Lumped element resonators and DM Radio

• Field-like dark matter
• Axions (spin 0) and hidden photons (spin 1)
• Lumped-element resonators (Cabrera & Thomas)
• Hidden-photon detection
• Axion detection
• Resonant enhancement
• DM Radio science reach
Particle-like and field-like dark matter

**Heavy Particles**
- Number density is small (small occupation)
- Tiny wavelength
- No detector-scale coherence
- Look for scattering of individual particles

\[ \lambda_{\text{coherence}} \approx 100 \text{ km} \times (10^{-8} \text{ eV/m}) \]

**Light Fields**
- Number density is large (must be bosons)
- Long wavelength
- Coherent within detector
- Look for classical, oscillating background field
The light-field dark matter zoo

DM mass:

$10^{-21}$ eV  
1 eV  
100 GeV

Light (field) DM
- Spin-0 scalar
- Spin-1 vector
- Higher spin (tensor) disfavored

Heavy (particle) DM
- WIMPs
- Etc. etc.

Light-field dark matter is a boson

1. Scalar field (spin-0)
2. Pseudoscalar (spin-0, but changes sign under parity inversion) “axion”
4. Pseudovector (spin-1, but changes sign on parity inversion)
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Resonant conversion of axions into photons

Pierre Sikivie (1983)

Primakoff Conversion

HEMT* Amplifier

Magnet

Cavity

*High Electron Mobility Transistor

Expected Signal

\[ \frac{\Delta \nu}{\nu} \sim 10^{-6} \]

Need to scan frequency

Thanks to John Clarke
"Hidden" photon: generic vector boson

- A new photon, but with a mass, and weak coupling
- Couples to ordinary electromagnetism via kinetic mixing

\[ \mathcal{L} \sim -2\varepsilon F^\mu_\nu F'^\mu_\nu \]

CMB photon

Hidden Photon DM drives EM currents

Hidden photon DM drives EM currents
Axions: plenty of room at the bottom

Wide range of unexplored parameter space

$g_{\gamma\gamma}$ [GeV$^{-1}$]

$\nu$V

$\mu$eV

meV

kHz

MHz

GHz

THz

$\nu = \frac{m_a}{2\pi}$
Wide range of unexplored parameter space
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Detecting String-Scale QCD Axion Dark Matter

Blas Cabrera
Scott Thomas

Dark Matter Axion Detection – Large $f_a/N$:

- Resonant LC Circuit

\[ \omega_0^2 = \frac{1}{LC} \]
\[ \gamma = \frac{R}{L} = \frac{\omega_0}{Q} \]


Also useful for hidden photons:
Arias et al., arxiv:1411.4986
Chaudhuri et al., arxiv: 1411.7382v2

On Resonance
\[ U = \frac{1}{2} L |I|^2 = \frac{1}{2} Q^2 \frac{M^2}{L} |I_a|^2 \]
Block EMI background with a superconducting shield

Superconducting shield

• In the subwavelength limit of DM Radio, you can approximate the signal from axions and hidden photons as an effective ac current filling all space, with frequency $f = \frac{mc^2}{h}$

• To detect this signal, we need to block out ordinary photons with a superconducting shield

Hollow, superconducting sheath (like a hollow donut)
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  • Hidden-photon detection
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How to measure effective hidden photon current

- Hidden photon effective ac current penetrates superconductors

$$\vec{J}_{\text{HP}}(t)$$
How to measure effective hidden photon current

- Hidden photon effective ac current penetrates superconductors
- Generates a REAL circumferential, quasi-static B-field
- Screening currents on superconductor surface flow to cancel field in bulk

$$\vec{B}_{HP}(t) = |\vec{B}_{HP}(t)| \hat{\phi}$$

Meissner Effect
How to measure effective hidden photon current

- Cut concentric slit at bottom of cylinder
- Screening currents return on outer surface
How to measure effective hidden photon current

- Cut concentric slit at bottom of cylinder
- Screening currents return on outer surface
- Add an inductive loop to couple some of the screening current to SQUID
• Field-like dark matter
• Axions (spin 0) and hidden photons (spin 1)
• Lumped-element resonators (Cabrera & Thomas)
• Hidden-photon detection
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How to measure effective axion current

