Angular power spectrum analysis for dark matter signals at neutrino telescopes

Marco Chianese

4th workshop on Particle Physics with Neutrino Telescopes

7-9 October 2019, Uppsala

- MC, Mele, Miele, Migliozzi, Morisi, **ApJ 851 (2017)**
- MC, Fiorillo, Miele, Morisi, Pisanti, **arXiv:1907.11222**
- Dekker, MC, Ando, **arXiv:1910:xxxxx**

UNIVERSITY OF AMSTERDAM

GRAPPA

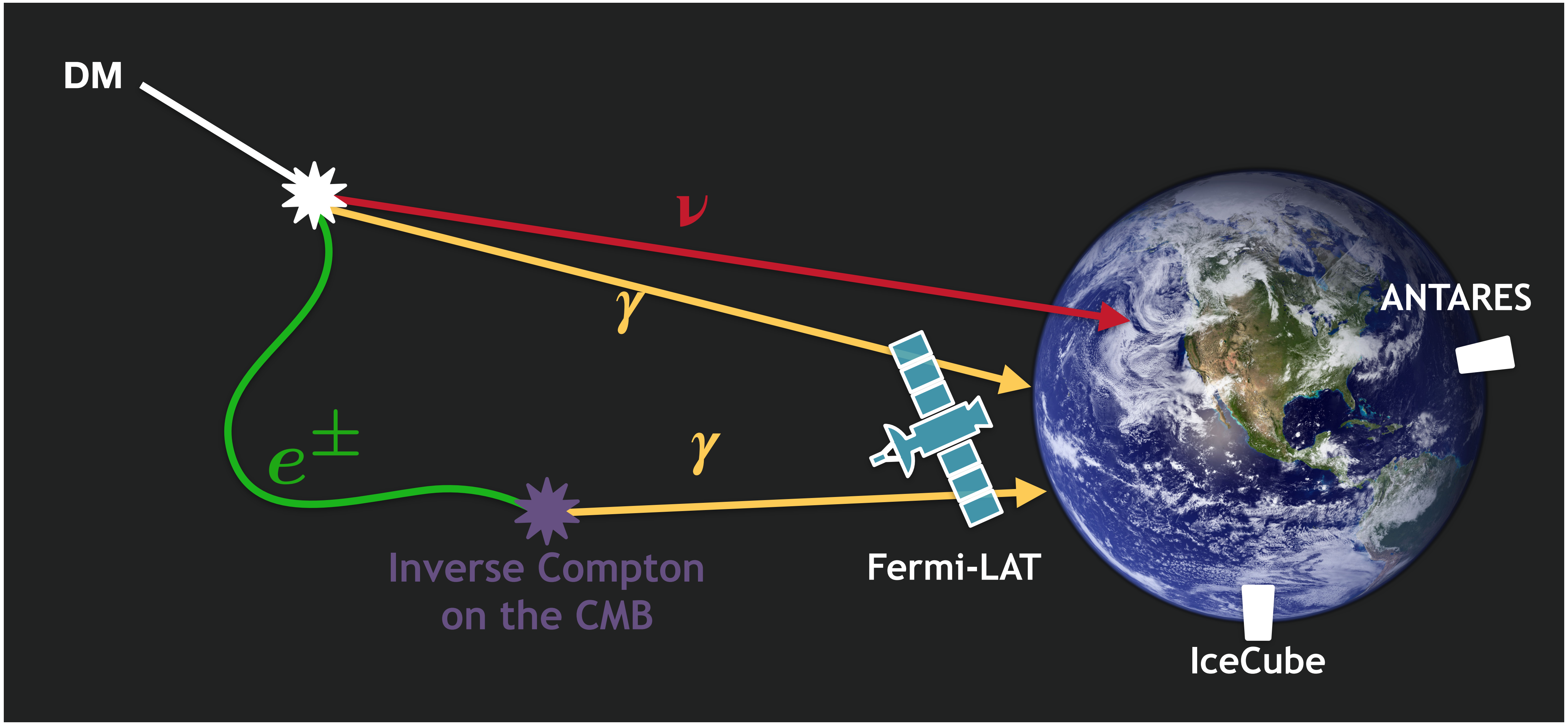
GRavitation AstroParticle Physics Amsterdam

Multi-messenger searches

Dark Matter (DM) particles can decay/annihilate producing:

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

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



Latest neutrino data @ ICRC 2019

High Energy Starting Events (HESE)

- Full sky
- High energy threshold

Schneider,
PoS ICRC2019 1004

Through-going muon neutrinos (TG)

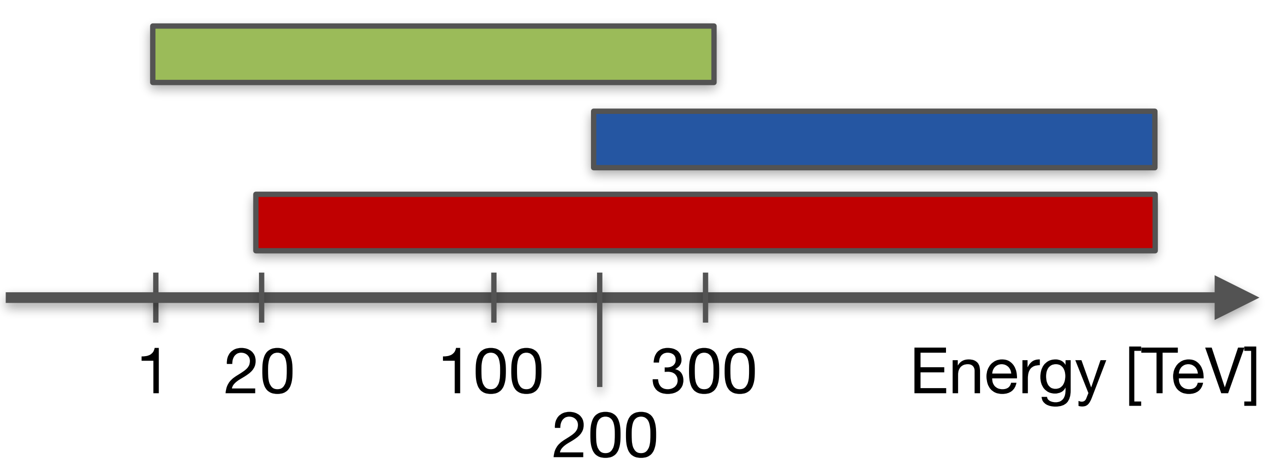
- Northern sky only
- Very high energy threshold

