IceCube Neutrino Events from Decaying Dark Matter

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based on P.Ko, ***YT***, 1508.02500(PLB)

Outline

- Introduction
  - IceCube Neutrino Events
- DM with Right-handed Neutrino Portal
- Numerical Results
- Summary

Neutrino Events at IceCube

IceCube, PRL 113, 101101

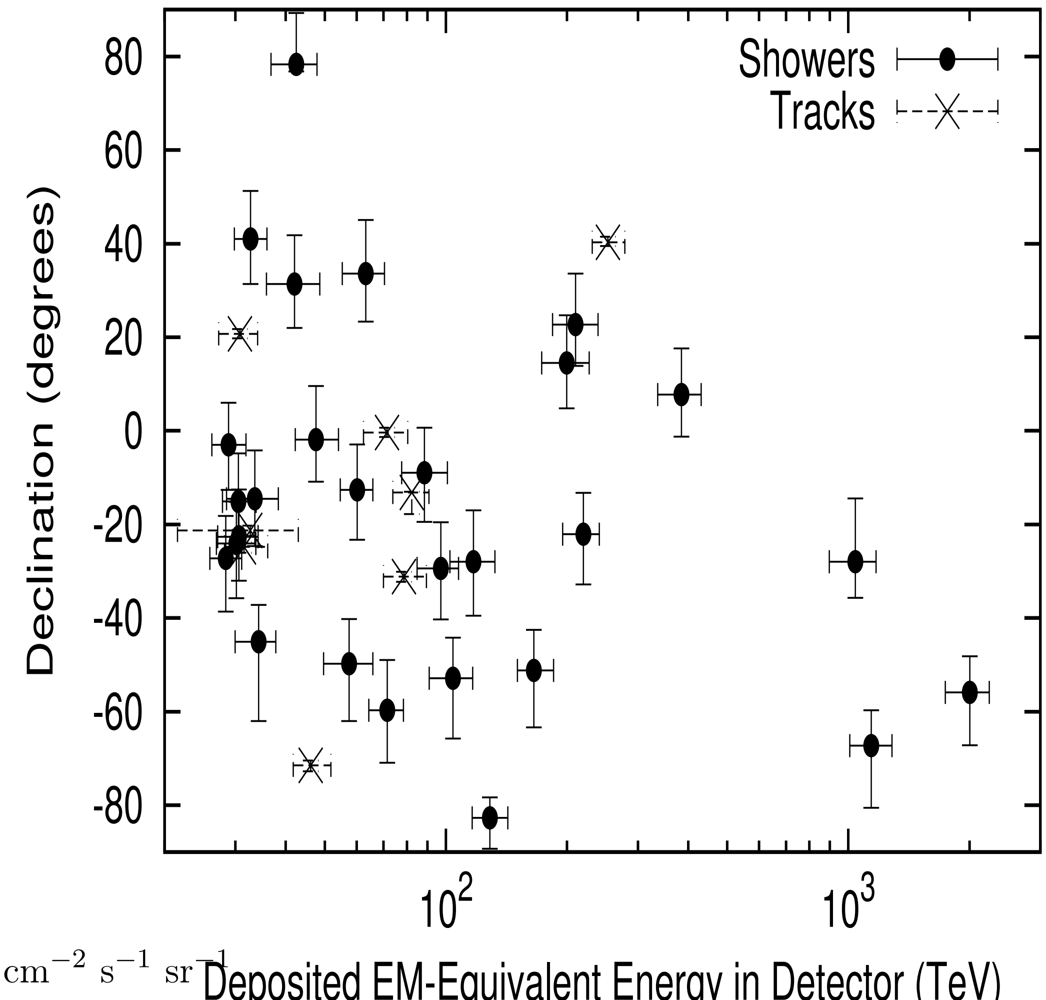
- Full 988-day data
- 30TeV — 2 PeV
- 37 events
- Muon Background

$$N_{\mu^\pm} = 8.4 \pm 4.2$$

- Atmospheric neutrino

$$N_{\nu+\bar{\nu}}^{all} = 6.6^{+5.9}_{-1.6} \ ,$$

- reject pure atm, 5.7σ
- Isotropy, equal flavor
- global fit flux



$$E^2 \frac{dJ_{\nu+\bar{\nu}}}{dE} = (0.95 \pm 0.3) \times 10^{-8} \text{GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Neutrino Events at IceCube

