Direct Detection of Light Dark Matter

Asher Berlin - Fermilab

Seattle Snowmass Summer Meeting
July 23, 2022

See also:
What Do We Know?

*dark matter resides in galaxies (including our own)*

**velocity:** $v_{\text{DM}} \sim 100 \text{ km/s} \sim 10^{-3} \, c$

**mass density:** $m_{\text{DM}} \, n_{\text{DM}} \sim \text{GeV/cm}^3$

Few heavy particles or many light particles?
What is the dark matter mass?
What Do We Know?

\[ 10^{-22} \text{ eV} \quad \text{eV} \quad \text{GeV} \quad M_{\text{pl}} \quad 10^{-10} \quad M_{\odot} \]
The search for WIMPs has been an incredible success.

What now?
The search for WIMPs has been an incredible success.

What now?

Maybe the dark matter and hierarchy problem are not solved together.

If so, the space of motivated signals is dramatically enlarged.

This motivates a strong diversification of the experimental program.
New Theoretical Targets

What are cosmologically-motivated and viable models?

What is new technology sensitive to?

Where are the biggest gaps in coverage?

When do we stop and reevaluate?
Going Further

**New Technology**

Opportunity to explore new physics at previously inaccessible scales.

How can these developments be steered to make the biggest impact on dark matter physics?

**Role of theory/theorists**

Creative repurposing of existing detectors.

Motivating/conceiving/designing new small-scale experiments.

This is especially crucial in emerging fields.

Theorists played a major role in most experiments/proposals that will be highlighted here.
Outline

Ultralight Axion Dark Matter

I.
\[\text{Resonant cavities} \]
\[\text{LC circuits} \]
\[\text{Dielectric haloscopes} \]
\[< \text{SQL} \]
\[\text{QCD-coupling, ...} \]

Light Particle Dark Matter

II.
\[\text{skipper CCDs} \]
\[\text{supercond. nanowires} \]
\[\text{low-gap materials, ...} \]

- \(10^{-22} \text{ eV}\)
- \(\text{eV}\)
- \(\text{GeV}\)
- \(M_{\text{pl}}\)
- \(10^{-10} \, M_{\odot}\)

DM mass
I. Ultralight Axion Dark Matter

Resonant cavities
LC circuits
Dielectric haloscopes
< SQL
QCD-coupling, ...

II. Light Particle Dark Matter

skipper CCDs
supercond. nanowires
low-gap materials, ...

Outline

<table>
<thead>
<tr>
<th>10^{-22} \text{ eV}</th>
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<th>M_{\text{pl}}</th>
<th>10^{-10} \text{ } M_{\odot}</th>
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<tbody>
<tr>
<td>axions</td>
<td>sub-GeV</td>
<td></td>
<td></td>
<td>DM mass</td>
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</table>
Axion Parameter Space

electromagnetically-coupled axions, \( \mathcal{L} \sim g_{a\gamma\gamma} a F \tilde{F} \)

(axion + \( B \) → photon)

existing bounds

large cavities

small cavities

QCD axion

standard ALP DM cosmology

KSVZ

DFSZ

10\(^{-21}\) eV  \( \cdots \) 10\(^{-12}\) eV  10\(^{-9}\) eV  10\(^{-6}\) eV  10\(^{-3}\) eV  1 eV

axion mass

resonant cavities
Axion Parameter Space

**electromagnetically-coupled axions, $\mathcal{L} \sim g_{a\gamma\gamma} a F\tilde{F}$**

(axion + $B \rightarrow$ photon)

$10^{-21}$ eV ... $10^{-12}$ eV $10^{-9}$ eV $10^{-6}$ eV $10^{-3}$ eV 1 eV

**Axion mass**

$\ll \mu$eV

resonant cavities

existing bounds

large cavities $\leftrightarrow$ small cavities

standard ALP DM cosmology

QCD axion

KSVZ, DFSZ

$\cos(\theta)$

$\sin(\theta)$

$\left| g_{a\gamma\gamma} \right|$ [GeV$^{-1}$]

$m_a$ [eV]
Below ~Micro-eV

**LC circuits (DMRadio)**

\[ \cos m_a t \]

\[ \omega_{LC} \sim \frac{1}{\sqrt{LC}} \sim m_a \ll \frac{1}{\text{length}} \]

\[ B \sim \text{few} \times T \]

**Heterodyne/Upconversion (SRF cavities)**

\[ \Delta \omega \sim m_a \ll \omega \sim \text{GHz} \]

\[ Q \sim \text{few} \times 10^{11} \]


Below ~Micro-eV

10^{-21} \text{ eV} \ldots 10^{-12} \text{ eV} 10^{-9} \text{ eV} 10^{-6} \text{ eV} 10^{-3} \text{ eV} 1 \text{ eV}

SRF \quad \text{LC} \quad \text{resonant cavities}

axion mass

existing bounds

QCD axion

standard ALP DM cosmology
Above ~Micro-eV
Above ~Micro-eV

Resonant Cavity (ADMX-EFR)

arXiv:2203.14923

combine signal from 18 smaller cavities

2-4 GHz ~ 8-16 μeV

Dielectric/Plasma

(MADMAX, LAMPOST, ALPHA)


MADMAX/LMPPOST: dielectric stacks

ALPHA: wire metamaterial

modify photon’s dispersion relation
Above \textasciitilde\text{Micro-eV}

\begin{itemize}
\item $10^{-21}$ eV
\item \ldots
\item $10^{-12}$ eV
\item $10^{-9}$ eV
\item $10^{-6}$ eV
\item $10^{-3}$ eV
\item 1 eV
\end{itemize}

\begin{itemize}
\item axion mass
\item SRF
\item LC
\item resonant cavities
\item cavity/dielectric/plasma/dish
\end{itemize}
Summary of Projections