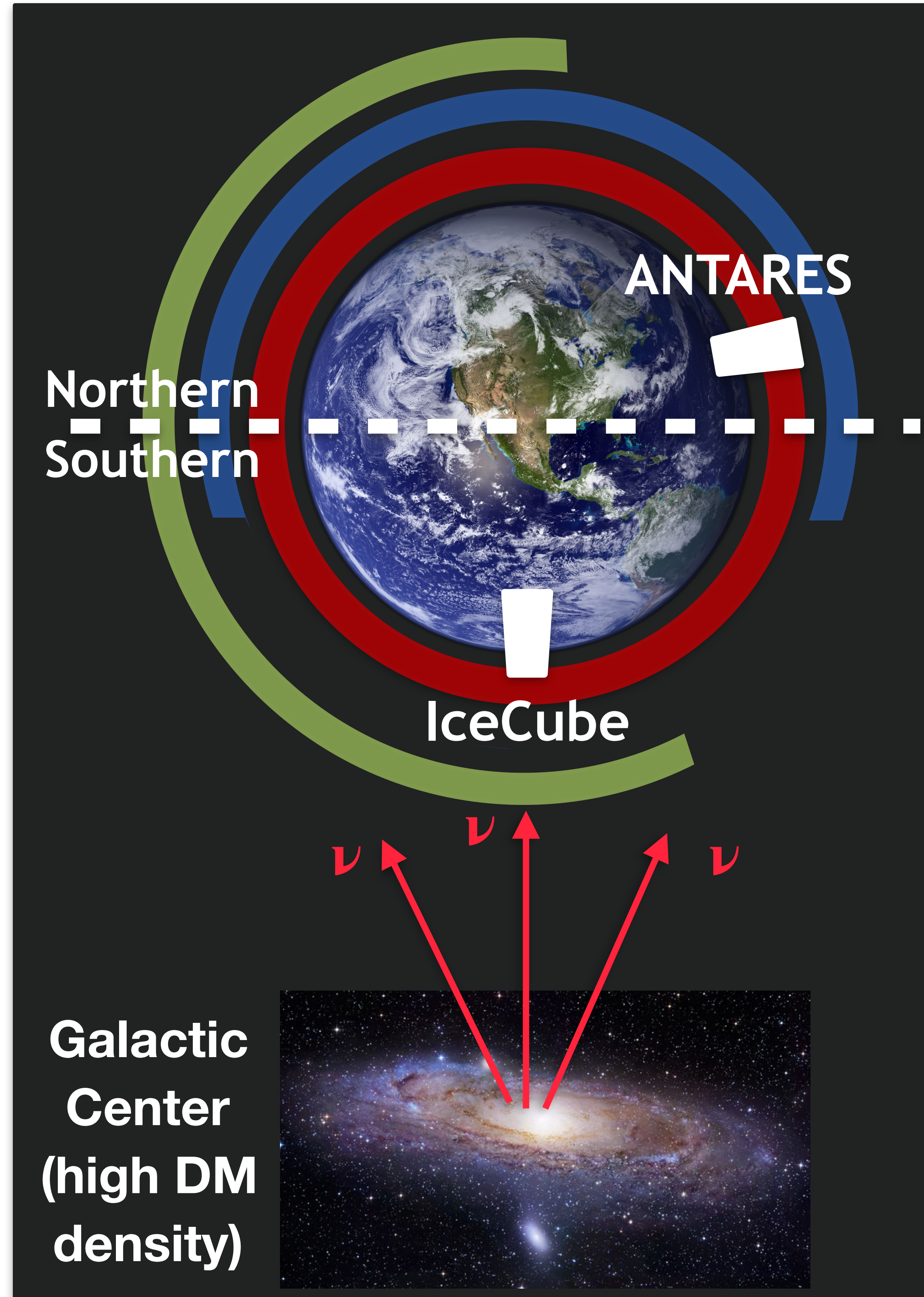
Stettner,
PoS ICRC2019 1017

ANTARES showers and tracks

- 33 events in 9 years
- 50 events in 11 years
- Energy up to ~ 300 TeV

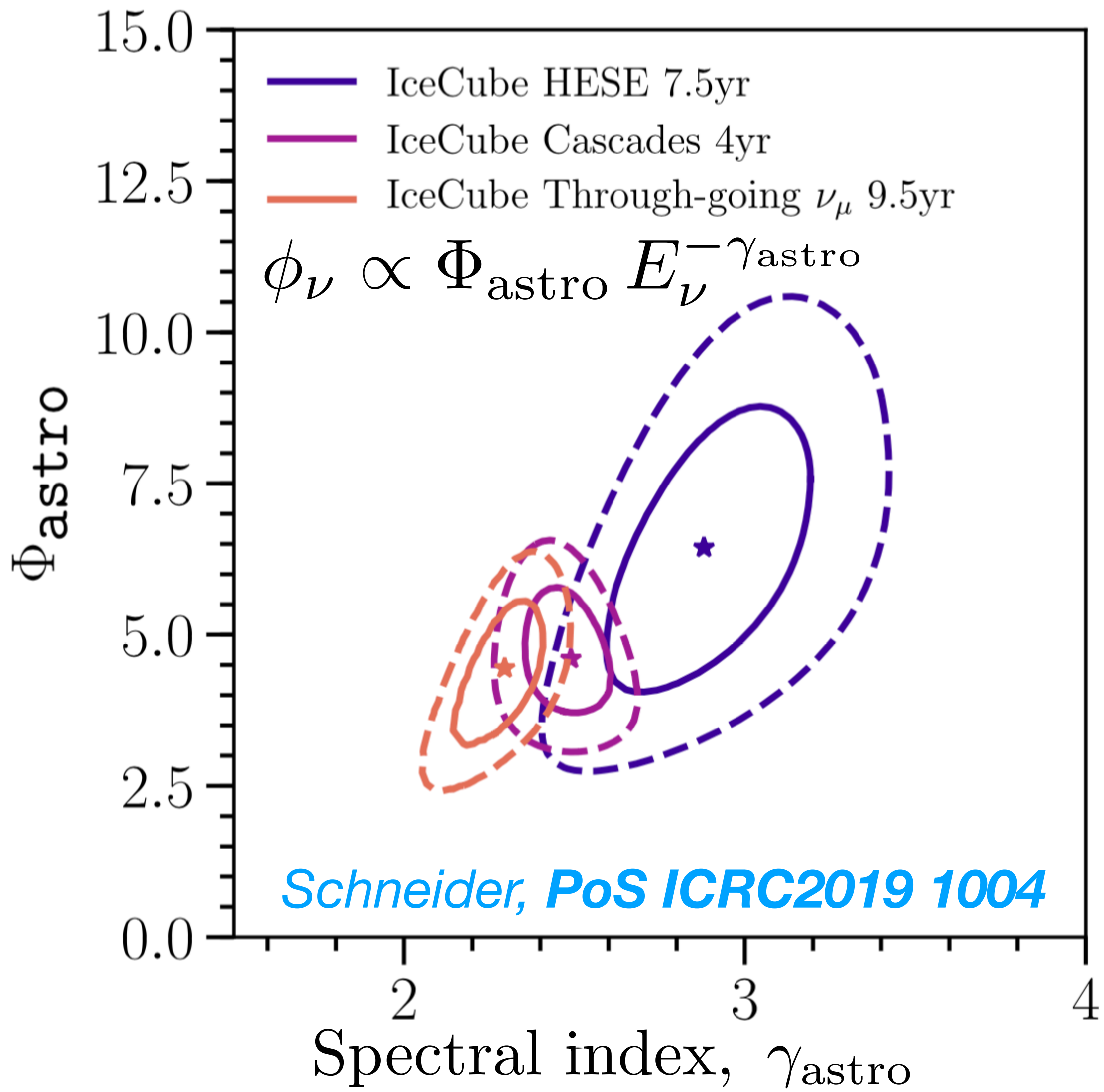
Fusco,
PoS ICRC2019 1177



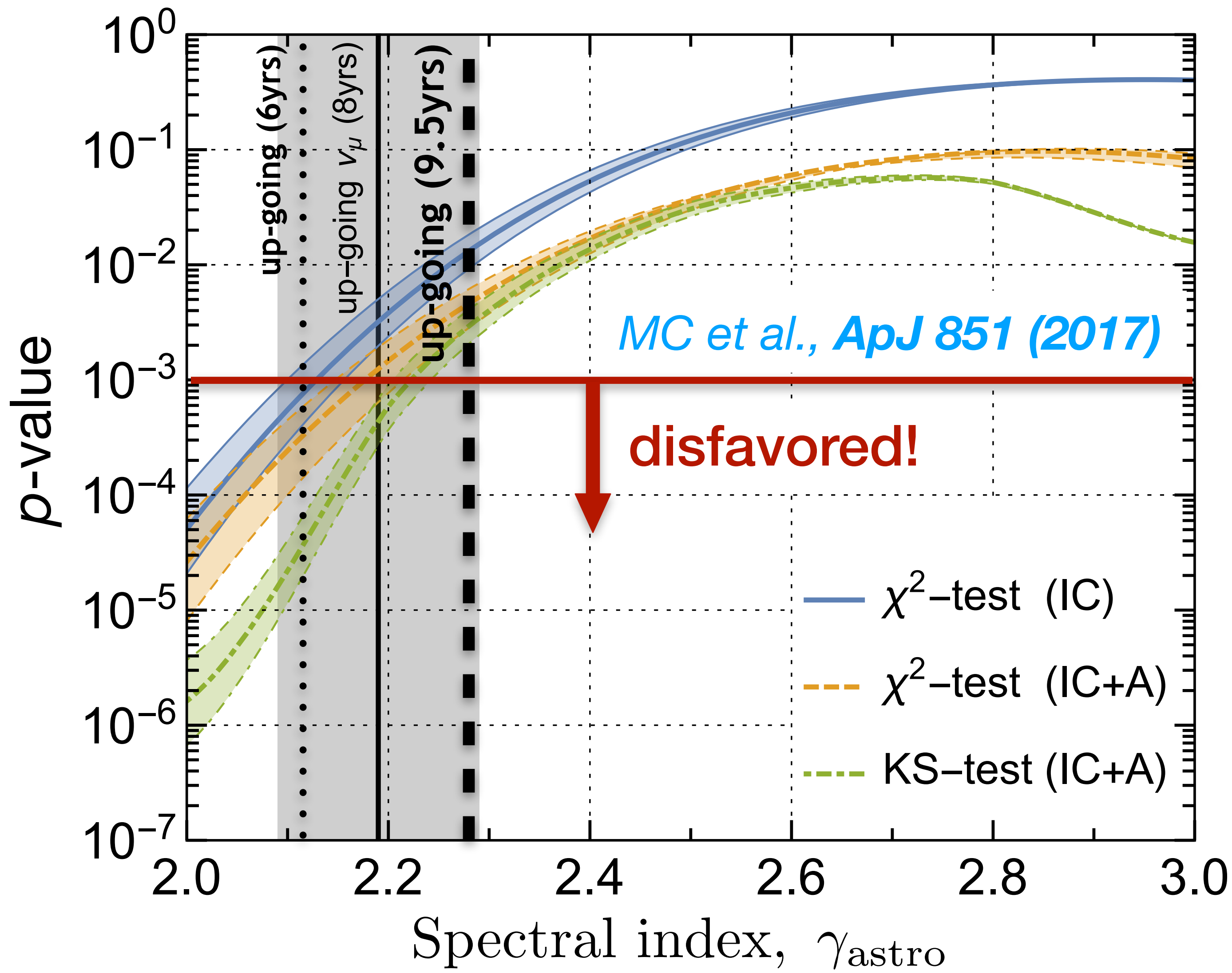


Tension with a single power-law

IceCube



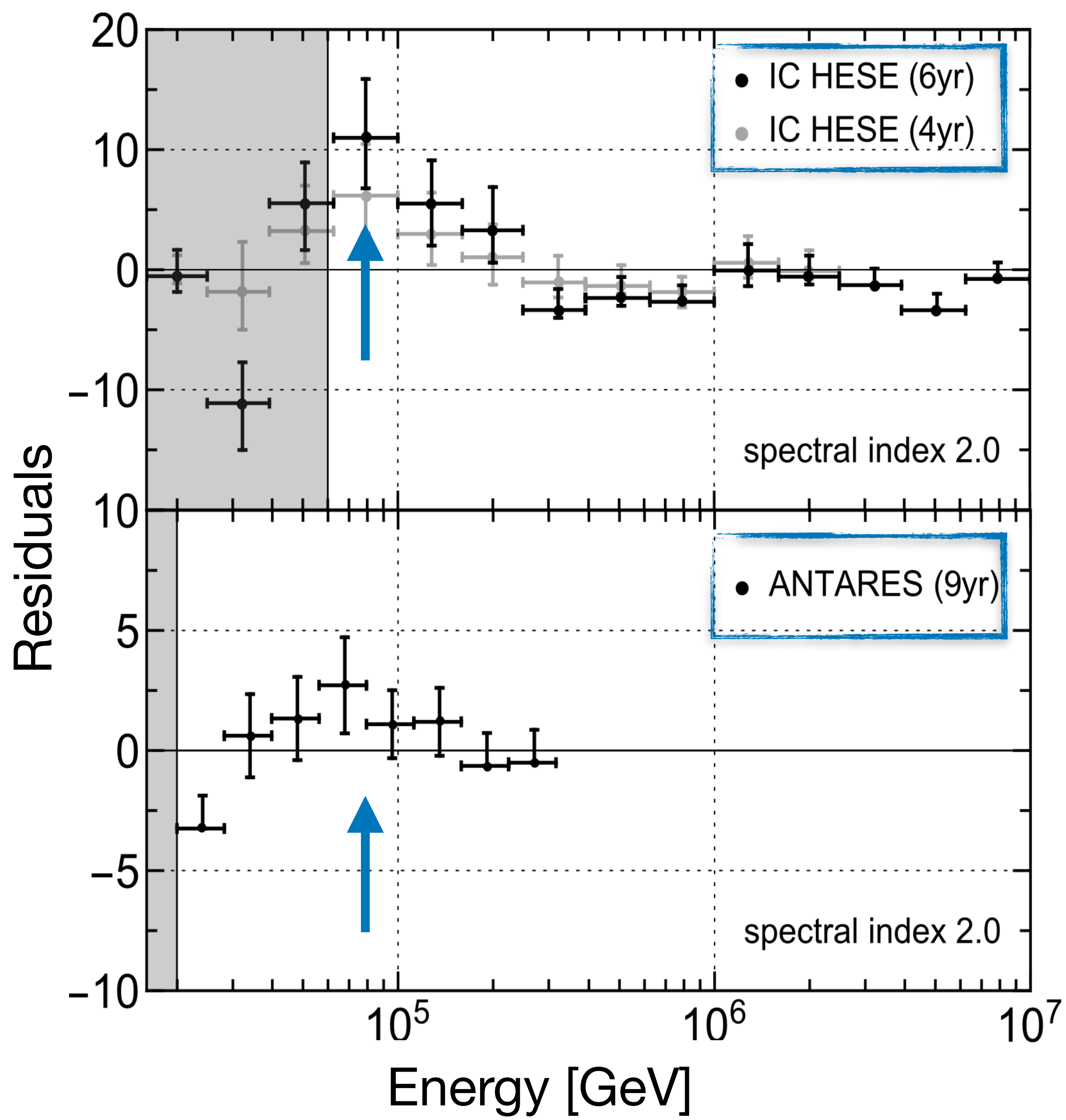
IceCube + ANTARES (our work)



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

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

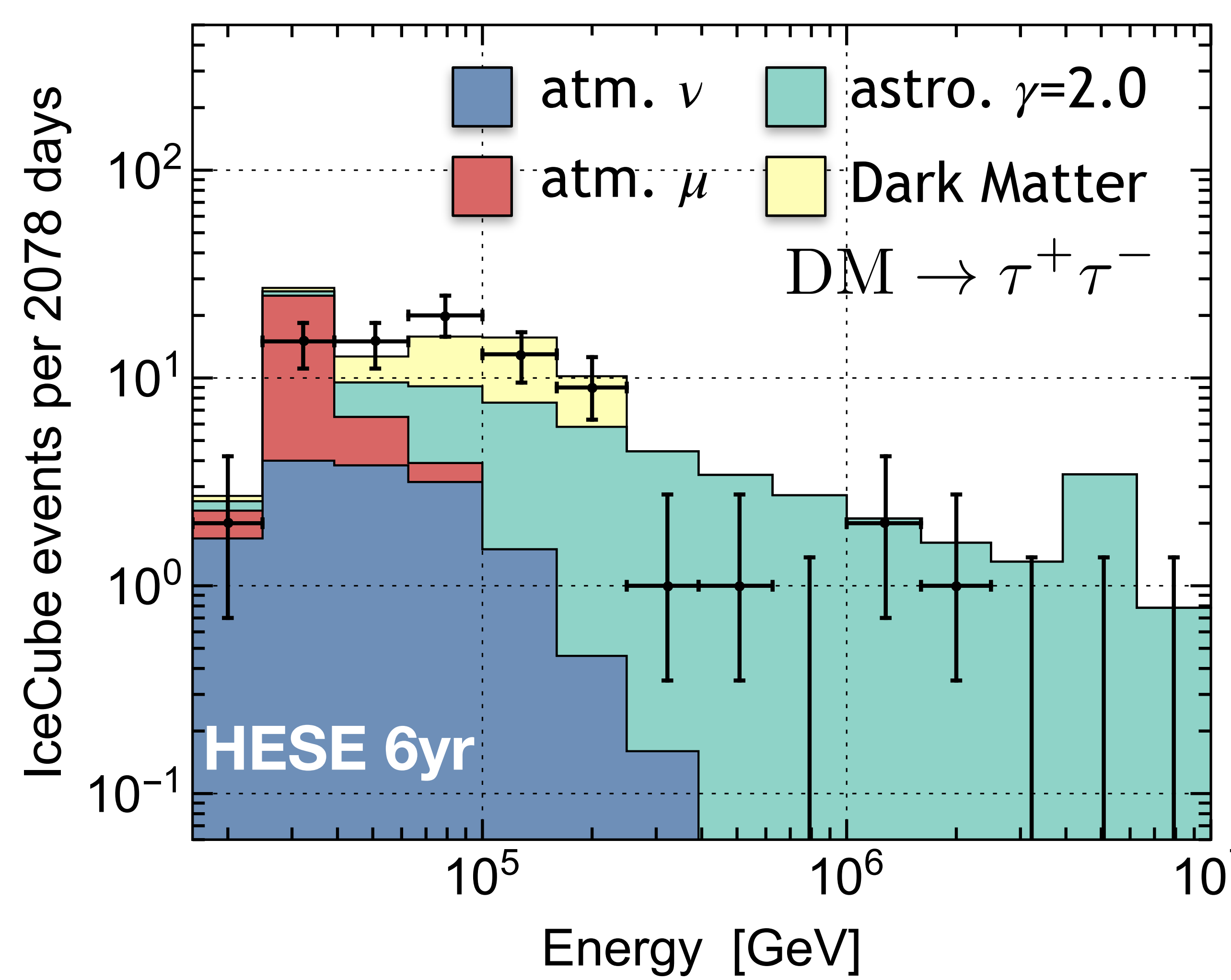
The low energy excess



Residuals w.r.t. an astrophysical power-law with spectral index 2.0:

- Fermi mechanism
- Through-going IceCube data
- Compatible with gamma-rays

Heavy Dark Matter at 100 TeV?



