Interpreting the IceCube neutrinos by decaying heavy dark matter

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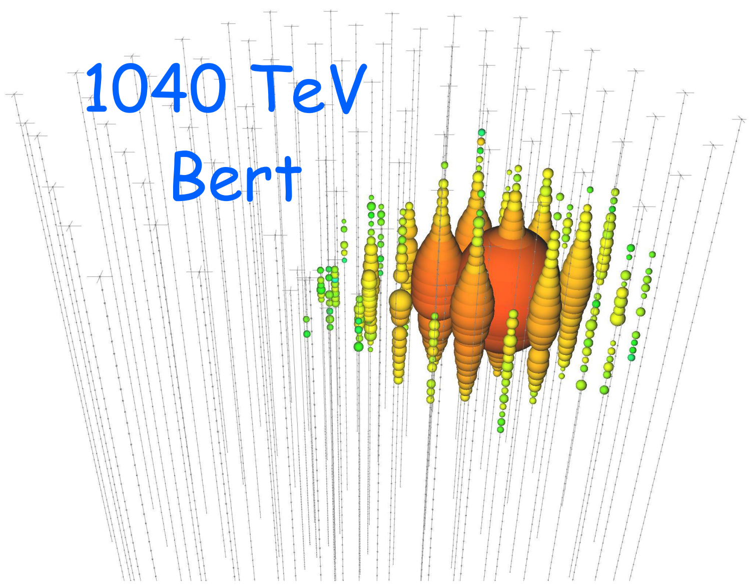
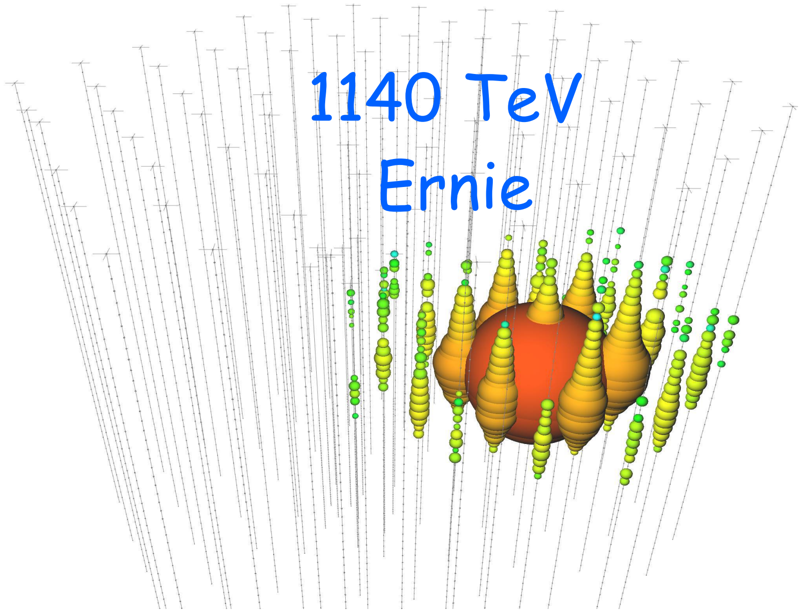
Observation of High Energy Neutrinos in IceCube

✓ The two PeV cascade events, 616 days livetime

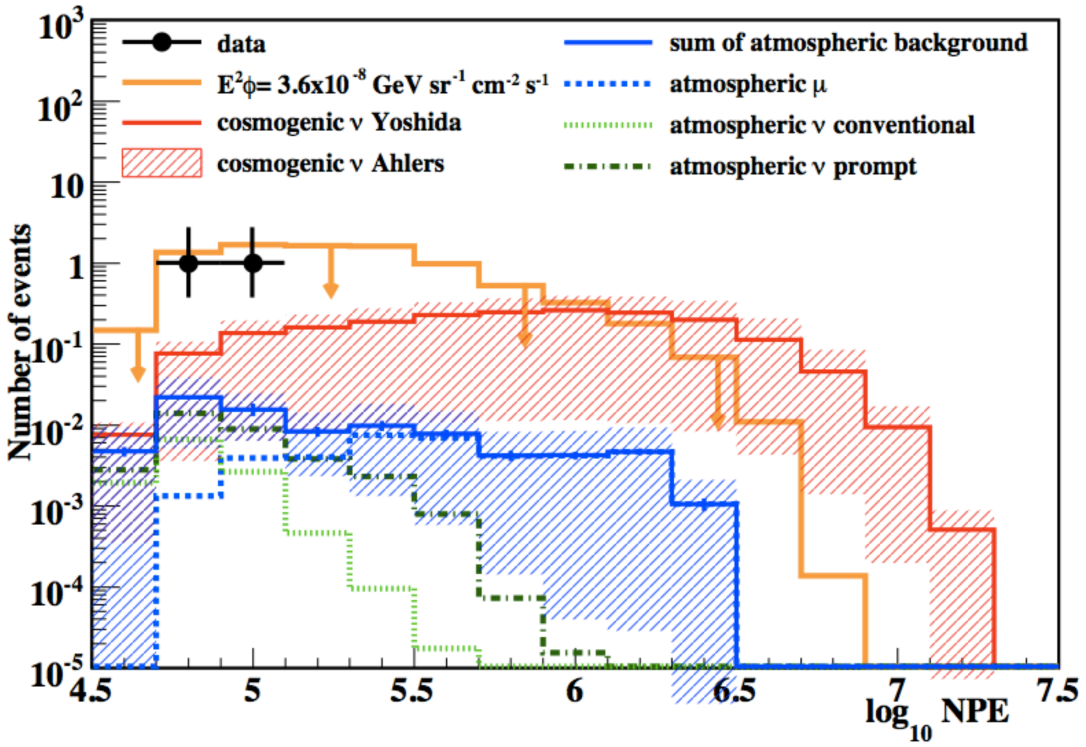


1040 TeV
Bert

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



1140 TeV
Ernie



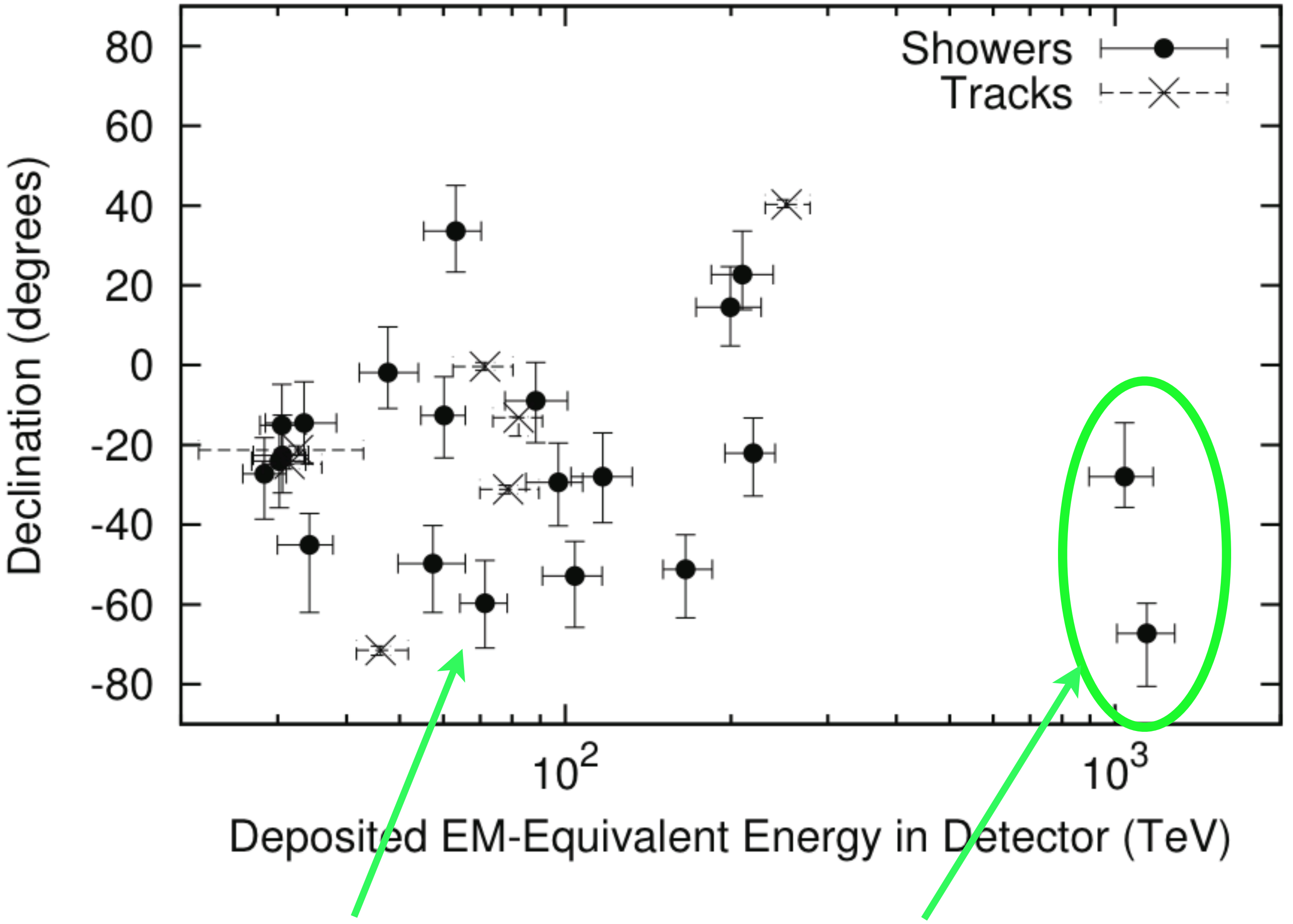
excess of events ~ 2.8σ

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

Observation of High Energy Neutrinos in IceCube

- ✓ Looking for lower energy contained events, 662 days livetime

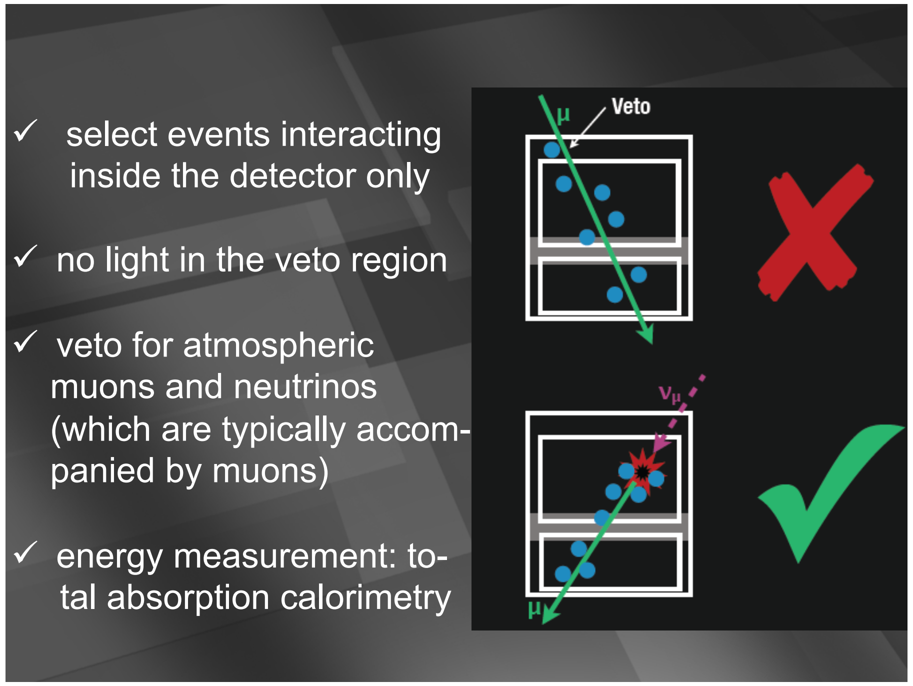
M. G. Aartsen et al. [IceCube Collaboration],
Science 342 (2013), [arXiv:1311.5238]



The whole family!

previous PeV
cascade events
(Bert and Ernie)

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

26 more events

excess of events ~ 4.3σ

Source(s) not identified!

Interpreting the IceCube events by decaying dark matter

B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida,

PRD (2013), [arXiv:1303.7320]

Two main diagnostics:

- ✓ Energy distribution
- ✓ Angular distribution

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

Energy distribution of neutrinos from decaying DM

✓ Galactic contribution:

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

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

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

Energy distribution of neutrinos from decaying DM

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

- ✓ extragalactic contribution:

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

Energy distribution of neutrinos from decaying DM

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

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quarks

neutrinos,
charged leptons

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

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

Energy distribution of neutrinos from decaying DM

✓ Galactic contribution:

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

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✓ extragalactic contribution:

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

quarks

neutrinos, charged leptons

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

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

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

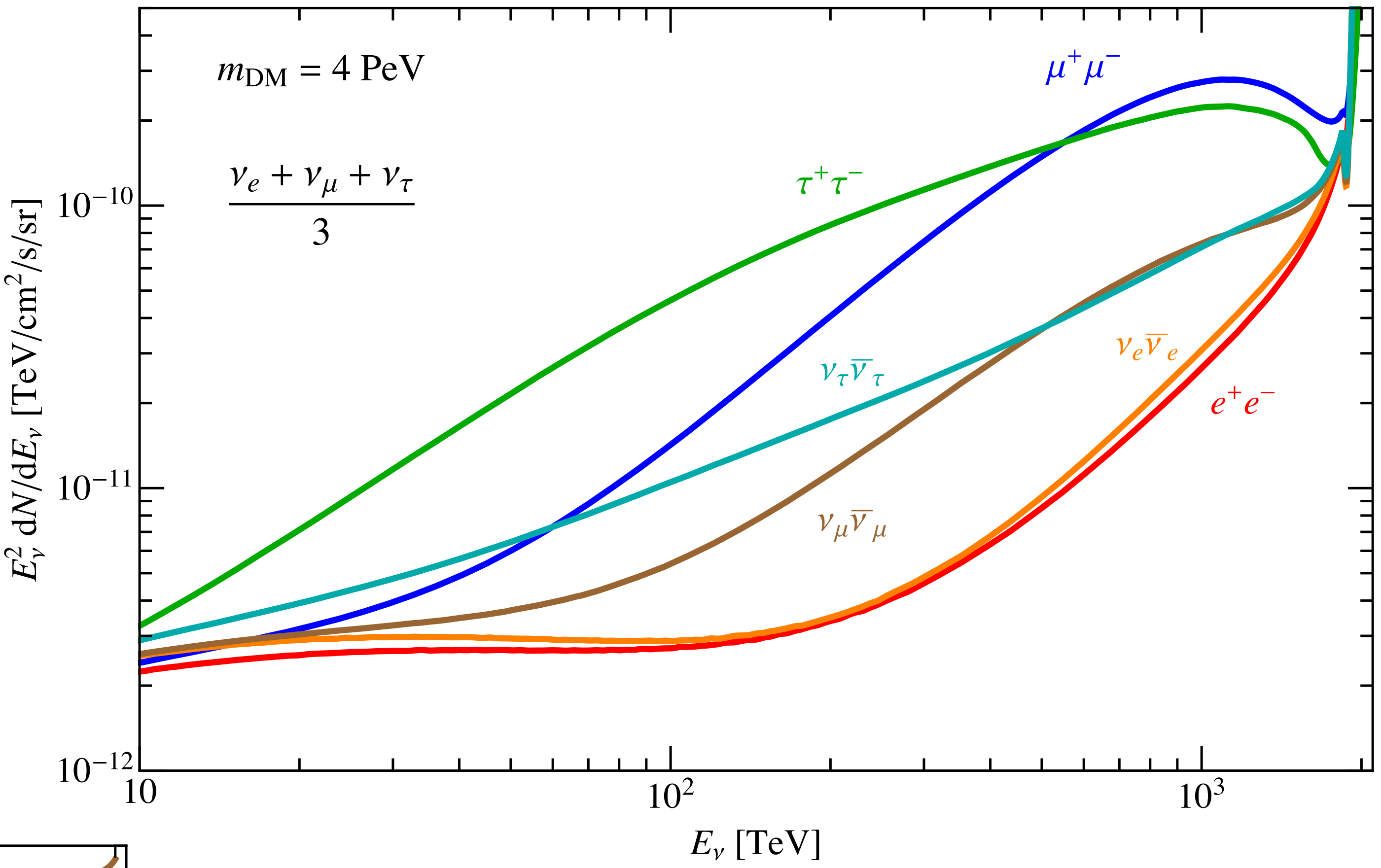
decoherent oscillation

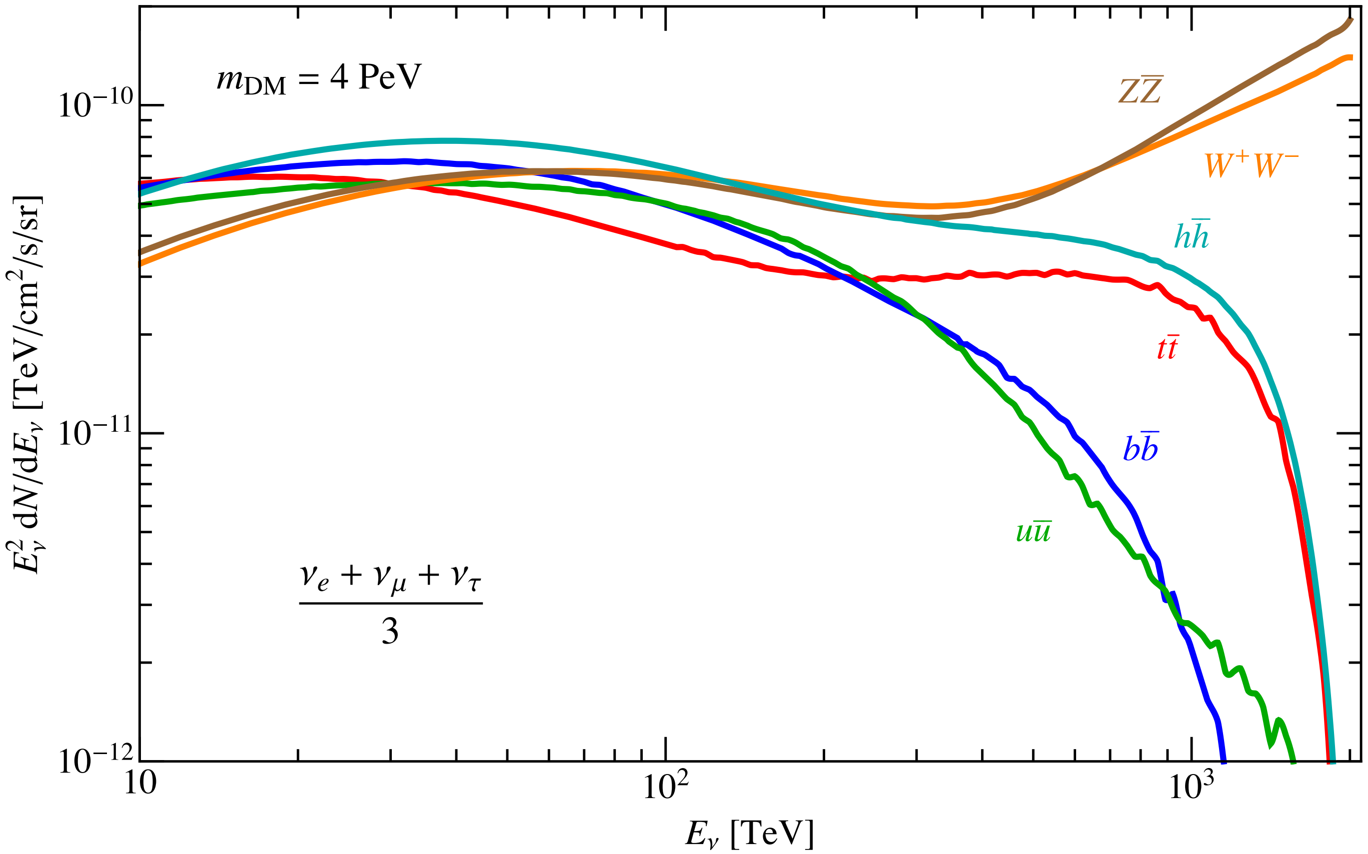
Flux of neutrinos from decaying DM

A. Bhattacharya, A. E., S. Palomares-Ruiz,
I. Sarcevic,
JCAP (2017) [arXiv:1706.05746]

m_{DM} = 4 PeV

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





EW corrections play an important role

PYTHIA 8.2

Flux of neutrinos from decaying DM

✓ an example:

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

intriguing features:

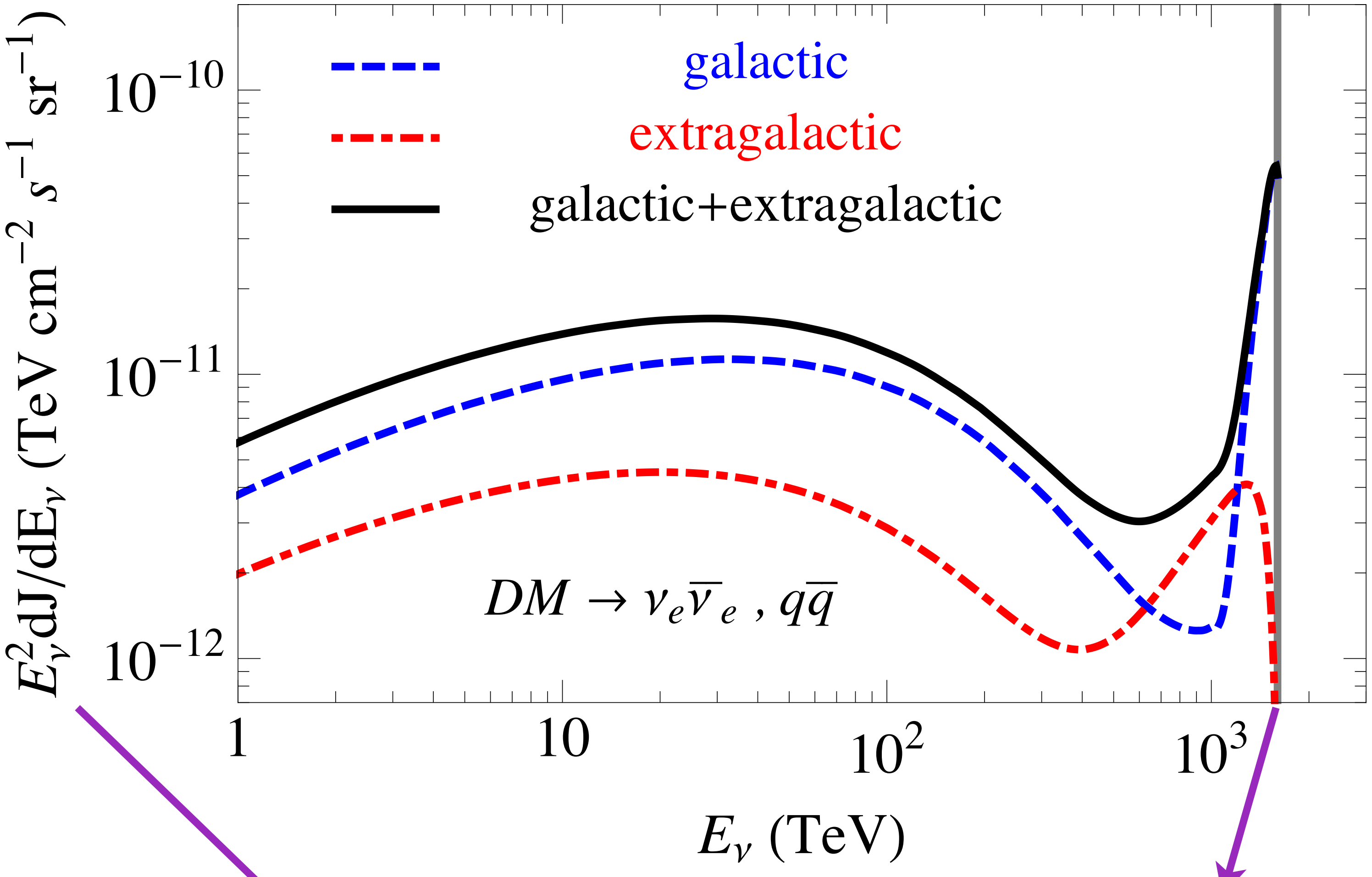
a cut-off at $m_{DM}/2$

a peak in ~ PeV

flux is not feature-less

populated spectrum in < 0.4 PeV

due to soft channel and EW cascades



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

$m_{DM}/2 = 1.6$ PeV

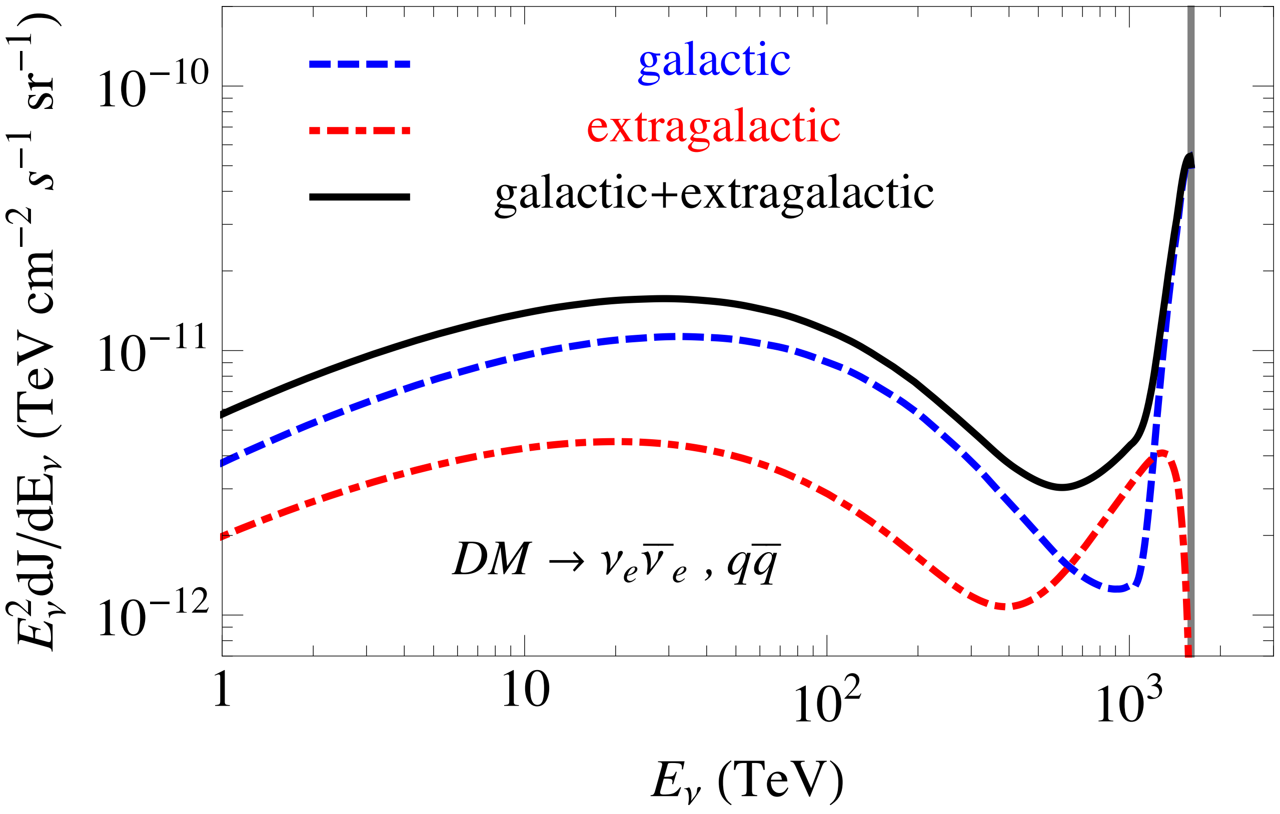
b_H controls the peak height at ~ PeV

τ_{DM} controls the low energy population

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

Flux of neutrinos from decaying DM

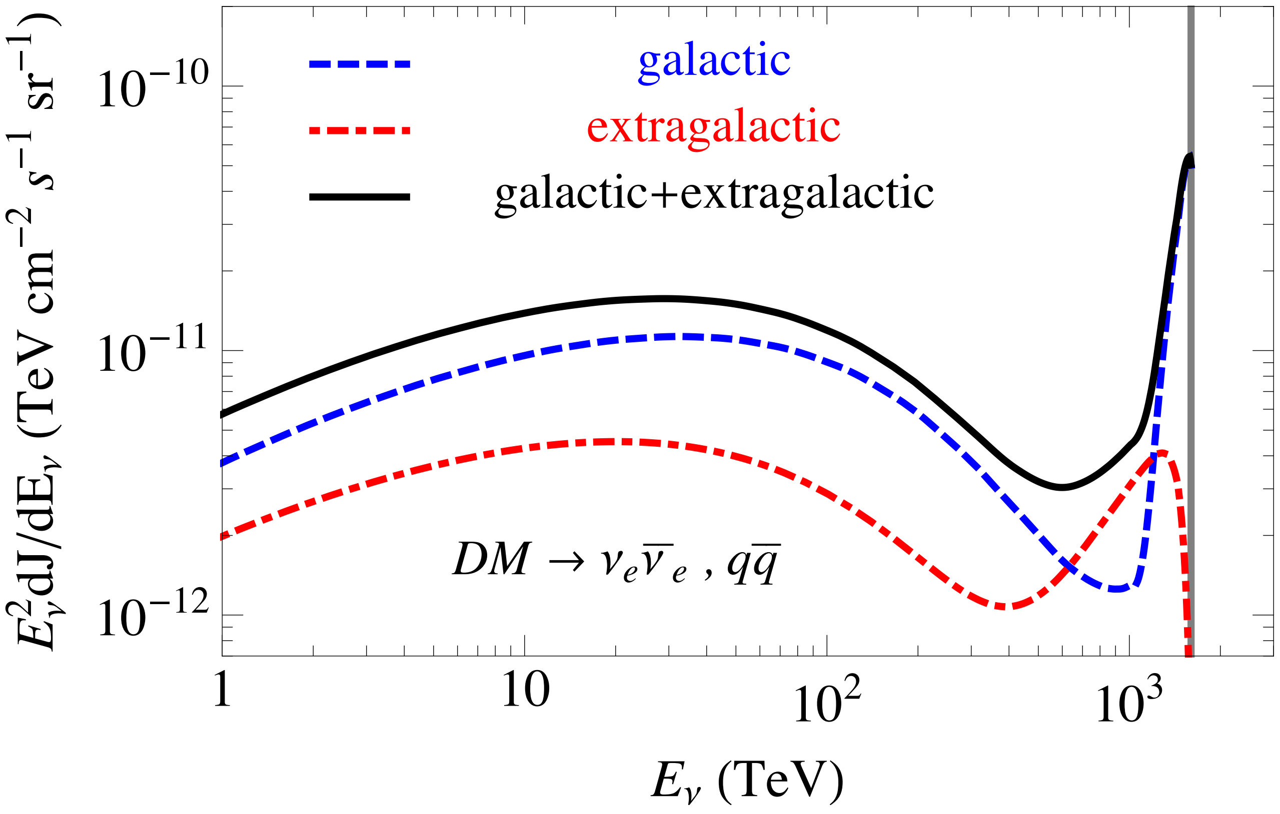
✓ fine-tuned decay channels ?

