From Neutrino Astronomy to Dark Matter-Neutrino Interactions
Part 2

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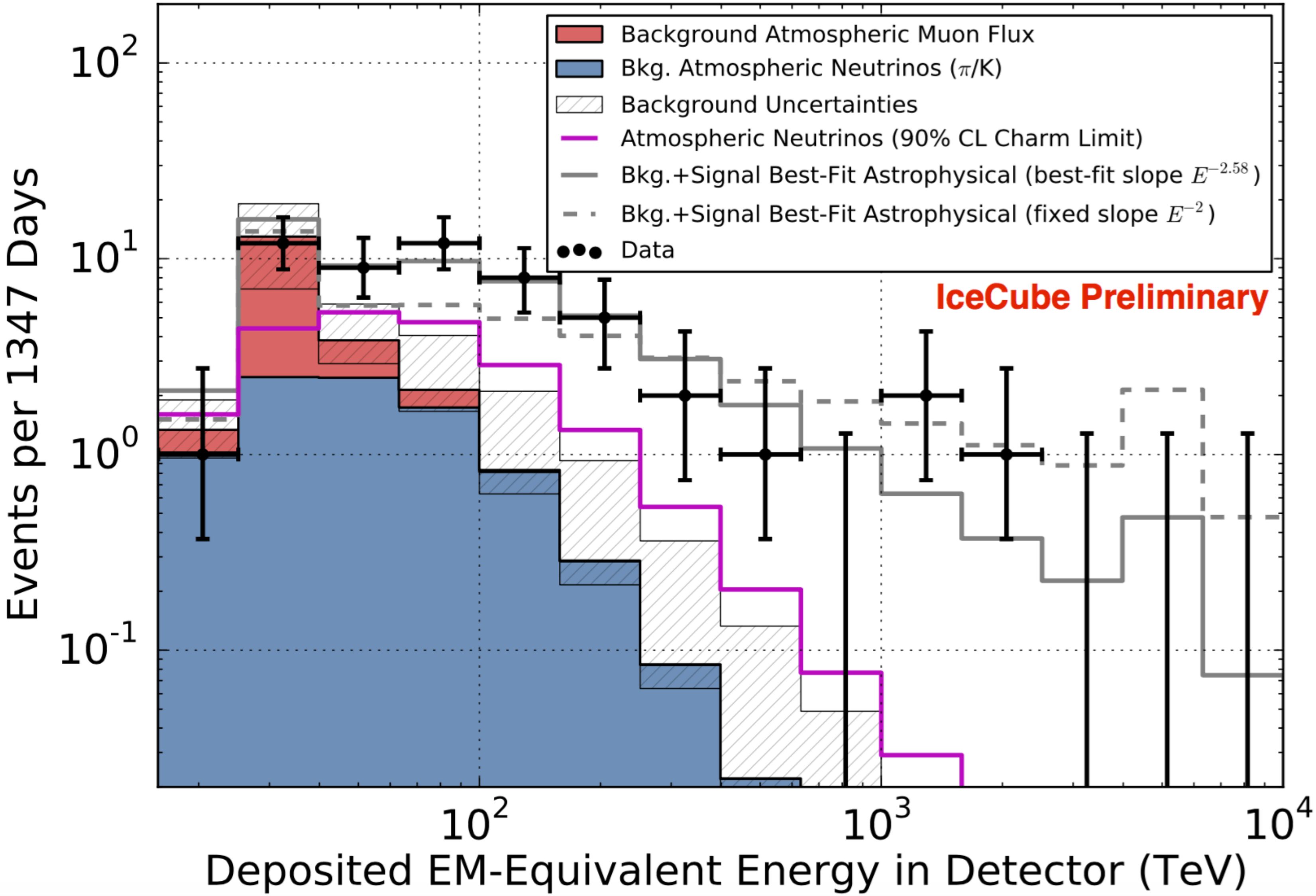
JCAP 1512 (arXiv:1507.01000)
PL B757 (arXiv:1601.02934)

Istituto Nazionale
di Fisica Nucleare

Two components



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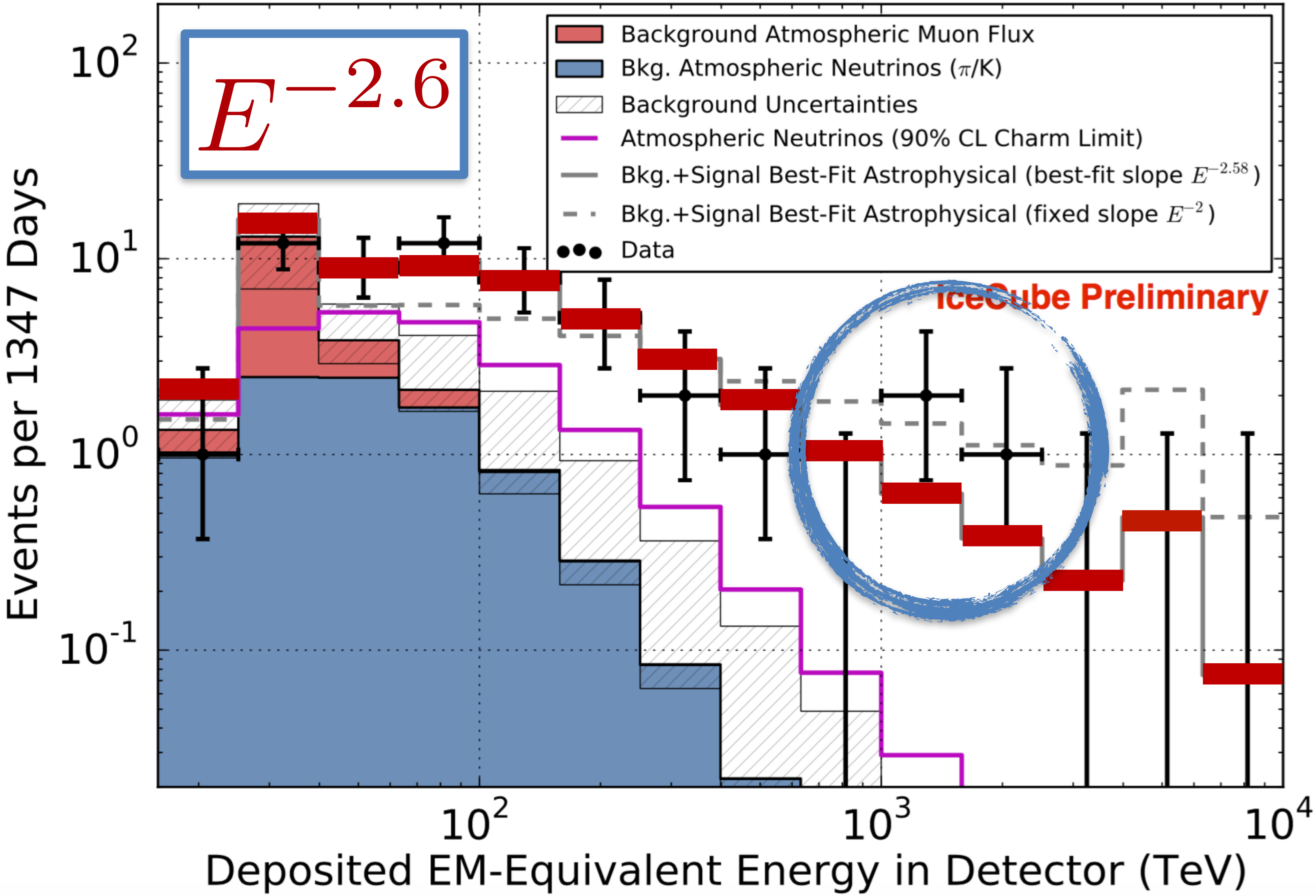

