Interpreting the IceCube events by decaying dark matter hints and constraints

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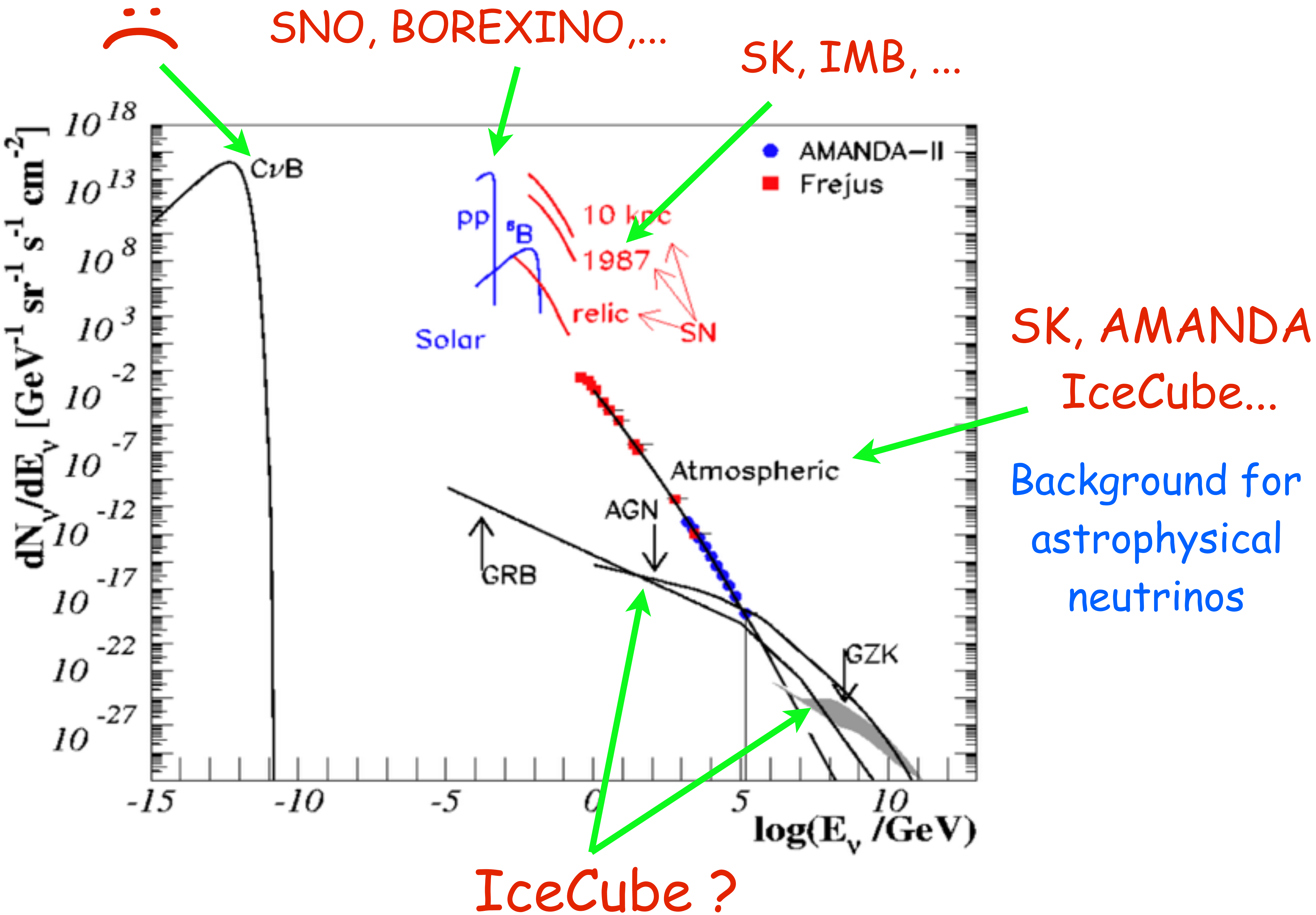
Theory Group

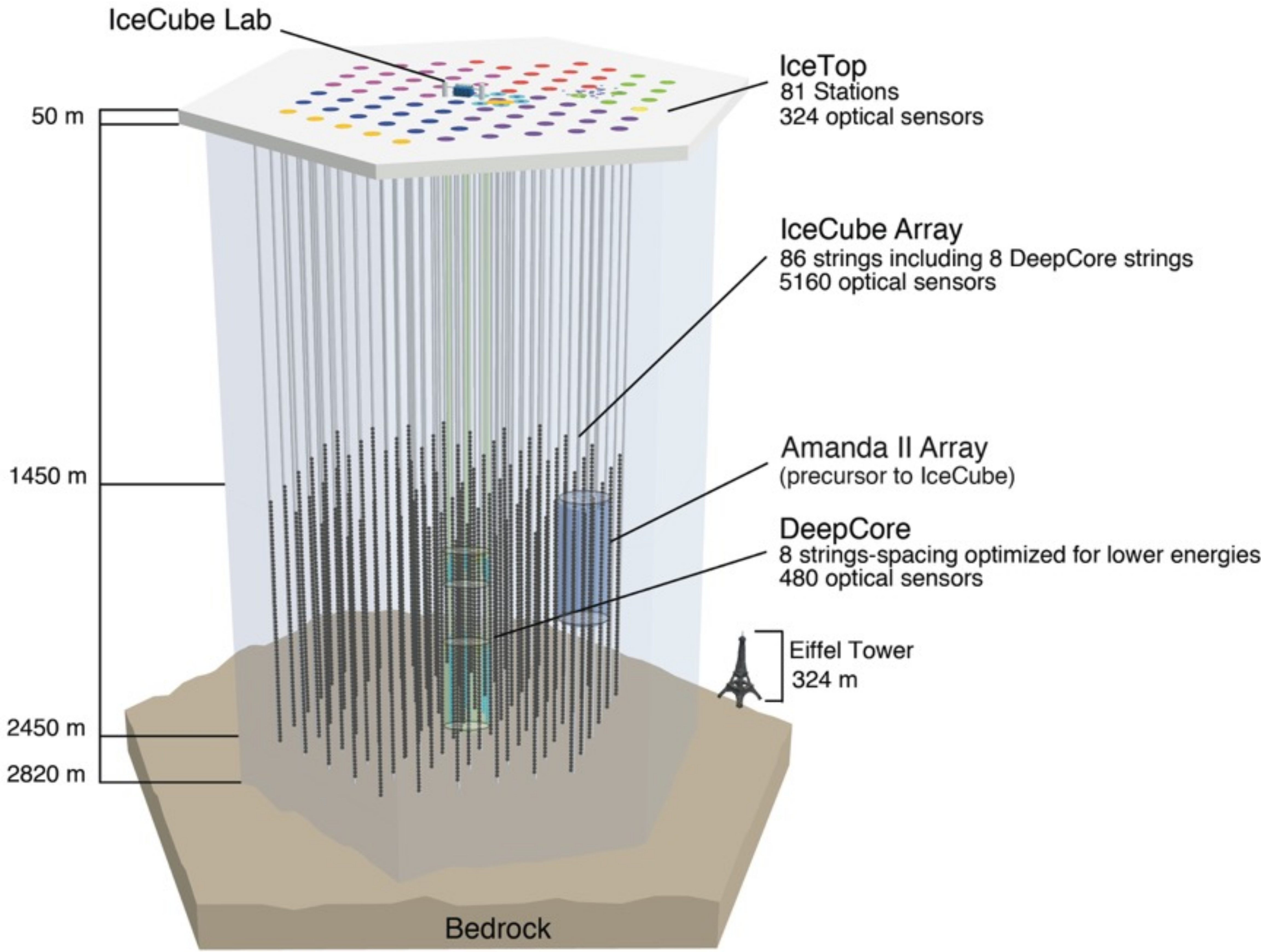
18/Dec/2015

DSU @ YITP

Neutrino Sky



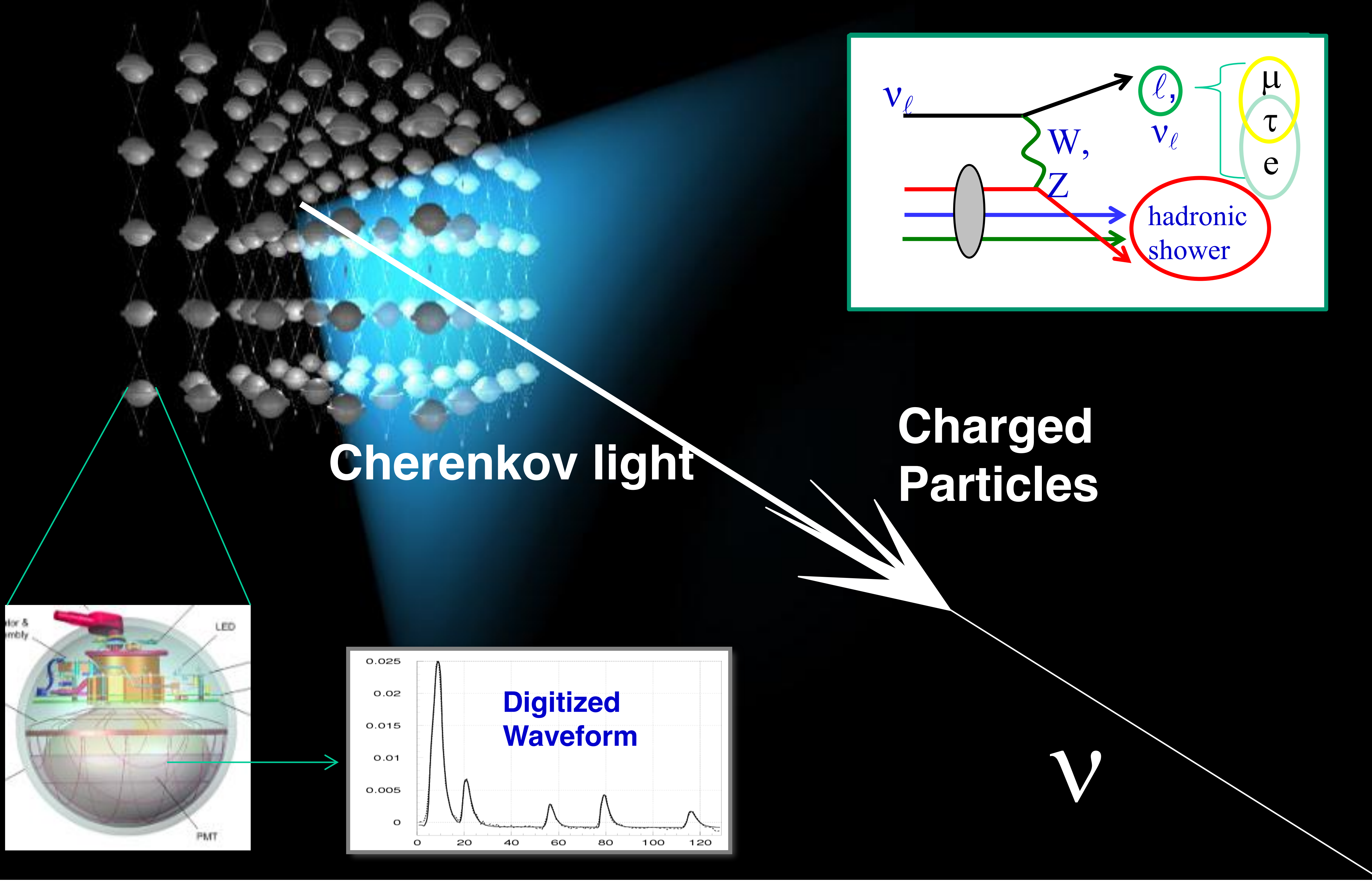
Background for astrophysical neutrinos


IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
Amanda II Array
(precursor to IceCube)
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock

Detection Principle

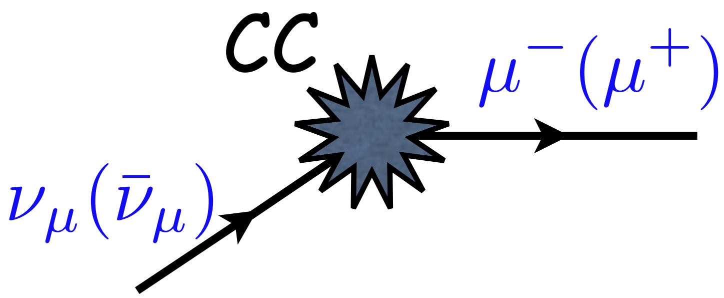
Slide from
A. Ishihara

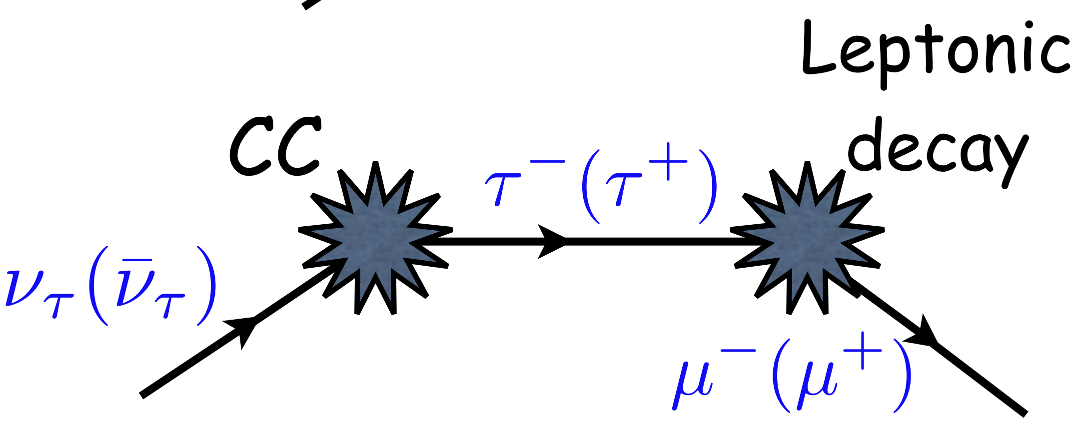
An array of photomultiplier tubes + Dark and transparent material

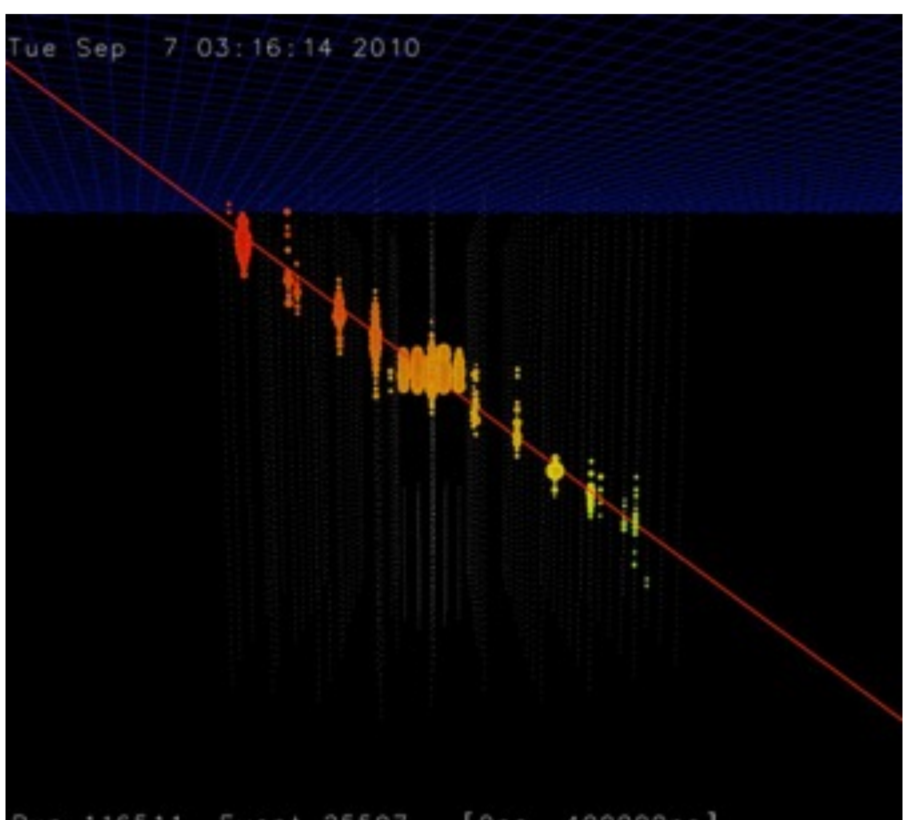


Flavoring at IceCube

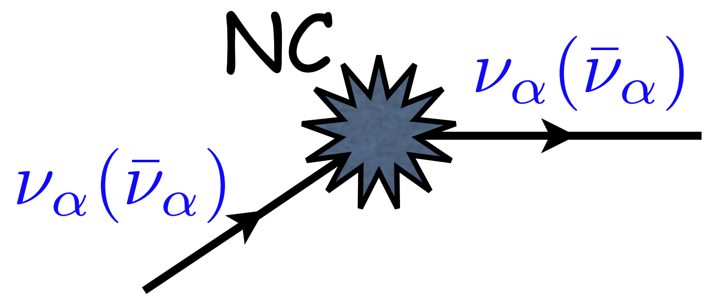
muon-track events

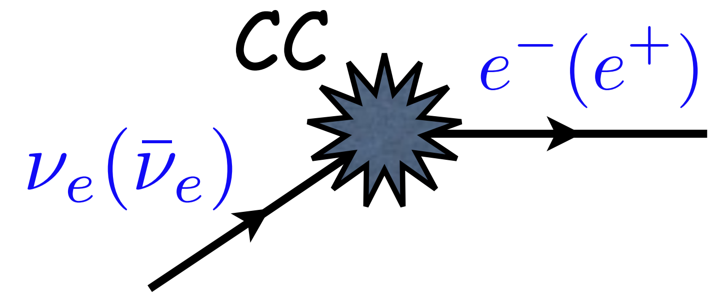


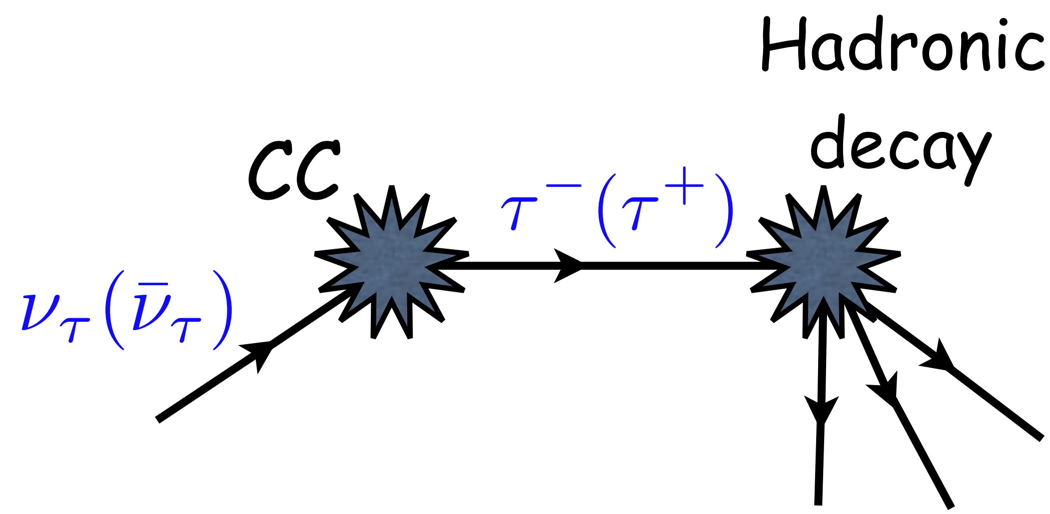




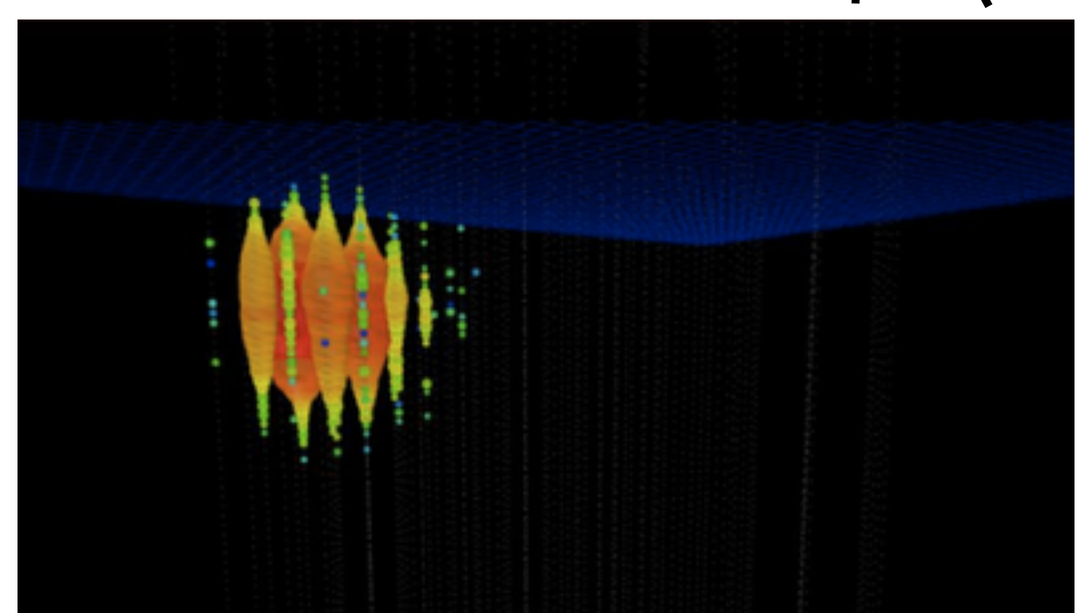
cascade events







figures from IceCube website

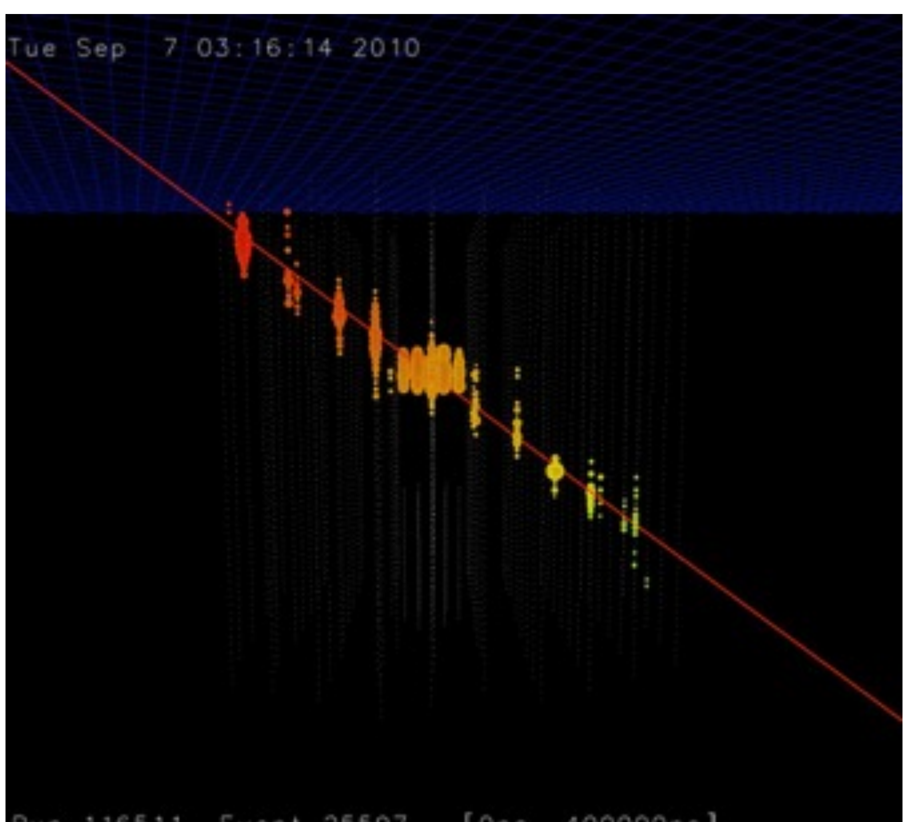


Flavoring at IceCube

muon-track events

great angular resolution (< 1°)

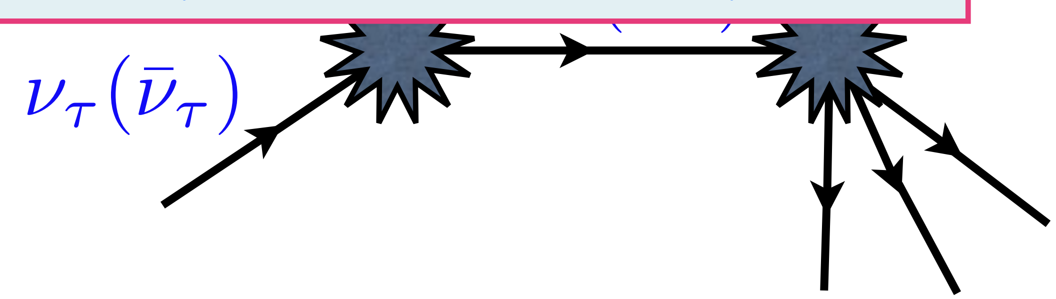
moderate energy resolution (σ_E ~ E)

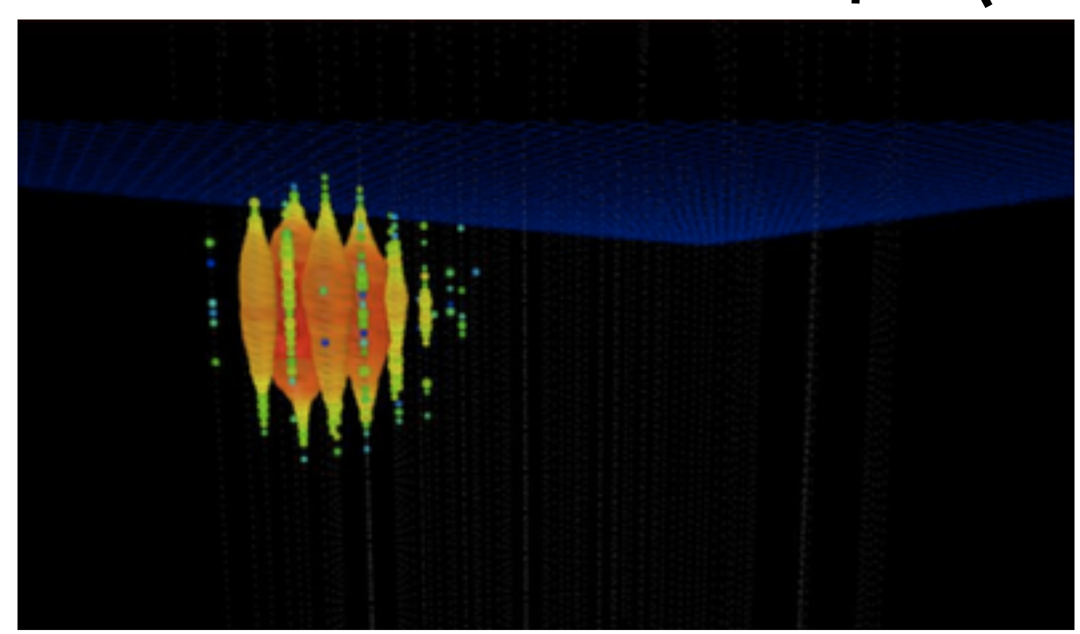


cascade events

poor angular resolution (< 10° - 20°)

great energy resolution (σ_E ~ 0.15 x E)



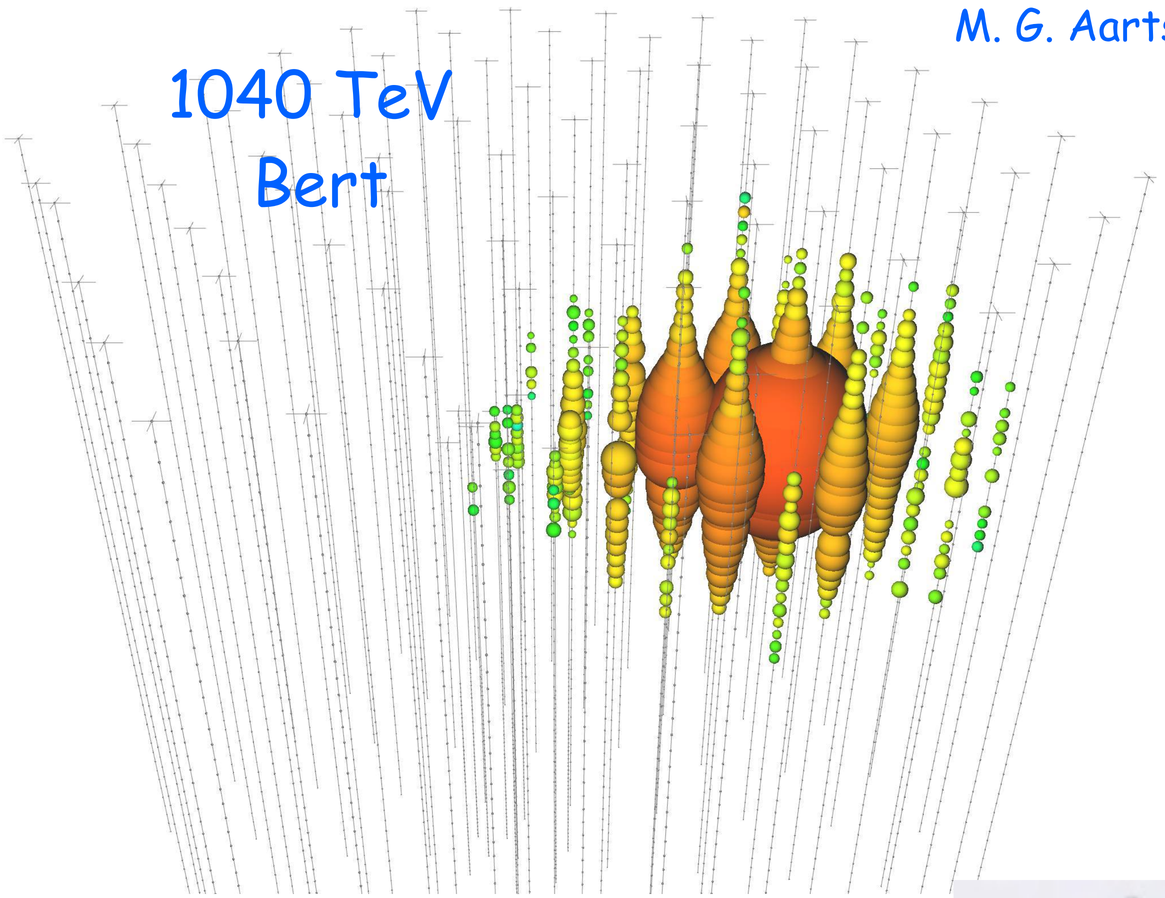


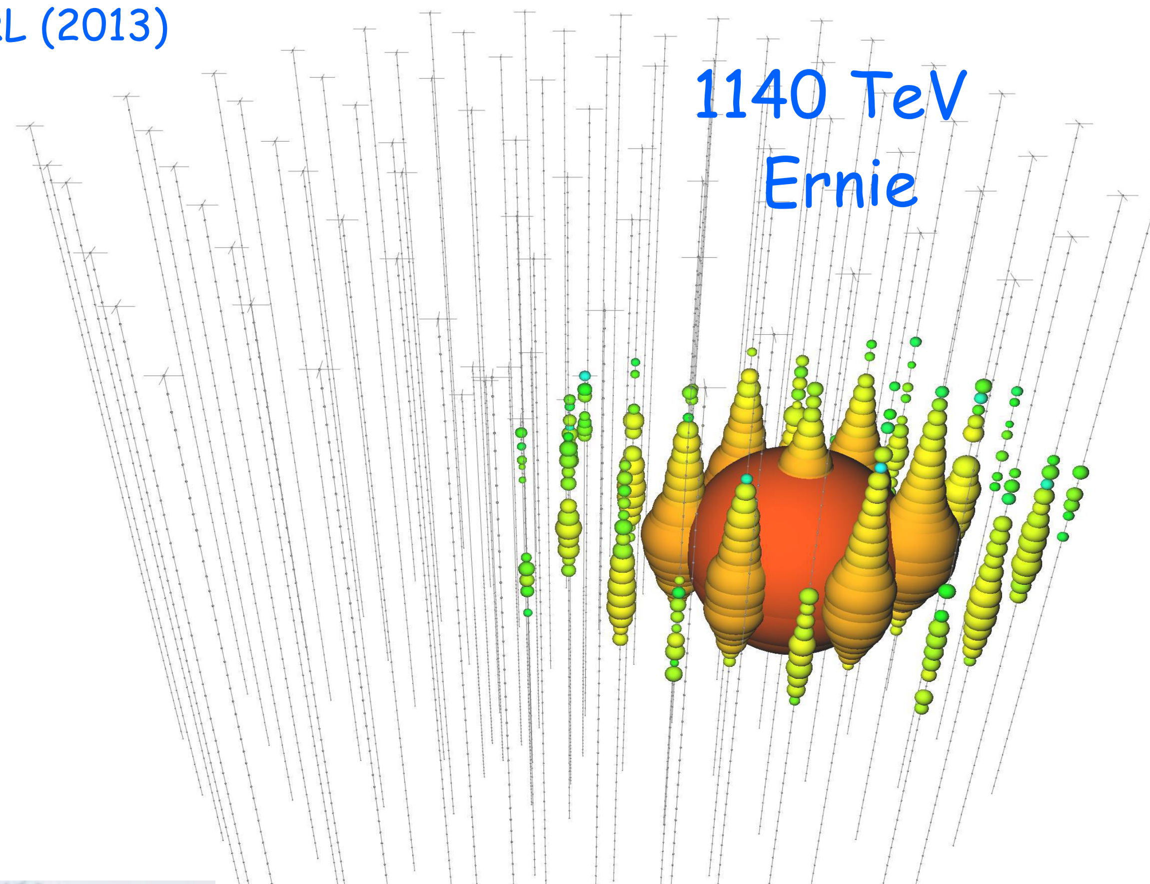
figures from IceCube website

Mission for IceCube began !

