Indirect Detection of Neutrino Portal
Dark Matter

Barmak Shams Es Haghi
U. Pittsburgh

with Brian Batell, Tao Han - arXiv:1704.08708

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Non-gravitational Interaction of DM: Renormalizable Portals

- Scalar portal: \((\lambda_1 S + \lambda_2 S^2)|H|^2\)
- Vector portal: \(B_{\mu\nu}V^{\mu\nu}\)
- Neutrino portal: \(LHN\)

Motivations For Neutrino Portal:
- Explains neutrino mass (via seesaw mechanism)
- Baryogengesis through leptogenesis
- Dark Matter
Model: \[ \mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \left[ \frac{1}{2}m_N NN + \frac{1}{2}m_\chi \chi \chi + yLHN + \lambda N \phi \chi + \text{h.c.} \right] \]

\[ Z_2 \text{ symmetry} \quad m_N < m_\chi < m_\phi \]

Parameters: \( \{\lambda, m_\phi, m_\chi, m_N\} \longrightarrow \{\langle \sigma v \rangle, m_\chi, m_N\} \)

\[ \langle \sigma v \rangle = \frac{\left[ \text{Re}(\lambda)^2(m_\chi + m_N) + \text{Im}(\lambda)^2(m_\chi - m_N) \right]^2}{16\pi[m_\phi^2 + m_\chi^2 - m_N^2]^2} \left( 1 - \frac{m_N^2}{m_\chi^2} \right)^{1/2} \]

Relic Abundance & Cosmology:

Thermal equilibrium: \( \langle \sigma v \rangle \sim \langle \sigma v \rangle_{\text{thermal}} \)

\[ \langle \sigma v \rangle_{\text{thermal}} = 2.2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

Mass range: Unitarity + Thermal WIMP + BBN

1 GeV \( < m_N < m_\chi \lesssim 20 \) TeV

Seesaw:

\[ m_\nu \sim \sqrt{(\Delta m_\nu)^{\text{atm}}} \sim 0.05 \text{ eV} \longrightarrow y \simeq 10^{-6} \left( \frac{m_N}{246 \text{ GeV}} \right)^{1/2} \]

Yukawa coupling is small, Direct Detection/Production at Collider are challenging.
Indirect Detection:
DM can have multiple annihilation channels

Quantity of interest:
Energy spectrum per DM annihilation in the photon, electron,... channels

Simulation ➞ Spectrum

Image Credit:
Sky & Telescope / Gregg Dinderman
Simulation Chain:

SM_HeavyN_NLO
Model Files
(SM+ 3 heavy neutrinos) →
MadGraph5_aMC@NLO
(Generating Events) →
Pythia
(Hadronize + Shower) → \( \frac{dN_{a,f}}{dE_a} \)
(Spectrum)

Alva, Han, Ruiz 2015
Degrande, Mattelaer, Ruiz, Turner 2016

\begin{align*}
    \chi \chi \rightarrow NN \\
    m_\chi = 20 \text{ GeV} \\
    m_\chi = 50 \text{ GeV} \\
    m_\chi = 100 \text{ GeV}
\end{align*}
DM annihilation products:

- **neutrino**: weakly interacting, so they escape
- **protons**: highly penetrating and poor at transferring energy
- **electron/positron & photon**: heating and ionization occurs primarily through them

\[
\left( \frac{dE}{dV dt} \right)_{\text{injected}} = \rho_{\text{DM}}^2 (z) \frac{\langle \sigma v \rangle}{m_{\text{DM}}} = (1 + z)^6 \rho_{\text{crit}}^2 \Omega_{DM,0}^2 \frac{\langle \sigma v \rangle}{m_{\text{DM}}}
\]

\[
\left( \frac{dE}{dV dt} \right)_{\text{deposited}} = f(z) \left( \frac{dE}{dV dt} \right)_{\text{injected}}
\]

