IceCube Neutrino Events from Decaying Dark Matter through Neutrino Portal

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

Outline

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

The Nobel Prize in Physics 2015

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Takaaki Kajita

Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald

Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

So, apparently, neutrinos are interesting and important.

The Nobel Prize in Physics 2015


Ill. N. Elmehed. © Nobel Media AB 2015.

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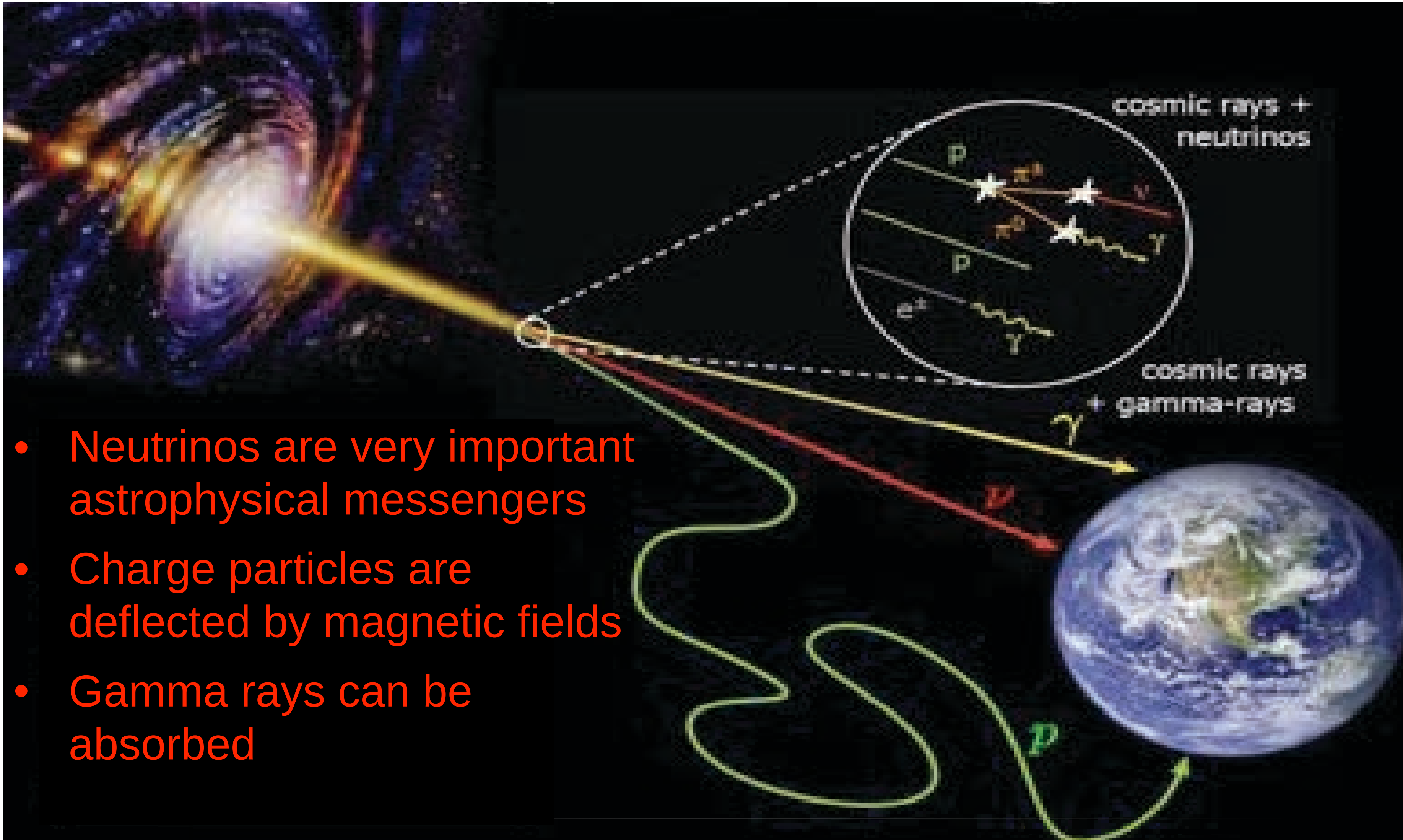
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

atmospheric neutrinos, GeV ***solar neutrinos, MeV***

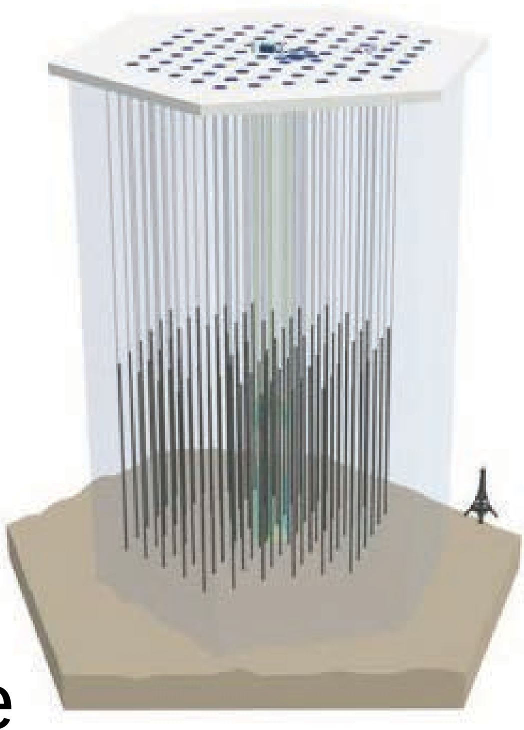
Astrophysical Neutrinos (TeV)



- Neutrinos are very important astrophysical messengers
- Charge particles are deflected by magnetic fields
- Gamma rays can be absorbed

Neutrino Telescopes for Astrophysical Neutrinos

IceCube

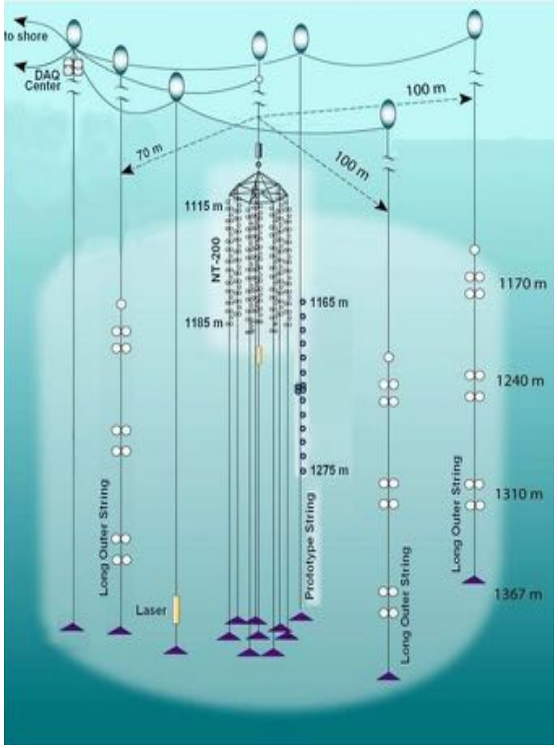


- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules(PMT) distributed over 86 strings
- Neutrinos are identified through *Cherenkov light* emission from secondary particles produced in the neutrino interaction with the ice
- E_{th}>100GeV

