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

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Based on works with
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Discovery Time...

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

So Far at the LHC

➔ 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) ~ gluino mass ≥ 1TeV

➔ For heavy squark mass, gluino mass is ≥ 700 GeV

➔ stop (squark) produced from gluinos, stop mass ≥ 400 GeV

➔ stop (squark) produced directly, stop mass ≥ 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 Sign(μ)

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

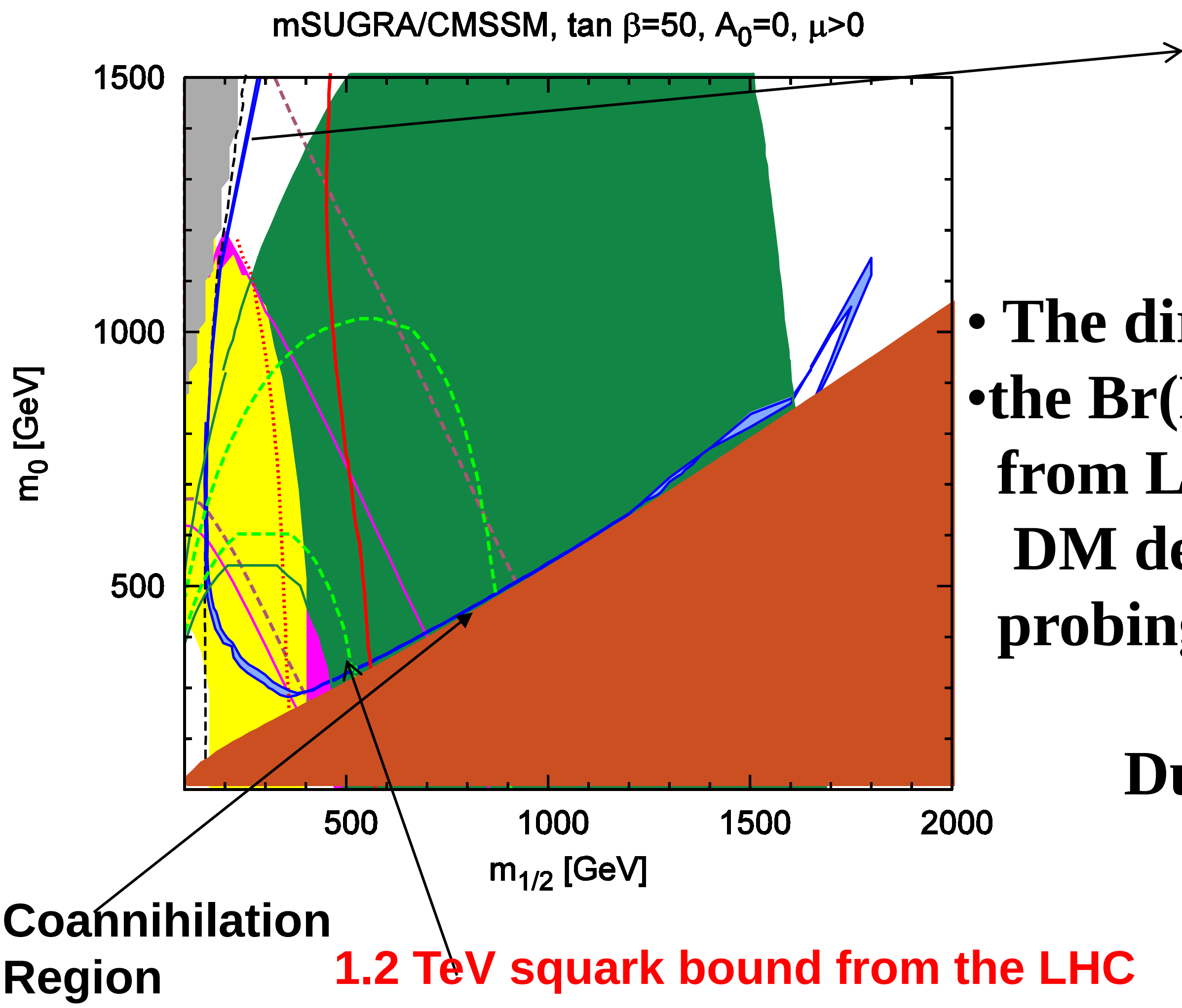
Motivations for B-L models:
B-L models are used (for several decades) to explain Neutrino mass