Introducing **Efficiency factor**: (universal: redshift-independent, model-independent)

\[
f_{\text{eff}}(m_{\text{DM}}) = \int_0^{m_{\text{DM}}} EdE \left[ 2 f_{\text{eff}}^{e^+}(E) \left( \frac{dN}{dE} \right)_{e^+} + f_{\text{eff}}^\gamma(E) \left( \frac{dN}{dE} \right)_{\gamma} \right] = \frac{2m_{\text{DM}}}{2m_{\text{DM}}}
\]

**Planck limit**:

\[
f_{\text{eff}}(m_{\text{DM}}) \frac{\langle \sigma v \rangle}{m_{\text{DM}}} < 4.1 \times 10^{-28} \text{ cm}^3/\text{s/GeV}
\]
Gamma rays from dwarf spheroidal galaxies (dSphs)

very clean sources for indirect detection:

• Large DM content
• Having few stars and little gas, negligible background

6 years of Fermi Large Area Telescope (LAT) data:

The Fermi analysis is based on a joint maximum likelihood analysis of 15 dSphs for gamma ray energies in the 500 MeV - 500 GeV range.

\[
\frac{d\Phi_a}{dE_a} = \frac{1}{4\pi} \frac{\langle \sigma_{ann} v \rangle}{2m_{DM}^2} \sum_f \frac{dN_{a,f}}{dE_a} B_f \times \int_V \rho_{DM}(\vec{x})^2 dV
\]

Flux

Particle Physics

Astrophysics (J-factor)
Antiprotons

Antiproton content of the astrophysical background is rare:

• its production costs us a lot of energy $\sim 7m_P$

• energy flux of cosmic rays is very steep peaked around 0.1 GeV

DM annihilation will produce as much antiproton as proton!

Antiprotons deflection by the Galactic magnetic field and their propagation may be seen as a diffusion process.

The Alpha Magnetic Spectrometer (AMS-02) has provided the most precise measurements of the cosmic ray proton and antiproton flux to date.
Used Einasto profile & the MED propagation scheme

\[ \chi^2(m_\chi, \langle \sigma v \rangle) - \chi^2_0 \leq 4 \]

\[ \chi^2_0 \] is the best fit assuming no primary DM antiproton source

Giesen, et al. 2015
Various analyses of Fermi-LAT data show an excess of gamma rays coming from the central region of the Milky Way.

Calore, Cholis, Weniger 2014

\[ \langle \sigma v \rangle = 3.08 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]
\[ m_X = 41.3 \text{ GeV} \]
\[ m_N = 22.6 \text{ GeV} \]
\[ \chi^2/\text{dof} = 14.12/23 \]
Future prospects

**Fermi-LAT:**
The upcoming change: fast discovery of new dSphs

**Fermi-LAT 15 years observations:**
improvement on the cross section by a factor of a few,
probing DM with masses larger than 100 GeV in neutrino portal.

**Ground-based imaging air Cherenkov telescopes like CTA:**
will be able to probe heavy TeV-scale DM annihilation
improve cross section sensitivity by an order of magnitude
Summary

• Neutrino portal is an economical and predictive model to explain thermal WIMP DM.

• Type-I seesaw model necessitates exploring indirect detection methods.

• Astrophysical data constrain the model, and it provides an interpretation of Galactic Center Gamma Ray Excess.

• Future detectors will be able to further probe heavy TeV-scale DM annihilation.
Thank you!
Backups
Photon Cooling Processes (ordered by increasing photon energy)

- Photoionization
- Compton scattering
- Pair production off nuclei and atoms
- Photon-photon scattering
- Pair production off CMB photons

Electron cooling process: electrons from the annihilation products, or from Compton scattering and pair production considered above lose their energy largely by inverse Compton scattering CMB photons.

\[ t_{\text{cool}} \equiv 1/(d \ln E/dt) \]
\[ t_H \equiv 1/H(z) \]
The quantity of interest in the likelihood analysis: the energy flux for kth dwarf and jth energy bin

\[ \varphi_{k,j} = \int_{E_{j,\text{min}}}^{E_{j,\text{max}}} E \Phi_{\gamma,k}(E) dE \]

