Dark Matter and IceCube Connections

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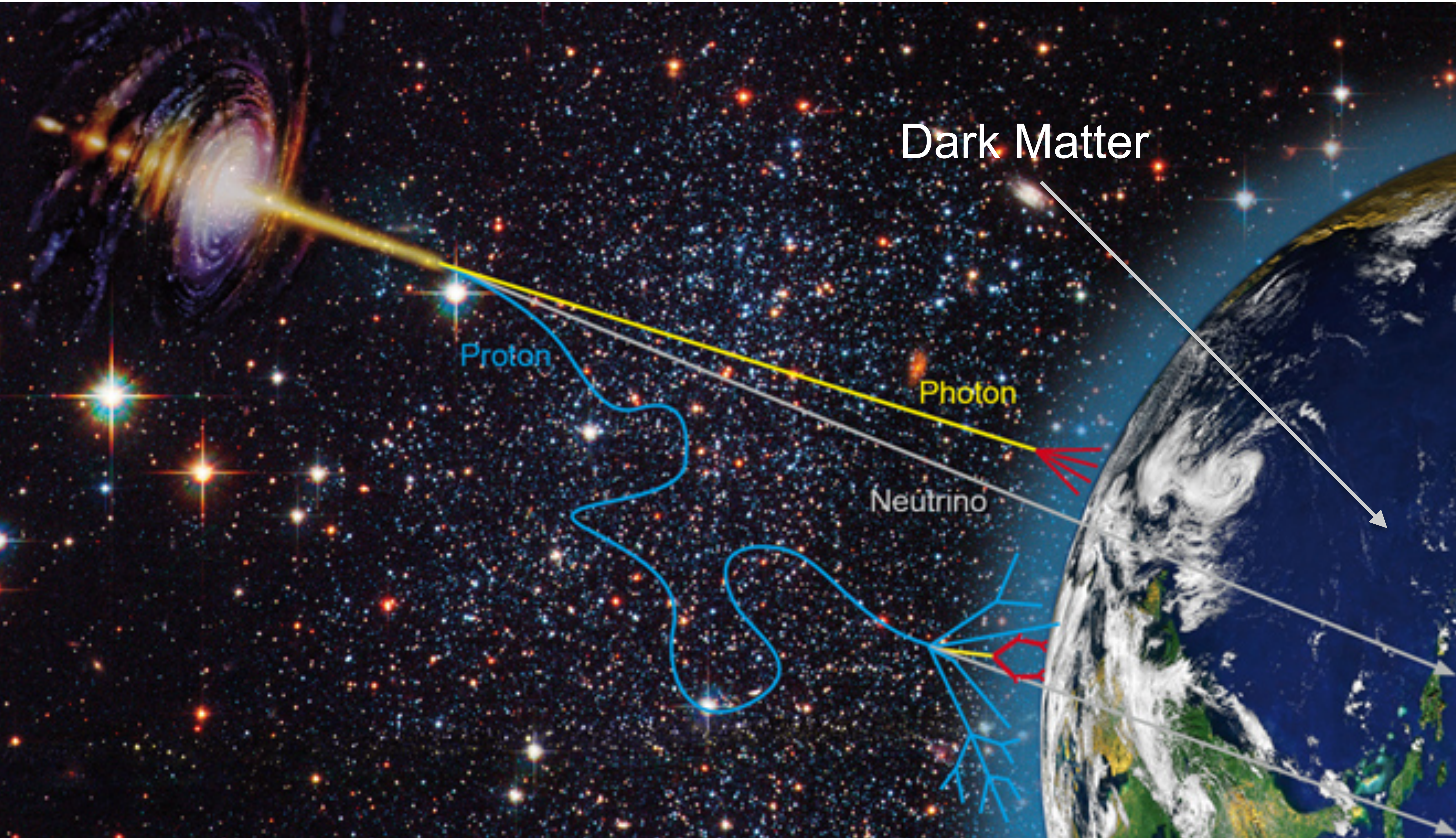
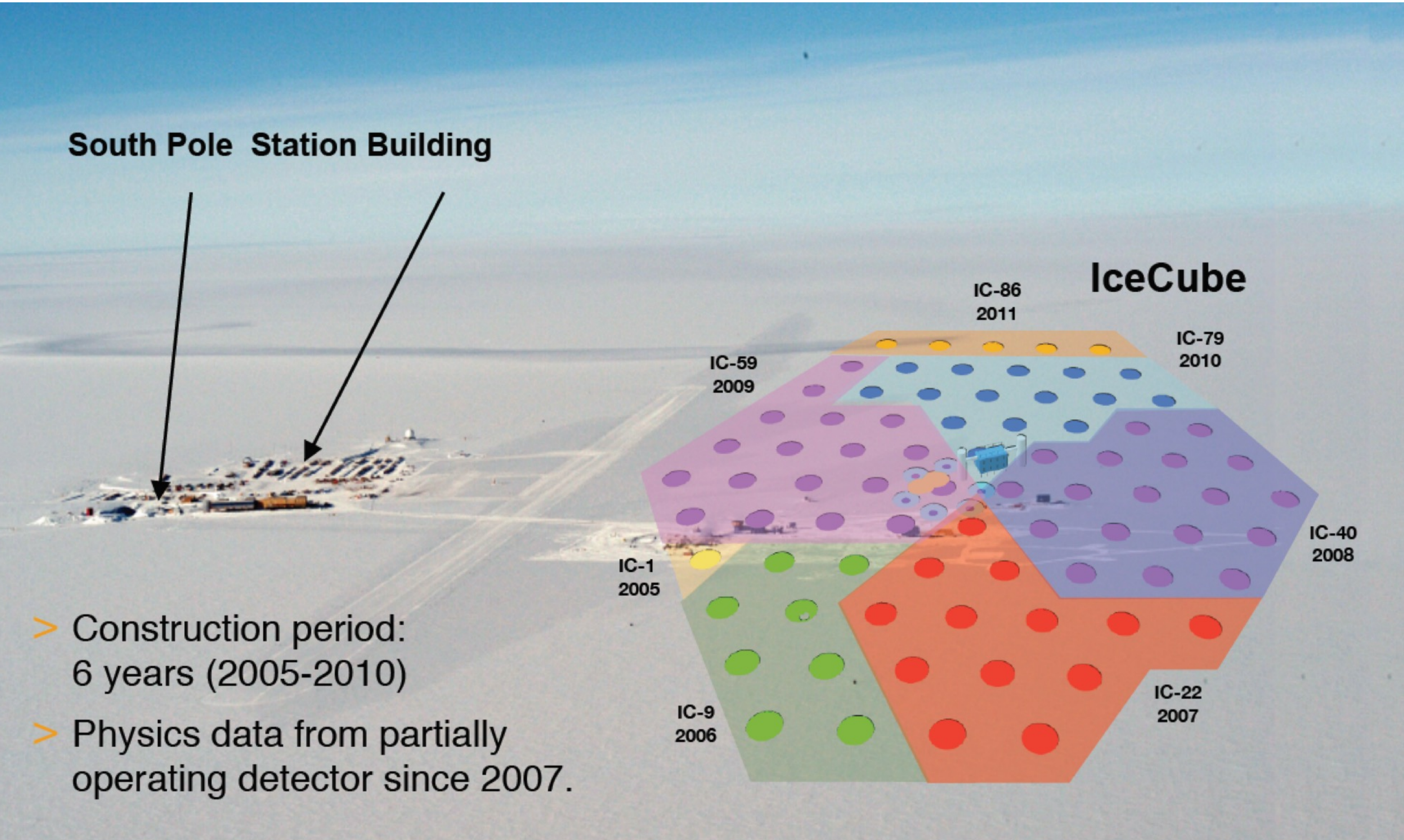
To be submitted soon: arxiv 1507.xxxx

Extraterrestrial neutrino



IceCube: introduction

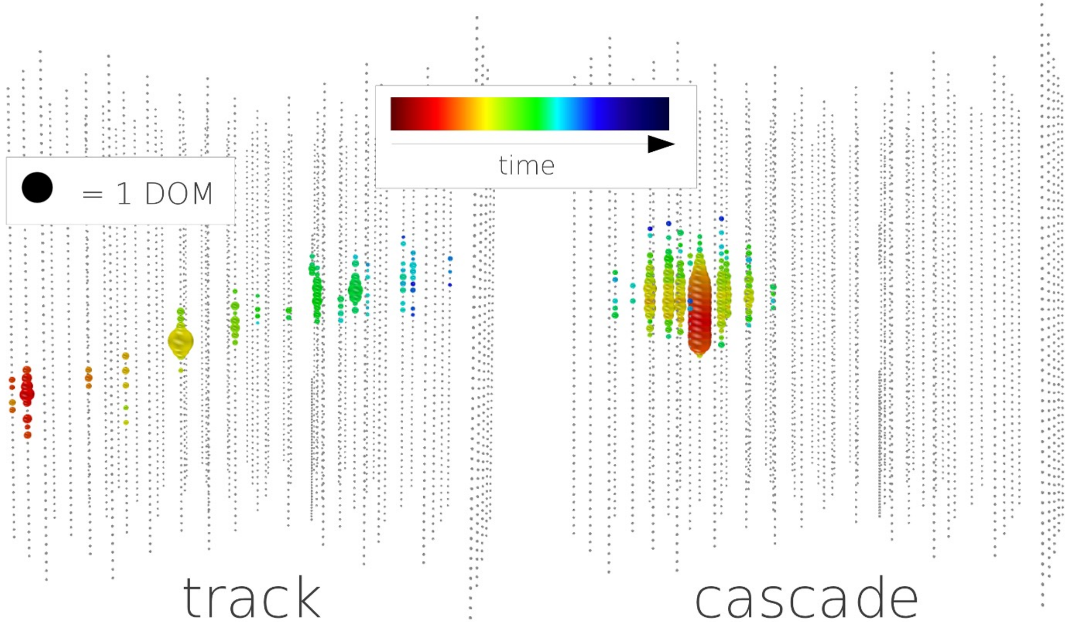


- Construction period:
  6 years (2005-2010)
- Physics data from partially operating detector since 2007.

IceCube: introduction

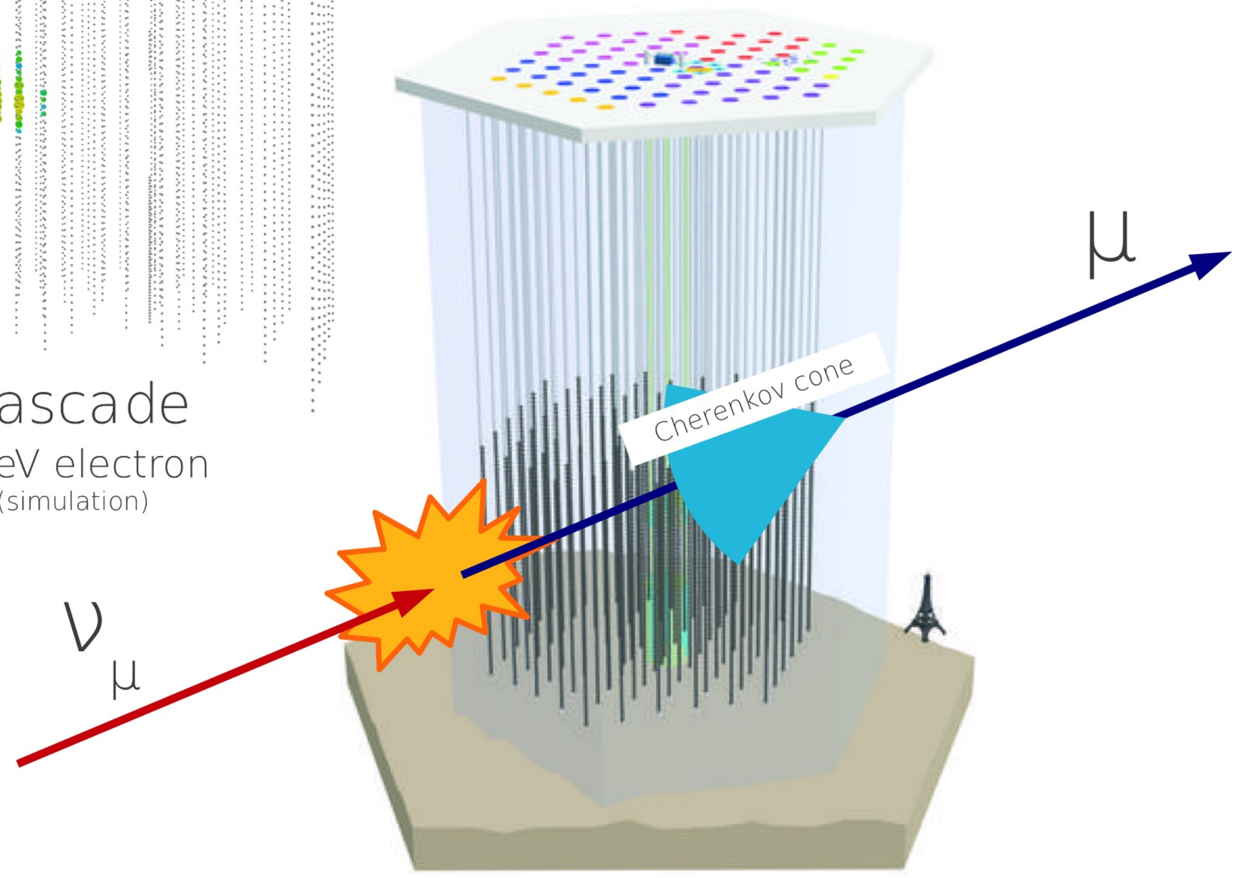
$\nu_e + N \rightarrow e + X$

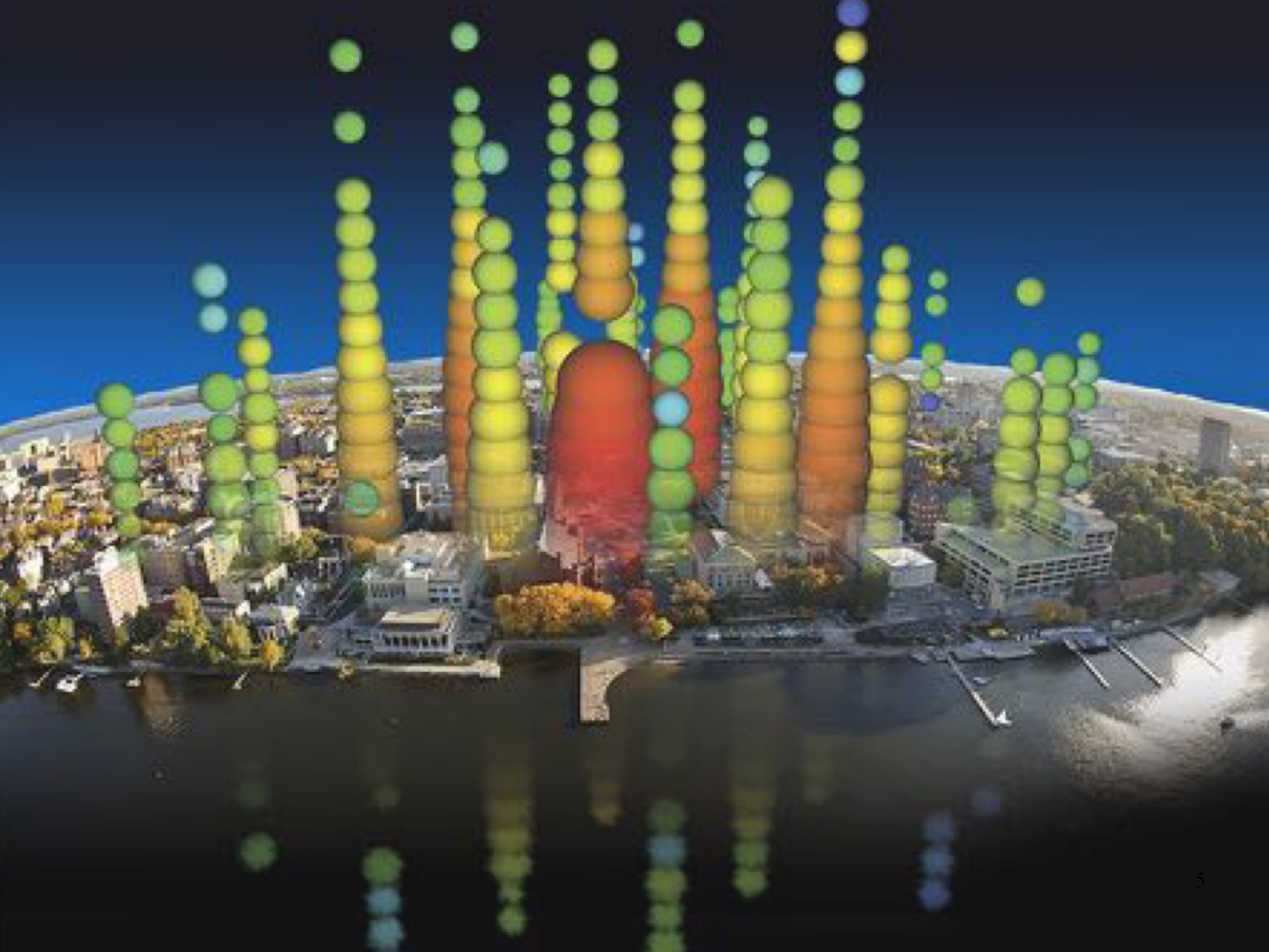
$\nu_\mu + N \rightarrow \mu + X$ $\nu_x + N \rightarrow \nu_x + X$



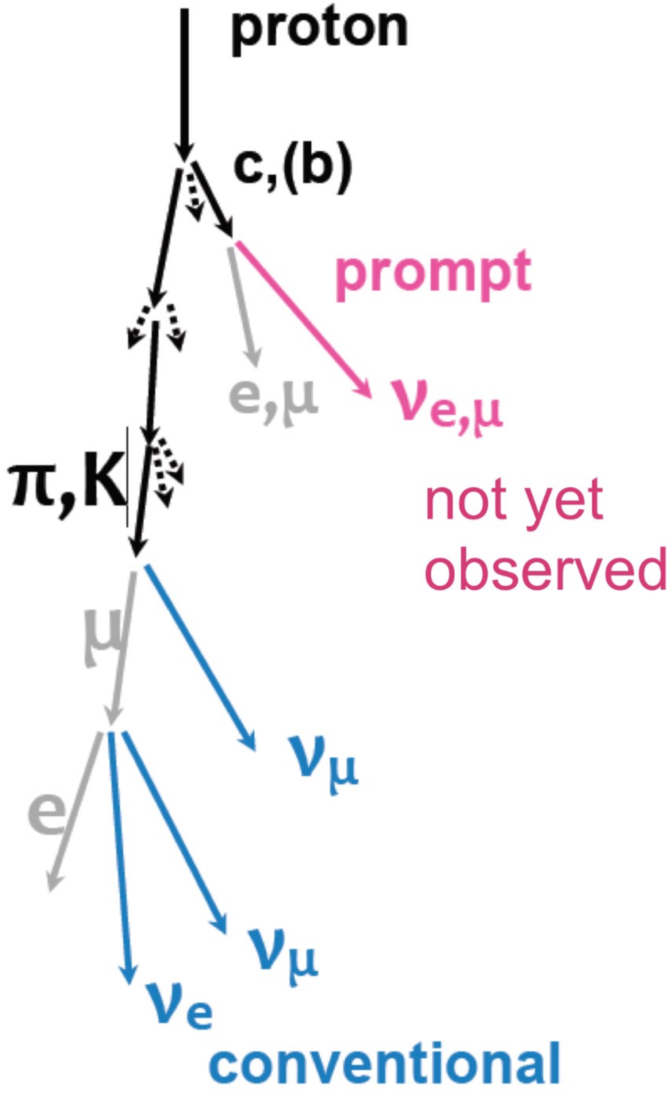
track
450 TeV muon
(simulation)

cascade
1 PeV electron
(simulation)

