Extragalactic and Galactic Gamma-Rays and Neutrinos from Dark Matter Annihilation

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We are about to enter into an era of major discovery.

Dark Matter: we need new particles to explain the content of the universe.

Standard Model: we need new physics.

Supersymmetry solves both problems!

The super-partners are distributed around 100 GeV to a few TeV.

LHC: directly probes TeV scale.

Fermi, IceCube are probing this scale indirectly through DM annihilation into photons, neutrinos [This talk].

Direct detection [XENON, CDMS, Cogent etc.] are also probing the new physics scale.
Recent Higgs search results from Atlas and CMS indicate excess of events beyond background which is consistent with a Higgs mass of around 125 GeV

- in the tight MSSM window: 115-135 GeV

squark mass (first generation) $\sim$ gluino mass $\geq$ 1 TeV

For heavy squark mass, gluino mass is $\geq$ 700 GeV

stop (squark) produced from gluinos, stop mass $\geq$ 400 GeV

stop (squark) produced directly, stop mass $\geq$ 180 GeV
Models for This Talk

1. mSUGRA/CMSSM: neutralino dark matter

   4 parameters + sign: $m_0$, $m_{1/2}$, $A_0$, $\tan\beta$ and $\text{Sign}(\mu)$

2. $\text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y \times \text{U}(1)_{B-L}$

Motivations for B-L models:
B-L models are used (for several decades) to explain Neutrino mass

   Right handed neutrino and corresponding sneutrino are included in this model

   $$ W = W_{\text{MSSM}} + y_D N^c H_u L + f H'_2 N^c N^c + \mu' H'_1 H'_2, $$

   Right sneutrinos can be dark matter candidates
The direct searches at the LHC, the $\text{Br}(B_s \rightarrow \mu \mu)$ measurement from LHC, Tevatron, and direct DM detection experiments are probing the parameter space.

Dutta, Mimura, Santoso

arXiv:1107.3020
mSUGRA Parameter space...

With Higgs mass...
Focus point:

Larger $m_0$ reduces $\mu \rightarrow$ larger Higgsino component in the neutralino

Annihilation dominantly produces $W^+ W^-$ final states

Stau neutralino Coannihilation:

Annihilation dominantly produces $b\bar{b}, \tau^+ \tau^-$ final states
However, due to the absence of $t$ at present, the annihilation cross-section is smaller than the freeze out time

Sneutrino Annihilation in the B-L model:

Sneutrino annihilation can produce right handed neutrinos $\rightarrow$ decay into left handed neutrinos + Higgs($h$)
Calculating $\gamma$-ray intensity

Particle side:
Annihilation Cross-section: $\sigma v$ ($v$: relative velocity), Dark matter mass $m_{\text{DM}}$, Photon spectrum per annihilation $dN_\gamma(E_\gamma) / dE_\gamma$ (Include radiative emission by charged products and decays of unstable products.)

Astro side:
Density Profile (NFW profile: $\rho_h(r) = \frac{\rho_s}{r \left(1 + \frac{r}{r_s}\right)^2}$), \[r_s = \frac{R_{\text{vir}}}{c}\]

Mass function: $dn(z)/dM$ (number densities of $M$ mass halos: Sheth-Tormen), velocity variance profile
\( \gamma \)-ray Intensity....

Extragalactic

\[ I_{\gamma, EG}(E_\gamma) = \sigma v \int \frac{dz}{H(z)} W((1 + z)E_\gamma, z) \langle \rho^2 \rangle(z). \]

Intensity Window function:

\[ W(E_\gamma, z) = \frac{1}{8\pi m^2} \frac{1}{(1 + z)^3} \frac{dN_{\gamma}}{dE_\gamma}(E_\gamma) e^{-\tau(E_\gamma, z)}, \]

\( \tau(E_\gamma, z) \) is the cosmic opacity to gamma rays

Mean square matter density:

\[ \langle \rho^2 \rangle(z) = \int dM \frac{dn}{dM} (M, z) \int d^3r \rho^2_h (r|M, z). \]

\[ \rho_h(r|M, z) = \frac{\rho_s(M, z)}{[r/r_s(M, z)][1 + r/r_s(M, z)]^2} \]

\[ \frac{dn}{dM} \int d^3r \rho^2_h \left( \frac{\rho^2}{M_\odot} \right) \]

\( z=1 \)

Sheth-Torman
$\gamma$-ray Intensity....