*MC, Miele, Morisi, Vitagliano, **PLB 757 (2016)***
*MC, Mele, Miele, Migliozzi, Morisi, **ApJ 851 (2017)***
*MC, Miele, Morisi, **PLB 773 (2017)***

Decaying Dark Matter flux

GALACTIC

$$\frac{d\phi^{DM}_{gal.}}{dE\,d\Omega} = \frac{1}{4\pi\, m_{DM}\, \tau_{DM}} \frac{dN_\nu}{dE} \int ds\, \rho\,(s,l,b)$$

EXTRA-GALACTIC

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

- *Different final states:*

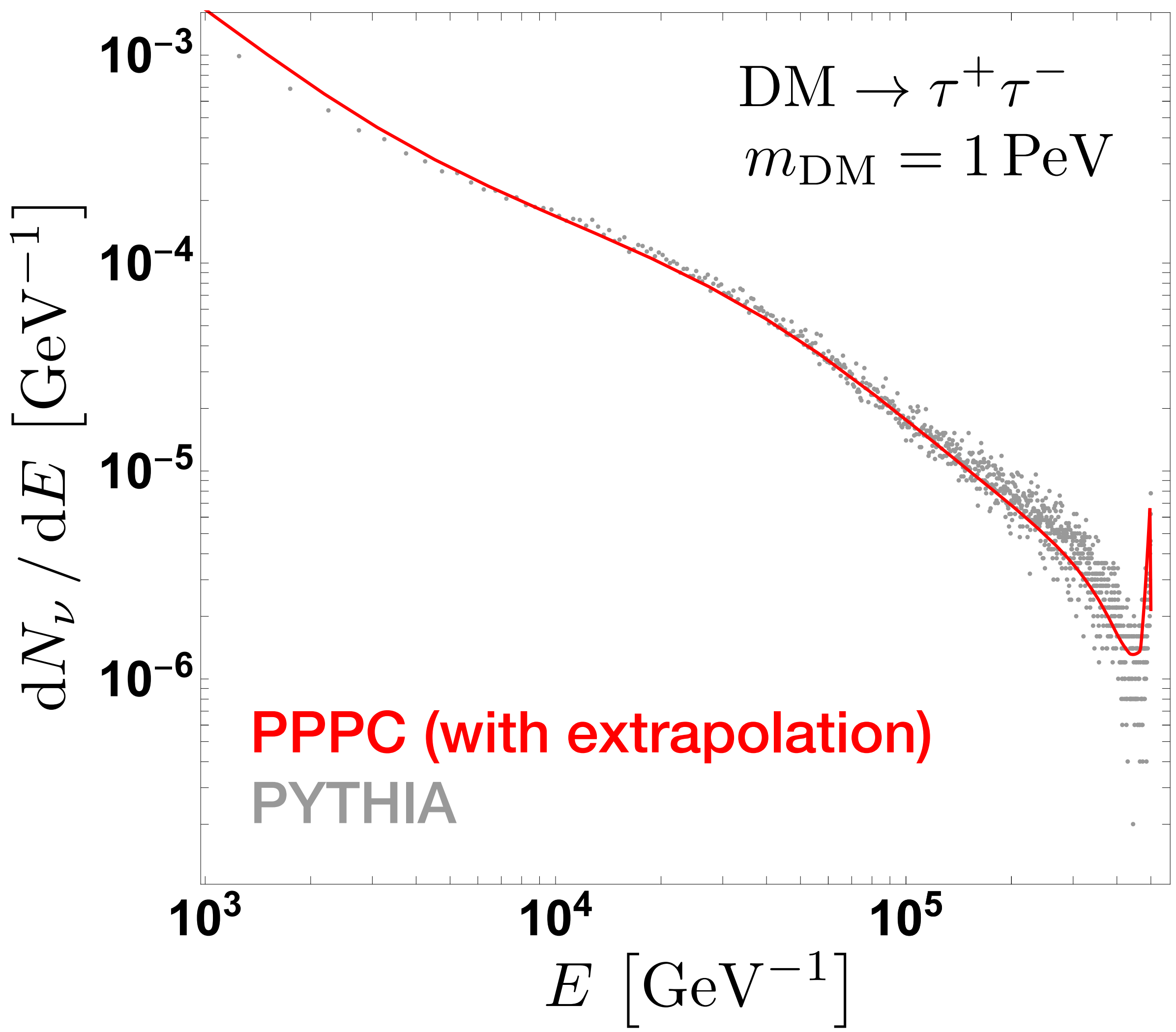
$DM \to \ell\bar{\ell}, \nu\nu$ leptophilic

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

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

Electroweak corrections are important!

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



Fit of neutrino energy spectrum

OUR HYPOTHESIS

(TWO-COMPONENT FLUX)

$$\frac{\mathrm{d}\phi^{\mathrm{signal}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} = \frac{\mathrm{d}\phi^{\mathrm{Astro}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} + \frac{\mathrm{d}\phi^{\mathrm{DM}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}$$

$A_{\mathrm{eff}}\left(E_\nu, \Omega\right)$

HESE effective area

In each bin of deposited energy:

- $\mu = N_T + N_S + N_{NC}$

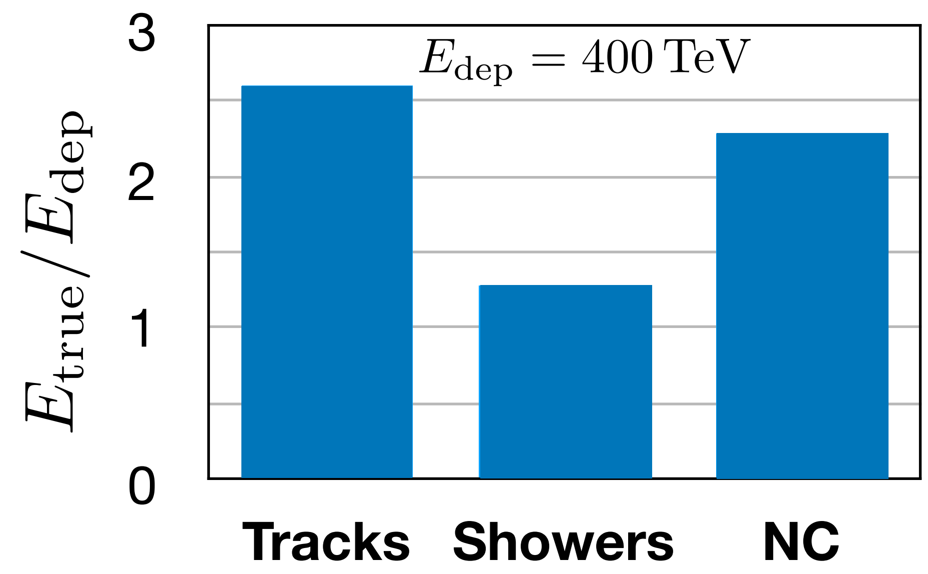
  Palladino et al., ***PRL 114 (2015)***

- $b = \mathrm{atm.\ background}$
- $n = \mathrm{HESE\ data}$

  Schneider, ***PoS ICRC2019 1004***

fit

True *vs* Deposited neutrino energy



Ruiz, Vincent, Mena, ***PRD 91 (2015)***

D'Amico, ***Astropart.Phys. 101 (2018)***

Maximum Likelihood

$$\mathcal{L} = \prod_i (\mu_i + b_i)^{n_i} \frac{e^{-(\mu_i + b_i)}}{n_i!}$$

with 4 free parameters

$\Phi_{\mathrm{astro}},\ \gamma_{\mathrm{astro}},\ m_{\mathrm{DM}},\ \tau_{\mathrm{DM}}$

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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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

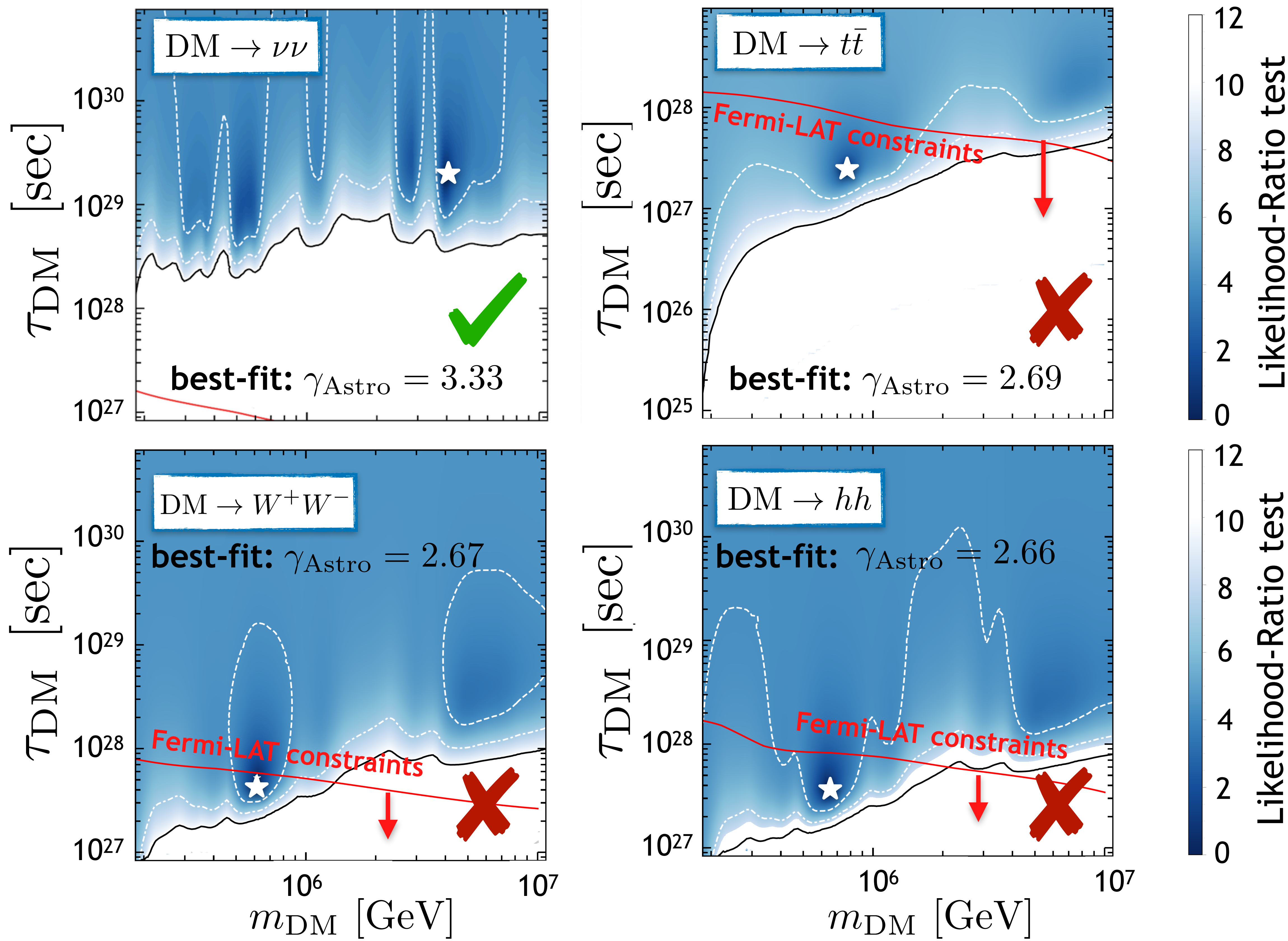
Spectral index larger than single PL

Spectral index smaller than single PL

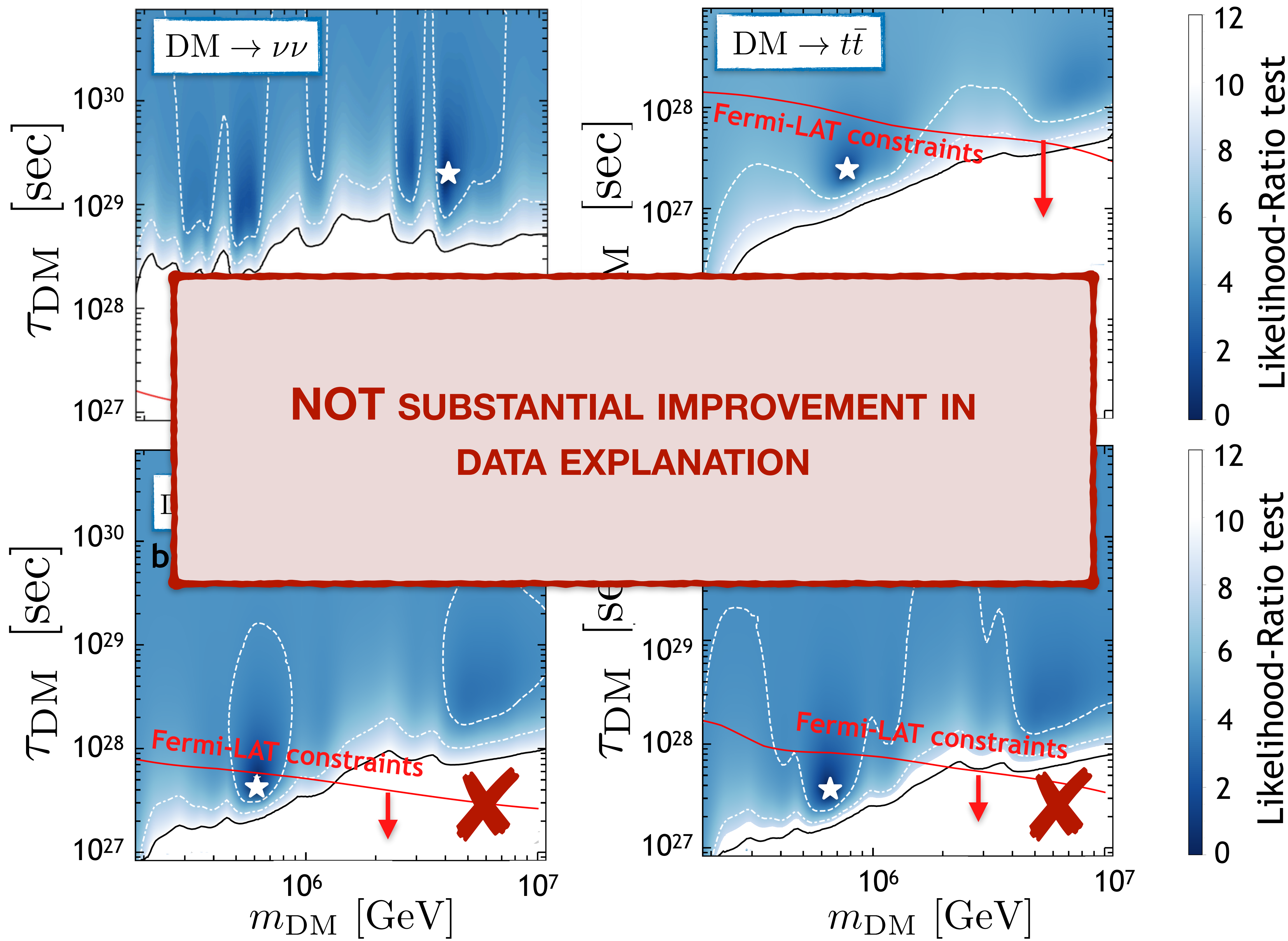
Hadronic/EW boson channels are excluded by Gamma-Rays

