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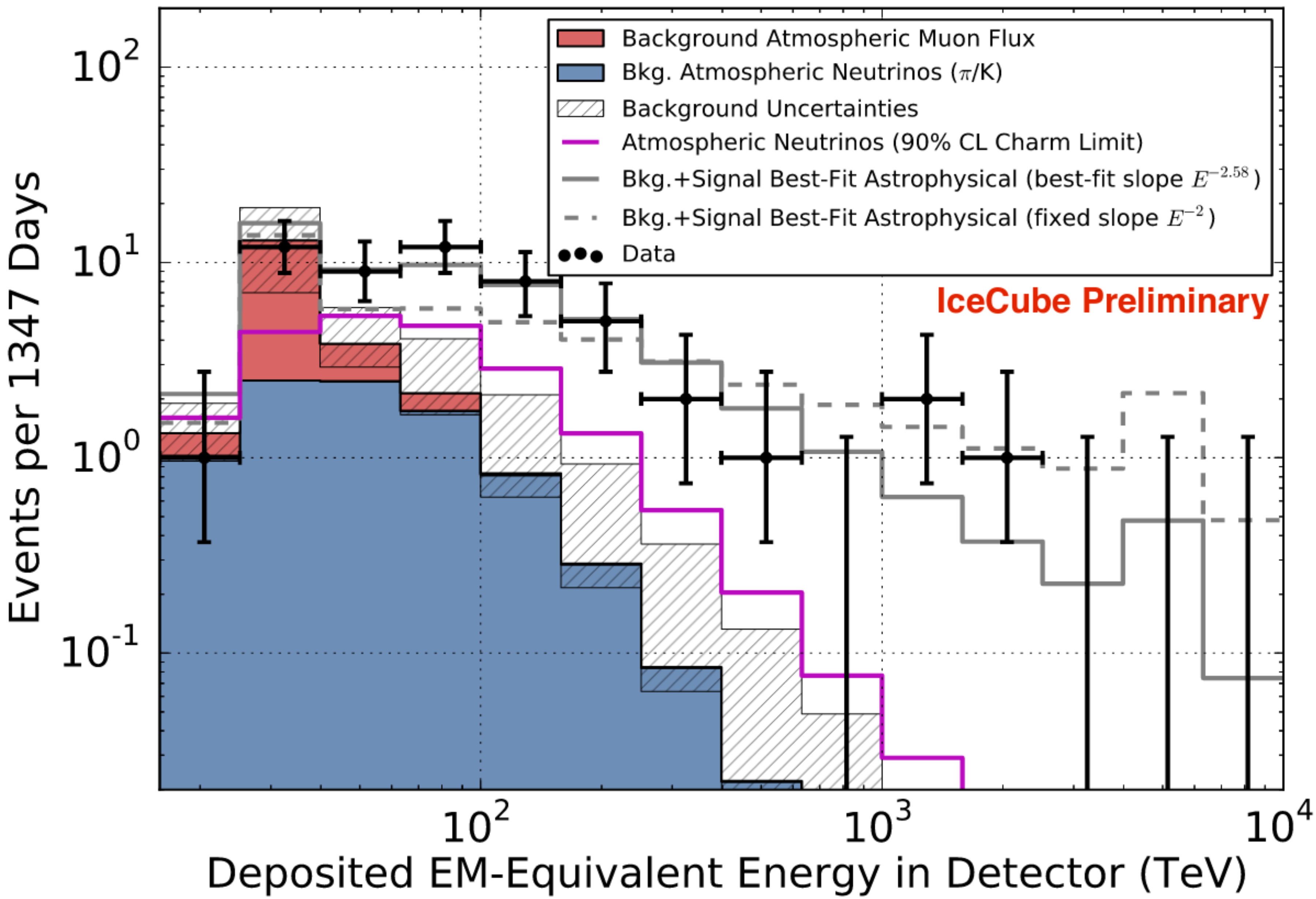
Constraints on the astrophysical flux and the dark matter decay with IceCube HESE data

Ina Sarcevic

University of Arizona

Work done in collaboration with Atri Bhattacharya, Arman Esmaili and Sergio Palomares-Ruiz

First Observation of HE Cosmic Neutrinos



- The IceCube fit for non-atmospheric neutrino flux for the HESE 4 year data:

$$\frac{d\Phi_{\mathrm{a}}}{dE_\nu} \propto E_\nu^{-2.58\pm0.25}$$

with the normalization

$$\phi_a \sim 2 \times 10^{-18}(E/100TeV)$$

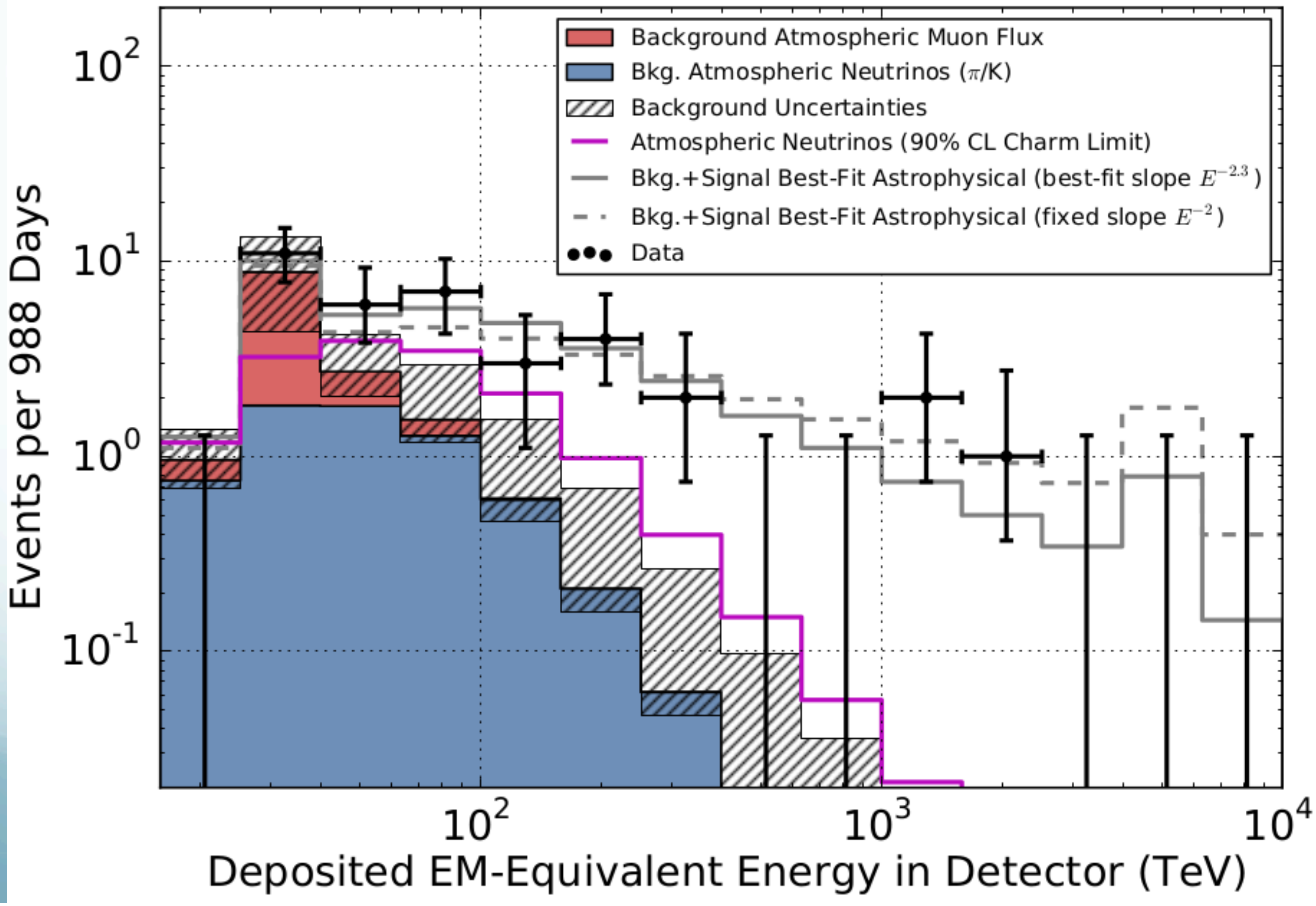
- A very different IceCube analysis of through-going muon tracks passing through the detector with higher energy threshold of 200TeV (6 year data) points to a much flatter flux

$$\frac{d\Phi_a}{dE_\nu} \propto E_\nu^{-2.13\pm0.13}$$

- There have been suggestions that the observed astrophysical flux can be better described with two-component power-law fits

$$\frac{d\Phi_a}{dE_\nu} = \begin{cases} A\,E_\nu^{-\alpha} \text{ when } E_\nu < E_0 \\ A\,E_0^{-\alpha}\,(E_\nu/E_0)^{-\beta} \text{ when } E_\nu \geqslant E_0 \end{cases}$$

Could Observed Astrophysical Neutrinos be Due to Charm from Astrophysical Sources?



