Departamento
de Física

Heavy Dark Matter - neutrino signatures

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Workshop on Perspectives on the Extragalactic Frontiers:
from Astrophysics to Fundamental Physics

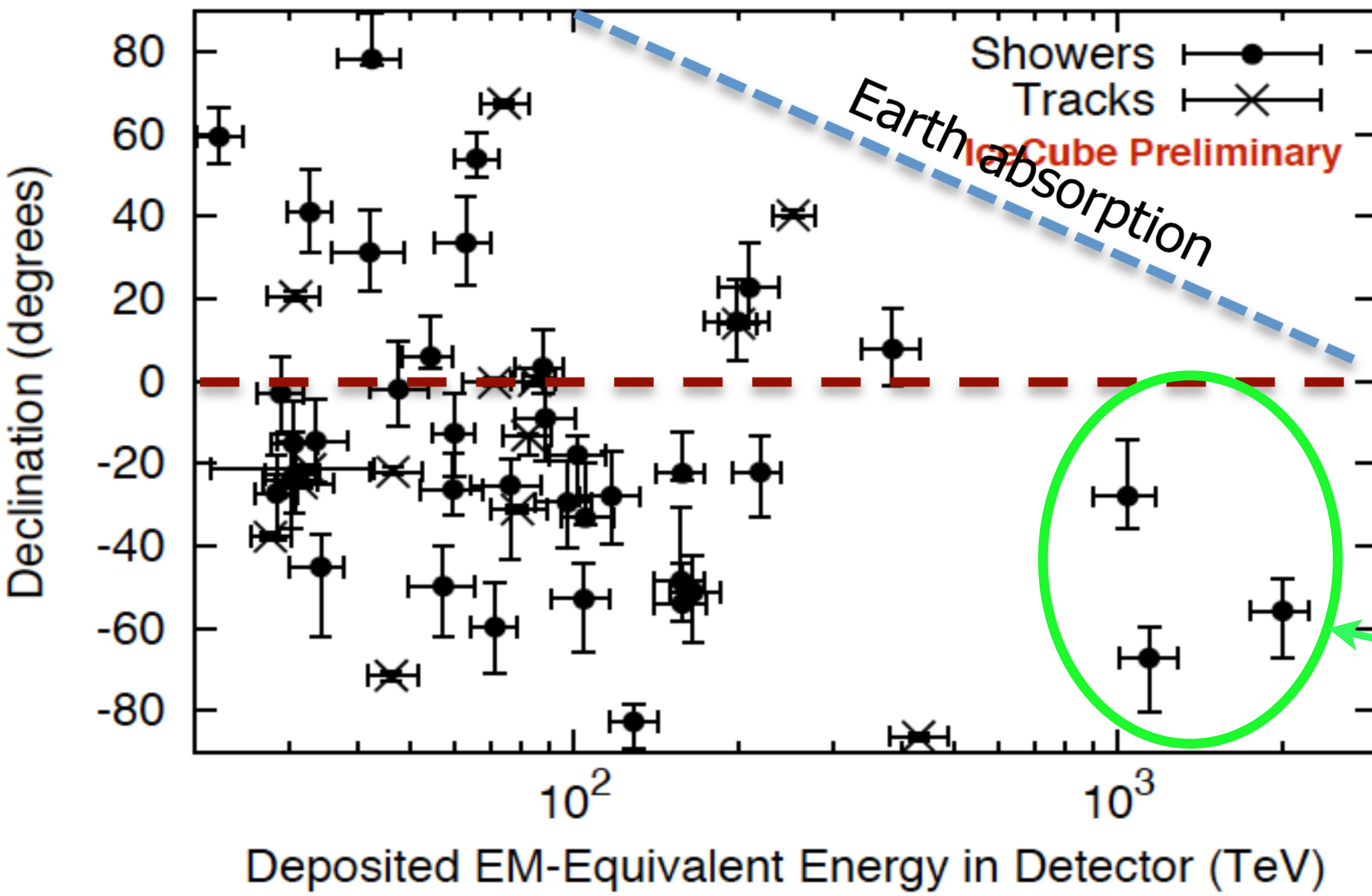
05/May/2016

IceCube data

✓ Looking for lower energy contained events, 1347 days livetime

IPA 2015

The whole family!



✓ totally 53+1 events

✓ three events with energy ~ PeV

4 years of data

excess of events ~ 7σ

which one?

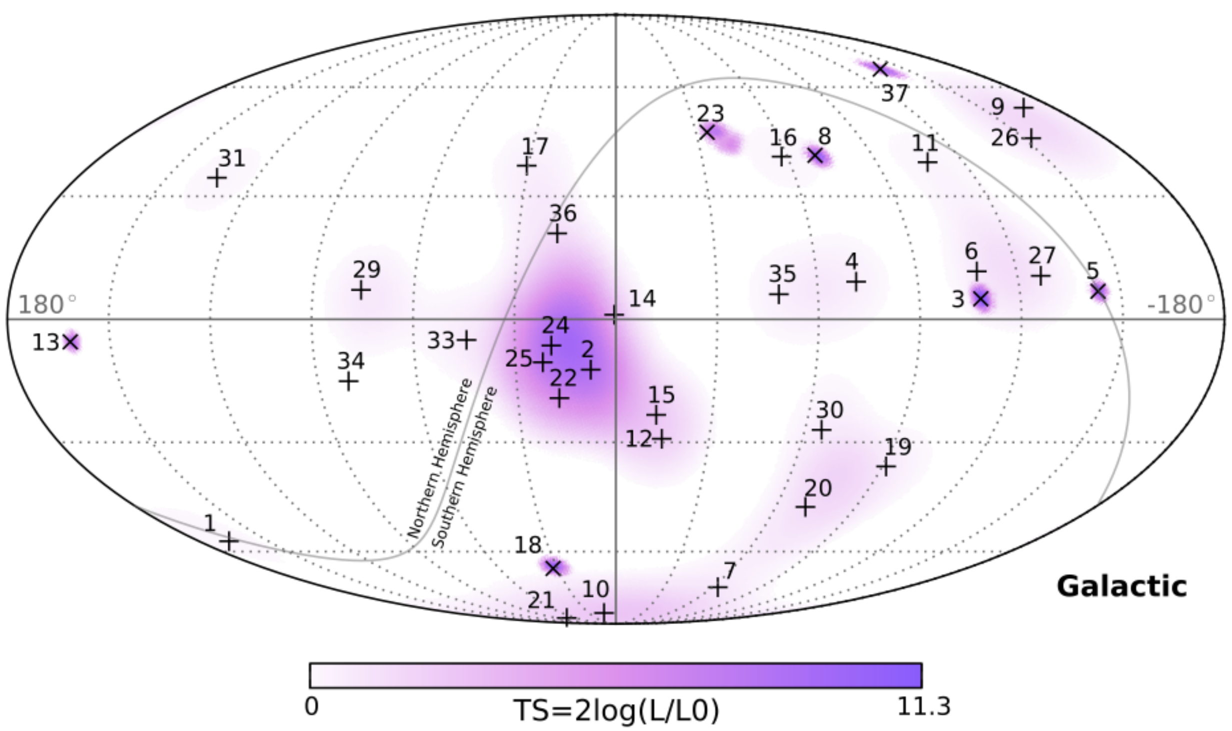
atmospheric ?

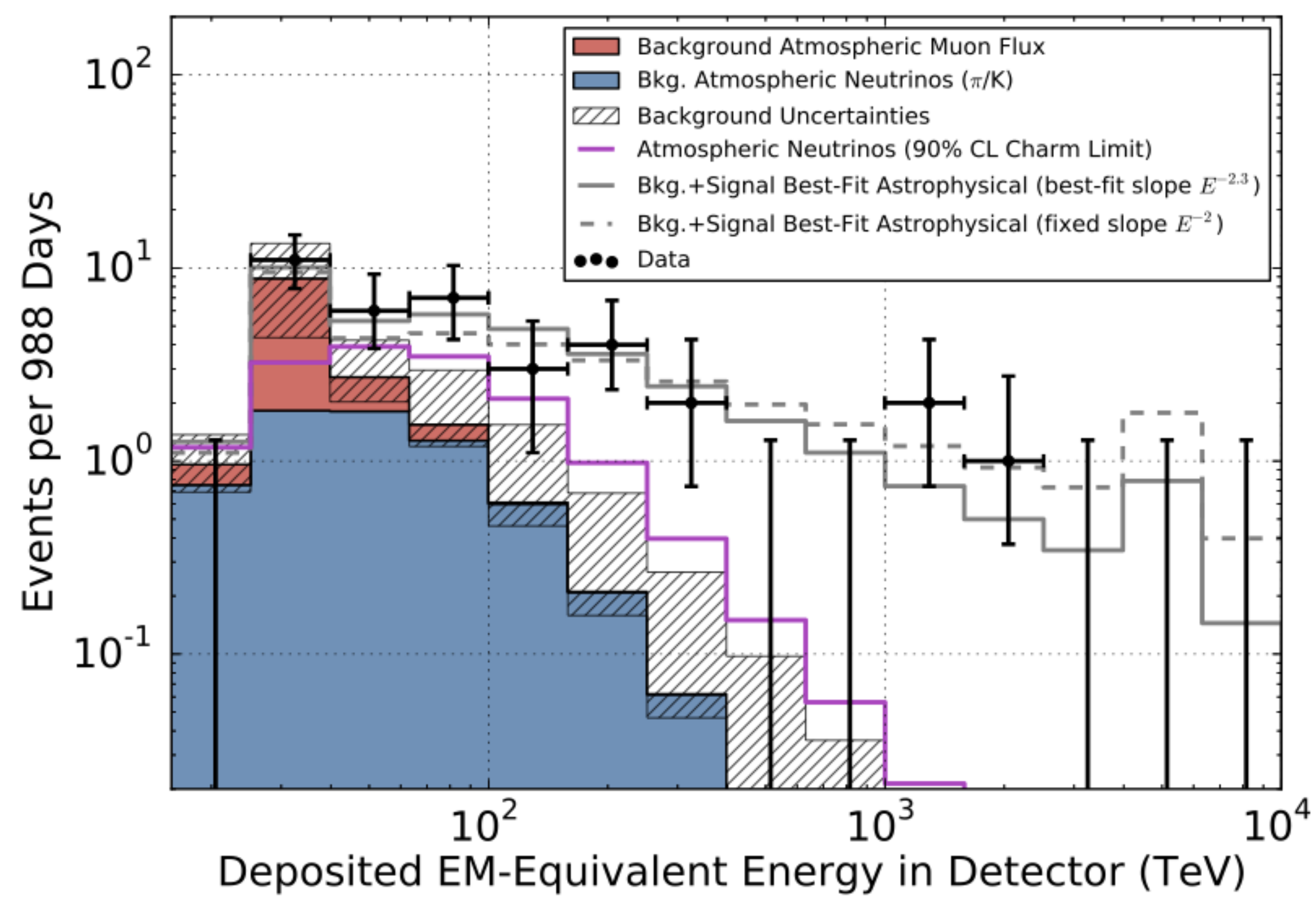
astrophysical ?

or something else ?

IceCube data

3 yrs data-set





IceCube data
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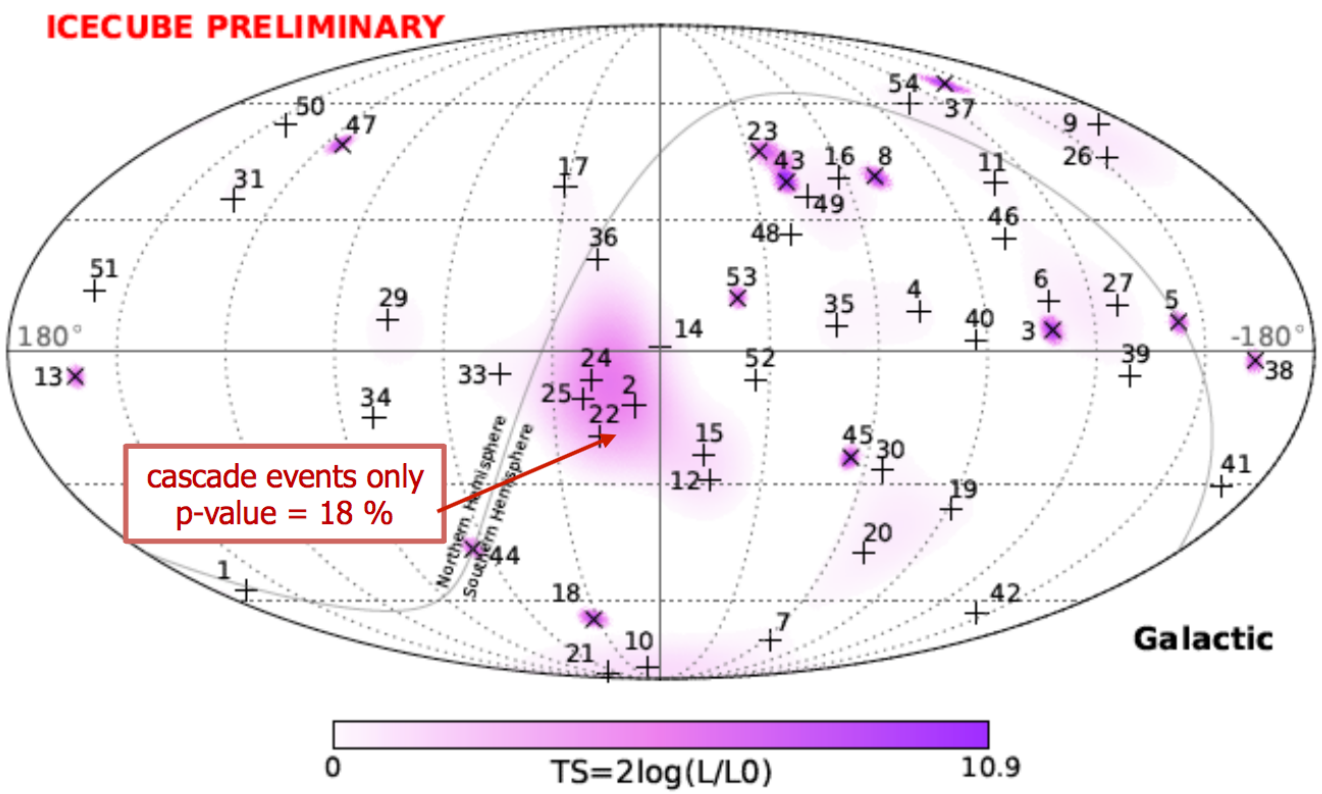
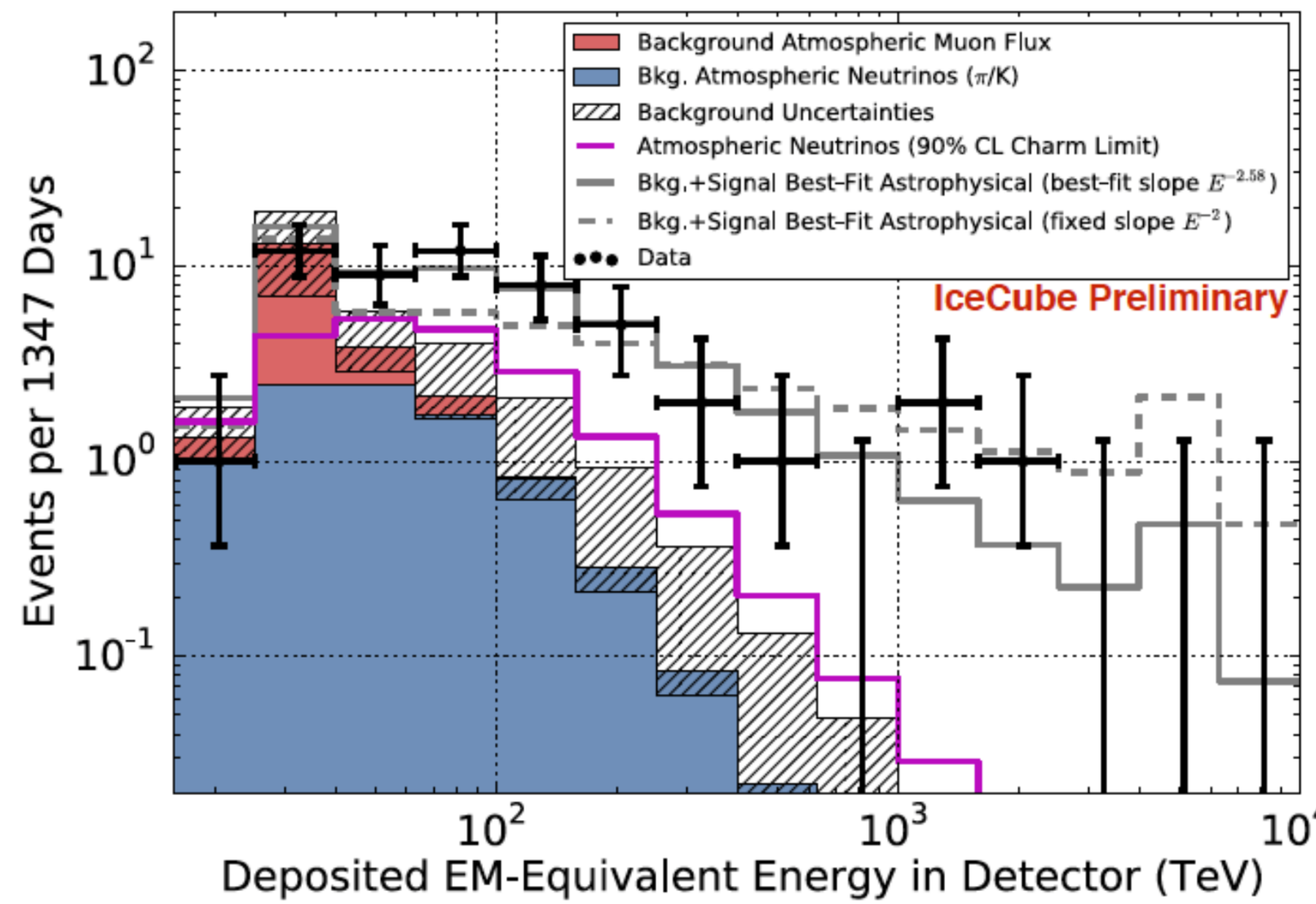
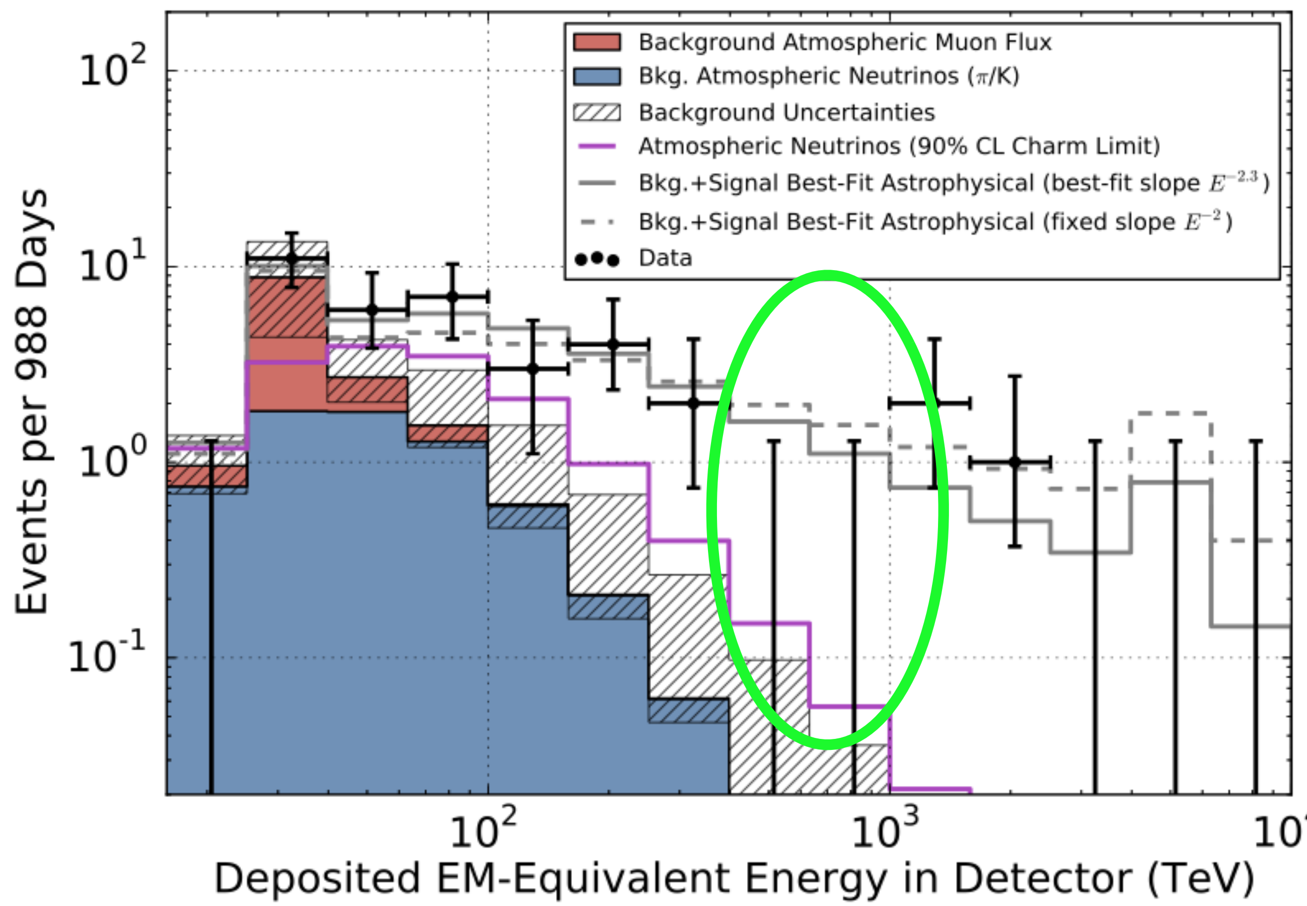




IceCube data

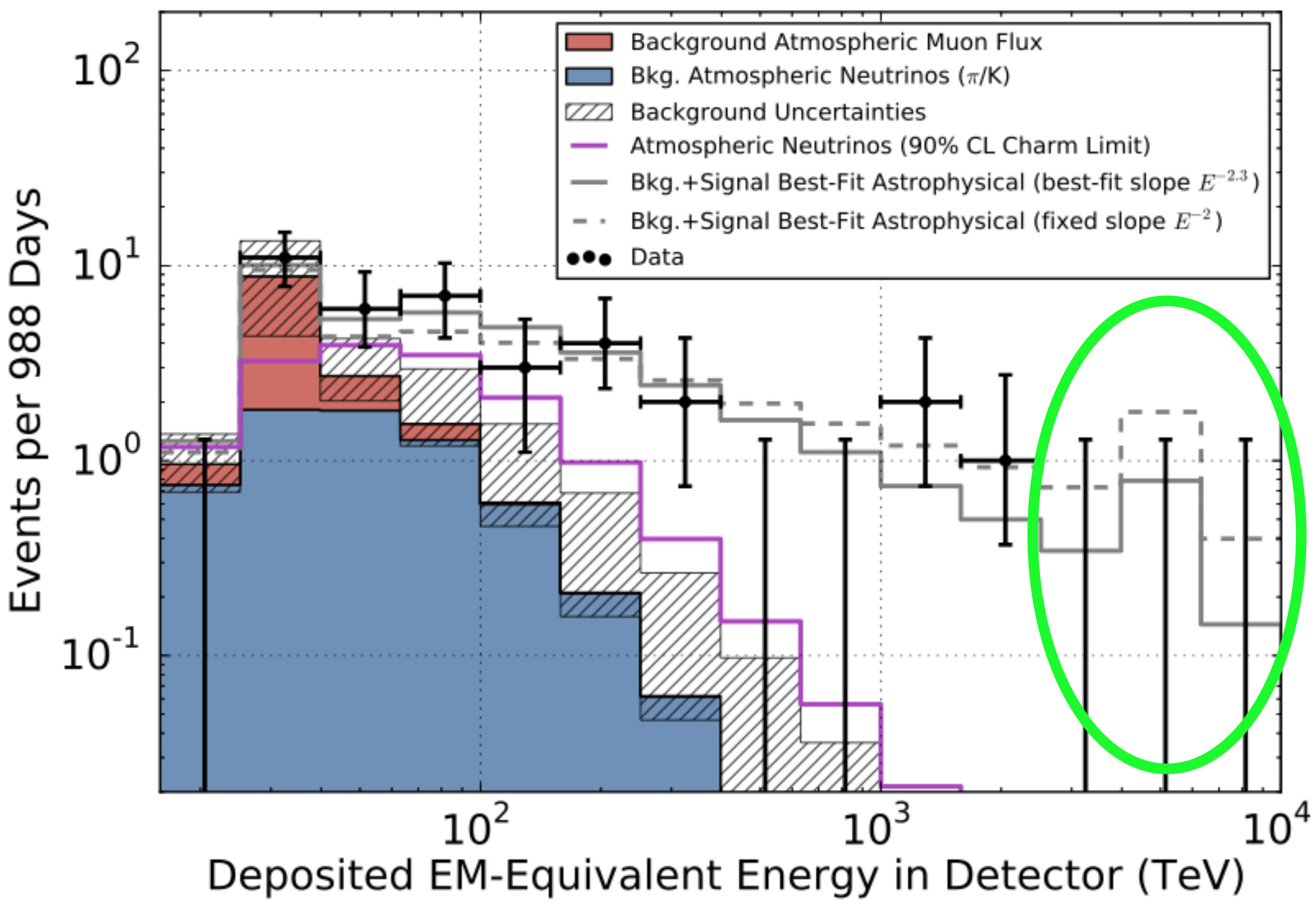
IceCube data

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



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

- ✓ deficit of events in the energy range ~ (400 - 1000) TeV
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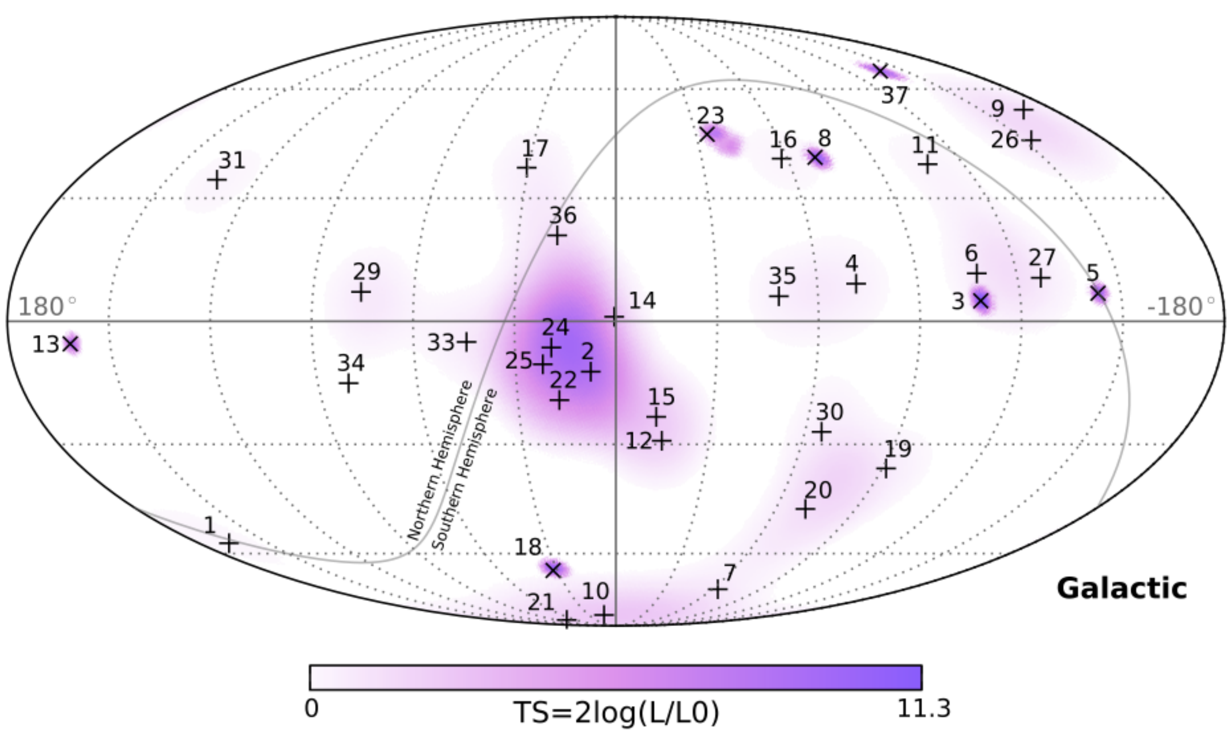
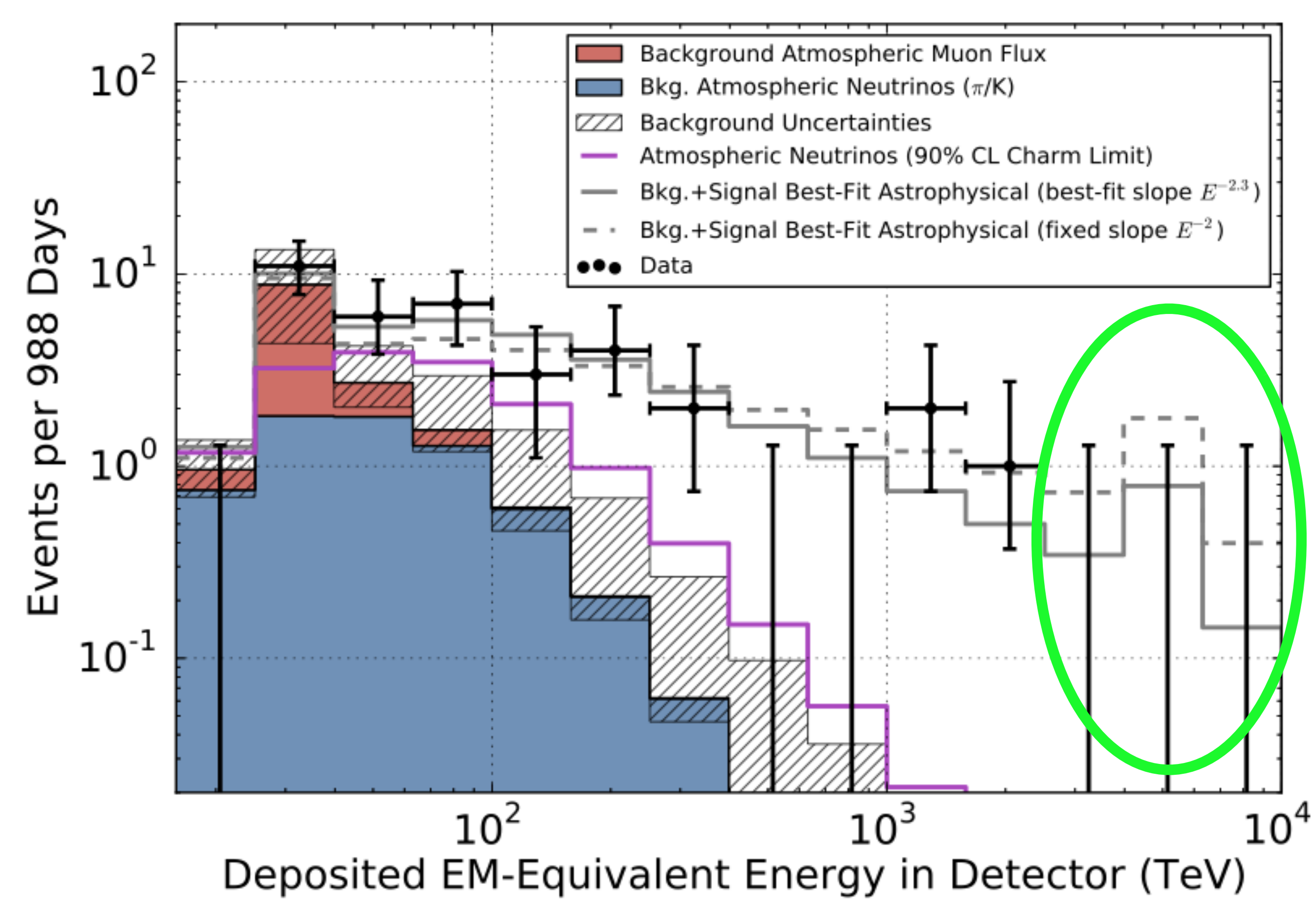
- ✓ angular distribution of events show mild anisotropies (enhanced toward GC)





