XXIV Workshop on Weak Interactions and Neutrinos

WIN 2013

Sep. 16 to 21, 2013 Natal, Brazil

Are IceCube neutrinos unveiling PeV-scale decaying dark matter?

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(UNICAMP - IFGW/DRCC - Brazil)

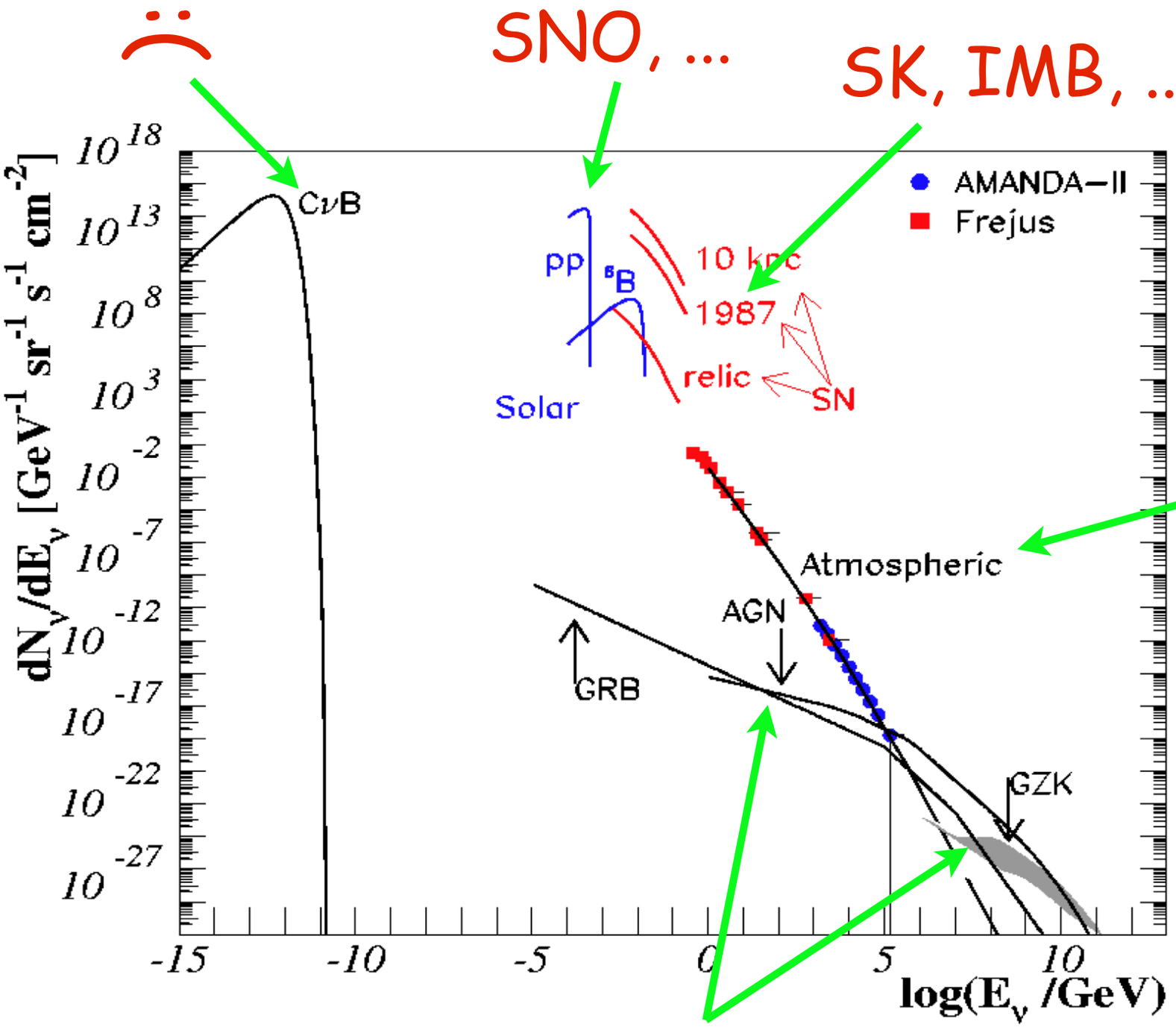
In collaboration with Pasquale Dario Serpico

19/Sep/2013

UNICAMP

FAPESP

Neutrino Sky



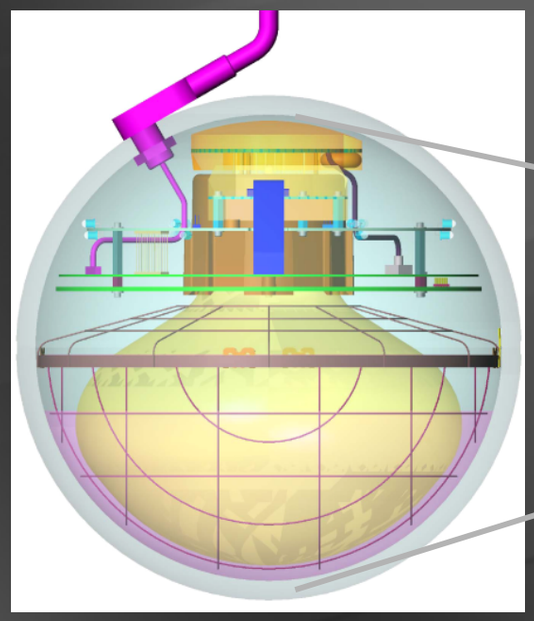
SK, AMANDA, IceCube...

Background for astrophysical neutrinos

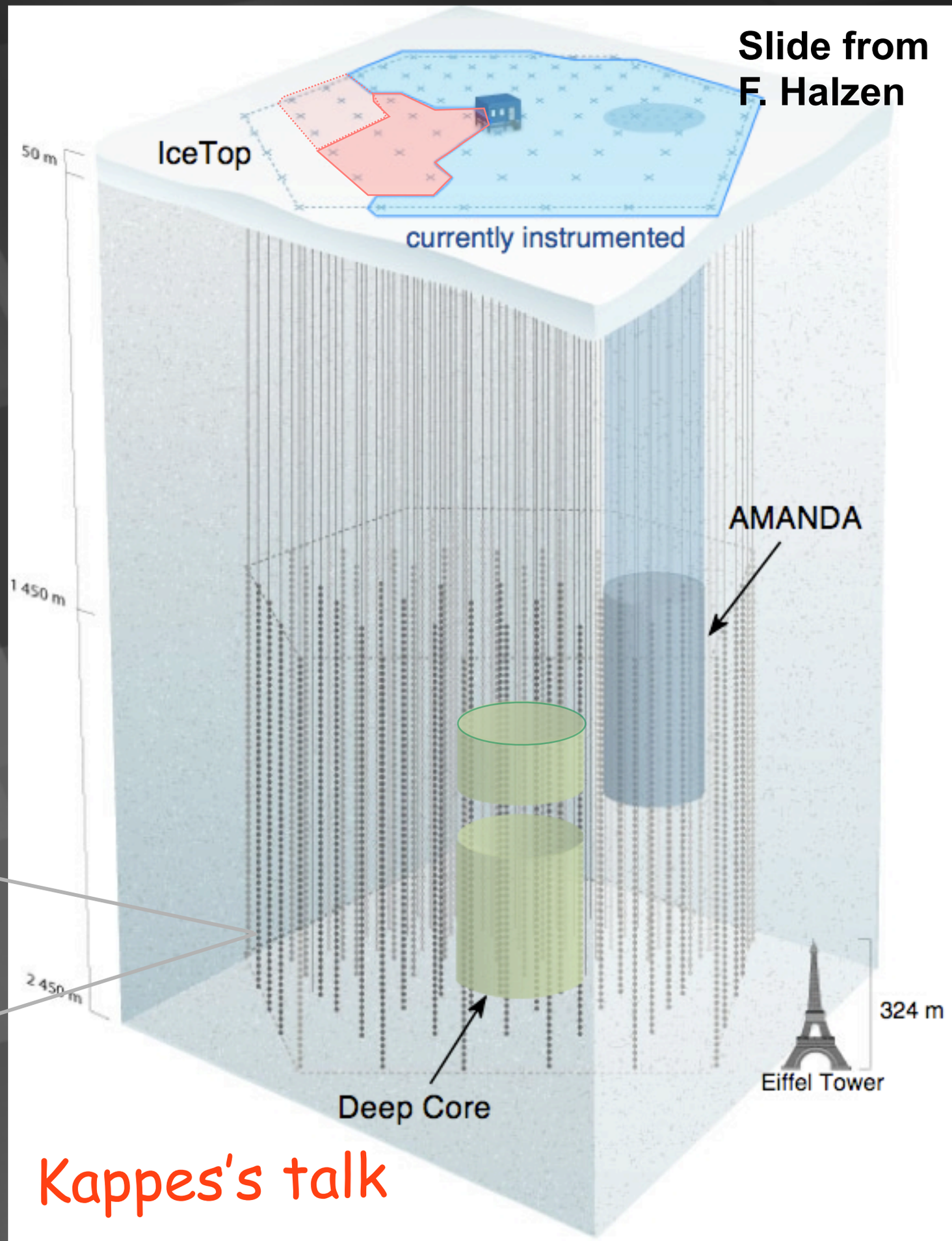
IceCube ?

IceCube / Deep Core

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



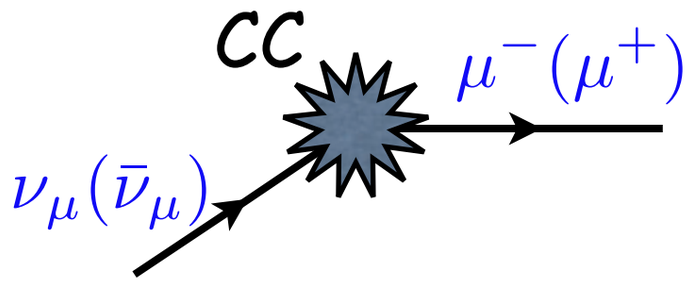
Digital Optical Module (DOM)

