Potential Dark Matter Signals at Neutrino Telescopes

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36th International Cosmic Ray Conference

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BASED ON:

- *MC, Miele, Morisi, Vitagliano, PLB 757 (2016)*
- *MC, Miele, Morisi, PLB 773 (2017)*
- *MC, Mele, Miele, Migliozzi, Morisi, ApJ 851 (2017)*
- *MC, Fiorillo, Miele, Morisi, Pisanti, arXiv:1907.11222*
- *Dekker, MC, Ando, arXiv:1908.XXXXX*

GRAPPA

GRavitation AstroParticle Physics Amsterdam

Neutrino data

High Energy Starting Events (HESE)

- Full sky
- High energy threshold

PoS (ICRC 2019) 1004

Through-going muon neutrinos (TG)

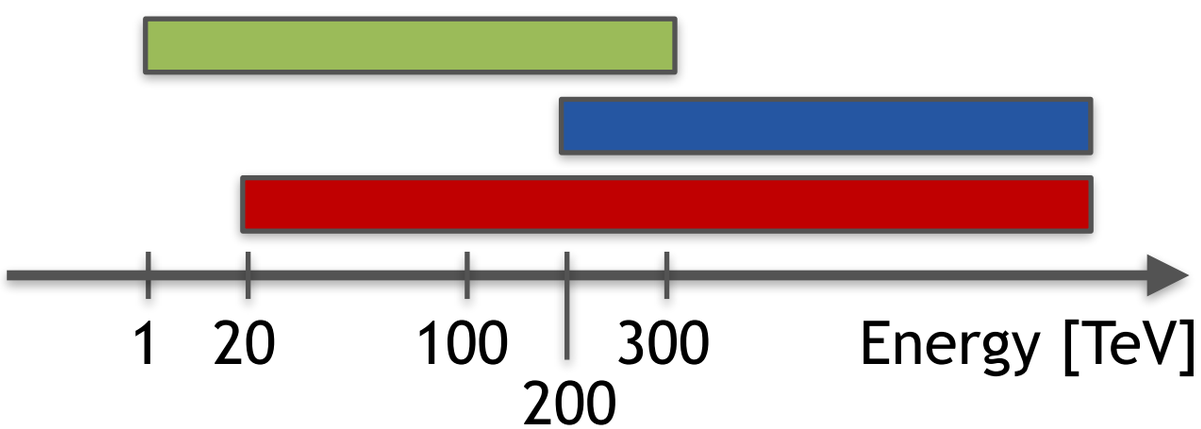
- Mainly Northern sky (up-going)
- Very high energy threshold

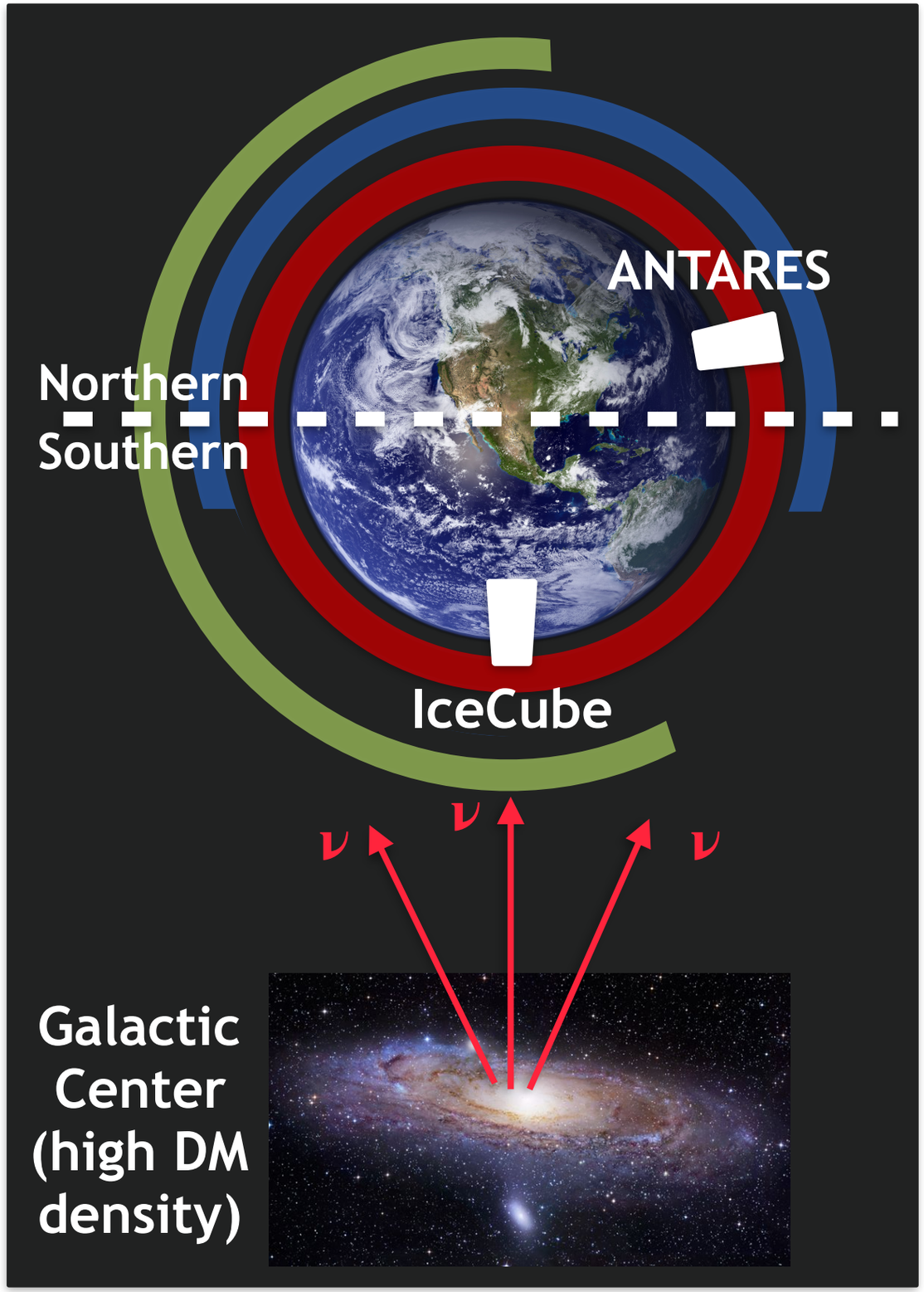
PoS (ICRC 2019) 1017

ANTARES data

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

PoS (ICRC 2019) 891

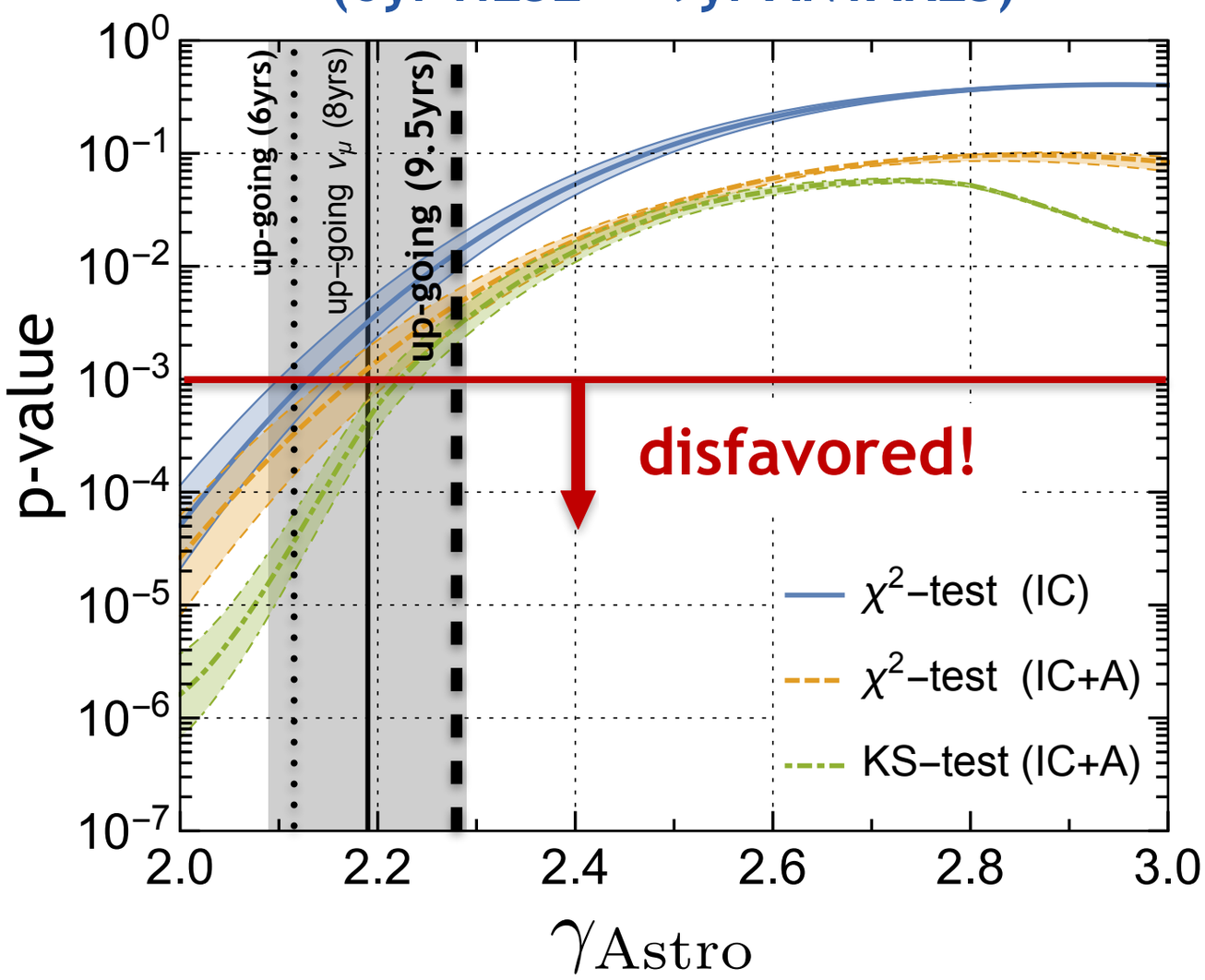




Tension with single power-law

A slight tension among different IceCube data samples disfavors at about ***95% C.L.*** the hypothesis of a single power-law neutrino flux.

