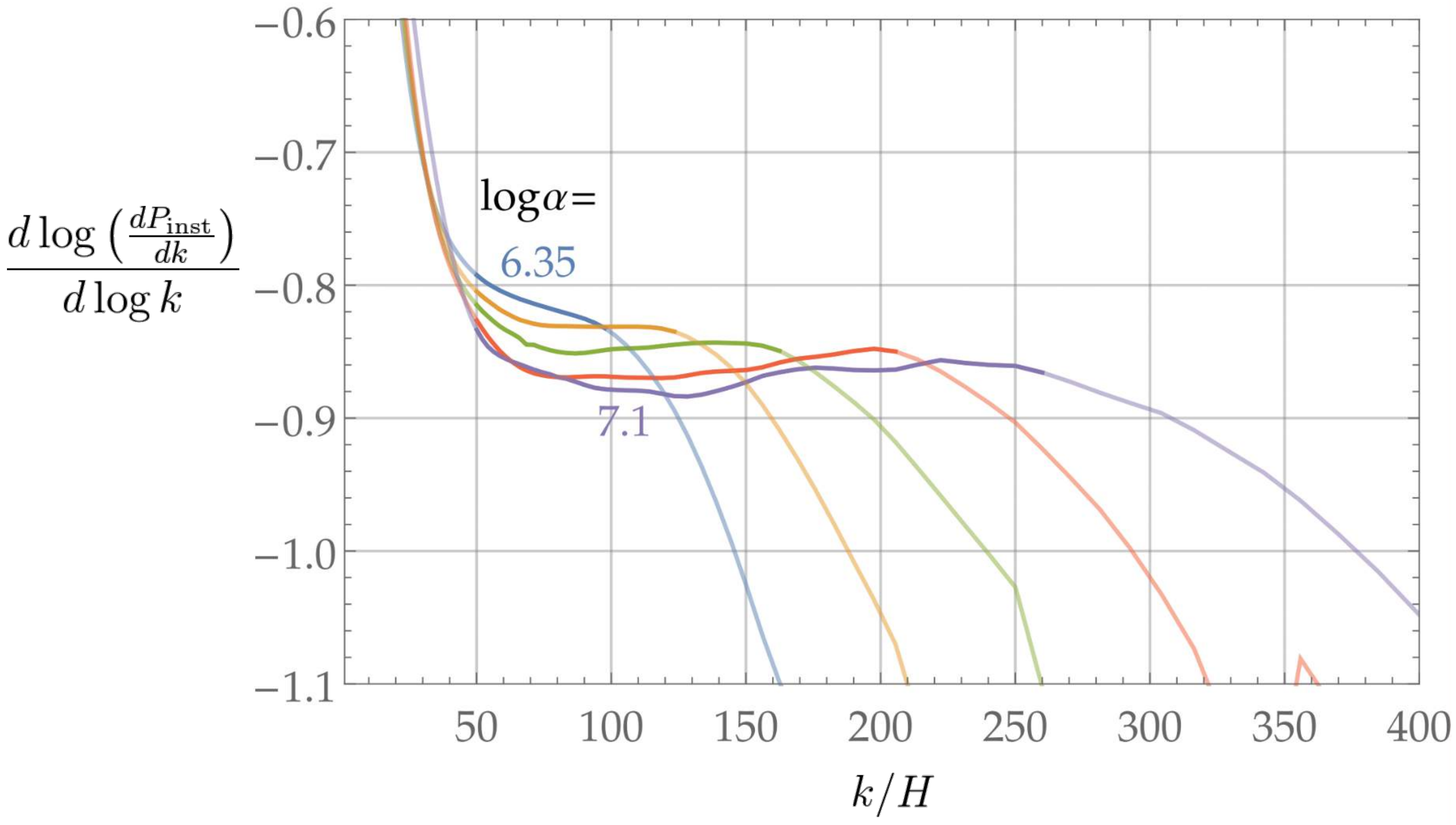
Instantaneous emission spectrum

This is the physically relevant thing to extrapolate



But evidence for a log dependence

