

Cosmic Axion Spin Precession Experiment (CASPER)

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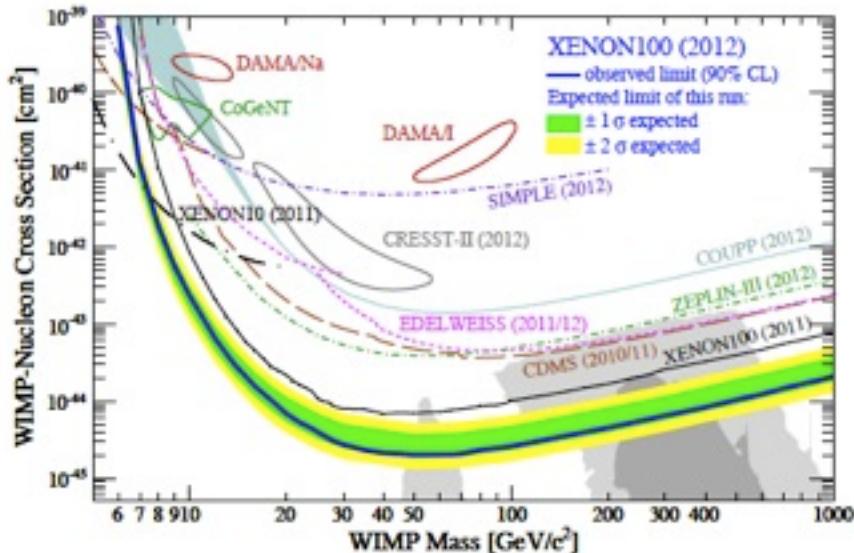
with

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Dark Matter Motivation

two of the best candidates: WIMPs and Axions



many experiments search for WIMPs

currently challenging to discover axions in most of parameter space

Important to find new ways to detect axions

Easy to generate axions from high energy theories

have a global PQ symmetry broken at a high scale f_a

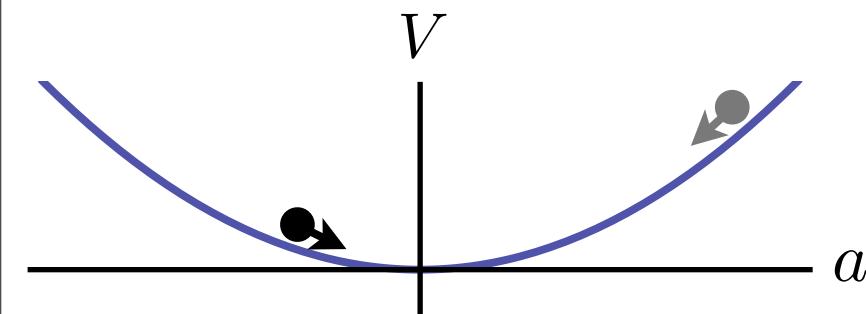
string theory or extra dimensions naturally have axions from non-trivial topology Svrcek & Witten (2006)

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

Cosmic Axions

misalignment production:

after inflation axion is a constant field, mass turns on at $T \sim \Lambda_{\text{QCD}}$ then axion oscillates



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

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

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

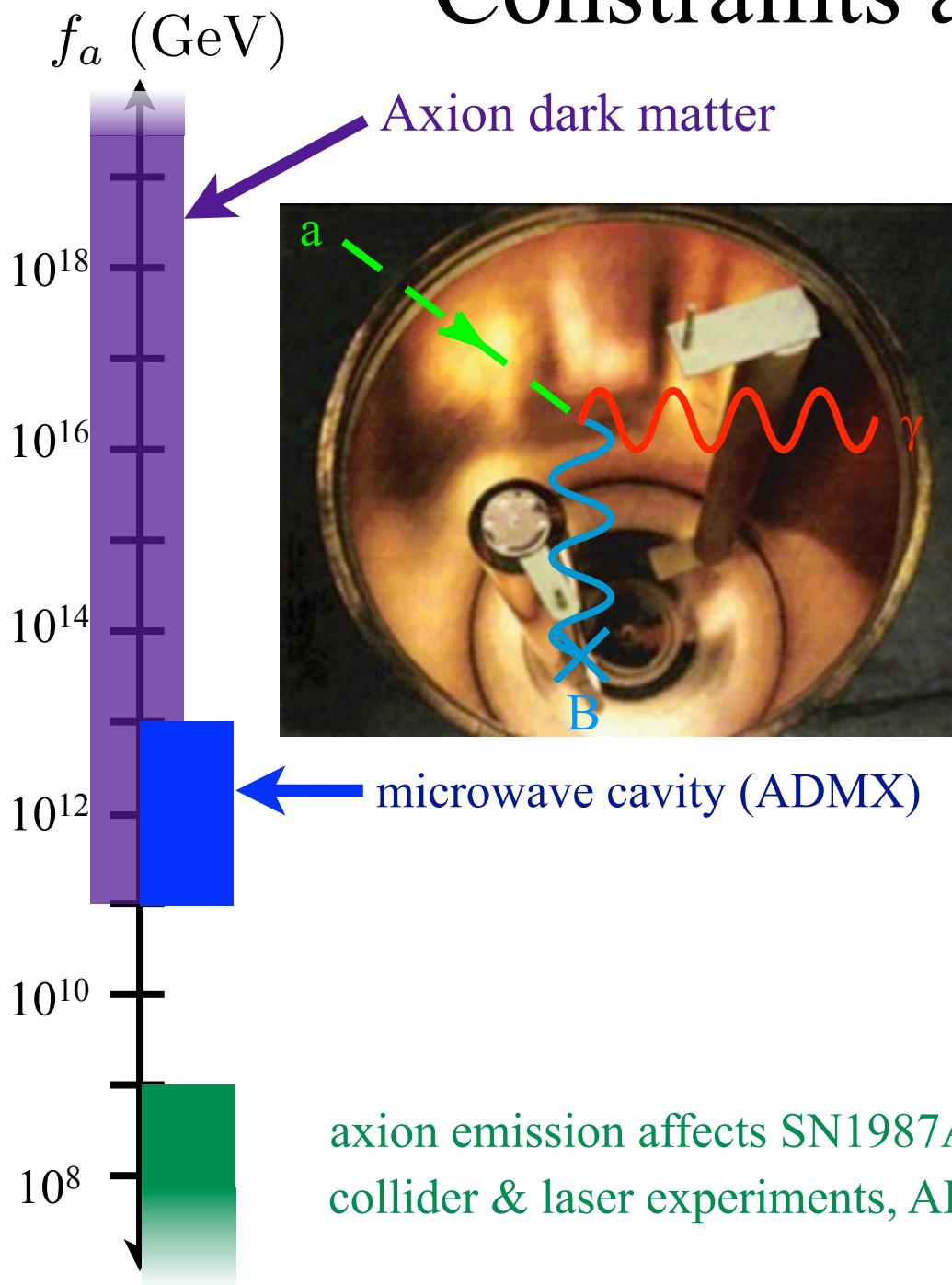
requires $\left(\frac{a_i}{f_a}\right) \sqrt{\frac{f_a}{M_{\text{Pl}}}} \sim 10^{-3.5}$ late time entropy production eases this

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

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

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

Constraints and Searches



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

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

size of cavity increases with f_a

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

axion emission affects SN1987A, White Dwarfs, other astrophysical objects
collider & laser experiments, ALPS, CAST

A Different Operator For Axion Detection

So how can we detect high f_a axions?

