

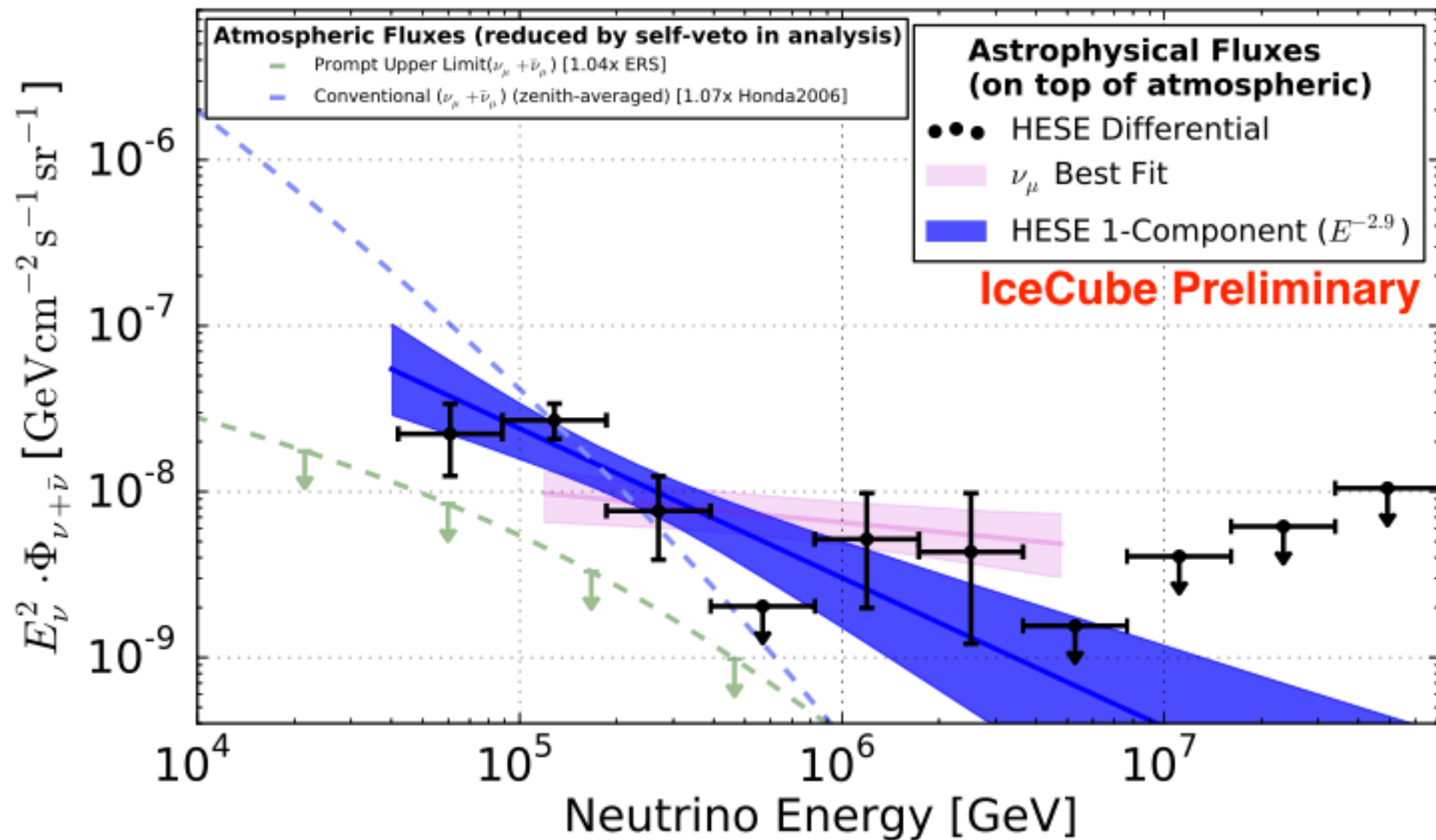
PeV-scale Supersymmetry Breaking and IceCube Neutrino Events

Mansi Dhuria
IIT Bombay, India

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Collaborator: V.Rentala

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IceCube Neutrino Events



Outline of the Talk

- 📍 Decaying Dark Matter as the origin of PeV-scale neutrino events observed by IceCube observatory.
- 📍 IceCube results $\longleftrightarrow$ PeV-scale supersymmetry.
- 📍 Viable supersymmetric Dark Matter candidates.

