PeV Decaying Leptophilic Dark Matter at IceCube

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LNGS
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arXiv:1507.01000

Outline

- IceCube data

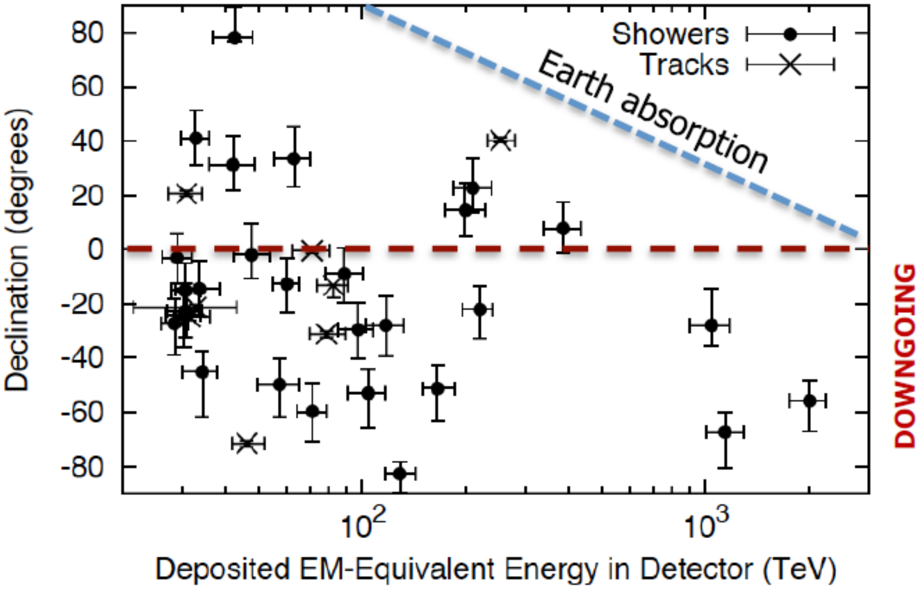
- Sources of high energy neutrinos

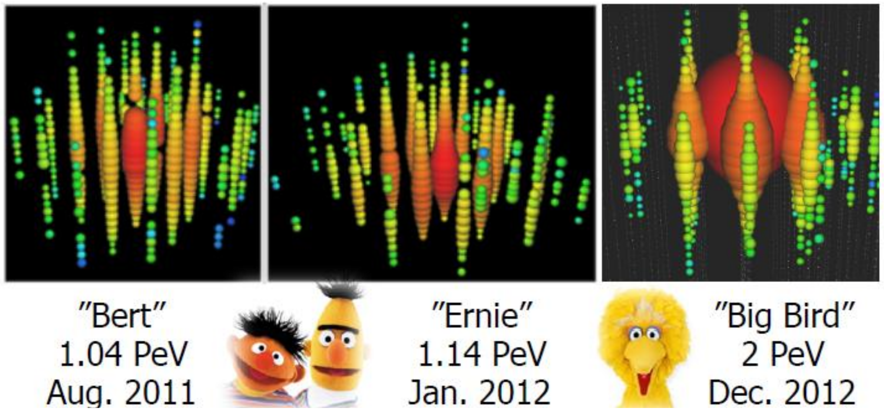
    - Astrophysical sources
    - Dark Matter (DM)

- Leptophilic PeV decaying Dark Matter

    - Models
    - Results

IceCube: 3 years events

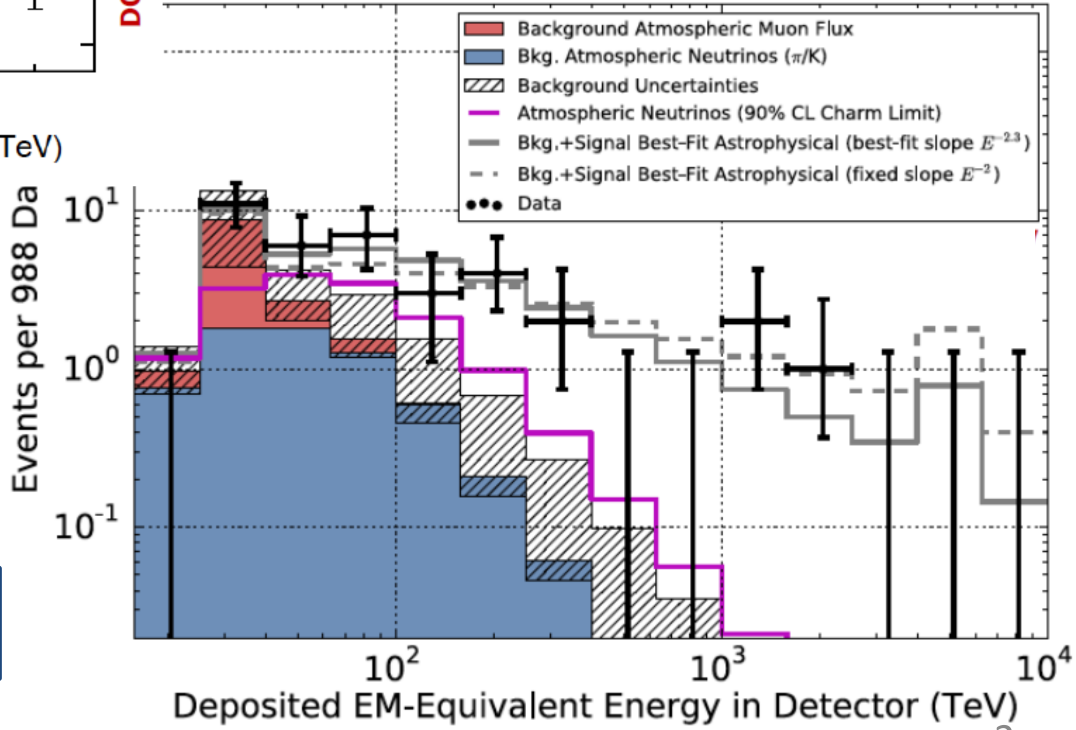




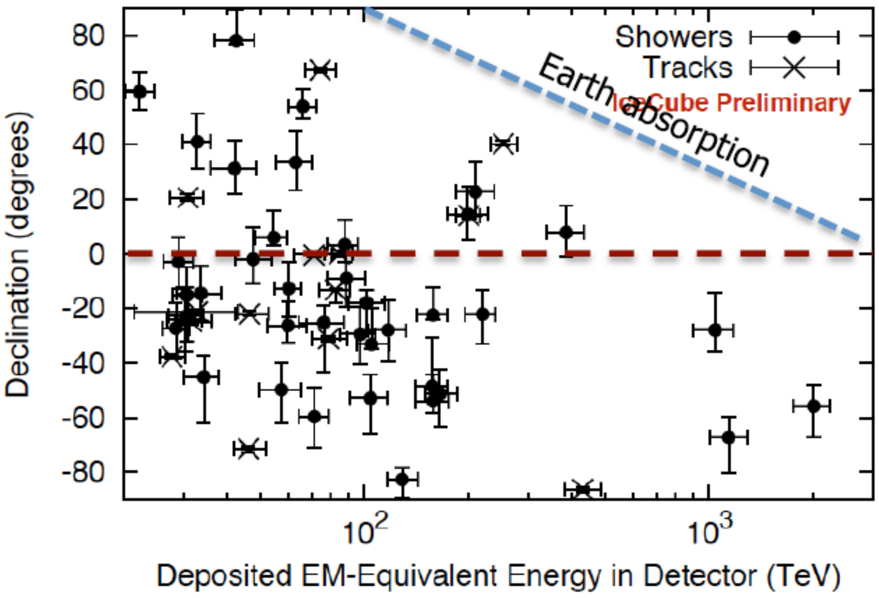
IceCube, PRL 113:101101 (2014)

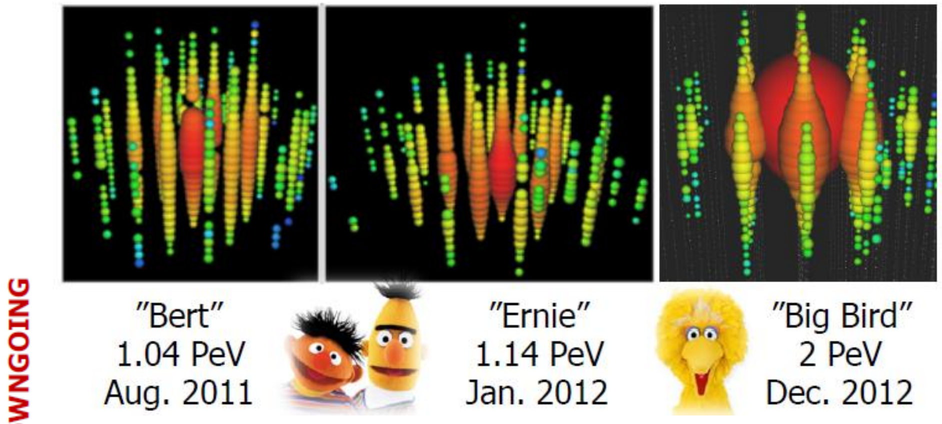
- 3 yrs: 37 events in 988 days
- Isotropic flux
- Atmospheric background:
  - $8.4 \pm 4.2\ \mu$
  - $6.6 + 5.9\ \nu$

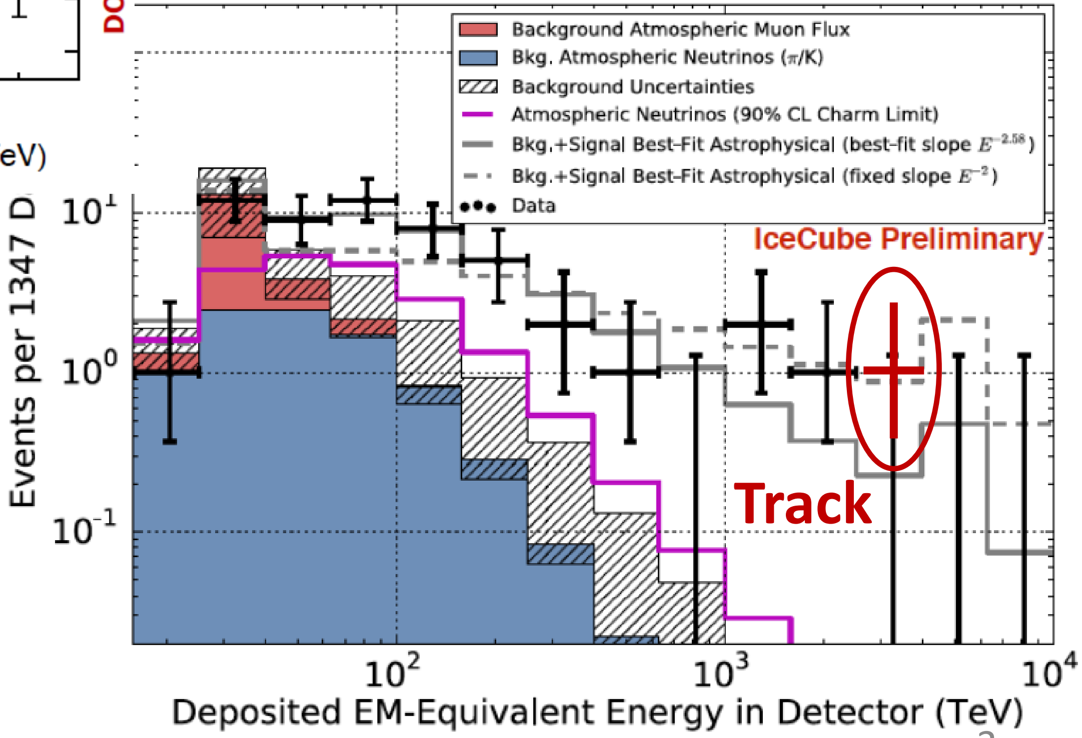
5.7 σ



IceCube: 4 years events





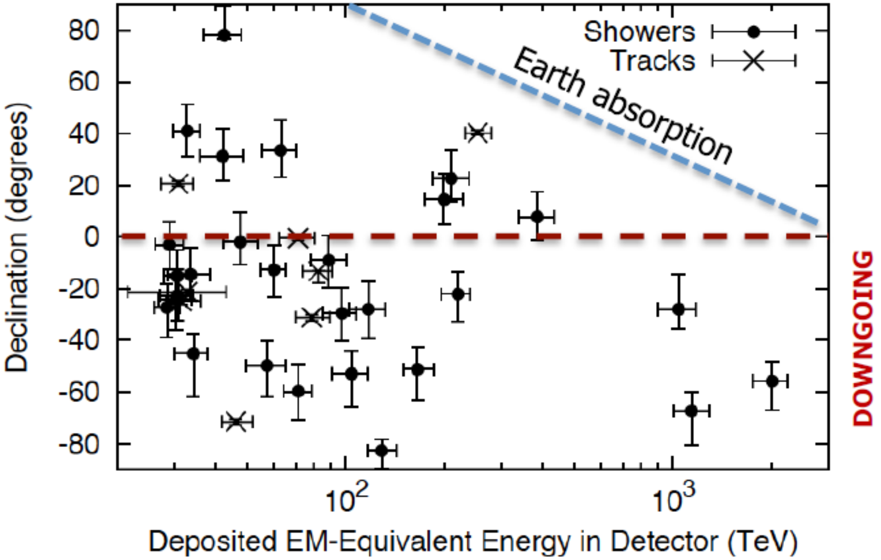


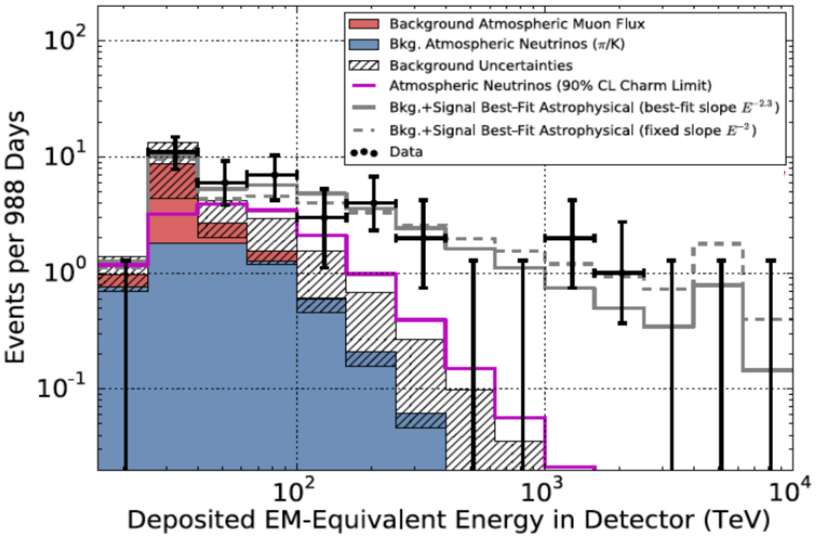
IPA 2015

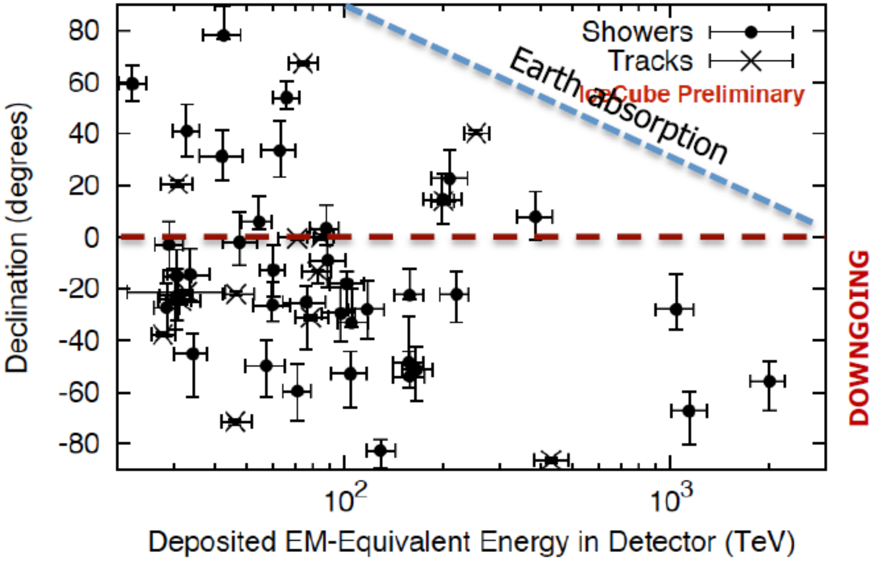
- 4 yrs: 54 events in 1347 days
- Isotropic flux
- Atmospheric background:
  - $8.4 \pm 4.2\ \mu$
  - $6.6 + 5.9\ \nu$