- Full 4-year data
- ~30TeV — 2 PeV
- 54 events
- Muon Background

$$N_{\mu^{\pm}} = 12.6 \pm 5.1$$

- Atmospheric neutrino

$$N^{all}_{\nu+\bar{\nu}} = 9.0^{+8.0}_{-2.2}$$

- reject pure atm, 6.5σ

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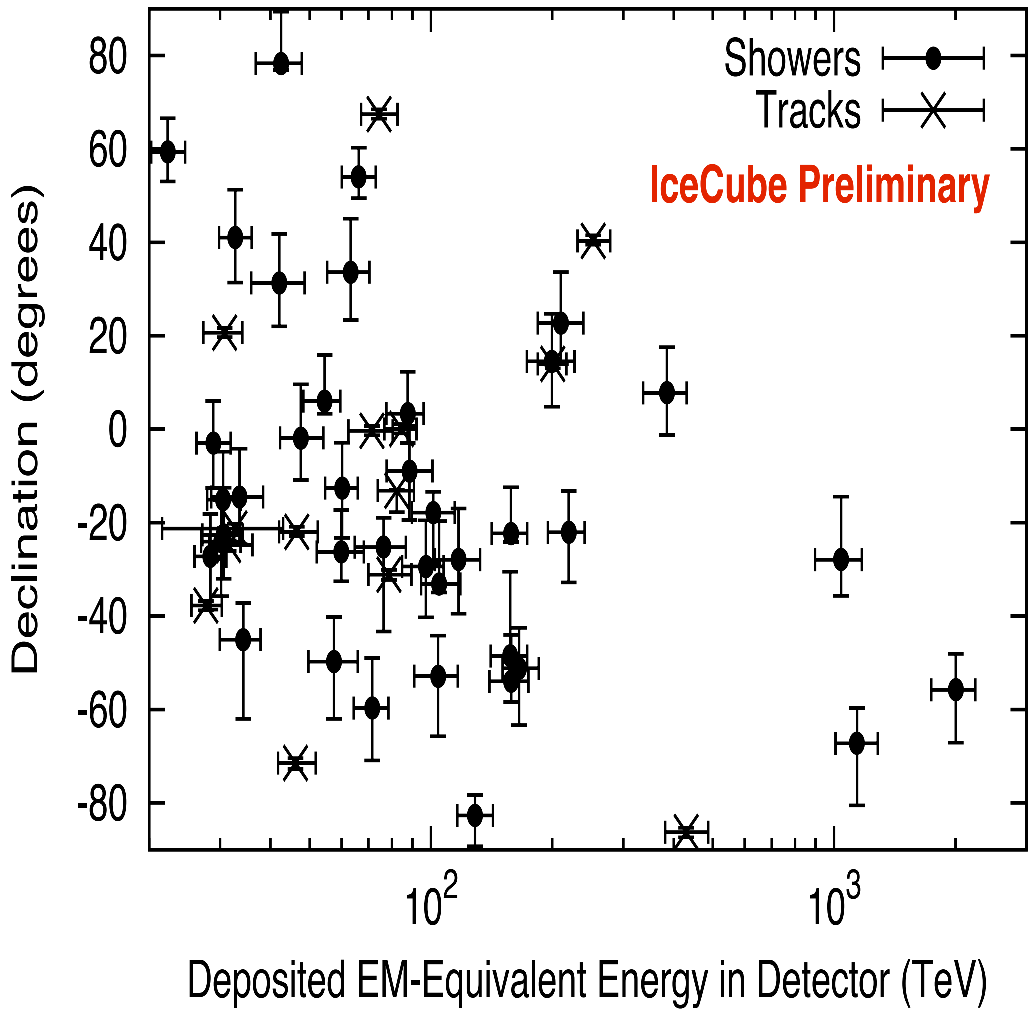
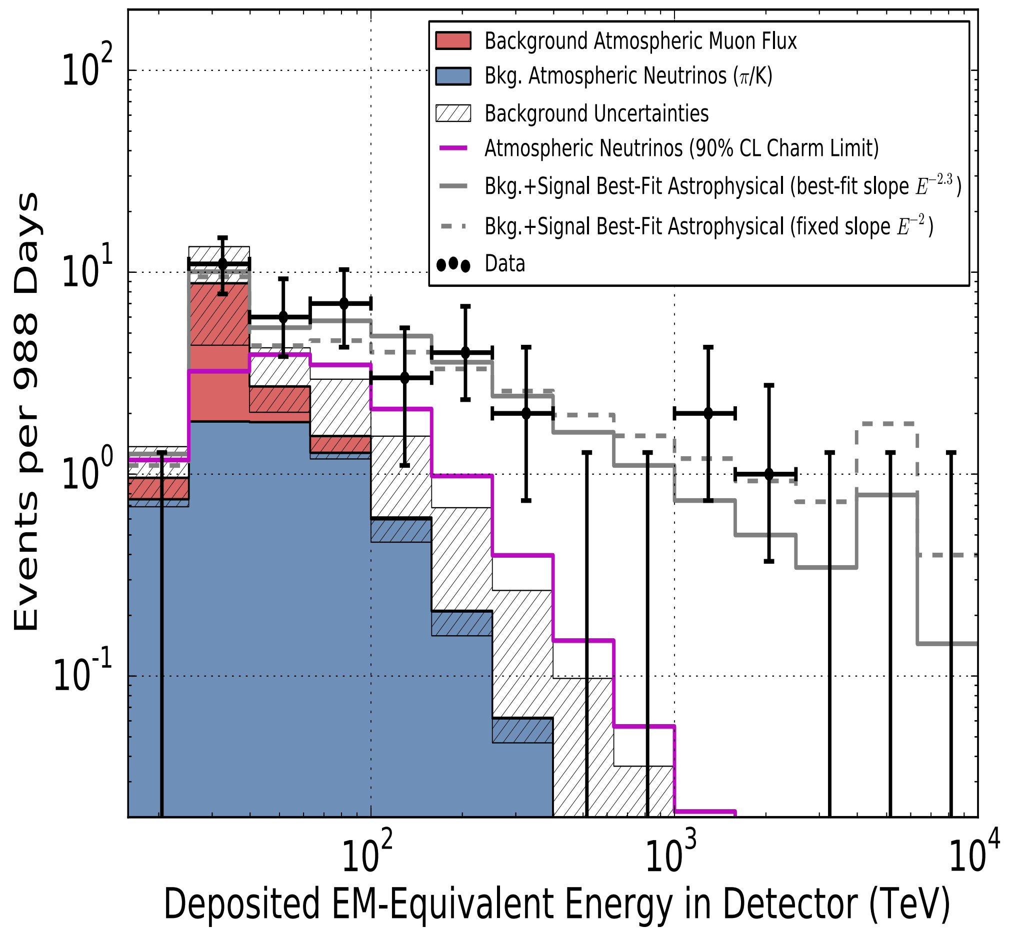


Astrophysical Sources

- Supernova Remnants
- Active Galactic Nuclei
- Gamma-Ray Burst

Usually assume some specific emission spectra and consider pγ and pp interactions



Power law

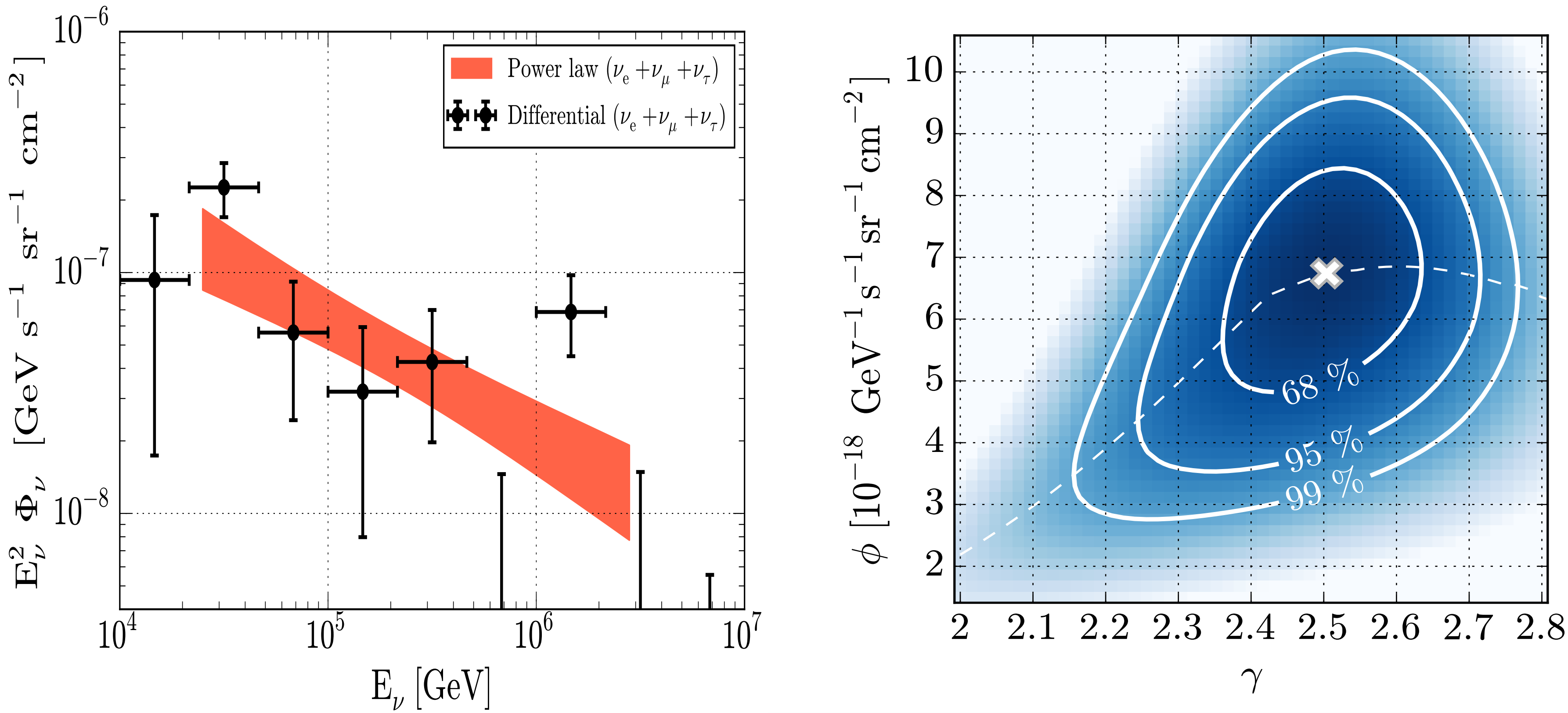
IceCube 1507.03991

- Assuming astrophysical flux arrives isotropically and equal flavor

$$\Phi_\nu = \phi \cdot \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$$

$$\gamma = 2.50 \pm 0.09$$

$$\phi = \left(6.7^{+1.1}_{-1.2}\right) \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$$



Spectral Fit

- Best fit spectral index

$$\gamma = 2.58$$

- Prefer softer spectrum
- Potential cut-off at about 2-5 PeV

challenge?