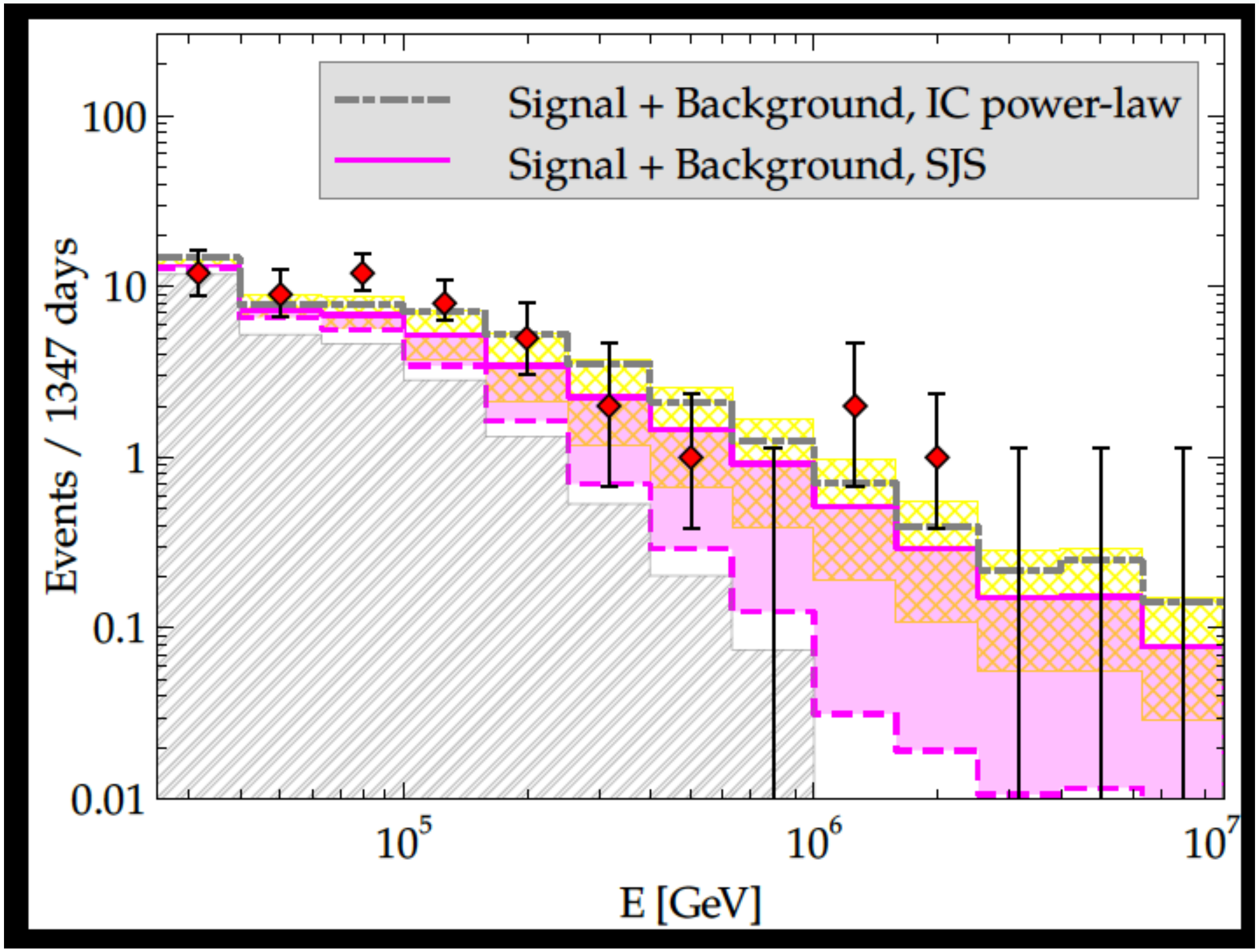


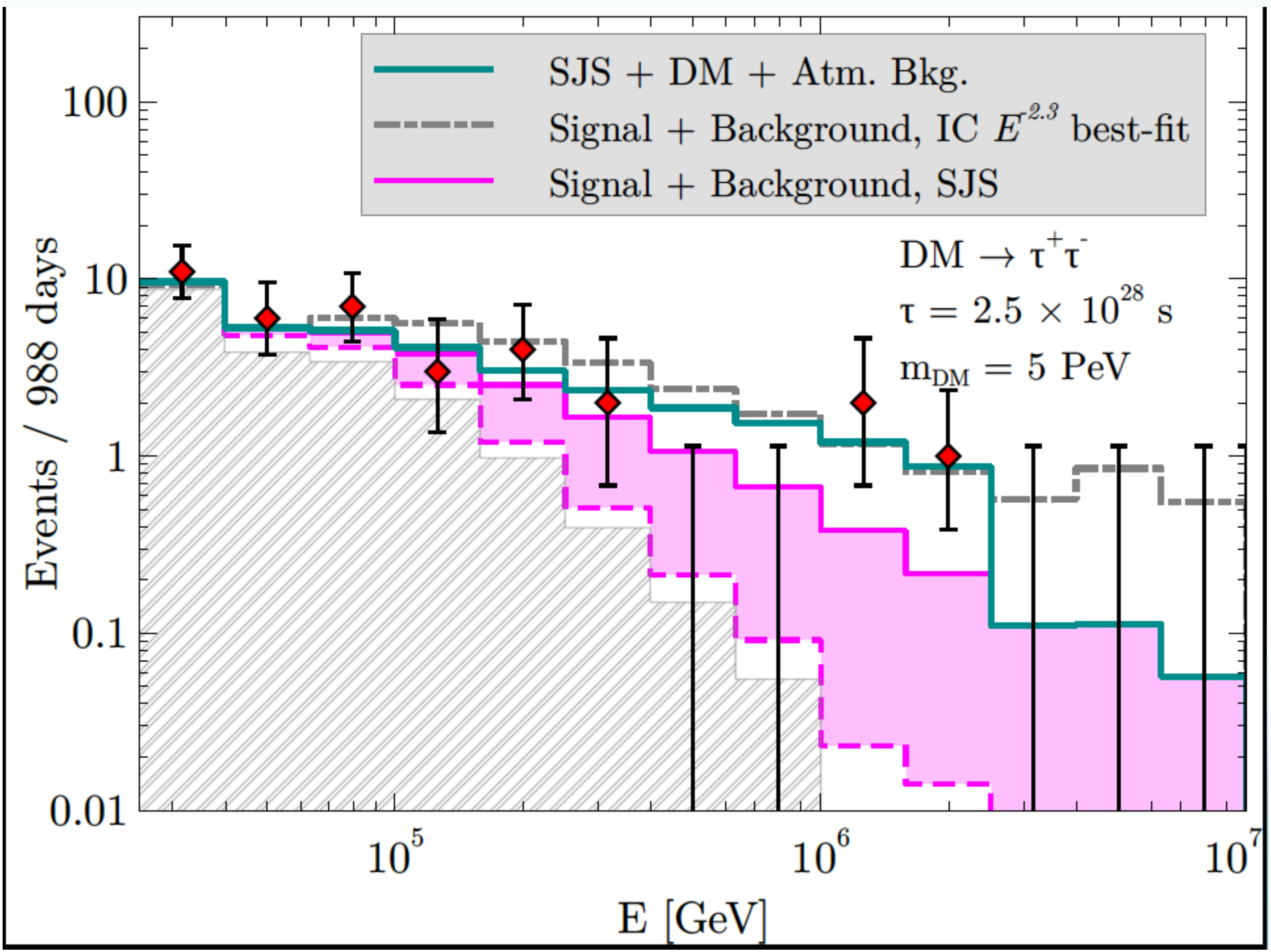
Figure 3: Predicted 988-day total (shower + track) event rates at IC from slow-jet sources for $L_j = 10^{50}$ erg s^{-1}, $\Gamma_j = 5$, $E'_{\rm max} = 10.2$ PeV and $\xi_{\rm sn} = 1$. The solid shaded histogram reflects the QCD scale uncertainties in the charm pair production cross section calculation, with the solid (dashed) histogram showing the upper (lower) range of the SJS diffuse plus atmospheric background number of events. The variation in event-rates relative to the solid histogram from uncertainties in the SN formation rate is shown as a yellow hatched area. Observed event-rates from [3] along with 1σ statistical error bars are shown (red diamonds), as is the total atmospheric neutrino + muon background estimated in the same reference (grey shaded region).

A. Bhattacharya, R. Enberg, M.H. Reno and I. Sarcevic, JCAP 06 (2015) 034

Could the observed neutrino flux have component from the dark matter decay in addition to the astrophysical source?