IceCube+ANTARES analysis
(6yr HESE + 9yr ANTARES)



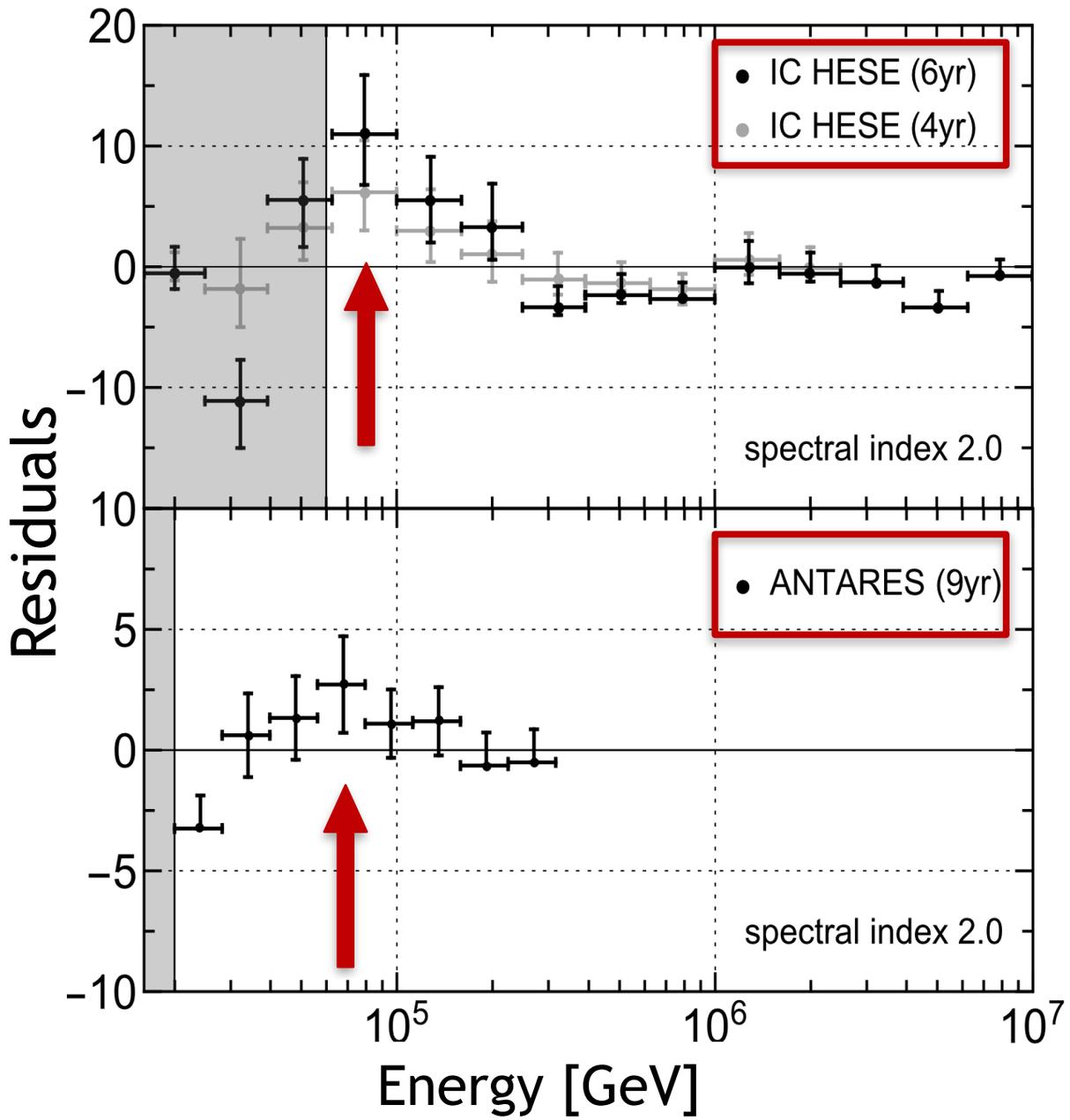
MC, Mele, Miele, Migliozzi, Morisi, ApJ 851 (2017)

$$\frac{d\phi^{\rm Astro}}{dE_\nu d\Omega} = \phi_0 \left(\frac{E_\nu}{100\ {\rm TeV}}\right)^{-\gamma_{\rm Astro}}$$

Data sample	Spectral index
HESE (6yrs)	$2.92^{+0.29}_{-0.33}$
Trough-going muon neutrinos (8yrs)	$2.19^{+0.10}_{-0.10}$
TXS 0506+056	$2.10^{+0.20}_{-0.20}$
HESE (7.5yrs)	$2.89^{+0.20}_{-0.19}$
Trough-going muon neutrinos (9.5yrs)	$2.28^{+0.08}_{-0.09}$

North/South asymmetry?
Two components?

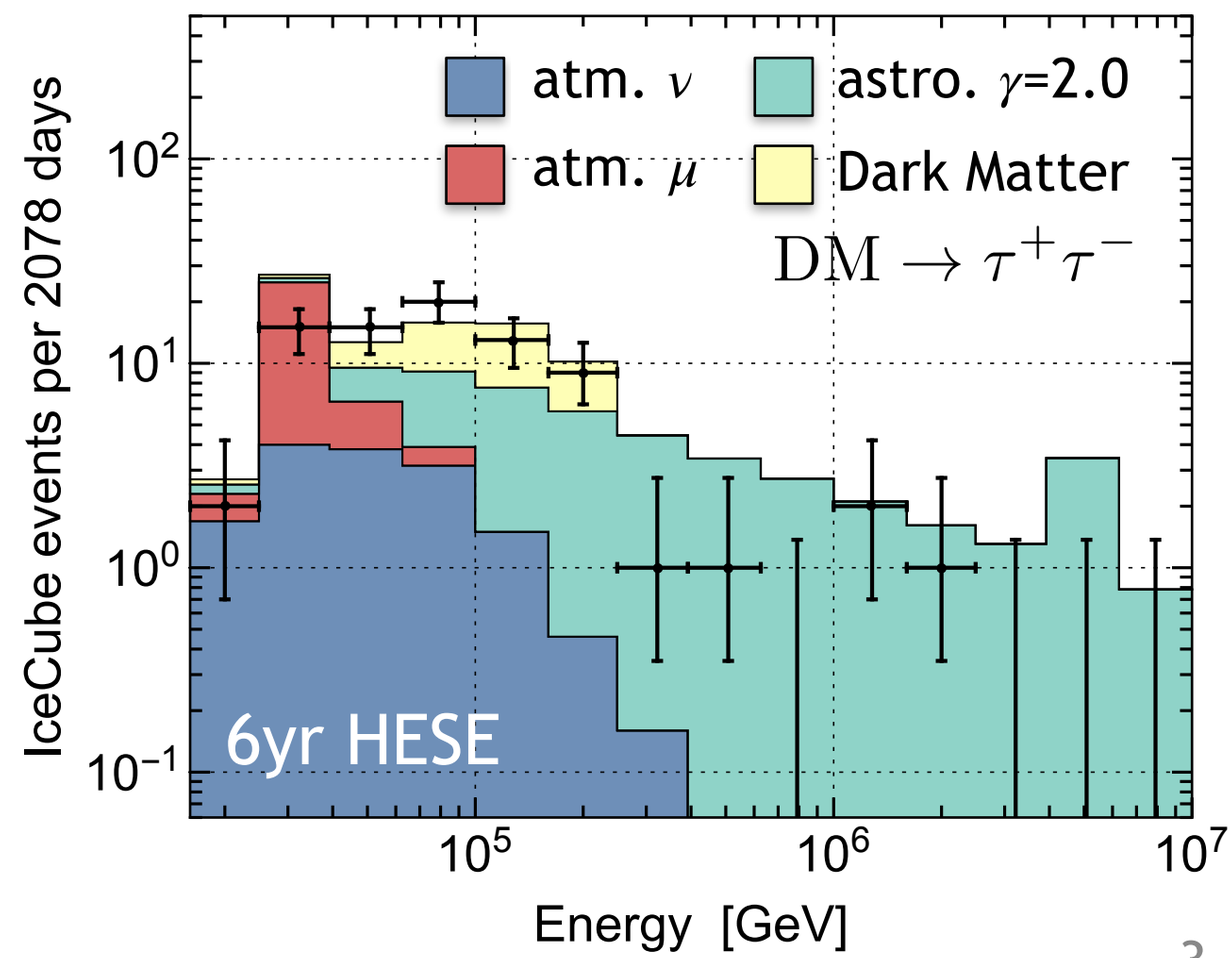
The low-energy excess



The benchmark spectral index of 2.0 is compatible with:

- standard Fermi acceleration mechanism
- up-going muon neutrino observations
- viable astrophysical sources

→ **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)

Neutrino flux: our assumption

In addition to the atmospheric background, we assume **two-component flux**:

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

The Dark Matter contribution mainly depends on:

- halo density profile of Milky Way

$$\frac{\mathrm{d}\phi^{\mathrm{DM}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} \propto$$

decay	annihilation
$\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}$	$\left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^2$

