Axion Detection With NMR

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with

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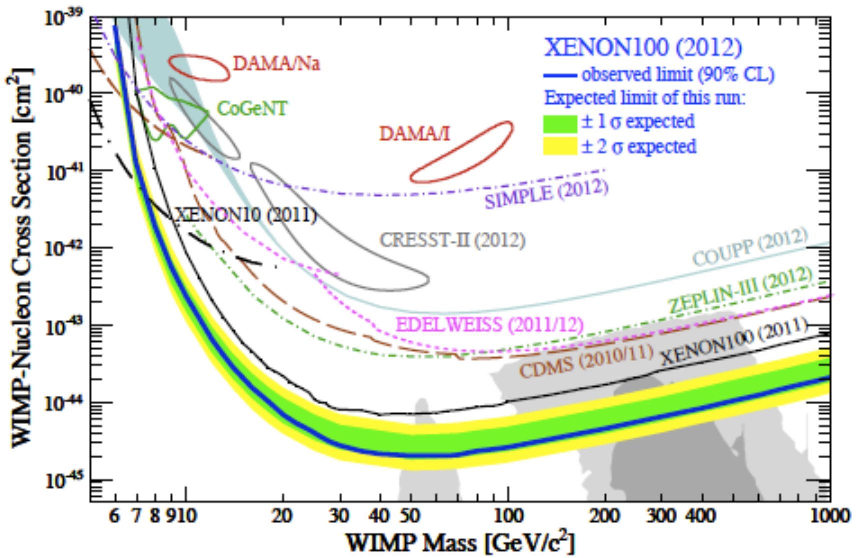
PRD **84** (2011) arXiv:1101.2691
+ to appear

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

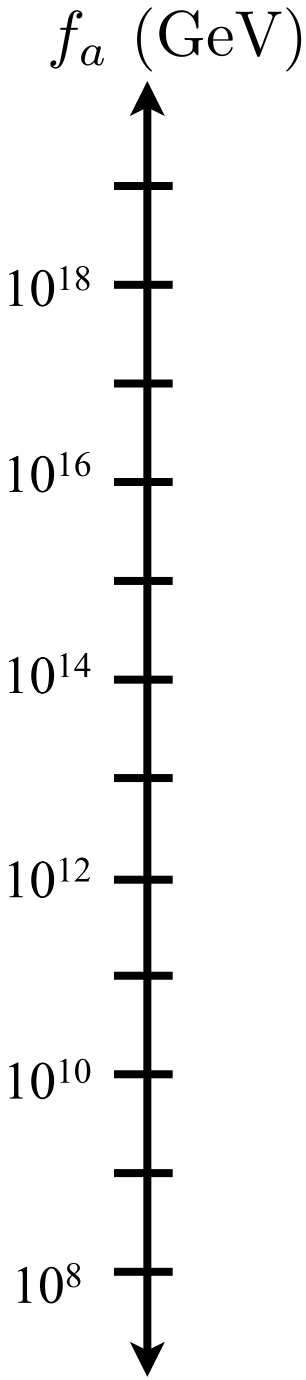
Easy to generate axions from high energy theories

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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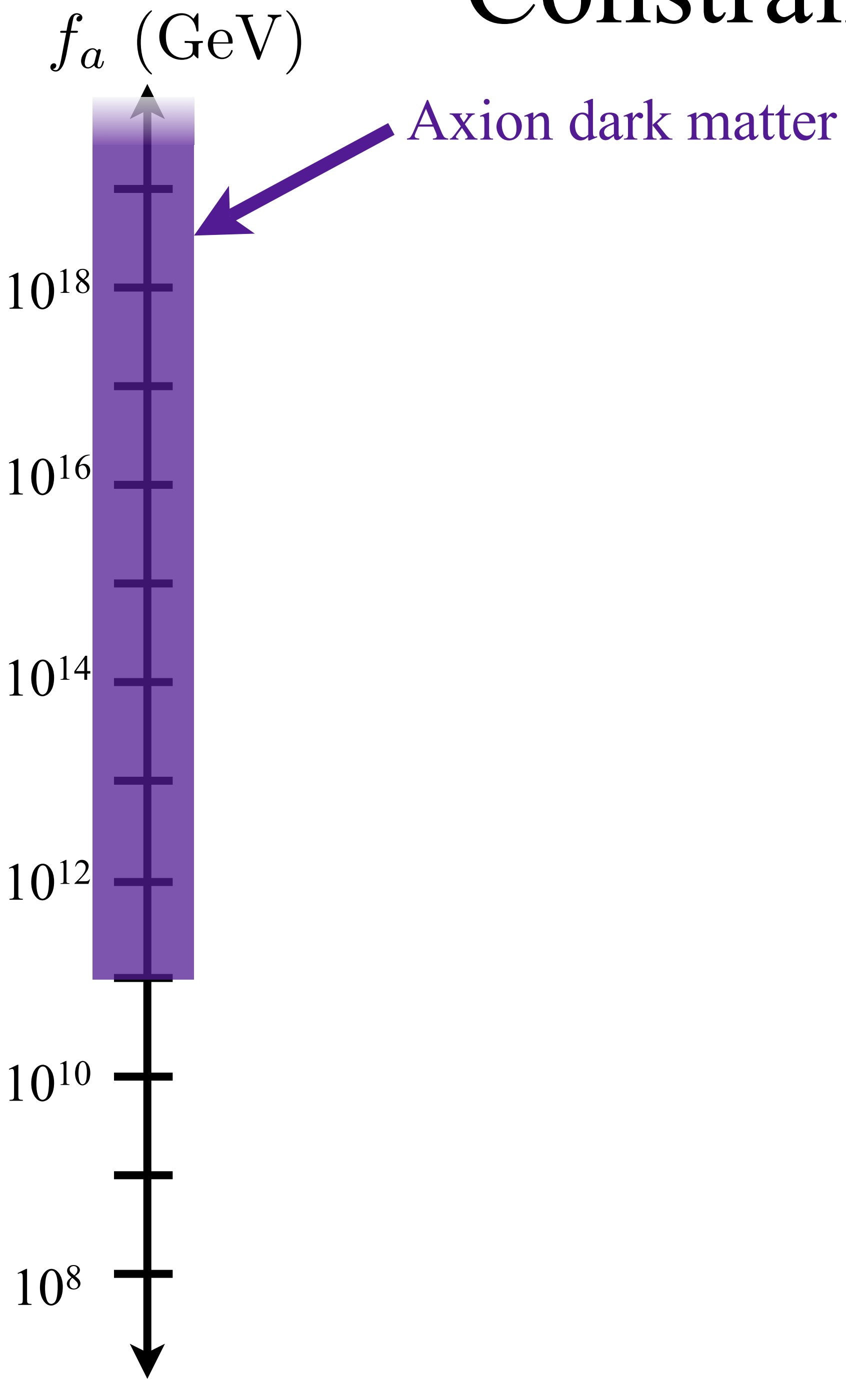

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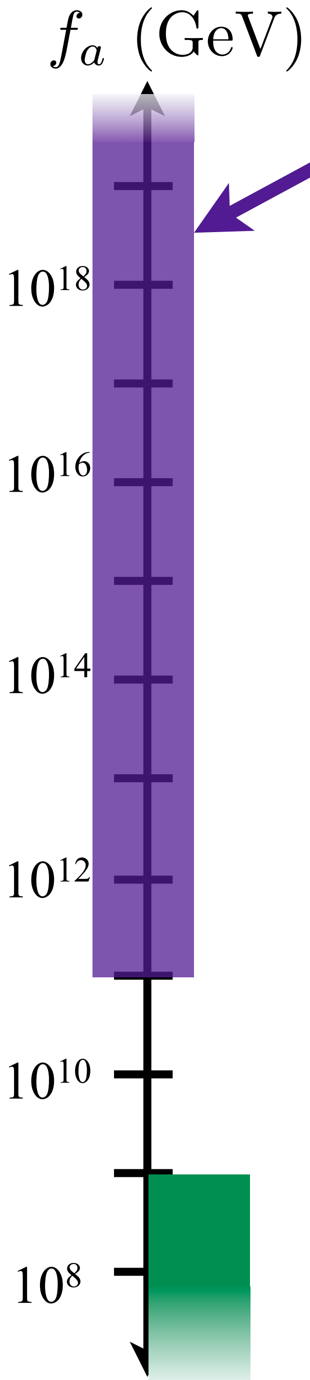
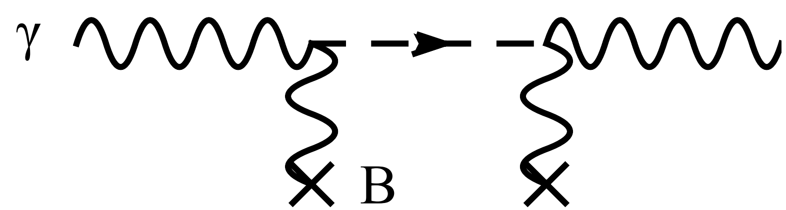


