New Methods for Discovering Light Fields

Peter Graham
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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  
   \( \text{spin } 0 \)

2. Hidden Sector Detection with EM Resonators  
   \( \text{spin } 1 \)

3. Gravitational Wave Detection with Atoms  
   \( \text{spin } 2 \)
1. Axion Detection with NMR  
2. Hidden Sector Detection with EM Resonators  
3. Gravitational Wave Detection with Atoms

All high phase space density 
Better thought of as fields
Axion Detection with NMR

with

Dmitry Budker
Micah Ledbetter
Surjeet Rajendran
Alex Sushkov

Dark Matter

Dark matter is proof of physics beyond Standard Model

heavy particle vs. light field

(WIMPs) (axions)
Dark Matter

Dark matter is proof of physics beyond Standard Model

heavy particle vs. light field
(WIMPs) (axions)

Search for single, hard particle scattering
Dark Matter

Dark matter is proof of physics beyond Standard Model

heavy particle vs. light field
(WIMPs)    (axions)

Search for single, hard particle scattering    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:

\[ a(t) \sim a_0 \cos (m_a t) \]

Axion is a natural dark matter candidate

Constraints and Searches

\[ \mathcal{L} \supset \frac{a}{f_a} F \tilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B} \]

astrophysical and laboratory bounds
Constraints and Searches

Axion dark matter

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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

Axion dark matter

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

Derivative Operator

Size of cavity increases with $f_a$

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

Microwave cavity (ADMX)

Astrophysical and laboratory bounds
Constraints and Searches

Axion dark matter

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Derivative Operator

size of cavity increases with $f_a$

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

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

microwave cavity (ADMX)

astrophysical and laboratory bounds

S. Thomas
A Different Operator For Axion Detection

How to detect high $f_a$ axions?

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

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

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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 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 \rightarrow \text{resonant enhancement}
Cosmic Axion Spin Precession Experiment (CASPER)

Larmor frequency = axion mass $\rightarrow$ 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

\[ f_a \text{ (GeV)} \]

Planck

GUT

Axion dark matter

microwave cavity (ADMX)

astrophysical constraints
CASPEr Discovery Potential

\[ f_a \ (\text{GeV}) \]

- Planck \(10^{18}\)
- GUT \(10^{16}\)
- Axion dark matter \(10^{14}\)
- Microwave cavity (ADMX) \(10^{12}\)
- Astrophysical constraints \(10^{10}\)

“NMR” searches
 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

**CASPEr Discovery Potential**

- **Planck**
  - $10^{18}$
  - “NMR” searches
- **GUT**
  - $10^{16}$
  - Axion dark matter
  - $10^{14}$
  - microwave cavity (ADMX)
  - $10^{12}$
  - $10^{10}$
  - $10^{8}$
  - astrophysical constraints
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): $\mathcal{L} \supset \varepsilon FF'$
Hidden Photon Motivation

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

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

mass basis:

\[
\mathcal{L} = -\frac{1}{4} \left( F_{\mu\nu} F^{\mu\nu} + F'_{\mu\nu} F''^{\mu\nu} \right) + \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu - e J_{EM}^\mu \left( A_\mu + \varepsilon A'_\mu \right)
\]

photon with small mass and suppressed couplings to all charged particles

longitudinal mode gives new phenomena

Will be misalignment produced (like axion) \( \Rightarrow \) natural dark matter

inflationary fluctuations \( H_I \sim 10^{14} \text{ GeV} \) \( \Rightarrow \) \( m_{\gamma'} \sim 10^{-6} \text{ eV} \sim 100 \text{ MHz} \)
Hidden Photon Dark Matter

oscillating $E'$ field (dark matter)

Lorentz breaking
Experimental Setup

- Superconducting shield
- Oscillating $E'$ field
- Conduction electrons respond to $E'$ field, generating $E$ and $B$ fields
Signal Inside Shielding

Conduction electrons respond to generating oscillating $E'$. The net effect is a $B$ field inside the box:

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

This field oscillates at $\omega = m_{\gamma'}$. 

$E'$ oscillates, and the shield is shown.
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

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

\[ h_{\text{eff}} = 100h \]
\[ \delta \phi = 10^{-4} \text{ rad}/\sqrt{\text{Hz}} \]
\[ T = 100 \text{ s} \]
\[ L = 1000 \text{ km} \]

Common interferometer laser

\[ L \sim 100 - 1000 \text{ km} \]
Laser Phase Noise

cancel laser noise using multiple baselines
Laser Phase Noise Insensitive Detector

Atoms act as clocks, measure light travel time.


Removes laser noise, allows single baseline detection.
Recent Experimental Results

Stanford Test Facility

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 $\sim 1$ Hz

observe many e-folds into 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 $T \sim \Lambda_{\text{QCD}}$ then axion oscillates

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


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 $\theta_i$ over flat in $f_a$

all $f_a$ in DM range (all axion masses $\lesssim \text{meV}$) 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 \( \sim 10^{16} \) GeV

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

e.g. thermal monopole density, Fischler & Preskill (1983)
high temperature mass,
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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QCD axion offers unique probe of high energy cosmology, an era difficult even for gravitational wave detectors
Ferroelectric

below critical temperature some materials have ferroelectric phase transition

ferroelectrics (e.g. PbTiO₃) have large effective internal electric fields:

\[ E^* = 3 \times 10^8 \frac{V}{cm} \]

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

may allow enhancement in E* by \( \sim \times \) few
a material sample has magnetization noise
noise arises from quantum spin projection

every spin necessarily has random quantum projection onto transverse direction

\[ M_n(\omega) \sim \frac{\mu N}{r^3} \sqrt{n r^3} \langle S(\omega) \rangle \sim \mu N \sqrt{\frac{n}{V}} \langle S(\omega) \rangle \]

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

Cosmic Axion Spin Precession Experiment (CASPER)

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

<table>
<thead>
<tr>
<th></th>
<th>( n )</th>
<th>( E^* )</th>
<th>( p )</th>
<th>( T_2 )</th>
<th>Max.  ( B_{ext} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>( 10^{22} \text{ cm}^3 )</td>
<td>( 3 \times 10^8 \text{ V cm} )</td>
<td>( 10^{-3} )</td>
<td>1 ms</td>
<td>10 T</td>
</tr>
<tr>
<td>Phase 2</td>
<td>( 3 \times 10^{19} \text{ cm}^3 )</td>
<td>( 3 \times 10^9 \text{ V cm} )</td>
<td>( 1 )</td>
<td>1 s</td>
<td>20 T</td>
</tr>
</tbody>
</table>

\begin{align*}
\text{example material: } & ^{207}\text{Pb} \implies \mu = 0.6\mu_N \quad \varepsilon_s \approx 10^{-2} \\
\text{take sample size: } & L \sim 10 \text{ cm} \quad \Rightarrow \text{we take SQUID magnetometer: } 10^{-16} \frac{T}{\sqrt{\text{Hz}}} \\
\text{(or multiple loops over smaller sample)} & \text{but atomic magnetometers } \sim 10^{-17} \frac{T}{\sqrt{\text{Hz}}} \\
\text{many options for increasing sensitivity} & \text{M.V. Romalis}
\end{align*}
Axion Limits on $\alpha f_a G \bar{G}$

$$d_N = -\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$
Axion Limits on $\frac{a}{f_a} G \tilde{G}$

$\begin{aligned}
g_{d} &\approx 10^{-10} \\
\text{mass (eV)} &\approx 10^{-14} - 10^{0}
\end{aligned}$

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