Abstract

Direct detection is a powerful means of searching for particle physics evidence of dark matter (DM) heavier than about a GeV with $\mathcal{O}$(kiloton) volume, low-threshold detectors. In many scenarios, some fraction of the DM may be boosted to large velocities enhancing and generally modifying possible detection signatures. We investigate the scenario where 100% of the DM is boosted at the Earth due to new attractive long-range forces. This leads to two main improvements in detection capabilities: 1) the large boost allows for detectable signatures of DM well below a GeV at large-volume neutrino detectors, such as DUNE, Super-K, Hyper-K, and JUNO, as possible DM detectors, and 2) the flux at the Earth's surface is enhanced by a focusing effect. In addition, the model leads to a significant anisotropy in the signal with the DM flowing dominantly vertically at the Earth's surface instead of the typical approximately isotropic DM signal. We develop the theory behind this model and also calculate realistic constraints using a detailed GENIE simulation of the signal inside detectors.

Dark Matter Raining on DUNE and Other Large Volume Detectors

Peter B. Denton

HET Lunch Discussion

October 18, 2024

2407.01670 (JHEP)
with Javier Acevedo and Joshua Berger

Brookhaven National Laboratory

Dark matter direct detection

DM direct detection is a good (best?) means of identifying the nature of DM

M. Goodman, E. Witten PRD 1985

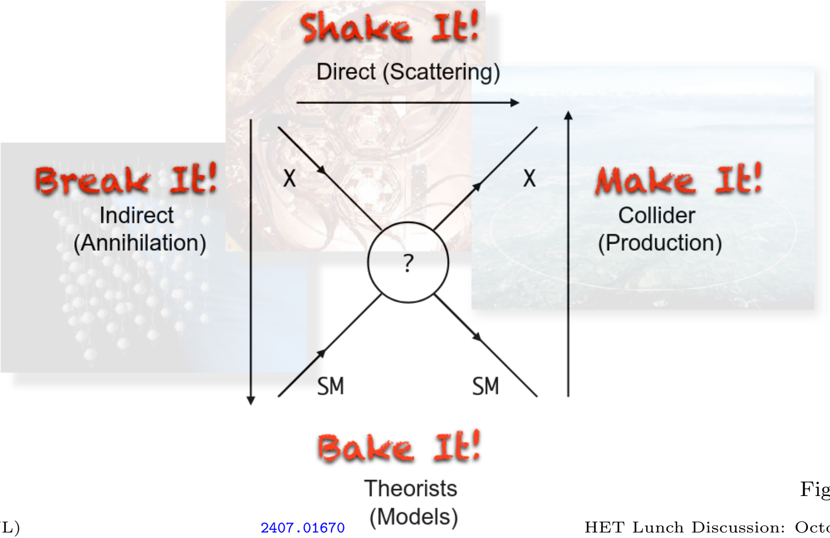
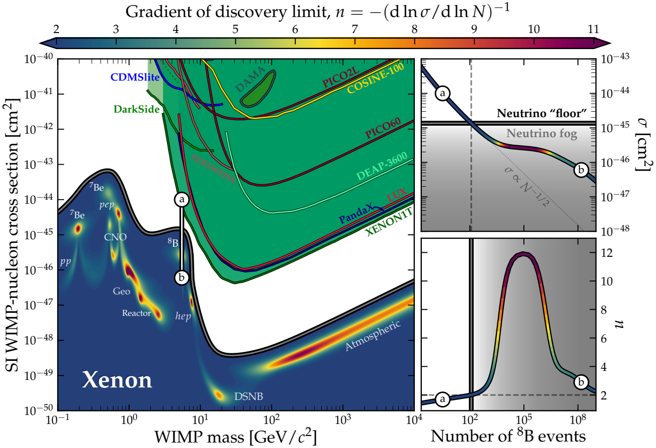


Fig. from Jodi Cooley

Dark matter direct detection status



C. O'Hare 2109.03116

- Lots of progress for $m_\chi \gtrsim$ few GeV
- Latest measurements pushing into ^{8}B solar neutrino flux