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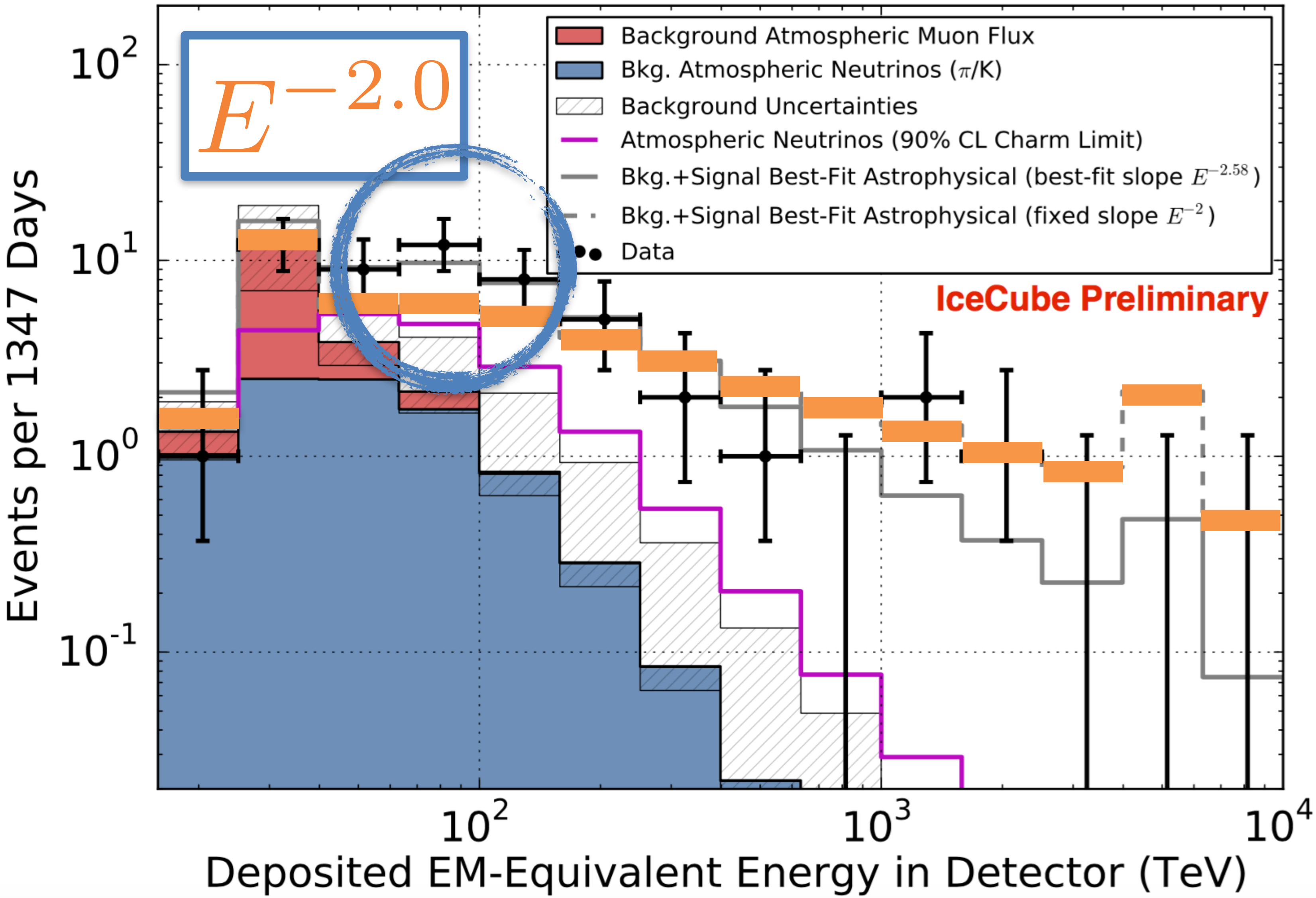
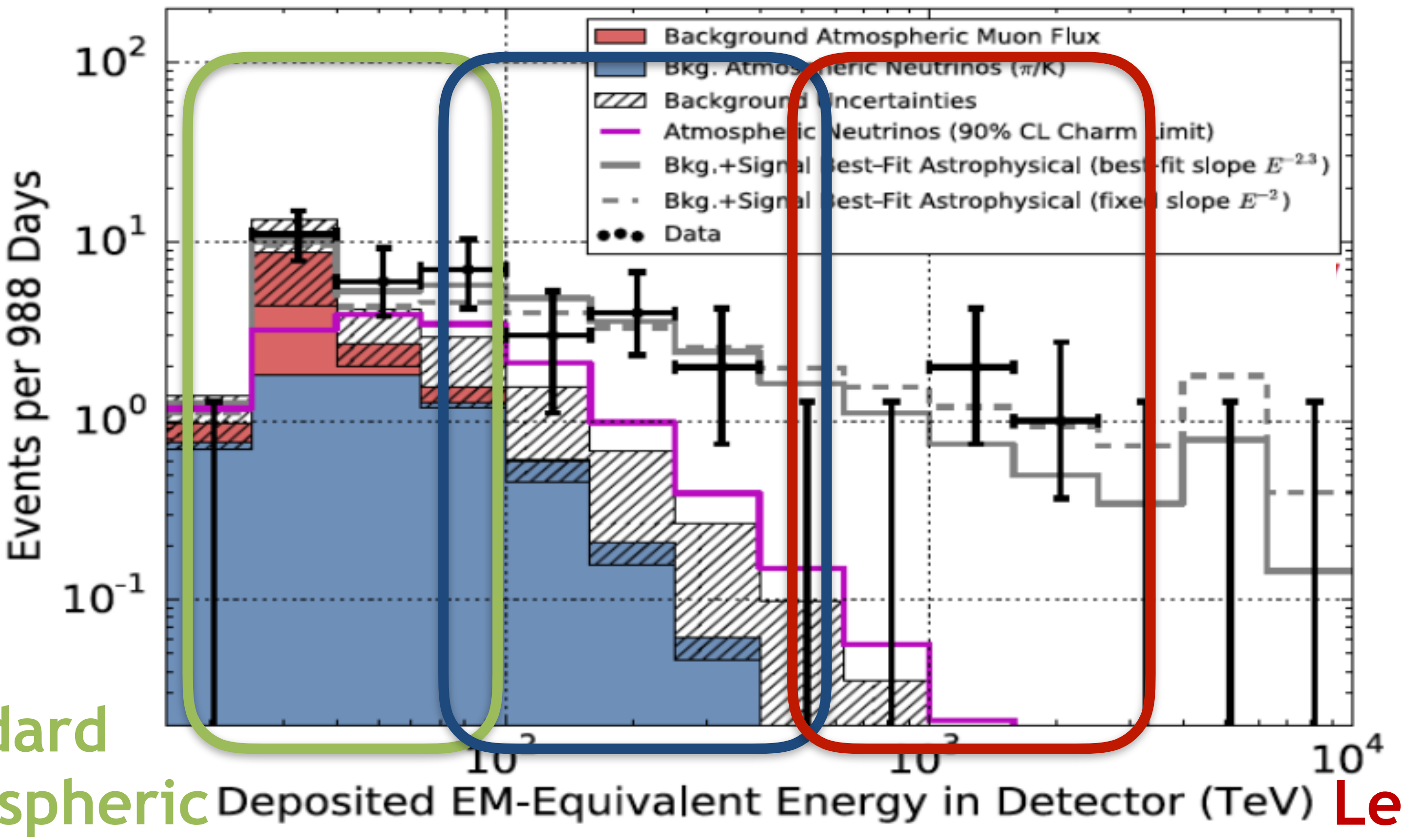


High energy neutrinos

What is the origin of PeV neutrinos?

Our assumption

Boucenna, CHIANESE, Mangano, Miele, Morisi, Pisanti, VITAGLIANO, JCAP 1502



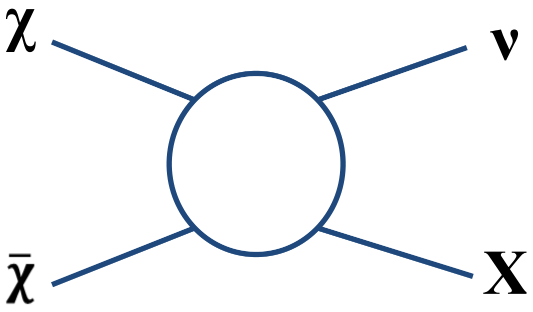
Standard atmospheric background

Some astrophysical source (SuperNova Remnants)

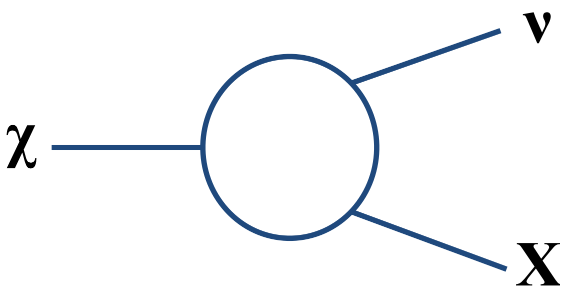
Decaying Leptophilic Dark Matter

Dark Matter at IceCube

Stable



Decay



For PeV DM the annihilation is negligible with respect to decay

Feldstein et al., PR D88 (2013)

$$\Gamma_{\mathrm{Events}} \propto \boxed{\left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^2} \langle \sigma_{\mathrm{Ann}} v \rangle \lesssim 1 \, \text{per few hundred years}$$

Annihilation

$$\Gamma_{\mathrm{Events}} \propto \boxed{\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}} \Gamma_{\mathrm{DM}} \sim \left(\frac{\lambda}{10^{-29}}\right)^2 / \, \text{year}$$

Decay

Decaying Dark Matter

In literature it has been argued that a very heavy decaying DM can explain the IceCube neutrino spectrum.

Feldstein et al., PR D88 (2013)
Esmaili, Serpico, JCAP 1311
Bai et al., arXiv:1311.5864
Ema et al., PL B733 (2014)
Bhattacharya et al., JHEP 1406
Higaki et al., JHEP 1407
Ema et al., JHEP 1410

Rott et al., PR D92 (2015)
Esmaili et al., JCAP 1412
Fong et al., JHEP 1502
Dudas et al., PR D91 (2015)
Murase et al., PRL 115 (2015)
Ko, Tang, PL B751 (2015)
Aisati et al., PR D93 (2016)

For a gauge-singlet fermionic DM the simplest operator is the renormalizable SM-DM coupling.

$$\mathcal{L} \supset g\,\overline{L}H^c\chi$$

Esmaili, Kang, Serpico, JCAP 1412

This coupling yields to a 2 bodies DM decay with some channels producing one primary neutrino.

2 bodies decay

Esmaili, Kang, Serpico, JCAP 1412

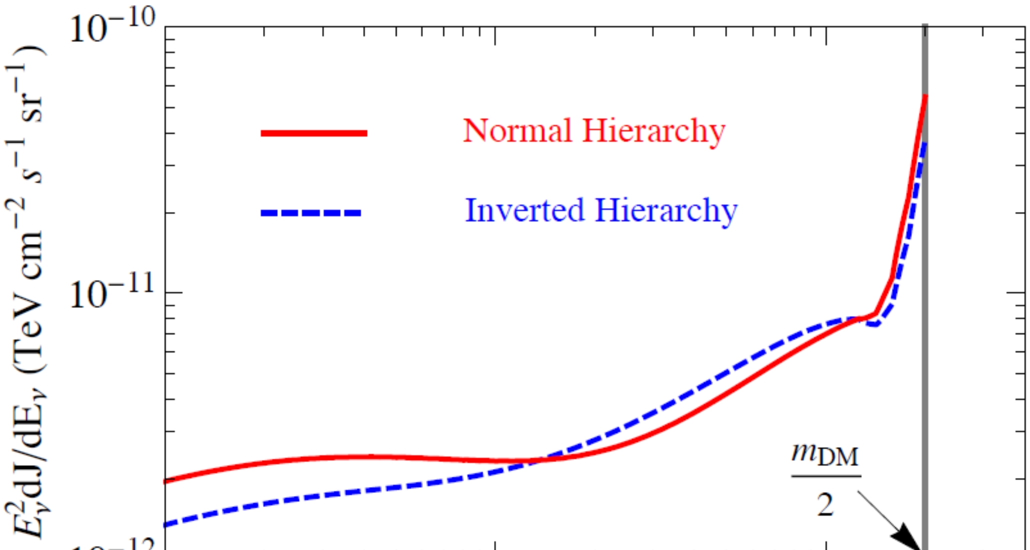
$$\mathcal{L} \supset g\,\overline{L}H^c\chi$$