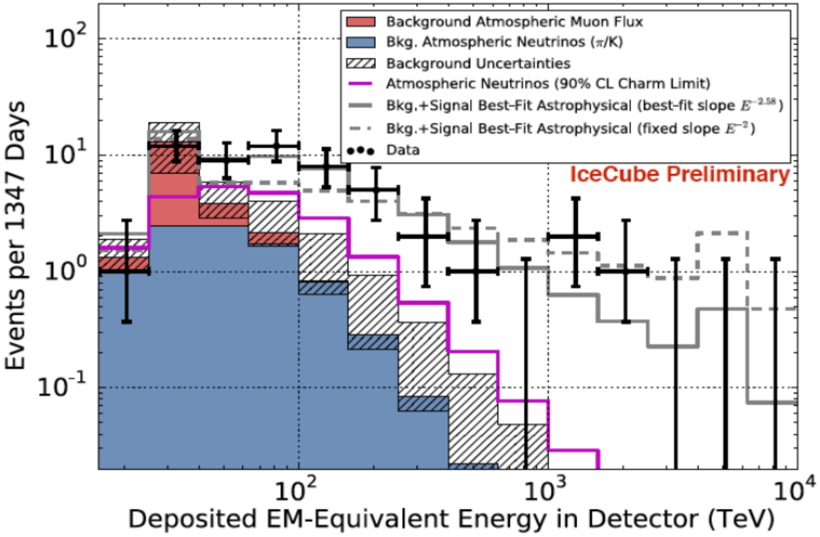
$\sim$7 σ

Key feautres









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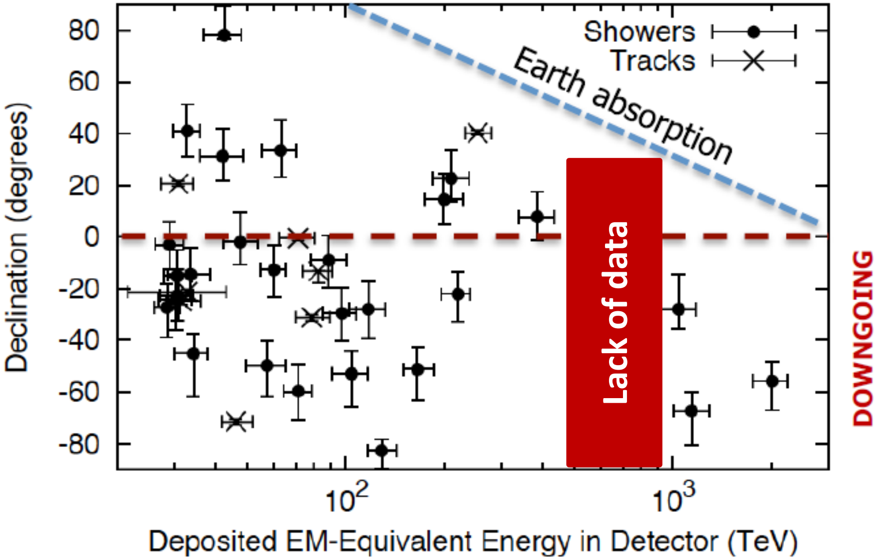
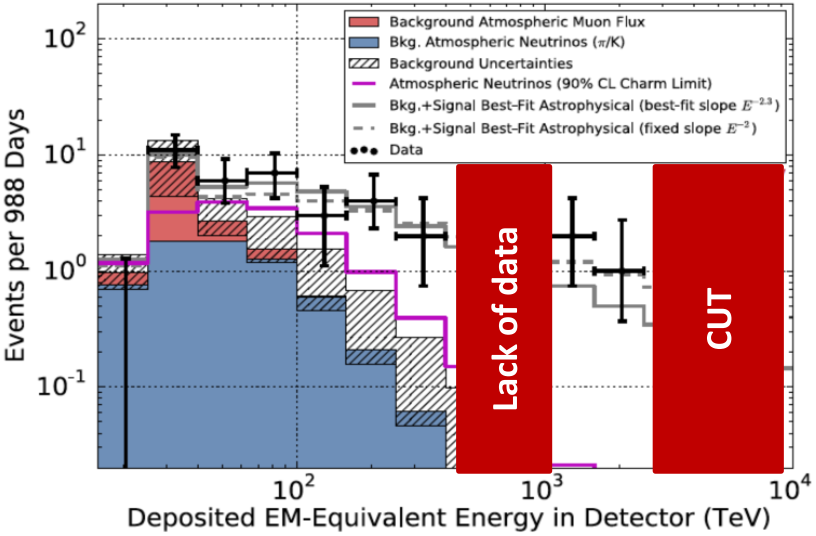
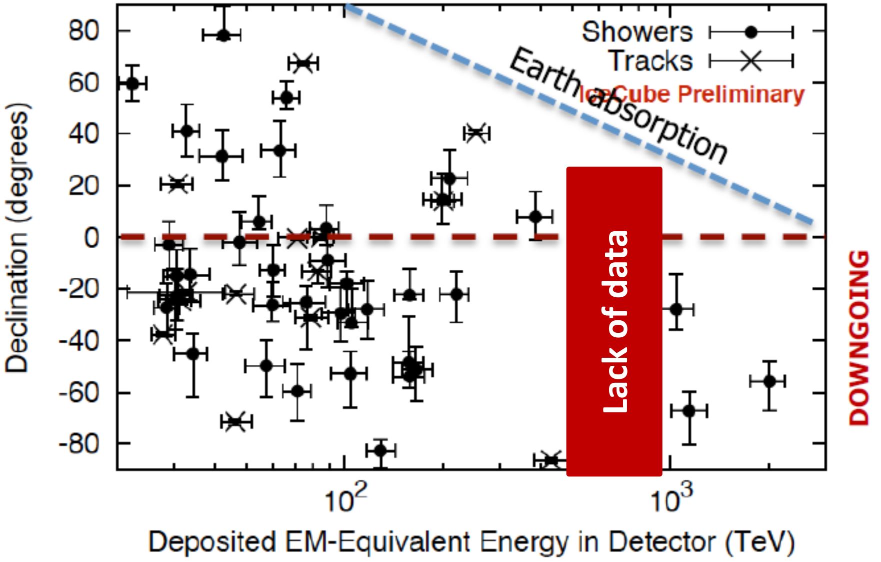
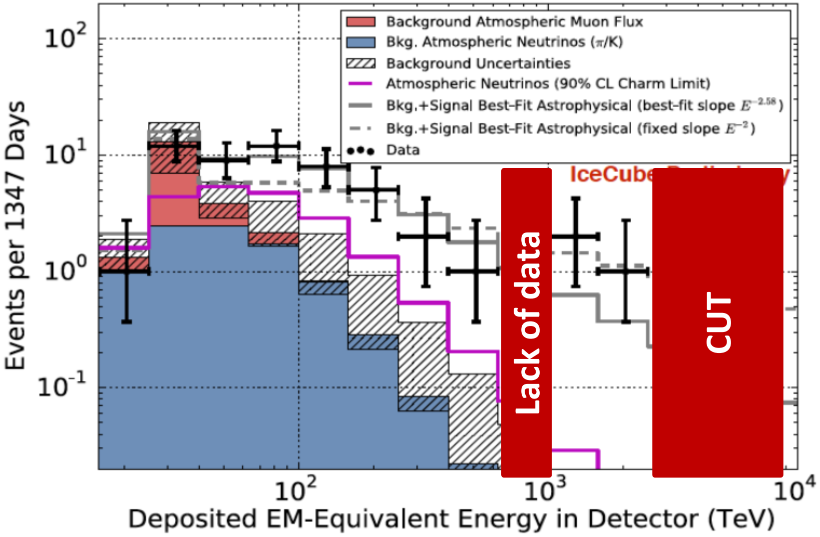








Astrophysical sources

- The measured IceCube data can be explained by some astrophysical scenario.
  - SuperNova Remnants
  - Gamma-Rays Burst
  - Active Galactic Nuclei
  - …

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

- The neutrinos are produced by Cosmic Rays through hadronic interactions.

pp interactions

expected for CR reservoirs, where CR escaping from their accellerators are confined in magnetized environments for a long time

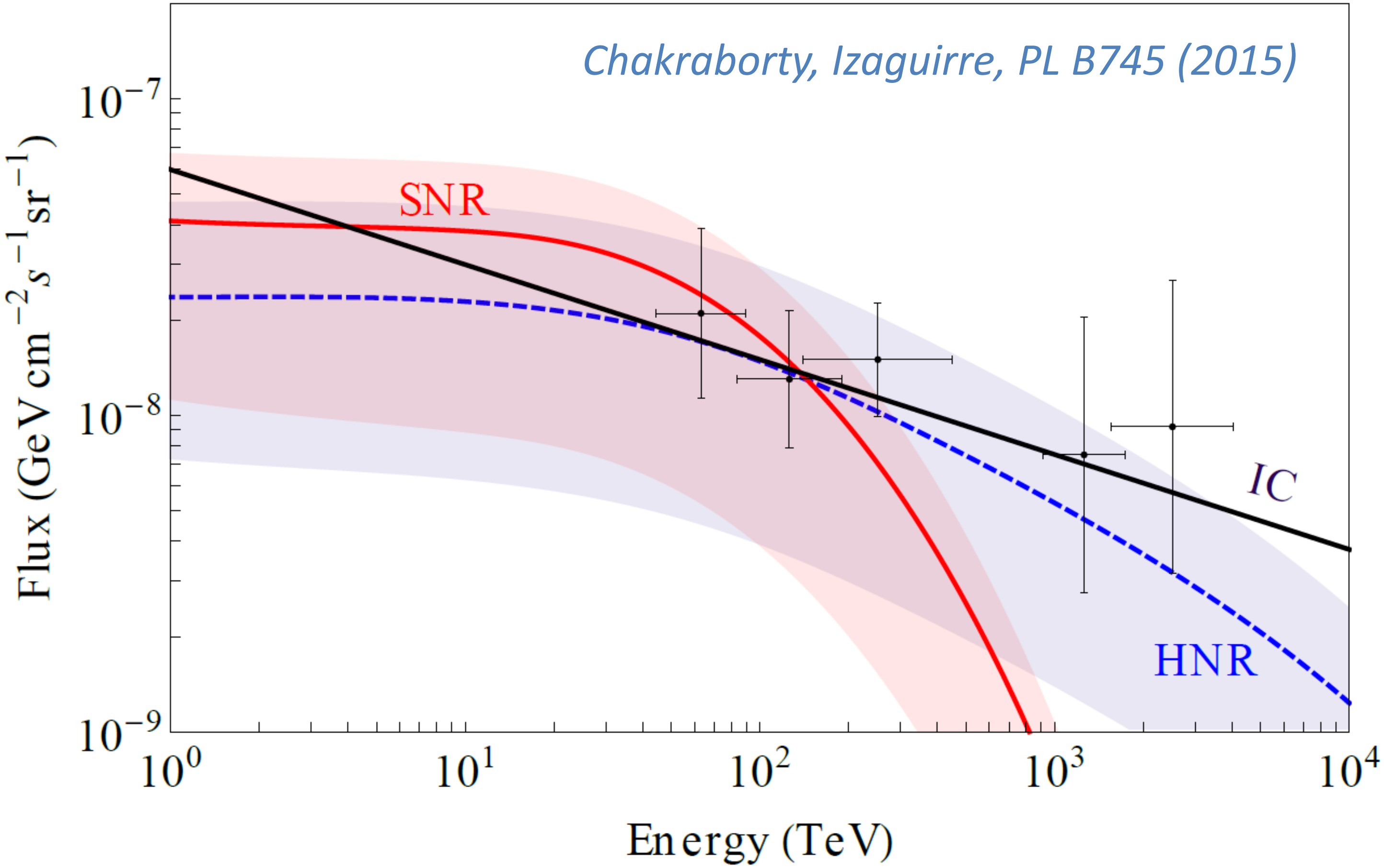
$p\gamma$ interactions

mostly cosmogenic interactions of CR in the intergalactic space

SuperNova Remnants

- SuperNovae Remnants are described by a Broken Power Law.

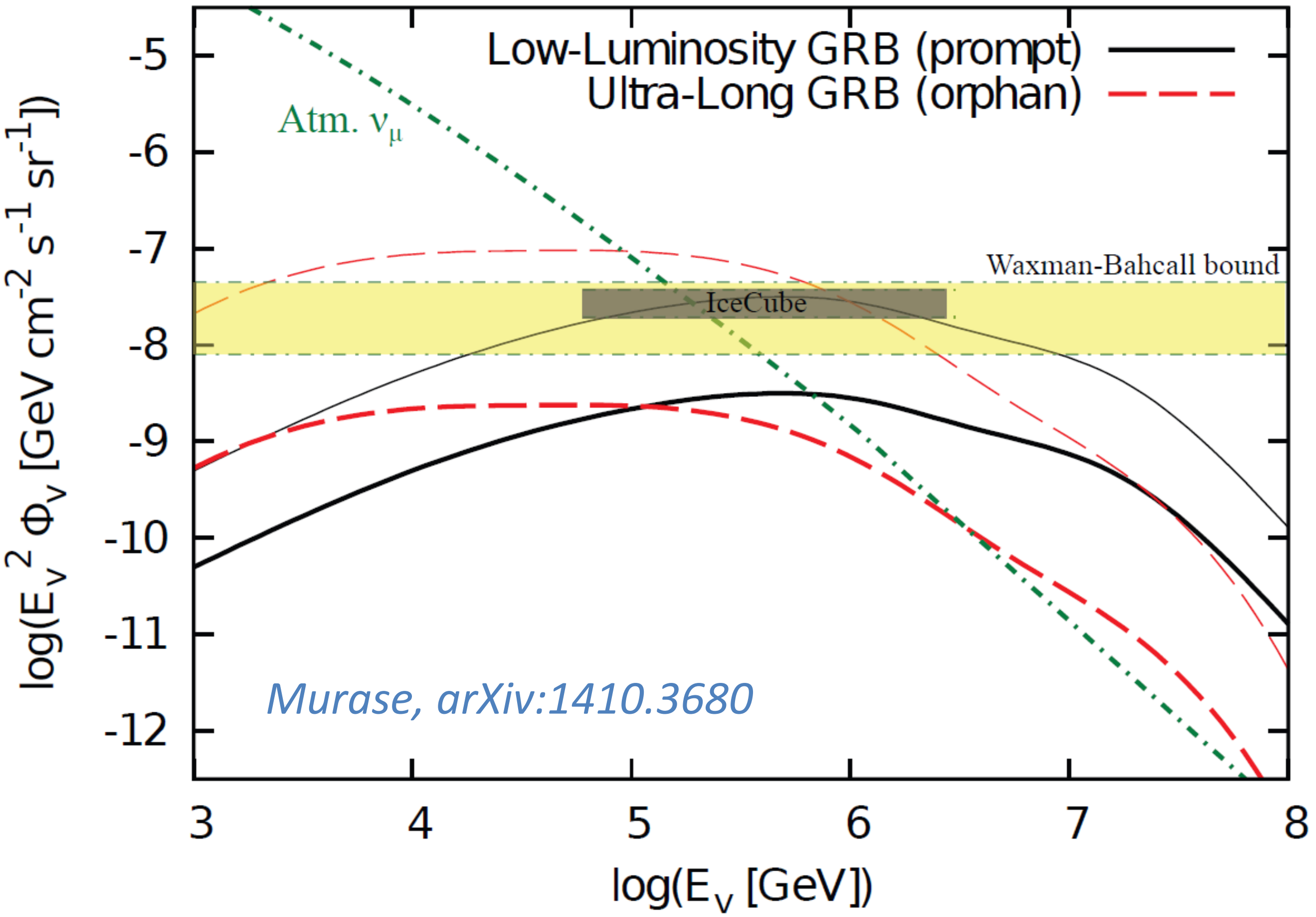
CUT-OFF $E_0 \sim \mathcal{O}$ **(100 TeV)**