IceCube neutrino events - parametric dependence

$$E_\nu^2 \frac{d\phi}{dE_\nu} \propto \left(\frac{\text{PeV}}{m_{\text{DM}}} \right) \left(\frac{\Omega_{\text{DM}}}{0.1} \right) \left(\frac{\Gamma_{\text{DM}}}{10^{-29} \text{ s}^{-1}} \right)$$

For general 2-body decay of Dark Matter

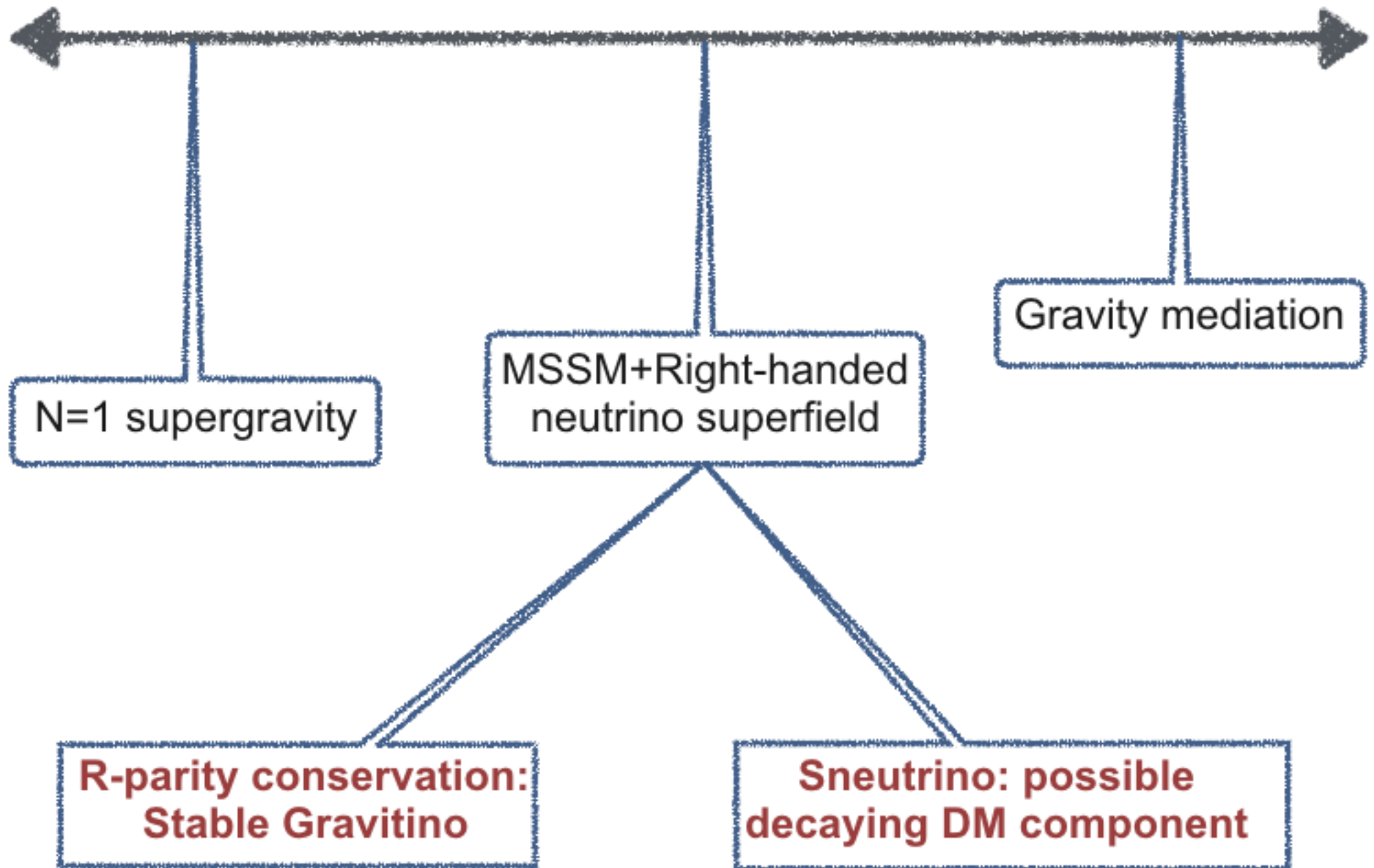
$$\Gamma_{\text{DM}} \sim \frac{y^2 m_{\text{DM}}}{16\pi} \rightarrow y \sim 10^{-29}$$

(for a DM component accounting for the whole DM of the universe !)

Possible PeV-scale supersymmetric DM candidates

- 📌 **Neutralino:** Difficult to produce thermally; R-parity has to be violated.
- 📌 **Gravitino:** R-parity has to be violated.
- 📌 **Right-handed sneutrino:** Possible viable DM component with R-parity conserved.

Particle Spectrum



Can decay of sneutrino explain the high energy IceCube neutrino events?