✓ The two PeV cascade events, 616 days livetime

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





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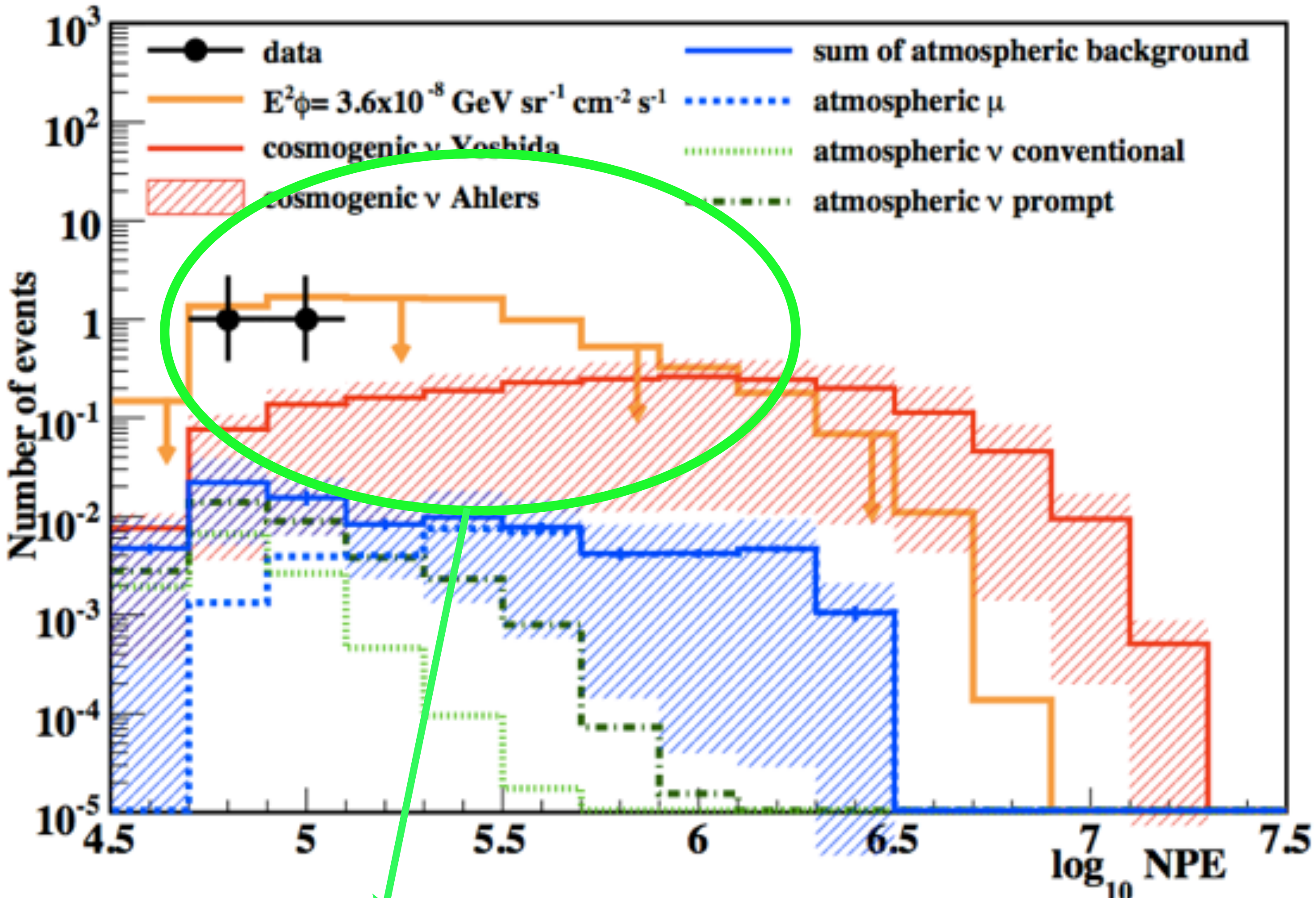
M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 111 (2013), [arXiv:1304.5356]



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 ?

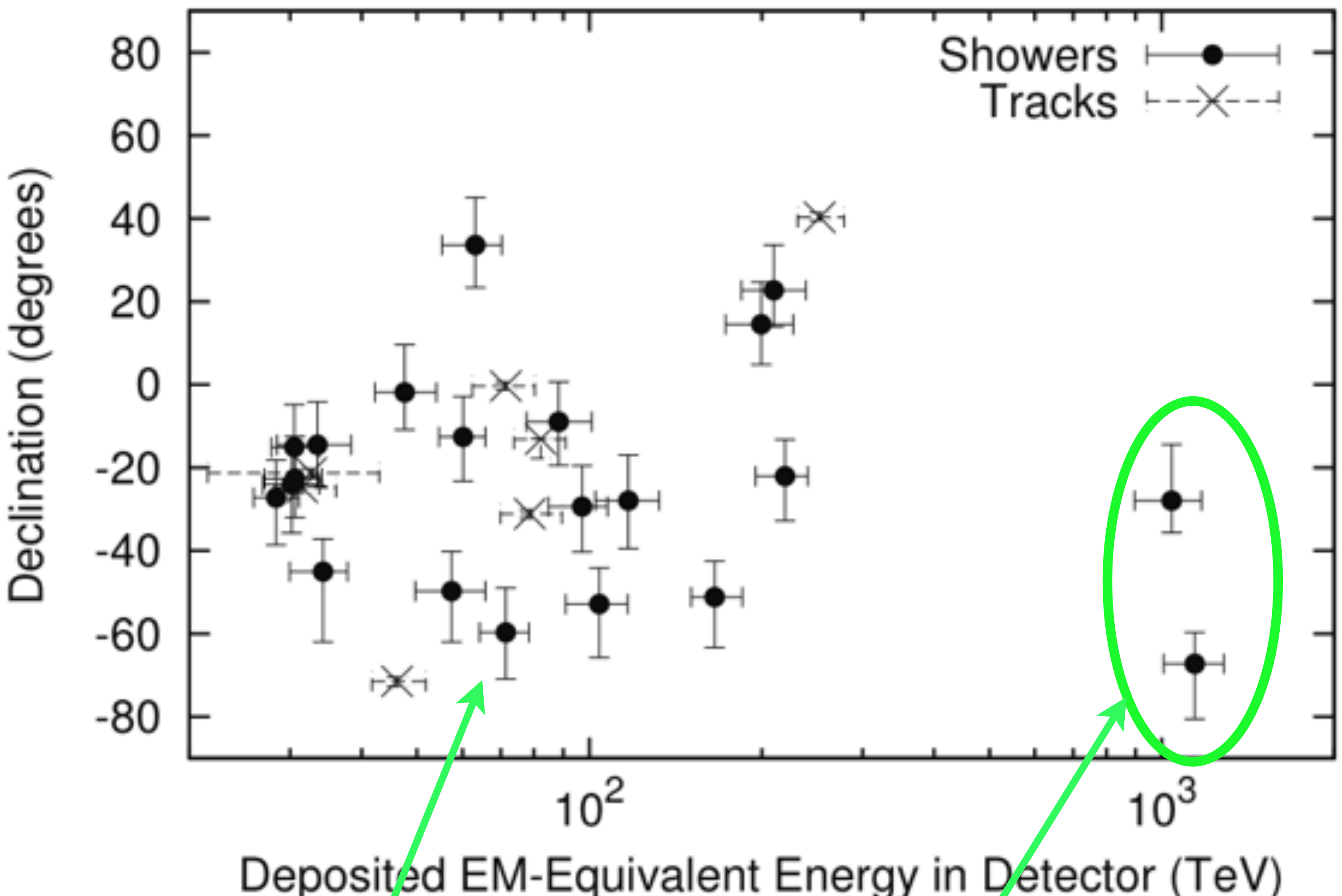
HESE analysis

- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry

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 !

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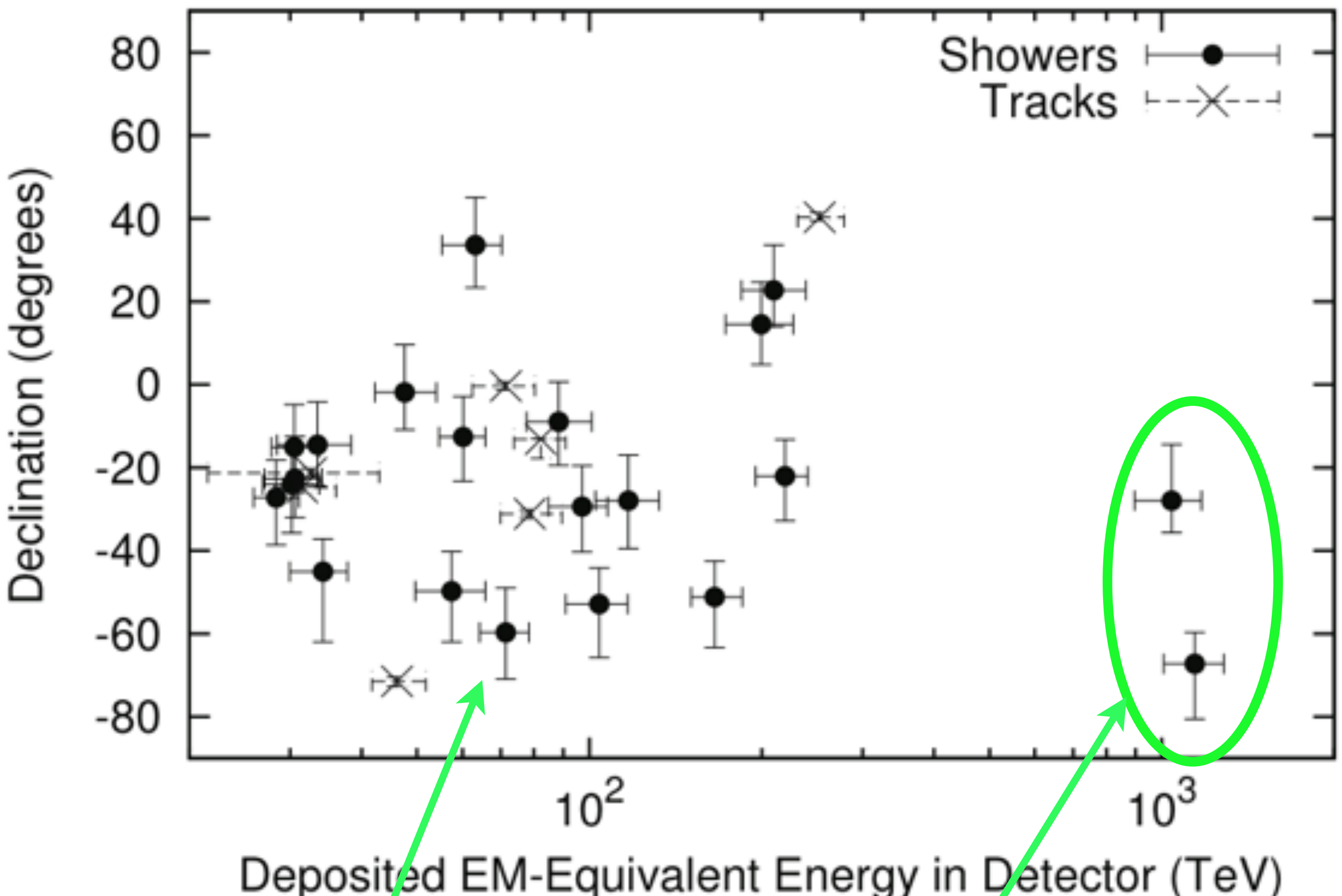

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✓ 26 more events

✓ 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 ?

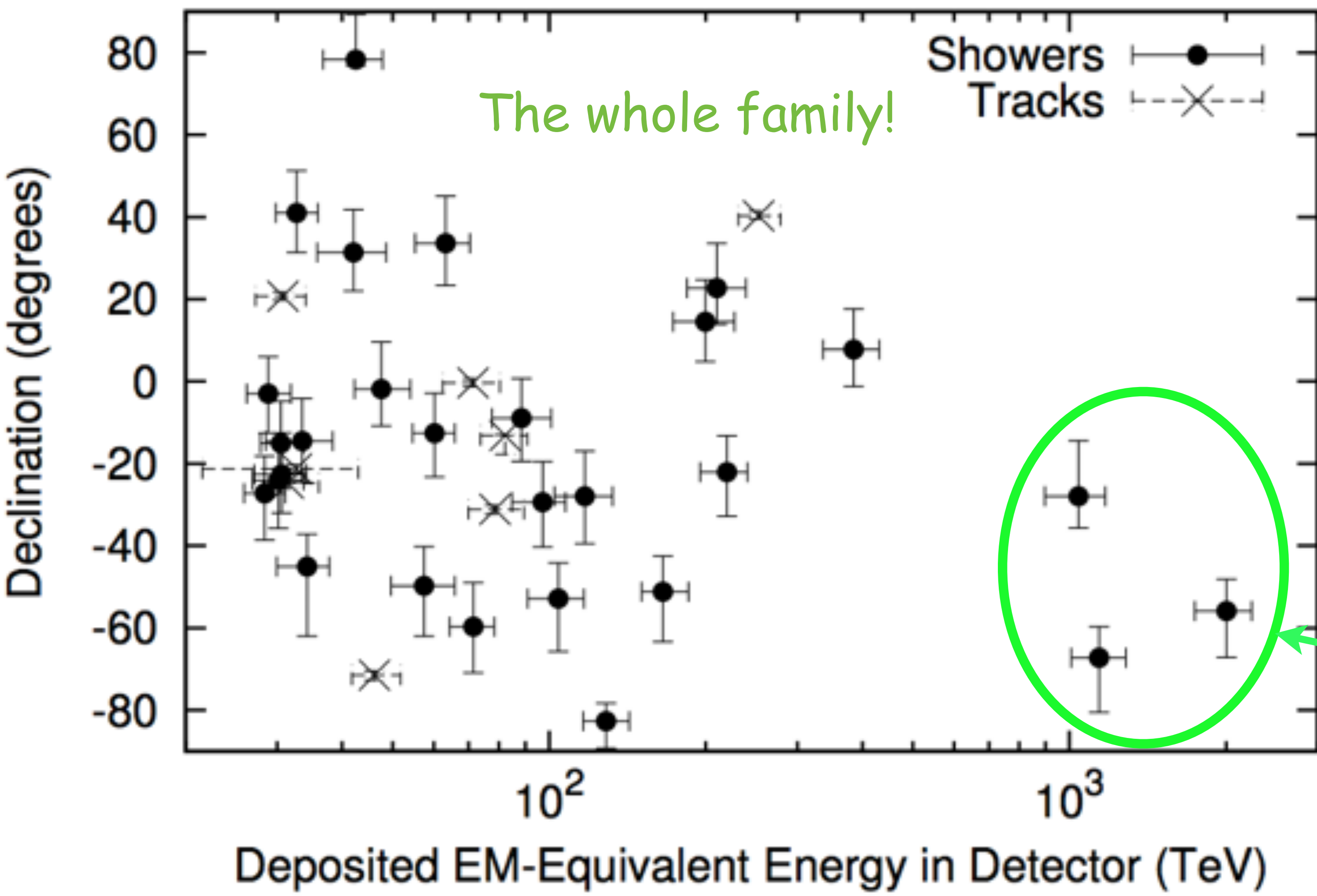
astrophysical ?

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]



✓ 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 ?

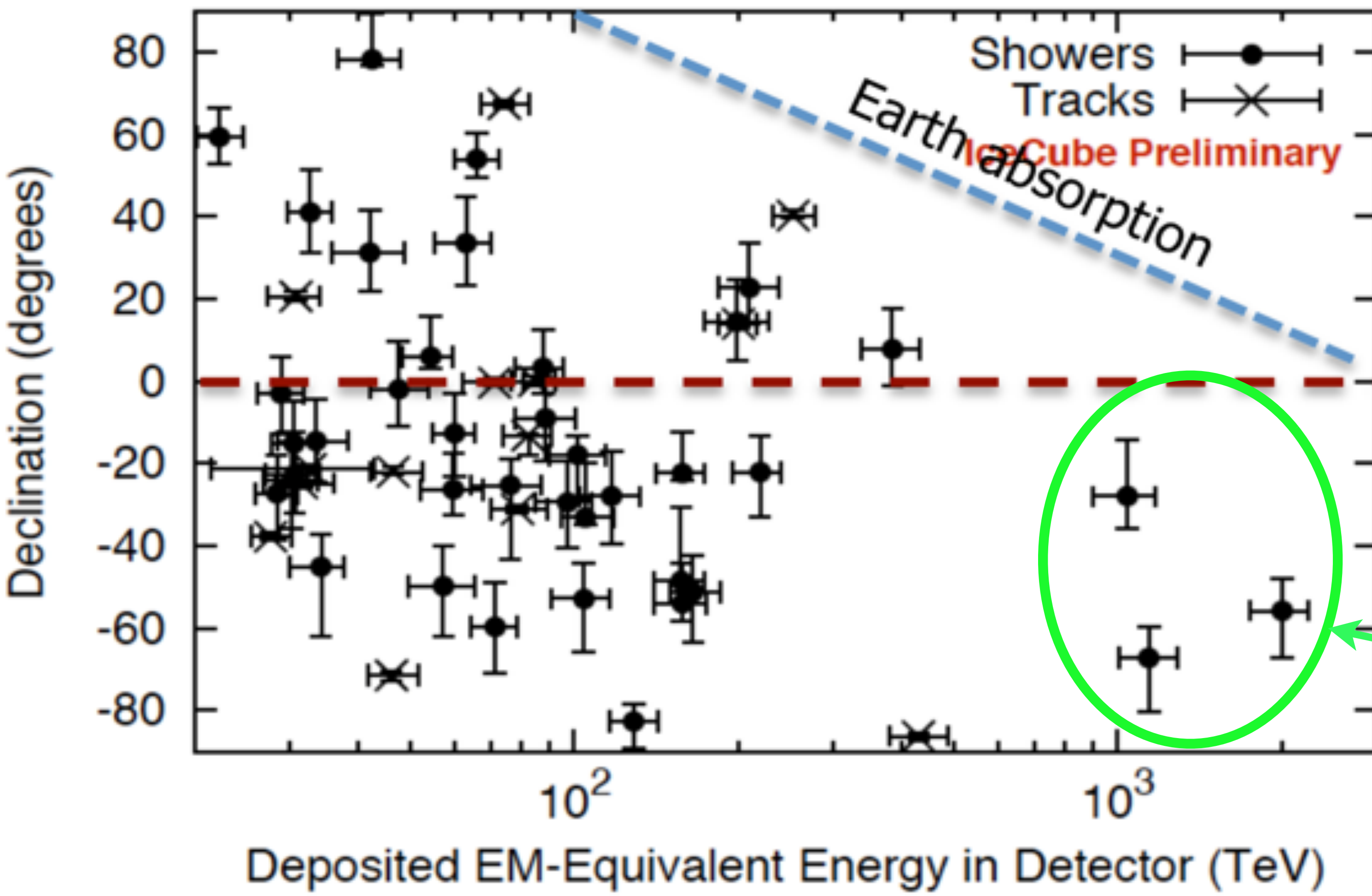
or something else ?

Mission for IceCube began !

✓ Looking for lower energy contained events, 1347 days livetime

IPA 2015

The whole family!



✓ totally 54 events

✓ still three events with energy ~ PeV

4 years of data

excess of events ~ 7σ

which one?

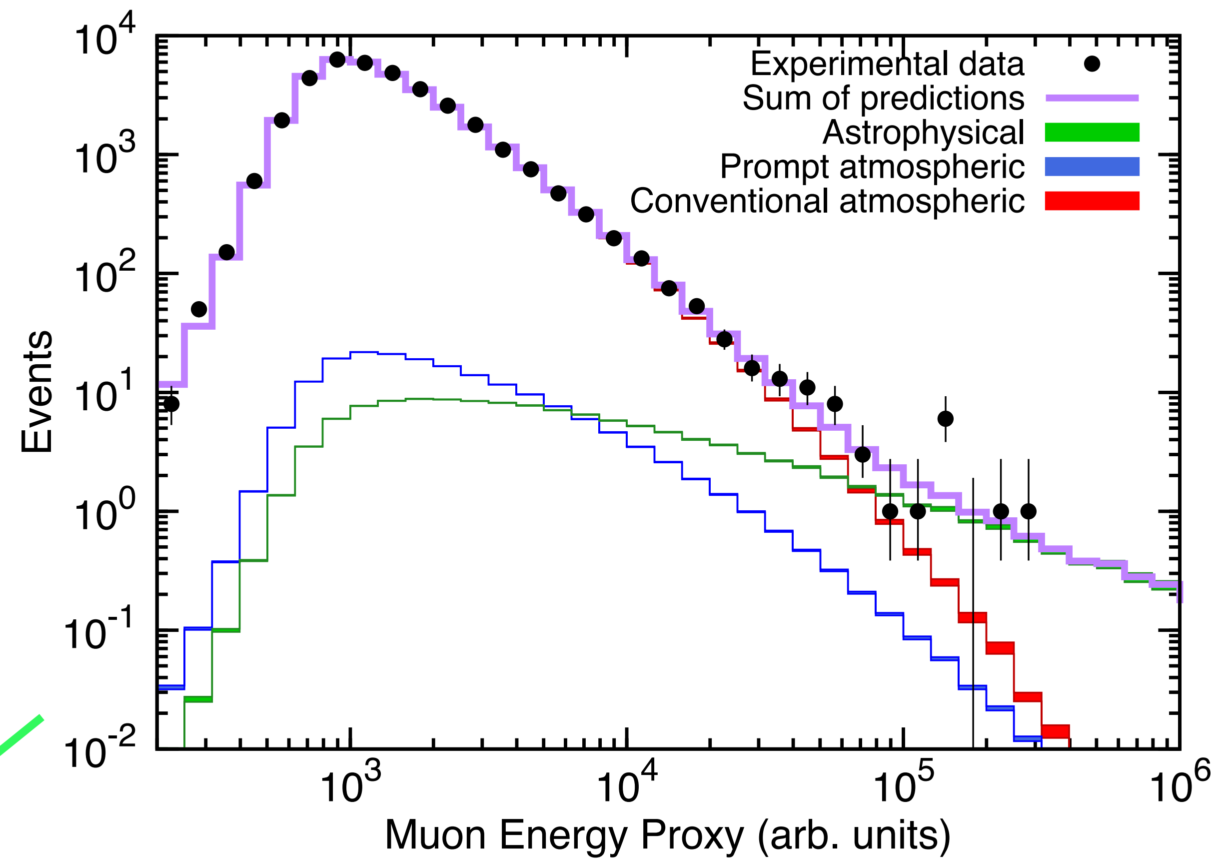
atmospheric ?

astrophysical ?

or something else ?

Mission for IceCube began !

✓ Looking for muon-track events, 660 days livetime



$$\Phi(E_\nu) = 9.9^{+3.9}_{-3.4} \times 10^{-19} \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-2} \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$$

, fitting the index: 2.2 ± 0.2

lowering the energy threshold of HESE analysis to 1 TeV

$$\Phi(E_\nu) = 2.06^{+0.4}_{-0.3} \times 10^{-18} \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-2.46\pm0.12} \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$$

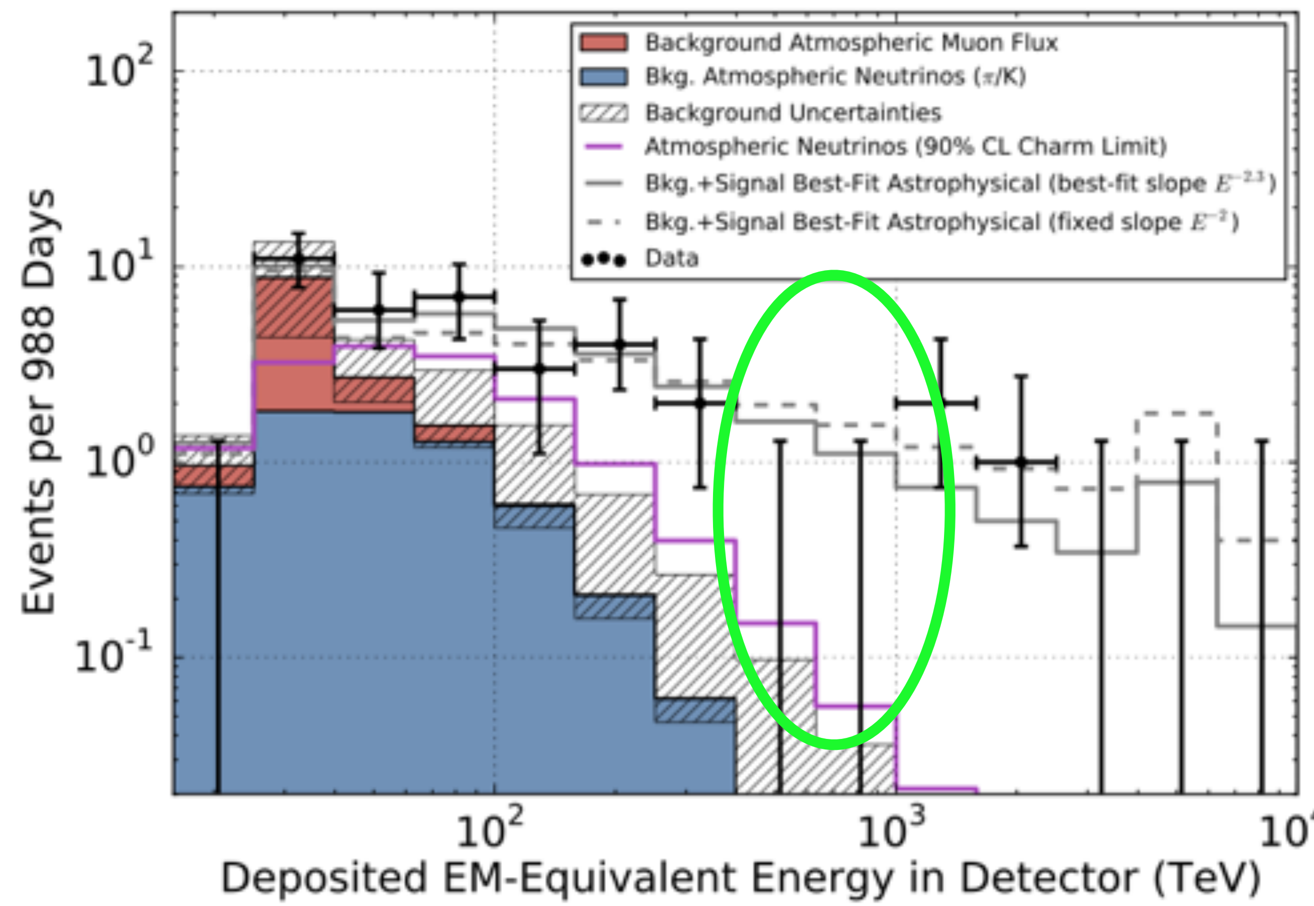
IceCube data

Some features of the observed spectrum

IceCube data

Some features of the observed spectrum

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

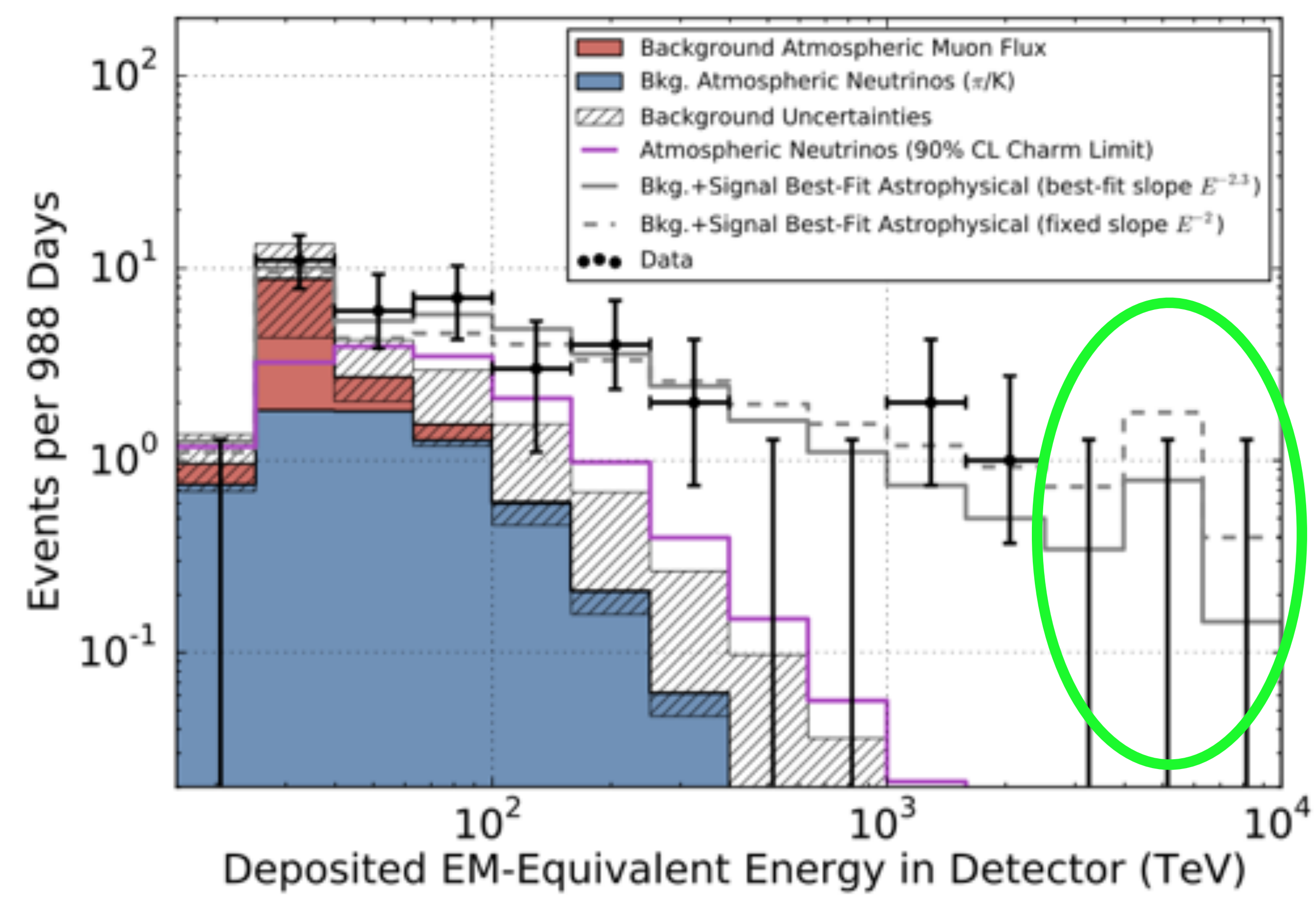


IceCube data

Some features of the observed spectrum

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

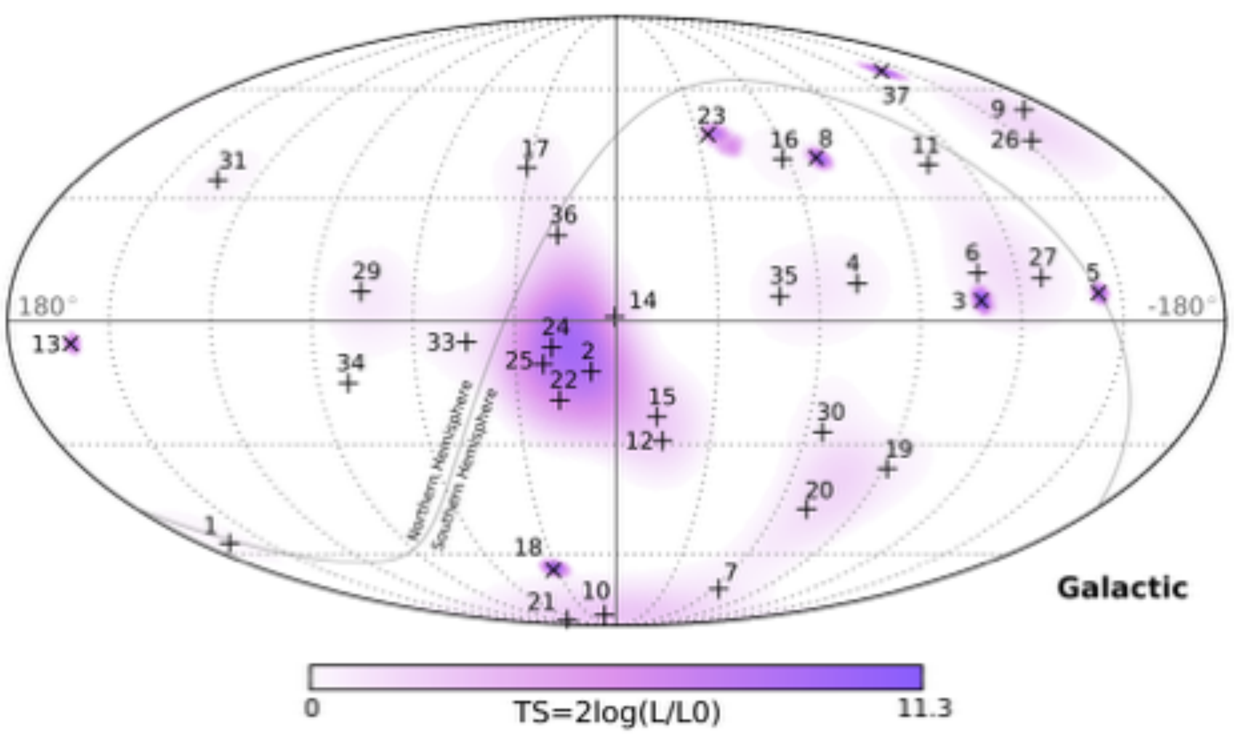
✓ cut-off in events: no events observed with energy > 2 PeV

