Dark Matter Detection with Angular Power Spectrum

Marco Chianese

5 March 2020, 1st Joint Nikhef+Grappa Neutrino Meeting

- MC, Fiorillo, Miele, Morisi, Pisanti, JCAP 1911 [arXiv:1907.11222]
- Dekker, MC, Ando, arXiv:1910:12917

UNIVERSITY OF AMSTERDAM

GRAPPA

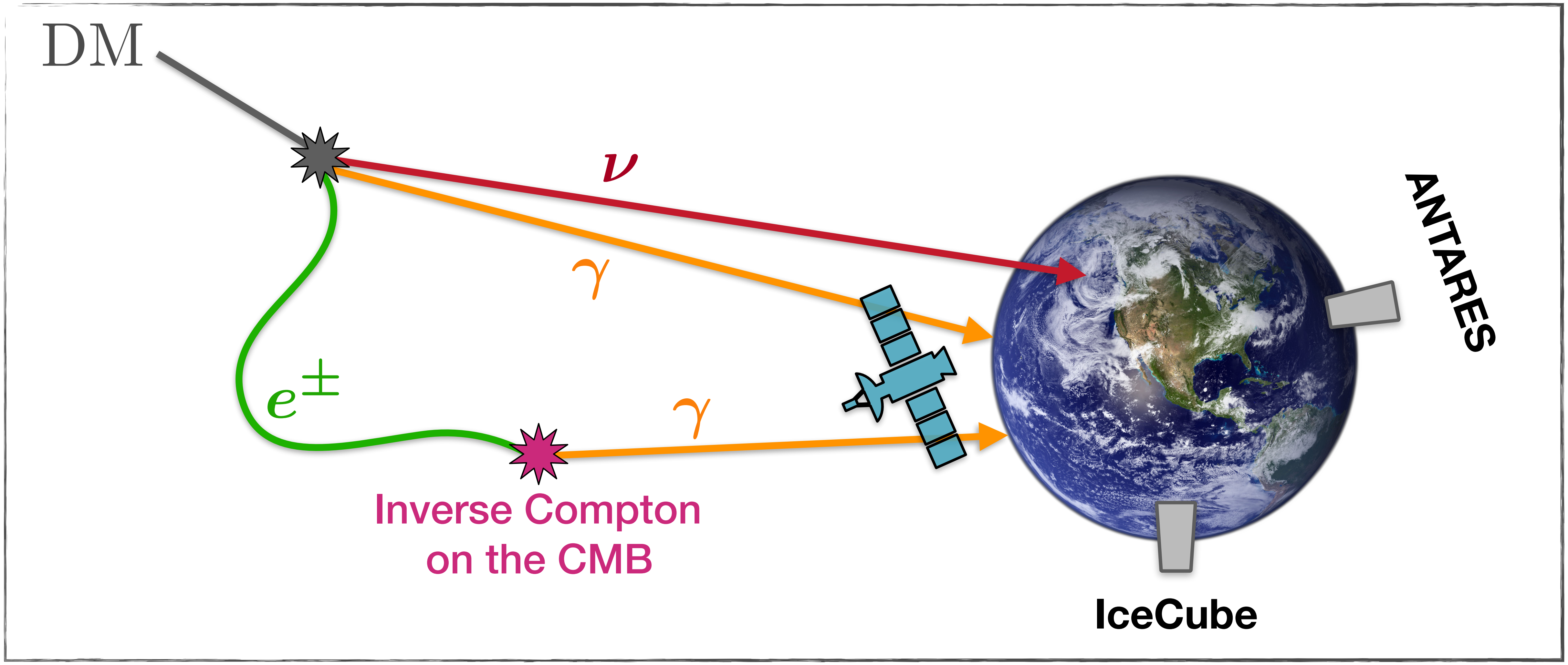
GRavitation AstroParticle Physics Amsterdam

Multi-messenger searches

Dark Matter particles can decay/annihilate producing:

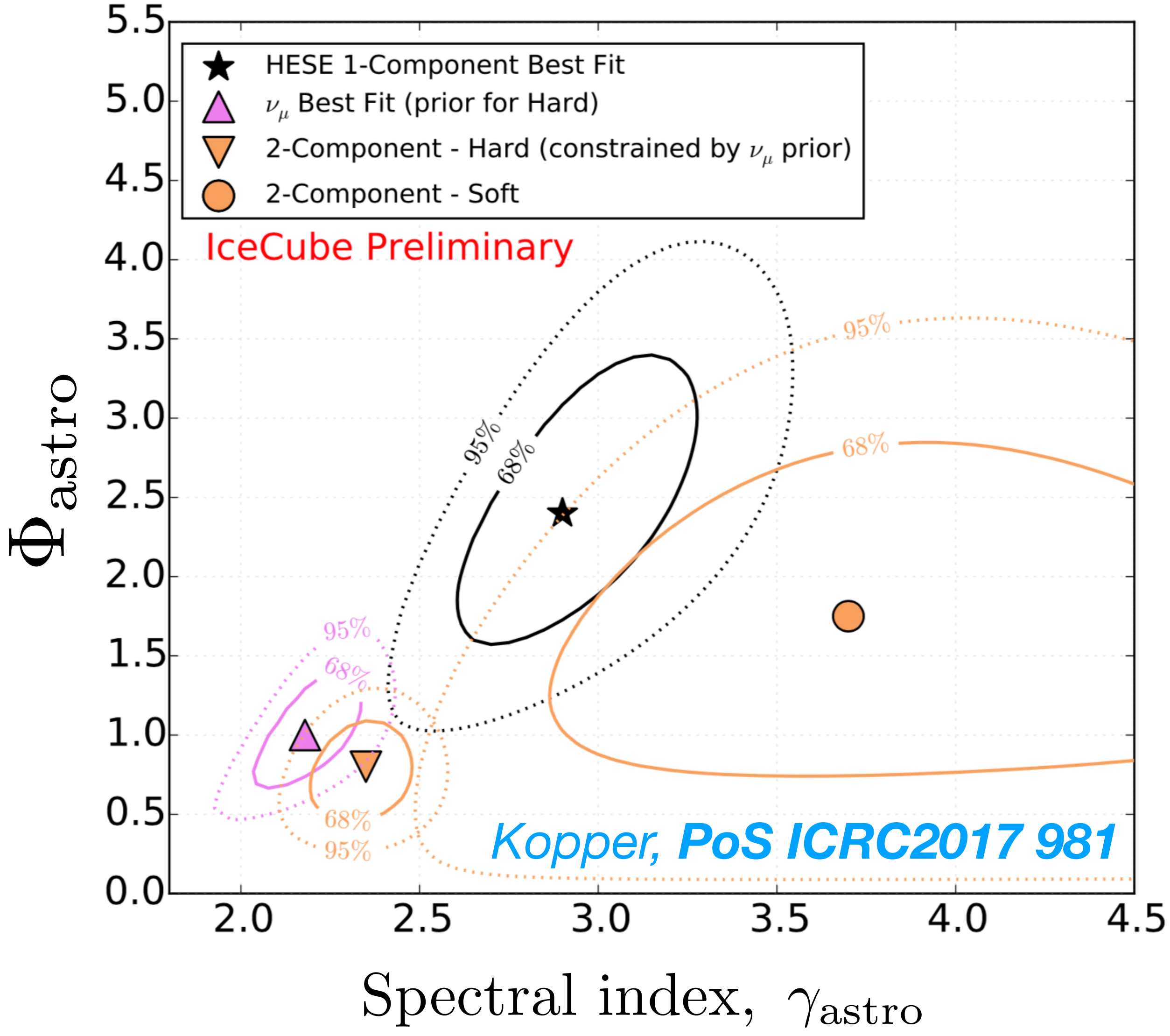
- **Neutrinos** travel in straight lines (IceCube and ANTARES/KM3NeT)
- **Gamma-rays** have to be propagated (Fermi-LAT, HAWC, H.E.S.S., CTA, …)

→ Neutrino and Gamma-Ray Telescopes provide important information about DM



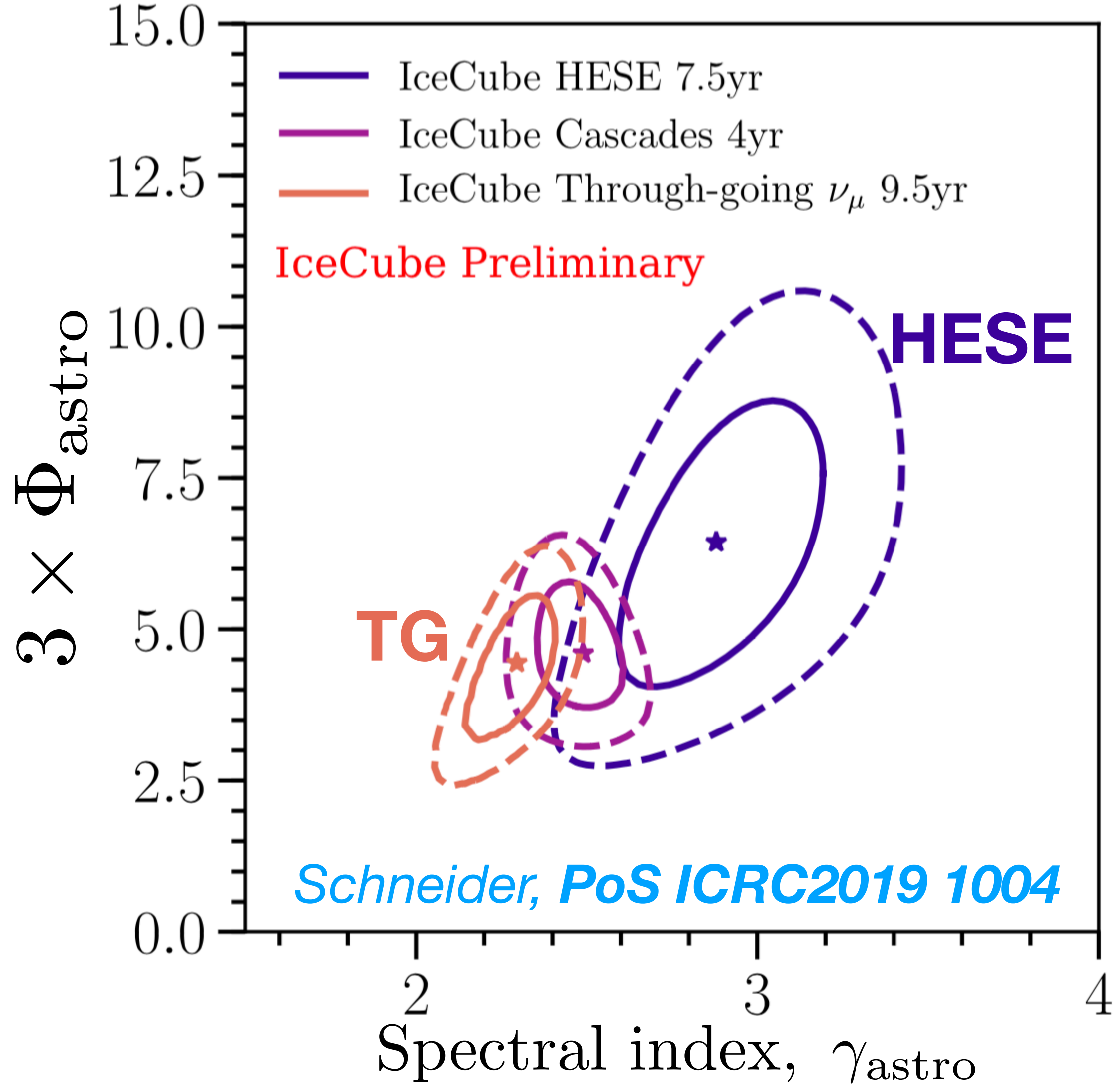
Tension with a single power-law

IceCube @ ICRC2017



*Kopper, **PoS ICRC2017 981***

IceCube @ ICRC2019



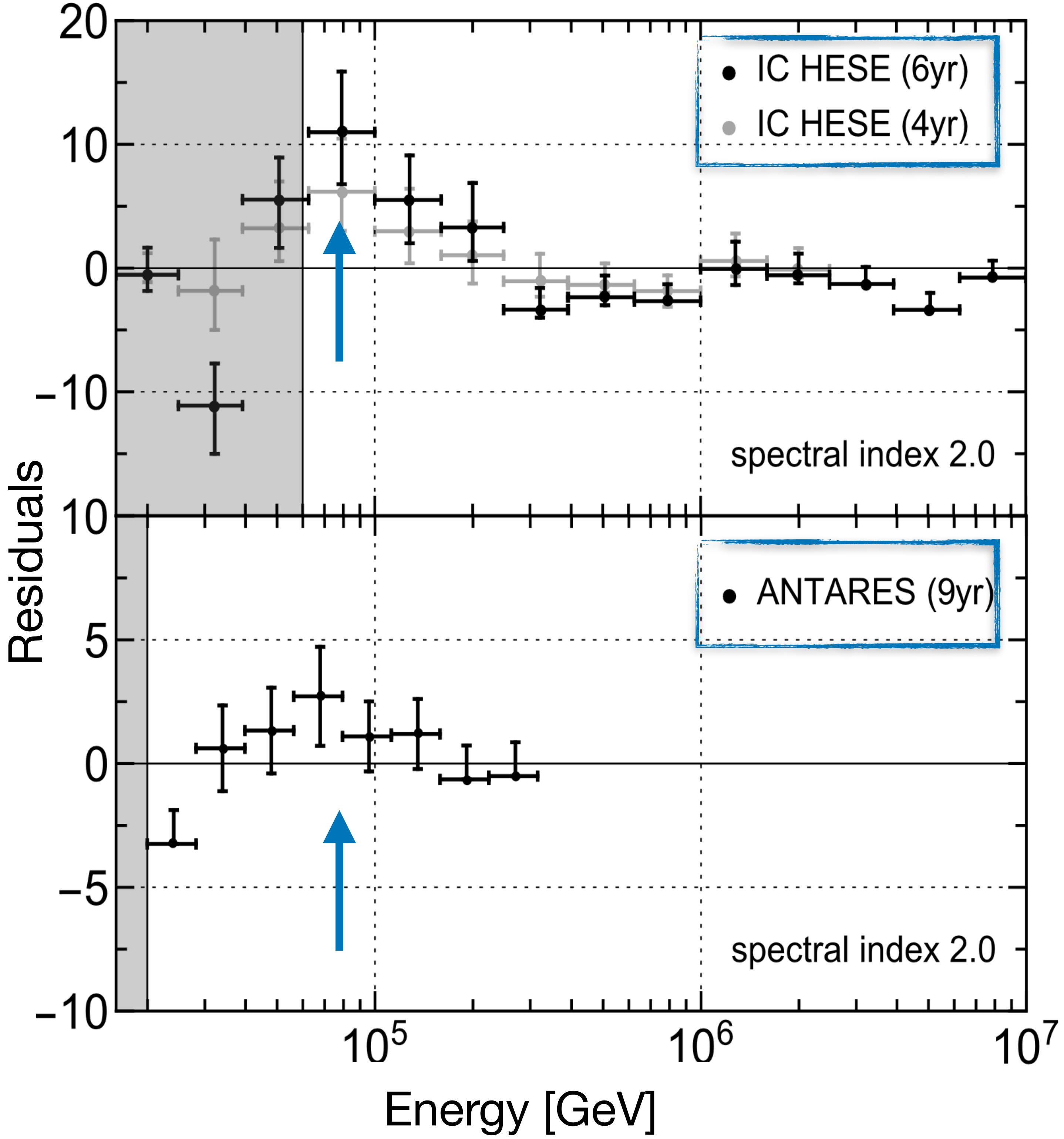
*Schneider, **PoS ICRC2019 1004***

- Fermi mechanism: $\gamma_{\mathrm{astro}} = 2.0$
- p-p sources: $\gamma_{\mathrm{astro}} \leq 2.2$
- Blazar TXS 0506+056: $\gamma_{\mathrm{astro}} = 2.1 \pm 0.2$

Tension between HESE (full sky) and Through-Going (Northern hemisphere)

The low energy excess

*MC, Mele, Miele, Migliozzi, Morisi, **ApJ 851 (2017)***

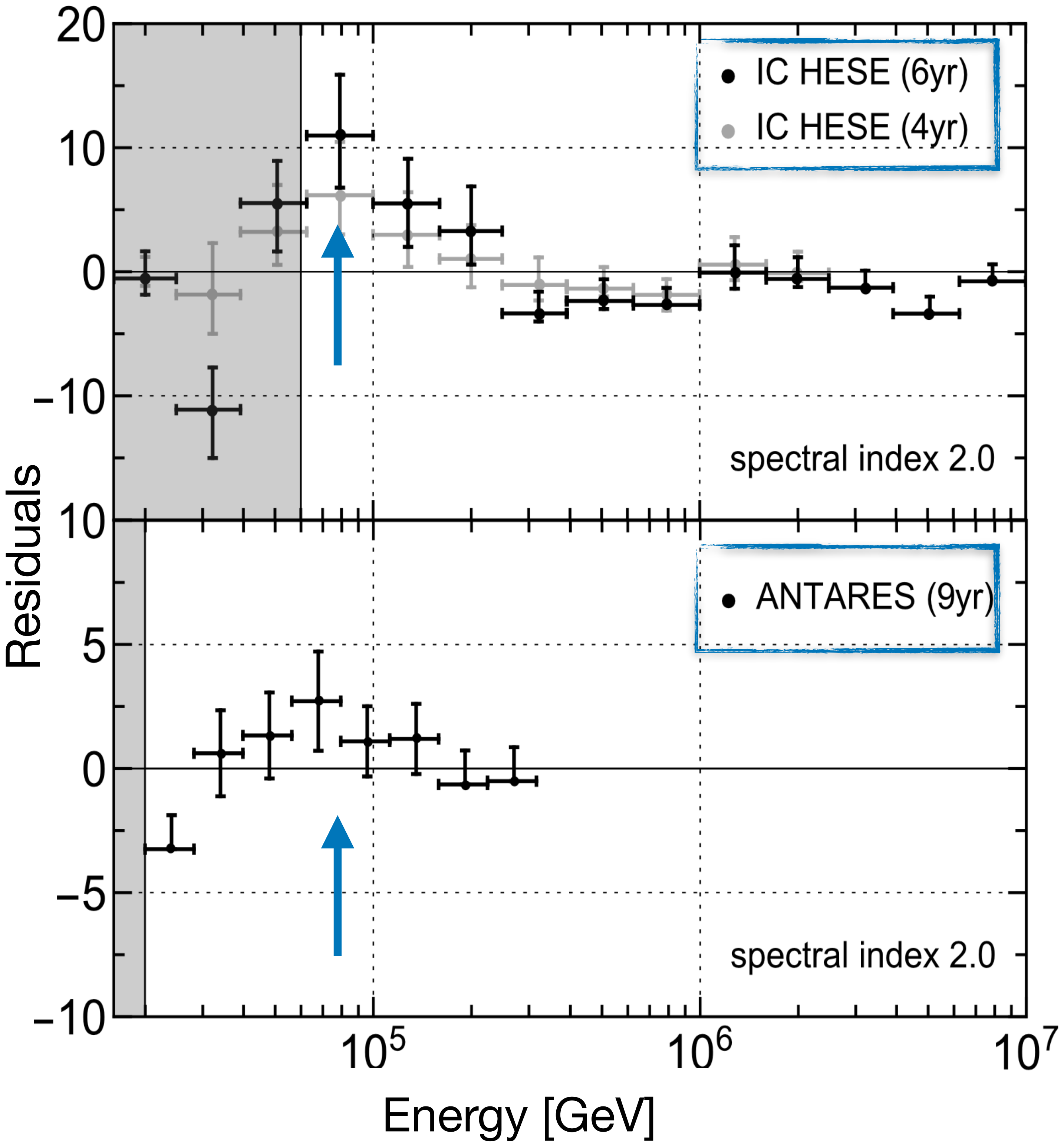


←

Residuals with respect to an astrophysical power-law with spectral index 2.0

The low energy excess

MC, Mele, Miele, Migliozzi, Morisi, ***ApJ 851 (2017)***



Possible explanations:

- Hidden astrophysical sources

Kimura, Murase, Toma, ***ApJ 806 (2015)***
Murase, Guetta, Ahlers, ***PRL 116 (2016)***
Tamborra, Ando, ***PRD 93 (2016)***
Senno, Murase, Meszaros, ***PRD 93 (2016)***
Denton, Tamborra, ***ApJ 855 (2018)***
Denton, Tamborra, ***JCAP 1804***

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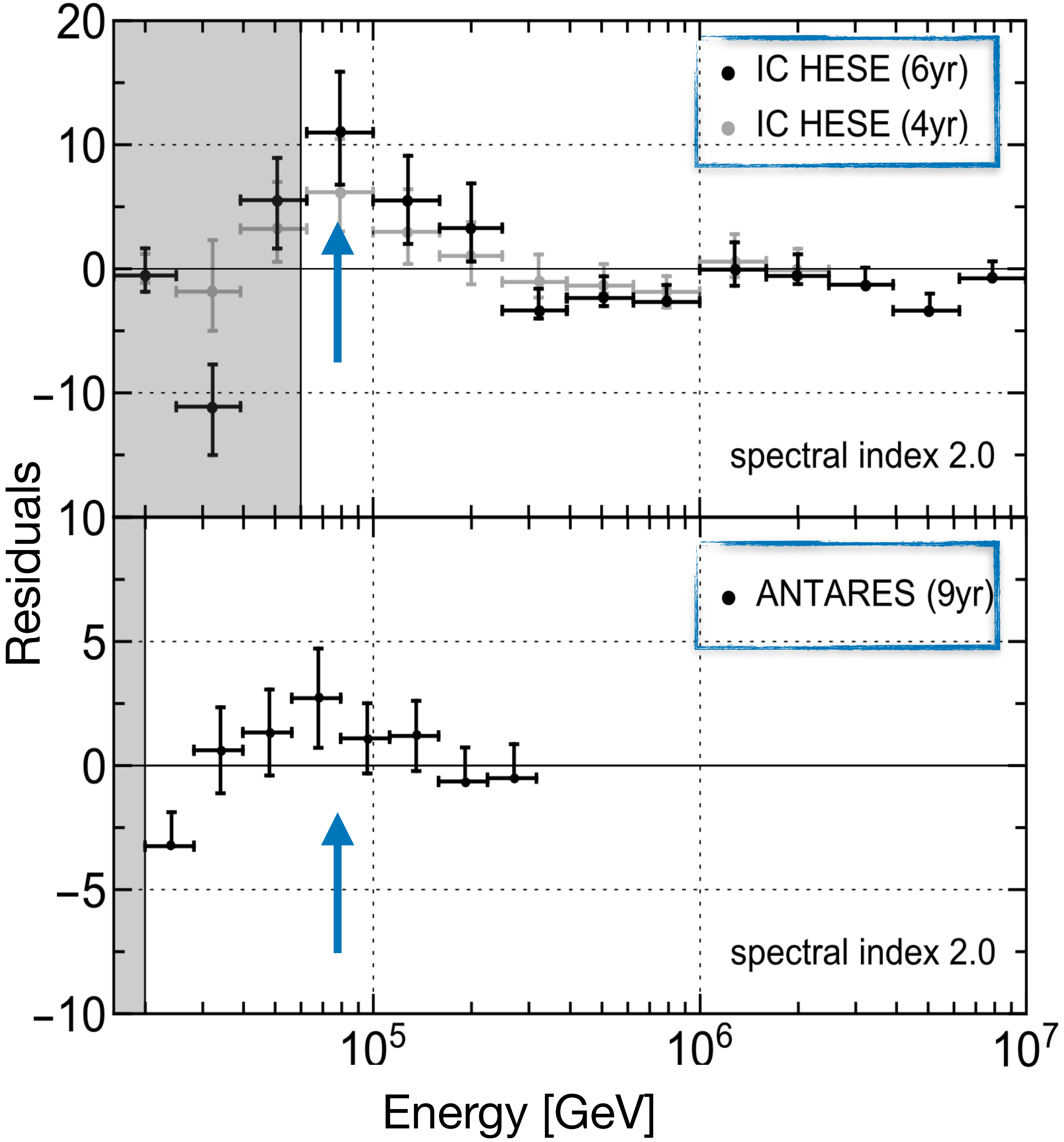

