DPF 2017

Probing Decaying Heavy Dark Matter with 4-year IceCube HESE data

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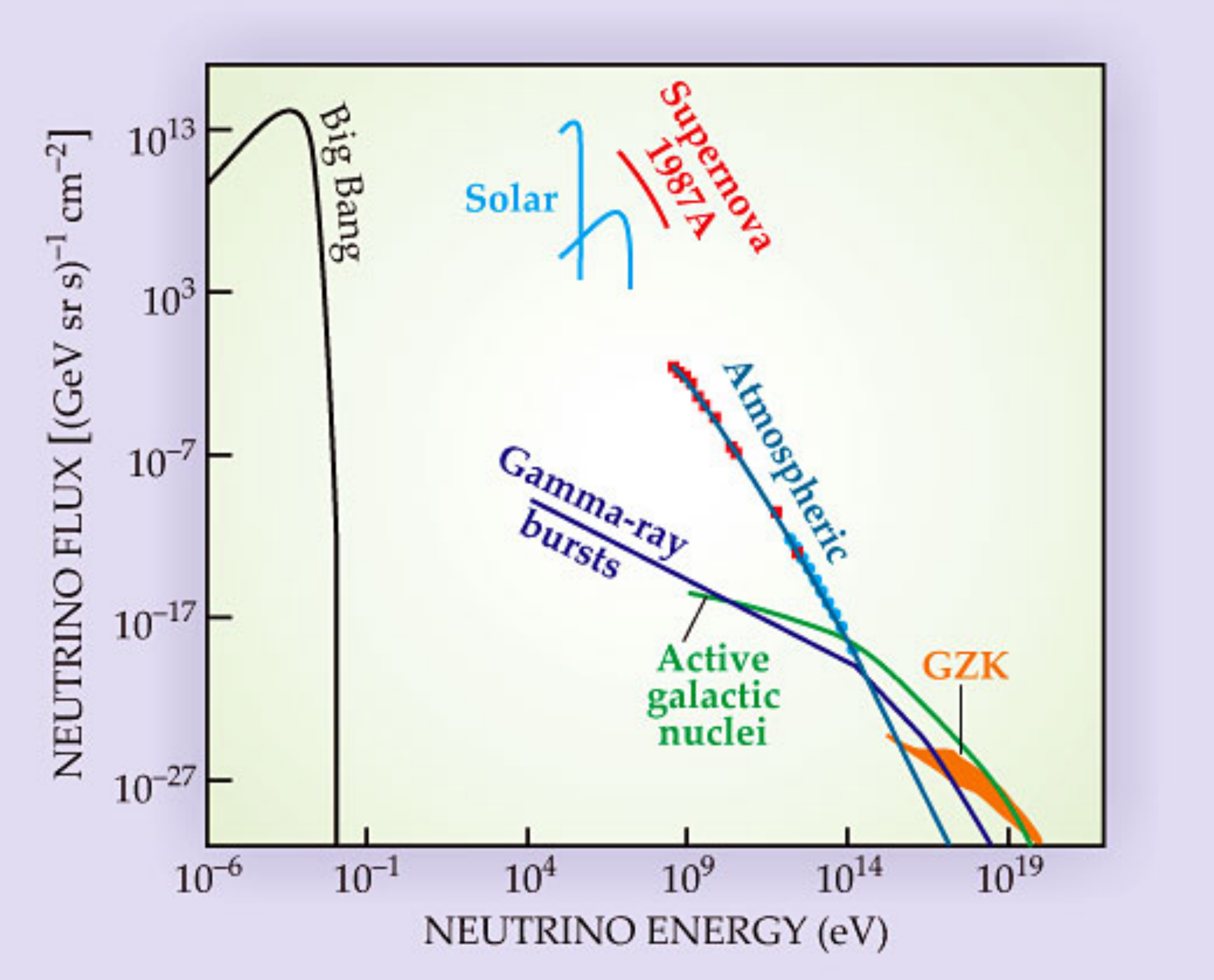
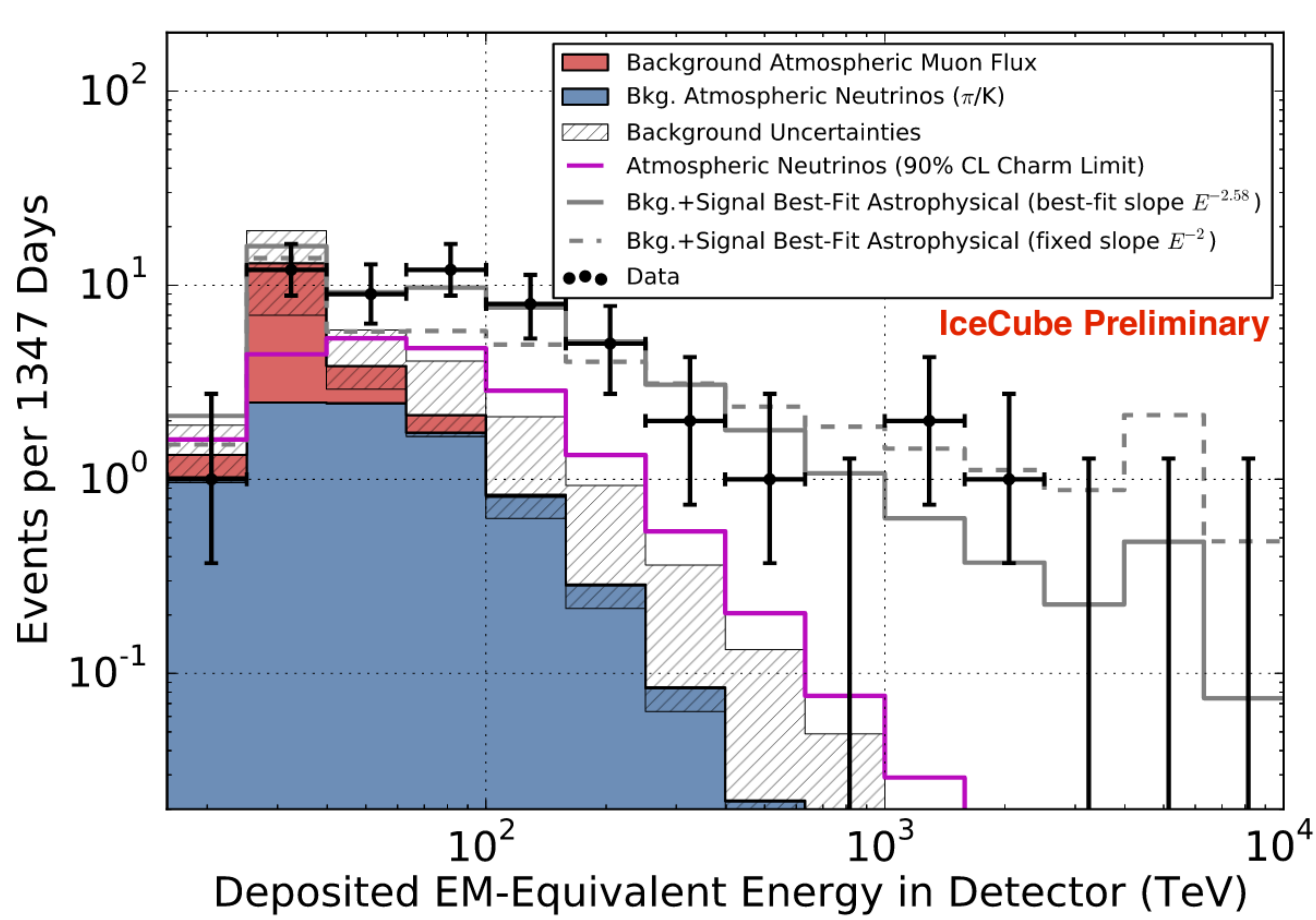
Atri Bhattacharya, Arman Esmaili, Sergio Palomares-Ruiz and Ina Sarcevic, arXiv: 1706.05746, JCAP 1707 (2017) no.07, 027.