A. Bhattacharya, M.H. Reno and I. Sarcevic,
JHEP 1406 (2014) 110

Atri Bhattacharya, Arman Esmaili, Sergio Palomares-Ruiz and Ina Sarcevic, (2017)



SJS + DM + Atm. Bkg.
Signal + Background, IC $E^{-2.3}$ best-fit
Signal + Background, SJS
DM → $\tau^+\tau^-$
$\tau = 2.5 \times 10^{28}$ s
$m_{DM} = 5$ PeV
Events / 988 days
E [GeV]
0.01
0.1
1
10
100
10^5
10^6
10^7

Neutrino Flux from Dark Matter Decay

- Flux is the sum of galactic and extragalactic contributions:

$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}$$

- Galactic contribution:

$$\frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu}(E_\nu, b, l) = \frac{1}{4\pi m_{\mathrm{DM}}\tau_{\mathrm{DM}}}\frac{dN_{\nu_\alpha}}{dE_\nu}\int_0^\infty \rho\left[r\left(s,b,l\right)\right] ds$$

- Extragalactic contribution:

$$\frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}(E_\nu) = \frac{\Omega_{\mathrm{DM}}\rho_c}{4\pi m_{\mathrm{DM}}\tau_{\mathrm{DM}}}\int_0^\infty dz\,\frac{1}{H(z)}\frac{dN_{\nu_\alpha}}{dE_\nu}\left[(1+z)E_\nu\right]$$

where $m_{\rm DM}$ and $\tau_{\rm DM}$ are respectively the DM mass and lifetime, dN_{ν_α}/dE_ν is the spectrum of $\nu_\alpha + \overline{\nu}_\alpha$ from DM decay, the distance to Galactic center is $r(s,b,l) = \sqrt{s^2 + R_\odot^2 - 2sR_\odot \cos b \cos l}$ with the Sun-Galactic center distance of $R_\odot = 8.5$ kpc; and ρ is the DM density profile of our Galaxy, which we assume to be of Navarro-Frenk-White type

$$\rho(r) = \frac{\rho_0}{r/r_c(1+r/r_c)^2}$$

where $r_c = 20$ kpc and $\rho_0 = 0.33$ GeV cm^{-3}

z is the redshift and ρ_c represents the critical density of the universe, $\rho_c = 5.6 \times 10^{-6}$ GeV cm^{-3}. The Hubble function is $H(z) = \sqrt{\Omega_\Lambda + \Omega_{\rm m}(1+z)^3}$, and using the results from the most recent Planck data [110] we take $\Omega_\Lambda = 0.6825$, $\Omega_{\rm m} = 0.3175$, $\Omega_{\rm DM} = 0.2685$ and $H_0 = 67.1$ km s^{-1}Mpc^{-1}.

Dark Matter Decay Modes

$$DM \to \bar{\nu}_\mu \nu_\mu$$

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

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

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

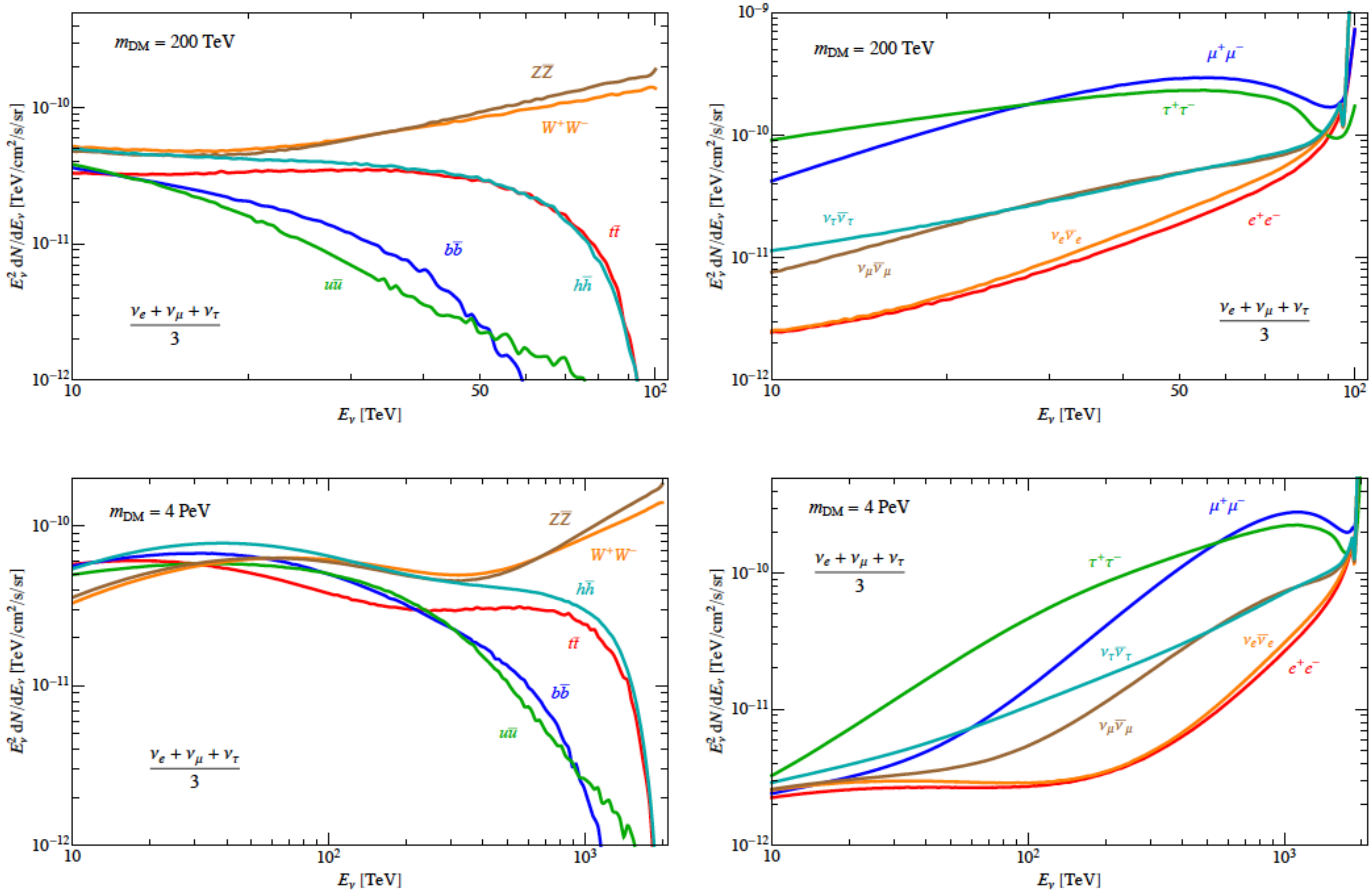
$$DM \to W^+W^-$$

$$DM \to \tau^+\tau^-$$

$$DM \to e^+e^-$$

$$DM \to \bar{\nu}_\tau \nu_\tau$$

Neutrino Fluxes from DM Decay



Likelihood Analysis to determine the best fit to HESE data

- The combined neutrino flux from an astrophysical power-law and DM decays can be represented in terms of 4 parameters:

  DM mass

  DM lifetime

  Astrophysical spectral index

  Astrophysical normalization

$$\Phi\left(E_\nu\right) \equiv \Phi(E_\nu; \tau_{DM}, m_{DM}, A, \gamma)$$
$$= \Phi_{DM}(E_\nu; \tau_{DM}, m_{DM}) + \Phi_{\mathrm{Ast}}(E_\nu; A, \gamma)$$

With these inputs, we compute the probability density functions (PDFs) for each observed event corresponding to the different event spectra classified as:

1. Downgoing neutrinos from DM decay (denoted as 'DM'),
2. Downgoing neutrinos from the astrophysical neutrino flux, assumed to follow a power-law nature ($d\Phi/dE_\nu \propto E_\nu^{-\gamma}$) (denoted as 'astro')
3. Downgoing conventional atmospheric neutrinos (ν_{atm}), and
4. Downgoing conventional atmospheric muons (μ_{atm}), and

their corresponding upgoing counterparts.

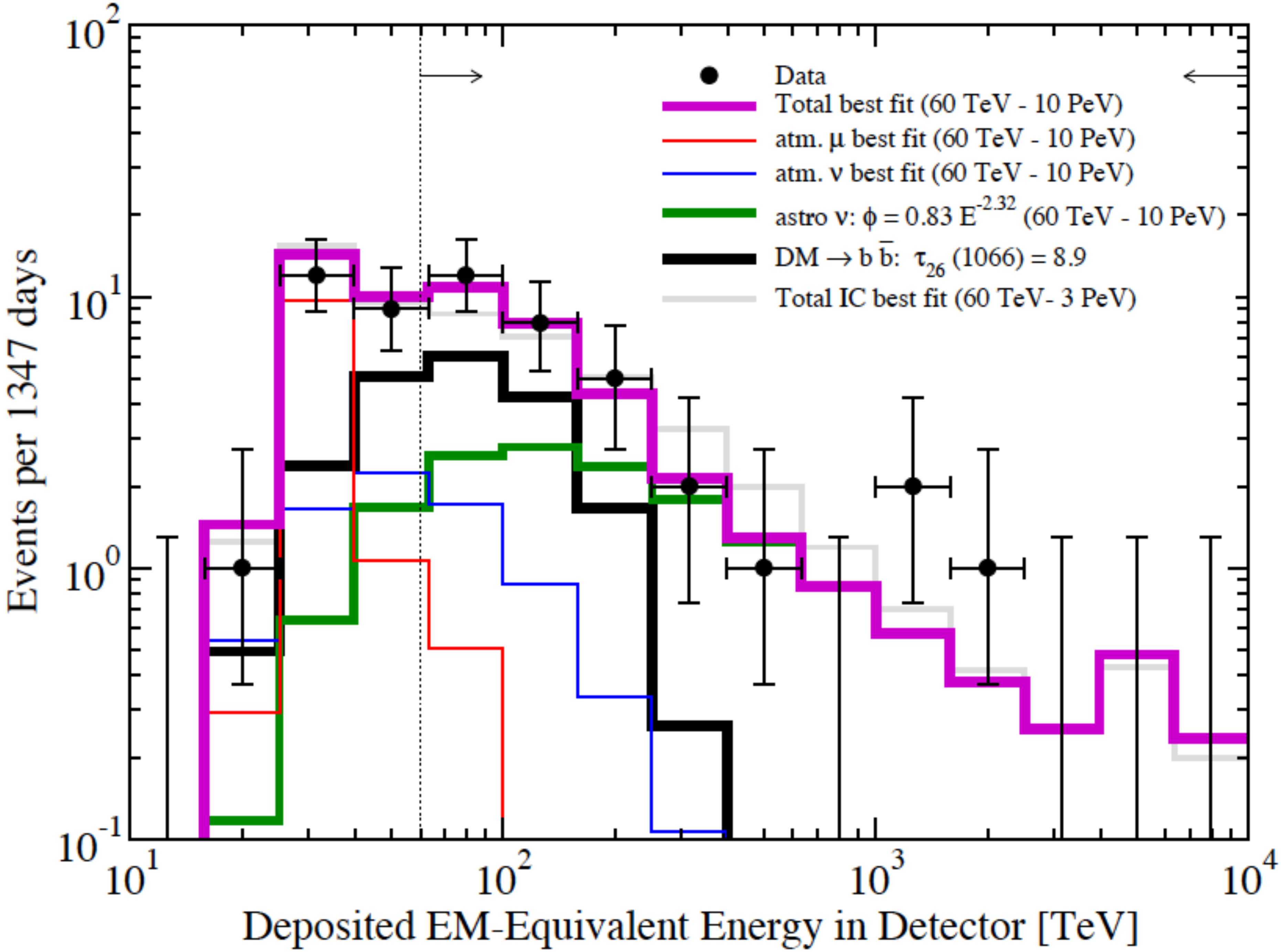
Once we calculate all the PDFs and the normalizations, we can build the likelihood to perform an unbinned extended maximum likelihood analysis. Each observed event is identified by the indexes $\{i, \theta, k\}$, which indicate: i = deposited energy of the event, θ = direction of the event ({up, down}) and k = topology of the event ({track, shower}).