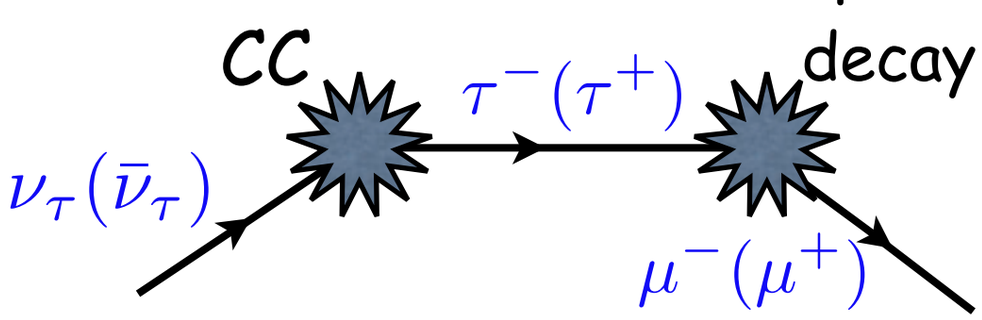


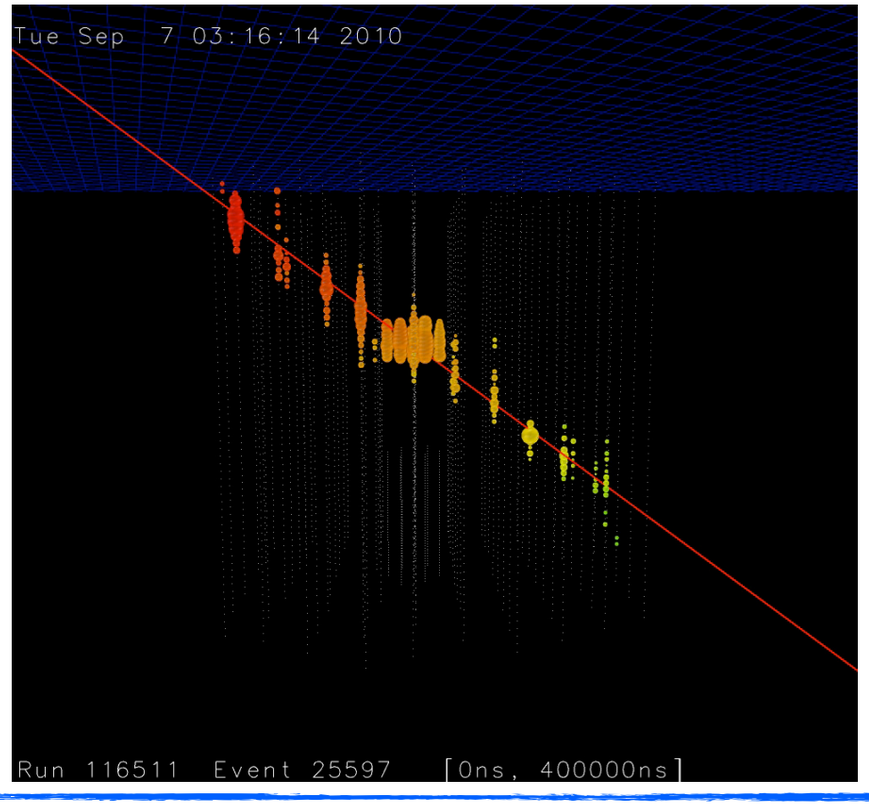
Kappes's talk

Flavoring at IceCube

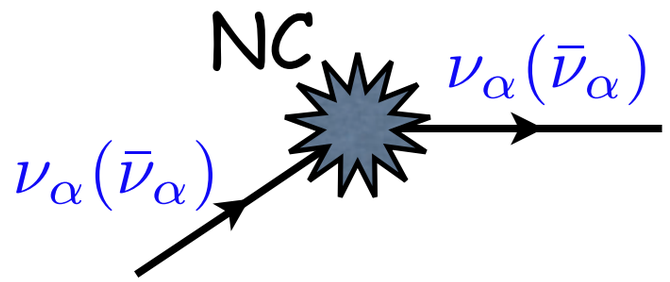
muon-track events

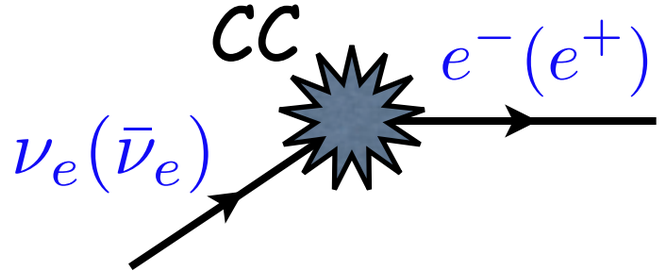


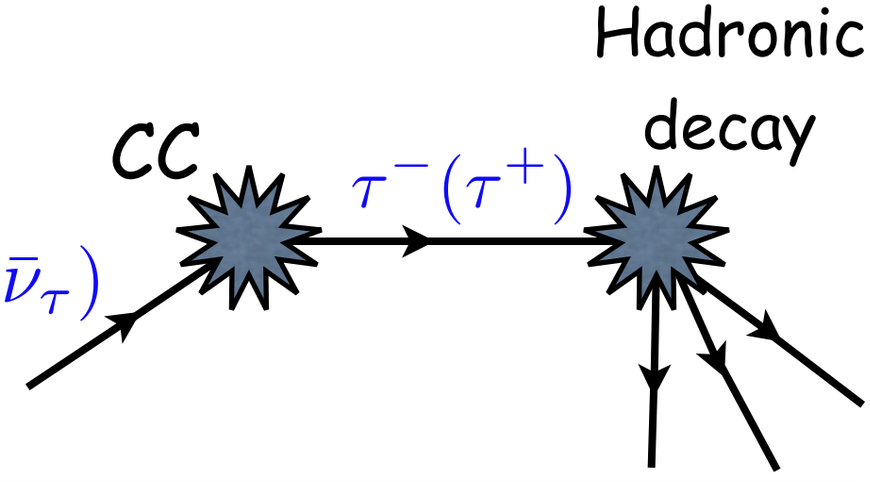


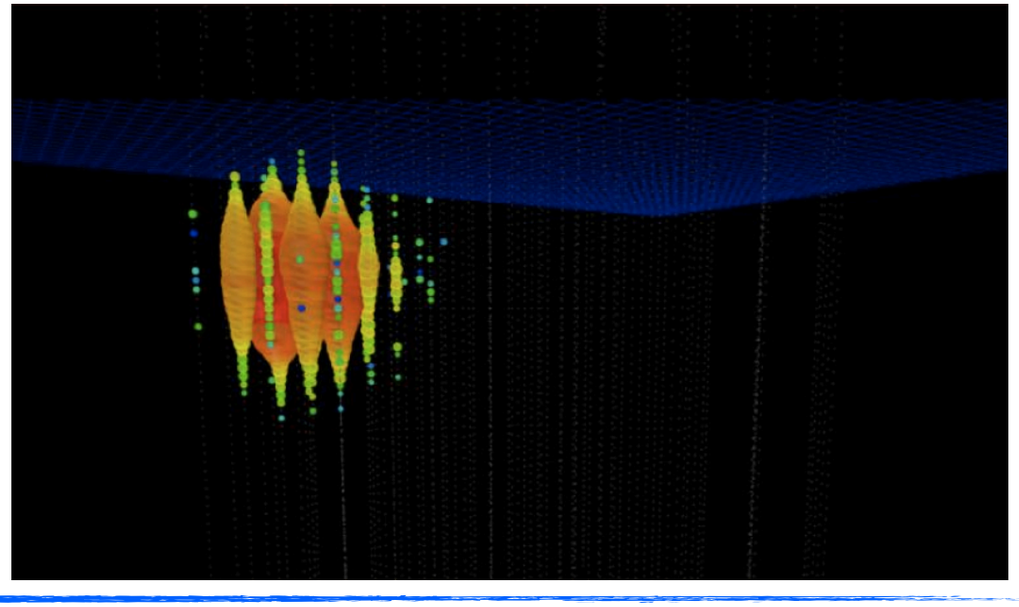


cascade events









Kappes's talk

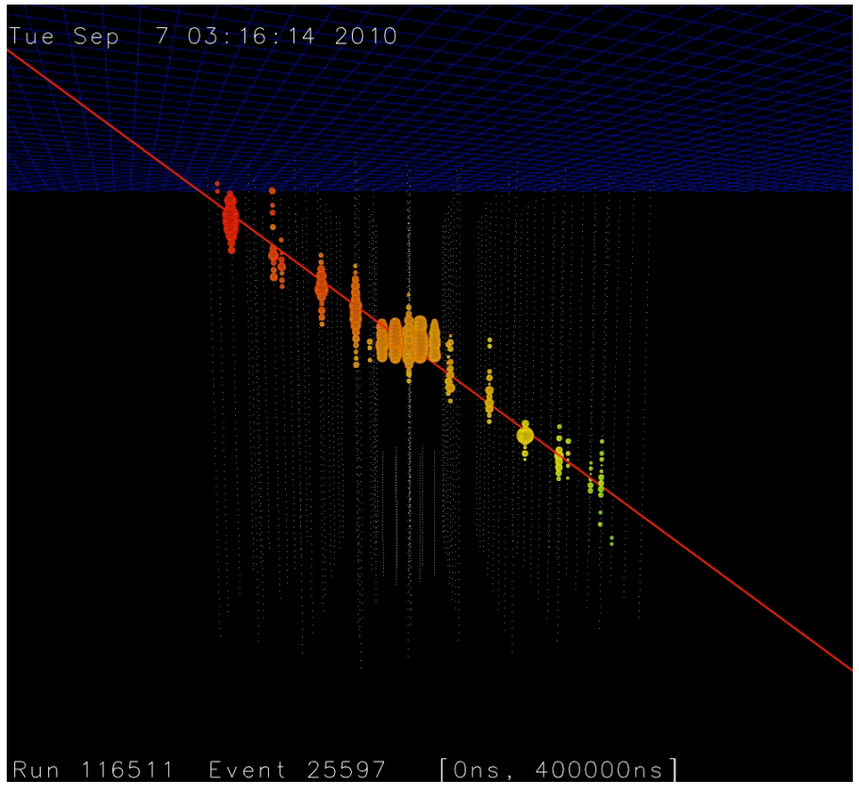
figures from IceCube website

Flavoring at IceCube

muon-track events

great angular resolution (< 1°)

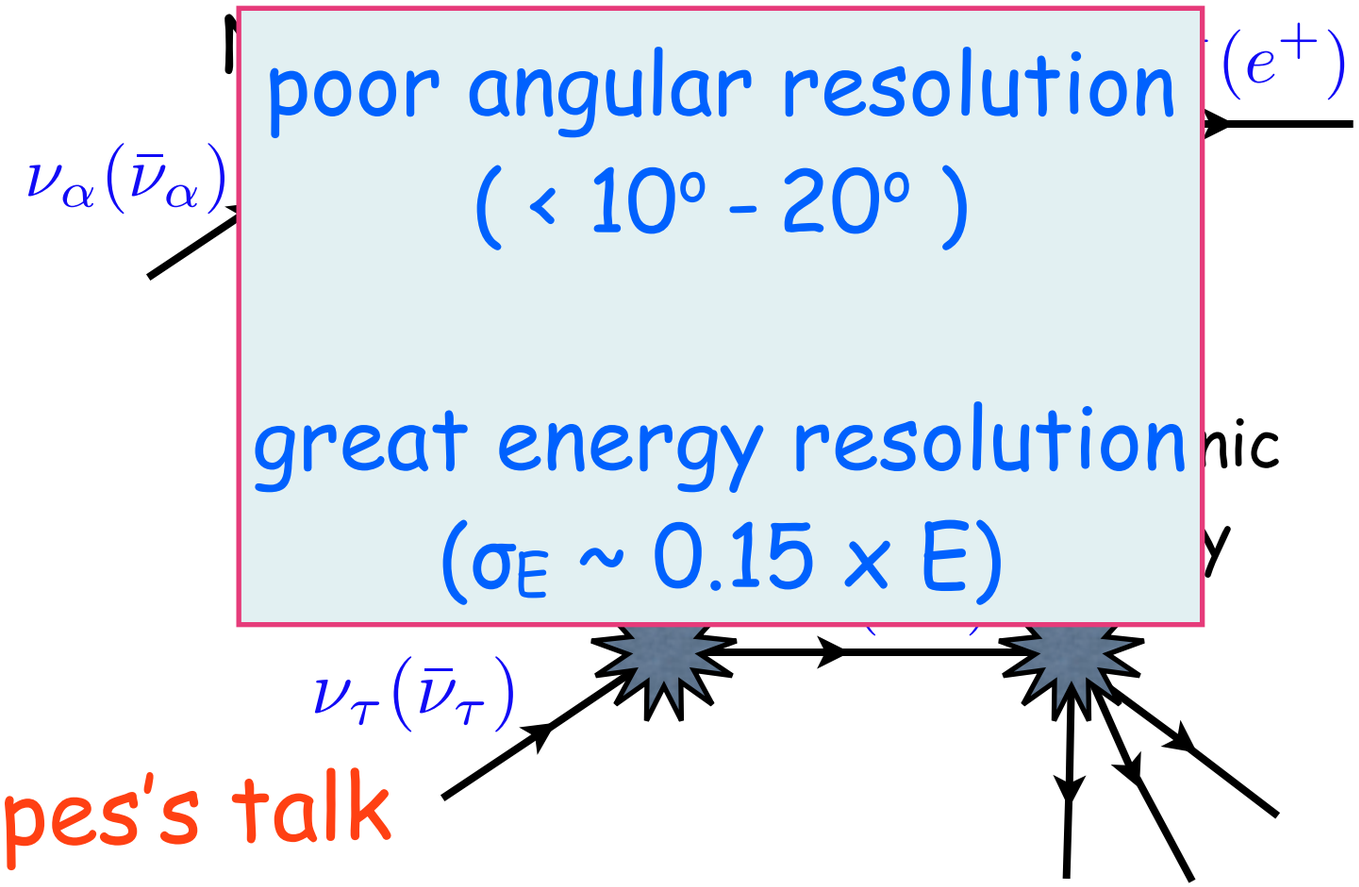
moderate energy resolution ($\sigma_E \sim E$)



cascade events

poor angular resolution (< 10° - 20°)

great energy resolution ($\sigma_E \sim 0.15 \times E$)



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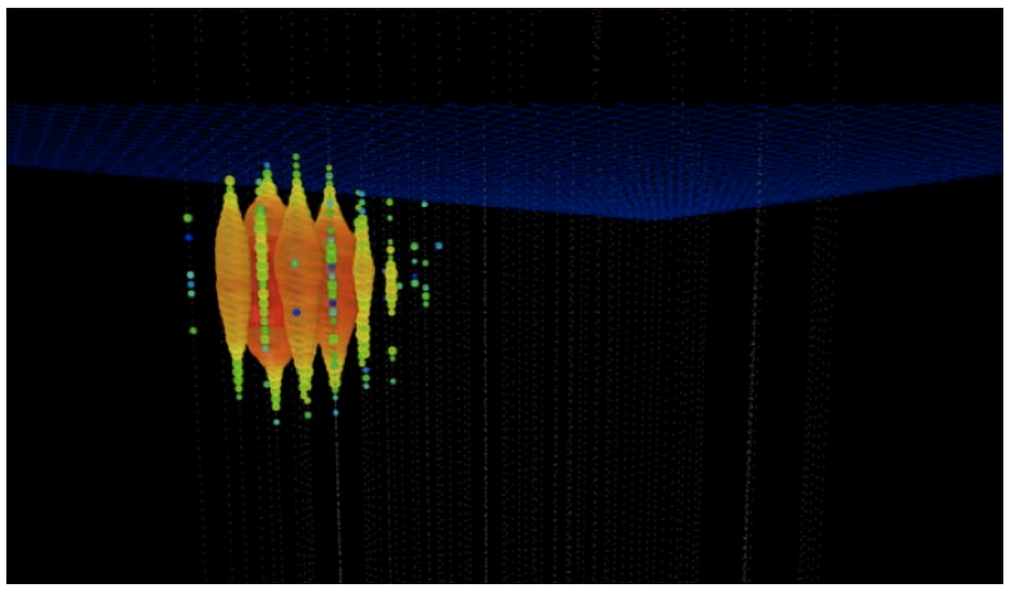
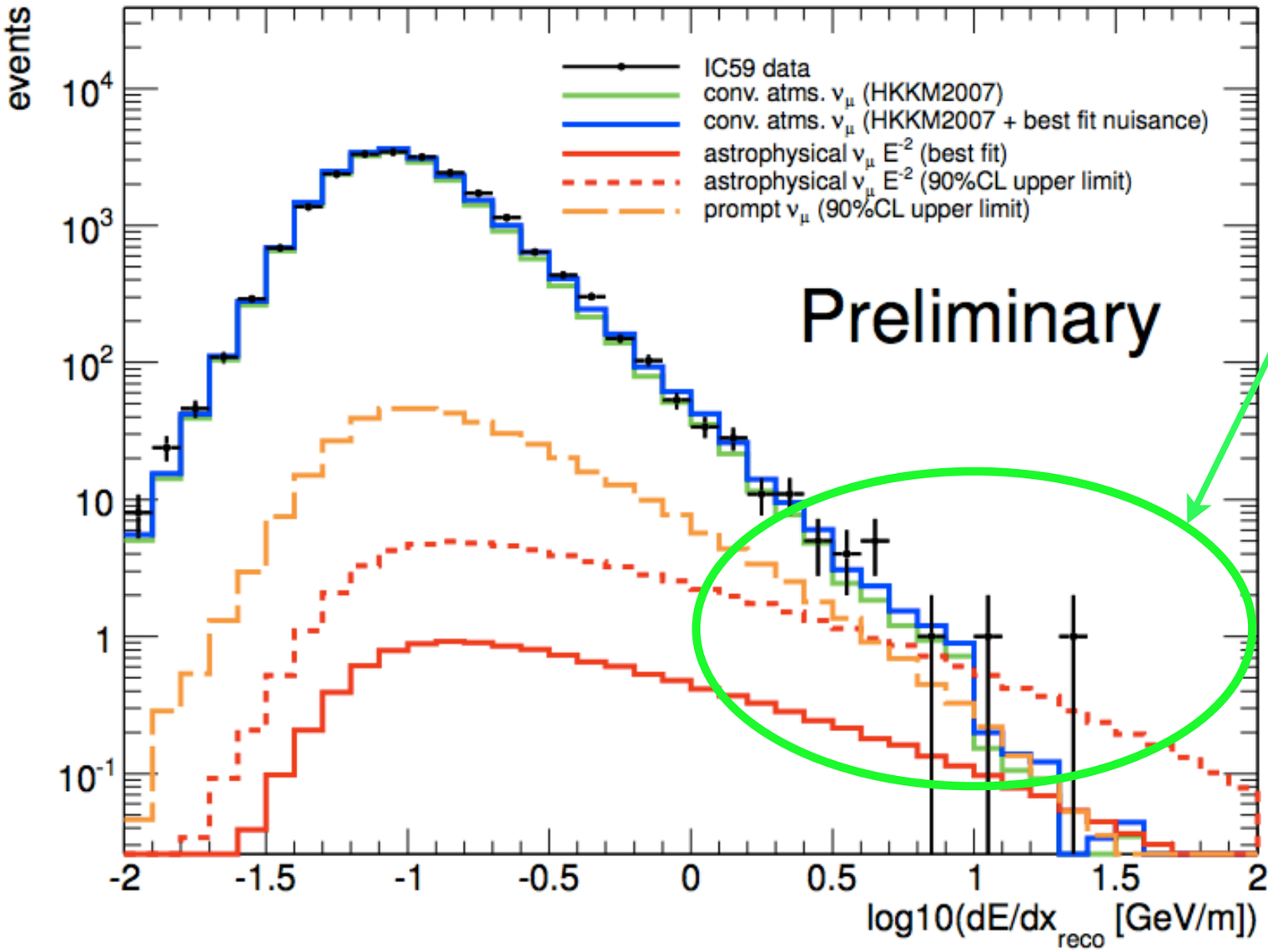


figures from IceCube website

Mission for IceCube began !

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



A. Schukraft [IceCube Collaboration], Nucl. Phys. Proc. Suppl. 266 (2013) [arXiv:1302.0127 [astro-ph.HE]]

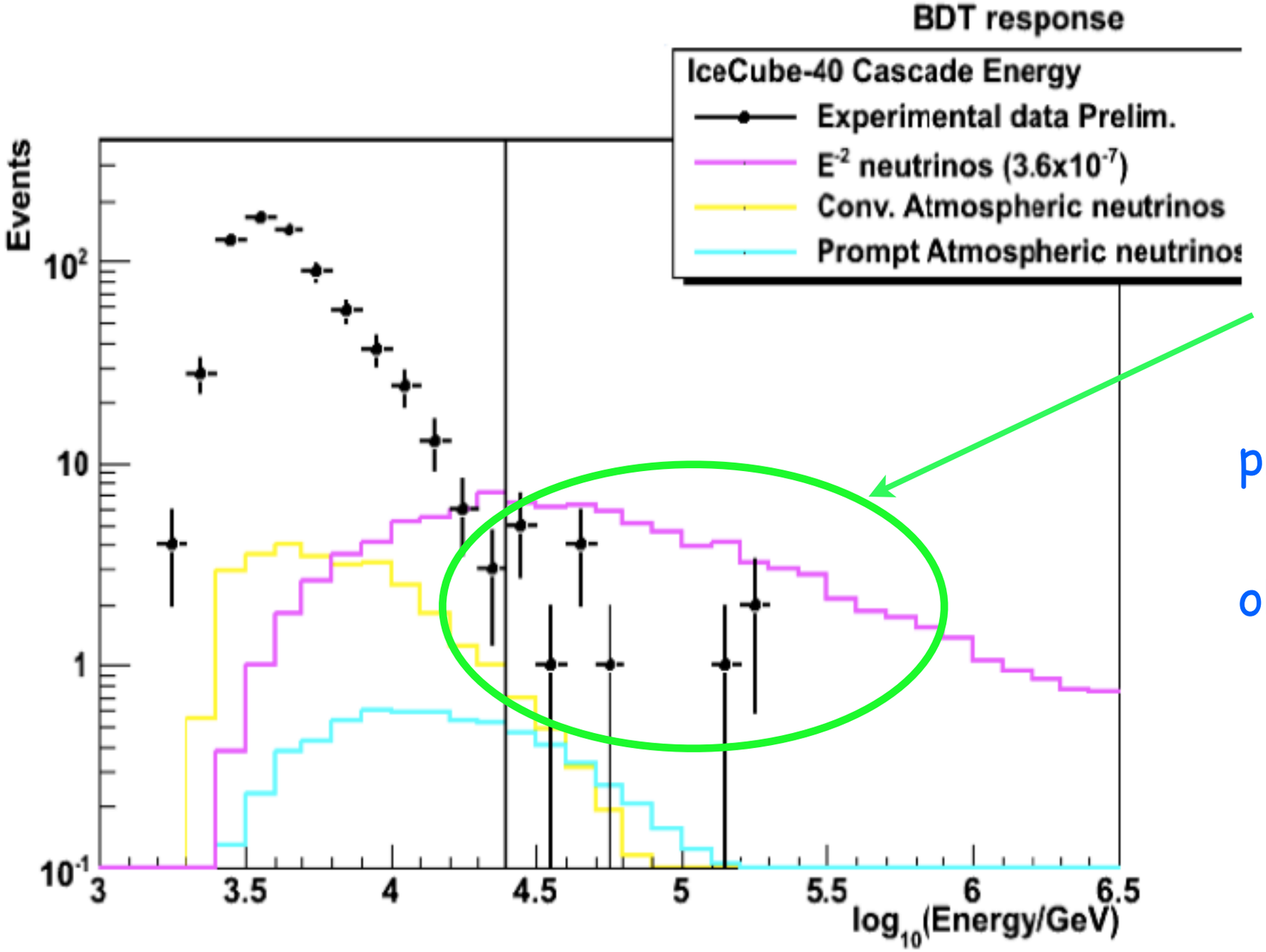
excess in high energy tail (~ 300 TeV)

prompt neutrinos ?
or
astrophysical neutrinos?