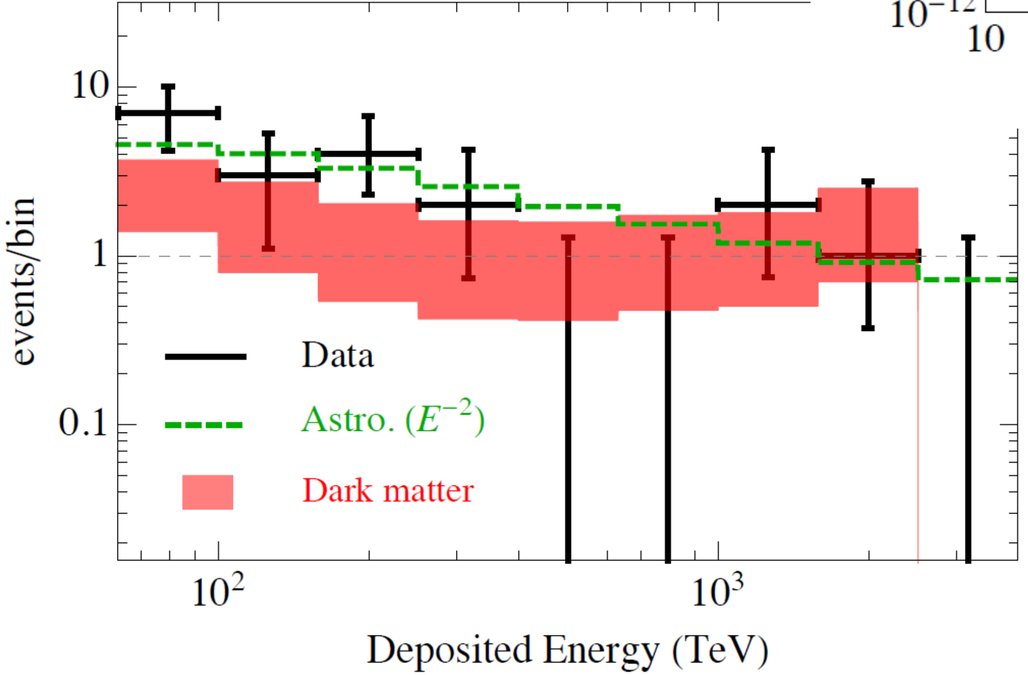
$\chi \to l^{\pm}W^{\mp}$

$\chi \to \nu_l Z$

$\chi \to \nu_l h$

quarks





$$g = \mathcal{O}\left(10^{-30}\right)$$

Decaying Leptophilic Dark Matter

We consider a SM-DM coupling with the following characteristics:

- non-renormalizable → **“natural” small coupling**

$$\frac{y}{M_{\mathrm{Pl}}^{n}}\chi\cdots$$

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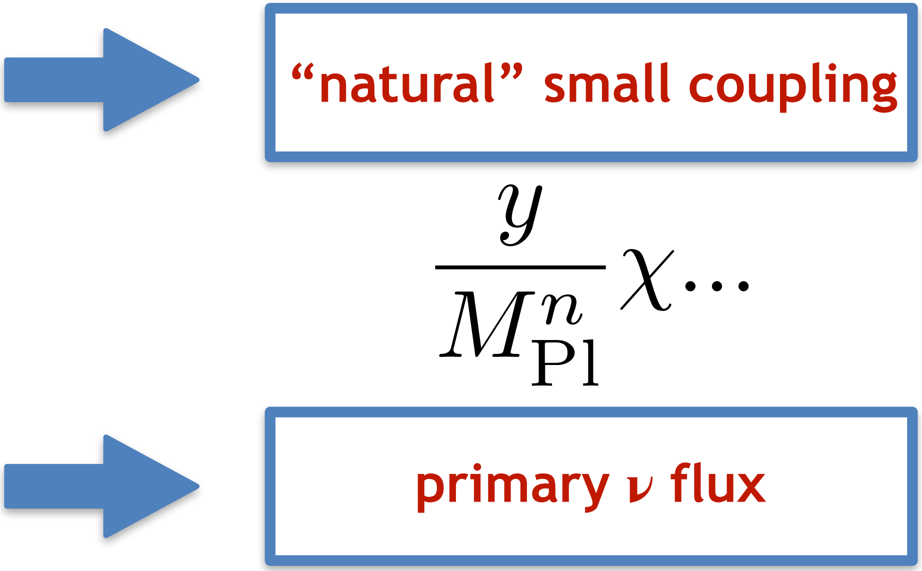

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- direct coupling with neutrino → **primary ν flux**

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- multi body final state → **spread ν flux**

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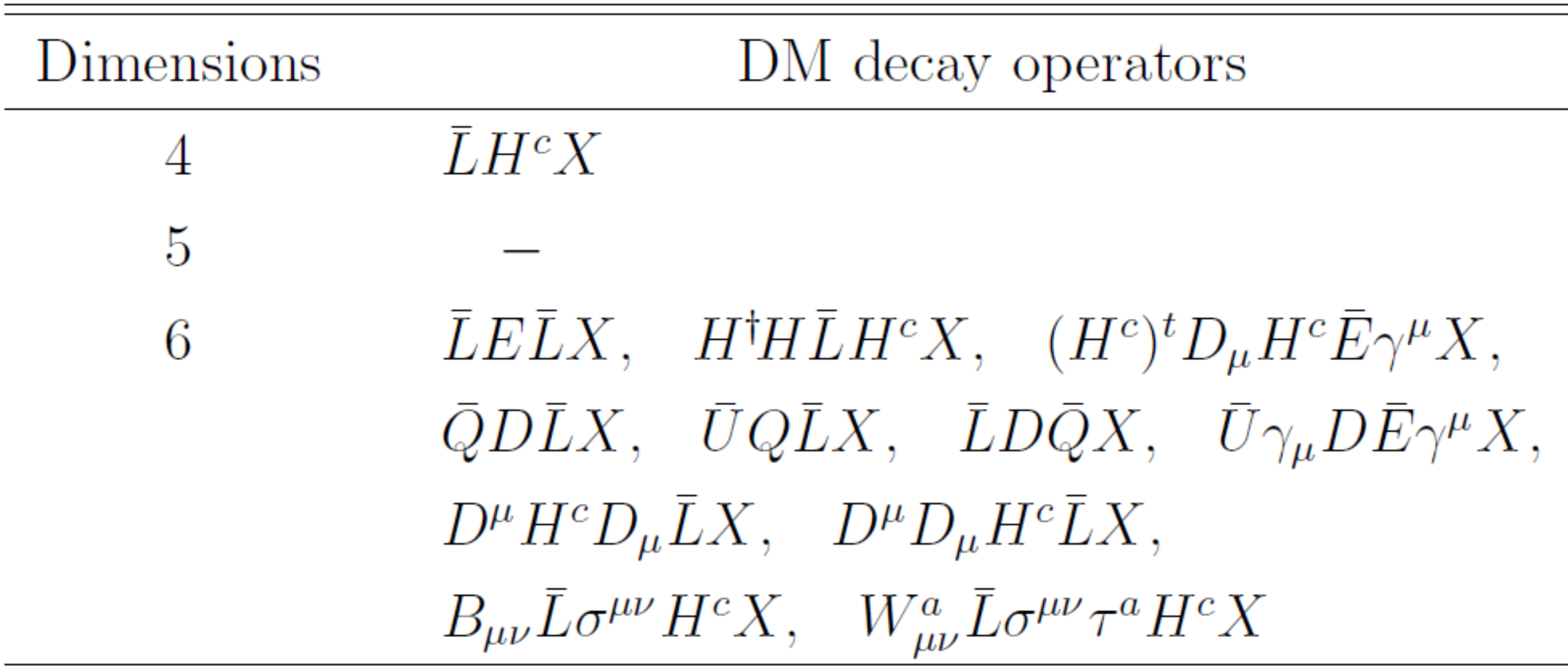
- multi body final state → **spread ν flux**
- leptophilic (no quarks) → **negligible contribution at low energy**

Decaying Leptophilic Dark Matter

There exists only one operator with those characteristics.

Haba et al., PL B695 (2011)



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

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“natural” small coupling
multi body decay

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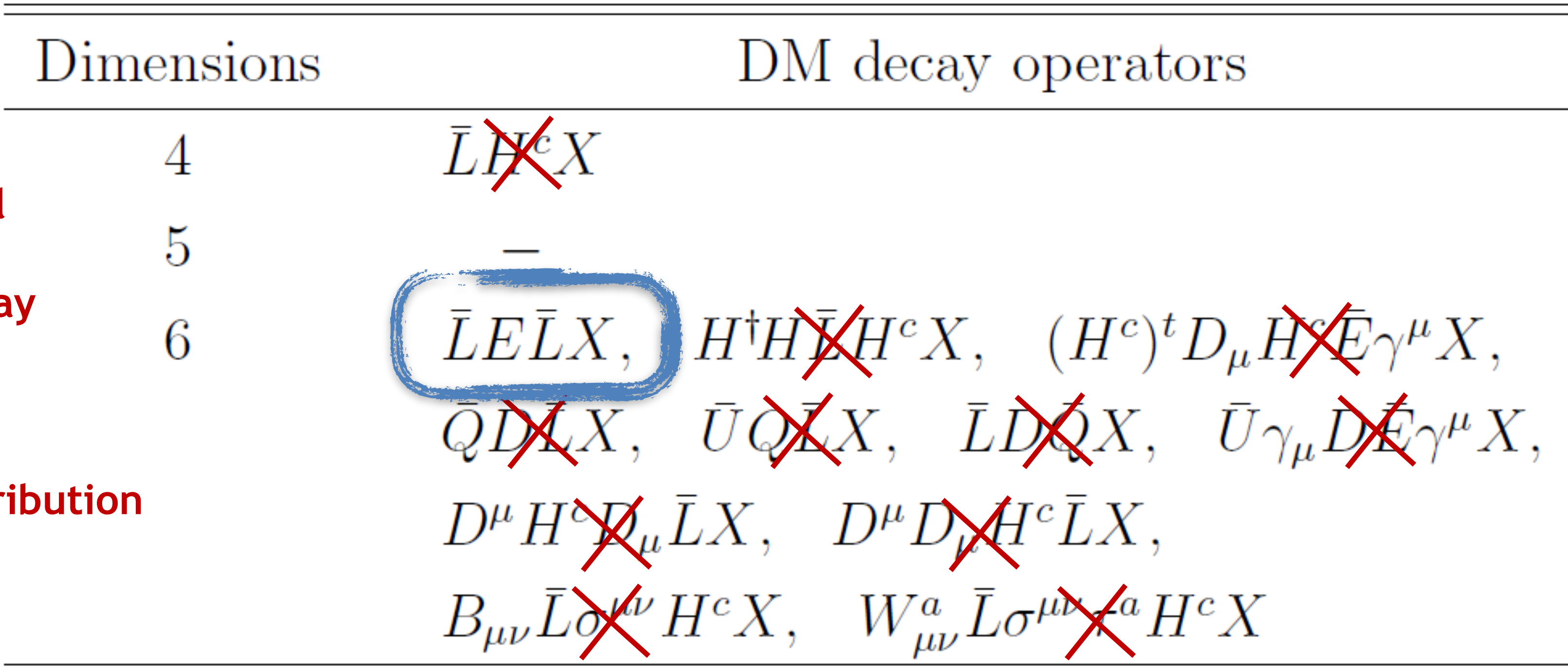
negligible contribution at low energy



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

Does a symmetry exist in order to have only this operator?