The general Lagrangian for right-handed neutrino superfields:

$$\mathcal{W} \supset M_N \hat{N}^c \hat{N}^c + y_N \hat{N}^c \hat{L} \cdot \hat{H}_u \left(1 + \frac{\Phi}{M_p} \right)$$

$$\mathcal{W} \supset \cancel{M_N \hat{N}^c \hat{N}^c} + y_N \cancel{\hat{N}^c \hat{L} \cdot \hat{H}_u} \left(1 + \frac{\Phi}{M_p} \right)$$

The interaction terms can be :

$$\begin{aligned} \mathcal{K} \supset & \frac{\hat{\Phi}^\dagger}{M_p} \hat{N}^c \hat{N}^c \left(1 + \frac{\hat{\Phi}^\dagger \hat{\Phi}}{M_p^2} \right) + \frac{\hat{\Phi}^\dagger}{M_p^2} \hat{N}^c \hat{L} \cdot \hat{H}_u \left(1 + \frac{\hat{\Phi}^\dagger \hat{\Phi}}{M_p^2} + \dots \right) \\ & + \frac{\hat{\Phi}^\dagger \hat{\Phi}}{M_p^2} \left(\hat{N}^{c\dagger} \hat{N}^c \right) + \text{h.c.} \end{aligned}$$

 **Yukawa coupling:** $y_N \sim F_X / M_p \sim \text{PeV} / M_p$

 **Scalar Trilinear coupling:** $A_N \sim y_N m_{\text{PeV}} \sim \text{PeV}^2 / M_p$

 **Mass of right-handed neutrino:** $M_N \sim \text{PeV}$

Neutrino Mass

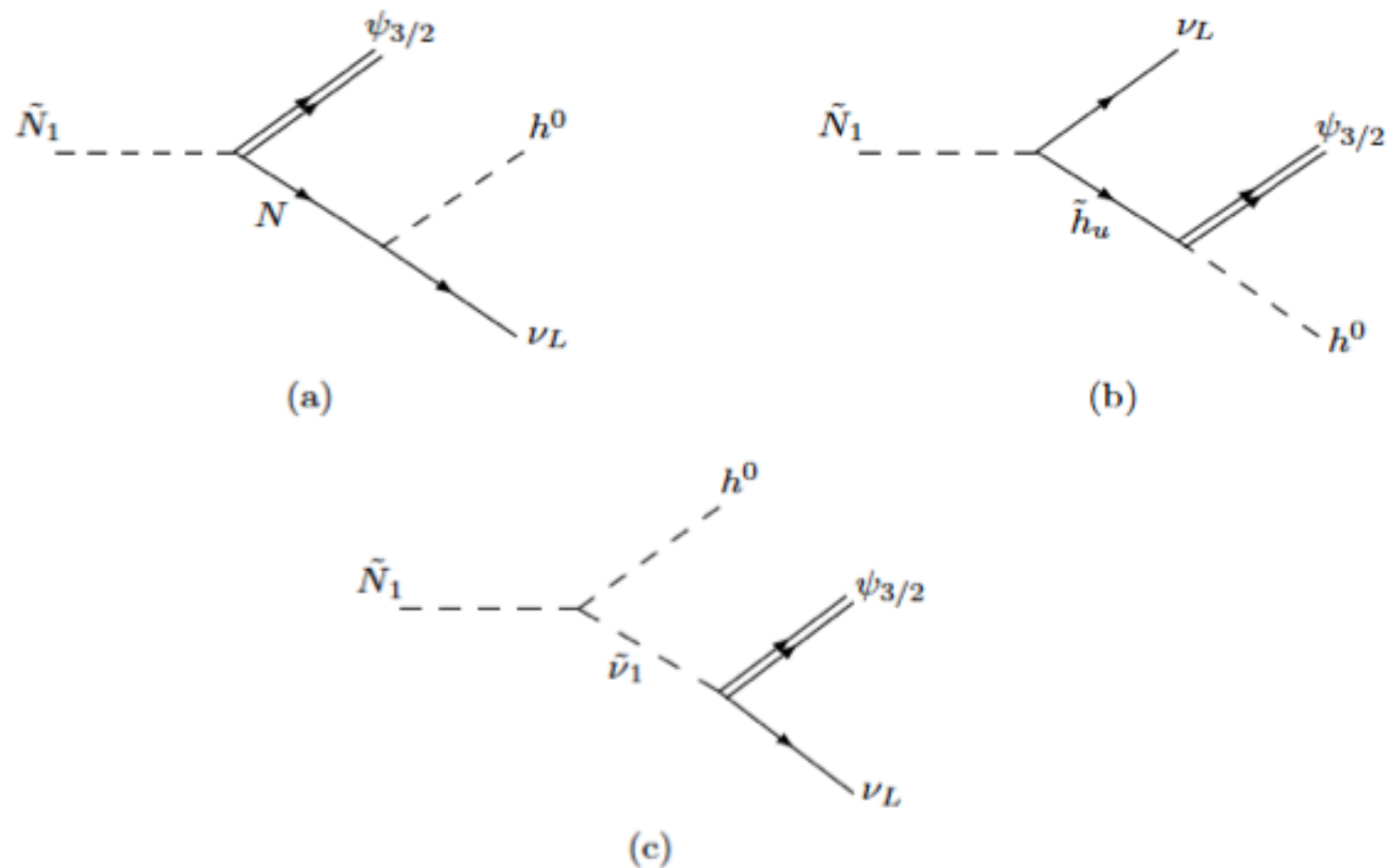
$$m_i = \begin{pmatrix} m_{\nu_L} & y_N v_u \\ y_N v_u & m_N \end{pmatrix}$$

$$m_{\nu_L} \sim \int d^2\theta d^2\bar{\theta} \frac{1}{M_*^2} (\hat{L} \cdot \hat{H}_d^\dagger) (\hat{L} \cdot \hat{H}_u)$$

