Searching for Sub-GeV Dark Matter with CENNS Experiments

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COHERENT Theory Workshop

[PdN, M. Pospelov & A. Ritz, in preparation]

Dark Matter - A Brief Review

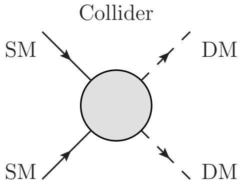
What is known:

- Abundance: 84% of the matter density, 27% of the energy density.
- Non-relativistic at freeze-out.
- Limits on lifetime (very long-lived, if not stable) and interactions (very weak, rarely self interacts).

This says very little about its particle nature. Still do not know:

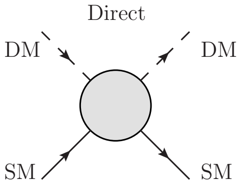
- Mass.
- Interactions with Standard Model matter.
  - So far have only observed its presence through gravitational interactions with baryonic matter.
  - May only interact gravitationally with the SM.

Searching for Dark Matter



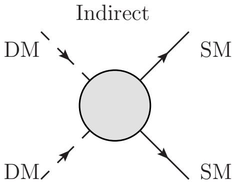
Produce dark matter in high energy collisions, search for missing energy.

Experiments: LHC, Tevatron



Build detectors deep underground and search for scatterings between cosmic dark matter and nuclei.

Experiments: XENON10/100/1T, DAMIC, (Super-)CDMS, CRESST, DAMA/LIBRA

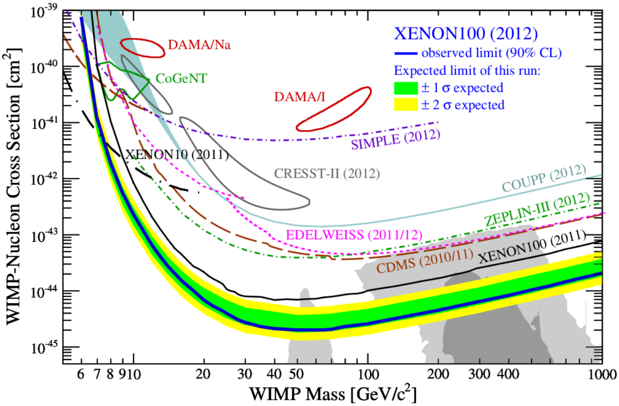


Use earth and space based telescopes to search for signals (photons or cosmic rays) from cosmic dark matter decays and annihilations.

Experiments: INTEGRAL, PAMELA, AMS-2, ATIC, HESS, FERMI

Direct Detection

Experimental limits for WIMP-Nucleon cross section



[XENON Collaboration 2012, arXiv:1207.5988 [astro-ph]]

Fixed Target Neutrino Experiments

Experiments that impact a proton beam on a nuclear target to produce a large number of $\pi^{\pm}$, whose decays result in similar numbers of neutrinos. We are interested in applications of two proposed CENNS experiments:

SNS (COHERENT):

- Phase III experiment calls for a ton-scale detector.
- We consider 1 ton of CsI[Na] located 30 meters from the target, 90° relative to the beamline.
- $\sim 10^{23}$ POT (protons on target) per year with 1 GeV kinetic energy.

BNB:

- Ton-scale liquid argon detector.
- We consider 1-ton of LAr located 20 meters from the target, 90° relative to the beamline.
- Projections made for $\sim 10^{21}$ 8 GeV POT (approximately five years of running with BNB).

Thermal Relic Dark Matter

One of the simplest WIMP dark matter production mechanisms is that of the thermal relic, where dark matter is a relic left over from early universe, before Big Bang Nucleosynthesis.

- While $T \gg m_{\mathrm{DM}}$, dark matter in thermal equilibrium with early universe.
- As T decreases, production becomes less efficient, and n_{DM} declines.
- Annihilation rate is suppressed, as it is proportional to n_{DM}^2. Dark matter is further diluted by the expansion of the universe.
- Annihilation ceases to have a major effect on the number density, and the dark matter freezes out.

