New Methods for Discovering Light Fields

Peter Graham
Stanford

Motivation

Want to discover new physics beyond the SM

Getting hard to probe higher energies, need bigger colliders

But UV physics can give light particles,
detectable in low energy experiments, hints of deep UV

possible candidates include…

Outline

1. Axion Detection with NMR

2. Hidden Sector Detection with EM Resonators

3. Gravitational Wave Detection with Atoms

Outline

1. Axion Detection with NMR	spin 0
2. Hidden Sector Detection with EM Resonators	spin 1
3. Gravitational Wave Detection with Atoms	spin 2

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↑

all high phase space density
better thought of as fields

Axion Detection with NMR

with

Dmitry Budker
Micah Ledbetter
Surjeet Rajendran
Alex Sushkov

PRX **4** (2014) arXiv: 1306.6089
PRD **88** (2013) arXiv: 1306.6088
PRD **84** (2011) arXiv: 1101.2691

Dark Matter

Dark matter is proof of physics beyond Standard Model

heavy particle vs. light field

(WIMPs) (axions)

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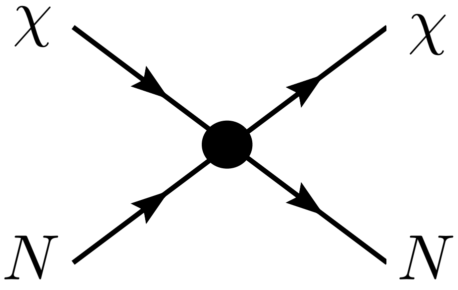
Search for single, hard particle scattering



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heavy particle vs. light field
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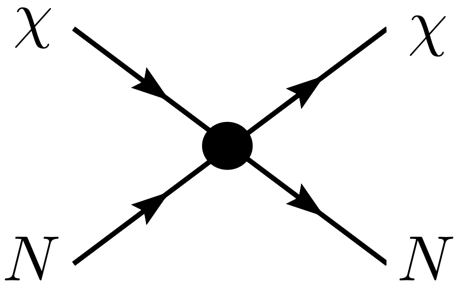


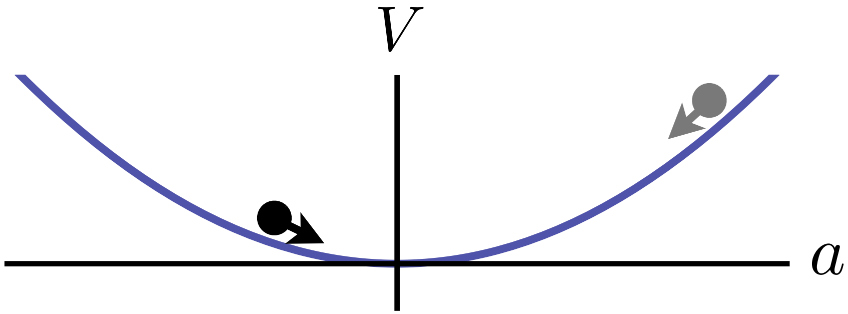
Large phase-space density

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

Detect coherent effects of entire field,
not single particle scatterings

Axion Dark Matter

All light fields produced by misalignment:



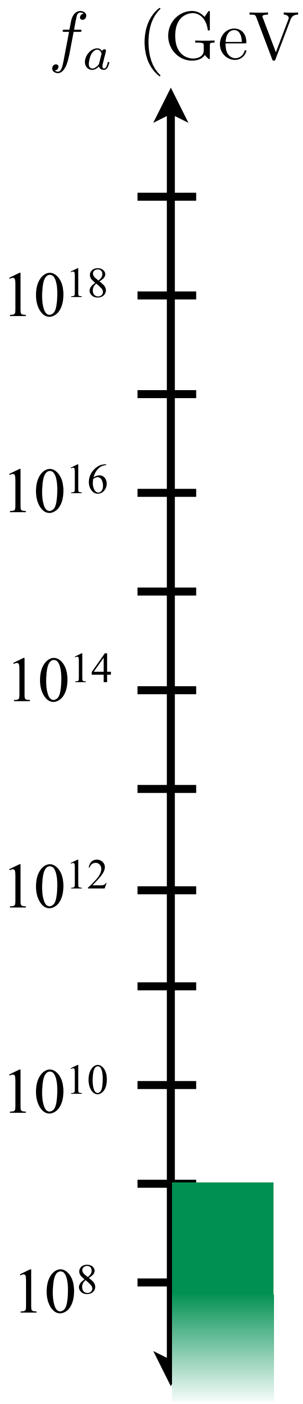
$$a(t) \sim a_0 \cos\left(m_a t\right)$$

Axion is a natural dark matter candidate

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

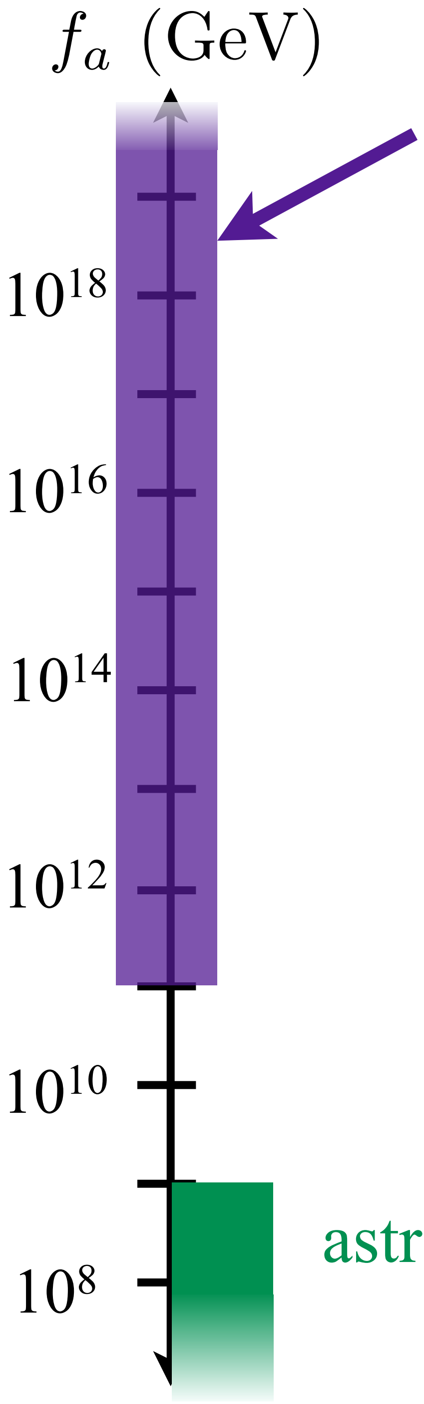
Constraints and Searches

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



astrophysical and laboratory bounds

Constraints and Searches



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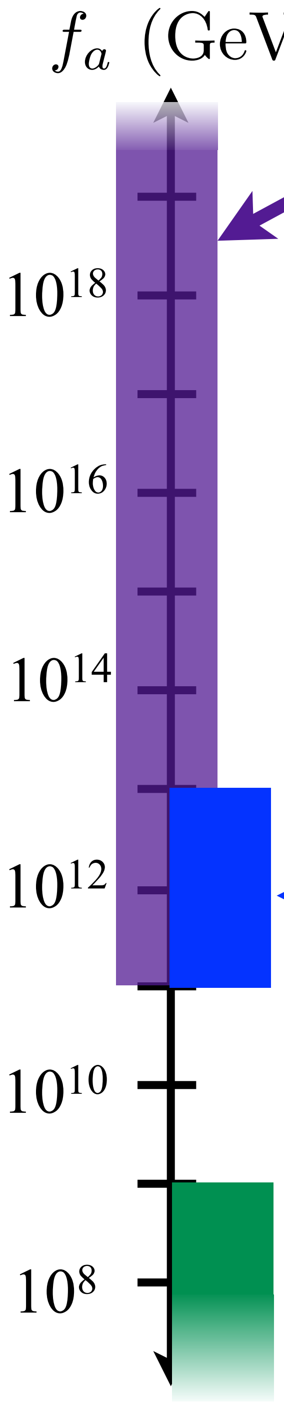

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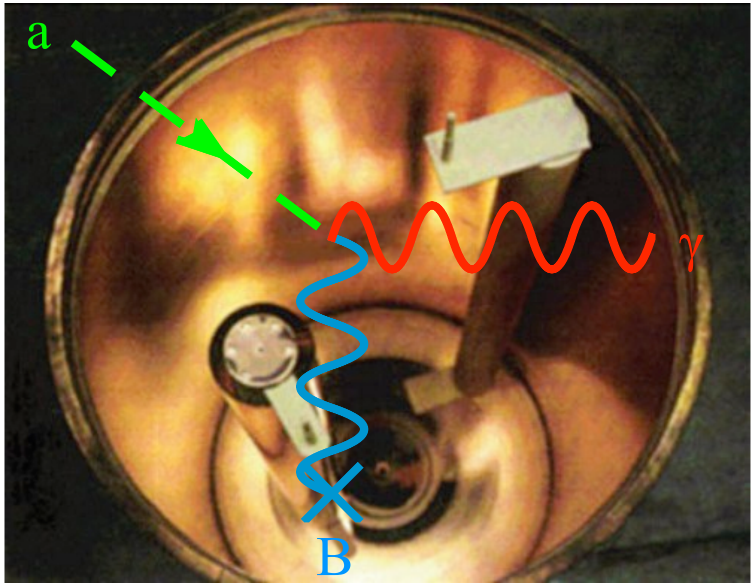


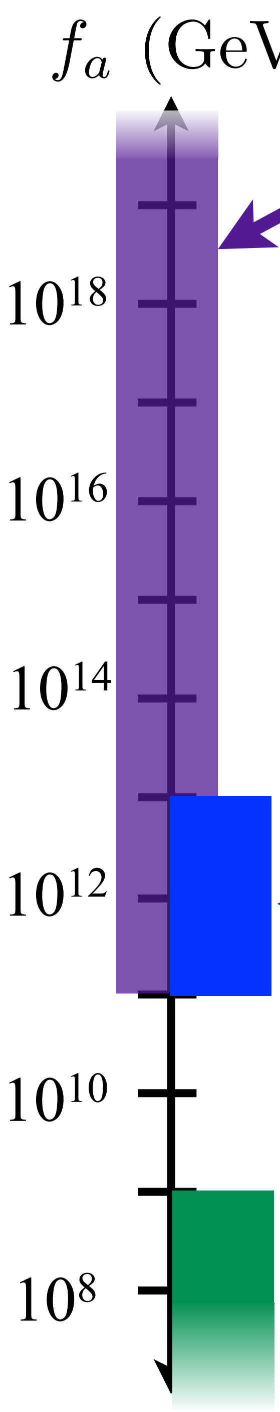
size of cavity increases with f_a

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

microwave cavity (ADMX)