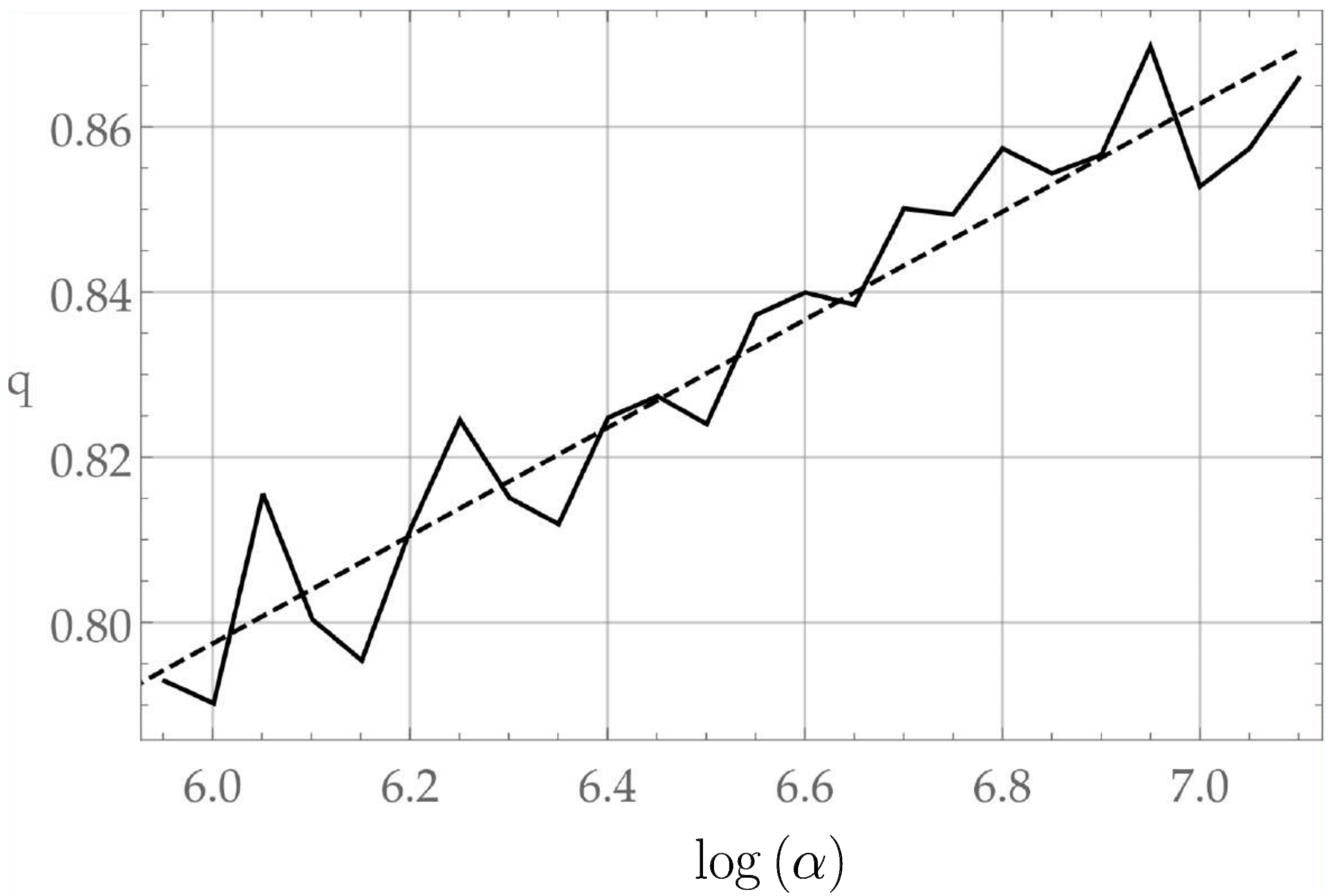
Fitting the power law



Slope of the instantaneous spectrum

Spectrum

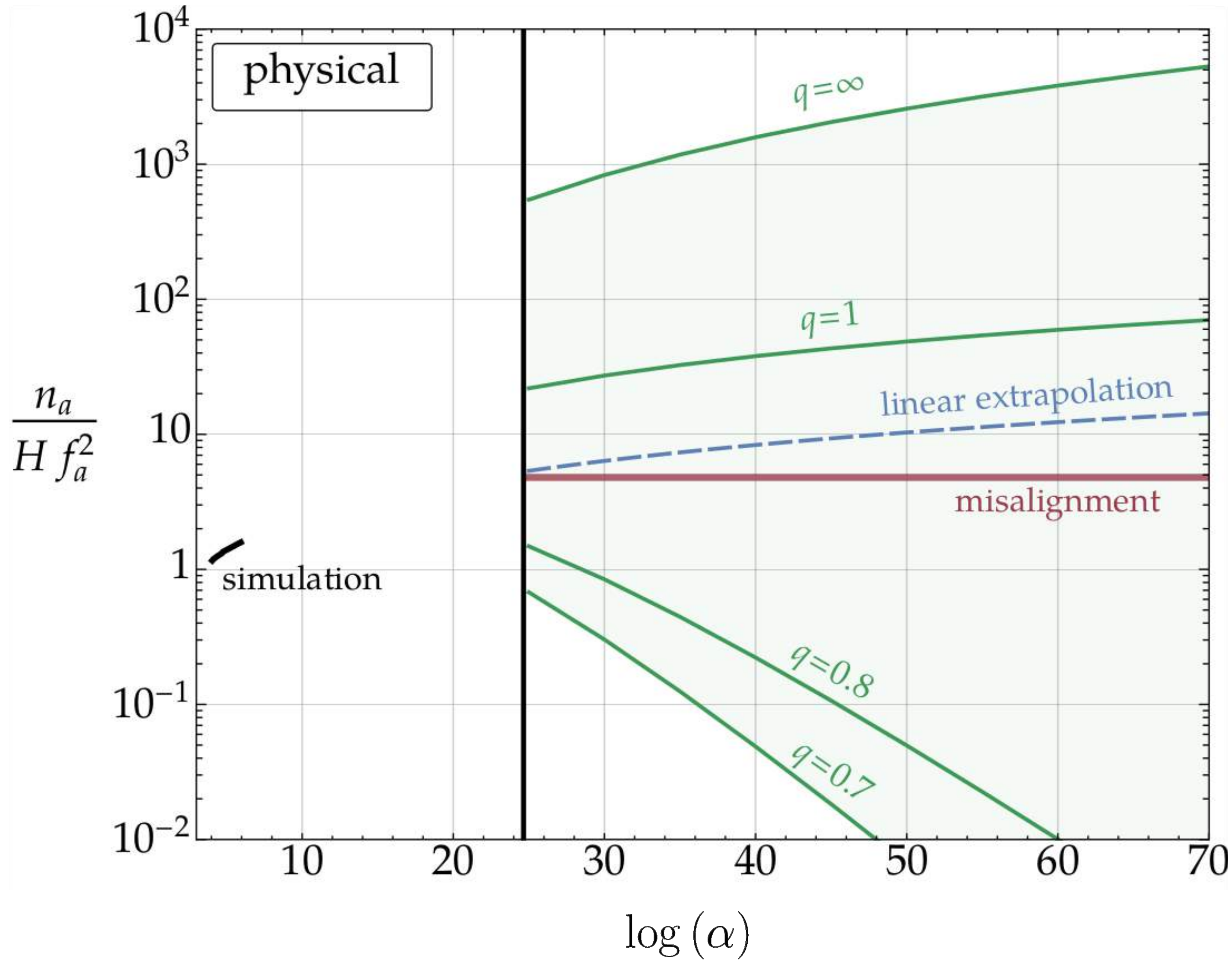
Best fit over the constant slope region:



Also seems to have a log dependence

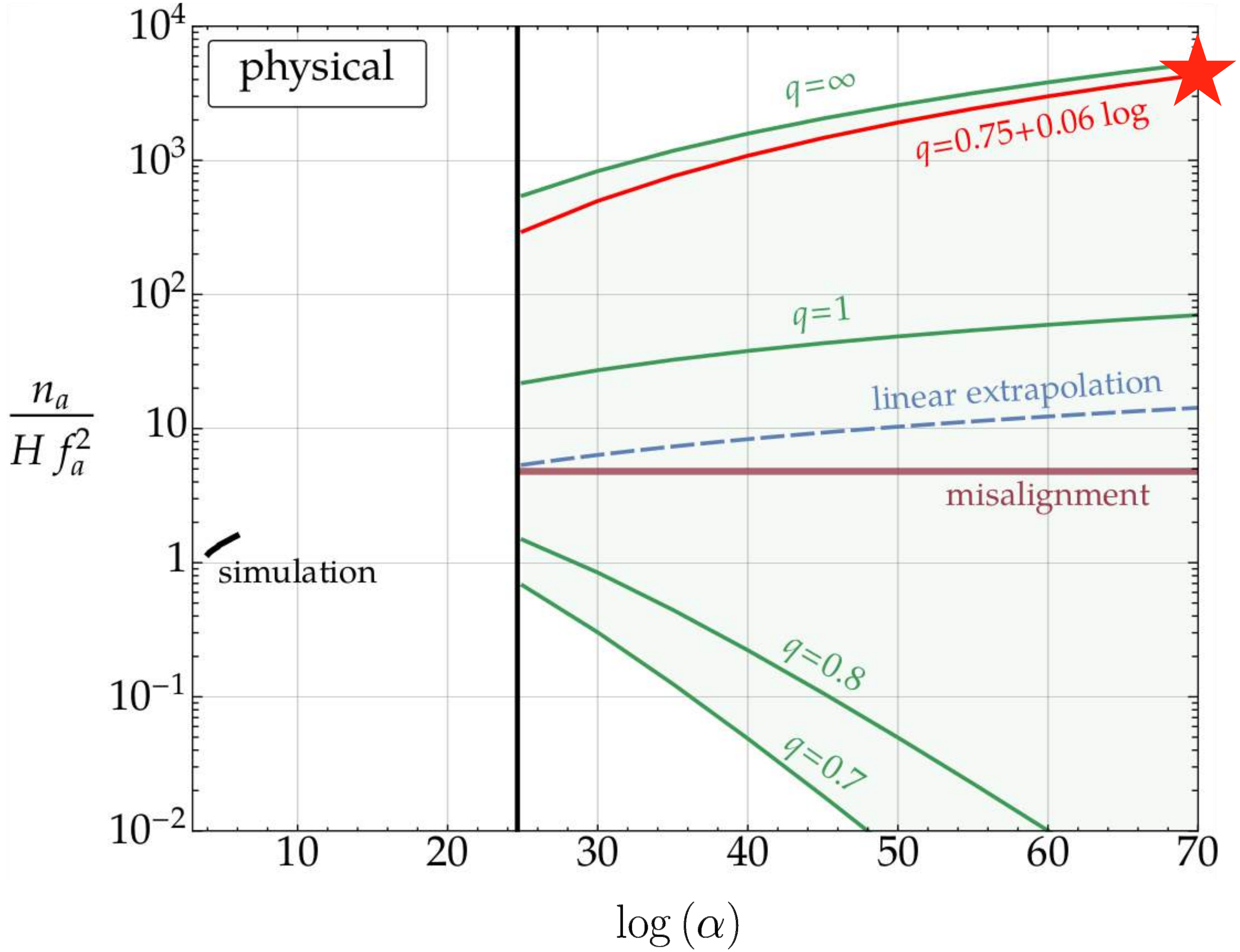
Axion number density

Extrapolate all the way to large logs

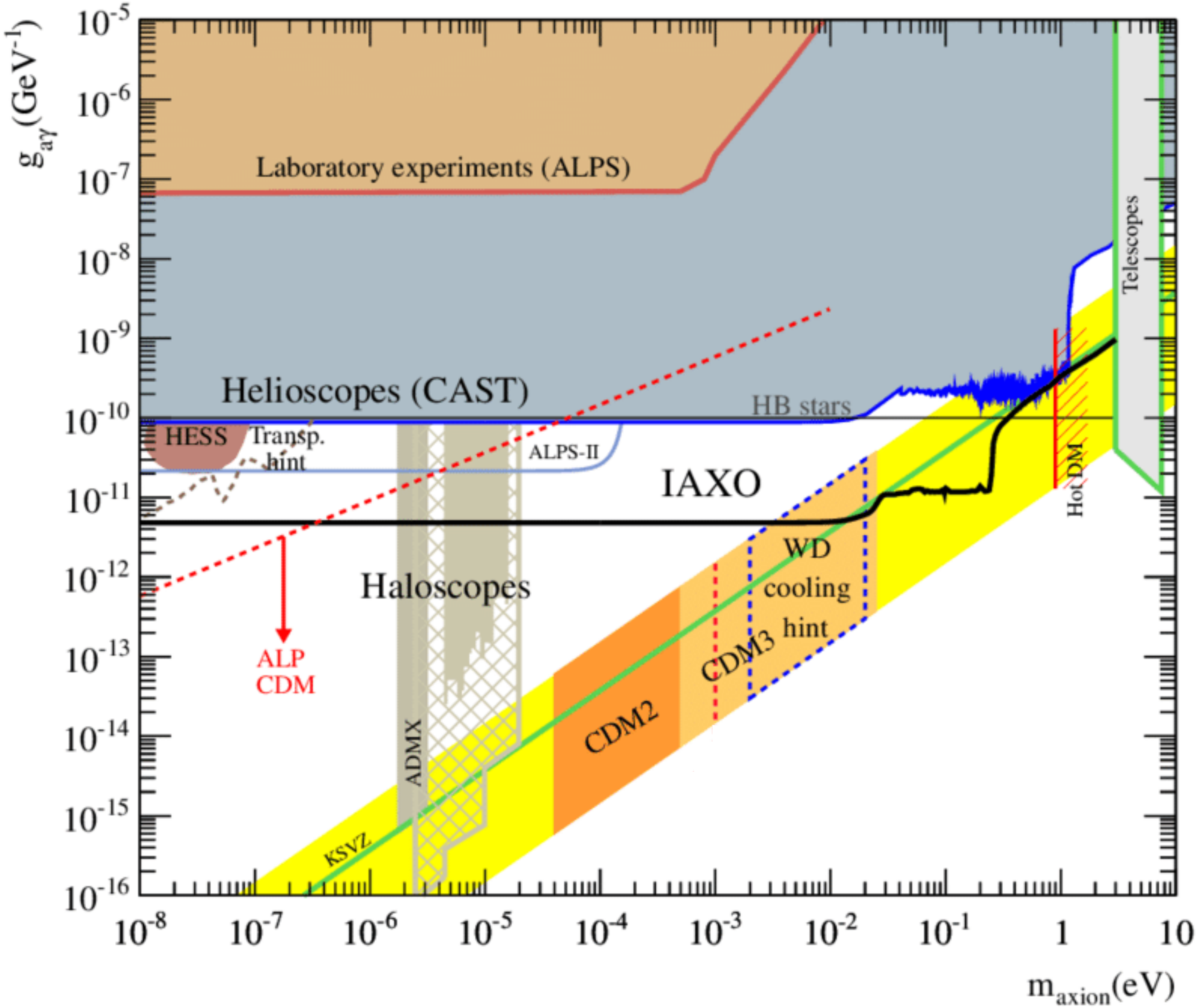


Axion number density

Extrapolate all the way to large logs



Impact on the relic abundance



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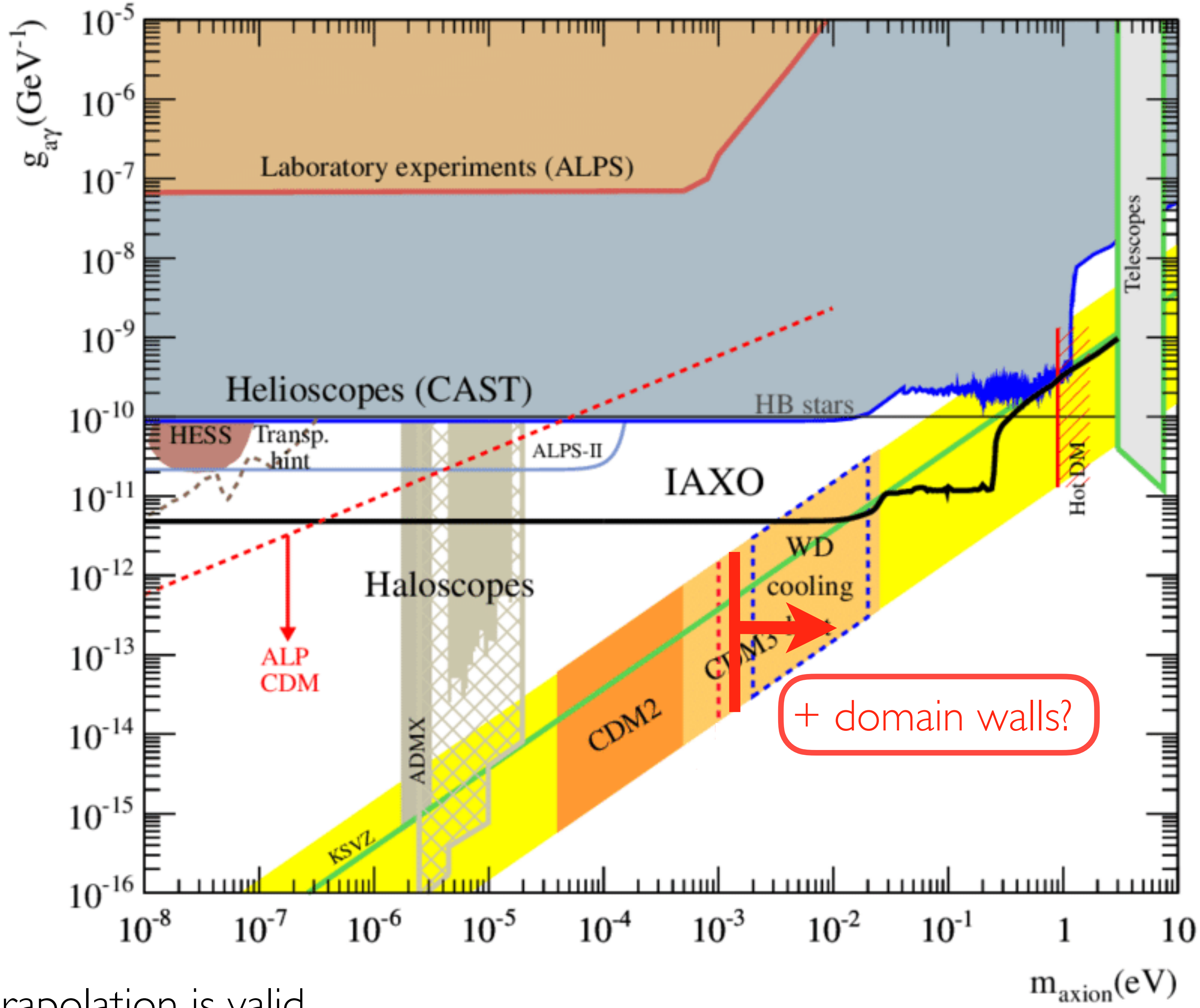


Assuming extrapolation is valid

Future work

- Circular loops (gain a factor of $\frac{3}{2}$ in the log)
- Gauge strings: no light degrees of freedom, extra insight into the decoupling?
- Domain walls / explicit PQ symmetry breaking
- Other BSM models with symmetry breaking
- Study symmetry restoration after inflation/ preheating

Conclusions

Cooling bounds

- Competitive with laboratory experiments
- Resonant production can strengthen constraints by more than a factor of 10

Axion strings

- Need a theoretical calculation to interpret experimental data
- Calculation is challenging, but we think we're doing the physically correct thing

Conclusions

Cooling bounds

- Competitive with laboratory experiments
- Resonant production can strengthen constraints by more than a factor of 10

Axion strings

- Need a theoretical calculation to interpret experimental data
- Calculation is challenging, but we think we're doing the physically correct thing