Scenario is insensitive to initial conditions of the universe. We can relate the annihilation cross section to the observed dark matter abundance

$$\frac{\Omega_{DM}}{\Omega_{\mathrm{matter}}} \sim \frac{1\mathrm{pbn}}{\langle \sigma v \rangle_{\mathrm{fo}}}$$

Lee-Weinberg Bound and Thermal Relics

The Lee-Weinberg bound tells us that for $m_{DM} <$ few GeV that annihilates via SM mediators with weak scale mass, the dark matter annihilation rate is too small and a thermal relic is overproduced in the early universe,

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{matter}}} > 1.$$

This bound can be circumvented by introducing new light mediators that allow for new dark matter annihilation channels.

Hidden Sector

Light Mediator

Standard Model

Dark matter candidates in these scenarios could potentially be created at low energies.

A Low Mass Dark Matter Scenario

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}m_V^2 V_\mu^2 + \epsilon V_\nu \partial_\mu F_{\mu\nu} + |(\partial_\mu - e' V_\mu)\chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_{h'}$$

- Originally motivated by INTEGRAL 511 keV signal from center of the galaxy.
  - Reproduce signal with $m_{DM} \sim 1 - 3\ \mathrm{MeV}$. [Boehm et al. '04, Fayet]
- V can be produced through kinetic mixing with γ at $\mathcal{O}(\kappa^2)$.
- χ serves as Dark Matter candidate, couples to SM through the V.
  - For $2m_\chi < m_V$, $\mathrm{Br}(V \to \chi\bar{\chi}) \sim 1$ and V decay is prompt.
  - For $2m_\chi > m_V$, $\mathrm{Br}(V \to \mathrm{SM}) \sim 1$. Model is sometimes called secluded.
- The $U(1)'$ coupling strength α' must be kept small to maintain perturbativity.
  - We set $\alpha' = 0.1$, but it can be varied quite widely.
- Requiring that $\Omega_\chi \sim \Omega_{\mathrm{matter}}$ relates κ, α', m_χ and m_V [Pospelov, Ritz & Voloshin '07] .

Experimental Constraints

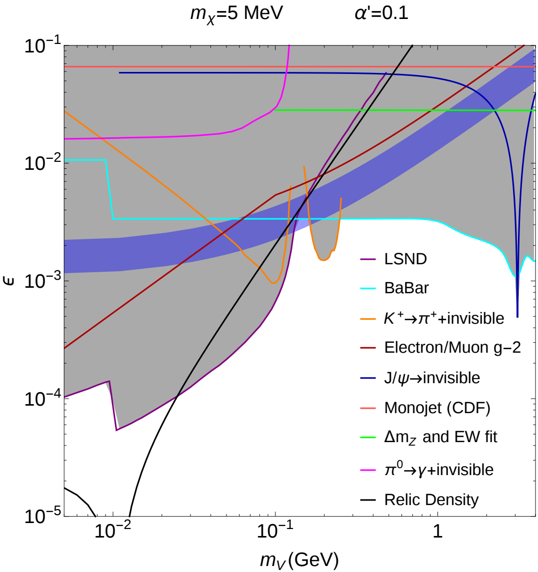
Cosmological:

- Big Bang Nucleosynthesis - So long as $m_{\mathrm{DM}} > 1 - 2$ MeV, freeze-out occurs before BBN [Serpico & Raffelt '04, Jedamzik & Pospelov '09] .
- Cosmic Microwave Background - Annihilation through p-wave, has little effect [Padmanabhan & Finkbeiner et al '05; Slatyer et al '08] .

Particle Physics:

- $g-2$ - Affects the value of $g-2$. Quite strong at low mass, but weakens with increasing mass [Fayet; Pospelov '08] .
  - Can also bring theoretical value of $g-2$ into closer agreement with experimental value.
- $V \to l^+l^-$ - Weak so long as $BR(V \to \chi\bar{\chi}) \sim 1$, holds for most of parameter space of interest. [Bjorken et al. '09; Batell et al '09; Reece & Wang '09; MAMI '11, APEX '11, BaBar'12, ...]
- Missing energy in rare decays
  - Sensitivity to low m_V provided by π, K decays. [E949]
  - Need to use J/ψ, $\Upsilon(1S)$ decays for higher masses of m_V. [BESII'08, BaBar'09, Fayet'09]
- Previous experimental searches have been recast (i.e. E137 [Batell '14] , LSND [PdN '09, Kahn '14]).