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

Dark Matter parameter space

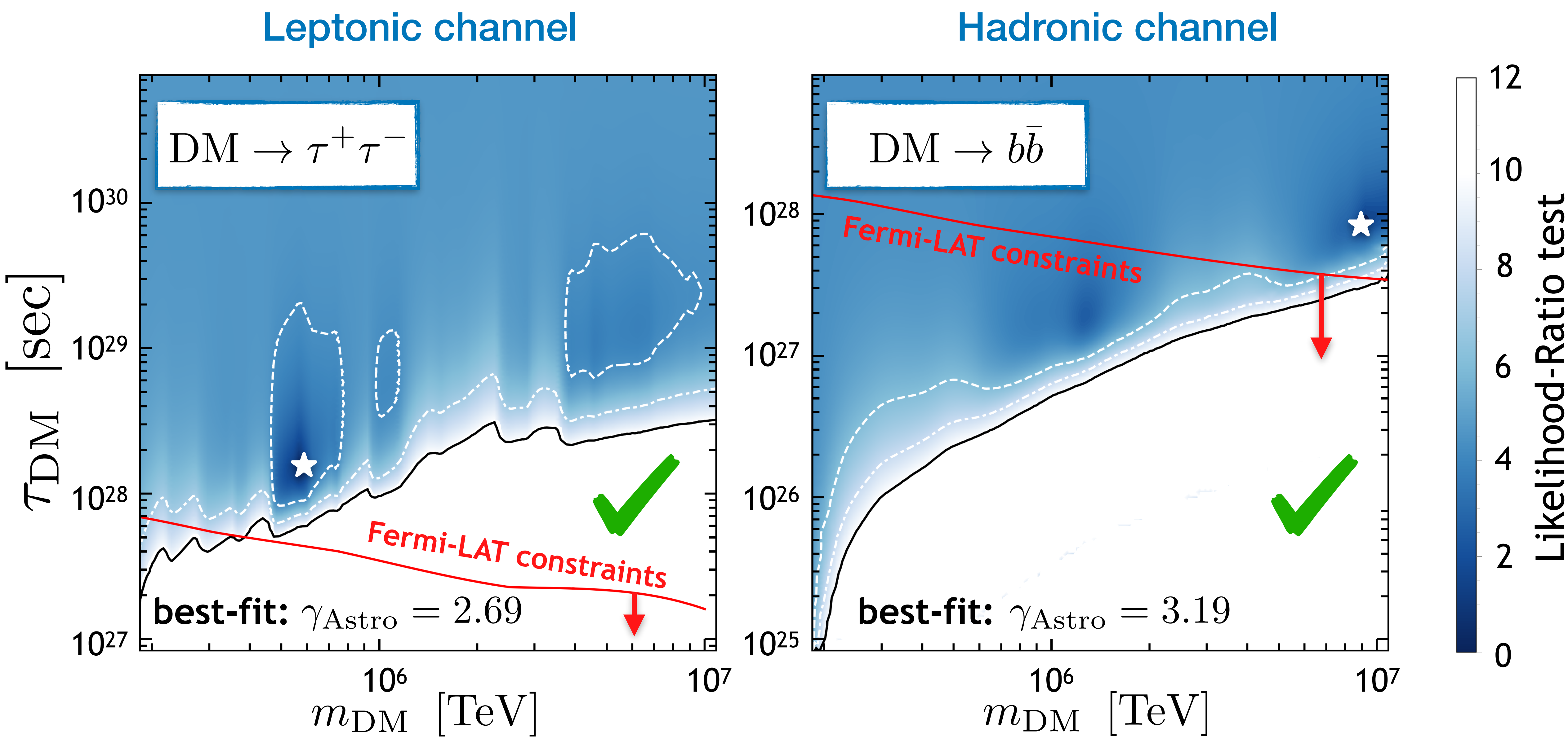


Dark Matter parameter space



NOT SUBSTANTIAL IMPROVEMENT IN DATA EXPLANATION

Dark Matter parameter space



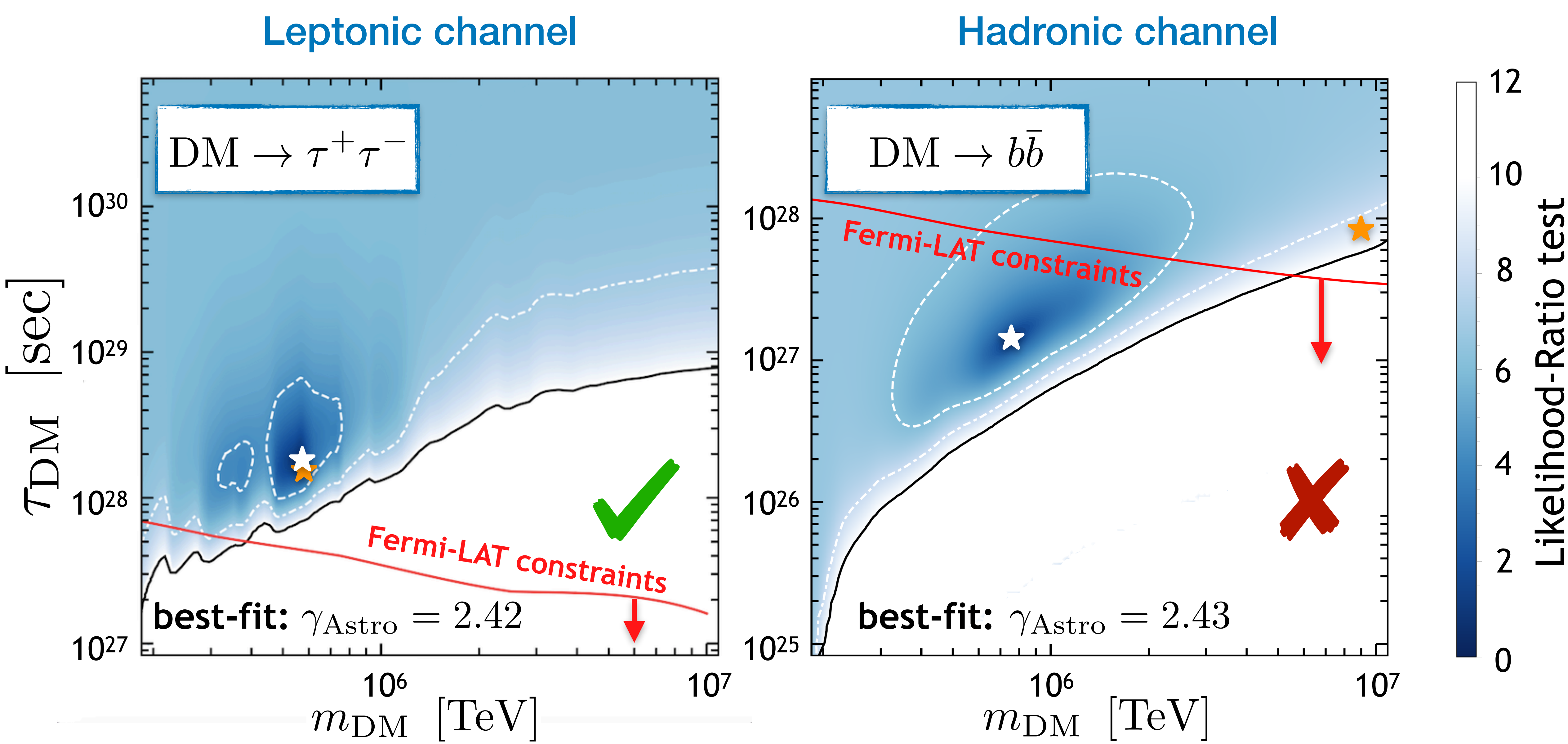
Astrophysical parameters
as nuisance parameters