PandaX 2407.10892
XENONnT 2409.17868

- Direct detection is much easier if m_χ is heavy enough to bump a nucleus hard enough

Similar story applies to electron scattering

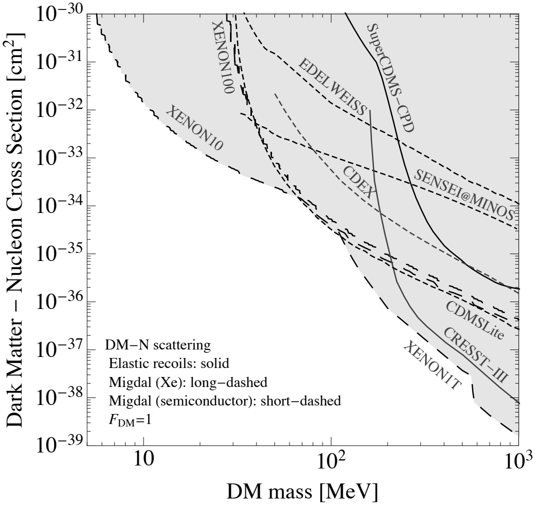
- Going below a GeV is possible, but hard
- Requires innovative detectors
- $\Rightarrow$ small volumes

Sub-GeV dark matter direct detection

To go to low mass DM:

- Scattering off electrons or phonons
- Solid state detectors
- Low-gap detectors
- ⋮

Constraints are:
10^{-32} cm^2 to 10^{-39} cm^2



Snowmass whitepaper 2203.08297

Boosted dark matter

What if some of DM is faster?

- Galactic DM is likely ∼thermal with $v \sim 10^{-3}$
- Numerous ideas to boost a subset of it to larger velocities for easier detection
  - Upscatter by CRs
    - This happens automatically
    - Affects $f_\chi \sim 10^{-5}$
    - Improves bounds by ~ 1 order of magnitude

    T. Bringmann, M. Pospelov 1810.10543
    N. Bell, J. Newstead, I. Shaukat-Ali 2309.11003
  - Evaporation from the Sun
    - Light DM $\lesssim 3$ GeV is captured in the Sun
    - Evaporates with larger velocity

    C. Kouvaris 1506.04316
    H. An et al. 1708.03642
  - Blazars

    A. Granelli, P. Ullio, J. Wang 2202.07598
  - Many other such ideas

Dark matter and long range forces

How to modify speed of 100% of DM

- Suggested by Hooman to *avoid* DM DD:
  - Ultralight mediator coupled to SM and DM
  - Sourced by the Earth with a repulsive sign
  - GeV DM has $KE \sim 0.5$ keV
  - Torsion balance constrains g_{SM}
  - Bullet cluster constrains g_χ

$$V(R_\oplus) \sim \text{MeV}\left(\frac{g_{SM}}{10^{-25}}\right)\left(\frac{g_\chi}{10^{-5}}\right)$$

H. Davoudiasl 1705.00028

Attractive dark matter

How to boost 100% of DM to high speeds

- Change the sign so it is attractive

$$v(R_\oplus) \sim \sqrt{\frac{-2V(R_\oplus)}{m_\chi}} \simeq 0.1$$

- Larger $v \Rightarrow$ larger recoils $\Rightarrow$ larger volume detectors in play
- This leads to a focusing enhancement

$$r \simeq \frac{v_{\rm final}}{v_{\rm initial}} \simeq 10^2$$

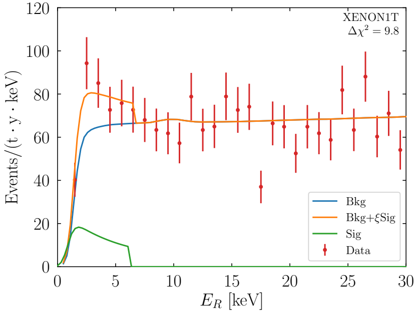
- DM velocity distribution: thermal $\to$ delta function
- Also include a short range interaction to scatter in the detector

