PeV-scale Supersymmetry breaking and IceCube neutrino

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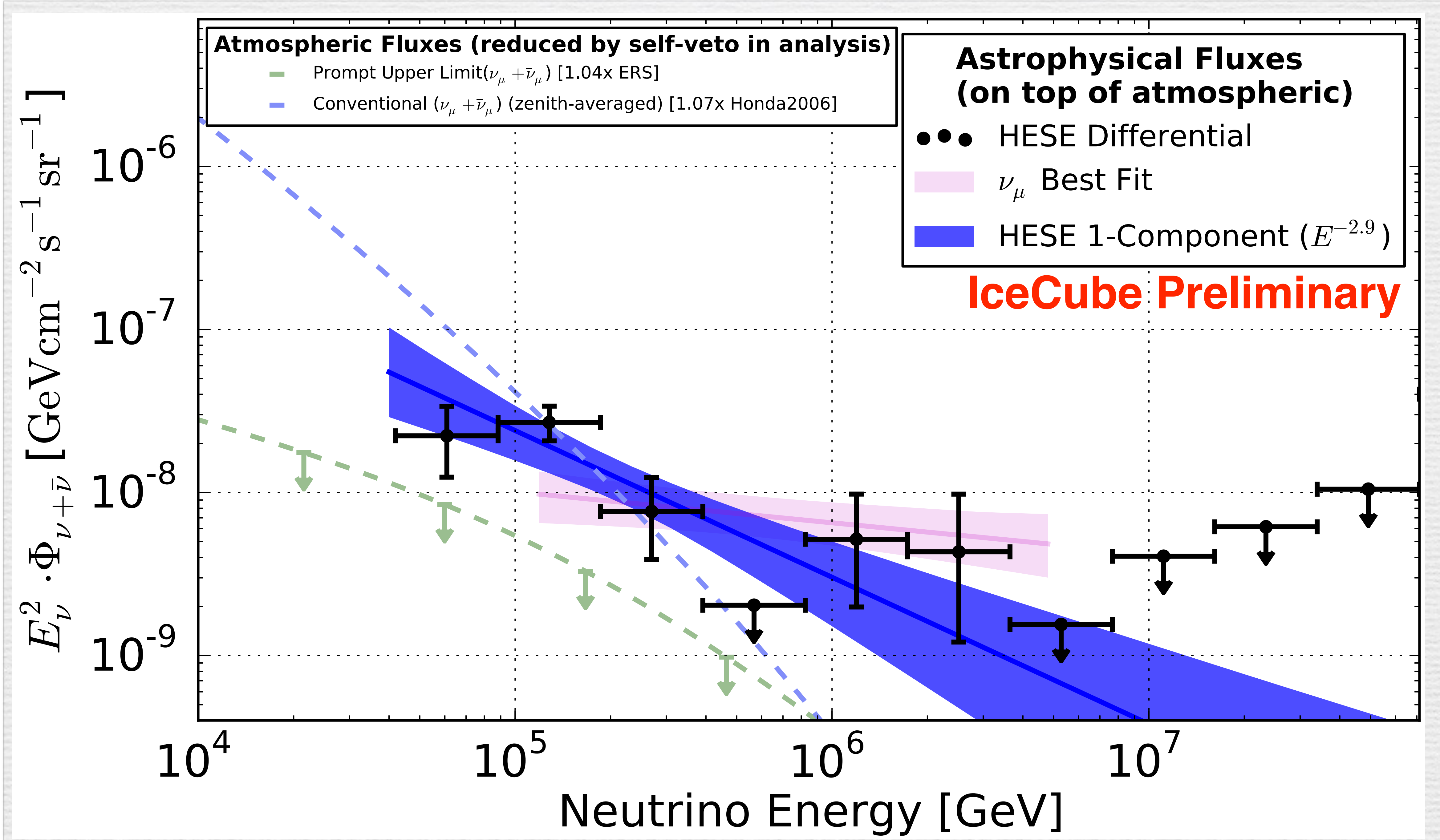
Ongoing work in collaboration with V.Rentala

Outline

- IceCube results $\longleftrightarrow$ PeV-scale supersymmetry
- Decaying Dark Matter as the origin of PeV-scale neutrino events as observed by IceCube observatory
- Realistic supersymmetric scenario (viable Dark Matter candidates, future prospects)



Atmospheric Fluxes (reduced by self-veto in analysis)
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
Astrophysical Fluxes
(on top of atmospheric)
HESE Differential
ν_μ Best Fit
HESE 1-Component ($E^{-2.9}$)
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^4
10^5
10^6
10^7
Neutrino Energy [GeV]

Ice-cube events - parametric dependence

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

For general 2-body decay of Dark Matter

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

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

Possibile PeV-scale decaying DM candidates

- **Neutralino**
- cannot produce required relic abundance as the cross-section would be limited by the unitarity bound.
- **Gravitino**
- for this to act as a viable decaying Dark matter component, R-parity has to be violated.
- **Sneutrino**
- can be a viable decaying DM component even when R-parity is conserved !

