The QCD axion and other new light particles

Ed Hardy

Based on work with:
Giovanni Grilli di Cortona, Marco Gorghetto,
Robert Lasenby, Javier Pardo Vega, &
Giovanni Villadoro

(JHEP 1601(2016)034,
JHEP 1702(2017)033)

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Why new light particles?

Motivated from UV and IR perspectives

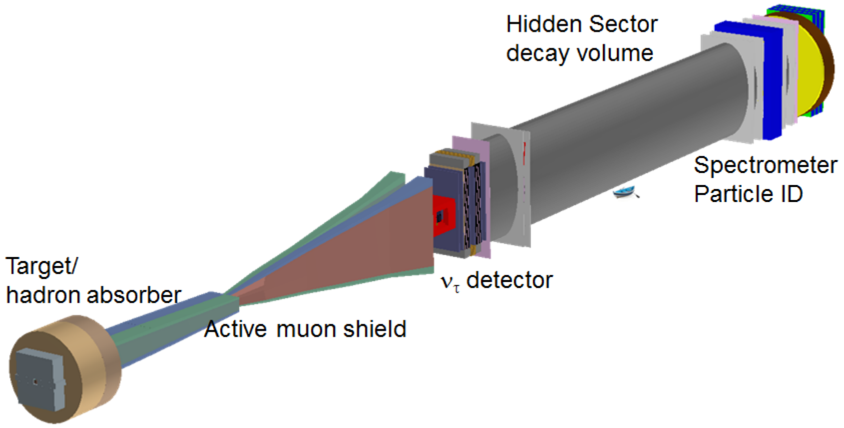
- Solve problems with the SM (QCD axion)
- Dark Matter candidates or portals to dark sectors/ mediate DM self-interactions
- Plausible in typical string compactifications
- Various almost interesting experimental anomalies

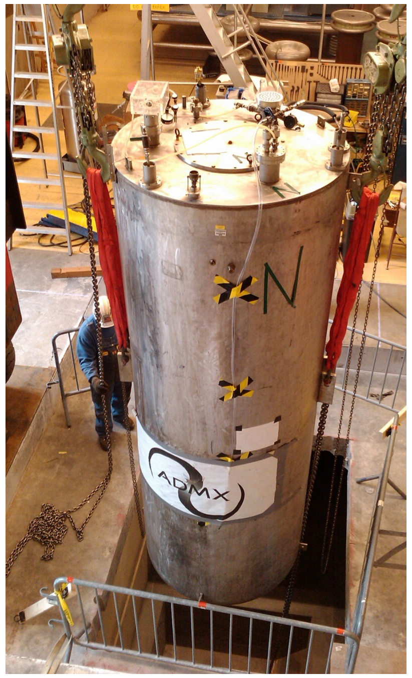
Less explored than other possibilities, experimental progress likely

No sharp prediction for where to look

What can theory contribute?

Many interesting experiments:





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

QCD axion

- properties at zero temperature
- as dark matter

Other new light particle possibilities

- Constraints from cooling and the importance of thermal effects

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!

QCD axion

Spontaneously broken
anomalous global U(1)

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

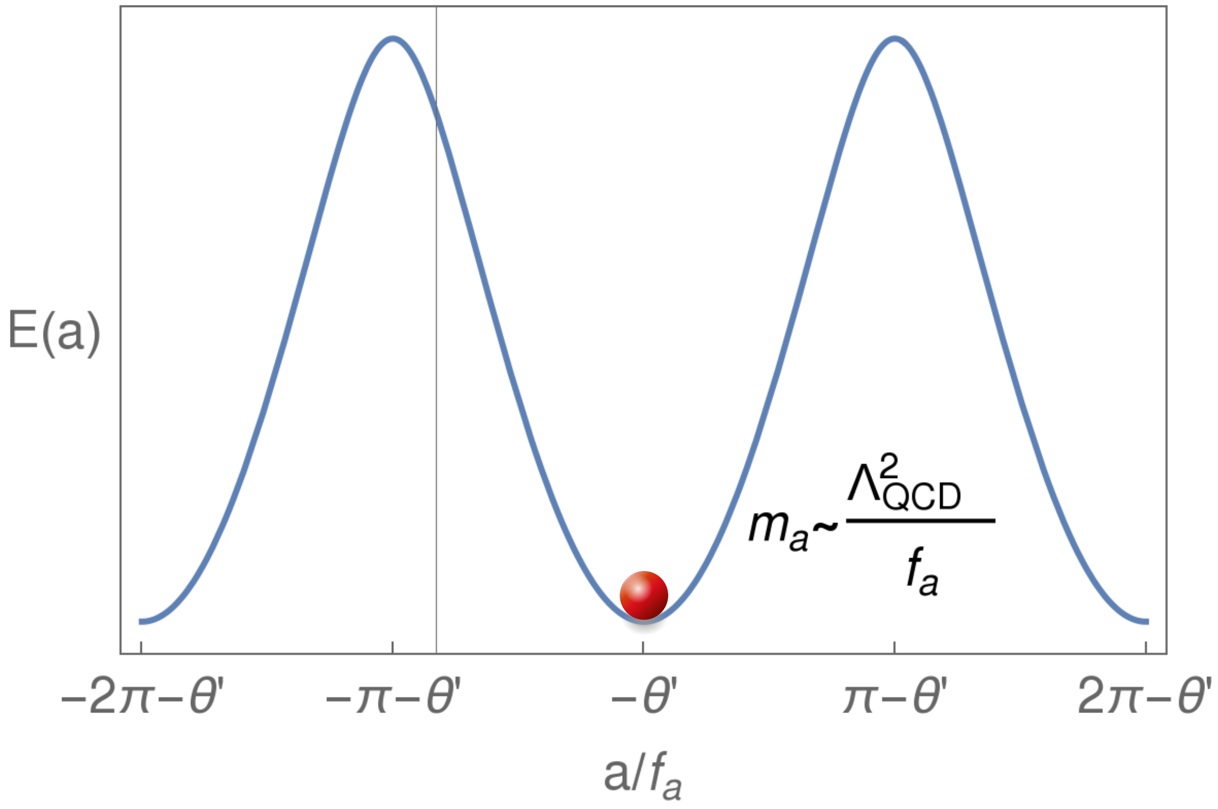
$$a \to a + \delta$$

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

QCD runs into strong coupling

→ axion potential

$$E(\theta) \geq E(0)$$



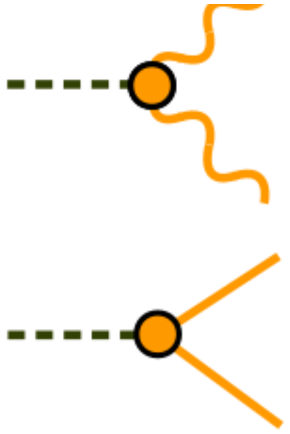
$$\theta_{\mathrm{tot}} = \langle a \rangle + \theta_0 + \arg\left(\mathrm{Det}\, M_q\right) = 0$$

Couplings

$$\mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$$

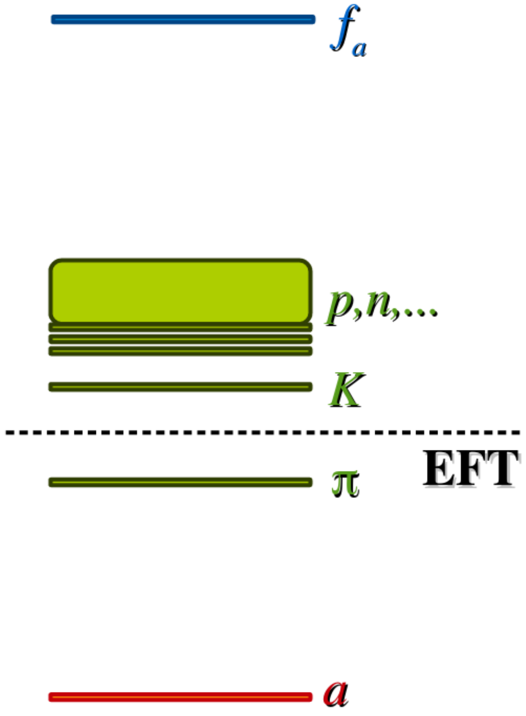
$$\frac{1}{4}\, a\, g^0_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$c^0_q \bar{q}\gamma^\mu\gamma_5 q \, \frac{\partial_\mu a}{2 f_a}$$



We can calculate using chiral perturbation theory:

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



Mass at NLO

$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

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

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
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Mass at NLO

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Lattice average

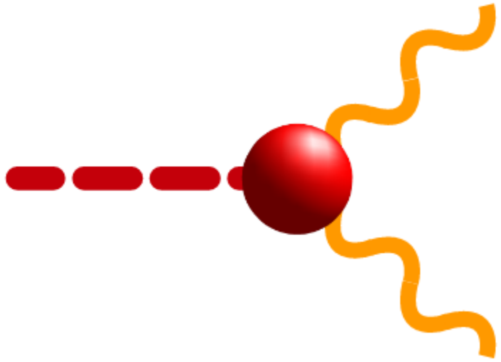
$$\boxed{z \equiv \frac{m_u^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV})}{m_d^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV})} = 0.48(3)}$$

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

[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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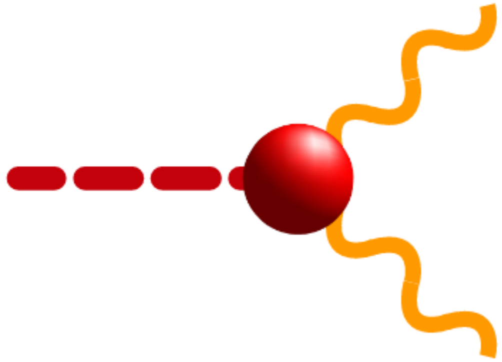
E / N =	
0	KSVZ
8/3	DSFZ, GUT, ...
2	Unificaxion, ...



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E / N =

0	KSVZ
8/3	DSFZ, GUT, ...
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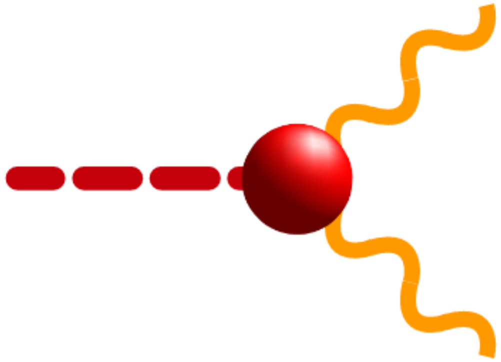
tree ~ - 2

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



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E / N =

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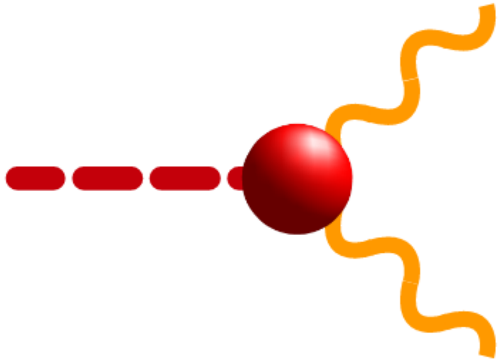

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E / N =

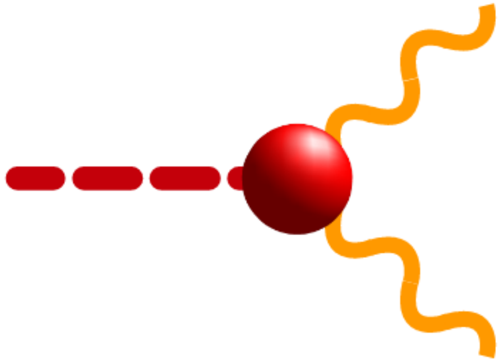
0	KSVZ
8/3	DSFZ, GUT, ...
2	Unificaxion, ...

tree ~ - 2

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

NLO: $= 0.033(6)$

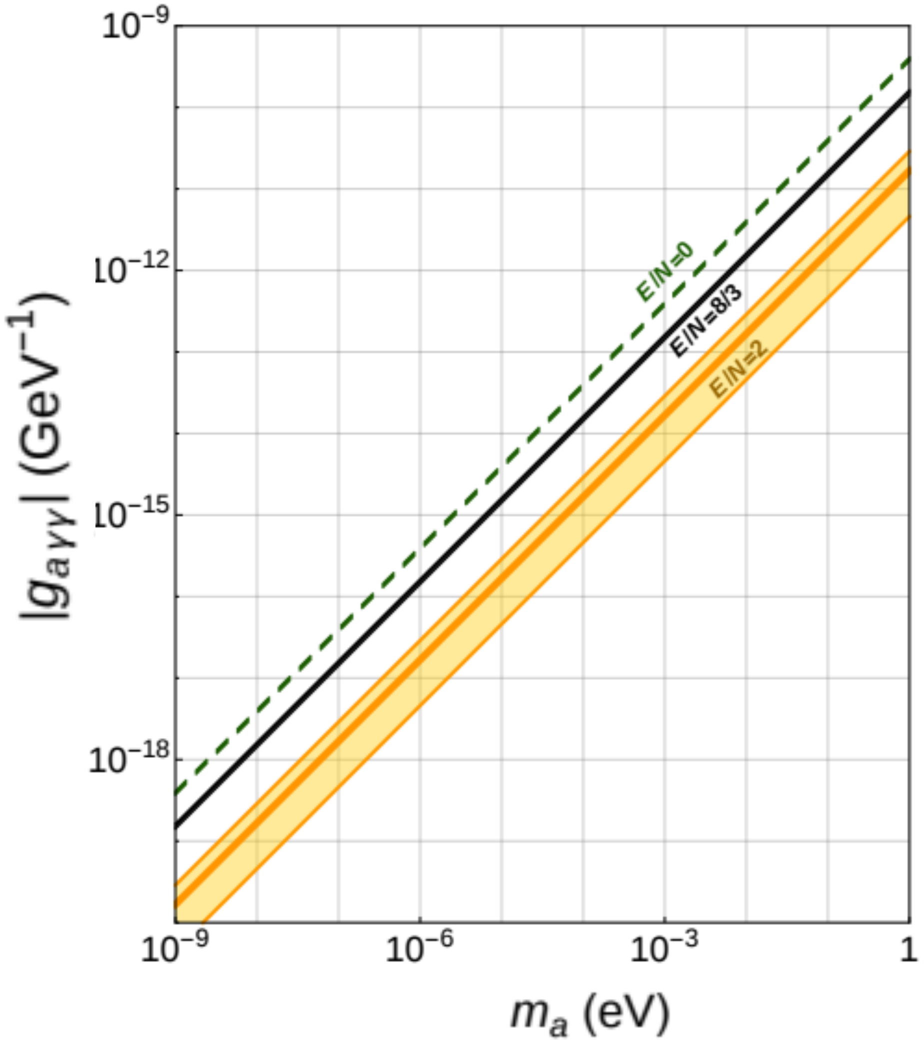
from $\pi \to \gamma\gamma$ $\eta \to \gamma\gamma$