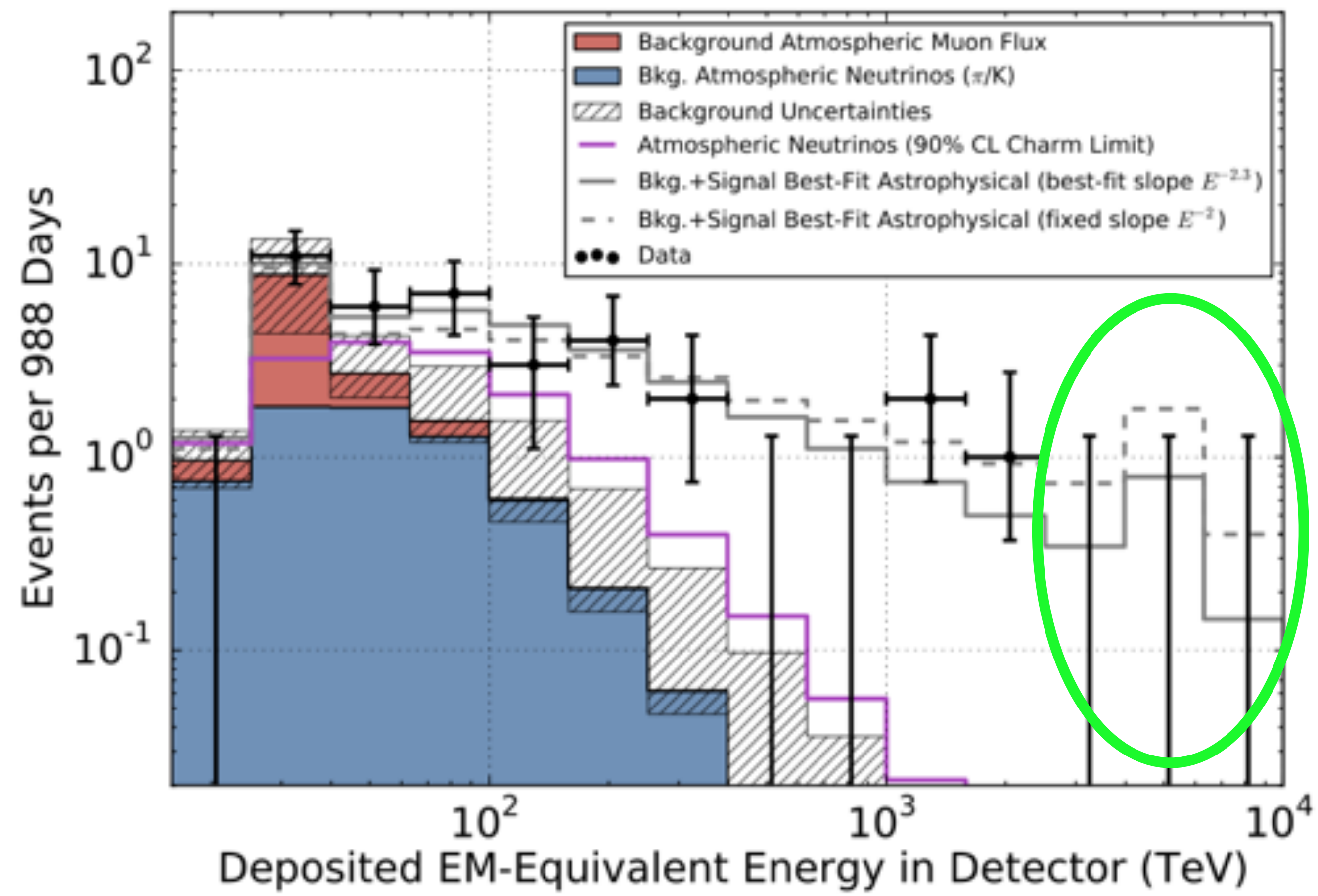


IceCube data

Some features of the observed spectrum

- ✓ 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)





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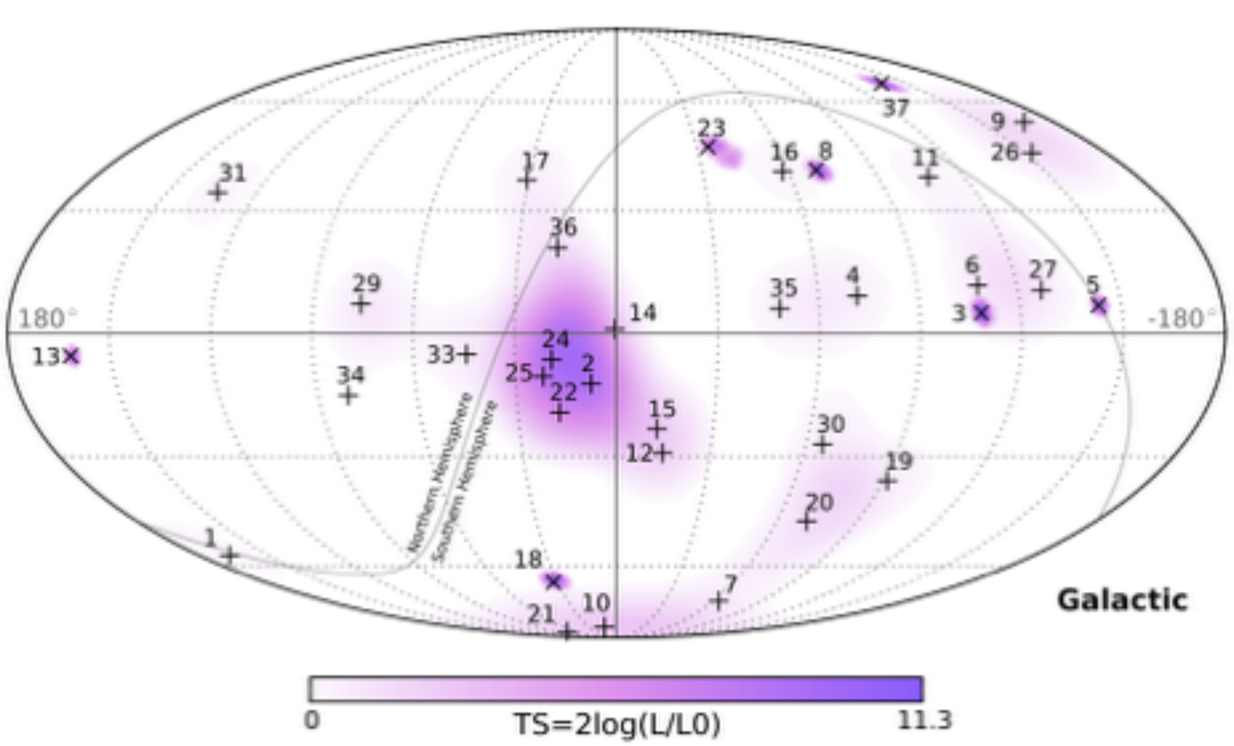
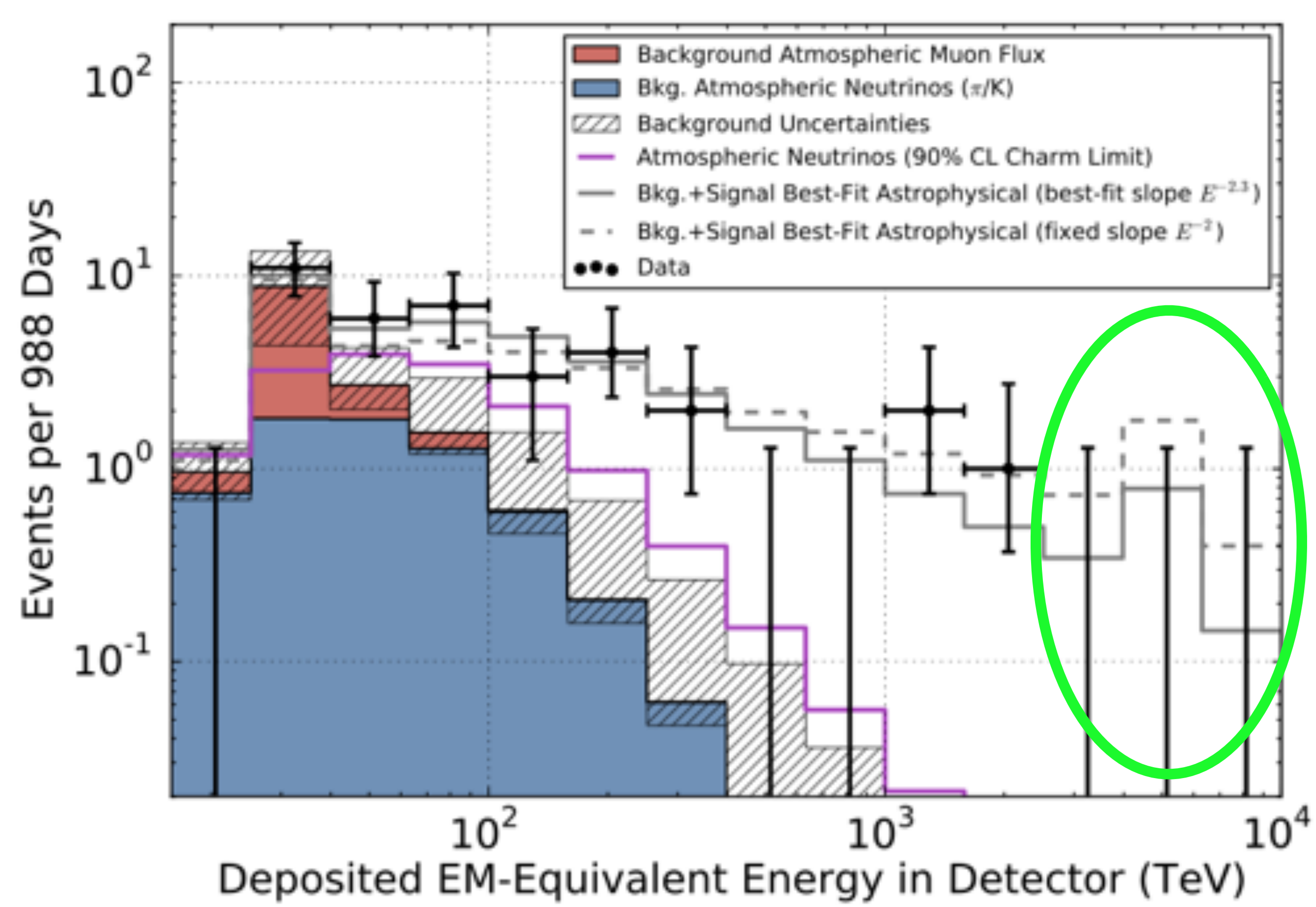
⚠ none of the above-mentioned issues are significant





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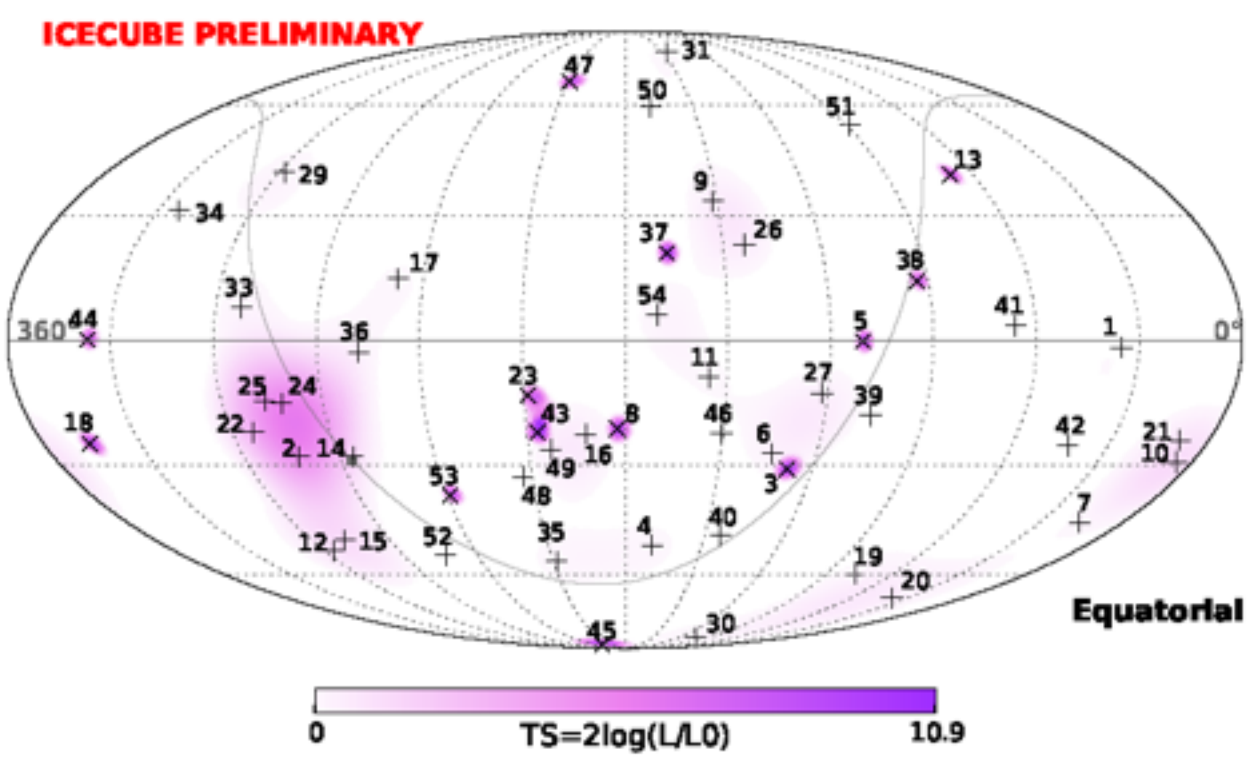

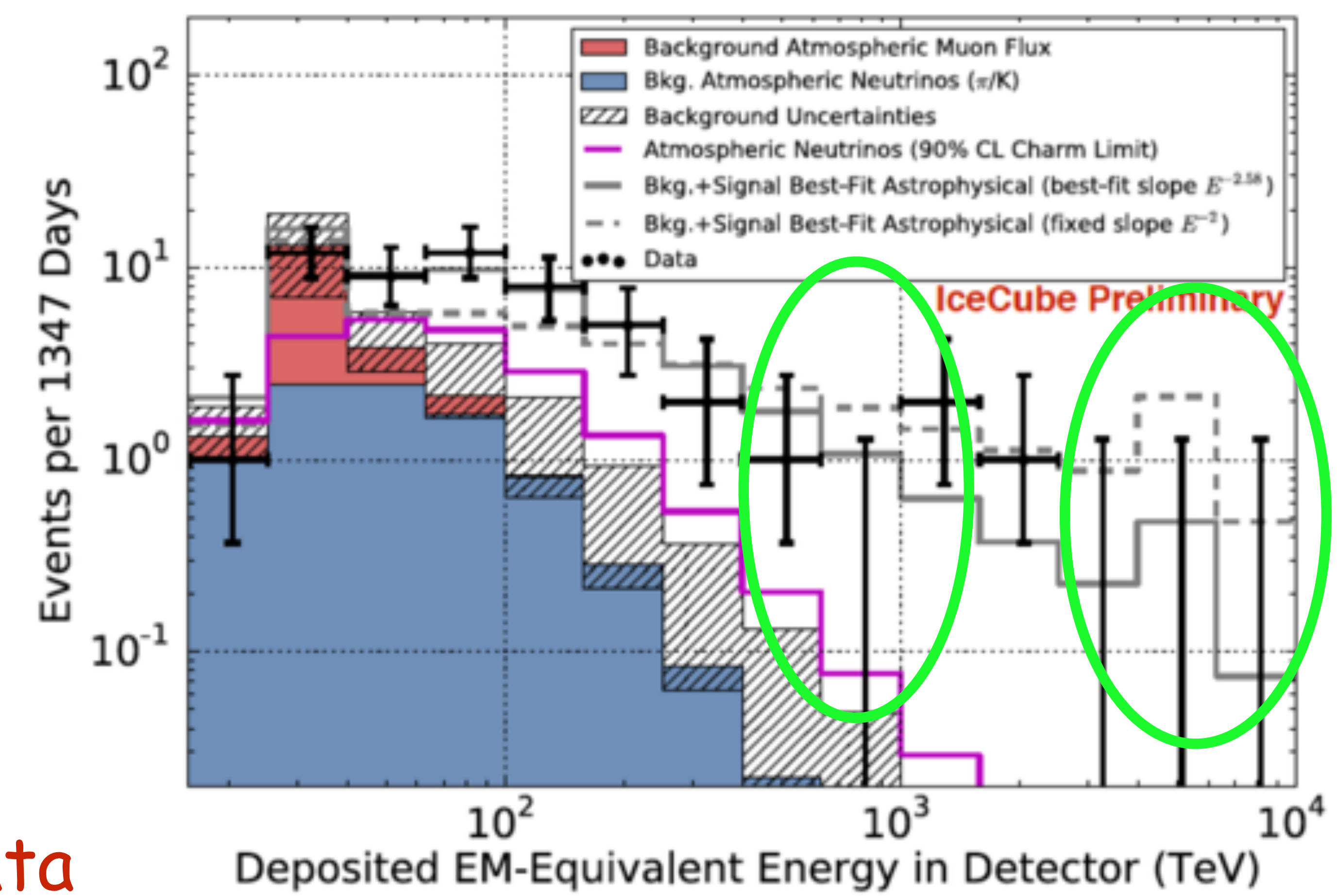

4 years of data

Interpretations of IceCube data

✓ "Conventional" interpretations of IceCube data

- Cosmic ray sources
- GRBs
- Galaxy clusters
- Star-forming galaxies
- AGNs
- Fermi bubbles
- Galactic Center activities
- •
- •
- •

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]].
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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]].

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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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Some class of sources are starting to be excluded

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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]].
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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

A. Esmaili, S. K. Kang and P. D. Serpico, JCAP 1412, 054 (2014), arXiv:1410.5979

A. Esmaili and P. D. Serpico, JCAP 1510 (2015), arXiv:1505.06486

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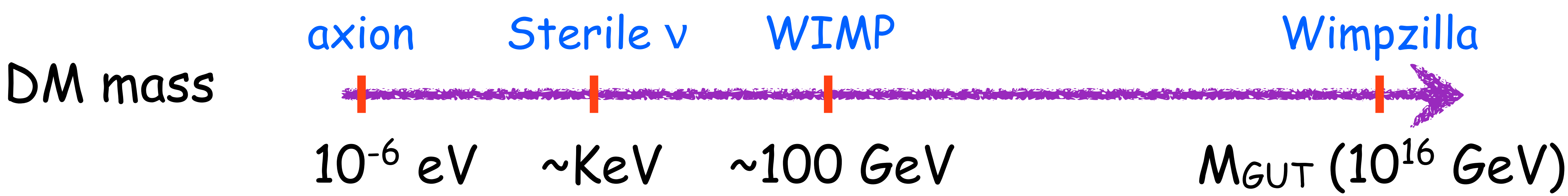
The idea

decaying dark matter

$$m_{\mathrm{DM}} \sim \mathcal{O}(\mathrm{PeV})$$



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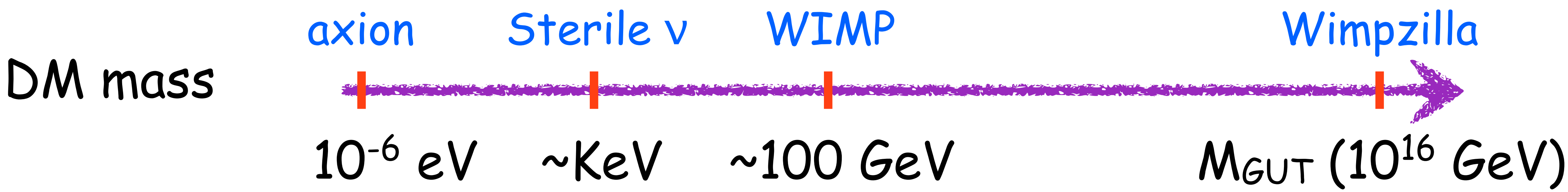
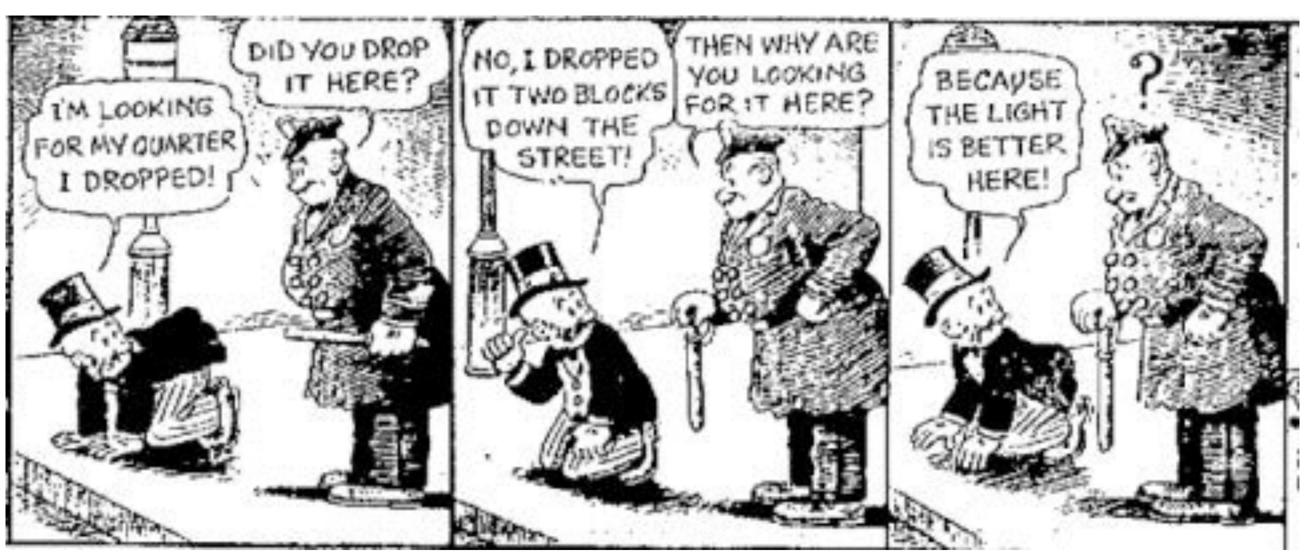


caution: streetlight effect



Mulla Nasreddin

The idea

decaying dark matter

$$m_{\rm DM} \sim \mathcal{O}(\rm PeV)$$

DM mass

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

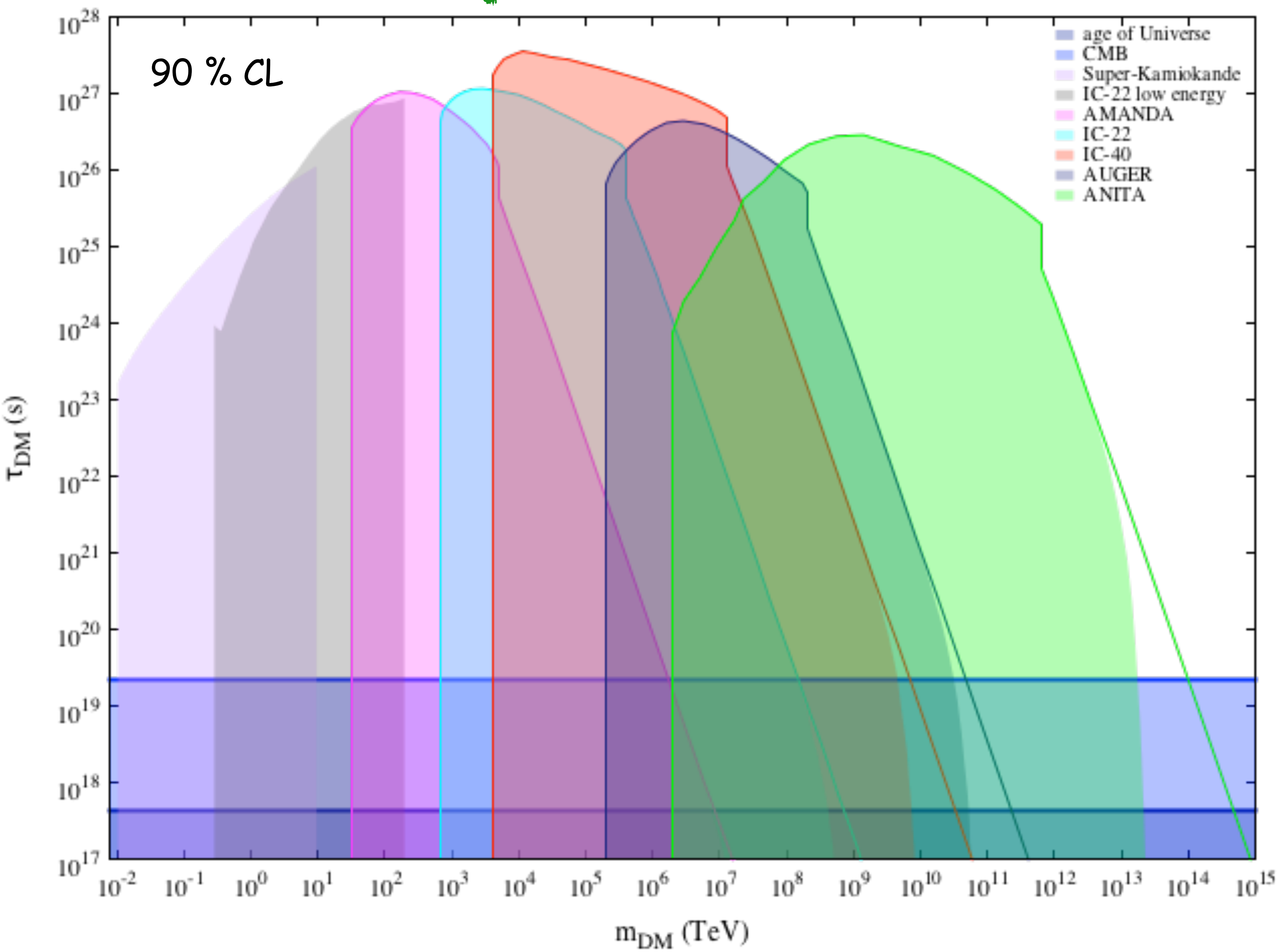
The idea

decaying dark matter

$$m_{\rm DM} \sim \mathcal{O}(\text{PeV})$$

$$\tau_{\rm DM} \sim \mathcal{O}(10^{28}\ \text{s})$$

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



using neutrino experiments

CMB

age of Universe

The idea

decaying dark matter

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$$\tau_{\rm DM} \sim \mathcal{O}(10^{28}\ \rm s)$$

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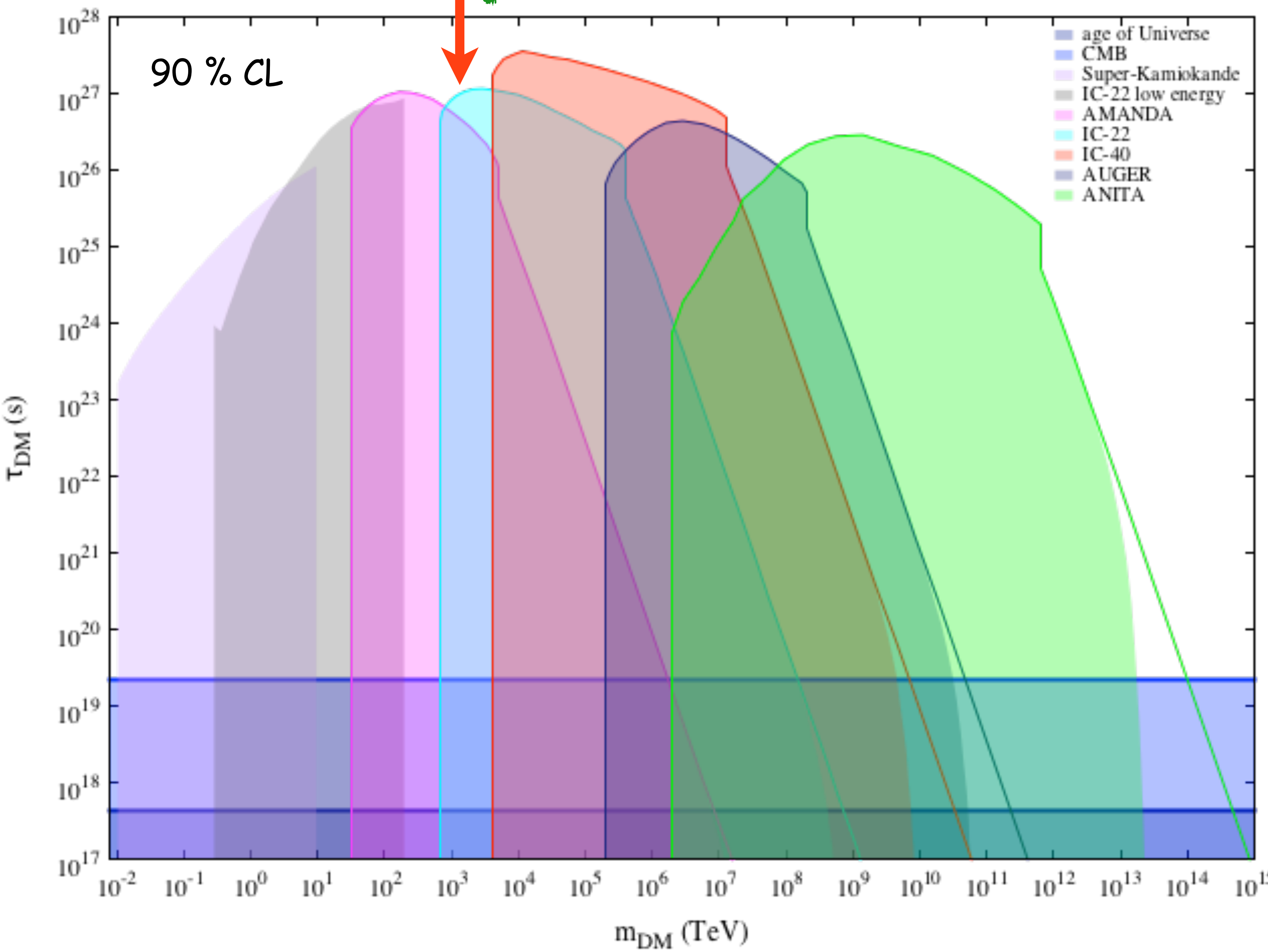

using neutrino experiments

CMB

age of Universe

The idea

decaying dark matter

$$m_{\rm DM} \sim \mathcal{O}({\rm PeV})$$

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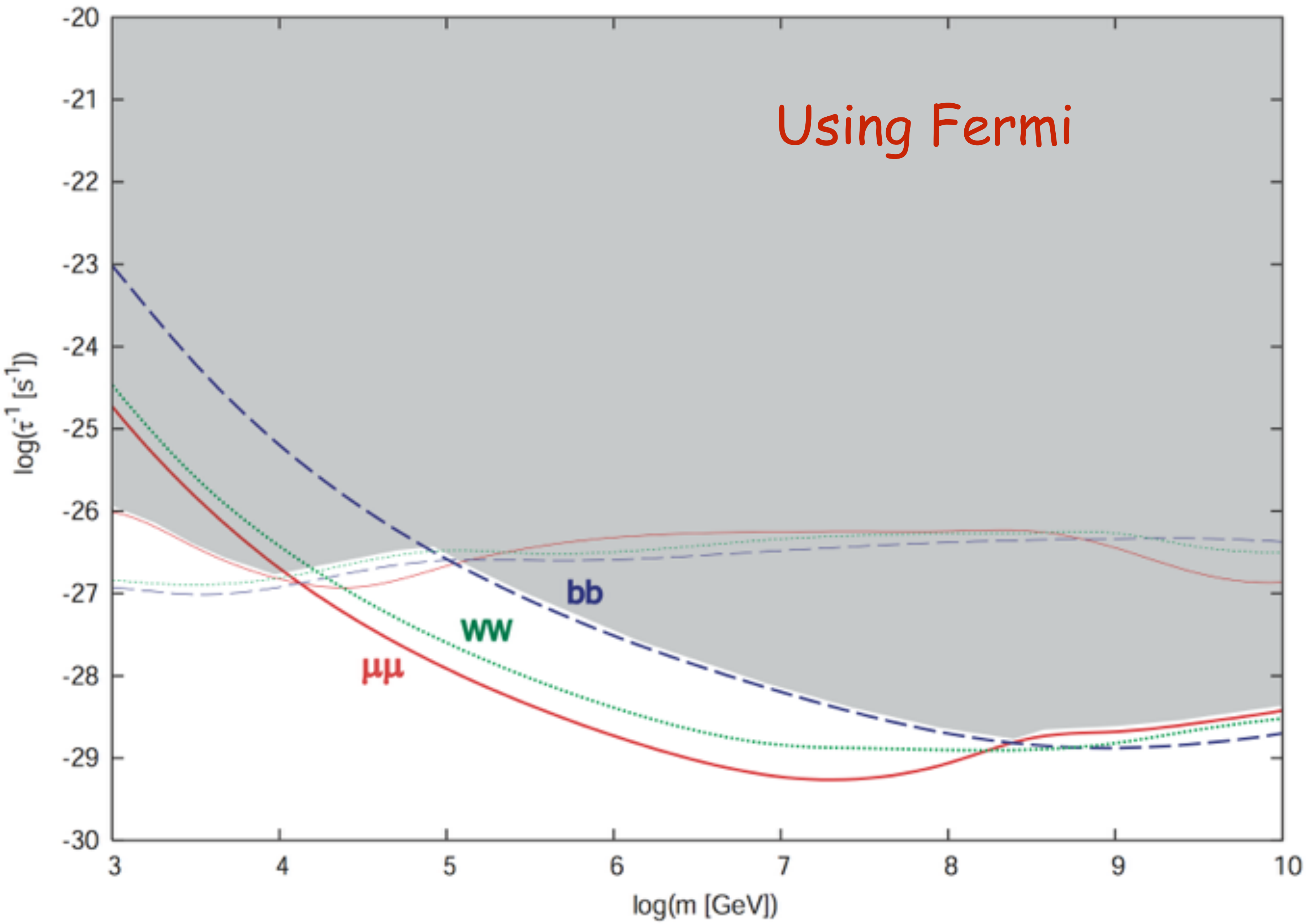

