Superconducting Detectors for Super Light Dark Matter

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YH, Yue Zhao and Kathryn Zurek, PRL 116, 011301
YH, Matt Pyle, Yue Zhao and Kathryn Zurek, 1512.04533
and works in progress
Outline

• Why?
• How?
• Rates & Results
Why?
The Universe is Dark

No suitable candidate within the Standard Model (SM).

Requires at least one new stable/extremely long lived particle to exist today.
Dark Matter Properties

• DM has 5 times the mass density of baryons

• Massive \((m=?)\)

• Suppressed interactions with QED and QCD

• Doesn’t very strongly self-interact
Dark Matter and Early Universe

Is possible to link DM with early universe cosmology

If new particle has $2 \rightarrow 2$ interactions with the SM, there will be a relic density left over

Dark Matter Freeze Out

Boltzmann eq.:

$$\partial_t n + 3H n = -(n^2 - n^2_{eq}) \langle \sigma_{ann} v \rangle$$

density/measured

SM

DM

SM

DM

DM

SM

SM

DM

DM

DM

SM

DM

time

( ← temperature)

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The WIMP Miracle

Correct thermal relic abundance:

\[ \langle \sigma_{\text{ann}} v \rangle \equiv \frac{\alpha^2}{m_{\text{DM}}^2} \sim 3 \times 10^{-26} \text{ cm}^3/\text{sec} \]

\[ m_{\text{DM}} \sim \alpha \times 30 \text{ TeV} \]

For weak coupling, weak scale emerges.

The dominant paradigm for \(~35\) years.
Searching for WIMPs

Direct production

Direct detection

Indirect detection

DM

SM

DM

SM

DM

SM

DM

SM

DM

SM

DM

SM

DM

SM

DM

SM

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WIMPs current status

Direct production

LHC searches for EW-ino DM

$\tilde{g}\tilde{g}$ production, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0_1$

Direct detection

LUX null results

Indirect detection

HESS pressing the thermal Wino

[Cohen, Lisanti, Pierce, Slatyer JCAP 1310, 061 (2013); Fan and Reece, JHEP 1310, 124 (2013)]

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Been searching...
Dominant paradigm is being challenged.
Sociology

Dominant paradigm is being challenged.

- Big puzzles
- Great if a solution gives an option for dark matter candidate
- Big ideas: SUSY, extra dimensions...
- Dark matter exists
- Explain on its own
- Perhaps decoupled from other puzzles
- Think outside the WIMP box

theoretically & experimentally
Beyond the WIMP

mass [GeV]
Beyond the WIMP

(See Peter's talk?)

Go lighter!
keV-GeV

mass [GeV]
Theory: example #1

• **Weakly coupled $2 \rightarrow 2$:**

\[
\langle \sigma v \rangle \sim \frac{\alpha^2}{m_{DM}^2} \quad \alpha \ll 1
\]

\[
m_{DM} \sim \alpha \times 30 \text{ TeV}
\]

[Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008]
Theory: example #2

- Asymmetric dark matter:

\[ m_{DM} \sim 5 \text{ GeV} \left( \frac{n_B - n_B}{n_{DM} - n_{DM}} \right) \]

[Kaplan, Luty, Zurek, 2009]
Theory: example #3

- **SIMPs:** \( n \rightarrow 2 \) self-annihilations

\[
m_{DM} \sim \alpha \left( \frac{T_{eq}}{M_{Pl}} \right)^{1/n}
\]

\[
m_{DM} \sim \alpha_{eff} \times 100 \text{ MeV}
\]

See also elastically decoupling dark matter (ELDERs)

[Carlson, Hall, Machacek, 1992; YH, Kuflik, Volansky, Wacker, 2014]

[Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2015]
Theory: example #4

- **Forbidden channels:**

\[ 2m_{\text{DM}} < m_{\text{thing}_1} + m_{\text{thing}_2} \]

\[ m_{\text{DM}} \sim \alpha \times (30 \text{ TeV}) \times e^{-x_F \Delta} \]

- freezeout temp'
- mass difference

[Griest, Seckel, 1991; D’Agnolo, Ruderman, 2015]
Beyond the WIMP

Theory:
Lots of activity in recent years
Beyond the WIMP

Experiment: Focus on direct detection of keV-GeV dark matter

mass [GeV]

$10^{-30}$ $10^{-6}$ $10^{-3}$ 1 $10^3$ $10^{50}$
How?
Direct Detection

What's going on?
Direct Detection

• Nuclear recoils: \[ E_{NR} = \frac{q^2}{2m_N} = \frac{(m_{DM}v)^2}{2m_N} \gtrsim E_{th} \sim \text{keV} \]

• For sub-GeV dark matter, scatter off electrons!

