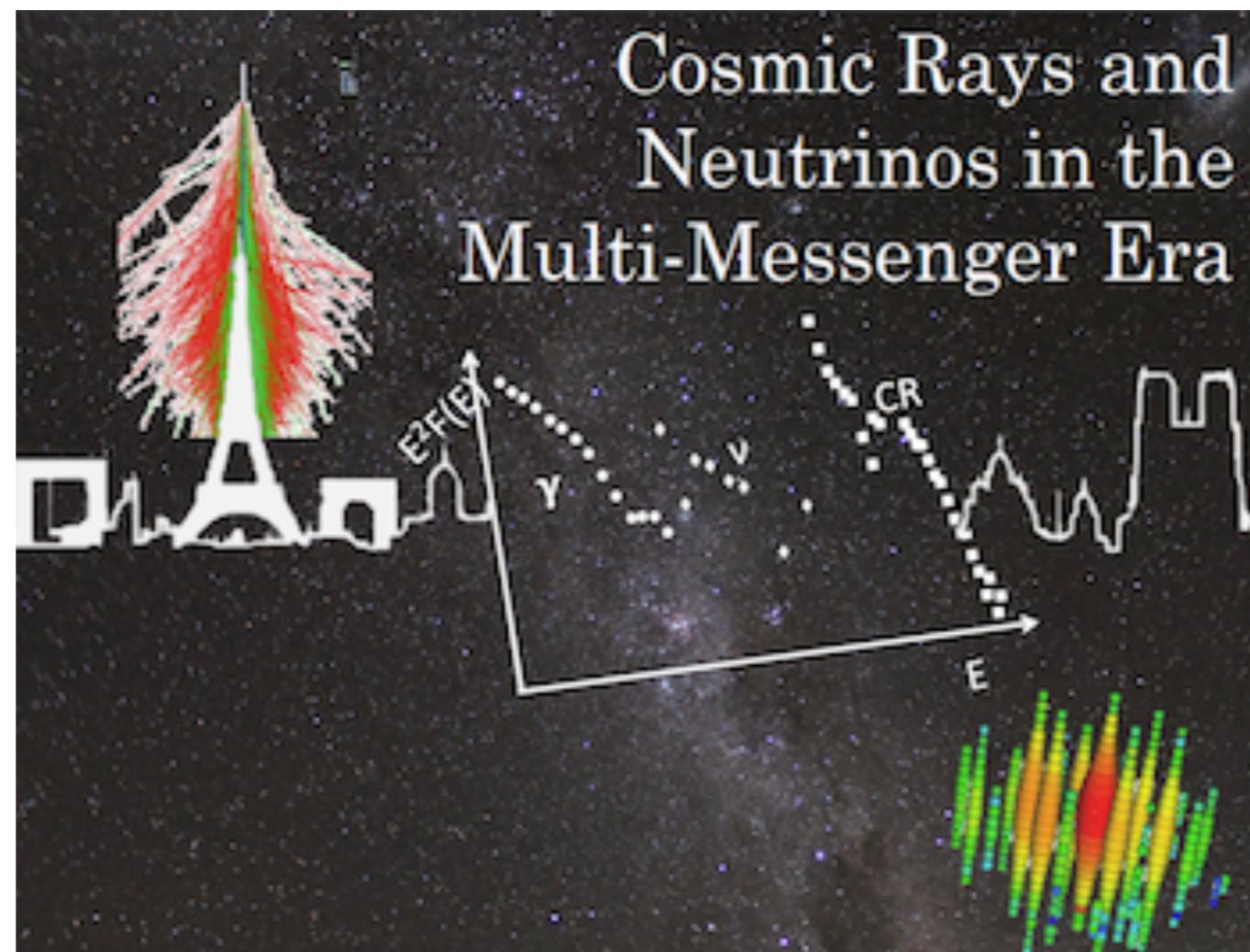


(Heavy) Dark Matter @ Neutrino Telescopes

Arman Esmaili

Pontifícia Universidade Católica
do Rio de Janeiro (PUC-Rio), Brazil



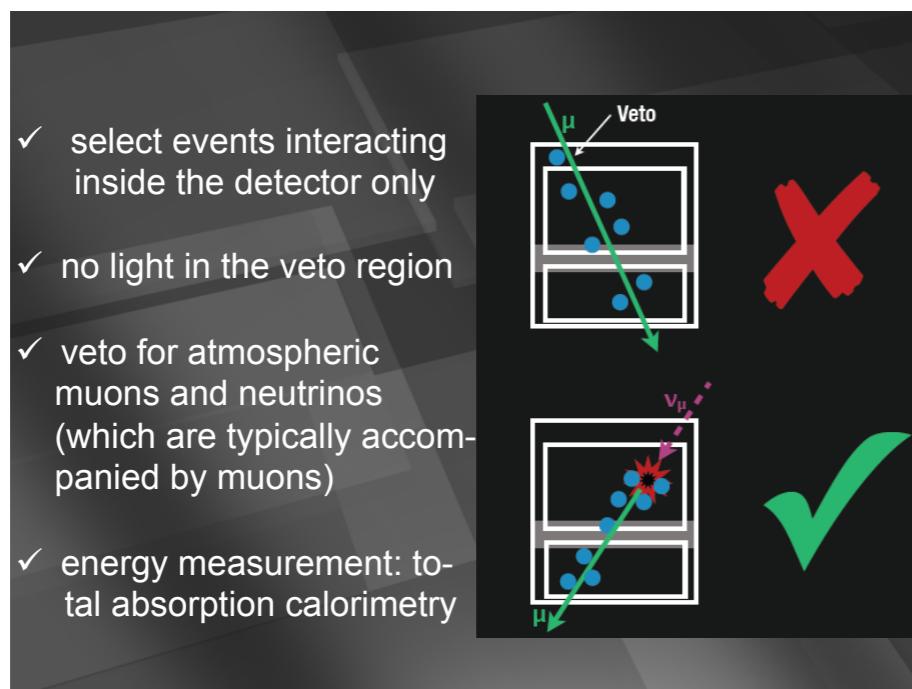
Observation of High Energy Neutrinos in IceCube

✓ The two PeV cascade events, 616 days livetime

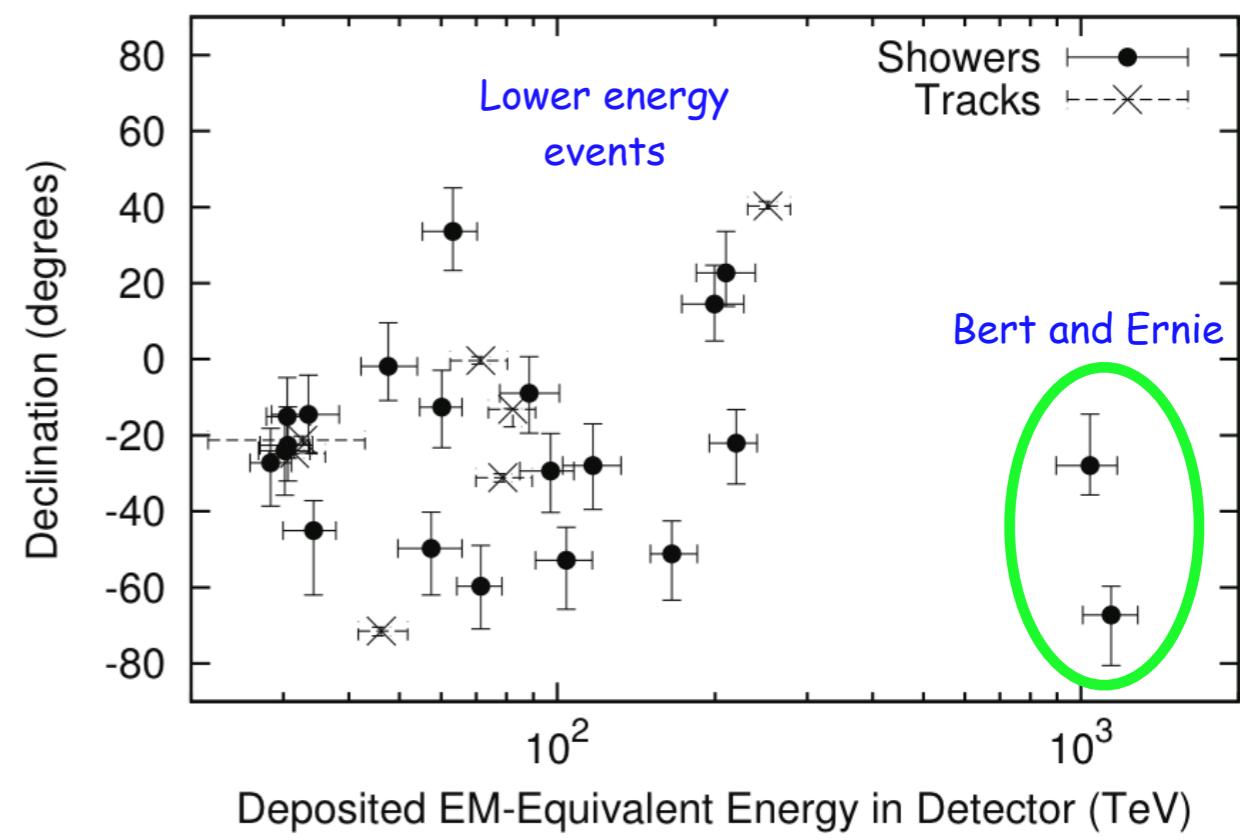
M. G. Aartsen et al, PRL (2013)



HESE analysis



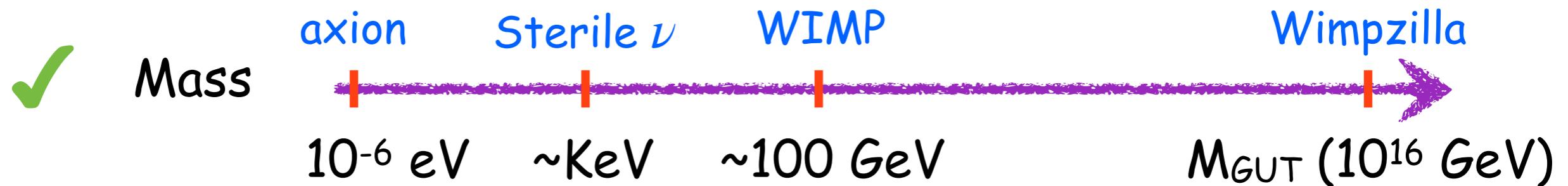
IceCube Coll., arXiv:1311.5238



A note on Dark Matter

DM exist!

What we do not know?



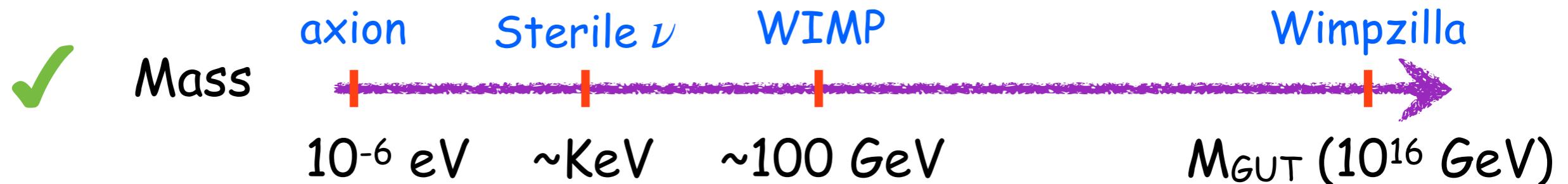
"WIMP" paradigm ?

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

A note on Dark Matter

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⚠ "WIMP" paradigm ?

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

caution: streetlight effect



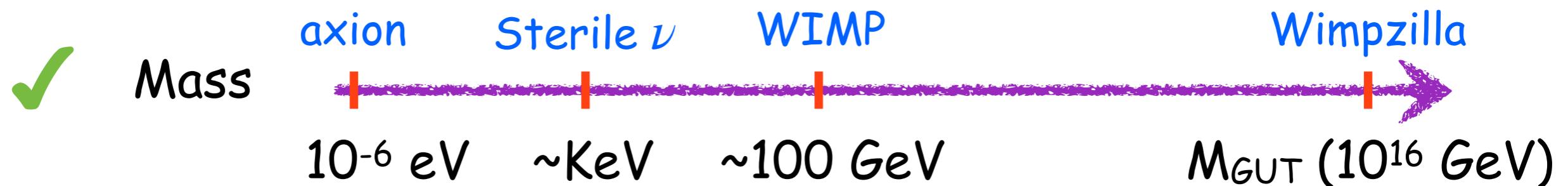
Mulla
Nasreddin



A note on Dark Matter

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⚠ “WIMP” paradigm ?

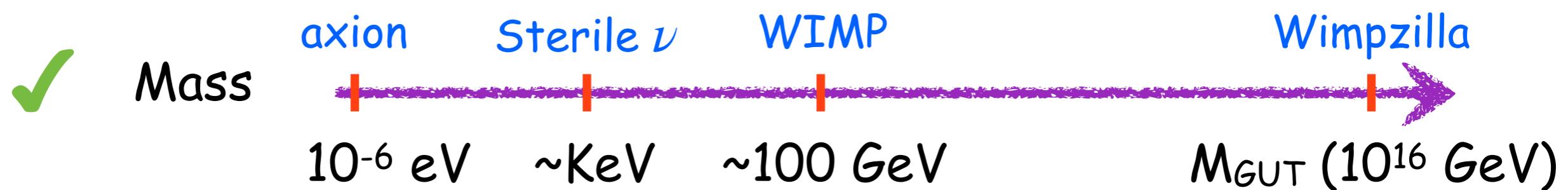
Note that WIMP paradigm is a “particle physics” conjecture, needs to be validated at colliders



A note on Dark Matter

DM exist!

What We Do Not Know?



⚠ "WIMP" paradigm ?

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

✓ Lifetime: stable (∞) or

$$\tau_{\text{DM}} > 4.3 \times 10^{17} \text{ s} \quad (\text{age of Universe})$$

$$\tau_{\text{DM}} > 2.2 \times 10^{19} \text{ s} \quad (\text{CMB}) \quad \text{Y. Gong and X. Chen, PRD77 (2008), arXiv:0802.2296}$$

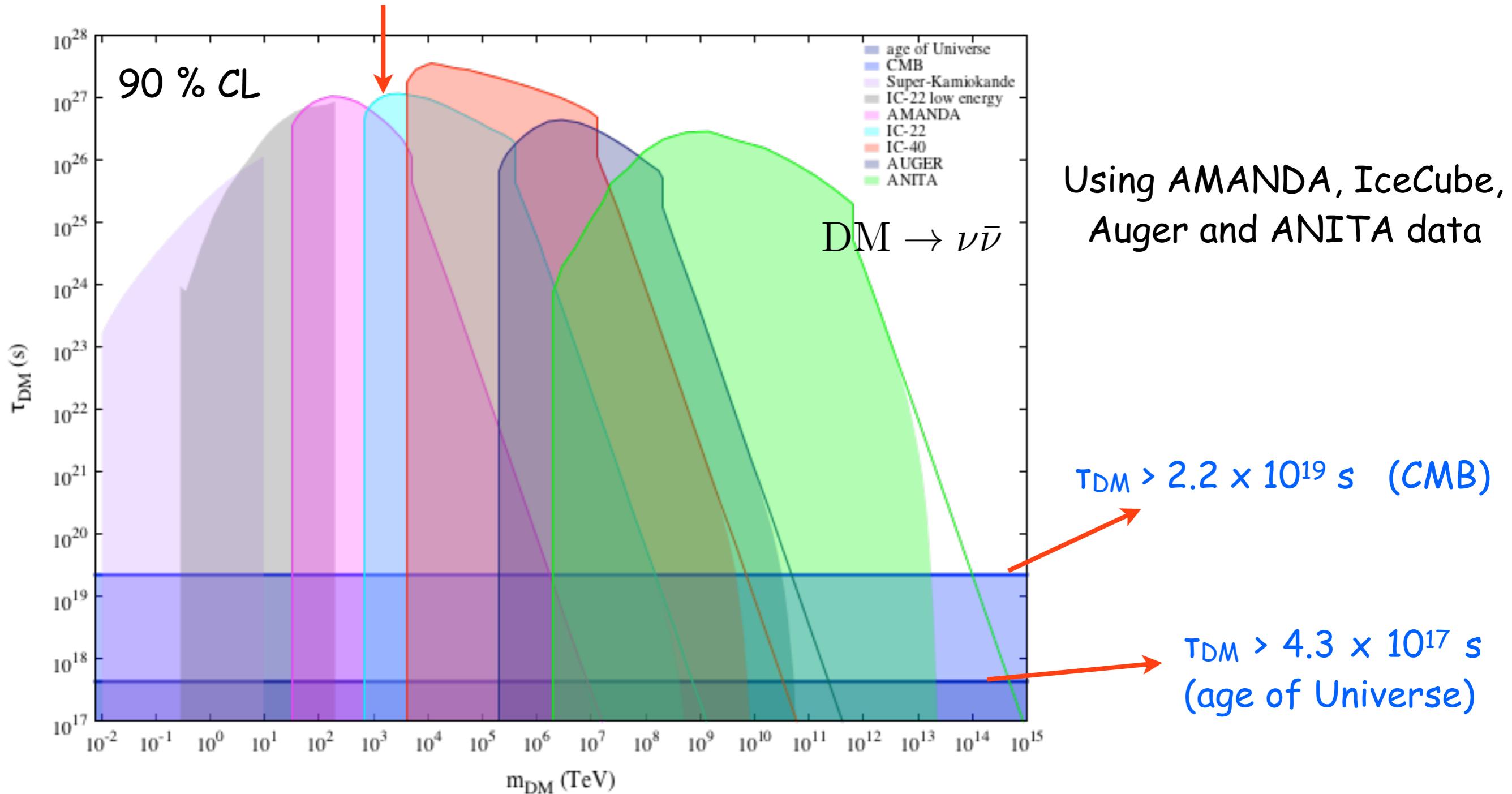
✓ Possible decay and/or annihilation channels

✓ ...

Limits on lifetime from neutrino experiments before IceCube discovery

✓ Lifetime: stable (∞) or
this talk

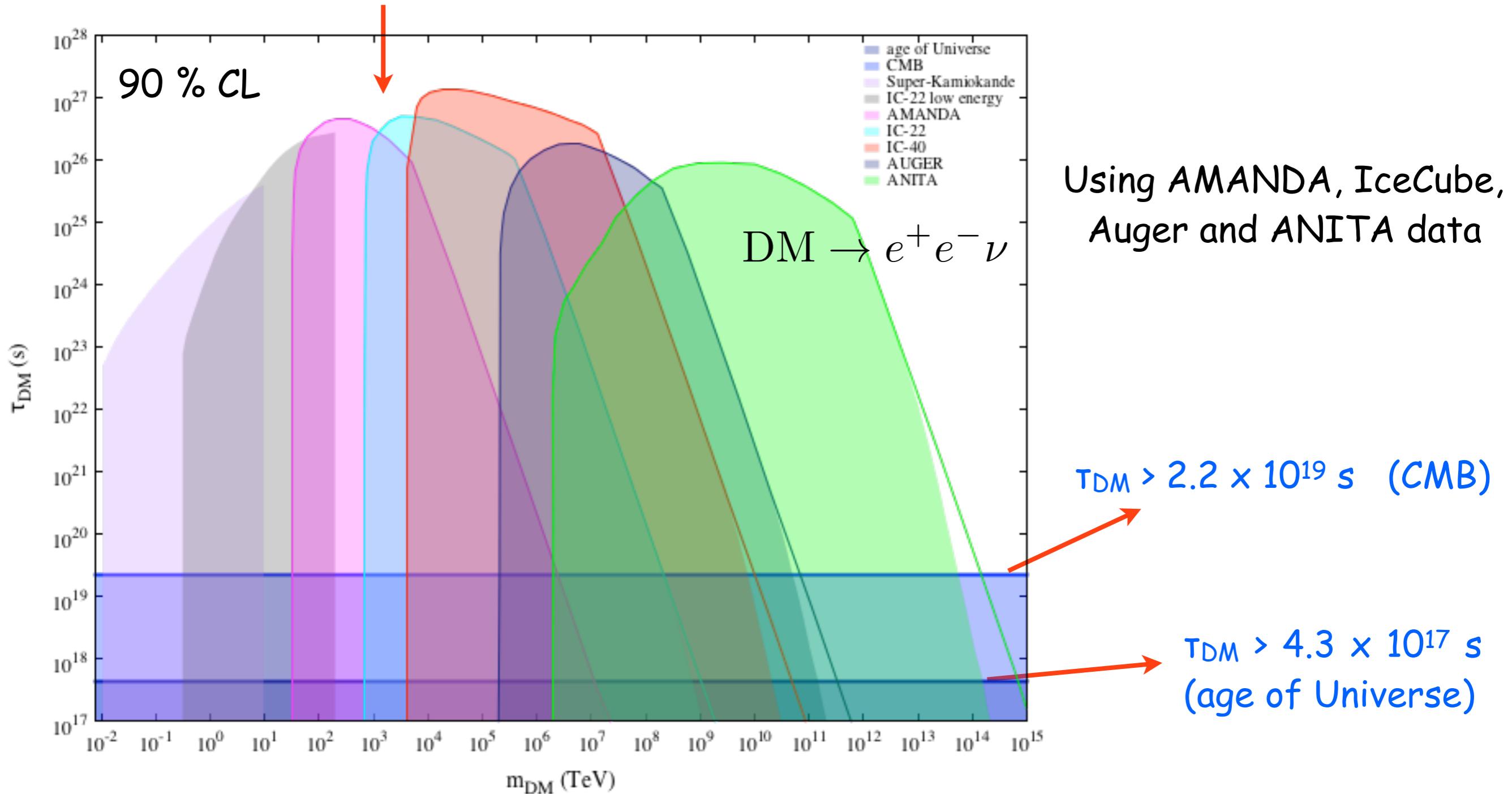
A.E., A. Ibarra and O. Peres
arXiv: 1205.5281



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A.E., A. Ibarra and O. Peres
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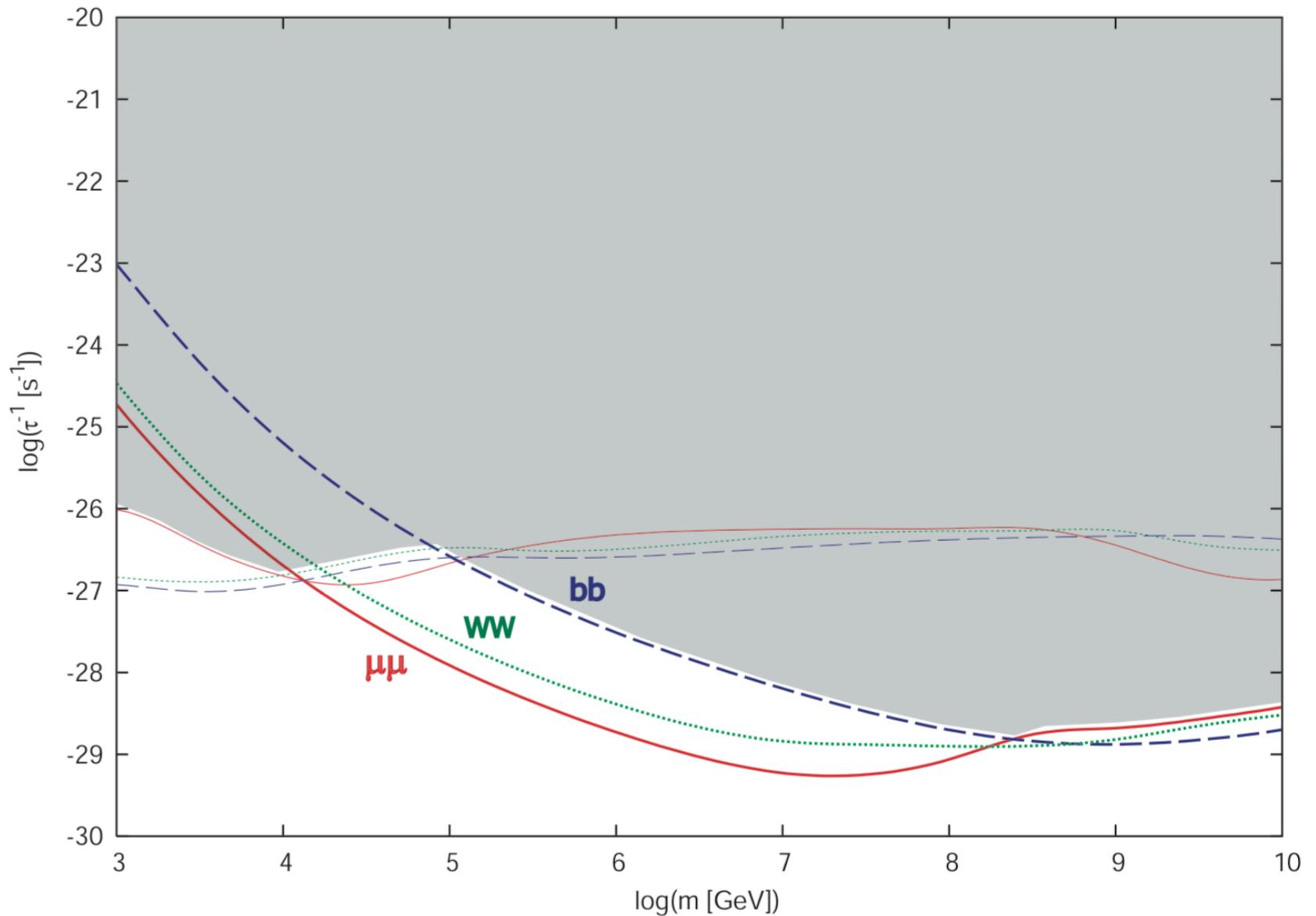


Limits on lifetime from gamma-ray experiments before IceCube discovery

✓ Lifetime: stable (∞) or

constraints from Fermi DGB data
Electromagnetic cascade

K. Murase and J. Beacom
arXiv: 1206.2595

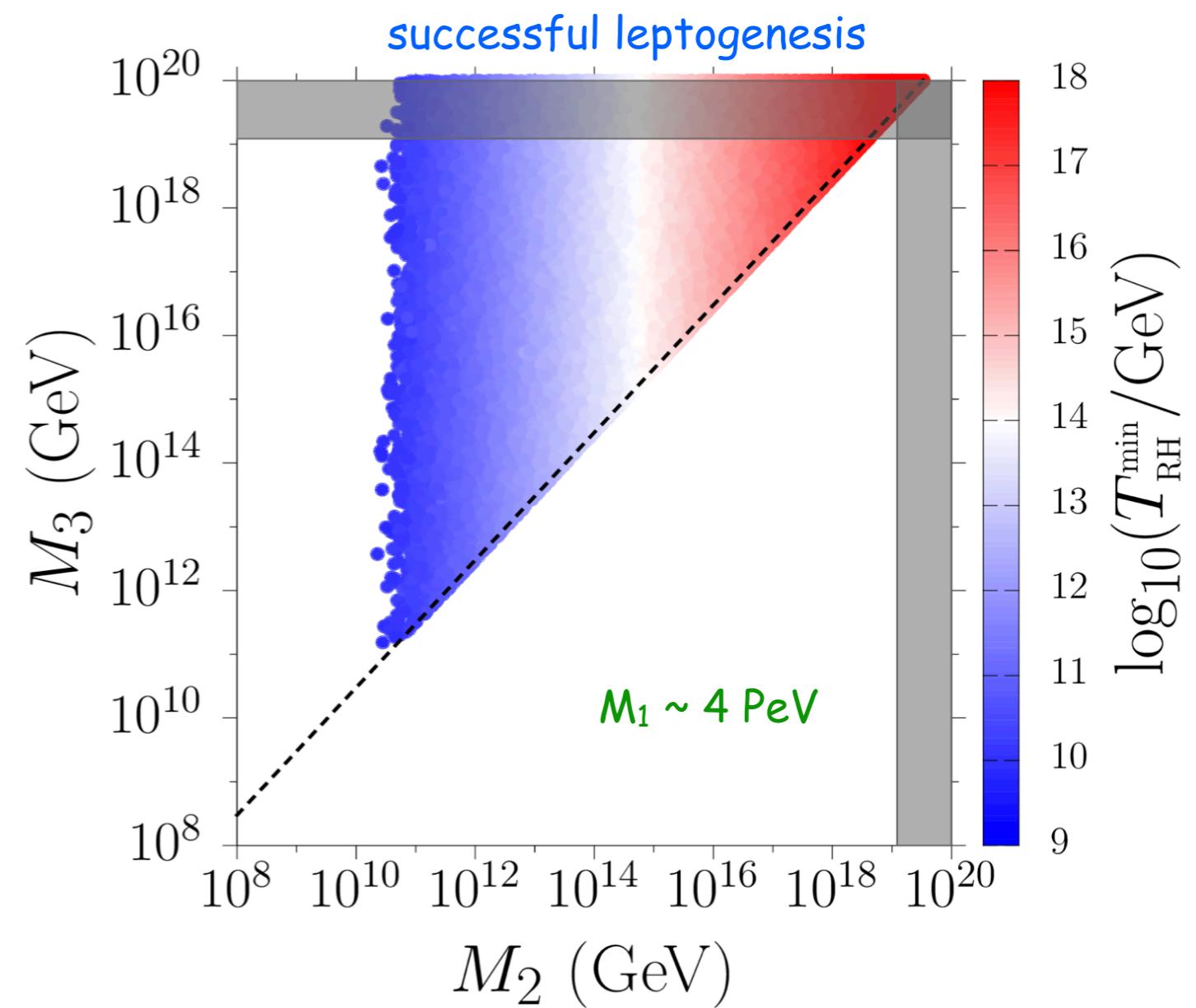


Model building in one slide

- ✓ Various models already exist in the literature.
- ✓ Left-right symmetric extension of the Standard Model, three additional right-handed neutrinos

A consistent model for leptogenesis, dark matter and the IceCube signal

M. Re Fiorentin, V. Niro, N. Fornengo;
arXiv:1606.04445



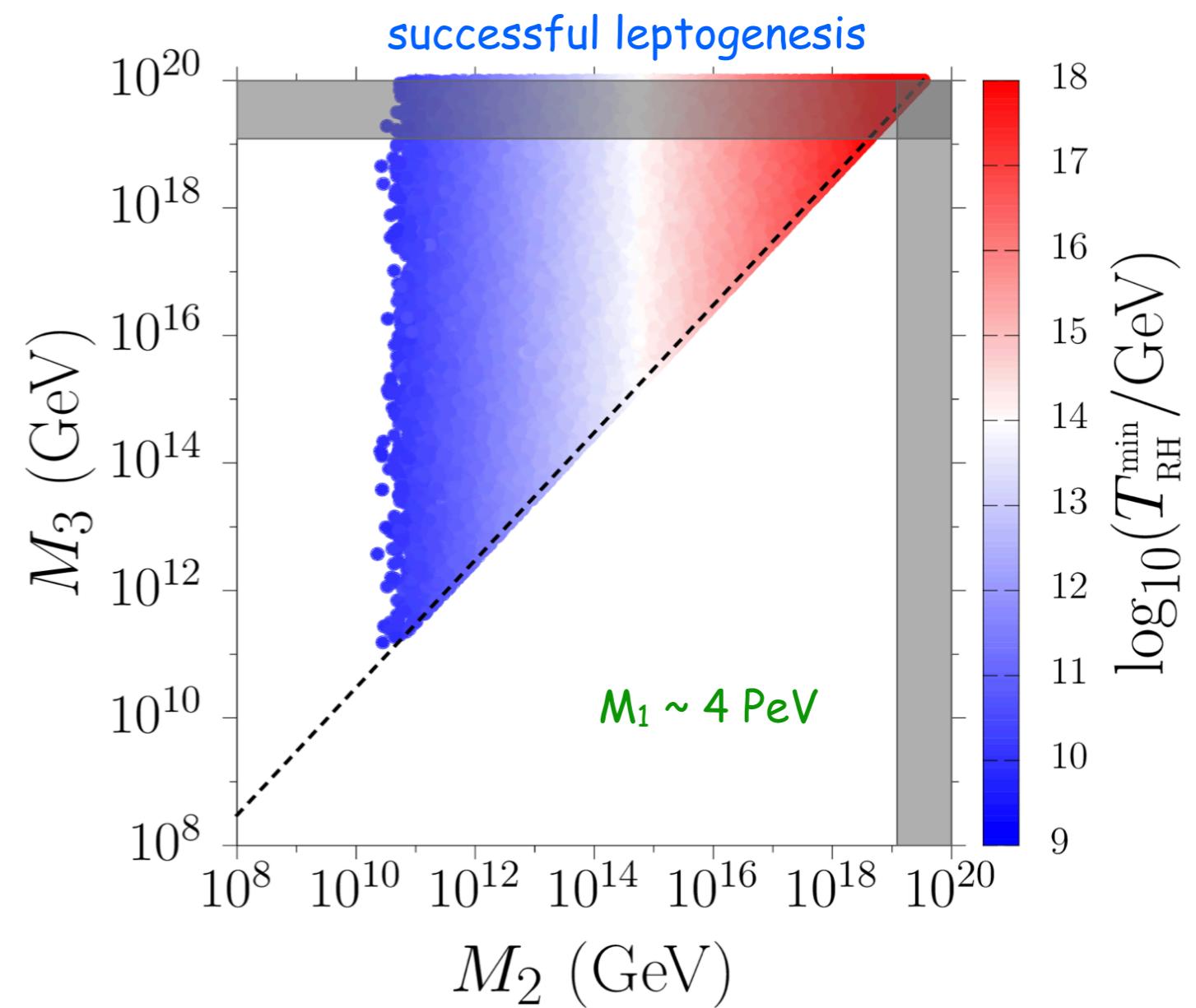
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M. Re Fiorentin, V. Niro, N. Fornengo;
arXiv:1606.04445