South Pole Glacier
1 km^3

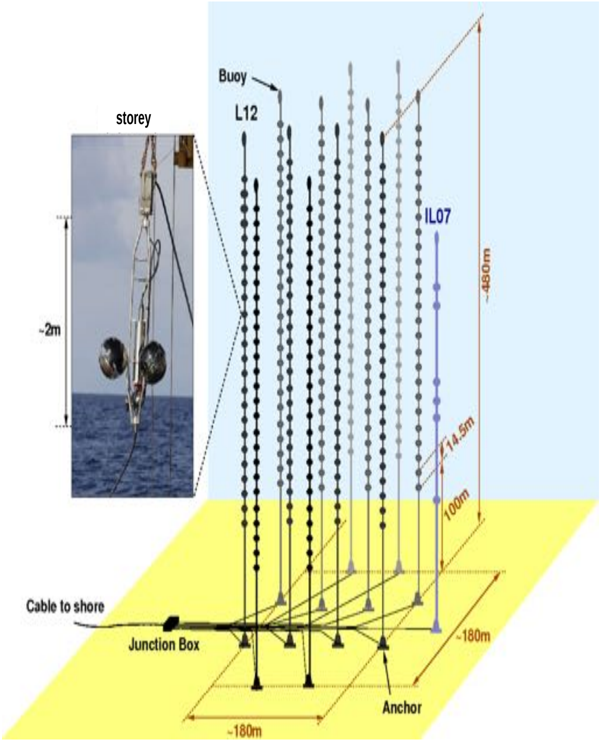
Neutrino Telescopes

NT-200+



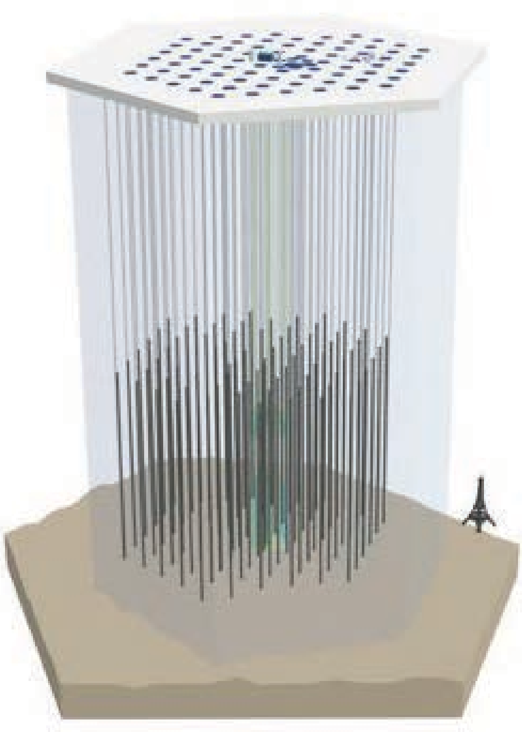
Lake Baikal
1/2000 km^3

Antares



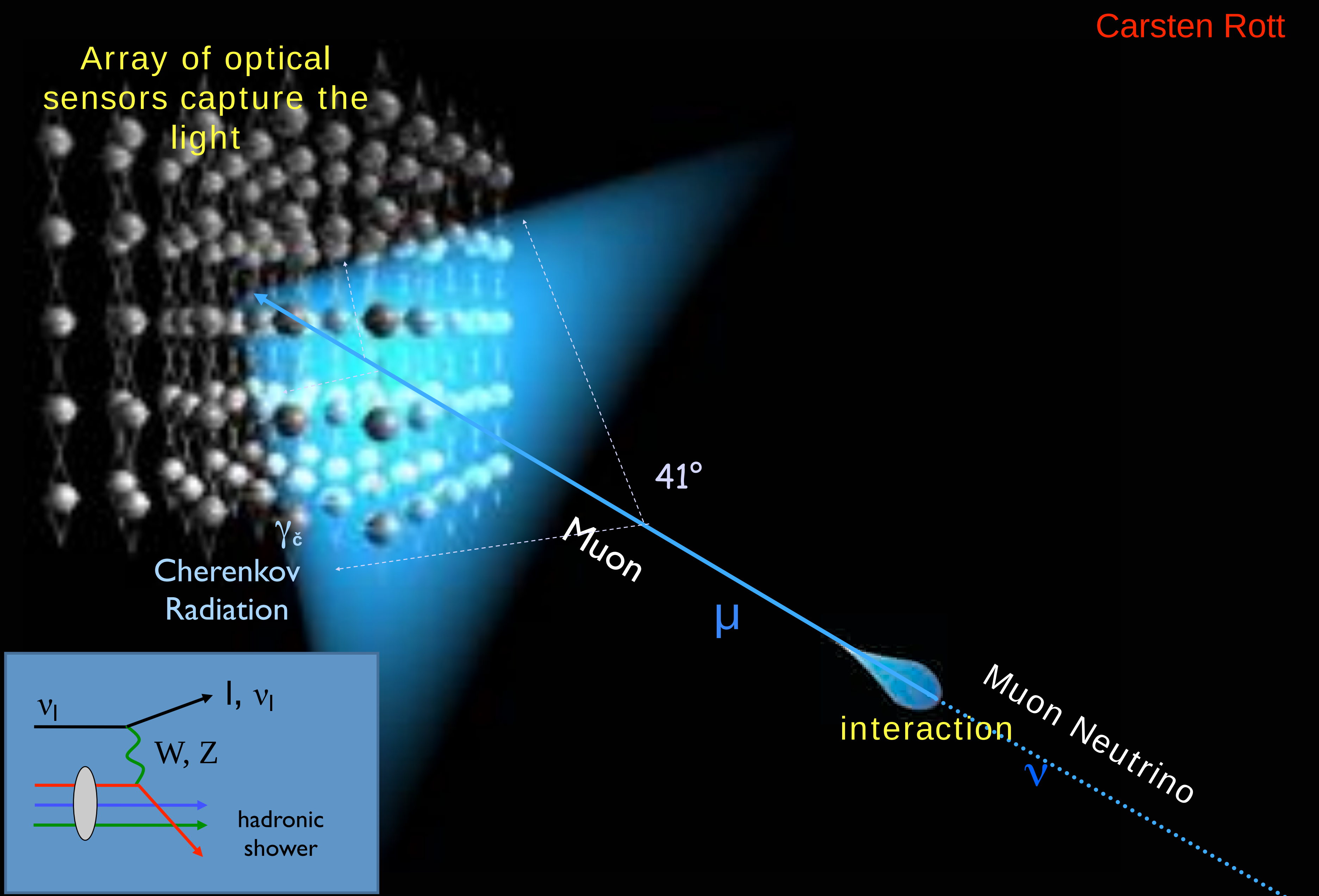
Mediterranean Sea
1/100 km^3

IceCube



South Pole Glacier
1 km^3

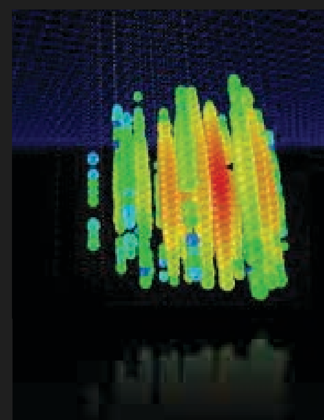
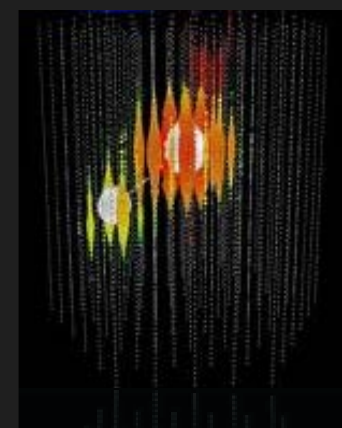
Principle of an optical Neutrino Telescope



Neutrino Signatures

Claudio Kopper, ICRC2015

time →

CC Muon Neutrino	Neutral Current / Electron Neutrino	CC Tau Neutrino
		
$\nu_\mu + N \to \mu + X$	$\nu_e + N \to e + X$ $\nu_x + N \to \nu_x + X$	$\nu_\tau + N \to \tau + X$
track (data)	cascade (data)	"double-bang" (≳10PeV) and other signatures (simulation)
factor of ≈ 2 energy resolution < 1° angular resolution at high energies	≈ ±15% deposited energy resolution ≈ 10° angular resolution (in IceCube) (at energies ≳ 100 TeV)	(not observed yet: τ decay length is 50 m/PeV)

Neutrino Events at IceCube

- Full 988-day data
- 30TeV — 2 PeV
- 37 events (9+28)
- Muon Background

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

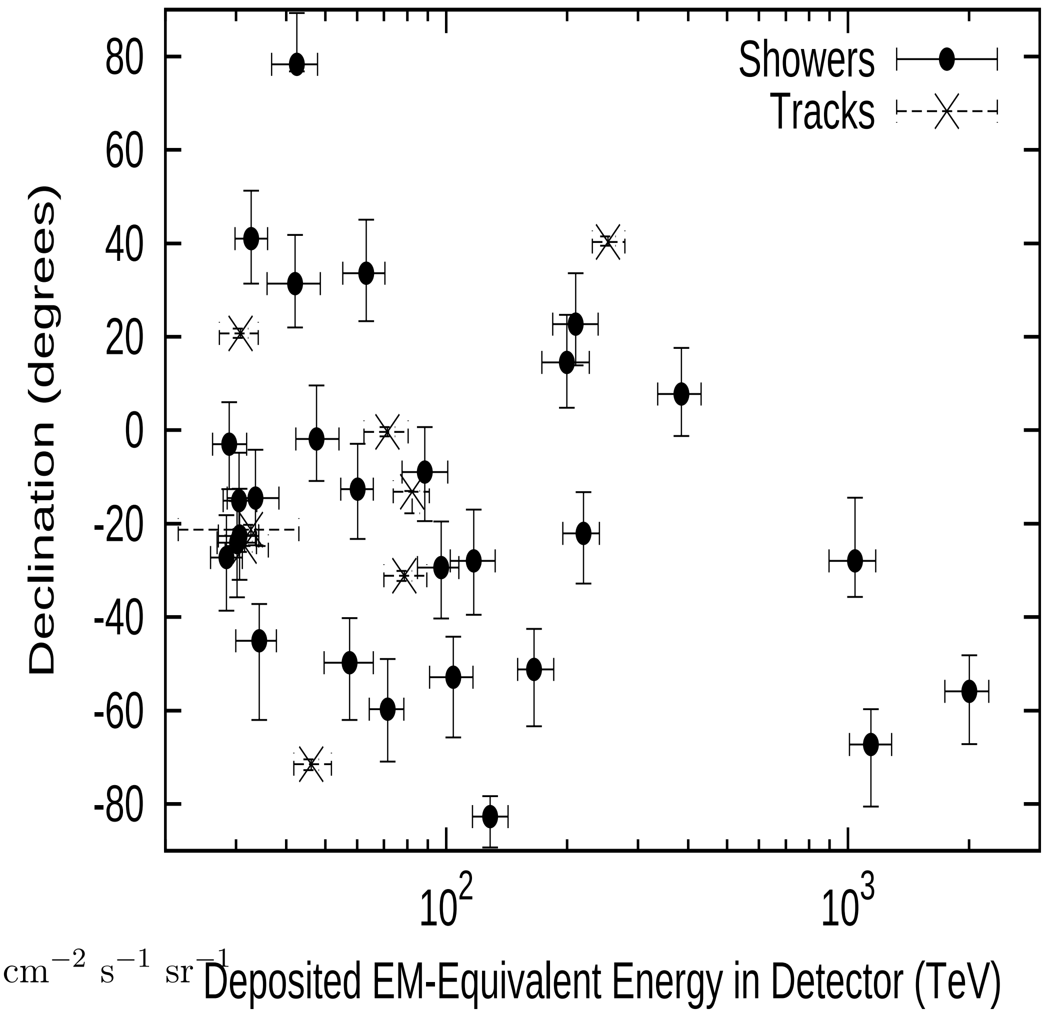
- Atmospheric neutrino

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

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

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

IceCube, PRL 113, 101101(2014)