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- Active neutrino decays

Denton, Tamborra, ***PRL 121 (2018)***

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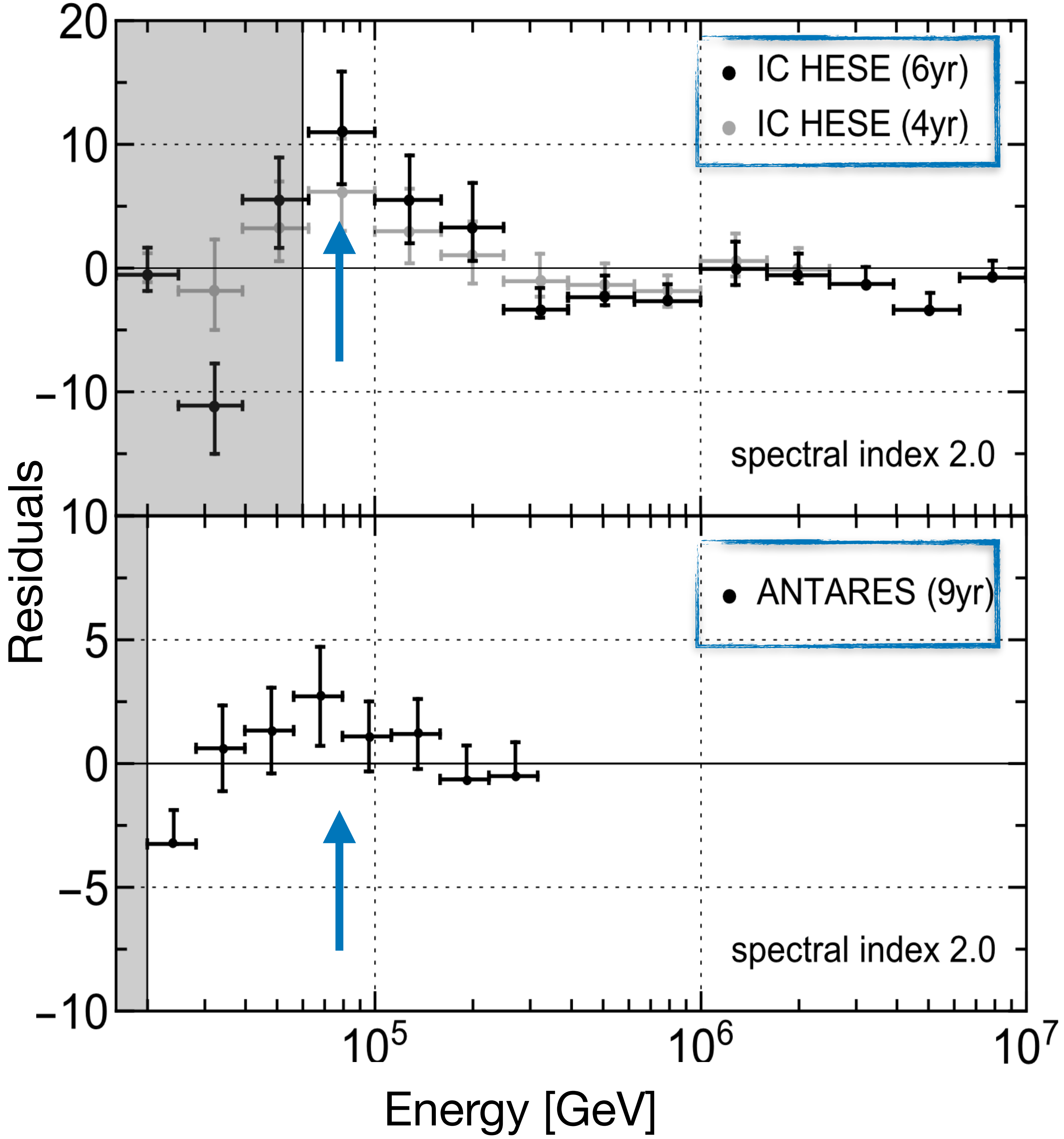

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Denton, Tamborra, ***ApJ 855 (2018)***
Denton, Tamborra, ***JCAP 1804***

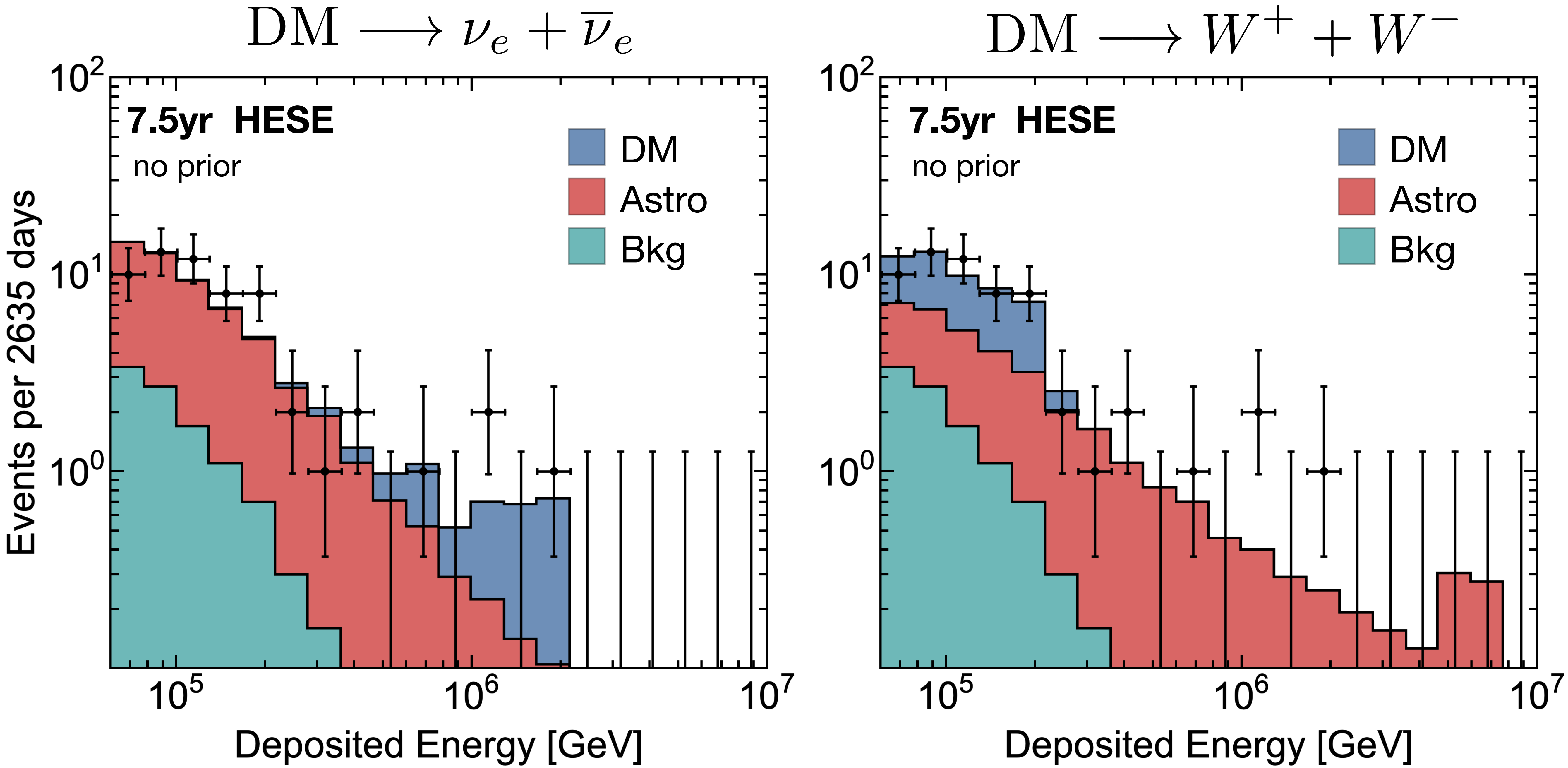
- Active neutrino decays

Denton, Tamborra, ***PRL 121 (2018)***

- **Heavy Dark Matter at 100 TeV**

MC, Miele, Morisi, Vitagliano, ***PLB 757 (2016)***
MC, Miele, Morisi, ***JCAP 1701***
MC, Miele, Morisi, ***PLB 773 (2017)***

Fits of IceCube spectrum

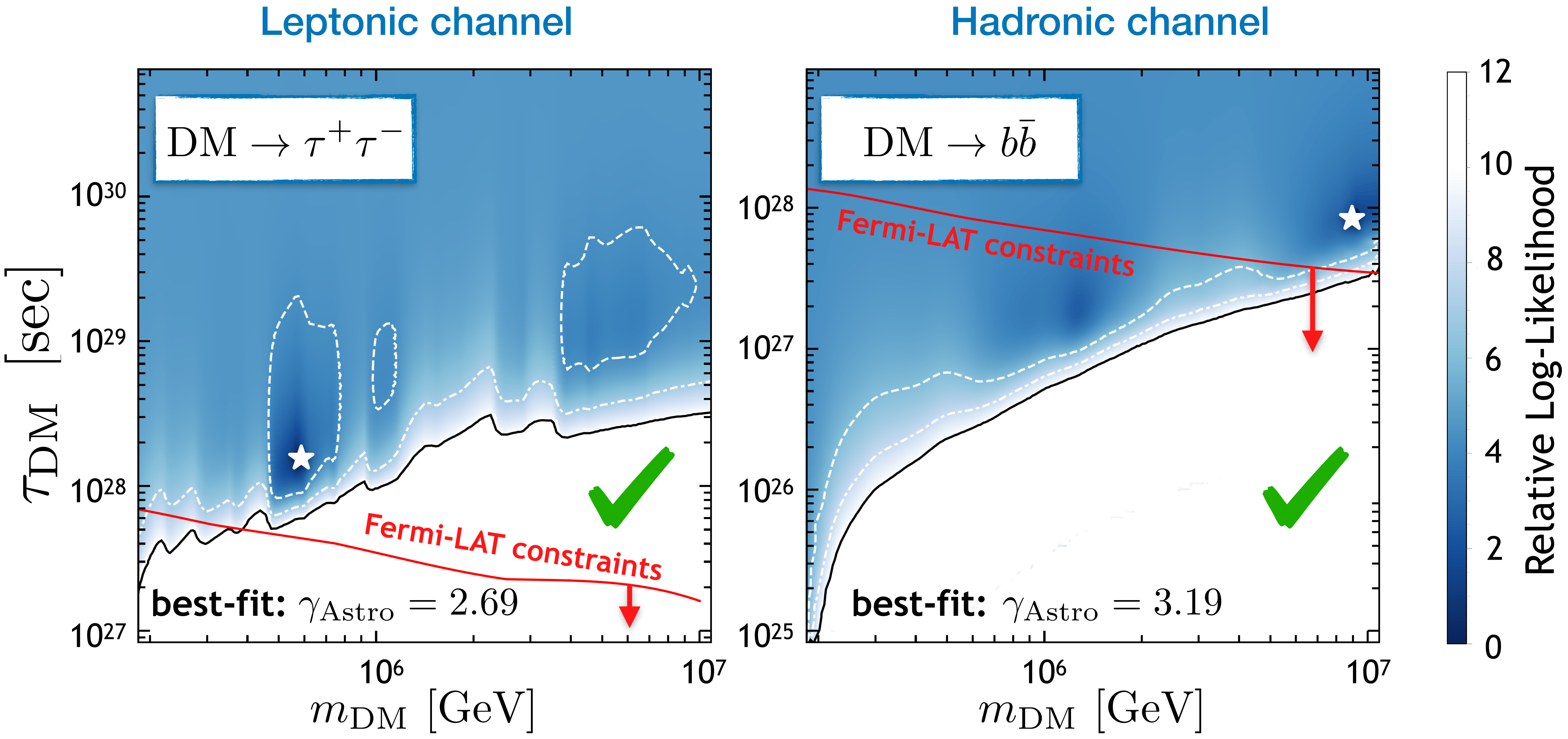


OUR HYPOTHESIS

(TWO-COMPONENT FLUX)

$$\frac{\mathrm{d}\phi^{\mathrm{signal}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} = \Phi_{\mathrm{astro}}\, E_\nu^{-\gamma_{\mathrm{astro}}} + \frac{\mathrm{d}\phi^{\mathrm{DM}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}$$

Leptonic *versus* hadronic channels

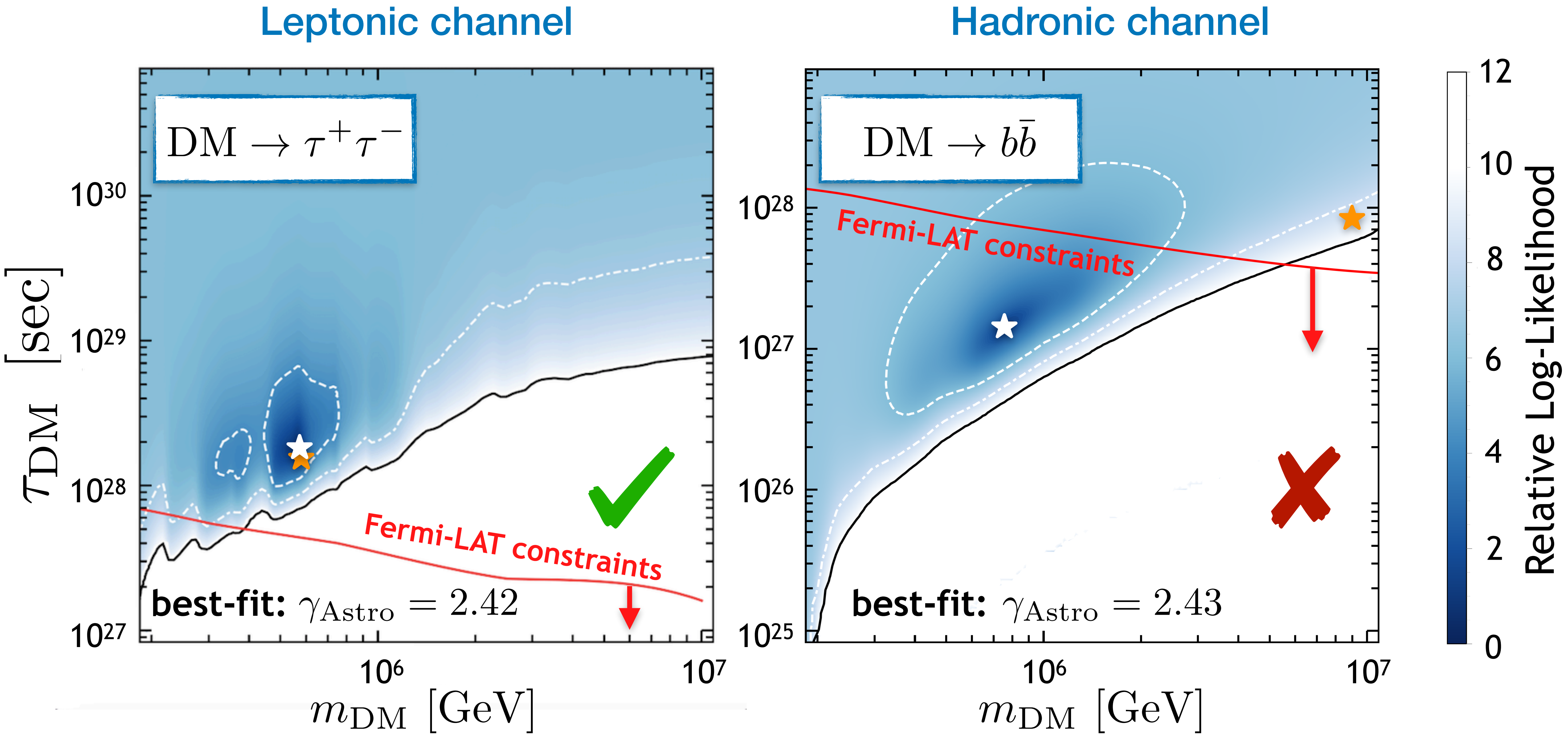


Astrophysical parameters as nuisance parameters →

WITHOUT **PRIOR**

$\Phi_{\mathrm{astro}}, \ \gamma_{\mathrm{astro}} \in [1.5, 5.0]$

Leptonic *versus* hadronic channels



Astrophysical parameters
as nuisance parameters

→

WITH **TG PRIOR**

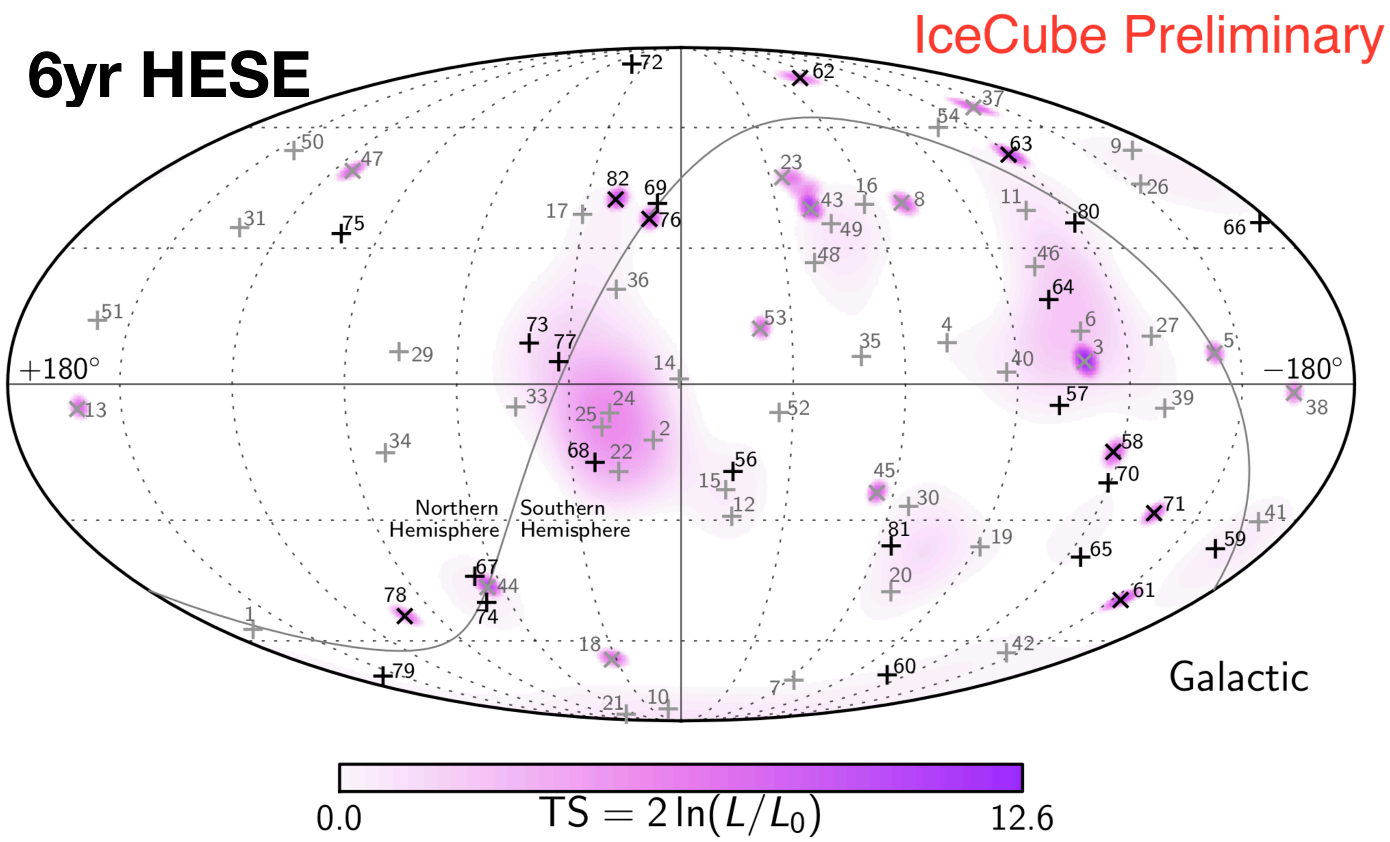
$$p\left(\Phi_{\mathrm{astro}}\right) = \mathcal{N}\left(\mu_\Phi^{\mathrm{TG}},\, \sigma_\Phi^{\mathrm{TG}}\right)$$

$$p\left(\gamma_{\mathrm{astro}}\right) = \mathcal{N}\left(\mu_\gamma^{\mathrm{TG}},\, \sigma_\gamma^{\mathrm{TG}}\right)$$

How can we discriminate a Dark Matter signal from other (astro) components?

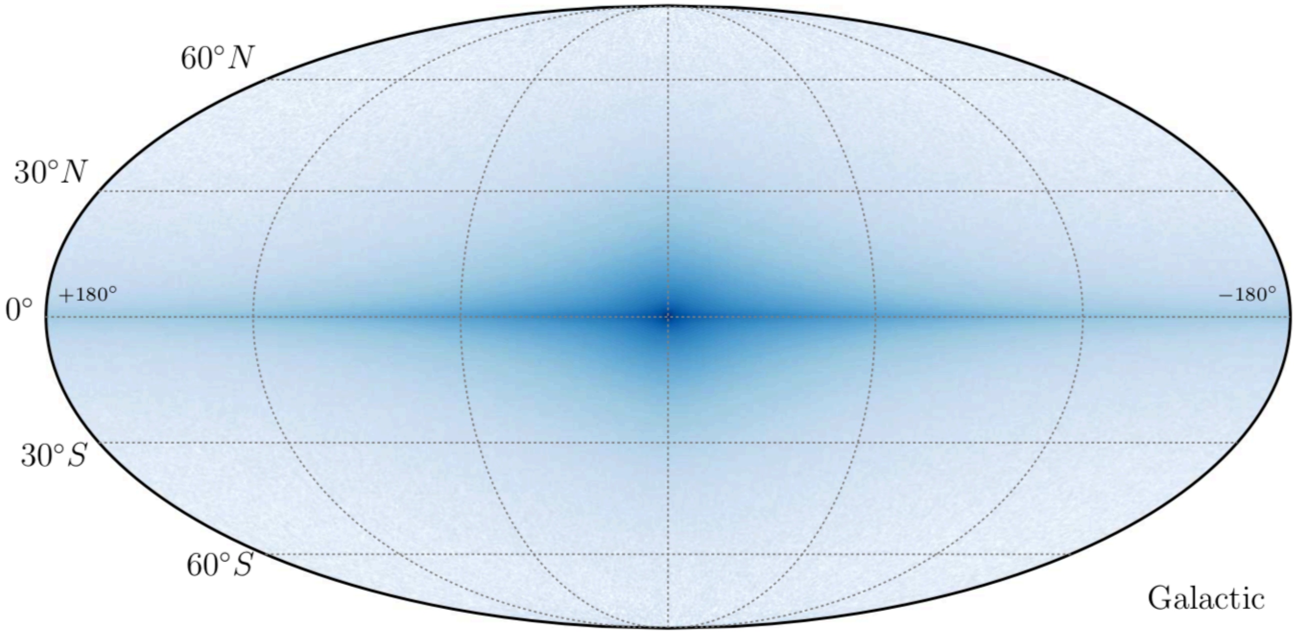
Dekker, MC, Ando, ***arXiv:1910:12917***

Angular analysis!