Scenario Parameter Space



Dark Matter production at FTNEs

Low mass dark matter could also be produced at these experiments, primarily through radiative processes. Of particular note to experiments studying CENNS:

- Radiative π^0 decays.
  - $\pi^0 \to V\gamma$, $V \to \chi\bar{\chi}$.
- π^- absorption in the target material, followed by photon emission.
  - $\pi^- + p \to V + n$, $V \to \chi\bar{\chi}$.
- Radiative Δ decay.
  - Probably sub-dominant, not currently included.

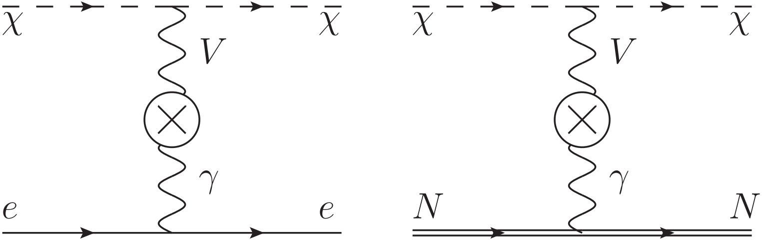
$p + N \rightarrow \pi^0 \rightarrow V\gamma$

- π^0's are produced alongside $\pi^{\pm}$'s, and in similar quantities.
- Analysis of this production channel at LSND placed best limits on 1 MeV to $\mathcal{O}(10 \text{ MeV})$ dark matter for $m_V < m_{\pi^0}$. [Batell '09] .
- Requires a parametrization of the π^0 distribution for each experiment.
- Fitting to the average of a π^+ and π^- distribution provides a reasonable approximation of the observed production distribution and rate.
  - Burman Smith distribution is suitable for beam energies of $\mathcal{O}(1GeV)$ and a variety of materials, used for the SNS source [Burman '89] .
  - Sanford Wang distributions with parameters fitted for BNB energies and the MiniBooNE target, used for BNB source. [Aguilar-Arevalo [MiniBooNE collaboration]] '09]
- These distributions may not be as reliable at large angles.

$p + N \rightarrow \pi^-, \pi^- + p \rightarrow n + V$

- Majority of π^- which are stopped in the target are absorbed by protons.
- Approximately 50% of these absorption events results in isotropic photon emission.
  - Photon has energy of $\sim 129\ MeV$. [R. MacDonald '76]
  - Other 50% of events result in π^0 emission, should be accounted for by previously mentioned distributions.
- Distribution of dark matter is isotropic, which is a large advantage for very off-axis experiments
- Dark matter production in this channel is suppressed by smaller number of π^-'s produced at lower energies.

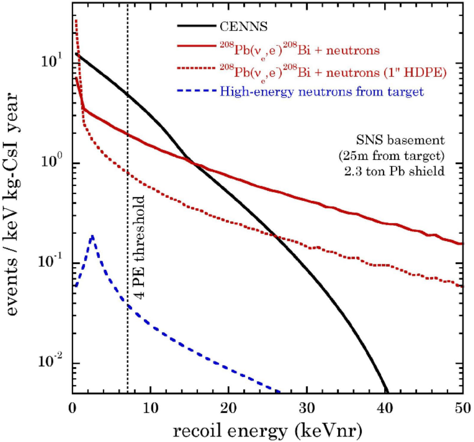
Detecting Dark Matter with Neutrino Detectors



- We can search for hidden sector dark matter through its interactions with nucleons or electrons.
- Coherent scattering adds a significant enhancement to DM-nucleus scattering signal, proportional to Z^2.
- Dark matter scattering signature resembles NCE (neutral current elastic) scattering.
- A simple counting experiment is unlikely to generate a sufficient number of events to exceed CENNS neutrino signal and other backgrounds.
  - Dark matter production is prompt, so it can benefit from any timing structure in the beam.