Symmetries and Models

Allowed

$$\frac{y_{\alpha\beta\gamma}}{M_{\text{Pl}}^2}\left(\overline{L_\alpha}\ell_\beta\right)\left(\overline{L_\gamma}\chi\right)$$

Forbidden

$$\overline{L}\cancel{H^c\chi}+\text{h.c.}$$

- We can use Abelian U(1) symmetry:

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

U(1) flavour indices

$$\{\mu, e, \tau\} + \{\tau, e, \mu\} + \{e, \mu, e\}$$

- We can use non-Abelian symmetries like A_4:

	L	ℓ	H	χ
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{1}$

A_4 flavour indices

$$\{e, \mu, \tau\} + \text{cyclic permutations}$$

Neutrino flux from DM

The differential neutrino flux from decaying DM has two components

$$\frac{\mathrm{d}J_\chi}{\mathrm{d}E_\nu}(E_\nu) = \frac{1}{4\pi}\int d\Omega \left(\underbrace{\frac{\mathrm{d}J_\chi^{\mathrm{G}}}{\mathrm{d}E_\nu}}_{\downarrow\ \text{Galactic}}(E_\nu, l, b) + \underbrace{\frac{\mathrm{d}J_\chi^{\mathrm{EG}}}{\mathrm{d}E_\nu}}_{\downarrow\ \text{ExtraGalactic}}(E_\nu) \right)$$

where

$$\frac{\mathrm{d}J_\chi^{\mathrm{G}}}{\mathrm{d}E_\nu}(E_\nu, l, b) = \frac{1}{4\pi\, M_\chi\, \tau_\chi} \sum_{\alpha=e,\mu,\tau} \boxed{\frac{\mathrm{d}N_{\nu+\bar{\nu}}^{\alpha}}{\mathrm{d}E_\nu}(E_\nu)} \int_0^\infty \mathrm{d}s\, \boxed{\rho_\chi(r(s,l,b))}$$

Montecarlo **Navarro-Frenk-White**

$$\frac{\mathrm{d}J_\chi^{\mathrm{EG}}}{\mathrm{d}E_\nu}(E_\nu) = \frac{\Omega_\chi \rho_{\mathrm{cr}}}{4\pi M_\chi \tau_\chi} \int_0^\infty \mathrm{d}z\, \frac{1}{H(z)} \sum_{\alpha=e,\mu,\tau} \boxed{\frac{\mathrm{d}N_{\nu+\bar{\nu}}^{\alpha}}{\mathrm{d}E_\nu}((1+z)E_\nu)}$$

Neutrino events

- Knowing the total differential neutrino flux

$$\frac{\mathrm{d}J}{\mathrm{d}E_\nu}(E_\nu) = \frac{\mathrm{d}J_\chi}{\mathrm{d}E_\nu}(E_\nu) + \frac{\mathrm{d}J_{\mathrm{Ast}}}{\mathrm{d}E_\nu}(E_\nu)$$

  where

$$E_\nu^2 \frac{dJ_{\mathrm{Ast}}}{dE_\nu}(E_\nu) = \underbrace{\overbrace{J_0 \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{2-\gamma}}^{\textbf{Unbroken Power Law}} \exp\left(-\frac{E_\nu}{E_0}\right)}_{\textbf{Broken Power Law}}$$

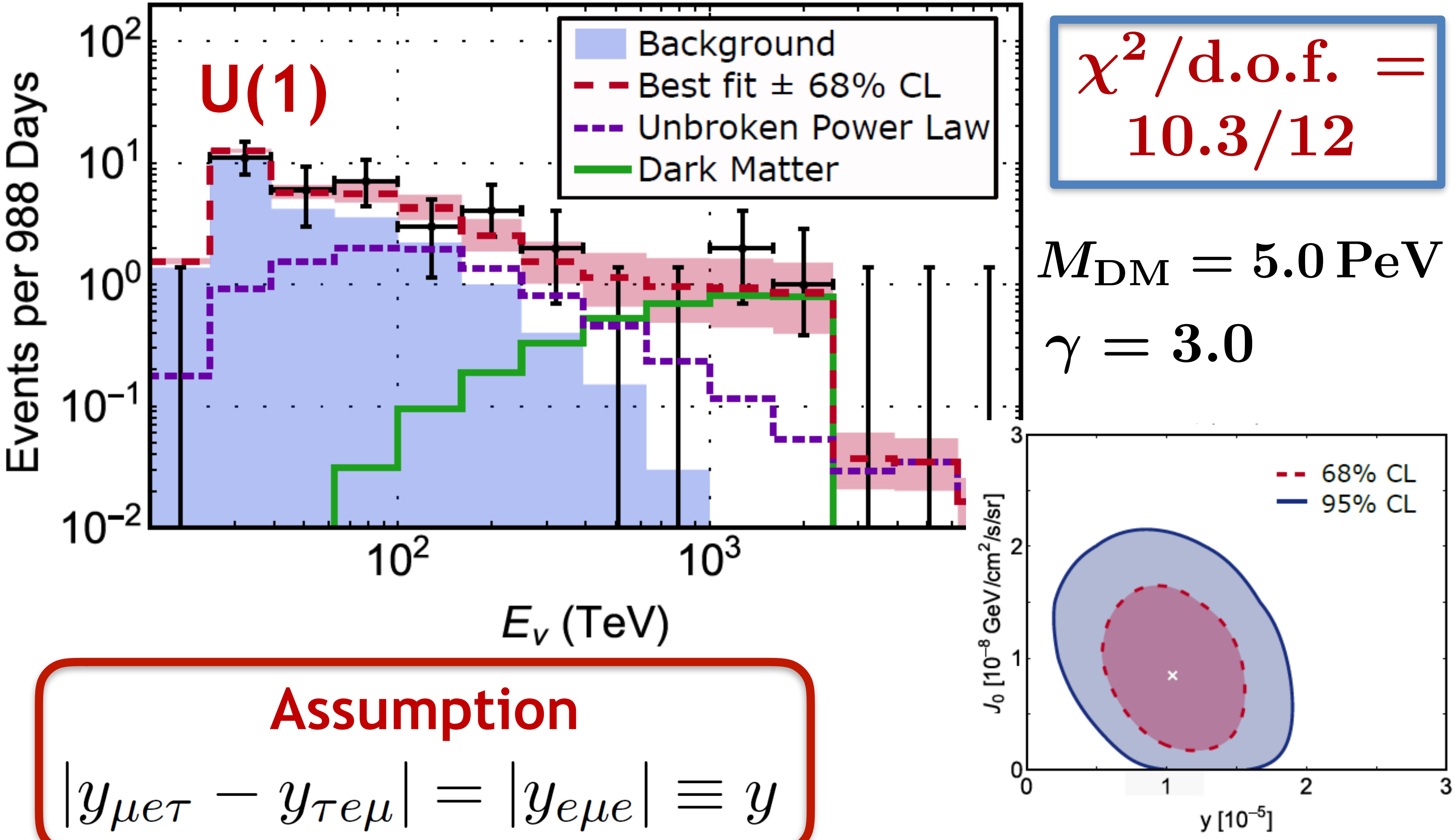
- Then, the number of neutrinos in a given energy bin $[E_i, E_{i+1}]$ is equal to

$$N_i = \underbrace{4\pi\Delta t}_{\text{Exposure time } \Delta t = 988\ \mathrm{days}} \int_{E_i}^{E_{i+1}} \mathrm{d}E \sum_{\alpha=e,\mu,\tau} \frac{\mathrm{d}J^{\alpha}_{\nu+\bar{\nu}}}{\mathrm{d}E} \underbrace{A_\alpha(E)}_{\text{Effective IceCube area}}$$

IceCube, Science 342 (2013)