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

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

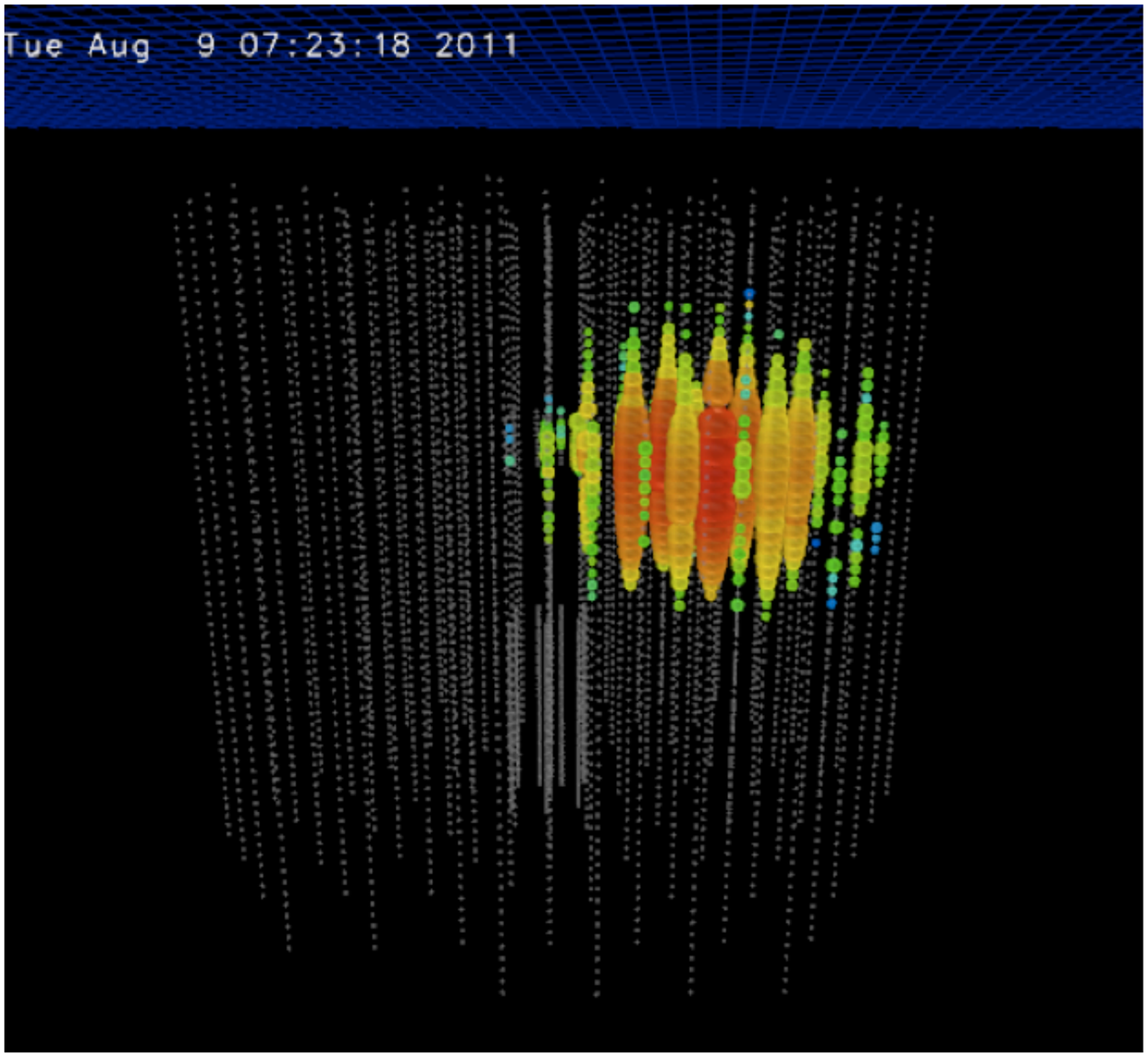
observed ~ 14

hint on astrophysical flux ~ 2.4σ

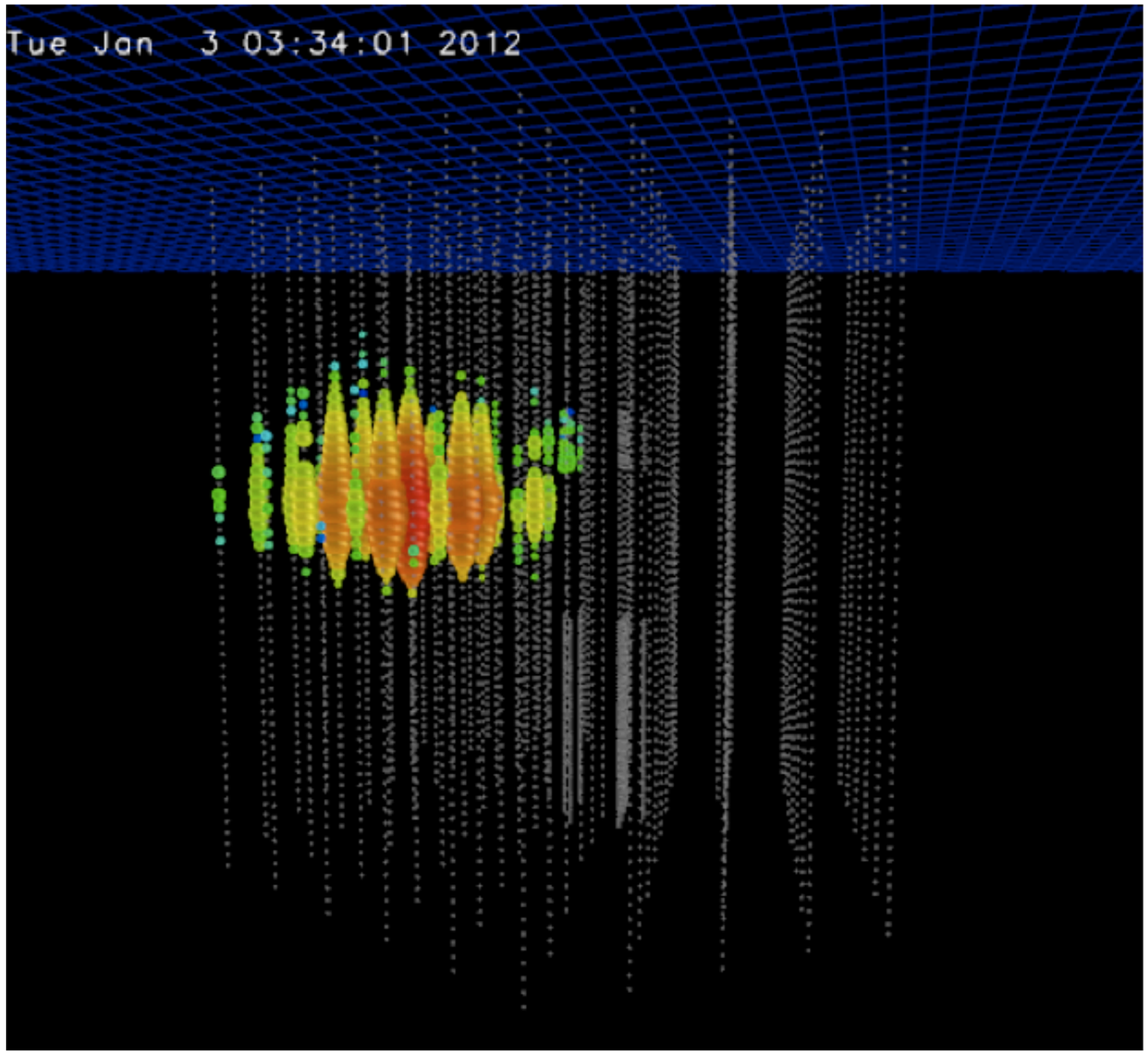
Mission for IceCube began !

✓ The two PeV cascade events, 616 days livetime

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



Bert
~ 1.05 PeV



Ernie
~ 1.15 PeV

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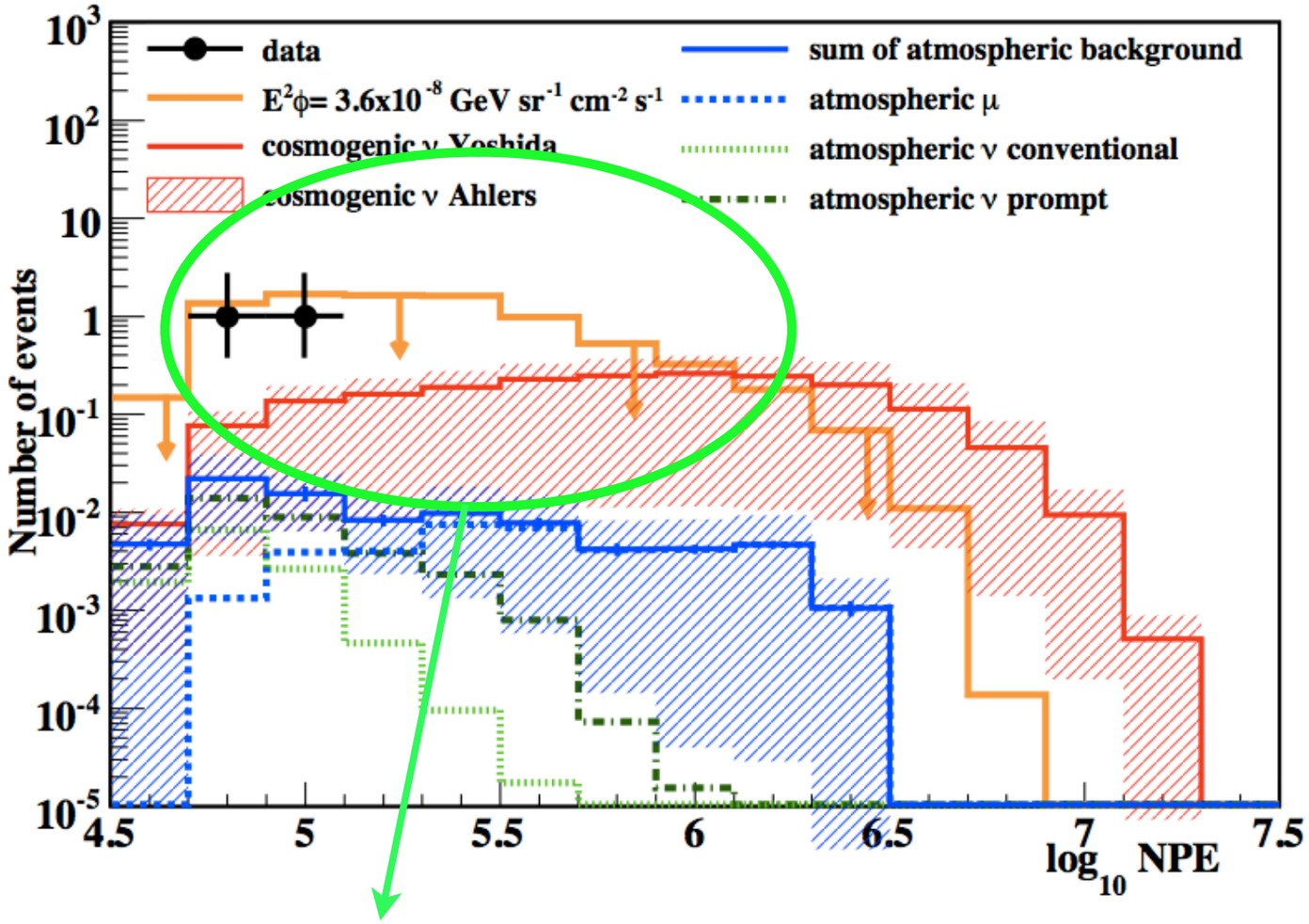


it is like a cut-off at ~ PeV

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

Roulet's talk

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

flavor composition ?
NC of υ_a or CC of υ_e

demands more statistics

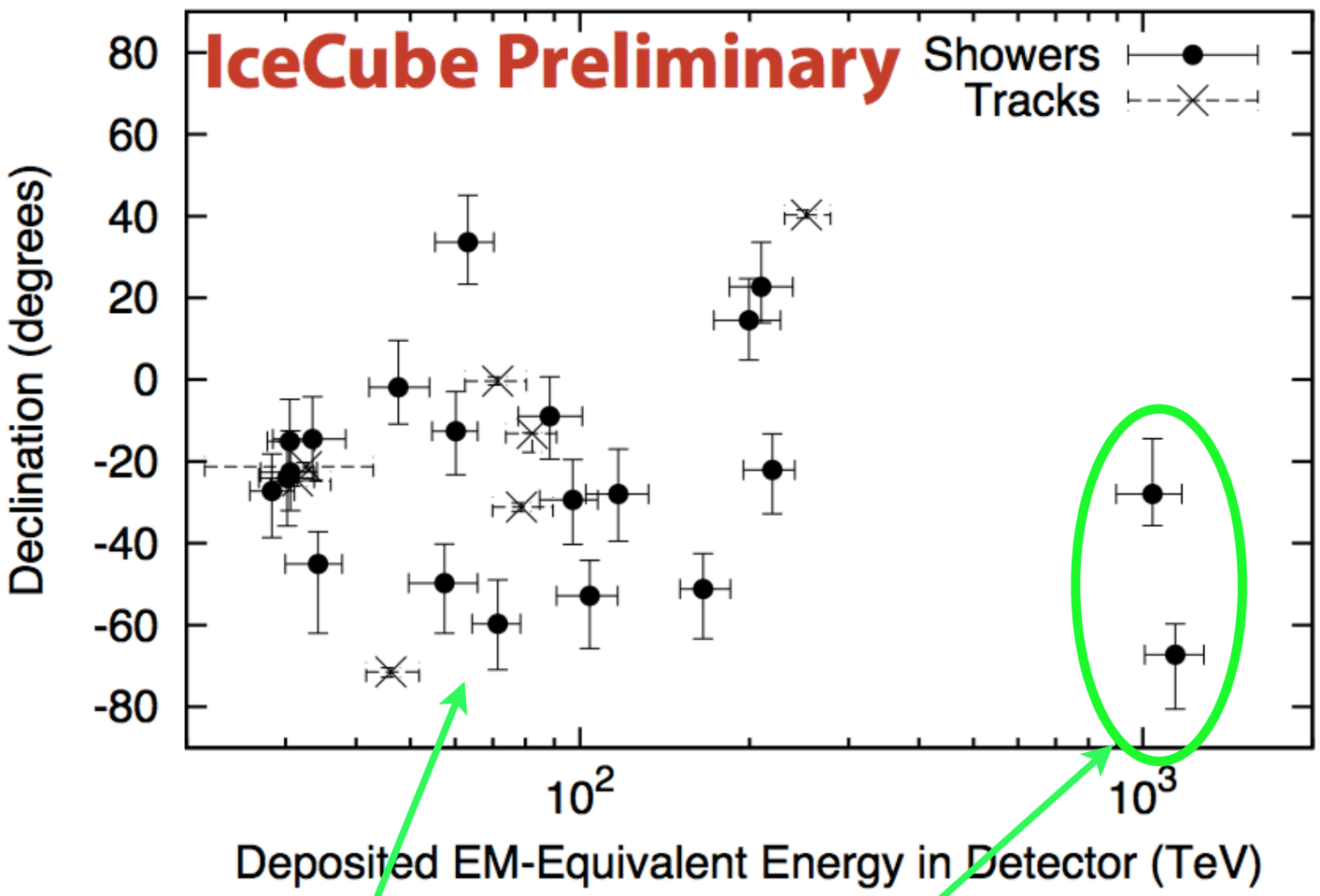
isotropy ?

Kappes's talk

Mission for IceCube began !