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

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

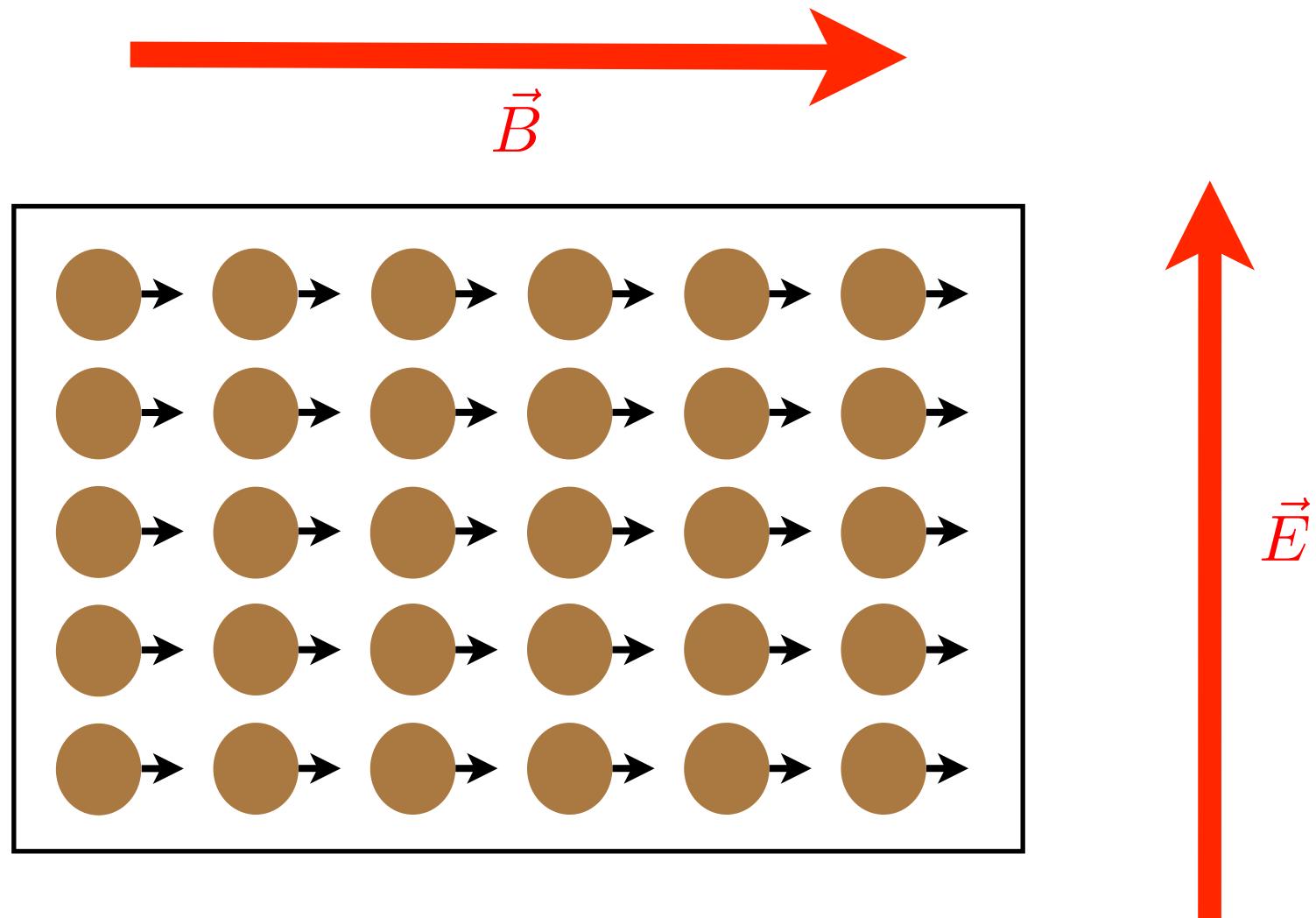
$$a(t) \sim a_0 \cos(m_a t) \quad \text{with} \quad m_a \sim \frac{(200 \text{ MeV})^2}{f_a} \sim \text{MHz} \left(\frac{10^{16} \text{ GeV}}{f_a} \right)$$

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

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

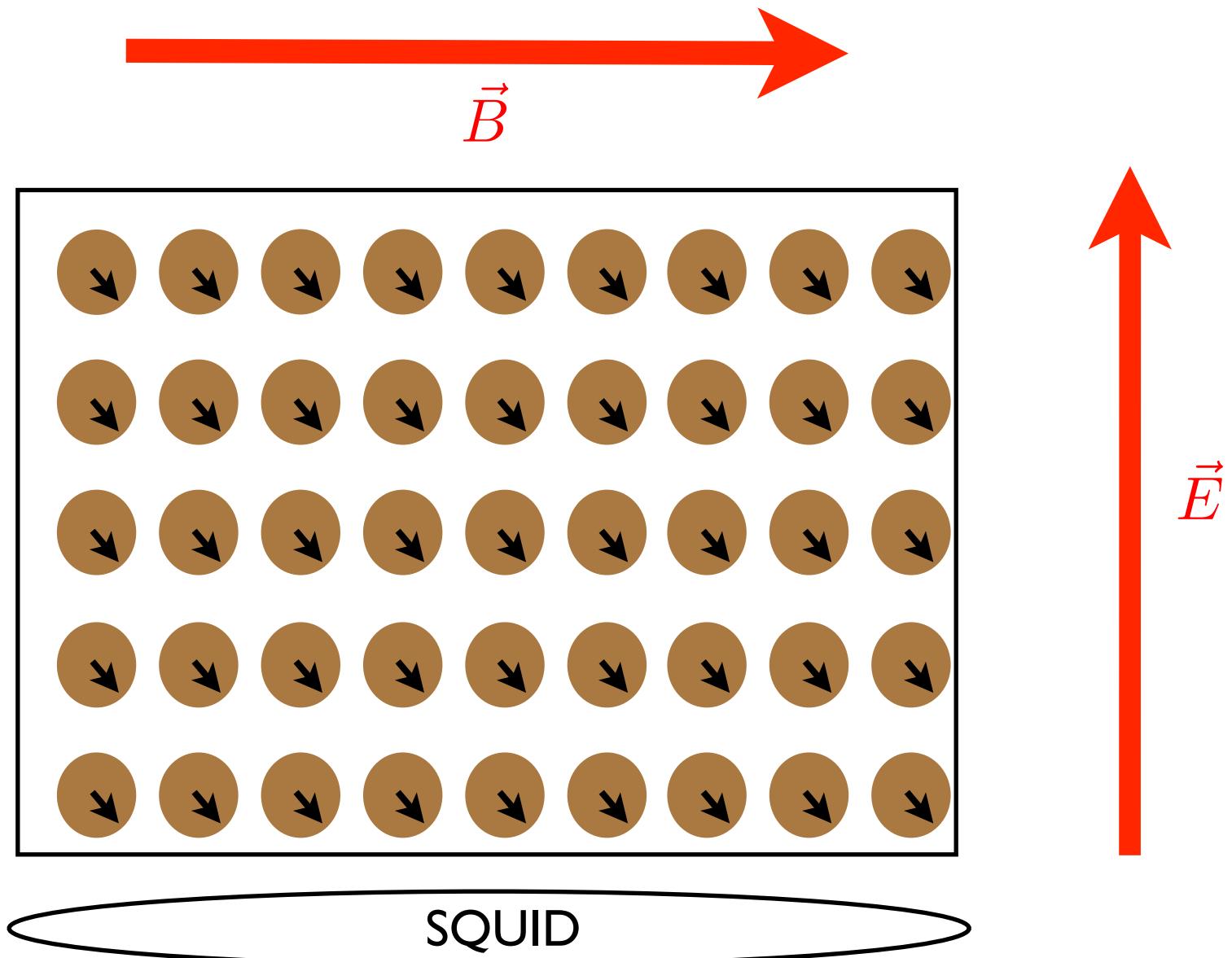
the axion gives all nucleons a rapidly oscillating EDM independent of f_a