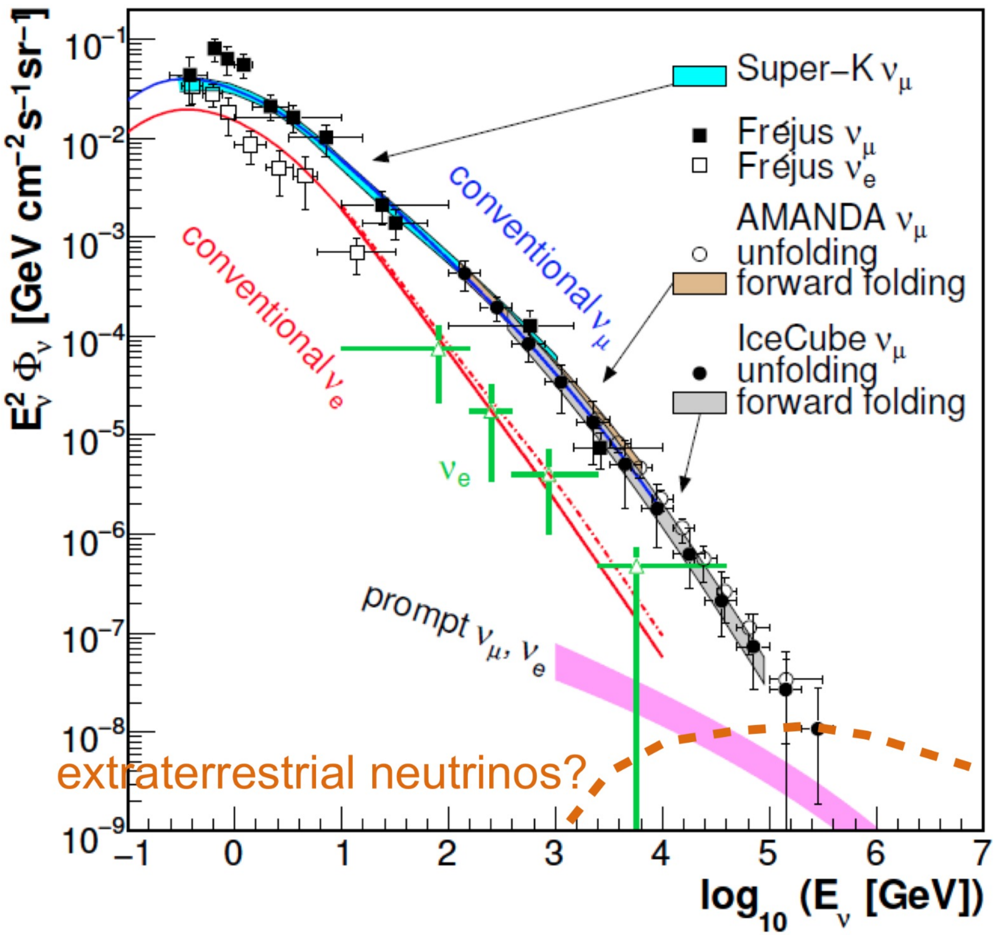




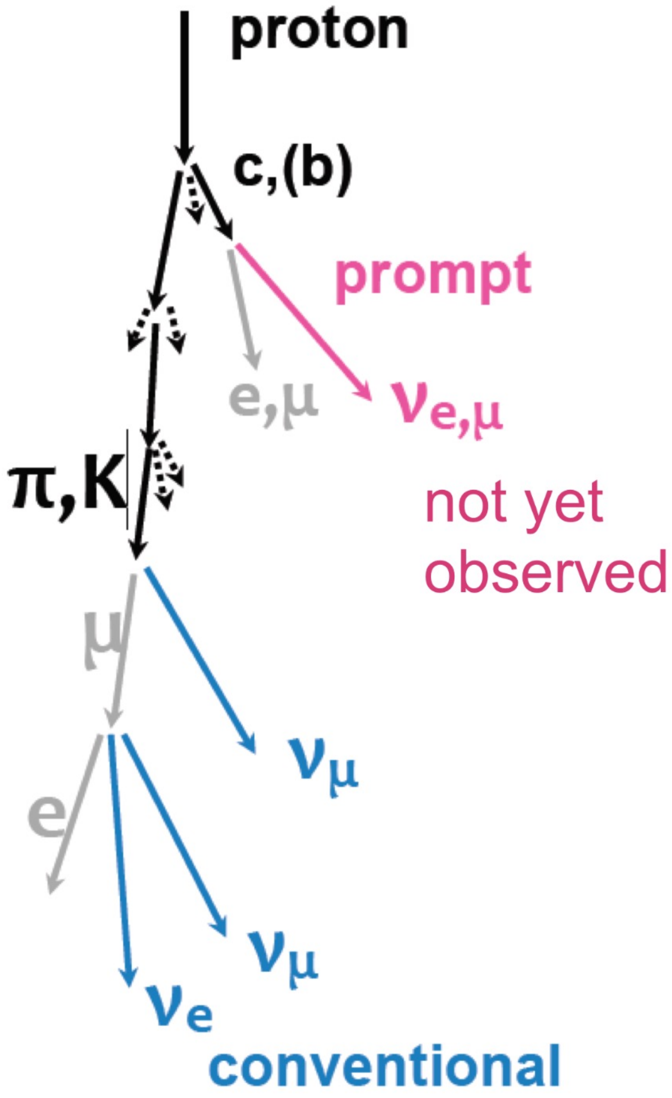
background

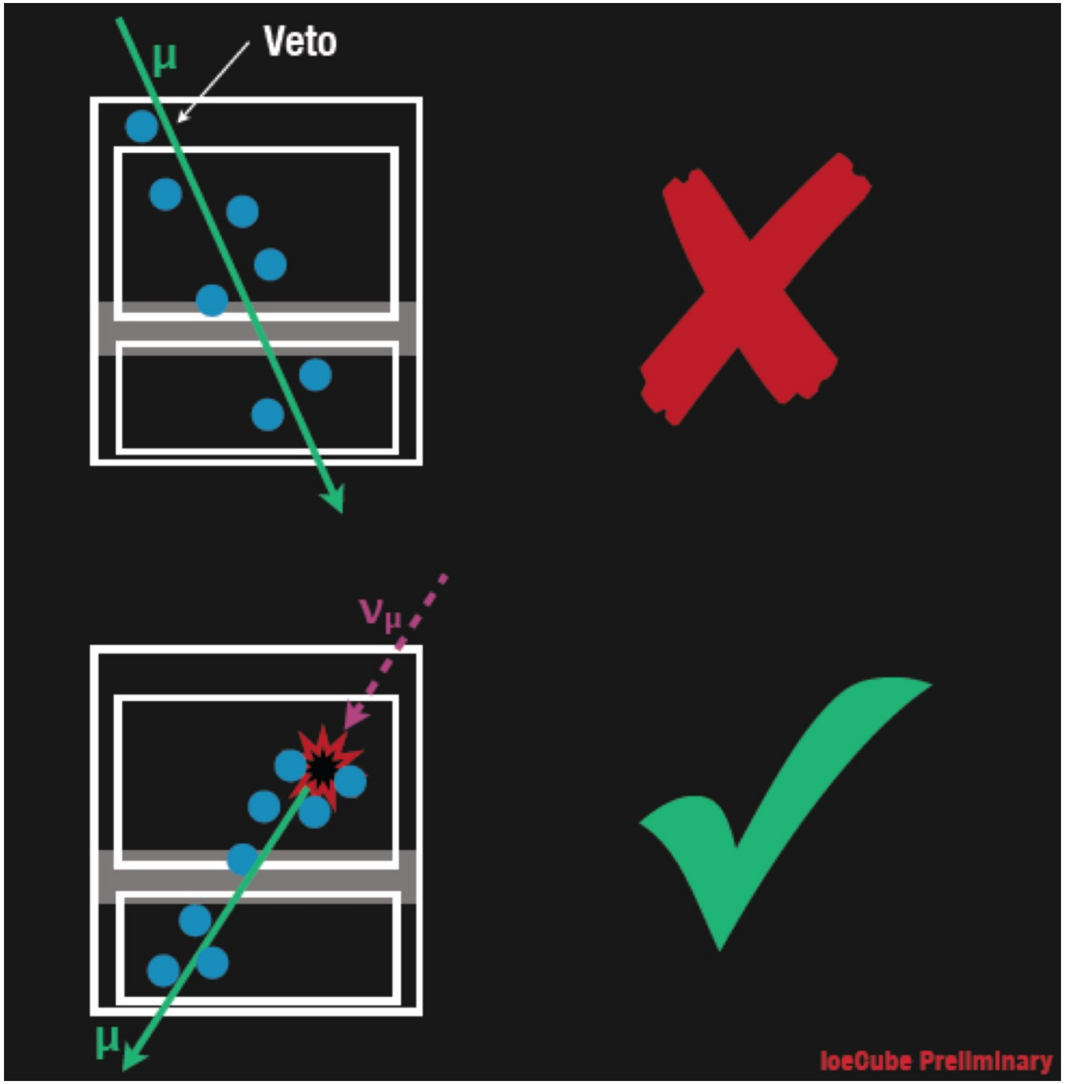


Most of the neutrino seen have Atmospheric origin



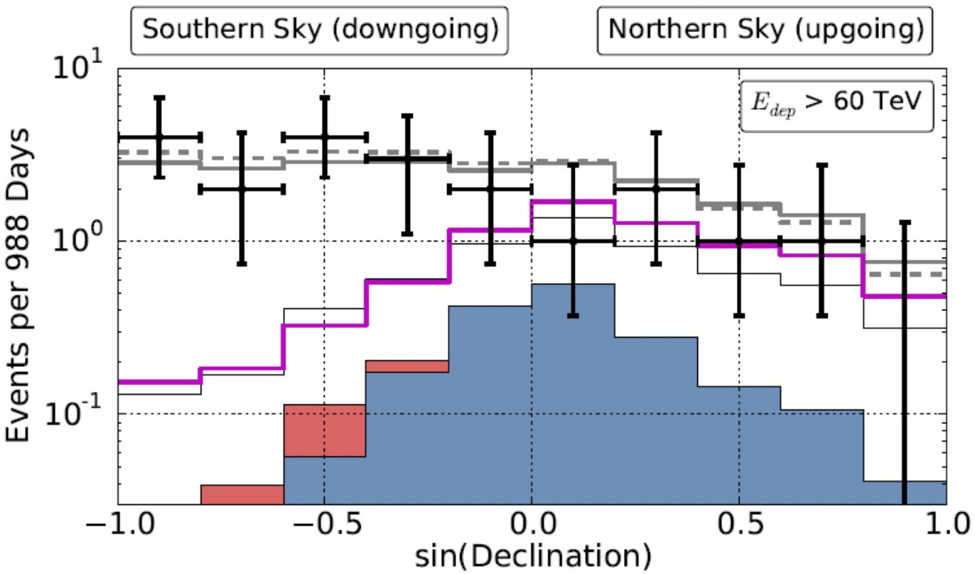
Veto atmospheric neutrino and muon

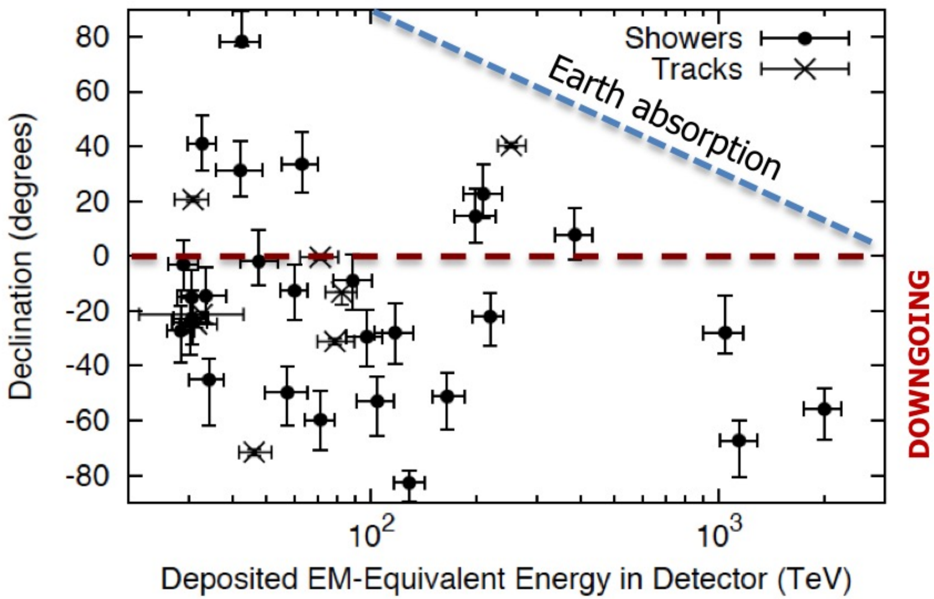




Arrival angle of events

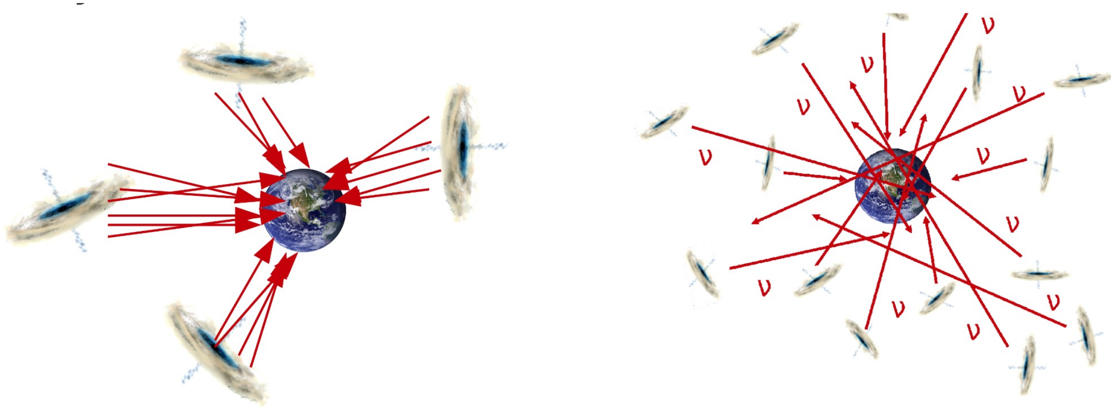
IceCube, PRL 113:101101 (2014)

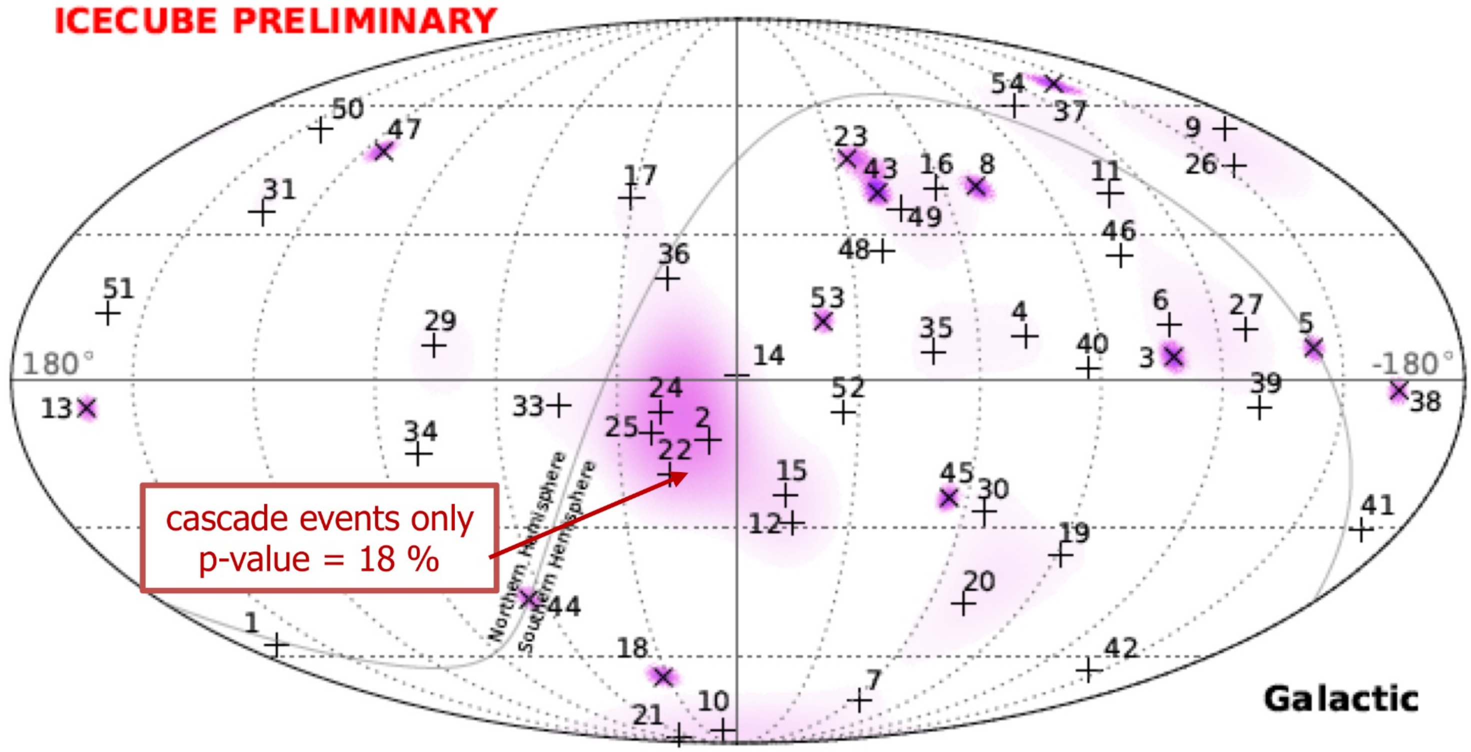




Prompt neutrino excluded

Diffuse?

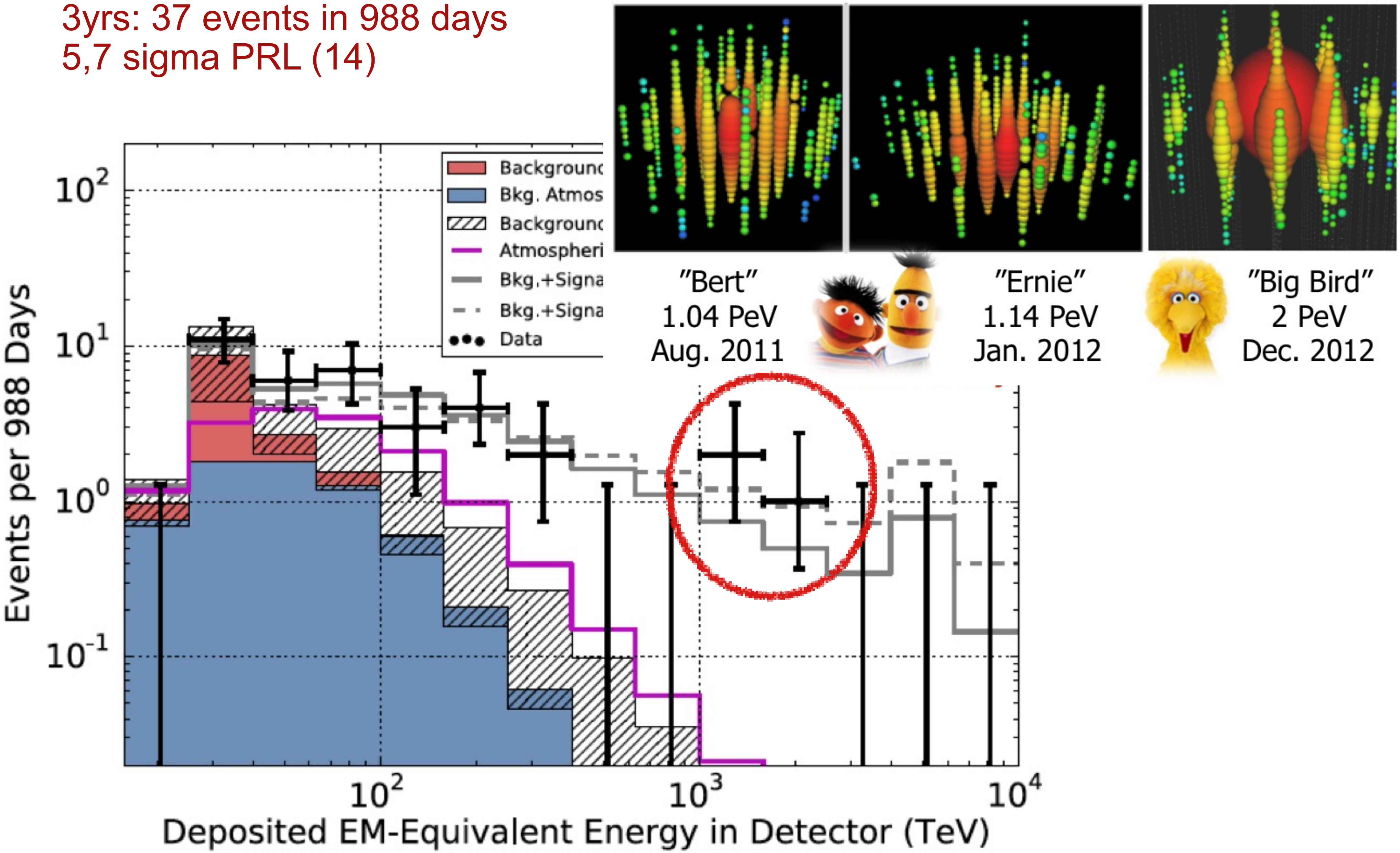




ICECUBE PRELIMINARY
180°
-180°
cascade events only
p-value = 18 %
Northern Hemisphere
Southern Hemisphere
Galactic

Evidence for extraterrestrial neutrino

3yrs: 37 events in 988 days
5,7 sigma PRL (14)



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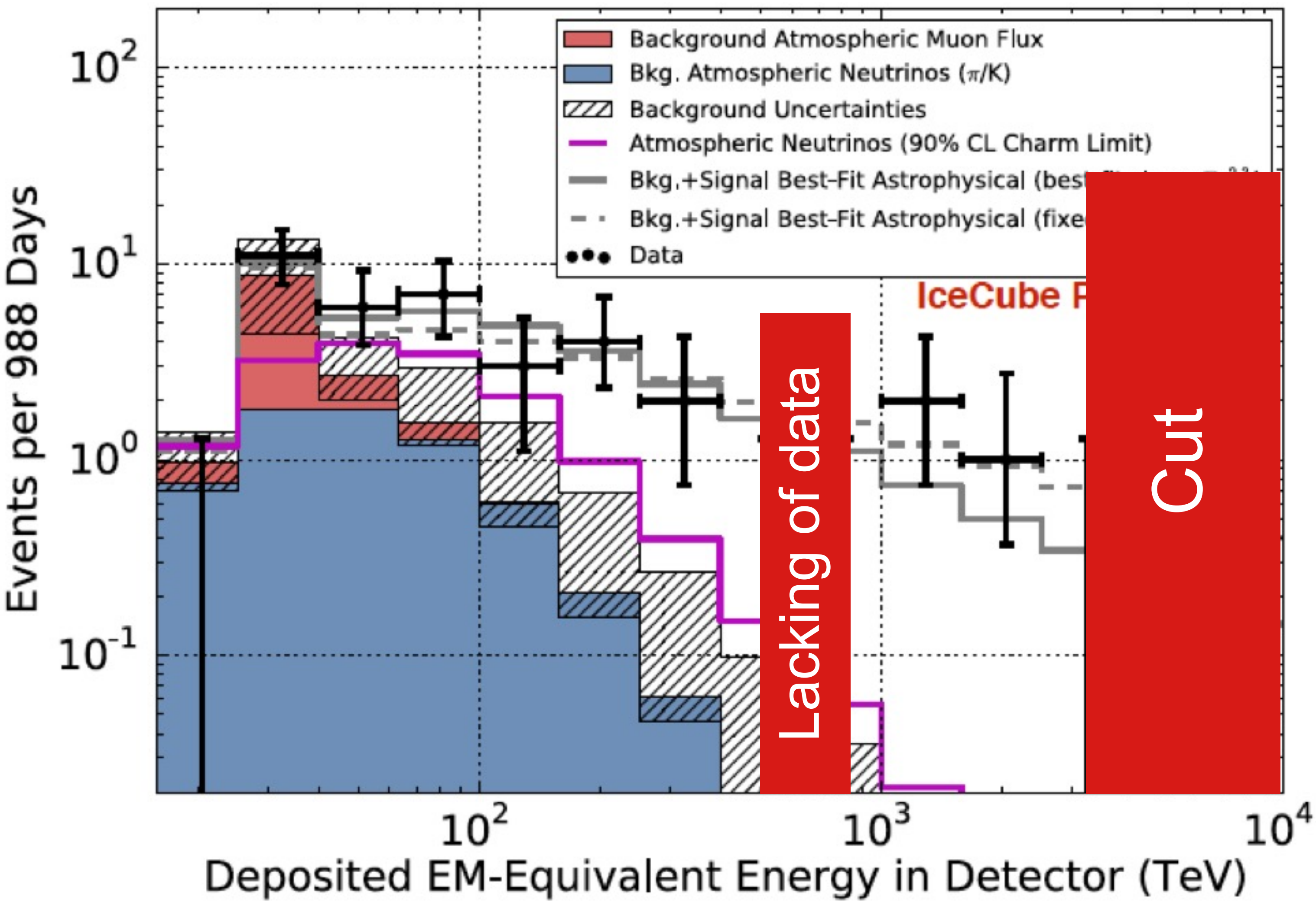

Dark Matter & IceCube

So far we do not have clear evidences of non gravitational dark matter detection

but

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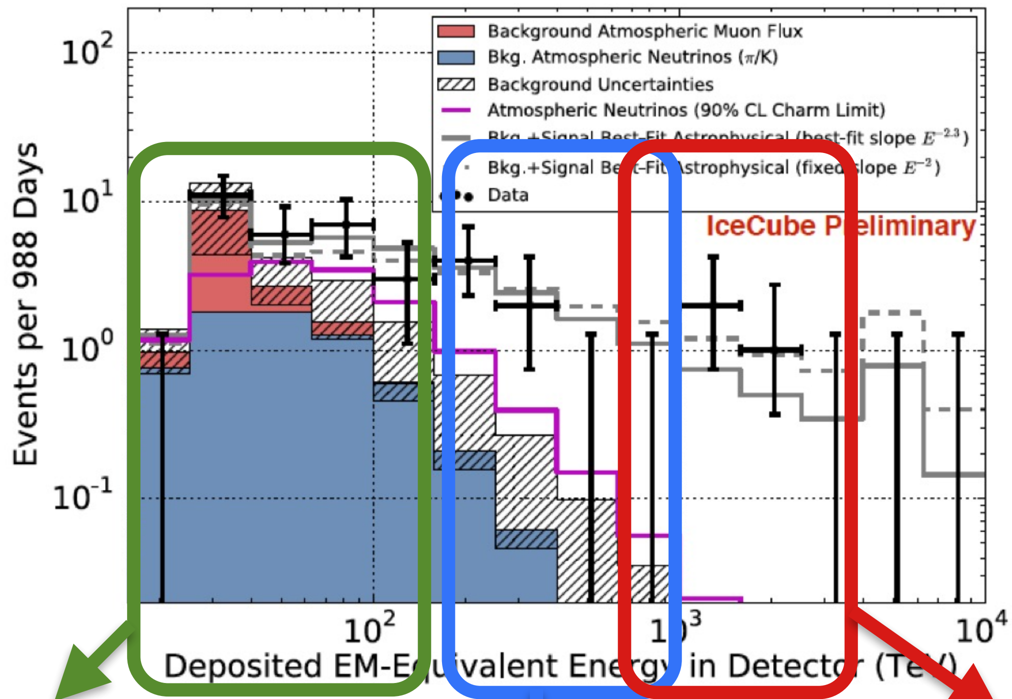
So far we do not have clear evidences of non gravitational dark matter detection

but

...hopefully IC can shed light on the DM problem

Origin of IceCube events: our assumption

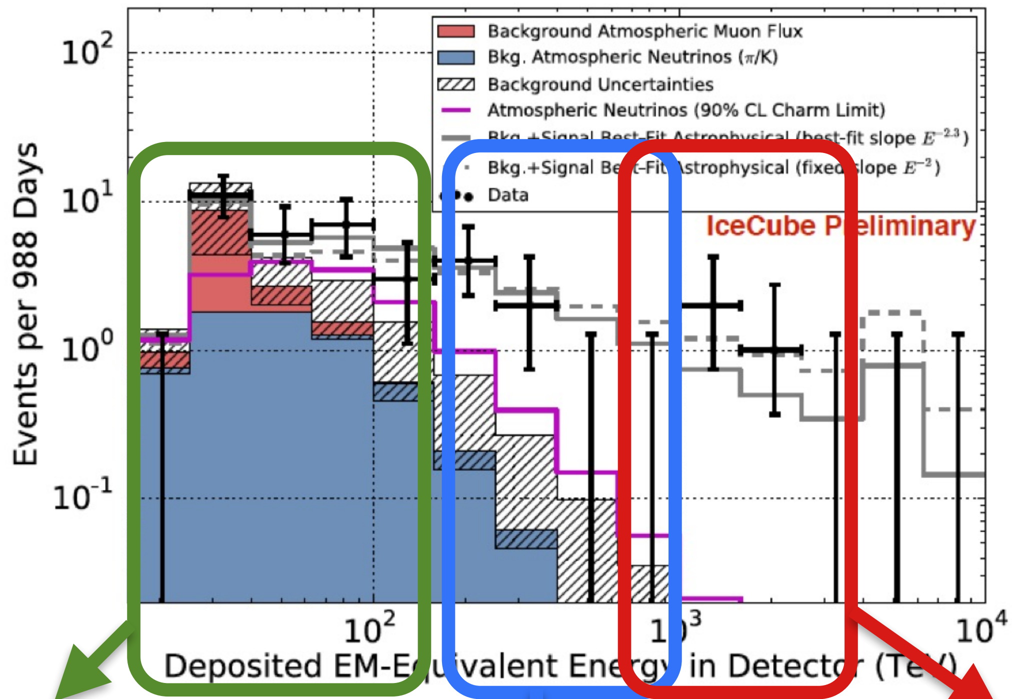


Standard atmospheric

Some astrophysical

PeV Decay
Dark matter

Origin of IceCube events: our assumption



Standard atmospheric

Some astrophysical

PeV Decay
Dark matter

- The lack of data above 2 PeV and between 300TeV-1PeV suggests the presence of different sources: one could be DM
- IC can provide important information on the nature of DM

Heavy dark matter: non-thermal production

m >> 100 TeV

$$\Omega_\chi h^2 \sim M_\chi^2 \langle \sigma v \rangle \left(\frac{g_\star}{200} \right)^{-3/2} \left(\frac{2000\, T_{RH}}{M_\chi} \right)^7$$

For instance production during the reheating of the universe

Chung, Kolb, Riotto, Production of massive particles during reheating, PRD60 (1999)[hep-ph/9809453]

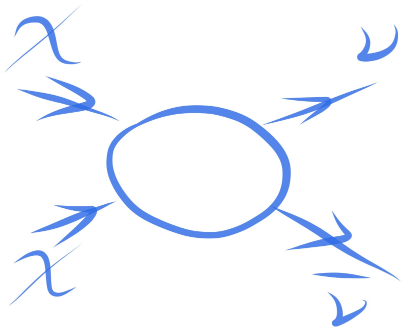
Chung, Kolb, Riotto, Nonthermal supermassive dark matter, PRL81 (1998) [hep-ph/9805473].