Particle spectrum

- N=1 supergravity
- MSSM+Right-handed neutrino superfield
  - R-parity conservation: Stable Gravitino
  - Sneutrino: possible decaying DM component
- Gravity mediation

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

The neutrino interaction terms are:

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

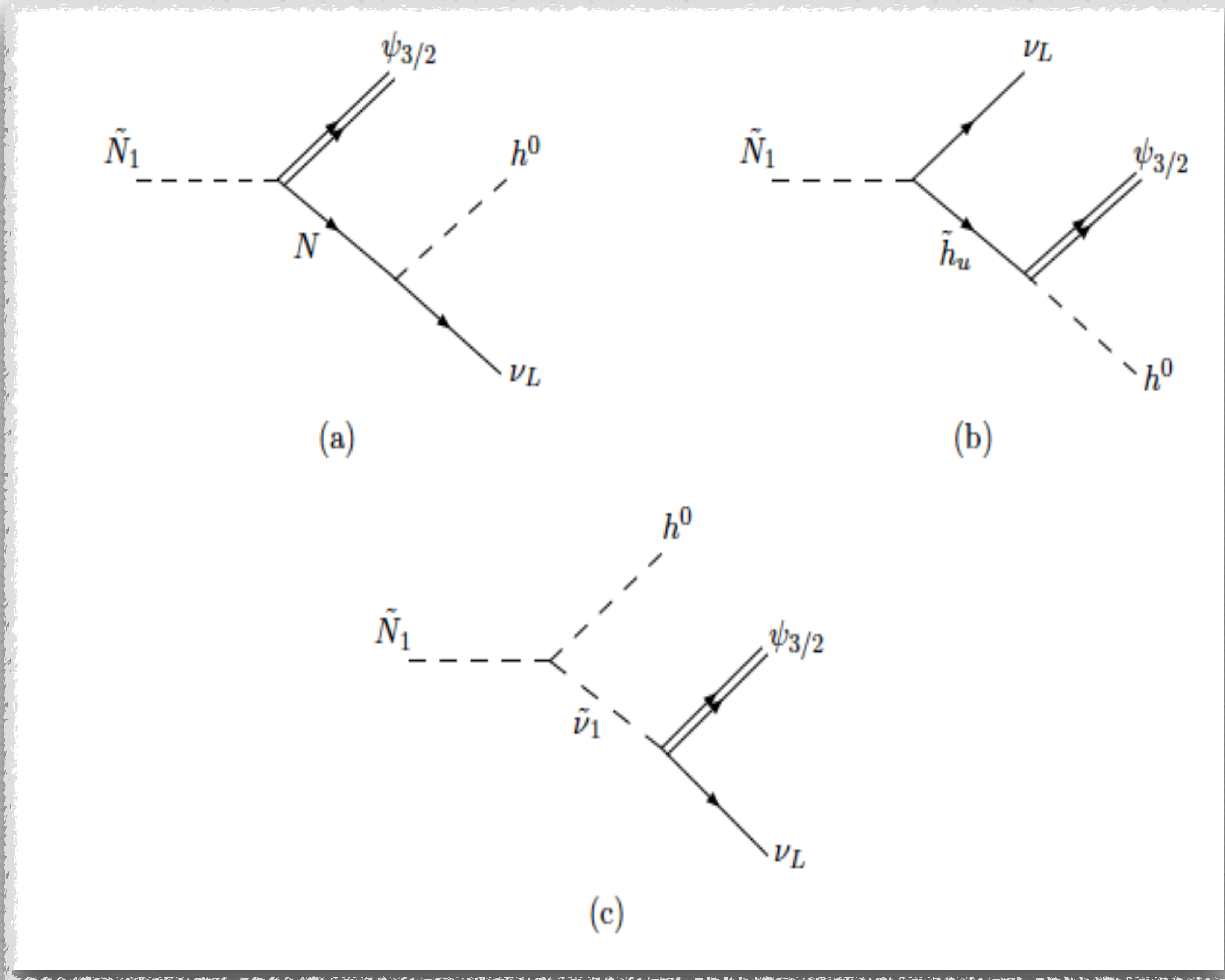
$$\mathcal{W} \supset \cancel{M_N \widehat{N}^c \widehat{N}^c} + y_N \cancel{\widehat{N}^c \widehat{L} \cdot} \widehat{H}_u \left(1 + \frac{\Phi}{M_p}\right)$$

The neutrino interaction terms are:

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

- **Yukawa coupling** $y_N \sim F_X/M_p \sim \mathrm{PeV}/M_p$
- **Scalar Trilinear coupling** $A_N \sim y_N m_{\mathrm{PeV}} \sim \mathrm{PeV}^2/M_p$
- **Mass of neutrino** $M_N \sim \mathrm{PeV}$

