Light Dark Matter

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This is a note for the Cornell PHENO talk: Light Dark Matter (LDM) models which have DM masses in the keV to GeV range are both experimentally and theoretically motivated. The corresponding parameter space of these models has not been reached by the current direct detection experiments. It then is interesting to look for other experimental constraints. In this talk, we introduce some examples – WIMPless, MeV and Sterile neutrino DM – to have a taste in the LDM model building, and talk about the possible direct detection bounds of sub-GeV DM proposed in [7]. We also mention the current cosmological and collider constraints on DM in the range of MeV to GeV scale studied in [8].

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I. WHY LIGHT DARK MATTER?

Dark Matter (DM) exists, but its identity is unknown. Since the idea of WIMP sucks under the experimental constraints, it is important to explore other theoretically motivated scenarios. An interesting possibility is *light* DM (LDM), *with masses in the keV to GeV range.* There are experimental and theoretical reasons to think about the DM in this range. In 2003, it was announced that the SPI spectrometer on board the INTEGRAL satellite had confirmed the presence of a very bright flux of 511 keV photons from the region of the Galactic Bulge. This emission corresponds to approximately 3×10^{42} positrons being injected per second in the inner kilo-parsecs of the Milky Way[1]. The signal is approximately spherically symmetric, with little of the emission tracing the Galactic Disk. It is somewhat difficult to explain the observed 511 keV emission with astrophysical mechanisms:

- It is not clear the known astrophysical sources are able to inject a large enough number of positrons to generate the observed signal: Type Ia supernovae cannot do it, and hypernovae, gamma ray bursts or microquassars are less clear.

- Even if such an astrophysical source exists, they would be expected to produce a signal that traces both the disk and bulge components of our galaxy.

Since the DM halo is roughly spherically symmetric, and the emission rate can be decided by the DM annihilation cross section, several LDM models have been built to explain the observed emission. Due to the narrow width observed in the 511 keV line, the positrons must be injected with energies less than a few MeV.

Besides the astrophysical reasons, the direct detection bounds on the LDM parameter space is totally unconstrained. Of course, things would become less interesting if the LDM models can never be probed by experiments. This is why I am going to show you that we do have constraints from colliders and cosmology in the LDM parameter space, and there is a proposed sub-GeV scale direct detection with the existing technologies. Before doing that, let us talk about some models first.

II. VARIOUS LDM MODELS

The LDM theory can naturally occur if DM does not couple strongly to the visible sector. To generate the 511 keV flux, the product of the couplings of the mediating particle to electrons and the DM must be: $g_\chi \times g_e \sim 10^{-5} - 10^{-7} \times (m_{\rm med}/10\,{\rm MeV})^2$. For models with $m_{\rm med} \gtrsim m_\chi$, and setting the g_e to be minimum (to avoid the experimental constraints like EDM), the allowed $g_\chi \sim 10^{-5}$. It is roughly the number of the ratio between the MeV DM mass and the electroweak scale. This is why many LDM models have the a mass of particle in the hidden sector from Weak scale dynamics but be suppressed by small couplings between the hidden and visible sectors.

There are many LDM models in the market, and it is not very helpful to get into details of every model. I will then only show you the 'spirit' for each of them.

II.1. WIMPless model

WIMPless model is not designed for LDM only, but it is a generalization of models having the WIMP miracle: $\Omega_\chi \propto 1/\langle \sigma v \rangle \sim m_{\rm EW}^2/g_{\rm EW}^4$ [2]. Using the idea of gauge-mediated SUSY breaking, when having the MSSM and DM sectors, the SUSY breaking generated fermion masses in the two sectors are

$$m_{\rm MSSM} \sim \frac{g^2}{16\pi^2}\frac{F}{M}, \qquad m_\chi \sim \frac{g_\chi^2}{16\pi^2}\frac{F}{M}. \tag{1}$$