Giudice, Kolb, Riotto, Largest temperature of the radiation era and its cosmological implications, PRD64 (2001) [hep-ph/0005123]

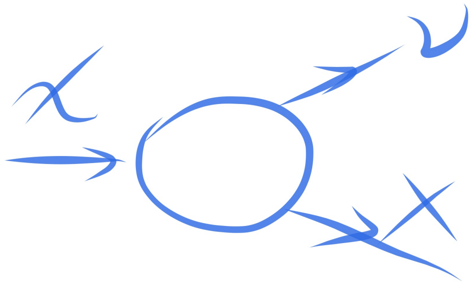
Harigaya, Kawasaki, Mukaida, Yamada, Dark Matter Production in Late Time Reheating, PRD89(2014) [arXiv:1402.2846

Dark Matter: stable vs decay

Stable



Decay



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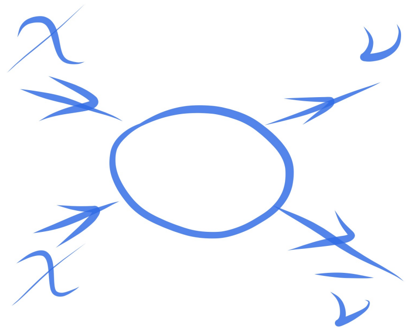
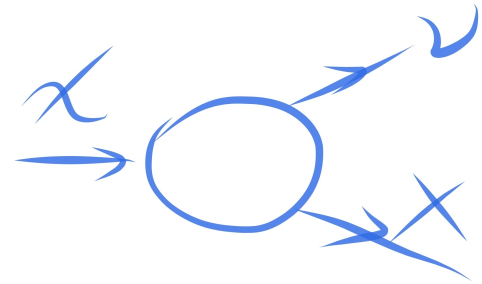


Decay



For PeV DM annihilation negligible respect decay

Fledstain et al, 1303.7320

$$\Gamma_{\rm Events} \sim V\, L_{\rm MW}\, n_{\rm N}\, \sigma_{\rm N} \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^2 \langle \sigma_{\rm Ann} v \rangle \lesssim 1 \text{ per few hundred years}$$

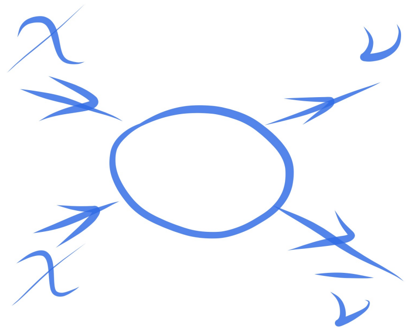
Annihilation

$$\Gamma_{\rm Events} \sim V\, L_{\rm MW}\, n_{\rm N}\, \sigma_{\rm N} \frac{\rho_{\rm DM}}{m_{\rm DM}} \Gamma_{\rm DM} \sim \left(\frac{\lambda}{10^{-29}}\right)^2 / \text{ year}$$

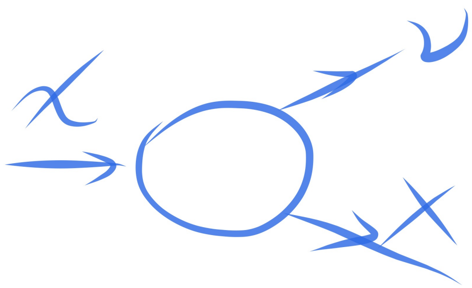
Decay

Dark Matter: stable vs decay

Stable



Decay



For PeV DM annihilation negligible respect decay

unless

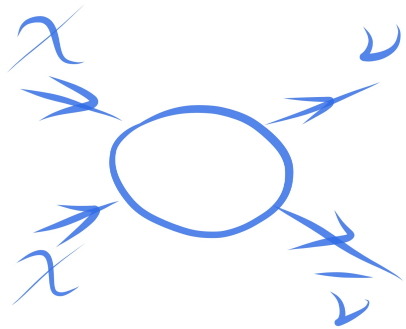
$$\Gamma_{\rm Events} \sim V\, L_{\rm MW}\, n_{\rm N}\, \sigma_{\rm N} \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^2 \langle \sigma_{\rm Ann} v \rangle$$

DM captured in large Celestial bodies like
the sun or cluster of galaxies, enhancing the density

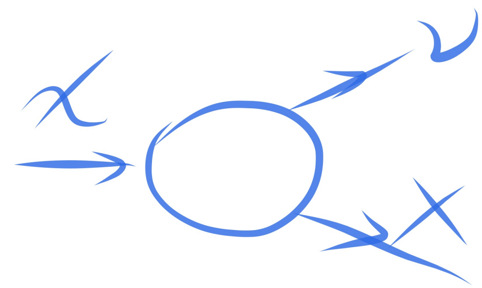
Silk et al, PRL(85), Gaisser et al, PRD(86), Gould AJ(88), ...

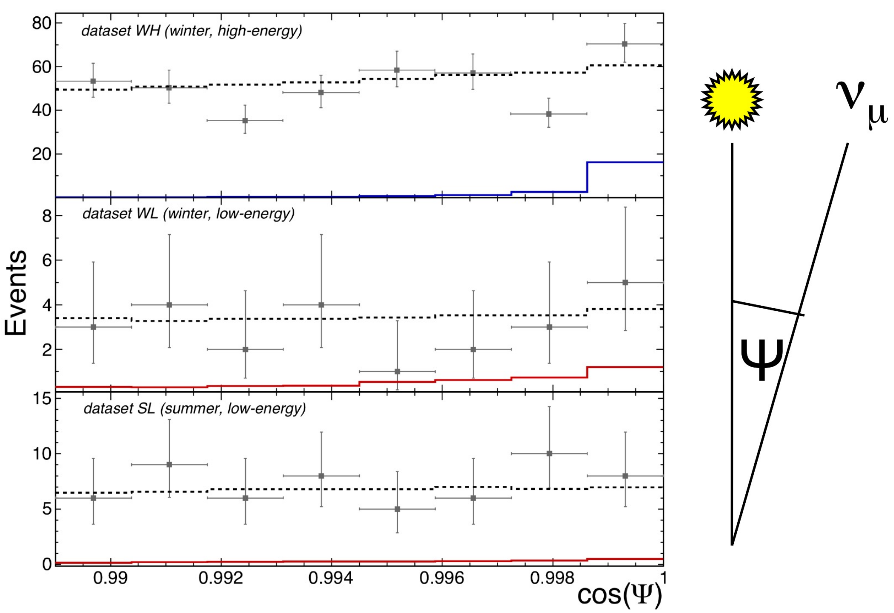
Dark Matter: stable vs decay

Stable

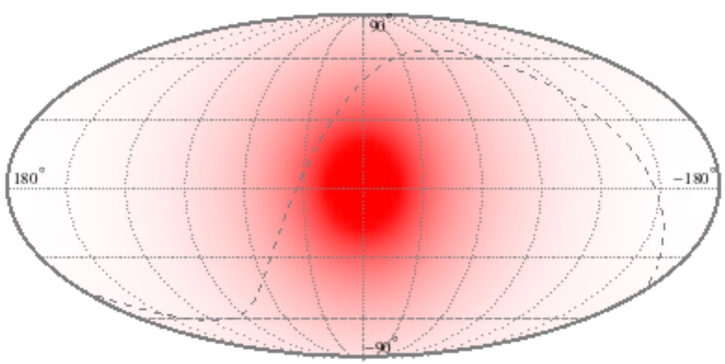


Decay





Search for DM in the sun, from IceCube

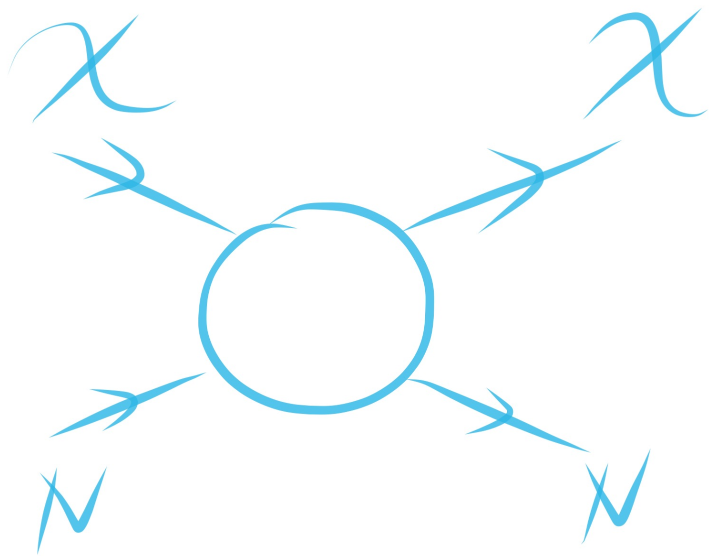


(a) PDF of DM decay

Esmaili, Kang, Serpico, JCAP14

Direct DM detection @ IceCube

$$m_\chi \sim \mathcal{O}(PeV)$$



Direct DM detection @ IceCube

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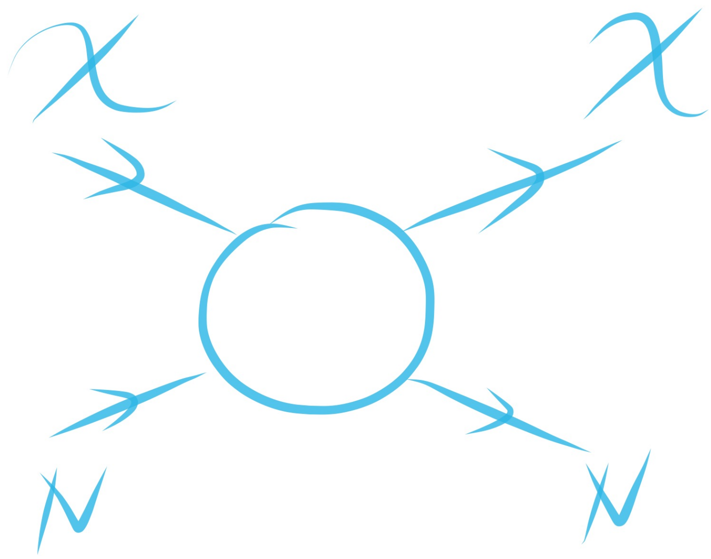
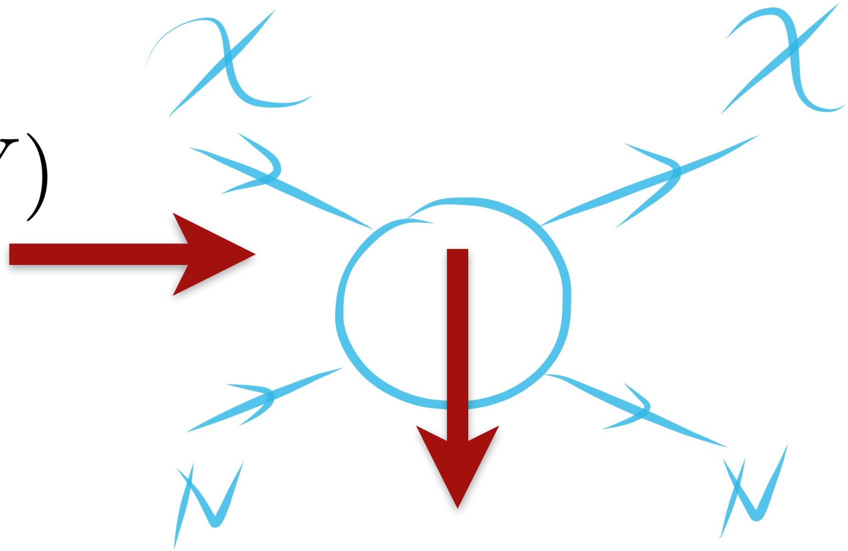


the amount of energy transferred in elastic scattering is negligible

...so "ordinary" DM with PeV mass (or bigger) can not be observed at IceCube

Boosted Dark Matter: preliminary

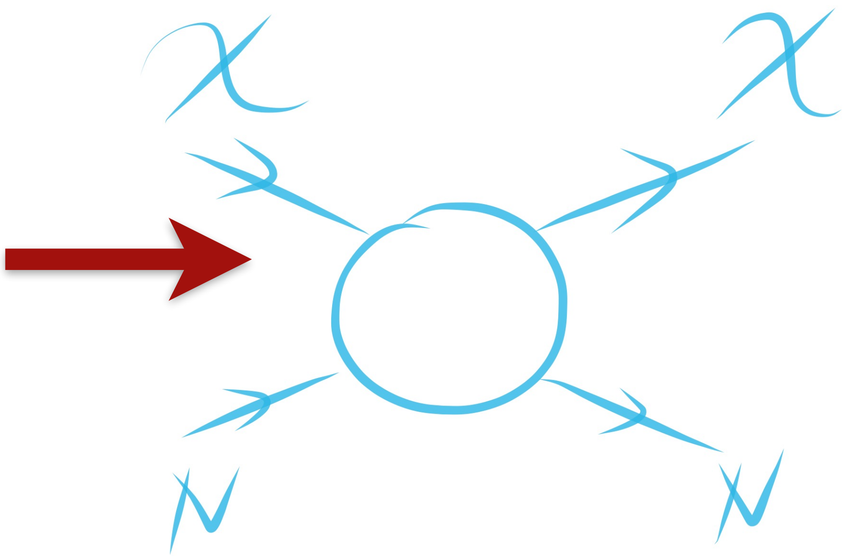
$E_{\rm kin} \sim \mathcal{O}(PeV)$



...but "boosted" DM could transfer enough energy to be detected at IceCube with

Bhattacharya et al JCAP15,
Agashe et al JCAP14
Berger et al JCAP15
Kopp et al JHEP15

Boosted Dark Matter: preliminary

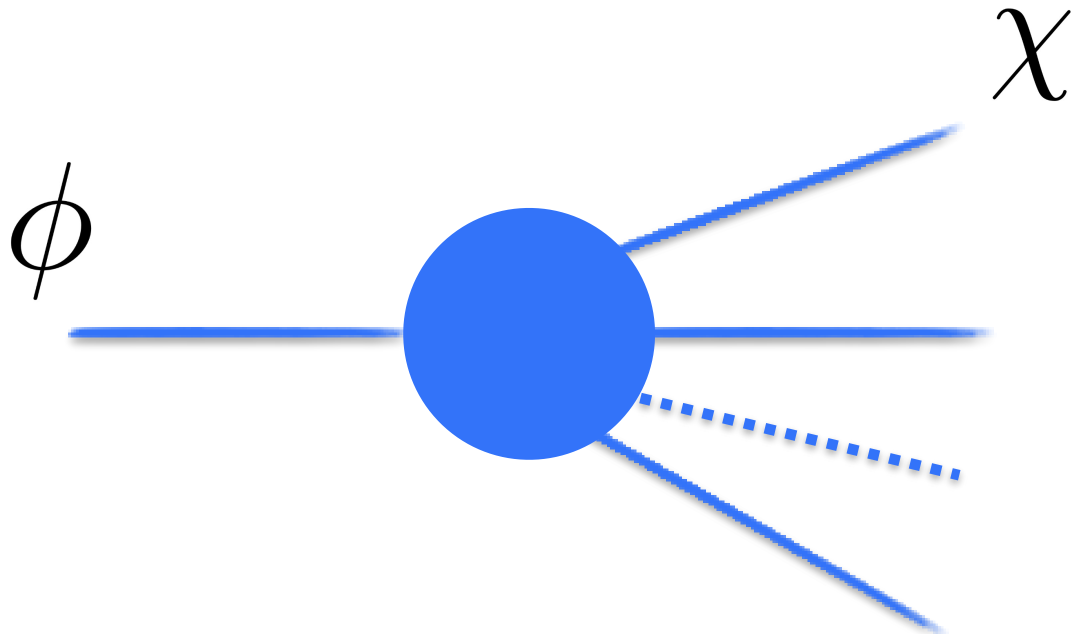


boosted DM interacts only by means of
neutral current and therefore give rise to shower events only

IceCube can rule out this framework if
a PeV track event will be detected

Boosted Dark Matter: preliminary

$$\Delta M \sim PeV$$



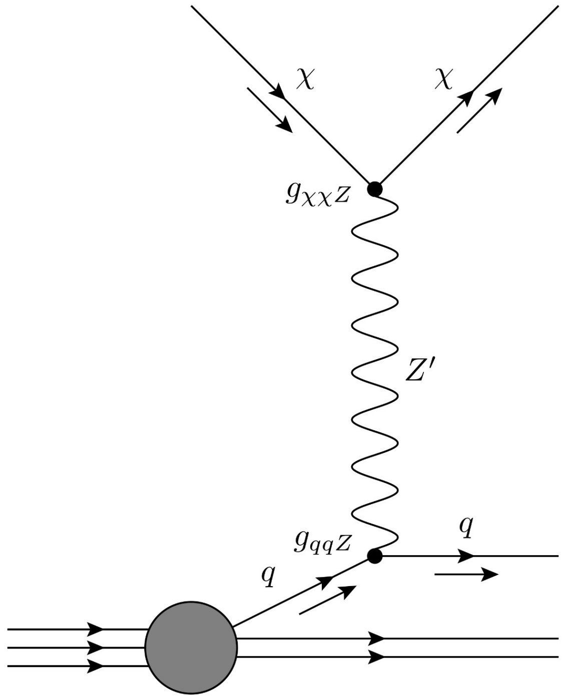
Two dark matter components, one stable and one decaying

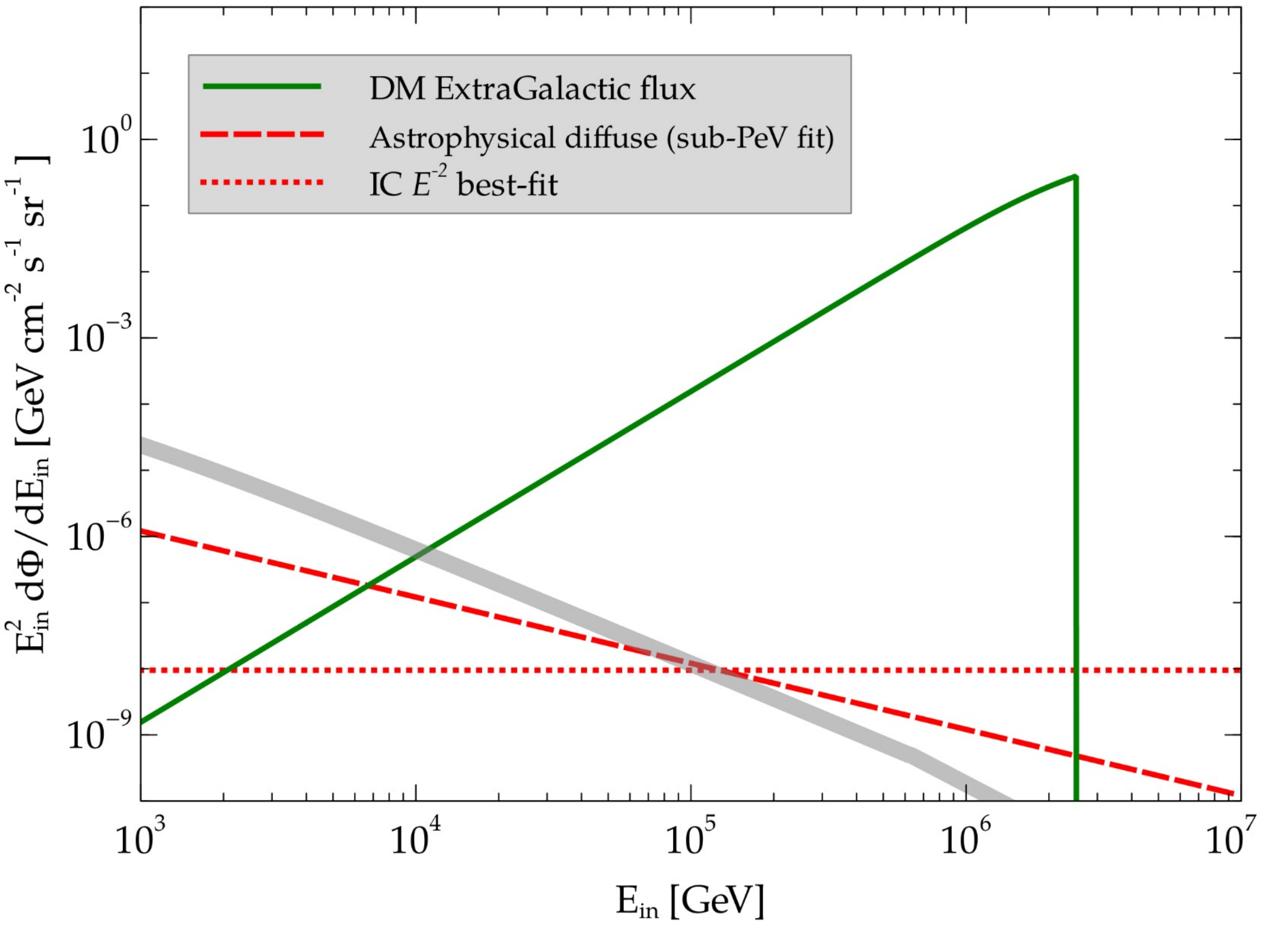
Boosted Dark Matter 1

Bhattacharya et al JCAP15,

$$\phi \to \bar{\chi}\chi$$

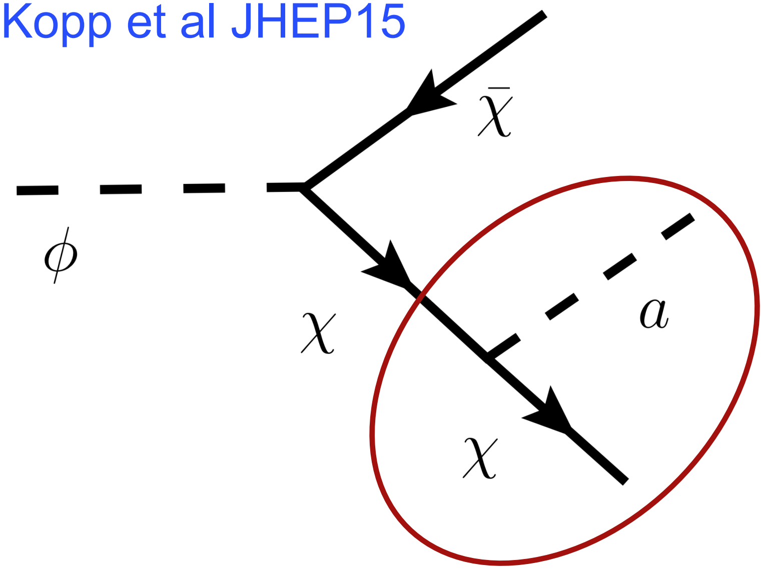
$$m_\phi \sim \mathcal{O}(10 PeV)$$
$$m_\phi \gg m_\chi$$



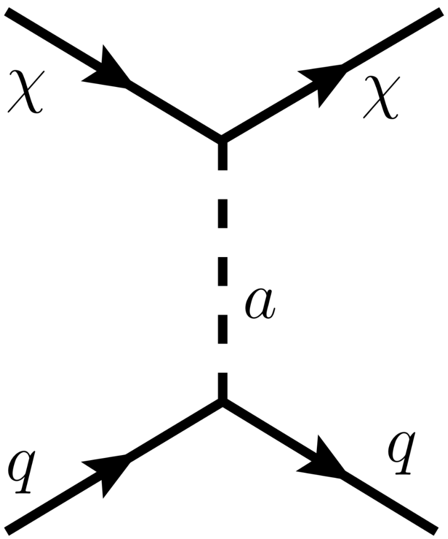


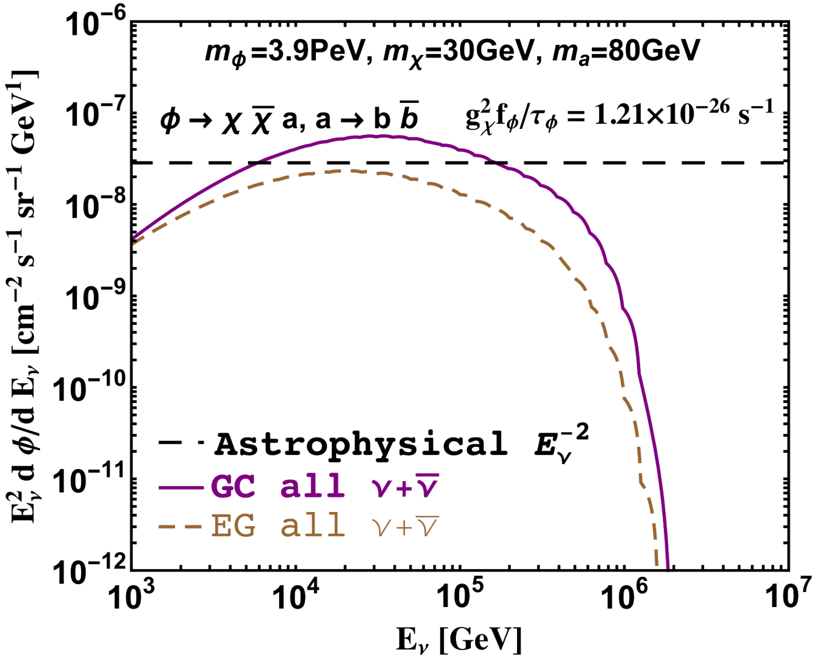
Boosted Dark Matter 2

Kopp et al JHEP15



Secondary neutrino





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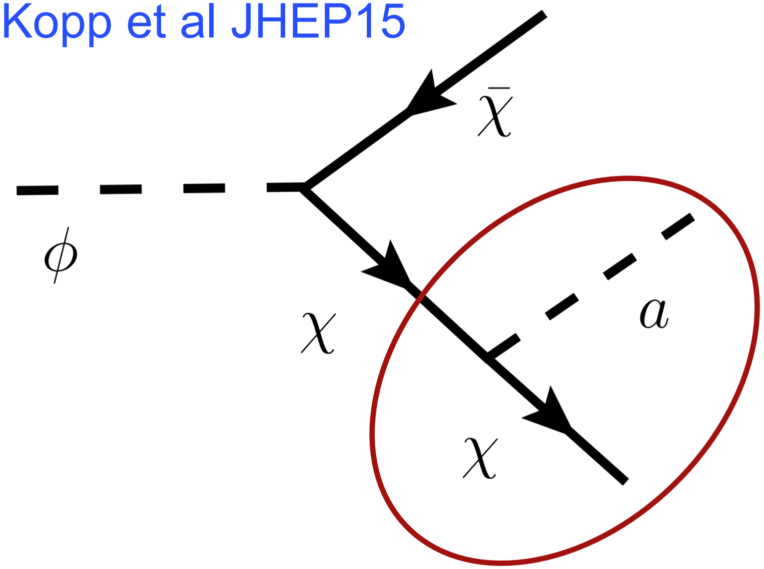