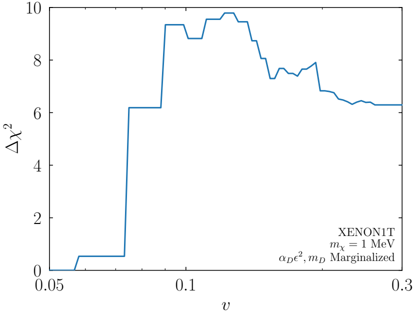
$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F_{D\mu\nu} - \frac{m_D^2}{2} A_{D\mu} A_D^\mu + i\, e_D A_{D\mu} \overline{\chi} \gamma^\mu \chi$$

- Also wanted to explain a 3.3σ excess

XENON1T 2006.09721
H. Davoudiasl, PBD, J. Gehrlein 2007.04989

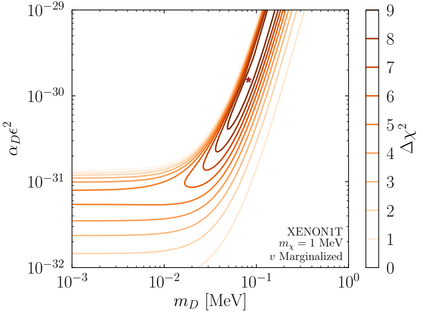
Attractive dark matter





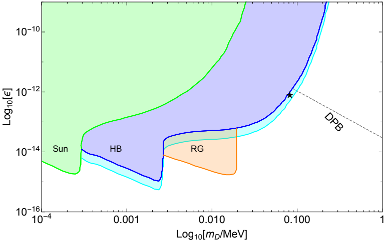
m_ϕ	g_n	g_χ
3×10^{-16} eV	10^{-26}	10^{-7}

α_D	m_D	ϵ	m_χ
2×10^{-6}	0.08 MeV	8×10^{-13}	1 MeV



Connections to astronomy

Short range interaction possibly hinted in anomalous horizontal branch cooling



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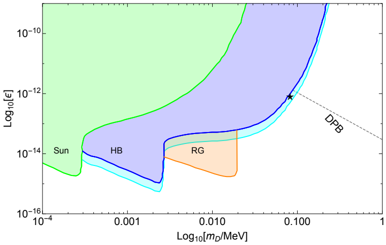

Anomaly went away

XENON1T 2207.11330

Beyond anomalies

Let's dive deeper into this model

Better places to look?

The models

DM (χ) talks to a light scalar (ϕ):

$$\mathcal{L} = i\bar{\chi}\not{\partial}\chi - m_\chi\bar{\chi}\chi + \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - g_\chi\phi\bar{\chi}\chi - g_{\rm SM}\phi\bar{\psi}_f\psi_f$$

or a light vector (A'):

$$\mathcal{L} = i\bar{\chi}\not{\partial}\chi - m_\chi\bar{\chi}\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2A'_\mu A'^\mu - g_\chi A'_\mu\bar{\chi}\gamma^\mu\chi - g_{\rm SM}A'_\mu\bar{\psi}_f\gamma^\mu\psi_f$$

Mass range:

$$R_\oplus < m_{\phi,A'}^{-1} \lesssim 1 \text{ AU}$$

This may well suppress upscattered DM in the Sun

Short range interaction

$$\mathcal{L} = \frac{1}{\Lambda^2}\sum_{f=q,e}\left(\overline{\psi}_f\,\gamma^\mu\,\psi_f\right)\,\left(\overline{\chi}\,\gamma_\mu\,\chi\right)$$