astrophysical and laboratory bounds

Constraints and Searches



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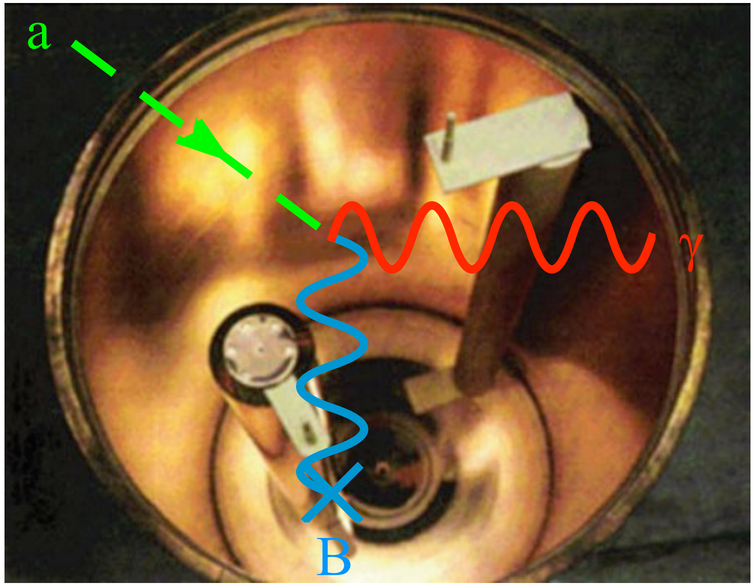

$$\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

Derivative Operator

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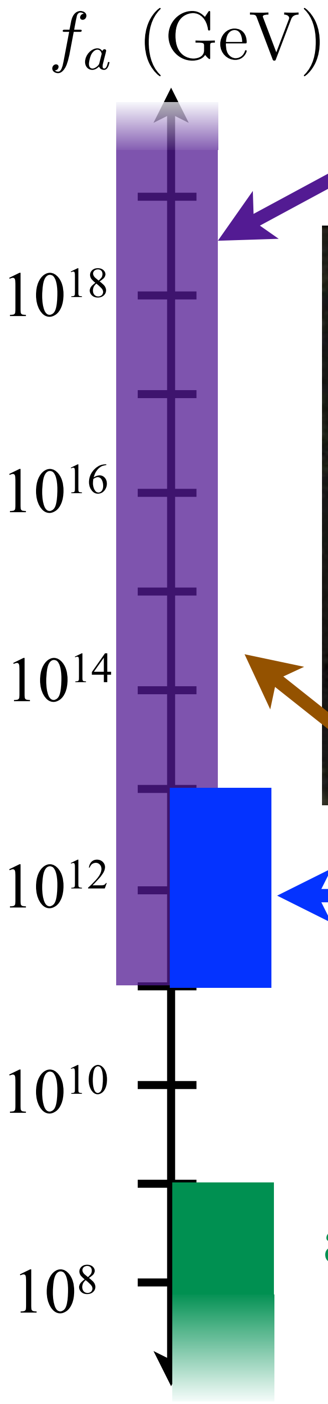

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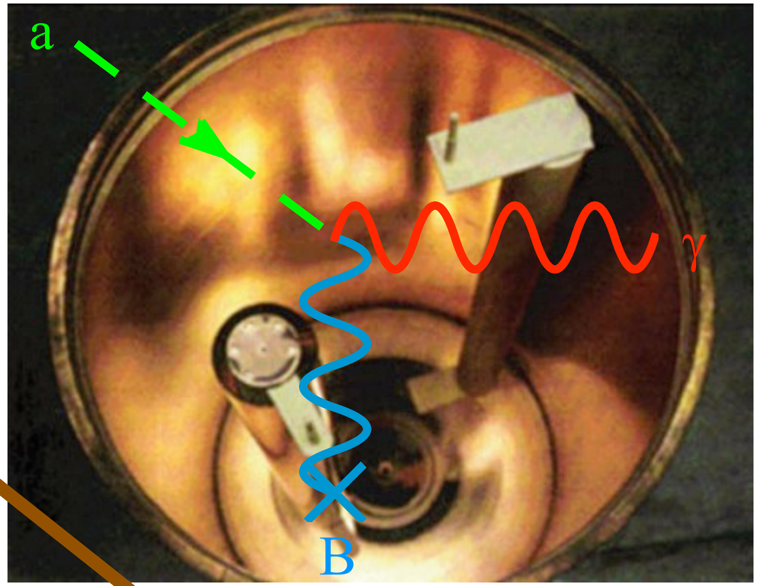

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Derivative Operator

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

microwave cavity (ADMX)

S. Thomas

astrophysical and laboratory bounds

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

A Different Operator For Axion Detection

How to detect high f_a axions?

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

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

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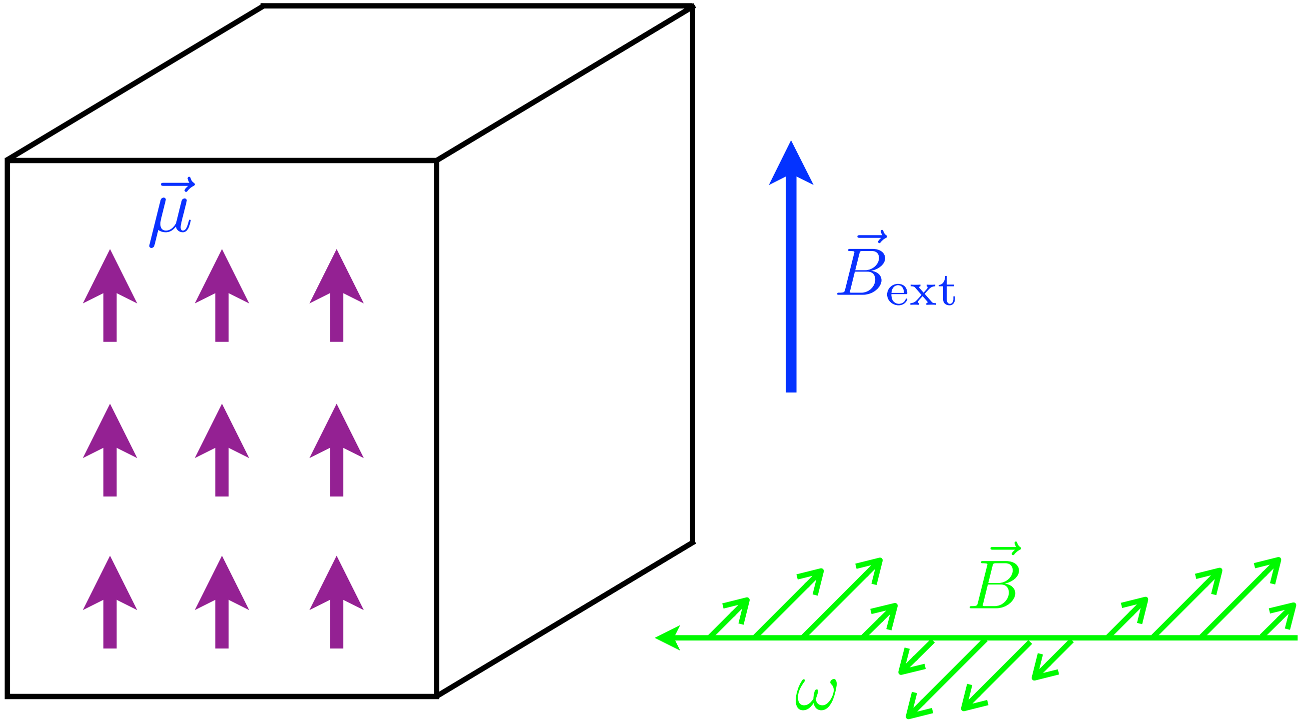
$a(t) \sim a_0 \cos\left(m_a t\right)$ with $m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz}\left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$

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

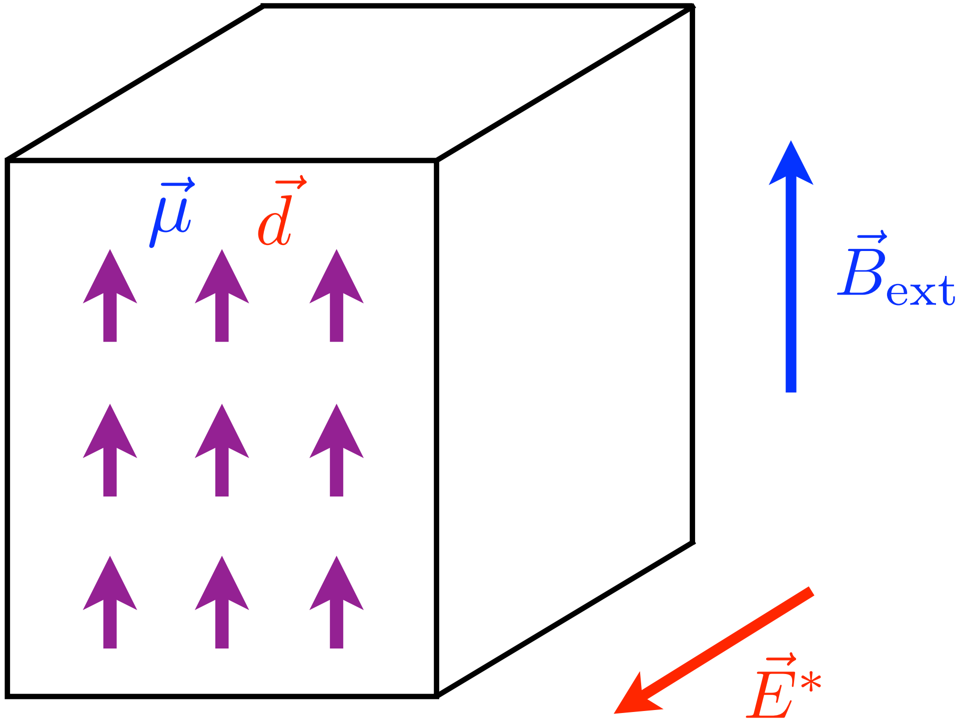
axion gives all nucleons an oscillating EDM independent of f_a,
non-derivative operator

Axions with NMR



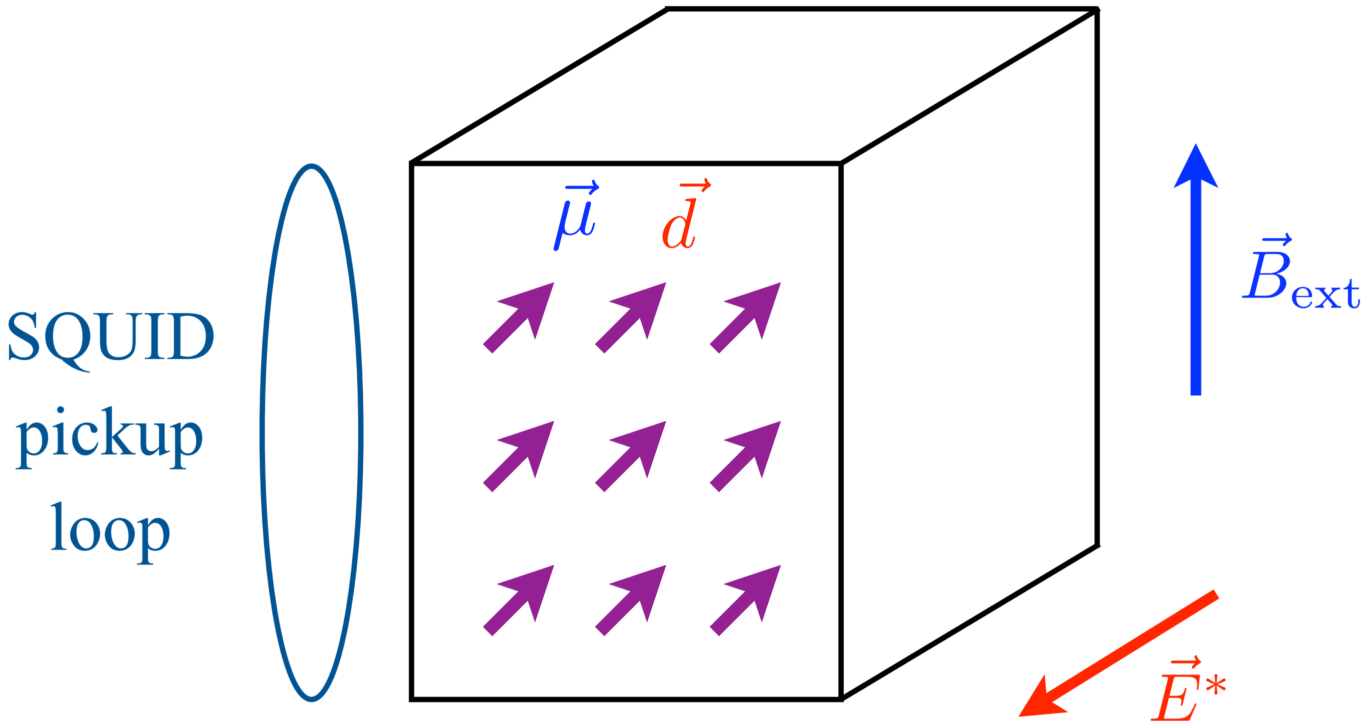
NMR resonant spin flip when Larmor frequency $2\mu B_{\text{ext}} = \omega$