Gamma-Ray Burst

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

→ **Correlation not observed yet!**



Murase, arXiv:1410.3680

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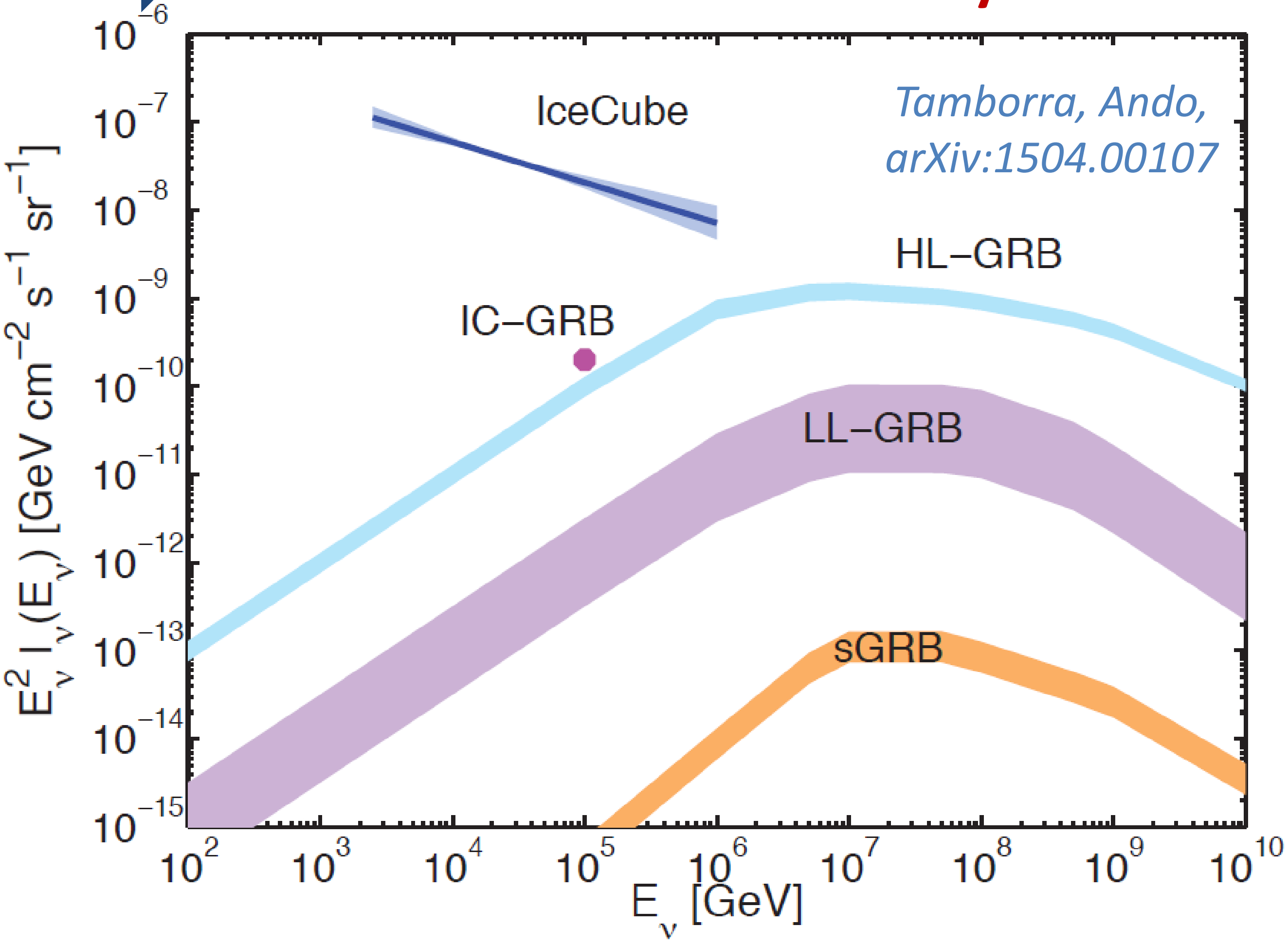
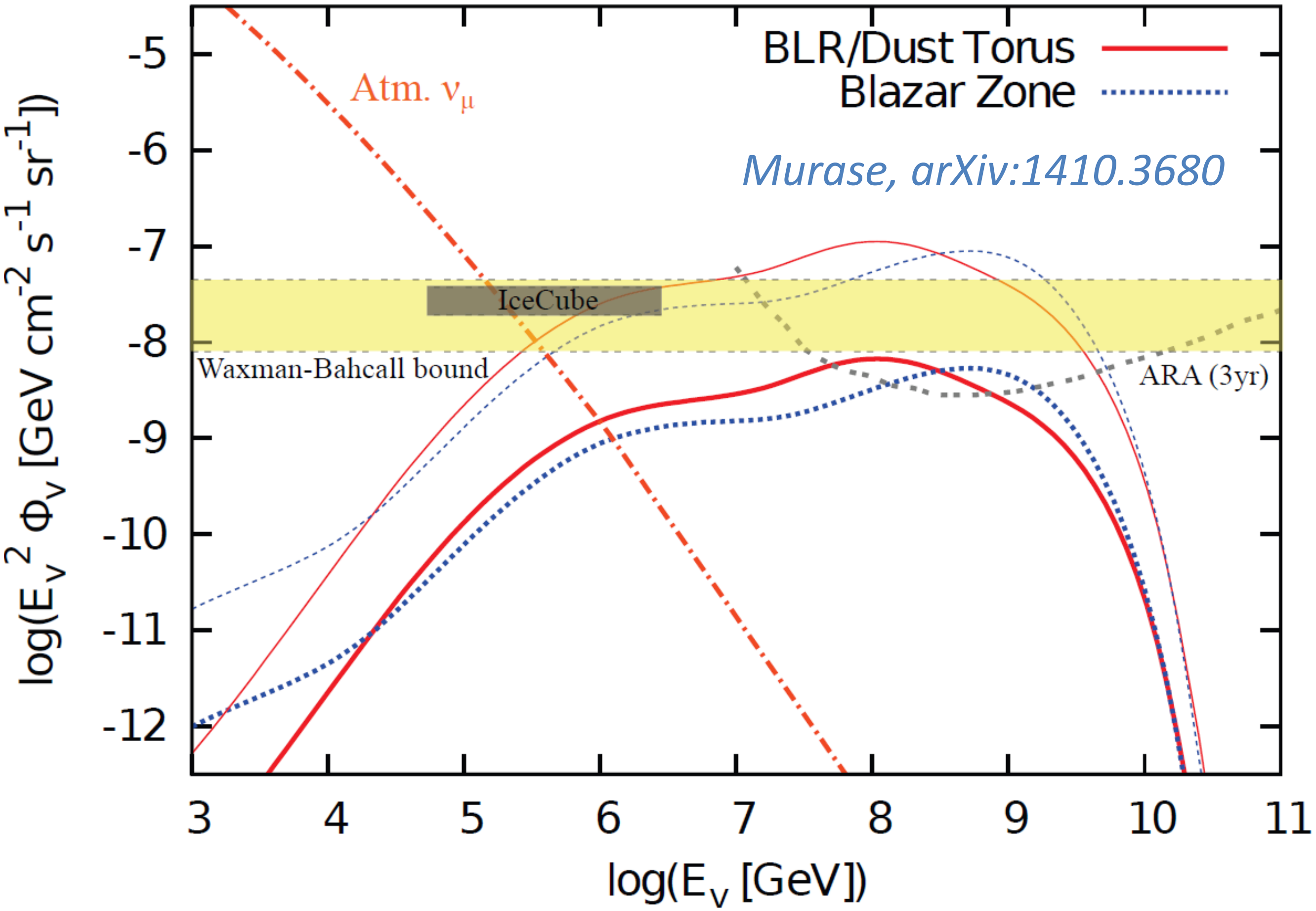


Active Galactic Nuclei

- AGN can explain only PeV neutrinos.

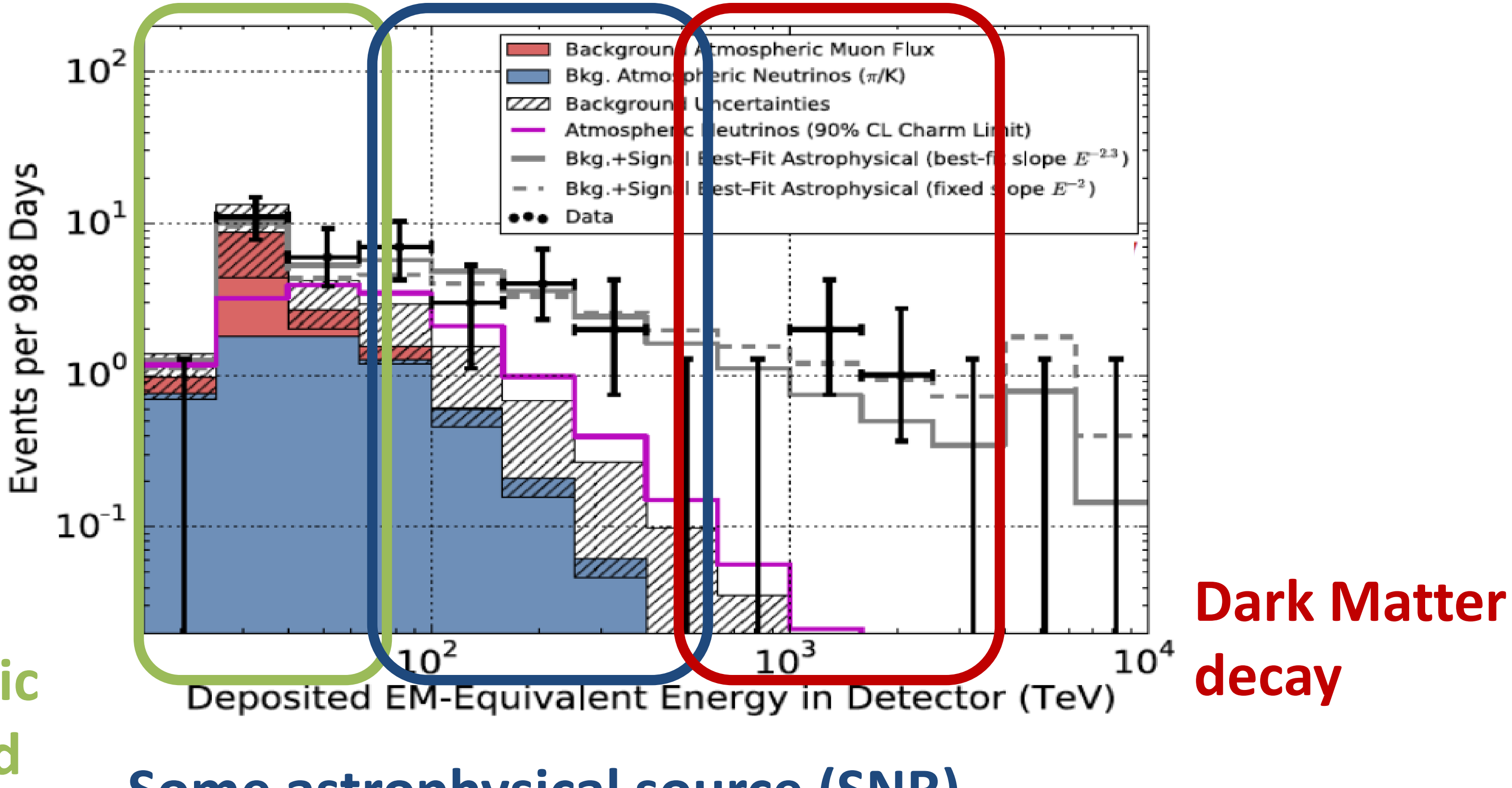
➡ **Large uncertainties!**



Murase, arXiv:1410.3680

Origin of IC events: our assumption

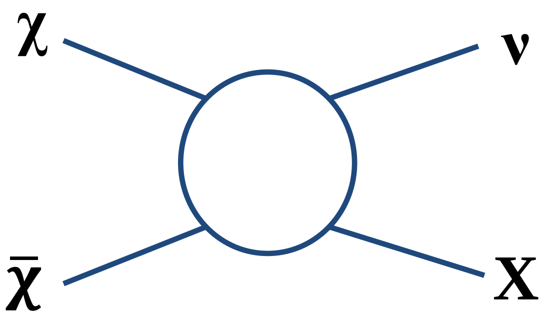
- IceCube events could be also related to the Dark Matter (DM).
- The **lack of data** (0.3-1.0 PeV) and the **cut-off** above 2 PeV are in favor of DM interpretaion.



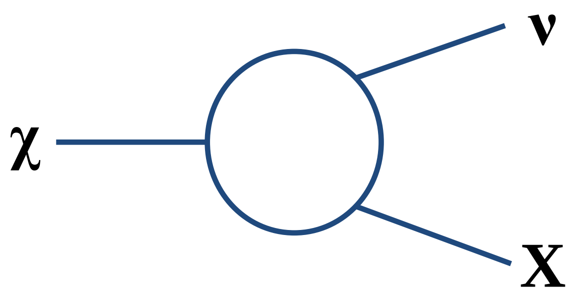
Some astrophysical source (SNR)

Dark Matter & IceCube

Stable



Decay



For PeV DM the annihilation is negligible with respect to decay

Feldstein et al, PR D88:015004 (2013)

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

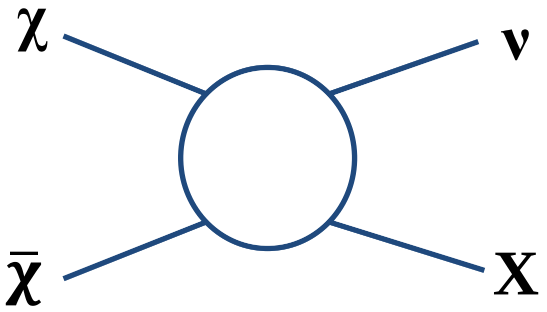
Annihilation

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

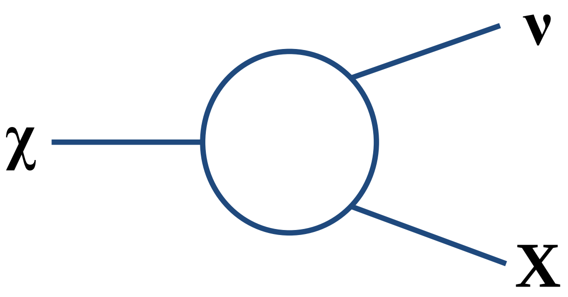
Decay

Dark Matter & IceCube

Stable



Decay



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unless *Feldstein et al, PR D88:015004 (2013)*

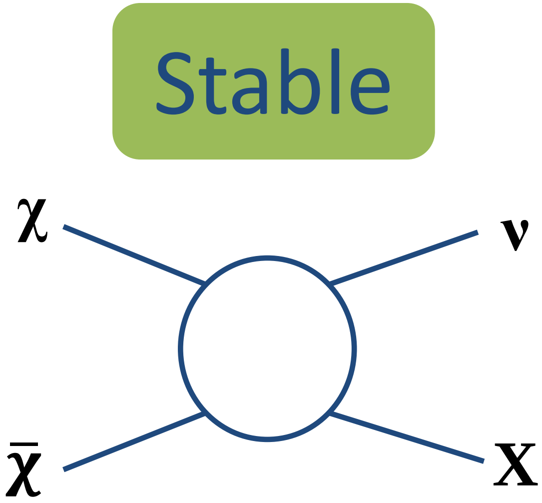
$$\Gamma_{\text{Events}} \sim V\, L_{\text{MW}}\, n_{\text{N}}\, \sigma_{\text{N}} \left(\frac{\rho_{\text{DM}}}{m_{\text{DM}}}\right)^2 \langle \sigma_{\text{Ann}} v \rangle$$