where $\ell = \{e, \mu, \tau\}$; $n = \{\nu, \bar{\nu}\}$; $\theta = \{\text{up, down}\}$; $k = \{\text{tr, sh}\}$, i = deposited energy of the event and and $(\alpha_e : \alpha_\mu : \alpha_\tau)$ indicates the flavor composition of the astrophysical (power-law) flux, which we set to the usual $(1:1:1)$

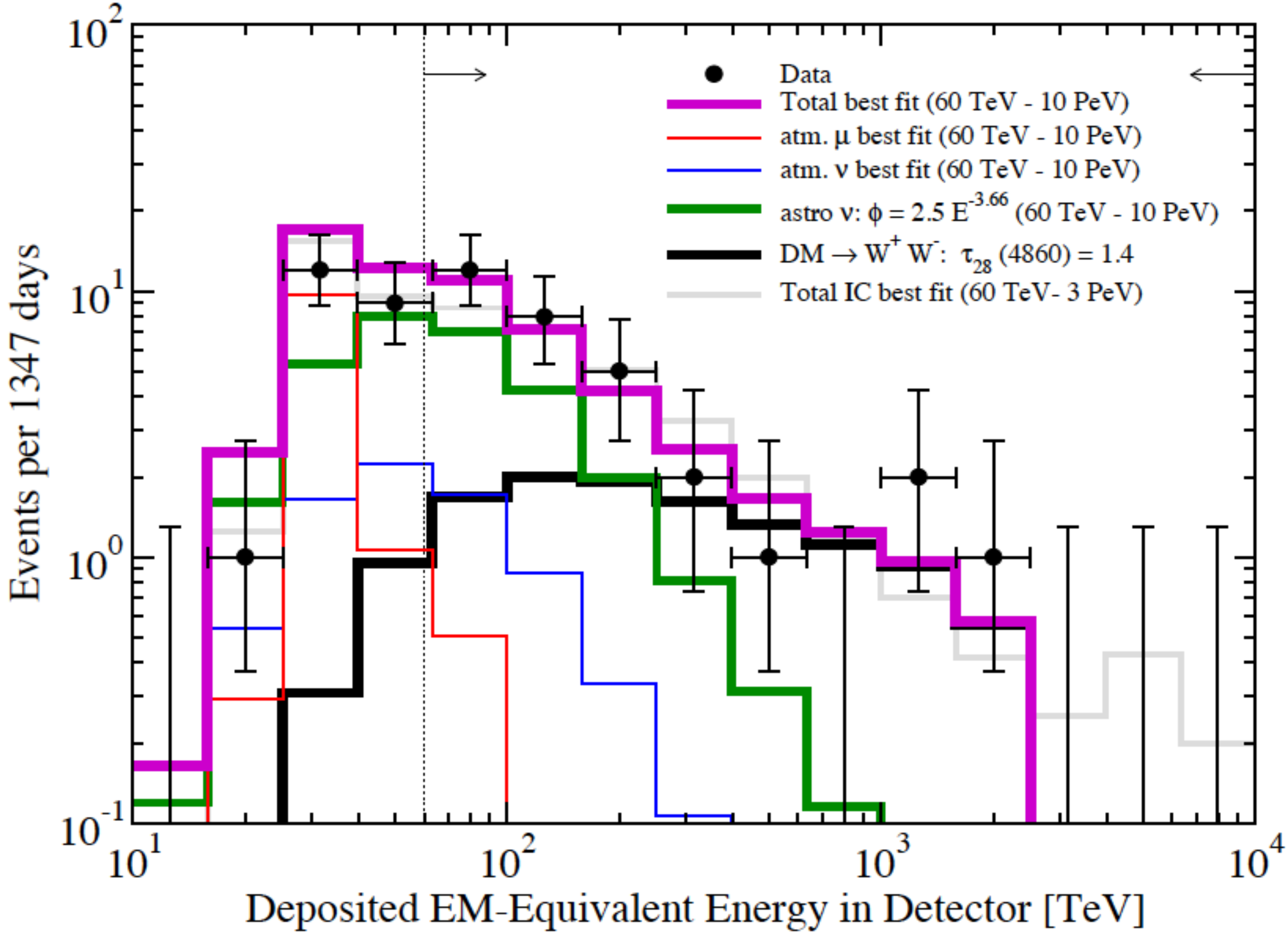
the likelihood for each event $\{i, \theta, k\}$ is given by:

$$\mathcal{L}^k_{i,\theta} = N_{\text{DM}}\,(\mathcal{P}_{\text{DM}})^k_{i,\theta}(m_{\text{DM}}, \text{channel}) \\ + N_{\text{Ast}}\,(\mathcal{P}_{\text{astro}})^k_{i,\theta}(\{\alpha\}, \gamma) + N_\nu\,(\mathcal{P}_{\nu\text{atm}})^k_{i,\theta} + N_p\,(\mathcal{P}_{\text{prompt}})^k_{i,\theta} + N_\mu\,(\mathcal{P}_{\mu\text{atm}})^k_{i,\theta}$$

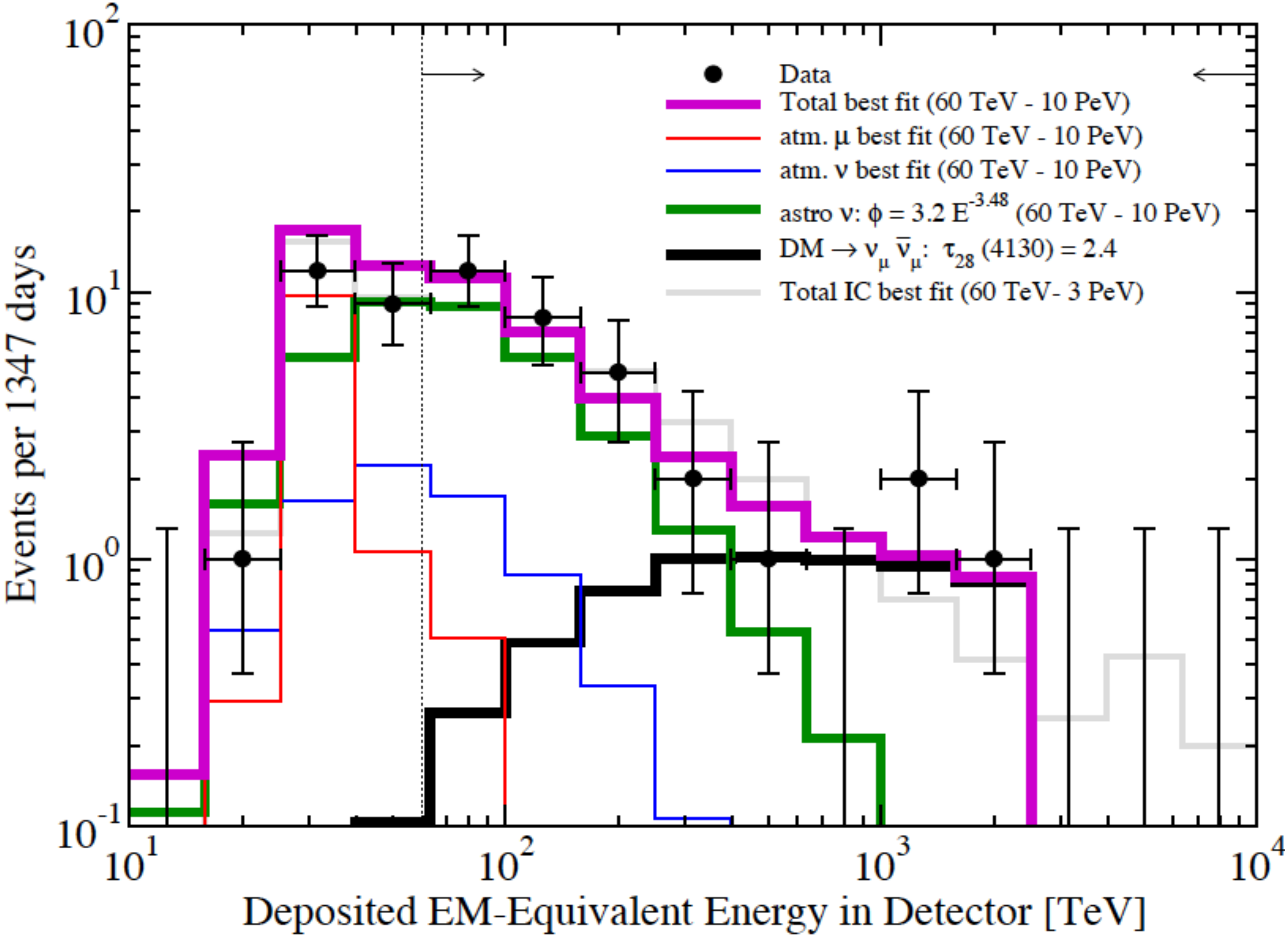
where N_{DM}, N_{Ast}, N_ν, N_p and N_μ are the number of events coming from DM decay, astrophysical (power-law) neutrino flux, atmospheric conventional neutrino flux , atmospheric prompt neutrinos and atmospheric muons, respectively.