✓ Looking for lower energy contained events, 662 days livetime

figure from Whitehorn's talk



children of Bert and Ernie !

previous two PeV cascade events

✓ 26 more events

✓ all the new events are lower in energy

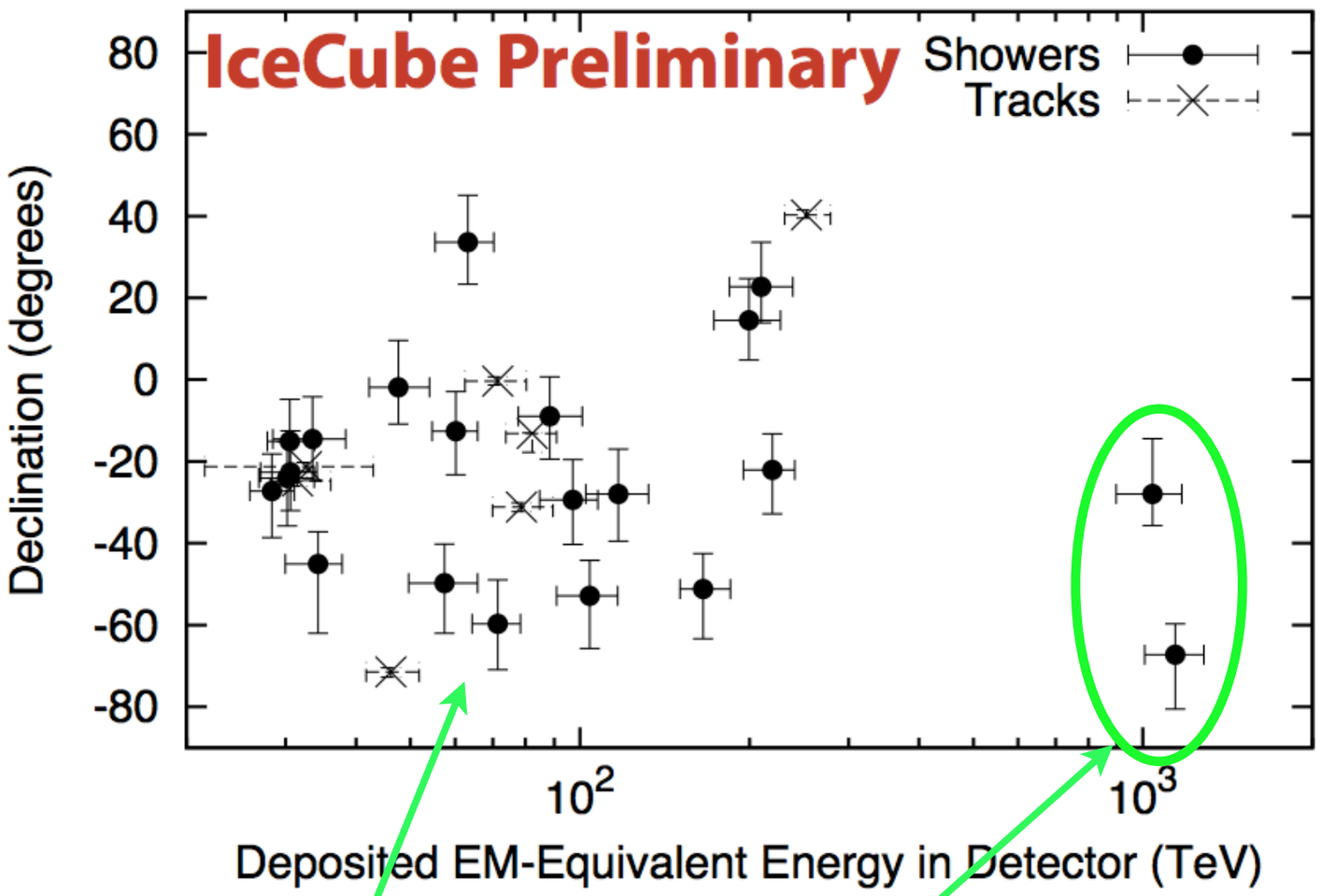
✓ expected bkg. (conventional+prompt) ~ 10.6(+4.5)(-3.5) sys.

excess of events ~ 4.3σ

Mission for IceCube began !

✓ Looking for lower energy contained events, 662 days livetime

figure from Whitehorn's talk



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children of Bert and Ernie !

previous two PeV cascade events

which one?

atmospheric ?

astrophysical ?

or something else ?

IceCube data

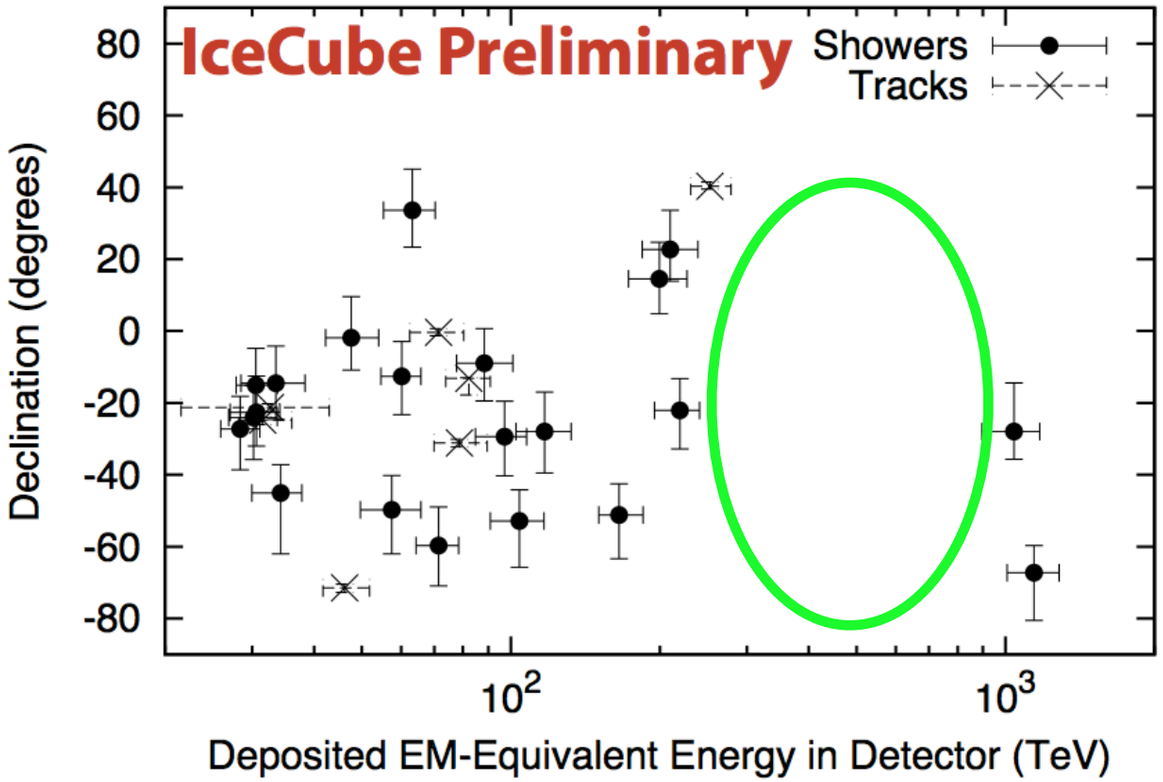
Problems with the astrophysical/atm interpretation of IceCube data

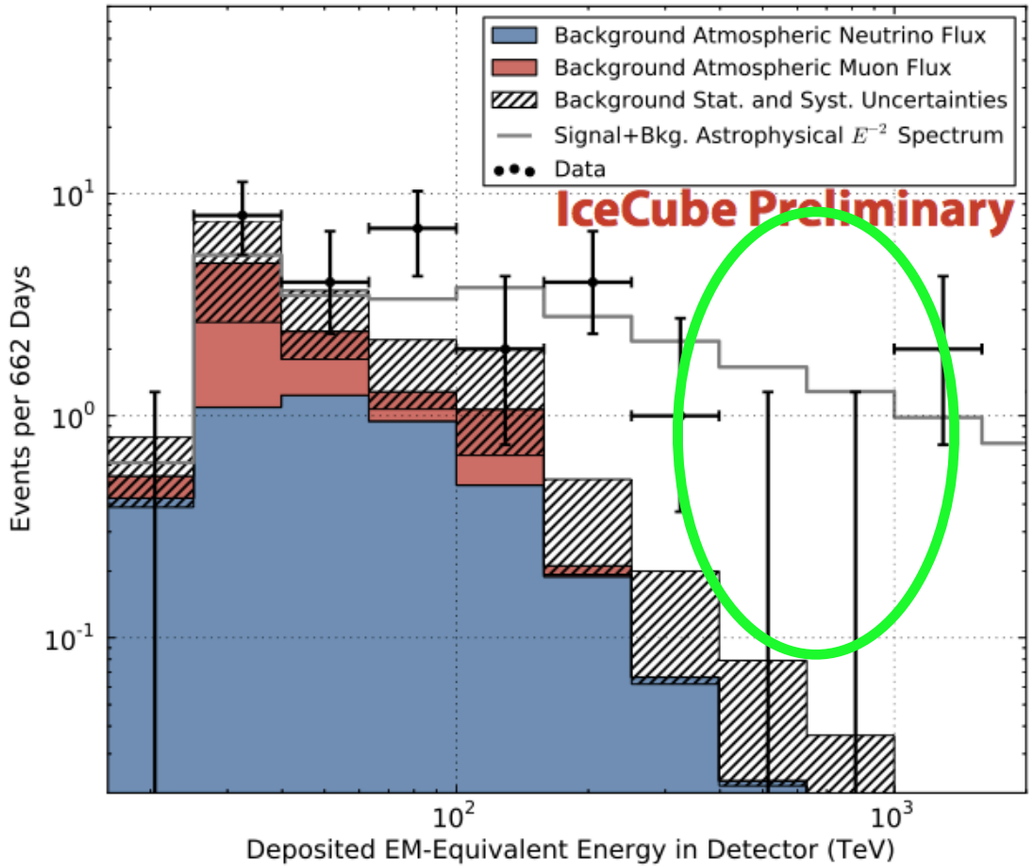
IceCube data

Problems with the astrophysical/atm interpretation of IceCube data

- ✓ deficit of events in the energy range ~ (300 - 1000) TeV
- ✓ cut-off in events: no events observed with energy > PeV

figures from Whitehorn's talk





IceCube data

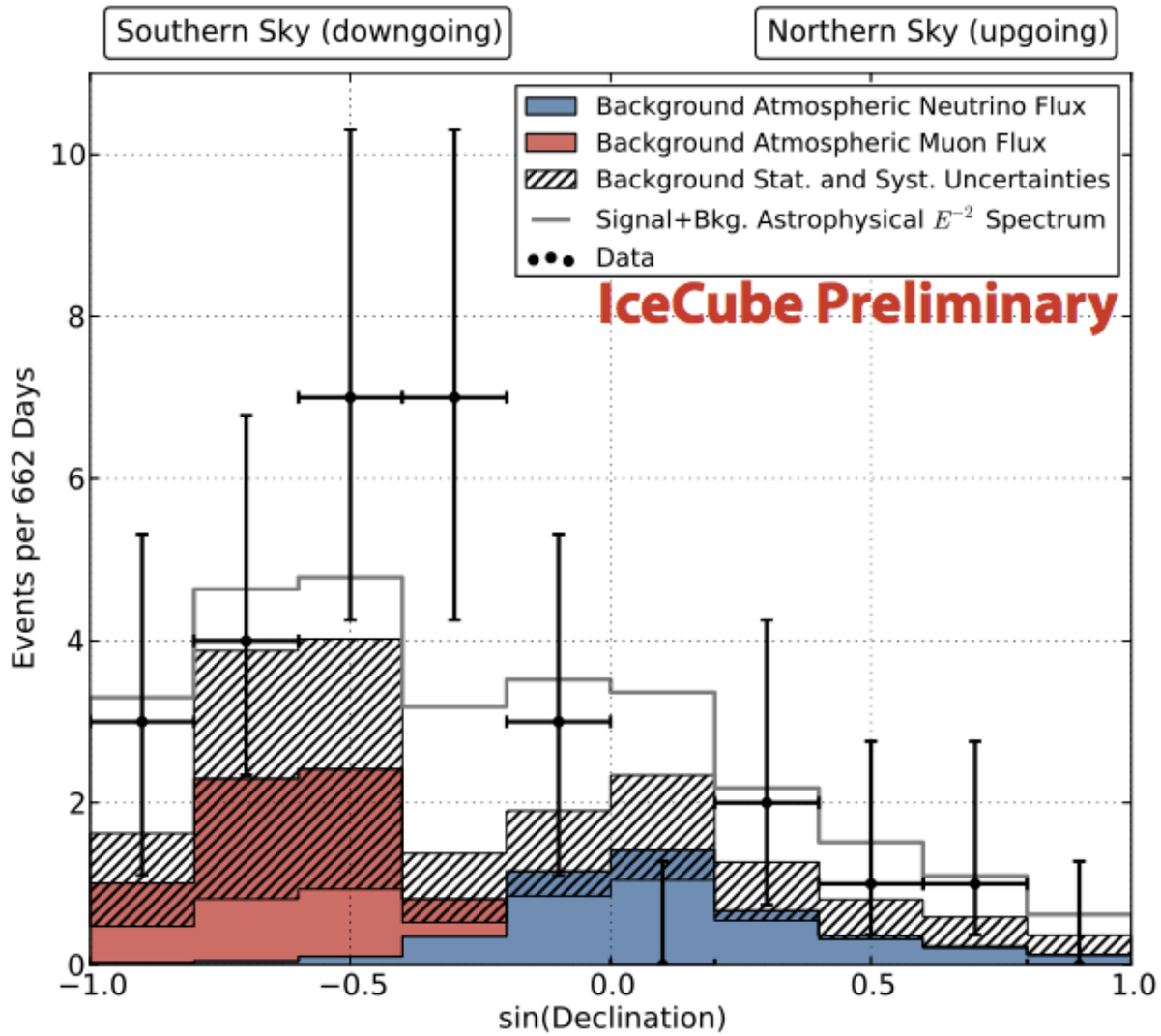
Problems with the astrophysical/atm interpretation of IceCube data

✓ zenith distribution of events

down-going/up-going events ~ 6
(Earth absorption for up-going events)

for an isotropic E^{-2} astrophysical spectrum ~ 1.8

P. Lipari, arXiv: 1308.2086



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✓ excess in the direction of Galactic Center

more statistics are needed to establish this excess

Galactic Center (sin δ ~ - 0.5)

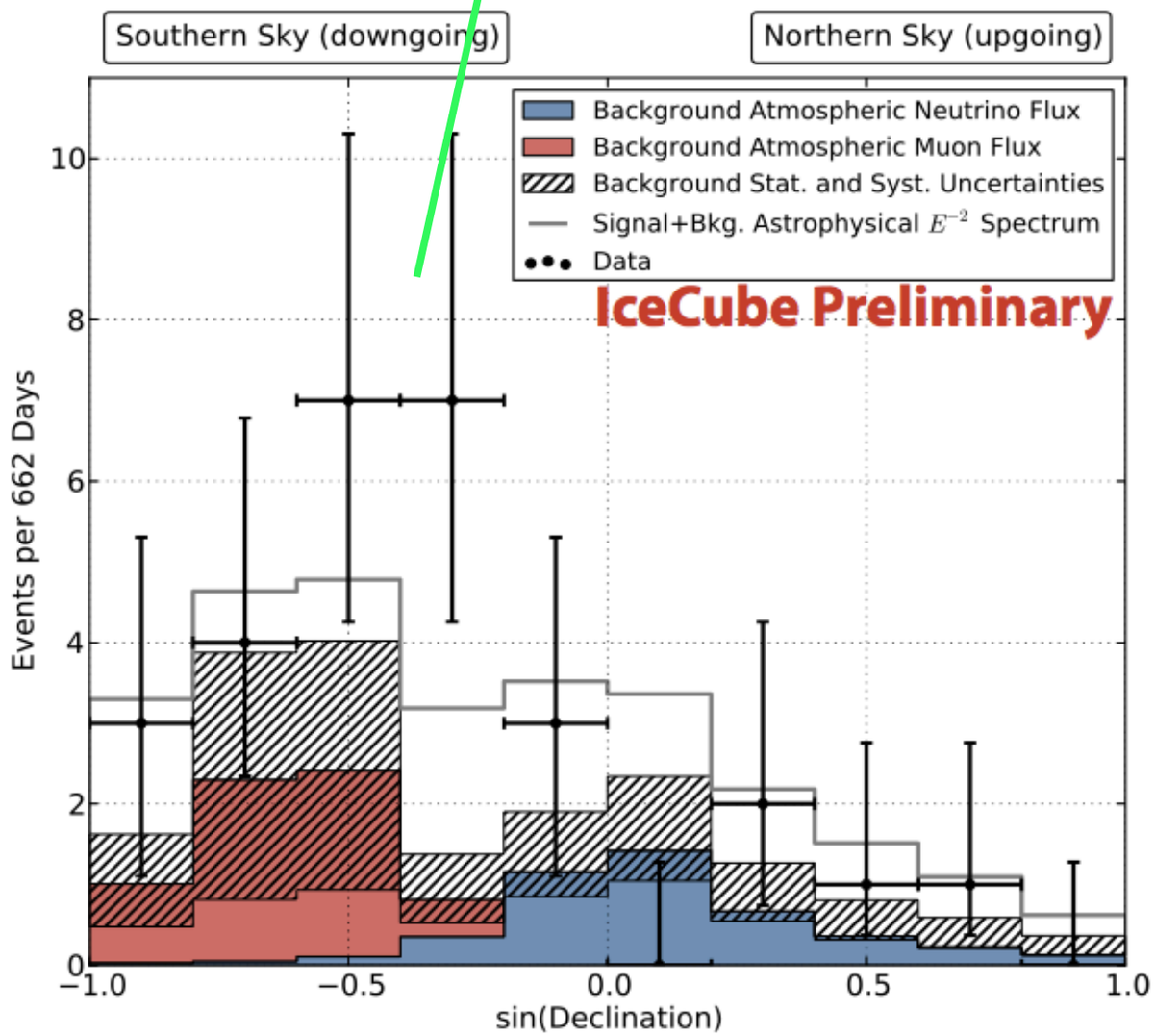

figure from Whitehorn's talk

IceCube data

"New Physics" interpretation of IceCube data

✓ "New Physics" interpretation of the two PeV cascades

enhancement of neutrino-quark scattering in "Leptoquark" scenario,
V. Barger and W. Keung, arXiv:1305.6907