Setup

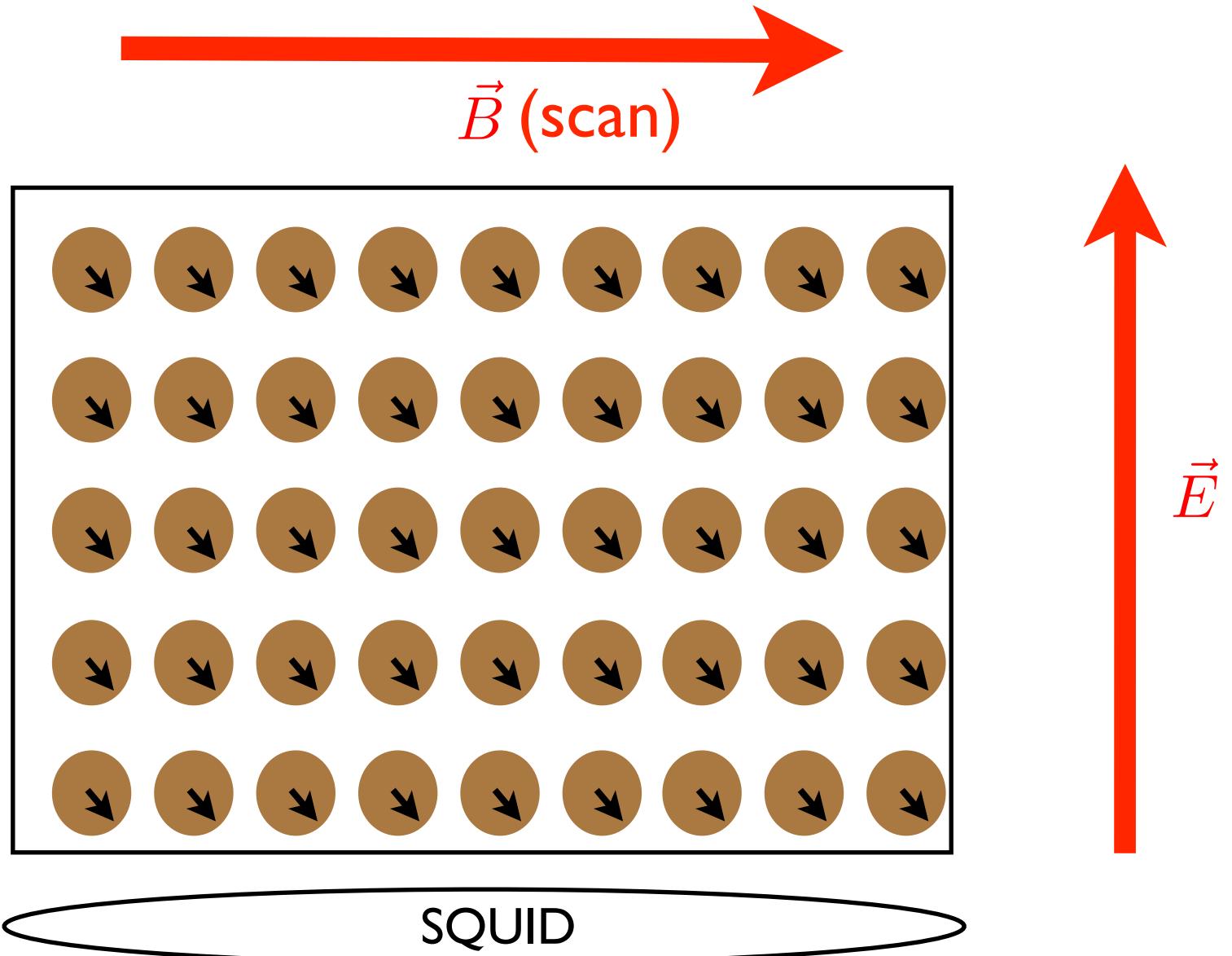


\vec{E}

Setup



Solid State Precision Magnetometry



$$\delta B \sim n\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin((2\mu_N B - m_a)t) \sin(2\mu_N B t)$$

Rough Estimate

$$\delta B \sim np\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin((2\mu_N B - m_a)t) \sin(2\mu_N B t)$$

$$n \sim \frac{10^{22}}{\text{cm}^3}$$

$$\mu_N \sim \frac{e}{\text{GeV}}$$

$$d_N \sim 10^{-34} \text{ e-cm}$$

$$p \sim \mathcal{O}\left(1\right)$$

$$E_{\text{eff}} \sim 10^6 \frac{\text{V}}{\text{cm}}$$

$$(\mu_N B - m_a)^{-1} \sim (10^{-6} m_a)^{-1} \sim t \sim 1 \text{ s} \left(\frac{f_a}{10^{16} \text{GeV}} \right)$$

$$\delta B \sim 10^{-2} \text{ fT}$$

Recap

$$\delta B \sim np\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin((2\mu_N B - m_a)t) \sin(2\mu_N B t)$$

$$n \sim \frac{10^{22}}{\text{cm}^3}$$

$$\mu_N \sim \frac{e}{\text{GeV}}$$

$$d_N \sim 10^{-34} \text{ e-cm}$$

$$p \sim \mathcal{O}(1)$$

(e.g. optical pumping)

$$E_{\text{eff}} \sim 10^6 \frac{\text{V}}{\text{cm}}$$

(e.g. polar crystal)