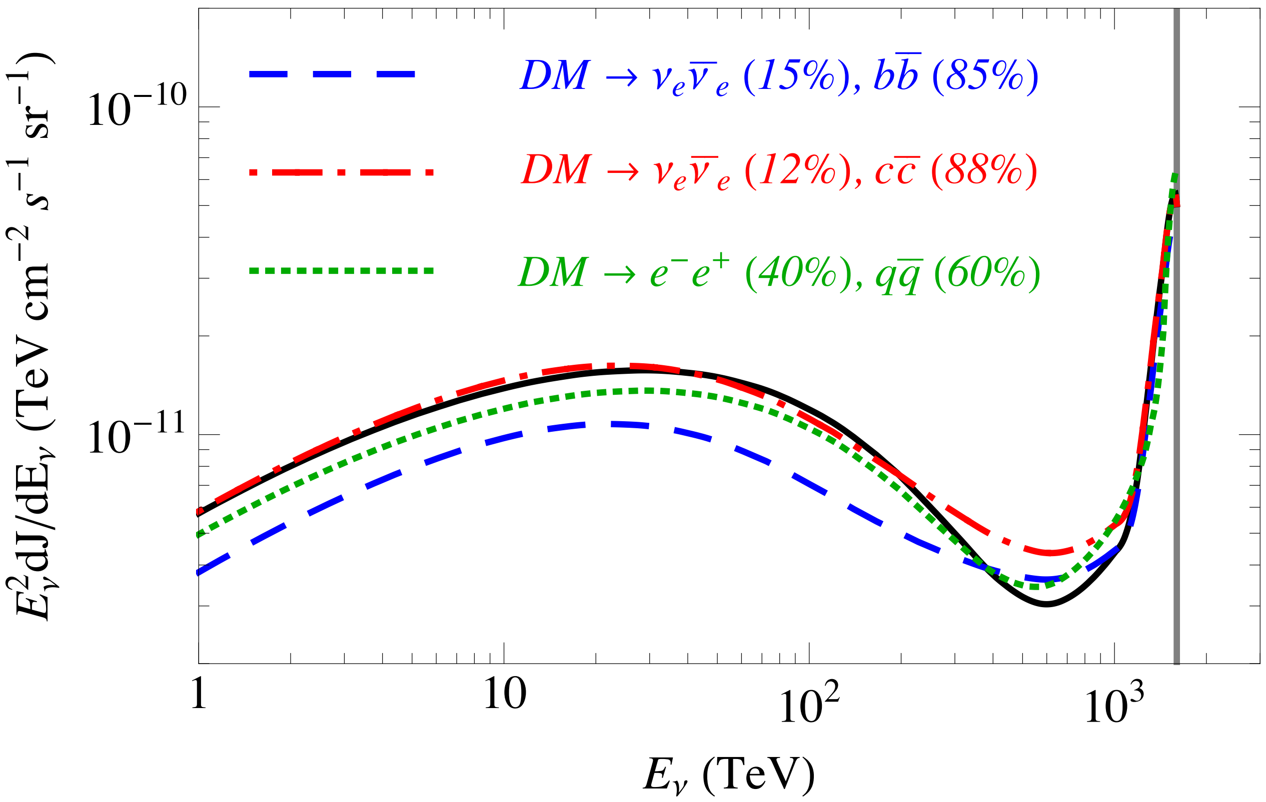


Flux of neutrinos from decaying DM

✓ fine-tuned decay channels ?

τ_{DM} = (1-3) x 10^{27} s



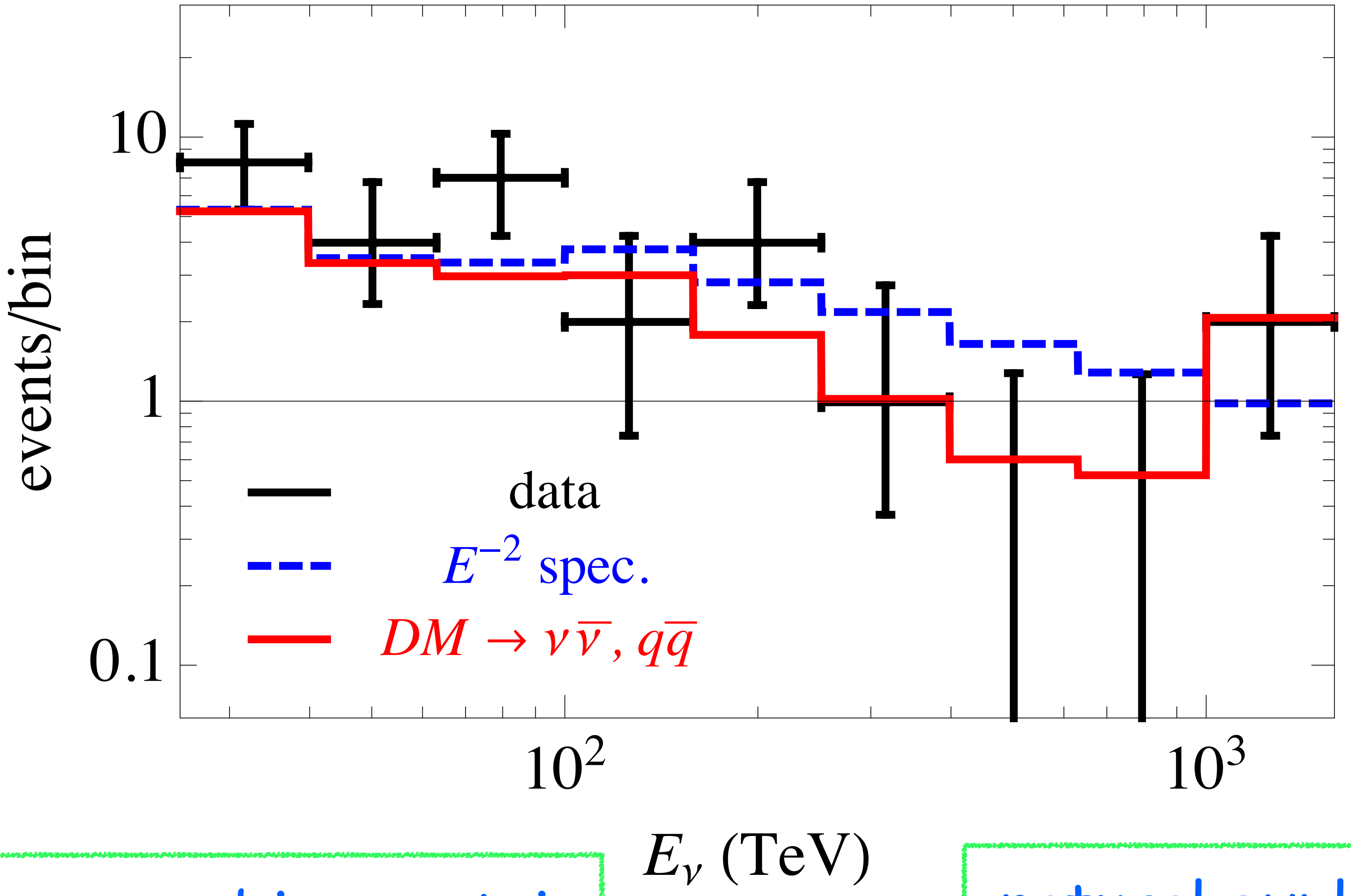


the intriguing features are generic

Confronting with energy distribution of IceCube data

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

2 years data set



the low energy bins contain large bkg. contribution

natural explanation for the lack of events > PeV

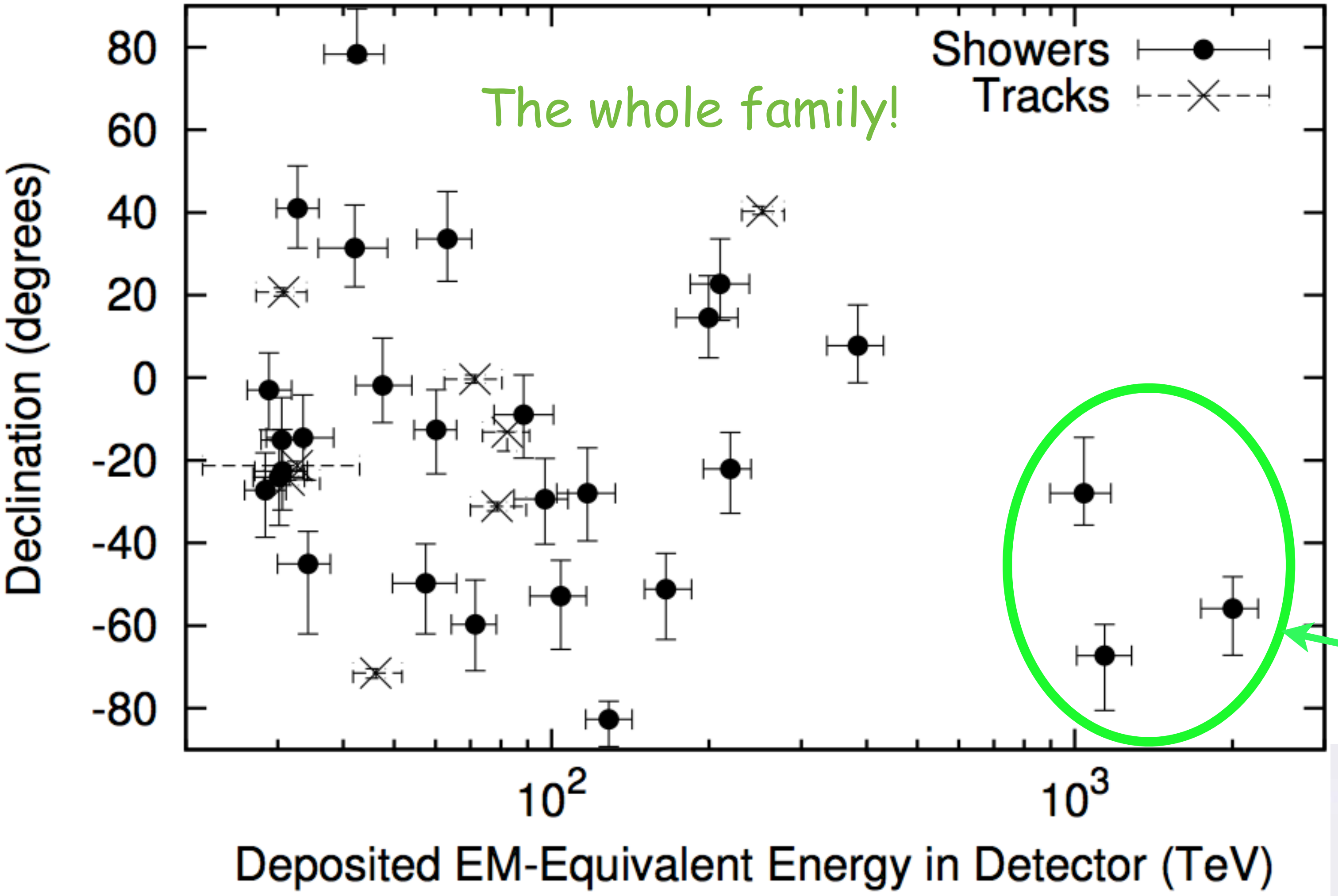
different decay channels lead to qualitatively same result

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

Observation of High Energy Neutrinos in IceCube

✓ Looking for lower energy contained events, 988 days livetime

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



The whole family!

✓ totally 37 events

✓ three events with energy ~ PeV

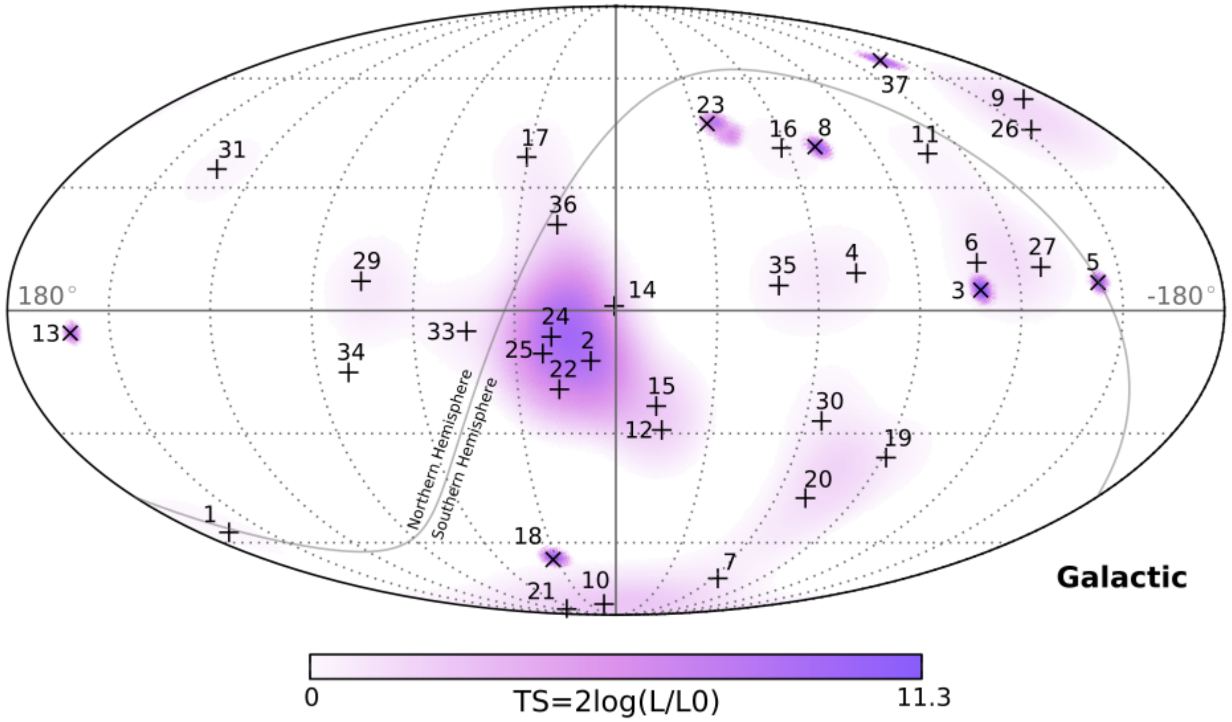
✓ expected bkg. (conventional+prompt)
~ 15.6(+10.1)(-5.8) sys.

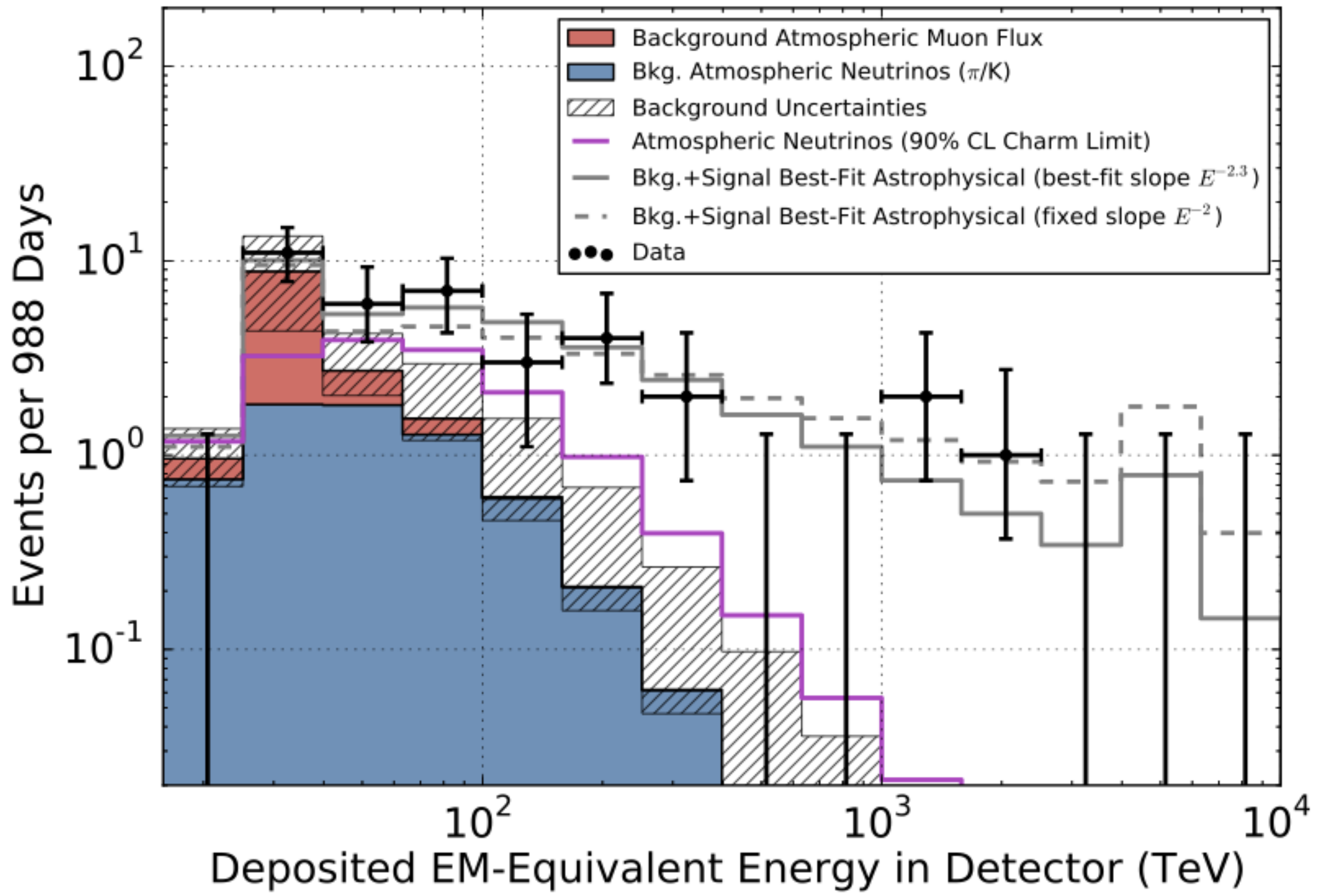
excess of events ~ 5.7σ

Source(s) not identified!

IceCube data

✓ Looking for lower energy contained events, 988 days livetime





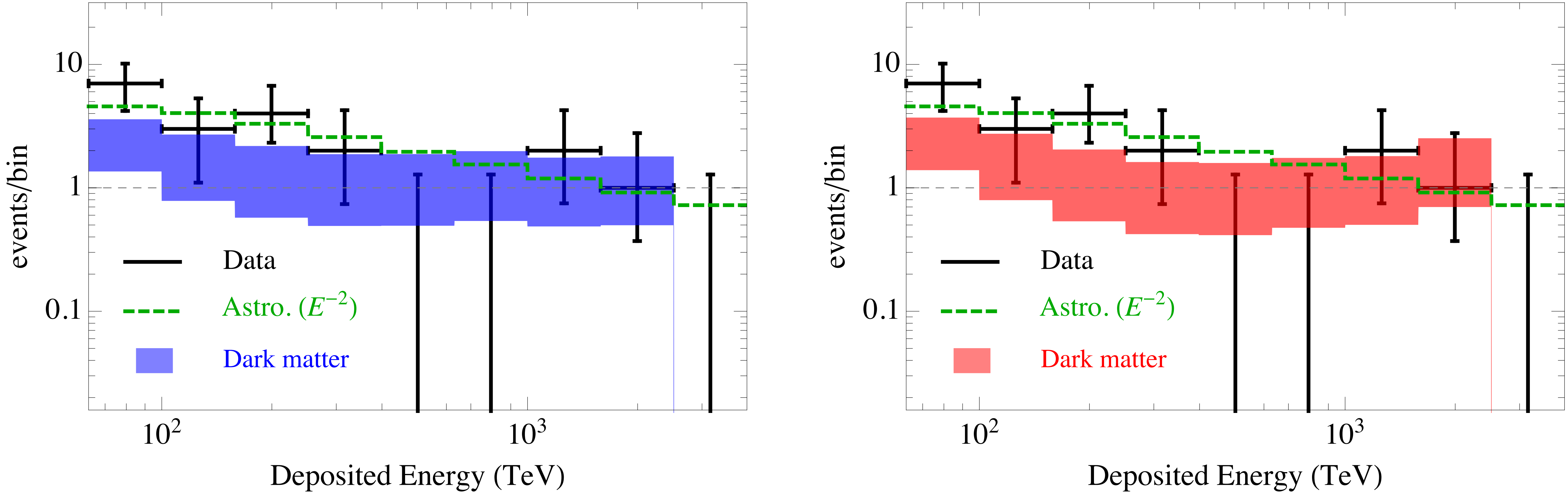
3 years of data

Confronting with energy distribution of IceCube data

3 years data set

A. E., S. K. Kang and P. Serpico,
JCAP (2014) [arXiv:1410.5979 [hep-ph]]

IH, $\tau_{DM} = 1.1 \times 10^{28}$ s $m_{DM} = 4$ PeV NH, $\tau_{DM} = 7.3 \times 10^{27}$ s



Calculation based on a model for DM: neutrino portal with dim-4 operator (heavy sterile neutrino), B-L symmetry (inflation), Leptogenesis (other sterile neutrinos), with production mechanism (either inflation decay or freeze-in mechanism)

T. Higaki, R. Kitano and R. Sato,

JHEP (2014) [1405.0013]

The predicted neutrino flux is fixed by the model

Confronting with energy distribution of IceCube data

3 years data set

A. E., S. K. Kang and P. Serpico,
JCAP (2014) [arXiv:1410.5979 [hep-ph]]

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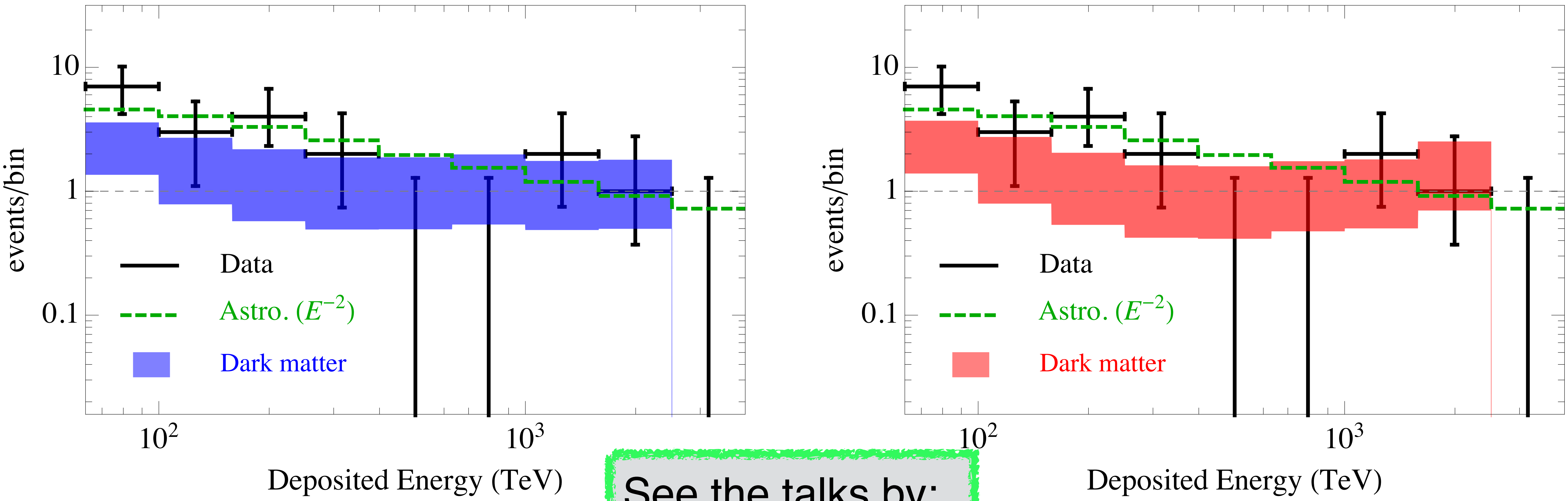

See the talks by:
Pasquale Di Bari
Viviana Niro
Thomas Hambye
Marco Chianese

Calculation based on a model ortal with dim-4
operator (heavy sterile neu etry (inflation),
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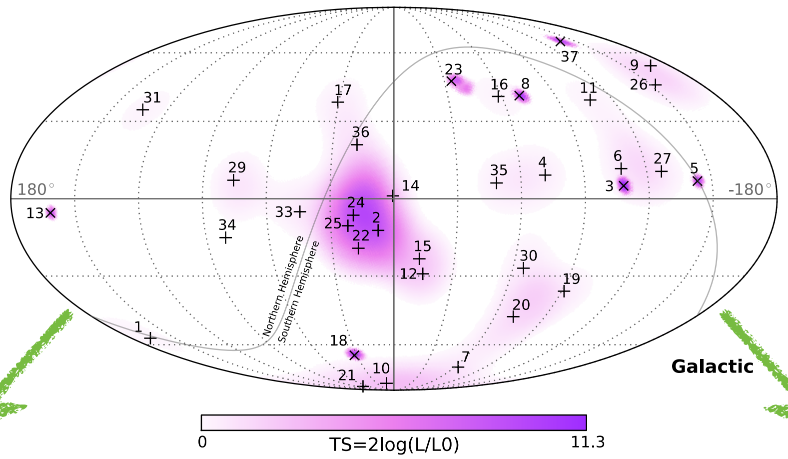
T. Higaki, R. Kitano and R. Sato,
JHEP (2014) [1405.0013]

The predicted neutrino flux is fixed by the model

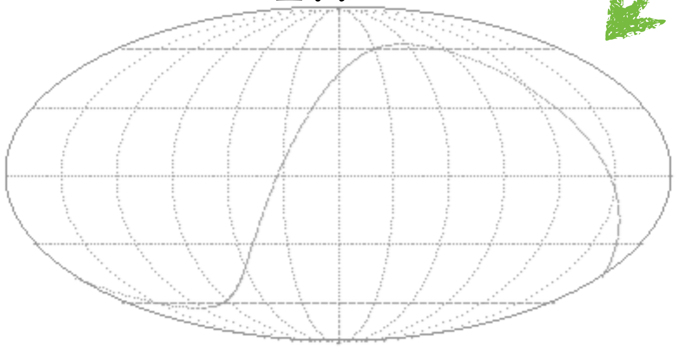
Angular distribution of neutrinos from decaying DM

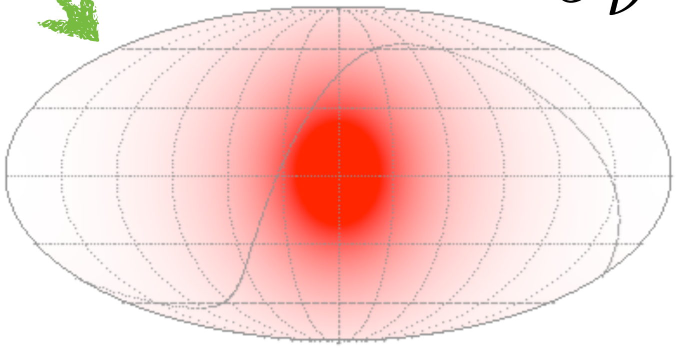
✓ We would compare

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



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





Angular distribution of neutrinos from decaying DM

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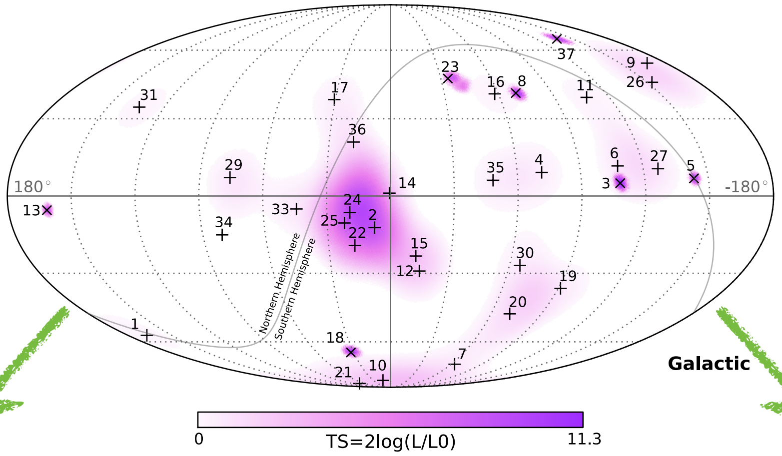

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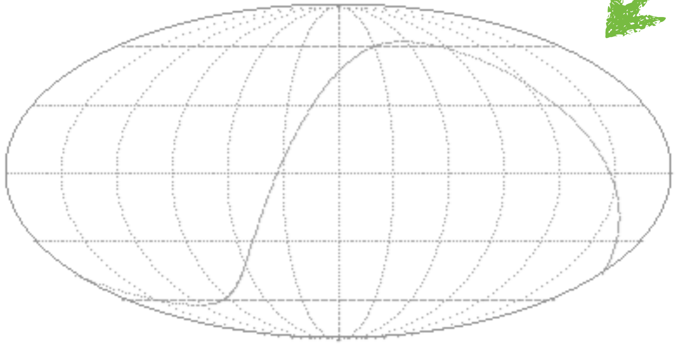

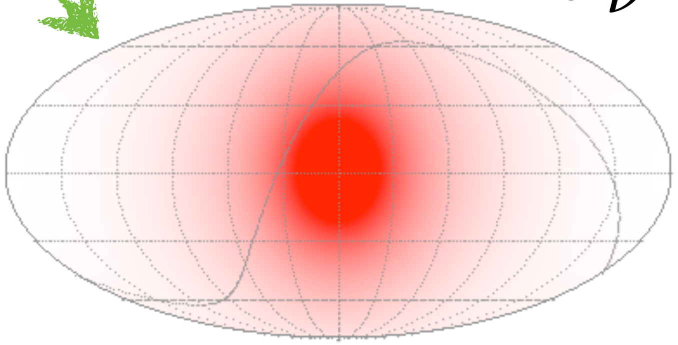

PDF of data

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

"flat sky" approximation

PDF of isotropic dis.