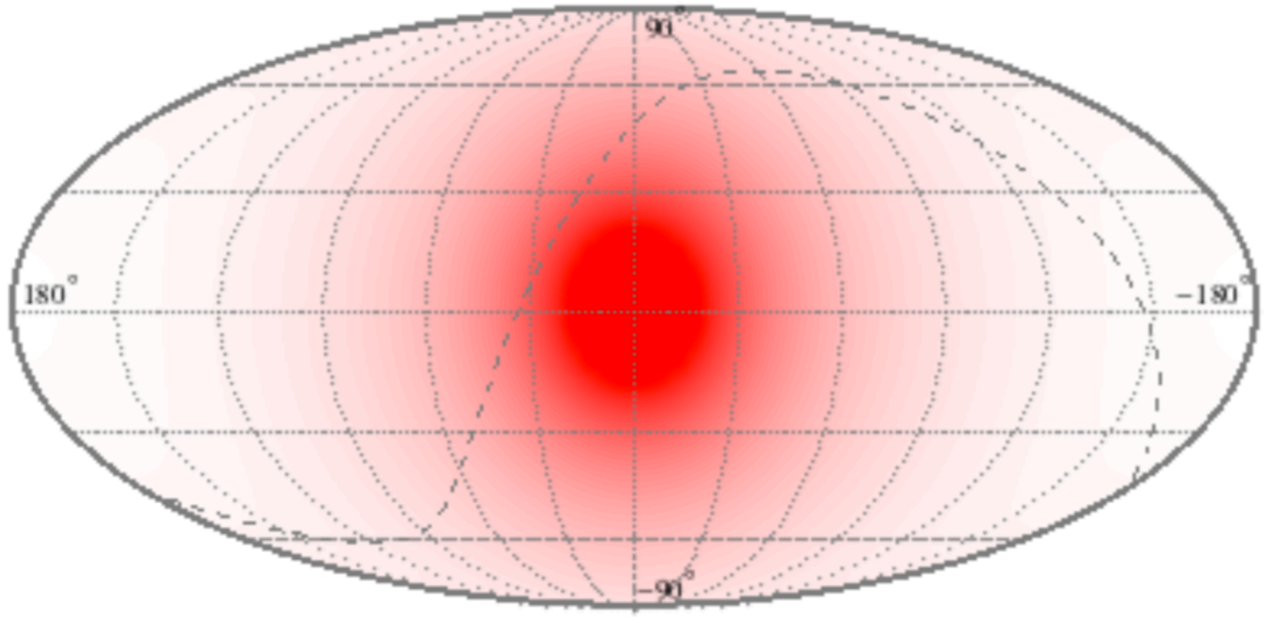
- Neutrino sky map compatible with isotropic flux (extragalactic sources)
- **BUT…** there may be a galactic component (tension between HESE and TG)

GALACTIC SOURCES



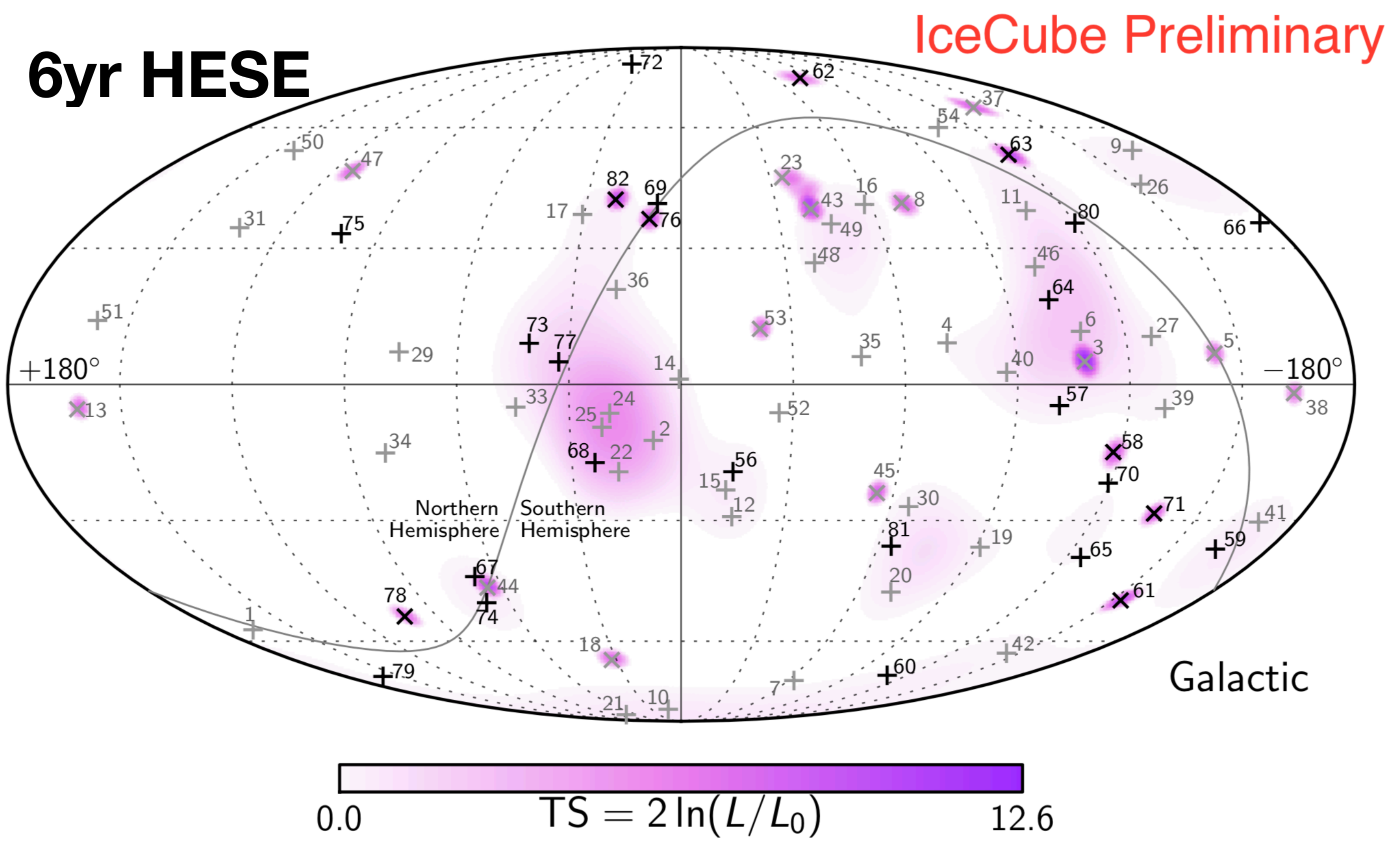
*Denton, Marfatia, Weiler, **JCAP 1708***

DECAYING DARK MATTER



*Esmaili, Kang, Serpico, **JCAP 1412***

Angular analysis!



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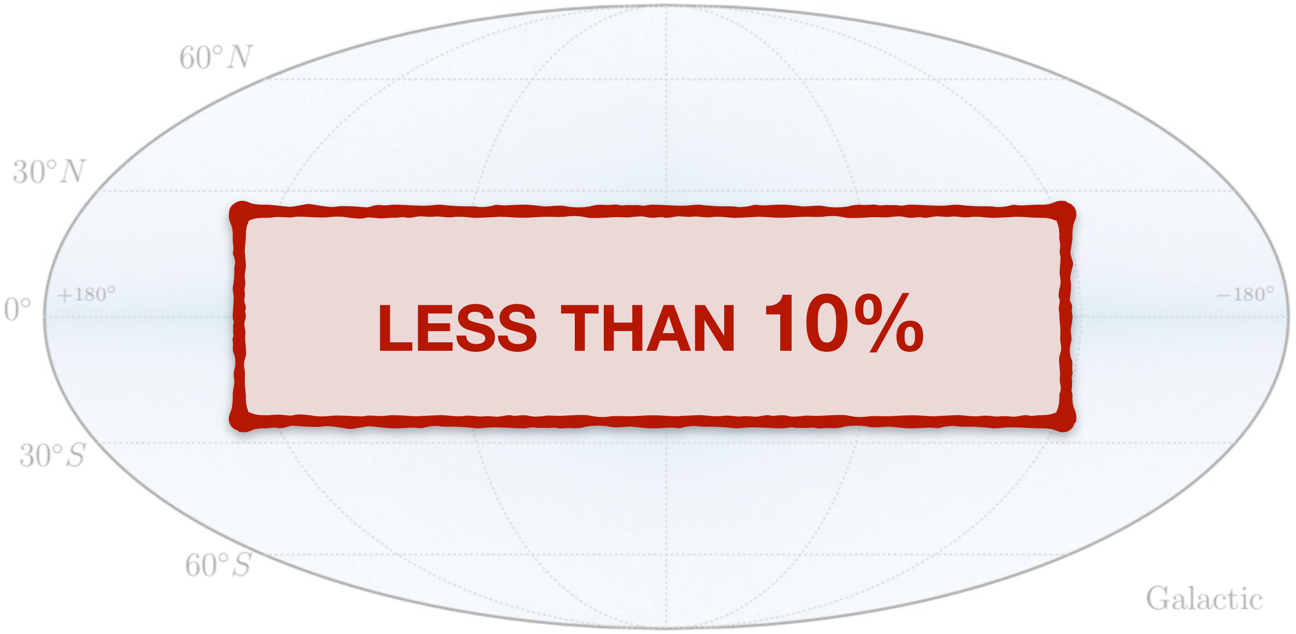
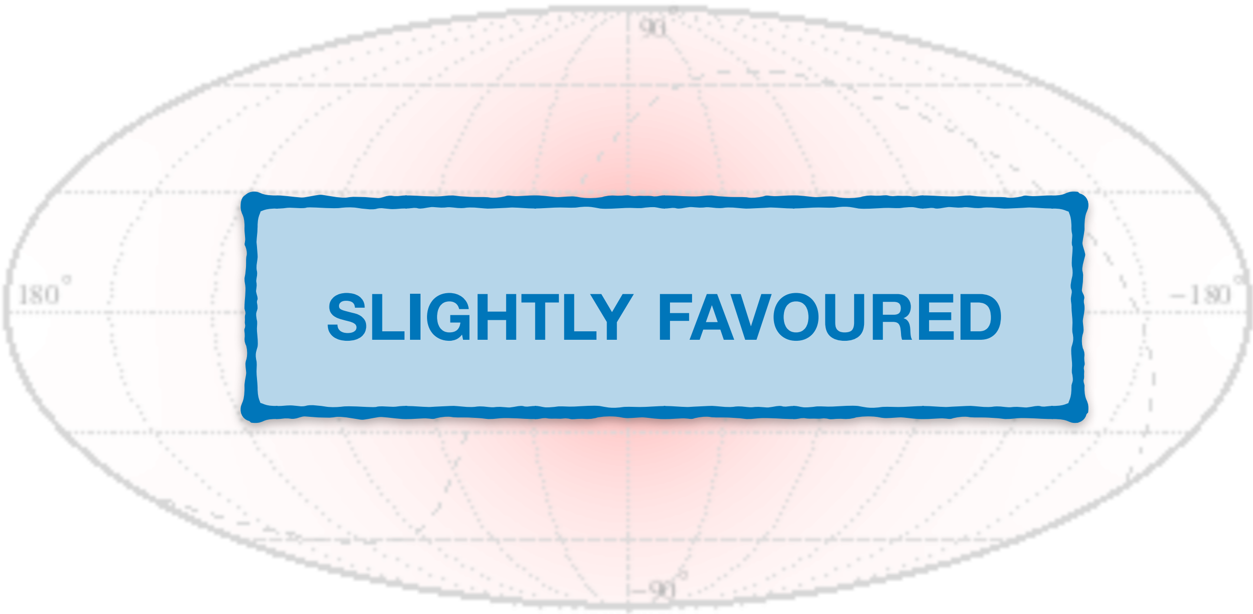


LESS THAN 10%

*Denton, Marfatia, Weiler, **JCAP 1708***

DECAYING DARK MATTER



SLIGHTLY FAVOURED

*Esmaili, Kang, Serpico, **JCAP 1412***

Anisotropy of Dark Matter flux

DECAY — GALACTIC

$$\frac{\mathrm{d}\phi^{\mathrm{DM}}_{\mathrm{gal.}}}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E} \int \mathrm{d}s\, \boldsymbol{\rho\left(s,l,b\right)}$$

DECAY — EXTRA-GALACTIC

$$\frac{\mathrm{d}\phi^{\mathrm{DM}}_{\mathrm{ext.gal.}}}{\mathrm{d}E\mathrm{d}\Omega} = \frac{\Omega_{\mathrm{DM}}\rho_c}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int \mathrm{d}z\, \frac{1}{H(z)} \left.\frac{\mathrm{d}N_\nu}{\mathrm{d}E}\right|_{E'=E(1+z)}$$

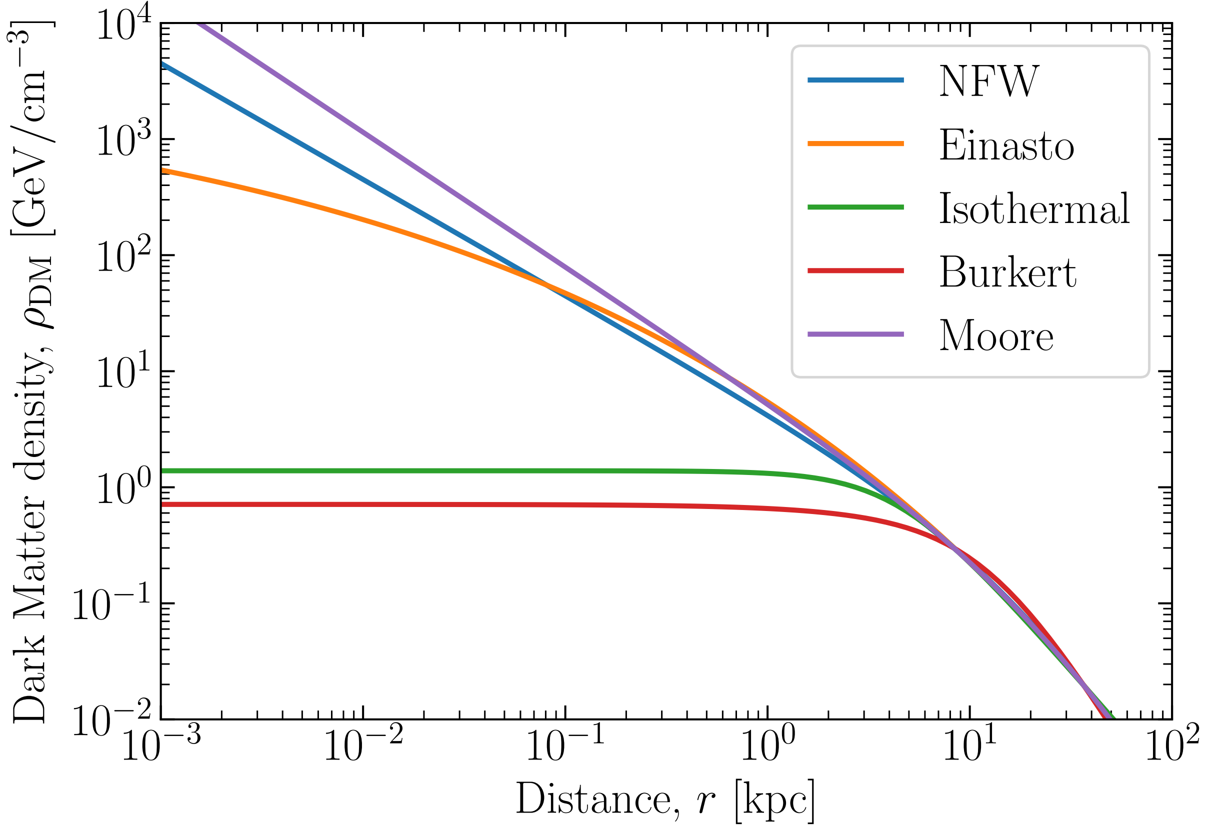
ANNIHILATION — GALACTIC

$$\frac{\mathrm{d}\phi^{\mathrm{DM}}_{\mathrm{gal.}}}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{2} \frac{\langle\sigma v\rangle}{4\pi\, m^2_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E} \int \mathrm{d}s\, \boldsymbol{\rho^2\left(s,l,b\right)}$$

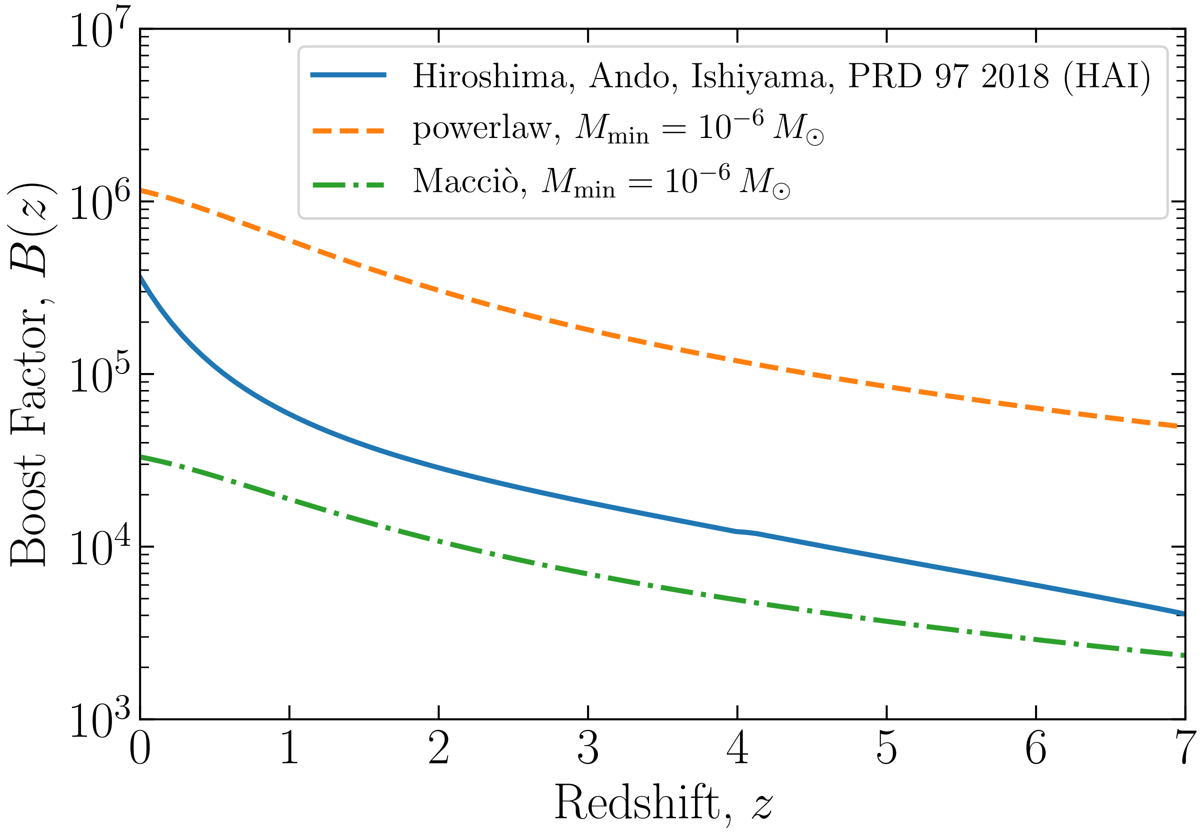
ANNIHILATION — EXTRA-GALACTIC

$$\frac{\mathrm{d}\phi^{\mathrm{DM}}_{\mathrm{ext.gal.}}}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{2} \frac{\langle\sigma v\rangle \left(\Omega_{\mathrm{DM}}\rho_{\mathrm{cr}}\right)^2}{4\pi\, m^2_{\mathrm{DM}}} \int \mathrm{d}z\, \frac{(z+1)^3 \boldsymbol{B(z)}}{H(z)} \left.\frac{\mathrm{d}N_\nu}{\mathrm{d}E}\right|_{E'=E(1+z)}$$

DM halo density profile



DM boost factor



Flux hypotheses

Null hypothesis

- Isotropic astrophysical flux: **7.5-yr HESE**

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = \frac{6.45}{3} \cdot \left(\frac{E}{100\text{TeV}}\right)^{\boxed{-2.89}} \cdot 10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

Model

- Isotropic astrophysical flux: **10-yr Through-going**

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = 1.44 \cdot \left(\frac{E}{100\text{TeV}}\right)^{\boxed{-2.28}} \cdot 10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