For $K \supset \hat{H}_d^\dagger \hat{H}_d$ and $W \sim m_{3/2} M_p^2$

$$\begin{aligned} m_{\nu_L} &\sim \frac{m_{3/2} v^2 \sin \beta \cos \beta}{M_*^2} \\ &\sim 0.1 \text{eV}, \quad \text{for } M_* \sim 10^{10} \text{GeV} \end{aligned}$$

Sneutrino Decay Modes



Life time of sneutrino: $\Gamma_{\tilde{N}_1 \rightarrow \nu_L h^0 \psi_{3/2}} \sim \frac{1}{2^{8.9} \pi^3} \frac{y_N^2 m_{\text{PeV}}^3}{M_p^2}$
 $\sim 10^{-48} \text{ GeV} \sim 10^{-24} \text{ sec}^{-1}.$

Right-handed sneutrino: produced via freeze-in mechanism

- $\tilde{h}_u$ (Higgsino) $\rightarrow \tilde{N}_1 \nu_L$ Mediated by dominant Yukawa coupling
- $\tilde{\nu}_1$ (Heavier sneutrino) $\rightarrow \tilde{N}_1 h^0$
- $\tilde{e}_L$ (Slepton) $\rightarrow \tilde{N}_1 W^\pm$

Relic abundance of sneutrino:

$$\Omega_{\tilde{N}_1} h^2 \approx 1.4 \times 10^{-6} \left(\frac{y_N}{0.5 \times 10^{-13}} \right)^2 \left(\frac{9.5 \text{ PeV}}{m_{\tilde{h}_u}} \right) \left(\frac{m_{\tilde{N}_1}}{6.5 \text{ PeV}} \right).$$

Sneutrino makes up a small fraction of the total DM of the universe!

Gravitino: produced via freeze-in mechanism

$$i \rightarrow \psi_{3/2} + \text{SM.}$$

$$q + \tilde{g} \rightarrow \psi_{3/2} + q;$$

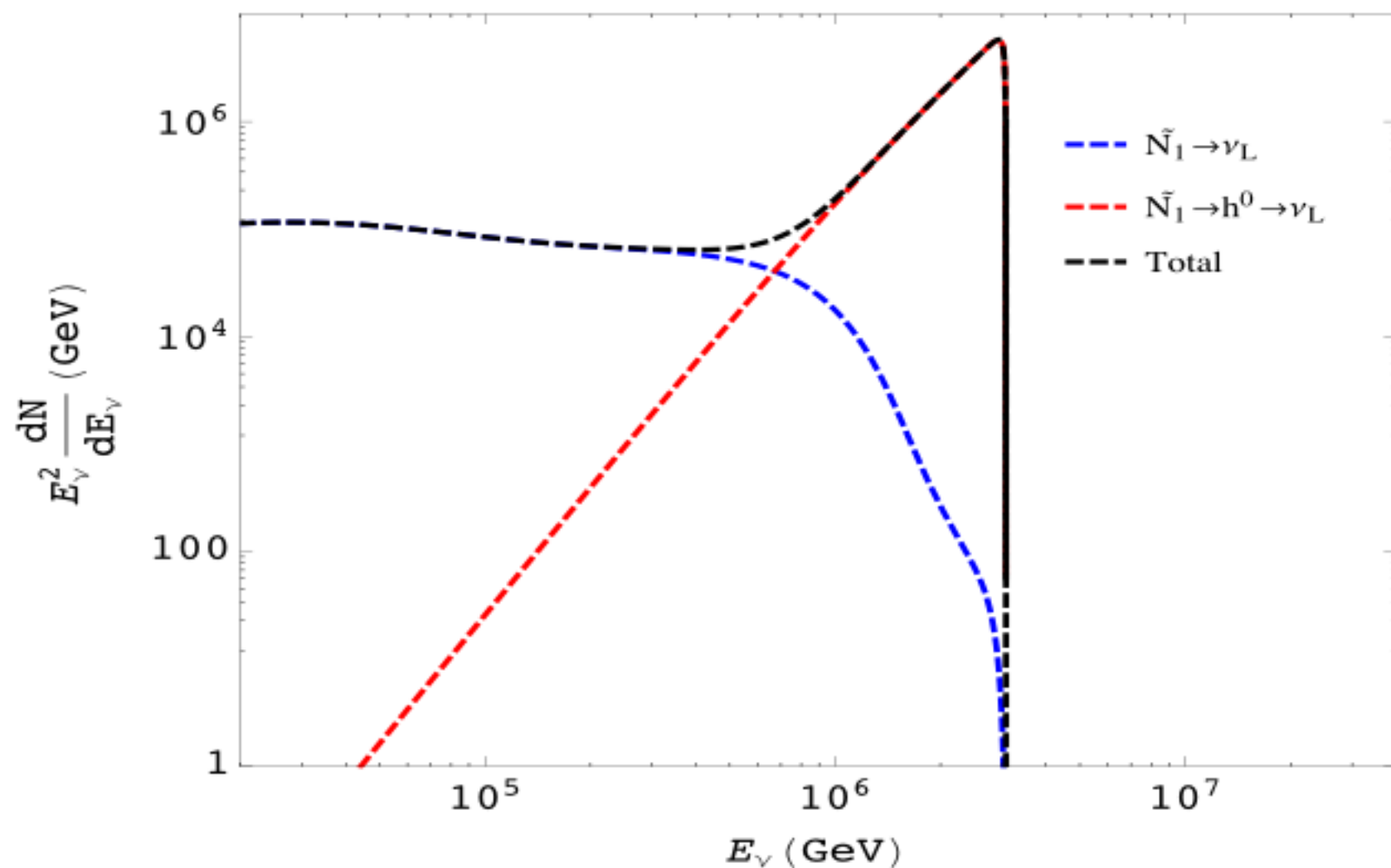
Relic abundance of gravitino:

$$\Omega_{3/2} h^2 \sim 0.12 \left(\frac{M_a}{10 \text{ PeV}} \right)^3 \left(\frac{1.5 \text{ PeV}}{m_{3/2}} \right) +$$
$$3.3 \times 10^{-18} \left(\frac{m_{\tilde{g}}}{7.5 \text{ PeV}} \right)^2 \left(\frac{1.5 \text{ PeV}}{m_{3/2}} \right)^2 \left(\frac{T_R}{10 \text{ PeV}} \right).$$

Gravitino makes up almost all of the DM of the universe!

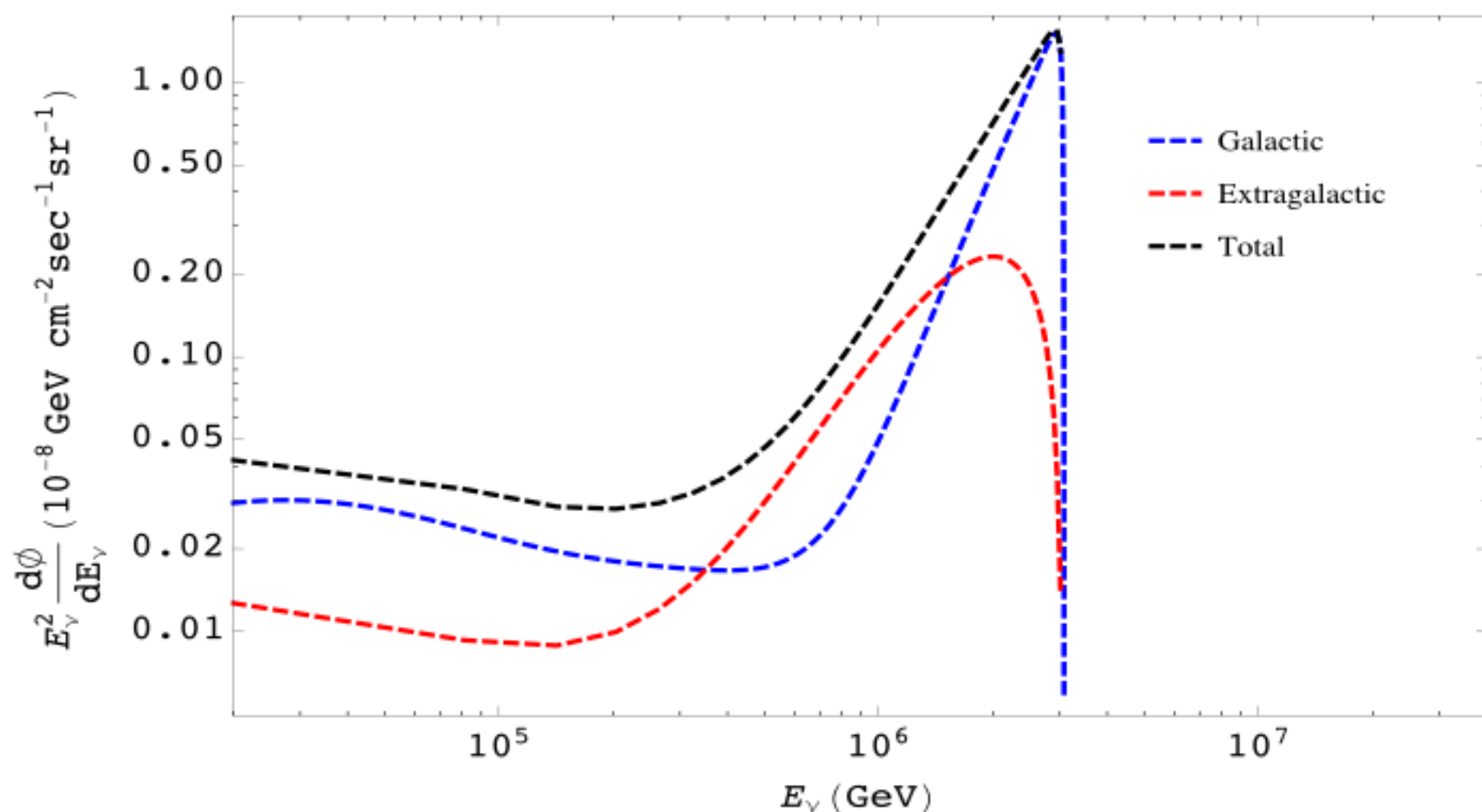
Neutrino Source Spectrum