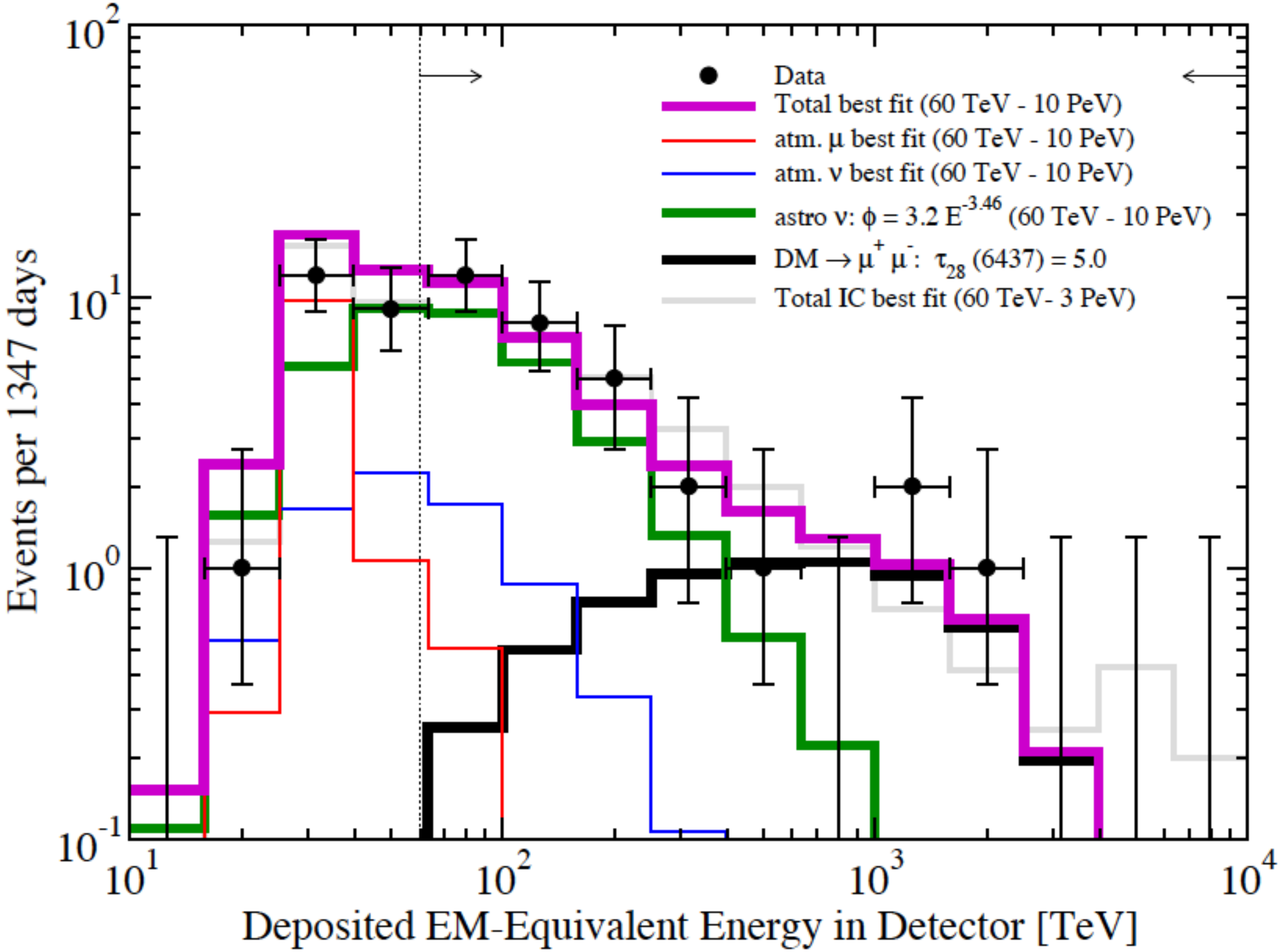
Data
Total best fit (60 TeV - 10 PeV)
atm. μ best fit (60 TeV - 10 PeV)
atm. ν best fit (60 TeV - 10 PeV)
astro ν: $\phi = 0.83\ E^{-2.32}$ (60 TeV - 10 PeV)
DM → b $\bar{b}$: τ_{26} (1066) = 8.9
Total IC best fit (60 TeV- 3 PeV)
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{1}
10^{2}
10^{3}
10^{4}



Data
Total best fit (60 TeV - 10 PeV)
atm. μ best fit (60 TeV - 10 PeV)
atm. ν best fit (60 TeV - 10 PeV)
astro ν: $\phi = 2.5\ E^{-3.66}$ (60 TeV - 10 PeV)
DM $\rightarrow W^+ W^-$: τ_{28} (4860) = 1.4
Total IC best fit (60 TeV- 3 PeV)
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]



Data
Total best fit (60 TeV - 10 PeV)
atm. μ best fit (60 TeV - 10 PeV)
atm. ν best fit (60 TeV - 10 PeV)
astro ν: φ = 3.2 E^-3.48 (60 TeV - 10 PeV)
DM → ν_μ ν̄_μ: τ_28 (4130) = 2.4
Total IC best fit (60 TeV- 3 PeV)
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]

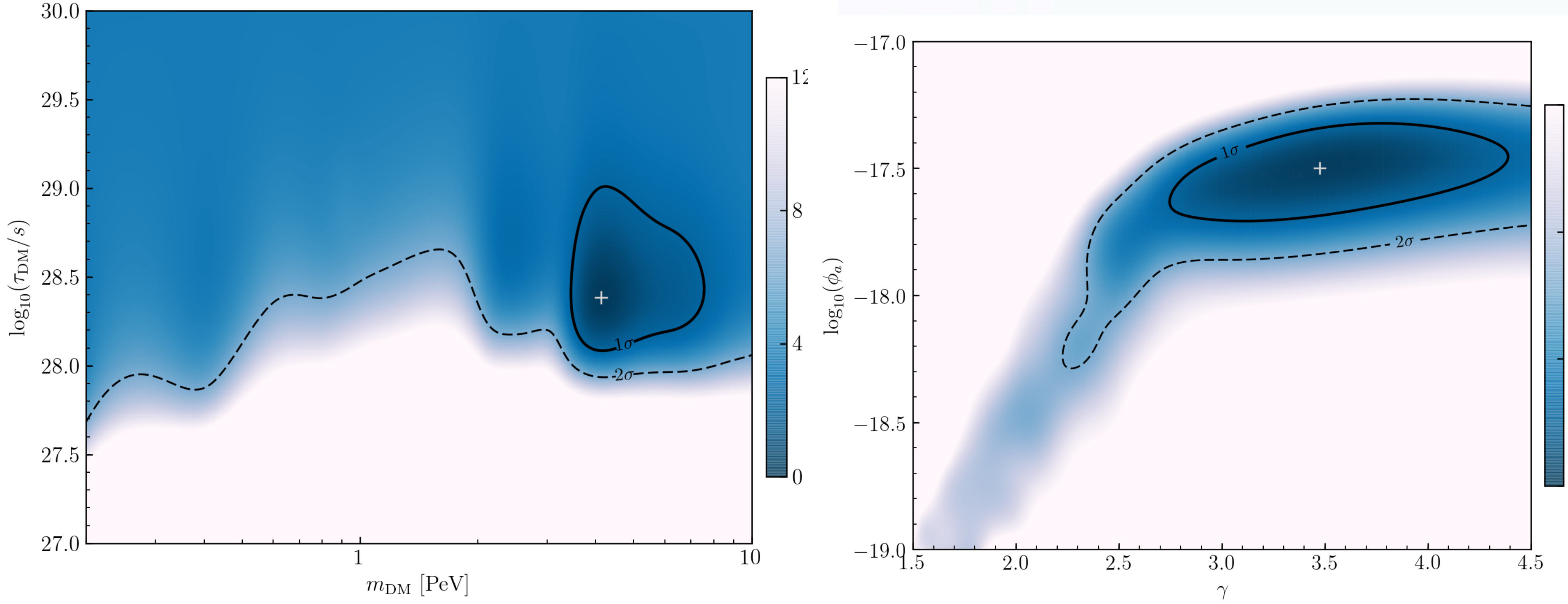


Data
Total best fit (60 TeV - 10 PeV)
atm. μ best fit (60 TeV - 10 PeV)
atm. ν best fit (60 TeV - 10 PeV)
astro ν: φ = 3.2 E^-3.46 (60 TeV - 10 PeV)
DM → μ+ μ-: τ28 (6437) = 5.0
Total IC best fit (60 TeV- 3 PeV)
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]
10^2
10^1
10^0
10^-1
10^1
10^2
10^3
10^4