Cosmic Axion Spin Precession Experiment (CASPEr)



Larmor frequency = axion mass ➔ resonant enhancement

Cosmic Axion Spin Precession Experiment (CASPEr)

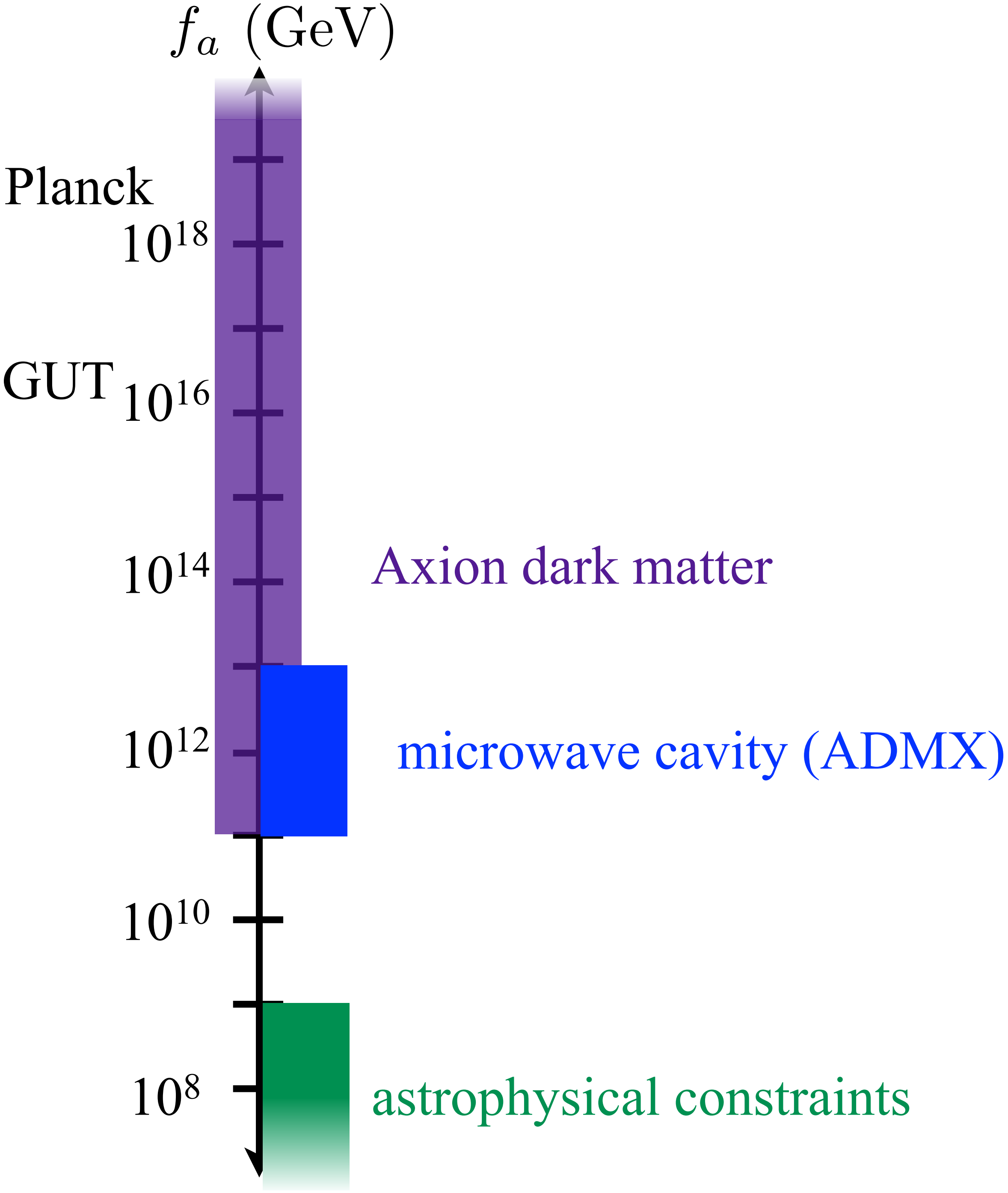


Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

ferroelectric (e.g. $PbTiO_3$), NMR pulse sequences (spin-echo,…),…
quantum spin projection (magnetization) noise small enough

CASPEr Discovery Potential



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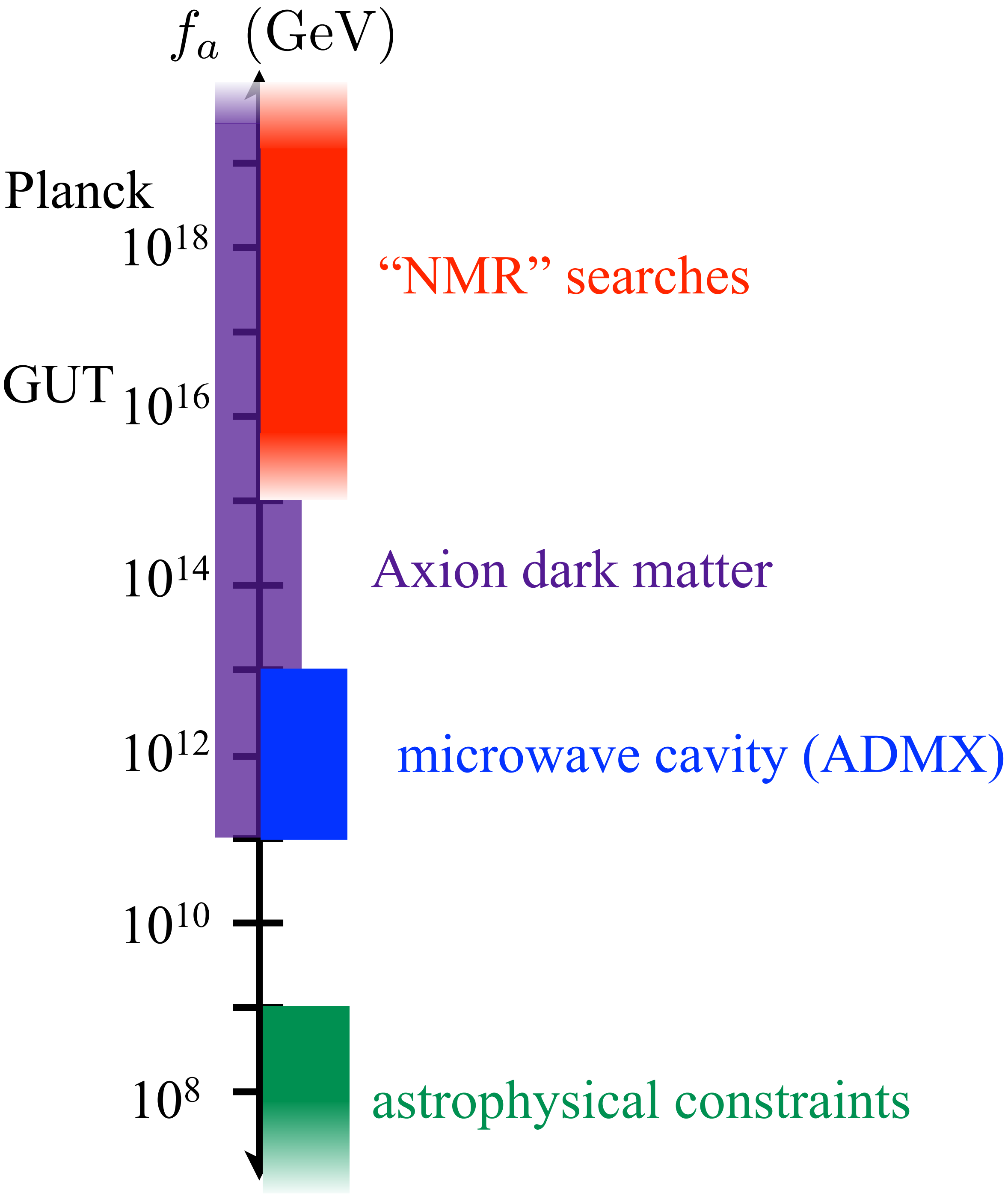

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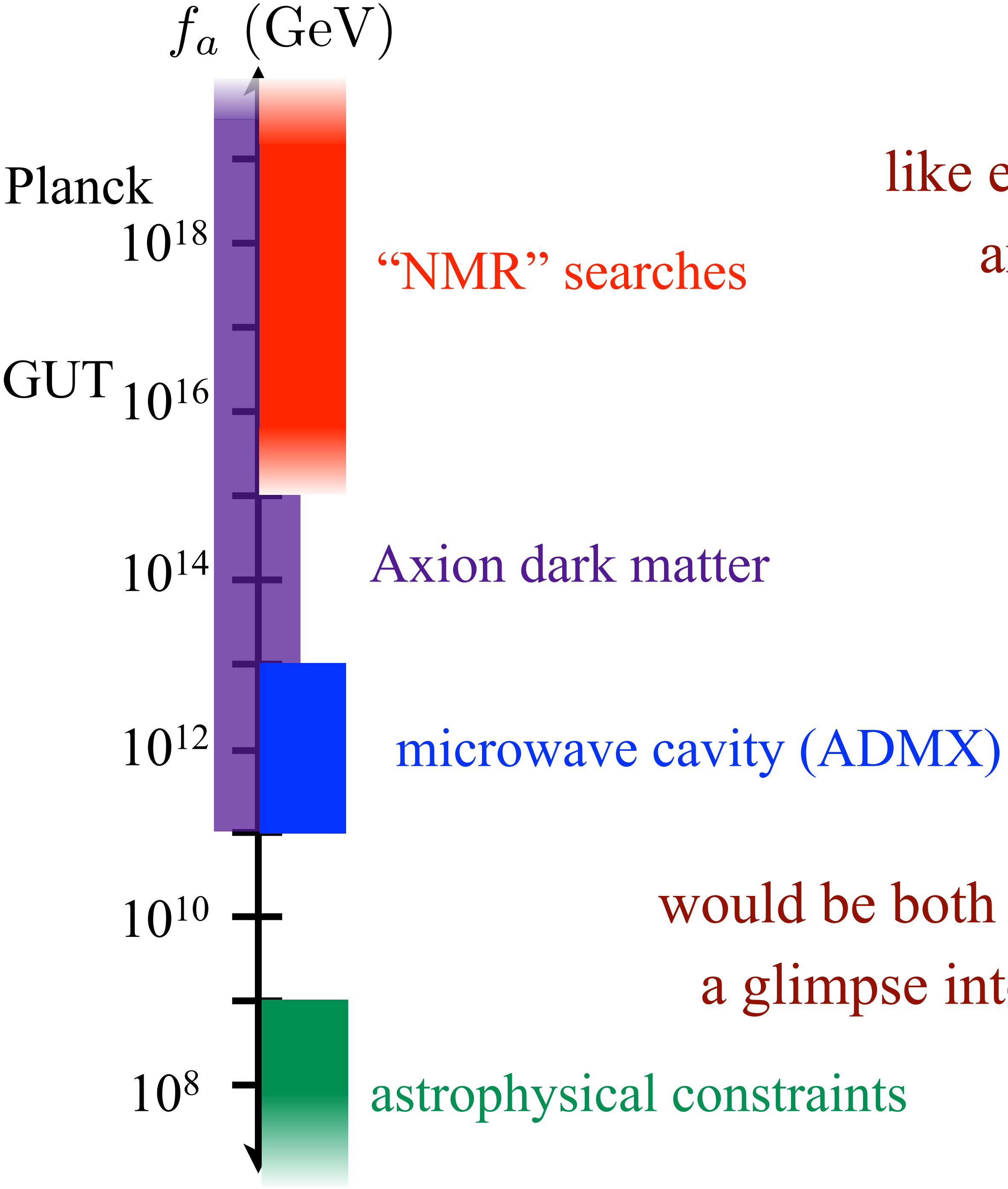