Sneutrino decay modes

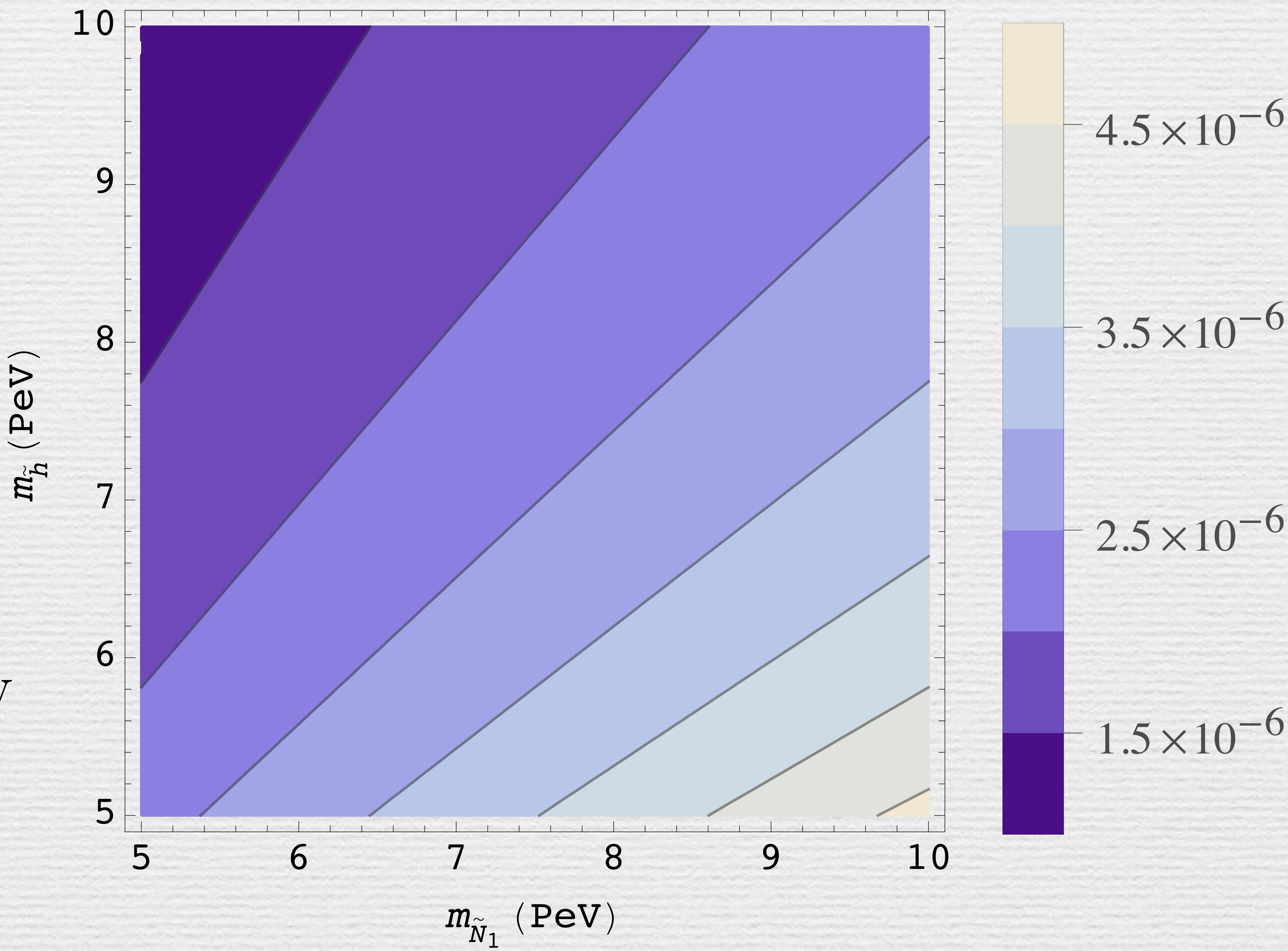


Life time of sneutrino: $\Gamma_{\tilde{N}_1 \to \nu_L h^0 \psi_{3/2}} \sim \frac{1}{2^8 . 9\pi^3} \frac{y_N^2 m_{\rm PeV}^3}{M_p^2}$

$$\sim 10^{-48}\ \mathrm{GeV} \sim 10^{-24}\ \mathrm{sec}^{-1}.$$

Right-handed sneutrino: produced via freeze-in mechanism

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



Benchmark points:

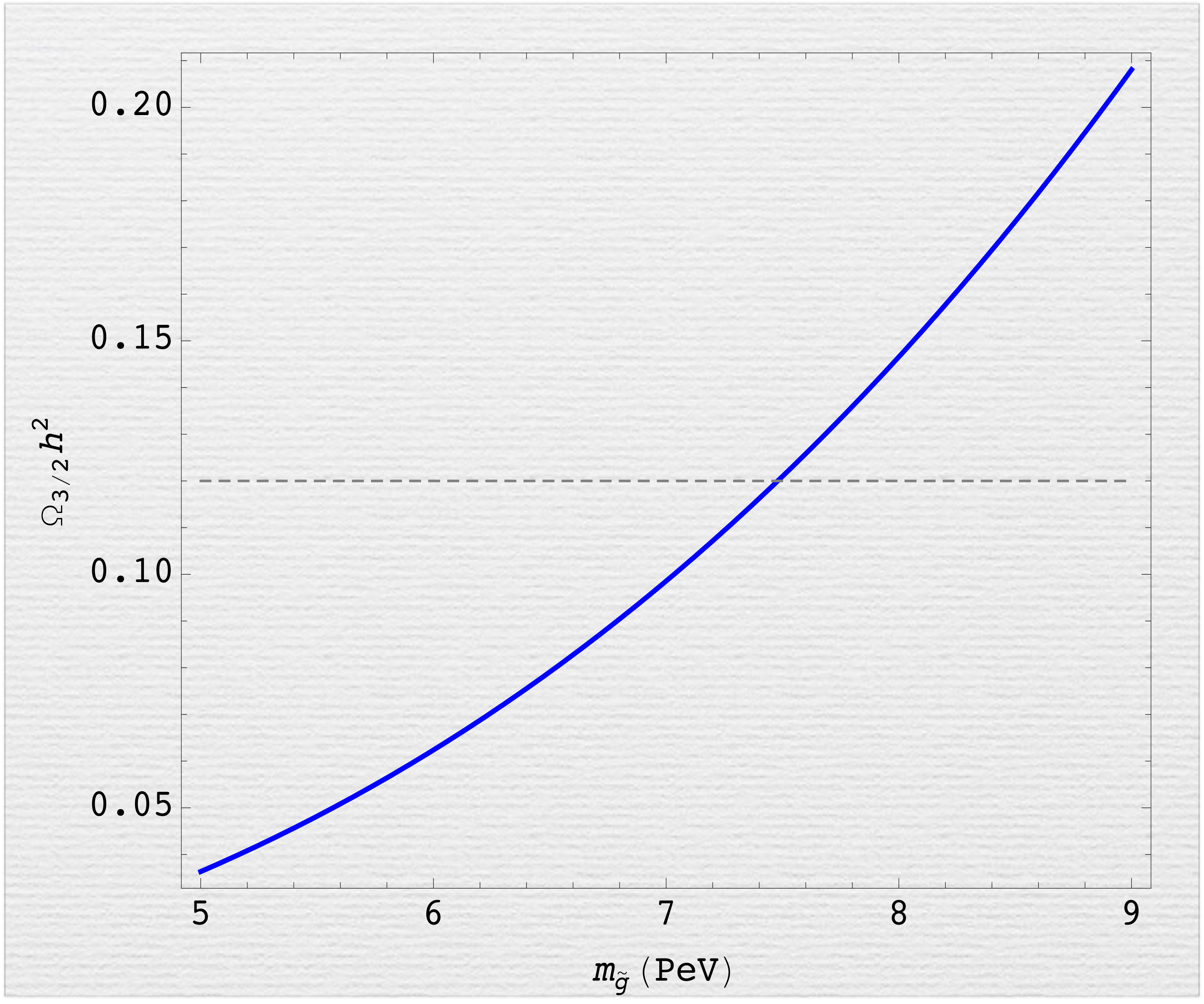
$$m_{\tilde{N}_1} \sim 6.5 \text{ PeV}, m_{\tilde{h}_u} \sim 9.5 \text{ PeV}$$

Gravitino: produced via freeze-in mechanism

- $\tilde{q} \to \psi_{3/2} + q$
- $q + \tilde{g} \to \psi_{3/2} + q$

$$Y_{3/2(\text{decay})} \approx \frac{45\ g_i}{(1.66)\ 2^7 \pi^4 g_*^S \sqrt{g^\rho}} \left(\frac{m_{\tilde{g}}^3}{m_{3/2}^2 M_p} \right)$$

$$Y_{3/2(\text{scattering})} \approx \frac{60}{1.66\ (2\pi)^7 g_*^S \sqrt{g^\rho}} \left(\frac{m_{\tilde{g}}^2\ T_R}{m_{3/2}^2 M_p} \right).$$

