



# Cosmic Axion Spin Precession Experiment (CASPEr)

**Surjeet Rajendran**

with

**Dmitry Budker**

**Peter Graham**

**Micah Ledbetter**

**Alex Sushkov**

PRD **88** (2013) arXiv:1306.6088,

PRX (2014) arXiv:1306.6089,

PRD **84** (2011) arXiv:1101.2691

# Overview

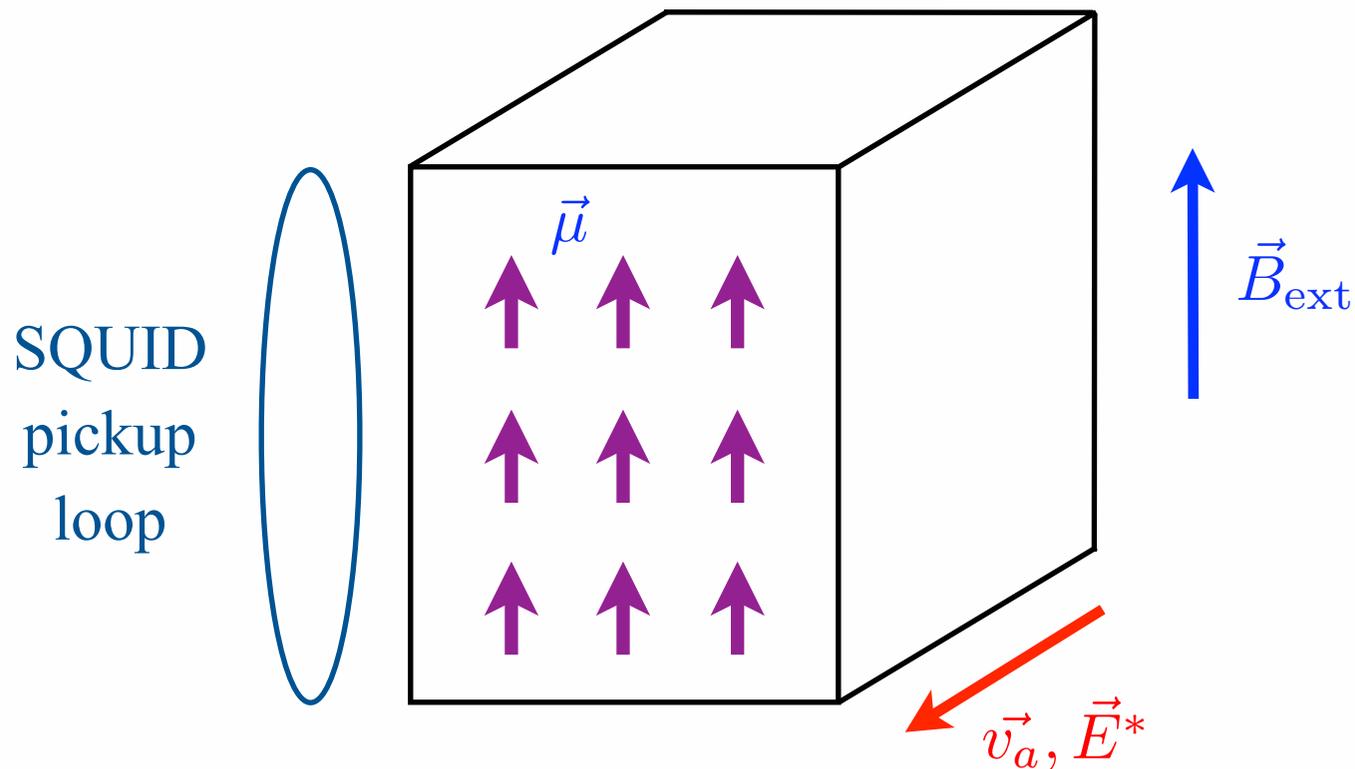
Axion dark matter causes precession of nucleon spins

Axis set by local velocity of axion or applied electric fields

# Overview

Axion dark matter causes precession of nucleon spins

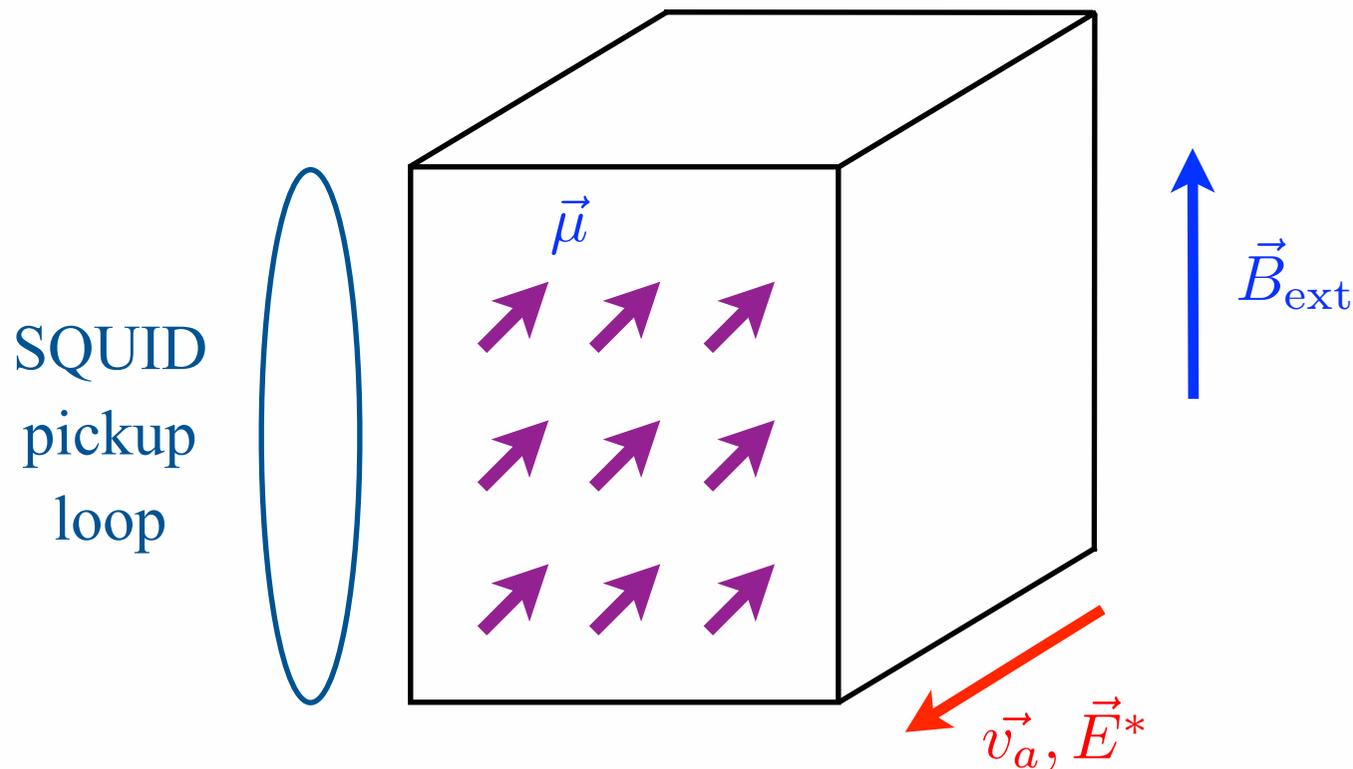
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Axis set by local velocity of axion or applied electric fields

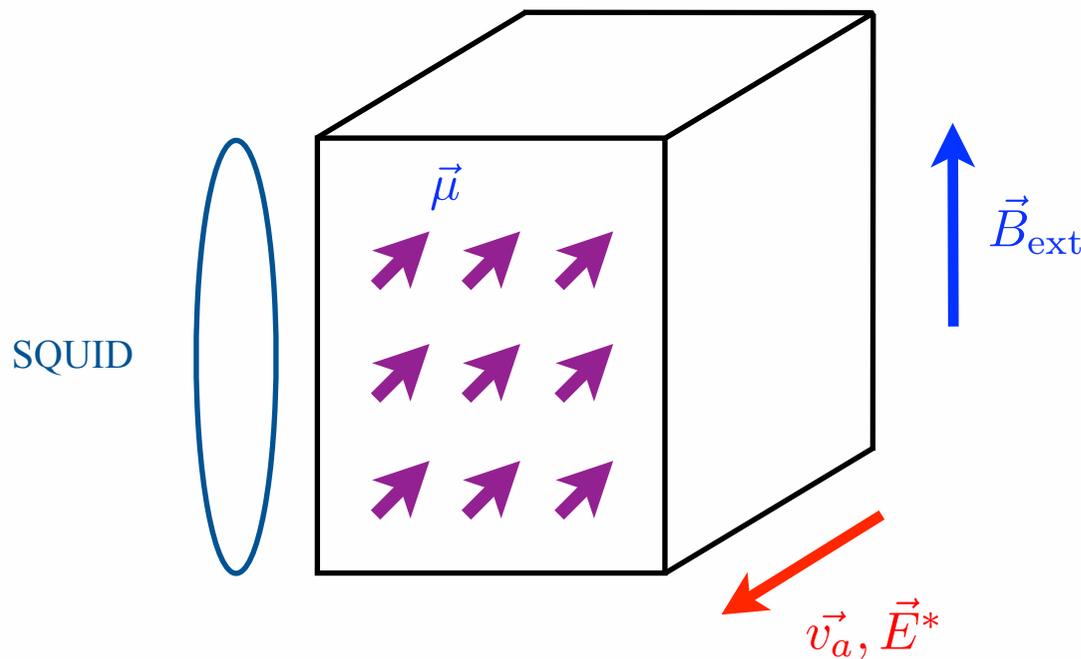


Significant reach with existing technology

# Overview

Axion dark matter causes precession of nucleon spins

Axis set by local velocity of axion or applied electric fields



1. Axion Dark Matter

2. Signal and Noise

3. Conclusions

# Axion Dark Matter

# Dark Matter

Dark matter is proof of physics beyond standard model

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heavy particle vs. light scalar field

(WIMPs)

(axions)

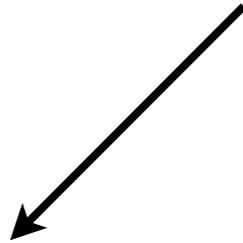
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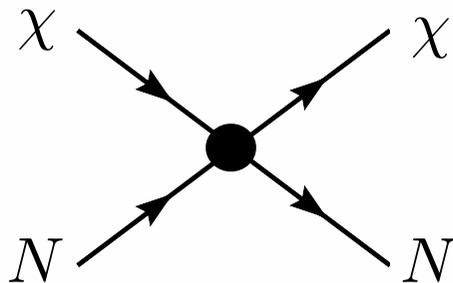
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Search for single particle scattering



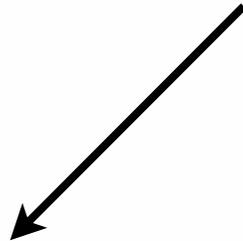
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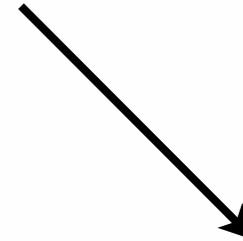
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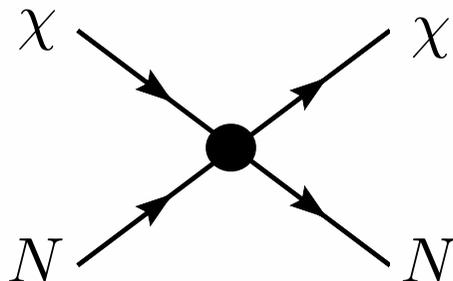


Search for single particle scattering



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

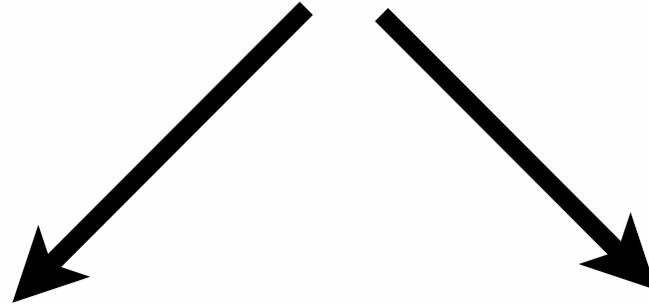
Global symmetry broken at high scale  $f_a$

Light Goldstone boson

# Axions

Global symmetry broken at high scale  $f_a$

Light Goldstone boson



Gauge Fields

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

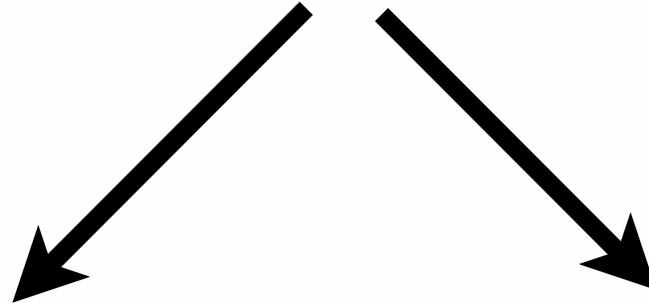
Fermions

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

# 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

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

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

eg: reduction of higher dimensional gauge forms

Svrcek & Witten (2006)

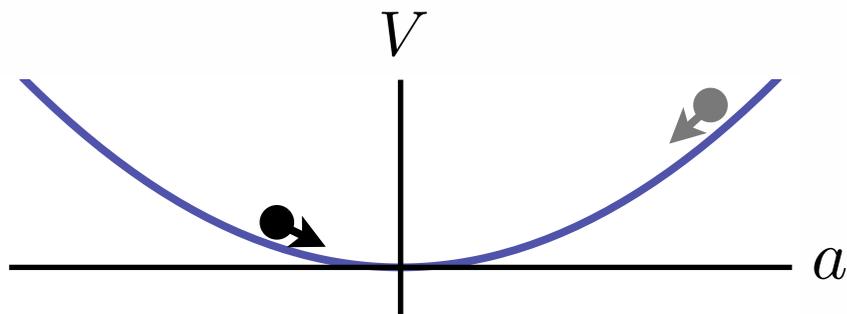
naturally expect large  $f_a \sim$  GUT ( $10^{16}$  GeV), string, or Planck ( $10^{19}$  GeV) scales

# 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  $\rho = \rho_{DM}$

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

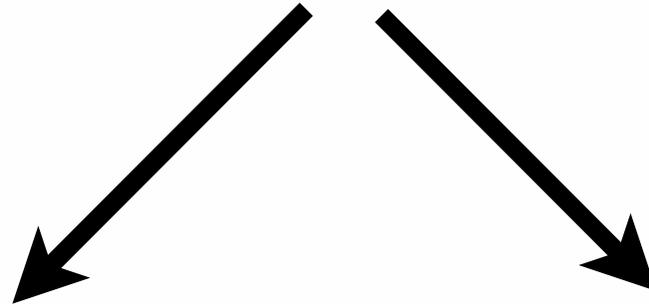
Currently challenging to discover axions in much of parameter space

Important to find new ways to detect axions

# Axions

Global symmetry broken at high scale  $f_a$

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Gauge Fields

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

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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):

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

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

if symmetry broken before inflation  $\rightarrow$  inflation can induce isocurvature perturbations of axion, weak constraint on ALPs probed by CASPER.

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

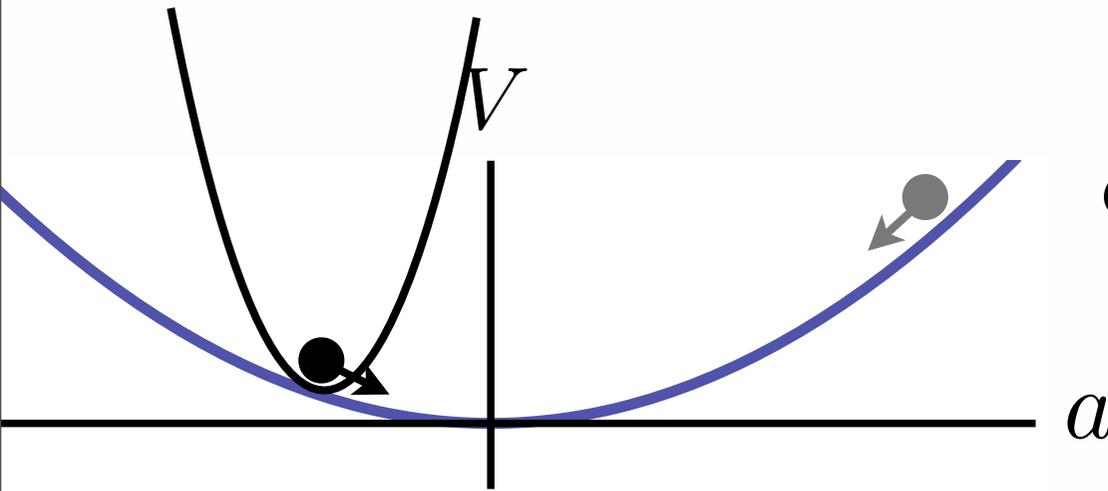
Requires knowing physics all the way up to GUT scale  $\sim 10^{16}$  GeV

**many** others possible.

# QCD Axion and BICEP

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

Need not be on during inflation.