Right handed neutrino and corresponding sneutrino are included in this model

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

Right sneutrinos can be dark matter candidates

mSUGRA Parameter space

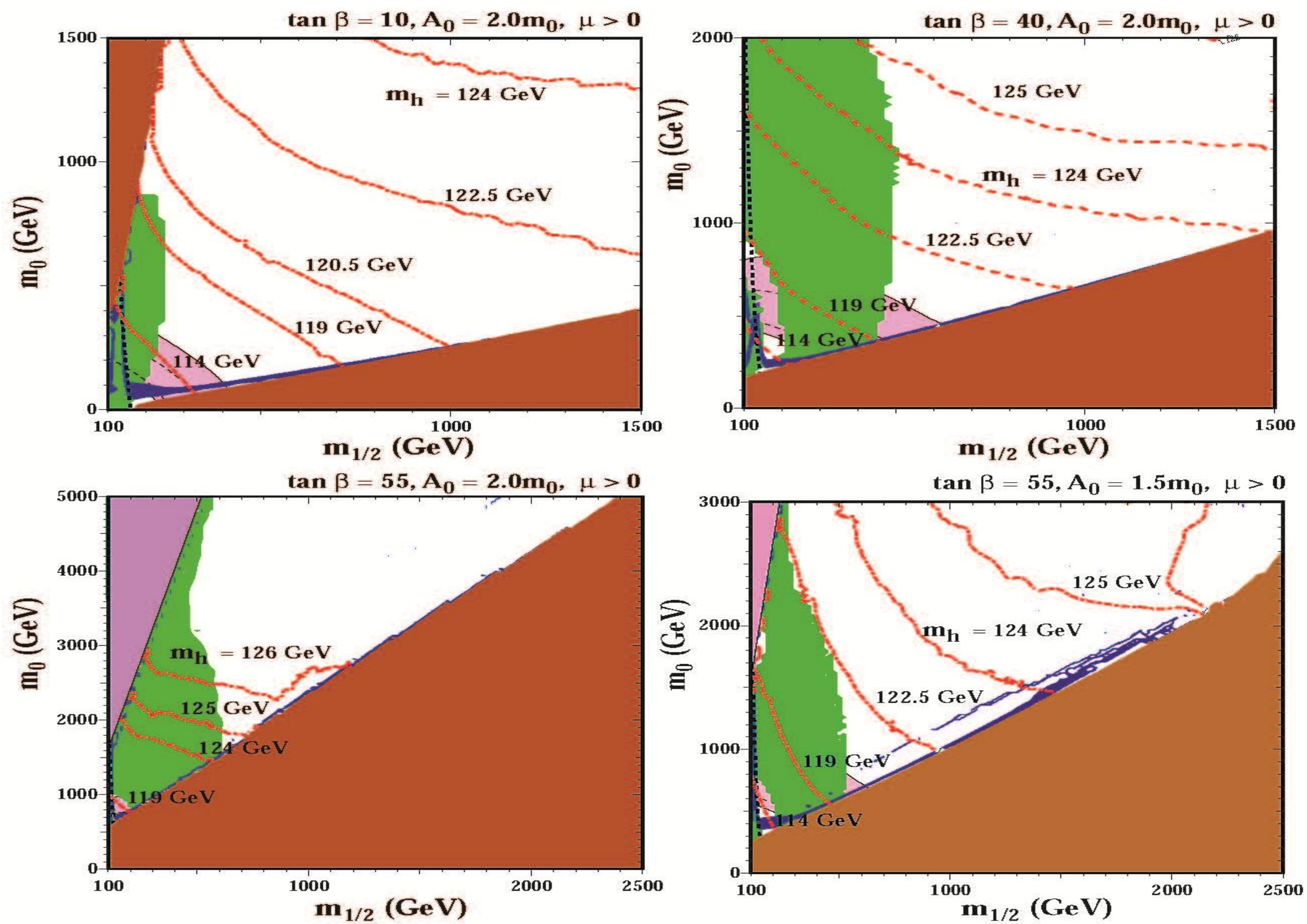


- The direct searches at the LHC,
- the Br($B_s \rightarrow \mu\,\mu$) measurement from LHC, Tevatron and direct DM detection experiments are probing the parameter space

Dutta, Mimura, Santoso

arXiv:1107.3020

mSUGRA Parameter space…



Olive, Ellis, 1202.3262

With Higgs mass…

Final States from DM annihilation

Focus point:

Larger m_0 reduces μ ➔ 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 ➔ decay into left handed neutrinos + Higgs(h)

γ-ray Intensity

Calculating γ-ray intensity

Particle side:
Annihilation Cross-section: σv (v: relative velocity), Dark matter mass m_{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: $\rho_h(r) = \dfrac{\rho_s}{\frac{r}{rs}(1+\frac{r}{r_s})^2}$), [$r_s=R_{vir}/c$]

Mass function: dn(z)/dM (number densities of M mass halos: Sheth-Tormen), velocity variance profile

γ-ray Intensity….

Extragalactic

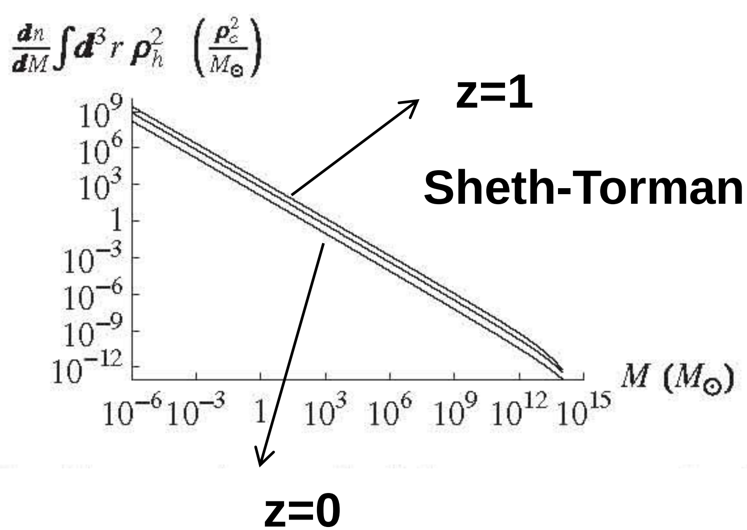
$$I_{\gamma,\mathrm{EG}}(E_\gamma) = \sigma v \int \frac{dz}{H(z)} W((1+z)E_\gamma, z)\langle\rho^2\rangle(z).$$

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: $\langle\rho^2\rangle(z) = \int dM \frac{dn}{dM}(M,z) \int d^3\mathbf{r}\,\rho_h^2(r|M,z).$

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



γ-ray Intensity….