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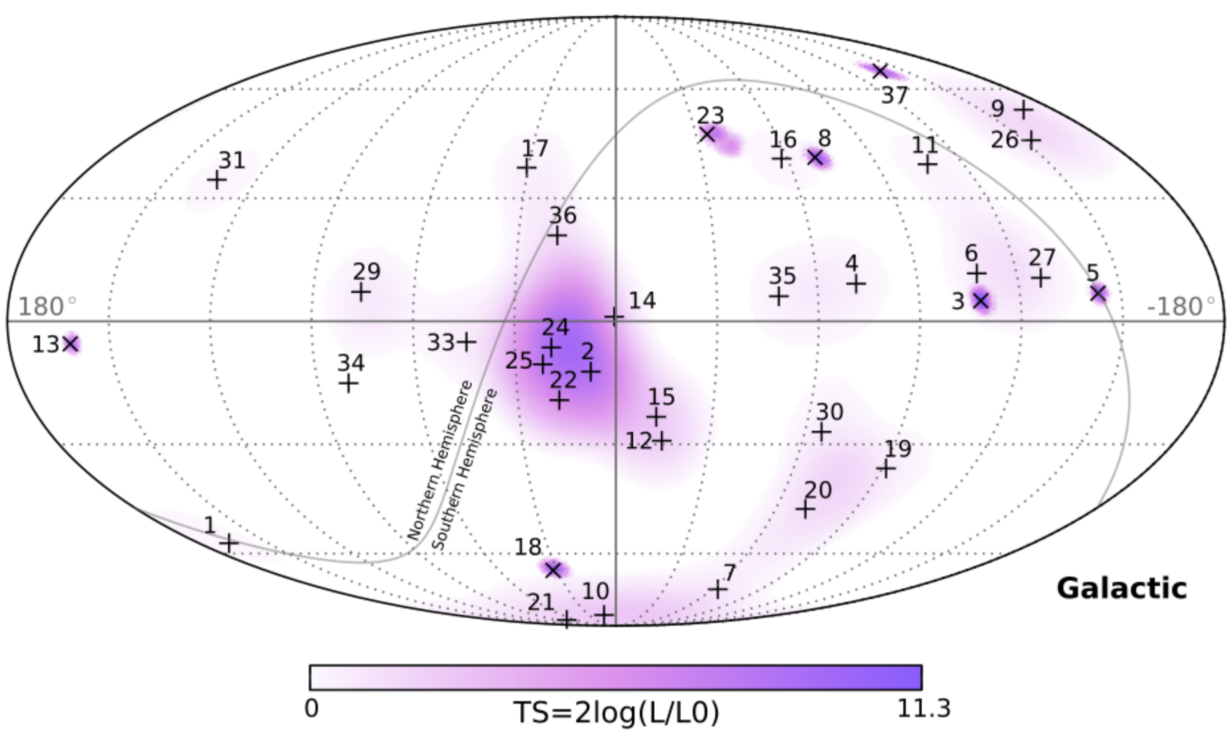

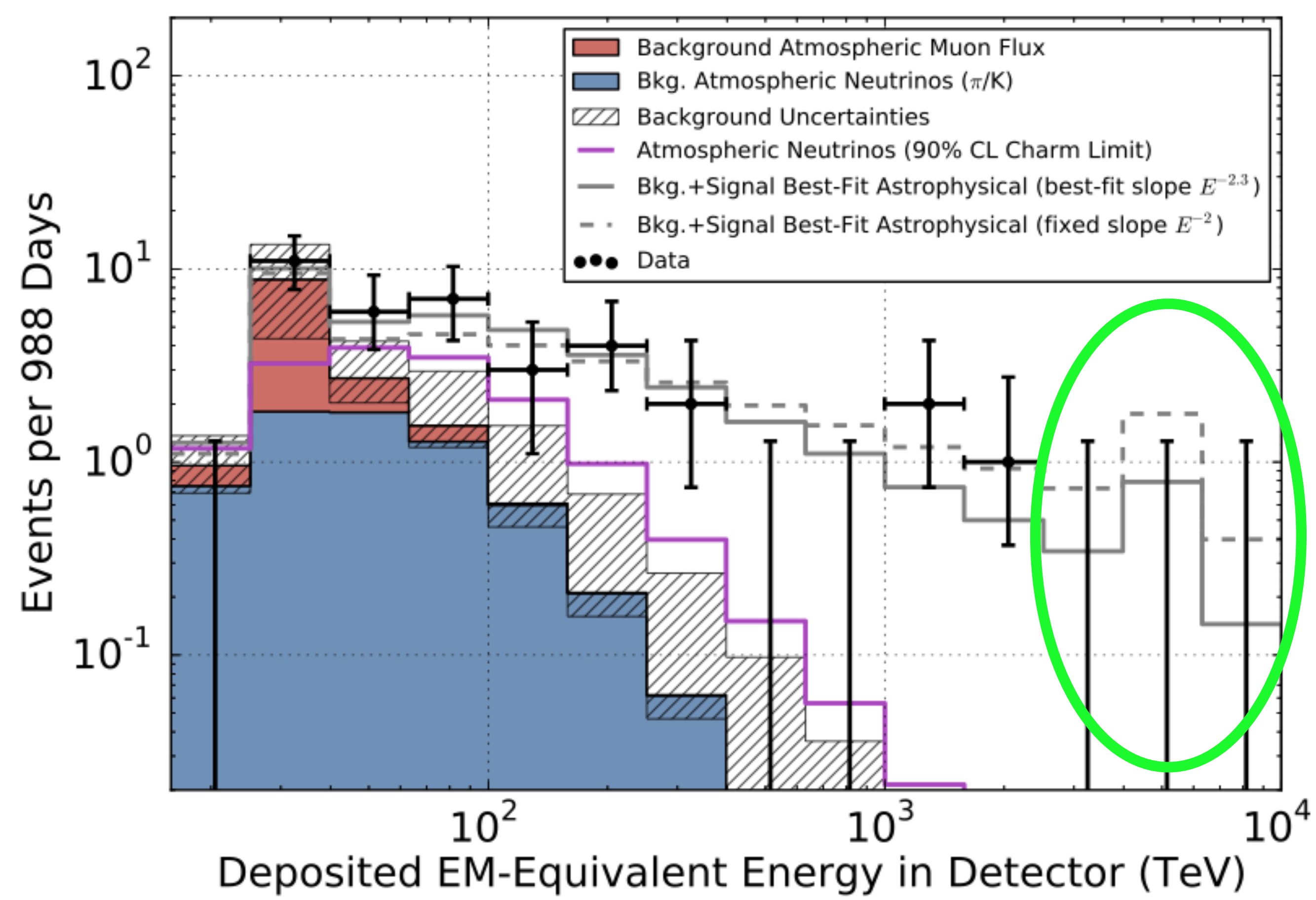

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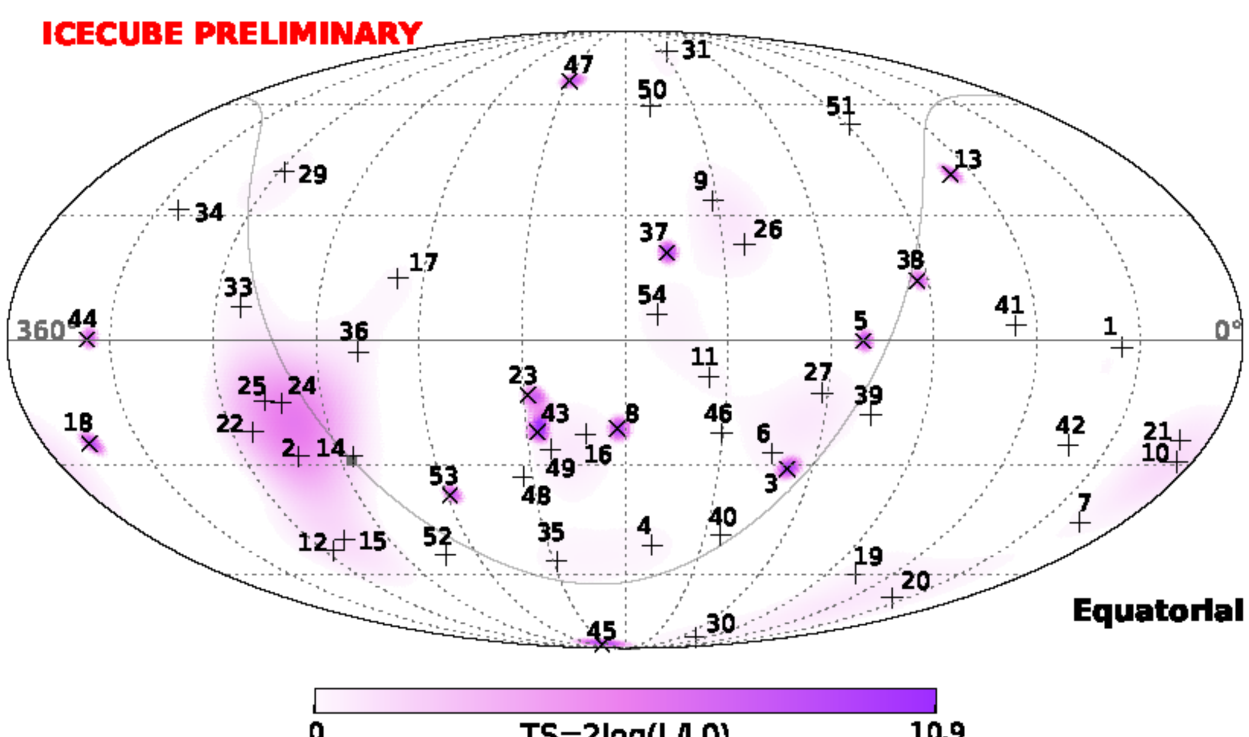

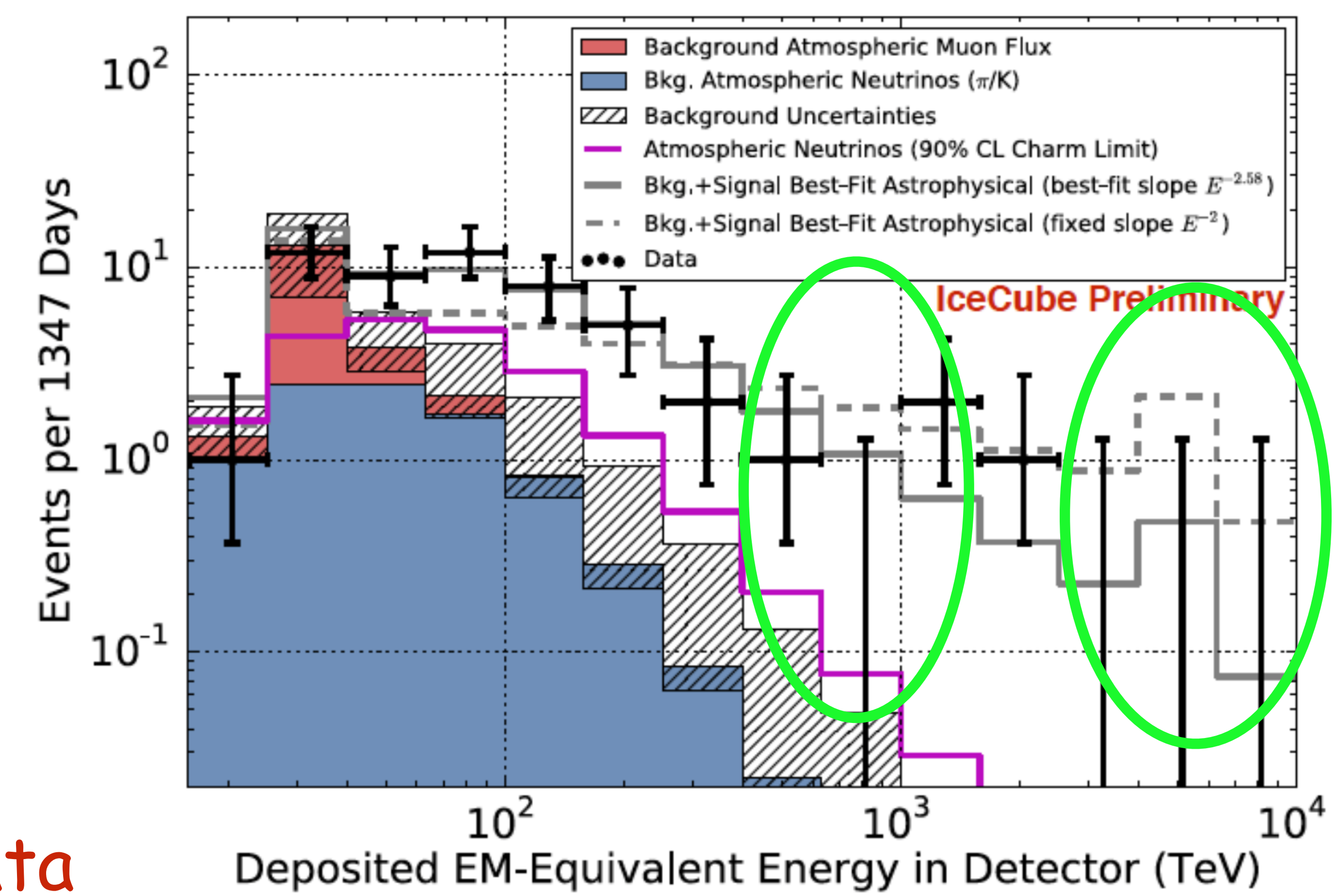

4 years of data

Interpretations of IceCube data

✓ "Conventional" interpretations of IceCube data

Cosmic ray sources

GRBs

Galaxy clusters

Star-forming galaxies

AGNs

Fermi bubbles

Galactic Center activities

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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]].
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L. A. Anchordoqui, H. Goldberg, M. H. Lynch, A. V. Olinto, T. C. Paul and T. J. Weiler, arXiv:1306.5021 [astro-ph.HE].
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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]].
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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]].
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A. Bhattacharya, M. H. Reno and I. Sarcevic, JHEP 1406, 110 (2014) [arXiv: 1403.1862 [hep-ph]].
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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, arXiv:1505.06486

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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?

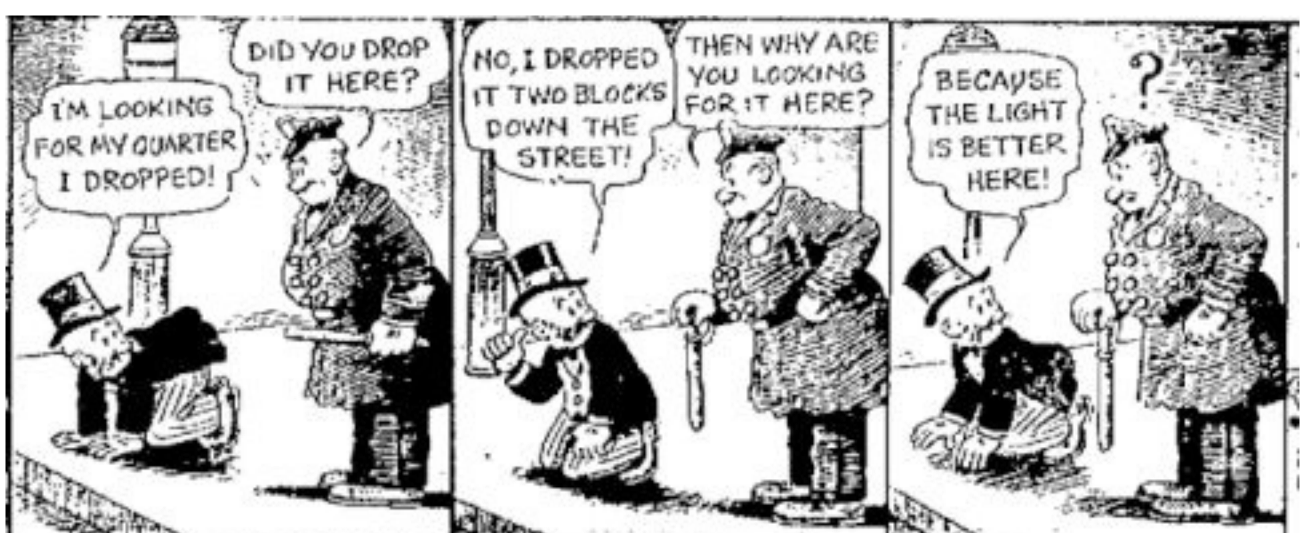
✓ Mass

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: streetlight effect



Mulla Nasreddin

A note on Dark Matter

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What We Do Not Know?

✓ Mass

	axion	Sterile ν	WIMP	Wimpzilla
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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