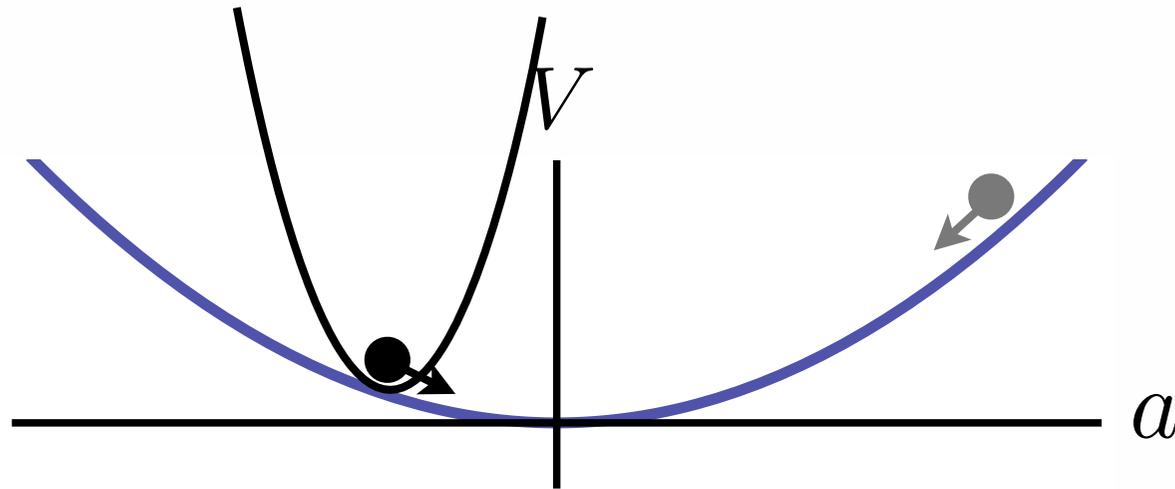
Axion oscillates earlier, damps to high temperature minimum.

Misalignment of minima gives axion dark matter.

Dark matter from choice of parameters instead of initial conditions.

# QCD Axion and BICEP

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e.g. thermal monopole density, Fischler & Preskill (1983)

high temperature mass,

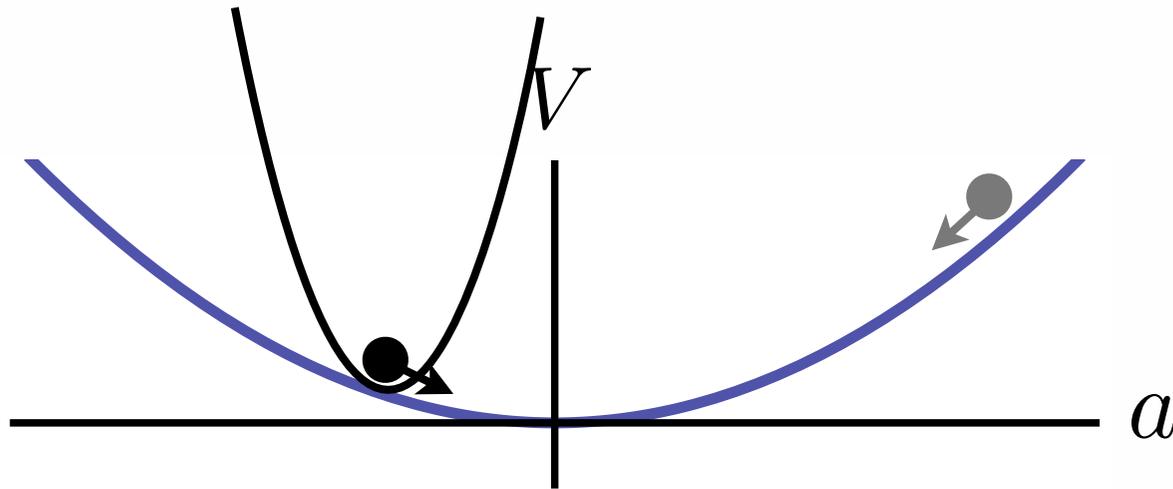
and many others e.g. Kaplan & Zurek (2005), Jeong & Takahashi (2013), G. Dvali (1995)

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,  
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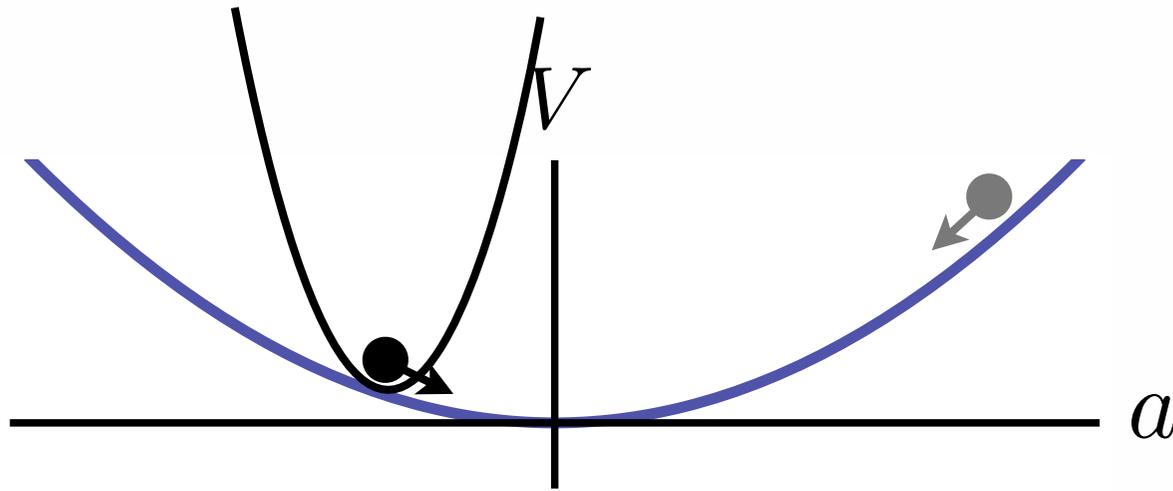
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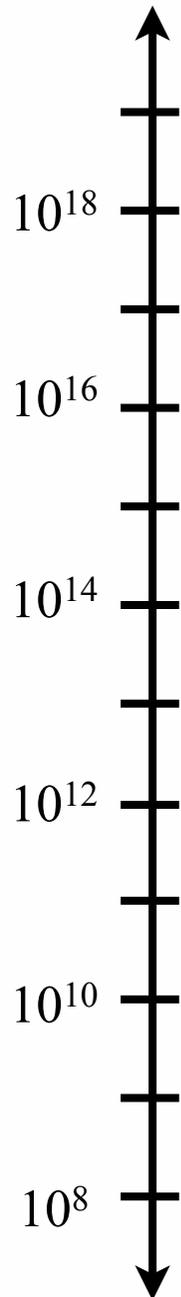
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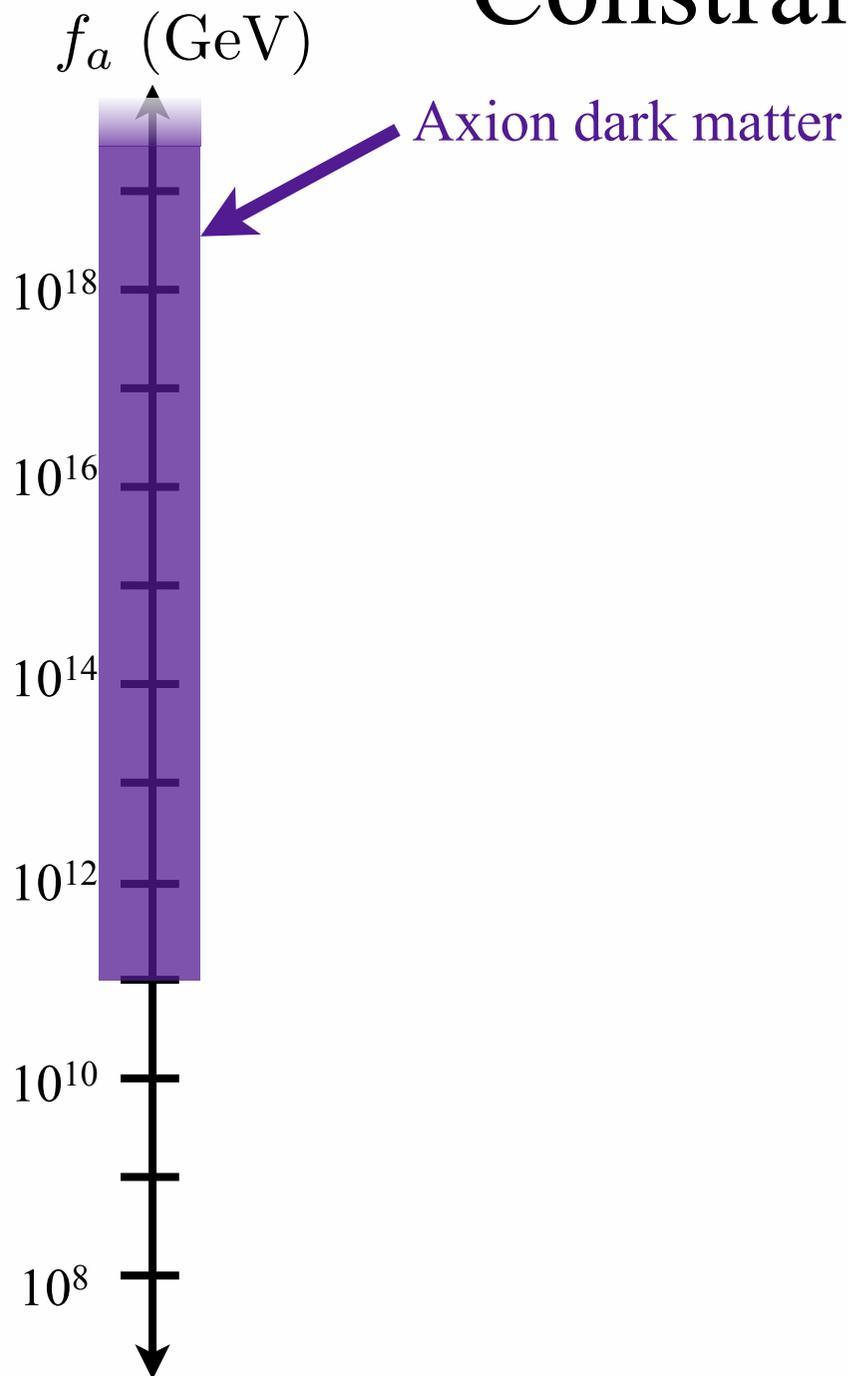
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# Constraints and Searches

$f_a$  (GeV)

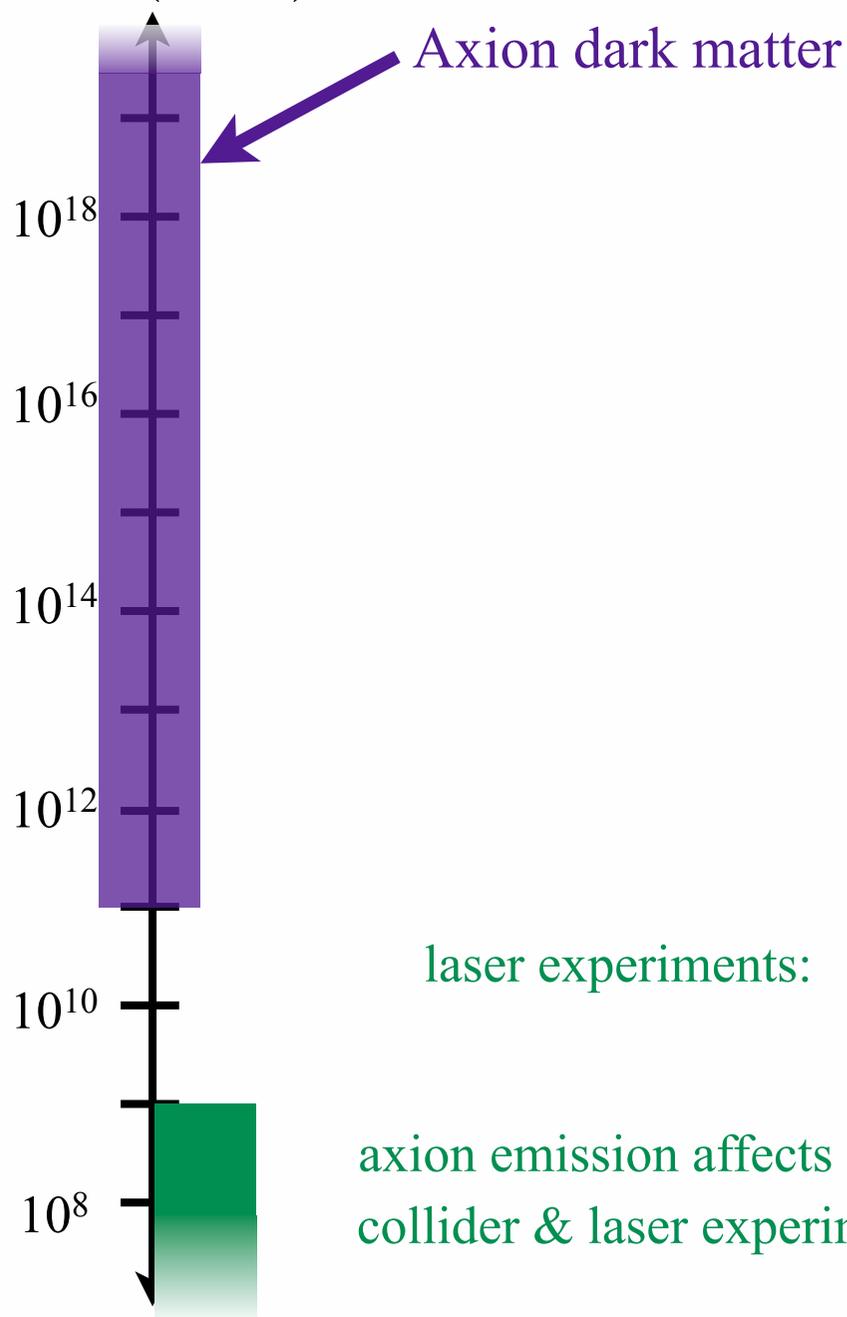


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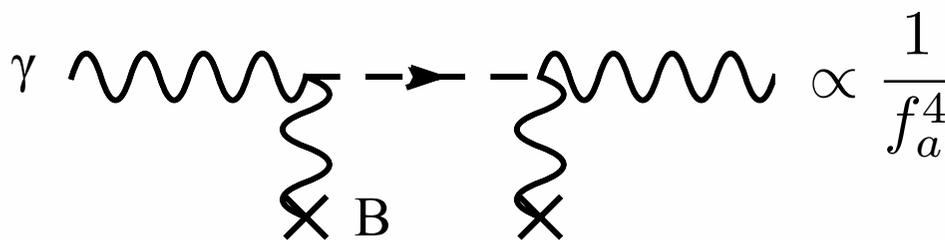