Neutrinoful Universe,
T. Higaki, R. Kitano and R. Sato, JHEP (2014)
arXiv:1405.0013



Interpreting the IceCube events by decaying dark matter

B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida,
PRD (2013), [arXiv:1303.7320]

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

Two main diagnostics:

✓ Energy distribution

✓ Angular distribution

Energy distribution of neutrinos from decaying DM

✓ Galactic contribution:

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

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

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

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Energy distribution of neutrinos from decaying DM

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

$$\frac{dN_\nu}{dE_\nu} = (1 - b_H) \left. \frac{dN_\nu}{dE_\nu} \right|_S + b_H \left. \frac{dN_\nu}{dE_\nu} \right|_H$$

quarks

neutrinos,

charged leptons

Energy distribution of neutrinos from decaying DM

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quarks

neutrinos,
charged leptons

at the
Earth

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

decoherent oscillation

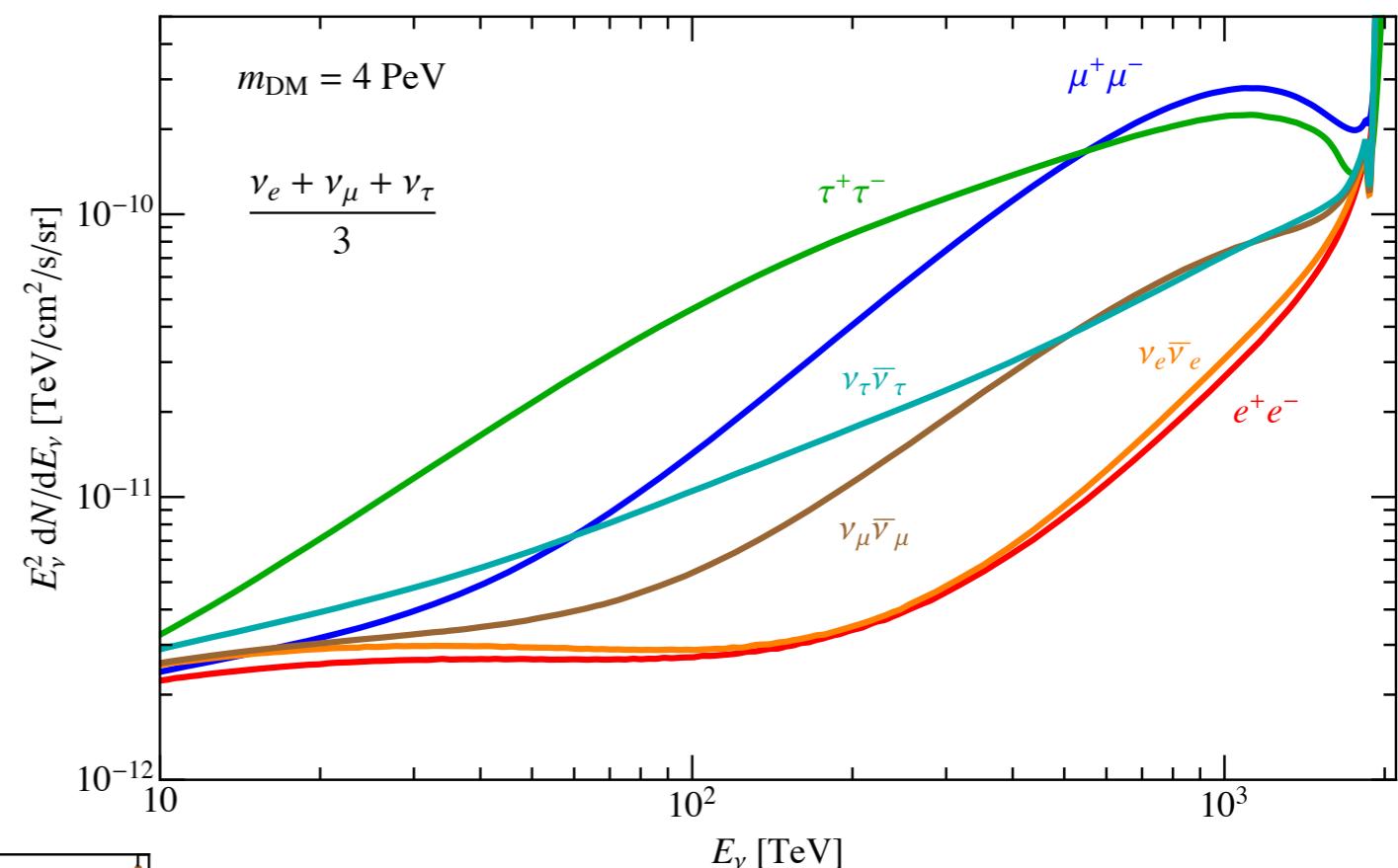
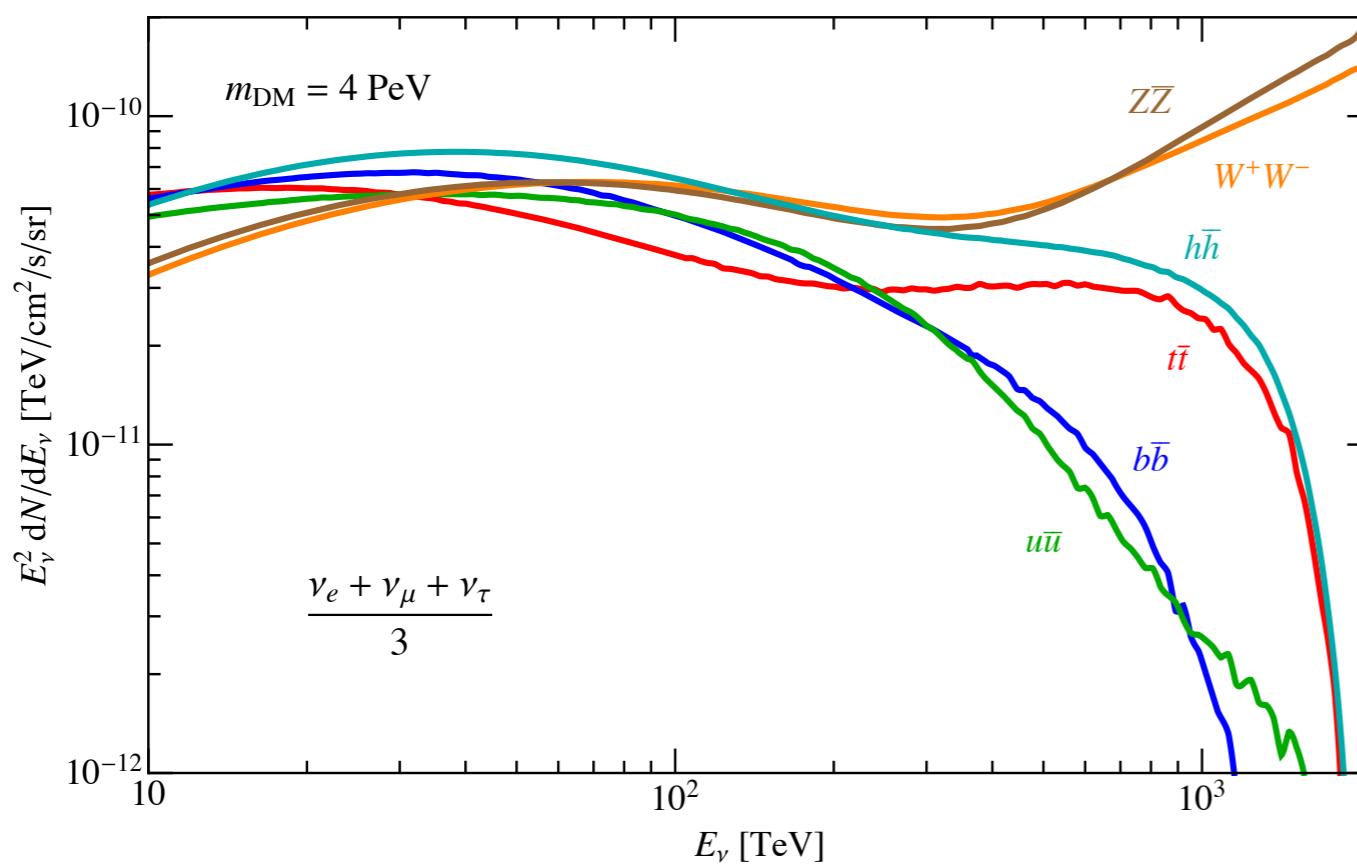
production
point

Flux of neutrinos from decaying DM

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

$$m_{\text{DM}} = 4 \text{ PeV}$$

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



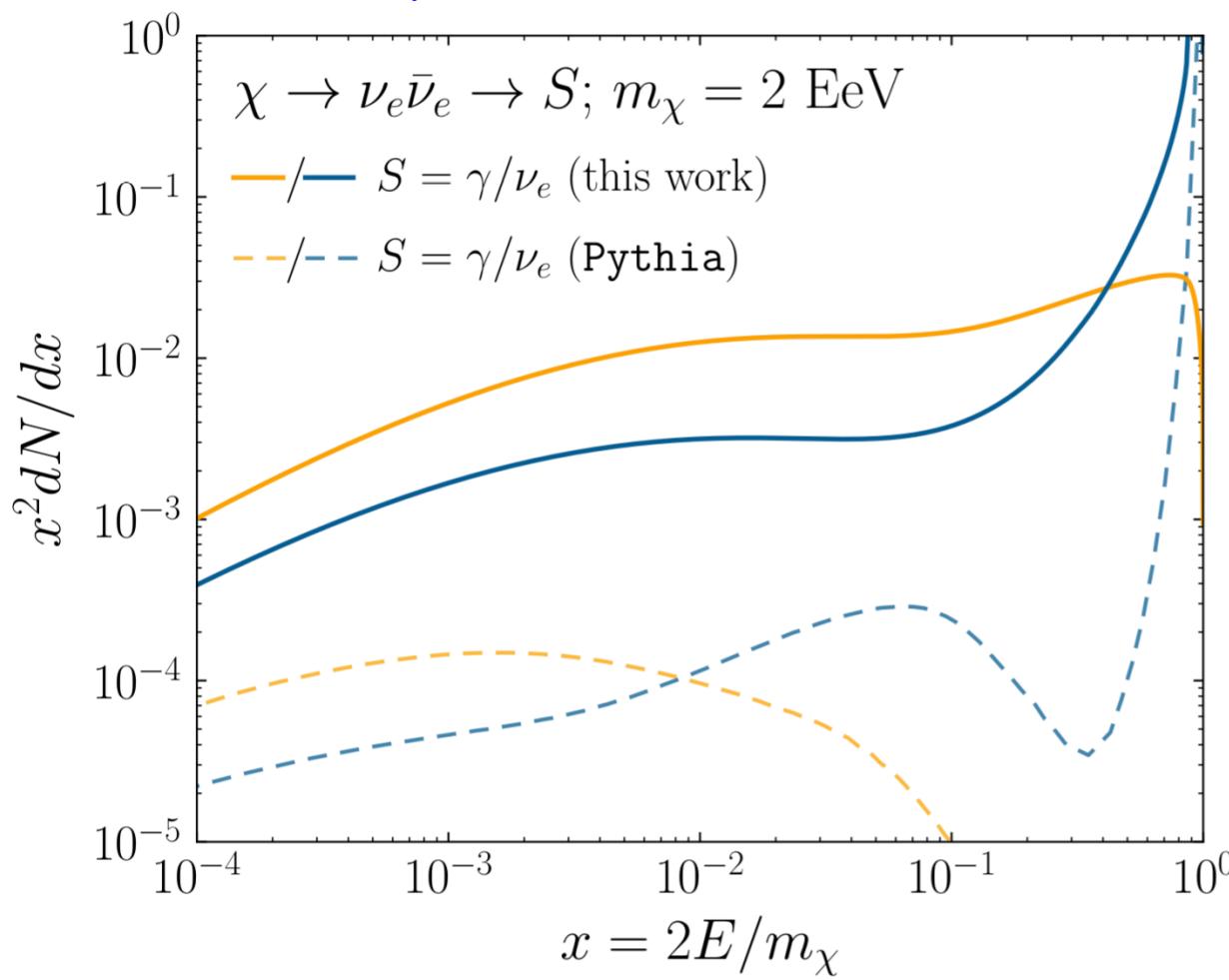
EW corrections play an
important role

PYTHIA 8.2

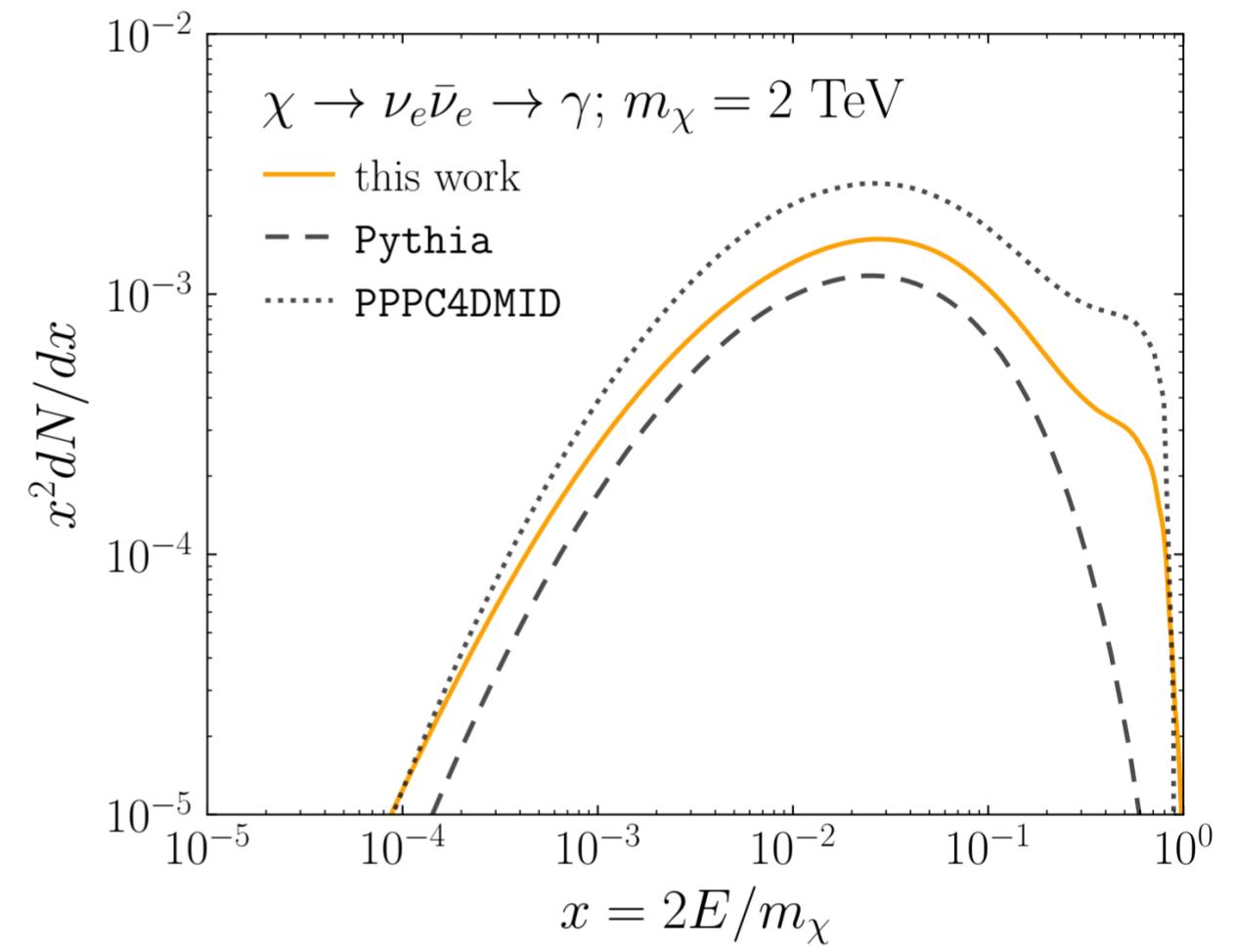
Flux of neutrinos from decaying DM

✓ Pythia 8.2 included the EW corrections, but not completely! for example, the triple gauge couplings in EW sector are missing.

The effect is more
important for heavier DM



Bauer, Rodd, Webber;
arXiv:2007.15001

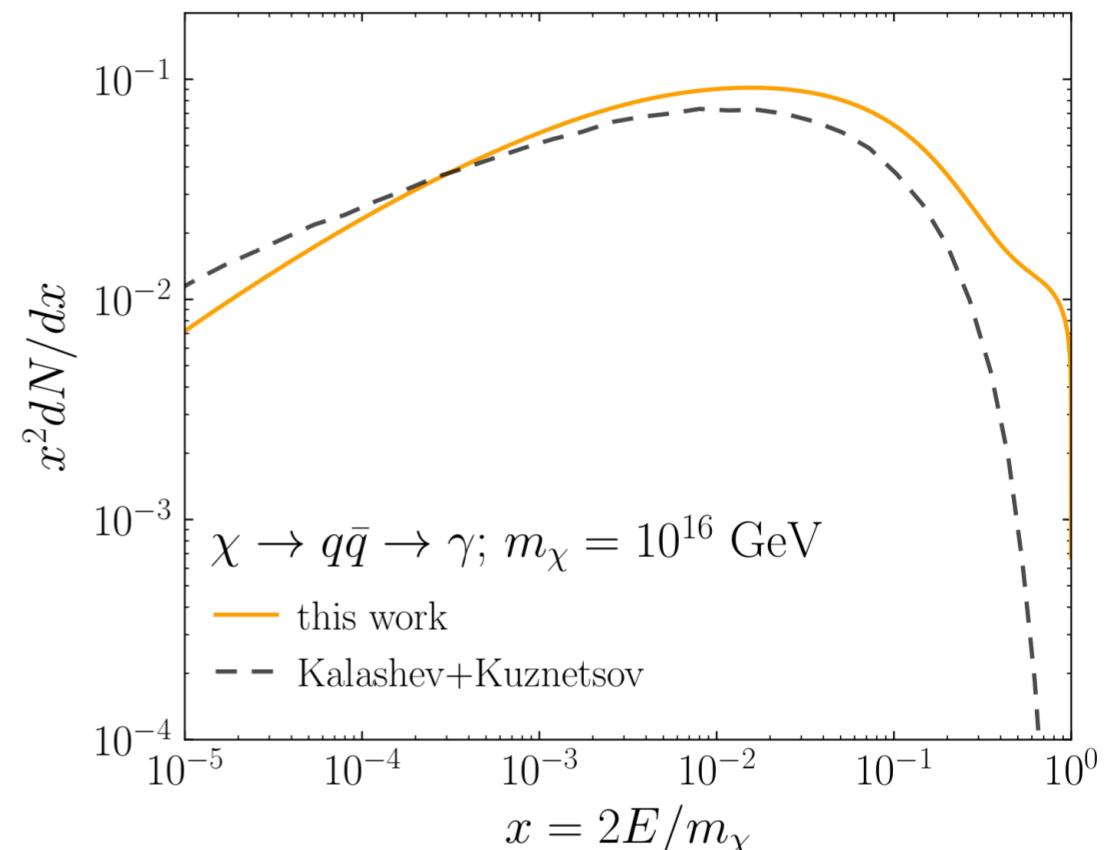


Flux of neutrinos from decaying DM

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Comparing with

Kalashev and Kuznetsov; arXiv: 1704.05300
based on DGLAP evolution of low energy scale
fragmentation function, based on
R. Aloisio, V. Berezinsky, and M. Kachelriess;
arXiv: 0307279



Bauer, Rodd, Webber; arXiv:2007.15001

<https://github.com/nickrodd/HDMspectra>

```
import numpy as np
from HDMspectra import HDMspectra

x = np.logspace(-4., 0., 1000)
dNdx = HDMspectra.spec(22, 5, x, 1.e9, './data/HDMspectra.hdf5')
```

Flux of neutrinos from decaying DM

✓ an example:

intriguing features:

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

a peak in \sim PeV

flux is not feature-less

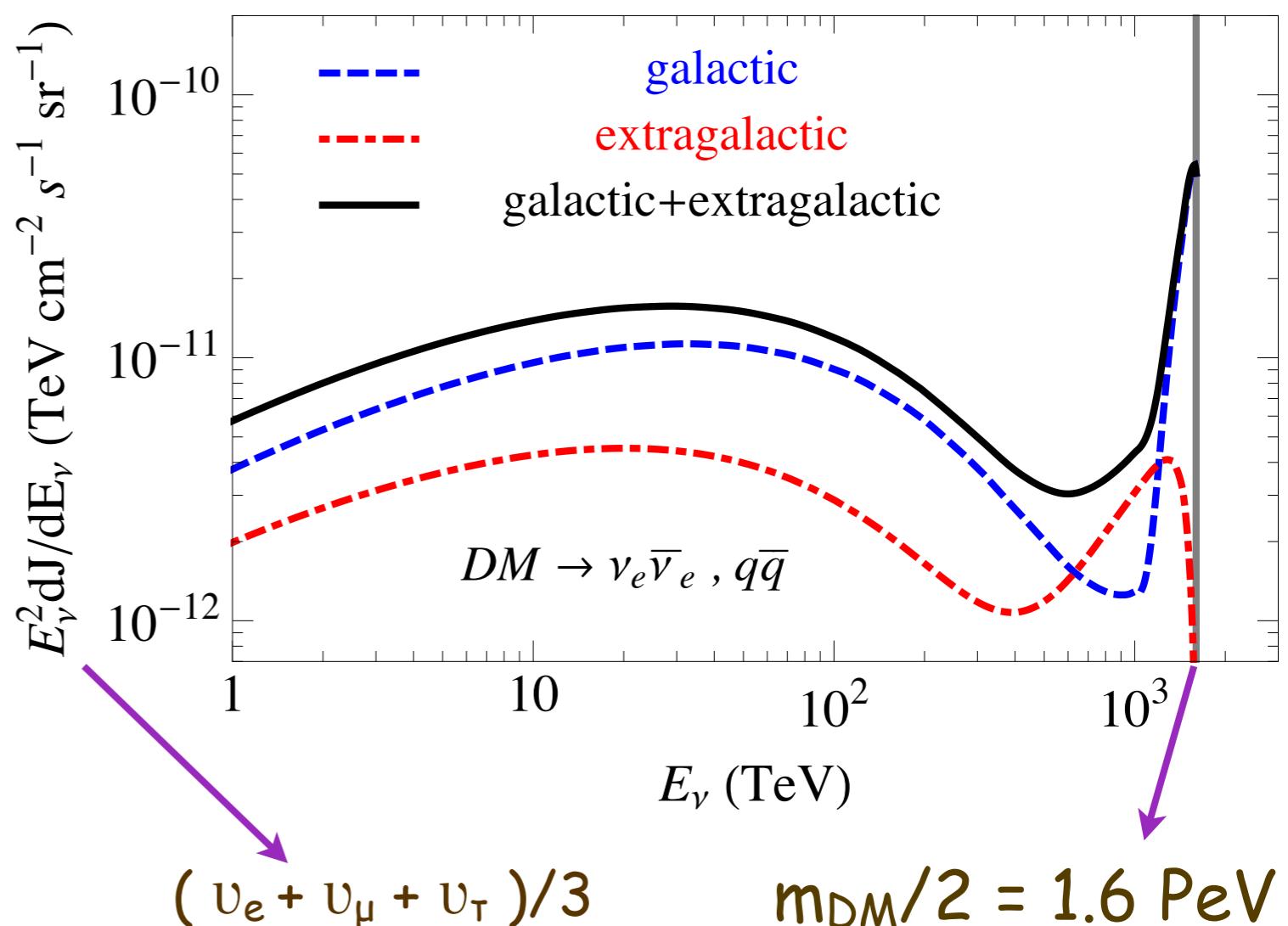
populated spectrum in < 0.4 PeV

due to soft channel and EW cascades

b_H controls the peak height at \sim PeV

T_{DM} controls the low energy population

A. E., Pasquale D. Serpico,
arXiv:1308.1105



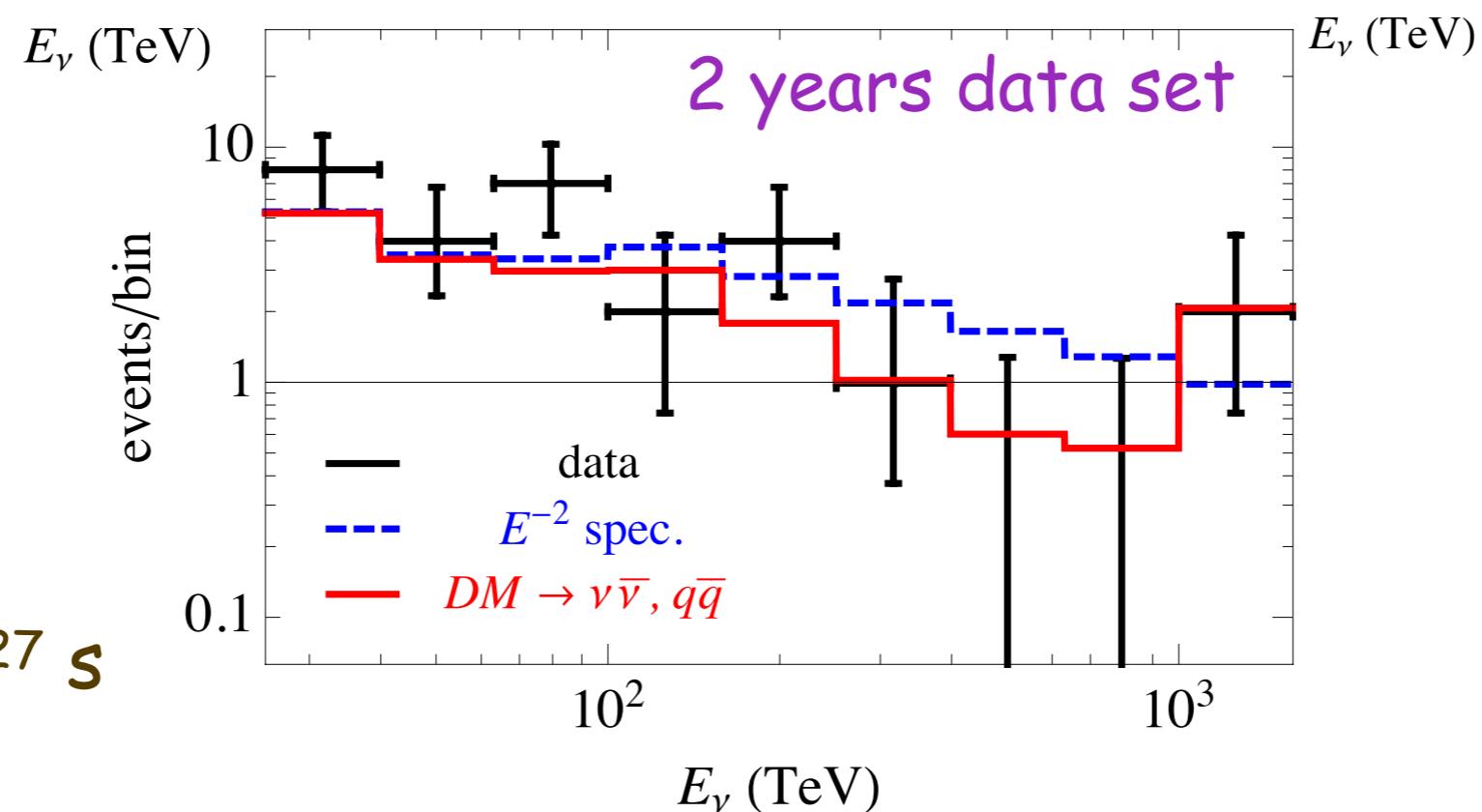
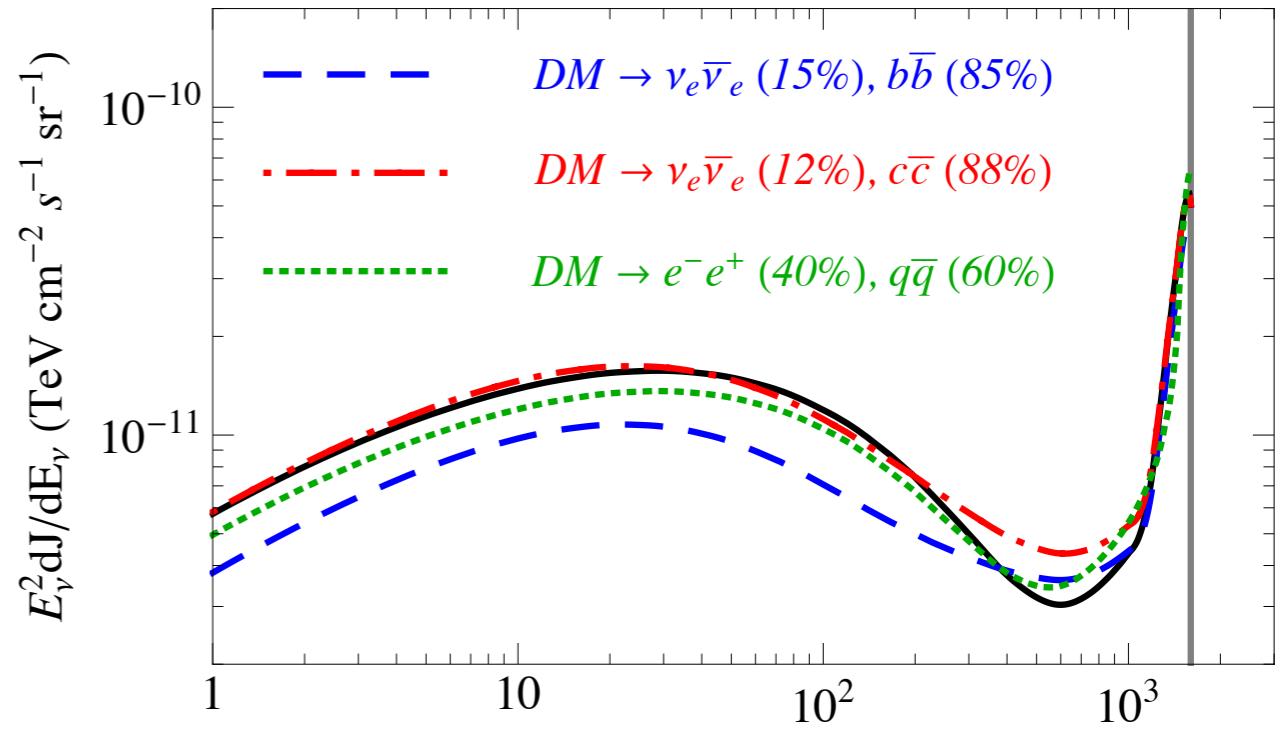
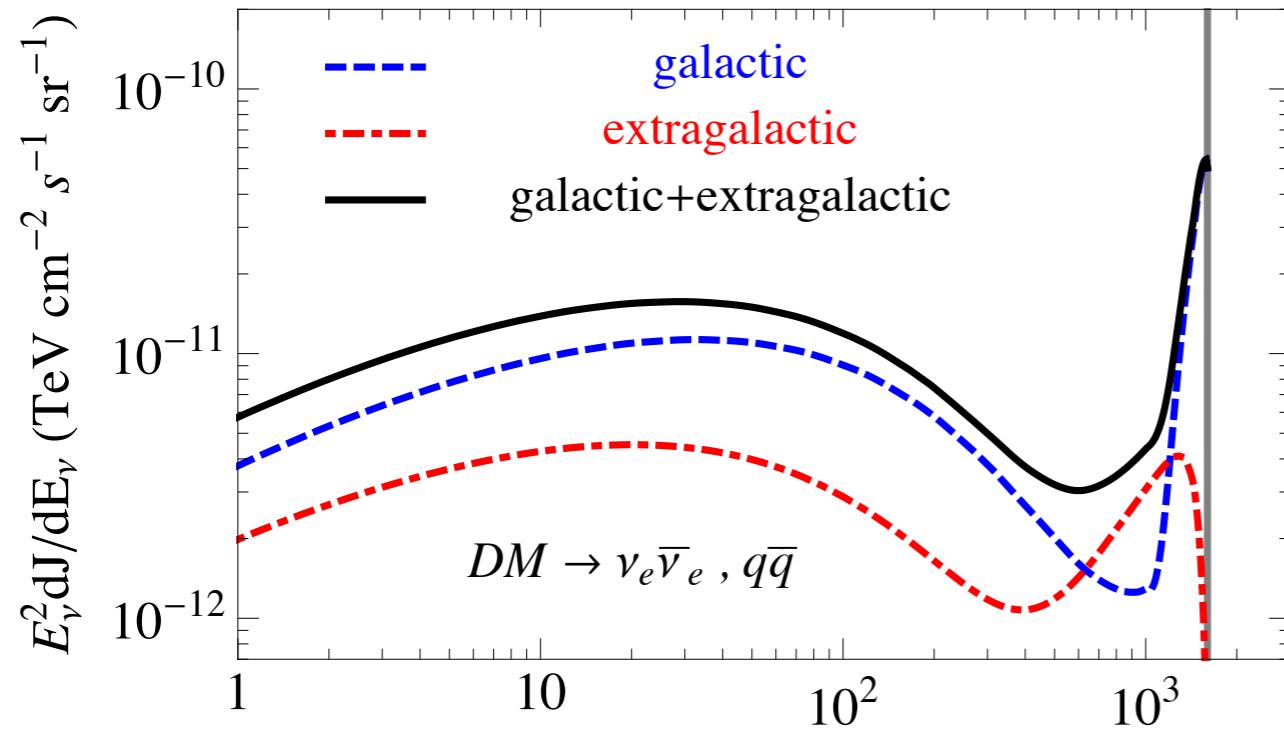
$b_H = 0.12$ and $T_{DM} = 2 \times 10^{27} \text{ s}$