Neutrino fluxes



First Observation of HE Cosmic Neutrinos



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

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

with the normalization

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

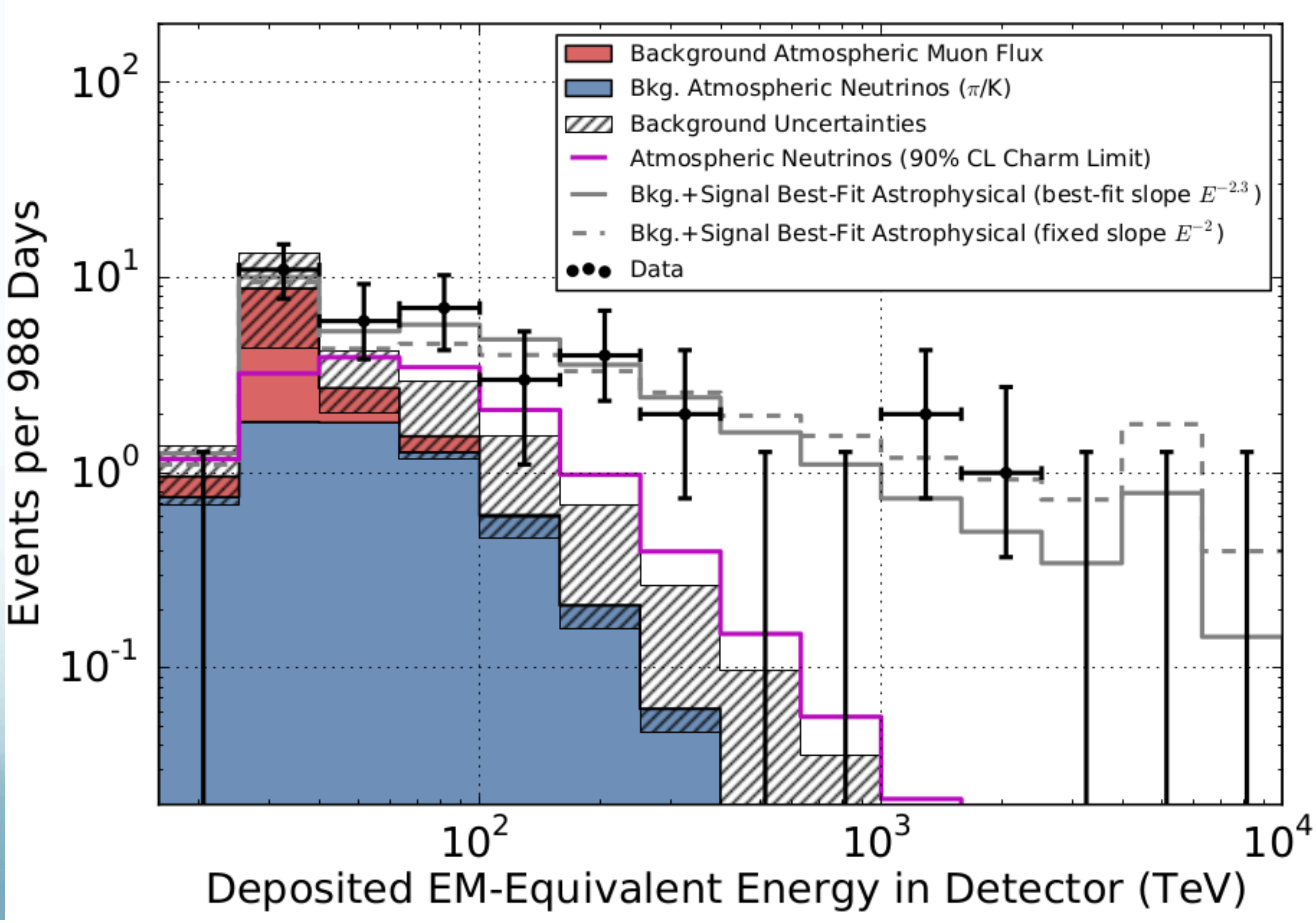
- A very different IceCube analysis of through-going muon tracks passing through the detector with higher energy threshold of 200TeV (6 year data) points to a much flatter flux