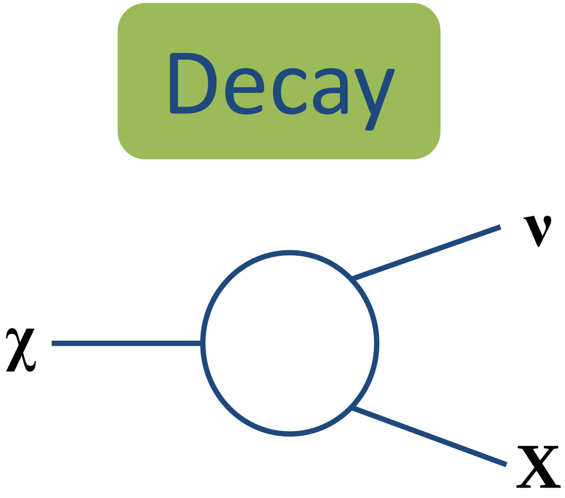
DM is captured in large Celestial bodies like the Sun or cluster of galaxies, enhancing the density

IceCube, PRL 110:131302 (2013)

IceCube, PR D88:122001 (2013)

Dark Matter & IceCube





For PeV DM the annihilation is negligible with respect to decay

unless *Feldstein et al, PR D88:015004 (2013)*

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

DM is boosted, increasing the relative velocity

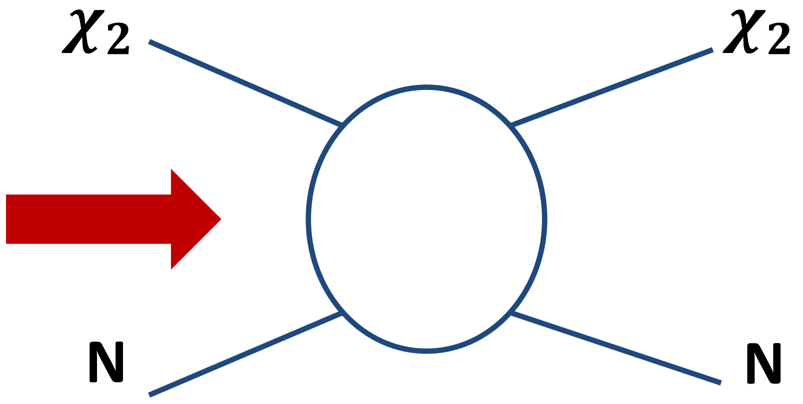
Agashe et al., JCAP14
Bhattacharya et al., JCAP15
Berger et al., JCAP 15
Kopp et al., JHEP15

Boosted Dark Matter

$$\chi_1 \longrightarrow \chi_2$$

$$\Delta m \sim PeV$$

boosted



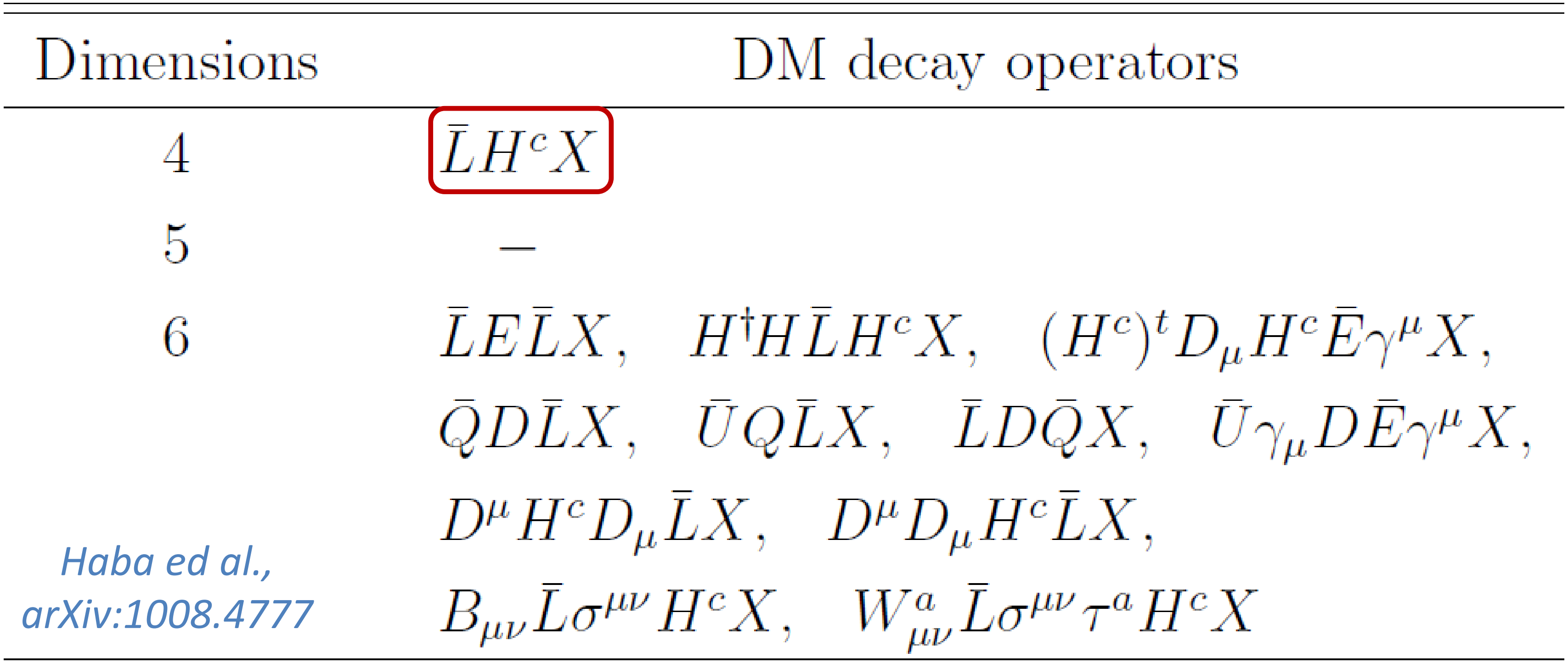
Direct detection!

Agashe et al., JCAP14
Bhattacharya et al., JCAP15
Berger et al., JCAP 15
Kopp et al., JHEP15

Ruled out by the 2.6 PeV track event!

Decaying Dark Matter

- In the scenario of decay, for a gauge-singlet fermionic DM the possible decay operators are



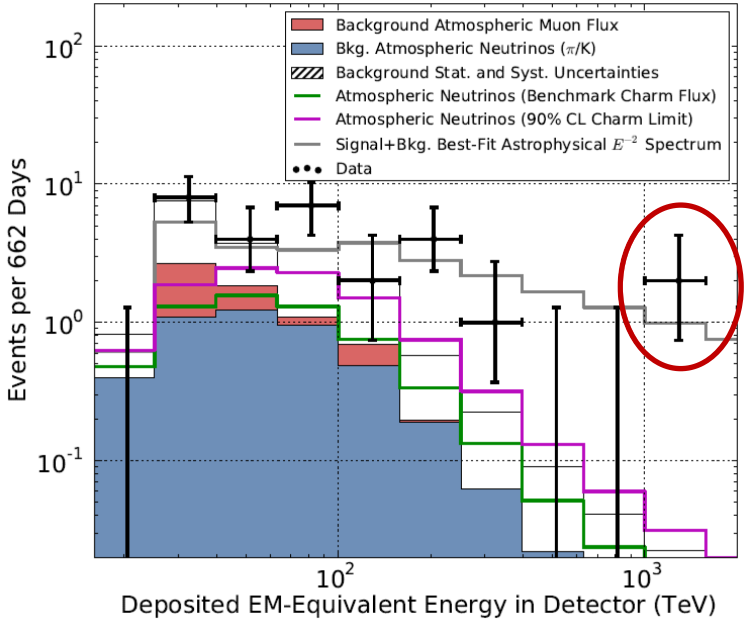
Dimensions	DM decay operators
4	$\boxed{\bar{L}H^cX}$
5	—
6	$\bar{L}E\bar{L}X, \quad H^\dagger H\bar{L}H^cX, \quad (H^c)^t D_\mu H^c\bar{E}\gamma^\mu X,$ $\bar{Q}D\bar{L}X, \quad \bar{U}Q\bar{L}X, \quad \bar{L}D\bar{Q}X, \quad \bar{U}\gamma_\mu D\bar{E}\gamma^\mu X,$ $D^\mu H^c D_\mu\bar{L}X, \quad D^\mu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

Haba ed al., arXiv:1008.4777

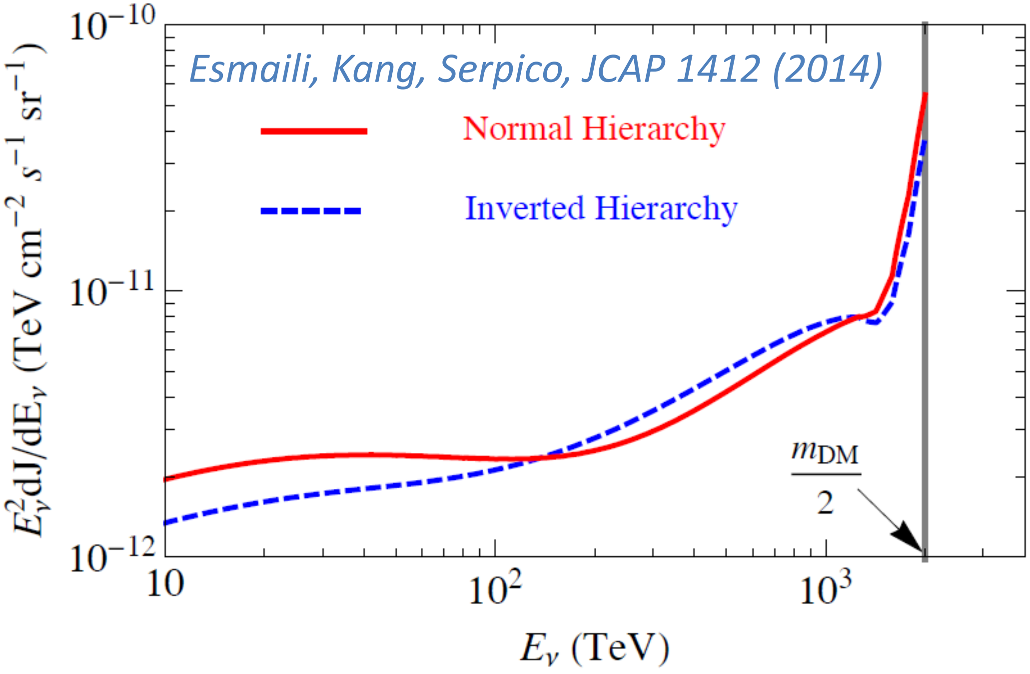
- The renormalizable SM-DM coupling yields to a 2 bodies DM decay with some channels producing one primary neutrino.

2 bodies decay

$$\mathcal{L} \supset y\bar{L}H^c\chi$$



IceCube, Science 342 (2013)



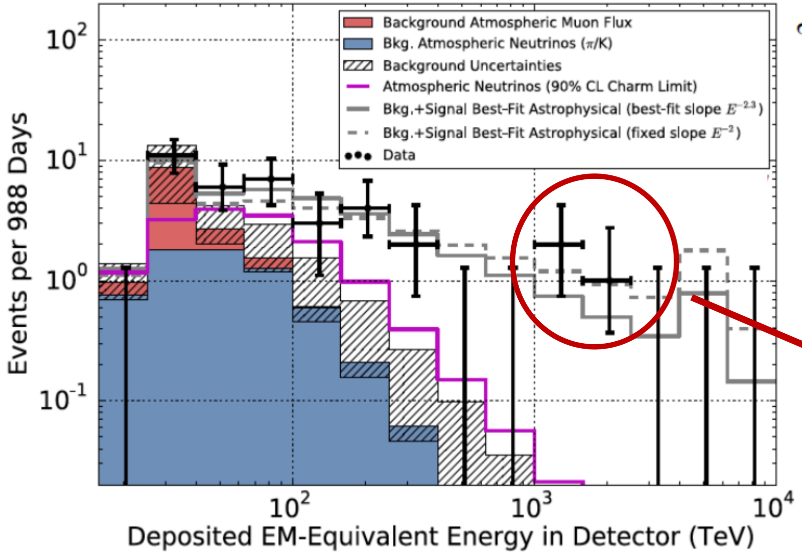
Esmaili, Kang, Serpico, JCAP 1412 (2014)

- 2yrs: only two events at 1 PeV

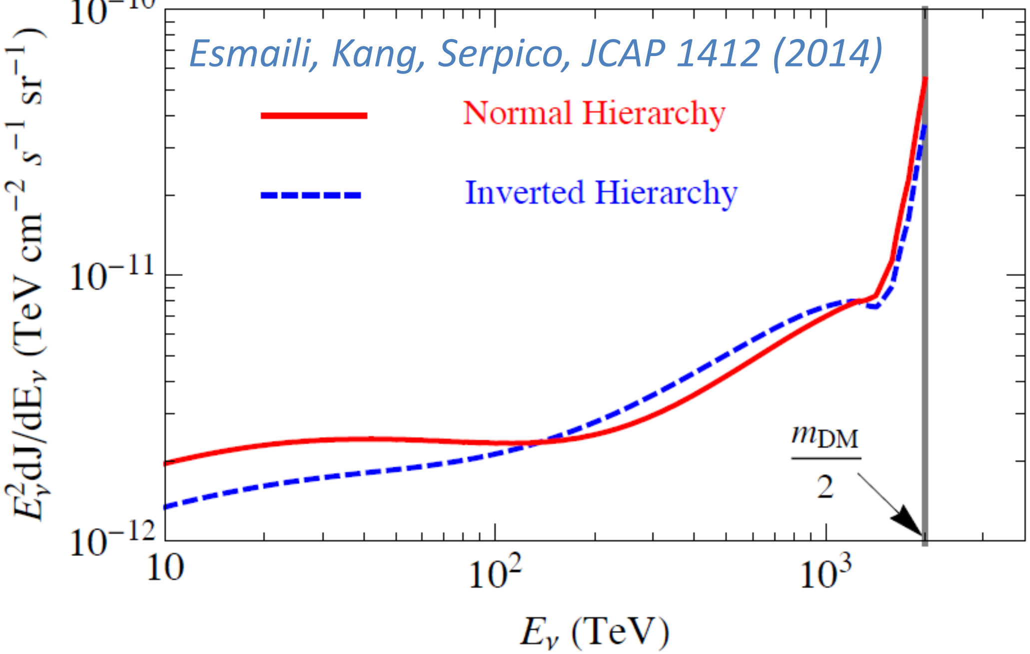
Sharp peak

2 bodies decay

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



IceCube, PRL 113:101101 (2014)



Esmaili, Kang, Serpico, JCAP 1412 (2014)

- 3yrs: two events at 1 PeV and one at 2 PeV

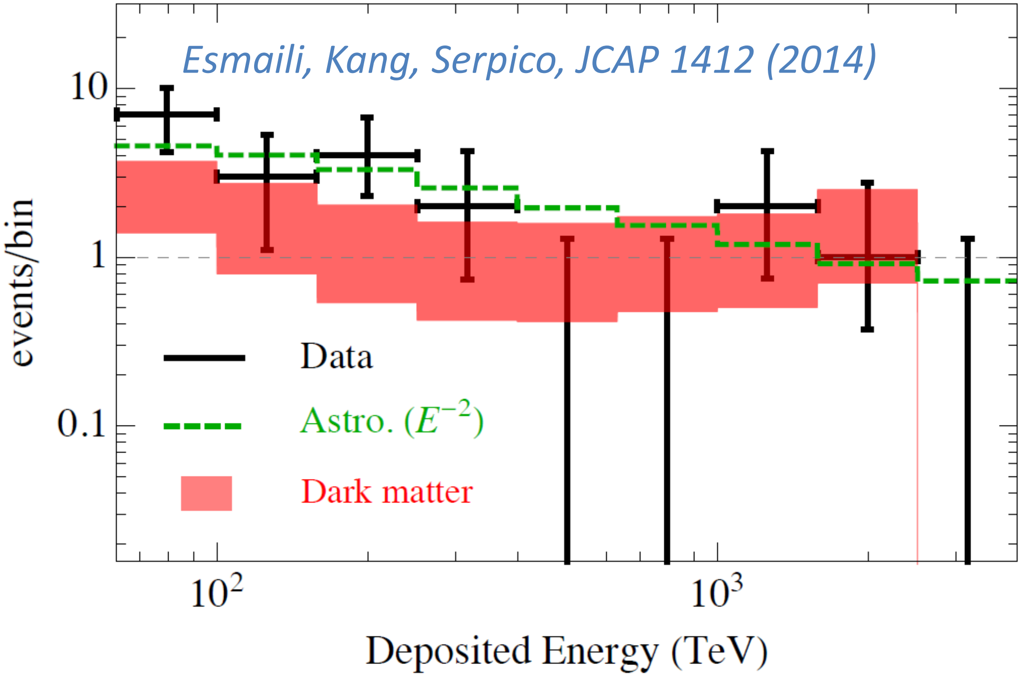
Sharp peak ruled out

2 bodies decay

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

$$\chi \to l^{\pm}W^{\mp}$$
$$\chi \to \nu_l Z$$
$$\chi \to \nu_l h$$

quarks


Esmaili, Kang, Serpico, JCAP 1412 (2014)

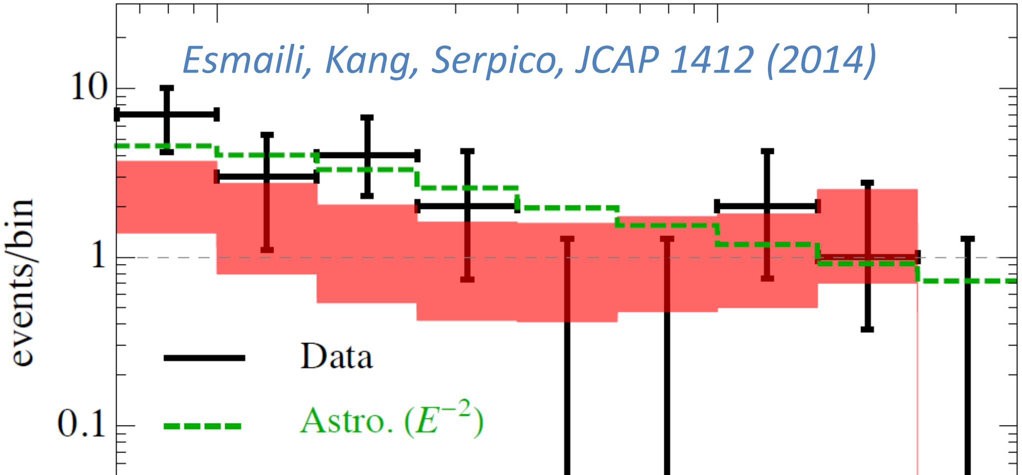
- Secondary neutrinos produced by **quarks** allow to fit all data even through 2 bodies decay with an **unnatural coupling**.

