Interpreting the IceCube events by decaying dark matter hints and constraints

Arman Esmaili

Laboratori Nazionali del Gran Sasso (LNGS)
Theory Group

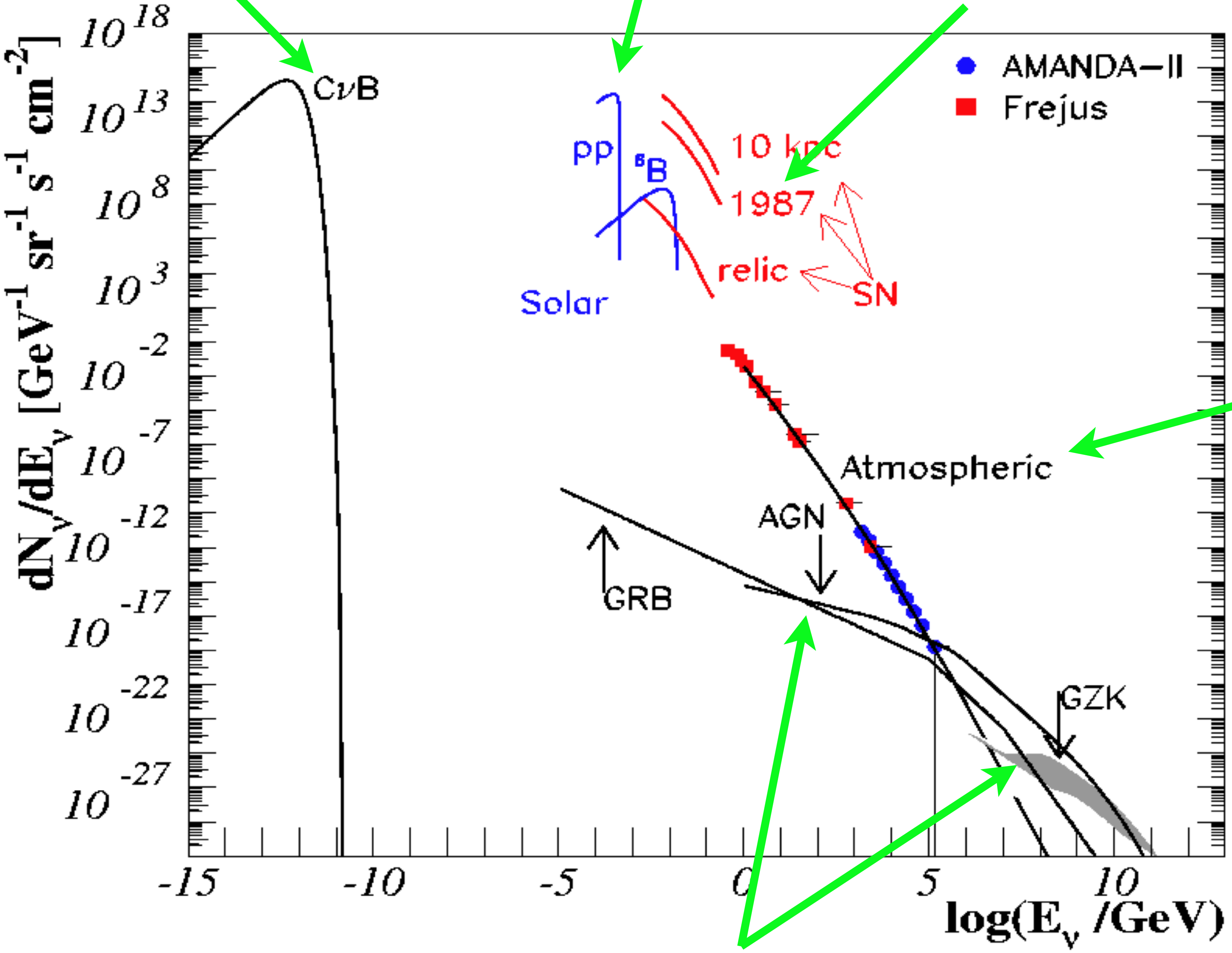
20/Nov/2014

Neutrino Sky

☹

SNO, BOREXINO,...

SK, IMB, ...



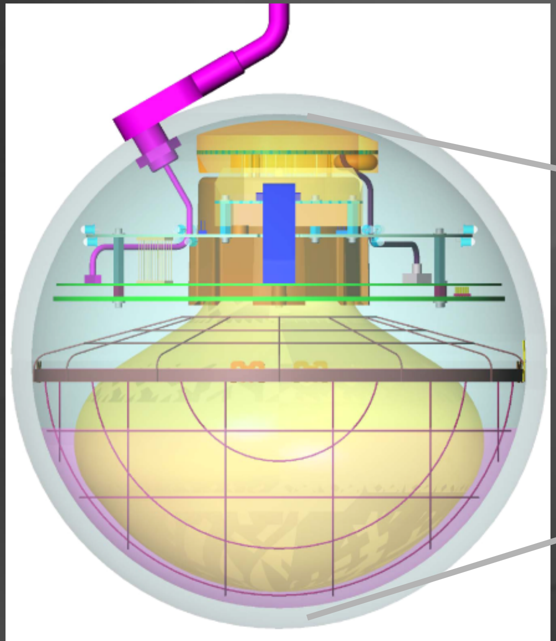
SK, AMANDA, IceCube...

Background for astrophysical neutrinos

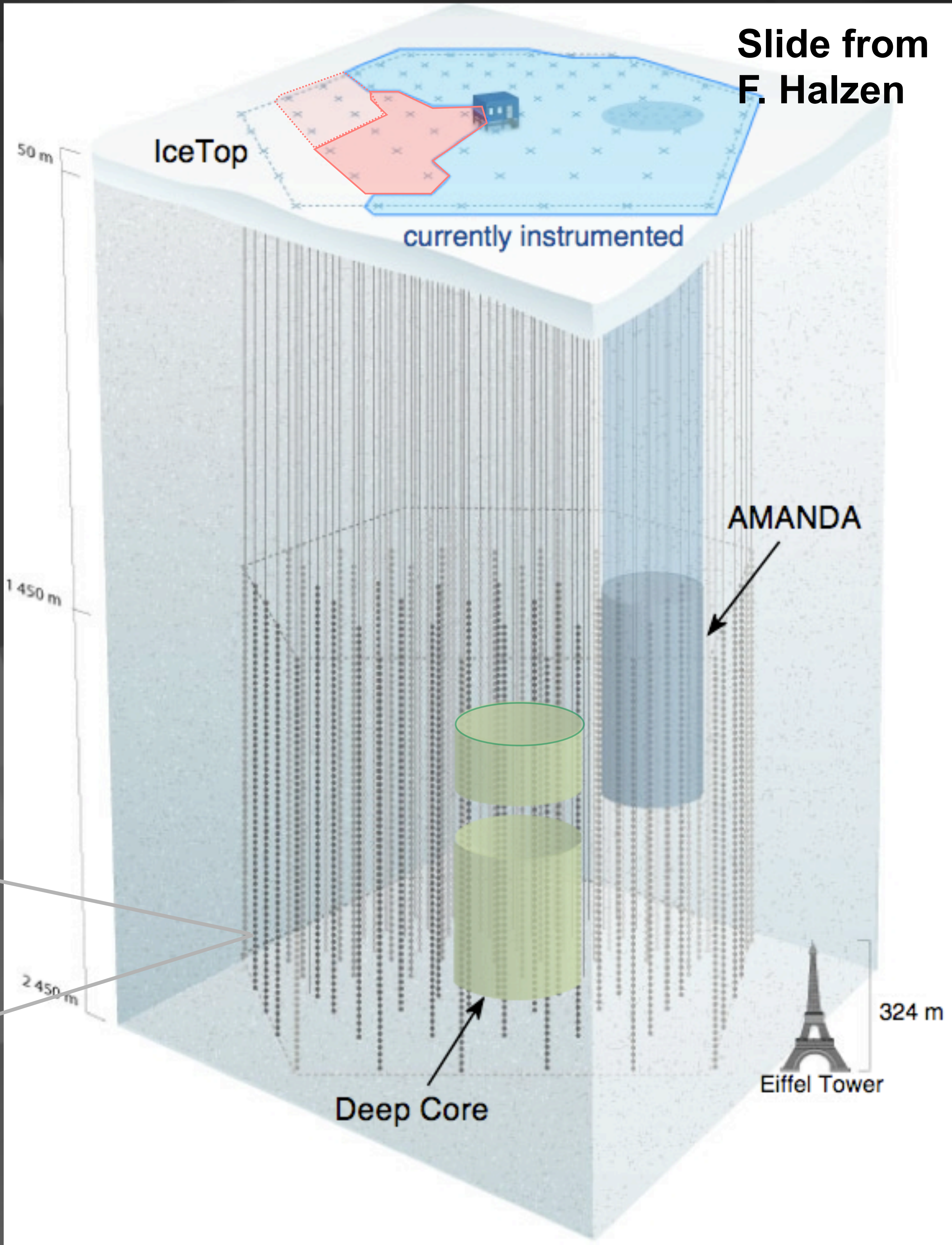
IceCube ?

IceCube / Deep Core

- 5320 optical modules on 86 strings (+ IceTop)
- detects ~220 neutrinos and 1.7x10^8 muons per day
- threshold 10 GeV
- angular resolution
  < 1 degree



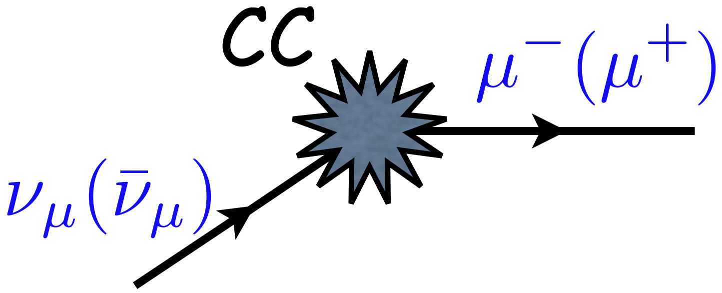
Digital Optical Module (DOM)

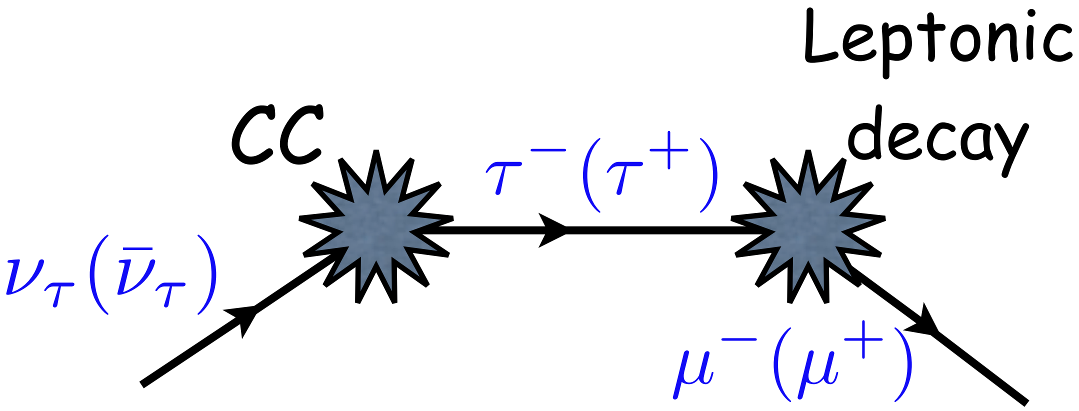


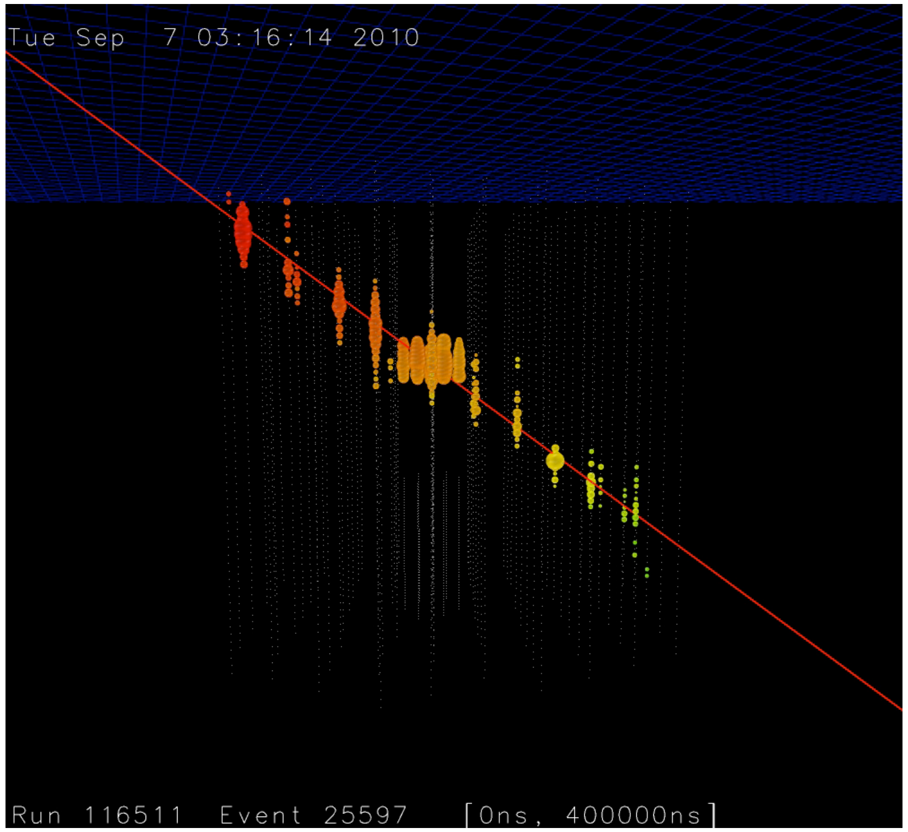
Slide from F. Halzen

Flavoring at IceCube

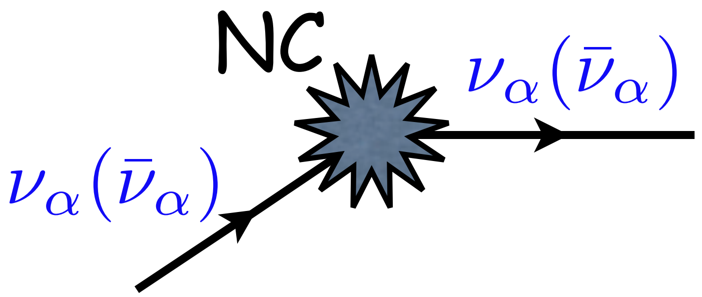
muon-track events

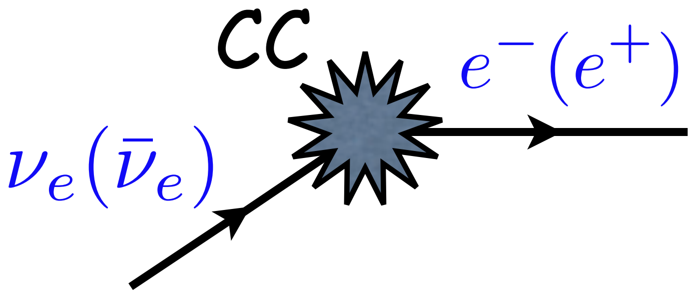


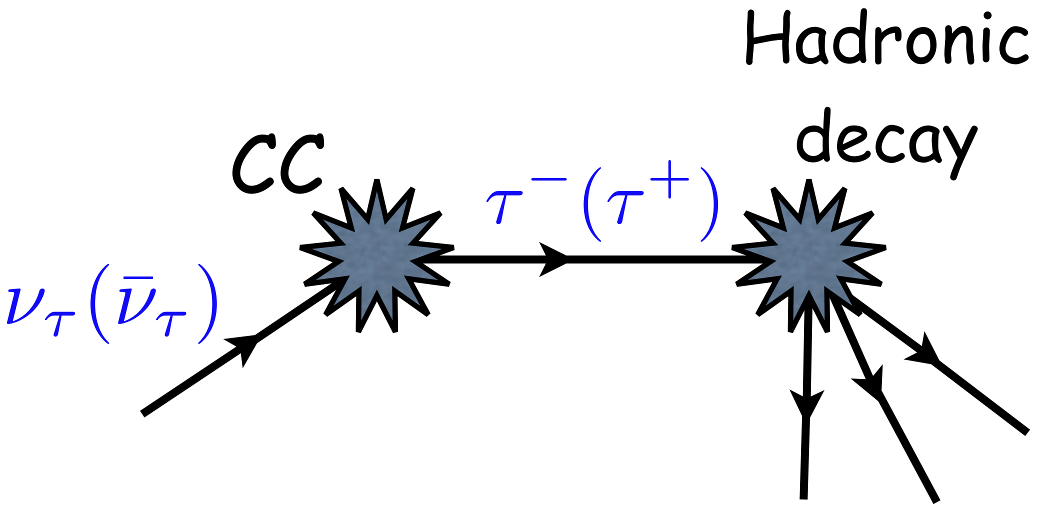


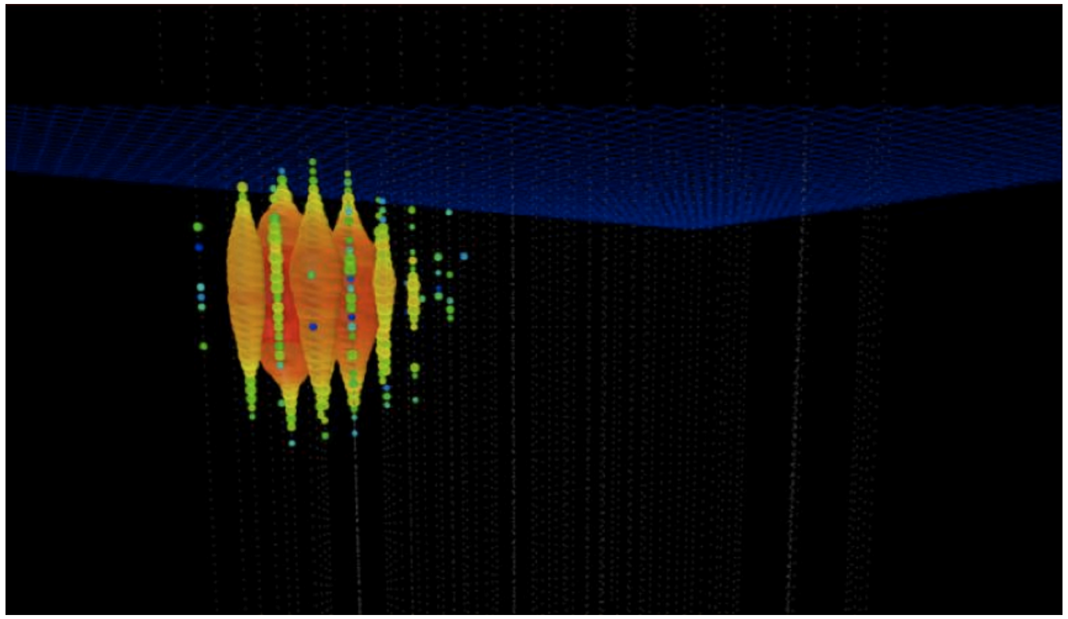


cascade events









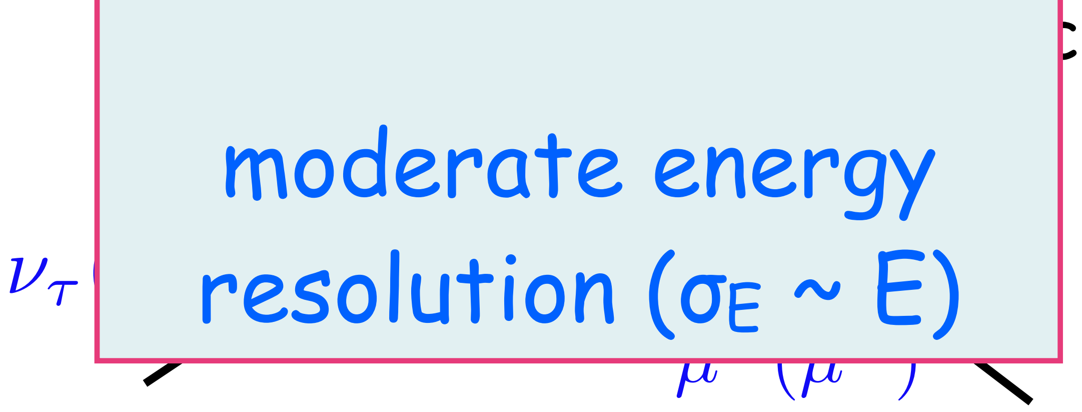
figures from IceCube website

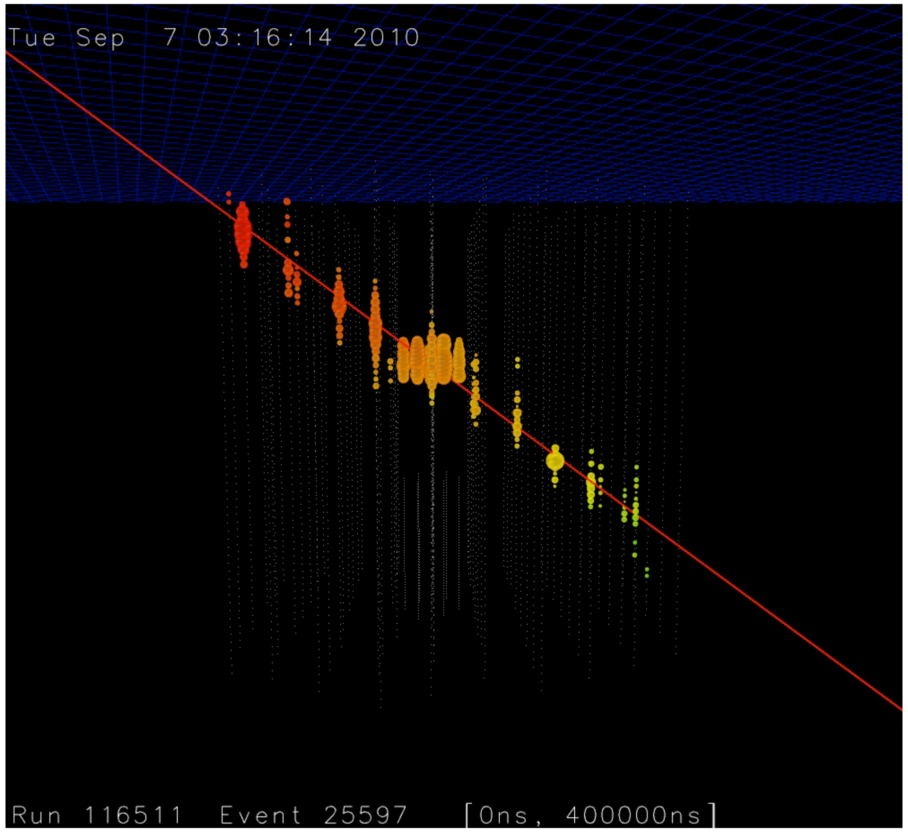
Flavoring at IceCube

muon-track events

great angular resolution (< 1°)

moderate energy resolution (σ$_E$ ~ E)



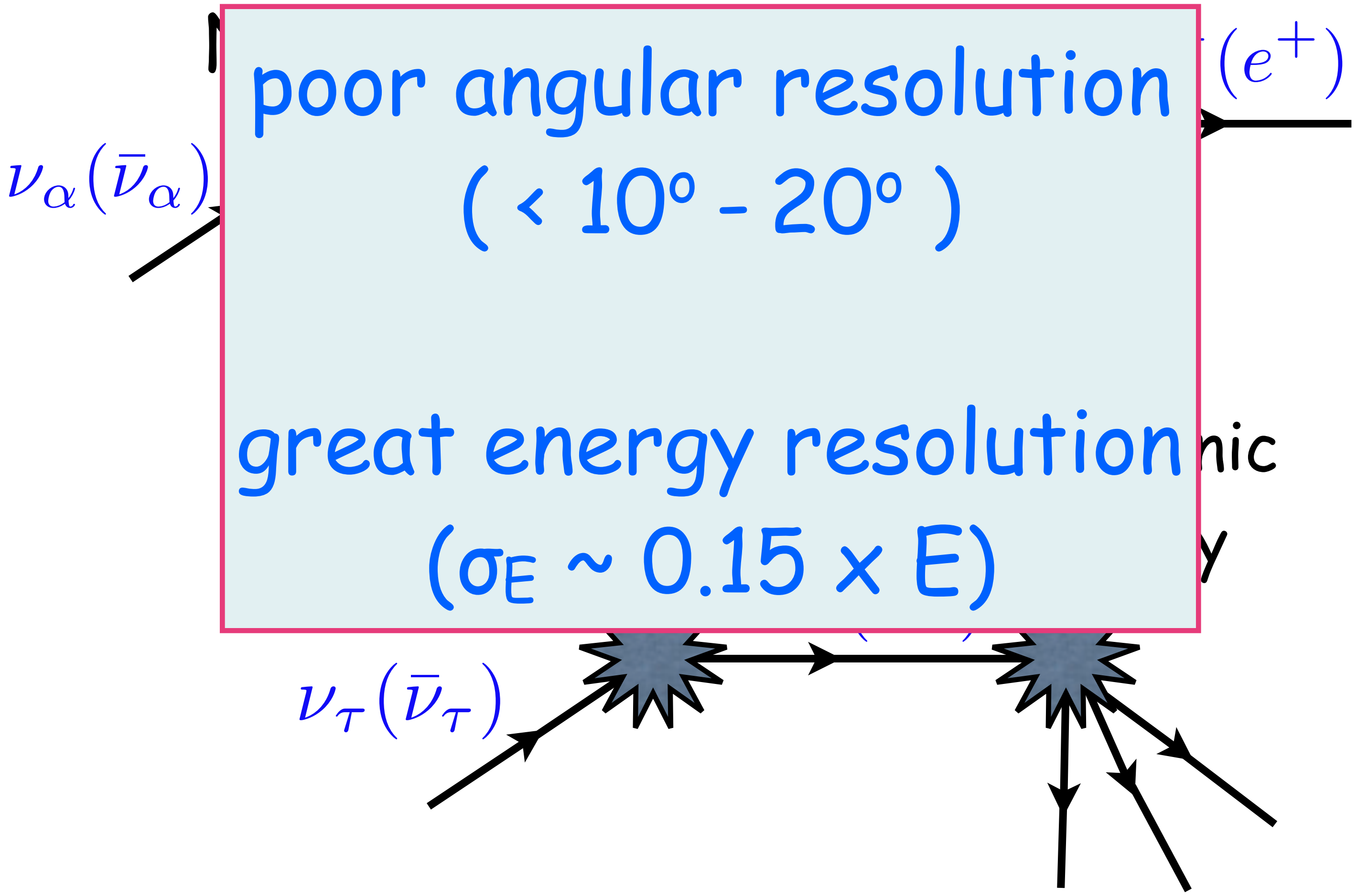


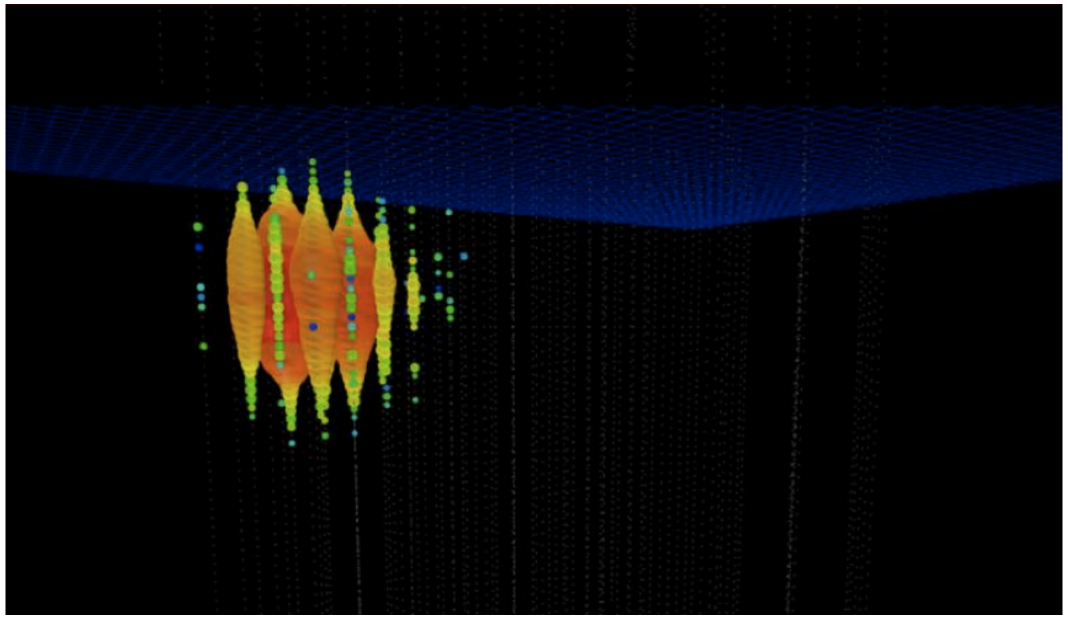
figures from IceCube website

cascade events

poor angular resolution (< 10° - 20°)

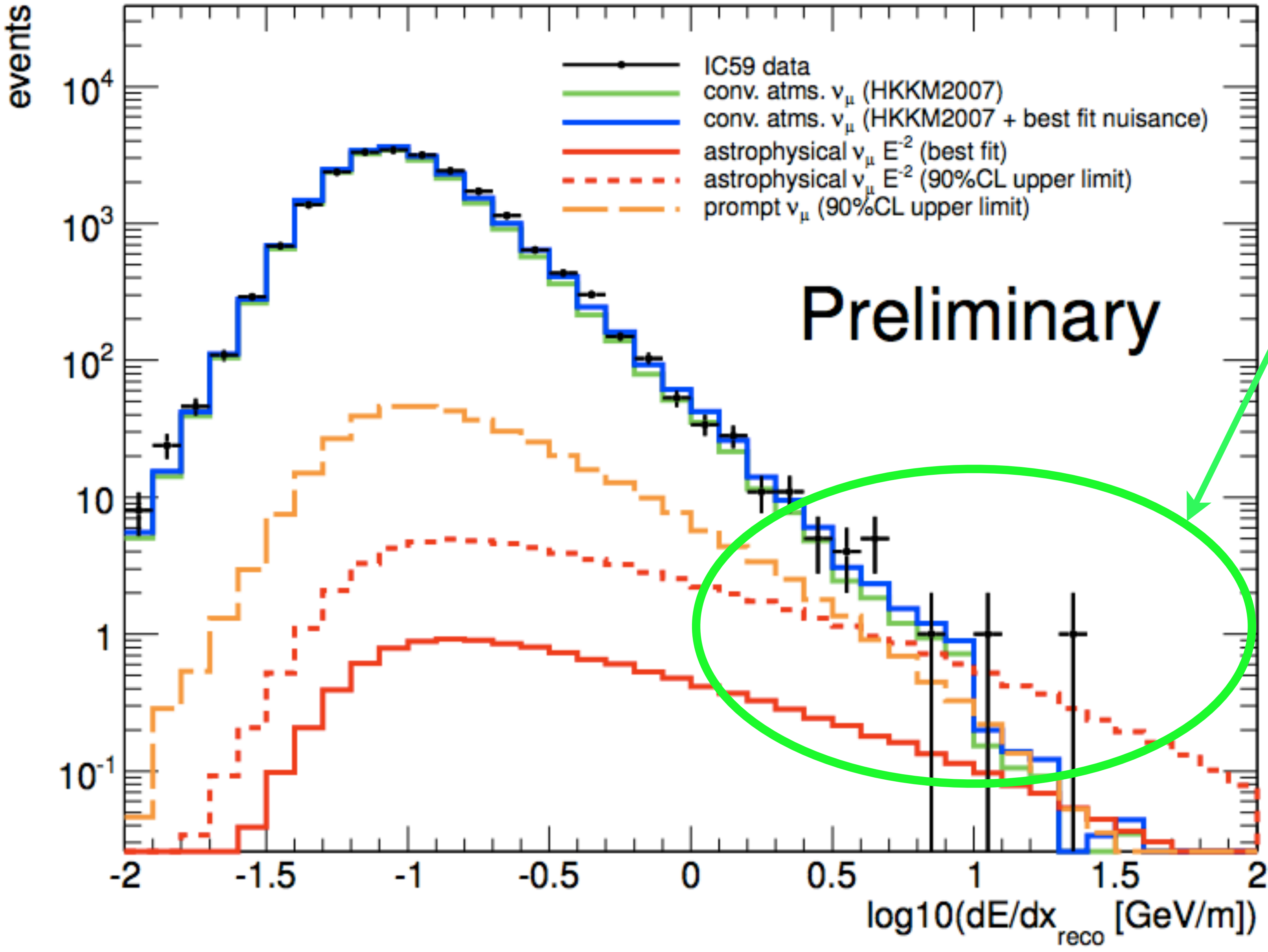
great energy resolution (σ$_E$ ~ 0.15 x E)





Mission for IceCube began !