1 up-going muon-track event
with ~2.6 PeV deposited energy,
estimated neutrino energy ~6-10 PeV

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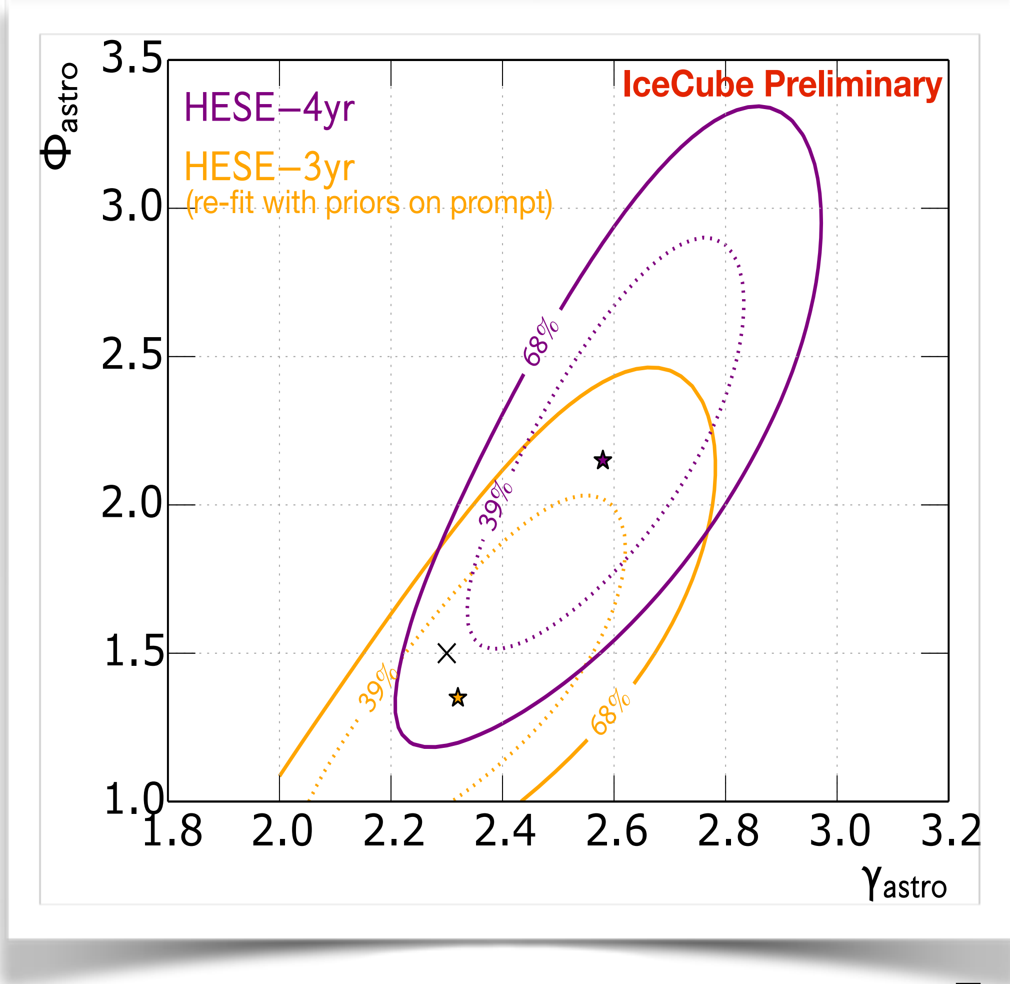
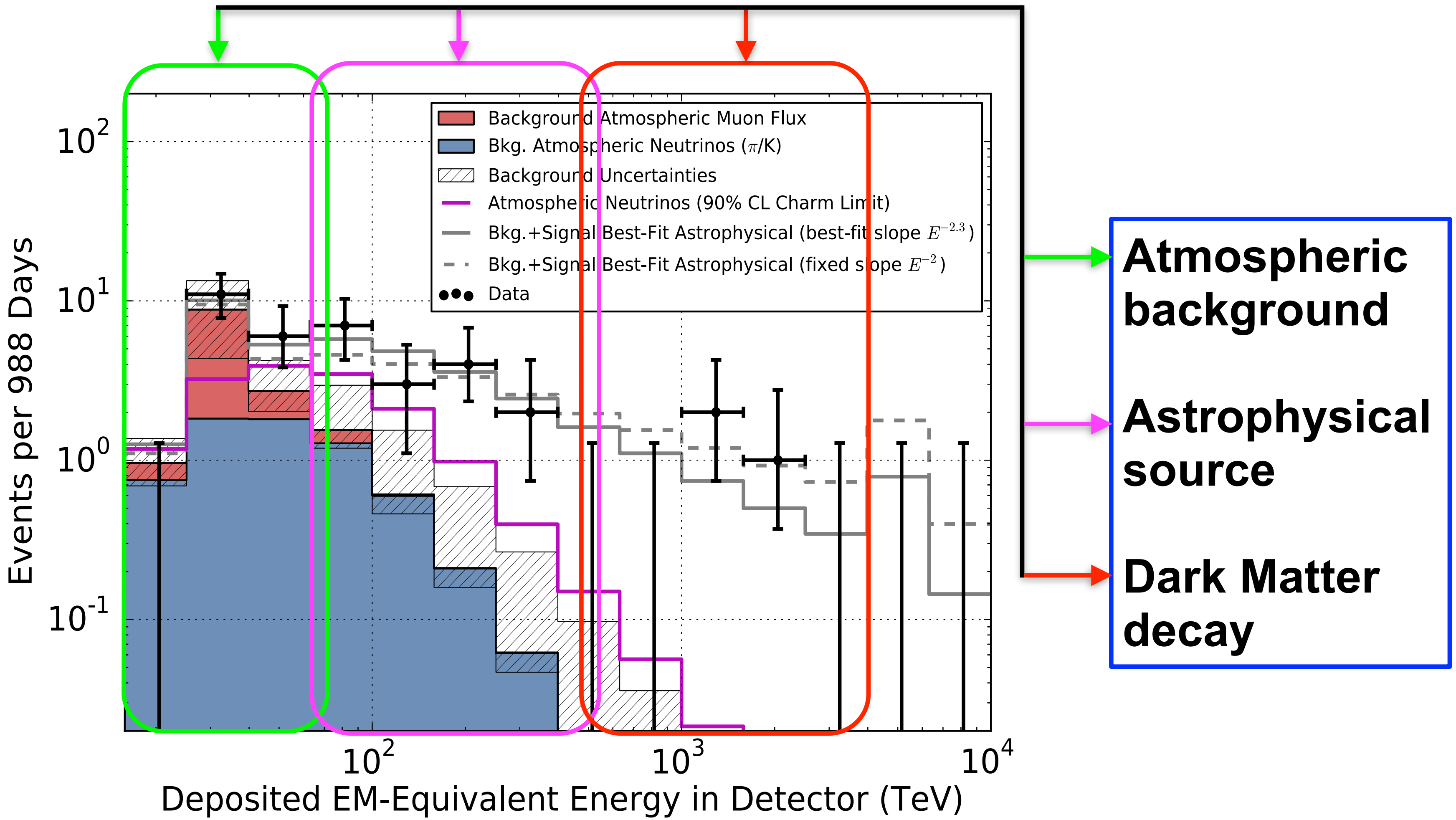


Framework

- Mixed contributions



DM Interpretations

- PeV dark matter
- late time decay, lifetime 10^27 — 10^28 s
- Non-thermal production
- For PeV neutrino events, DM should have decay channels to neutrino directly.
- It might be possible to explain the "possible", *but not statistically significant*, gap between 0.5—1 PeV.