K. Murase and J. Beacom
JCAP (2012) [arXiv: 1206.2595]

The idea

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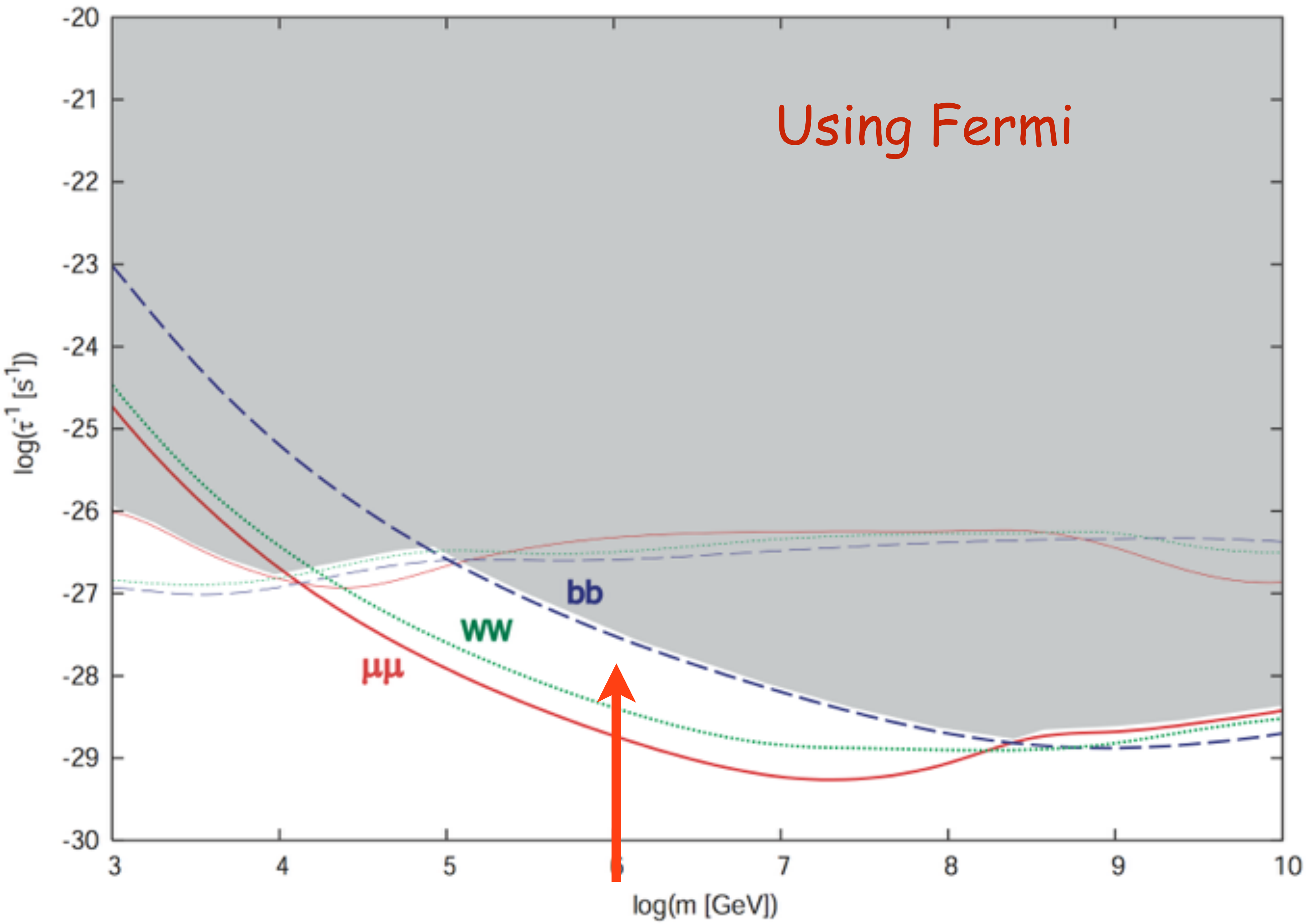
$$m_{\rm DM} \sim \mathcal{O}(\mathrm{PeV})$$

$$\tau_{\rm DM} \sim \mathcal{O}(10^{28}\ \mathrm{s})$$



K. Murase and J. Beacom
JCAP (2012) [arXiv: 1206.2595]

The idea

The 2nd approach of Mambrini's talk

decaying dark matter

$$m_{\rm DM} \sim \mathcal{O}({\rm PeV})$$

$$\tau_{\rm DM} \sim \mathcal{O}(10^{28}\ {\rm s})$$

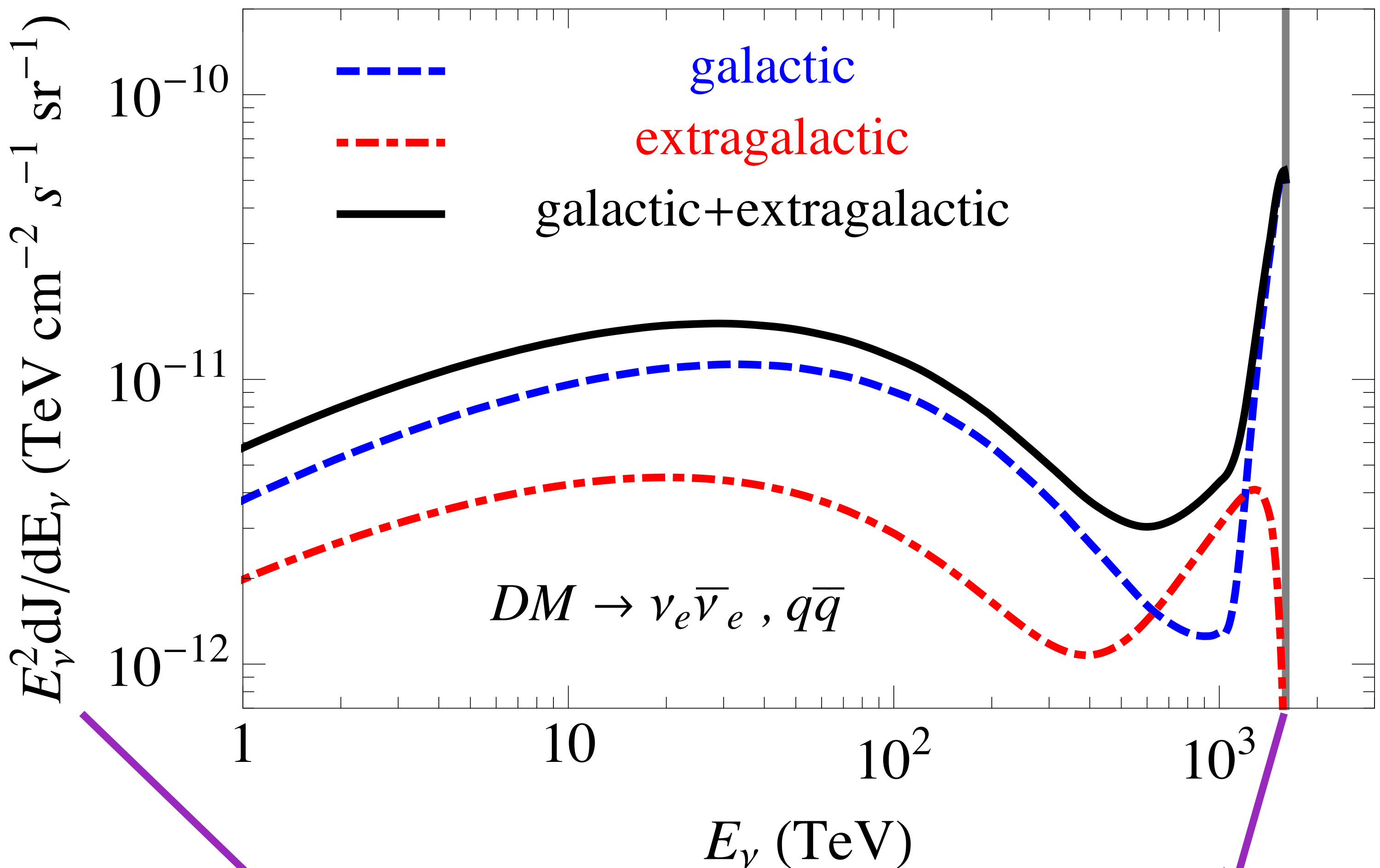
From model-building point of view

R-parity violating gravitino hidden sector gauge boson singlet fermion in extra-dim	Feldstein, Kusenko, Matsumoto, Yanagida PRD (2013) [arXiv: 1303.7320]
Sterile neutrino	Higaki, Kitano and Sato JHEP (2014) [arXiv: 1405.0013]
Sterile neutrino + U(1) gauge	Ko and Tang PLB (2015) [arXiv: 1508.02500]
mirror dark matter	Berezhiani [arXiv: 1506.09040]
EFT leptophilic DM	Boucenna et. al., [arXiv: 1507.01000]
scalar + sterile neutrino	Dudas, Mambrini, Olive, PRD [arXiv: 1412.3459]

The idea

decaying dark matter
$m_{\rm DM} \sim \mathcal{O}(\text{PeV})$
$\tau_{\rm DM} \sim \mathcal{O}(10^{28}\ \text{s})$

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



$(\nu_e + \nu_\mu + \nu_\tau)/3$ $\quad m_{\rm DM}/2 = 1.6$ PeV

Galactic

$$\frac{d\Phi_{\rm gal}}{dE_\nu} = \frac{1}{4\pi m_{\rm DM}\tau_{\rm DM}} \frac{dN_\nu}{dE_\nu} \int_0^\infty ds\ \rho_{DM}[r(s,l,b)]$$

extra-Galactic

$$\frac{d\Phi_{\rm eg}}{dE_\nu} = \frac{\Omega_{\rm DM}\rho_c}{4\pi m_{\rm DM}\tau_{\rm DM}} \int_0^\infty dz\ \frac{1}{H(z)} \frac{dN_\nu}{dE_\nu}[E_\nu(1+z)]$$

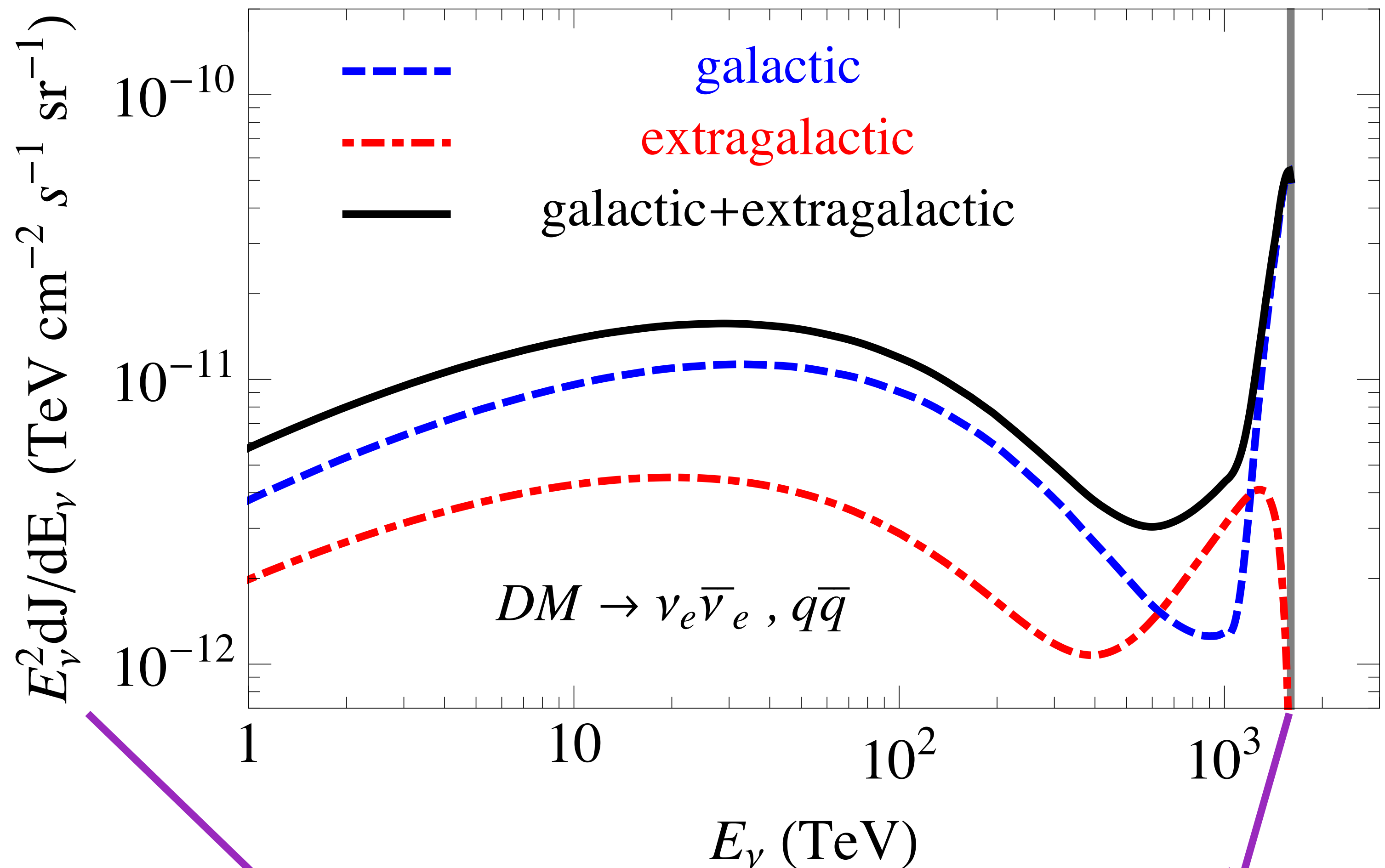
The idea

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

decaying dark matter

$m_{\rm DM} \sim \mathcal{O}(\rm PeV)$

$\tau_{\rm DM} \sim \mathcal{O}(10^{28}\ \rm s)$



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

$m_{\rm DM}/2 = 1.6$ PeV

quarks

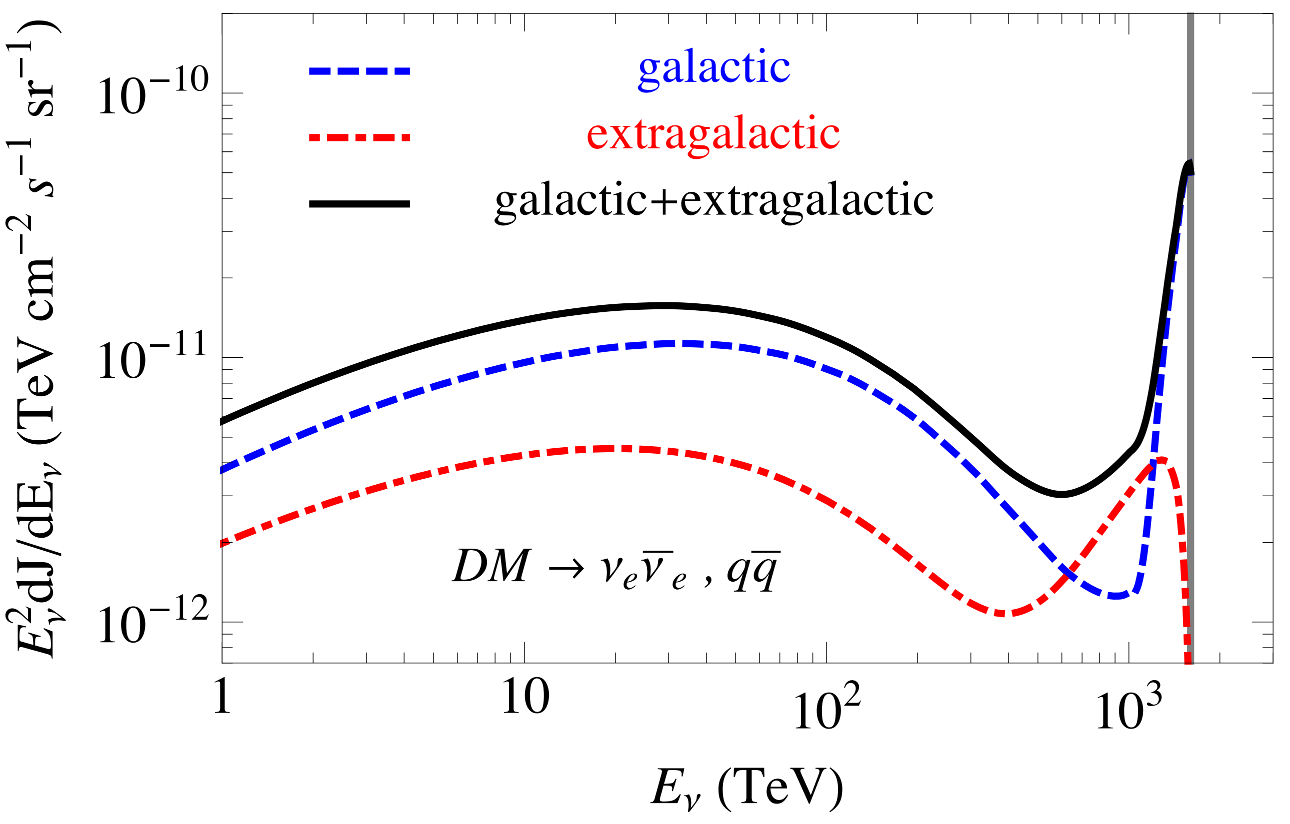
$$\frac{dN_\nu}{dE_\nu} = (1 - b_{\rm H}) \left.\frac{dN_\nu}{dE_\nu}\right|_{\rm S} + b_{\rm H} \left.\frac{dN_\nu}{dE_\nu}\right|_{\rm H}$$

neutrinos, charged leptons

Galactic
$$\frac{d\Phi_{\rm gal}}{dE_\nu} = \frac{1}{4\pi m_{\rm DM}\tau_{\rm DM}} \frac{dN_\nu}{dE_\nu} \int_0^\infty ds\ \rho_{DM}[r(s,l,b)]$$

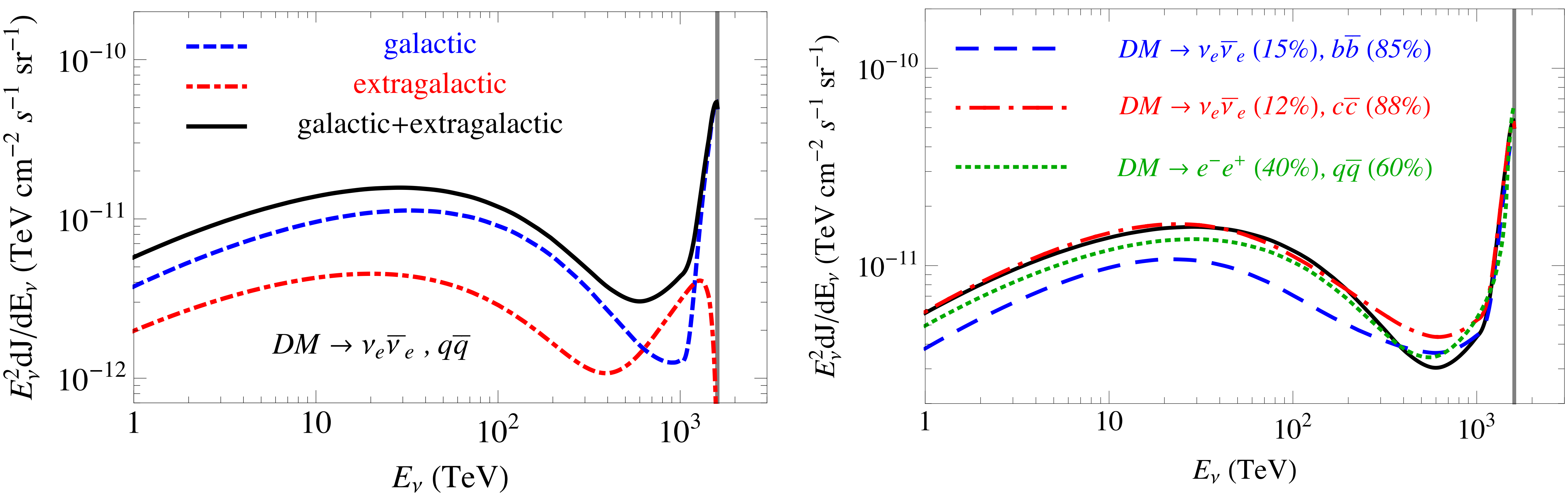
extra-Galactic
$$\frac{d\Phi_{\rm eg}}{dE_\nu} = \frac{\Omega_{\rm DM}\rho_c}{4\pi m_{\rm DM}\tau_{\rm DM}} \int_0^\infty dz\ \frac{1}{H(z)} \frac{dN_\nu}{dE_\nu}[E_\nu(1+z)]$$

✓ fine-tuned decay channels ?



✓ fine-tuned decay channels ?

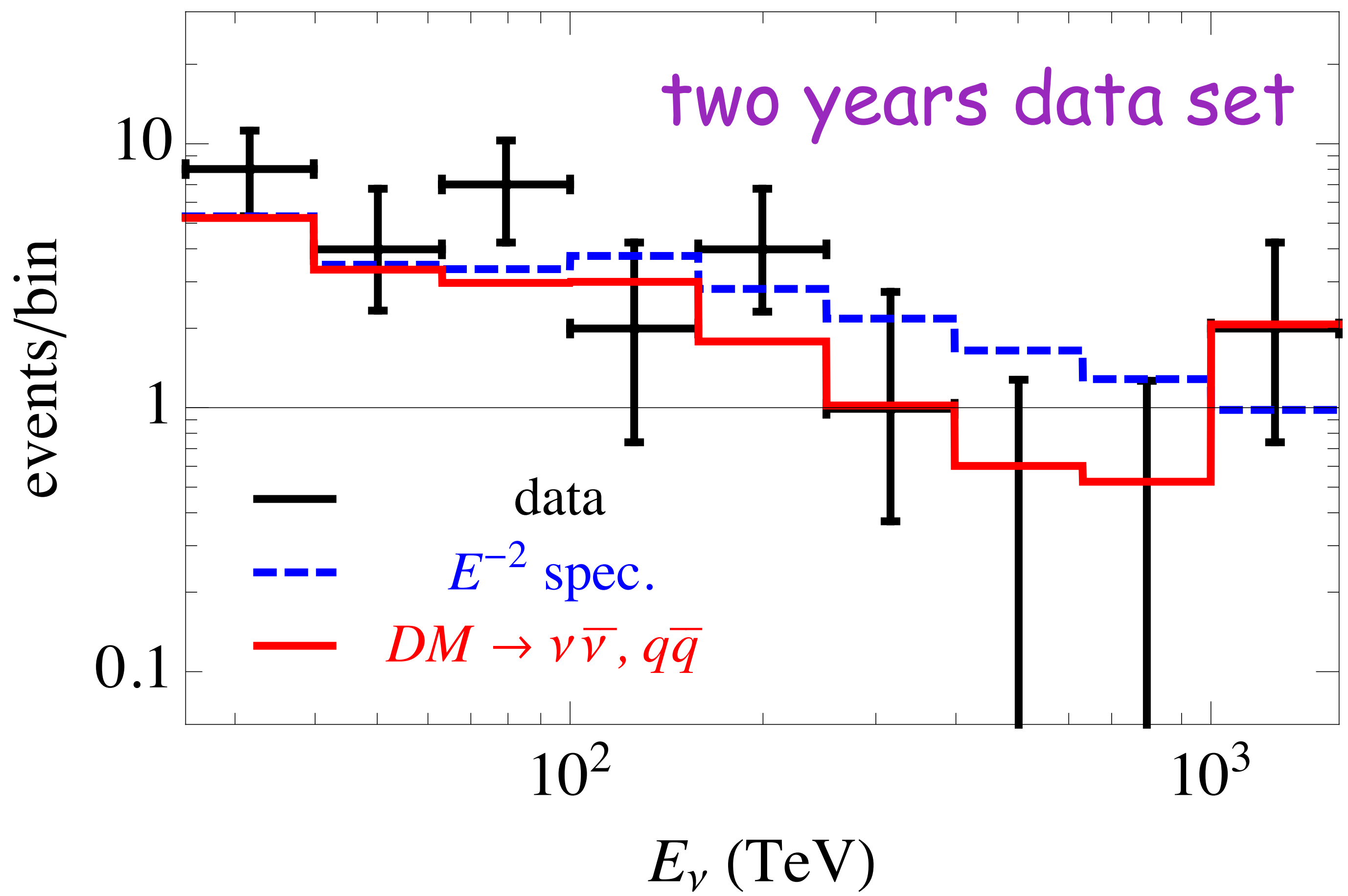
τ_{DM} = (1-3) x 10^{27} s



the intriguing features are generic

Confronting with energy distribution of IceCube data

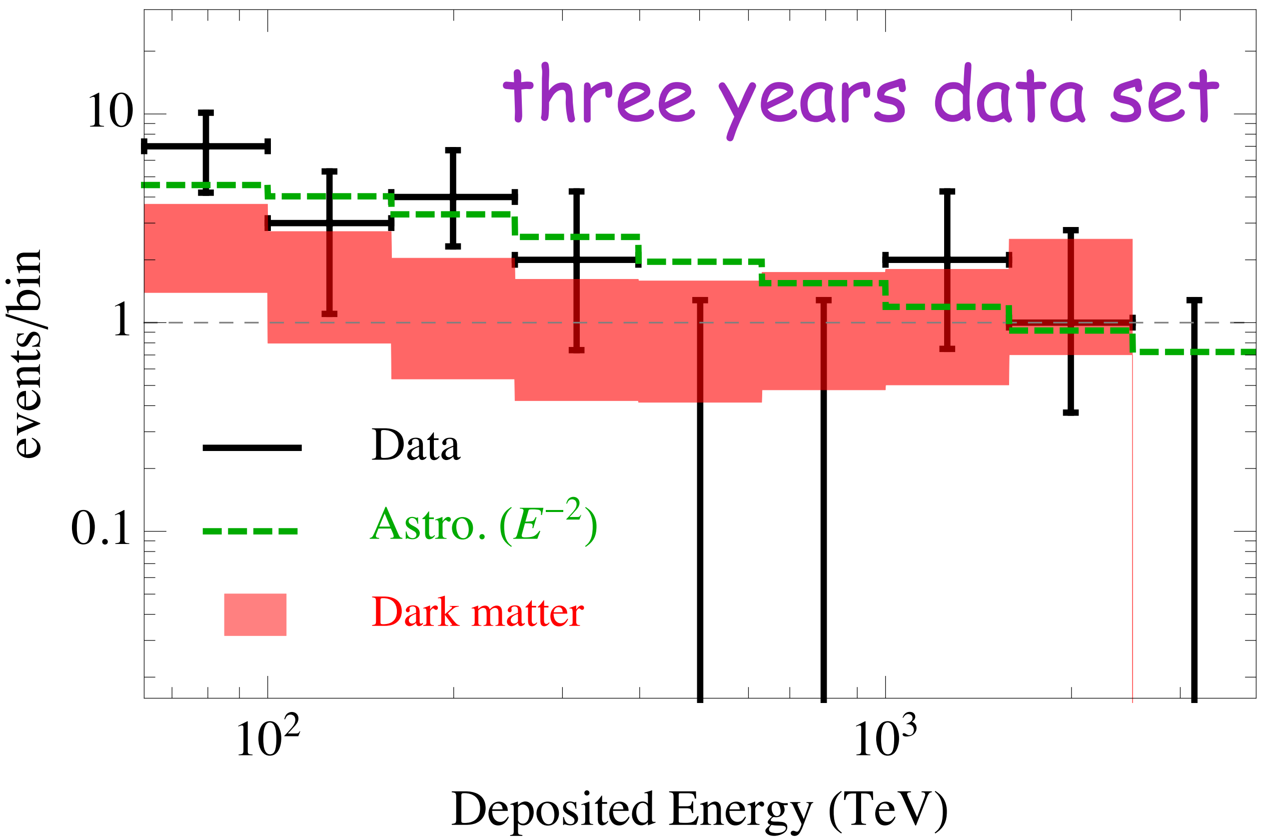
$b_H = 0.12$ and $\tau_{DM} = 2 \times 10^{27}$ s