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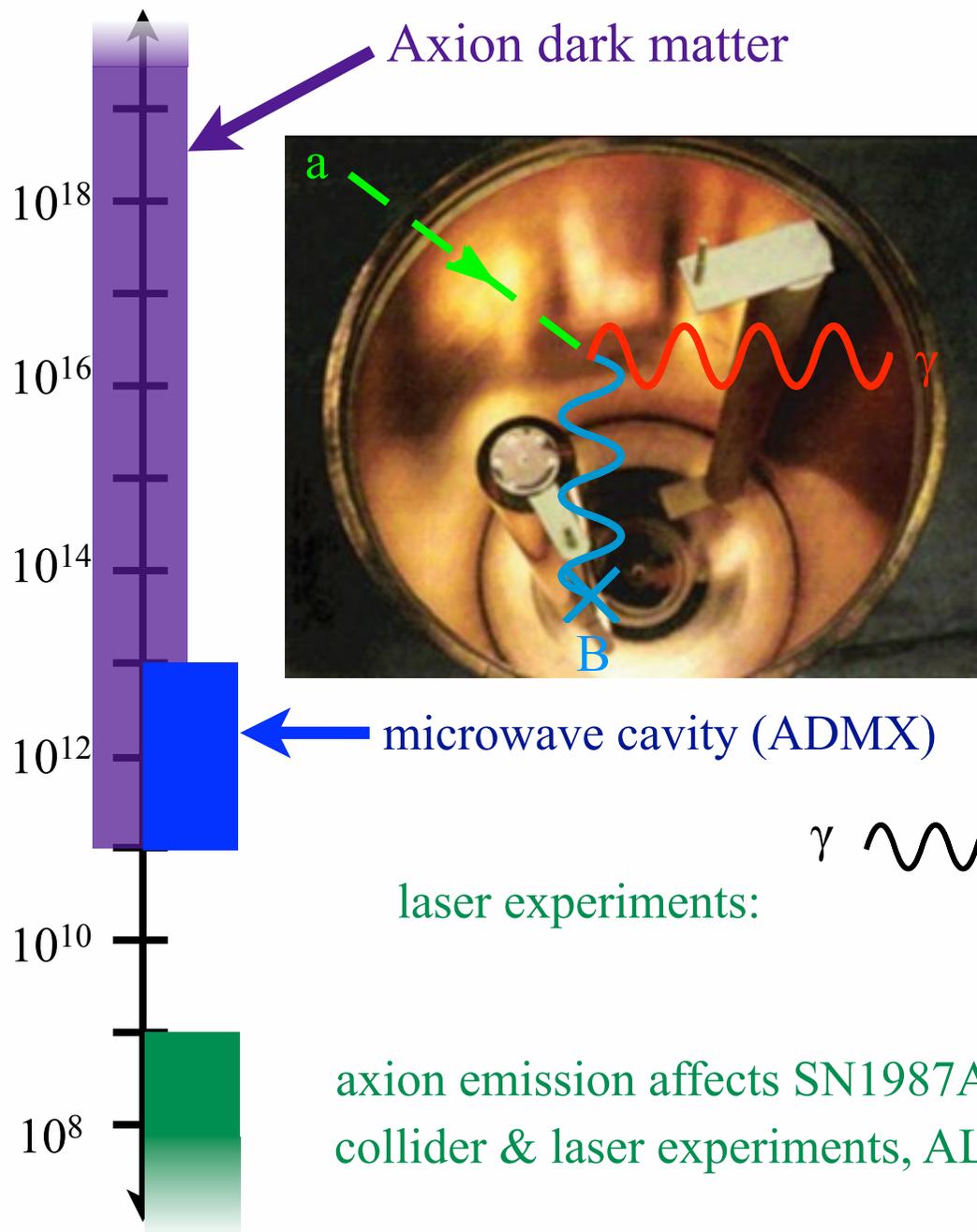


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axion-photon conversion suppressed  $\propto \frac{1}{f_a^2}$

size of cavity increases with  $f_a$

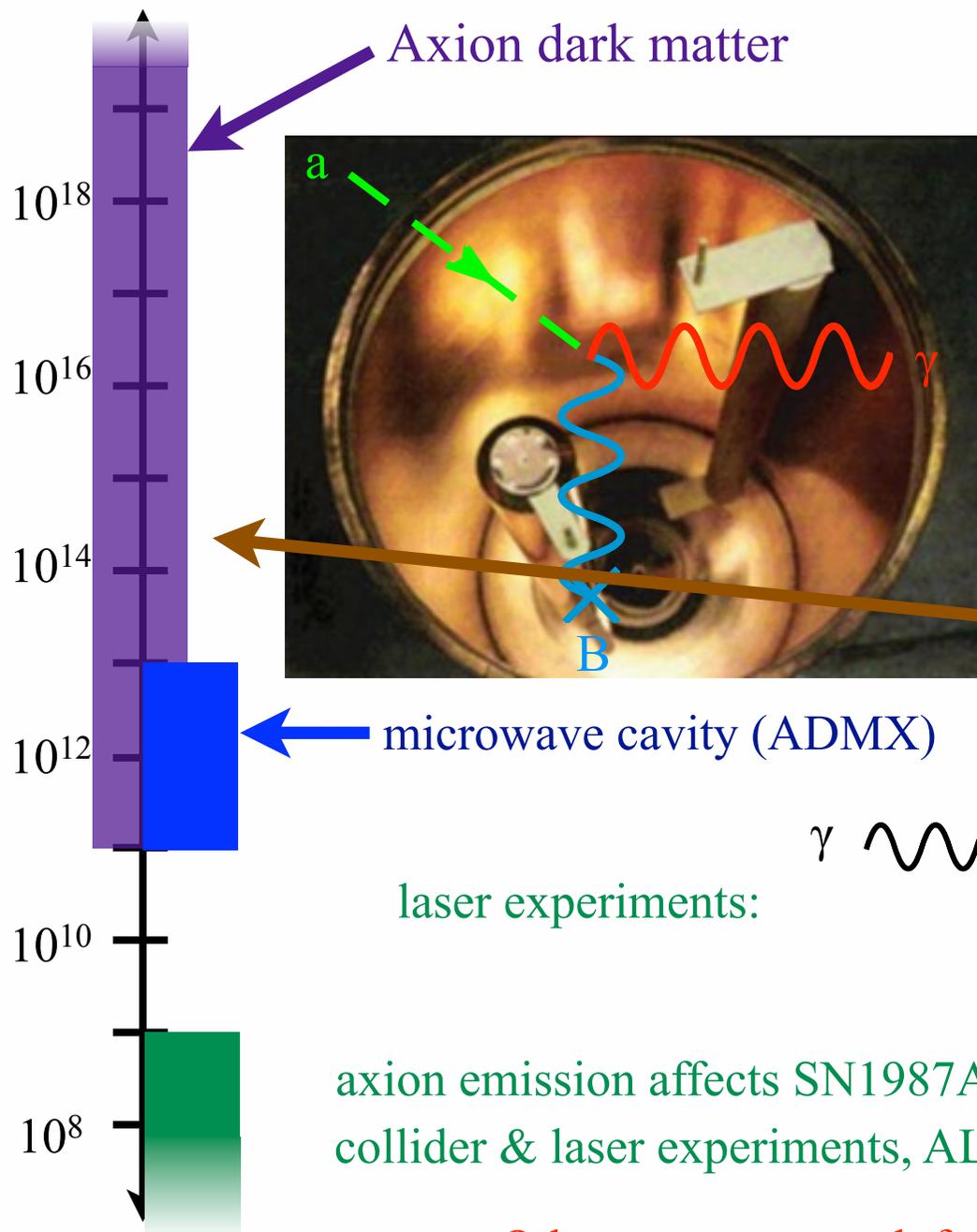
signal  $\propto \frac{1}{f_a^3}$

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

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

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S. Thomas

laser experiments:

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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  $\left( \text{using } \frac{a}{f_a} G \wedge G \right)$

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

# A Different Operator For Axion Detection

So how can we detect high  $f_a$  axions?

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

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

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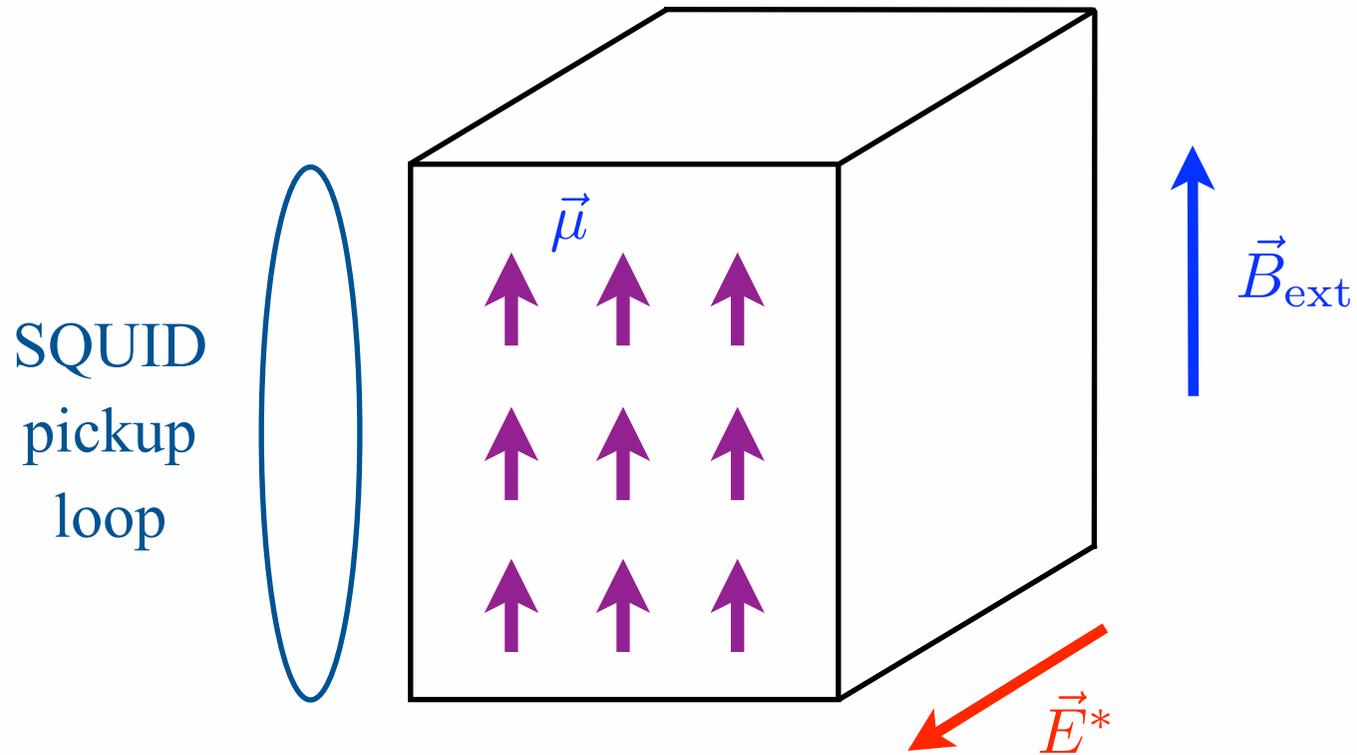
$a(t) \sim a_0 \cos(m_a t)$  with  $m_a \sim \frac{(200 \text{ MeV})^2}{f_a} \sim \text{MHz} \left( \frac{10^{16} \text{ GeV}}{f_a} \right)$

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

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

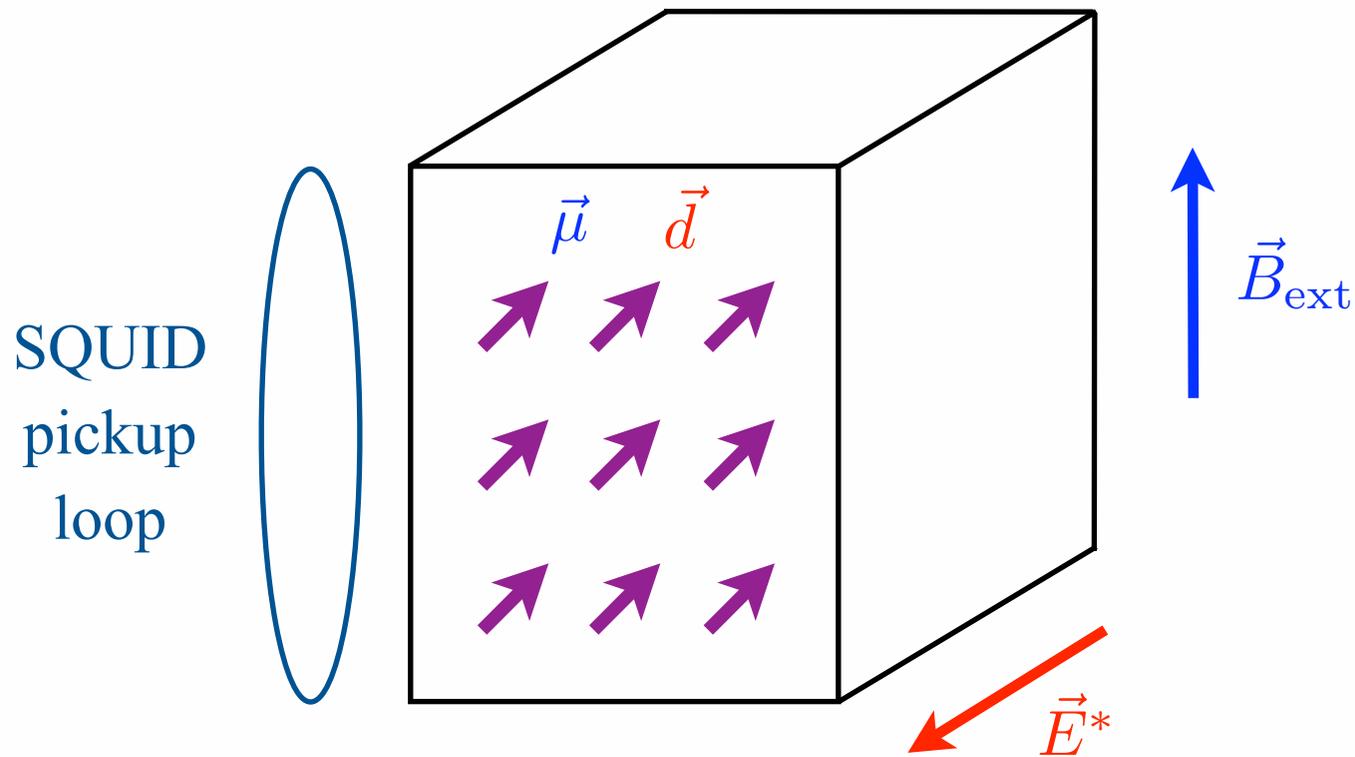
axion gives all nucleons an oscillating EDM (kHz-GHz) independent of  $f_a$ ,  
a non-derivative operator

# NMR Technique



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

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applied E field causes precession of nucleus

SQUID measures resulting transverse magnetization

Larmor frequency = axion mass  $\implies$  resonant enhancement

resonance  $\rightarrow$  scan over axion masses by changing  $B_{\text{ext}}$

# Transverse Magnetization Signal

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

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

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

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## Schiff suppression

E.g. Material Choice  $^{207}\text{Pb} \implies \mu = 0.6\mu_N$   $\epsilon_S \approx 10^{-2}$   $E^* \approx 3 \times 10^8 \frac{\text{V}}{\text{cm}}$   
 nuclear magnetic moment Electric field

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

polarization fraction

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$d_n \sim 10^{-34} e \cdot \text{cm} \implies \delta M \sim 10^{-2} \text{ fT} \left( \frac{\text{MHz}}{m_a} \right)$   
axion induced dipole moment 17

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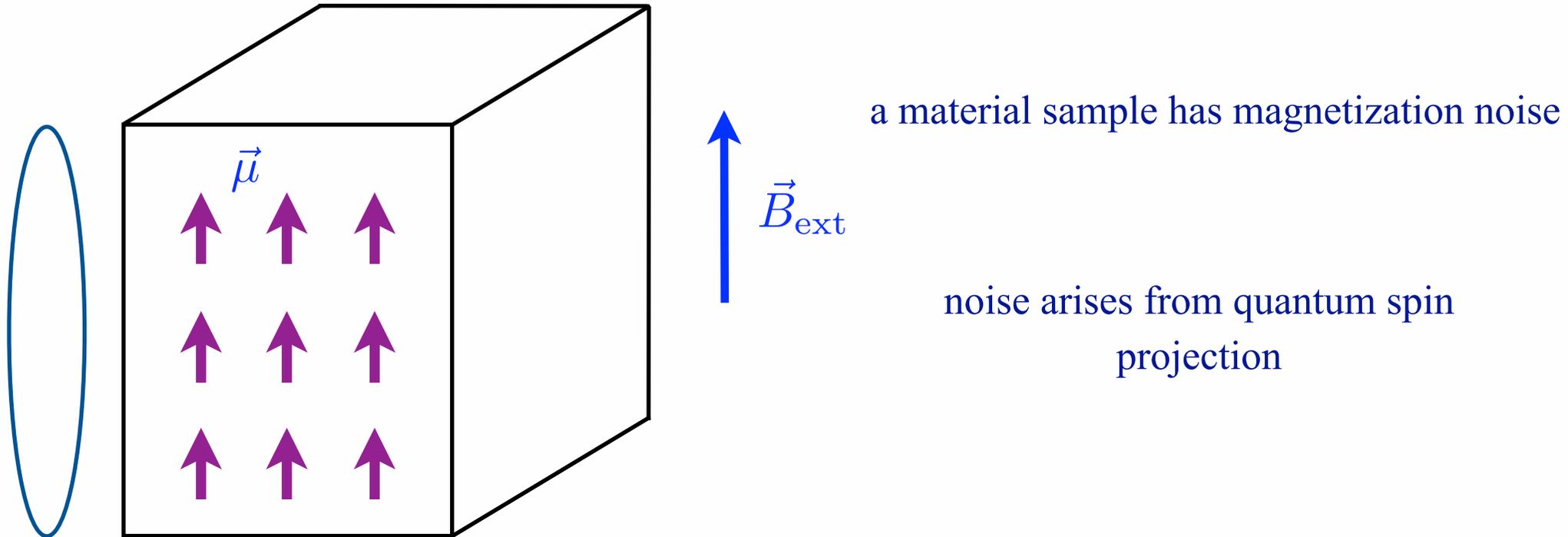
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Polar samples