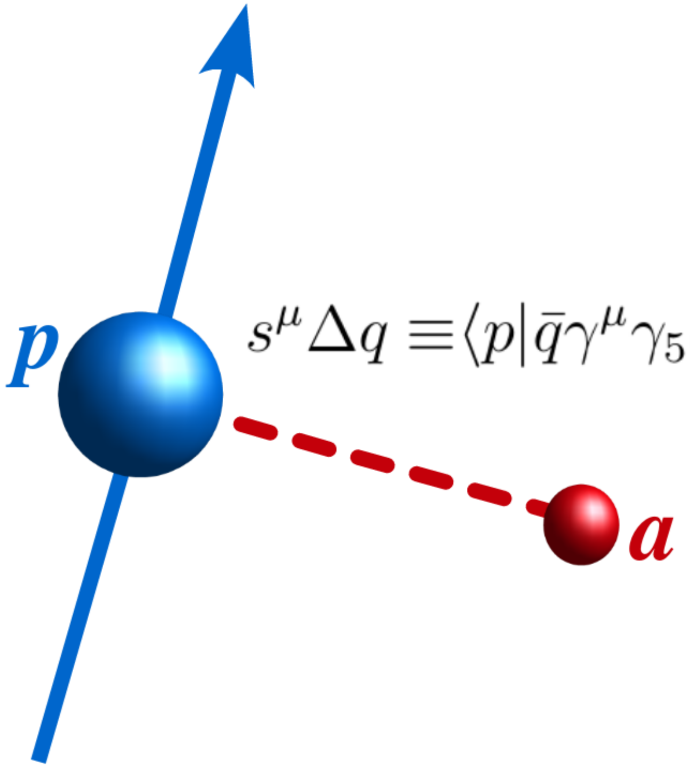
Photon coupling at NLO

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left\{\frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u} + \frac{m_\pi^2}{f_\pi^2}\frac{8m_u m_d}{(m_u + m_d)^2}\left[\frac{8}{9}\left(5\tilde{c}_3^W + \tilde{c}_7^W + 2\tilde{c}_8^W\right) - \frac{m_d - m_u}{m_d + m_u} l_7^r\right]\right\}$$

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



Coupling to matter fields



$s^\mu \Delta q \equiv \langle p | \bar{q} \gamma^\mu \gamma_5 q | p \rangle_Q$

$$\boxed{\frac{\partial_\mu a}{2 f_a} c_N \bar{N} \gamma^\mu \gamma_5 N}$$

$$\begin{aligned} c_p &= \boxed{-0.48(3)} + 0.89(2) c_u^0 - 0.38(2) c_d^0 - 0.036(4) c_s^0 \\ &\quad \boxed{- 0.013(5) c_c^0 - 0.009(2) c_b^0 - 0.0036(4) c_t^0} \\ c_n &= \boxed{-0.03(3)} + 0.89(2) c_d^0 - 0.38(2) c_u^0 - 0.036(4) c_s^0 \\ &\quad \boxed{- 0.013(5) c_c^0 - 0.009(2) c_b^0 - 0.0036(4) c_t^0} \end{aligned}$$

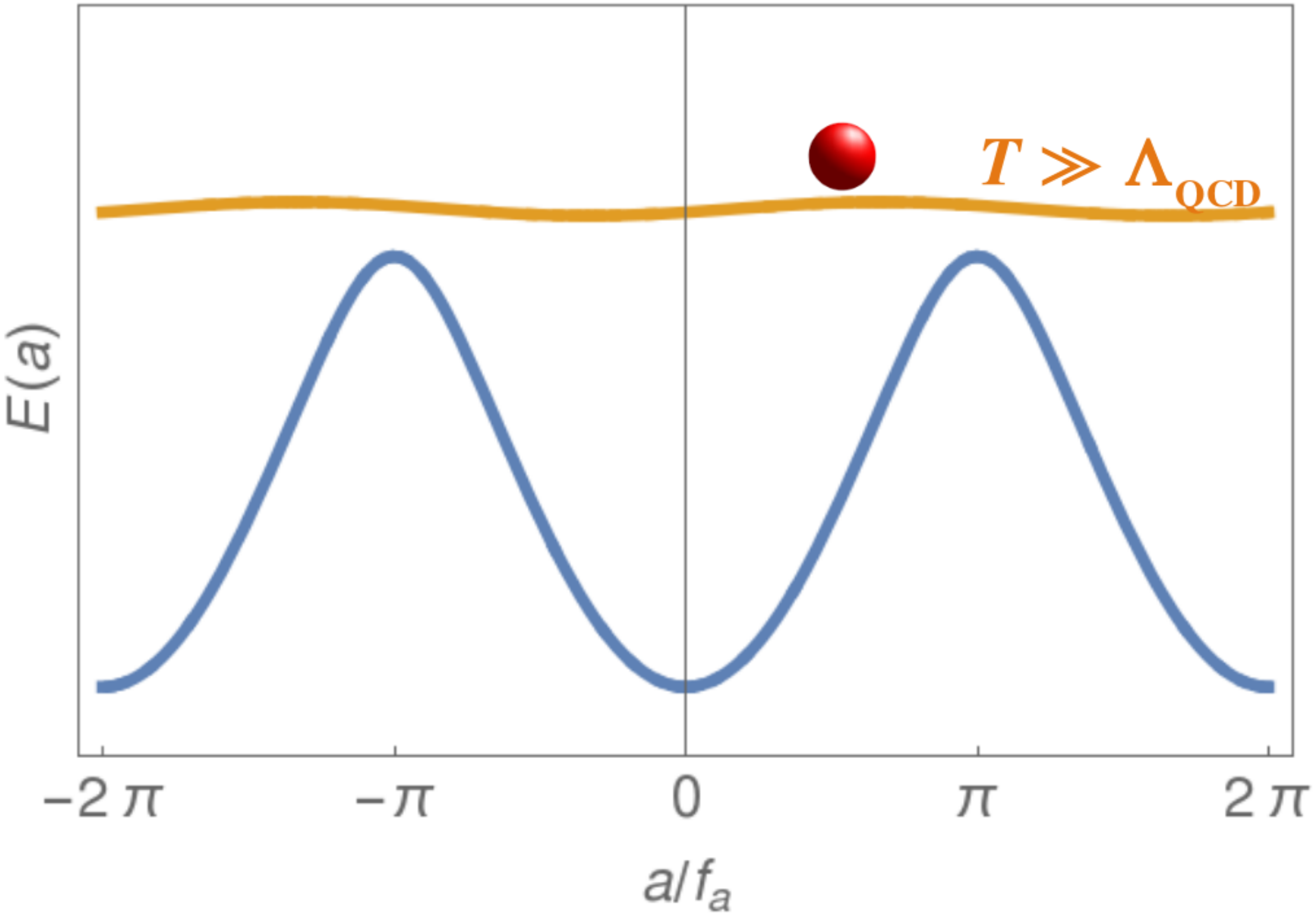
From RGE effects

Model independent couplings

Dark matter

Extra bonus feature, can automatically be the dark matter

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



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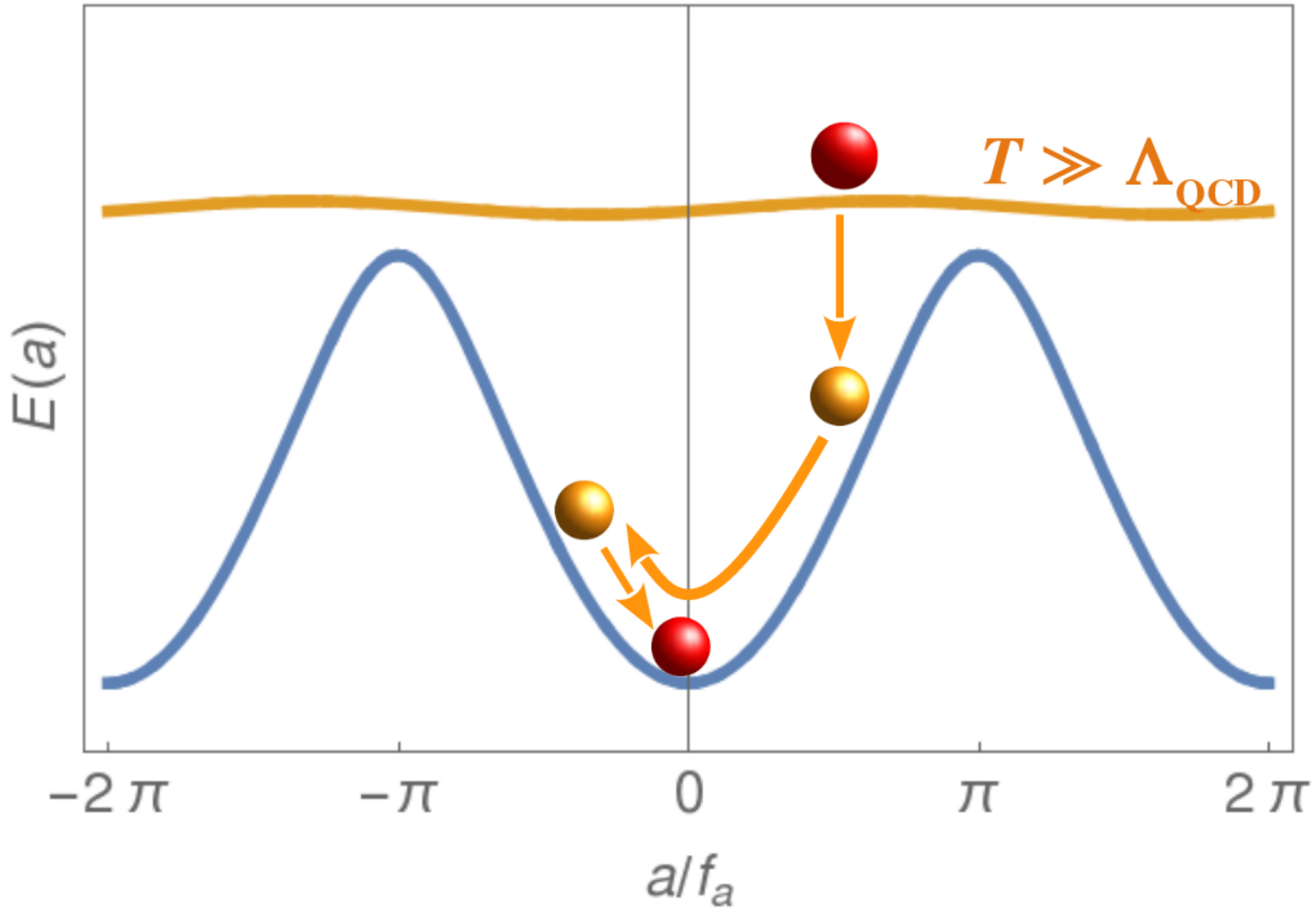
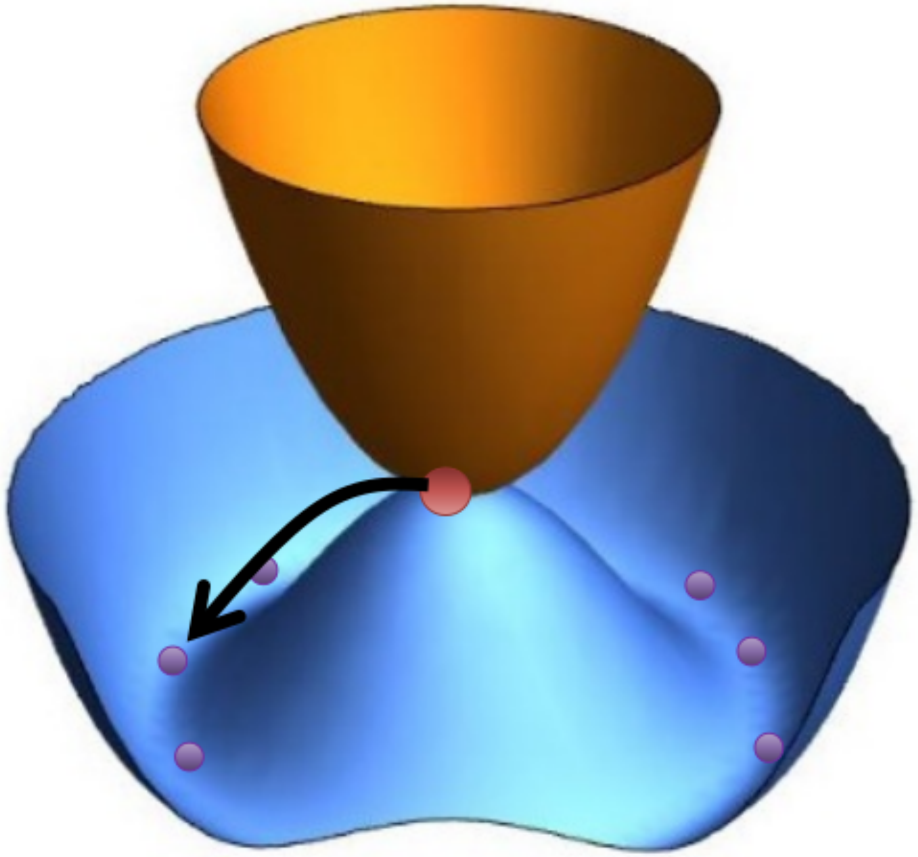


