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,
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
Axis set by local velocity of axion or applied electric fields
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

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
Dark Matter

Dark matter is proof of physics beyond standard model

heavy particle vs. light scalar field

(WIMPs) (axions)
Dark Matter

Dark matter is proof of physics beyond standard model

heavy particle vs. light scalar field

(WIMPs)  (axions)

Search for single particle scattering
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
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

$$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma_5 \psi$$
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 $T \sim \Lambda_{QCD}$

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


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 $f_a$

Light Goldstone boson

Gauge Fields

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

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

Current Searches

QCD axion (CASPER)

Fermions

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

Axion-like Particles (CASPER)

Monday, 28 April 14
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 → 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.
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 → 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.
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 → 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

\[ H_{\text{inf}} \sim 10^{14} \text{ GeV} \]

for QCD axion, constrains one cosmological history.

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

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.

\[ V \]
\[ \alpha \]

- 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
Need a \textbf{high temperature, transient mass, sometime before QCD phase transition.}

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

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.
QCD Axion and BICEP

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

E.g. thermal monopole density, high temperature mass, and many others. 
Fischler & Preskill (1983)

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

\( f_a \) (GeV)

\[ 10^8 \]
\[ 10^{10} \]
\[ 10^{12} \]
\[ 10^{14} \]
\[ 10^{16} \]
\[ 10^{18} \]
Constraints and Searches

$f_a$ (GeV)

Axion dark matter
Axion dark matter affects SN1987A, White Dwarfs, other astrophysical objects

Collider & laser experiments, ALPS, CAST

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

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

Axion dark matter

\[ \gamma \rightarrow \text{Decay} \]

laser experiments:

\[ \frac{1}{f_a^4} \]
Constraints and Searches

Axion dark matter

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 $f_a$

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

axion emission affects SN1987A, White Dwarfs, other astrophysical objects

collider & laser experiments, ALPS, CAST
Constraints and Searches

Axion dark matter

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 \( f_a \)

signal \( \propto \frac{1}{f_a^3} \)


S. Thomas

microwave cavity (ADMX)

laser experiments:

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

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 \[ d \sim 3 \times 10^{-16} \frac{a}{f_a} e \text{ cm} \]
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 $d \sim 3 \times 10^{-16} \frac{a}{f_a} e \text{ cm}$

$a(t) \sim a_0 \cos (m_a t)$ 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 $\rho_{DM} \sim m_a^2 a^2 \sim (200 \text{ MeV})^4 \left( \frac{a}{f_a} \right)^2 \sim 0.3 \frac{\text{GeV}}{\text{cm}^3}$

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

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

applied E field causes precession of nucleus

SQUID measures resulting transverse magnetization

$Larmor$ frequency $= axion$ mass $\Longrightarrow$ resonant enhancement

resonance $\Rightarrow$ scan over axion masses by changing $B_{ext}$
Transverse Magnetization Signal

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

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

Signal scales with large density: \( n = 10^{22} \frac{1}{\text{cm}^3} \)

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

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

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 \( ^{207}\text{Pb} \implies \mu = 0.6\mu_N \quad \varepsilon_S \approx 10^{-2} \quad E^* \approx 3 \times 10^8 \frac{\text{V}}{\text{cm}} \)

nuclear magnetic moment

Electric field
Transverse Magnetization Signal

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

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

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

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

Technology \( p \approx 1 \quad T_2 \approx 1 \text{ s} \)

polarization fraction
Transverse Magnetization Signal

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

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

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

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

Technology \( p \approx 1 \quad T_2 \approx 1 \text{ s} \)

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

axion induced dipole moment
Transverse Magnetization Signal

\[ M(t) \approx n \mu \epsilon_S d n E^* p \frac{\sin ((2\mu B_{ext} - m_a) t)}{2\mu B_{ext} - m_a} \sin (2\mu B_{ext} t) \]

Signal scales with large density: \( n = 10^{22} \frac{1}{\text{cm}^3} \)

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

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

Technology \( p \approx 1 \quad T_2 \approx 1 \text{ s} \)

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

A material sample has magnetization noise arising 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)