✓ muon-track events at IceCube-59, 348 days livetime.



excess in high energy tail (~ 300 TeV)

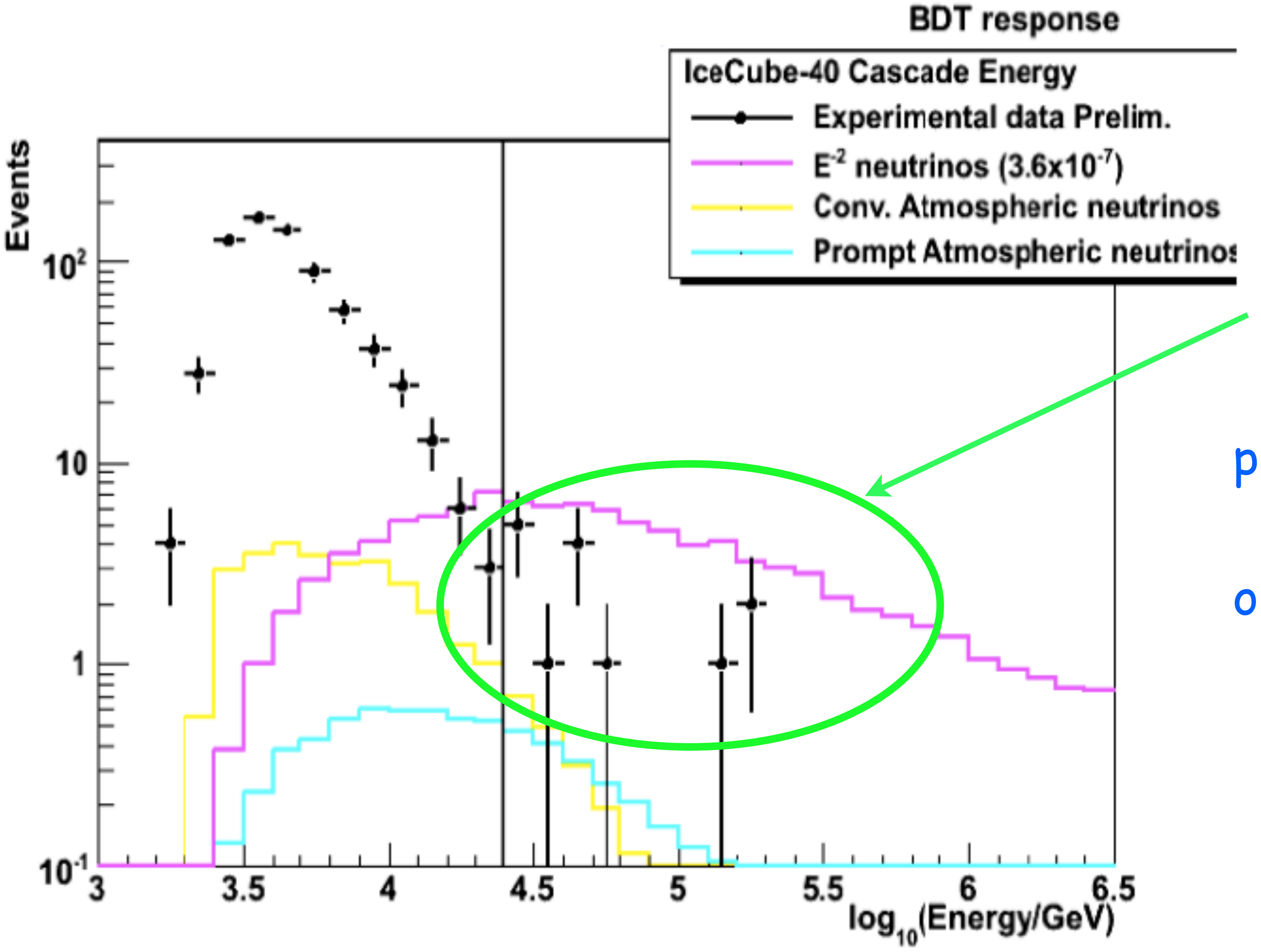
prompt atm neutrinos ?
or
astrophysical neutrinos?

analysis shows preference to astrophysical origin of excess, significance ~ 2.1σ

A. Schukraft [IceCube Collaboration]
Nucl. Phys. Proc. Suppl. 266 (2013) [arXiv:1302.0127]

Mission for IceCube began !

- ✓ cascade events at IceCube-40, 367 days livetime.



E. Middell, PhD thesis

excess in high energy tail (> 100 TeV)

prompt+conventional ~ 4

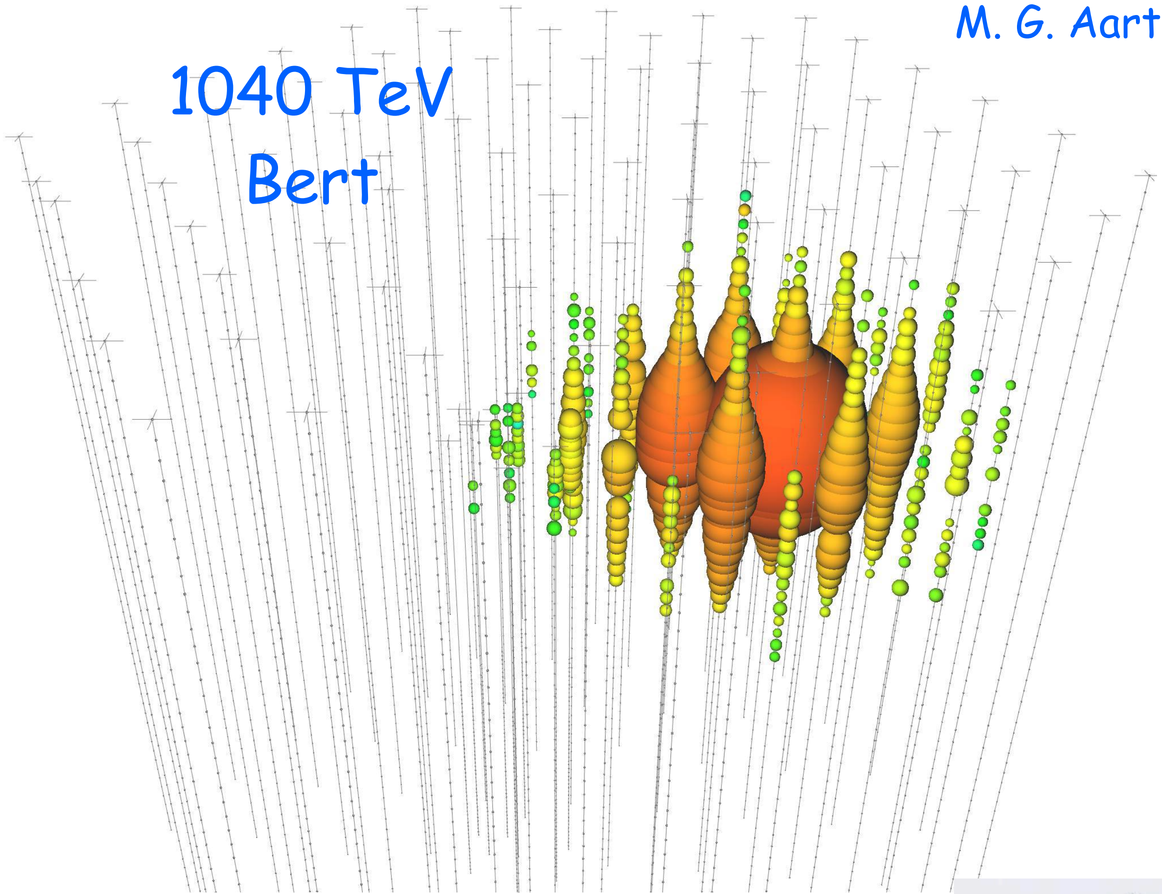
observed ~ 14

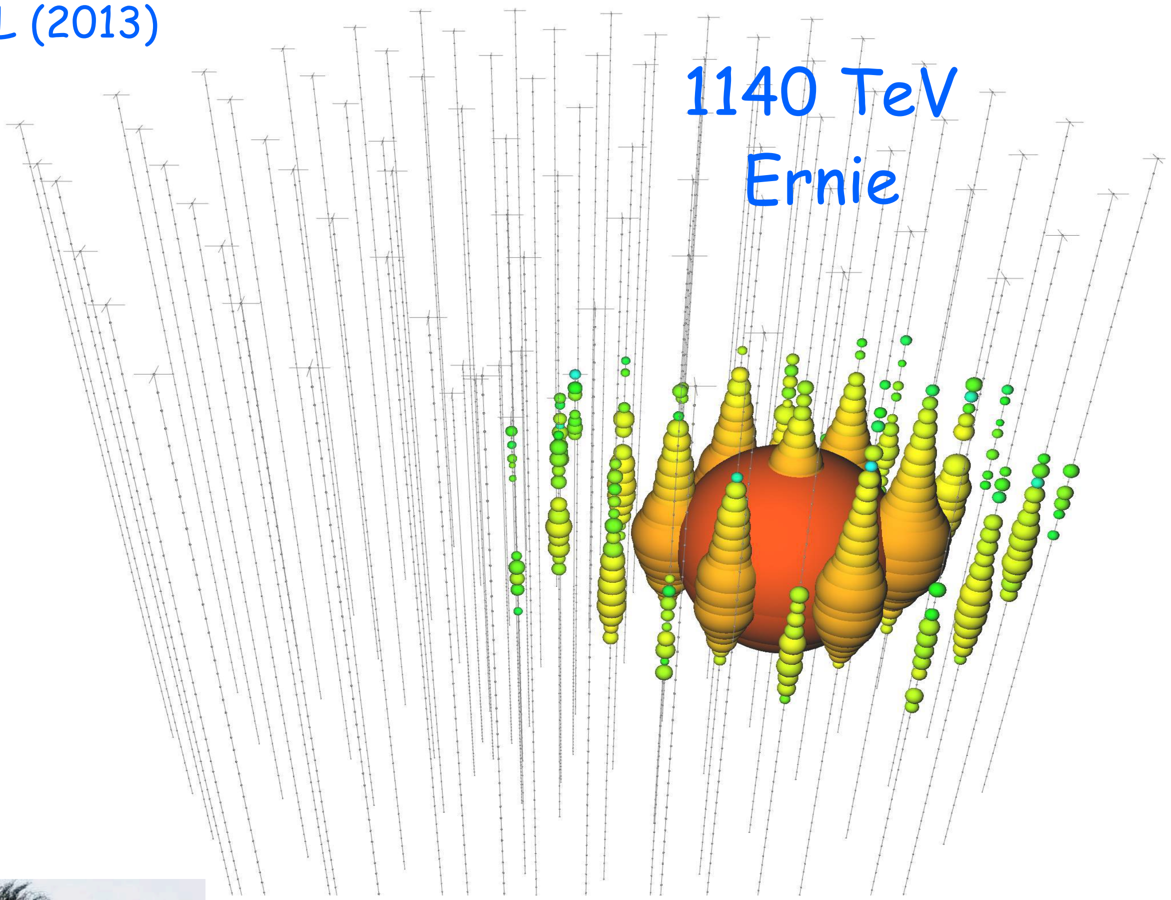
hint on astrophysical flux $\sim 2.4\sigma$

Mission for IceCube began !

✓ The two PeV cascade events, 616 days livetime

M. G. Aartsen et al, PRL (2013)

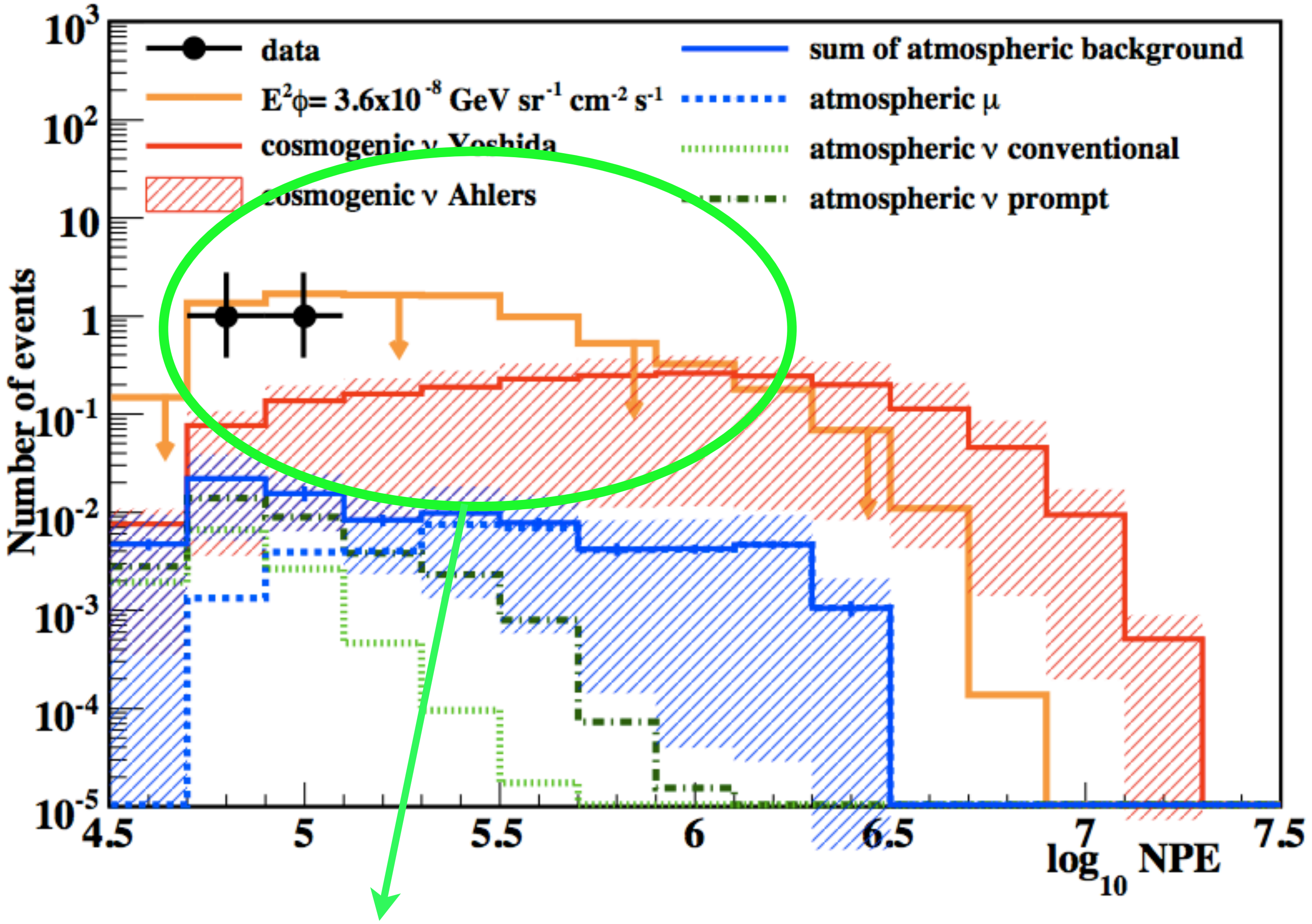




Mission for IceCube began !

✓ The two PeV cascade events, 616 days livetime

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 111 (2013), [arXiv:1304.5356]



it is like a cut-off at ~ PeV

expected bkg. (conventional+prompt) ~ 0.08(-0.057)(+0.041) sys.

excess of events ~ 2.8σ

GZK ? too low energy, more events should be seen in higher energies

astrophysical ? an E^{-2} spectrum would give ~ 9 more events in higher energies

demands more statistics

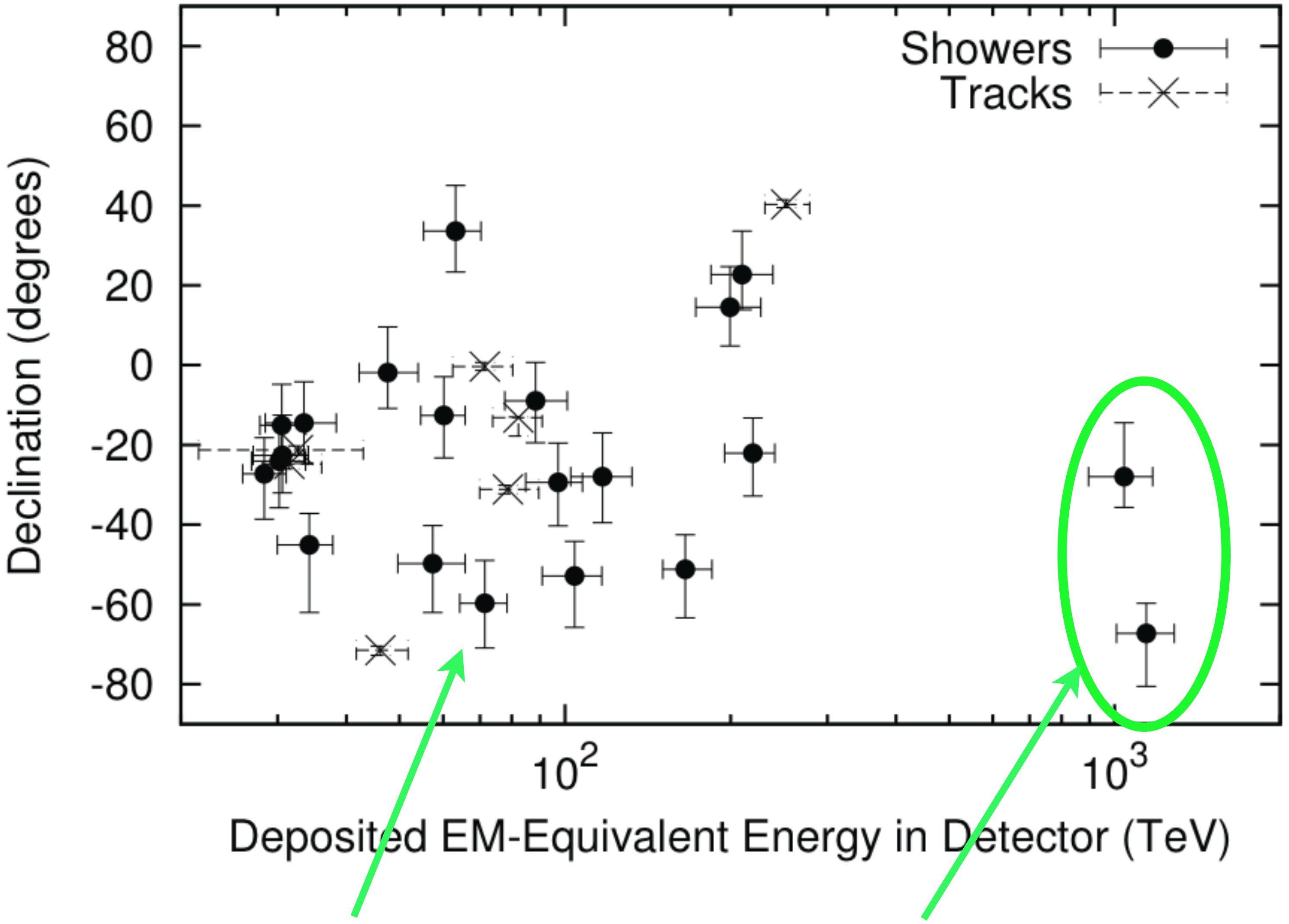
flavor composition ?
NC of ν_α or CC of ν_e

isotropy ?

Mission for IceCube began !

✓ Looking for lower energy contained events, 662 days livetime

M. G. Aartsen et al. [IceCube Collaboration],
Science 342 (2013), [arXiv:1311.5238]



The whole family!

previous PeV
cascade events
(Bert and Ernie)

✓ 26 more events

✓ all the new events are lower in energy

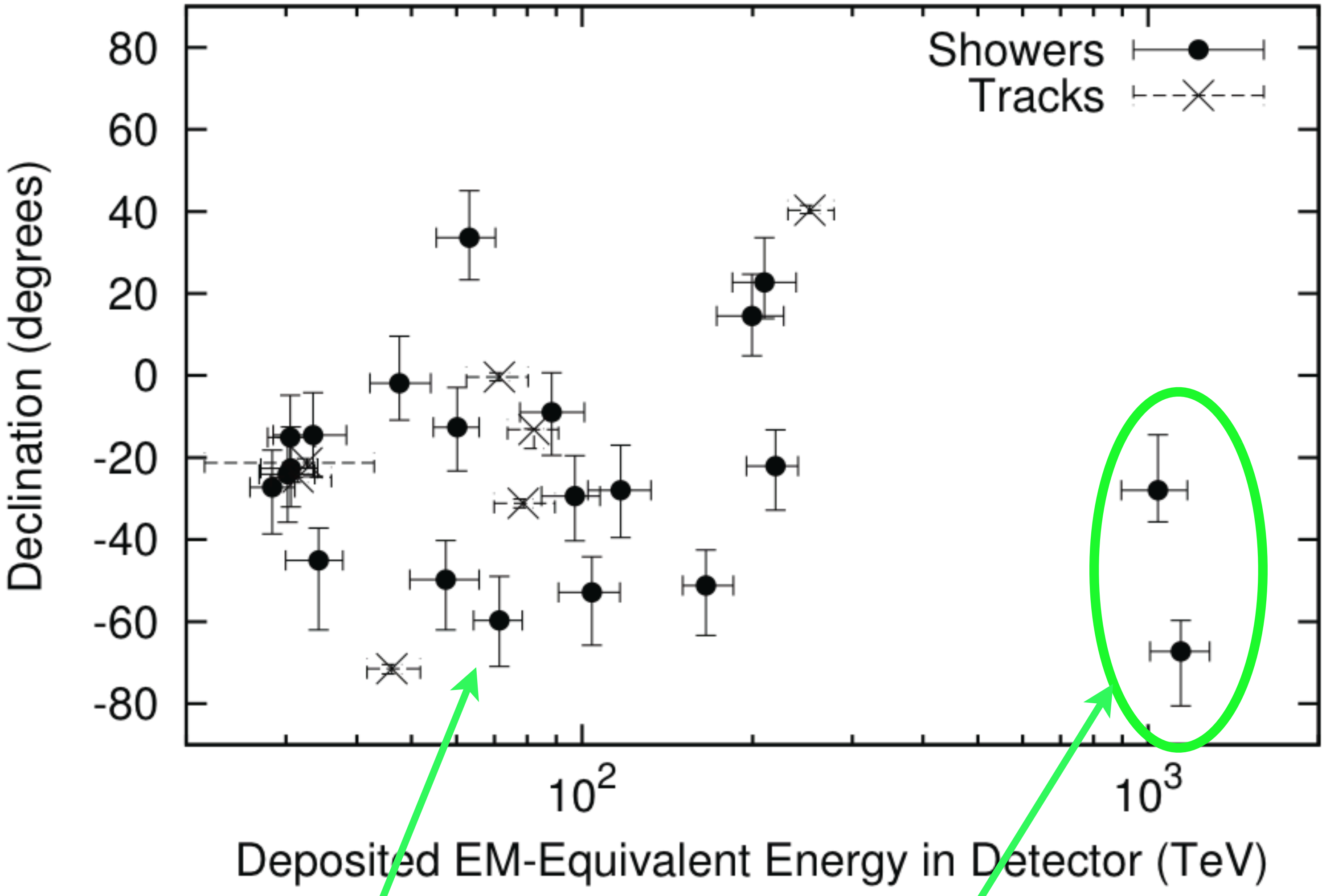
✓ expected bkg. (conventional+prompt) ~ 10.6(+4.5)(-3.5) sys.

excess of events ~ 4.3σ

Mission for IceCube began !

✓ Looking for lower energy contained events, 662 days livetime

M. G. Aartsen et al. [IceCube Collaboration],
Science 342 (2013), [arXiv:1311.5238]



The whole family!

previous PeV cascade events (Bert and Ernie)

✓ 26 more events

✓ all the new events are lower in energy

✓ expected bkg. (conventional+prompt) ~ 10.6(+4.5)(-3.5) sys.

excess of events ~ 4.3σ

which one?

atmospheric ?

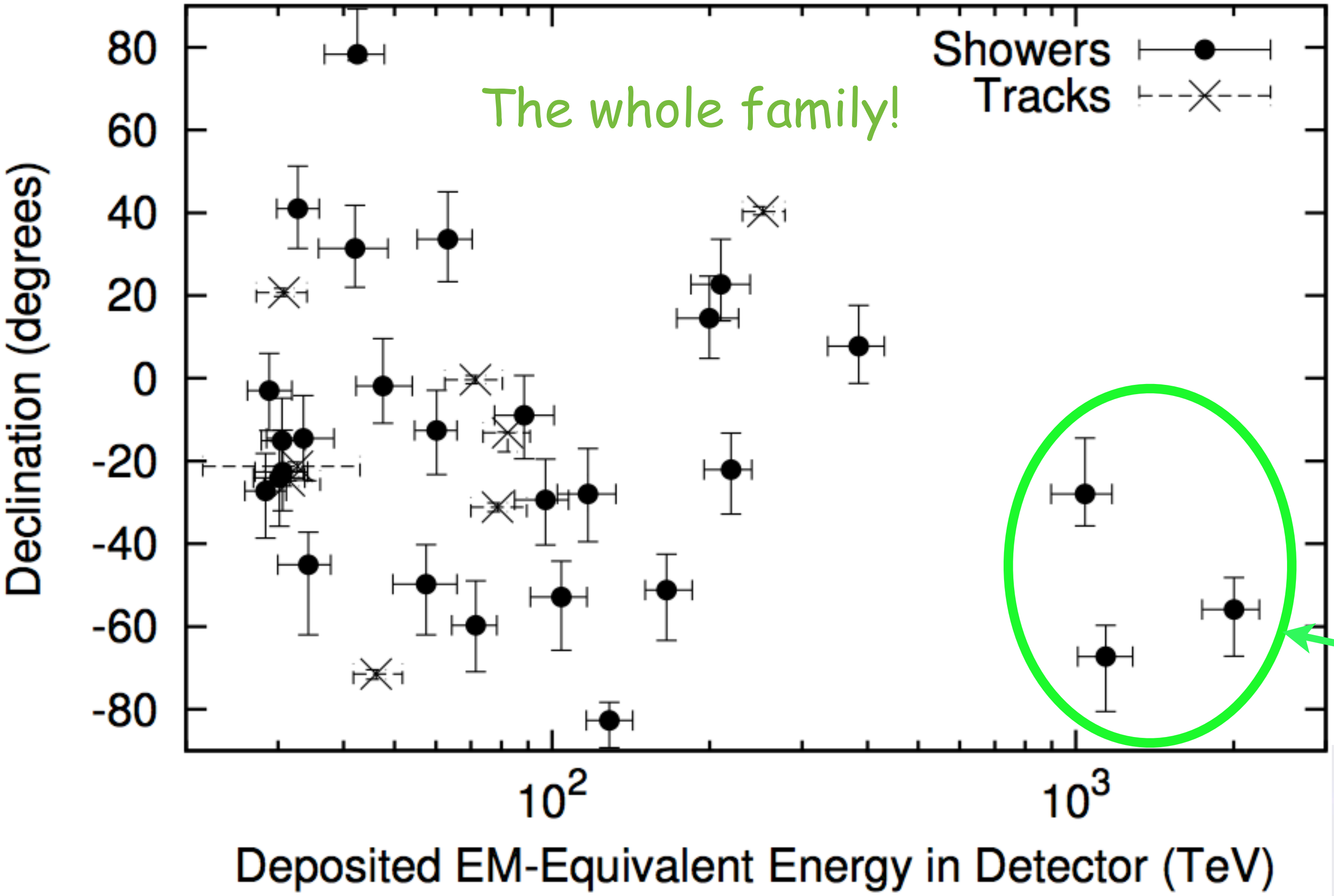
astrophysical ?

or something else ?

Mission for IceCube began !

✓ Looking for lower energy contained events, 988 days livetime

M. G. Aartsen et al. [IceCube Collaboration],
PRL 113 (2014), [arXiv:1405.5303]



The whole family!

✓ totally 37 events

✓ three events with energy ~ PeV

✓ expected bkg. (conventional+prompt)
~ 15.6(+10.1)(-5.8) sys.

excess of events ~ 5.7σ

which one?

atmospheric ?

astrophysical ?

or something else ?

