Multi-messenger constraints on asymmetric dark matter

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Baryonic and dark matter

Dark matter and **Baryon** make up 27% and 4% of the total energy density of the Universe

$\Omega_{\rm DM} h^2 \sim 0.14$ $\Omega_{\rm B} h^2 \sim 0.022$

1. Present day mass density of DM is a factor of five higher than VM (Planck Collaboration, 2018)

$$\Omega_{\rm DM} \simeq 5\, \Omega_{\rm b}$$

$\Longrightarrow$ strong connection between the physics and evolution of baryonic matter and dark matter

- Assuming (i) dark matter at the TeV scale $m_{\rm DM} \sim 0.1 - 1$ TeV (ii) produced thermally in the early Universe $\Longrightarrow$ cross-section of weak strength – **WIMPs** ($n_{\rm DM} \sim 10^{-3} n_B$)

- WIMP scenario – the similarity in abundance between DM and baryons then must be taken to be a coincidence – strongly constrained by direct and indirect detection bounds

Baryon - DM coincidence problem

If it were not for Baryogenesis...

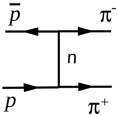
- DM mass density can be explained by the WIMP mechanism

$$\Omega_{\rm DM} \propto m_{\rm DM} n_{\rm DM} \simeq 0.1 \times \left(\frac{10^{-9}\ {\rm GeV}^{-2}}{\langle \sigma v \rangle} \right) \tag{1}$$

⟹ observed density is explained by choosing appropriate mass and couplings

But...

- Baryon density is too low due to its large annihilation cross-section



$$\langle \sigma v \rangle \sim \frac{4\pi}{m_n^2} \sim 10\ {\rm GeV}^{-2}$$

Hence, without asymmetry,

$\Omega_{\rm DM} : \Omega_b = 1 : 10^{-10}$

- Visible matter at the current epoch is due to the baryon asymmetry of the Universe

$$\eta(b) = \frac{n_b - n_{\bar{b}}}{s} \simeq 10^{-10}$$

n = number density and s = entropy density (constant for isentropic expansion of the Universe)

Asymmetric dark matter

- DM density at the current epoch is similarly due to DM particle-antiparticle asymmetry

$$m_{\mathrm{DM}} \sim 5 m_b \eta(b)/\eta(DM) \sim \mathcal{O}(1)\ \mathrm{GeV} \tag{2}$$

[Barr, Chivukula, Farhi (1990), D. B. Kaplan (1992), D. E. Kaplan, Luty and Zurek (2009)]

Two main mechanisms

- Sharing:

– SM and DM sectors share a primordial asymmetry produced in an arbitrary sector
– Asymmetry is thermally distributed in the two sectors
– $\eta(DM)/\eta(B)$ is related to the degrees of freedom in the two sectors

[Petraki & Volkas (2013), Zurek (2013)]

- Cogenesis:

– The asymmetries in the two sectors are produced by the same process.
– DM - SM interactions – out of thermal equilibrium
– $\eta(DM)/\eta(B)$ depends on the branching ratio of the asymmetry

- Among various possibilities, ADM with the sharing mechanism through B-L connecting operators with thermal Leptogenesis is very well motivated !

– B-L symmetry is well-motivated in the SM (softly broken)
– Thermal Leptogenesis is very successful for the baryogenesis

Dark baryon and photon

- We focus on models of composite ADM
  - Large annihilation cross-section
  - $m_{\mathrm{DM}} \sim \mathcal{O} \sim 1$ GeV without fine-tuning
  - Models are rather complicated
  - Entropy in the dark sector should be transferred to SM – **dark photons**

Dark photon has kinetic mixing with SM photons

$$\mathcal{L}_{A'\text{-}A} = \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu \tag{3}$$

- Composite ADM with dark photon [Ibe, Kamada, Kobayashi, Nakano (2018)]
  - dark matter = dark protons or dark neutrons ($m_{N'} \sim \mathcal{O}(1)$ GeV)
    $p', \bar{p}', n', \bar{n}'$
  - dark baryons annihilate into dark pions ($m_{\pi'} \sim \mathcal{O}(100)$ MeV $-\mathcal{O}(1)$ GeV)
    π', π'^+, π'^-
  - dark pions annihilate/decay into dark photons ($m_{\gamma'} < m_{\pi'} < m_{N'}$)
    γ'

*** Thermal component does not annihilate directly into SM particles*

Thus, the dark sector ends up with dark baryonic matter and dark photons due to the asymmetry

$$\Omega_{p'} : \Omega_{n'} \sim 1 : 1$$

SM particles

- Dark photons eventually decay into pair of electrons or muons (Lifetime $\mathcal{O}(1)$ sec)
- Dark nucleon decays into anti-neutrinos (Lifetime $\sim 10^{24}$ s)

$$N' \to \pi' + \overline{\nu} \tag{4}$$

$$\pi' \to A'A'^{(*)} \to e^+e^-e^+e^-(\gamma) \tag{5}$$

Composite ADM leads to monochromatic anti-neutrino signal

- Neutrino detectors sensitive to $\mathcal{O}(100)$ MeV $-\mathcal{O}(10)$ GeV – Super-Kamiokande
- e^+/e^- in the Galaxy can be constrained by AMS-O2 data
- e^+e^- leads to inverse-Compton and synchrotron emission – Fermi-LAT γ-ray flux