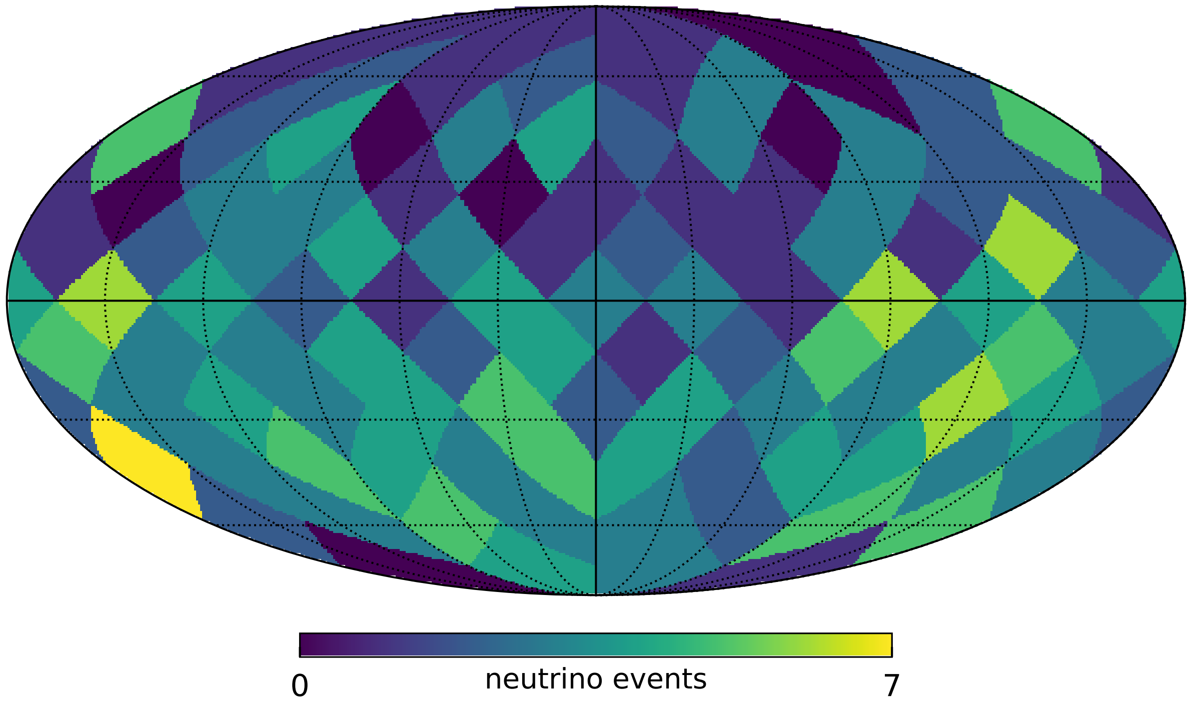
- Dark matter flux

$$N_{\text{tot}}\left(\theta,\phi\right) = \underbrace{N_{\text{atm.}} + N_{\text{astro}} + N_{\text{DM, ext.gal.}}}_{\text{Nearly-isotropic above 60 TeV}} + \underbrace{N_{\text{DM, gal.}}}_{\text{Anisotropic}}$$

Monte Carlo simulations to generate sky maps

Angular Power Spectrum

NULL HYPOTHESIS (ASTRO)

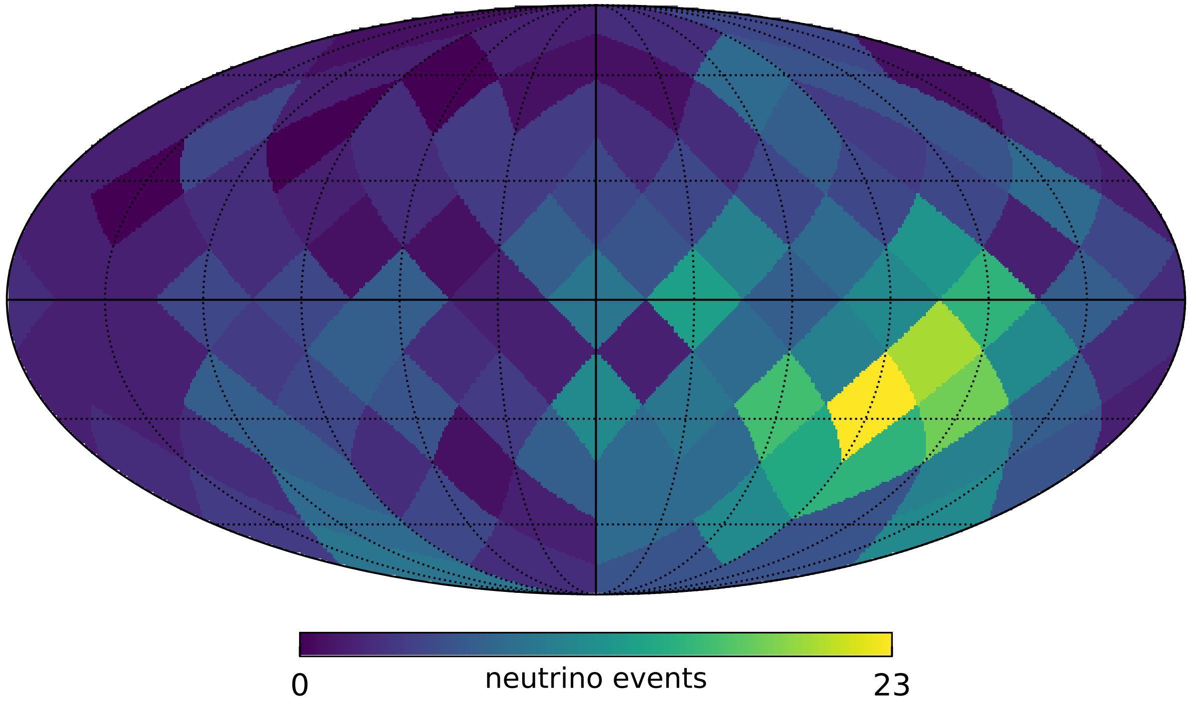


Angular Power Spectrum

$$N(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi)$$

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

MODEL (ASTRO + DEC. DM)



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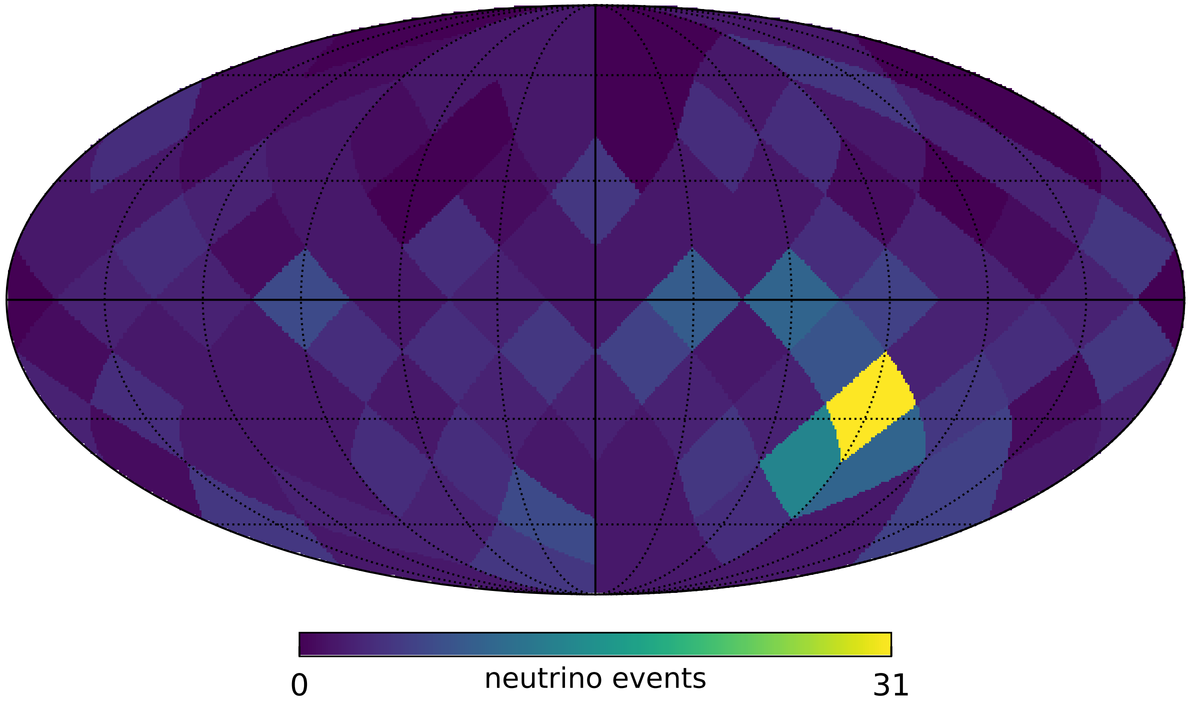
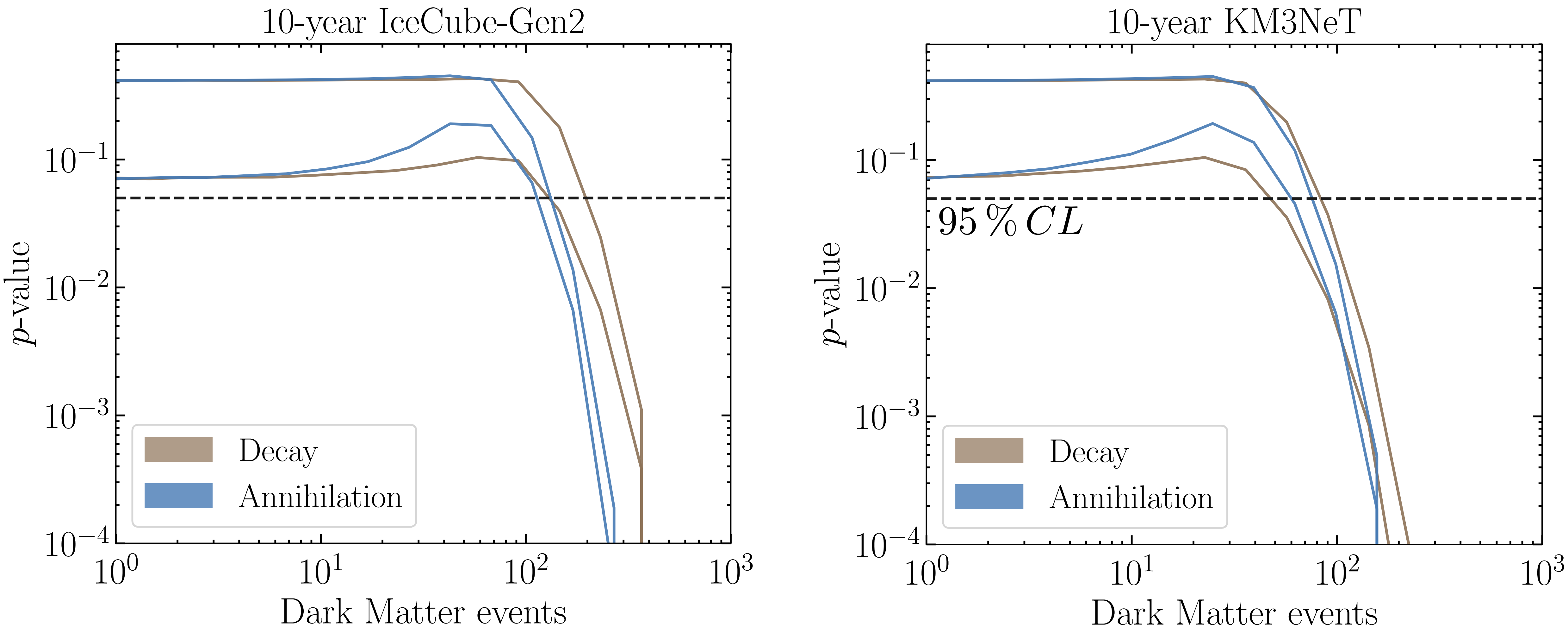


10-yr IceCube-gen2

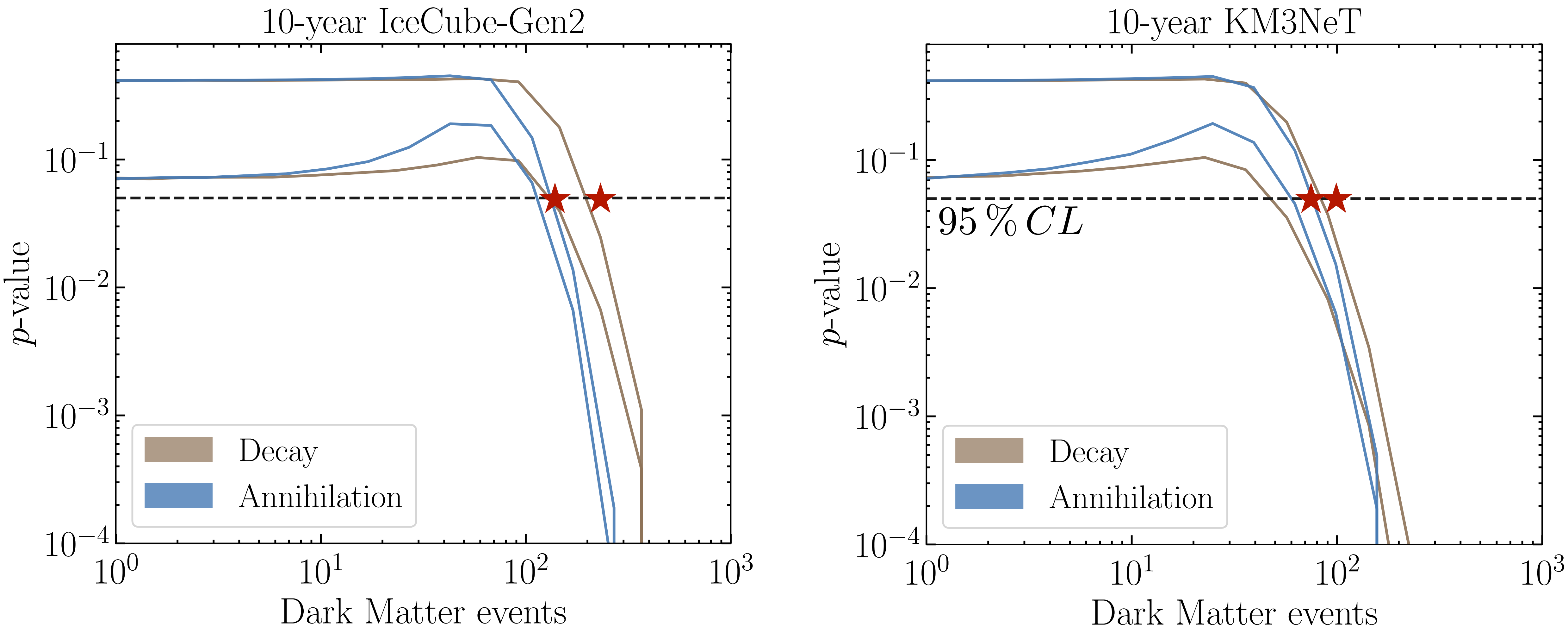
Forecast analysis: 10-year



Model

- Decay: $\mathrm{DM} \to \tau^+\tau^- \quad m_{\mathrm{DM}} = 400\,\mathrm{TeV}$
- Annihilation: $\mathrm{DM\,DM} \to \tau^+\tau^- \quad m_{\mathrm{DM}} = 200\,\mathrm{TeV}$
- NFW and HAI boost factor

Forecast analysis: 10-year



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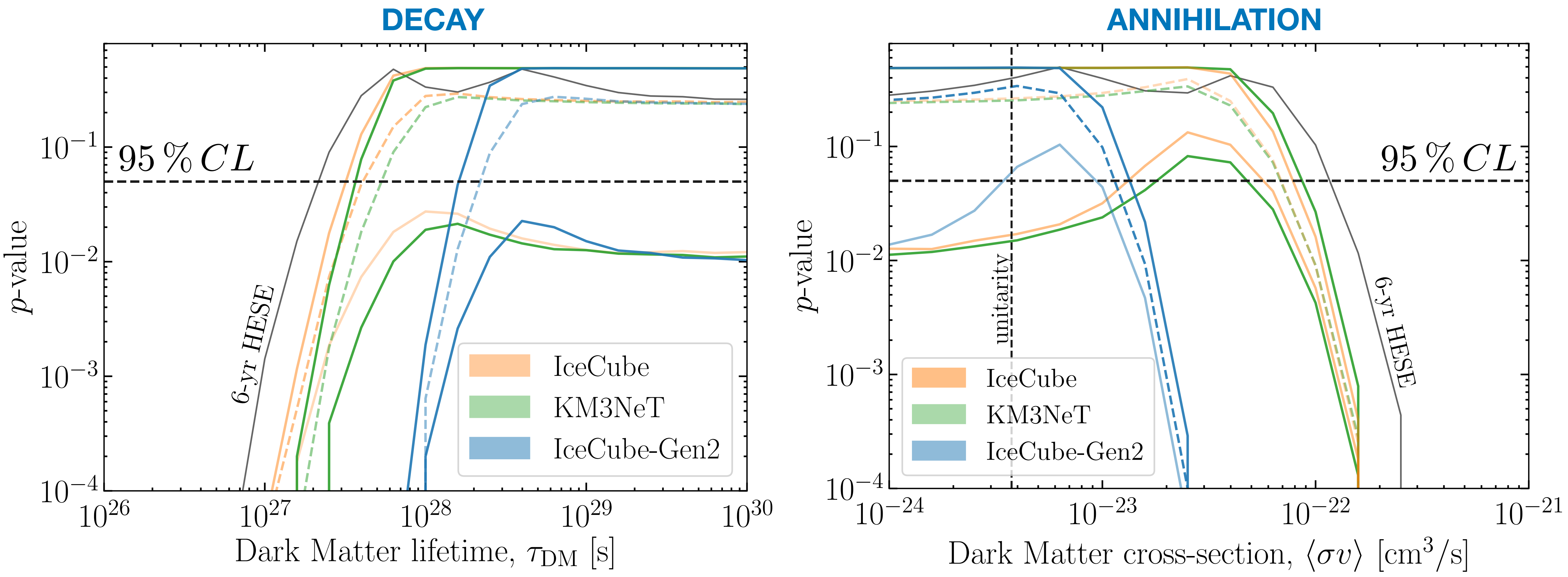
Constraints on total DM events from anisotropy

Forecast analysis: 10-year



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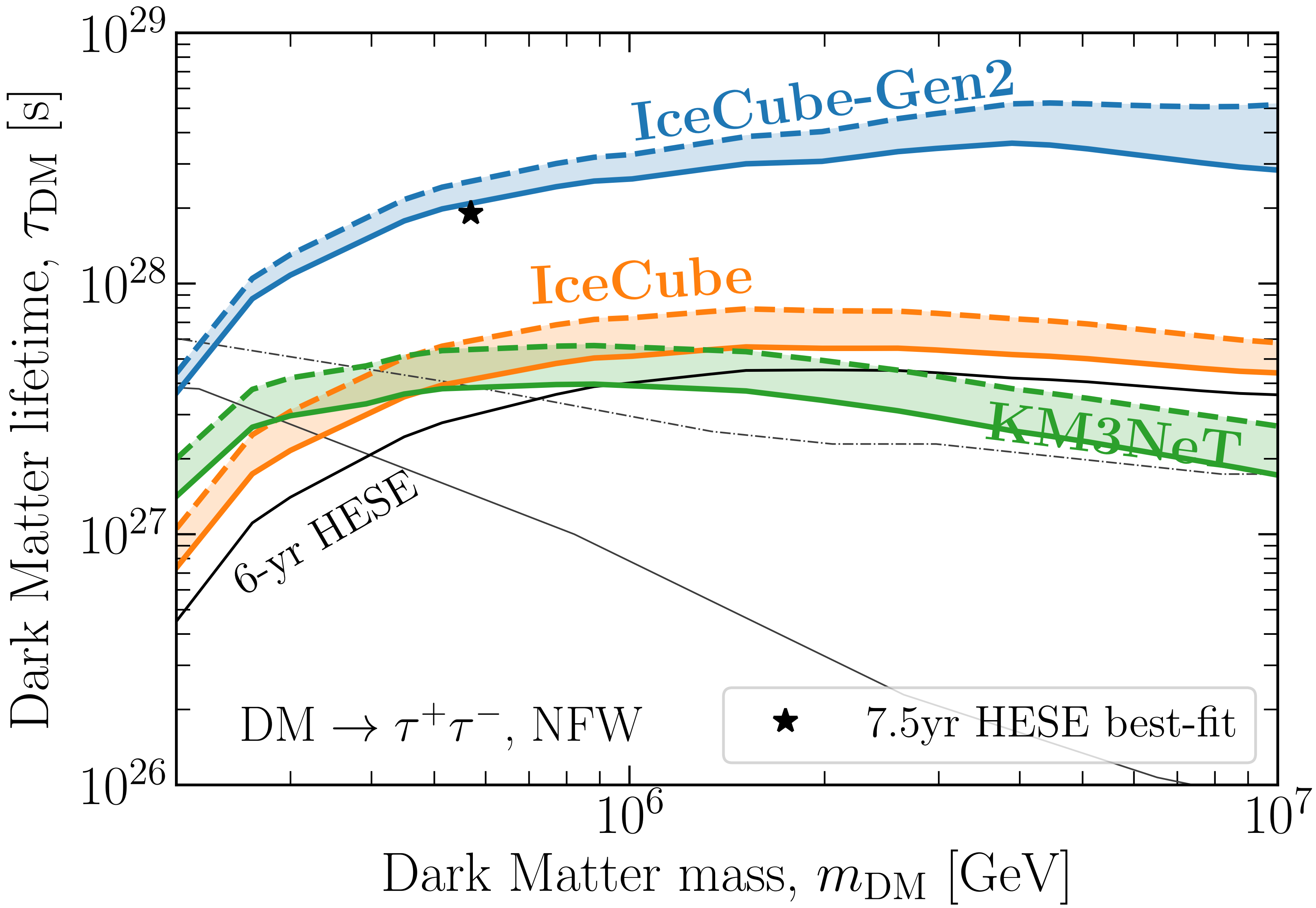
Constraints on total DM events from anisotropy

↓

Constraints on DM lifetime and cross-section

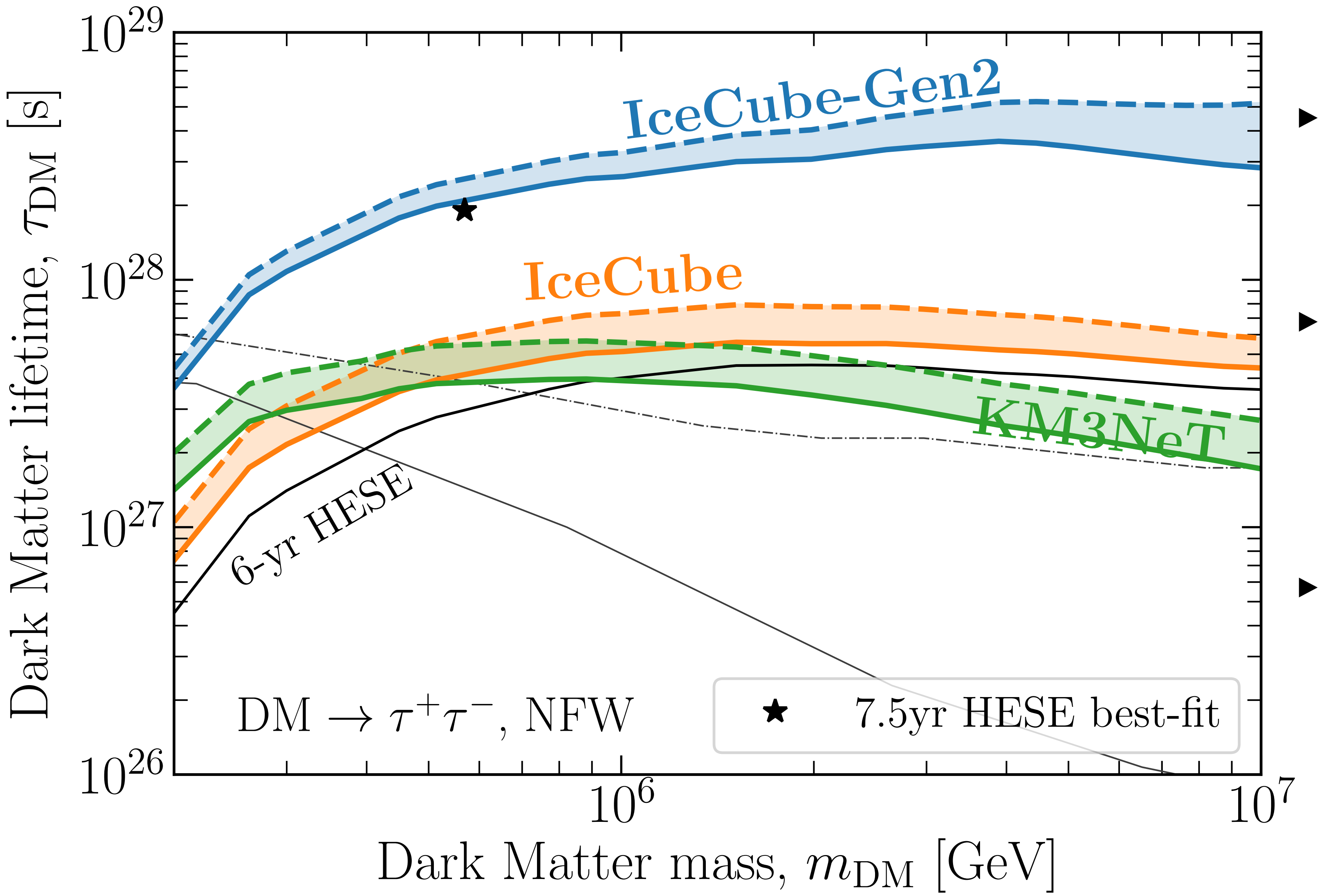
Decaying Dark Matter



- Exclusion at 95% CL after 10 years of observations
- Bands covering the median and the conservative 95% sensitivity from Monte Carlo
- Gamma-ray constraints shown with grey lines: HAWC (solid) and global (dot-dashed)