Neutrino Events at IceCube

- Full 4-year data
- ~30TeV — 2 PeV
- 54 events (15+39)
- Muon Background

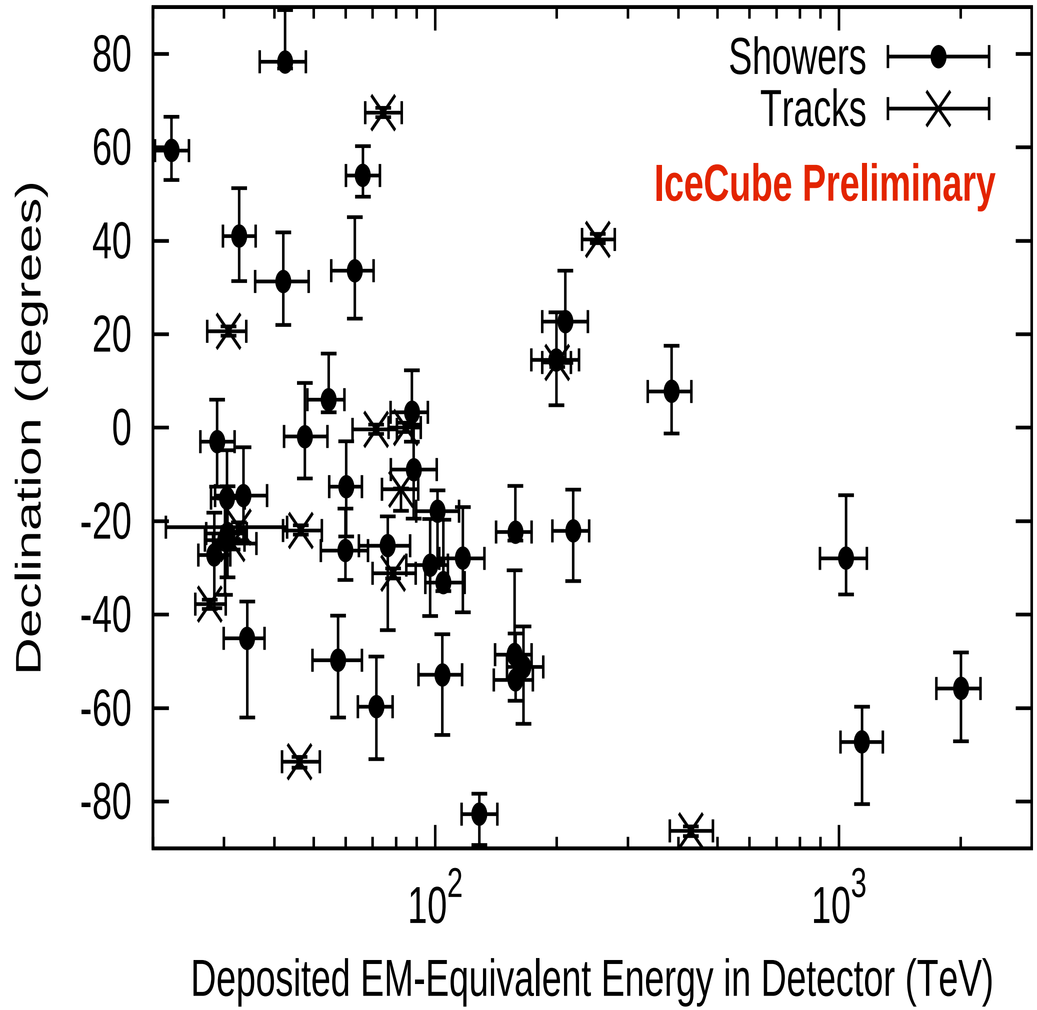
$$N_{\mu^\pm} = 12.6 \pm 5.1$$

- Atmospheric neutrino

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

- reject pure atm, 6.5σ

Claudio Kopper, ICRC2015

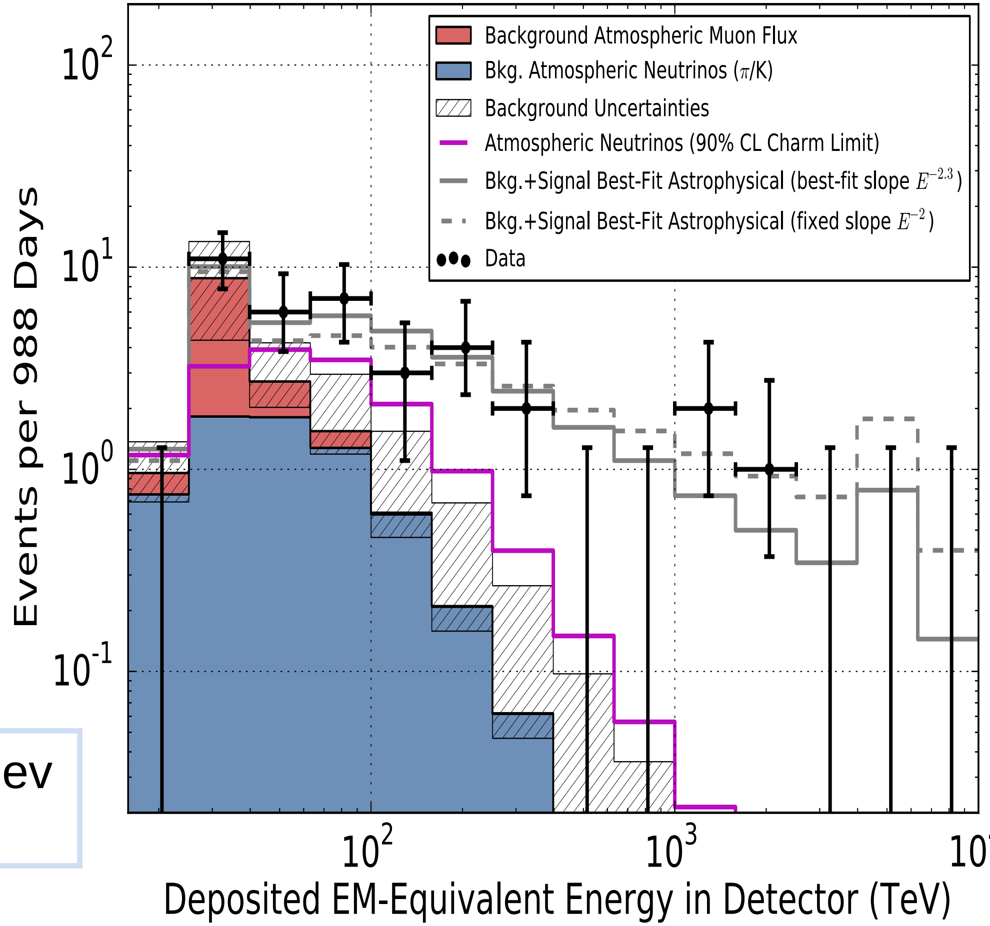


Astrophysical Sources

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

Usually start with some specific emission spectra and consider pγ and pp interactions

IceCube, PRL 113, 101101(2014)