Axion dark matter

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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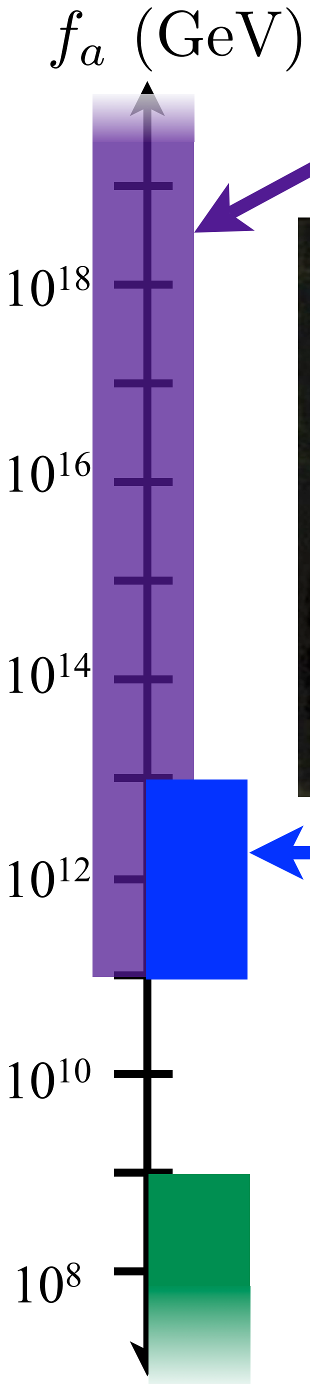

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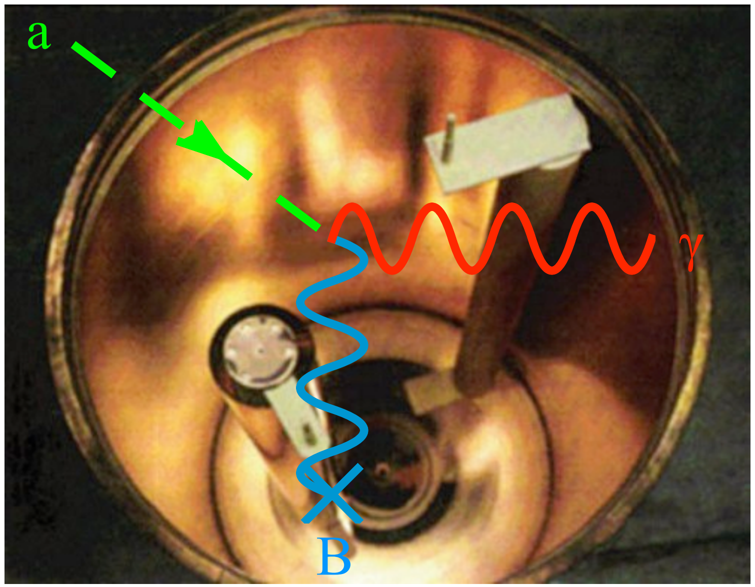

axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

size of cavity increases with f_a

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

microwave cavity (ADMX)

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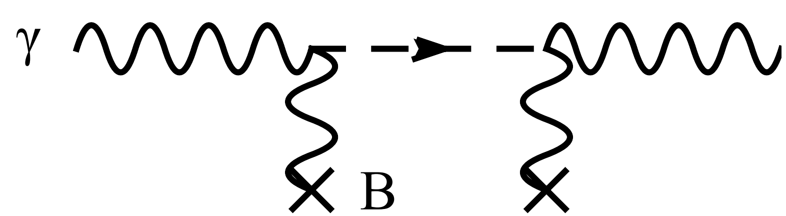

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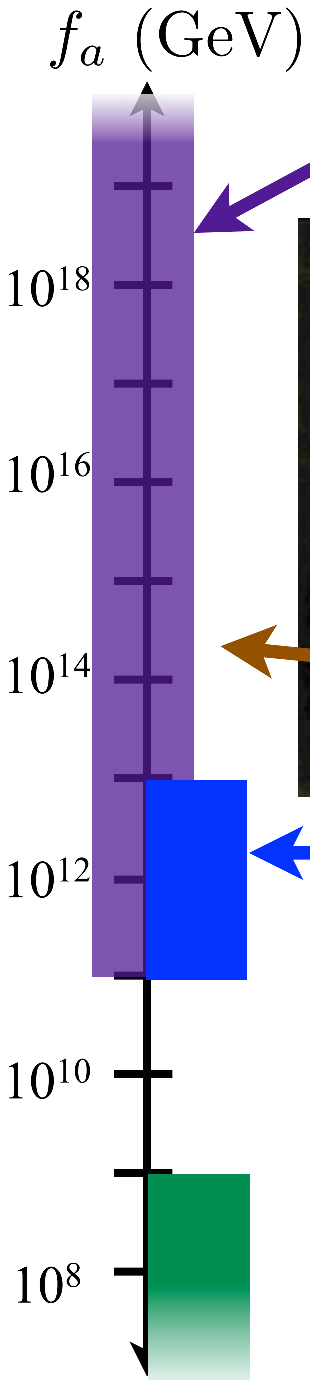

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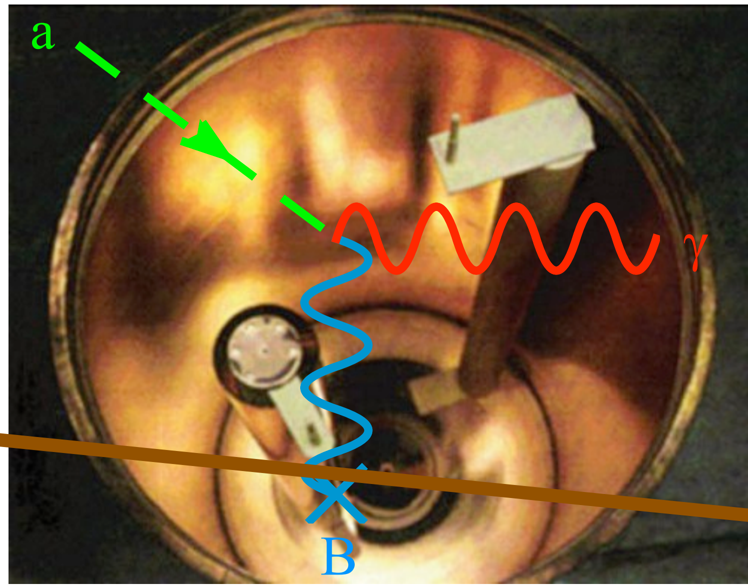

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S. Thomas

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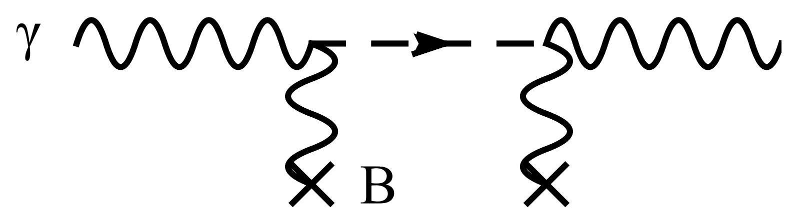

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Other ways to search for high f_a axions?