Flux of neutrinos from decaying DM



fine-tuned decay channels ?

$$\tau_{\text{DM}} = (1-3) \times 10^{27} \text{ s}$$



Confronting with energy distribution of IceCube data

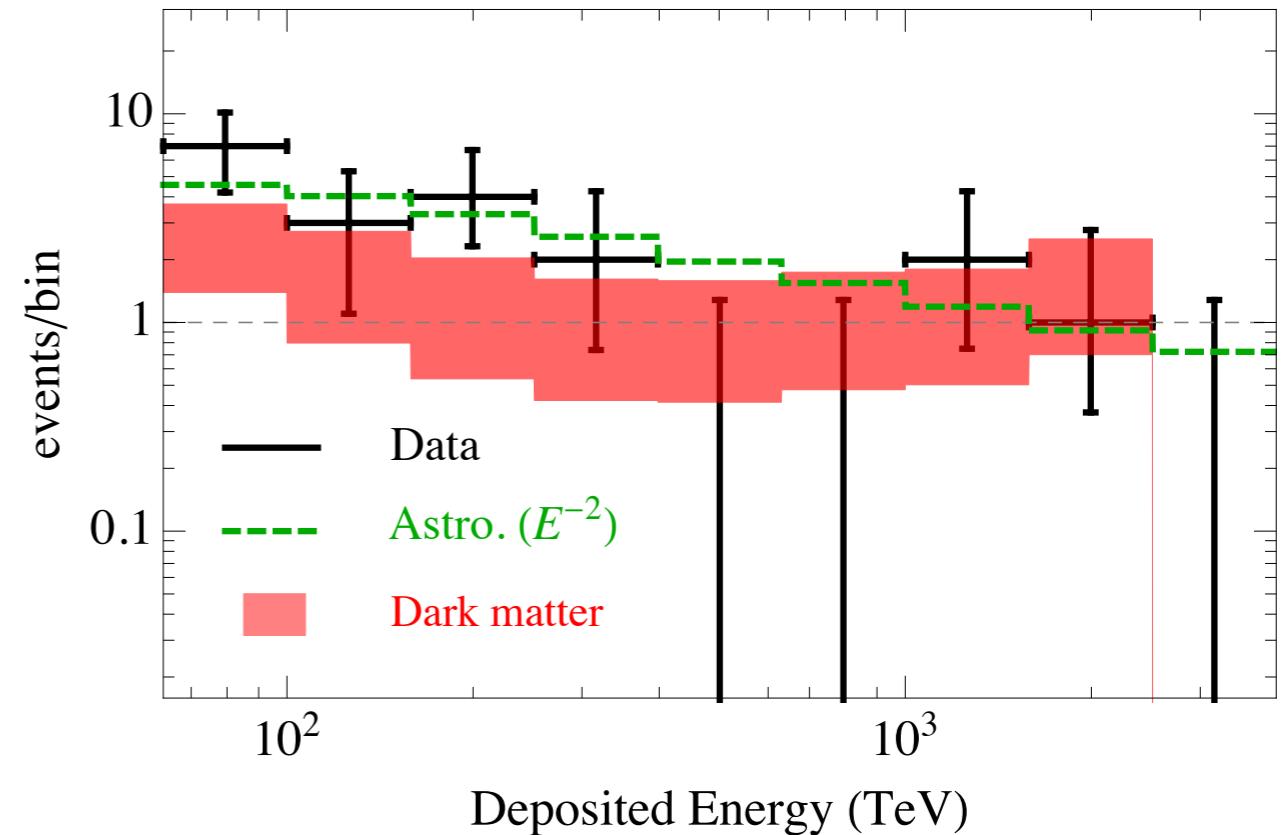
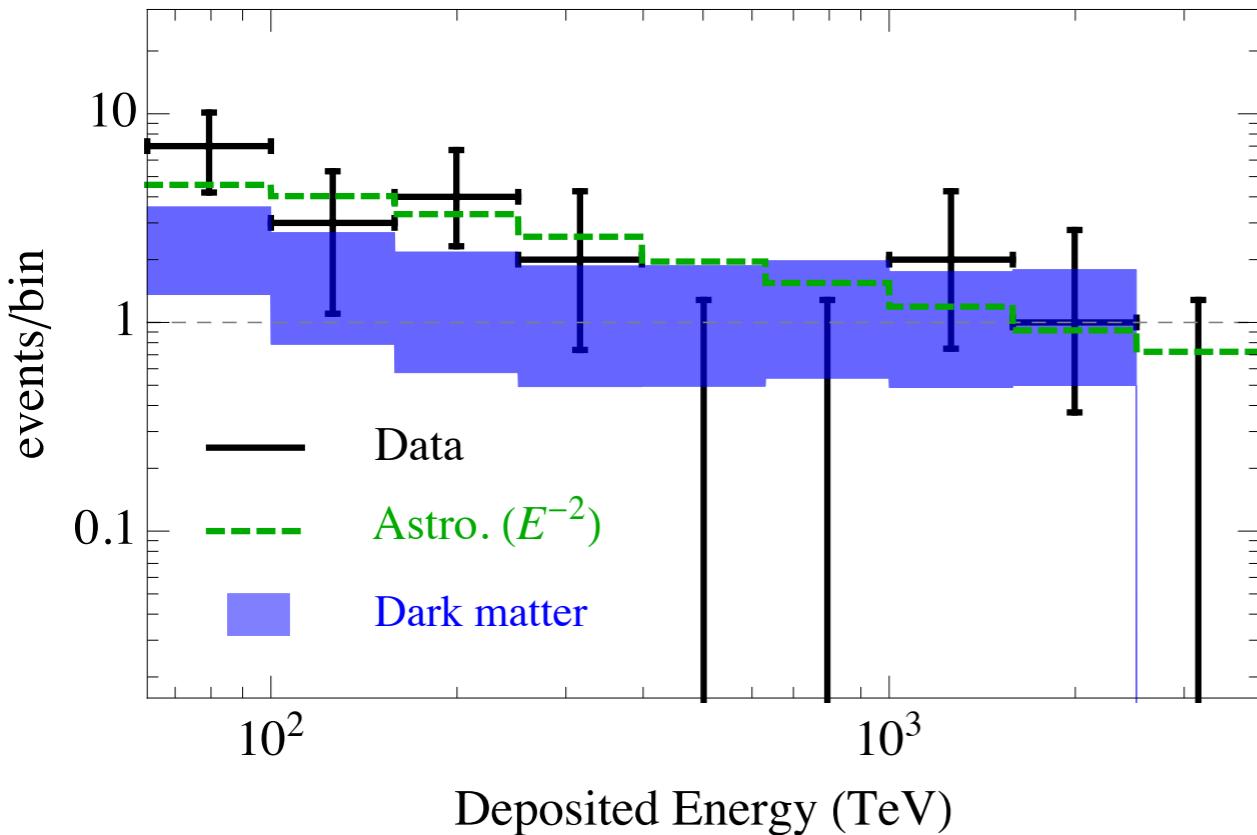
3 years data set

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

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

$m_{\text{DM}} = 4 \text{ PeV}$

NH, $\tau_{\text{DM}} = 7.3 \times 10^{27} \text{ s}$



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)

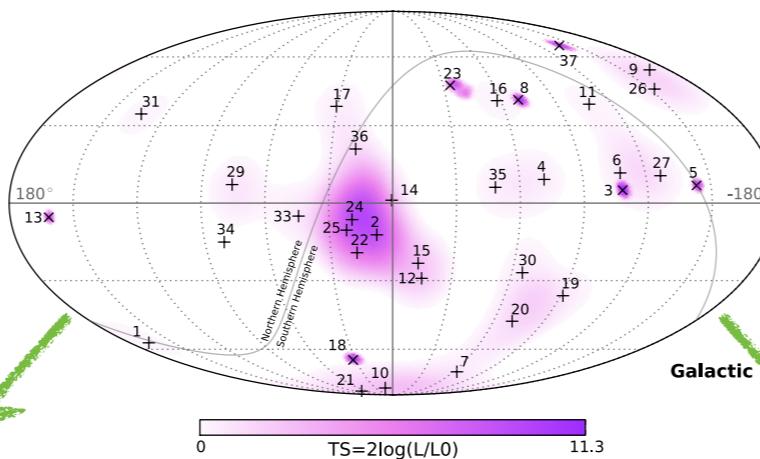
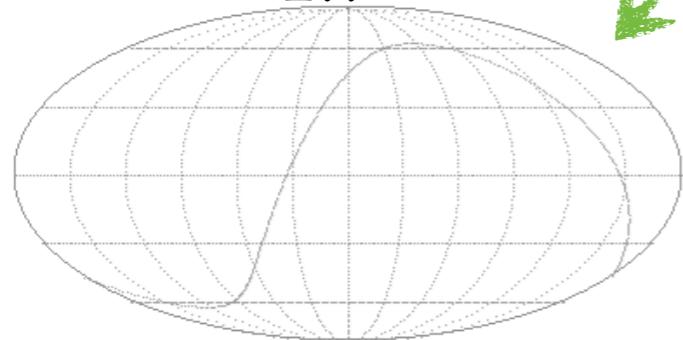
T. Higaki, R. Kitano and R. Sato,
JHEP (2014) [1405.0013]

The predicted neutrino flux is fixed by the model

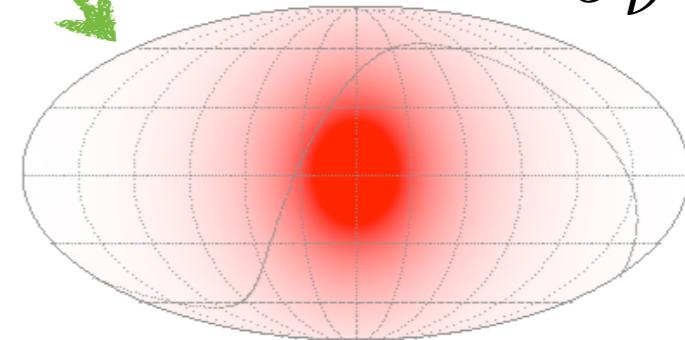
Angular distribution of neutrinos from decaying DM

✓ We would compare

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



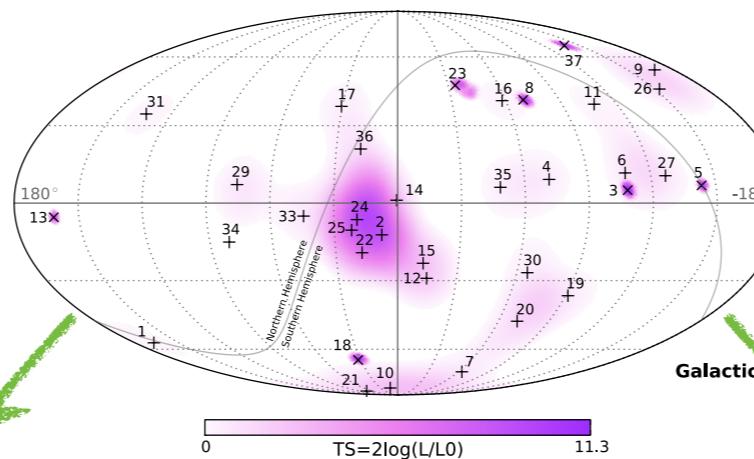
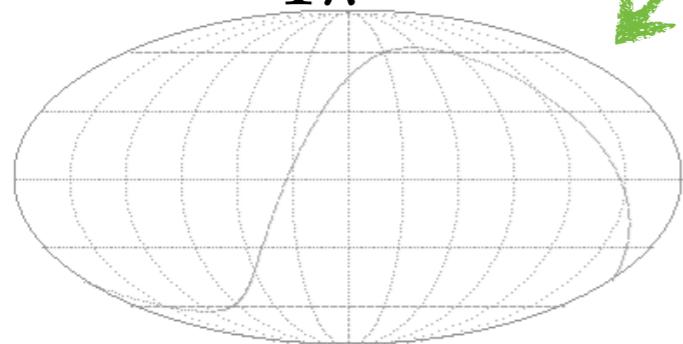
$$p^{\text{DM}} = \frac{1}{J_\nu} \frac{d^2 J_\nu}{db dl}$$



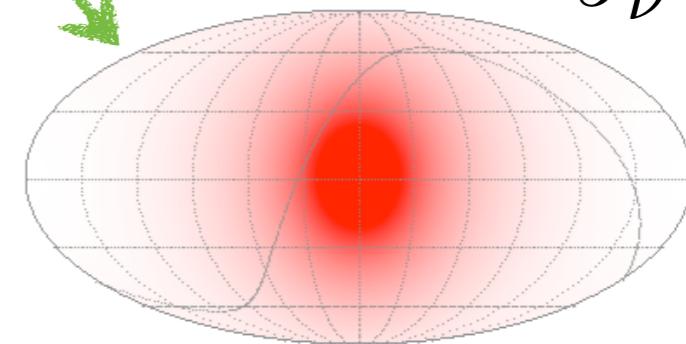
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PDF of data

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

"flat sky"
approximation

PDF of
isotropic dis.

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

PDF of DM

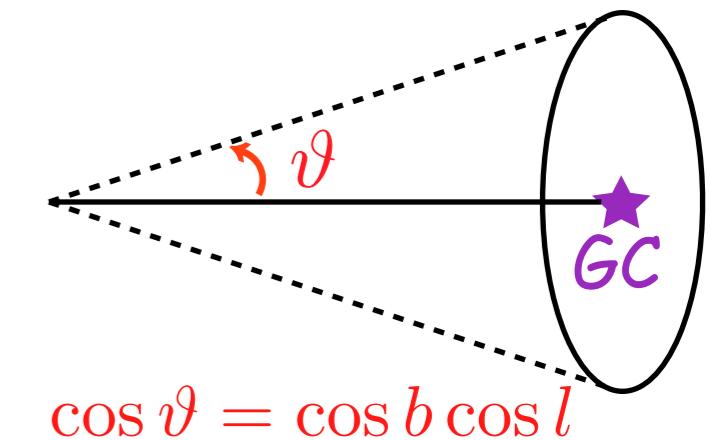
$$p^{\text{DM}}(b, l) = \frac{1}{J_\nu} \frac{d^2 J_\nu}{db dl} = \frac{\int_0^\infty \rho[r(s, b, l)] ds + \Omega_{\text{DM}} \rho_c \beta}{4\pi(\eta + \Omega_{\text{DM}} \rho_c \beta)}$$

Angular distribution of neutrinos from decaying DM

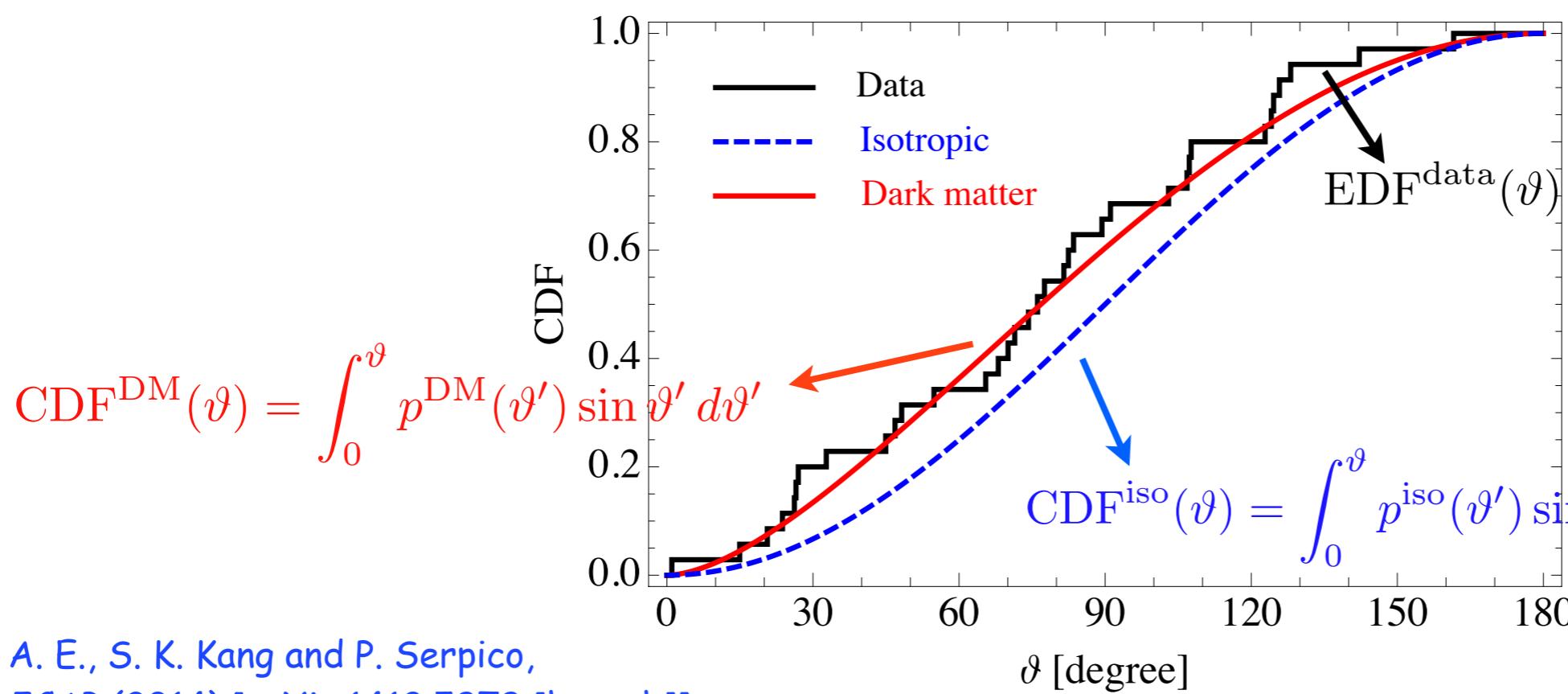
✓ Kolmogorov-Smirnov test: a powerful non-parametric test

The 2-dim KS test have some ambiguities

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



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



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

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

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

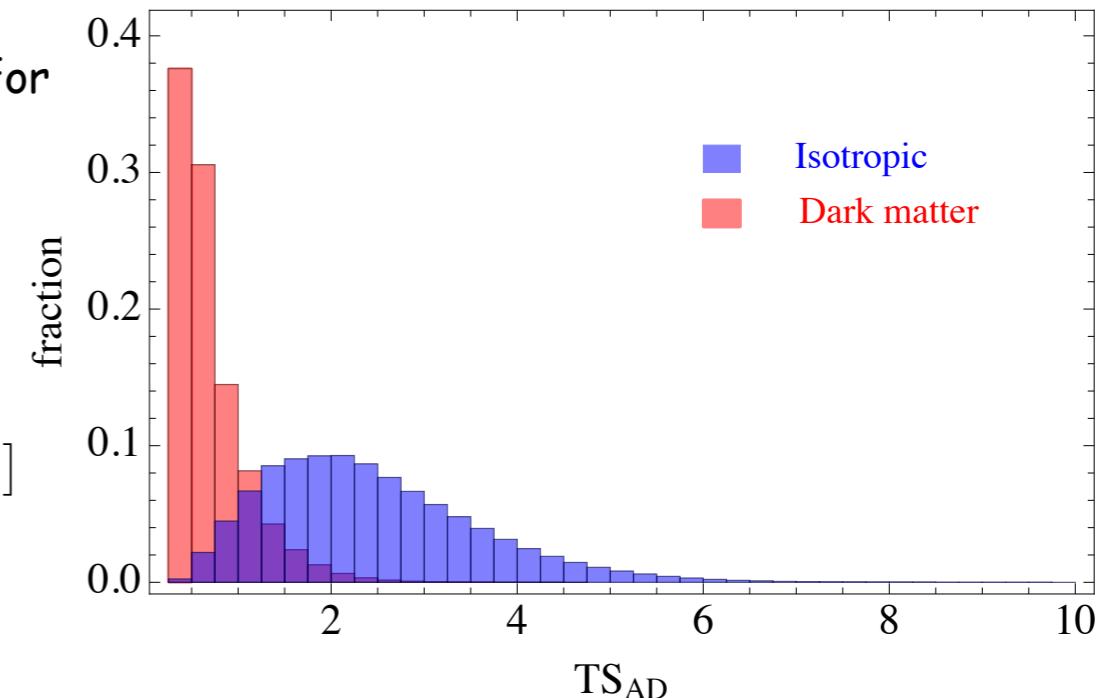
Angular distribution of neutrinos from decaying DM

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

Test Statistics

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

statistically larger TS for isotropic distribution



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

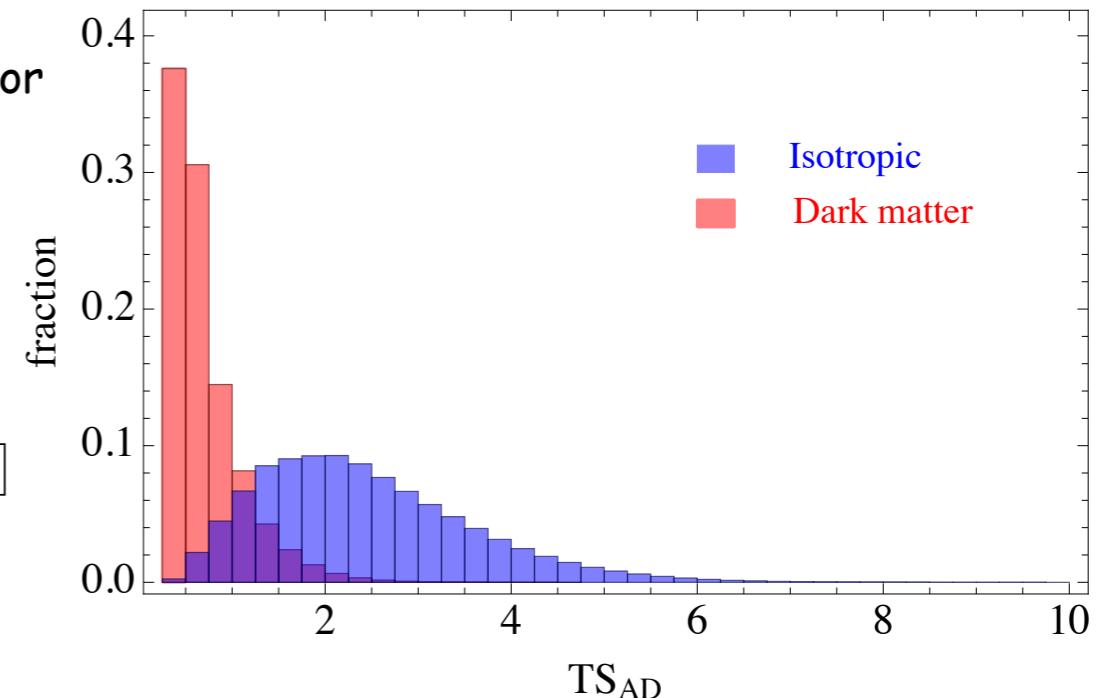
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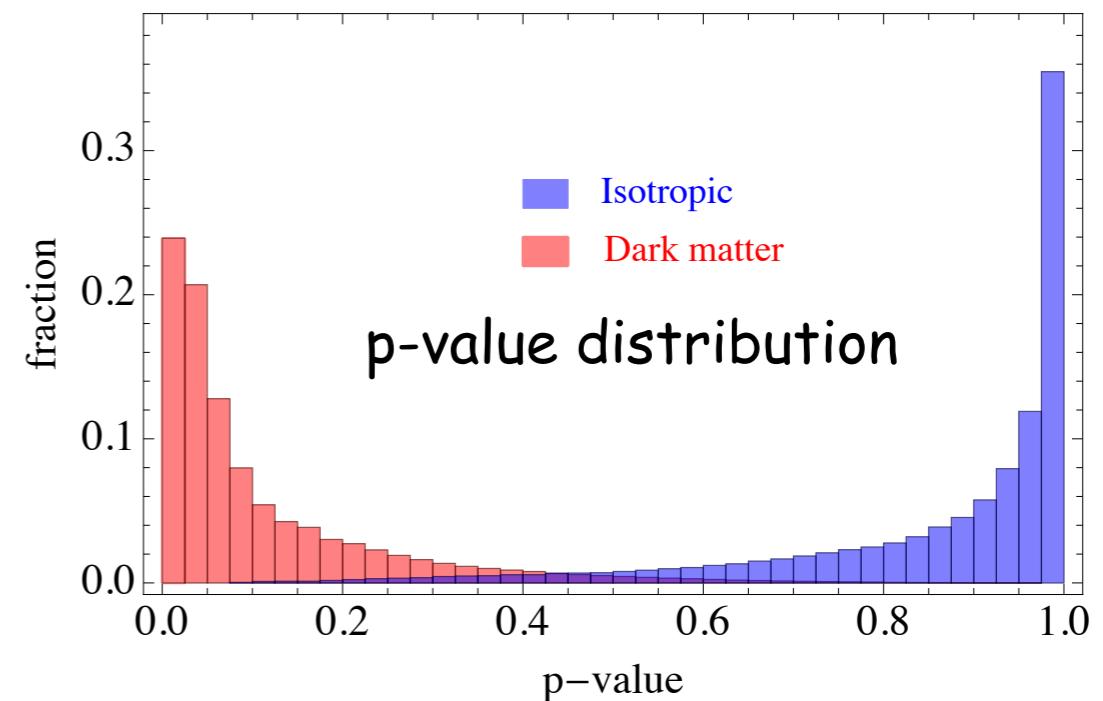


again, generating a sample (10^5) of isotropically distributed set of 20 events

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%

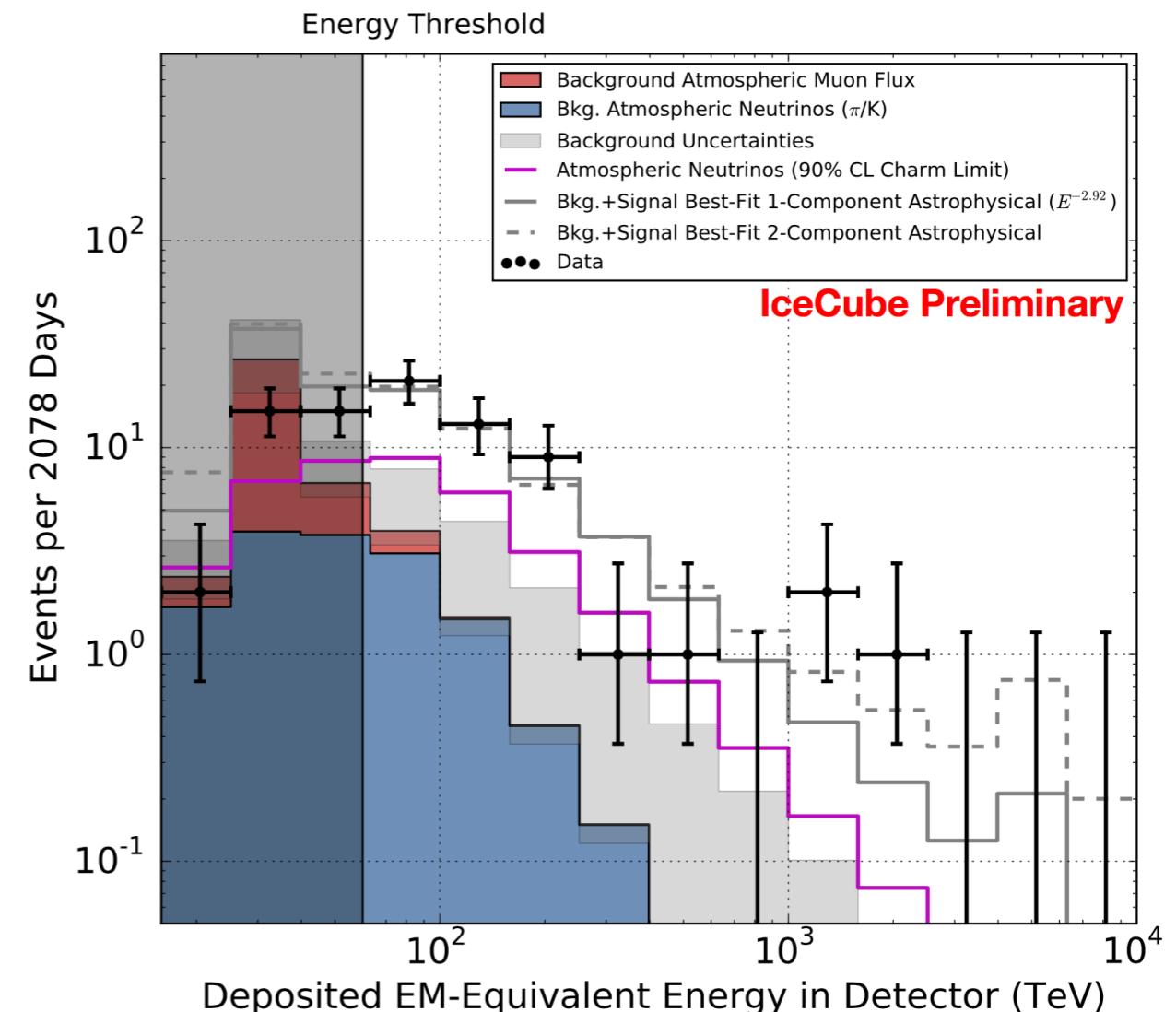
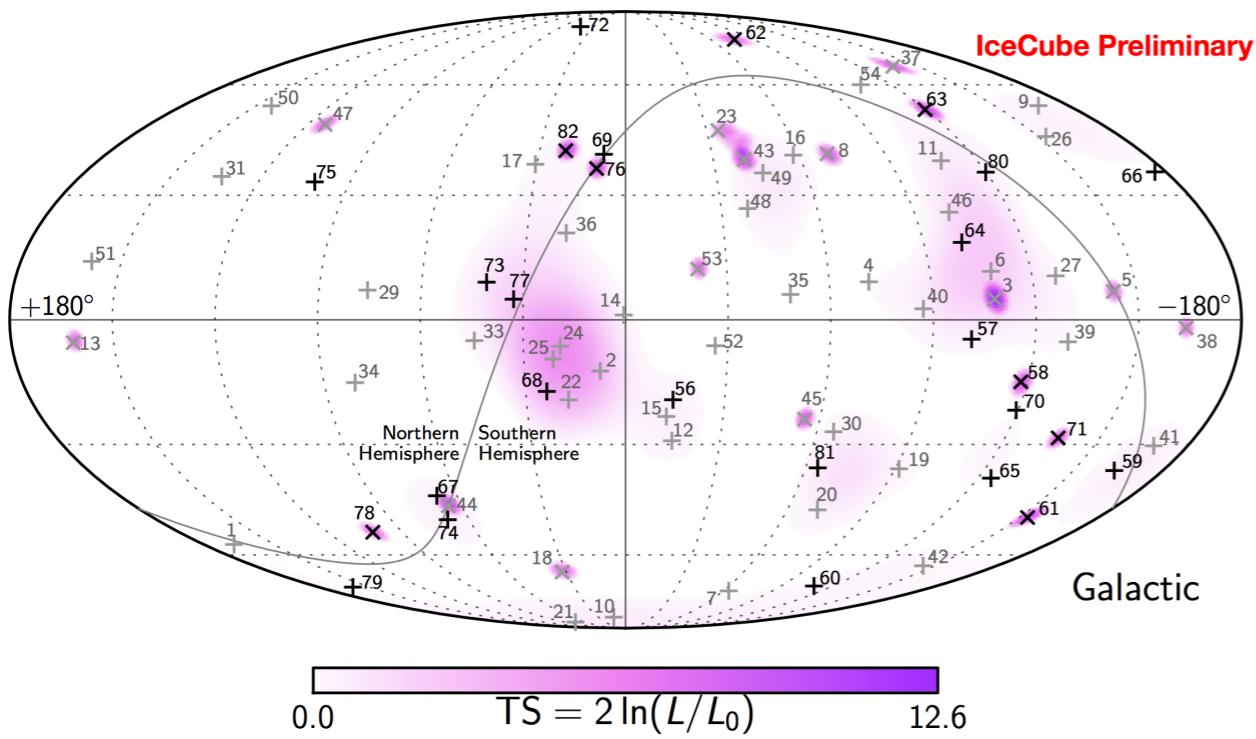
less than 2σ preference for DM dis.