Ahlers, Bahcall, Beacom, Essey, Kalashev
Kusenko, Leob, Murase, Waxman, *et al*

Power law

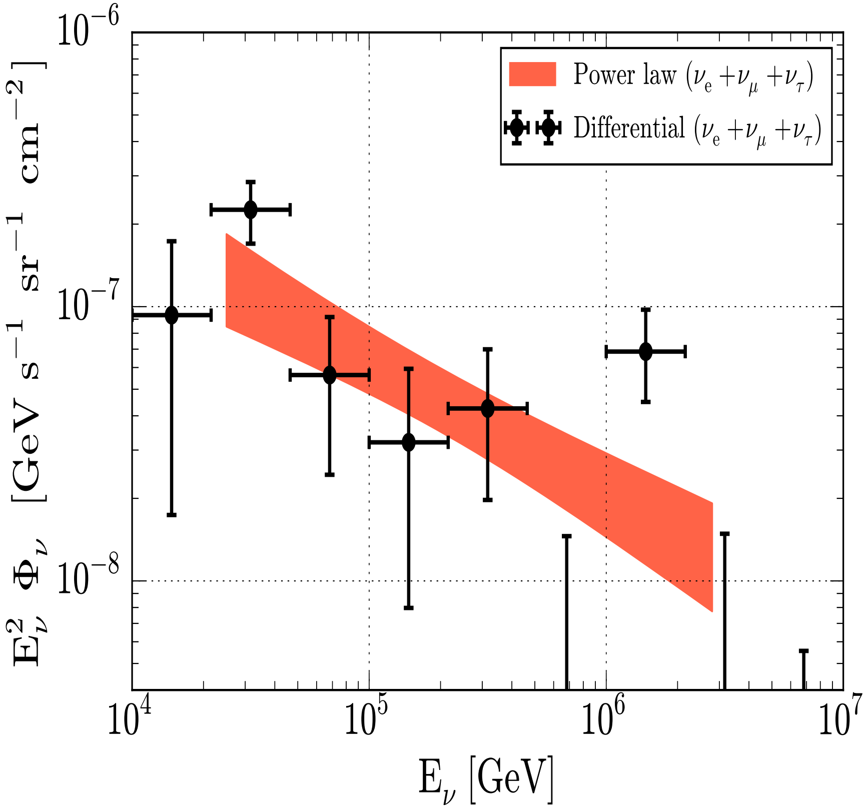
IceCube 1507.03991

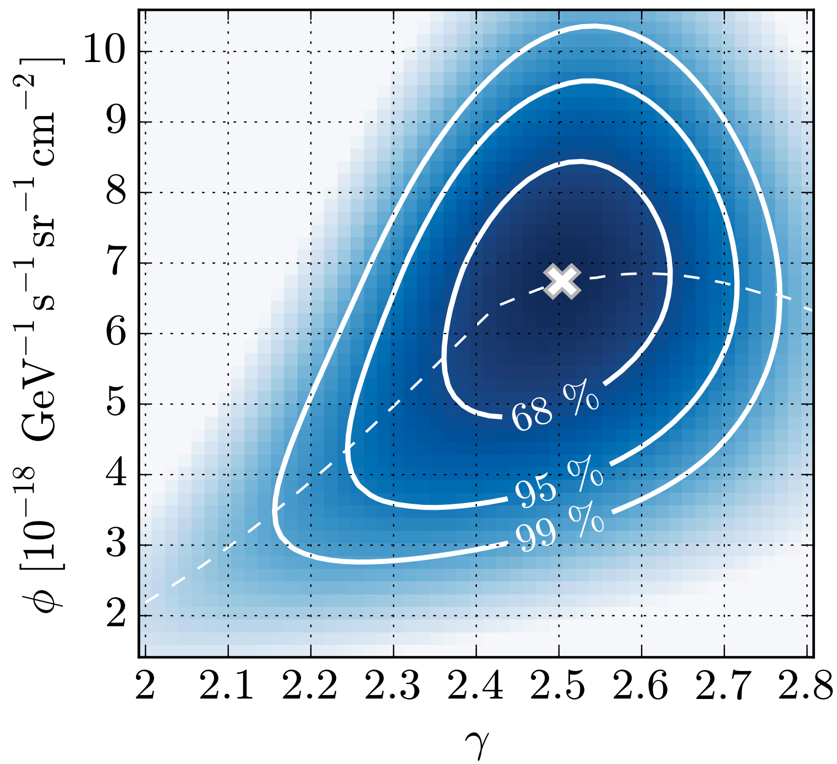
- Assuming astrophysical flux arrives isotropically and equal flavor

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

$$\gamma = 2.50 \pm 0.09$$

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





Spectral Fit

- Best fit spectral index

$$\gamma = 2.58$$

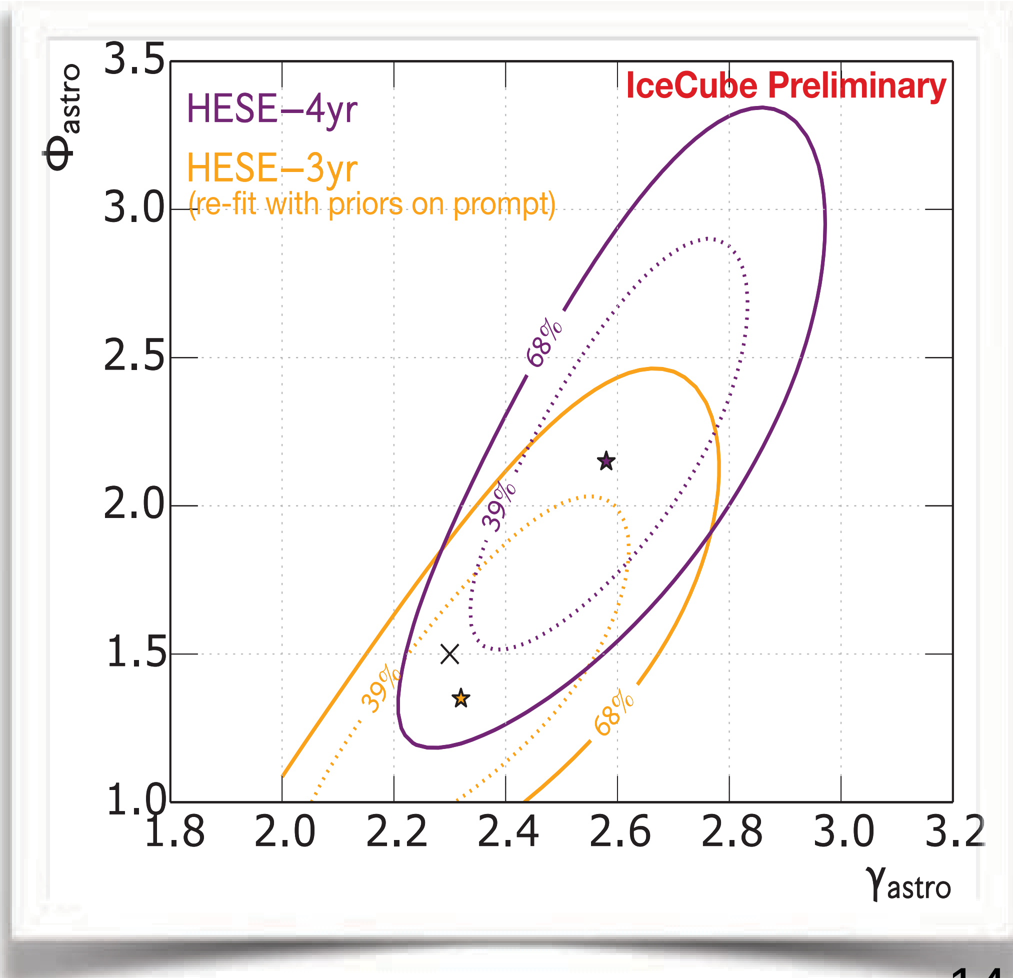
- Prefer softer spectrum
- Potential cut-off at about 2-5 PeV

challenge?

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

γ<2.1–2.3, EG diffuse γ-ray

Claudio Kopper, ICRC2015



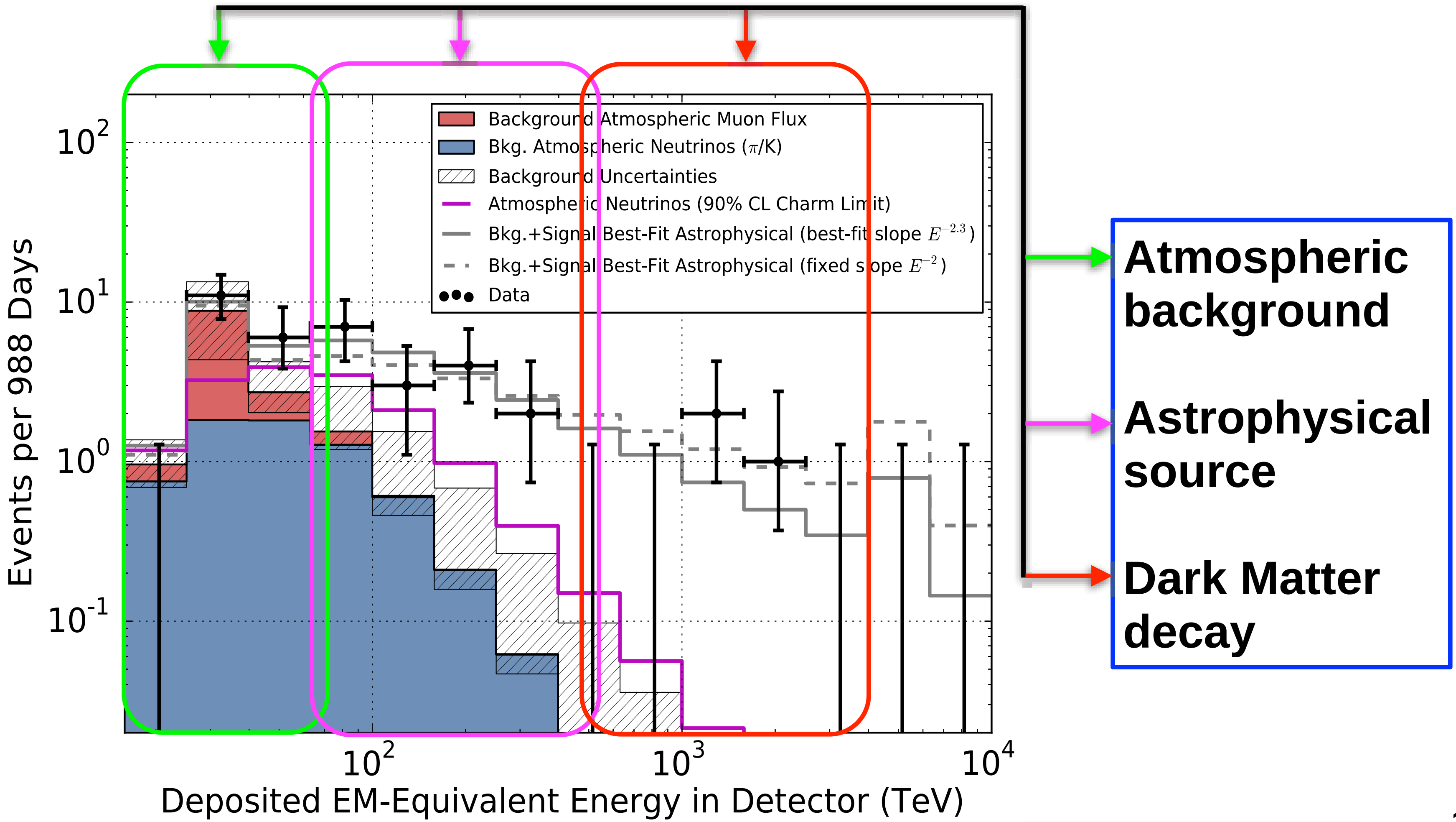
Dark Matter

Disclaimer!