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

but…

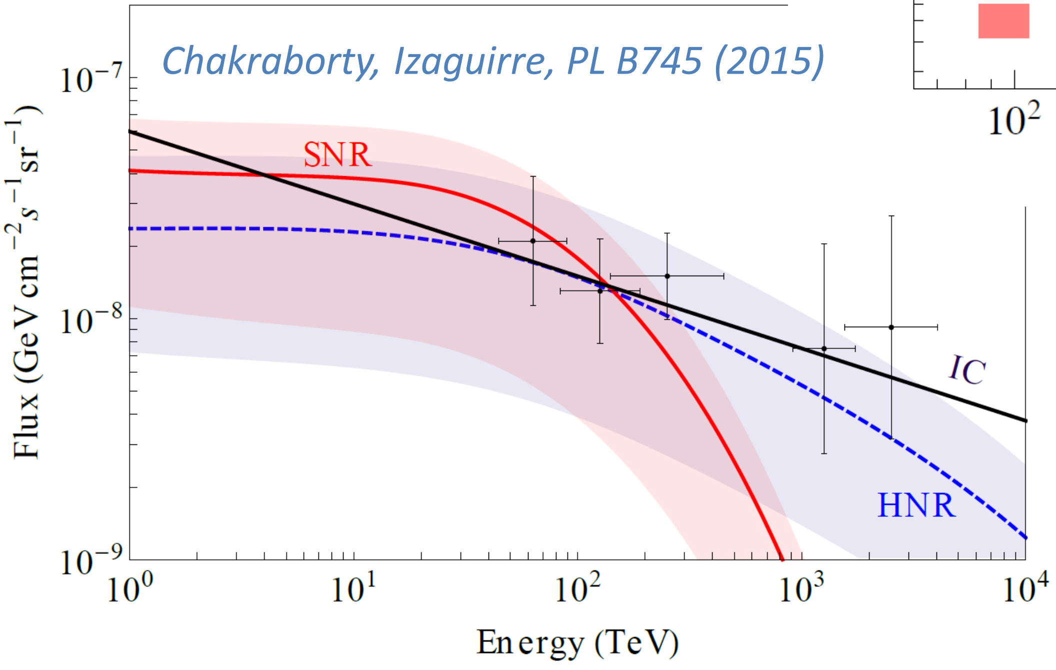
2 bodies decay

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



Esmaili, Kang, Serpico, JCAP 1412 (2014)

SuperNova Remnant



Chakraborty, Izaguirre, PL B745 (2015)

Could be in contrast with known astrophysical sources!

Decaying Dark Matter

- We want to 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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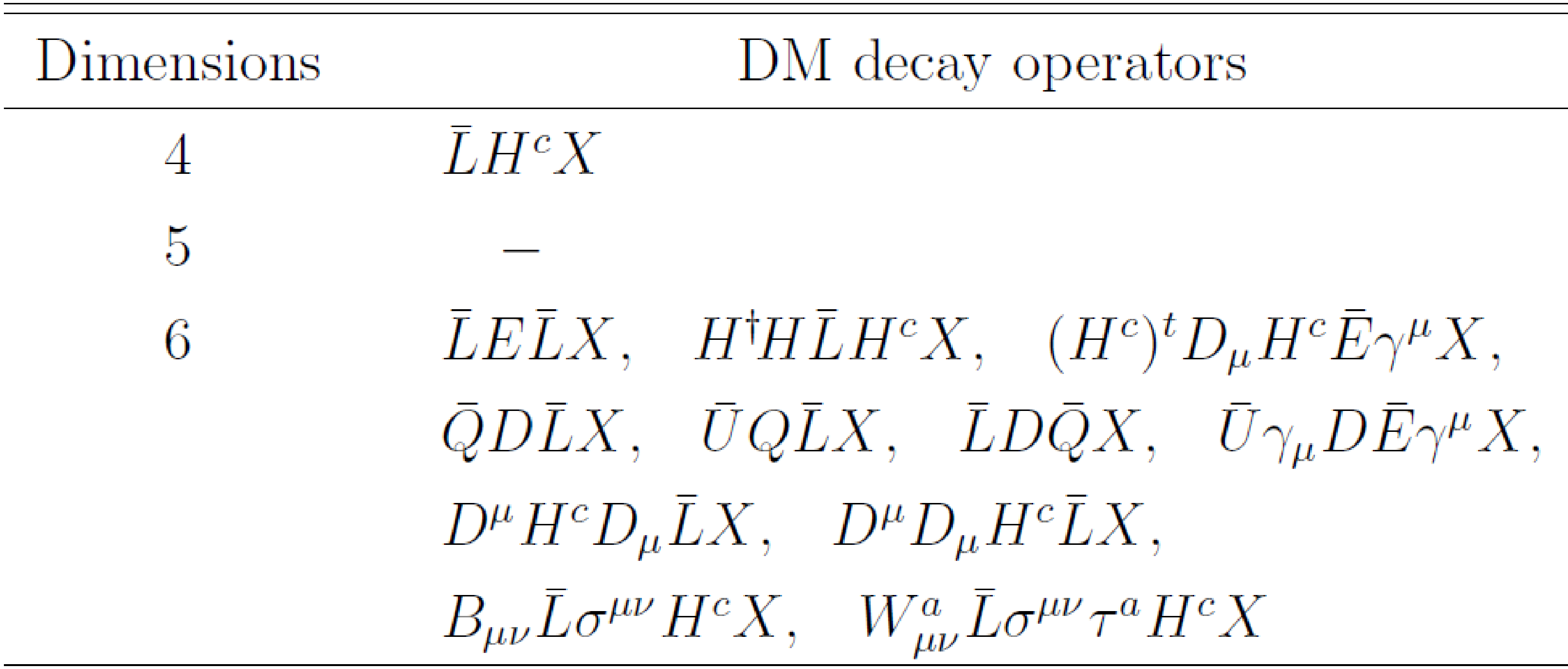
  - direct coupling with neutrino → **primary *ν* flux**
  - multi body final state → **spread *ν* flux**
  - leptophilic (no quarks) → **negligible contribution at low energy**

Decaying Dark Matter

- There exsist only one operator with those characteristcs.

Haba ed al., arXiv:1008.4777



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"natural" small coupling
multi body decay

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“natural” small coupling
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primary ν flux

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"natural" small coupling
multi body decay

primary ν flux

negligible contribution
at low energy

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

Symmetries and Models

Allowed

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

Forbidden

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

- We can use Abelian U(1) symmetry:

	L_e, ℓ_e	L_μ, ℓ_μ	L_τ, ℓ_τ	ϕ	χ
$U(1)_\chi$	1	4	2	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	ϕ	χ
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$

A_4 flavour indices

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

Neutrino flux from DM

- The differential neutrino flux from decaying DM has two components:

Galactic

$$\frac{d\phi_\nu}{dE_\nu}(E_\nu) = \frac{1}{M_{DM}\tau_{DM}}\left(\frac{1}{4\pi}\boxed{\frac{dN_\nu}{dE_\nu}[E_\nu]}\right)\frac{1}{4\pi}\int d\Omega\int_0^\infty ds\,\boxed{\rho\left[r\left(s,l,b\right)\right]}$$

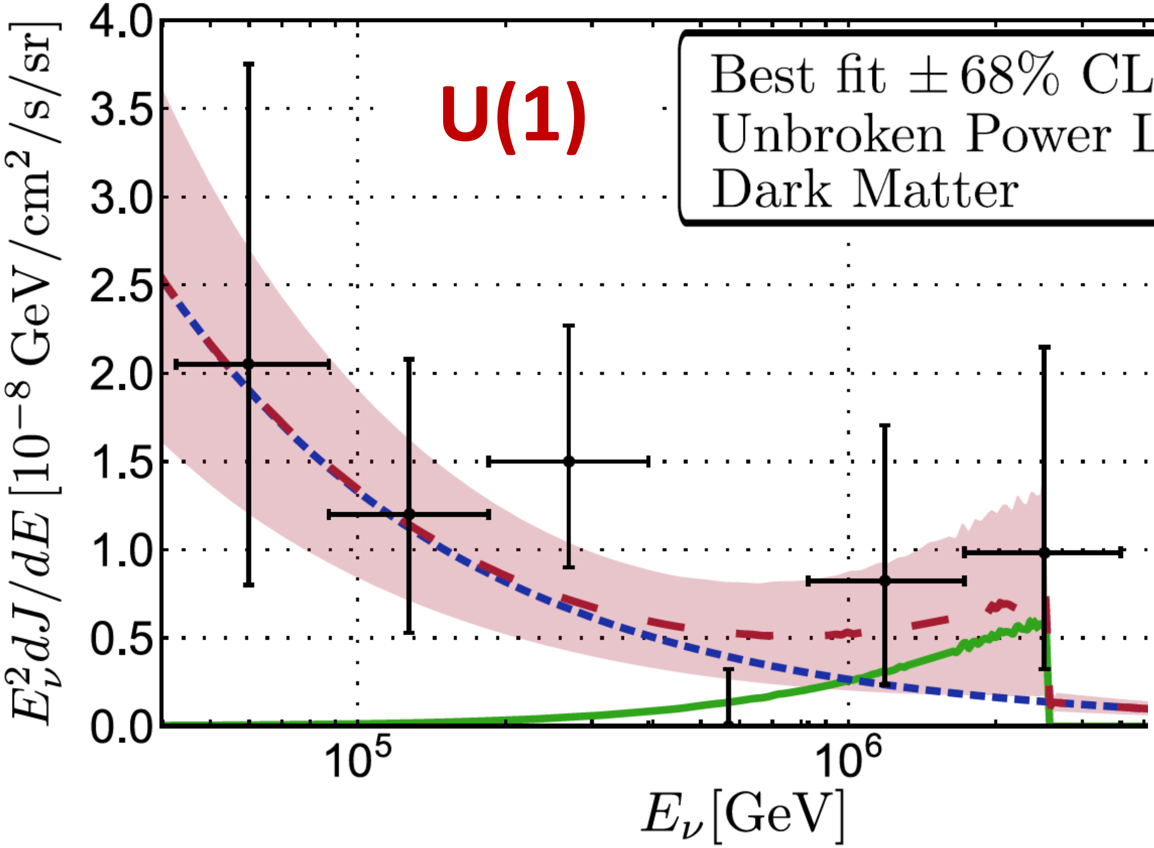
Navarro-Frenk-White

Extragalactic

$$\frac{d\phi_\nu}{dE_\nu}(E_\nu) = \frac{\Omega_{DM}\rho_c}{M_{DM}\tau_{DM}}\frac{1}{H_0}\int_0^\infty dz\left(\frac{1}{4\pi}\boxed{\frac{dN_\nu}{dE_\nu}\left[(1+z)\,E_\nu\right]}\right)\frac{1}{\sqrt{(\Omega_\Lambda+\Omega_m)\,z^3}}$$