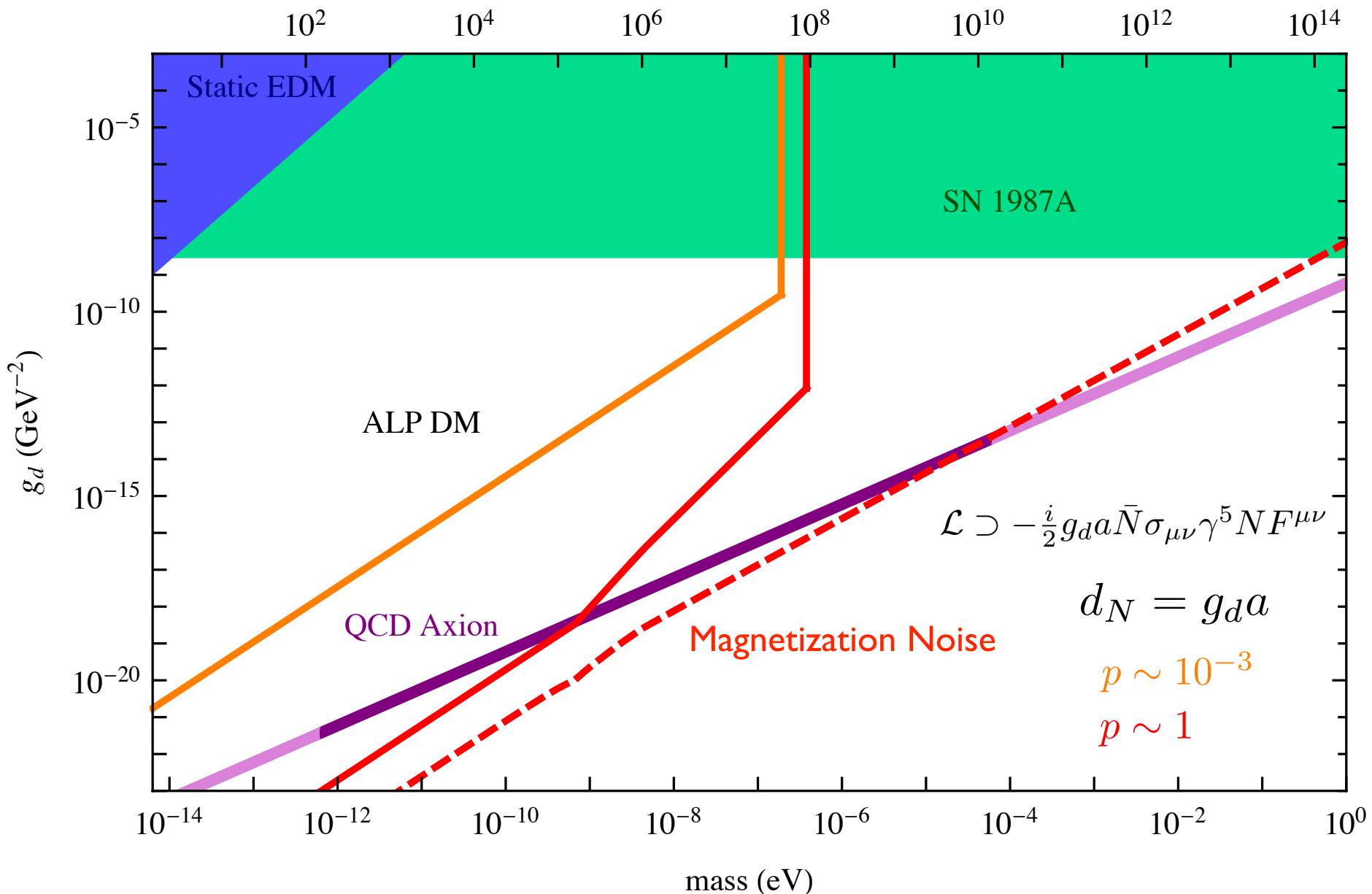
$$(\mu_N B - m_a)^{-1} \sim (10^{-6} m_a)^{-1} \sim t \sim 1 \text{ s} \left(\frac{f_a}{10^{16} \text{GeV}} \right)$$

(dynamic decoupling ($T_2 \gg 1s$) and $m_a < \text{MHz}$)