→

<u>WITHOUT</u> **PRIOR**

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

Dark Matter parameter space

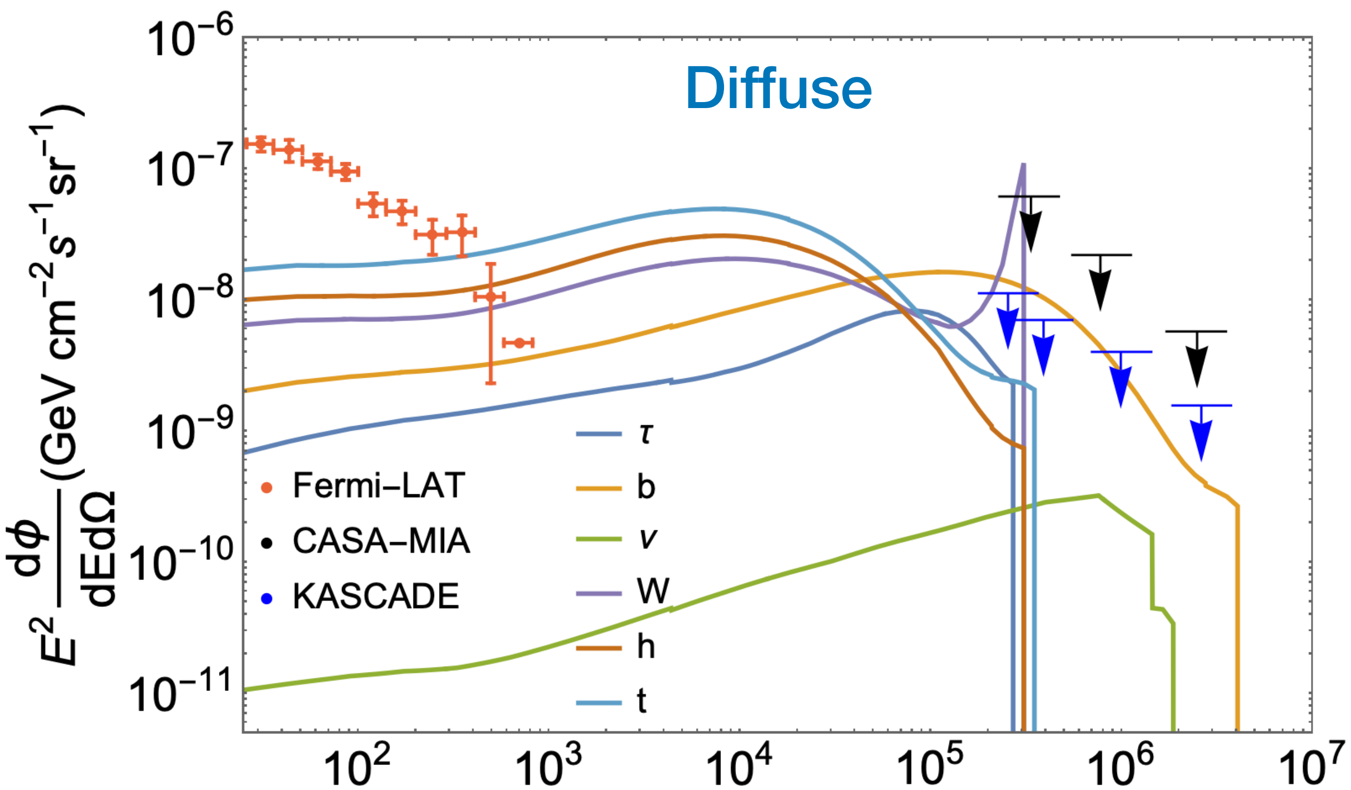


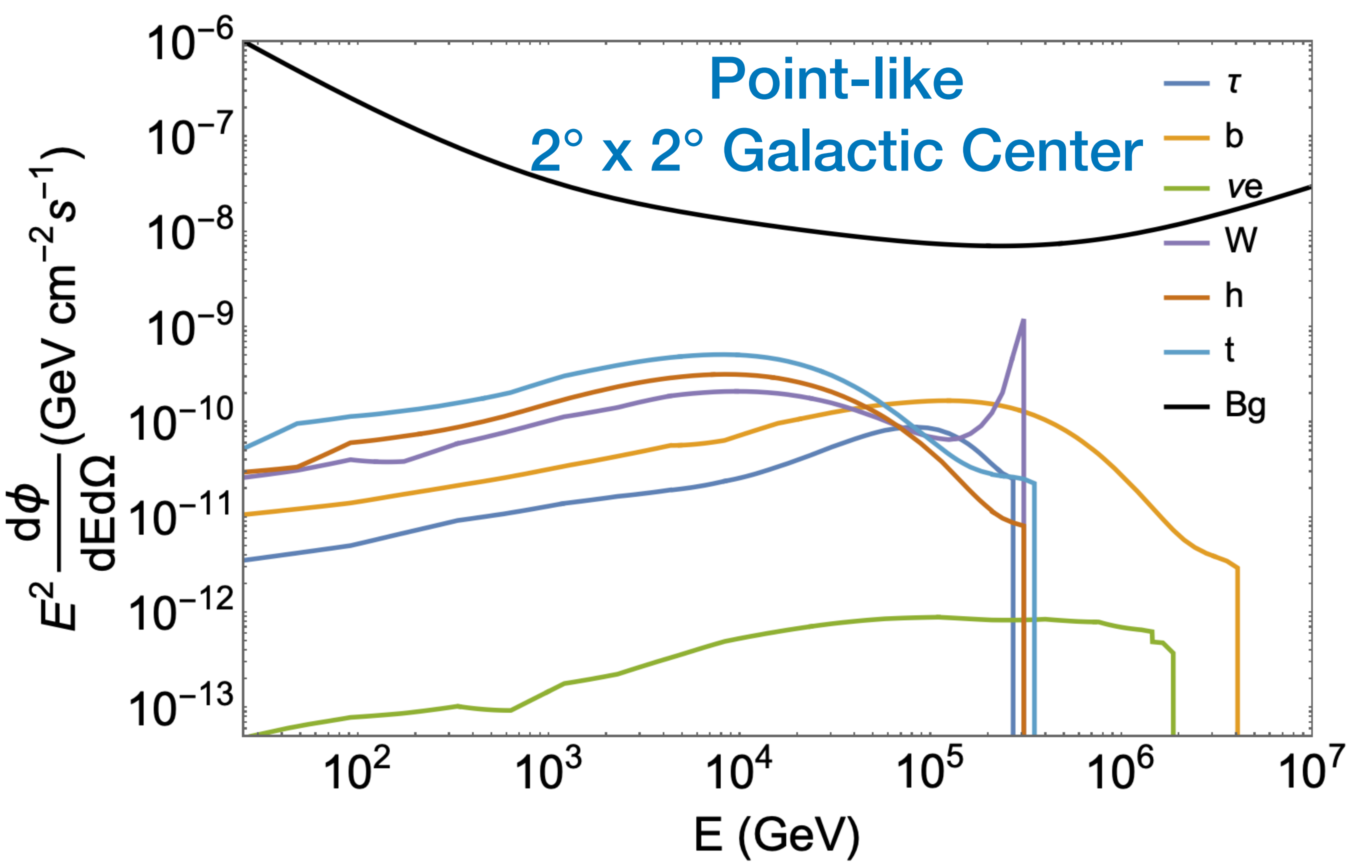
Astrophysical parameters as nuisance parameters → ***WITH* TG PRIOR**

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

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

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)

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

already excluded (✘)

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

Anisotropy of Dark Matter flux

Decay — Galactic

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

Decay — Extra-Galactic

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

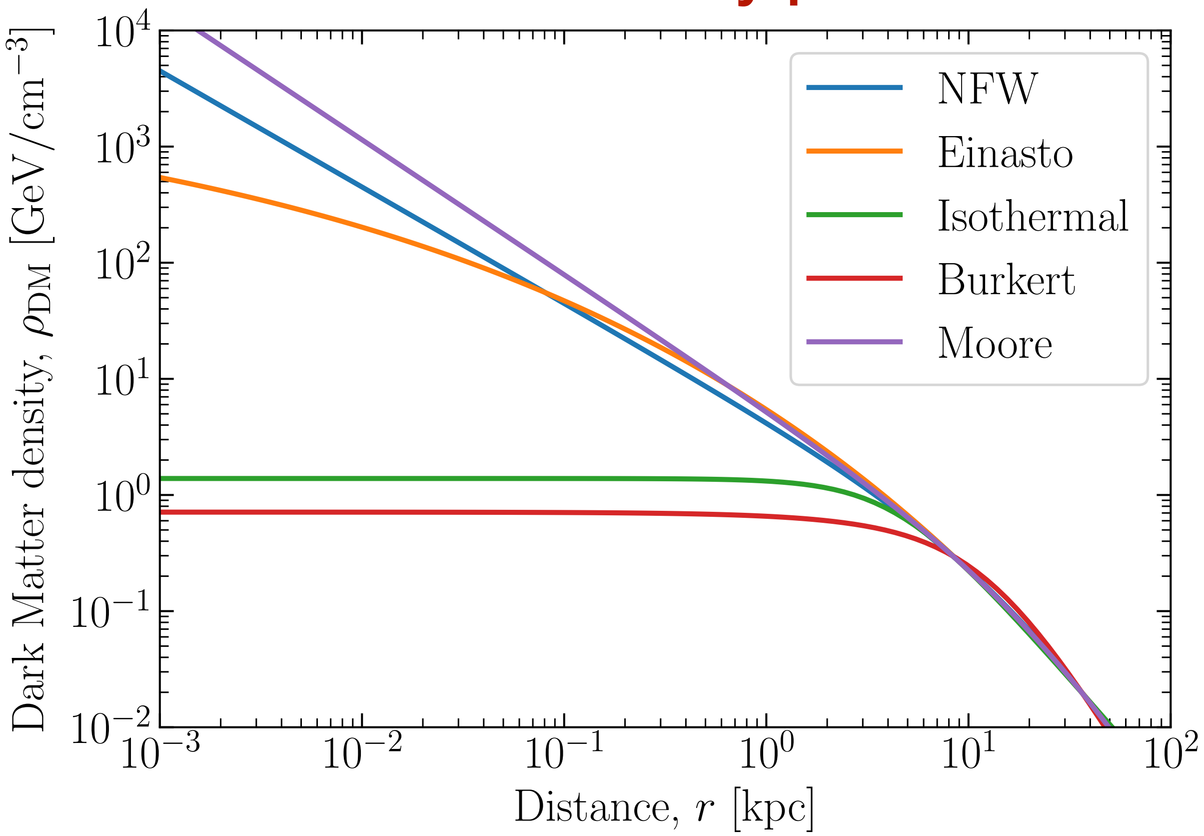
Annihilation — Galactic

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

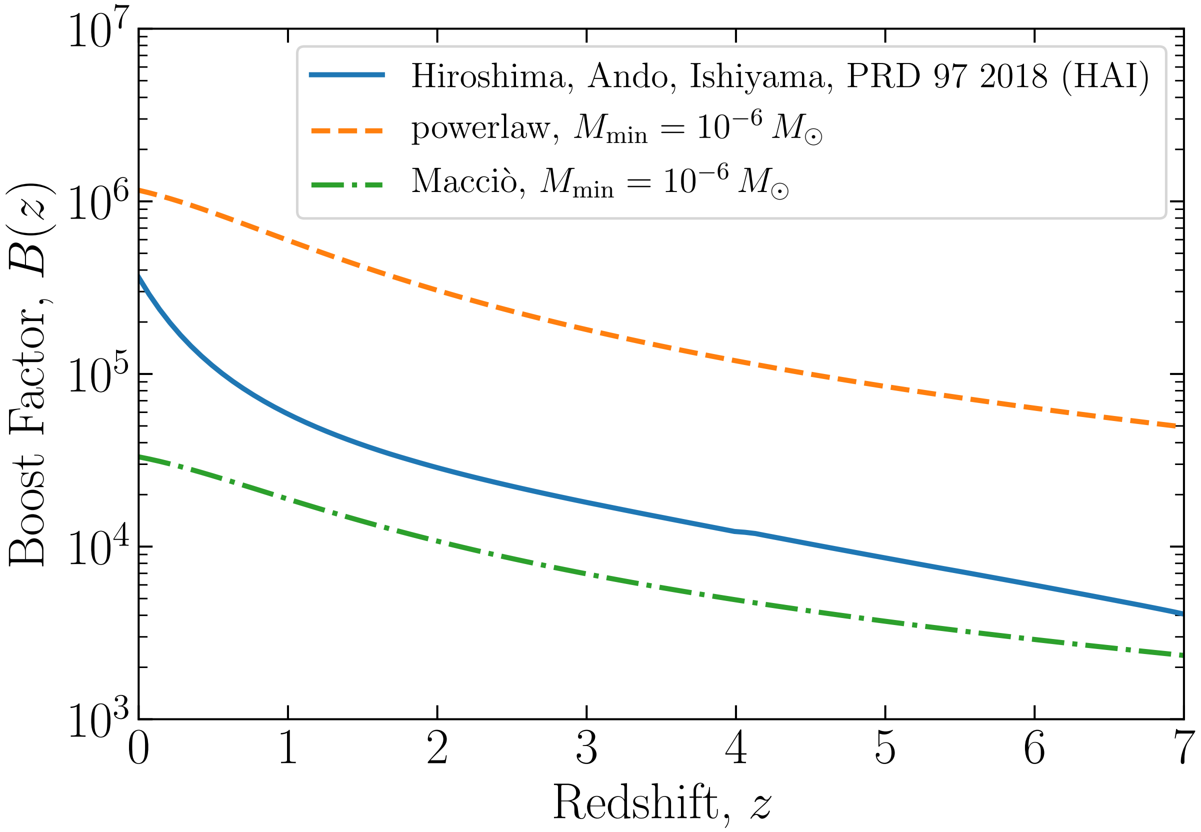
Annihilation — Extra-Galactic

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

DM halo density profile



DM boost factor



Anisotropy crucial for DM discrimination

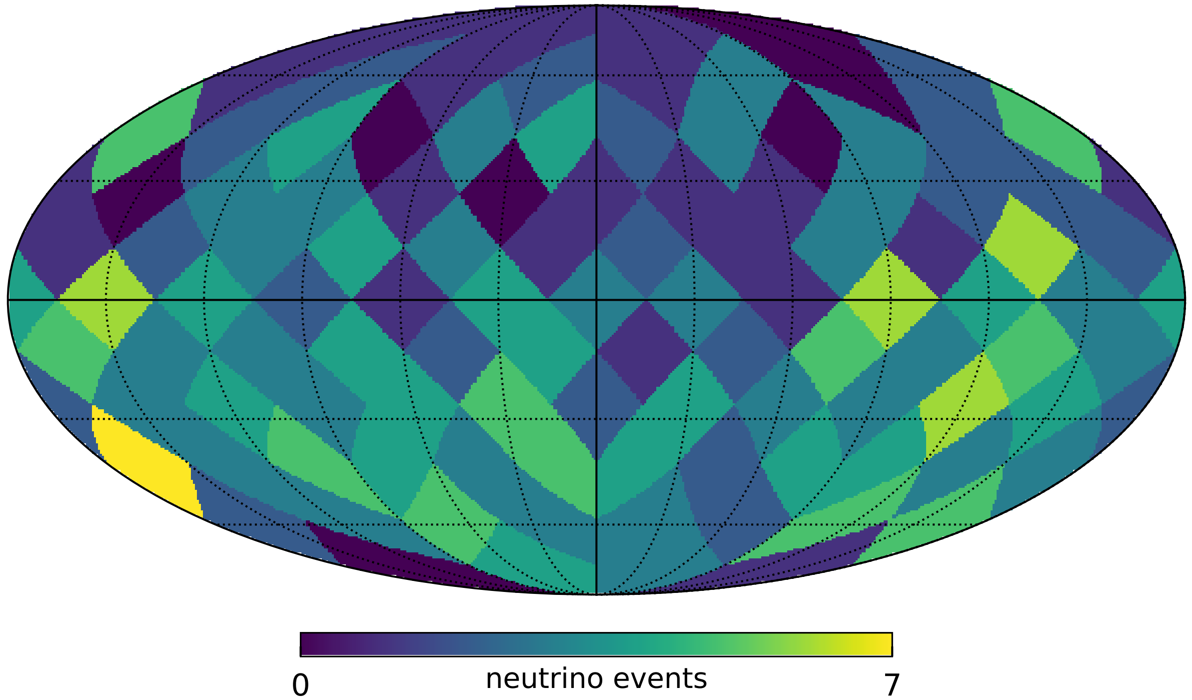
Forecast Analysis

Null hypothesis	‣ **Isotropic astrophysical flux:** 7.5-yr HESE $$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = \frac{6.45}{3} \cdot \left(\frac{E}{100\text{TeV}}\right)^{-2.89} \cdot 10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$
Model	‣ **Isotropic astrophysical flux:** 10-yr Through-going $$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = 1.44 \cdot \left(\frac{E}{100\text{TeV}}\right)^{-2.28} \cdot 10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$ ‣ **Dark matter flux** $$N_{\text{tot}}(\theta, \phi) = \underbrace{N_{\text{atm.}} + N_{\text{astro}} + N_{\text{DM, ext.gal.}}}_{\text{Nearly-isotropic above 60 TeV}} + \underbrace{N_{\text{DM, gal.}}}_{\text{Anisotropic}}$$ *(integrated over energy with effective area)*

Monte Carlo simulations to generate sky maps

Sky maps from MC

NULL HYPOTHESIS (ASTRO)