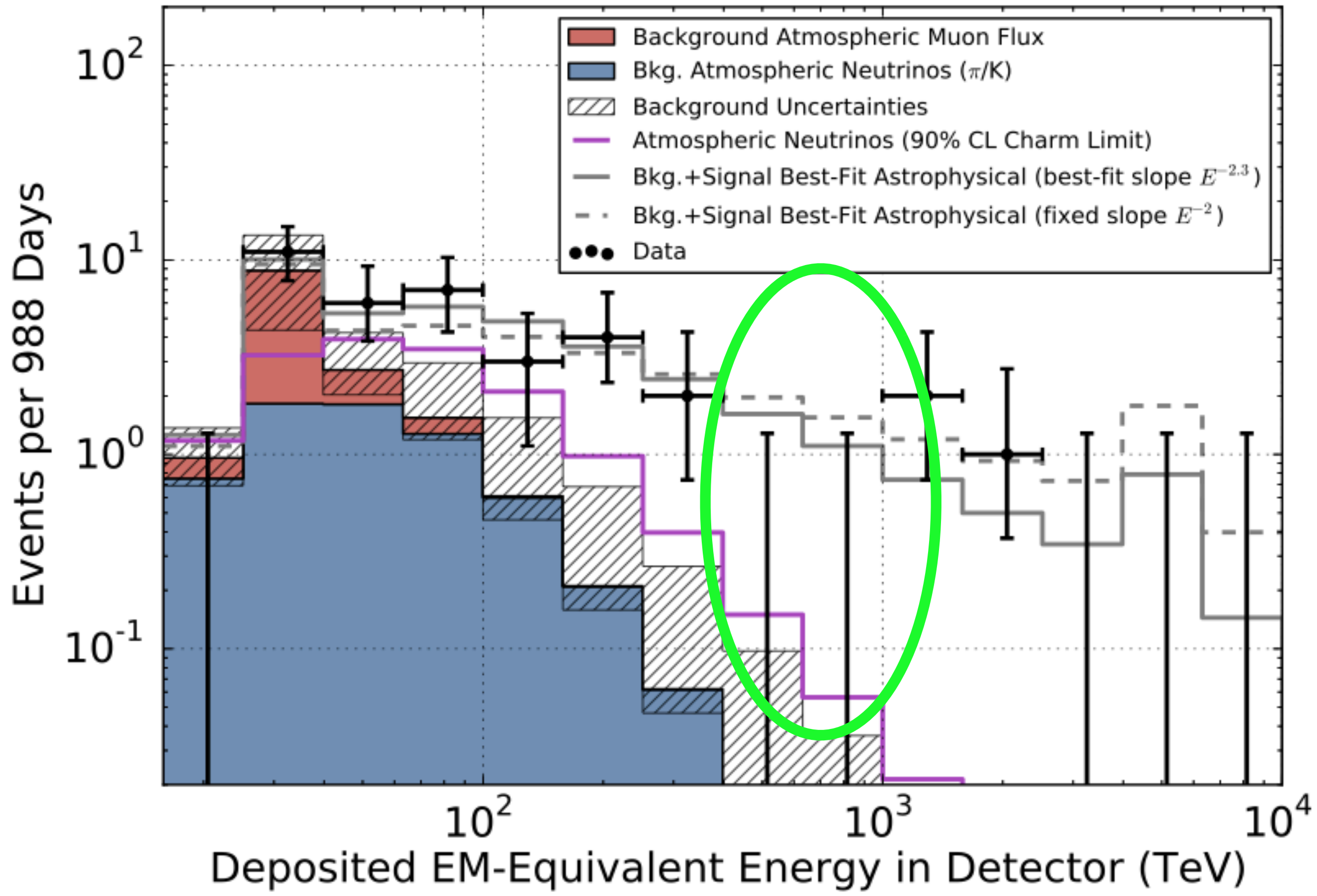
IceCube data

Problems with the astrophysical/atm interpretation of IceCube data

IceCube data

Problems with the astrophysical/atm interpretation of IceCube data

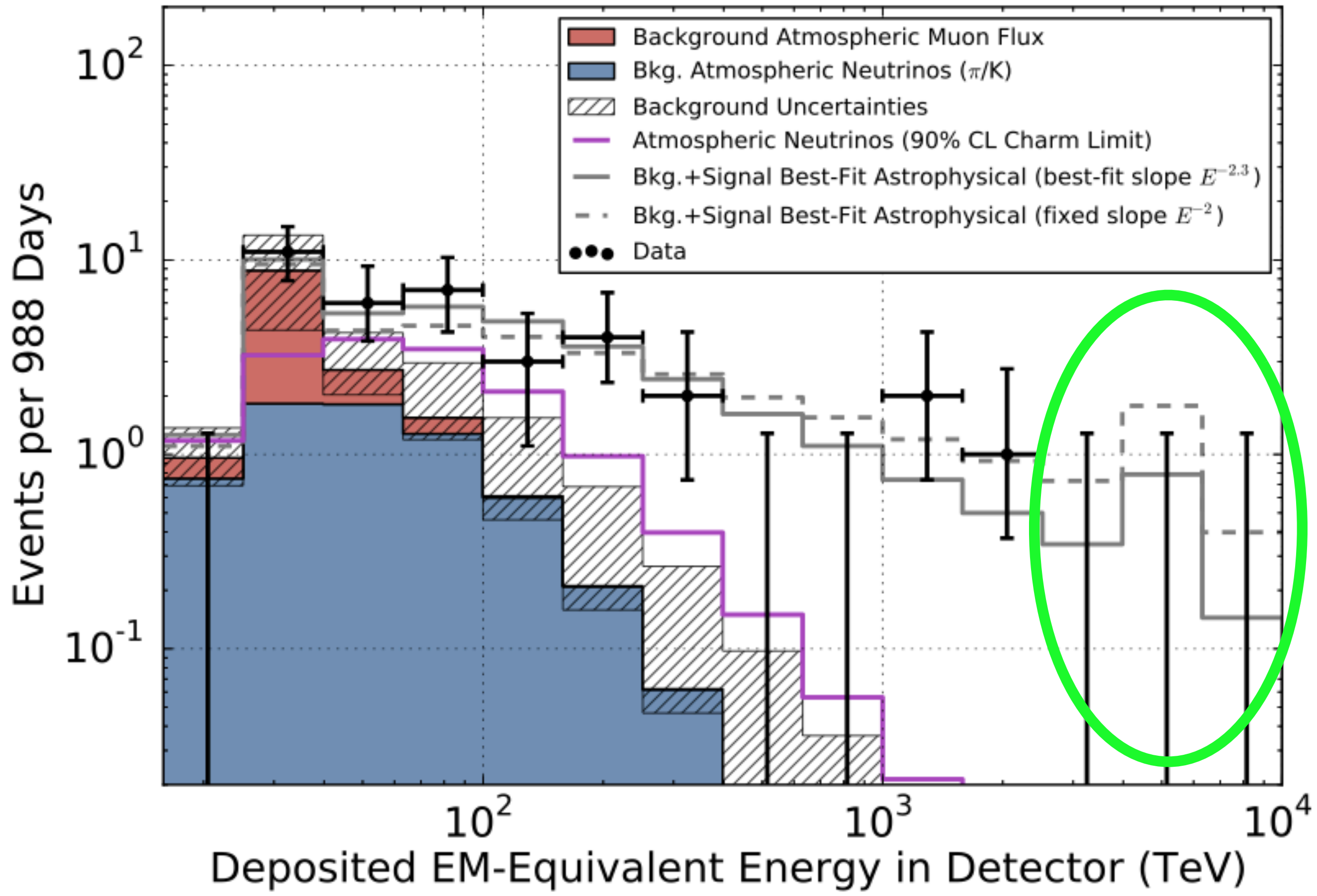
✓ deficit of events in the energy range ~ (400 - 1000) TeV



IceCube data

Problems with the astrophysical/atm interpretation of IceCube data

- ✓ deficit of events in the energy range ~ (400 - 1000) TeV
- ✓ cut-off in events: no events observed with energy > 2 PeV



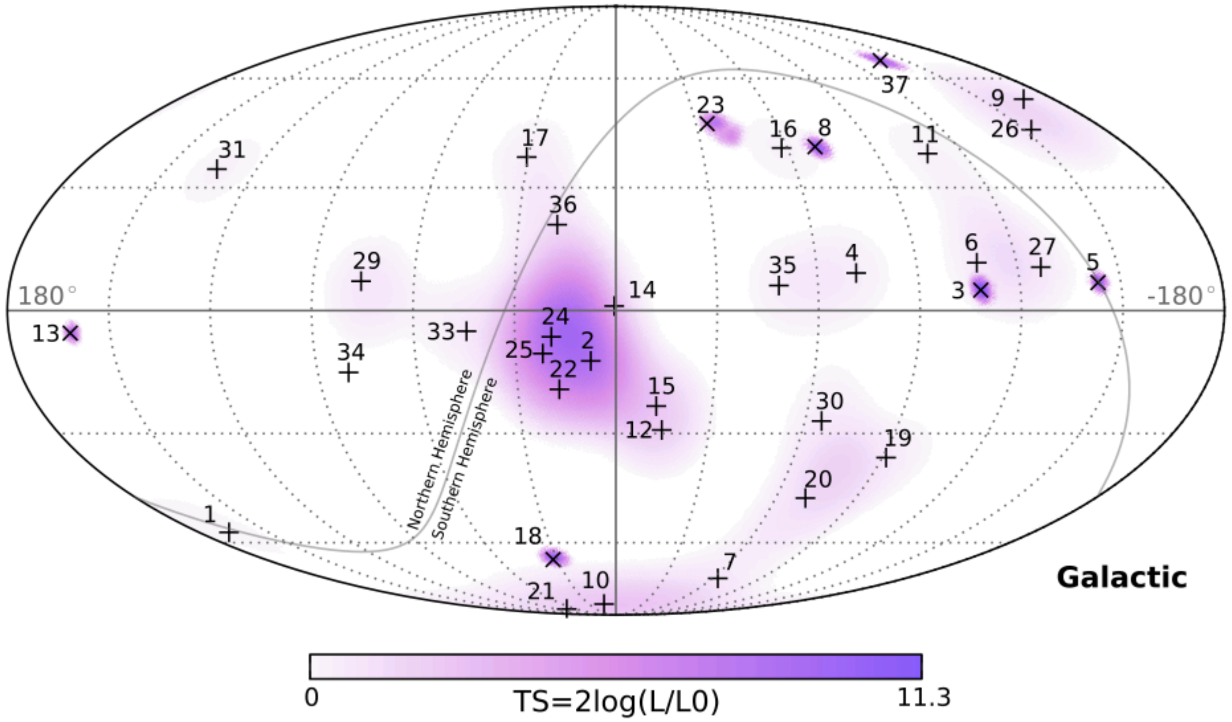
IceCube data

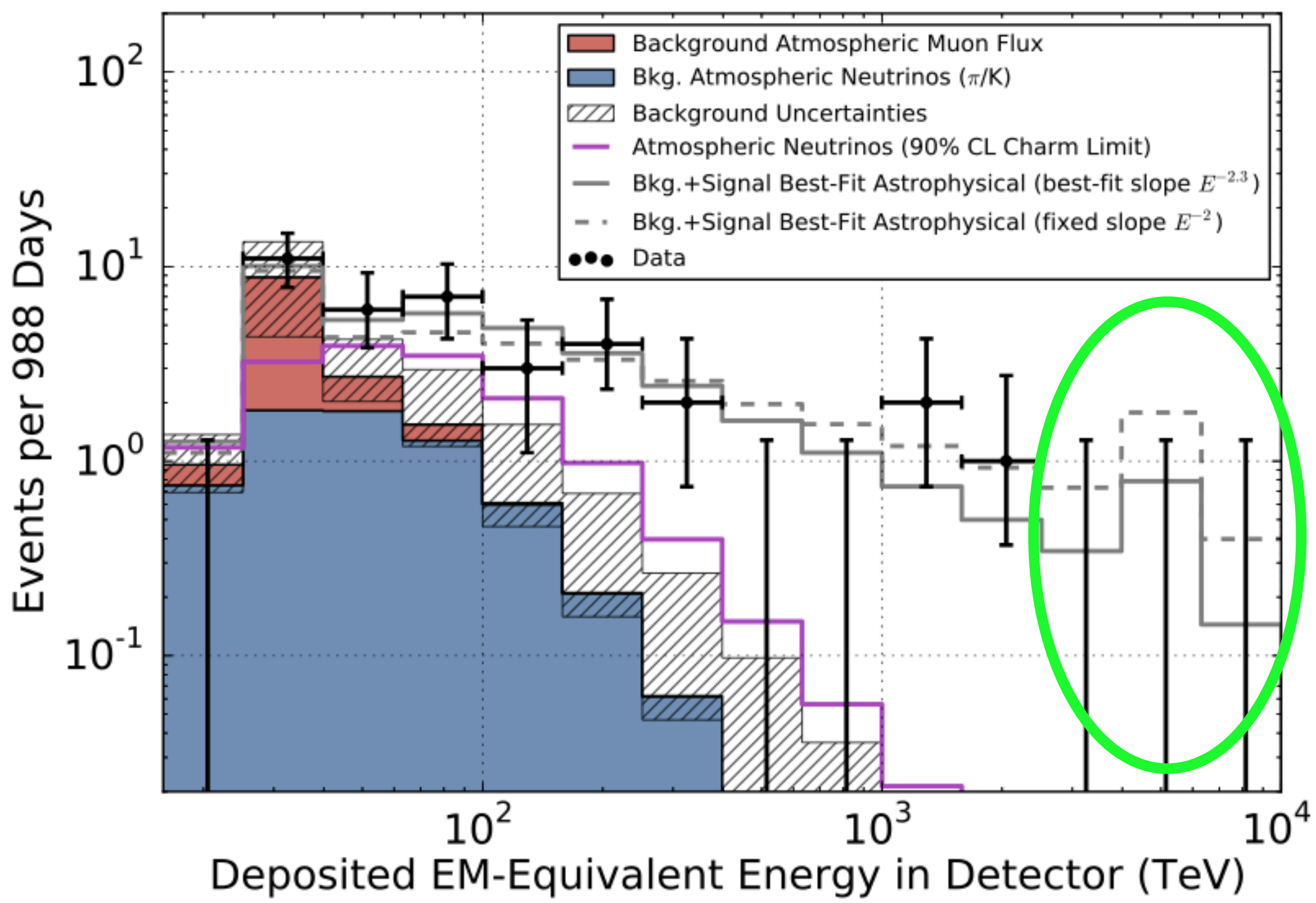
Problems with the astrophysical/atm interpretation of IceCube data

✓ deficit of events in the energy range ~ (400 - 1000) TeV

✓ cut-off in events: no events observed with energy > 2 PeV

✓ angular distribution of events show mild anisotropies (enhanced toward GC)





IceCube data

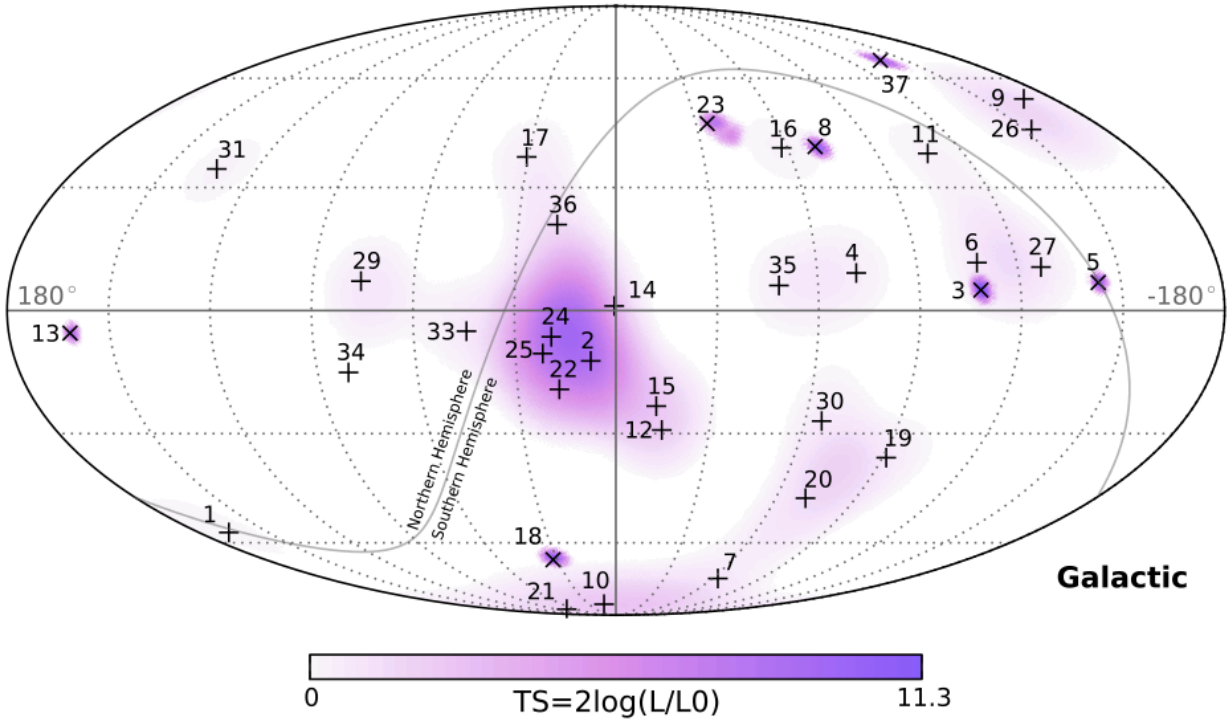
Problems with the astrophysical/atm interpretation of IceCube data

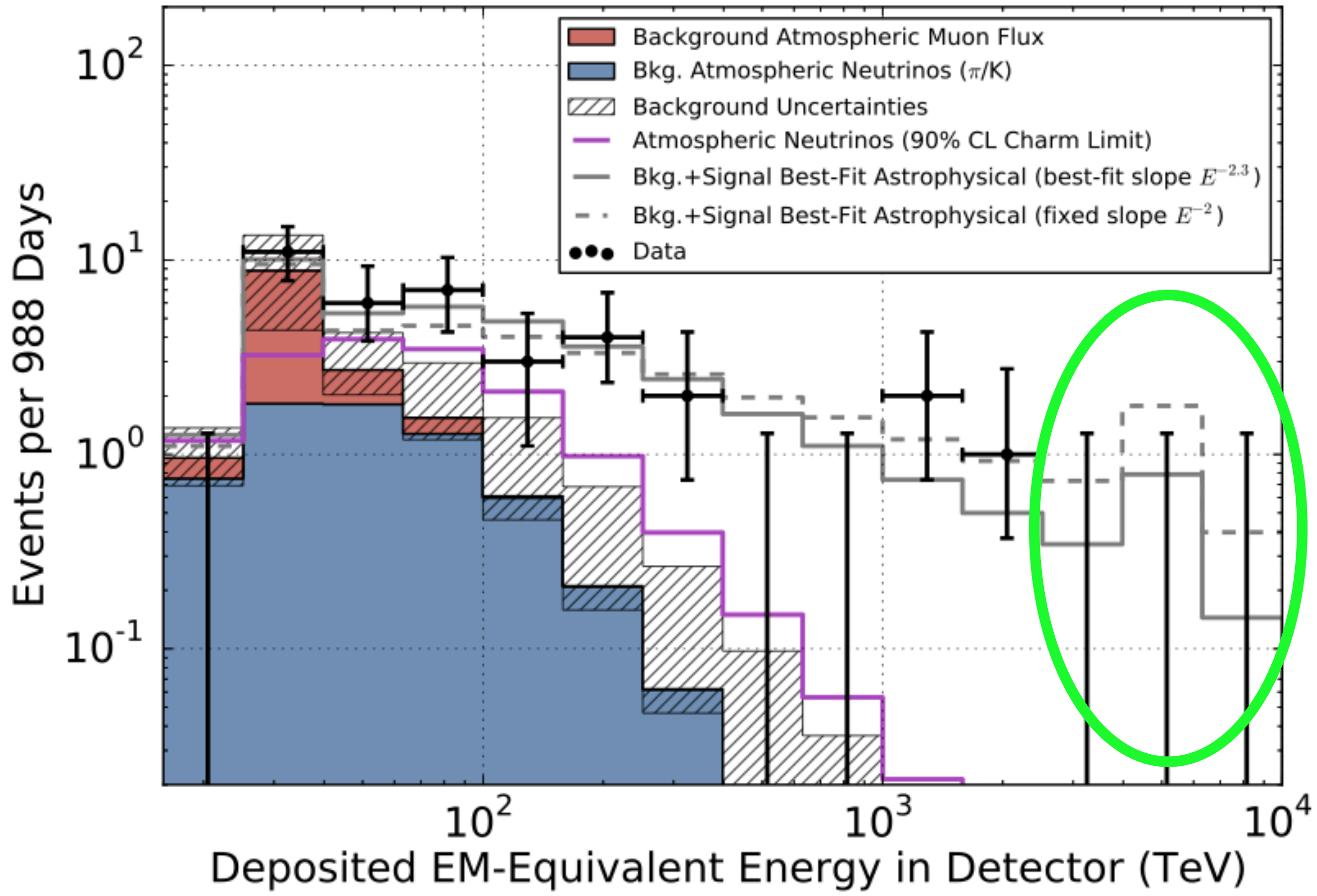
✓ deficit of events in the energy range ~ (400 - 1000) TeV

✓ cut-off in events: no events observed with energy > 2 PeV

✓ angular distribution of events show mild anisotropies (enhanced toward GC)

⚠ none of the above-mentioned issues are significant





Interpretations of IceCube data

✓ "Conventional" interpretations of IceCube data

Cosmic ray sources

GRBs

Galaxy clusters

Star-forming galaxies

AGNs

Fermi bubbles

Galactic Center activities

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M. D. Kistler, T. Stanev and H. Yuksel, arXiv:1301.1703 [astro-ph.HE]
K. Murase and K. Ioka, Phys. Rev. Lett. 111, no. 12, 121102 (2013) [arXiv:1306.2274 [astro-ph.HE]].
K. Murase, M. Ahlers and B. C. Lacki, Phys. Rev. D 88, no. 12, 121301 (2013) [arXiv: 1306.3417 [astro-ph.HE]].
L. A. Anchordoqui, H. Goldberg, M. H. Lynch, A. V. Olinto, T. C. Paul and T. J. Weiler, arXiv:1306.5021 [astro-ph.HE].
R. Laha, J. F. Beacom, B. Dasgupta, S. Horiuchi and K. Murase, Phys. Rev. D 88, 043009 (2013) [arXiv:1306.2309 [astro-ph.HE]].
S. Razzaque, Phys. Rev. D 88, 081302 (2013) [arXiv:1309.2756 [astro-ph.HE]].
C. Y. Chen, P. S. Bhupal Dev and A. Soni, Phys. Rev. D 89, no. 3, 033012 (2014) [arXiv:1309.1764 [hep-ph]].
M. Ahlers and K. Murase, Phys. Rev. D 90, 023010 (2014) [arXiv:1309.4077 [astro-ph.HE]].
I. Tamborra, S. Ando and K. Murase, JCAP 1409, no. 09, 043 (2014) [arXiv:1404.1189 [astro-ph.HE]].
M. Kachelriess and S. Ostapchenko, Phys. Rev. D 90, 083002 (2014) [arXiv: 1405.3797 [astro-ph.HE]].
M. Ahlers and F. Halzen, arXiv:1406.2160 [astro-ph.HE].
Y. Bai, A. J. Barger, V. Barger, R. Lu, A. D. Peterson and J. Salvado, Phys. Rev. D 90, 063012 (2014) [arXiv:1407.2243 [astro-ph.HE]].
A. Bhattacharya, R. Enberg, M. H. Reno and I. Sarcevic, arXiv:1407.2985 [astro-ph.HE].
C. Lunardini, S. Razzaque, K. T. Theodoseau and L. Yang, Phys. Rev. D 90, 023016 (2014) [arXiv:1311.7188 [astro-ph.HE]].

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For a review

L. A. Anchordoqui, V. Barger, I. Cholis, H. Goldberg, D. Hooper, A. Kusenko, J. G. Learned and D. Marfatia et al., Journal of High Energy Astrophysics 1-2, 1 (2014) [arXiv:1312.6587 [astro-ph.HE]].

Interpretations of IceCube data

✓ “New Physics” interpretations of IceCube data

Lepto-quarks

Secret neutrino interactions

resonant absorption on cosmic neutrino background

supermassive long-lived particles

Dark matter decay

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Y. Ema, R. Jinno and T. Moroi, Phys. Lett. B 733, 120 (2014) [arXiv:1312.3501 [hep-ph]].
K. Ioka and K. Murase, PTEP 2014, (2014) [arXiv:1404.2279 [astro-ph.HE]].
K. C. Y. Ng and J. F. Beacom, Phys. Rev. D 90, 065035 (2014) [arXiv:1404.2288 [astro-ph.HE]].
M. Ibe and K. Kaneta, Phys. Rev. D 90, 053011 (2014) [arXiv:1407.2848 [hep-ph]].
V. Barger and W. Y. Keung, Phys. Lett. B 727, 190 (2013) [arXiv:1305.6907 [hep-ph]].
B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, Phys. Rev. D 88, no. 1, 015004 (2013) [arXiv:1303.7320 [hep-ph]].
Y. Bai, R. Lu and J. Salvado, arXiv:1311.5864 [hep-ph].
A. Bhattacharya, M. H. Reno and I. Sarcevic, JHEP 1406, 110 (2014) [arXiv:1403.1862 [hep-ph]].
J. Zavala, Phys. Rev. D 89, 123516 (2014) [arXiv:1404.2932 [astro-ph.HE]].
A. Bhattacharya, R. Gandhi and A. Gupta, arXiv:1407.3280 [hep-ph].
C. Rott, K. Kohri and S. C. Park, arXiv:1408.4575 [hep-ph].
T. Higaki, R. Kitano and R. Sato, JHEP 1407, 044 (2014) [arXiv:1405.0013 [hep-ph]].

A. Esmaili and P. D. Serpico, JCAP 1311, 054 (2013) [arXiv:1308.1105 [hep-ph]].

A. Esmaili, S. K. Kang and P. D. Serpico, arXiv:1410.5979 [hep-ph].

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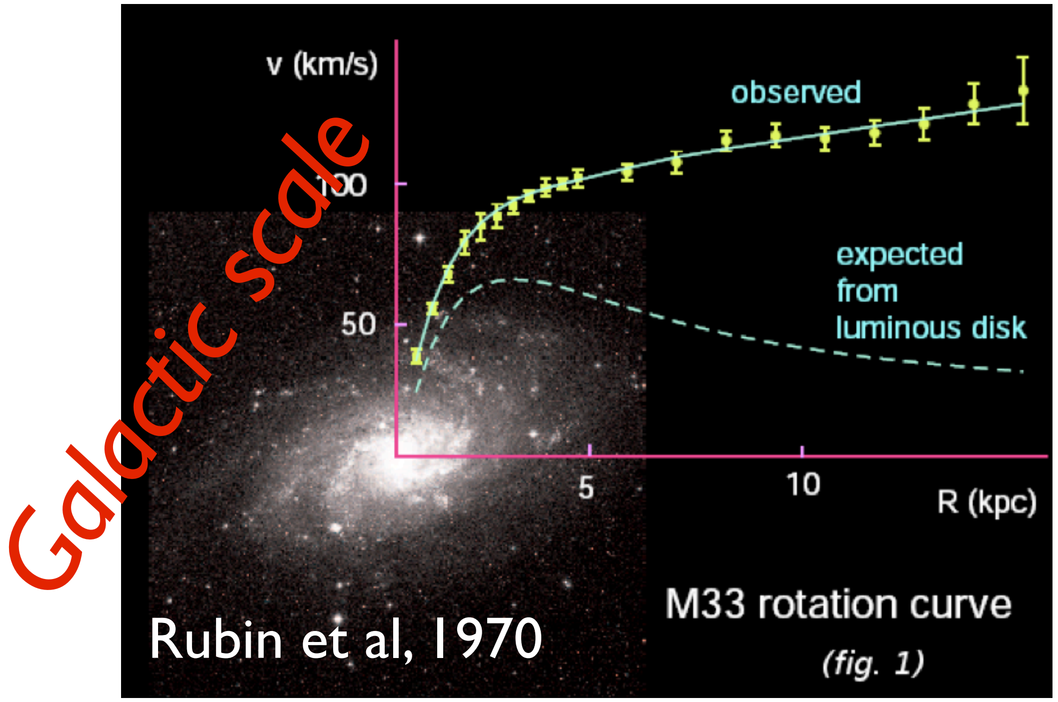
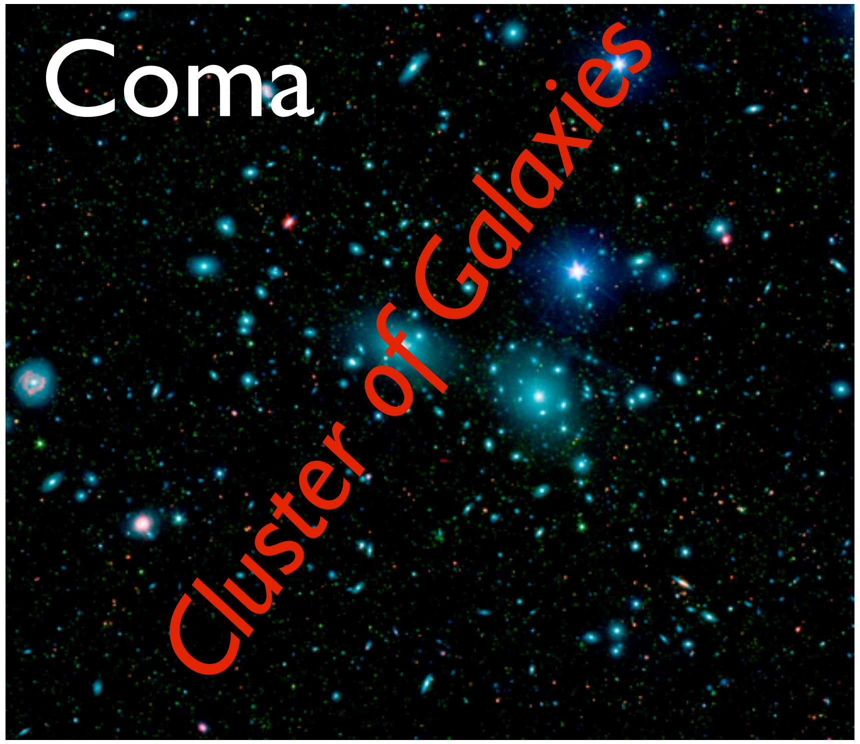
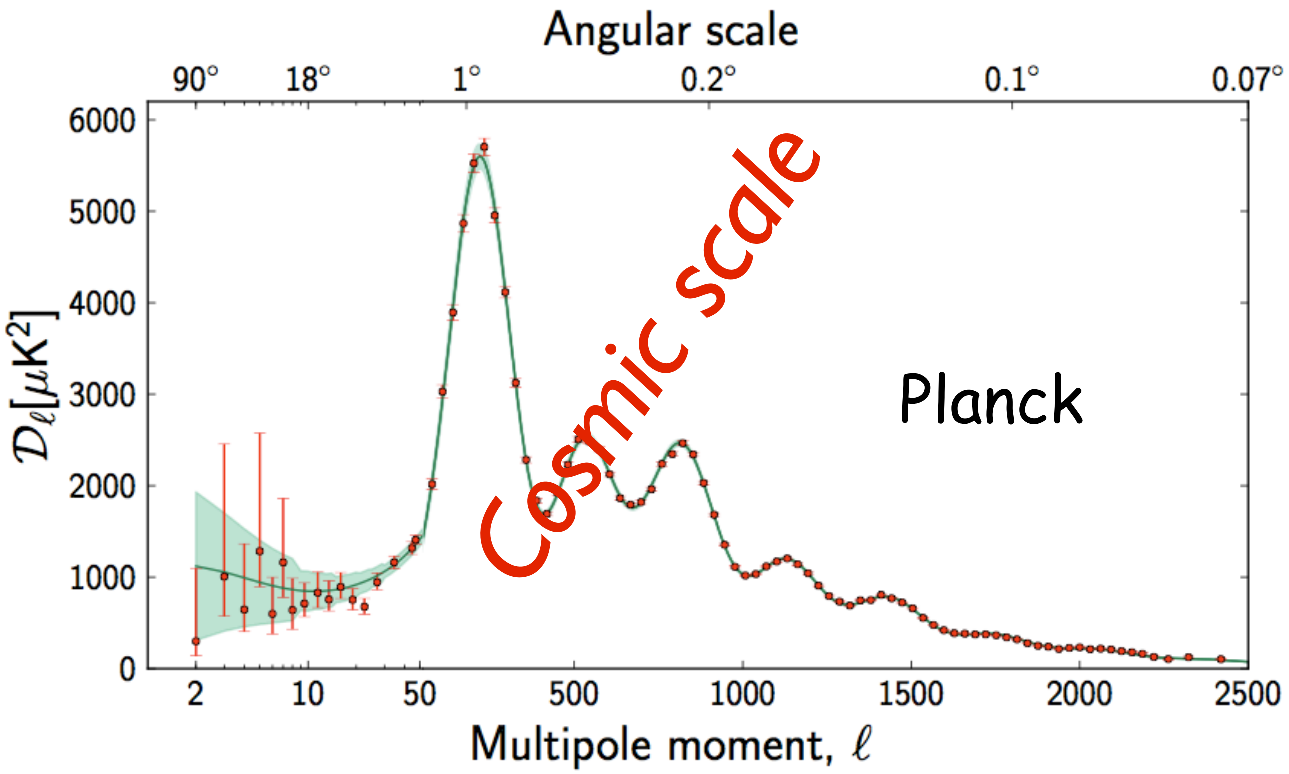
A note on Dark Matter

DM exist!







A note on Dark Matter

DM exist!

What We Know?

- ✓ Non Baryonic
- ✓ No electric and color charges
- ✓ Cold (or perhaps warm)
- ✓ Long lived (not necessarily stable)

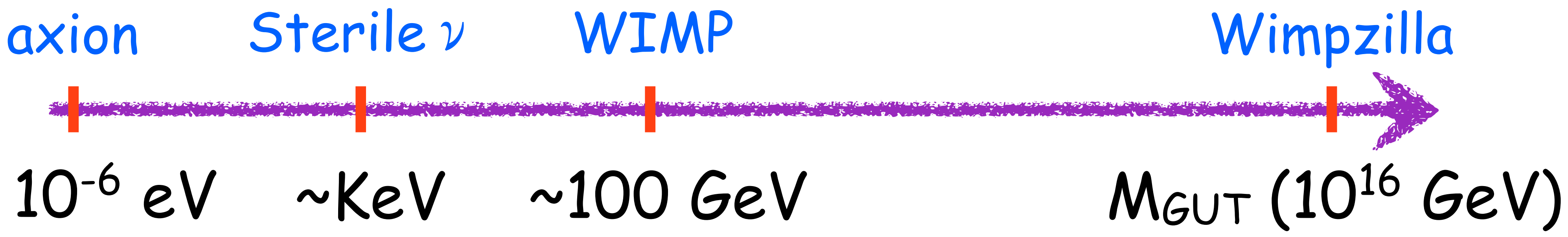
All of these come from gravitational effects

A note on Dark Matter

DM exist!

What We Do Not Know?

✓ Mass



⚠ "WIMP" paradigm ?

Note that WIMP paradigm is a "particle physics" conjecture, needs to be validated at colliders

A note on Dark Matter

DM exist!

What We Do Not Know?

