Axion Detection With NMR

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with

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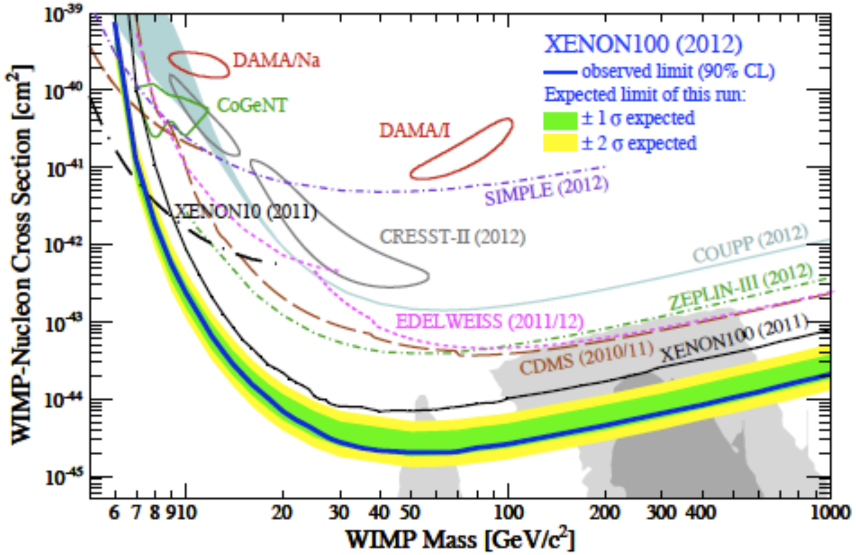
PRD **84** (2011) arXiv:1101.2691
+ to appear

Dark Matter Motivation

two of the best candidates: WIMPs and Axions



many experiments search for WIMPs,
only one (ADMX) can search for axion DM

currently challenging to discover axions in
most of parameter space

Important to find new ways to detect axions

the QCD axion solves the Strong CP problem

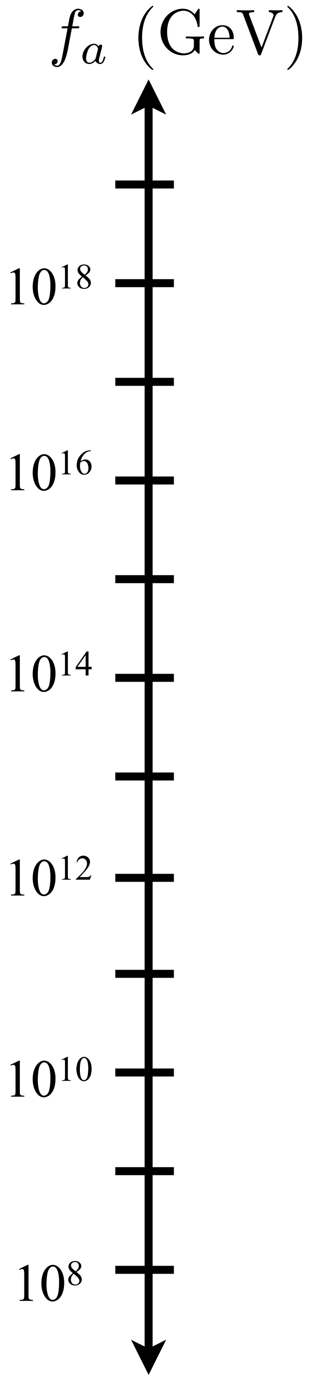
Easy to generate axions from high energy theories

have a global PQ symmetry broken at a high scale f_a

string theory or extra dimensions naturally have
axions from non-trivial topology Svrcek & Witten (2006)

naturally expect large $f_a \sim$ GUT (10^{16} GeV), string, or Planck (10^{19} GeV) scales

Constraints and Searches



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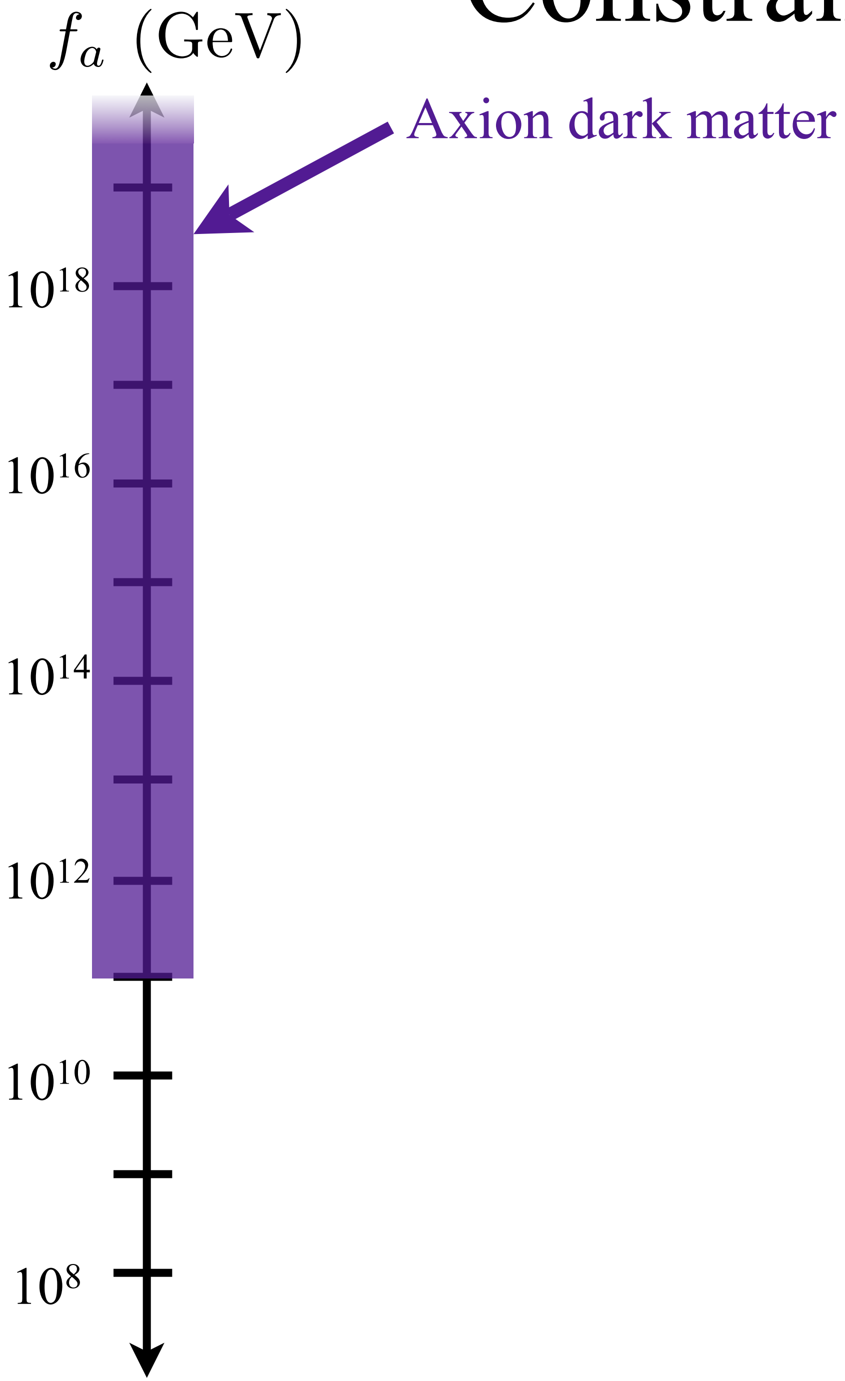