A. E. and P. D. Serpico,
JCAP (2013) [1308.1105]

Confronting with energy distribution of IceCube data

sterile neutrino model



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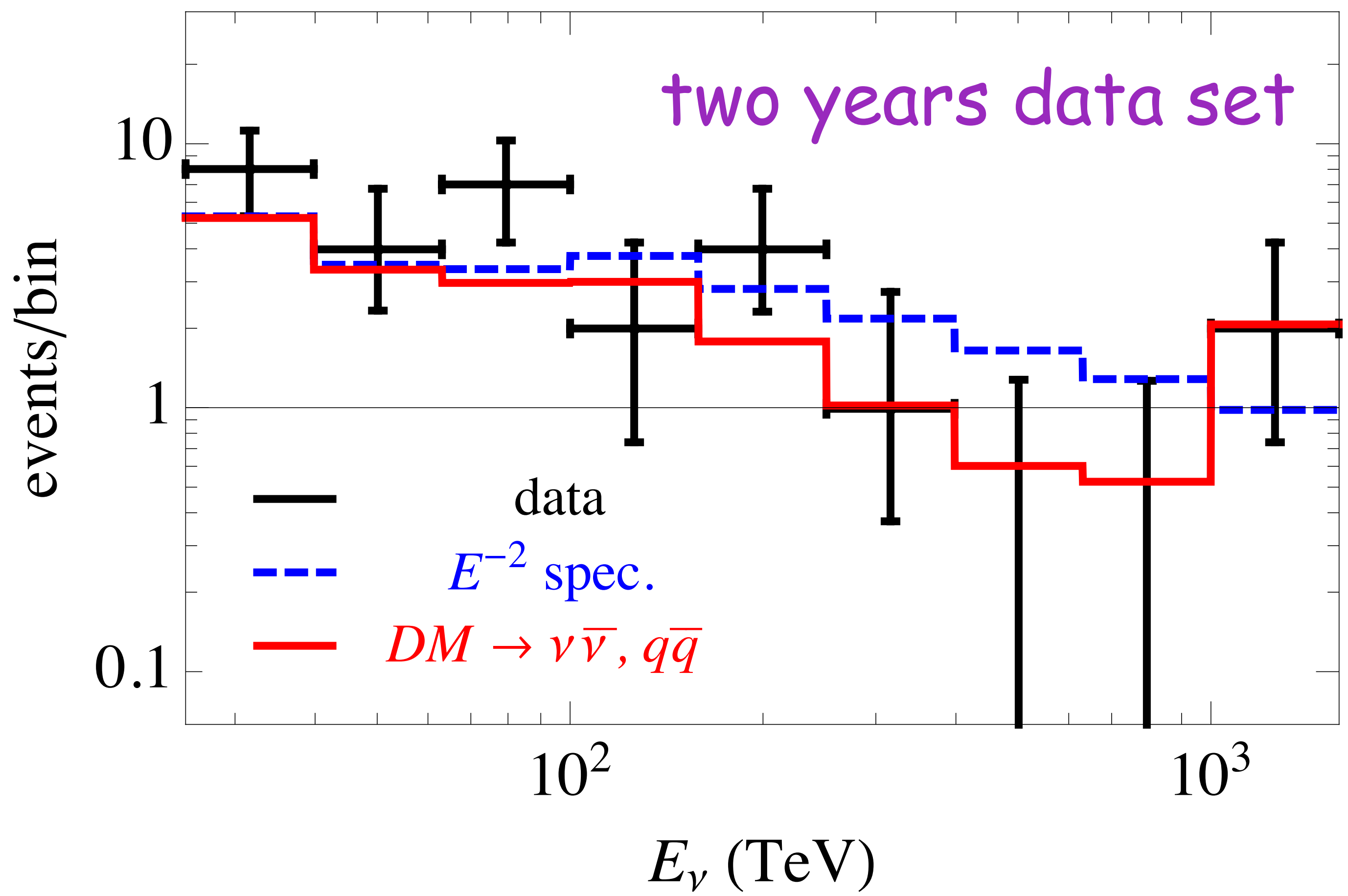
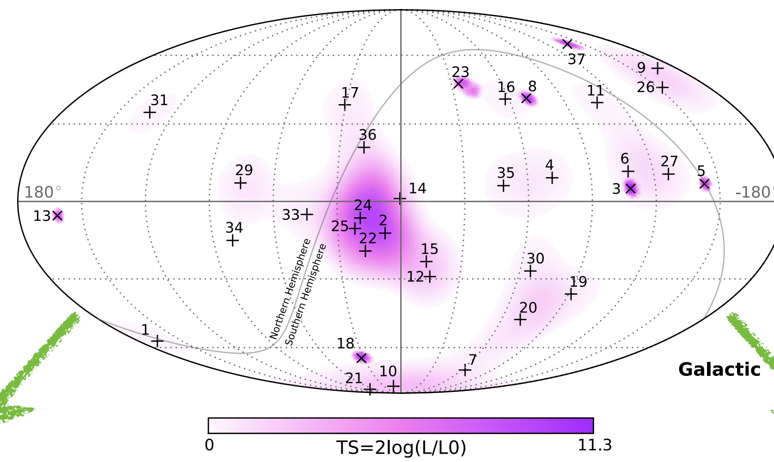


A. E., S. K. Kang and P. D. Serpico, JCAP (2014) [1410.5979]

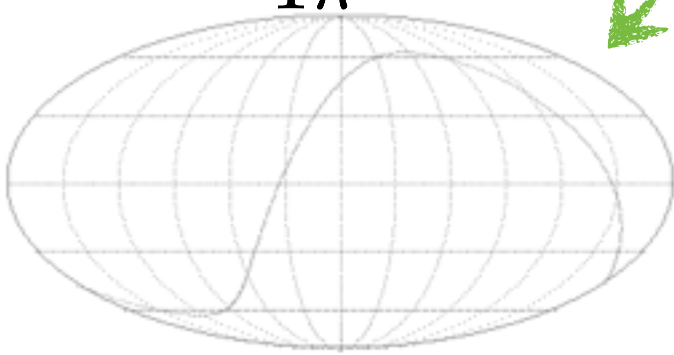
A. E. and P. D. Serpico, JCAP (2013) [1308.1105]

Angular distribution of neutrinos from decaying DM

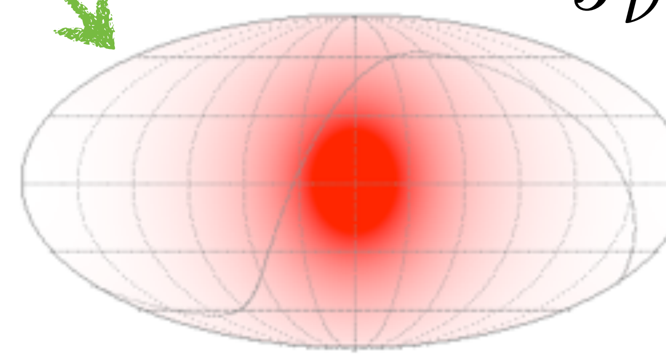
✓ We would compare



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



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



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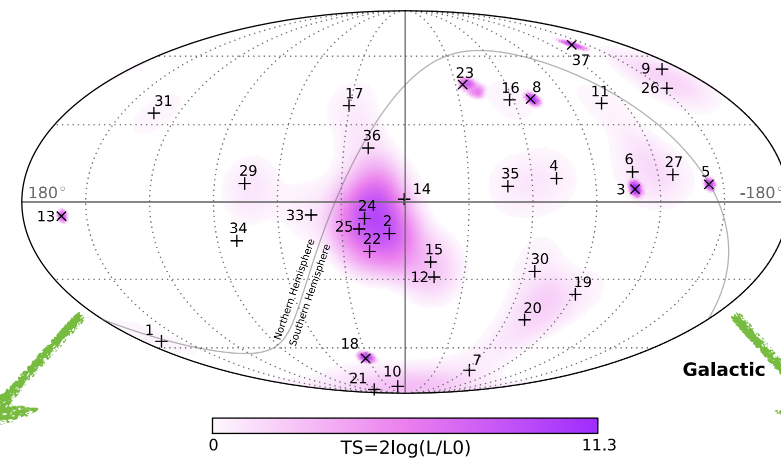

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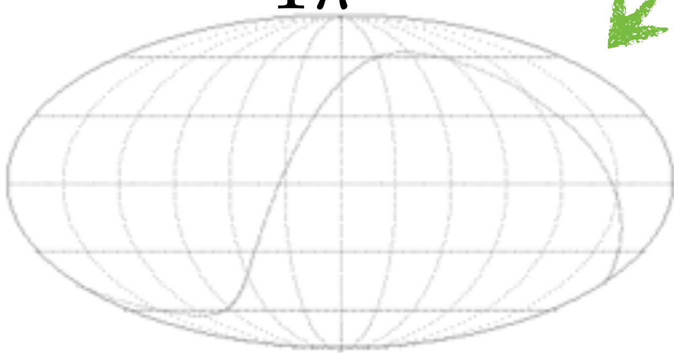

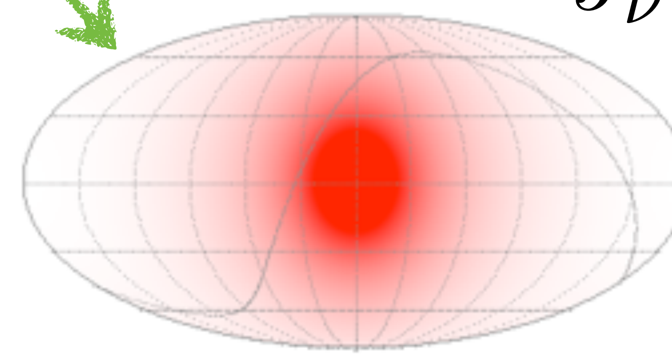

PDF of data

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

"flat sky" approximation

PDF of isotropic dis.

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

PDF of DM

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

Angular distribution of neutrinos from decaying DM

✓ Likelihood analysis

Number of signal events

Test Statistics

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

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

N = 35 ? too optimistic!

Angular distribution of neutrinos from decaying DM

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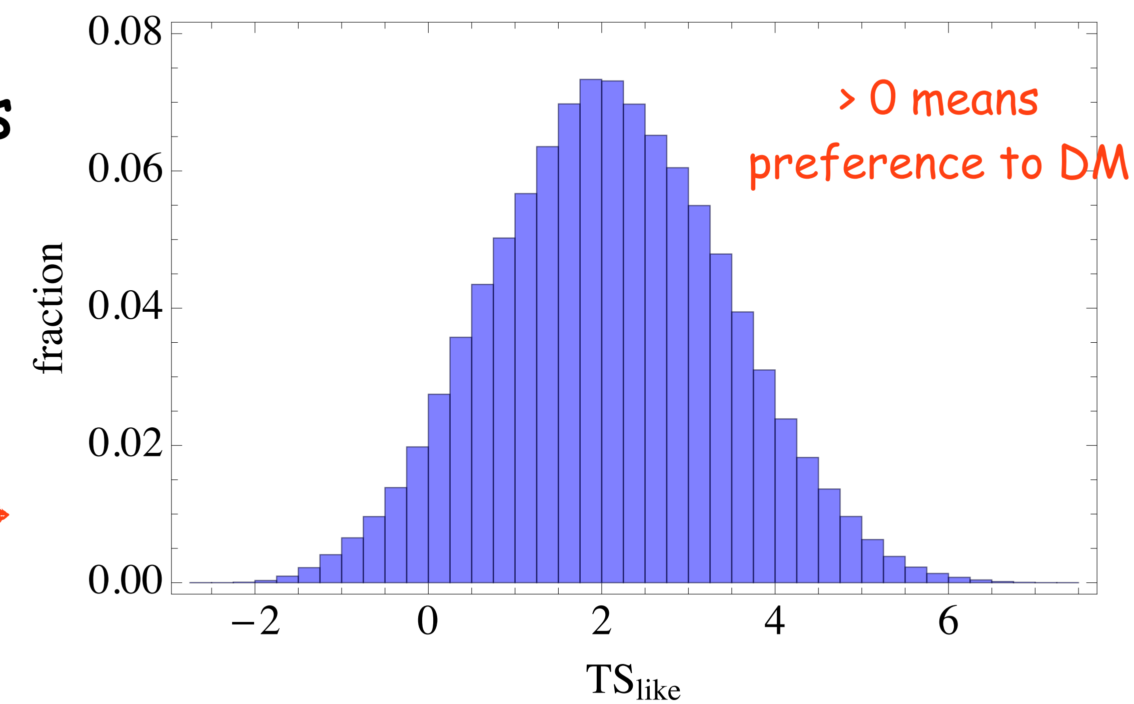
N = 35 ? too optimistic!

✓ 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)



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

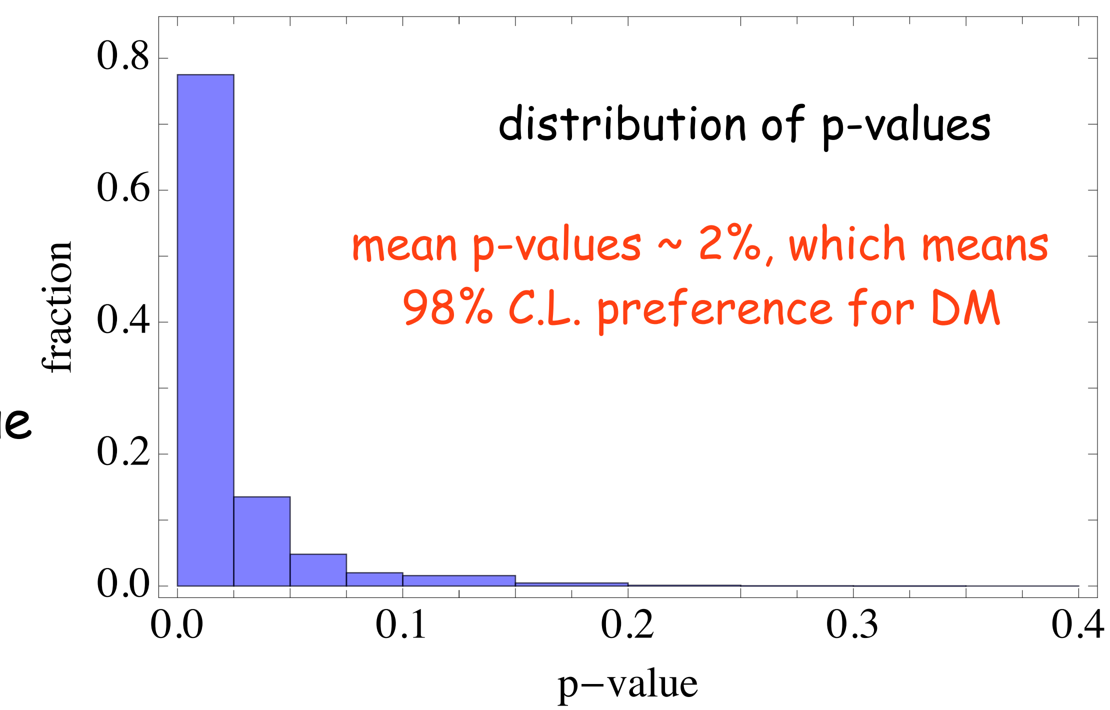
Quantifying the preference

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

↓

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

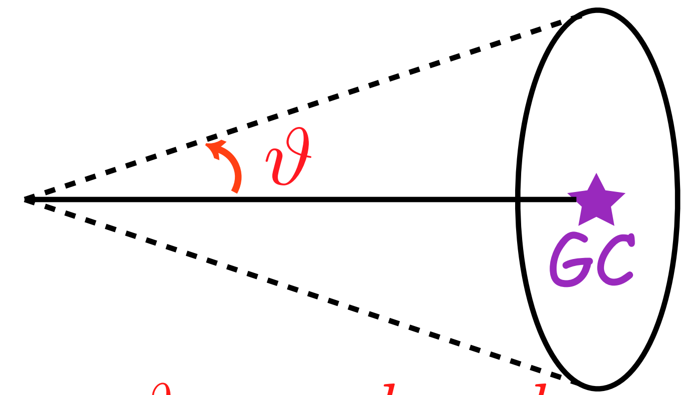
p-value →



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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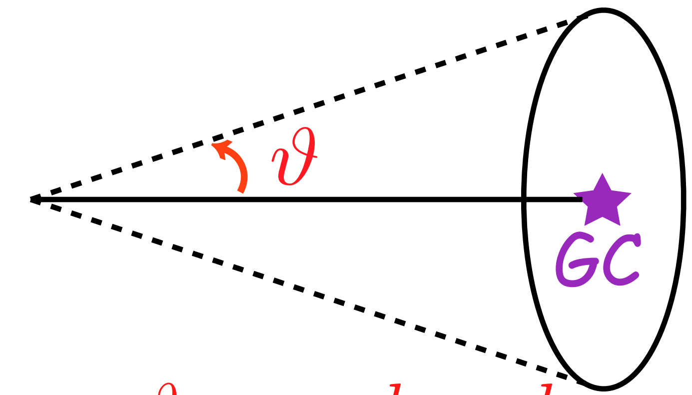

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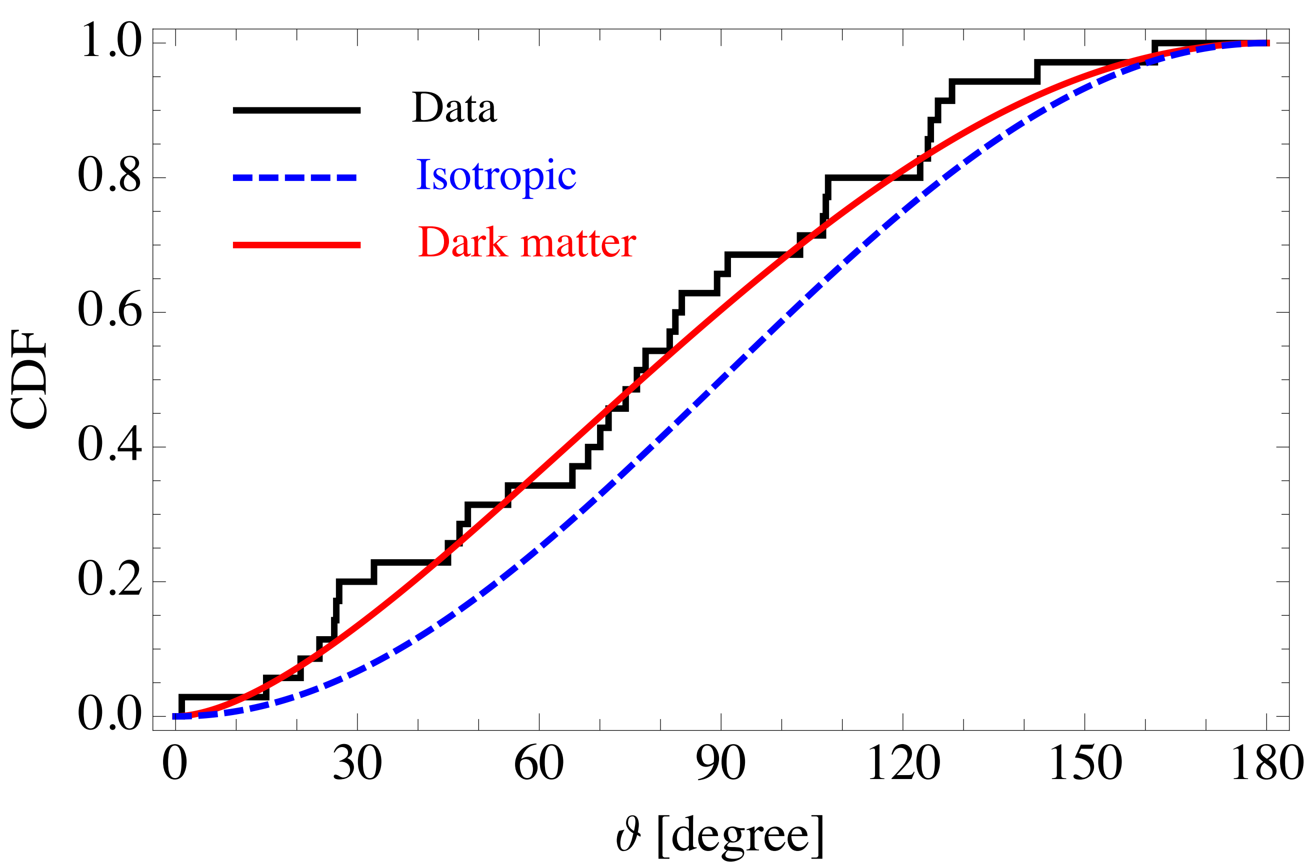

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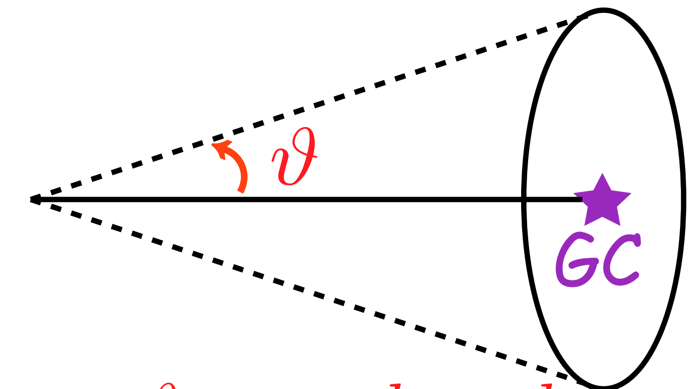

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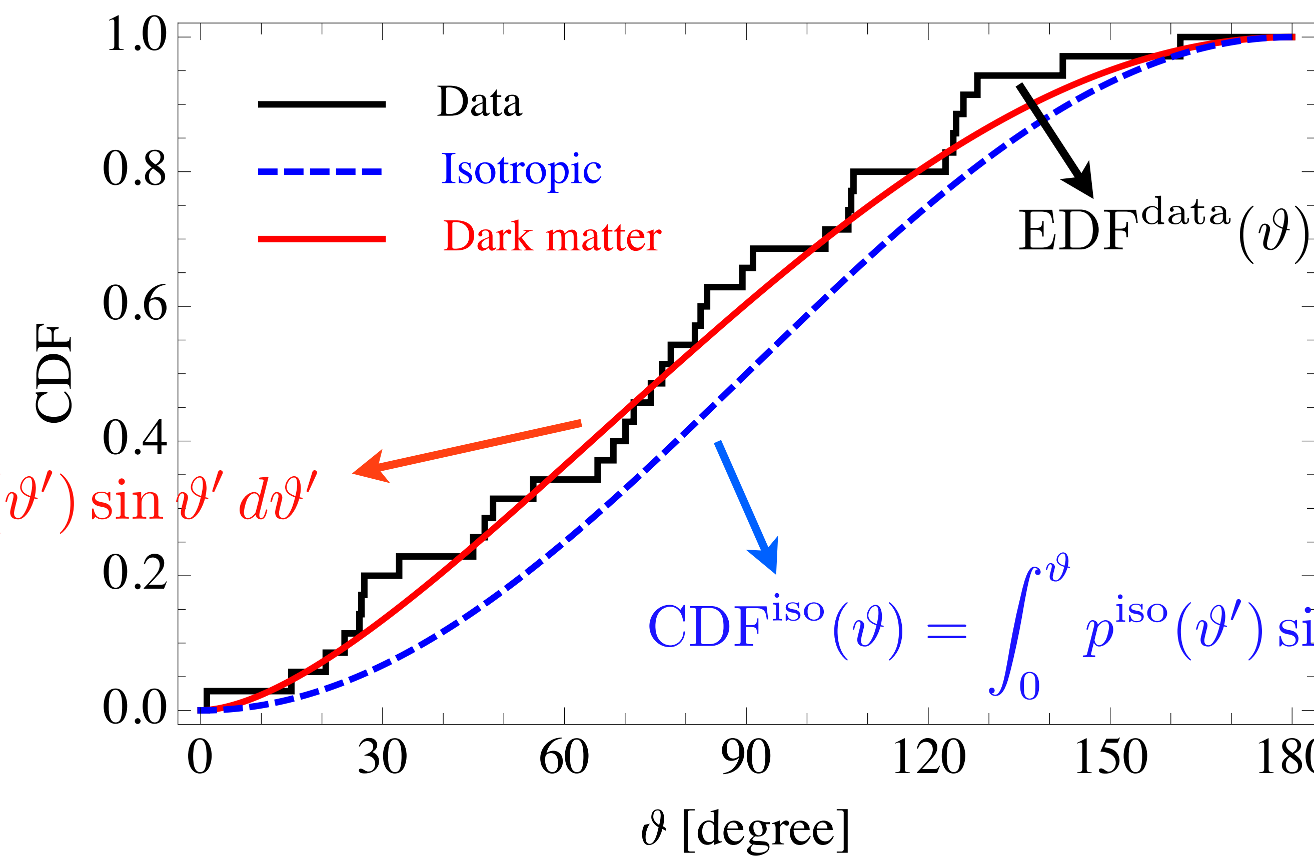


$$\mathrm{EDF}^{\rm data}(\vartheta) = \frac{1}{N}\sum_{i=1}^{N}\Theta(\vartheta - \vartheta_i)$$

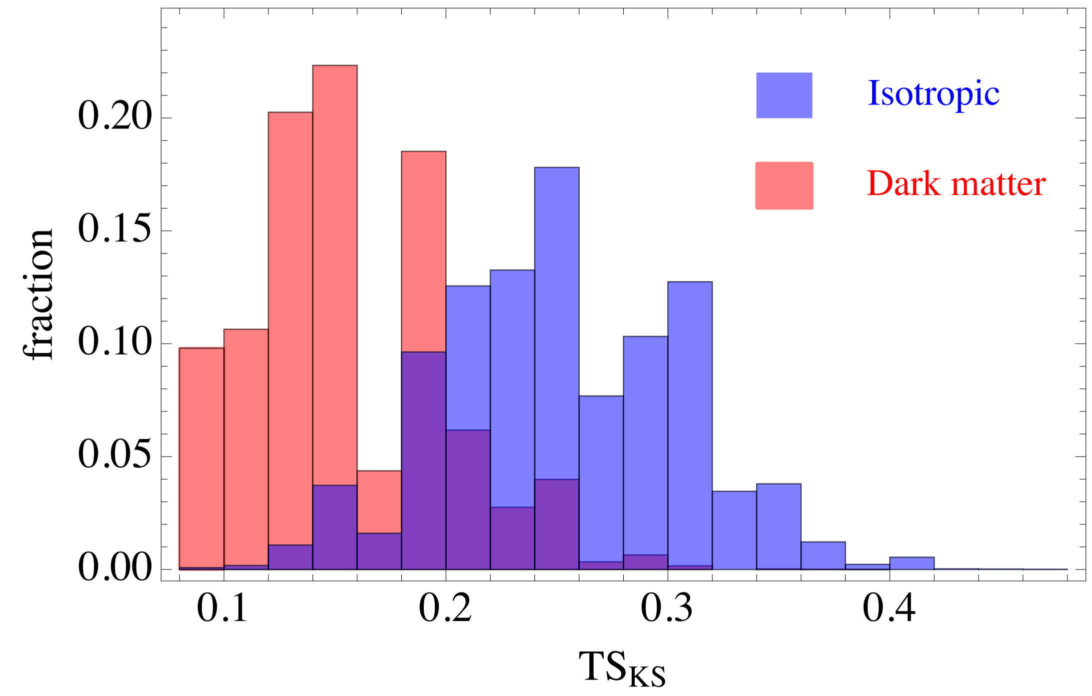
$$\mathrm{CDF}^{\rm DM}(\vartheta) = \int_0^{\vartheta} p^{\rm DM}(\vartheta')\sin\vartheta'\,d\vartheta'$$

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

Angular distribution of neutrinos from decaying DM

✔ Kolmogorov-Smirnov test:

statistically larger TS for isotropic distribution



Test Statistics

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

Angular distribution of neutrinos from decaying DM

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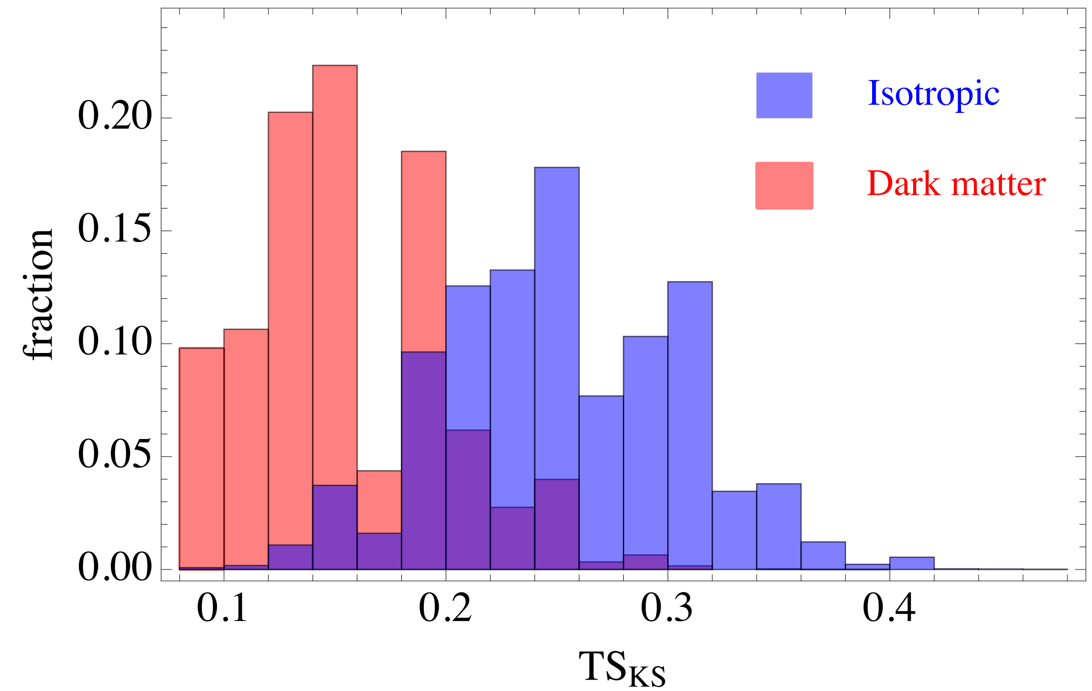


Test Statistics

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

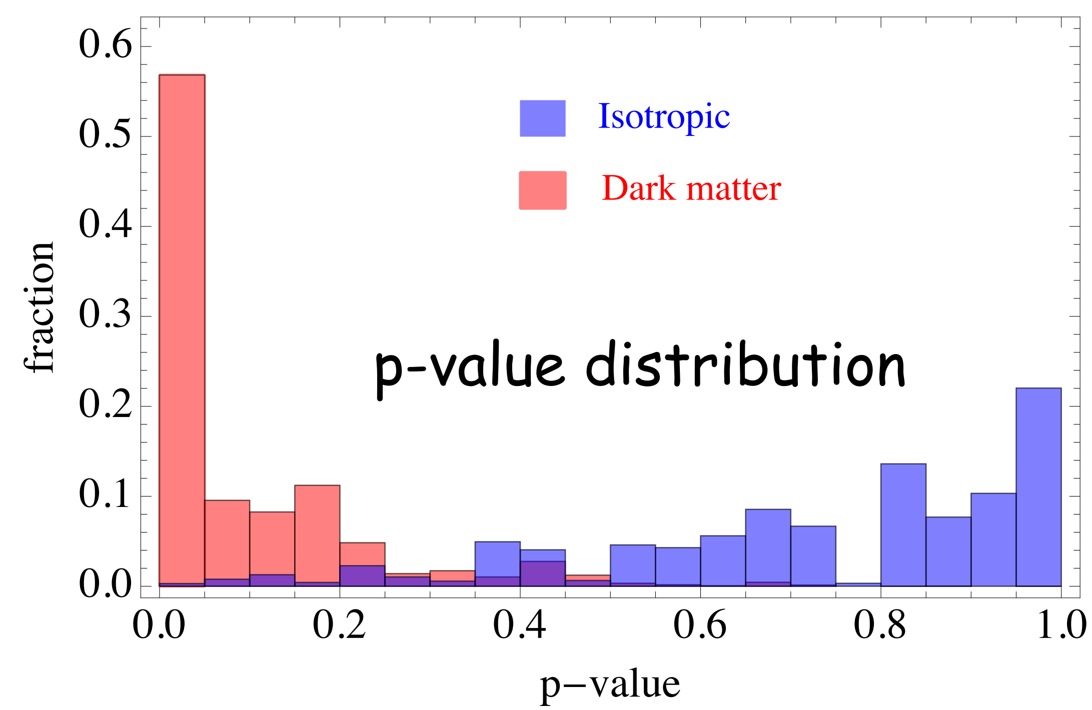
again, generating a sample (10^5) of isotropically distributed set of 20 events

↓

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

↓

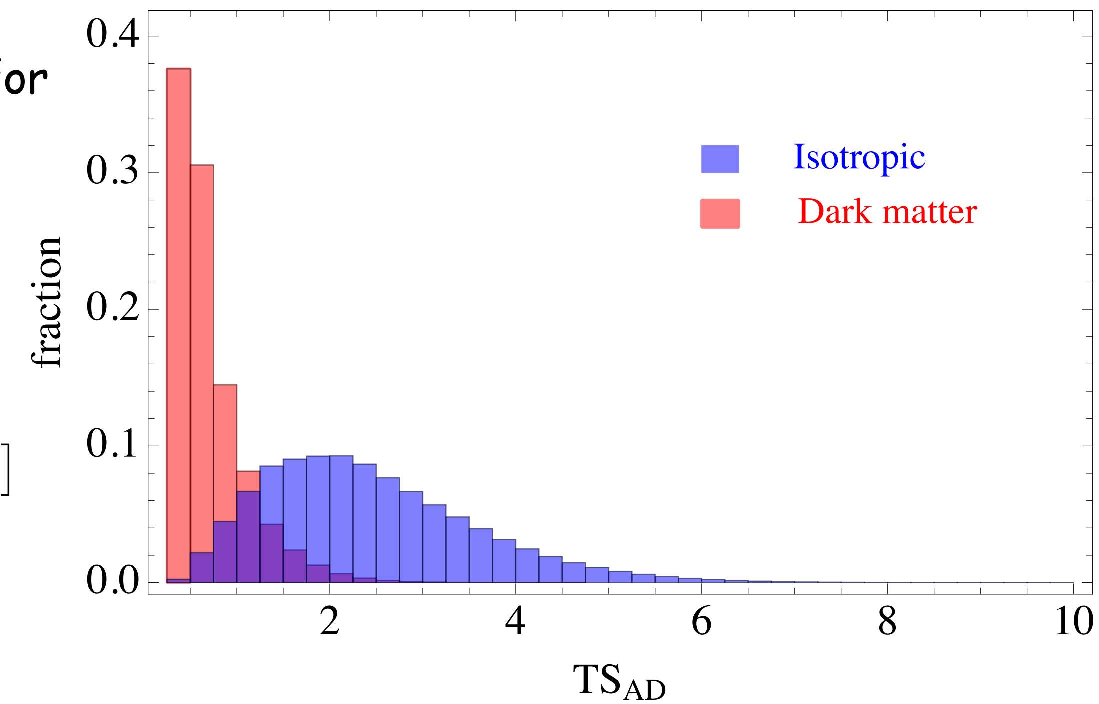
less than 2σ preference for DM dis.



