Cosmic Axion Spin Precession Experiment (CASPEr)

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with
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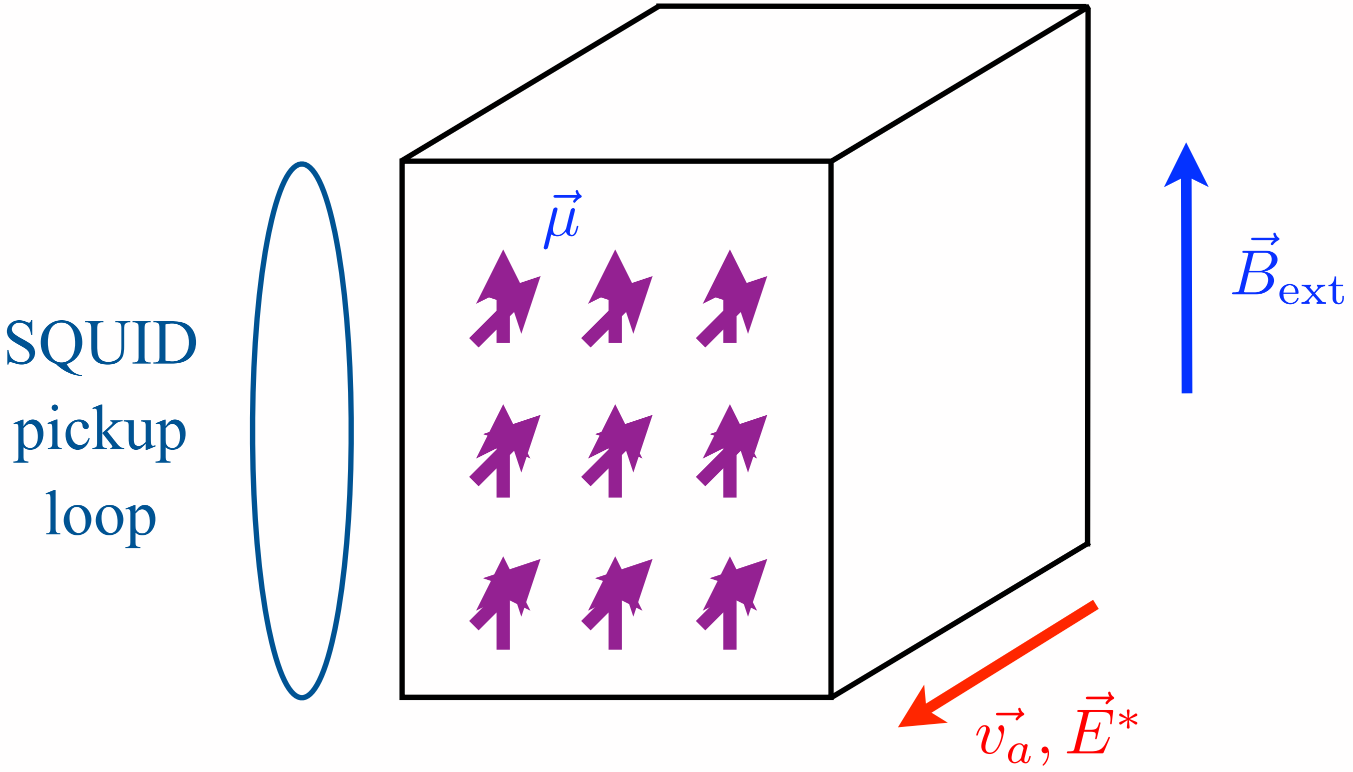
Peter Graham
Micah Ledbetter
Alex Sushkov

PRD **88** (2013) arXiv:1306.6088,
PRX (2014) arxXiv:1306.6089,
PRD **84** (2011) arXiv:1101.2691

Overview

Axion dark matter causes precession of nucleon spins

Axis set by local velocity of axion or applied electric fields



Significant reach with existing technology

Overview

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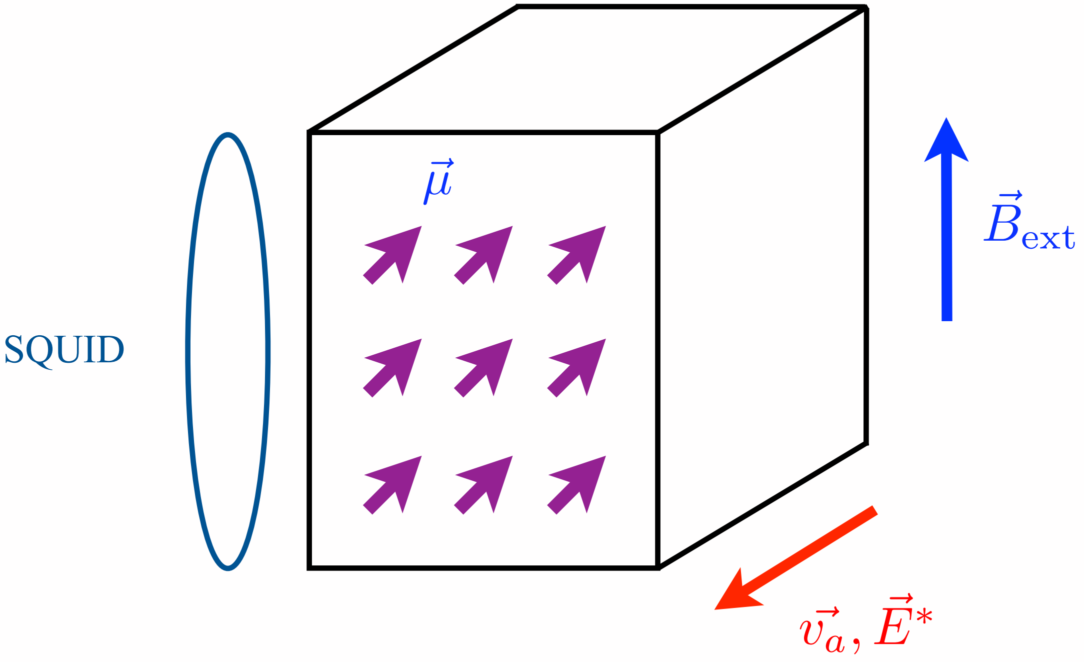


1. Axion Dark Matter
2. Signal and Noise
3. Conclusions

Axion Dark Matter

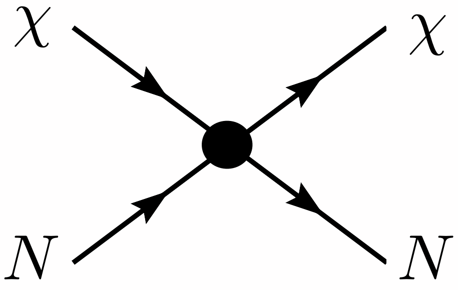
Dark Matter

Dark matter is proof of physics beyond standard model

heavy particle vs. light scalar field

(WIMPs) (axions)

Search for single particle scattering



Large phase-space density

Described as classical field *a(t,x)*

Search for coherent effects of the entire field, not single hard-particle scatterings

Axions

Global symmetry broken at high scale f_a

Light Goldstone boson

Gauge Fields

$$\frac{a}{f_a} F \wedge F, \ \frac{a}{f_a} G \wedge G$$

Fermions

$$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

string theory or extra dimensions naturally have axions from non-trivial topology

eg: reduction of higher dimensional gauge forms

Svrcek & Witten (2006)

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

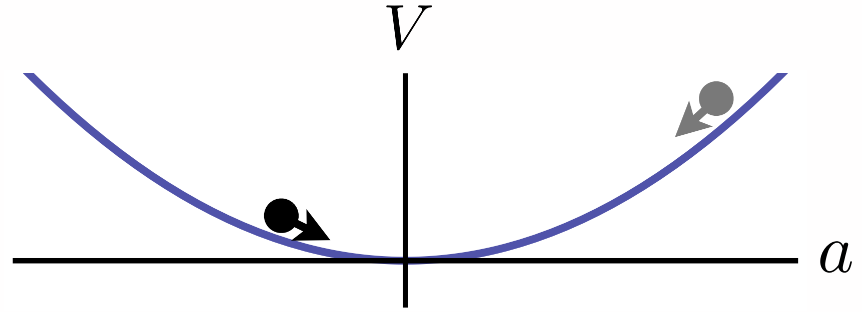
Axion Dark Matter

Misalignment production:

Field has some initial value in the early universe,

oscillations carry energy density, natural dark matter.

For QCD axion mass turns on at $T \sim \Lambda_{QCD}$



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

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

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

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

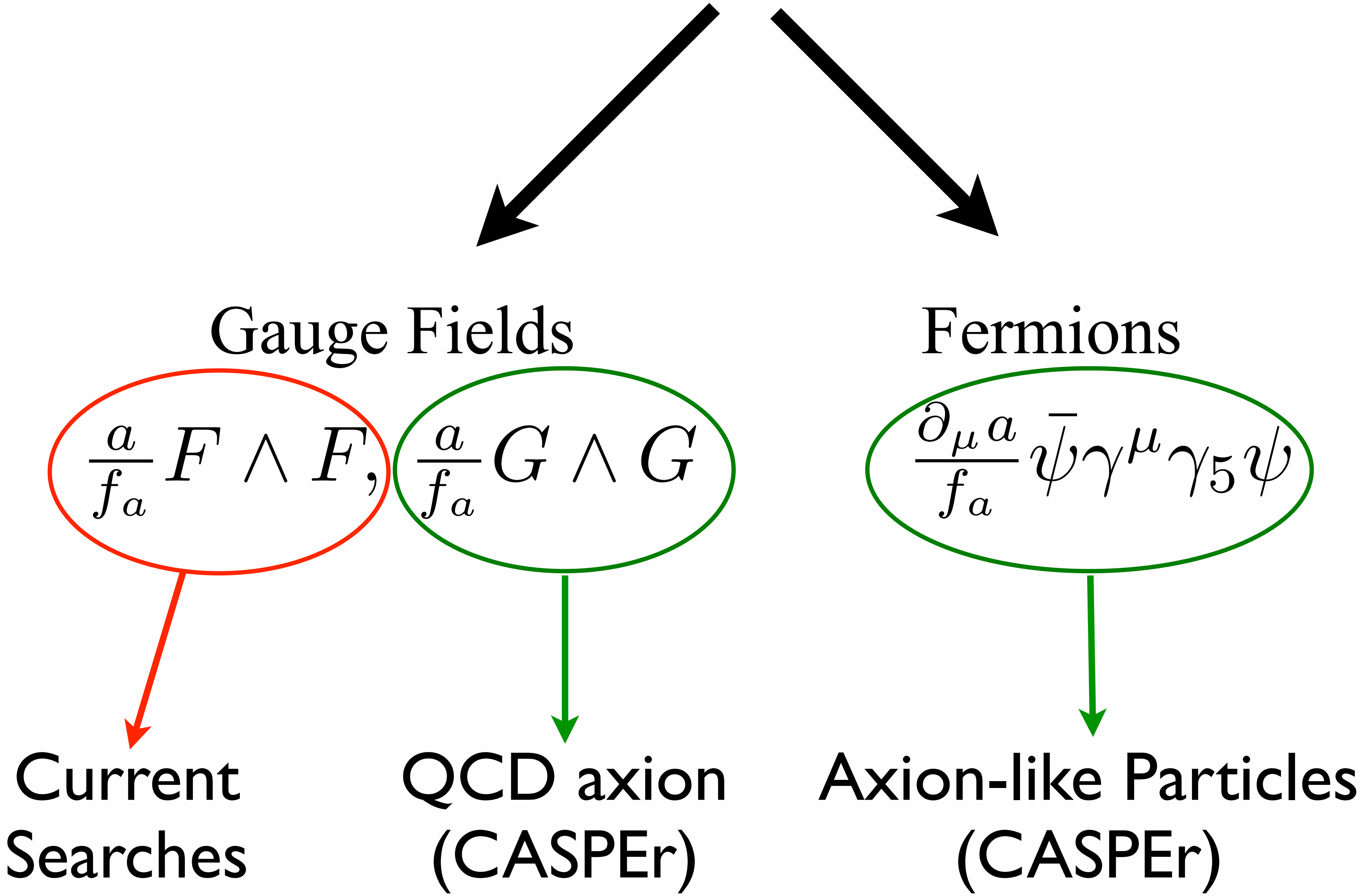
Currently challenging to discover axions in much of parameter space