→ **Analysis on angular distribution**

- Non-parametric tests
- Angular Power spectrum

- Different final states

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

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

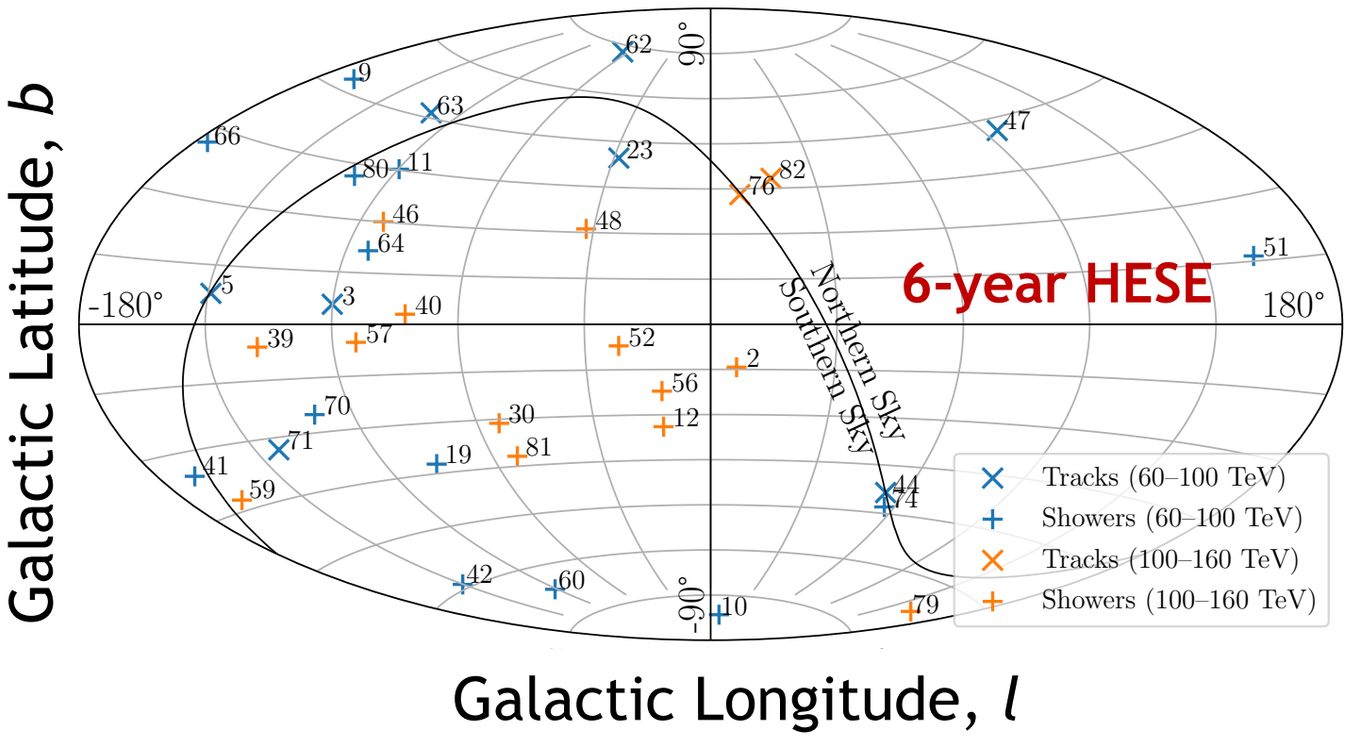
$\mathrm{DM} \to W^+W^-, ZZ, hh$ **EW bosons**

→ **Analysis on energy spectrum**

- Analysis of 7.5 HESE data
- Multi-messenger study with gamma-rays

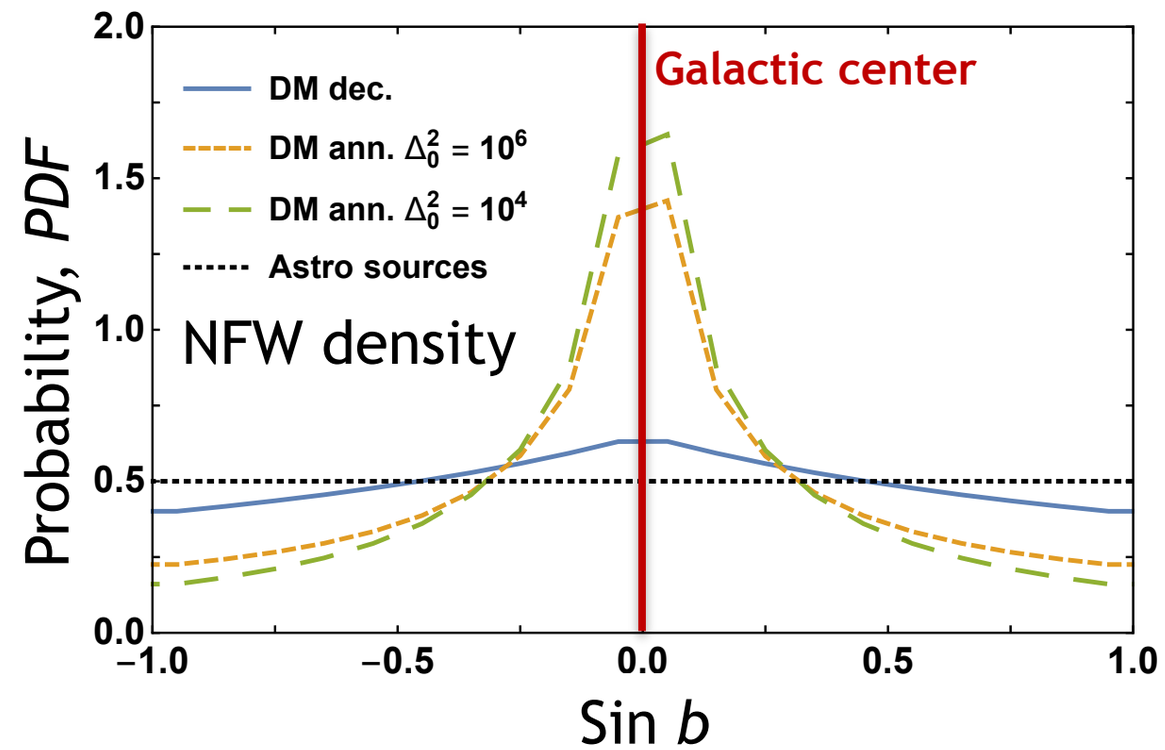
Analysis on Angular Distribution

Observable: sky map (60-160 TeV)



60-100 TeV 100-160 TeV

Theory: Angular distribution



Astrophysical sources and Dark Matter can be discriminated by the fact that they have different angular distributions!!!

Two scenarios:

1. the low energy excess is entirely explained by Dark Matter
2. two-component flux with the addition of an astrophysical power-law

Current results: Dark Matter only

Scenario		4-year HESE (60-100 TeV)		6-year HESE (60-160 TeV)	
		KS	AD	KS	AD
DM decay	NFW	0.06 - 0.16	0.03 - 0.14	0.07 - 0.58	0.13 - 0.60
	Isoth.	0.08 - 0.22	0.11 - 0.74	0.21 - 0.77	0.05 - 0.19
DM annih. $\Delta_0^2 = 10^4$	NFW	$(0.3-0.9)\times 10^{-4}$	$(0.3-3.8)\times 10^{-4}$	$\leq 3.6\times 10^{-5}$	$\leq 3.0\times 10^{-6}$
	Isoth.	$(0.9-2.8)\times 10^{-3}$	$(1.0-5.0)\times 10^{-3}$	$\leq 5.7\times 10^{-4}$	$\leq 9.9\times 10^{-5}$
DM annih. $\Delta_0^2 = 10^6$	NFW	0.02 - 0.05	0.02 - 0.07	0.05 - 0.42	0.06 - 0.32
	Isoth.	0.10 - 0.28	0.08 - 0.29	0.19 - 0.89	0.33 - 0.91

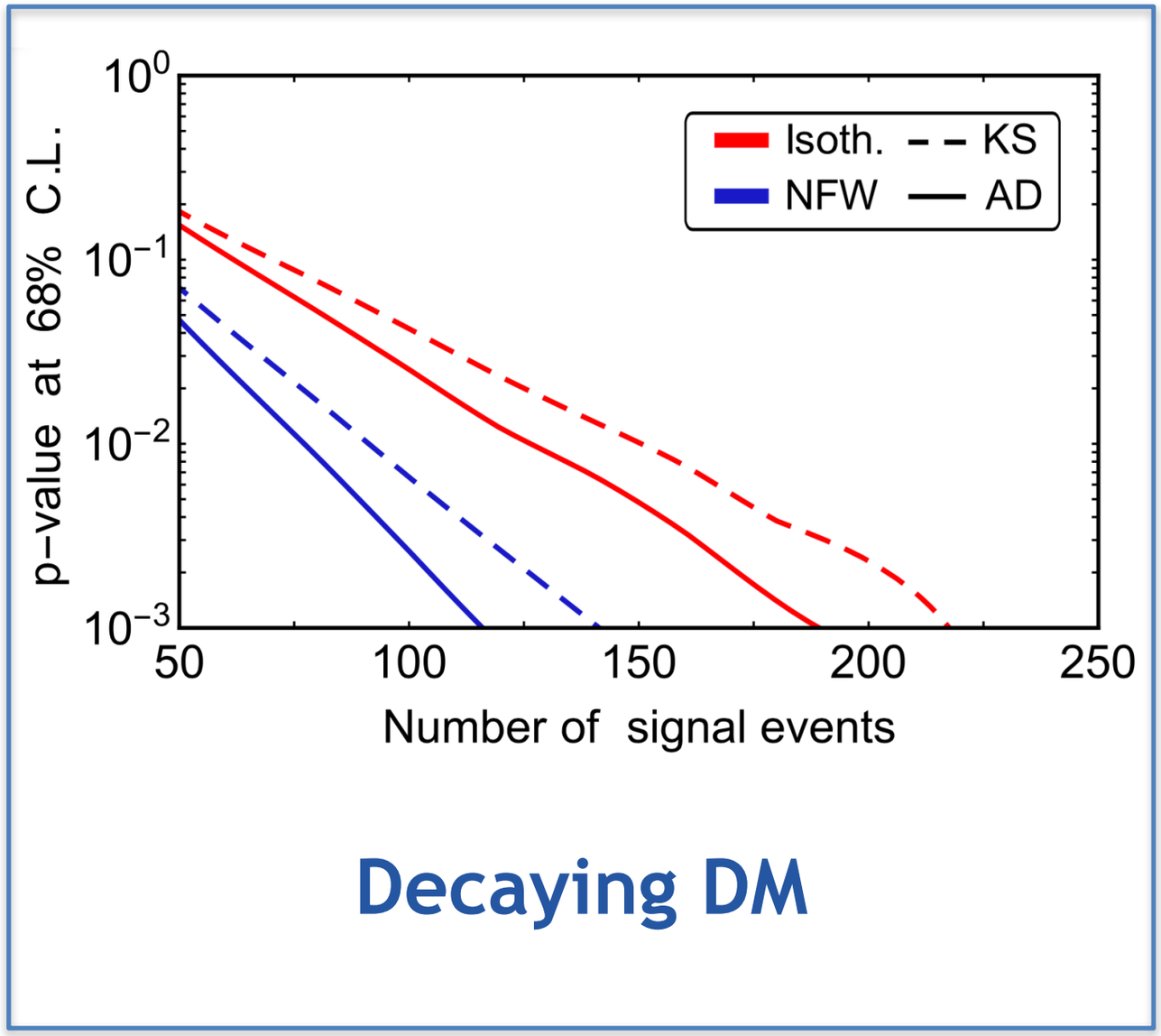
Few events of 6-year HESE between 100-160 show a correlation with the Galactic Center (Dark Matter density): weak constraint *wrt* 4-year HESE.

The annihilating Dark Matter scenario with a small boost factor Δ_0 (neutrino flux highly not isotropic) is confirmed to be excluded.