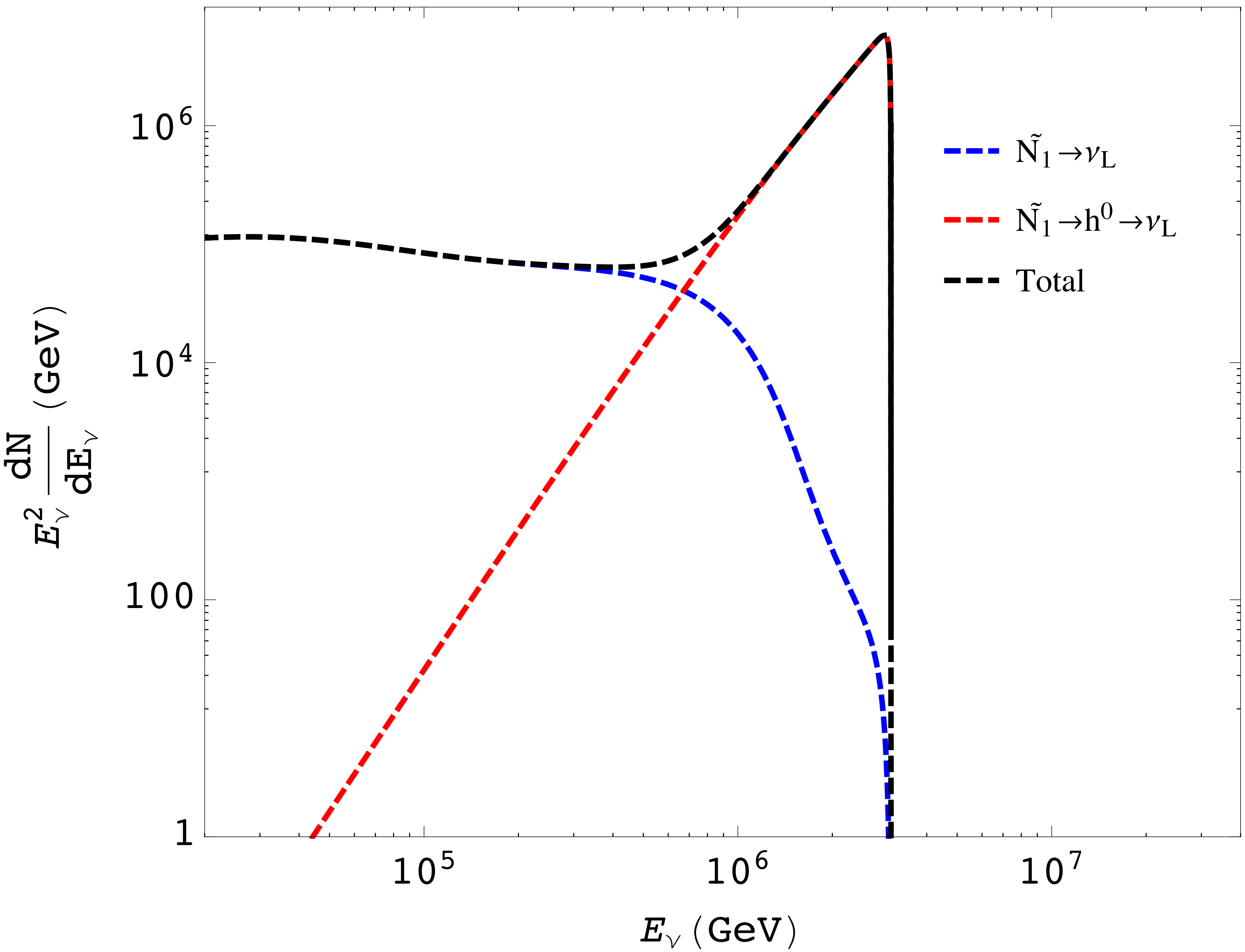


Benchmark points:

$$m_{\tilde{g}} \sim 7.5\ \text{PeV}, m_{3/2} \sim 3\ \text{PeV}, m_{\tilde{N}_1} \sim 6.5\ \text{PeV}$$

