# PeV Decaying Leptophilic Dark Matter at IceCube

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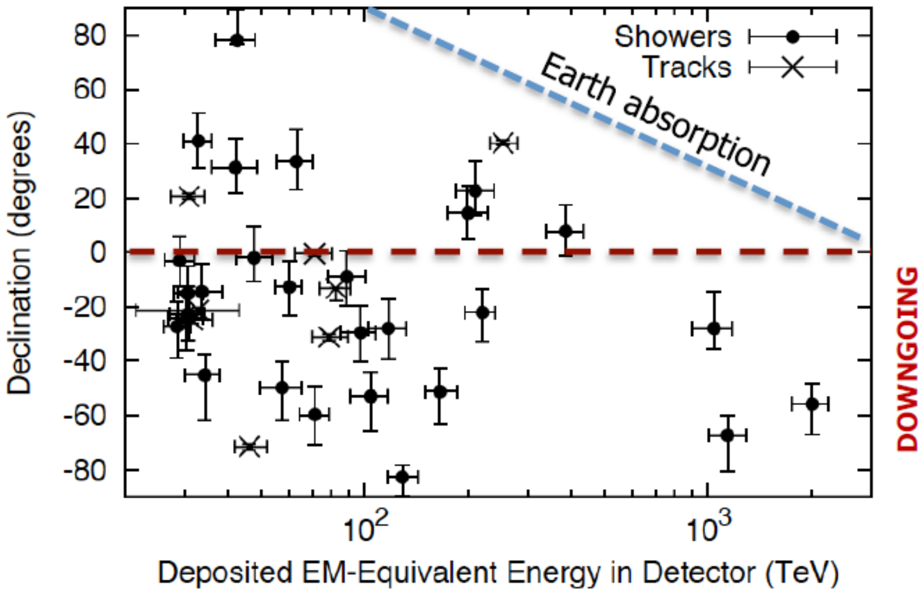
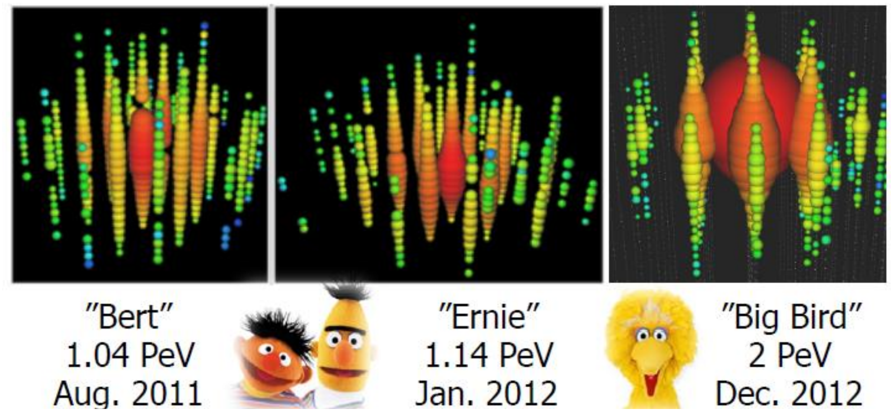
in collaboration with Boucenna, Mangano, Miele, Morisi, Pisanti, Vitagliano

arXiv:1507.01000

Istituto Nazionale di Fisica Nucleare

# IceCube: 3 years events

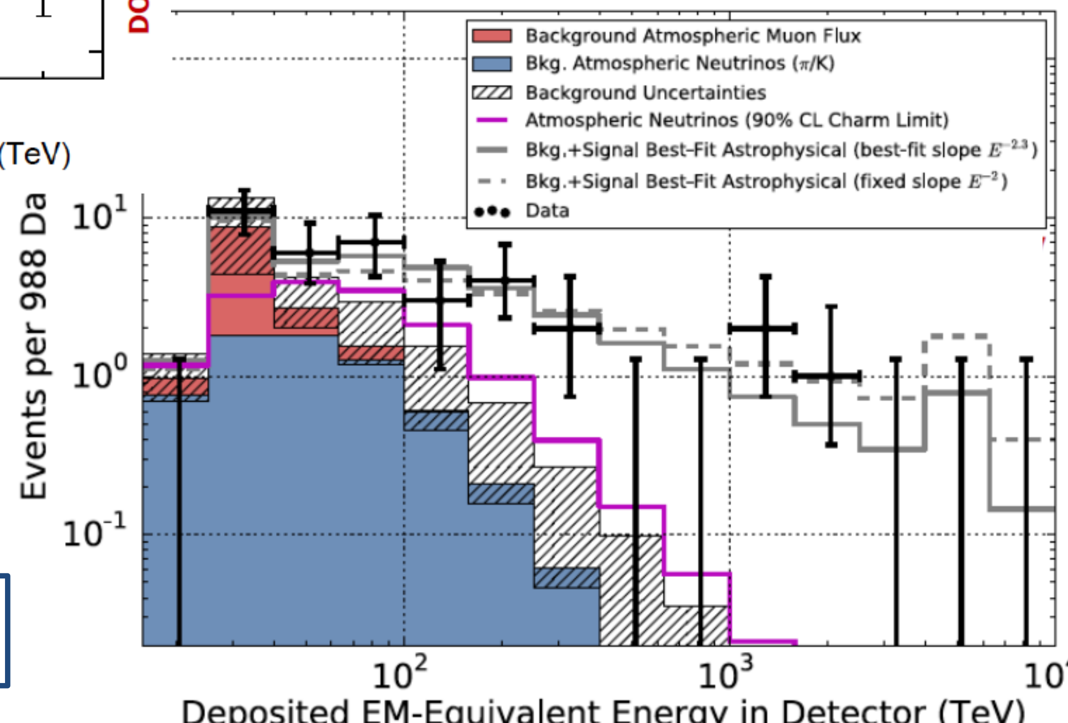


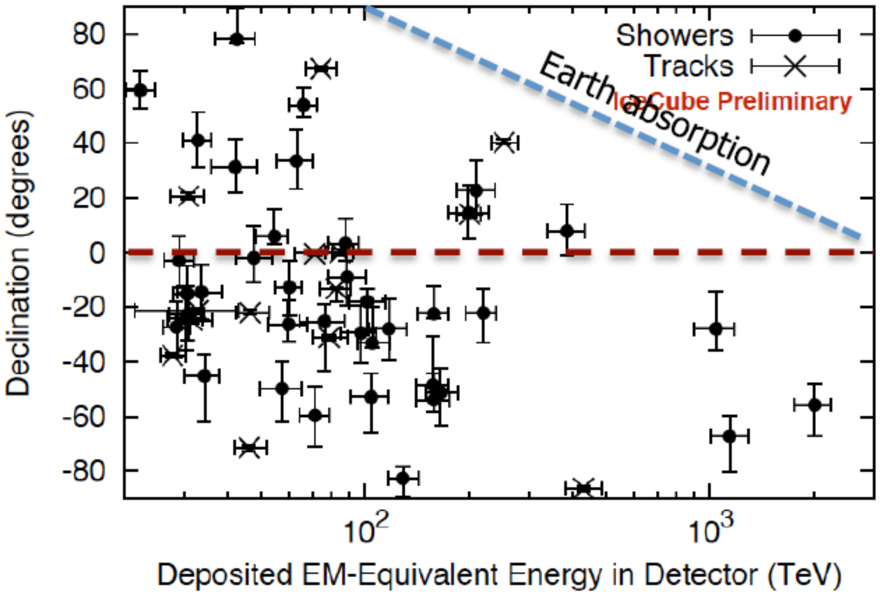

*IceCube, PRL 113:101101 (2014)*

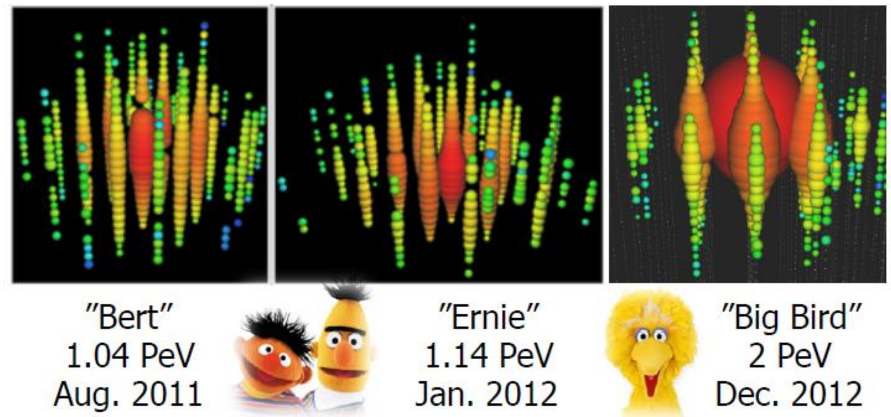
- 3 yrs: 37 events in 988 days
- Isotropic flux
- Atmospheric background:
  - $8.4 \pm 4.2\ \mu$
  - $6.6 + 5.9\ \nu$

**5.7 σ**



# IceCube: 4 years events

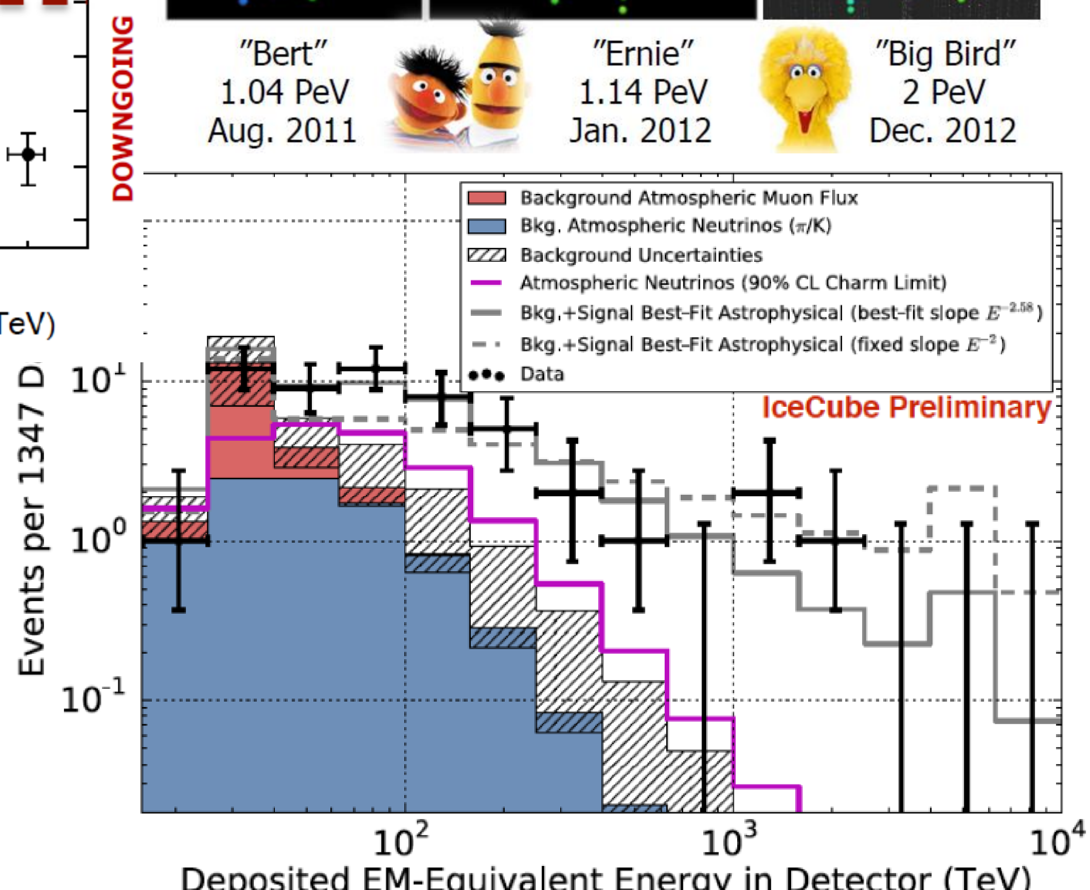


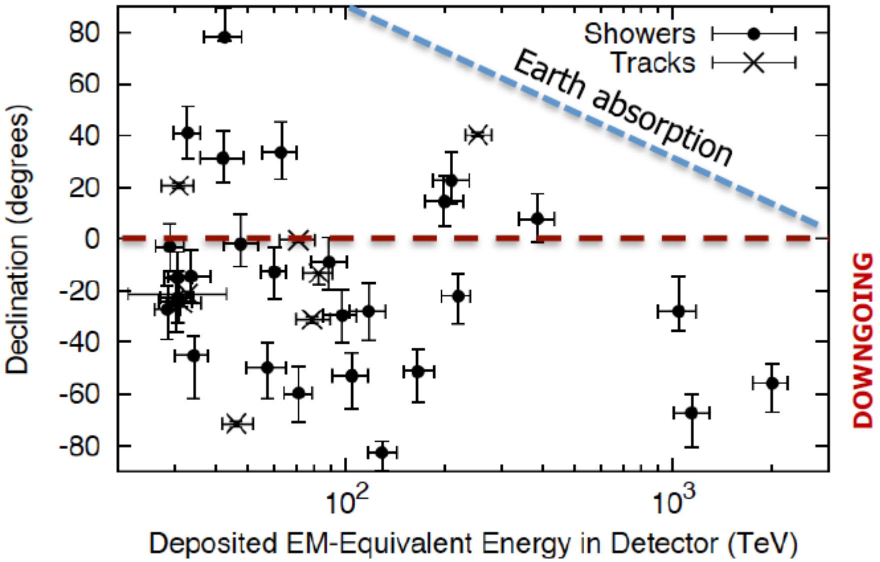

*IPA 2015*

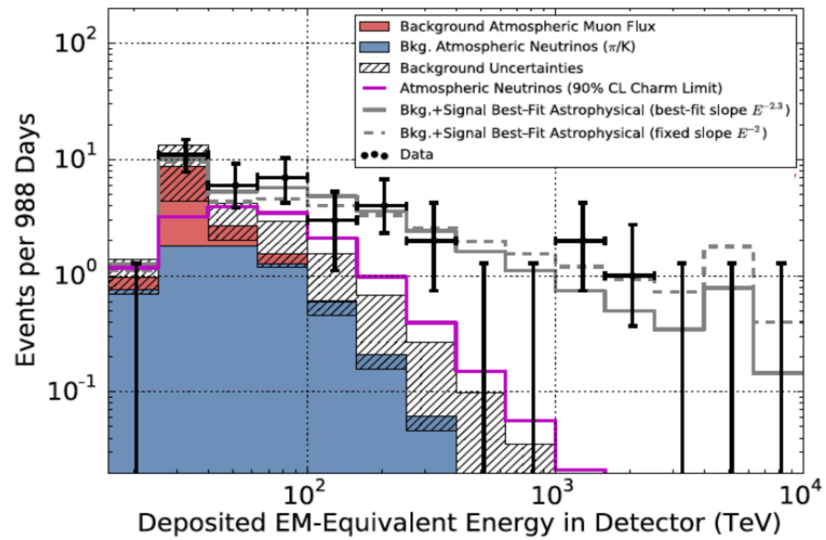
- 4 yrs: 54 events in 1347 days
- Isotropic flux
- Atmospheric background:
  - $8.4 \pm 4.2\ \mu$
  - $6.6 + 5.9\ \nu$