Model Setup

P.Ko,***YT***, 1508.02500(PLB)

- Right-handed neutrino portal, *N*
- Dark sector with gauge symmetry
- Assume $U_X(1)$ and $\chi - \text{dark matter}, Q' = 1$

  $\Phi - \text{dark Higgs}, Q' = 1$

  $X - \text{dark photon}$
- Lagrange

$$
\begin{aligned}
\mathcal{L} =& \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{N} i\partial\!\!\!/ N - \left(\frac{1}{2} m_N \bar{N}^c N + y\bar{L}\widetilde{H} N + \text{h.c.}\right) \\
& - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu} F_Y^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi, H) \\
& + \bar{\chi}\left(i D\!\!\!\!/ - m_\chi\right)\chi - \left(f\bar{\chi}\Phi N + \text{h.c.}\right),
\end{aligned}
$$

Integrate heavy *N*

When *N* is much heavier than dark matter χ , we can integrate *N* and get effective operators

$$\frac{yf}{m_N}\bar{\chi}\Phi H^\dagger L + h.c.,$$

after spontaneous symmetry breaking,

$$H \to \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ v_H + h(x) \end{array}\right) \quad \text{and} \quad \Phi \to \frac{v_\phi + \phi(x)}{\sqrt{2}}.$$

$v_\phi \ll \mathrm{PeV}$

we have (common factor yf/2)

$$\frac{v_\phi v_H}{m_N}\bar{\chi}\nu, \;\; \frac{v_\phi}{m_N}\bar{\chi}h\nu, \;\; \frac{v_H}{m_N}\bar{\chi}\phi\nu, \;\; \frac{1}{m_N}\bar{\chi}\phi h\nu,$$

Mixing

- kinetic mixing leads to

$$(B^\mu, W_3^\mu, X^\mu) \to (A^\mu, Z^\mu, Z'^\mu)$$

- $\lambda_{\Phi H}\Phi^\dagger\Phi H^\dagger H$ gives

$$(h, \phi) \to (H_1, H_2)$$

- Z' and H_2(or X and ϕ) can decay into standard model particle pairs.

Decay Modes

$$\frac{v_\phi v_H}{m_N}\bar{\chi}\nu, \;\; \frac{v_\phi}{m_N}\bar{\chi}h\nu, \;\; \frac{v_H}{m_N}\bar{\chi}\phi\nu, \; \frac{1}{m_N}\bar{\chi}\phi h\nu,$$

Decay Modes

$$\frac{v_\phi v_H}{m_N}\bar{\chi}\nu,\quad \frac{v_\phi}{m_N}\bar{\chi}h\nu,\quad \frac{v_H}{m_N}\bar{\chi}\phi\nu,\quad \frac{1}{m_N}\bar{\chi}\phi h\nu,$$

$$\chi \to W^\pm l^\mp, Z\nu, h\nu \text{ with BR } \simeq 2:1:1$$

$$\chi \to Z'\nu, \phi\nu \text{ with BR } \simeq 1:1$$

Goldstone boson equivalence theorem

$$\bar{\chi}\Phi N \to \frac{v_\phi}{\sqrt{2}}\chi N$$

Decay Modes

$$\frac{v_\phi v_H}{m_N}\bar{\chi}\nu, \quad \frac{v_\phi}{m_N}\bar{\chi}h\nu, \quad \frac{v_H}{m_N}\bar{\chi}\phi\nu, \quad \frac{1}{m_N}\bar{\chi}\phi h\nu,$$

$$\chi \to W^\pm l^\mp, Z\nu, h\nu \text{ with BR } \simeq 2:1:1$$

$$\chi \to Z'\nu, \phi\nu \text{ with BR } \simeq 1:1$$

$$\chi \to h\nu, \phi\nu \text{ with BR } \simeq v_\phi^2 : v_H^2$$

Goldstone boson equivalence theorem

$$\bar{\chi}\Phi N \to \frac{v_\phi}{\sqrt{2}}\chi N$$

Decay Modes

$$\frac{v_\phi v_H}{m_N}\bar{\chi}\nu, \quad \frac{v_\phi}{m_N}\bar{\chi}h\nu, \quad \frac{v_H}{m_N}\bar{\chi}\phi\nu, \quad \boxed{\frac{1}{m_N}\bar{\chi}\phi h\nu,}$$

$$\chi \to W^\pm l^\mp, Z\nu, h\nu \text{ with BR } \simeq 2:1:1$$

Goldstone boson equivalence theorem

$$\bar{\chi}\Phi N \to \frac{v_\phi}{\sqrt{2}}\chi N$$

$$\chi \to Z'\nu, \phi\nu \text{ with BR } \simeq 1:1$$

$$\chi \to h\nu, \phi\nu \text{ with BR } \simeq v_\phi^2 : v_H^2$$

$$\chi \to Z'/\phi + h\nu/Z\nu/W^\pm l^\mp$$

Three body decay

Decay Modes

$$\frac{v_\phi v_H}{m_N}\bar{\chi}\nu, \ \frac{v_\phi}{m_N}\bar{\chi}h\nu, \ \frac{v_H}{m_N}\bar{\chi}\phi\nu, \ \frac{1}{m_N}\bar{\chi}\phi h\nu,$$

$$\chi \to W^\pm l^\mp, Z\nu, h\nu \text{ with BR } \simeq 2:1:1$$

$$\chi \to Z'\nu, \phi\nu \text{ with BR } \simeq 1:1$$

$$\chi \to h\nu, \phi\nu \text{ with BR } \simeq v_\phi^2 : v_H^2$$

$$\chi \to Z'/\phi + h\nu/Z\nu/W^\pm l^\mp$$

Goldstone boson equivalence theorem

$$\bar{\chi}\Phi N \to \frac{v_\phi}{\sqrt{2}}\chi N$$

Three body decay

In principle, all decay channels need to be included, however

3-body decays dominate

$$\frac{\Gamma_3\left(\chi\to\phi h\nu\right)}{\Gamma_2\left(\chi\to h\nu,\phi\nu\right)}\simeq\frac{1}{16\pi^2}\frac{m_\chi^2}{v_\phi^2+v_H^2}\gg 1$$