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

- 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?



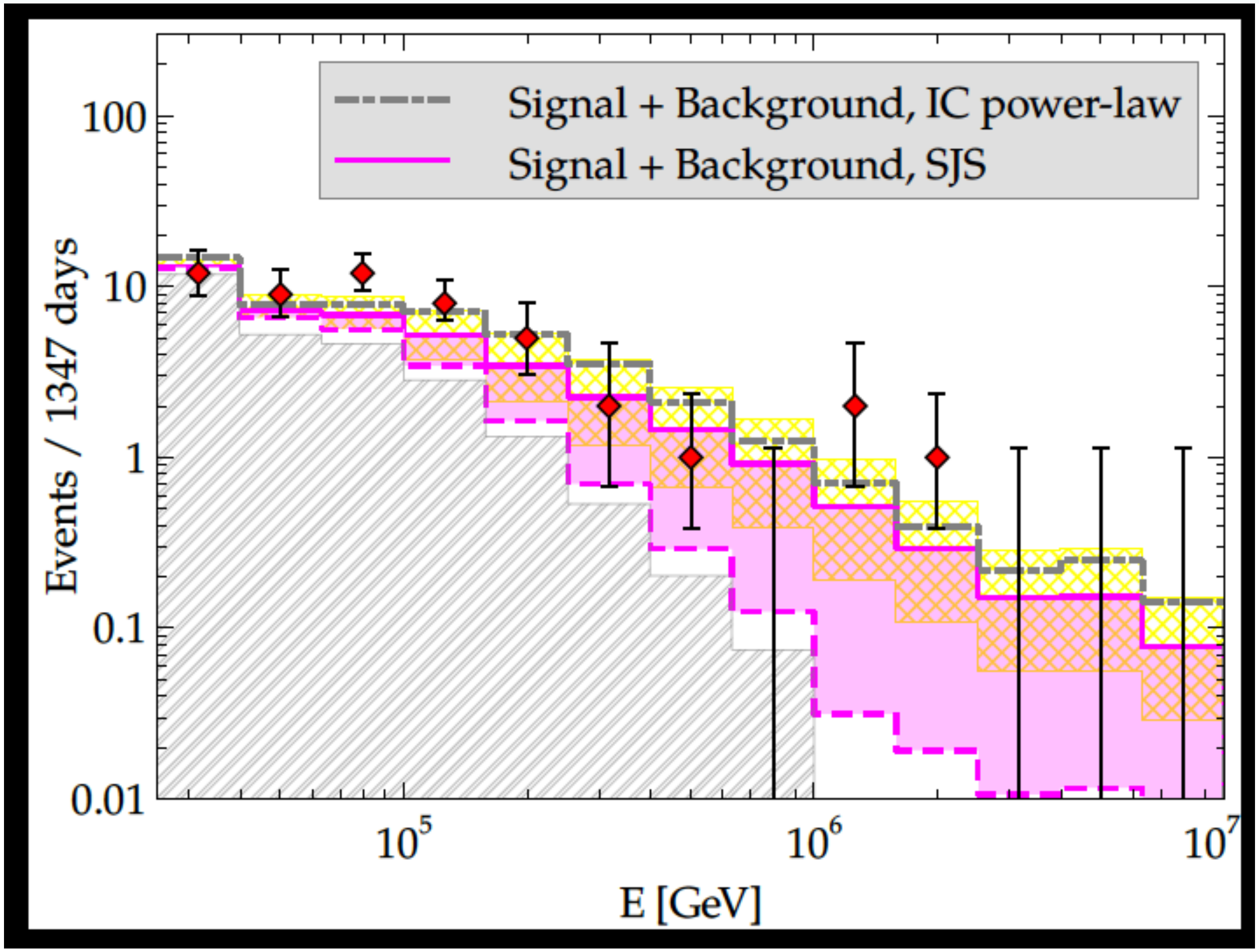


Figure 3: Predicted 988-day total (shower + track) event rates at IC from slow-jet sources for $L_j = 10^{50}$ erg s^{-1}, $\Gamma_j = 5\,, E'_{\rm max} = 10.2$ PeV and $\xi_{\rm sn} = 1$. The solid shaded histogram reflects the QCD scale uncertainties in the charm pair production cross section calculation, 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?

- Could the observed neutrino flux be due to only dark matter decaying into multiple channels?

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

A. Bhattacharya, A. Esmaili, S. Palomares-Ruiz and I. Sarcevic,