"neutrino line" from decaying dark matter at PeV scale
B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, arXiv:1303.7320

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✓ "New Physics" interpretation of **all the IceCube data** (TeV-PeV)

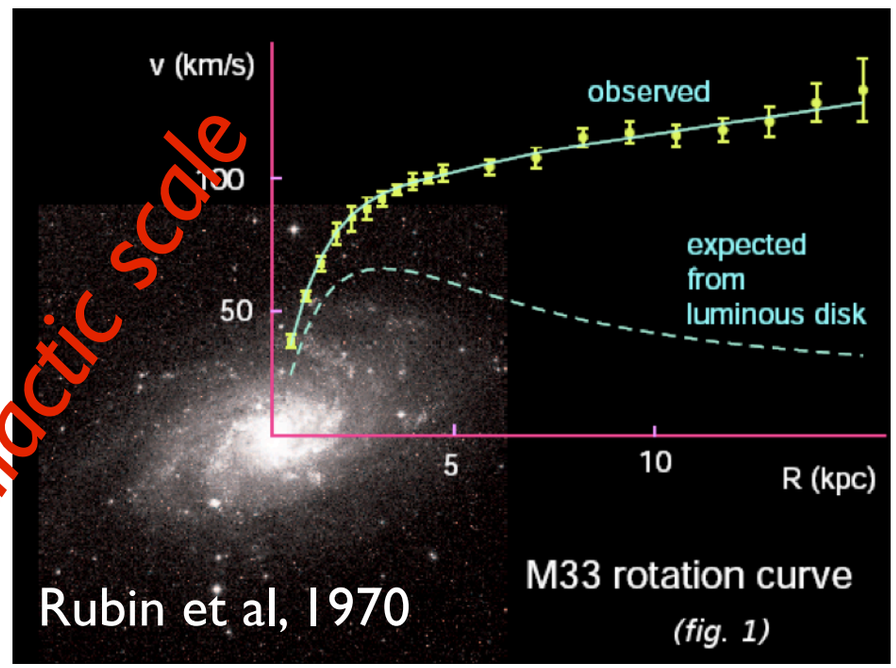
decaying dark matter (m_{DM} ~ PeV)
A. E., Pasquale D. Serpico, arXiv:1308.1105

A note on Dark Matter

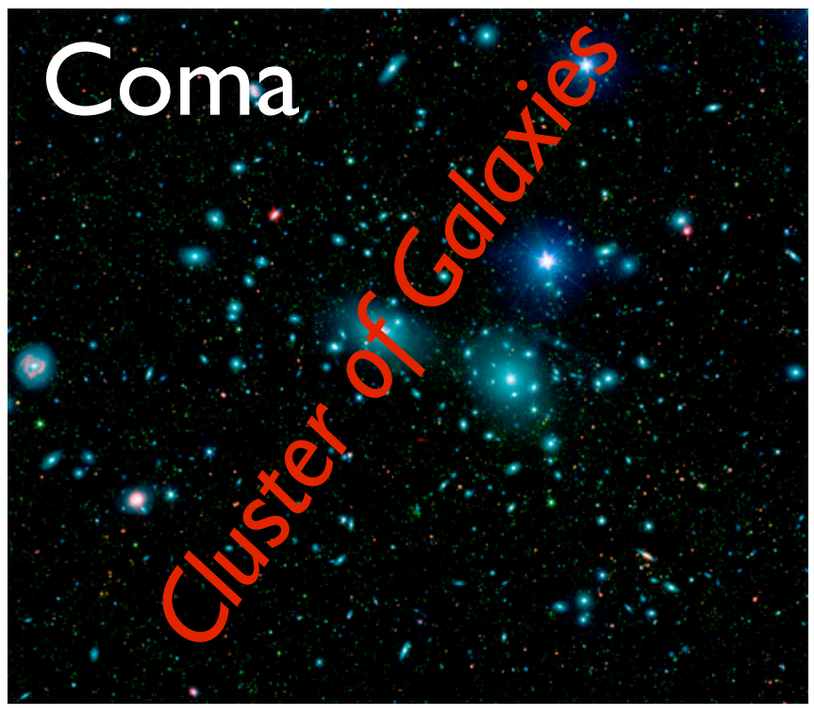
Gelmini's talk

DM exist!

Galactic scale

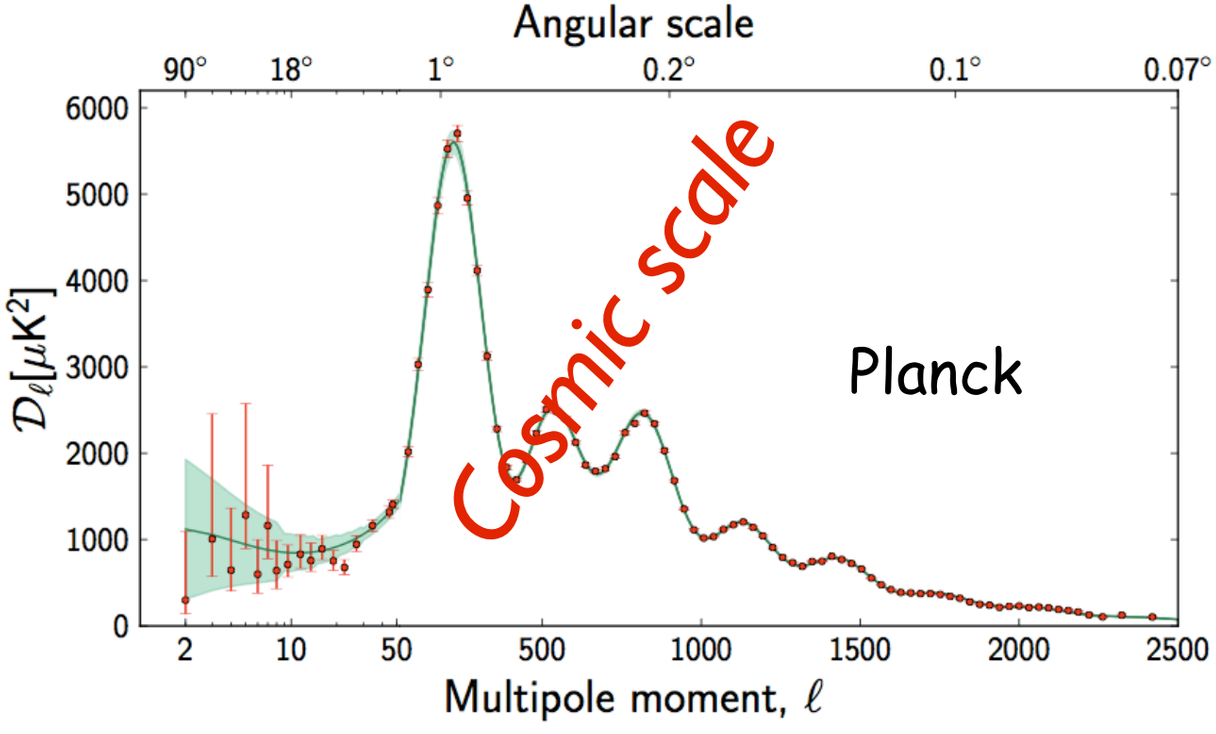


Cluster of Galaxies



Bullet Cluster

Cosmic scale



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)

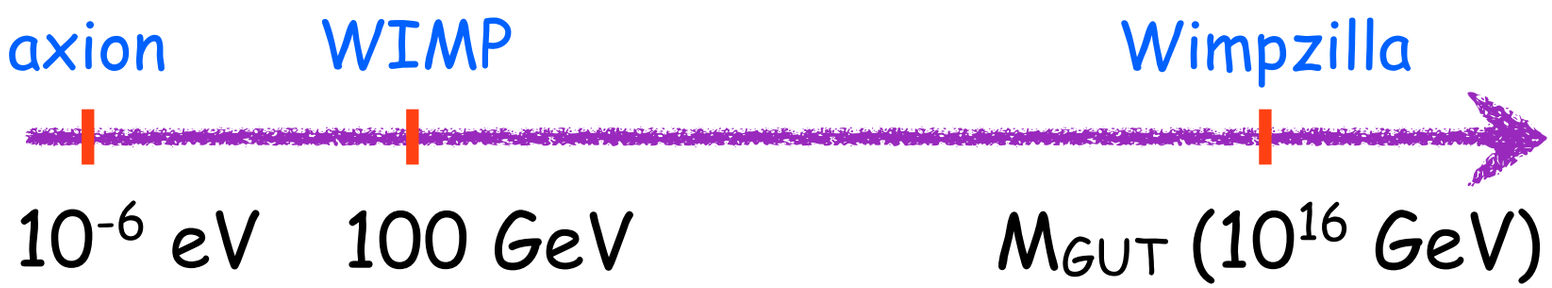
All of these come from gravitational effects

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

✓ 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

✓ ...

A note on Dark Matter

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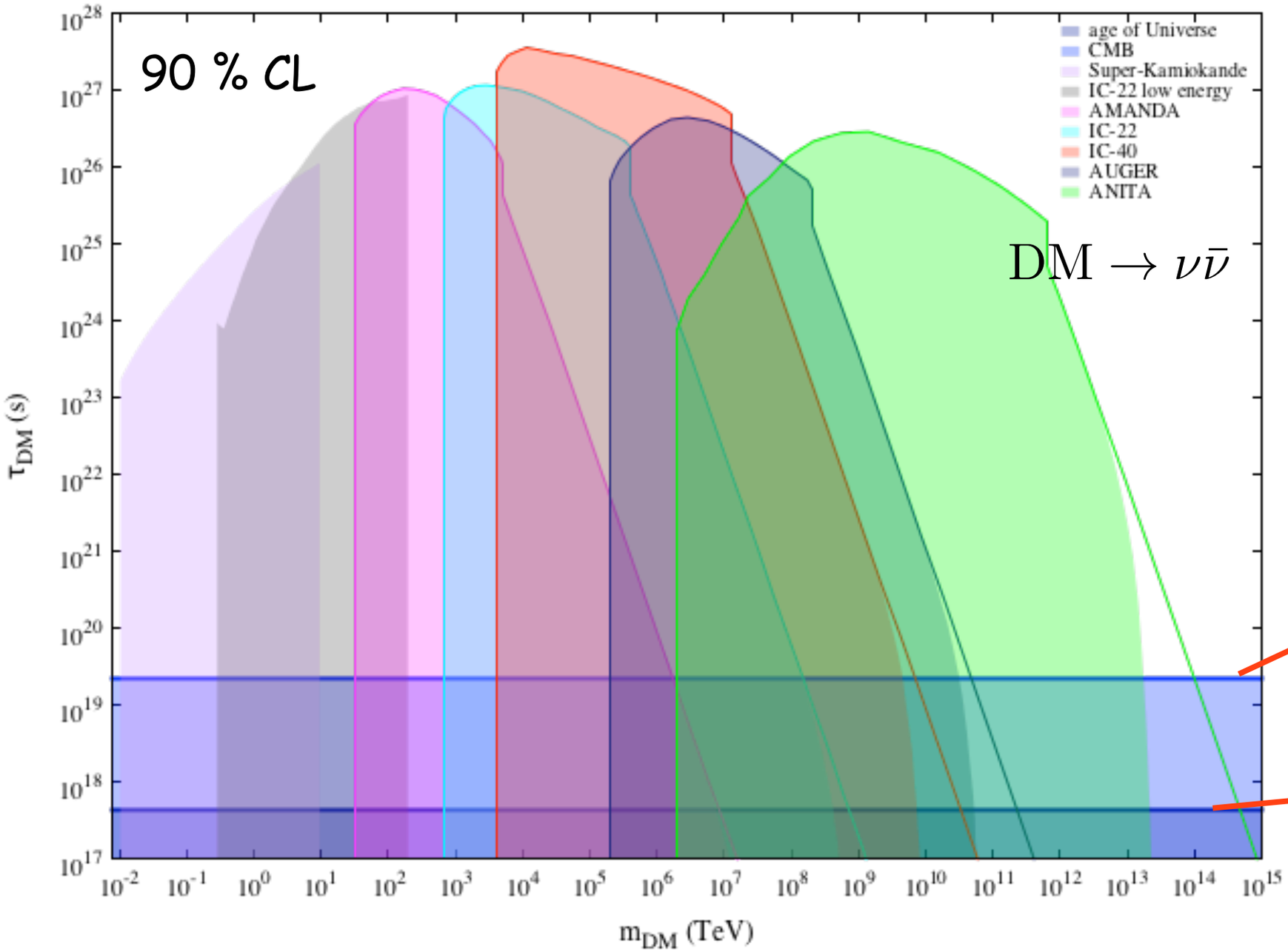
A.E., Alejandro Ibarra and Orlando L. G. Peres
JCAP (2012) arXiv: 1205.5281



Using AMANDA, IceCube, Auger and ANITA data

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A note on Dark Matter

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this talk

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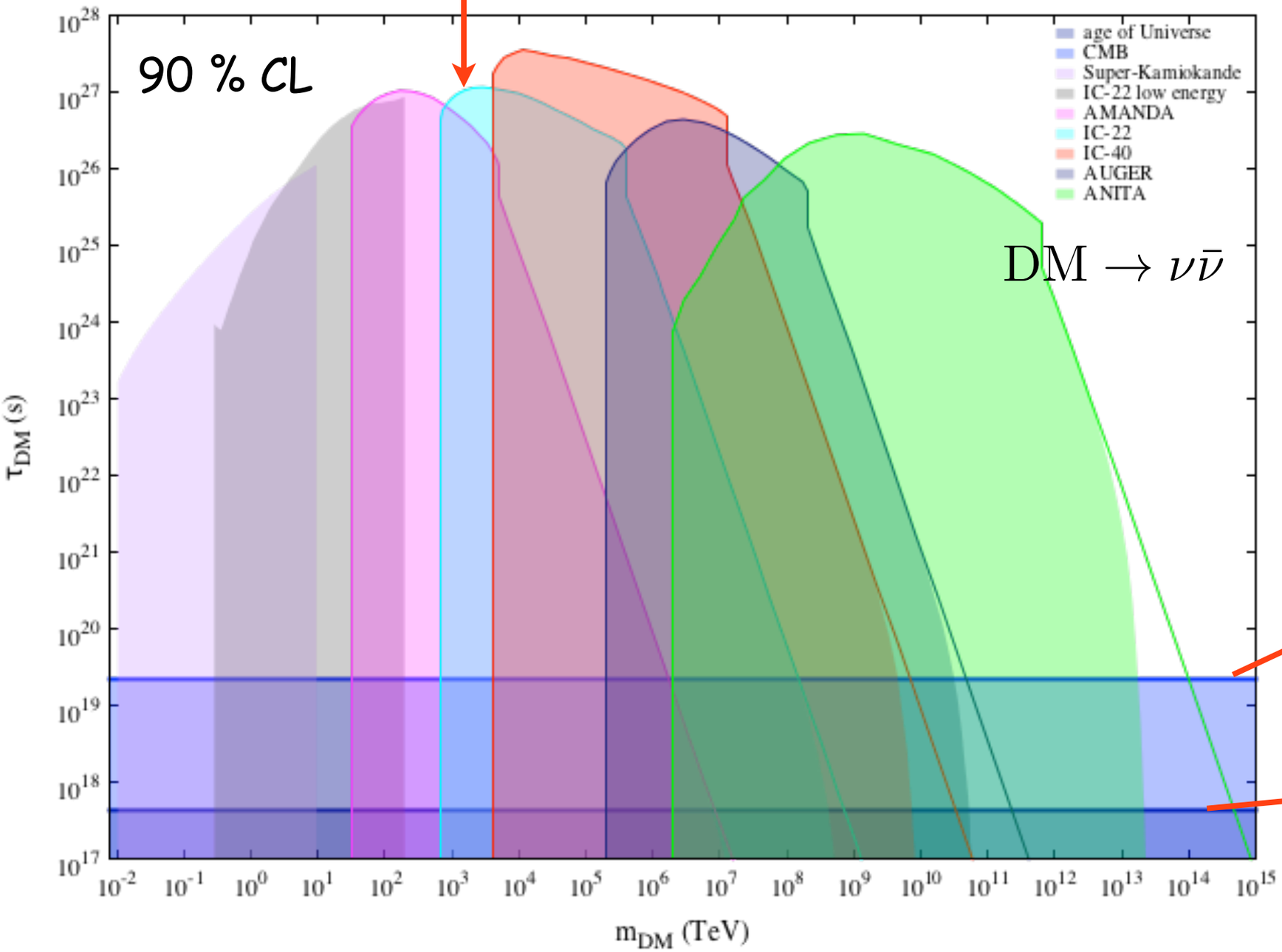

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Flux of neutrinos from decaying DM

✓ Galactic contribution:

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

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NFW

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

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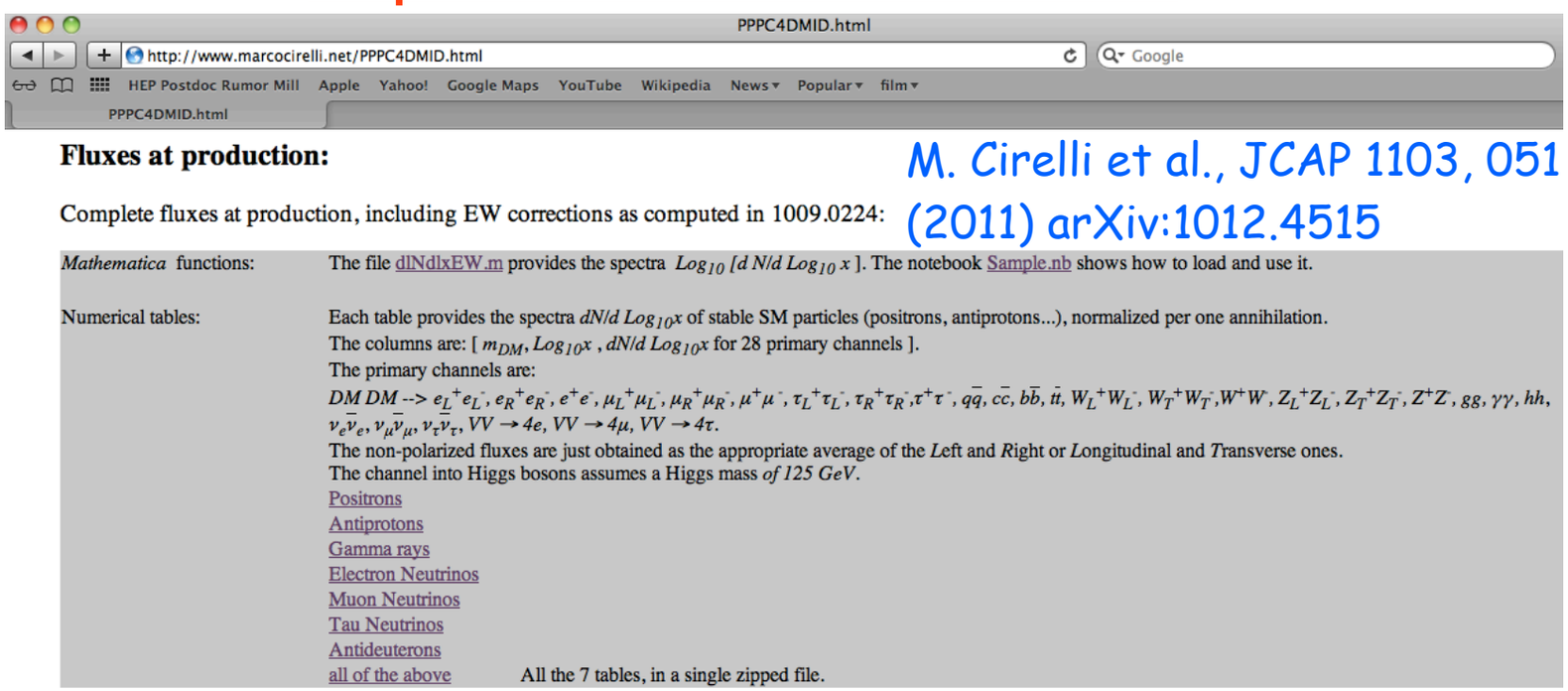
energy spectrum of neutrinos at production point

http://www.marcocirelli.net



M. Cirelli et al., JCAP 1103, 051 (2011) arXiv:1012.4515

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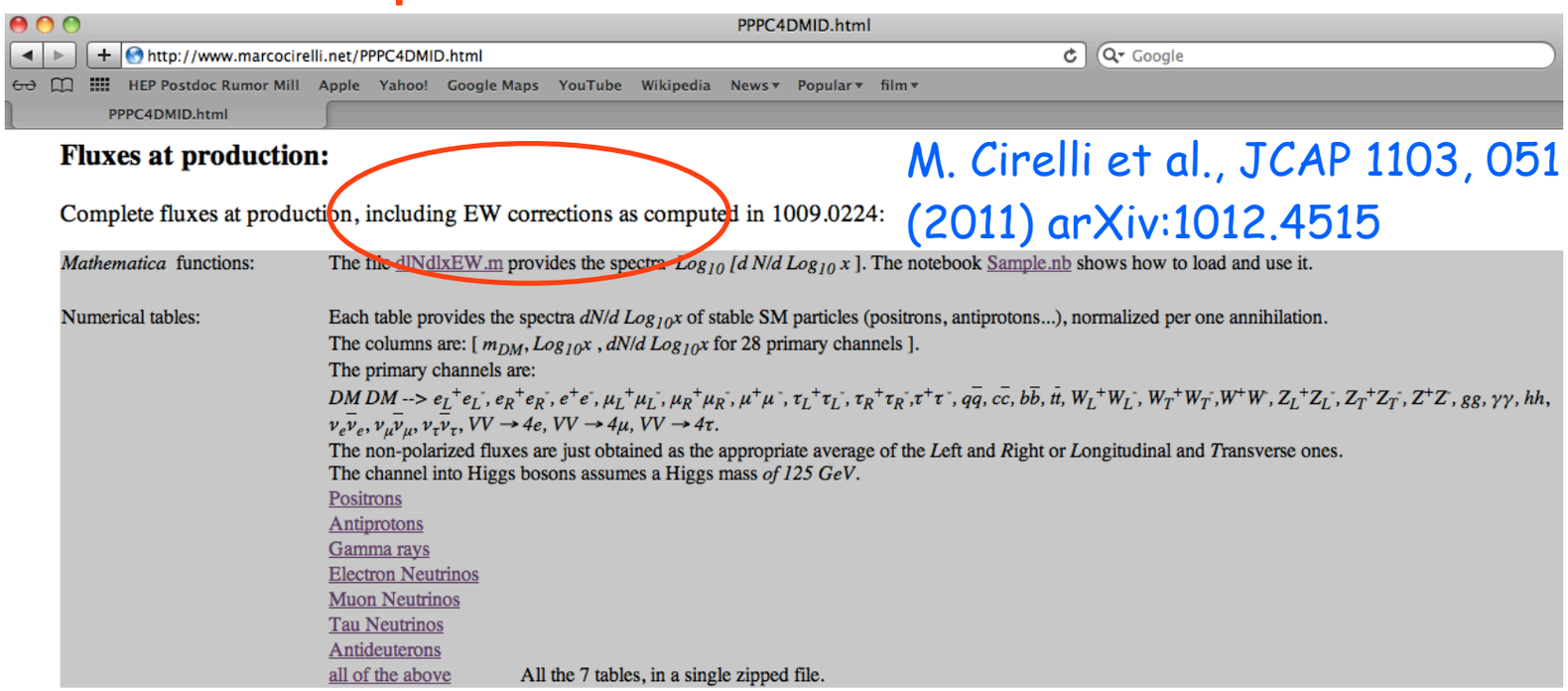

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energy spectrum for various decay channels ("soft" and "hard"), including EW corrections are provided

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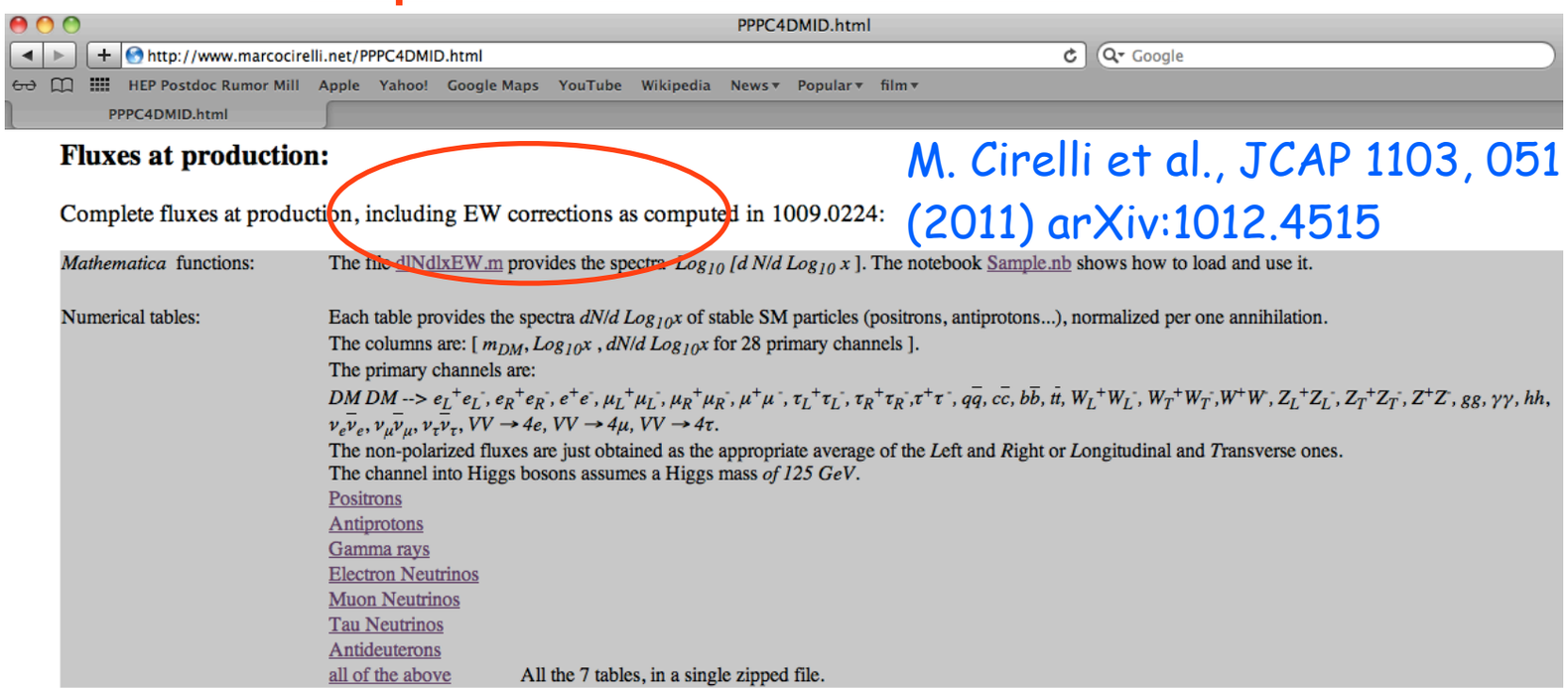

M. Cirelli et al., JCAP 1103, 051 (2011) arXiv:1012.4515

energy spectrum for various decay channels ("soft" and "hard"), including EW corrections are provided

we carefully rescale the spectra for ~ PeV scale DM

"educated guess"

Flux of neutrinos from decaying DM

✓ extragalactic contribution:

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

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✓ branching ratios to "soft" and "hard" channels

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

Flux of neutrinos from decaying DM

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quarks

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

neutrinos, charged leptons

Flux of neutrinos from decaying DM

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✓ branching ratios to "soft" and "hard" channels

quarks

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

neutrinos, charged leptons

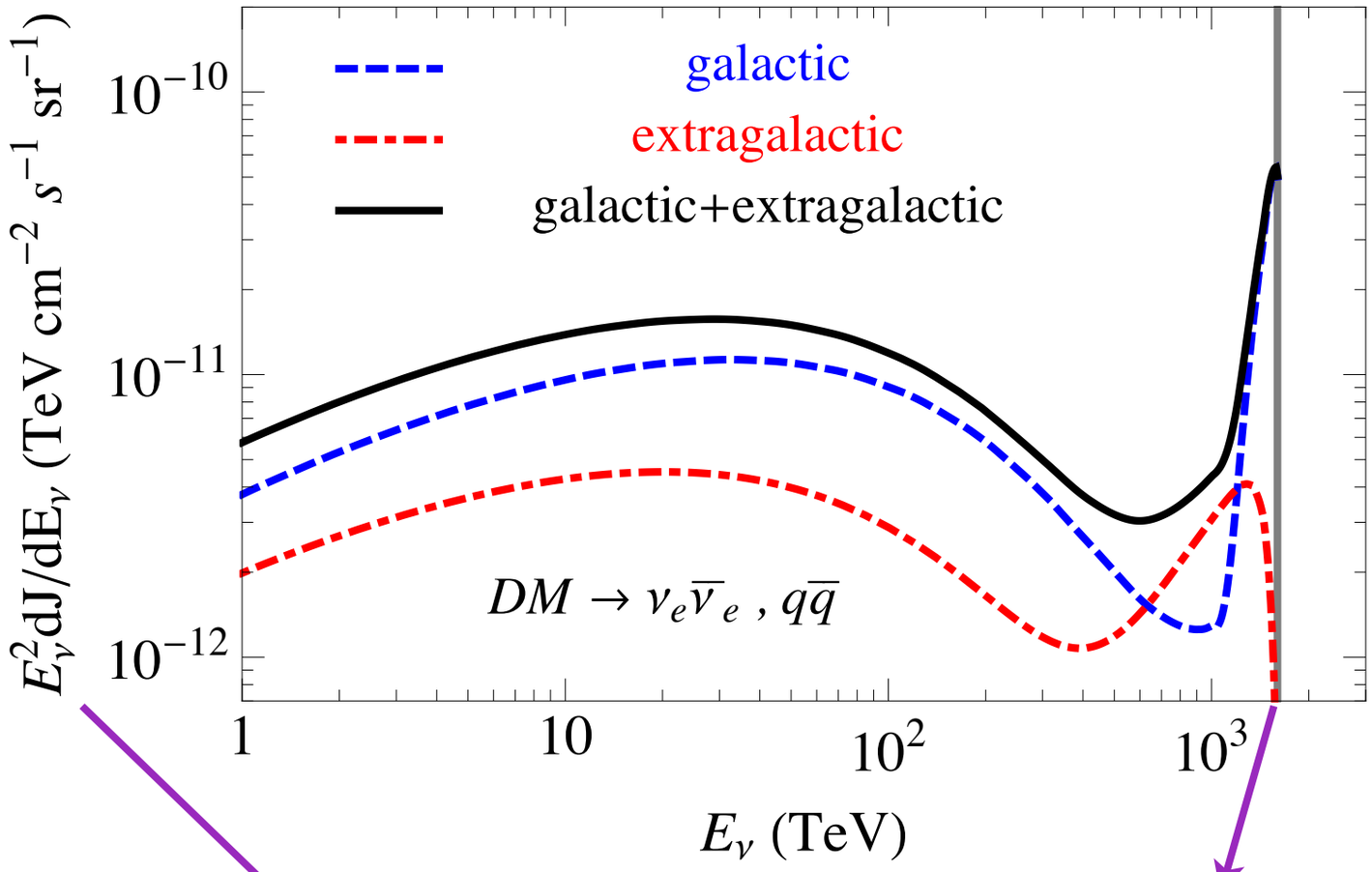
at the Earth $\begin{pmatrix} J_e \\ J_\mu \\ J_\tau \end{pmatrix} = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ & P_{\mu\mu} & P_{\mu\tau} \\ & & P_{\tau\tau} \end{pmatrix} \begin{pmatrix} I_e \\ I_\mu \\ I_\tau \end{pmatrix}$ production point

decoherent oscillation

Flux of neutrinos from decaying DM

✓ an example:

A. E., Pasquale D. Serpico, arXiv:1308.1105



$(\upsilon_e + \upsilon_\mu + \upsilon_\tau)/3$

$m_{DM}/2 = 1.6$ PeV

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

Flux of neutrinos from decaying DM

✓ an example:

intriguing features:

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

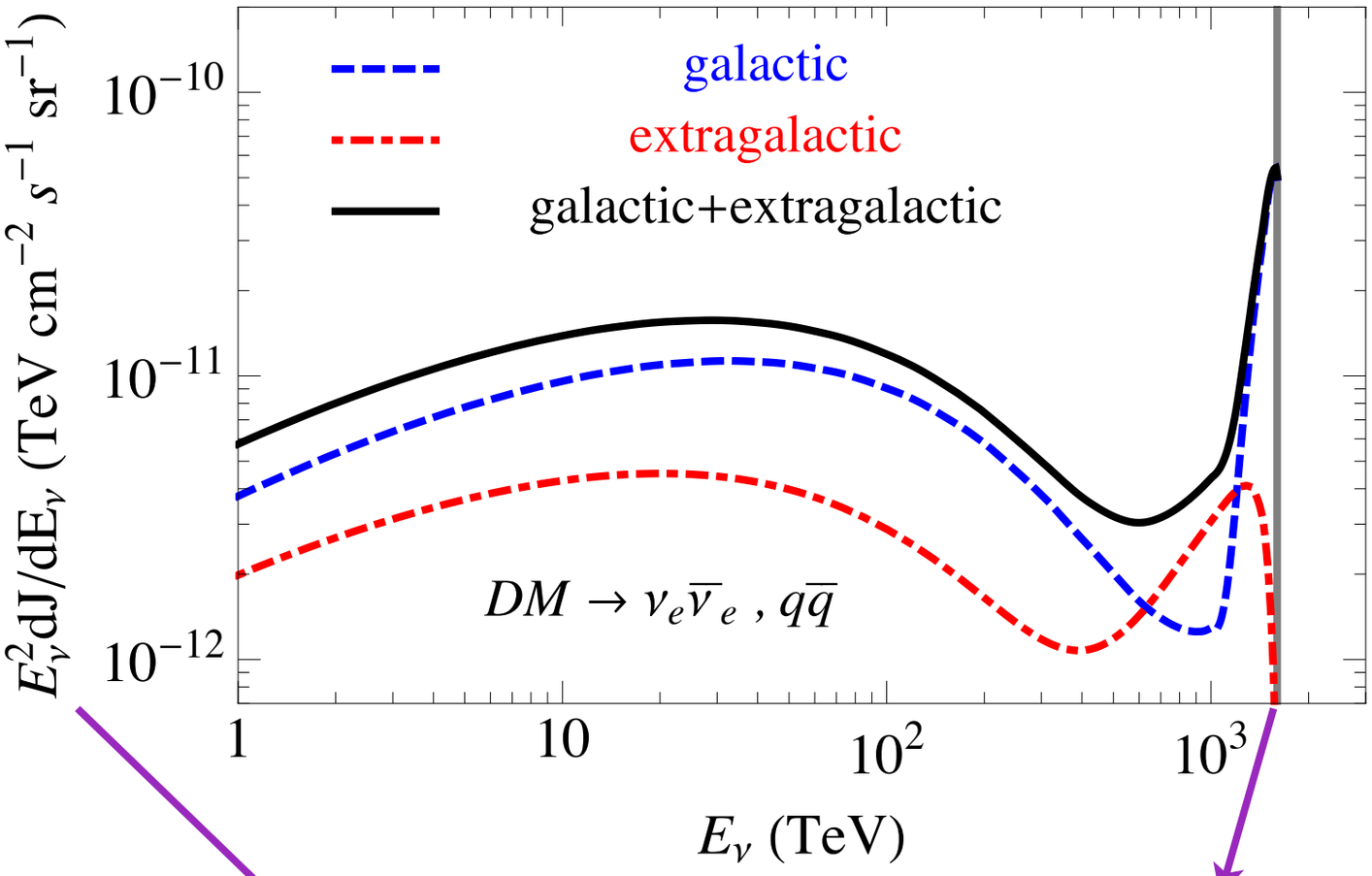
a peak in ~ PeV

a dip in ~ (0.3-1) PeV

populated spectrum in < 0.3 PeV

due to soft channel and EW cascades

A. E., Pasquale D. Serpico, arXiv:1308.1105



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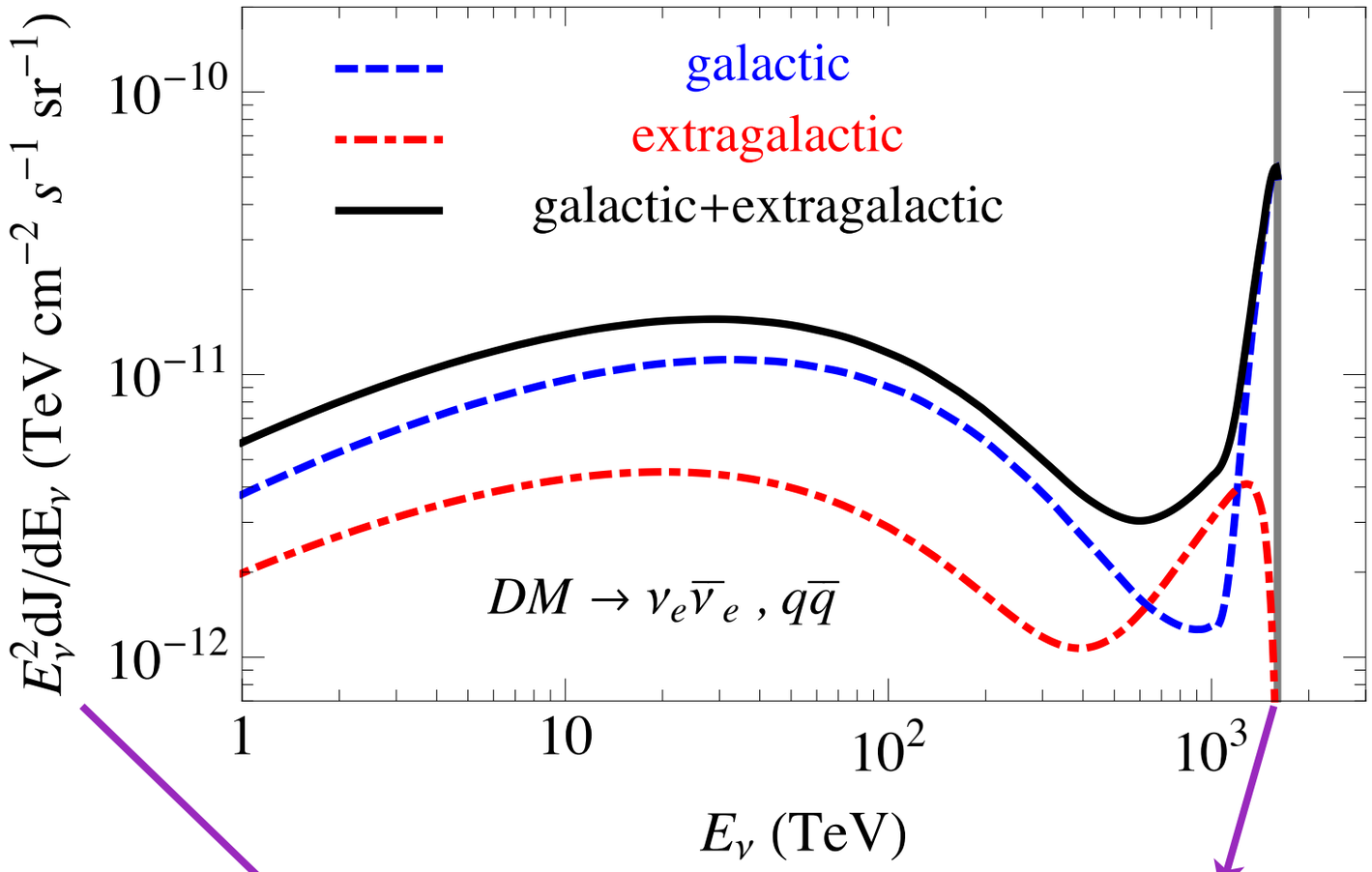


$(\upsilon_e + \upsilon_\mu + \upsilon_\tau)/3$

$m_{DM}/2$ = 1.6 PeV

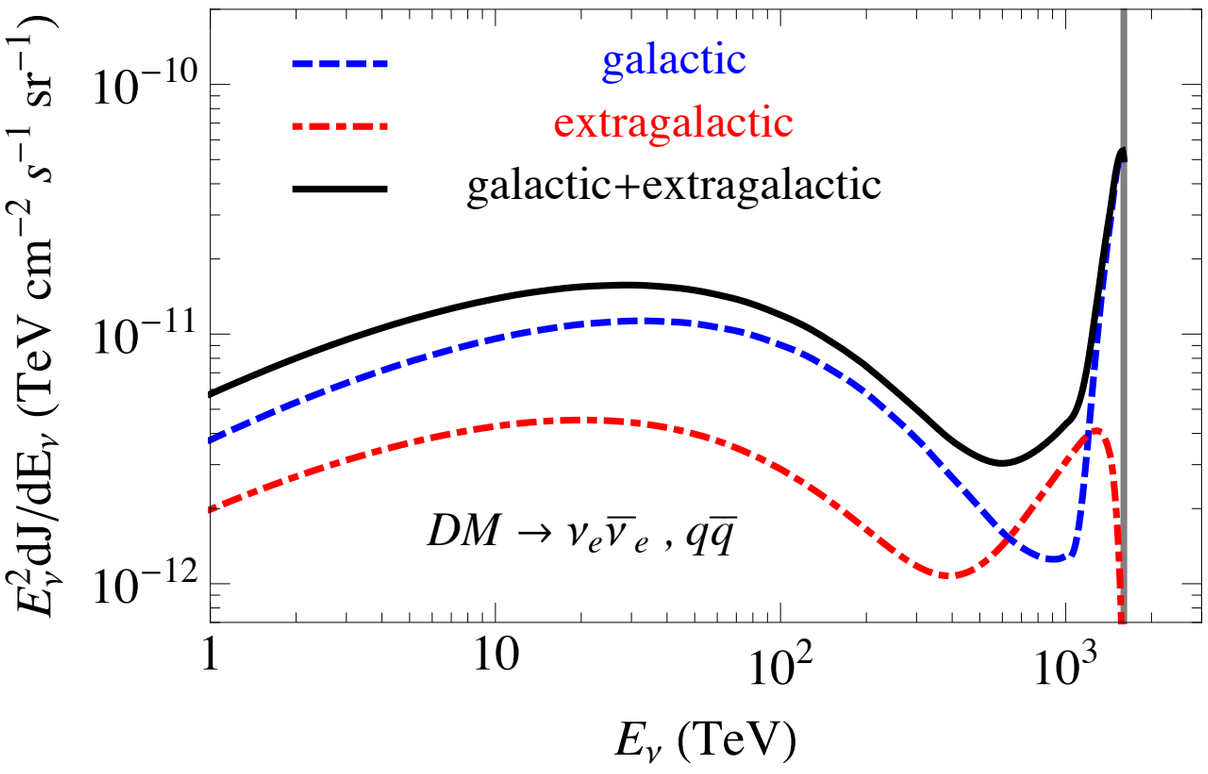
b_H controls the peak height at ~ PeV

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

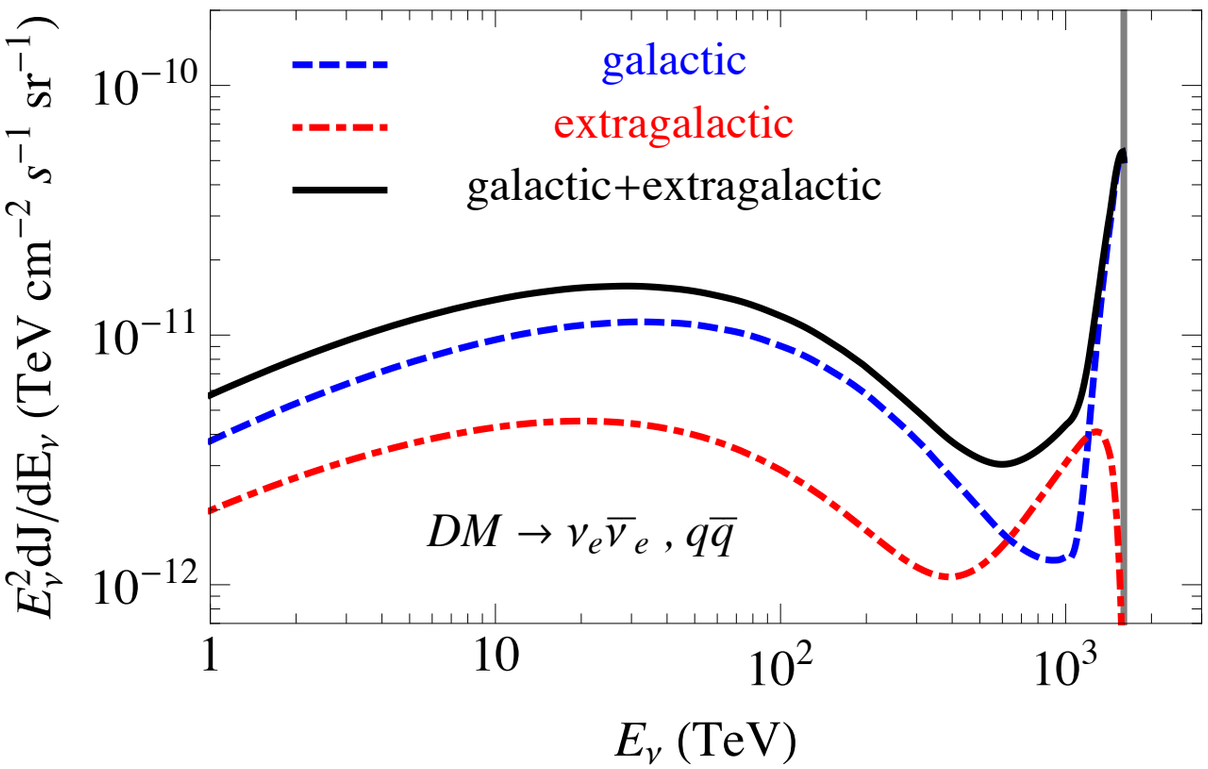
✓ fine-tuned decay channels ?

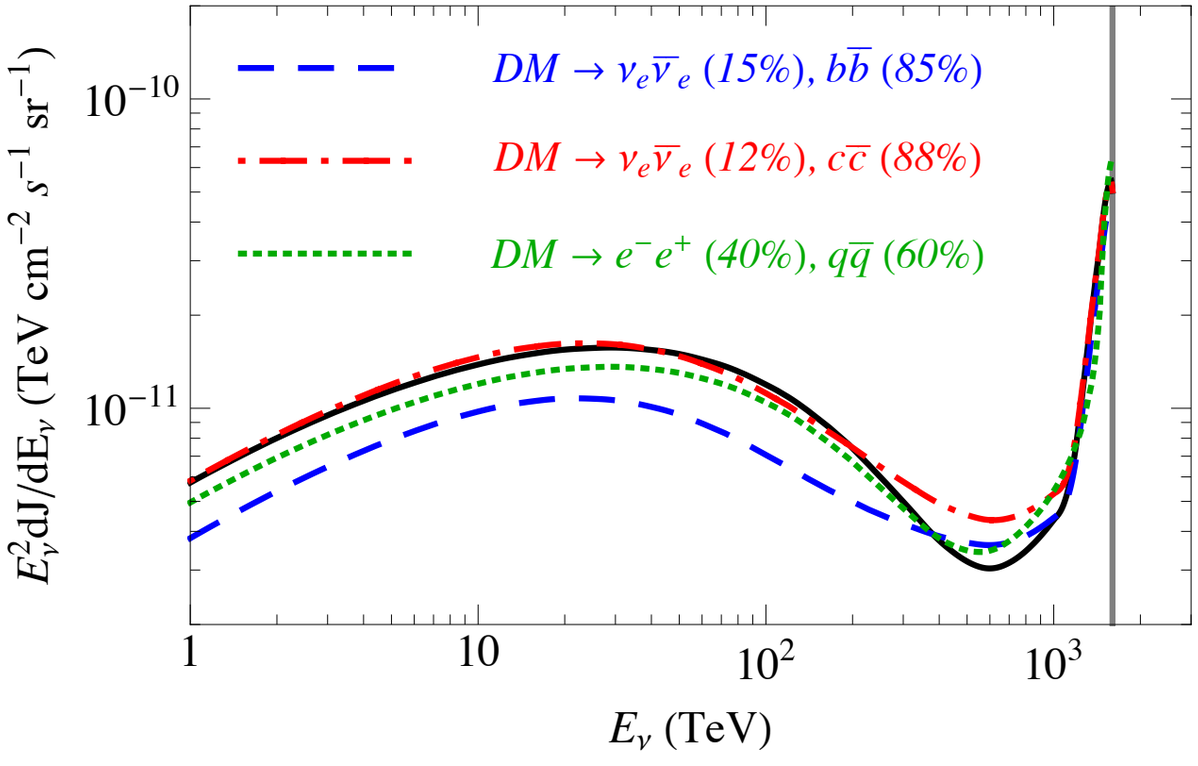


Flux of neutrinos from decaying DM

✓ fine-tuned decay channels ?