Decay spectra (Two-body decay case)

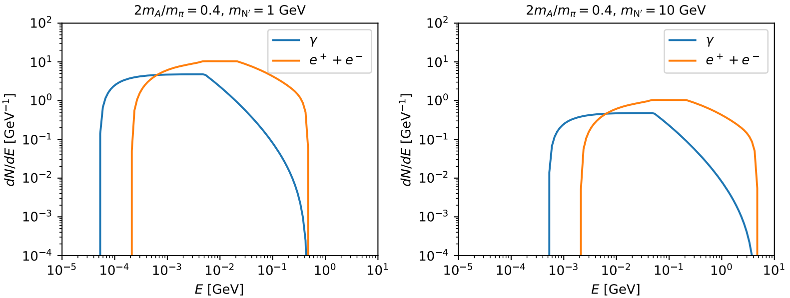


Figure: The spectrum of $\gamma, e^+/e^-$ when two-body decay of dark pion is kinematically allowed, $\epsilon = 2m_A/m_\pi = 0.4$.

In progress:

- The original composite ADM model with 3-body decay ($\epsilon = 1.4$)
- Chiral model of composite ADM ($\epsilon = 0.4, 1.4$)

Galactic and extragalactic contribution

- DM density distribution profile given by a generalized NFW profile,

$$\rho_{\rm DM}(R) = \rho_\odot \left(\frac{R}{R_\odot}\right)^{-\gamma} \left(\frac{1+R/R_c}{1+R_\odot/R_c}\right)^{-(3-\gamma)}, \tag{6}$$

where $\gamma = 1.2$, $R_\odot = 8.5$ kpc, $R_c = 20$ kpc, $\rho_\odot c^2 = 0.43$ GeV/cm^3

- The Galactic line of sight component of the flux of S coming from the direction θ is given as

$$\Phi_G(E,\theta) = \frac{1}{4\pi m_{\rm DM}\tau_{\rm DM}} \frac{dN_s}{dE} \int_0^{s_{\rm max}(\theta)} \rho_{\rm DM}(R(s))ds$$

- The contribution from extragalactic DM is important for neutrinos

$$\Phi_{\rm EG}(E) = \frac{\Omega_{\rm DM}\rho_c}{4\pi m_{\rm DM}} \int dz \left|\frac{dt}{dz}\right| F(z) \frac{dN_s}{dE}(z_s = z) \tag{7}$$

Electrons and positrons

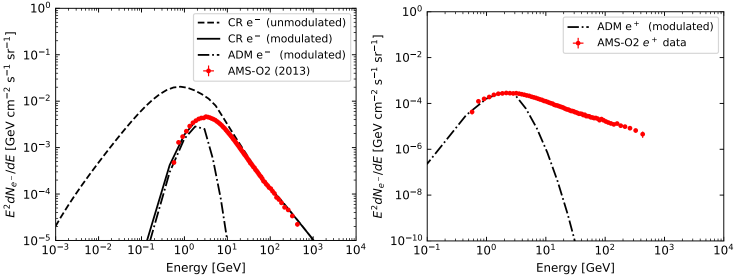


Figure: Electron and positron spectrum after propagation in the Galaxy (calculated using GALPROP) for $m_{\mathrm{DM}} = 10$ GeV and $2m_A/m_\pi = 0.4$

- We use GALPROP to calculate the e^+/e^- spectra for the diffusion model that fits the cosmic ray electron spectrum
- Main energy loss processes of electrons are inverse-Compton and synchrotron emission

γ rays and neutrinos

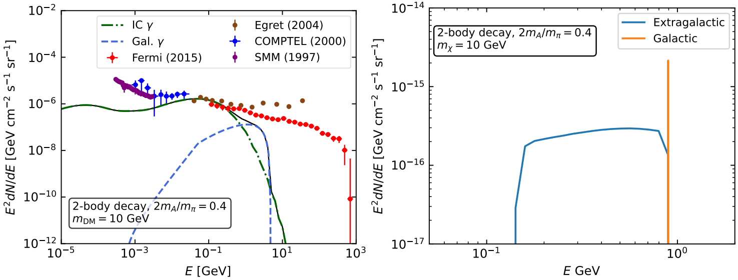


Figure: γ rays and ν-s for $2m_A/m_\pi = 0.4$ and $m_{\rm N'} = 10$ GeV for the two-body decay model

- Extragalactic γ-rays are absorbed in the optical/UV/IR background and are not included
- The extragalactic contribution smoothens the monochromatic neutrino spectrum
- We use the effective areas for fully contained events at the Super-K detector to put constraints on the decay rate for 3-yr of observation of all-flavor neutrino flux

Summary

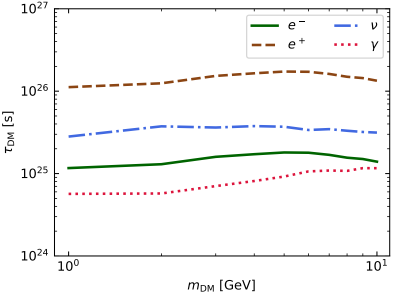


Figure: Constraints on ADM decay rate through various channels

Results

- Positrons provide the most stringent constraints on the dark nucleon decay
- However, using Hyper-K detector (8.3x volume), constraints can be more significant depending on the atmospheric background.
- For 3-body decay case ($\epsilon = 1.4$), positron flux may be reduced, leading to weaker constraints