- The spectrum is consistent with single power-law arriving neutrino flux
- Astrophysical sources are not definitely clear at the moment, and there is *no compelling* evidence for dark matter explanation
- Nevertheless, neutrinos from DM *decay* may have some testable features

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 could have decay channels to neutrino *directly*.
- It might be possible to explain the "possible" gap (*not statistically significant*) between 0.5 —1 PeV.

Neutrino Portal

- Gauge invariant operator $\bar{L}\widetilde{H}$, couples to dark matter χ through $y\bar{L}\widetilde{H}\chi$.
- To explain the IceCube PeV neutrino events, the yukawa coupling should be around $y \sim 10^{-29}$.

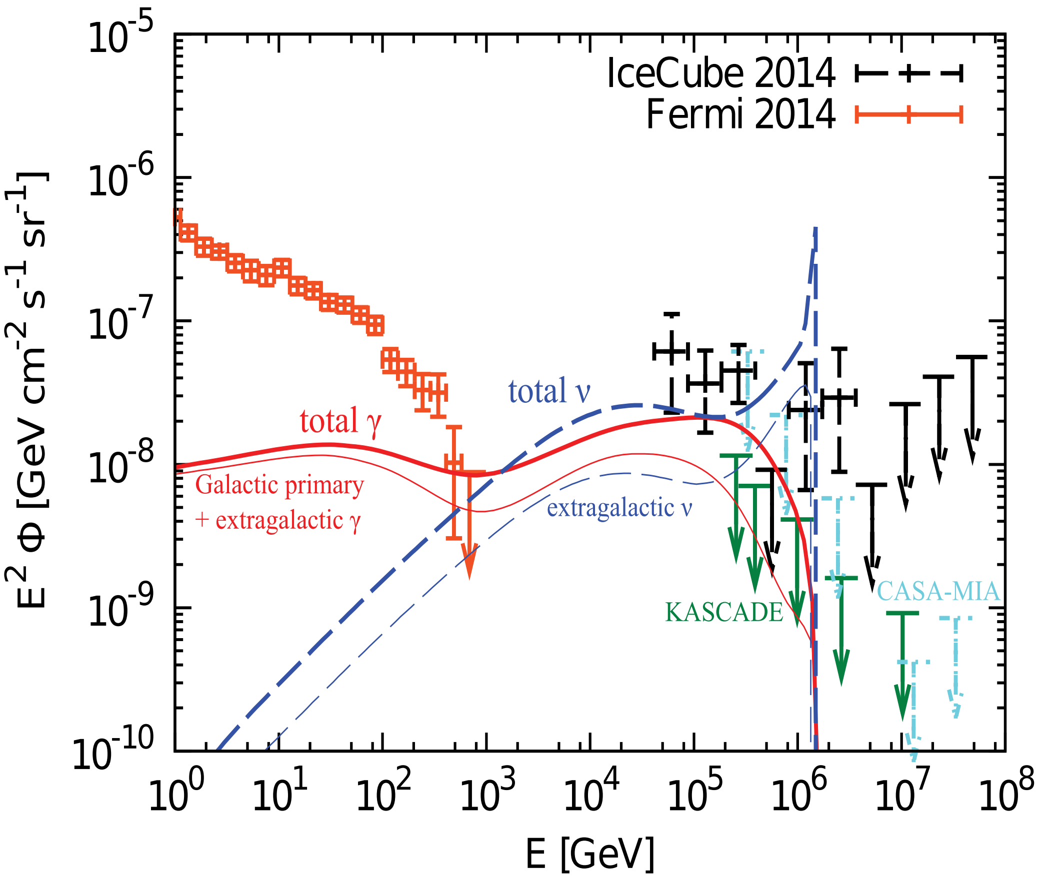
Feldstein, Kusenko, Matsumoto & Yanagida, 1303.7320

- Although incredible small coupling, but still *technically natural*.

$y\bar{L}\widetilde{H}\chi$ vs IceCube

- Spectrum is very sharp mainly because of two body decay.
- May not be viable any more if considering highly energetic muon tracking event.
- Gamma ray can put strong bounds.

Murase, Laha, Ando & Ahlers, 1503.04663(PRL)



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

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

Model Setup

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- Right-handed neutrino portal, *N*
- Dark sector with gauge symmetry
- Assume $U_X(1)$ and χ – dark matter, $Q' = 1$

  Φ – dark Higgs, $Q' = 1$

  X – dark photon
- Lagrange

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N} i \partial\!\!\!/ N - \left(\frac{1}{2} m_N \bar{N}^c N + y \bar{L} \widetilde{H} N + \text{h.c.} \right)$$

$$- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2} \sin\epsilon X_{\mu\nu} F_Y^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi, H)$$

$$+ \bar{\chi} \left(i D\!\!\!\!/ - m_\chi \right) \chi - \left(f \bar{\chi} \Phi N + \text{h.c.} \right),$$

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,

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

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

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

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

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

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

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

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

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

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

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

Three body decay

Decay Modes

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

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

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

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

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

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.

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 $m_N > m_\chi$

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

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

Parameter Estimation

- We can estimate

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

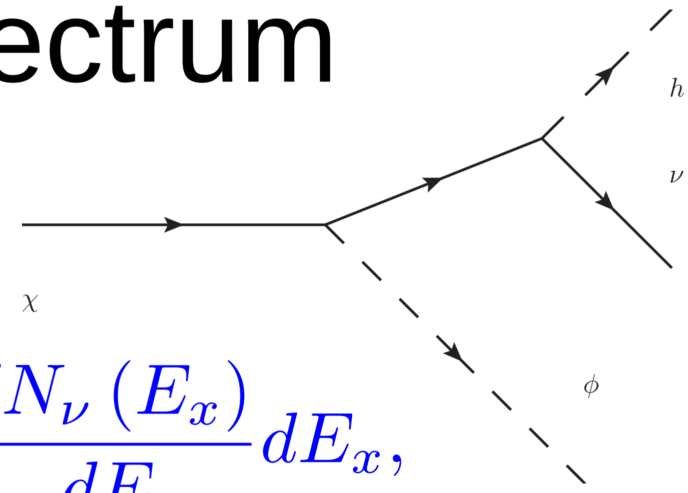
$$\Rightarrow \frac{yf}{m_N} \sim 10^{-36}\text{GeV}^{-1},$$

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

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

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

Neutrino Spectrum



- Spectrum is given by

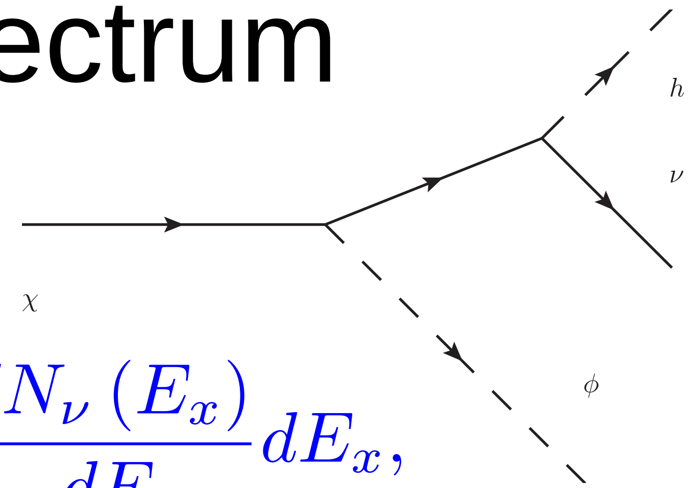
$$\frac{dN}{dE}(x \to \nu) = \int \frac{1}{\Gamma}\frac{d\Gamma}{dE_x}\frac{dN_\nu(E_x)}{dE}dE_x,$$