Since the $m_{\rm MSSM}$ is about electroweak scale and g is order one, we have (for $m_\chi \sim 1$ MeV)

$$\frac{m_\chi^2}{g_\chi^4} \sim \frac{m_{\rm EW}^2}{g_{\rm EW}^4}, \qquad g_\chi^2 \sim \frac{m_\chi^2}{m_{\rm EW}} \sim 10^{-5}. \tag{2}$$

The first equality gives the right relic density, and the other one gives the right coupling for the 511 keV flux (as discussed in the beginning). A more precise constraints including the BBN bound is

$$10^{-3} \lesssim g_\chi \lesssim 3, \qquad 10\,\text{MeV} \lesssim \text{m}_\chi \lesssim 10\,\text{TeV}. \tag{3}$$

II.2. MeV DM

It is not surprised the 'MeV DM' models show up in the MeV DM discussion. The motivation for this type of models is really to explain the 511 keV flux. It has been shown in [3] that the DM particles with a MeV scale mass can inject the required rate of positrons into the Galactic Bulge through the P-wave annihilation (such that $\sigma v \propto v^2$), while producing the right relic abundance at the same time.

There are several MeV DM models. Here I give an example of the one that generates the light scale in a SUSY model [4]. The final (low energy) particle content in this model has an MeV-scale DM which annihilates to electrons through an MeV-scale mediator with an $\mathcal{O}(10^{-5})$ effective coupling. To relate the small mass and the coupling, the DM and mediator masses are generated radiatively through the loops carrying the small coupling.

The hidden sector contains a chiral super field Φ and a vector super field V. The gauge boson in V associates with a $\text{U}(1)_h$ symmetry and couples to the SM particles through a kinetic mixing. The fermionic component of Φ is the DM, and the scalar component gets a vev that breaks the $U(1)_h$. The breaking also gives the gauge boson of V (the mediator) a mass. The scalar of Φ gets a vev through the D-term (gives the ϕ^4) and the two loop corrections containing V and fermions (gives the negative mass square). The small gauge coupling between V and the SM fermion plays an important role in the loops, and the vev is proportional to this small coupling. It then be able to achieve the goal of having $m_\chi \sim$MeV, and $g_\chi \sim m_\chi/M_{\rm EW} \sim 10^{-5}$ as discussed before.

II.3. Sterile neutrino DM

Sterile neutrinos are the SM gauge singlets that couple to the active neutrinos through Yukawa. A light (keV) sterile neutrino can be a DM candidate and has a better fit to the structure formation comparing to the cold DM (CDM)[1] (a nice review [5]). Because of the small Yukawa, the keV sterile neutrinos are out of equilibrium at high temperatures. They are not produced in the freeze-out from equilibrium. However, there are several ways in which the relic population of sterile neutrinos could have been produced. In this note we focus on the mechanism that comes from neutrino oscillation (Dodelson-Widrow) [6].

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[1] The free stream length of the CDM is too short and would generate small structures that are not observed in the density fluctuation spectrum.

The production by oscillation happens at low temperatures, below 1 GeV, and only depends on the mass of the sterile neutrino and its mixing with the active neutrinos. It does not depend on the UV physics that generates the small neutrino masses. There are different models that produce the sterile neutrino density, but all of them need to take into account the contribution from the oscillations. Neutrino oscillation converted some of the active neutrinos (in equilibrium) to sterile neutrinos (out of equilibrium). Matter and the quantum damping effects the oscillation, and the effective mixing angle between the active and sterile neutrinos in 'plasma' can be parametrized into a function

$$\sin^2 2\theta \approx \frac{\left(\Delta m^2/2p\right)\sin^2 2\theta}{(\Delta m^2/2p)\sin^2 2\theta + (\Delta m^2/2p\,\cos 2\theta - V_m - V_T)^2} \tag{4}$$