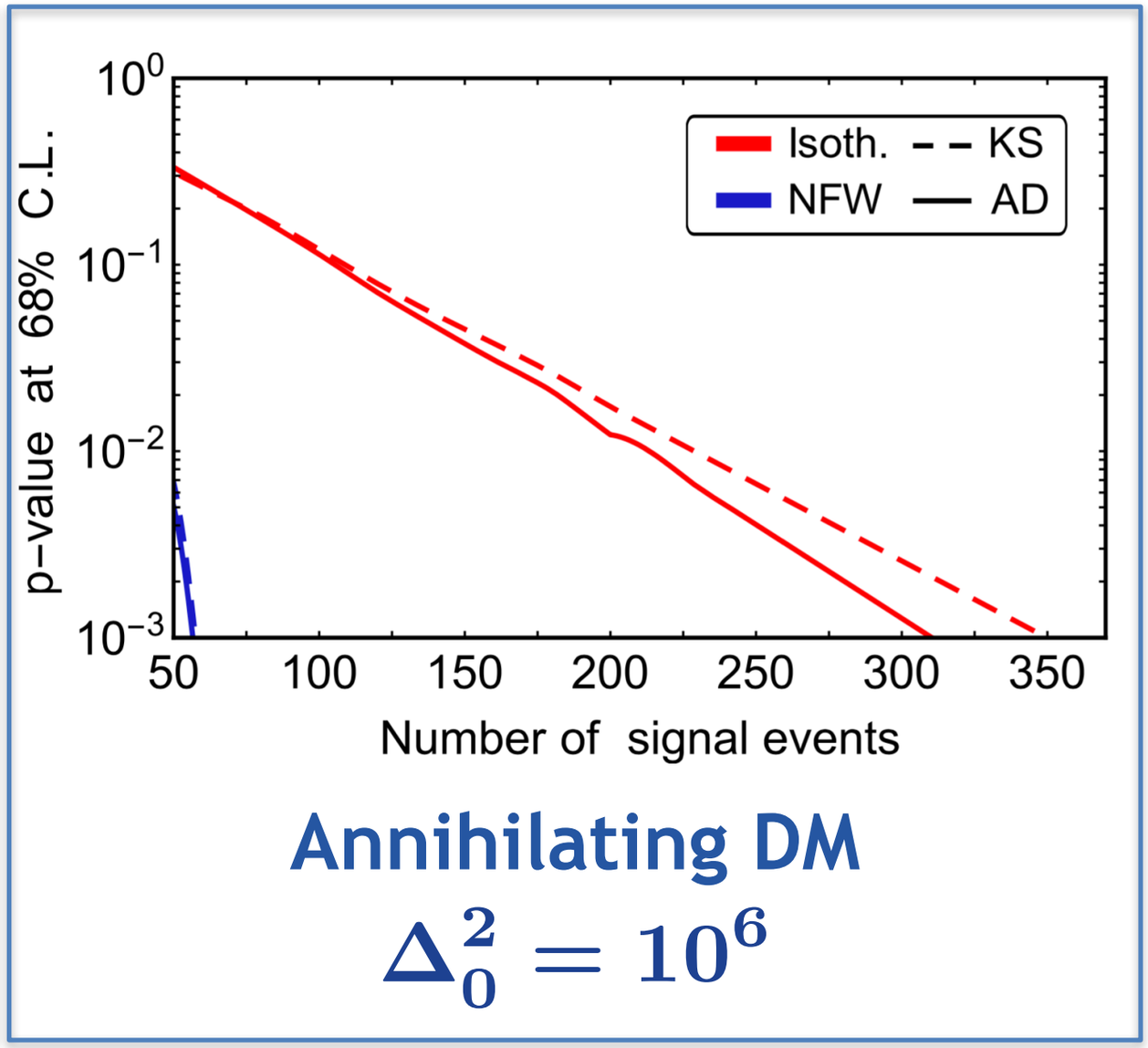
MC, Miele, Morisi, Vitagliano, PLB 757 (2016)
MC, PoS (ICRC 2019) 514

Forecast: Dark Matter only

Few hundreds neutrino events are required to exclude that the low-energy excess is *entirely* due to a Dark Matter signal.



Decaying DM



Annihilating DM

$$\Delta_0^2 = 10^6$$

MC, Miele, Morisi, Vitagliano, PLB 757 (2016)

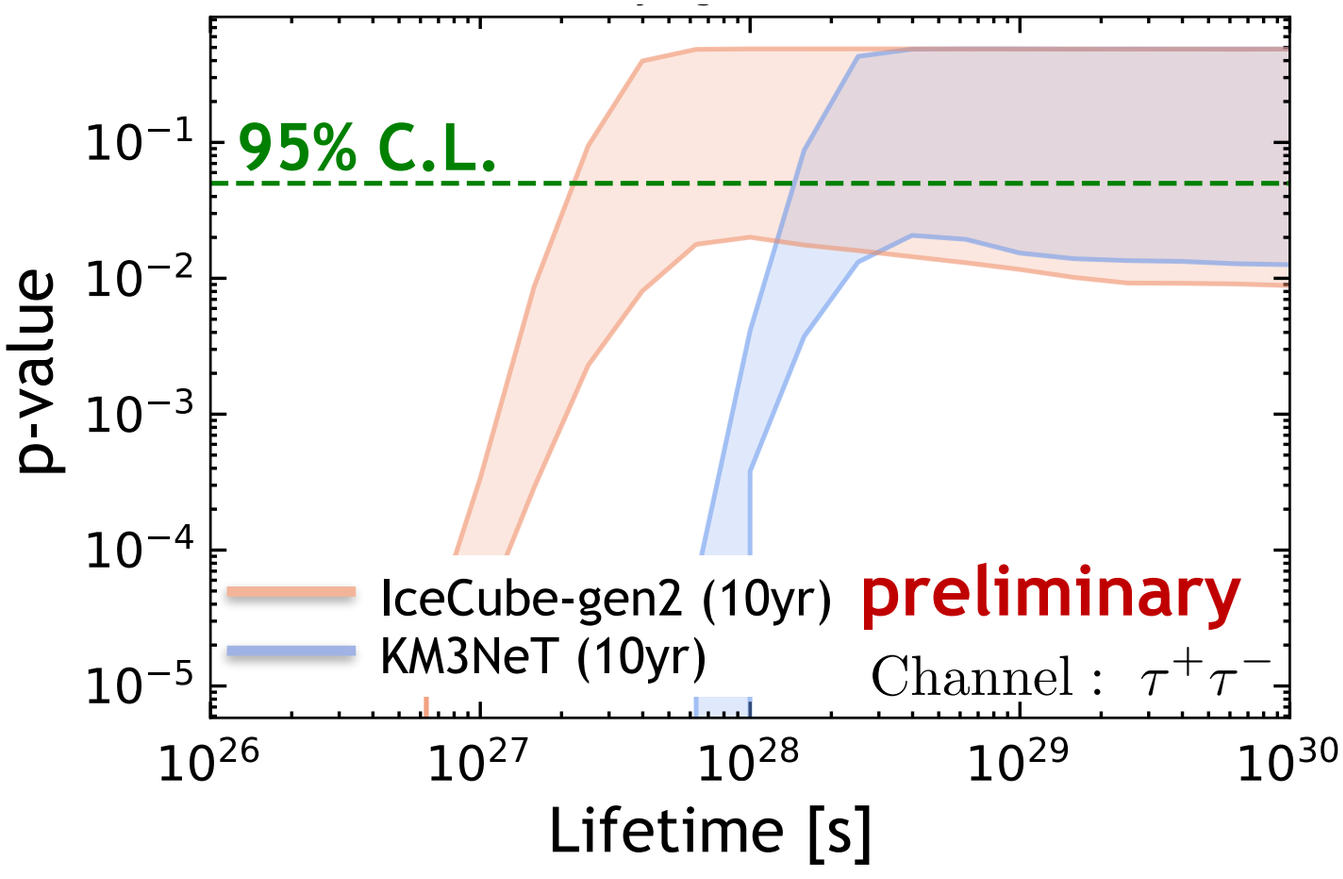
Forecast: two-component flux

By means of a Monte Carlo simulations assuming isotropy (extragalactic sources), we perform an angular power-spectrum analysis to study future potential bounds on Dark Matter signals on top of an astrophysical power-law flux.

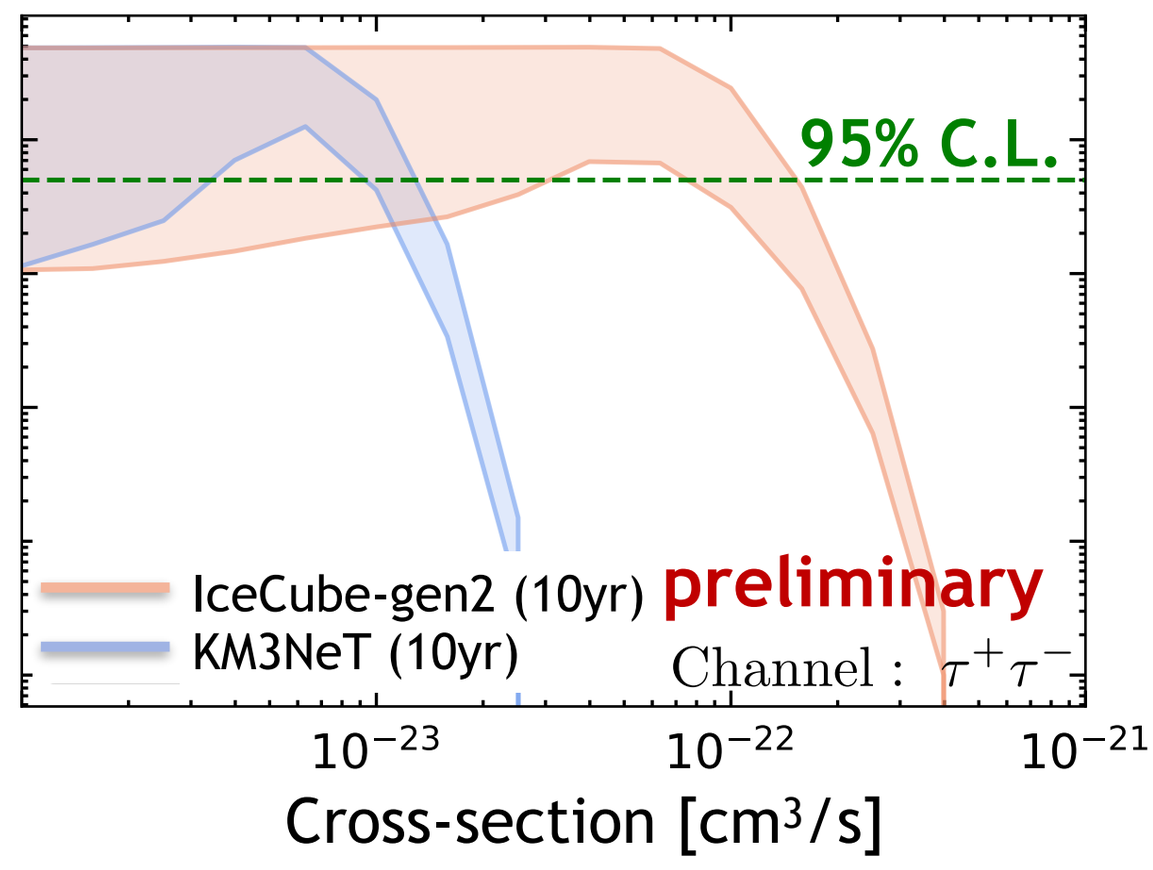
$$\frac{\mathrm{d}\phi^{\mathrm{signal}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} = \phi_0 \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-2.19\pm0.10} + \frac{\mathrm{d}\phi^{\mathrm{DM}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}$$