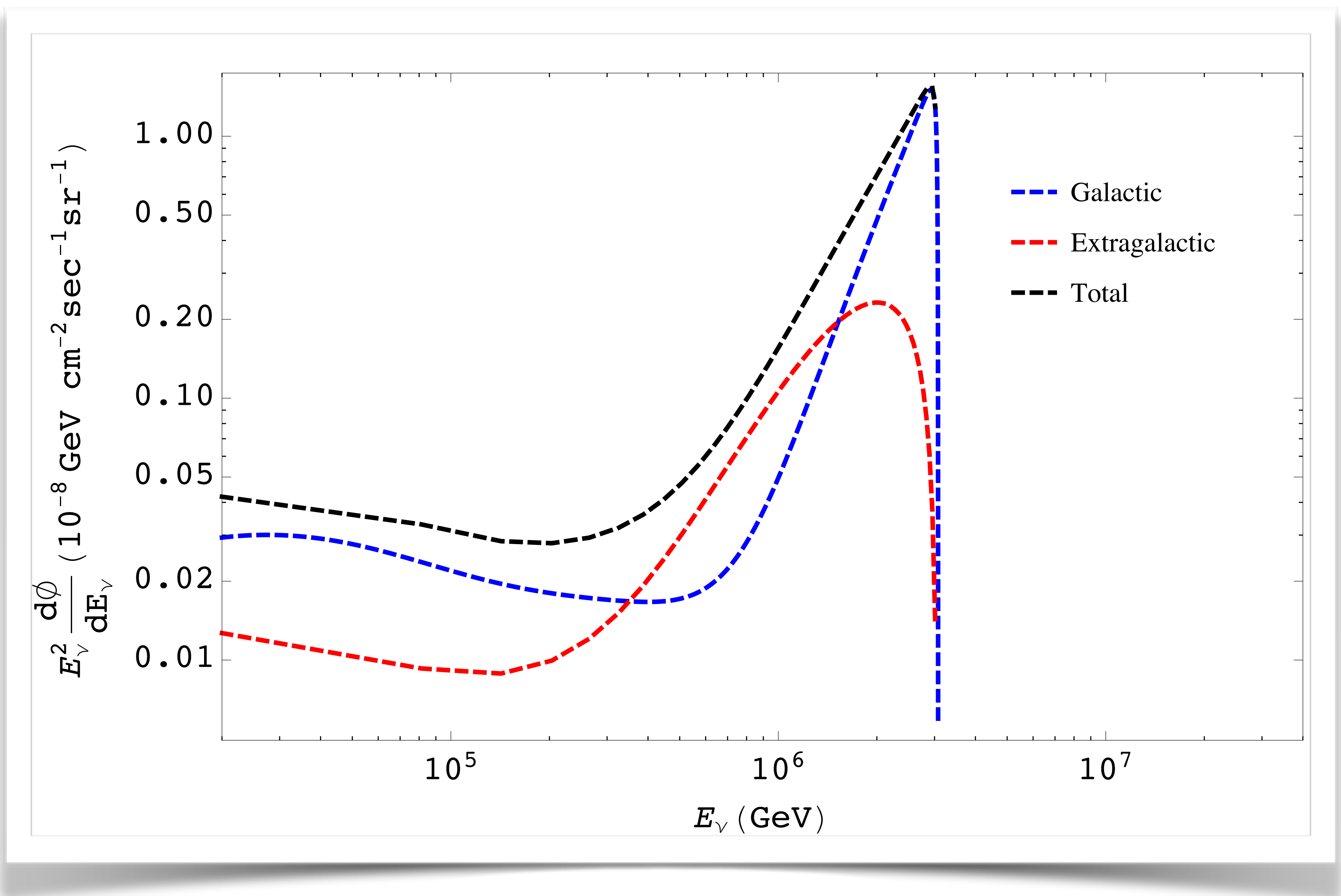
Neutrino source spectrum

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

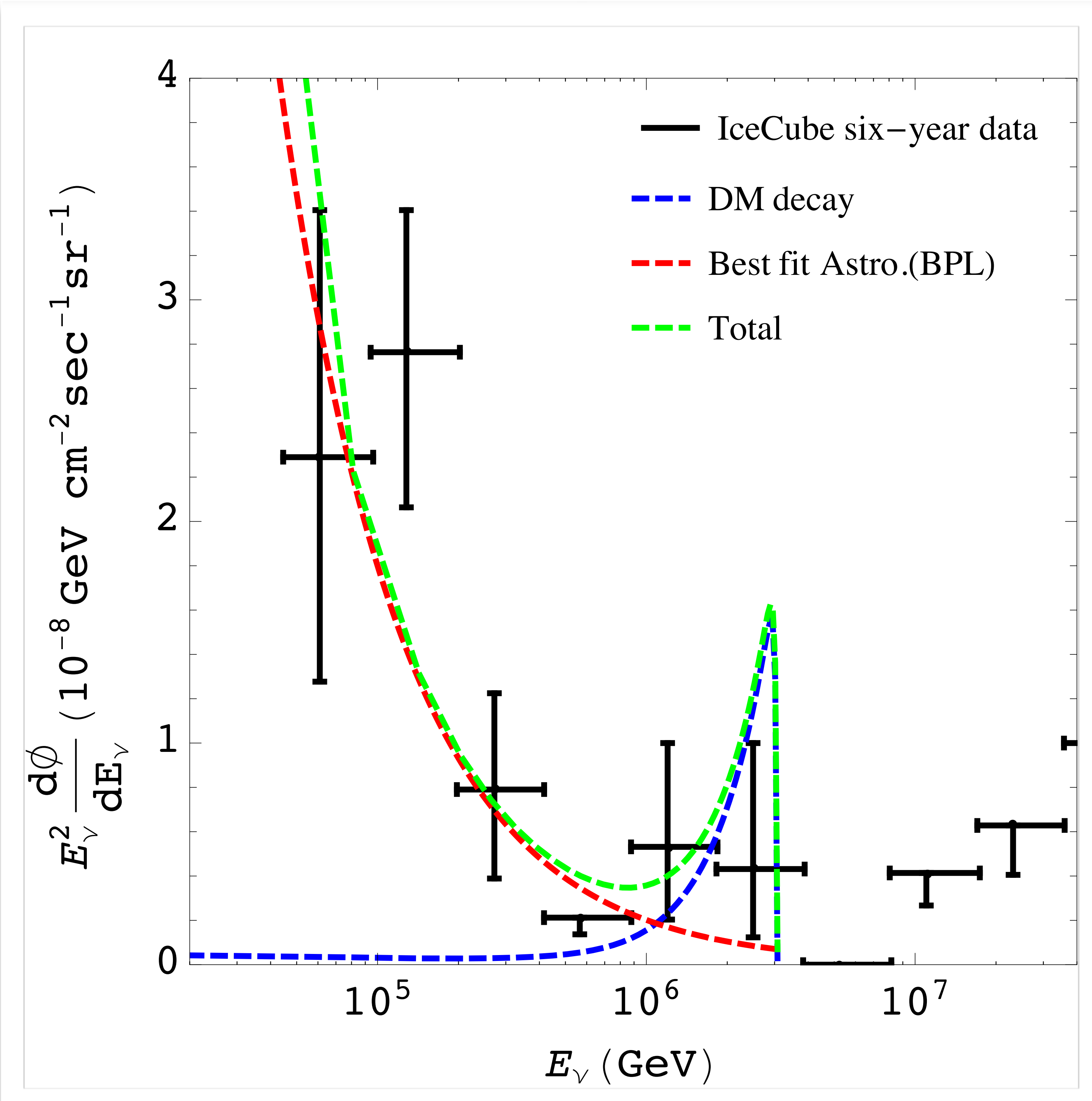


Neutrino flux spectrum

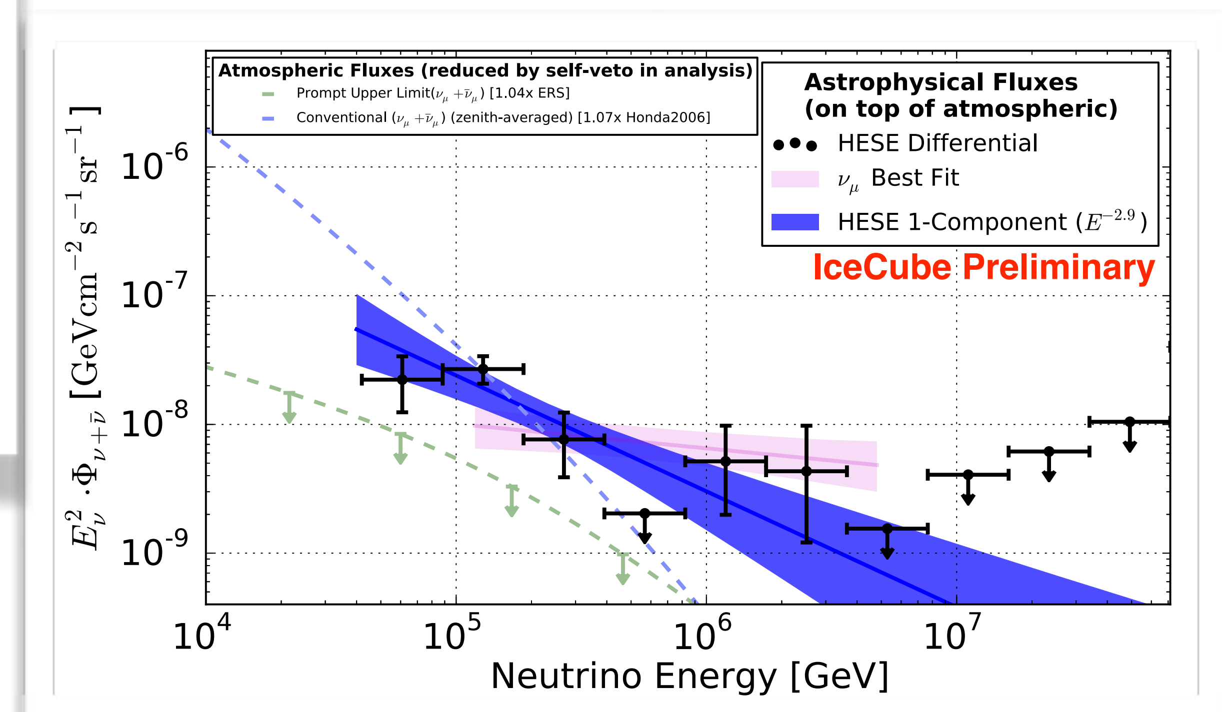
$$E_\nu^2 \frac{d\phi}{dE_\nu} = E_\nu^2 \left[\frac{d\phi_{\rm astro.}}{dE_\nu} + \frac{1}{4\pi} \int d\Omega \left(\frac{d\phi}{dE_\nu}({\rm galactic}) + \frac{d\phi}{dE_\nu}({\rm extragalactic}) \right) \right]$$