Light Scalar Dark Matter

A WIMP is a heavy particle ➔ very low phase space density

other possibility is a light particle ➔ high phase space density if $m \lesssim 0.01\,\mathrm{eV}$

since $\rho_{\mathrm{DM}} \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.04\,\mathrm{eV})^4$

the axion provides a well-motivated example of such a DM candidate

general class is “Axion-Like Particles” (ALPs)

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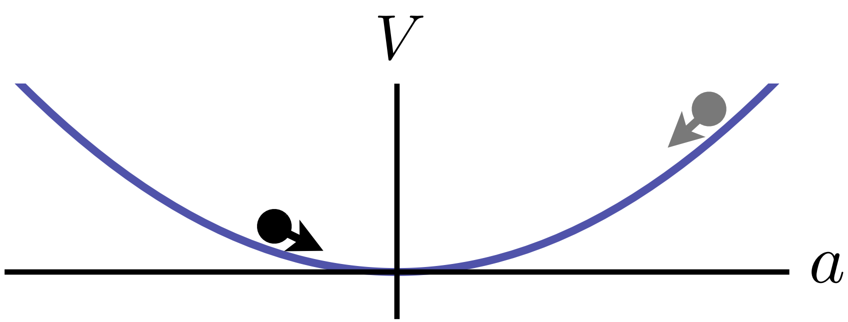
such light scalar DM can often be described as a field: $a\,(t,\vec{x})$

➜ search for coherent effects of the entire field, not single hard particle scatterings

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 $\rho = \rho_{\rm DM}$

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

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

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

all f_a in DM range (all axion masses ≲ meV) equally reasonable

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

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

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

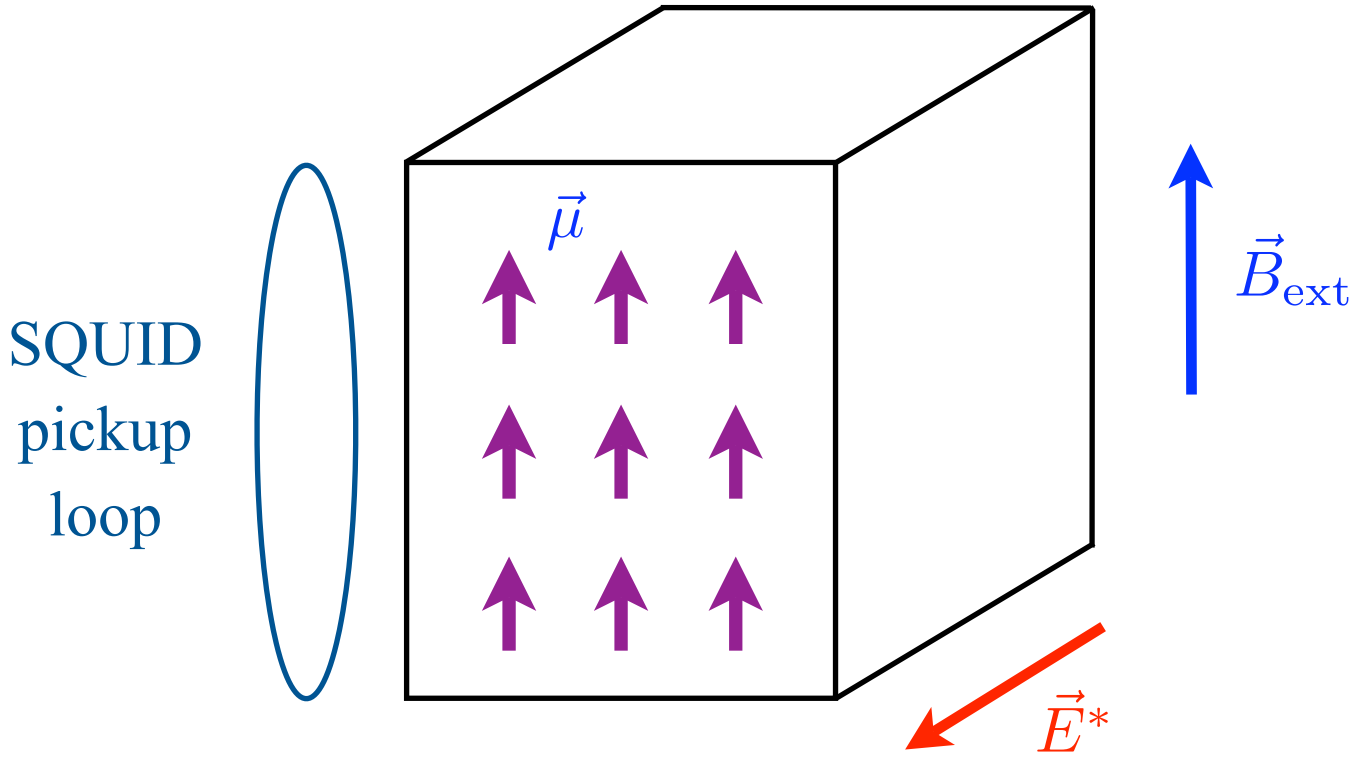
standard EDM searches are not sensitive to oscillating EDM

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



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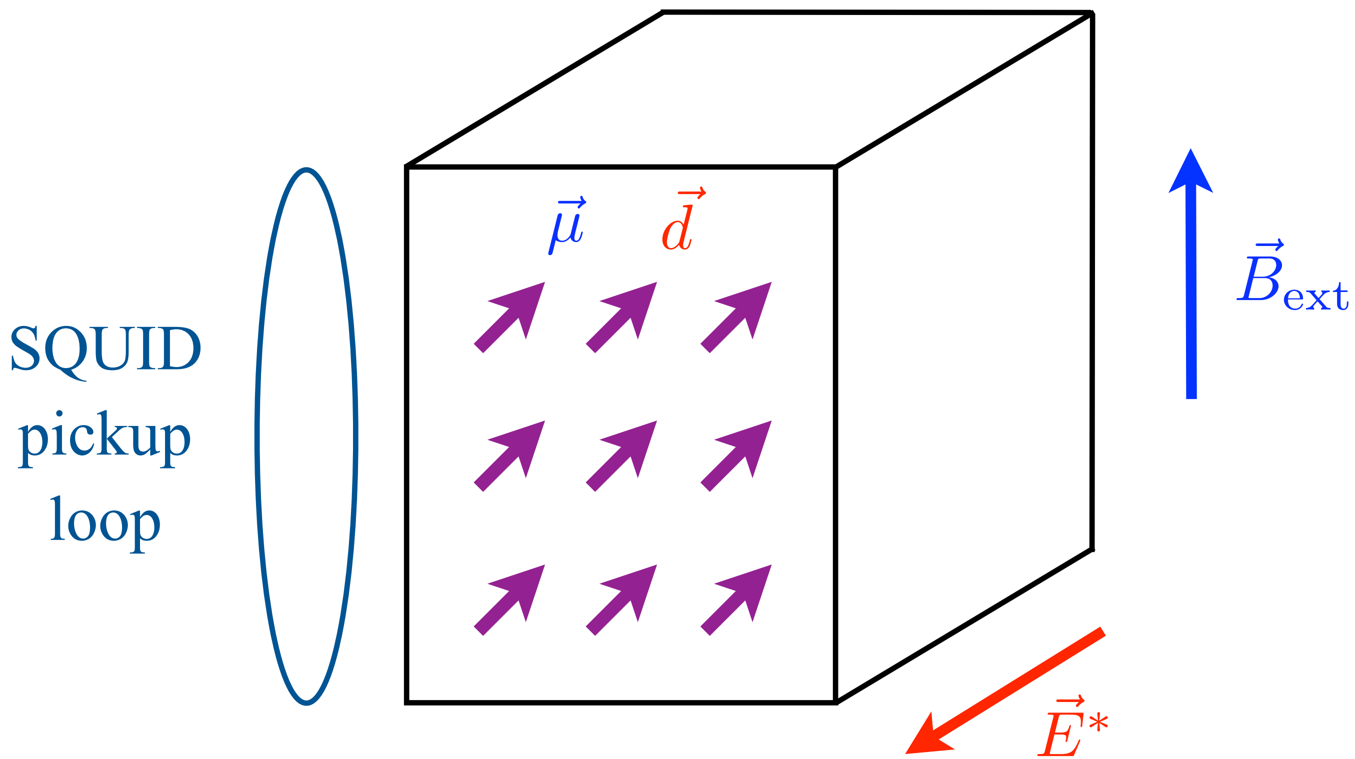

high nuclear spin alignment achieved in several systems, persists for $T_1 \sim$ hours

applied E field causes precession of nucleus

SQUID measures resulting transverse magnetization

builds on e^- EDM experiments Lamoreaux (2002)