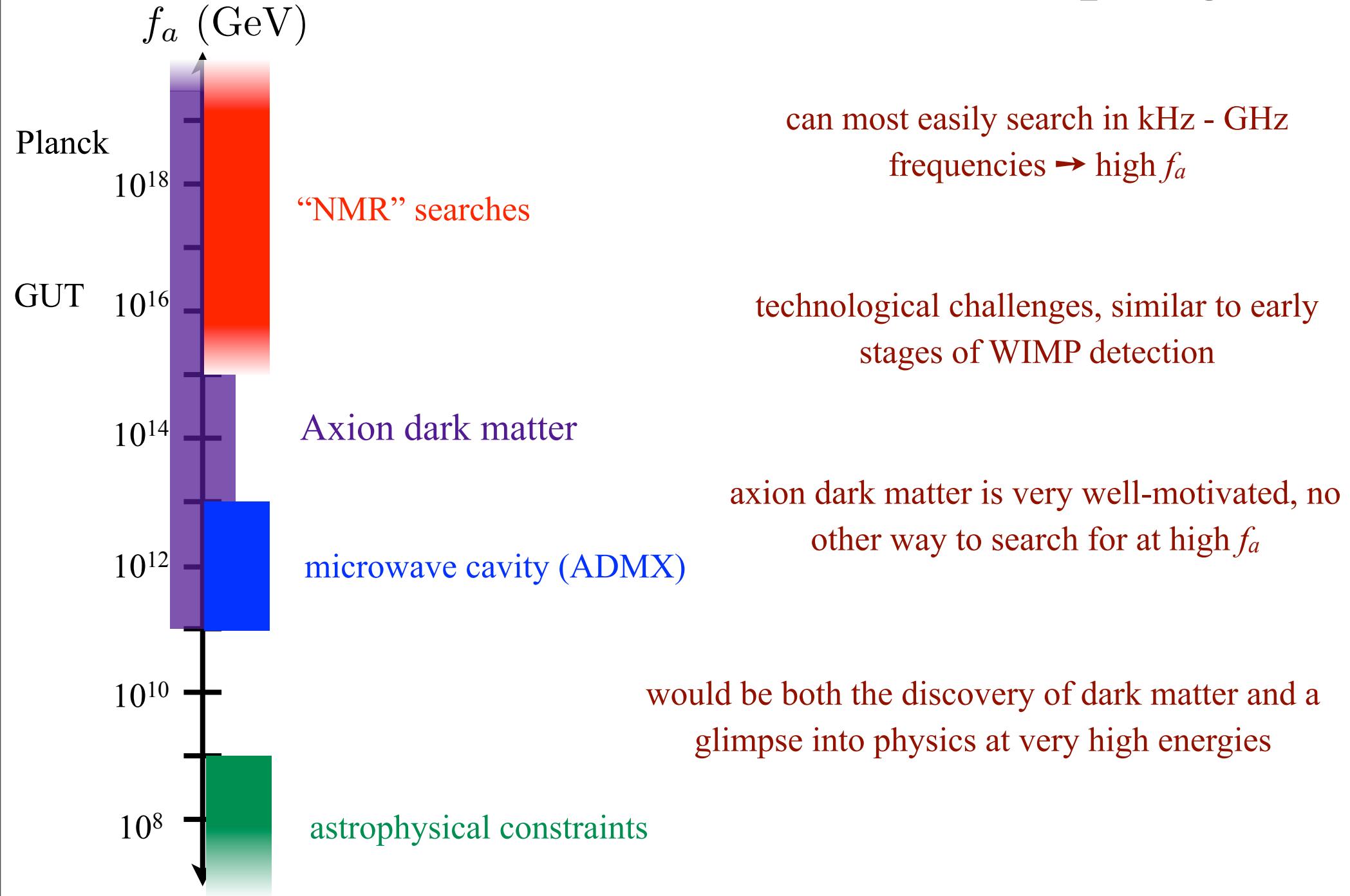
$$\delta B \sim 10^{-2} \text{ fT}$$

Projected Sensitivity in Lead Titanate

frequency (Hz)