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

PDF of DM

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

Angular distribution of neutrinos from decaying DM

✓ Likelihood analysis

Number of signal events

Test Statistics

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

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

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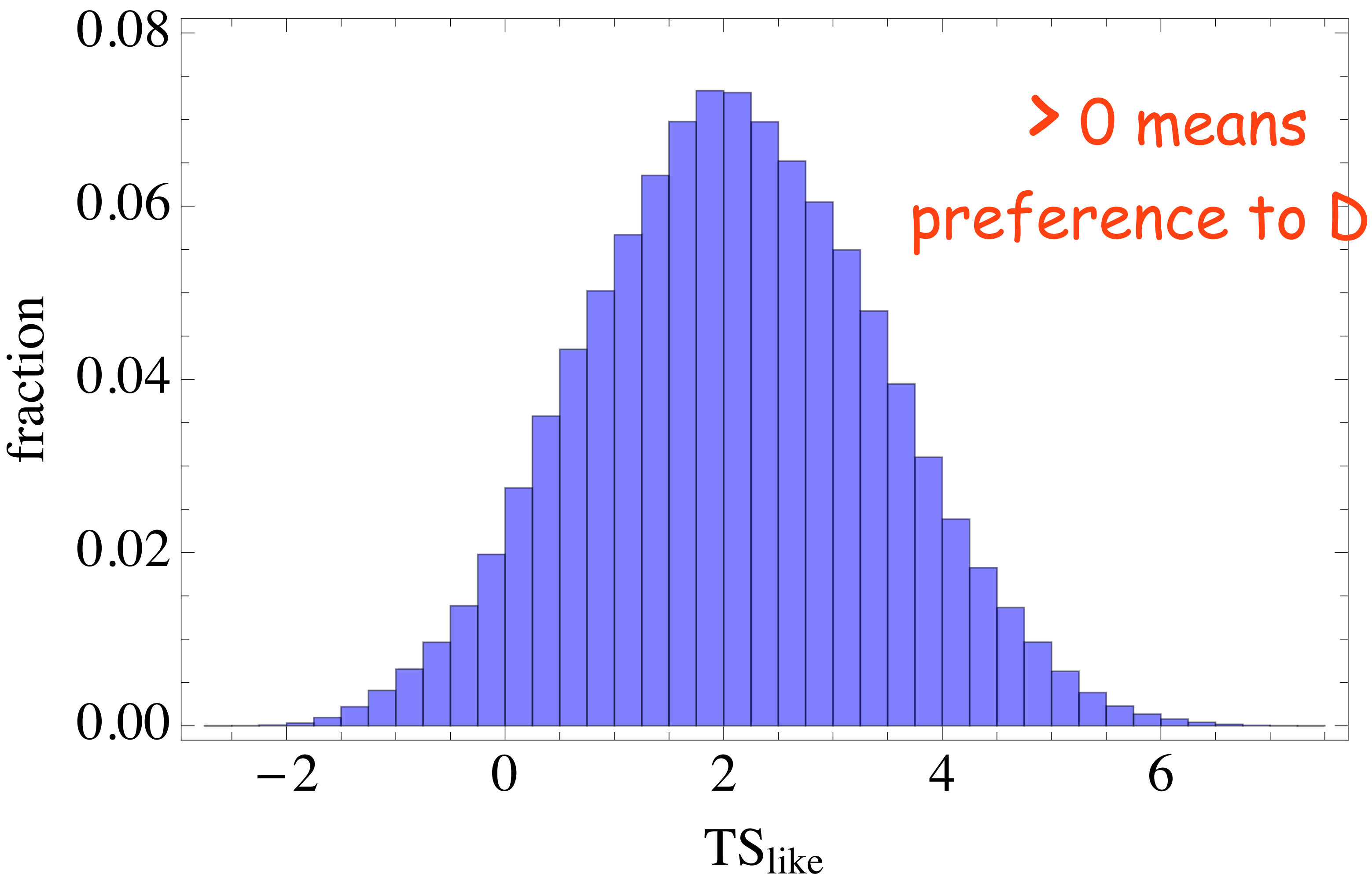
ways of selecting the bkg events among the low energy events $\binom{26}{15}$



> 0 means preference to DM

A. E., S. K. Kang and P. Serpico, JCAP (2014) [arXiv:1410.5979 [hep-ph]]

Angular distribution of neutrinos from decaying DM

✓ Likelihood analysis

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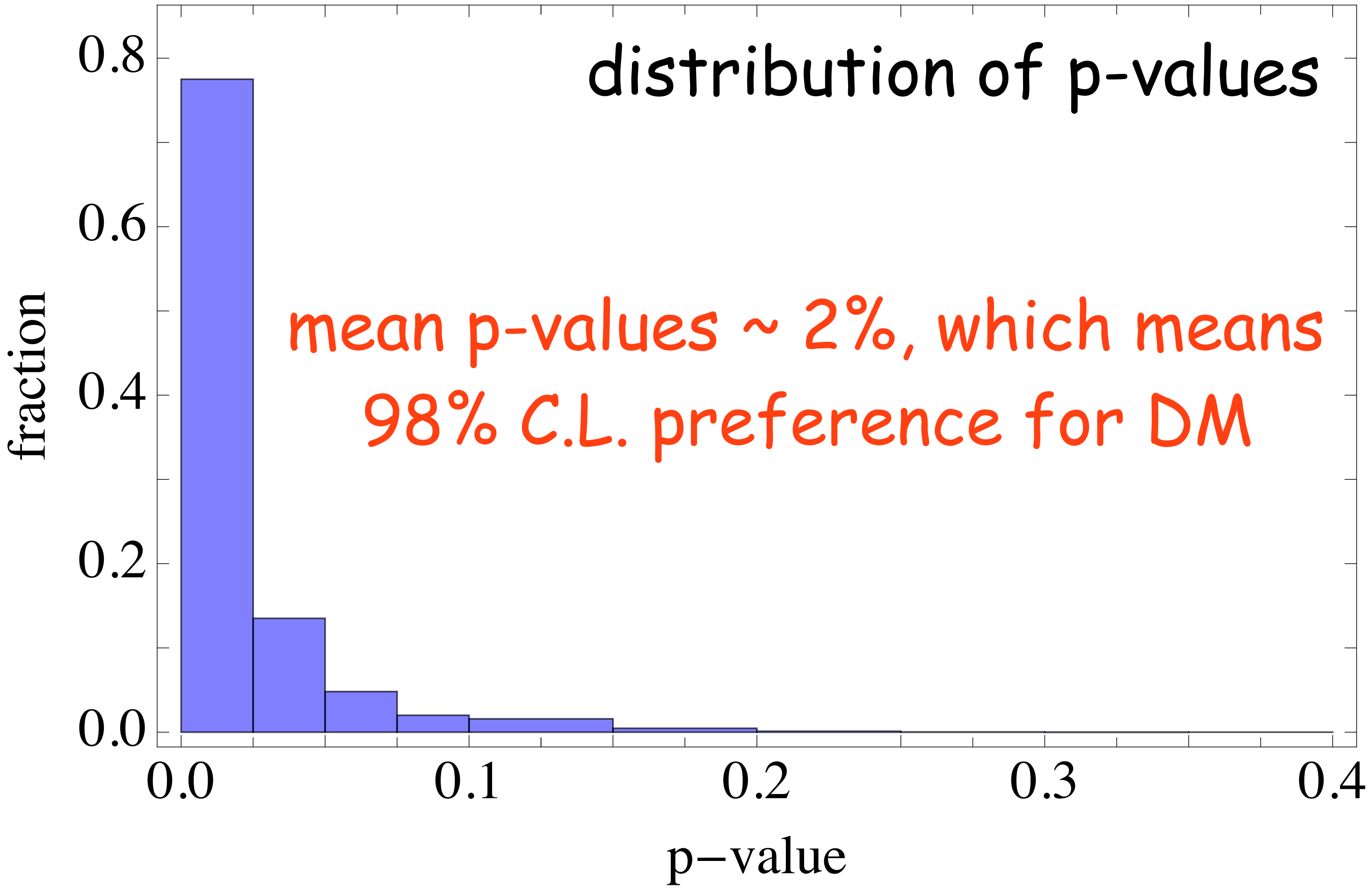
ways of selecting the bkg events among the low energy events $\binom{26}{15}$



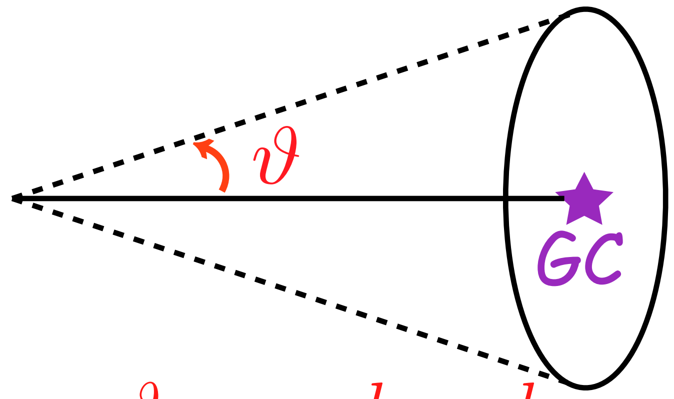
mean p-values ~ 2%, which means 98% C.L. preference for DM

A. E., S. K. Kang and P. Serpico, JCAP (2014) [arXiv:1410.5979 [hep-ph]]

Angular distribution of neutrinos from decaying DM

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

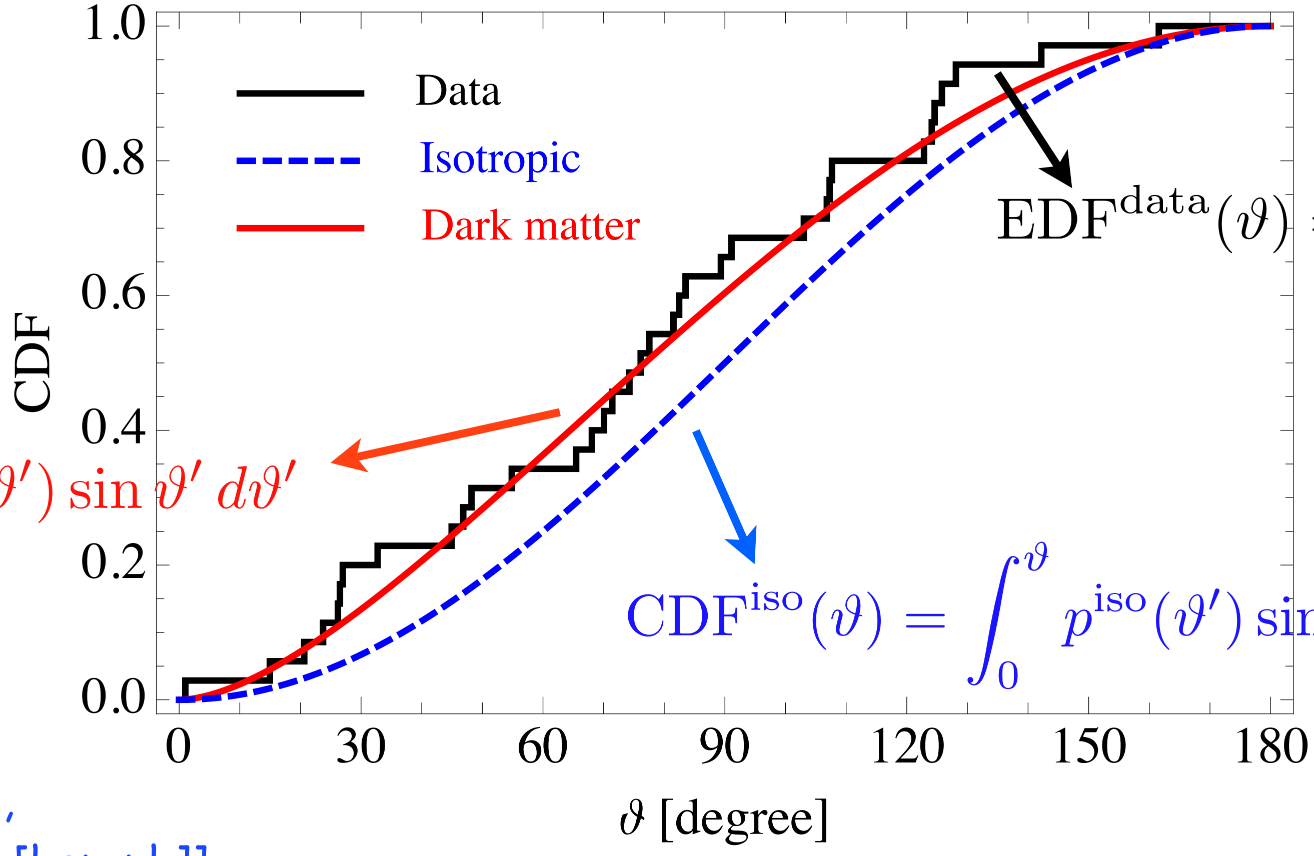
The 2-dim KS test have some ambiguities



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

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

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



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

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

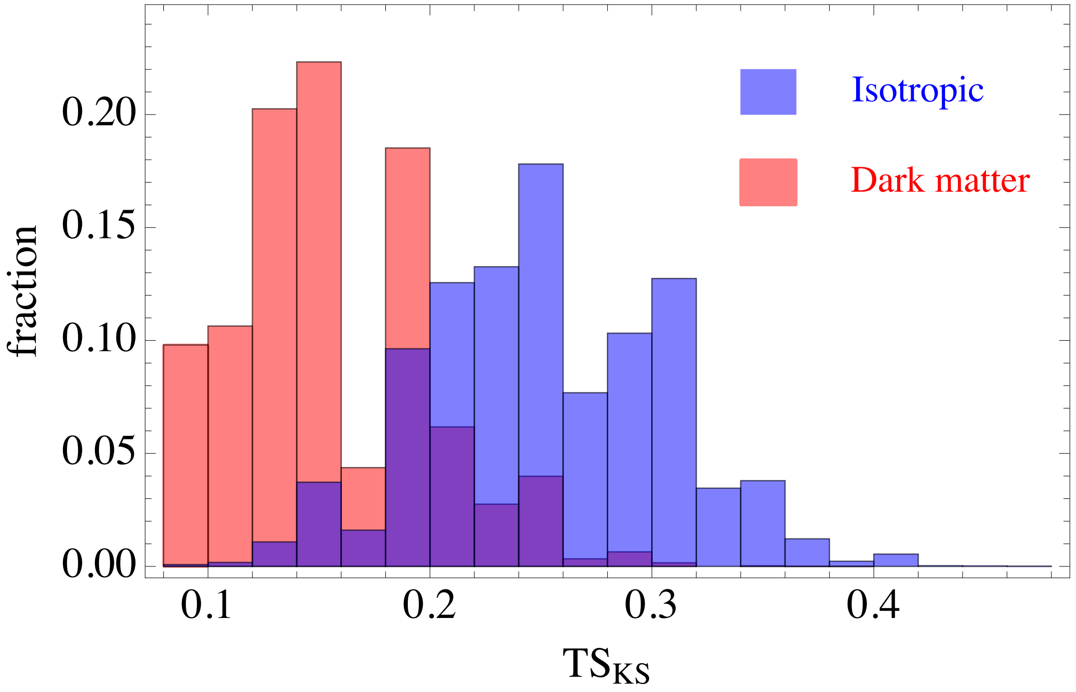
$$\text{CDF}^{\rm iso}(\vartheta) = \int_0^\vartheta p^{\rm iso}(\vartheta')\sin\vartheta'\,d\vartheta' = \frac{1-\cos\vartheta}{2}$$

A. E., S. K. Kang and P. Serpico,
JCAP (2014) [arXiv:1410.5979 [hep-ph]]

Angular distribution of neutrinos from decaying DM

✓ Kolmogorov-Smirnov test:

statistically larger TS for isotropic distribution



A. E., S. K. Kang and P. Serpico, JCAP (2014) [arXiv:1410.5979 [hep-ph]]

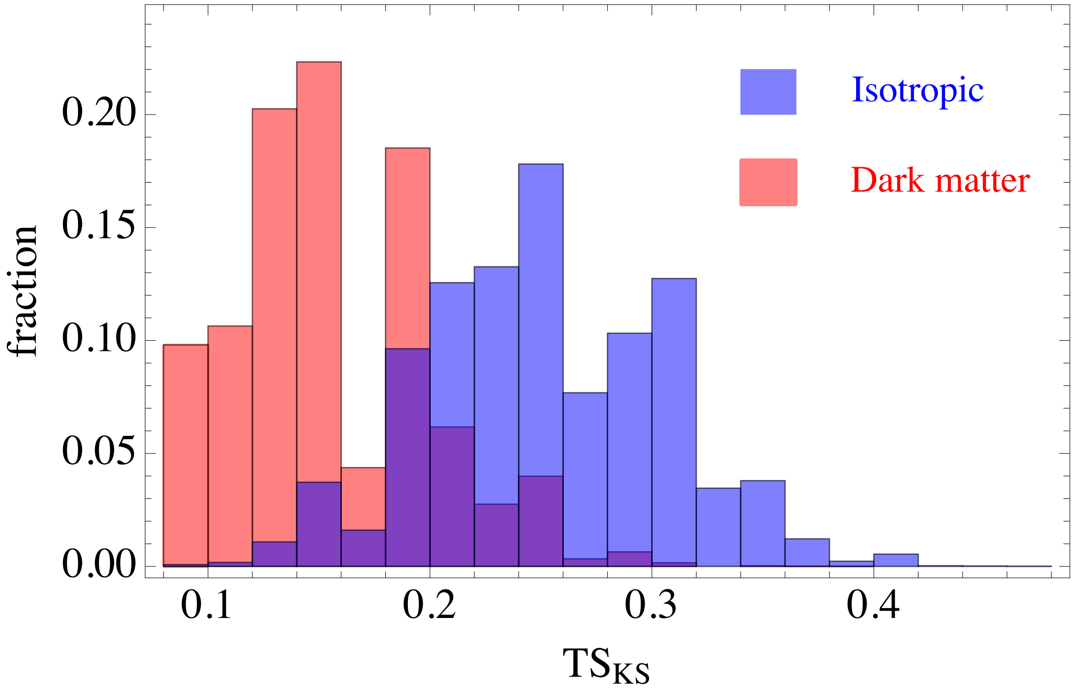
Test Statistics

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

Angular distribution of neutrinos from decaying DM

✓ Kolmogorov-Smirnov test:

statistically larger TS for isotropic distribution



Test Statistics

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

A. E., S. K. Kang and P. Serpico, JCAP (2014) [arXiv:1410.5979 [hep-ph]]

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

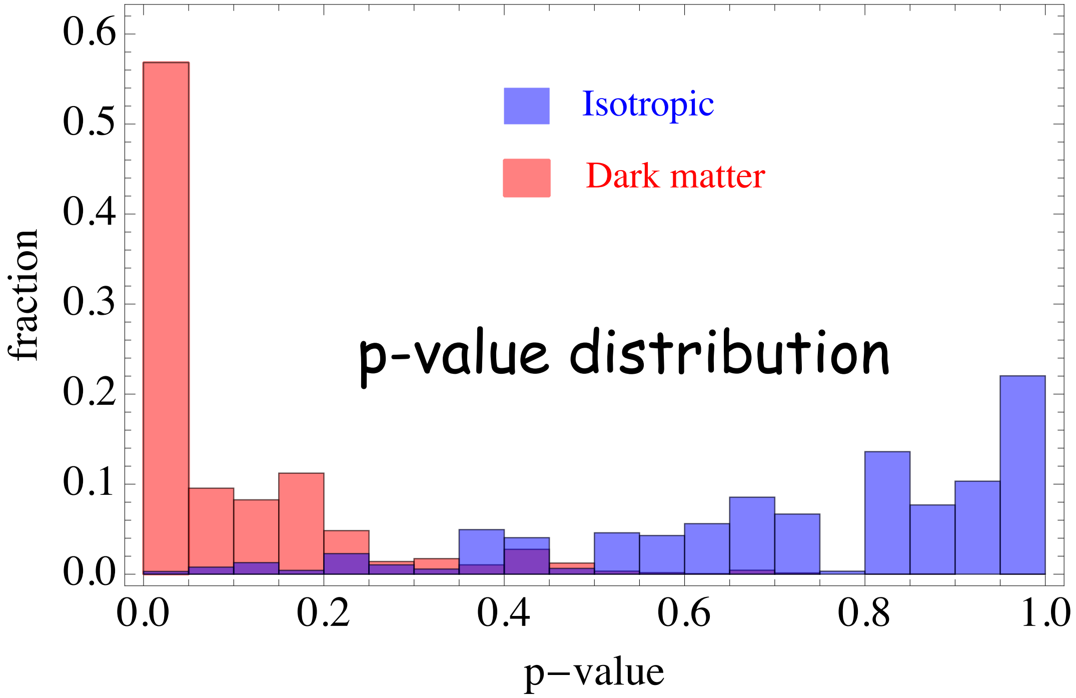
↓

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

for data vs isotropic dis. it is 73%

↓

less than 2σ preference for DM dis.



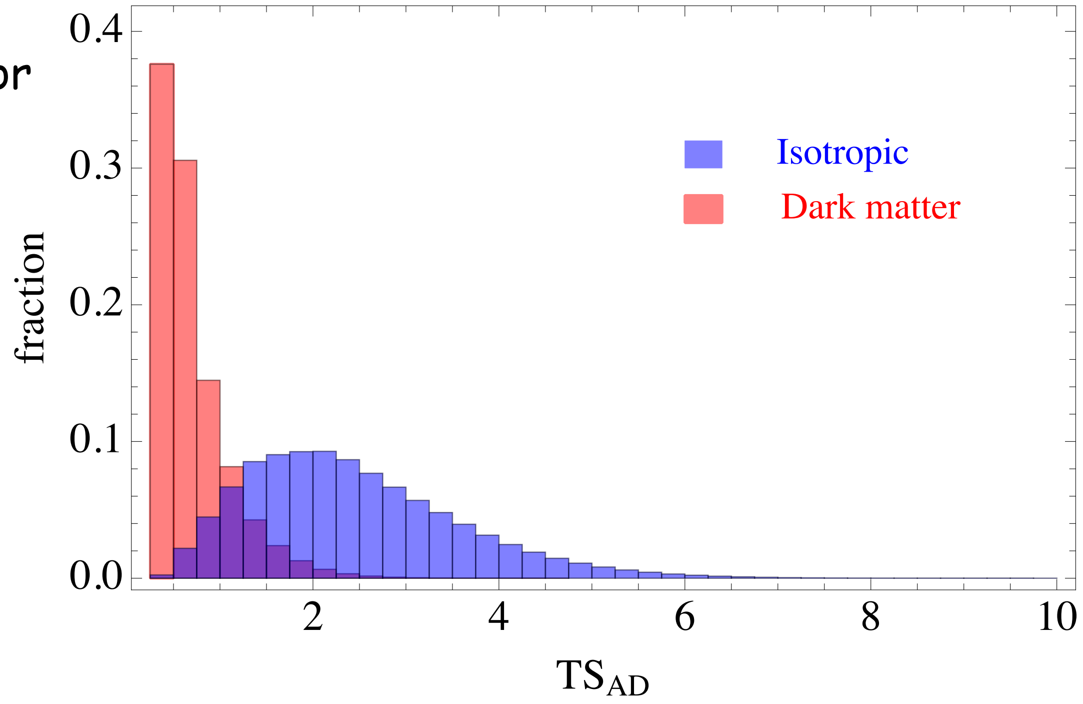
Angular distribution of neutrinos from decaying DM

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

Test Statistics

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

statistically larger TS for isotropic distribution

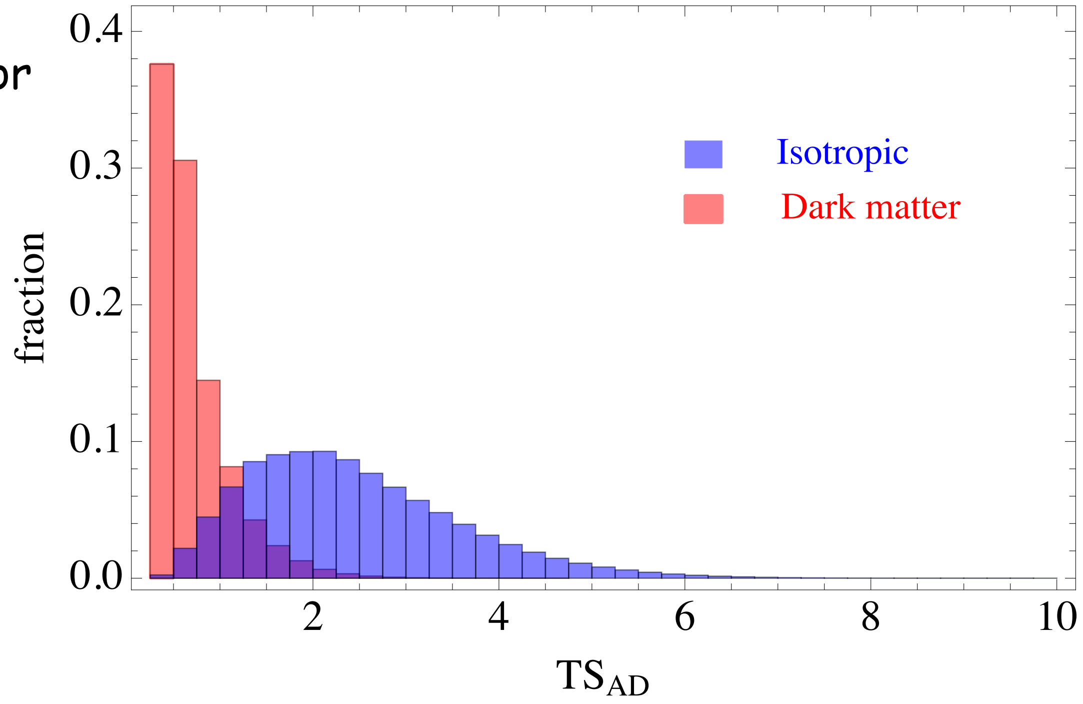


A. E., S. K. Kang and P. Serpico,
JCAP (2014) [arXiv:1410.5979 [hep-ph]]

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

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

A. E., S. K. Kang and P. Serpico, JCAP (2014) [arXiv:1410.5979 [hep-ph]]

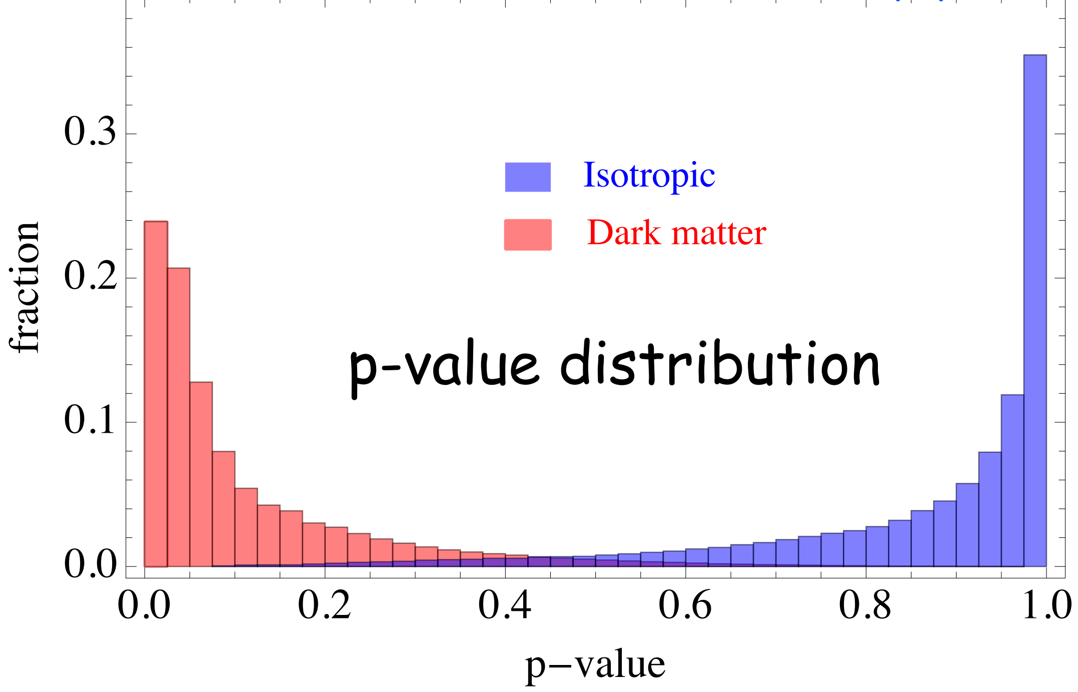
again, generating a sample (10^5) of isotropically distributed set of 20 events

↓

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.

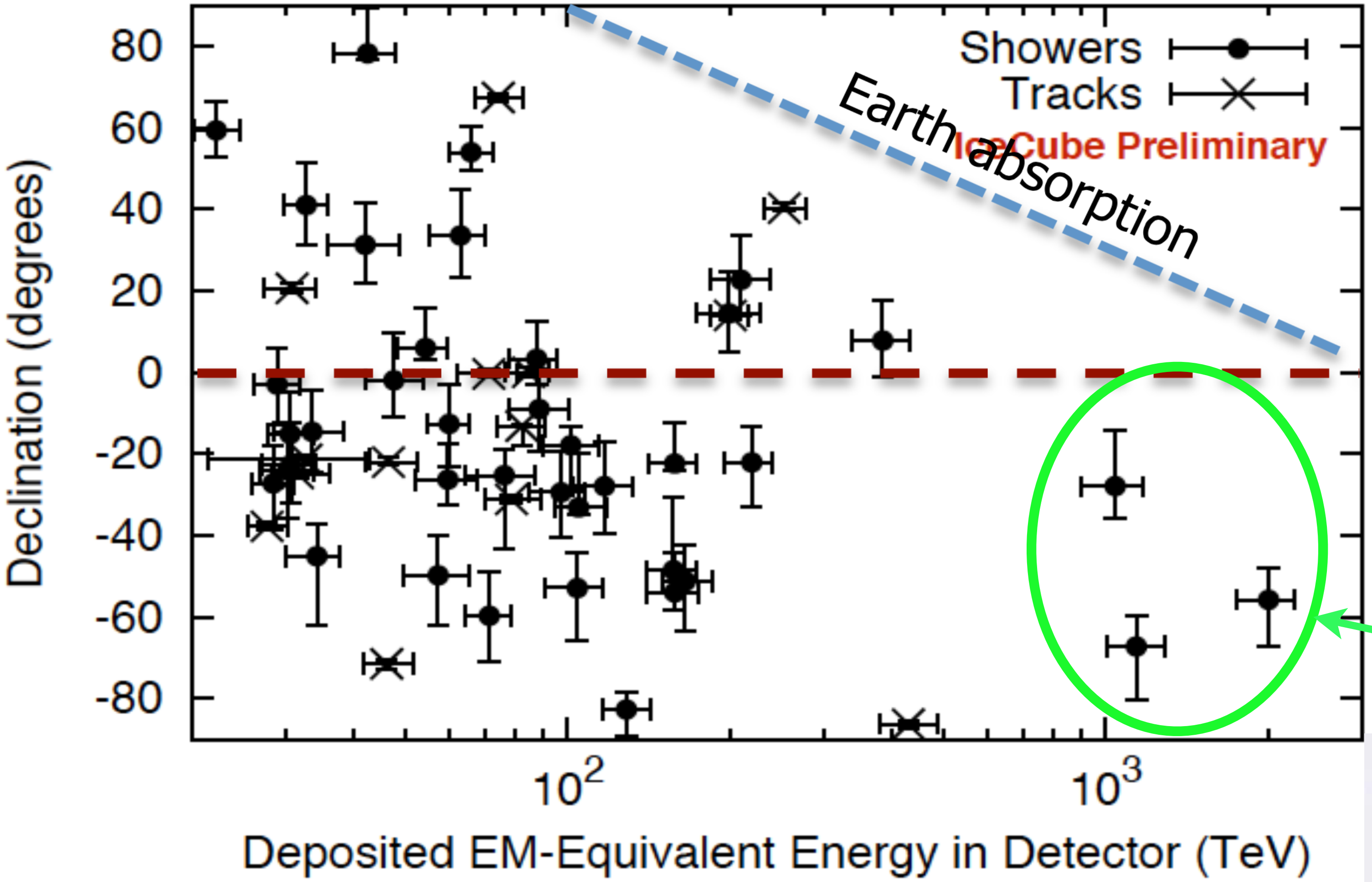


Observation of High Energy Neutrinos in IceCube

- ✓ Looking for lower energy contained events, 1347 days livetime

IPA 2015

The whole family!