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



IceCube data

✓ Looking for lower energy contained events, 2078 days livetime



6 years of data

Confronting with energy and angular distributions of IceCube data

- ✓ More refined analysis of the 6 years data set

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

single power-law
astro flux

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

fitting parameters

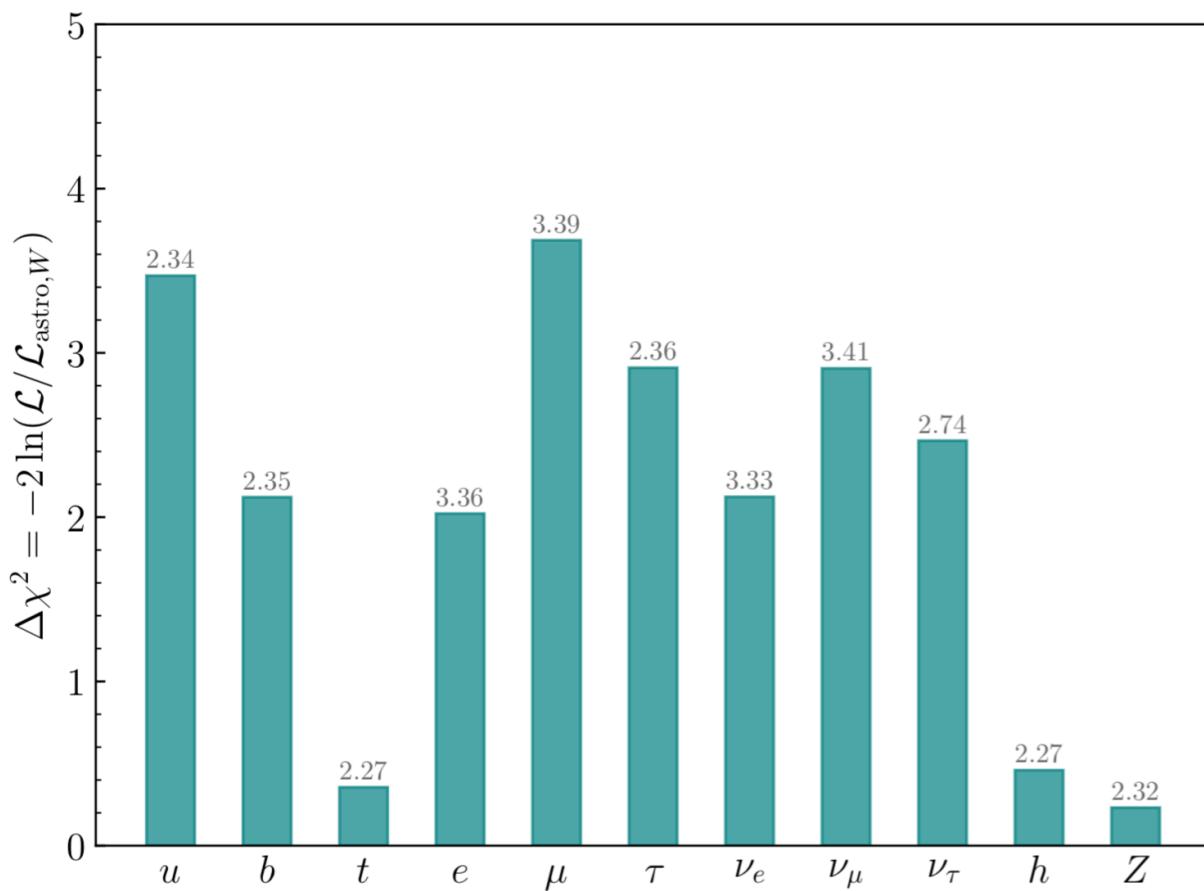
$$\theta = \{\tau_{\text{DM}}, m_{\text{DM}}, \phi_a, \gamma\}$$

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

Confronting with energy distribution of IceCube data

6 years data set

DM decays (single channel) plus astrophysical power-law flux: Best-fit values



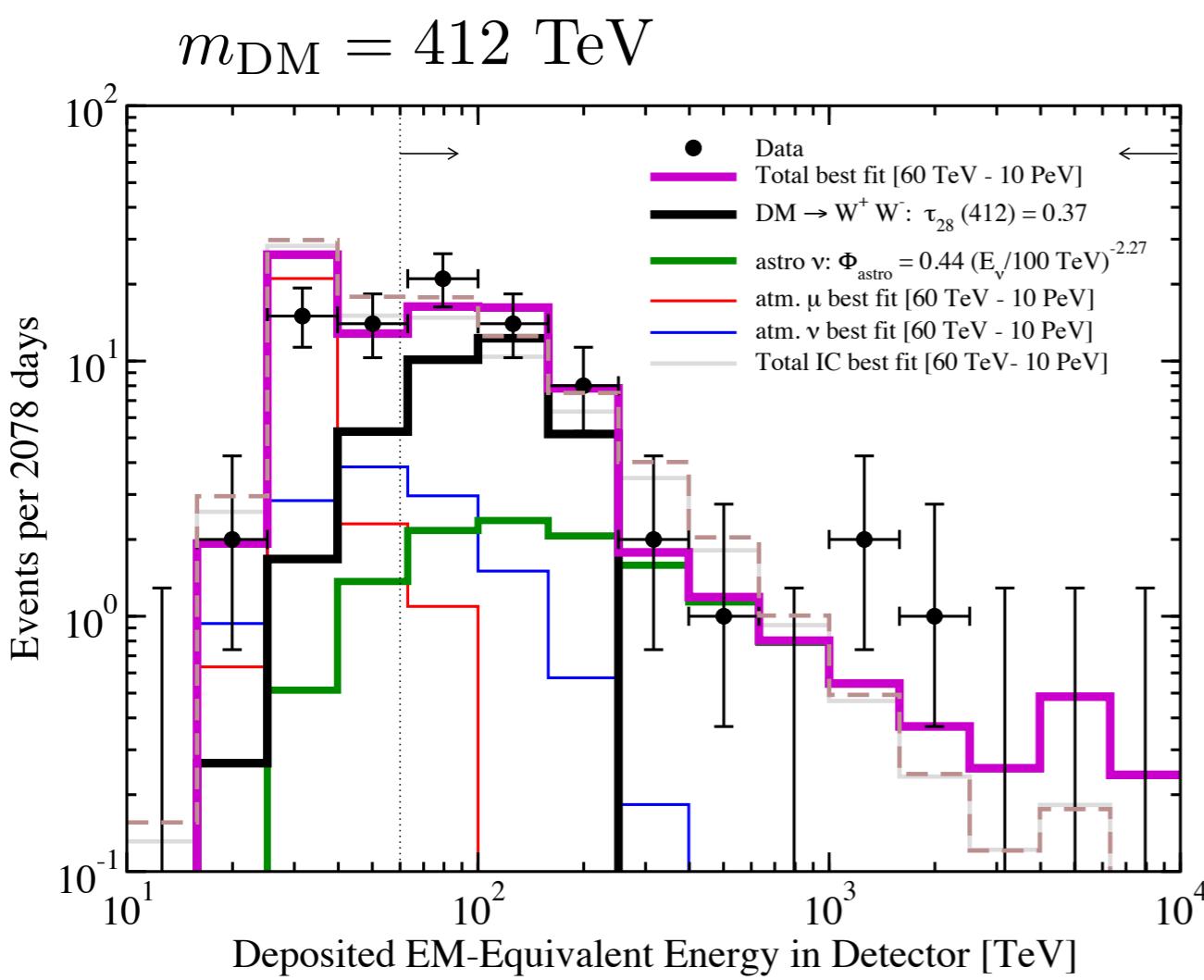
Decay channel	$\tau_{\text{DM}} [10^{28} \text{ s}] (N_{\text{DM}})$	$m_{\text{DM}} [\text{TeV}]$	$\phi_{\text{astro}} (N_{\text{astro}})$	γ
$u\bar{u}$	0.11 (28.4)	1761	0.52 (13.0)	2.34
$b\bar{b}$	0.07 (26.9)	1103	0.58 (14.3)	2.35
$t\bar{t}$	0.11 (28.7)	598	0.45 (12.5)	2.27
W^+W^-	0.37 (28.5)	412	0.47 (12.6)	2.29
ZZ	0.43 (27.8)	407	0.52 (13.3)	2.32
hh	0.12 (28.8)	611	0.45 (12.6)	2.27
e^+e^-	2.20 (4.0)	4160	3.53 (37.3)	3.36
$\mu^+\mu^-$	9.77 (4.9)	6583	3.51 (36.5)	3.39
$\tau^+\tau^-$	0.89 (27.4)	472	0.59 (14.3)	2.36
$\nu_e\bar{\nu}_e$	4.12 (3.6)	4062	3.52 (37.7)	3.33
$\nu_\mu\bar{\nu}_\mu$	4.63 (5.0)	4196	3.52 (36.4)	3.41
$\nu_\tau\bar{\nu}_\tau$	0.96 (16.6)	341	1.58 (24.9)	2.74

A. Bhattacharya, A. E., S. Palomares-Ruiz,
I. Sarcevic, [arXiv:1903.12623]

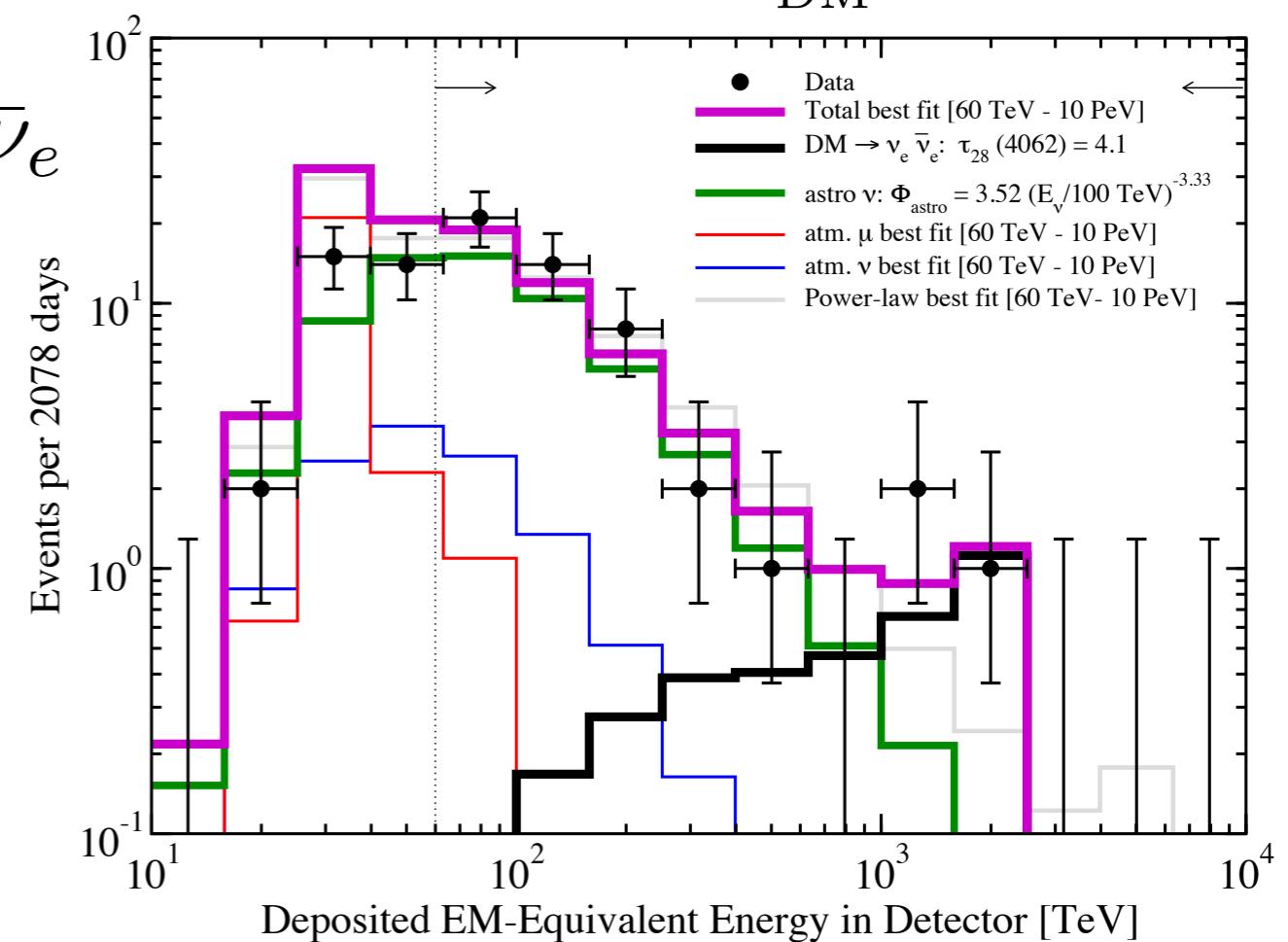
DM decays (single channel) plus astrophysical power-law flux: Channel-by-channel comparison of $\Delta\chi^2$ at best fit ($\text{DM} \rightarrow W^+W^-$)

Confronting with energy distribution of IceCube data

6 years data set



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



A. Bhattacharya, A. E., S. Palomares-Ruiz,
I. Sarcevic, [arXiv:1903.12623]

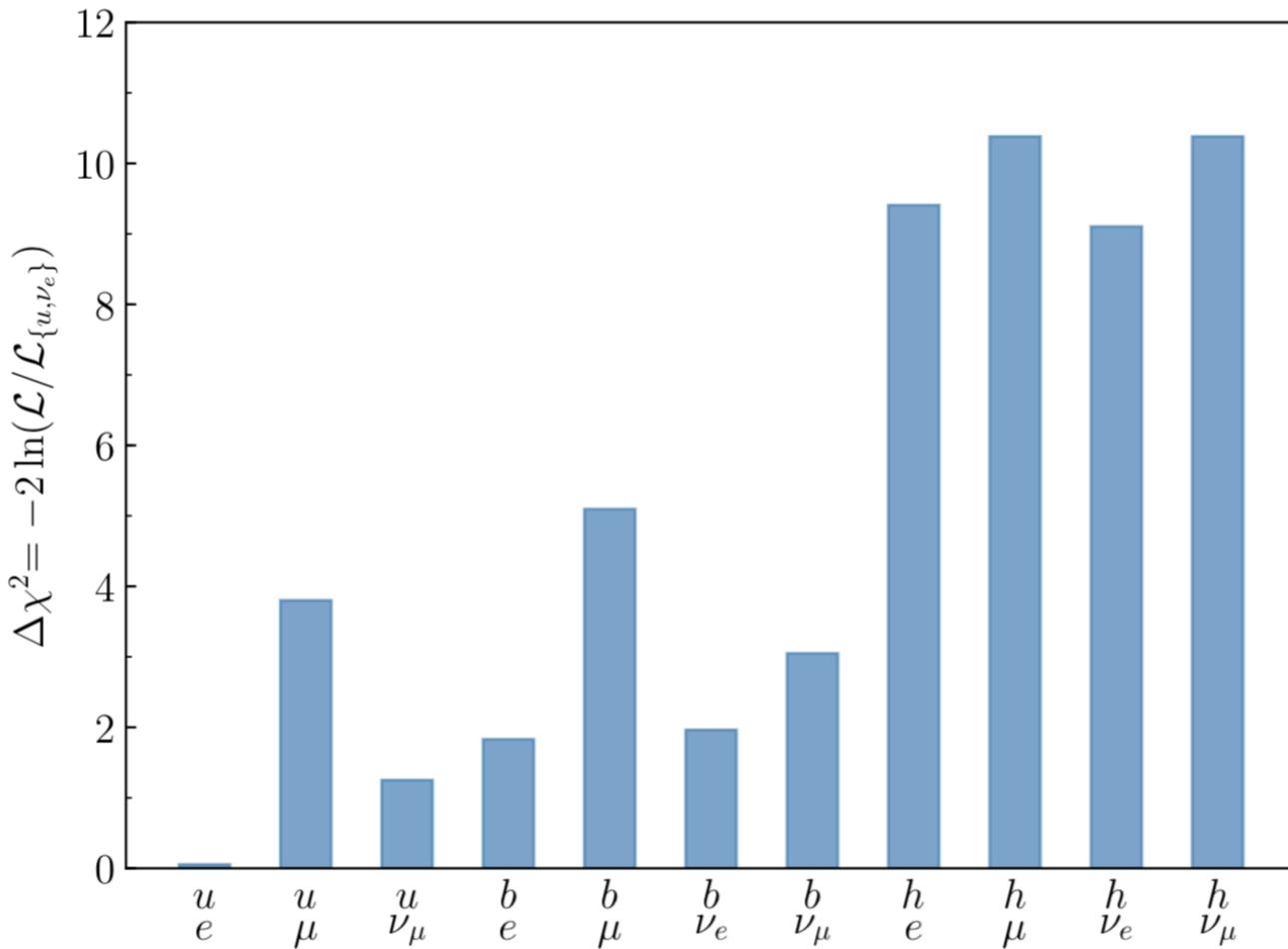
$\text{DM} \rightarrow W^+ W^-$

Confronting with energy distribution of IceCube data

6 years data set

DM-only two-channel decay: Best-fit values

A. Bhattacharya, A. E., S. Palomares-Ruiz,
I. Sarcevic, [arXiv:1903.12623]

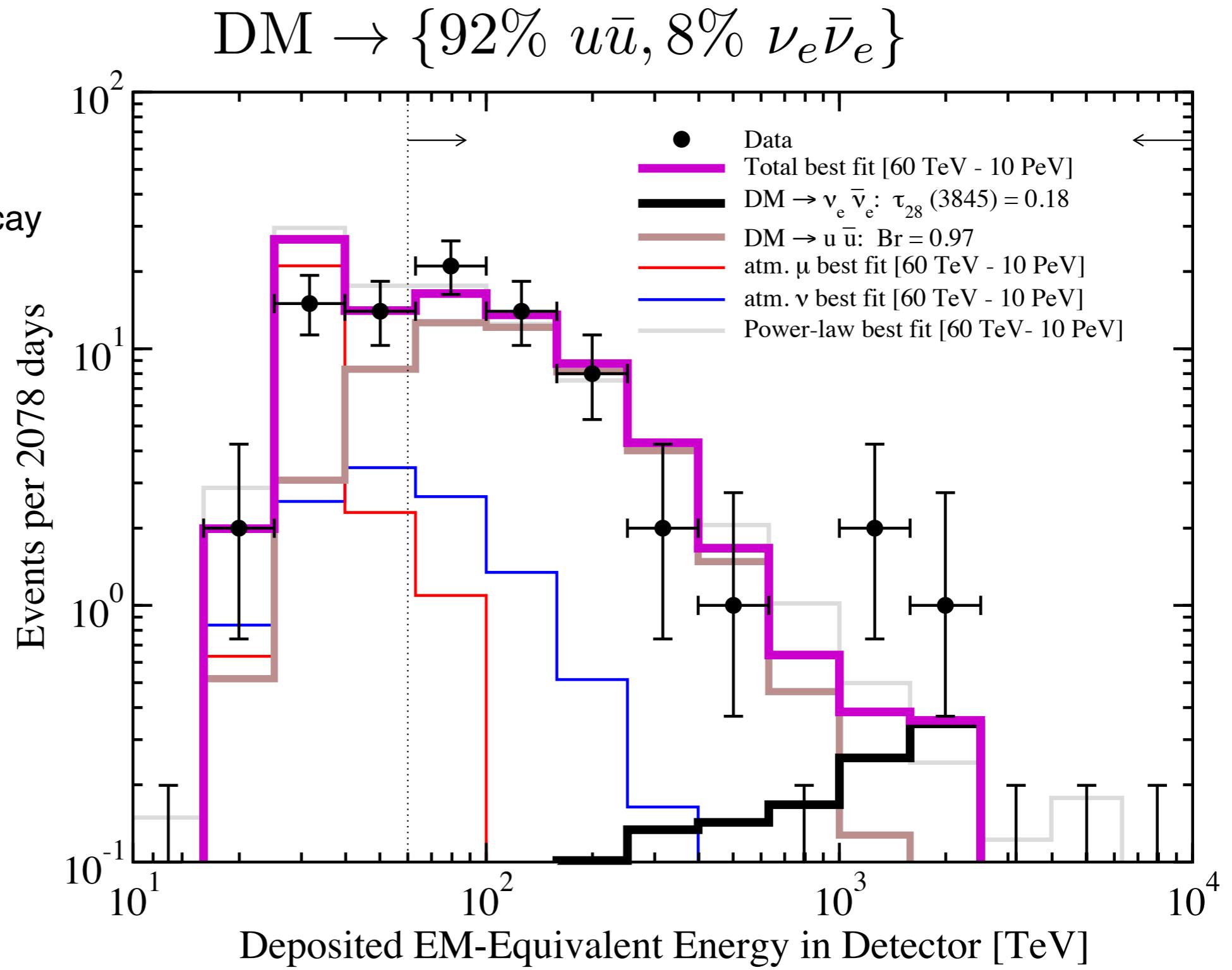


DM-only two-channel decay: Channel-by-channel comparison of $\Delta\chi^2$ at best fit
($\text{DM} \rightarrow \{u\bar{u}, \nu_e\bar{\nu}_e\}$)

Confronting with energy distribution of IceCube data

Event rate:

DM-only two-channel decay



6 years data set

A. Bhattacharya, A. E., S. Palomares-Ruiz,
I. Sarcevic, [arXiv:1903.12623]

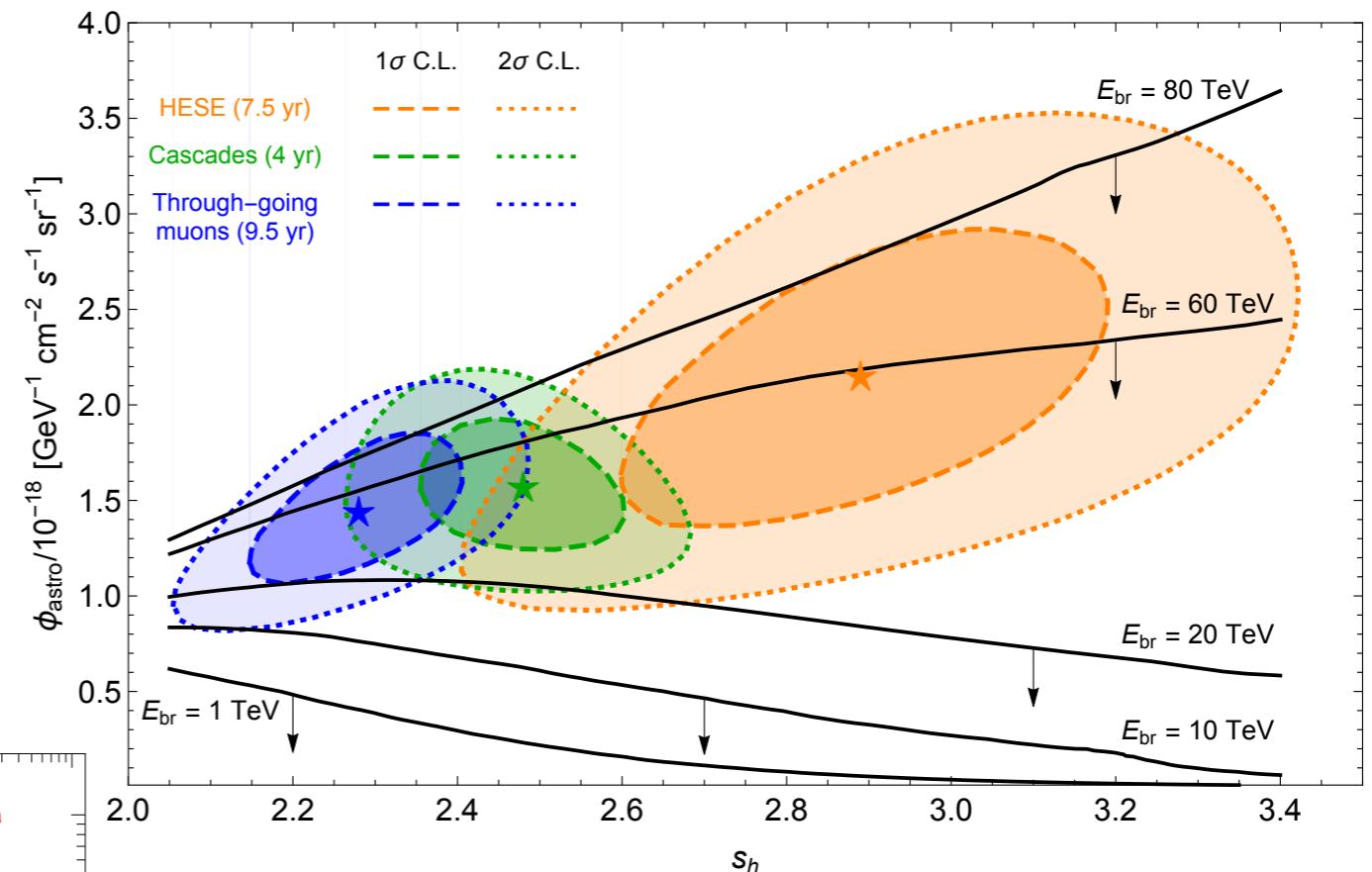
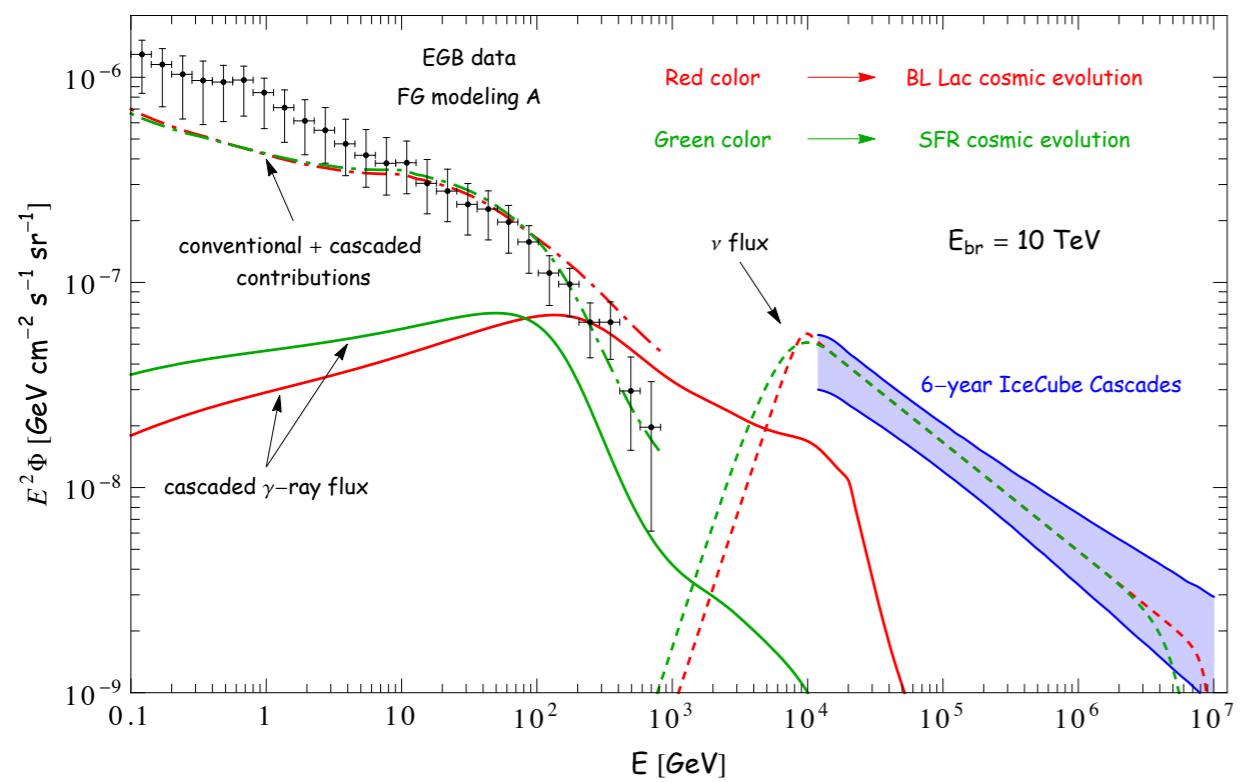
Low energy part of IceCube data