if Larmor frequency matches axion mass get resonant enhancement

Transverse Magnetization Signal

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

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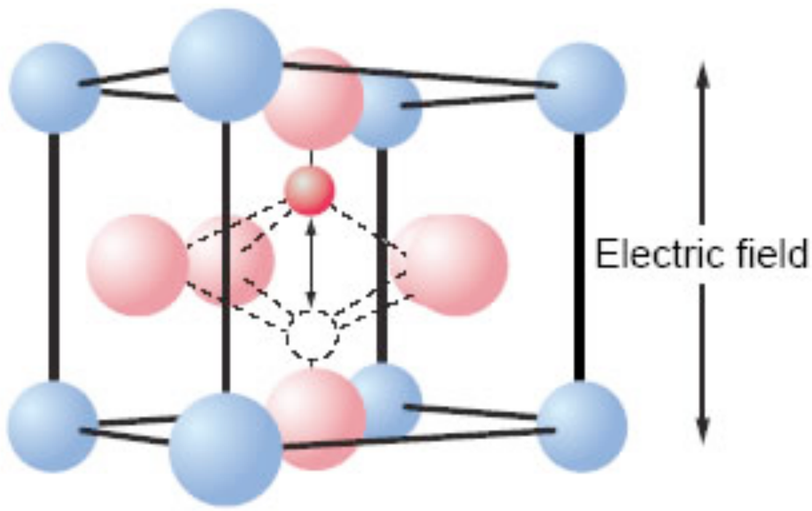
measures an amplitude ("phase") and not a rate

Ferroelectric

below critical temperature some materials have ferroelectric phase transition



ferroelectrics (e.g. $PbTiO_3$) have large effective internal electric fields:

$$E^* = 3 \times 10^8 \frac{\mathrm{V}}{\mathrm{cm}}$$

We don't need to flip directions dynamically, so any polar crystal should work

may allow enhancement in E* by $\sim \times$ few

Resonant Enhancement

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

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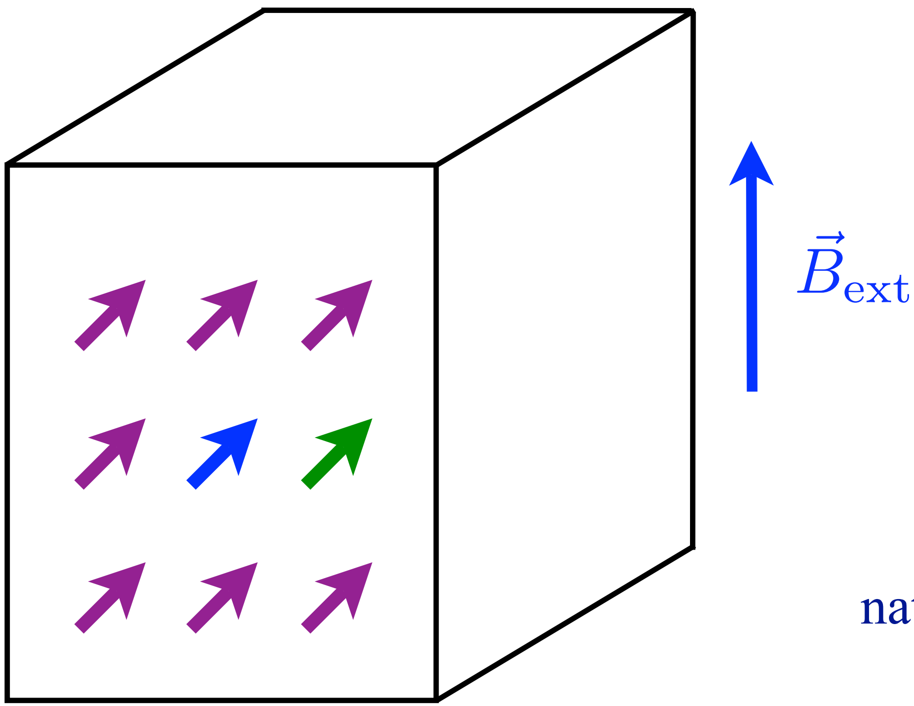

local B-field inhomogeneities:

$$\vec{B}(\vec{r_1}) \neq \vec{B}(\vec{r_2})$$

and spin-spin interactions source transverse spin dephasing

naturally: $T_2 \sim \left(\mu_N \left(\frac{\mu_N}{\mathring{A}^3}\right)\right)^{-1} \sim 1\ \text{ms}$

designed NMR pulse sequences can improve (dynamic decoupling)

demonstrated T_2 = 1300 s in Xe

Cosmic Axion Spin Precession Experiment (CASPEr)

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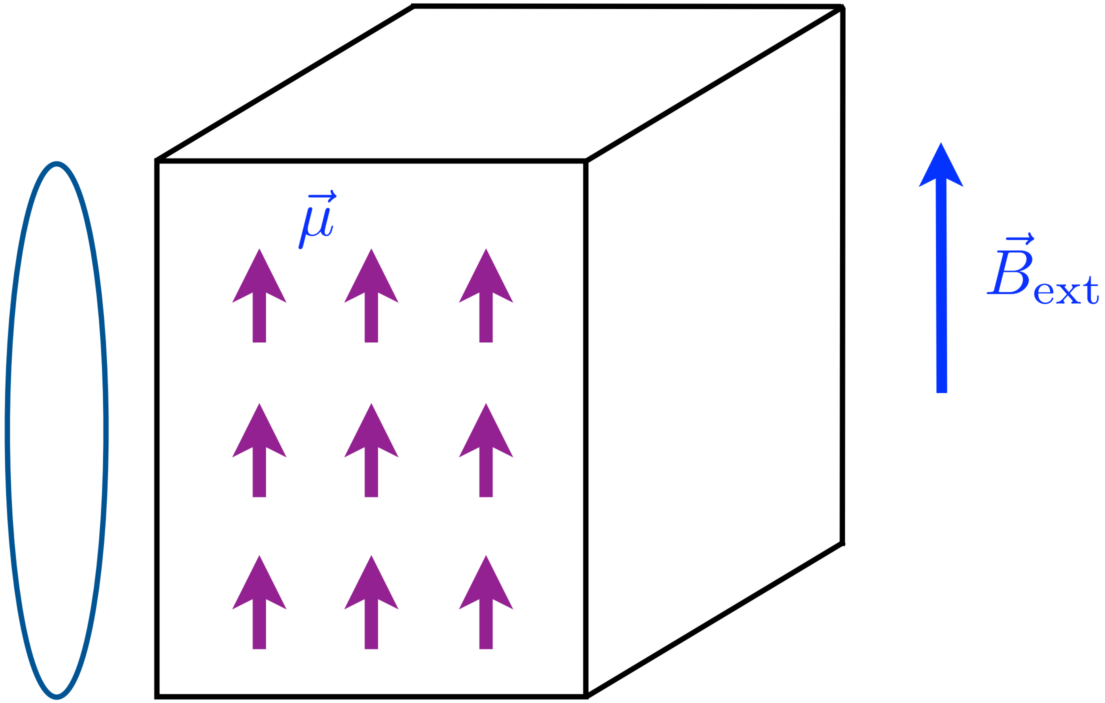
with designed NMR pulse sequences:

	Phase 1	Phase 2		
polarization fraction	$p = 10^{-3}$	$p \approx 1$	optical pumping	many options for increasing sensitivity
T_2	10^{-3} s	1 s	dynamic decoupling	