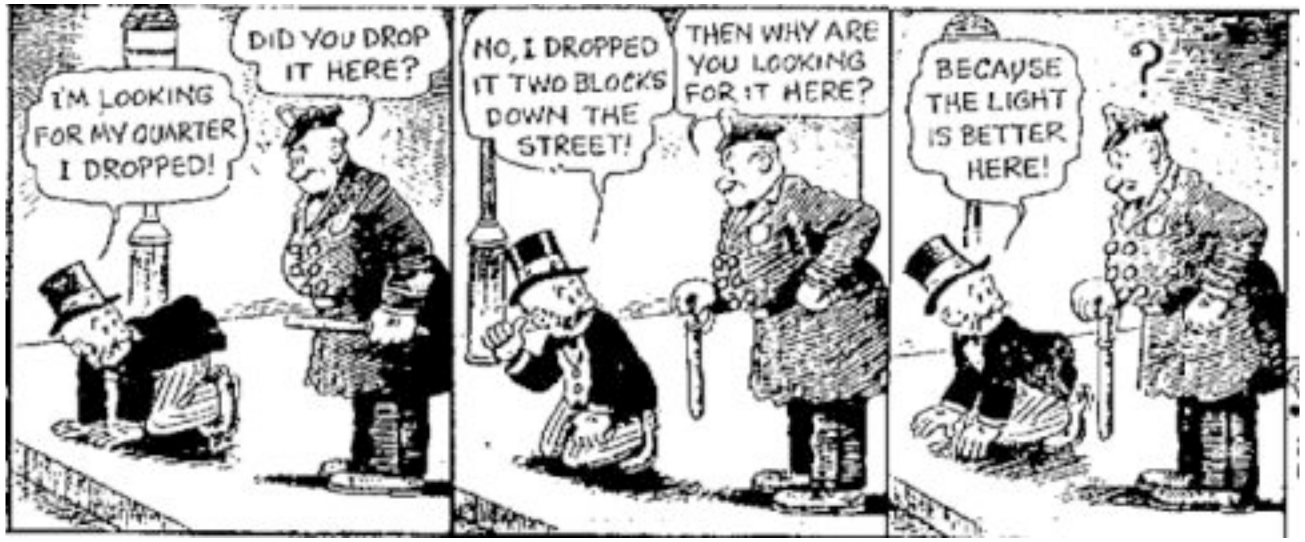
✓ Mass

axion	Sterile ν	WIMP	Wimpzilla
10^{-6} eV	~KeV	~100 GeV	M_{GUT} (10^{16} GeV)

⚠ "WIMP" paradigm ?

Note that WIMP paradigm is a "particle physics" conjecture, needs to be validated at colliders

caution: street light effect



Mulla Nasreddin

A note on Dark Matter

DM exist!

What We Do Not Know?

✓ Mass

axion — Sterile ν — WIMP — Wimpzilla

10^{-6} eV — ~KeV — ~100 GeV — M_{GUT} (10^{16} GeV)

⚠ "WIMP" paradigm ?

Note that WIMP paradigm is a "particle physics" conjecture, needs to be validated at colliders

A note on Dark Matter

DM exist!

What We Do Not Know?

✓ Mass

⚠ "WIMP" paradigm ?

Note that WIMP paradigm is a "particle physics" conjecture, needs to be validated at colliders

✓ Lifetime: stable (∞) or

$\tau_{DM} > 4.3 \times 10^{17}$ s (age of Universe)

$\tau_{DM} > 2.2 \times 10^{19}$ s (CMB) Y. Gong and X. Chen, PRD77 (2008), arXiv:0802.2296

✓ Possible decay and/or annihilation channels

✓ ...

Limits on lifetime from neutrino experiments

before recent IceCube data

$$16 - 2.5 \times 10^3 \text{ TeV}$$

AMANDA

$$340 - 2 \times 10^5 \text{ TeV}$$

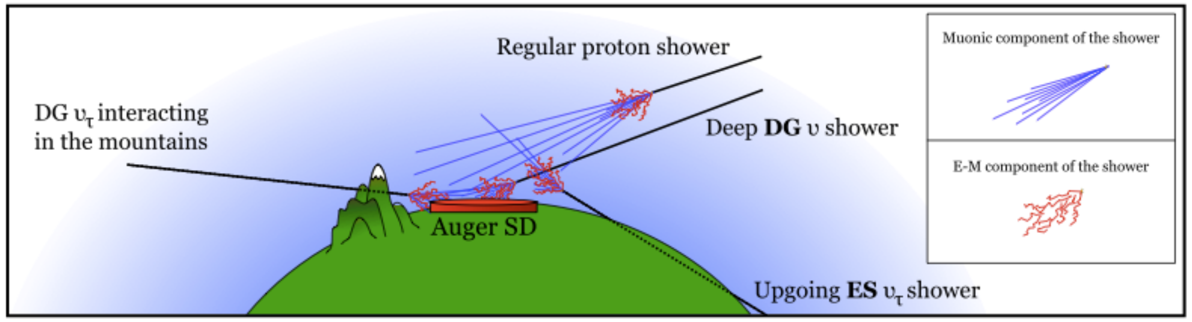
IceCube-22

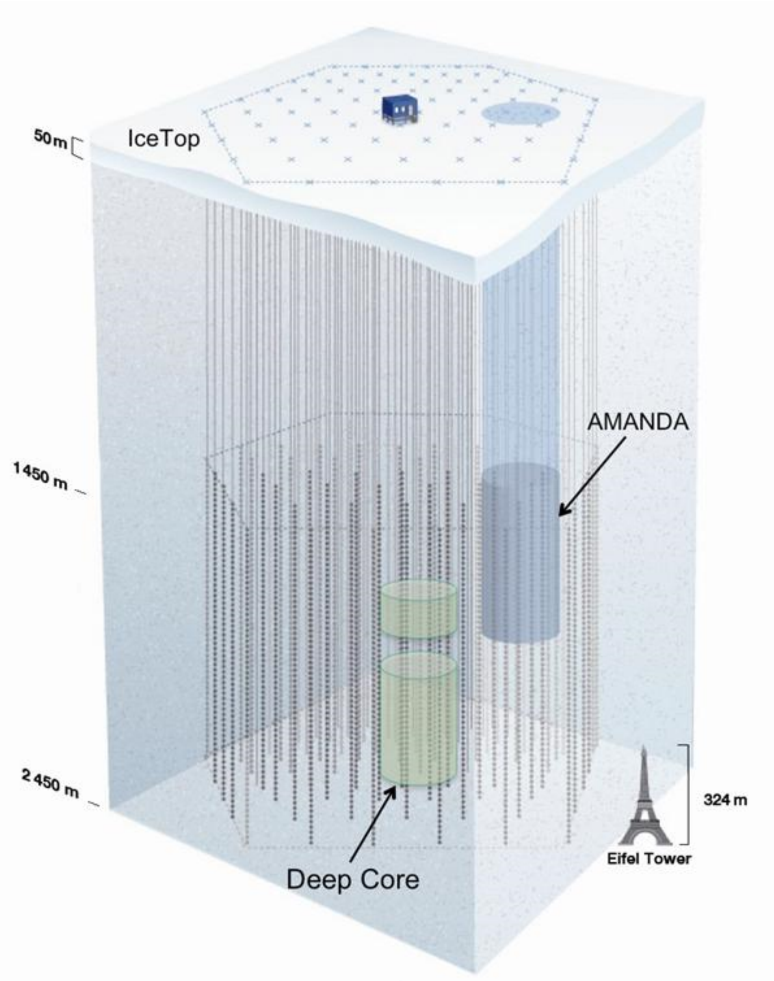
$$3 \times 10^3 - 6.3 \times 10^6 \text{ TeV}$$

IceCube-40

$$10^5 - 10^8 \text{ TeV}$$

Auger



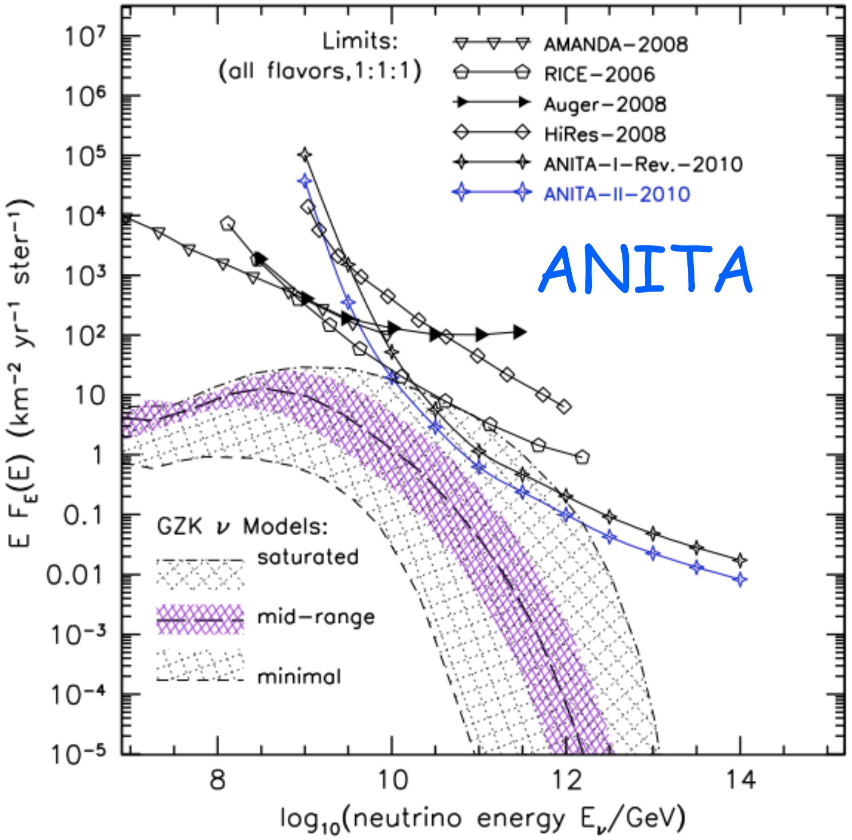


$$10^6 - 3.2 \times 10^{11} \text{ TeV}$$

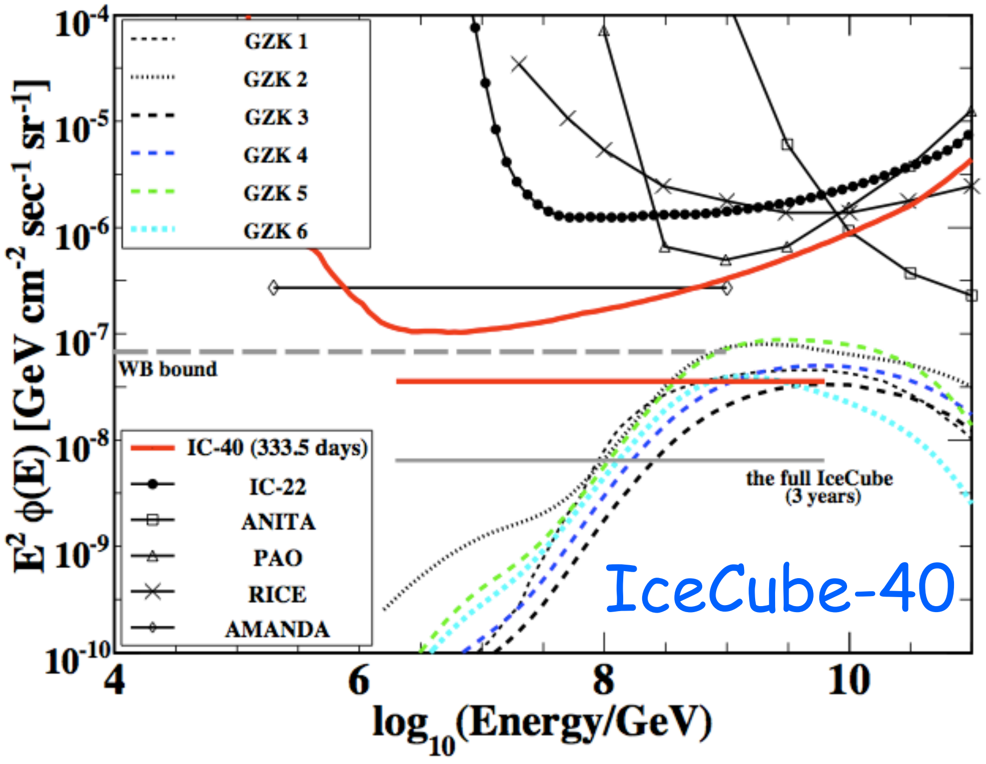
ANITA

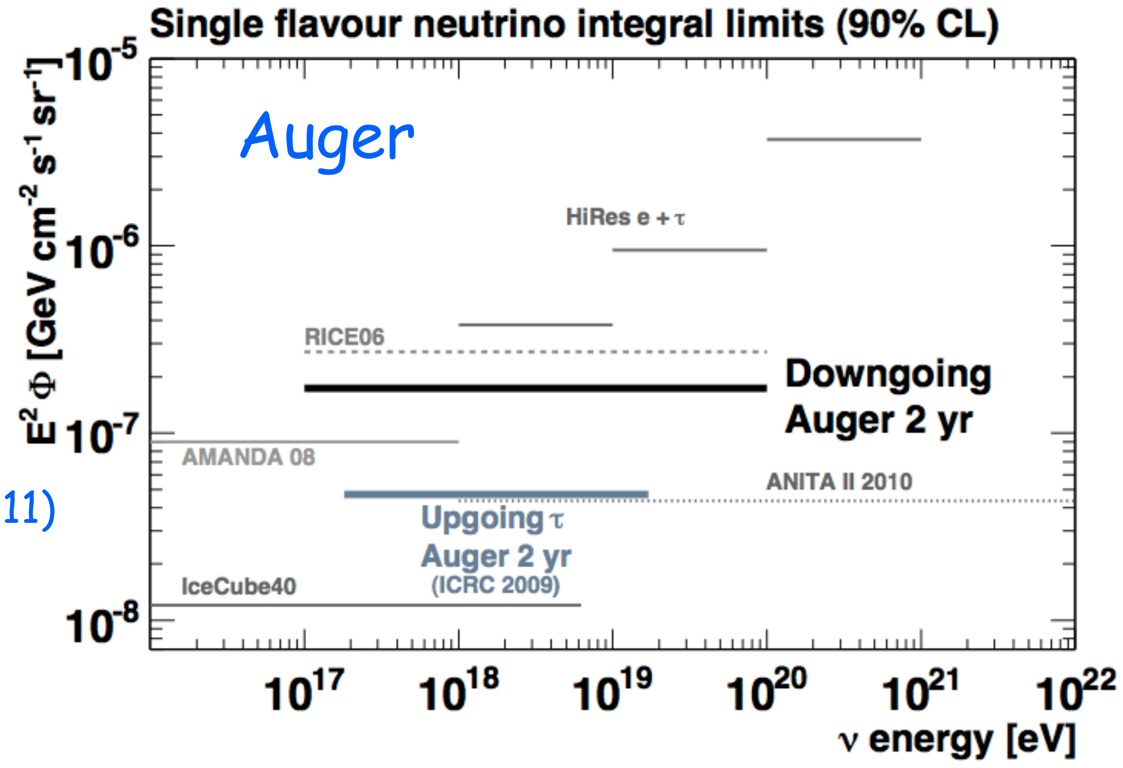
Experiments

P. Gorham et al. [ANITA Collaboration], Phys.Rev.D85 (2012)
arXiv:1011.5004, arXiv:1003.2961



R. Abbasi et al. [IceCube Collaboration], Phys.Rev.D83 (2011)
arXiv:1103.4250





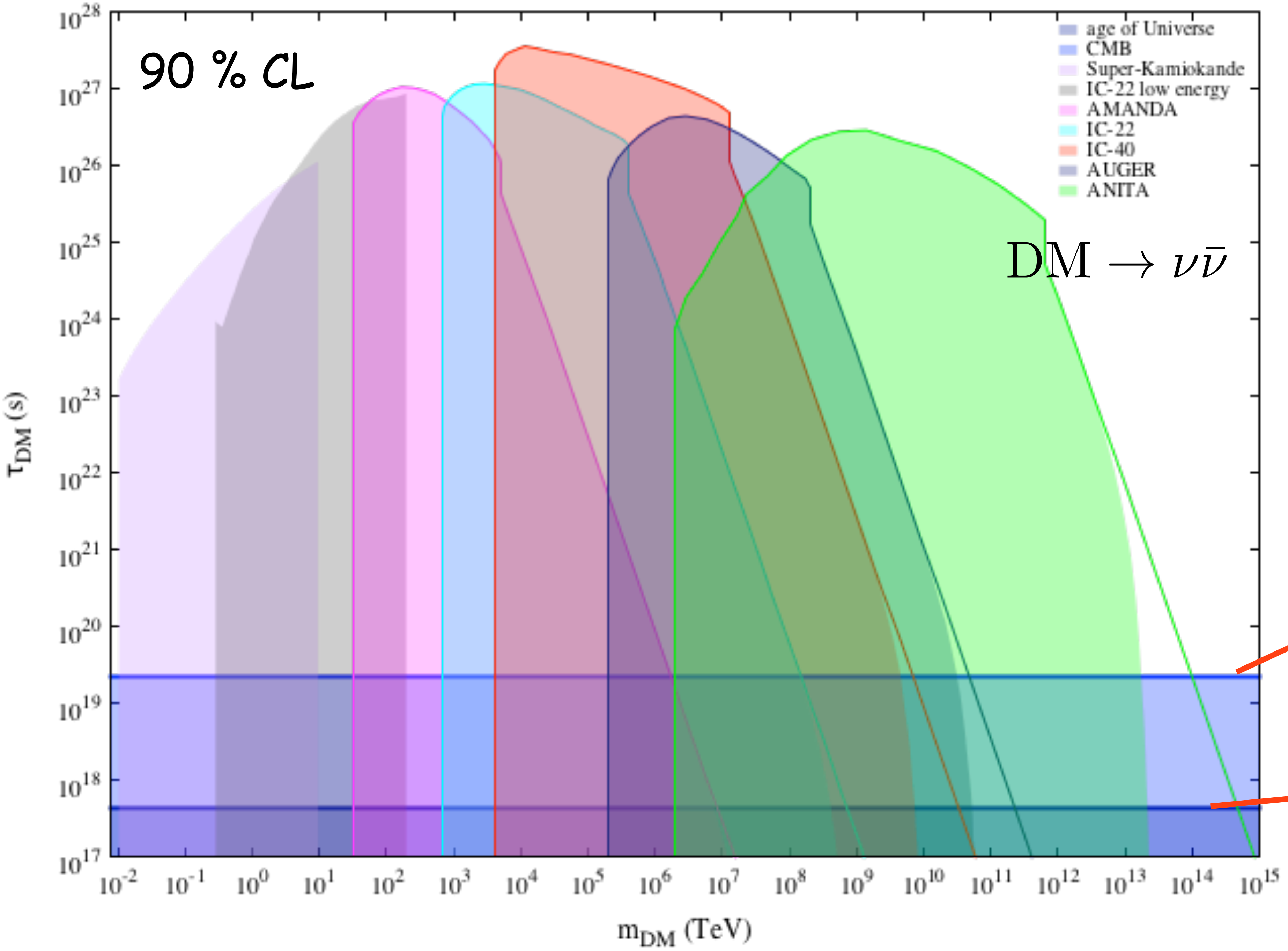
P. Abreu et al. [Pierre Auger Collaboration], Phys.Rev.D84 (2011)
arXiv:1202.1493

Limits on lifetime from neutrino experiments

before recent IceCube data

✓ Lifetime: stable (∞) or

A.E., Alejandro Ibarra and Orlando L. G. Peres
JCAP (2012) [arXiv: 1205.5281]



Using AMANDA, IceCube, Auger and ANITA data

$\tau_{DM} > 2.2 \times 10^{19}$ s (CMB)

$\tau_{DM} > 4.3 \times 10^{17}$ s (age of Universe)

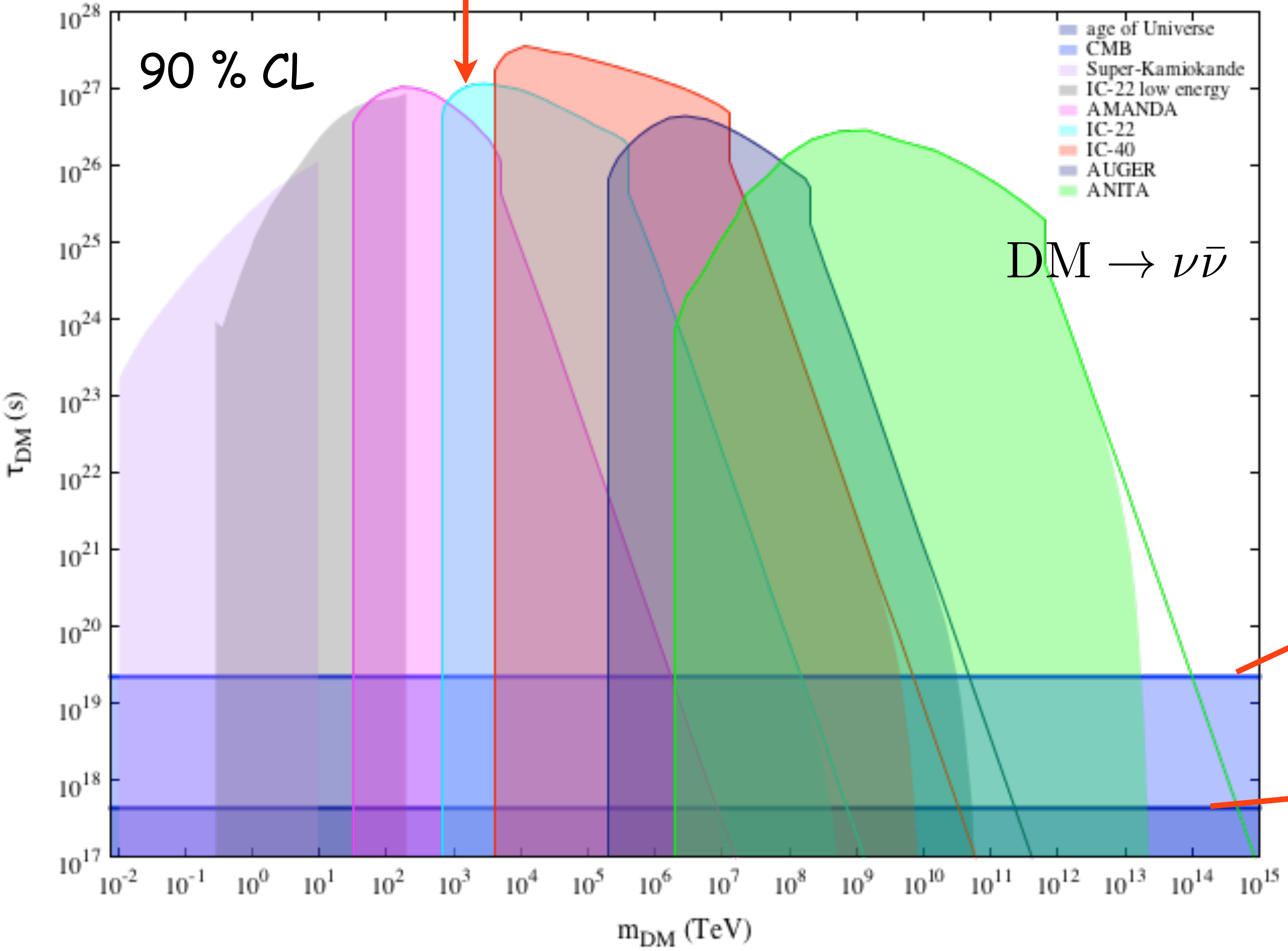
Limits on lifetime from neutrino experiments

before recent IceCube data

- ✓ Lifetime: stable (∞) or

this talk

A.E., Alejandro Ibarra and Orlando L. G. Peres
JCAP (2012) [arXiv: 1205.5281]



Using AMANDA, IceCube, Auger and ANITA data

$\tau_{\mathrm{DM}} > 2.2 \times 10^{19}$ s (CMB)

$\tau_{\mathrm{DM}} > 4.3 \times 10^{17}$ s (age of Universe)

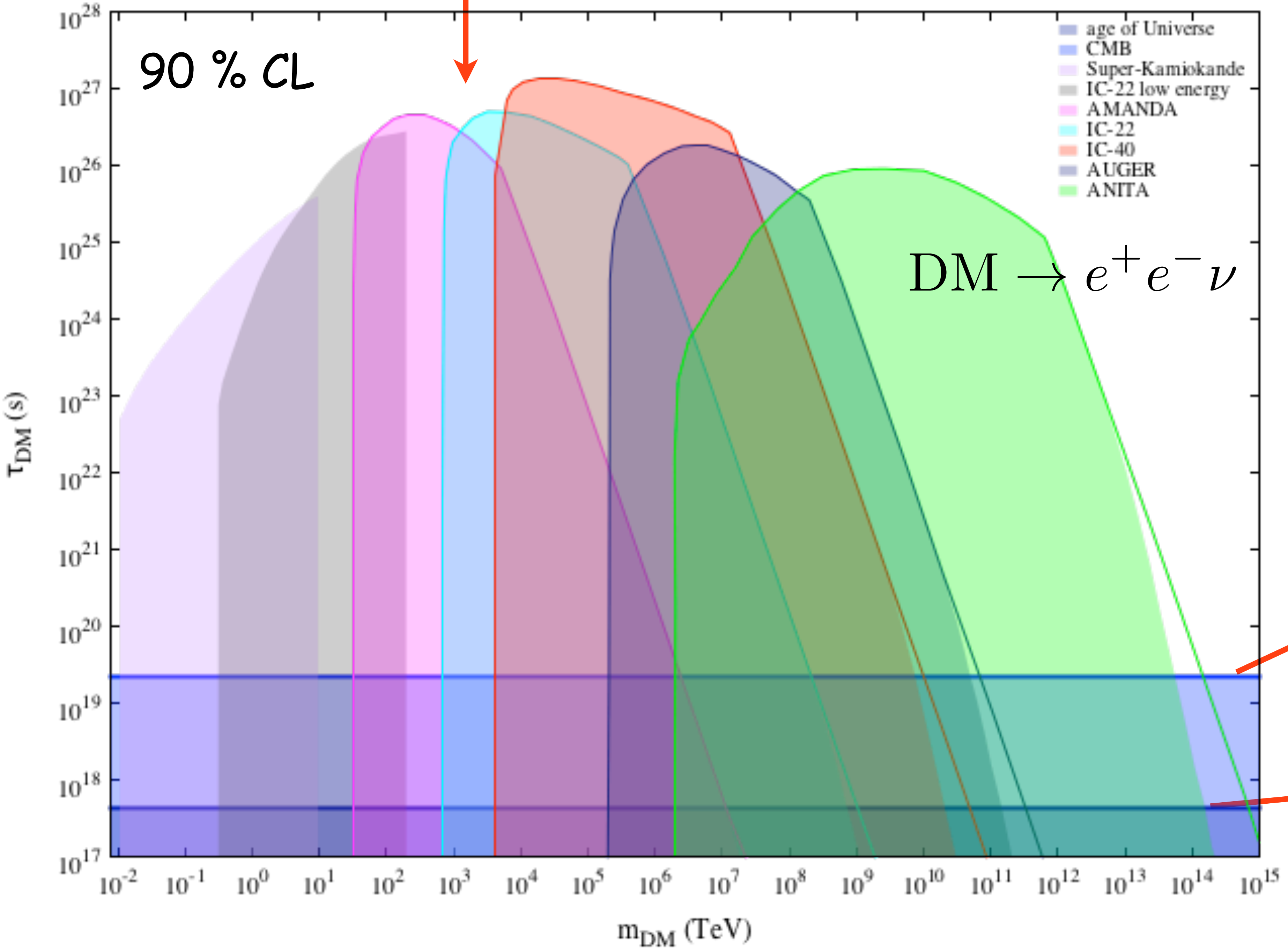
Limits on lifetime from neutrino experiments

before recent IceCube data

✓ Lifetime: stable (∞) or

this talk

A.E., Alejandro Ibarra and Orlando L. G. Peres
JCAP (2012) [arXiv: 1205.5281]



Using AMANDA, IceCube, Auger and ANITA data

$\tau_{DM} > 2.2 \times 10^{19}$ s (CMB)

$\tau_{DM} > 4.3 \times 10^{17}$ s (age of Universe)

Interpreting the IceCube events by decaying dark matter

Two main diagnostics:

- ✓ Energy distribution
- ✓ Angular distribution

Energy distribution of neutrinos from decaying DM

- ✓ **Galactic contribution:**

NFW $\rho_{\text{halo}}(r) \simeq \dfrac{\rho_h}{r/r_c(1+r/r_c)^2}$

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

$$r(s,l,b) = \sqrt{s^2 + R_\odot^2 - 2sR_\odot \cos b \cos l}$$

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✓ extragalactic contribution:

$$\frac{{\rm d}J_{\rm eg}}{{\rm d}E_\nu} = \frac{\Omega_{\rm DM}\rho_{\rm c}}{4\pi m_{\rm DM}\tau_{\rm DM}} \int_0^\infty {\rm d}z\, \frac{1}{H(z)} \frac{{\rm d}N_\nu}{{\rm d}E_\nu}[(1+z)E_\nu]$$

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M. Cirelli et. al., JCAP (2011)

energy spectrum of neutrinos
at production point
(including the EW corrections)

quarks

neutrinos,
charged leptons

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = (1-b_{\rm H}) \left.\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\right|_{\rm S} + b_{\rm H} \left.\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\right|_{\rm H}$$

Energy distribution of neutrinos from decaying DM

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at the Earth

$$\begin{pmatrix} J_e \\ J_\mu \\ J_\tau \end{pmatrix} = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ & P_{\mu\mu} & P_{\mu\tau} \\ & & P_{\tau\tau} \end{pmatrix} \begin{pmatrix} I_e \\ I_\mu \\ I_\tau \end{pmatrix}$$

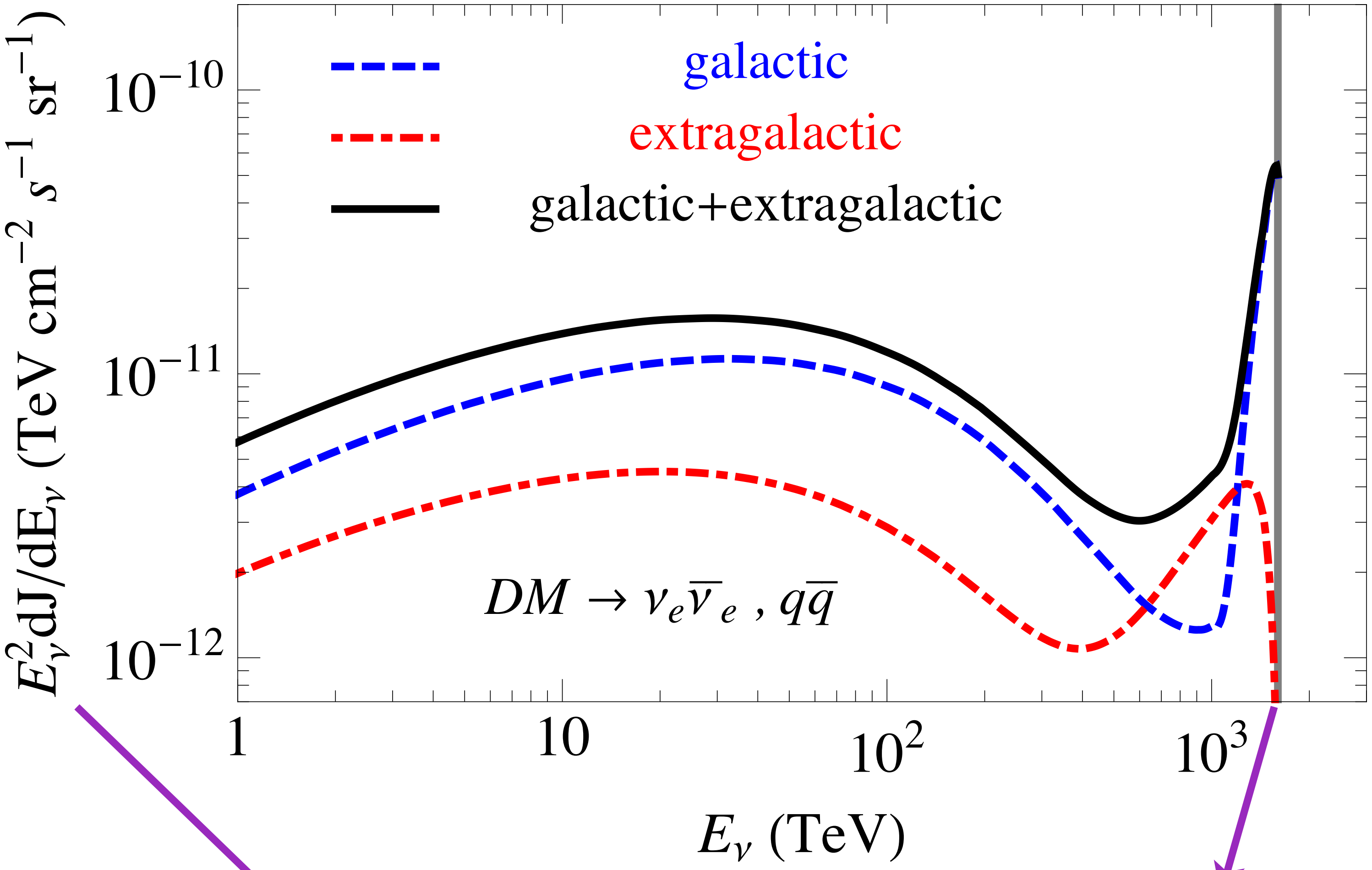
production point

decoherent oscillation

Flux of neutrinos from decaying DM

✓ an example:

A. E., Pasquale D. Serpico,
JCAP (2013) [arXiv:1308.1105]



$(\nu_e + \nu_\mu + \nu_\tau)/3$

$m_{DM}/2 = 1.6$ PeV

$b_H = 0.12$ and $\tau_{DM} = 2 \times 10^{27}$ s

Flux of neutrinos from decaying DM

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intriguing features:

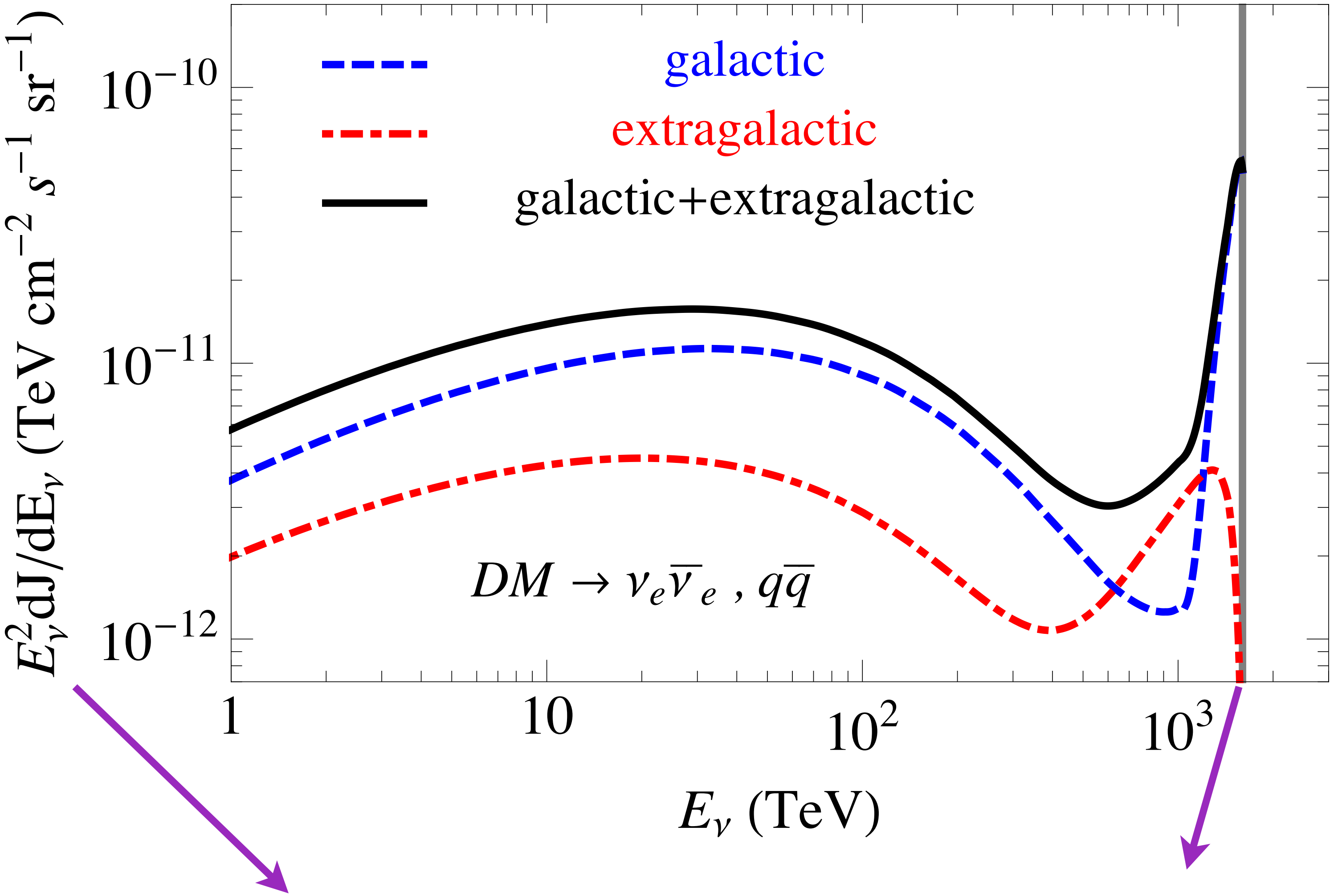
a cut-off at $m_{DM}/2$

a peak in ~ PeV

a dip in ~ (0.4-1) PeV

populated spectrum in < 0.4 PeV

due to soft channel and EW cascades



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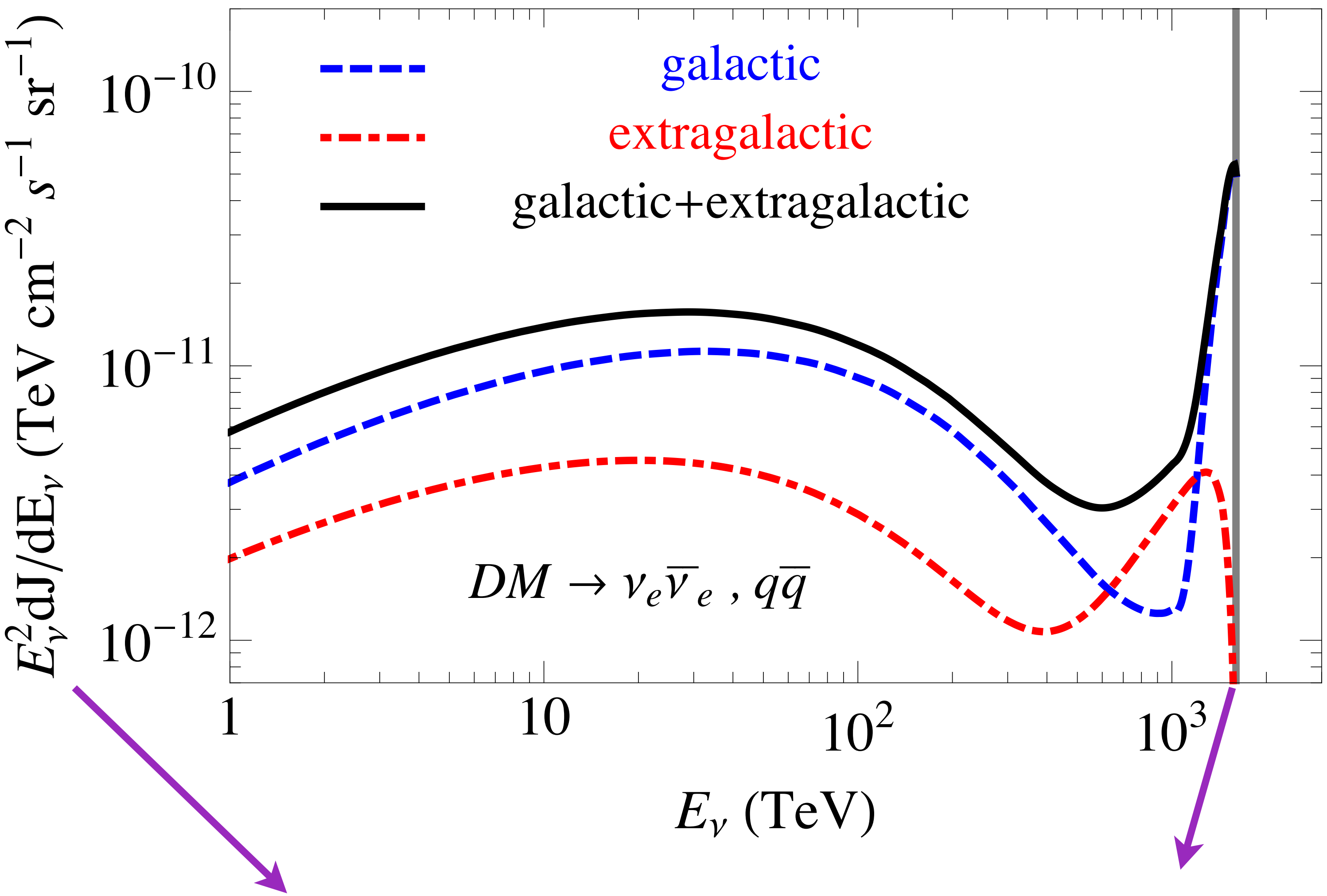


$(\nu_e + \nu_\mu + \nu_\tau)/3$

$m_{DM}/2 = 1.6$ PeV

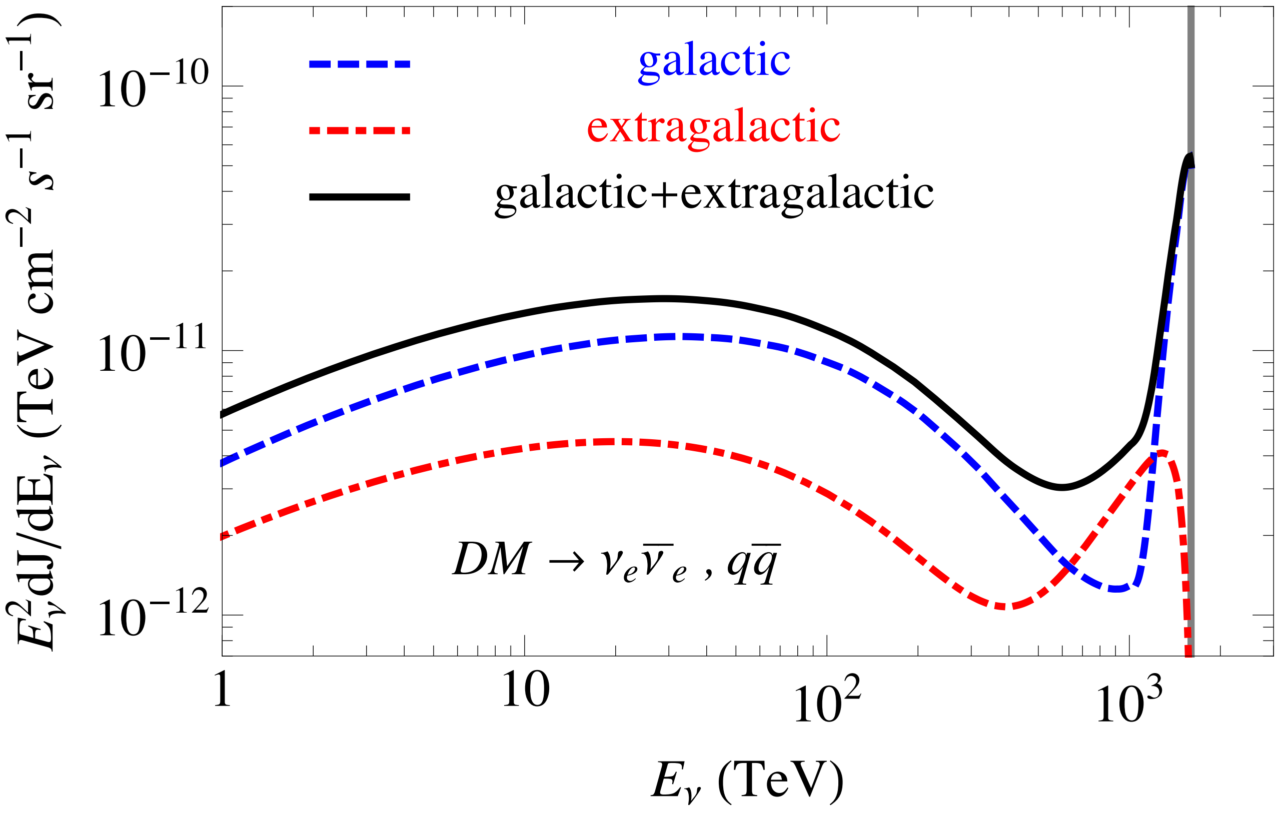
b_H controls the peak height at ~ PeV

τ_{DM} controls the low energy population

$b_H = 0.12$ and $\tau_{DM} = 2 \times 10^{27}$ s

Flux of neutrinos from decaying DM

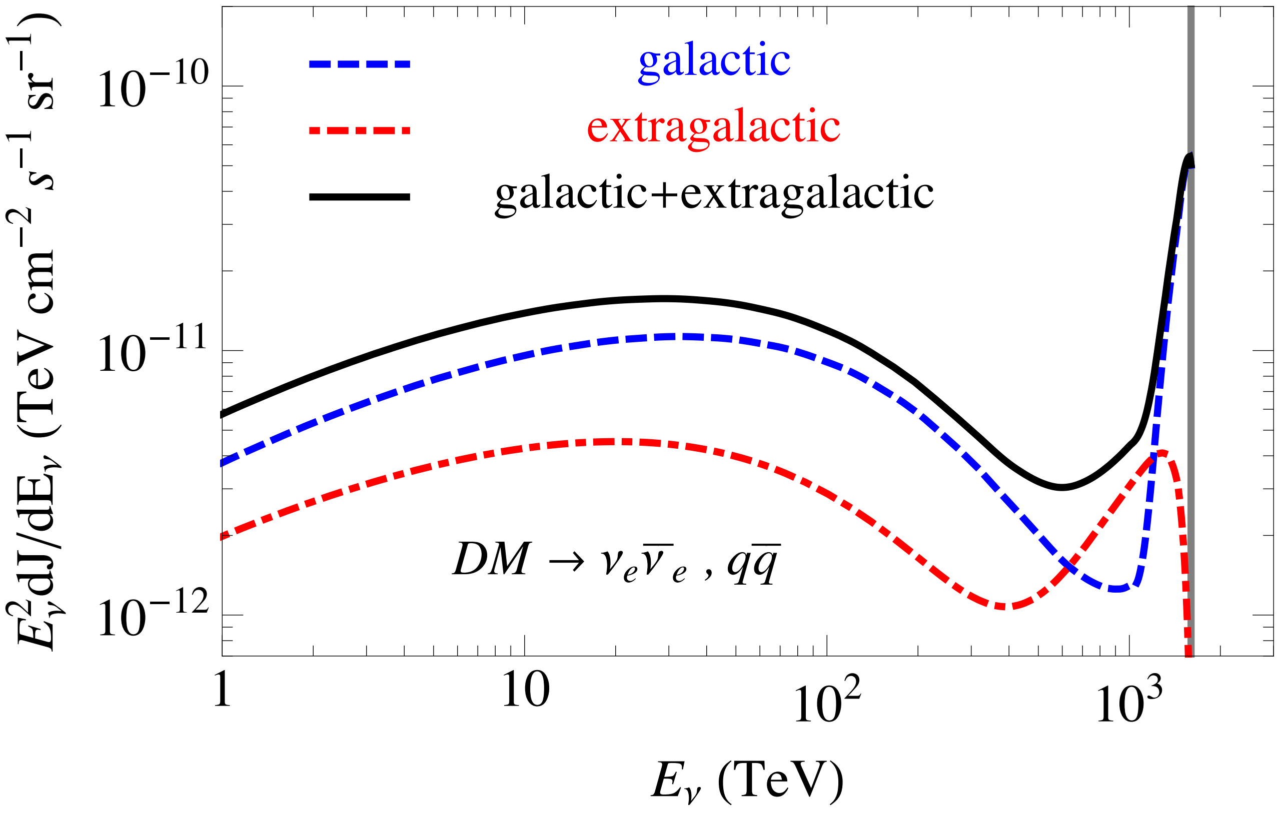
✓ fine-tuned decay channels ?

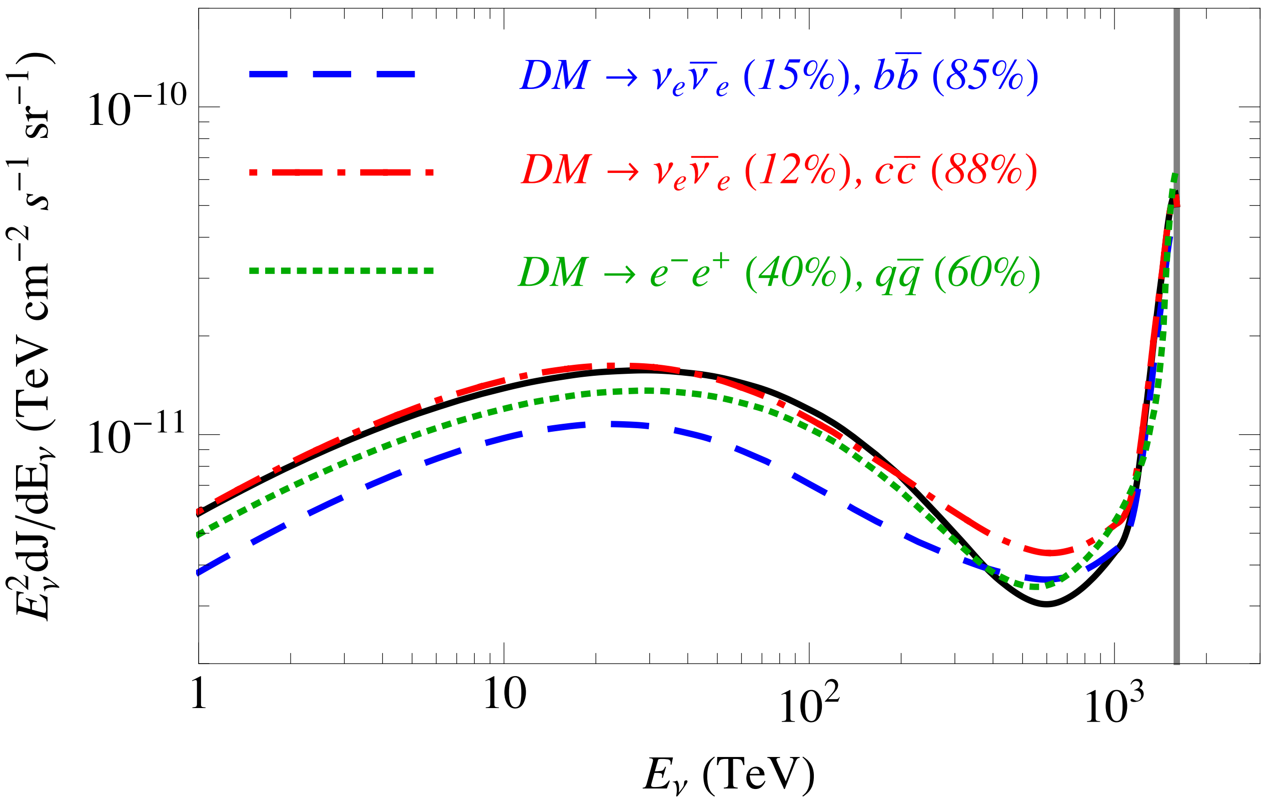


Flux of neutrinos from decaying DM

✓ fine-tuned decay channels ?

τ_{DM} = (1-3) x 10^{27} s





the intriguing features are generic

Flux of neutrinos from decaying DM

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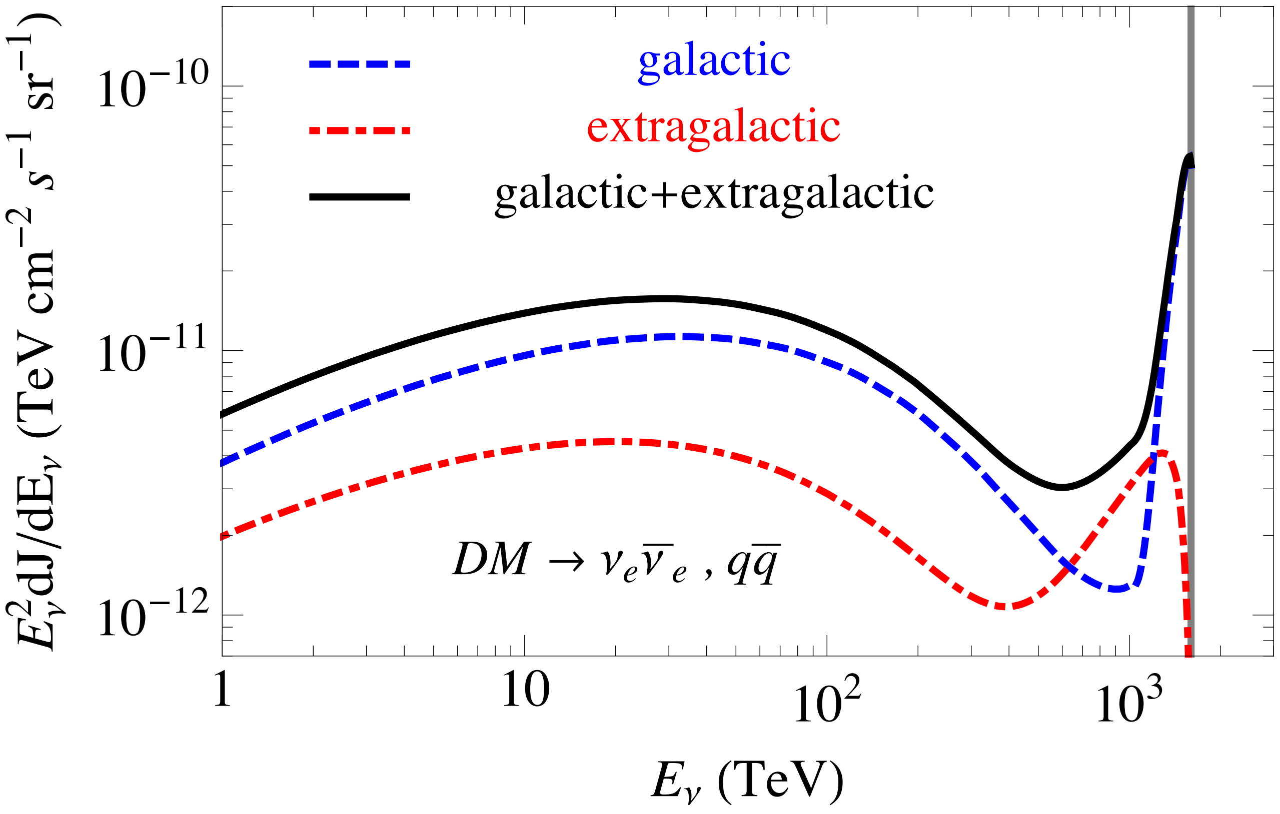
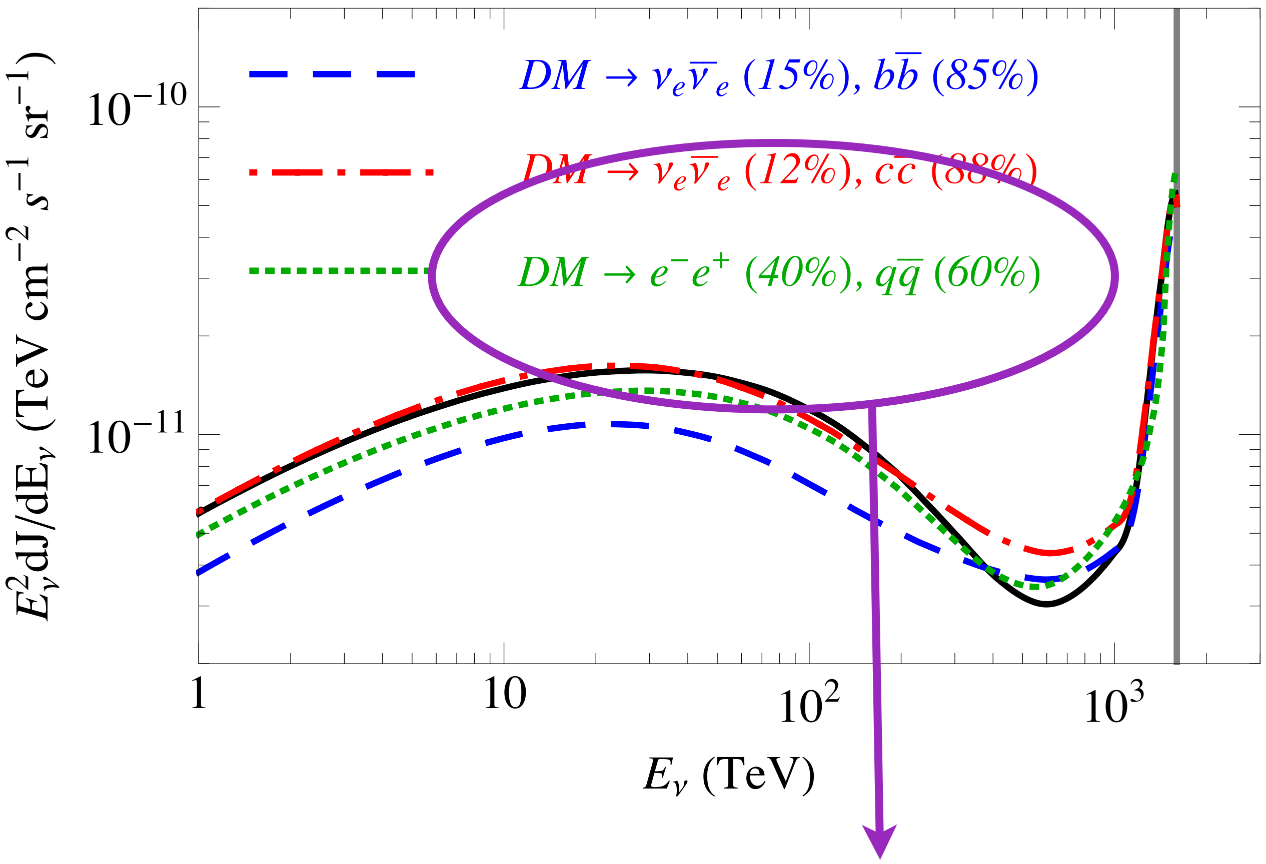




the crucial role of EW cascades

the intriguing features are generic

Confronting with energy distribution of IceCube data

✓ branching ratio b_H gives the two PeV events

✓ soft channel and lifetime τ_{DM} gives the upturn in low energy

the value of τ_{DM} is compatible with the bounds derived from neutrinos and gamma rays

✓ natural explanation for the lack of events > PeV

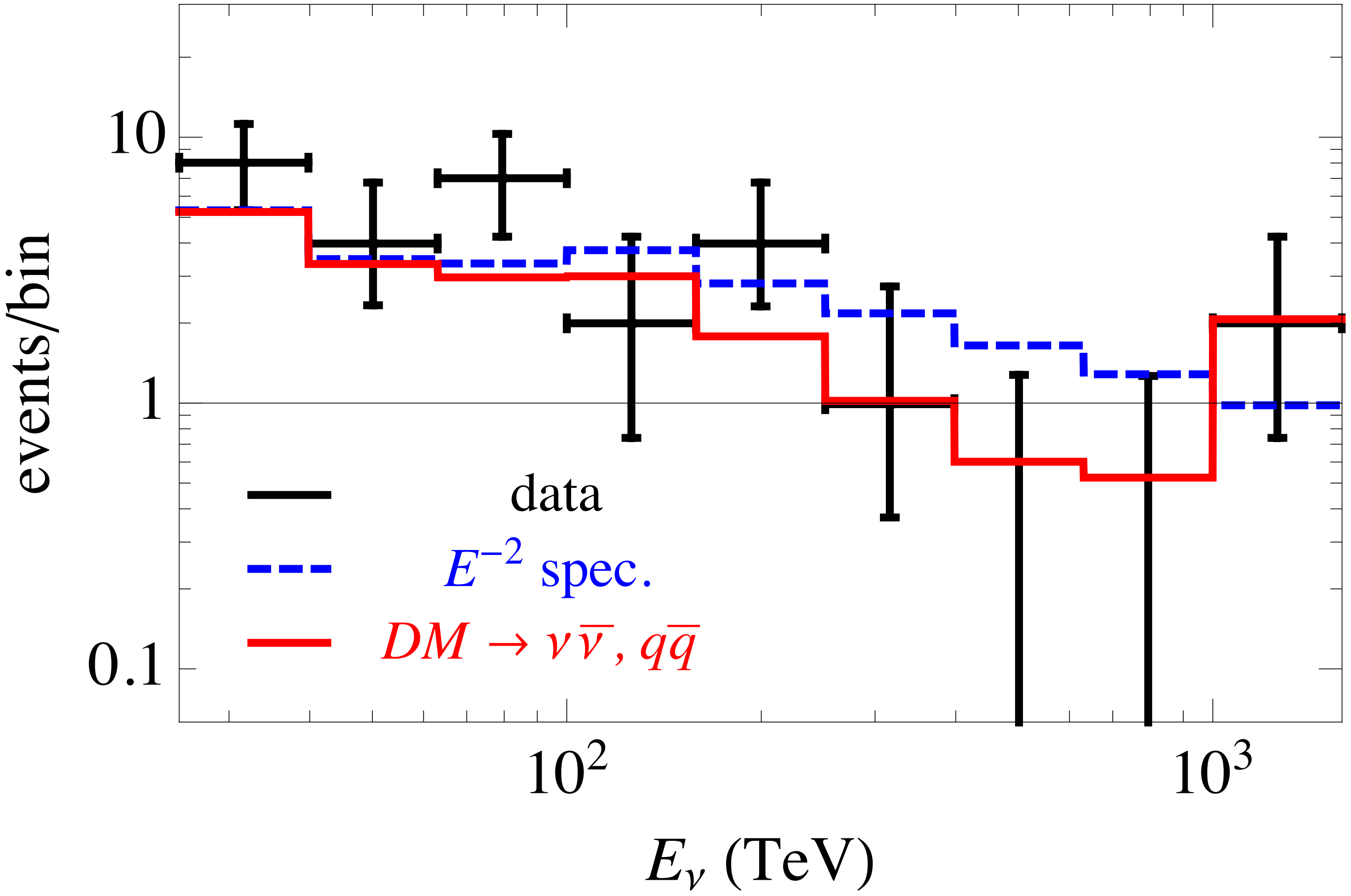
the value of m_{DM} can be changed within the current uncertainty of the highest energy events

✓ the low energy bins contain large bkg. contribution

the important discriminators of DM vs astrophysical model are high energy bins, where clearly data shows preference to DM model

two years data set

$b_H = 0.12$ and $\tau_{DM} = 2 \times 10^{27}$ s



✓ different decay channels lead to qualitatively same result

Confronting with energy distribution of IceCube data

three years data set

SM sector ↔ Dark sector

portal type:

$$\mathcal{L}_{\rm protal} = \frac{\mathcal{O}_{\rm SM}\mathcal{O}_{\rm DM}}{\Lambda^{d-4}}$$

Confronting with energy distribution of IceCube data

three years data set

SM sector ⟷ Dark sector

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"neutrino" portal: $$\mathcal{O}_{\rm SM} \to HL$$

A. Falkowski, J. Juknevich and J. Shelton
arXiv:0908.1790 [hep-ph].

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✓ d = 4 : $\mathcal{O}_{\rm DM} \to N$

heavy sterile neutrino, DM candidate

T. Higaki, R. Kitano and R. Sato, JHEP (2014)
[arXiv:1405.0013 [hep-ph]].

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UV completion: $$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

$$m_\phi \sim 10^{13}\ \mathrm{GeV}$$

"Higgs" field ϕ_{B-L} plays the role of inflaton

$$T_R \sim 10^7\ \mathrm{GeV}$$

Confronting with energy distribution of IceCube data

three years data set

Leptogenesis: $\phi \to N_2 N_2$ $\quad M_2 \sim 10^{12}\ \mathrm{GeV} \longrightarrow \frac{n_B}{s} \sim 10^{-10}$

DM abundance: $$\Omega_{N_1} \simeq 0.2 \left(\frac{M_1}{4\ \mathrm{PeV}} \right)^3 \left(\frac{T_R}{3 \times 10^7\ \mathrm{GeV}} \right)^{-1}$$

DM lifetime: $$\tau_{N_1} \simeq 8 \times 10^{28}\ \mathrm{s} \left(\frac{M_1}{1\ \mathrm{PeV}} \right)^{-1} \left(\frac{10^{-29}}{|y_N|^2} \right)$$