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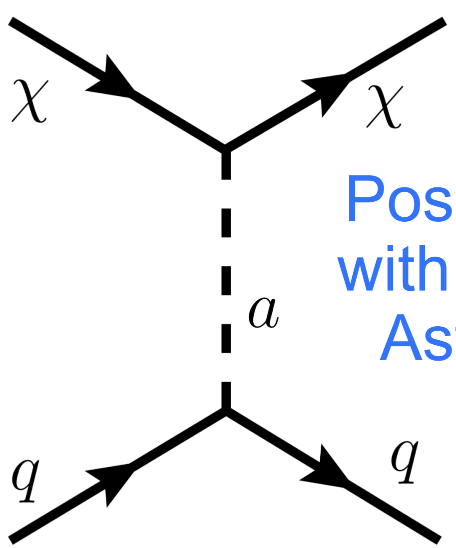
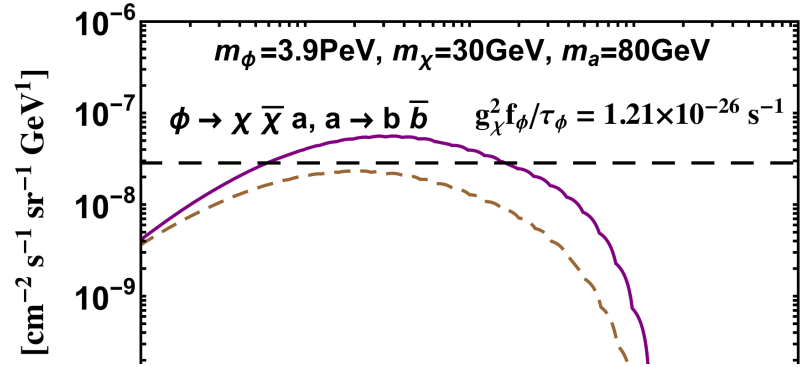
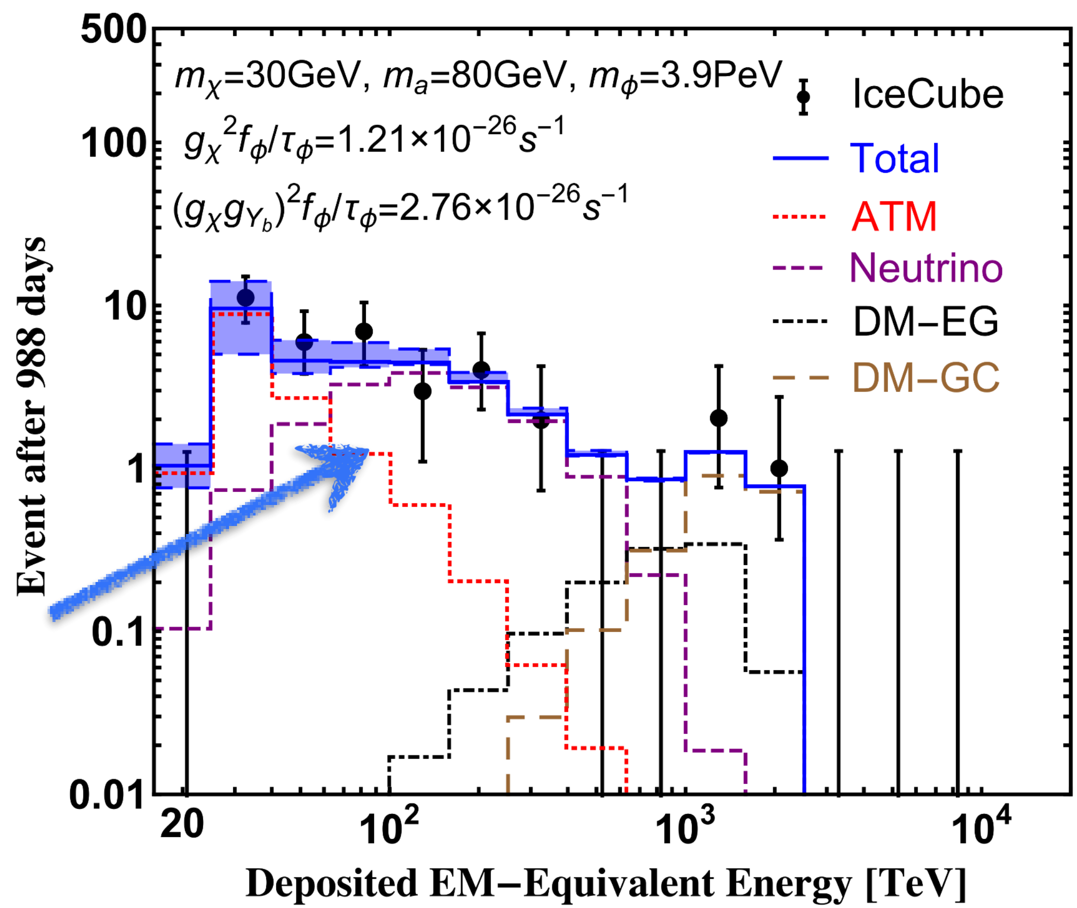


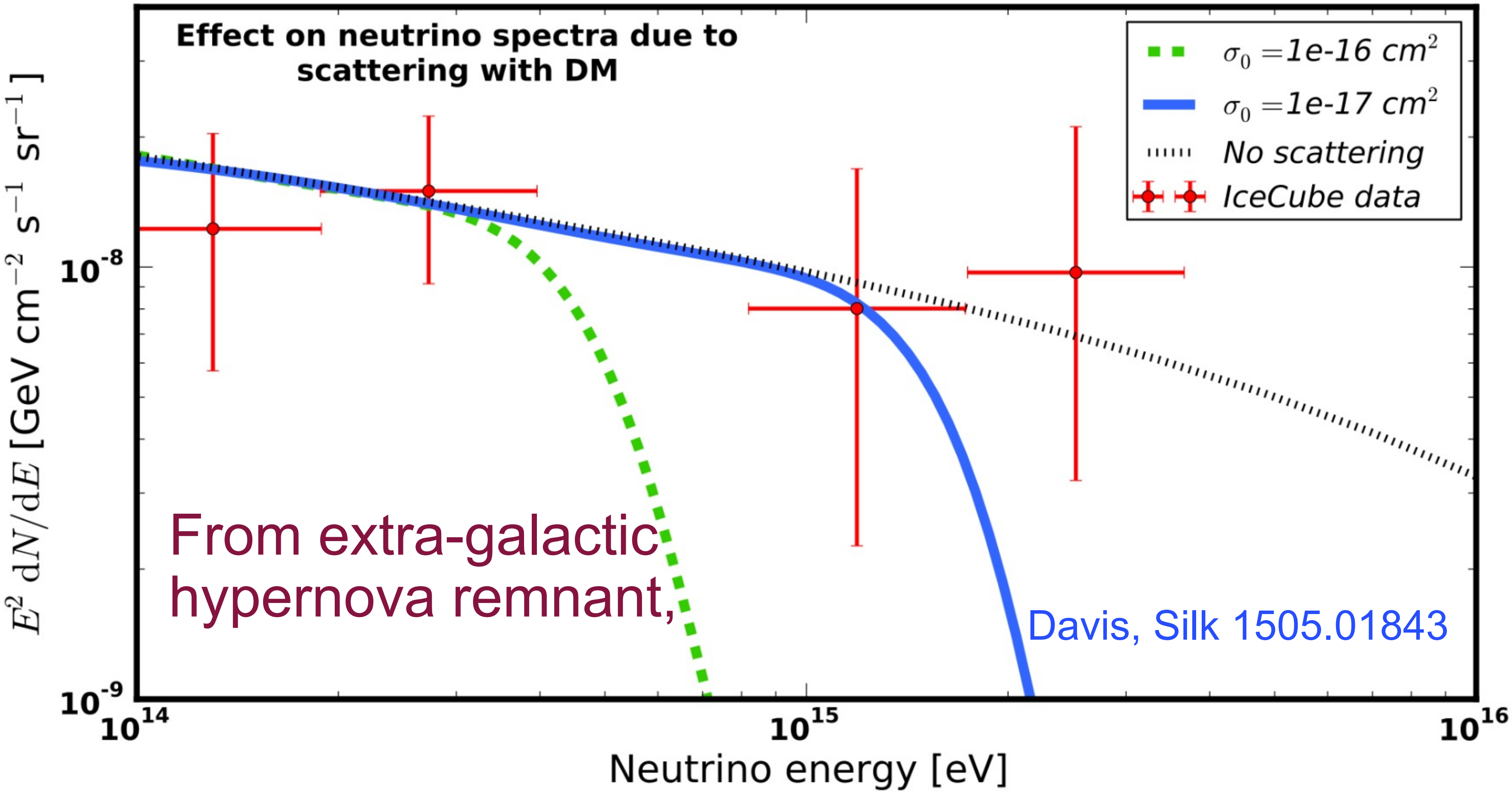
Possible tension with other known Astro-sources





Scattering with dark matter

- High energy neutrino originated from some astrophysical component like hypernova remnant, scatter with extra-galactic and galactic dark matter



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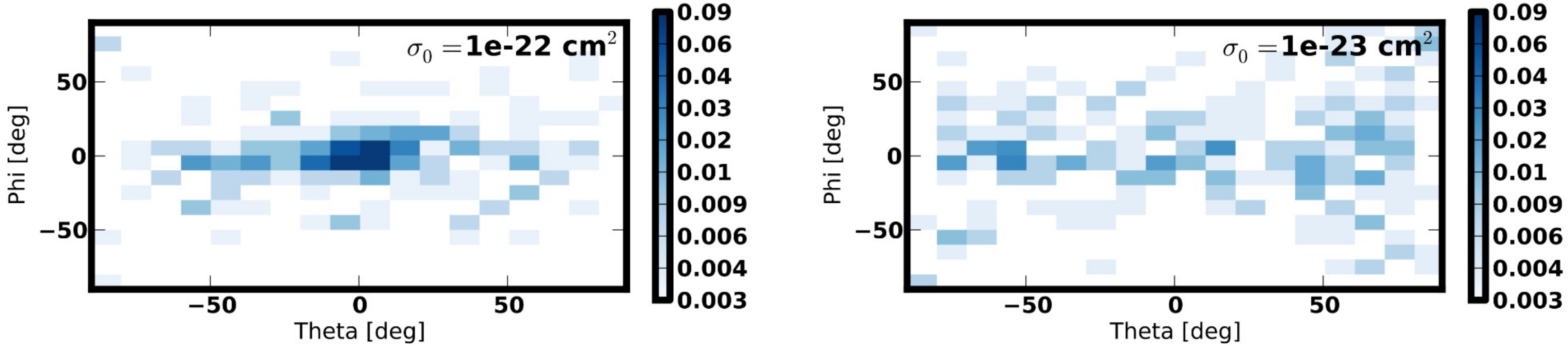
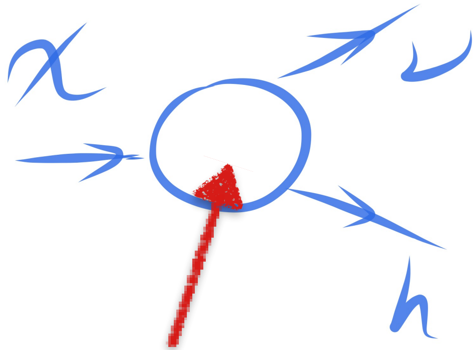


Distribution of 1PeV neutrino in the galactic center

Davis, Silk 1505.01843

Decay dark matter

2 body decay



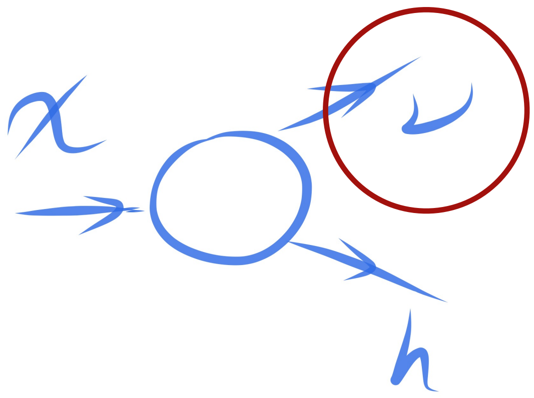
$$\lambda \sim \mathcal{O}(10^{-30})$$

The coupling must be unnaturally small (DM long lived)

- Assuming the DM to be a fermion singlet
- In the Standard Model there is only one 2-body decay coupling
- The DM is basically an heavy sterile neutrino

$$\chi \to h^0 \nu_i$$

2 body decay



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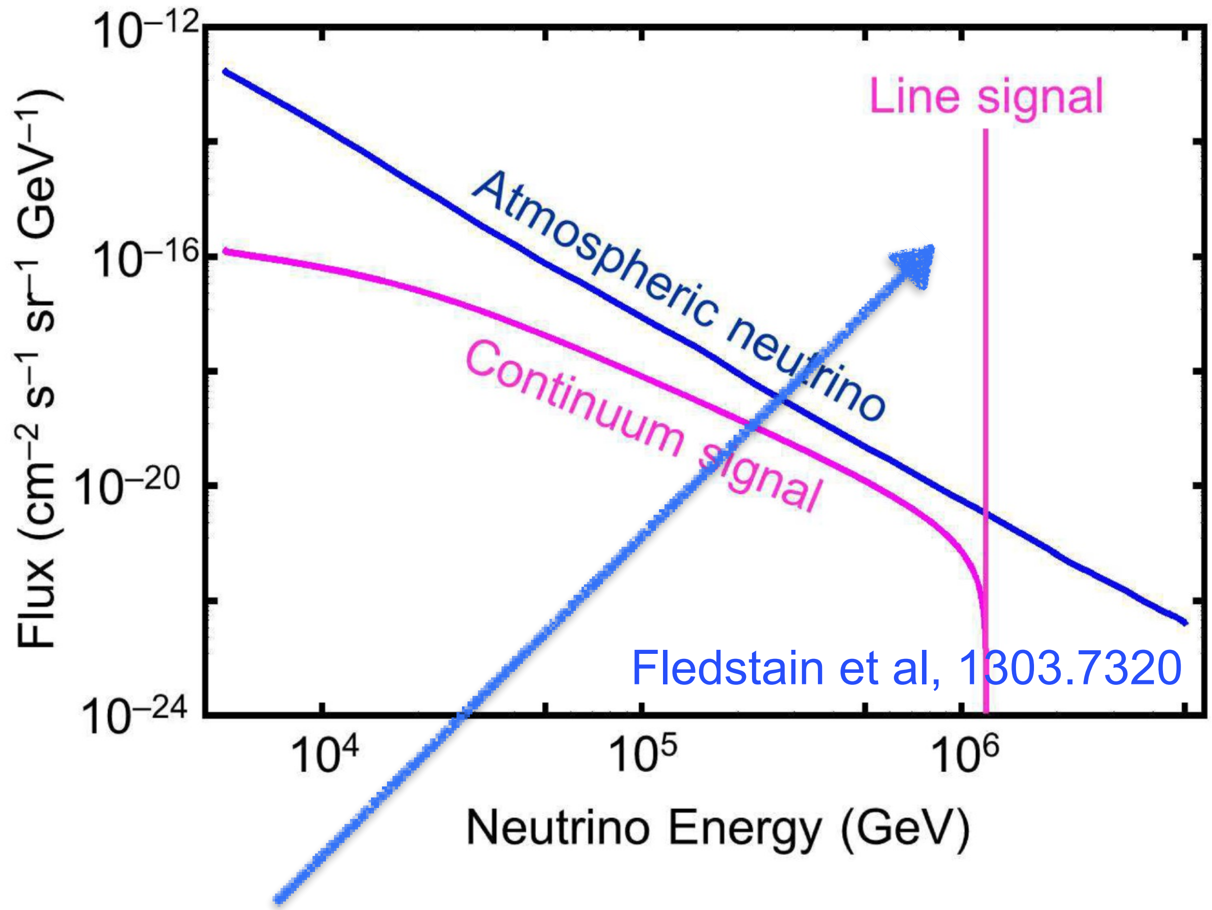
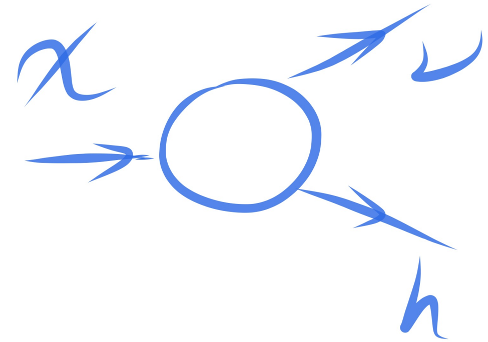
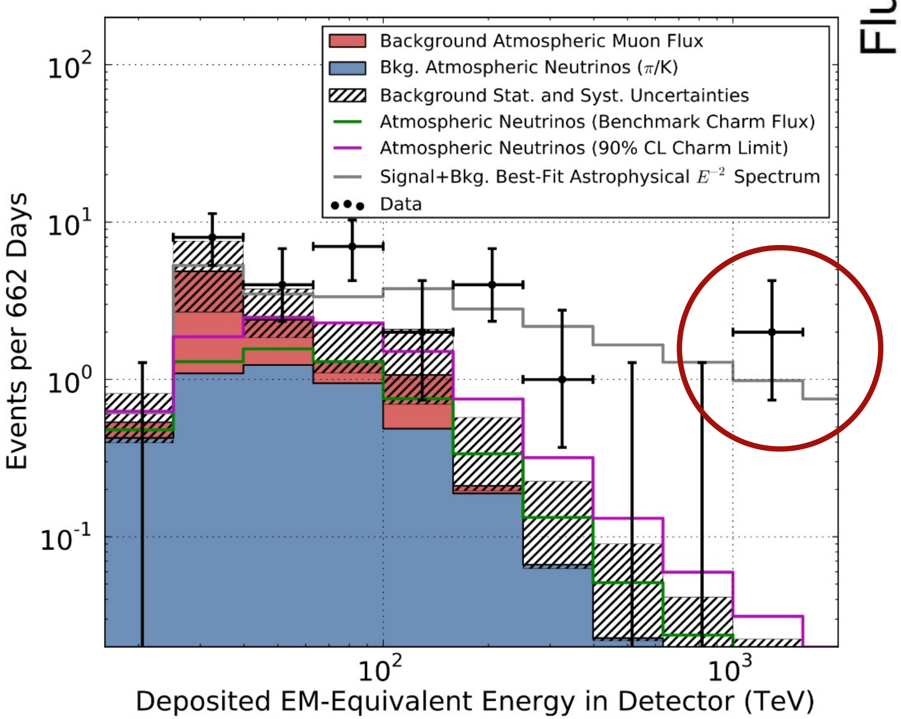


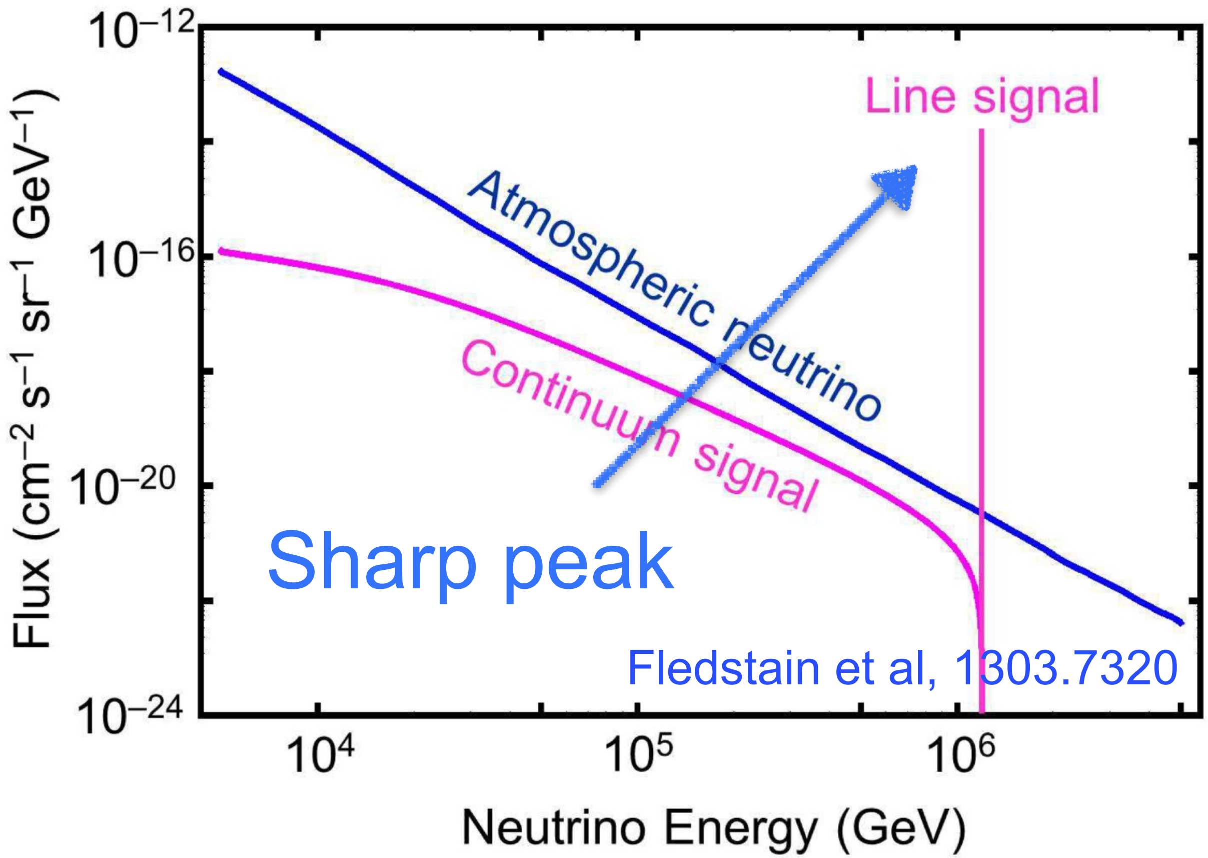
Sharp peak from the two body decay

2 body decay



$$\chi \to h^0 \nu_i$$

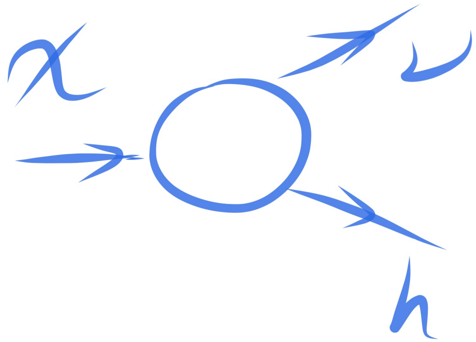




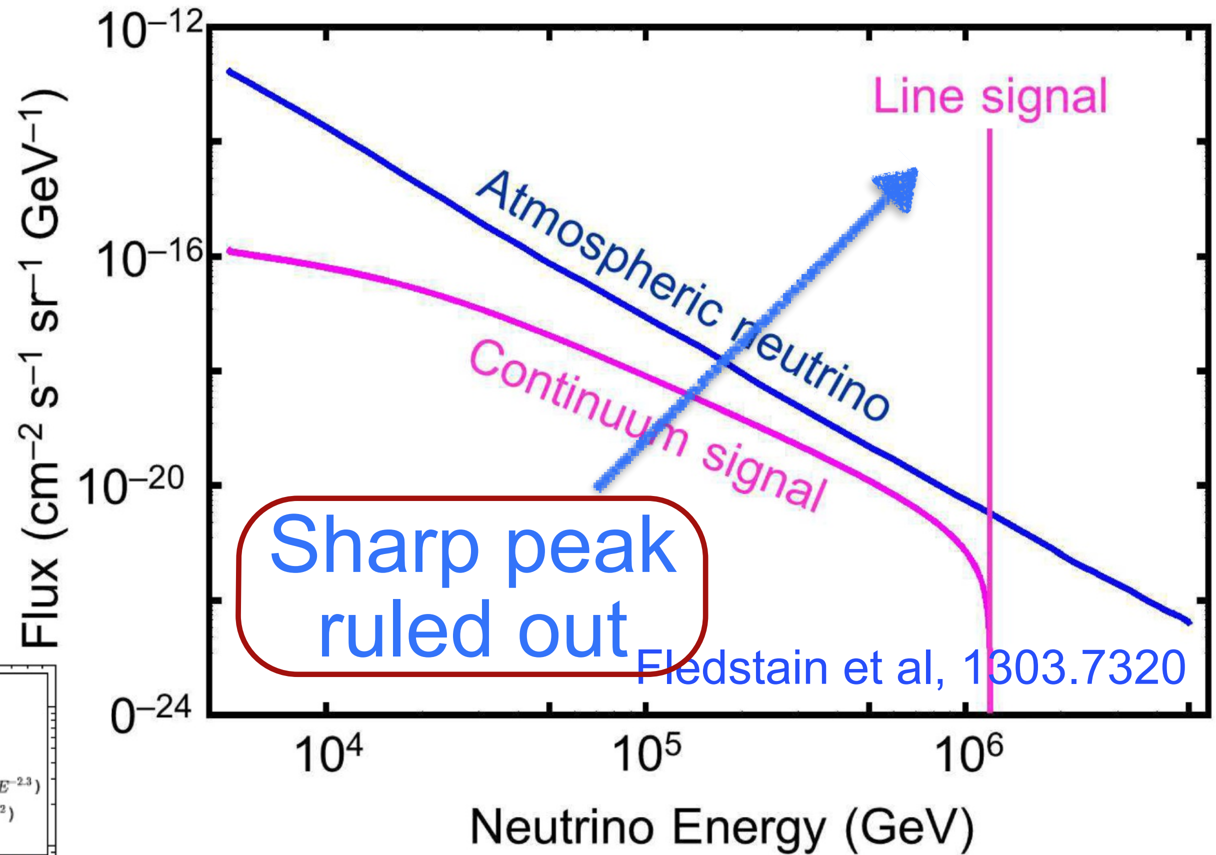
2yrs: 28 events in 662 days, Sience13

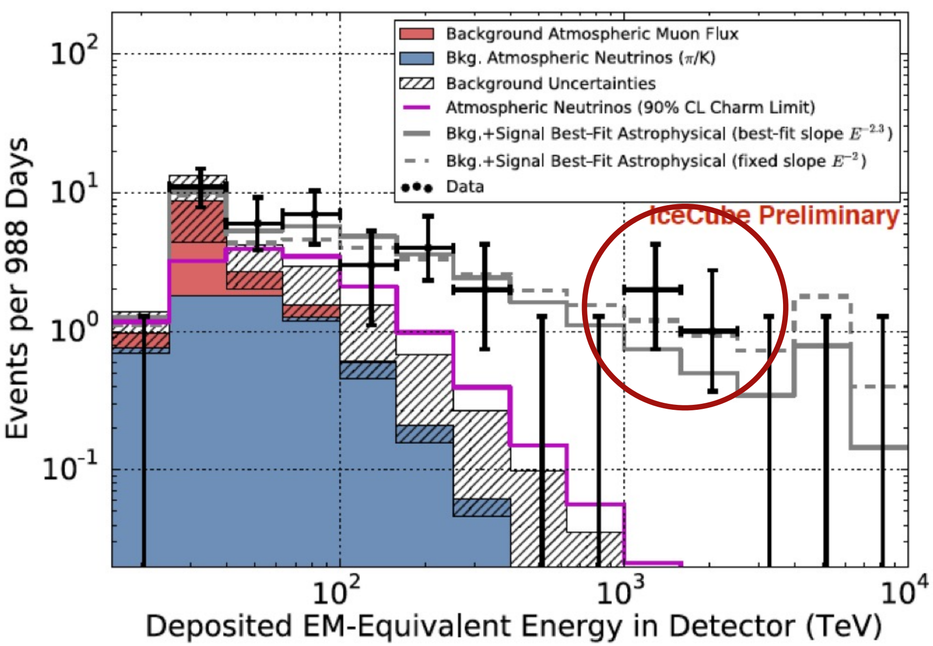
Only two events at 1 PeV, but....