technological challenges,
like early stages of WIMP detection,
axions deserve similar effort

Trahms group has results
Budker group starting expt.

no other way to search
for axions at high f_a

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

Hidden Sector Detection with EM Resonators

(to appear)

with

Kent Irwin
Saptarshi Chaudhuri
Jeremy Mardon
Surjeet Rajendran
Yue Zhao

Hidden Photon Motivation

Many theories/vacua have additional, decoupled sectors, new U(1)’s

Natural coupling (dim. 4 operator): $\mathcal{L} \supset \varepsilon F F'$

Hidden Photon Motivation

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mass basis:

$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - eJ^\mu_{EM}\left(A_\mu + \varepsilon\, A'_\mu\right)$$

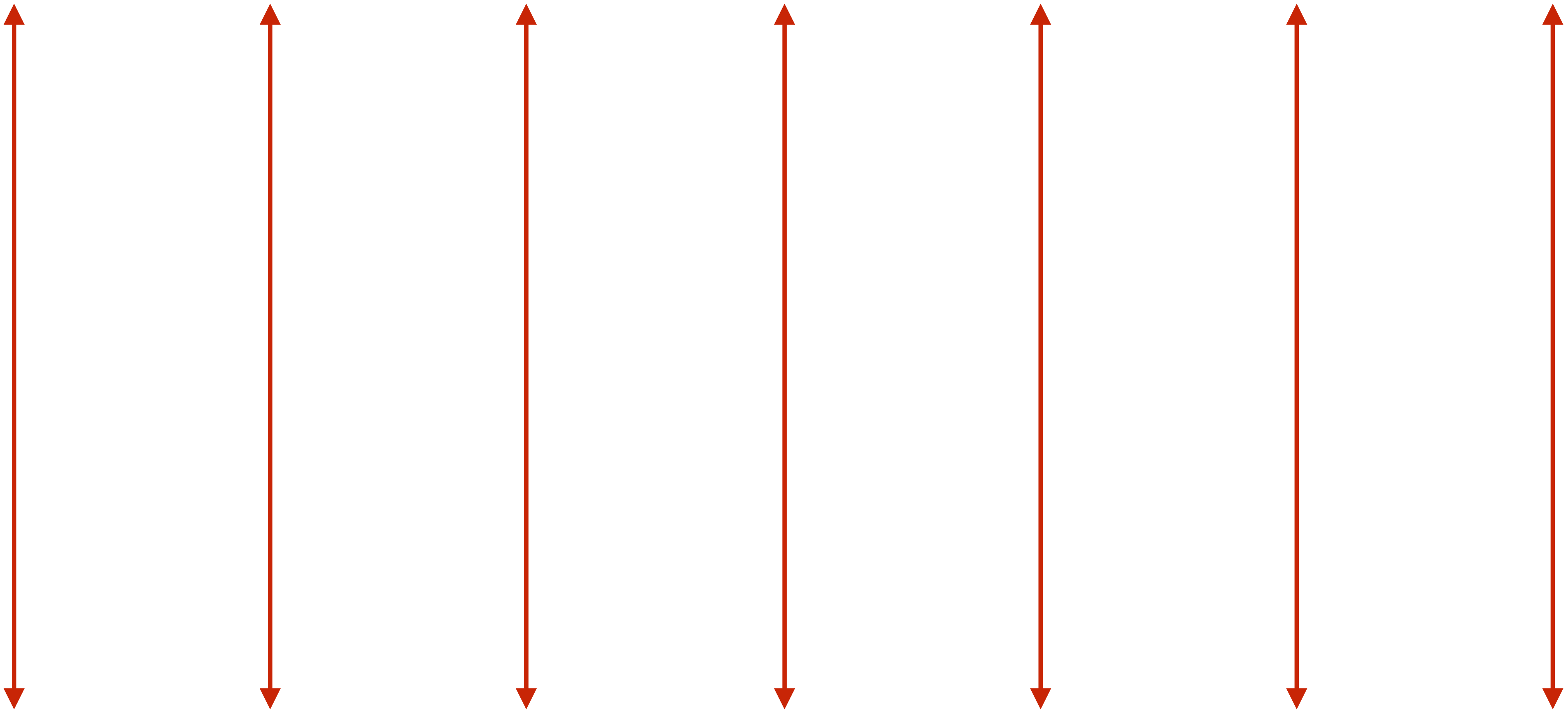
photon with small mass and suppressed couplings to all charged particles

longitudinal mode gives new phenomena

Will be misalignment produced (like axion) ➜ natural dark matter

inflationary fluctuations $H_I \sim 10^{14}$ GeV ➜ $m_{\gamma'} \sim 10^{-6}\text{eV} \sim 100$ MHz

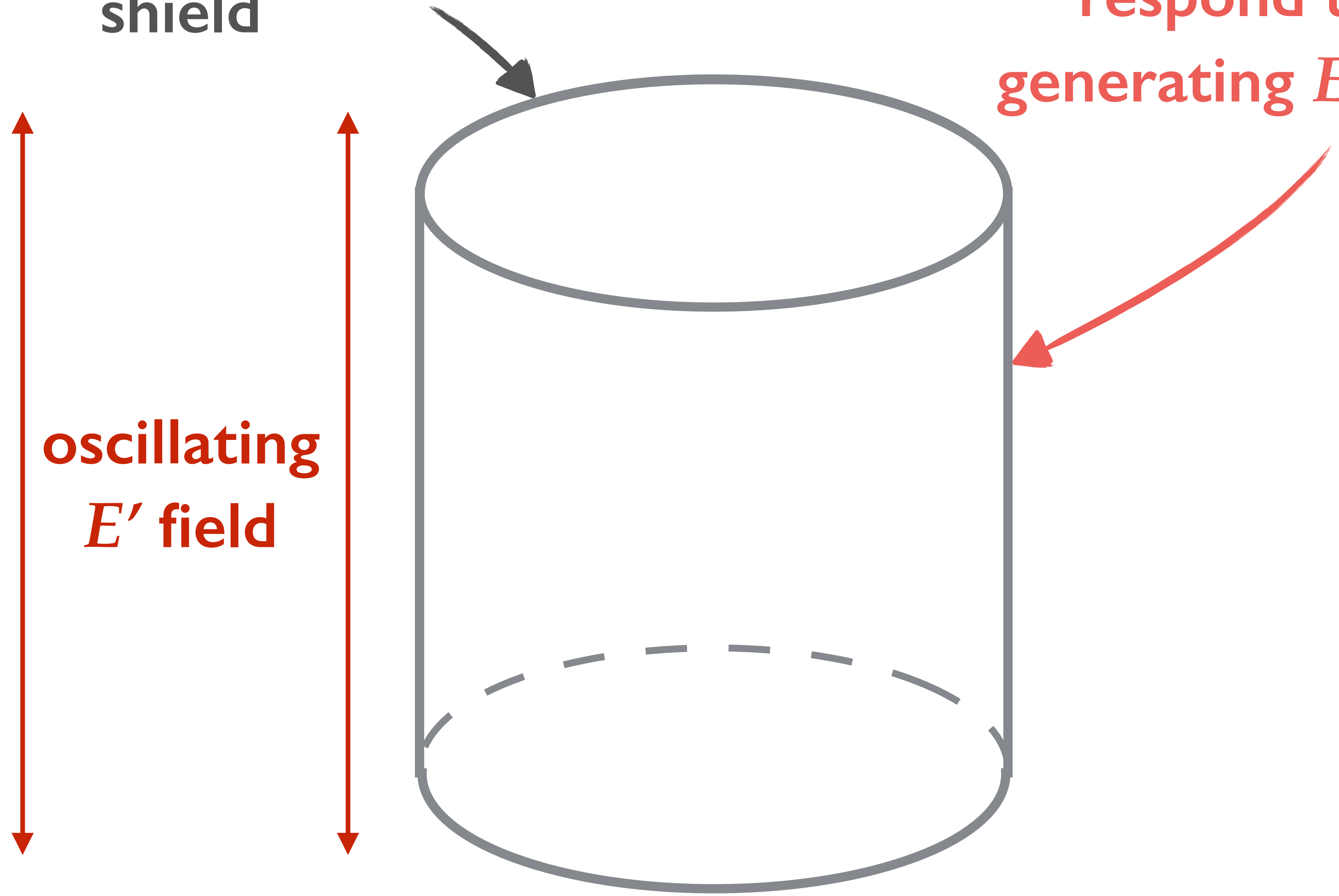
Hidden Photon Dark Matter



oscillating E' field (dark matter)