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

<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} ) ( \frac{1}{cm^3} )</td>
<td>( 3 \times 10^8 ) ( \frac{V}{cm} )</td>
<td>( 10^{-3} )</td>
<td>1 ms</td>
<td>10 T</td>
</tr>
<tr>
<td>Phase 2</td>
<td>( 10^{22} ) ( \frac{1}{cm^3} )</td>
<td>( 3 \times 10^8 ) ( \frac{V}{cm} )</td>
<td>( 1 )</td>
<td>1 s</td>
<td>20 T</td>
</tr>
</tbody>
</table>

example material: \( ^{207}\text{Pb} \rightarrow \mu = 0.6\mu_N \quad \epsilon_s \approx 10^{-2} \)

take sample size: \( L \sim 10 \text{ cm} \quad \Rightarrow \) we take SQUID magnetometer: \( 10^{-16} \frac{T}{\sqrt{Hz}} \)

(or multiple loops over smaller sample)

but atomic magnetometers \( \sim \) \( 10^{-17} \frac{T}{\sqrt{Hz}} \)

many options for increasing sensitivity

M.V. Romalis
Axion Limits on $\frac{a}{f_a} F \tilde{F}$

A. Ringwald (2012)
Axion Limits on \( \frac{a}{f_a} G\tilde{G} \)
frequency (Hz)

<table>
<thead>
<tr>
<th>mass (eV)</th>
<th>( g_d ) (GeV(^{-2} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{-14} )</td>
<td>( 10^{-20} )</td>
</tr>
<tr>
<td>( 10^{-12} )</td>
<td>( 10^{-15} )</td>
</tr>
<tr>
<td>( 10^{-10} )</td>
<td>( 10^{-10} )</td>
</tr>
<tr>
<td>( 10^{-8} )</td>
<td>( 10^{-5} )</td>
</tr>
<tr>
<td>( 10^{-6} )</td>
<td>( 10^{-2} )</td>
</tr>
<tr>
<td>( 10^{-4} )</td>
<td>( 10^{0} )</td>
</tr>
</tbody>
</table>

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

- Static EDM
- SN 1987A
- ALP DM

mass (eV) ~ year to scan frequencies

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

Verify signal with spatial coherence of axion field
Axion Wind

use nuclear spins coupled to axion DM

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

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

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

Parameters

\[ n = 10^{22} \frac{1}{\text{cm}^3} \]
\[ v \sim 10^{-3} \]
\[ \rho_{DM} \approx 0.3 \frac{\text{GeV}}{\text{cm}^3} \]
\[ \tau_a \sim \frac{2\pi}{m_a v^2} \sim 1 \text{ s} \left( \frac{\text{MHz}}{m_a} \right) \]

Material Choice

\[ \mu_{Xe} = 0.35 \mu_N \]

Technology

\[ p \approx 1 \]
\[ T_2 \gtrsim \tau_a \sim 1 \text{ s} \]
\[ \delta M \sim 10^3 \text{ fT} \left( \frac{g_{aNN}}{10^{-10} \text{GeV}^{-1}} \right) \]
Quick Estimate

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

**Parameters**

\[ n = 10^{22} \frac{1}{\text{cm}^3} \]
\[ \nu \sim 10^{-3} \]
\[ \tau_a \sim \frac{2\pi}{m_a\nu^2} \sim 1 \text{ s} \left( \frac{\text{MHz}}{m_a} \right) \]
\[ \rho_{DM} \approx 0.3 \frac{\text{GeV}}{\text{cm}^3} \]

**Material Choice**

\[ \mu_{Xe} = 0.35\mu_N \]

**Technology**

\[ p \approx 1 \]
\[ T_2 \gtrsim \tau_a \sim 1 \text{ s} \]
\[ m_a \lesssim \text{MHz} \]

\[ \delta M \sim 10^3 \text{ fT} \left( \frac{g_{aNN}}{10^{-10} \text{GeV}^{-1}} \right) \]
Cosmic Axion Spin Precession Experiment (CASPER)

for axion wind and other types of DM:

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

<table>
<thead>
<tr>
<th></th>
<th>Element</th>
<th>Density (n)</th>
<th>Magnetic Moment ((\mu))</th>
<th>(T_2)</th>
<th>Max. B</th>
<th>Magnetometer Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Xe</td>
<td>1.3 (\times) 10^{22} (\frac{1}{\text{cm}^3})</td>
<td>0.35 (\mu_N)</td>
<td>1300 s</td>
<td>10 T</td>
<td>10^{-15} (\frac{T}{\sqrt{\text{Hz}}})</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10^{-17} (\frac{T}{\sqrt{\text{Hz}}})</td>
</tr>
</tbody>
</table>

\(p \approx 1\)

take sample size: \(L \sim 10 \text{ cm}\)

(or multiple loops over smaller sample)

many options for increasing sensitivity
Limits on Axion-Nucleon Coupling

\[ g_{aNN} \sim \text{year to scan one decade of frequency} \]
Limits on Axion-Nucleon Coupling

Existing experiments e.g. He/Xe comag

QCD Axion

ALP DM

SN 1987A

New Force

~ year to scan one decade of frequency

$g_{aNN} \left( \partial_{\mu} a \right) \bar{N} \gamma_{\mu} \gamma_{5} N$
Summary
WIMPs

Hard scattering is good for heavy dark matter.