Important to find new ways to detect axions

Axions

Global symmetry broken at high scale f_a

Light Goldstone boson



Gauge Fields

$$\frac{a}{f_a} F \wedge F, \quad \frac{a}{f_a} G \wedge G$$

Fermions

$$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

Current Searches

QCD axion (CASPEr)

Axion-like Particles (CASPEr)

Axions and the CMB

Assuming BICEP detected gravitational waves in the CMB (some tension with Planck):

$$H_{\rm inf} \sim 10^{14}\ {\rm GeV}$$

if symmetry broken after inflation → topological defects (strings + domain walls), constrained by observations

if symmetry broken before inflation → inflation can induce isocurvature perturbations of axion, weak constraint on ALPs probed by CASPEr.

for QCD axion, constrains **one** cosmological history.

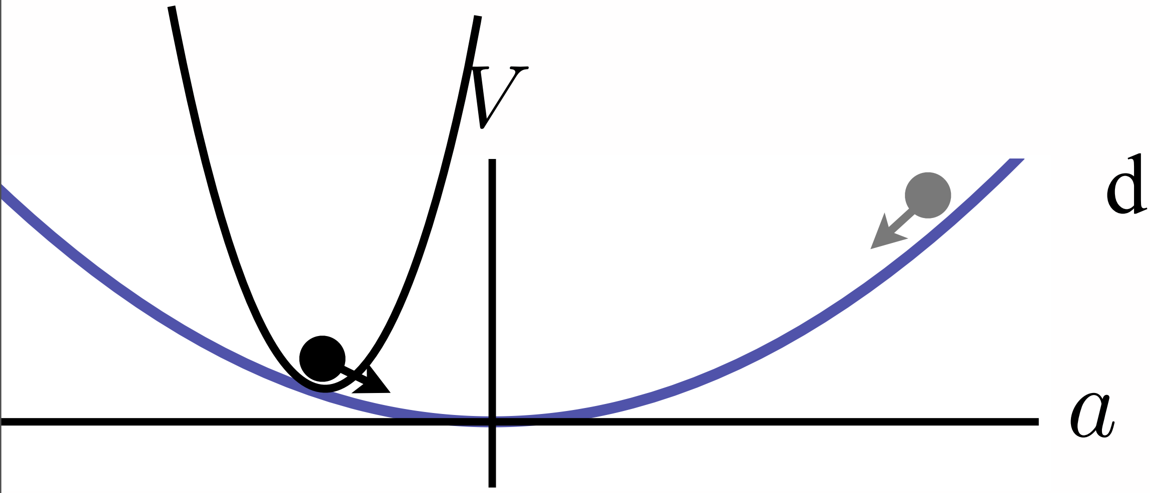
Requires knowing physics all the way up to GUT scale $\sim 10^{16}\ {\rm GeV}$

many others possible.

QCD Axion and BICEP

Need a high temperature, transient mass, sometime before QCD phase transition.

Need not be on during inflation.



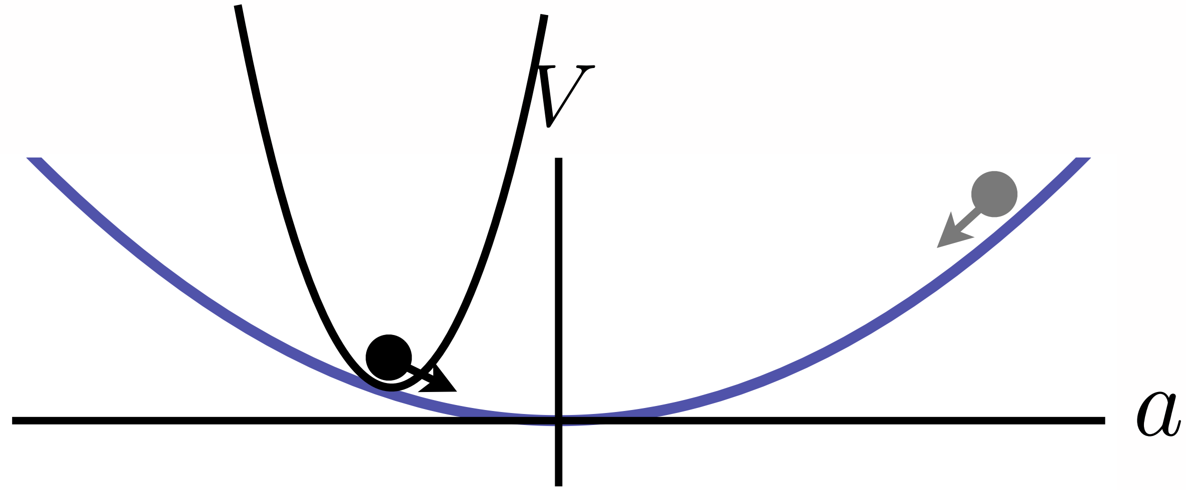
Axion oscillates earlier, damps to high temperature minimum.

Misalignment of minima gives axion dark matter.

Dark matter from choice of parameters instead of initial conditions.

QCD Axion and BICEP

Need a high temperature, transient mass, sometime before QCD phase transition.

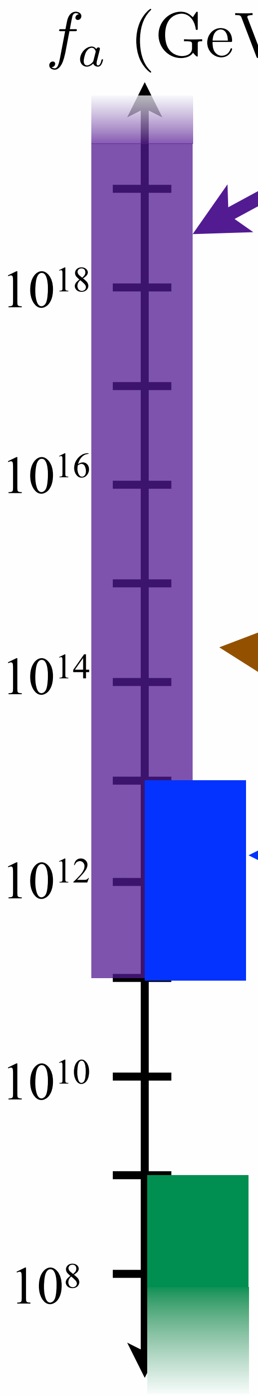


e.g. thermal monopole density, Fischler & Preskill (1983)
high temperature mass,
and many others e.g. Kaplan & Zurek (2005), Jeong & Takahashi (2013), G. Dvali (1995)

Bound depends upon high energy physics, while strong CP, axion dark matter rely upon low energy physics.

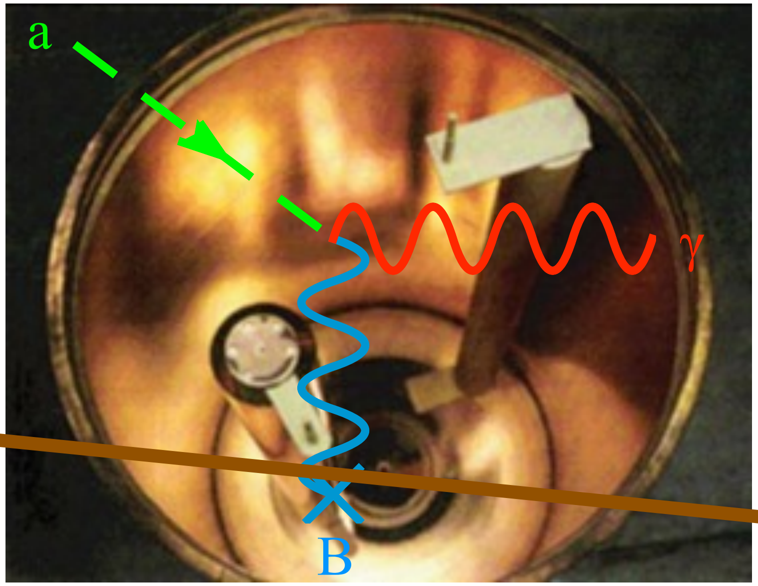
QCD axion offers unique probe of high energy cosmology,
an era difficult even for gravitational wave detectors

Constraints and Searches



Axion dark matter

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



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

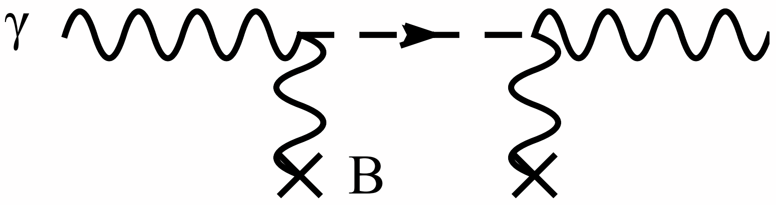
size of cavity increases with f_a

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

S. Thomas

microwave cavity (ADMX)

laser experiments:



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

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

Other ways to search for light (high f_a) axions?