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

Conclusions

Cooling bounds

- Competitive with laboratory experiments
- Resonant production can strengthen constraints by more than a factor of 10

Axion strings

- Need a theoretical calculation to interpret experimental data
- Calculation is challenging, but we think we're doing the physically correct thing

Close interaction between theory and experiment is essential to make the most of opportunities

Now is an exciting time to be working in this area

Thanks

Circular loops

Current work: perfectly circular loop

One fewer spatial dimension,

3D:

$$N_{\text{step}} \sim e^{3(\log \alpha)}$$

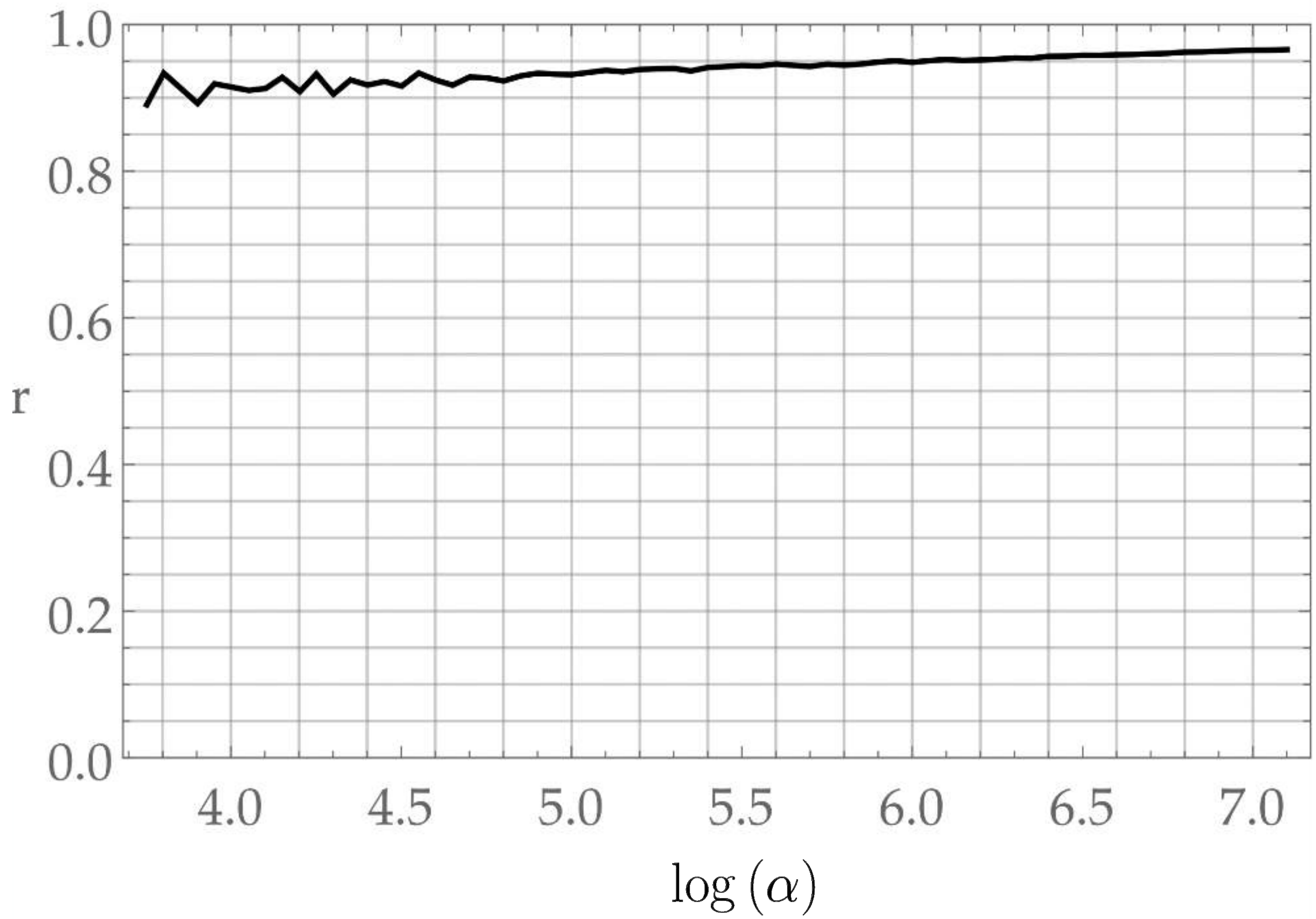
2D:

$$N_{\text{step}} \sim e^{2(\log \alpha)}$$

gain a factor of $\frac{3}{2}$ in the log

Emission ratio to axions

Consistent with an increasing emission to axions vs. heavy radial modes



Part III: Gravitational waves

From a first order phase transition in a hidden sector

Warm hidden sector

Effectively zero
temperature
hidden sector

Mass at NLO

$$m_a^2 = \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2}\left[1+2\frac{m_\pi^2}{f_\pi^2}\left(h_1^r - h_3^r - l_4^r + \frac{m_u^2 - 6m_u m_d + m_d^2}{(m_u+m_d)^2} l_7^r\right)\right]$$

[Grilli di Cortona, EH, Vega, Villadoro, JHEP 1601 (2016) 034]

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Lattice average

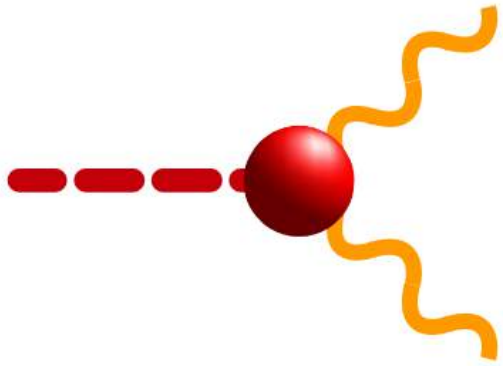
$$\boxed{z \equiv \frac{m_u^{\overline{\rm MS}}(2\ \text{GeV})}{m_d^{\overline{\rm MS}}(2\ \text{GeV})} = 0.48(3)}$$

$$\boxed{m_a = 5.70(6)(4)\ \mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)}$$