Dark matter

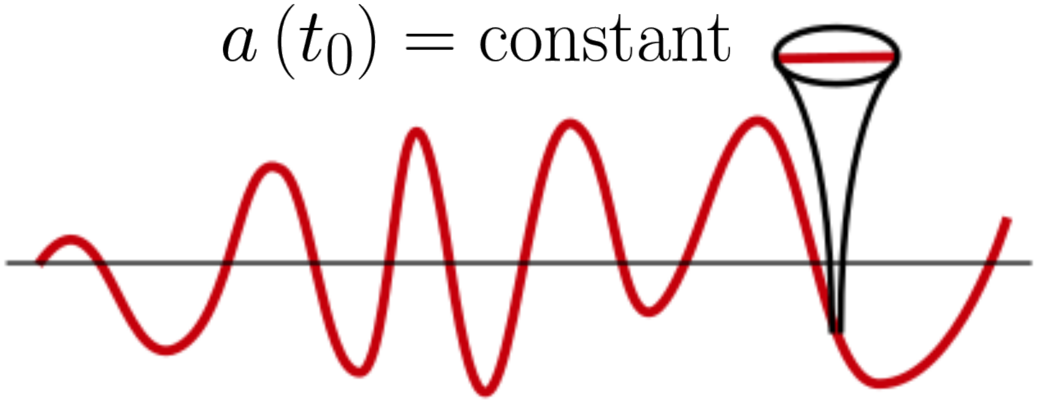
Immediately after U(1) breaking, the axion field is random over the universe:



Dark matter scenarios

$f_a > H_I$	$f_a < H_I$

$a\left(t_0\right) = \text{constant}$

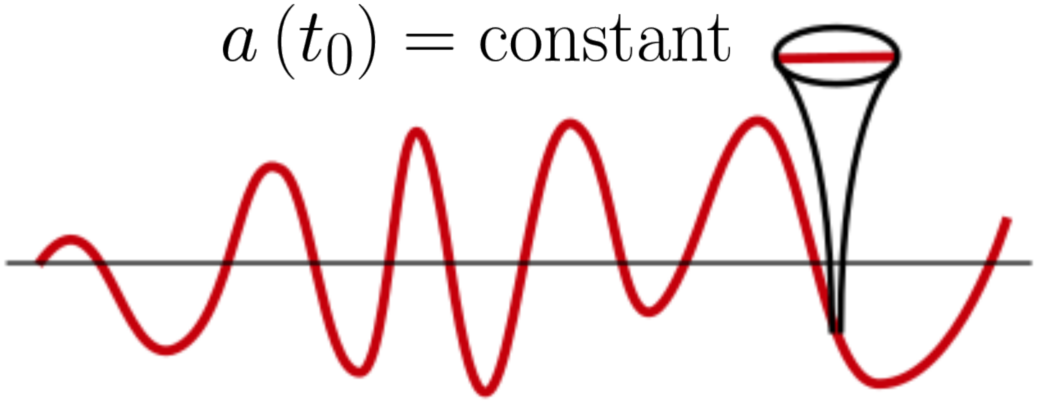


only contribution from misalignment
but not calculable

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

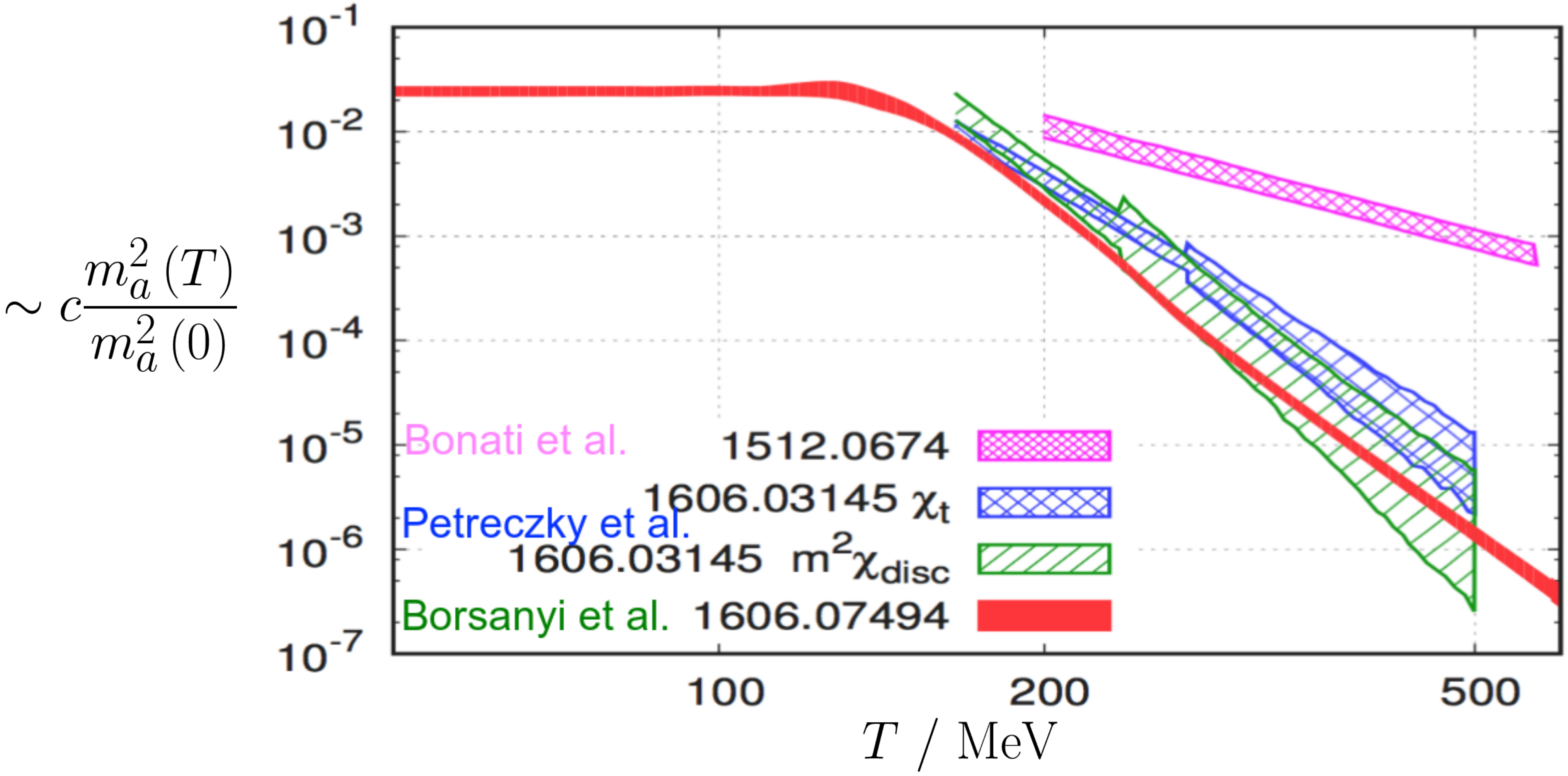
(For large f_a, i.e. small masses, the axion still solves the Strong CP problem, but is not DM)

Dark matter scenarios

$f_a > H_I$	$f_a < H_I$
$a\left(t_0\right) = \text{constant}$	$a\left(t_0\right) = \text{random}$
	misalignment contribution fixed $\theta_0^2 \approx \frac{\langle a^2 \rangle}{f_a^2} \approx (2.2)^2$
only contribution from misalignment but not calculable	extra axion from strings + domain walls large uncertainties
$\theta_0 < \pi \quad \Leftrightarrow \quad f_a \gtrsim 10^{12}\ \text{GeV}$	$\Omega_a > \Omega_a^{mis} \quad \Leftrightarrow \quad f_a < f_a^{mis} \sim 10^{12}\ \text{GeV}$

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

Temperature dependence of mass



[Borsanvi et al. 1606.079411]

Main uncertainty in maximum DM axion mass if U(1) breaking before inflation

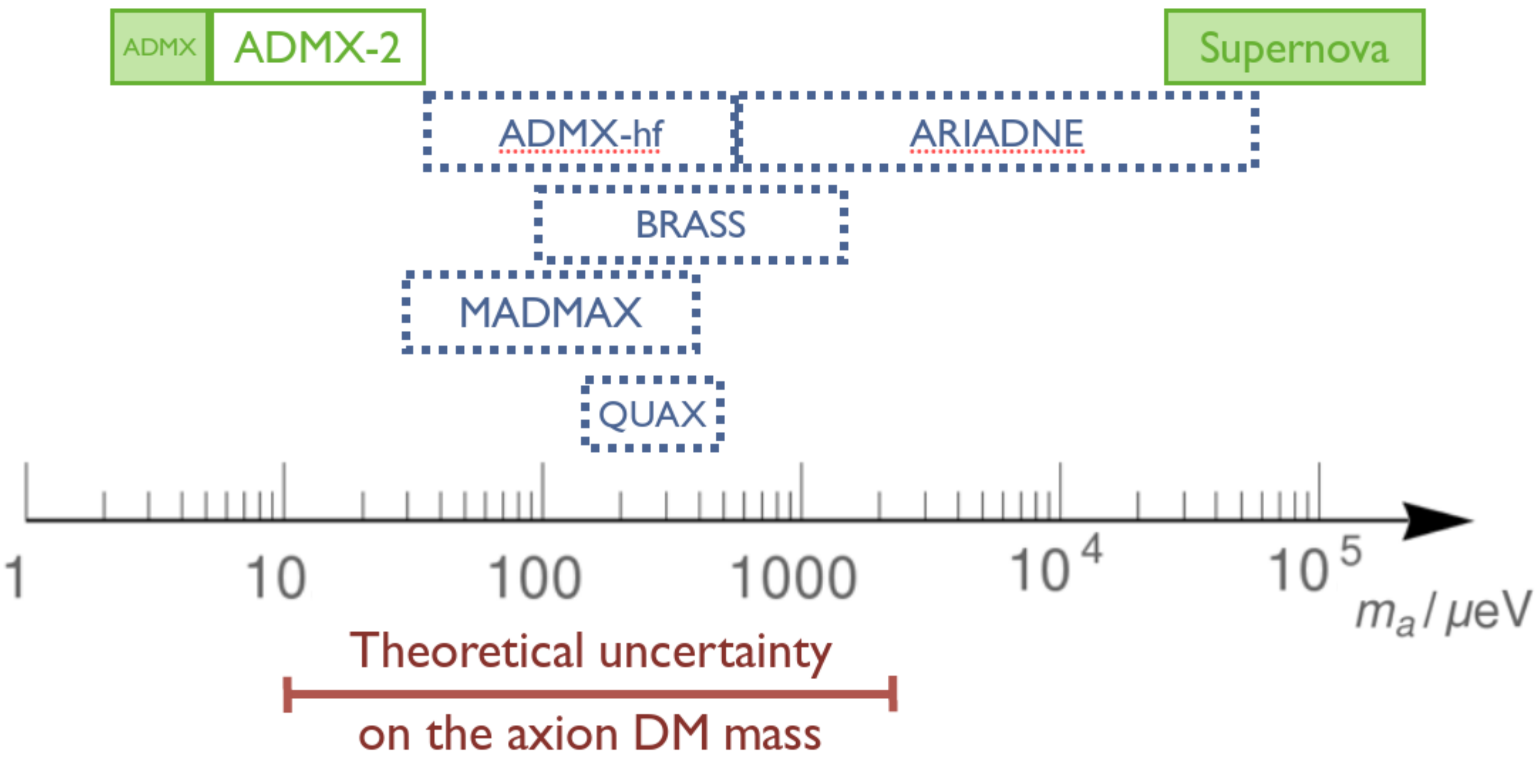
U(1) breaking after inflation

In principle extremely predictive

unique DM axion mass

Existing data (filled) and ongoing experiments (empty),

and possible future experiments (dotted) :