Signal and Noise

New Operators for Axion Detection with NMR

1. The QCD Axion $\left(\text{using } \dfrac{a}{f_a} G \wedge G\right)$

2. Axion Like Particles (ALPs) $\left(\text{using } \dfrac{\partial_\mu a}{f_a} \bar{N} \gamma_\mu \gamma_5 N\right)$

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

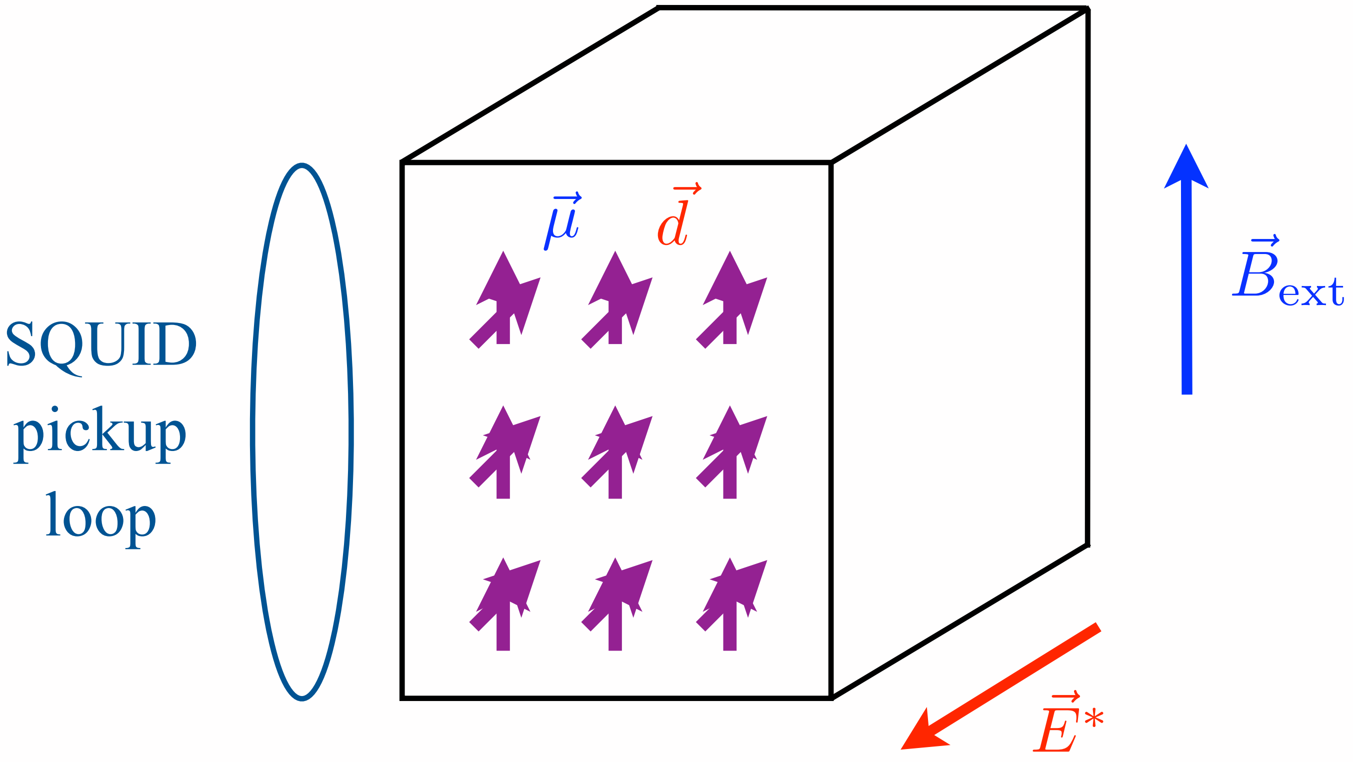
$a(t) \sim a_0 \cos\left(m_a t\right)$ with $m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz}\left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$

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

axion gives all nucleons an oscillating EDM (kHz-GHz) independent of f_a,
a non-derivative operator

NMR Technique



high nuclear spin orientation achieved in several systems, persists for T_1 ~ hours

applied E field causes precession of nucleus

SQUID measures resulting transverse magnetization

Larmor frequency = axion mass $\Longrightarrow$ resonant enhancement

resonance ➜ scan over axion masses by changing B_{ext}

Transverse Magnetization Signal

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

signal scales with large density: $n = 10^{22}\,\frac{1}{\text{cm}^3}$

resonant enhancement limited by axion coherence time $\tau_a \sim \frac{2\pi}{m_a v^2} \sim 1\text{ s}\left(\frac{\text{MHz}}{m_a}\right)$

Schiff suppression

E.g. Material Choice $^{207}\text{Pb} \implies \mu = 0.6\mu_N \quad \epsilon_S \approx 10^{-2} \quad \boxed{E^* \approx 3\times 10^8\,\frac{\text{V}}{\text{cm}}}$

nuclear magnetic moment

Electric field

Polar samples

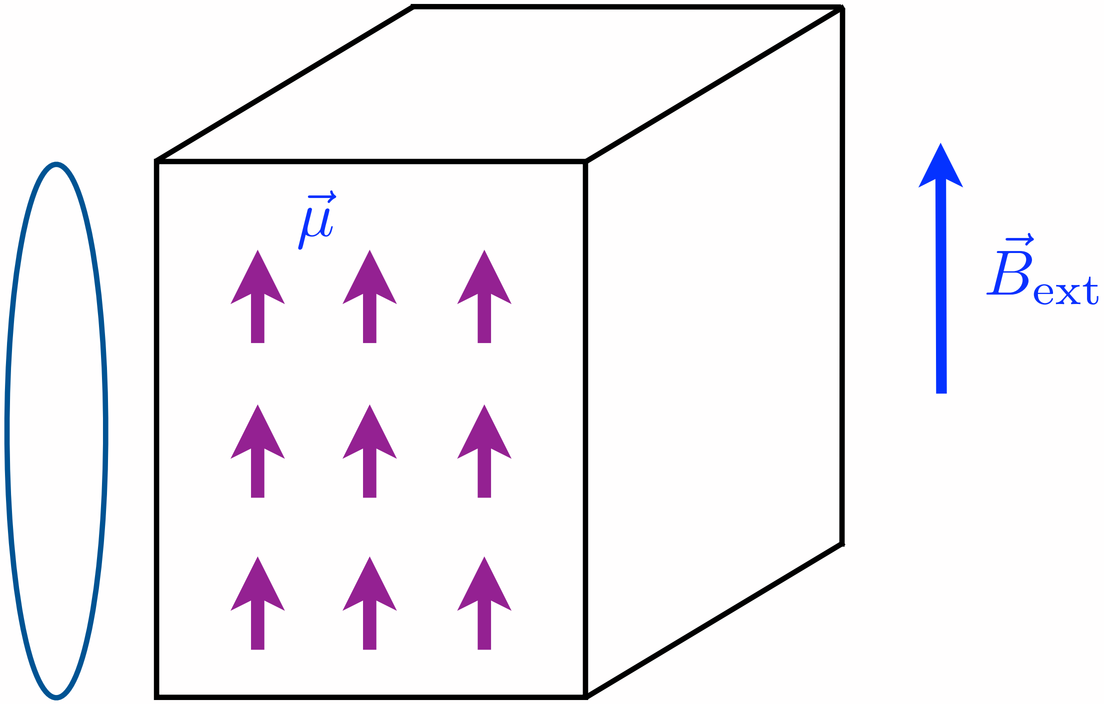
Technology $p \approx 1 \quad \boxed{T_2 \approx 1\text{ s}}$

polarization fraction

$$d_n \sim 10^{-34}\,e\cdot\text{cm} \implies \delta M \sim 10^{-2}\text{ fT}\left(\frac{\text{MHz}}{m_a}\right)$$

axion induced dipole moment

Magnetization Noise



a material sample has magnetization noise

noise arises from quantum spin projection

every spin necessarily has random quantum projection onto transverse direction

$$M_n(\omega) \sim \frac{\mu_N}{r^3}\sqrt{nr^3}\langle S(\omega)\rangle \sim \mu_N\sqrt{\frac{n}{V}}\langle S(\omega)\rangle$$

$S\left(\omega\right)$ is Lorentzian, peaked at Larmor frequency, bandwidth ~ $1/T_2$

T. Sleator, E. L. Hahn, C. Hilbert, and J. Clarke, PRL 55, 171742 (1985)

Cosmic Axion Spin Precession Experiment (CASPEr)

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

	n	E^*	p	T_2	Max. B_{ext}
Phase 1	$10^{22}\,\frac{1}{\text{cm}^3}$	$3\times 10^8\,\frac{\text{V}}{\text{cm}}$	10^{-3}	1 ms	10 T
Phase 2			1	1 s	20 T

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

take sample size: $L \sim 10$ cm ➜ we take SQUID magnetometer: $10^{-16}\,\frac{\text{T}}{\sqrt{\text{Hz}}}$

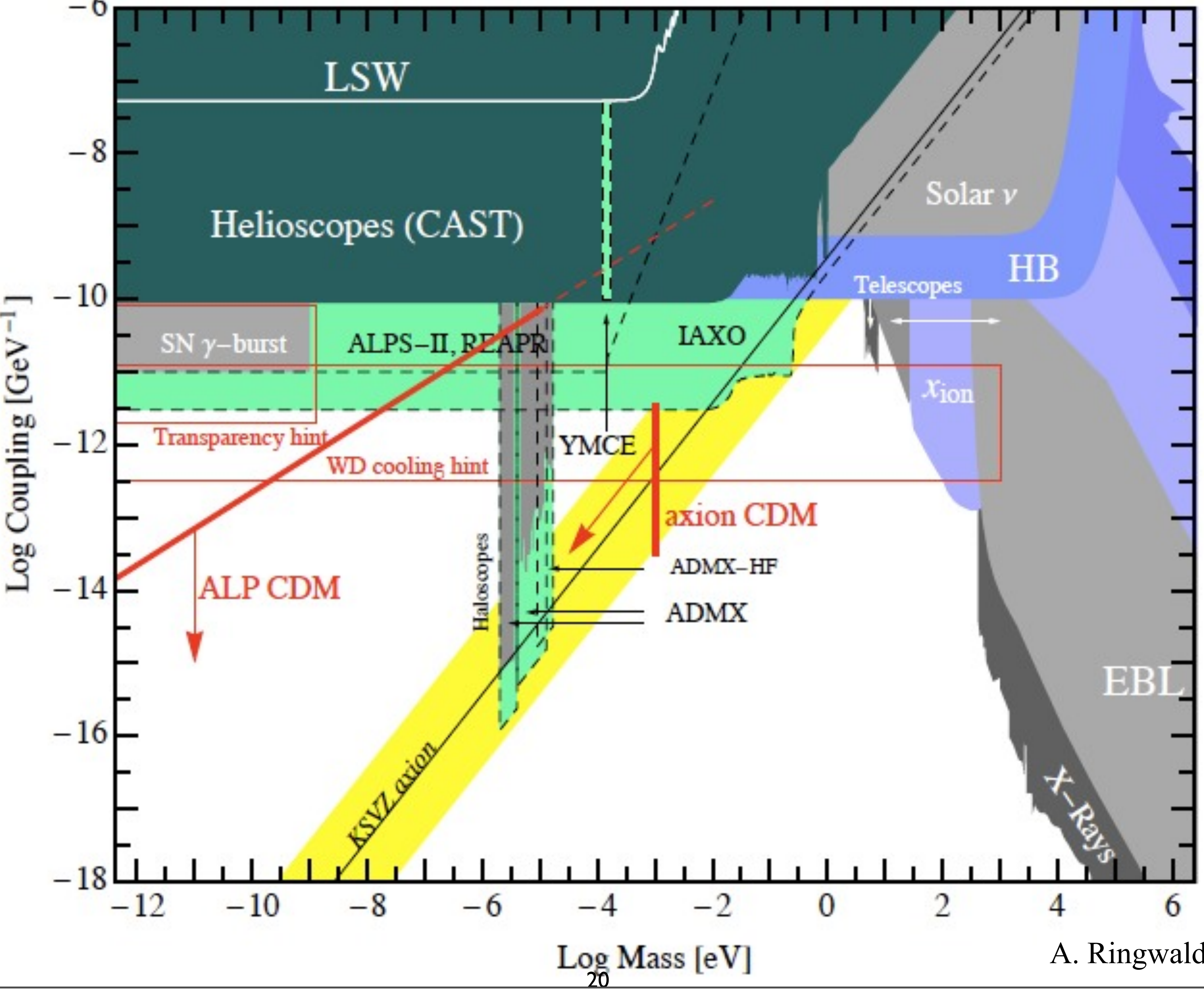
(or multiple loops over smaller sample)