Can vary this to vary $F_{\rm DM}$

Motion in this long-range force

$$E = \text{const.} = \begin{cases} \frac{m_\chi}{\sqrt{1-v_\chi^2}} + V_0(r) & \text{(vector)} \\ \frac{m_\chi + \Phi(r)}{\sqrt{1-v_\chi^2}} & \text{(scalar)} \end{cases}$$

$$v_\chi(r) = \begin{cases} \sqrt{\frac{\left(1-\frac{V_0(r)}{m_\chi}\right)^2 - 1}{\left(1-\frac{V_0(r)}{m_\chi}\right)^2}} & \text{(vector)} \\ \sqrt{1 - \left(1 + \frac{\Phi(r)}{m_\chi}\right)^2} & \text{(scalar)} \end{cases}$$

Vector adds to energy

Scalar adds to mass

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Vector adds to energy

Scalar adds to mass

$$V_0(r), \Phi(r) = -g_\chi g_{\rm SM} \frac{N_\oplus}{4\pi r} e^{-m_{\phi,A'} r}$$

For possible quartic couplings see:
H. Davoudiasl, PBD 2301.09651
PBD 2301.11106

S5 code: github.com/PeterDenton/Spherically-Symmetric-SelfInteracting-Scalar-Solver

Deeper investigation

DM may be captured in the Earth

- Capture rate is likely enhanced by long range interaction
- Captured DM will enhance the potential (and thus enhance the capture rate)
- DM is focused on the Earth by the interaction
- Focusing also enhances the local DM density within the Earth

Scalar weirdness

- Appears that $m_{\text{eff}} \equiv m_\chi + \Phi(r)$ may go through zero
- EOM only depend on $|m_{\text{eff}}|$ so the changing sign makes no difference
- This implies $v = c$ and infinite acceleration
- Unclear what happens at the boundary
- Expect radiation losses to regularize this

Radiation losses

Radiation loss rate: integrate in “boost” space from $\gamma = 1$ to γ at $R_\oplus$:

$$\Delta E_{\rm rad} = \frac{g_\chi m_\chi}{3 g_{\rm SM} N_\oplus} \times \begin{cases} \displaystyle\int_1^{\gamma_\oplus} \frac{2\gamma\left(1+(\gamma-1)^2\right)(\gamma-1)^{3/2}}{\sqrt{\gamma+1}}\, d\gamma & \text{(vector)} \\ \displaystyle\int_1^{\gamma_\oplus} \frac{\gamma(\gamma-1)^{3/2}}{\sqrt{\gamma+1}}\, d\gamma & \text{(scalar)} \end{cases}$$

After computations:

- Radiation losses never relevant for vector case

Given upper limits on couplings

- Radiation losses are not relevant in the scalar case for boosts considered $\gamma \lesssim 10^3$

More scalar case weirdness

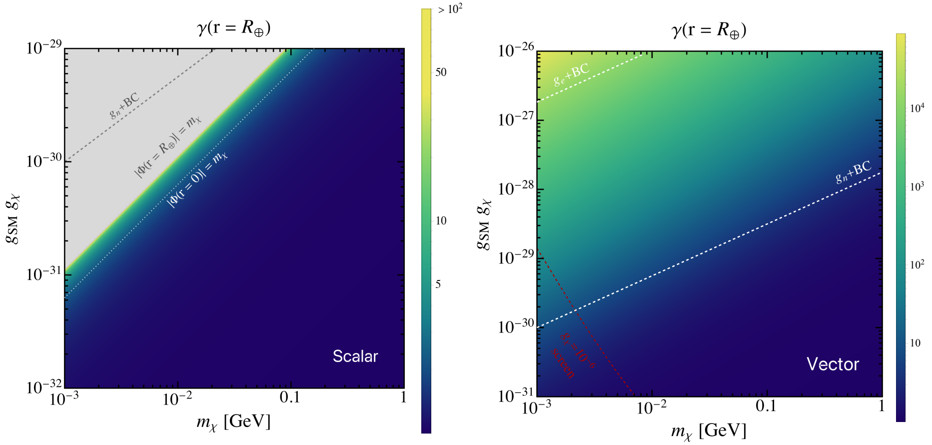
Weirdness at $m_\chi + \Phi(r) = 0$ boundary