✓ 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

$16 - 2.5 \times 10^3$ TeV

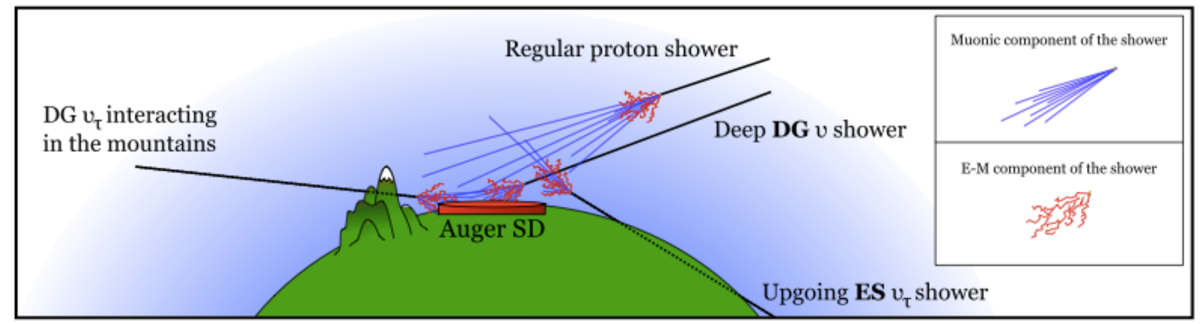
AMANDA

$10^5 - 10^8$ TeV

Auger

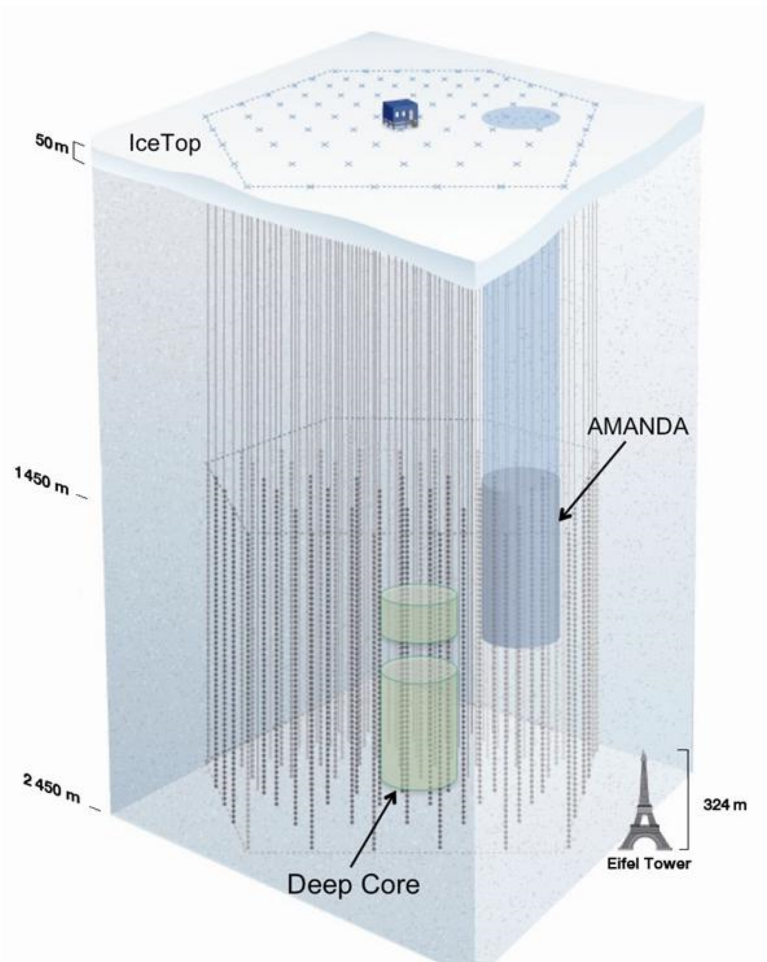
$340 - 2 \times 10^5$ TeV

IceCube-22



$3 \times 10^3 - 6.3 \times 10^6$ TeV

IceCube-40

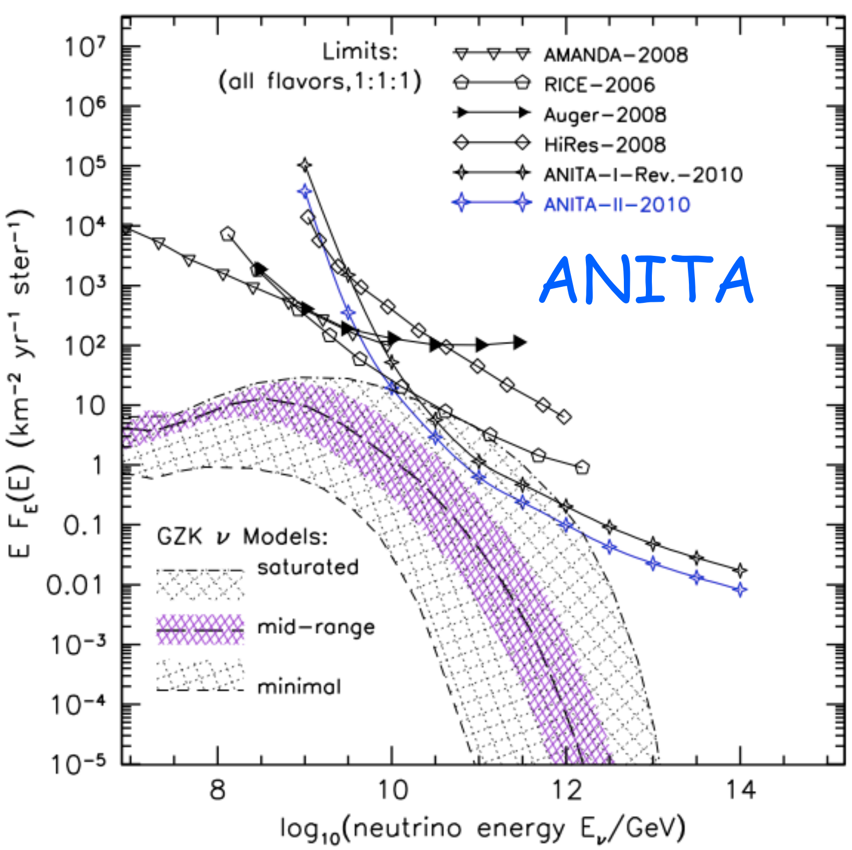


$10^6 - 3.2 \times 10^{11}$ TeV

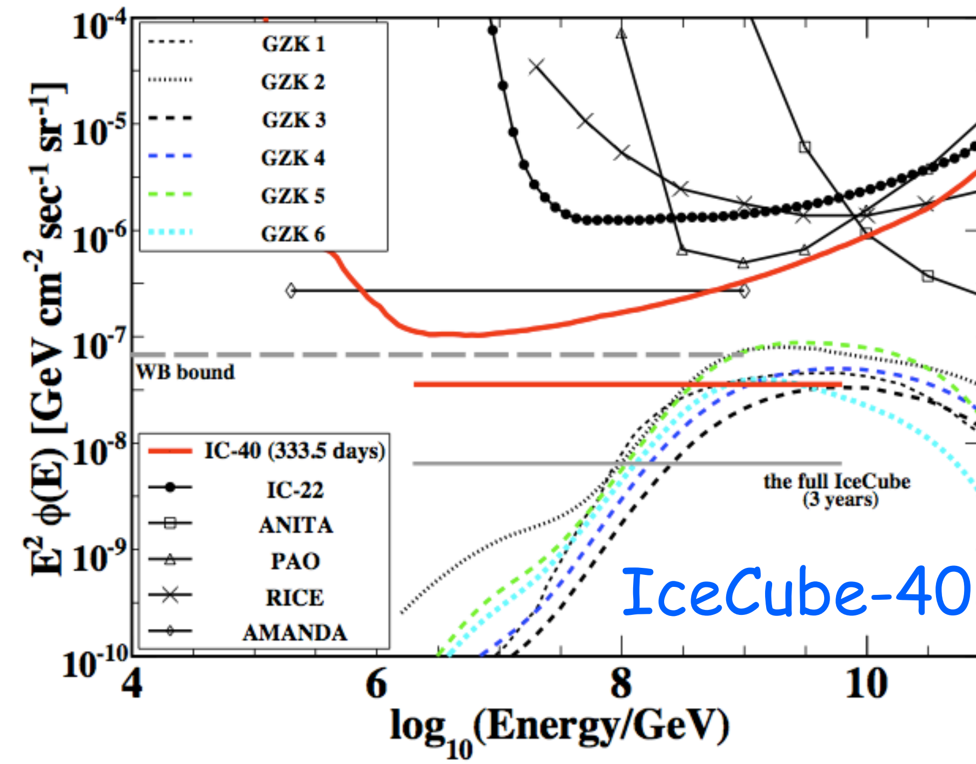
ANITA

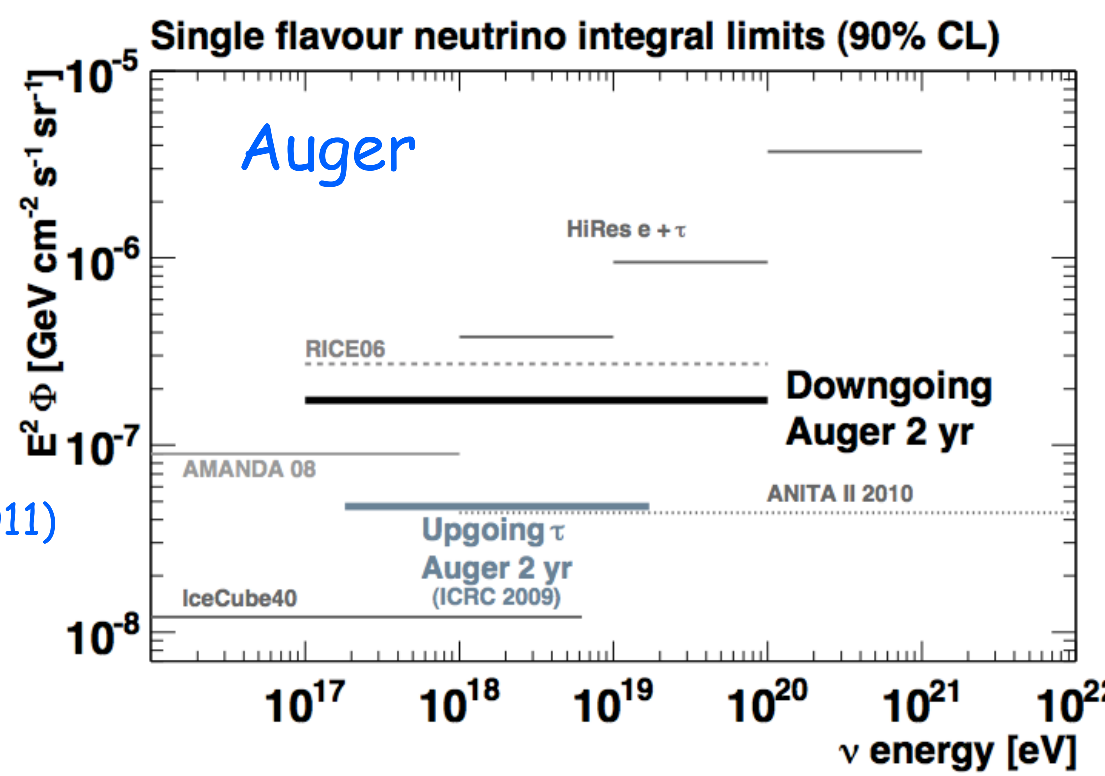
Experiments

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

Decaying Dark Matter

$$\Phi = k E_\nu^{-2}$$

	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

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

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

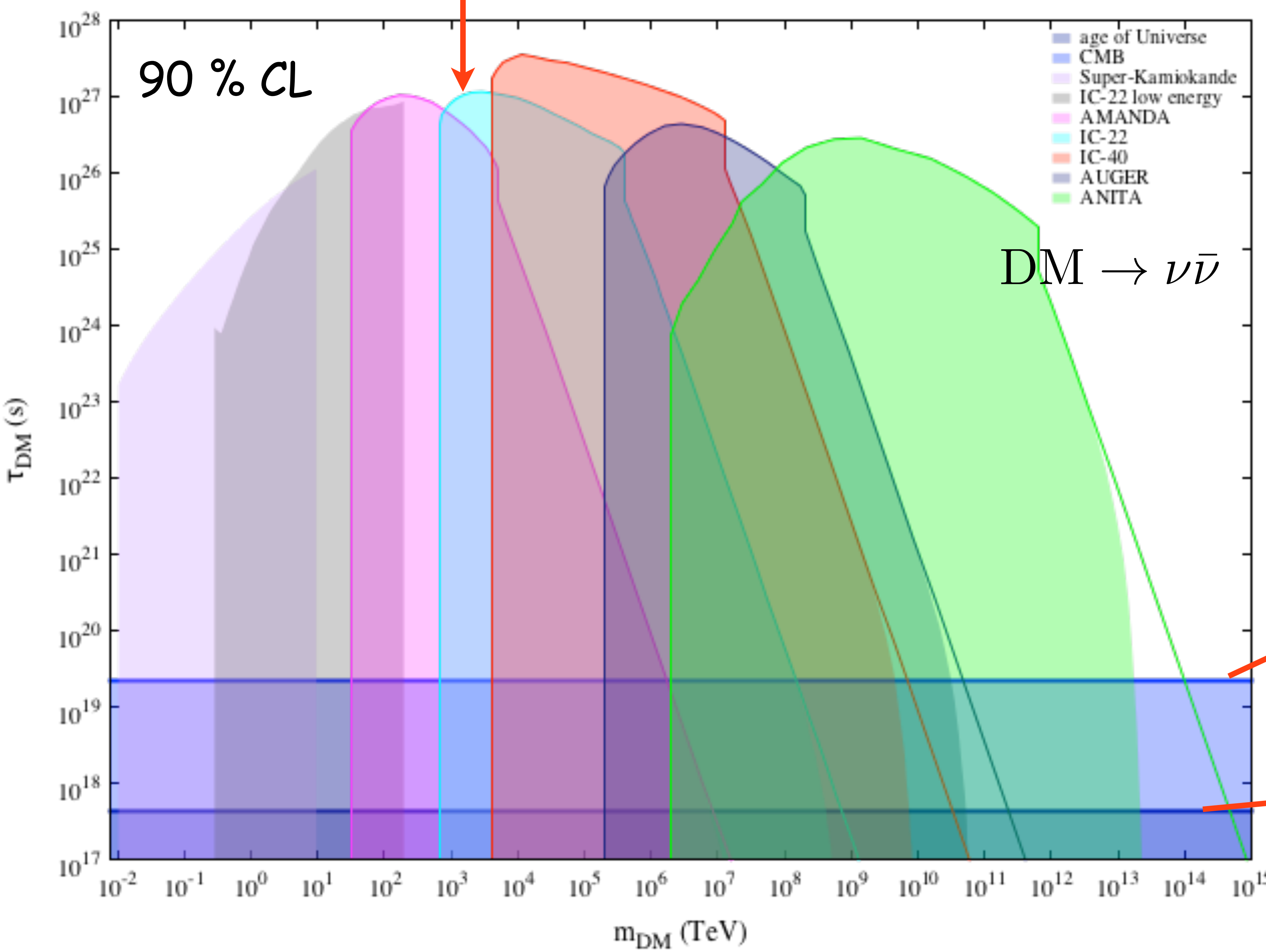
Limits on lifetime from neutrino experiments

before recent IceCube data

✓ Lifetime: stable (∞) or

this talk

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



Using AMANDA, IceCube, Auger and ANITA data

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

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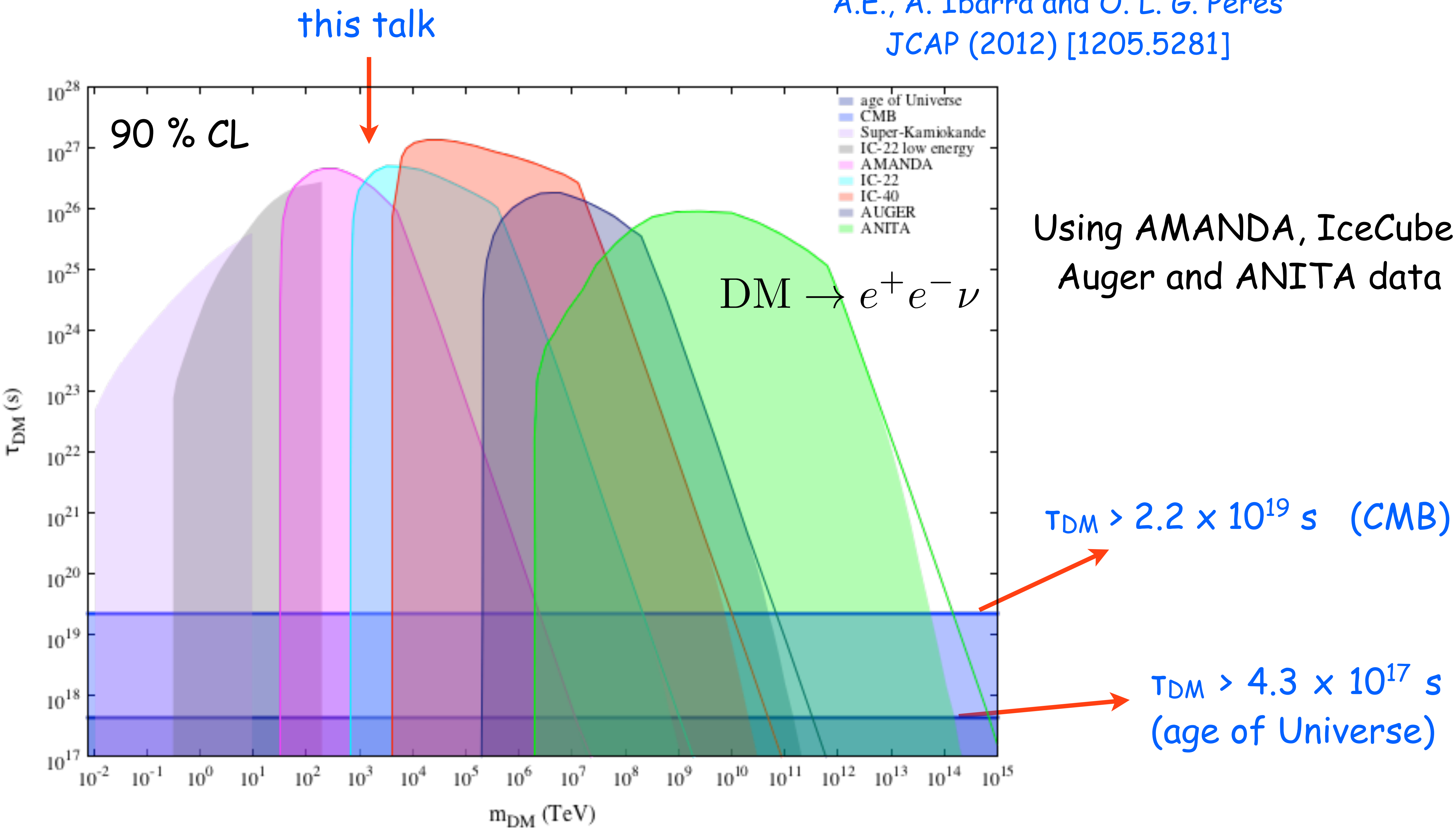

Using AMANDA, IceCube, Auger and ANITA data

Energy distribution of neutrinos from decaying DM

✓ **Galactic contribution:**

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

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

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

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✓ extragalactic contribution:

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

Energy distribution of neutrinos from decaying DM

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

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

quarks

neutrinos, charged leptons

Energy distribution of neutrinos from decaying DM

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quarks (S term); neutrinos, charged leptons (H term)

at the Earth

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

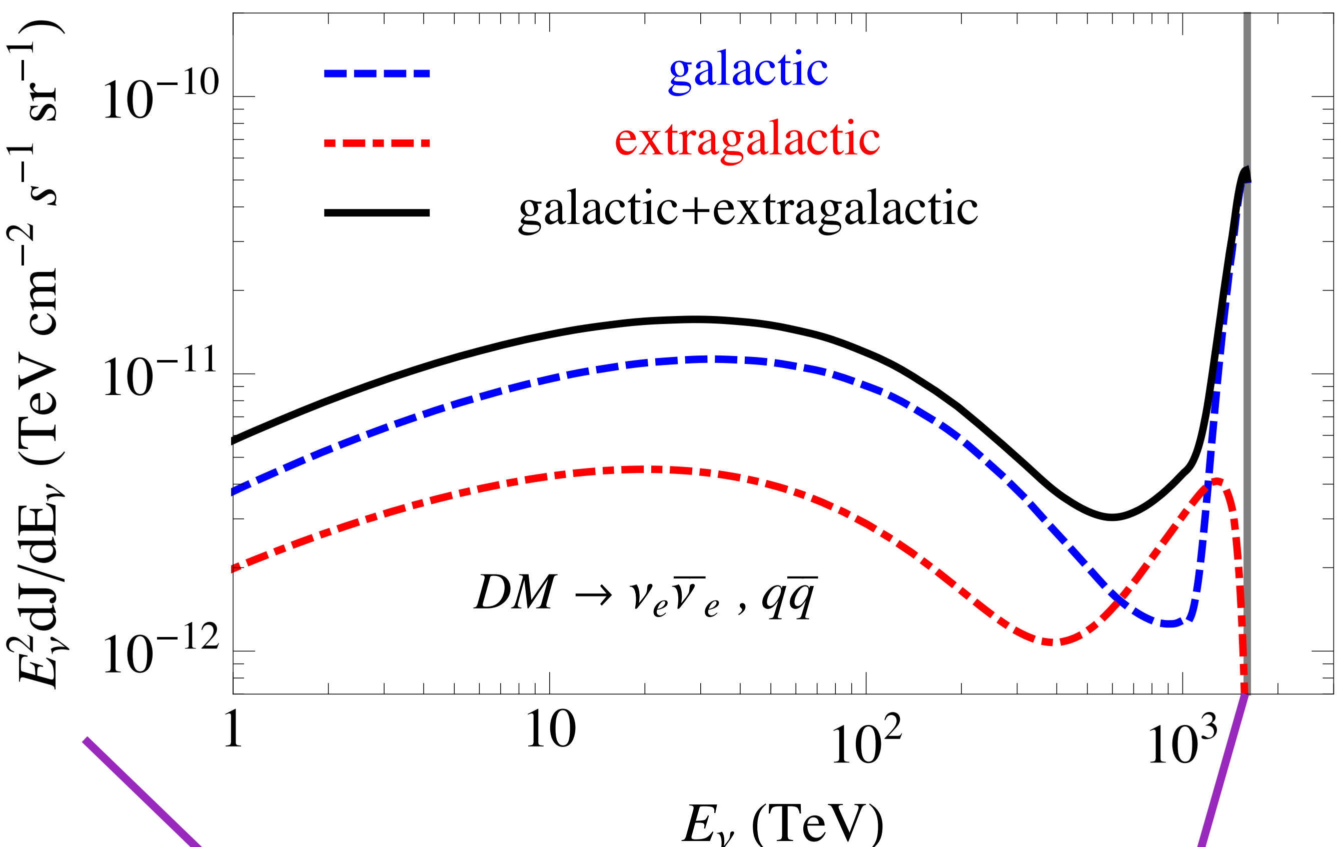
production point

decoherent oscillation

Flux of neutrinos from decaying DM

✓ an example:

A. E., P. Serpico,
JCAP (2013) [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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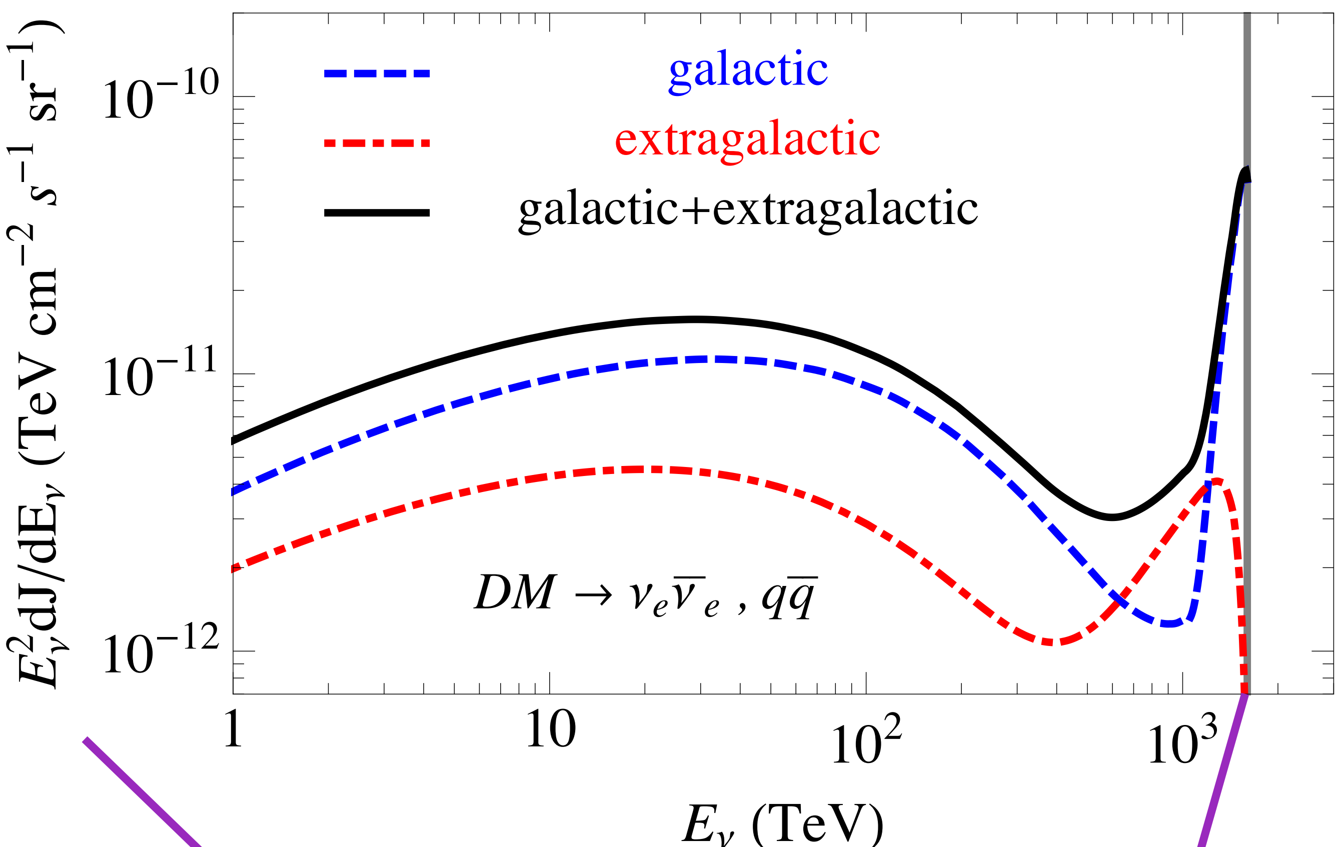

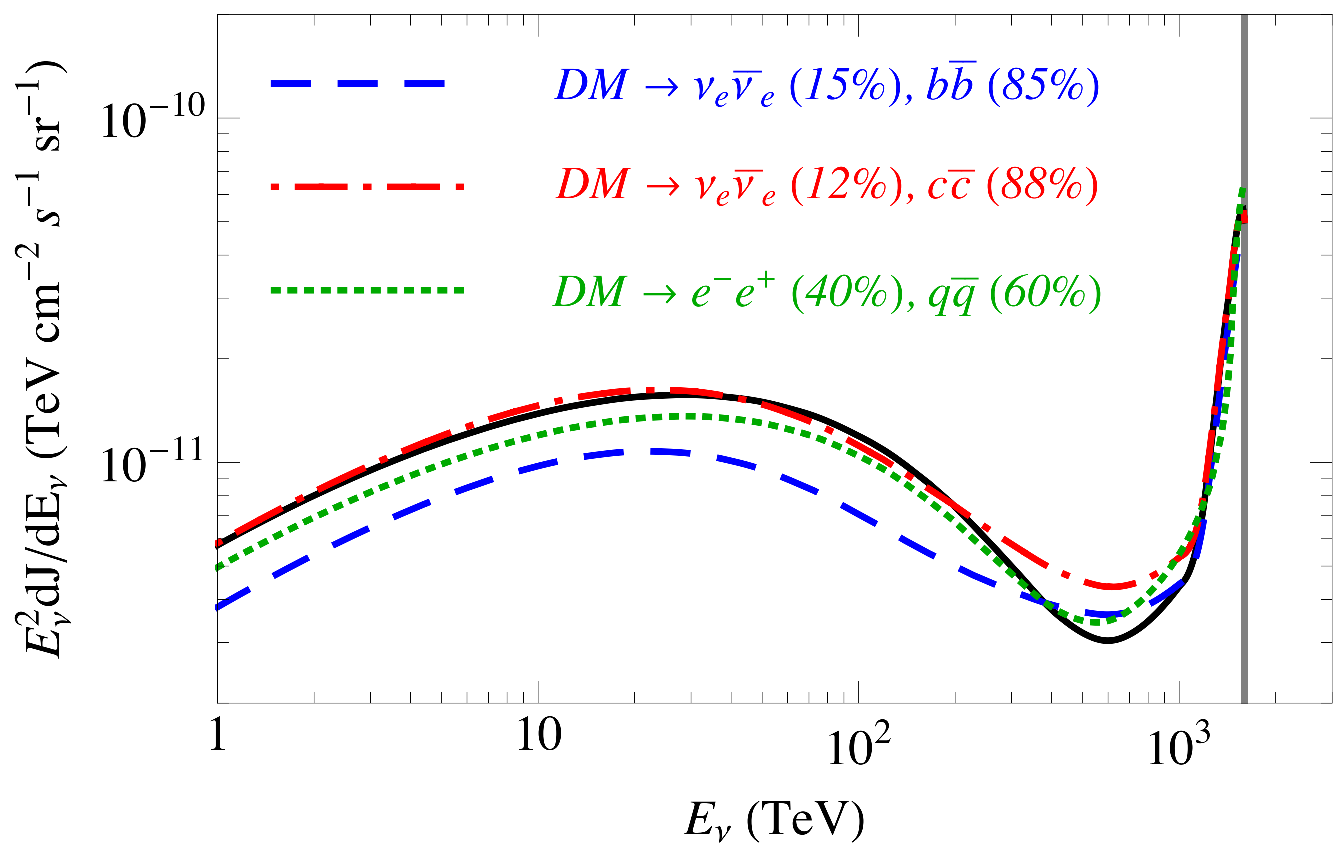

$(\nu_e + \nu_\mu + \nu_\tau)/3$

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Confronting with energy distribution of IceCube data

two years data set

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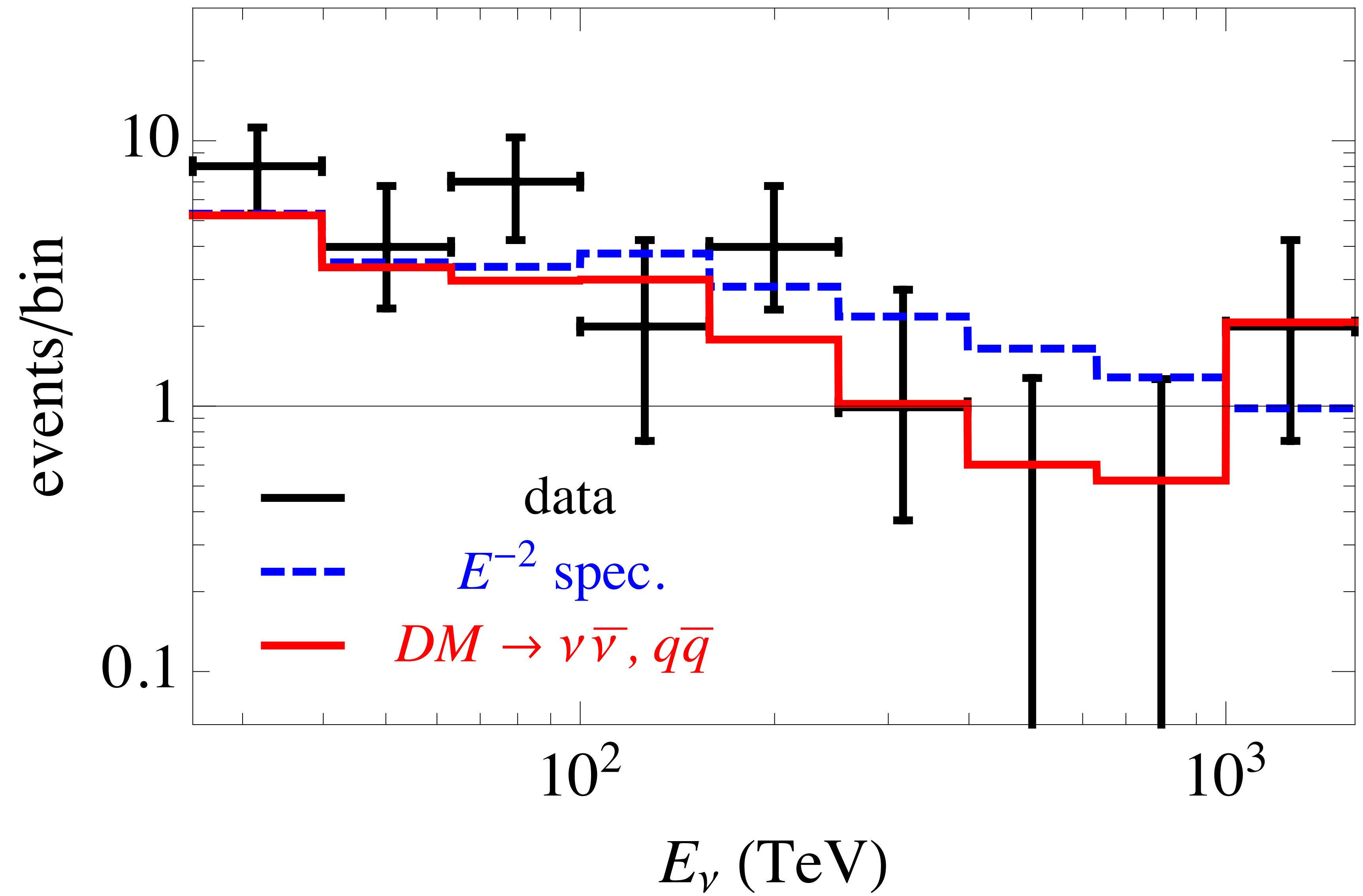

Confronting with energy distribution of IceCube data

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

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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

Confronting with energy distribution of IceCube data

three years data set

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Higgs field of B-L ← $m_\phi \gg m_N$ inflaton decay

production mechanism:

$m_\phi \ll m_N$ freeze-in

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

Confronting with energy distribution of IceCube data

three years data set

SM sector ⟷ Dark sector

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

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

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

✓ 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

DM decay channels:

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

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

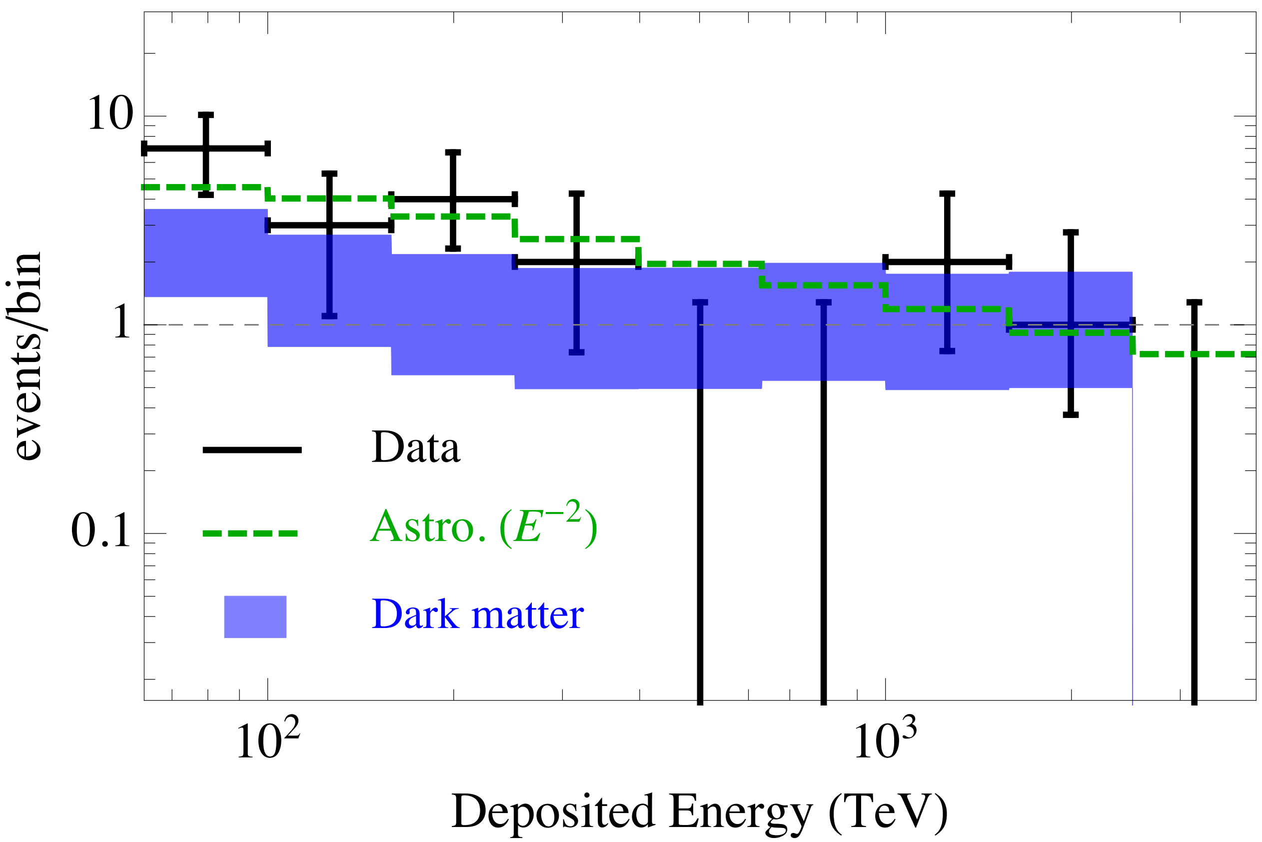
Confronting with energy distribution of IceCube data

three years data set

IH

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

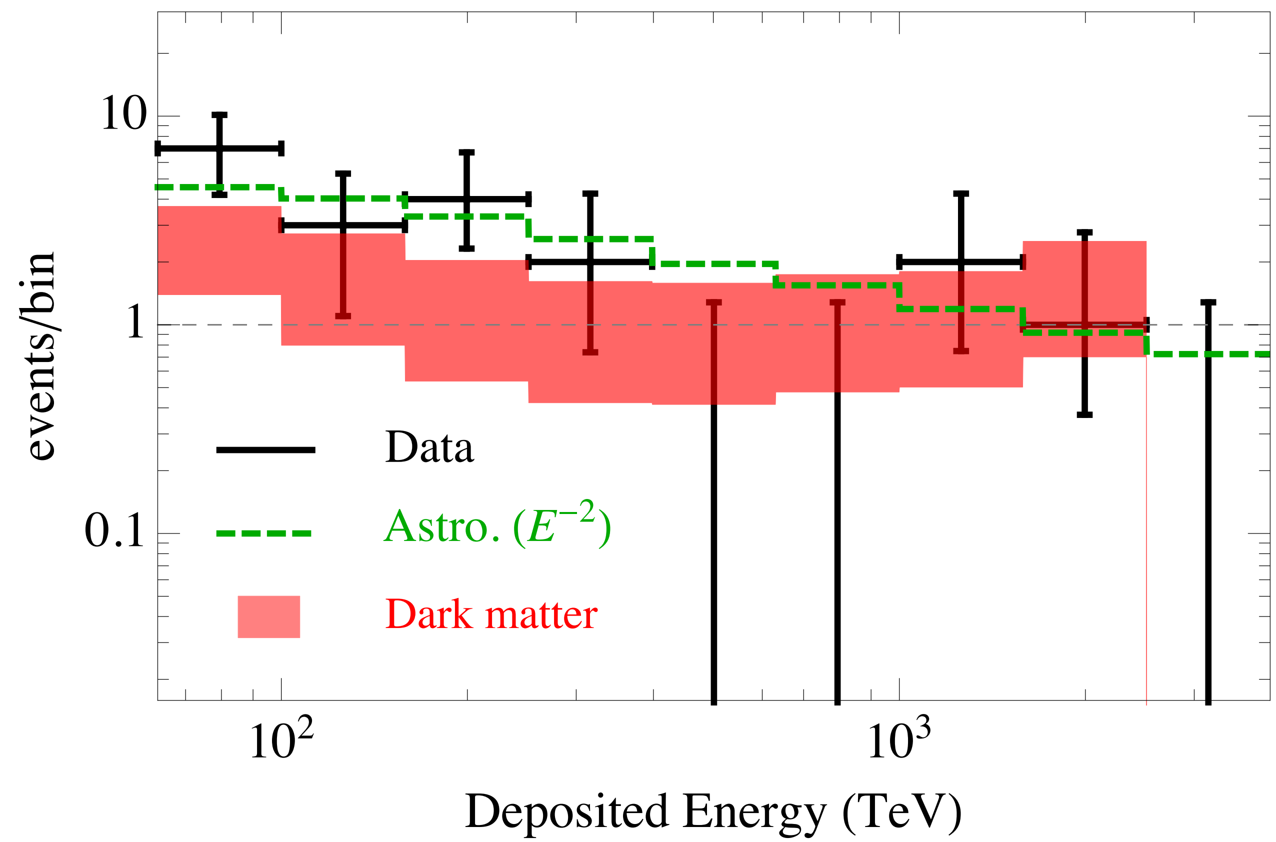
shaded: ±1σ



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

SM sector ⟷ Dark sector

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

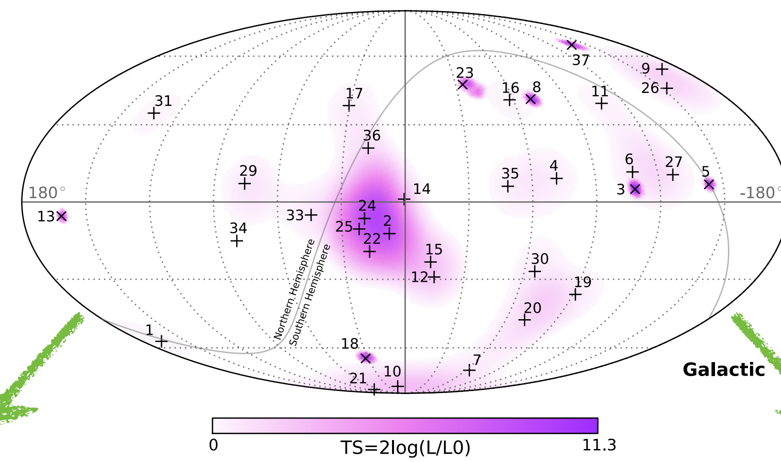
✓ d = 6 : other portals

✓ 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.

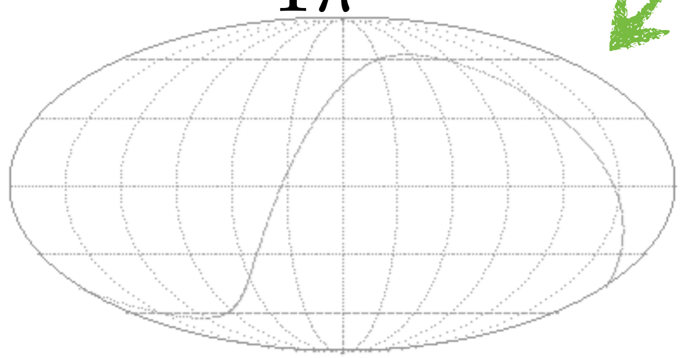
Three body decay -> Morisi talk

Angular distribution of neutrinos from decaying DM

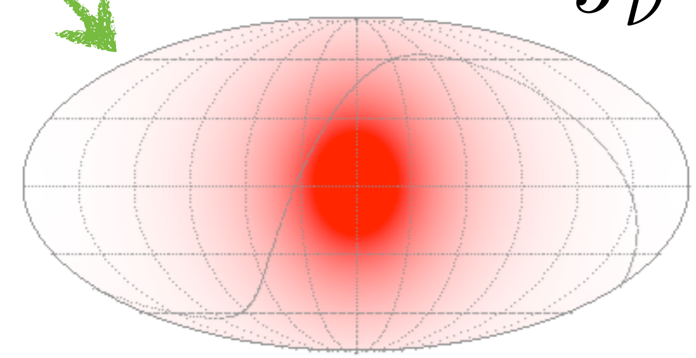
✔ We would compare



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



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



Angular distribution of neutrinos from decaying DM

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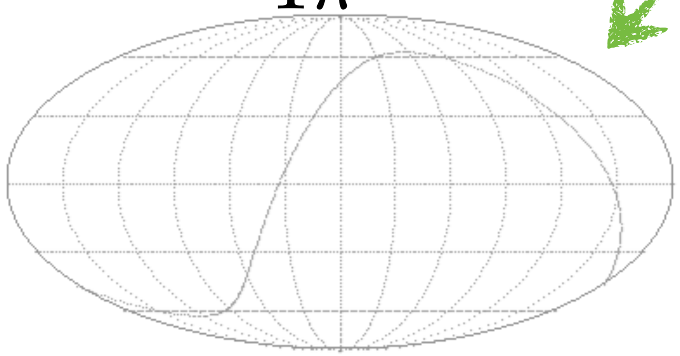

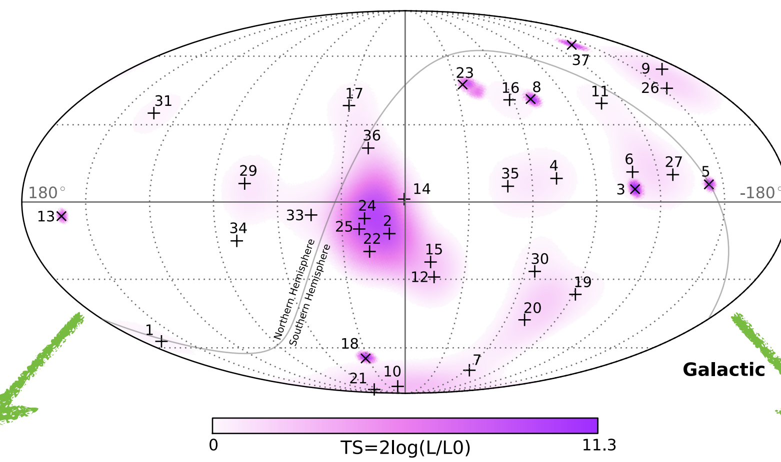

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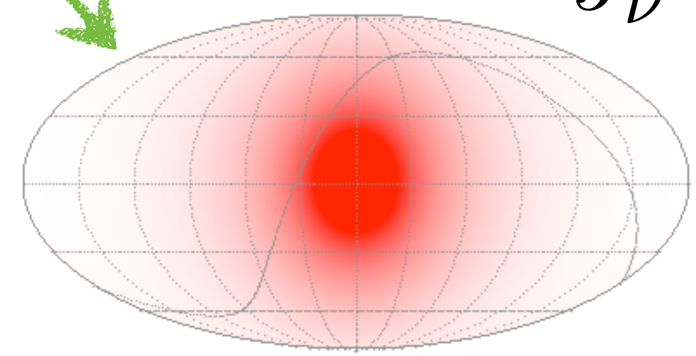

PDF of data

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

"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

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

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

N = 35 ? too optimistic!

Angular distribution of neutrinos from decaying DM

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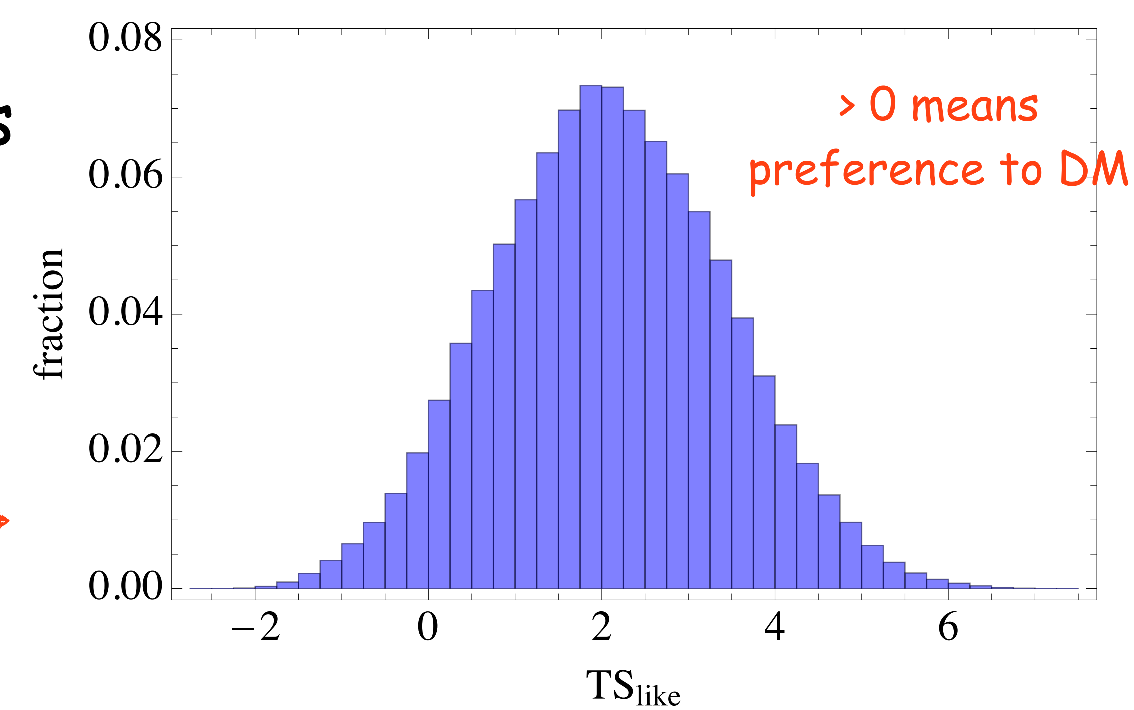
N = 35 ? too optimistic!

✓ 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 $\mathrm{TS_{like}}$ for all these realizations (mean value = 2.1) ➔



Angular distribution of neutrinos from decaying DM

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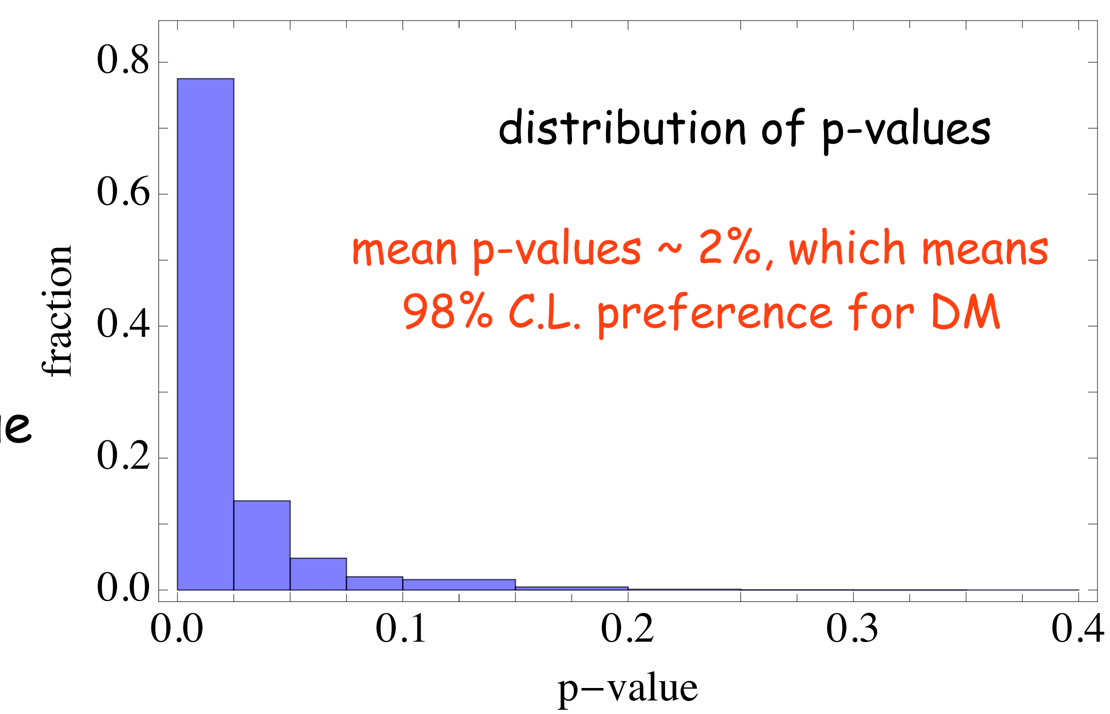
Quantifying the preference

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

↓

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

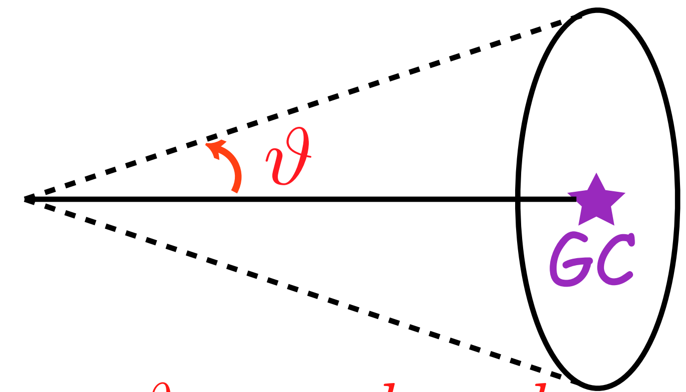
p-value →



Angular distribution of neutrinos from decaying DM

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

The 2-dim KS test have some ambiguities



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

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

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

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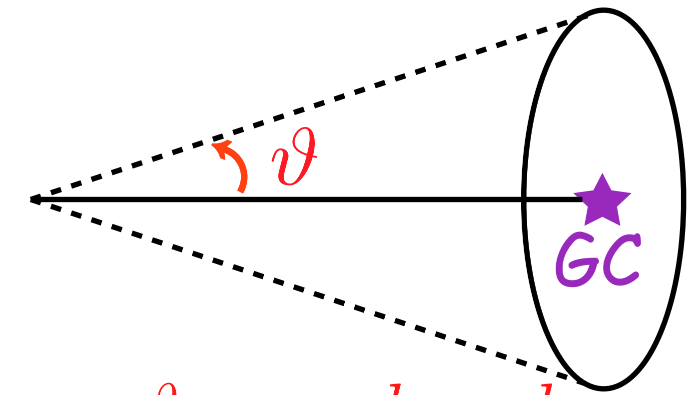

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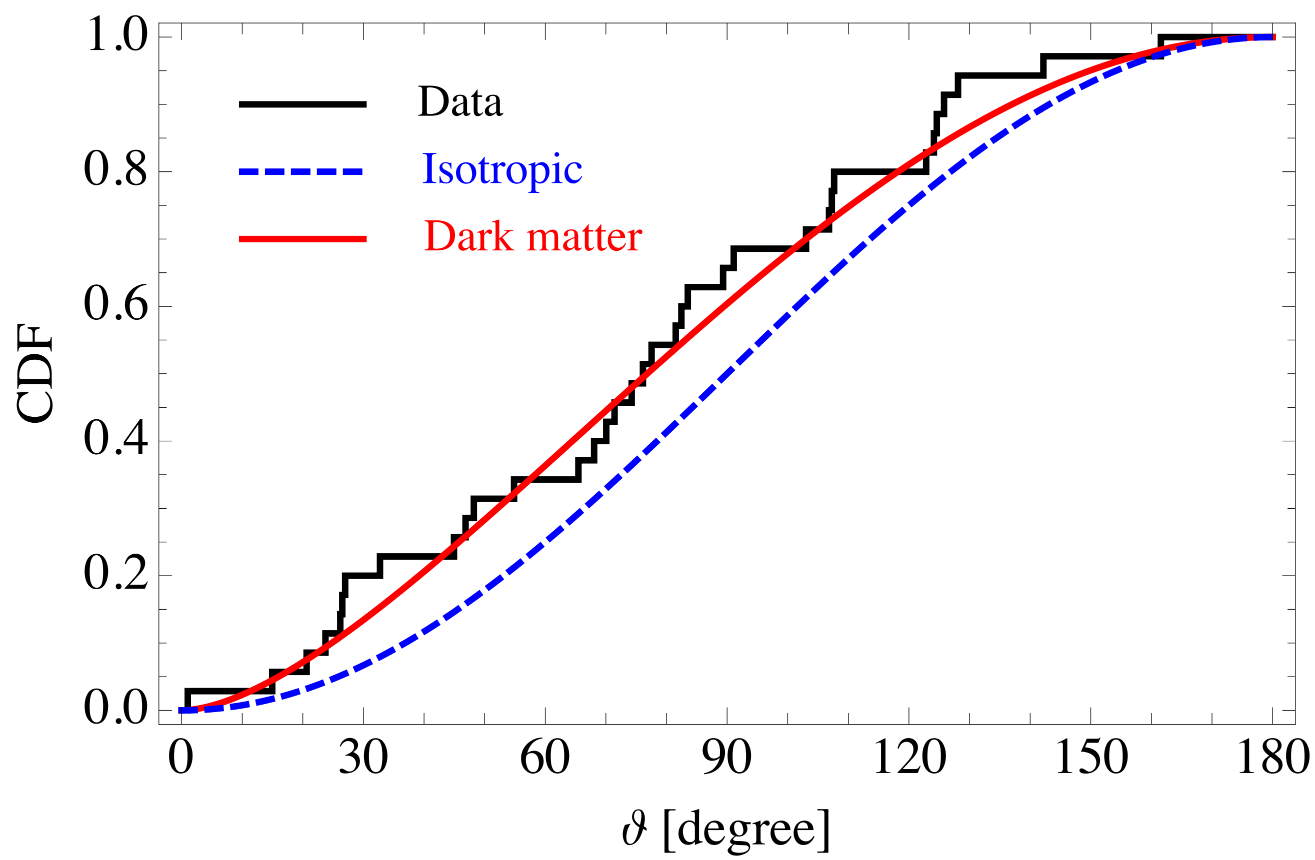

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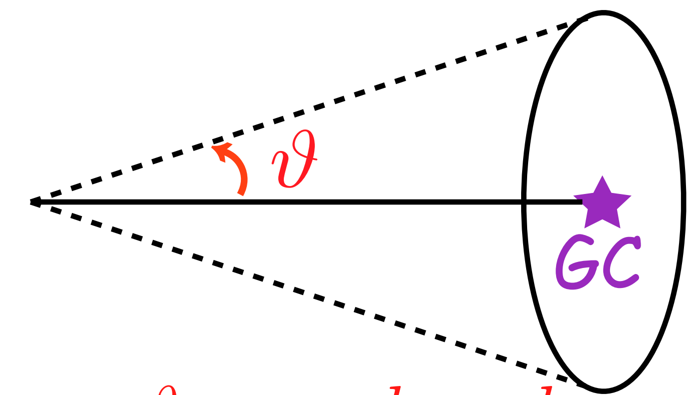

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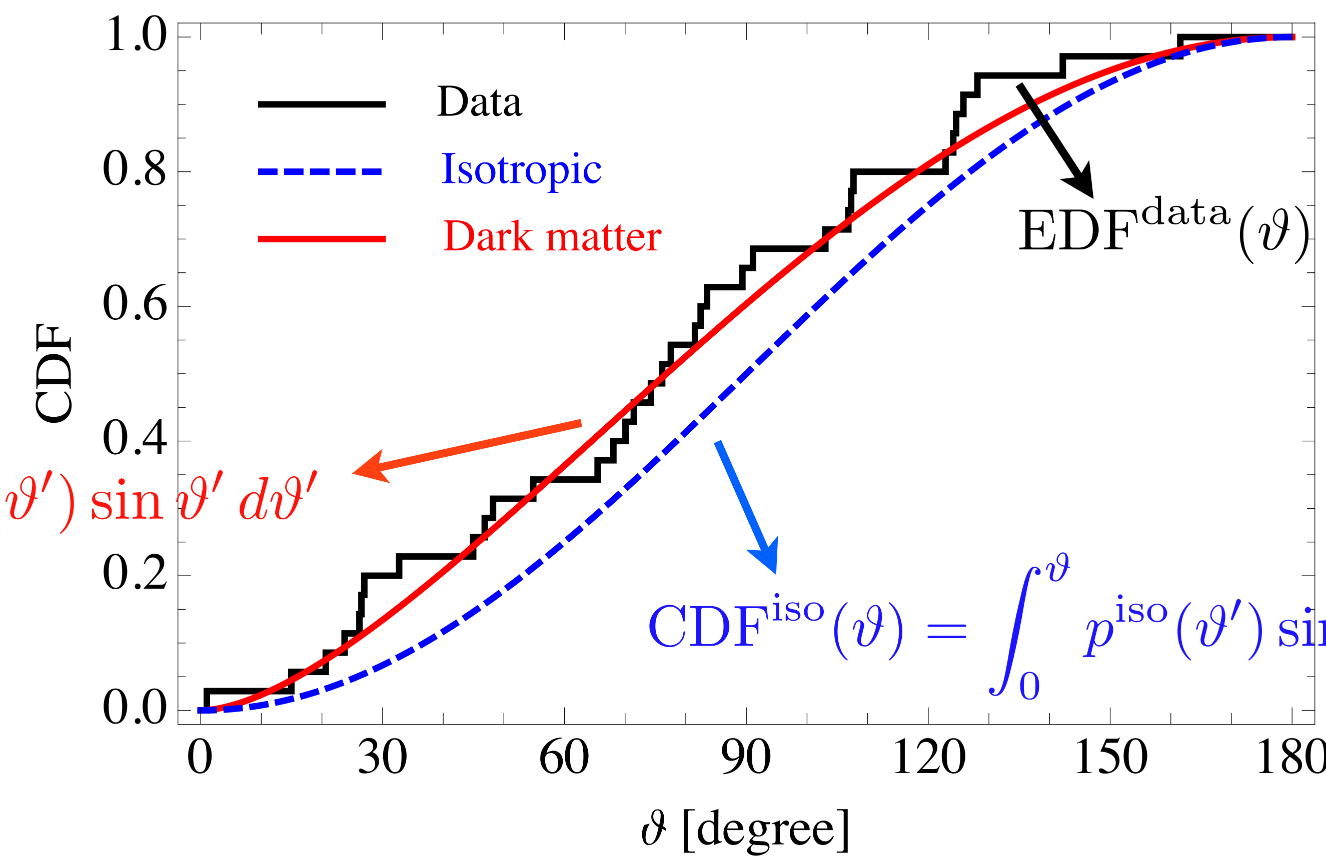

$${\rm EDF}^{\rm data}(\vartheta) = \frac{1}{N}\sum_{i=1}^{N}\Theta(\vartheta - \vartheta_i)$$

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

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

Angular distribution of neutrinos from decaying DM

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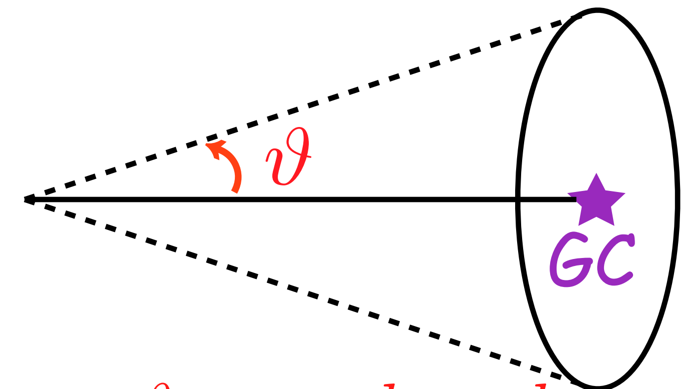

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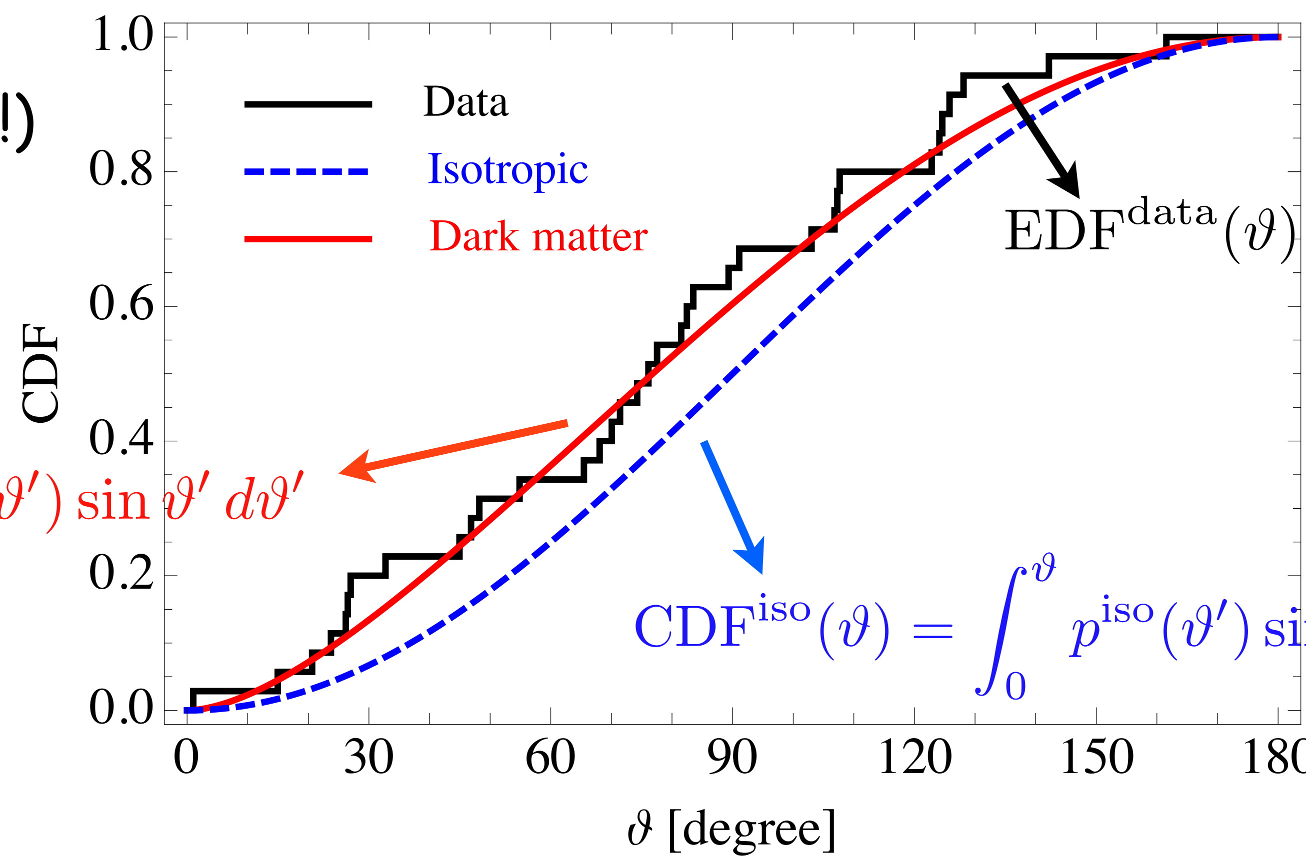