but atomic magnetometers ~ $10^{-17}\,\frac{\text{T}}{\sqrt{\text{Hz}}}$

M.V. Romalis

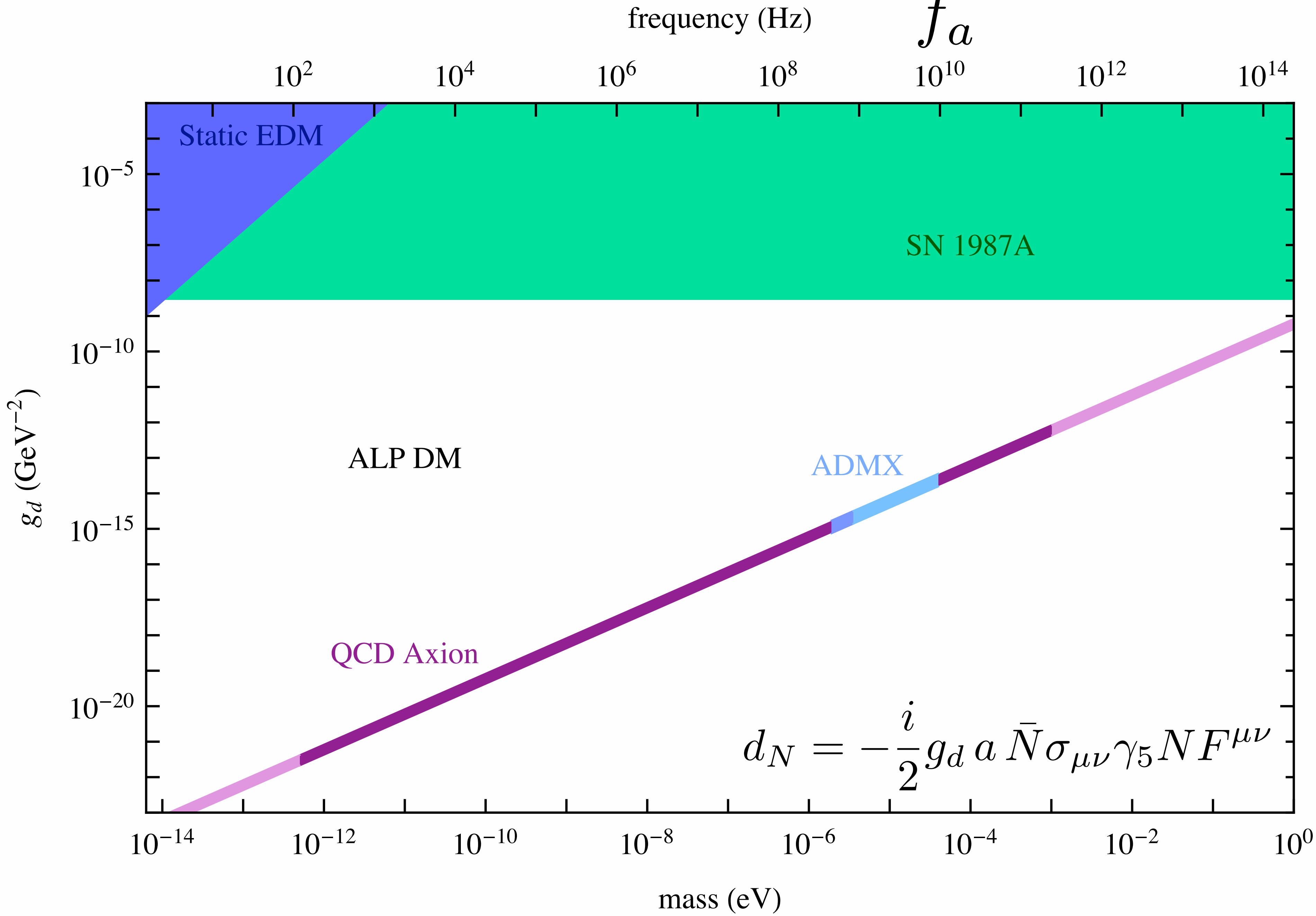
many options for increasing sensitivity

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



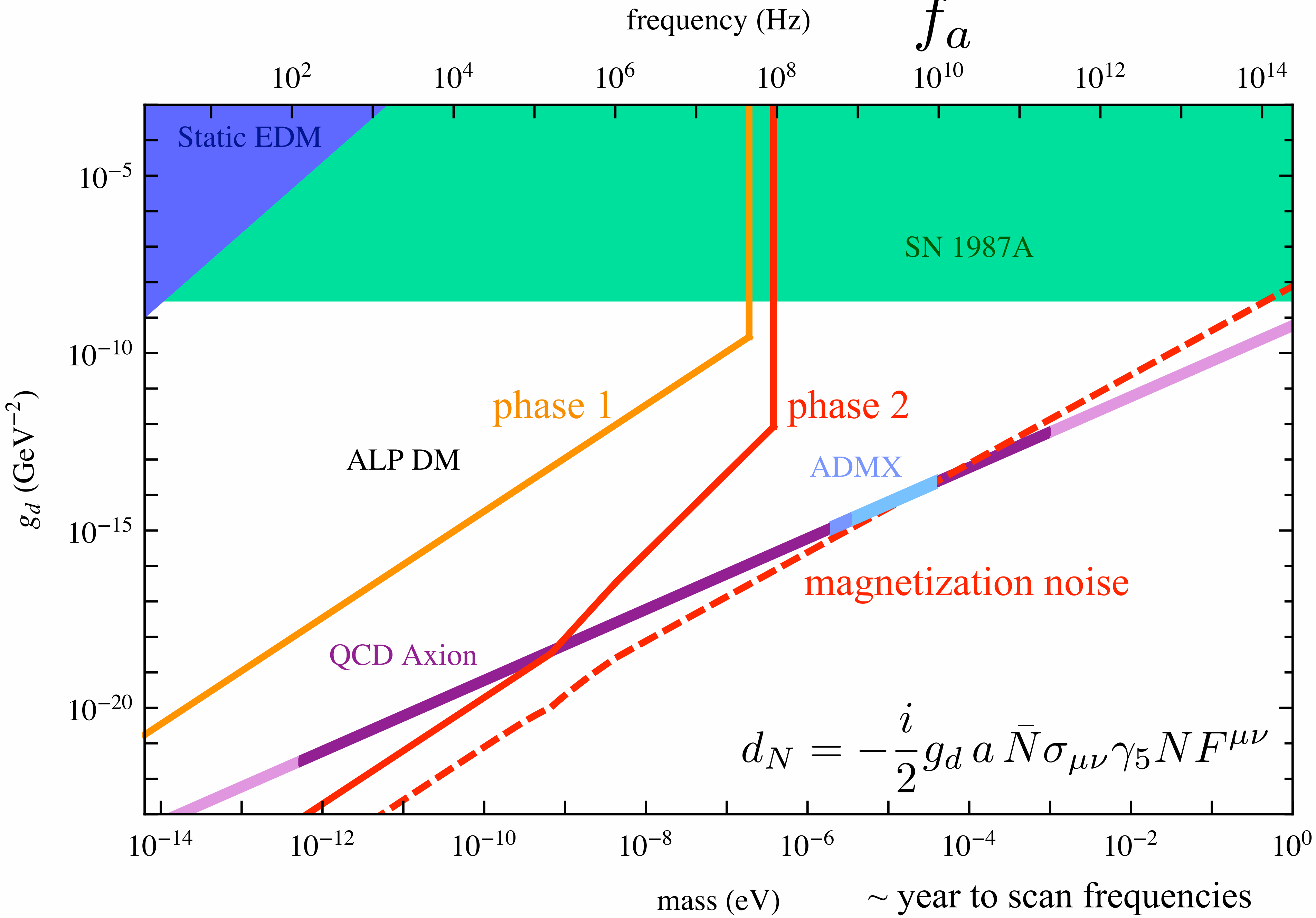
A. Ringwald (2012)

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 $\frac{a}{f_a} G\widetilde{G}$

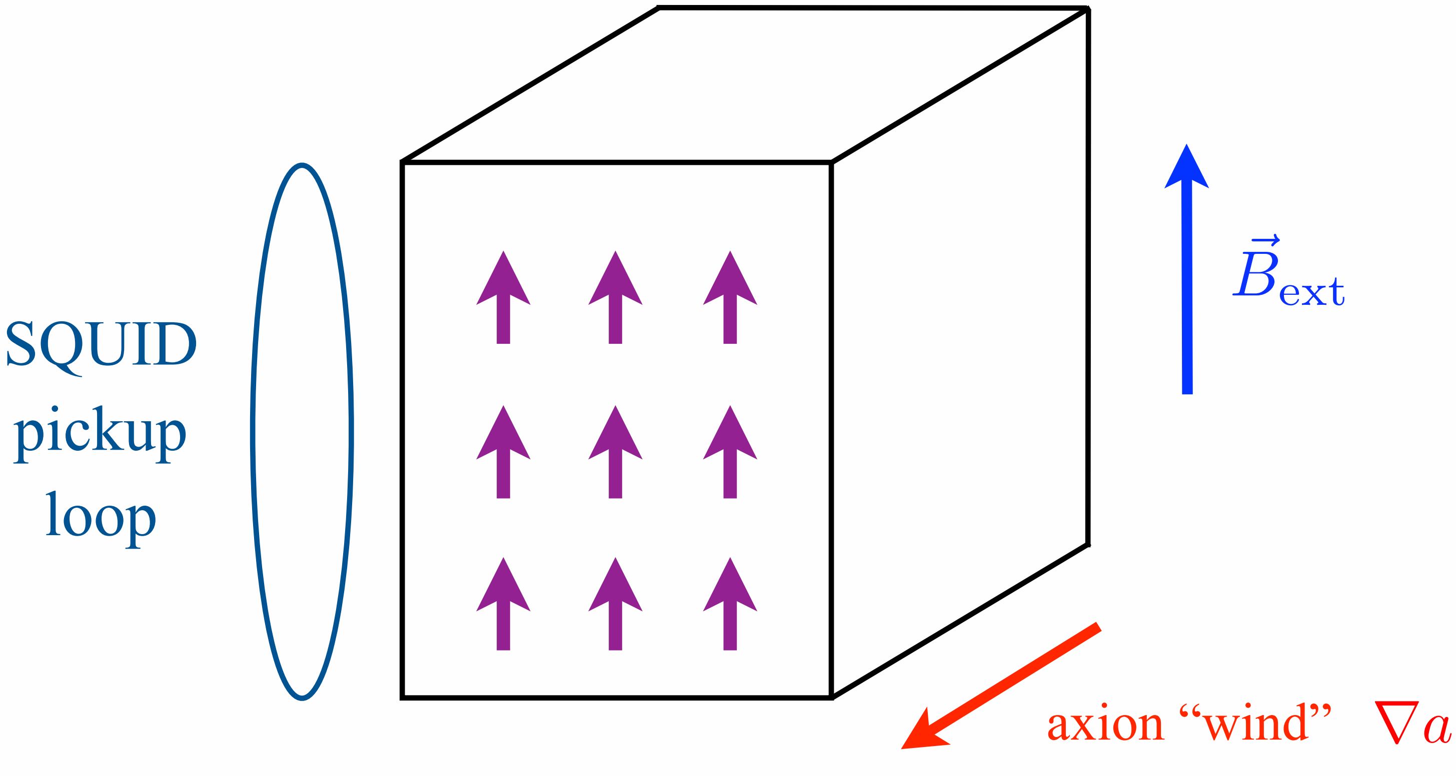


$$d_N = -\frac{i}{2} g_d \, a \, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