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

- We calculate the differential decay width

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

Neutrino Spectrum



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

Pythia, PPPC4DM

- We calculate the differential decay width

Massless limit $M_i \ll M_\chi$

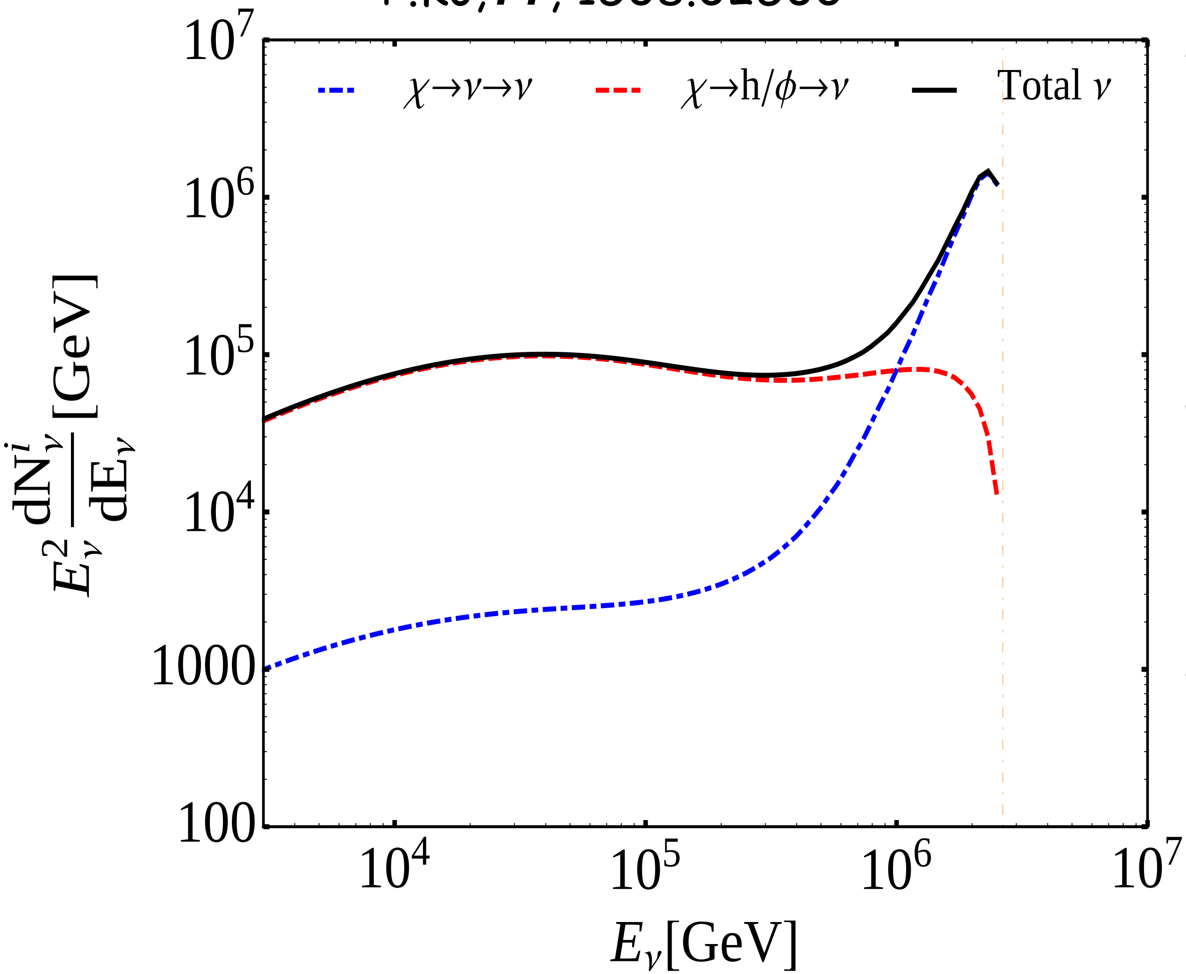
$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_\nu} \simeq 24E_\nu^2/m_\chi^3,\ 0 < E_\nu < m_\chi/2,$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_h} \simeq 12E_h(m_\chi - E_h)/m_\chi^3,\ 0 < E_h < m_\chi/2,$$

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

Spectrum at production

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



- 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

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

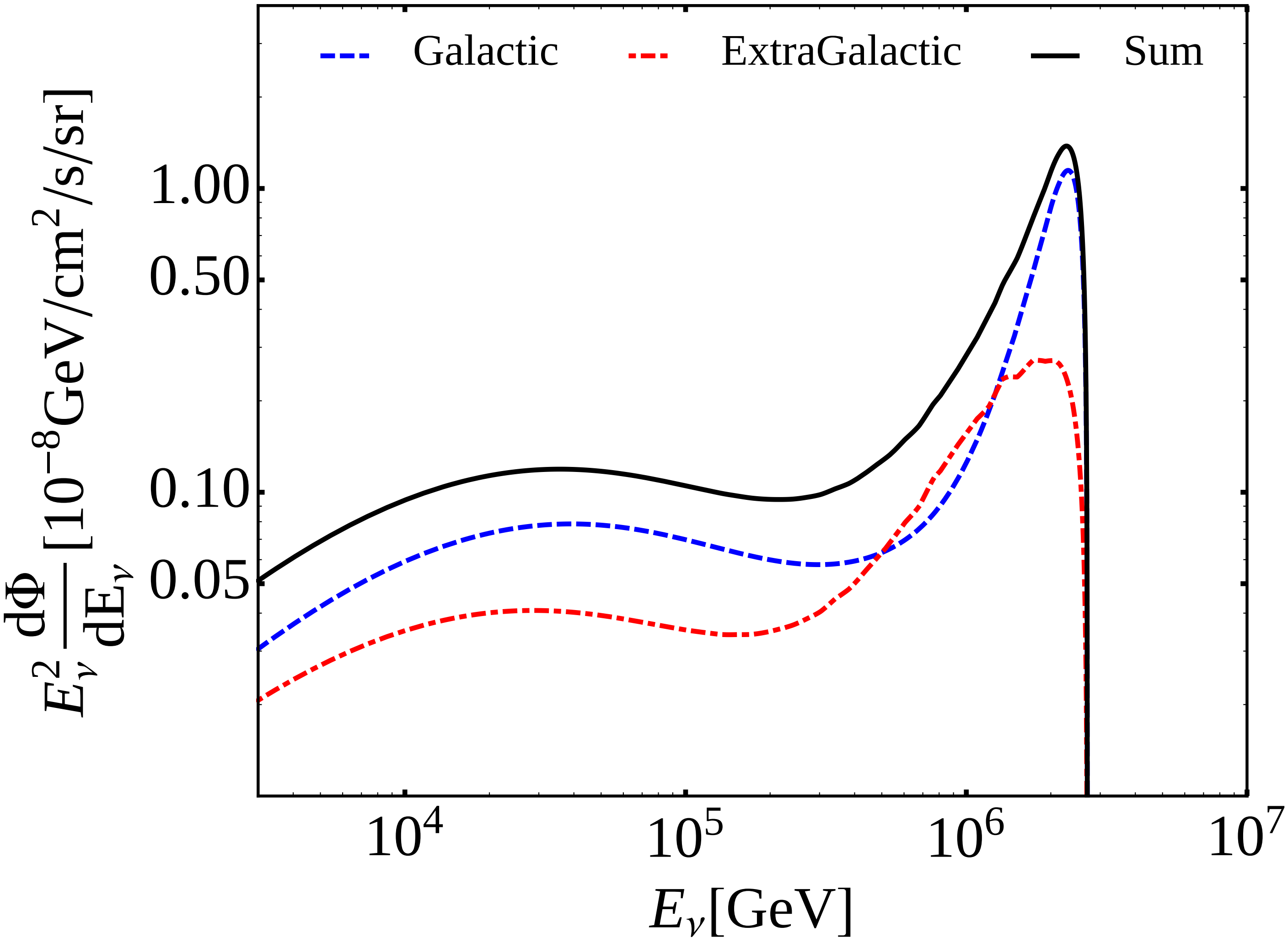
NFW DM density profile

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

- 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):

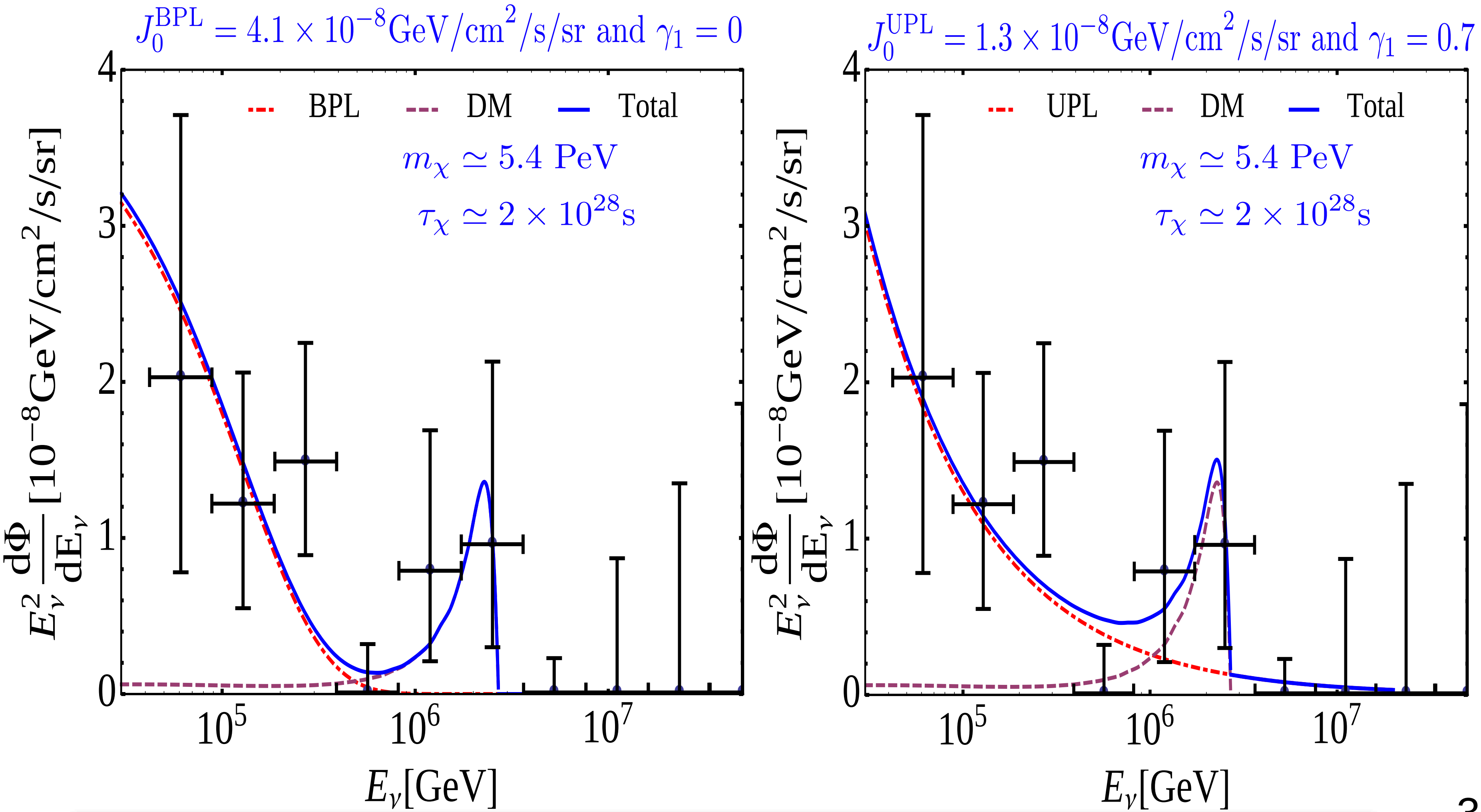
$$E_\nu^2 \frac{\mathrm{d}J_{\mathrm{Ast}}}{\mathrm{d}E_\nu}(E_\nu) = J_0 \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma},$$