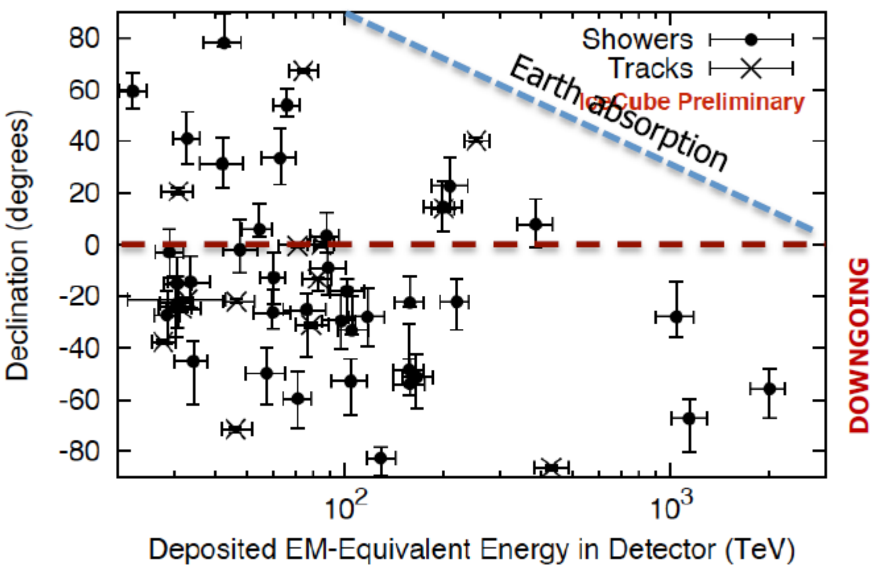
**~7 σ**

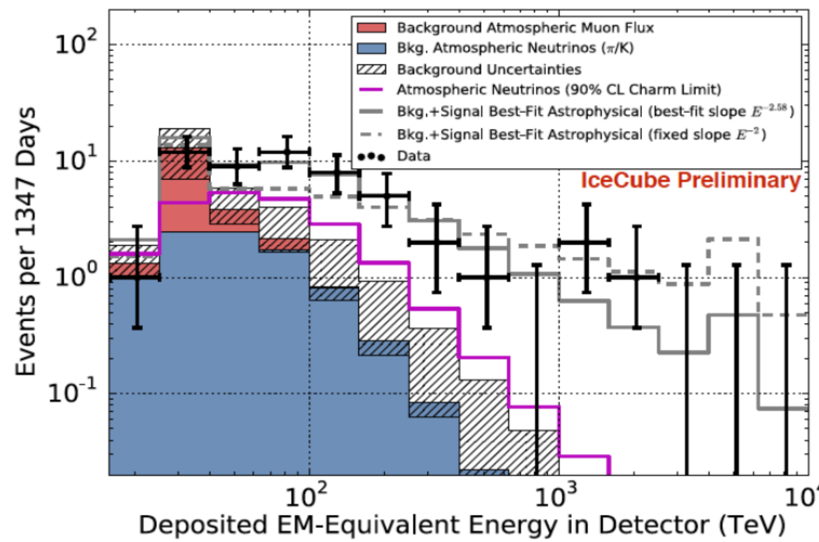


# Key feautres



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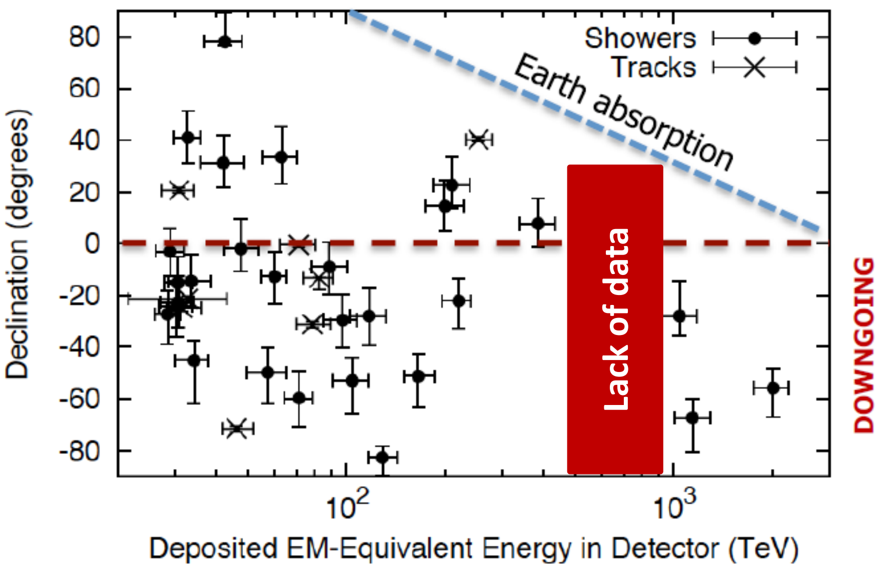
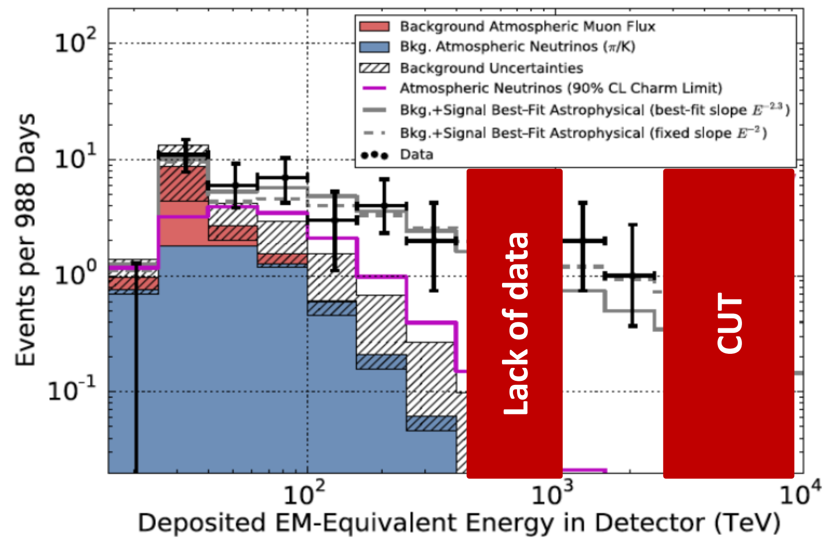
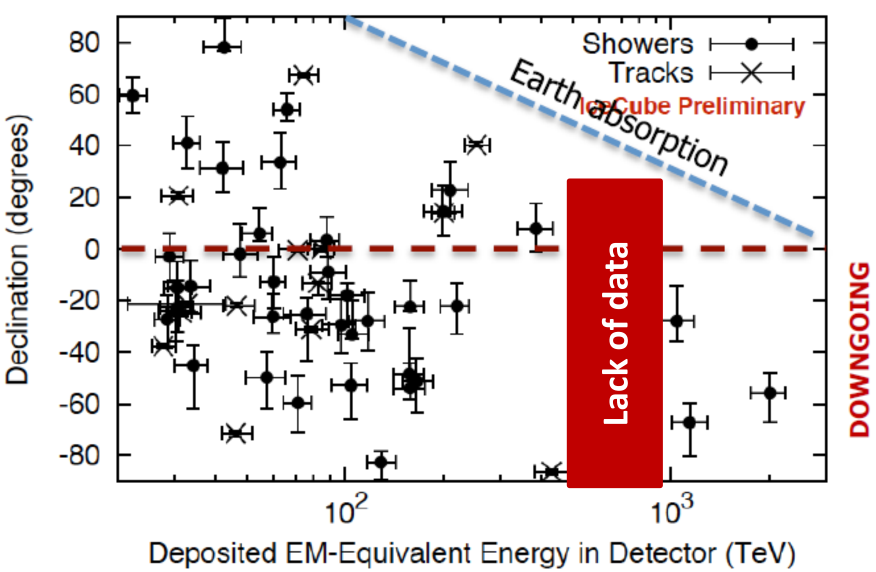
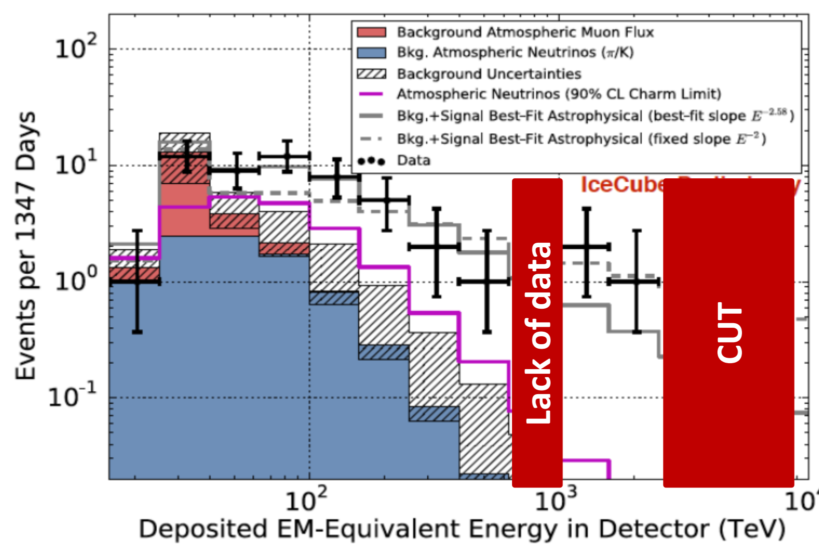


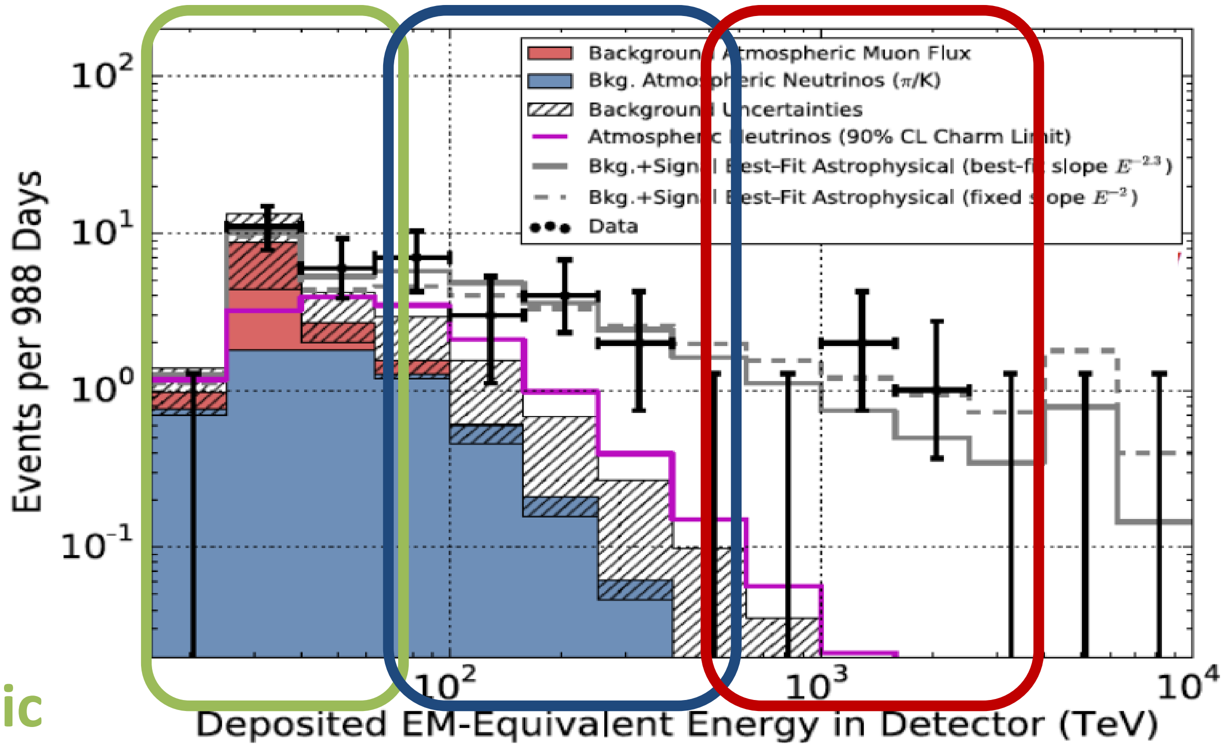



# Origin of IC events: our assumption

- IceCube events could be also related to the Dark Matter (DM).
- We know very few about DM, and IceCube can provide important information and give indications on the direction for future DM experiments.




Standard atmospheric background

Some astrophysical source

Dark Matter decay

# Astrophysical sources

- The measured IceCube data can be explain by some astrophysical sources:
  - SuperNova Remnants (SNR)
  - Active Galactic Nuclei (AGN)
  - Gamma-Rays Burst (GRB)

  **see Tamborra talk**

**$pp$ and $p\gamma$ interactions**

- The astrophysical neutrino flux can be parametrized as

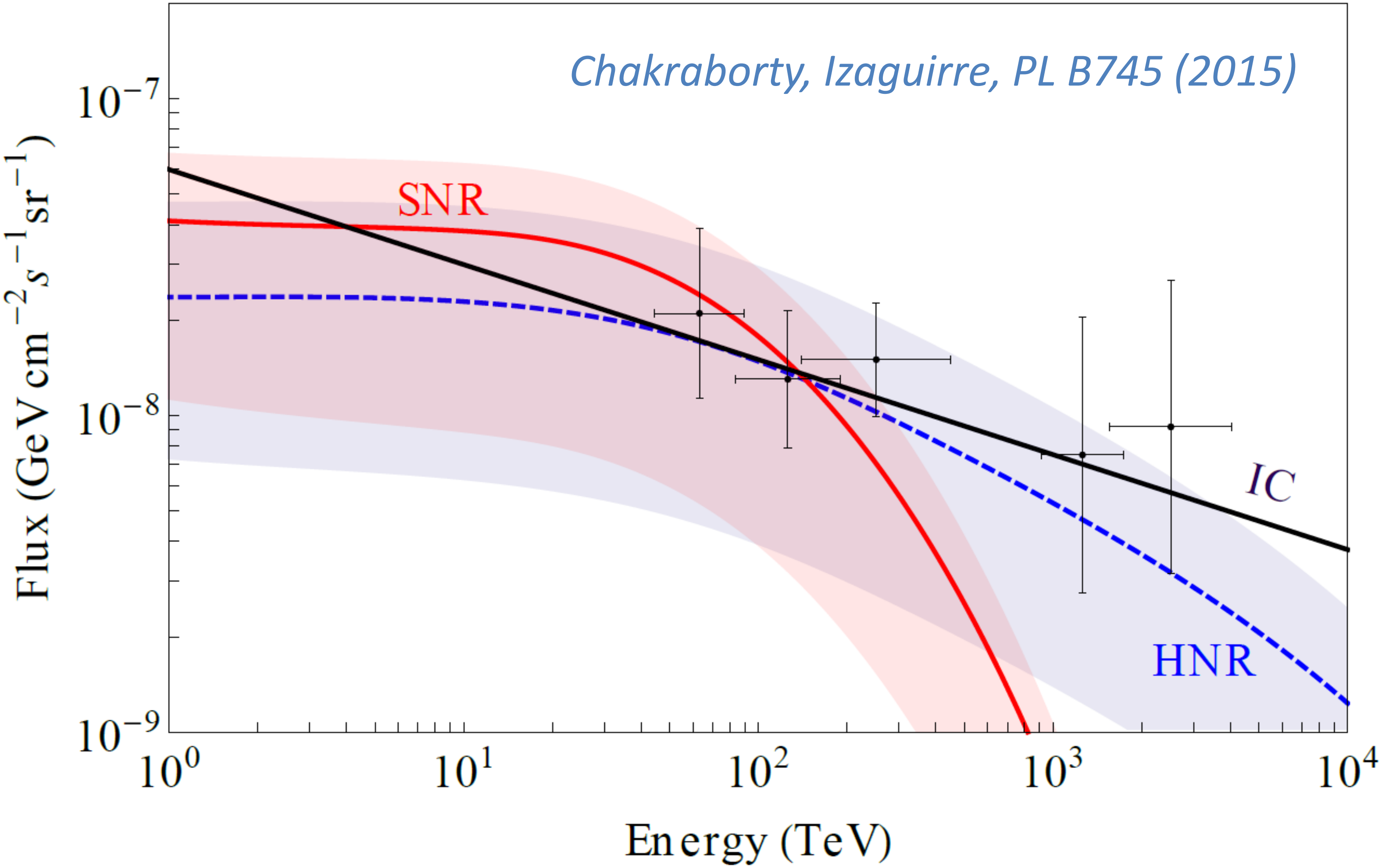
**Unbroken Power Law**

$$E_\nu^2 \frac{dJ_{\rm Ast}}{dE_\nu}(E_\nu) = J_0 \left( \frac{E_\nu}{100\ \mathrm{TeV}} \right)^{2-\gamma} \exp\left( -\frac{E_\nu}{E_0} \right)$$