- ✓ totally 54 events
- ✓ still three events with energy ~ PeV

$$\Phi \propto E^{-\gamma} : \gamma = 2.58 \pm 0.25$$

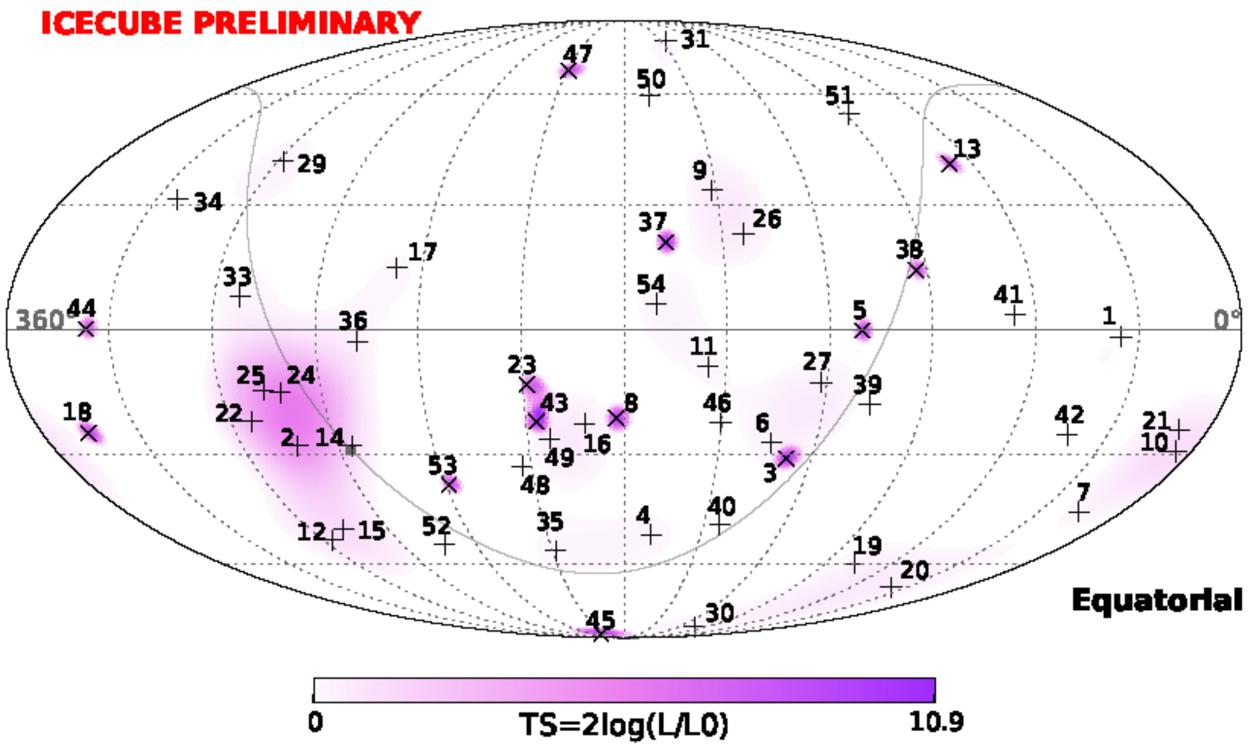
4 years of data

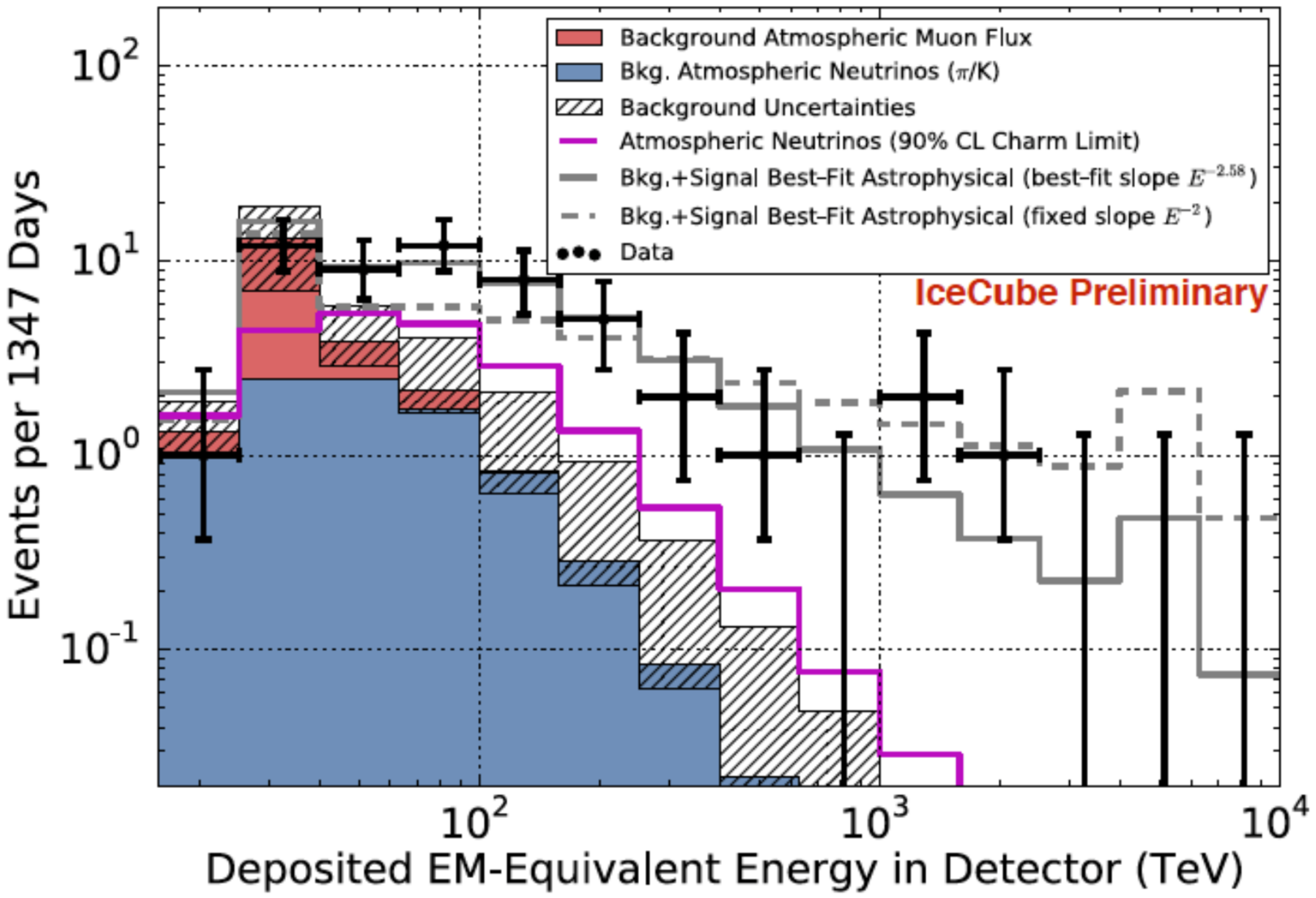
excess of events ~ 7σ

Source(s) not identified!

IceCube data

✓ Looking for lower energy contained events, 1347 days livetime





4 years of data

Confronting with energy distribution of IceCube data

4 years data set

✓ More refined analysis of the 4 years data set

$$\frac{d\Phi^c}{dE_\nu}(E_\nu;\tau_{\rm DM},m_{\rm DM},\phi_a,\gamma)=\frac{d\Phi^c_{\rm DM}}{dE_\nu}(E_\nu;\tau_{\rm DM},m_{\rm DM})+\frac{d\Phi_{\rm astro}}{dE_\nu}(E_\nu;\phi_a,\gamma)$$

single power-law
astro flux

$$\left.\frac{d\Phi_{{\rm astro},\nu_\alpha}}{dE_\nu}\right|_\oplus=\phi_a\left(\frac{E_\nu}{100\ {\rm TeV}}\right)^{-\gamma}$$

fitting parameters

$$\boldsymbol{\theta}=\{\tau_{\rm DM},m_{\rm DM},\phi_a,\gamma\}$$

Confronting with energy distribution of IceCube data

4 years data set

fitting parameters

✓ Likelihood analysis, taking into account the angular (up-going / down-going) and energy distribution simultaneously, tau regeneration, etc.

$$\mathcal{L}^c(\boldsymbol{\theta}) = \frac{e^{-N_{\rm DM}-N_{\rm astro}-N_\nu-N_\mu}}{N_{\rm obs}!}\prod_{i=1}^{N_{\rm obs}}\mathcal{L}_i^c(\boldsymbol{\theta})$$

$$\mathcal{L}_i^c(\boldsymbol{\theta}) = N_{\rm DM}\,\mathcal{P}^c_{{\rm DM},i}(m_{\rm DM}) + N_{\rm astro}\,\mathcal{P}_{{\rm astro},i}(\gamma) + N_\nu\,\mathcal{P}_{\nu,i} + N_\mu\,\mathcal{P}_{\mu,i}$$

Energy range [10TeV,10PeV] : $N_\nu = 9.0$ and $N_\mu = 12.6$

Energy range [60TeV,10PeV] : $N_\nu = 3.3$ and $N_\mu = 0.6$

Confronting with energy distribution of IceCube data

4 years data set

fitting parameters

✓ Likelihood analysis, taking into account the angular (up-going / down-going) and energy distribution simultaneously, tau regeneration, etc.

$$\mathcal{L}^c(\boldsymbol{\theta}) = \frac{e^{-N_{\rm DM}-N_{\rm astro}-N_\nu-N_\mu}}{N_{\rm obs}!}\prod_{i=1}^{N_{\rm obs}} \mathcal{L}_i^c(\boldsymbol{\theta})$$

$$\mathcal{L}_i^c(\boldsymbol{\theta}) = N_{\rm DM}\,\mathcal{P}^c_{{\rm DM},i}(m_{\rm DM}) + N_{\rm astro}\,\mathcal{P}_{{\rm astro},i}(\gamma) + N_\nu\,\mathcal{P}_{\nu,i} + N_\mu\,\mathcal{P}_{\mu,i}$$

$$\mathcal{P}^c_{{\rm DM},i}(m_{\rm DM}) = \frac{1}{\sum_{\ell,H',T'}\int_{E_{\rm min}}^{E_{\rm max}} dE_{\rm dep}\,\frac{d\left(N^c_{\rm DM}\right)^{T'}_{\ell,H'}}{dE_{\rm dep}}}\sum_{\ell}\frac{d\left(N^c_{\rm DM}\right)^{T_i}_{\ell,H_i}}{dE_{{\rm dep},i}}$$

$${\rm TS}^c_{\rm 2D}(\boldsymbol{\theta}_{\bf test}) = -2\,\ln\frac{\mathcal{L}^c(\boldsymbol{\theta}_{\rm test},\widehat{\boldsymbol{\nu}}(\boldsymbol{\theta}_{\bf test}))}{\mathcal{L}^c(\widehat{\boldsymbol{\theta}})}$$

Confronting with energy distribution of IceCube data

4 years data set

A. Bhattacharya, A. E., S. Palomares-Ruiz, I. Sarcevic, JCAP (2017) [arXiv:1706.05746]

Best-fit values of $\boldsymbol{\theta} = \{\tau_{\rm DM}, m_{\rm DM}, \phi_a, \gamma\}$

10^{-18} [$\rm GeV^{-1} cm^{-2} s^{-1} sr^{-1}$]

[10 TeV — 10 PeV]

Decay channel	$N_{\rm DM}(\tau_{\rm DM}[10^{28}\ {\rm s}])$	$m_{\rm DM}$ [TeV]	$N_{\rm astro}(\phi_{\rm astro})$	γ
$u\,\bar{u}$	14.6 (0.033)	521	22.2 (1.4)	2.48
$b\,\bar{b}$	21.2 (0.082)	1040	14.7 (0.73)	2.29
$t\,\bar{t}$	18.1 (0.59)	11167	18.4 (1.6)	3.64
$W^+\,W^-$	11.9 (1.5)	4864	24.7 (2.2)	3.43
$Z\,Z$	11.1 (1.6)	4811	25.5 (2.3)	3.40
$h\,h$	18.5 (0.86)	8729	18.1 (1.5)	3.69
$e^+\,e^-$	4.6 (1.3)	4131	31.9 (2.8)	3.20
$\mu^+\,\mu^-$	5.8 (5.5)	6513	30.9 (2.7)	3.26
$\tau^+\,\tau^-$	7.1 (4.8)	6836	29.6 (2.6)	3.30
$\nu_e\,\bar{\nu}_e$	3.6 (2.7)	4048	32.6 (2.8)	3.16
$\nu_\mu\,\bar{\nu}_\mu$	6.0 (2.6)	4151	30.8 (2.7)	3.27
$\nu_\tau\,\bar{\nu}_\tau$	6.4 (2.4)	4132	30.3 (2.7)	3.29

Confronting with energy distribution of IceCube data

4 years data set

A. Bhattacharya, A. E., S. Palomares-Ruiz, I. Sarcevic, JCAP (2017) [arXiv:1706.05746]

Best-fit values of $\boldsymbol{\theta} = \{\tau_{\rm DM}, m_{\rm DM}, \phi_a, \gamma\}$

10^{-18} [$\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$]

[60 TeV — 10 PeV]

Decay channel	$N_{\rm DM}(\tau_{\rm DM}[10^{28}\ {\rm s}])$	$m_{\rm DM}$ [TeV]	$N_{\rm astro}(\phi_{\rm astro})$	γ
$u\,\bar{u}$	10.2 (0.021)	522	16.6 (1.2)	2.42
$b\,\bar{b}$	12.9 (0.089)	1066	13.8 (0.83)	2.32
$t\,\bar{t}$	16.1 (0.58)	11134	10.7 (1.9)	3.91
$W^+\,W^-$	11.3 (1.4)	4860	15.5 (2.5)	3.66
$Z\,Z$	10.5 (1.6)	4800	16.3 (2.6)	3.61
$h\,h$	13.6 (0.17)	606	13.2 (0.76)	2.29
$e^+\,e^-$	5.0 (1.2)	4116	21.9 (3.2)	3.33
$\mu^+\,\mu^-$	6.3 (5.0)	6437	20.7 (3.2)	3.46
$\tau^+\,\tau^-$	7.6 (4.4)	6749	19.3 (3.0)	3.53
$\nu_e\,\bar{\nu}_e$	3.7 (2.6)	4041	22.7 (3.2)	3.24
$\nu_\mu\,\bar{\nu}_\mu$	6.4 (2.4)	4133	20.6 (3.2)	3.48
$\nu_\tau\,\bar{\nu}_\tau$	6.7 (2.3)	4117	20.1 (3.1)	3.50

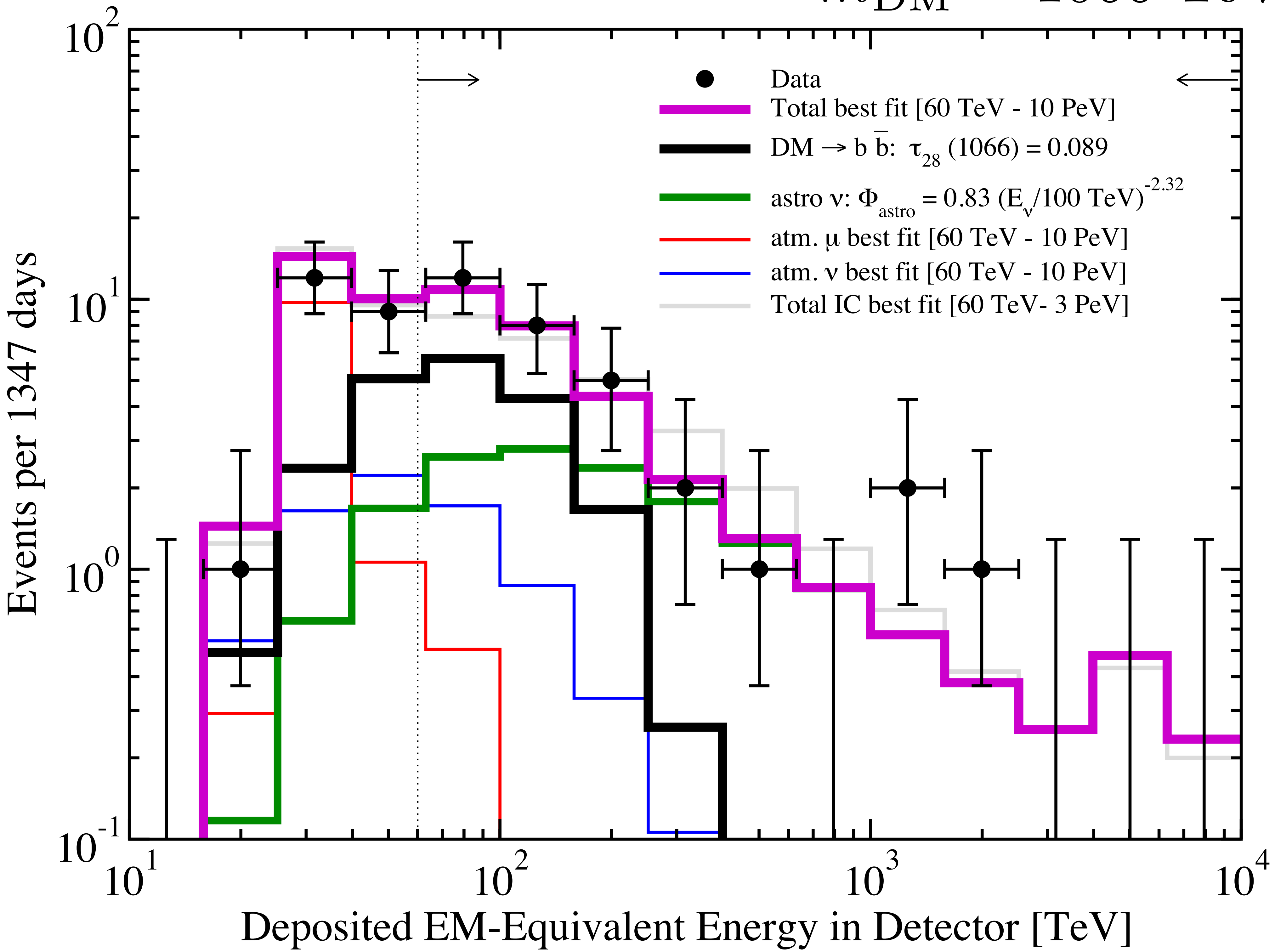
Confronting with energy distribution of IceCube data

Event rate:

$$\mathrm{DM} \to b\bar{b}$$

4 years data set

$m_{\mathrm{DM}} = 1066$ TeV



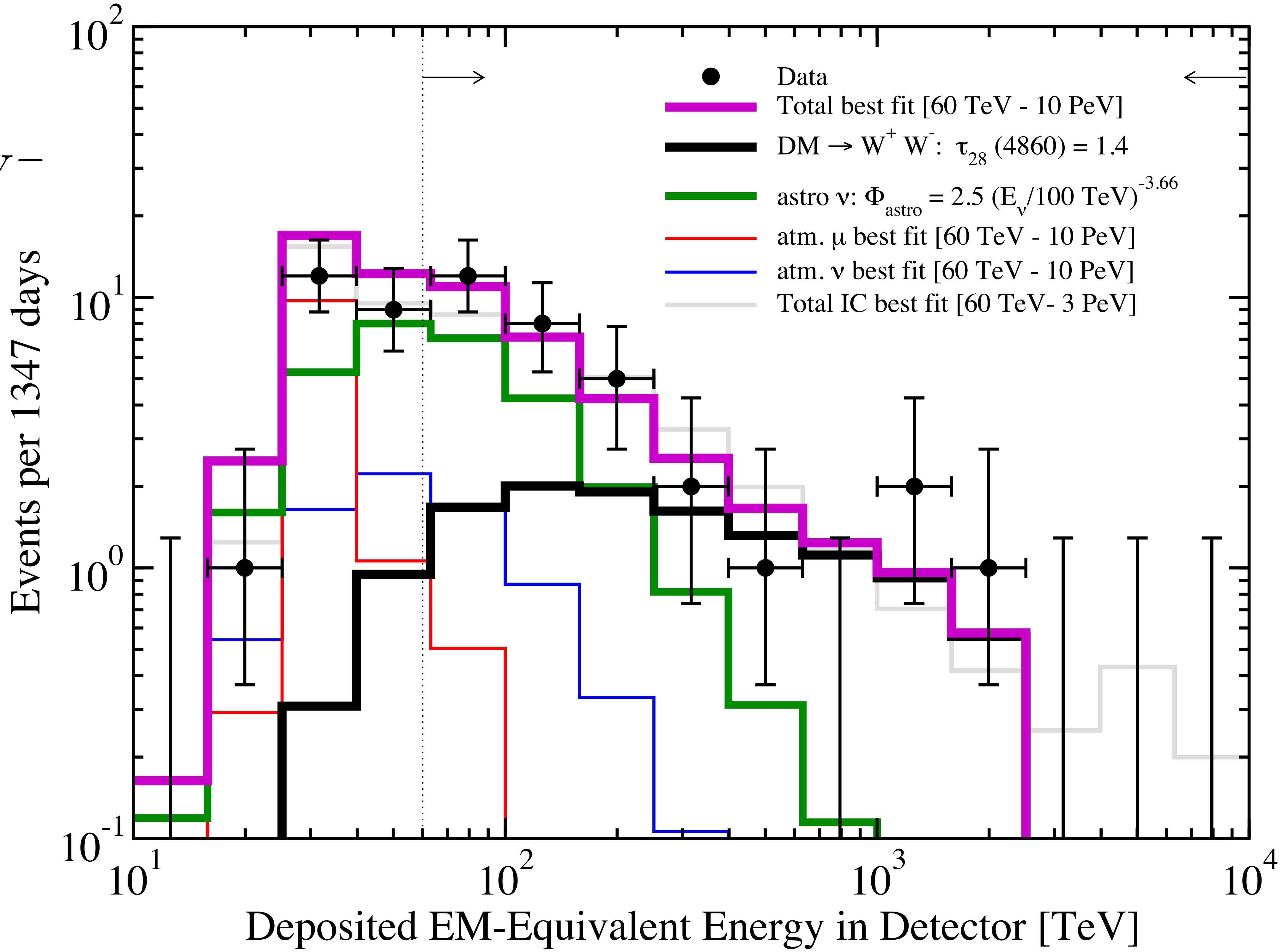
Confronting with energy distribution of IceCube data

4 years data set

$m_{\rm DM} = 4860$ TeV

Event rate:

$\mathrm{DM} \to W^+W^-$



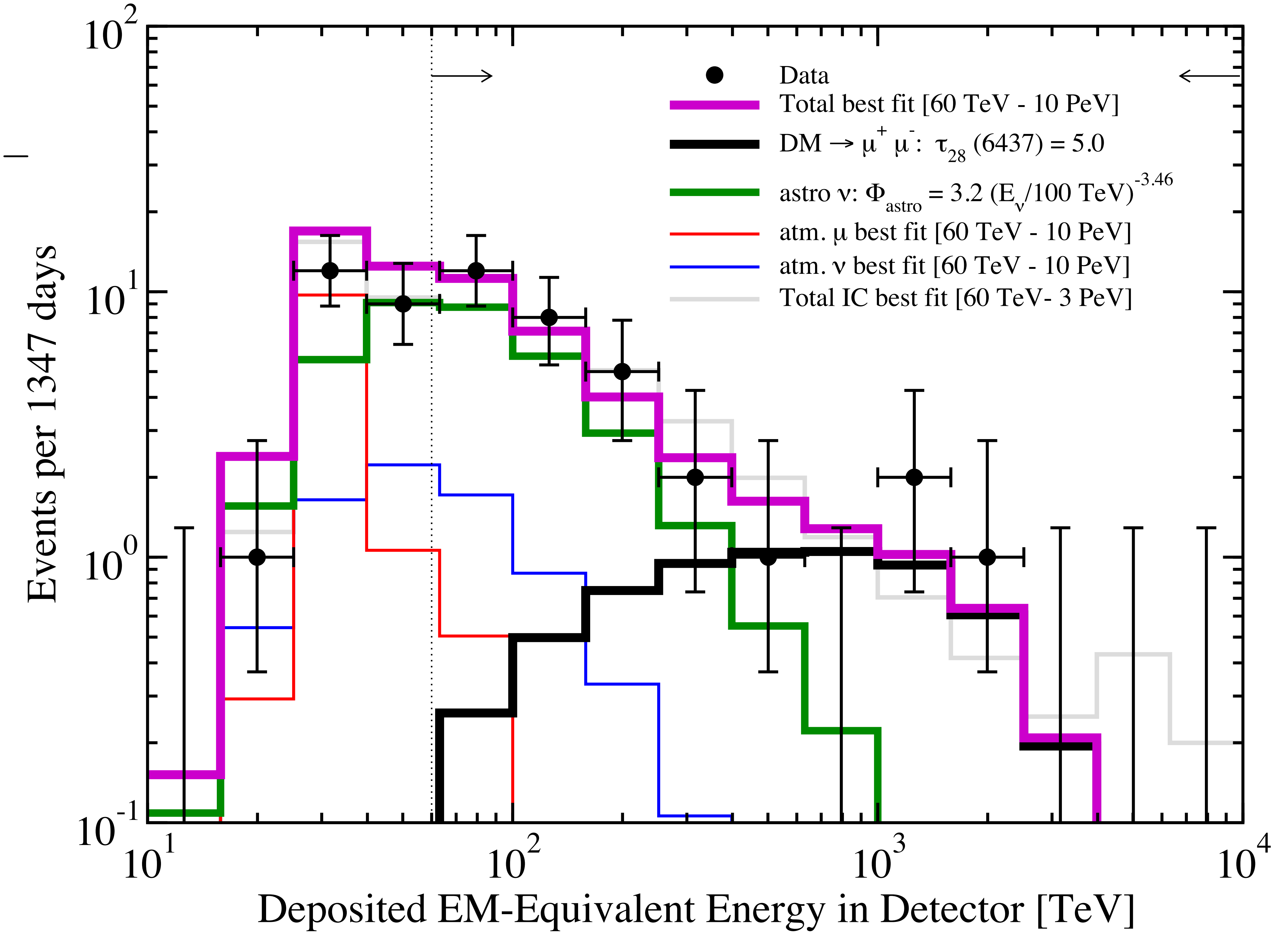
Confronting with energy distribution of IceCube data

4 years data set

$m_{\rm DM} = 6437$ TeV

Event rate:

$\rm DM \to \mu^+ \mu^-$



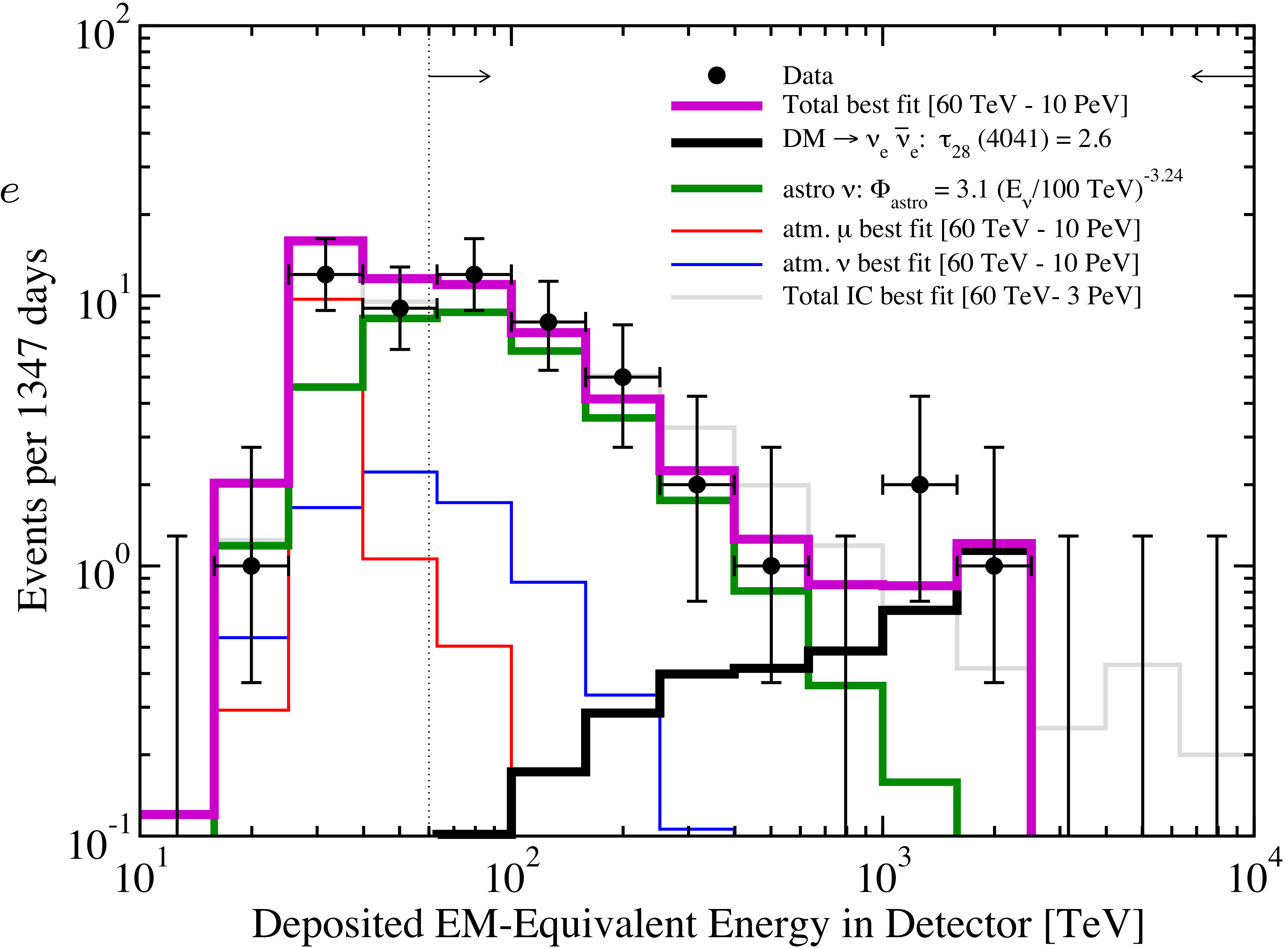
Confronting with energy distribution of IceCube data