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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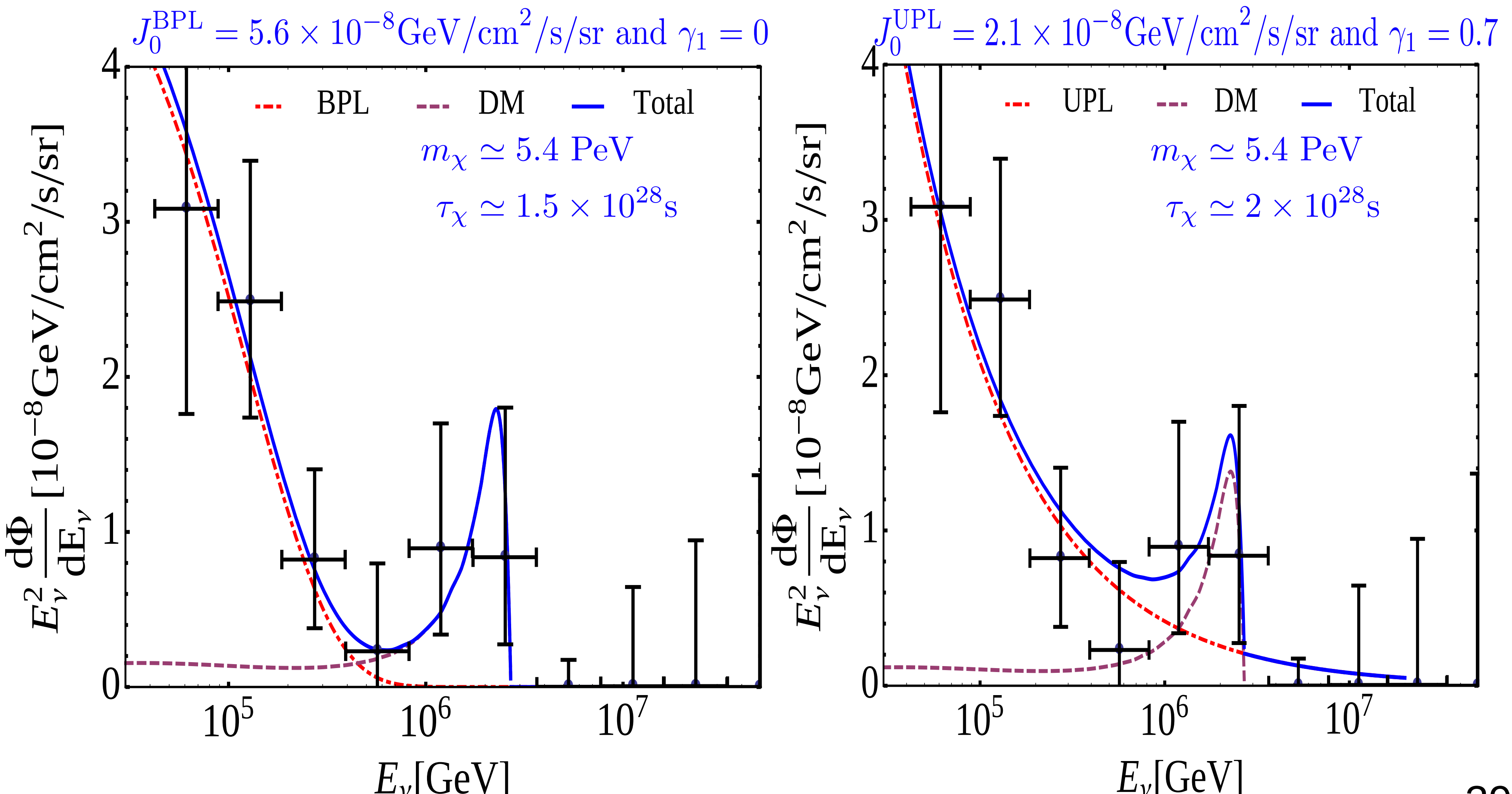

Heavier DM

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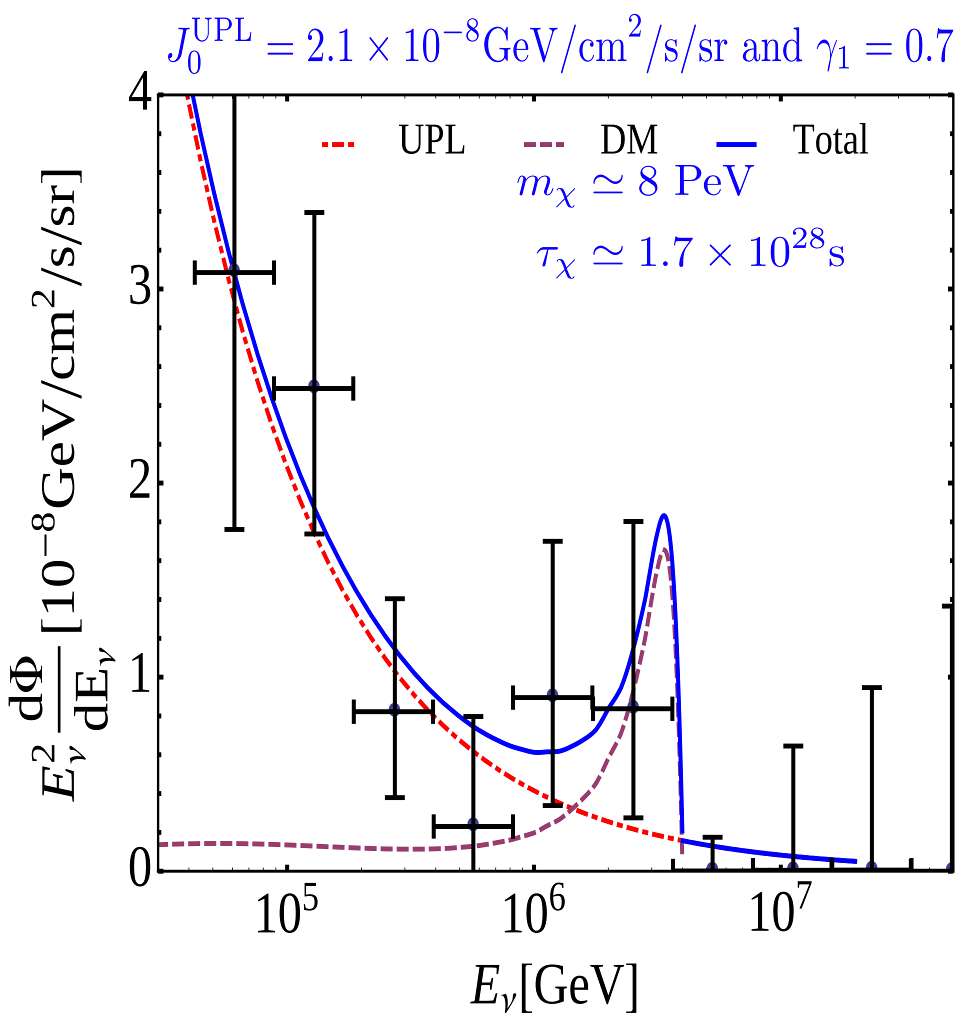
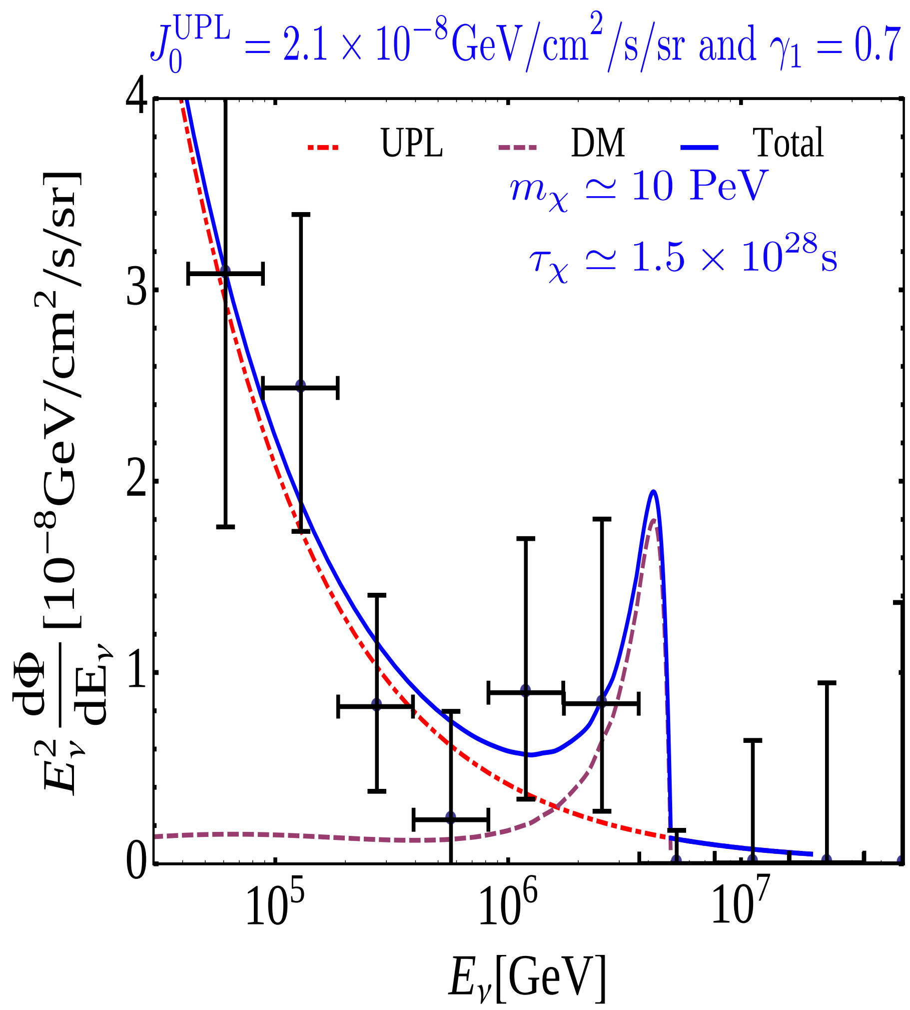