Kinetic energy available: \[ E_D \sim \mu_r v^2 \]

\[ m_{DM} \sim \text{MeV} \Rightarrow E_D \sim \text{eV} \quad \text{electron ionization, semiconductors} \]

[Essig, Mardon, Volansky, PRD 85, 076007 (2012); Graham, Kaplan, Rajendran, Walters, PDU 1, 32 (2012)]
Direct Detection

• Nuclear recoils: 
\[ E_{NR} = \frac{q^2}{2m_N} = \frac{(m_{DM}v)^2}{2m_N} \gtrsim E_{th} \sim \text{keV} \]

• For sub-GeV dark matter, scatter off electrons!

Kinetic energy available: 
\[ E_D \sim \mu_r v^2 \]

\[ m_{DM} \sim \text{MeV} \implies E_D \sim \text{eV} \]

\[ m_{DM} \sim \text{keV} \implies E_D \sim \text{meV} \]

electron ionization, semiconductors
Direct Detection

• Nuclear recoils: \[ E_{NR} = \frac{q^2}{2m_N} = \frac{(m_{DM}v)^2}{2m_N} \gtrsim E_{th} \sim \text{keV} \]

• For sub-GeV dark matter, scatter off electrons!

Kinetic energy available: \[ E_D \sim \mu_e v^2 \]

- \( m_{DM} \sim \text{MeV} \Rightarrow E_D \sim \text{eV} \) (electron ionization, semiconductors)
- \( m_{DM} \sim \text{keV} \Rightarrow E_D \sim \text{meV} \) (Superconductors!)

[YH, Zhao and Zurek, PRL 116, 011301
YH, Pyle, Zhao and Zurek 1512.04533]
Kinematics

Target at rest:

\[ E_D \sim \frac{q^2}{2m_T} \]

- **Target = N:**
  
  \[ q_{\text{max}} \sim 2\mu_r v_{\text{DM}} \sim 2m_{\text{DM}} v_{\text{DM}} \]
  
  Even for \[ \sigma_E \sim \text{eV} \], only \[ m_{\text{DM}} \sim \mathcal{O}(100\text{'s MeV}) \] detectable

- **Target = e:**

  \[ m_{\text{DM}} \sim \text{keV} \quad \Rightarrow \quad E_D \sim 10^{-6} \text{ eV} \]
  
  \[ m_{\text{DM}} \sim \text{MeV} \quad \Rightarrow \quad E_D \sim \text{eV} \quad \text{[semiconductors]} \]

Even \[ \sigma_E \sim \text{meV} \] won’t allow sensitivity to keV DM
Kinematics

Target w/ velocity:

\[ E_D \sim \left( \frac{\vec{q}^2}{2m_T} + \vec{q} \cdot \vec{v}_T \right) + \delta \]

- \( m_{DM} \gg m_T \): DM barely affected
  \[ v_T \rightarrow v_T + 2v_{DM} \]
  \[ E_D^{\text{max}} = \frac{1}{2}m_T [(v_T + 2v_{DM})^2 - v_T^2] \]

- \( m_{DM} \ll m_T \): Target can fully stop the DM
  \[ E_D^{\text{max}} \sim \frac{1}{2}m_{DM}v_{DM}^2 \]
  \[ \sigma_E \sim \text{meV} \quad \text{for} \quad m_{DM} \sim \text{keV} ! \]
Kinematics

Target w/ velocity:

\[ E_D \sim \left( \frac{q^2}{2m_T} + \vec{q} \cdot \vec{v}_T \right) + \delta \]

Fermi-degenerate materials have velocity!

Focus on superconductor targets.
Superconductor Cheat Sheet

• Ground state of superconductor = Cooper pairs; Binding energy (gap) $\Delta \lesssim \text{meV}$

• The idea:
  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs, creating quasiparticles $\rightarrow$ detect
Superconductor Cheat Sheet

• For energies exceeding the gap, scatter with free electrons in a Fermi-degenerate sea (“coherence factor” $\to 1$)

• Ram an electron, create quasiparticles which random walk until collected by e.g. a Transition Edge Sensor (TES)

Heat calorimeter

TESs used to detect microwaves and x-rays in astro applications (e.g. ACT, SPT, SuperCDMS)