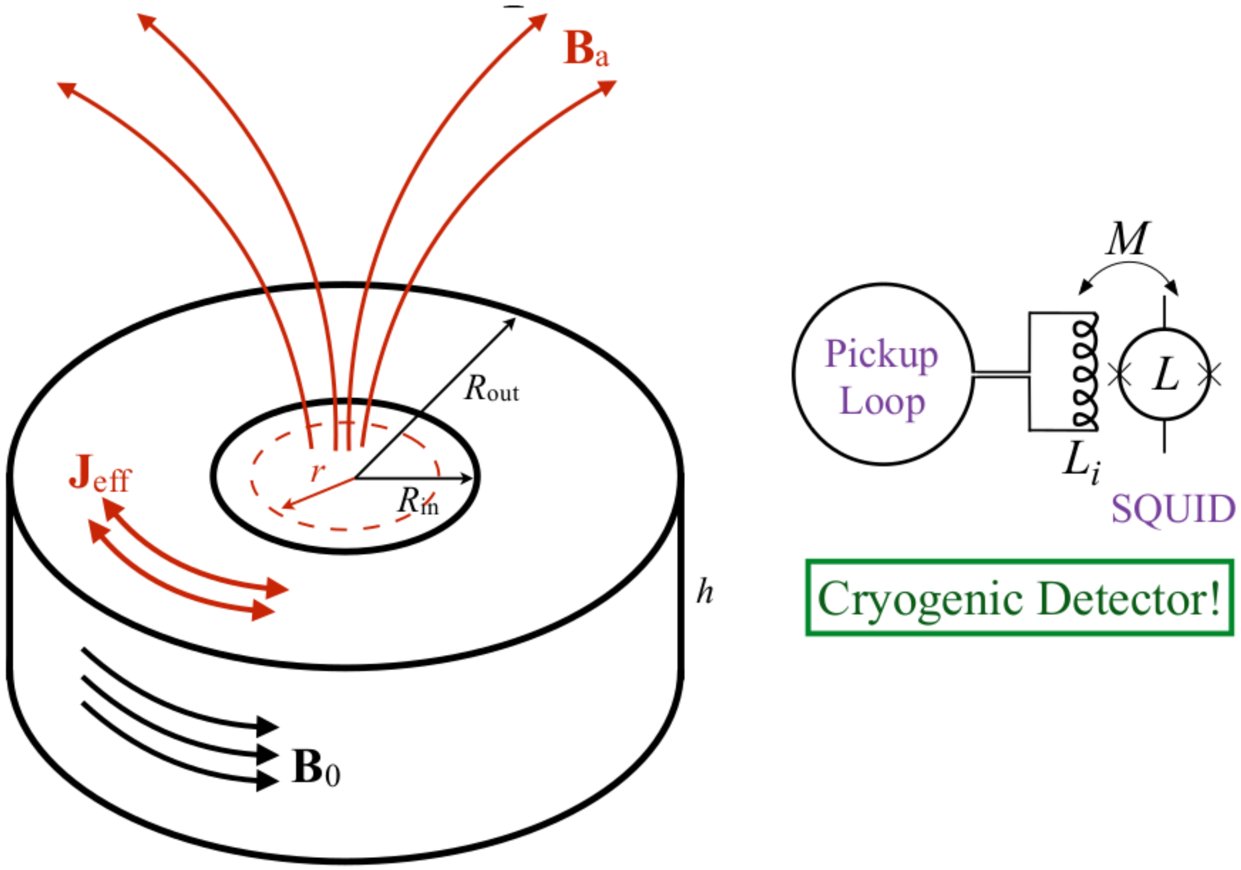


Reliable prediction: interpret ongoing experiments, design future experiments

Precise agreement with an experimental discovery → minimum inflation scale

Experimental searches

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



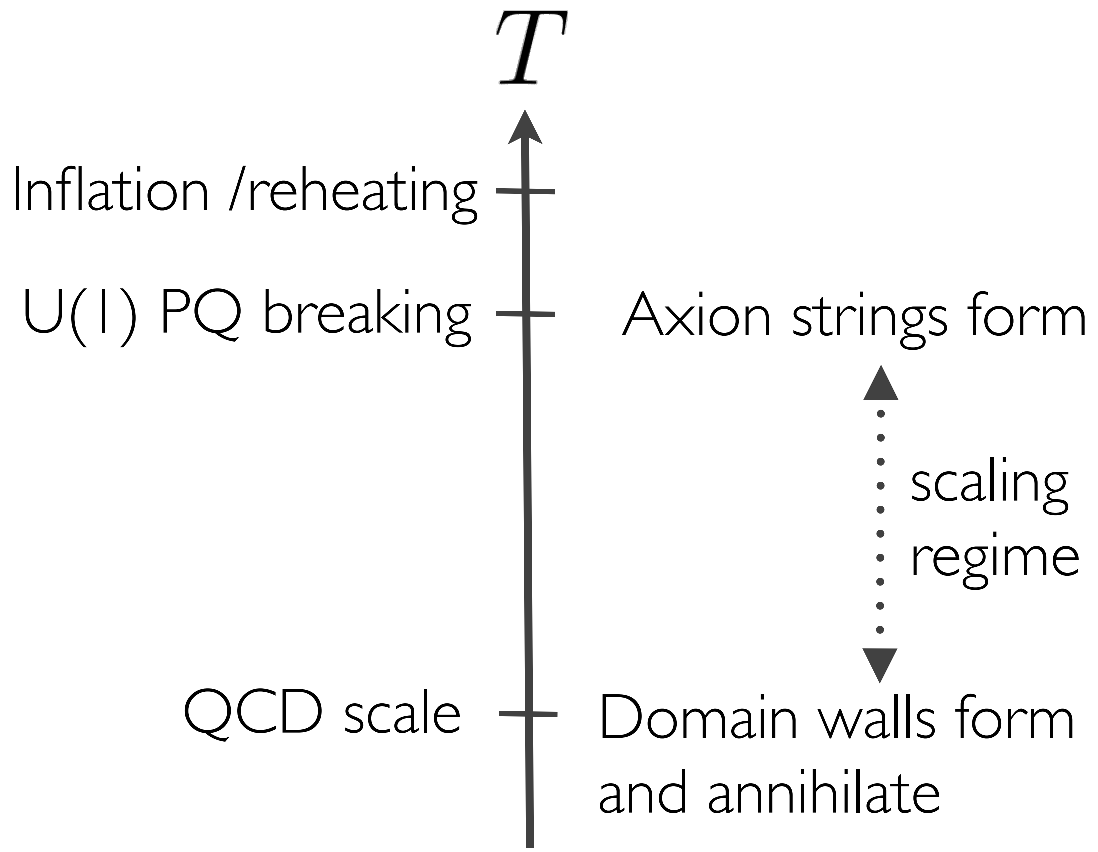
- Toroidal magnet with fixed magnetic field
- Axion DM generates oscillating current around the ring
- Produces oscillating magnetic field
- Detected by a sensitive pickup loop

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]

String and domain walls



Inflation /reheating

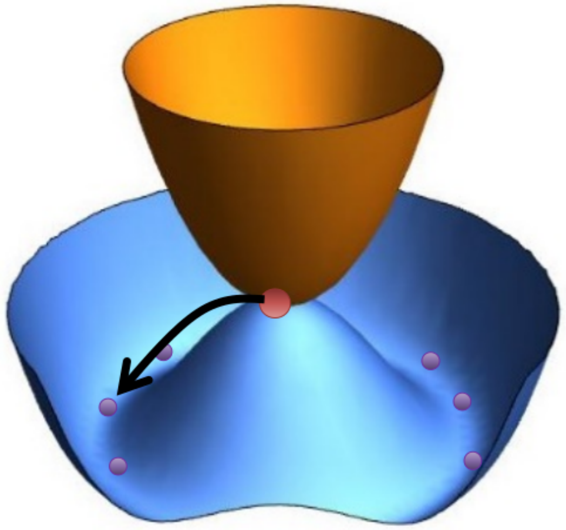
U(1) PQ breaking

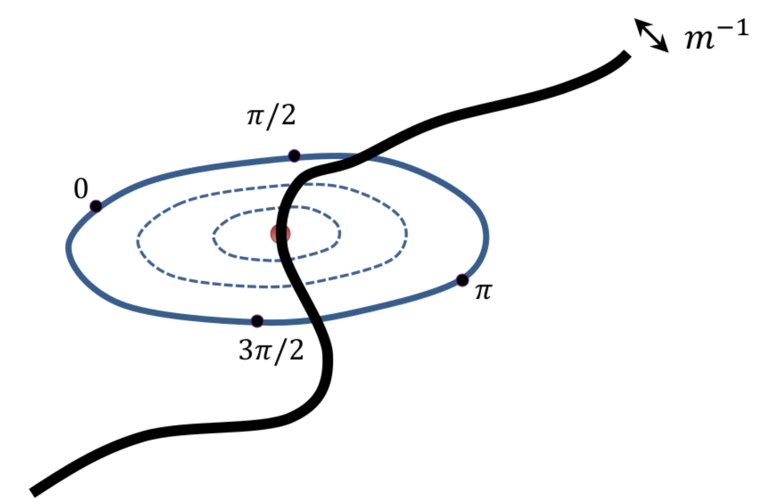
Axion strings form

scaling
regime

QCD scale

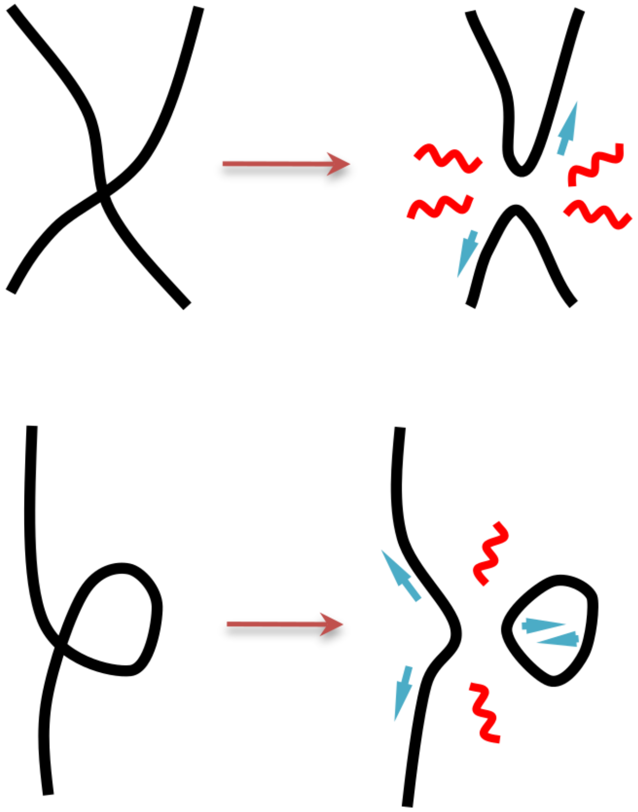
Domain walls form
and annihilate

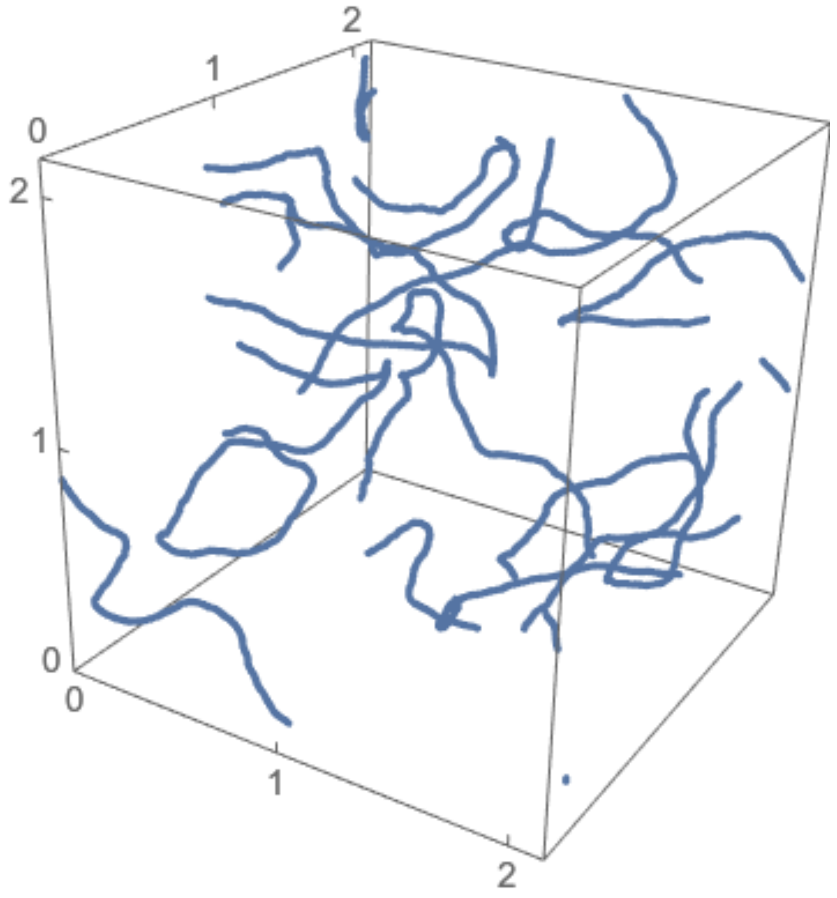




Significant proportion of DM axions
produced by strings and domain walls

String and domain walls





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

Instead resort to numerical simulations

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 $H^{-1} \simeq \frac{M_{\text{pl}}}{T^2} \simeq \frac{M_{\text{pl}}}{\Lambda_{\text{QCD}}^2}$

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

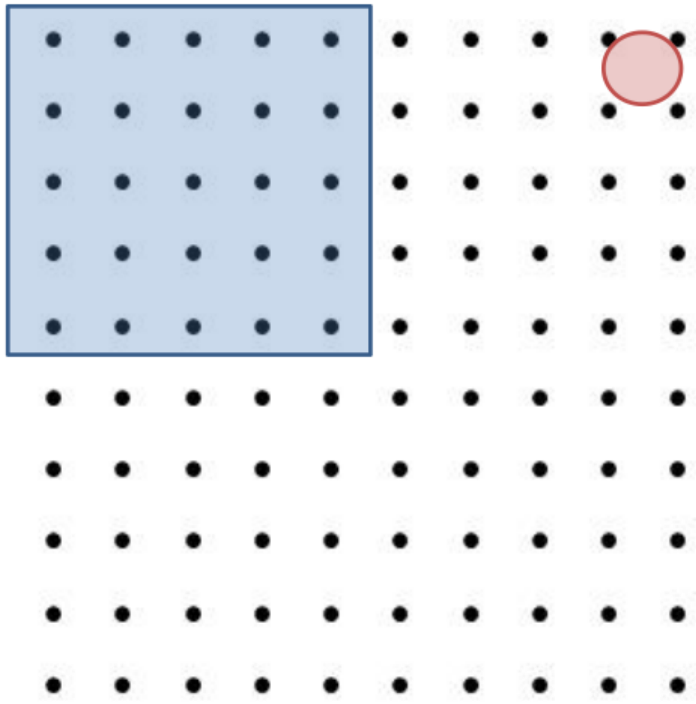
$$\text{tension} = \frac{E}{L} \sim \pi f_a^2 \log\left(\frac{f_a}{H}\right) =: \pi f_a^2 \log(\alpha)$$

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

Why it's hard

Numerical simulations need

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



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

physical: $\log\alpha \sim 70$

Even using clusters/ parallelisation, can only simulate grids with $\sim 1000^3$ points