Unbroken Power Law

Boucenna, CHIANESE, Mangano, Miele, Morisi, Pisanti, VITAGLIANO, JCAP 1502



$$\chi^2/\mathrm{d.o.f.} = 10.3/12$$

$$M_{\mathrm{DM}} = 5.0\,\mathrm{PeV}$$

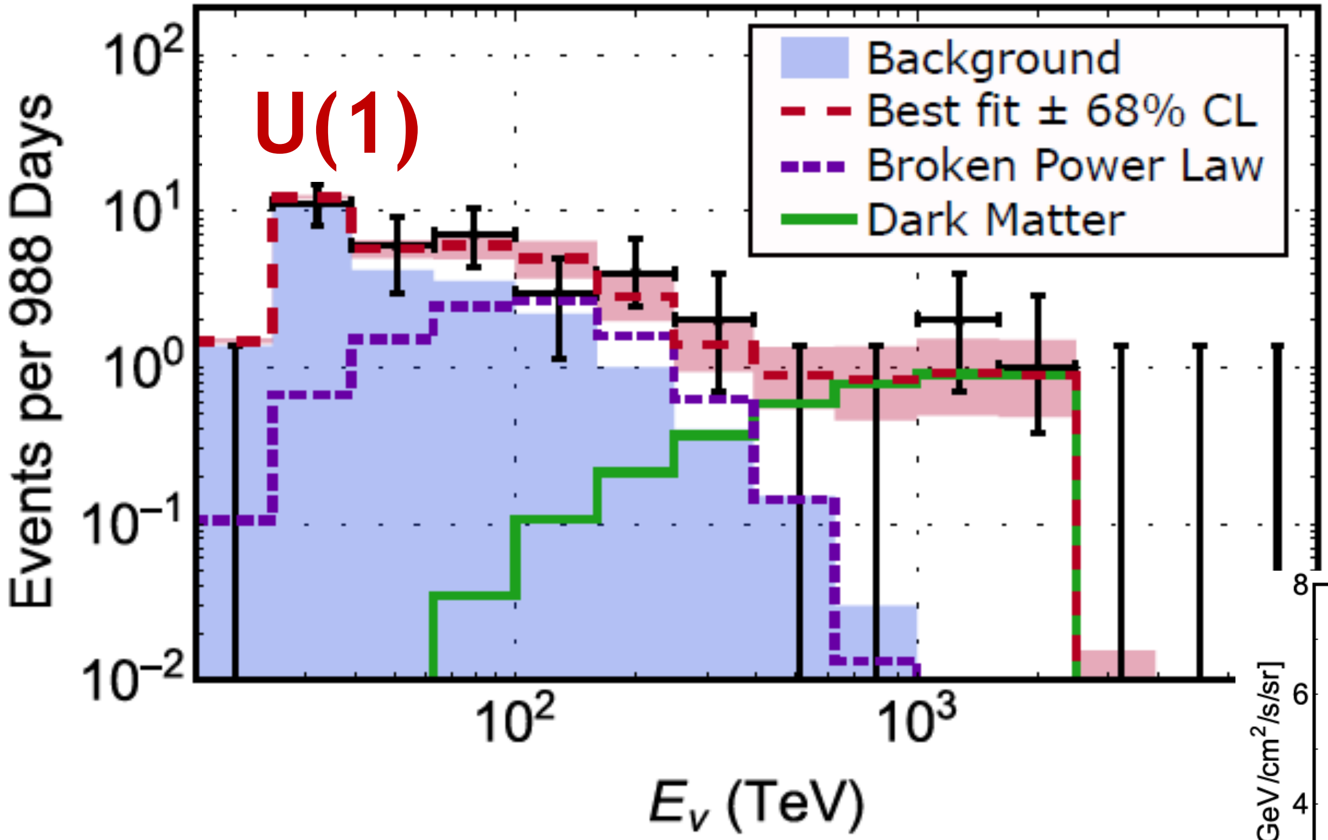
$$\gamma = 3.0$$

Assumption

$$|y_{\mu e\tau} - y_{\tau e\mu}| = |y_{e\mu e}| \equiv y$$

Broken Power Law

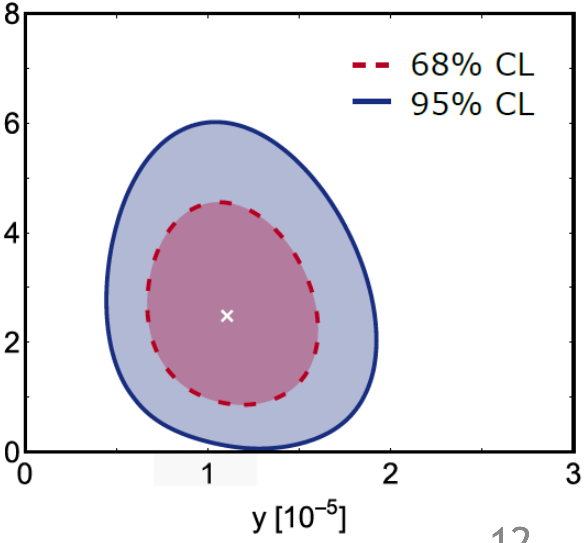
Boucenna, CHIANESE, Mangano, Miele, Morisi, Pisanti, VITAGLIANO, JCAP 1502



$$\chi^2/\mathrm{d.o.f.} = 9.2/12$$

$$M_{\mathrm{DM}} = 5.0\,\mathrm{PeV}$$

$$\gamma = 2.0$$



Assumption

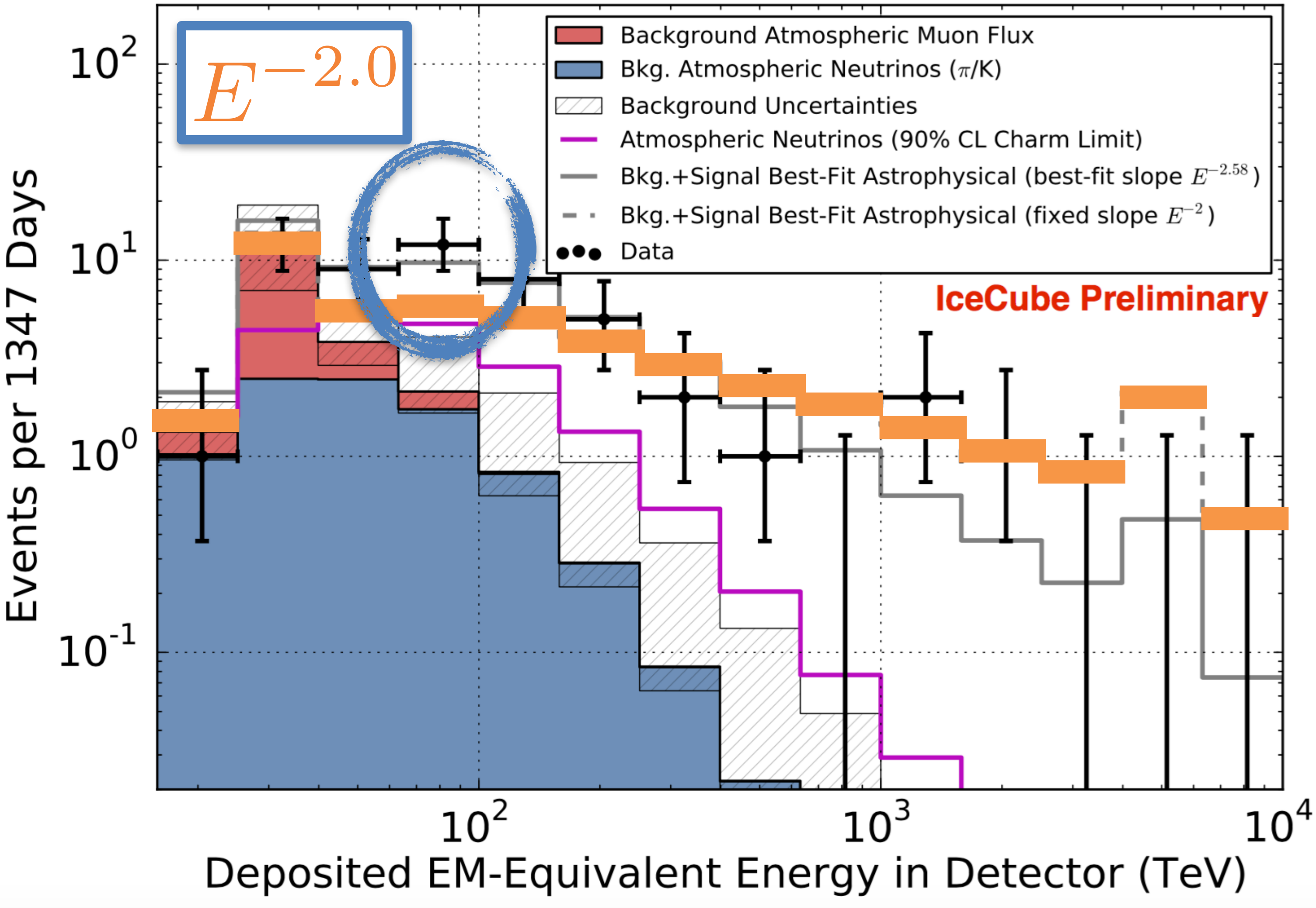
$$|y_{\mu e \tau} - y_{\tau e \mu}| = |y_{e \mu e}| \equiv y$$

Low energy neutrinos

Low energy neutrino excess

Low energy excess

The latest IceCube data show a 2-sigma excess in the energy range 60-100 TeV with respect to a power-law having spectral index 2.

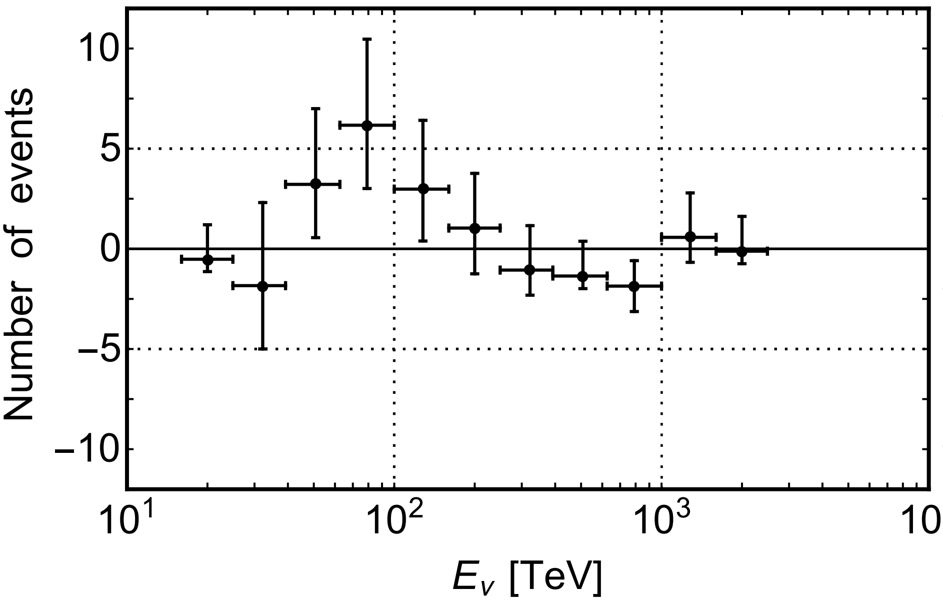


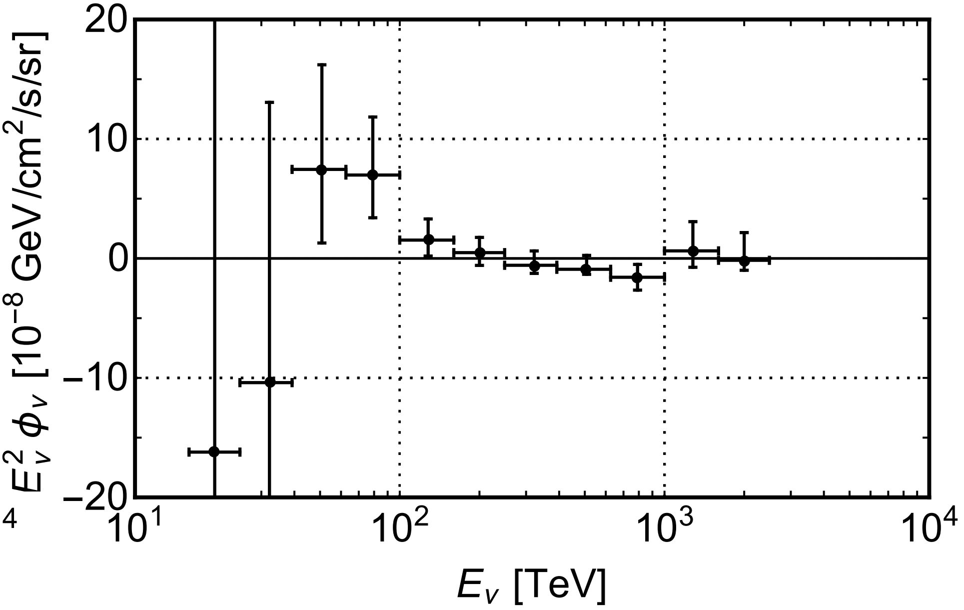
Low energy excess

The 2-sigma excess is with respect to the sum of:

- atmospheric neutrinos and muons
- astrophysical component described by a power-law

$$\phi_\nu^{\mathrm{Astro}} \propto E^{-2}$$





CHIANESE, Miele, Morisi, VITAGLIANO, PL B757 (2016)

Origin of the excess

Assuming that such an excess has a genuine physical origin, it is of interest to pursue a study in order to unveil its nature.