✓ Tension between Fermi EGB and IceCube data

A. Capanema, A.E., K. Murase
arXiv: 2002.07192

Poster: A. Capanema

~ 3σ tension for $E_{br} = 10$ TeV
~ $(4-5)\sigma$ tension for $E_{br} = 1$ TeV



Tension is robust, independent of the cosmic evolution of sources, conventional contribution to EGB, foreground modeling for EGB, etc

A. Capanema, A.E., P. Serpico
arXiv: 2007.07911

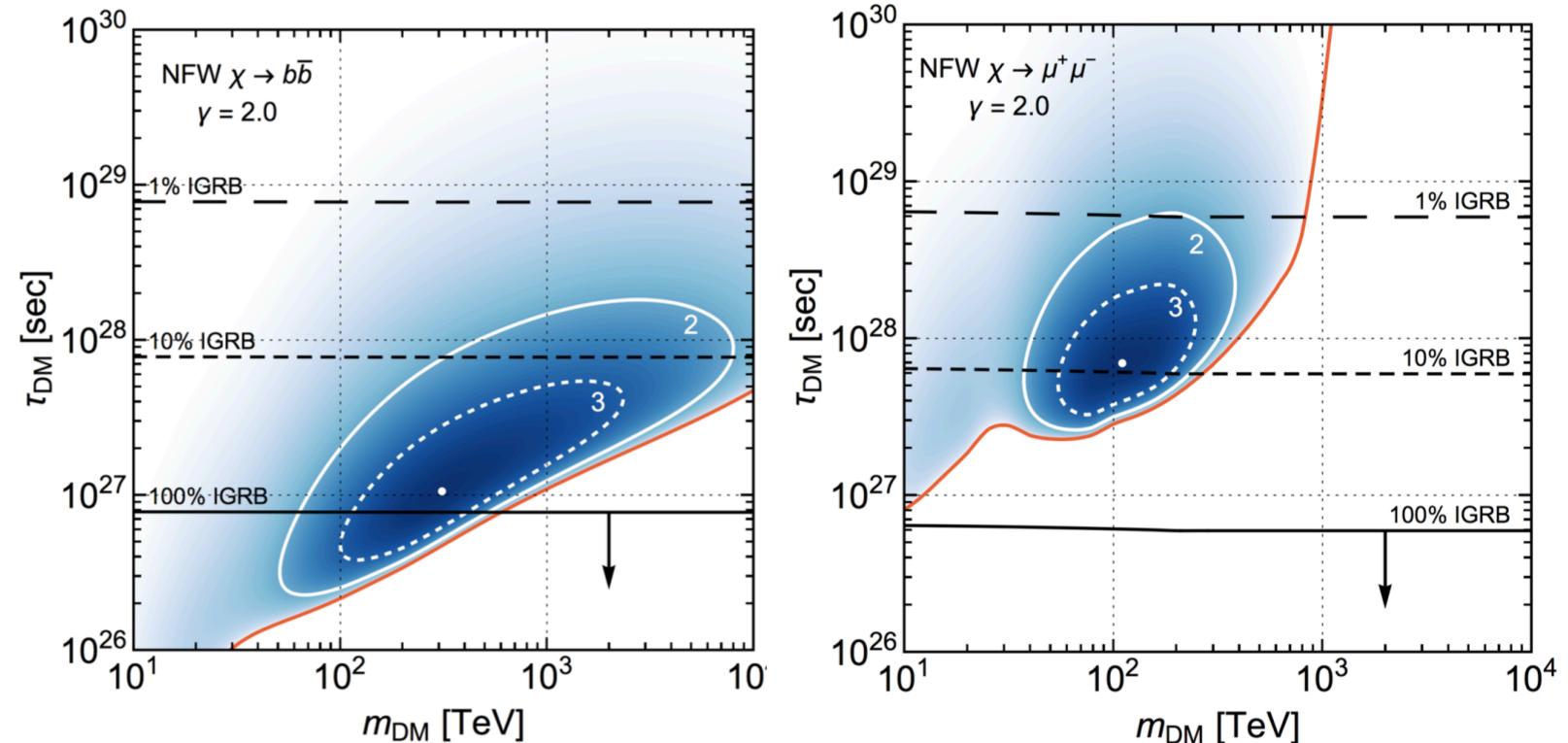
Dark matter interpretation of IceCube neutrinos



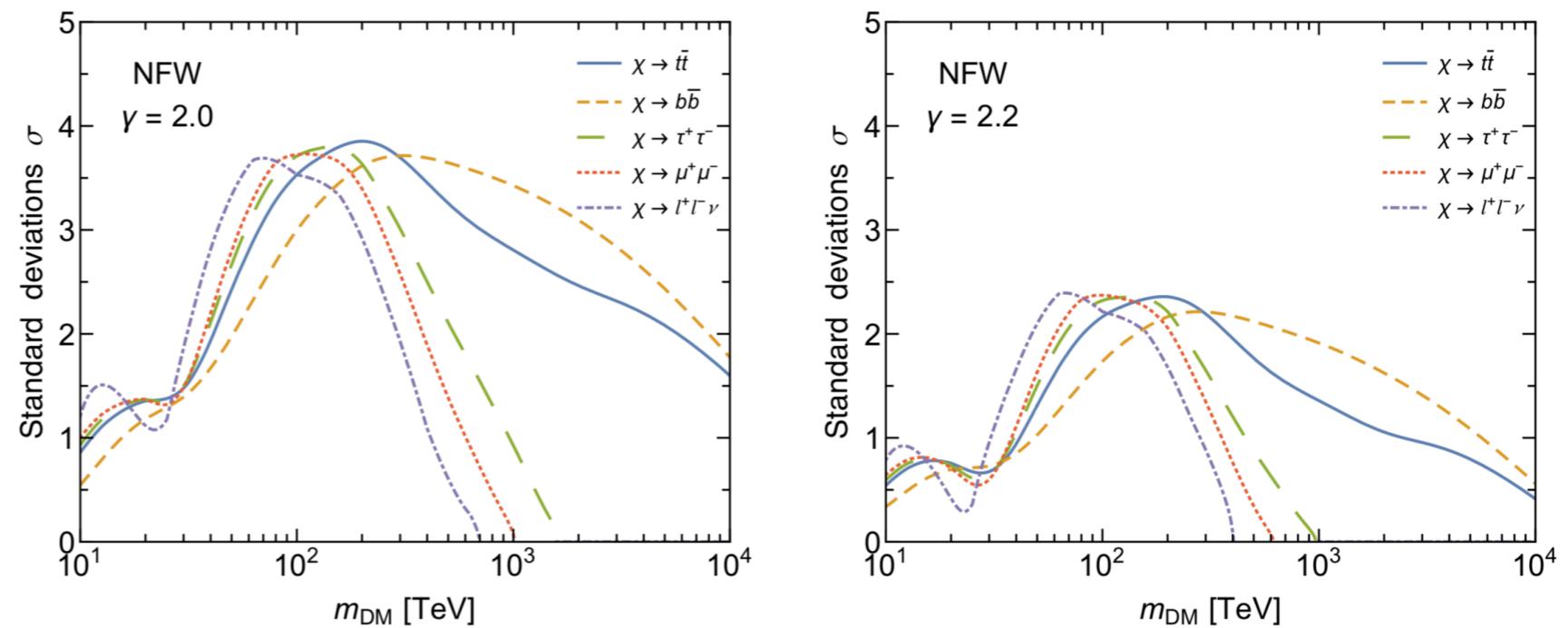
2-years MESE IceCube events, a slight excess in the energy range 10-100 TeV

Two-components scenario:
astrophysical power-law + Dark Matter

M. Chianese, G. Miele and S. Morisi
arXiv: 1610.04612



Likelihood-ratio analysis: 3.9σ for a
DM interpretation of the IceCube
low energy excess;



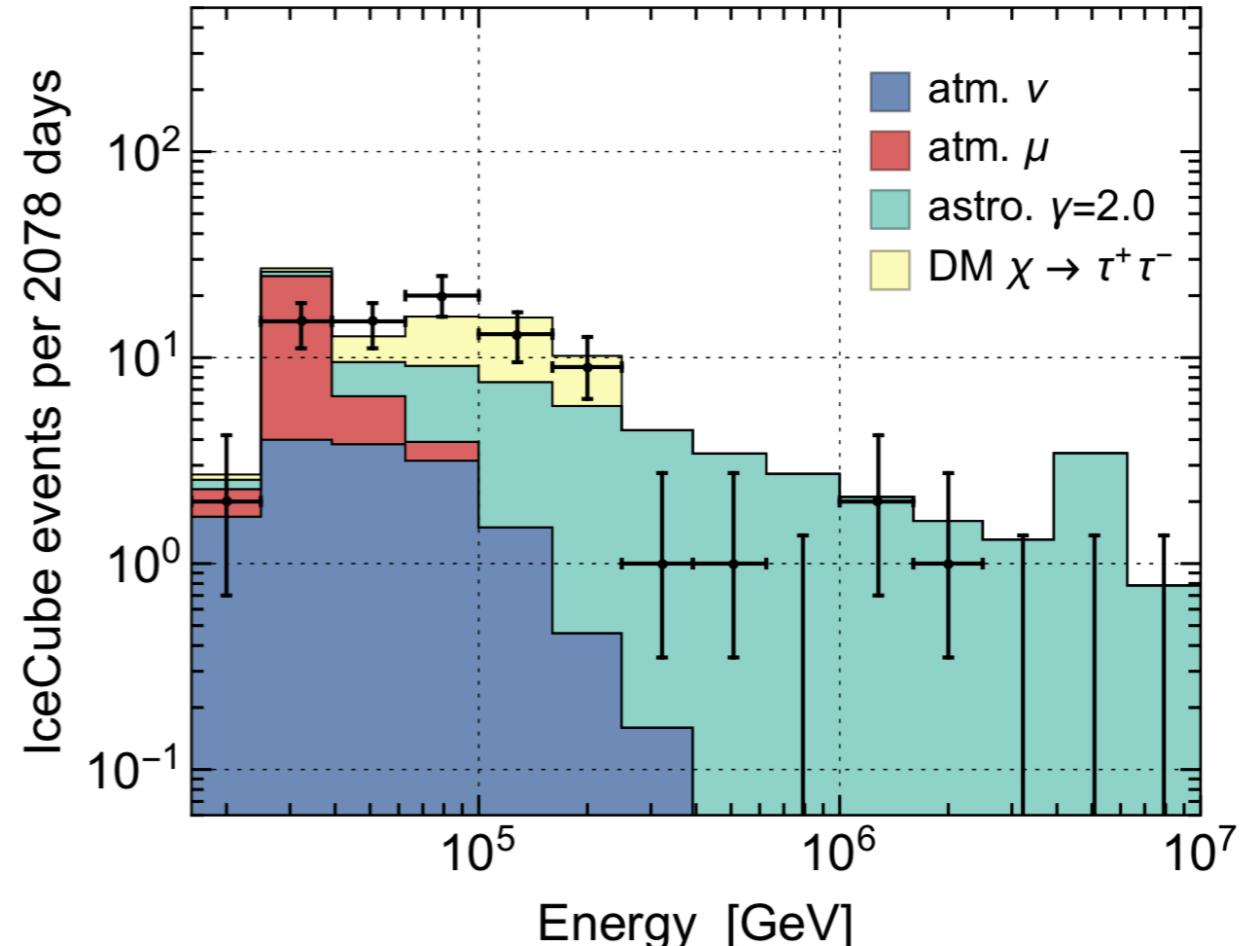
Dark matter interpretation of IceCube neutrinos

✓ 6-year HESE data and ~ hundred TeV decaying DM

$$M_{DM} = 400 \text{ TeV} \text{ and } \tau_{DM} = 1.6 \times 10^{28} \text{ s}$$

M. Chianese, G. Miele and S. Morisi
arXiv:1707.05241

Two-components scenario:
astrophysical power-law + Dark Matter

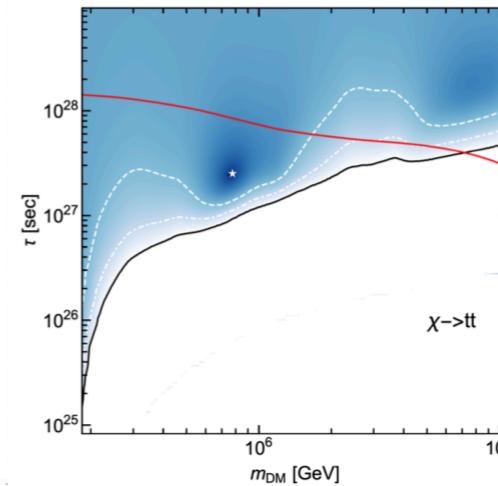
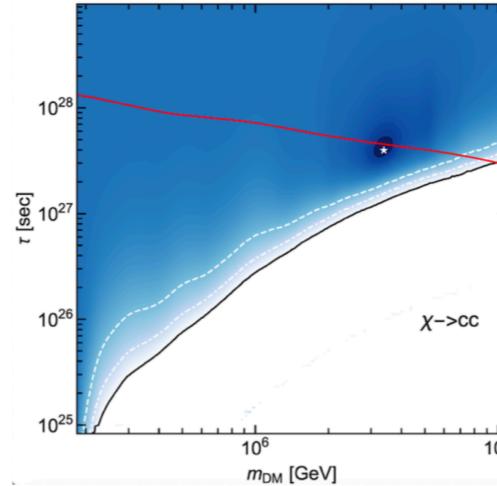
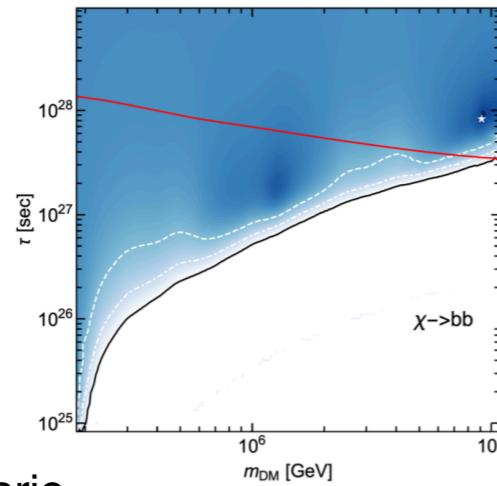


Adopting a spectral index in the range [2.0,2.2], compatible with the upgoing muon neutrinos data and with pp scenario, the 6-years HESE data show an $\sim 2.6 \sigma$ excess in the number of events in the energy range 40–200 TeV

Dark matter interpretation of IceCube neutrinos

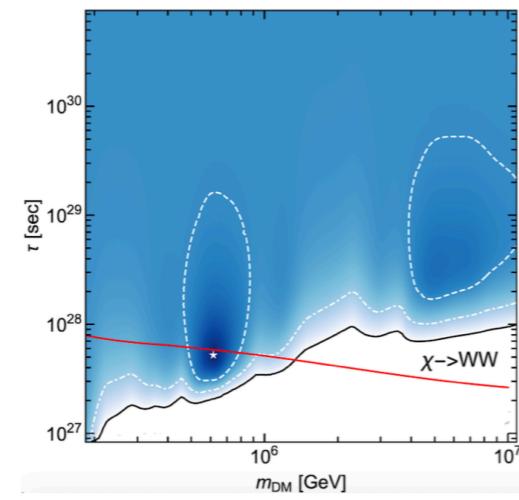
✓ 7.5 years IceCube HESE data

M. Chianese, D. Fiorillo, G. Miele, S. Morisi and O. Pisanti, arXiv: 1907.11222

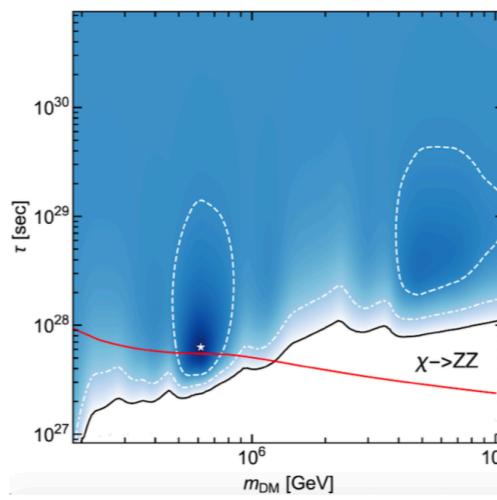


Two-components scenario

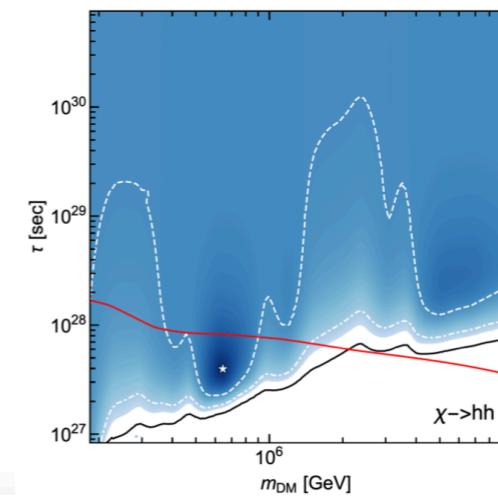
(a) Channel $b\bar{b}$



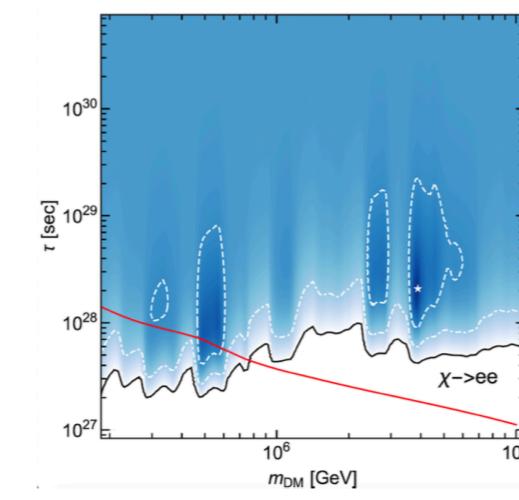
(b) Channel $c\bar{c}$



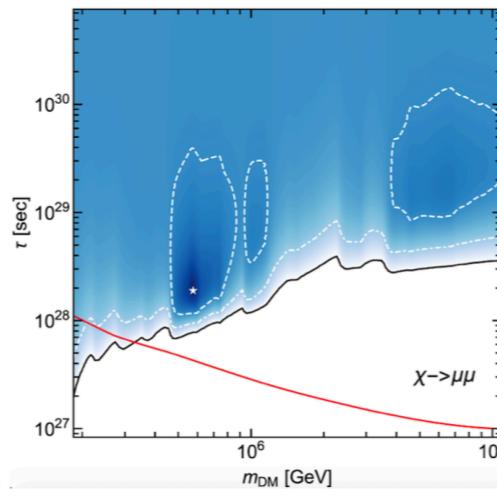
(c) Channel $t\bar{t}$



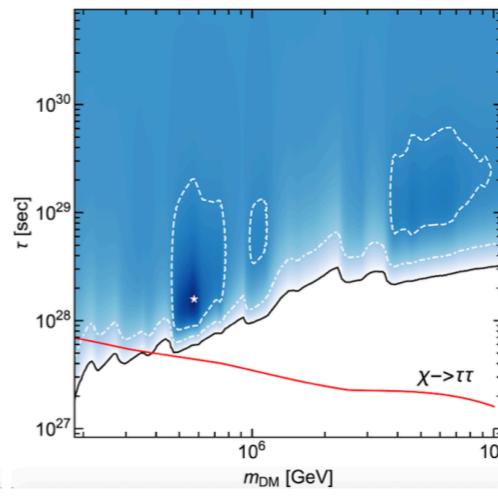
(a) Channel W^+W^-



(b) Channel ZZ

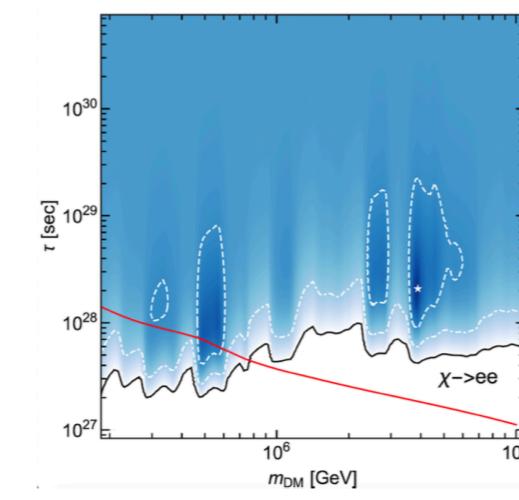


(c) Channel hh

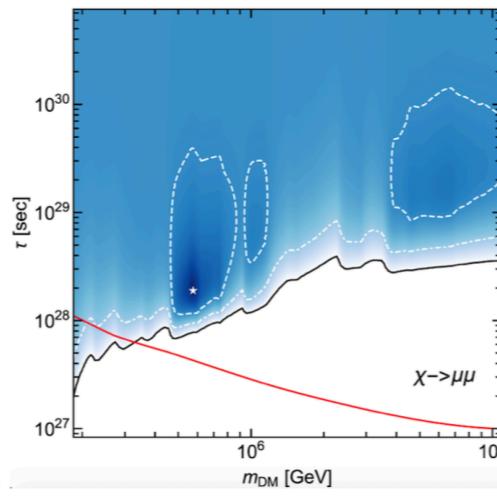


Red line -> Fermi limit

(d) Channel e^+e^-



(e) Channel $\mu^+\mu^-$



(f) Channel $\tau^+\tau^-$



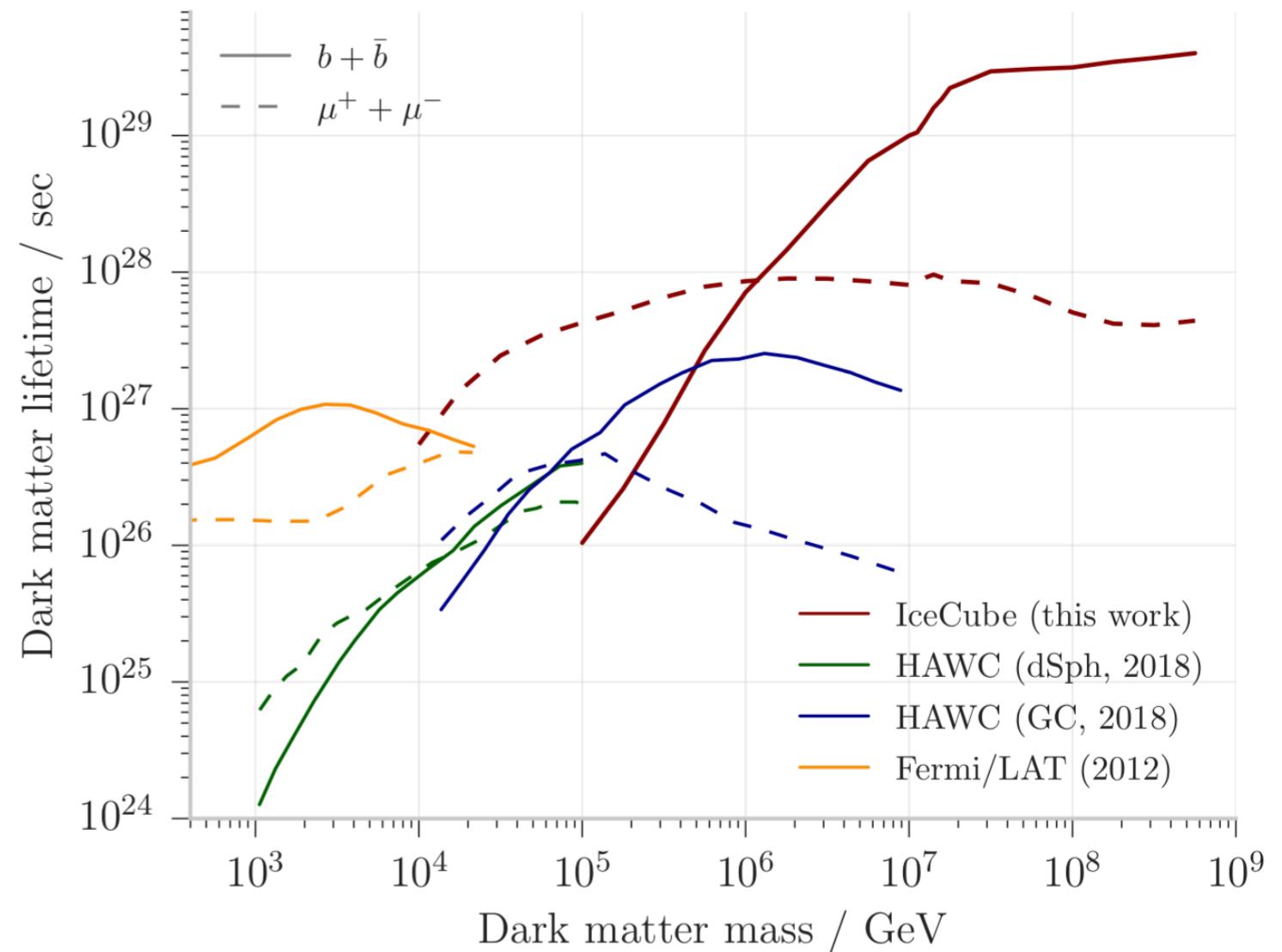
Dark matter interpretation of IceCube neutrinos

✓ IceCube Coll. analysis

From the paper (red color is mine):

“However, neither analysis identified a significant dark matter excess in the data, and models in which the cosmic neutrinos flux arises entirely from dark matter decay (yes, for 100% b.r. to one channel. But for that there were no need of an analysis!) are disfavored”.

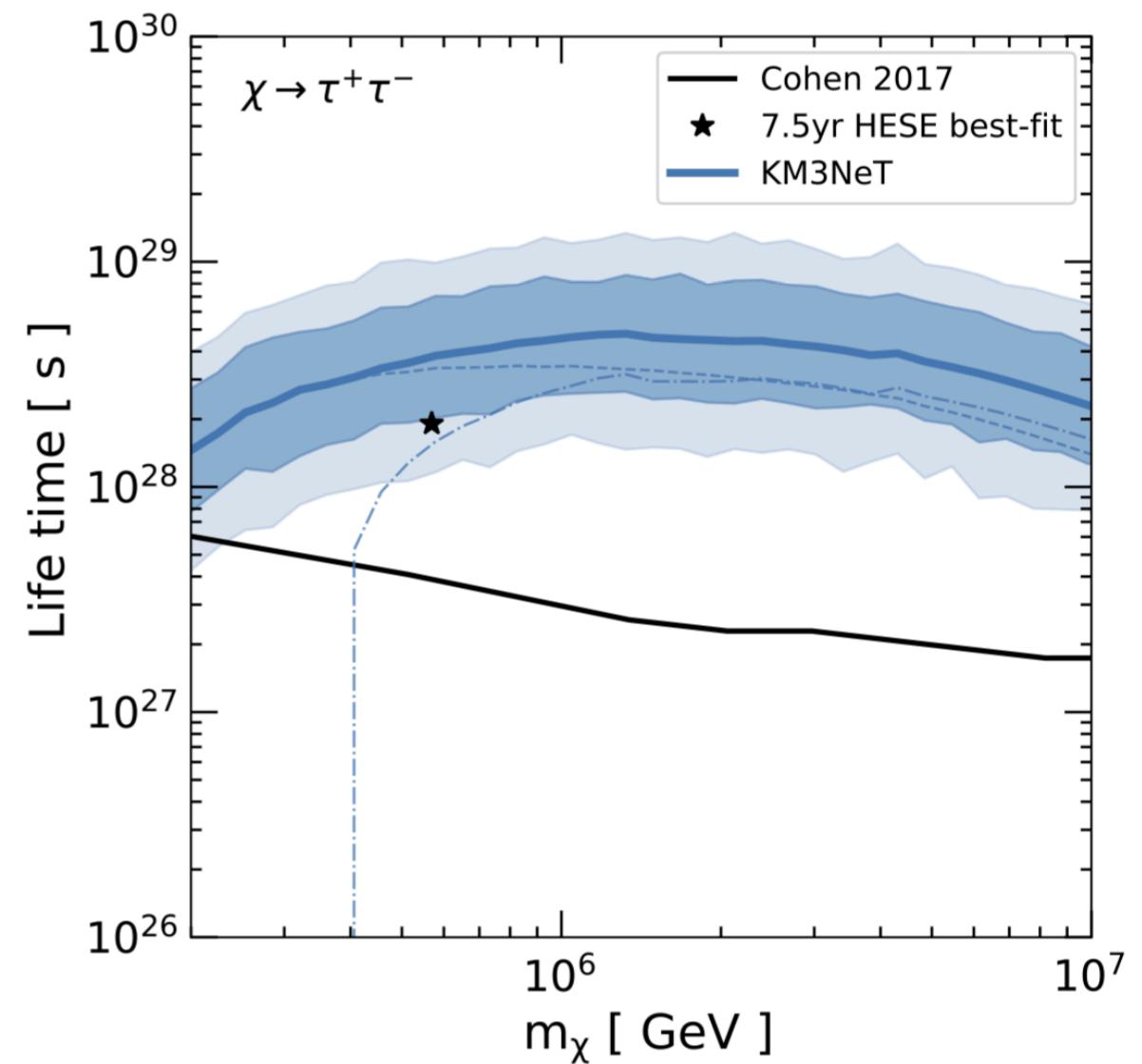
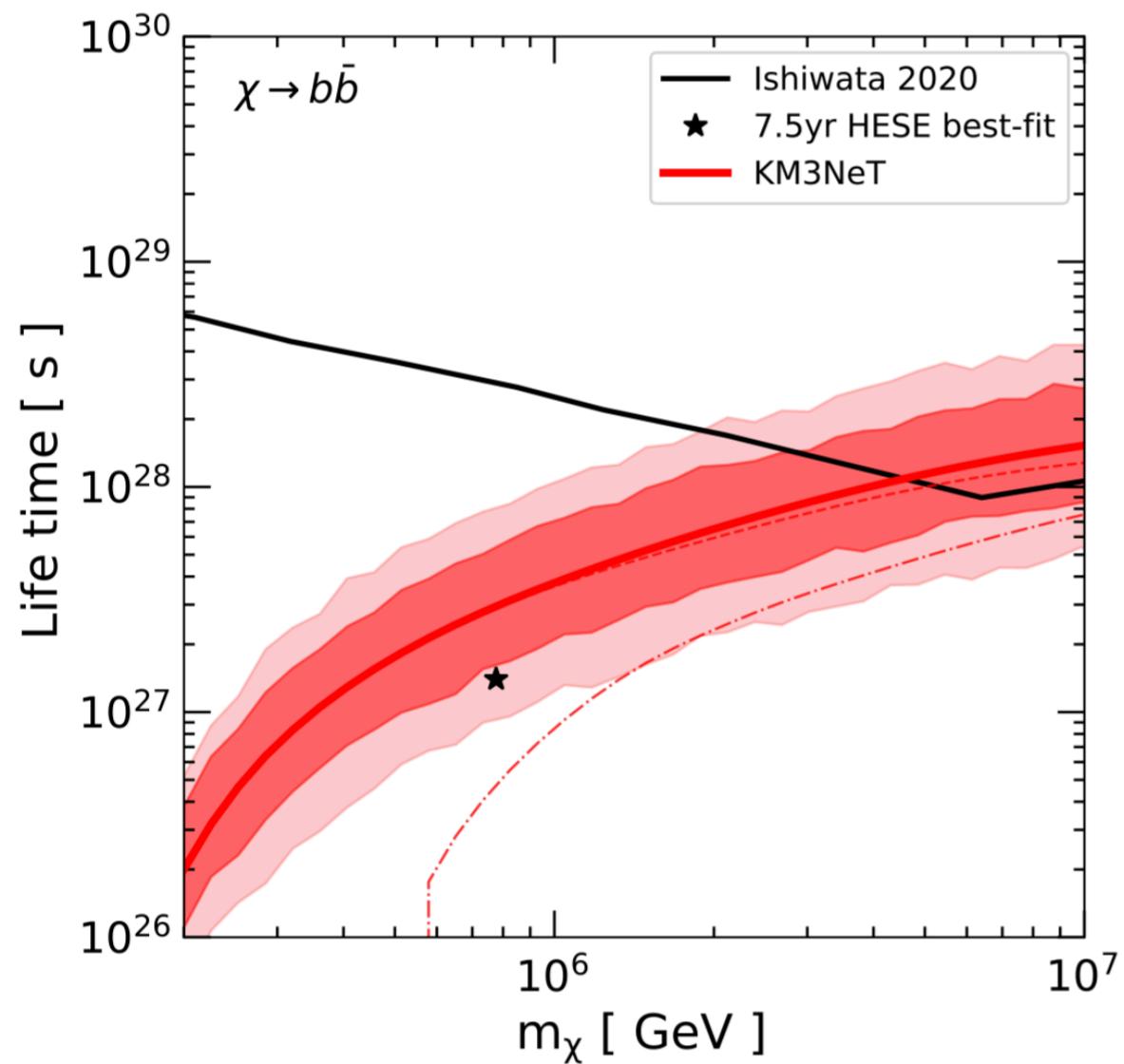
IceCube Coll.
arXiv:1804.03848