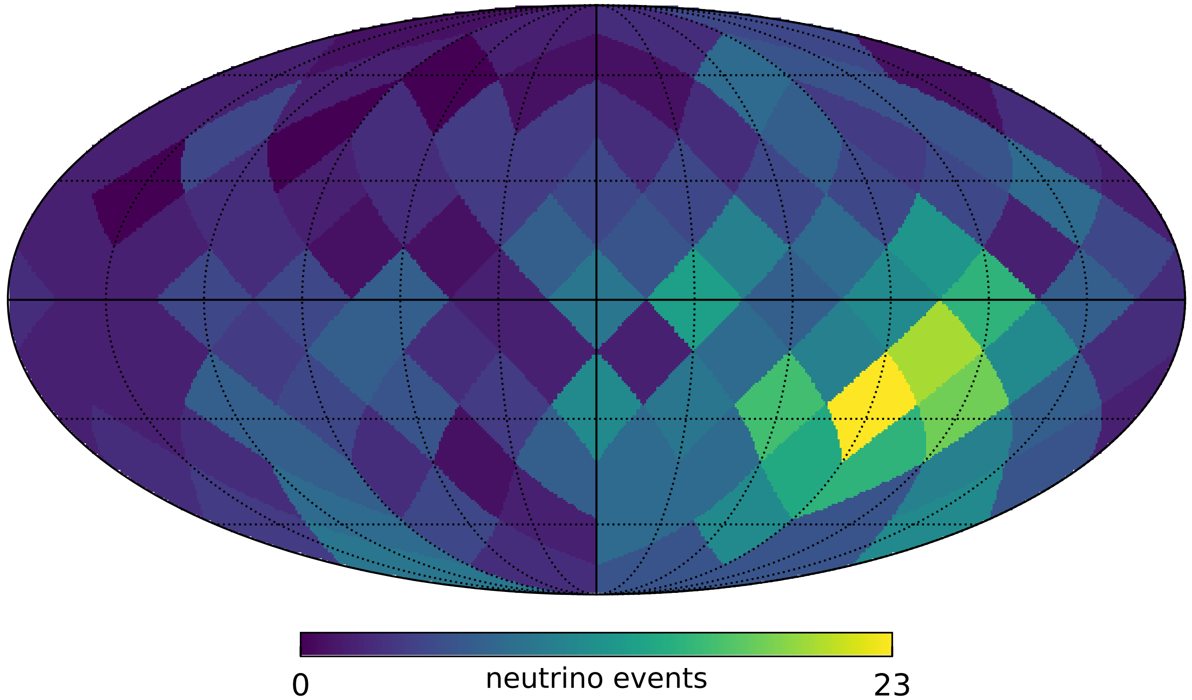


Angular Power Spectrum

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

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

MODEL (ASTRO + DEC. DM)



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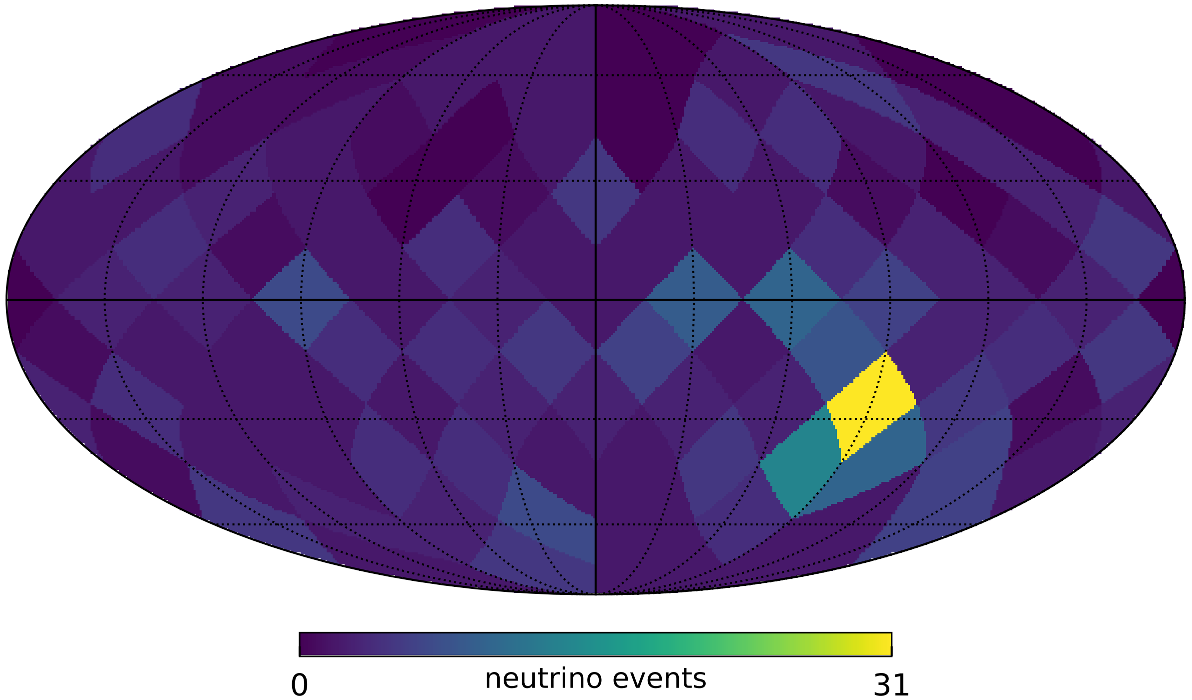
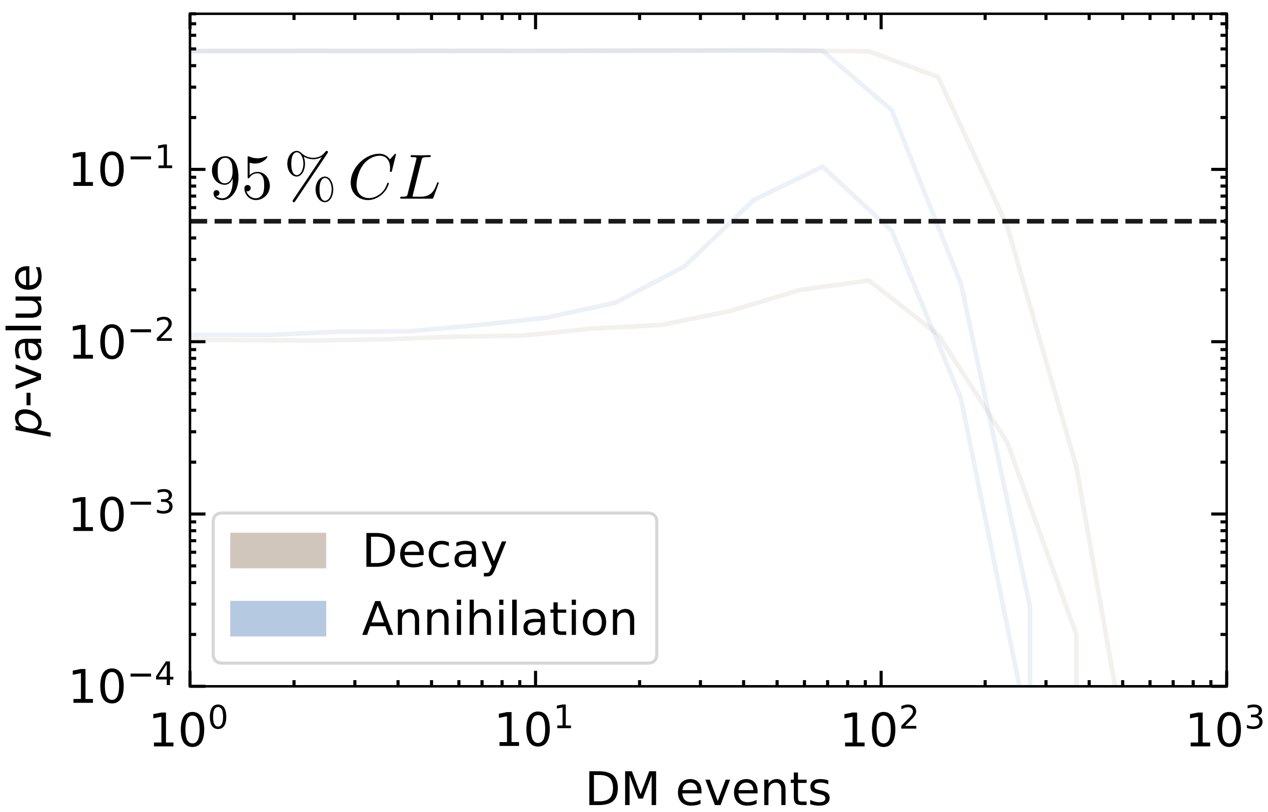