arXiv:1706.05746, JCAP 1707 (2017) no.7, 027.

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:

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

Dark Matter Decay Modes

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

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

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

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

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

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

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

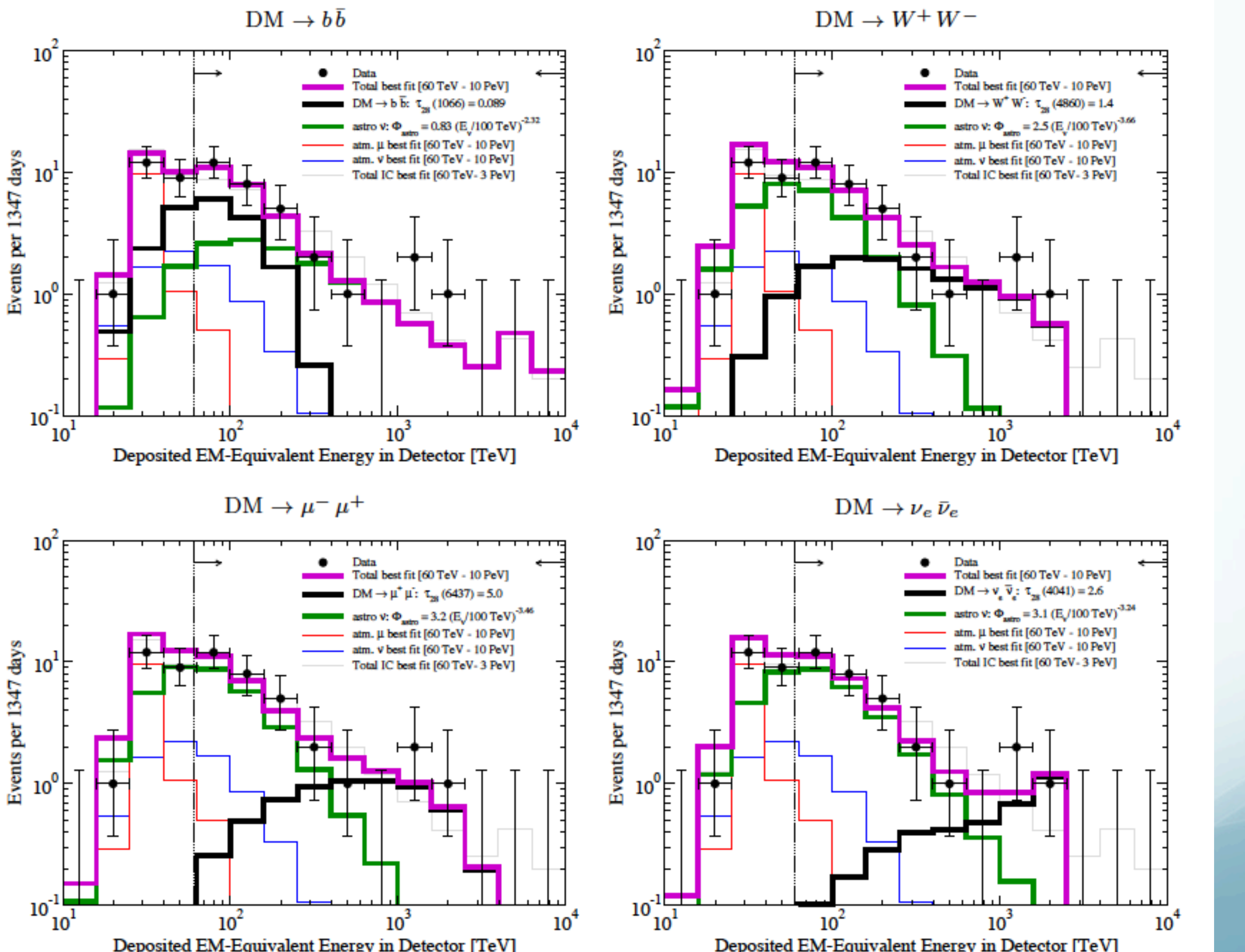
$$DM \to \bar{\nu}_\tau \nu_\tau$$

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}).