**Broken Power Law**

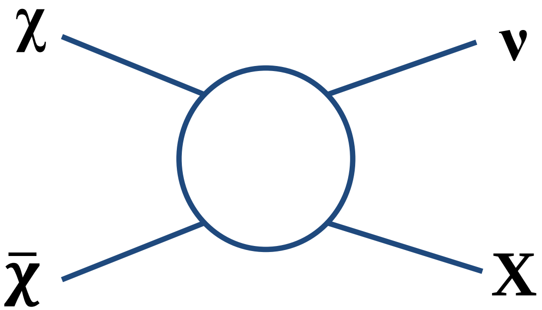
# Astrophysical sources: SNR

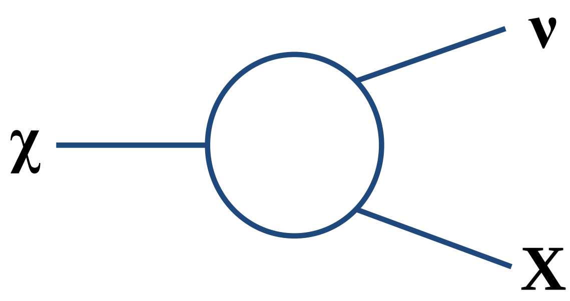
- SNR are described by a Broken Power Law with a cut-off $\boldsymbol{E_0 = \mathcal{O}(100\ \mathrm{TeV})}$.



# Dark Matter & IceCube

**Stable** | **Decay**




**For PeV DM the annihilation is negligible with respect to decay**

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

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

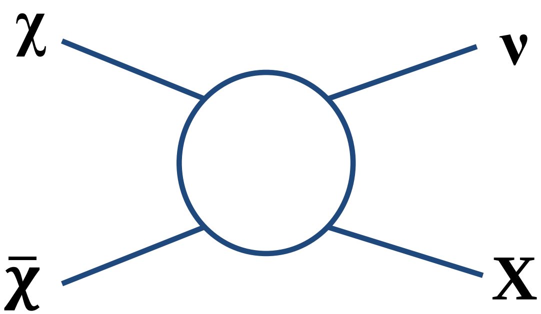
**Annihilation**

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

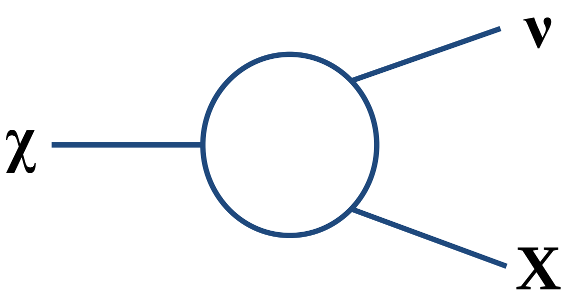
**Decay**

# Dark Matter & IceCube

**Stable**




**Decay**




**For PeV DM the annihilation is negligible with respect to decay**

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

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

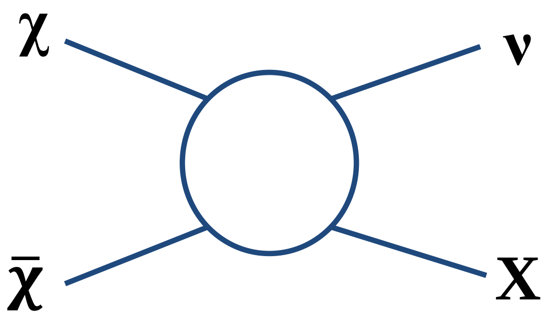
**DM is captured in large Celestial bodies like the Sun or cluster of galaxies, enhancing the density**

*IceCube, PRL 110:131302 (2013)*

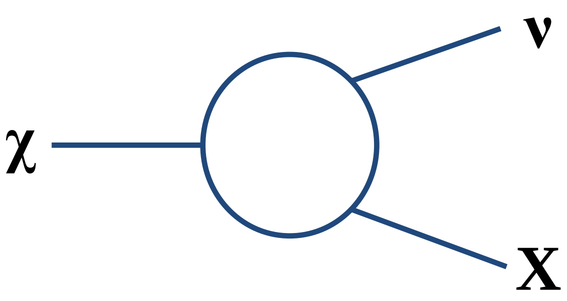
*IceCube, PR D88:122001 (2013)*

# Dark Matter & IceCube

**Stable**




**Decay**




**For PeV DM the annihilation is negligible with respect to decay**

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

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

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

**DM is boosted, increasing the relative velocity**

# Decaying Dark Matter

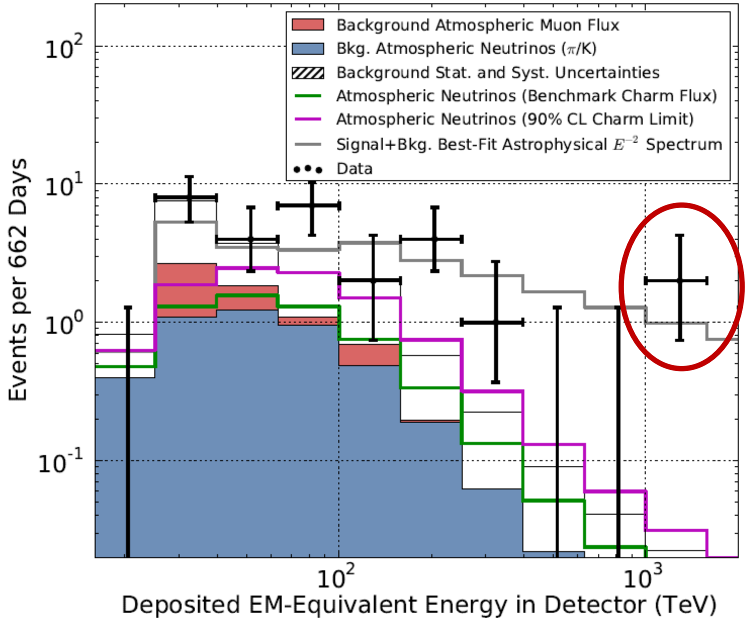
- In the scenario of decay, for a gauge-singlet fermionic DM the possible decay operators are

| Dimensions | DM decay operators |
|---|---|
| 4 | $\bar{L}H^cX$ |
| 5 | $-$ |
| 6 | $\bar{L}E\bar{L}X, \quad H^\dagger H\bar{L}H^cX, \quad (H^c)^t D_\mu H^c\bar{E}\gamma^\mu X,$ |
| | $\bar{Q}D\bar{L}X, \quad \bar{U}Q\bar{L}X, \quad \bar{L}D\bar{Q}X, \quad \bar{U}\gamma_\mu D\bar{E}\gamma^\mu X,$ |
| | $D^\mu H^c D_\mu \bar{L}X, \quad D^\mu D_\mu H^c\bar{L}X,$ |
| *Haba ed al., arXiv:1008.4777* | $B_{\mu\nu}\bar{L}\sigma^{\mu\nu}H^cX, \quad W^a_{\mu\nu}\bar{L}\sigma^{\mu\nu}\tau^a H^cX$ |

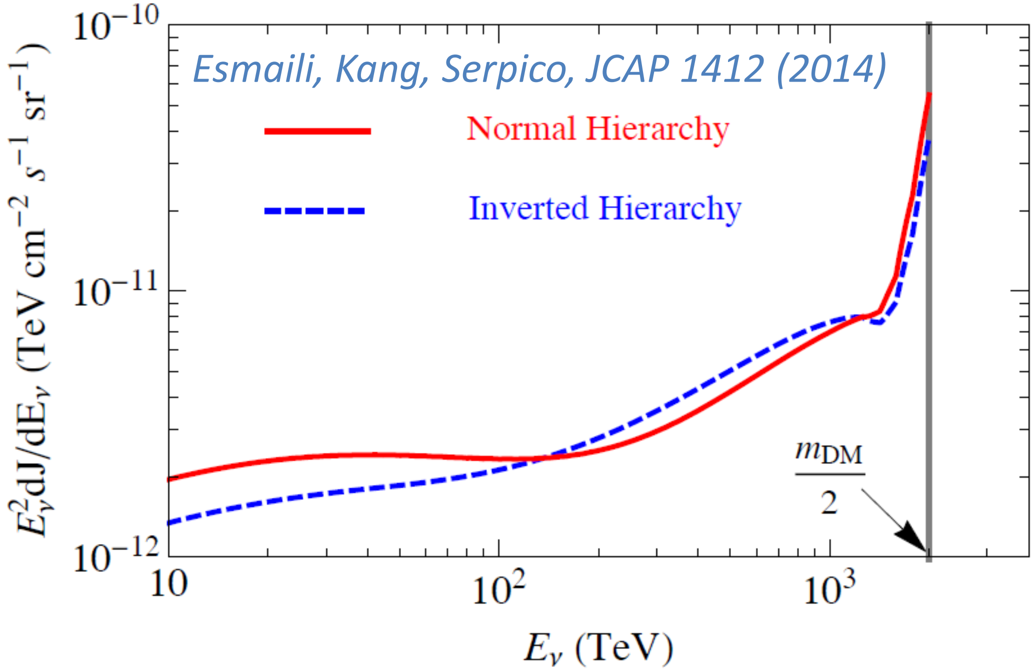
- The renormalizable SM-DM coupling yields to a 2 bodies DM decay with some channels producing one primary neutrino.