Angular distribution of neutrinos from decaying DM

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

statistically larger TS for isotropic distribution



Test Statistics

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

Angular distribution of neutrinos from decaying DM

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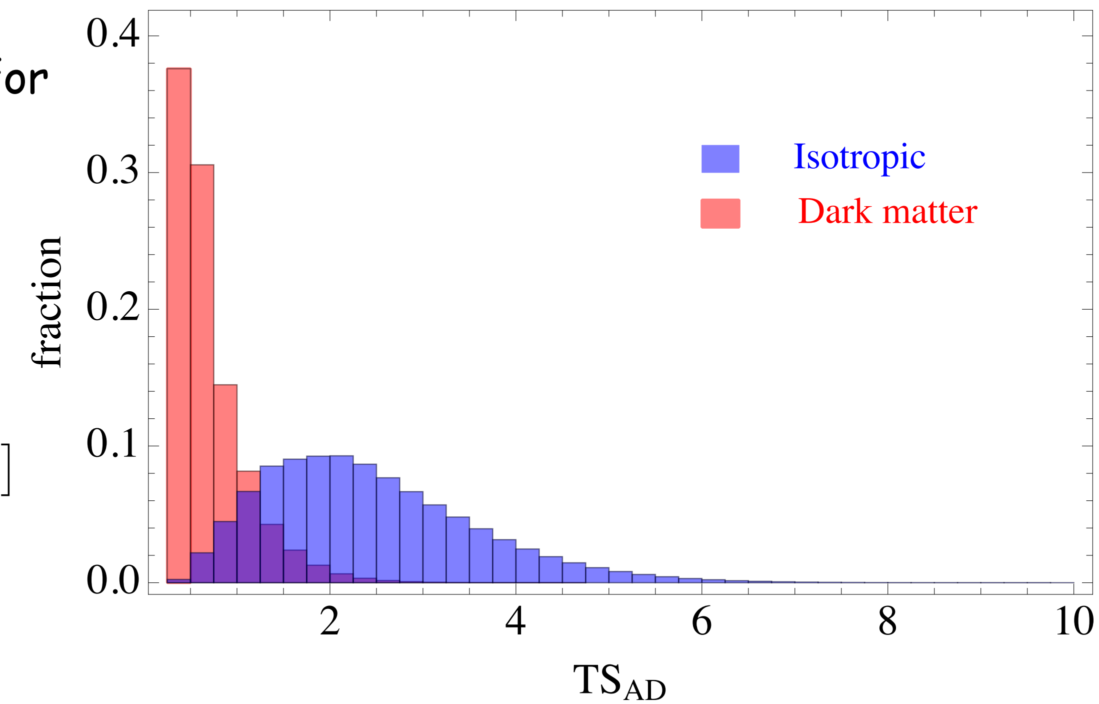

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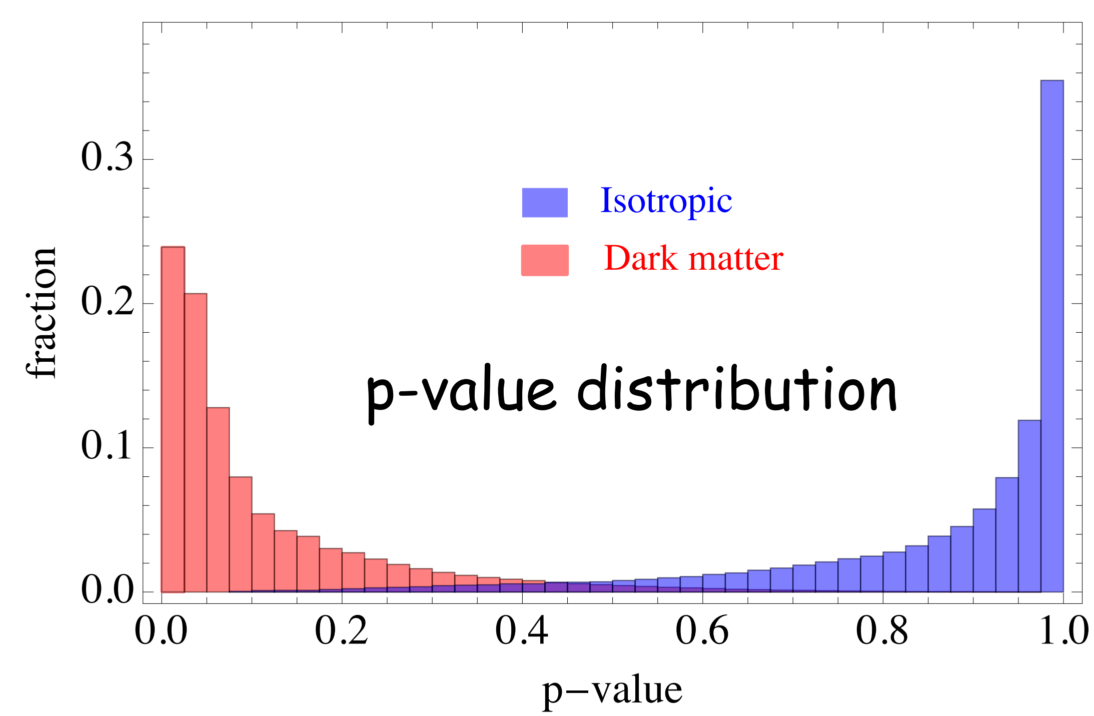
again, generating a sample (10^5) of isotropically distributed set of 20 events

↓

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.



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 < $10^{(2-3)}$ GeV

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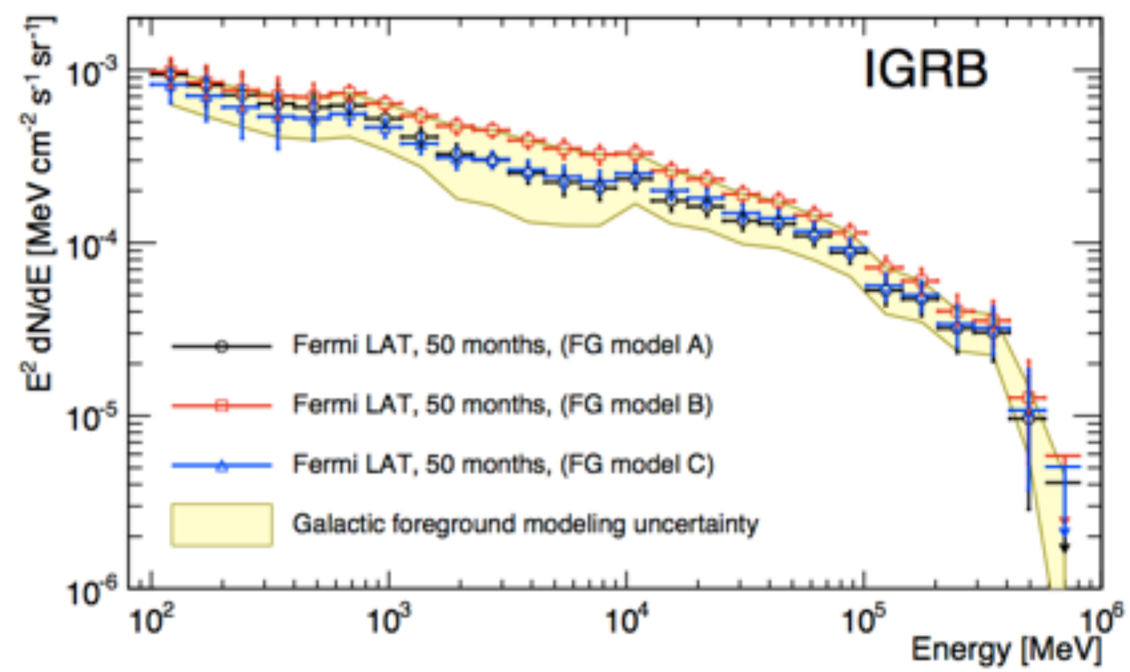
✓ Isotropic diffuse gamma-ray background by Fermi-LAT

M. Ackermann et al. [The Fermi LAT Collaboration], arXiv:1410.3696 [astro-ph.HE].



integrated energy density

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

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

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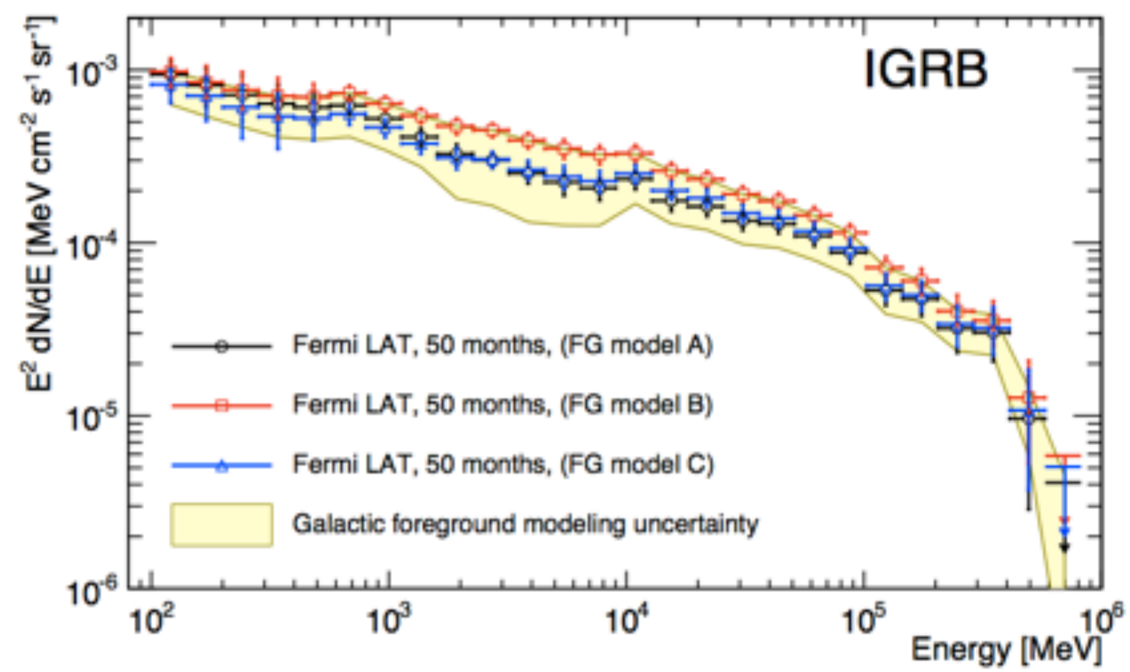

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$$E_1 \sim \mathcal{O}(1)\ \mathrm{GeV} \qquad E_2 \sim \mathcal{O}(100)\ \mathrm{GeV}$$

total electromagnetic energy budget (NH case)

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

✓

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 < $10^{(2-3)}$ GeV

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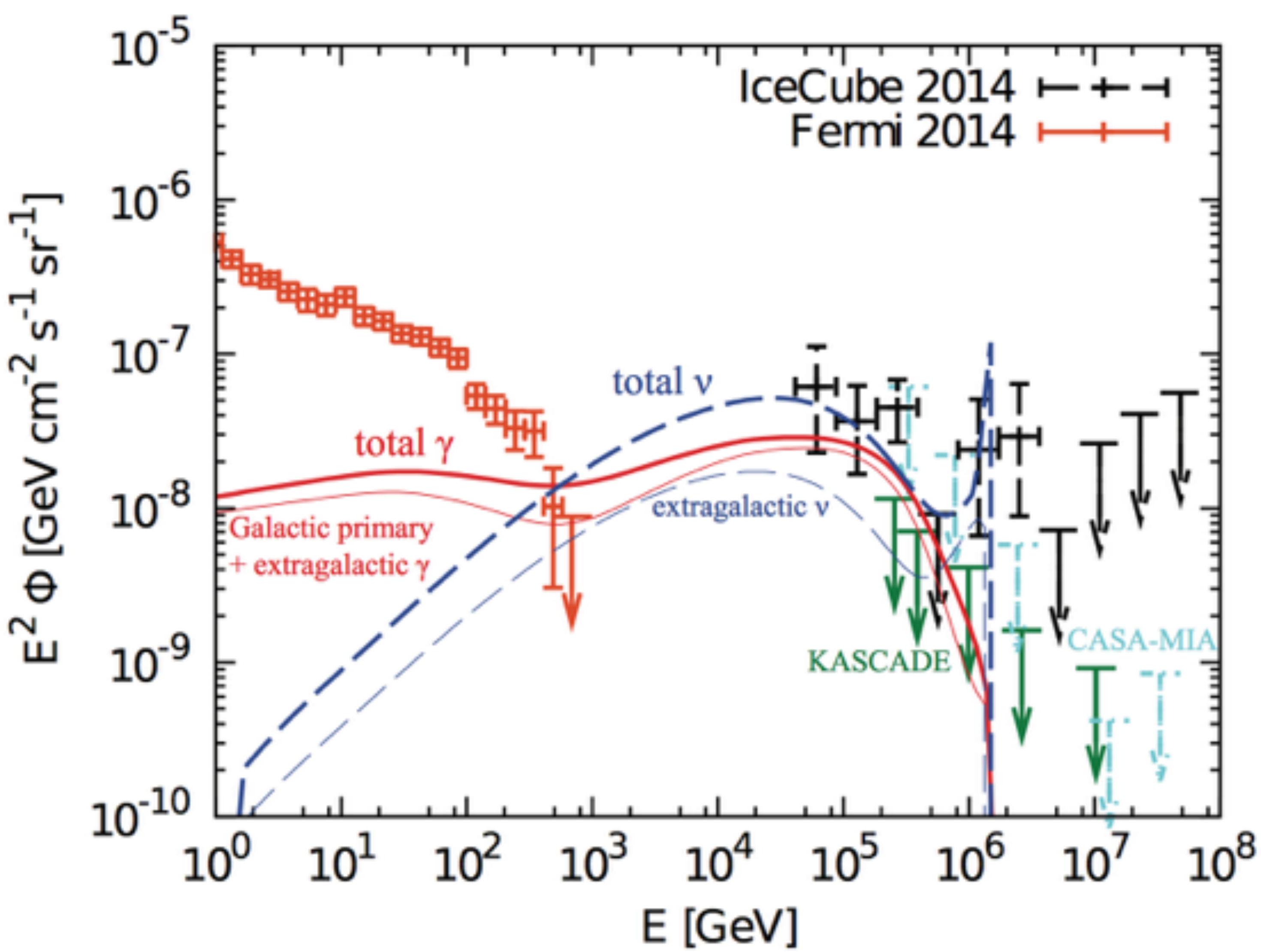
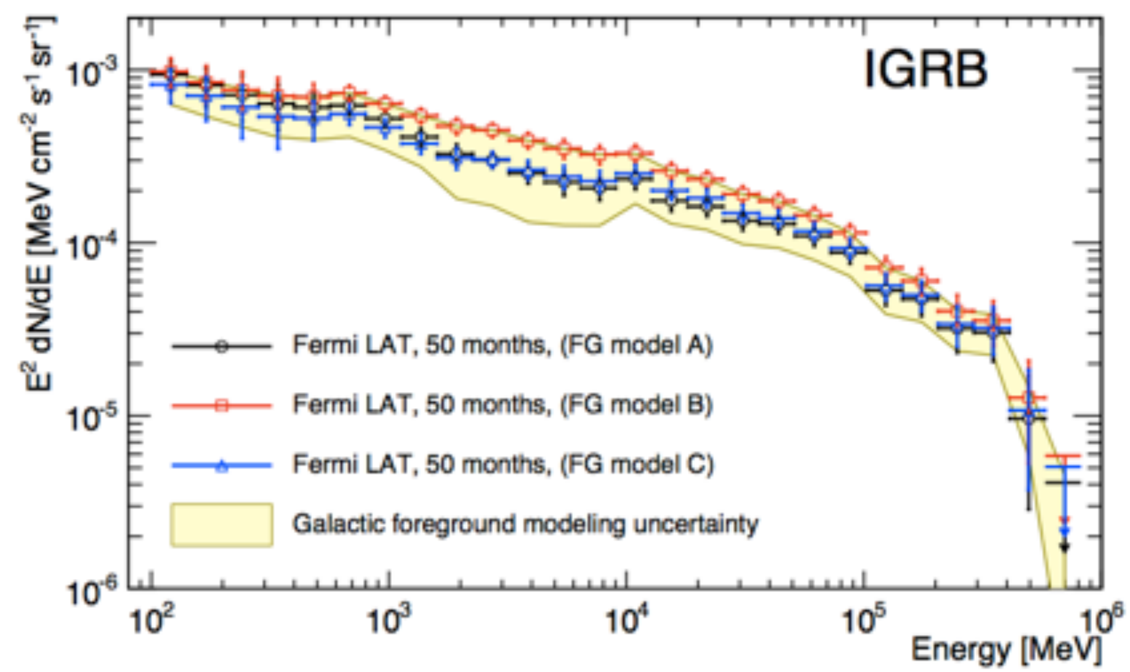


Murase, Laha, Ando, Ahlers, arXiv:1503.04663

M. Ackermann et al. [The Fermi LAT Collaboration], arXiv:1410.3696 [astro-ph.HE].



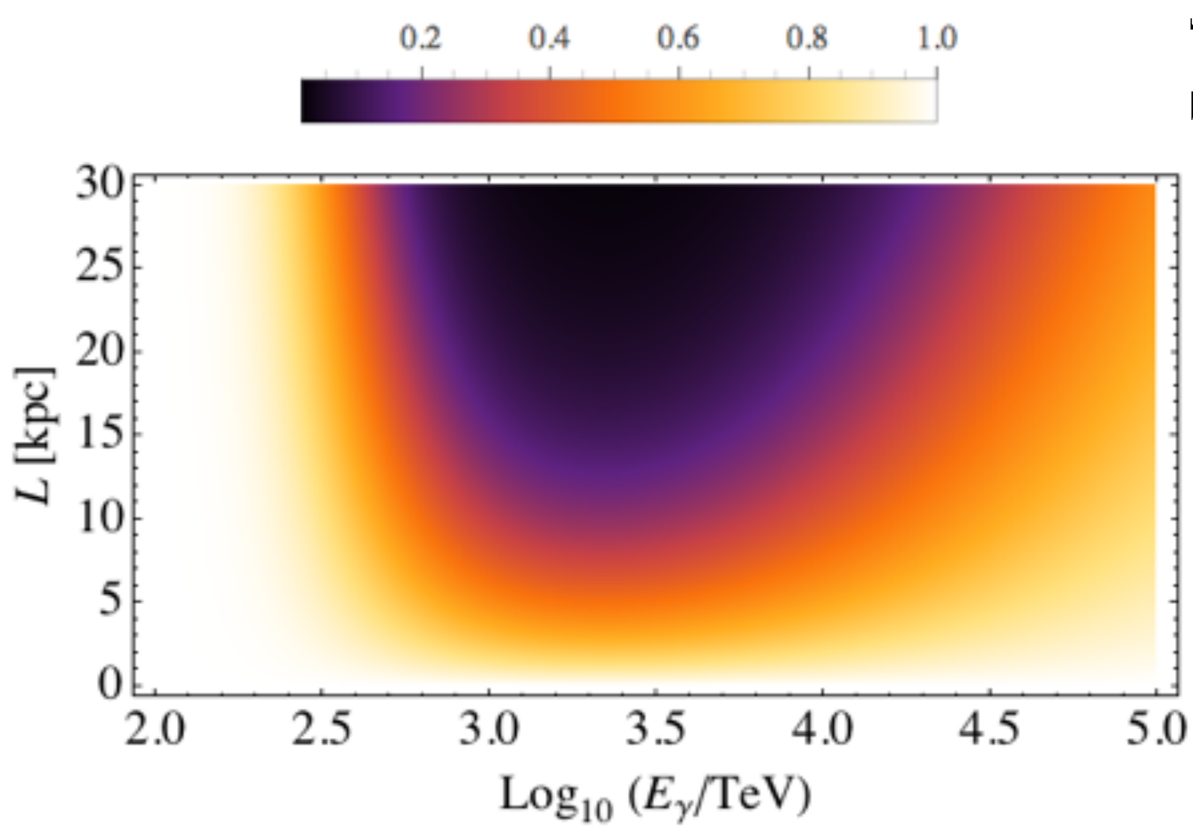
Gamma ray bounds

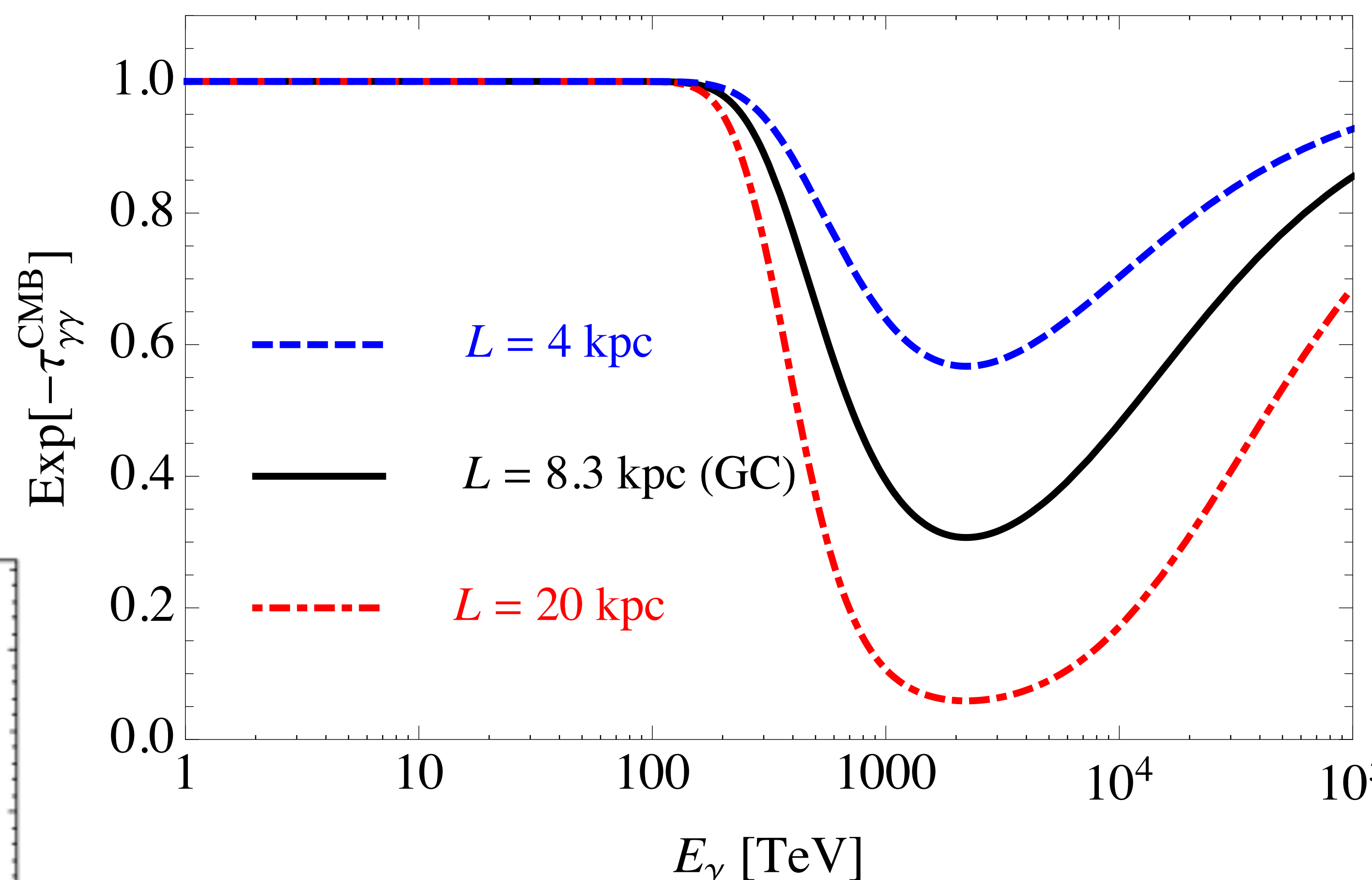
✓ Galactic component

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

A. E. and P. Serpico, arXiv:1505.06486

Absorption due to pair production on CMB photons





Absorption at ~ PeV

Gamma ray bounds

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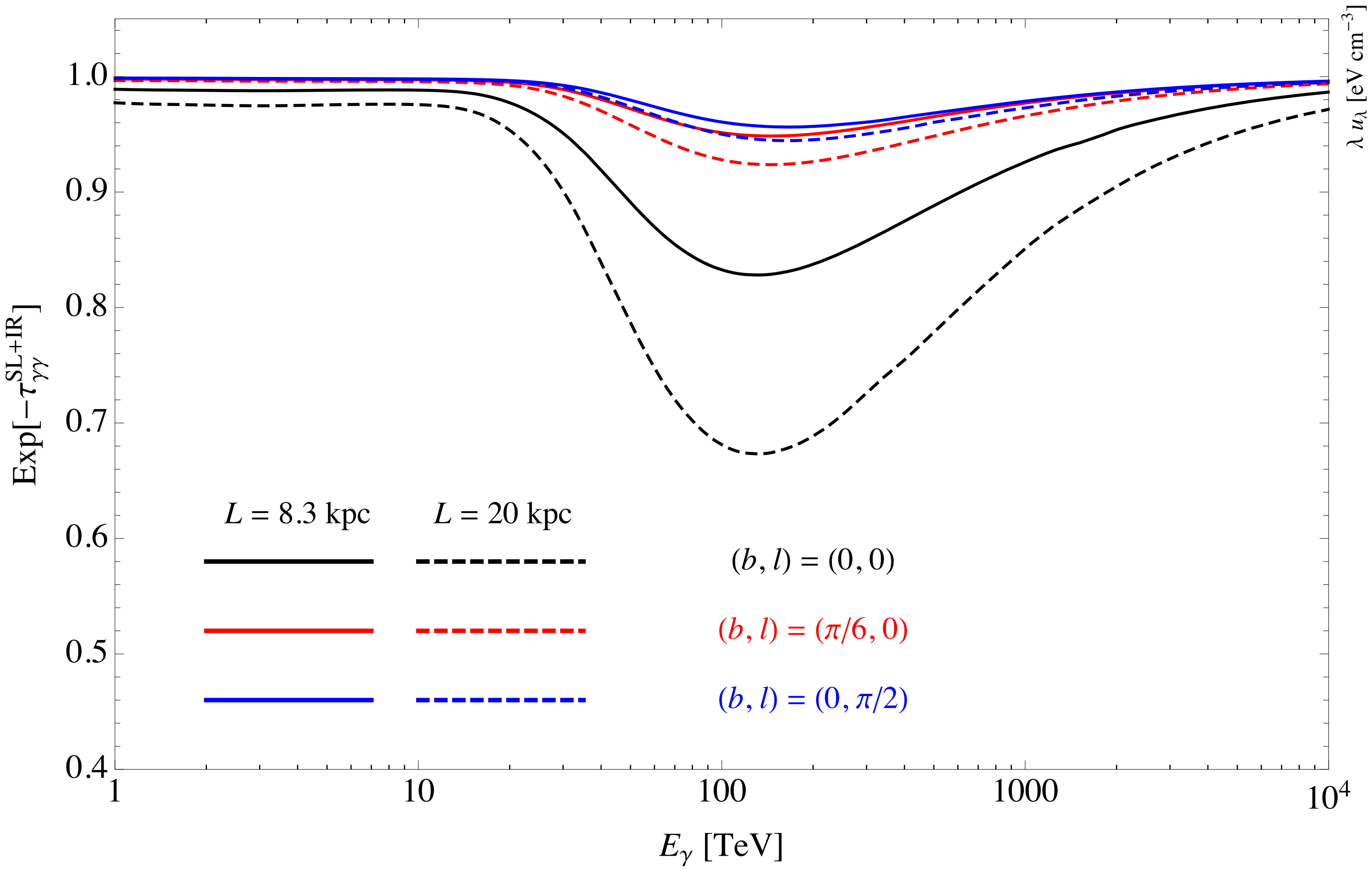
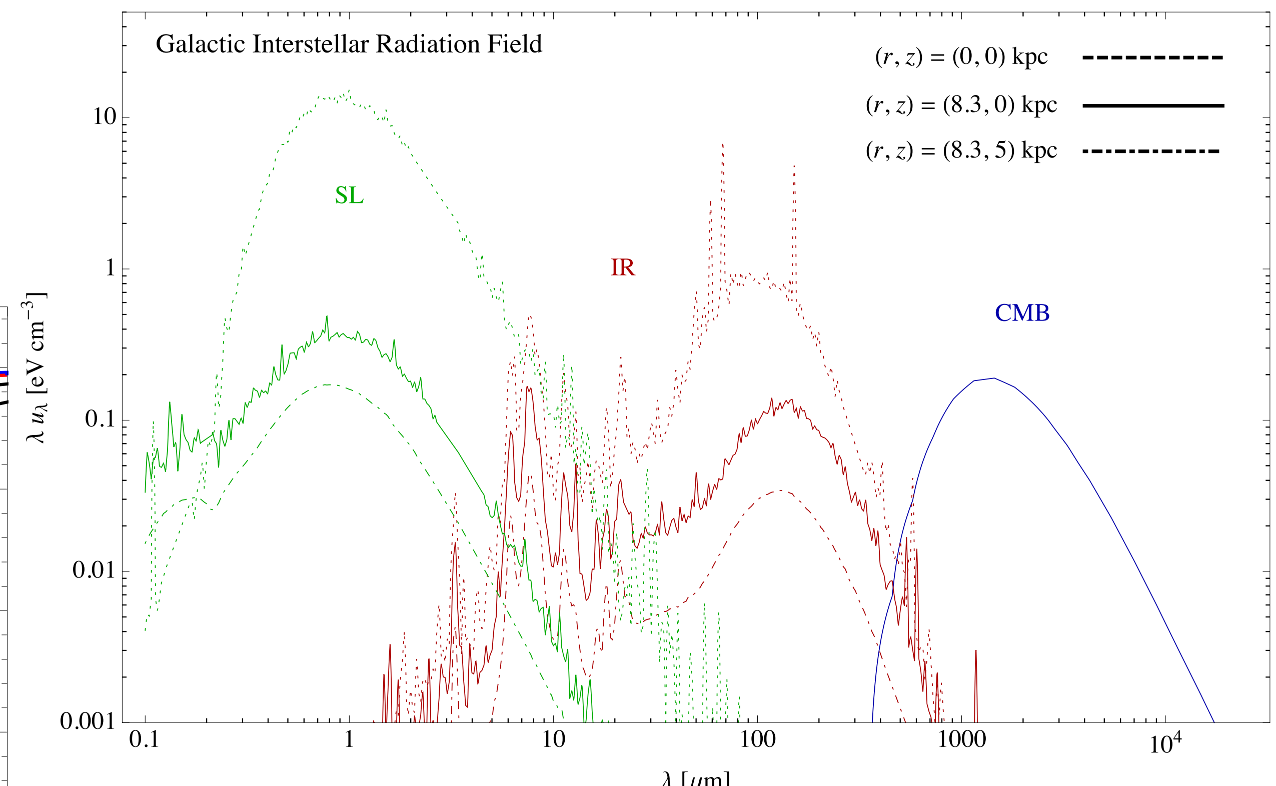
at ~ PeV, the absorption length of gamma-rays are comparable to Galactic distances → neither full absorption or cascade development, nor full transparency