Lorentz breaking

Experimental Setup

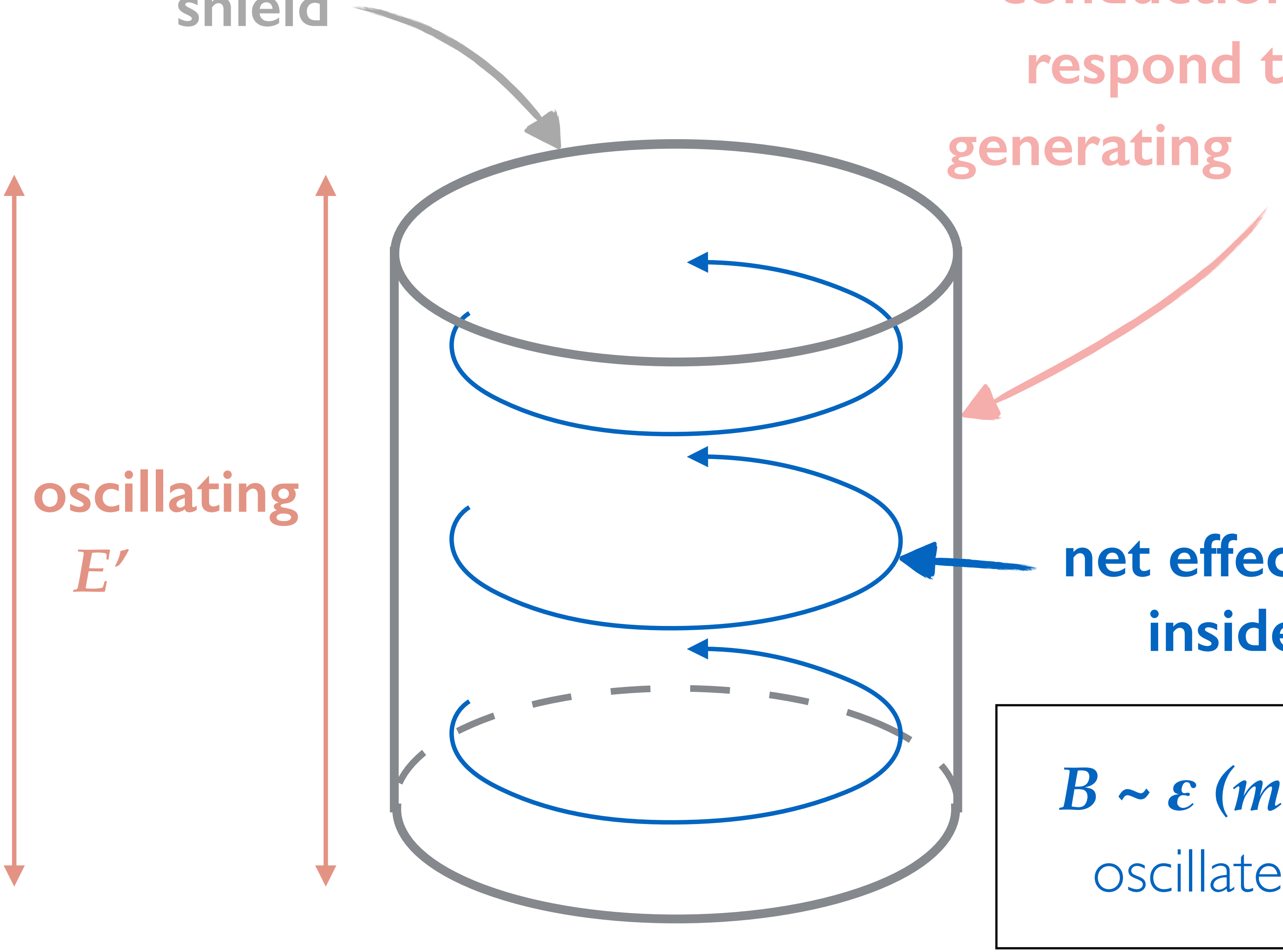


superconducting shield

conduction electrons respond to E' field, generating E and B fields

oscillating E' field

Signal Inside Shielding



shield

conduction electrons respond to generating

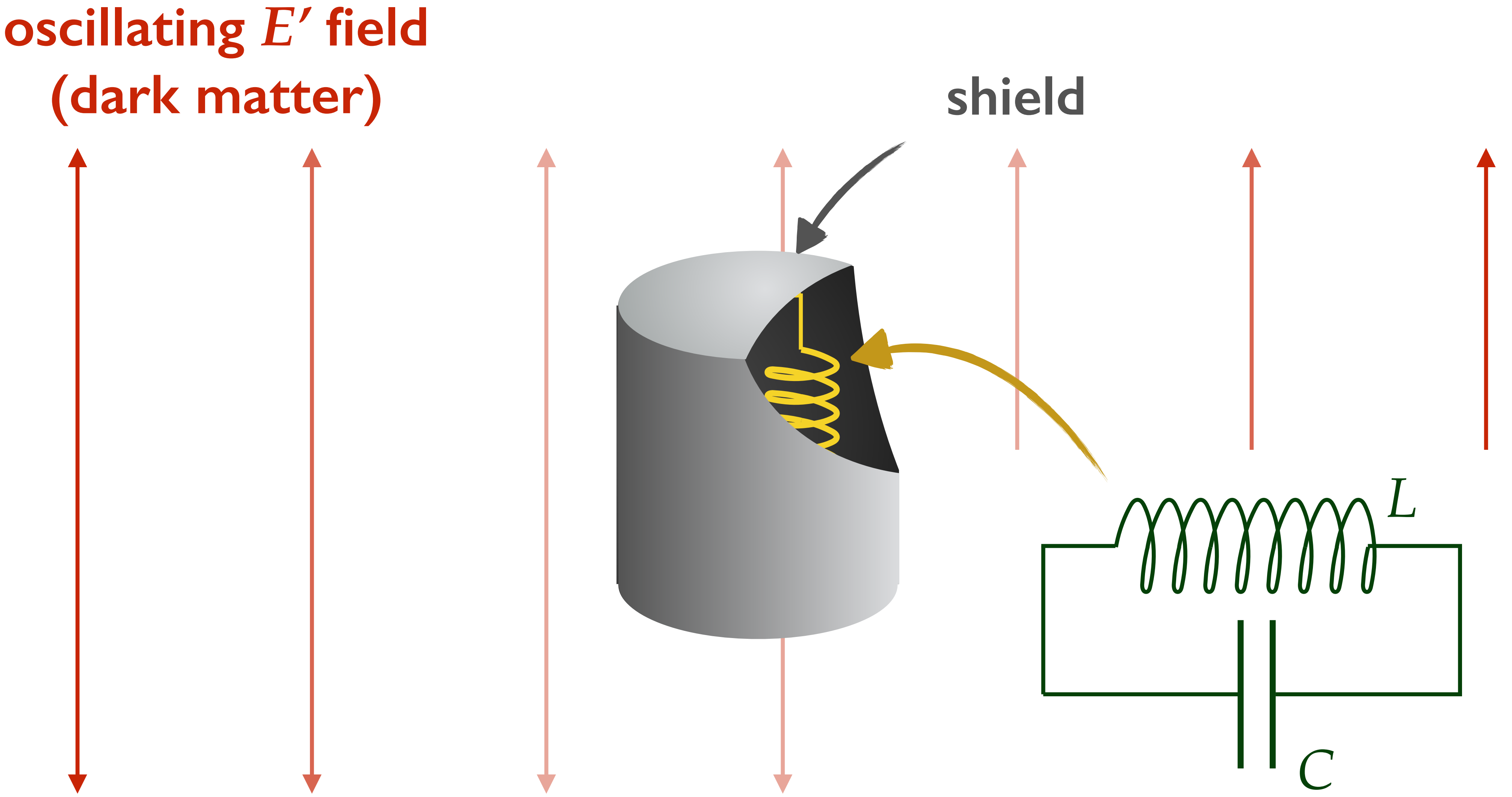
oscillating E'

net effect is a B field inside the box

$$B \sim \varepsilon\,(m_{\gamma'} R) \times 10^{-5}\ \mathrm{T}$$

oscillates at $\omega = m_{\gamma'}$

Experimental Setup



oscillating E' field
(dark matter)

shield

Tunable resonant LC circuit
(a radio)

Reach $\varepsilon \sim 10^{-17}$

Gravitational Wave Detection with Atom Interferometry

with

Savas Dimopoulos
Jason Hogan
Mark Kasevich
Surjeet Rajendran

PRL **110** (2013) arXiv: 1206.0818
PLB **678** (2009) arXiv: 0712.1250
PRD **78** (2008) arXiv: 0806.2125

Gravitational Wave Motivation

Gravitational waves open a new window to the universe

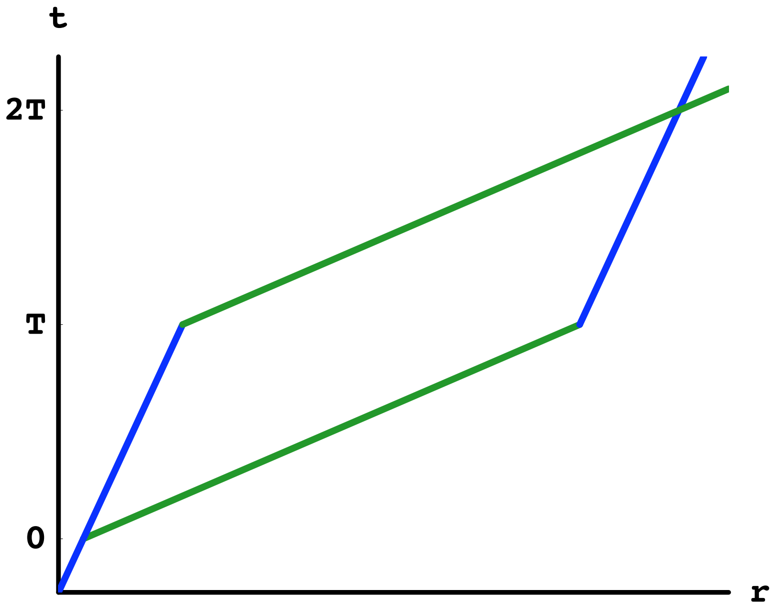
Sourced by mass, not charge
- unique astrophysical information (WD’s, NS’s, BH’s)
- probe near horizon geometry of BH

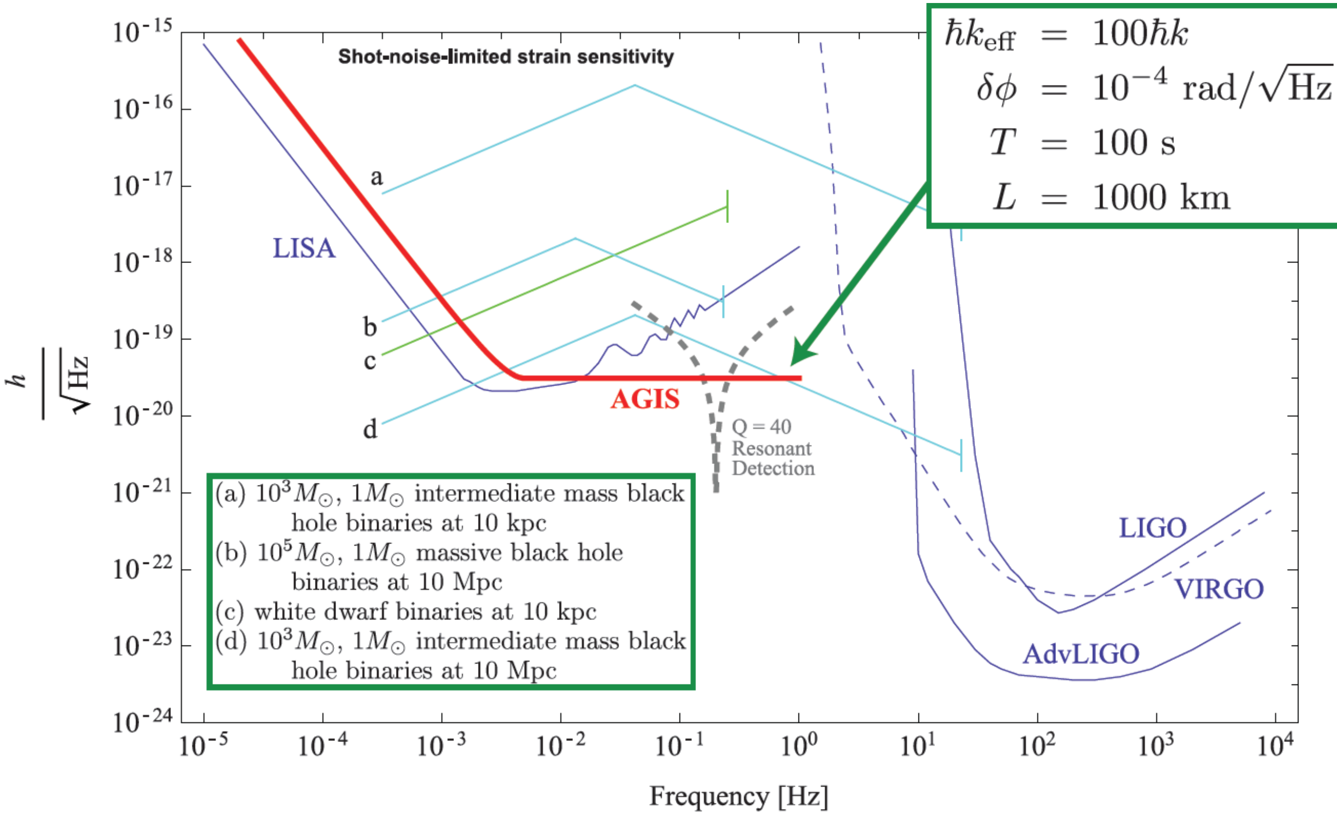
Directly observe universe before last scattering
- gravitational waves from inflation