# 2 bodies decay

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




*IceCube, Science 342 (2013)*

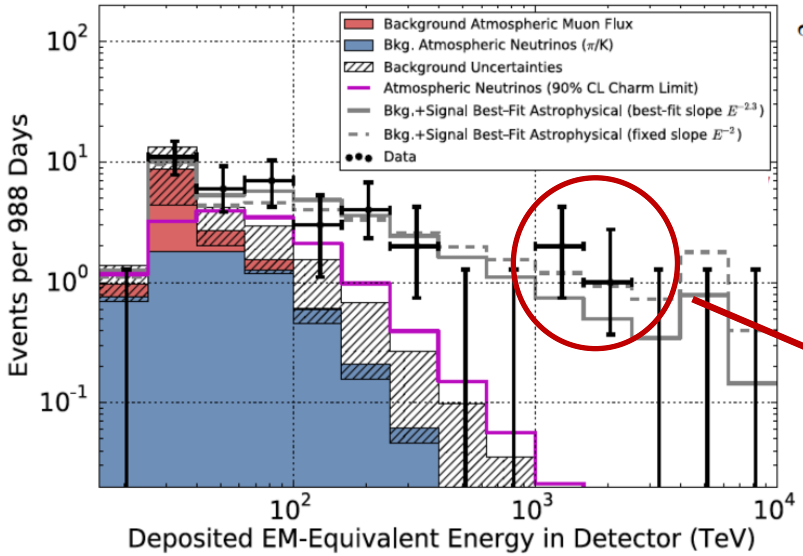



- 2yrs: only two events at 1 PeV

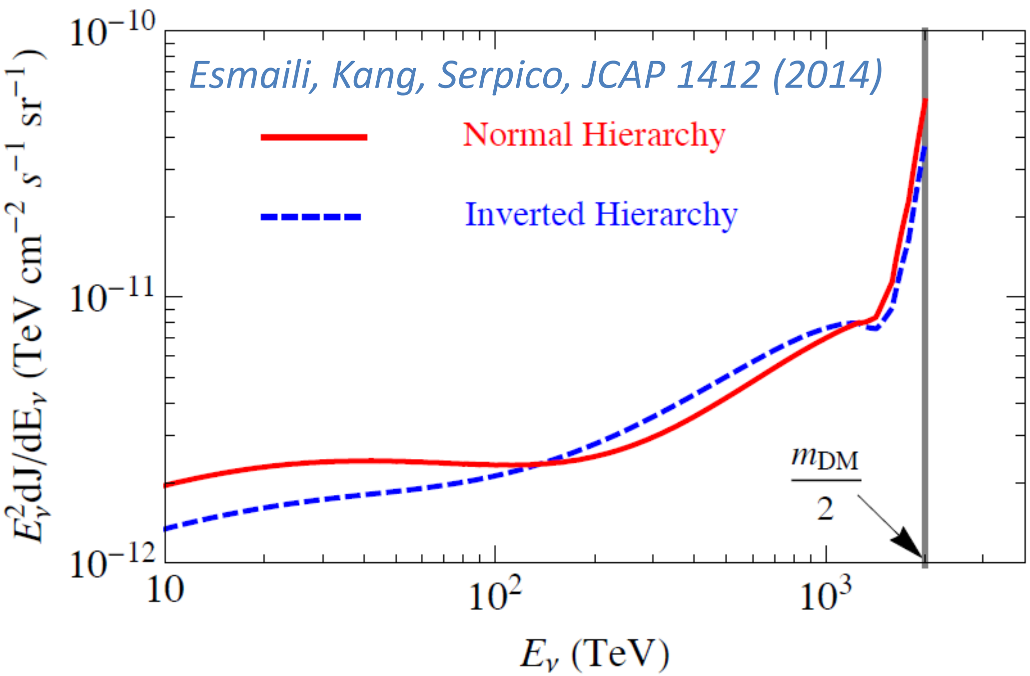
**Sharp peak**

# 2 bodies decay

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




*IceCube, PRL 113:101101 (2014)*




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

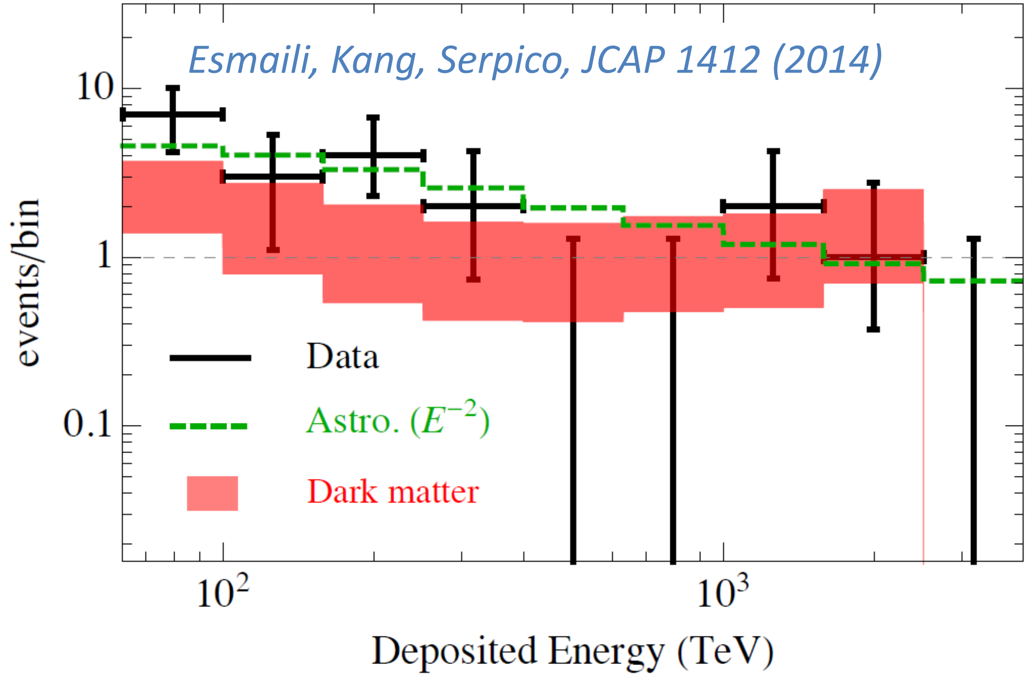
**Sharp peak ruled out**

# 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**



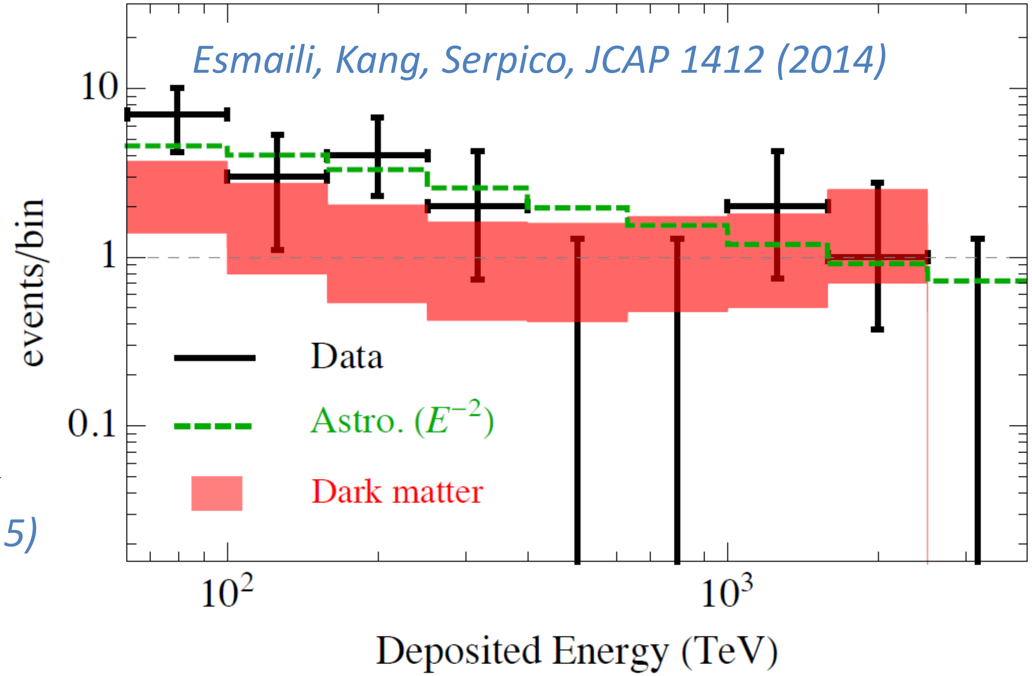

- Secondary neutrinos produced by **quarks** allow to fit all data even through 2 bodies decay with an **unnatural coupling**.

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

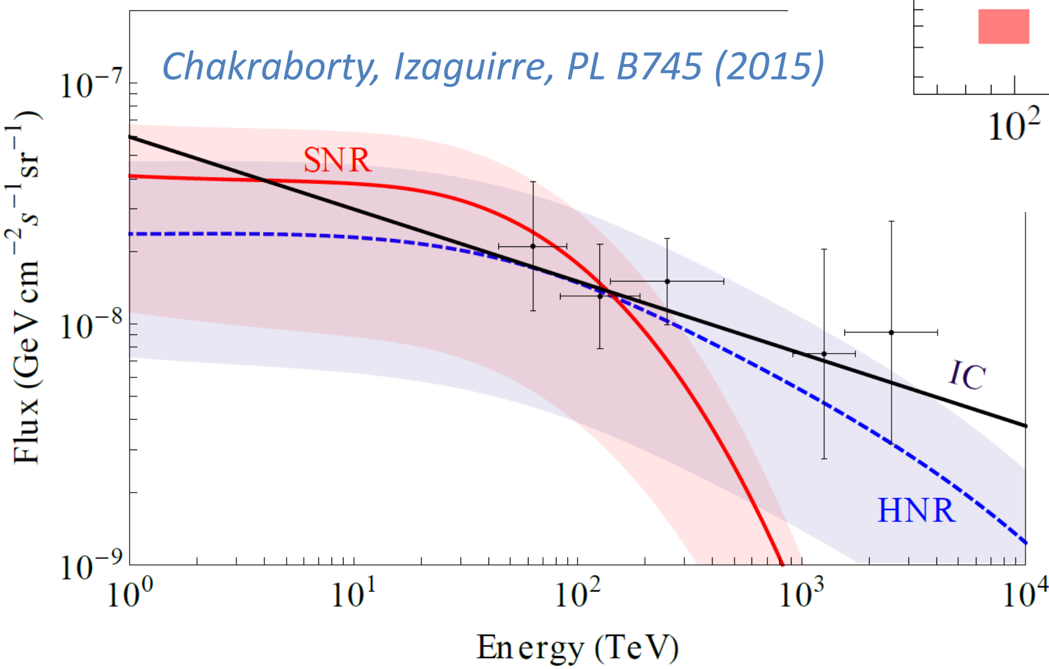
**but…**

# 2 bodies decay

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




**SuperNova Remnant**




**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**

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

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

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

  - 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*

| Dimensions | DM decay operators |
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| 4 | $\bar{L}H^c X$ |
| 5 | — |
| 6 | $\bar{L}E\bar{L}X\,,\quad H^\dagger H\bar{L}H^c X\,,\quad (H^c)^t D_\mu H^c \bar{E}\gamma^\mu X\,,$ |
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"natural" small coupling
multi body decay

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primary ν flux

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# Decaying Dark Matter

- There exsist only one operator with those characteristcs.

*Haba ed al., arXiv:1008.4777*

**"natural" small coupling**
**multi body decay**

**primary ν flux**

**negligible contribution**
**at low energy**

| Dimensions | DM decay operators |
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| 4 | $\bar{L}H^c X$ |
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**Does a symmetry exist in order to have only this operator?**

# Symmetries and Models

**Allowed**

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

**Forbidden**

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

- We can use Abelian U(1) symmetry:

| | $L_e, \ell_e$ | $L_\mu, \ell_\mu$ | $L_\tau, \ell_\tau$ | $\phi$ | $\chi$ |
|---|---|---|---|---|---|
| $U(1)_\chi$ | 1 | 4 | 2 | 0 | 3 |

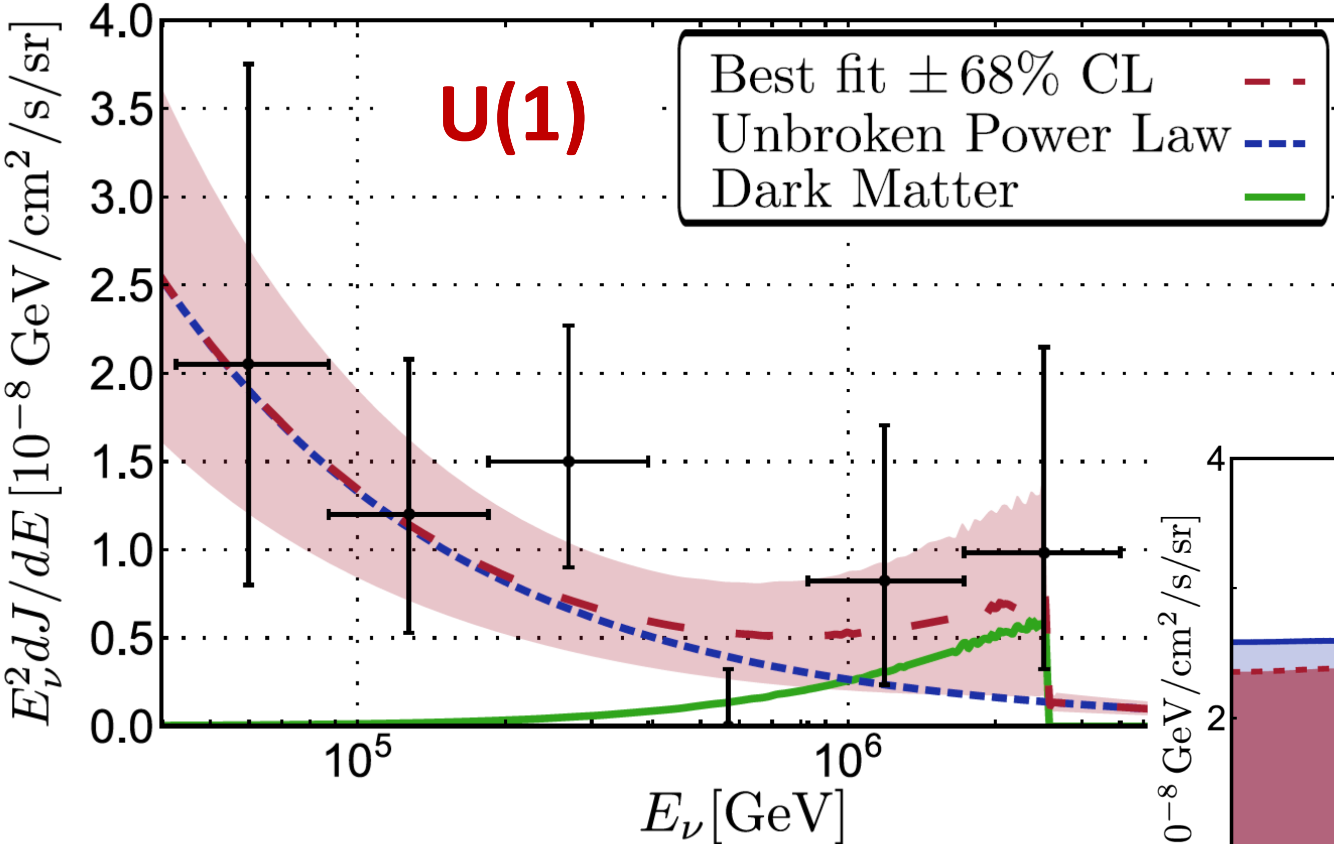
$$\{\mu, e, \tau\} + \{\tau, e, \mu\} + \{e, \mu, e\}$$

- We can use non-Abelian symmetries like $A_4$:

| | $L$ | $\ell$ | $\phi$ | $\chi$ |
|---|---|---|---|---|
| $A_4$ | **3** | **3** | **1** | **1** |