We perform statistical tests of hypothesis on the angular distribution in the arrival direction of neutrinos in 60-100 TeV.

- astrophysical galactic sources (galactic plane)
- astrophysical extragalactic sources (isotropic distribution)

Astrophysical scenarios

- decaying Dark Matter
- annihilating Dark Matter

Dark Matter scenarios

Due to the low statistics, we consider just one additional component to the neutrino background at a time.

Angular distributions

In case of astrophysical scenarios, the expected angular distributions in the arrival directions are

$$p^{\mathrm{gal}}(\sin b, l) = \frac{\Theta(\sin b + \sin b_{\mathrm{gal}}) - \Theta(\sin b - \sin b_{\mathrm{gal}})}{4\pi \sin b_{\mathrm{gal}}}$$

Galactic latitude

Angular size of Galactic Plane

$$b_{\mathrm{gal}} \in [2^\circ, 4^\circ]$$

Fermi-LAT, APJ 750 (2012)

$$p^{\mathrm{iso}}(\sin b, l) = \frac{1}{4\pi}$$

Angular distributions

In case of Dark Matter scenarios, we have

$$p^{\mathrm{dec}}(\cos\theta) \propto \int_0^\infty \underline{\rho_h[r(s,\cos\theta)]}\mathrm{d}s + \Omega_{\mathrm{DM}}\rho_c\,\beta$$

DM halo density

$$p^{\mathrm{ann}}(\cos\theta) \propto \int_0^\infty \underline{\rho_h^2[r(s,\cos\theta)]}\mathrm{d}s + (\Omega_{\mathrm{DM}}\rho_c)^2\,\underline{\Delta_0^2}\,\beta$$

Navarro-Freni-White (NFW)
Isothermal (Isoth.)

Clumpiness factor

where

$$\beta = \int_0^{\frac{100}{60}-1} \frac{\mathrm{d}z}{H(z)} = \frac{0.56}{H_0}$$

→ Maximum contribution to 60-100 TeV from redshift $z > 0$

$$\cos\theta = \cos b\cos l$$

Analysis

We perform two different *non-parametric* statistical tests:

- Kolmogorov-Smirnov (KS)
- Anderson-Darling (AD)

In the energy range 60-100 TeV, IceCube has detected **12** events but **5** events are background.

We also consider the angular uncertainty affecting the reconstruction of the arrival direction.

Montecarlo on experimental error

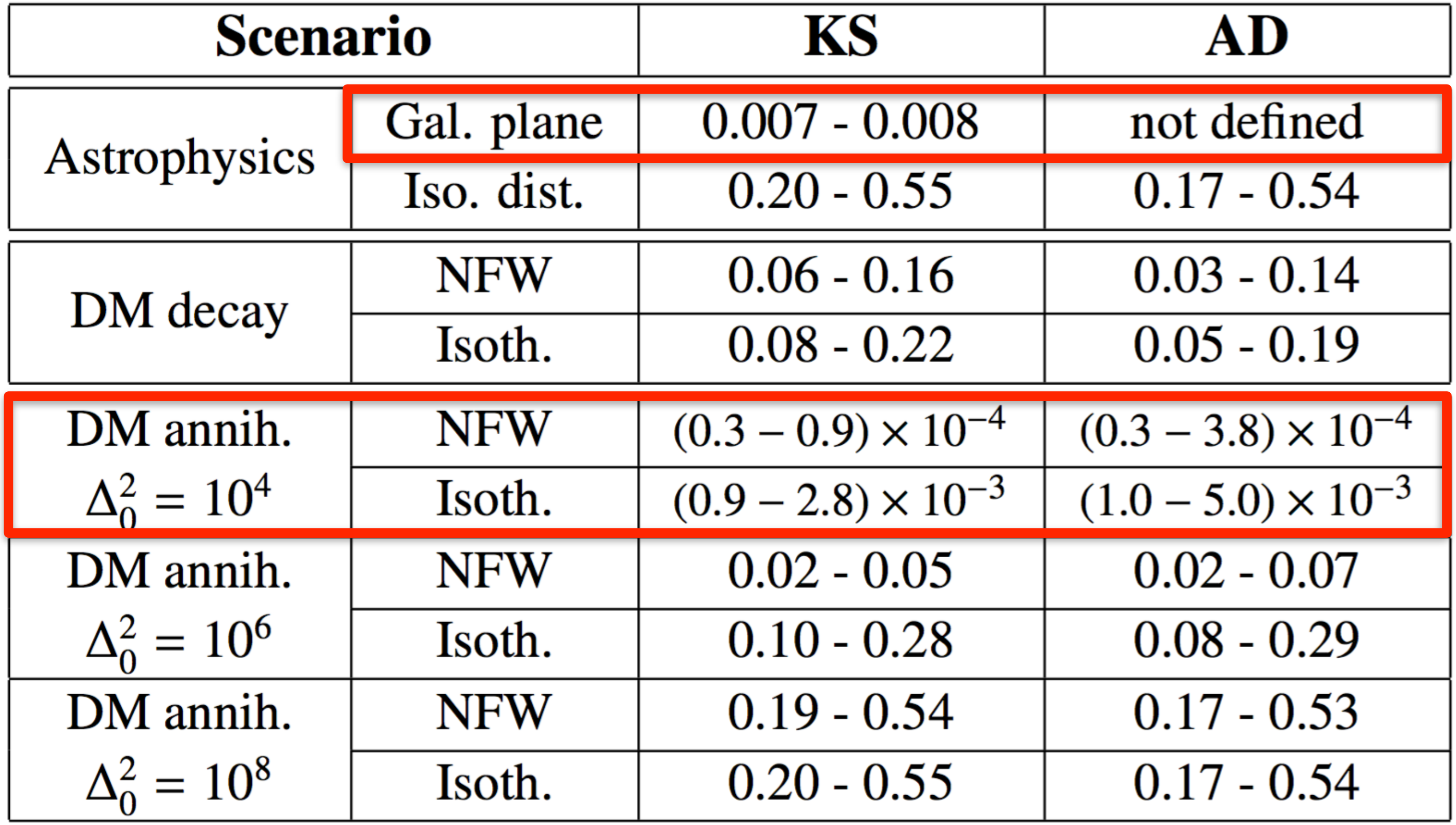
$$\boxed{\frac{12!}{5!\,7!}} \times \boxed{100} \quad \text{different combinations}$$

Averaged on background combinations

Results

Background averaged range of *p*-values for all the cases.

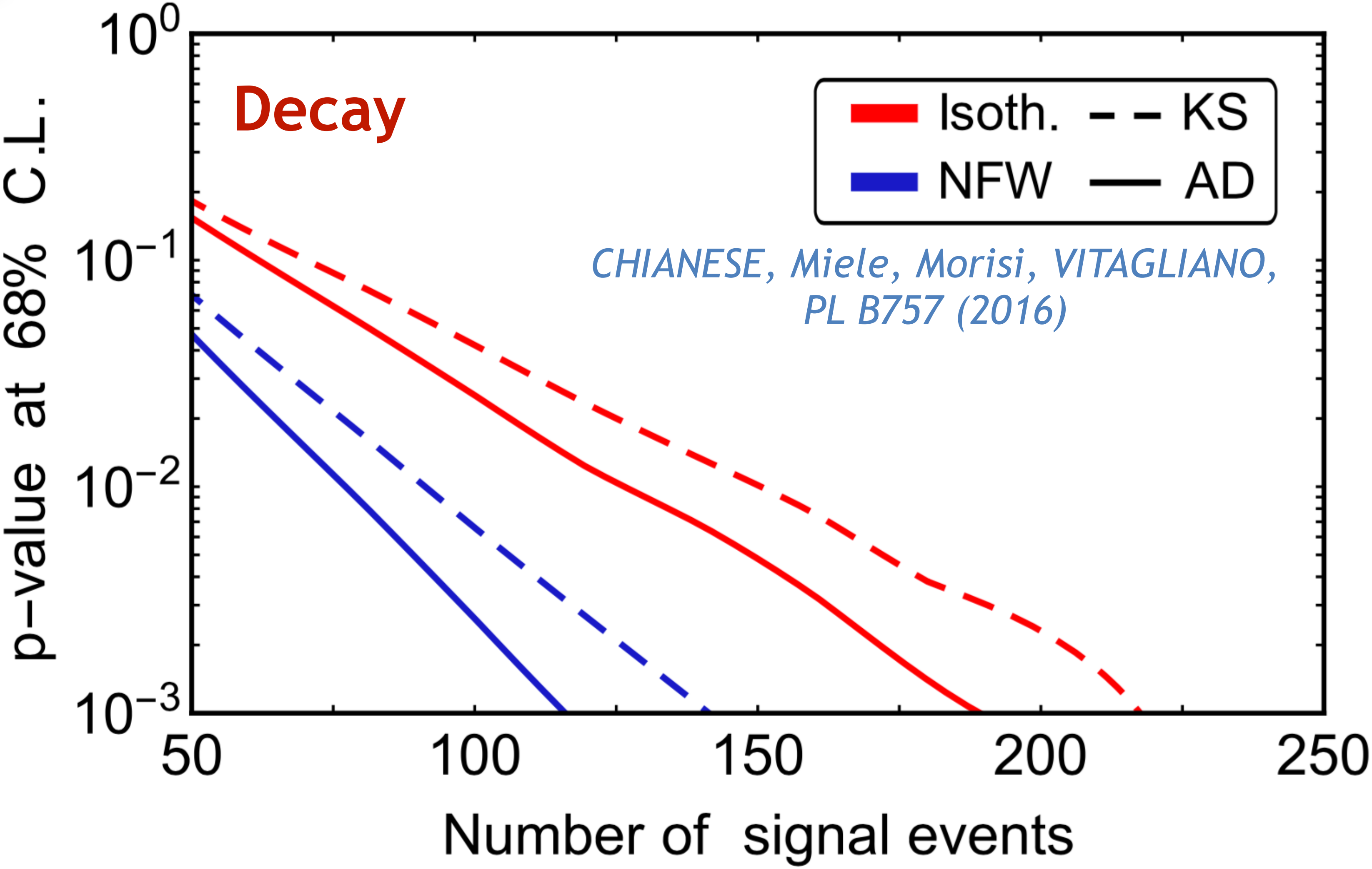
CHIANESE, Miele, Morisi, Vitagliano, PL B757 (2016)