Here V_m and V_T are the effective matter and temperature potentials. In the limit of small angles and lepton asymmetry (so the matter effect is small), the mixing angle can be parametrized as

$$\sin\theta_m \approx \frac{\sin\theta}{1 + 0.27\zeta\left(\frac{T}{100\,\mathrm{MeV}}\right)^6\left(\frac{keV^2}{\Delta m^2}\right)^2}. \tag{5}$$

Thermal effects suppress the the effective mixing significantly for temperatures $T > 150\,(m/\mathrm{keV})^{1/3}$ MeV. If the sterile neutrinos interact only through mixing, all the interaction rates are suppressed by the mixing angle $\sin^2 2\theta_m$, and they can *never* be in thermal equilibrium in the early universe. The relic population of the sterile then is not a result of freeze-out.

In the relevant range of parameters, one can approximate

$$\Omega_s \sim 0.2\left(\frac{\sin^2\theta}{3\times 10^{-9}}\right)\left(\frac{m_s}{3\,\mathrm{keV}}\right)^{1.8}. \tag{6}$$

The relic density and the X-ray bounds **what's the bound?** force the sterile neutrino mass to be 1-3 keV. There are some problems of this scenario. First, it does not satisfy the Luman-α bounds. Moreover, with the small mixing angle and large mediator mass ($\sim M_W$), I do not think it gives the large enough 511 keV flux.

II.4. Asymmetric DM

See

II.5. Bosonic super-WIMP

II.6. Axino

II.7. Gravitino

III. LDM DETECTION

The current direct detection experiments only probe the region with the mass of the DM particles $\gtrsim 10$ GeV. It then is important to consider constraints from other kind of searches. Here we discuss the searches following two different approaches, one is to improve the current direct detection experiments using the electron and molecular recoil, the other one is to combine constraints from the astrophysical and collider searches.

III.1. Direct detection of sub-GeV DM

III.1.1. Basic proposal

The discussion follows the paper [7]. Focusing on the MeV to GeV range DM, the paper argue that XENON10 and maybe also XENON100, LUX, and CDMS can allow the direct detection of these LDM. The bound may be significantly improved for dedicated experiments in the future.

For LDM, the average energy transfer in an elastic nuclear recoil is

$$E_{nr} = q^2/2m_N \simeq 1\ eV \times (m_{\rm DM}/100\,{\rm MeV})^2\,(10\,{\rm GeV/m_N})\,, \tag{7}$$

where m_N is the mass of the nucleus, $q \sim m_{\rm DM}v$ is the momentum transferred, and $v \simeq 10^{-3}$ is the DM velocity. This *nuclear* recoil energy is well below the lowest thresholds in existing direct detection experiments. However, the total energy available in the scattering is much larger

$$E_{\rm tot} \simeq m_{\rm DM}v^2/2 \simeq 50\,eV \times (m_{\rm DM}/100\,{\rm MeV})^2\,, \tag{8}$$

and could lead to signals from the following possibilities:

- *Electron ionization (DM-electron scattering).*
- *Electron excitation (DM-electron scattering).*
- *Molecular dissociation (DM-nuclear scattering).***why is the required energy so small?**

These processes require energies of 1-10 eV, and can be caused by the scattering of DM with mass as small as $\mathcal{O}$(MeV). The more promising detectable signals from these possibilities are

- *Individual electrons:* An electron may be ionized by DM-electron scattering. The amplifier can produce a large enough signal. We will focus on this signal in the discussion.
- *Individual photons:* De-excitation of the atoms produces photons. The DM-signal requires multi-photon signals to be identified. This makes the detection more difficult.
- *Individual ions:* Ions can be produced by ionizing electrons or as the result of molecule dissociation. The technology of detecting ions still need to be established.
- *Heat/phonons:* These signals are important if the charge carriers do not drift away from the scattering site. They may be detectable with ultra-low threshold bolometers[].

We focus on the detection of individual electrons produced by DM-electron scattering.