~ year to scan frequencies

Verify signal with spatial coherence of axion field

Axion Wind



use nuclear spins coupled to axion DM

$$g_{\text{aNN}}\left(\partial_\mu a\right)\bar{N}\gamma^\mu\gamma_5 N \implies H_N \supset g_{\text{aNN}}\vec{\nabla}a.\vec{S}_N$$

effects suppressed by v ~ 10^{-3}

Similar to EDM experiment but no Schiff suppression, no E-field (polar crystal)

makes a directional detector for axions (and gives annual modulation)

also works for any other spin-coupled DM (e.g. dark photon)

Quick Estimate

$$M(t) \approx np\mu \left(g_{\mathrm{aNN}} \sqrt{2\rho_{DM}} v \right) \frac{\sin\left((2\mu B_{\mathrm{ext}} - m_a)\, t \right)}{2\mu B_{\mathrm{ext}} - m_a} \sin\left(2\mu B_{\mathrm{ext}} t \right)$$

Parameters

$$n = 10^{22} \frac{1}{\mathrm{cm}^3}$$

$$\rho_{\mathrm{DM}} \approx 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

$$v \sim 10^{-3}$$

$$\tau_a \sim \frac{2\pi}{m_a v^2} \sim 1\ \mathrm{s} \left(\frac{\mathrm{MHz}}{m_a} \right)$$

Material Choice

$$\mu_{\mathrm{Xe}} = 0.35 \mu_N$$

Technology

$$p \approx 1$$

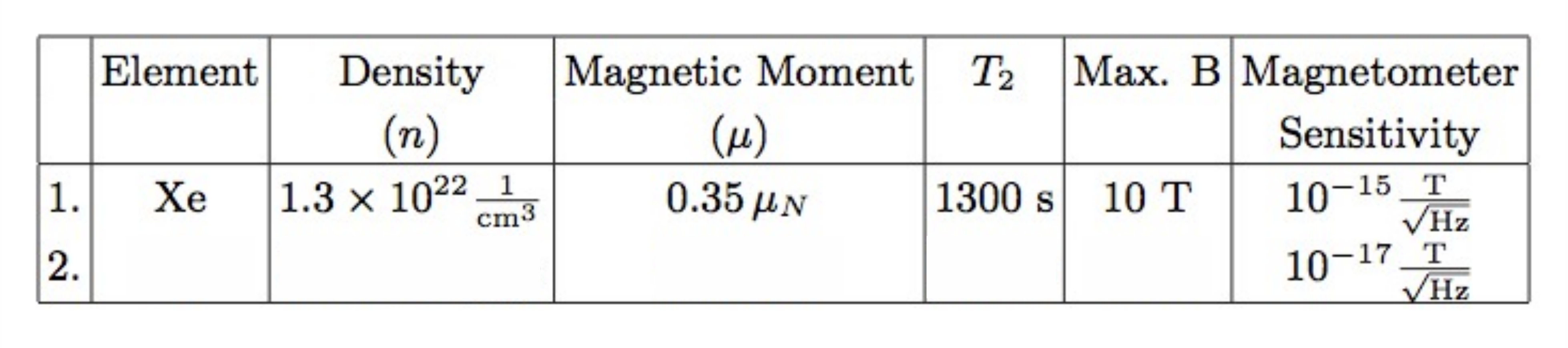
$$\boxed{T_2 \gtrapprox \tau_a \sim 1\ \mathrm{s}} \quad m_a \lessapprox\ \mathrm{MHz}$$

$$\delta M \sim 10^3\ \mathrm{fT} \left(\frac{g_{\mathrm{aNN}}}{10^{-10} \mathrm{GeV}^{-1}} \right)$$

Cosmic Axion Spin Precession Experiment (CASPEr)

for axion wind and other types of DM:

$$M(t) \approx np\mu \left(g_{\mathrm{aNN}} \sqrt{2\rho_{DM}} v \right) \frac{\sin\left(\left(2\mu B_{\mathrm{ext}} - m_a \right) t \right)}{2\mu B_{\mathrm{ext}} - m_a} \sin\left(2\mu B_{\mathrm{ext}} t \right)$$



	Element	Density (n)	Magnetic Moment (μ)	T_2	Max. B	Magnetometer Sensitivity
1.	Xe	$1.3 \times 10^{22}\,\frac{1}{\mathrm{cm}^3}$	$0.35\,\mu_N$	1300 s	10 T	$10^{-15}\,\frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$
2.						$10^{-17}\,\frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$

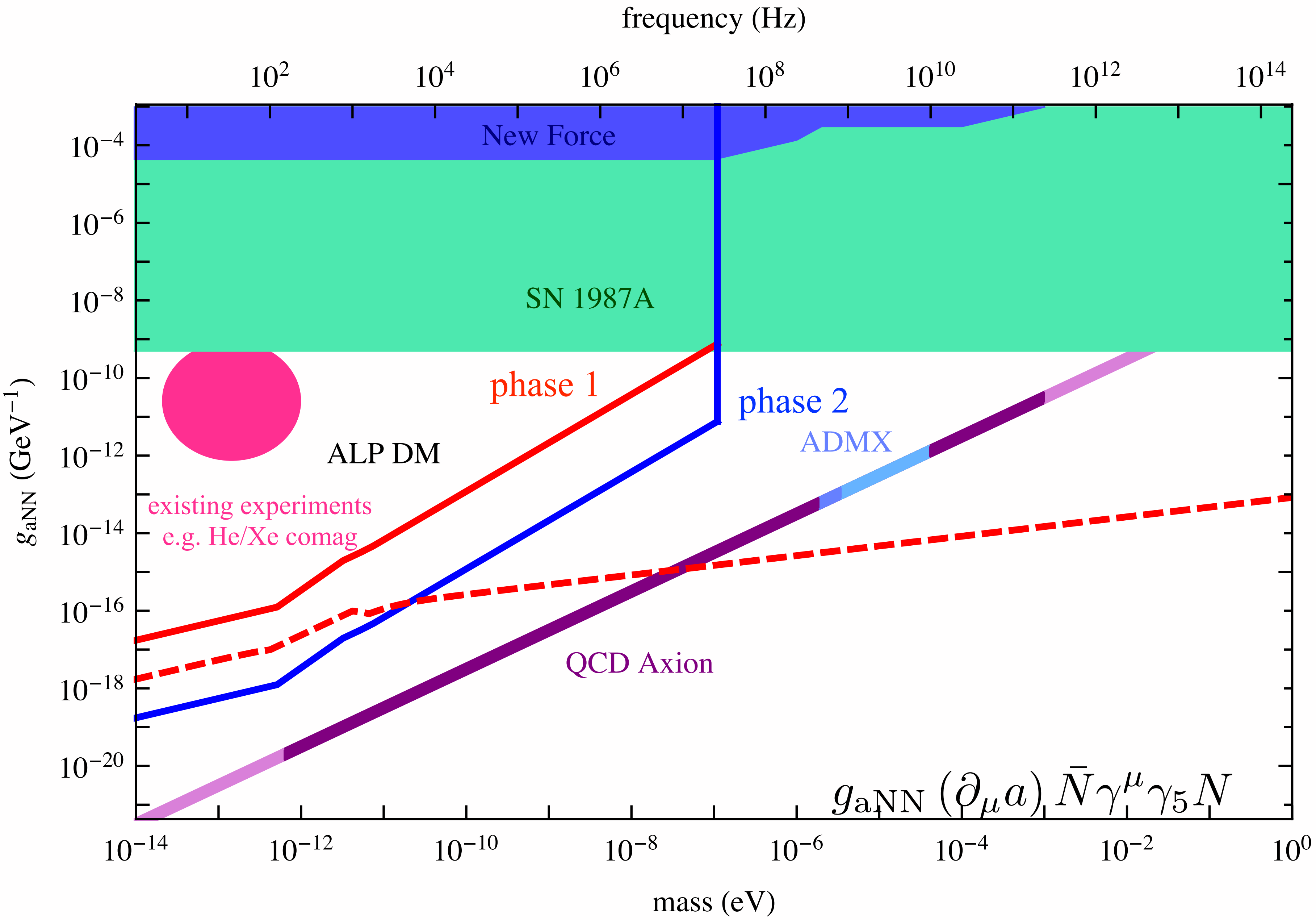
$$p \approx 1$$

take sample size: $L \sim 10$ cm

(or multiple loops over smaller sample)

many options for increasing sensitivity

Limits on Axion-Nucleon Coupling



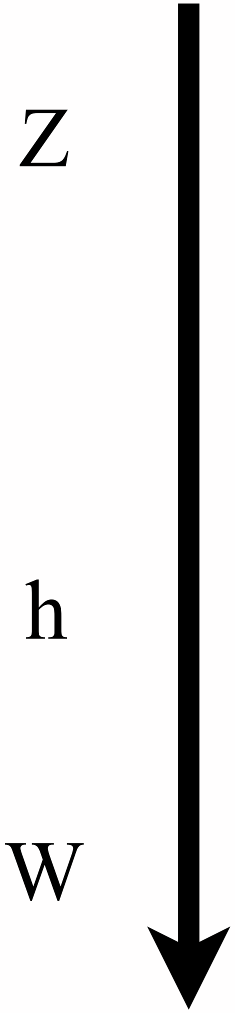
~ year to scan one decade of frequency

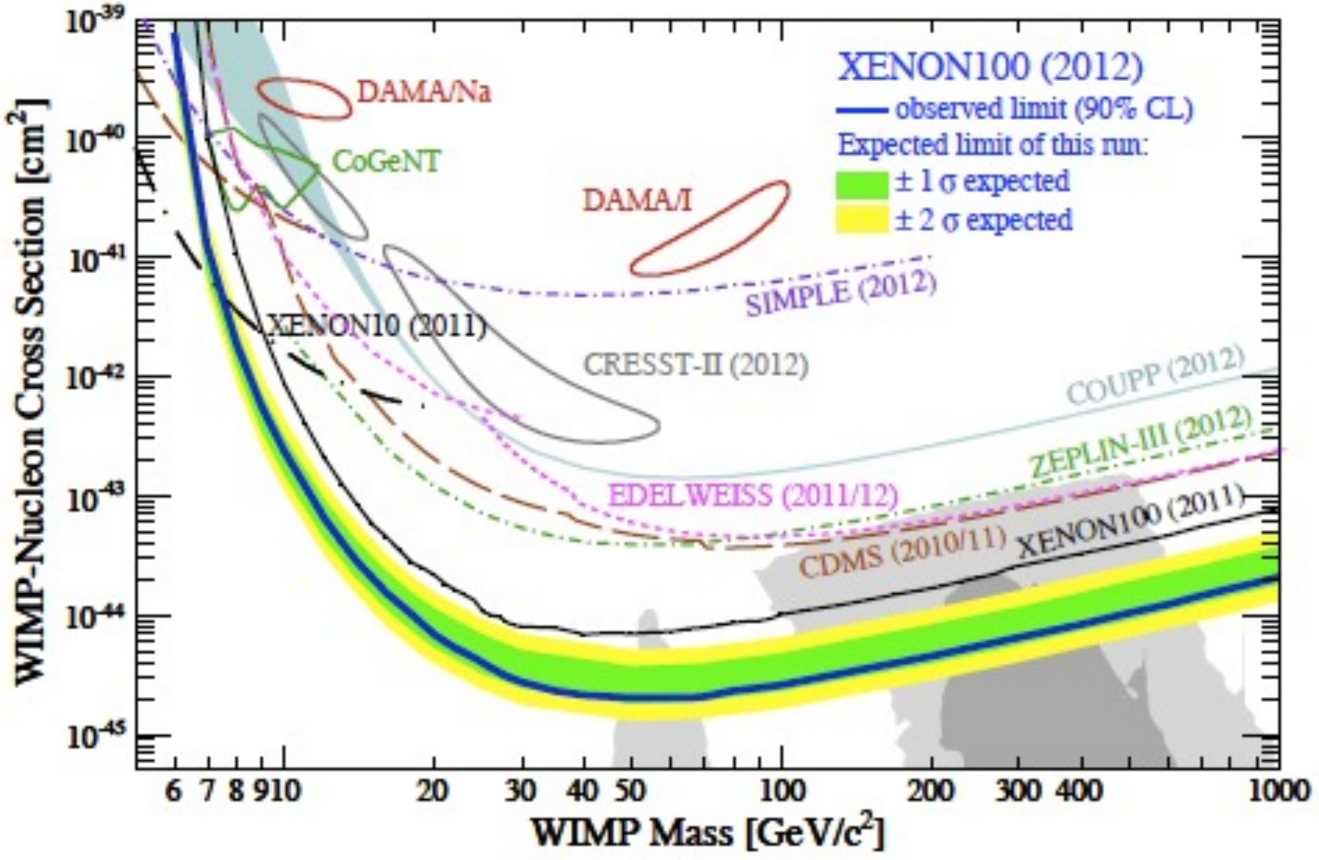
Summary

WIMPs

Hard scattering is good for heavy dark matter.