Direct Detection

- Direct detection constrains the DM-nucleon scattering cross section

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

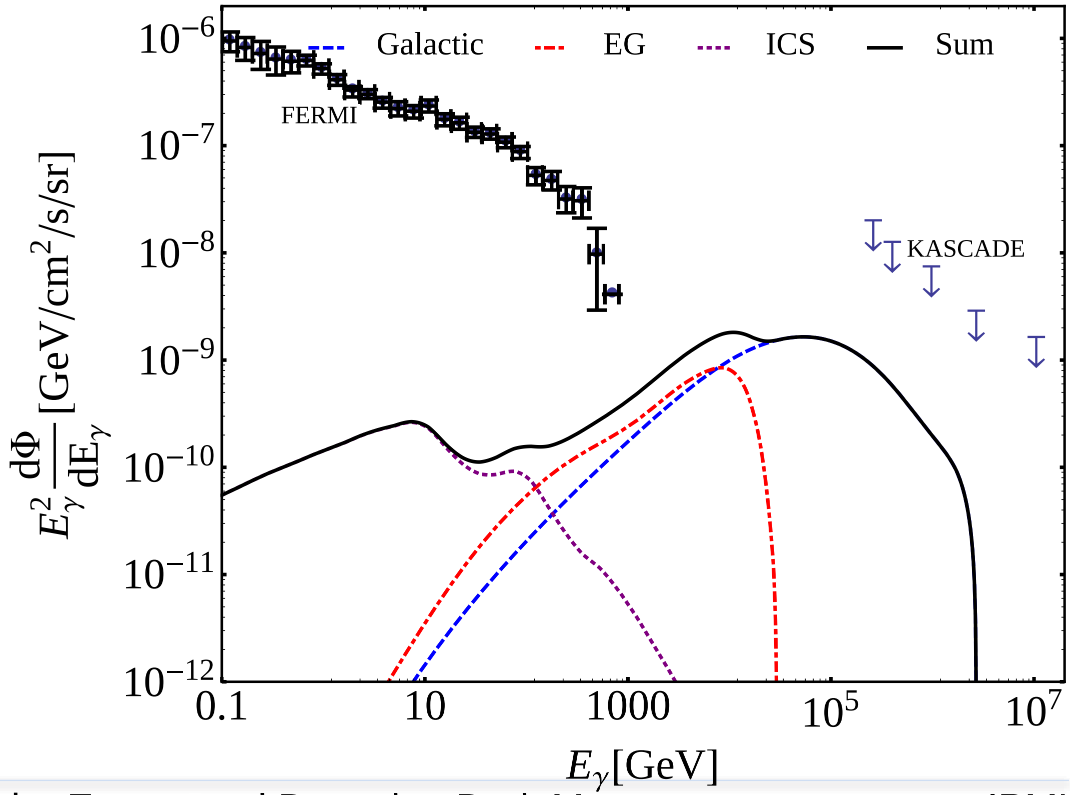
- Currently, the most stringent bound is from LUX limit

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

- 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-I

- Model with discrete symmetry

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

- Lagrangian

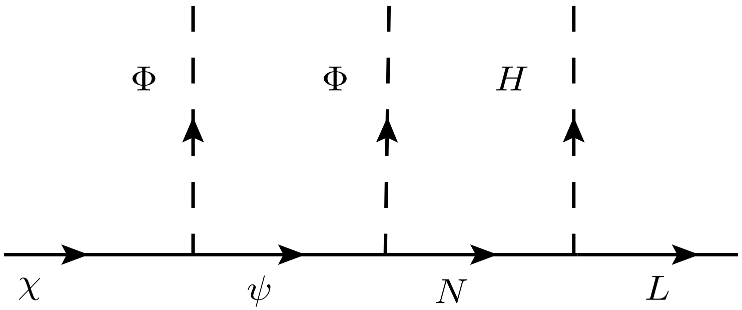
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N} i \partial\!\!\!/ N - \left(\frac{1}{2} m_N \bar{N}^c N + y \bar{L} \widetilde{H} N + \text{h.c.} \right)$$
$$+ \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \bar{\chi} \left(i \partial\!\!\!/ - m_\chi \right) \chi - \left(f \bar{\chi} \phi N + \text{h.c.}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

- Similar for IceCube but no signal for direct detection

Discussion-II

- We can generalize to a wide class of models,
- charge assignment

$$(Q_\chi, Q_\psi, Q_\Phi) = (2, 1, 1).$$



- with $(f\,\bar{\chi}\,\Phi\,\psi + g_I\,\bar{\psi}\,\Phi\,N_I + \text{h.c.})$

$$\lambda_{\text{eff}} \sim \frac{yfg}{4\sqrt{2}}\frac{m_\chi}{m_\psi}\frac{m_\chi}{m_N} \sim 10^{-29}$$

- 4-body > 3-body > 2-body, again due to symmetry br.

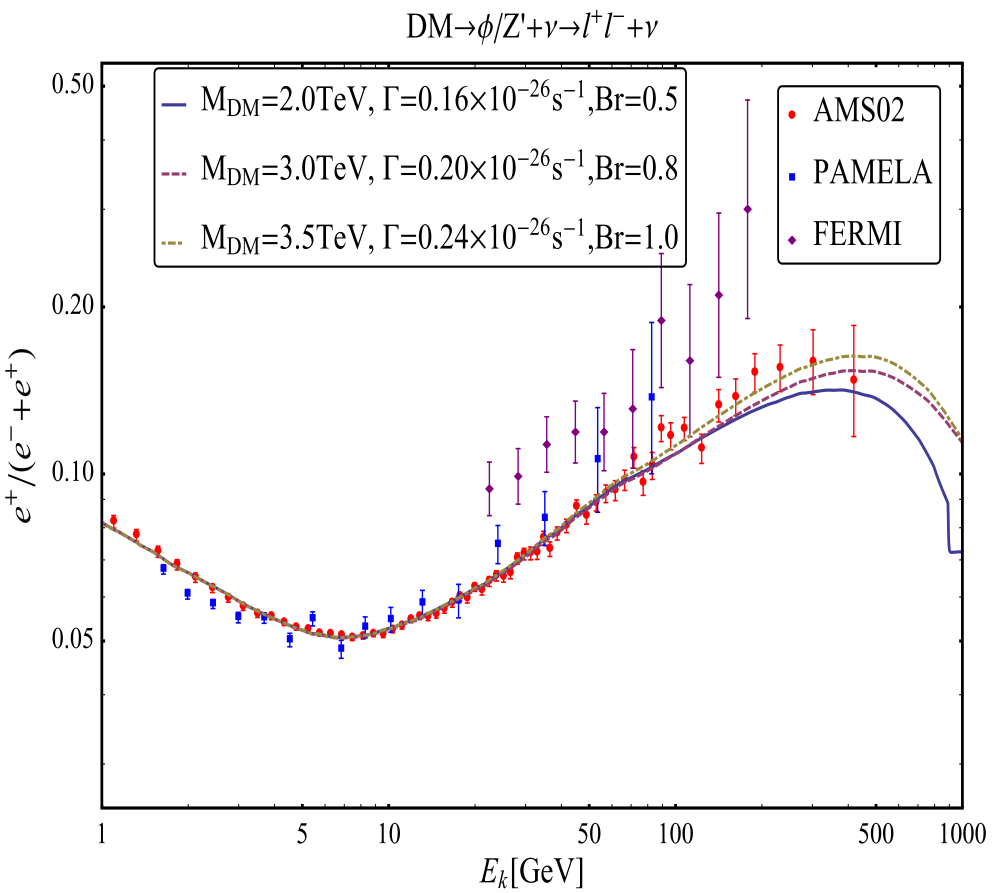
Discussion-III

- If the DM mass is small enough, its dominant decay channels are two-body decays.

$$\frac{\Gamma_{3\text{-body}}}{\Gamma_{2\text{-body}}} \propto \frac{1}{(4\pi)^2}\frac{m_\chi^2}{v_H^2}.$$

- For TeV scale DM, it might explain the AMS02 positron excess.

P. Ko, ***YT***, 1410.7657(PLB)



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.