III.1.2. Direct detection rates

The DM-electron scattering is enhanced when having the attractive potential around the nucleus. This is because the 'effective mass' of the electron is larger when being inside the potential well, and the allowed recoil energy is higher. The phase space for the scattering then becomes larger. This effect can be described by the Fermi-factor (a form factor from beta decays) $F(p, Z_{\rm eff}) = |\psi_{\rm exact}(0)/\psi_{\rm free}(0)|^2$. In the non-relativistic limit

$$F(p, Z_{eff}) = \frac{2\pi\eta}{1-e^{-2\pi\eta}}, \qquad \eta = Z_{\rm eff}\frac{\alpha\, m_e}{p}. \tag{9}$$

$F(p, Z_{\text{eff}})$ grows as $1/p$, as a slowly-escaping electron is more affected by the potential well. This is nothing but the Sommerfeld enhancement, but occurring to an outgoing rather than an incoming state. On the other hand, the scattering would be suppressed if the electron's binding energy is too big. The energy for the DM-electron scattering has to be around the size of the atomic process (let's call this typical scale in phase space as q_0), otherwise the effect is suppressed. For the required DM velocity to overcome the binding energy

$$v > v_{min} = \frac{\Delta E_B + E_R}{q} + \frac{q}{2m_\chi}, \tag{10}$$

given that the typical size of the DM velocity is $10^{-3}c$, the scattering with $\Delta E_B \gtrsim 10^{-3} q_0$ receives a suppression relative to the free electron scattering. Combing the above enhancement and suppression mechanisms together, in order to enhance the scattering cross section, we would like to have a potential well with a small volume q_0^{-3}. This can be achieved by having elements with high Z, which exhibit a deep potential, while another is to minimize ΔE_e by using semi-conductors targets.

Assume DM interacts directly with electrons, and parametrize its coupling in a model-independent way. The reference cross section $\bar{\sigma}_e$ is

$$\bar{\sigma}_e \equiv \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2} \overline{|\mathcal{M}_{\chi e}(q)|^2}\Big|_{q^2=\alpha^2 m_e^2}, \tag{11}$$

where the generic amplitude is

$$\overline{|\mathcal{M}_{\chi e}(q)|^2} = \overline{|\mathcal{M}_{\chi e}(q)|^2}\Big|_{q^2=\alpha^2 m_e^2} \times |F_{\text{DM}}(q)|^2. \tag{12}$$

The paper then calculate the differential cross sections for the DM scattering that ionizes the electron in atoms or crystals. We can look at the plots directly. The plot on the left shows the detection limit for a dark photon model. In which the heavy mediator (the dark photon) generates a form factor $F_{DM} = 1$. The plot on the left is for an MeV DM model. Where the light mediator gives a form factor $\alpha^2 m_e^2/q^2$.