- 2-body decays only results from symmetry breaking when $m_N > m_\chi$

$$\begin{aligned}\mathcal{L} =&\mathcal{L}_{\rm SM}+\frac{1}{2}\bar{N}i\partial\!\!\!/ N-\left(\frac{1}{2}m_N\bar{N}^c N+y\bar{L}\widetilde{H}N+\text{h.c.}\right)\\&-\frac{1}{4}X_{\mu\nu}X^{\mu\nu}-\frac{1}{2}\sin\epsilon X_{\mu\nu}F_Y^{\mu\nu}+D_\mu\Phi^\dagger D^\mu\Phi-V(\Phi,H)\\&+\bar{\chi}\left(iD\!\!\!\!/-m_\chi\right)\chi-\left(f\bar{\chi}\Phi N+\text{h.c.}\right),\end{aligned}$$

$$\frac{\Gamma_{2-\rm body}}{\Gamma_{3-\rm body}}\sim\frac{v^2}{m_\chi^2}$$

Parameter Estimation

- We can estimate

$$\Gamma_3\left(\chi \to \phi h \nu\right) \sim \frac{m_\chi^3}{96\pi^3}\left(\frac{yf}{m_N}\right)^2 \sim \frac{1}{10^{28}\mathrm{sec}}$$

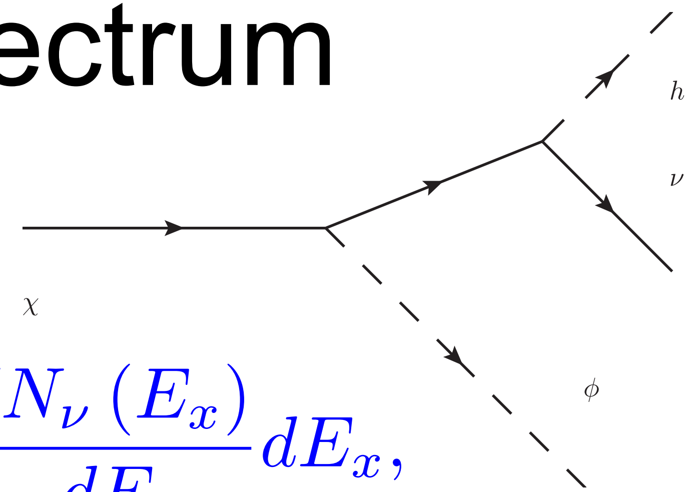
$$\Rightarrow \frac{yf}{m_N} \sim 10^{-36}\mathrm{GeV}^{-1},$$

- small *y* and *f* but *technically natural*
- If *N* is responsible for active neutrino mass through type-I seesaw $y \sim 10^{-5}\sqrt{\frac{m_N}{\mathrm{PeV}}}$ then we shall have

$$y \sim 1,\ f \sim 10^{-22} \text{ for } m_N \sim 10^{14}\mathrm{GeV}$$

$$y \sim 10^{-5},\ f \sim 10^{-25} \text{ for } m_N \sim \mathrm{PeV}$$

Neutrino Spectrum



- Spectrum is given by

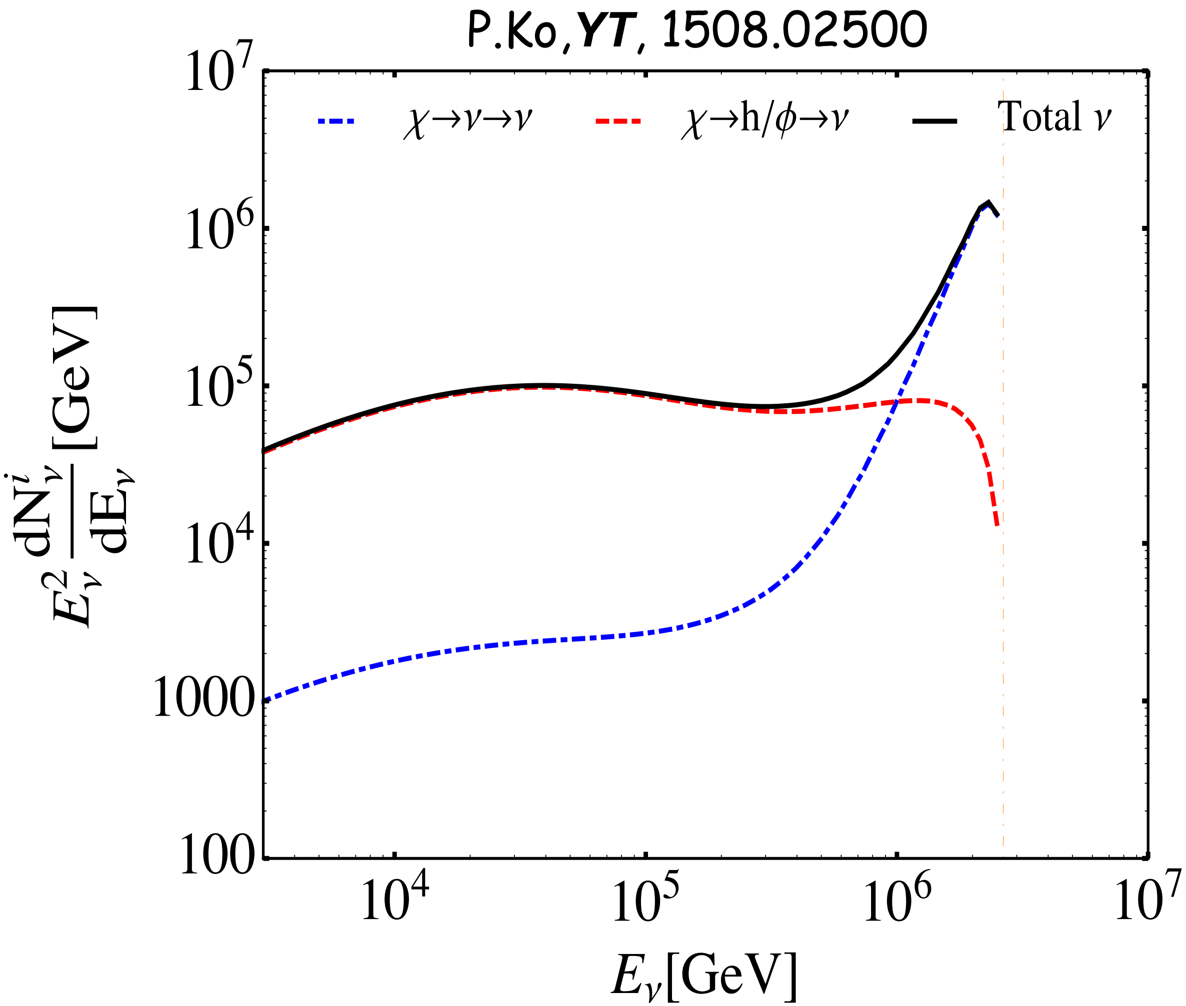
$$\frac{dN}{dE}(x \to \nu) = \int \frac{1}{\Gamma}\frac{d\Gamma}{dE_x}\frac{dN_\nu(E_x)}{dE}dE_x,$$

where $x = \nu, h, W, Z, Z', \phi$

- We calculate the differential decay width

$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_\nu} \simeq 24E_\nu^2/m_\chi^3,\ 0 < E_\nu < m_\chi/2,$$
$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_h} \simeq 12E_h\left(m_\chi - E_h\right)/m_\chi^3,\ 0 < E_h < m_\chi/2,$$
$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_\phi} \simeq 12E_\phi\left(m_\chi - E_\phi\right)/m_\chi^3,\ 0 < E_\phi < m_\chi/2.$$

Spectrum at production



- Decay channels with neutrino are most important for high energy
- Low energy part is most contributed by other states.
- The are one order of magnitude difference between high and low parts.