Magnetization Noise



a material sample has magnetization noise

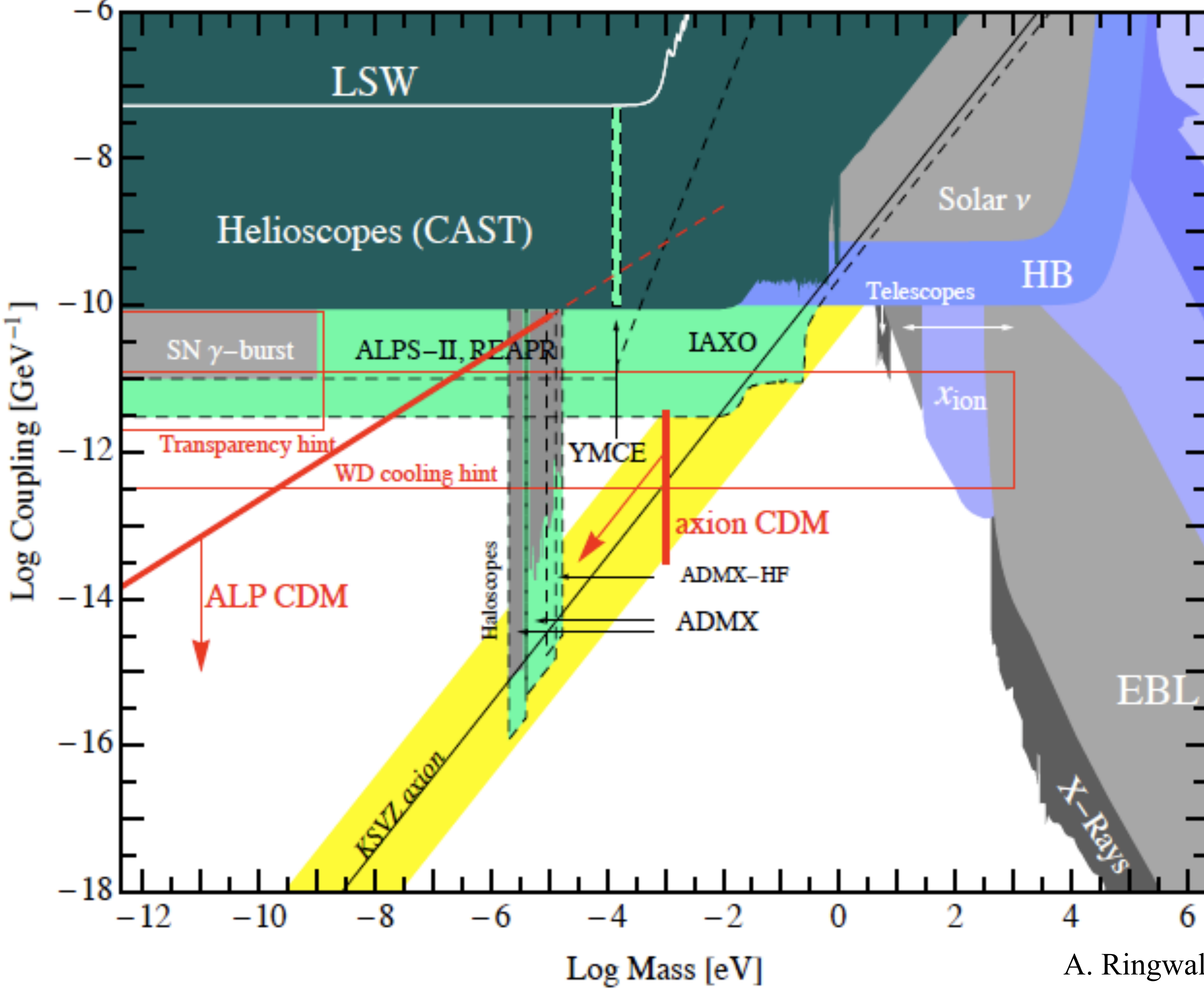
irreducible noise arises from quantum spin projection

every spin necessarily has random quantum projection onto transverse direction

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

an approximate estimate, in a particular sample magnetization noise must be measured