4 years data set

$m_{\rm DM} = 4041$ TeV

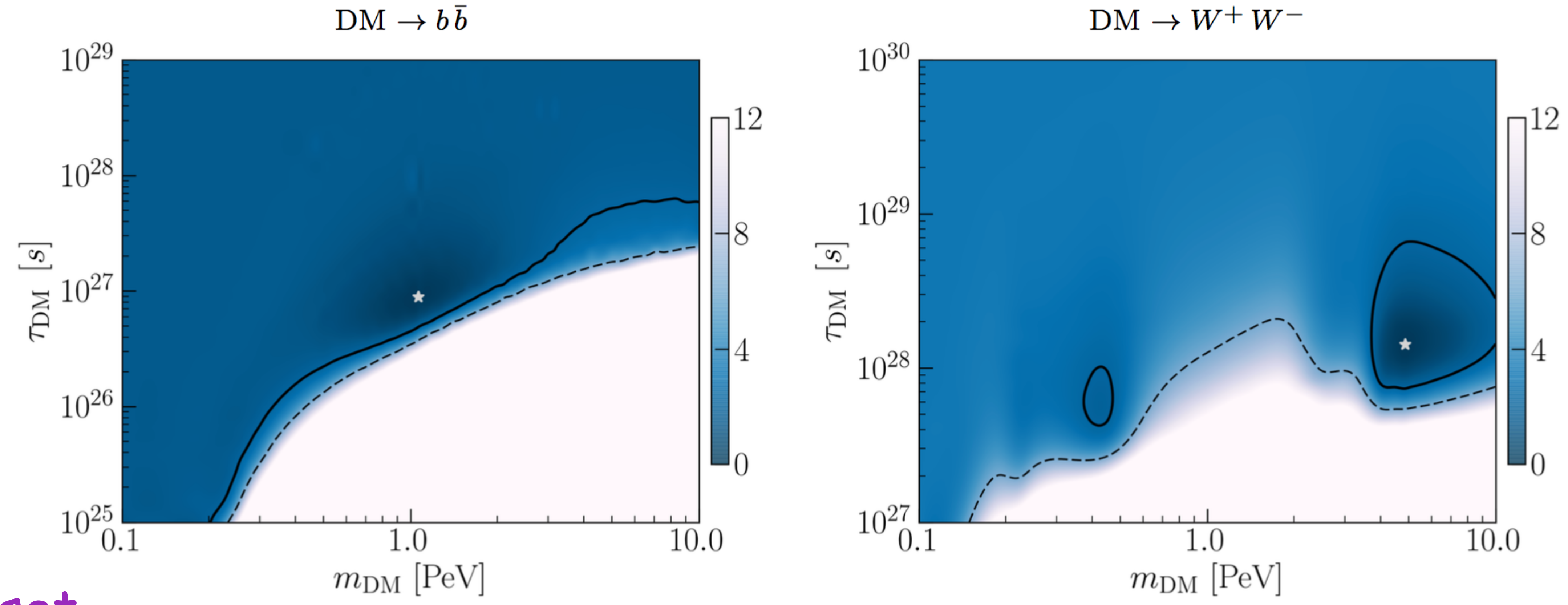
Event rate:

$\mathrm{DM} \rightarrow \nu_e \bar{\nu}_e$

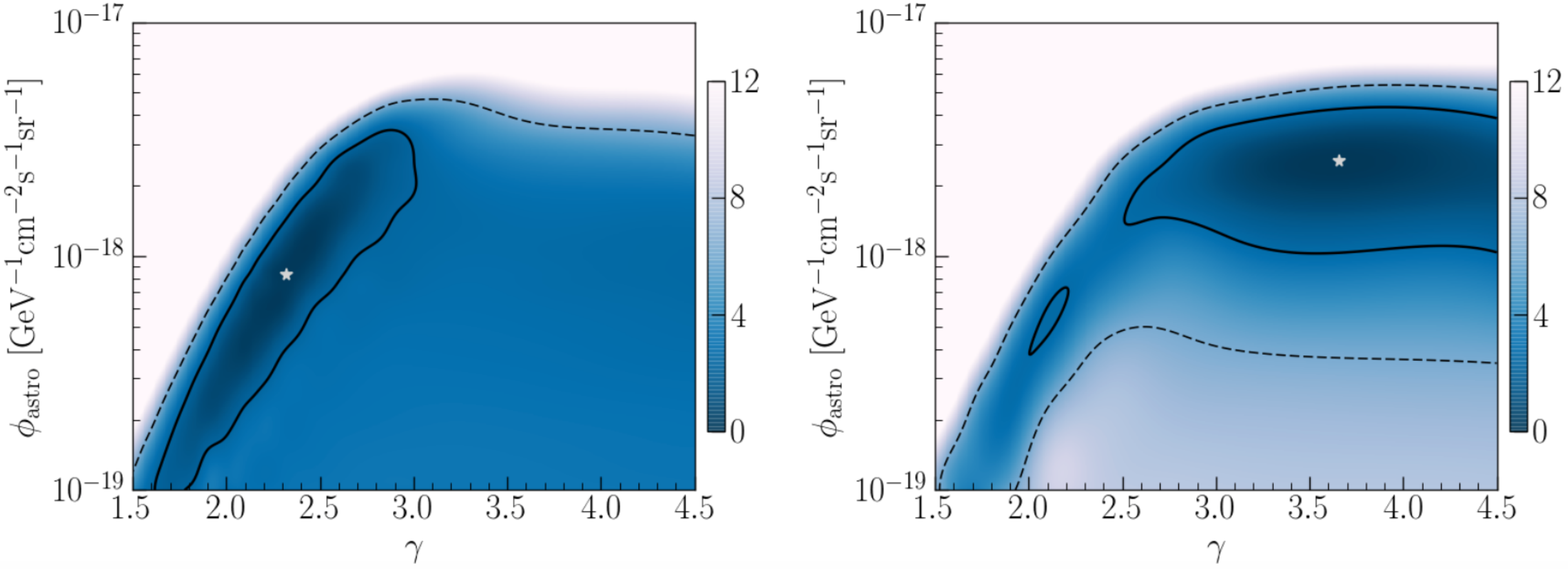


Confronting with energy distribution of IceCube data

preferred regions:

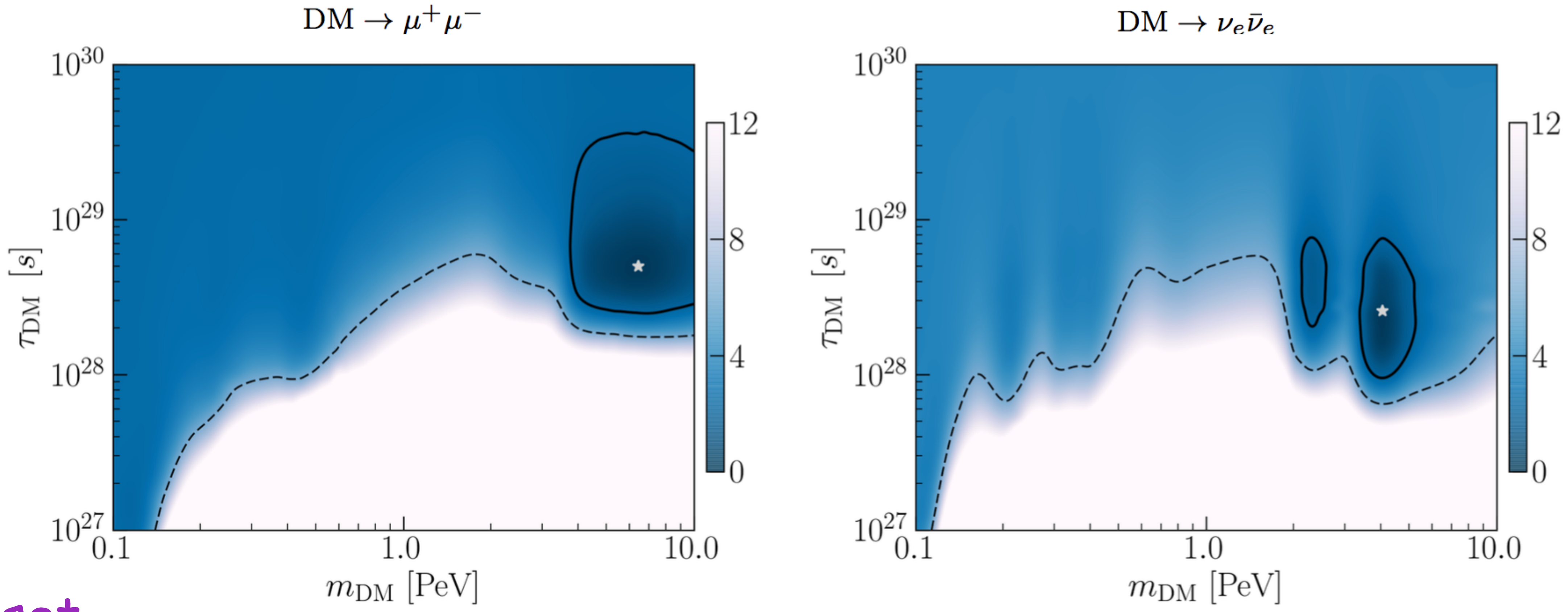


4 years data set

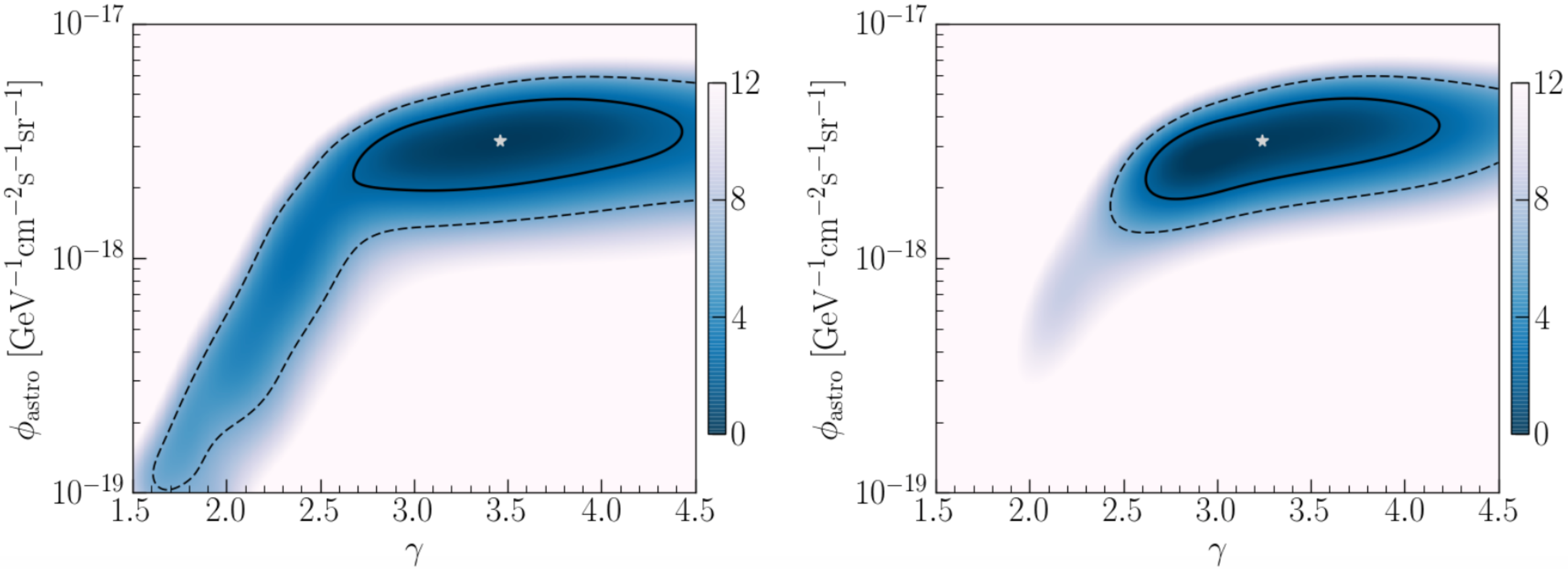


Confronting with energy distribution of IceCube data

preferred regions:



4 years data set



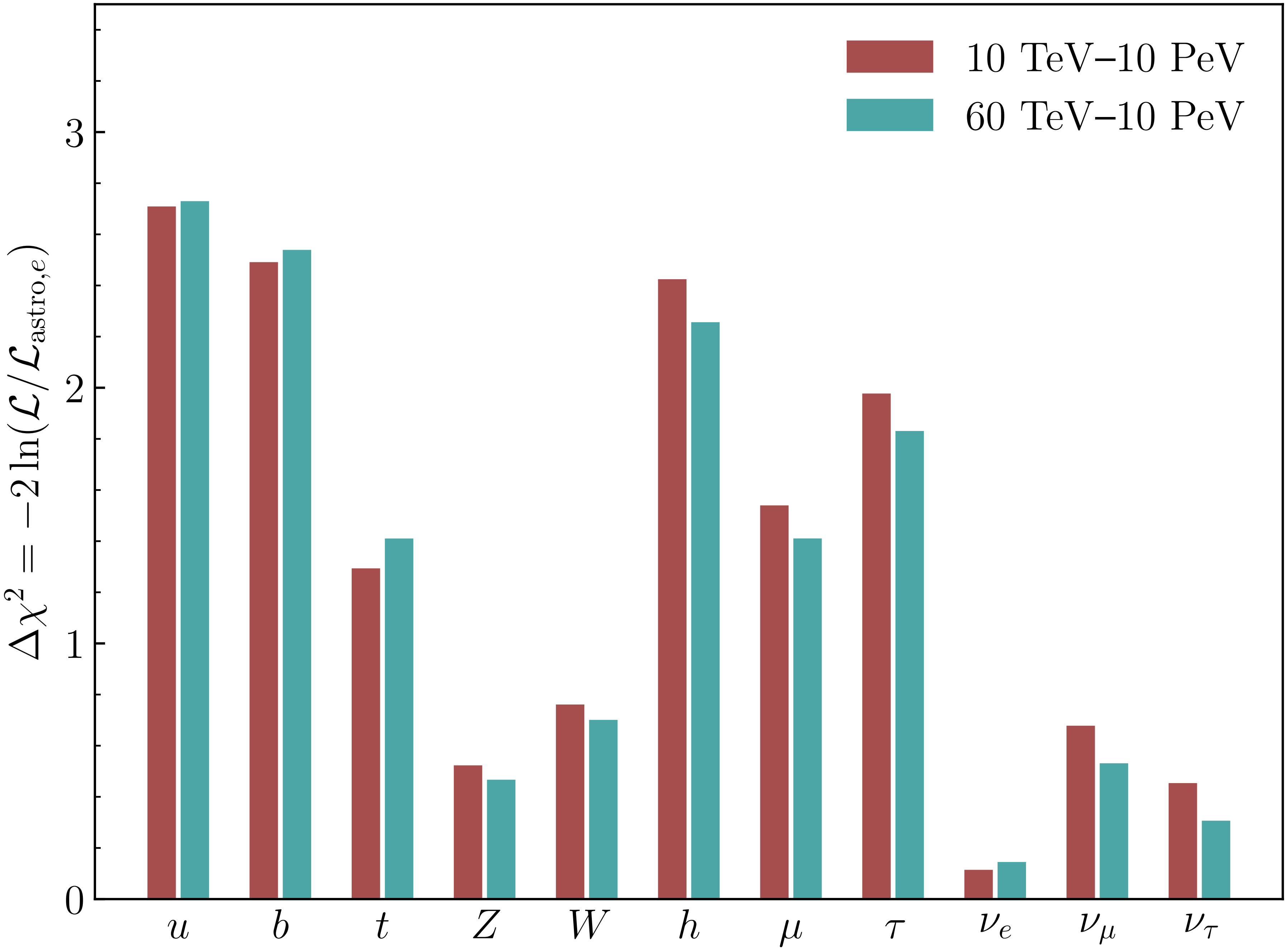
Confronting with energy distribution of IceCube data

4 years data set

All the channels: the case of astro + DM (one channel decay)

with respect to

$$\mathrm{DM} \rightarrow e^{-}e^{+}$$

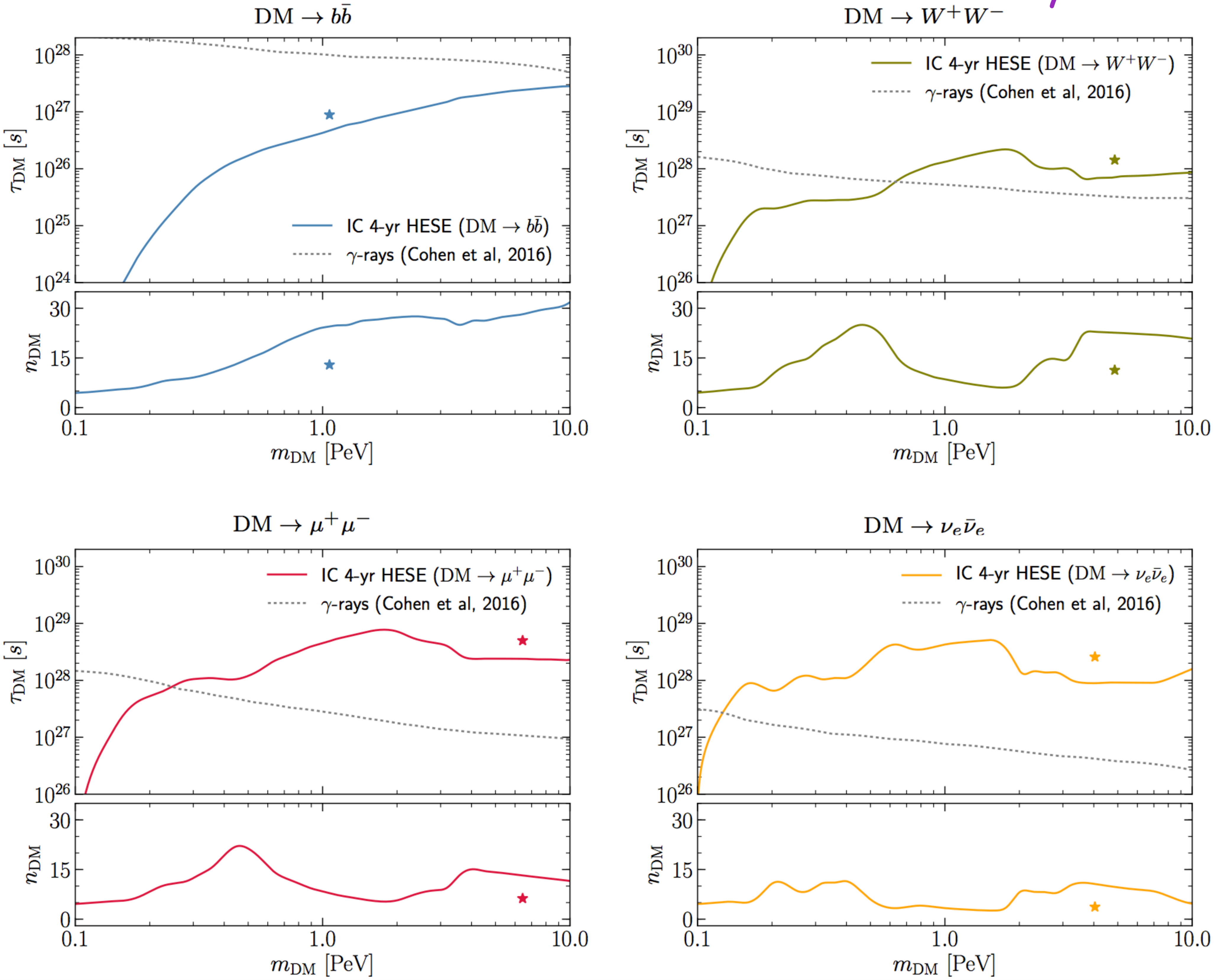


limits on DM from IceCube data

T. Cohen, K. Murase, N. L. Rodd, B. R. Safdi and Y. Soreq,

arXiv:1612.05638

4 years data set



Confronting with energy distribution of IceCube data

Multiple channel DM decay:

4 years data set

$$\boldsymbol{\theta}_{2c} = \{N_{\rm DM}, m_{\rm DM}, {\rm BR}\}$$

Decay channels	$N_{\rm DM}$ ($\tau_{\rm DM}$ [10^{28} s])	$m_{\rm DM}$ [TeV]	BR
$u\,\bar{u}$, $e^+\,e^-$	26.6 (0.22)	3991	0.84
$u\,\bar{u}$, $\nu_e\,\bar{\nu}_e$	26.7 (0.19)	3902	0.92
$b\,\bar{b}$, $e^+\,e^-$	26.5 (0.22)	4042	0.84
$b\,\bar{b}$, $\mu^+\,\mu^-$	26.4 (0.25)	5444	0.94
$b\,\bar{b}$, $\nu_e\,\bar{\nu}_e$	26.6 (0.19)	3933	0.92
$b\,\bar{b}$, $\nu_\mu\,\bar{\nu}_\mu$	26.6 (0.20)	4023	0.93
$b\,\bar{b}$, $\tau^+\,\tau^-$	26.5 (0.25)	5539	0.94
$t\,\bar{t}$, $\nu_\mu\,\bar{\nu}_\mu$	26.1 (0.32)	8866	1.00
$W^+\,W^-$, $\mu^+\,\mu^-$	25.3 (0.22)	4633	1.00
$W^+\,W^-$, $\nu_\mu\,\bar{\nu}_\mu$	25.3 (0.22)	4633	1.00
$h\,h$, $\mu^+\,\mu^-$	26.3 (0.28)	7031	1.00
$h\,h$, $\nu_e\,\bar{\nu}_e$	26.3 (0.20)	4103	0.92

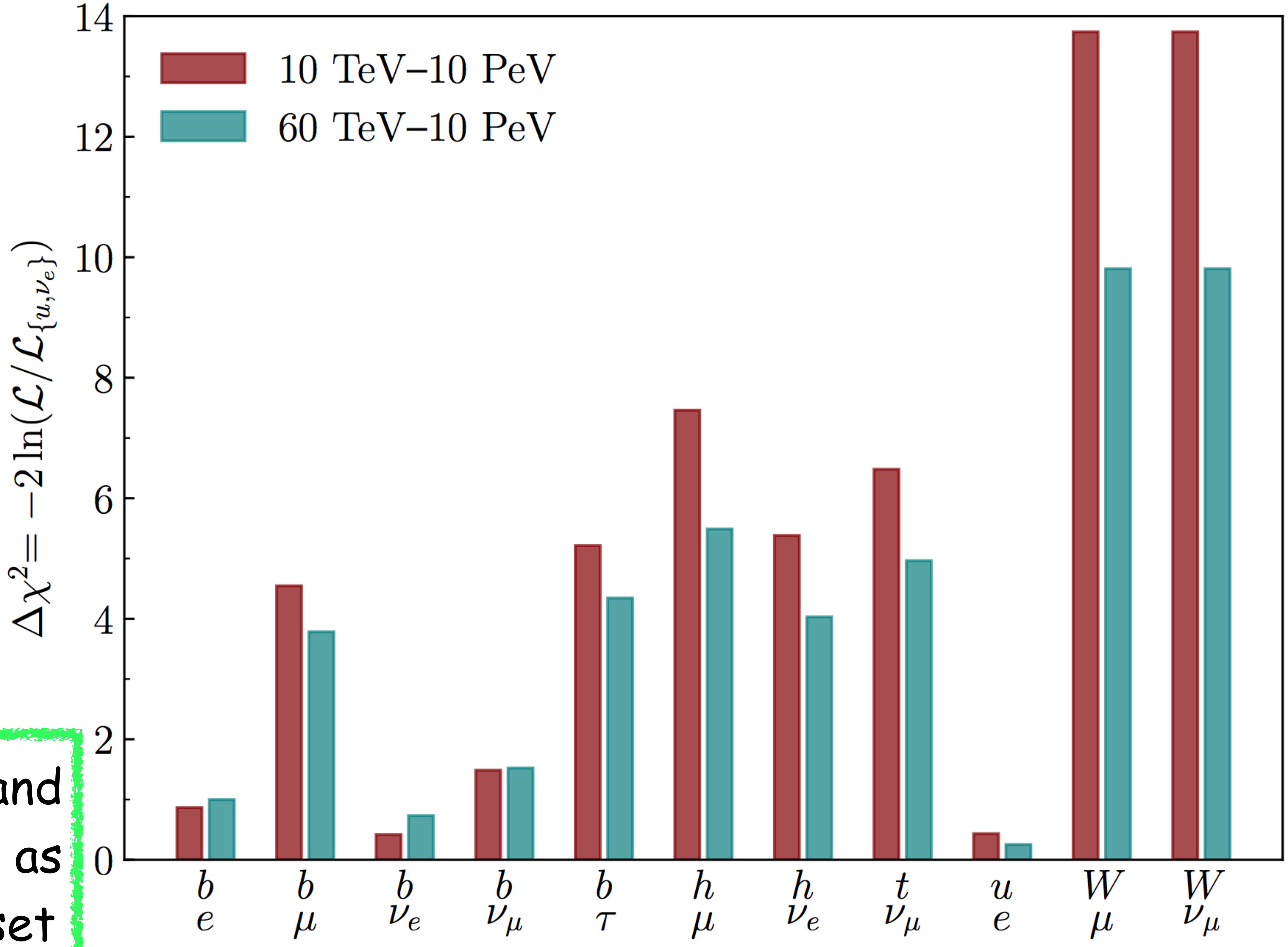
Confronting with energy distribution of IceCube data

4 years data set

Multiple channel DM decay:

with respect to

$$\mathrm{DM} \to \{u\bar{u}, \nu_e\bar{\nu}_e\}$$



The best-fit channel and DM-mass is the same as IceCube 2-years dataset

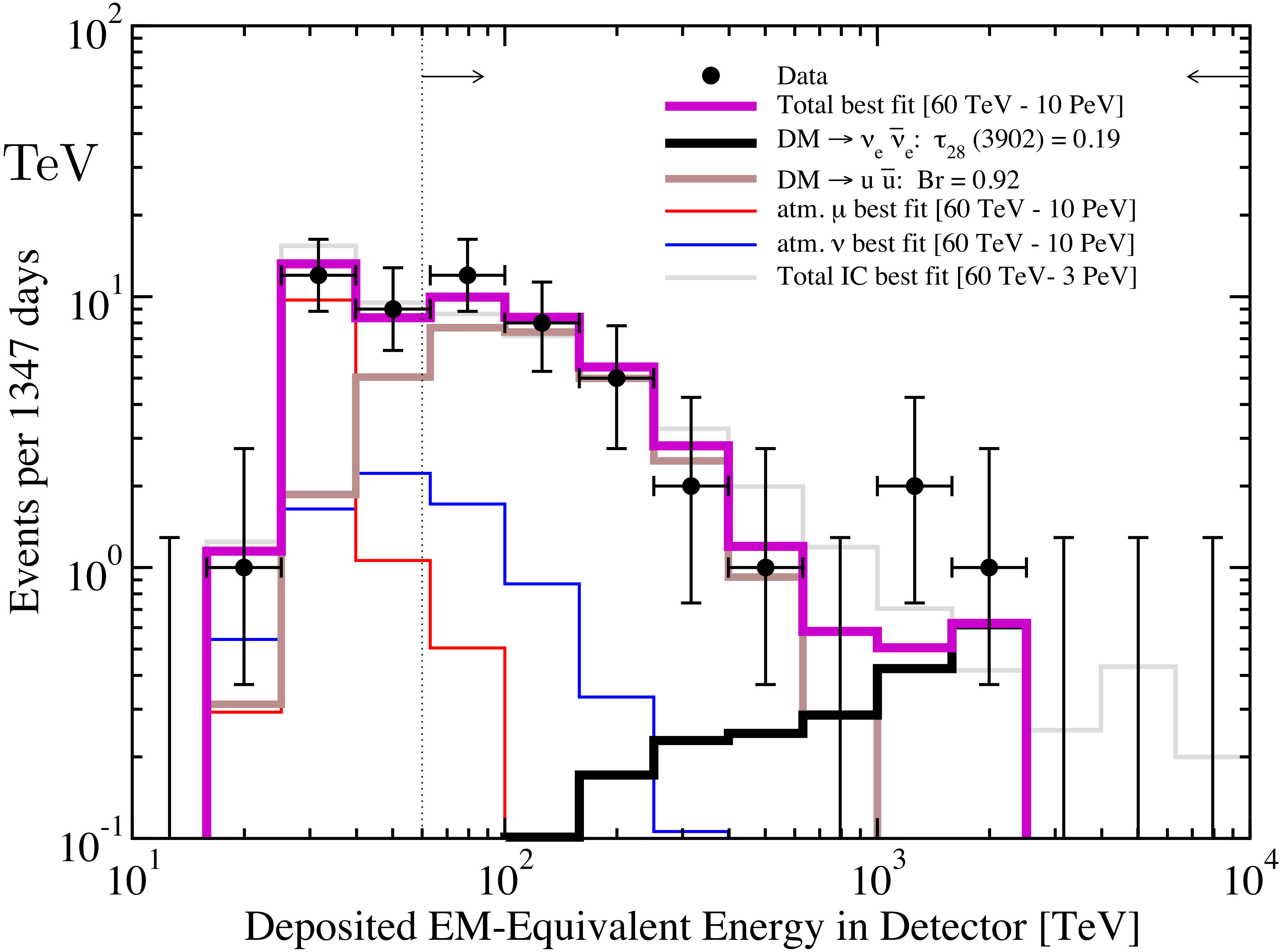
Confronting with energy distribution of IceCube data