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Superconductor Cheat Sheet

- Current status? Not there yet

<table>
<thead>
<tr>
<th>TES</th>
<th>$T_c$ [mK]</th>
<th>Volume [μm × μm × nm]</th>
<th>Power Noise [W/√Hz]</th>
<th>$\sigma_{E}^{\text{now}}$ [meV]</th>
<th>$\sigma_{E}^{\text{scale}}$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W [3]</td>
<td>125</td>
<td>$25 \times 25 \times 35$</td>
<td>$2.72 \times 10^{-18}$</td>
<td>120</td>
<td>1.1</td>
</tr>
<tr>
<td>Ti [5]</td>
<td>50</td>
<td>$6 \times 0.4 \times 56$</td>
<td>$2.97 \times 10^{-20}$</td>
<td>47</td>
<td>22</td>
</tr>
<tr>
<td>MoCu [6]</td>
<td>110.6</td>
<td>$100 \times 100 \times 200$</td>
<td>$4.2 \times 10^{-19}$</td>
<td>295.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

- Need to beat noise
- Energy resolution $\sigma_E \propto \sqrt{T^3 V}$

Reduce temperature and volume for $O$(meV) resolution
Detector Concept

Basic device idea:
Large exposure but high energy resolution = excitation concentration
(E.g. SuperCDMS)

Absorber $\rightarrow$
Collection fins $\rightarrow$
TES

Design by Matt Pyle
Detector Concept

- Quasiparticle lifetime of order a millisecond

- With velocity $10^{-2}c$, plenty of time to random walk and get absorbed before recombine

Design by Matt Pyle
Detector Concept

Comments:
• Low energy deposits: gapless absorber such as a metal
• But better: metal in superconducting phase so that the gap controls the thermal noise
• **Proof of concept**
Rates & Results
Rates

Scatter off electrons in Fermi-degenerate metal – Pauli blocking

\[ E_F \sim 10 \text{ eV} \]

\[
\langle n_e \sigma v_{rel} \rangle = \int \frac{d^3p_3}{(2\pi)^3} \frac{\langle |M|^2 \rangle}{16E_1E_2E_3E_4} S(E_D, |q|)
\]

\[
S(E_D, |q|) = 2 \int \frac{d^3p_2}{(2\pi)^3} \frac{d^3p_4}{(2\pi)^3} (2\pi)^4 \delta^4(P_1 + P_2 - P_3 - P_4) \times f_2(E_2)(1 - f_4(E_4))
\]

Pauli blocking \( \sim \frac{E_D}{E_F} \sim 10^{-4} \)
Rates

\[ \frac{dR}{d\log_{10}E_D} \text{ [yr}^{-1}\text{kg}^{-1}] \]

Recoil energy \( E_D \) [eV]

100 MeV DM

10 keV DM

light mediator

heavy mediator

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Rates

\[ \sigma = \frac{16\pi\alpha_e\alpha_X}{(m^2_\phi - q^2)^2} \mu^2_{ex} \]

Low momentum dominates

Pauli blocking dominates

100 MeV DM

10 keV DM

Signal rates
Superconductors with 1 meV or 10 meV threshold

Reach

Massive mediator

\[ \tilde{\sigma}_{DD} \text{ [cm}^2\text{]} \]

\[ 10^{-33} - 10^{-39} \]

\[ 10^{-6} - 10^{-1} \]

\[ m_X [\text{GeV}] \]

\[ \text{kg-year reach} \]

\[ \tilde{\sigma}^{\text{heavy}}_{\text{DD}} = \frac{16\pi\alpha_e\alpha_X}{m_\phi^4} \mu_{eX}^2 \]
Superconductors with 1 meV or 10 meV threshold

\[ \sigma_{DD} \propto 16\pi \alpha_e \alpha_X \frac{\mu_{eX}^2}{q_{\text{ref}}^4} \]

\[ q_{\text{ref}} \equiv \mu_{eX} v_X \]

\[ \alpha_e \alpha_X = 10^{-27} \]

Reach
Light mediator

kg-year reach
Summary

• Proposed new class of detectors using superconductors

• Sensitive to $O(\text{meV})$ energy deposits $\rightarrow$ keV dark matter

• R&D to lower noise such that $O(\text{meV})$ energies are detectable. (Port over everything being done now for semiconductors.)

• Other absorbers, other calorimeters  

• Populate the models space
Prospects

Superconductors!

electron-ionization, semiconductors ($\sigma_{DM-e}$)

Xenon10...

WIMP program ($\sigma_{DM-N}$)

$E_D > \text{meV}$

$E_D > \text{eV}$

keV  MeV  GeV
Prospects

Model zoo

- QCD axion
- sterile neutrino
- moduli w/ vector mediation

Hitoshi @ BCTP, Tahoe 2015

- gravitino
- SIMP
- asymmetric DM

WIMP
- non-thermal
- defects

mass [GeV]

Semi-conductors

Superconductors!

WIMP program

New ideas?

Experimental playground

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“Make dark matter great again.”
Thanks!