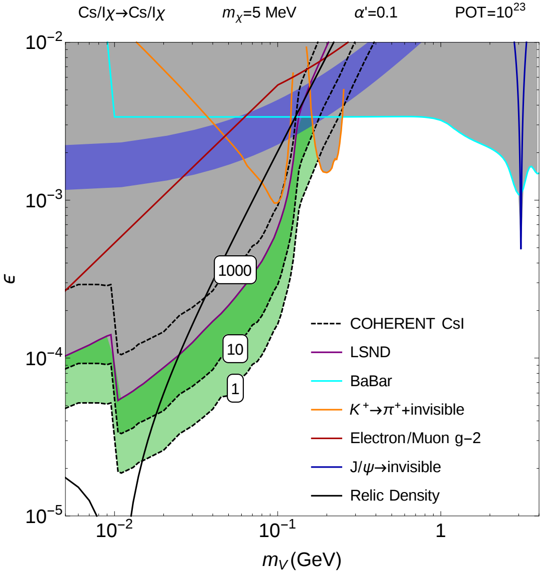
Detecting Dark Matter with Neutrino Detectors

- Cuts on recoil energy spectrum could reduce background. Coherent nucleus-dark matter scattering tends to produce a harder recoil energy distribution than CENNS.
- For our SNS projections, we cut recoil energies below 40 keV.



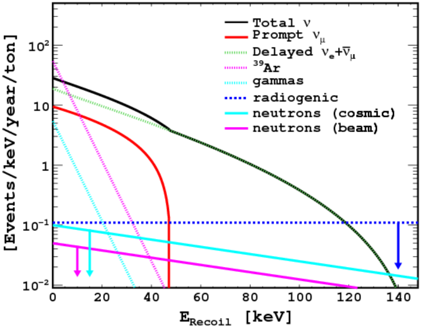
[Collar '14, arXiv:1407.7524]

Searching with the SNS



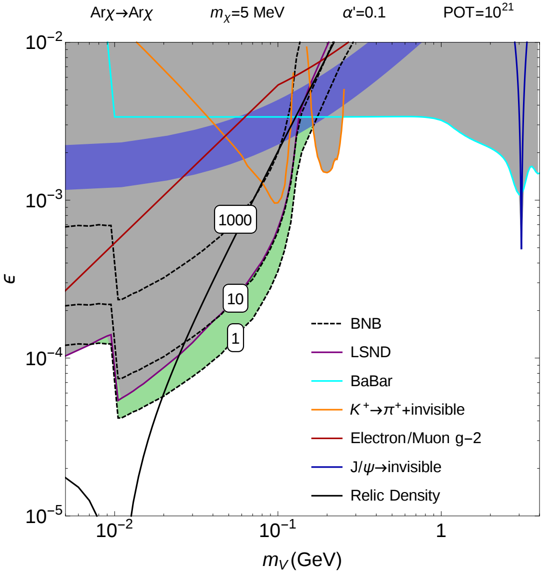
Detecting Dark Matter with Neutrino Detectors

- Cuts on recoil energy spectrum required. Coherent nucleus-dark matter scattering tends to produce a harder recoil energy distribution than CENNS.
- For our BNB projections, we cut recoil energies below 50 keV.



[Brice '13, arXiv:1311.5958]

Searching with the BNB



Conclusion

- Thermal relic WIMP with a sub-GeV mass and interactions mediated by a light U(1)′ vector boson provides a viable dark matter candidate.
- This candidate escapes many of the best limits imposed by standard direct, indirect and collider searches.
  - While new limits are being placed on the parameter space, a great deal of viable parameter space remains unconstrained. Electron fixed target experiments could reduce this further.

    [see i.e. arXiv:1307.6554, arXiv:1403.6826, arXiv:1406.3028, arXiv:1406.2698, arXiv:1411.1404]
  - Simple variations on the benchmark scenario, such as a baryonically coupled V mediator, possess different sets of constraints.
- CENNS experiments possess sensitivity to hidden sector states, with the ability to search for viable dark matter candidates.
  - It is possible for these experiments to search for light DM while studying CENNS events.

Acknowledgements

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