**Galactic**

$$I_{\gamma,G}(E_\gamma, \psi) = \frac{\sigma v}{8\pi m^2} \frac{dN_{\gamma}}{dE_\gamma}(E_\gamma) \hat{J}(\psi)$$

**J-factor** is the line of sight integration of the square dark matter density

$$\hat{J}(\psi) = \int_{0}^{r_{\text{max}}(\psi)} dr \left[ \rho_h \left( \sqrt{r^2 - 2rR_\odot \cos \psi + R_\odot^2} \right) \right]^2$$

$$r_{\text{max}}(\psi) = R_\odot \cos \psi + \sqrt{R_{\text{vir},G}^2 - R_\odot^2 \sin^2 \psi}.$$
Dark Matter Annihilation

Dark matter annihilation cross-section:

\[ \sigma v = a + b v^2 \]

\(a, b\) are constants

If S wave is suppressed then the cross-section is dominated by P wave \(\Rightarrow b v^2 \gg a\)

\(\Rightarrow \sigma v\) is much smaller today compared to the freeze-out time

Thermal Relic Density:

At freezeout, \(\sigma v = 3 \times 10^{-26} \text{cm}^3/\text{s}\)

High \(b/a\) lowers the cross-section at small \(v\)

In order to get large annihilation cross-section with large \(b/a\), we need to go to non-thermal scenarios where enhanced annihilation cross-section may be needed to explain the dark matter content

γ-ray (Extragalactic)

At a position r, integrate $\sigma v(r)$ over the local velocity distribution to find the mean

$[\sigma v]_h(r) = a + \lambda b \sigma^2_{uh}(r)$

$a, b$ are fixed to satisfy $\sigma v = a + b v^2_{freeze\ out}$

Use halo velocity profile to find universal halo annihilation cross-section profile

$$\langle I_\gamma \rangle (E_\gamma) = [\sigma v]_0 \int \frac{dz}{H(z)} W((1 + z) E_\gamma, z) \left\langle \rho^2 \left(1 + \frac{\lambda b}{a} \sigma^2_u\right) \right\rangle (z)$$

Where:

$$\left\langle \rho^2 \left(1 + \frac{\lambda b}{a} \sigma^2_u\right) \right\rangle (z) = \int d^3r dM \frac{dn}{dM} (M, z) \rho^2_h(r | M, z) \left[1 + \frac{\lambda b}{a} \sigma^2_{uh}(r | M, z) \right]$$

\(\gamma\)-ray (Extragalactic)

Focus point, \(b/a=1.8\), DM mass 150 GeV

Bulk region, \(b/a=57\), DM mass: 62 GeV

Coannihilation, \(b/a=379\), DM mass: 150 GeV

Coannihilating cross-section is not available at the present time.

\[ E_\gamma^2 \langle I_\gamma \rangle \text{ (GeV/cm}^2/\text{s/sr)} \]

\[ E_\gamma \text{ \(m_{DM}\)} \]
It is possible to have scenarios where $b/a$ is very large.

\[ E_\gamma^2 \langle I_\gamma \rangle \text{ (GeV/cm}^2\text{s/sr)} \]

mSUGRA Coannihilation, $b/a = 4.8$

MSSM x U(1)$_{B-L}$

Sneutrino annihilation via s-channel $Z'$ into fermion anti fermion pair

**Galactic and Extragalactic $\gamma$–Ray**

**Focus Point:** $\tan\beta=10$; $M_{DM}=150$ GeV

Annihilation is primarily into $W^+W^-$ pair, $\sigma v=1.9 \times 10^{-26}$ cm$^3$/s