Galactic

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

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

$$\hat{J}(\psi) \equiv \int_0^{r_{\max}(\psi)} dr \left[\rho_h \left(\sqrt{r^2 - 2rR_\odot \cos\psi + R_\odot^2} \,|\, M_\mathrm{G}, 0 \right) \right]^2$$

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

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 ➔ b v^2>>a

➔ σv is much smaller today compared to the freeze-out time

Thermal Relic Density:
At freezeout, $\sigma v = 3\times10^{-26}\,cm^3/s$
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

B.D., L. Leblond, K. Sinha, Phys.Rev. D80 (2009) 035014

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 $\sigma v = a + b\, v^2_{\text{freeze out}}$

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

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

Where:

$$\left\langle \rho^2 \left(1 + \frac{\lambda b}{a}\sigma_u^2\right)\right\rangle(z) = \int \mathrm{d}^3\mathbf{r}\,\mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M}(M,z)\rho_h^2(r|M,z)\left[1 + \frac{\lambda b}{a}\sigma_{uh}^2(r|M,z)\right]$$

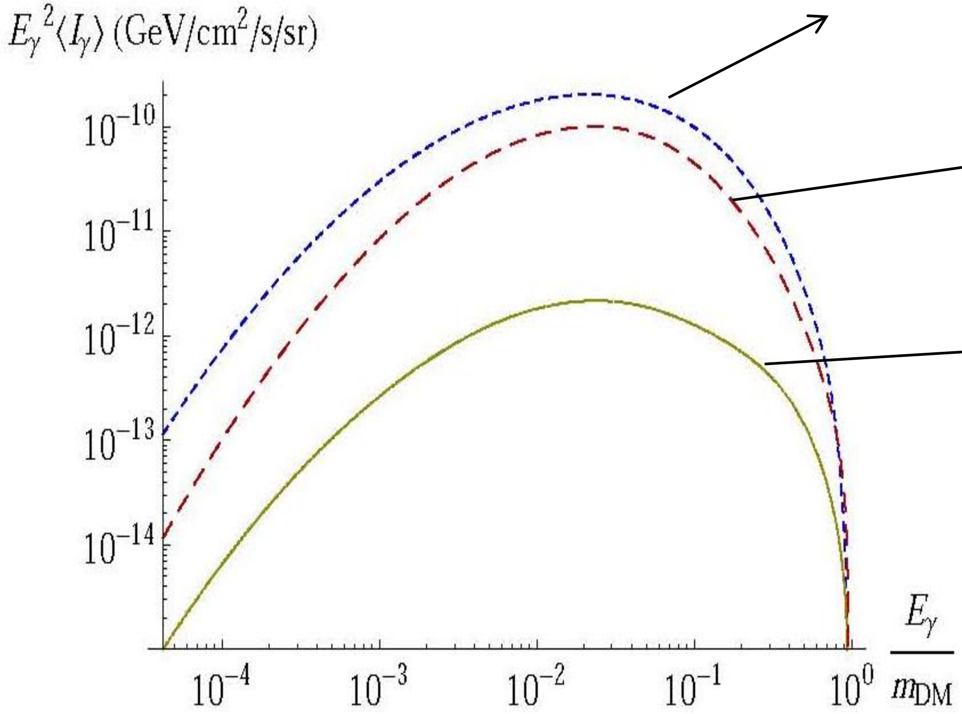
S. Campbell, B.D., E. Komatsu, Phys. Rev. D 82, 095007 (2010)

γ-ray (Extragalactic)

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

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

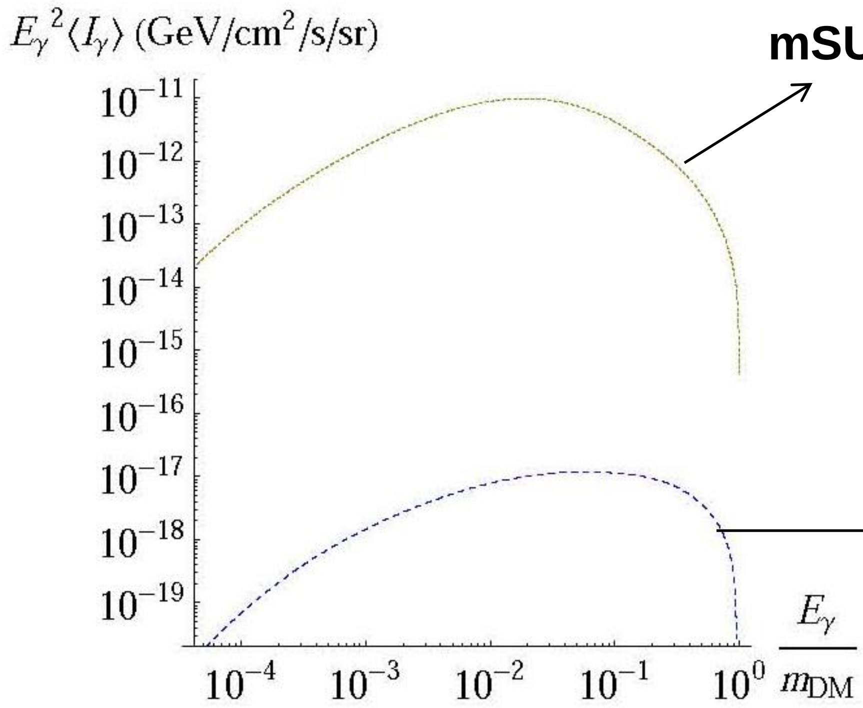
Coannihilation, b/a=379,
DM mass: 150 GeV



