SEARCHING FOR ULTRA-LIGHT HIDDEN PHOTONS

with:

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1. Ultra-light hidden photons: theory

2. Searching for ultra-light hidden photons

3. The importance of the longitudinal mode

4. Searching for hidden photon dark matter
ULTRA-LIGHT HIDDEN PHOTONS
“Ultra-light hidden photons”

Hidden Photons:
Kinetically-mixed, massive, $U(1)'$ gauge boson $A'$:

\[
\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{A'} + \mathcal{L}_{\text{kin. mix}} \\
\quad (-\frac{1}{4} F'^2 + \frac{1}{2} m_{\gamma'}^2 A'_{\mu}^2)
\]

Kinetic mixing $\varepsilon \ll 1$

Ultra-light:
Macroscopic Compton wavelength

\[
\lambda_{\text{Compton}} = 1 \text{ m} \times (10^{-6} \text{ eV}/m_{\gamma'})
\]
A THOUGHT ON TINY MASSES

$$\lambda_{\text{Compton}} = 1 \text{ m} \times (10^{-6} \text{ eV}/m_{\gamma'})$$

How to generate $m_{\gamma'} \approx 10^{-6} \text{ eV}$?

Stuckelberg mass vs. Higgs mechanism

<table>
<thead>
<tr>
<th>$m_{\gamma'}$ generated at string scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\gamma'}$ generated dynamically</td>
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<tr>
<td>Constraints on light Higgs states</td>
</tr>
<tr>
<td>Higgs decouples as $g_D \to 0$</td>
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<tr>
<td>Assume light states decoupled</td>
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</table>

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**What does this new field do?**

Macroscopic, mixes with photon

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{A'} + \mathcal{L}_{\text{kin. mix}} \]

\[ (-\frac{1}{4} F'^2 + \frac{1}{2} m_{\gamma'}^2 A'_{\mu}^2) \]

\[ -2\varepsilon F_{\mu\nu} F'_{\mu\nu} \]

**Mass basis**

- **massless** photon with coupling \( eA_\mu J^\mu \)
- **massive** hidden photon with coupling \( e\varepsilon A'_{\mu} J^\mu \)

**Interaction basis**

- **interacting** photon
- **non-interacting** hidden photon
- **mass mixing** \( \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & 1 \end{pmatrix} m_{\gamma'}^2 \)

Macroscopic, mixes with photon

\[ \frac{1}{4} F'^2 + \frac{1}{2} m_{\gamma'}^2 A'_{\mu}^2 \]

\[ -2\varepsilon F_{\mu\nu} F'_{\mu\nu} \]
2 Important Points

**Important point 1**

all effects decouple when $m_\gamma^2 \to 0$

**Interaction basis**

- **interacting** photon
- **non-interacting** hidden photon

- mass mixing $\begin{pmatrix} 0 & \varepsilon \\ \varepsilon & 1 \end{pmatrix} m_\gamma^2$
ULTRA-LIGHT HIDDEN-PHOTON CONSTRAINTS

\[ \lambda_{\text{Compton}} = \frac{2\pi}{m_{\gamma'}} \]

\( R_{\text{earth}} \) km m mm

\( \log_{10} \varepsilon \)

\( \log_{10} m_{\gamma'} \text{[eV]} \)

Jupiter Earth Coulomb CMB HB Sun

from 1002.0329, 1302.3884
DETECTING ULTRA-LIGHT HIDDEN PHOTONS
our motto: Fields leak through shields
DETECTING THE HIDDEN PHOTON

our motto: Fields leak through shields

Surjeet Rajendran, UC Berkeley
our motto: Fields leak through shields
Detecting the hidden photon

Signal size: first estimate

— Source fields \((E, B)_{source}\)
— \(\varepsilon\) to produce hidden photon
— \(\varepsilon\) for hidden photon to backreact on sensor

\[\rightarrow (E, B)_{detected} \sim \varepsilon^2 (E, B)_{source}\]
Detecting the hidden photon

Signal size: first estimate

- Source fields \((E, B)_{\text{source}}\)
- \(\varepsilon\) to produce hidden photon
- \(\varepsilon\) for hidden photon to backreact on sensor

\[\rightarrow (E, B)_{\text{detected}} \sim \varepsilon^2 (E, B)_{\text{source}}?\]

\[\rightarrow (E, B)_{\text{detected}} \sim \ldots \varepsilon^2 (E, B)_{\text{source}}\]

missing factor to give decoupling as \(m_\gamma \rightarrow 0\)
Detecting the hidden photon

Improve with resonance

Diagram:
- Source of field
- Wave $e^{i\omega t}$
- Shield (perfect conductor)
- Resonator tuned to frequency $\omega$
- Field sensor
DETECTING THE HIDDEN PHOTON