- Toroidal coil produces DC magnetic field inside superconducting cylinder
- Axions interact with DC field, generates effective AC current along direction of applied field

\[ \vec{J}_a = |\vec{J}_a| \phi \]
How to measure effective axion current

- Toroidal coil produces DC magnetic field inside superconducting cylinder
- Axions interact with DC field, generates effective AC current along direction of applied field
- Produces REAL quasi-static AC magnetic field

\[ \vec{B}_a(t) \]
How to measure effective axion current

- Screening currents in superconductor flow to cancel field in bulk

Meissner Effect
How to measure effective axion current

- Cut a slit from top to bottom of the superconducting cylinder
- Screening currents continue along outer surface
How to measure effective axion current

- Cut a slit from top to bottom of the superconducting cylinder
- Screening currents continue along outer surface
- Use inductive loop to couple screening current to SQUID
• Field-like dark matter
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Hidden Photon Detector

- Broadband sensitivity

Axion Detector

- Require long integration times for good sensitivity

- Interfering EMI pickup very difficult to manage

Poor signal-to-noise ratio

ABRACADABRA
Y. Kahn et al.

Broadband detection: poor signal to noise
Resonant enhancement

- Coherent fields can be enhanced through the use of a resonator
- Add a tunable lumped-element resonator to ring up the magnetic fields sourced by local dark matter
- Tune dark matter radio over frequency span to hunt for signal

Hidden Photon Configuration
Coherent fields can be enhanced through the use of a resonator

Add a tunable lumped-element resonator to ring up the magnetic fields sourced by local dark matter

Tune dark matter radio over frequency span to hunt for signal
• Field-like dark matter
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• **DM Radio science reach**
DM Radio science reach: hidden photons (lumped-element)

\[ f = \frac{m_{\gamma'}}{2\pi} \]
DM Radio science reach: axions

\[ f = \frac{m_a}{2\pi} \]

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**kHz**  | **MHz**  | **GHz**  | **THz**
---|---|---|---

**SN 1987a γ-ray**

**30 L DETECTOR**
- \( T = 0.01 \text{K}, \ B = 0.1 \ \text{T} \)
- \( 0.5 \ \text{T} \)

**1 m³ DETECTOR, \( T = 0.01 \ \text{K} \)**

**QCD axion**

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**g_{\gamma\gamma} [\text{GeV}^{-1}]**

- \( 10^{-18} \)
- \( 10^{-16} \)
- \( 10^{-14} \)
- \( 10^{-12} \)

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**m_a**

- \( \text{peV} \)
- \( \text{neV} \)
- \( \mu\text{eV} \)
- \( \text{meV} \)
**750 mL Pathfinder funded, under construction**

- Focus on hidden photons
- $T=4K$ (Helium Dip Probe)
- Frequency/Mass Range:
  - $100 \text{ kHz} - 10 \text{ MHz}$
  - $500 \text{ peV} - 50 \text{ neV}$
- Coupling Range: $\varepsilon : 10^{-9} - 10^{-11}$
- Readout: DC SQUIDs

**4K Dip Probe**

Inserts into Cryoperm-lined helium dewar

Detector inside superconducting shield

67 inches

9.5 inches

Design Overview of the DM Radio Pathfinder Experiment

Resonant frequency tuning

Scan time
- 30 days/decade
- 3-6 months total

Ultra-coarse tuning
- fixed sapphire plate fully inserted/removed (tune C)
- change number of turns in solenoid coil (tune L)

Coarse tuning
- position of sapphire dielectric plates (3)

Fine tuning
- position of sapphire needle
- position of niobium needle

$$\frac{\Delta f}{f} \approx 1 \times 10^{-6} \text{ per } .001'' \text{ of motion}$$
Present status - Pathfinder

- Probe construction complete
- Machining of niobium shield/SQUID annex complete, additional niobium parts being machined for scanning
- SQUIDs and readout electronics tested / working
- Now testing fixed resonators to evaluate Q, material properties, then scan
- **Initial science constraints Summer 2017**
Conclusions

DM Radio:
A Superconducting Lumped-Element Dark Matter Detector
For Axions and Hidden Photons