8-year through-going muon neutrinos

Decaying m_{DM} = 400 TeV

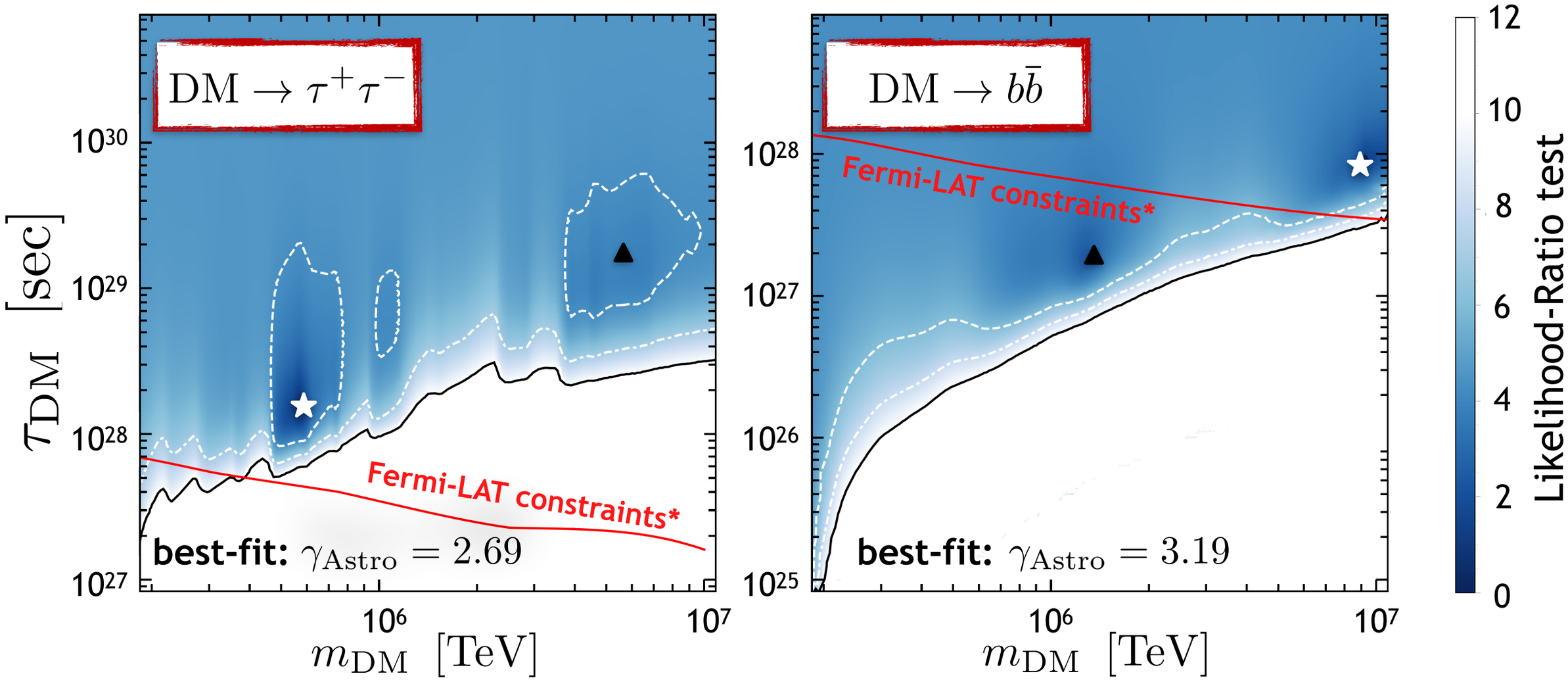


Annihilating m_{DM} = 200 TeV



Dekker, MC, Ando, arXiv:1908.XXXXX

7.5yr HESE: Decaying Dark Matter



Features of the analysis:

- Relation between true and deposited energy included
- Nuisance astrophysical parameters: $\phi_0,\ \gamma_{\mathrm{Astro}} \epsilon\, [1.5, 5.0]$
- Second competitive best-fit (black triangle)

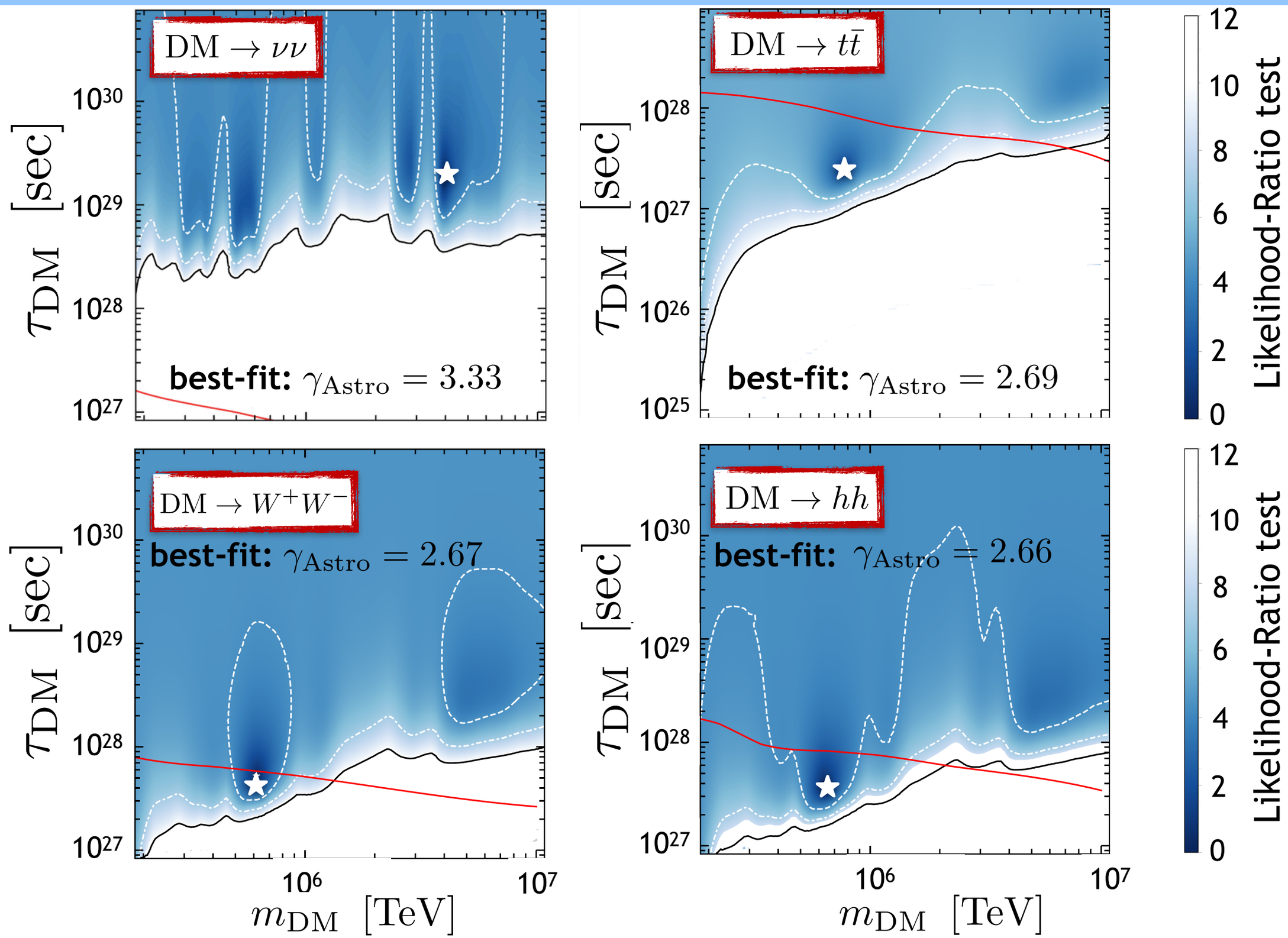
Dark Matter Flux

$$\frac{\mathrm{d}\phi^{\mathrm{DM}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} \propto \frac{1}{\tau_{\mathrm{DM}}\, m_{\mathrm{DM}}}$$