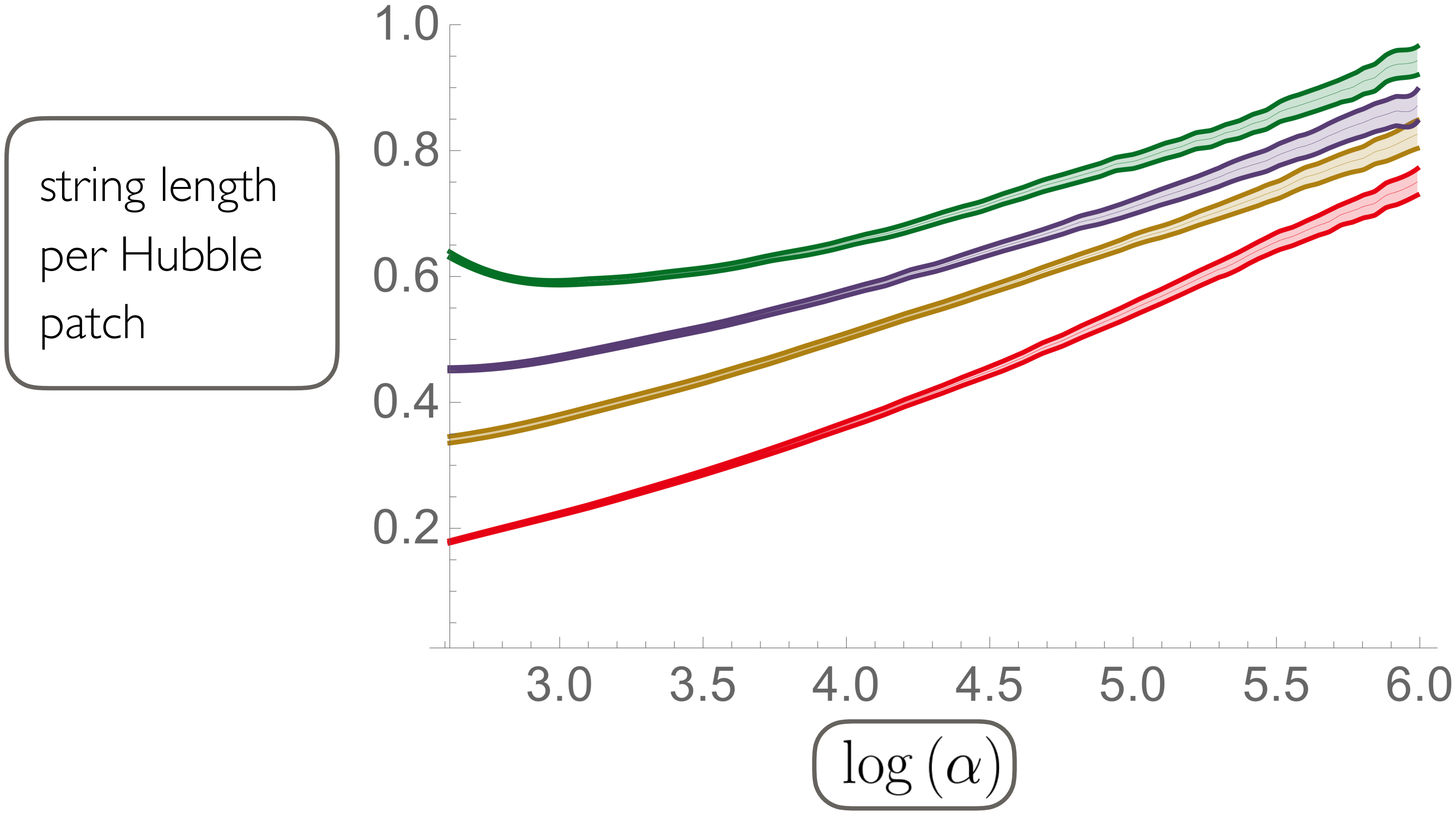
Current attempts just give results at small scale separation

Instead we extrapolate

String length per Hubble volume

Energy in string network at QCD phase transition ~ length of strings per Hubble volume

We find a log increase, robust to changing the initial conditions



If extrapolation is valid, grows to ~15 at QCD scale

Changes the prediction for the axion DM mass by a factor ~ 10

[Azatov, Gorghetto, EH, Villadoro, ongoing]

Energy from strings to axions

Theoretical expectation:

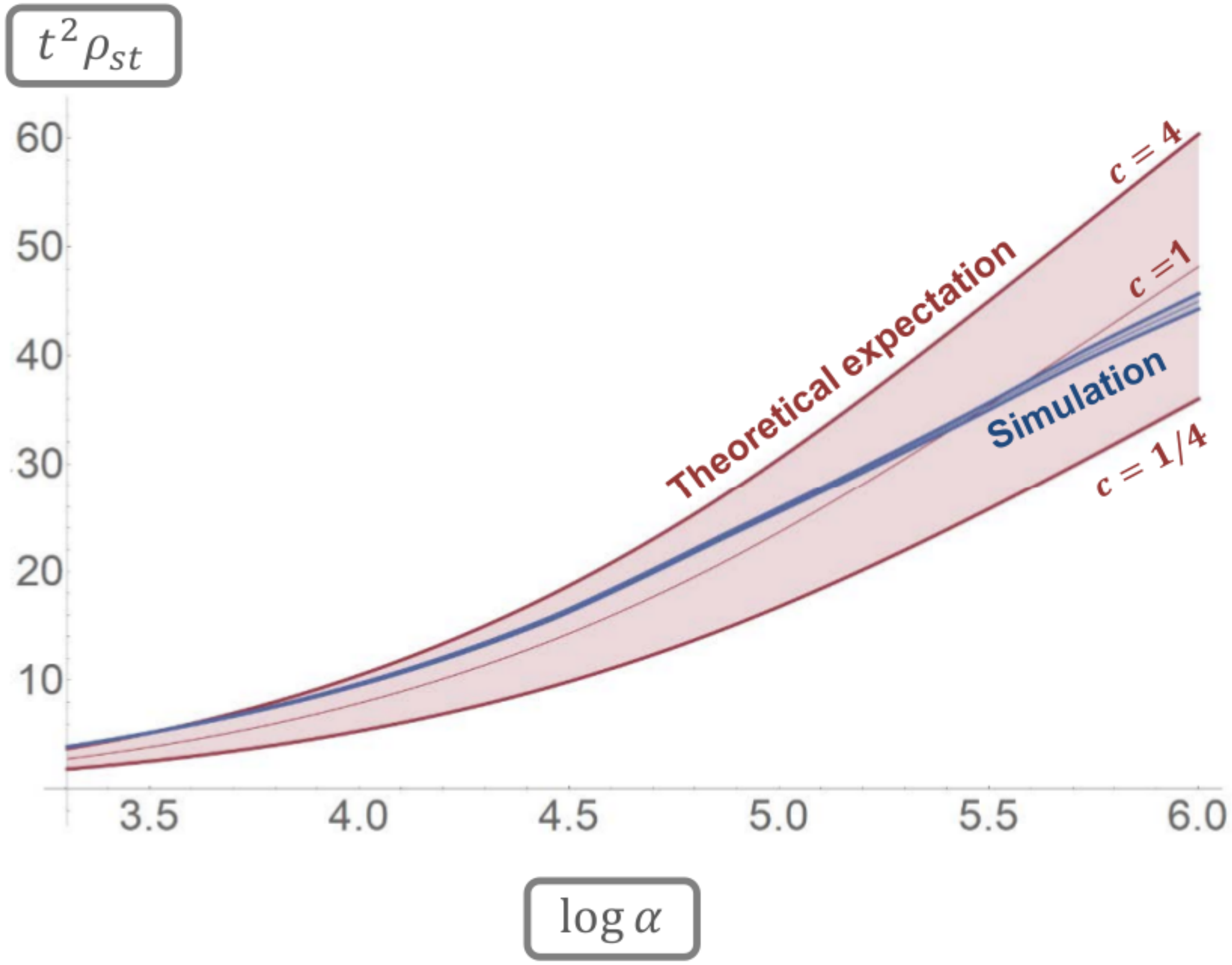
Energy per unit length of **one** string $= \pi f_a^2 \log \alpha$

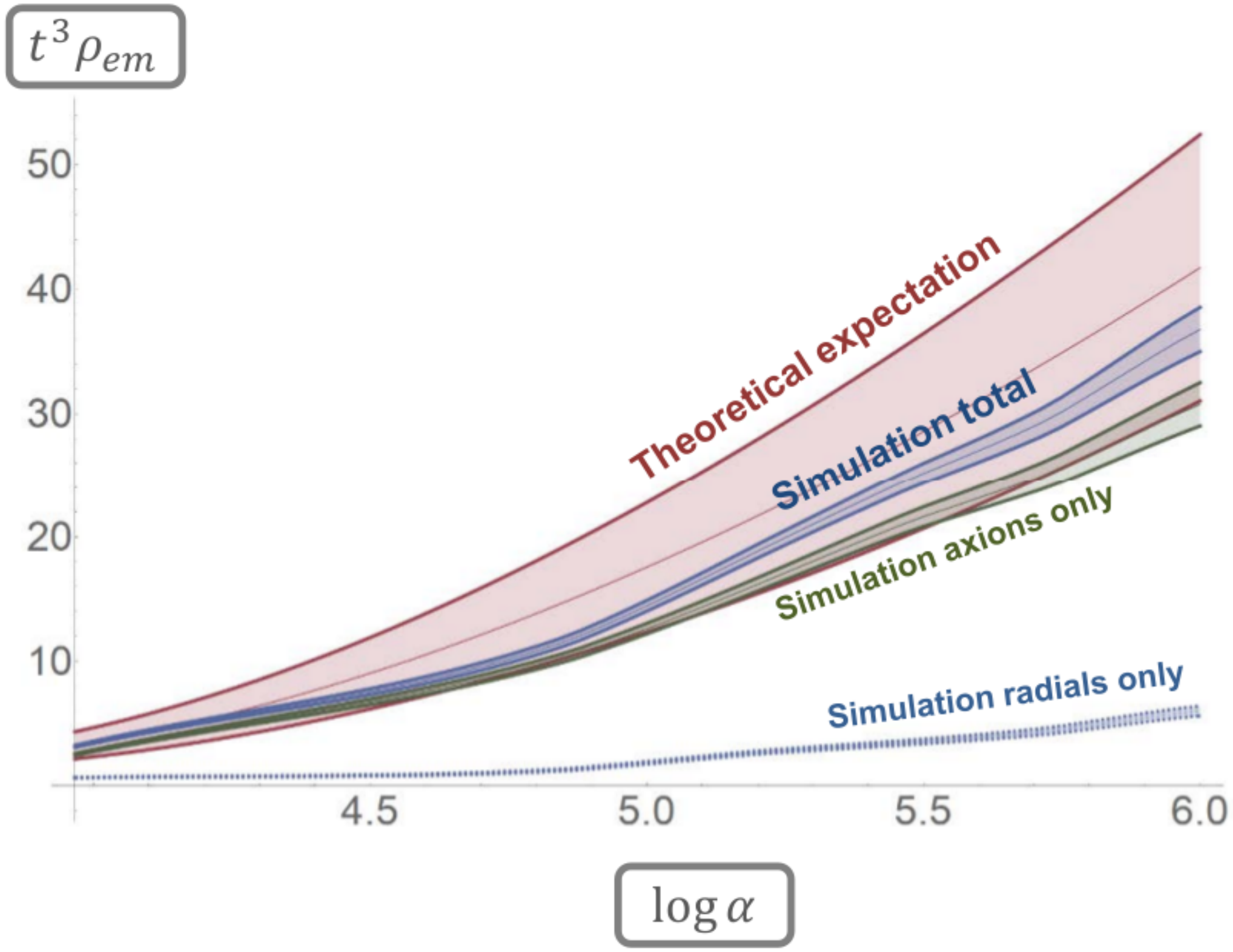
Energy density of the network

$$\rho_{st} = \xi \frac{\mu}{t^2} \qquad (\xi \sim \log \alpha)$$

Energy emission from strings

$$\rho_{em} = \frac{\delta(\rho_{free} - \rho_{st})}{\delta t}$$





Cooling bounds on other new light particles

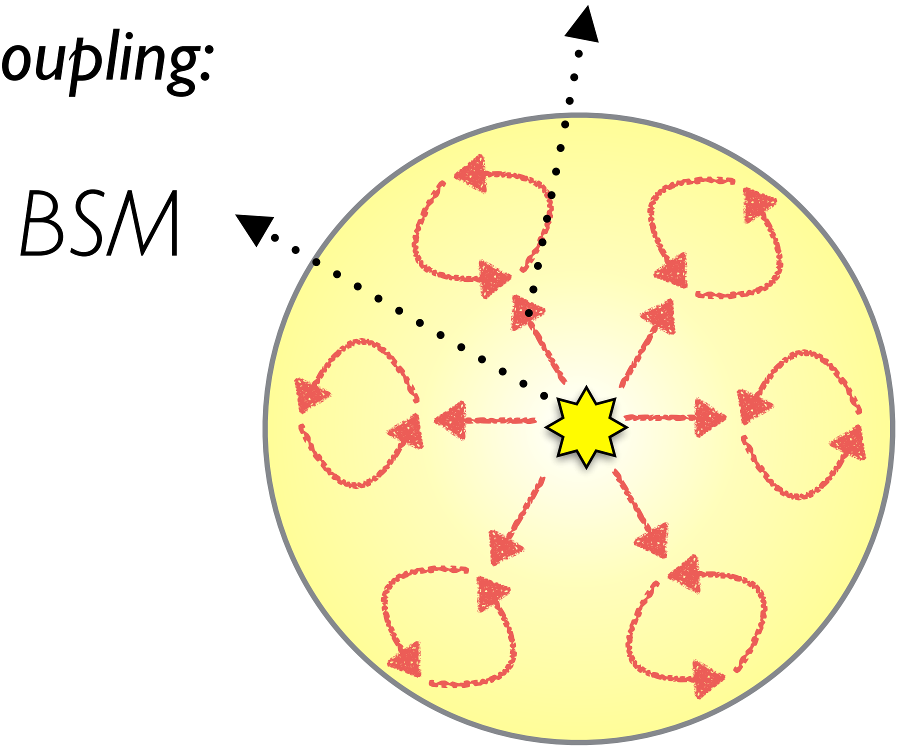
Cooling bounds

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

Leads to anomalous energy transport, often called "cooling"

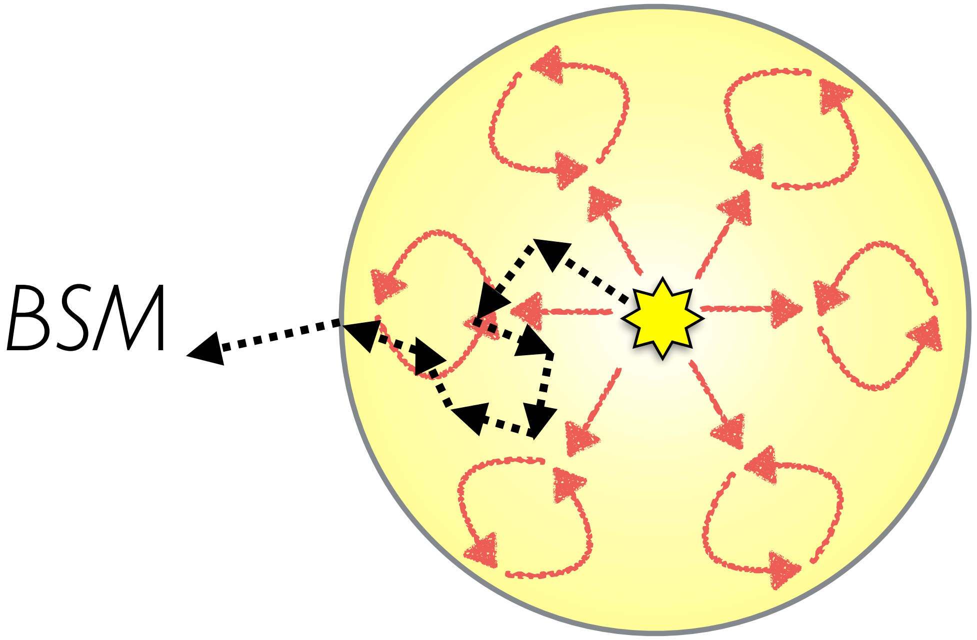
Especially systems that have inefficient SM energy-loss:, e.g. surface photon emission