4 years data set

$$\mathrm{DM} \to \{92\%\ u\bar{u}, 8\%\ \nu_e\bar{\nu}_e\}$$

Event rate:

$$m_{\mathrm{DM}} = 3902\ \mathrm{TeV}$$



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

Gamma ray bounds

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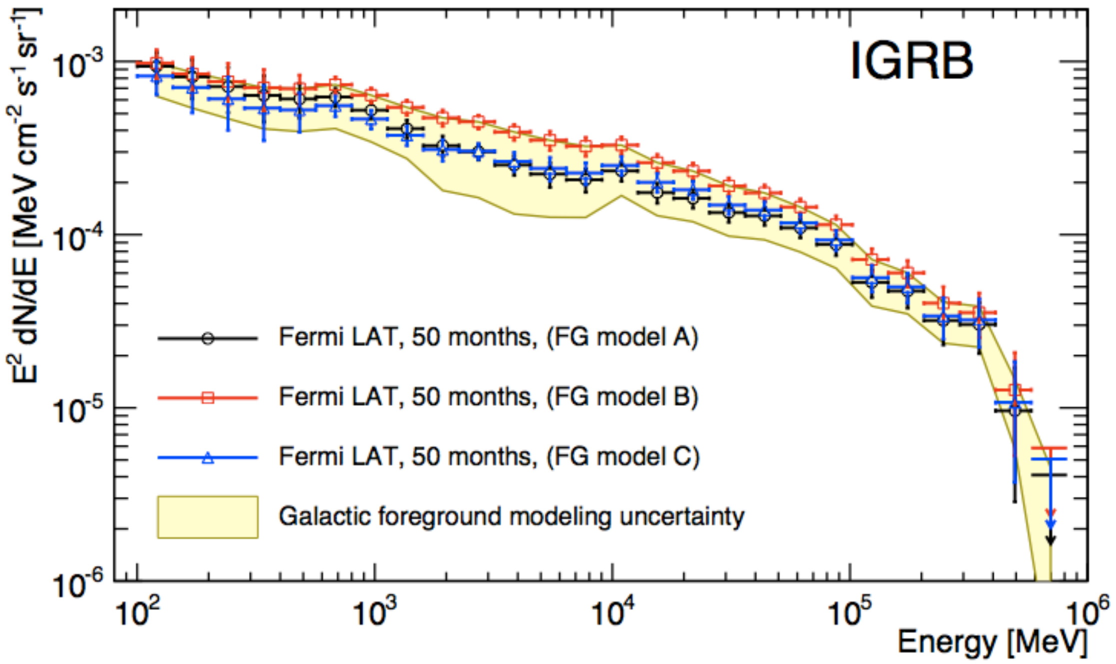
✓ Isotropic diffuse gamma-ray background by Fermi-LAT

integrated energy density

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

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

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



total electromagnetic energy budget (NH case)

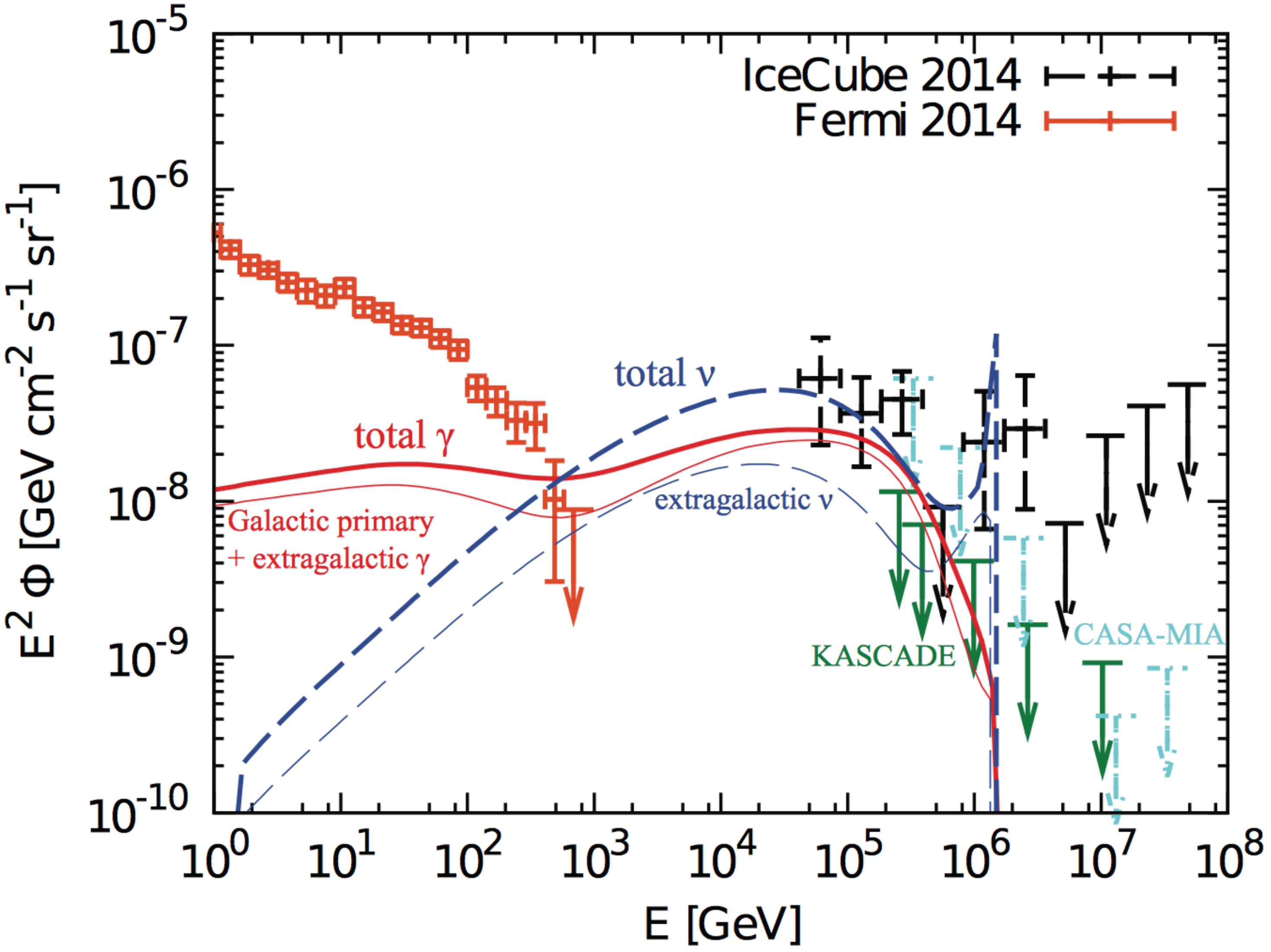
$$\frac{4\pi}{c}\int \sum_{\mathrm{i=gal,extragal}} \left[E_\gamma \, \frac{\mathrm{d}\varphi_\gamma}{\mathrm{d}E_\gamma}\Big)^{\mathrm{i}} + E_e \, \frac{\mathrm{d}\varphi_{e^\pm}}{\mathrm{d}E_e}\Big)^{\mathrm{i}} \right] \mathrm{d}E \simeq 5.2 \times 10^{-8} \, \mathrm{eV/cm}^3$$

✓

Gamma ray bounds

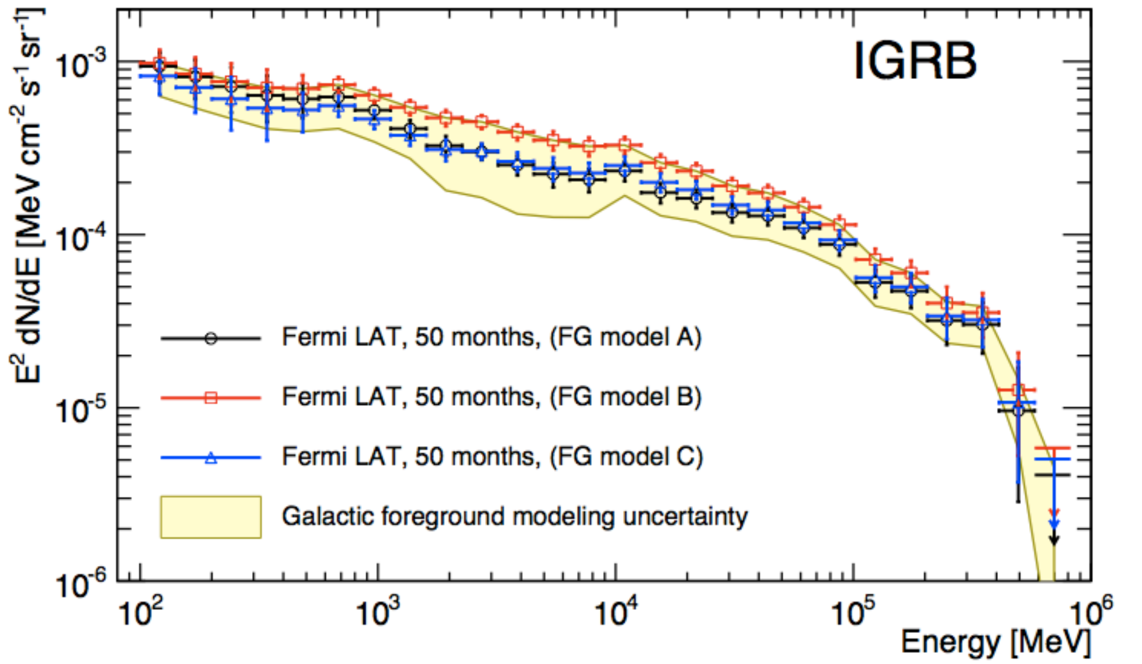
Universe is opaque for gamma-rays with E > 1 TeV → cascades develop: gamma-ray interaction with interstellar radiation field and CMB → gamma-rays populate at lower energies < $10^{(2-3)}$ GeV

✓ Isotropic diffuse gamma-ray background by Fermi-LAT



Murase, Laha, Ando, Ahlers, arXiv:1503.04663

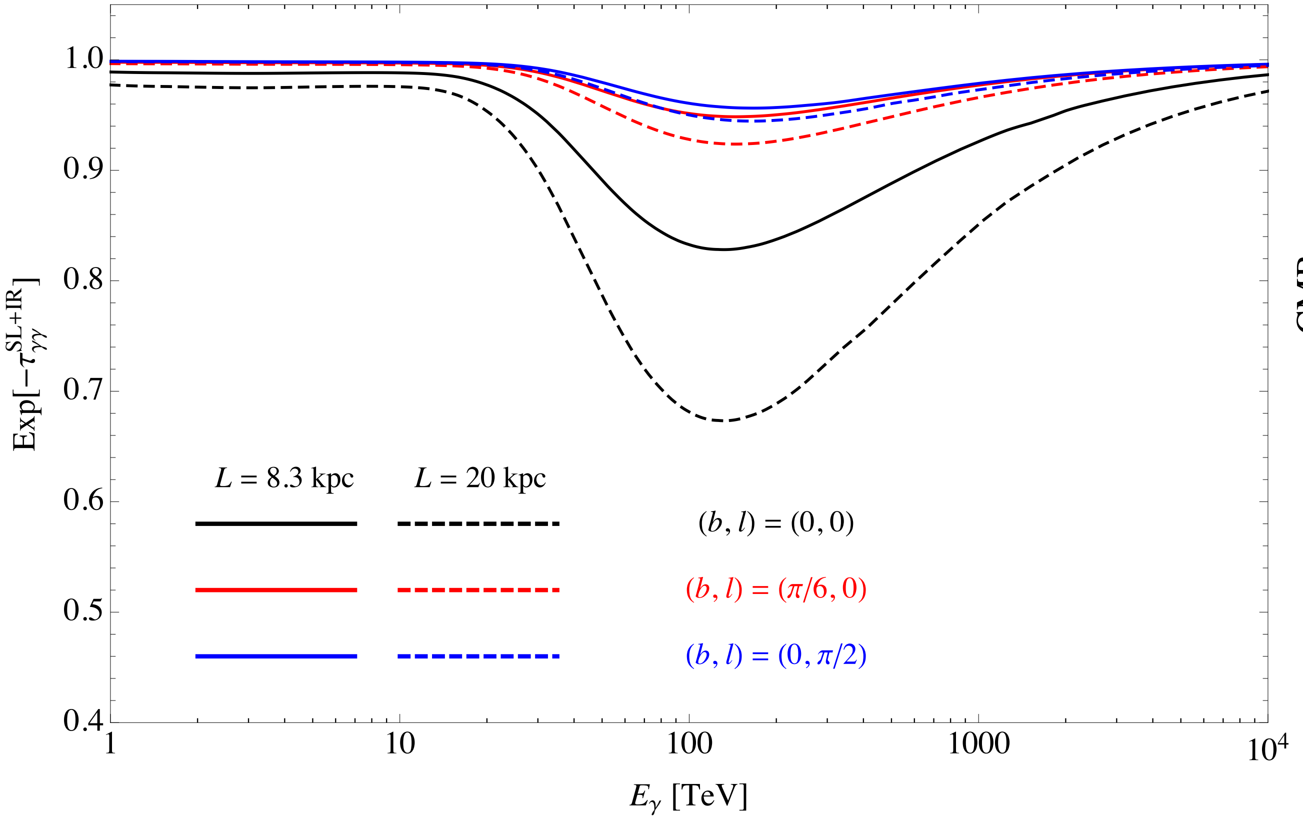
M. Ackermann et al. [The Fermi LAT Collaboration], arXiv:1410.3696 [astro-ph.HE].



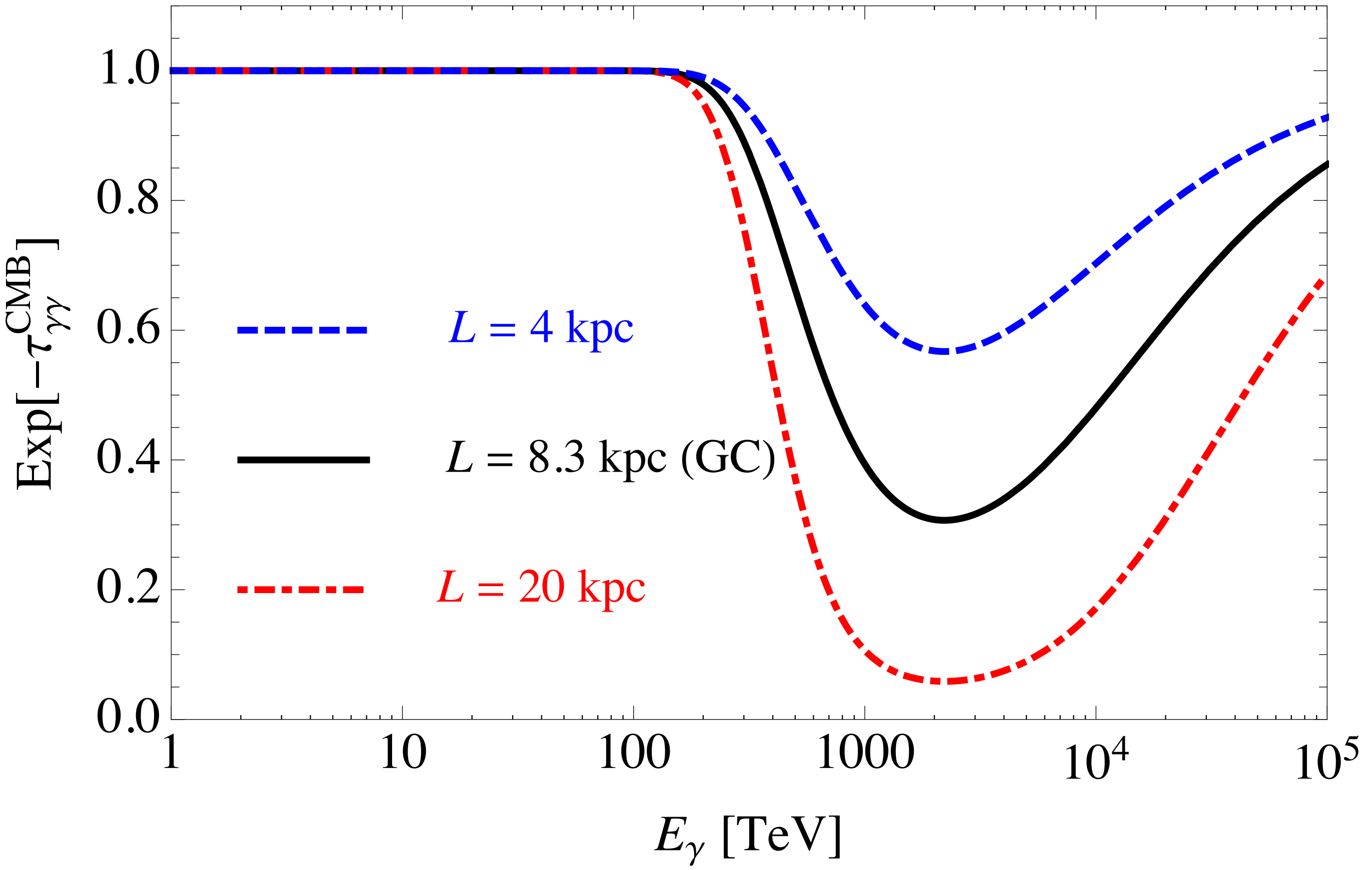
Gamma ray bounds

✓ Galactic component

at ~ PeV, the absorption length of gamma-rays
are comparable to Galactic distances



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



Absorption at ~ 100 TeV

Absorption due to pair production
on SL+IR photons

Absorption at ~ PeV

Absorption due to pair production
on CMB photons

Gamma ray bounds

✓ Galactic component

at ~ PeV, the absorption length of gamma-rays
are comparable to Galactic distances