Every new band opened has revealed unexpected discoveries

Atomic Gravitational Wave Interferometric Sensor (AGIS)

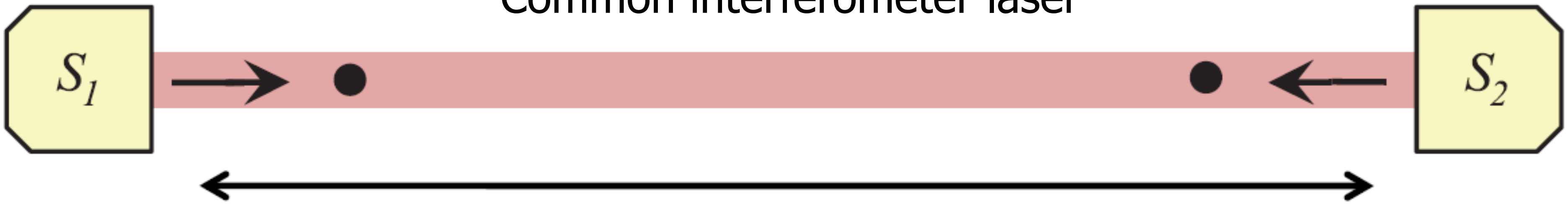
Atom in accelerometer sequence, GW modulates interferometer phase





$$\begin{aligned} \hbar k_{\mathrm{eff}} &= 100\hbar k \\ \delta\phi &= 10^{-4}\ \mathrm{rad}/\sqrt{\mathrm{Hz}} \\ T &= 100\ \mathrm{s} \\ L &= 1000\ \mathrm{km} \end{aligned}$$

Common interferometer laser



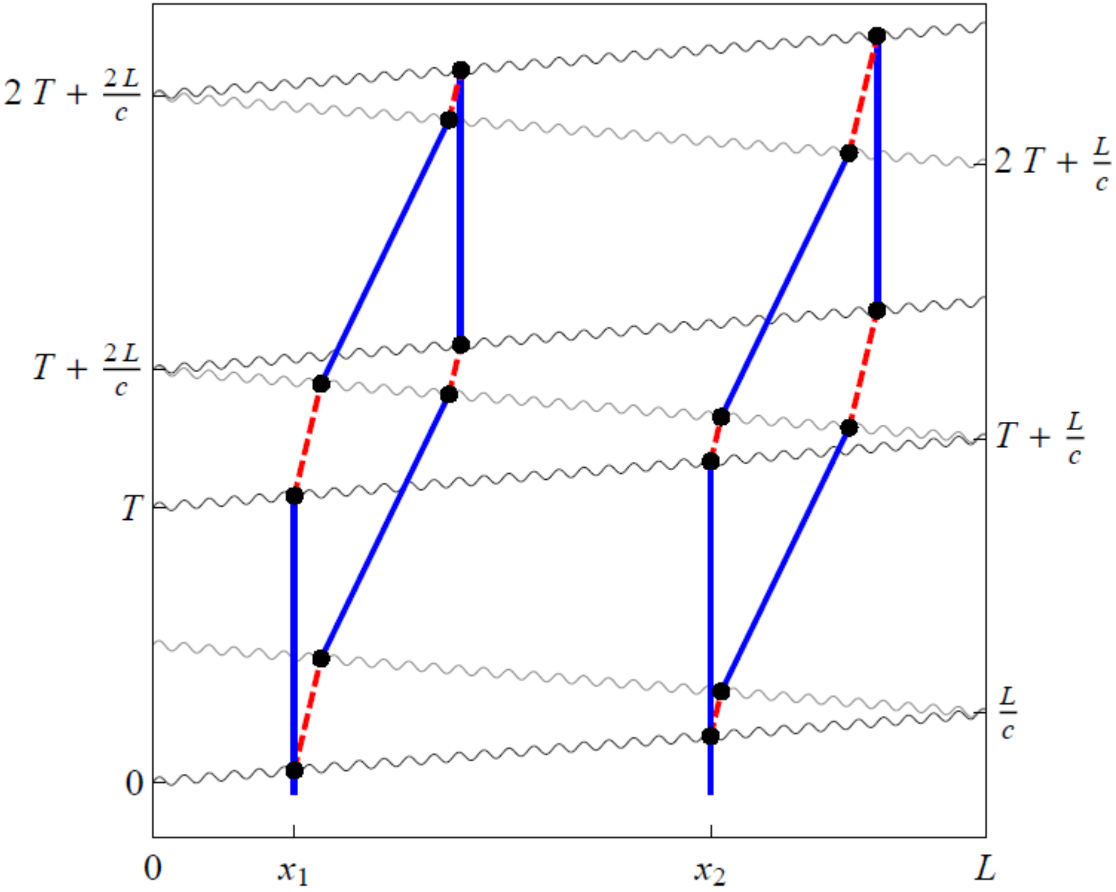
L ~ 100 - 1000 km

Laser Phase Noise

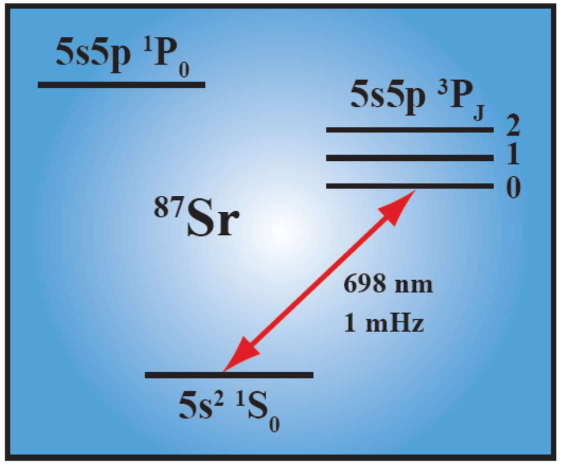
cancel laser noise using multiple baselines

Laser Phase Noise Insensitive Detector

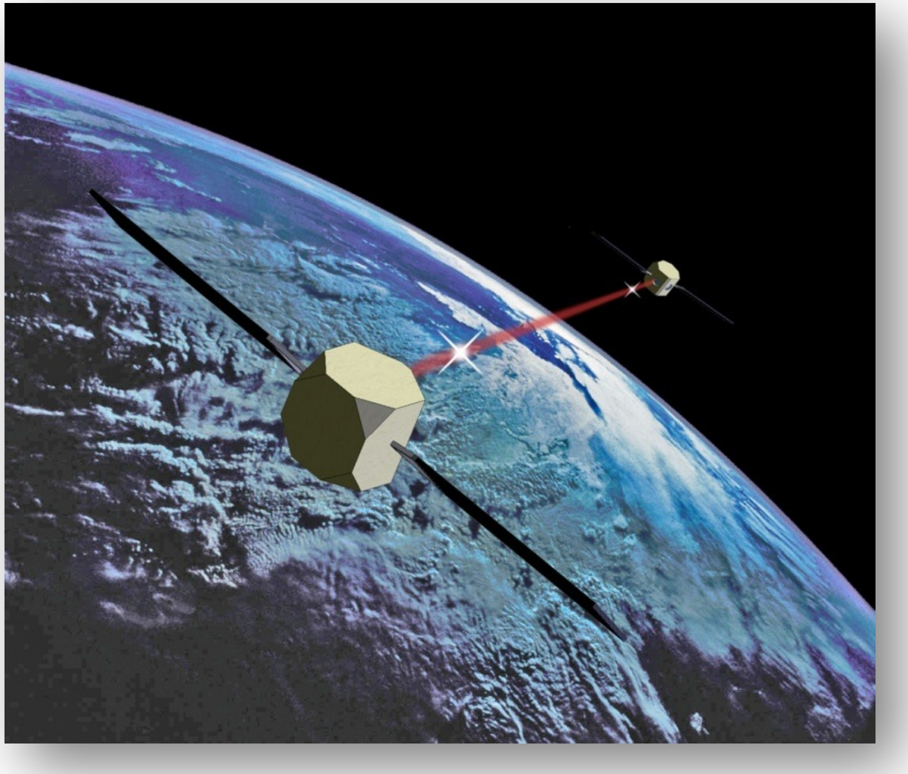
atoms act as clocks, measure light travel time



Graham, et al., PRL **110** (2013)



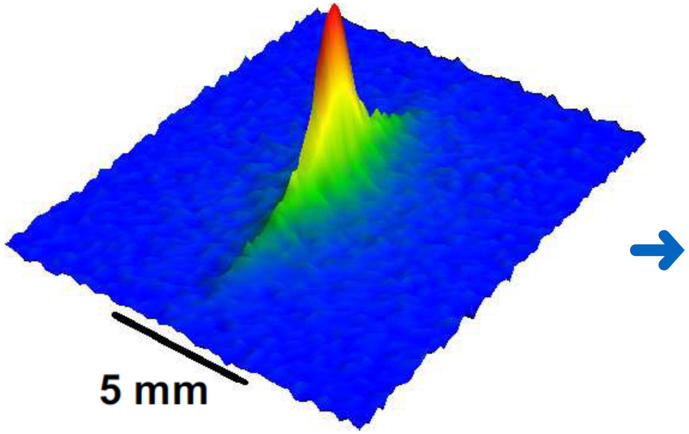
Clock transition in candidate atom ^{87}Sr



