Light Dark Matter at Neutrino Experiments

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Sub-GeV Dark Matter: Why?

~ unconstrained by current experiments

but lots of new ideas to test it!

US cosmic visions 1707.04591

Neutrino coherent scattering

GeV
Sub-GeV Dark Matter: Why?

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Connection with observed anomalies

e.g. in B decays and/or in muon g-2

e.g. FS Straub 1704.06188, 1809.11061
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First considered in Boehm Fayet 2003

Lots of proposals for DM abundance, e.g. SIMPs

Hochberg+ 1402.5143,…

Connection with Hierarchy Problem (Relaxion DM)

Leptogenesis

Falkowski+ 1712.07652

Fonseca Morgante 1809.04534
Banerjee Kim Perez 1810.01889
Challenges to Direct Detection

“Standard” Direct Detection challenged by low DM masses

$\nu_{\text{DM}}^{\text{halo}} \approx 10^{-3} c$

$E_{\text{NR}} = \frac{q^2}{2m_N} \leq \frac{2\mu_{XN}^2 v_X^2}{m_N} \lesssim 190 \text{ eV} \times \left( \frac{m_X}{500 \text{ MeV}} \right)^2 \left( \frac{16 \text{ GeV}}{m_N} \right)$

“Standard” way-out: go to materials and concepts sensitive to smaller recoils

See e.g. US cosmic visions 1707.04591

Semiconductors
Superconductors
Superfluid Helium

....
A New Idea for Direct Detection

DM interacts with SM by assumption

High-velocity DM component *unavoidably* generated by *Cosmic-ray scatterings*!
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First use of this interaction: Cappiello Ng Beacom 1810.07705 (looked at modifications in CR spectra)
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A New Idea for Direct Detection

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Electron flux

Boschini+ 1801.04059
Induced Recoils on Earth

Energy thresholds above MeV become OK → go to biggest existing detectors!

σ_e = 10^{-30} \text{ cm}^2, \quad N_e \equiv \int dV n_e = 7.5 \times 10^{33} \text{ (i.e. } N_e \text{ at SK)}

\begin{align*}
K_e(\frac{dN_{DM}}{dK_e}) [\text{year}^{-1}] & \\
\sigma_e = 10^{-30} \text{ cm}^2, \quad N_e = \int dV n_e = 7.5 \times 10^{33} \text{ (i.e. } N_e \text{ at SK)}
\end{align*}

see Bringmann Pospelov 1810.10543 for analogous idea w/DM-nucleon interactions
Existing Useful Data

We **repurposed** data in “Search for **Boosted Dark Matter Interacting With Electrons** in **Super-K**”

Super-K collaboration, PRL 120 (2018), 1711.05278

2 DM particles $m_A > m_B$

$B$ interacts with electrons

Agashe+ 1405.7370
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Detection of this DM independent of acceleration mechanism can use published analysis!

| 100 MeV $< E_{vis} < 1.33$ GeV | 1.33 GeV $< E_{vis} < 20$ GeV | $E_{vis} > 20$ GeV |
|-------------------------------|-------------------------------|------------------|
| Data $\nu$-MC $\epsilon_{sig}$ (0.5 GeV) Data $\nu$-MC $\epsilon_{sig}$ (5 GeV) Data $\nu$-MC $\epsilon_{sig}$ (50 GeV) |
| FCFV 15206 14858.1 97.7% 4908 5109.7 93.8% 118 107.5 84.9% |
| & single ring 11367 10997.4 95.8% 2868 3161.8 93.3% 71 68.2 82.2% |
| & e-like 5655 5571.5 94.7% 1514 1644.2 93.0% 71 68.1 82.2% |
| & 0 decay-e 5049 5013.8 94.7% 1065 1207.2 93.0% 13 15.7 82.2% |
| & 0 neutrons 4042 3992.9 93.0% 658 772.6 91.3% 3 7.4 81.1% |

TABLE I. Number of events over the entire sky passing each cut in 2628.1 days of SK4 data, simulated $\nu$-MC background expectation, and signal efficiency at representative energy after each cut.
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|--------------------------------|-----------------------------|-----------------|
| Data  | $\nu$-MC | $\epsilon_{sig}(0.5$ GeV) | Data  | $\nu$-MC | $\epsilon_{sig}(5$ GeV) | Data  | $\nu$-MC | $\epsilon_{sig}(50$ GeV) |
| FCFV  | 15206    | 14858.1            | 97.7%          | 4908  | 5109.7           | 93.8%          | 118   | 107.5           | 84.9%          |
| & single ring | 11367 | 10997.4            | 95.8%          | 2868  | 3161.8           | 93.3%          | 71    | 68.2           | 82.2%          |
| & e-like   | 5655   | 5571.5            | 94.7%          | 1514  | 1644.2           | 93.0%          | 71    | 68.1           | 82.2%          |
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~ Analogous procedure for MiniBooNE (1807.06137) and DUNE (1610.03486)
Our New Limits
Beyond the Vanilla Case

We assumed: i) constant $\sigma_e$

ii) Unspecified Dark Sector
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If instead:

$\sigma_e$ grows at low energies (like low-mass mediator) → our limit rel. weaker than grey ones

$\sigma_e$ grows at high energies (like for SM neutrinos) → our limit rel. stronger than grey ones

$\gtrsim$ keV splitting in the dark sector (“like” Higgsinos) → gray limits evaporate, our stays!