Weak coupling:



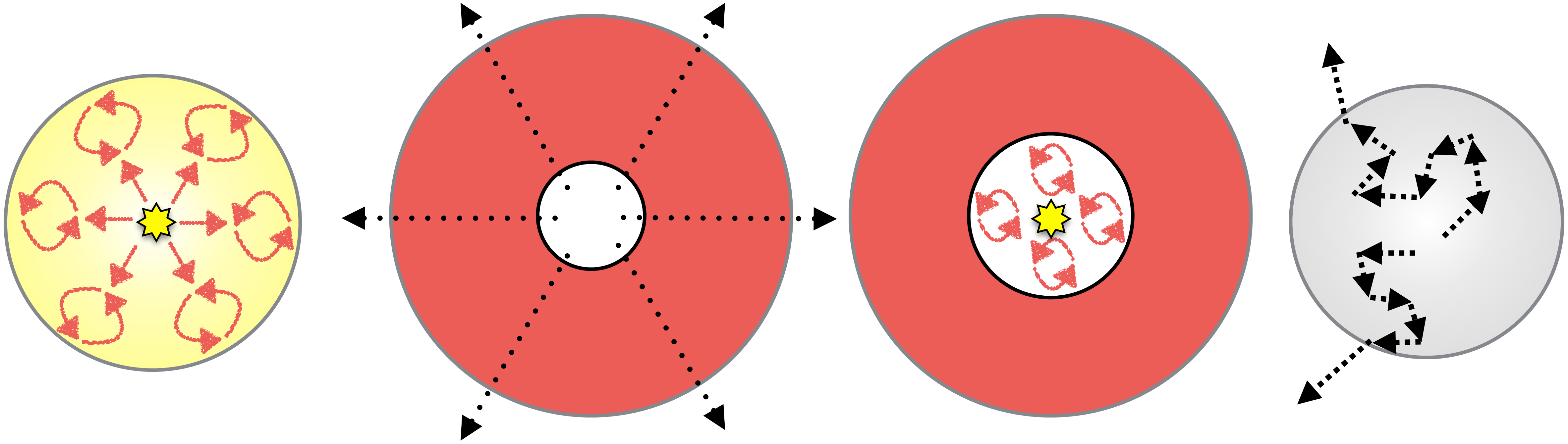
BSM volume emission

Strong coupling:



BSM heat transfer

Systems to observe



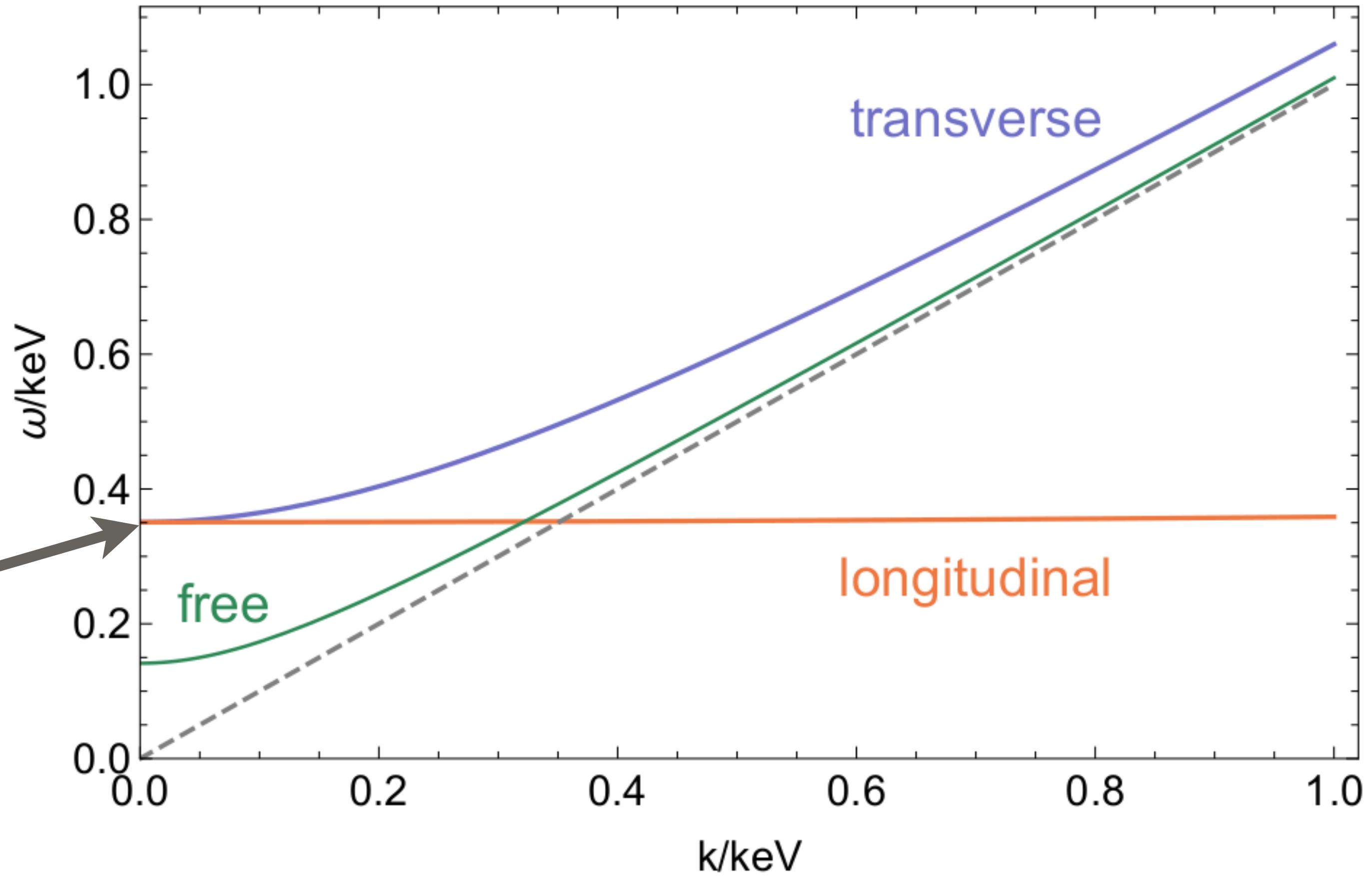
	Sun	RG	HB	SN
T_{core}	keV	10 keV	10 keV	50 MeV
ϵ_{max}	$0.2\ \text{erg g}^{-1}\ \text{s}^{-1}$	$10\ \text{erg g}^{-1}\ \text{s}^{-1}$	$10\ \text{erg g}^{-1}\ \text{s}^{-1}$	$10^{19}\ \text{erg g}^{-1}\ \text{s}^{-1}$
	Solar structure	Core mass at helium ignition	Helium burning lifetime	SN1987A neutrino burst

Need for plasma effects

Previous calculations assumed "kinetic theory" approach

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

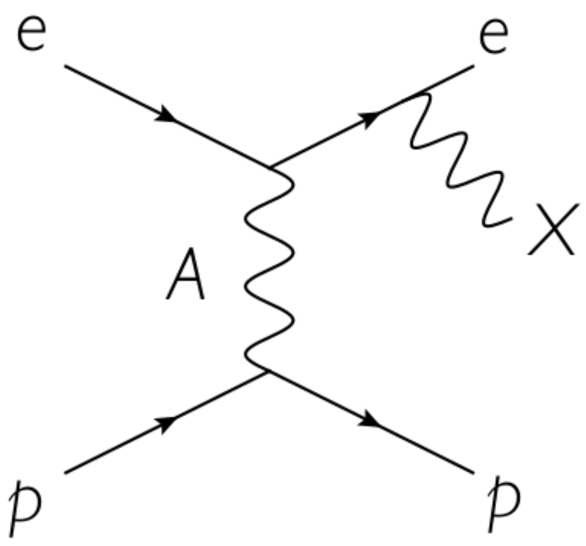
But plasma effects: photon longitudinal mode, resonances, sometimes suppressed emission



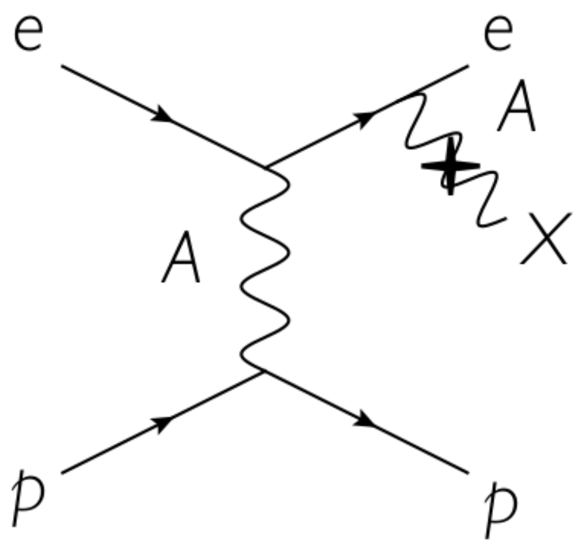
Plasma frequency of medium

[E.H, R. Lasenby, JHEP 1702 (2017) 033]

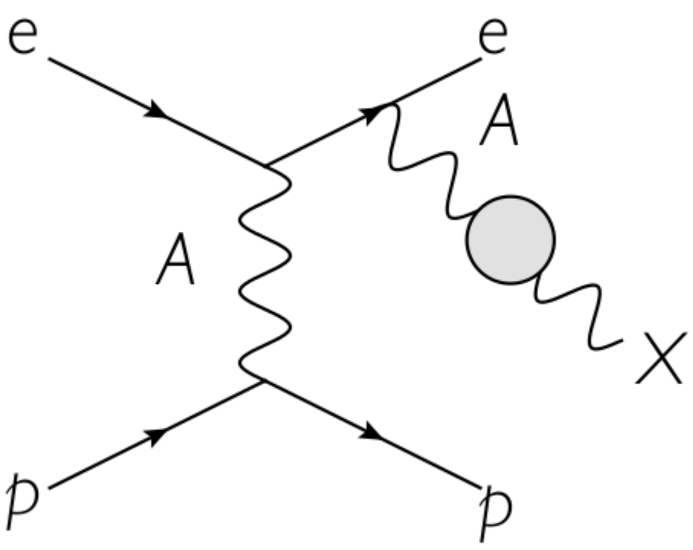
Cooling bounds



“Naive”
production rate



If X not a propagation
eigenstate, have mixing
contributions



Propagation
eigenstates in medium
not the same as those
in vacuum

Higgs portal scalar

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

mass eigenstates after rotating $\begin{pmatrix} H \\ \Phi \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$

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

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

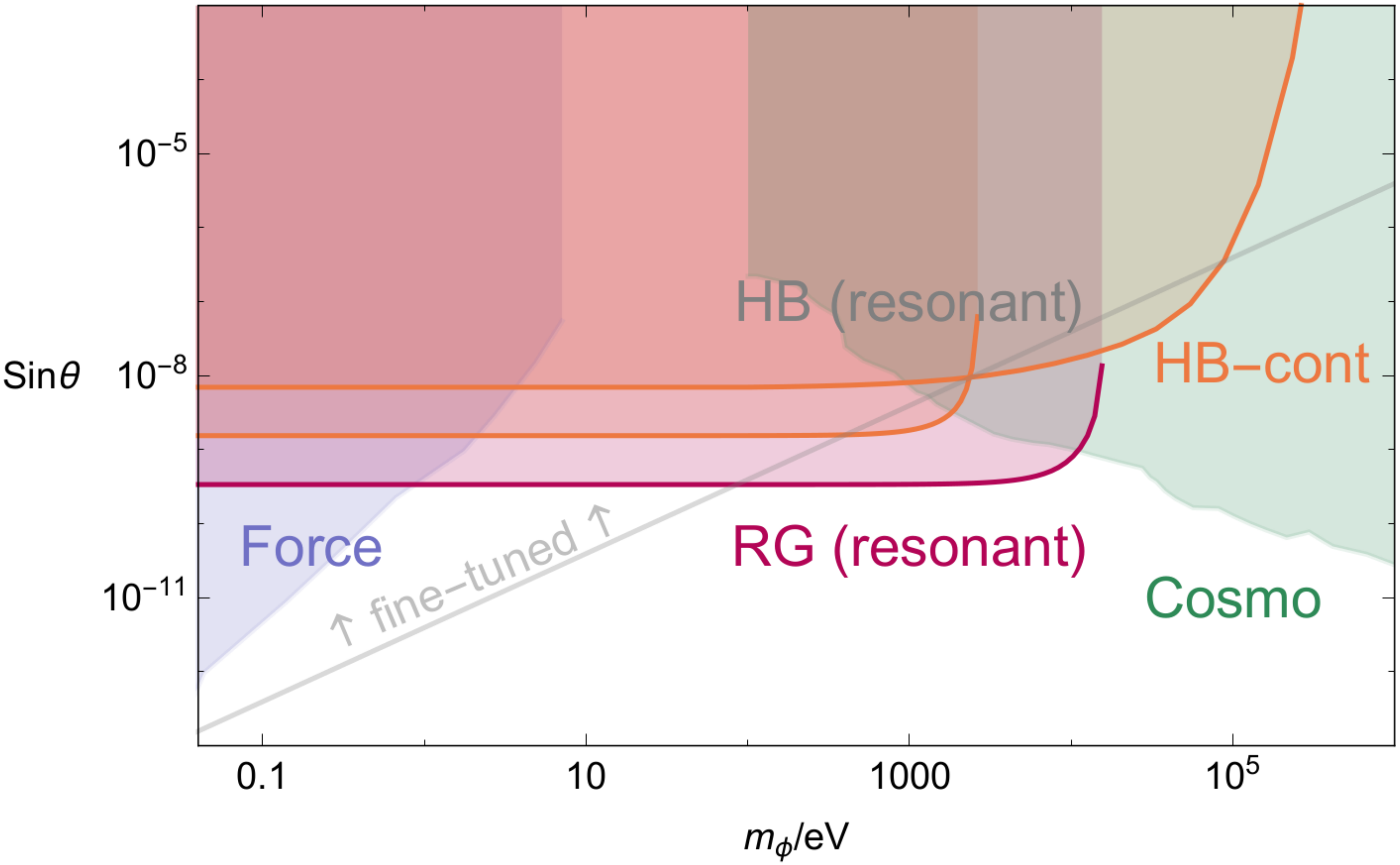
No scalar states in low energy SM, so no mixing in vacuum