Dark matter interpretation of IceCube neutrinos

✓ Sensitivity of KM3NeT to decaying dark matter

K. Ng et al, arXiv: 2007.03692



Gamma ray bounds

Universe is opaque for
gamma-rays with $E > 1 \text{ TeV}$



cascades develop: gamma-ray
interaction with EBL and
CMB



gamma-rays populate at
lower energies $< 10^{(2-3)} \text{ GeV}$

Gamma ray bounds

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

✓ Isotropic diffuse gamma-ray background by Fermi-LAT

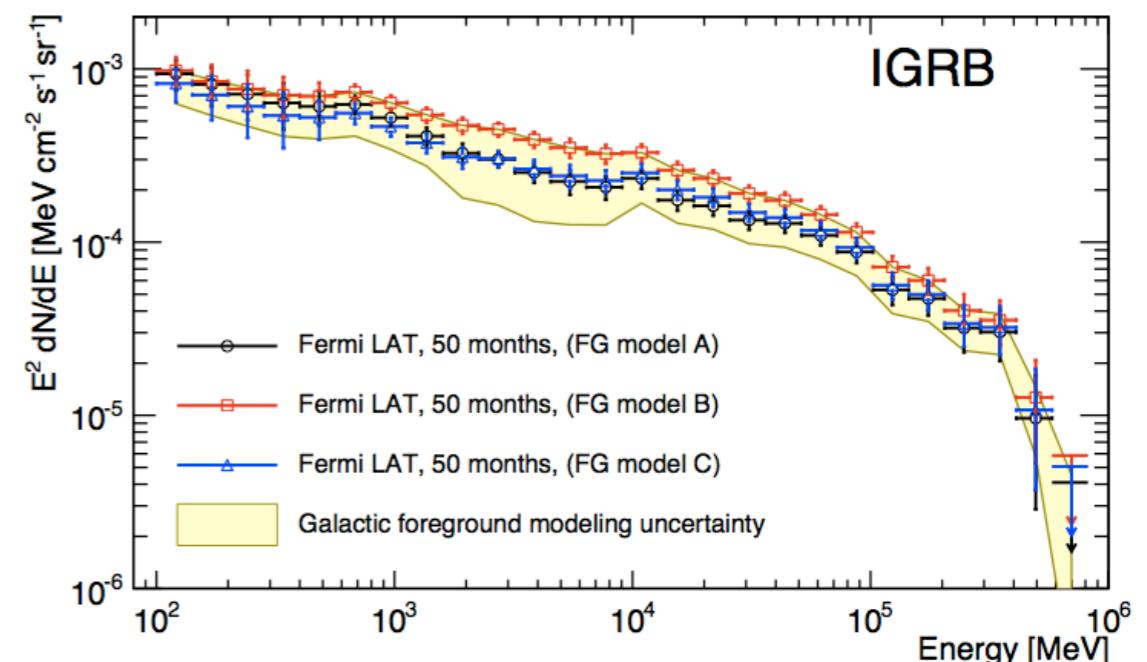
M. Ackermann et al. [The Fermi LAT Collaboration], arXiv:1410.3696 [astro-ph.HE].

integrated energy density

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

$$E_1 \sim \mathcal{O}(1) \text{ GeV}$$

$$E_2 \sim \mathcal{O}(100) \text{ GeV}$$



total electromagnetic energy budget

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



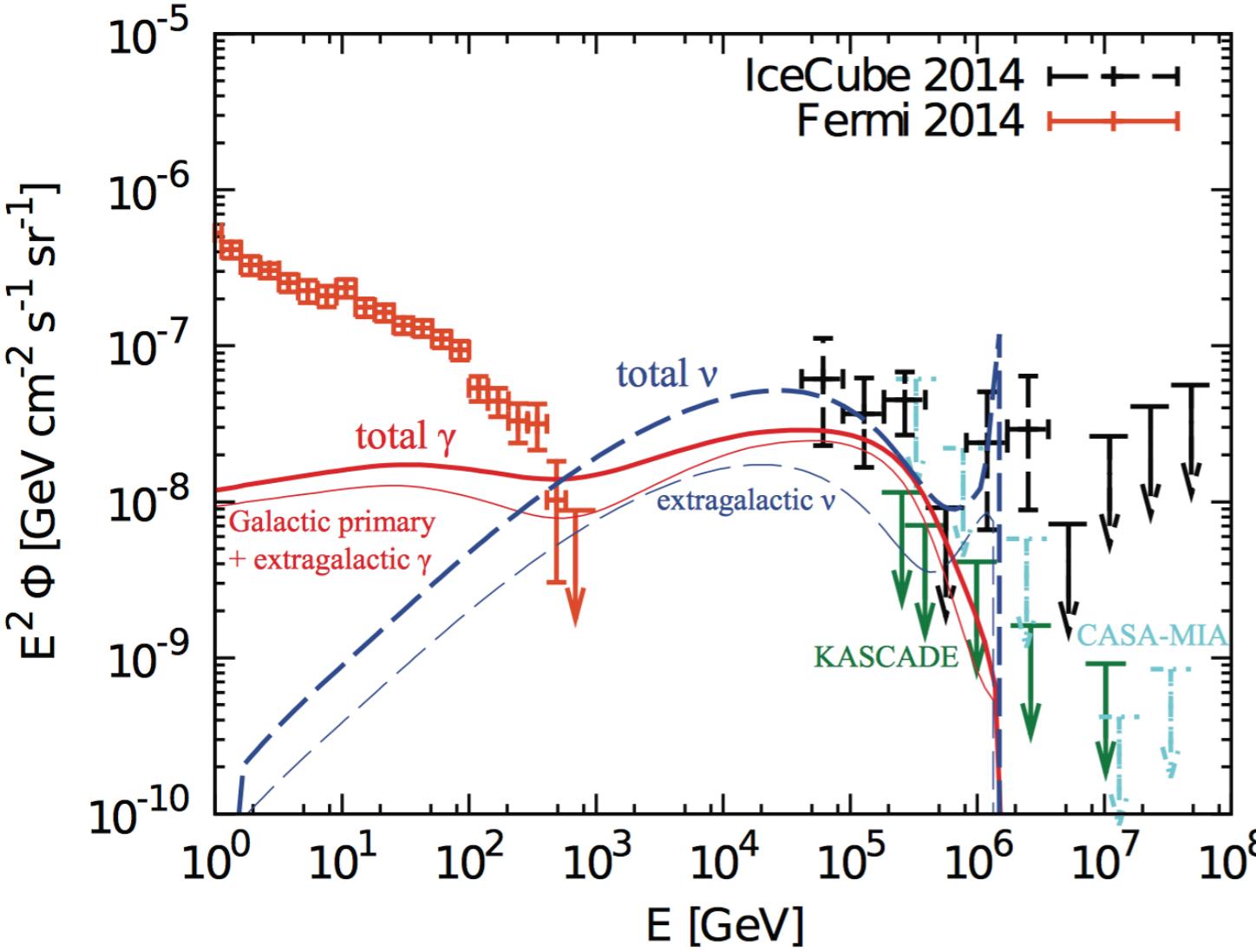
Gamma ray bounds

Universe is opaque for gamma-rays with $E > 1 \text{ TeV}$

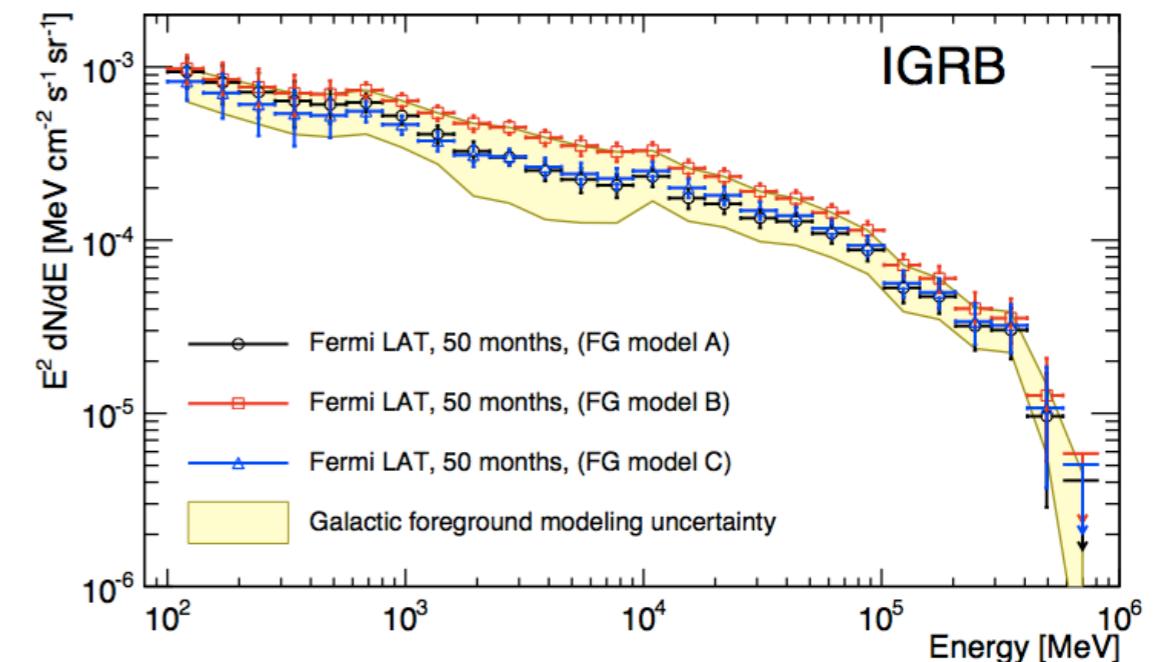
cascades develop: gamma-ray interaction with interstellar radiation field and CMB

gamma-rays populate at lower energies $< 10^{(2-3)} \text{ GeV}$

✓ Isotropic diffuse gamma-ray background by Fermi-LAT



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



Murase, Laha, Ando, Ahlers,
arXiv:1503.04663

Gamma ray bounds

✓ Multi-TeV high Galactic latitude diffuse gamma-ray flux

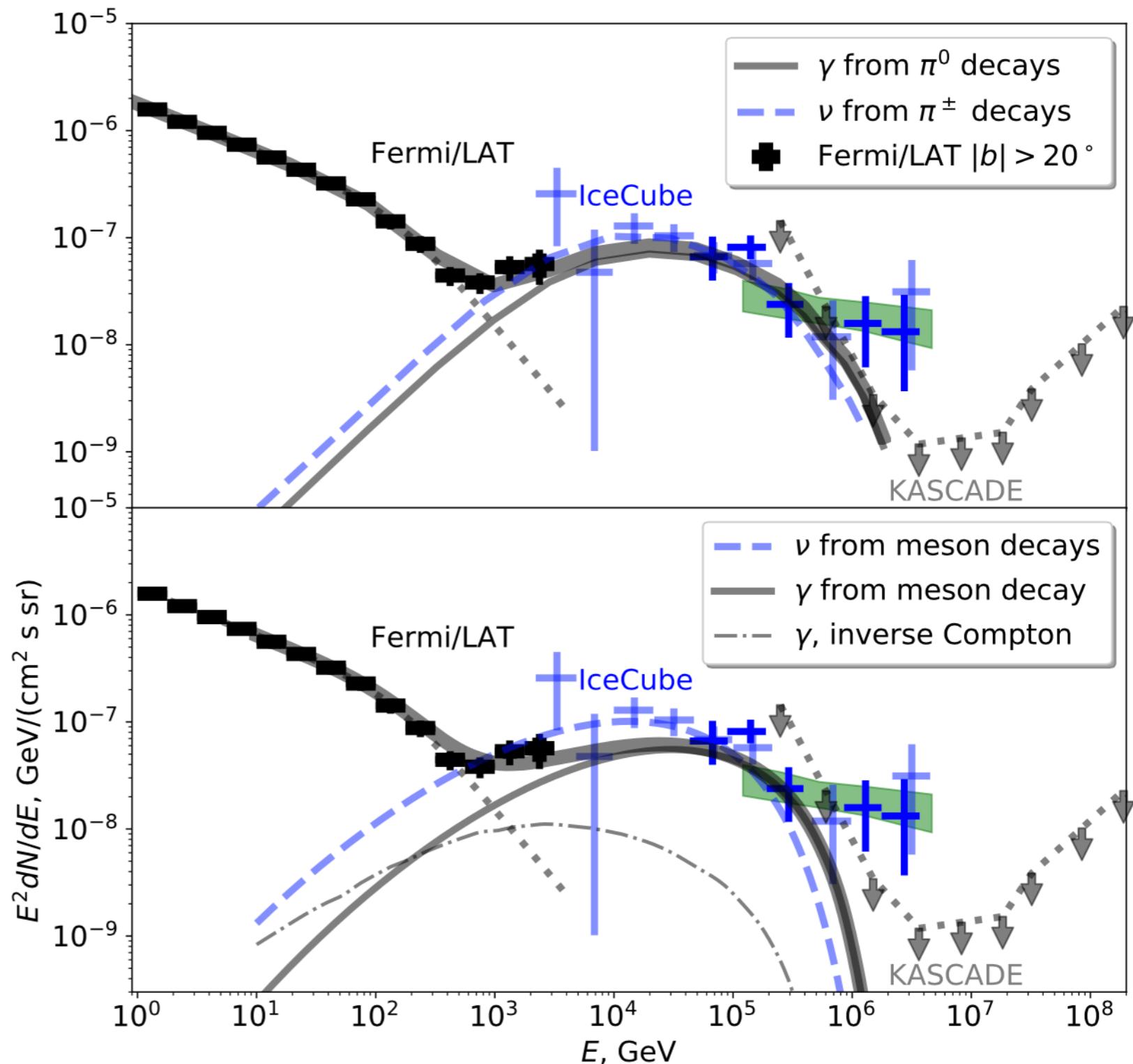
Michael's talk

1) Injected cosmic ray by
a recent nearby PeVatron

2) Cosmic ray interaction
in large scale halo around
the Milky Way

3) Decay of the dark
matter particles

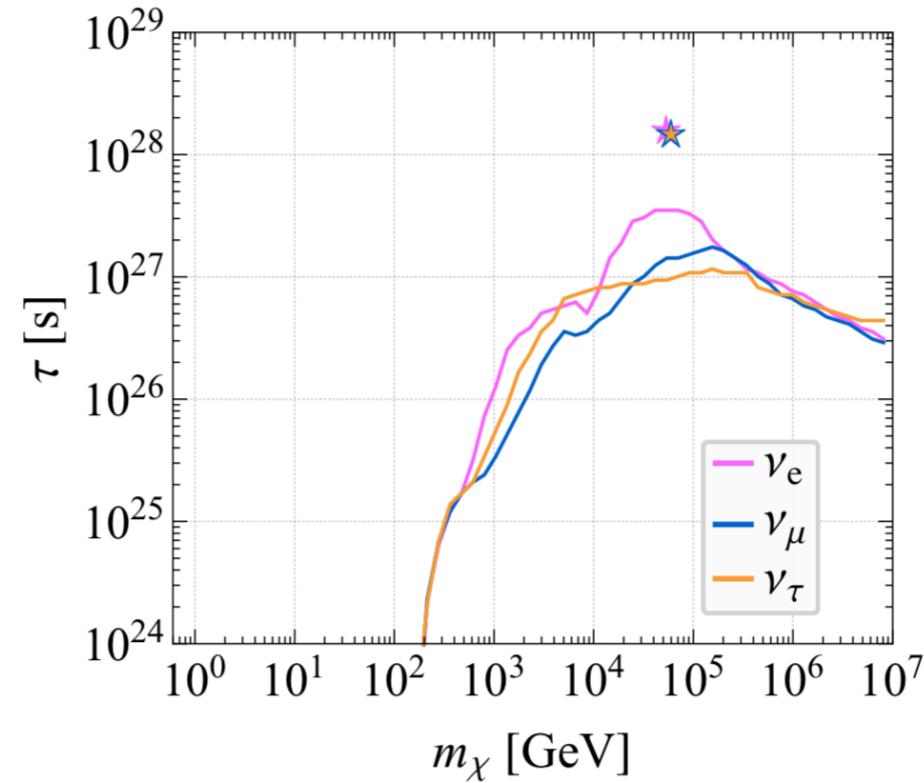
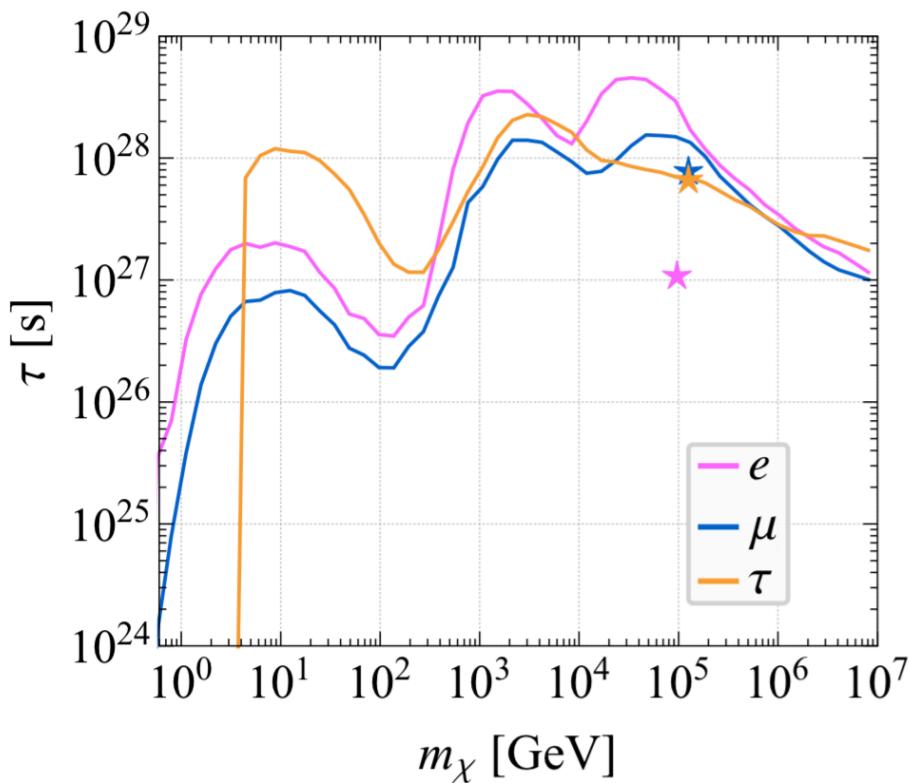
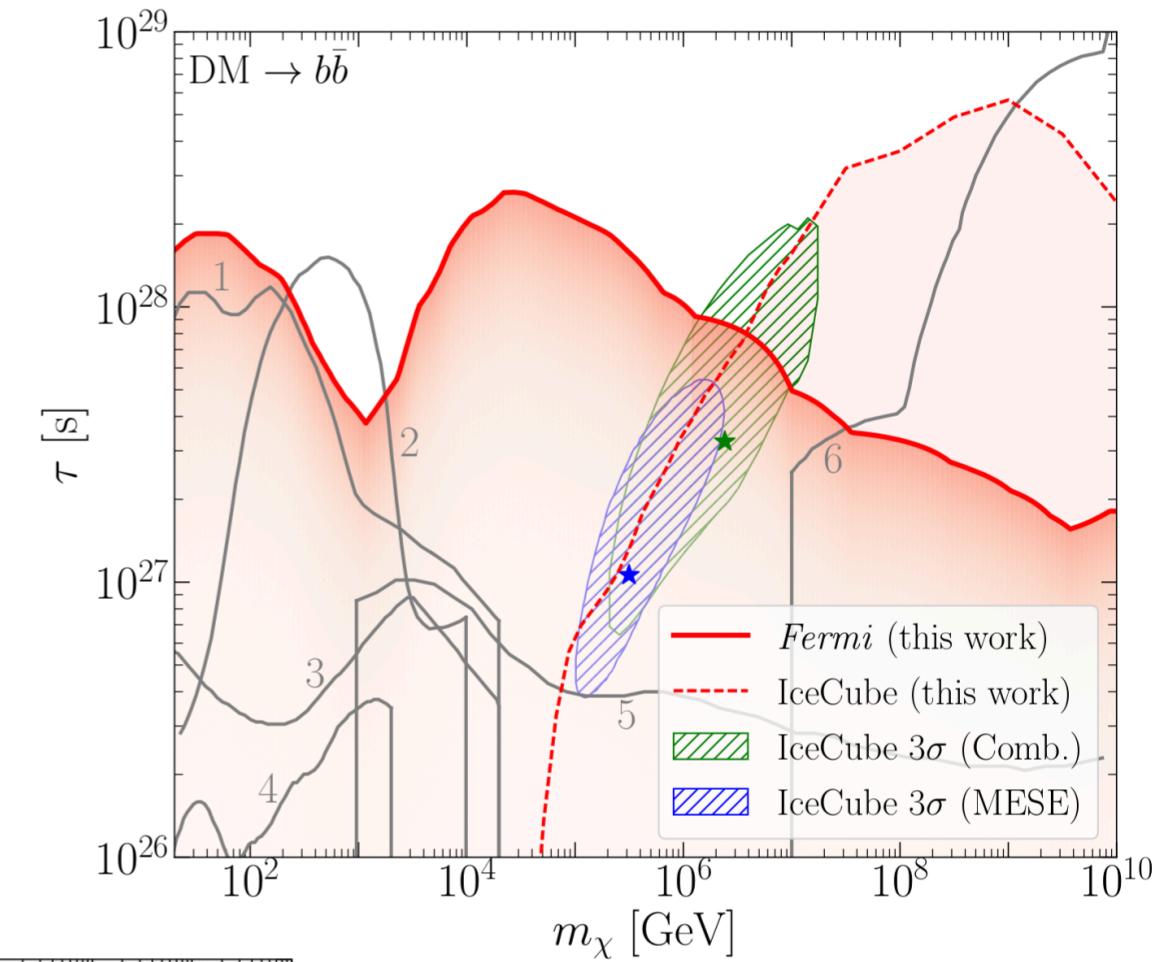
A.Neronov, M.Kachelriess, D.V.Semikoz
arXiv:1802.09983

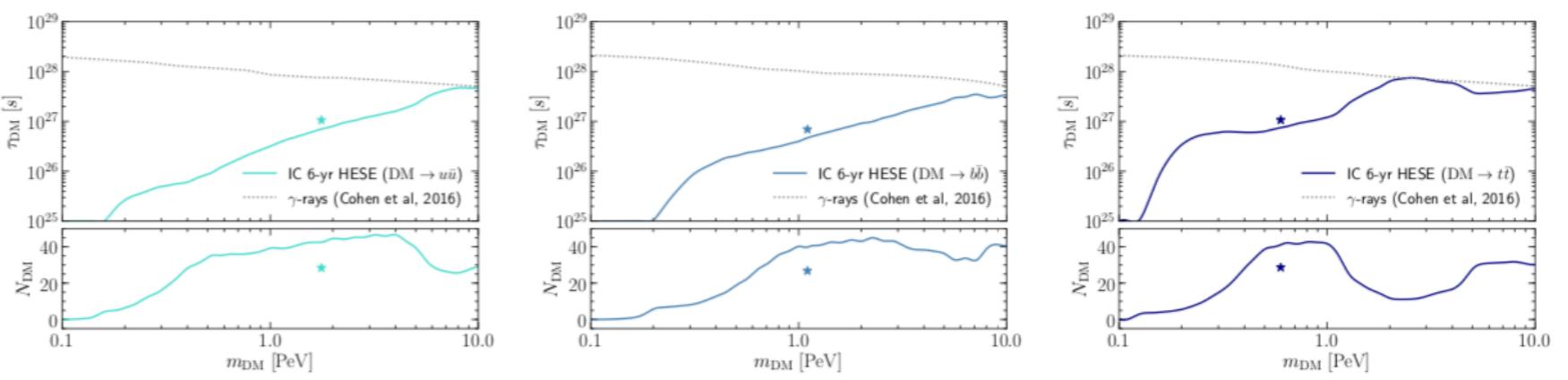


Gamma ray bounds

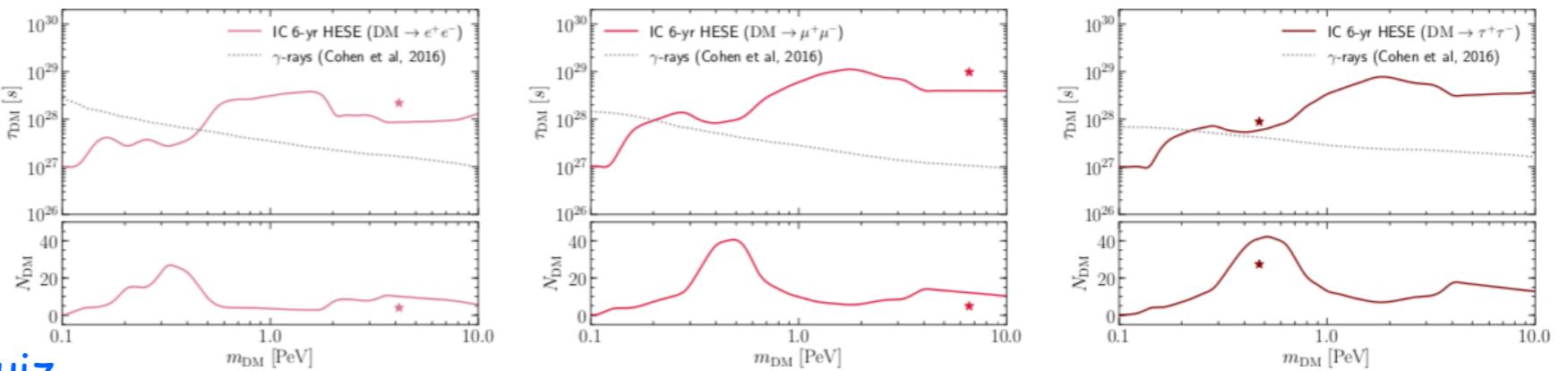
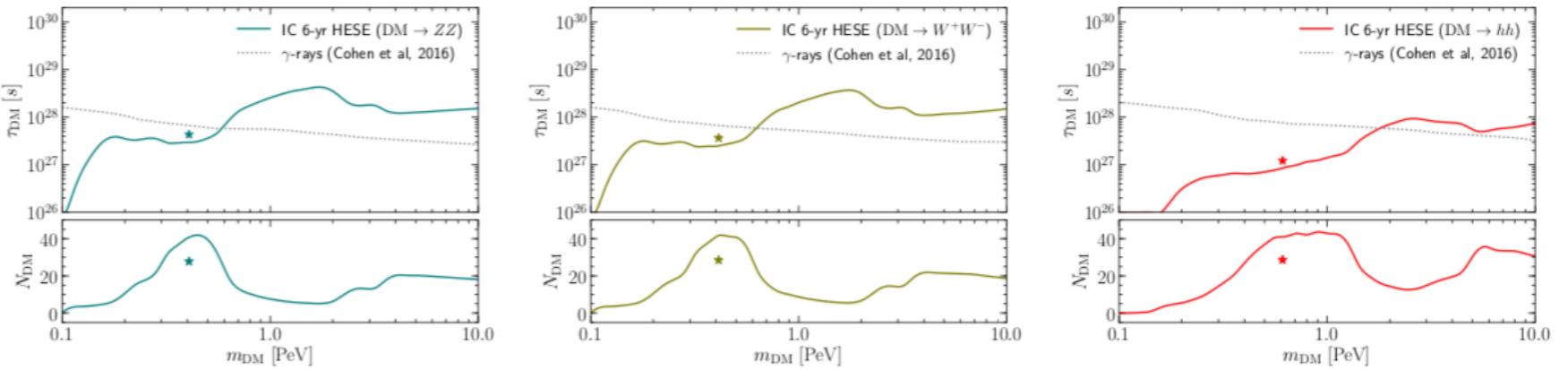
✓ Utilizing the Fermi measurement of the gamma-ray spectrum toward the Inner Galaxy, $|b| > 20^\circ$, $\text{ROI} < 40^\circ$

T. Cohen, K. Murase, N. L. Rodd, B. R. Safdi, and Y. Soreq
arXiv: 1612.05638

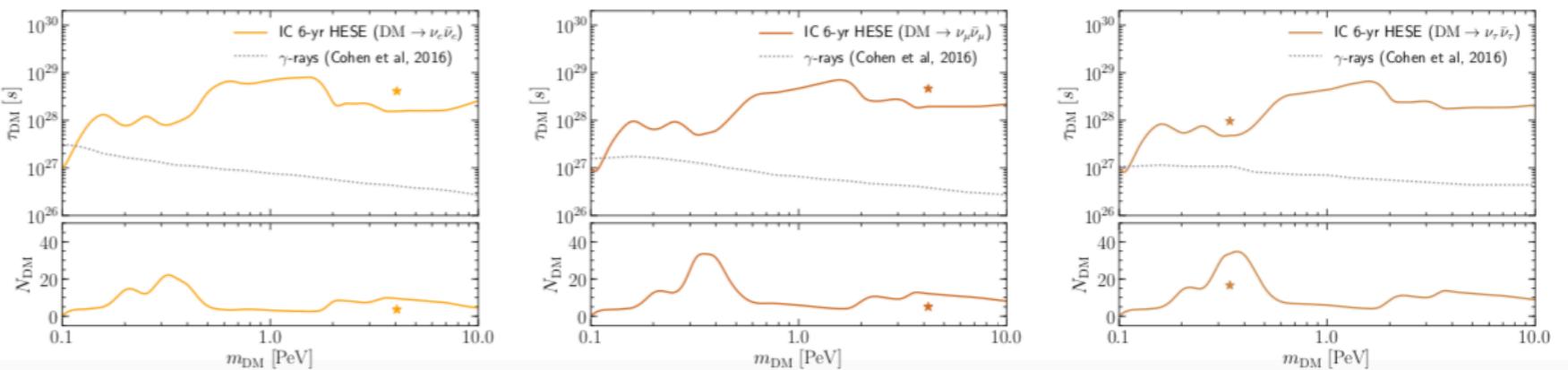




Gamma-ray limits from
T. Cohen, K. Murase, N. L.
Rodd, B. R. Safdi, and Y. Soreq
arXiv: 1612.05638