[see e.g. Darmé+ 1710.08430, 1807.10314]
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In concrete models other limits may play a role (especially at $M_{DM} \lesssim \text{MeV}$)

e.g. BBN, Star Cooling,…(many again evaded if small splitting in dark sector)

In progress Ema FS Sato

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Models with Mass Splitting

$\chi_1$ Dark Matter

$\chi_2$ DM heavier partner

$A$ Mediator

Cosmic ray electrons

Electrons in detector
Models with Mass Splitting

\( \chi_1 \) Dark Matter

\( \chi_2 \) DM heavier partner

A Mediator

WANTED:

few 10's MeV \( \gtrsim m_2 - m_1 \gtrsim \) keV

otherwise not enough flux of DM (too few energetic CR electrons)

Evade other DD techniques

Cosmic ray electrons

Electrons in detector
Few 10's MeV \gtrsim m_2 - m_1 \gtrsim \text{keV}

m_2 \gtrsim 10 \text{ MeV}

m_1 \gtrsim 0.5 \text{ MeV}
Cosmology

**BBN**

few 10’s MeV \( \gtrsim m_2 - m_1 \gtrsim \text{keV} \)

\[ m_2 \gtrsim 10 \text{ MeV} \]

\[ m_1 \gtrsim 0.5 \text{ MeV} \]

\[ m_2 \gtrsim m_A \]

**DM abundance**

Case \( m_2 \gtrsim m_A \)

\[ m_A > m_1 \gtrsim m_A / 3 \]

“Forbidden” DM scenario

D’Agnolo Ruderman 1505.07107

Allows for correct abundance w/large couplings
CRs DD vs Other Constraints

Let us first make the most of the splitting can make signal distinguishable from atmospheric $\nu$ background at Super-K, Hyper-K,…

[Kim Park Shin 1612.06867 for boosted DM]

Memo: few $10^{\prime}s$ MeV $\gtrsim m_2 - m_1 \gtrsim$ keV $m_2 \gtrsim 10$ MeV $m_1 \gtrsim 0.5$ MeV $m_2 \gtrsim m_A > m_1 \gtrsim m_A/3$

$m_{X_1} = 0.8m_A$, $m_{X_2} = 1.6m_A$, $\alpha_X = 0.5$
Outlook

More on models - include CR proton acceleration

Go to even larger volumes?  **IceCube**

“We can go to GeV thresholds, maybe even lower”  
*Marek Kowaski*

Go to lower electron energy thresholds?

see Zhu Li Beacom+ 1811.07912 for exploration in the case of DUNE
Back up
Case $m_A \gtrsim m_2$

**DM abundance**

$$T_{FO} \approx m_2/20$$

$$m_1 \lesssim T_{FO}/3 \quad \text{DM rel at FO} \quad \rightarrow \quad \text{Hot DM!}$$

But: dilution via entropy injection after FO can rescue

[e.g. via decays of Higgs field that dominated energy budget]

This should happen after FO and before BBN

$$T_{FO} > T_{BBN} \approx 3 \text{ MeV} \quad \Rightarrow \quad m_2 \gtrsim 100 \text{ MeV}$$

So only high energy CRs work…(maybe protons?)

$$m_1 \gtrsim T_{FO}/3 \quad \text{DM non-rel at FO}$$

Beam dump etc win over CR DD
Distribution of Accelerated DM Component

\[ \sigma_e = 10^{-30} \text{ cm}^2 \]

\[ M_{\text{DM}} = 0.1 \text{ MeV} \]

\[ M_{\text{DM}} = 0.1 \text{ keV} \]
Earth Attenuation

\[ \sigma_e = 10^{-30} \text{ cm}^2 \]

Approximate but conservative treatment
For numerical one see e.g. Emken Kouvaris 1802.04764
A new light particle in B decays?

\[ 2m_\mu < m_V < m_B \]

\[ \mathcal{L} = \left[ (g_{bs} \bar{s}_L \gamma_\nu b_L + \text{h.c.}) + g_{\mu V} \bar{\mu} \gamma_\nu \mu + g_{\mu A} \bar{\mu} \gamma_\nu \gamma_5 \mu + g_{\chi} \bar{\chi} \gamma_\nu \chi \right] V^\nu \]

Resonance interferes with SM prediction

Choose signs to have dip and then peak in \( q^2 = m_{\mu\mu}^2 \)

\[ m_V^2 \gtrsim 6 \text{ GeV}^2 \]

Where to hide the resonance?

If broad enough, it can be hidden in charmonium region, where SM poorly known

\[ H = -N \sum_i C_i O_i \]

\[ O_9 = (\bar{s} \gamma_\nu P_L b)(\bar{\mu} \gamma_\nu \mu) \]

\[ C_{9,10}^V = \frac{g_{bs} g_{\mu V,A} / N}{q^2 - m_V^2 + i m_V \Gamma_V} \]

Testable as soon as they measure higher \( q^2 \)
A new light particle in B decays?

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$$\mathcal{L} = \left[ (g_{bs} \bar{s}_L \gamma_\nu b_L + \text{h.c.)} + g_{\mu V} \bar{\mu} \gamma_\nu \mu + g_{\mu A} \bar{\mu} \gamma_\nu \gamma_5 \mu + g_{\chi} \bar{\chi} \gamma_\nu \chi \right] V^\nu$$

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Choose signs to have dip and then peak in $q^2 = m_{\mu\mu}^2$

$$m_V^2 \gtrsim 6 \text{ GeV}^2$$

$$\mathcal{H} = -N \sum_i C_i \mathcal{O}_i$$

Could be Light Dark Matter Candidate!

Either Asymmetric or Thermal

Testable as soon as they measure higher $q^2$