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

Allows resonant production when $m_\phi \lesssim$ plasma frequency

Higgs portal scalar

$$g_{\phi\bar{e}e}/g_{\phi\bar{N}N} \simeq 2\times10^{-3} > m_e/m_n \simeq 5\times10^{-4}$$

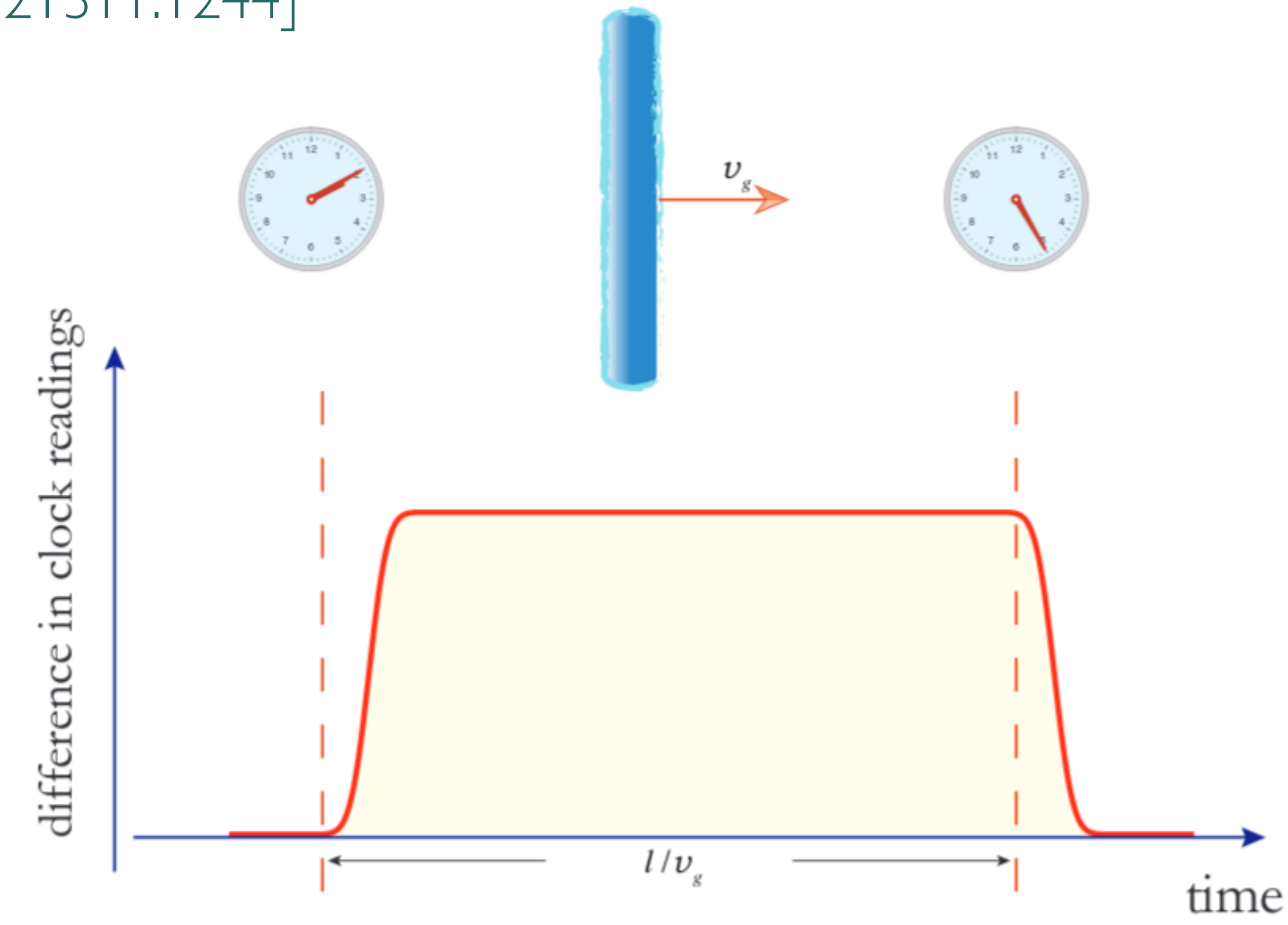


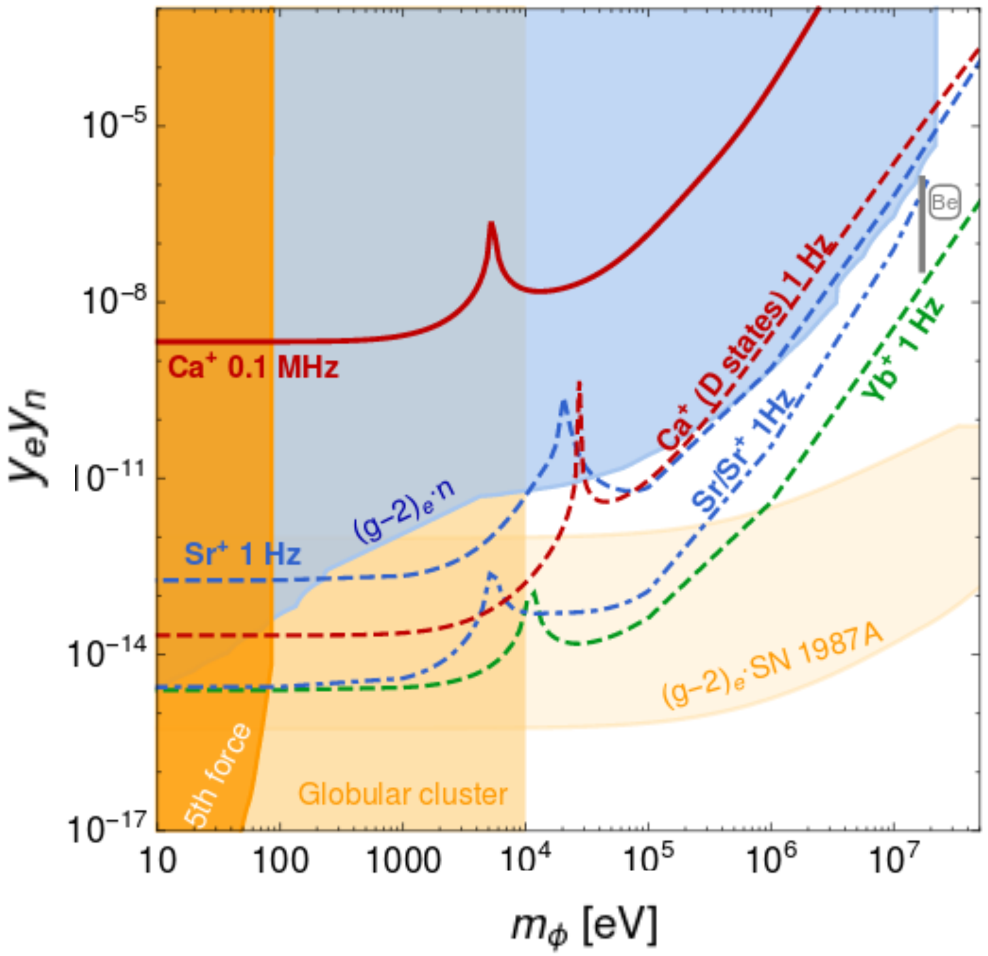
New experiments: light scalars

Interesting proposals using high precision low energy experiments (along with existing constraints)

Atomic clocks

Transient change in speed due to dark matter objects/ e.g. domain walls, dilaton DM [Derevianko & Pospelov, 121311.1244]





Precision spectroscopy

Compare measurements and theory predictions of spectral lines

[Delaunay et al. 1709.02817]

Dark photons

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

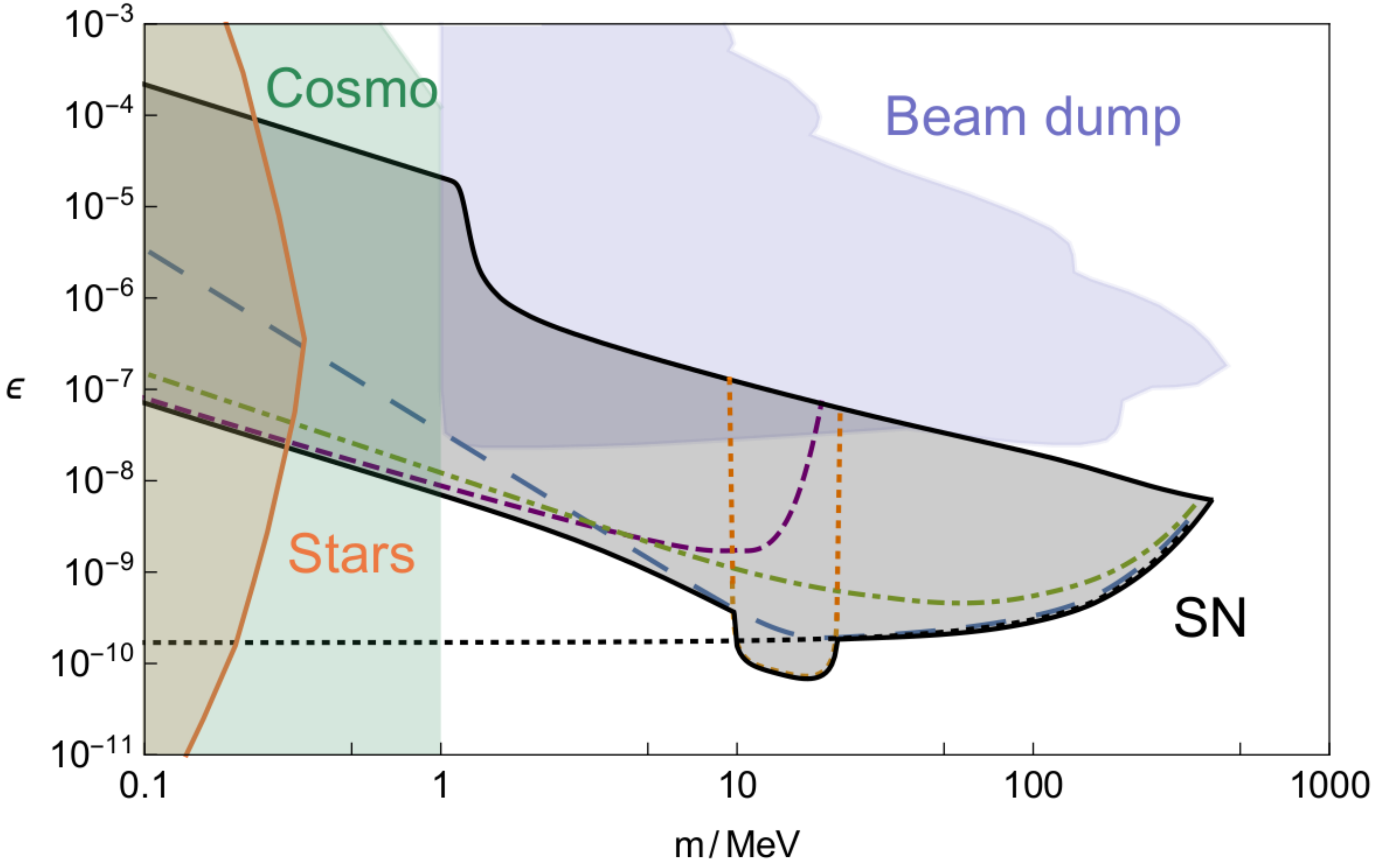
$$\boxed{\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{1}{4}F'^2 + \frac{1}{2}m^2 A'^2 + eJ(A + \epsilon A')}$$

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

Kinetic mixing induced by heavy states charged under visible and hidden sector U(1) is not suppressed

$$\Delta\epsilon \sim \frac{g' e}{12\pi^2} \log\left(\frac{\Lambda_{\mathrm{UV}}}{M^2}\right)$$

Dark photon supernova



- Too much energy loss would disrupt neutrino burst
- Constrains region probed by future beam dump experiments

Summary

QCD axion:

- Zero temperature properties have been calculated precisely
- Calculation of DM abundance is ongoing work, aiming for a reliable prediction
- Potentially order of magnitude change compared to previous work

Cooling bounds:

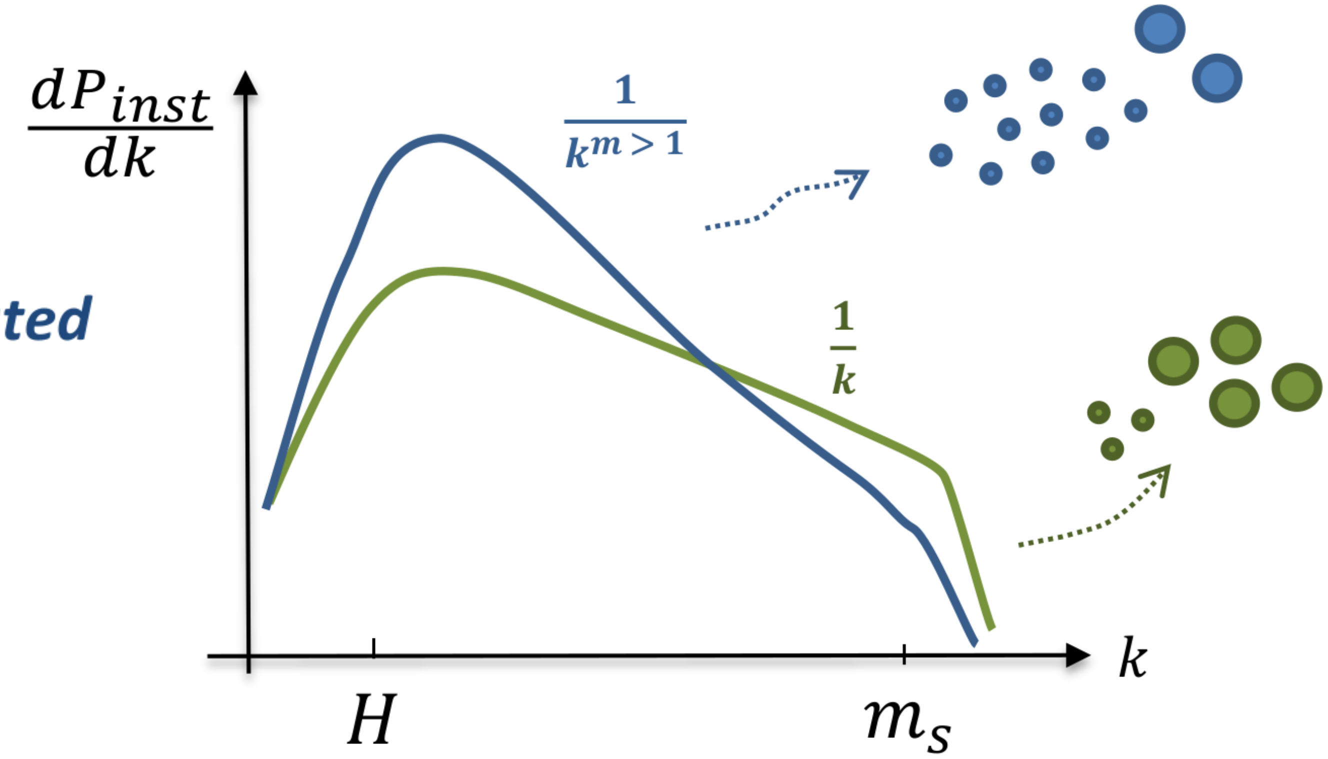
- Competitive with laboratory / collider experiments
- To calculate these reliably, must include finite temperature corrections
- Resonant production strengthens bounds by more than a factor of 10

Conclusions

- Light particles are a motivated scenario for new physics, both from UV model building and phenomenology perspectives
- Experimental progress is reasonably cheap and fast, many exciting new ideas
- Theoretical input is important, and significant uncertainties remain

Thanks

Distribution of axion momenta



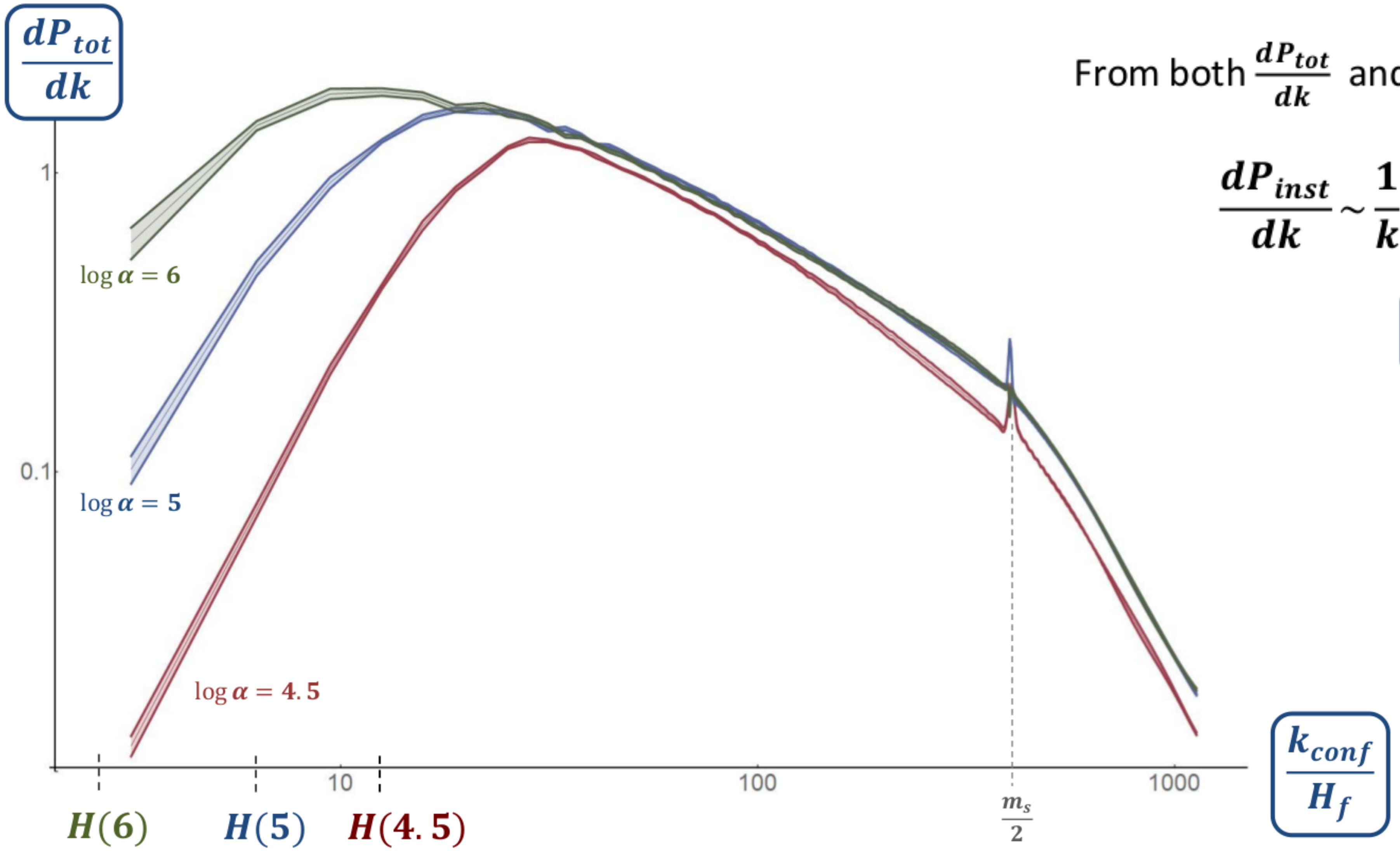
$\frac{dP_{inst}}{dk}$ $\equiv$ ***spectrum of axions radiated***

(1) $\frac{dP_{inst}}{dk} \sim \frac{1}{k^m}$ "soft" spectrum with $\langle k^{-1} \rangle \propto H^{-1}$ Davis, Shellard, Dabholkar, … '89-'99

$\boxed{m > 1}$

(2) $\frac{dP_{inst}}{dk} \sim \frac{1}{k}$ "hard" spectrum with $\langle k^{-1} \rangle \propto \frac{H^{-1}}{\log \alpha}$ Sikivie et al. '89

Spectrum from simulation



From both $\frac{dP_{tot}}{dk}$ and $n_{ax} = \int \frac{dk}{k}\frac{dP_{tot}}{dk}$:

$$\frac{dP_{inst}}{dk} \sim \frac{1}{k} \quad \text{for } \log\alpha \lesssim 6$$

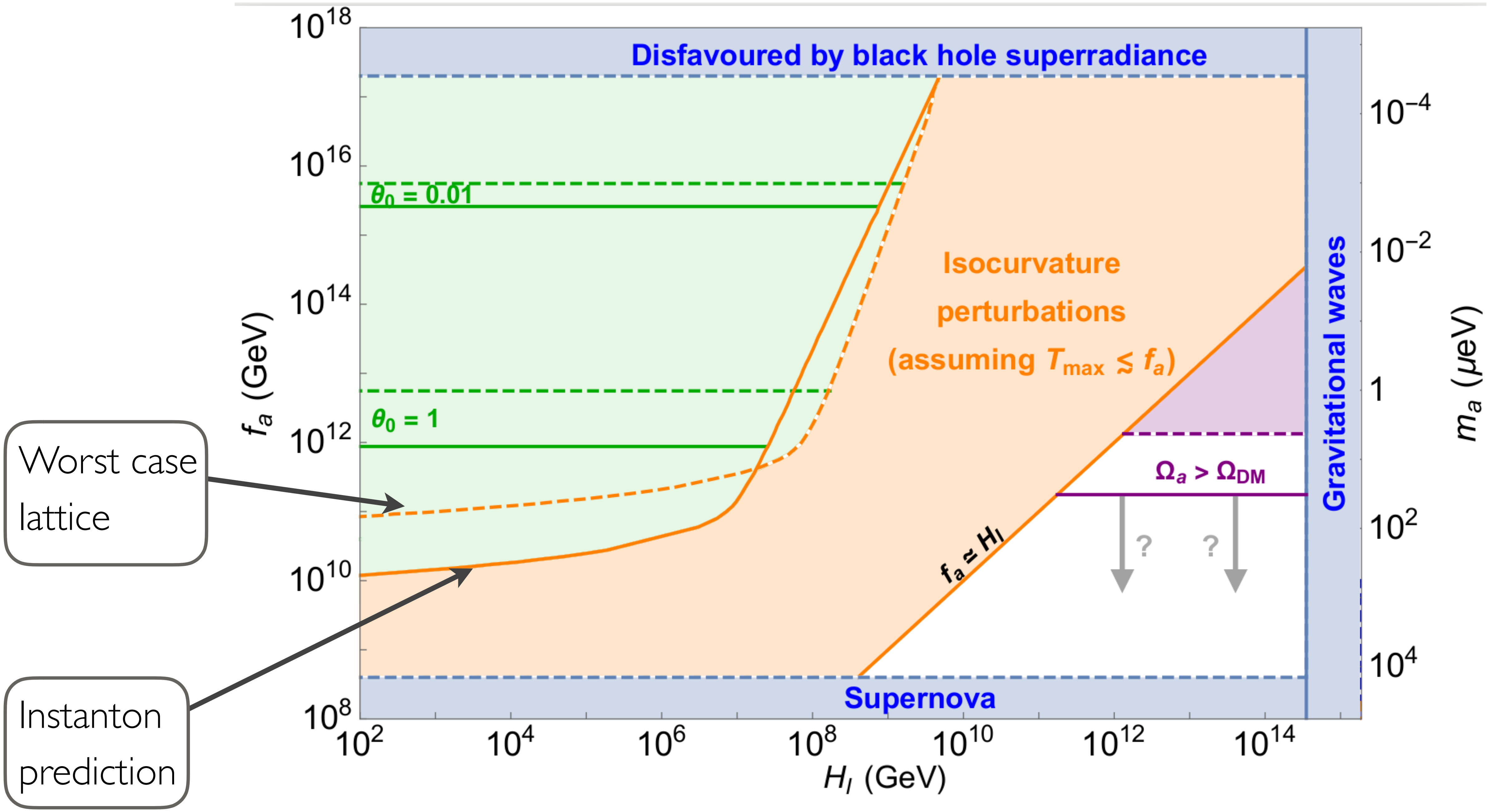
Preliminary!

$$\frac{n_{strings}}{n_{misal}} = 0.8\ \underset{\overset{\uparrow}{\sim 10}}{\xi(H_*)}\ F(m)$$

$F(m = 1) = 1$

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

Cosmology



Worst case lattice

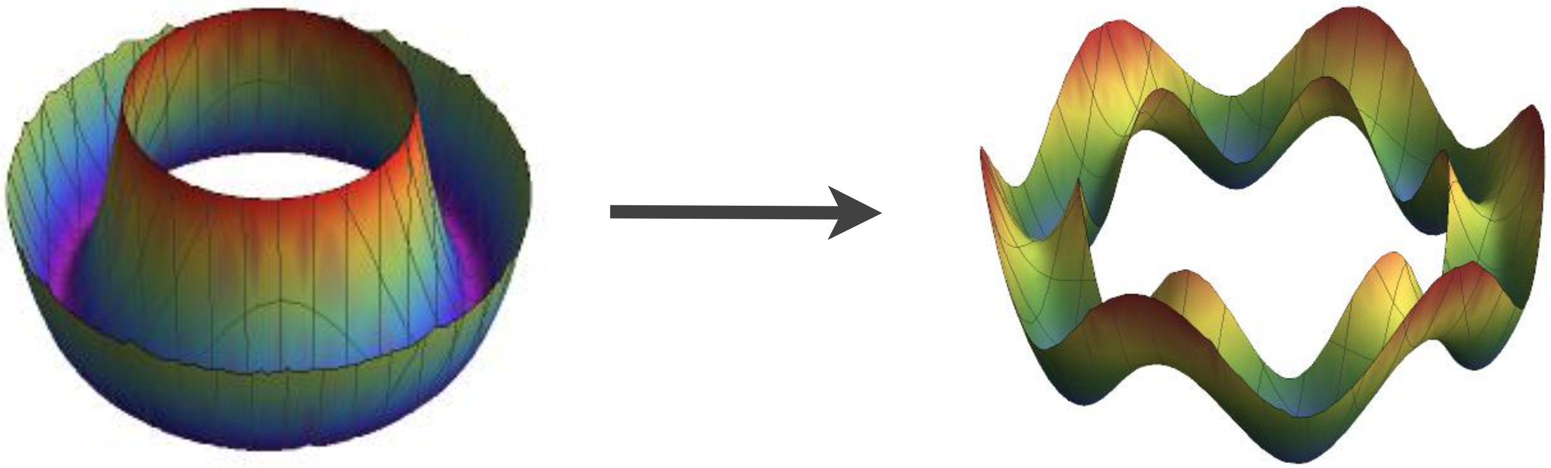
Instanton prediction

If PQ symmetry is broken before inflation, constant axion VEV over observable universe

Domain walls

Two populations of axions released due to topology: those emitted by strings just before axion mass turns on, and those emitted when the network is destroyed (along with the misalignment contribution)

Need to also 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

Possibly crucial dynamics have previously been neglected

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?