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

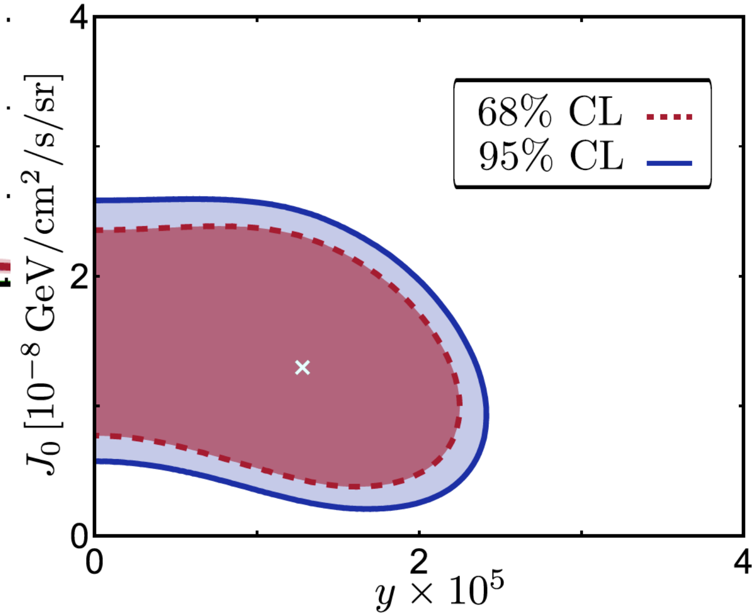
# Unbroken Power Law




$\chi^2/dof = 0.98$

$M_{DM} = 5.1$ PeV

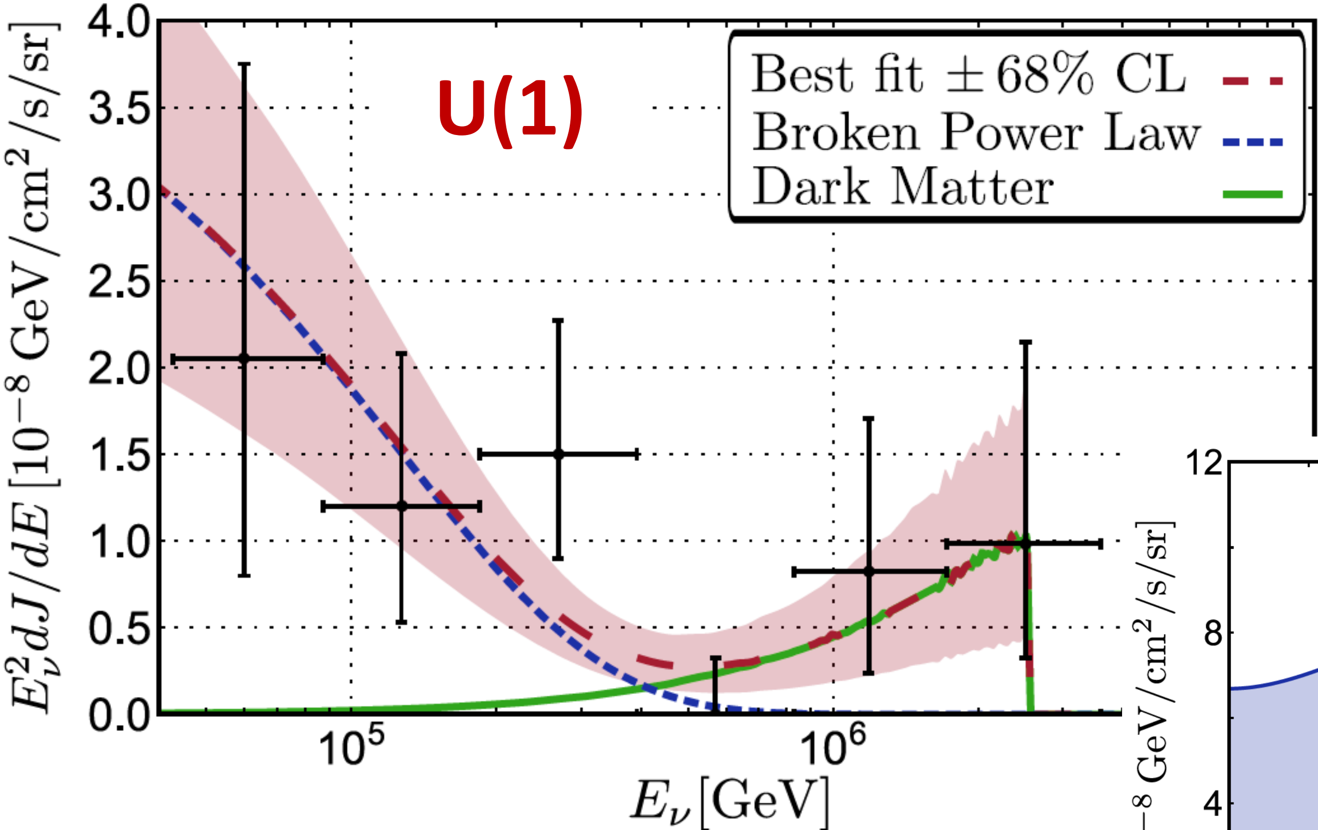
$\gamma = 2.7$




**Assumption**

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

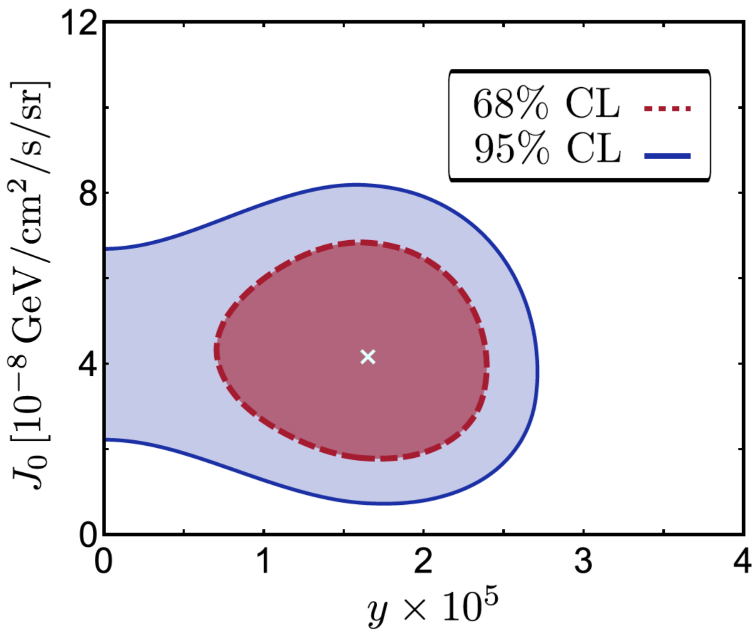
# Broken Power Law




$\chi^2/dof = 0.72$

$M_{DM} = 5.1$ PeV

$\gamma = 2.0$

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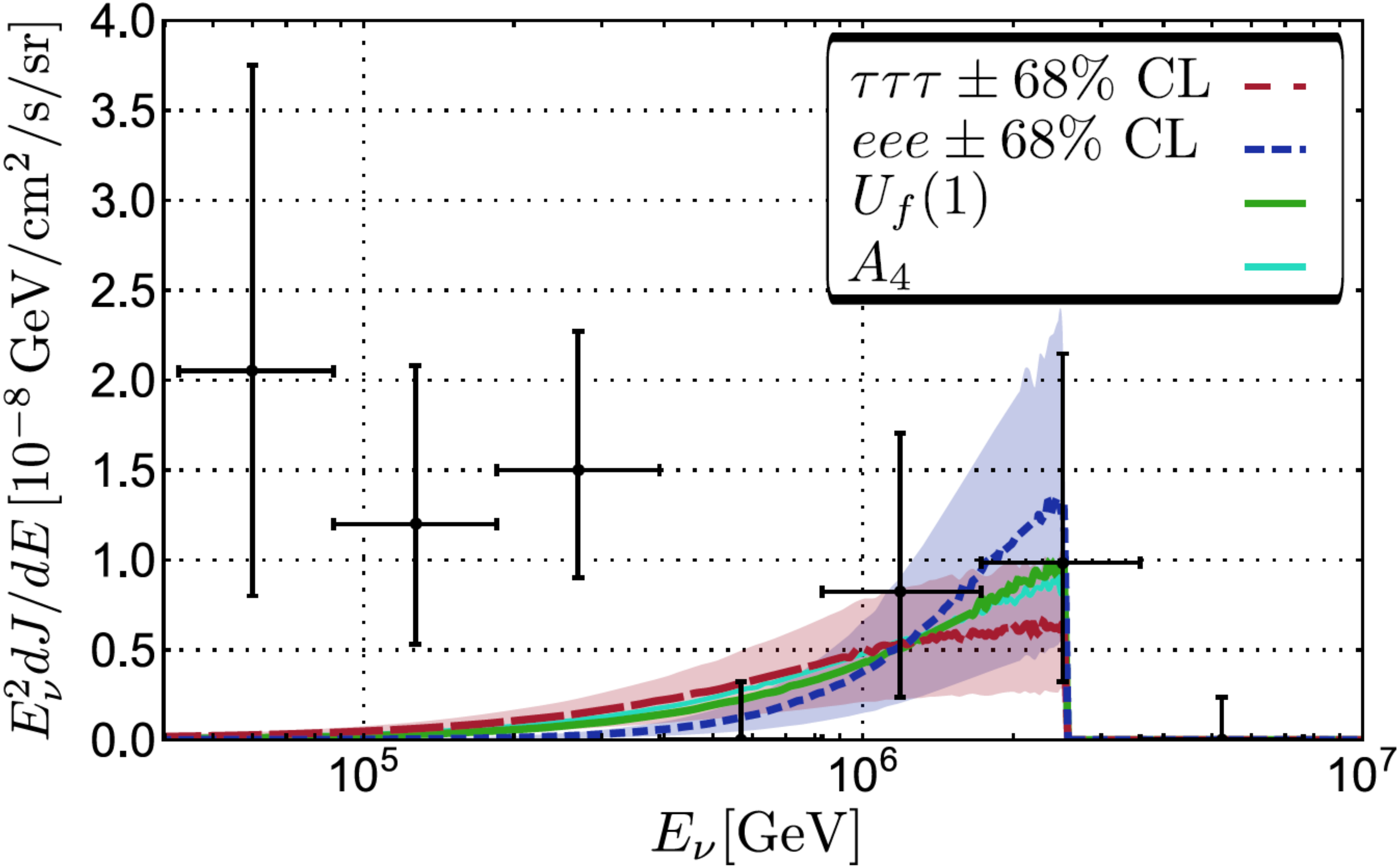
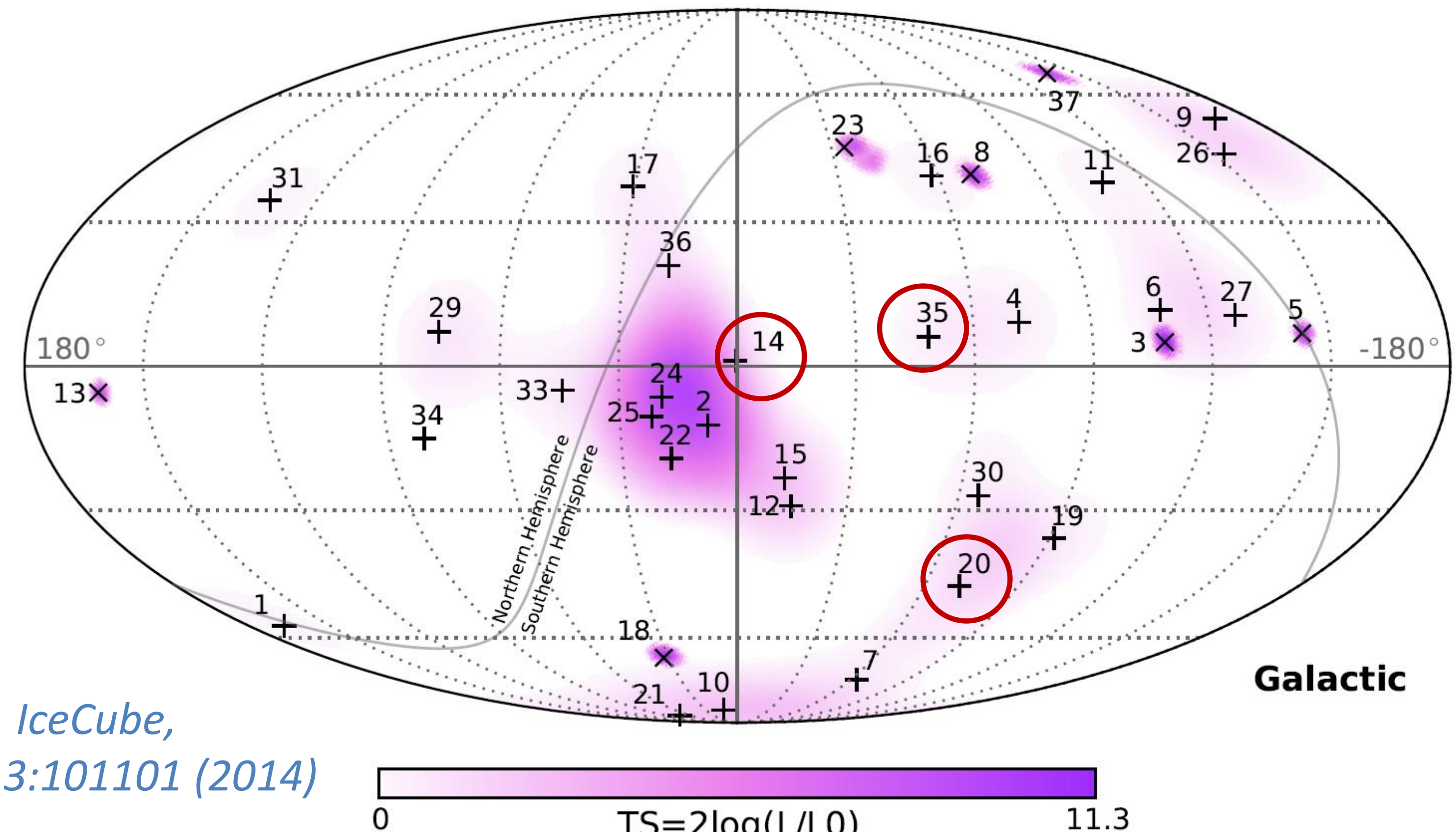
# $U(1)$ vs $A_4$



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

# Galactic vs Extragalactic

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




*IceCube,*
*PRL 113:101101 (2014)*

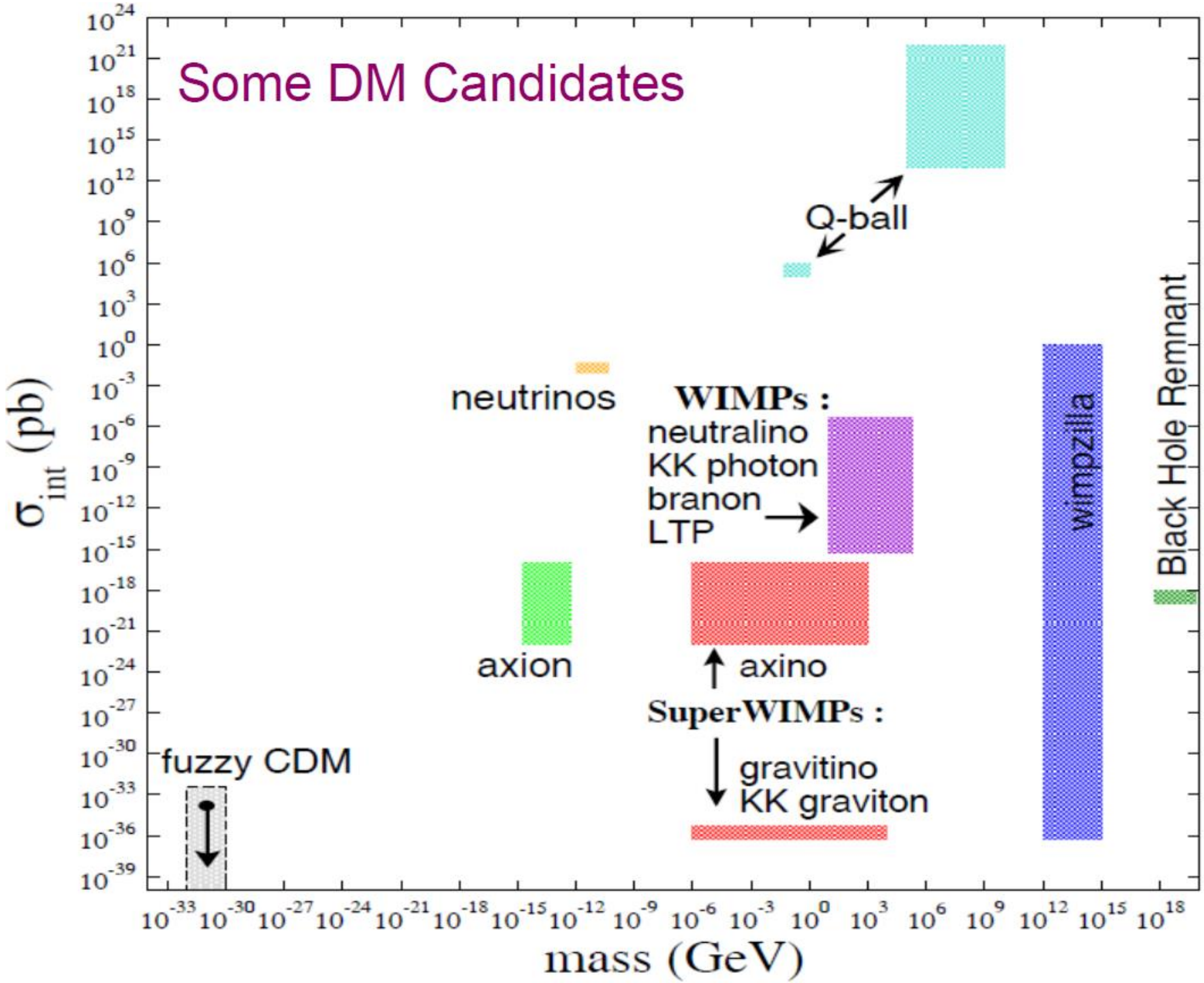
# Outlook: gamma-rays

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

**C**herenkov
**T**elescope
**A**array

- 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 , AGN, GRB);
    - 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 with IceCube and other experiment (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.
- 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 with IceCube and other experiment (like CTA).
- We need **more statistics** to understand the origin of high energy neutrinos (IceCube 2gen with 10 events per years).