[Grilli di Cortona, EH, Vega, Villadoro, JHEP 1601 (2016) 034]

Photon coupling at NLO

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left\{\frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}\right\}$$



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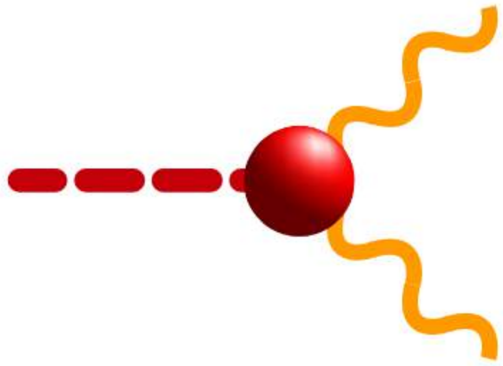
E / N =

0	KSVZ
8/3	DSFZ, GUT, ...
2	Unificaxion, ...



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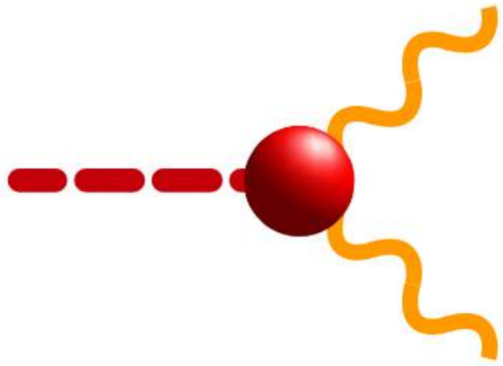
tree ~ - 2

$$a \rightarrow \pi \rightarrow \gamma\gamma$$



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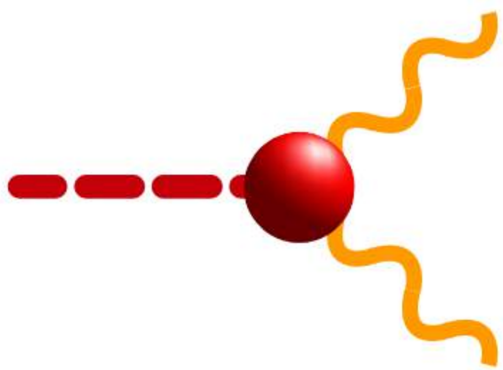
$a \to \pi \to \gamma\gamma$



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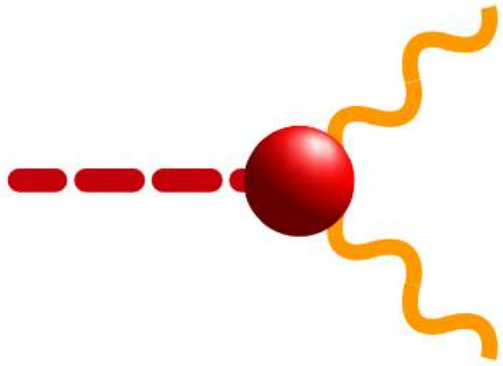
tree ~ - 2

$a \to \pi \to \gamma\gamma$

NLO: $= 0.033(6)$

from $\pi \to \gamma\gamma$ $\eta \to \gamma\gamma$



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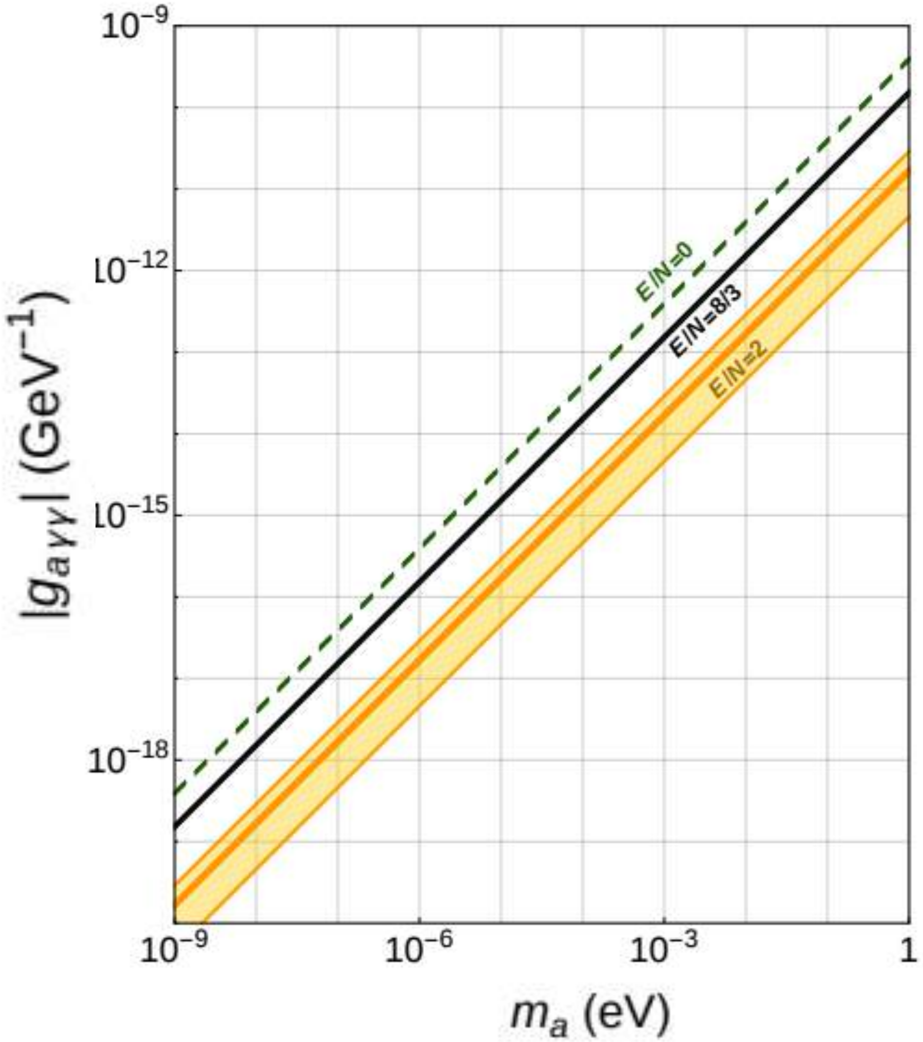
$$\boxed{g_{a\gamma\gamma} = \left[0.203(3)\frac{E}{N} - 0.39(1)\right]\frac{m_a}{\mathrm{GeV}^2}}$$