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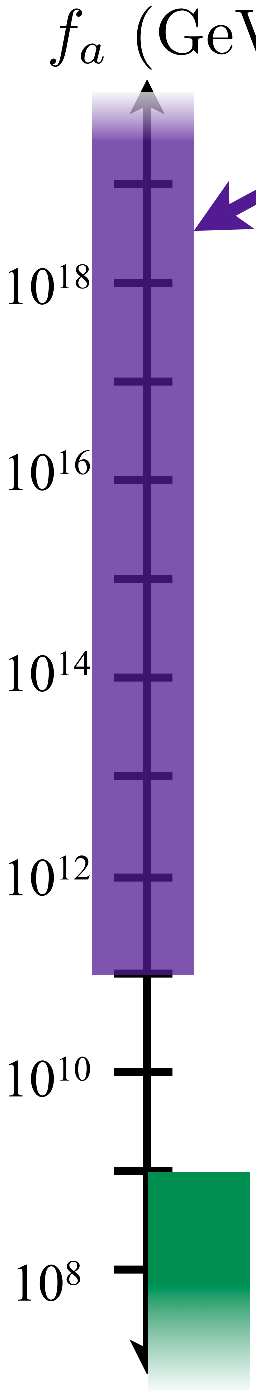
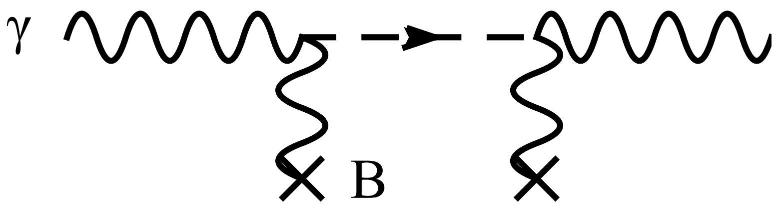


Axion dark matter

in most models: $\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B}$

laser experiments:



$\propto \frac{1}{f_a^4}$

axion emission affects SN1987A, White Dwarfs, other astrophysical objects

collider & laser experiments, ALPS, CAST

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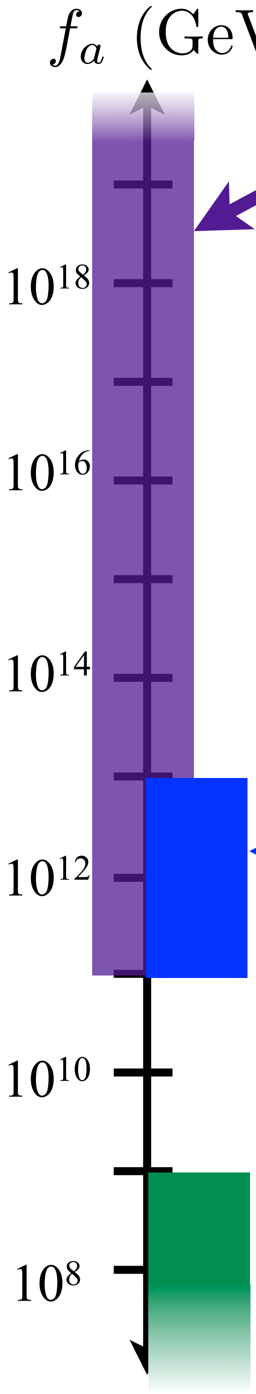

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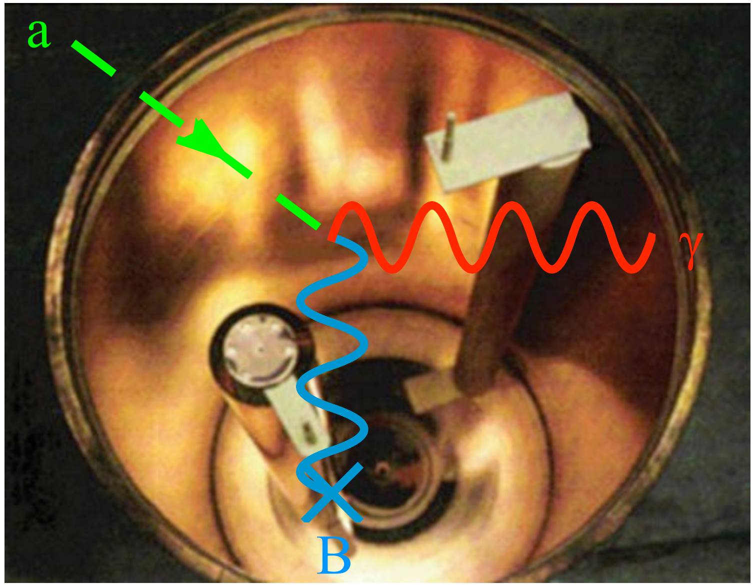

axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

size of cavity increases with f_a

signal $\propto \frac{1}{f_a^3}$

microwave cavity (ADMX)

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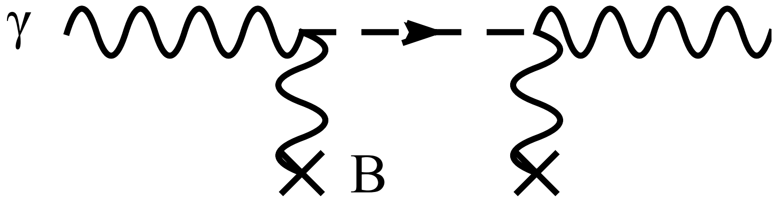

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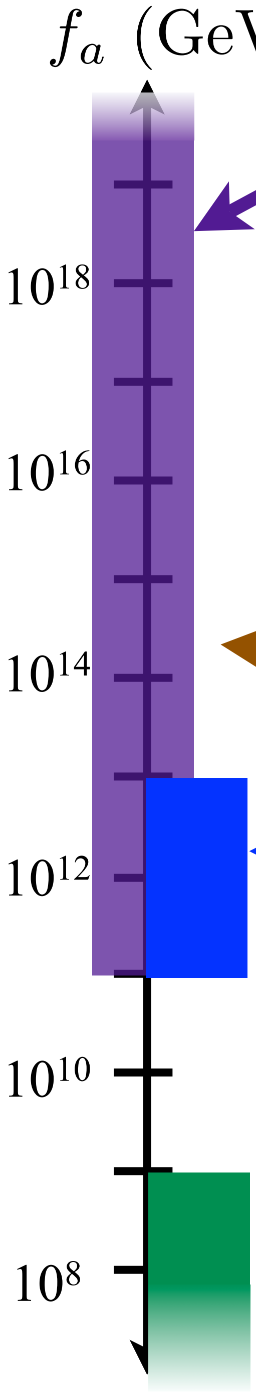

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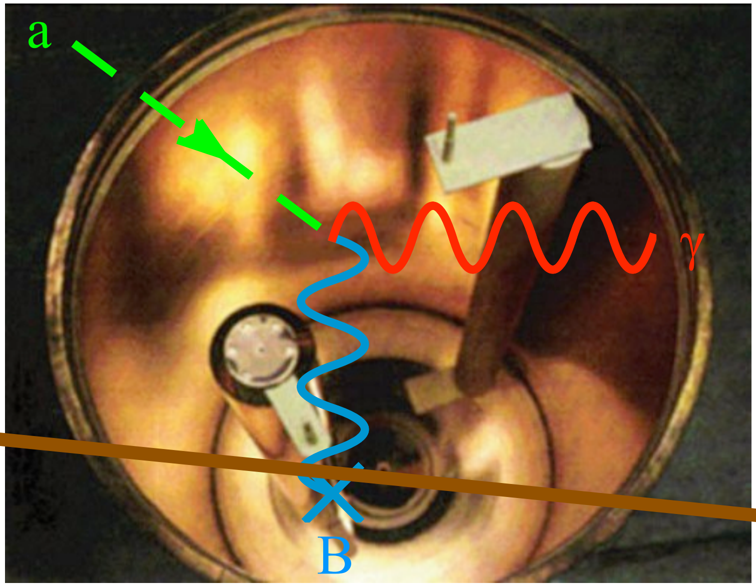

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S. Thomas

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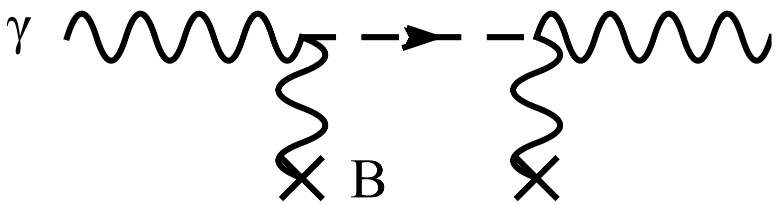

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axion emission affects SN1987A, White Dwarfs, other astrophysical objects

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Other ways to search for high f_a axions?