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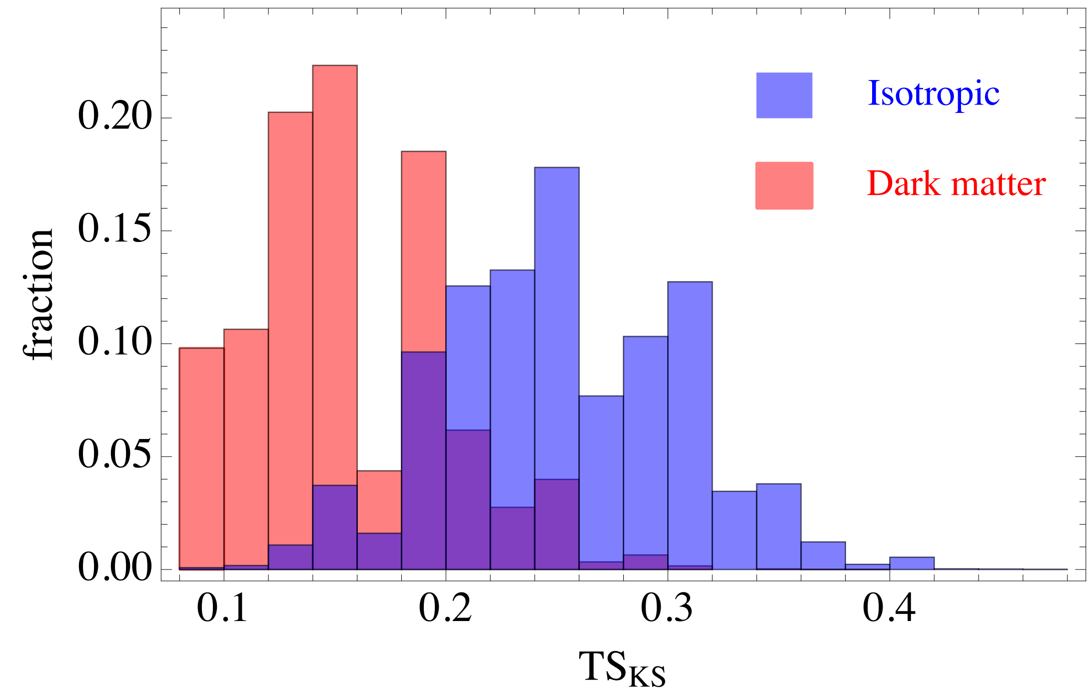
Angular distribution of neutrinos from decaying DM

✓ 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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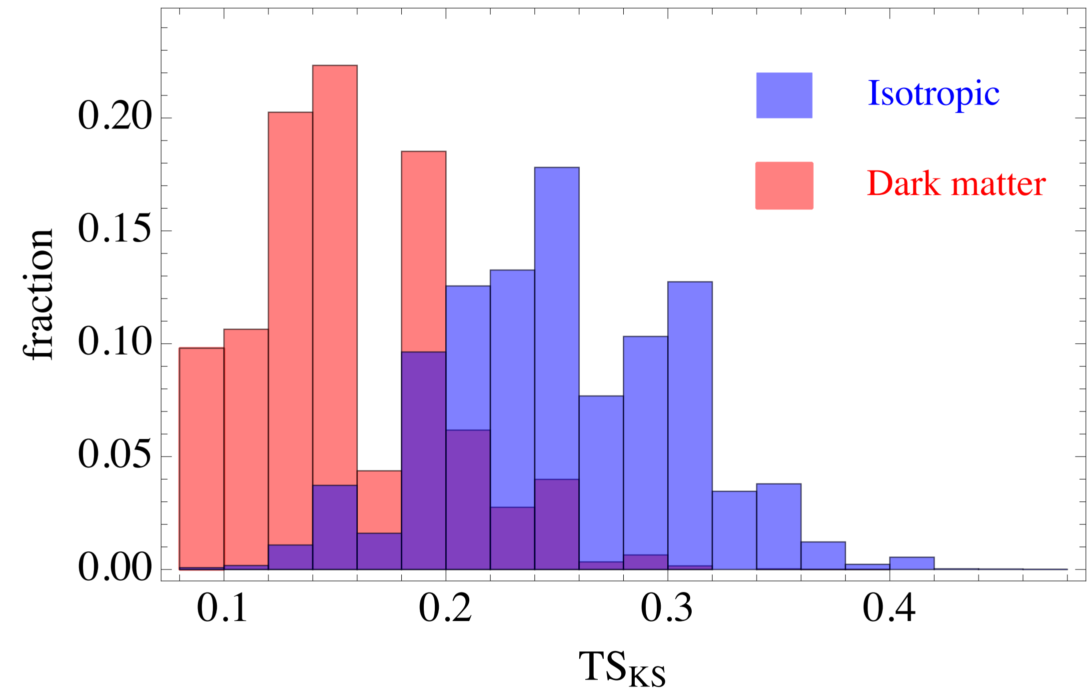


Test Statistics

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

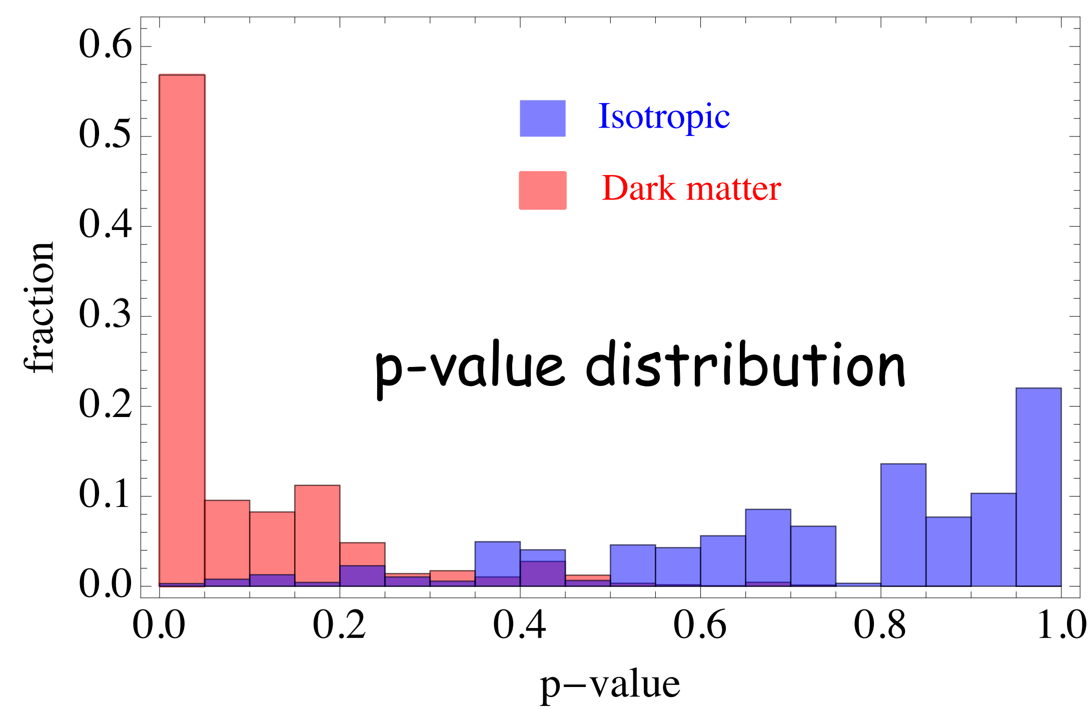
again, generating a sample (10^5) of isotropically distributed set of 20 events

↓

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%

↓

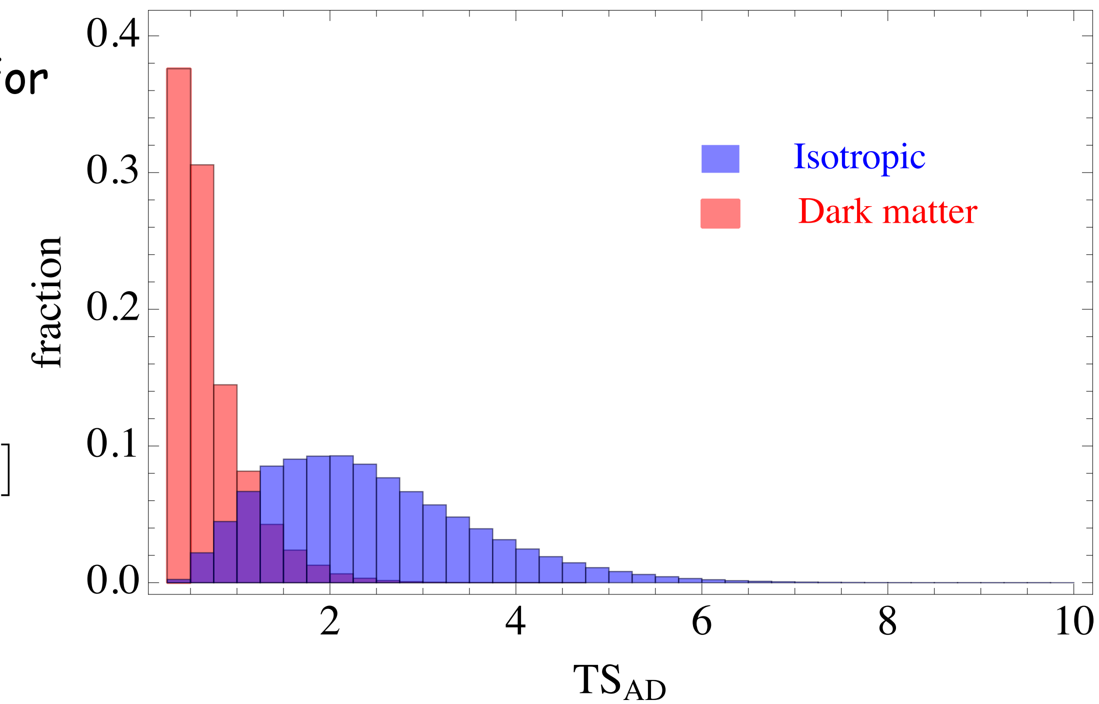
less than 2σ preference for DM dis.



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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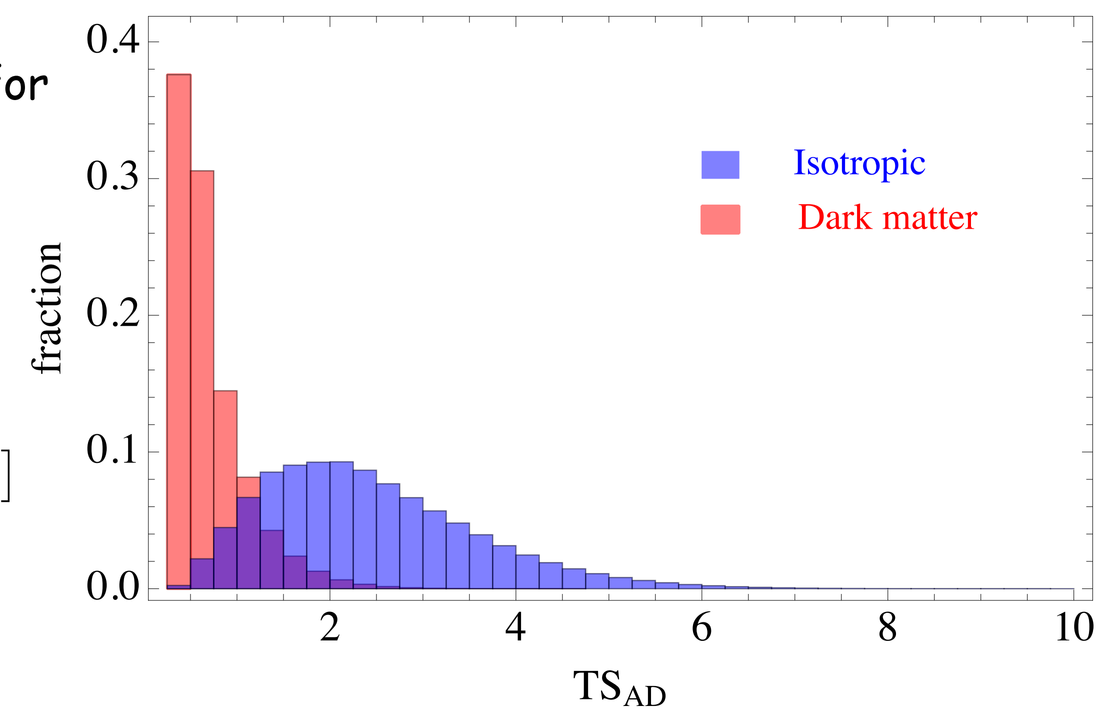

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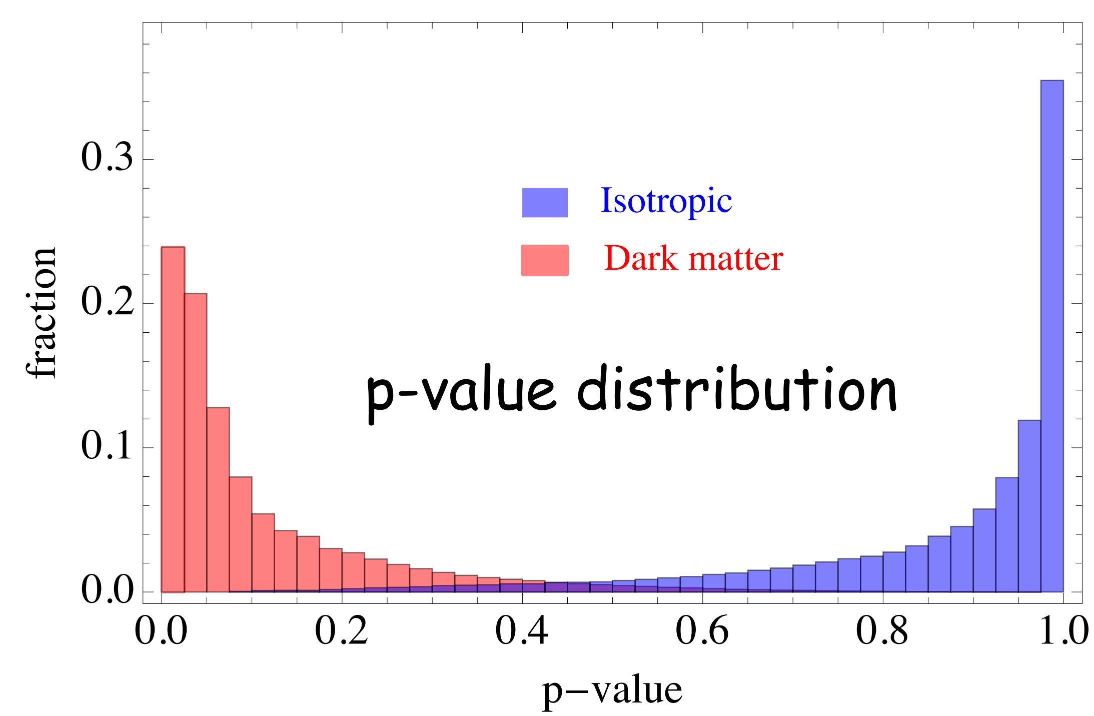
again, generating a sample (10^5) of isotropically distributed set of 20 events

↓

on the average, 11% of generated isotropic sample have smaller TS_{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.



Angular distribution of neutrinos from decaying DM

✓ Some issues:

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

Angular distribution of neutrinos from decaying DM

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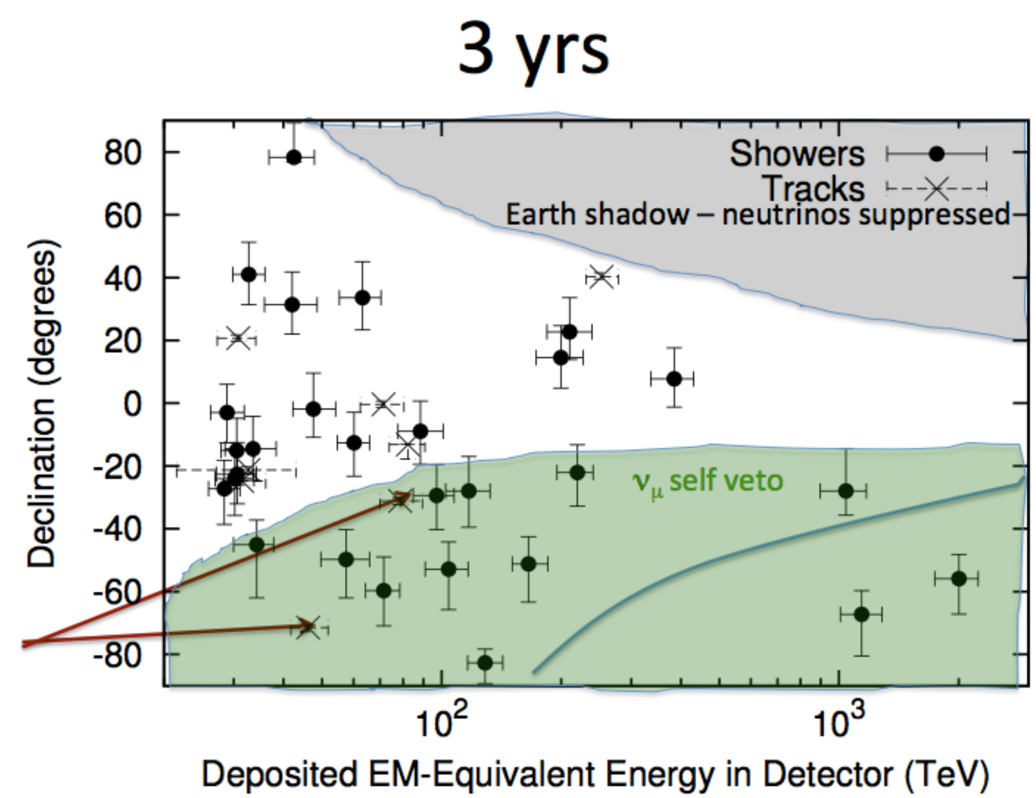
Figure from T. Gaisser

Background rejection? →



Angular distribution of neutrinos from decaying DM

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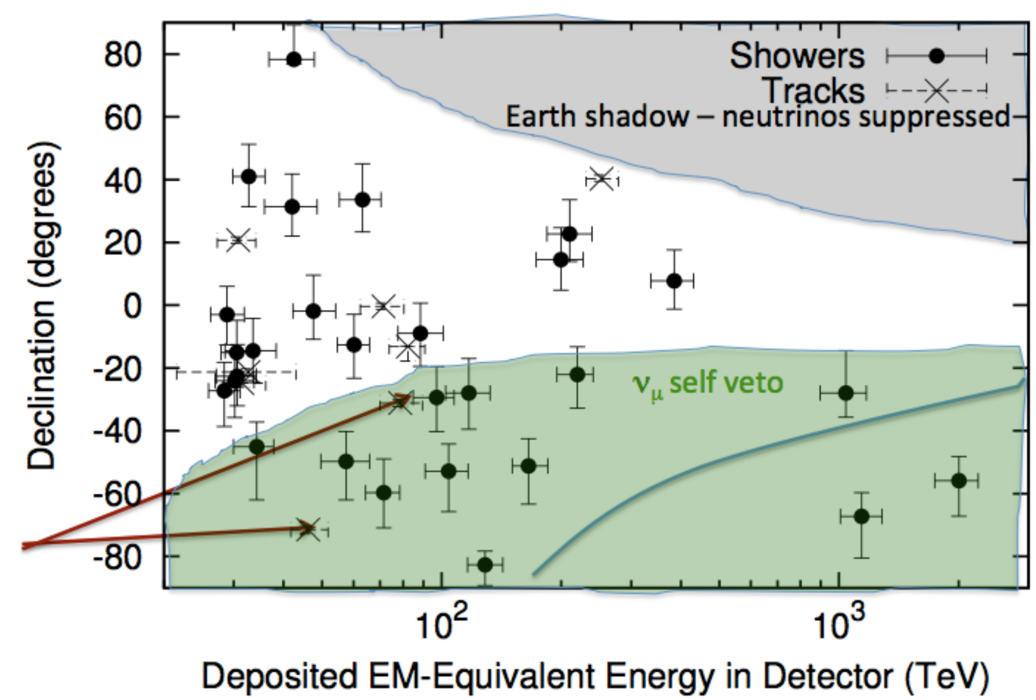
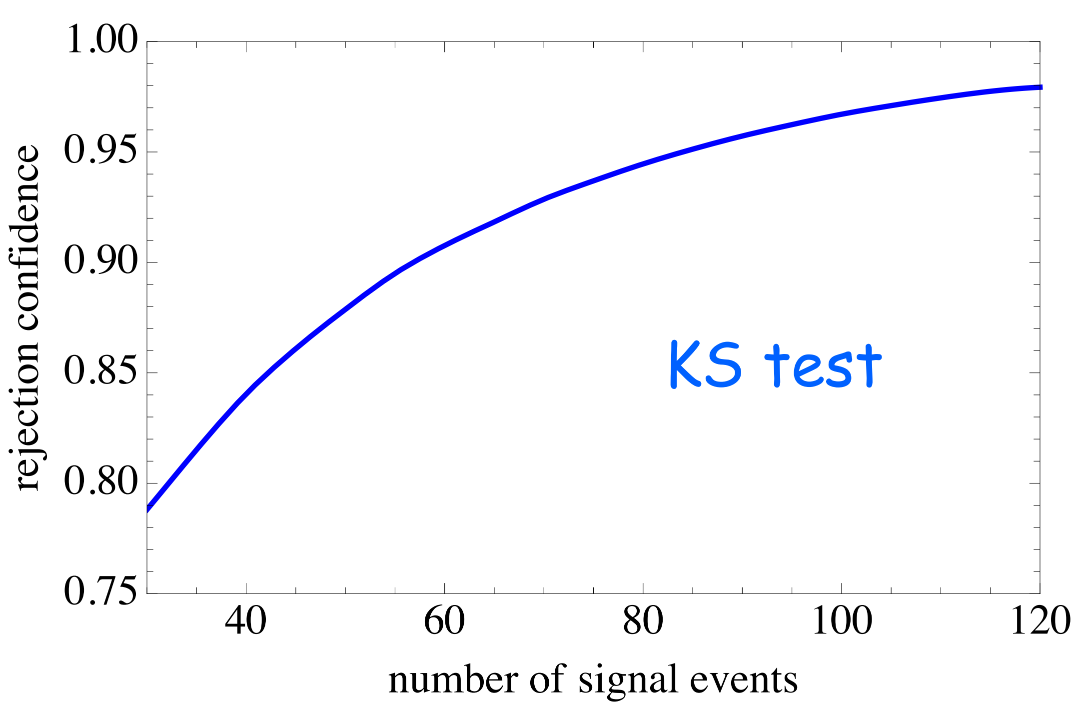
3 yrs



Background rejection? → 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 < $10^{(2-3)}$ GeV

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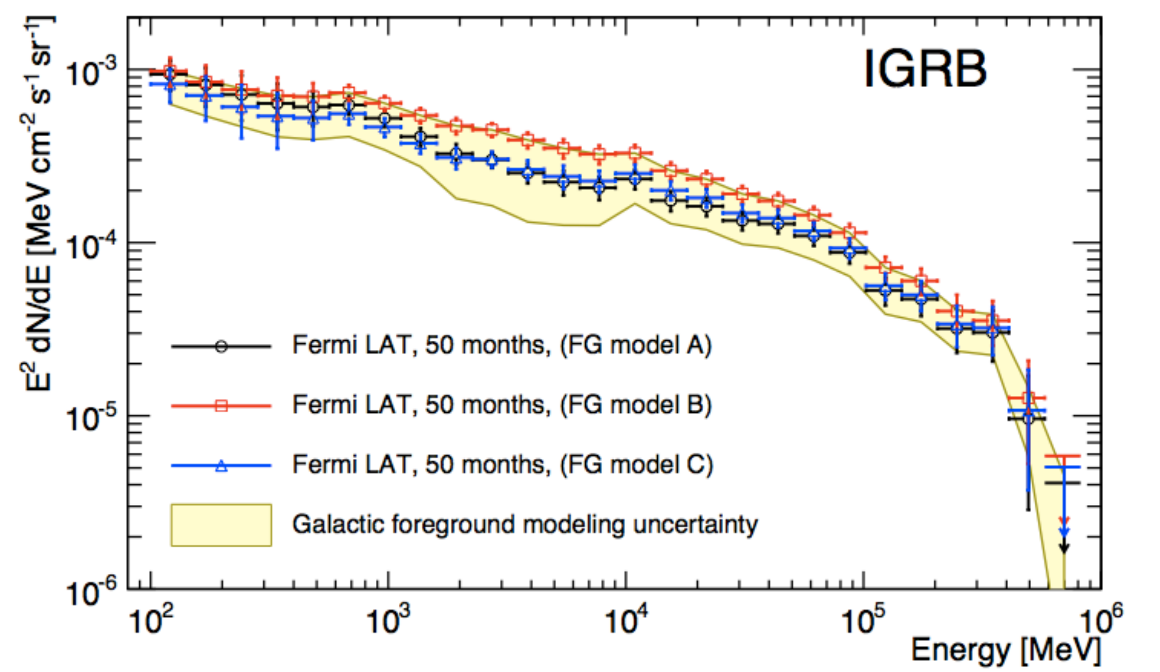
✓ Isotropic diffuse gamma-ray background by Fermi-LAT

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

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



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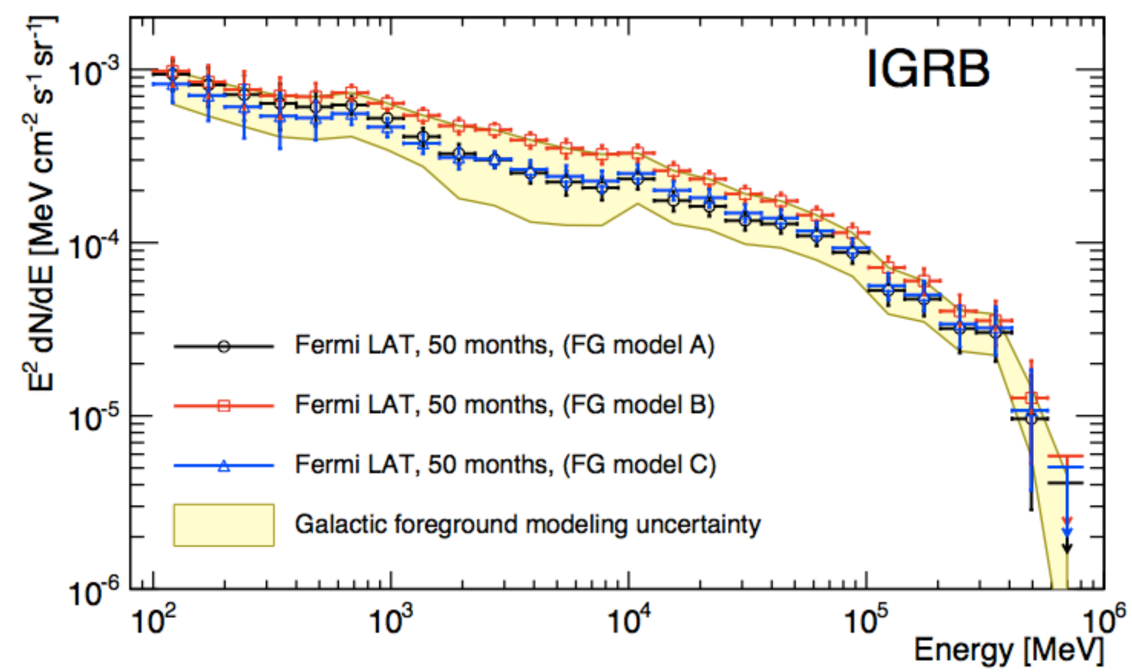

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$$E_1 \sim \mathcal{O}(1)\ \mathrm{GeV} \qquad\qquad E_2 \sim \mathcal{O}(100)\ \mathrm{GeV}$$

total electromagnetic energy budget (NH case)