DM → b b̄
Data
Total best fit [60 TeV - 10 PeV]
DM → b b̄: τ28 (1066) = 0.089
astro ν: Φastro = 0.83 (Eν/100 TeV)^-2.32
atm. μ best fit [60 TeV - 10 PeV]
atm. ν best fit [60 TeV - 10 PeV]
Total IC best fit [60 TeV- 3 PeV]
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]
DM → W+ W−
Data
Total best fit [60 TeV - 10 PeV]
DM → W+ W-: τ28 (4860) = 1.4
astro ν: Φastro = 2.5 (Eν/100 TeV)^-3.66
atm. μ best fit [60 TeV - 10 PeV]
atm. ν best fit [60 TeV - 10 PeV]
Total IC best fit [60 TeV- 3 PeV]
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]
DM → μ− μ+
Data
Total best fit [60 TeV - 10 PeV]
DM → μ+ μ-: τ28 (6437) = 5.0
astro ν: Φastro = 3.2 (Eν/100 TeV)^-3.46
atm. μ best fit [60 TeV - 10 PeV]
atm. ν best fit [60 TeV - 10 PeV]
Total IC best fit [60 TeV- 3 PeV]
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]
DM → νe ν̄e
Data
Total best fit [60 TeV - 10 PeV]
DM → νe ν̄e: τ28 (4041) = 2.6
astro ν: Φastro = 3.1 (Eν/100 TeV)^-3.24
atm. μ best fit [60 TeV - 10 PeV]
atm. ν best fit [60 TeV - 10 PeV]
Total IC best fit [60 TeV- 3 PeV]
Events per 1347 days
Deposited EM-Equivalent Energy in Detector [TeV]

Table 2. Best-fit values for $\boldsymbol{\theta} = \{N_{\rm DM}(\tau_{\rm DM}), m_{\rm DM}, N_{\rm astro}(\phi_{\rm astro}), \gamma\}$, where $\phi_{\rm astro}$ is given in units of 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}. The deposited energy interval is [60 TeV – 10 PeV].

Decay channel	$N_{\rm DM}(\tau_{\rm DM}[10^{28}$ s$])$	$m_{\rm DM}$ [TeV]	$N_{\rm astro}(\phi_{\rm astro})$	γ
$u\bar{u}$	10.2 (0.02)	522	16.6 (1.15)	2.42
$b\bar{b}$	12.9 (0.09)	1066	13.8 (0.83)	2.32
$t\bar{t}$	16.1 (0.58)	11134	10.7 (1.87)	3.91
W^+W^-	11.3 (1.43)	4860	15.5 (2.54)	3.66
ZZ	10.5 (1.56)	4800	16.3 (2.63)	3.61
hh	13.6 (0.17)	606	13.2 (0.76)	2.29
e^+e^-	5.0 (1.15)	4116	21.9 (3.16)	3.33
$\mu^+\mu^-$	6.3 (5.00)	6437	20.7 (3.16)	3.46
$\tau^+\tau^-$	7.6 (4.37)	6749	19.3 (3.03)	3.53
$\nu_e\bar{\nu}_e$	3.7 (2.58)	4041	22.7 (3.15)	3.24
$\nu_\mu\bar{\nu}_\mu$	6.4 (2.39)	4133	20.6 (3.16)	3.48
$\nu_\tau\bar{\nu}_\tau$	6.7 (2.27)	4117	20.1 (3.12)	3.50