Coannhilating cross-section is not available at the present time

γ-ray (Extragalactic)

It is possible to have scenarios where b/a is very large



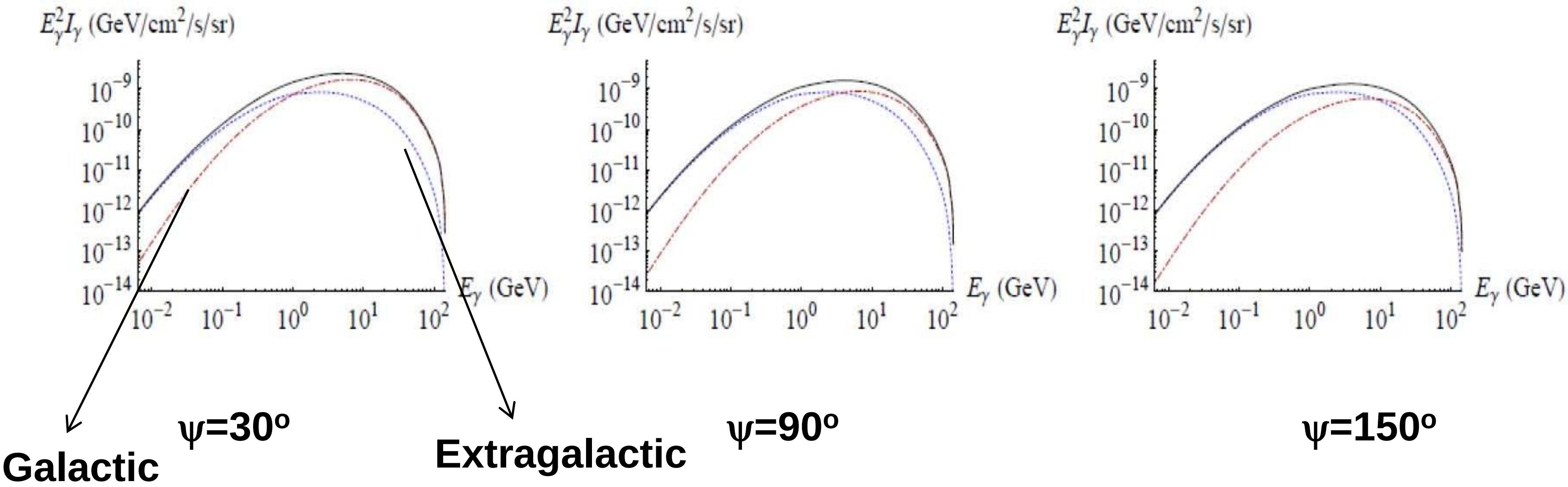
mSUGRA Coannihilation, b/a=4.8

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

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

S. Campbell, B.D., E. Komatsu, Phys. Rev. D 82, 095007 (2010)

Galactic and Extragalactic γ–Ray



Focus Point: tanβ=10; M_{DM}=150 GeV

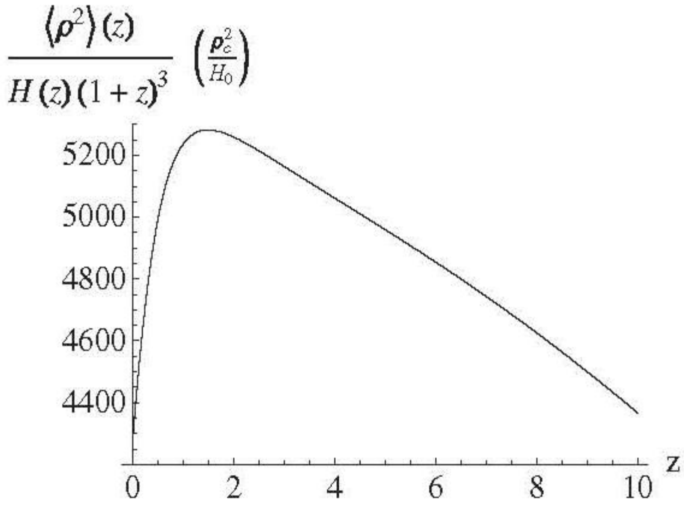
Annihilation is primarily into W^+W^- pair, $\sigma v = 1.9\ 10^{-26}$ cm³/s

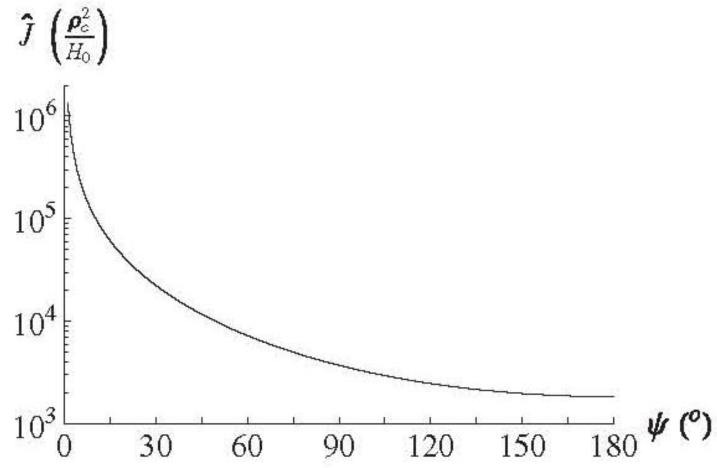
- **Extragalactic signal is higher at lower energy due to cosmological redshifting**
- **The relative importance of galactic and extragalactic signal depends on different choices of parameters**