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

✓

Gamma ray bounds

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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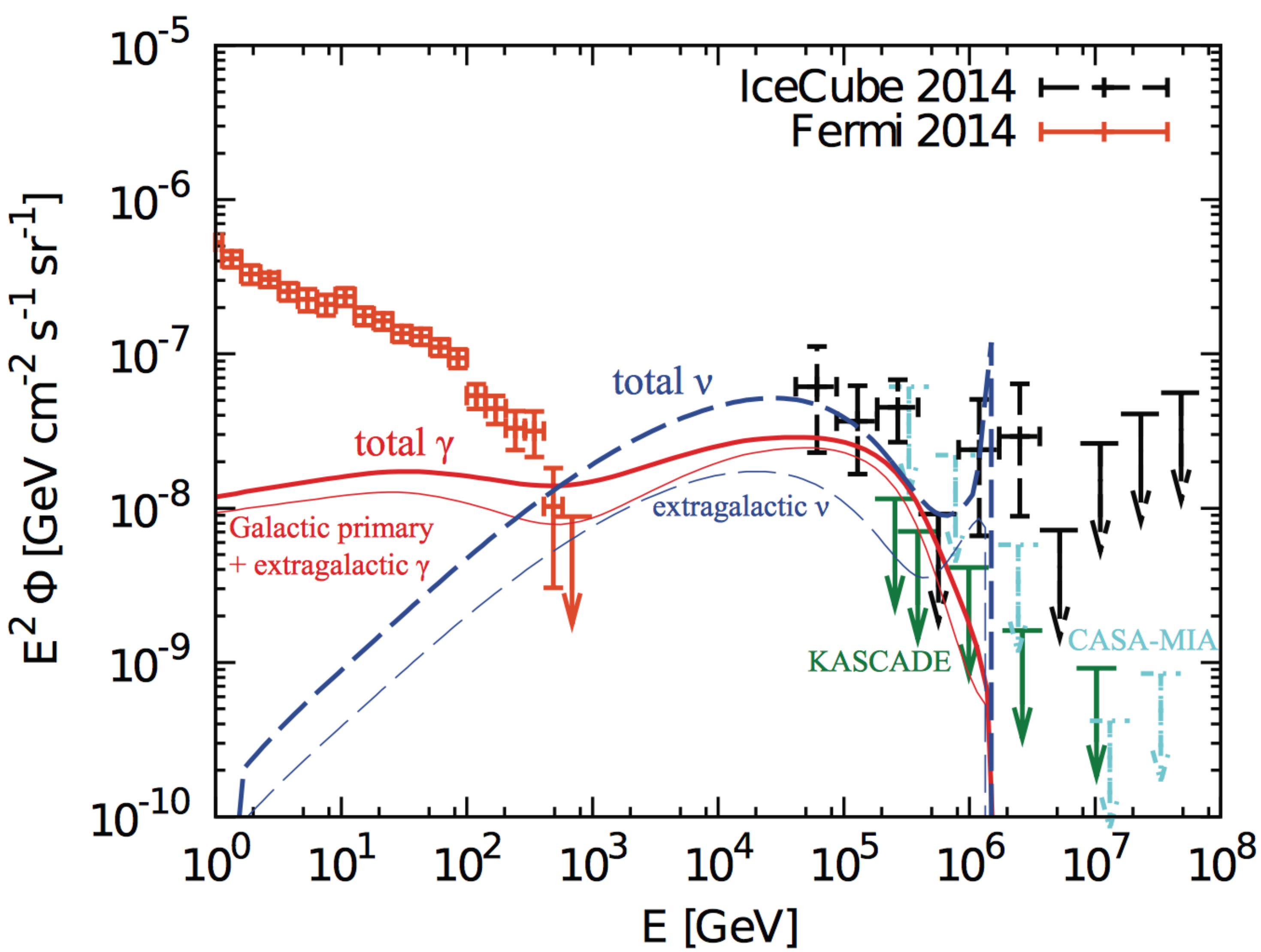
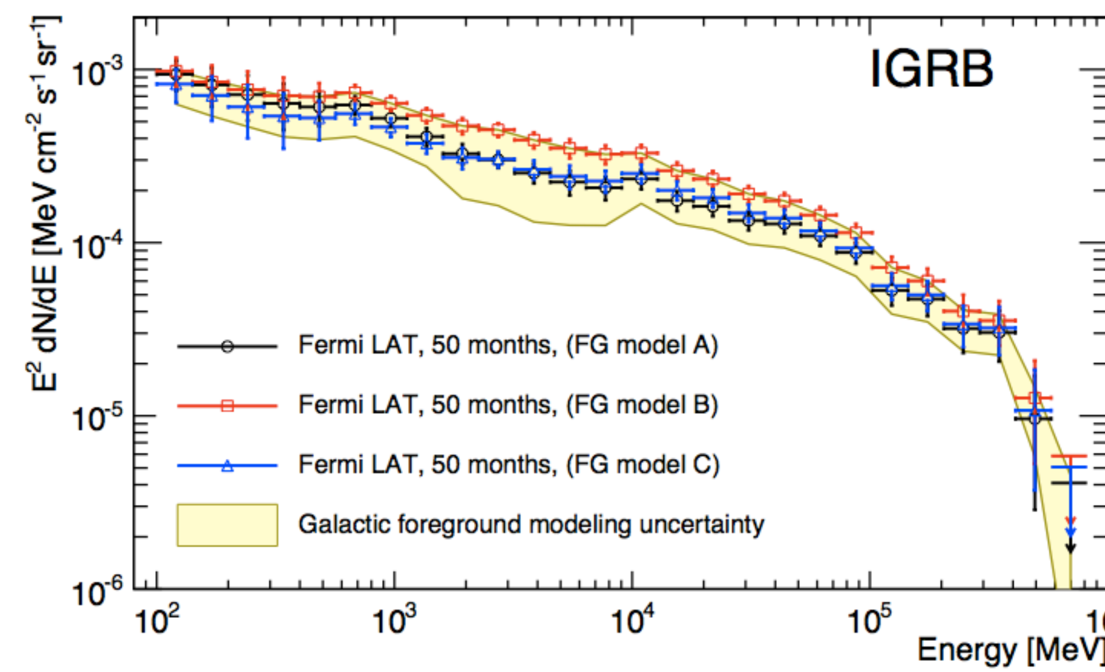


Murase, Laha, Ando, Ahlers, arXiv:1503.04663

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



Ahlers talk

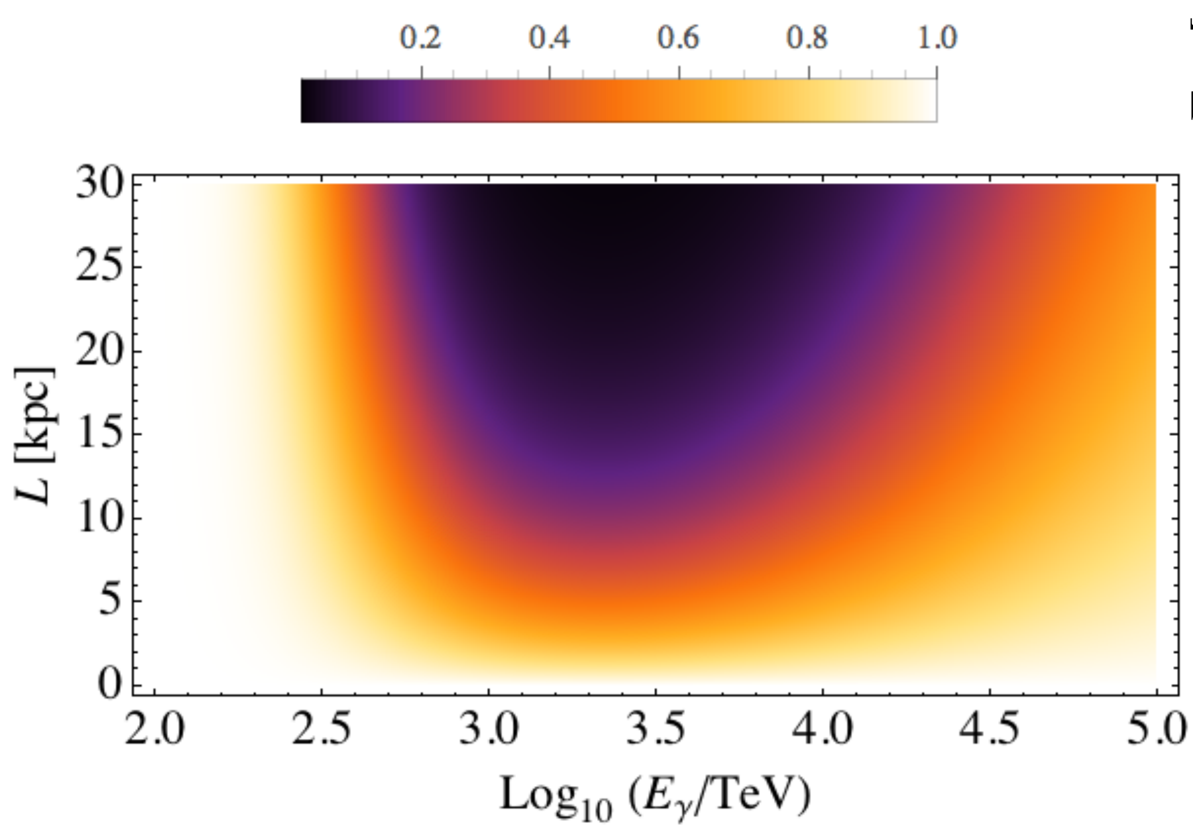
Gamma ray bounds

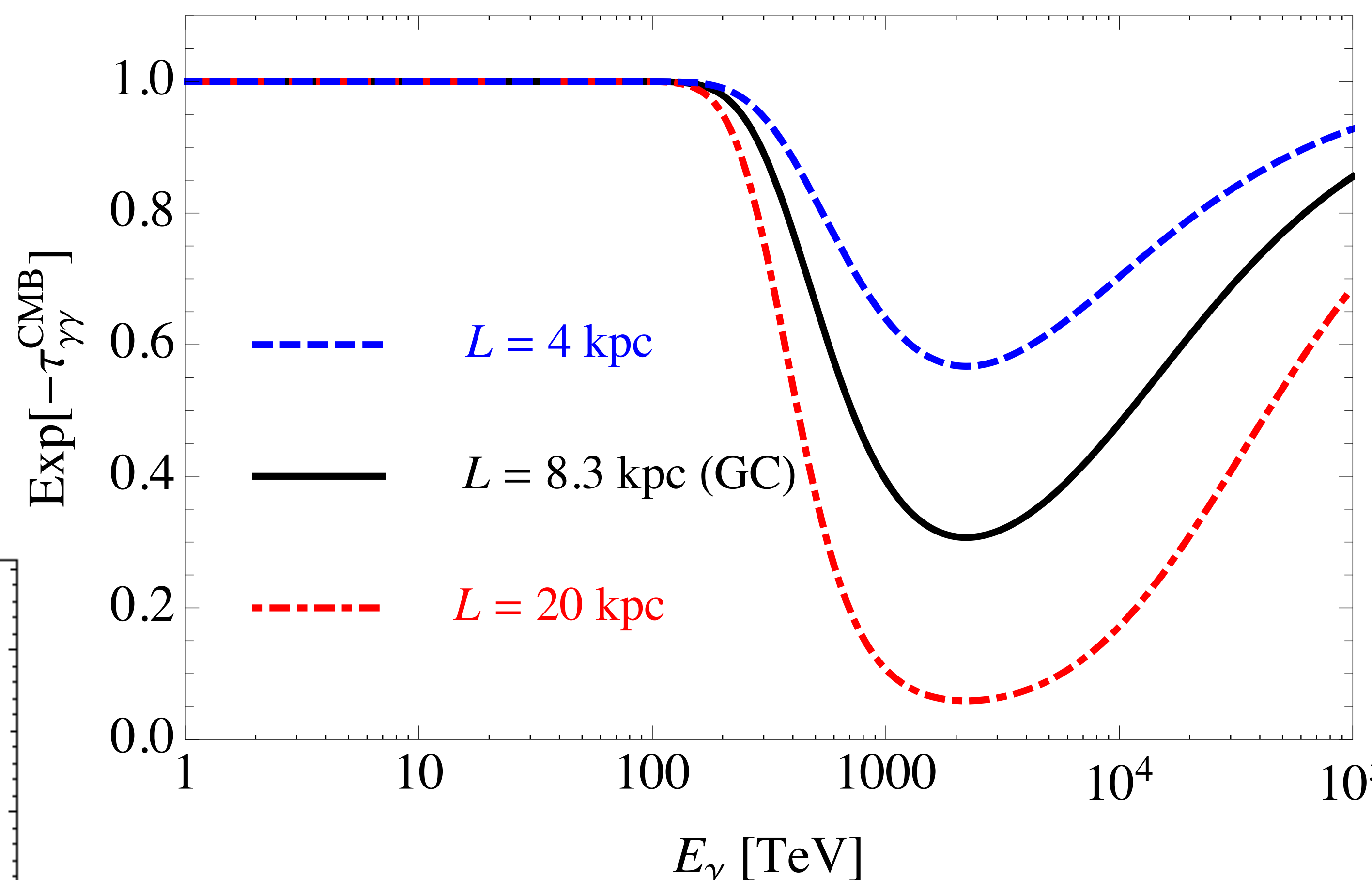
✓ Galactic component

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, JCAP 2015, [1505.06486]

Absorption due to pair production on CMB photons





Absorption at ~ PeV

Gamma ray bounds

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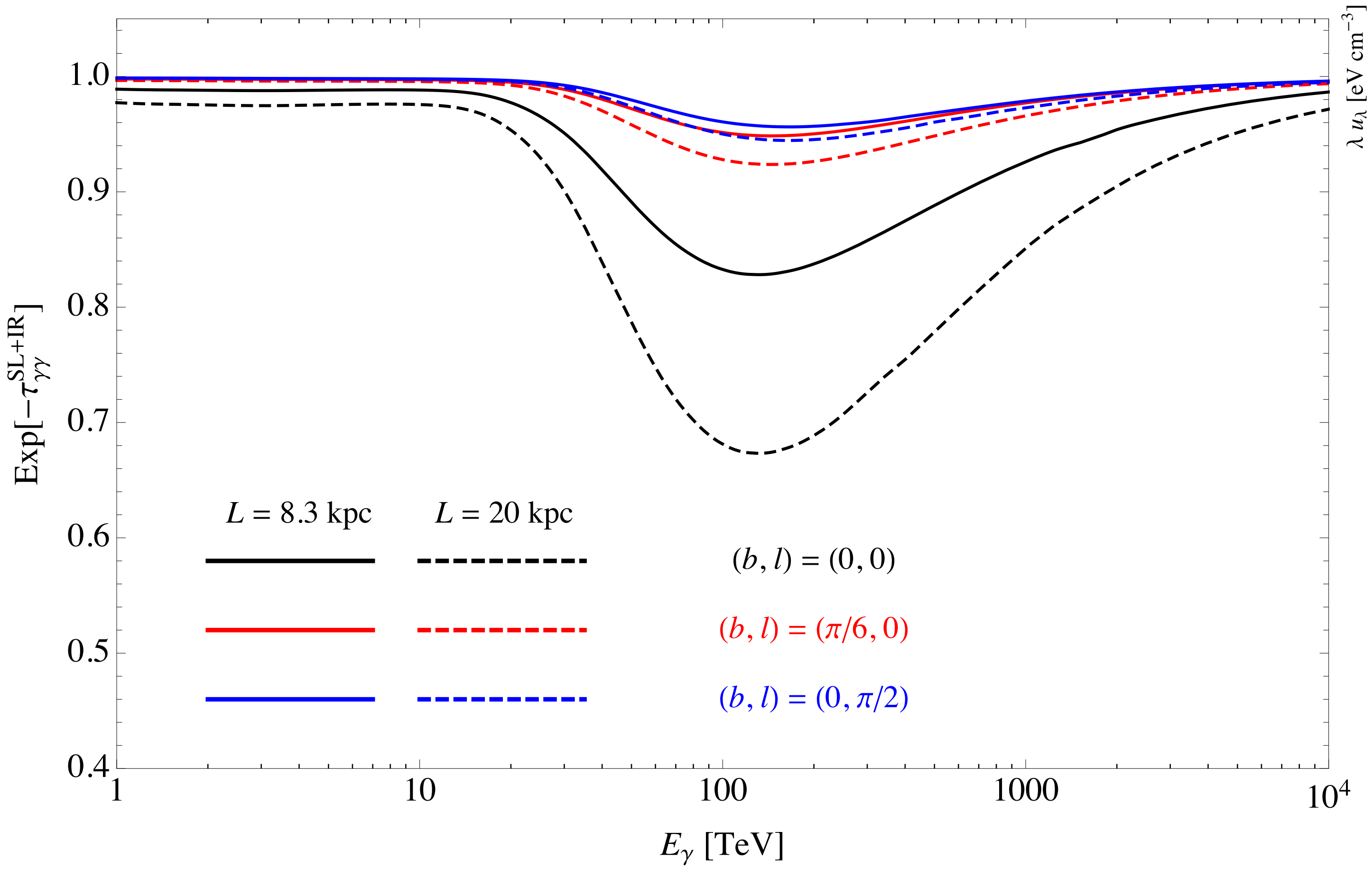
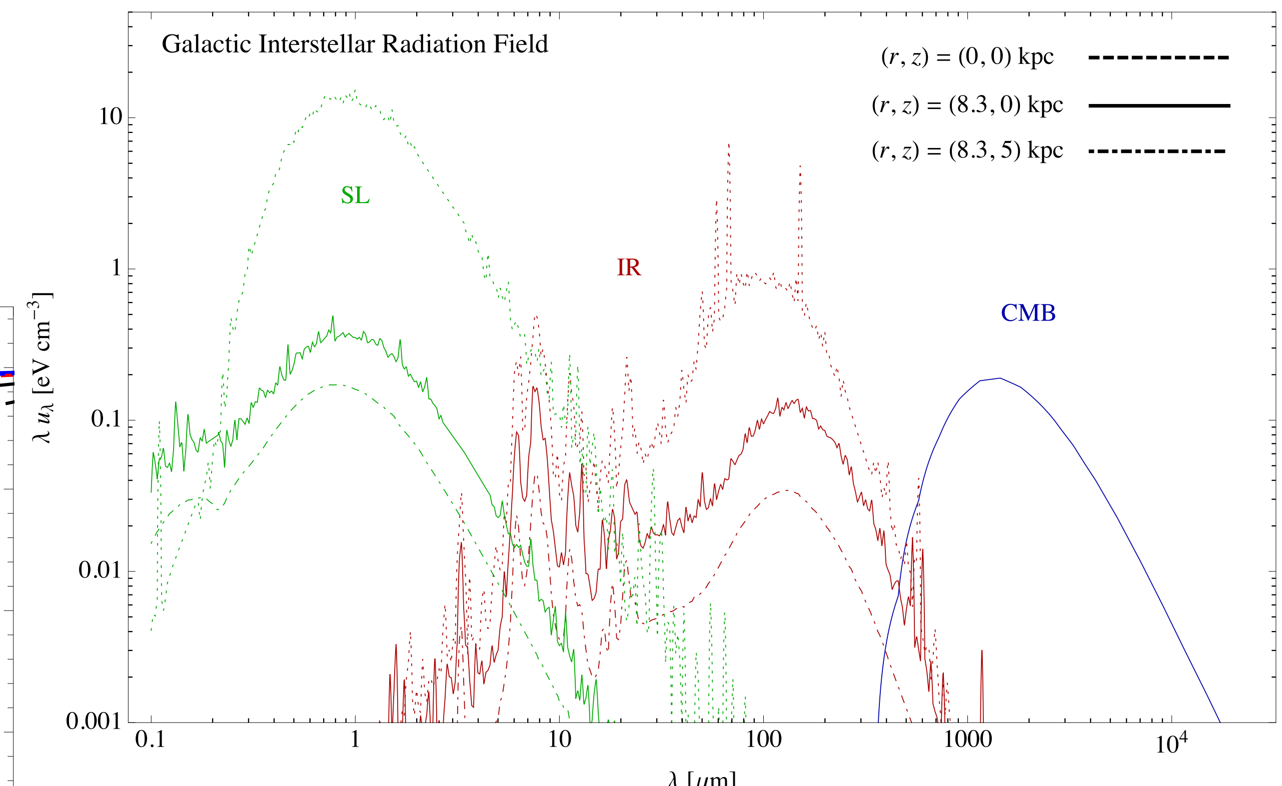
Absorption due to pair production on SL+IR photons





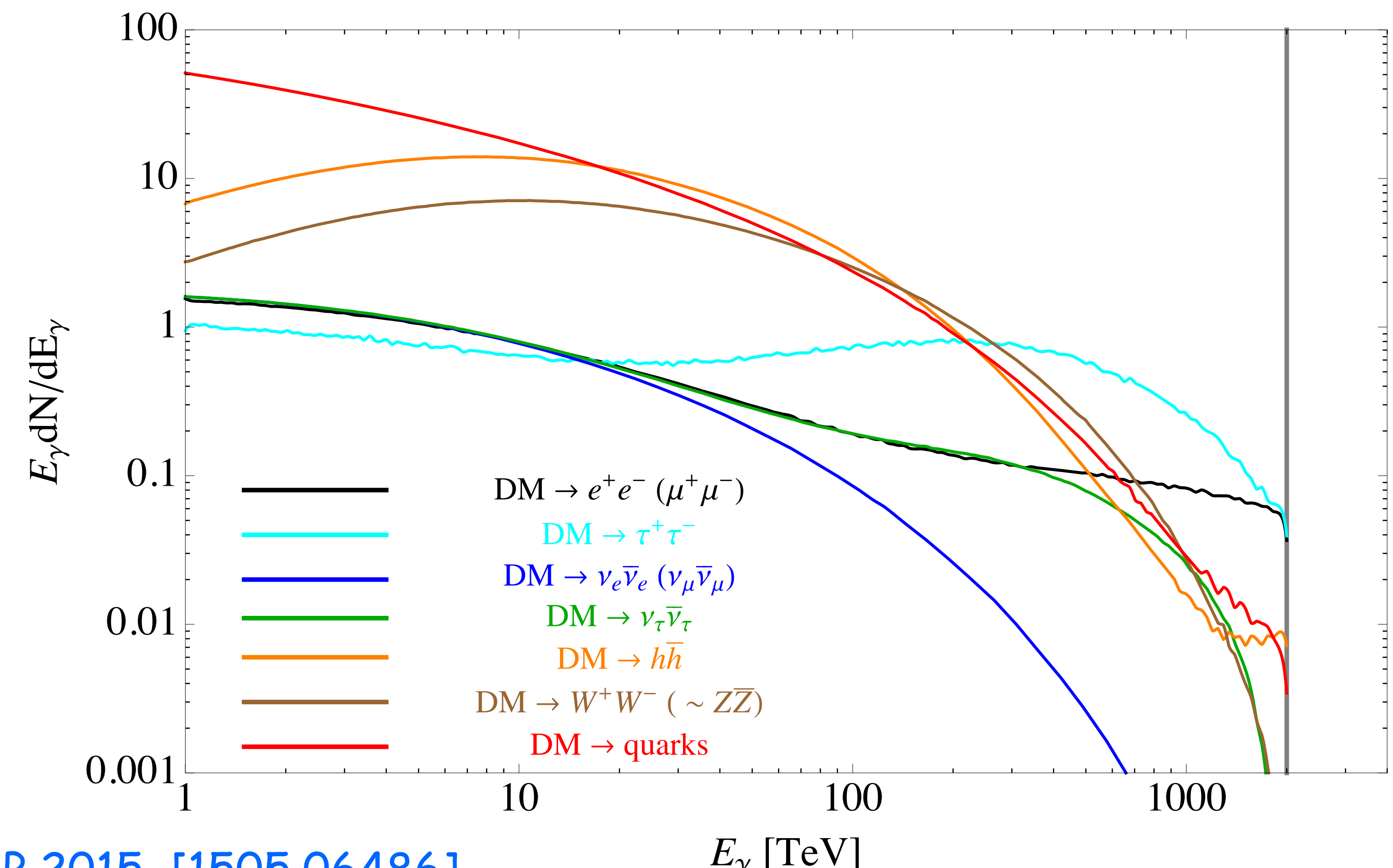
Absorption at ~ 100 TeV

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



calculated by PYTHIA 8.2

A. E. and P. Serpico, JCAP 2015, [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

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

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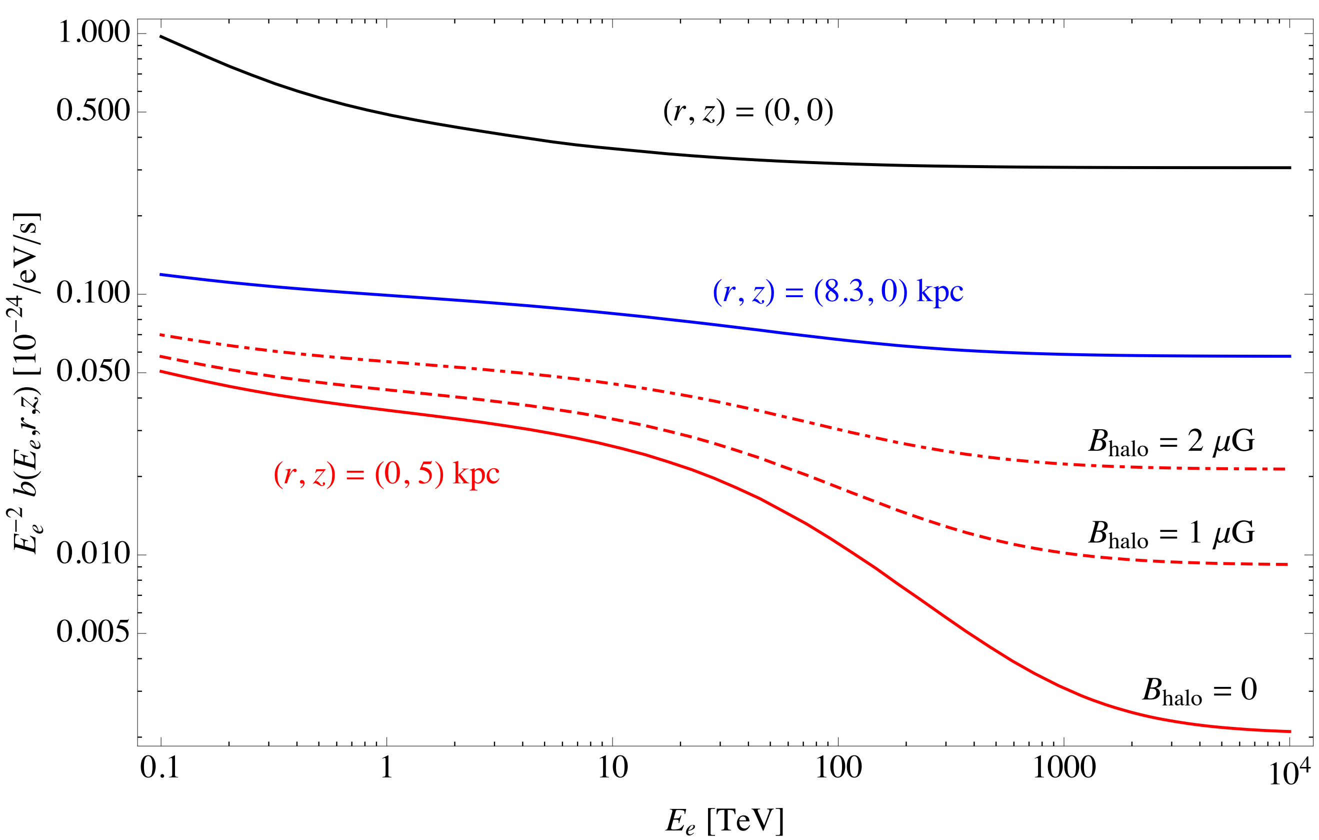
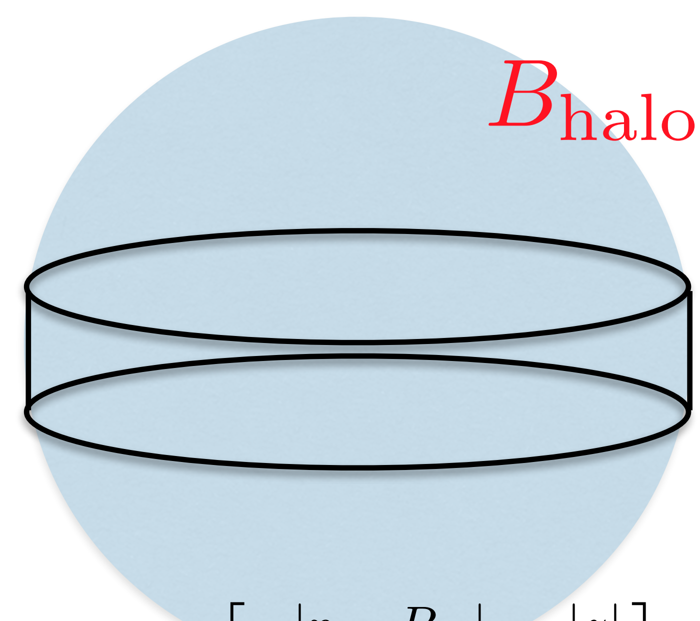
$$\frac{\mathrm{d}n_e}{\mathrm{d}E_e}(E_e,\vec{x}) = \frac{1}{m_{\rm DM}\,\tau_{\rm DM}} \frac{\rho_{\rm h}(\vec{x})}{b(E_e,\vec{x})} \int_{E_e}^{m_{\rm DM}/2} \frac{\mathrm{d}N_e}{\mathrm{d}E'_e}(E'_e)\, I_{\rm diff}(E_e, E'_e, \vec{x})\, \mathrm{d}E'_e$$



$$b(E_e,\vec{x}) \equiv -\frac{\mathrm{d}E_e}{\mathrm{d}t} = b_{\rm IC}(E_e,\vec{x}) + b_{\rm syn}(E_e,\vec{x})$$