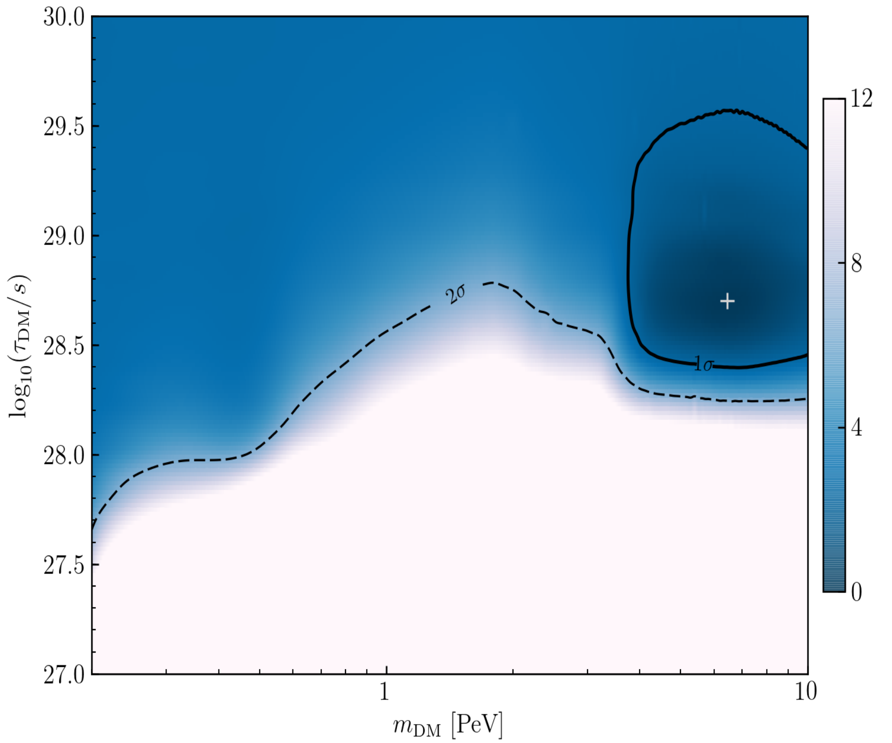
. Best-fits to parameter space (60 TeV threshold) $\left[\tau_{27} = \tau_{\rm DM}/\left(10^{27}\ {\rm s}\right)\right]$

Channel	$m_{\rm DM}$ [TeV]	$N_{\rm DM}$	τ_{27}	$N_{\rm a}$	ϕ_{18}	γ
$b\bar{b}$	1066.09	12.92	0.89	13.79	0.83	2.32
W^+W^-	4859.92	11.31	14.26	15.50	2.54	3.66
$\mu^+\mu^-$	6436.76	6.26	50.12	20.66	3.16	3.46
$\nu_\mu\bar{\nu}_\mu$	4130.00	6.34	24.21	20.57	3.16	3.48

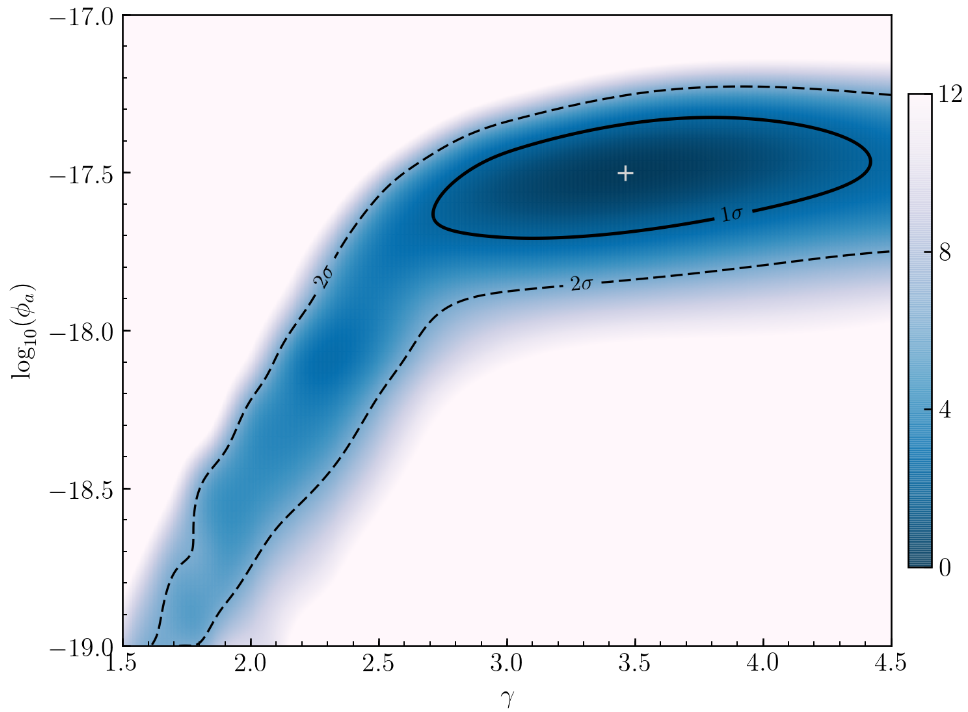
$DM \to \nu_\mu \bar{\nu}_\mu$



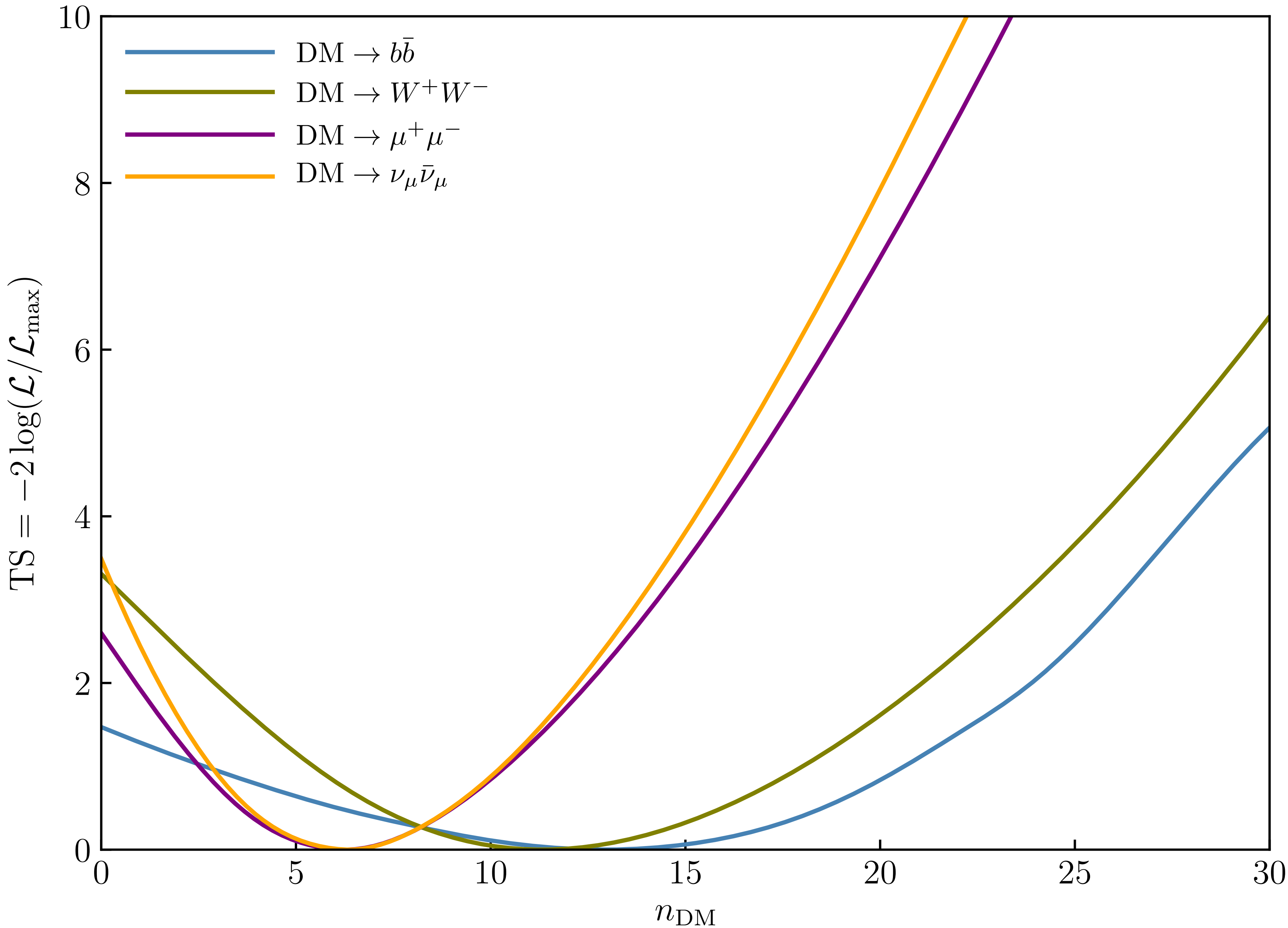
$DM \to \mu^+\mu^-$



30.0
29.5
29.0
28.5
28.0
27.5
27.0
1
10
$m_{\rm DM}$ [PeV]
$\log_{10}(\tau_{\rm DM}/s)$
2σ
1σ
12
8
4
0