DM decay channels:

$$\mathrm{Br}(\ell^\pm W^\mp) = 2\mathrm{Br}(\nu_\ell Z) = 2\mathrm{Br}(\nu_\ell h) = |U_{\ell 1}|^2$$ NH

$$\mathrm{Br}(\ell^\pm W^\mp) = 2\mathrm{Br}(\nu_\ell Z) = 2\mathrm{Br}(\nu_\ell h) = |U_{\ell 3}|^2$$ IH

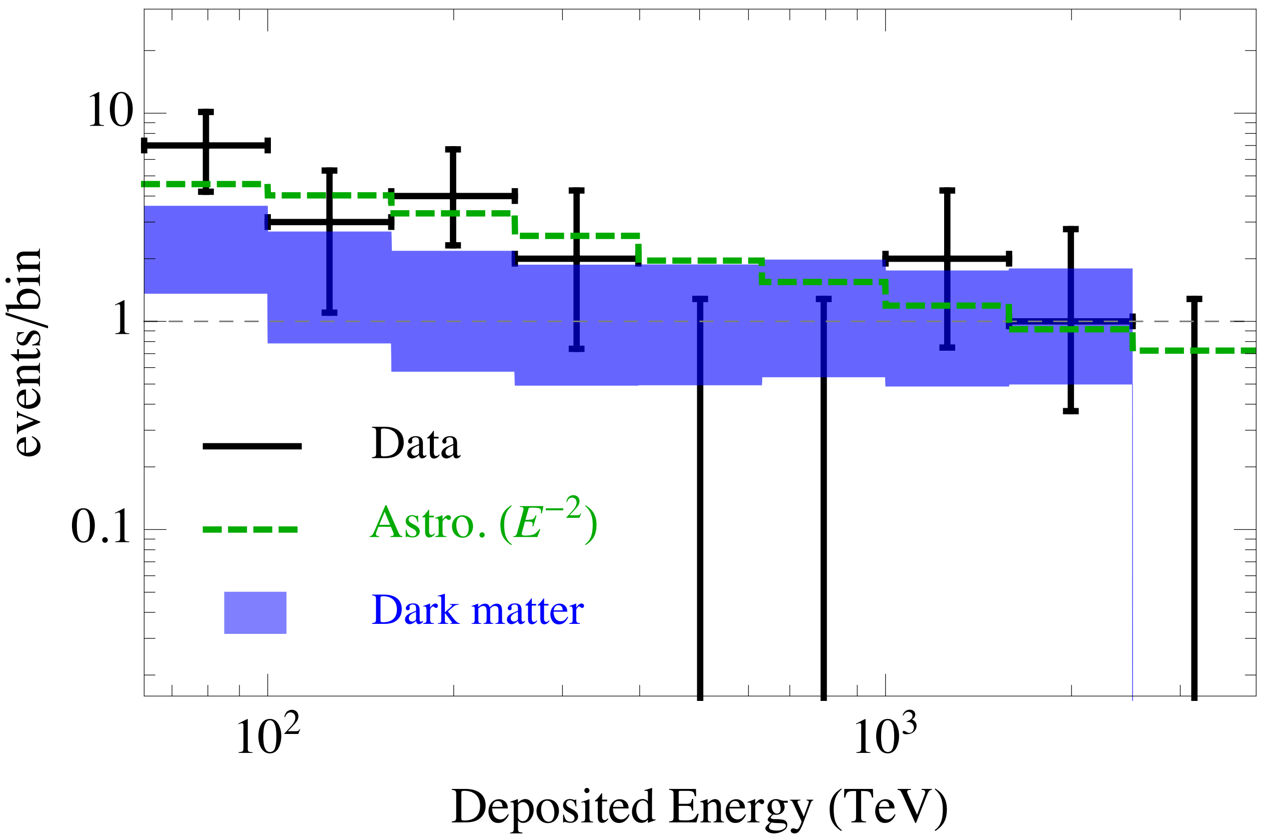
Confronting with energy distribution of IceCube data

three years data set

IH

$\tau_{DM} = 1.1 \times 10^{28}$ s

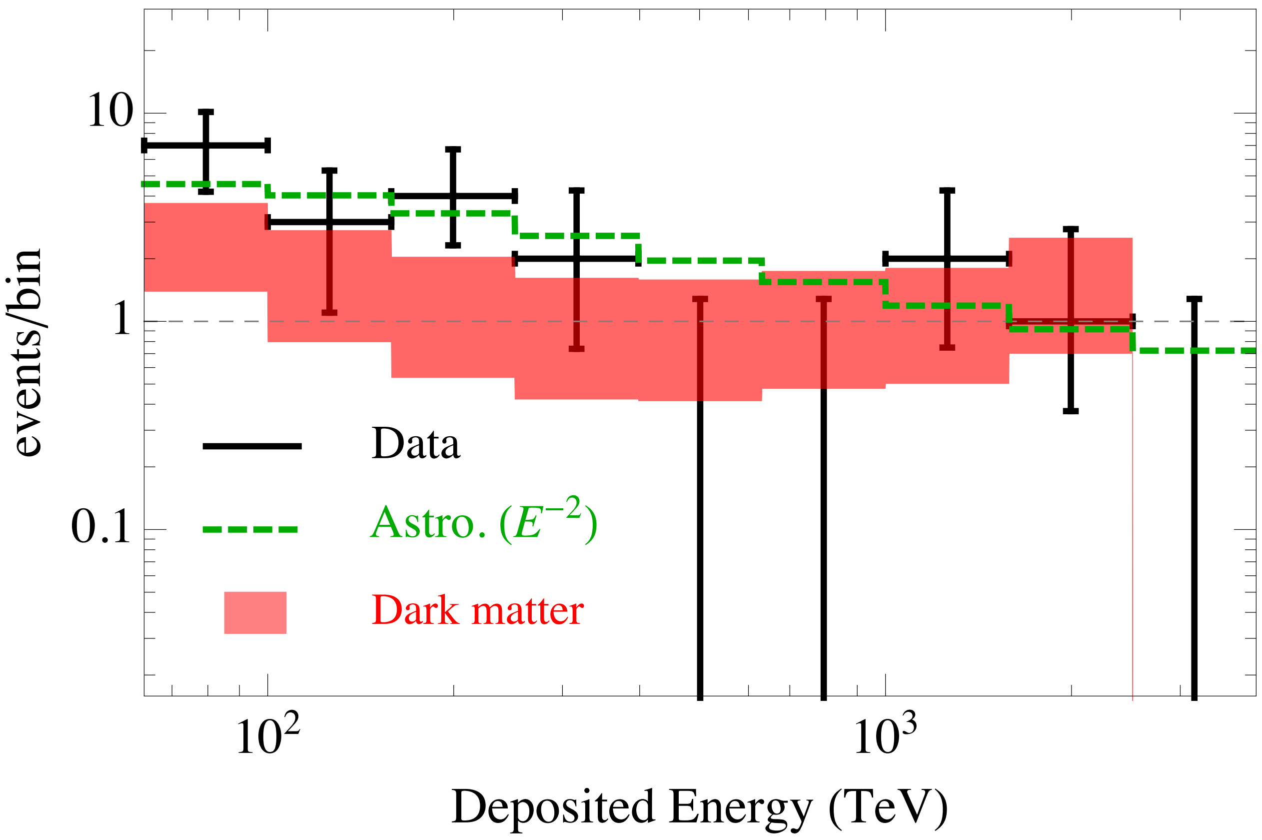
shaded: ±1σ



NH

$\tau_{DM} = 7.3 \times 10^{27}$ s

shaded: ±1σ



m_{DM} = 4 PeV

Confronting with energy distribution of IceCube data

three years data set

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✓ d =4: $\mathcal{O}_{\rm DM} \to N$

production mechanism:

$m_\phi \gg m_N$ inflaton decay

$m_\phi \ll m_N$ freeze-in

$g\phi NN \ , \ g \simeq 10^{-6}$

Confronting with energy distribution of IceCube data

three years data set

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✓ d = 5 : $\mathcal{O}_{\rm DM} \to \chi\phi$ singlet fermion and scalar (Asymmetric DM)

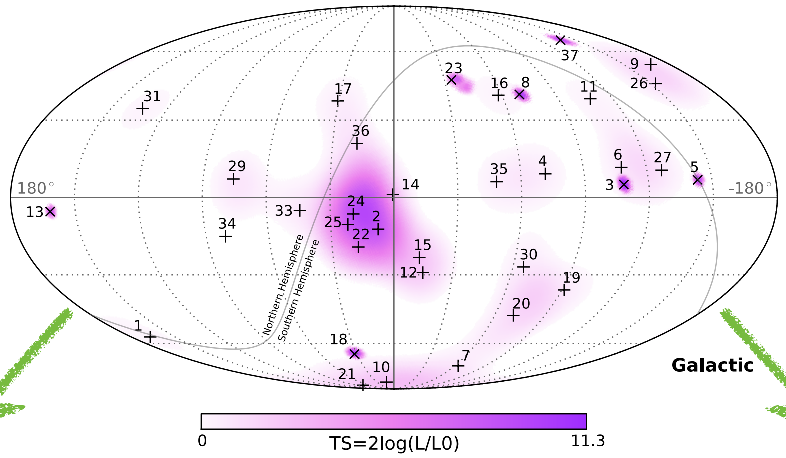
✓ d = 6 : other portals

✓ For d > 4 there are more freedom in branching ratios. We have shown that for the most constrained model (d=4) a good fit to the data can be obtained. Obviously better fits can be achieved for d > 4.

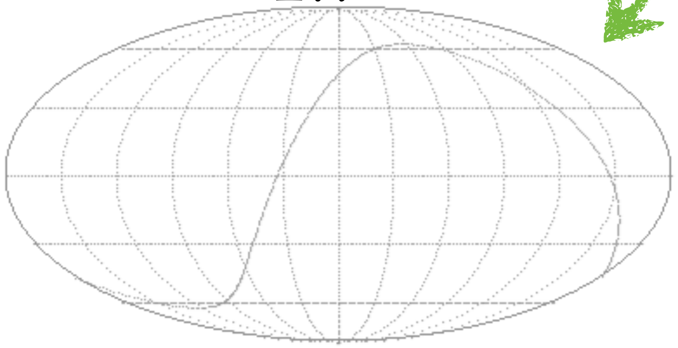
Angular distribution of neutrinos from decaying DM

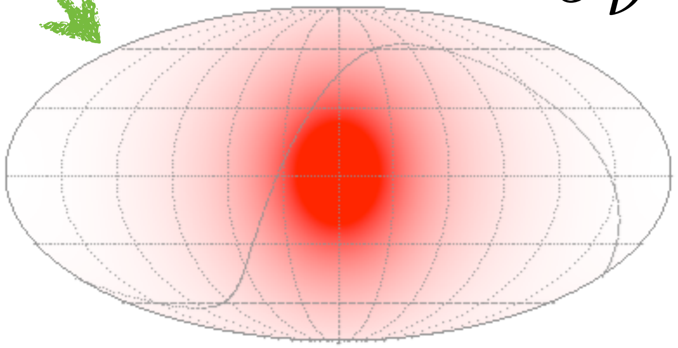
- ✓ We would compare

$$p^{\rm iso} = \frac{1}{4\pi}$$



$$p^{\rm DM} = \frac{1}{J_\nu}\frac{{\rm d}^2 J_\nu}{{\rm d}b\,{\rm d}l}$$





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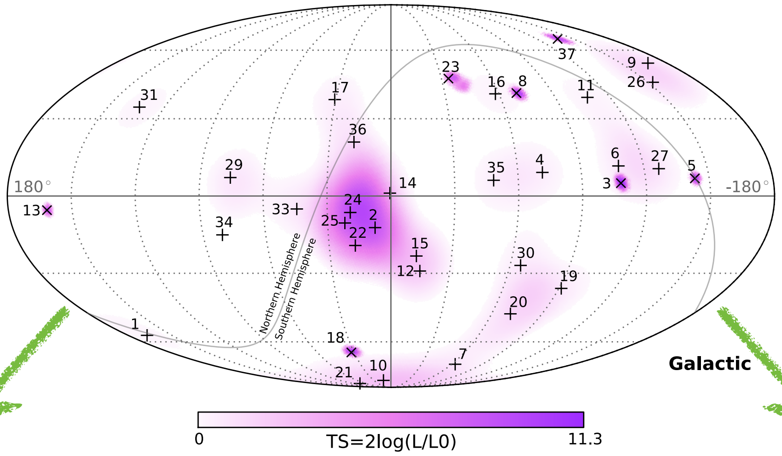

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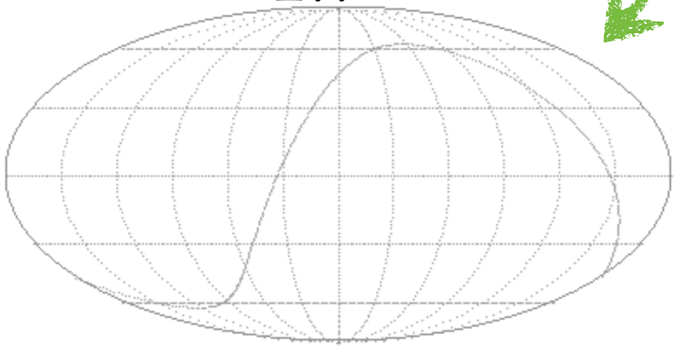

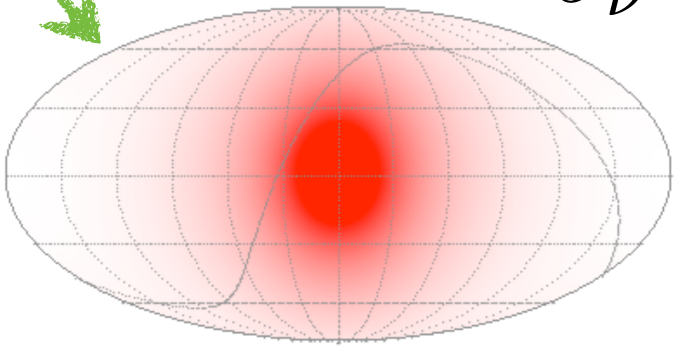

PDF of data

$$p_i(b,l) = \frac{1}{2\pi\sigma_i^2}\exp\left[-\frac{|\vec{x}-\vec{x}_i|^2}{2\sigma_i^2}\right]$$

"flat sky" approximation

PDF of isotropic dis.

$$p^{\mathrm{iso}} = \frac{1}{4\pi}$$

PDF of DM

$$p^{\mathrm{DM}}(b,l) = \frac{1}{J_\nu}\frac{\mathrm{d}^2 J_\nu}{\mathrm{d}b\,\mathrm{d}l} = \frac{\int_0^\infty \rho[r(s,b,l)]\mathrm{d}s + \Omega_{\mathrm{DM}}\rho_c\beta}{4\pi(\eta + \Omega_{\mathrm{DM}}\rho_c\beta)}$$

Angular distribution of neutrinos from decaying DM

✓ Likelihood analysis

Number of signal events

Test Statistics

$$\mathrm{TS}_{\mathrm{like}} = 2\sum_{i=1}^{N}\left(\ln f_i - \ln p_i^{\mathrm{iso}}\right) = 2\ln\left(\prod_{i=1}^{N} f_i\right) - 2N\ln\left(\frac{1}{4\pi}\right)$$

$$f_i = \int p_i(b,l)\; p^{\mathrm{DM}}(b,l)\cos(b)\;\mathrm{d}b\;\mathrm{d}l = \frac{1}{2\pi\sigma_i^2}\int e^{-\frac{|\vec{x}_i-\vec{x}|^2}{2\sigma_i^2}}\; p^{\mathrm{DM}}(b,l)\cos(b)\;\mathrm{d}b\;\mathrm{d}l$$

N = 35 ? too optimistic!

Angular distribution of neutrinos from decaying DM

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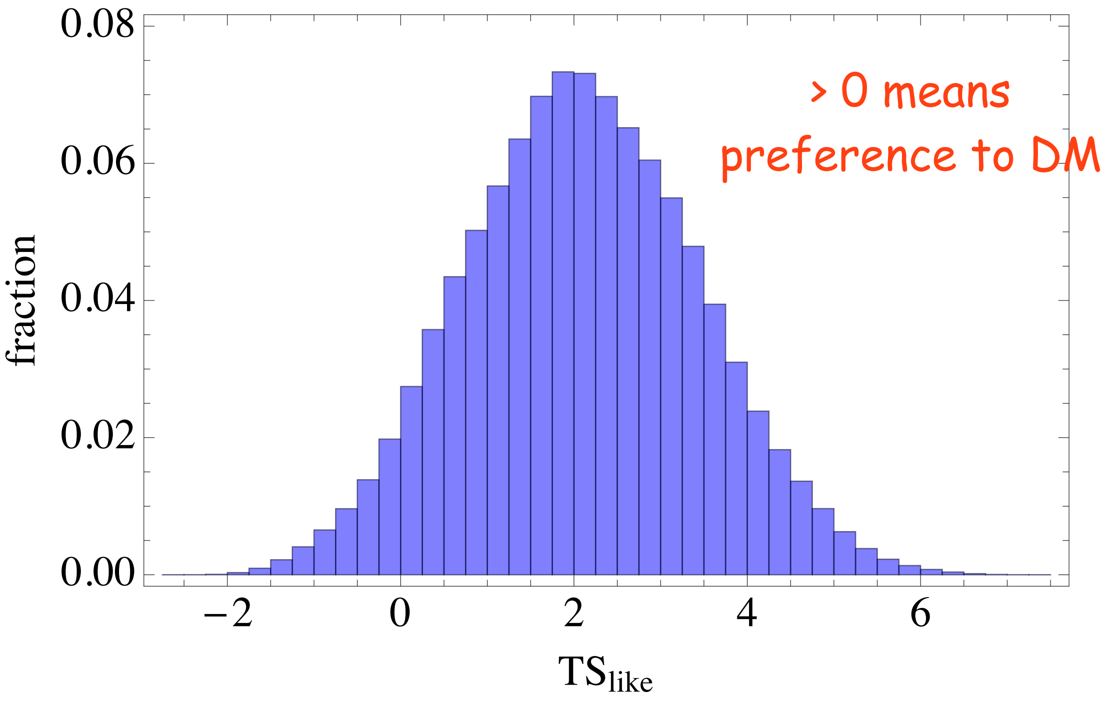
N = 35 ? too optimistic!

✓ let's assume N_b = 15 and all the events with E > 150 TeV are signal events

→ $\binom{26}{15}$ ways of selecting the bkg events among the low energy events

Distribution of $\mathrm{TS}_{\rm like}$ for all these realizations (mean value = 2.1) →



> 0 means preference to DM

Angular distribution of neutrinos from decaying DM

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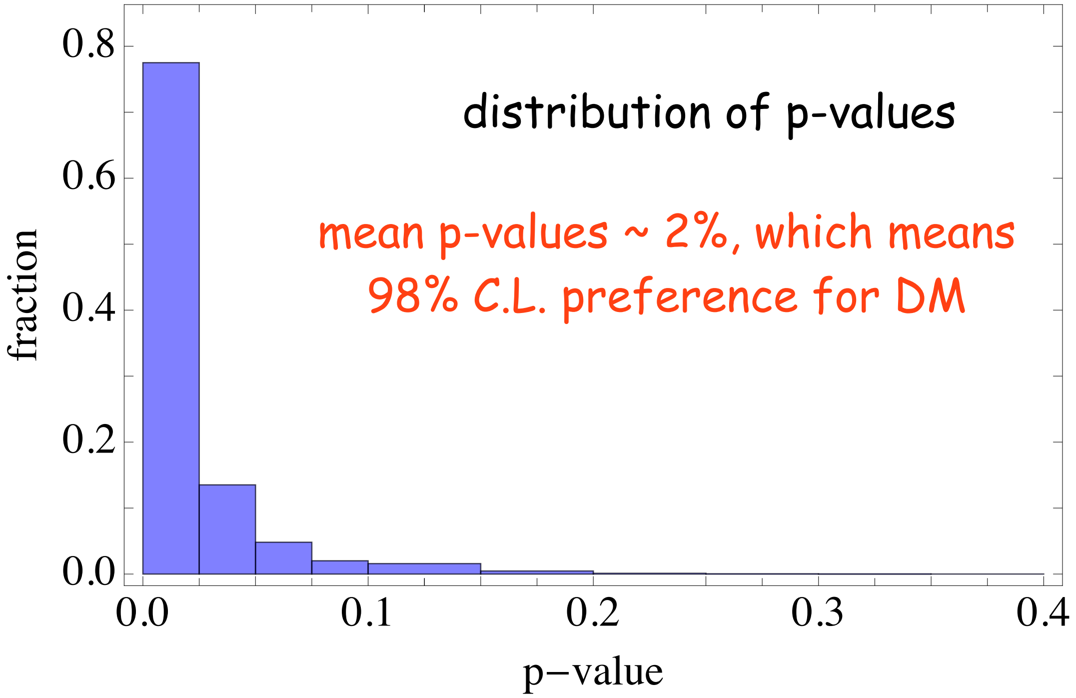
Quantifying the preference

generating a sample (10^5) of isotropically distributed set of 20 events

↓

p-value → for each realization of bkg choosing, p-value is the fraction of generated events which have smaller $\mathrm{TS}_{\rm like}$ than the one computed by observed data

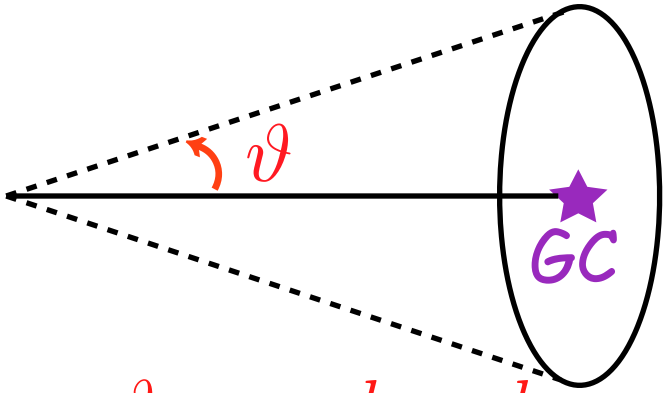


mean p-values ~ 2%, which means 98% C.L. preference for DM

Angular distribution of neutrinos from decaying DM

✓ **Kolmogorov-Smirnov test:** a powerful non-parametric test

The 2-dim KS test have some ambiguities



$\cos\vartheta = \cos b \cos l$

$$p^{\rm iso}(\vartheta) = \int_0^{2\pi} p^{\rm iso}(\vartheta,\varphi)\,{\rm d}\varphi = \int_0^{2\pi} \frac{1}{4\pi}\,{\rm d}\varphi = \frac{1}{2}$$

$$p^{\rm DM}(\vartheta) = \int_0^{2\pi} p^{\rm DM}(\vartheta,\varphi)\,{\rm d}\varphi = \frac{\int_0^\infty \rho[r(s,\vartheta)]{\rm d}s + \Omega_{\rm DM}\rho_c\beta}{2(\eta+\Omega_{\rm DM}\rho_c\beta)}$$

Angular distribution of neutrinos from decaying DM

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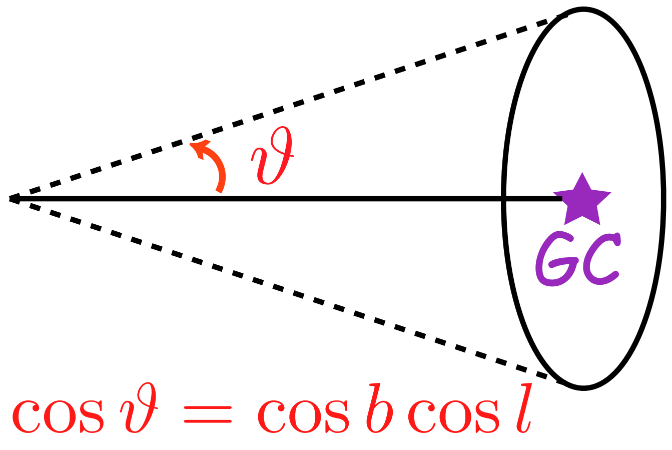

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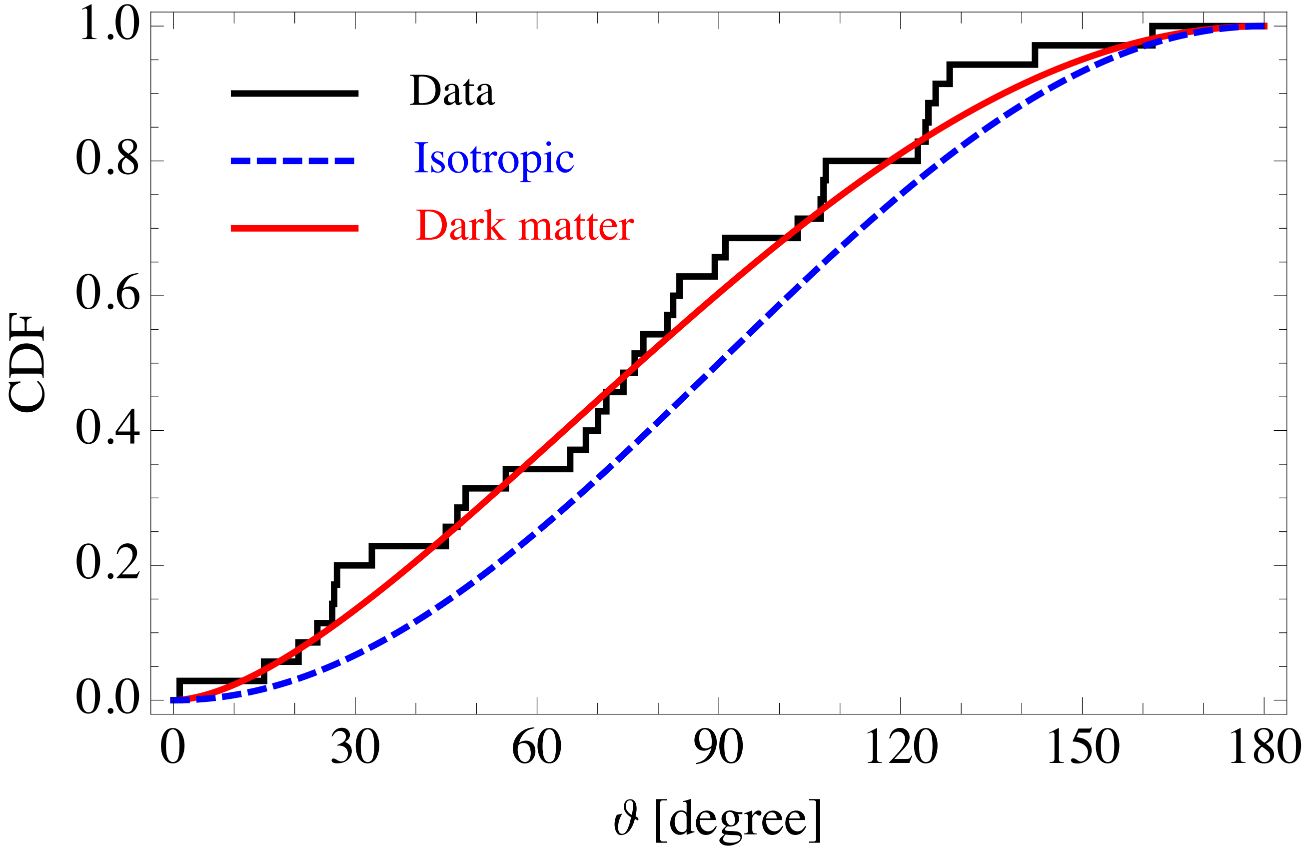

Angular distribution of neutrinos from decaying DM

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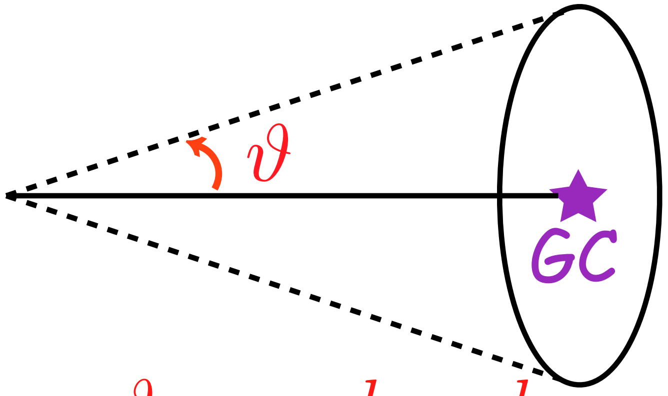

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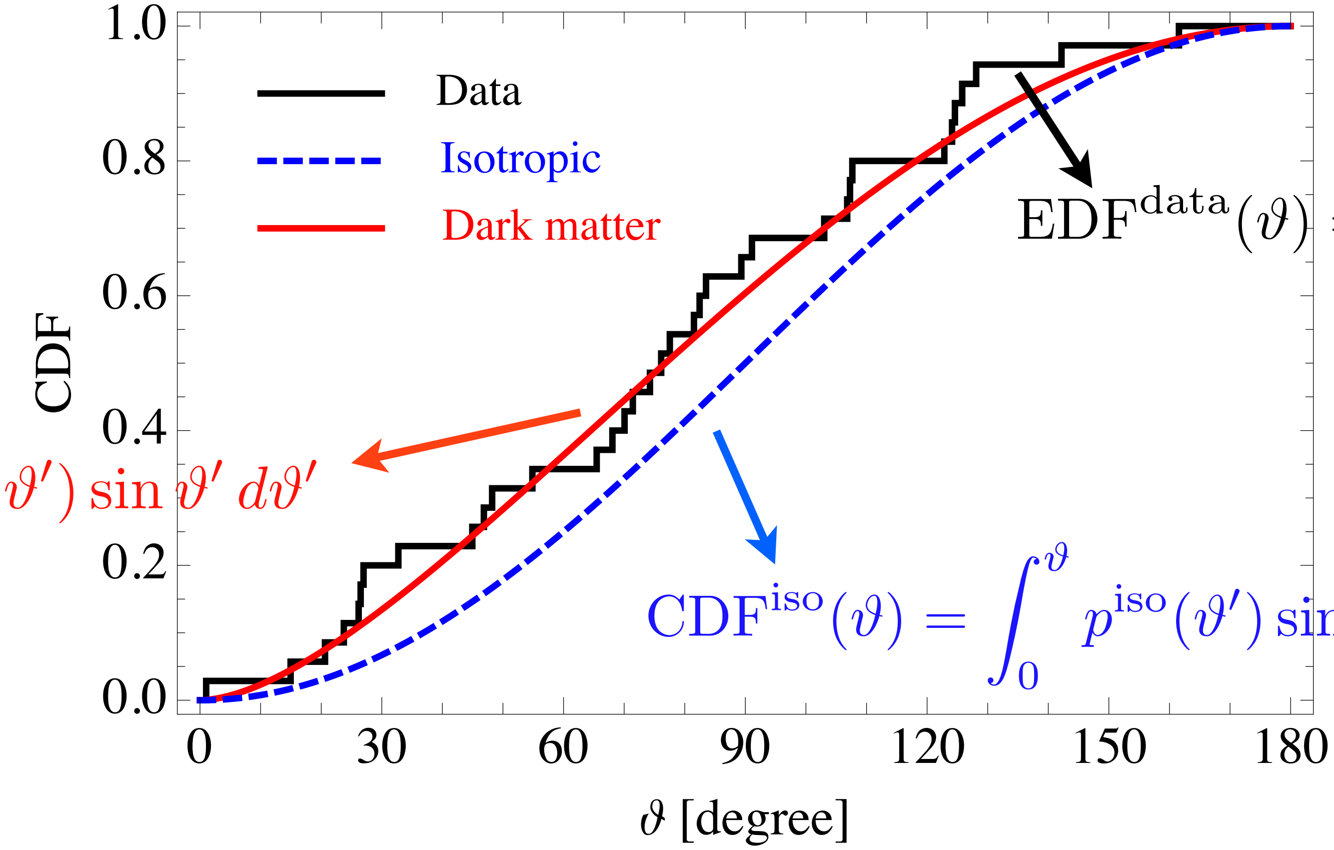
$$p^{\rm DM}(\vartheta) = \int_0^{2\pi} p^{\rm DM}(\vartheta,\varphi)\,{\rm d}\varphi = \frac{\int_0^\infty \rho[r(s,\vartheta)]{\rm d}s + \Omega_{\rm DM}\rho_c\beta}{2(\eta + \Omega_{\rm DM}\rho_c\beta)}$$



$$\mathrm{EDF}^{\rm data}(\vartheta) = \frac{1}{N}\sum_{i=1}^{N}\Theta(\vartheta - \vartheta_i)$$