A Different Operator For Axion Detection

So how can we detect high f_a axions?

Strong CP problem: $\mathcal{L} \supset \theta \, G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16} \, \theta \, e \, \mathrm{cm}$

the axion: $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G} + m_a^2 a^2$ creates a nucleon EDM $d \sim 3 \times 10^{-16} \, \frac{a}{f_a} \, e \, \mathrm{cm}$

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$a(t) \sim a_0 \cos(m_a t)$ with $m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz}\left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$

axion dark matter $\rho_{\mathrm{DM}} \sim m_a^2 a^2 \sim (200\mathrm{MeV})^4 \left(\frac{a}{f_a}\right)^2 \sim 0.3\, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

so today: $\left(\frac{a}{f_a}\right) \sim 3 \times 10^{-19}$ independent of f_a

the axion gives all nucleons a rapidly oscillating EDM independent of f_a

A Different Operator For Axion Detection

the axion gives all nucleons a rapidly oscillating EDM

thus all (free) nucleons radiate

standard EDM searches are not sensitive to oscillating EDM

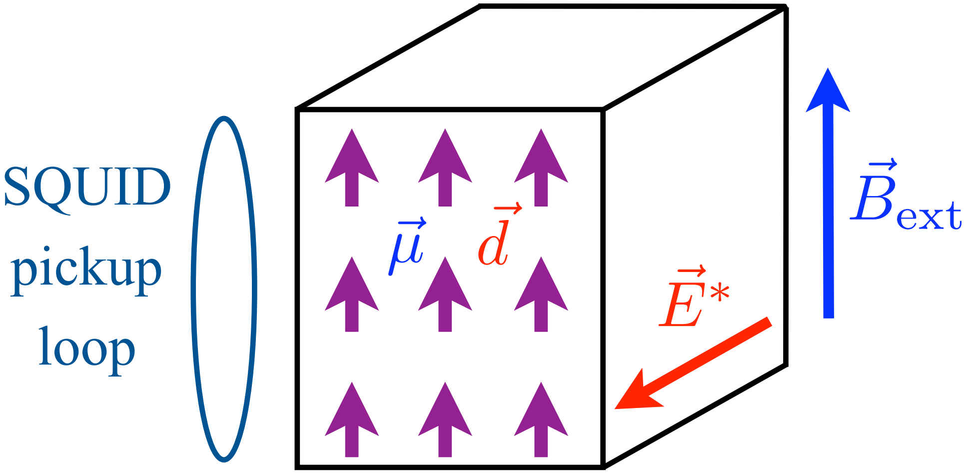
We’ve considered two methods for axion detection:

1. EDM affects atomic energy levels (cold molecules) PRD **84** (2011) arXiv:1101.2691

2. collective effects of the EDM in condensed matter systems (to appear)

NMR Technique

high nuclear spin alignment achieved in several systems, persists for $T_1 \sim$ hours



applied E field causes precession of nucleus

SQUID measures resulting transverse magnetization

builds on e^- EDM experiments   Lamoreaux (2002)

$$M(t) \approx np\mu E^* \epsilon_S d_n \frac{\sin\left(\left(2\mu B_{\text{ext}} - m_a\right) t\right)}{2\mu B_{\text{ext}} - m_a} \sin\left(2\mu B_{\text{ext}} t\right)$$

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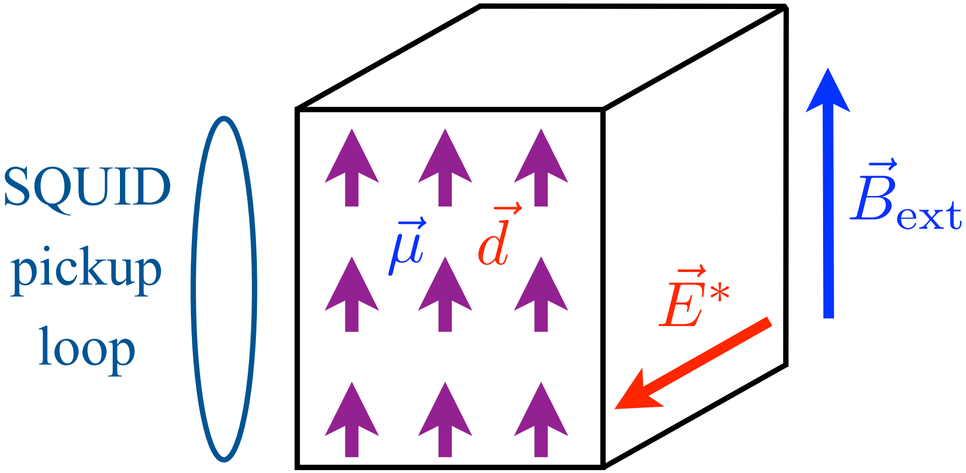

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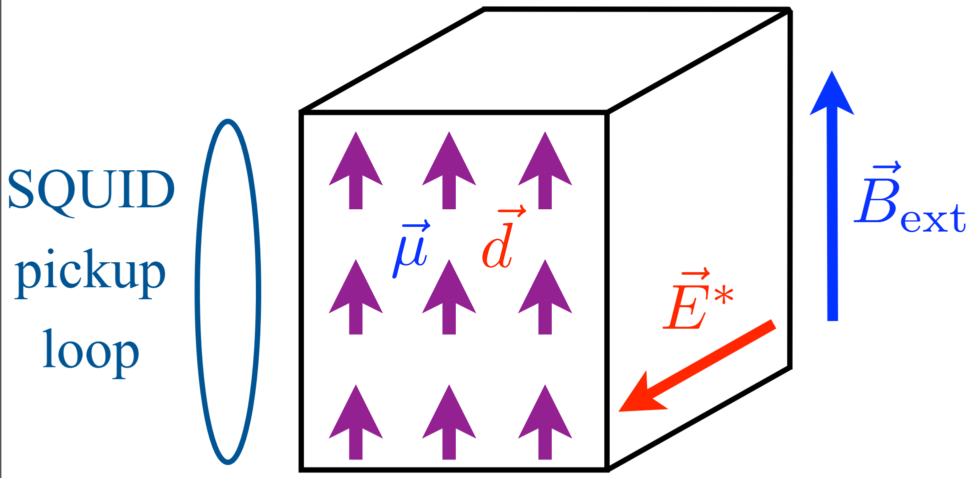

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example numbers: $^{207}\text{Pb} \implies n = 10^{22}\,\frac{1}{\text{cm}^3}$ $\mu = 0.6\mu_N$ $\epsilon_s \approx 10^{-2}$

ferroelectric (e.g. PbTiO_3) or any polar crystal: $E^* = 3 \times 10^8\,\frac{\text{V}}{\text{cm}}$

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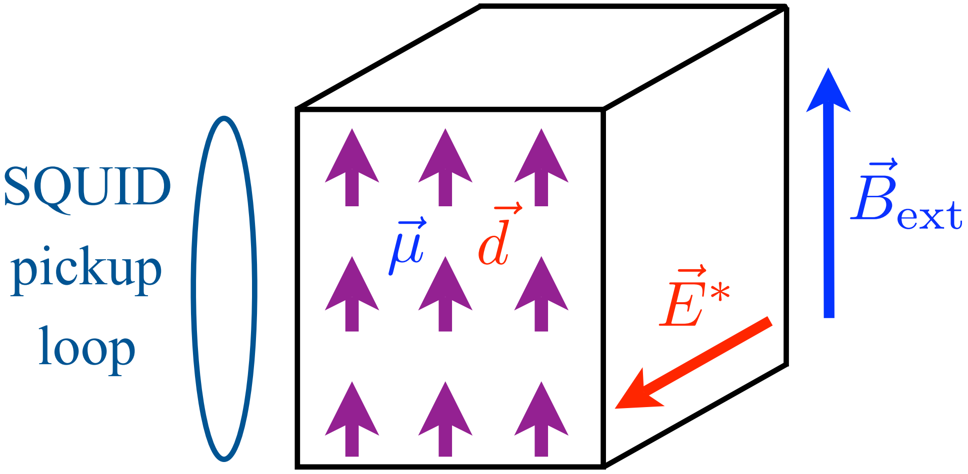