*HAWC: Abeysekara et al., **JCAP 1802**;*
*Global: Cohen, Murase, Rodd, Safdi, Soreq, **PRL 119 (2017)***

Decaying Dark Matter



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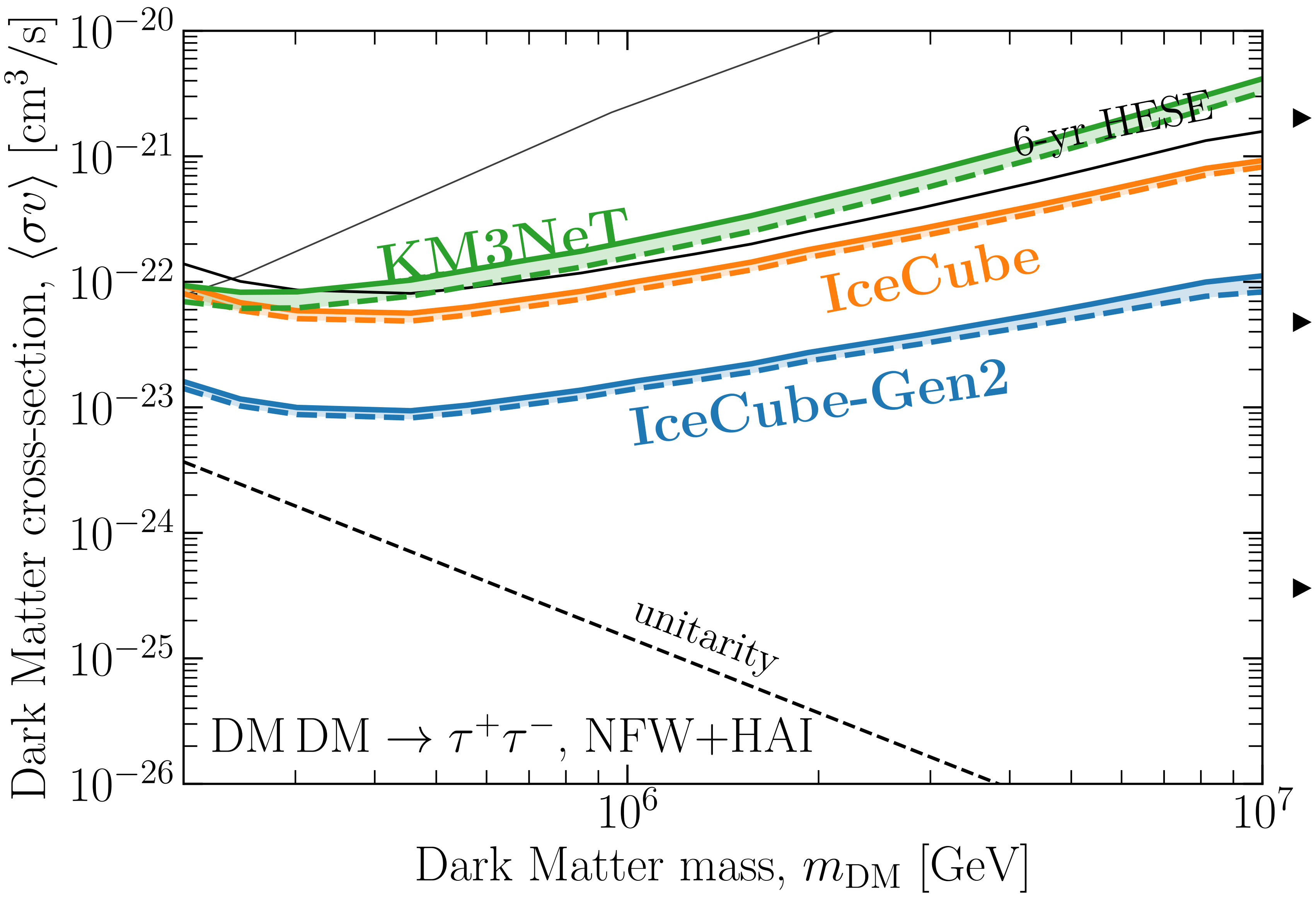
ICECUBE-GEN2 WILL FIRMLY PROBE THE DARK MATTER HYPOTHESIS

Annihilating Dark Matter



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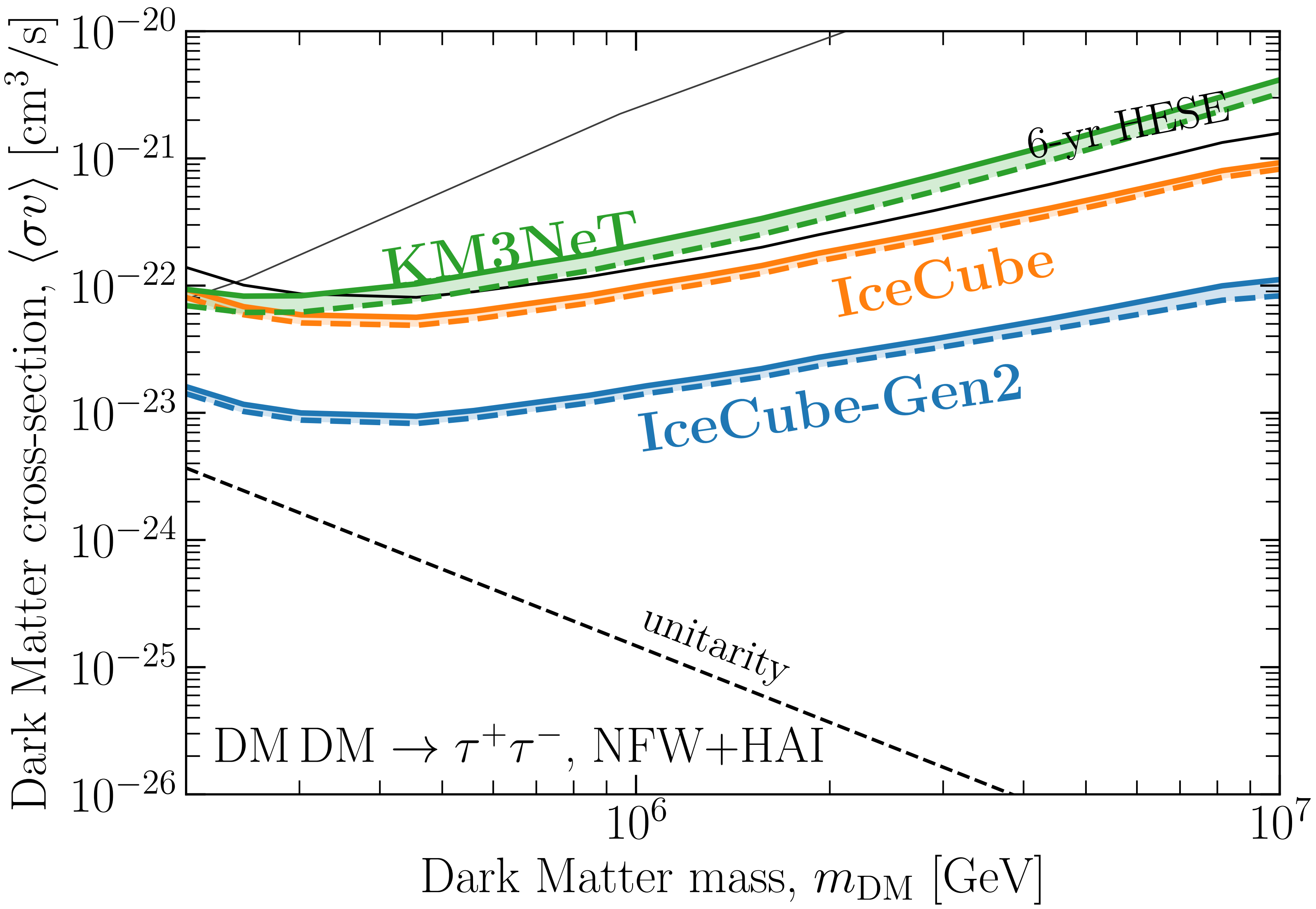

Exclusion at 95% CL after 10 years of observations

Bands covering the median and the conservative 95% sensitivity from Monte Carlo

Gamma-ray constraints shown with grey lines: HAWC (solid)

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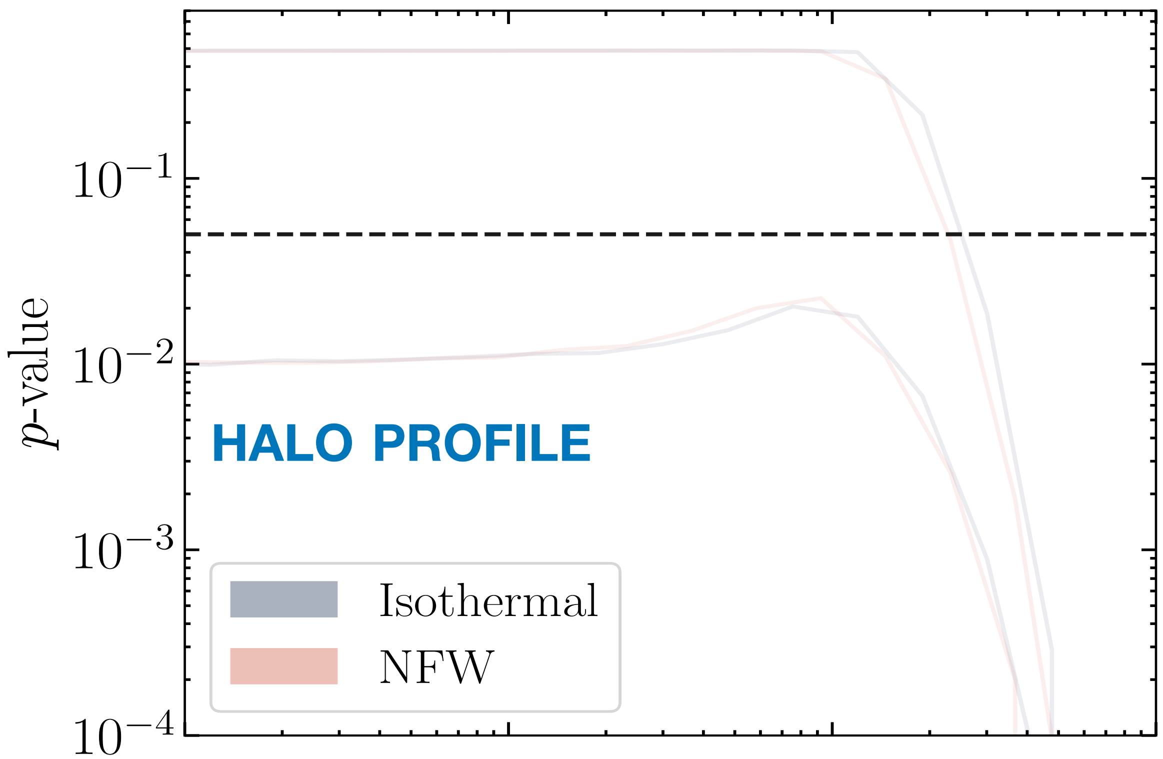
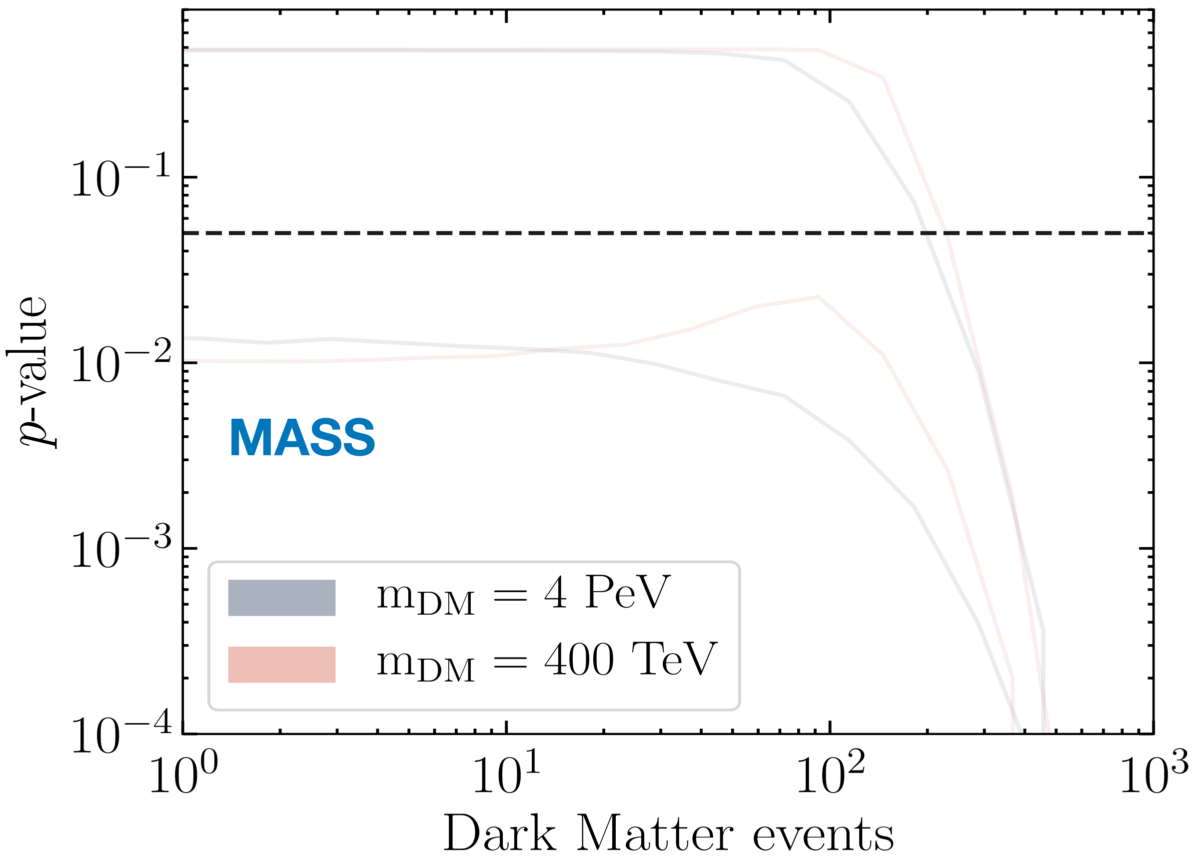
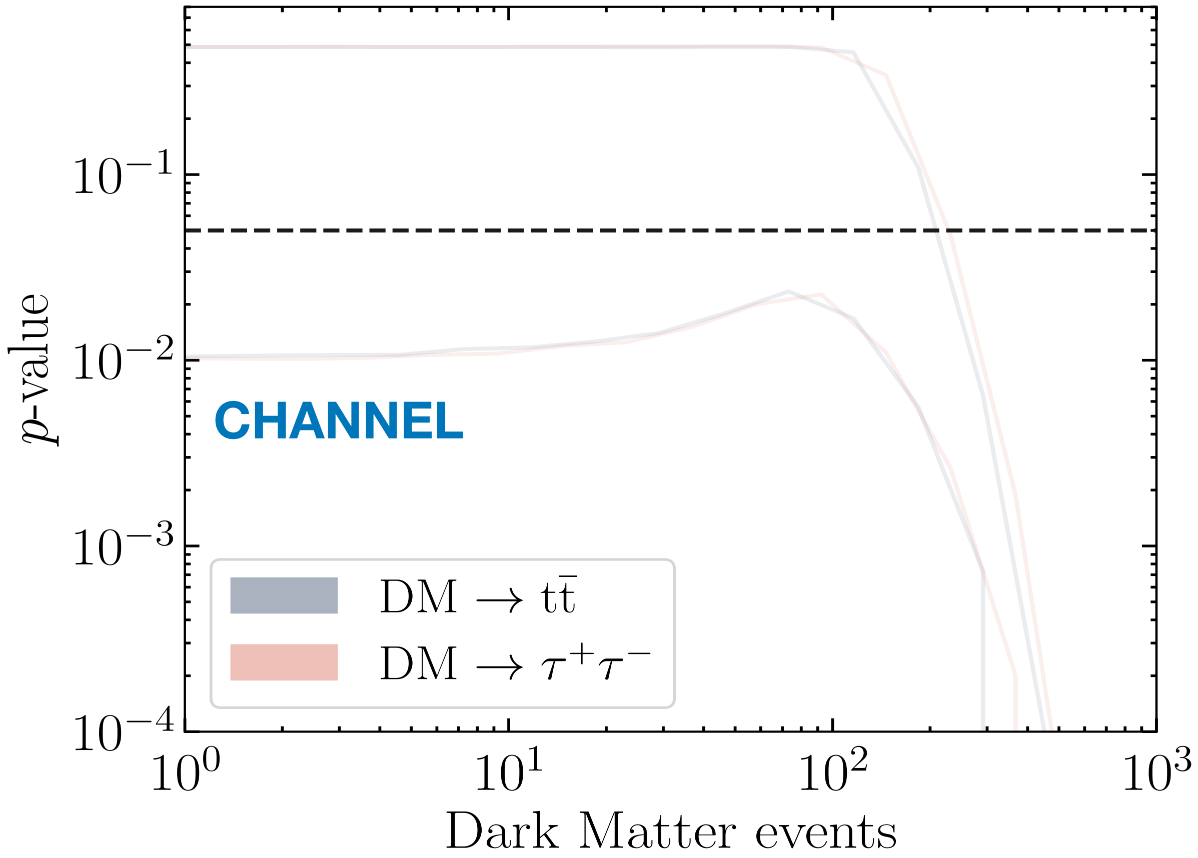
STRONGER CONSTRAINTS WRT GAMMA-RAYS, BUT *UNITARITY*