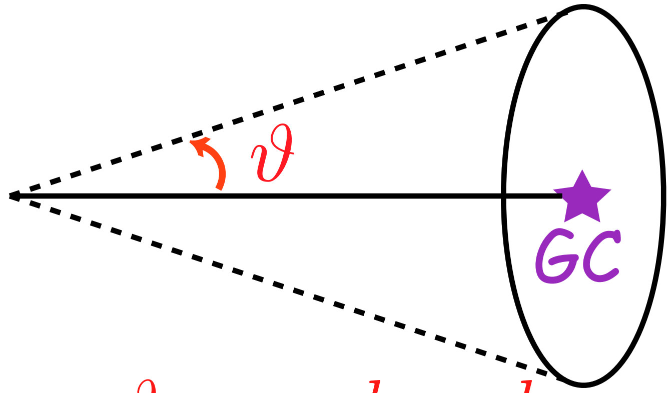
$$\mathrm{CDF}^{\rm DM}(\vartheta) = \int_0^{\vartheta} p^{\rm DM}(\vartheta')\sin\vartheta'\,d\vartheta'$$

$$\mathrm{CDF}^{\rm iso}(\vartheta) = \int_0^{\vartheta} p^{\rm iso}(\vartheta')\sin\vartheta'\,d\vartheta' = \frac{1-\cos\vartheta}{2}$$

Angular distribution of neutrinos from decaying DM

✓ **Kolmogorov-Smirnov test:** a powerful non-parametric test

The 2-dim KS test have some ambiguities



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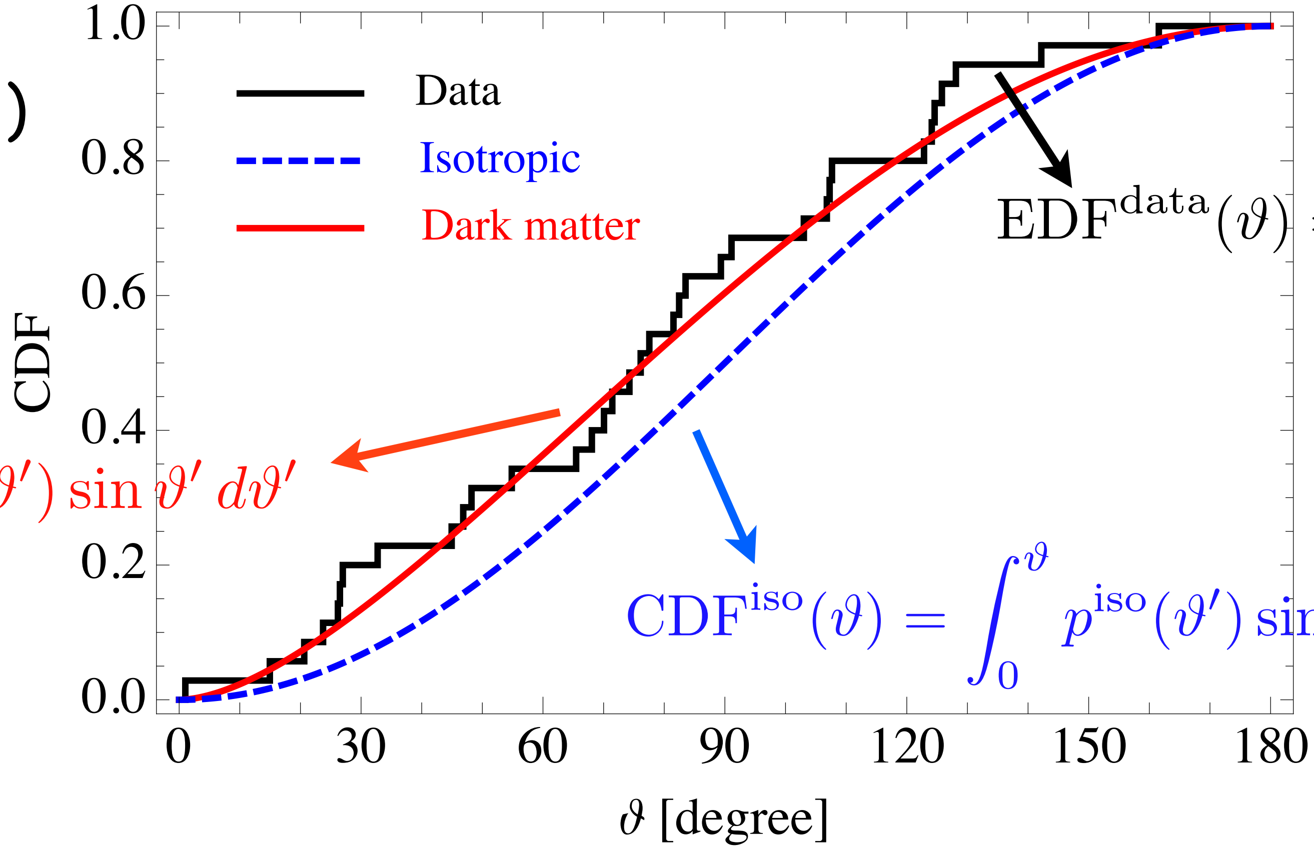
N = 35 (too optimistic!)



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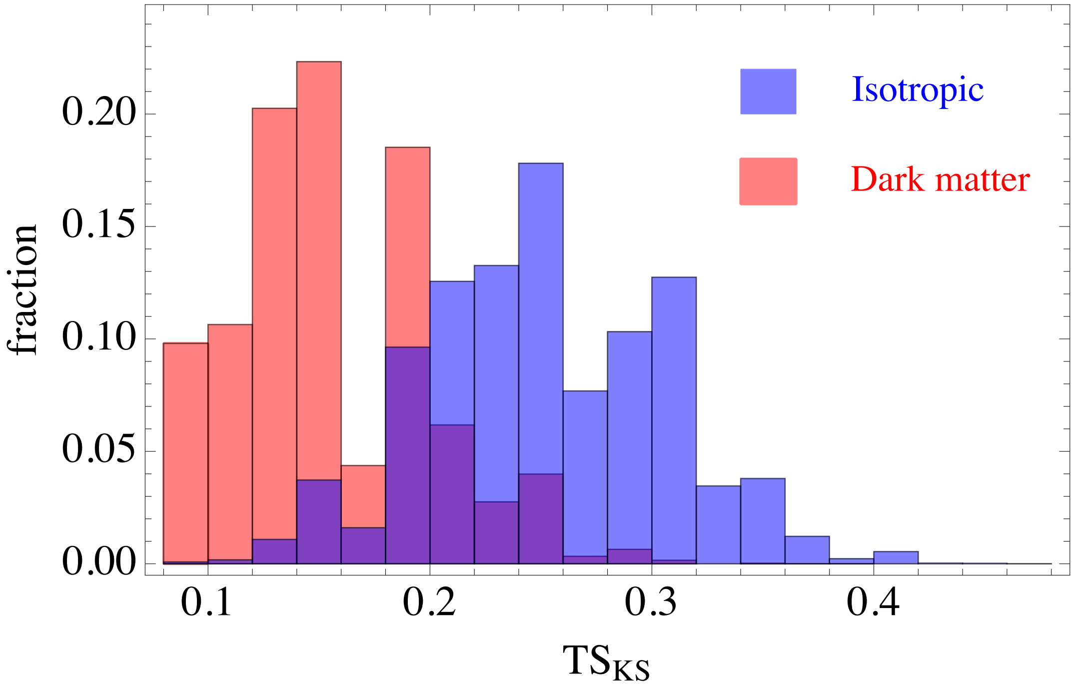
Angular distribution of neutrinos from decaying DM

✓ Kolmogorov-Smirnov test:

Test Statistics

$$\mathrm{TS}_{\mathrm{KS}} = \max_{1\leq i\leq N} \left\{ \mathrm{CDF}^{\mathrm{DM}}(\vartheta_i) - \frac{i-1}{N}, \frac{i}{N} - \mathrm{CDF}^{\mathrm{DM}}(\vartheta_i) \right\}$$

statistically larger TS for isotropic distribution



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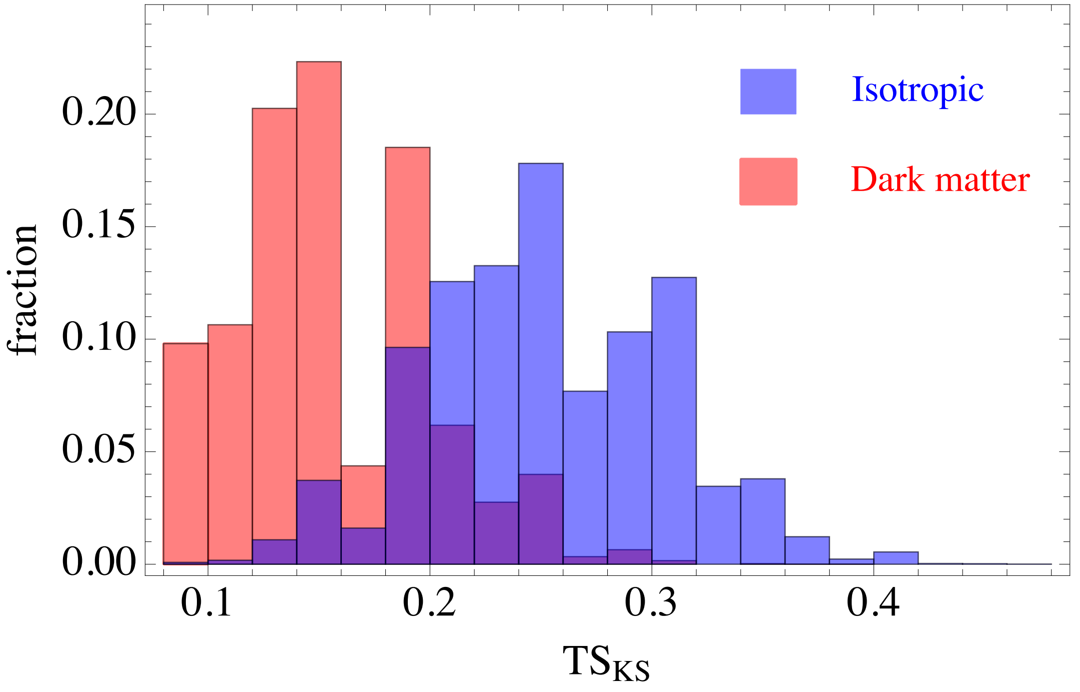

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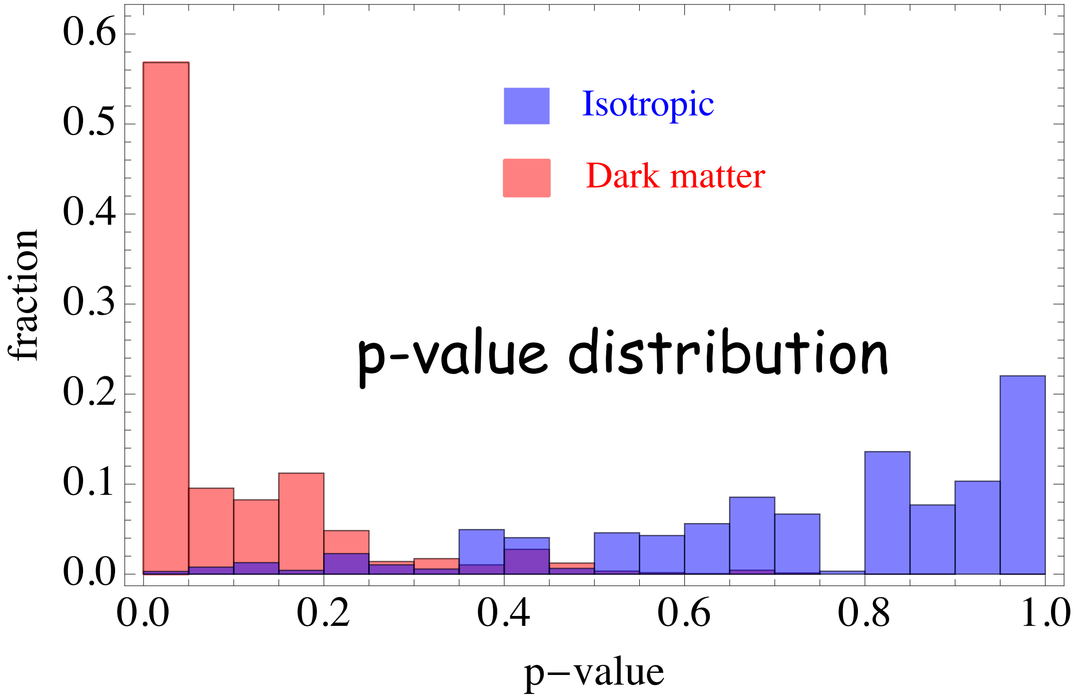
again, generating a sample (10^5) of isotropically distributed set of 20 events

↓

on the average, 10% of generated isotropic sample have smaller $\mathrm{TS}_{\mathrm{KS}}$ than the values obtained for data vs DM dis.
for data vs isotropic dis. it is 73%

↓

less than 2σ preference for DM dis.



p-value distribution

Angular distribution of neutrinos from decaying DM

✓ **Anderson-Darling test:** a powerful non-parametric test, especially sensitive to the end points

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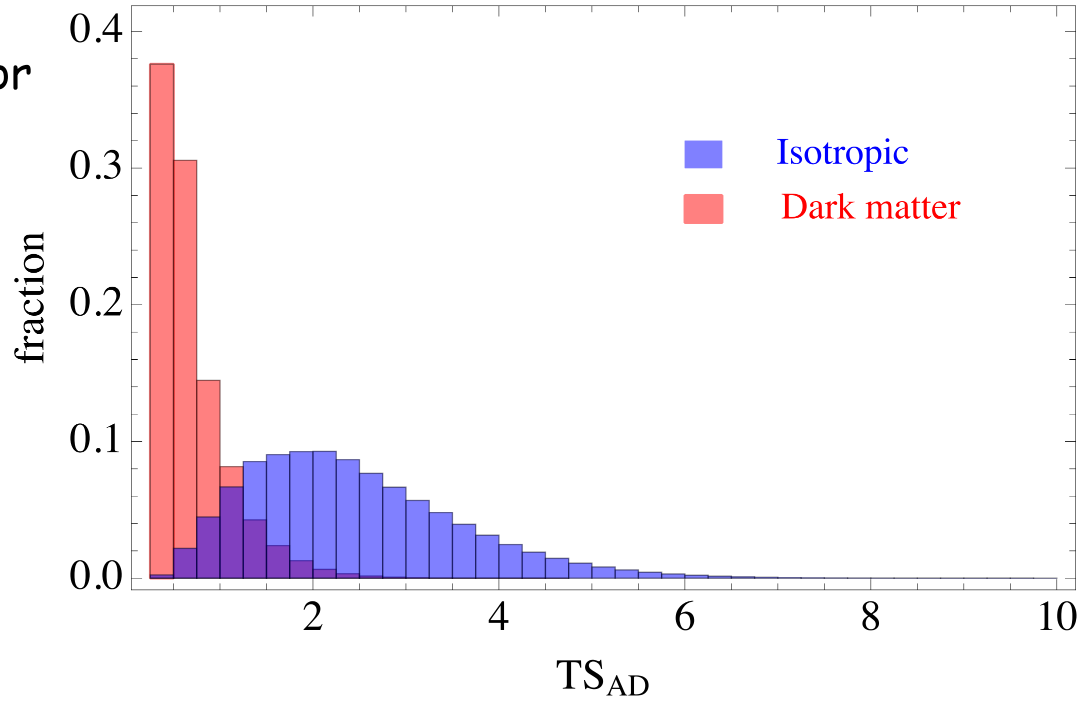

Test Statistics

$$\mathrm{TS_{AD}} = -N - \frac{1}{N}\sum_{i=1}^{N}(2i-1)\left[\ln\left(\mathrm{CDF^{DM}}(\vartheta_i)\right) + \ln\left(1-\mathrm{CDF^{DM}}(\vartheta_{N+1-i})\right)\right]$$

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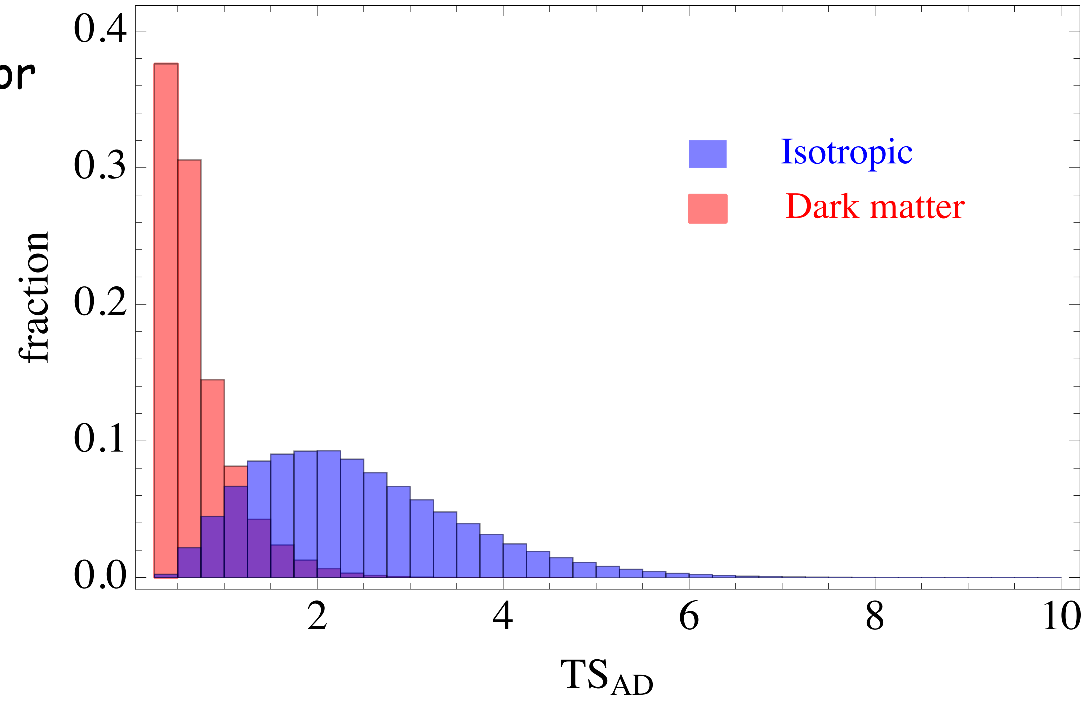

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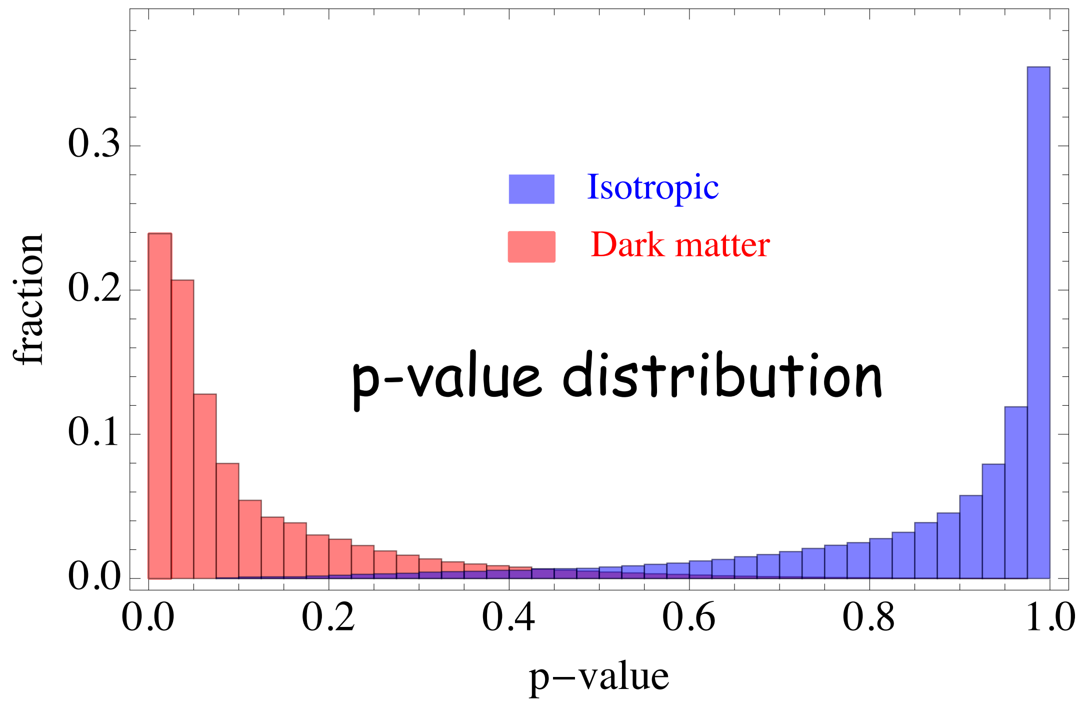
again, generating a sample (10^5) of isotropically distributed set of 20 events

↓

on the average, 11% of generated isotropic sample have smaller $\mathrm{TS}_{\mathrm{KS}}$ than the values obtained for data vs DM dis.
for data vs isotropic dis. it is 86%

↓

less than 2σ preference for DM dis.



p-value distribution

Angular distribution of neutrinos from decaying DM

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Angular resolution in KS and AD tests? → even after shifting all the events to higher ϑ values still the preference for DM persist

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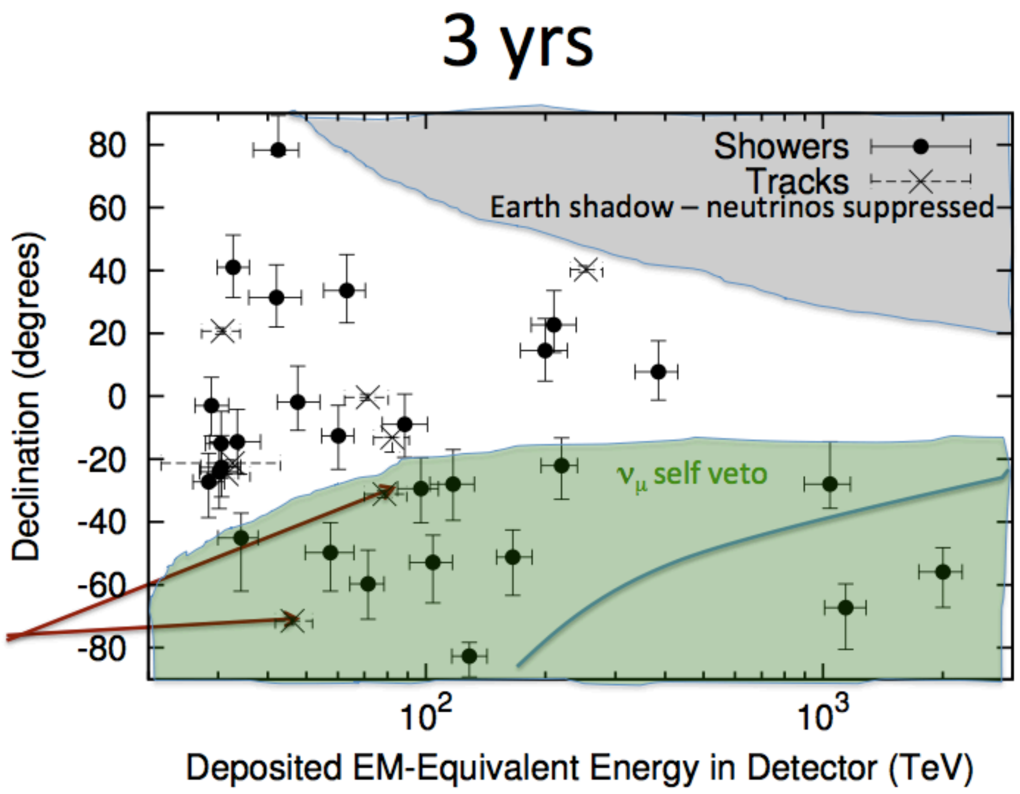
Background rejection? → Figure from T. Gaisser



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even after shifting all the events to higher ϑ values still the preference for DM persist

Background rejection?

3 yrs

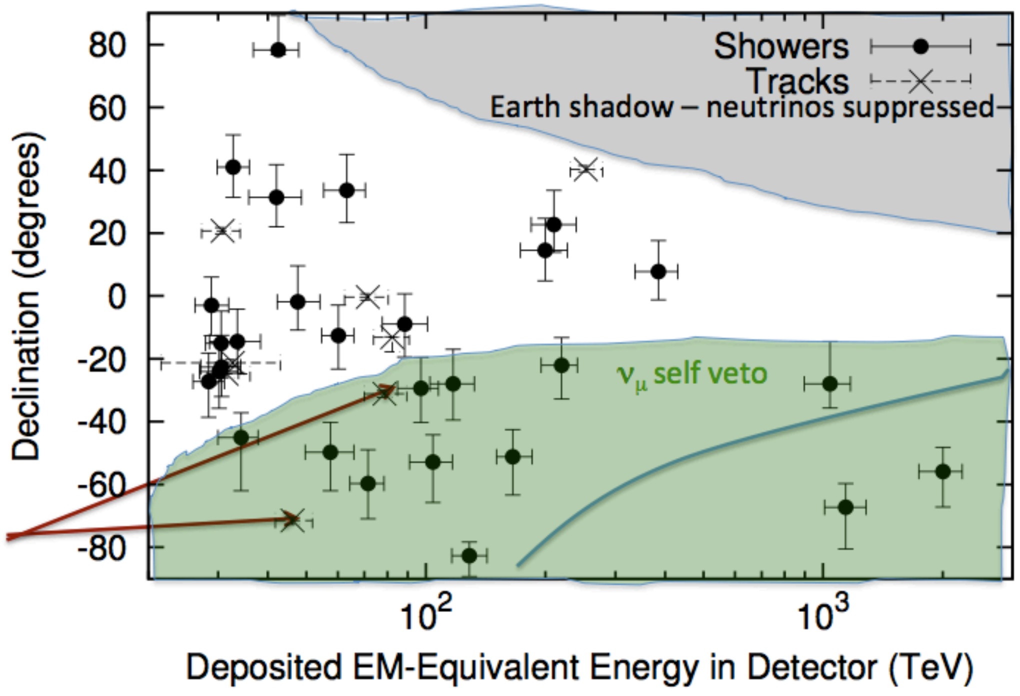
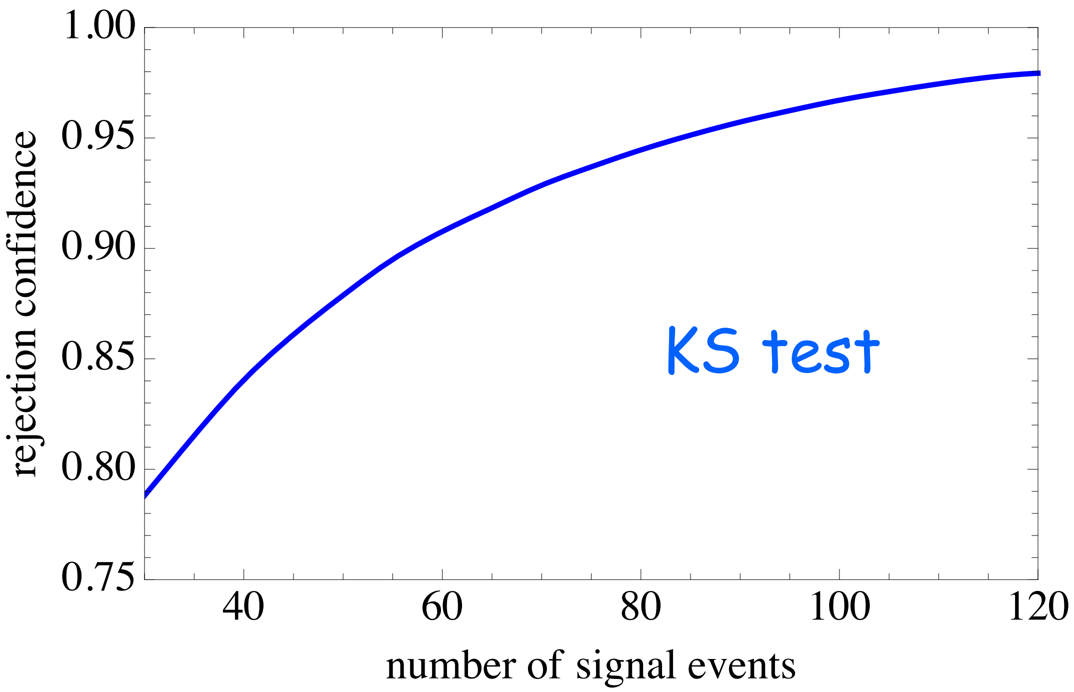


Figure from T. Gaisser

How many events are needed for a 3σ discrimination?