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

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

# Magnetization Noise



every spin necessarily has random quantum projection onto transverse direction

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

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

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

# Cosmic Axion Spin Precession Experiment (CASPEr)

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

	$n$	$E^*$	$p$	$T_2$	Max. $B_{\text{ext}}$
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:  $^{207}\text{Pb} \implies \mu = 0.6\mu_N \quad \epsilon_S \approx 10^{-2}$

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

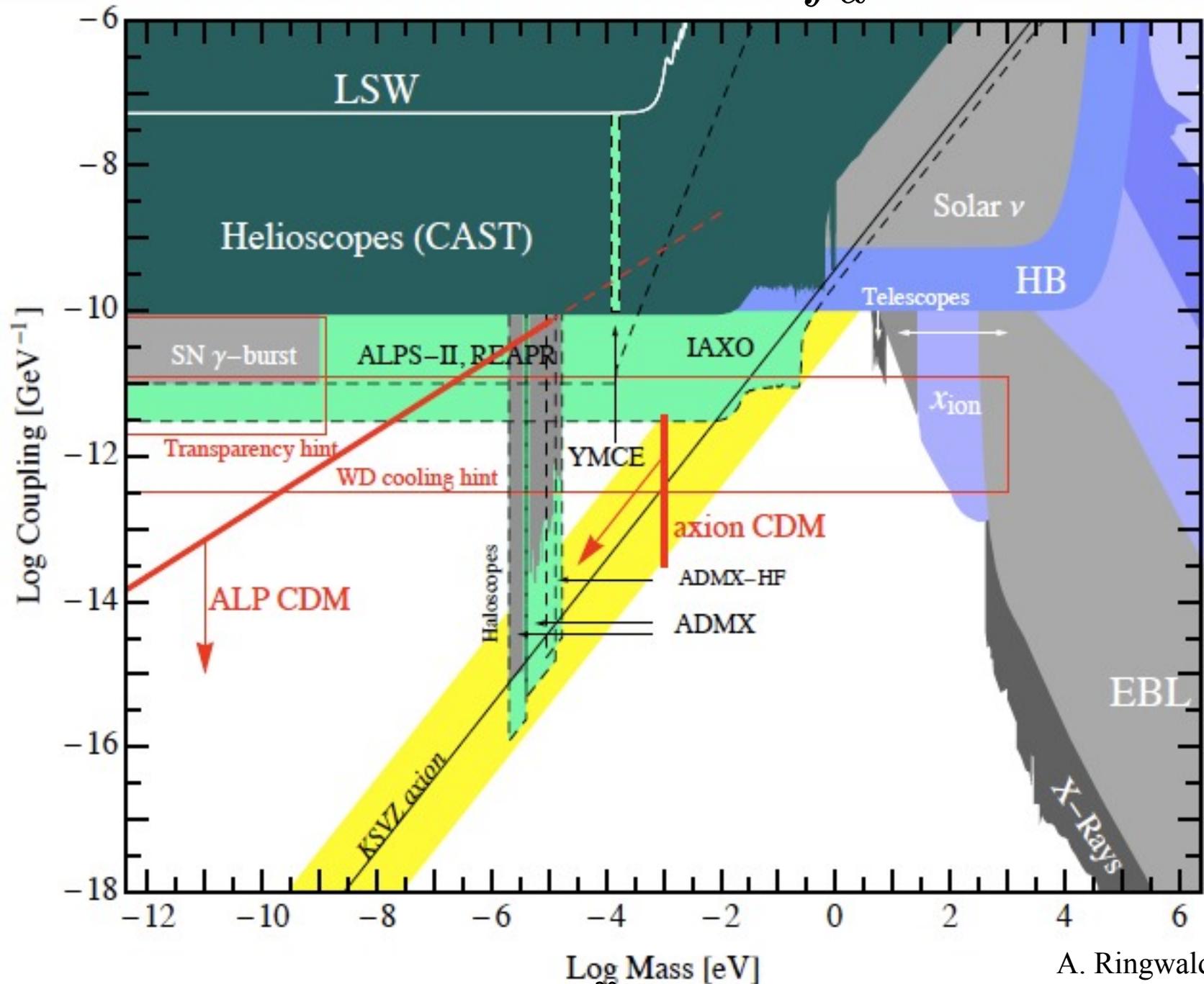
(or multiple loops over smaller sample)

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

many options for increasing sensitivity

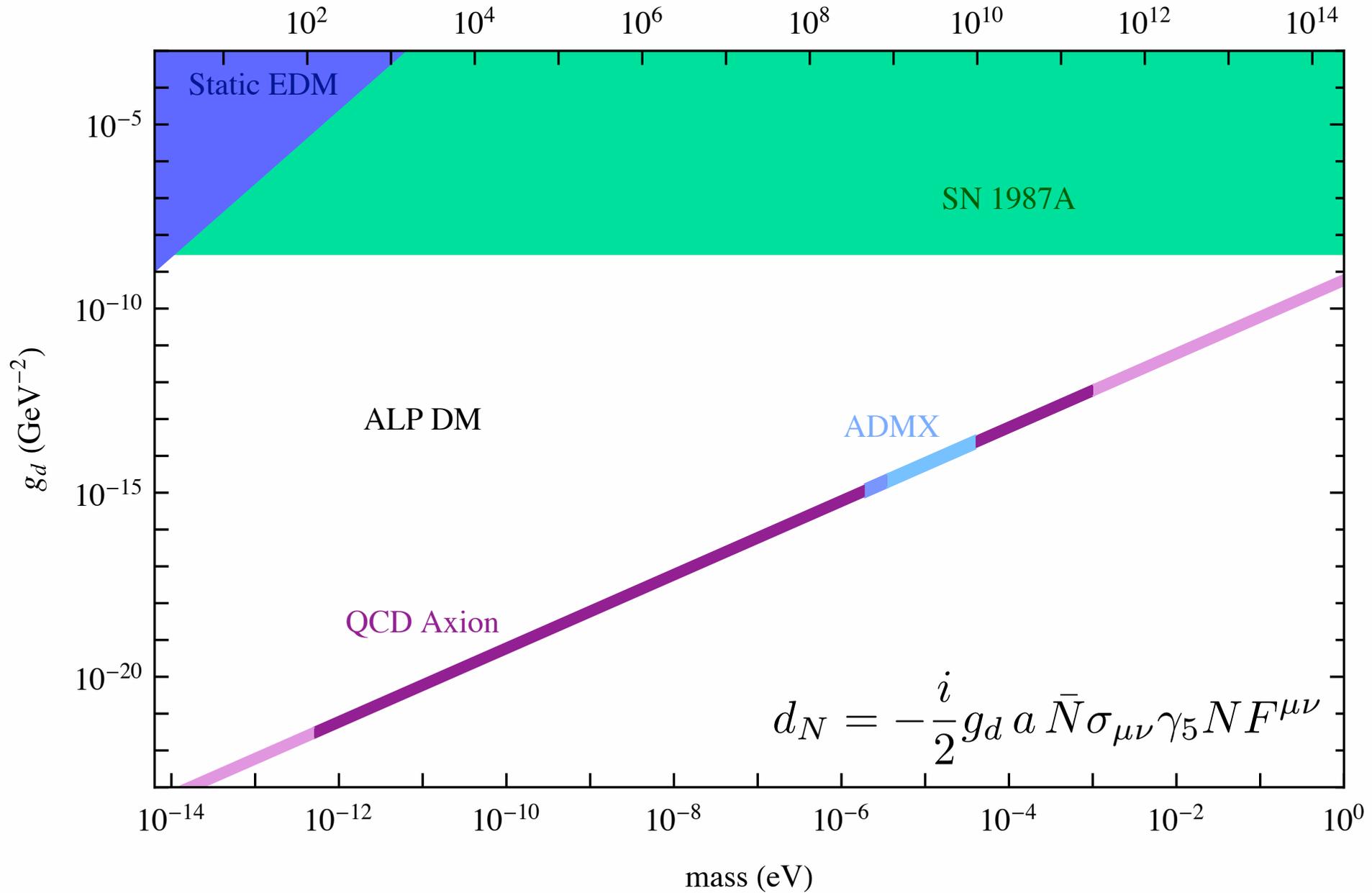
M.V. Romalis

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

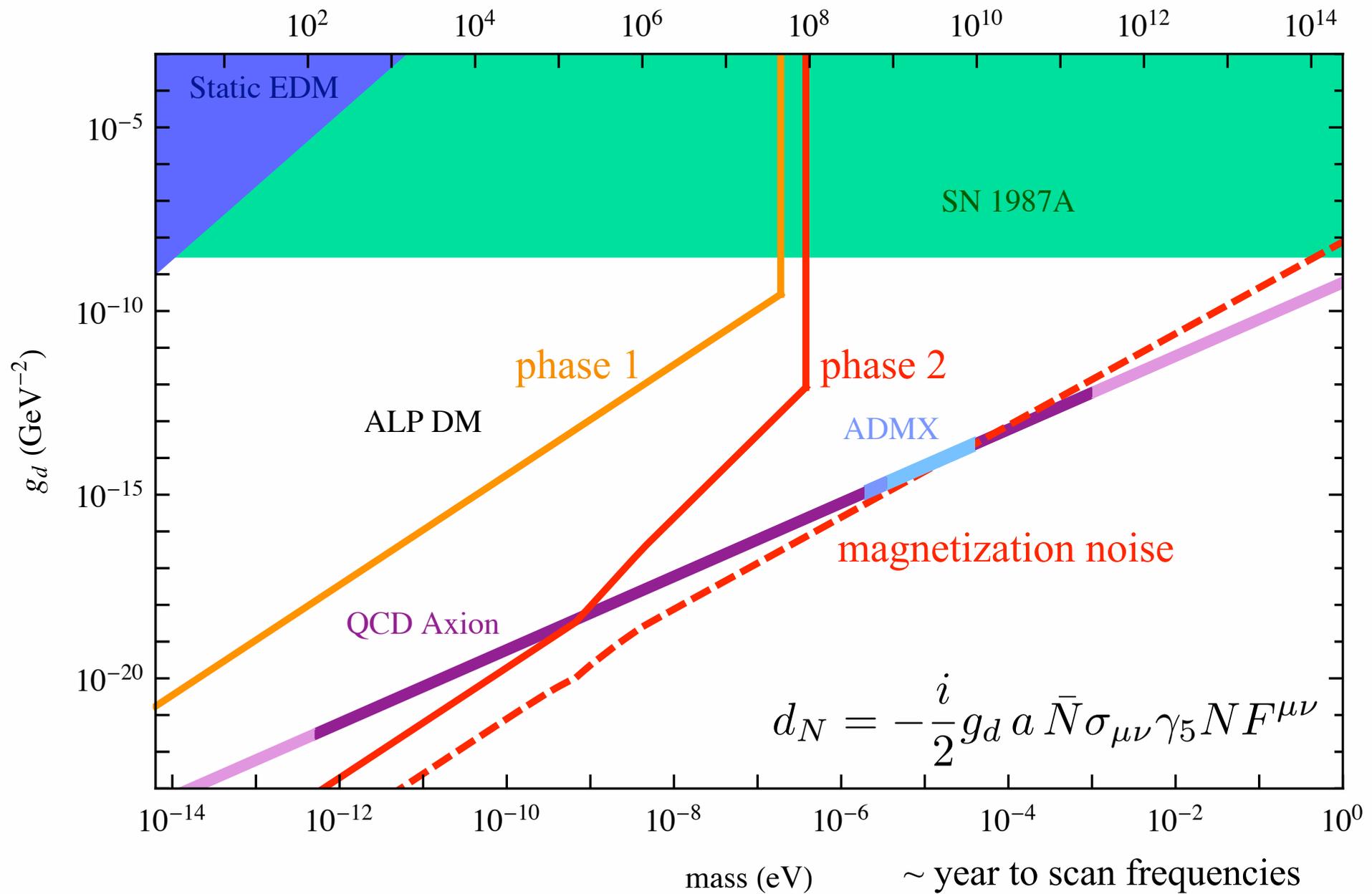


A. Ringwald (2012)

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



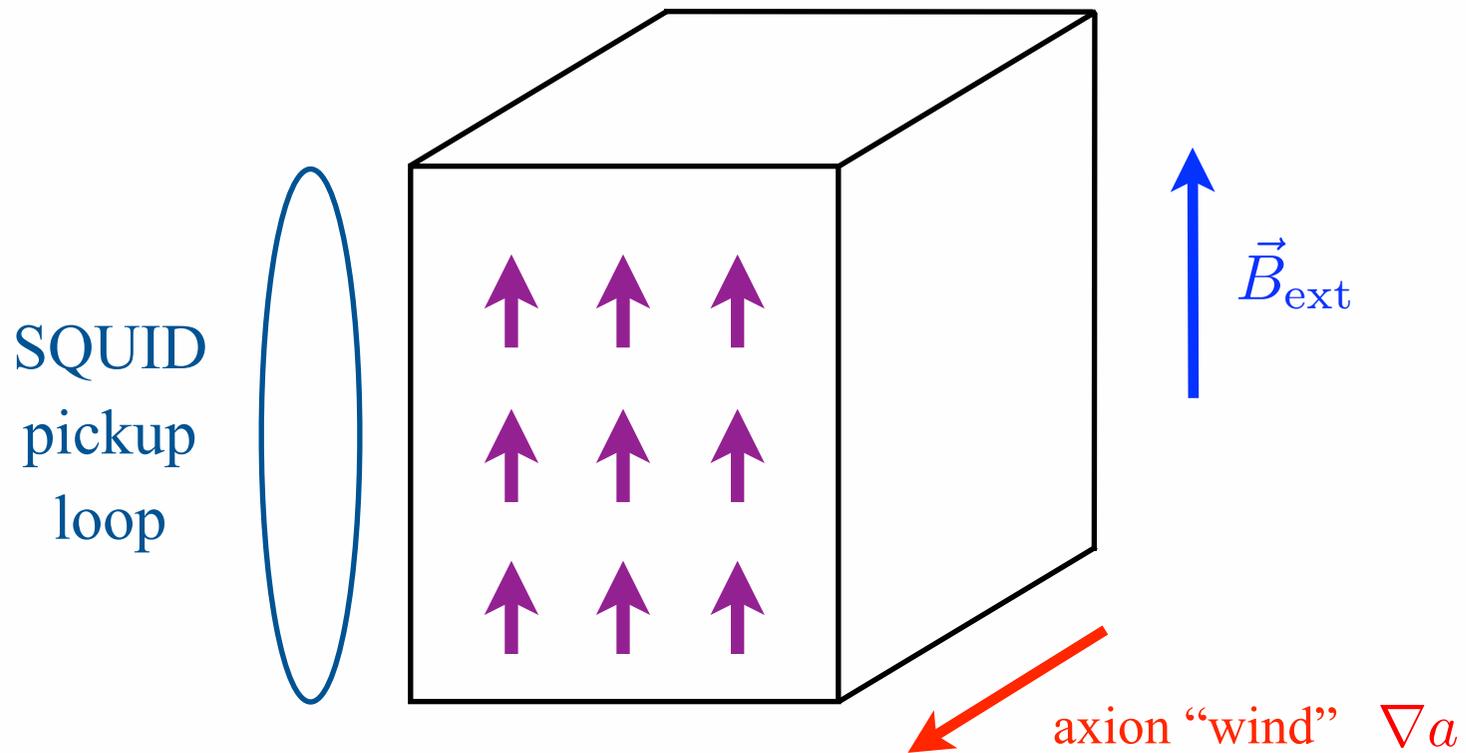
# Axion Limits on $\frac{a}{f_a} G\tilde{G}$



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

Verify signal with spatial coherence of axion field

# Axion Wind



use nuclear spins coupled to axion DM

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

effects suppressed by  $v \sim 10^{-3}$

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

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

## Parameters

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

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

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

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

## Material Choice

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

## Technology

$$p \approx 1$$

$$T_2 \gtrsim \tau_a \sim 1 \text{ s}$$

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

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$$T_2 \gtrsim \tau_a \sim 1 \text{ s}$$

$$m_a \lesssim \text{MHz}$$

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

# Cosmic Axion Spin Precession Experiment (CASPEr)

for axion wind and other types of DM:

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

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

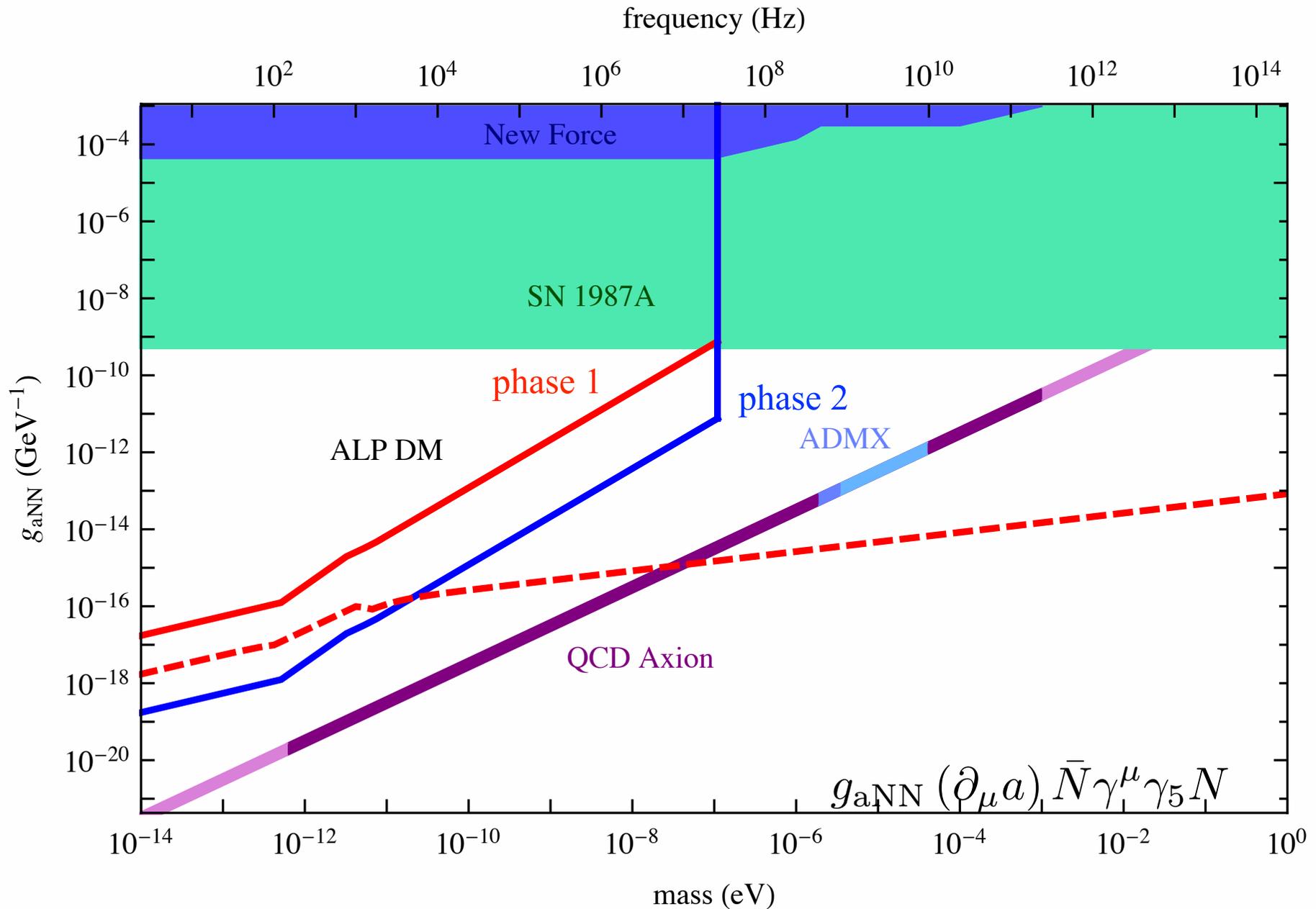
$$p \approx 1$$

take sample size:  $L \sim 10$  cm

(or multiple loops over smaller sample)

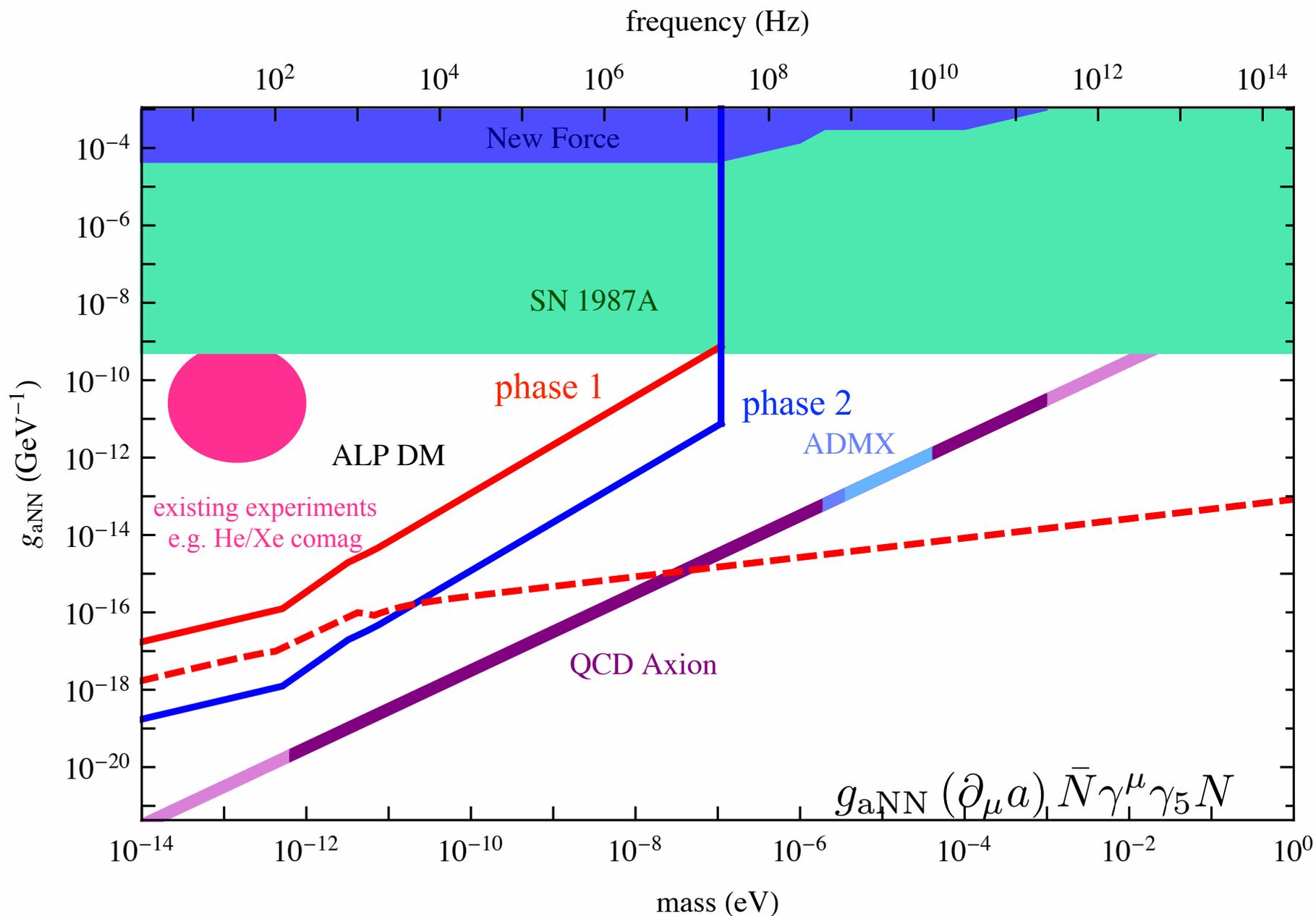
many options for increasing sensitivity

# Limits on Axion-Nucleon Coupling



~ year to scan one decade of frequency

# Limits on Axion-Nucleon Coupling



~ year to scan one decade of frequency

# Summary

# WIMPs

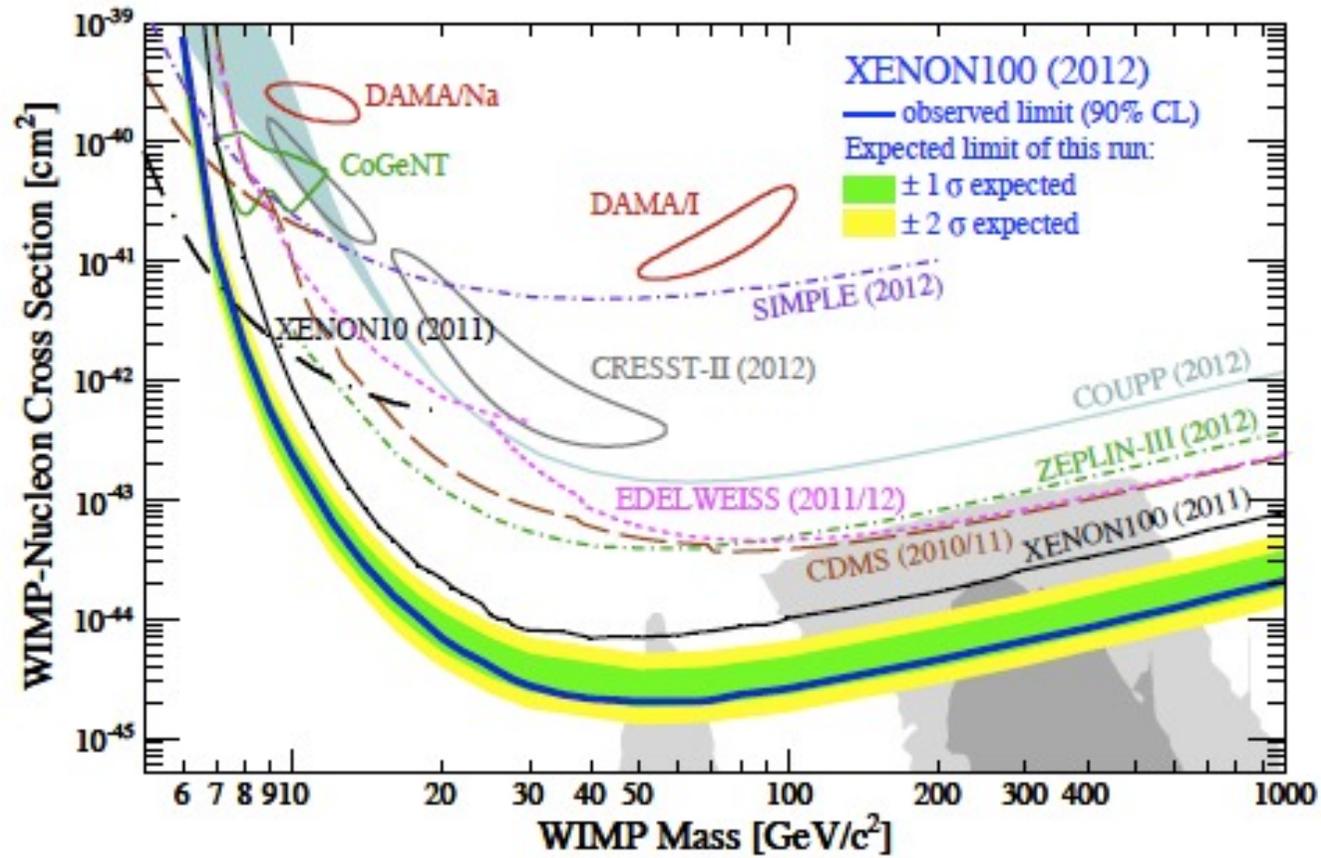
Hard scattering is good for heavy dark matter.

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

Z

h

W



# WIMPs

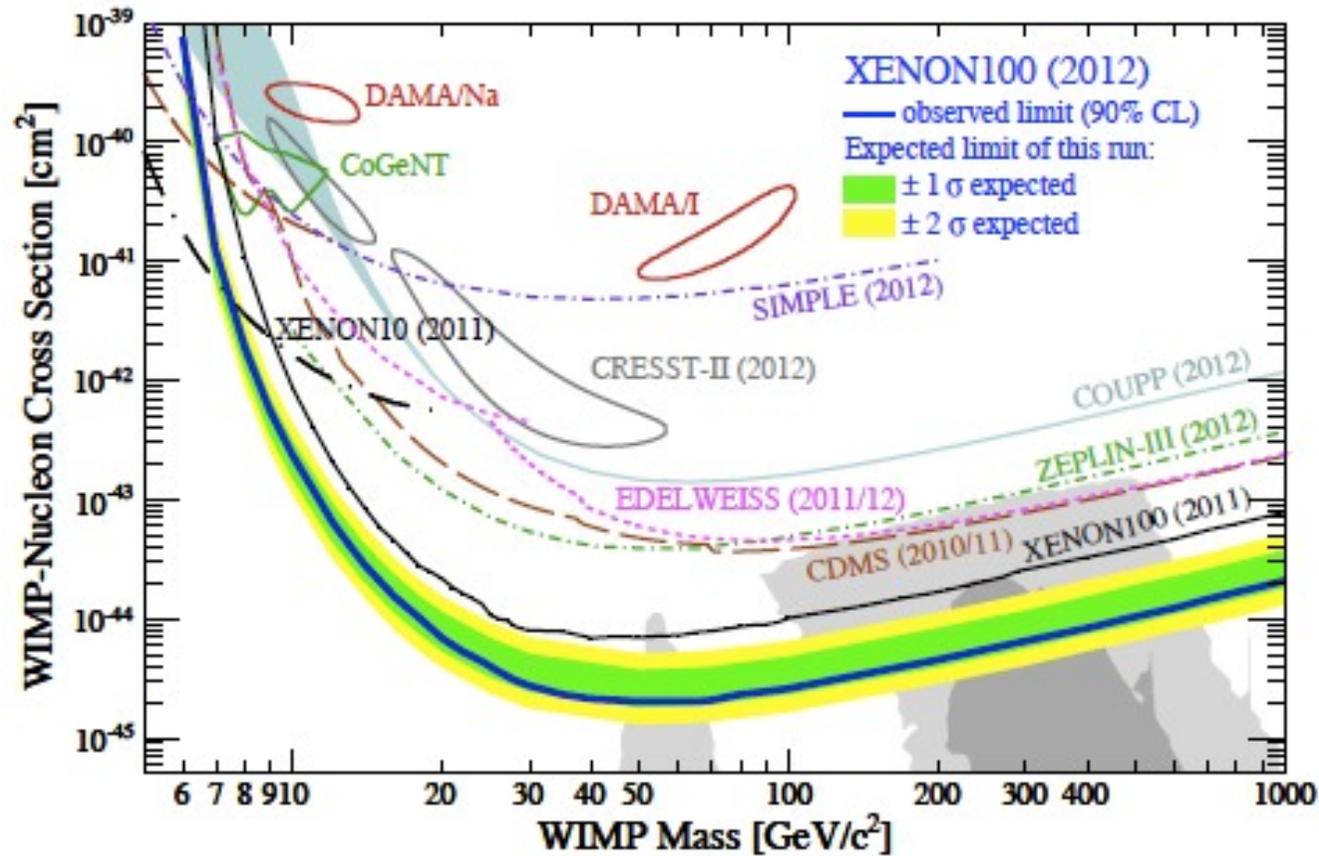
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Z