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



A. Ringwald (2012)

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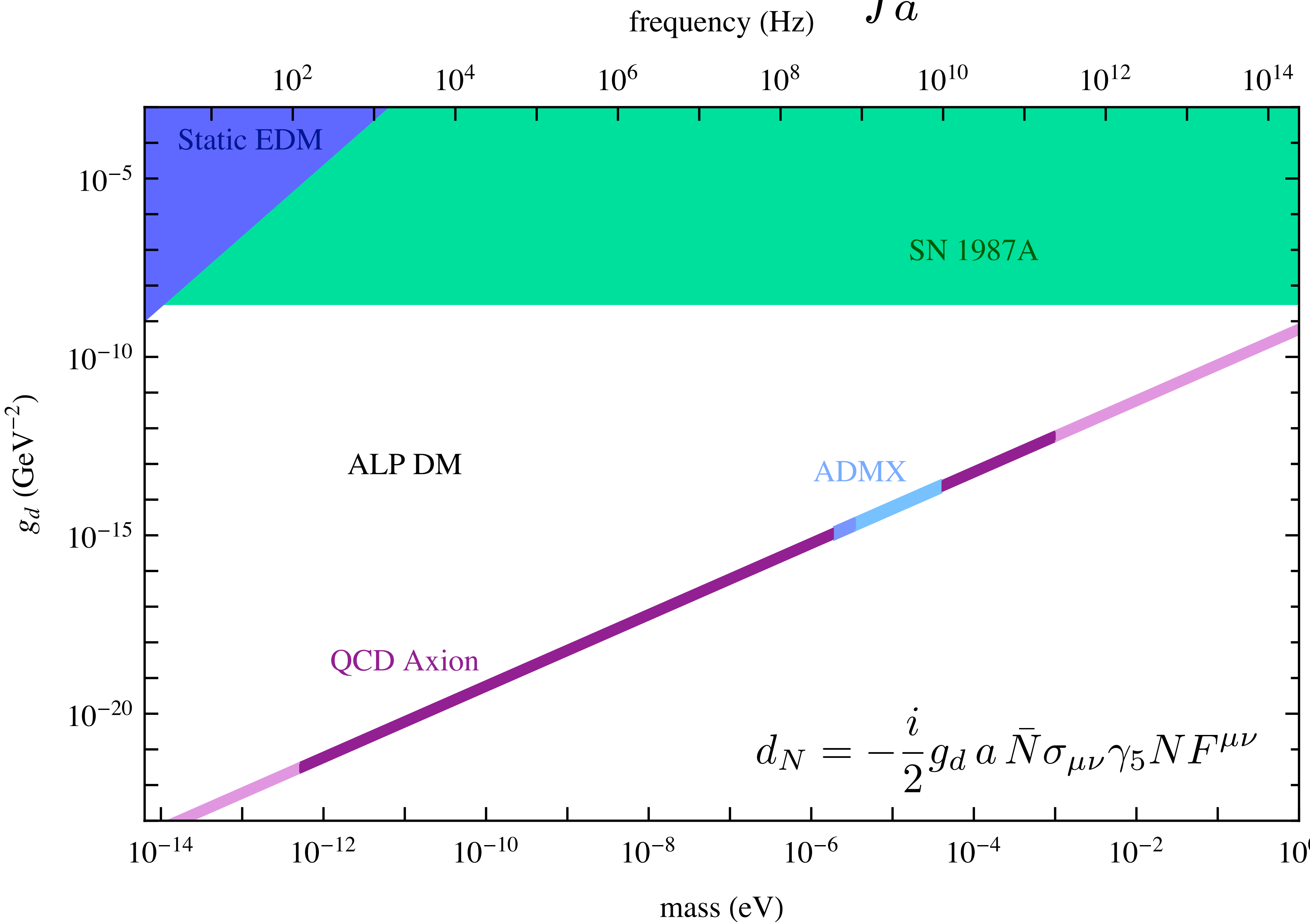
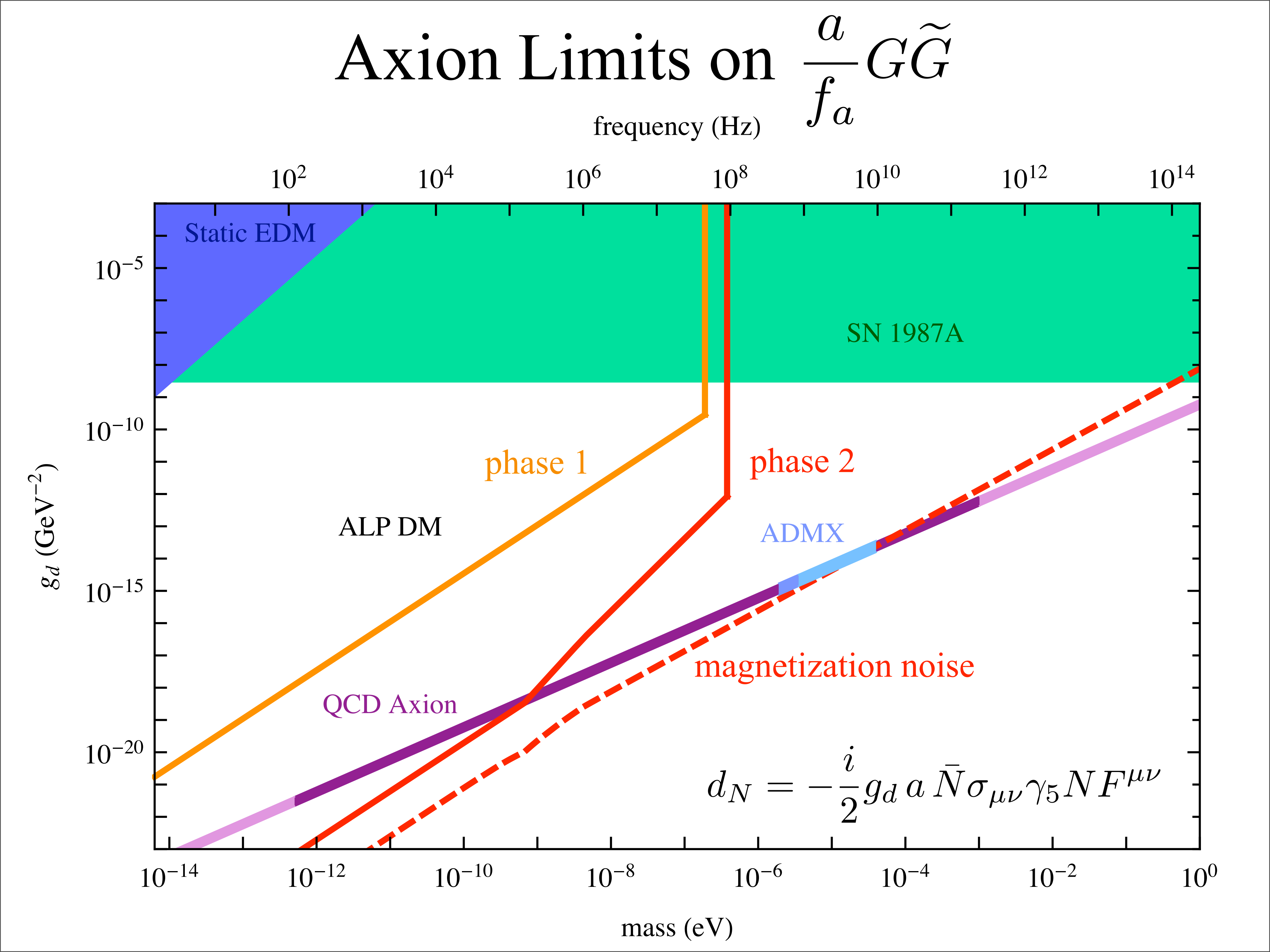
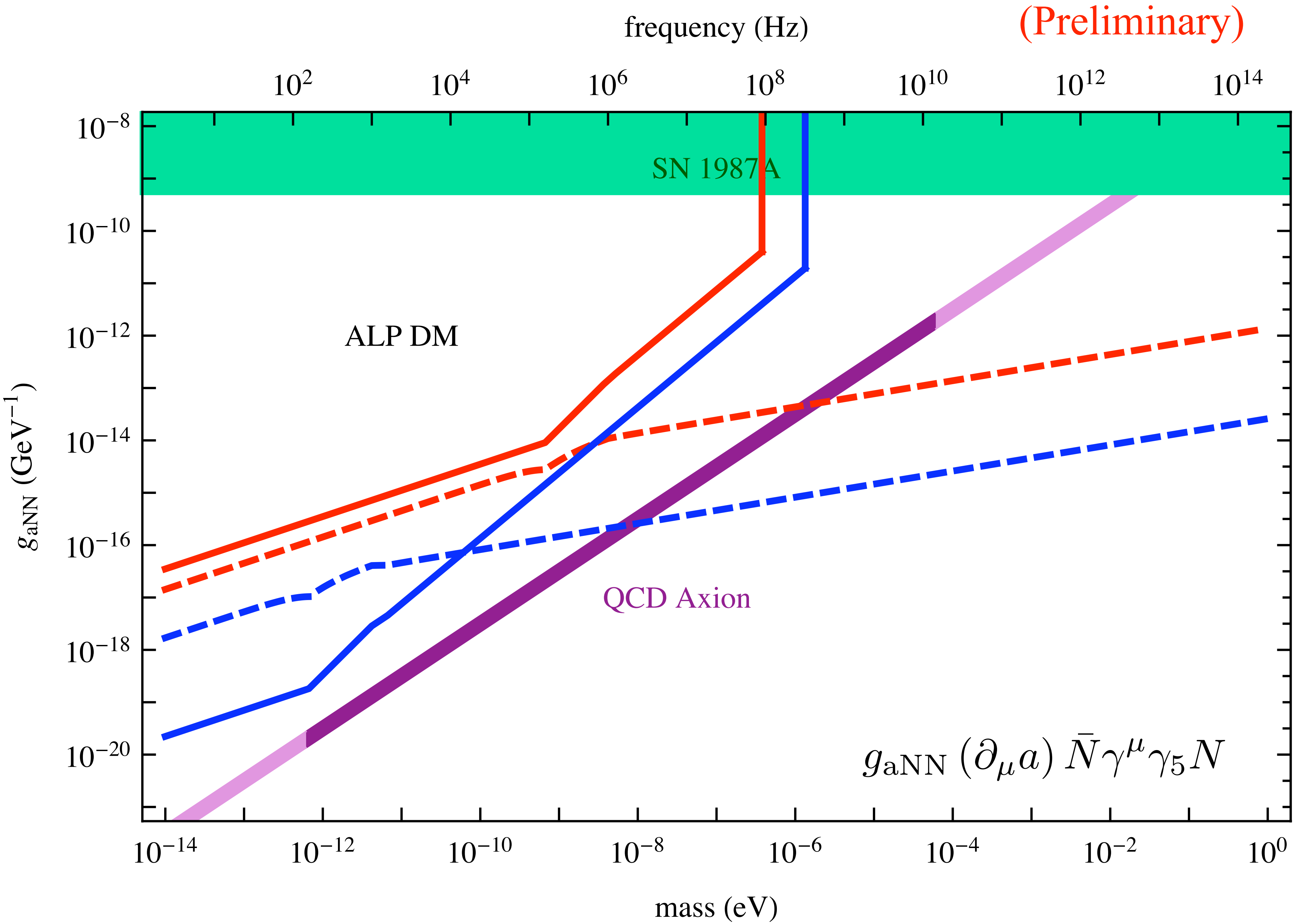