Goodman & Witten (1985): $\sigma \sim 10^{-38}\,\mathrm{cm}^2$

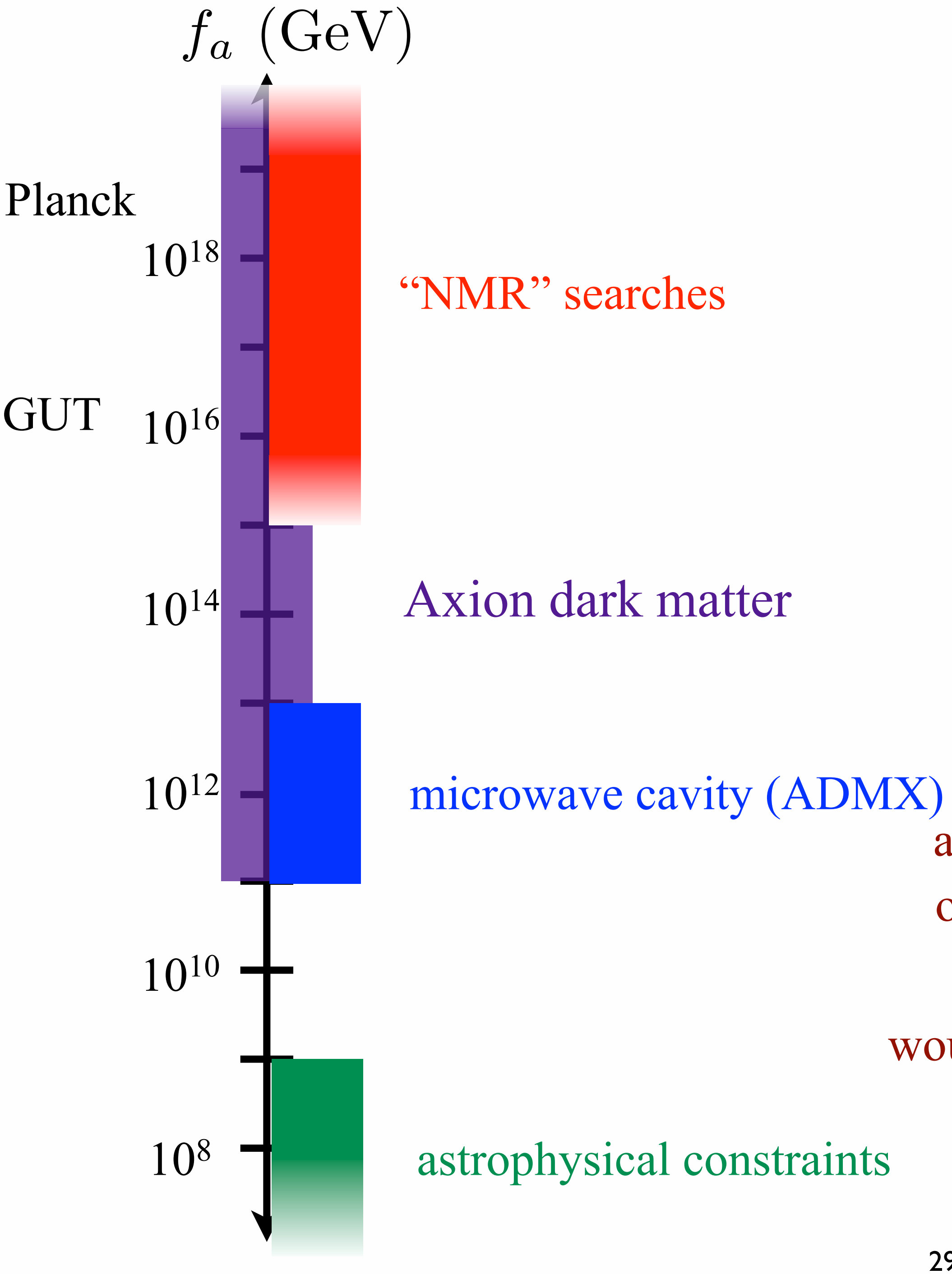




Oscillating moments coupled to spin are natural for light dark matter.

(axions, dark photons...)

CASPEr Discovery Potential



laboratory experiment

significant reach in kHz - 10 MHz
frequencies ➞ high f_a

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

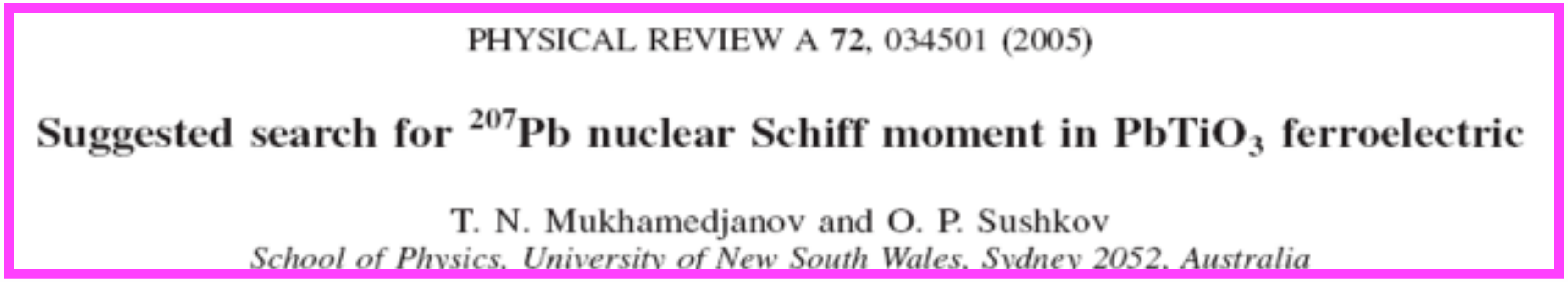
technology broadly useful for community.

axion dark matter is very well-motivated, no
other way to search for light axions (high f_a)

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

Backup

Where does the improvement come from?


PHYSICAL REVIEW A 72, 034501 (2005)

Suggested search for ^{207}Pb nuclear Schiff moment in $PbTiO_3$ ferroelectric

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School of Physics, University of New South Wales, Sydney 2052, Australia

$PbTiO_3$ is a ferroelectric crystal, creating large effective electric field

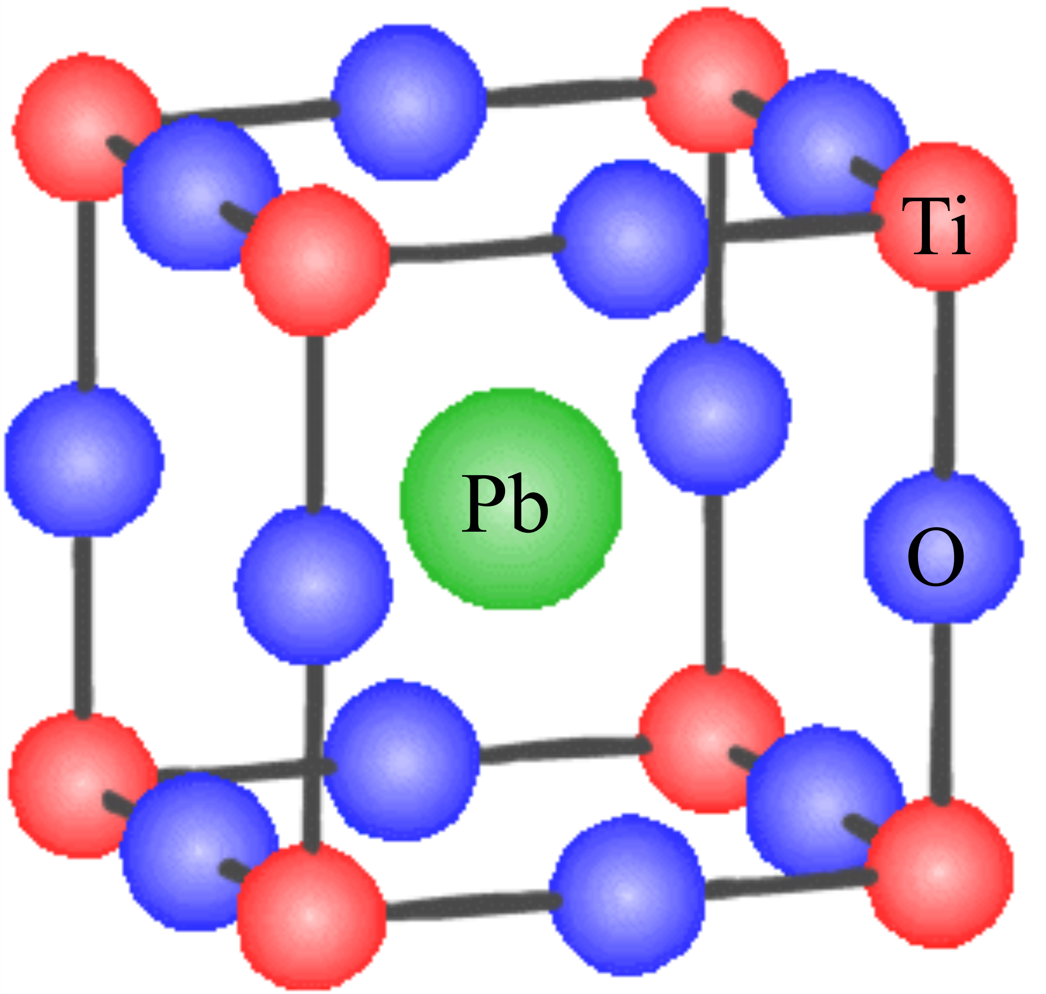
$$E^* \approx 10^8\,\mathrm{V/cm}$$

(as in diatomic molecules)