$\tau_{DM} = (1\text{-}3) \times 10^{27}$ s





the intriguing features are generic

Flux of neutrinos from decaying DM

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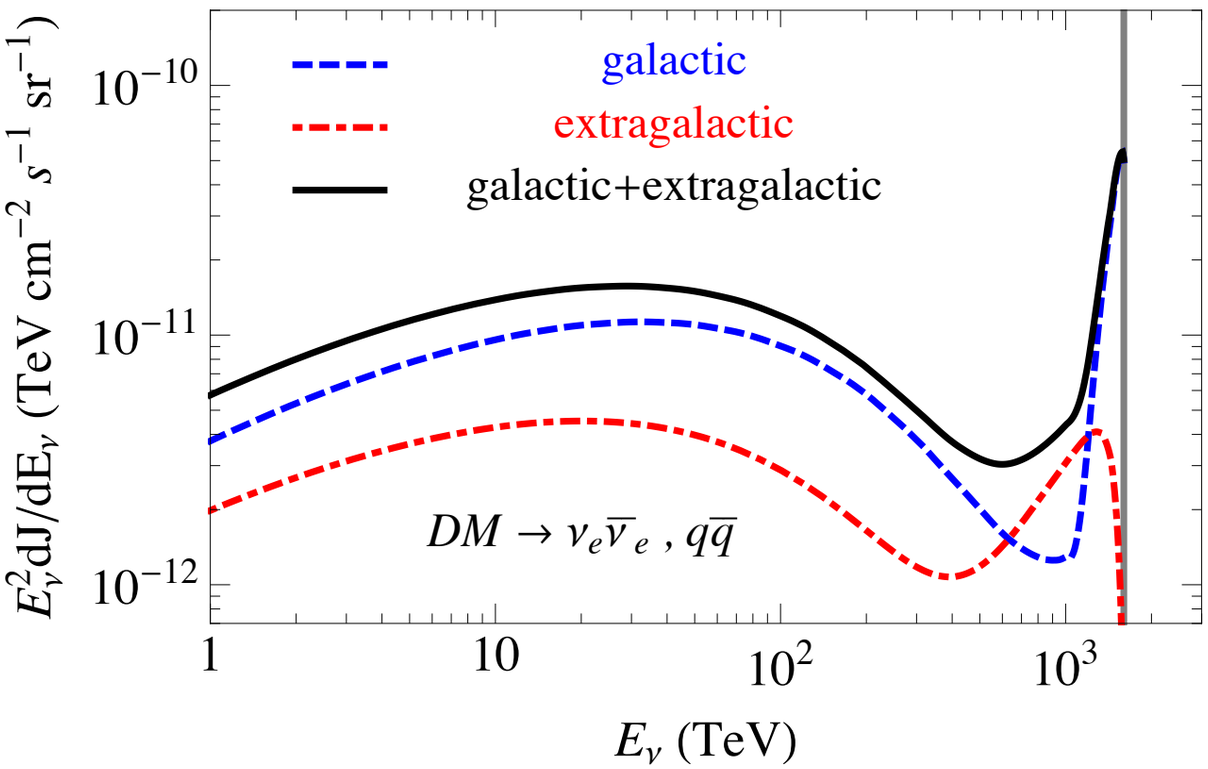
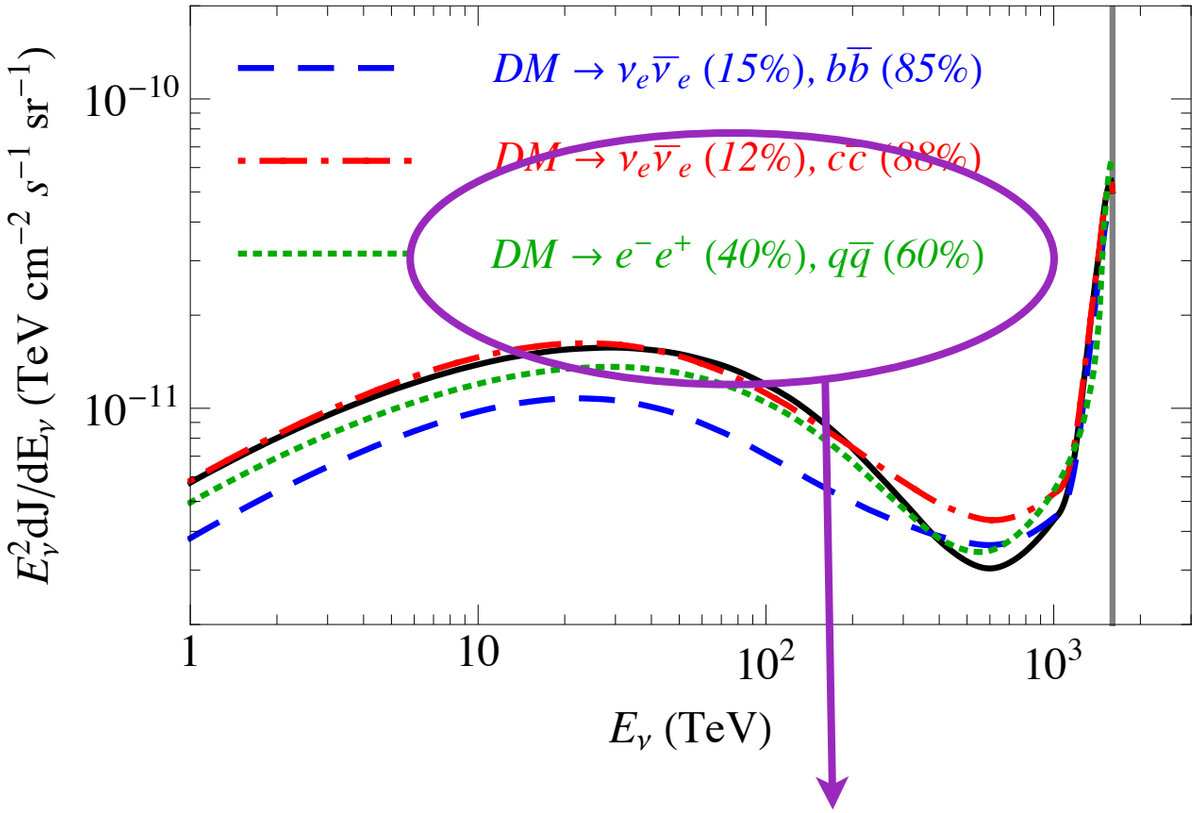




the crucial role of EW cascades

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

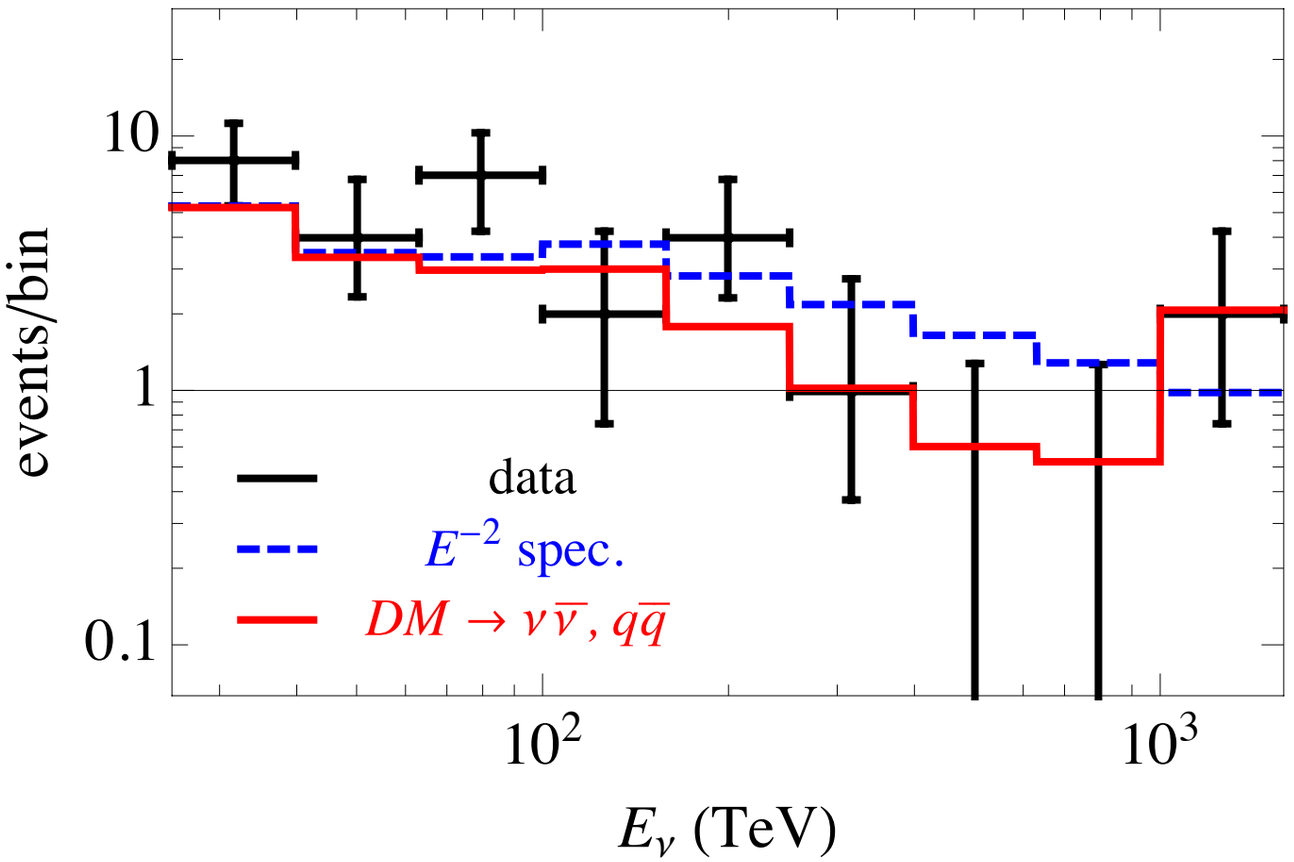
✓ natural explanation for the lack of events > PeV

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

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



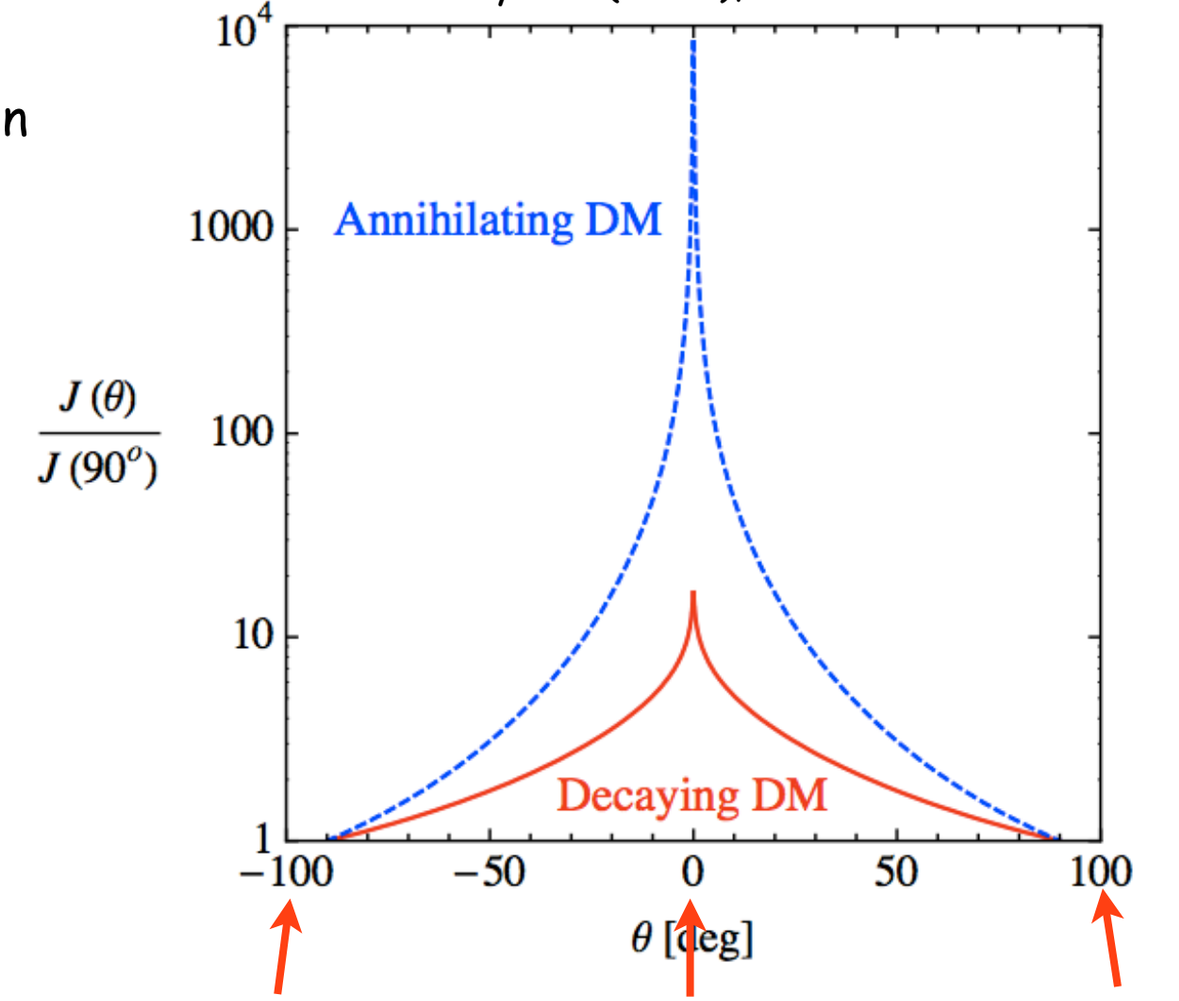
✓ different decay channels lead to qualitatively same result

angular distribution

✓ We are off-centered in Milky Way
(~ 8.5 kpc)

it is well-known that the flux from decay/annihilation of DM would show anisotropy due to the off-center position of Solar System in Milky Way

P. D. Serpico and D. Hooper,
New J. Phys. 11 (2009), arXiv:0902.2539



θ : angle to the GC

angular distribution

✓ We are off-centered in Milky Way (~ 8.5 kpc)

it is well-known that the flux from decay/annihilation of DM would show anisotropy due to the off-center position of Solar System in Milky Way

✓ Galactic Center is above horizon at IceCube site during the whole year

$$\frac{\#\text{ events with } \theta < 30^{o}}{\text{total \# events}} \sim \begin{cases} \text{DM decay} & 15\ \% \\ \text{isotropic} & 7\ \% \end{cases}$$

with the current statistics it is difficult to distinguish these numbers.

more future data can discriminate these scenarios

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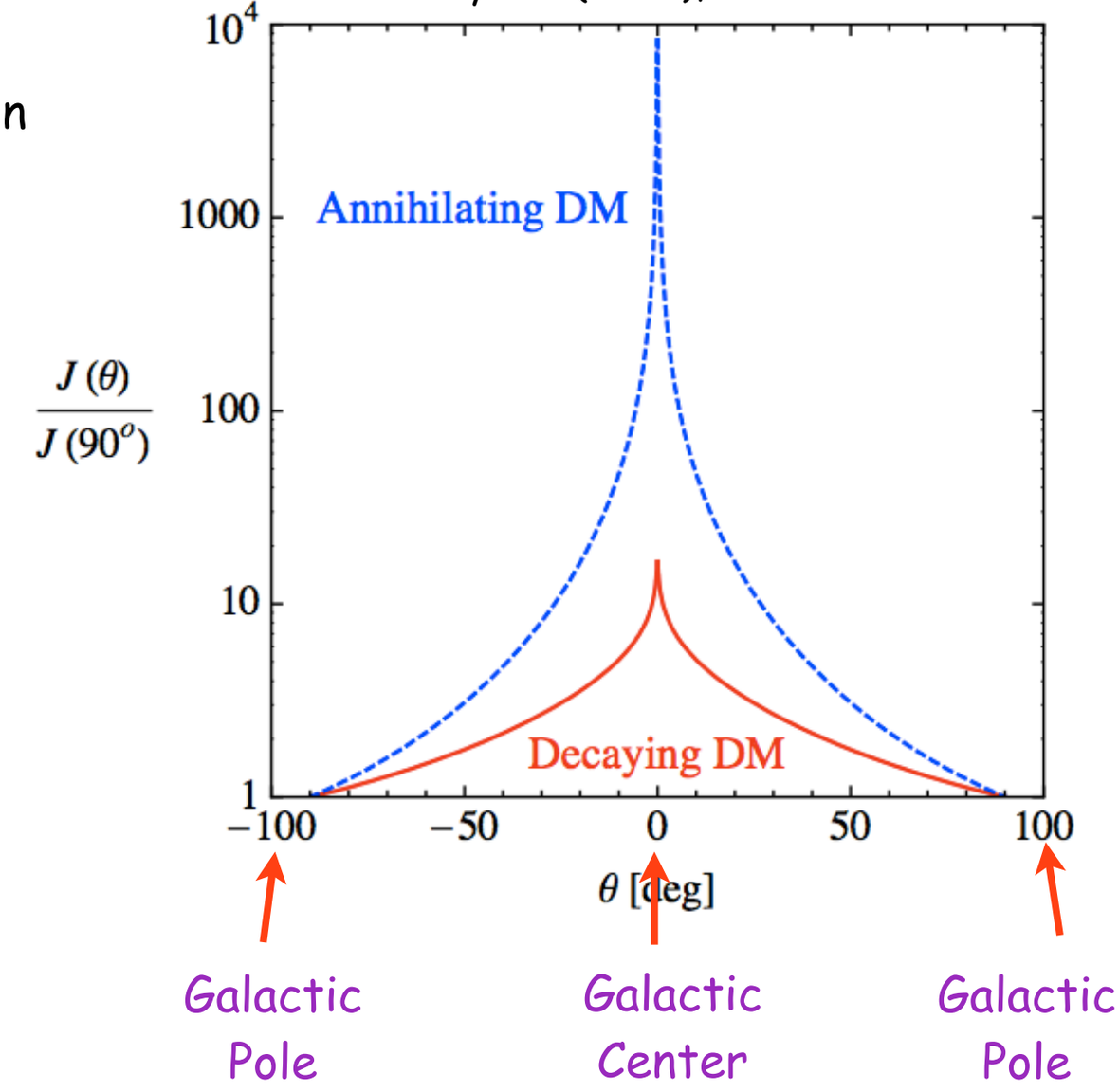

θ : angle to the GC

conclusions

✓ The excess of events observed by IceCube in the energy range ~ 30 TeV - 1 PeV is an evidence for astrophysical flux or other "New Physics" induced fluxes

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✓ Several features of the observed events motivate us for a DM interpretation: cut-off at ~ PeV, dip in (300 - 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.

✓ With more statistics in the next few years, the DM interpretation of IceCube events can be tested: persistence of the dip in ~ (300 - 1000) TeV and angular correlation with Galactic Center.

Thank you !