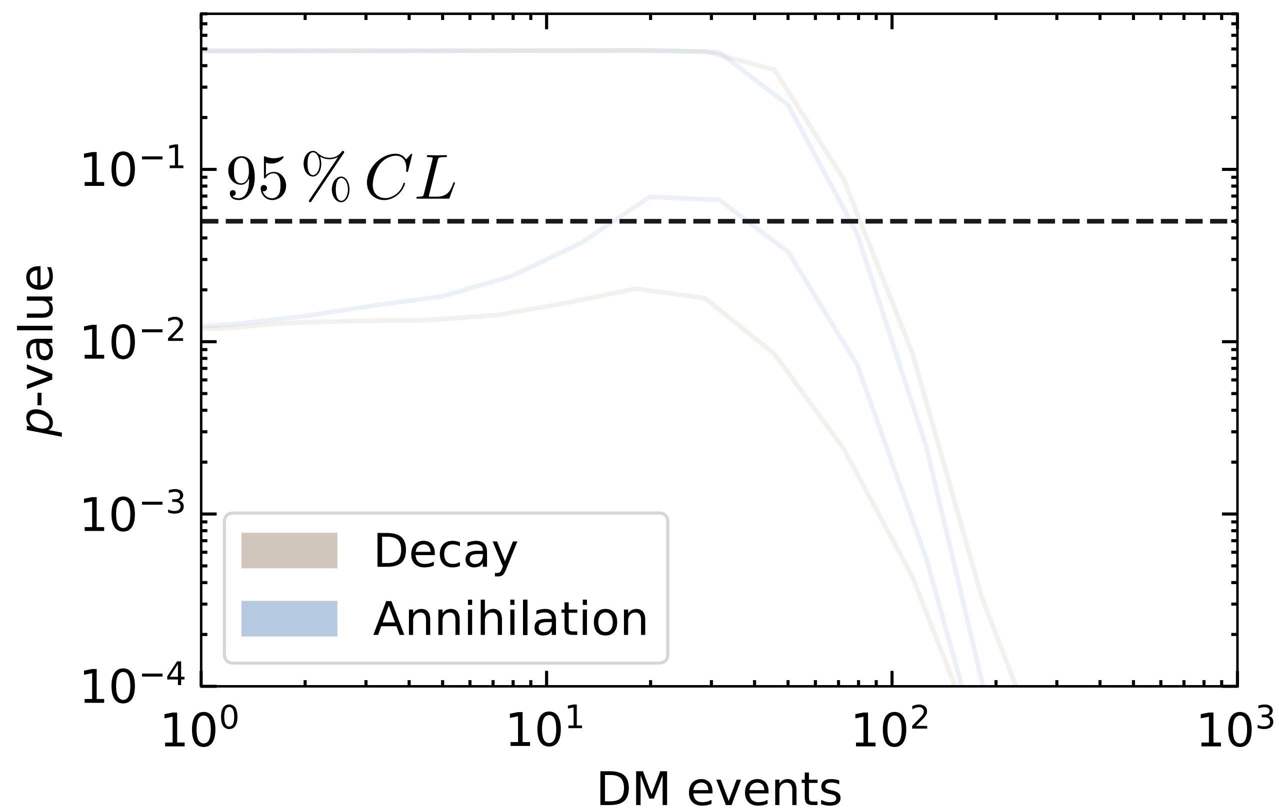
10-yr IceCube-gen2

P-values - 10 years

IceCube-Gen2



KM3NeT

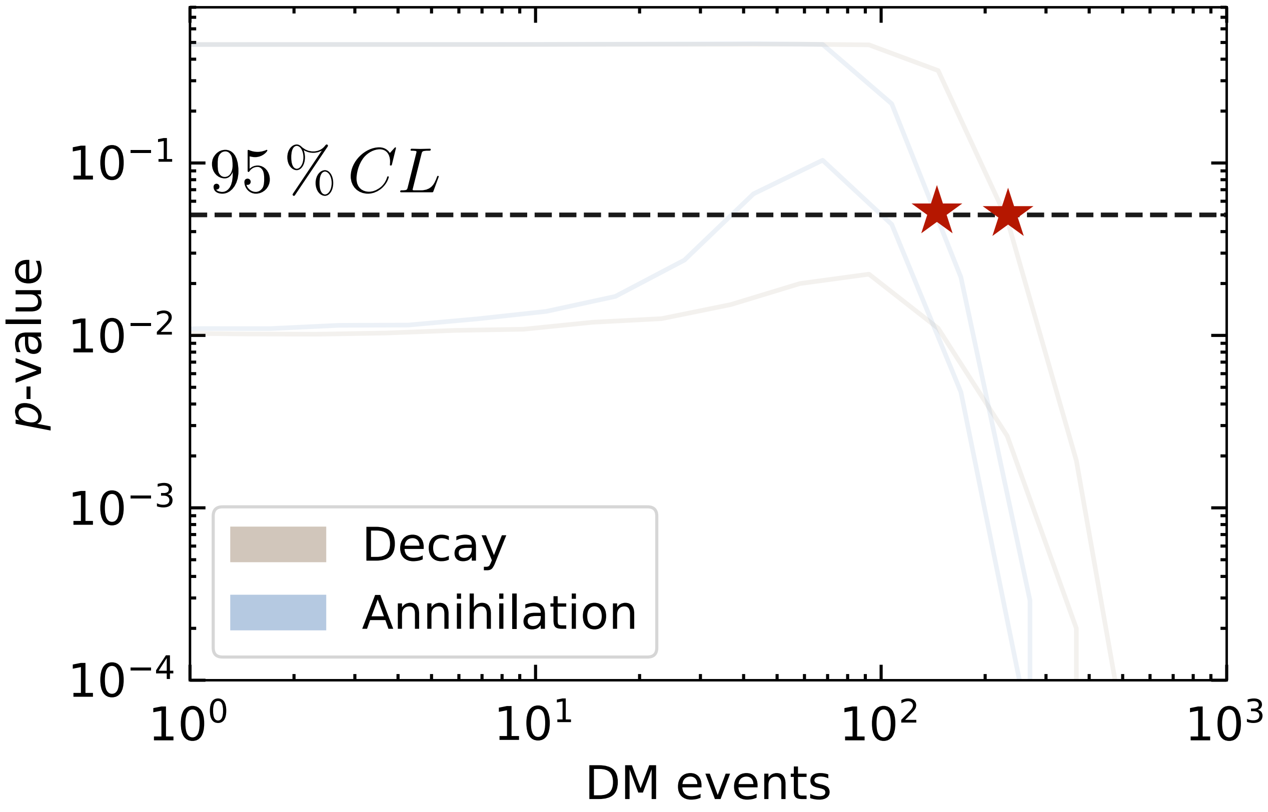


Model

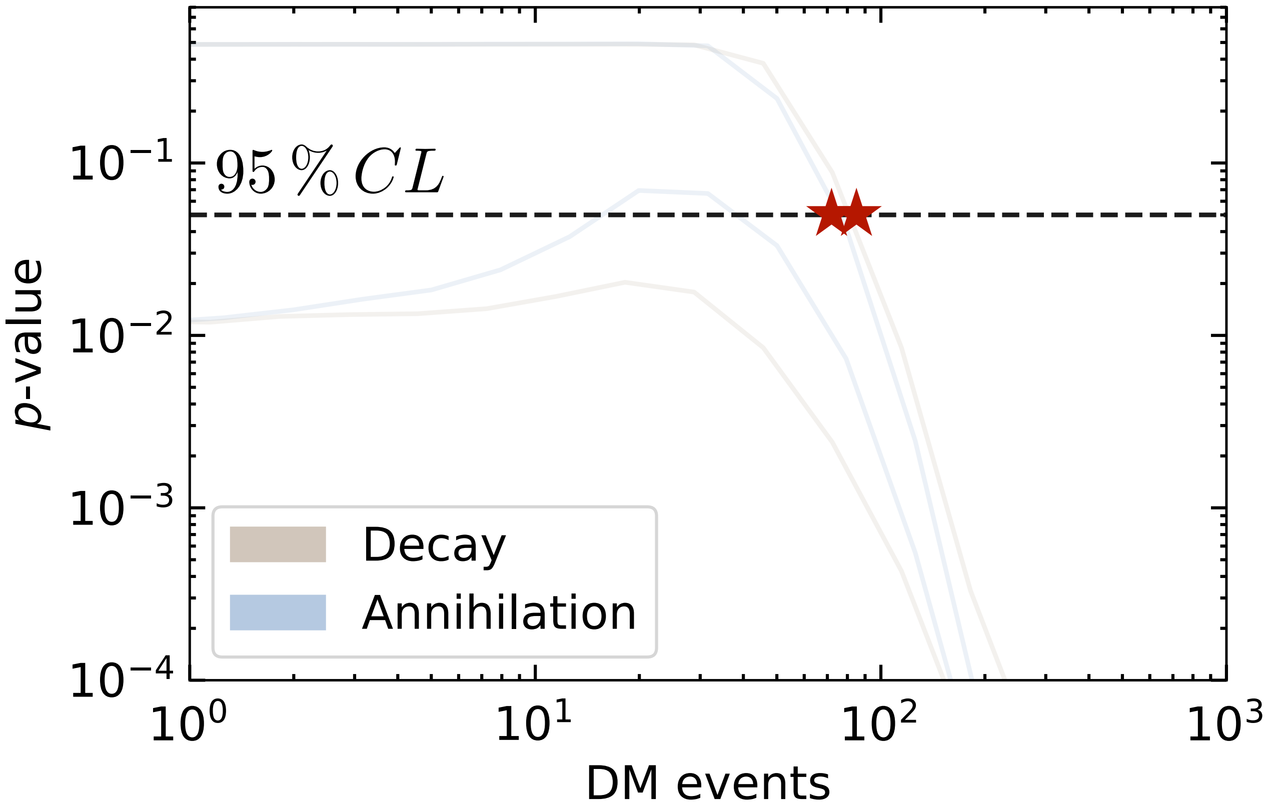
- Decay: $\mathrm{DM} \to \tau^+\tau^- \quad m_{\mathrm{DM}} = 400\,\mathrm{TeV}$
- Annihilation: $\mathrm{DM\,DM} \to \tau^+\tau^- \quad m_{\mathrm{DM}} = 200\,\mathrm{TeV}$
- NFW and HAI boost factor

P-values - 10 years

IceCube-Gen2



KM3NeT



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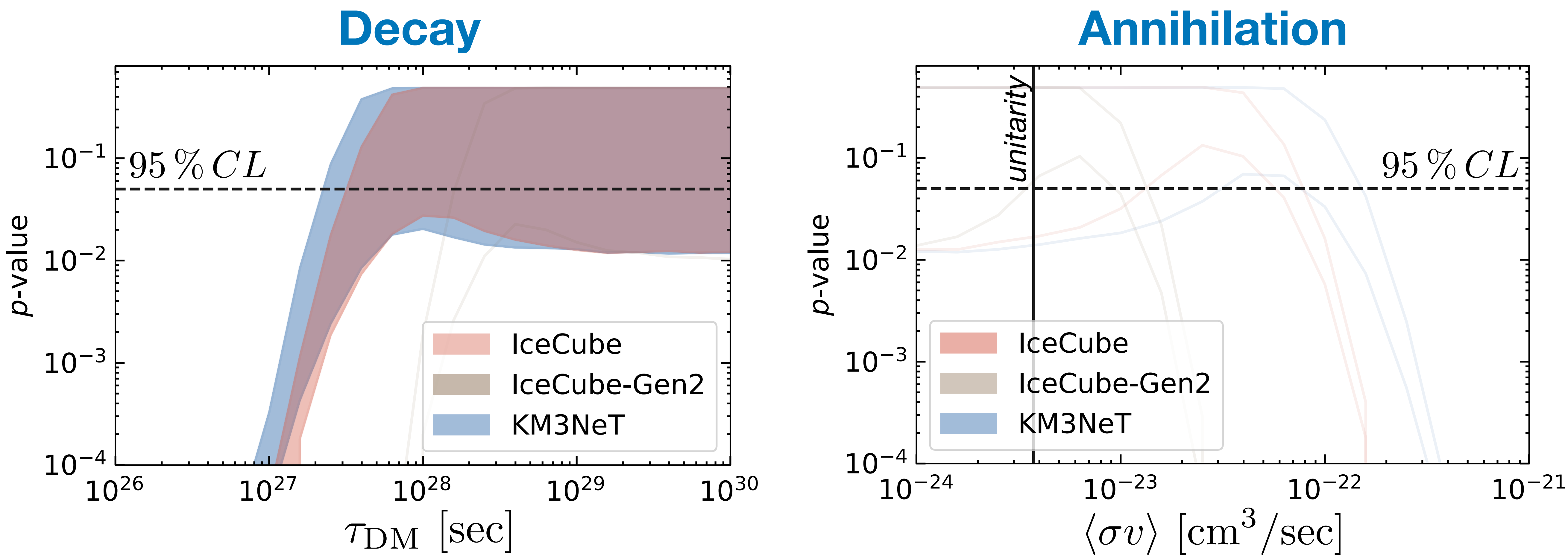
Constraints on total DM events from anisotropy

P-values - 10 years



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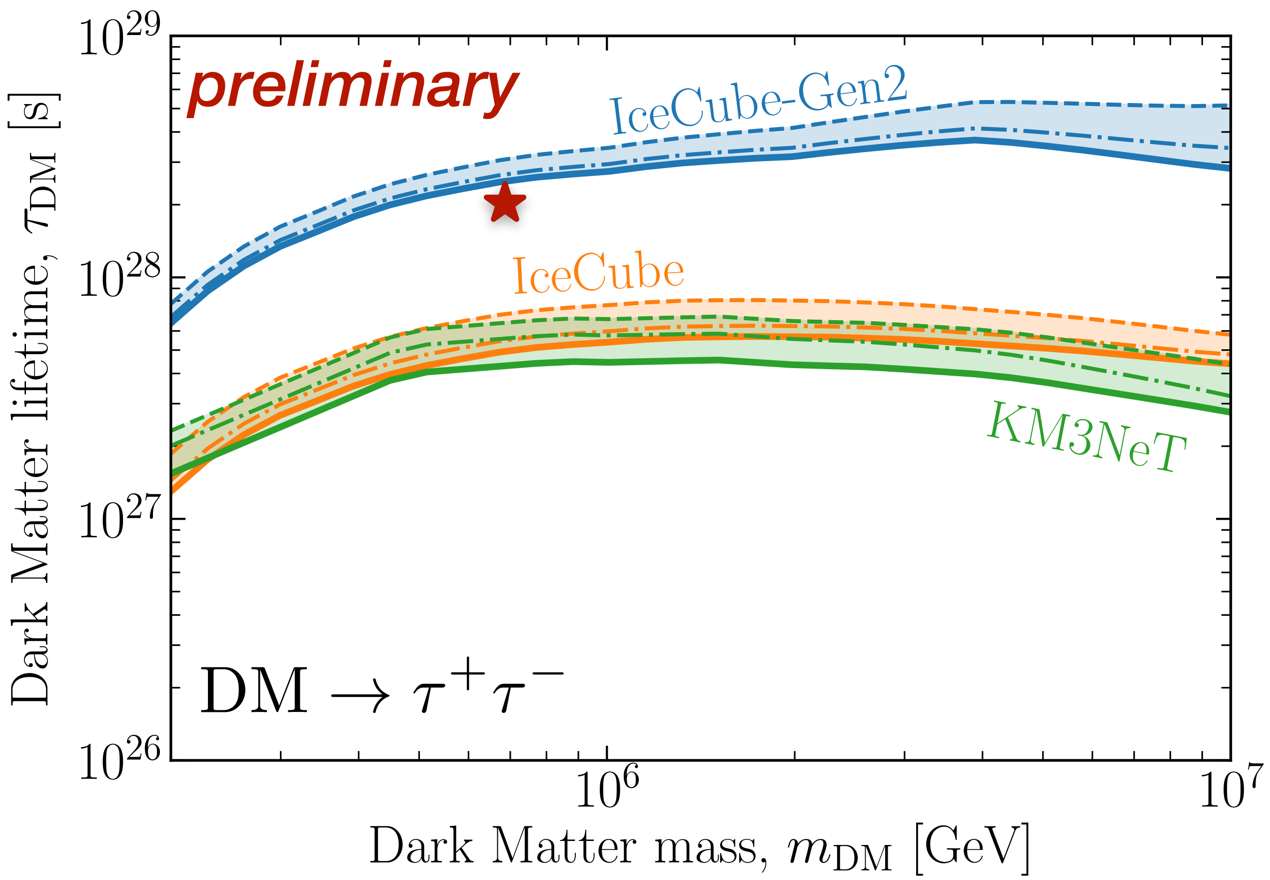
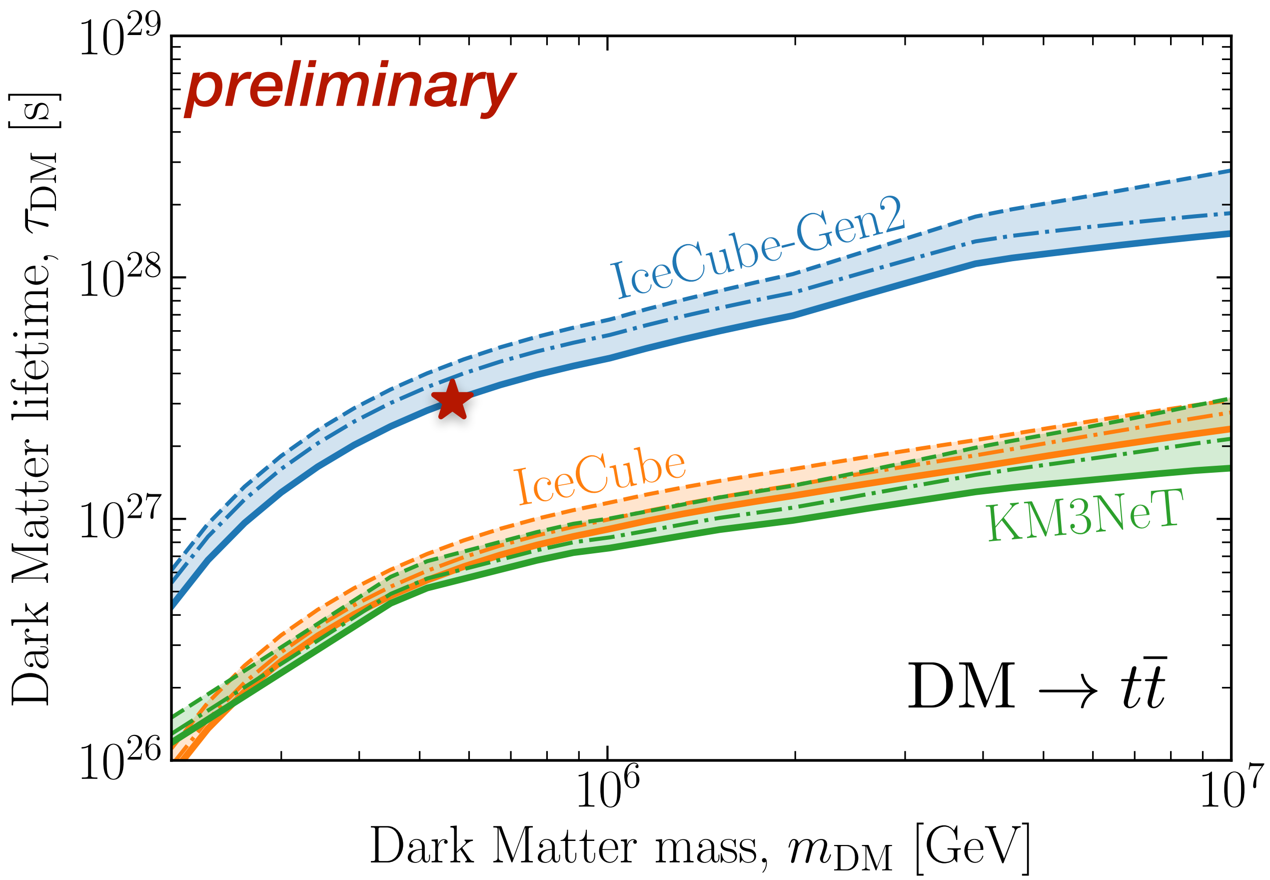
Constraints on total DM events from anisotropy