2 body decay



$$\chi \to h^0 \nu_i$$

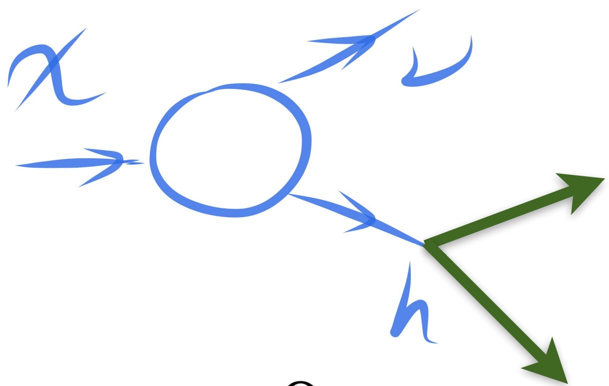




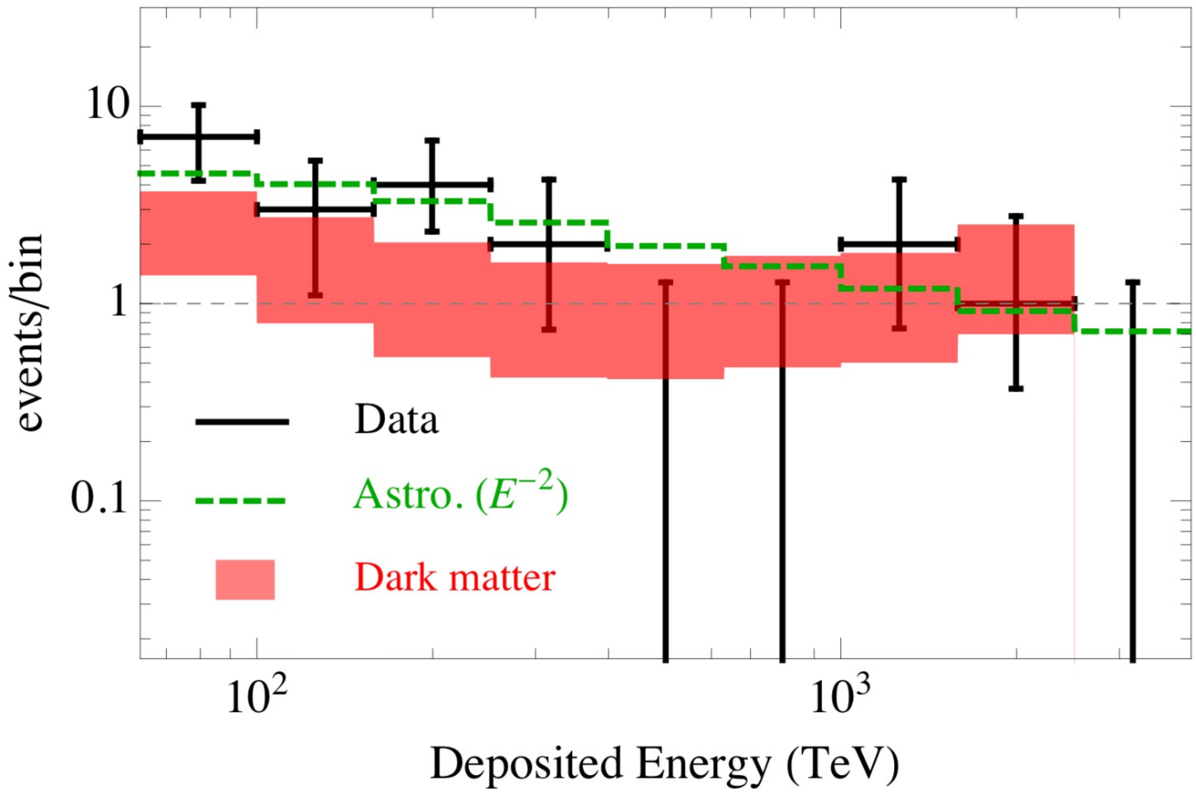
3yrs: 37 events in 988 days, PRL (14)

two events at 1 PeV, and one at 2 PeV

2 body decay



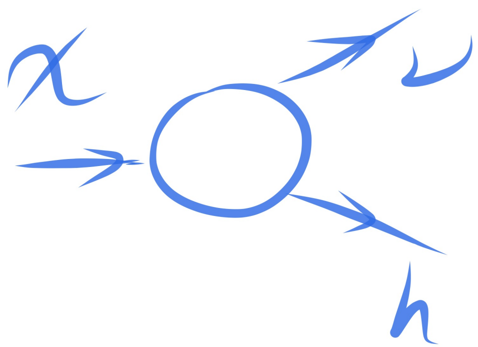
$$\chi \to h^0 \nu_i$$



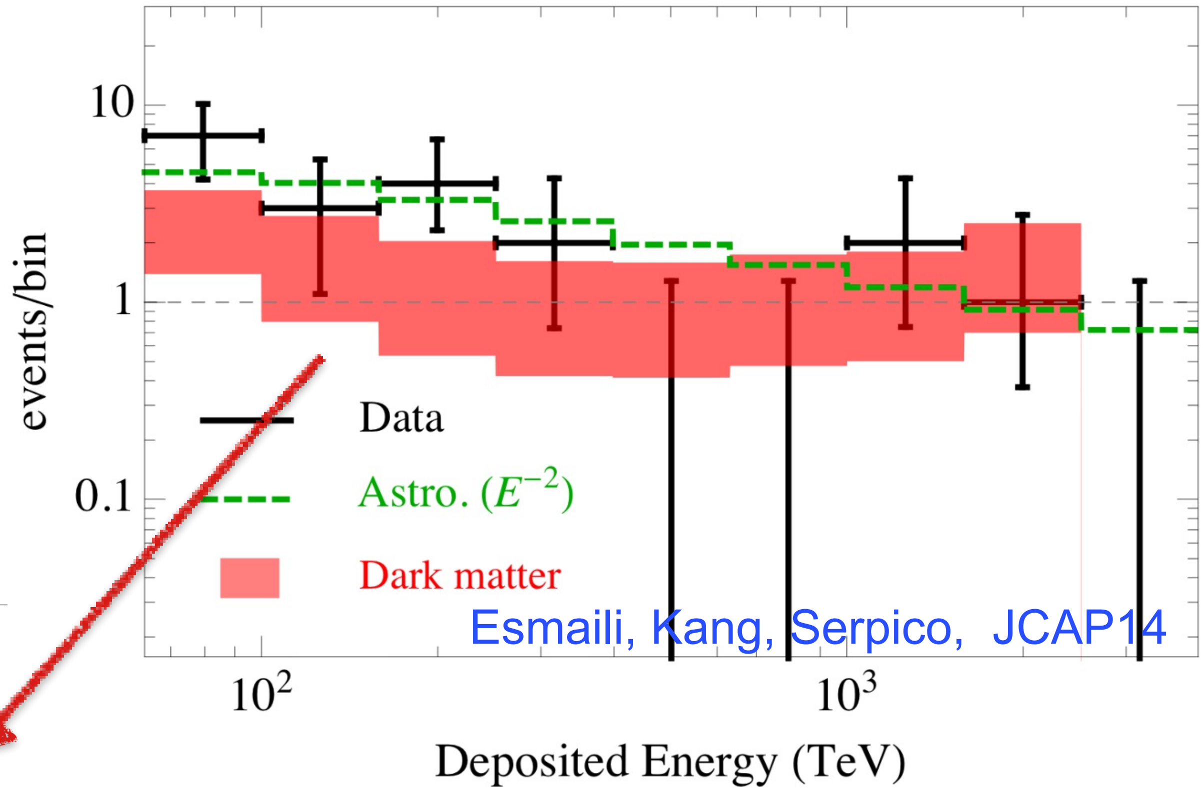
Esmaili, Kang, Serpico, JCAP14

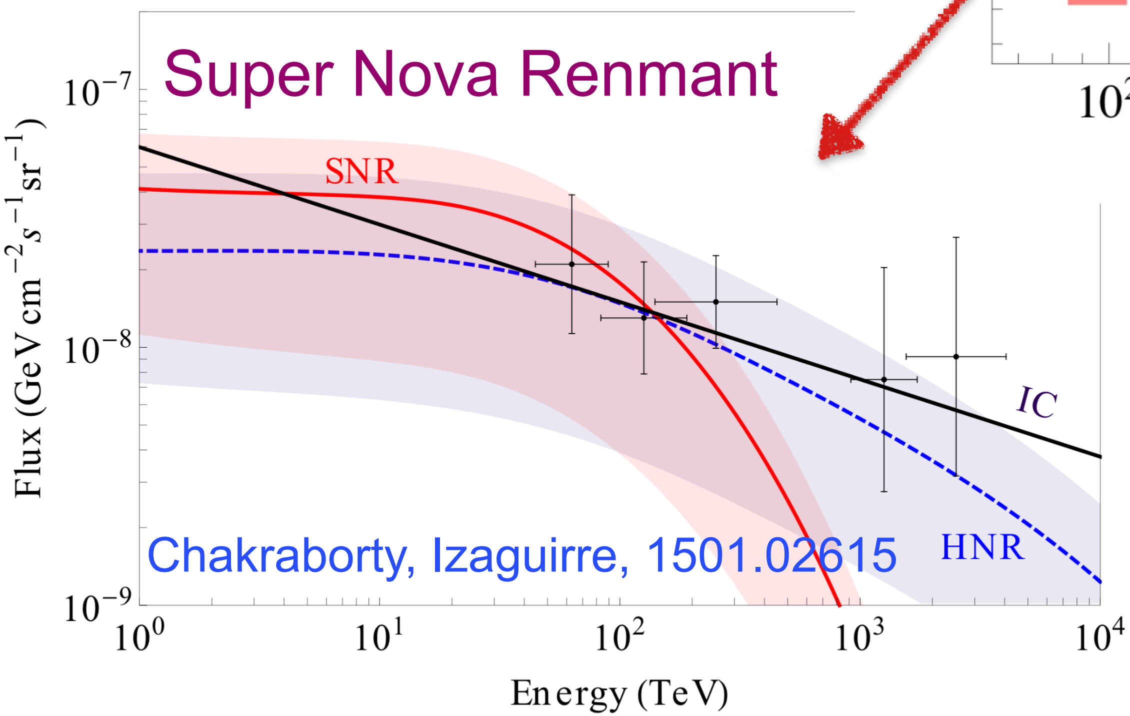
Secondary neutrinos allow to fit all data even with the 2 bodies decay, but...

2 body decay



$$\chi \rightarrow h^0 \nu_i$$

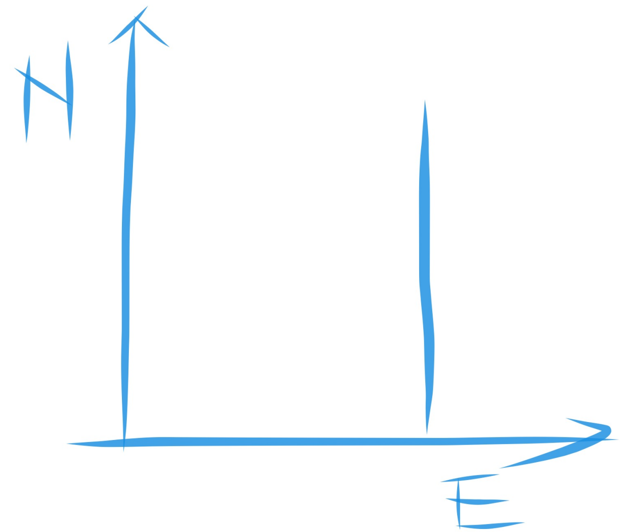


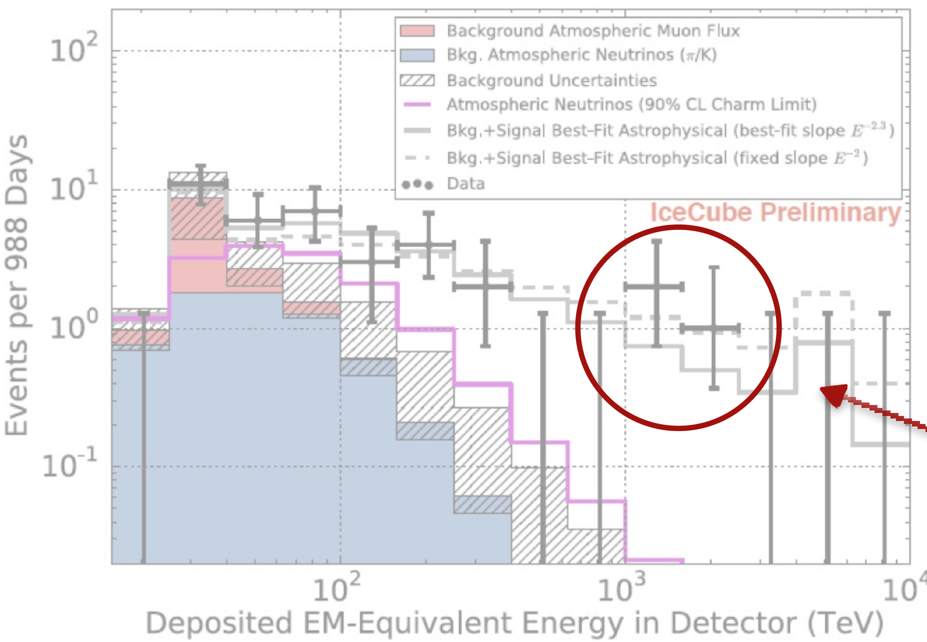


Could be in contrast with known astrophysical sources

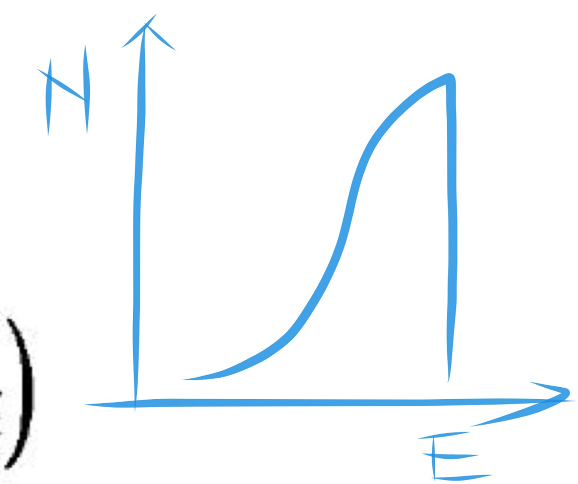
2 body vs 3 body decay

$$\frac{d\Gamma}{dE} \sim \delta(E - m_\chi/2)$$





seems better



$$\frac{d\Gamma}{dE} = \left(\frac{g_w}{M_W c}\right)^4 \frac{m_\mu^2 E^2}{2\hbar(4\pi)^3}\left(1 - \frac{4E}{3m_\mu c^2}\right)$$

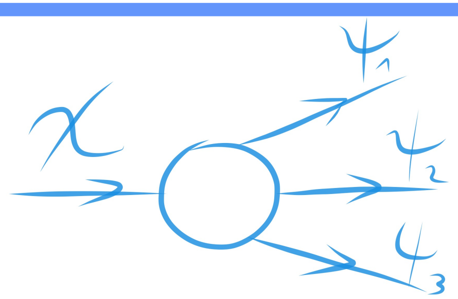
DM & 3 body decay: our assumption

We assume the dark matter to be a fermion isospin singlet

3 body decay: our requirements

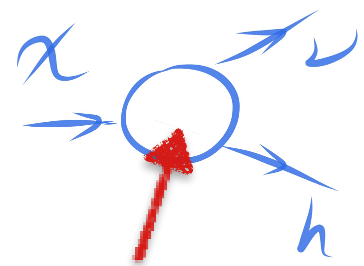
- Effective coupling suppressed by a large scale

3 body decay: our requirements



$$\frac{y}{\Lambda^2}\chi\overline{f_1}f_2\overline{f_3}$$

- Effective coupling suppressed by a large scale



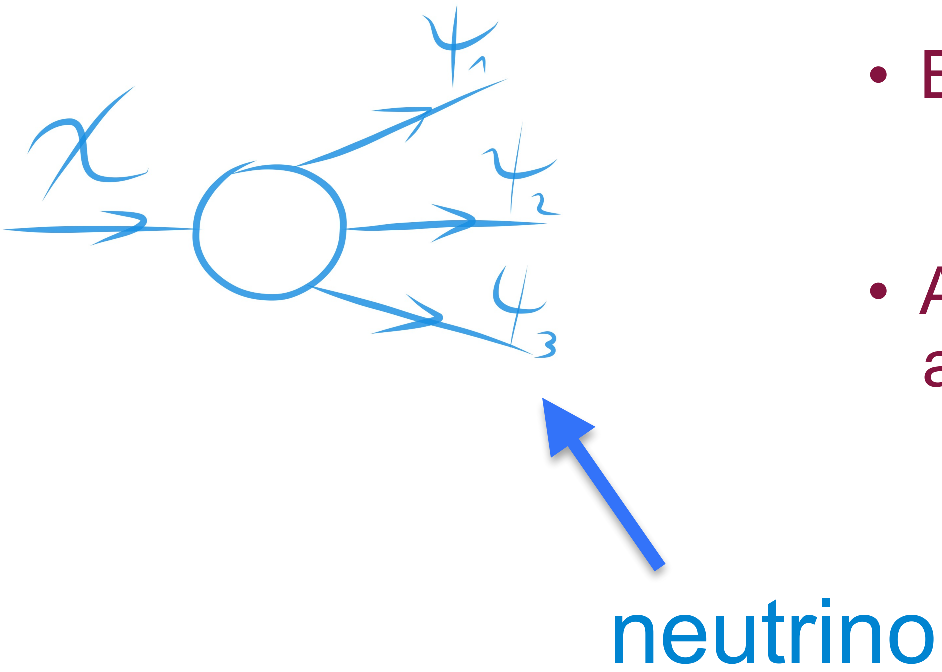
$$\lambda \sim \mathcal{O}(10^{-30})$$

In the 2body case
unnatural small coupling

$$G_F\overline{f_1}f_2\overline{f_3}f_4 \qquad G_F \sim \frac{1}{M_W^2}$$

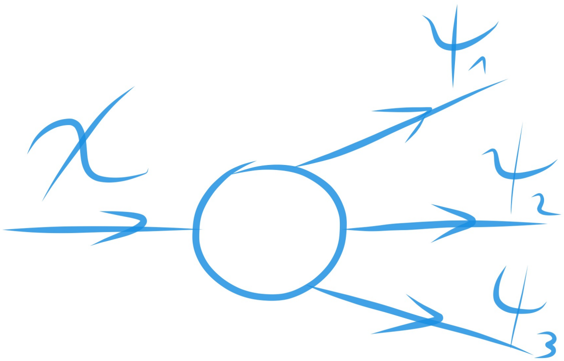
Like in the Fermi 4-points interaction

3 body decay: our requirements

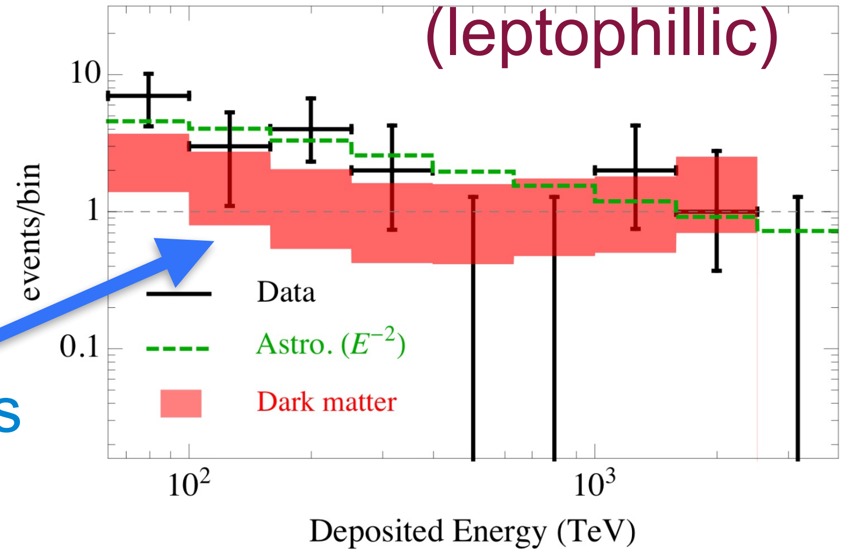


- Effective coupling suppressed by a large scale
- At least one coupling with neutrino allowing for primary neutrino flux

3 body decay: our requirements



- Effective coupling suppressed by a large scale
- At least one coupling one neutrino allowing for primary neutrino flux
- No couplings with quarks otherwise too many secondary neutrinos (leptophillic)



Eventually problems with SNR

DM couplings with the standard model

$$\chi \to h^0 \nu_i$$

$$\chi \to \overline{u}\, d\, \overline{\ell}$$

$$\chi \to \overline{u}\, u\, \overline{\nu}_k$$

$$\chi \to \overline{d}\, d\, \overline{\nu}_k$$

$$\chi \to \overline{\ell_i}\, \ell_j \overline{\nu}_k$$

....

DM couplings with the standard model

$\chi \to h^0 \nu_i$

- two body decay

$\chi \to \overline{u}\, d\, \overline{\ell}$

$\chi \to \overline{u}\, u\, \overline{\nu}_k$

$\chi \to \overline{d}\, d\, \overline{\nu}_k$

$\chi \to \overline{\ell_i}\, \ell_j \overline{\nu}_k$

....

- three body decay

DM couplings with the standard model

$$\chi \to h^0 \nu_i$$

- two body decay

$$\chi \to \overline{u}\, d\, \overline{\ell}$$

- no primary neutrino

$$\chi \to \overline{u}\, u\, \overline{\nu}_k$$

$$\chi \to \overline{d}\, d\, \overline{\nu}_k$$

- three body decay

$$\chi \to \overline{\ell_i}\, \ell_j \overline{\nu}_k$$

....

DM couplings with the standard model

$\chi \to h^0 \nu_i$

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$\chi \to \overline{d}\, d\, \overline{\nu}_k$

- quarks giving too many secondary neutrino

$\chi \to \overline{\ell_i}\, \ell_j \overline{\nu}_k$

- three body decay

....