Improve with resonance

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Detecting the hidden photon

Signal size: first estimate

- Source fields \((E, B)_{\text{source}}\)
- \(\varepsilon\) to produce hidden photon
- \(\varepsilon\) for hidden photon to backreact on sensor
- \(Q \gg 1\) resonant enhancement

\[ \rightarrow (E, B)_{\text{detected}} \sim \varepsilon^2 (E, B)_{\text{source}} \]

\[ \rightarrow (E, B)_{\text{detected}} \sim (...) Q \varepsilon^2 (E, B)_{\text{source}} \]

missing factor to give decoupling as \(m_\gamma \rightarrow 0\)
**Signal Size Take 2**

- **Interaction basis**
  - *interacting* photon
  - *non-interacting* hidden photon
- Mass mixing \( \left( \begin{array}{c} 0 \\ \varepsilon \\ 1 \end{array} \right) m_{\gamma'}^2 \)
Interaction basis

- *interacting* photon
- *non-interacting* hidden photon

mass mixing $\begin{pmatrix} 0 & \varepsilon \\ \varepsilon & 1 \end{pmatrix} m_{\gamma'}^2$
Signal Size Take 2

Interaction basis

— interacting photon
— non-interacting hidden photon

mass mixing \((\begin{pmatrix} 0 & \varepsilon \\ \varepsilon & 1 \end{pmatrix}) m_{\gamma'}^2\)
\[ (E, B)_{\text{detected}} \sim (m_\gamma A L^2/\omega^2) Q \varepsilon^2 (E, B)_{\text{source}} \]

“Light Shining through Walls” experiments
— The ALPs axion search uses this setup (+ static B-field)
— Can immediately repurpose for hidden photons
— Laser cavities: probes \( \mu \text{m} \) wavelengths

Ahlers et al 0706.2836
**MICROWAVE CAVITIES**

Microwave cavities are ideal

— amazing resonators: $Q \sim 10^{10}$
— 2 cavities can be tuned to same frequency
— cm-m wavelengths
— same signal scaling as above

Early-stage experiments

— Povey et al 1003.0964
— ADMX 1007.3766
— CROWS 1310.8098
CERN Resonant Weakly-Interacting Sub-eV Particle Search (CROWS)
THE IMPORTANCE OF THE LONGITUDINAL MODE
**Signal size take 3: Longitudinal waves**

**Mass basis**
- **massless** photon with coupling $eA_{\mu}J^{\mu}$
- **massive** hidden photon with coupling $eeA'_{\mu}J^{\mu}$

**Interaction basis**
- **interacting** photon
- **non-interacting** hidden photon
- mass mixing $\begin{pmatrix} 0 & \varepsilon \\ \varepsilon & 1 \end{pmatrix} m_{\gamma'}^2$
Mass basis

- *massless* photon with coupling $eA_\mu J^\mu$
- *massive* hidden photon with coupling $eeA'_\mu J^\mu$

longitudinal mode $A'_L$

with coupling $ee$ to electric charge
**Signal Size Take 3: Longitudinal Waves**

Mass basis

- **massless** photon
  
  with coupling $eA_\mu J^\mu$

- **massive** hidden photon
  
  with coupling $eeA'_\mu J^\mu$

longitudinal mode $A'_L$

with

coupling $ee$ to electric charge
**Signal size take 3: Longitudinal waves**

\[ A'_z \propto \varepsilon J_z \]

\[ E'_z = -\partial_z A'_0 - \partial_0 A'_z \]

\[ \partial_t A'_0 = -\partial_z A'_z \quad \text{(from of EoM for } A') \]

\[ E'_z = (-i/\omega)(\omega^2 - k^2)A'_z \propto m_\gamma^2/\omega A'_z \]

\[ \varepsilon E'_z \propto (\varepsilon^2 m_\gamma^2/\omega) J_z \]

**Mass basis**

- **massless photon** with coupling \( eA_\mu J^\mu \)
- **massive hidden photon** with coupling \( \varepsilon eA'_\mu J^\mu \)

**longitudinal mode** \( A'_L \)

with coupling \( \varepsilon e \) to electric charge

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Signal Size Take 3: Longitudinal Waves

\[ \epsilon E'_z \propto (\epsilon^2 m_{\gamma'}^2/\omega) J_z \]

\[ \rightarrow (E, B)_{\text{detected}} \sim (m_{\gamma'}^4 L^2/\omega^2) Q \epsilon^2 (E, B)_{\text{source}} \]

\[ \rightarrow (E, B)_{\text{detected}} \sim (m_{\gamma'}^2/\omega^2) Q \epsilon^2 (E, B)_{\text{source}} \]
Microwave cavities are ideal

— amazing resonators: $Q \sim 10^{10}$
— 2 cavities can be tuned to same frequency
— self-shielding
— cm-m wavelengths
— same signal scaling as above