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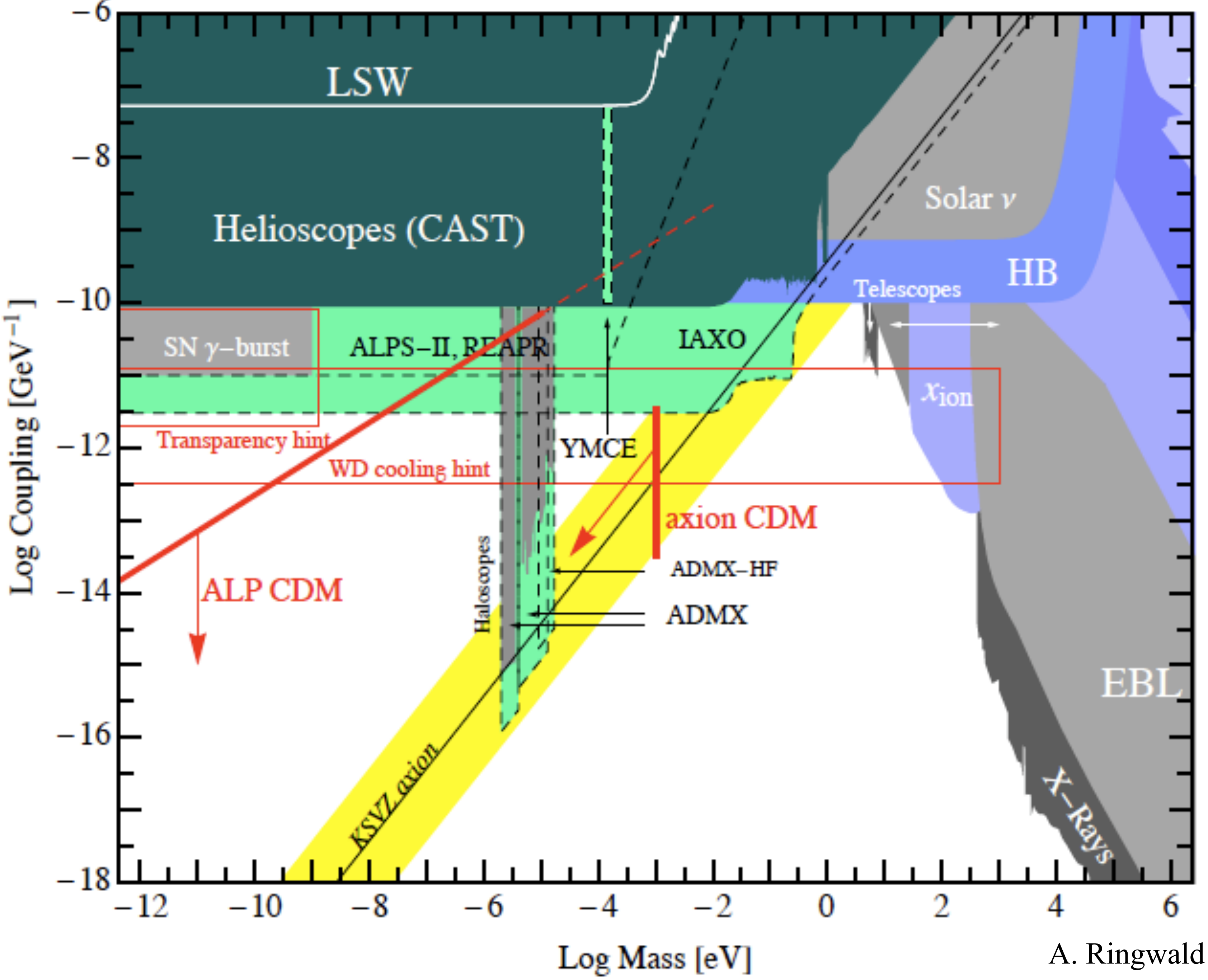
		Phase 1	Phase 2
transverse relaxation time	$T_2 \sim$	10^{-3} s	1 s

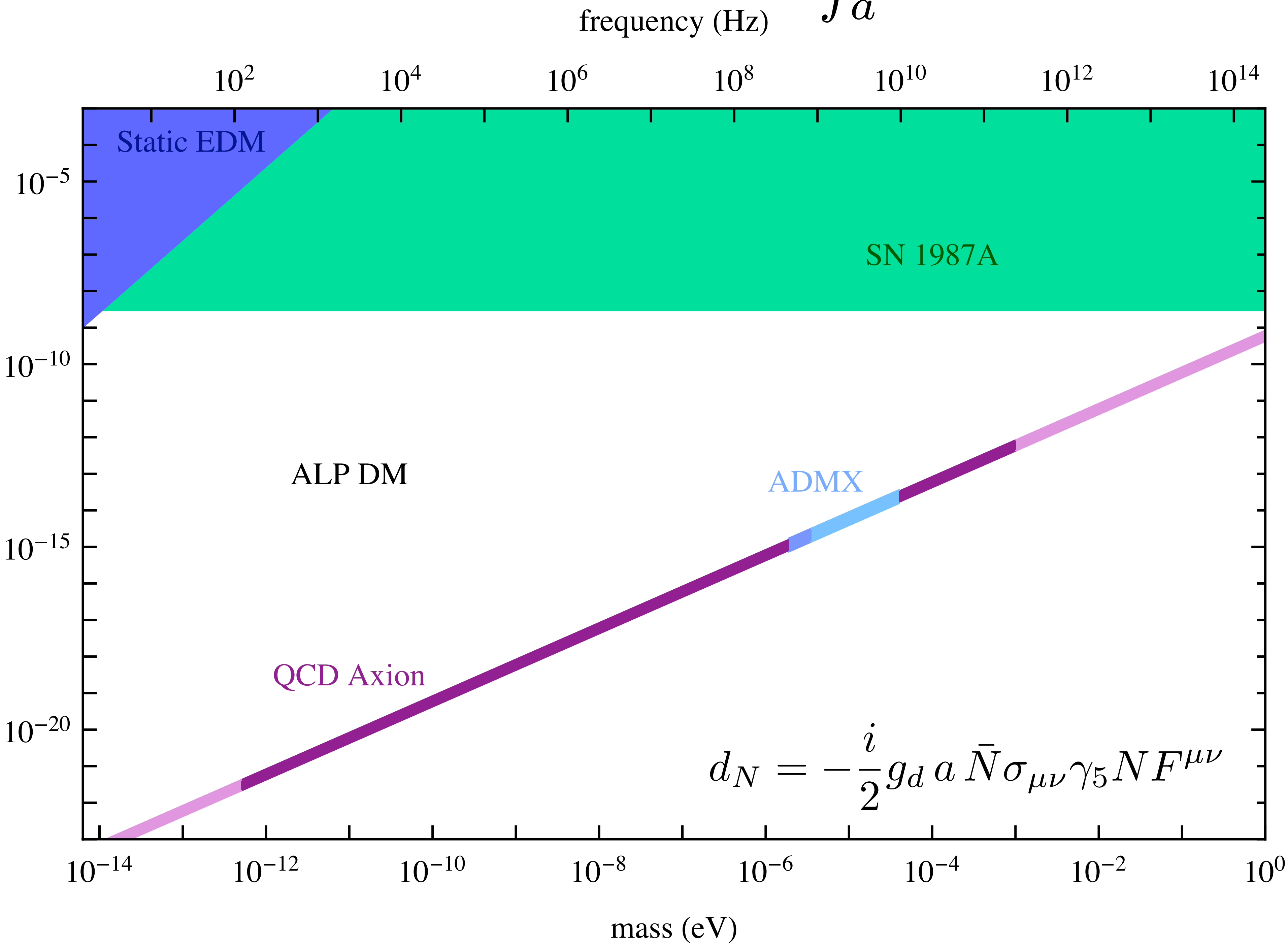
dynamic decoupling
(demonstrated T_2 = 1300 s in Xe)