A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

Absorption due to pair production on SL+IR photons





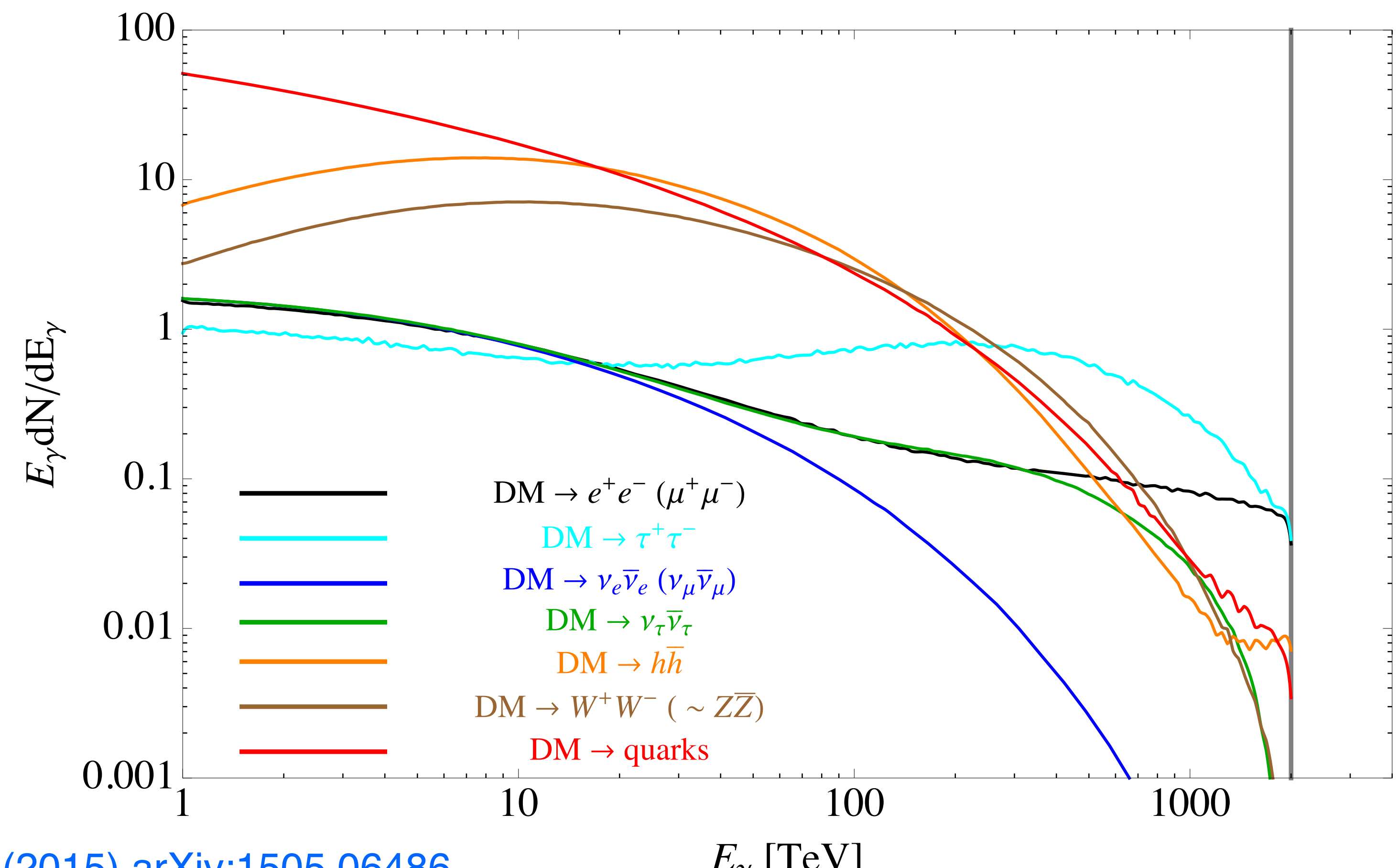
Absorption at ~ 100 TeV

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

Prompt component
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, b, l) = \frac{1}{4\pi\, m_{\rm DM}\, \tau_{\rm DM}} \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \int_0^\infty \rho_{\rm h}[\varrho(s,b,l)]\, e^{-\tau_{\gamma\gamma}(E_\gamma,s,b,l)}\, ds$$



calculated by PYTHIA 8.2

A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

Gamma ray bounds

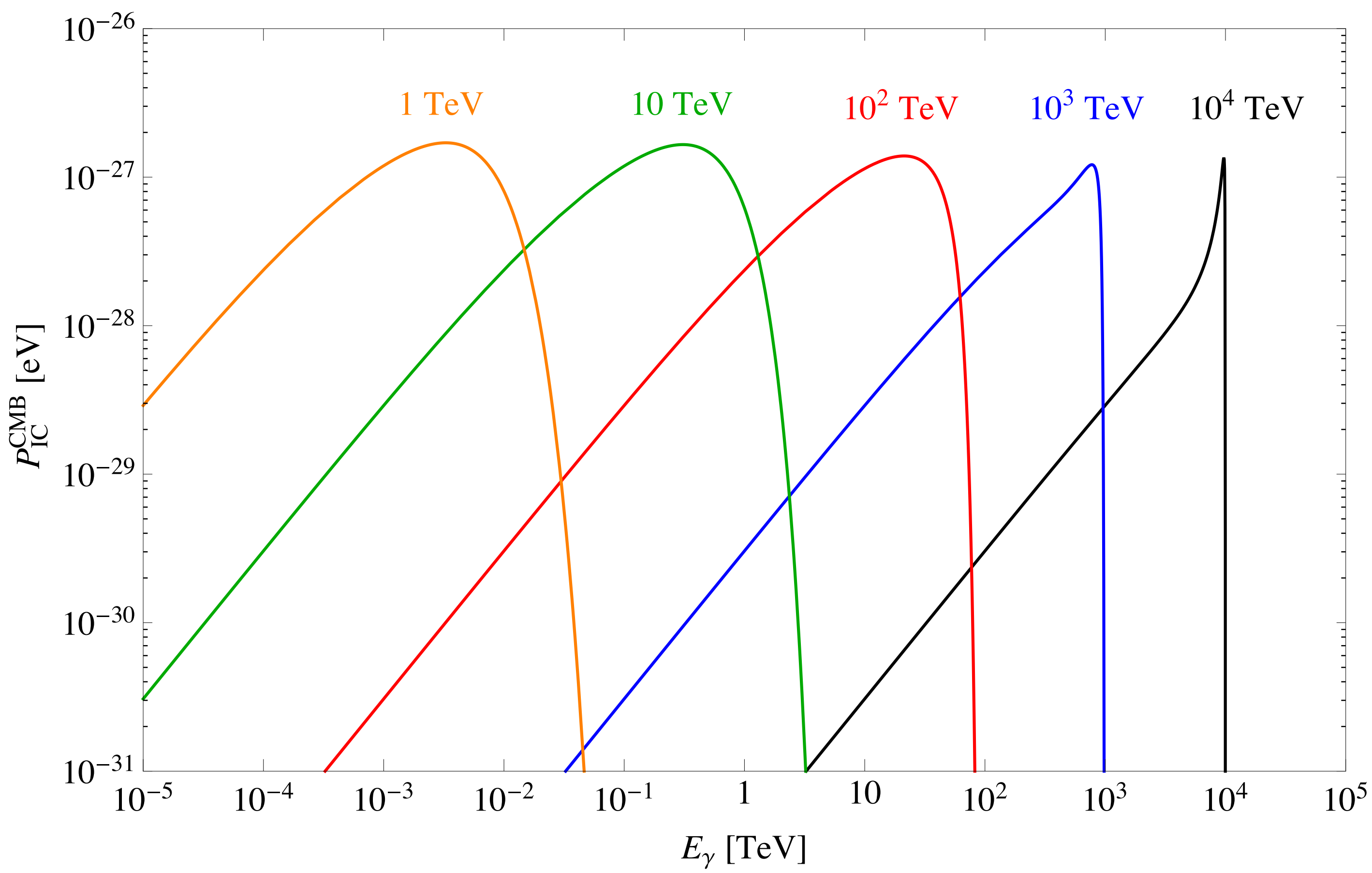
✔ Galactic component

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

inverse-Compton component

$$\frac{d\Phi_{IC}}{dE_\gamma}(E_\gamma,b,l)=\frac{1}{4\pi E_\gamma}\int_0^\infty ds\, e^{-\tau_{\gamma\gamma}(E_\gamma,s,b,l)}\int_{m_e}^{m_{DM}/2} dE_e \frac{dn_e}{dE_e}(E_e,\varrho)\, P_{IC}(E_e,E_\gamma,\varrho)$$

$$P_{IC}=P_{IC}^{CMB}+P_{IC}^{SL+IR}$$



A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

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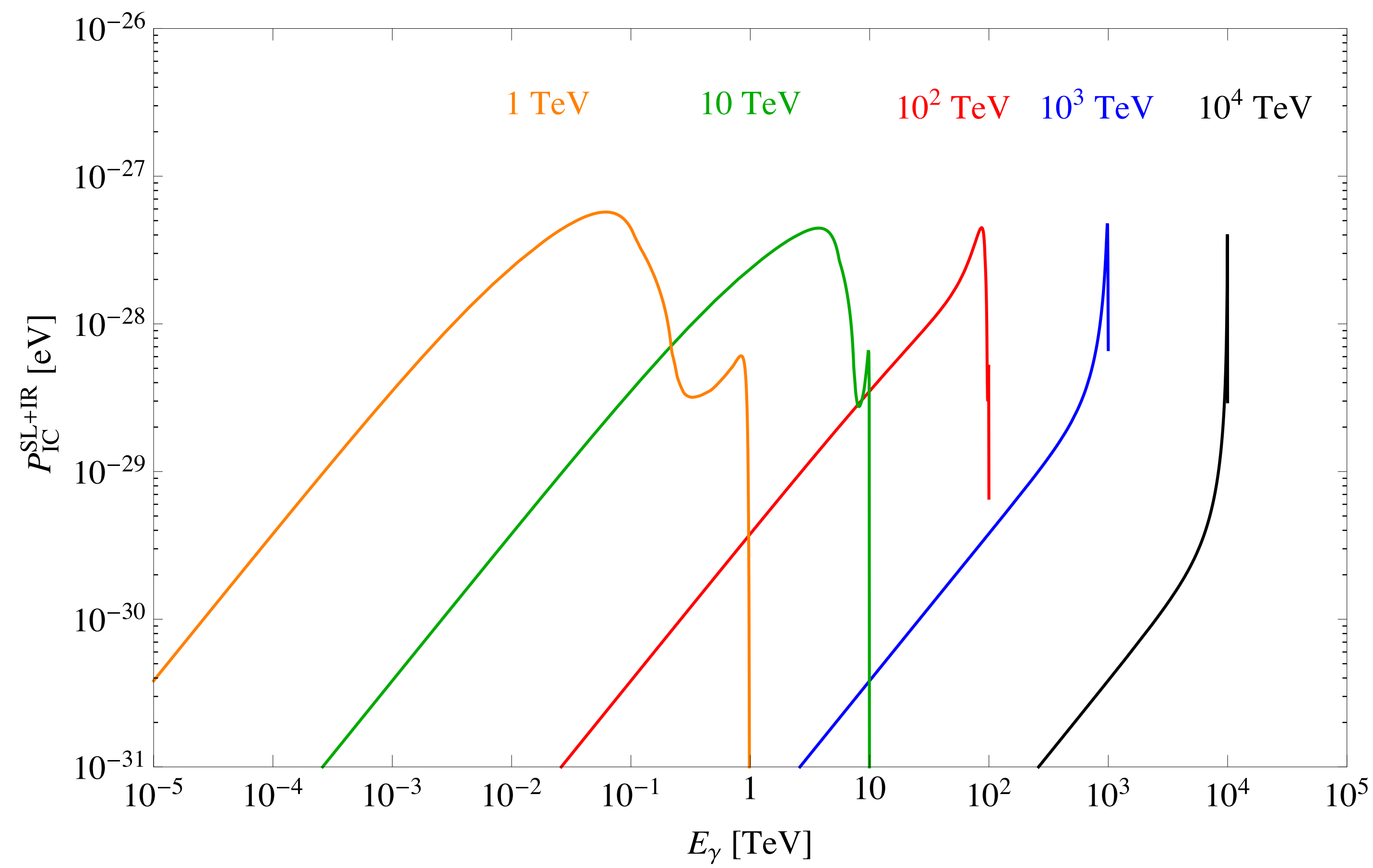
$$P_{\mathrm{IC}}=P_{\mathrm{IC}}^{\mathrm{CMB}}+P_{\mathrm{IC}}^{\mathrm{SL+IR}}$$



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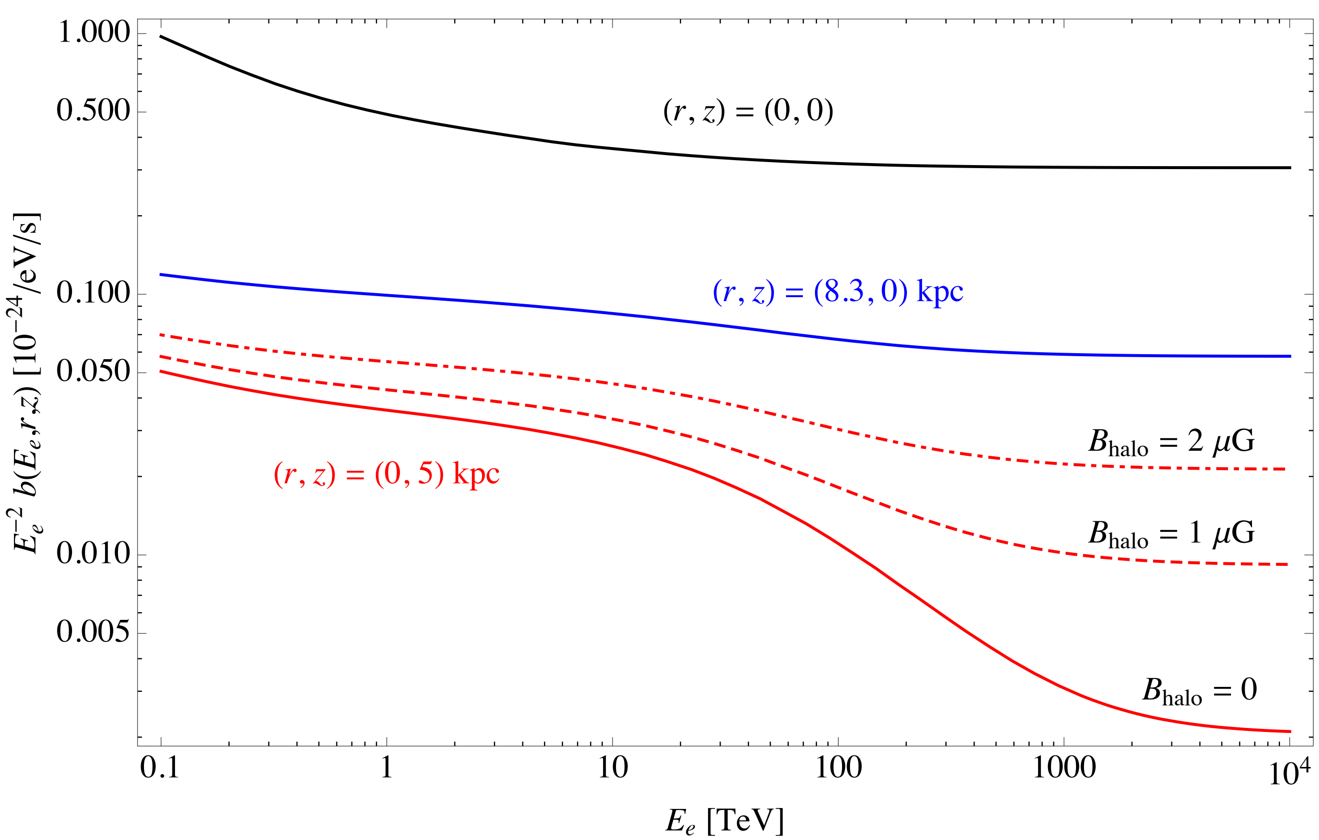
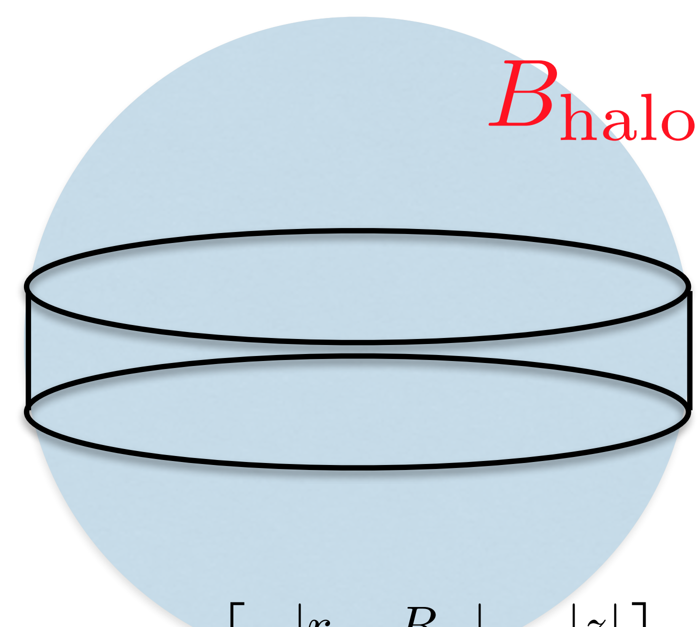
$$\frac{dn_e}{dE_e}(E_e, \vec{x}) = \frac{1}{m_{DM}\,\tau_{DM}}\frac{\rho_h(\vec{x})}{b(E_e,\vec{x})}\int_{E_e}^{m_{DM}/2}\frac{dN_e}{dE'_e}(E'_e)\, I_{diff}(E_e, E'_e, \vec{x})\, dE'_e$$



$$b(E_e, \vec{x}) \equiv -\frac{dE_e}{dt} = b_{IC}(E_e,\vec{x}) + b_{syn}(E_e,\vec{x})$$



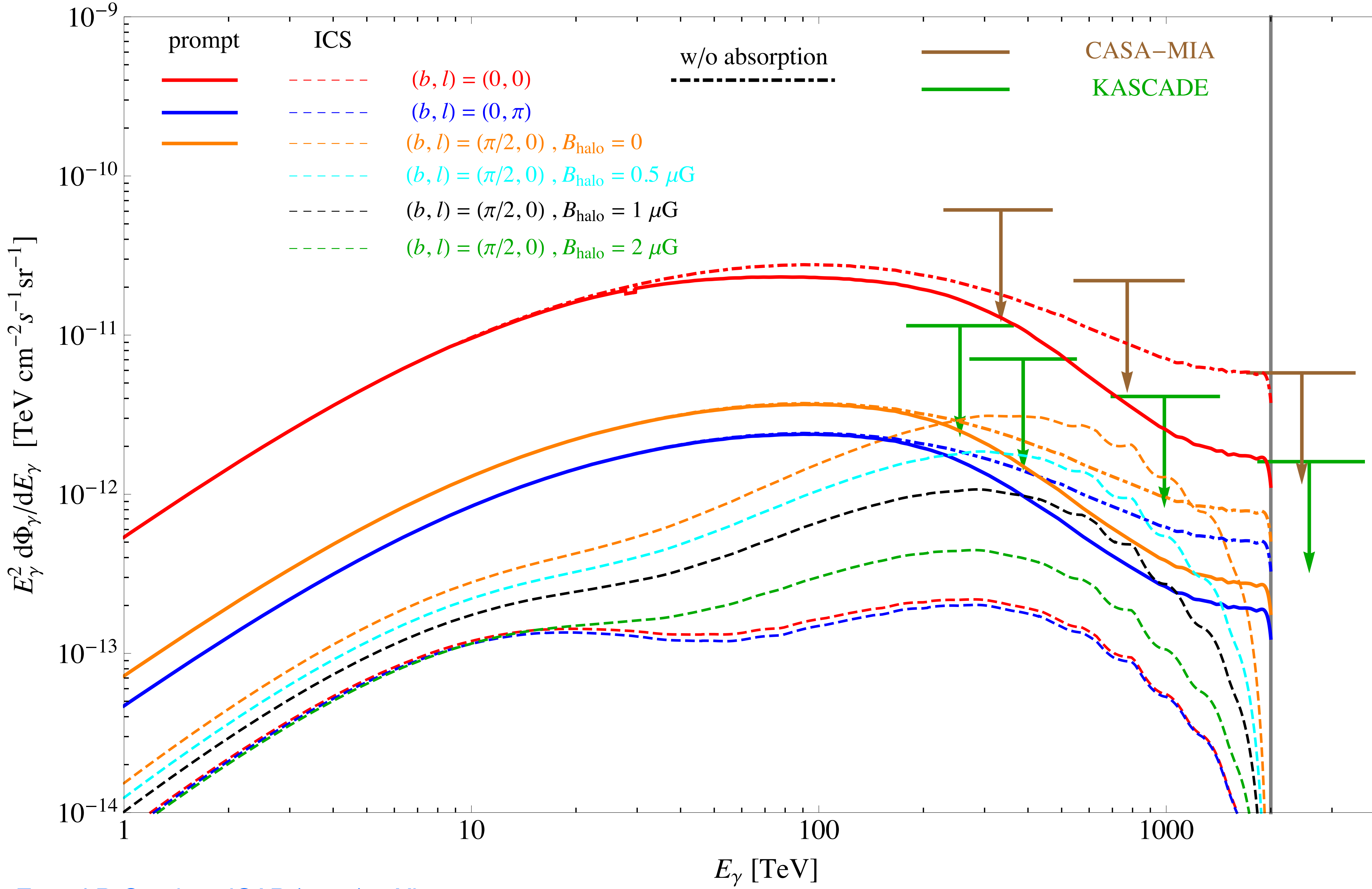
$$B_{reg}(\vec{x}) = B_0\ \exp\left[-\frac{|r - R_\odot|}{r_B} - \frac{|z|}{z_B}\right]$$

A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

Gamma ray bounds

✓ Galactic component

$\tau_{DM} = 10^{28}$ s and m_{DM} = 4 PeV



A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

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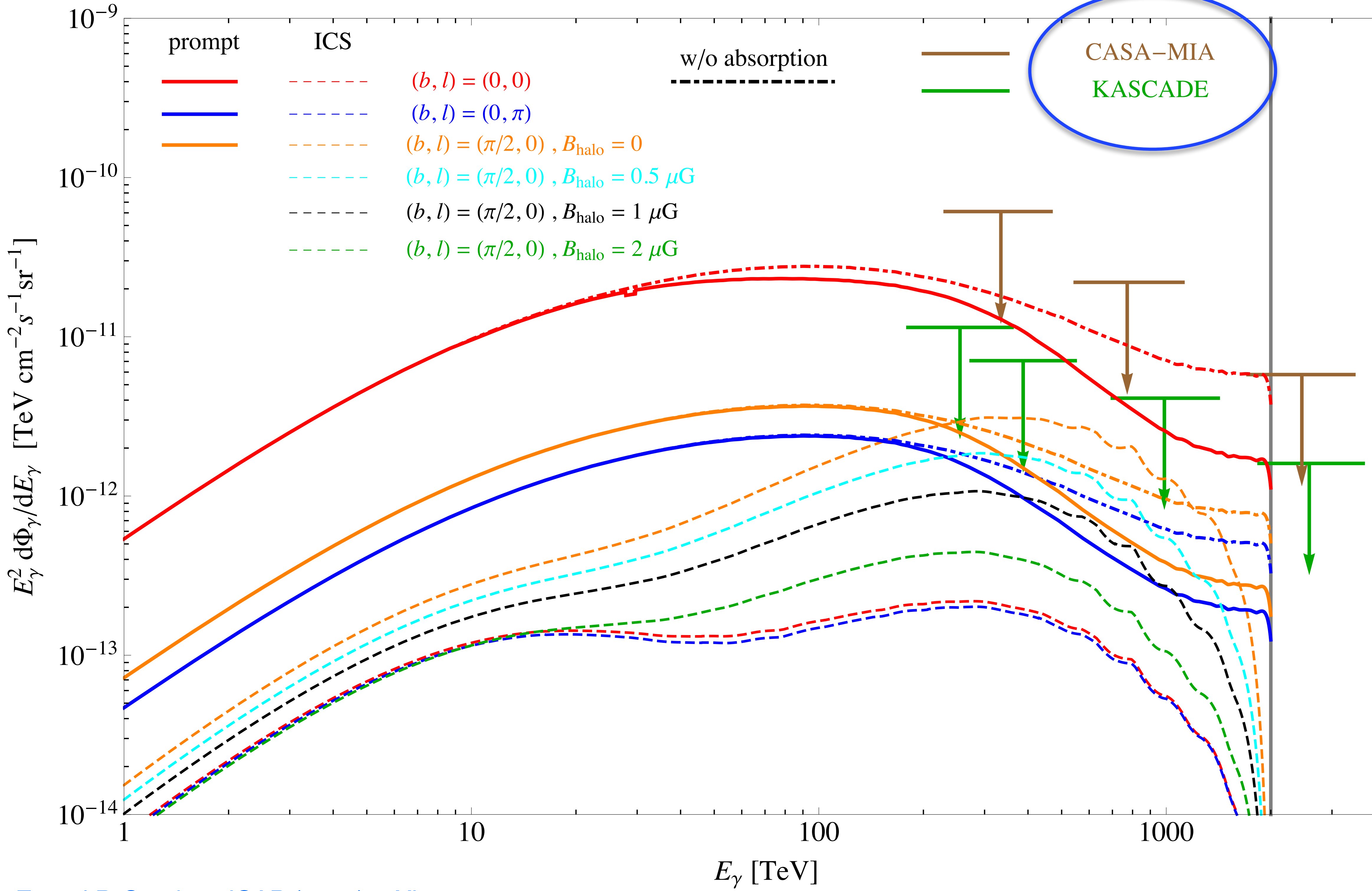
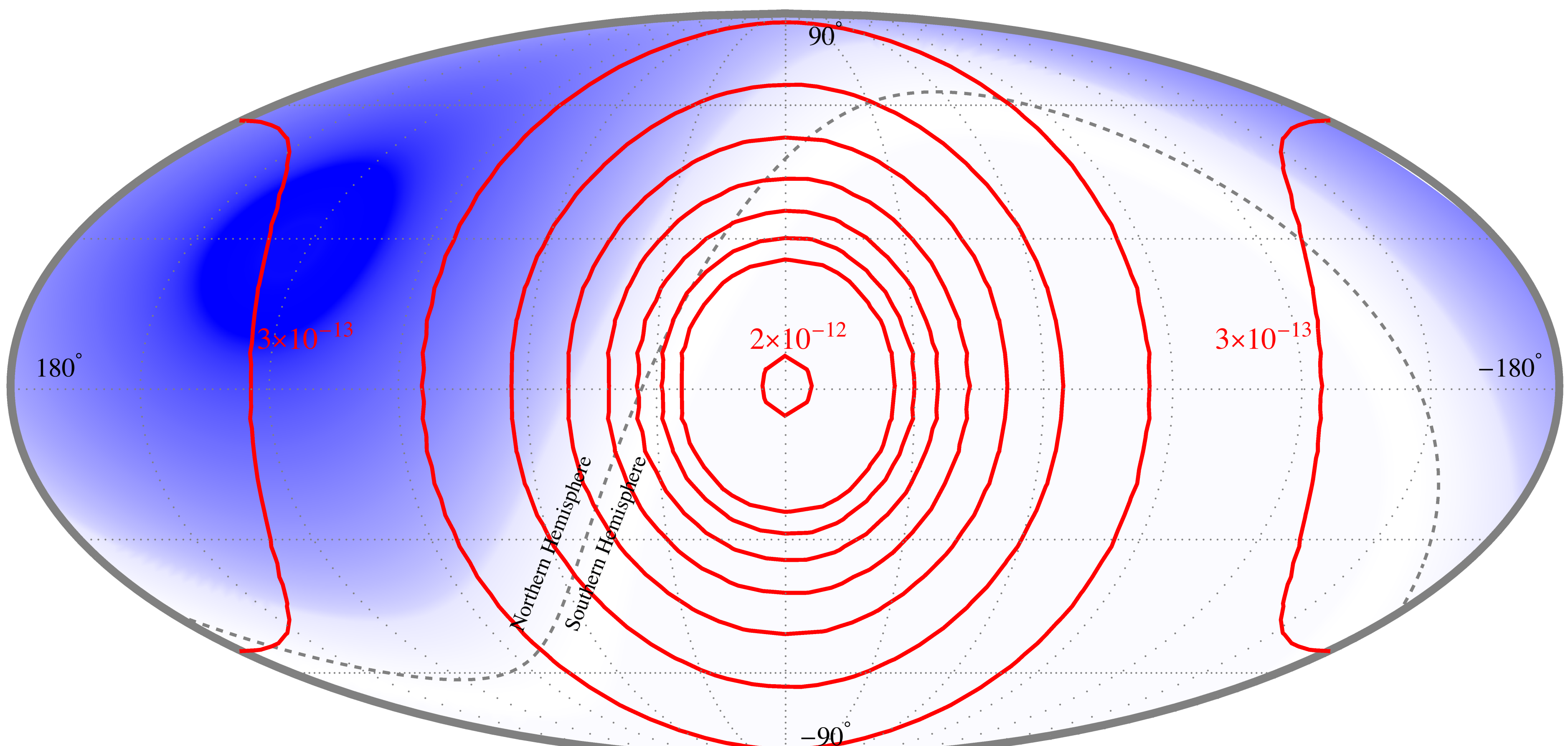