- Extragalactic signal is higher at lower energy due to cosmological redshifting
- The relative importance of galactic and extragalactic signal depends on different choices of parameters

Galactic and Extragalactic $\gamma$–Ray

$$\frac{I_{\gamma, BG}(E_\gamma)}{I_{\gamma, G}(E_\gamma, \psi)} = \int dz \left[ \frac{\langle \rho^2 \rangle(z)}{H(z)(1 + z)^3 \hat{j}(\psi)} \right] \times \left[ \frac{dN_\gamma}{dE_\gamma} \left( (1 + z)E_\gamma \right) \right] \delta(z_1 - z_2) \delta(\psi - \psi_1)$$

Galactic $\gamma$-ray intensity diverges as the line of sight approaches galactic center

However, it will be difficult to observe the dark matter annihilation around that region due to astrophysical contamination

- Substructures can increase the extragalactic signal considerably
We have not included the effects of substructures.

Substructure can increase the annihilation rate by a factor of 100 or so depending on minimum halo mass size.

Based on simulations, substructures would increase the galactic signal by a factor of few.
In MSSM, type models the neutrinos appear from $W$, $b$ and $\tau$ final states from the DM decays

In MSSMx $U(1)_{B-L}$ models: DM particle Sneutrino_R ($\tilde{N}$) annihilation can produce neutrino final states

- These models may contain small amount of photons

![Diagram of neutrino annihilation](attachment:image.png)

IceCube and Fermi jointly can probe these models
Focus Point: $\tan\beta = 10$; $M_{DM} = 150$ GeV

- The W decays produce a prompt component

- The prompt feature is washed out in the extragalactic spectrum due to redshifting

- Both galactic and extragalactic are contributing in this simplistic scenario

• The galactic signal is much stronger from the galactic center (assuming NFW cusp).

• Similar results for $\gamma$-rays.

• Subhalos and uncertainties in the minimum halo scale, halo concentrations, and distribution at the core/cusp need to be appropriately quantified.
Gamma-ray intensity from annihilating 150 GeV dark matter for $\psi > 18^\circ$.

• A model producing $W^+W^-$ is indistinguishable from a model annihilating to $b\bar{b}$.

• The neutrino signal breaks the $\gamma$-ray degeneracy between $W$ and $b$ producing annihilations.

• All-sky $\nu+\bar{\nu}$ event rate per detector mass.

• Leptonic $W$ or $\tau$ decays produce prompt neutrinos, which are absent from $b$ decays.
Annihilation to Neutrinos

All-sky event rates for 150 GeV sneutrino dark matter that annihilates to two 135 GeV right-handed neutrinos (each flavor equally represented), each of which decays to a light neutrino and 120 GeV standard model Higgs particle.
Anihilation into $\nu$’s

- The secondary neutrinos produced from the Higgs decay result in a broad, soft spectrum, whereas the neutrinos produced directly from $N^c$ decays produce a narrower peak at lower energies on the order of the mass difference between the $N^c$ and the Higgs.

- Due to the Higgs decays, there is also a gamma-ray component to the signal.

If Higgs mass is small—negligible compared to the right sneutrino (DM) mass:

- The spectrum of the produced light neutrinos is at the energy of the right sneutrino.

- This simple scenario results in a prominent neutrino line feature.
- Signal to background improves with high angular precision, but rates become very low.
- Can improve with higher energy resolution (smaller bin size).

ν final states and IceCube

Sneutrinos annihilate to produce to Right-handed neutrinos

mSUGRA: Focus point

**Conclusion**

Simultaneous observation of gamma-rays and neutrinos allows for more constrained conclusions about models.

The signal contains both galactic and extragalactic component.

Final state intensity depends on the annihilation cross-section, density profiles of the cores and halos substructures.

Neutrinos may be more suited than the gamma rays for observing a signal from the galactic center.