$$\frac{dN}{dE_\nu} = \frac{1}{\Gamma} \frac{d\Gamma}{dE_\nu} + \int \frac{1}{\Gamma} \frac{d\Gamma}{dE_{h^0}} \frac{dN_\nu(E_{h^0})}{dE_\nu} dE_{h^0}$$

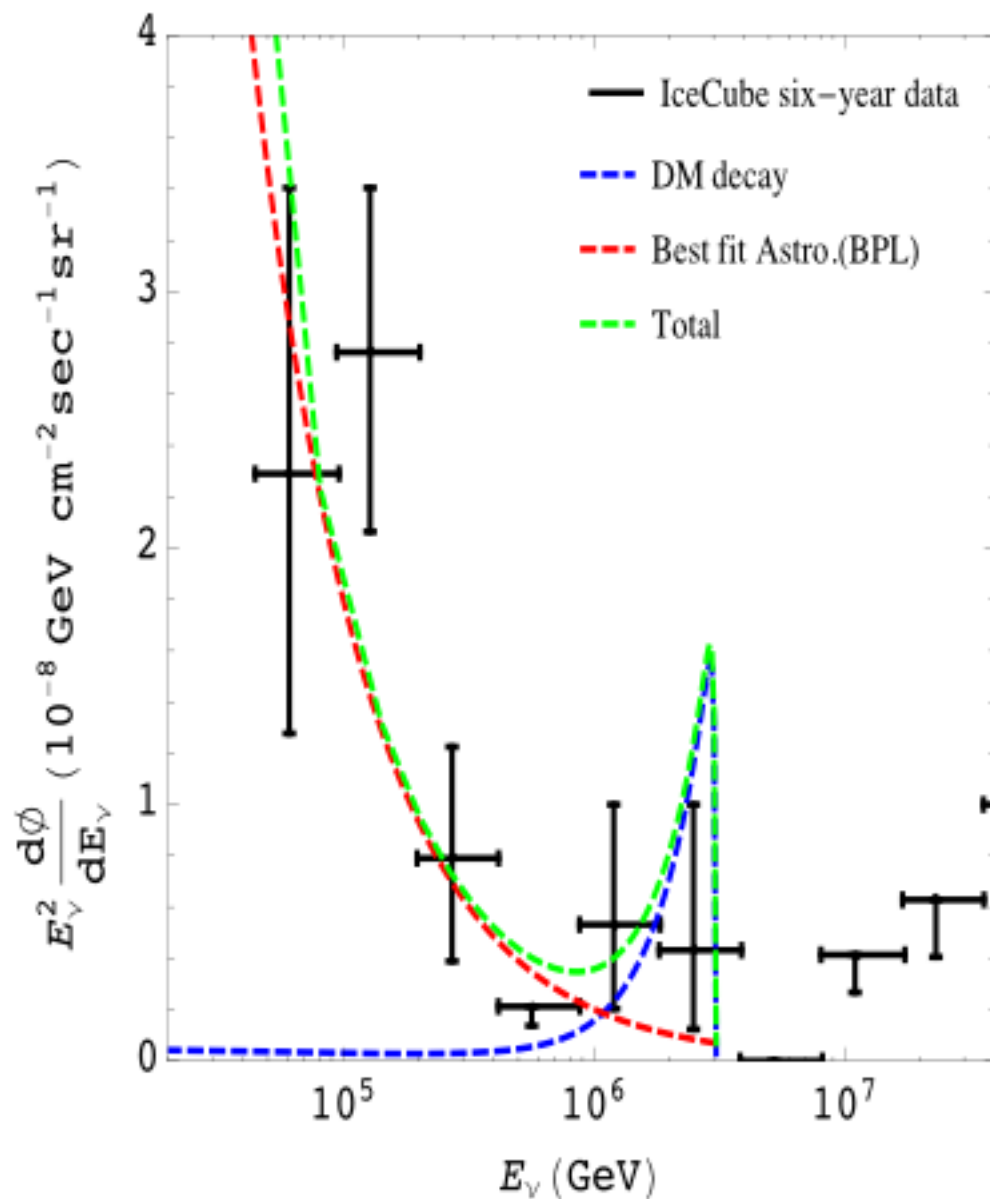


Neutrino flux spectrum

$$E_\nu^2 \frac{d\phi}{dE_\nu} = E_\nu^2 \left[\frac{d\phi_{\text{astro.}}}{dE_\nu} + \frac{1}{4\pi} \int d\Omega \left(\frac{d\phi}{dE_\nu}(\text{galactic}) + \frac{d\phi}{dE_\nu}(\text{extragalactic}) \right) \right]$$