Axion Limits on $\frac{a}{f_a} F\widetilde{F}$



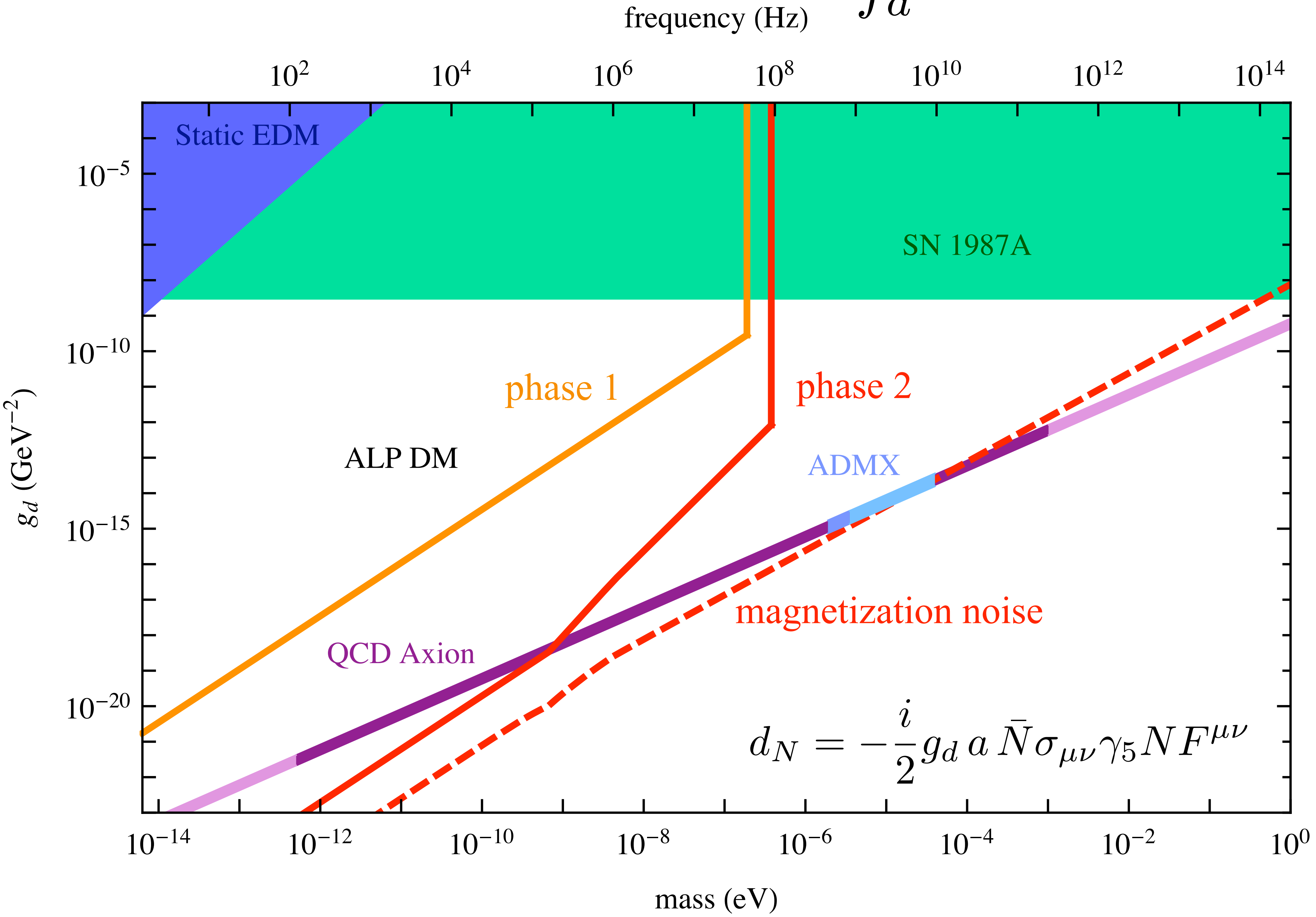
A. Ringwald (2012)

Axion Limits on $\frac{a}{f_a}G\widetilde{G}$



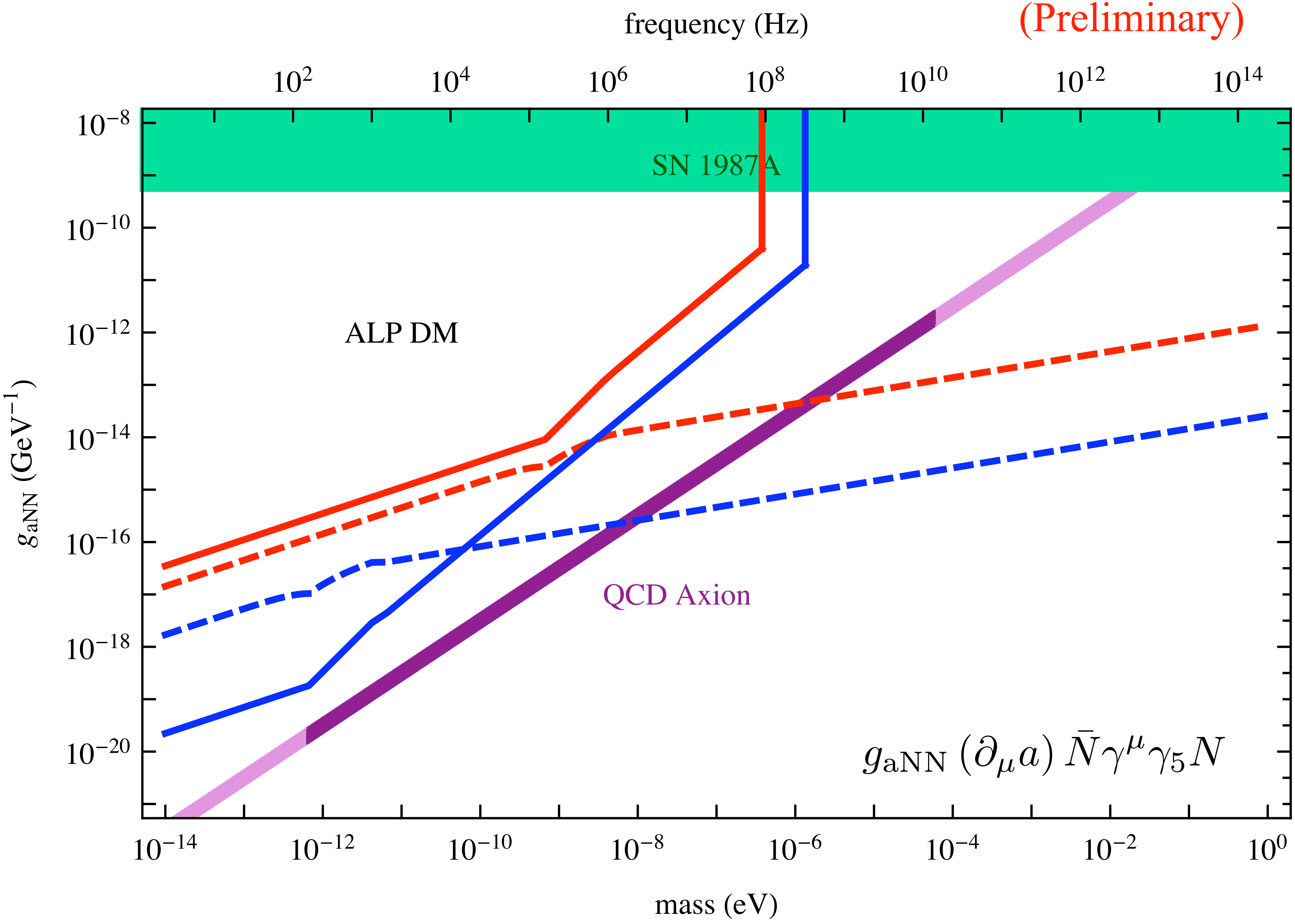
$$d_N = -\frac{i}{2} g_d\, a\, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