Neutrino Flux at Earth

- Both Galactic and Extragalactic flux included,
- galactic

$$\left.\frac{d\Phi_\nu^G}{dE_\nu}\right|_{E_\nu=E} = \frac{1}{4\pi}\sum_i \Gamma_i \int_0^\infty dr \frac{\rho_\chi^G(r')}{m_\chi} \left.\frac{dN_\nu^i}{dE_\nu}\right|_{E_\nu=E},$$

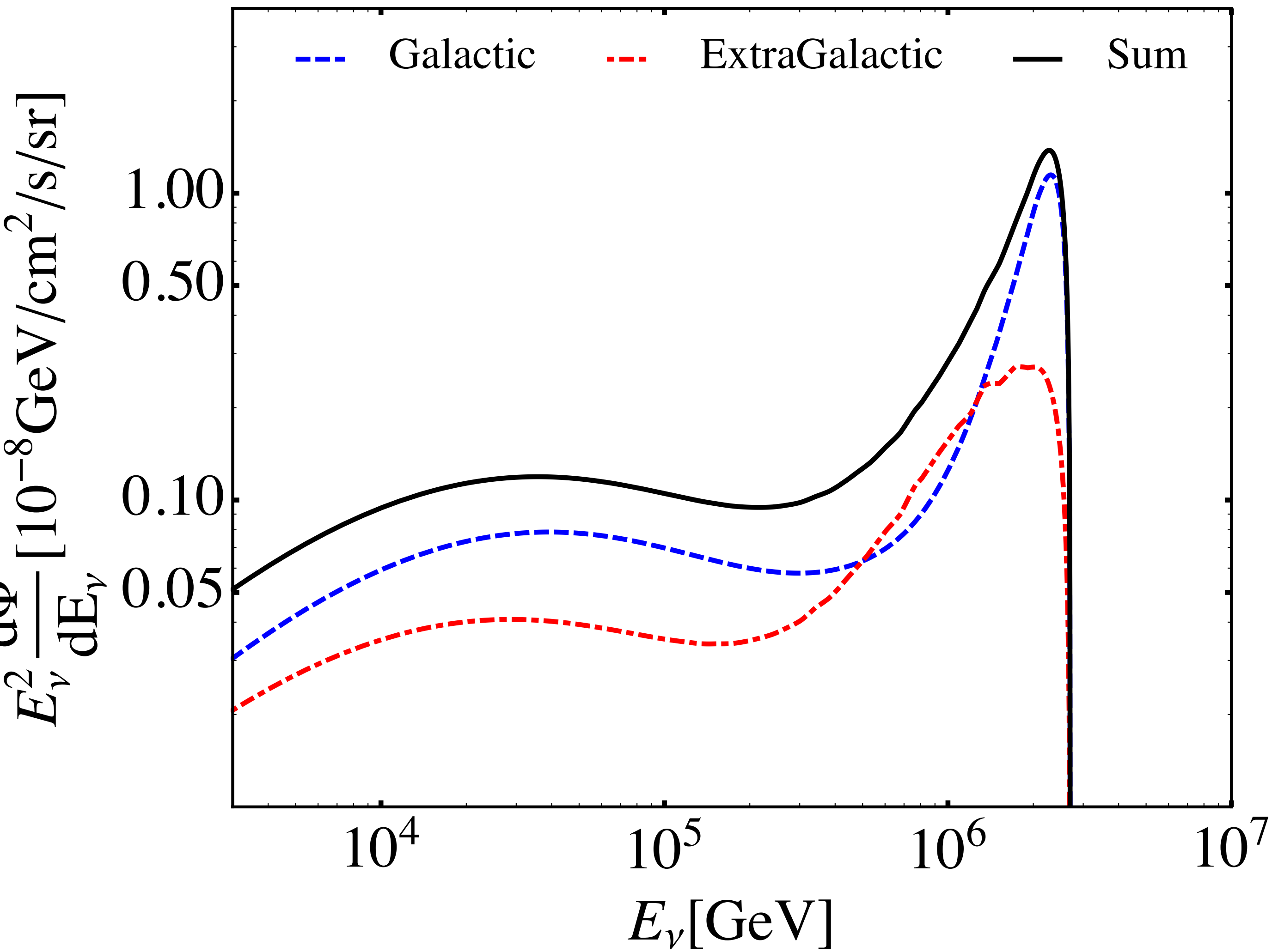
NFW DM density profile

$$\rho_\chi^G(r') = \rho_\odot \left[\frac{r_\odot}{r'}\right]\left[\frac{1+r_\odot/r_c}{1+r'/r_c}\right]^2$$

- extragalactic

$$\left.\frac{d\Phi_\nu^{EG}}{dE_\nu}\right|_{E_\nu=E} = \frac{\rho_c\Omega_\chi}{4\pi m_\chi}\sum_i \Gamma_i \int_0^\infty \frac{dz}{\mathcal{H}} \left.\frac{dN_\nu^i}{dE_\nu}\right|_{E_\nu=(1+z)E},$$

Neutrino Flux at Earth



Astrophysical Flux

Astrophysical neutrinos are responsible for the low energy spectrum

Two Cases:

i) Unbroken Power Law (UPL):