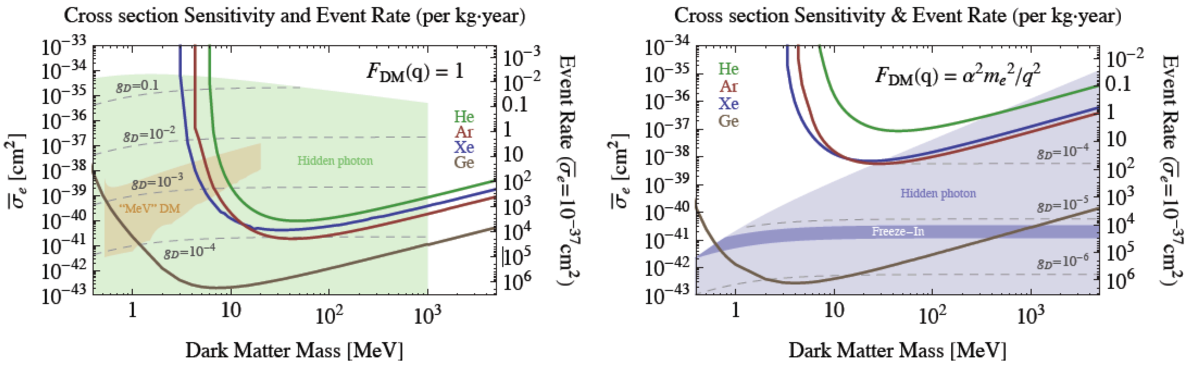

FIG. 2: The cross section exclusion reach (left axis) at 95% confidence level for 1 kg·year of exposure, assuming only the irreducible neutrino background. This corresponds to the cross section for which 3.6 events are expected after 1 kg·year. The right axis shows the event rate assuming a cross section of $\overline{\sigma}_e = 10^{-37}$ cm^2. Results are shown for xenon (blue), argon (red), germanium (brown), and helium (green) targets. **Left:** Models with no DM form-factor. The green shaded area indicates the allowed region for $U(1)_D$ (hidden photon) models with $m_{A_D} \gtrsim 10$ MeV. The orange shaded area is the region in which a particular model of "MeV" DM can explain the INTEGRAL 511 keV γ-rays from the galactic bulge [9]. **Right:** Models with a very light scalar or vector mediator, for which $F_{\text{DM}} = \alpha^2 m_e^2/q^2$. The blue region indicates the allowed parameter space for a hidden $U(1)_D$ model with a very light ($\ll$ keV) hidden photon. The darker blue band corresponds to the "Freeze-In" region. For illustration, constant g_D contours are shown with dashed lines, assuming $m_{A_D} = 8$ MeV and $\varepsilon = 2 \times 10^{-3}$ (left plot) and $m_{A_D} = 1$ meV and $\varepsilon = 7 \times 10^{-9}$ (right plot). For more details see the text and the Appendix.

III.1.3. Backgrounds

The paper gives qualitative discussion of several possible backgrounds.

- *Radioactive impurities:* Radioactive decays typically deposit energy well above a keV and should be easily separated from the DM signal.

- *Surface events:* Higher energy surface events may appear to have spuriously low energies due to partial signal collection. New experimental designs for the position reconstruction may be necessary to reject the very low energy events.

- *Secondary events:* The primary signal of a higher-energy background may be accompanied by a number of low energy events. Such a background could be reduced by vetoing events occurring to close in time to a large event.

- *Neutrons:* The neutron background is shielded in current direct detection experiments. The modification of designs to minimize the very low background is necessary.

- *Neutrinos:* Neutrino scattering with electrons and nuclei generates a small but irreducible background. This may set the ultimate limit to the reach of LDM direct detection experiments. The paper calculate the background and include it in the direct detection plots.

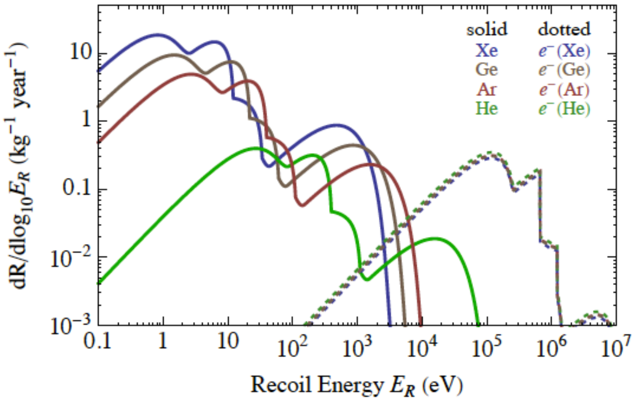

FIG. 1: Background solar neutrino rates per kg·year. Solid lines show *nuclear* recoil spectra for neutrinos scattering with xenon (blue), germanium (brown), argon (red), and helium (green). These are not expected to significantly contribute to the ionized electron signal from LDM-electron scattering. Dotted lines, with same color coding as above, show rates for neutrino scattering off electrons. These rates are small and peak at higher energies than LDM-electron scattering.