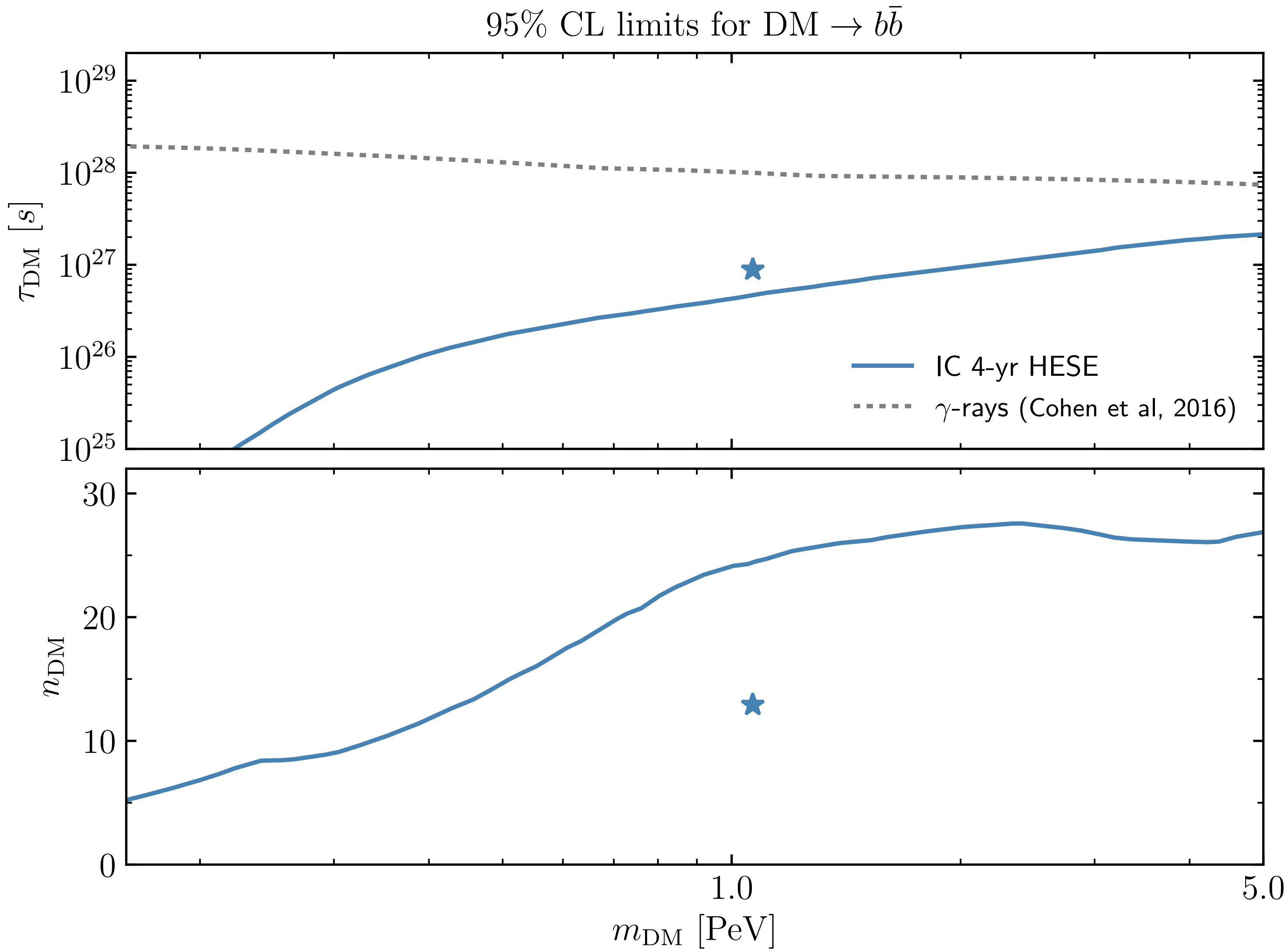


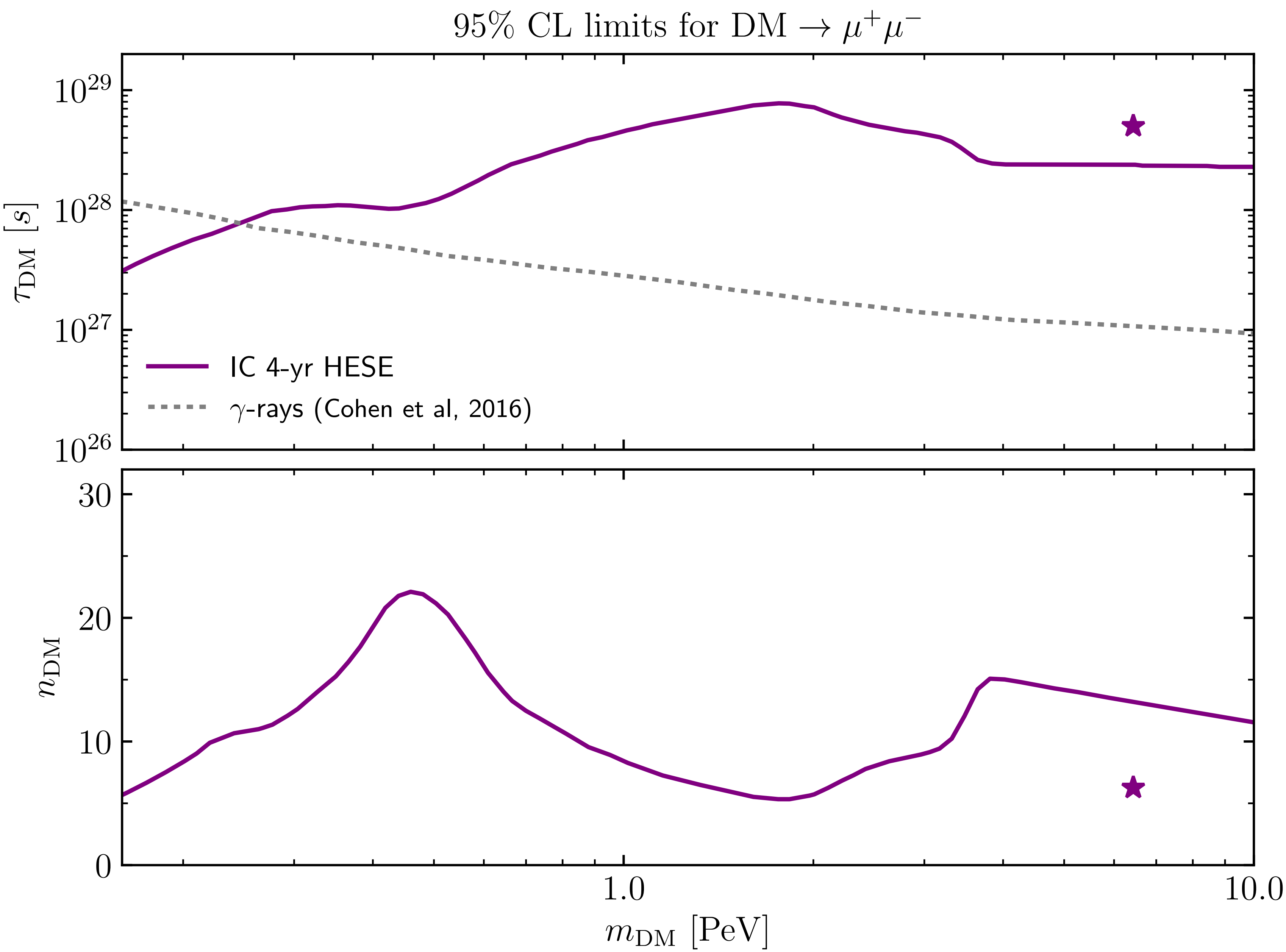
−17.0
−17.5
−18.0
−18.5
−19.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
γ
$\log_{10}(\phi_a)$
2σ
1σ
12
8
4
0