Prompt component

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

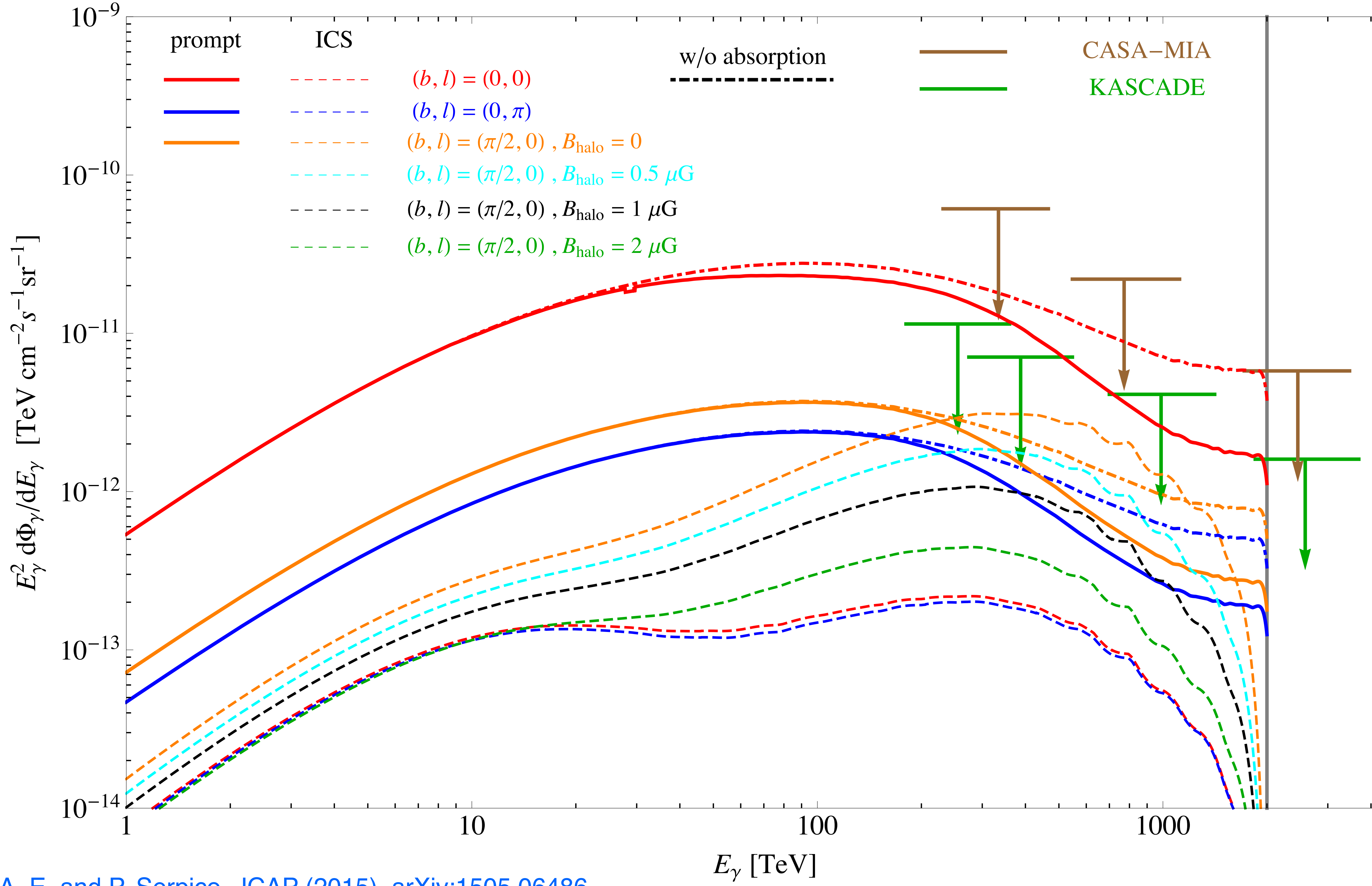
inverse-Compton component

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

Gamma ray bounds

✓ Galactic component

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

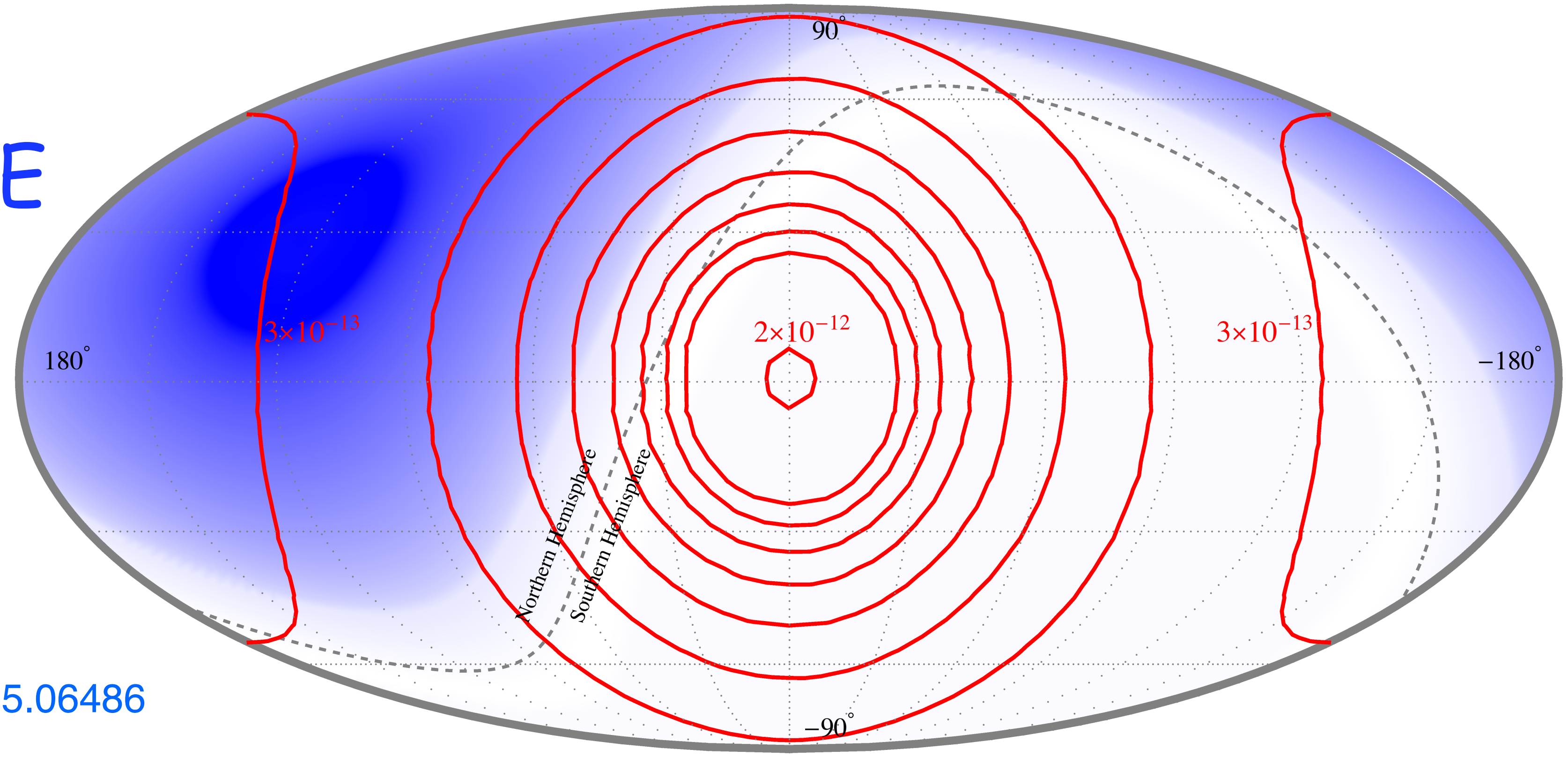


A. E. and P. Serpico, JCAP (2015), arXiv:1505.06486

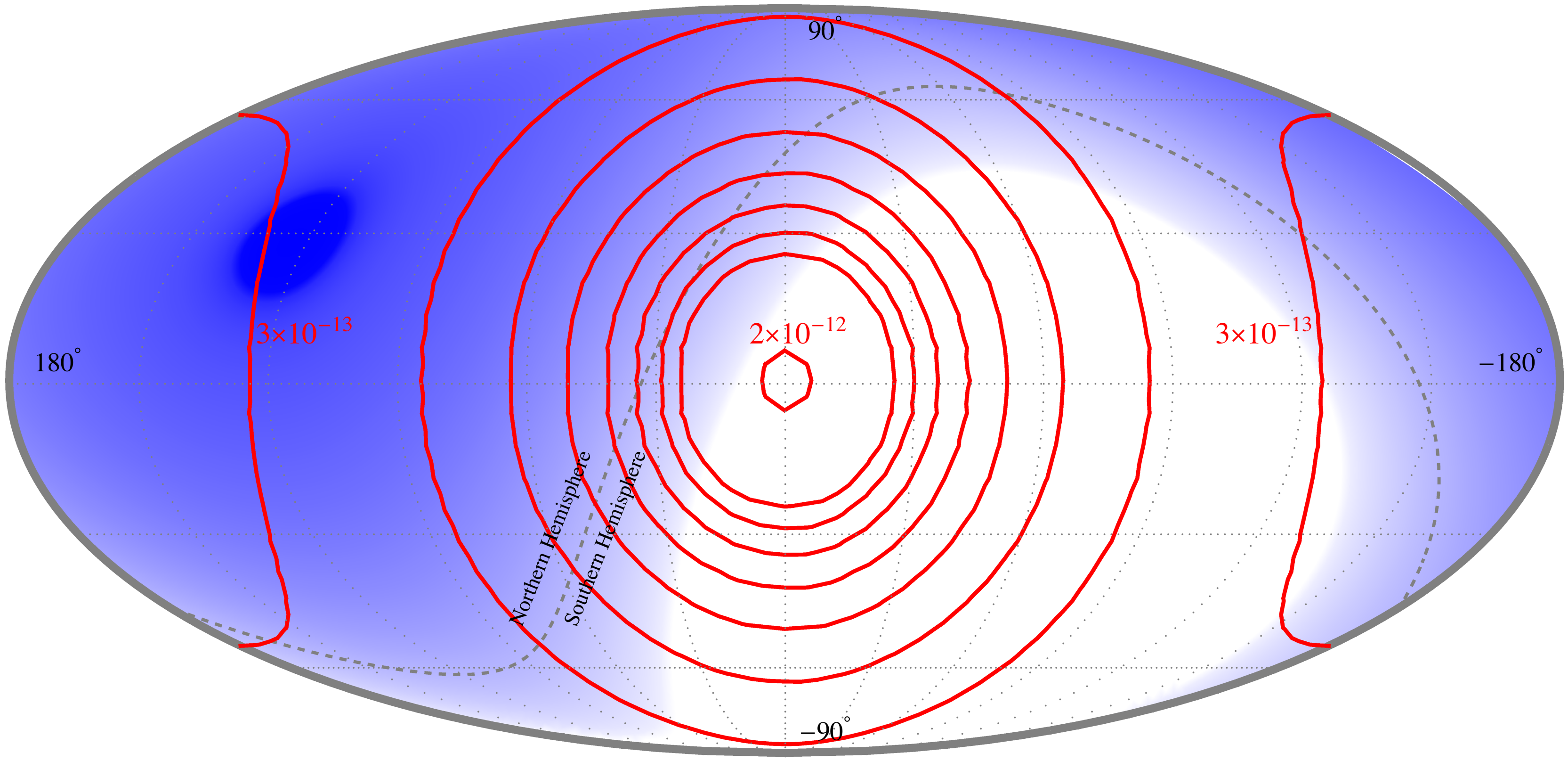
Gamma ray bounds

✓ Galactic component

KASCADE



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



CASA-MIA

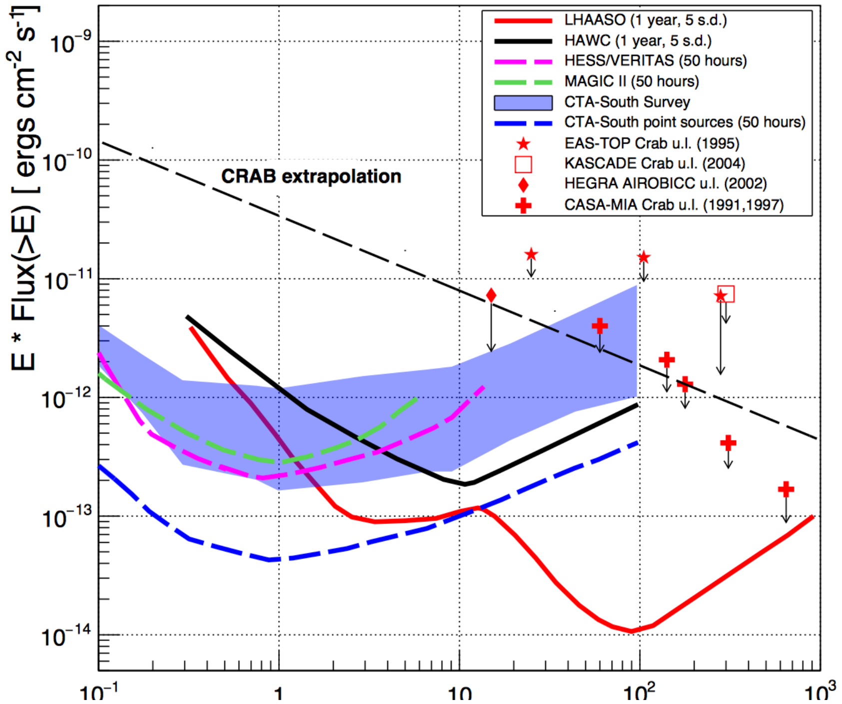
Gamma ray bounds

✓ Galactic component

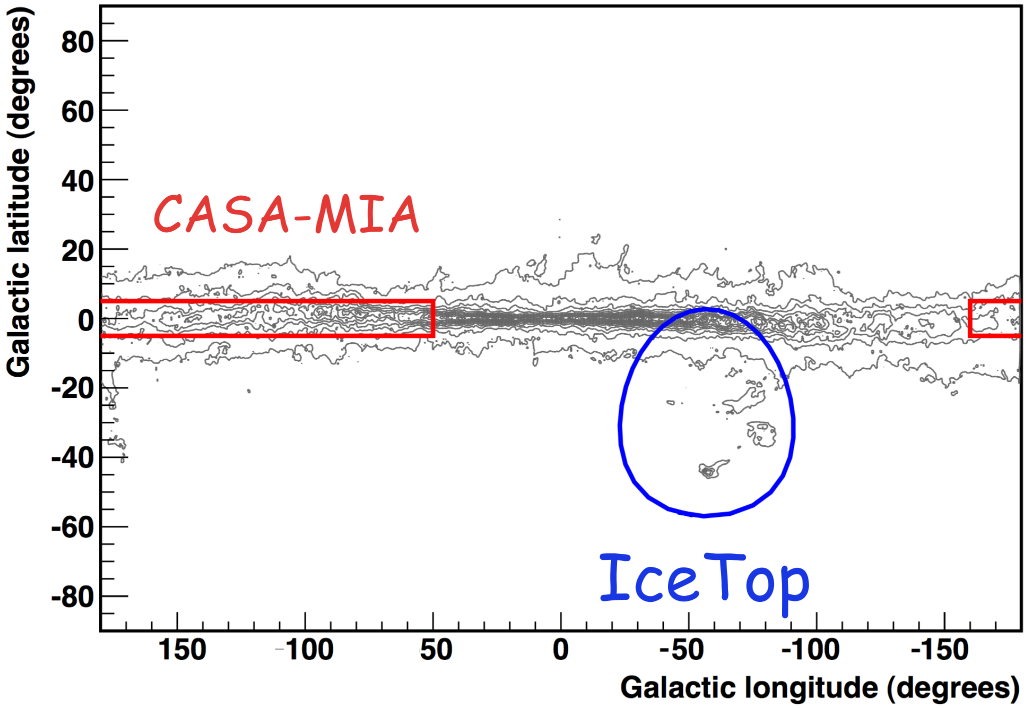
Future experiments

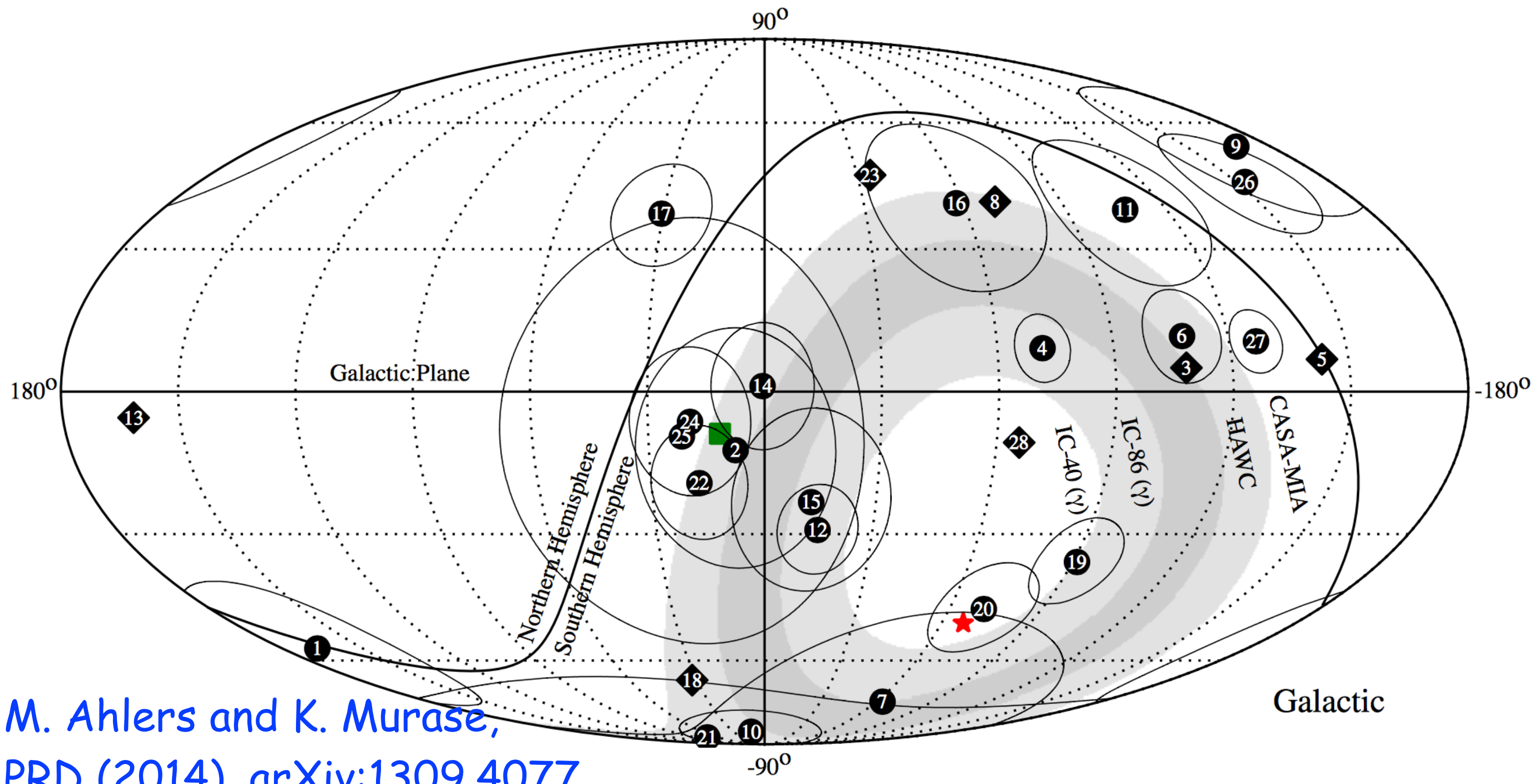
HAWC

LHAASO

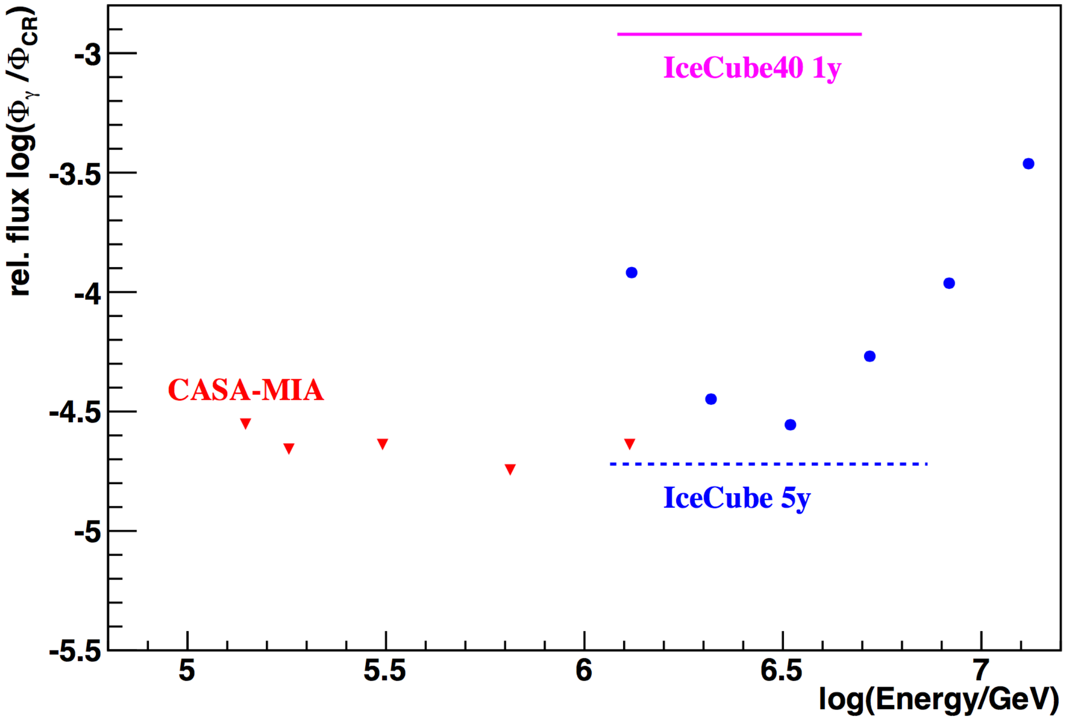


IceTop





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



Gamma ray bounds

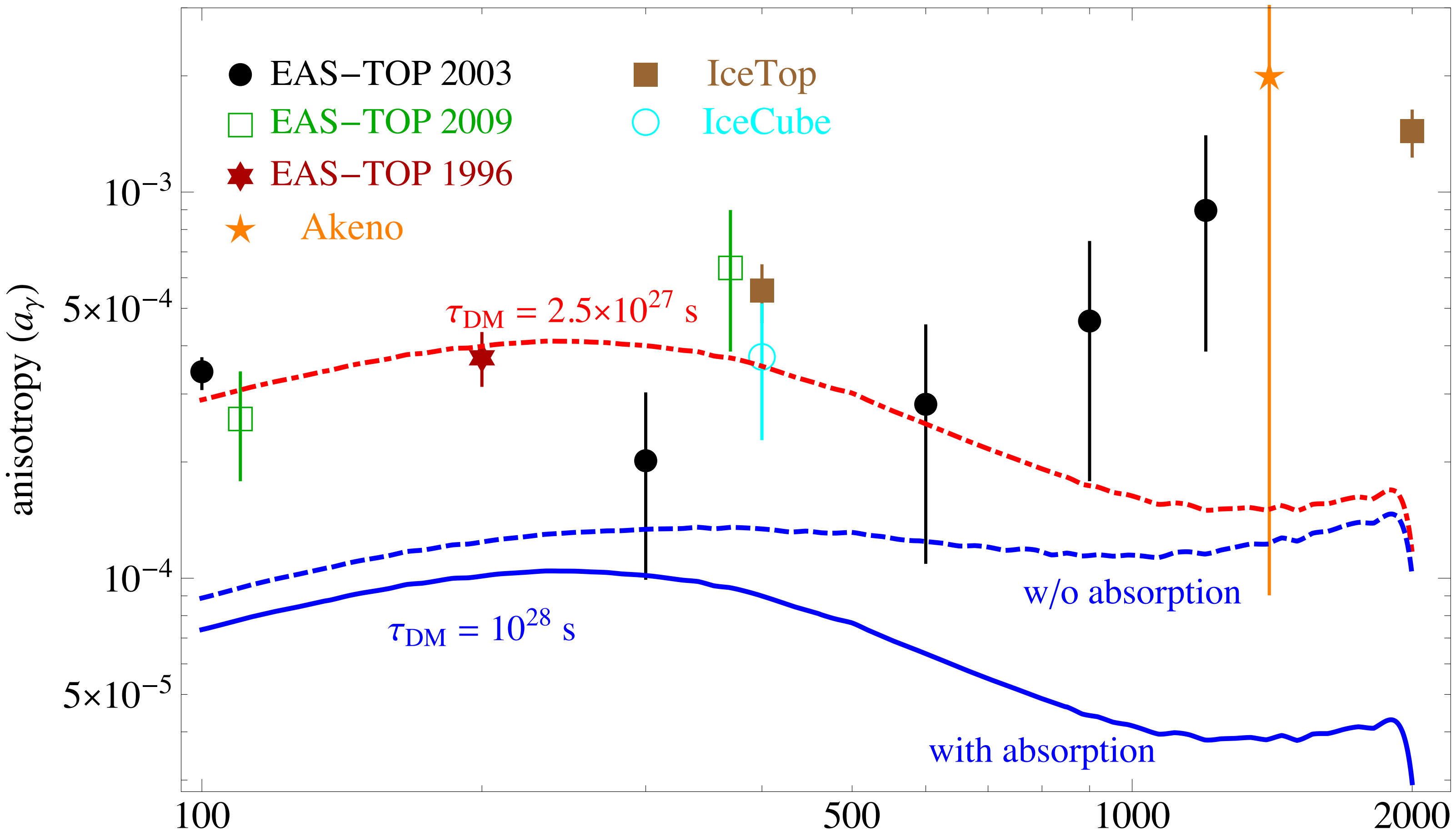
- ✓ Galactic component

Anisotropy

$$a_\gamma = \frac{\left.\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma}\right|_{\mathrm{GC}} - \left.\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma}\right|_{\mathrm{anti-GC}}}{\frac{\mathrm{d}\Phi_{\mathrm{CR}}}{\mathrm{d}E}}$$

→ Total CR flux

- ✓ No need to γ/hadron discrimination
- ✓ Absorption suppress the anisotropy
- ✓ The bound 2.5x10^{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

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.

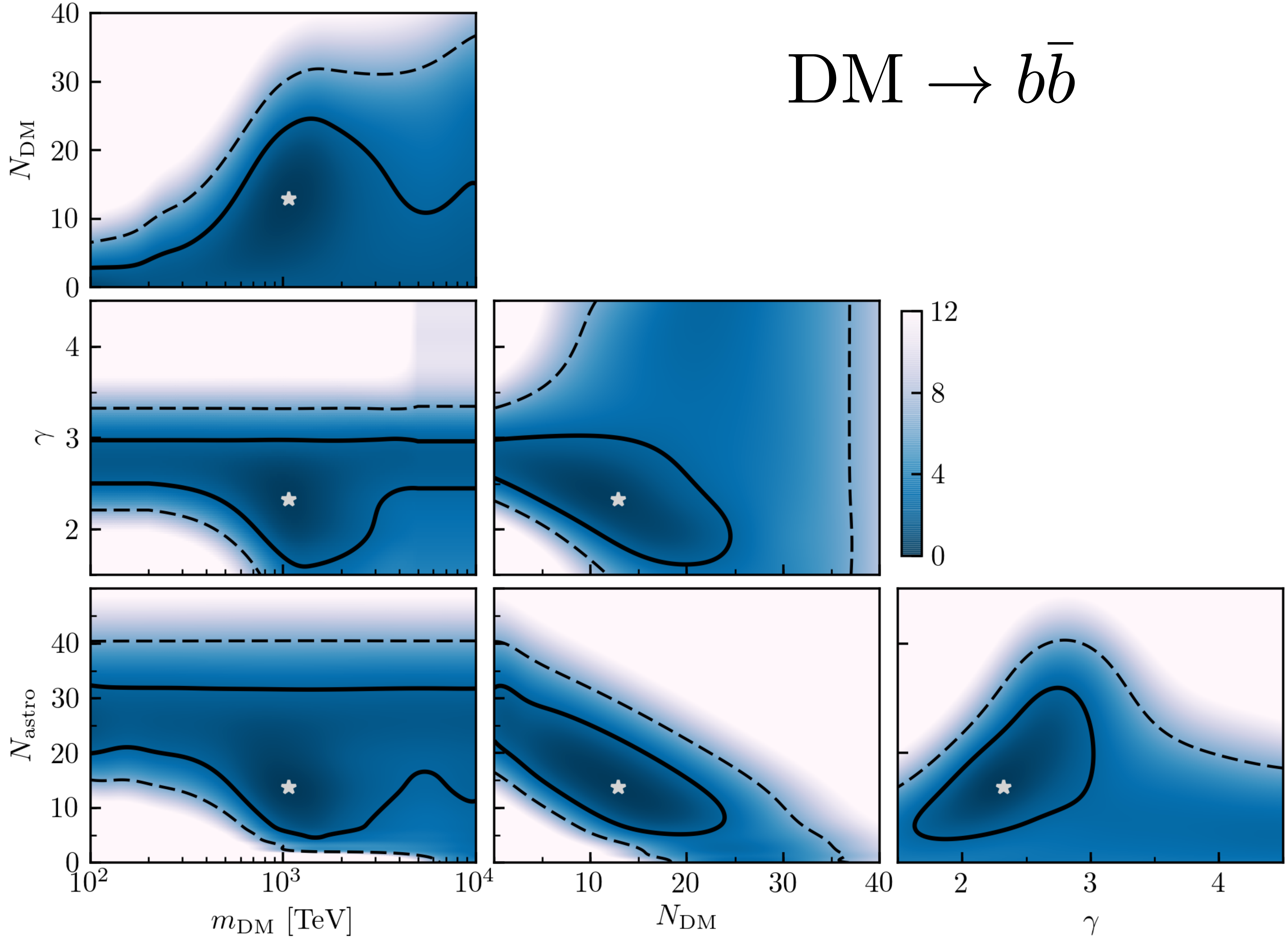
- ✓ We argued that a PeV-scale decaying DM, with generic decay channels, can naturally explain these features. The required lifetime is allowed by the current limits. Both the energy and angular distributions mildly prefer DM interpretation.

- ✓ 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

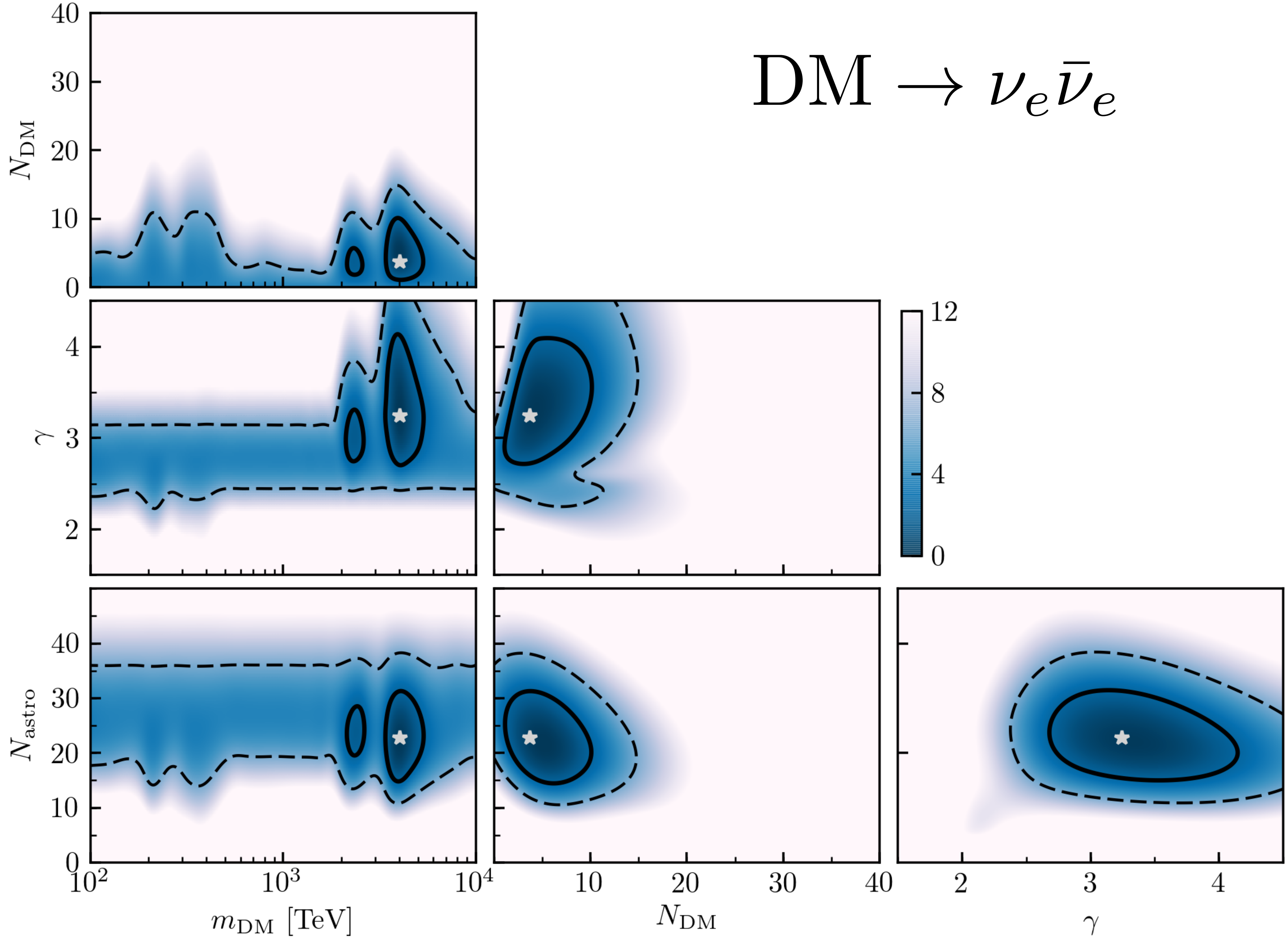
Thank you !

Parameter correlations



Parameter correlations

$$\mathrm{DM} \to \nu_e \bar{\nu}_e$$



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.

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

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

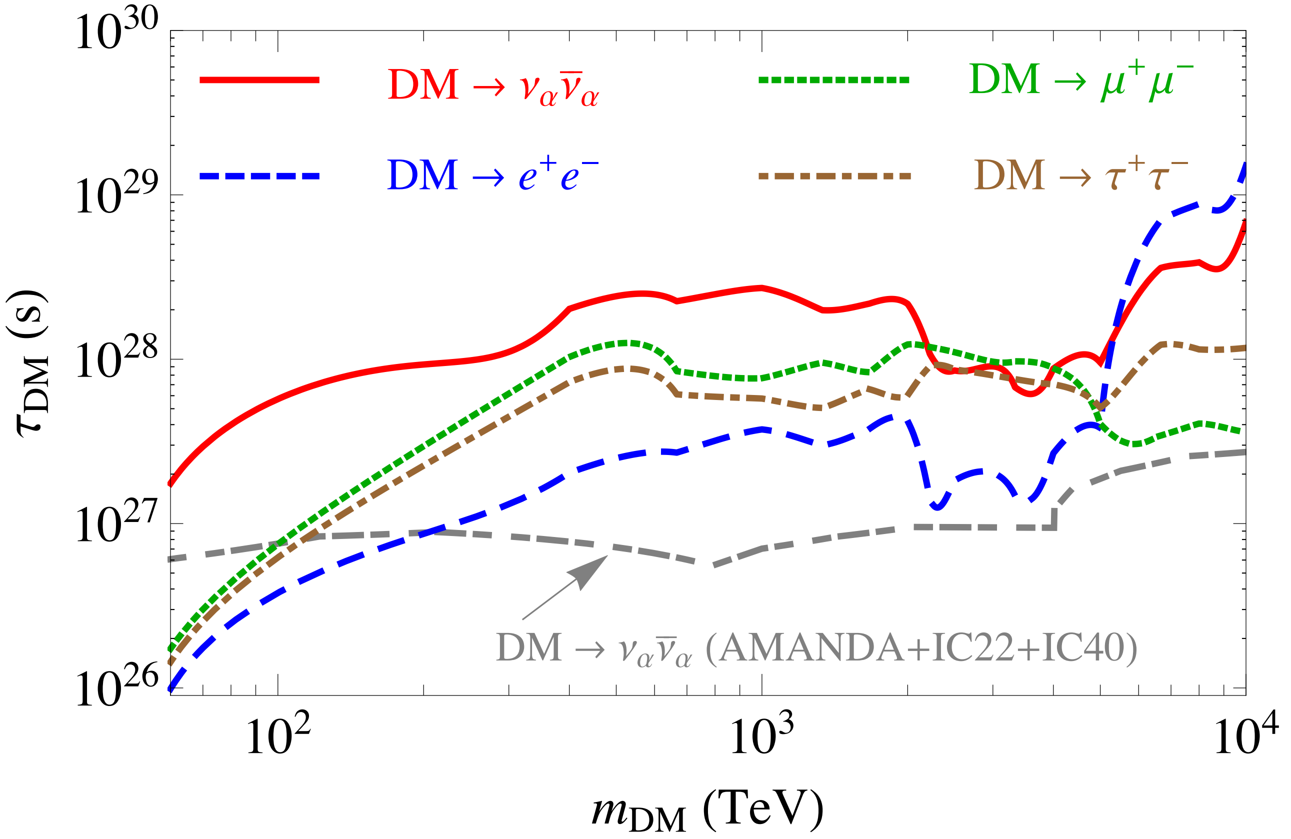
or

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

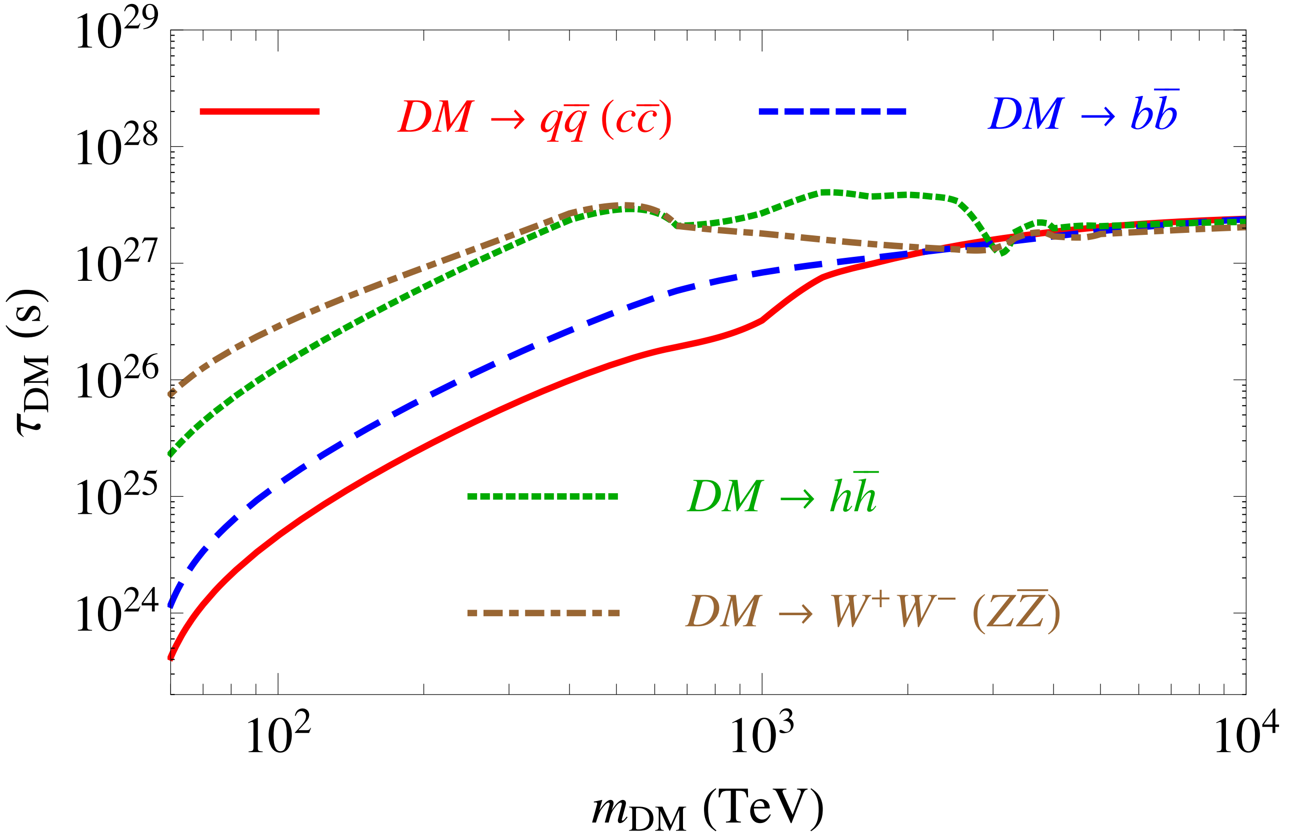
Constraining DM properties

✓ 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

✓ Annihilation cross section

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

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The isotropic components of neutrino flux from DM annihilation:

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

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

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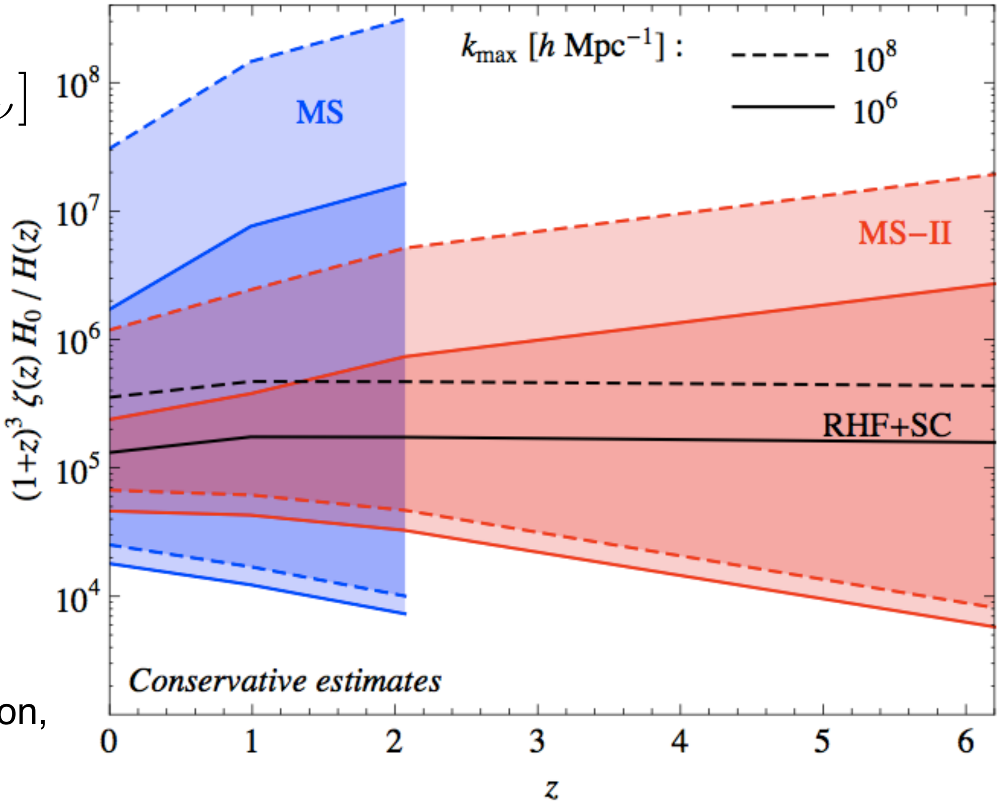
The cosmic flux from all redshift