Scenario		KS	AD
Astrophysics	Gal. plane	0.007 - 0.008	not defined
	Iso. dist.	0.20 - 0.55	0.17 - 0.54
DM decay	NFW	0.06 - 0.16	0.03 - 0.14
	Isoth.	0.08 - 0.22	0.05 - 0.19
DM annih. $\Delta_0^2 = 10^4$	NFW	$(0.3 - 0.9) \times 10^{-4}$	$(0.3 - 3.8) \times 10^{-4}$
	Isoth.	$(0.9 - 2.8) \times 10^{-3}$	$(1.0 - 5.0) \times 10^{-3}$
DM annih. $\Delta_0^2 = 10^6$	NFW	0.02 - 0.05	0.02 - 0.07
	Isoth.	0.10 - 0.28	0.08 - 0.29
DM annih. $\Delta_0^2 = 10^8$	NFW	0.19 - 0.54	0.17 - 0.53
	Isoth.	0.20 - 0.55	0.17 - 0.54

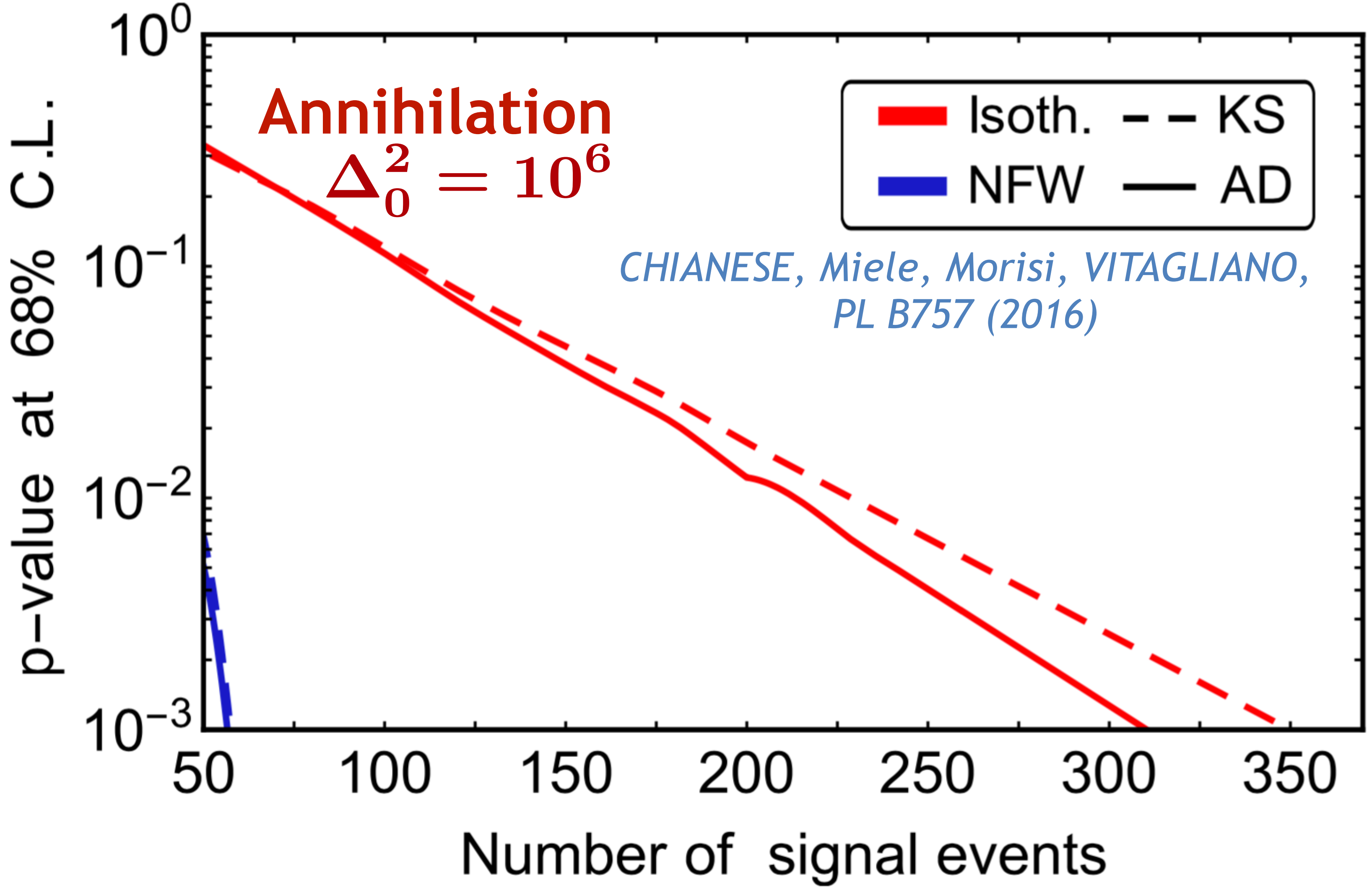
Forecast analysis

Number of signal events required to distinguish the decaying DM angular distribution from isotropic one.



Forecast analysis

Number of signal events required to distinguish the annihilating DM angular distribution from isotropic one.



CHIANESE, Miele, Morisi, VITAGLIANO, PL B757 (2016)

Conclusions

We had the first observation of extraterrestrial high energy neutrinos at IceCube.

IceCube events could be related to the Dark Matter problem, in particular:

- PeV neutrinos could be originated by a leptophilic decaying Dark Matter
- the 2-sigma excess in the energy range 60-100 TeV could be related to a Dark Matter scenario

IceCube can provide important information and give indications on the direction for future DM experiments.

The need of **more statistics** at low and high energy emphasizes the importance of future Neutrino Telescope (IceCube-2gen and KM3NeT).

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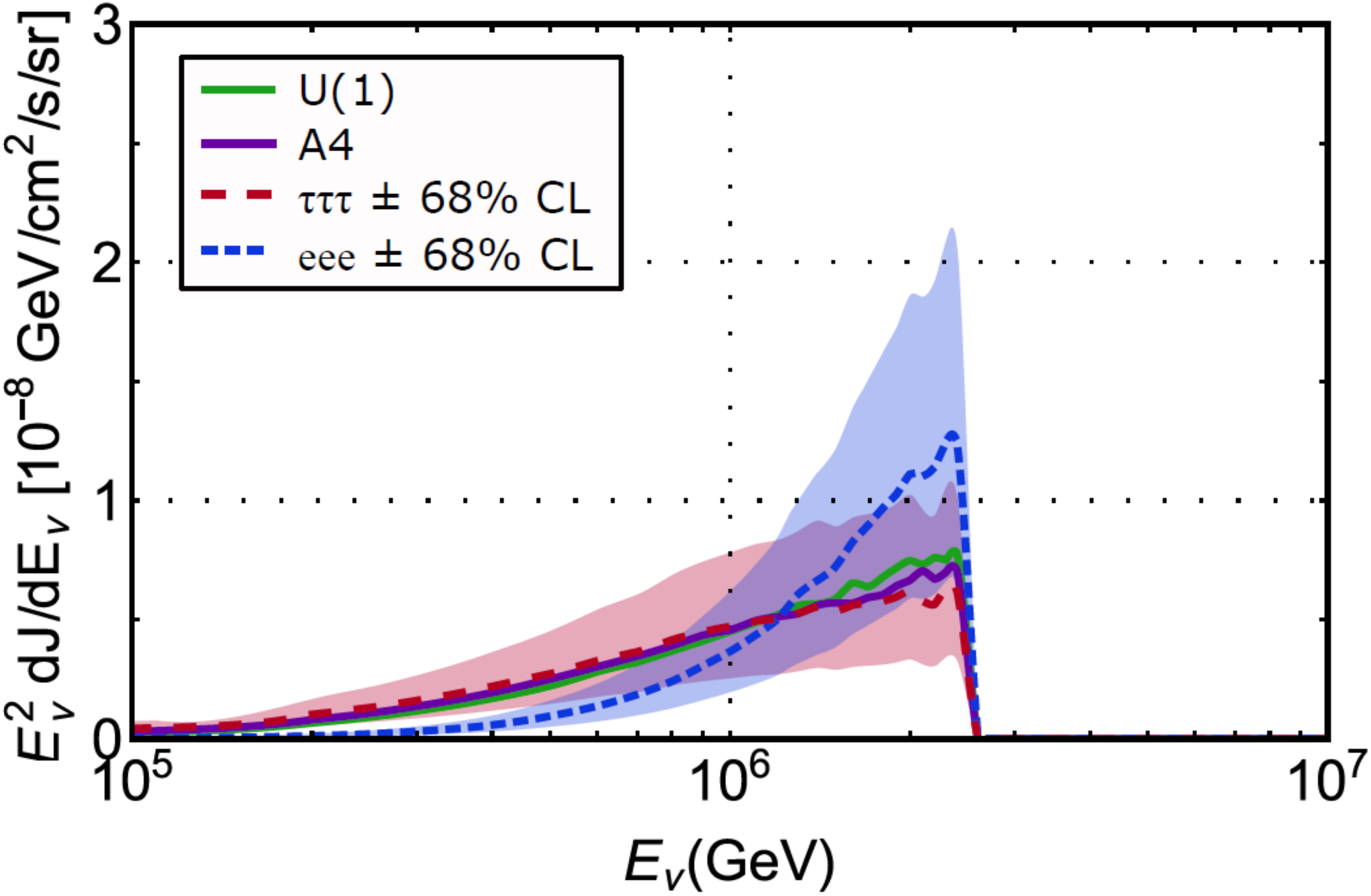
Thanks for your attention