**Thanks 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 $\nu_\mu$
- Angular resolution ~1° at 50% CL

$$\nu_\mu + N \to \mu + X$$

## Shower

- CC and NC interactions
- Mostly $\nu_e$ and $\nu_\tau$
- Angular resolution ~15° at 50% CL

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

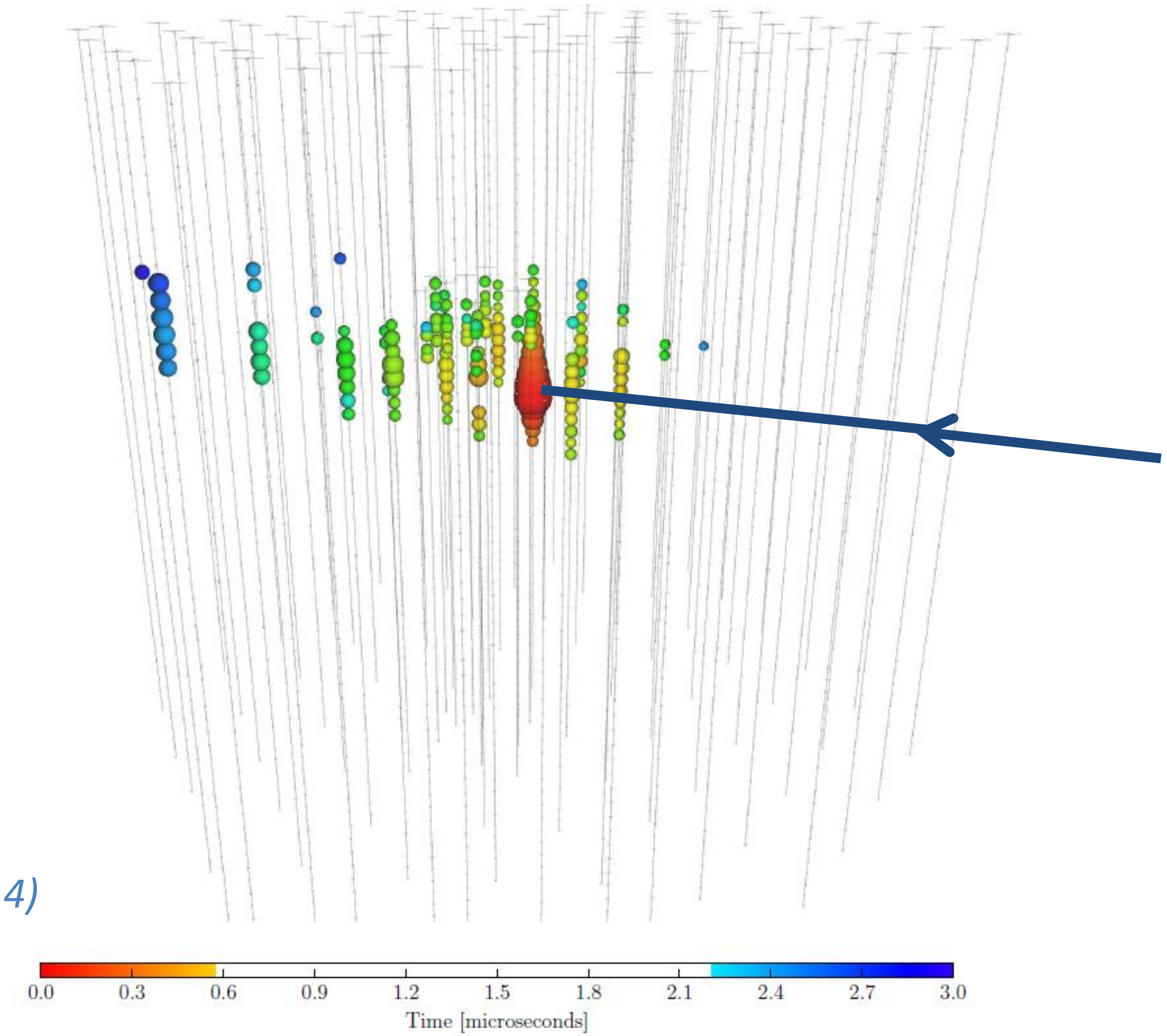
# Track

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

Declination:
20.7°±1.2°

Northern Sky
**Upgoing**

*IceCube, PRL 113:101101 (2014)*



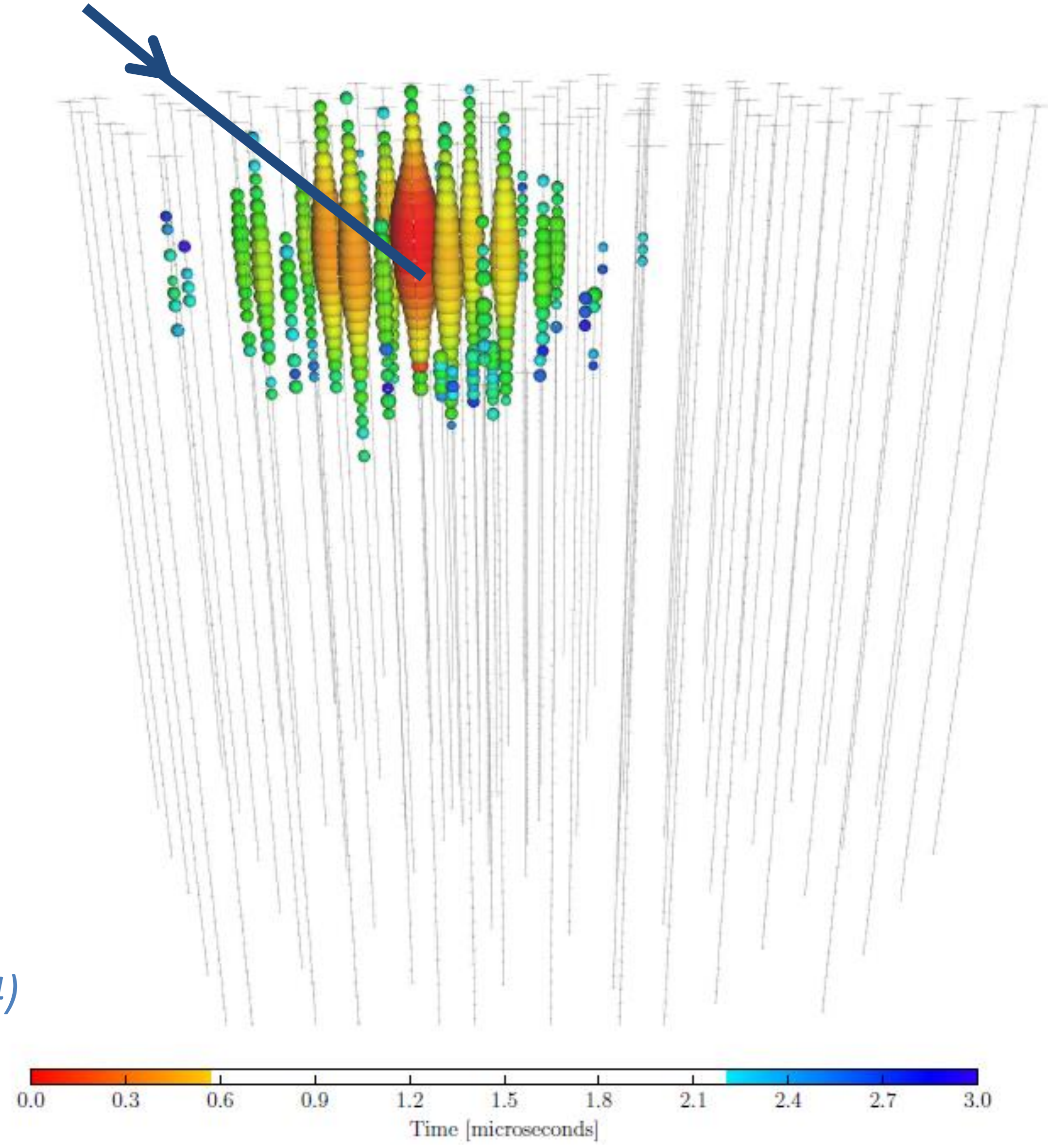
# Shower

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

Declination:
-55.8°±15.9°

Southern Sky
**Downgoing**

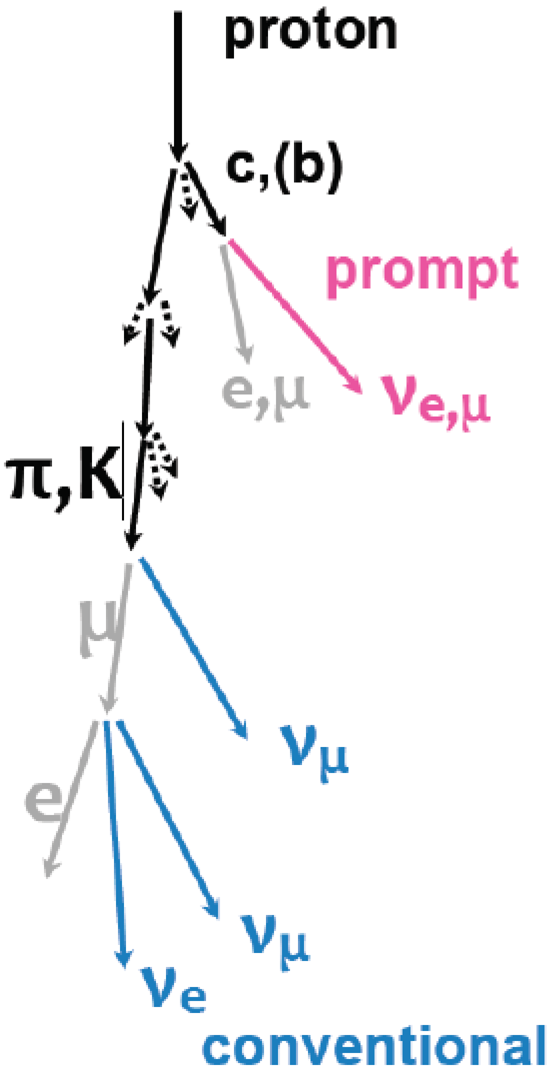
*IceCube, PRL 113:101101 (2014)*



# 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 $\pi$ 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.

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