MC, Fiorillo, Miele, Morisi, Pisanti, arXiv:1907.11222

**Cohen et al., PRL17*

7.5yr HESE: Decaying Dark Matter



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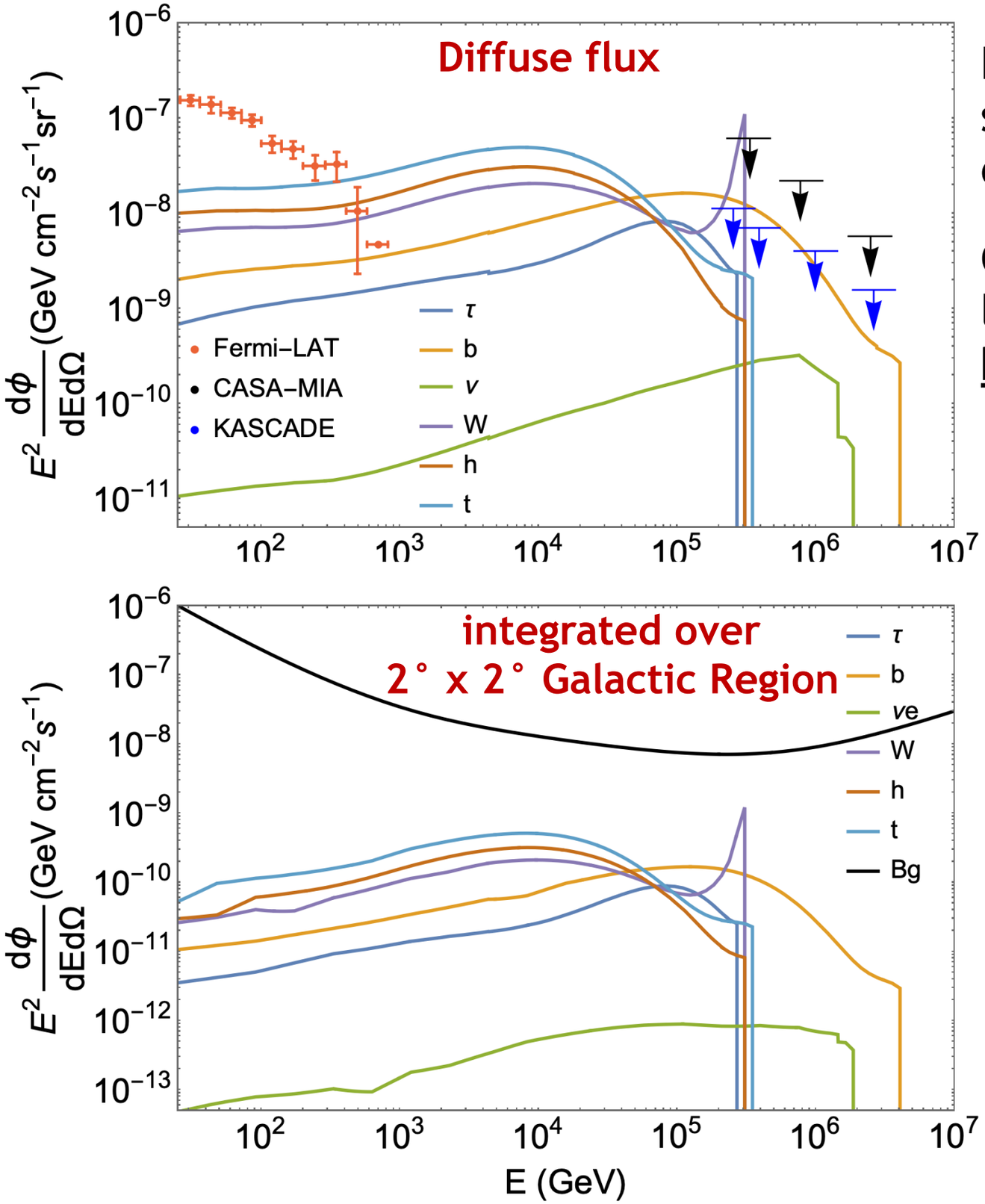
**Cohen et al., PRL17*

Gamma-ray signals



Experiments like Fermi-LAT provide the strongest gamma-rays constraints on decaying dark matter.

Gamma-rays detectors optimized for point-like searches (as CTA) are dominated by **background** towards the Galactic center.

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

MC, Fiorillo, Miele, Morisi, Pisanti, arXiv:1907.11222

see also: M. Pierre et al., JCAP 1410, 024; Ibarra et al., JCAP 1509, 048; CTA, EPJ Web Conf. 209, 01038 (2019)

Conclusions

The latest IceCube data (7.5yr HESE and 10yr TG) seem to still confirm the presence of **two-component neutrino flux**.

A robust way to look for a Dark Matter signal is analyzing neutrino angular map.

→ Stay tuned: forecast with *IC-gen2* and *KM3NeT exploiting angular information only (angular power spectrum)*

The **7.5-year HESE data** prefer a second **Dark Matter signal at 68% C.L.** for some decay channels.

→ Stay tuned: inclusion of through-going muon neutrinos

Multi-messenger with gamma-rays: Fermi-LAT will still provide the most stringent constraints as compered to future CTA.

Conclusions

The latest IceCube data (7.5yr HESE and 10yr TG) seem to still confirm the presence of **two-component neutrino flux**.

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Thank you for your attention

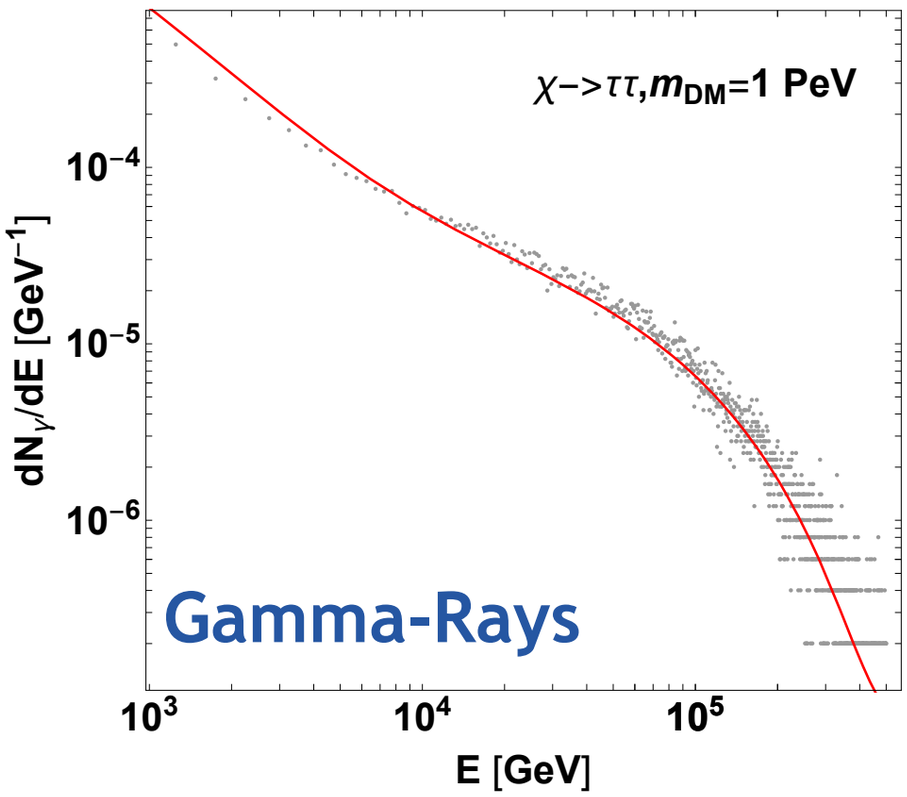
Backup Slides

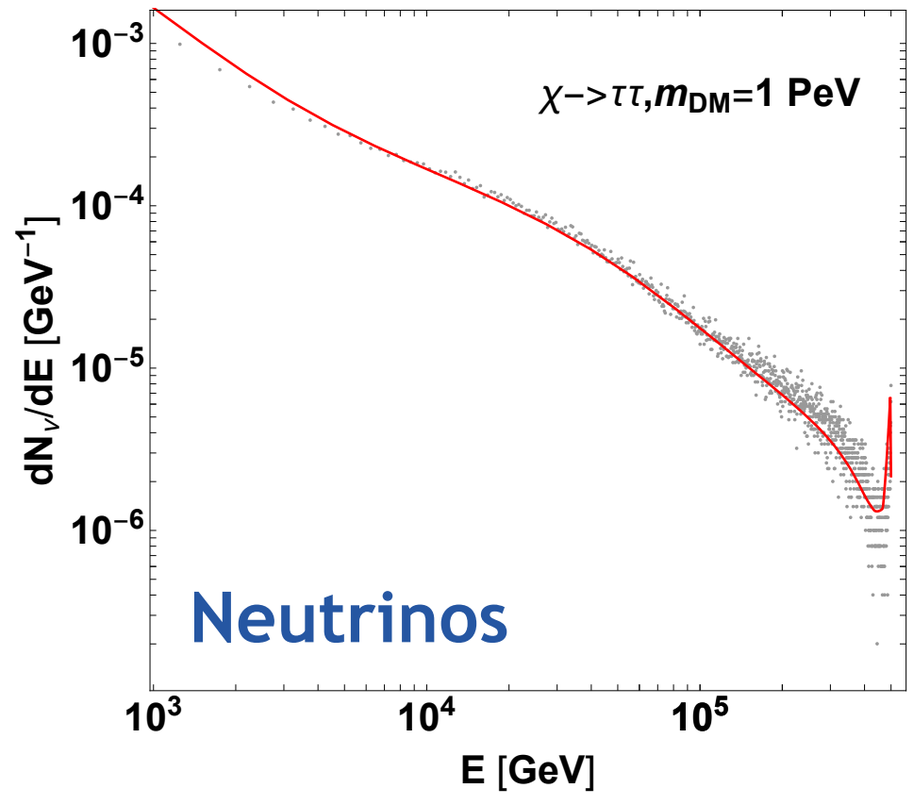
7.5 HESE: all channels

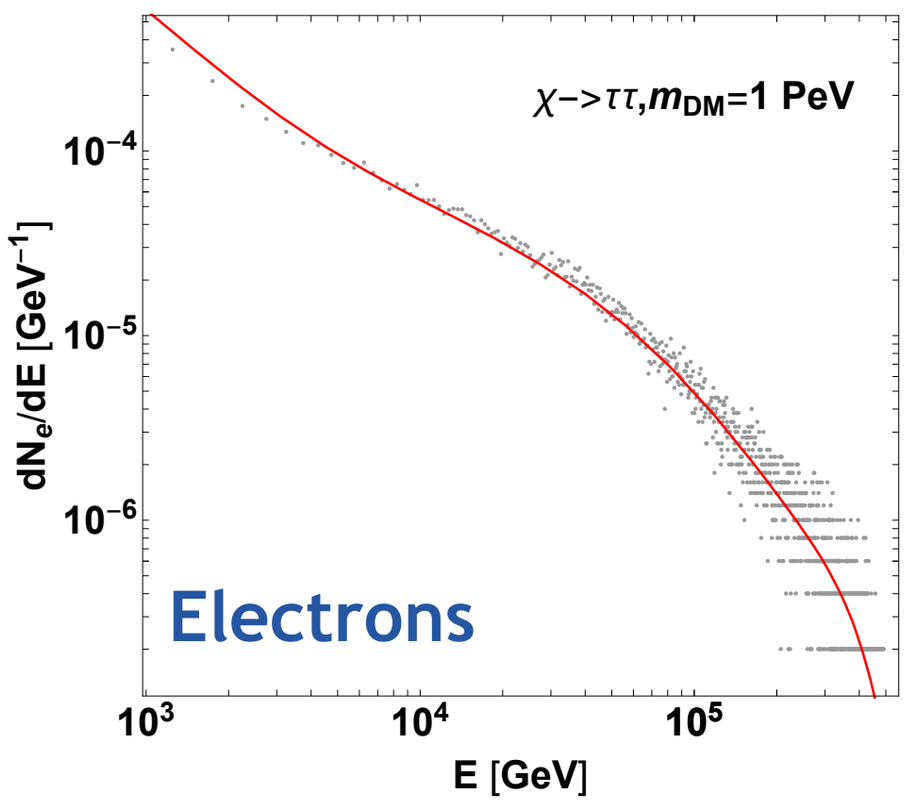
Channel	$\phi_0^{\rm best}(\times 10^{-15}$f.u.)	$\gamma^{\rm best}$	$\tau^{\rm best}(\times 10^{28}$s)	$m_{\rm DM}^{\rm best}$(TeV)
$\nu_e\nu_e$	2.24	3.33	19.10	4017.35
$\nu_\mu\nu_\mu$	2.24	3.33	19.10	4017.35
$\nu_\tau\nu_\tau$	2.24	3.33	19.10	4017.35
e^+e^-	2.14	3.86	2.09	3846.63
$\mu^+\mu^-$	0.66	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