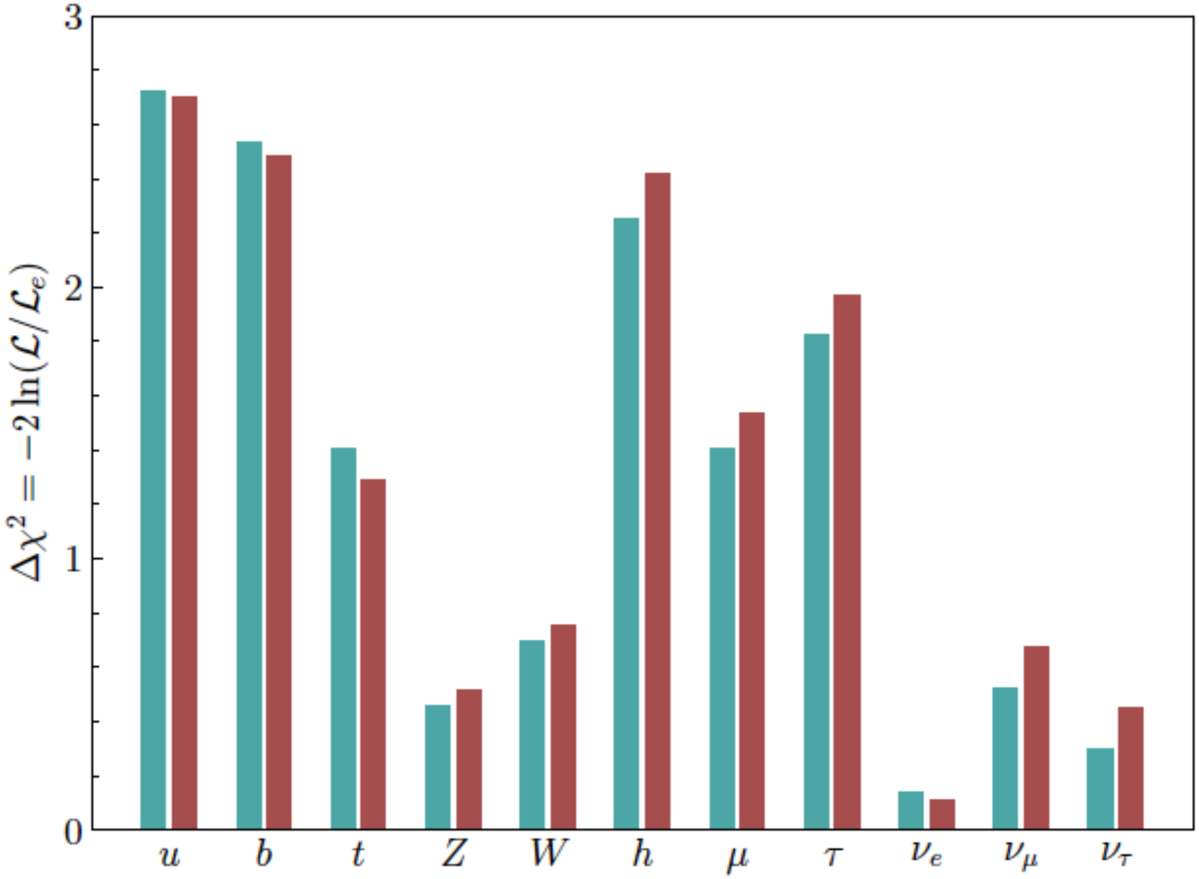
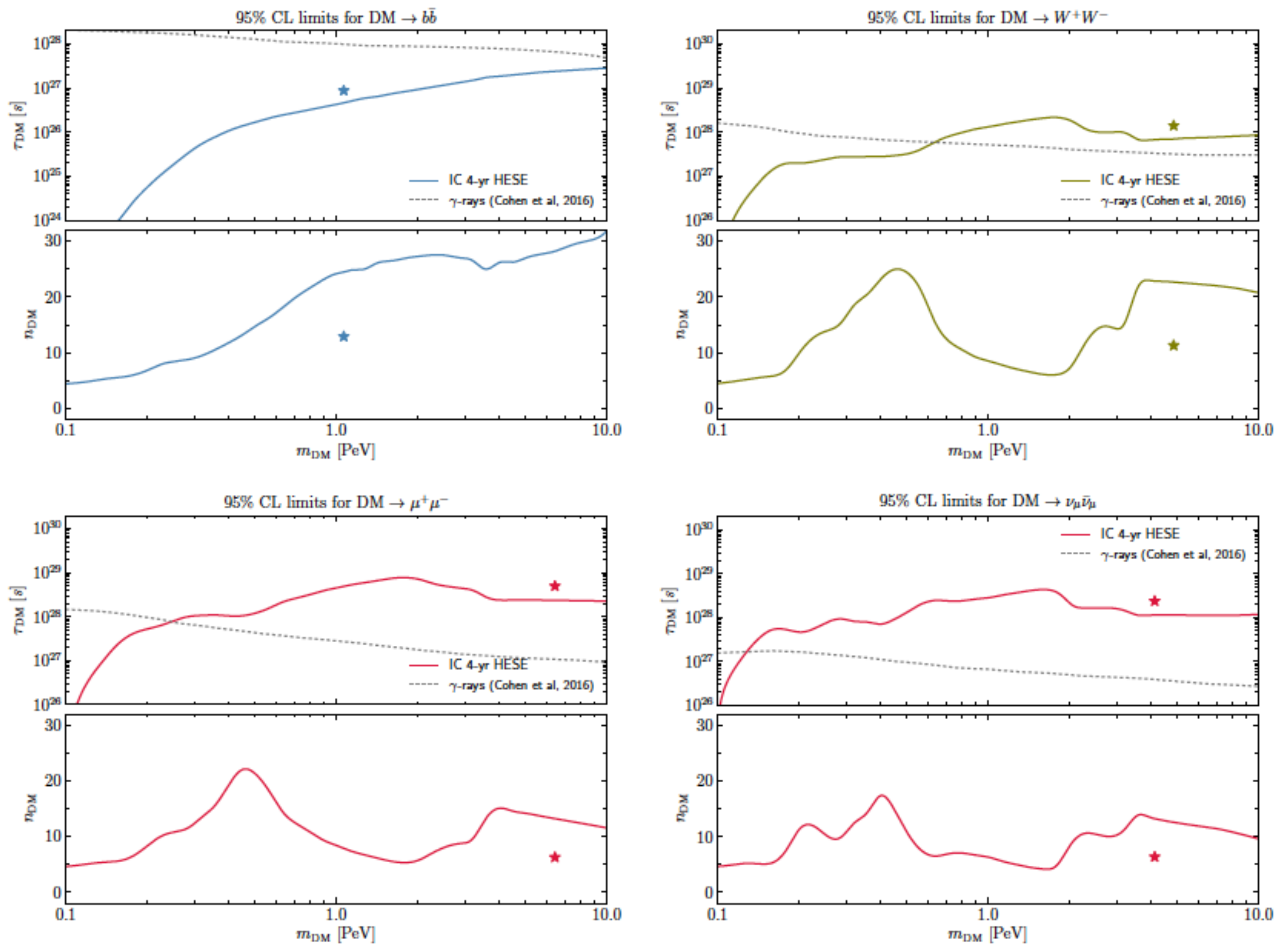


Figure 5. Channel-by-channel comparison of $\Delta\chi^2$ at best-fit, computed against the DM $\rightarrow$ e^+e^- channel, which gives the overall best-fit. Results for 60 TeV threshold (green) and 10 TeV threshold (brown) are qualitatively similar and indicate the preference for harder spectra.