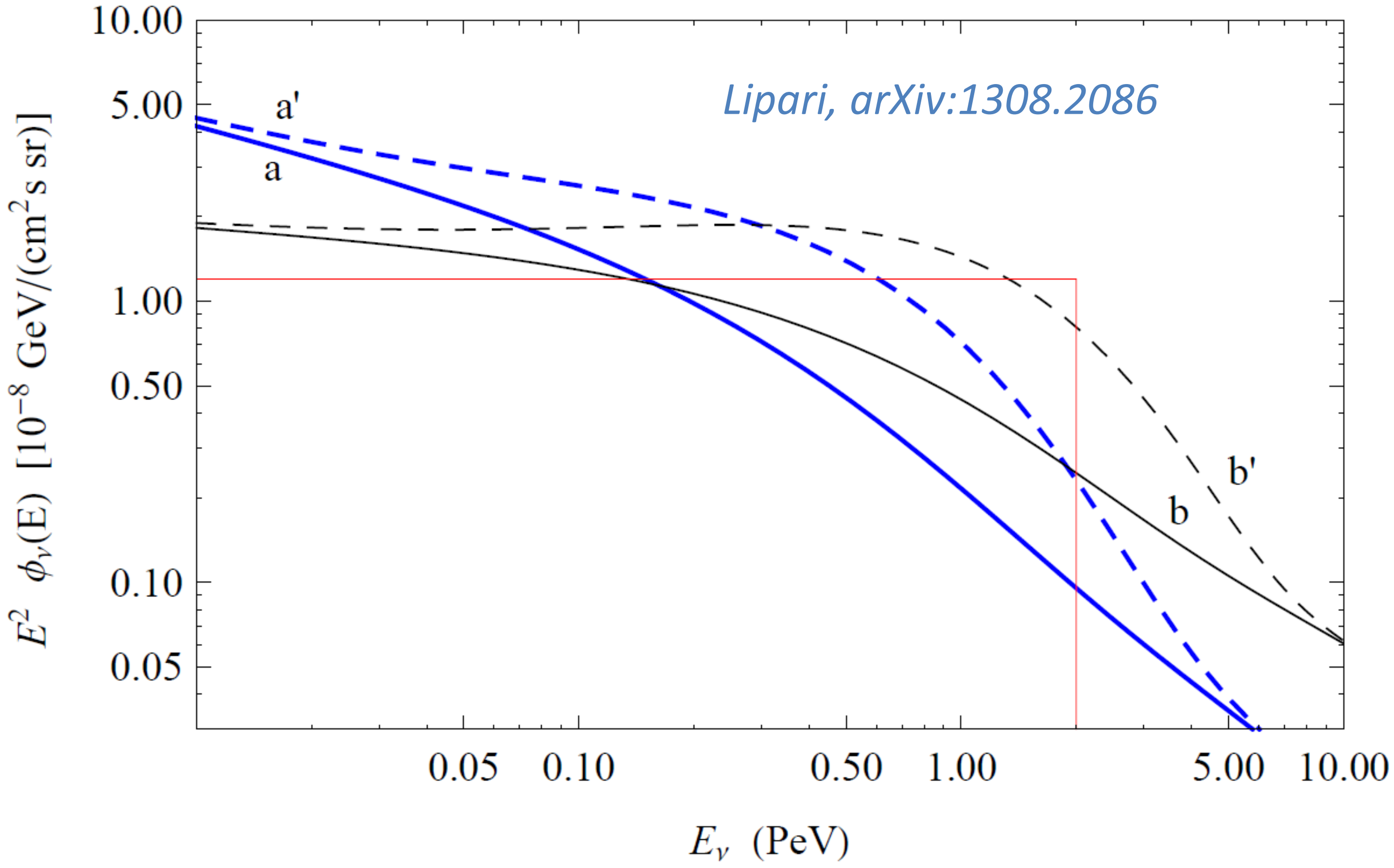
**prompt neutrinos**

harder spectrum

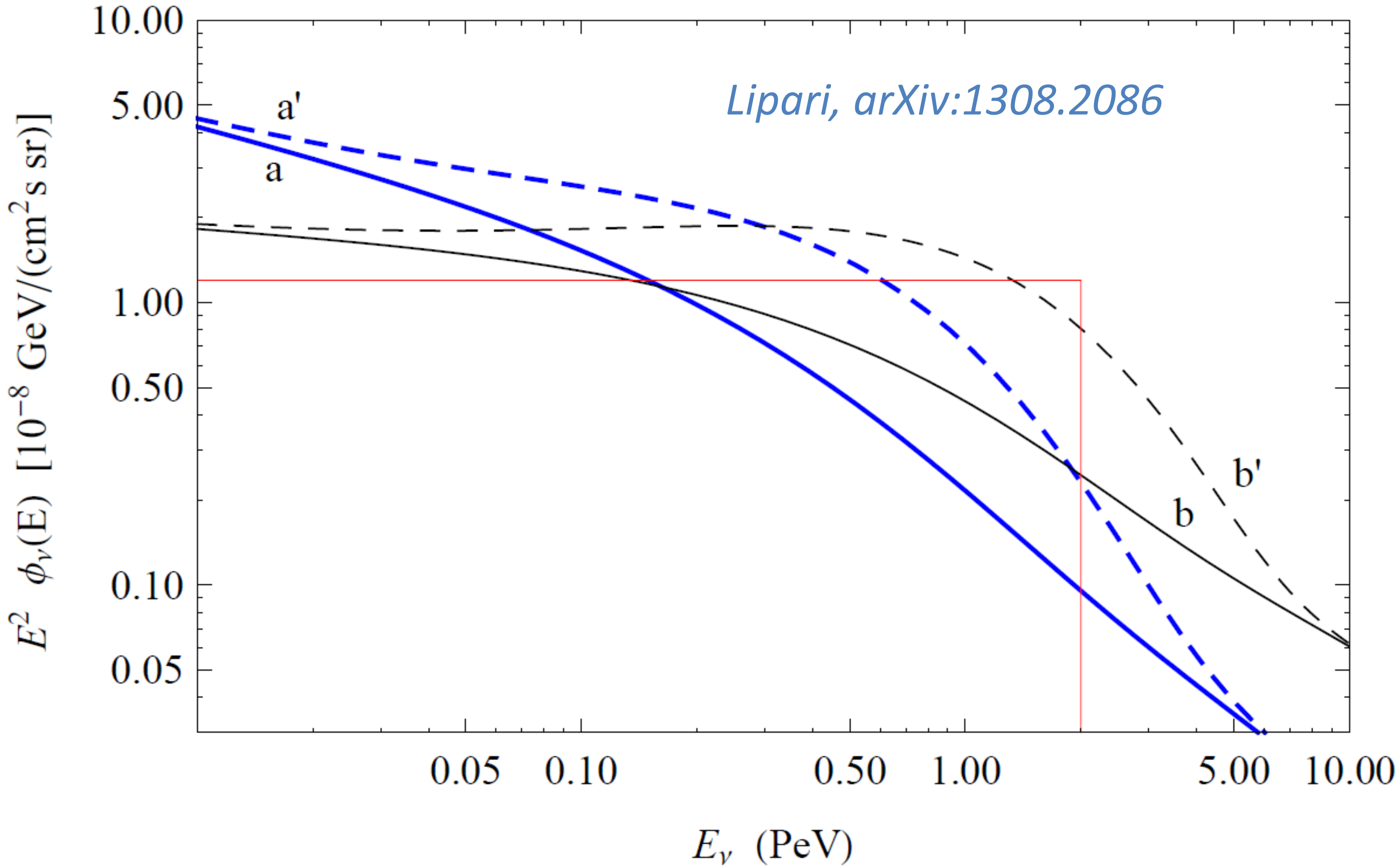
15-20% suppression with respect to the $\nu_\mu$ flux

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

# Prompt neutrinos



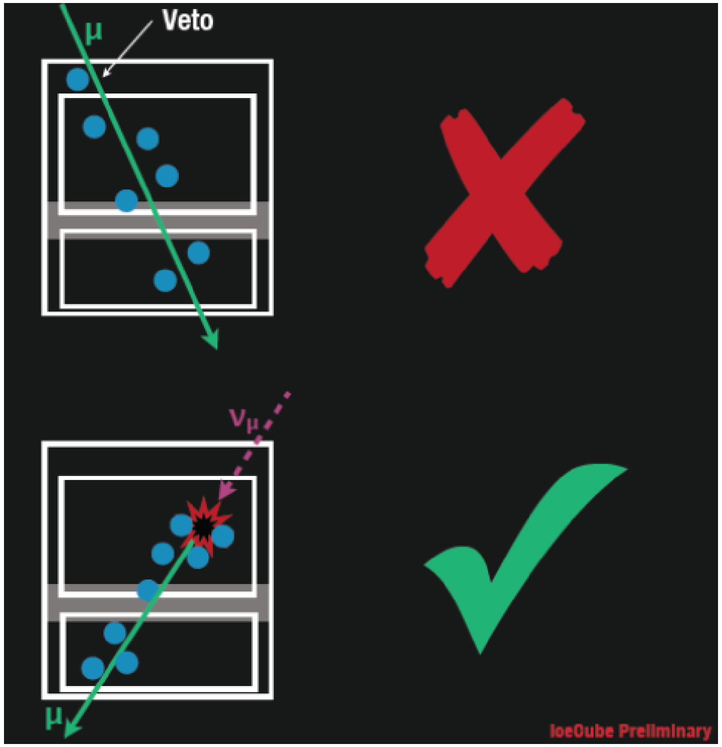
# Prompt neutrinos

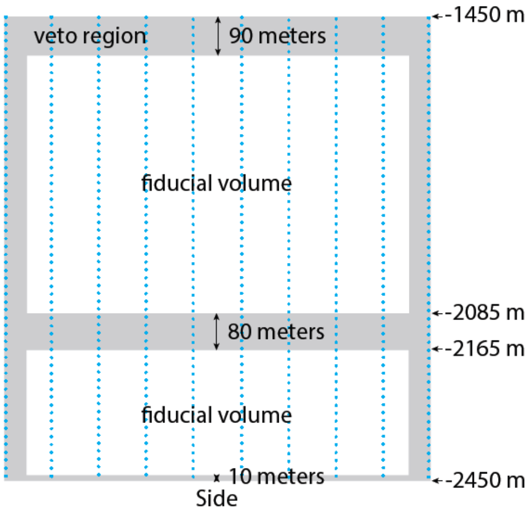


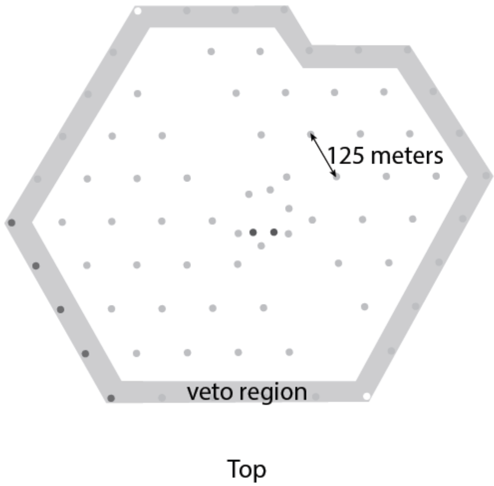

**Could the IceCube neutrino excess be explained only in terms of prompt atmospheric flux?**

# Background: μ veto

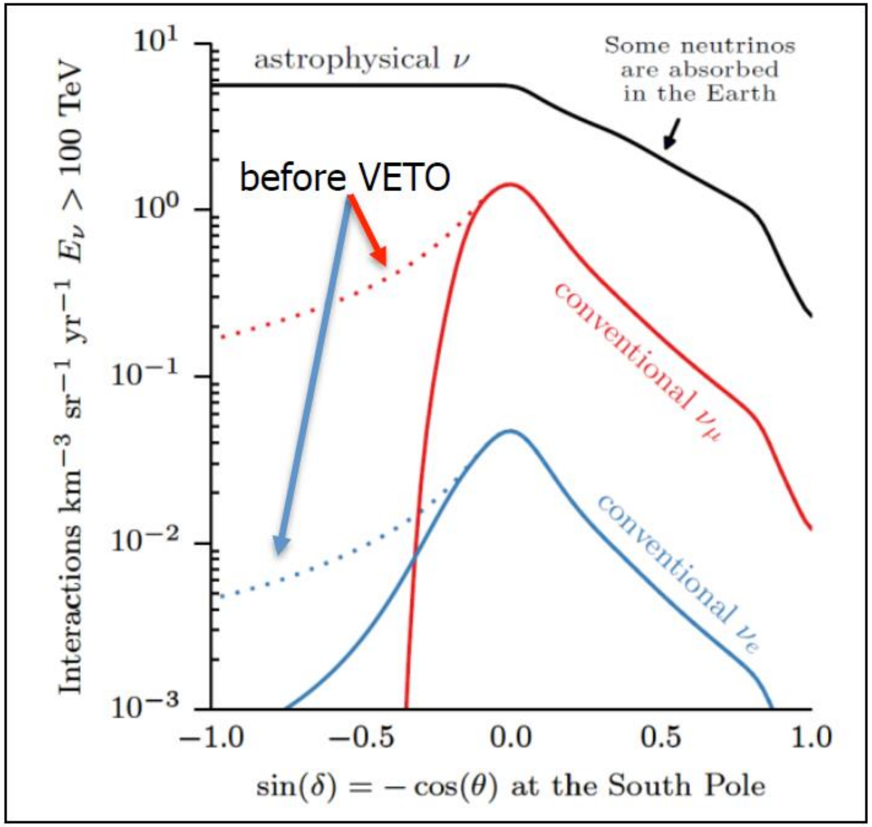
- The detector discards the events in which:
  - high energy muons produce first light in the veto region;
  - the deposited energy is lower than 30 TeV.
- For upgoing particles, the Earth is a filter.