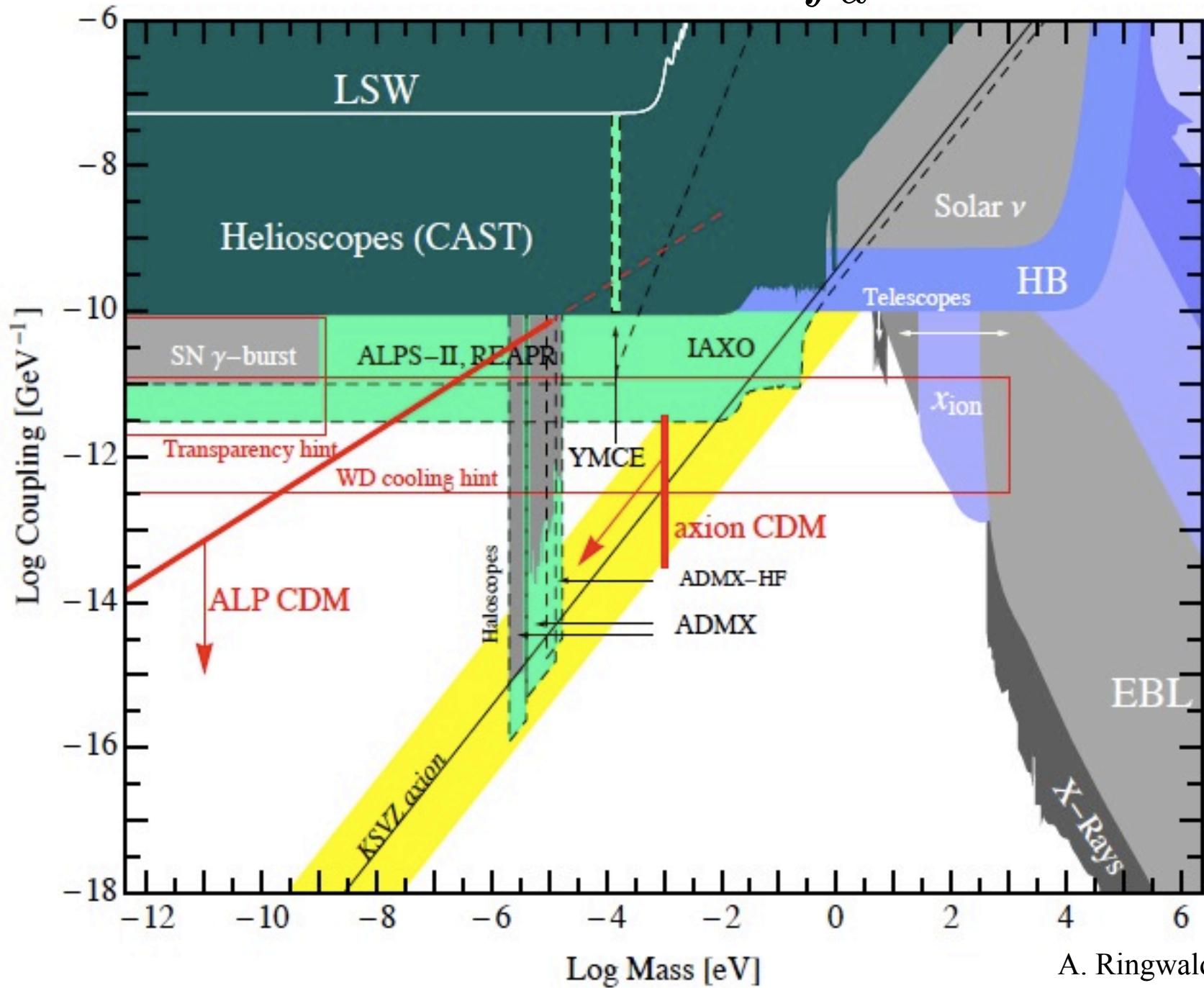


Axion Searches with Gluon Coupling



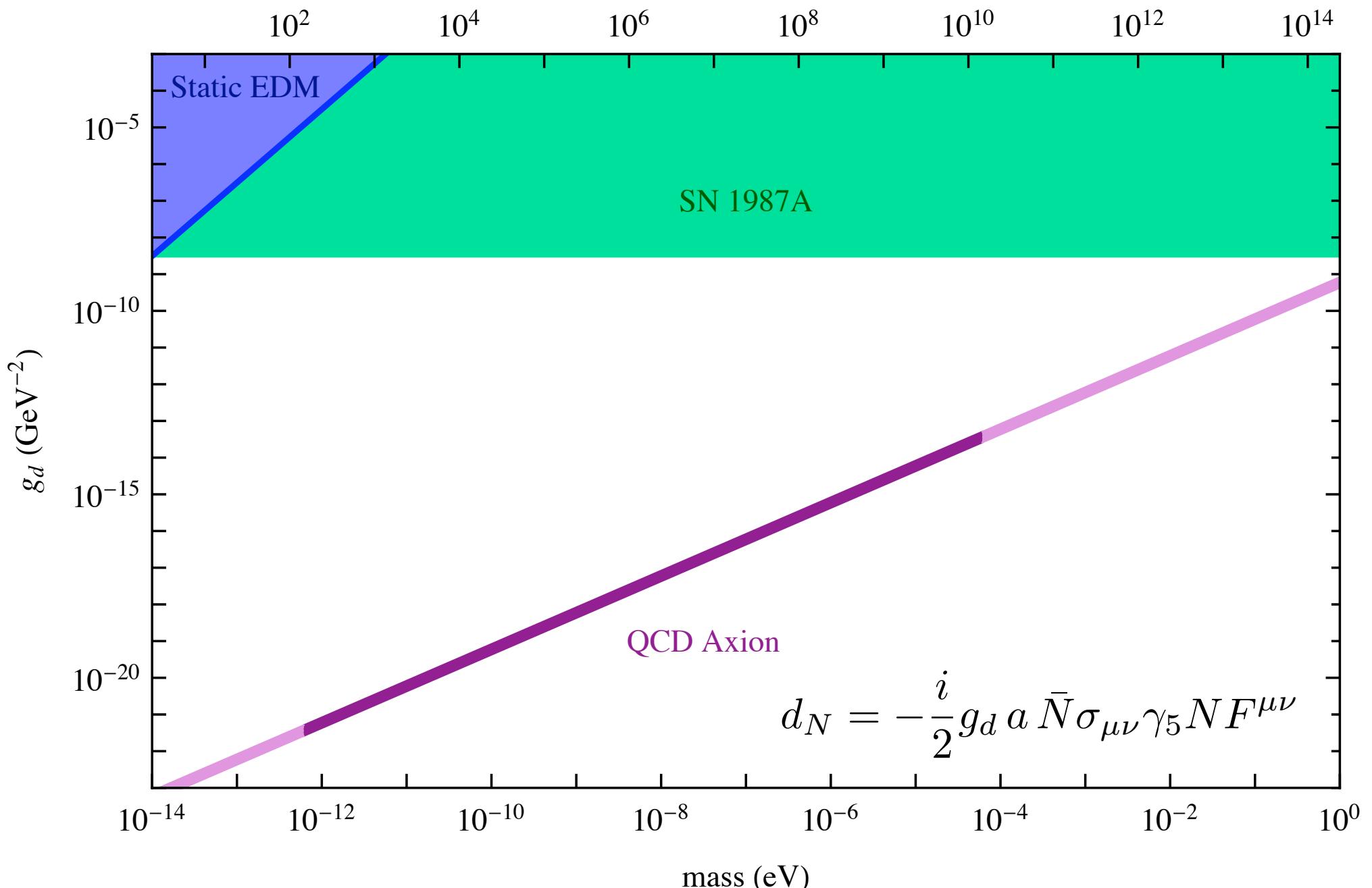
Backup

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

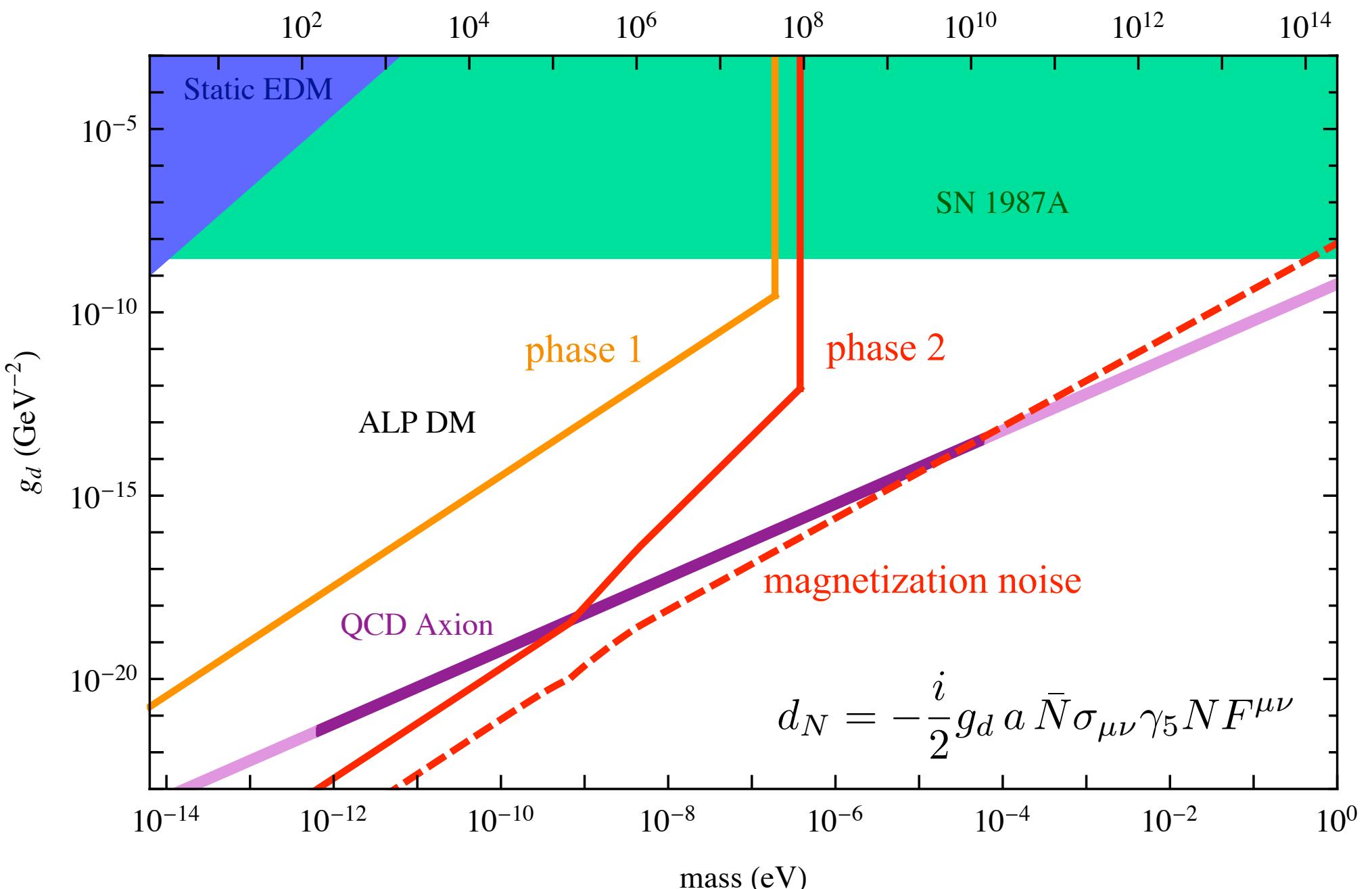


Axion Limits on $\frac{a}{f_a} G \tilde{G}$

frequency (Hz)



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



Cosmic Axion Spin Precession Experiment (CASPEr)

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

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

and nuclear spin transverse relaxation time T_2

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

	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	

Cosmic Axion Spin Precession Experiment (CASPEr)

signal scales with large density of nuclei:

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

resonant enhancement

scan over axion masses by changing B_{ext}

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

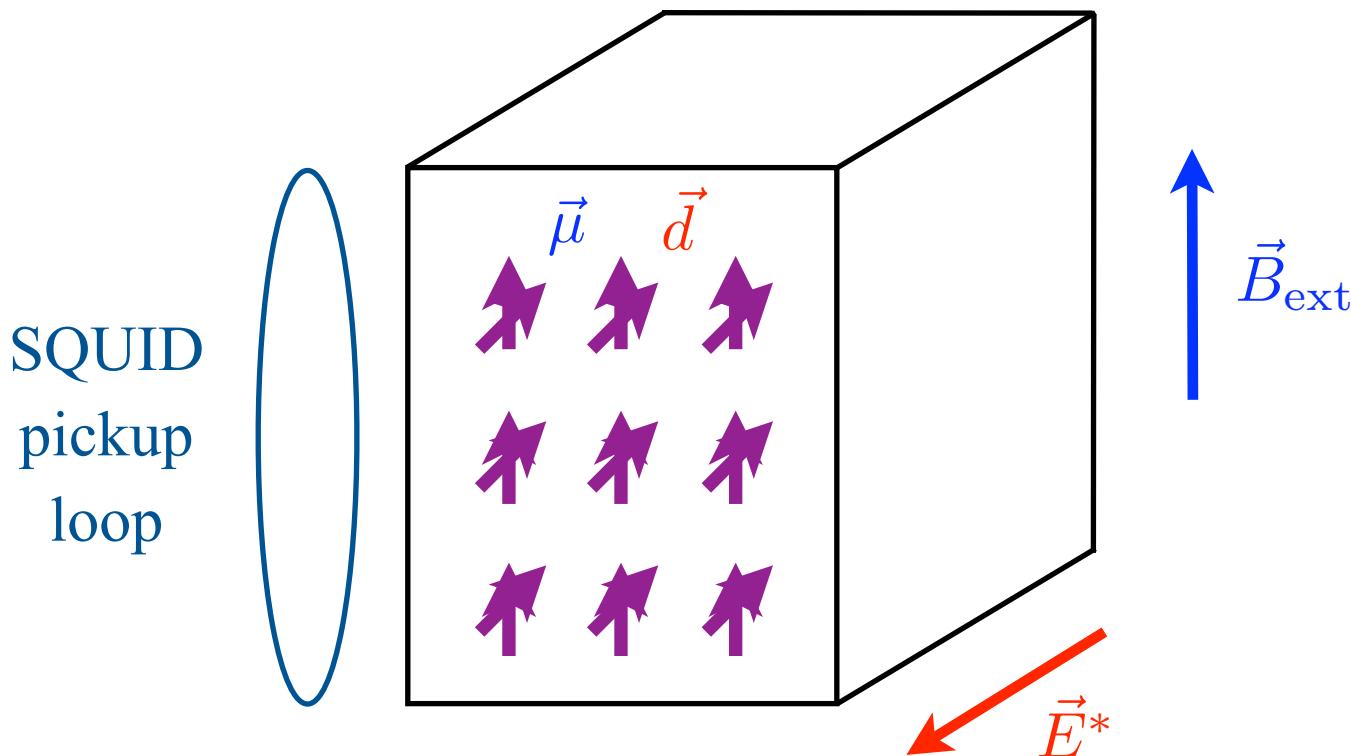
$$n = 10^{22} \frac{1}{\text{cm}^3} \quad L \sim 10 \text{ cm}$$

high nuclear spin alignment achieved in several systems (e.g. PbTiO_3), persists for $T_I \sim$ hours

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 $10^{-17} \frac{\text{T}}{\sqrt{\text{Hz}}}$

NMR Technique



high nuclear spin alignment achieved in several systems (e.g. PbTiO_3), persists for $T_1 \sim \text{hours}$

applied E field causes precession of nucleus

SQUID measures resulting transverse magnetization

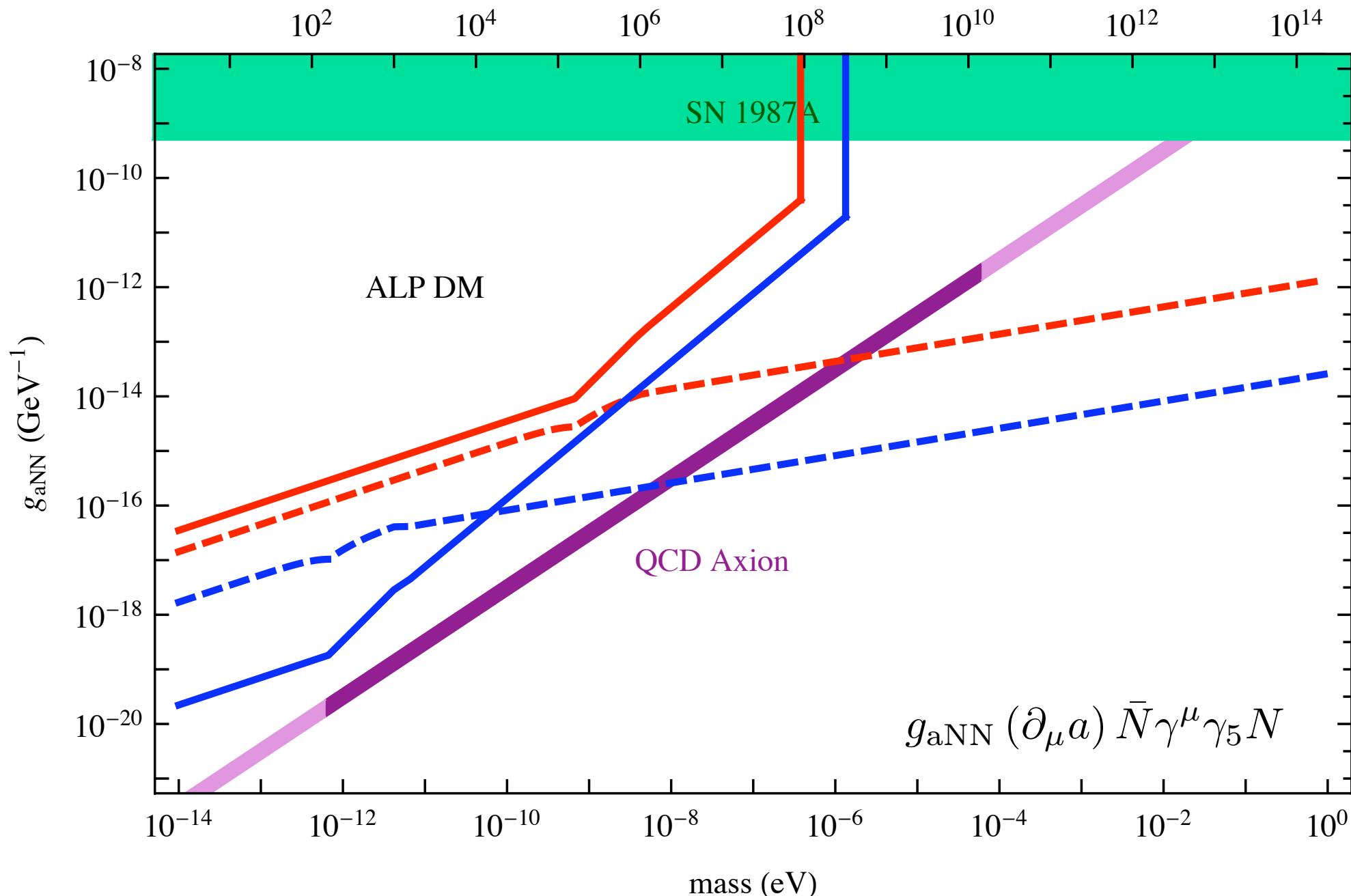
builds on e^- EDM experiments Lamoreaux (2002)