Axion Limits on $\frac{a}{f_a}G\widetilde{G}$

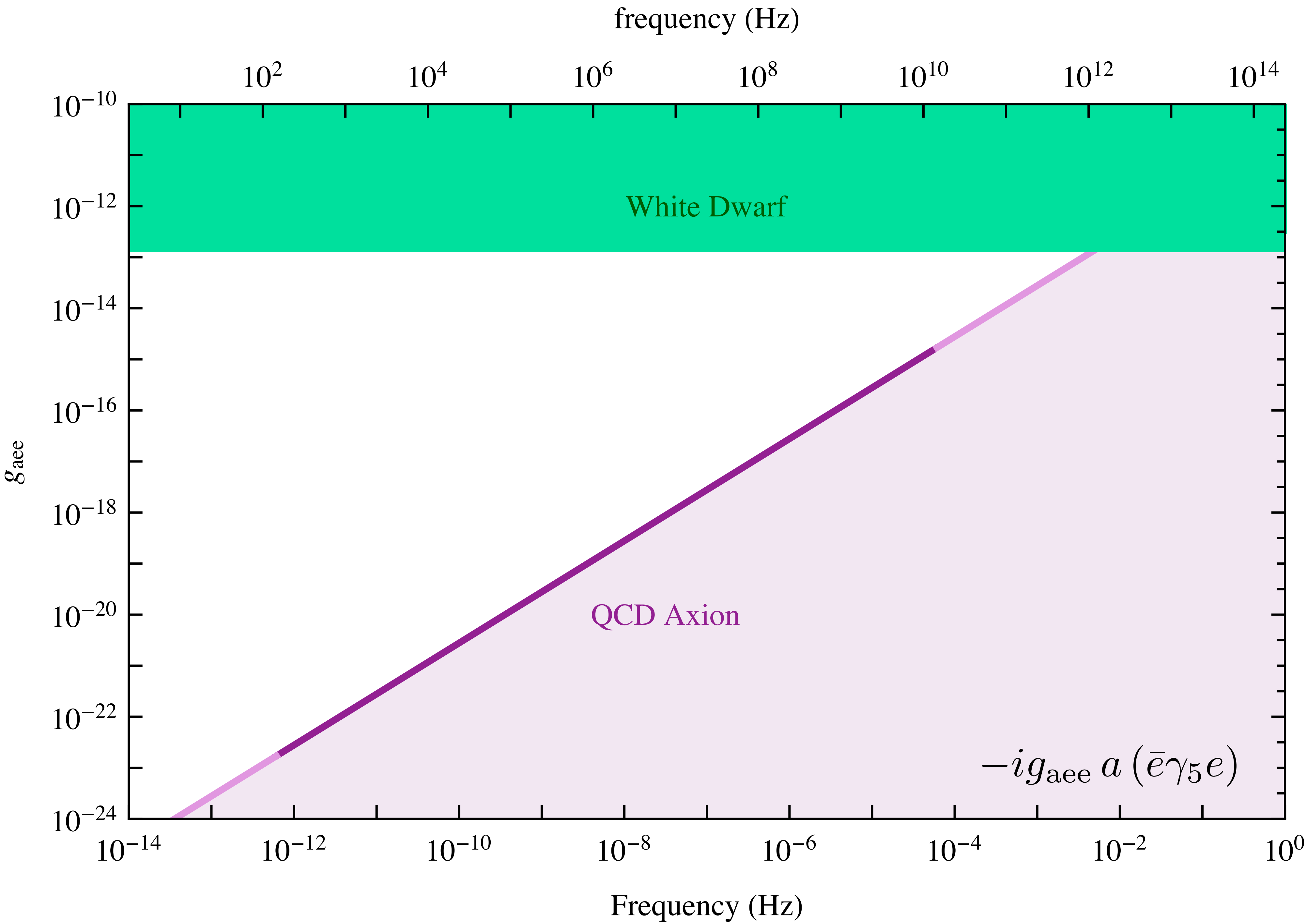


Limits on Axion-Nucleon Coupling

(Preliminary)



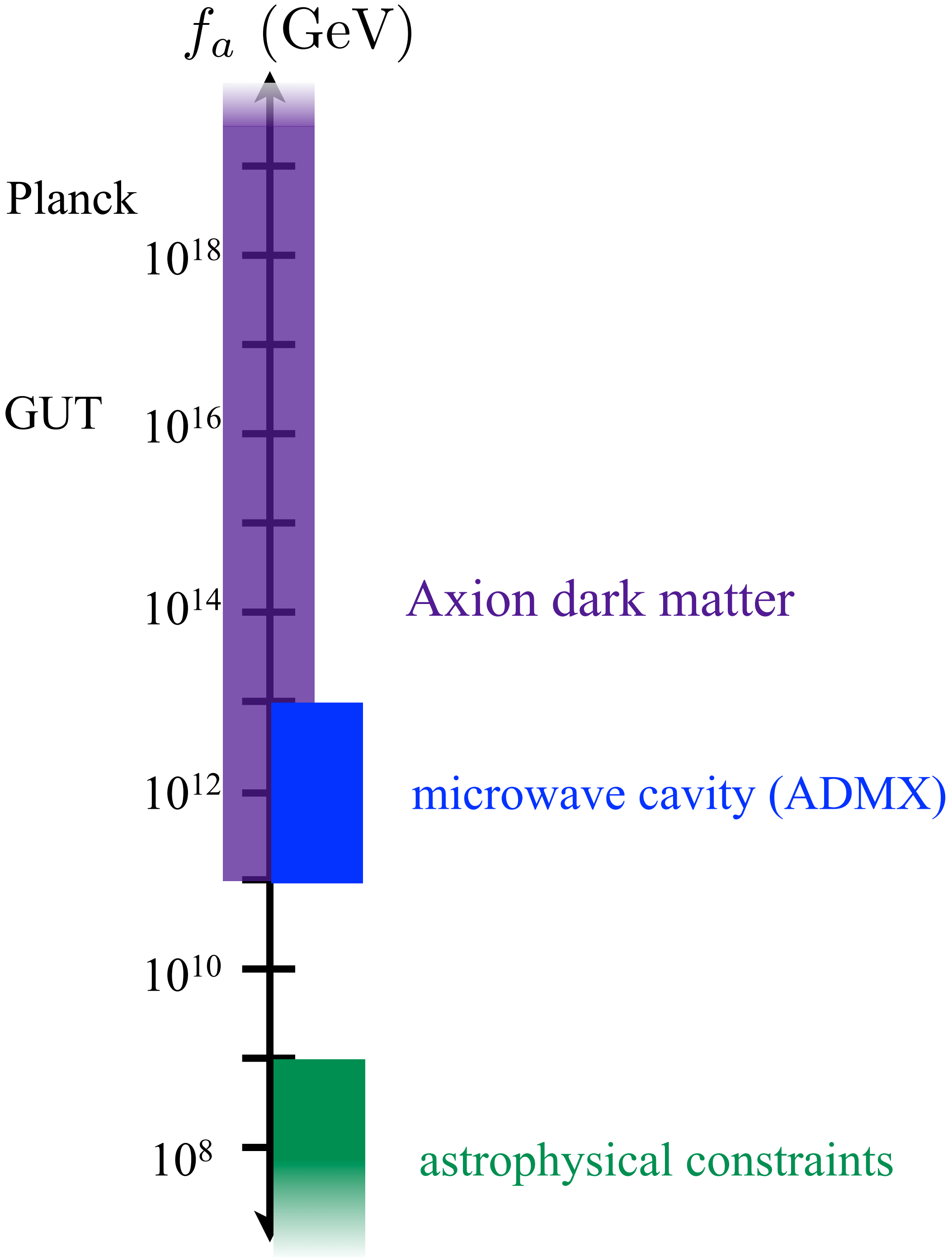
Limits on Axion-Electron Coupling



Summary

- EDM is non-derivative coupling for axion (avoids axion wavelength suppressions) + amplitude measurement ➜ can reach high f_a
- Many options for future improvements (magnetometers, T_2, sample volume, material, polar crystal)
- AC signal gives resonant enhancement, helps reject noise
- Verify signal with spatial coherence of axion field
- Signal $\propto \sqrt{\rho}$ so can search for subdominant component of dark matter