Gamma ray bounds

Universe is opaque for gamma-rays with E > 1 TeV → cascades develop: gamma-ray interaction with interstellar radiation field and CMB → gamma-rays populate at lower energies, 1 - 100 GeV

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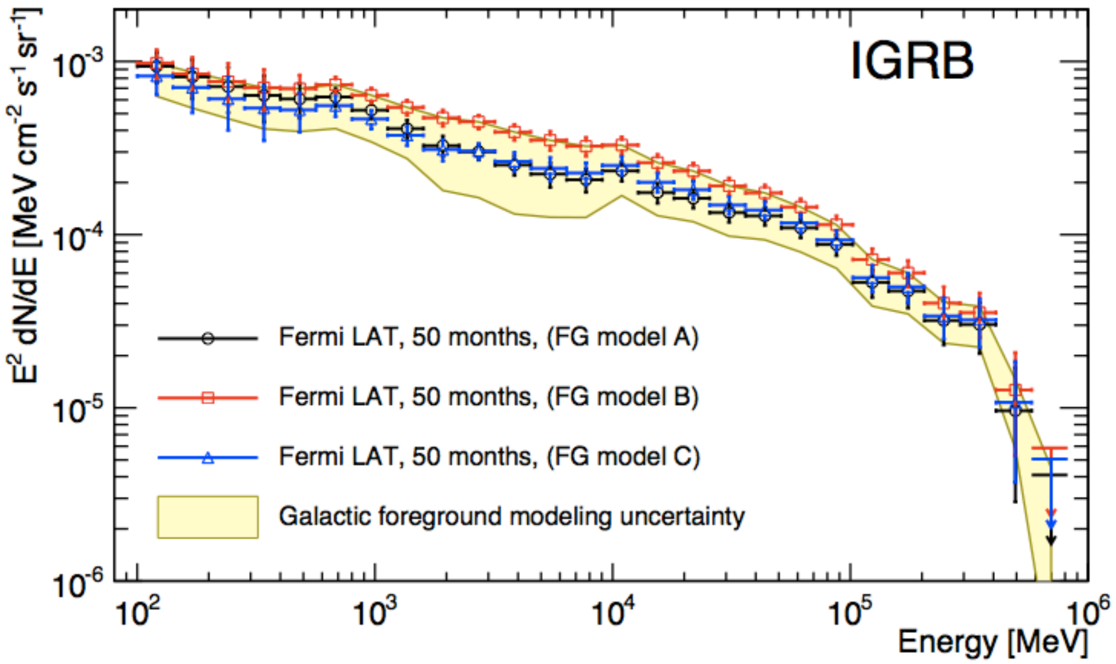

integrated energy density

$$\omega_\gamma = \frac{4\pi}{c}\int_{E_1}^{E_2} E_\gamma \frac{\mathrm{d}\varphi_\gamma}{\mathrm{d}E_\gamma}\,\mathrm{d}E_\gamma \lesssim 4.4\times 10^{-7}\,\mathrm{eV/cm}^3$$

$$E_1 \sim \mathcal{O}(1)\ \mathrm{GeV} \qquad E_2 \sim \mathcal{O}(100)\ \mathrm{GeV}$$

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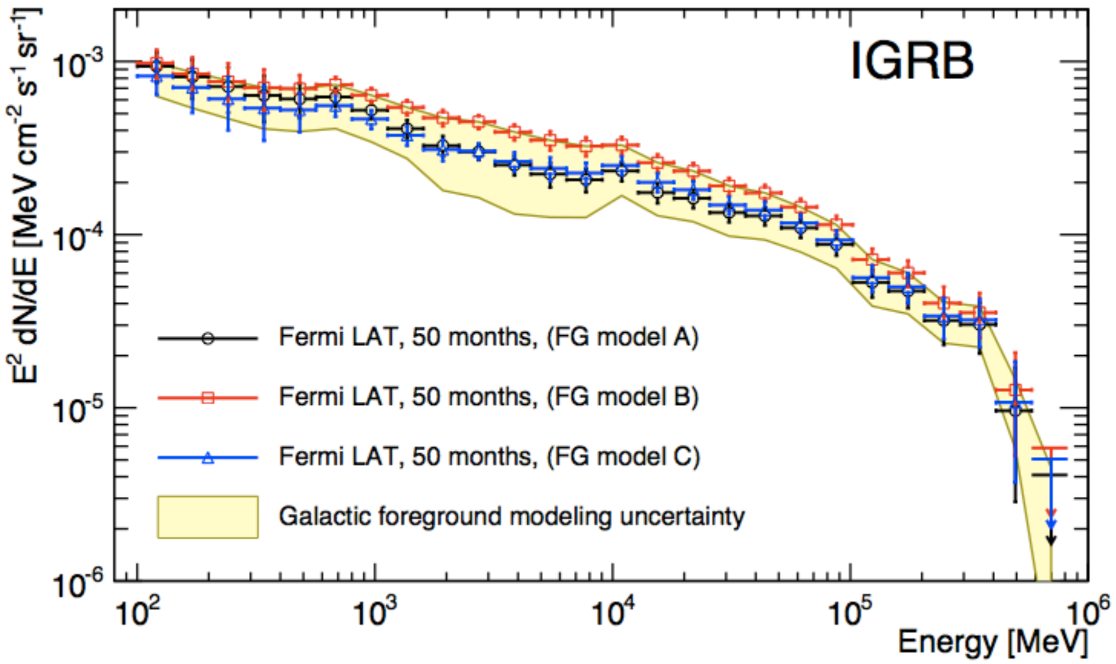

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total electromagnetic energy budget (NH case)

$$\frac{4\pi}{c}\int \sum_{\mathrm{i=gal,extragal}} \left[E_\gamma \left.\frac{\mathrm{d}\varphi_\gamma}{\mathrm{d}E_\gamma}\right)^{\mathrm{i}} + E_e \left.\frac{\mathrm{d}\varphi_{e^\pm}}{\mathrm{d}E_e}\right)^{\mathrm{i}} \right] \mathrm{d}E \simeq 5.2\times 10^{-8}\,\mathrm{eV/cm^3}$$

✓

Gamma ray bounds

✓ Galactic component

at ~ PeV, the absorption length of gamma-rays are comparable to Galactic distances → neither full absorption or cascade development, nor full transparency

a complicated 3D problem

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CASA-MIA bounds

the integrated flux of γ-ray above 330 TeV must be below 1.0×10^{-13} cm^{-2}s^{-1}sr^{-1}

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For DM decay
(NH case)
unattenuated flux

→

the integrated flux of ɣ-ray above 330 TeV is 1.2x10^{-14} cm^{-2}s^{-1}sr^{-1}

the integrated flux of ɣ-ray above 775 TeV is 8.8x10^{-15} cm^{-2}s^{-1}sr^{-1} ✓

What can we learn about DM if the IceCube events originate from conventional astrophysical flux?

constraining:

✓ DM lifetime

✓ annihilation cross section

Constraining DM properties

✓ DM lifetime

contribution of DM to the events in each bin should be smaller than N_{limit}

bin #	$\log_{10}(E_\nu/\text{TeV})$	$N_{\text{astro}}(E_\nu^{-2} \div E_\nu^{-2.3})$	N_{data}	$N_{\text{limit}}\ (E_\nu^{-2} \div E_\nu^{-2.3})$	N_{limit}
#1	1.4 – 1.6	9.46 ÷ 10	11	7.8 ÷ 7.46	16.6
#2	1.6 – 1.8	4.31 ÷ 5.3	6	6.53 ÷ 5.87	10.5
#3	1.8 – 2.0	4.55 ÷ 5.68	7	7.41 ÷ 6.58	11.8
#4	2.0 – 2.2	3.97 ÷ 4.82	3	3.98 ÷ 3.73	6.68
#5	2.2 – 2.4	3.32 ÷ 3.56	4	5.15 ÷ 5.01	8.00
#6	2.4 – 2.6	2.59 ÷ 2.42	2	3.65 ÷ 3.71	5.32
#7	2.6 – 2.8	1.96 ÷ 1.62	0	2.3 ÷ 2.3	2.3
#8	2.8 – 3.0	1.55 ÷ 1.1	0	2.3 ÷ 2.3	2.3
#9	3.0 – 3.2	1.2 ÷ 0.74	2	4.31 ÷ 4.64	5.32
#10	3.2 – 3.4	0.92 ÷ 0.5	1	3.3 ÷ 3.51	3.89
#11	3.4 – 3.6	0.73 ÷ 0.35	0	2.3 ÷ 2.3	2.3
#12	3.6 – 3.8	1.72 ÷ 0.76	0	2.3 ÷ 2.3	2.3

Poisson statistics:

at q% C.L.

$$\frac{q}{100} = \frac{\int_0^{N^i_{\text{limit}}} L(N^i_{\text{data}}, N)\, \mathrm{d}N}{\int_0^{\infty} L(N^i_{\text{data}}, N)\, \mathrm{d}N}$$

$$L(N^i_{\text{data}}, N) = \frac{(N + N^i_{\text{astro}})^{N^i_{\text{data}}}}{N^i_{\text{data}}!} e^{-(N+N^i_{\text{astro}})}$$

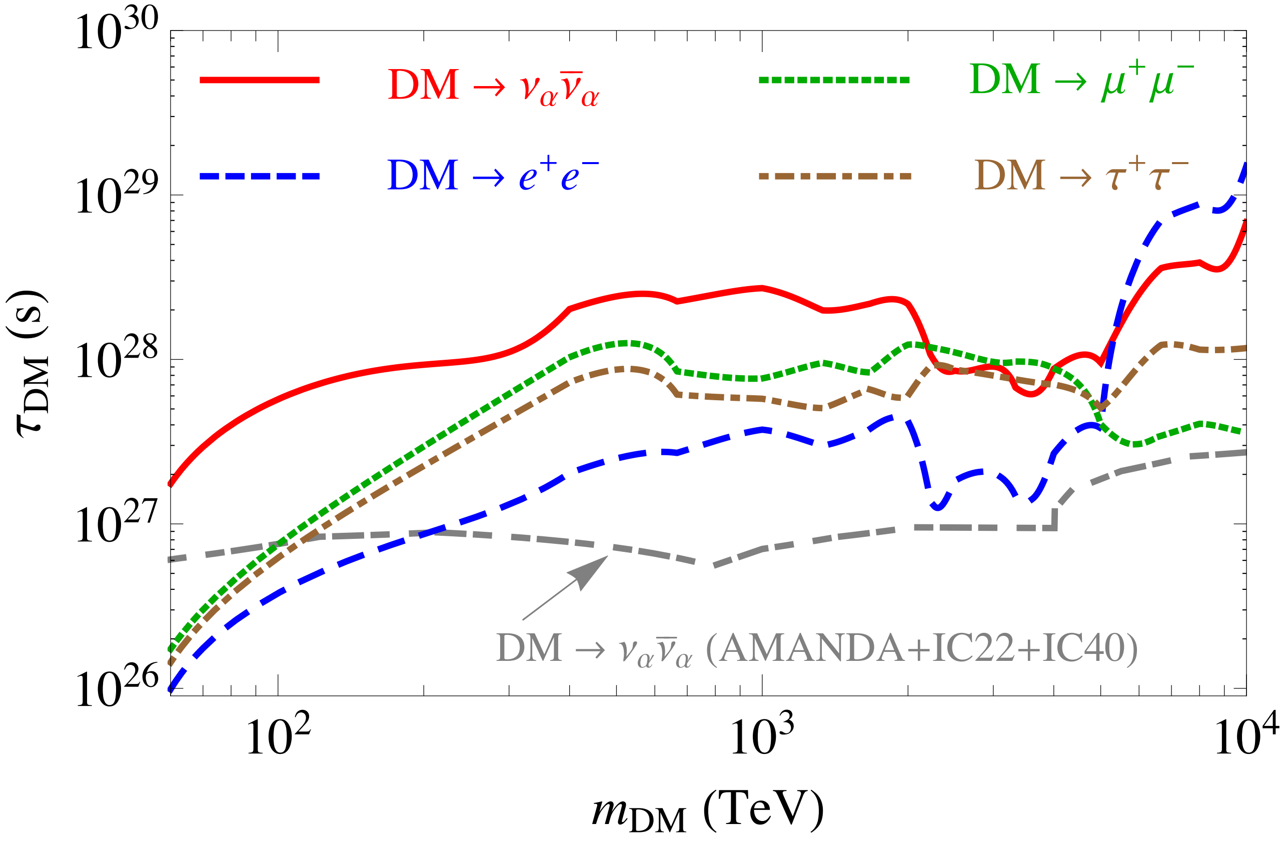
or

$$L(N^i_{\text{data}}, N) = \frac{(N)^{N^i_{\text{data}}}}{N^i_{\text{data}}!} e^{-N}$$

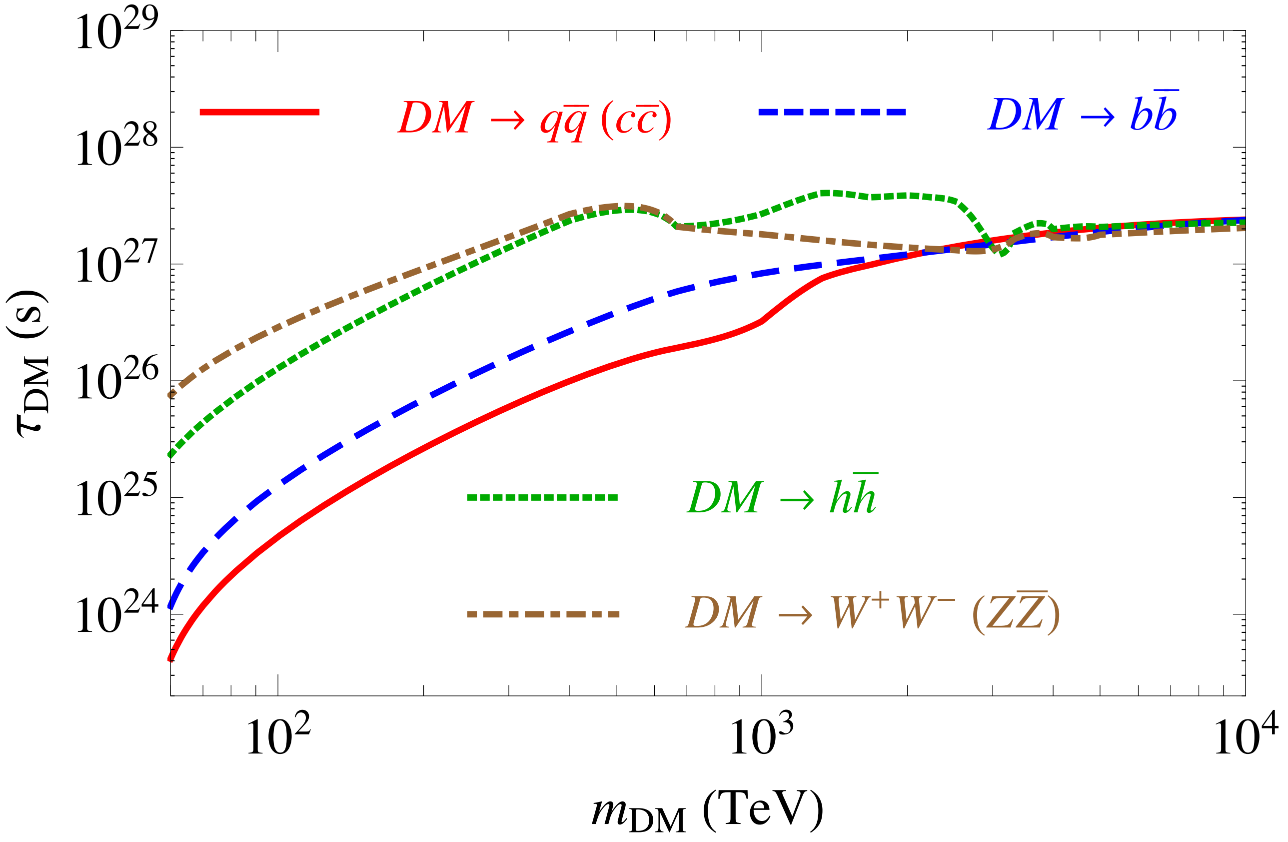
Constraining DM properties

✓ limits on DM lifetime (90% C.L.)

leptonic channels



hadronic/gauge channels



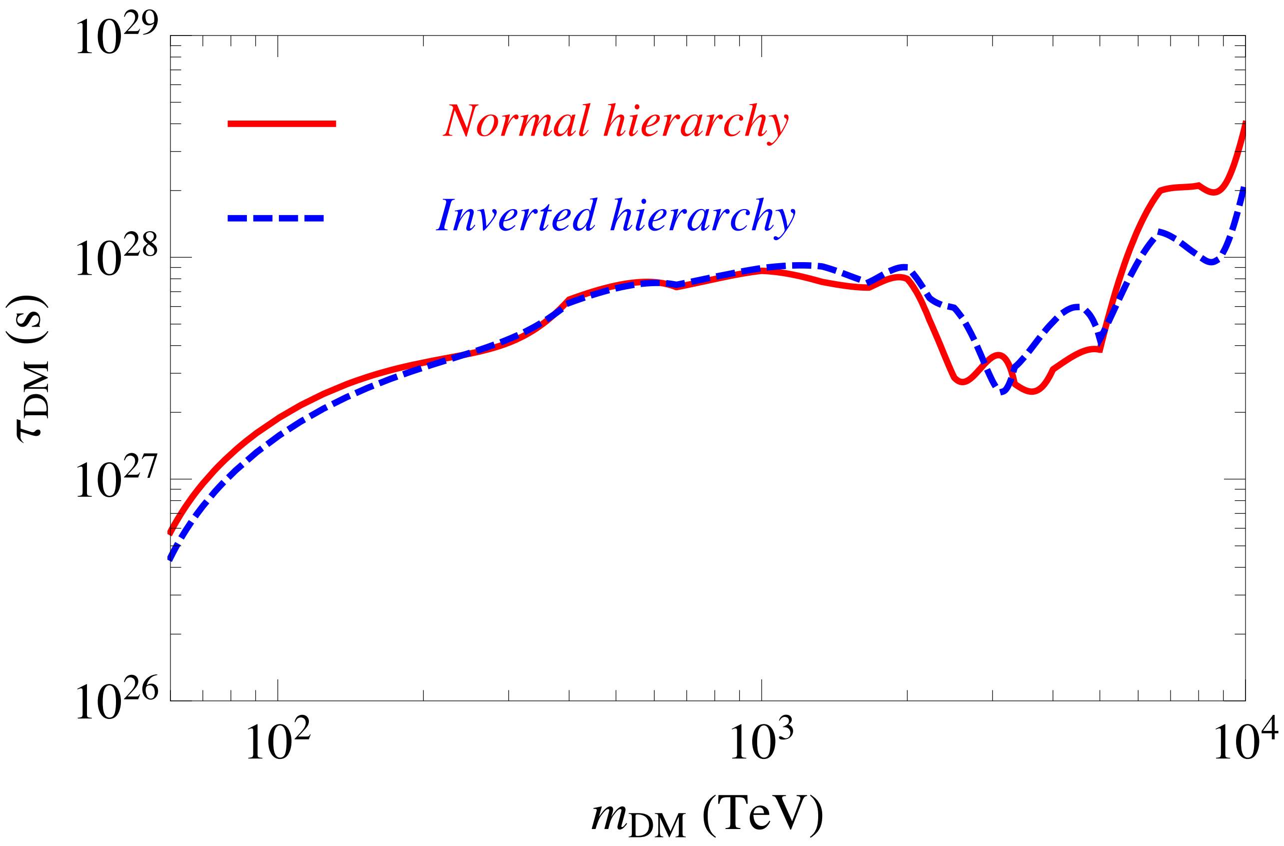
✓ at least one order of magnitude stronger lower limit on the DM lifetime, in the relevant DM mass range

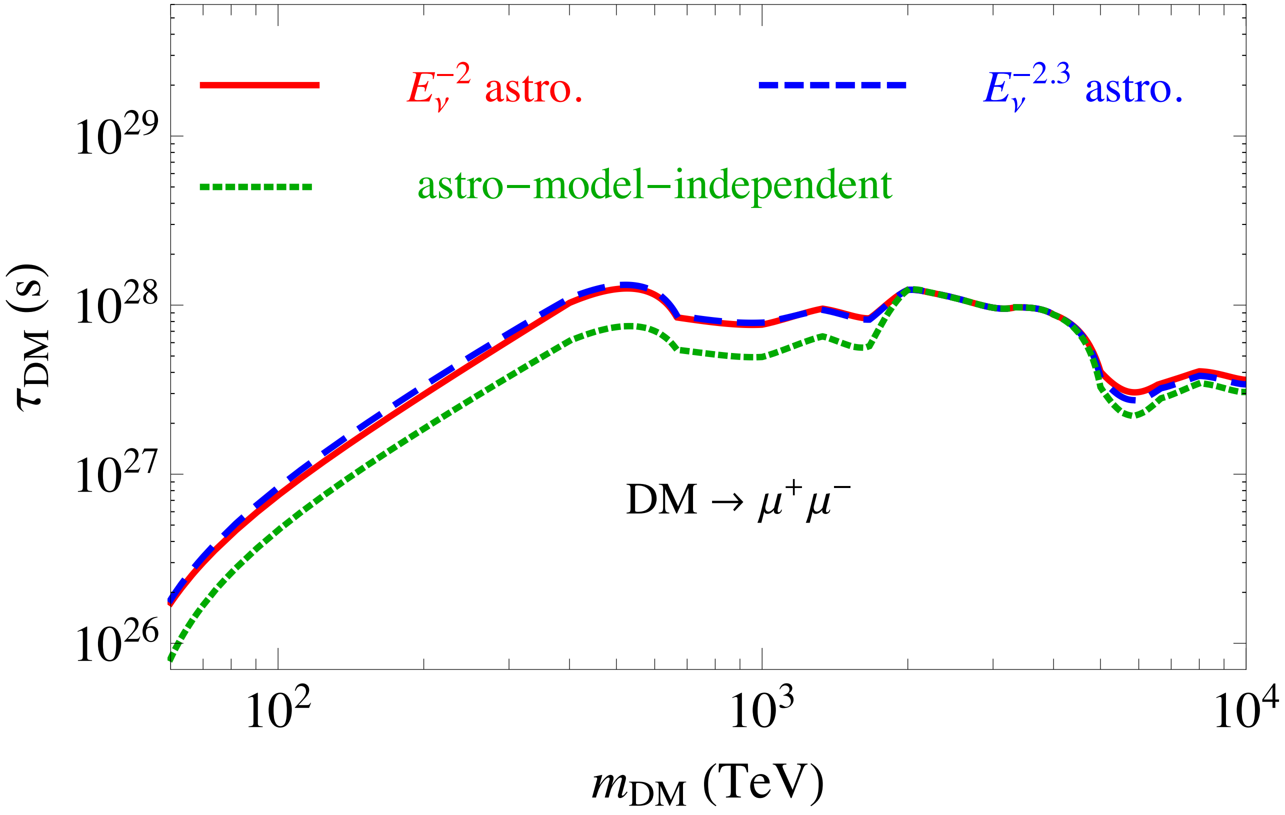
✓ for a specific model, different channels should be scaled according to the corresponding branching ratios

Constraining DM properties

✓ limits on DM lifetime (90% C.L.)

NH and IH cases





dependence on the astro. model?

Constraining DM properties

✓ Annihilation cross section

The lower part (< 100 TeV) of the observed spectrum can be used to probe <σv>

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The isotropic components of neutrino flux from DM annihilation:

The residual isotropic flux from the Galactic halo (anti-GC direction)

$$\frac{\mathrm{d}J_{\mathrm{iso}}^{\mathrm{ann}}}{\mathrm{d}E_\nu} = \frac{\langle\sigma v\rangle}{2}\frac{1}{4\pi m_{\mathrm{DM}}^2}\frac{\mathrm{d}N}{\mathrm{d}E_\nu}(\mathrm{l.o.s.})_{\mathrm{anti-GC}} \text{ where } (\mathrm{l.o.s.})_{\mathrm{anti-GC}} = \int_0^\infty \rho^2[r(s, b=0, l=\pi)]\ \mathrm{d}s$$

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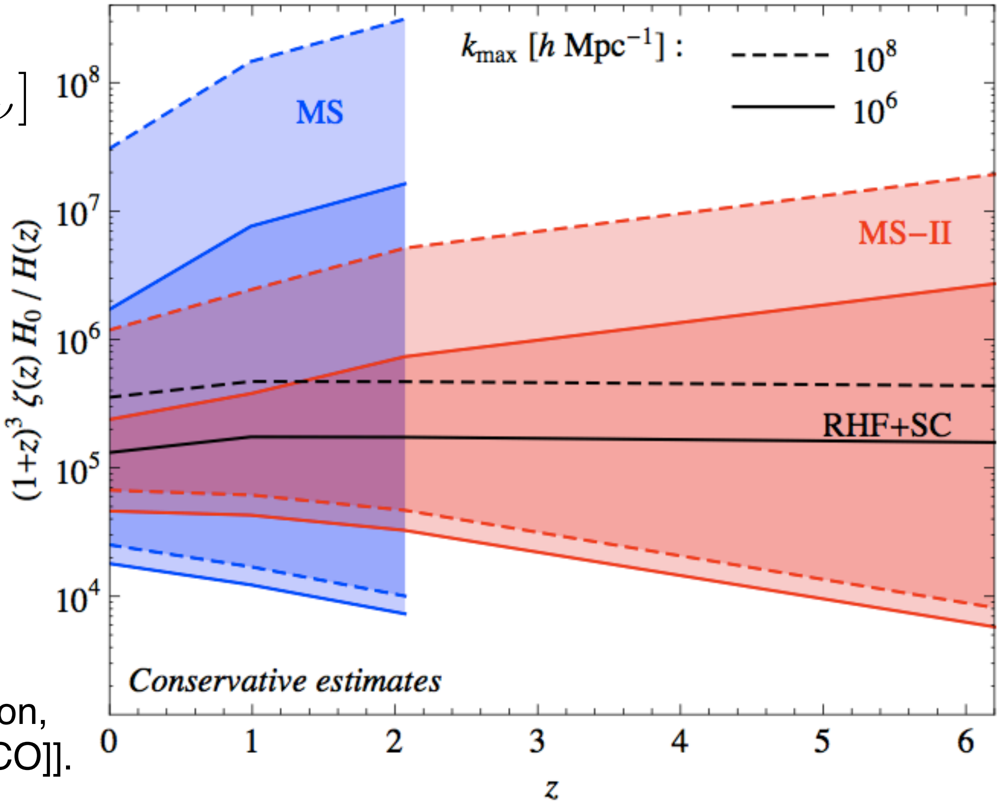
The cosmic flux from all redshift

$$\frac{\mathrm{d}J_{\mathrm{cos}}^{\mathrm{ann}}}{\mathrm{d}E_\nu} = \frac{\langle\sigma v\rangle}{2}\frac{\Omega_{\mathrm{DM}}^2\rho_c^2}{4\pi m_{\mathrm{DM}}^2}\frac{c}{H_0}\int_0^\infty \frac{(1+z)^3\zeta(z)\mathrm{d}z}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}\frac{\mathrm{d}N}{\mathrm{d}E_\nu}[(1+z)\,E_\nu]$$

$\zeta(z)$ flux multiplier (DM clustering)



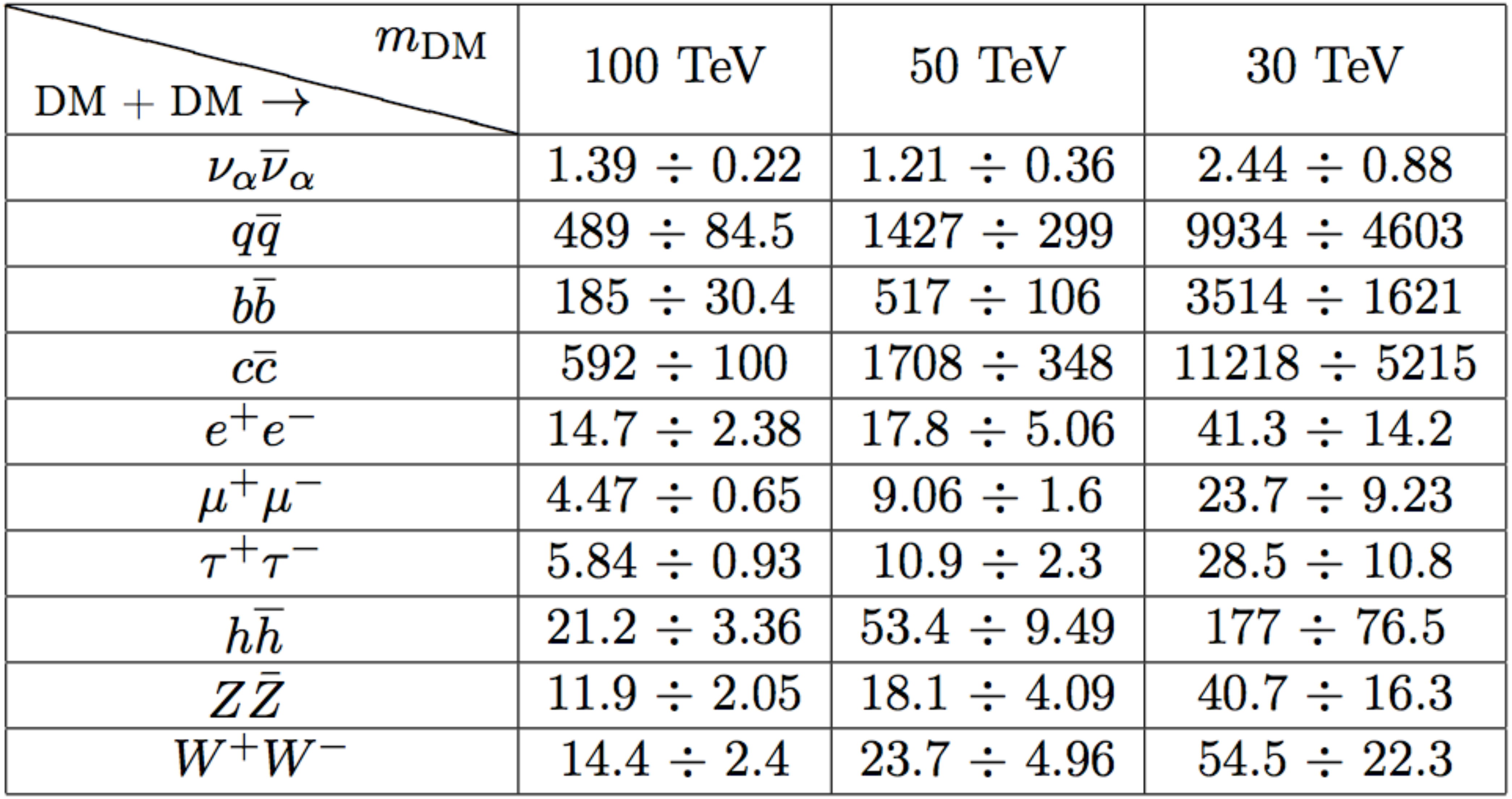
E. Sefusatti, G. Zaharijas, P. D. Serpico, D. Theurel and M. Gustafsson, Mon. Not. Roy. Astron. Soc. 441, (2014) [arXiv:1401.2117 [astro-ph.CO]].

Constraining DM properties

✓ upper limits on annihilation cross section <σv> (90% C.L.)

minimum ÷ maximum value used for ζ(z)

unit of <σv> is 10^{-22} cm^3s^{-1}



$m_{\rm DM}$ DM + DM $\rightarrow$	100 TeV	50 TeV	30 TeV
$\nu_\alpha\bar{\nu}_\alpha$	$1.39 \div 0.22$	$1.21 \div 0.36$	$2.44 \div 0.88$
$q\bar{q}$	$489 \div 84.5$	$1427 \div 299$	$9934 \div 4603$
$b\bar{b}$	$185 \div 30.4$	$517 \div 106$	$3514 \div 1621$
$c\bar{c}$	$592 \div 100$	$1708 \div 348$	$11218 \div 5215$
e^+e^-	$14.7 \div 2.38$	$17.8 \div 5.06$	$41.3 \div 14.2$
$\mu^+\mu^-$	$4.47 \div 0.65$	$9.06 \div 1.6$	$23.7 \div 9.23$
$\tau^+\tau^-$	$5.84 \div 0.93$	$10.9 \div 2.3$	$28.5 \div 10.8$
$h\bar{h}$	$21.2 \div 3.36$	$53.4 \div 9.49$	$177 \div 76.5$
$Z\bar{Z}$	$11.9 \div 2.05$	$18.1 \div 4.09$	$40.7 \div 16.3$
W^+W^-	$14.4 \div 2.4$	$23.7 \div 4.96$	$54.5 \div 22.3$

✓ for some final states (neutrinos, charged leptons) the limit is a bit stronger than the unitary bound

conclusions

- ✓ The excess of events observed by IceCube in the energy range ~ 30 TeV - 2 PeV is an evidence for astrophysical flux or other “New Physics” induced fluxes

---

- ✓ Several features of the observed events motivate us for a DM interpretation: cut-off at ~ 2 PeV, dip in (400 - 1000) TeV and anisotropy.

- ✓ We argued that a PeV-scale decaying DM, with generic decay channels, can naturally explain these features. The required lifetime is allowed by the current limits. Both the energy and angular distributions mildly prefer DM interpretation.

- ✓ With more statistics in the next few years, the DM interpretation of IceCube events can be tested: especially the angular distribution can resolve the issue. The persistence of the dip feature in ~ (400 - 1000) TeV also can be supportive.

Thank you !

Decaying Dark Matter

$$\Phi = kE_\nu^{-2}$$

	k	E^{min}-E^{max} (TeV)	N_{bg}	N_{sig}	N_{limit}
AMANDA	7.4×10^{-8}	$16 - 2.5\times10^3$	6	7	5.4
IceCube-22	1.6×10^{-7}	$340 - 2\times10^5$	0.6	3	6.1
IceCube-40	3.6×10^{-8}	$2\times10^3 - 6.3\times10^6$	0.1	0	2.3
Auger	1.7×10^{-7}	$10^5 - 10^8$	0	0	2.3
ANITA	1.3×10^{-7}	$10^6 - 3.2\times10^{11}$	0.97	1	3.3

$$N_{\rm exp} = T\Delta\Omega \sum_\alpha \left[\int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} \Phi_{\nu_\alpha+\bar\nu_\alpha} A_{\rm eff}^\alpha(E_\nu) dE_\nu \right]$$

$$q/100 = \frac{\int_0^{N_{\rm limit}} L(N_{\rm sig}|N)dN}{\int_0^\infty L(N_{\rm sig}|N)dN} \quad \textbf{where} \quad L(N_{\rm sig}|N) = \frac{(N+N_{\rm bg})^{N_{\rm sig}}}{N_{\rm sig}!} e^{-(N+N_{\rm bg})}$$

Decaying Dark Matter

✓ extragalactic contribution:

$$H(z) = H_0 \sqrt{\Omega_\Lambda + \Omega_{\rm m}(1+z)^3}$$

$$\frac{{\rm d}J_{\rm eg}}{{\rm d}E_\nu} = \frac{\Omega_{\rm DM}\rho_{\rm c}}{4\pi m_{\rm DM}\tau_{\rm DM}} \int_0^\infty {\rm d}z \, \frac{1}{H(z)} \, \frac{{\rm d}N_\nu}{{\rm d}E_\nu} \left[(1+z)E_\nu\right] e^{-s_\nu(E_\nu, z)}$$

Opacity

$$s_\nu(E_\nu, z) = \begin{cases} 7.4 \times 10^{-17}(1+z)^{7/2}(E_\nu/\,{\rm TeV}), & \text{for } 1 \ll z < z_{\rm eq} \\ 1.7 \times 10^{-14}(1+z)^{3}(E_\nu/\,{\rm TeV}), & \text{for } z \gg z_{\rm eq} \end{cases}$$

at the Earth

$$\begin{pmatrix} J_e \\ J_\mu \\ J_\tau \end{pmatrix} = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ & P_{\mu\mu} & P_{\mu\tau} \\ & & P_{\tau\tau} \end{pmatrix} \begin{pmatrix} I_e \\ I_\mu \\ I_\tau \end{pmatrix}$$

production point

decoherent oscillation

Event 8 (Track)