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

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



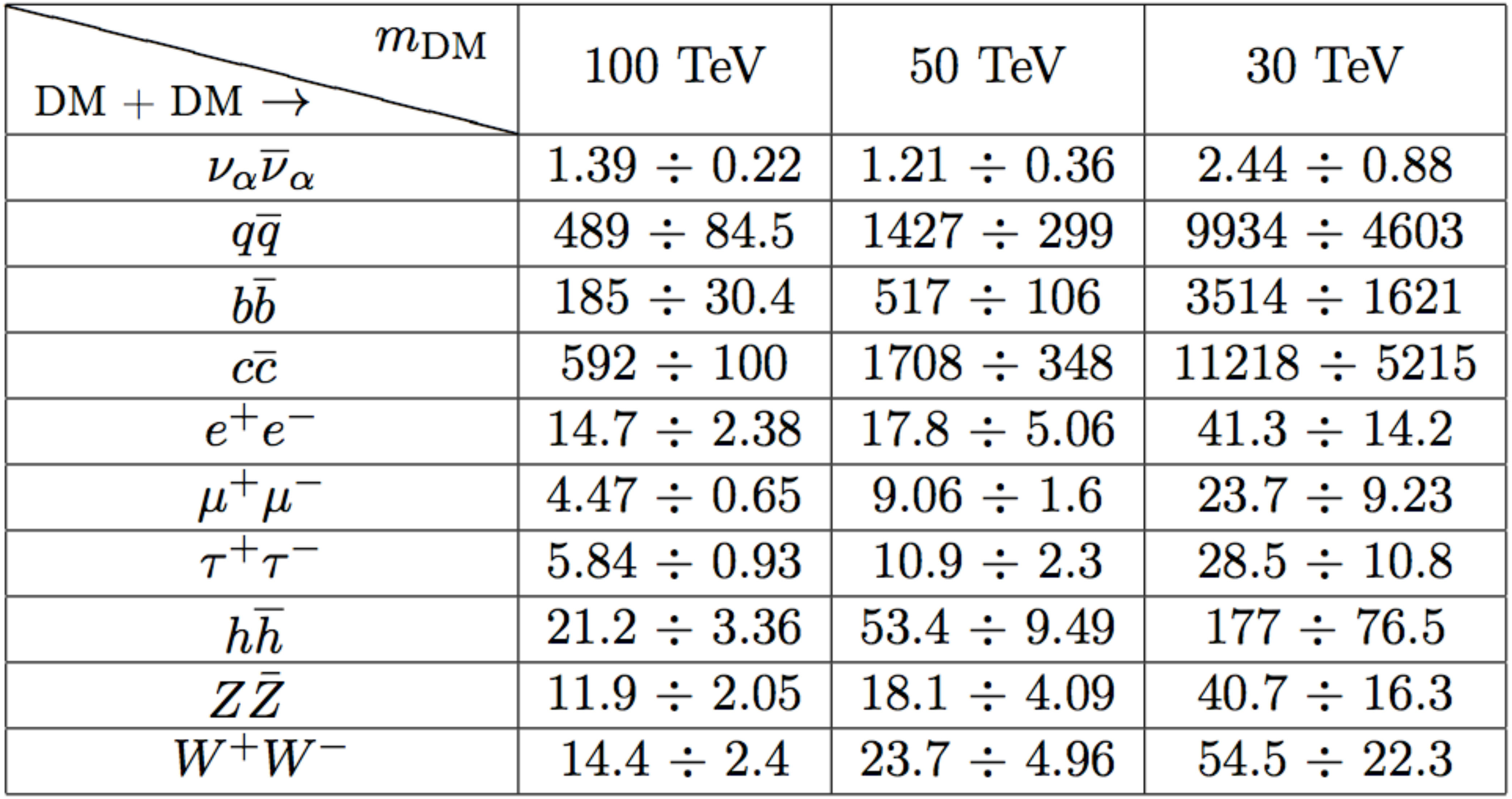
E. Sefusatti, G. Zaharijas, P. D. Serpico, D. Theurel and M. Gustafsson, Mon. Not. Roy. Astron. Soc. (2014) [arXiv:1401.2117].

Constraining DM properties

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

minimum ÷ maximum value used for ζ(z)

unit of <σv> is 10^{-22} cm^3s^{-1}



$m_{\rm DM}$ / DM + 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

A note on Dark Matter

DM exist!

What We Do Not Know?

✓ Mass

axion — 10^{-6} eV

Sterile$_\nu$ — ~KeV

WIMP — ~100 GeV

Wimpzilla — M_{GUT} (10^{16} GeV)

⚠ "WIMP" paradigm ?

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

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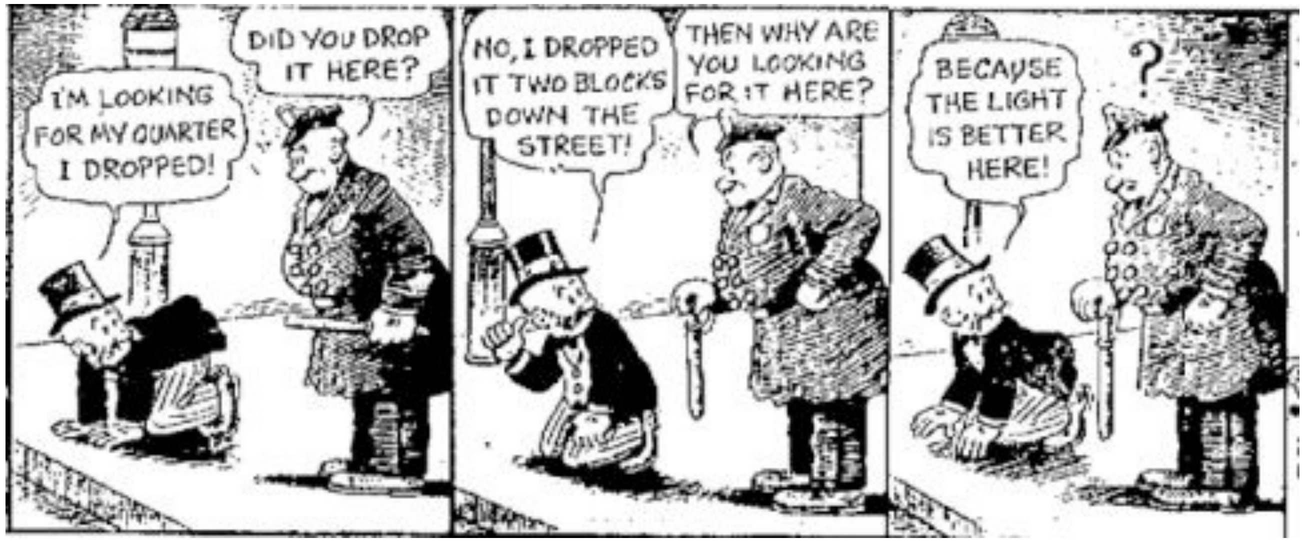
caution: streetlight effect



Mulla Nasreddin

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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

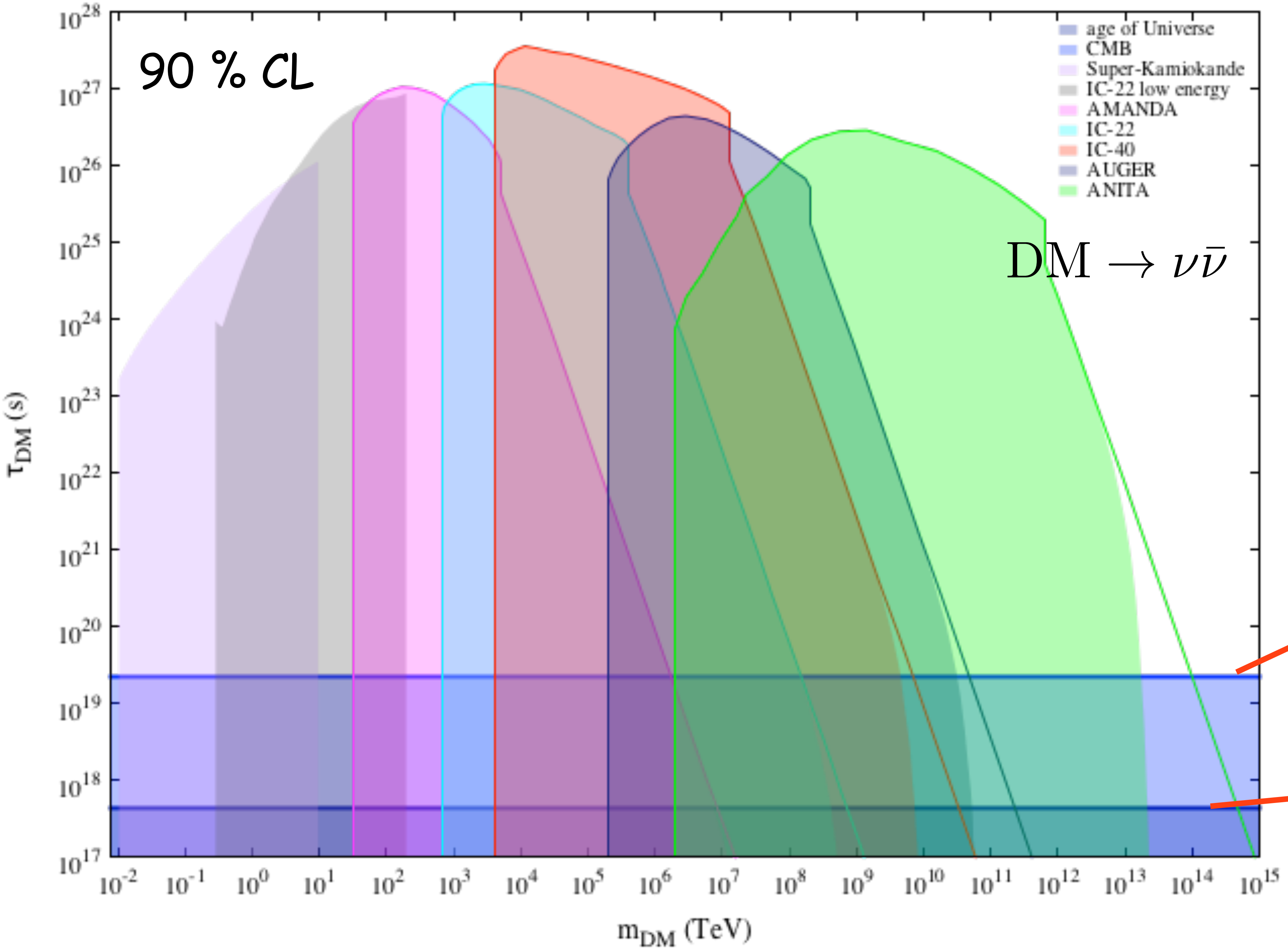
✓ ...

Limits on lifetime from neutrino experiments

before recent IceCube data

✓ Lifetime: stable (∞) or

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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this talk

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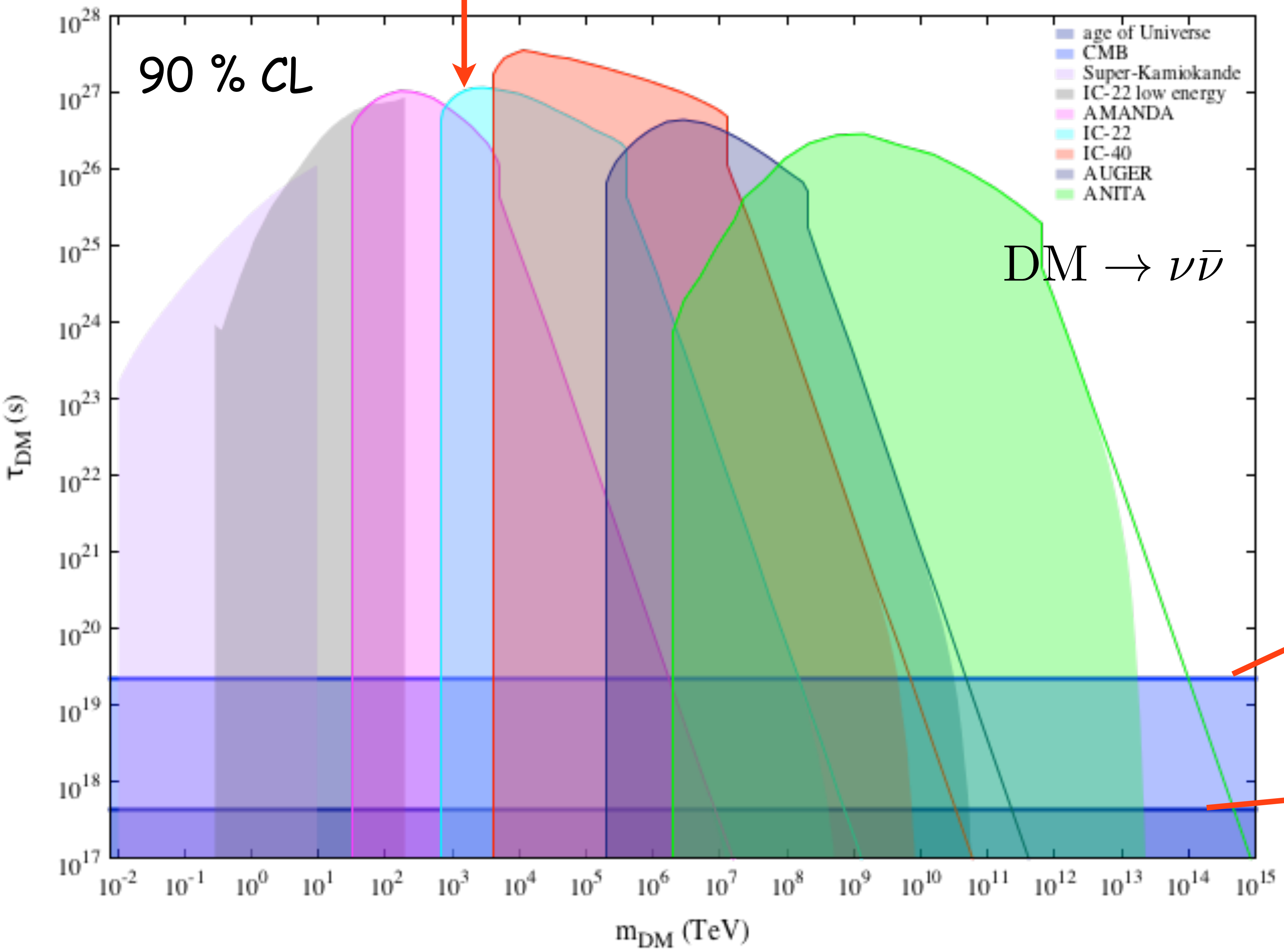

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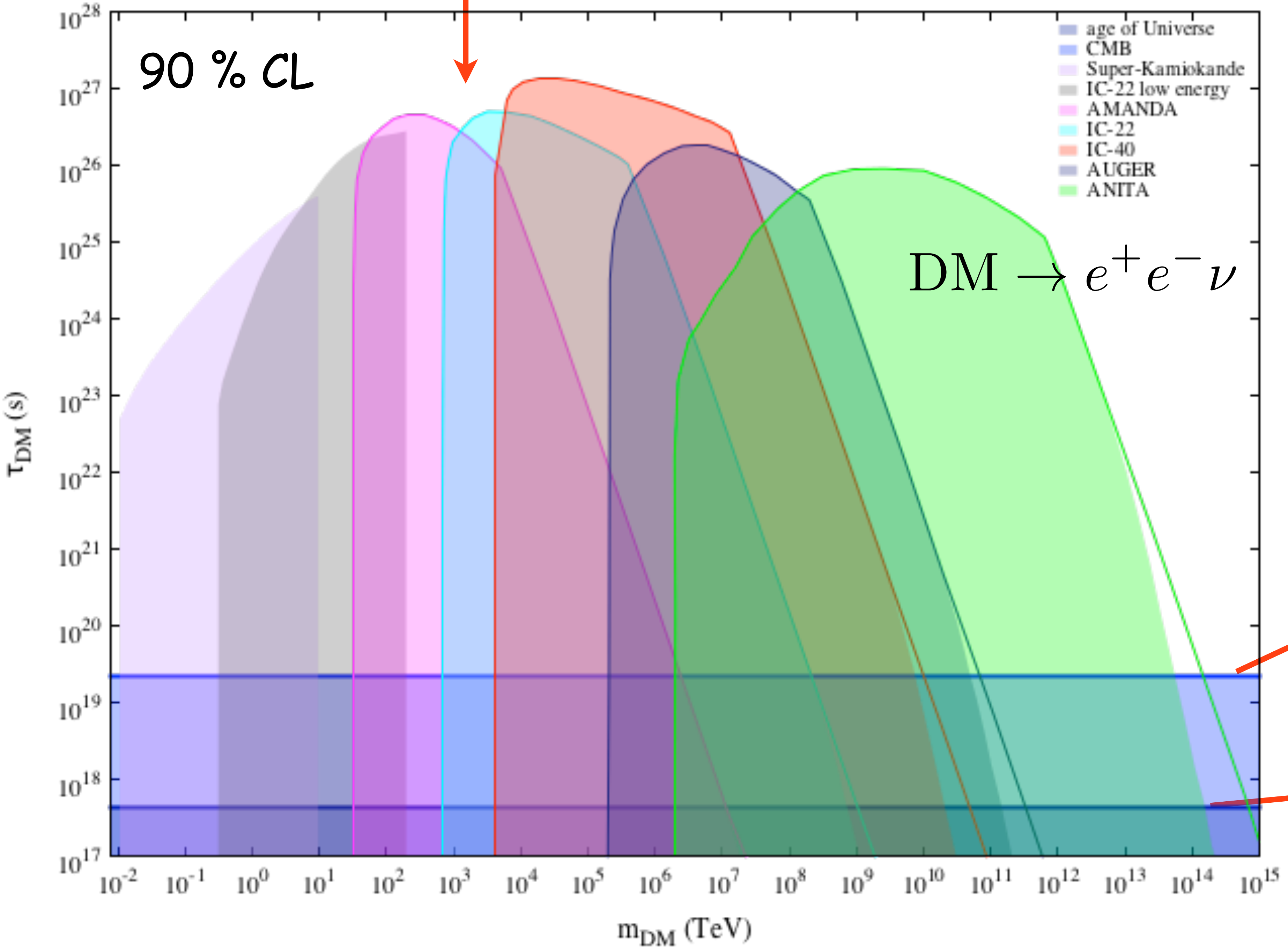

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$\tau_{\mathrm{DM}} > 2.2 \times 10^{19}$ s (CMB)

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Confronting with energy distribution of IceCube data

three years data set

SM sector ↔ Dark sector

portal type:

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

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

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

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

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

Confronting with energy distribution of IceCube data

three years data set

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

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

SM sector ⟷ Dark sector

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

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

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

✓ d = 6 : other portals

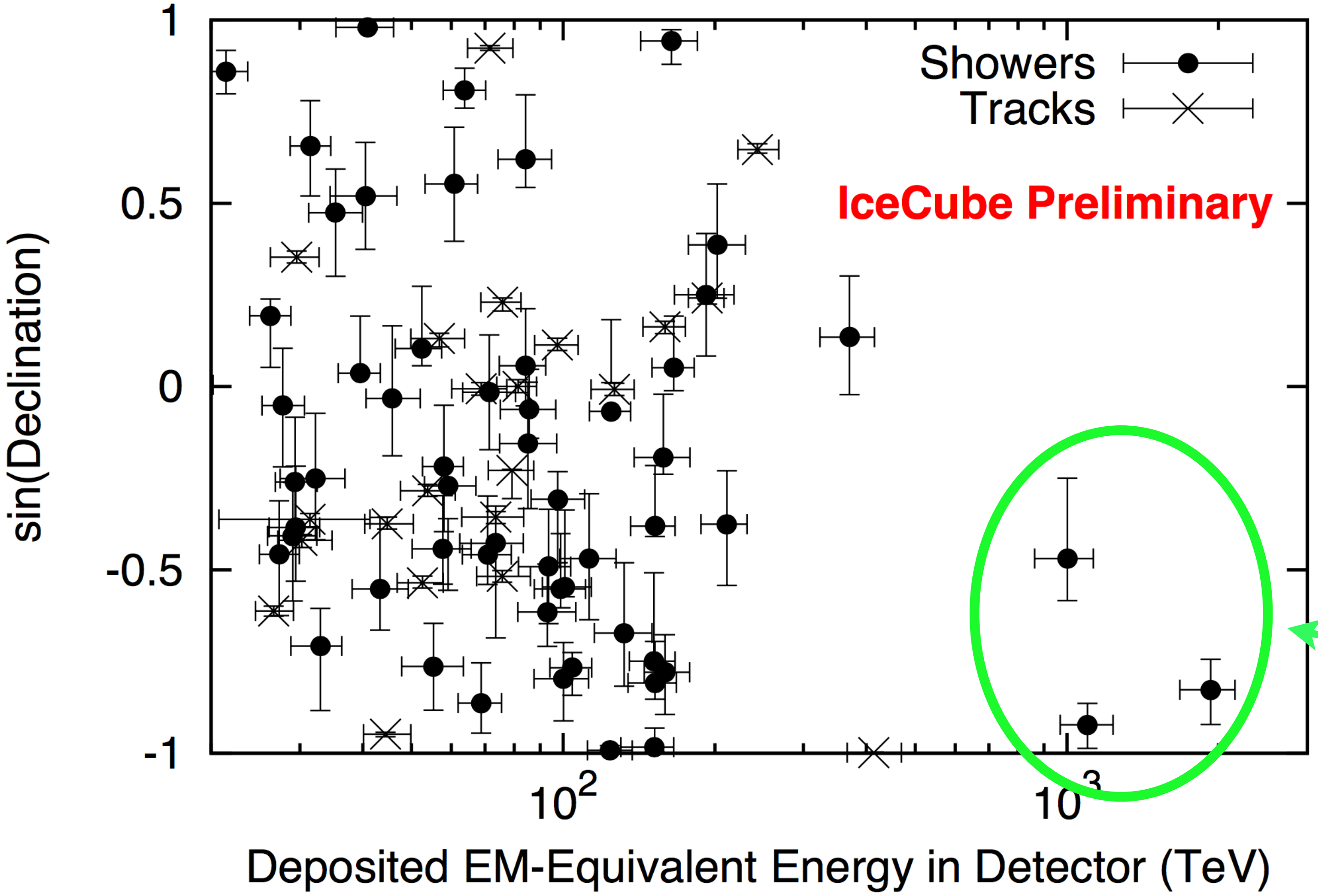
✓ For d > 4 there are more freedom in branching ratios. We have shown that for the most constrained model (d=4) a good fit to the data can be obtained. Obviously better fits can be achieved for d > 4.

Observation of High Energy Neutrinos in IceCube

✓ Looking for lower energy contained events, 2078 days livetime

ICRC 2017

The whole family!



Source(s) not identified!

✓ totally 82 events

✓ still three events with energy ~ PeV

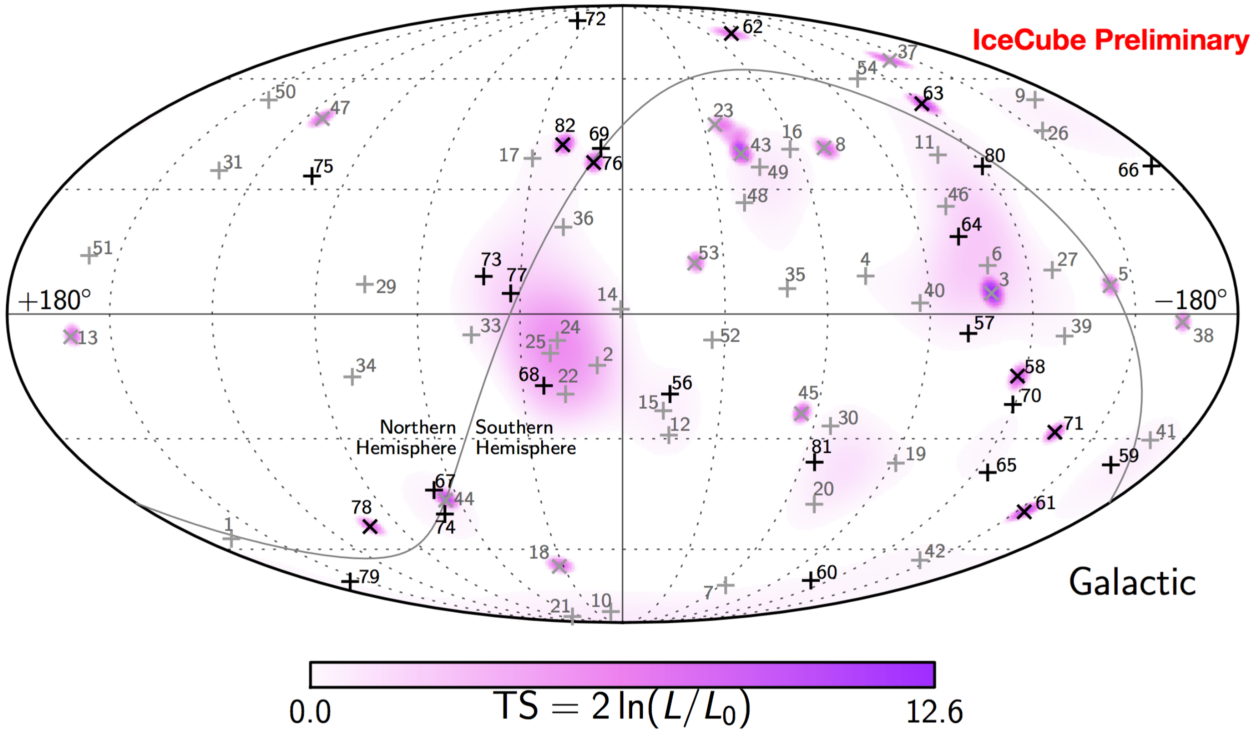
$$\Phi \propto E^{-\gamma} : \quad \gamma = 2.9 \pm 0.3$$

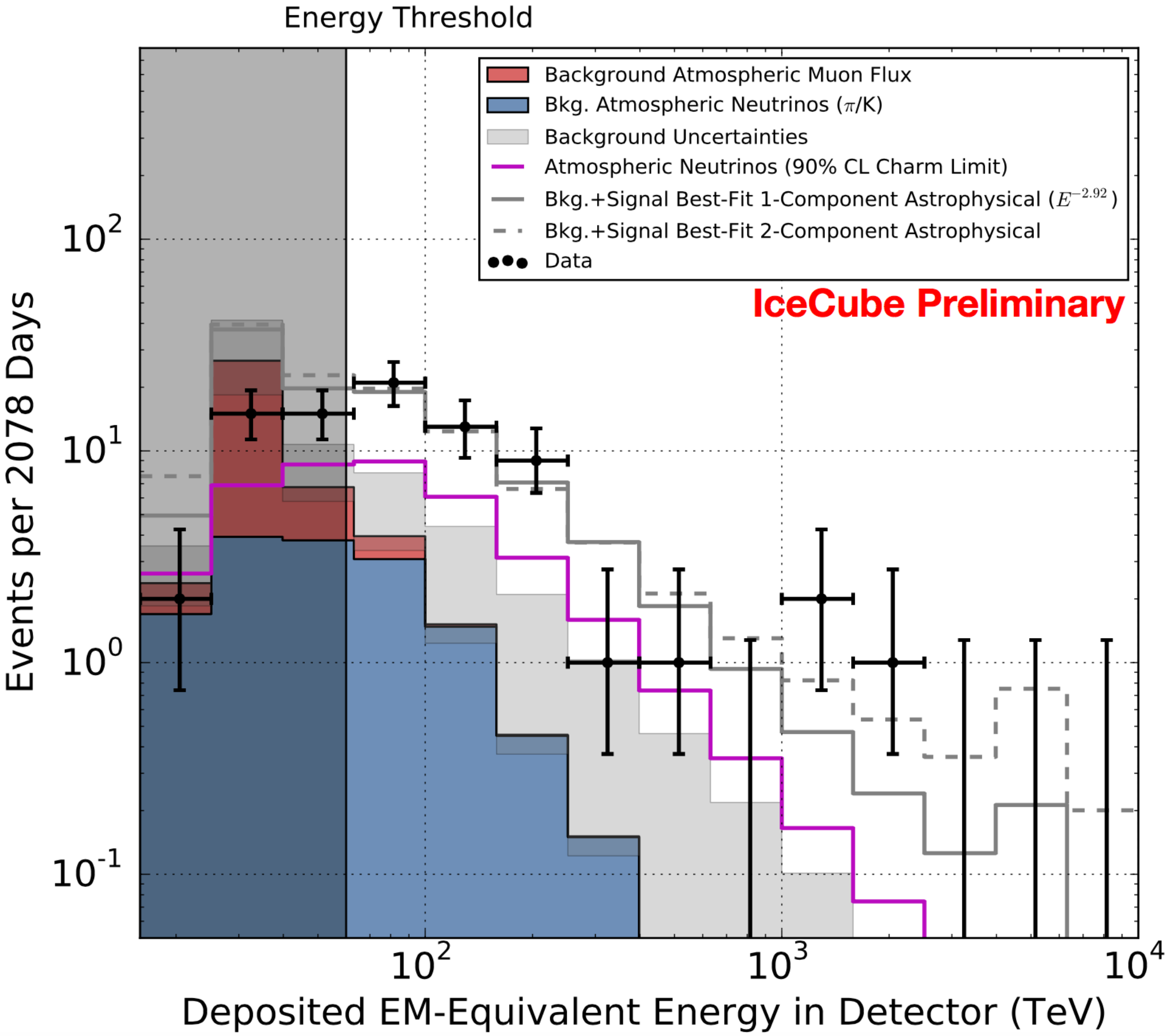
6 years of data

excess of events > 7σ

IceCube data

- ✓ Looking for lower energy contained events, 2078 days livetime





6 years of data