Removes laser noise, allows single baseline detection

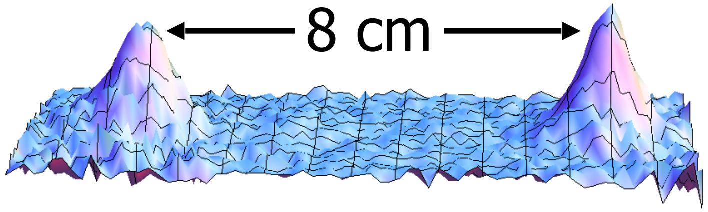
Recent Experimental Results

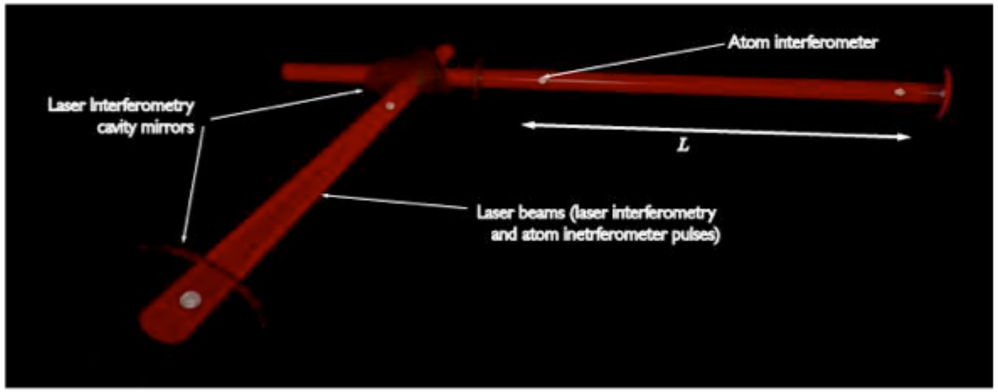
Stanford Test Facility



➜ 50 pK

Macroscopic splitting of atomic wavefunction:



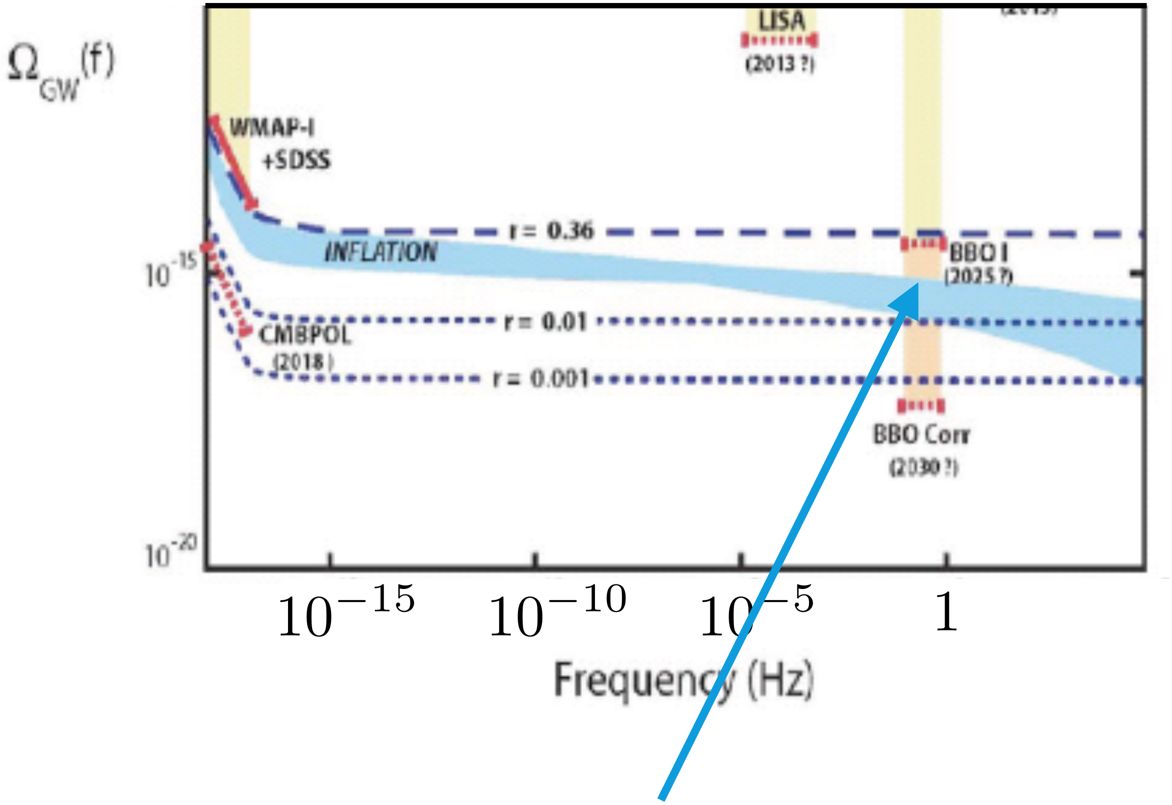


MIGA; ~1 km baseline (P. Bouyer, France)

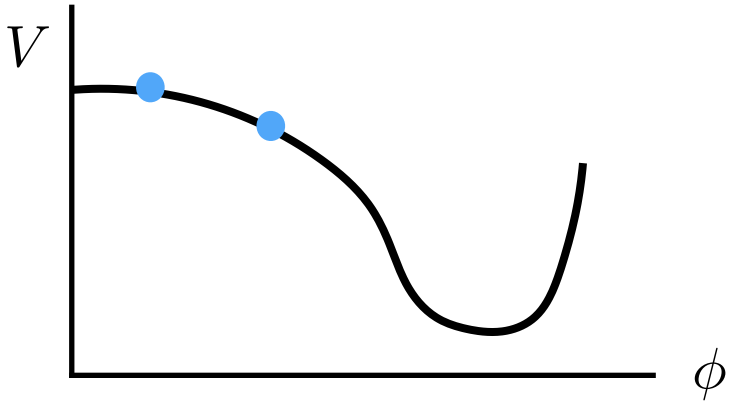
Resonant Detection and Inflation

(Preliminary!)

Atomic detector can run in resonant mode,
may be able to reach highest level of GW’s from inflation



detect at ~1 Hz



observe many e-folds in to inflation

probe inflation potential

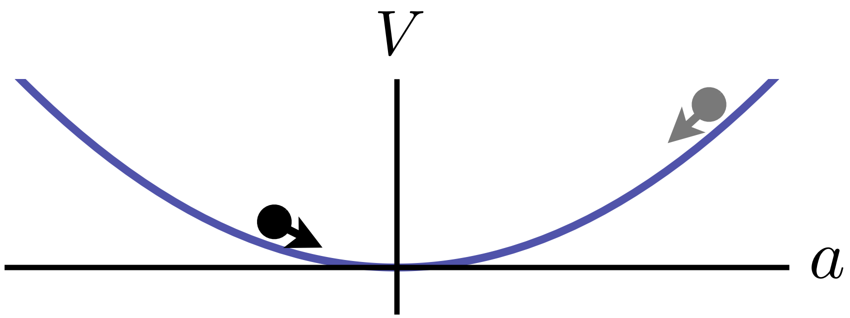
Gravitational waves will be major part of future of astronomy, astrophysics and cosmology

Backup slides

Cosmic Axions

misalignment production:

in early universe axion is a constant field, mass turns on at T ~ Λ_{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 $\rho = \rho_{\mathrm{DM}}$

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

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

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

Axions and the CMB

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

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, constraints most relevant for QCD axion, weak constraint on ALPs probed by CASPEr

but this requires knowing physics all the way up to GUT scale $\sim 10^{16}\ \mathrm{GeV}$

constrains **one** cosmological history, **many** others possible
(including for QCD axion)

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)

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

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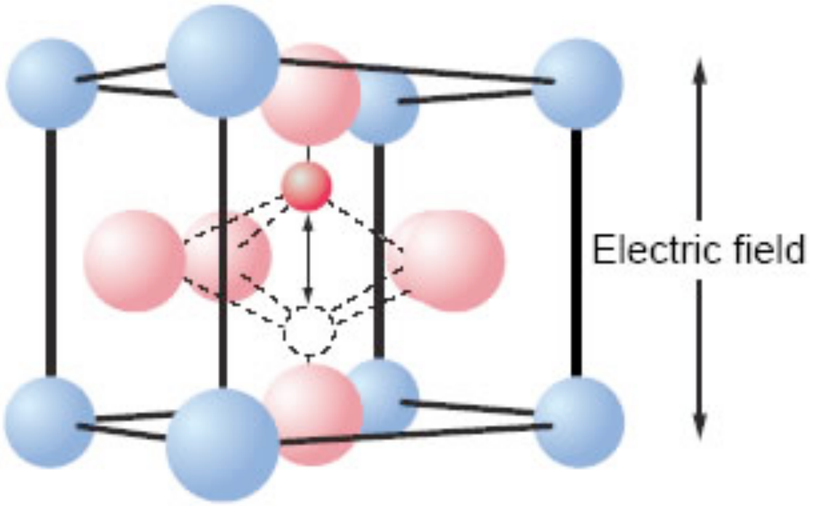
Ferroelectric

below critical temperature some materials have ferroelectric phase transition



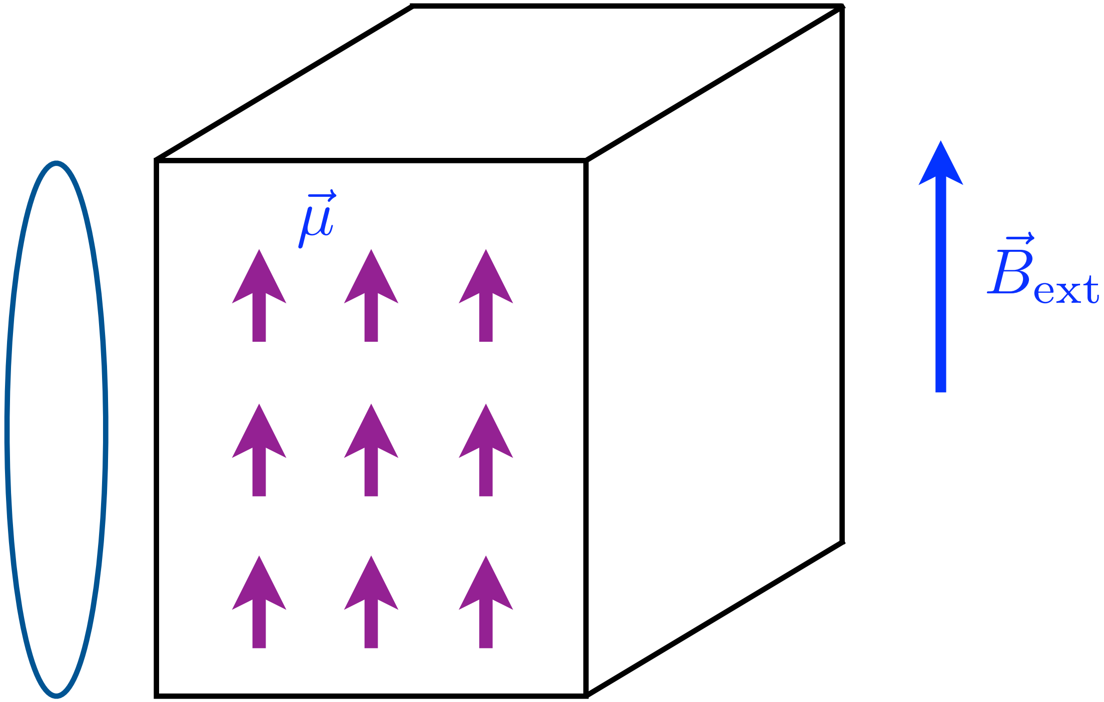
ferroelectrics (e.g. $PbTiO_3$) have large effective internal electric fields:

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

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

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

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

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

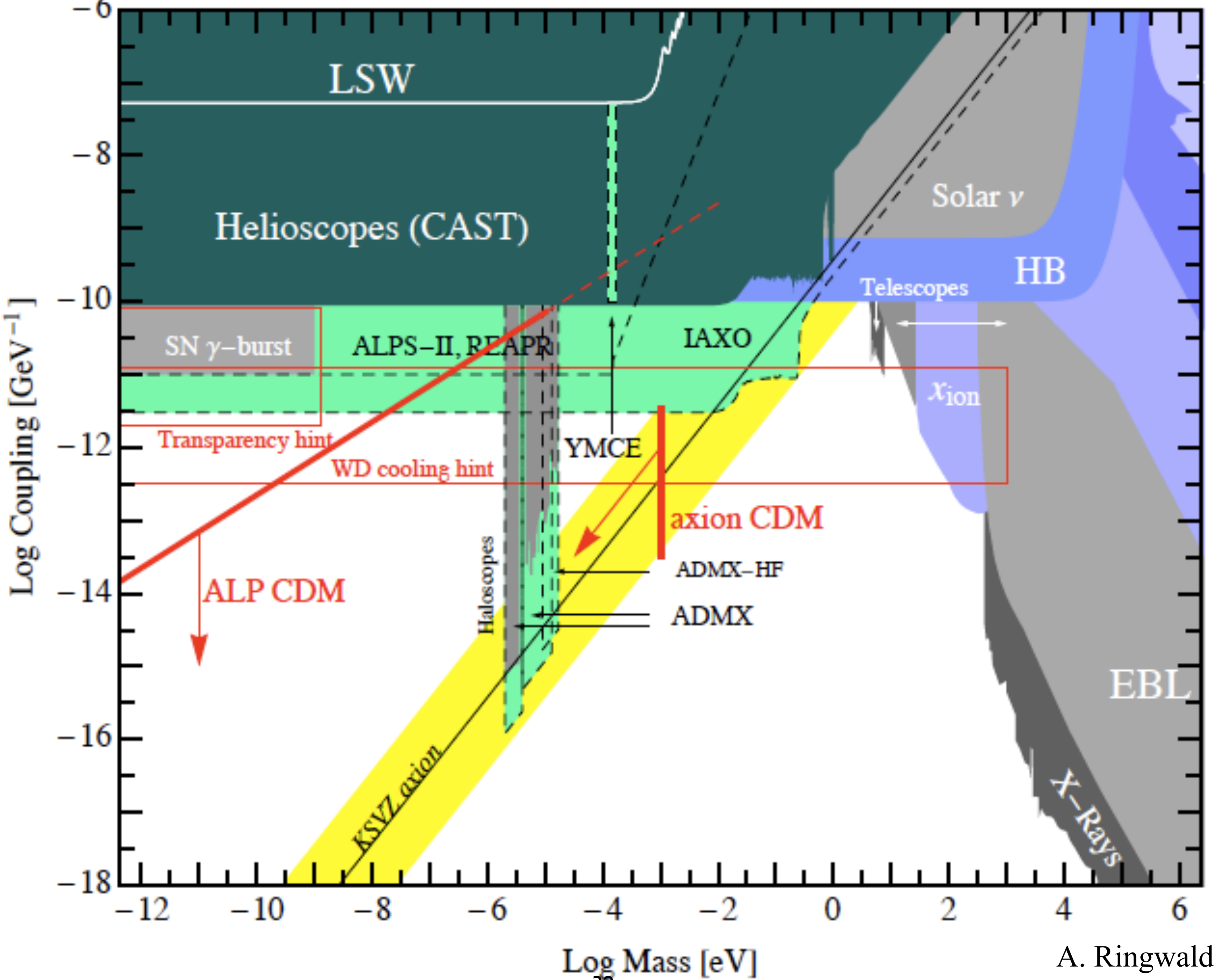
(or multiple loops over smaller sample)

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

M.V. Romalis

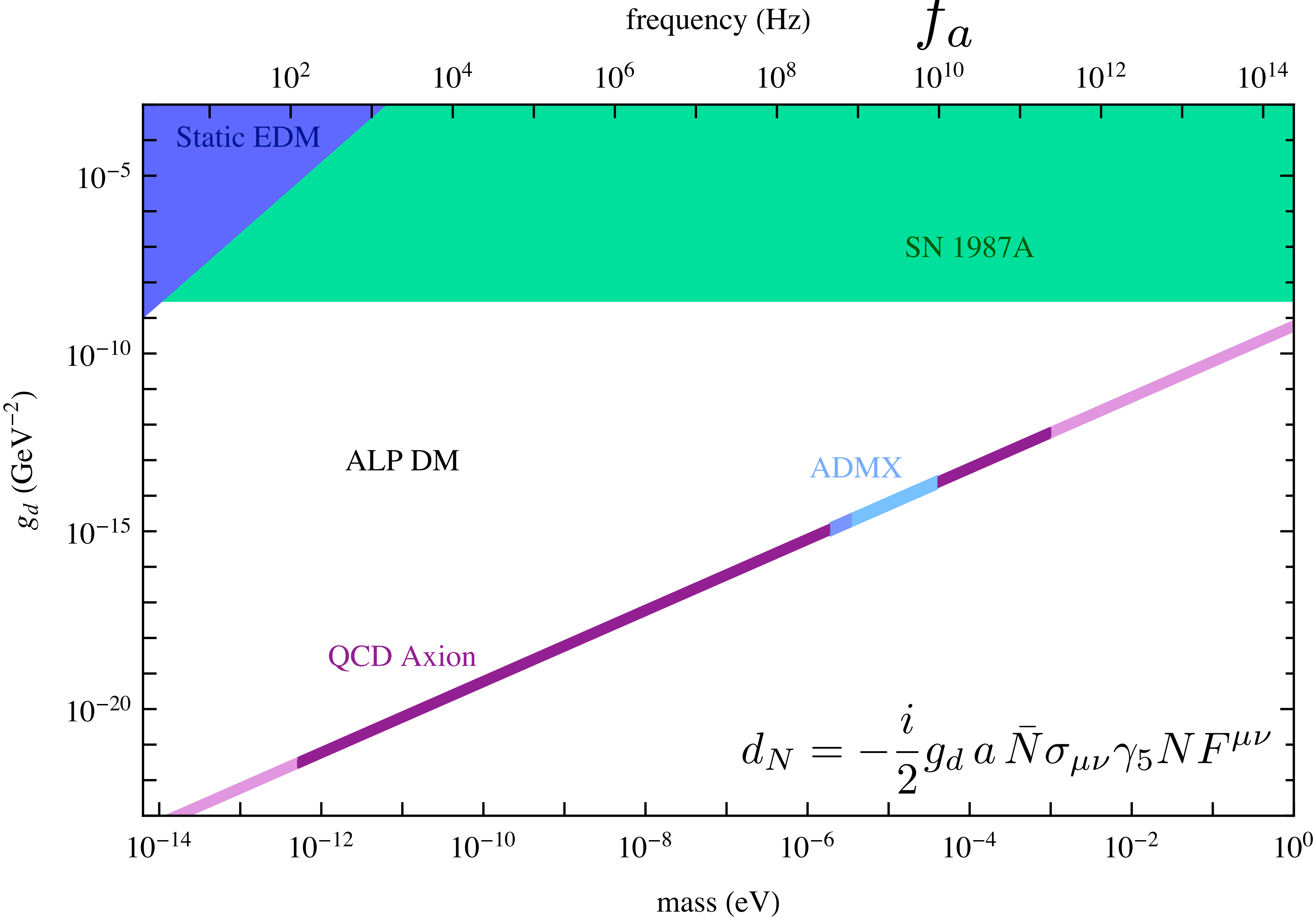
many options for increasing sensitivity

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



A. Ringwald (2012)

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



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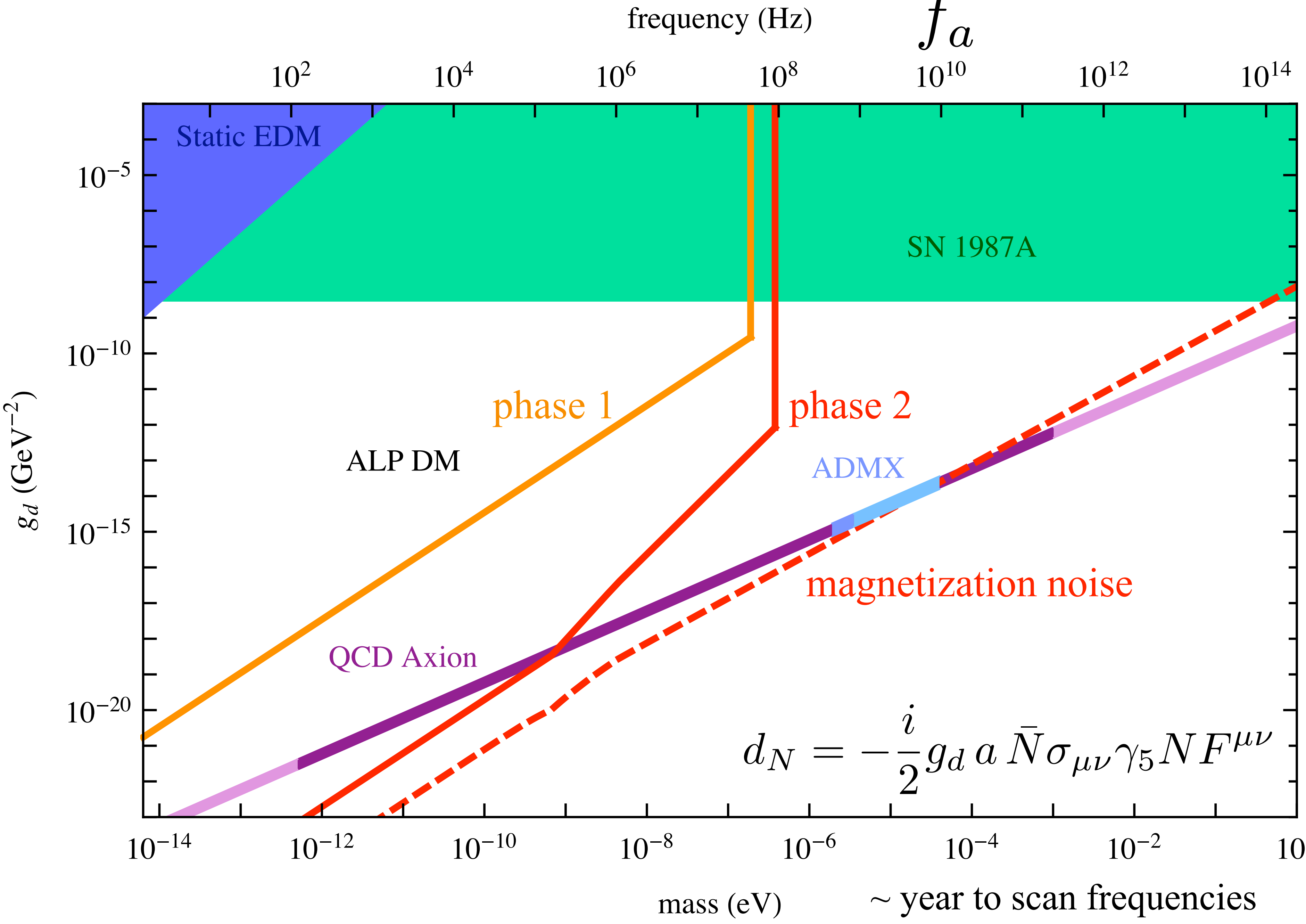

$$d_N = -\frac{i}{2} g_d\, a\, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

~ year to scan frequencies

Verify signal with spatial coherence of axion field

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