h

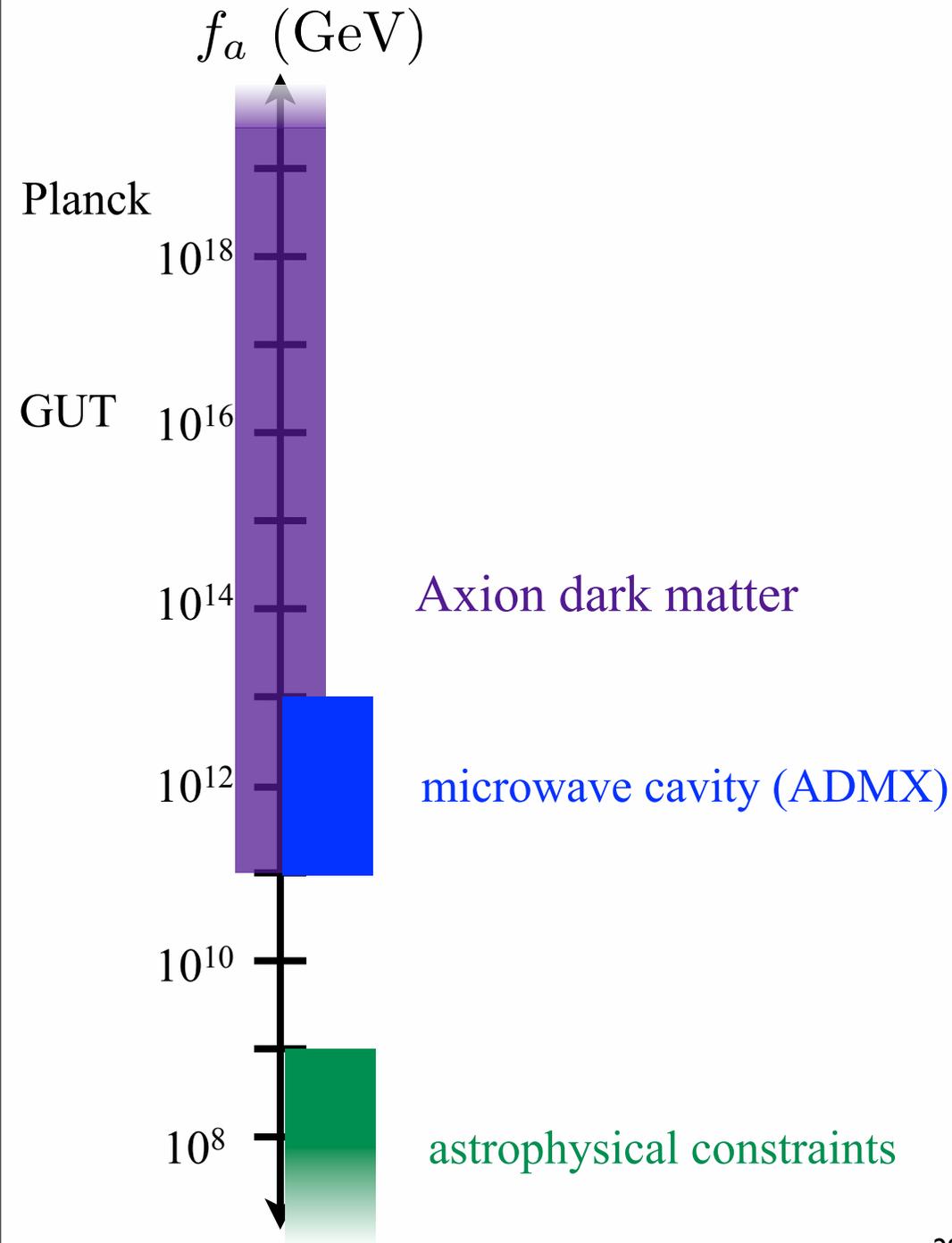
W



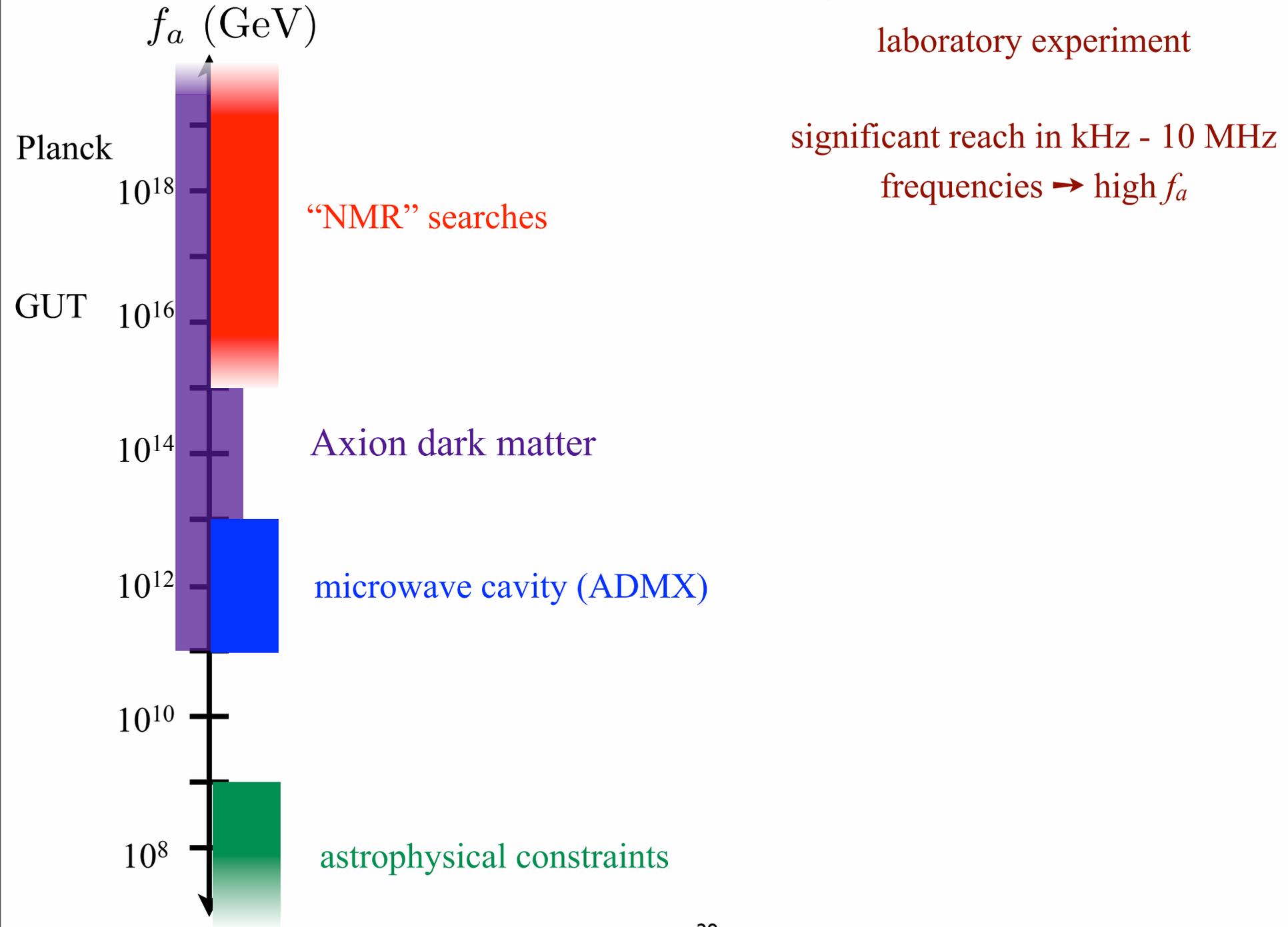
Oscillating moments coupled to spin are natural for light dark matter.

(axions, dark photons...)

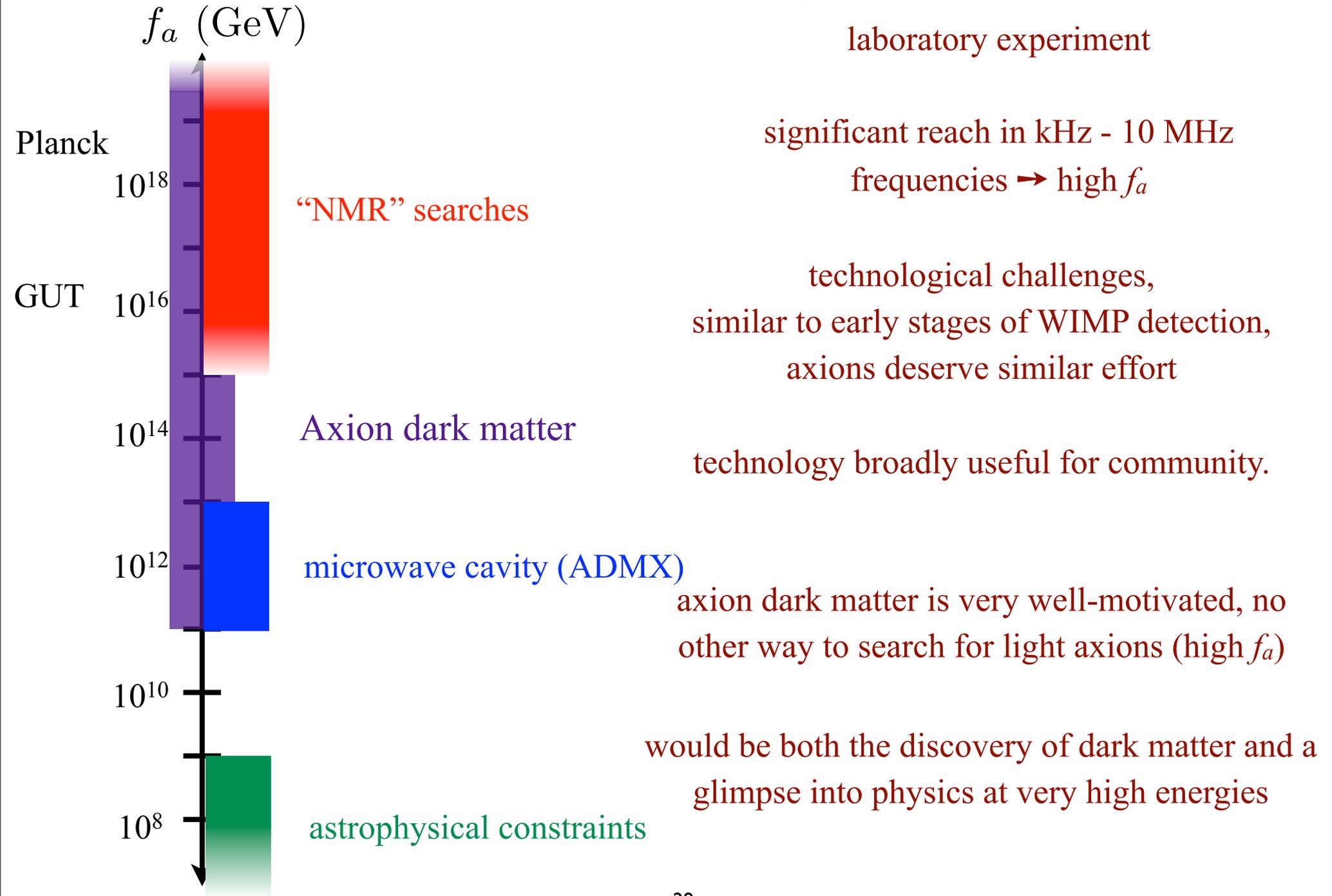
# CASPEr Discovery Potential



# CASPEr Discovery Potential



# CASPEr Discovery Potential



# Backup

# Where does the improvement come from?

PHYSICAL REVIEW A 72, 034501 (2005)

**Suggested search for  $^{207}\text{Pb}$  nuclear Schiff moment in  $\text{PbTiO}_3$  ferroelectric**

T. N. Mukhamedjanov and O. P. Sushkov

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

$\text{PbTiO}_3$  is a ferroelectric crystal, creating large effective electric field

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

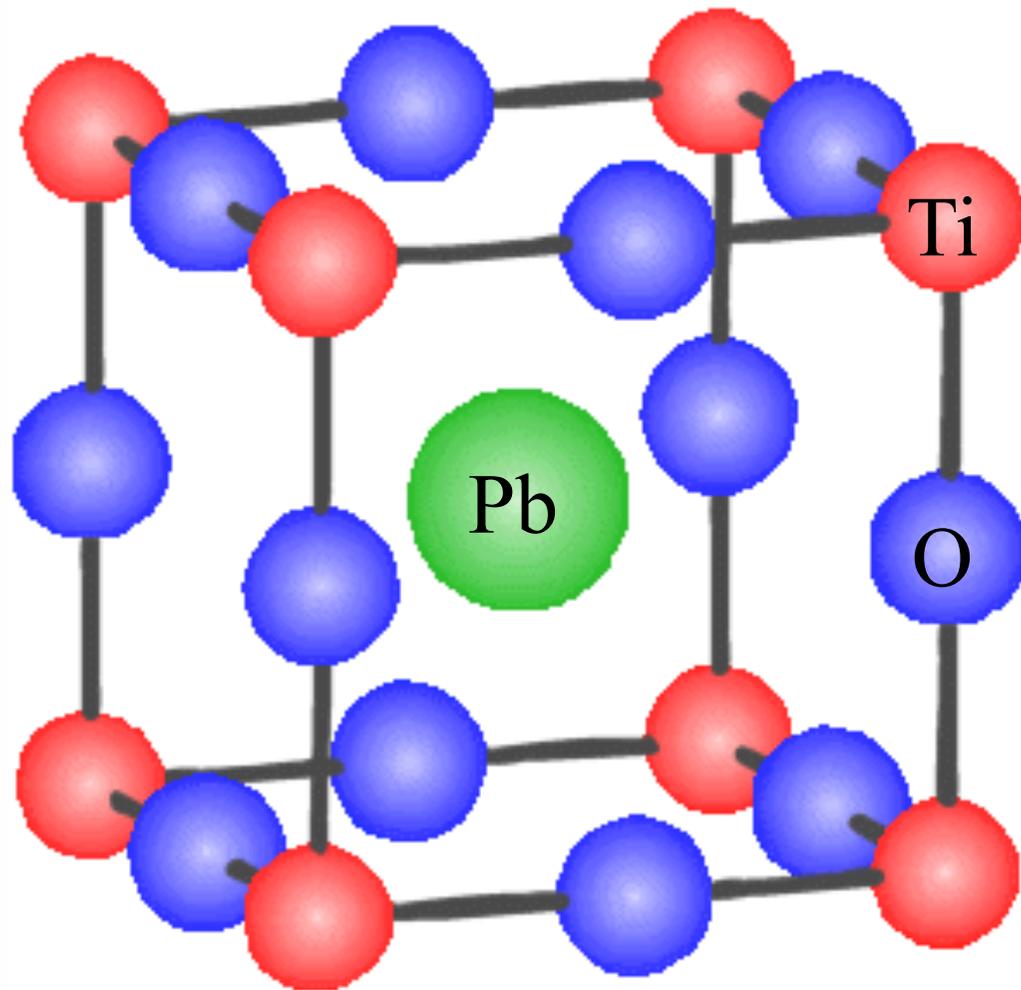
(as in diatomic molecules)

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

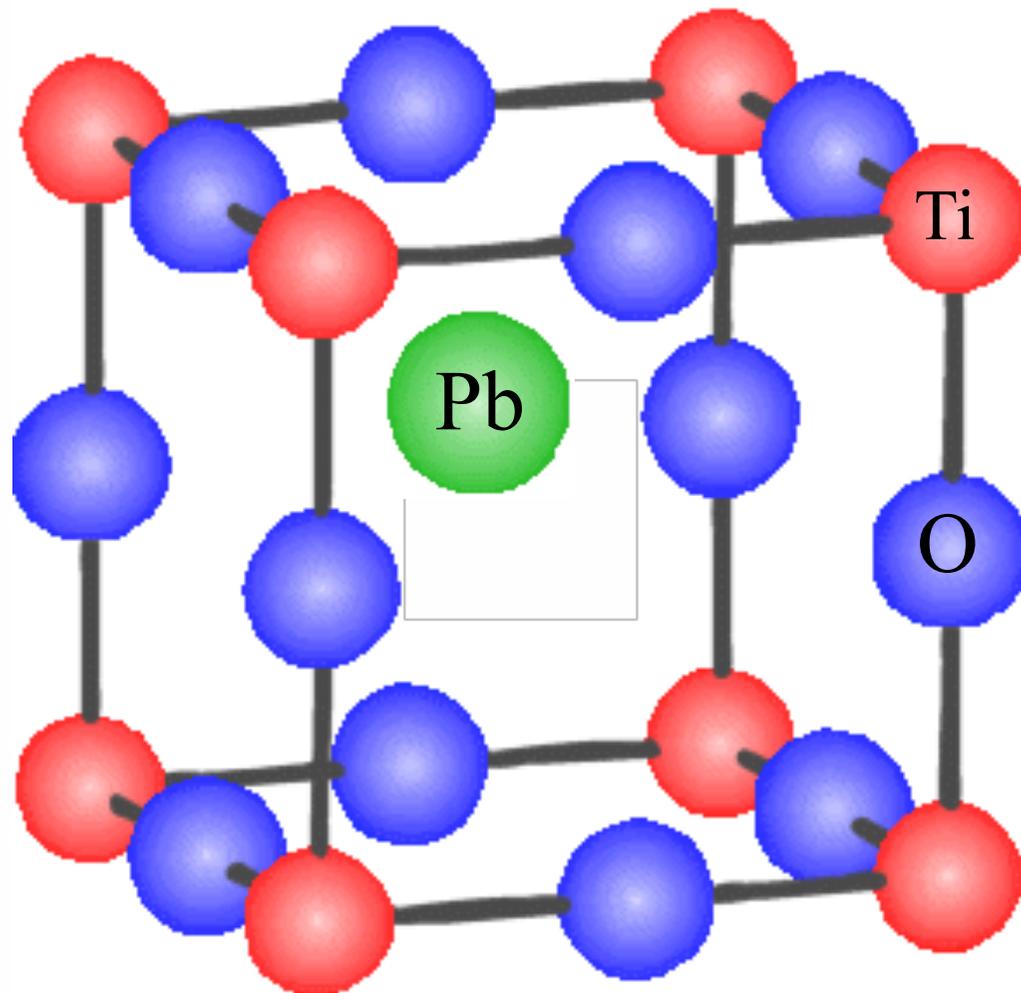
High nuclear orientation needed

Optical pumping of transient paramagnetic color centers?