- Couplings g_χ and $g_{\rm SM}$ can be large enough for this to exist
- Particles can approach this boundary
- Could lead to a cloud of particles near $r_{\rm crit}$
- For some regions of parameter space expect a reflection of particles

We stay away from this case

Key parameters

It is clear that the key kinematic parameter is the boost

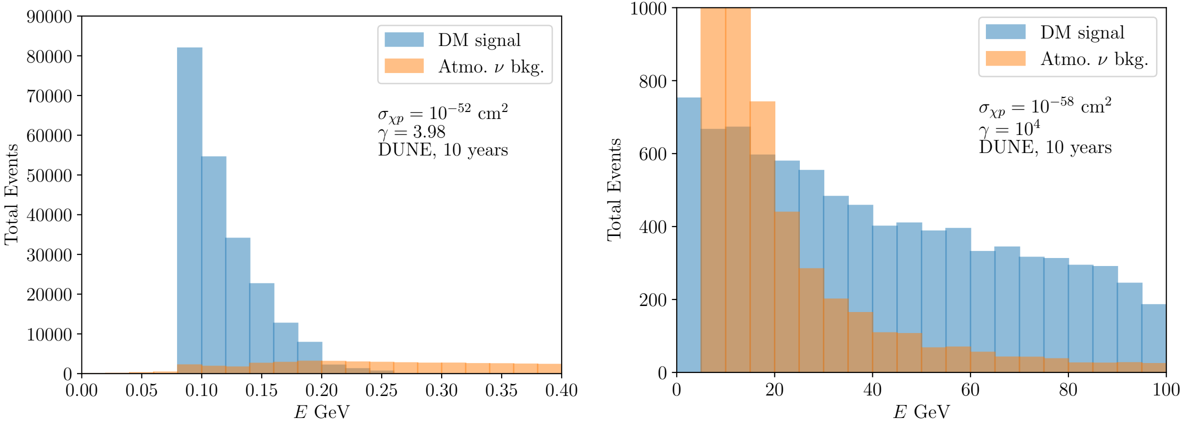


Screening: DM capture in the Earth repels DM

g_f+BC is the limit on $g_\chi g_{\rm SM}$ from torsion and bullet cluster

Signals

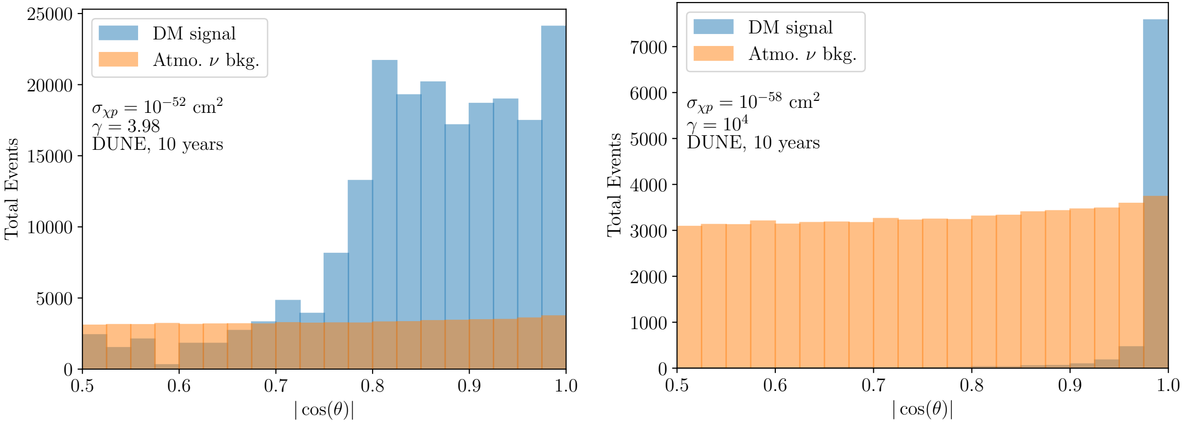
Run modified GENIE for different detectors