DM couplings with the standard model

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$$\chi \to \overline{d}\, d\, \overline{\nu}_k$$

- quarks giving too many secondary neutrino

$$\chi \to \overline{\ell_i}\, \ell_j \overline{\nu}_k$$

- Leptophillic coupling

DM couplings with the standard model

Dimensions	DM decay operators
4	$\bar{L}H^cX$
5	$-$
6	$\bar{L}E\bar{L}X$, $H^\dagger H\bar{L}H^cX$, $(H^c)^t D_\mu H^c\bar{E}\gamma^\mu X$, $QDLX$, $\bar{U}Q\bar{L}X$, $\bar{L}D\bar{Q}X$, $\bar{U}\gamma_\mu D\bar{E}\gamma^\mu X$, $D^\mu H^c D_\mu \bar{L}X$, $D^\mu D_\mu H^c\bar{L}X$, $B_{\mu\nu}\bar{L}\sigma^{\mu\nu}H^cX$, $W^a_{\mu\nu}\bar{L}\sigma^{\mu\nu}\tau^a H^cX$

Haba et al., 1008.4777

- This interaction can be selected by means of for example flavor symmetries

Abelian

	L_e, ℓ_e	L_μ, ℓ_μ	L_τ, ℓ_τ	ϕ	χ
$U(1)_f$	4	2	1	0	3

Non-Abelian

	L	ℓ	ϕ	χ
A_4	**3**	**3**	**1**	**1**

Leptophillic 3-body decay

$$\chi \to \overline{\ell_i}\,\ell_j \overline{\nu}_k \quad i, j, k = e, \mu, \tau$$

Leptophillic 3-body decay

$$\chi \to \overline{\ell_i}\, \ell_j \overline{\nu}_k \quad i, j, k = e, \mu, \tau$$

1. $\chi \to \overline{e}\, e \overline{\nu}_e$ → No secondary neutrinos

2. $\chi \to \overline{\tau}\, \tau \overline{\nu}_\tau$ → Max number of secondary neutrinos

Leptophillic 3-body decay

$$\chi \to \overline{\ell_i}\,\ell_j\overline{\nu}_k \quad i,j,k = e,\mu,\tau$$

1 $\chi \to \overline{e}\,e\overline{\nu}_e$ → No secondary neutrinos

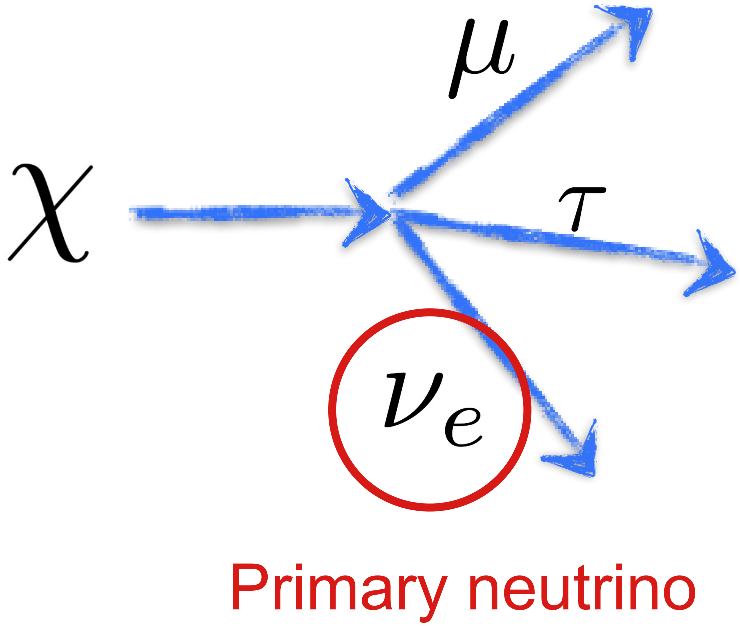
2 $\chi \to \overline{\tau}\,\tau\overline{\nu}_\tau$ → Max number of secondary neutrinos

3 $\chi \to \overline{e}\,\mu\overline{\nu}_\tau + \text{cyclic permutations}$ → Non-Abelian A4

4 $\chi \to \overline{\mu}\,e\overline{\nu}_\tau + \overline{\tau}\,e\overline{\nu}_\mu + \overline{e}\,\mu\overline{\nu}_e$ → Abelian

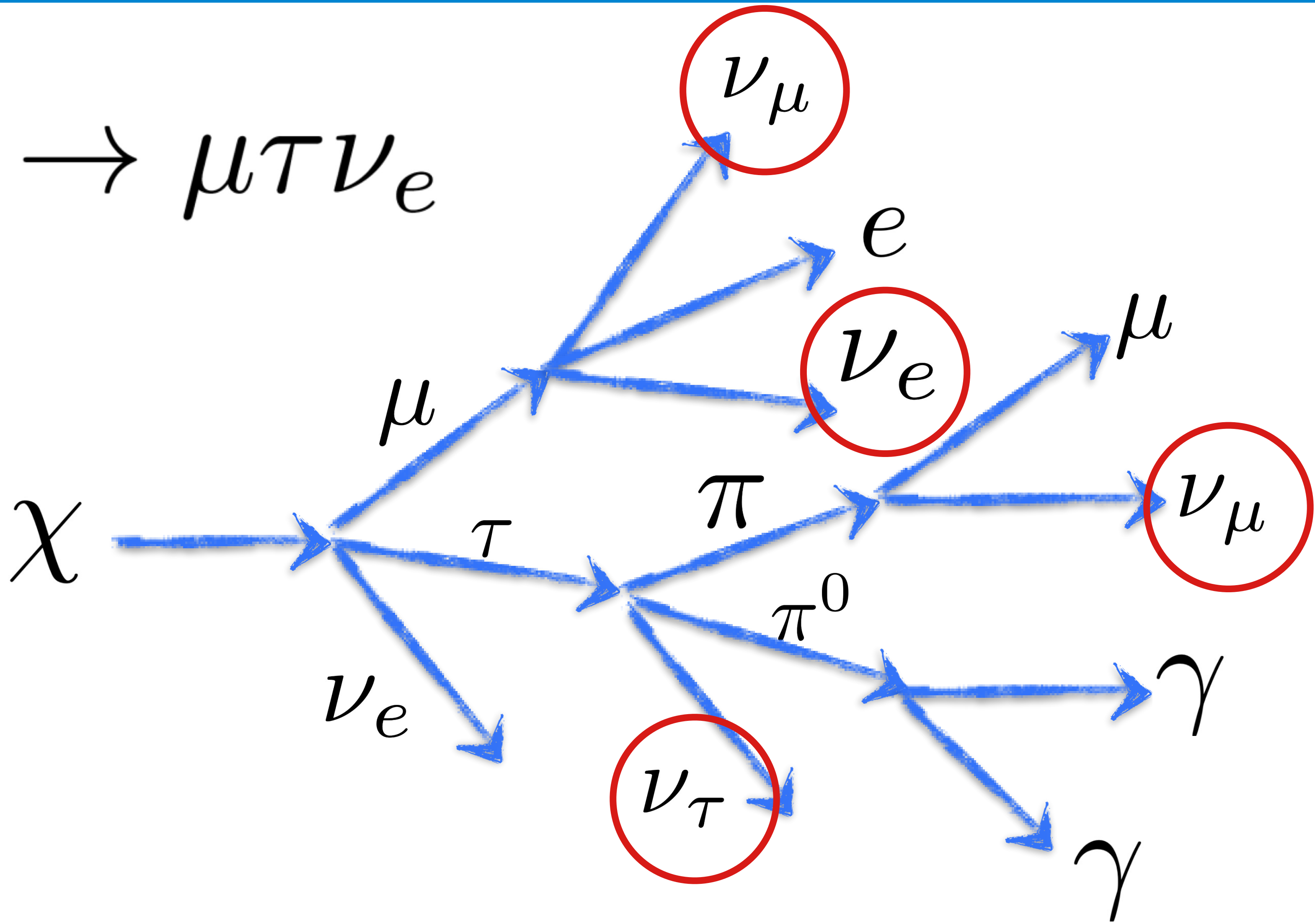
decay example

$$\chi \to \mu \tau \nu_e$$



decay example

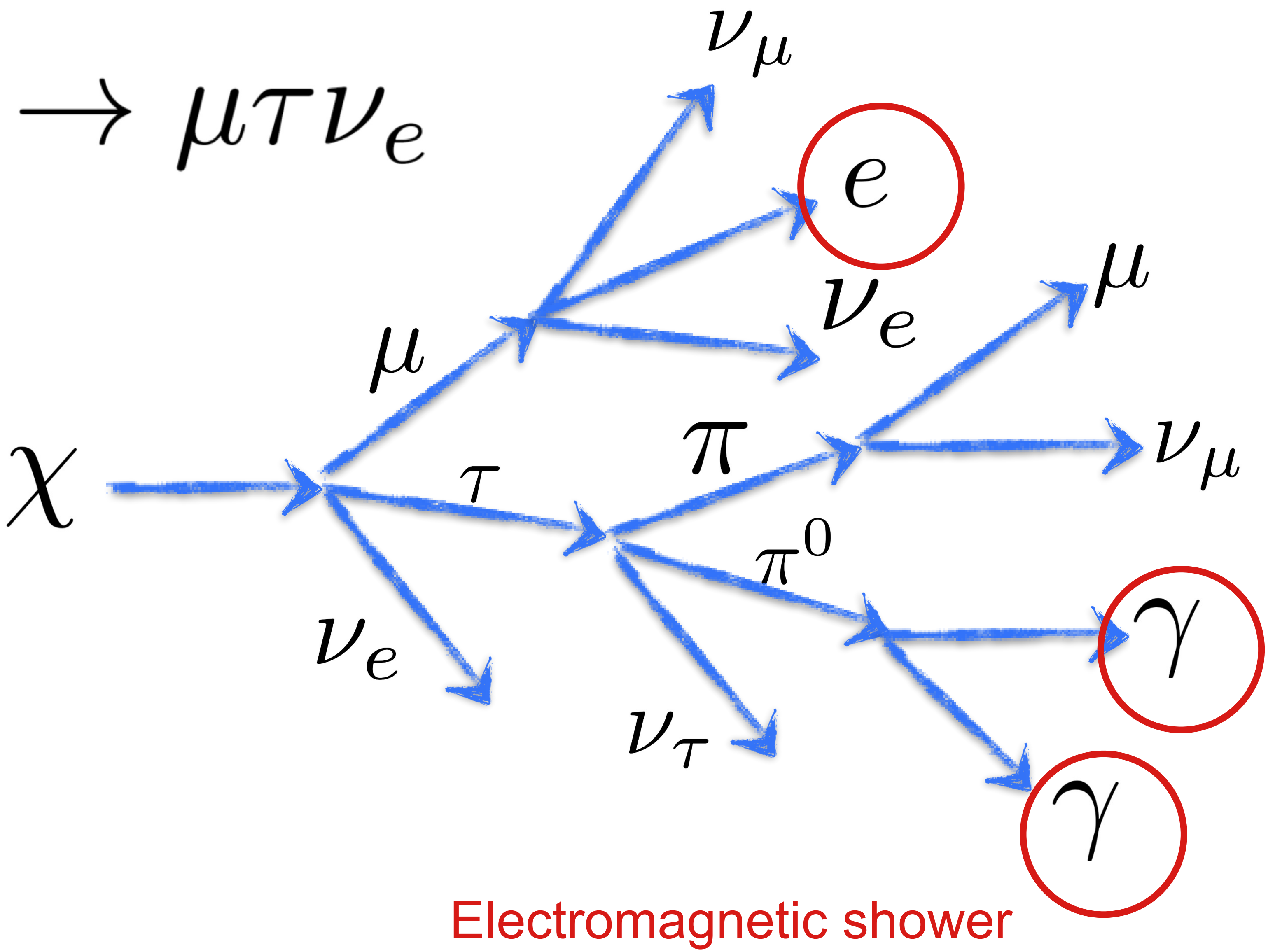
$$\chi \to \mu \tau \nu_e$$



Secondary neutrino

decay example

$$\chi \to \mu\tau\nu_e$$



gamma-ray bounds

- The gamma-ray flux is constrained by the *Fermi* data.

$$\omega_\gamma = \frac{4\pi}{c}\int_{E_1}^{E_2} E_\gamma \frac{\mathrm{d}\varphi_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma \lesssim 4.4\times10^{-7}\,\mathrm{eV/cm}^3$$

- The total electromagnetic energy produced by decaying DM is

$$\frac{4\pi}{c}\int\left[\underbrace{E_\gamma\frac{d\phi_\gamma}{dE_\gamma}}_{\gamma \text{ from } \pi^0} + \underbrace{E_e\frac{d\phi_e}{dE_e}}_{e^+ \text{ and } e^-} + \underbrace{E_\mu\frac{d\phi_\mu}{dE_\mu}}_{\text{right-handed } \mu}\right] \simeq 6.3\times10^{-8}\,\mathrm{eV/cm}^3$$

γ from π^0

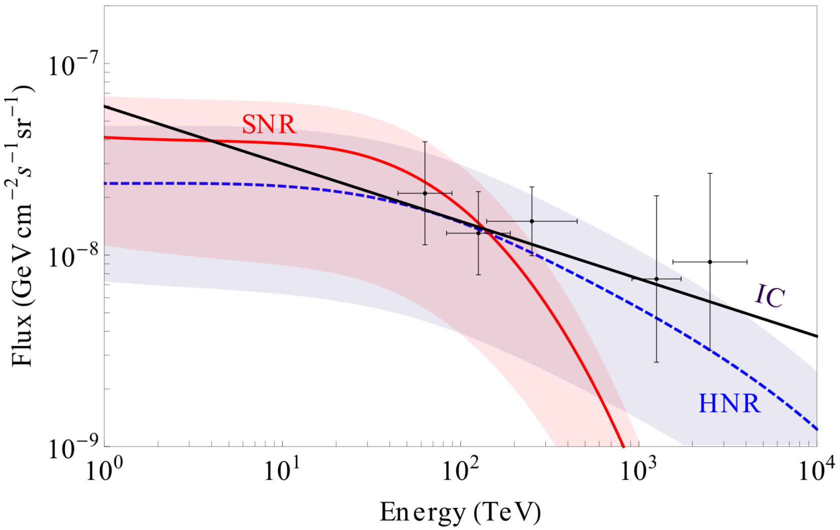
right-handed μ

e^+ and e^-

Analysis

$$\phi_{\rm TOT} = \phi_{\rm astro} + \phi_\chi$$

some astro component
like SNR



$$\phi_\chi = J^G + J^{EG}$$

Dark matter Decay:
Galactic
Extra-Galactic

Decay dark matter Component

Galactic vs Extra-Galactic

Galactic

$$\frac{\mathrm{d}J_\chi^{\mathrm{G}}}{\mathrm{d}E_\nu}(l,b) = \frac{1}{4\pi\, M_\chi\, \tau_\chi}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_0^\infty \mathrm{d}s\ \rho_\chi[r(s,l,b)]$$

$$\rho_\chi(r) \simeq \frac{\rho_\chi}{r/r_c(1+r/r_c)^2}$$

Navarro-Frenk-White

Galactic vs Extra-Galactic

Galactic

$$\frac{\mathrm{d}J_\chi^{\mathrm{G}}}{\mathrm{d}E_\nu}(l,b) = \frac{1}{4\pi\, M_\chi\, \tau_\chi}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_0^\infty \mathrm{d}s\ \rho_\chi[r(s,l,b)]$$

$$\rho_\chi(r) \simeq \frac{\rho_\chi}{r/r_c(1+r/r_c)^2}$$

Navarro-Frenk-White

Extra-Galactic

$$\frac{\mathrm{d}J_\chi^{\mathrm{EG}}}{\mathrm{d}E_\nu} = \frac{\Omega_\chi \rho_{\mathrm{c}}}{4\pi M_\chi \tau_\chi}\int_0^\infty \mathrm{d}z\, \frac{1}{H(z)}\, \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\,[(1+z)E_\nu]$$

Galactic vs Extra-Galactic

Galactic

Esmaili, Kang, Serpico, JCAP14

$$\frac{dJ_\chi^{G}}{dE_\nu}(l,b) = \frac{1}{4\pi\, M_\chi\, \tau_\chi} \frac{dN_\nu}{dE_\nu} \int_0^\infty ds\, \rho_\chi[r(s,l,b)]$$

Numerical coefficient

$$1.7 \times 10^{-12} \left(\frac{1\,\mathrm{PeV}}{m_{\mathrm{DM}}}\right) \left(\frac{10^{27}\,\mathrm{s}}{\tau_{\mathrm{DM}}}\right) (\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr})^{-1}$$

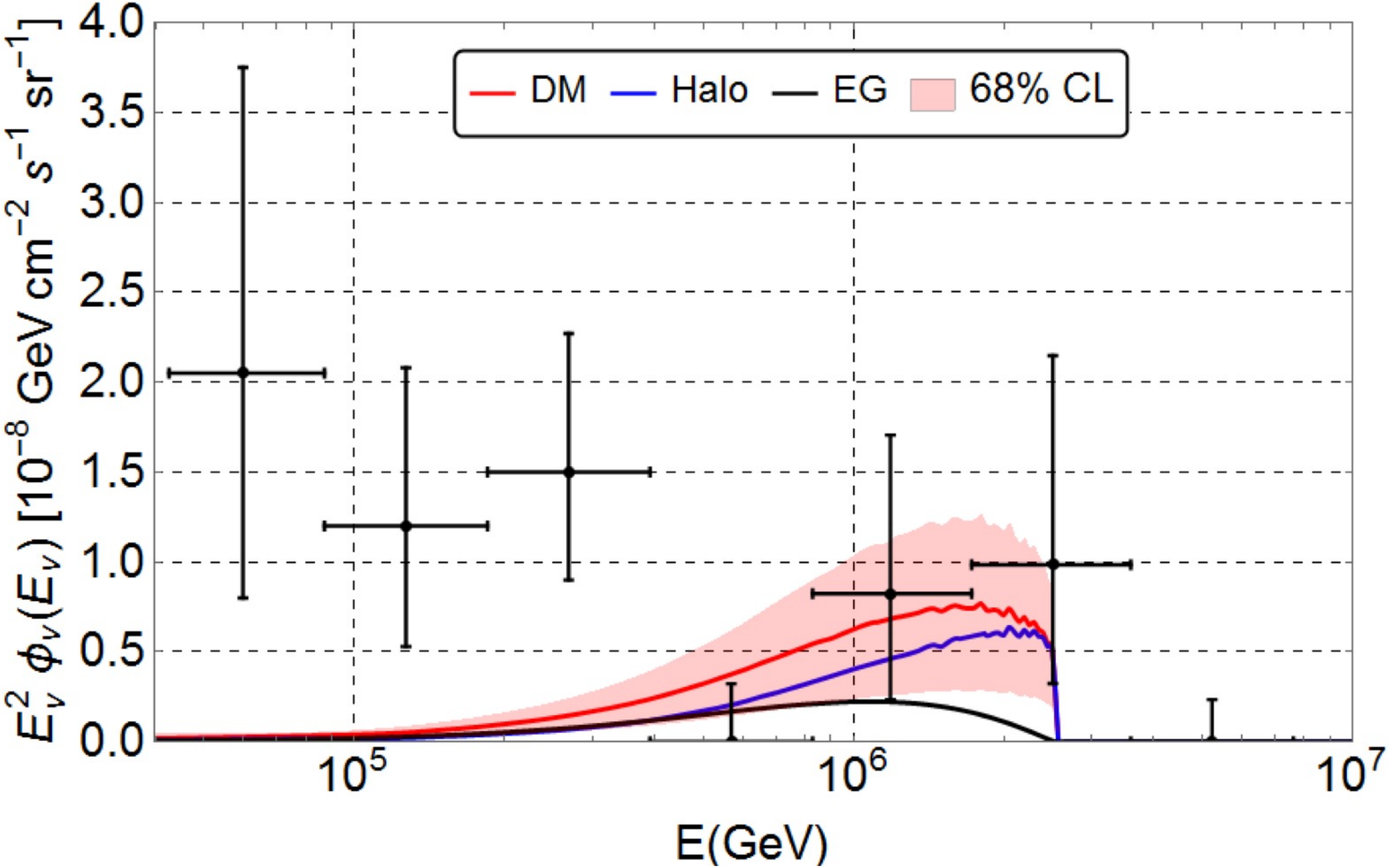
Extra-Galactic

$$\frac{dJ_\chi^{EG}}{dE_\nu} = \frac{\Omega_\chi \rho_c}{4\pi M_\chi \tau_\chi} \int_0^\infty dz\, \frac{1}{H(z)} \frac{dN_\nu}{dE_\nu}[(1+z)E_\nu]$$

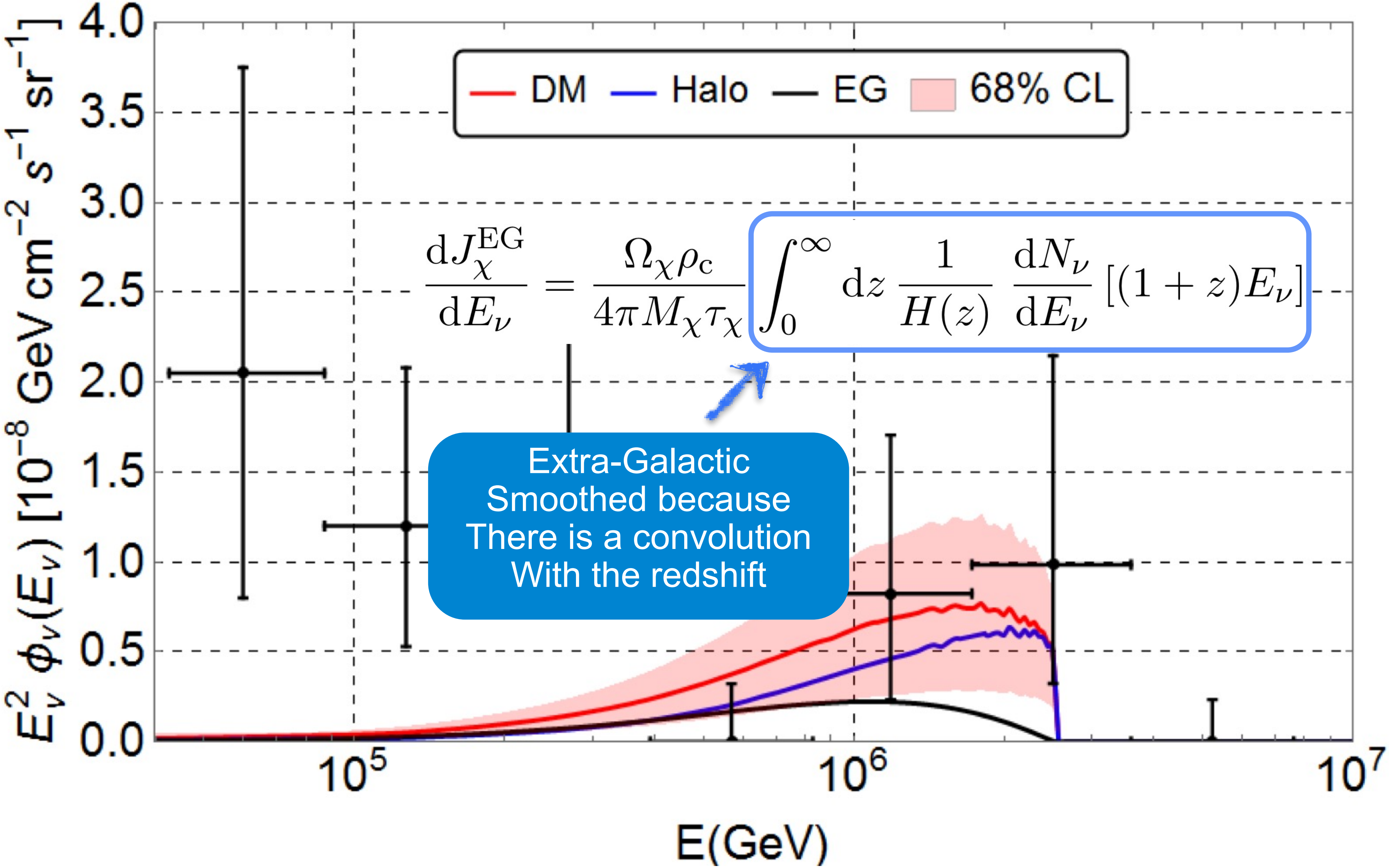
Numerical coefficient

$$1.4 \times 10^{-12} \left(\frac{1\,\mathrm{PeV}}{m_{\mathrm{DM}}}\right) \left(\frac{10^{27}\,\mathrm{s}}{\tau_{\mathrm{DM}}}\right) (\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr})^{-1}$$

Galactic vs Extra-Galactic



Galactic vs Extra-Galactic



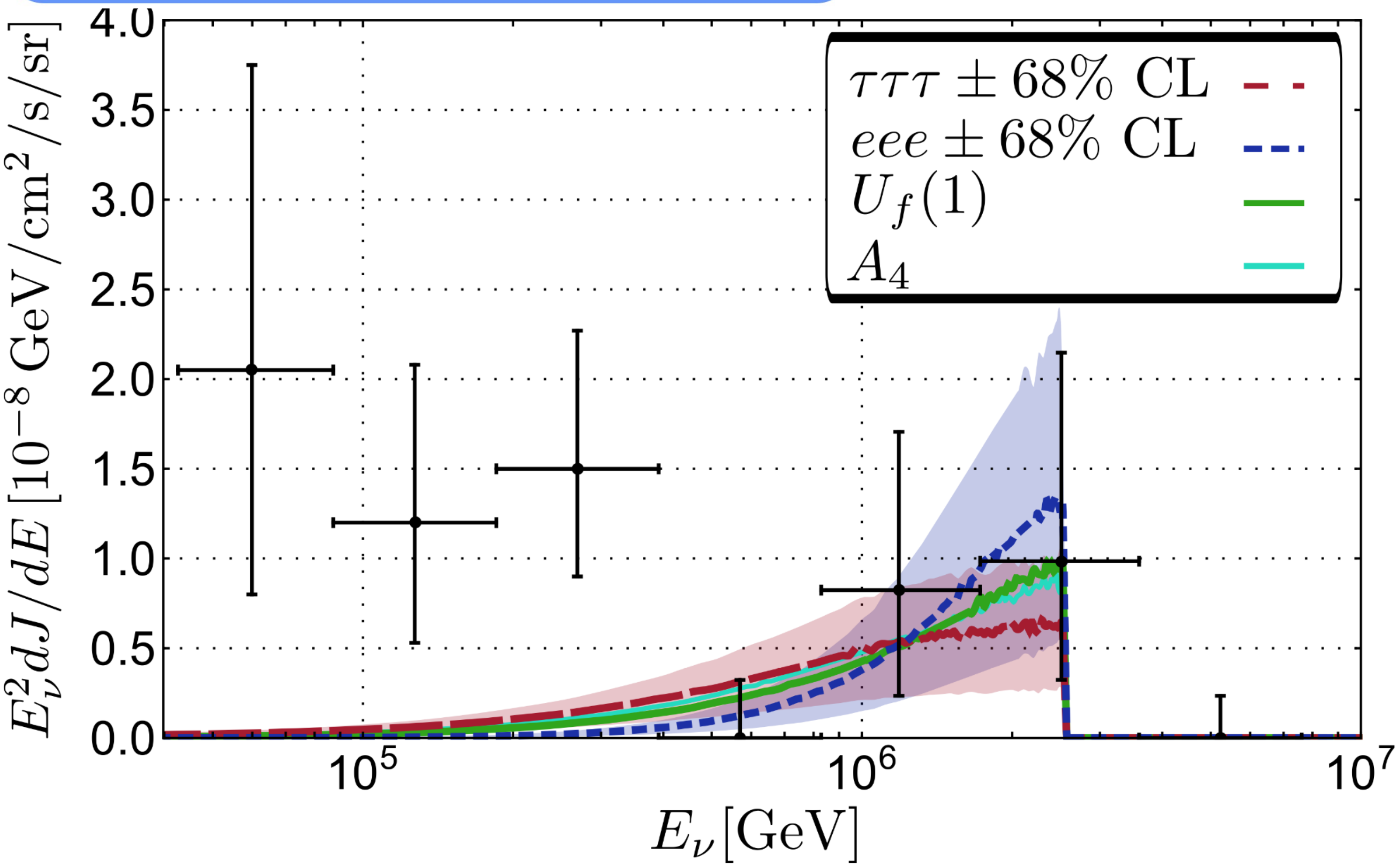
$$\frac{\mathrm{d}J_\chi^{\mathrm{EG}}}{\mathrm{d}E_\nu} = \frac{\Omega_\chi \rho_c}{4\pi M_\chi \tau_\chi} \int_0^\infty \mathrm{d}z\, \frac{1}{H(z)}\, \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\left[(1+z)E_\nu\right]$$