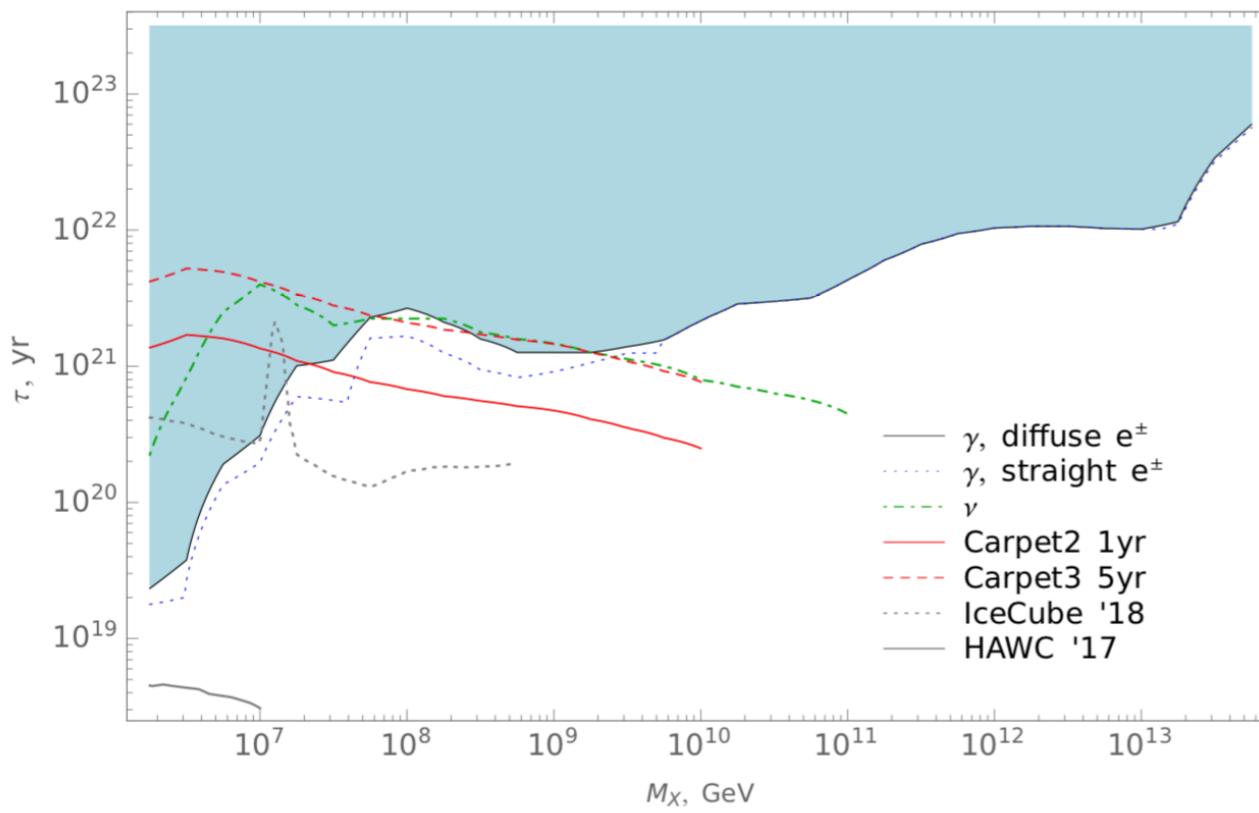
A. Bhattacharya, A. E., S. Palomares-Ruiz,
I. Sarcevic, [arXiv:1903.12623]



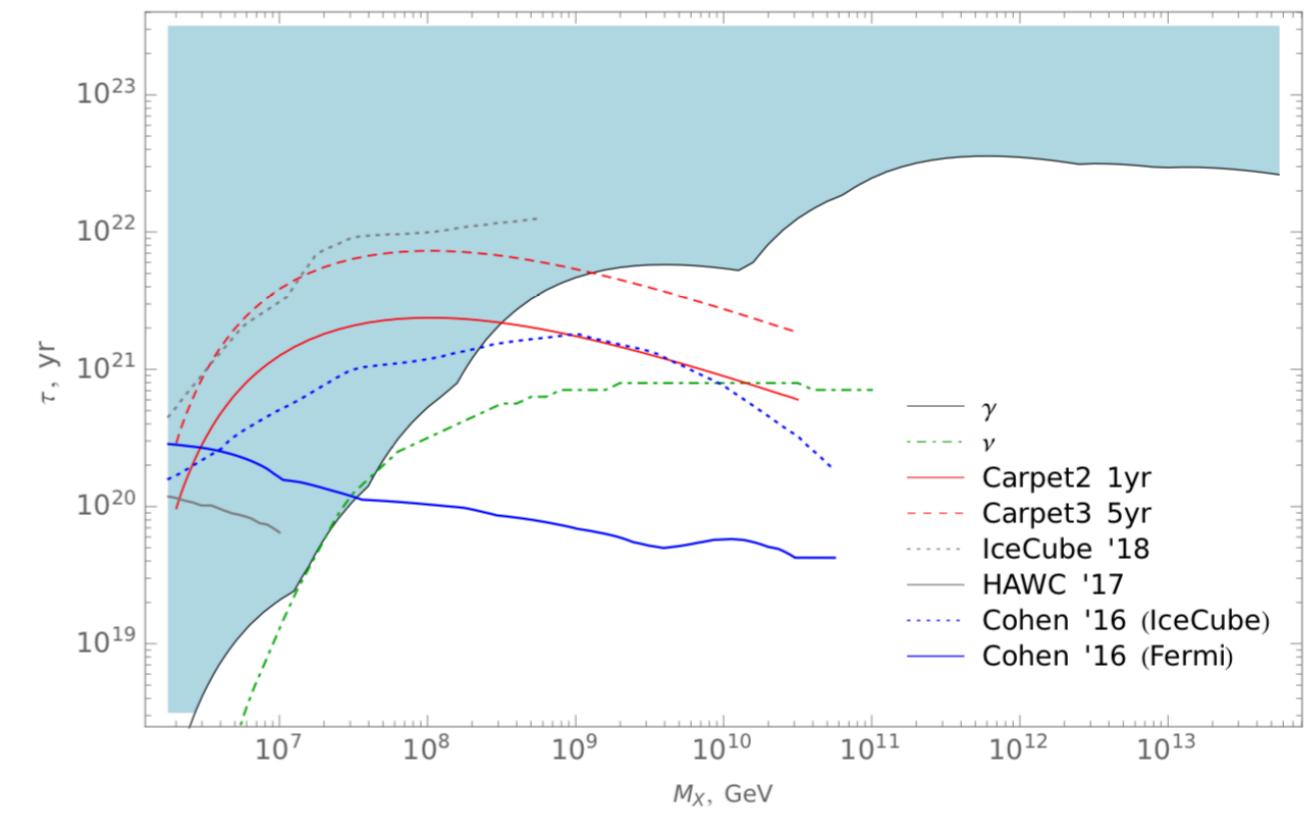
Probing (super)heavy DM

✓ DM mass $10^6 \leq M_X \leq 10^{16}$ GeV decaying on tree level into $X \rightarrow \nu\bar{\nu}$, $X \rightarrow e^+e^-$ and $X \rightarrow q\bar{q}$. Leptonic decay channels can explain the IceCube highest energy neutrino signal without overproducing high-energy photons for $M_X < 5.5 \times 10^7$ GeV and $1.5 \times 10^8 < M_X < 1.5 \times 10^9$ GeV. Hadronic decays contradict the gamma-ray limits for almost the whole range of M_X .

M. Kachelrieß, O. E. Kalashev and M. Yu. Kuznetsov
arXiv: 1805.04500



(a) $X \rightarrow \nu\bar{\nu}$



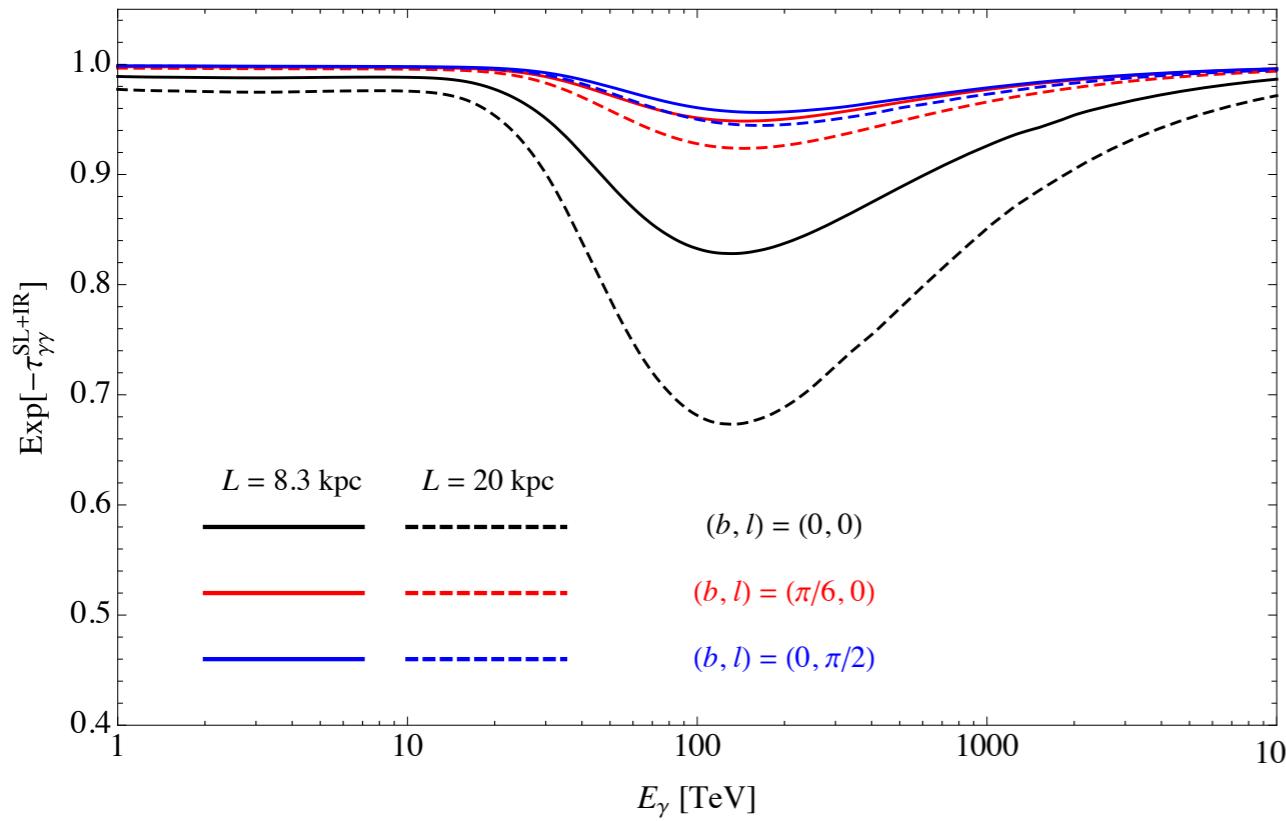
(b) $X \rightarrow q\bar{q}$

Gamma ray bounds

✓ Galactic component

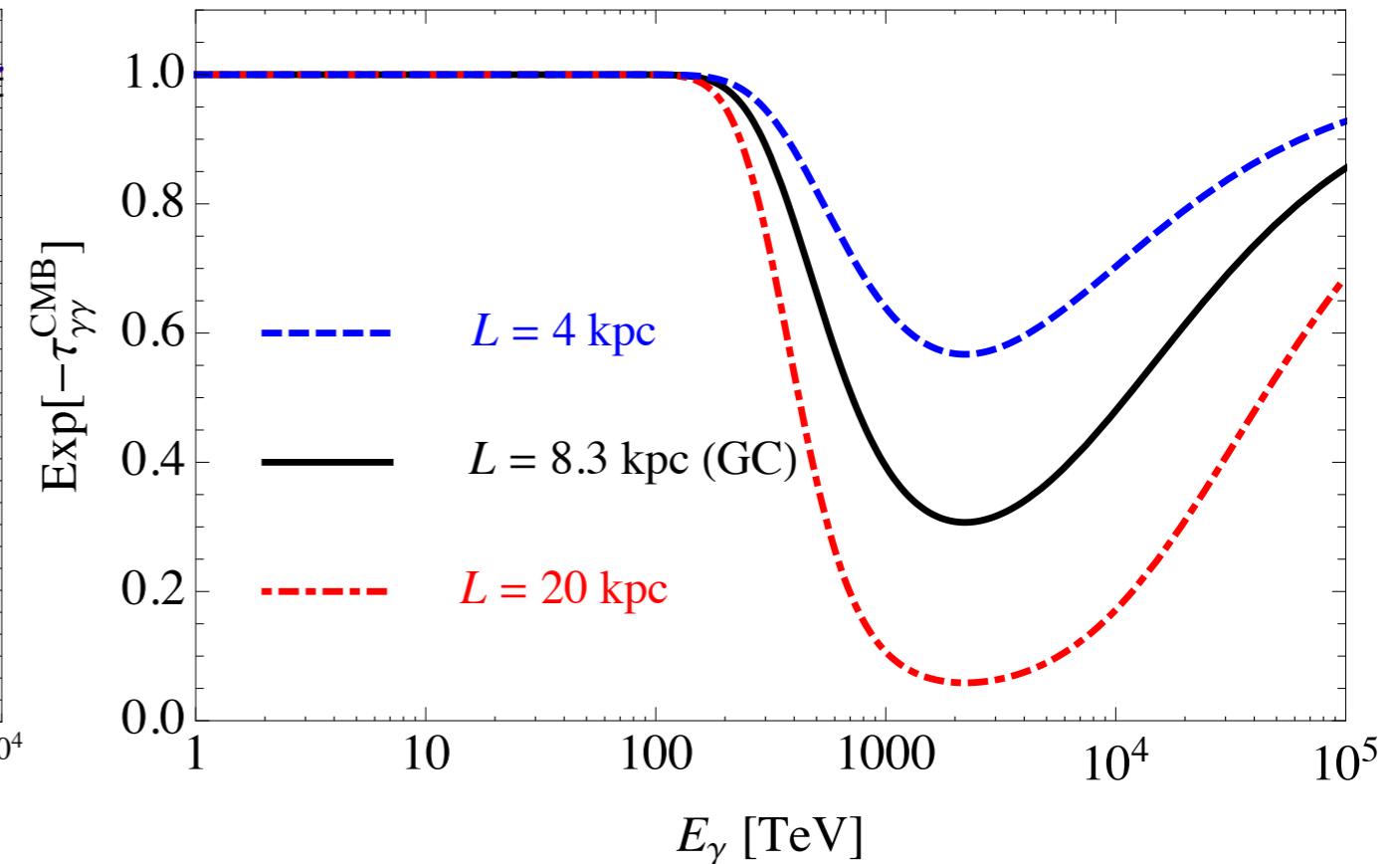
at \sim PeV, the absorption length of gamma-rays
are comparable to Galactic distances

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 \sim PeV

Absorption due to pair production
on CMB photons

Gamma ray bounds

✓ Galactic component

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

Prompt component

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

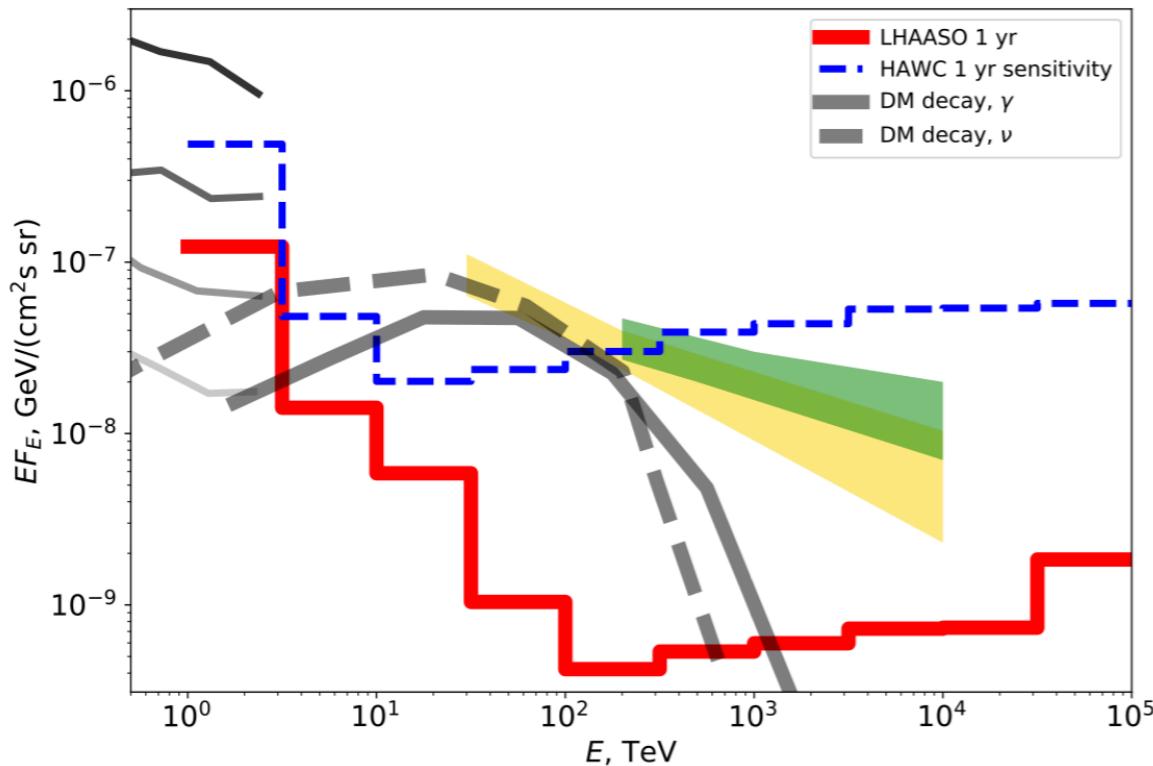
inverse-Compton component

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

Gamma ray bounds

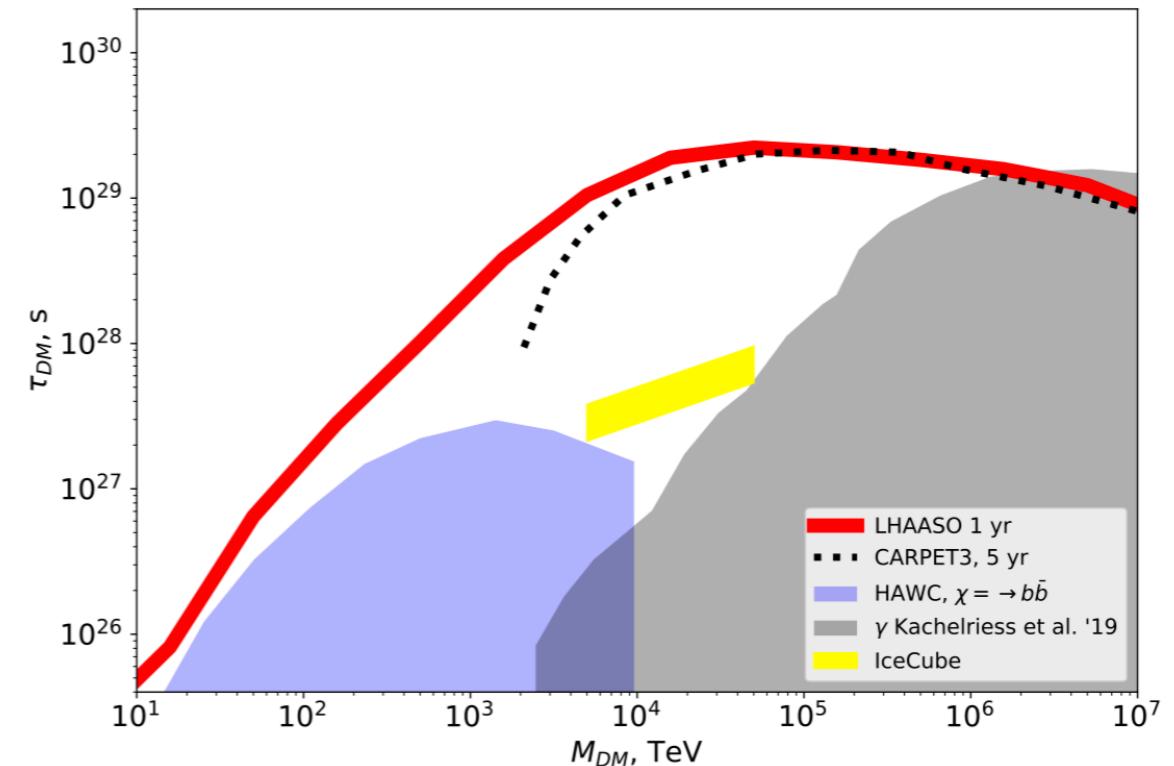
✓ LHAASO sensitivity for diffuse gamma-ray signals from the Galaxy

A. Neronov, D. Semikoz, arXiv: 2001.11881



sensitivity of LHAASO and HAWC to the expected sky-averaged signal from decaying DM with

$$M_{DM} = 5 \text{ PeV} \text{ and } \tau_{DM} = 3 \times 10^{27} \text{ s}$$

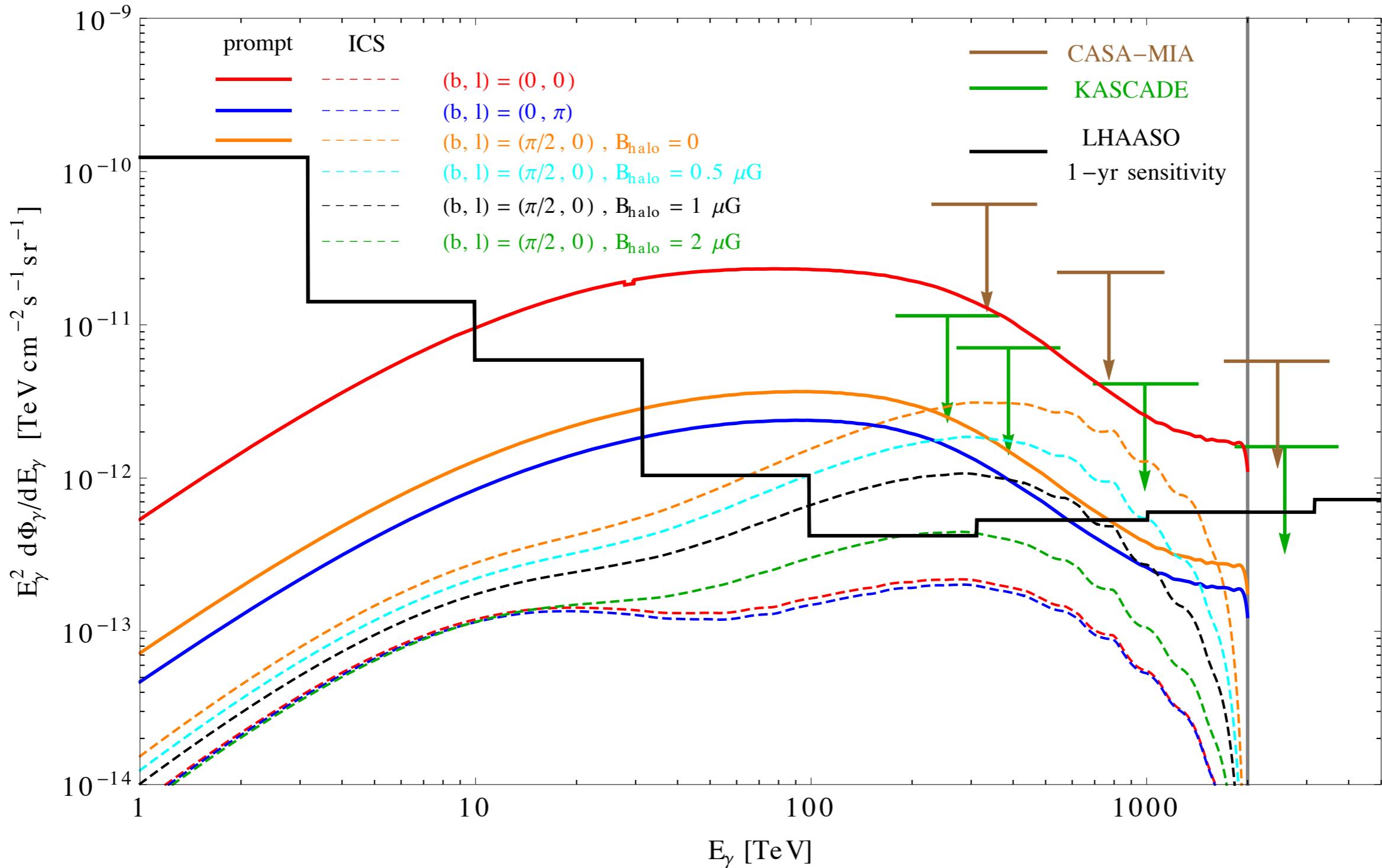


Sensitivity of LHAASO to dark matter decay time (for DM decaying into quarks). Yellow band shows the range of decay times with sizeable contribution to IceCube. Blue and grey shaded regions show the existing bounds imposed by HAWC and ultra-high-energy cosmic ray experiments. Dashed curves are from the HAWC search of the DM decay signal in the Fermi Bubble regions

Gamma ray bounds

✓ Galactic component

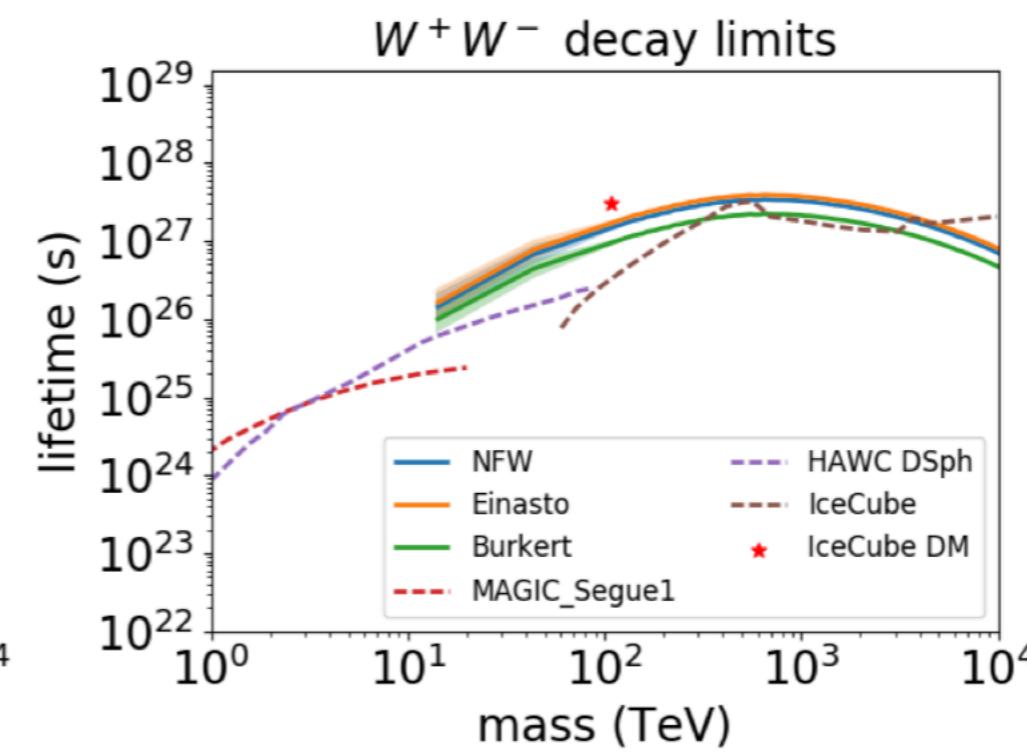
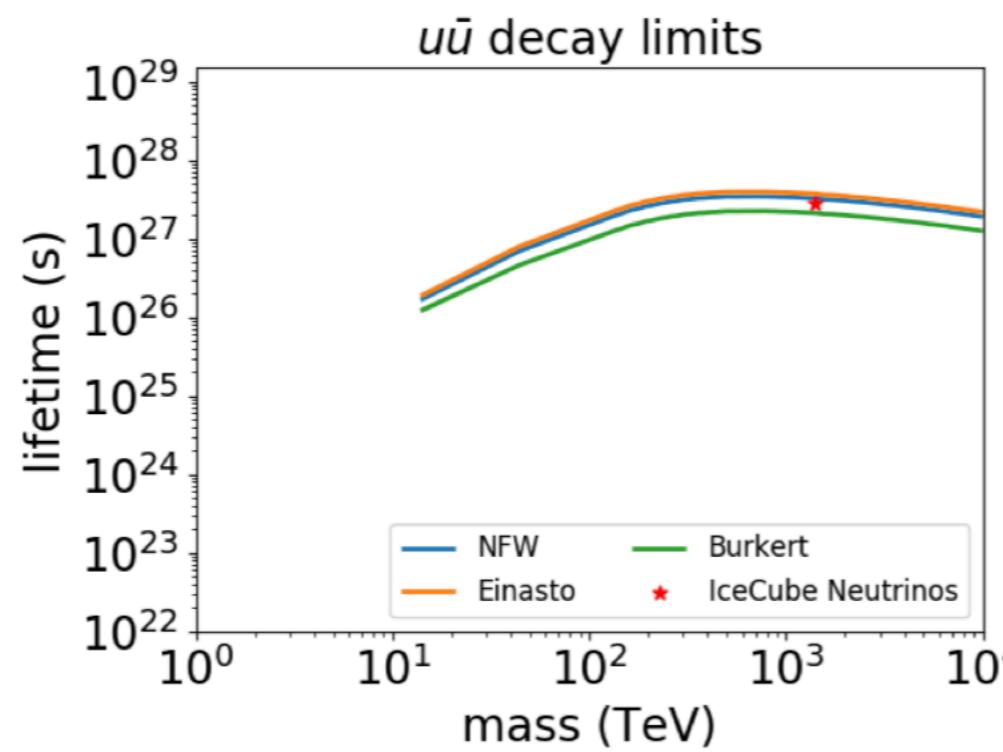
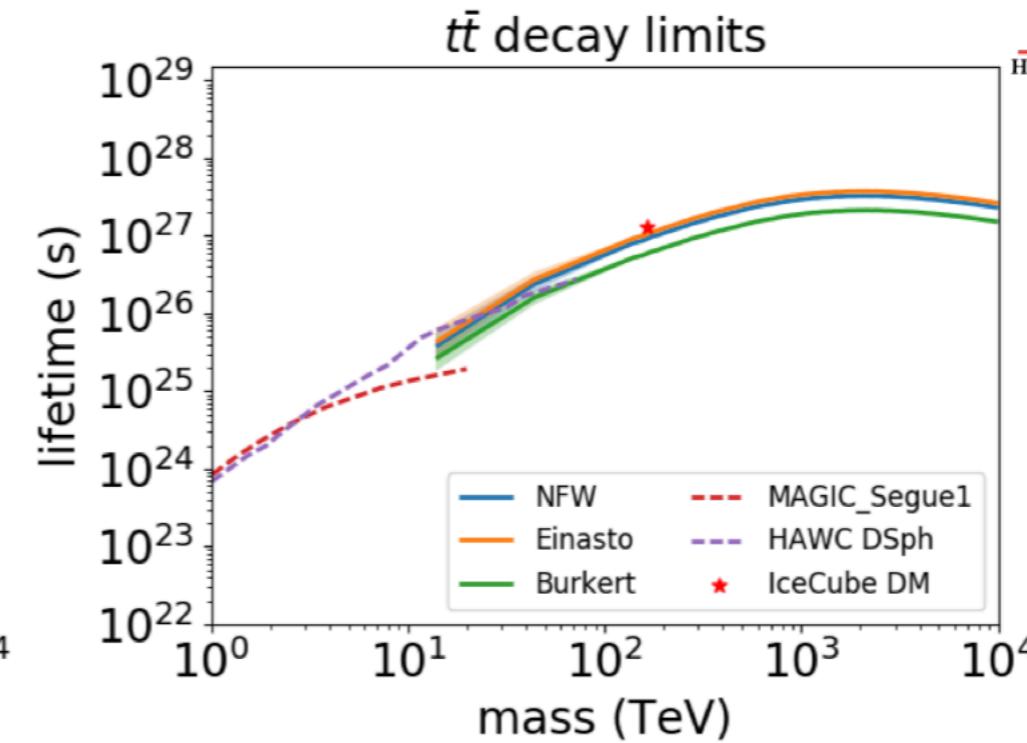
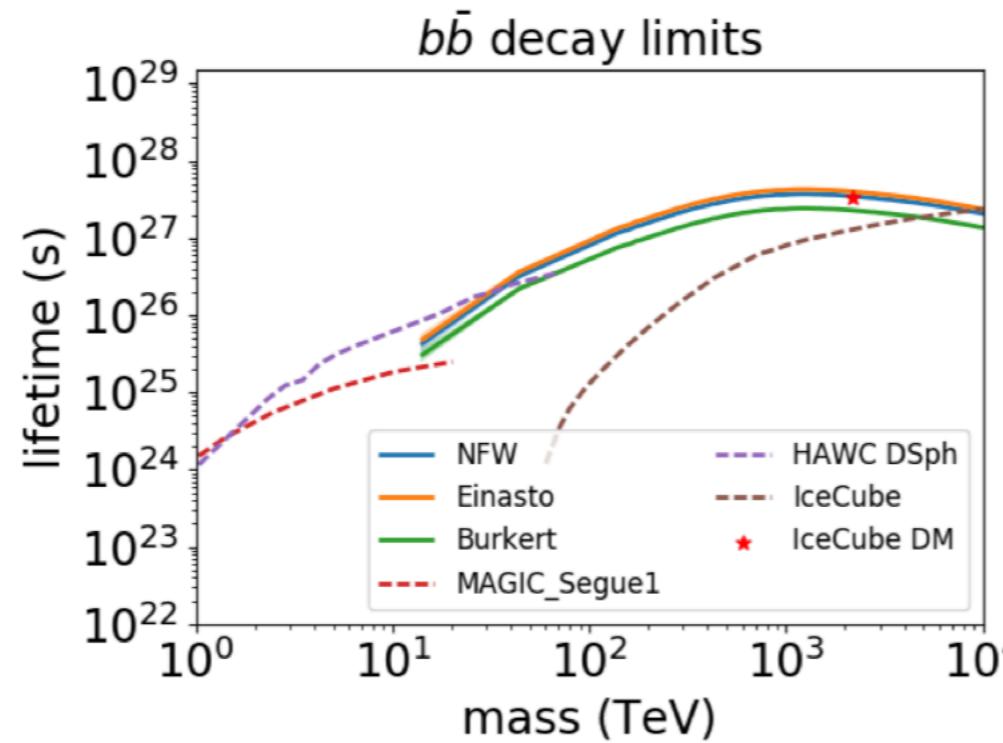
$$\tau_{\text{DM}} = 10^{28} \text{ s} \quad \text{and} \quad m_{\text{DM}} = 4 \text{ PeV}$$