R. Allahverdi, S. Campbell, B.D. Phys. Rev. D 85, 035004 (2012)

Galactic and Extragalactic γ–Ray

$$\frac{I_{\gamma,\mathrm{EG}}(E_\gamma)}{I_{\gamma,\mathrm{G}}(E_\gamma,\psi)} = \int dz \left[\frac{\langle\rho^2\rangle(z)}{H(z)(1+z)^3\hat{J}(\psi)}\right] \times \left[\frac{\frac{dN_\gamma}{dE_\gamma}((1+z)E_\gamma)}{\frac{dN_\gamma}{dE_\gamma}(E_\gamma)}\right] e^{-\tau((1+z)E_\gamma,z)}$$





Galactic γ-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**

Galactic and Extragalactic γ–Ray

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

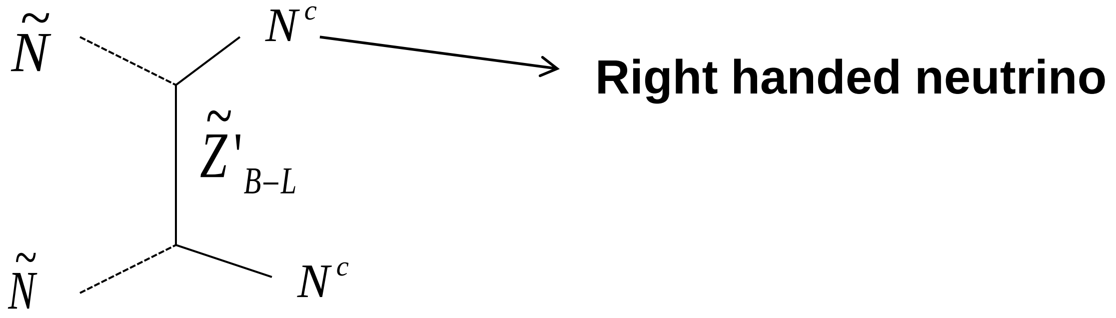
Based on simulations, substructures would increase the galactic signal by a factor of few

Dark Matter Annihilation into ν's

In MSSM, type models the neutrinos appear from W, b and τ final states from the DM decays

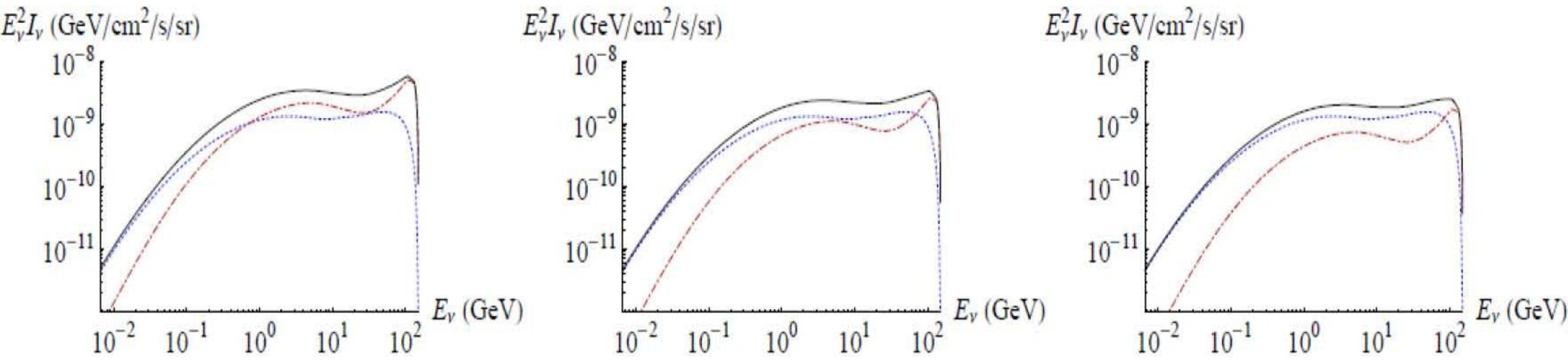
In MSSMx $U(1)_{B-L}$ models: DM particle Sneutrino_R ($\tilde{N}$) annihilation can produce neutrino final states