MC, Fiorillo, Miele, Morisi, Pisanti, arXiv:1907.11222

PPPC vs PYTHIA







Perfect agreement between PYTHIA and the rescaling of the fluxes provided by PPPC

PYTHIA: Sjöstrand et al., Comput. Phys. Commun. 191, 159 (2015)
PPPC: Cirelli et al., JCAP 1103, 051

Neutrinophilic Dark Matter

A 100 TeV neutrinophilic Dark Matter (neutrino line) has the weakest gamma-ray constraints. From a model building perspective, the main features are:

- a scalar Dark Matter embedded into a SU(2) triplet

$$\Delta = \begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^0 & -\Delta^+ \end{pmatrix} \quad \text{with} \quad \mathcal{L}_\nu = \frac{1}{2}\lambda_{ij} L_i^T C^{-1} i\tau_2 \Delta\, L_j + \text{h.c.}$$

- the requirement of a new global symmetry in the leptonic sector

→ **Dirac nature of active neutrinos**

- a low-reheating temperature of the Universe of about 1 TeV

Standard freeze-out production through EW

$$m_{\rm DM} = \mathcal{O}\left(1\ \text{TeV}\right)$$

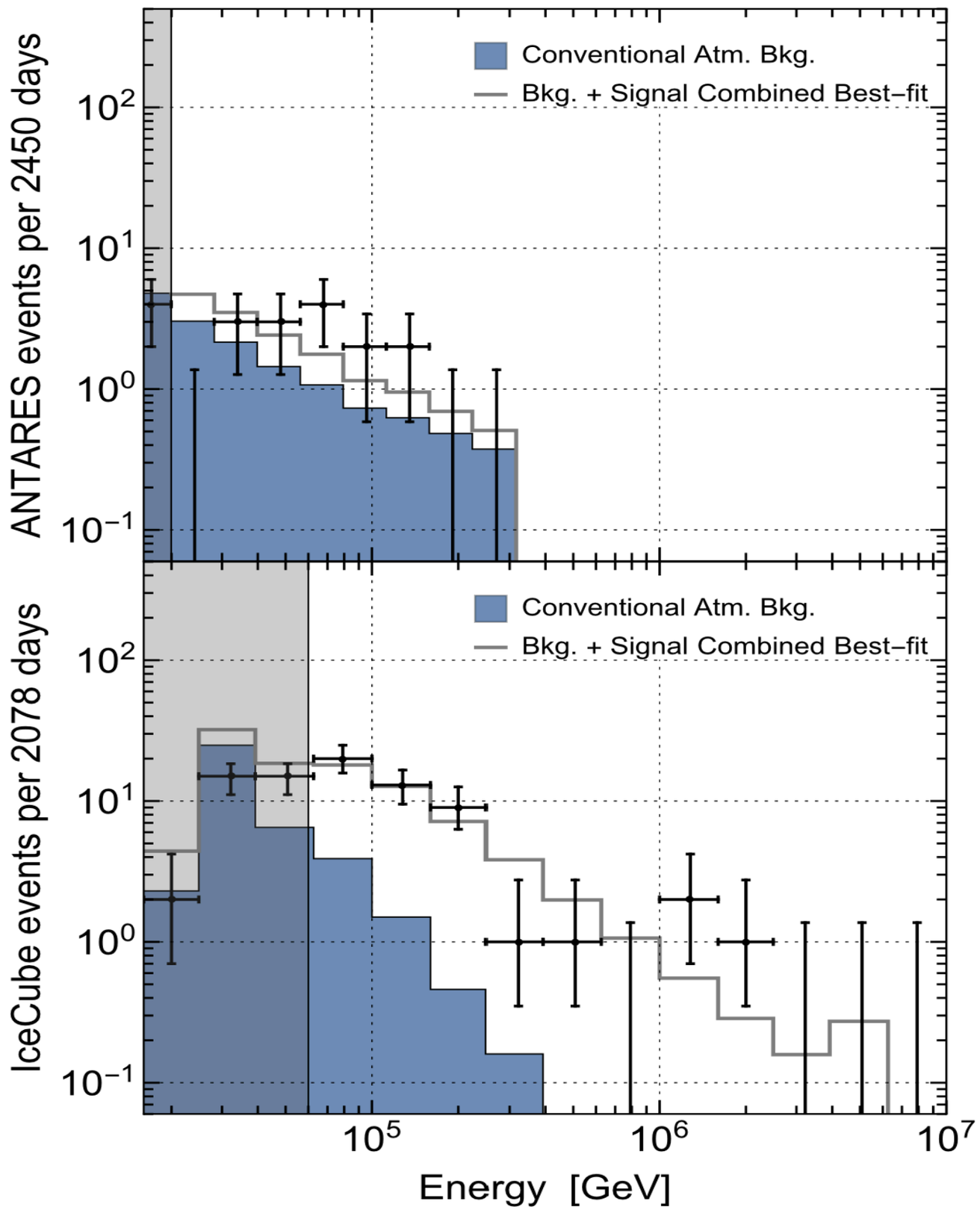
Cirelli, Fornengo, Strumia, Nucl. Phys. B753 (2006)

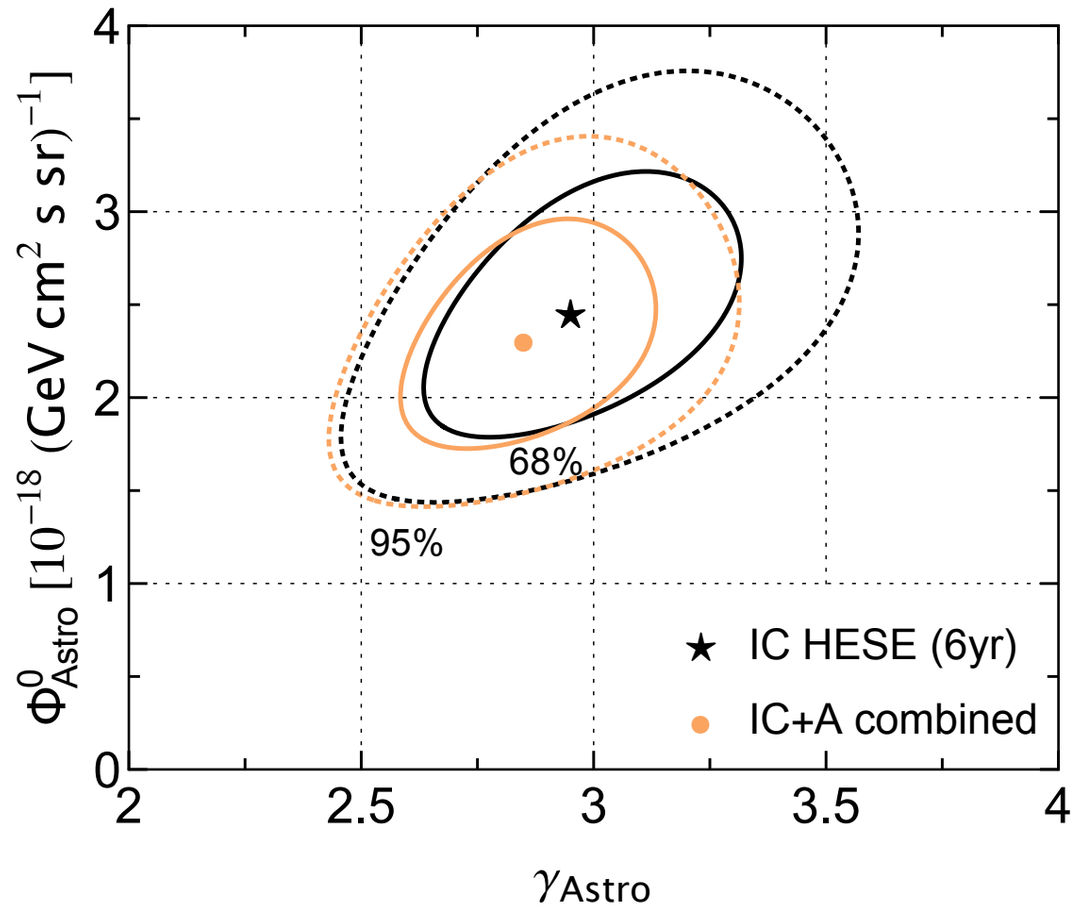
→

$$T_{\rm RH} \simeq 660 \left(\frac{m_{\rm DM}}{100\ \text{TeV}}\right)^{1/2} \text{GeV}$$