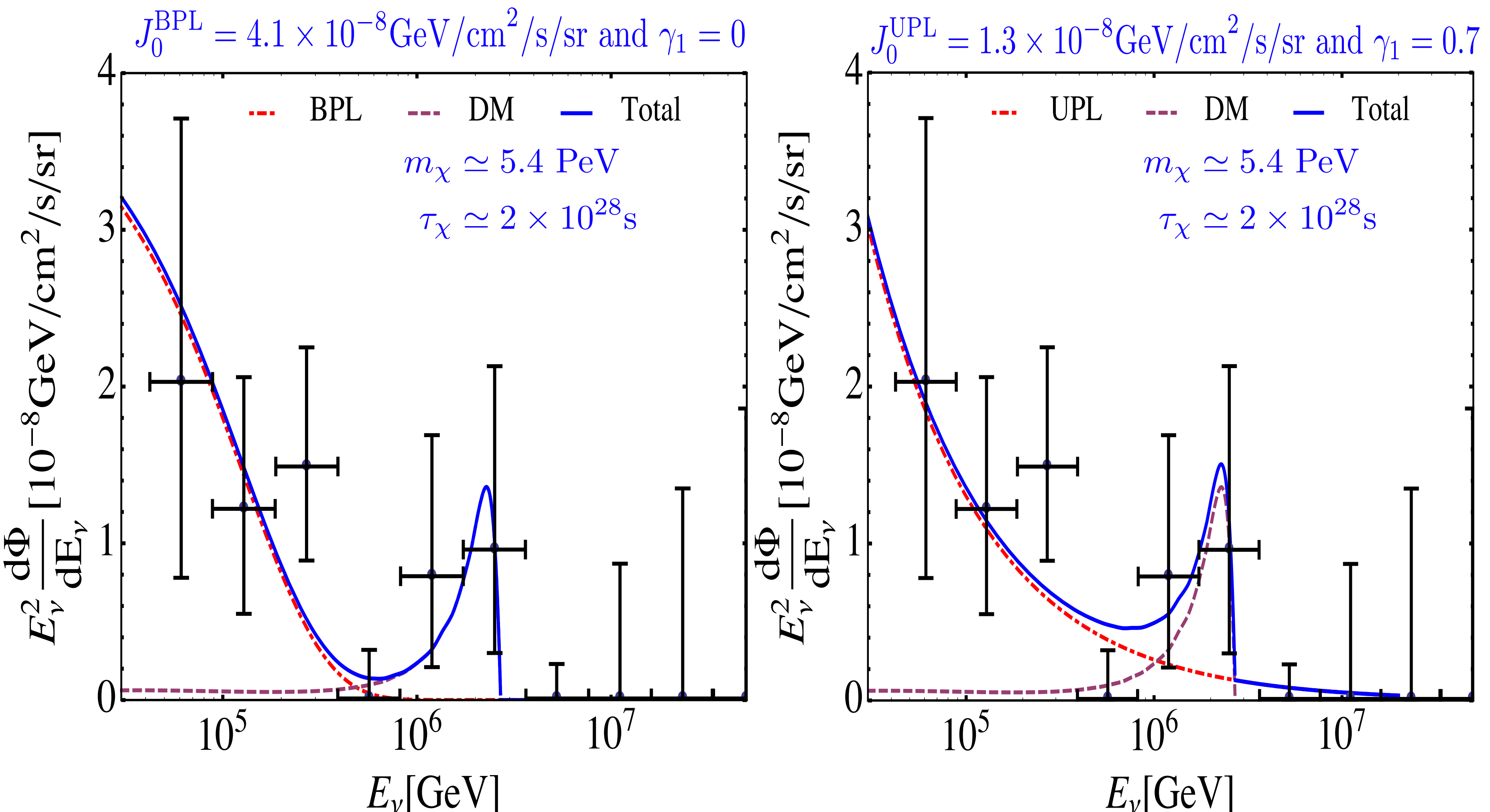
$$E_\nu^2 \frac{\mathrm{d}J_{\mathrm{Ast}}}{\mathrm{d}E_\nu}(E_\nu) = J_0 \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma} ,$$

ii) Broken Power Law (BPL):

$$E_\nu^2 \frac{\mathrm{d}J_{\mathrm{Ast}}}{\mathrm{d}E_\nu}(E_\nu) = J_0 \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma} \exp\left(-\frac{E_\nu}{E_0}\right) ,$$

3-year spectrum

P.Ko, ***YT***, 1508.02500



4-year spectrum

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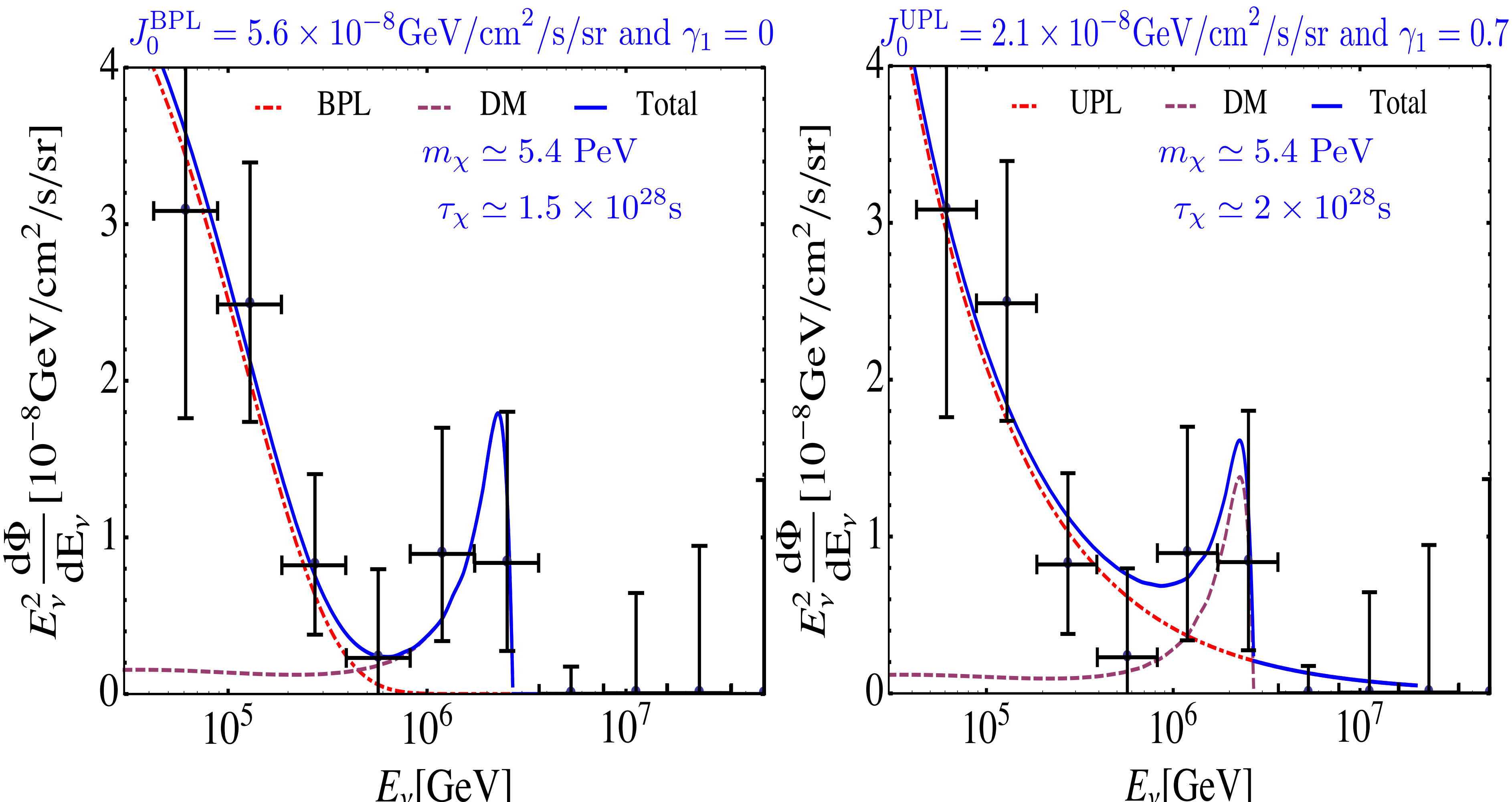