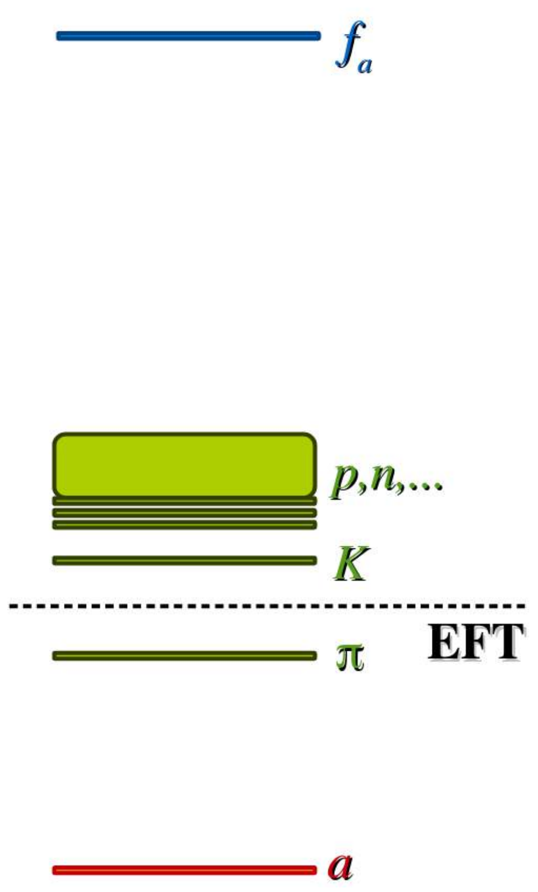


Properties at NLO

We can calculate using chiral perturbation theory:

[Georgi, Kaplan, Randall]

$$\boxed{\mathcal{L}_{\rm QCD}\left(a,q,G,F\right) \to \mathcal{L}_{\rm CPT}\left(a,\pi,F\right)}$$



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[Grilli di Cortona, EH, Vega, Villadoro, JHEP 1601 (2016) 034]

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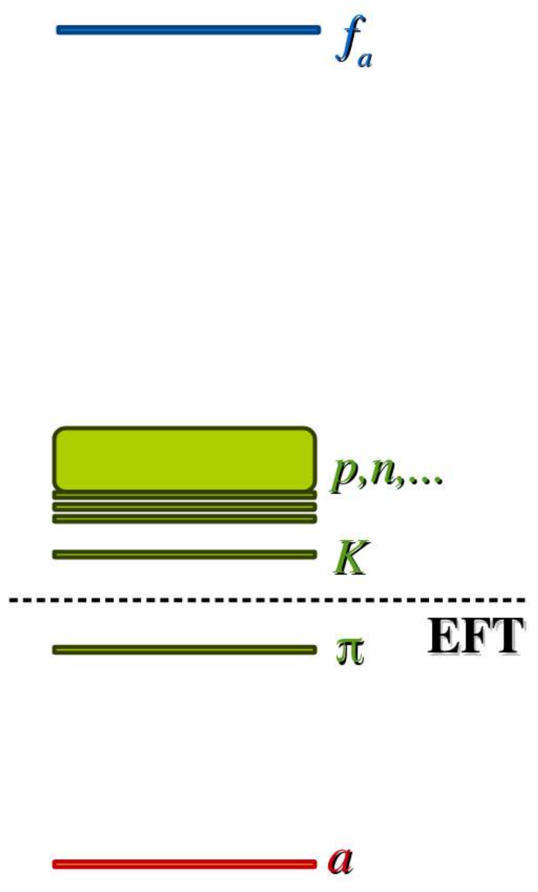