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

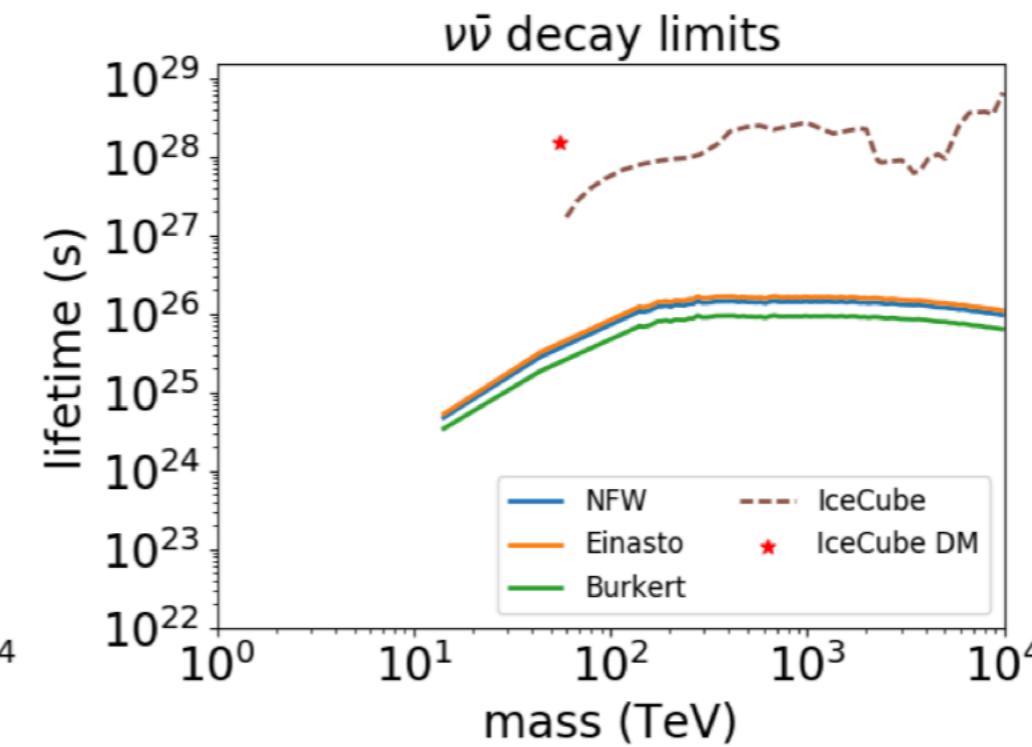
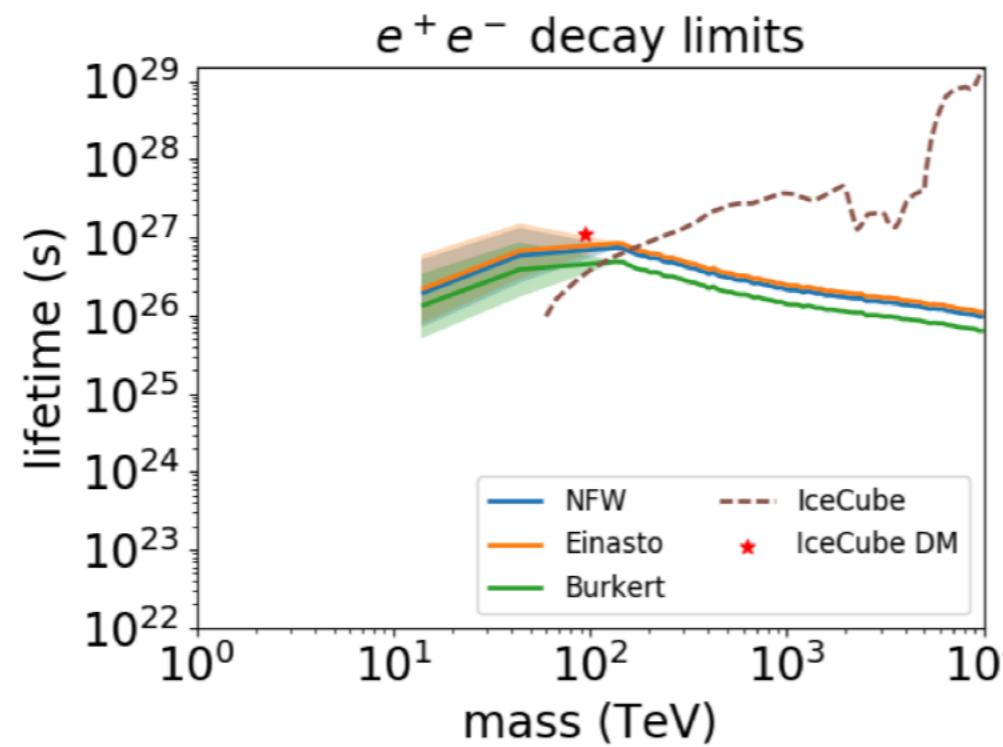
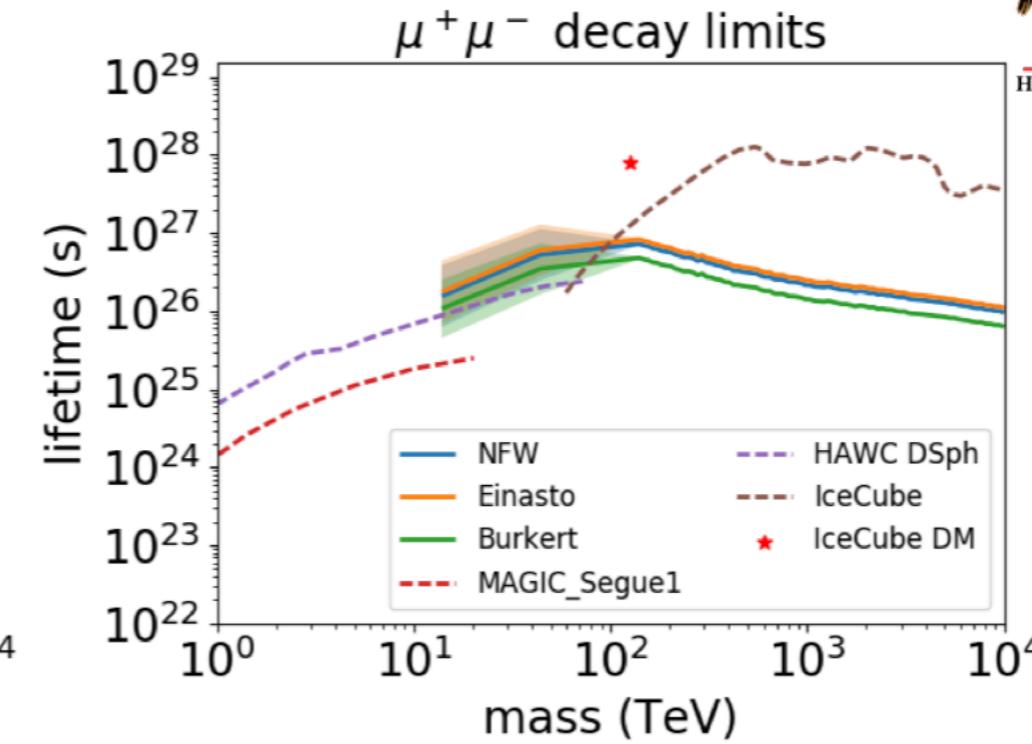
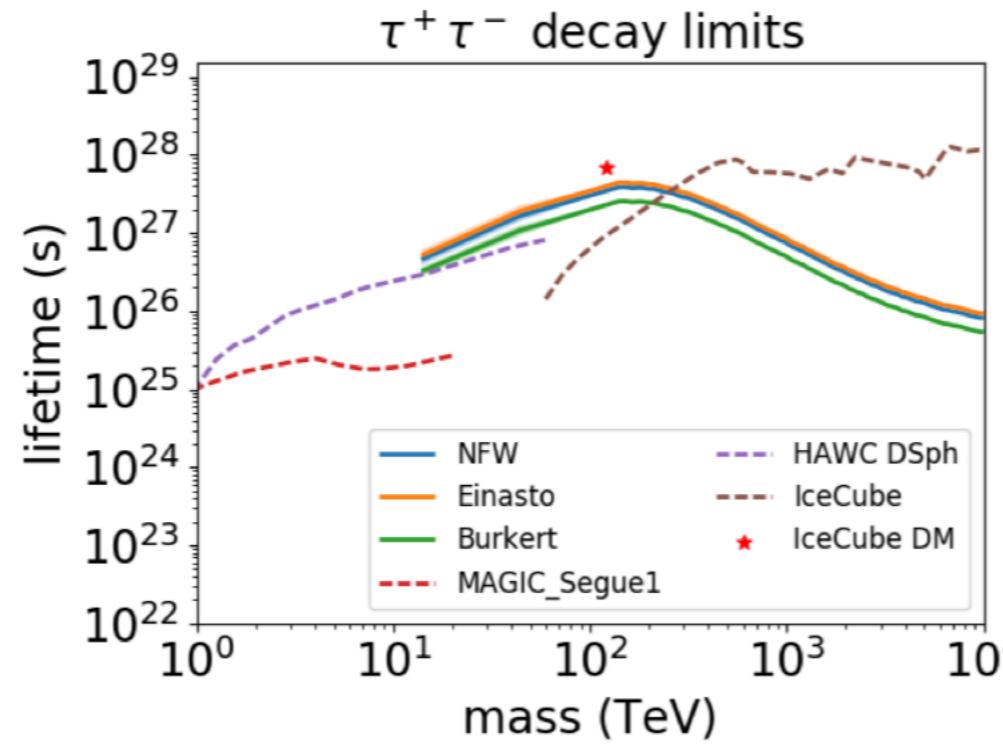
Gamma ray bounds

✓ Galactic component



Gamma ray bounds

✓ Galactic component



Cosmic ray bounds

✓ Galactic component

Anisotropy

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

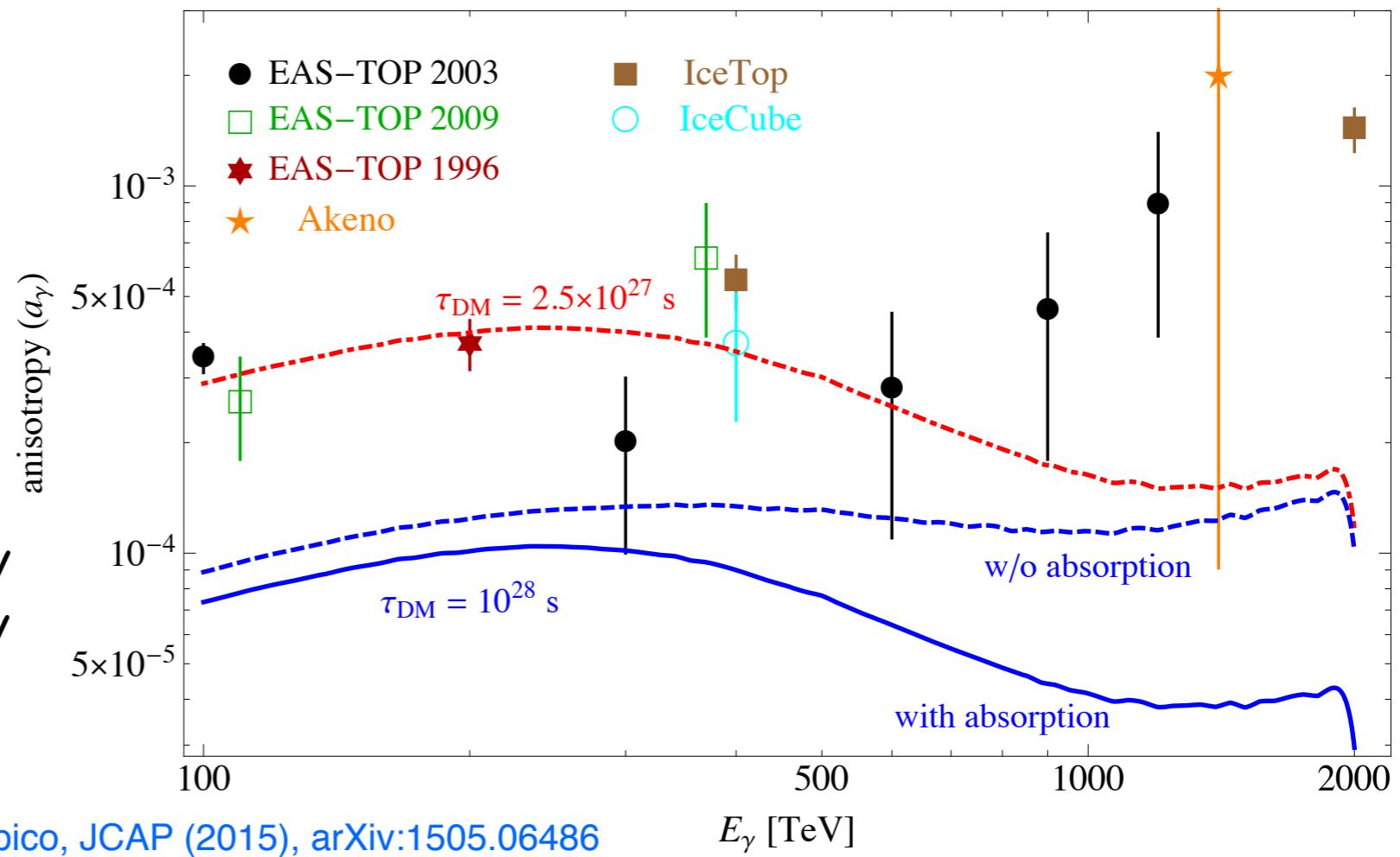
Total CR flux

✓ 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



conclusions

✓ Existence of neutrinos in the energy range $\sim 1 \text{ TeV} - 10 \text{ PeV}$ is established by IceCube. It can be used to search for "New Physics".

✓ Currently, the observed flux can be interpreted by heavy decaying DM (with generic decay channels), either as (sub)dominant contribution or as the only source.

✓ The required lifetime is allowed by the current limits for some channels (leptonic, gauge bosons) and excluded marginally for others (hadronic). Both the energy and angular distributions mildly prefer DM interpretation.

✓ The decaying DM scenario can be tested by the current and future gamma-ray (EAS) detectors. Also, anisotropy measurements in the CR flux would be constraining.

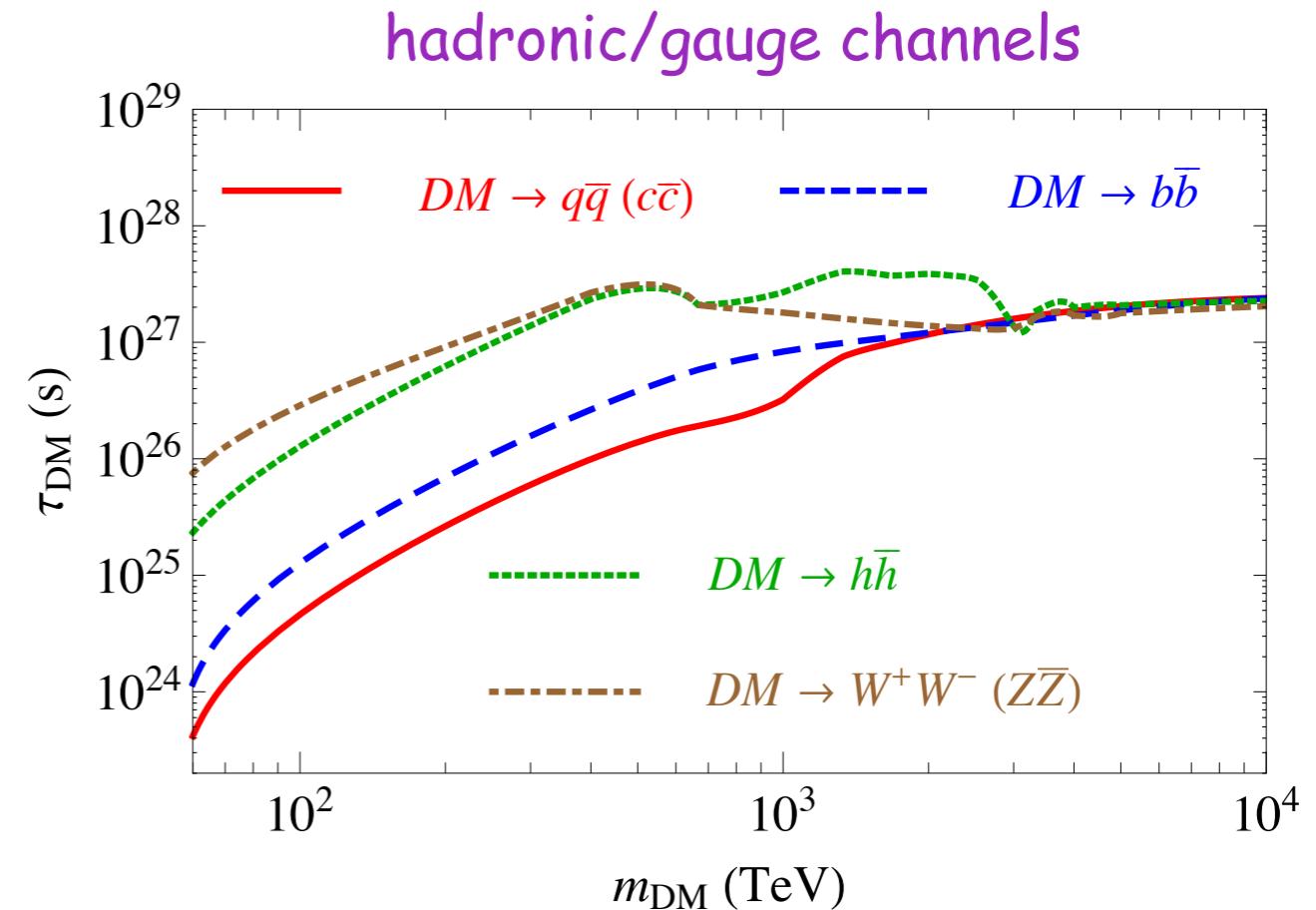
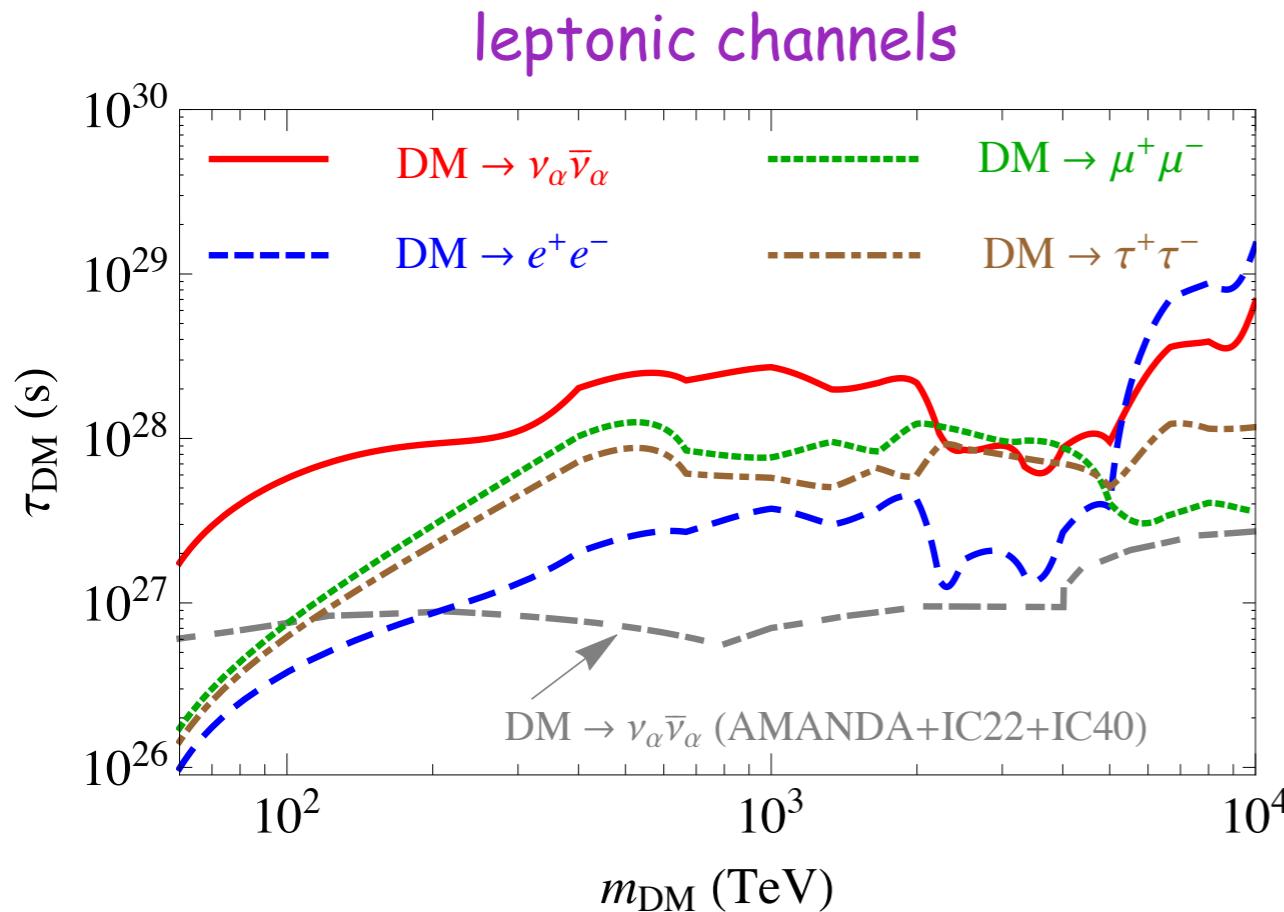
conclusions



Thank you !

Constraining DM properties

✓ limits on DM lifetime (90% C.L.)



- ✓ 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 $\langle\sigma v\rangle$

Constraining DM properties

✓ Annihilation cross section

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

The isotropic components of neutrino flux from DM annihilation:

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

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

Constraining DM properties

✓ Annihilation cross section

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

The isotropic components of neutrino flux from DM annihilation:

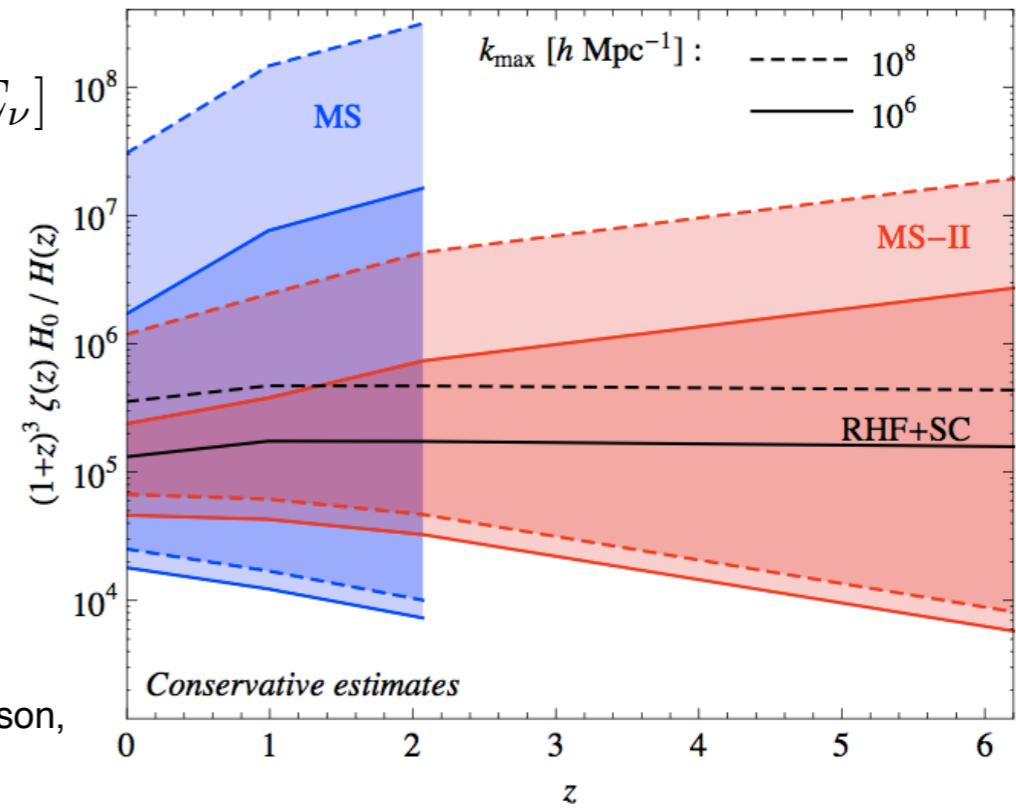
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The cosmic flux from all redshift

$$\frac{dJ_{\text{cos}}^{\text{ann}}}{dE_\nu} = \frac{\langle\sigma v\rangle}{2} \frac{\Omega_{\text{DM}}^2 \rho_c^2}{4\pi m_{\text{DM}}^2 H_0} \frac{c}{H_0} \int_0^\infty \frac{(1+z)^3 \zeta(z) dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \frac{dN}{dE_\nu} [(1+z) E_\nu]$$

$\zeta(z)$ 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 $\langle\sigma v\rangle$ (90% C.L.)

minimum ÷ maximum value used for $\zeta(z)$ unit of $\langle\sigma v\rangle$ is $10^{-22} \text{ cm}^3 \text{s}^{-1}$

m_{DM} $\text{DM} + \text{DM} \rightarrow$	100 TeV	50 TeV	30 TeV
$\nu_\alpha \bar{\nu}_\alpha$	1.39 ÷ 0.22	1.21 ÷ 0.36	2.44 ÷ 0.88
$q\bar{q}$	489 ÷ 84.5	1427 ÷ 299	9934 ÷ 4603
$b\bar{b}$	185 ÷ 30.4	517 ÷ 106	3514 ÷ 1621
$c\bar{c}$	592 ÷ 100	1708 ÷ 348	11218 ÷ 5215
e^+e^-	14.7 ÷ 2.38	17.8 ÷ 5.06	41.3 ÷ 14.2
$\mu^+\mu^-$	4.47 ÷ 0.65	9.06 ÷ 1.6	23.7 ÷ 9.23
$\tau^+\tau^-$	5.84 ÷ 0.93	10.9 ÷ 2.3	28.5 ÷ 10.8
$h\bar{h}$	21.2 ÷ 3.36	53.4 ÷ 9.49	177 ÷ 76.5
$Z\bar{Z}$	11.9 ÷ 2.05	18.1 ÷ 4.09	40.7 ÷ 16.3
W^+W^-	14.4 ÷ 2.4	23.7 ÷ 4.96	54.5 ÷ 22.3

✓ for some final states (neutrinos, charged leptons) the limit is a bit stronger than the unitary bound

Confronting with energy distribution of IceCube data

three years data set

SM sector



Dark sector

portal type:

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

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

"neutrino" portal:

$$\mathcal{O}_{\text{SM}} \rightarrow HL$$

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

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$$d = 4 : \quad \mathcal{O}_{\text{DM}} \rightarrow N$$

heavy sterile neutrino, DM candidate

T. Higaki, R. Kitano and R. Sato, JHEP (2014)
arXiv:1405.0013

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✓ $d = 4 : \mathcal{O}_{\text{DM}} \rightarrow N$

heavy sterile neutrino, DM candidate

T. Higaki, R. Kitano and R. Sato, JHEP (2014)
arXiv:1405.0013

UV completion:

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

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

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

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

Confronting with energy distribution of IceCube data

three years data set

Leptogenesis: $\phi \rightarrow N_2 N_2$ $M_2 \sim 10^{12}$ GeV $\xrightarrow{\text{green arrow}} \frac{n_B}{s} \sim 10^{-10}$

DM abundance: $\Omega_{N_1} \simeq 0.2 \left(\frac{M_1}{4 \text{ PeV}} \right)^3 \left(\frac{T_R}{3 \times 10^7 \text{ GeV}} \right)^{-1}$

DM lifetime: $\tau_{N_1} \simeq 8 \times 10^{28} \text{ s} \left(\frac{M_1}{1 \text{ PeV}} \right)^{-1} \left(\frac{10^{-29}}{|y_N|^2} \right)$

DM decay channels: $\text{Br}(\ell^\pm W^\mp) = 2\text{Br}(\nu_\ell Z) = 2\text{Br}(\nu_\ell h) = |U_{\ell 1}|^2$ NH

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

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

✓ d=4: $\mathcal{O}_{\text{DM}} \rightarrow N$

production mechanism:

$$m_\phi \gg m_N \quad \text{inflaton decay}$$

$$m_\phi \ll m_N \quad \text{freeze-in}$$

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

Confronting with energy distribution of IceCube data

three years data set

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



$d = 5$:

$$\mathcal{O}_{\text{DM}} \rightarrow \chi \phi$$

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 $d > 4$.