Backup slides

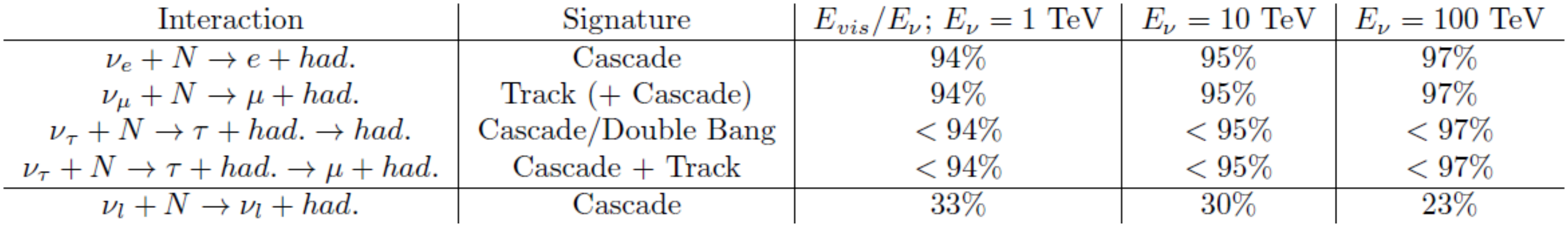
Different Flavor Models

Boucenna, CHIANESE, Mangano, Miele, Morisi, Pisanti, VITAGLIANO, JCAP 1502



Deposited and neutrino energies

To statistically estimate the ratio between the deposited and neutrino energies a MonteCarlo simulation of the apparatus is required.



Interaction	Signature	E_{vis}/E_ν; $E_\nu = 1$ TeV	$E_\nu = 10$ TeV	$E_\nu = 100$ TeV
$\nu_e + N \to e + had.$	Cascade	94%	95%	97%
$\nu_\mu + N \to \mu + had.$	Track (+ Cascade)	94%	95%	97%
$\nu_\tau + N \to \tau + had. \to had.$	Cascade/Double Bang	$< 94\%$	$< 95\%$	$< 97\%$
$\nu_\tau + N \to \tau + had. \to \mu + had.$	Cascade + Track	$< 94\%$	$< 95\%$	$< 97\%$
$\nu_l + N \to \nu_l + had.$	Cascade	33%	30%	23%

IceCube, JINST 9 (2014)

When for a bin of the deposited energy a significant statistics is collected one could apply the average ratio

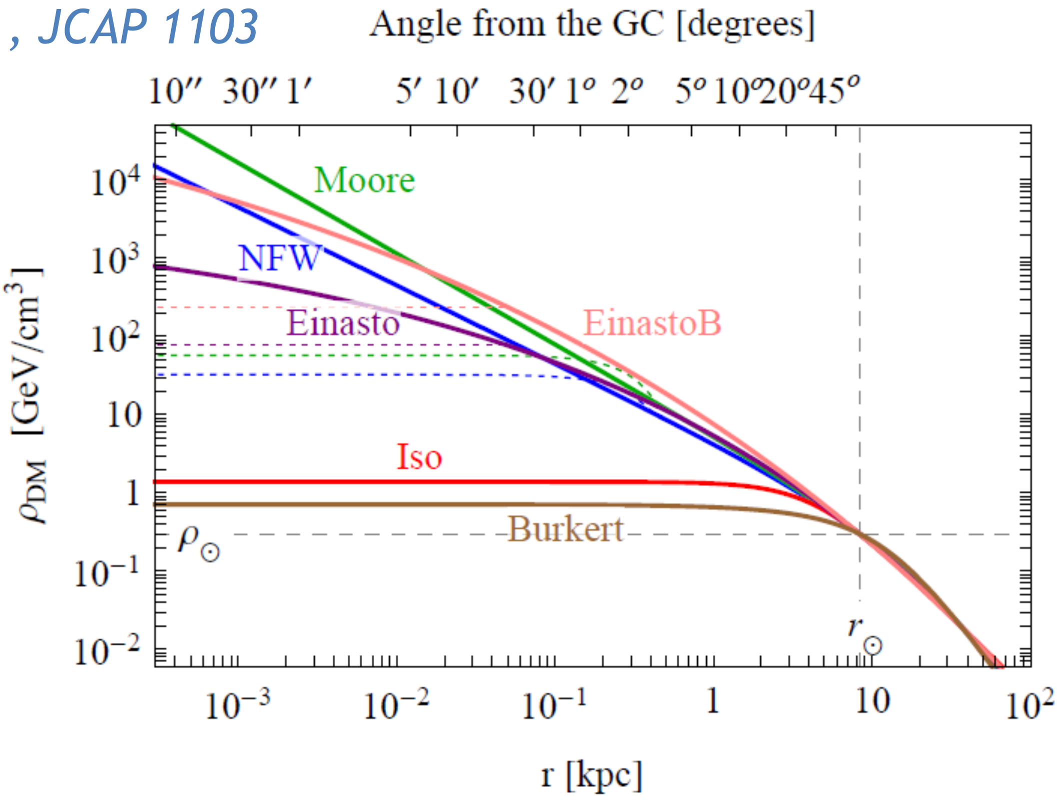
$$\frac{E_{\rm dep}}{E_\nu} = \frac{97\%\,\sigma^{CC} + 23\%\,\sigma^{NC}}{\sigma^{CC} + \sigma^{NC}} \sim 75\%$$

Dark Matter density profiles

Navarro-Frenk-White: $$\rho_{\rm NFW}(\mathbf{r}) = \rho_s \frac{r_s}{\mathbf{r}}\left(1+\frac{\mathbf{r}}{r_s}\right)^{-2}$$

Isothermal: $$\rho_{\rm Iso}(\mathbf{r}) = \frac{\rho_s}{1+(\mathbf{r}/r_s)^2}$$

Cirelli et al., JCAP 1103



Neutrino energy spectrum

- To evalute the neturino energy specturum dN_ν/dE_ν, we have developed a MonteCarlo in *Mathematica*.

- There are **6** decay channels with the same Branching Ratio.

$$\mathrm{Br}\left(\chi \to e^{\pm}\mu^{\mp}\nu_\tau\right) = \mathrm{Br}\left(\chi \to \mu^{\pm}\tau^{\mp}\nu_e\right) = \mathrm{Br}\left(\chi \to \tau^{\pm}e^{\mp}\nu_\mu\right) = \frac{1}{6}$$

- We take into all the secondary neutrinos.

$$\mu \to e + \nu_e + \nu_\mu \quad \sim 100\%$$

$$\tau \to e + \nu_e + \nu_\tau \quad \sim 17.8\%$$

$$\tau \to \mu + \nu_\mu + \nu_\tau \quad \sim 17.4\%$$

$$\tau \to \pi + \nu_\tau \quad \sim 10.8\%$$

$$\tau \to \pi + \pi^0 + \nu_\tau \quad \sim 25.5\%$$

$$\tau \to \pi + \pi^0 + \pi^0 + \nu_\tau \quad \sim 9.3\%$$

$$\tau \to \pi + \pi^+ + \pi^- + \nu_\tau \quad \sim 9.0\%$$

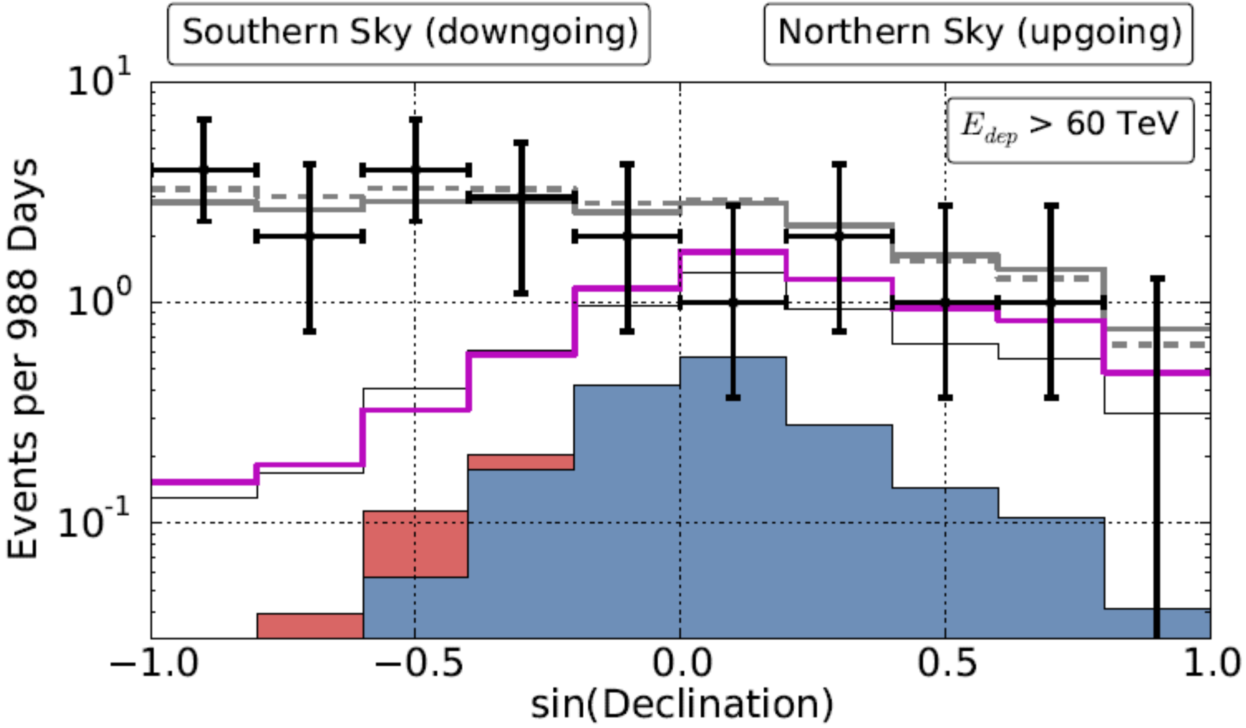
- **2 neutrinos**
- **3 neutrinos**
- **γ-rays**

→ constraint from *FERMI*

Isotropy

- The observed IceCube flux is **isotropic**.

IceCube, PRL 113 (2014)



Prompt neutrinos cannot explain the IceCube data!

See also: Halzen, Wille, 1601.03044