Limits on DM lifetime



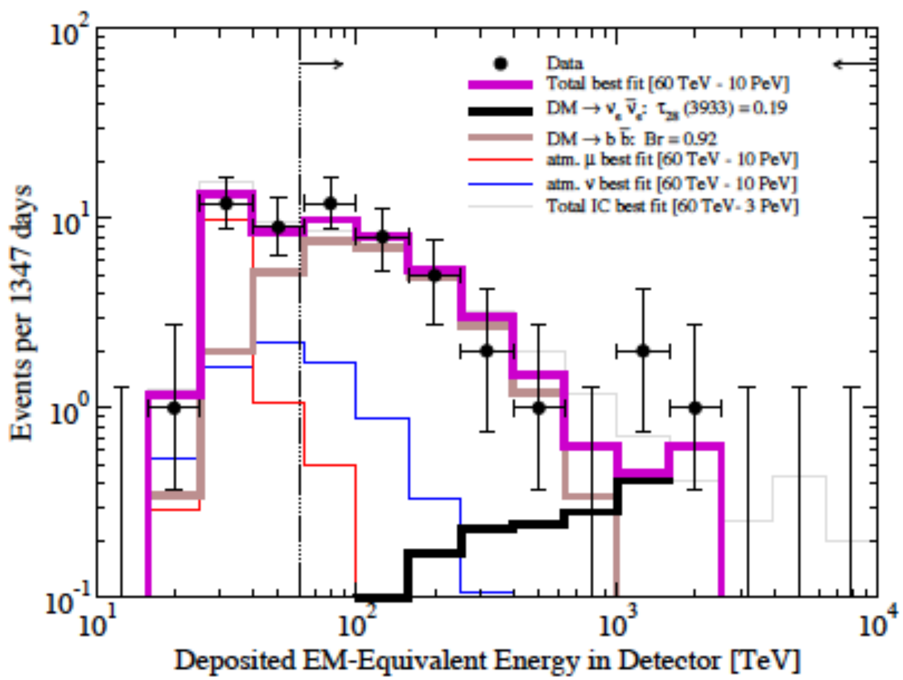
Could Dark Matter alone account for IceCube HESE events?

- Consider DM decay into two channels, one that would describe low energy data and the other high energy (PeV) events
- We have considered different combinations, finding best fit parameters for: DM mass, lifetime and branching fraction (only 3 parameters, less than in case of DM+ASTRO)

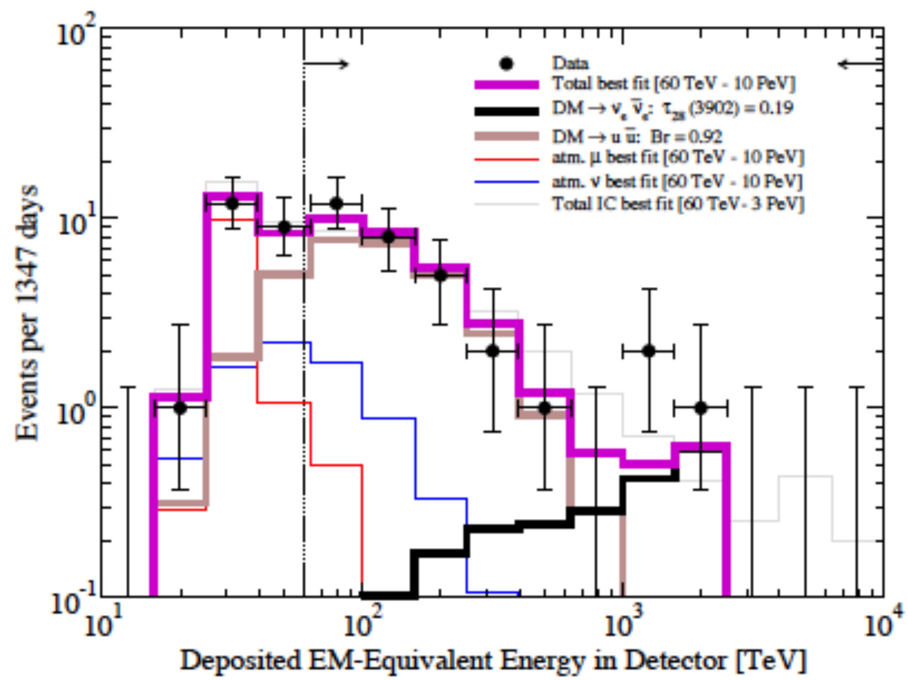
Table 5. Best-fit values for DM-only two-channel decays (DM $\to p_1\,\bar{p}_1,\ p_2\,\bar{p}_2$) defined by $\boldsymbol{\theta}_{2c} = \{N_{\rm DM}, m_{\rm DM}, {\rm BR}\}$, where ${\rm BR} = \Gamma_{{\rm DM}\to p_1\,\bar{p}_1} / (\Gamma_{{\rm DM}\to p_1\,\bar{p}_1} + \Gamma_{{\rm DM}\to p_2\,\bar{p}_2})$ is the branching ratio for decays to $p_1\,\bar{p}_1$. The EM-equivalent deposited energy interval is [60 TeV–10 PeV].