$$m_\chi = 0.1 \text{ GeV}$$

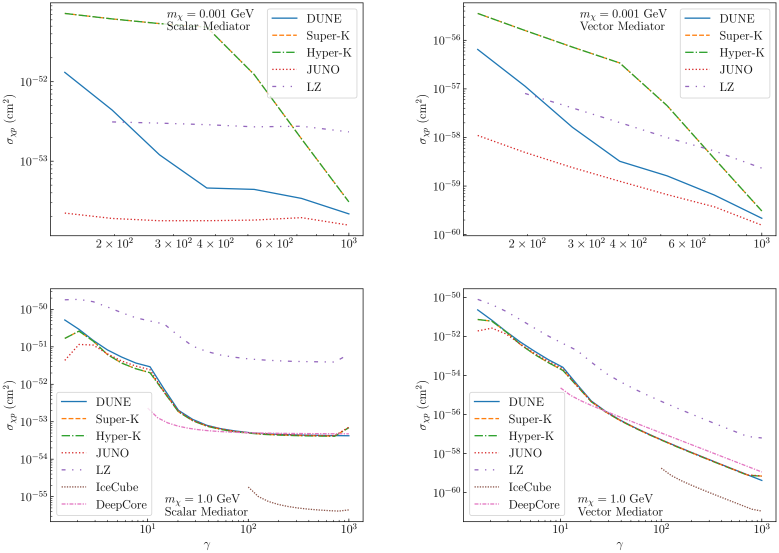
Signals

Run modified GENIE for different detectors



$$m_\chi = 0.1 \text{ GeV}$$

The constraints



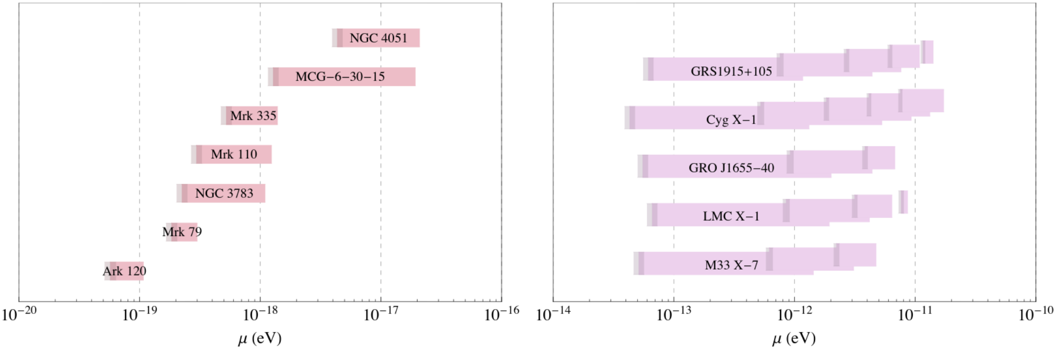
Conclusions

- Ultralight bosons have a rich phenomenology
- Boosted DM modifies constraints considerably
- Direct detection experiments are sensitive to this now
- DM rain is 100% of the DM boosted and coming straight up/down
- Sensitive to couplings $\gtrsim$ 10 orders of magnitude smaller
- Discussions with experimentalists about performing the search

Thanks!

Backups

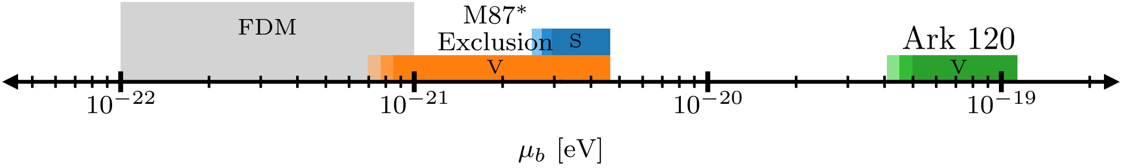
Previous ultralight boson constraints



Spin-1 constraints

M. Baryakhtar, R. Lasenby, M. Teo 1704.05081

New constraints from M87*



Bosons with masses in the regions in color are ruled out.