Dependence on DM properties: decay



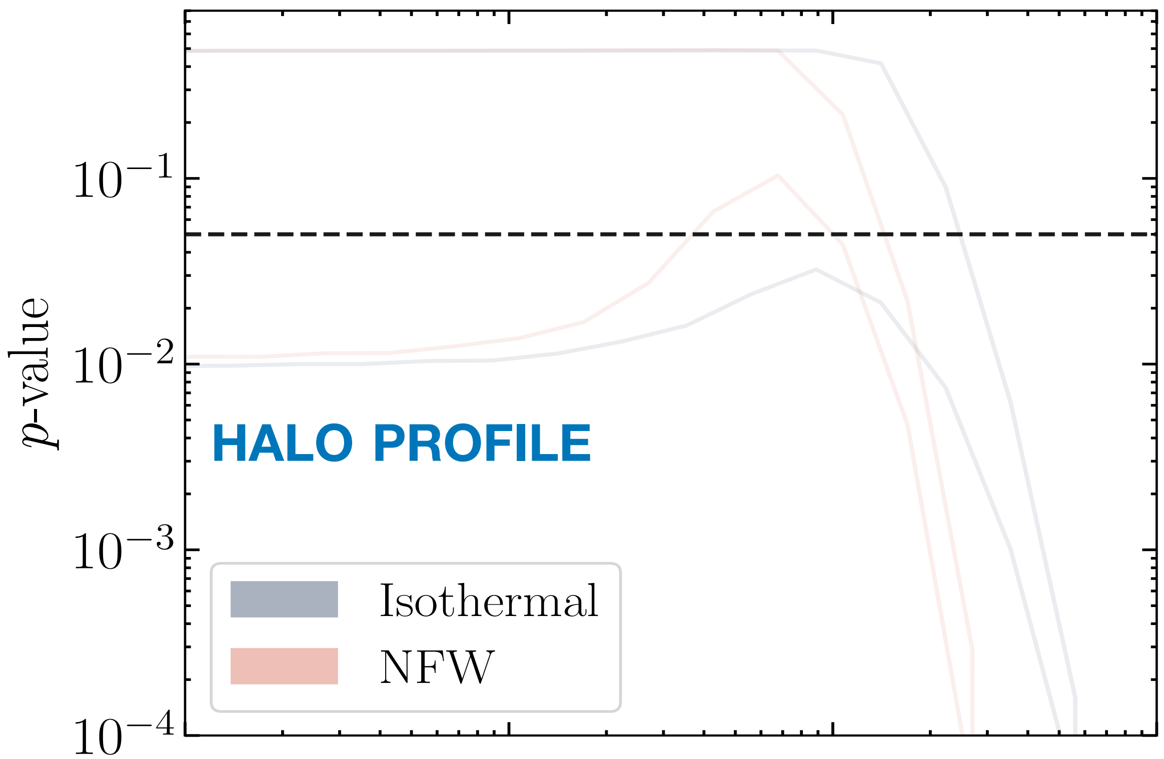


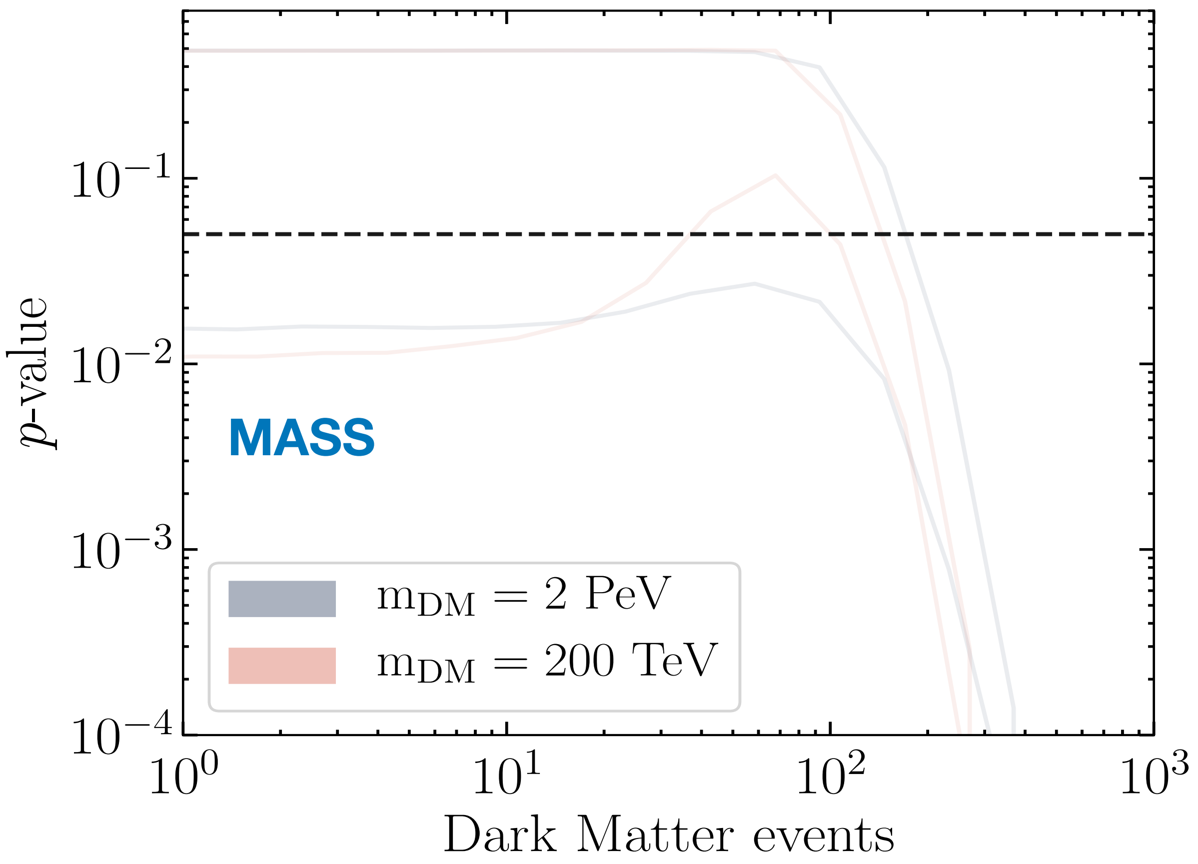


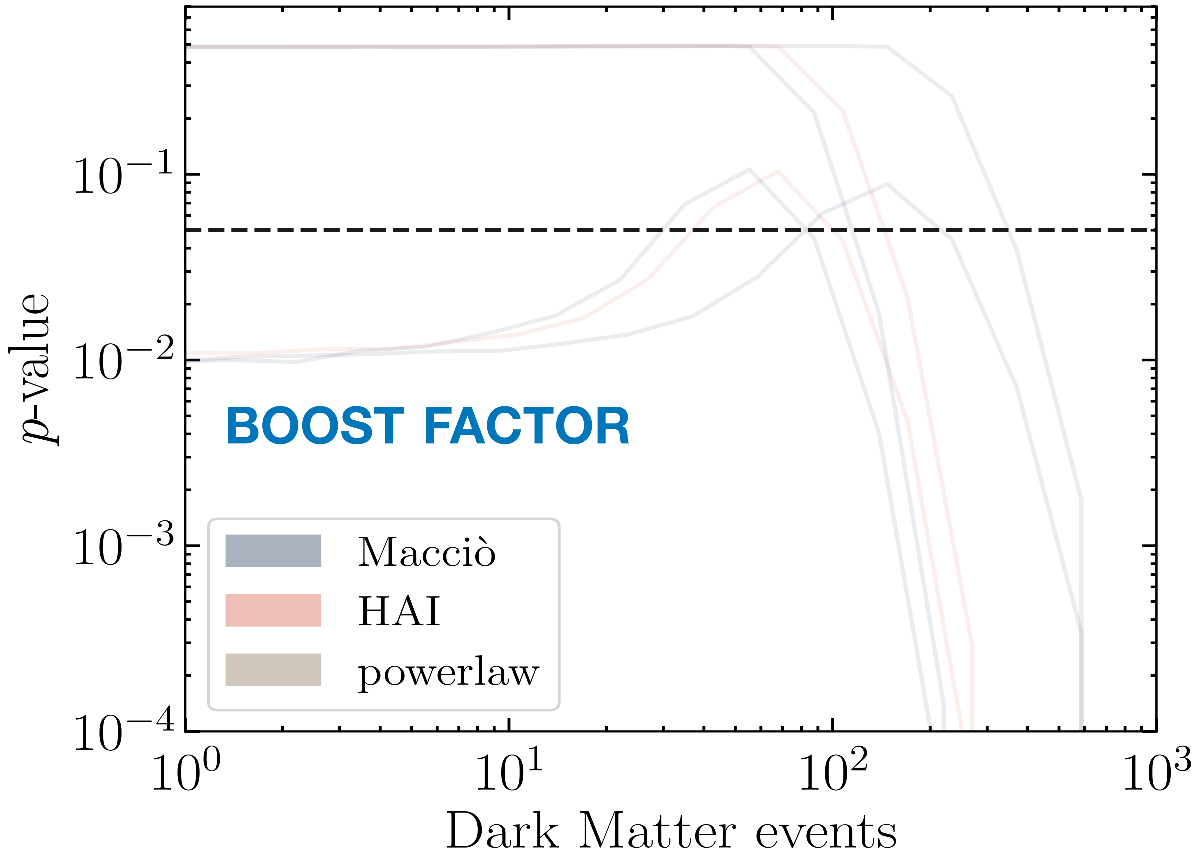
- Exclusion limits on the total DM events do not significantly change.
- The constraints change when plotted against the lifetime.

Set model-independent limits on the total DM events

Dependence on DM properties: annihilation



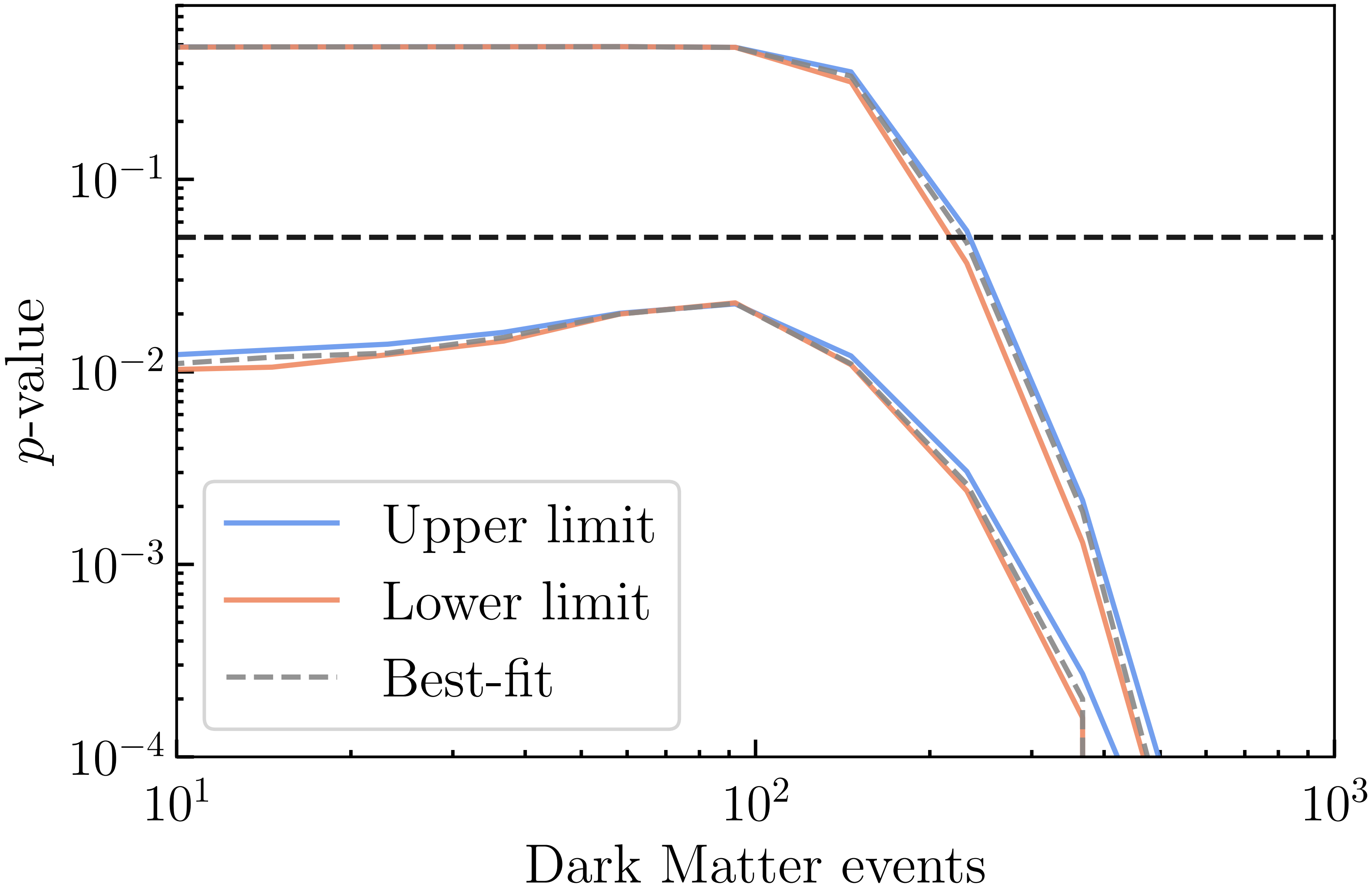




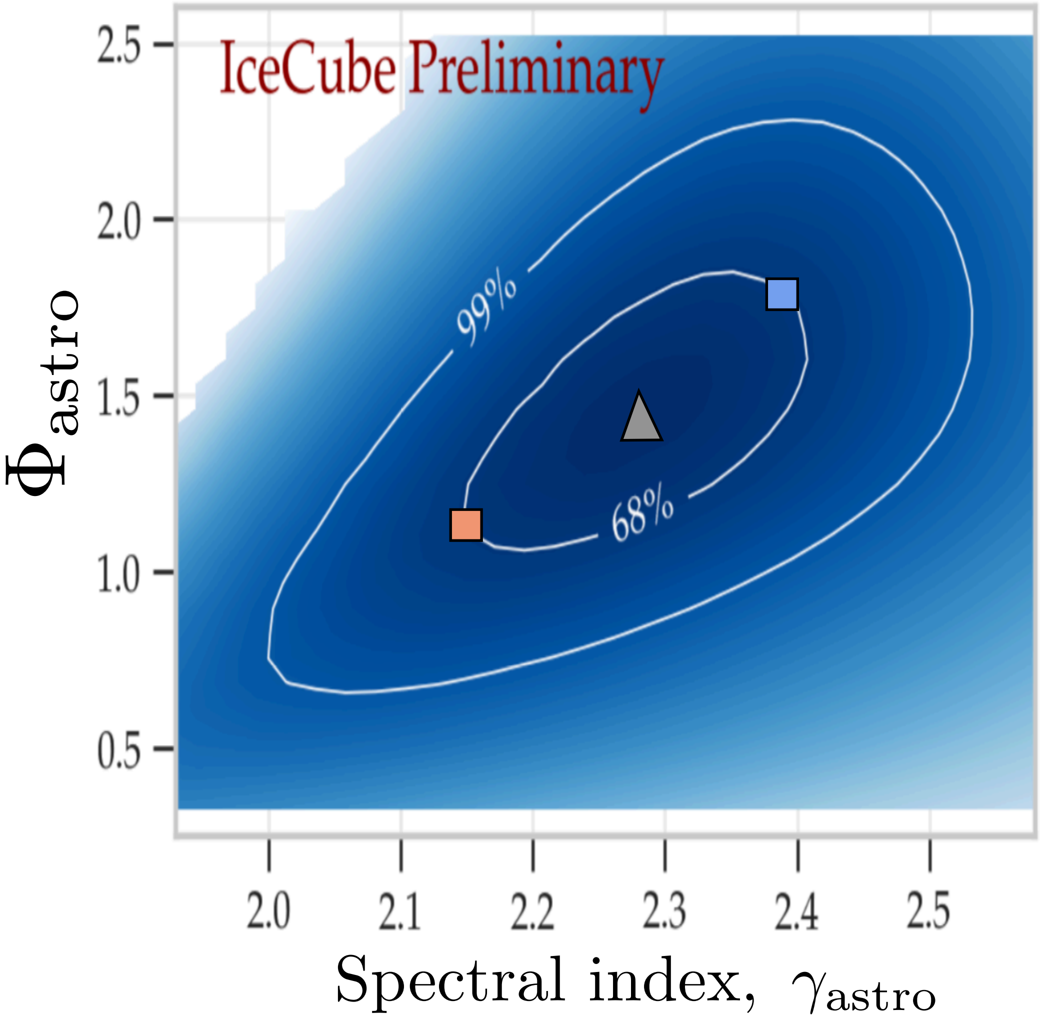
- Slightly stronger dependence on DM mass
- Constraints 70% weaker with isothermal
- Strong dependence on boost factor

The constraints on the benchmark scenario can be easily rescaled

Dependence on astrophysical power-law



10yr through-going muon neutrinos



Stettner, ***PoS ICRC2019 1017***

- No significant dependence when varying the astrophysical power-law
- Robust constraints and sensitivity to Dark Matter parameter space

Conclusions

- Tension among different neutrino data suggesting a multi-component flux.

MC, Mele, Miele, Migliozzi, Morisi, ***ApJ 851 (2017)***

- We have analyzed the 7.5-year HESE data with decaying DM + astrophysical power-law, *with* and *without* the **through-going muon neutrinos prior**.
  - Preference of a second Dark Matter component at 68% C.L.
  - Multi-messenger: diffuse searches (Fermi-LAT) more sensitive than point-like ones (CTA).

★ **Take-home: decaying leptophilic dark matter is a viable scenario!**

MC, Fiorillo, Miele, Morisi, Pisanti, ***JCAP 1911***

- **Angular Power Spectrum** is a powerful tool for Dark Matter discrimination!
  - Future sensitivity to DM parameters using IceCube and KM3NeT exposures

★ **IC-Gen2 will firmly test the DM hypothesis exploiting angular information only!**

Dekker, MC, Ando, ***arXiv:1910:12917***

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Dekker, MC, Ando, ***arXiv:1910:12917***

Thanks for listening

Backup slides

Dark Matter at neutrino telescopes

Aisati, Gustafsson, Hambye, ***PR D92 (2015)***
MC, Miele, Morisi, Vitagliano, ***PLB 757 (2016)***
MC, Miele, Morisi, ***JCAP 1701***
MC, Miele, Morisi, ***PLB 773 (2017)***
Hirishima, Kitano, Kohri, Murase, ***PR D97 (2018)***
Sui, Dev, ***JCAP 1807***
MC, Miele, Morisi, Peinado, ***JCAP 1812***

GLOBAL ANALYSES

ANTARES, ***PLB 769 (2017)***
Battacharya, Esmaili, Ruiz, Sarcevic, ***JCAP 1707***
IceCube, ***EPJ C78 (2018)***
Battacharya, Esmaili, Ruiz, Sarcevic, ***JCAP 1905***
MC, Fiorillo, Miele, Morisi, Pisanti, ***JCAP 1911***
Argüelles (IceCube), ***PoS ICRC2019 839***
Dekker, MC, Ando, ***arXiv:1910.12917***

Anisimov, Di Bari, ***PR D80 (2009)***
Feldstein, Kusenko, Matsumoto, Yanagida, ***PR D88 (2013)***
Esmaili, Serpico, ***JCAP 1311***
Bai, Lu, Salvado, ***JHEP 01 (2016)***
Ema, Jinno, Moroi, ***PLB 733 (2014)***
Bhattacharya, Reno, Sarcevic, ***JHEP 06 (2014)***
Zavala, ***PR D89 (2014)***
Higaki, Kitano, Sato, ***JHEP 07 (2014)***
Ema, Jinno, Moroi, ***JHEP 10 (2014)***
Rott, Kohri, Park, ***PR D92 (2015)***
Esmaili, Kang, Serpico, ***JCAP 1412***
Fong, Minakata, Panes, Funchal, ***JHEP 02 (2015)***
Dudas, Mambrini, Olive, ***PR D91 (2015)***
Koop, Liu, Wang, ***JHEP 04 (2015)***
Murase, Laha, Ando, Ahlers, ***PRL 115 (2015)***
Anchordoqui et al, ***PR D92 (2015)***
MC+, ***JCAP 1512***
Ko, Tang, ***PLB 751 (2015)***
Dev, Ghosh, Rodejohann, ***PLB 762 (2016)***
Fiorentin, Niro, Fornengo, ***JHEP 11 (2016)***
Dev, Kazanas, Mohapatra, Tepliz, Zhang, ***JCAP 1608***
Di Bari, Ludl, Ruiz, ***JCAP 1611 (2016)***
MC, Merle, ***JCAP 1704***
Borah et al., ***JHEP 09 (2017)***
Kachelriess, Kalashev, Kuznetsov, ***PR D98 (2018)***
Pandey, Majumdar, Halder, Banerjee, ***arXiv:1905.08662***
Pandey, Majumdar, Halder, ***arXiv:1909.06839***

General thoughts on DM signals

For heavy DM, the annihilation rates are negligible with respect to the decay ones. In case of m_{DM} = 1 PeV, we have:

Feldstein, Kusenko, Matsumoto, Yanagida, ***PR D88 (2013)***

- **Annihilation**

$$\Gamma_{\mathrm{events}} \propto \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^2 \langle \sigma\, v \rangle \lesssim 1 \text{ per few hundred years}$$

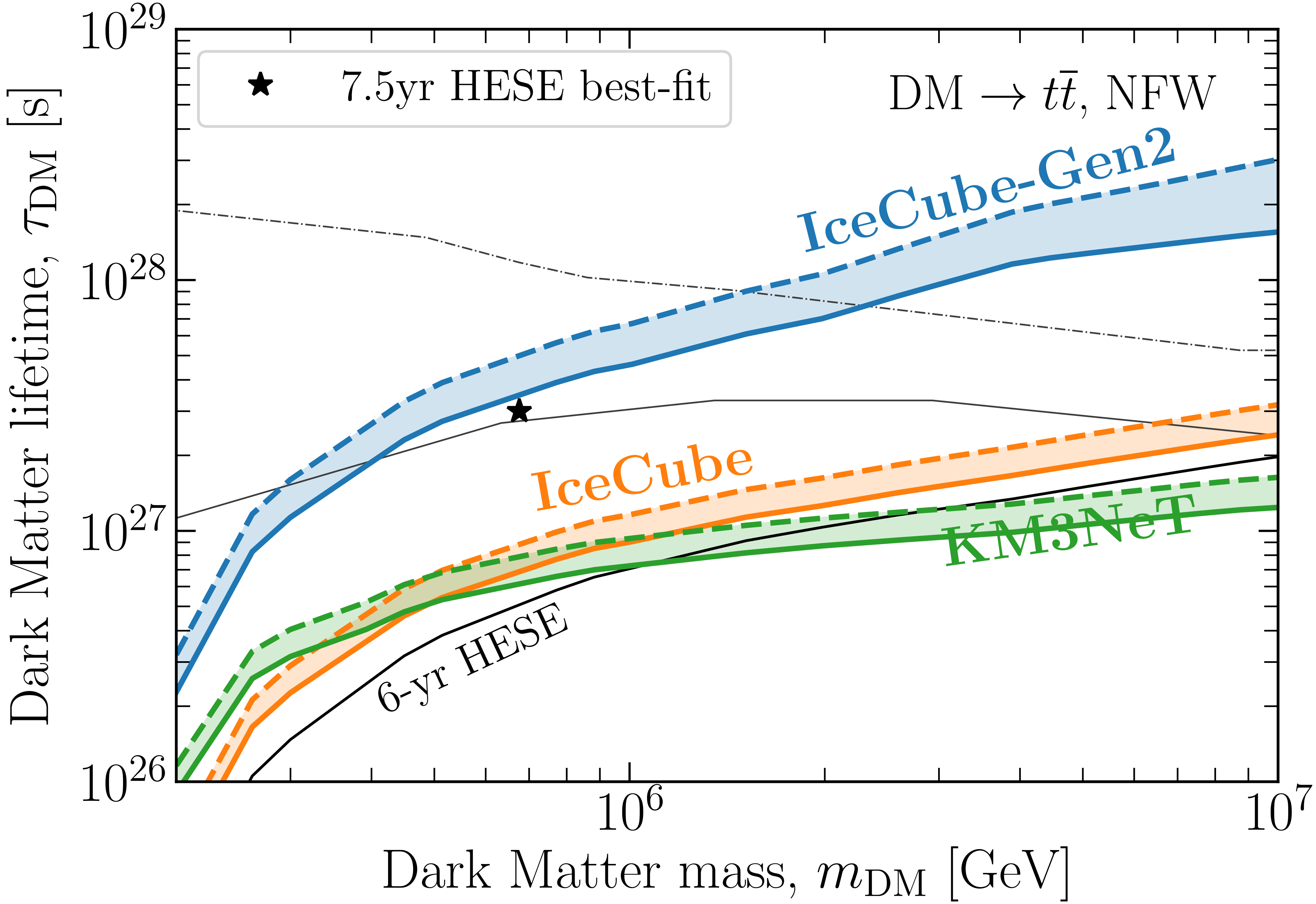
Unitarity limit: $\langle \sigma\, v \rangle \leq 1.5 \times 10^{-23} \frac{\mathrm{cm}^3}{\mathrm{s}} \left[\frac{300 \text{ km/s}}{v}\right] \left[\frac{100 \text{ TeV}}{m_{\mathrm{DM}}}\right]^2$