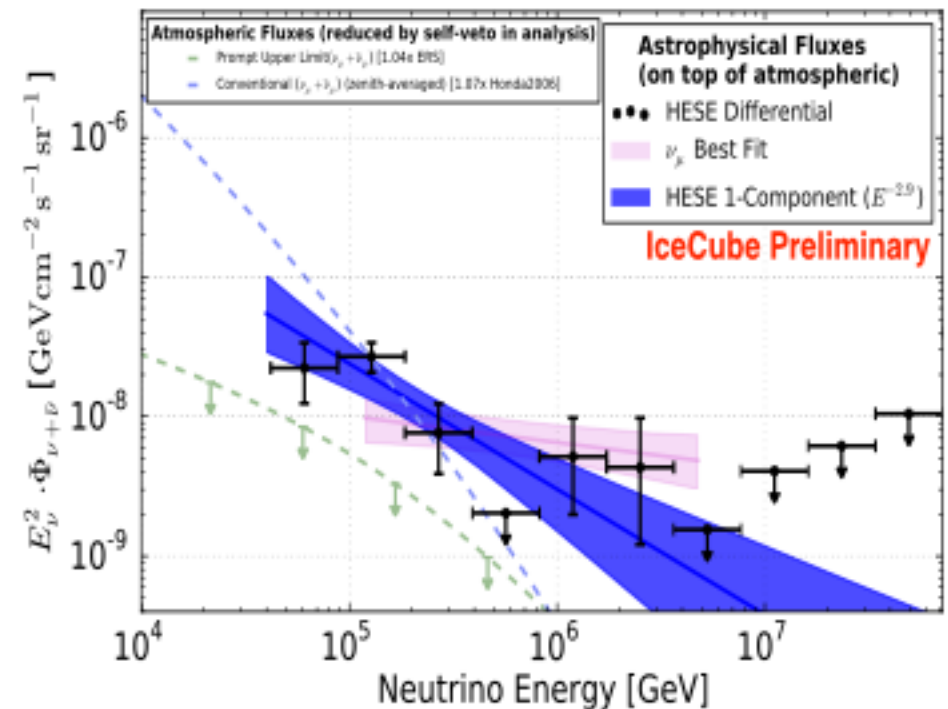


Total flux including astrophysical background

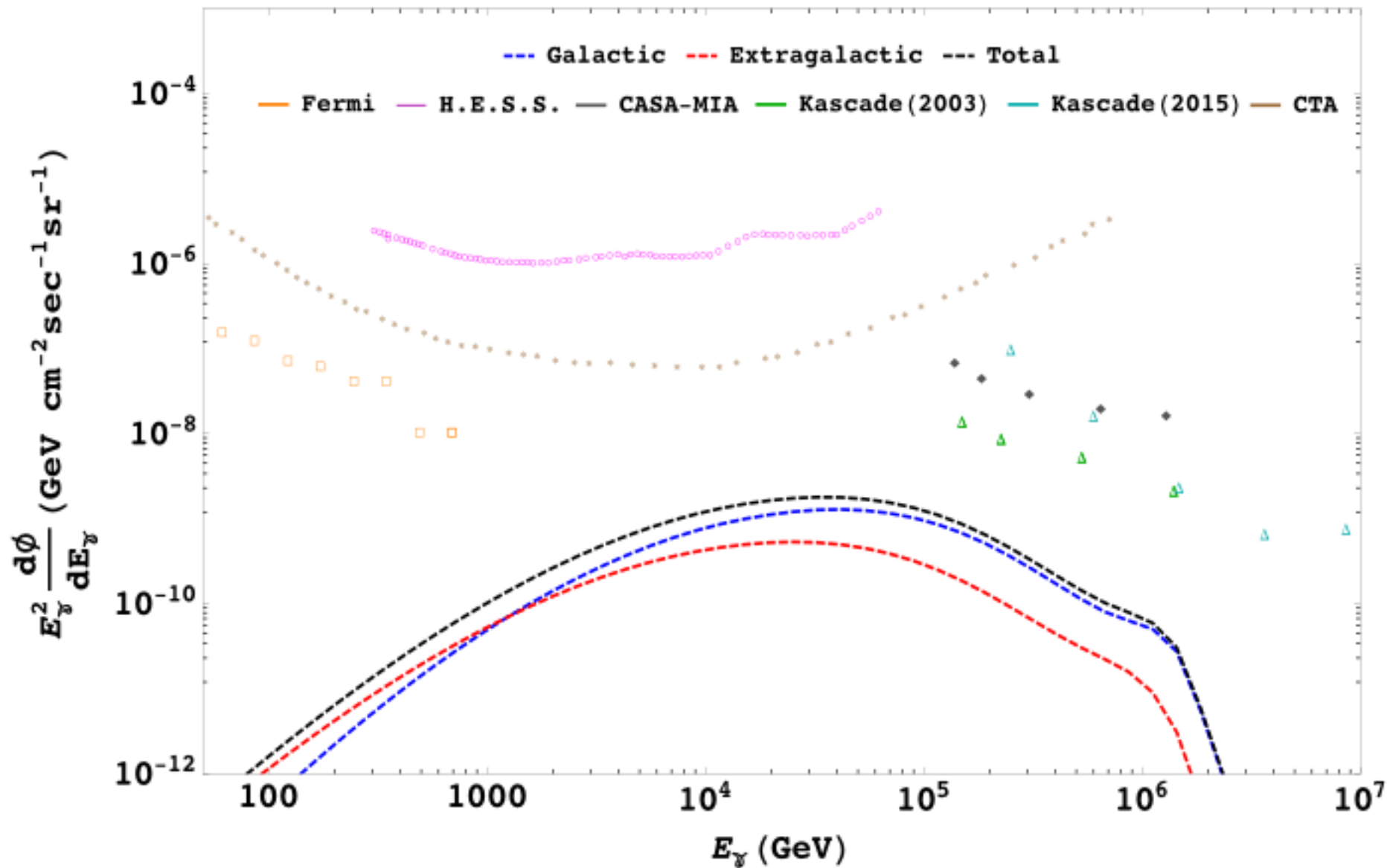


$$E_\nu^2 \frac{d\phi}{dE_\nu} \propto \left(\frac{\text{PeV}}{m_{\text{DM}}} \right) \left(\frac{\Omega_{\text{DM}}}{0.1} \right) \left(\frac{\Gamma_{\text{DM}}}{10^{-29} \text{ s}^{-1}} \right)$$

10^{-6} 10^{-24} s^{-1}



Gamma-ray Spectrum



Conclusions

With the main assumption of PeV-scale superpartners and PeV-scale reheating temperature

-  **Gravitino makes up almost all of the DM of the universe.**
-  **Right-handed sneutrino makes up a very small fraction of DM, yet its decay explains the IceCube neutrino flux.**
-  **The gamma ray flux obtained from decay of sneutrino is within the limits given by various sets of observations.**

**Thanks for Your Kind
Attention!**

$$R(\hat{N}^c) = R(\hat{H}_u) = R(\hat{H}_d) = 1/2, \quad R(\hat{X}) = 1$$

$$R(\hat{L}) = R(\hat{Q}) = 0, \quad R(\hat{e}^c) = R(\hat{u}^c) = R(\hat{d}^c) = 3/2$$

$$\begin{aligned}\mathcal{K} = & \frac{\widehat{\Phi}^\dagger}{M_p} \widehat{H}_u \widehat{H}_d + \frac{\widehat{\Phi}^\dagger}{M_p} \widehat{N}^c \widehat{N}^c \left(1 + \frac{\widehat{\Phi}^\dagger \widehat{\Phi}}{M_p^2} \right) + \frac{\widehat{\Phi}^\dagger}{M_p^2} \widehat{N}^c \widehat{L} \cdot \widehat{H}_u \left(1 + \frac{\widehat{\Phi}^\dagger \widehat{\Phi}}{M_p^2} + \dots \right) \\ & + \frac{\widehat{\Phi}^\dagger \widehat{\Phi}}{M_p^2} \left(\widehat{L}^\dagger \widehat{L} + \widehat{N}^{c\dagger} \widehat{N}^c \right) + \frac{1}{M_*^2} \left(\widehat{L} \cdot \widehat{H}_d^\dagger \right) \left(\widehat{L} \cdot \widehat{H}_u \right) + \text{h.c.},\end{aligned}$$

Parameters	Dependence on $\langle X \rangle$ and F_X	Numerical values
Scalar/squark mass (m_i)	F_X/M_p	$\mathcal{O}(1)$ PeV
Higgsino mass parameter (μ)	F_X/M_p	$\mathcal{O}(1)$ PeV
Higgs mixing parameter (B_μ)	$\frac{\mu}{16\pi^2} (g_a^2 M_a)$	$\mathcal{O}(1)$ PeV
RH neutrino mass (m_N)	F_X/M_p	$\mathcal{O}(1)$ PeV
Lepton number violating B-term (B_N)	$\langle X \rangle F_X^* F_X / M_p^3$	$\mathcal{O}(10^{-12})$ PeV ²
Trilinear scalar couplings (A_i) (except involving sneutrino)	F_X/M_p	$\mathcal{O}(1)$ PeV
Sneutrino trilinear scalar coupling (A_N)	$\frac{y_N M_a}{16\pi^2}$	$\mathcal{O}(10^{-15})$ PeV
Neutrino Yukawa coupling (y_N)	F_X^* / M_p^2	$\mathcal{O}(10^{-13})$