Heavier DM

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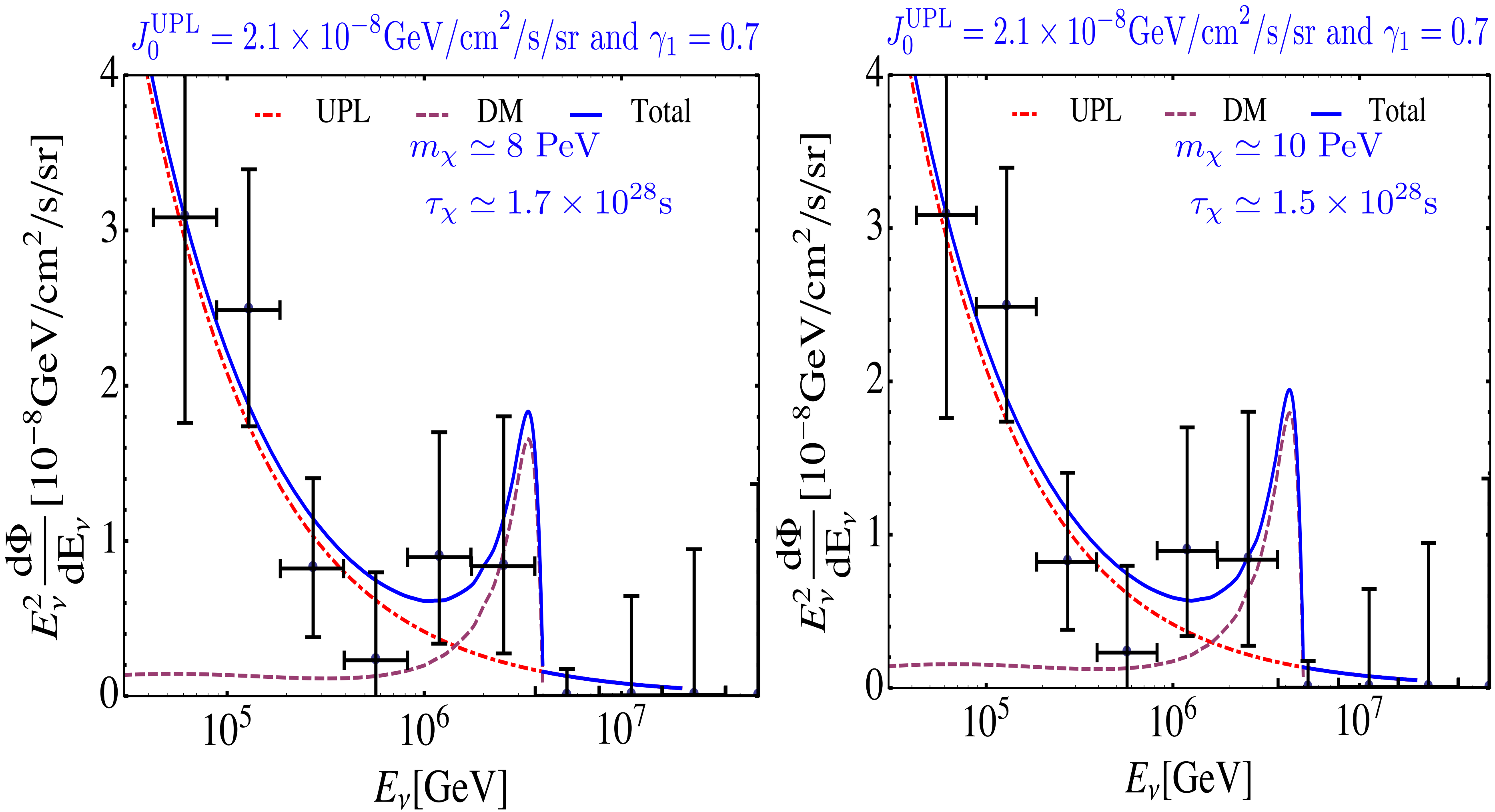


Direct Detection

- Direct detection constrains the DM-nucleon scattering cross section

$$\sigma_{\chi N} \sim \left(\frac{m_Z^2}{m_{Z'}^2}\right)^2 \sin^2\epsilon \times 10^{-39}\mathrm{cm}^2.$$

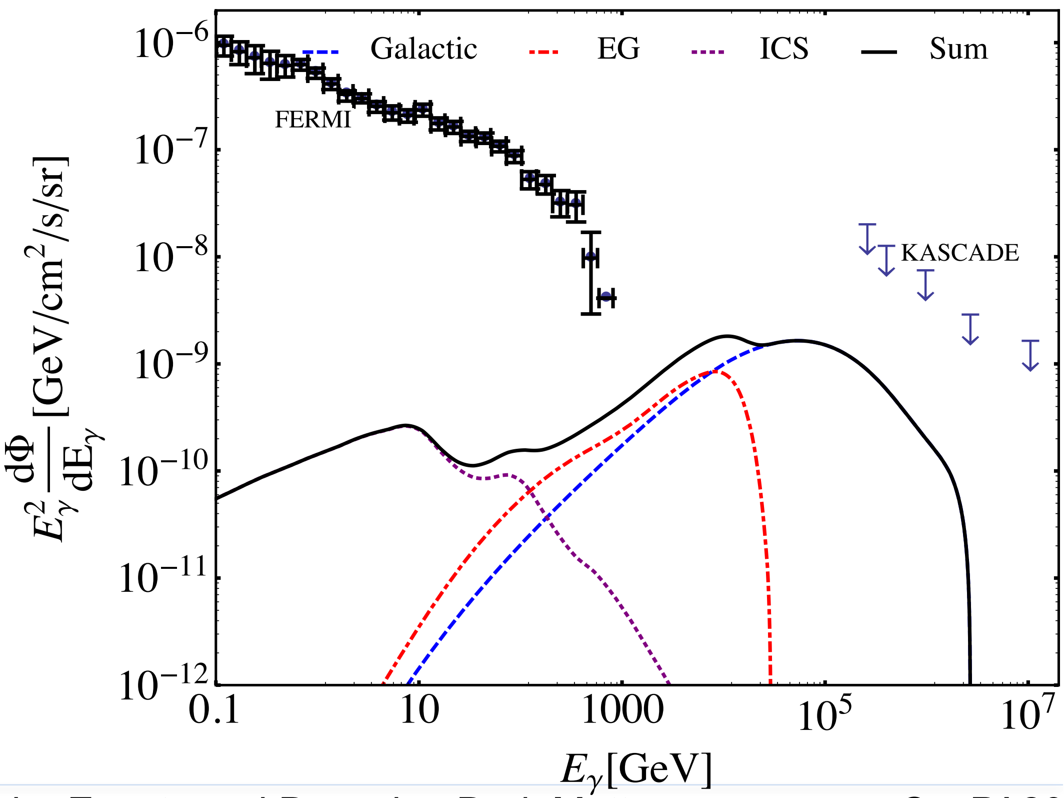
- Currently, the most stringent bound is from LUX limits

$$\sigma_{\chi N} < 10^{-45}\mathrm{cm}^2 \times \frac{m_\chi}{100\mathrm{GeV}},$$

- which can be easily satisfied for *TeV Z'* and $\epsilon \lesssim 0.1$

Other Indirect Signals

- Charged particles, like positrons, and gamma-ray are also produced,
- For decaying PeV DM, lifetime ~ 10^28s is still allowed



Discussion

- Model with discrete symmetry

$$\chi \to -\chi$$
$$\phi \to -\phi$$

- Lagrangian

$$\begin{aligned}\mathcal{L} =& \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{N} i \partial\!\!\!/ N - \left(\frac{1}{2} m_N \bar{N}^c N + y \bar{L} \widetilde{H} N + \text{h.c.}\right) \\ & + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi - \left(f \bar{\chi}\phi N + \text{h.c.}\right) - V(\phi, H),\end{aligned}$$

- Similar for IceCube but no signal for direct detection

Summary

- IceCube has definitely observed astrophysical neutrinos, with several PeV events.
- Interesting explanations include dark matter and astrophysics.
- PeV events could be due to heavy dark matter decay with $m_\chi \sim 5\ \mathrm{PeV}, \tau_\chi \sim 10^{28}\mathrm{s}$
- We propose a DM model based on *U(1)* gauge symmetry and right-handed neutrino portal, DM's three-body-decay could be responsible for the observed PeV events.

Thanks for your attention.