10^{-21} \text{ eV} \ldots 10^{-12} \text{ eV} \quad 10^{-9} \text{ eV} \quad 10^{-6} \text{ eV} \quad 10^{-3} \text{ eV} \quad 1 \text{ eV}

axion mass

SRF/LC \quad \text{cavity/dielectric/plasma/dish}
QCD Coupling

\[ \mathcal{L} \sim g_{agg} a G \tilde{G} \]

NMR-like Signal in Ferroelectrics (CASPER-electric)

arXiv:1306.6089

Oscillating neutron EDM $\rightarrow$ Rabi flopping/Tilted magnetization

\begin{align*}
10^{-21} \text{ eV} & \quad \cdots \quad 10^{-12} \text{ eV} & 10^{-9} \text{ eV} & 10^{-6} \text{ eV} & 10^{-3} \text{ eV} & 1 \text{ eV} \\
\text{axion mass}
\end{align*}

SRF NMR LC resonant cavities cavity/dielectric/plasma/dish
Opportunities in Axion Detection

**EM-coupled DM at ~meV~THz**

**QCD-coupled DM at >μeV~GHz**

**New Theory Targets**
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skipper CCDs
supercond. nanowires
low-gap materials, ...

DM mass

10^{-22} \text{ eV} \quad \text{eV} \quad \text{GeV} \quad M_{\text{pl}} \quad 10^{-10} M_{\odot}
Kinematic Matching

*Dark Matter Scattering*

Current state of the art (silicon band gap)

Inelastic scatters $\rightarrow$ better kinematic matching at small masses

(*ignoring absorption for sake of time*)
Multitude of Proposed Materials

From minimal mention in Snowmass-2013 to now...
(multiple target materials spanning many couplings within theory space)

- Solid-state charge detectors
  (CCDs, semiconductor crystals + dopants)
- Exotic narrow gap semiconductors,
  Dirac Materials
  (La$_3$Cd$_2$As$_6$, Eu$_5$In$_2$Sb$_6$, ZrTe$_5$)
- Polar Materials
  (GaAs, SiC, Al$_2$O$_3$, SiO$_2$)
- Molecules/vibrational modes
  (CO, HF)
- Superfluids/superconductors
  (He, Al)
- Organic Scintillators +...

\[ \bar{\sigma}_e \left[ \text{cm}^2 \right] \]
\[ m_\chi \left[ \text{MeV} \right] \]

only small target exposures required
to explore new parameter space
Multitude of Proposed Sensors

**SNSPDs**

**KIDs**

**TESs**

**skipper CCDs**

lowering thresholds and backgrounds

**superconducting nanowires**

arXiv:1903.05101

(a) $i_{bias}$

(b) DM scattering or absorption

non-destructive repeated charge counting

dark count $< 10^{-3} \text{ e/pix/day}$

dopants to lower threshold from eV to 10 meV?

**skipper CCDs, SENSEI**

arXiv:1706.00028

infrared/optical photon counting

dark count $\sim 1$ per day
A Better Understanding of the Material Response

For any DM coupling to electron density, scattering is determined by dielectric function

\[ \Gamma(v_\chi) = \int \frac{d^3q}{(2\pi)^3} |V(q)|^2 \left[ 2 \frac{q^2}{e^2} \text{Im} \left( \frac{1}{\epsilon(q, \omega_q)} \right) \right] \]
What other cosmologically-motivated, predictive, viable, and detectable models exist below an MeV?
Collective Excitations of Dark Matter

Direct *Deflection* of Dark Matter

*Inducing and detecting collective “ripples” in the dark matter “fluid”*

Direct *Deflection*

A large number density implies more than just large flux, it enables inducing *enhanced* collective effects into the classical DM fluid. This is easier to do for smaller masses.
Direct Deflection of Dark Matter


($\pm$)

DM wind

$\chi^\pm$

oscillating electric field

$E_{\text{def}} e^{i\omega t}$

no kinematic barrier,
small momentum enhancement

(\sim DM Radio with fixed frequency and electric pickup)
New parameter space within reach (ultimate sensitivity) for 0.1 (10) m³ volumes, 10³ (10⁷) Q-factors, and 4 K (100 mK) temperatures.
Opportunities in Low-Threshold Direct Detection

New Material Targets

- Solid-state charge detectors
- Exotic narrow gap semiconductors
- Polar Materials
- Molecules/vibrational modes
- Superfluids/superconductors
- Dirac Materials
- Organic Scintillators
- +...?

Signal Calculation

\[ \chi \quad \chi \]
\[ V(q) \]
\[ \epsilon(q, \omega) \]

precise understanding of material response

keV-MeV Theory Targets

Experimental Developments

What are novel backgrounds?

How to detect single phonons/magnons, ...?
Outlook

Now is an important time

We are now beginning to explore physics beyond the Standard Model at scales currently inaccessible with previous technology.

How can technologies coming online be steered to make the biggest impact on fundamental physics?

A shift in our priors has motivated a larger set of signals. Many bang-for-buck experiments $>_{\text{single catch-all experiment.}}$

Theory and experiment are evolving together in this effort. The role of theorists is crucial in emerging fields.

see “Snowmass2021 Theory Frontier: Theory Meets the Lab”
arXiv:2203.10089