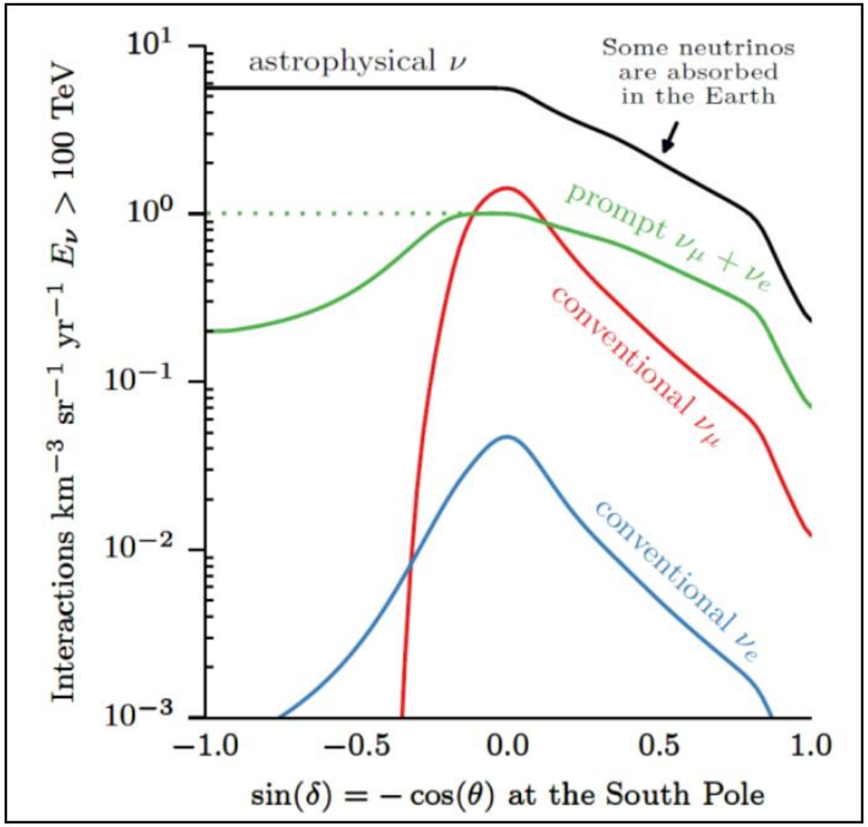


# Background suppression



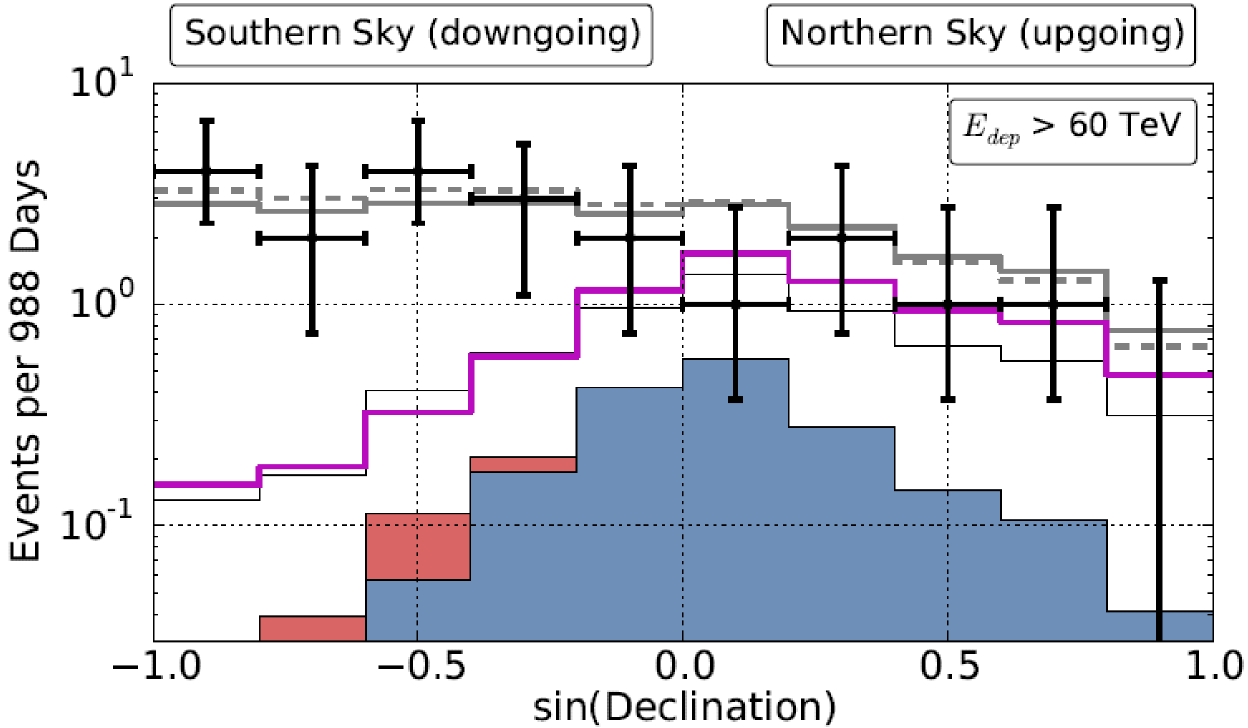

*Gaisser, Jeno, Karle, Van Sante, PR D90:023009 (2014)*

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

# Isotropy

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

*IceCube, PRL 113:101101 (2014)*

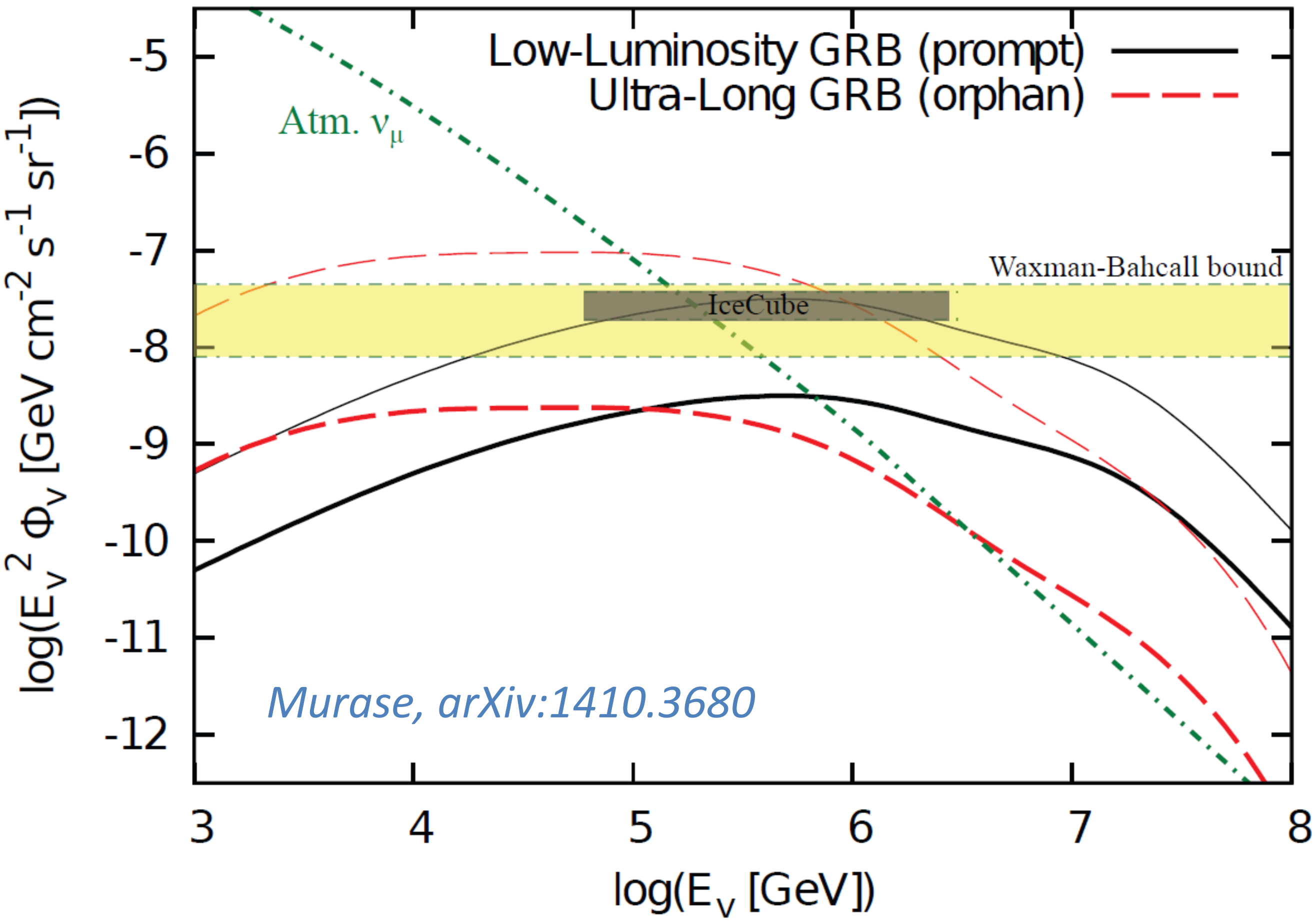



**Prompt neutrinos cannot explain the IceCube data!**

# Gamma-Ray Burst

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

→ **Correlation not observed yet!**



# Gamma-Ray Burst

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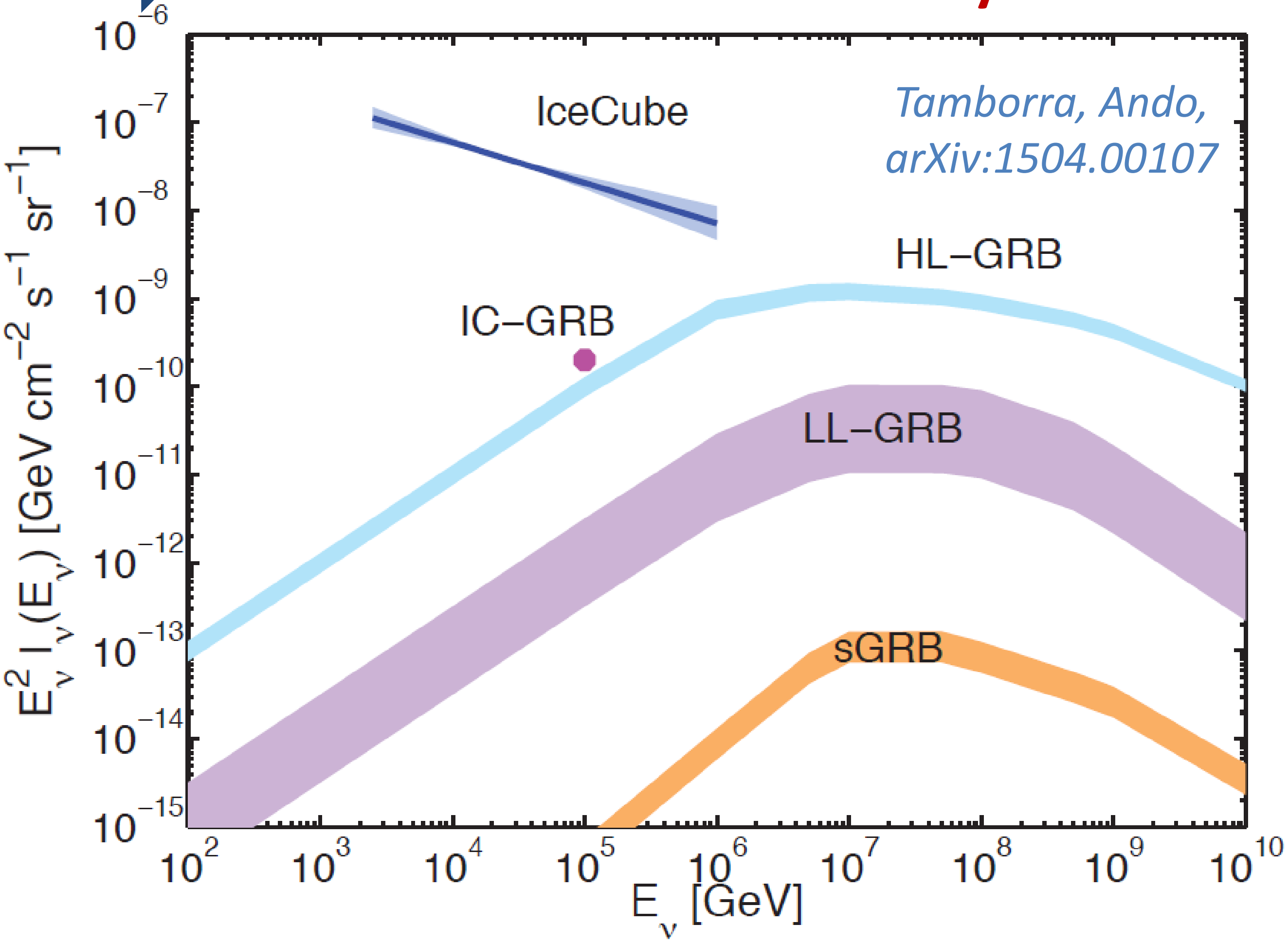
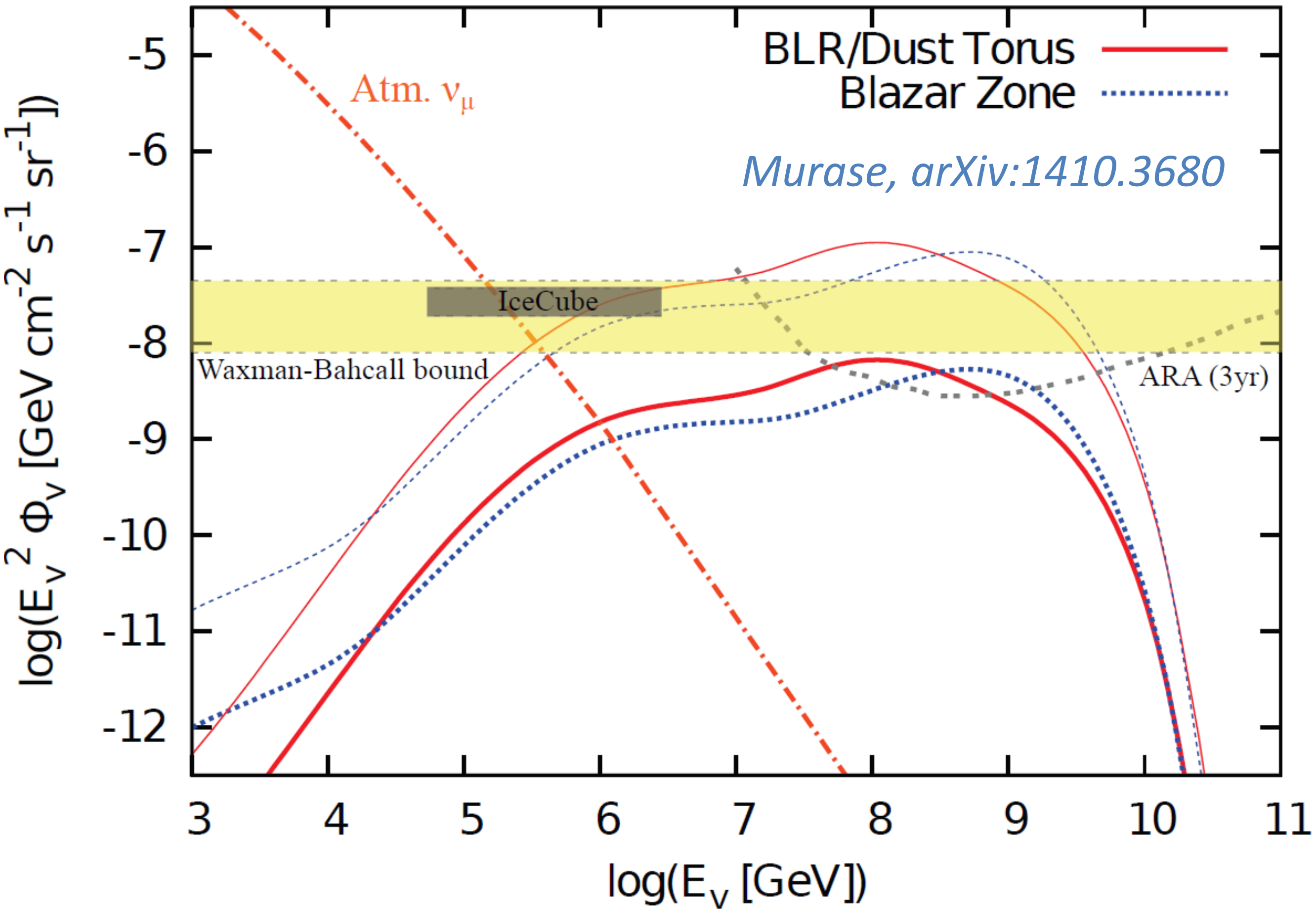


# Active Galactic Nuclei

- AGN can explain only PeV neutrinos.

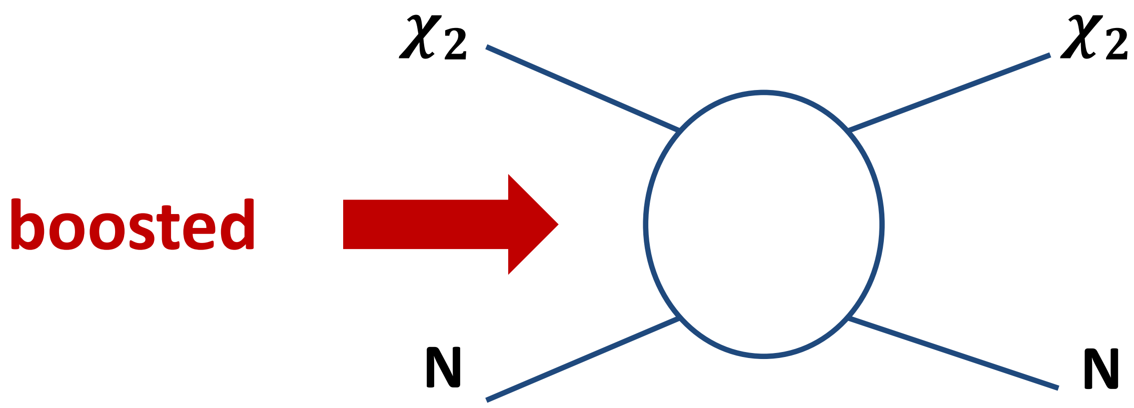
→ **Large uncertainties!**



# Boosted Dark Matter

$$\chi_1 \rightarrow \chi_2$$

$$\Delta m \sim PeV$$




**Direct detection!**

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

# Neutrino flux from DM

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

## Galactic

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

## Extragalactic

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

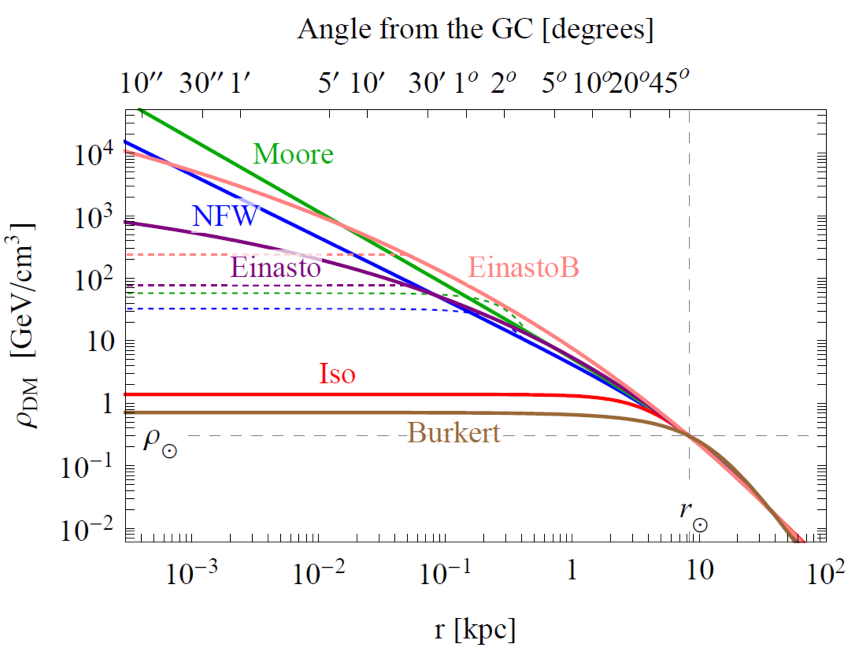
# DM density profile

- 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 $dN_\nu/dE_\nu$, 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.

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

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

→ constraint from *FERMI*

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

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

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

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

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

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