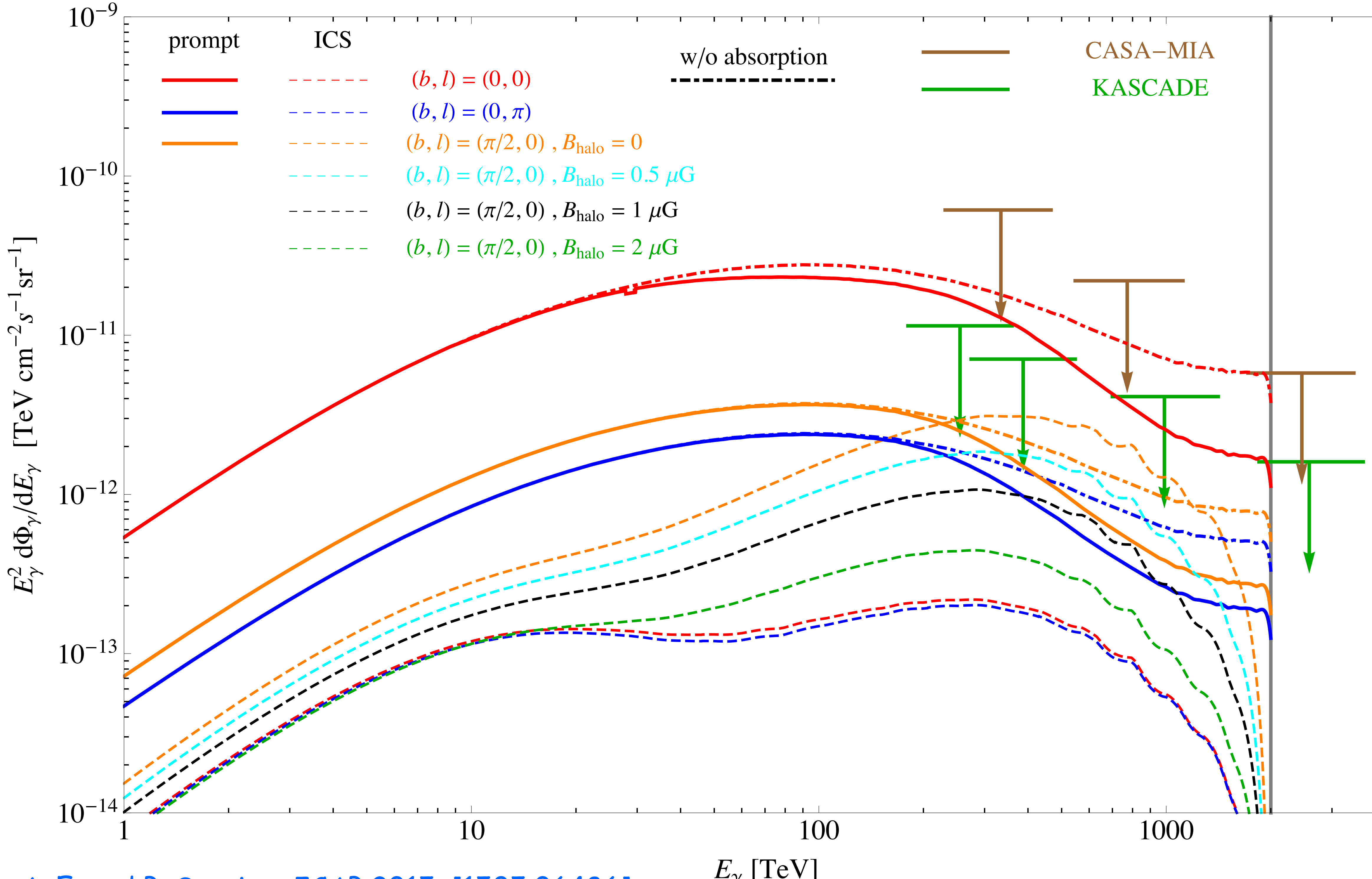
$$B_{\rm reg}(\vec{x}) = B_0\ \exp\left[-\frac{|r-R_\odot|}{r_B} - \frac{|z|}{z_B}\right]$$

A. E. and P. Serpico, JCAP 2015, [1505.06486]

Gamma ray bounds

✓ Galactic component

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

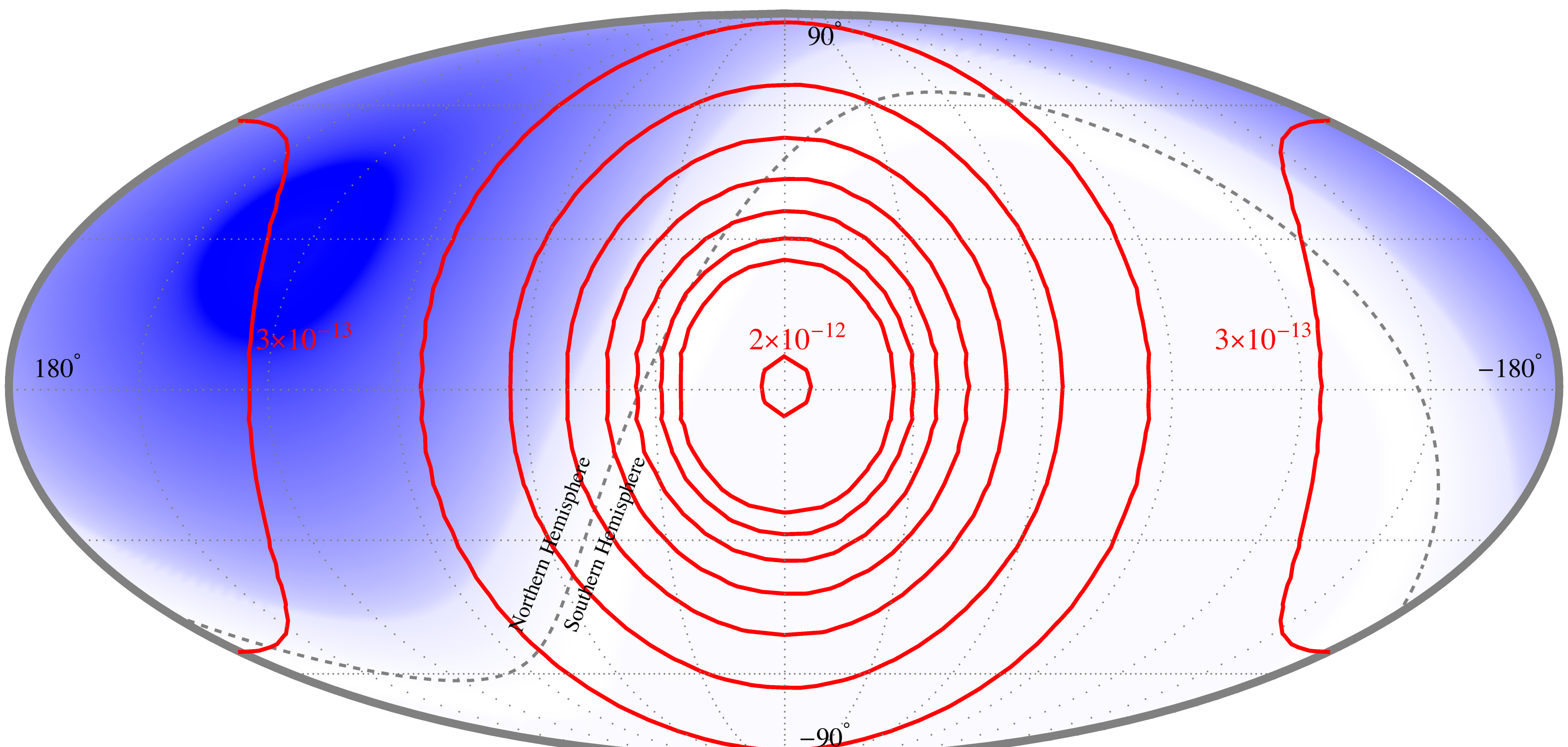


A. E. and P. Serpico, JCAP 2015, [1505.06486]

Gamma ray bounds

✓ Galactic component

KASCADE

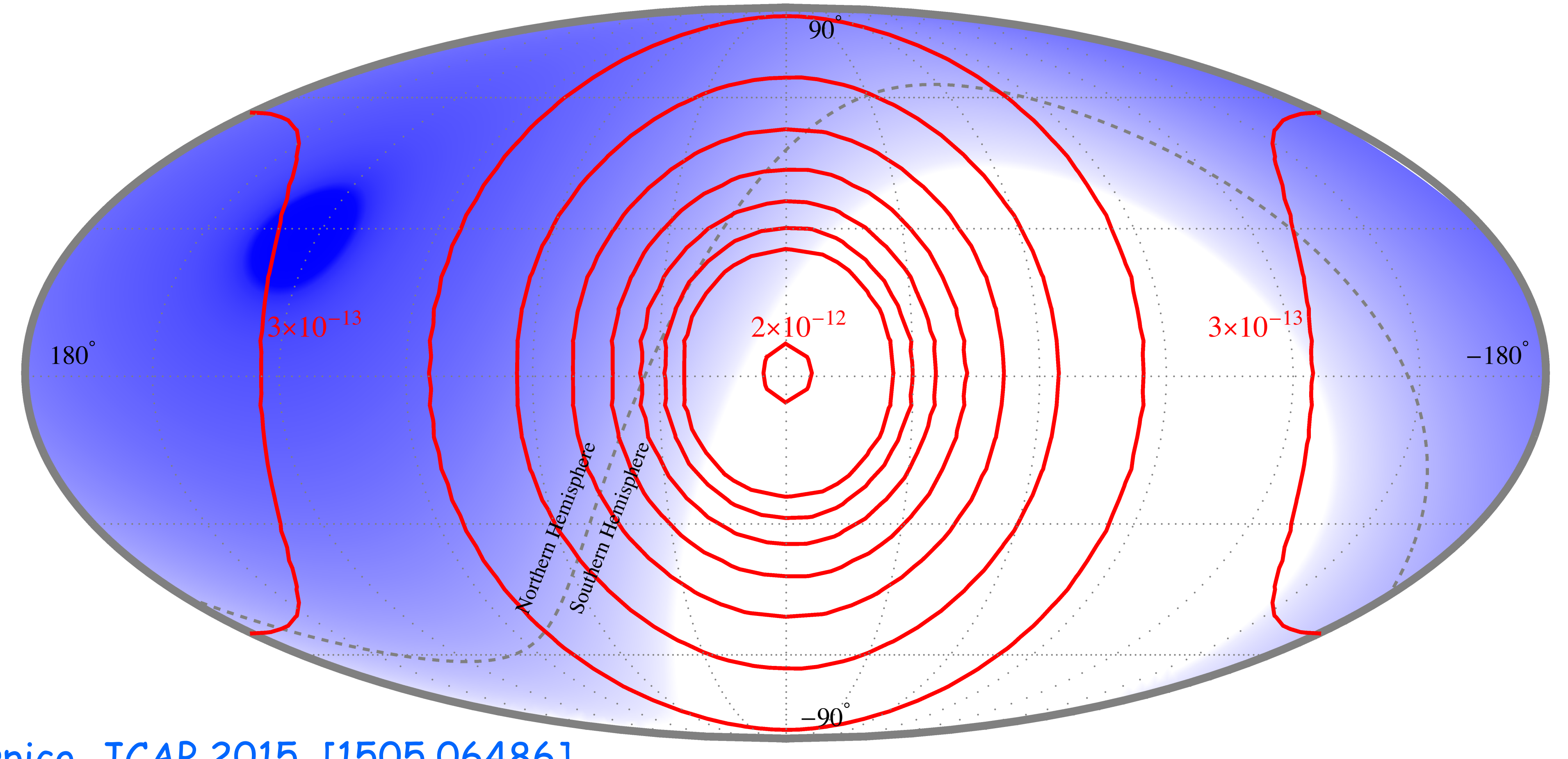


A. E. and P. Serpico, JCAP 2015, [1505.06486]

Gamma ray bounds

✓ Galactic component

CASA-MIA



A. E. and P. Serpico, JCAP 2015, [1505.06486]

Gamma ray bounds

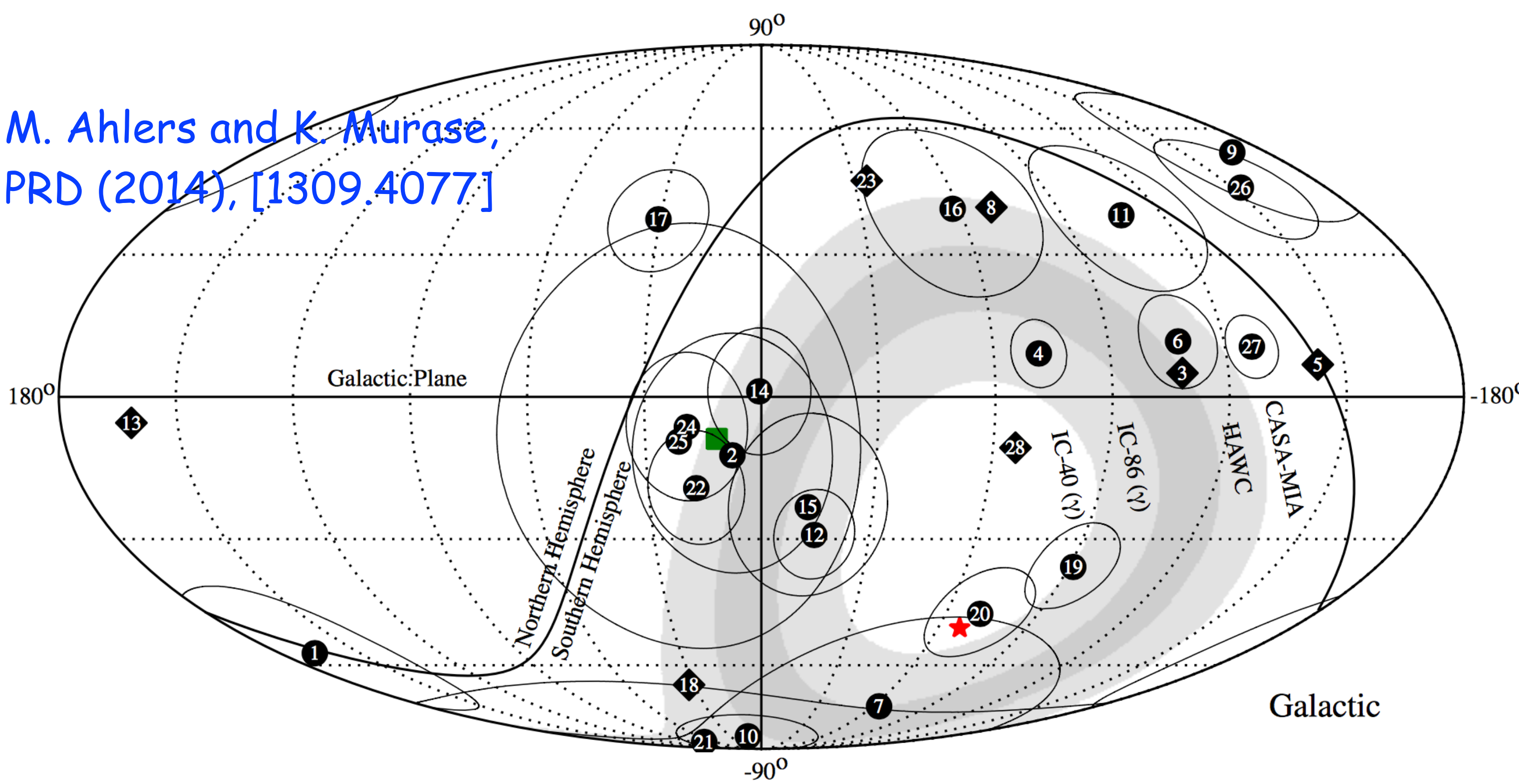
✓ Galactic component

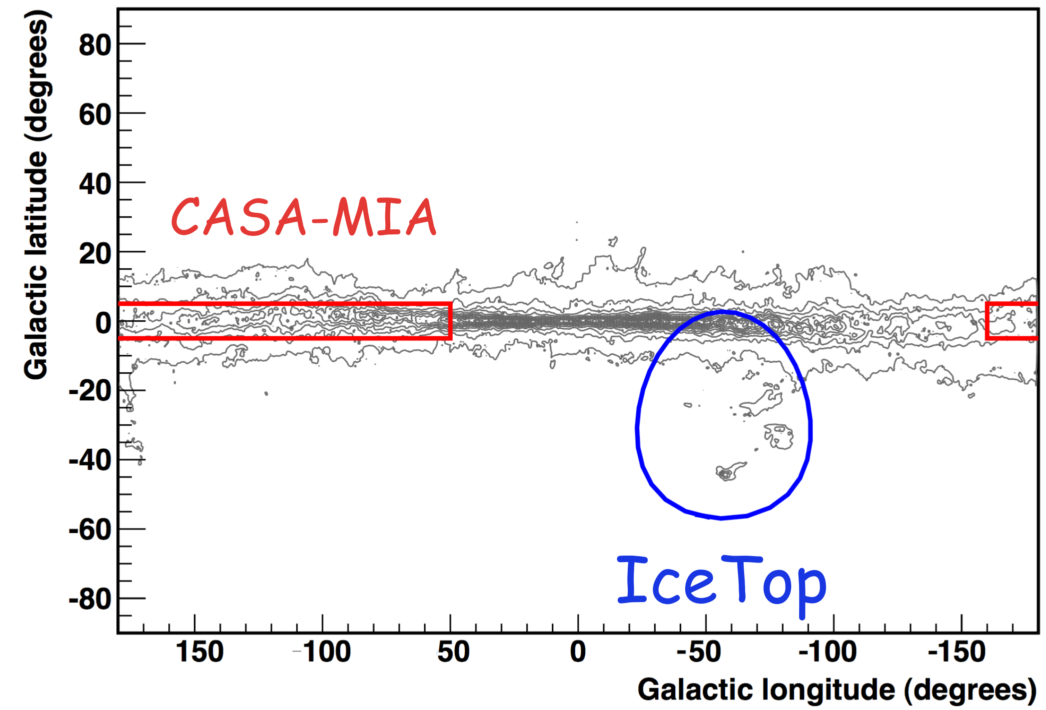
Future experiments

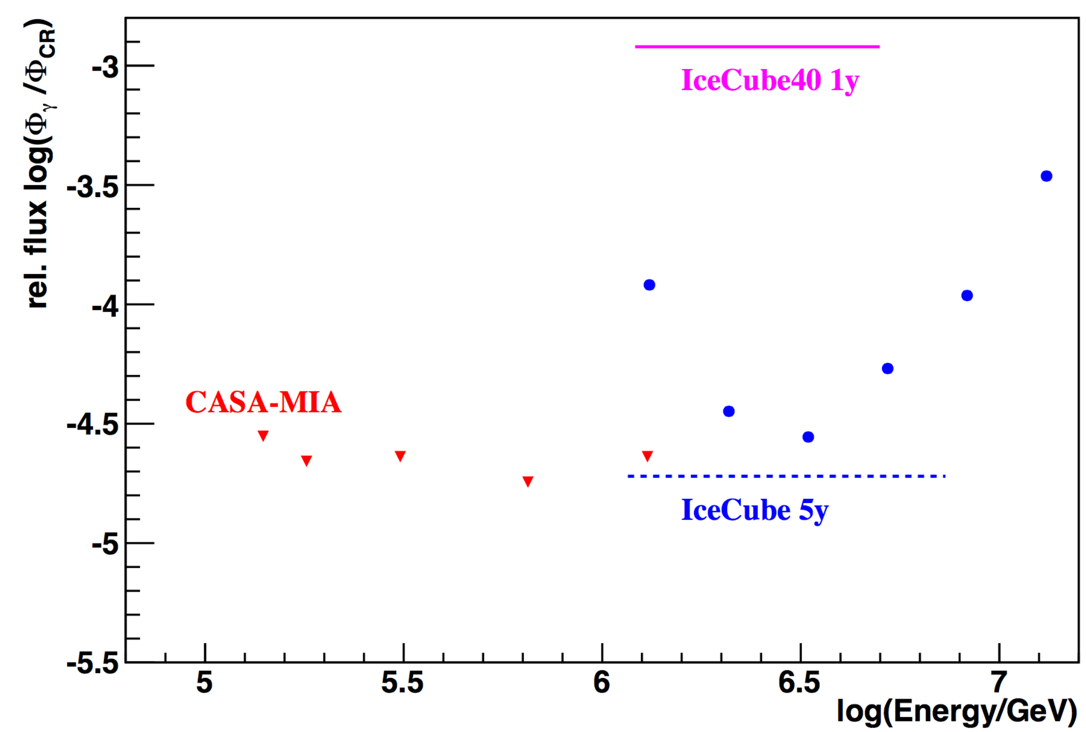
HAWC

IceTop

M. Ahlers and K. Murase, PRD (2014), [1309.4077]







Gamma ray bounds

✓ Galactic component

Anisotropy

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

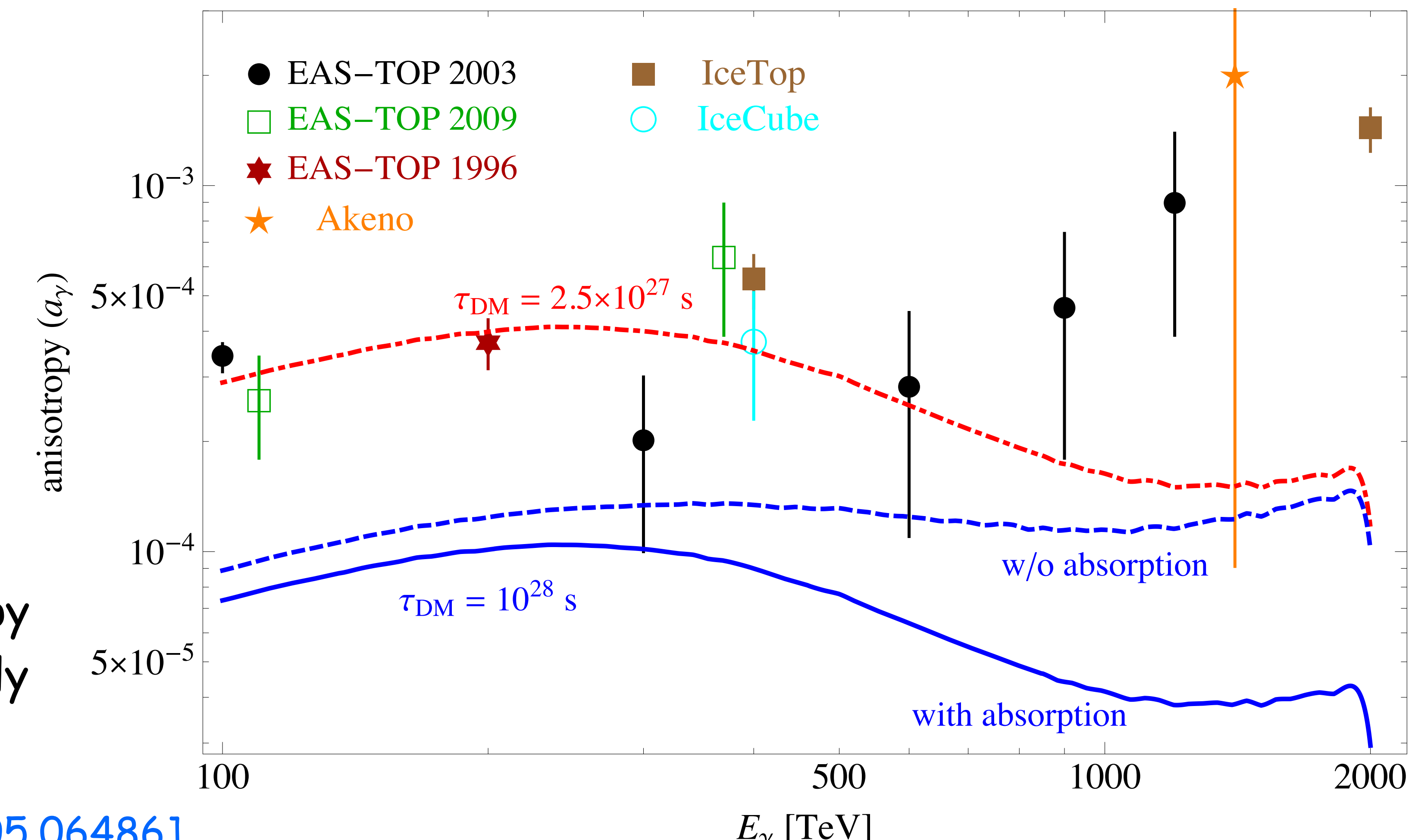
Total CR flux

✓ 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, [1505.06486]

Gamma ray bounds

- ✓ Galactic component

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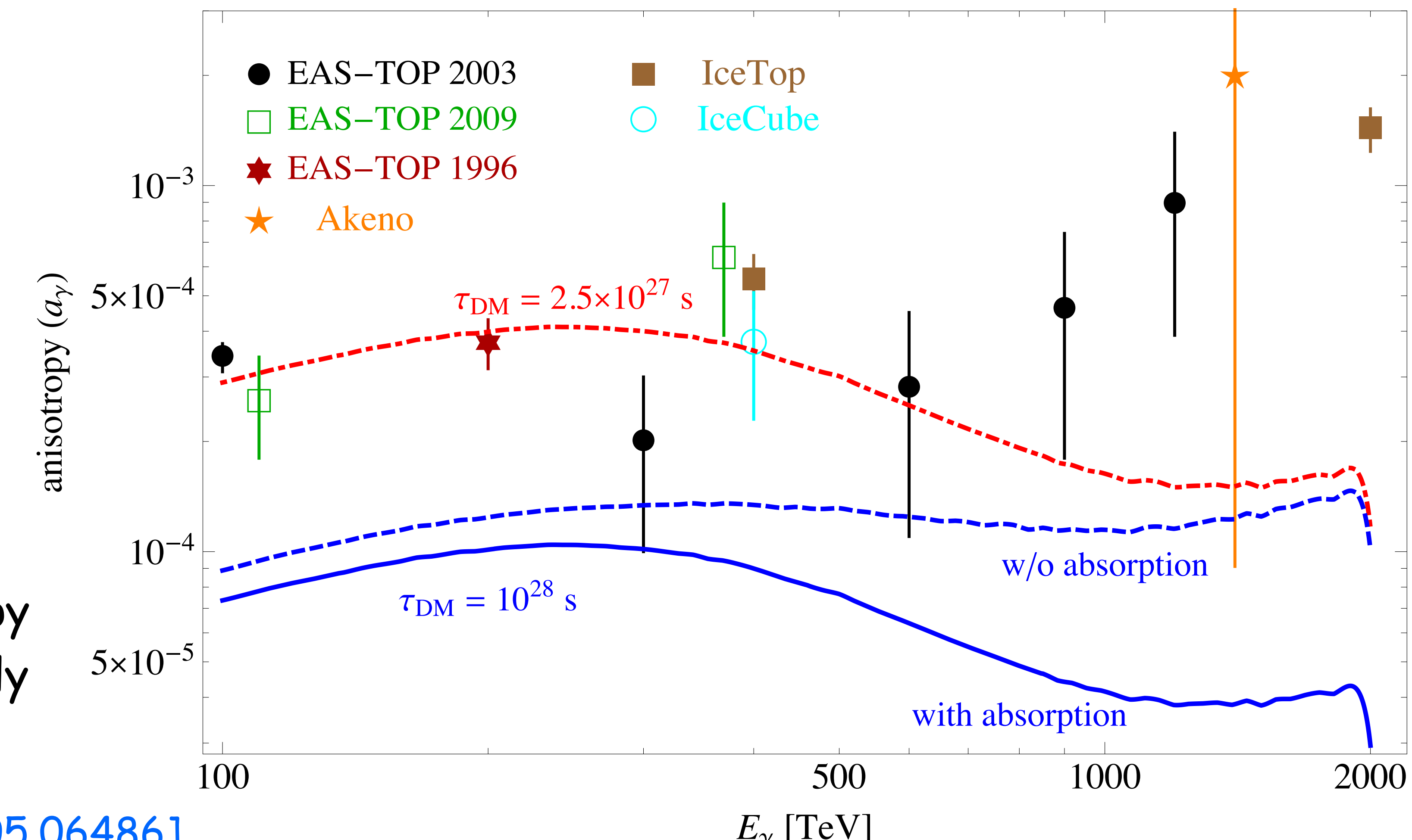


A. E. and P. Serpico, JCAP 2015, [1505.06486]

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 !