additional long-lived unstable particles

Combined analysis: IC + ANTARES





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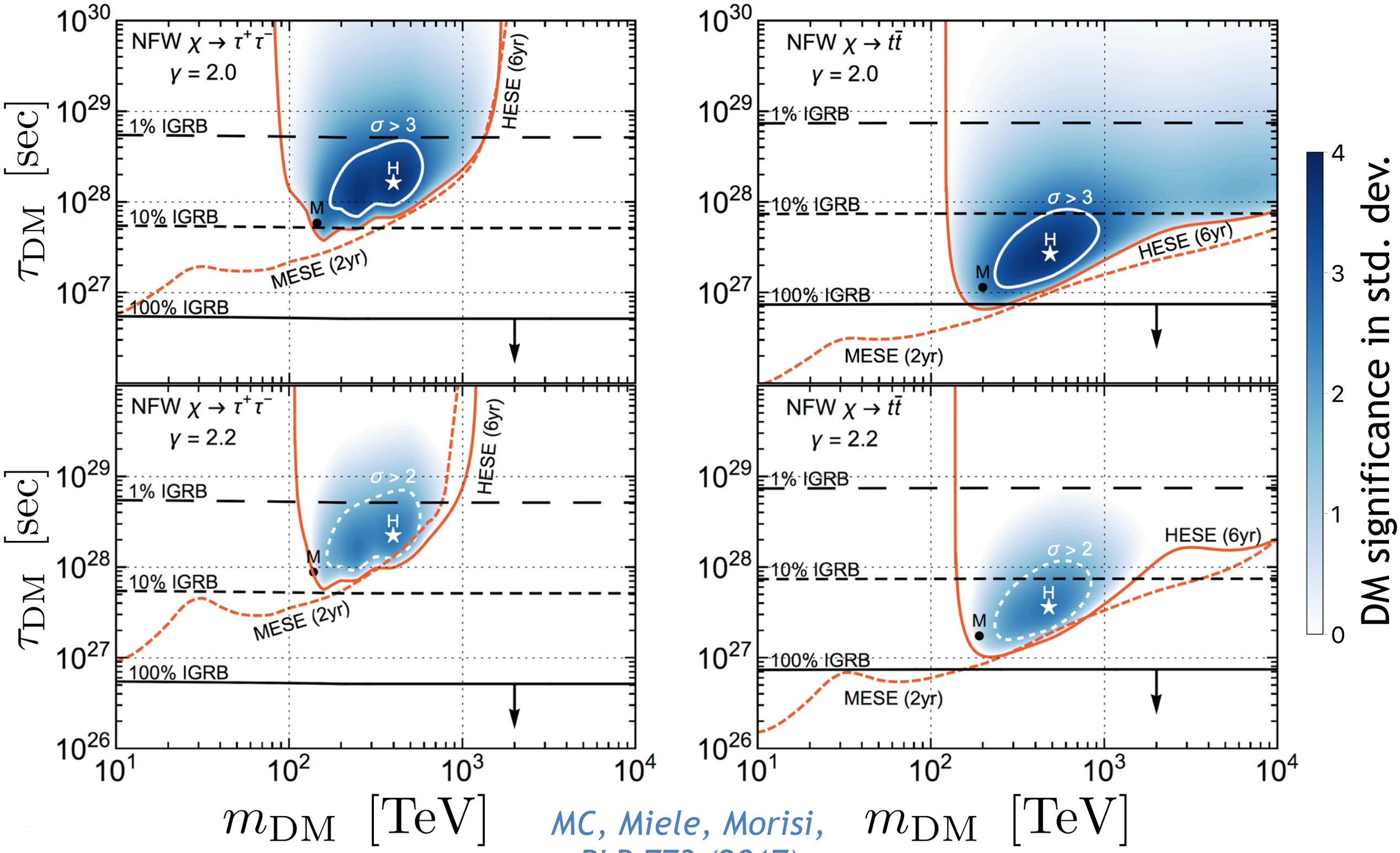
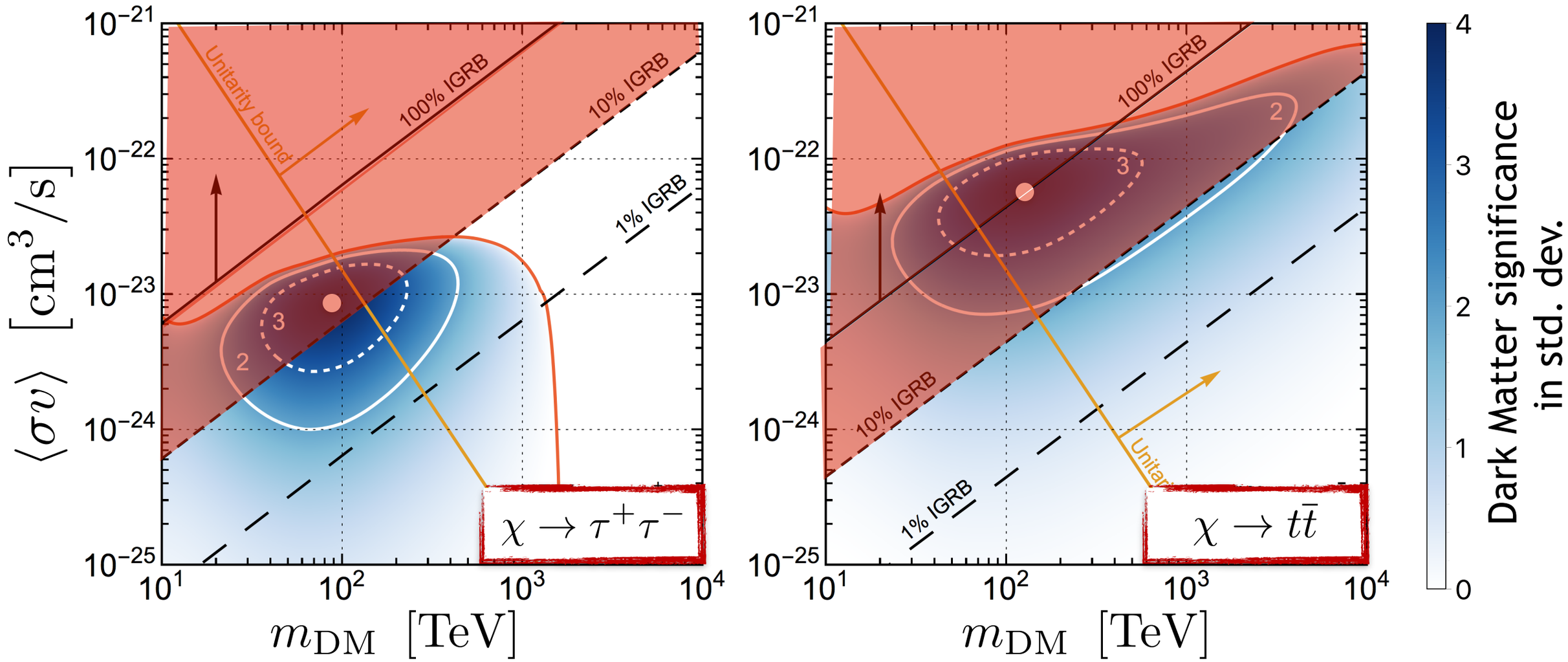
MC, Mele, Miele, Migliozzi, Morisi, ApJ 851 (2017)

6yr HESE: Decaying Dark Matter



MC, Miele, Morisi, PLB 773 (2017)

Annihilating Dark Matter



Dark Matter Flux

$$\frac{d\phi^{\rm DM}_{\rm ann.}}{dE_\nu d\Omega} \propto \frac{\langle \sigma v \rangle}{m^2_{\rm DM}}$$

Unitarity of cross-section

$$\langle \sigma\, v \rangle \leq 1.5 \times 10^{-23} \frac{\rm cm^3}{\rm s} \left(\frac{100\ \rm TeV}{m_{\rm DM}} \right)^2$$

MC, Miele, Morisi, JCAP 1701

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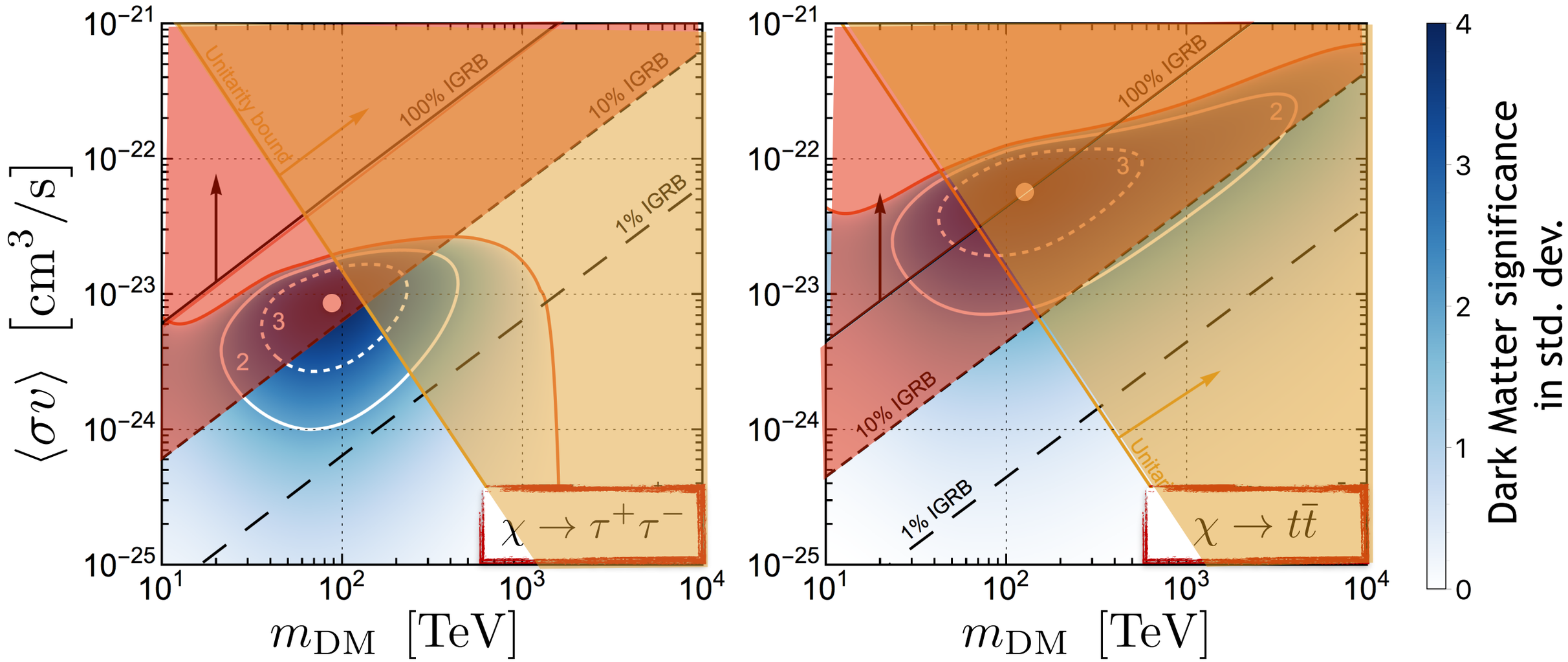

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MC, Miele, Morisi, JCAP 1701