A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

Gamma ray bounds

✓ Galactic component

KASCADE

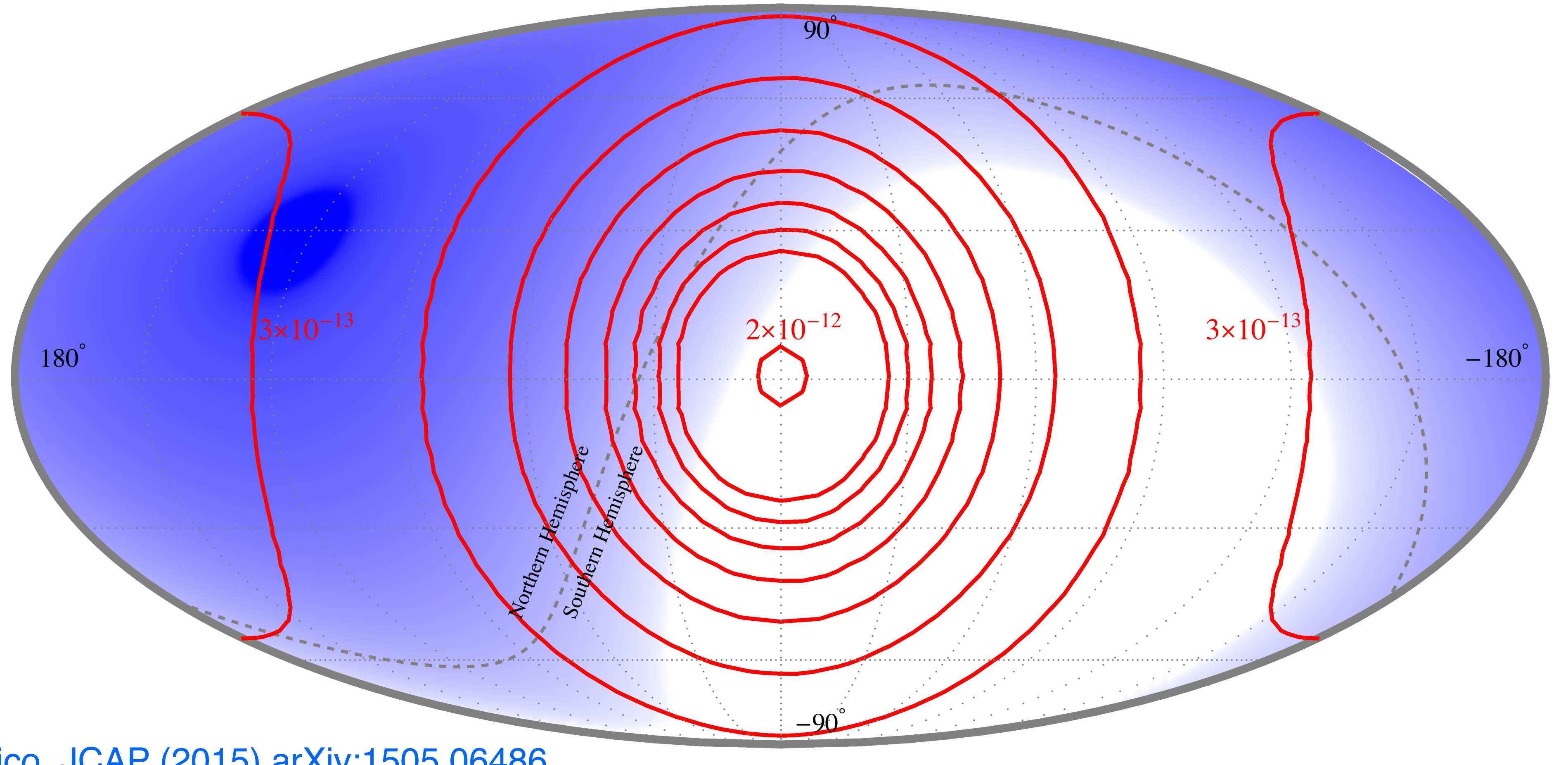


A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

Gamma ray bounds

✓ Galactic component

CASA-MIA



A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

Gamma ray bounds

✓ Galactic component

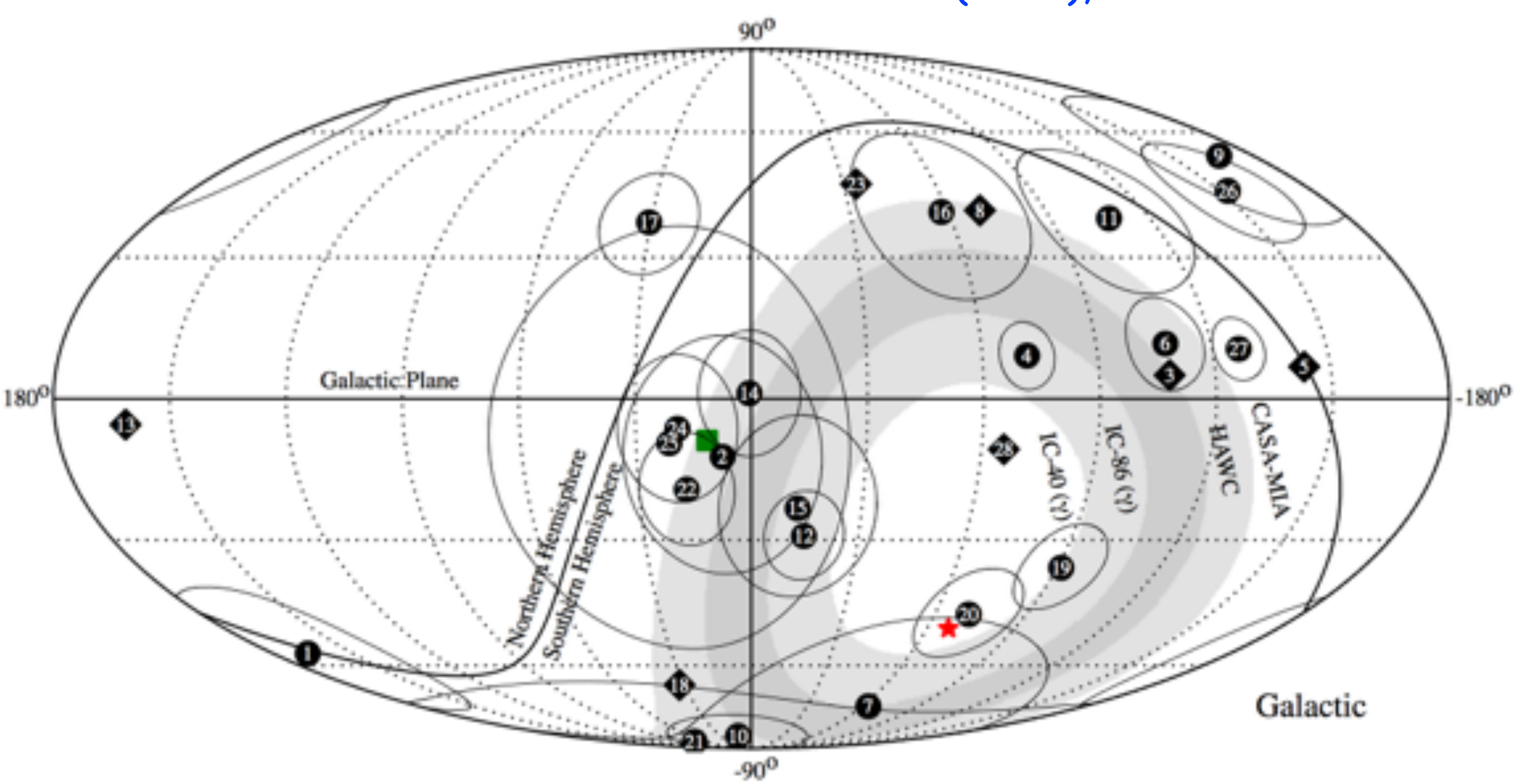
Future experiments

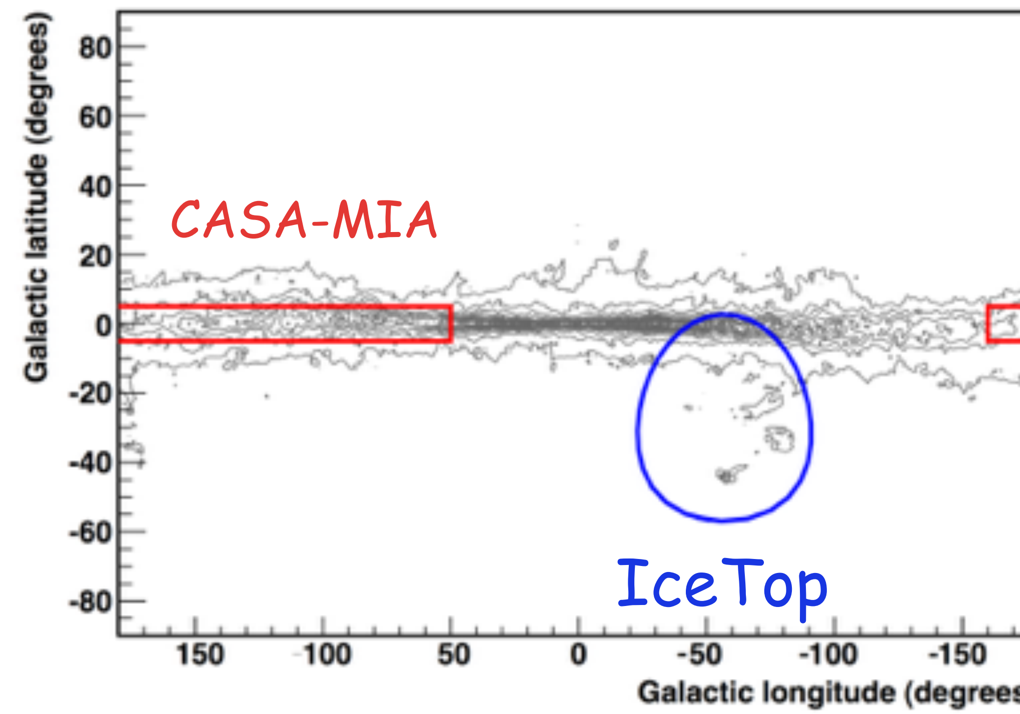
IceTop

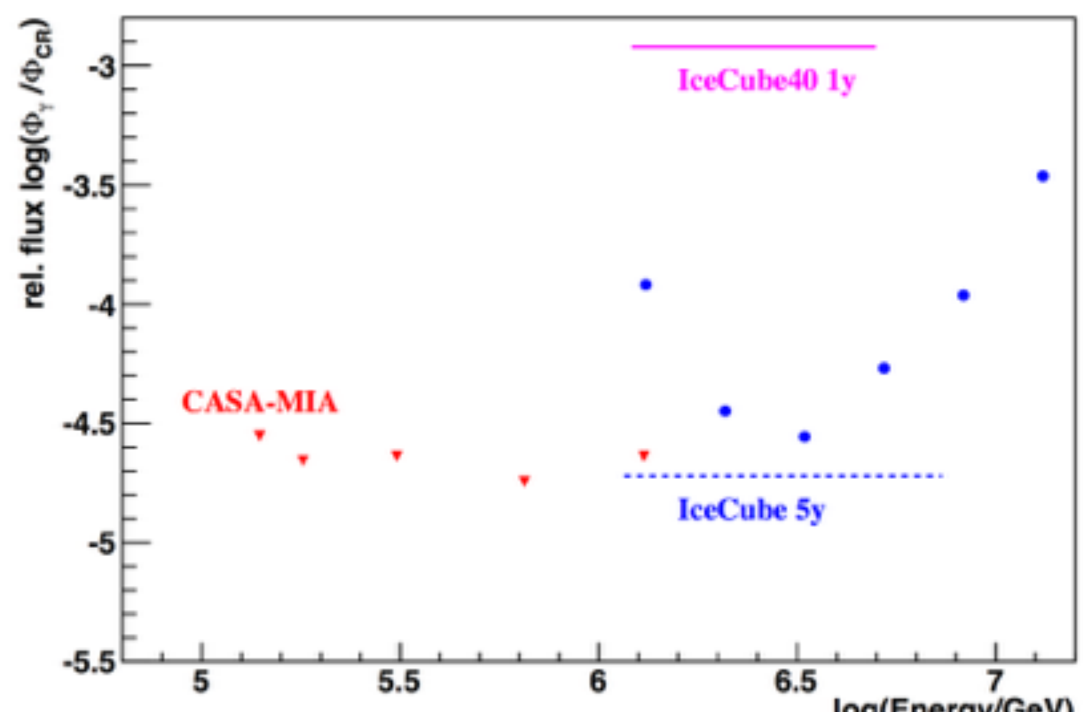
HAWC

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

M. Ahlers and K. Murase,
PRD (2014), arXiv:1309.4077







Gamma ray bounds

✓ Galactic component

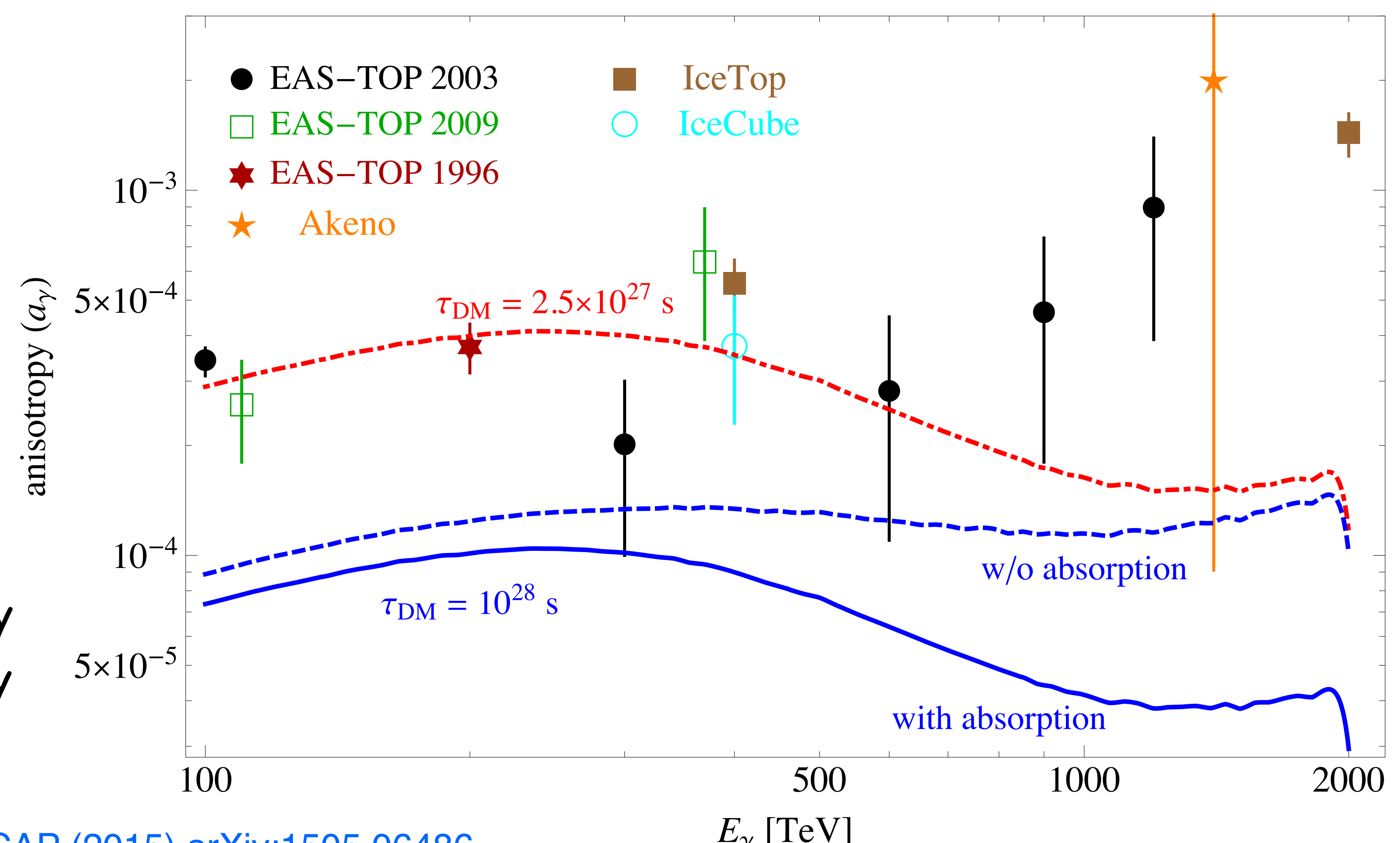
Anisotropy
$$a_\gamma = \frac{\left.\frac{d\Phi_\gamma}{dE_\gamma}\right|_{GC} - \left.\frac{d\Phi_\gamma}{dE_\gamma}\right|_{anti-GC}}{\frac{d\Phi_{CR}}{dE}}$$
Total CR flux

✓ No need to γ/hadron discrimination

✓ Absorption suppress the anisotropy

✓ The bound 2.5×10^{27} s can be set

✓ Adding the phase info of anisotropy would improve the limits significantly



A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

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→ Total CR flux

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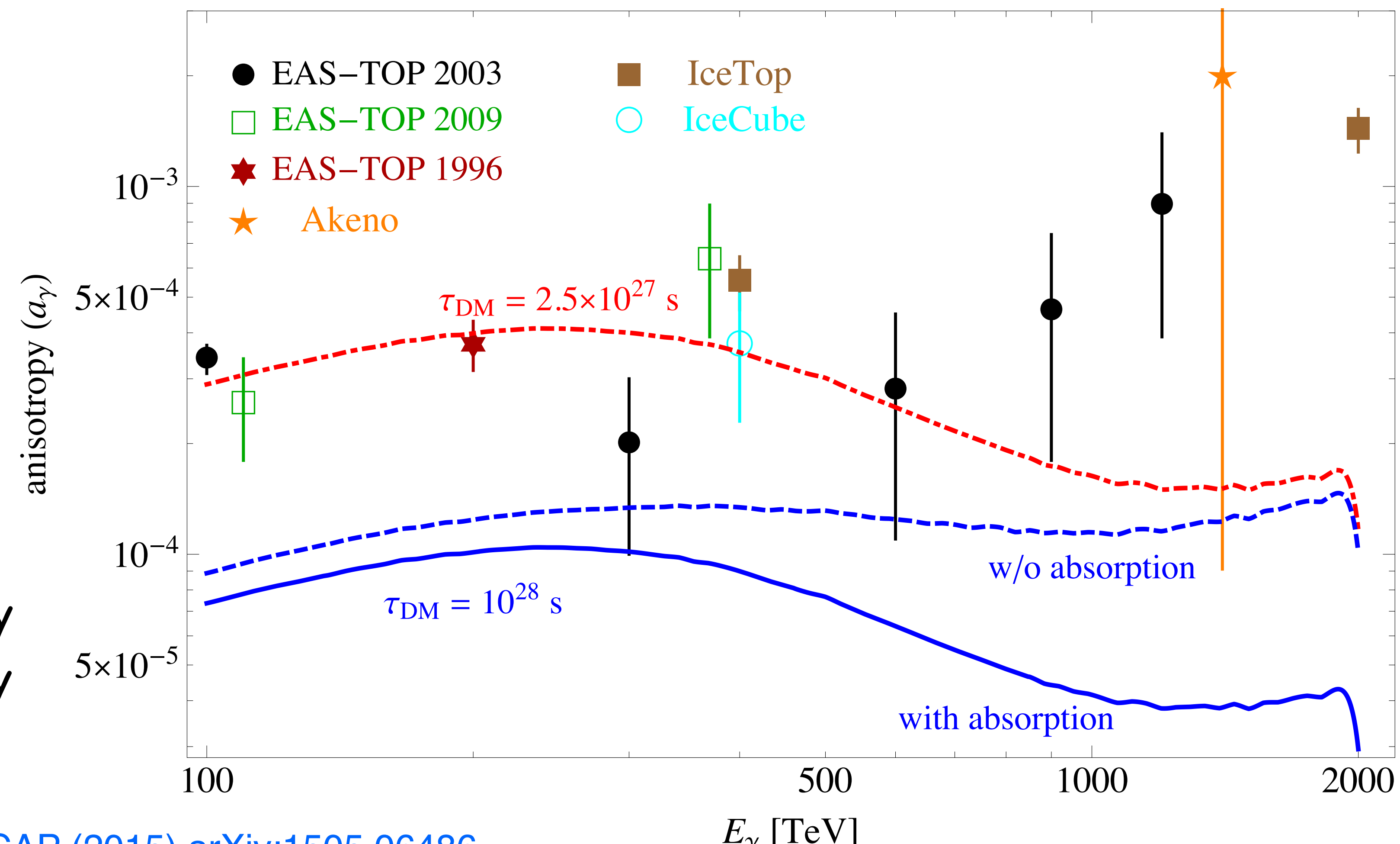

A. E. and P. Serpico, JCAP (2015) arXiv:1505.06486

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, a mild dip in the (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. The gamma-ray flux expected in this scenario can be detected by the next generation of EAS detectors. Also, anisotropy measurements in the CR flux would be constraining.

conclusions

Thank you !

Confronting with energy distribution of IceCube data

three years data set

SM sector ⟷ Dark sector

portal type:

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

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three years data set

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

A. Falkowski, J. Juknevich and J. Shelton
arXiv:0908.1790

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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

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arXiv:1405.0013

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

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

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

$T_R \sim 10^7$ GeV

Confronting with energy distribution of IceCube data

three years data set

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

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

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

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

✓ 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.

Constraining DM properties

✓ DM lifetime

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

bin #	$\log_{10}(E_\nu/\text{TeV})$	$N_{\rm astro}(E_\nu^{-2} \div E_\nu^{-2.3})$	$N_{\rm data}$	$N_{\rm limit}\ (E_\nu^{-2} \div E_\nu^{-2.3})$	$N_{\rm limit}$
#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.

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

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

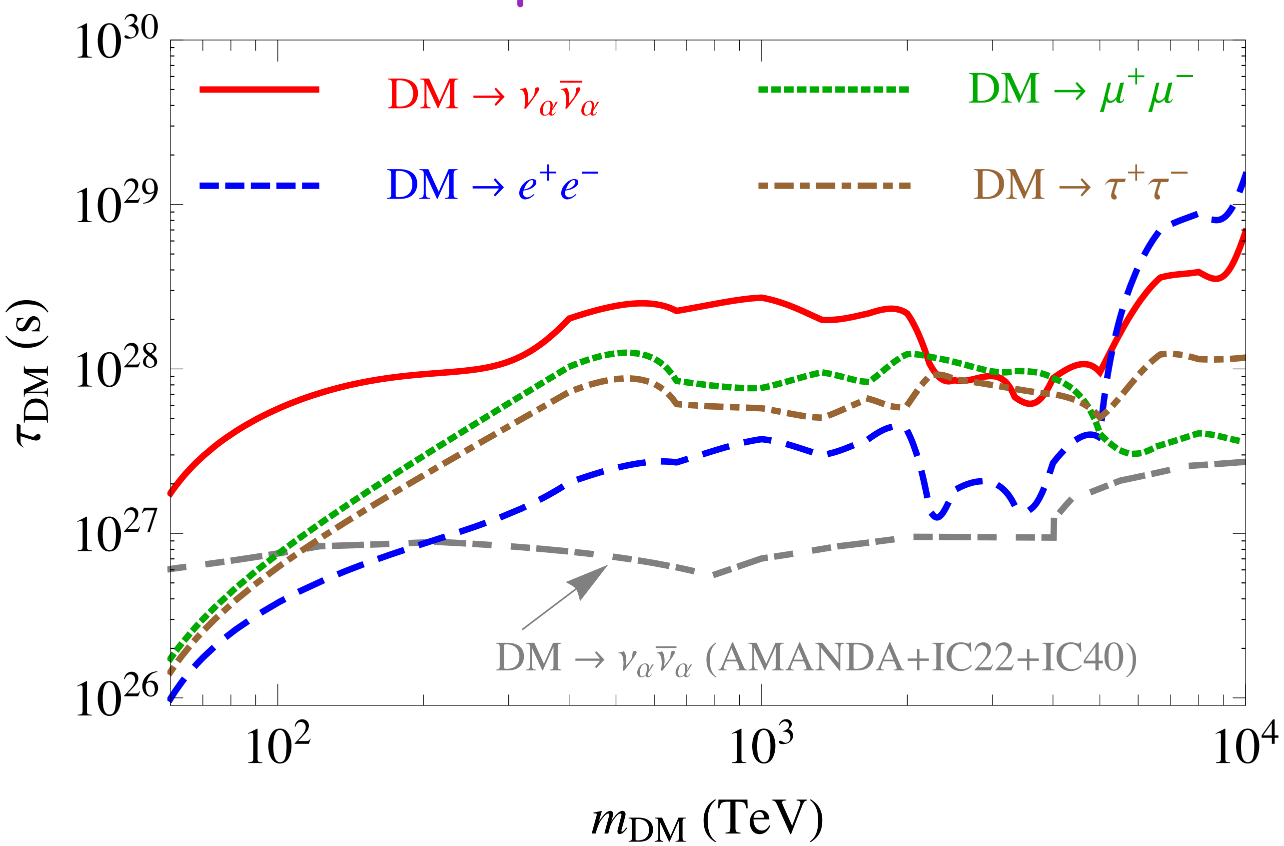
or

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

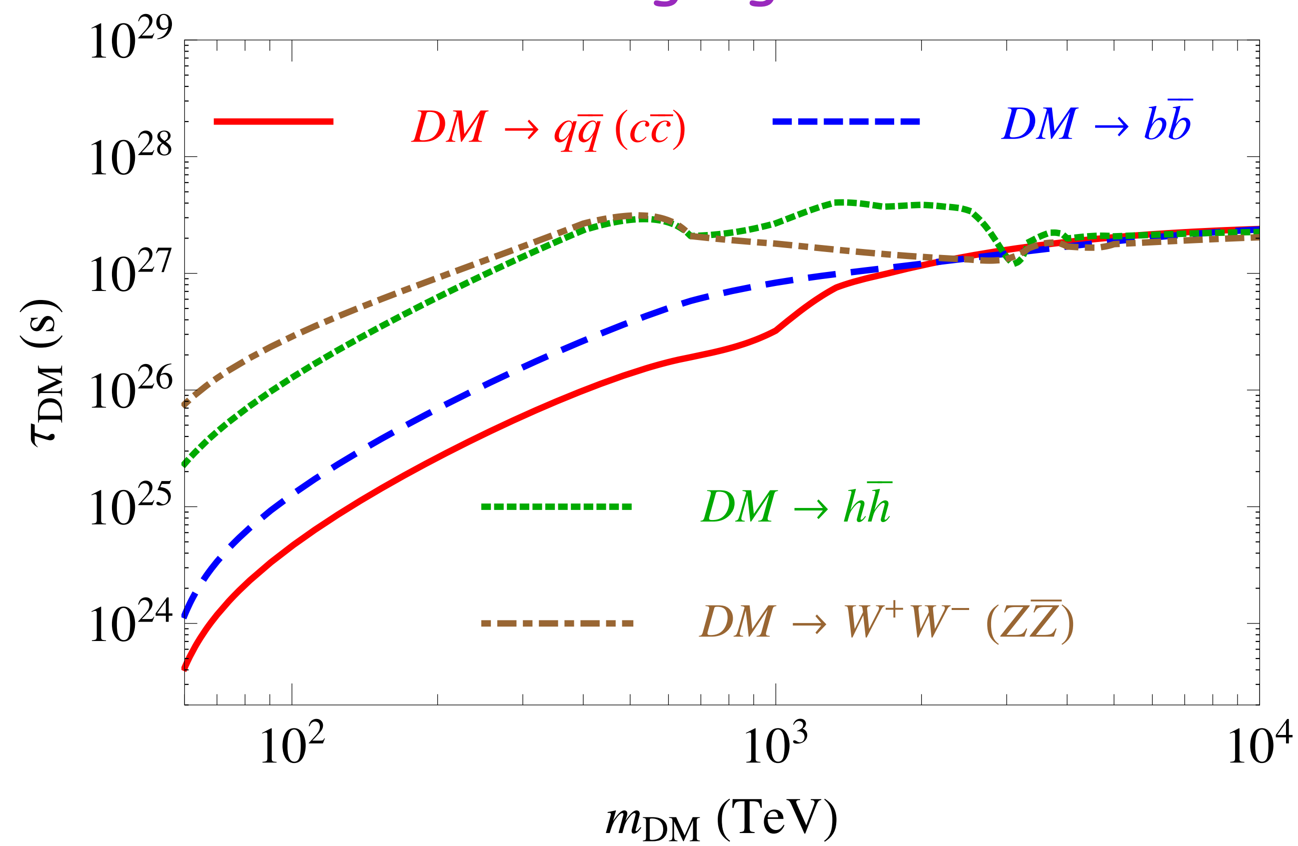
Constraining DM properties

✓ limits on DM lifetime (90% C.L.)

leptonic channels



hadronic/gauge channels



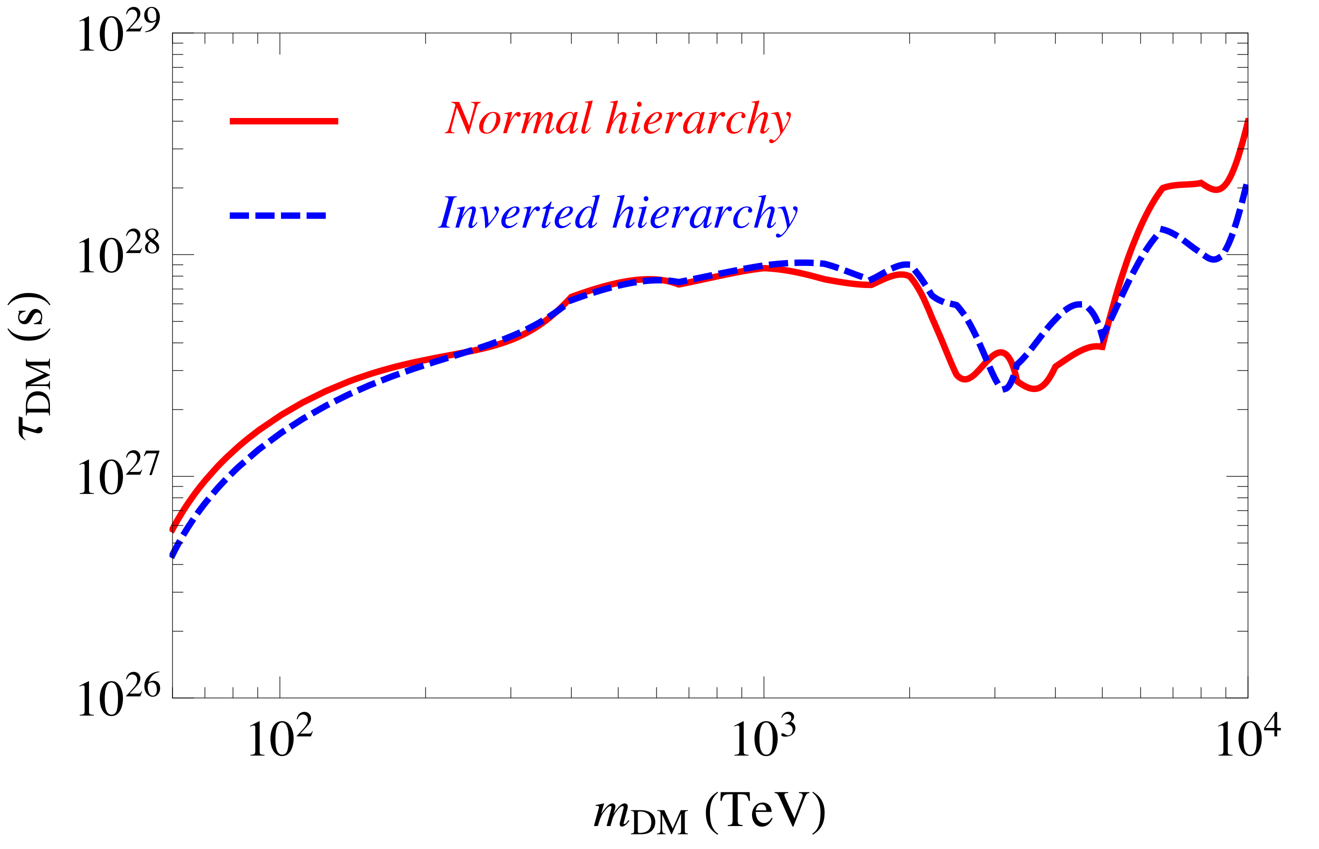
✓ at least one order of magnitude stronger lower limit on the DM lifetime, in the relevant DM mass range

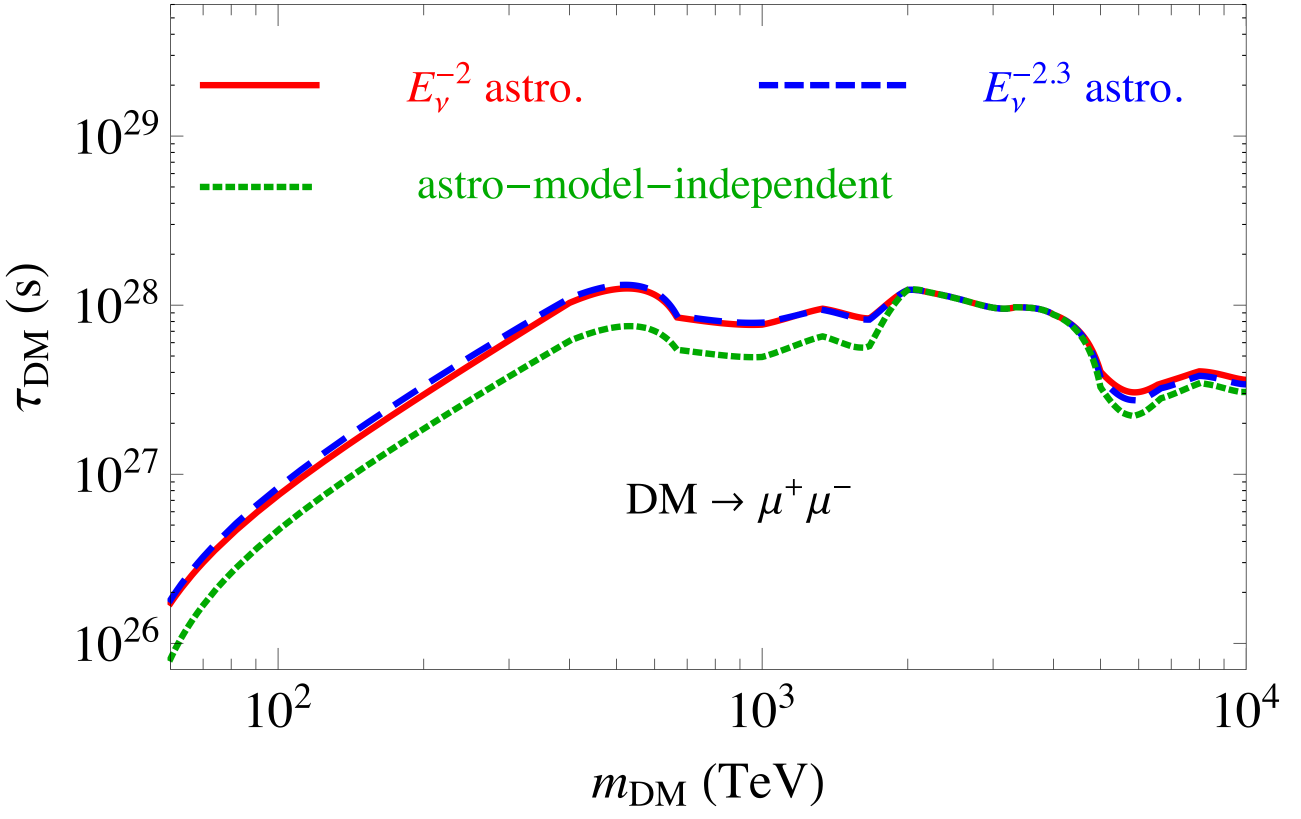
✓ for a specific model, different channels should be scaled according to the corresponding branching ratios

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>

Constraining DM properties

✓ Annihilation cross section

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

The isotropic components of neutrino flux from DM annihilation:

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

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

Constraining DM properties

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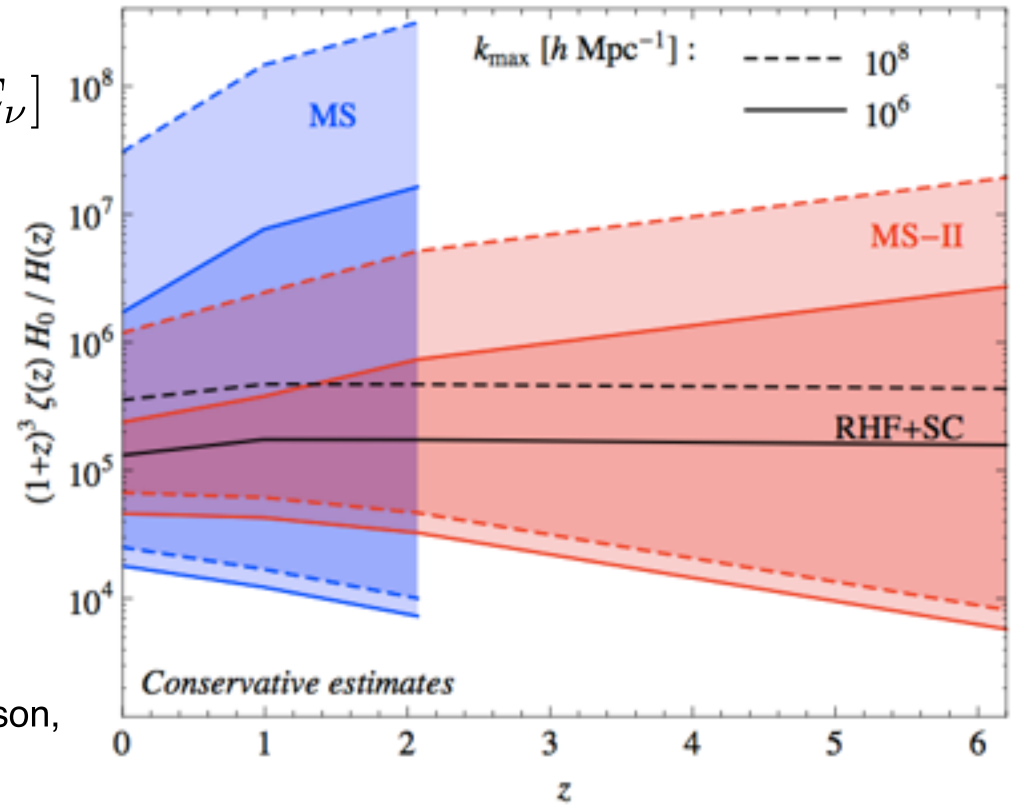
The cosmic flux from all redshift

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

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



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

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^{3}s^{-1}

DM + DM → \ $m_{\rm DM}$	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