- **These models may contain small amount of photons**



IceCube and Fermi jointly can probe these models

Galactic and Extragalactic ν



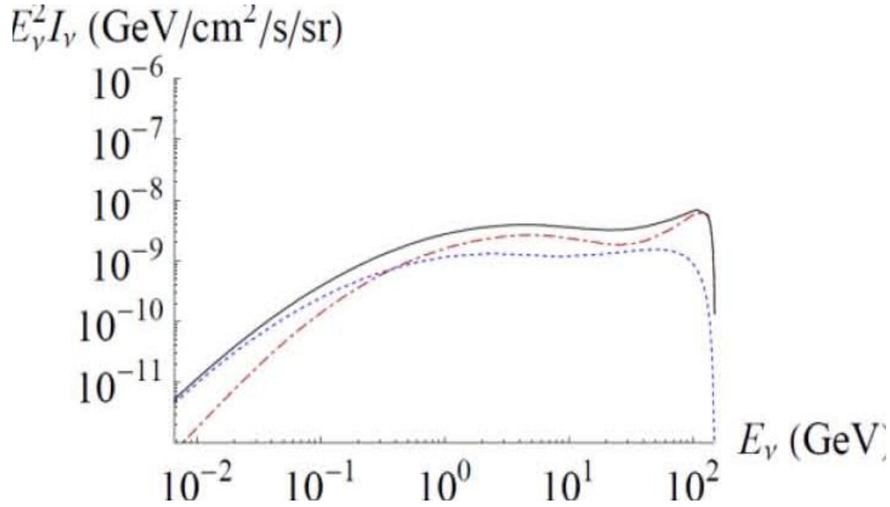
ψ=30º **ψ=90º** **ψ=150º**

Focus Point: tanβ=10; M_{DM}=150 GeV

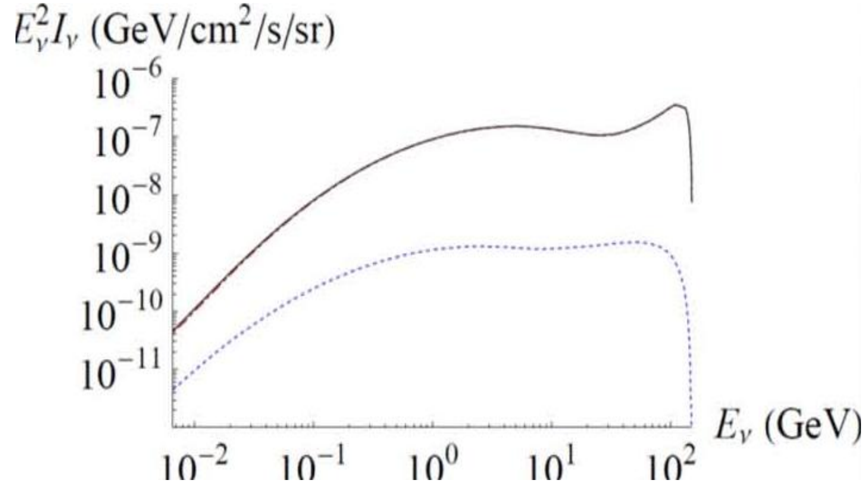
- **The W decays produce a prompt component**
- **The prompt feature is washed out in the extragalactic spectrum due to redshifting**
- **Both galactic and extragalactic are contributing in this simplistic scenario**

R. Allahverdi, S. Campbell, B.D. Phys. Rev. D 85, 035004 (2012)

ν All Sky vs. the Galactic Center



$\Psi \geq 18^o$



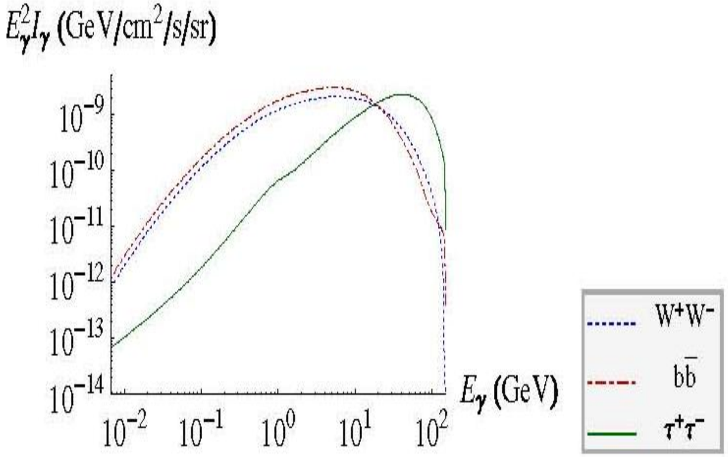
$0^o \leq \Psi \leq 5^o$

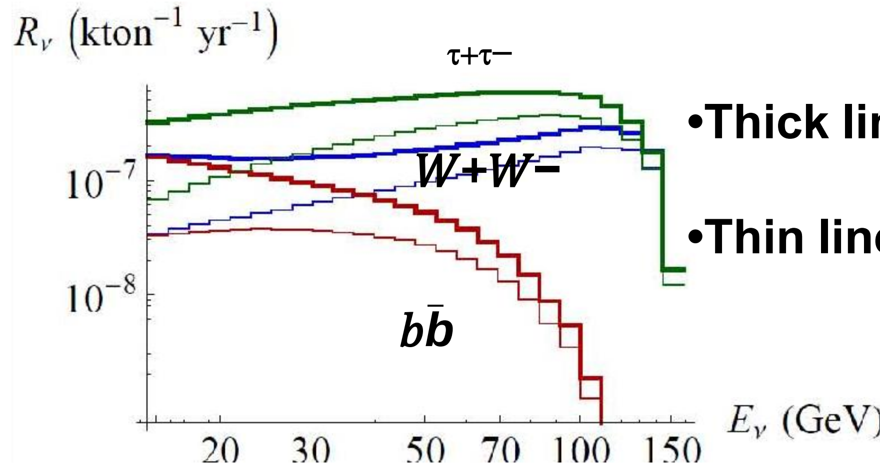
- **The galactic signal is much stronger from the galactic center (assuming NFW cusp).**

- **Similar results for γ-rays.**

- **Subhalos and uncertainties in the minimum halo scale, halo concentrations, and distribution at the core/cusp need to be appropriately quantified.**

γ Rays vs ν





- **Thick lines: ν_e or ν_μ**
- **Thin lines: ν_τ**

Gamma-ray intensity from annihilating 150 GeV dark matter for ψ>18^o.