Extra-Galactic
Smoothed because
There is a convolution
With the redshift

Comparing benchmark models

1. $\chi \to \overline{e}\, e \overline{\nu}_e$
2. $\chi \to \overline{\tau}\, \tau \overline{\nu}_\tau$

3. $\chi \to \overline{e}\, \mu \overline{\nu}_\tau$ + cyclic permutations — Non-Abelian A4
4. $\chi \to \overline{\mu}\, e \overline{\nu}_\tau + \overline{\tau}\, e \overline{\nu}_\mu + \overline{e}\, \mu \overline{\nu}_e$ — Abelian



Astro component

Modeling astrophysical component

$$\phi_{\mathrm{TOT}} = \phi_{\mathrm{astro}} + \phi_{\chi}$$

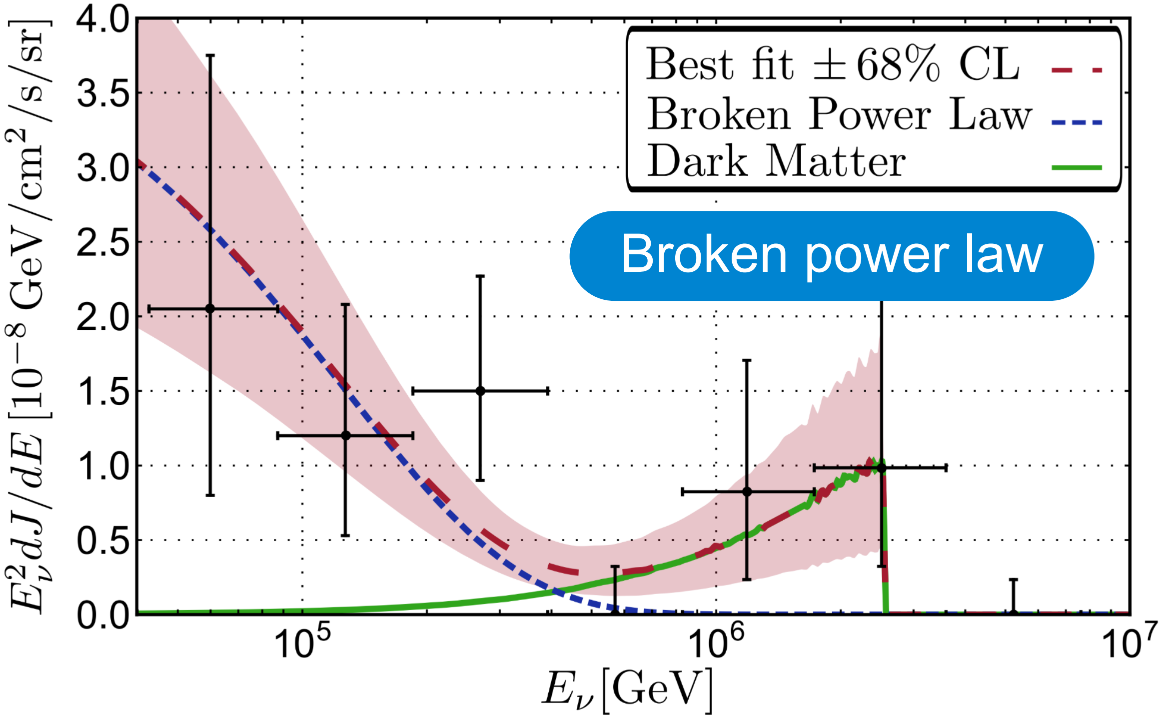
Power Law

$$\phi_{\mathrm{astro}} = \phi_0 \, E^{-\gamma}$$

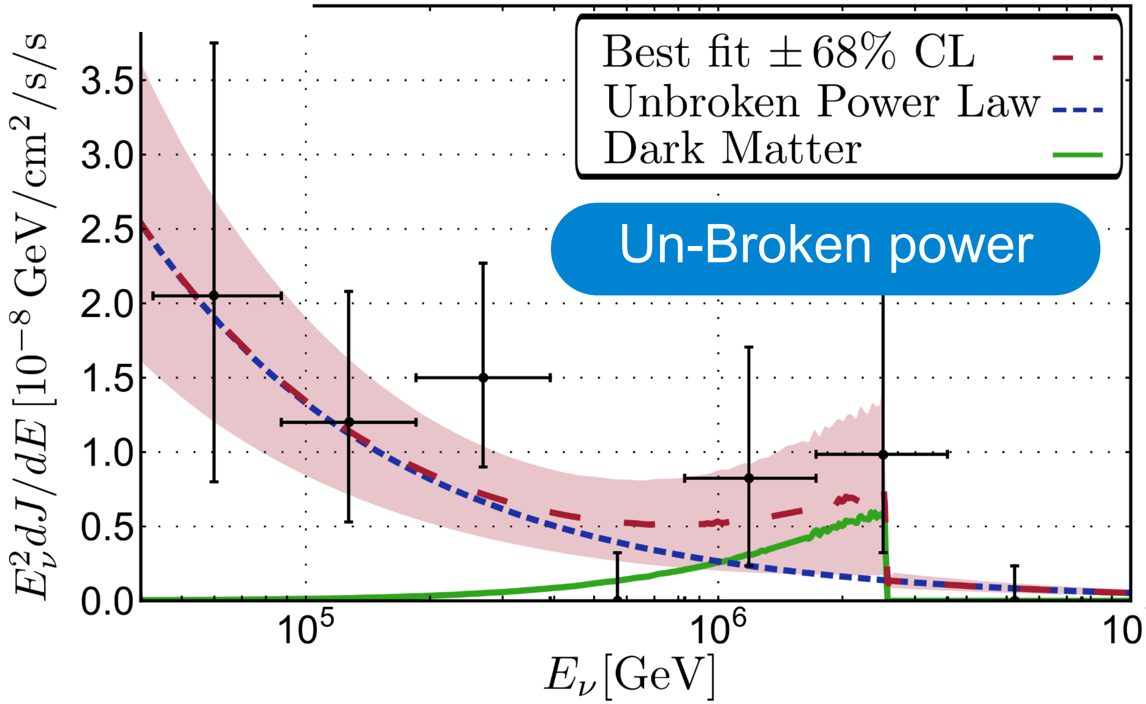
Broken Power Law

$$\phi_{\mathrm{astro}} = \phi_0 \, E^{-\gamma} \cdot e^{-E/E_0}$$

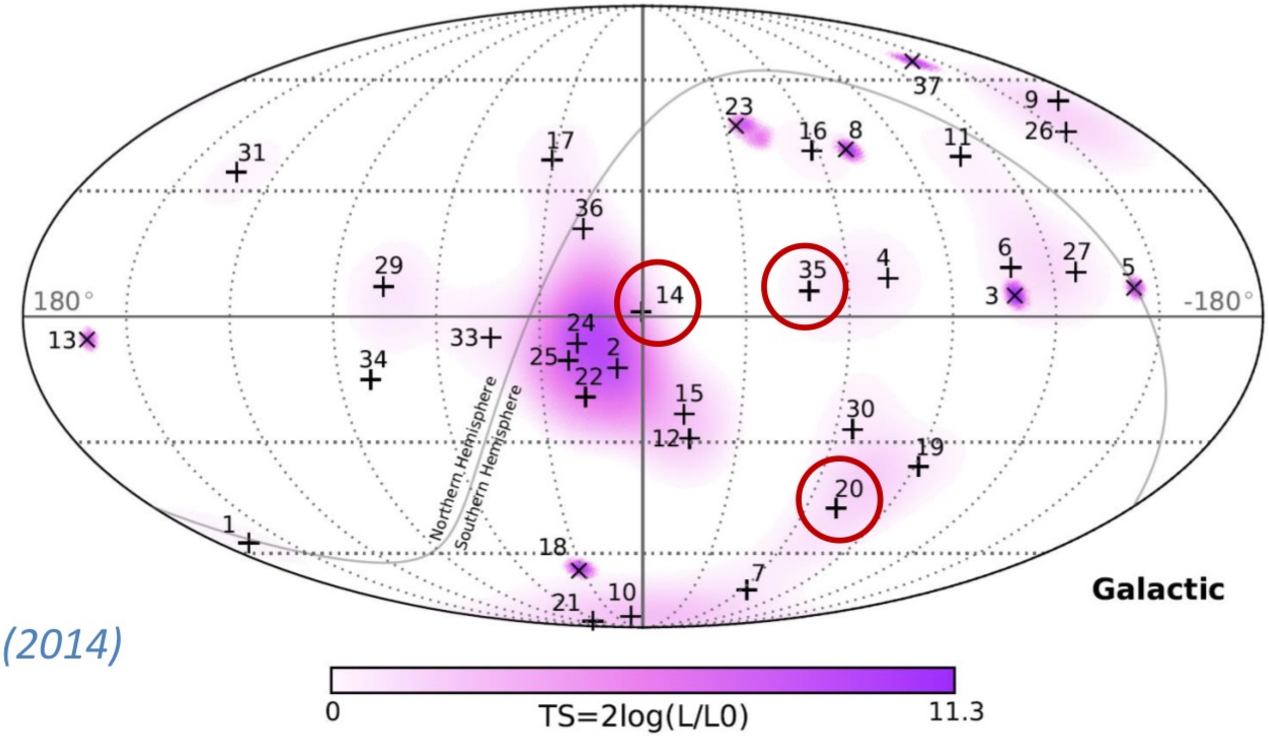
Combining decay dark matter and Astrophysical components



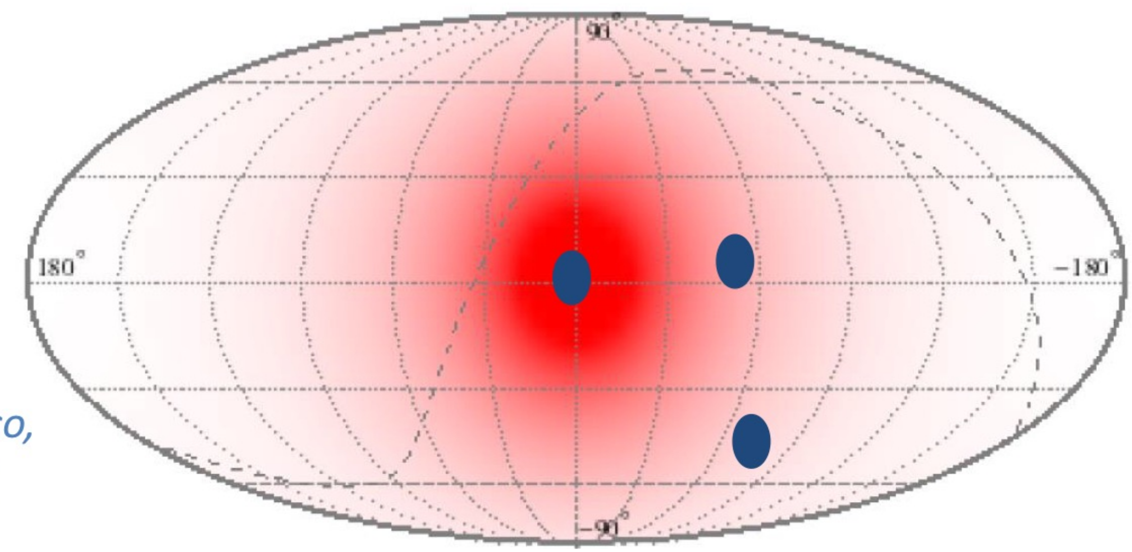
4 $\chi \to \overline{\mu}\, e\overline{\nu}_\tau + \overline{\tau}\, e\overline{\nu}_\mu + \overline{e}\, \mu\overline{\nu}_e$



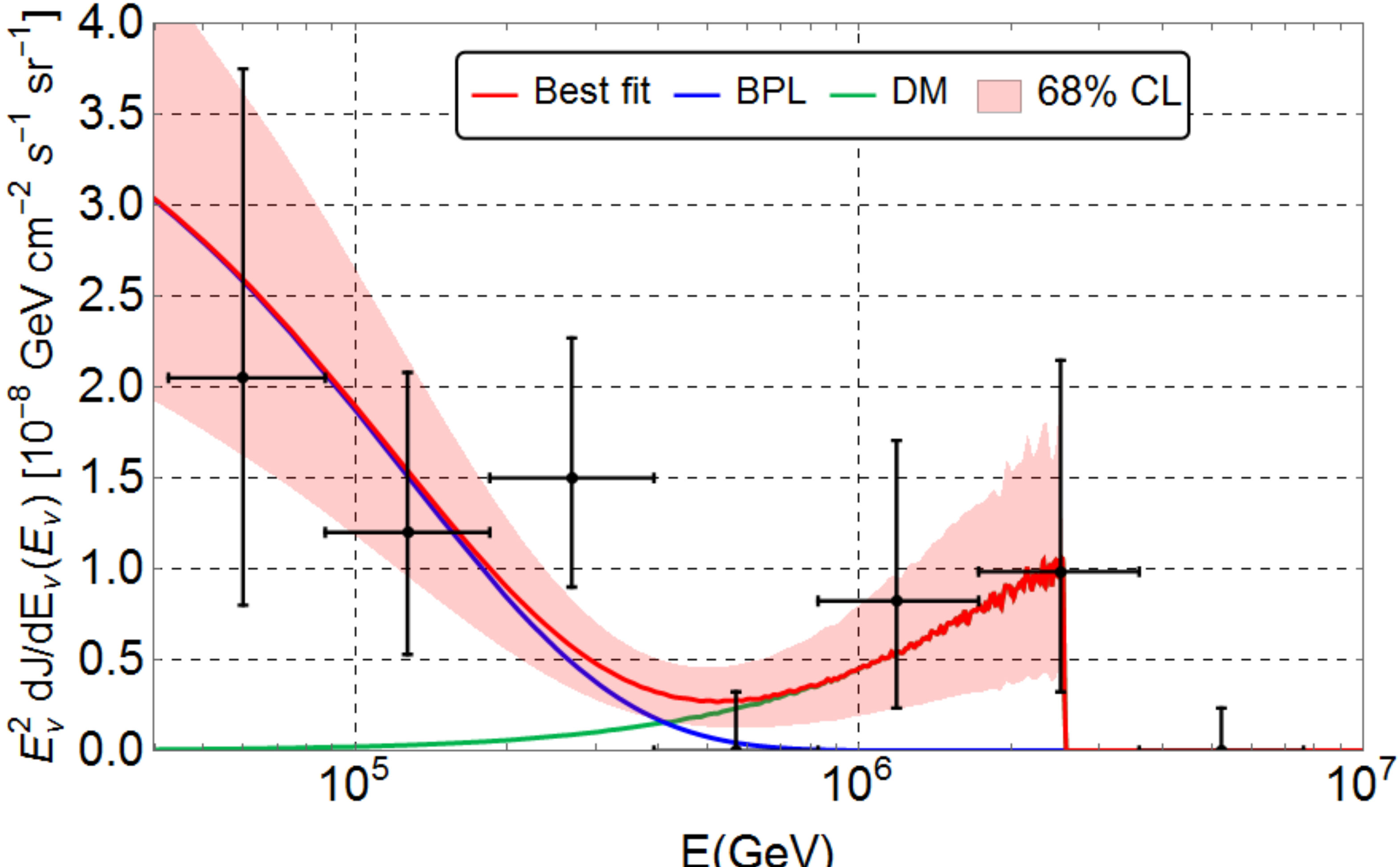
Is it possible to experimentally distinguish dark matter from other astrophysical sources at IceCube?



IceCube,
PRL 113:101101 (2014)

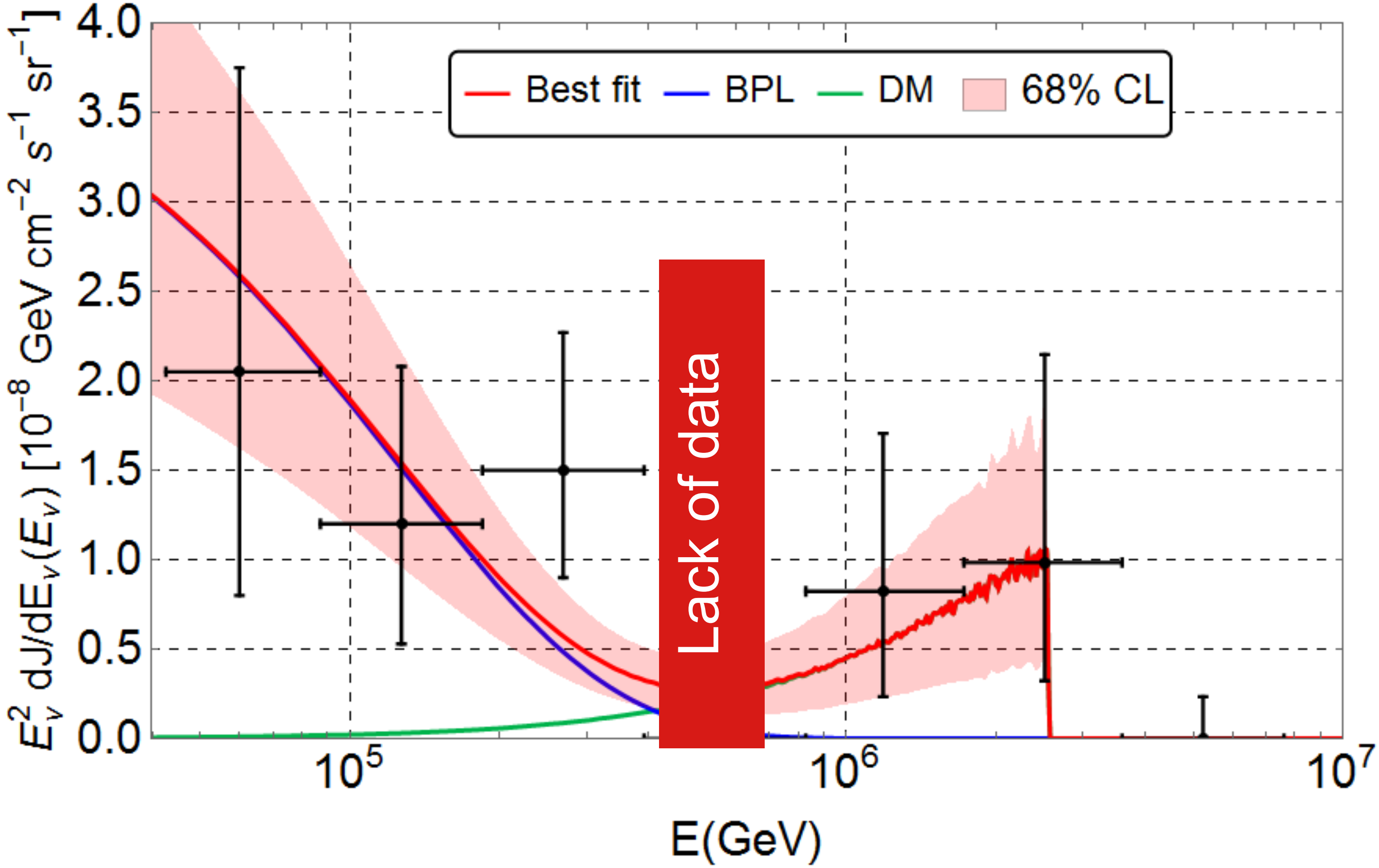


Esmaili, Kang, Serpico,
JCAP 1412 (2014)

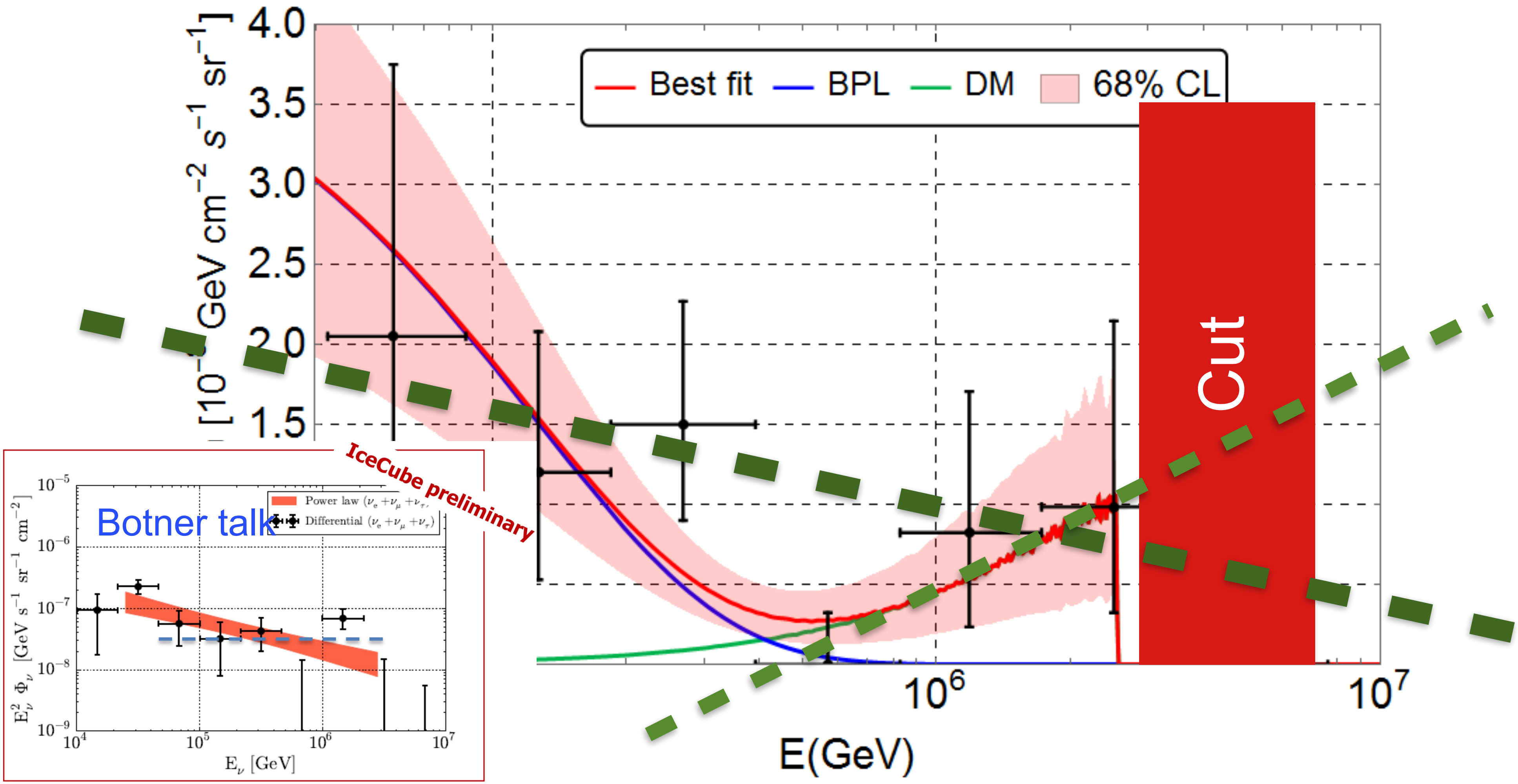


Best fit
BPL
DM
68% CL
$E_\nu^2\,dJ/dE_\nu(E_\nu)\ [10^{-8}\ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}]$
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^5
10^6
10^7
E(GeV)