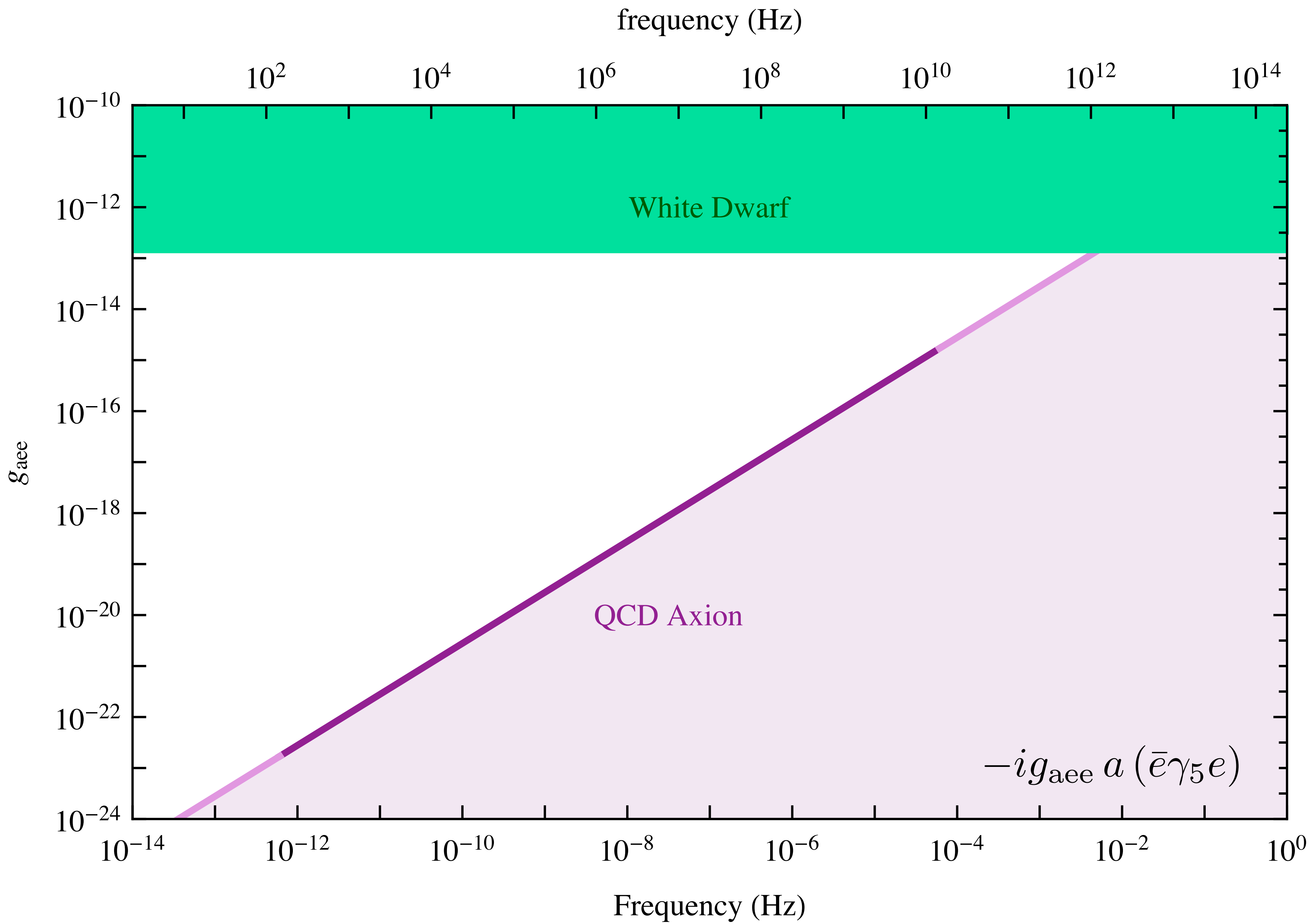


Axion Limits on $\frac{a}{f_a} G\widetilde{G}$
frequency (Hz)
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
Static EDM
SN 1987A
10^{-5}
10^{-10}
10^{-15}
10^{-20}
g_d (GeV^{-2})
phase 1
phase 2
ALP DM
ADMX
magnetization noise
QCD Axion
$d_N = -\frac{i}{2} g_d \, a \, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^0
mass (eV)

Limits on Axion-Nucleon Coupling



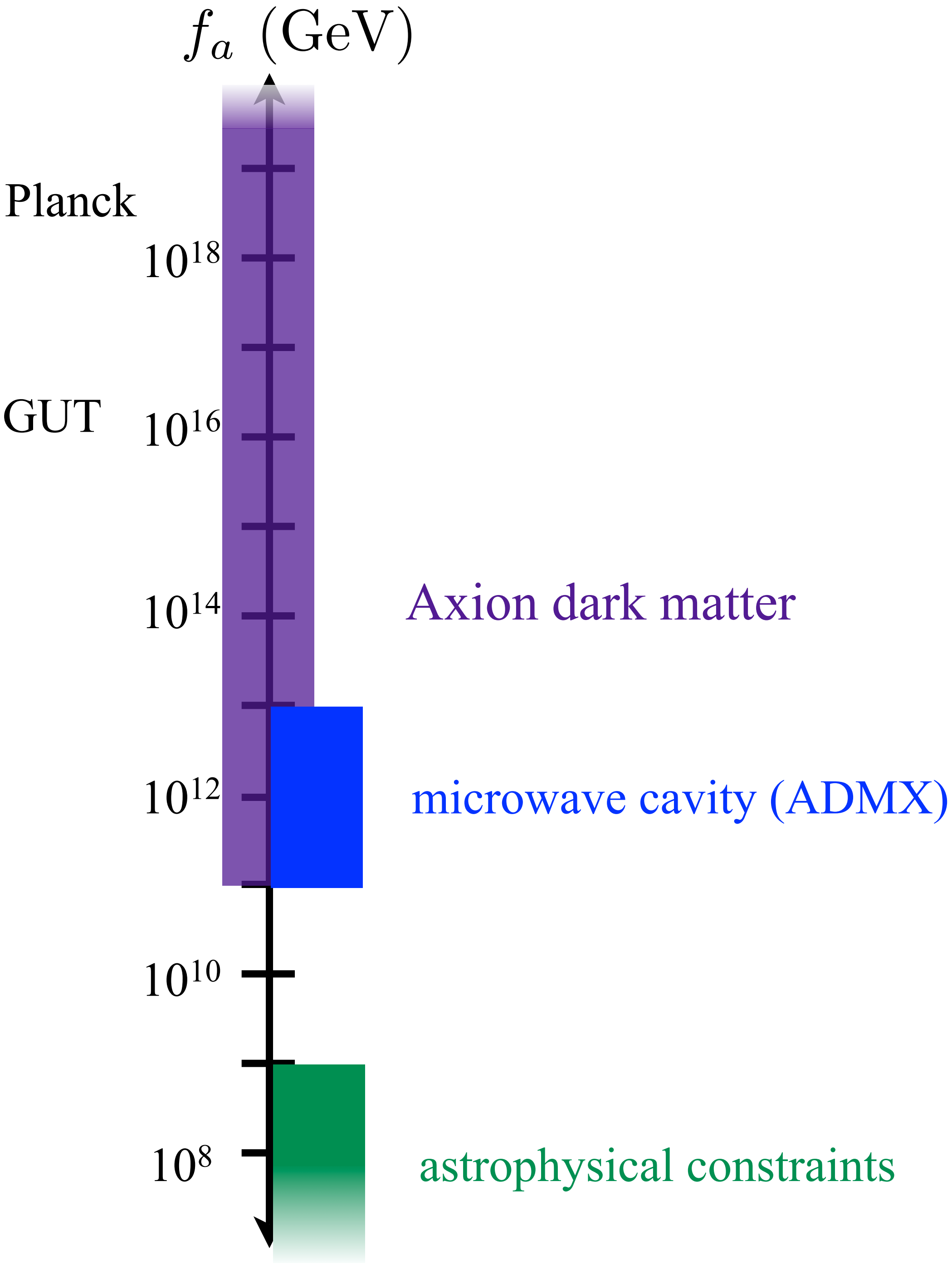
Limits on Axion-Electron Coupling



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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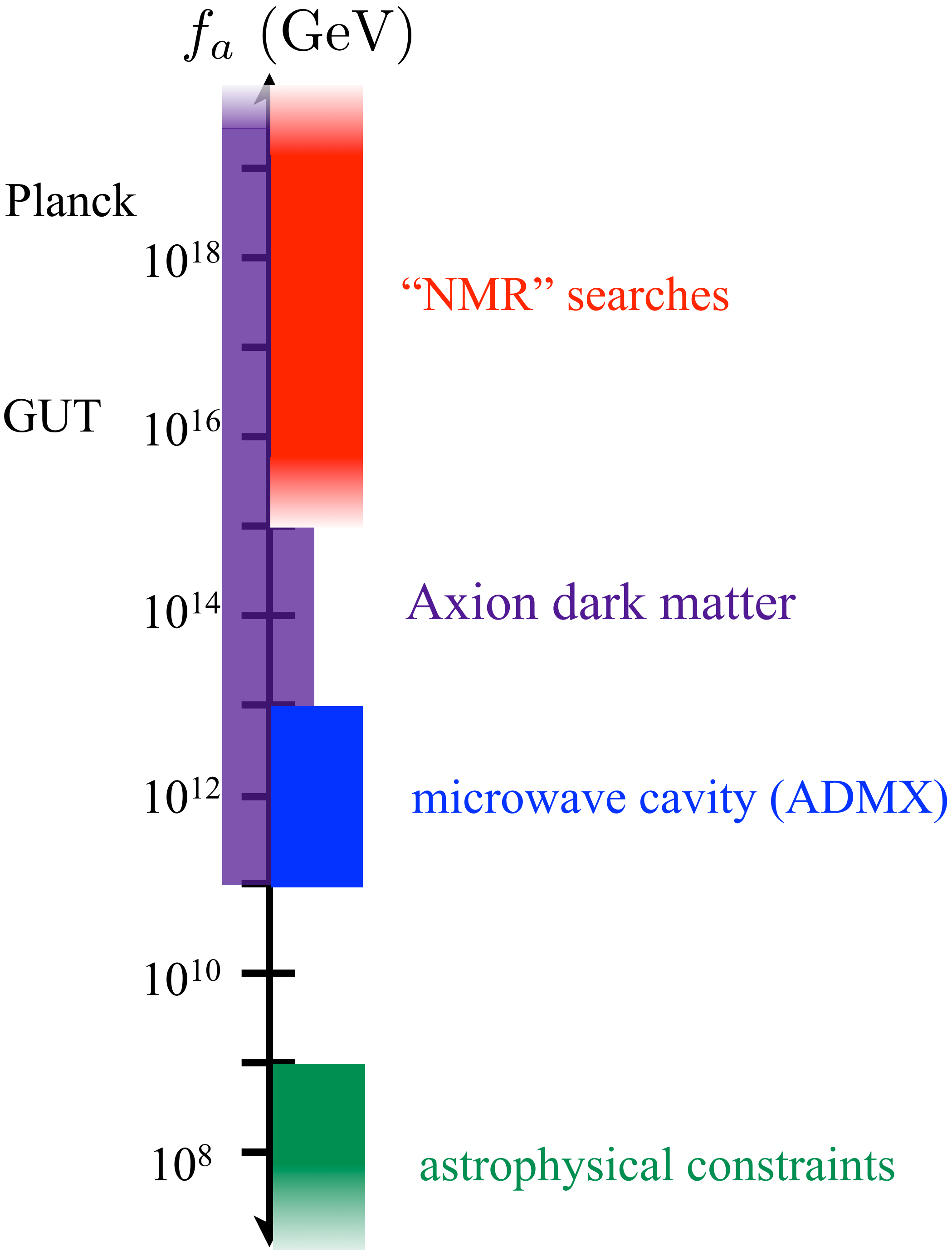