For each dwarf and energy bin, Fermi/LAT provides likelihood, as a function of flux

\[ \mathcal{L}_k(m_{DM}, \langle \sigma v \rangle, J_k) = \mathcal{L}N(J_k | \bar{J}_k, \sigma_k) \prod_j \mathcal{L}_{k,j}(\varphi_{k,j}(m_{DM}, \langle \sigma v \rangle, J_k)) \]

\( J \)-factor, introduced as as a nuisance parameter

\[ \mathcal{L}N(J_k | \bar{J}_k, \sigma_k) = \frac{1}{\ln(10) J_k \sqrt{2\pi \sigma_k}} e^{-\frac{(\log_{10}(J_k) - \log_{10}(\bar{J}_k))^2}{2\sigma_k^2}} \]

\[ \mathcal{L}(m_{DM}, \langle \sigma v \rangle, \{J_i\}) = \prod_k \mathcal{L}_k(m_{DM}, \langle \sigma v \rangle, J_k) \]

\[ \Delta \ln \mathcal{L}(m_{DM}, \langle \sigma v \rangle) = \ln \mathcal{L}(m_{DM}, \langle \sigma v \rangle, \{\hat{J}_i\}) - \ln \mathcal{L}(m_{DM}, \langle \sigma v \rangle, \{\hat{J}_i\}) \]

\[ \Delta \ln \mathcal{L}(m_{DM}, \langle \sigma v \rangle) \leq 2.71/2 \]
DM density profile (in the galaxy) from N-body simulations:

NFW: \( \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r} \left( 1 + \frac{r}{r_s} \right)^{-2} \)

Einasto: \( \rho_{\text{Ein}}(r) = \rho_s \exp \left\{ -\frac{2}{\alpha} \left[ \left( \frac{r}{r_s} \right)^\alpha - 1 \right] \right\} \)

Isothermal: \( \rho_{\text{Iso}}(r) = \frac{\rho_s}{1 + (r/r_s)^2} \)

Burkert: \( \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1 + r/r_s)(1 + (r/r_s)^2)} \)

Moore: \( \rho_{\text{Moo}}(r) = \rho_s \left( \frac{r_s}{r} \right)^{1.16} \left( 1 + \frac{r}{r_s} \right)^{-1.84} \)

<table>
<thead>
<tr>
<th>DM halo</th>
<th>( \alpha )</th>
<th>( r_s ) [kpc]</th>
<th>( \rho_s ) [GeV/cm(^3)]</th>
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<tr>
<td>Moore</td>
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Antiproton diffusion process

\[
\frac{\partial f}{\partial t} - \mathcal{K}(K) \cdot \nabla^2 f + \frac{\partial f}{\partial z} \left( \text{sign}(z) f V_{\text{conv}} \right) = Q - 2h\delta(z)(\Gamma_{\text{ann}} + \Gamma_{\text{non-ann}})
\]

\[
f(t, \vec{r}, K) = dN_{\bar{p}}/dK \quad K = E - m_p
\]

diffusion coefficient function: \( \mathcal{K}(K) = \mathcal{K}_0 \beta(p/\text{GeV})^\delta \)

source term from DM annihilation: \( Q = \frac{1}{2} \left( \frac{\rho(\vec{x})}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN_{\bar{p}}^f}{dK} \)

\[
\Phi_{\bar{p}}(K, \vec{r}_\odot) = \frac{v_{\bar{p}}}{4\pi} \left( \frac{\rho(\vec{x})}{m_{\text{DM}}} \right)^2 R(K) \sum_f \frac{1}{2} \langle \sigma v \rangle_f \frac{dN_{\bar{p}}^f}{dK}
\]

<table>
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<tr>
<th>Model</th>
<th>( \delta )</th>
<th>( \mathcal{K}_0(\text{kpc}^2/\text{Myr}) )</th>
<th>( V_{\text{conv}}(\text{km/s}) )</th>
<th>( R(\text{kpc}) )</th>
<th>( L(\text{kpc}) )</th>
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PPPC 4 DM ID