III.1.4. Few words about the annual modulation

Besides neutrinos, the background to LDH scattering are currently largely unknown. An important handle to distinguish signal from background is therefore the annul modulation of the DM scattering rate. The paper gives a discovery reach using the annal modulation.

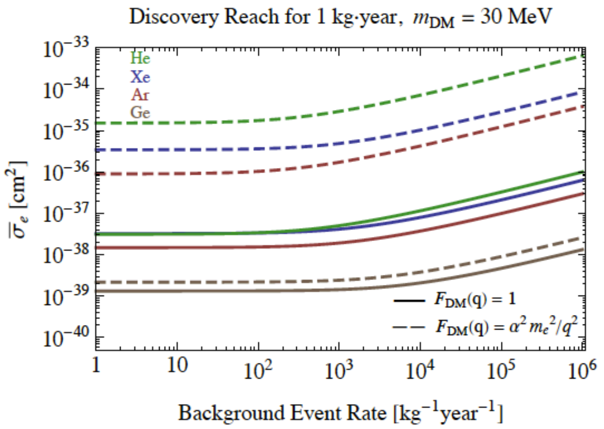

FIG. 4: The discovery reach using annual modulation, as a function of the background event rate, for $m_{\mathrm{DM}} = 30$ MeV and 1 kg·year exposure. Results are shown for xenon (blue), argon (red), germanium (brown) and helium (green) targets, assuming either no DM interaction form-factor (solid lines) or $F_{\mathrm{DM}} = \alpha^2 m_e^2/q^2$ (dashed lines). The annual modulation is $\mathcal{O}(10\%)$ in all cases. The reach scales as $\sqrt{\text{exposure}}$ (exposure) for large (small) background rates.

III.2. Cosmological, astrophysical and collider constraints

See [8]

[1] P. Jean, J. Knoedlseder, V. Lonjou, M. Allain, J.-P. Roques, G. Skinner, B. Teegarden, G. Vedrenne, P. von Ballmoos, B. Cordier, P. Caraveo, R. Diehl, P. Durouchoux, P. Mandrou, J. Matteson, N. Gehrels, V. Schoenfelder, A. Strong, P. Ubertini, G. Weidenspointner, and C. Winkler, "Early spi/integral measurements of galactic 511 kev line emission from positron annihilation," `astro-ph/0309484v1`. `http://arxiv.org/abs/astro-ph/0309484v1`.

[2] J. L. Feng and J. Kumar, "The wimpless miracle: Dark matter particles without weak-scale masses or weak interactions," `0803.4196v3`. `http://arxiv.org/abs/0803.4196v3`.

[3] C. Boehm, D. Hooper, J. Silk, and M. Casse, "Mev dark matter: Has it been detected?," `astro-ph/0309686v3`. `http://arxiv.org/abs/astro-ph/0309686v3`.

[4] D. Hooper and K. M. Zurek, "A natural supersymmetric model with mev dark matter," `0801.3686v3`. `http://arxiv.org/abs/0801.3686v3`.

[5] A. Kusenko, "Sterile neutrinos: the dark side of the light fermions," `0906.2968v3`. `http://arxiv.org/abs/0906.2968v3`.

[6] S. Dodelson and L. M. Widrow, "Sterile neutrinos as dark matter," `hep-ph/9303287v1`. `http://arxiv.org/abs/hep-ph/9303287v1`.

[7] R. Essig, J. Mardon, and T. Volansky, "Direct detection of sub-gev dark matter," `1108.5383v2`. `http://arxiv.org/abs/1108.5383v2`.

[8] T. Lin, H.-B. Yu, and K. M. Zurek, "On symmetric and asymmetric light dark matter," `1111.0293v1`. `http://arxiv.org/abs/1111.0293v1`.