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

DM $\rightarrow \{92\%\, b\,\bar{b},\ 8\%\, \nu_e\, \bar{\nu}_e\}$



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



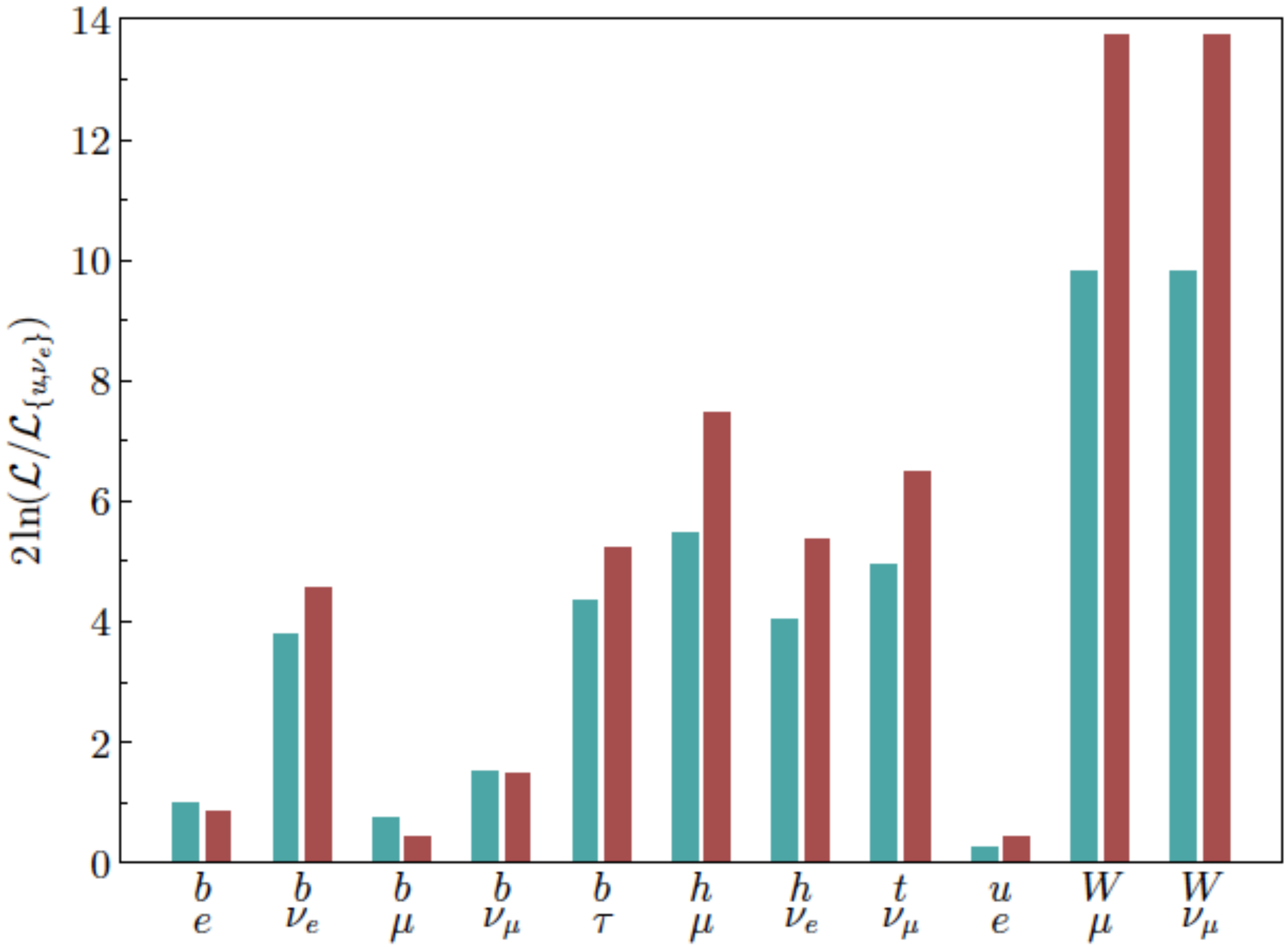


Figure 7. Channel-by-channel comparison of $\Delta\chi^2$ at best-fit, computed against the DM $\to \{u\bar{u},\, e^+e^-\}$ combination, which gives the overall best-fit. Results for 60 TeV threshold (green) and 10 TeV threshold (brown) are qualitatively similar and indicate the preference for combinations of a soft and a very hard spectra.

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 leptons, 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
- 6-year IceCube data provides 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
- Interesting possibility that IC HESE data is from decaying heavy DM only: DM mass in PeV range and DM decay into quarks and leptons