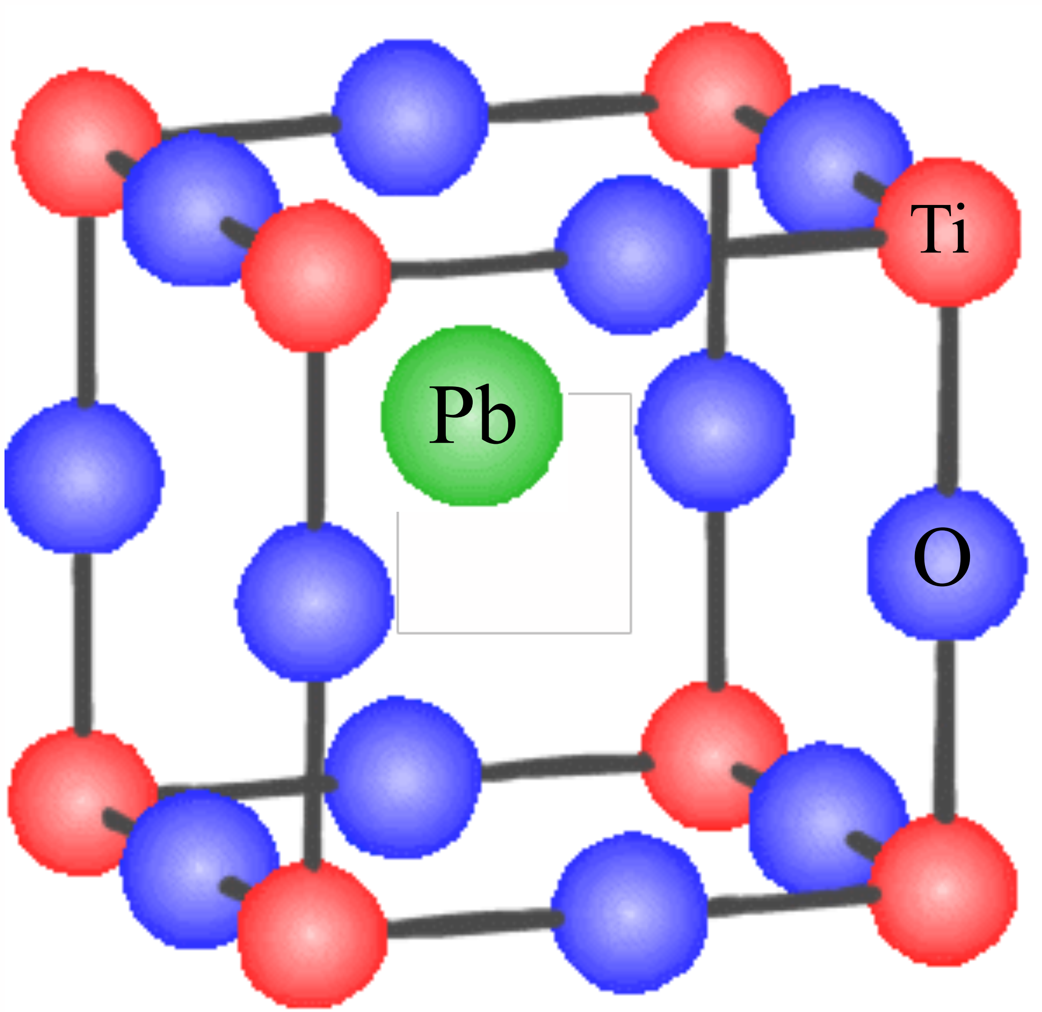
e.g. ACME Collaboration [Science (2013)]

High nuclear orientation needed
Optical pumping of transient paramagnetic color centers?

Effective Electric Field in $PbTiO_3$



Effective Electric Field in $PbTiO_3$



Materials for Oscillating EDM Search

- **$PbTiO_3$** → we have a lot of experience: NMR, T_1 and T_2 measurements [L.Bouchard, A.Sushkov, D.Budker, 2008]
- Many other **non-centrosymmetric solids** with high-Z atoms, eg: $(Pb,La)(Zr,Ti)O_3$, $(1-x)[Pb(Mg_{1/3}Nb_{2/3})O_3]-x[PbTiO_3]$ (PMN-PT), $PbSiO_3$, etc.

  Some (eg: PLZT) have been used for optical studies, possible nuclear spin polarization with optical pumping?
- **Liquid Xe in polar cages** → R&D needed, upcoming slides

Systematics

Key point: signal frequency (kHz → GHz) = axion mass independent of experimental conditions

Possible systematics:

1) Vibrations of magnet or pickup loop
   → experimental design and vibration characterization and rejection

2) Sample vibrations + spatial magnetic field gradients
   → as above + lowest frequencies have smallest B_{ext}

3) Fluctuations in B_{ext}
   → superconducting magnet

4) External fluctuating magnetic fields

Experimental design with multiple samples and/or SQUID pickup loops

Dynamical Decoupling

nature
COMMUNICATIONS

ARTICLE

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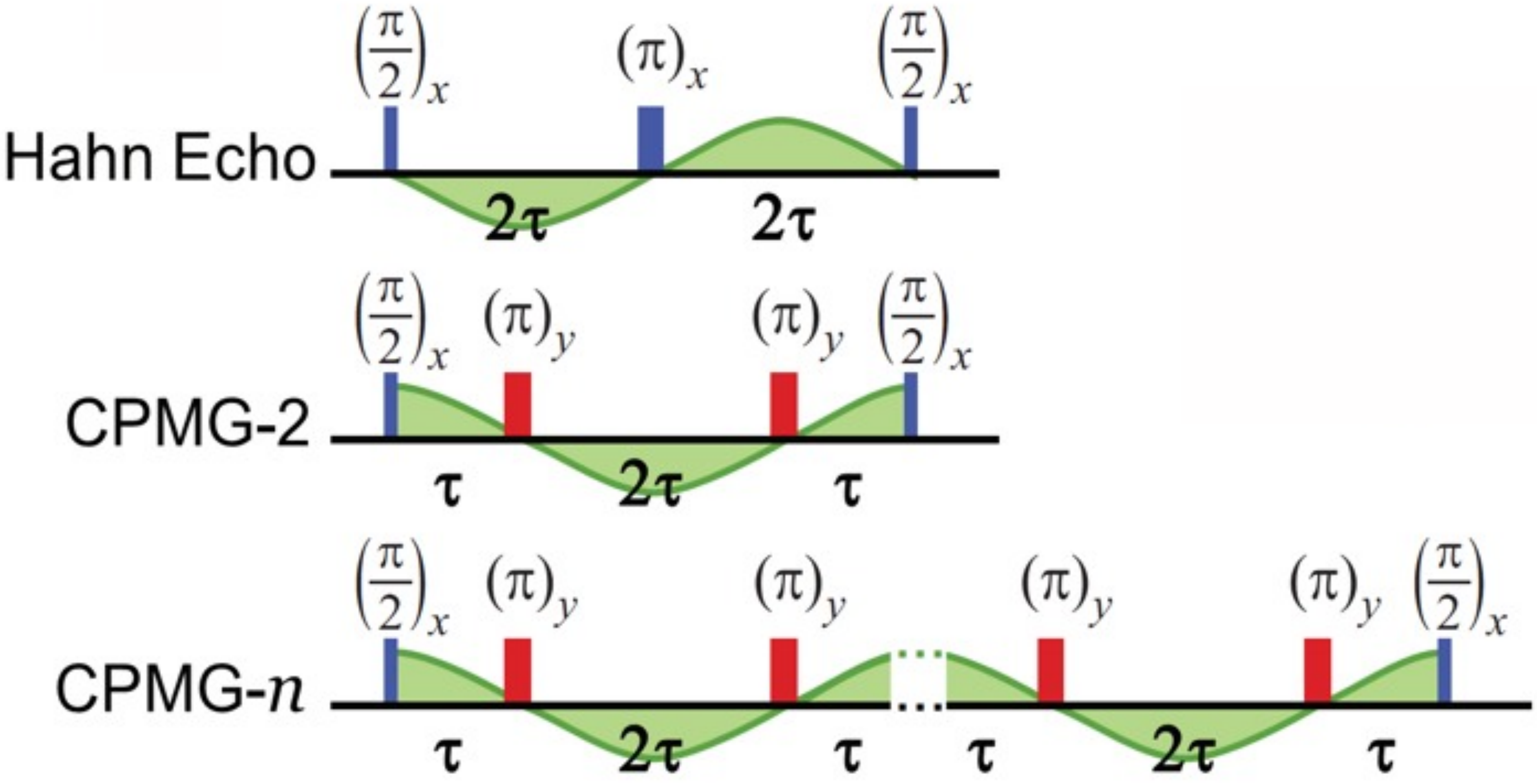
Solid-state electronic spin coherence time approaching one second

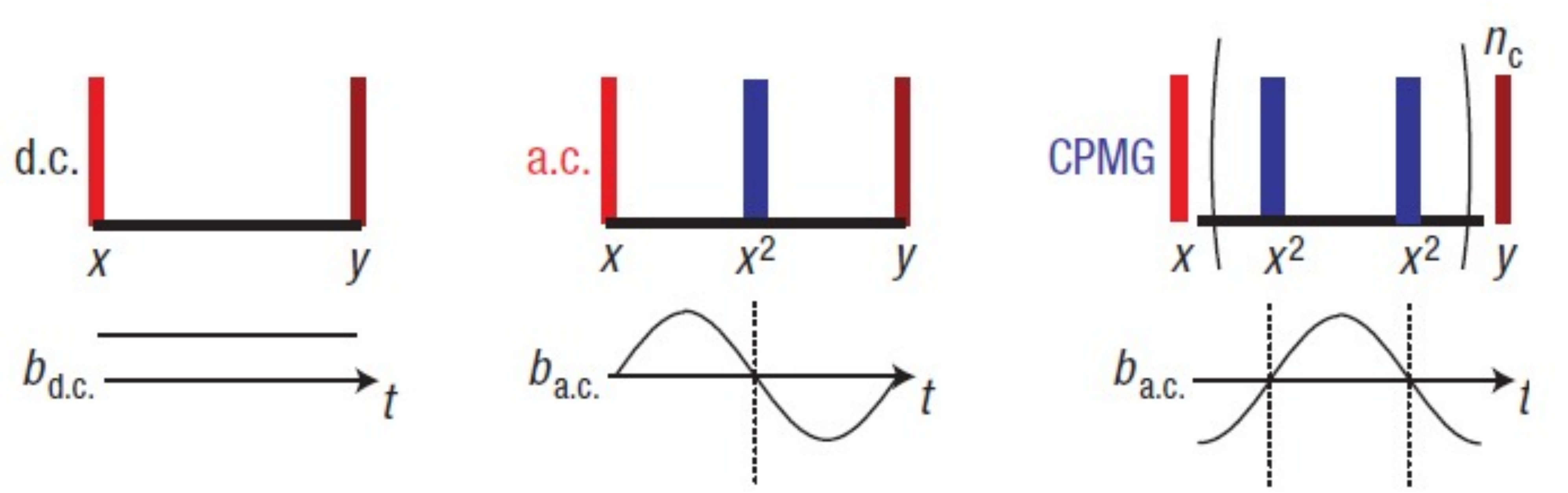
N. Bar-Gill[1,2], L.M. Pham[3], A. Jarmola[4], D. Budker[4,5] & R.L. Walsworth[1,2]

Pulse sequence



L. M. Pham, N. Bar-Gill, C. Belthangady, D. Le Sage, P. Cappellaro, M. D. Lukin, A. Yacoby, and R. L. Walsworth, Phys. Rev. B **86** 045214 (2012)