Relaxed in case of very cold DM substructures
Zavala, ***PR D89 (2014)***

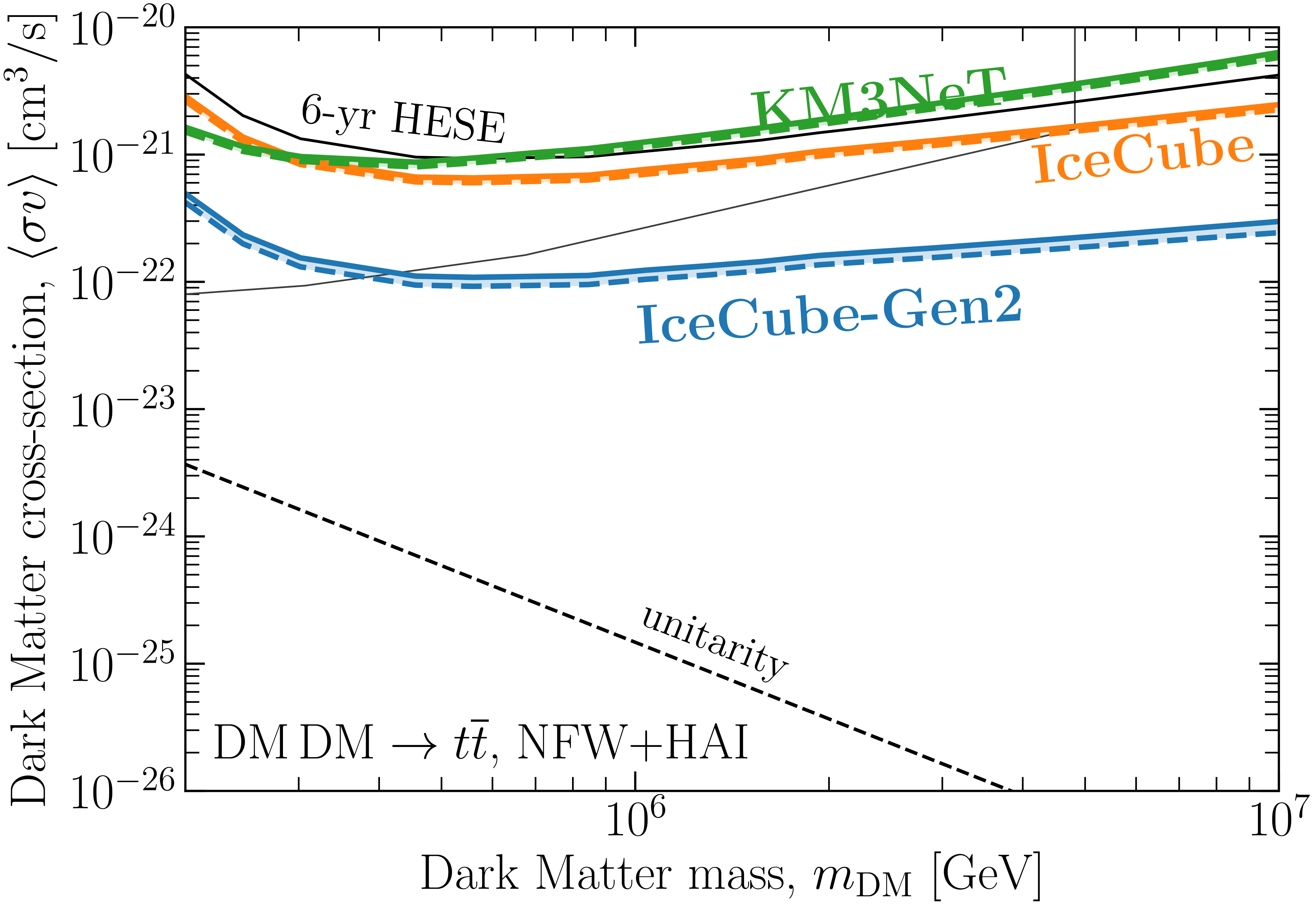
- **Decay**

$$\Gamma_{\mathrm{events}} \propto \frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}} \frac{1}{\tau_{\mathrm{DM}}} \sim \left(\frac{18^{28} \text{ sec}}{\tau_{\mathrm{DM}}}\right) /\text{year}$$

Decaying Dark Matter: top channel



Annihilating Dark Matter: top channel



Neutrino sky maps

$$N_\nu\left(\theta,\phi\right) = \int_{\Delta\Omega} \mathrm{d}\Omega \int_{E_{\mathrm{th}}}^{E_{\mathrm{max}}} \mathrm{d}E_\nu \sum_\alpha f_\alpha \frac{\mathrm{d}\Phi_{\nu_\alpha+\bar{\nu}_\alpha}}{\mathrm{d}E_\nu\,\mathrm{d}\Omega} \mathcal{E}_\alpha(E_\nu,\Omega)\,\mathrm{vis}(\Omega)$$

Number of neutrino events in a region of the sky $\Delta\Omega$ identified by the position θ (declination) and ϕ (right ascension)

Total neutrino flux

Neutrino sky maps

$$N_\nu\left(\theta,\phi\right) = \int_{\Delta\Omega} \mathrm{d}\Omega \int_{E_{\mathrm{th}}}^{E_{\mathrm{max}}} \mathrm{d}E_\nu \sum_\alpha f_\alpha \frac{\mathrm{d}\Phi_{\nu_\alpha+\bar{\nu}_\alpha}}{\mathrm{d}E_\nu\,\mathrm{d}\Omega}\,\mathcal{E}_\alpha(E_\nu,\Omega)\,\mathrm{vis}(\Omega)$$

Integrated over energy

$$E_{\mathrm{th}} = 60\ \mathrm{TeV}$$

$$E_{\mathrm{max}} = m_{\mathrm{DM}},\ m_{\mathrm{DM}}/2$$

annihilation

decay

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annihilation

decay

Topology

- Showers in IceCube:

$$f_e = f_\tau = 1\,, \quad f_\mu = 0$$

- Tracks in KM3NeT:

$$f_e = f_\tau = 0\,, \quad f_\mu \simeq 0.8$$

Neutrino sky maps

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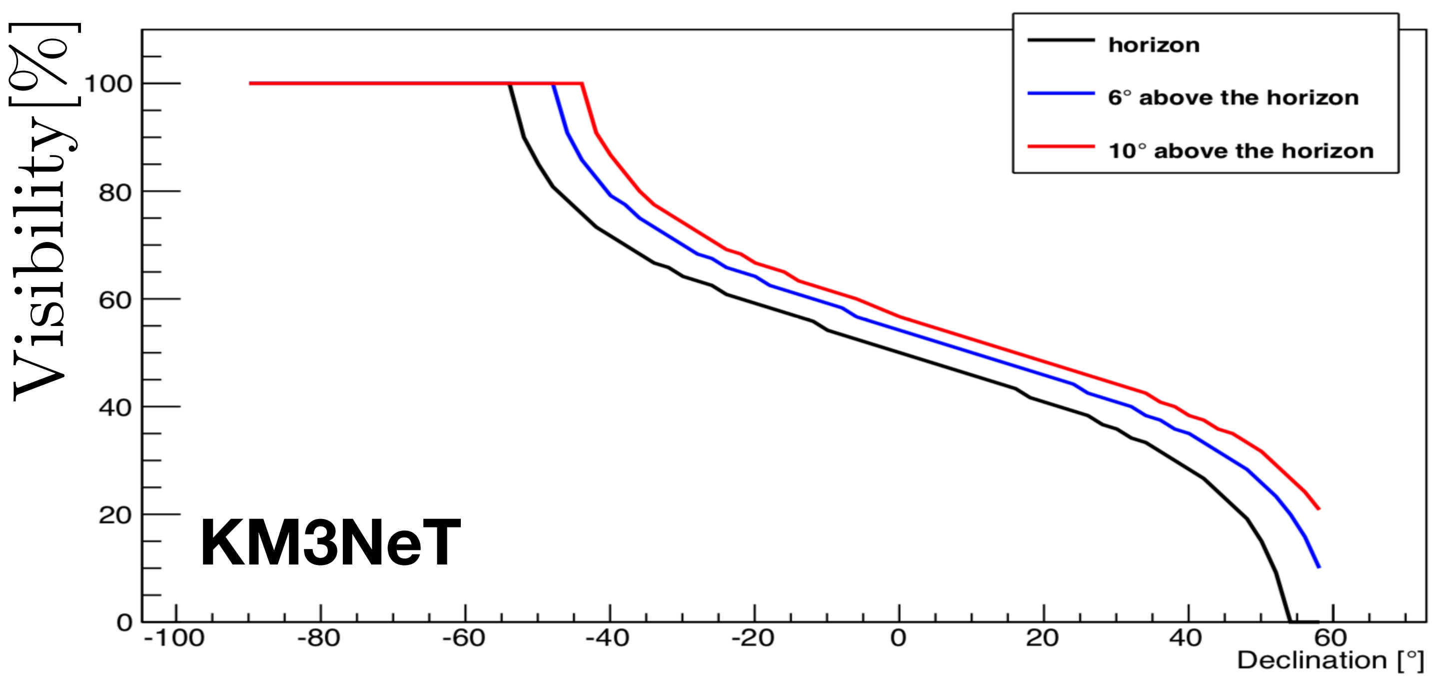
Detector properties

$\mathcal{E}_\alpha$: effective area

→ HESE (IceCube)

→ TG (KM3NeT)



- IceCube visibility is 100% thanks to self-veto

Marco Chianese | GRAPPA

Decaying Dark Matter flux

GALACTIC

$$\frac{\mathrm{d}\phi^{\mathrm{DM}}_{\mathrm{gal.}}}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathbf{d}\boldsymbol{N_\nu}}{\mathbf{d}\boldsymbol{E}} \int \mathrm{d}s\, \rho\,(s,l,b)$$

EXTRA-GALACTIC

$$\frac{\mathrm{d}\phi^{\mathrm{DM}}_{\mathrm{ext.gal.}}}{\mathrm{d}E\mathrm{d}\Omega} = \frac{\Omega_{\mathrm{DM}}\rho_c}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int \mathrm{d}z\, \frac{1}{H(z)} \left.\frac{\mathbf{d}\boldsymbol{N_\nu}}{\mathbf{d}\boldsymbol{E}}\right|_{\boldsymbol{E'=E(1+z)}}$$

- *Different final states:*

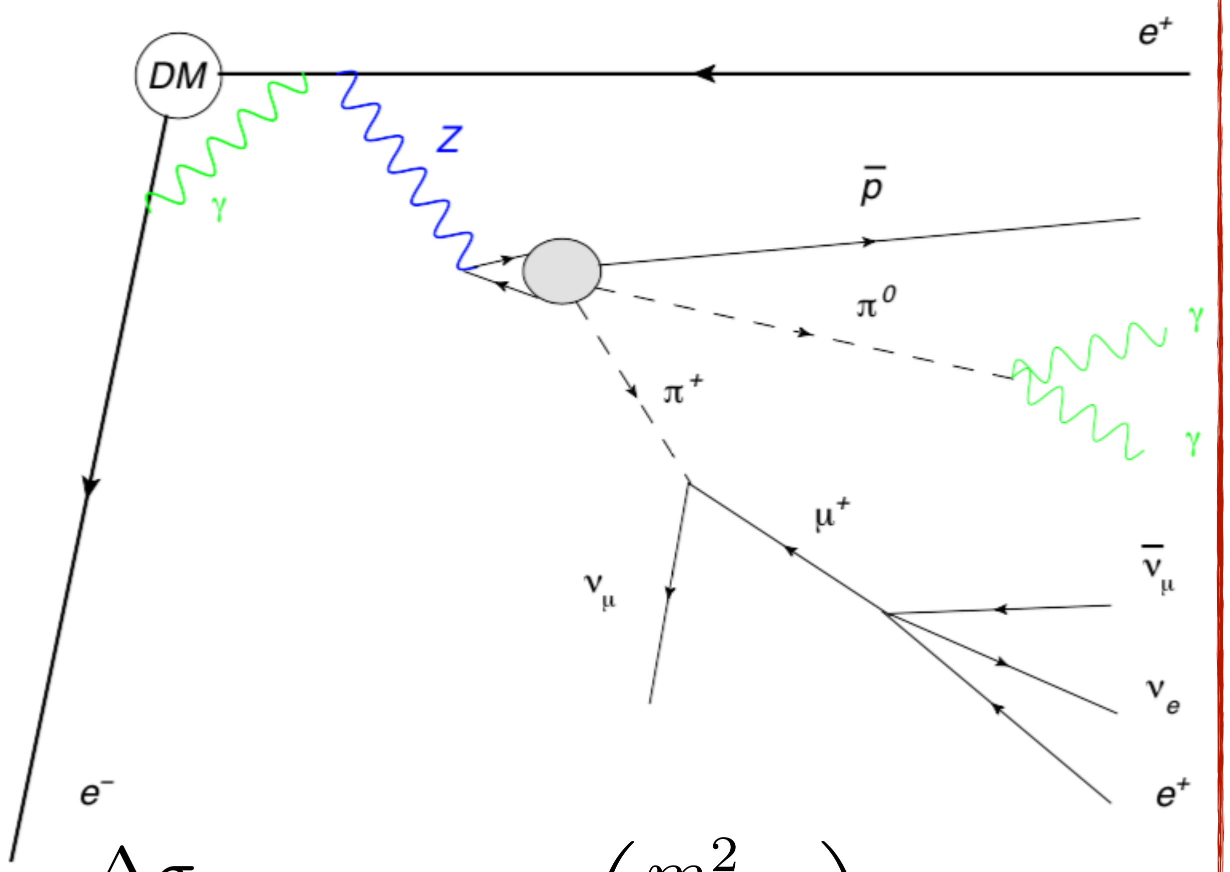
$\mathrm{DM} \to \ell\bar{\ell}, \nu\nu$ leptophilic

$\mathrm{DM} \to q\bar{q}$ hadrons

$\mathrm{DM} \to W^+W^-, ZZ, hh$ EW bosons

Electroweak corrections are important!

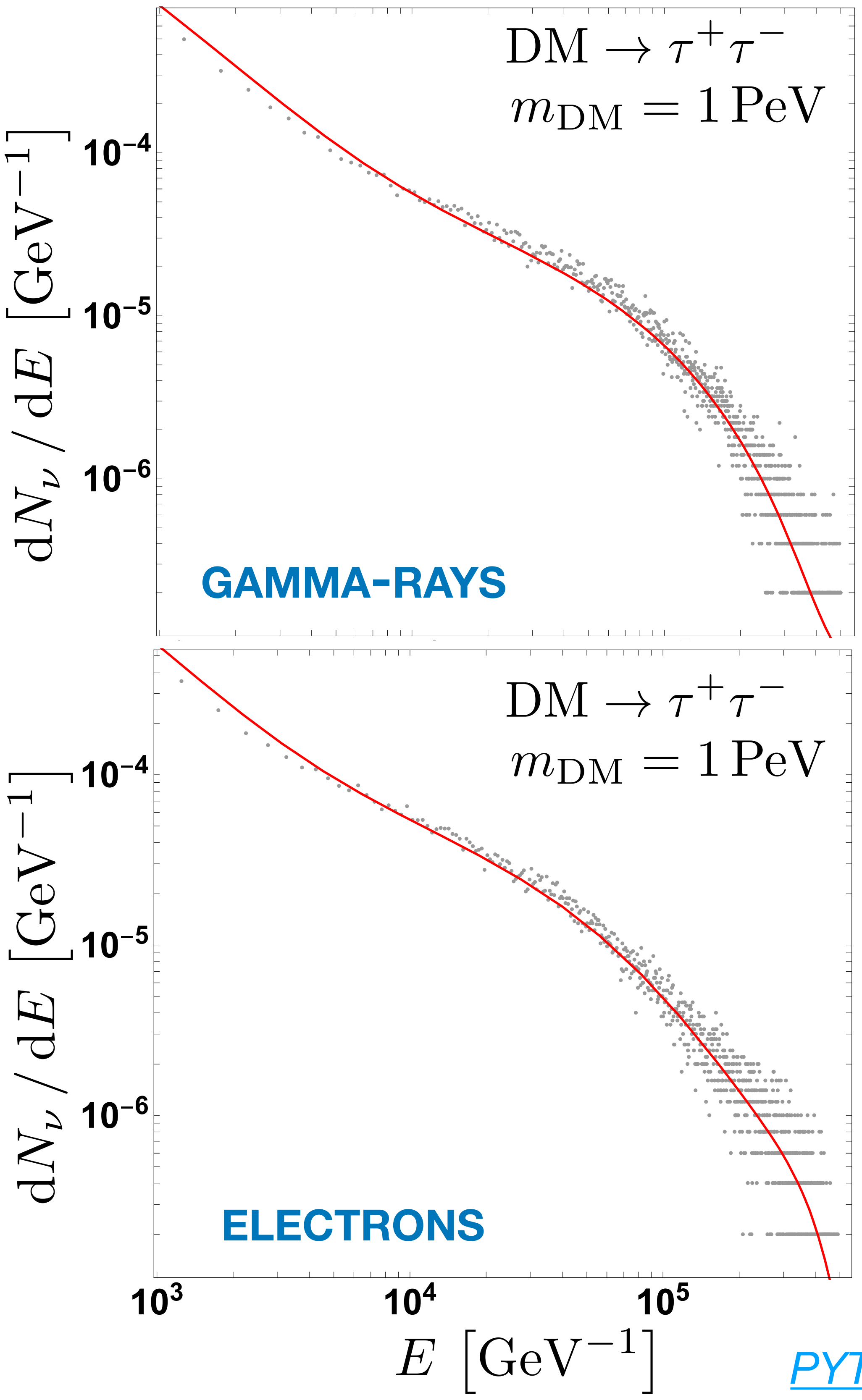
*Ciafaloni et al., **JCAP 1103***

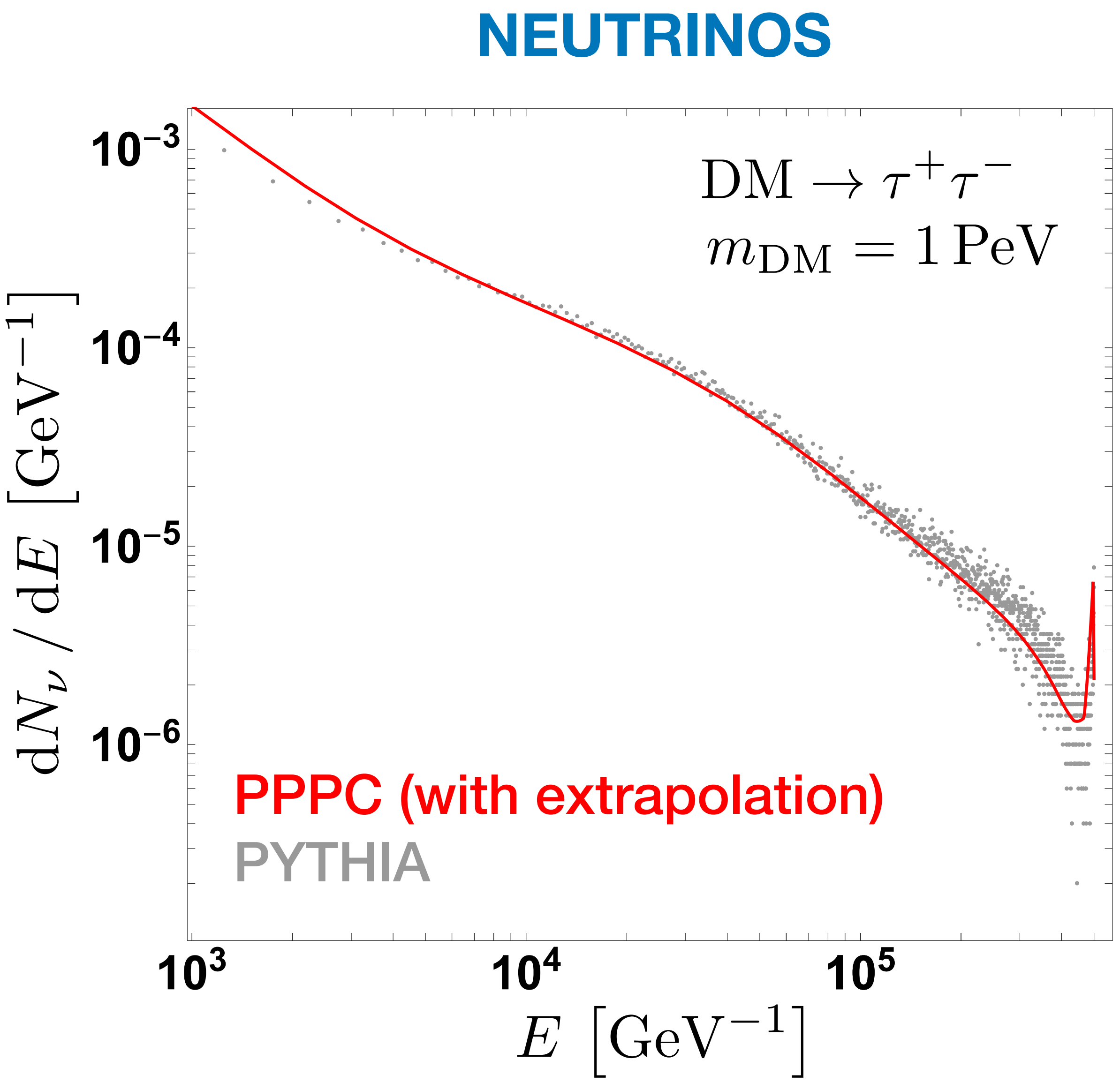


$$\frac{\Delta\sigma}{\sigma} \sim \alpha_{\mathrm{EW}} \ln^2\left(\frac{m^2_{\mathrm{DM}}}{M^2_Z}\right) \simeq 75\%$$

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

Neutrino spectrum: PPPC vs PYTHIA

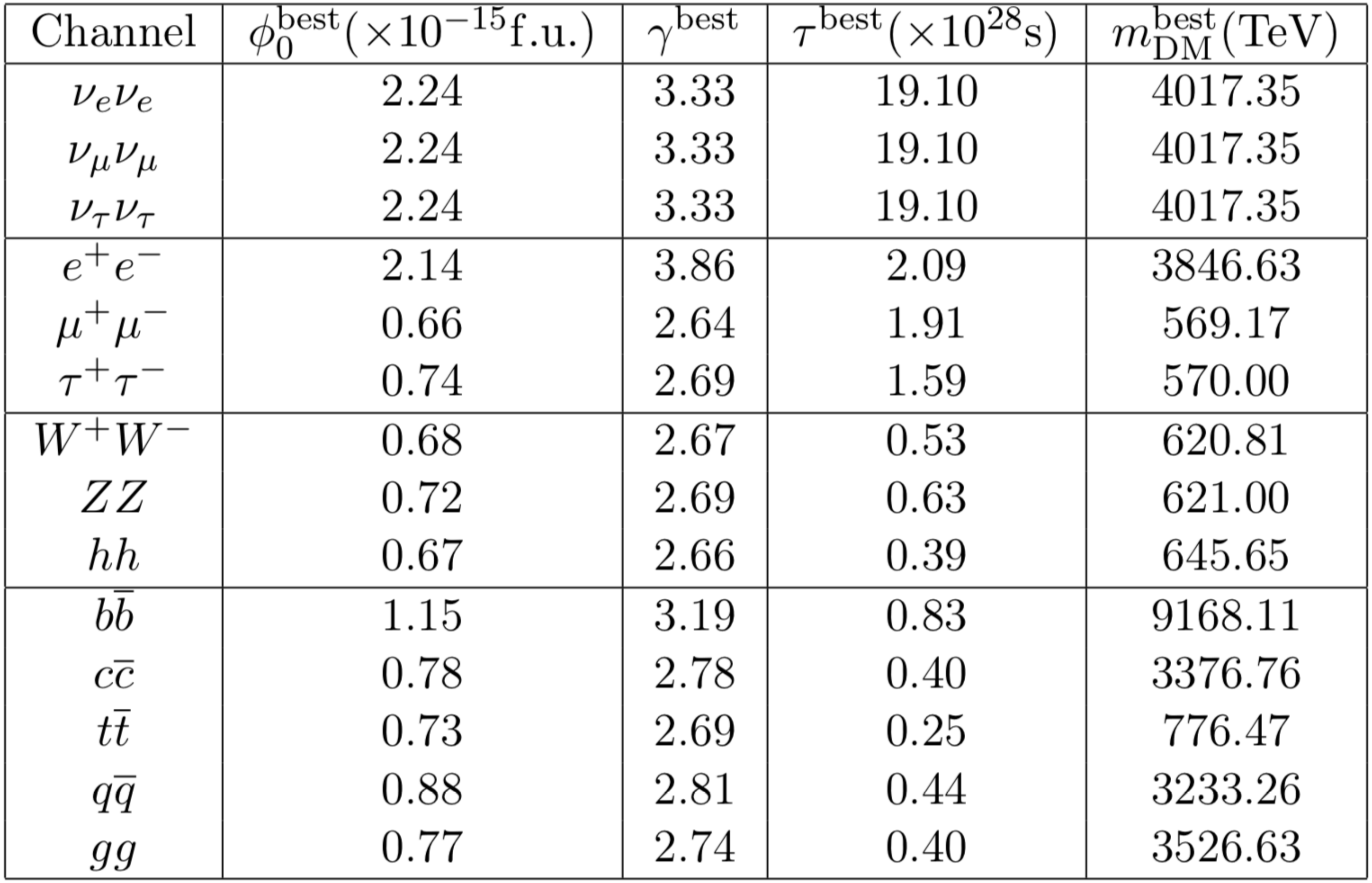




Perfect agreement between **PYTHIA** and the rescaling of the fluxes provided by **PPPC** up to 100 TeV