Improved from

$(m_\gamma^4/\omega^4) \varepsilon^2$

to

$(m_\gamma^2/\omega^2) \varepsilon^2$

Early-stage experiments

— Povey et al 1003.0964
— ADMX 1007.3766
— CROWS 1310.8098

Jaekel & Ringwald 0707.2063
CERN Resonant Weakly-Interacting Sub-eV Particle Search (CROWS)
\[ \lambda_{\text{Compton}} = \frac{2\pi}{m_{\gamma'}} \]

Future experiments

Previous sensitivity projection

Future high-\(Q\) microwave cavity experiment

CMB

\(R_{\text{Earth}}\)

Coulomb

Jupiter

Earth

CMB

HB

Sun

ALPS II

\(\log_{10} \varepsilon\)

\(\log_{10} m_{\gamma'} \text{[eV]}\)
**FUTURE EXPERIMENTS**

**Stage 1:** $B_{em}=1 \text{T}$, size $\sim 10 \text{ cm}$, $Q=10^{10}$, $T=4\text{K}$, 1 month

**Stage 2:** $B_{em}=1 \text{T}$, size $\sim 1 \text{ m}$, $Q=10^{12}$, $T=0.1\text{K}$, 1 year
DM DETECTION WITH A RADIO INSIDE A FARADAY CAGE
Hidden-Photon DM is an oscillating $E'$ field with

- $\rho_{DM} \approx E'^2$
- Random direction (Lorentz breaking, but hard to tell)
- Frequency $\omega = m_{\gamma'}$
- Coherence time $t \sim 1/(\sigma^2 \omega) \sim 10^6/\omega$

Cosmology

- Energy density dilutes as $1/a(t)^2$ when $H > m_{\gamma'}$
- Avoid this with non-minimal coupling $\mathcal{L} \supset (1/12) R A'_{\mu}^2$
  - Large mass from graviton loops?
  - Overproduced by inflationary perturbations if $R = 0.2$
- Is there a safe way to produce it? (I can’t answer that yet)
Like an electric field that penetrates conducting shields

\[- E' \approx \sqrt{\rho_{\text{DM}}} \approx 2000 \text{ V/m} \]

Has fixed frequency

\[- \omega = m_{\gamma'}, \ \delta\omega/\omega = 10^{-6} \]

Can excite an electromagnetic resonator

**electromagnetic cavities**

\[- \text{ADMX is automatically sensitive!} \]

Arias et al 1201.5902

\[- \text{restricted to } m_{\gamma'} \sim 10^{-4} - 10^{-6} \text{ eV} \]

(set by cavity size)
**Hidden-Photons as Dark Matter**

Like an electric field that penetrates conducting shields

\[ E' \approx \sqrt{\rho_{DM}} \approx 2000 \text{ V/m} \]

Has fixed frequency

\[ \omega = m_{\gamma'}, \quad \delta \omega / \omega = 10^{-6} \]

Can excite an electromagnetic resonator

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**Electromagnetic Cavities**

- ADMX is automatically sensitive!
  
  Arias et al 1201.5902

- Restricted to \( m_{\gamma'} \sim 10^{-4} - 10^{-6} \text{ eV} \)
  
  (set by cavity size)

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**LC Circuits**

- Resonators

- Much wider and lower frequency range than cavities

- Can probe much lower masses

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S. Chaudhuri et al. 1411.7382
EXPERIMENTAL SETUP

oscillating $E'$ field (dark matter)
EXPERIMENTAL SETUP

oscillating $E'$ field (dark matter)

Metal box to shield backgrounds (Faraday cage)
THE SIGNAL INSIDE THE BOX

Metal box

oscillating $E'$ field

conduction electrons in wall respond to $E'$ field, generating $E$ and $B$ fields
The Signal Inside The Box

- Metal box
- Oscillating $E'$
- Conduction electrons in wall respond to generating
- Net effect is a $B$ field inside the box

$$B \sim \varepsilon (m_{\gamma'} R) \times 10^{-5} \, \text{T}$$
oscillates at $\omega = m_{\gamma'}$
EXPERIMENTAL SETUP

- oscillating $E'$ field (dark matter)
- Metal box to shield backgrounds (Faraday cage)
- Tunable resonant LC circuit (a radio)
**EXPECTED REACH**

**Stage 1:** size $\sim$50 cm, $T=4\text{K}$, $Q=10^6$, 1 year scan

Stage 2: size $\sim$1 m, $T=10\text{mK}$, $Q=10^6$, 1 year scan
**EXPECTED REACH**

**Stage 1:** size ~50 cm, $T = 4\text{K}$, $Q=10^6$, 1 year scan

**Stage 2:** size ~1 m, $T = 10\text{mK}$, $Q=10^6$, 1 year scan

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