numerical calculation

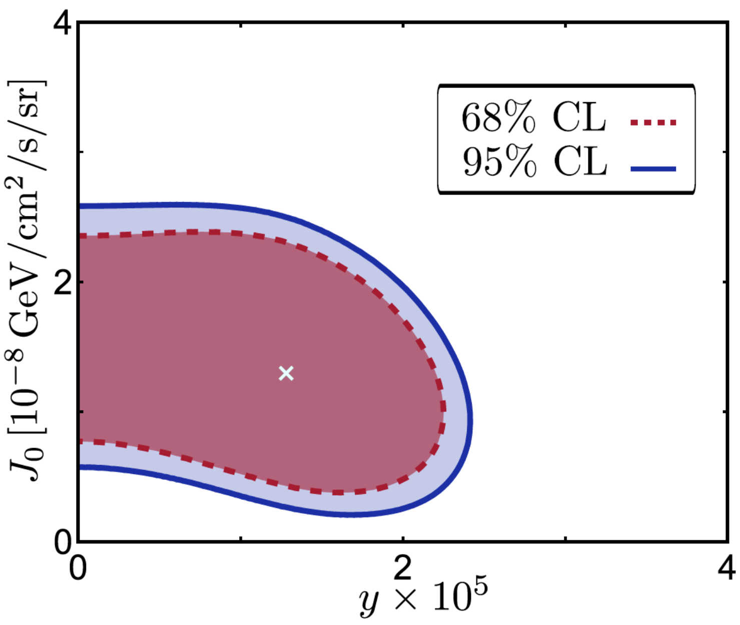
Unbroken Power Law



$\chi^2/dof = 0.98$

$M_{DM} = 5.1$ PeV

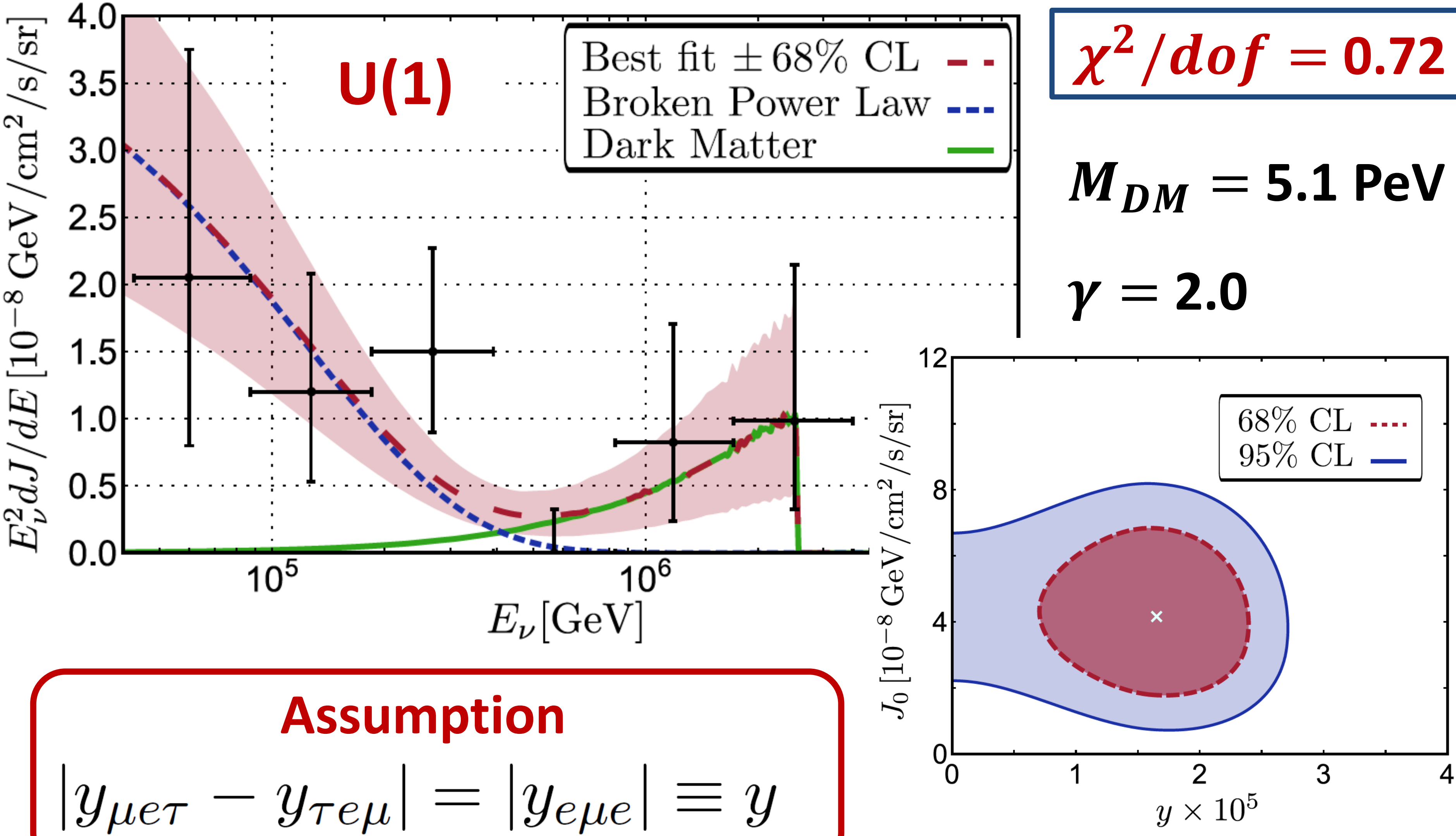
$\gamma = 2.7$



Assumption

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

Broken Power Law



$\chi^2/dof = 0.72$

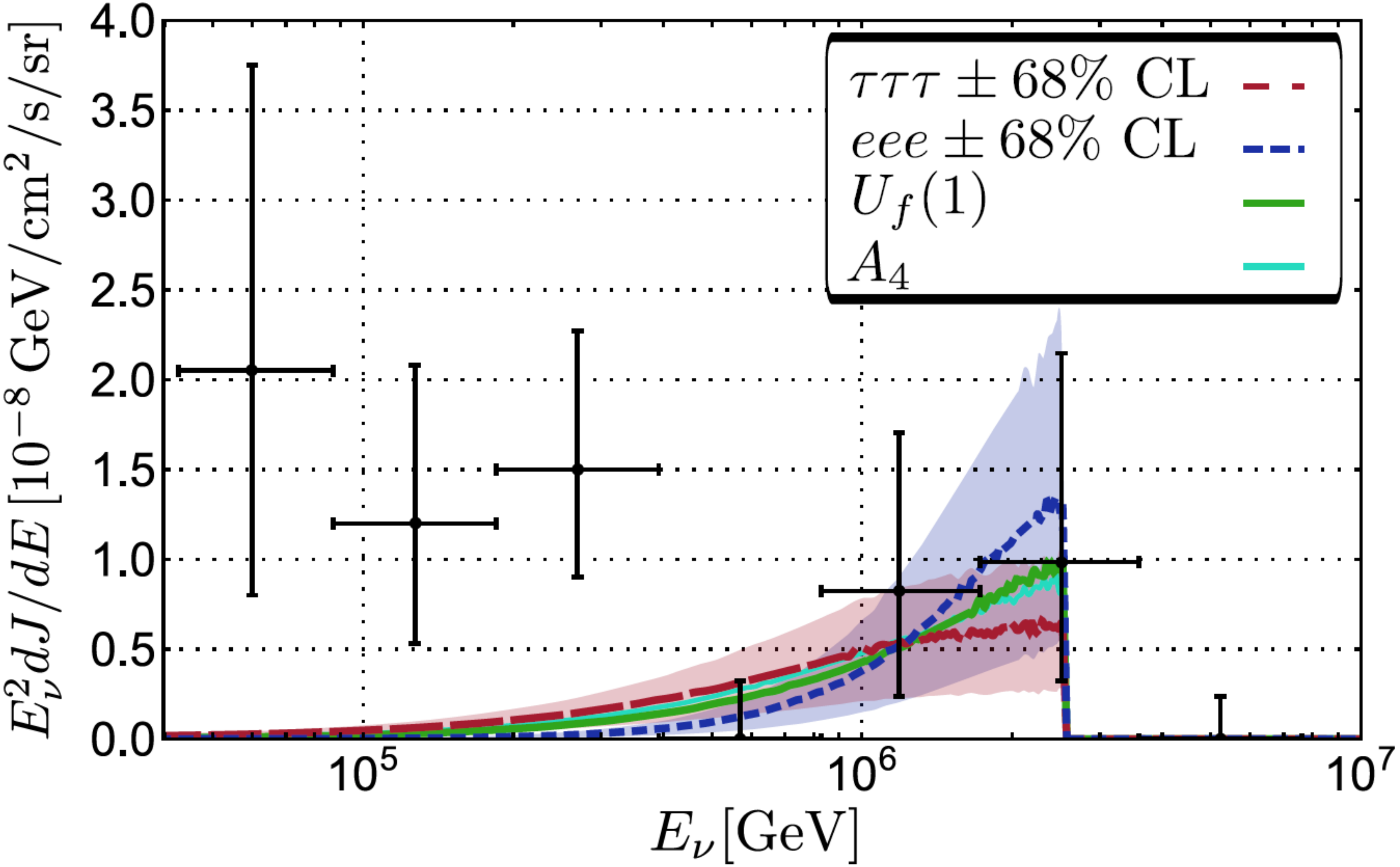
$M_{DM} = 5.1$ PeV

$\gamma = 2.0$

Assumption

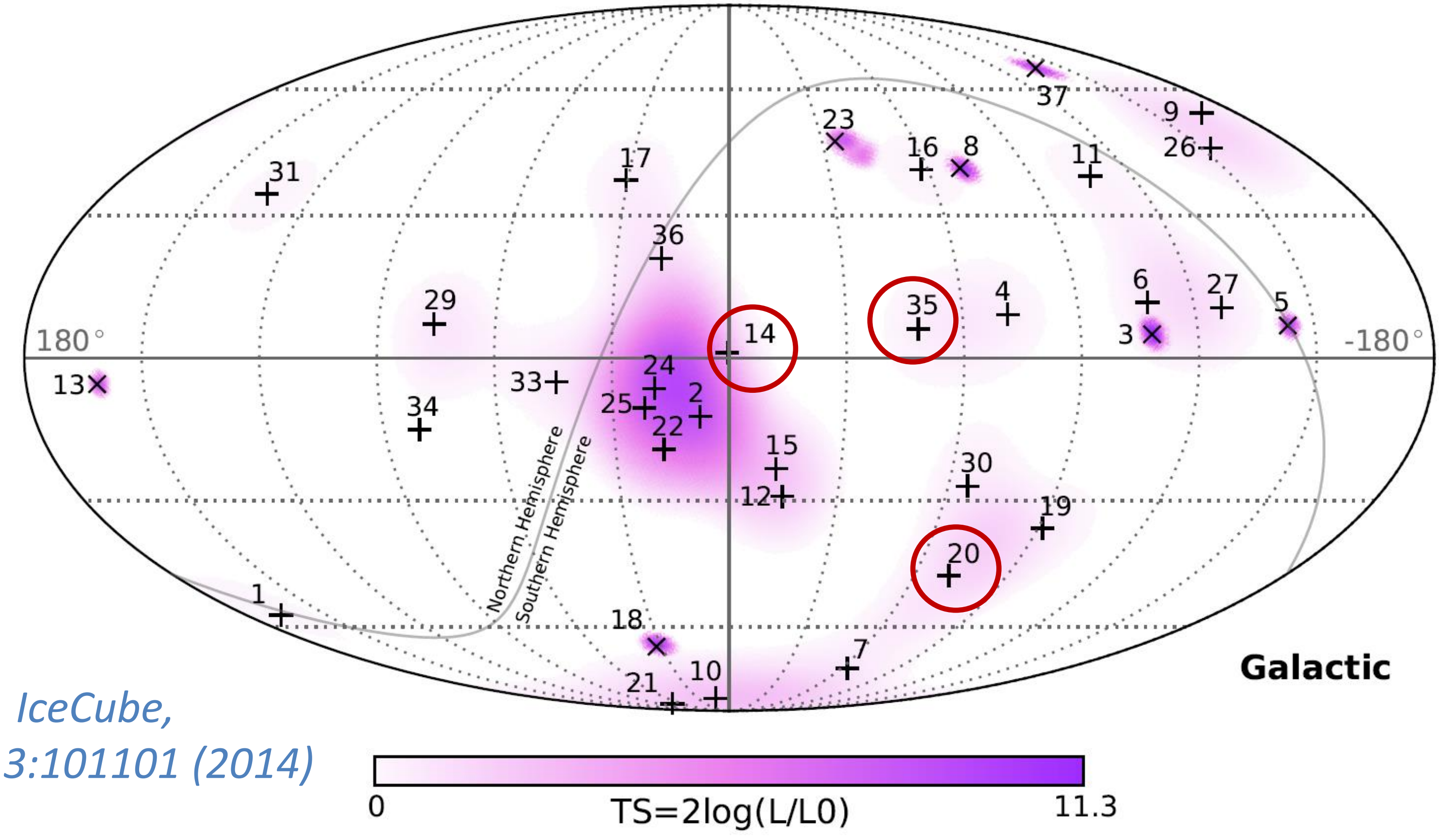
$$|y_{\mu e\tau} - y_{\tau e\mu}| = |y_{e\mu e}| \equiv y$$

$U(1)$ vs A_4


$E_\nu^2 dJ/dE\,[10^{-8}\,\mathrm{GeV/cm^2/s/sr}]$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
10^5
10^6
10^7
$E_\nu\,[\mathrm{GeV}]$
$\tau\tau\tau \pm 68\%$ CL
$eee \pm 68\%$ CL
$U_f(1)$
A_4

Galactic vs Extragalactic

- Galactic and Extragalactic DM neutrino fluxes are of the same order of magnitude.



IceCube,
PRL 113:101101 (2014)

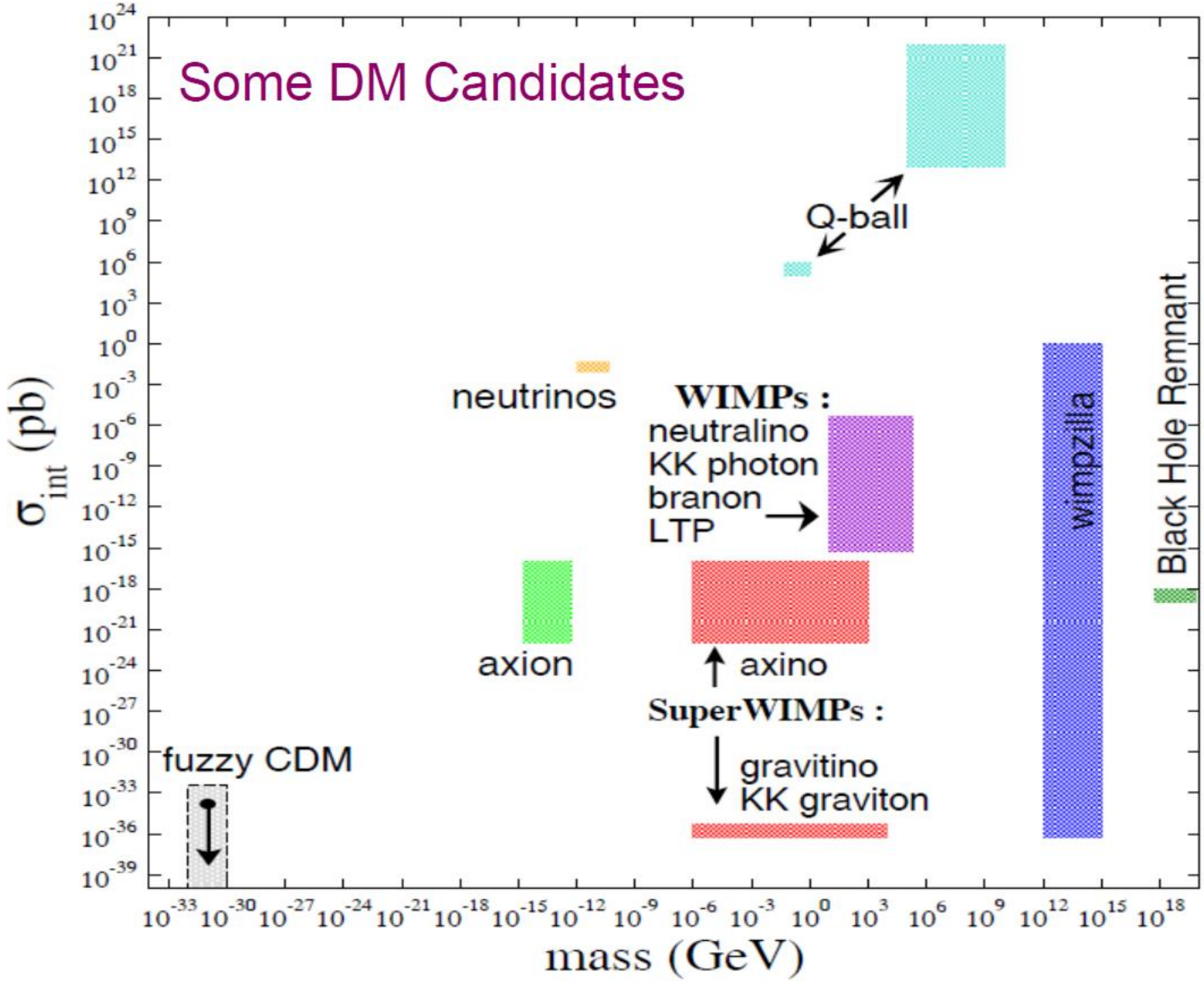
Outlook: gamma-rays

- The gamma-rays can be observed by other experiment.

Cherenkov
Telescope
Aarray

- Energy range from below 100 GeV to above 100 TeV.

Outlook: candidate?



from Dark Matter Scientific Assessment Group (DMSAG) report (2007)
https://science.energy.gov/~/media/hep/pdf/files/pdfs/dmsagreportjuly18_2007.pdf

Conclusions

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

- The origin is a mystery (low statistics):

  - Astrophysical sources (SRN , GRB, AGN);
  - Dark Matter decay.

- The decaying DM scenario is very intriguing since it can provide important information and give indications on the direction for future DM experiments.

- The **lack of data** (0.3-1.0 PeV) and the **cut-off** above 2 PeV are in favor of DM interpretaion.

Conclusions

- We have studied the possibility that the PeV events are due to DM decay, taking into account a non-renormalizable SM-DM coupling.

- The Broken Power Law (like SNR) and the DM signal are in good agreement with the IceCube data.

- The DM scenario can be easily tested in the future (**lack of data** and **sharp cut-off**) with IceCube and other experiments (like CTA).

- We need **more statistics** to understand the origin of high energy neutrinos (IceCube 2gen with 10 events per years).

Conclusions

- We have studied the possibility that the PeV events are due to DM decay, taking into account a non-renormalizable SM-DM coupling.
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Thank you for your attention

Backup slides

Neutrino detection

- Neutrinos are detected in IceCube by observing the Cherenkov light produced in ice by charged particles created when neutrinos interact.

- The deposited energy is measured with a precision of ~15% above 10 TeV.