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

Hard scattering is good for heavy dark matter.

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

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

(axions, dark photons...)

Monday, 28 April 14
CASPEr Discovery Potential

\[ f_\alpha \text{ (GeV)} \]

- Planck
  - $10^{18}$
- GUT
  - $10^{16}$
  - $10^{14}$
  - $10^{12}$
- Microwave cavity (ADMX)
  - $10^{10}$
- Astrophysical constraints
  - $10^{8}$

Axion dark matter
CASPEr Discovery Potential

$f_a$ (GeV)

Planck
$10^{18}$

“NMR” searches

GUT
$10^{16}$

Axion dark matter

$10^{14}$

microwave cavity (ADMX)

$10^{12}$

$10^{10}$

$10^{8}$

astrophysical constraints

laboratory experiment

significant reach in kHz - 10 MHz frequencies ➔ high $f_a$
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.

technology broadly useful for community.

microwave cavity (ADMX)

"NMR" searches

laboratory experiment

significant reach in kHz - 10 MHz frequencies $\rightarrow$ high $f_a$

technological challenges, similar to early stages of WIMP detection, axions deserve similar effort
Backup
Where does the improvement come from?

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 PbTiO$_3$
Effective Electric Field in PbTiO$_3$
Materials for Oscillating EDM Search

- **PbTiO₃** → we have a lot of experience: NMR, T₁ and T₂ measurements [L.Bouchard, A.Sushkov, D.Budker, 2008]

- Many other **non-centrosymmetric solids** with high-Z atoms, eg: (Pb,La)(Zr,Ti)O₃, (1–x)[Pb(Mg₁/₃Nb₂/₃)O₃]–x[PbTiO₃] (PMN–PT), PbSiO₃, 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

Solid-state electronic spin coherence time approaching one second

N. Bar-Gill¹,², L.M. Pham³, A. Jarmola⁴, D. Budker⁴,⁵ & R.L. Walsworth¹,²
Dynamical Decoupling

Article

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

Solid-state electronic spin coherence time approaching one second

N. Bar-Gill\textsuperscript{1,2}, L.M. Pham\textsuperscript{3}, A. Jarmola\textsuperscript{4}, D. Budker\textsuperscript{4,5} & R.L. Walsworth\textsuperscript{1,2}
Pulse sequence

AC Magnetometry

High-sensitivity diamond magnetometer with nanoscale resolution

J. M. Taylor, P. Cappellaro, L. Childress, L. Jiang, D. Budker, P. R. Hemmer, A. Yacoby, R. Walsworth and M. D. Lukin

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

Axion Wind Search

$g_{\alpha\alpha} \left( \partial_{\mu} a \right) N \gamma^\mu \gamma_5 N$

$g_{\alpha\alpha}$ (GeV$^{-1}$)

mass (eV)

frequency (Hz)

Small Sample

Years

R&D 1-2

Scalable

Liquid Xenon Technology

SN 1987A

New Force

ALP DM

ADMX

Liquid Xenon Technology

Scalable
CASPEr: Timeline

Axion Wind Search

$g_{\text{aNN}} (\partial_{\mu}\alpha) N\gamma^{\mu}\gamma_5 N$

$g_{\text{aNN}}$ (GeV$^{-1}$)

mass (eV)

frequency (Hz)

Years

R&D
1-2

Phase 1
3-5

Small Sample

Liquid Xenon Technology

Scalable
CASPER: Timeline

QCD Axion Goal

\[ d_N = -\frac{i}{2} g_d a \bar{N} \sigma_{\mu \nu} \gamma_5 N F_{\mu \nu} \]

Small Sample

Scalable

Polar Xenon cages, Ferroelectrics,...

Monday, 28 April 14
CASPER: Timeline

QCD Axion Goal

Small Sample

Scalable

Polar Xenon cages, Ferroelectrics,...

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

Monday, 28 April 14
CASPEr: Timeline

QCD Axion Goal

\[ d_N = -\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 NF^{\mu\nu} \]

- Small Sample
- Scalable
- Polar Xenon cages, Ferroelectrics,...
Backup slides
Axion Coherence

How large can T be?

Spatial homogeneity of the field?

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

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

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