if Larmor frequency matches axion mass get resonant enhancement

Limits on Axion-Nucleon Coupling

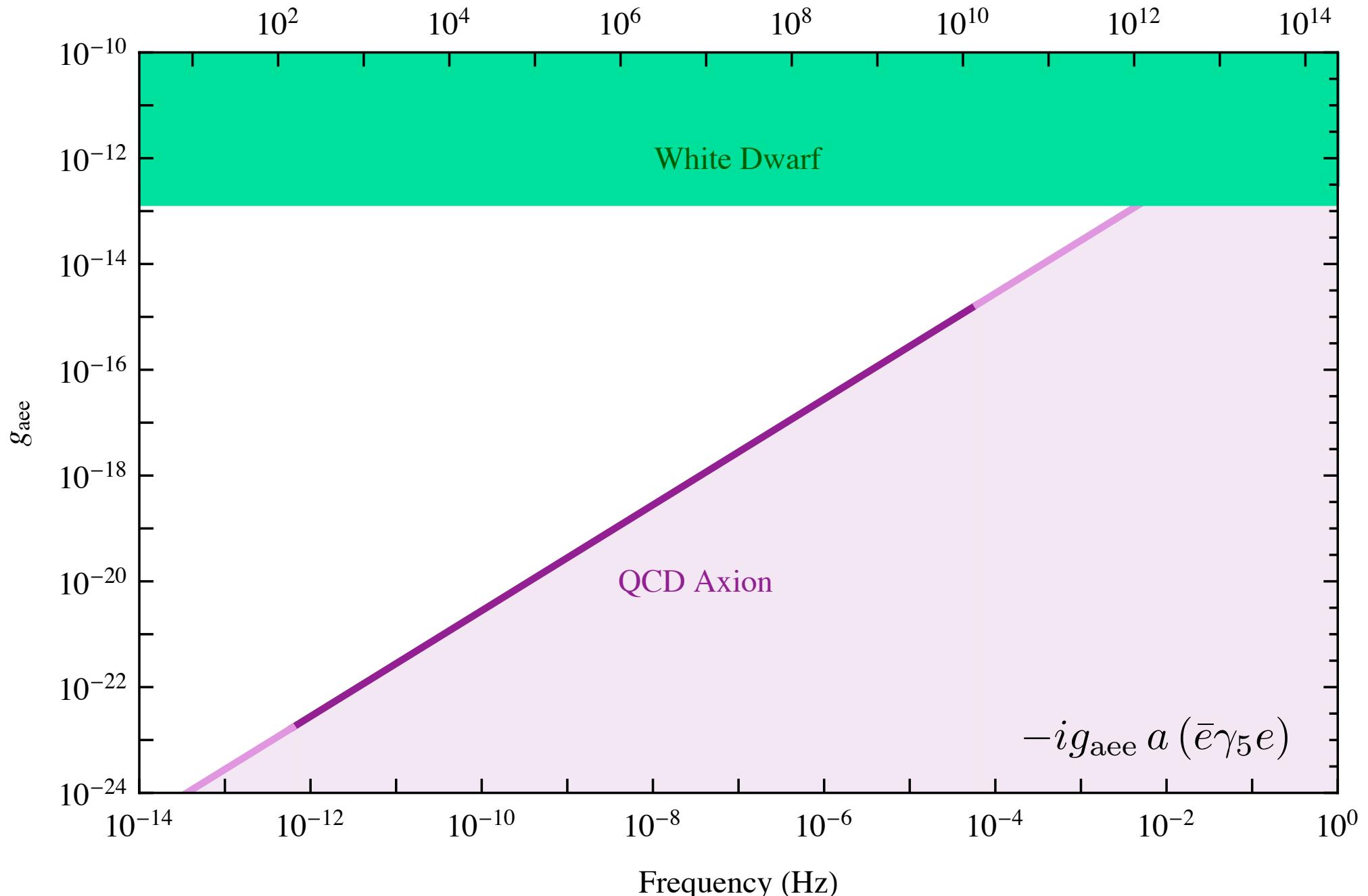
frequency (Hz)

(Preliminary)



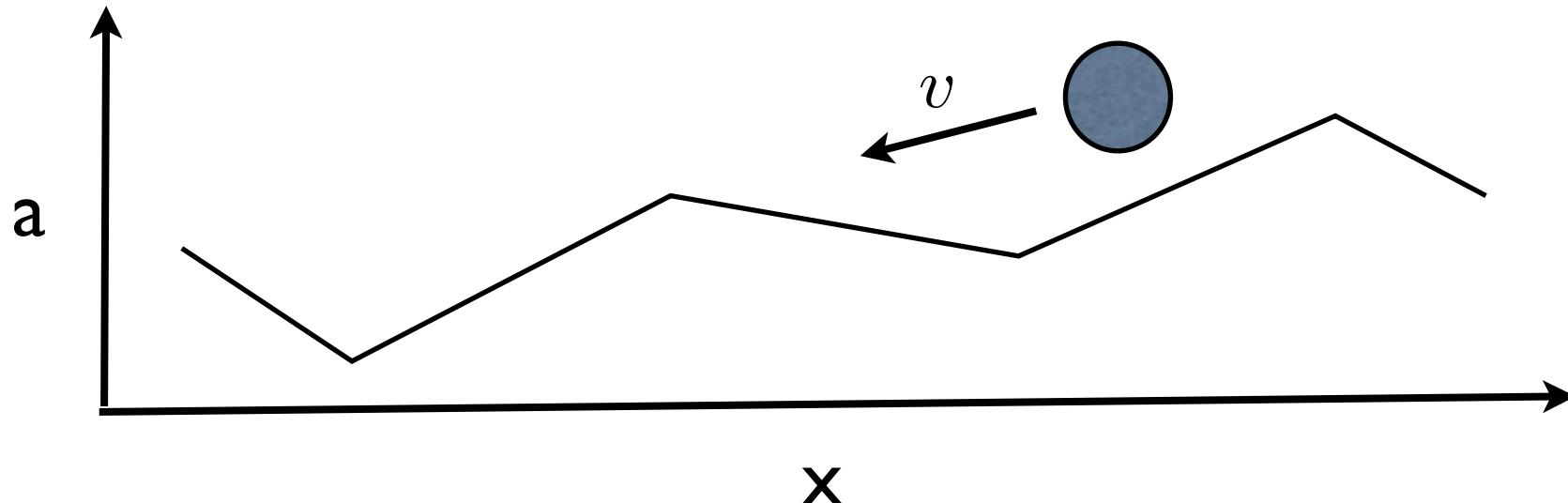
Limits on Axion-Electron Coupling

frequency (Hz)



Axion Coherence

How large can T be?



Spatial homogeneity of the field?

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

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

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

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)