Track

- CC interactions
- Mostly ν_μ
- Angular resolution ~1° at 50% CL

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

Shower

- CC and NC interactions
- Mostly ν_e and ν_τ
- Angular resolution ~15° at 50% CL

$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

Track

$$E_{dep} = 30.8^{+3.3}_{-3.5}\ \mathrm{TeV}$$

Declination:

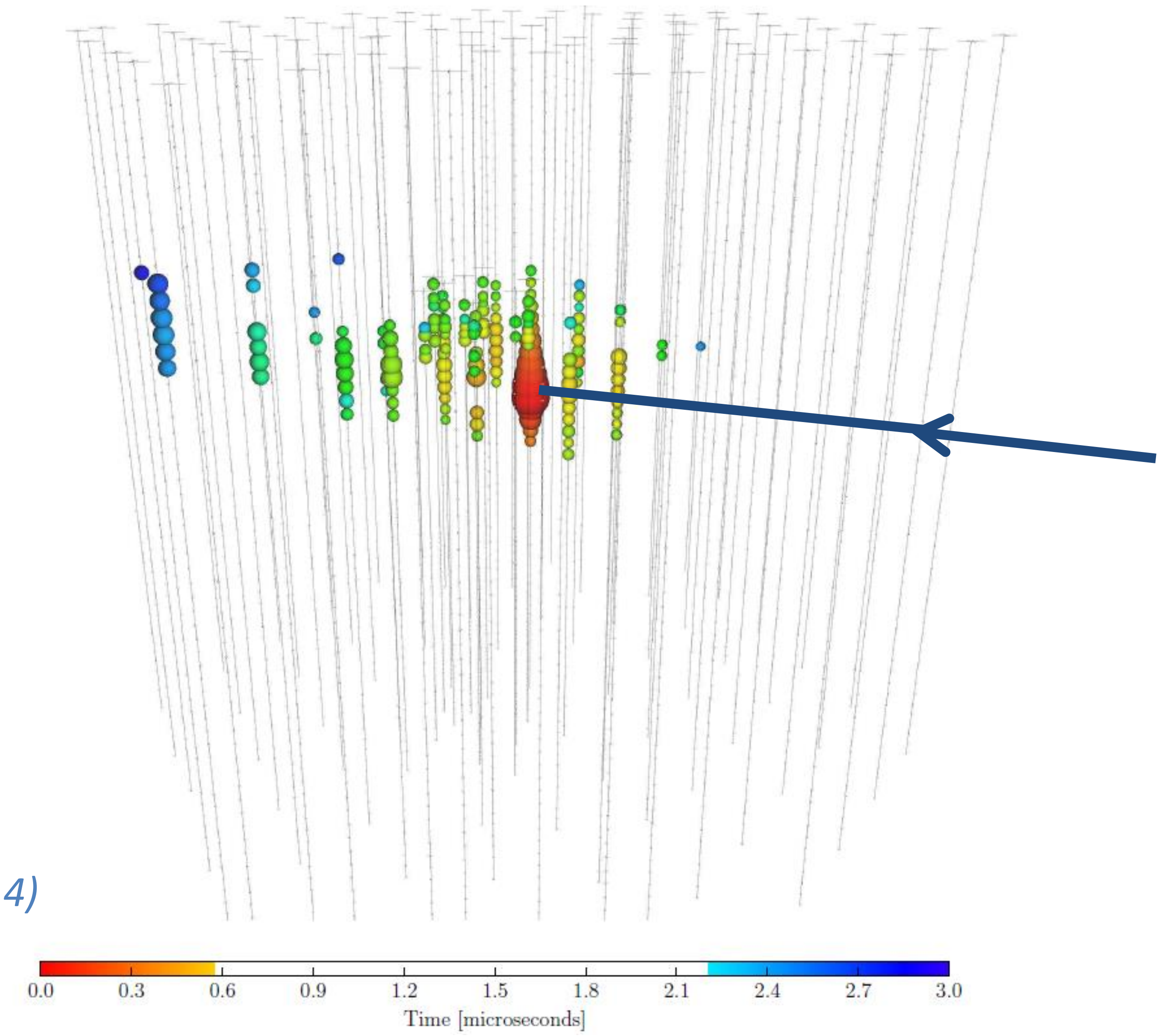
20.7°±1.2°

↓

Northern Sky

Upgoing

IceCube, PRL 113:101101 (2014)



Shower

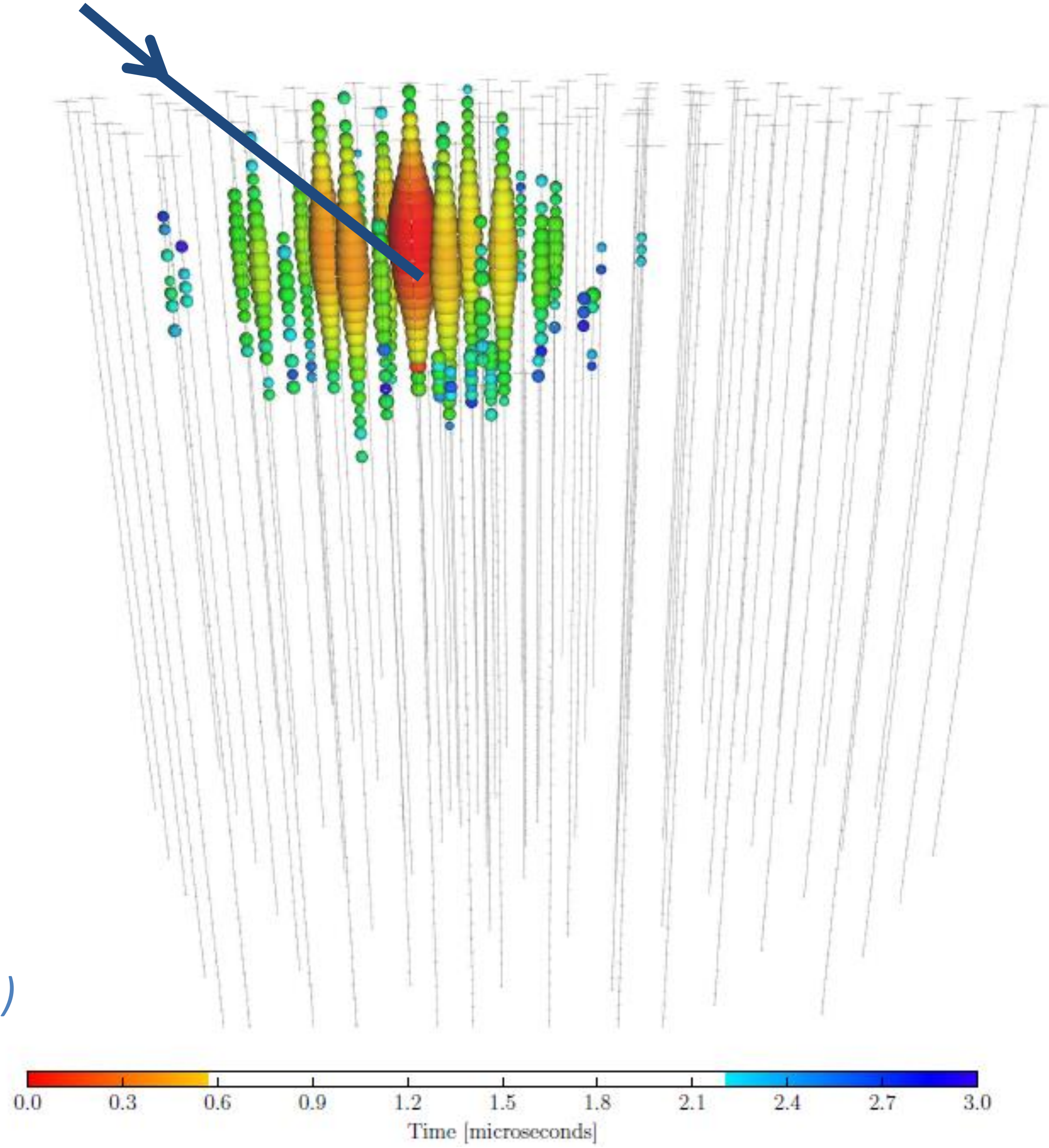
$$E_{dep} = 2004^{+236}_{-262}\ \text{TeV}$$

Declination:
-55.8°±15.9°

↓

Southern Sky
Downgoing

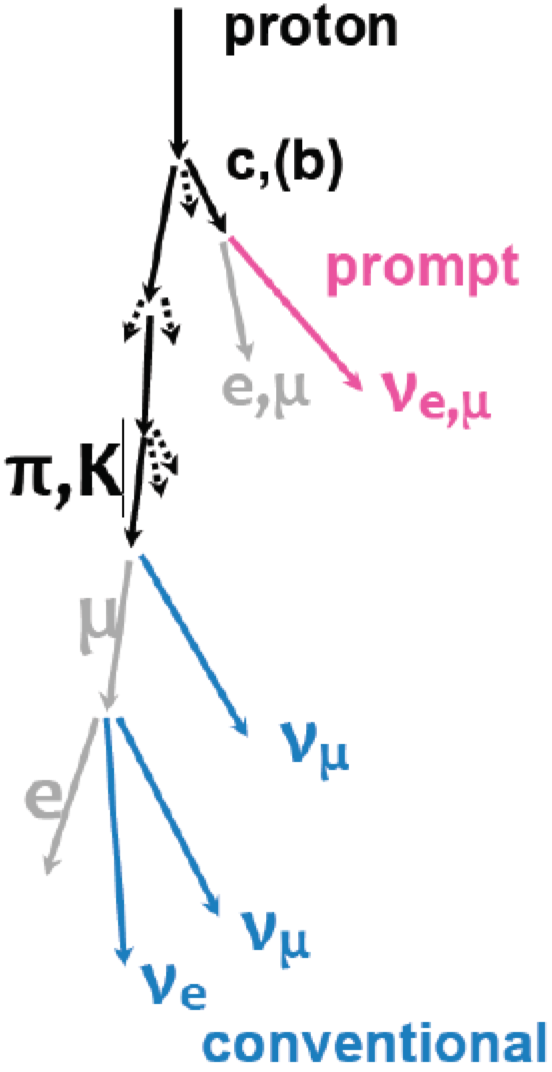
IceCube, PRL 113:101101 (2014)



Background

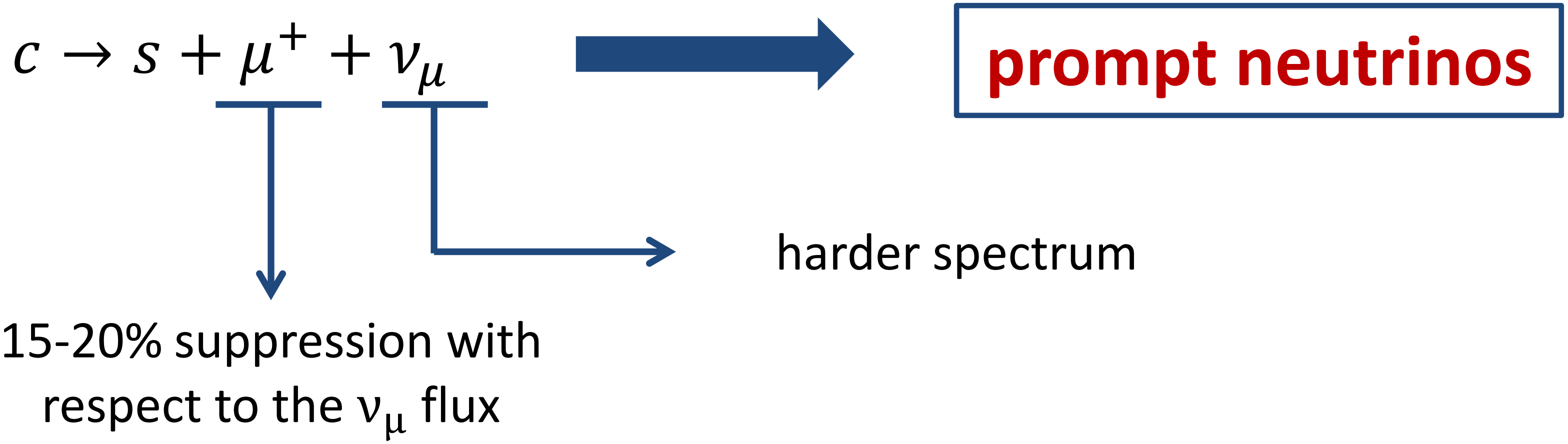
- The interactions of Cosmic Rays (CR) with the atmosphere produce two types of neutrino background.
- The **conventional** background is neutrinos produced by the decays of π and K.
- The **prompt** background corresponds to neutrinos coming from the decay of charm.

Terrestial or extraterrestial neutrinos?



Prompt neutrinos

- While the decay of charged pions and kaons becomes strongly suppressed at high energy (long lifetimes), the decay of charmed particles becomes the dominant source of the atmospheric fluxes for E > 10 TeV.



$$c \rightarrow s + \mu^{+} + \nu_{\mu}$$

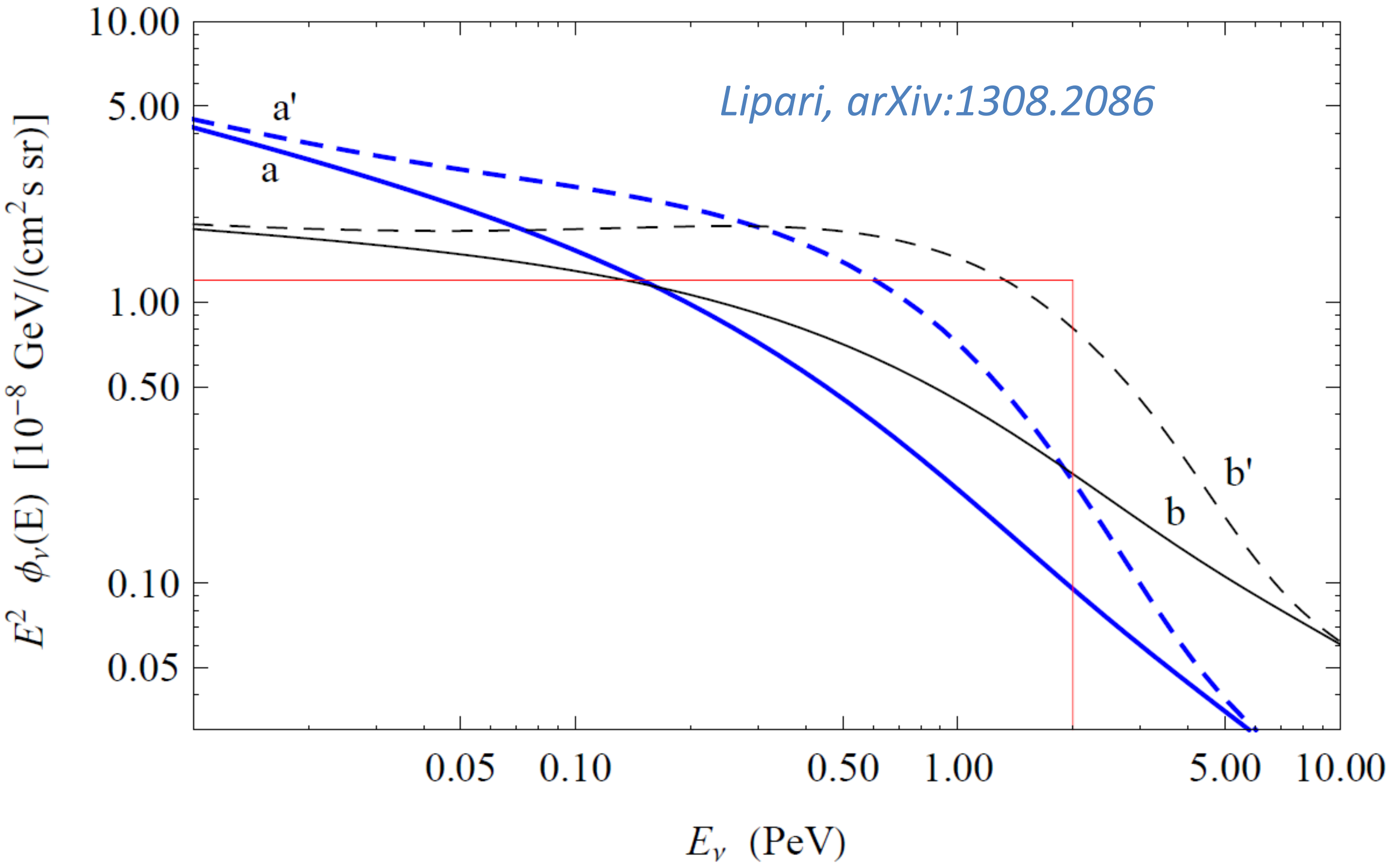
prompt neutrinos

harder spectrum

15-20% suppression with respect to the ν_{μ} flux

- The prompt ν flux is affected by large uncertainties:
  - nucleon composition of CR;
  - non-perturbative charm production cross section.