Axion Searches with Gluon Coupling



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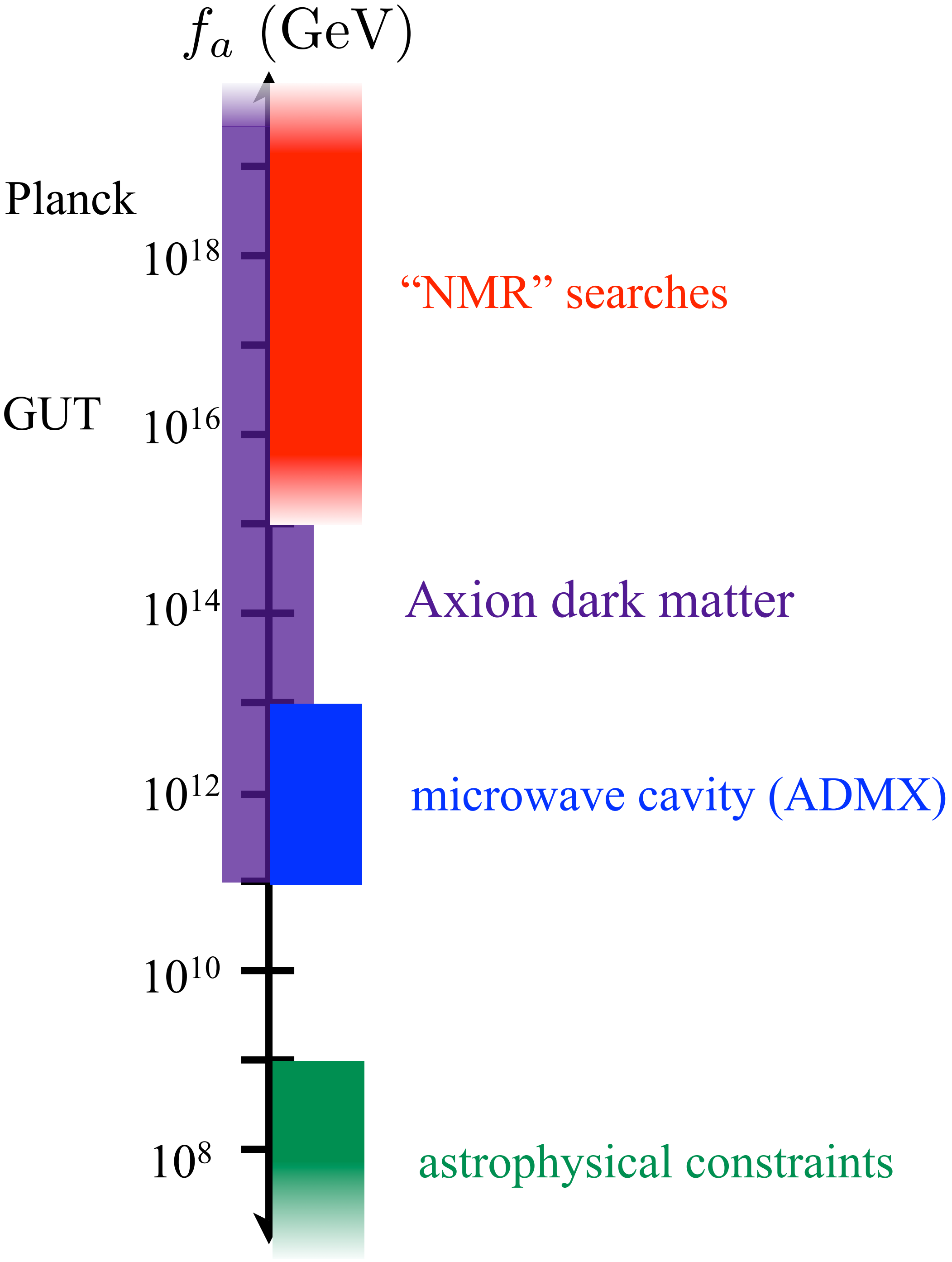

can most easily search in kHz - GHz
frequencies → high f_a

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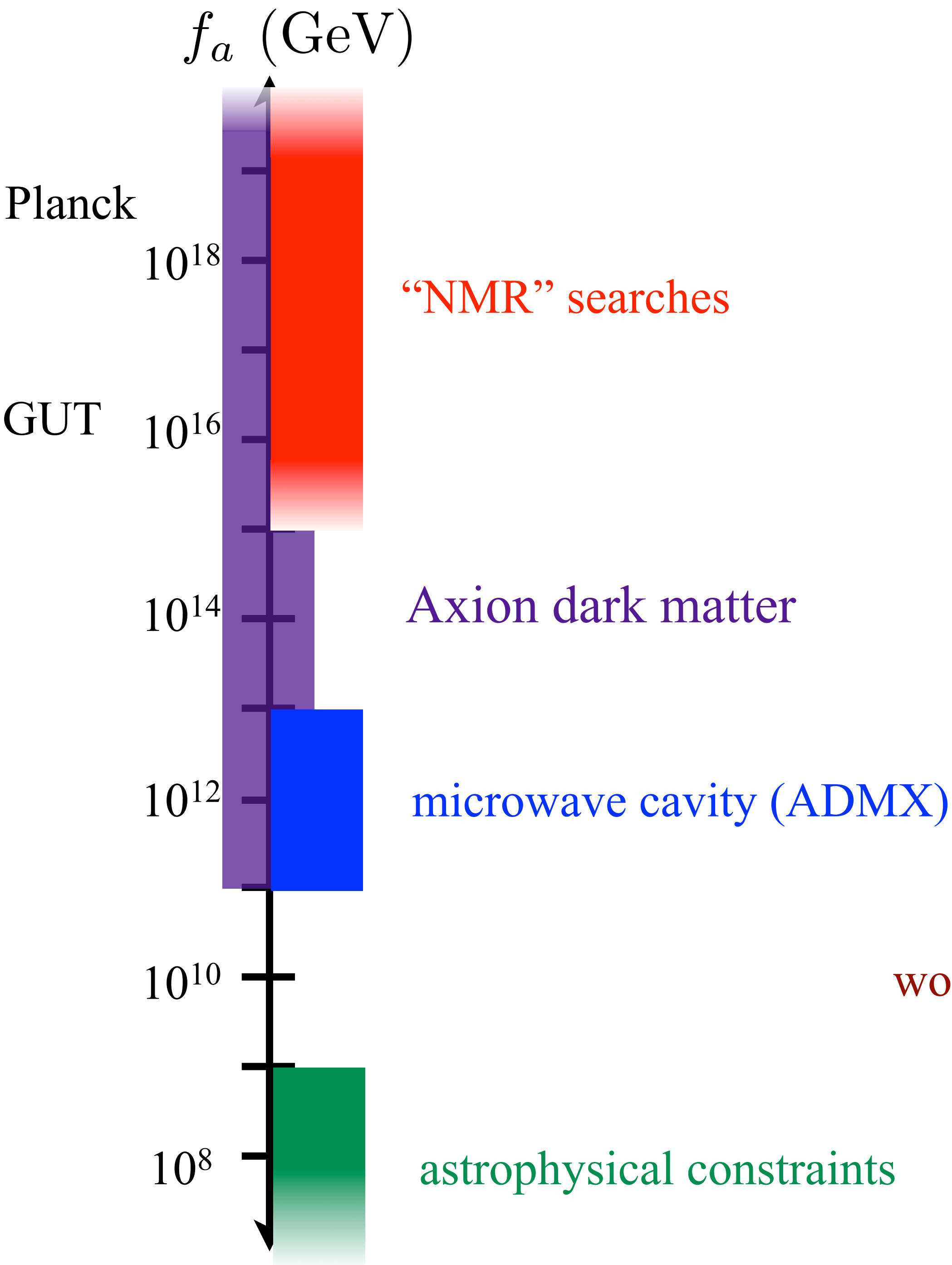


can most easily search in kHz - GHz
frequencies ➞ high f_a

technological challenges,
similar to early stages of WIMP detection,
axions deserve similar effort