# Effective Electric Field in $\text{PbTiO}_3$



# Effective Electric Field in $\text{PbTiO}_3$



# Materials for Oscillating EDM Search

- **PbTiO<sub>3</sub>** → we have a lot of experience: NMR, T<sub>1</sub> and T<sub>2</sub> measurements [L.Bouchard, A.Sushkov, D.Budker, 2008]
- Many other **non-centrosymmetric solids** with high-Z atoms, eg: (Pb,La)(Zr,Ti)O<sub>3</sub>, (1-x)[Pb(Mg<sub>1/3</sub>Nb<sub>2/3</sub>)O<sub>3</sub>]-x[PbTiO<sub>3</sub>] (PMN-PT), PbSiO<sub>3</sub>, 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  $B_{\text{ext}}$
- 3) Fluctuations in  $B_{\text{ext}}$   
→ superconducting magnet
- 4) External fluctuating magnetic fields

Experimental design with multiple samples and/or SQUID pickup loops

# Dynamical Decoupling



## ARTICLE

Received 27 Nov 2012 | Accepted 20 Mar 2013 | Published 23 Apr 2013

DOI: [10.1038/ncomms2771](https://doi.org/10.1038/ncomms2771)

# Solid-state electronic spin coherence time approaching one second

N. Bar-Gill<sup>1,2</sup>, L.M. Pham<sup>3</sup>, A. Jarmola<sup>4</sup>, D. Budker<sup>4,5</sup> & R.L. Walsworth<sup>1,2</sup>

# Dynamical Decoupling



## ARTICLE

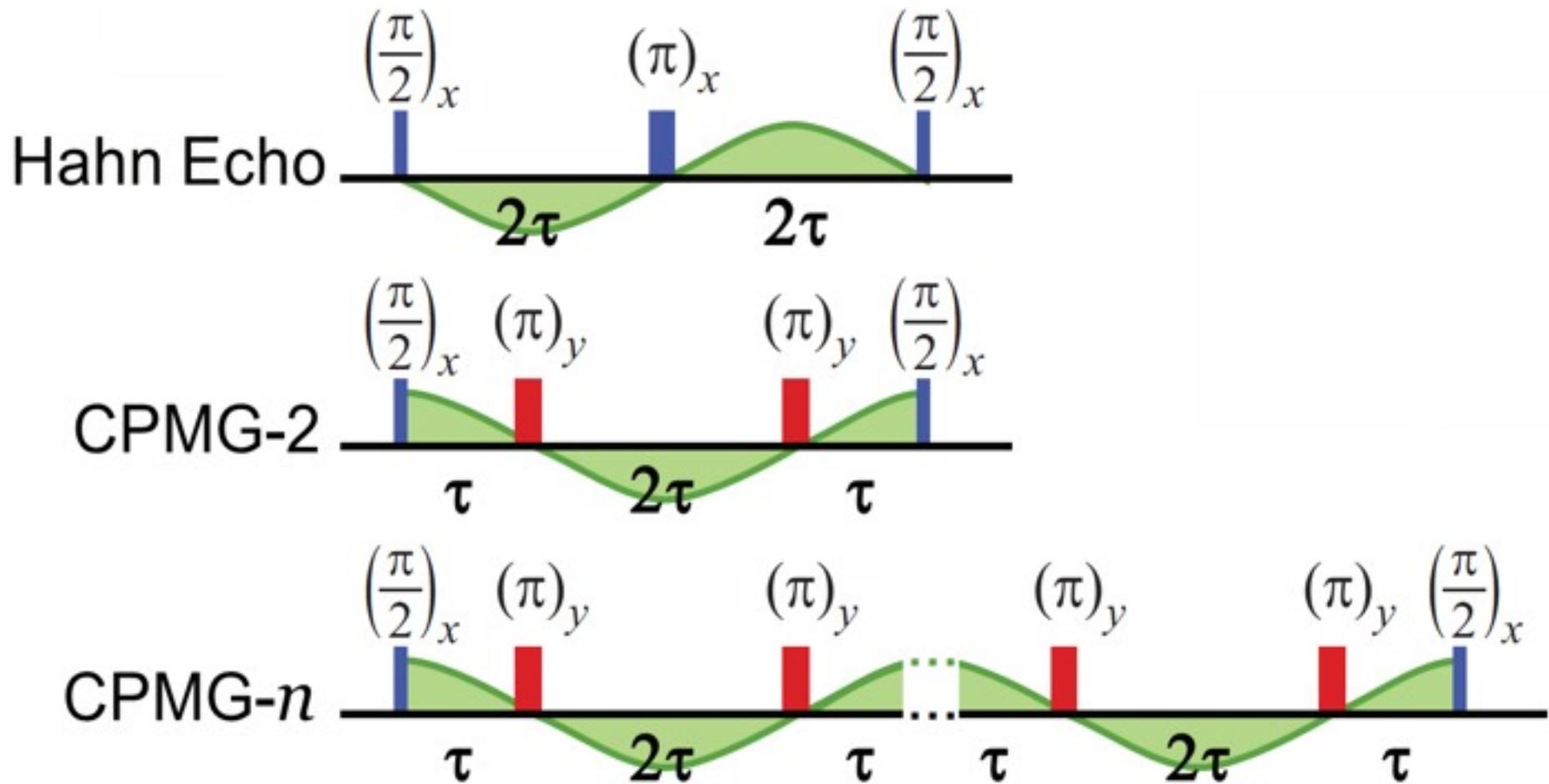
Received 27 Nov 2012 | Accepted 20 Mar 2013 | Published 23 Apr 2013

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# Solid-state **electronic spin** coherence time approaching one second

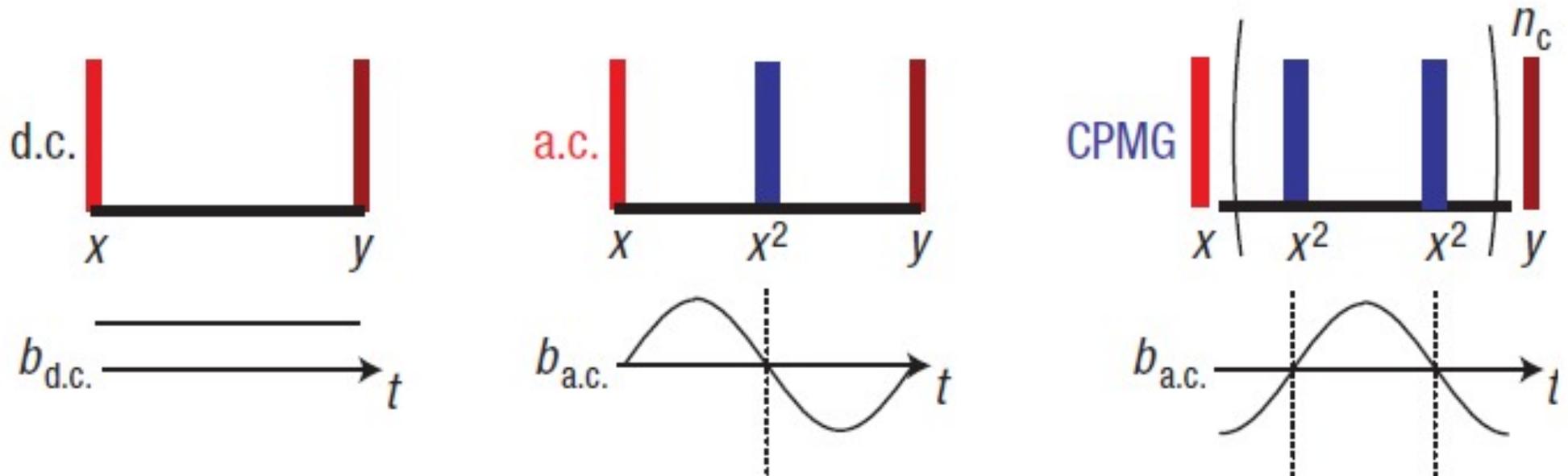
N. Bar-Gill<sup>1,2</sup>, L.M. Pham<sup>3</sup>, A. Jarmola<sup>4</sup>, D. Budker<sup>4,5</sup> & R.L. Walsworth<sup>1,2</sup>

# 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



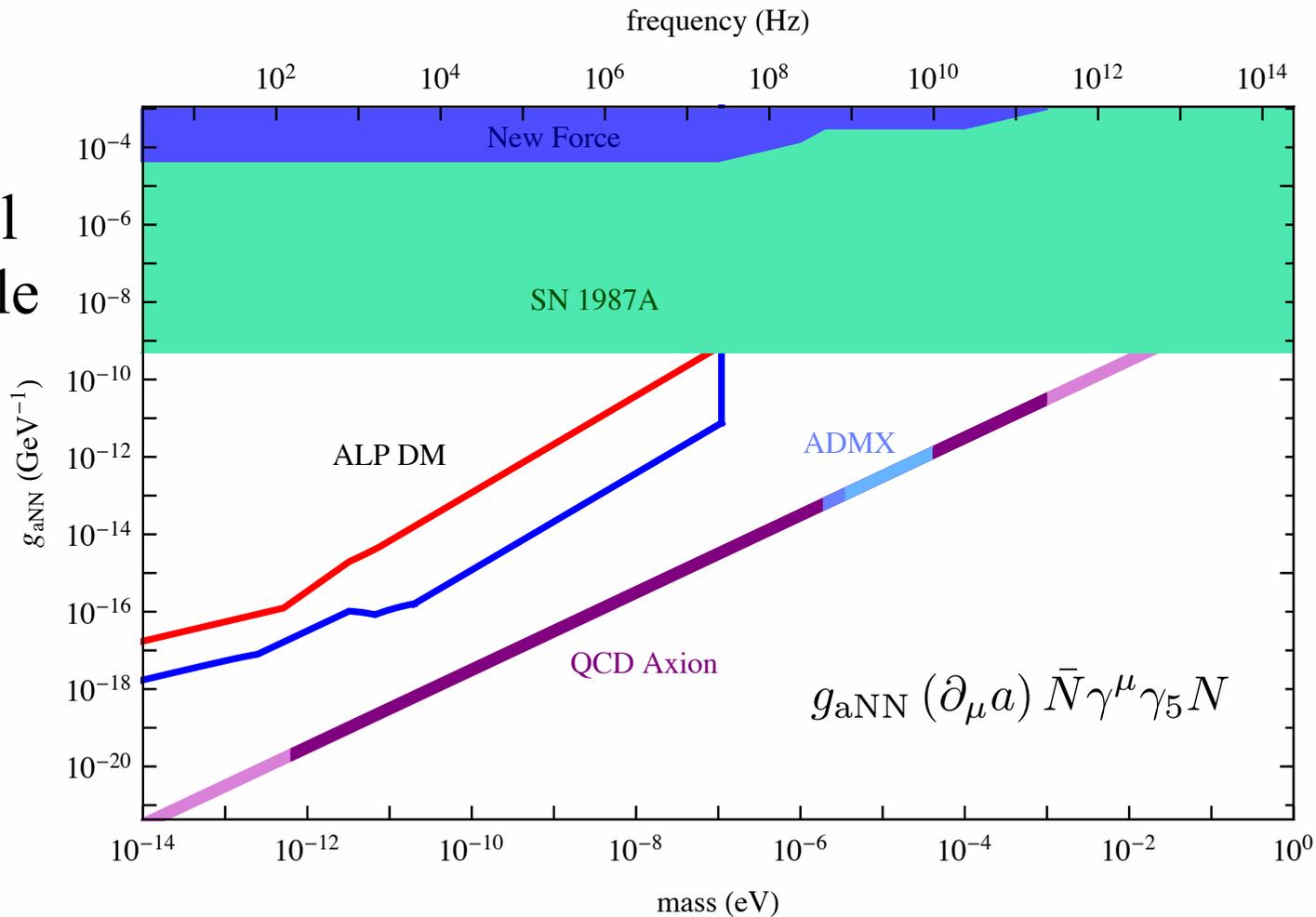
High-sensitivity diamond magnetometer  
with nanoscale resolution

J. M. TAYLOR<sup>1\*</sup>, P. CAPPELLARO<sup>2,3\*</sup>, L. CHILDRESS<sup>2,4</sup>, L. JIANG<sup>2</sup>, D. BUDKER<sup>5</sup>, P. R. HEMMER<sup>6</sup>,  
A. YACOBY<sup>2</sup>, R. WALSWORTH<sup>2,3</sup> AND M. D. LUKIN<sup>2,3†</sup>

nature physics | VOL 4 | OCTOBER 2008 | [www.nature.com/naturephysics](http://www.nature.com/naturephysics)