↓

Constraints on DM lifetime and cross-section

Sensitivity on DM lifetime



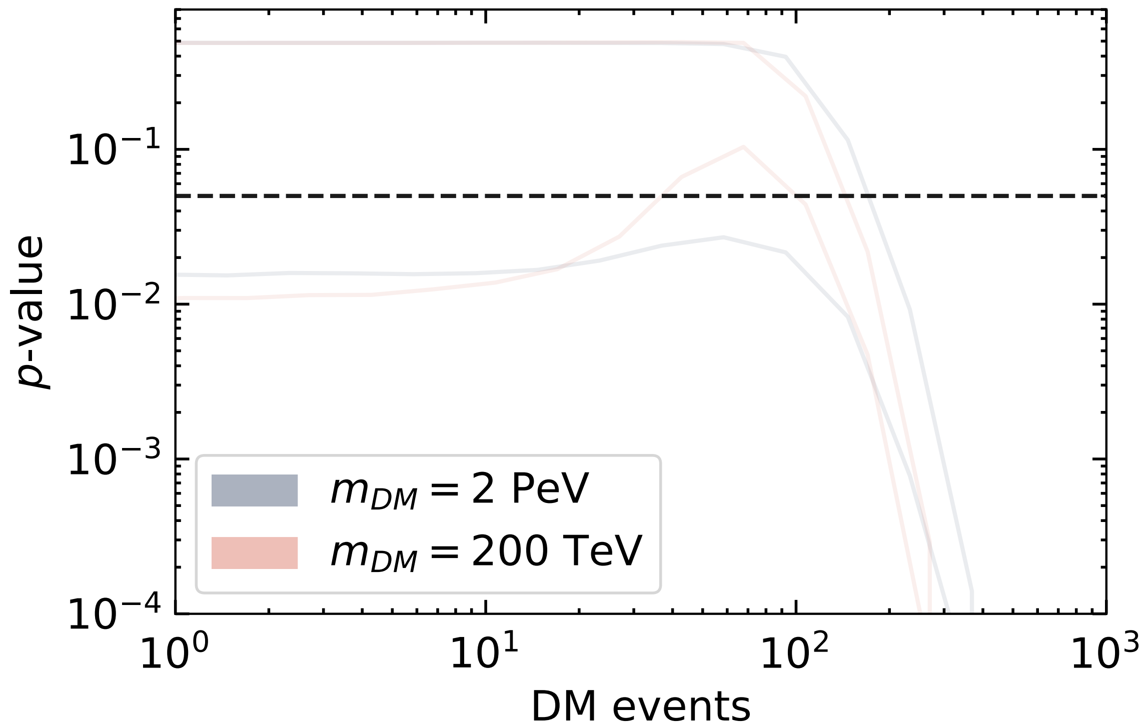


- Forecast bands of exclusion at 95% CL after 10 years
- Different lines of mean, lower 68% and 95% sensitivity from sky-map simulation
- The red star is the 7.5-year HESE best-fit

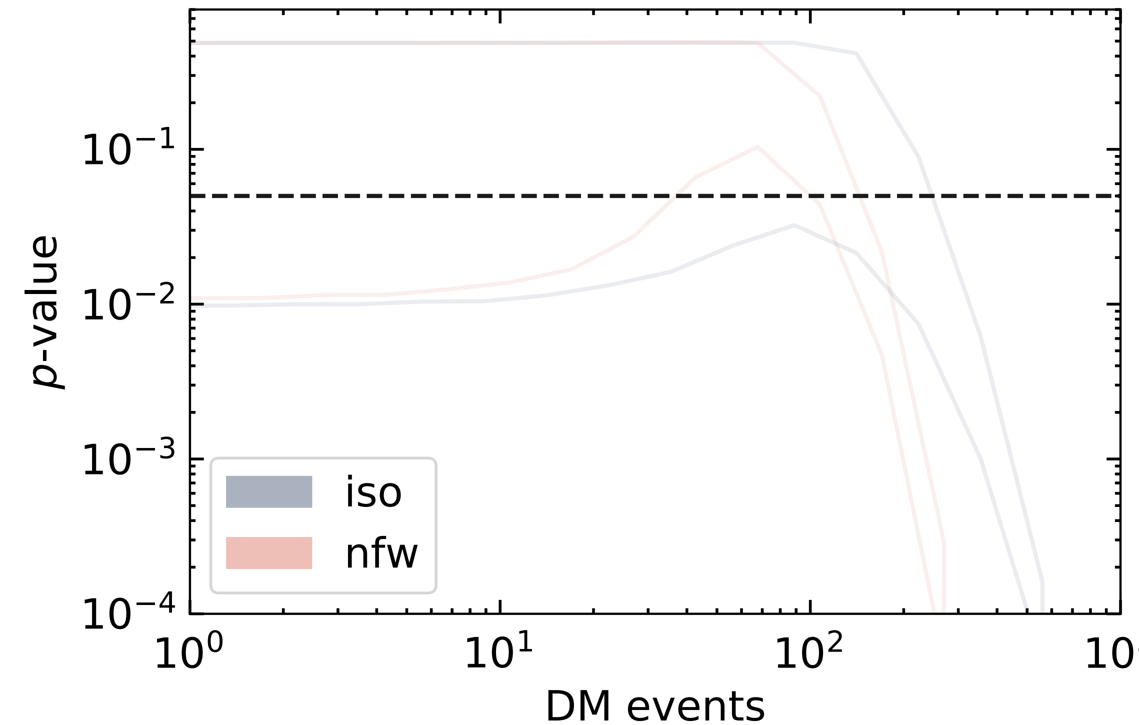
Only angular information exploited (APS) ⟶ Robust limits

Annihilation: dependence on DM properties

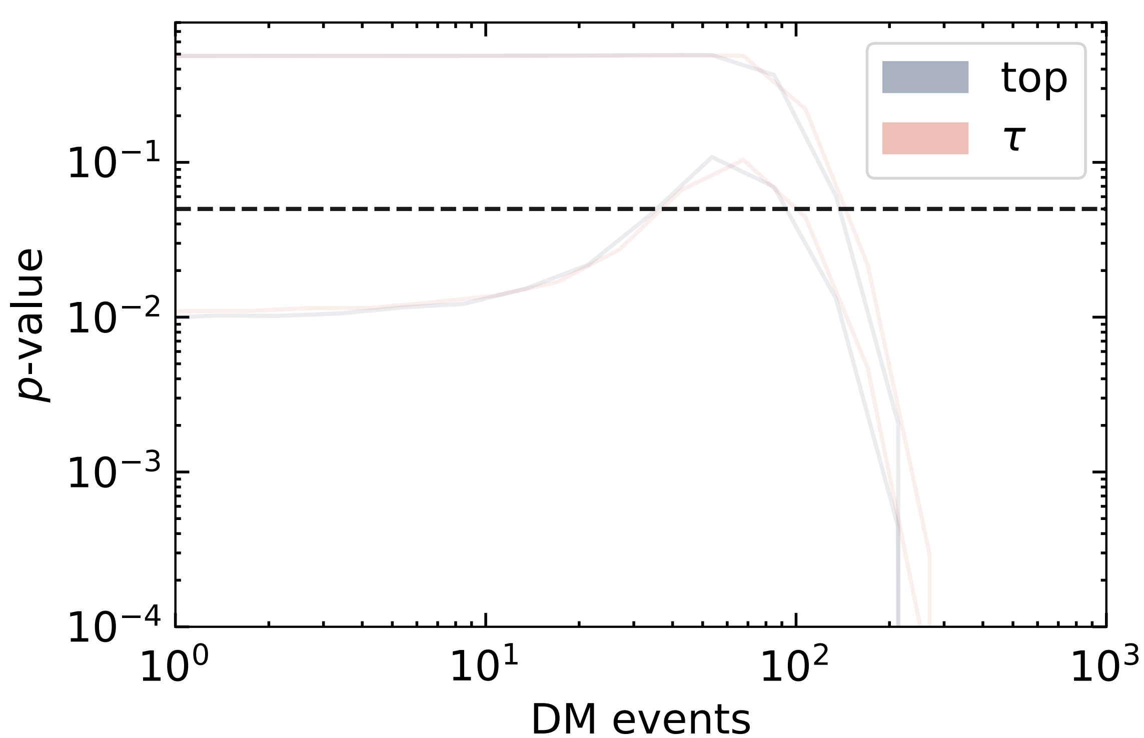
Mass



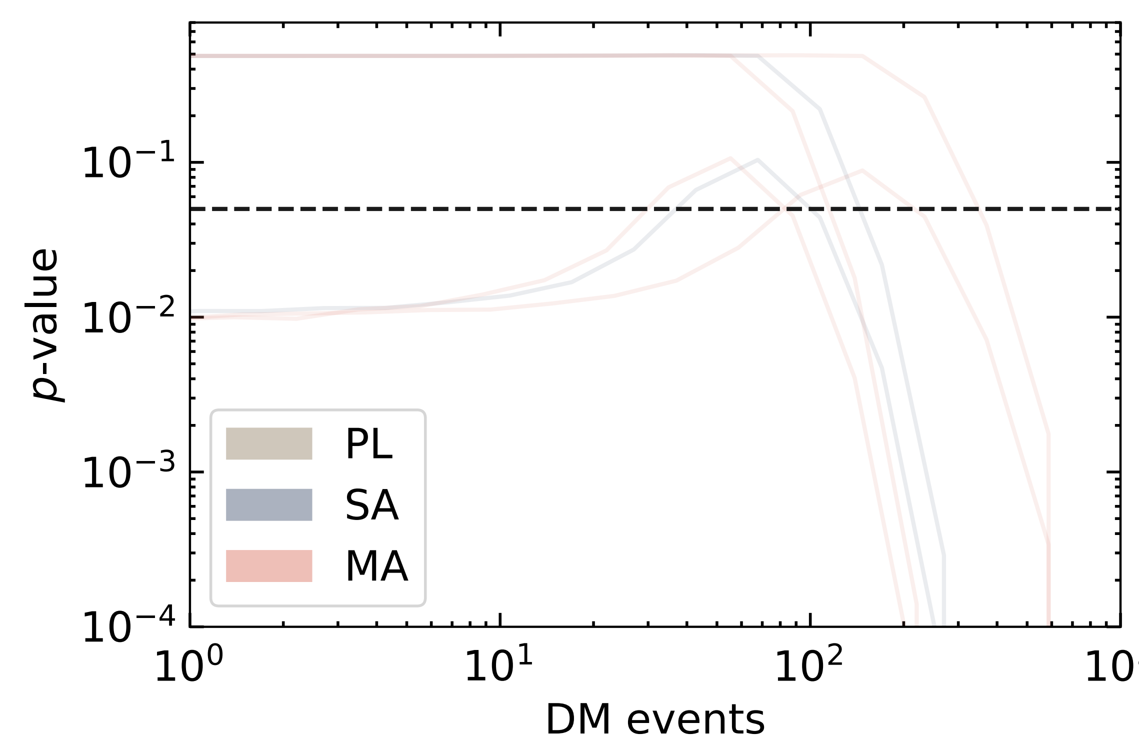
Halo density profile



Channel



Boost factor



Conclusions

- 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 is at 68% C.L. for some decay channels.
  - Multi-messenger: diffuse searches (Fermi-LAT) more sensitive than point-like ones (CTA)

- **Angular Power Spectrum** is a powerful tool for Dark Matter discrimination!
  - Future sensitivity to DM parameters using IceCube and KM3NeT exposures
  - **IceCube-Gen2** will firmly test the DM hypothesis exploiting angular information only.

Conclusions

- 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 is at 68% C.L. for some decay channels.
  - Multi-messenger: diffuse searches (Fermi-LAT) more sensitive than point-like ones (CTA)

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