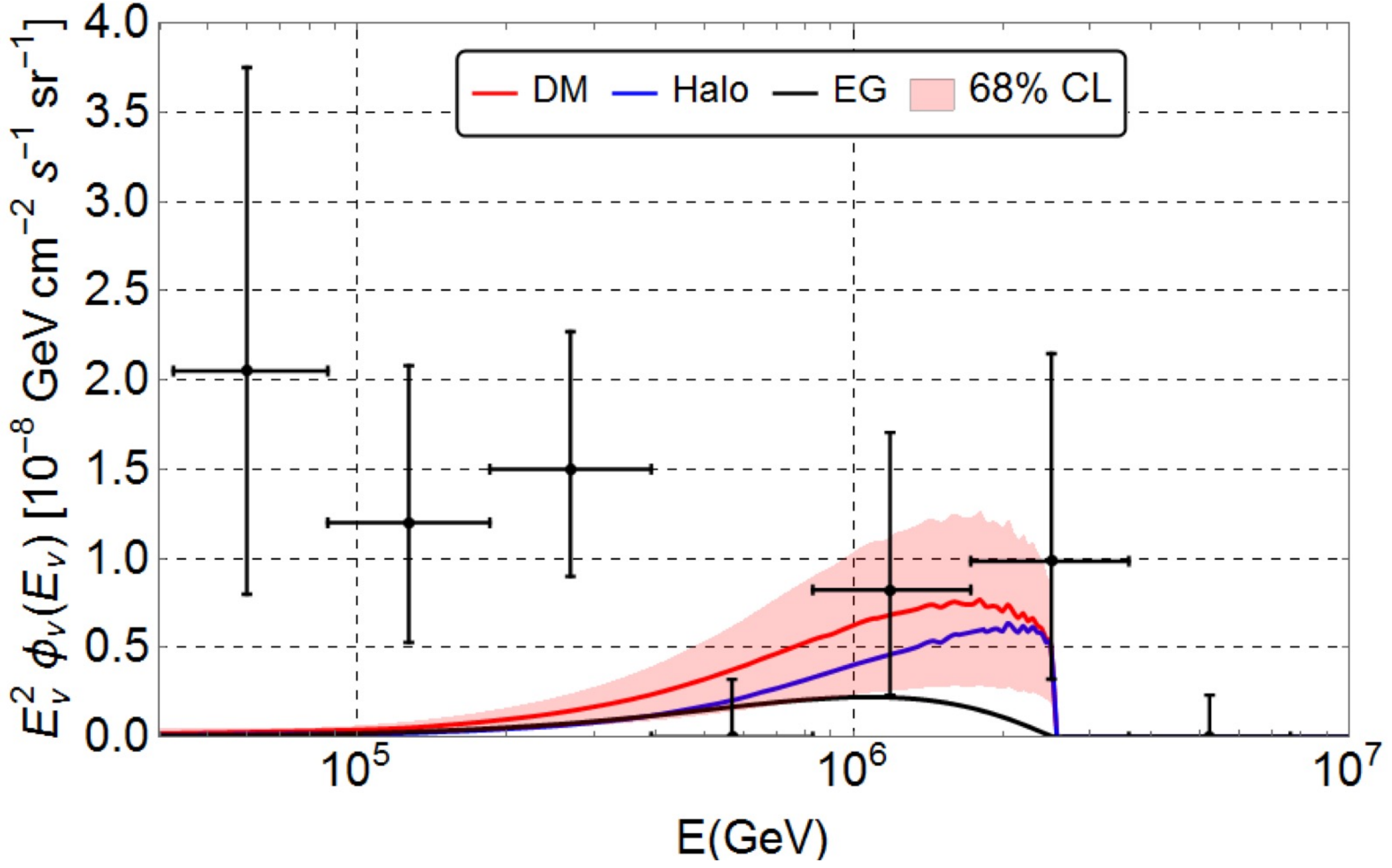
- if events will be observed in the 400-1000 PeV range dark matter is disfavor



- Dark matter decay gives a sharp cut in the neutrino flux with increasing flux
- If above PeV a power law will be observed, dark matter is disfavor

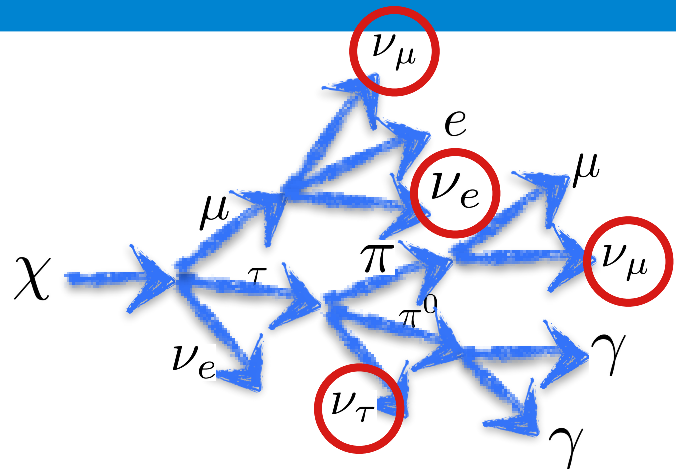


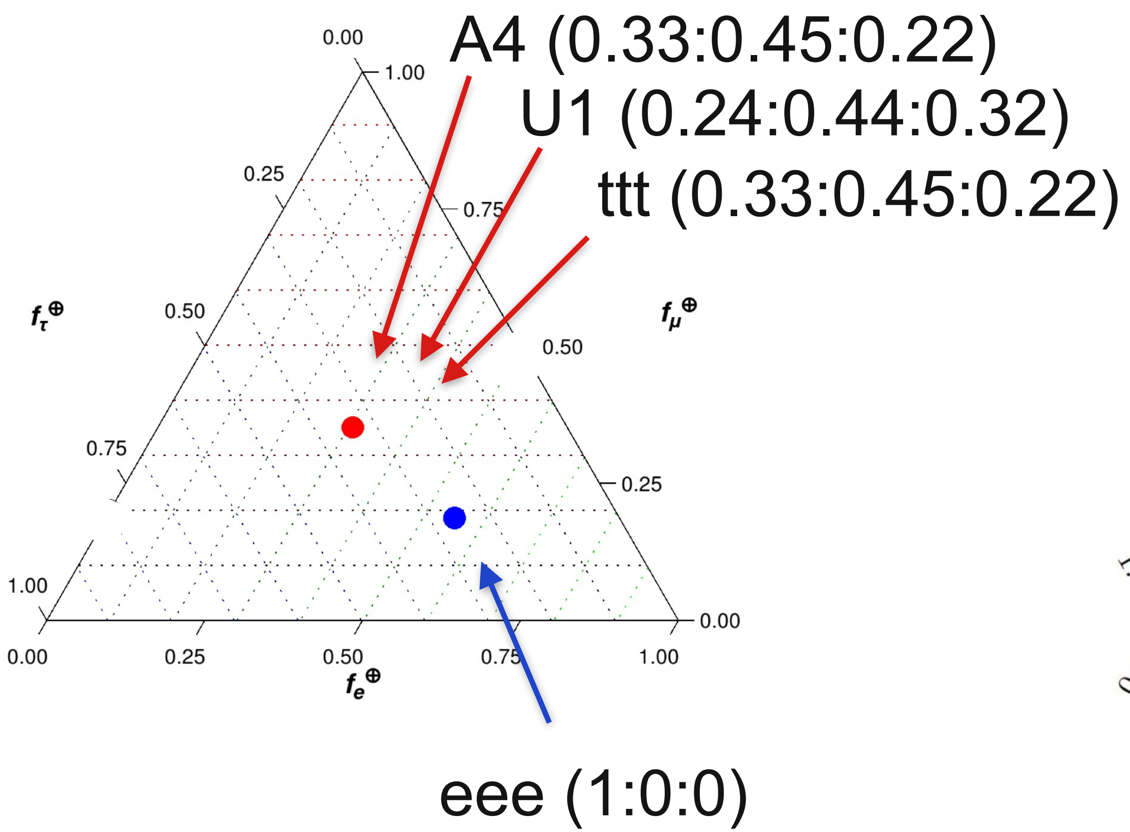
Galactic vs Extra-Galactic

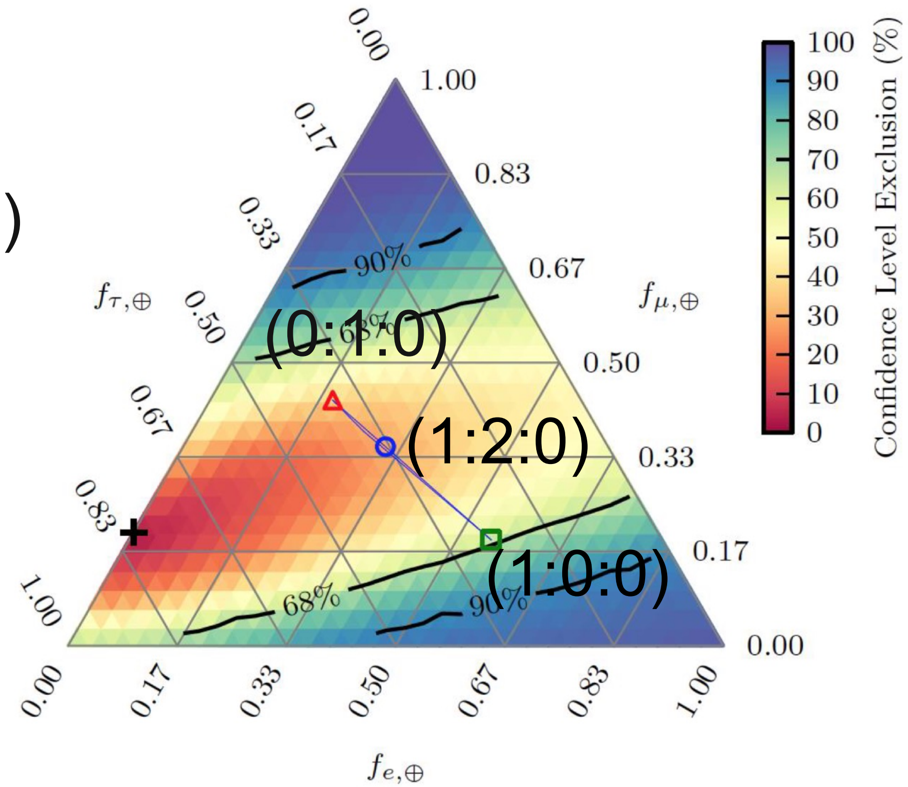


- Galactic and Extra-Galactic have different energy spectrum

Flavor ratio at source







IceCube, PRL 114:171102 (2015)

conclusions

- IceCube PeV events could be related to dark matter
- We discussed decaying dark matter and we compared the 2 and 3 body decay cases
- 3 body leptophillic decay case seems to describe data better if low energy astrophysical sources are also considered in the analysis

Work in progress

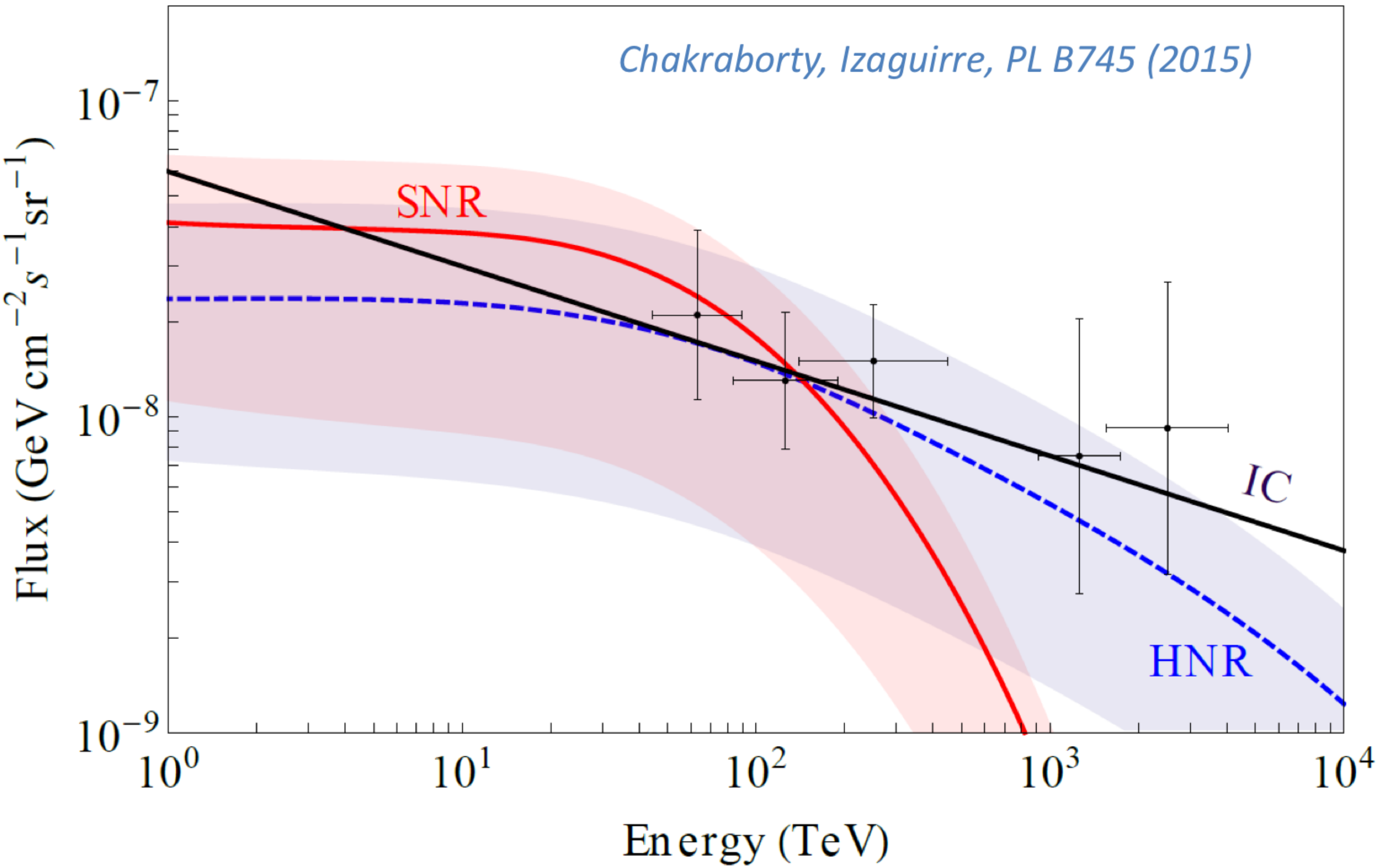
- DM can be distinguished from astrophysical background if some correlation with the galactic center will be observed and If lack of events at 400 TeV and cut at few PeV scale will be confirmed
- Could be interesting the observation of tracks at PeV
- flavor ratio could be used to distinguish models

Backup slides

Supernova Remnants

- Neutrinos carry almost 5% of the energy of the proton.

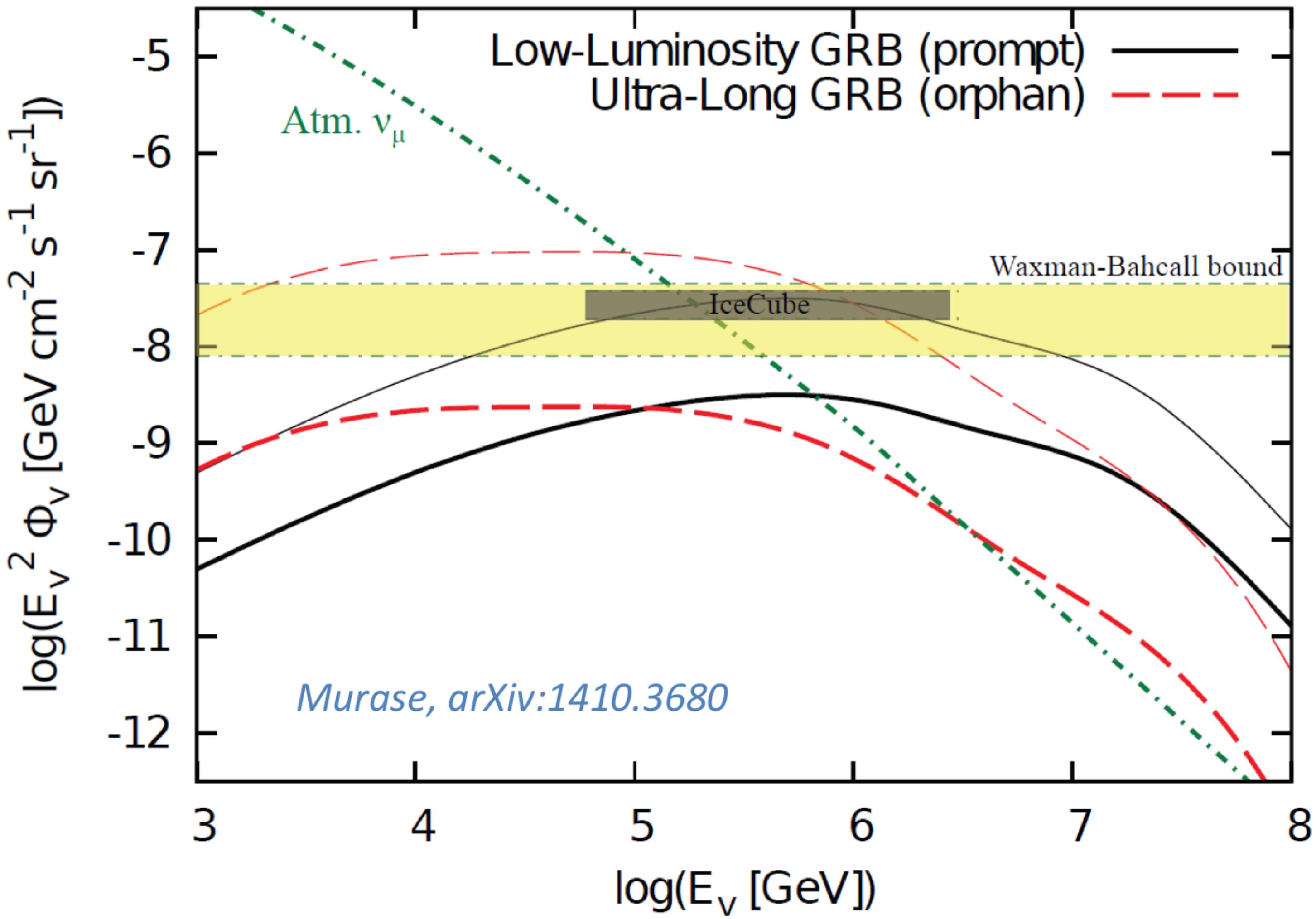
➡ **CUT-OFF** $E \sim \mathcal{O}$ **(100 TeV)**



Gamma-Ray Burst

- Strong correlations with the gamma-rays produced by hadronic interactions.

Correlation not observed yet!



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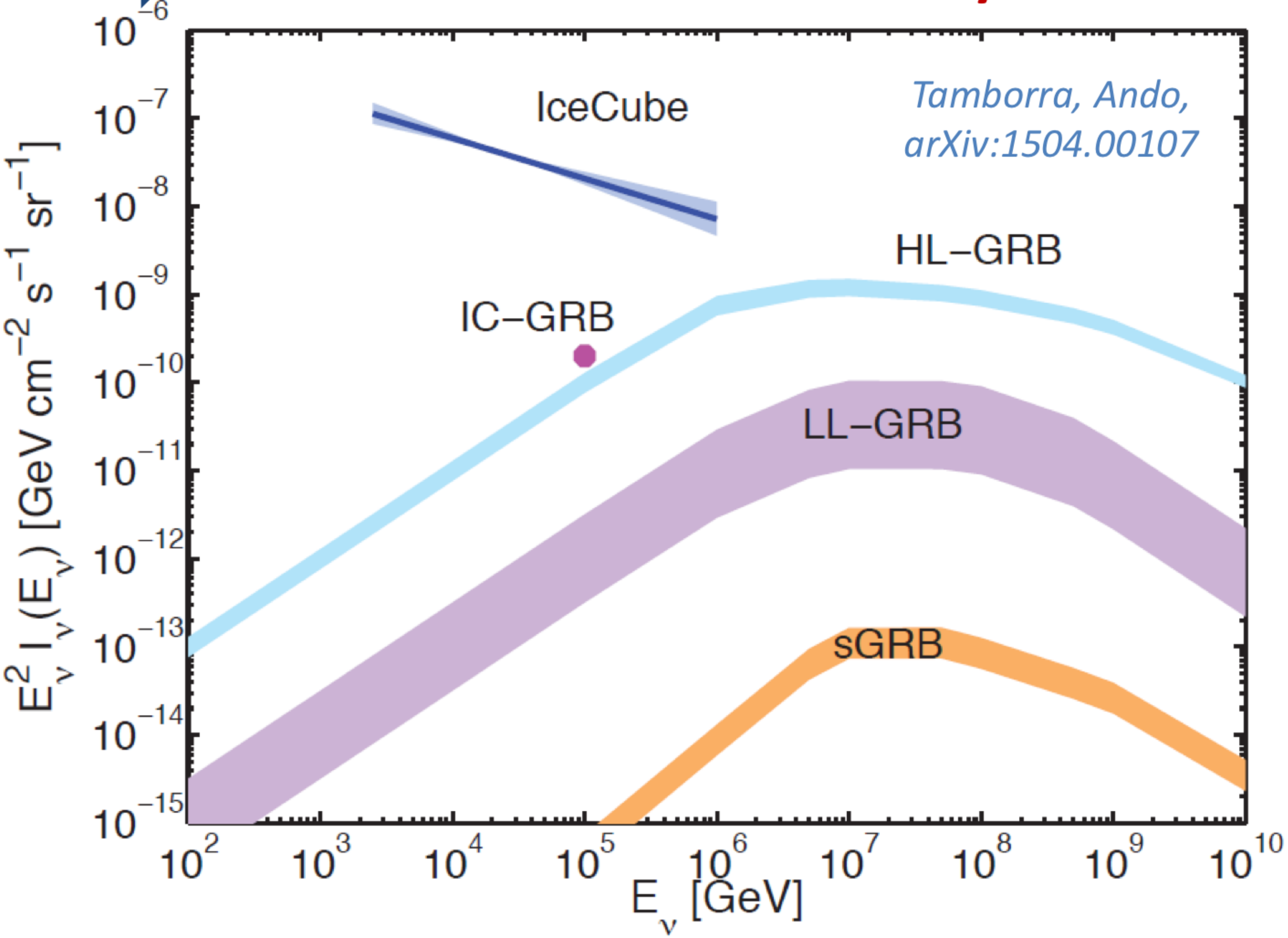
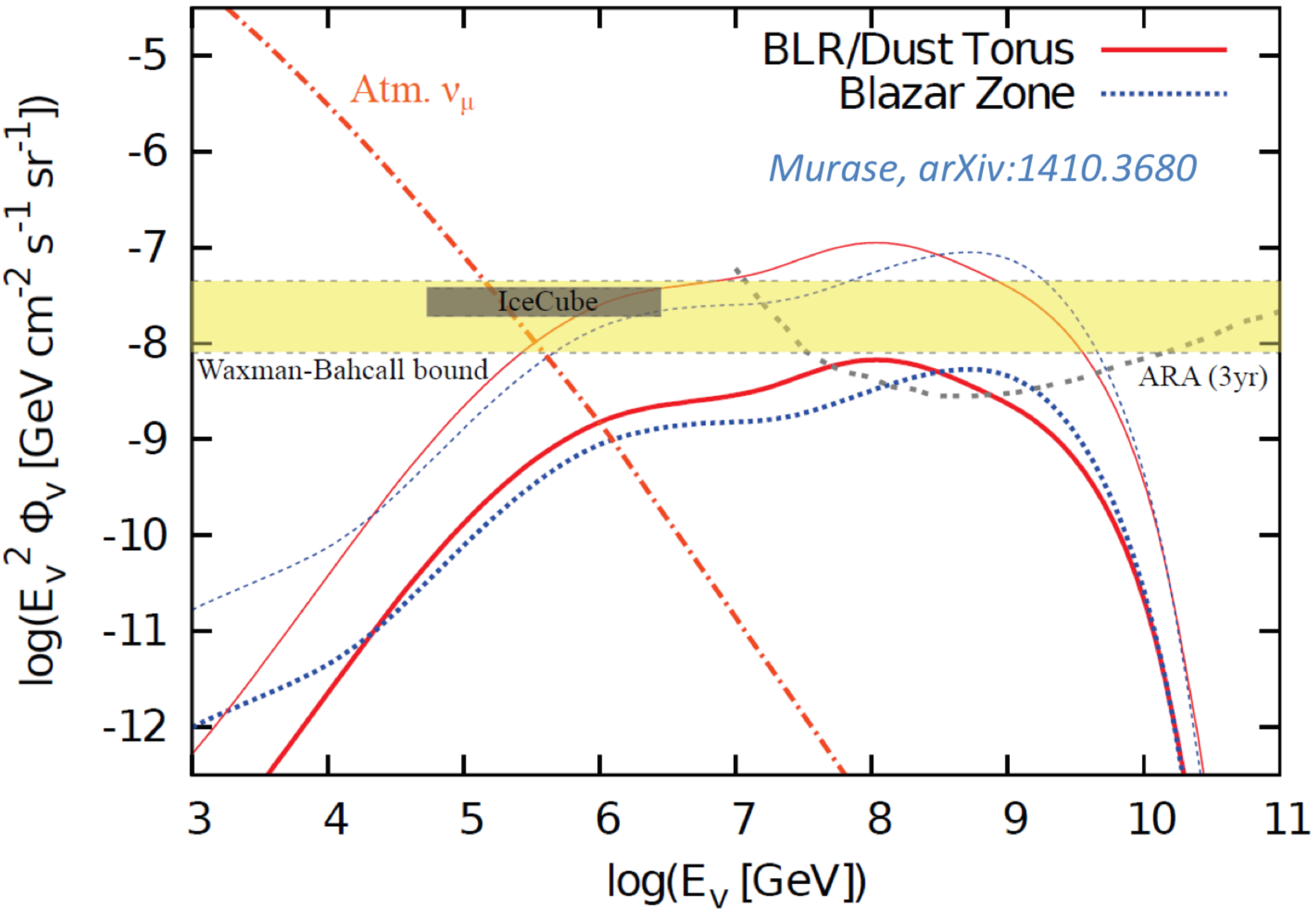


Active Galactic Nuclei

- AGN can explain only PeV neutrinos.

→ **Large uncertainties!**



IceCube:events