# CASPER: Timeline

## Axion Wind Search

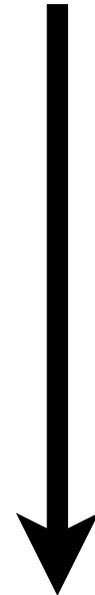


Small  
Sample



Scalable

Years

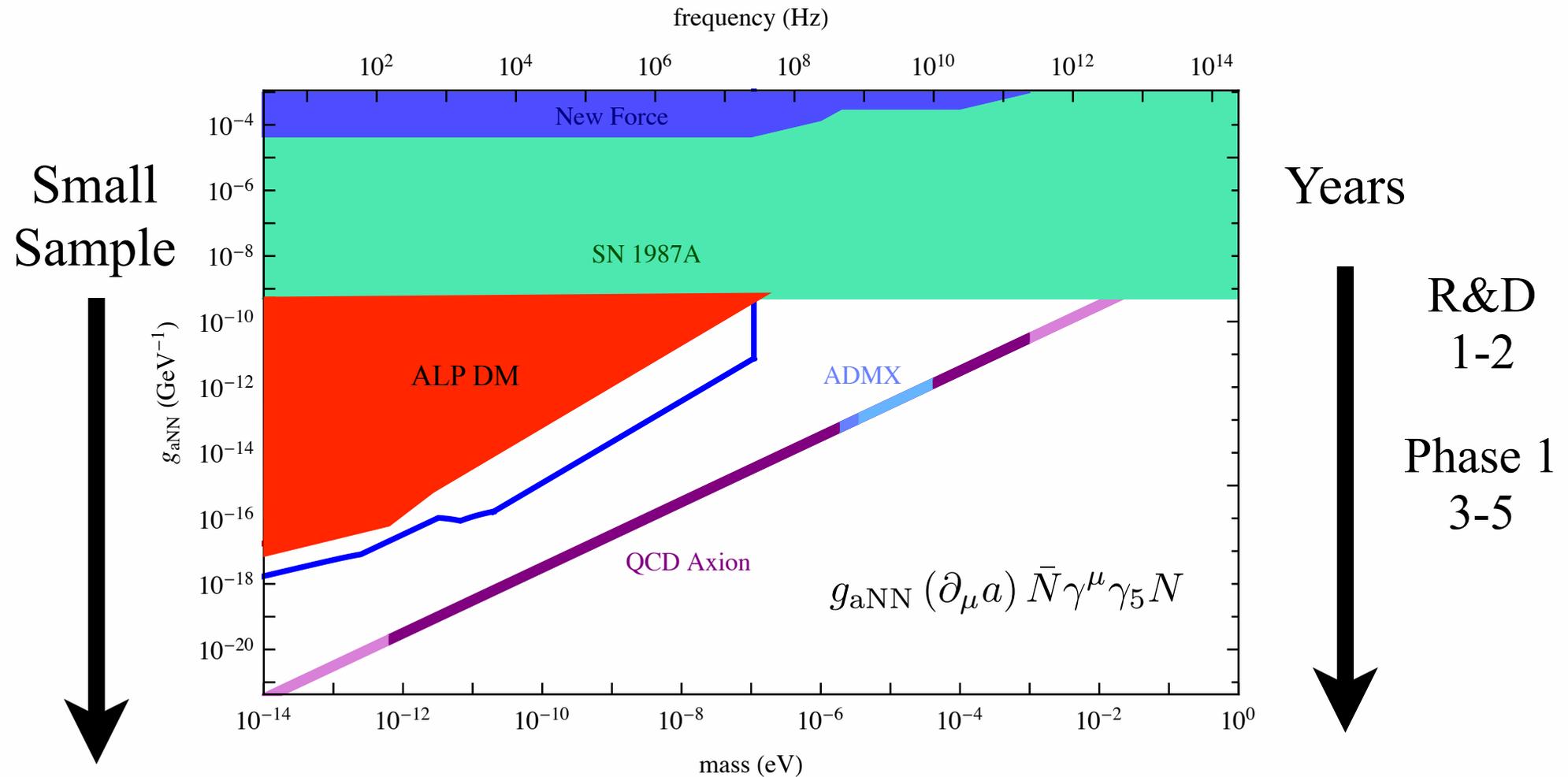


R&D  
1-2

Liquid Xenon Technology

# CASPER: Timeline

## Axion Wind Search

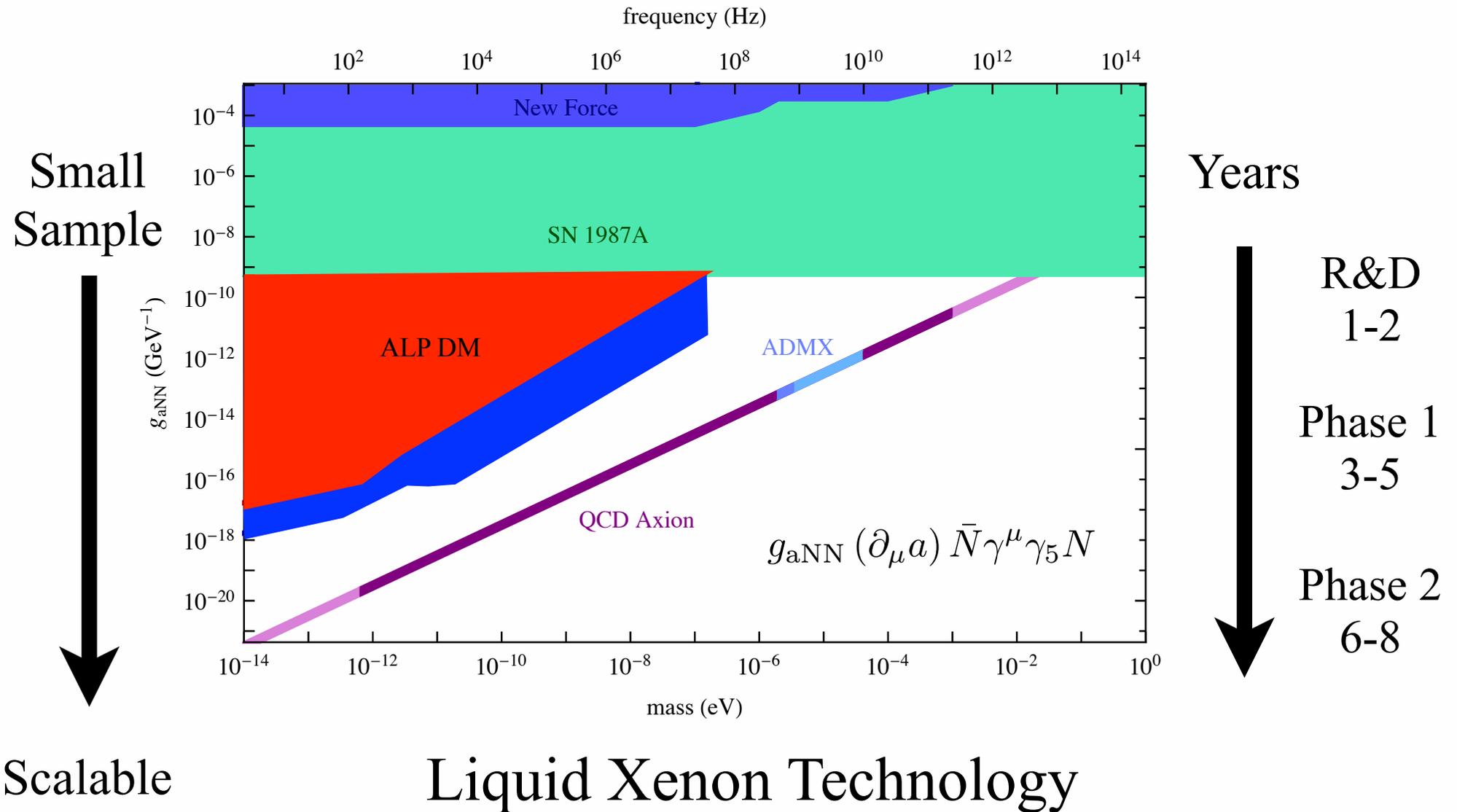


Scalable

Liquid Xenon Technology

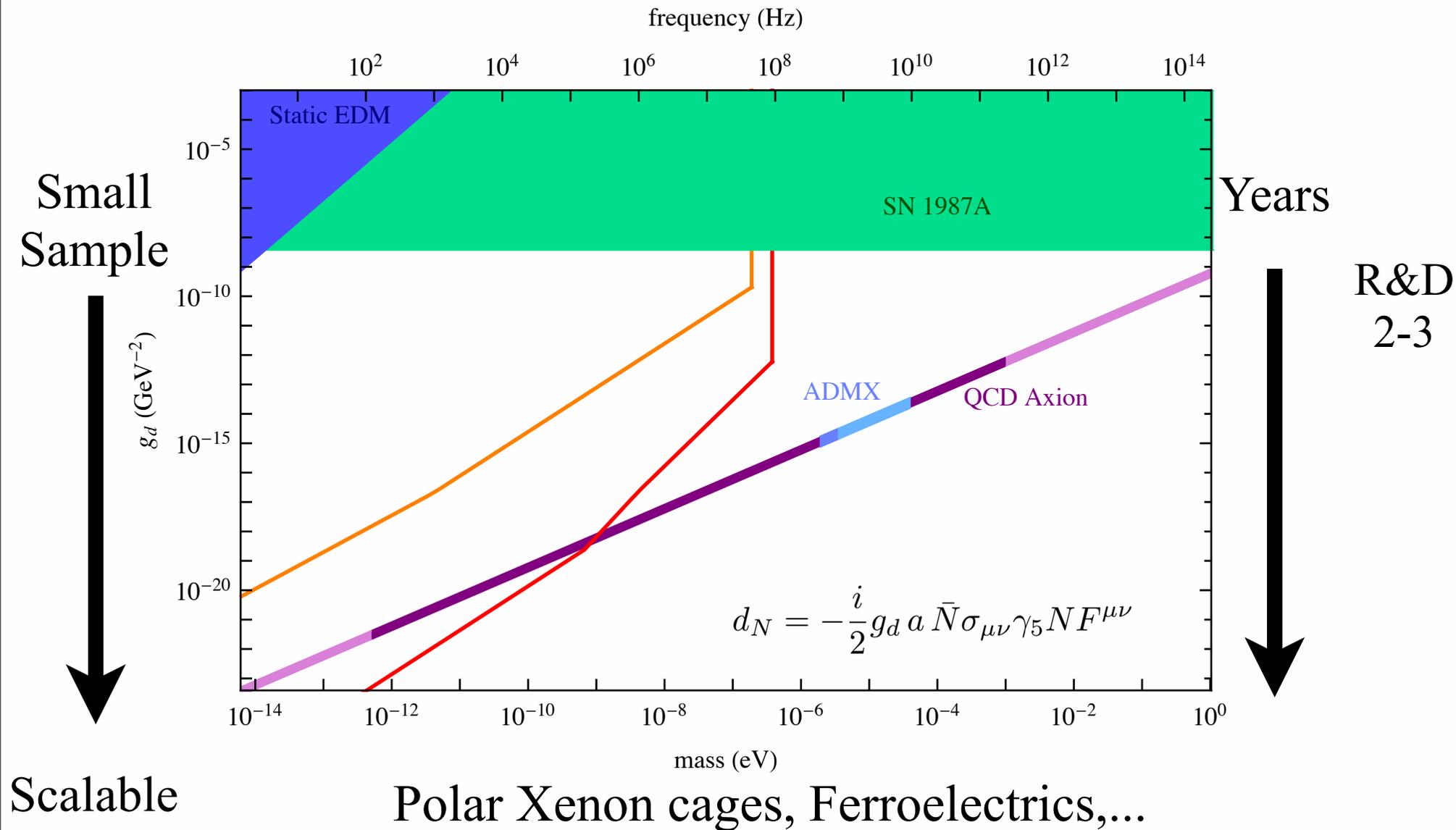
# CASPER: Timeline

## Axion Wind Search



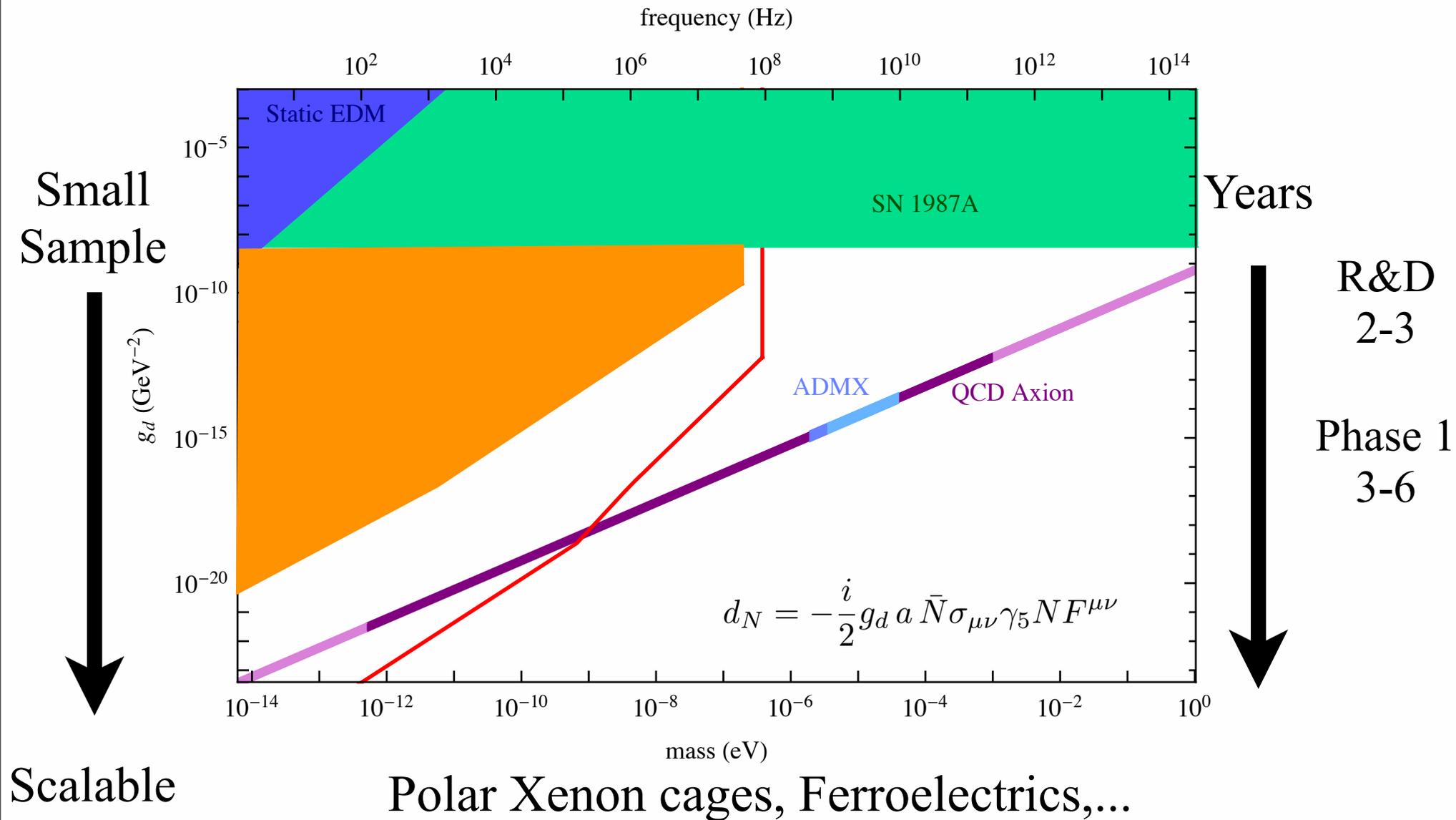
# CASPER: Timeline

## QCD Axion Goal



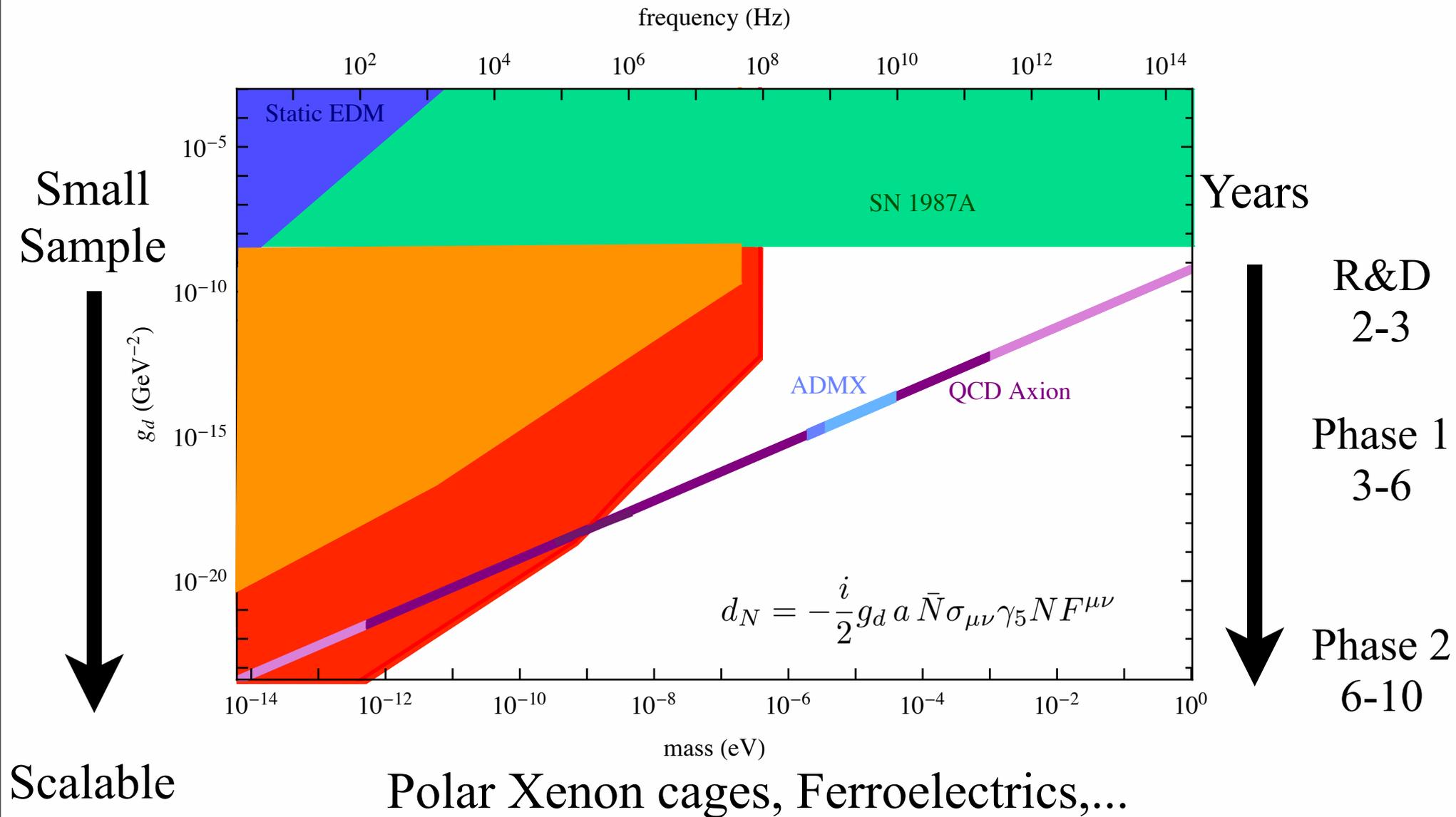
# CASPER: Timeline

## QCD Axion Goal



# CASPER: Timeline

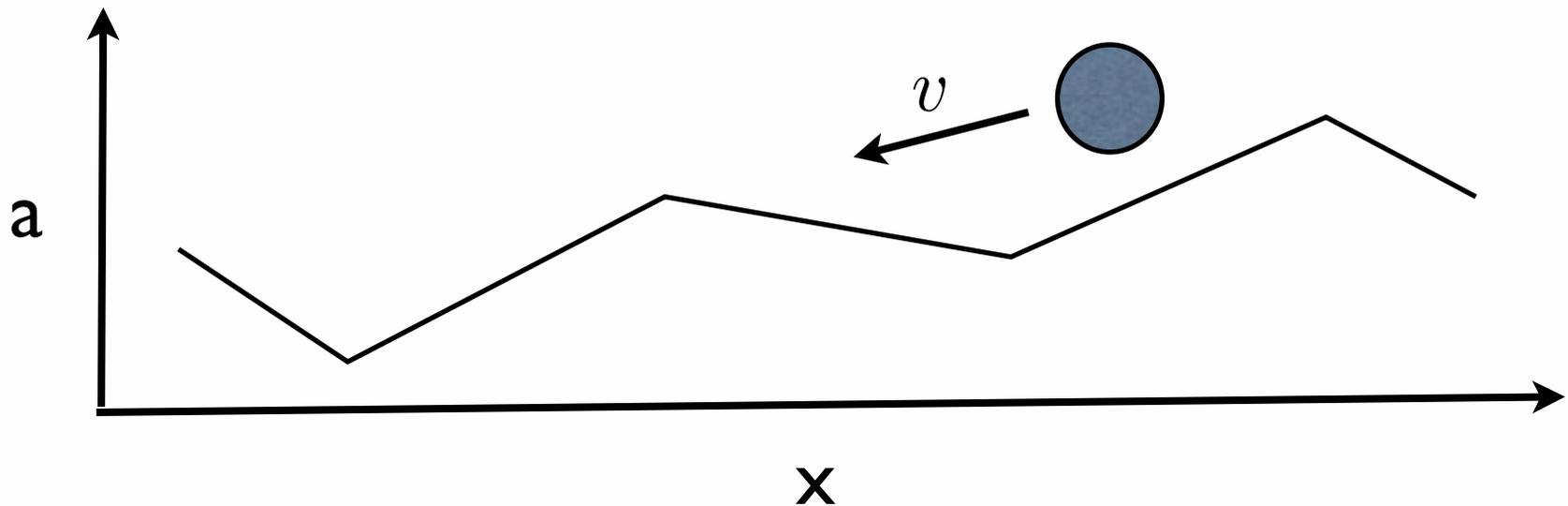
## QCD Axion Goal



# Backup slides

# Axion Coherence

How large can  $T$  be?



Spatial homogeneity of the field?

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

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

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