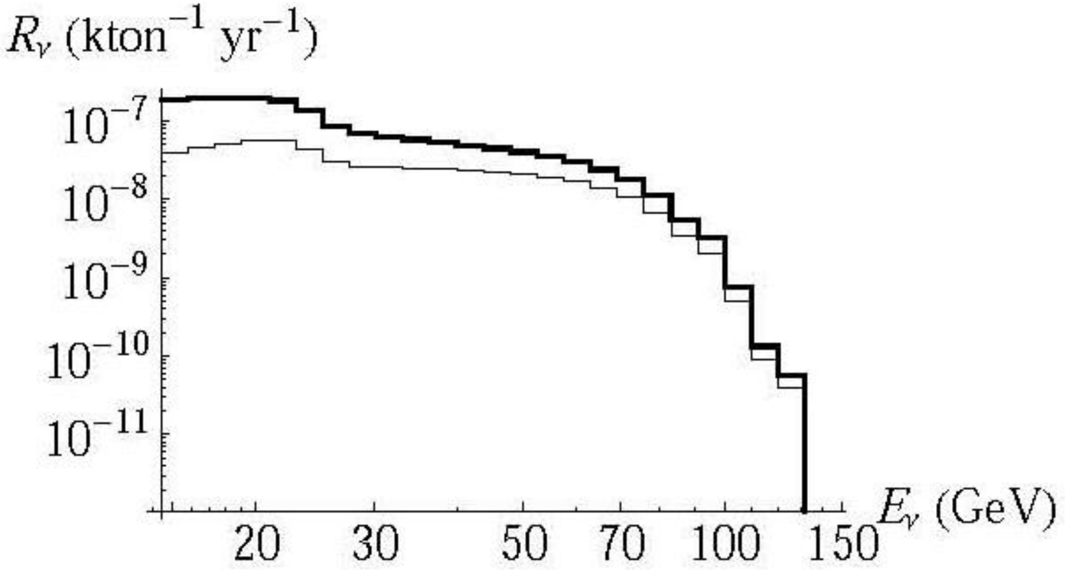
- **A model producing W+W− is indistinguishable from a model annihilating to $b\bar{b}$.**

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

- **Leptonic W or τ decays produce prompt neutrinos, which are absent from b decays.**

- **The neutrino signal breaks the γ-ray degeneracy between W and b producing annihilations.**

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

Annihilation into ν'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**

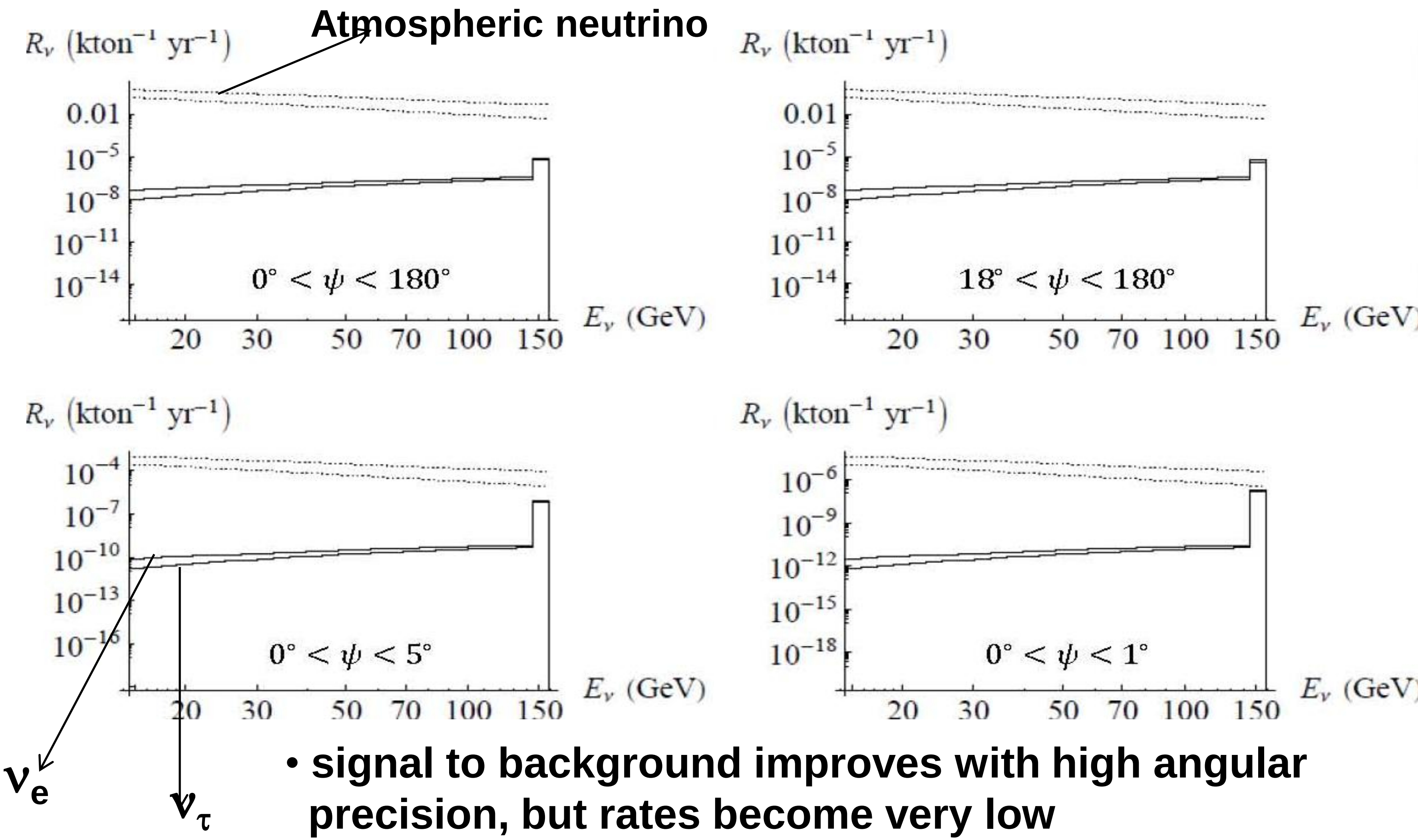
- **Due to the Higgs decays, there is also a gamma-ray component to the signal**