AC Magnetometry



High-sensitivity diamond magnetometer with nanoscale resolution

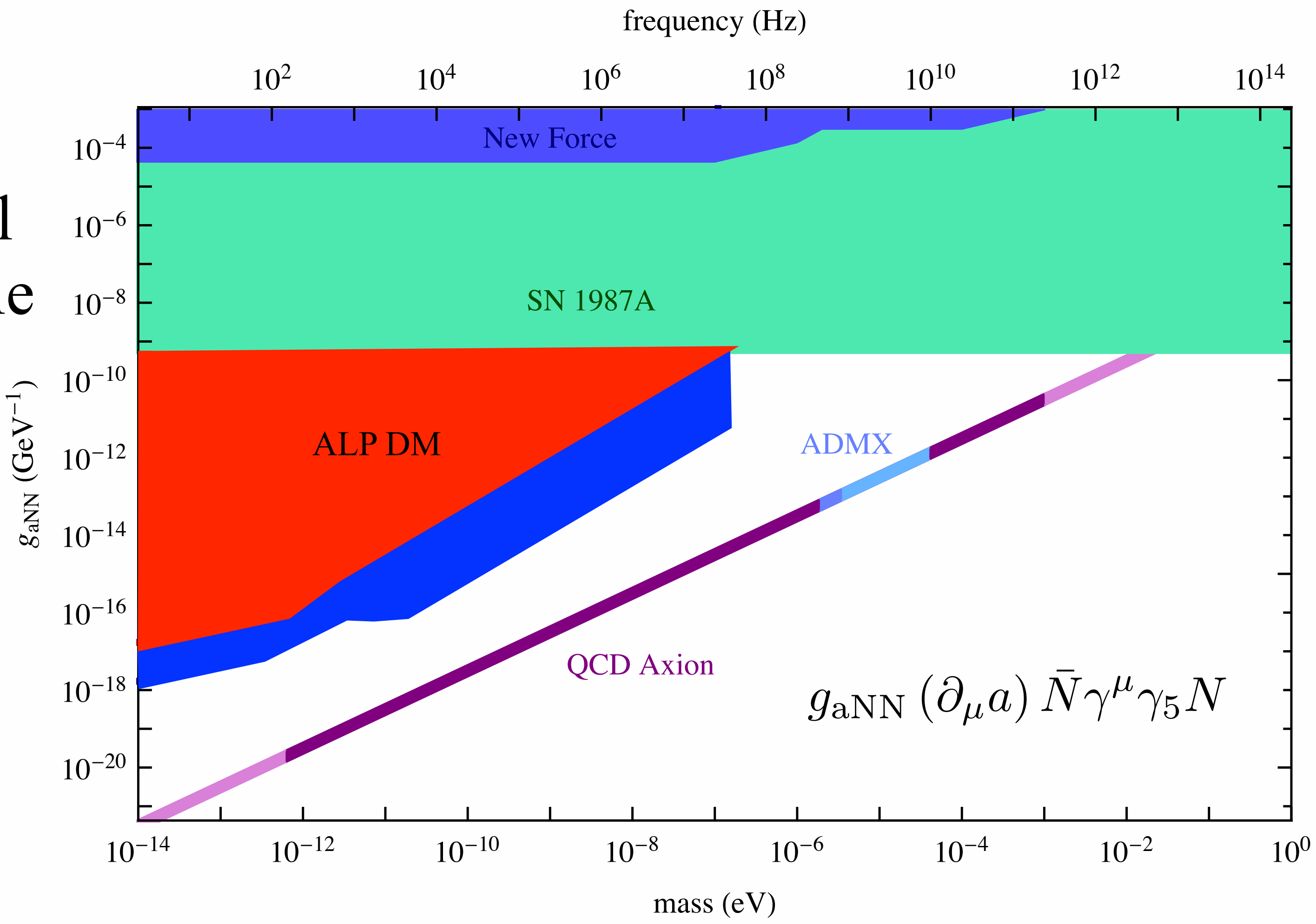
J. M. TAYLOR[1]*, P. CAPPELLARO[2,3]*, L. CHILDRESS[2,4], L. JIANG[2], D. BUDKER[5], P. R. HEMMER[6], A. YACOBY[2], R. WALSWORTH[2,3] AND M. D. LUKIN[2,3]†

nature physics | VOL 4 | OCTOBER 2008 | www.nature.com/naturephysics

CASPEr: Timeline

Axion Wind Search

Small
Sample



Years

R&D
1-2

Phase 1
3-5

Phase 2
6-8

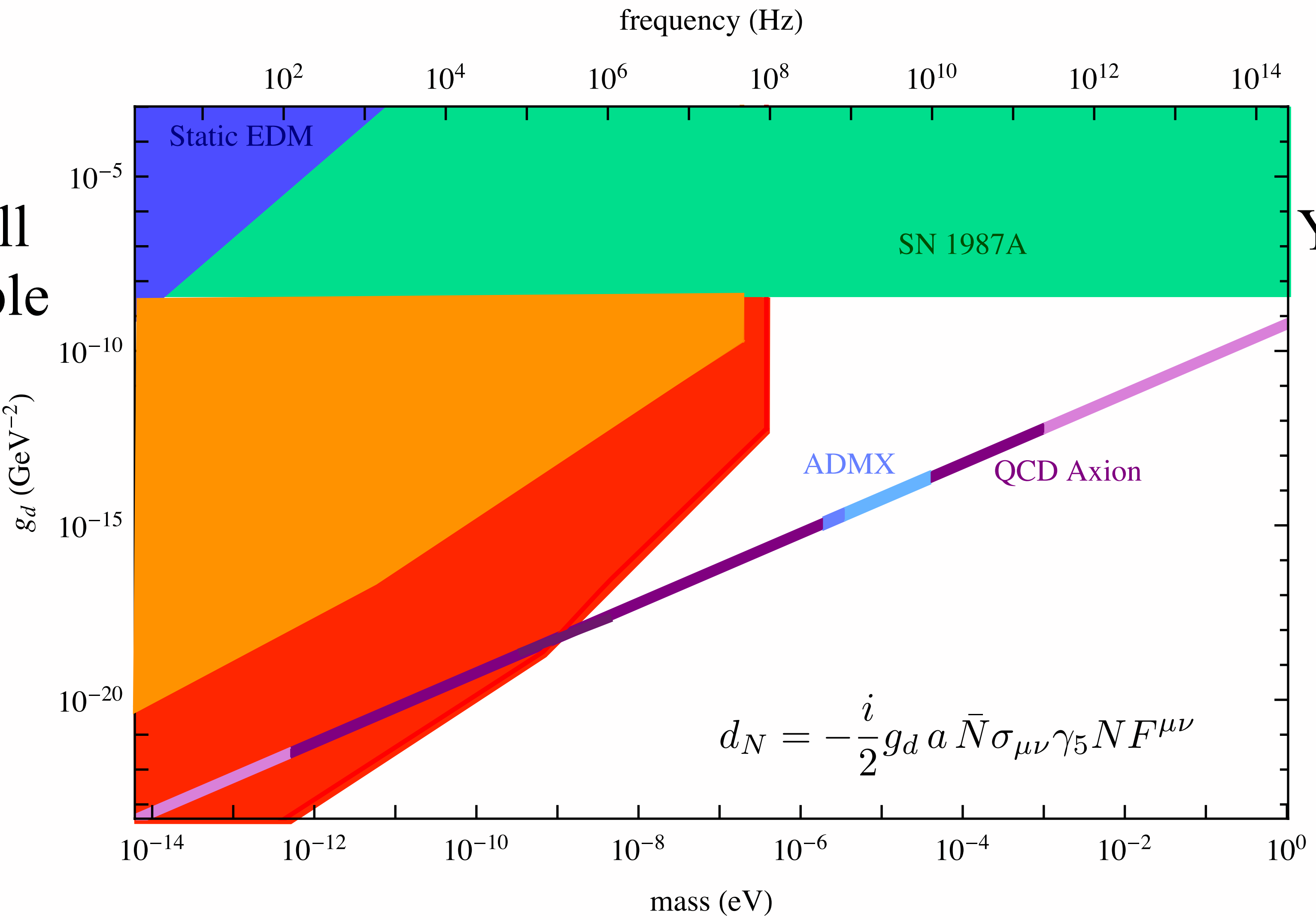
Scalable

Liquid Xenon Technology

CASPEr: Timeline

QCD Axion Goal

Small
Sample



Scalable

Years

R&D
2-3

Phase 1
3-6

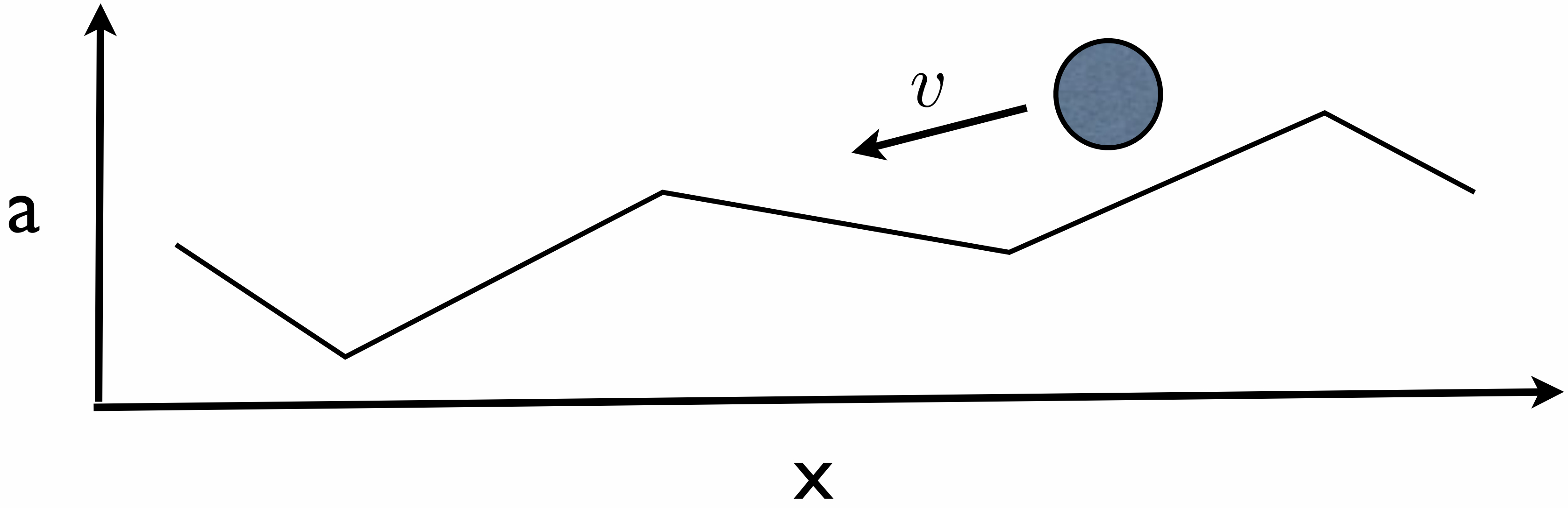
Phase 2
6-10

Polar Xenon cages, Ferroelectrics,...

Backup slides

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 = $\dfrac{\Delta\omega}{\omega} \sim \dfrac{\frac{1}{2} m_a v^2}{m_a} \sim 10^{-6}$

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