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

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

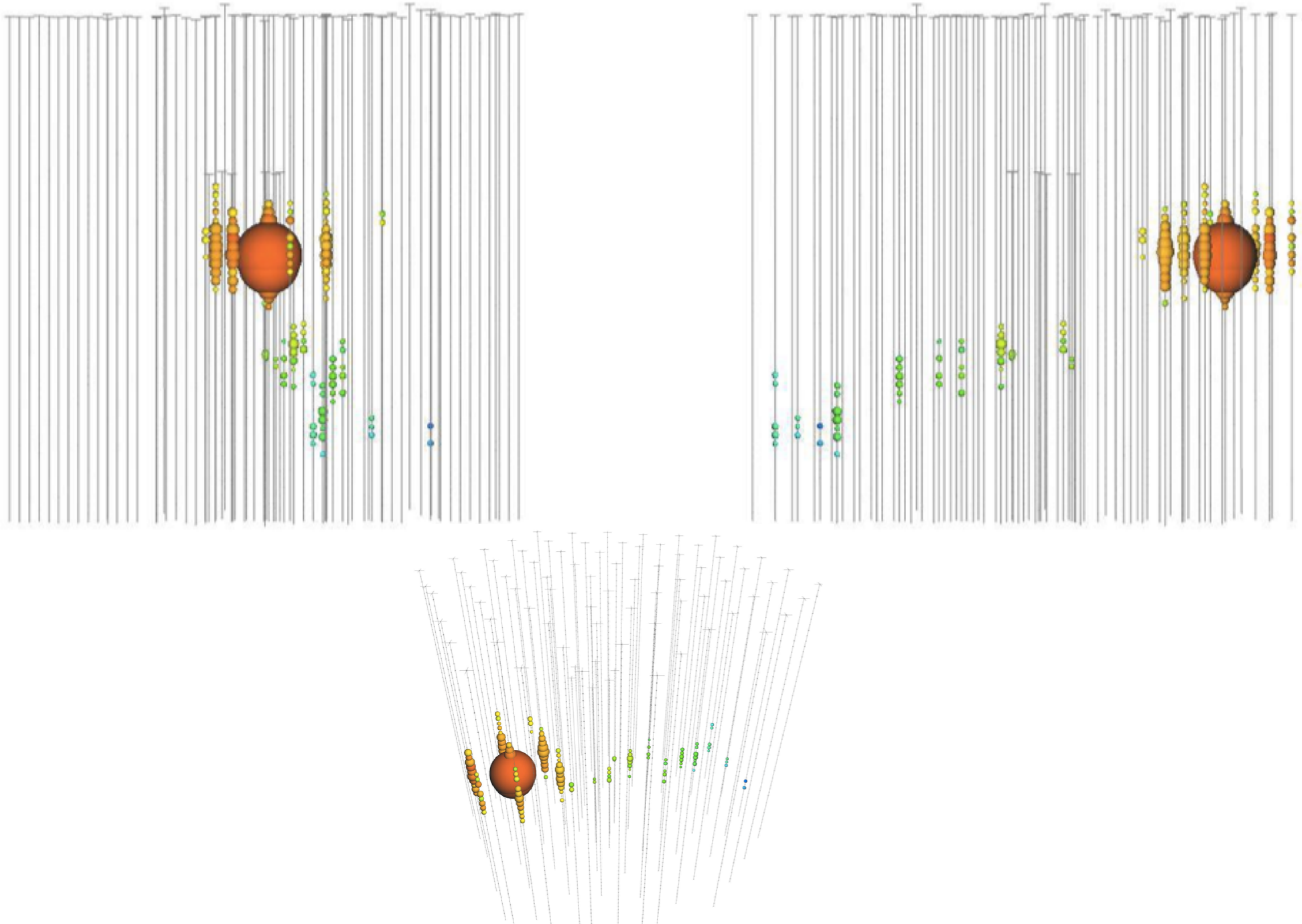
at the Earth

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

production point

decoherent oscillation

Event 8 (Track)



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

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

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

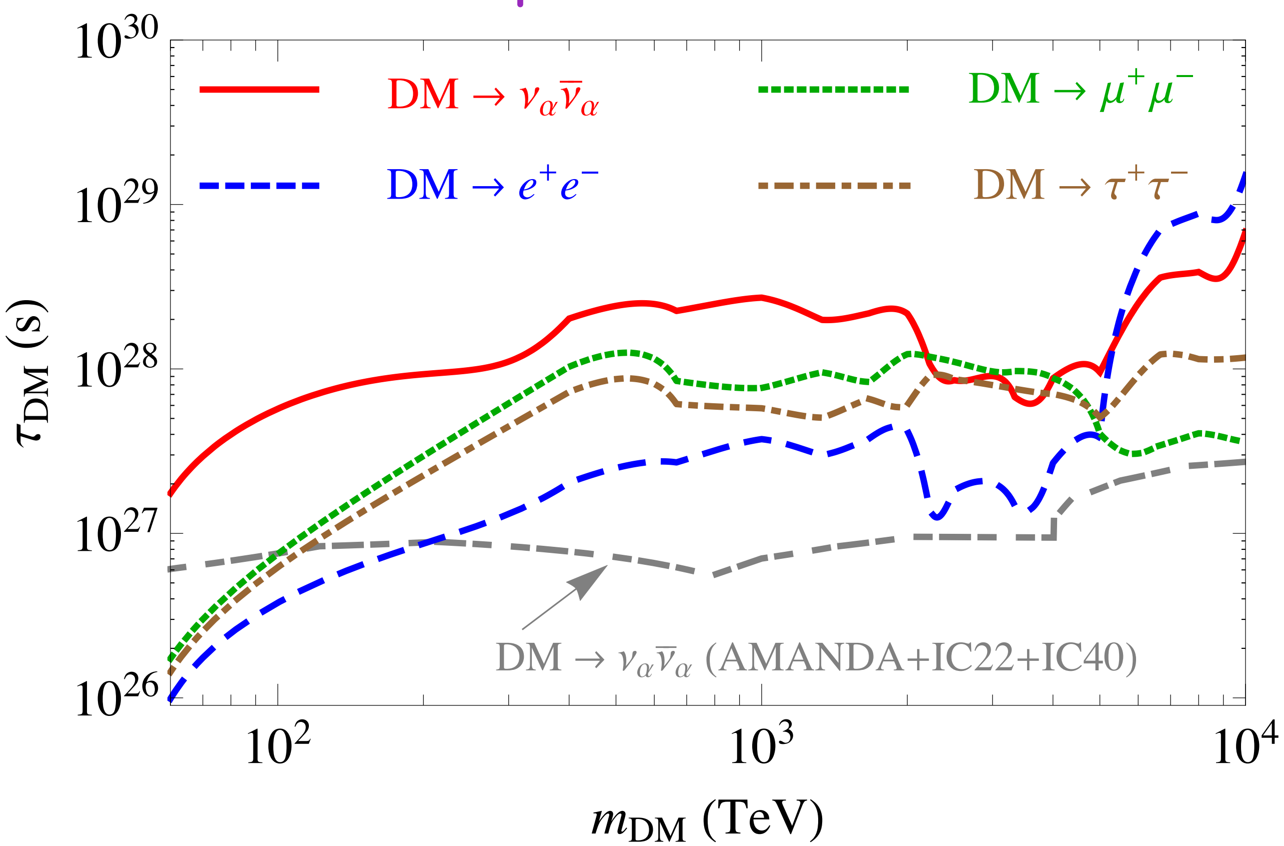
or

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

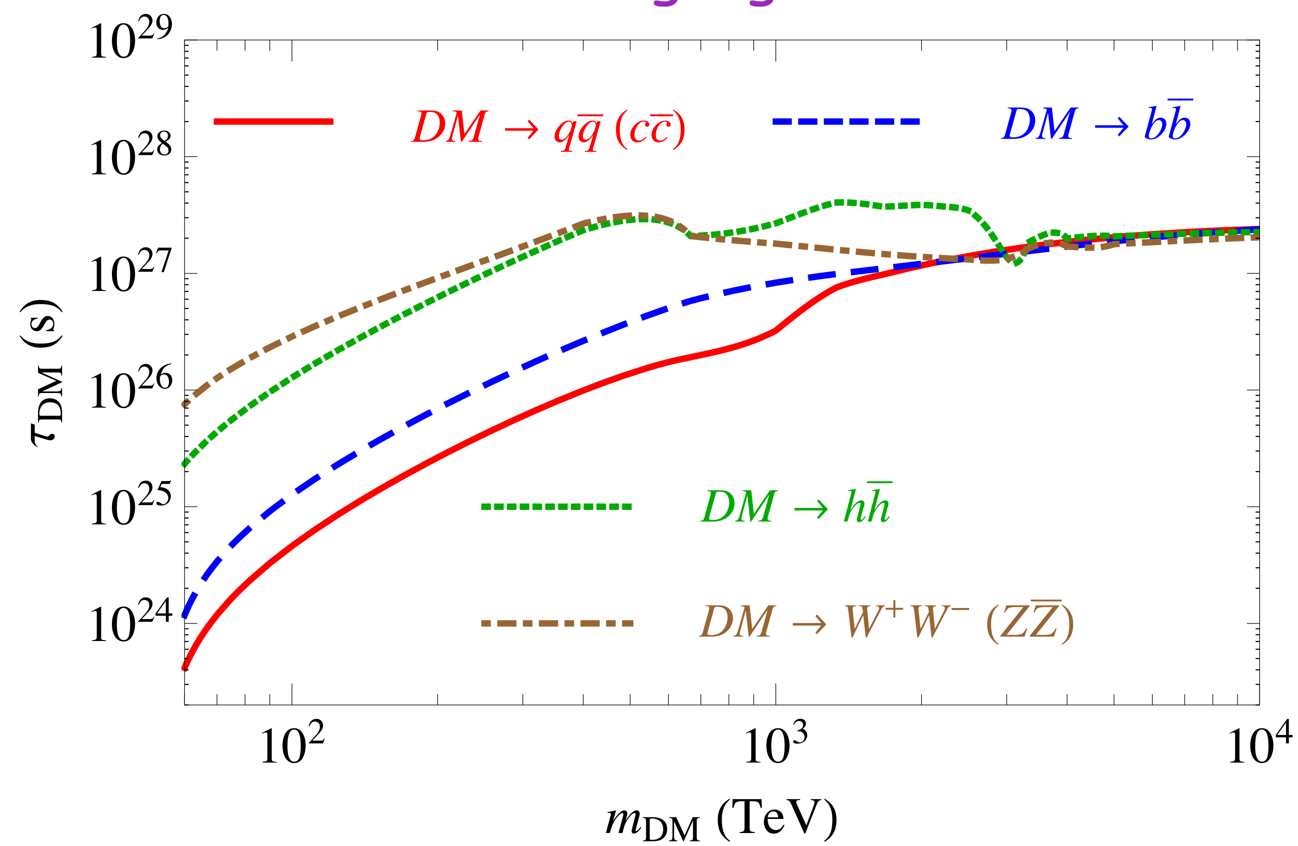
Constraining DM properties

✓ limits on DM lifetime (90% C.L.)

leptonic channels



hadronic/gauge channels



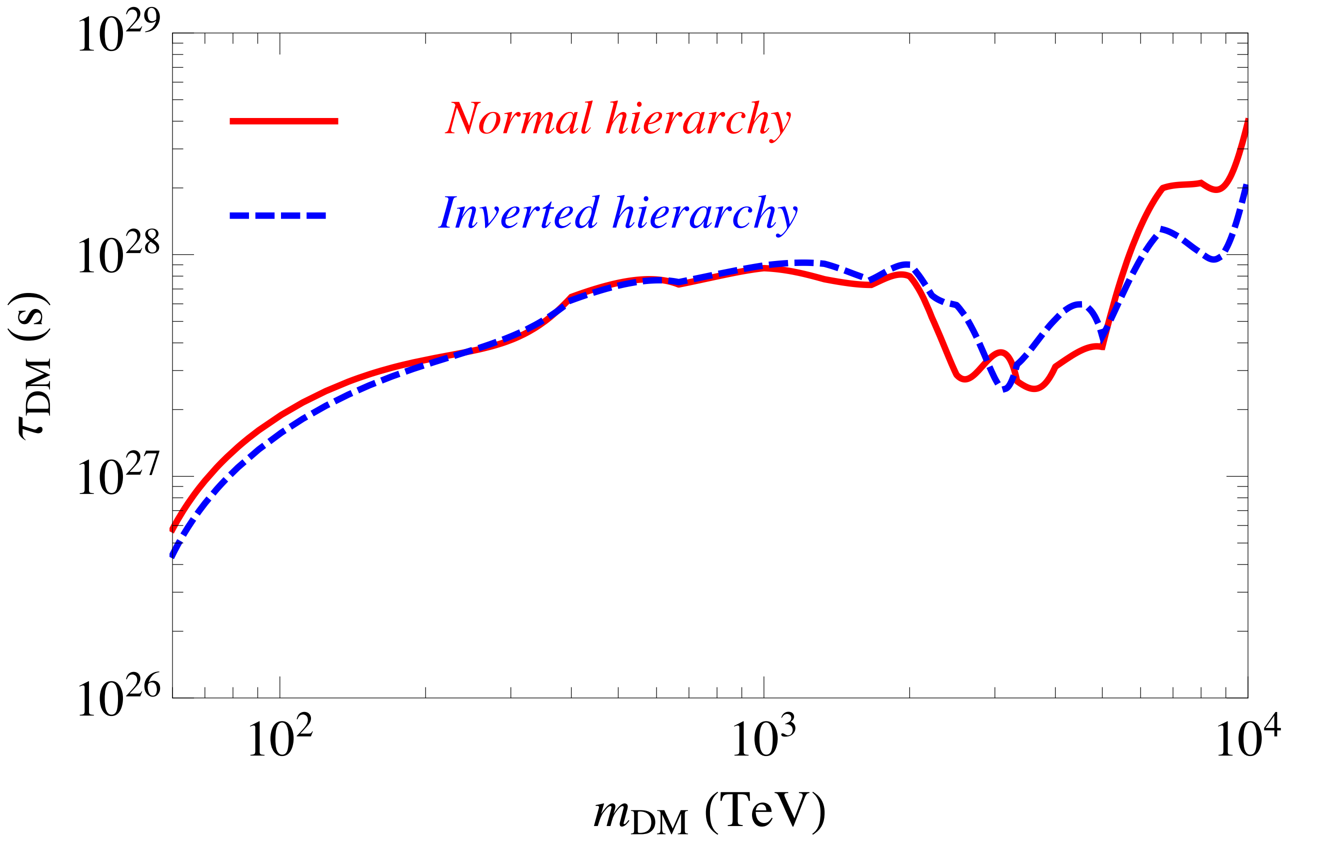
✓ at least one order of magnitude stronger lower limit on the DM lifetime, in the relevant DM mass range

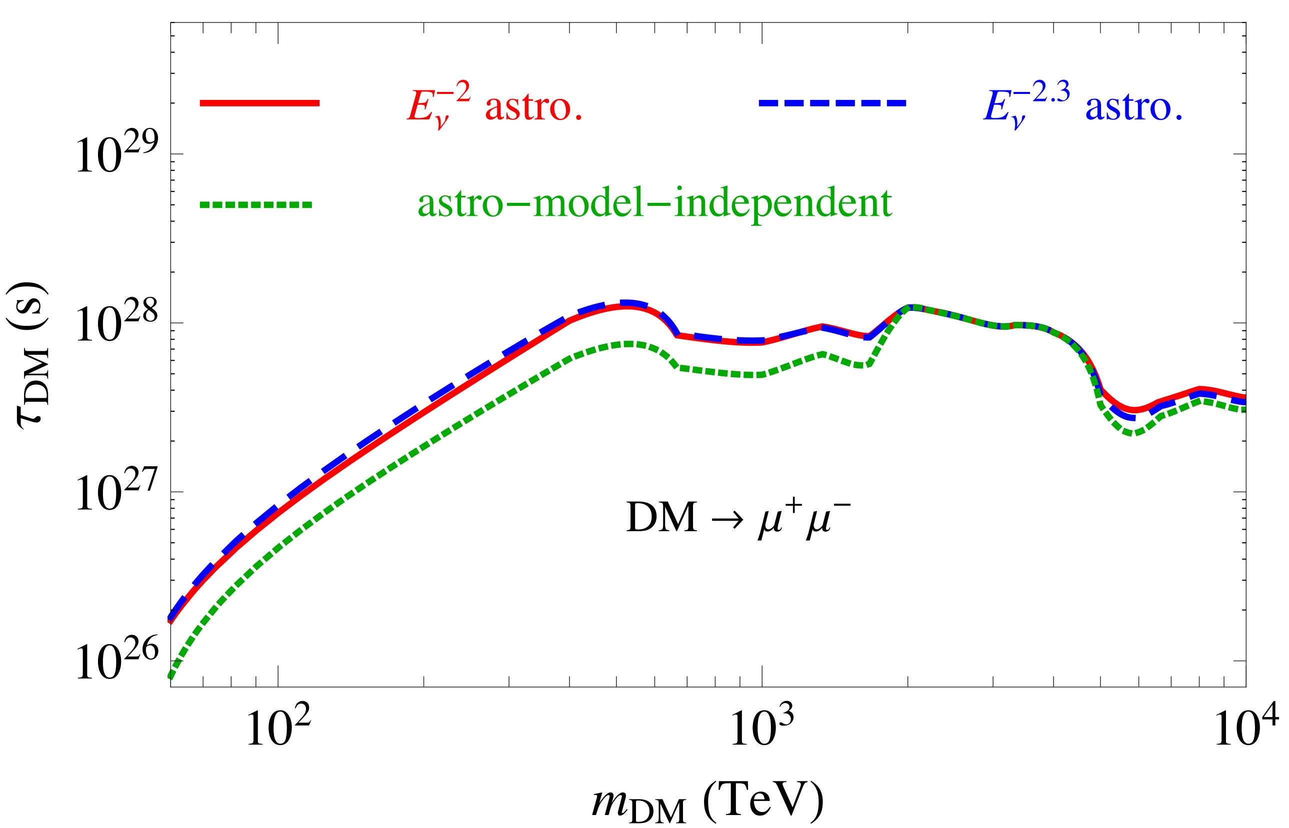
✓ for a specific model, different channels should be scaled according to the corresponding branching ratios

Constraining DM properties

✔ limits on DM lifetime (90% C.L.)

NH and IH cases →





← dependence on the astro. model?

✓ Annihilation cross section

The lower part (< 100 TeV) of the observed spectrum can be used to probe $\langle \sigma v \rangle$

✓ 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)

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

Constraining DM properties

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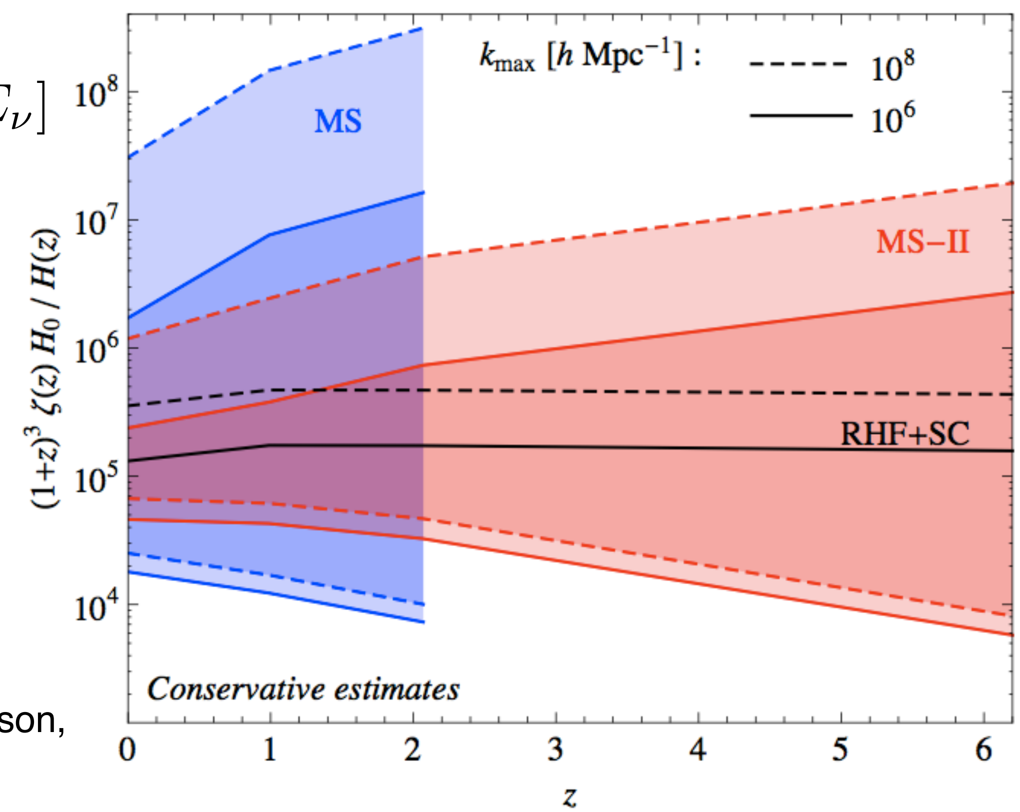
The cosmic flux from all redshift

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

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



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

Constraining DM properties

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

minimum ÷ maximum value used for $\zeta(z)$ 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

Gamma ray bounds

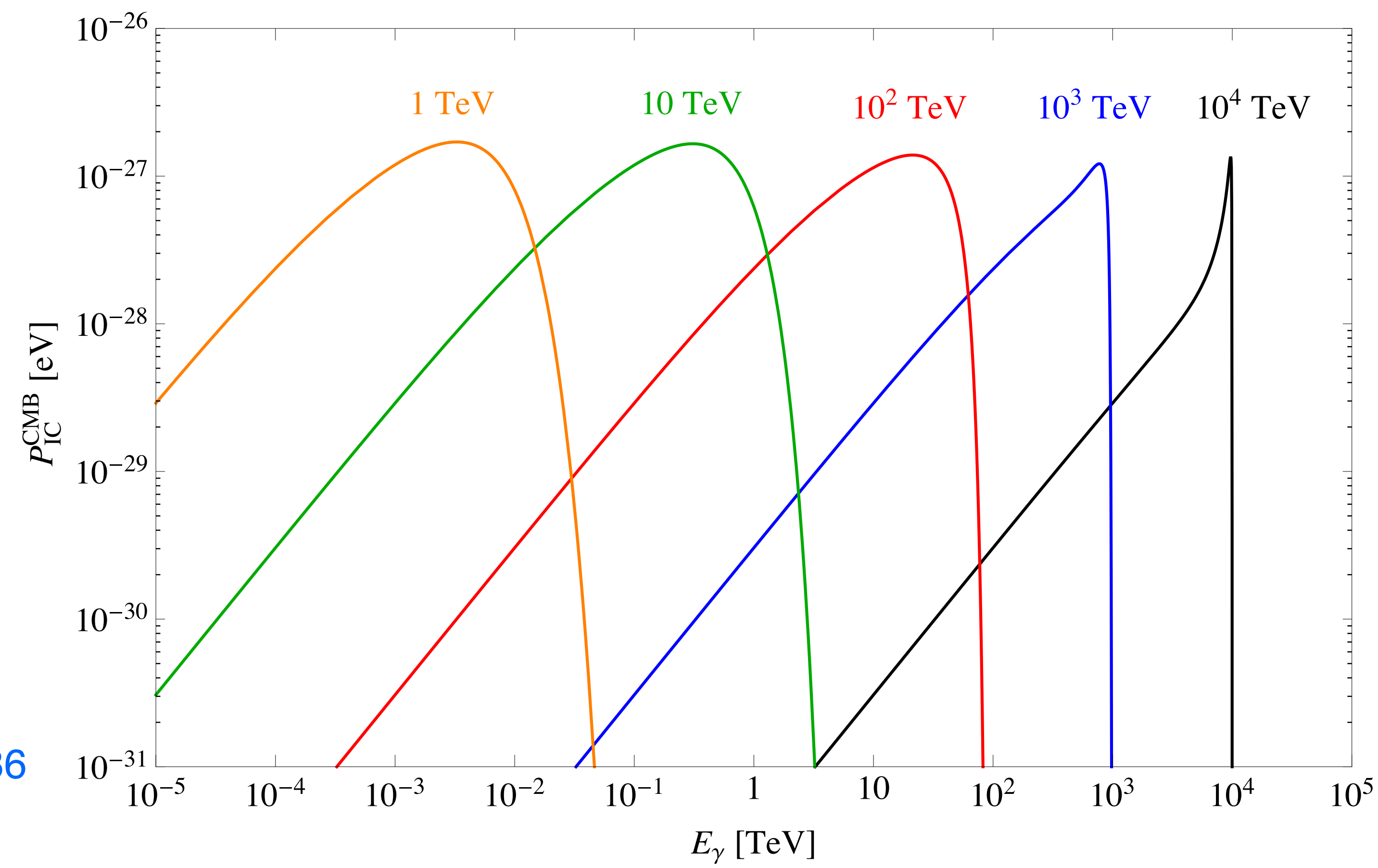
✓ Galactic component

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

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

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



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

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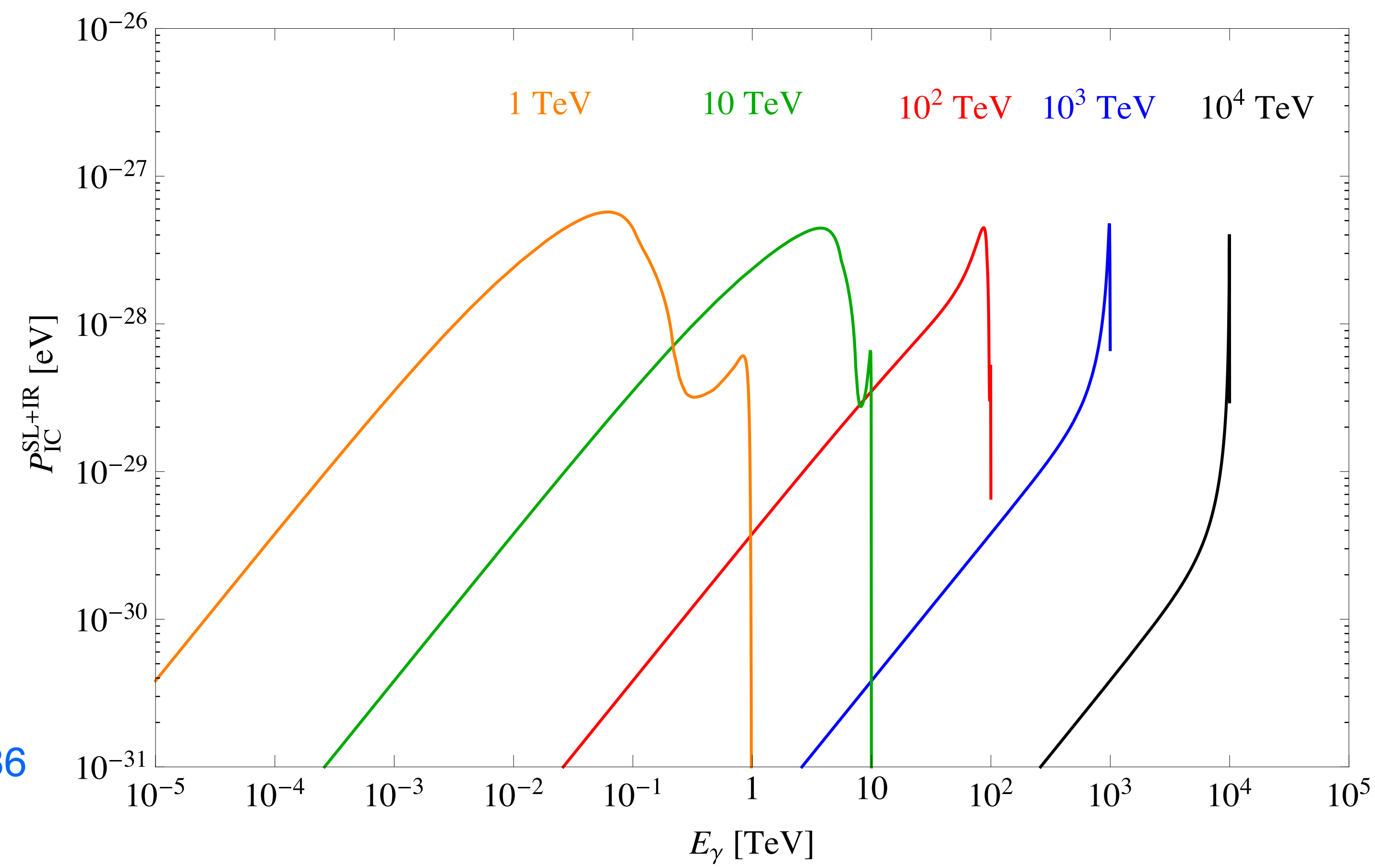
$$P_{\rm IC}=P_{\rm IC}^{\rm CMB}+P_{\rm IC}^{\rm SL+IR}$$



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