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**

Annihilation to Neutrinos

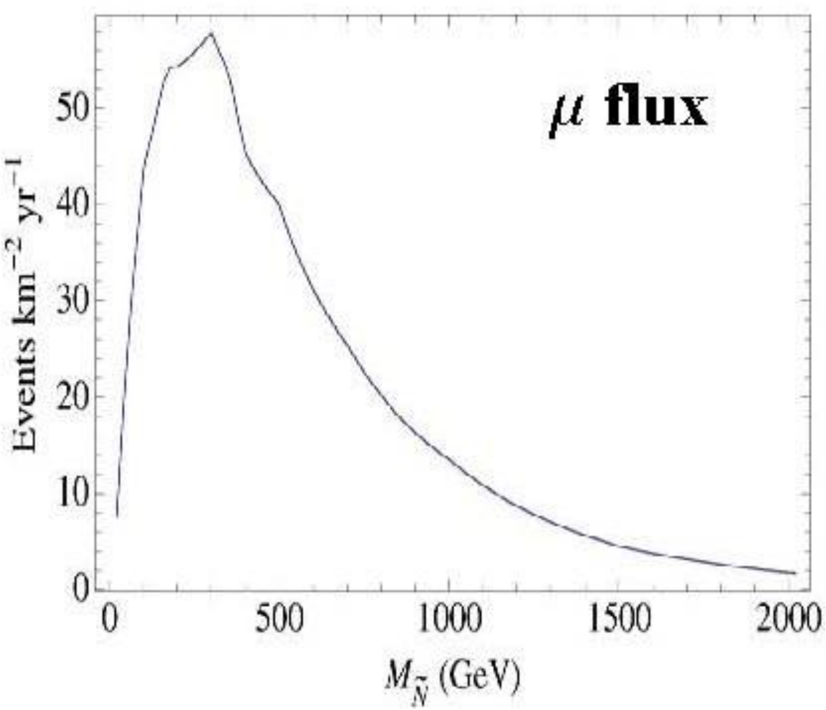


- **signal to background improves with high angular precision, but rates become very low**
- **can improve with higher energy resolution (smaller bin size)**

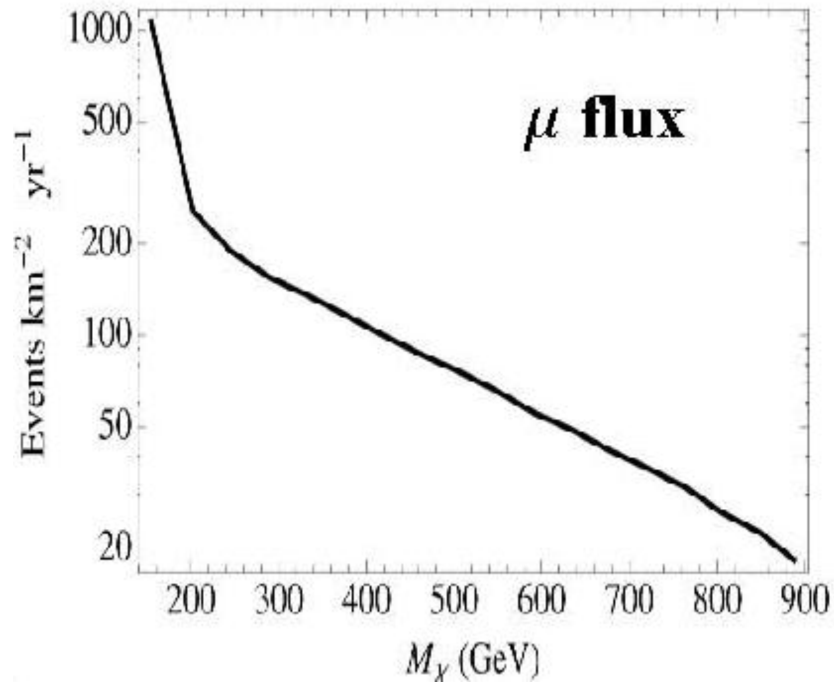
R. Allahverdi, S. Campbell, B.D. Phys. Rev. D 85, 035004 (2012)

ν final states and IceCube

Sneutrinos annihilate to produce to Right-handed neutrinos



mSUGRA: Focus point



R. Allahverdi, S. Bornhauser, B. D., K. Richardson-Mcdaniel, Phys.Rev. D80 (2009) 055026

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