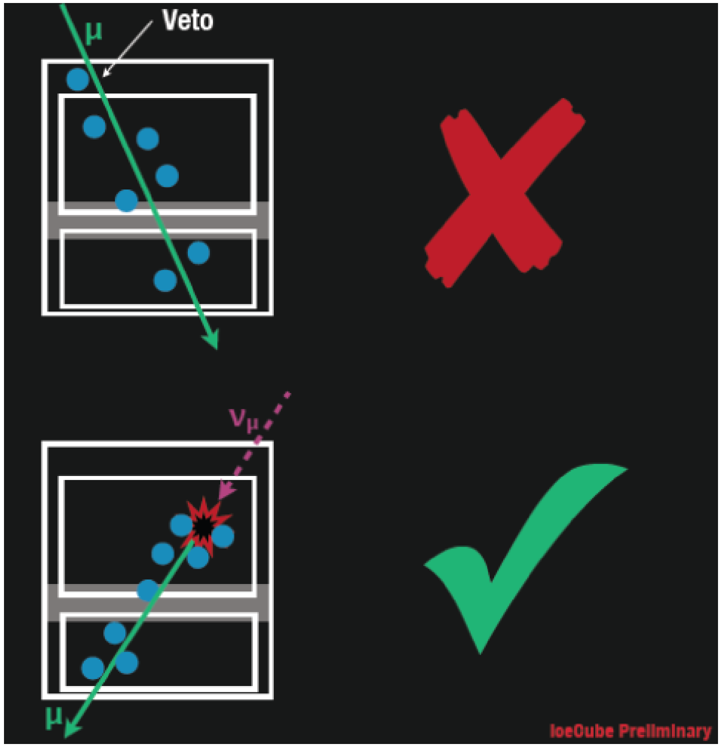
Prompt neutrinos

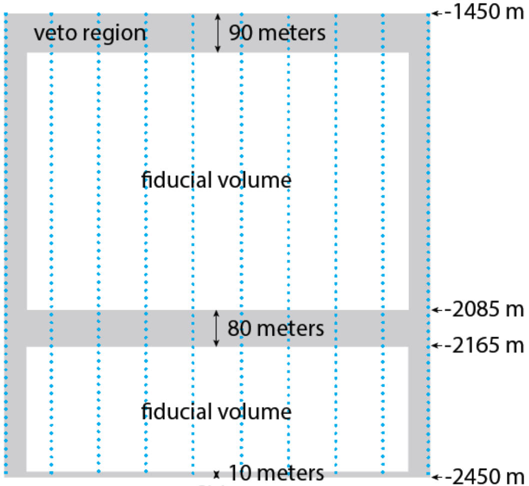


Could the IceCube neutrino excess be explained only in terms of prompt atmospheric flux?

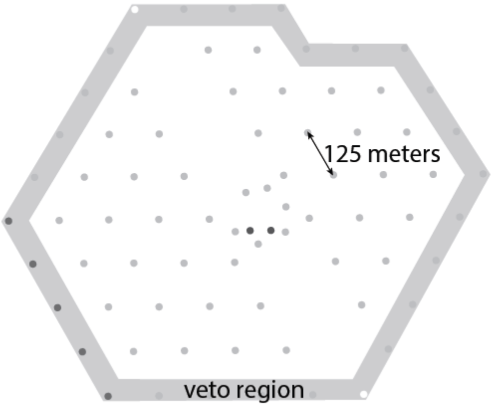
Background: μ veto

- The detector discards the events in which:
    - high energy muons produce first light in the veto region;
    - the deposited energy is lower than 30 TeV.
- For upgoing particles, the Earth is a filter.



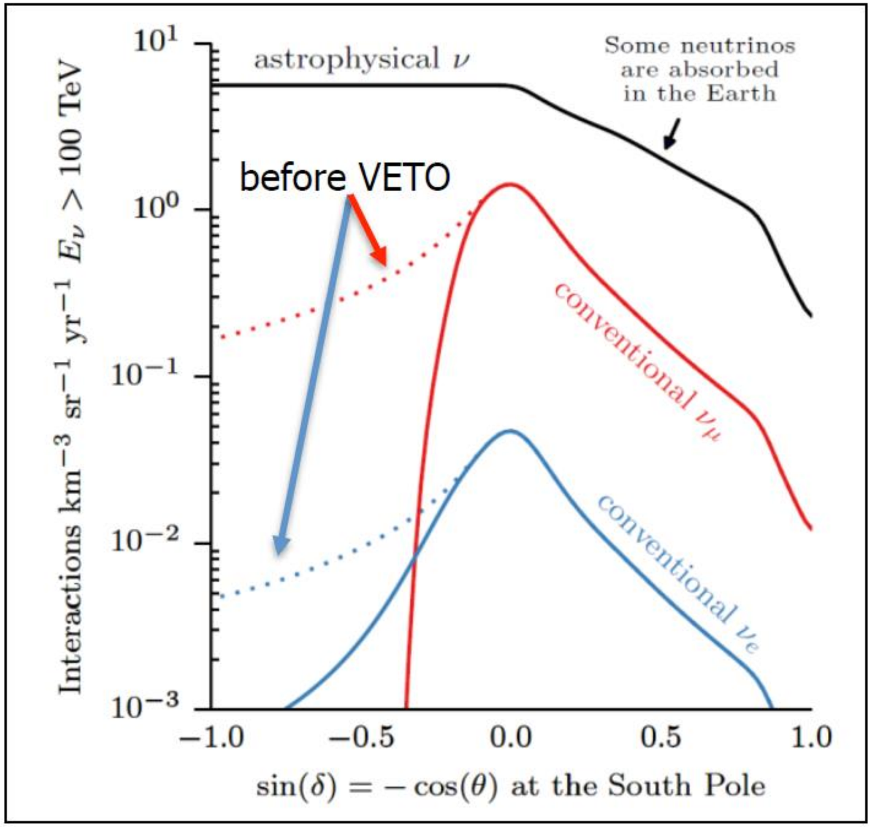


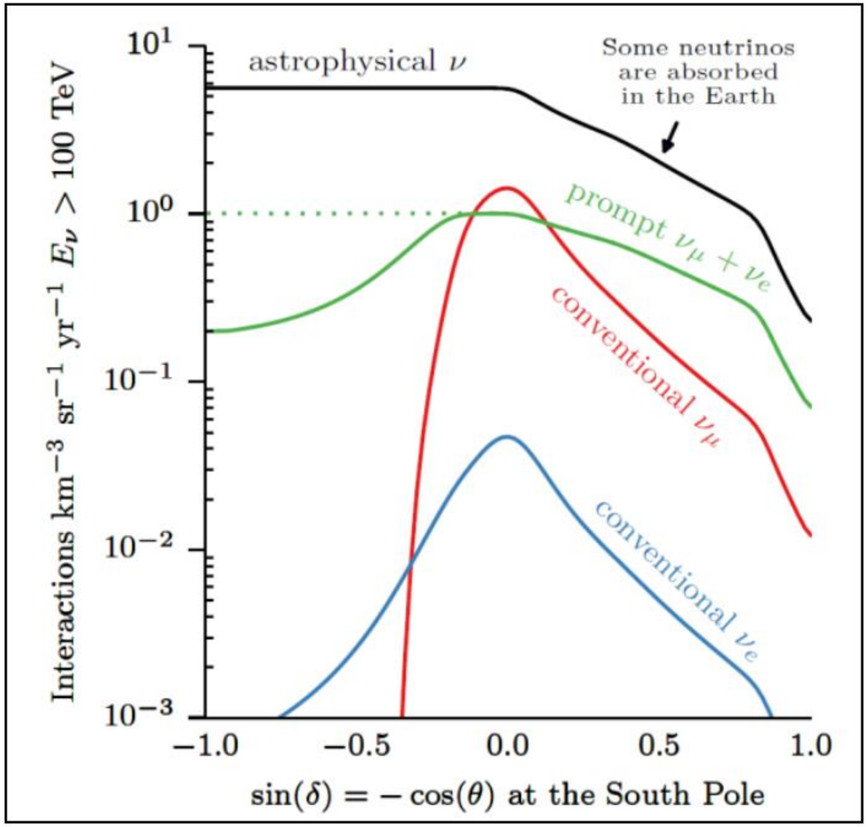
Side



Top

Background suppression





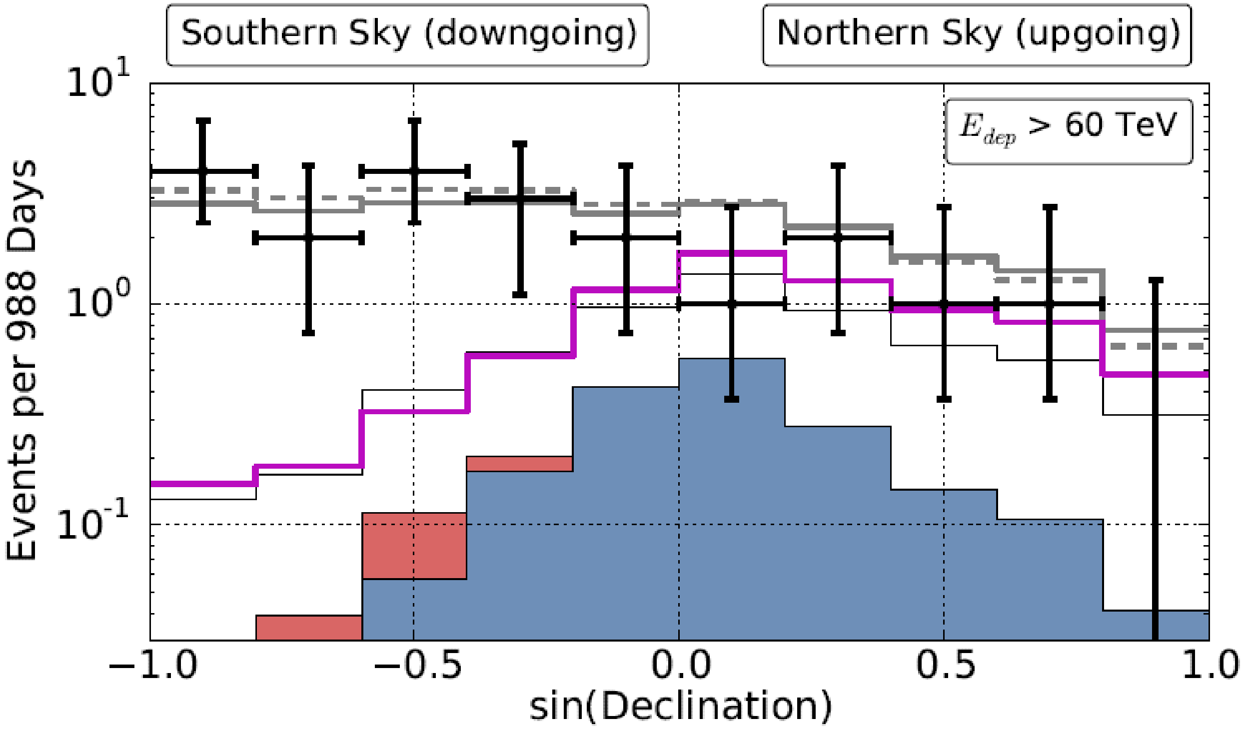
Gaisser, Jeno, Karle, Van Sante, PR D90:023009 (2014)

Enberg et al., arXiv:1502,01076 (2015)

Downgoing and upgoing isotropy

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

IceCube, PRL 113:101101 (2014)



Prompt neutrinos (background) cannot explain the IceCube data!

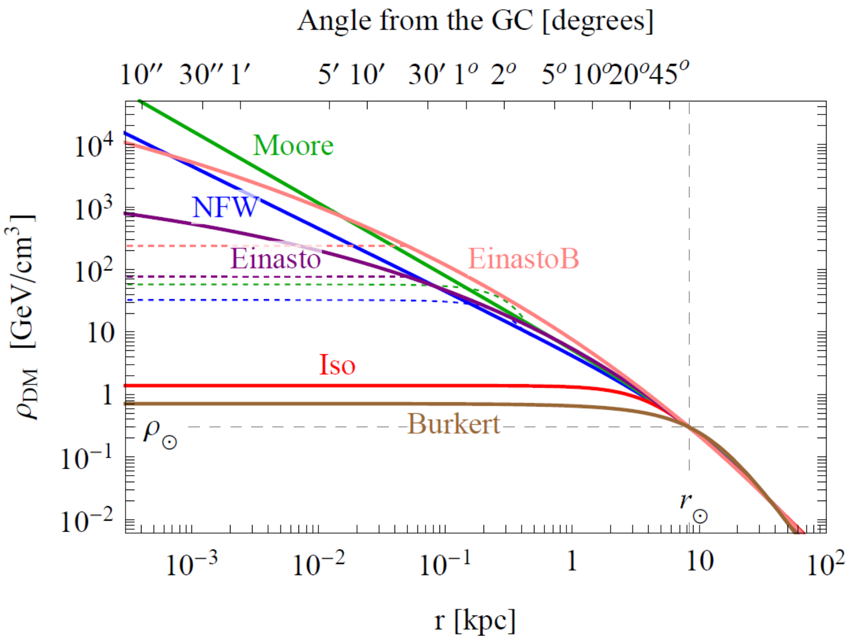
DM density profile

- We have different kinds of DM density profile:

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

Einasto: $$\rho_{\rm Ein}(\mathbf{r}) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{\mathbf{r}}{r_s}\right)^{\alpha} - 1\right]\right\}$$

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



Astrophysical uncertainties!

Cirelli et al., JCAP 1103 (2011)

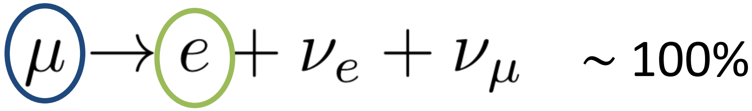
Neutrino energy spectrum

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

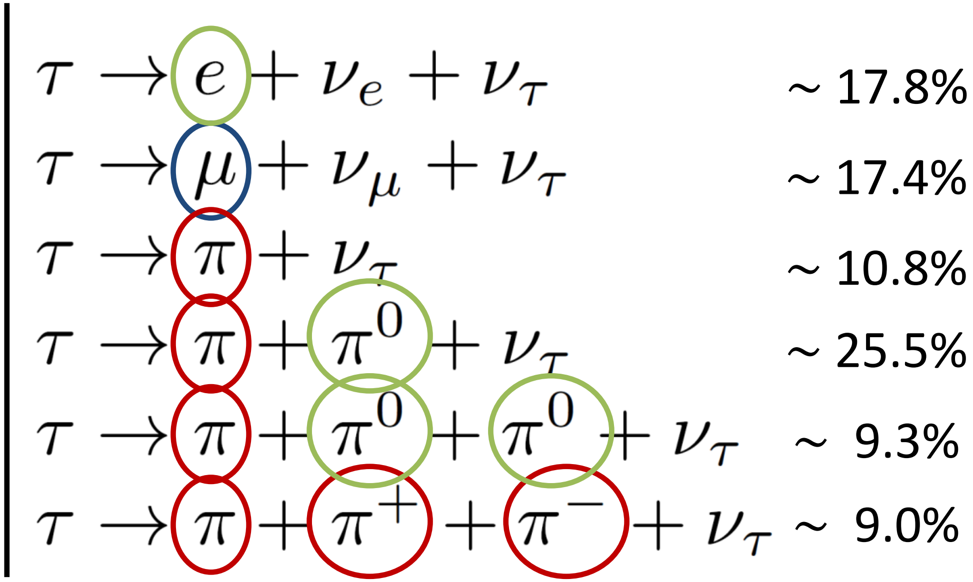
- There are **6** decay channels with the same Branching Ratio.

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

- 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*