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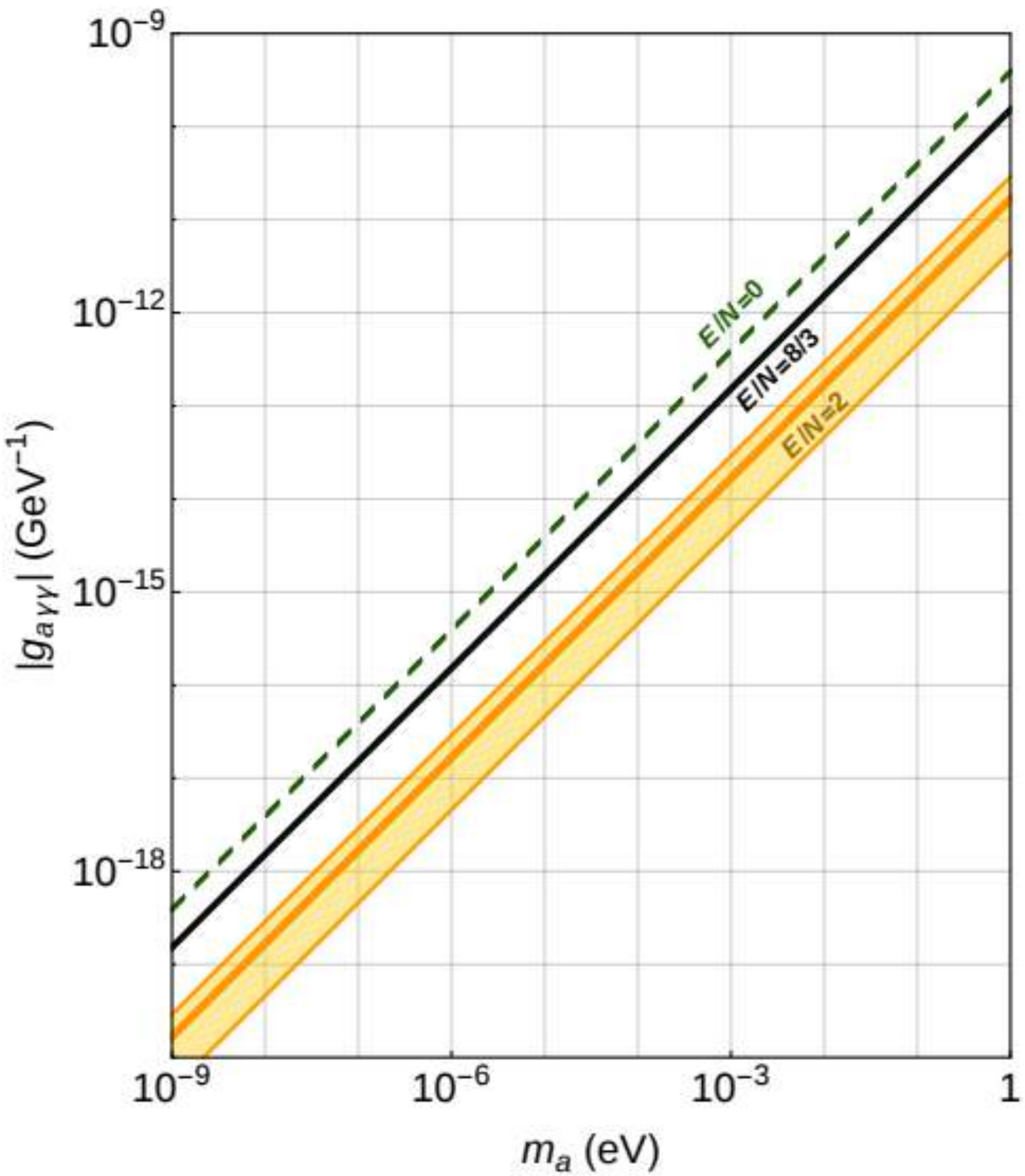
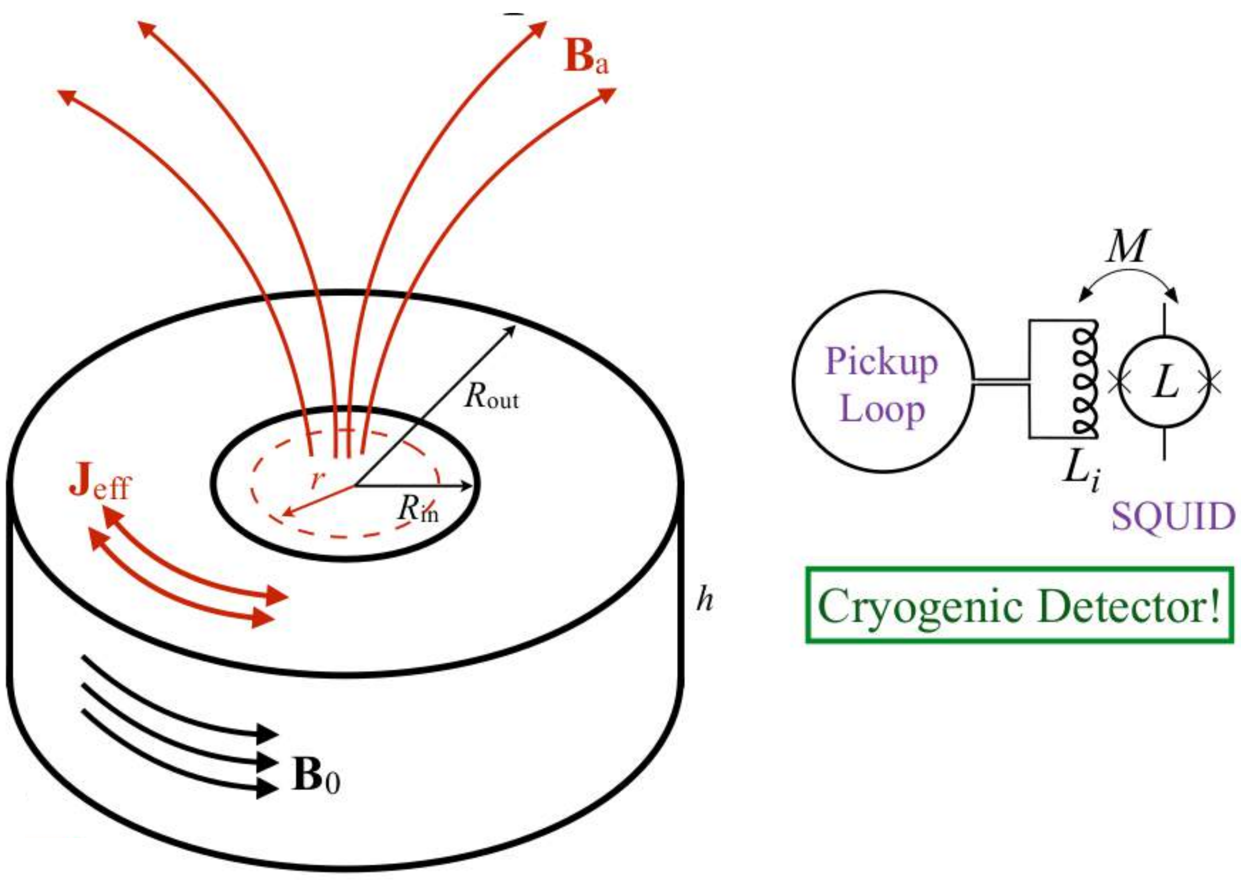


Experimental searches

Many interesting ideas, e.g. Abracadabra [Kahn et al. 1602.01086]



- Toroidal magnet with fixed magnetic field
- Axion DM generates oscillating current around the ring
- Produces oscillating magnetic field
- Detected by a sensitive pickup loop

Other approaches to detect light axions, e.g. using NMR,
Ariadne [Arvanitaki & Geraci 1403.1290]

Often will be able to determine axion mass very precisely $\delta m/m \sim 10^{-6}$

Insight into velocity distribution of axions in the galaxy / dark matter streams
[O'Hare & Green 1701.03118]