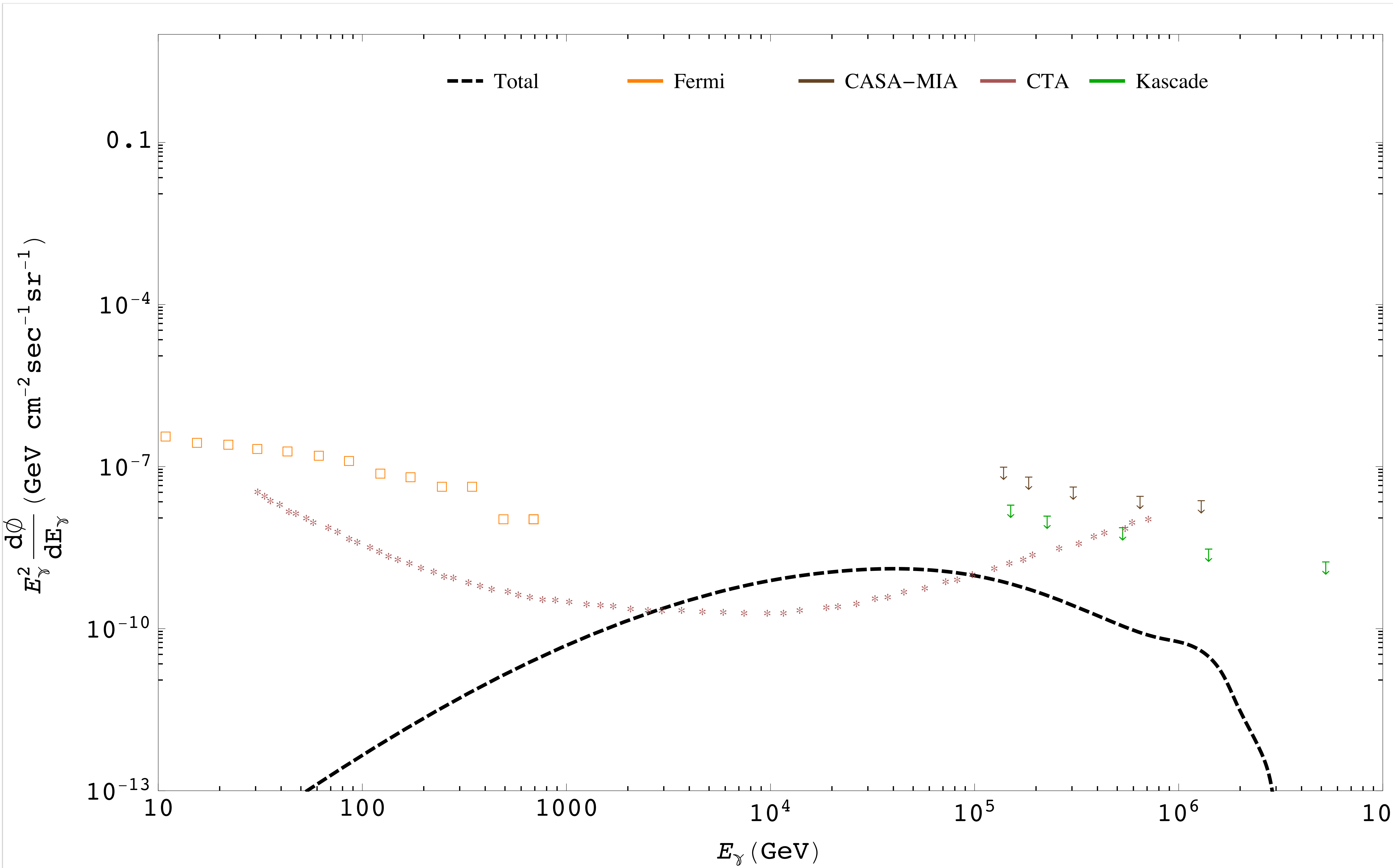
Total flux including astrophysical background



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



Gamma-ray spectrum



Conclusions

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

i. Gravitino makes up almost all of the DM of the universe.
ii. Right-handed sneutrino makes up a very small fraction of DM, yet its decay explains the IceCube neutrino flux.
iii. The gamma ray flux obtained from decay of sneutrino might be observed by future gamma-ray telescopes.

Thanks for your kind attention !

Neutrino mass

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

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

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

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

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

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

$$Y_{\tilde{N}_1(\mathrm{decay})} \sim \frac{135\ g_{\tilde{h}_u}}{2^7\pi^4\ (1.66)\ g_*^S\sqrt{g^\rho}} \left(\frac{y_N^2 M_p}{m_{\tilde{h}_u}}\right)$$

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

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)	$\frac{\mu}{16\pi^2}\left(g_a^2 M_a\right)$	$\mathcal{O}(1)$ 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	$\mathcal{O}(10^{-13})$