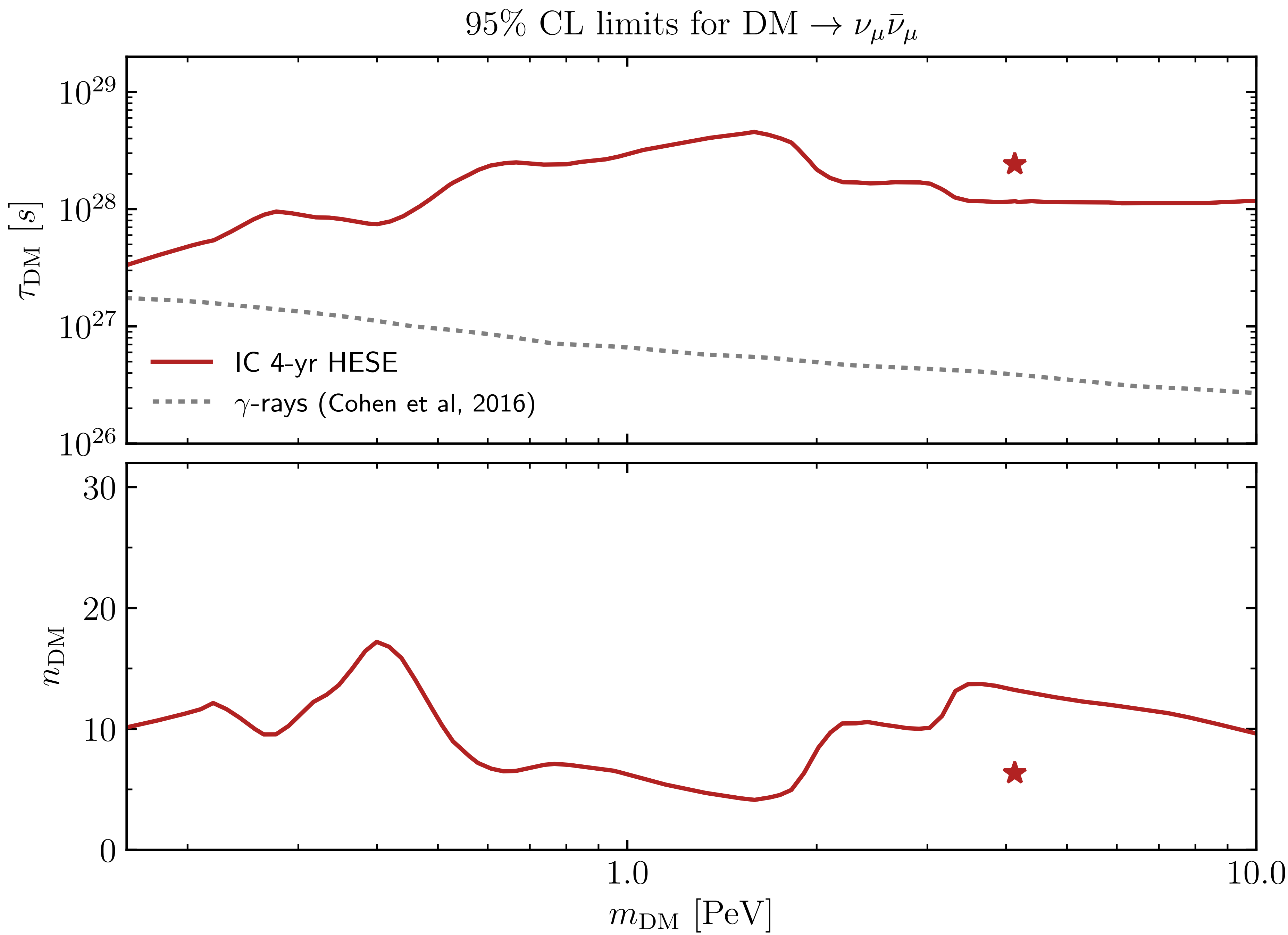
$\mathrm{DM} \to b\bar{b}$
$\mathrm{DM} \to W^+W^-$
$\mathrm{DM} \to \mu^+\mu^-$
$\mathrm{DM} \to \nu_\mu\bar{\nu}_\mu$
$\mathrm{TS} = -2\log(\mathcal{L}/\mathcal{L}_{\max})$
n_{DM}
0
2
4
6
8
10
0
5
10
15
20
25
30

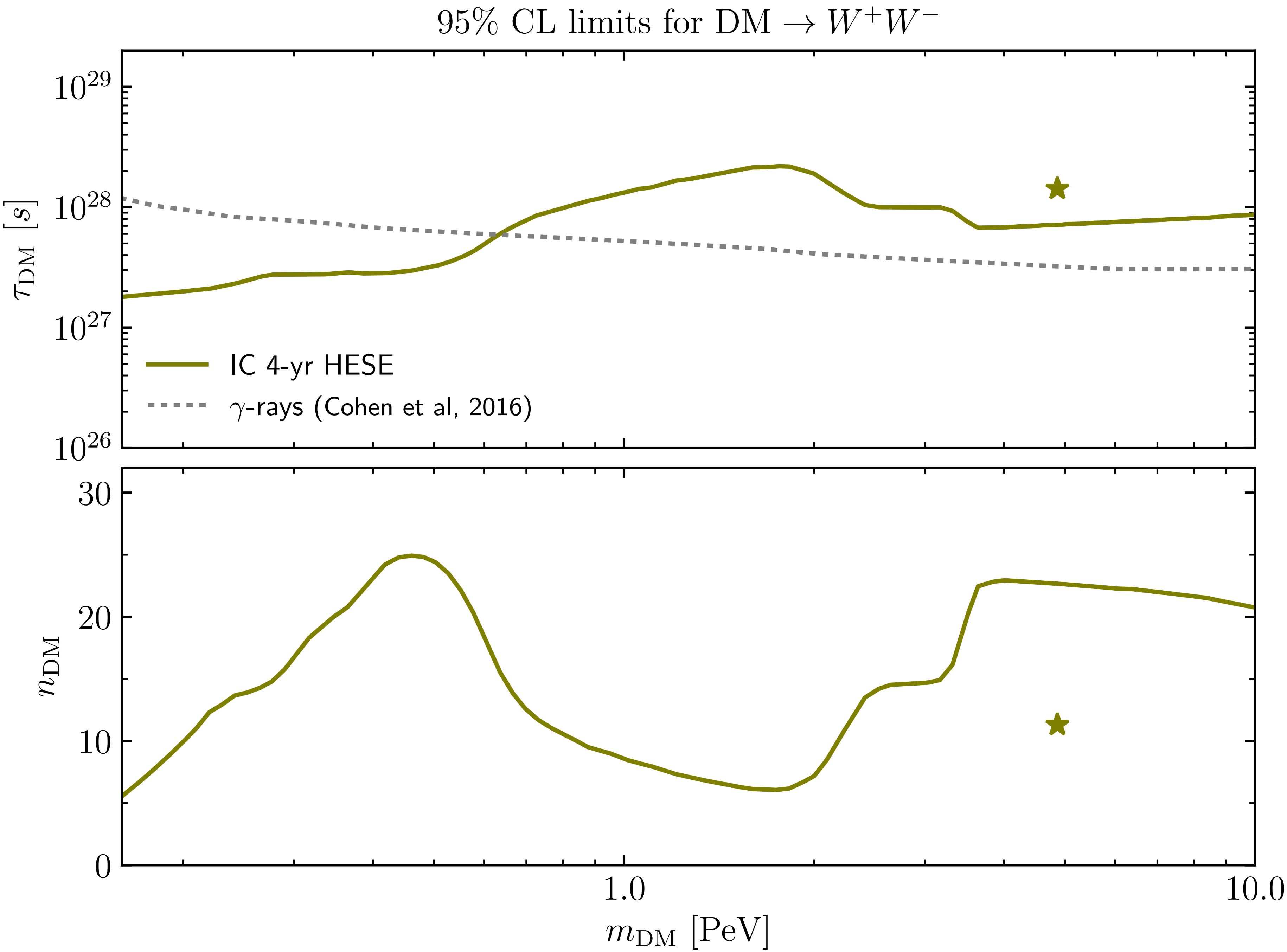
Limits on DM lifetime





95% CL limits for DM → $\mu^+\mu^-$
τ_{DM} [s]
10^{29}
10^{28}
10^{27}
10^{26}
IC 4-yr HESE
γ-rays (Cohen et al, 2016)
n_{DM}
30
20
10
0
1.0
10.0
m_{DM} [PeV]


95% CL limits for DM → $\nu_\mu\bar{\nu}_\mu$
τ_{DM} [s]
10^{29}
10^{28}
10^{27}
10^{26}
IC 4-yr HESE
γ-rays (Cohen et al, 2016)
n_{DM}
30
20
10
0
1.0
10.0
m_{DM} [PeV]



95% CL limits for DM → W^+W^-
10^{29}
10^{28}
10^{27}
10^{26}
τ_{DM} [s]
IC 4-yr HESE
γ-rays (Cohen et al, 2016)
30
20
10
0
n_{DM}
1.0
10.0
m_{DM} [PeV]

Summary

- We find that HESE data can be best described with the combination of the astrophysical neutrino flux and the dark matter decay
- Best fit values for DM mass and lifetime depend on the channel, for DM decay into muon neutrinos or muons, DM mass is of the order of several PeV, describing PeV events, while astrophysical flux describes lower energy flux
- DM decay into $b\bar{b}$ is disfavored

- We find limits on DM lifetime for wide range of DM mass, which are stronger than those obtained from gamma-ray data
- Future IceCube data could provide even further confirmation of the lack of events beyond few PeV, thus confirming that astrophysical flux cuts off and PeV events observed so far might be due to the DM decay component