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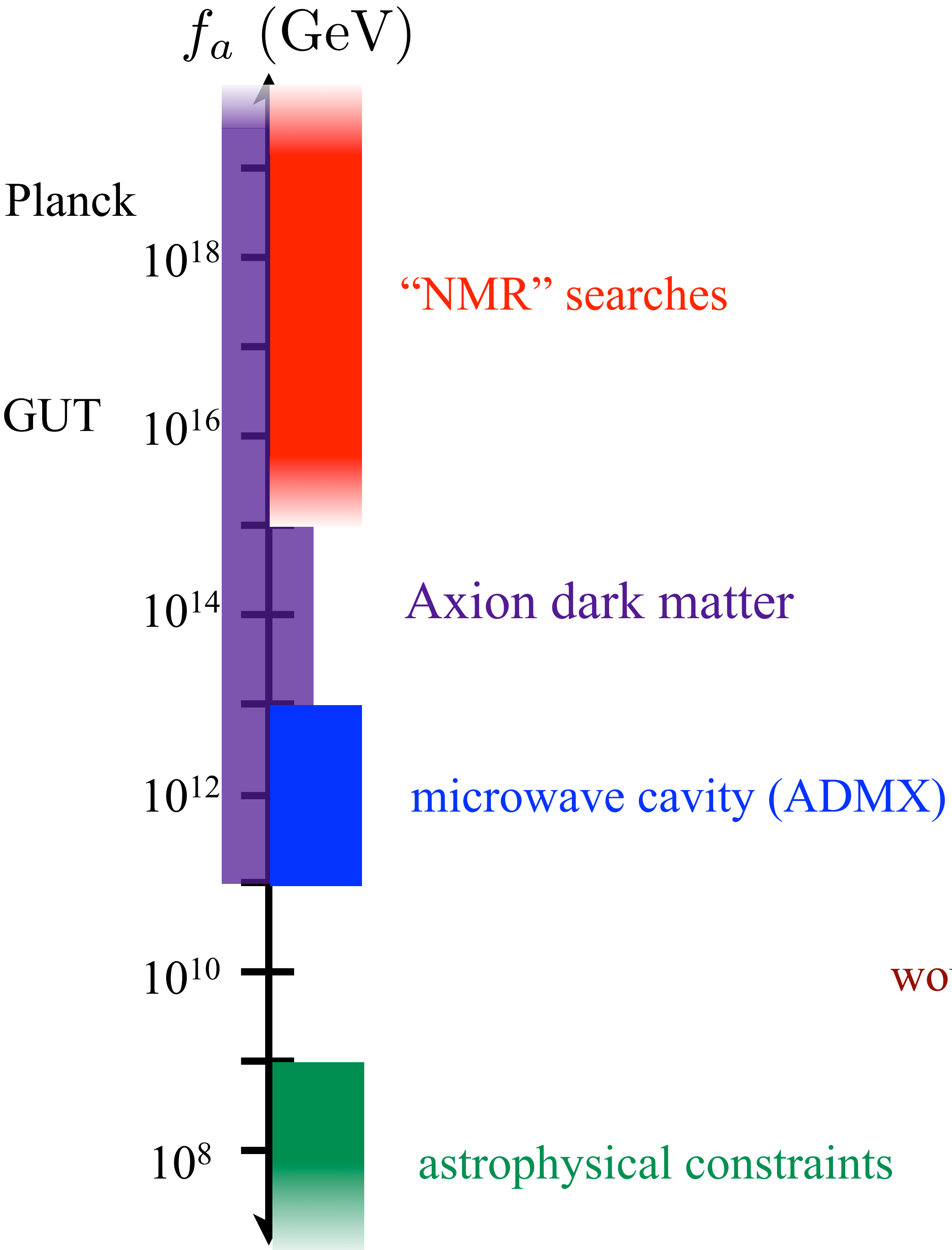

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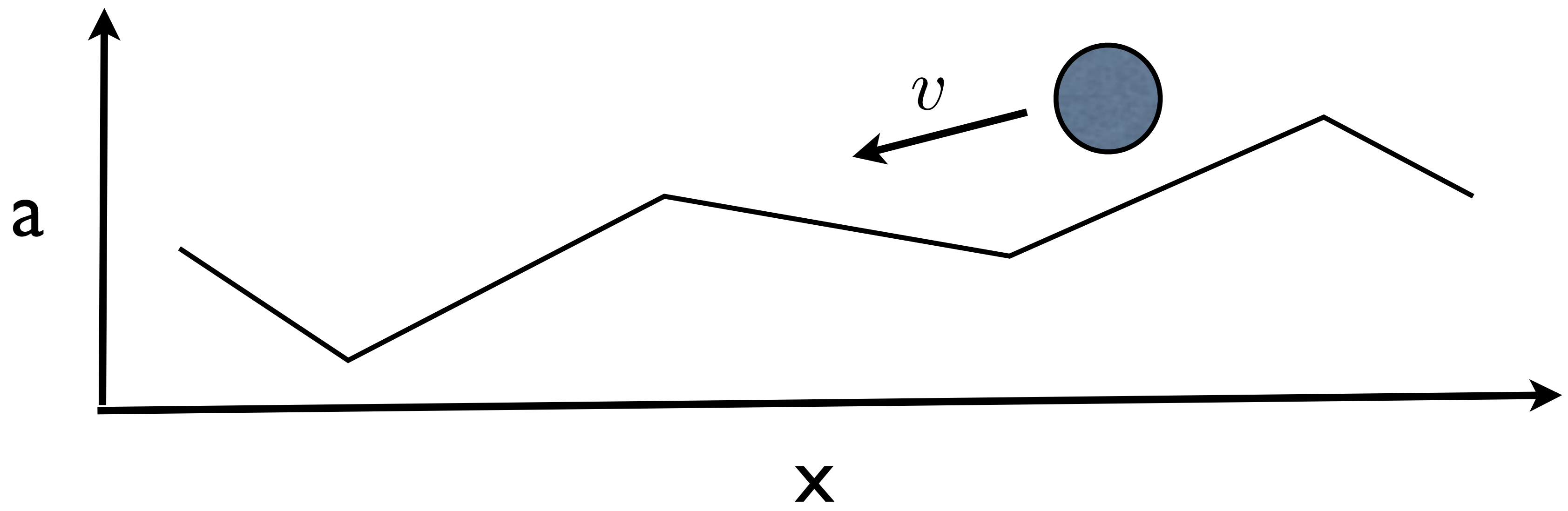
technological challenges,
similar to early stages of WIMP detection,
axions deserve similar effort

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

Axion Coherence

How large can T be?



Spatial homogeneity of the field?

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

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

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