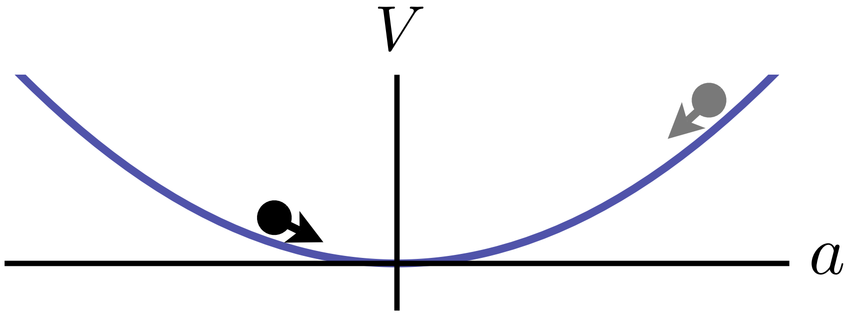
axion dark matter is very well-motivated,
no other way to search for at high f_a

would be both the discovery of dark matter and a
glimpse into physics at very high energies

Cosmic Axions

misalignment production:

after inflation axion is a constant field, mass turns on at T ~ Λ_{QCD} then axion oscillates



$$a(t) \sim a_0 \cos\left(m_a t\right)$$

Preskill, Wise & Wilczek, Abott & Sikivie, Dine & Fischler (1983)

axion easily produces correct abundance $\rho = \rho_{\mathrm{DM}}$

requires $\left(\dfrac{a_i}{f_a}\right)\sqrt{\dfrac{f_a}{M_{\mathrm{Pl}}}} \sim 10^{-3.5}$ late time entropy production eases this

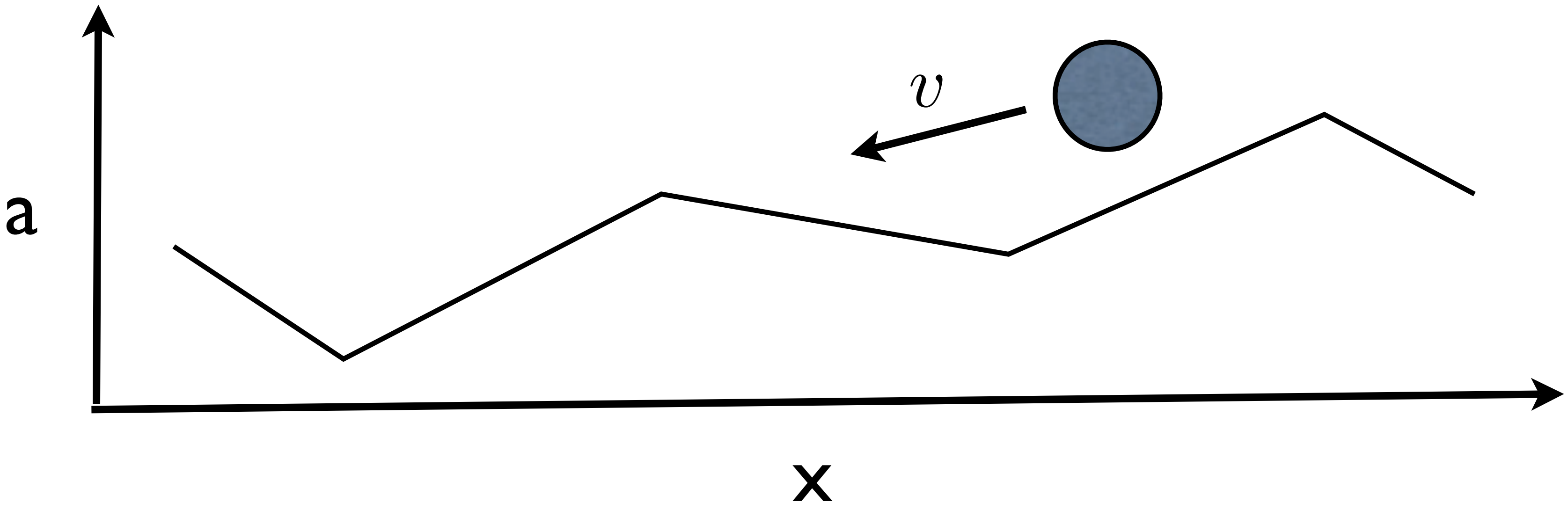
e.g. $\dfrac{f_a}{M_{\mathrm{Pl}}} \sim 10^{-7}$ $\quad \dfrac{a_i}{f_a} \sim 1$ or $\dfrac{f_a}{M_{\mathrm{Pl}}} \sim 10^{-3}$ $\quad \dfrac{a_i}{f_a} \sim 10^{-2}$

inflationary cosmology does not prefer flat prior in θ_i over flat in f_a

all f_a in DM range (all axion masses $\lesssim$ meV) equally reasonable

Axion Coherence

How large can T be?



Spatial homogeneity of the field?

Classical field a(x) with velocity v $\sim 10^{-3} \Longrightarrow \dfrac{\nabla a}{a} \sim \dfrac{1}{m_a\, v}$

spread in frequency (energy) of axion = $\dfrac{\Delta\omega}{\omega} \sim \dfrac{\frac{1}{2} m_a v^2}{m_a} \sim 10^{-6}$

$$T \sim \frac{1}{m_a\, v^2} = 1 \text{ s} \left(\frac{f_a}{10^{16}\ \text{GeV}} \right)$$

Cosmic Axion Spin Precession Experiment (CASPEr)

signal scales with large density of nuclei:

$$M(t) \approx np\mu E^* \epsilon_S d_n \boxed{\frac{\sin\left(\left(2\mu B_{\text{ext}} - m_a\right) t\right)}{2\mu B_{\text{ext}} - m_a}} \sin\left(2\mu B_{\text{ext}} t\right)$$

resonant enhancement

scan over axion masses by changing B_{ext}

example numbers: $^{207}\text{Pb} \implies \quad \mu = 0.6\mu_N \qquad \epsilon_s \approx 10^{-2}$

$$n = 10^{22}\,\frac{1}{\text{cm}^3} \qquad L \sim 10\ \text{cm}$$

ferroelectric (or any polar crystal): $E^* = 3 \times 10^8\,\frac{\text{V}}{\text{cm}}$

we take SQUID magnetometer: $10^{-16}\,\frac{\text{T}}{\sqrt{\text{Hz}}}$ but SERF magnetometers are $10^{-17}\,\frac{\text{T}}{\sqrt{\text{Hz}}}$

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resonant enhancement limited by axion coherence time $\tau_a \sim \dfrac{2\pi}{m_a v^2}$

and nuclear spin transverse relaxation time T_2

Magnetization (quantum spin projection) noise: $S\left(\omega\right) = \dfrac{1}{8}\left(\dfrac{T_2}{1 + T_2^2\left(\omega - 2\mu_N B\right)^2}\right)$

with designed NMR pulse sequences:

	Phase 1	Phase 2	
polarization fraction	$p = 10^{-3}$	$p \approx 1$	optical pumping (demonstrated p ~ 0.5 in Xe)
T_2	10^{-3} s	1 s	dynamic decoupling (demonstrated T_2 = 1300 s in Xe)

many options for increasing sensitivity