PYTHIA: Sjöstrand et al., ***Comput. Phys. Commun. 159 (2015)***
PPPC: Cirelli et al., ***JCAP 1103***

Latest analysis on 7.5yr HESE



Channel	$\phi_0^{\rm best}(\times 10^{-15}{\rm f.u.})$	$\gamma^{\rm best}$	$\tau^{\rm best}(\times 10^{28}{\rm s})$	$m_{\rm DM}^{\rm best}({\rm TeV})$
$\nu_e\nu_e$	2.24	3.33	19.10	4017.35
$\nu_\mu\nu_\mu$	2.24	3.33	19.10	4017.35
$\nu_\tau\nu_\tau$	2.24	3.33	19.10	4017.35
e^+e^-	2.14	3.86	2.09	3846.63
$\mu^+\mu^-$	0.66	2.64	1.91	569.17
$\tau^+\tau^-$	0.74	2.69	1.59	570.00
W^+W^-	0.68	2.67	0.53	620.81
ZZ	0.72	2.69	0.63	621.00
hh	0.67	2.66	0.39	645.65
$b\bar{b}$	1.15	3.19	0.83	9168.11
$c\bar{c}$	0.78	2.78	0.40	3376.76
$t\bar{t}$	0.73	2.69	0.25	776.47
$q\bar{q}$	0.88	2.81	0.44	3233.26
gg	0.77	2.74	0.40	3526.63

$${\rm f.u.} \equiv {\rm TeV}^{-1}{\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}$$

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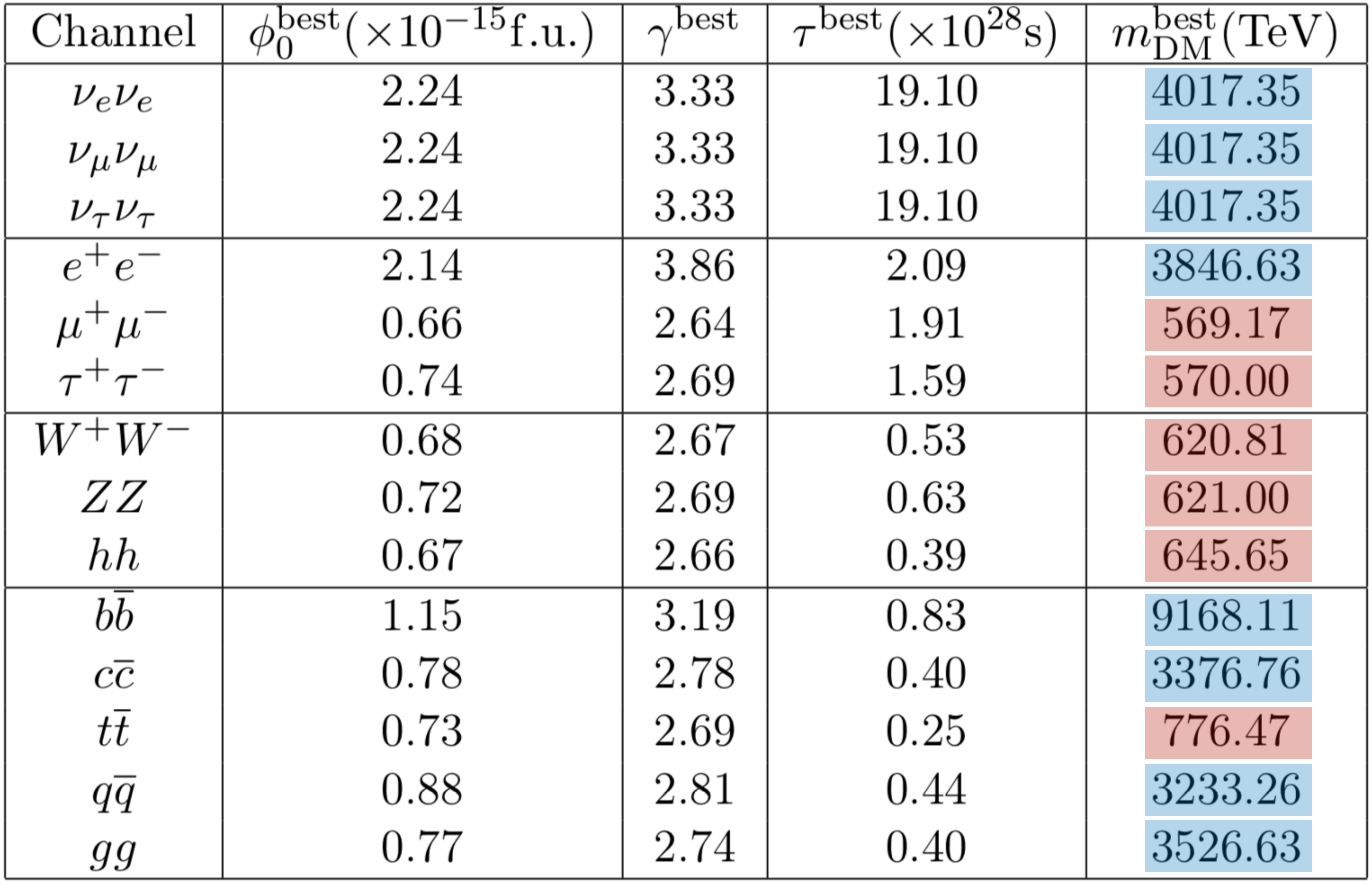

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__DM flux__

TeV scale

PeV scale

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DM flux

TeV scale

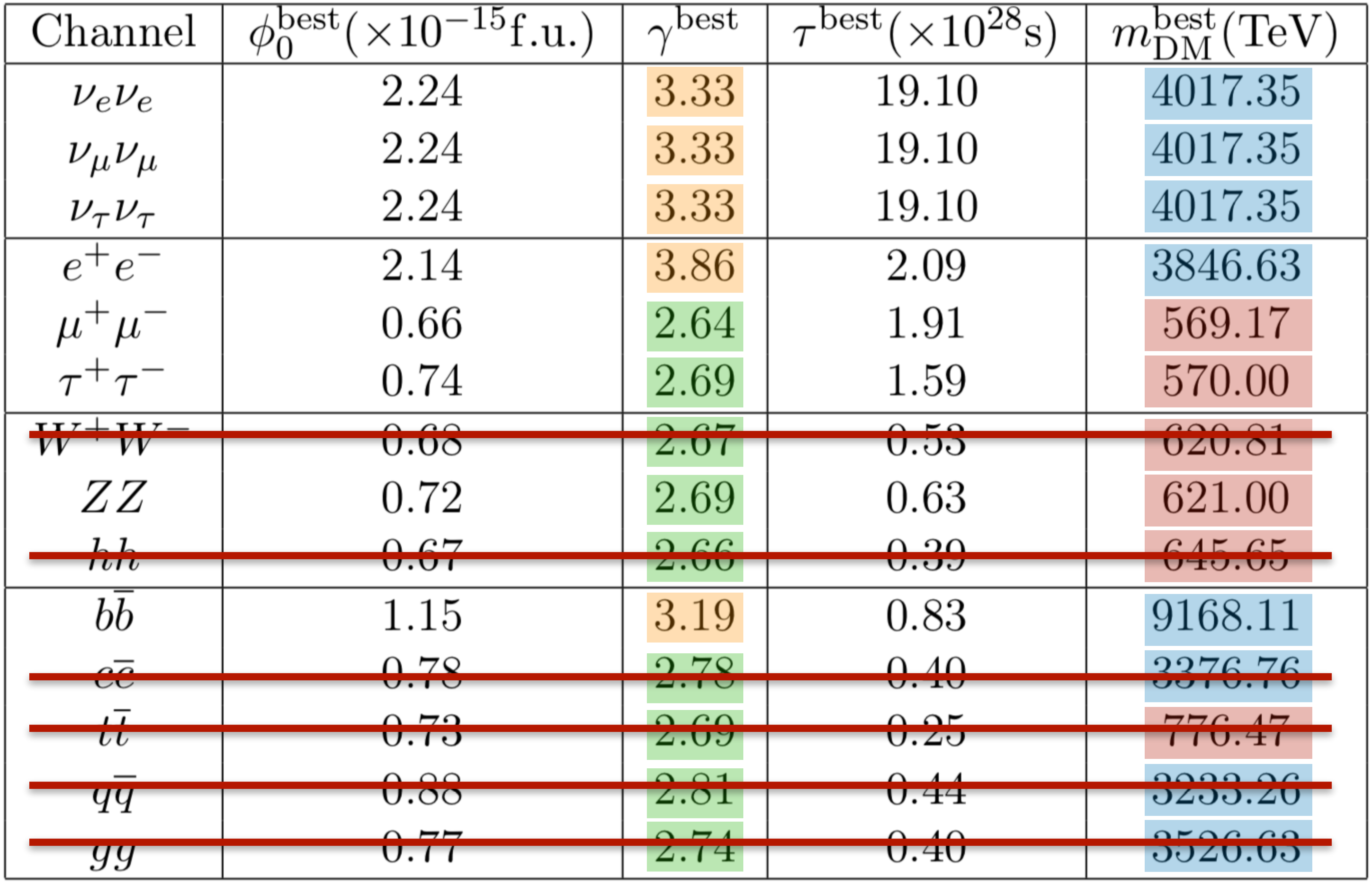
PeV scale

Astro flux

Spectral index larger than single PL

Spectral index smaller than single PL

Latest analysis on 7.5yr HESE



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$${\rm f.u.} \equiv {\rm TeV}^{-1}{\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}$$

DM flux

TeV scale

PeV scale

Astro flux

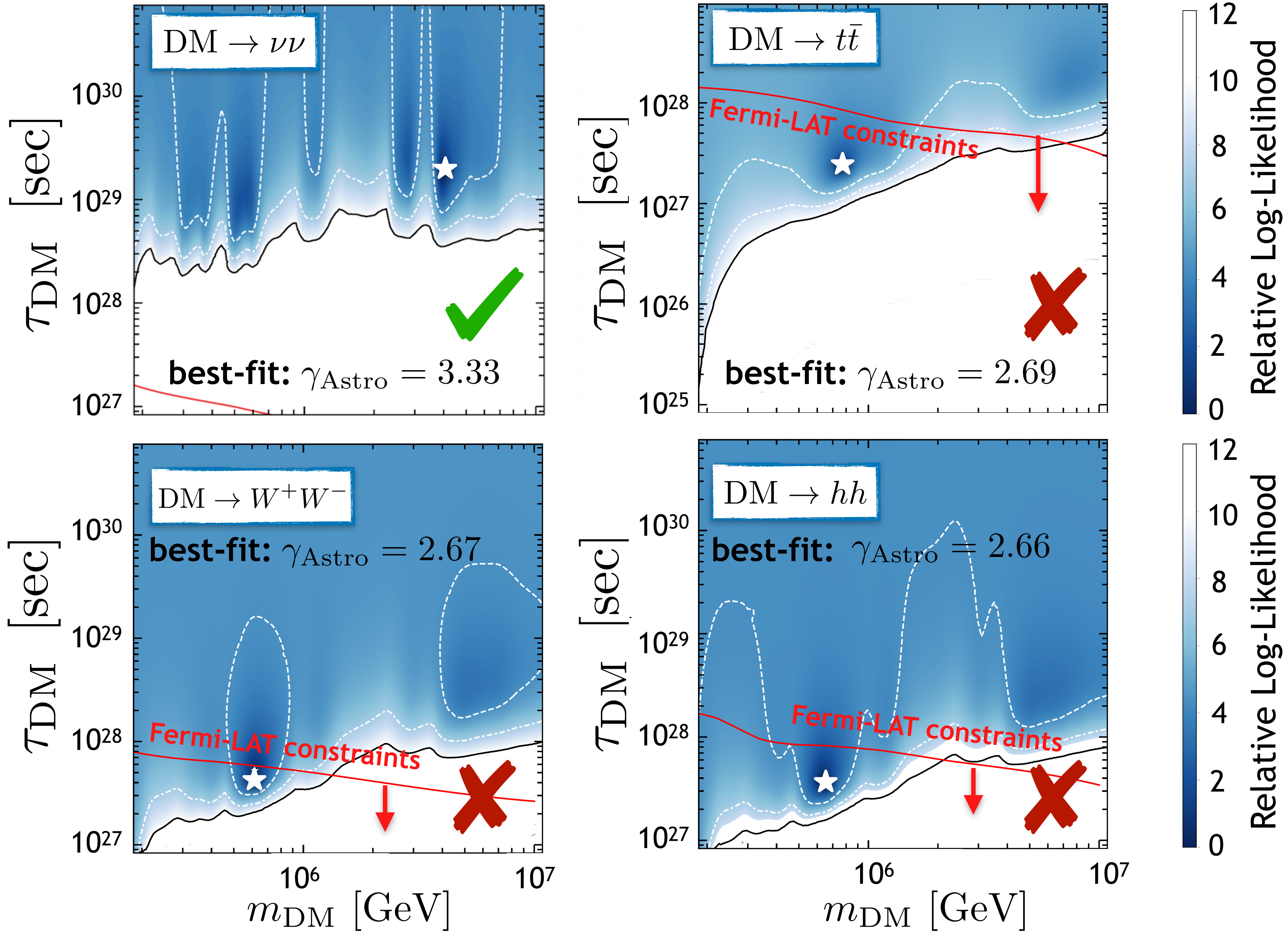
Spectral index larger than single PL

Spectral index smaller than single PL

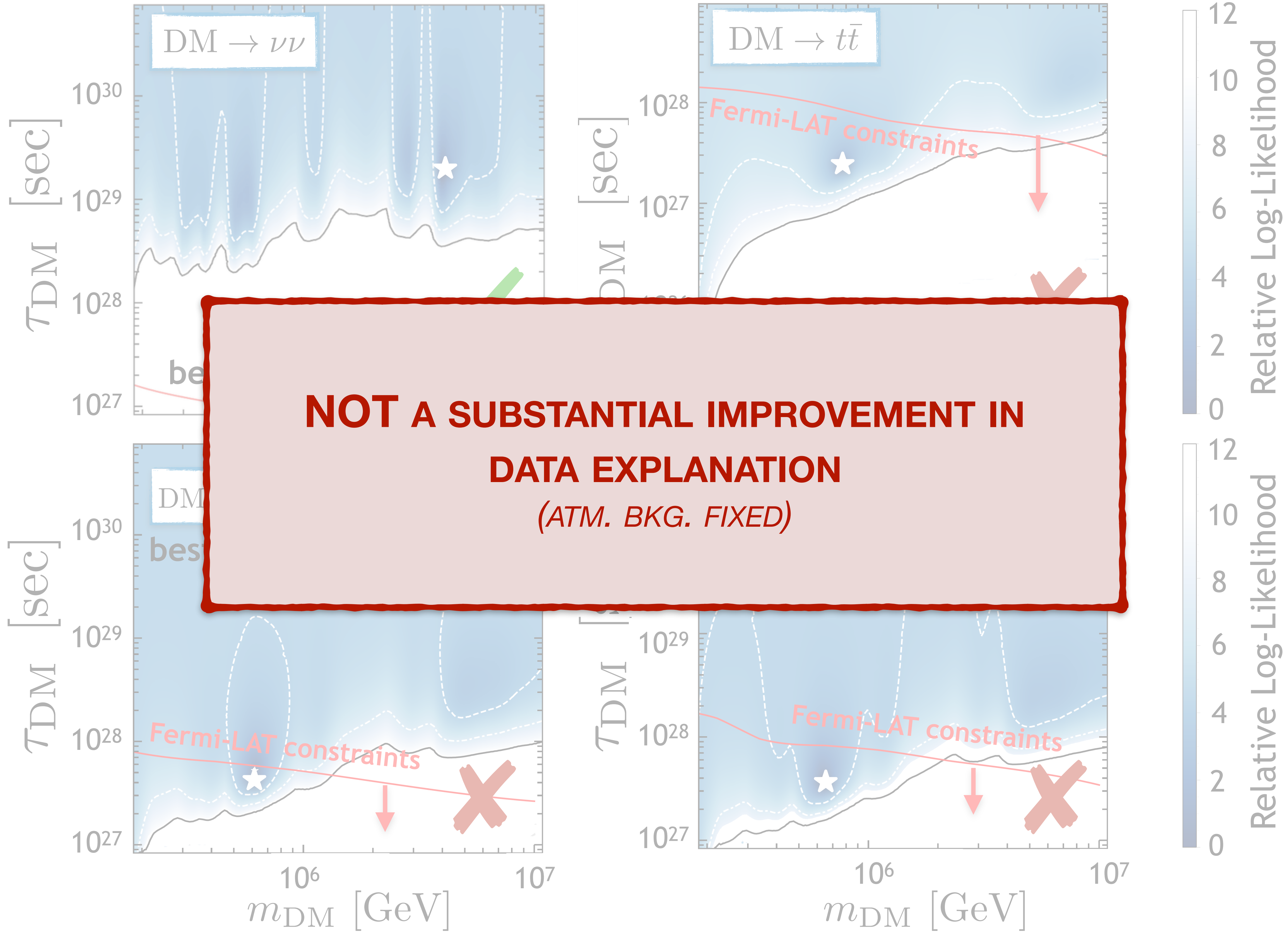
Hadronic/EW boson channels are excluded by Gamma-Rays

*Gamma-rays constraints: Cohen et al., **PRL 119 (2017)**; Blanco and Cooper, **JCAP 1903**; Ishiwata et al., **ariXiv:1907.11671***

Dark Matter parameter space



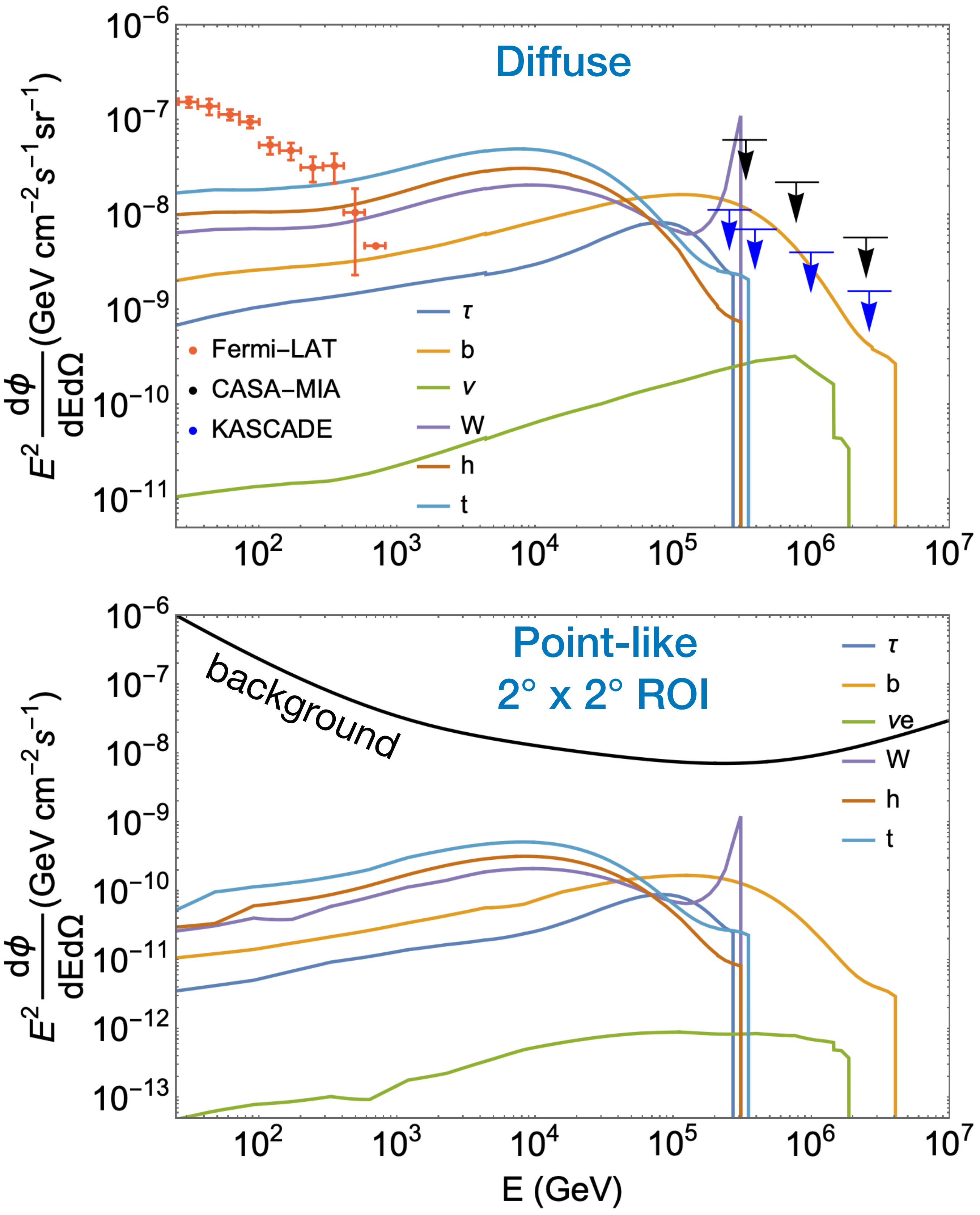
Dark Matter parameter space



NOT A SUBSTANTIAL IMPROVEMENT IN DATA EXPLANATION

(ATM. BKG. FIXED)

Gamma-ray searches



- Diffuse searches provide the strongest constraints on decaying Dark Matter.
- Point-like searches towards the Galactic Center (as CTA) are dominated by background.

CTA sensitivity (50 hours)

already excluded

	Channel	N_σ CTA sensitivity
	$\nu\nu$	0.00066
	$\tau^+\tau^-$	0.046
✗	W^+W^-	0.23
✗	hh	0.35
	$b\bar{b}$	0.11
✗	$t\bar{t}$	0.56

see also: M. Pierre et al., ***JCAP 1410****; Ibarra et al.,* ***JCAP 1509****; CTA,* ***EPJ Web Conf. 209, 01038 (2019)***