The low-energy excess at ANTARES and IceCube Neutrino Telescopes: a potential Dark Matter signature

Marco Chianese

Dark Ghosts

13-14 November 2018, Brussels

BASED ON:

- *MC, Miele, Morisi, Vitagliano, PLB 757 (2016)*
- *MC, Miele, Morisi, JCAP 1701*
- *MC, Miele, Morisi, PLB 773 (2017)*
- *MC, Mele, Miele, Migliozzi, Morisi, ApJ 851 (2017)*
- *MC, Miele, Morisi, Peinado, arXiv:1808.02486*

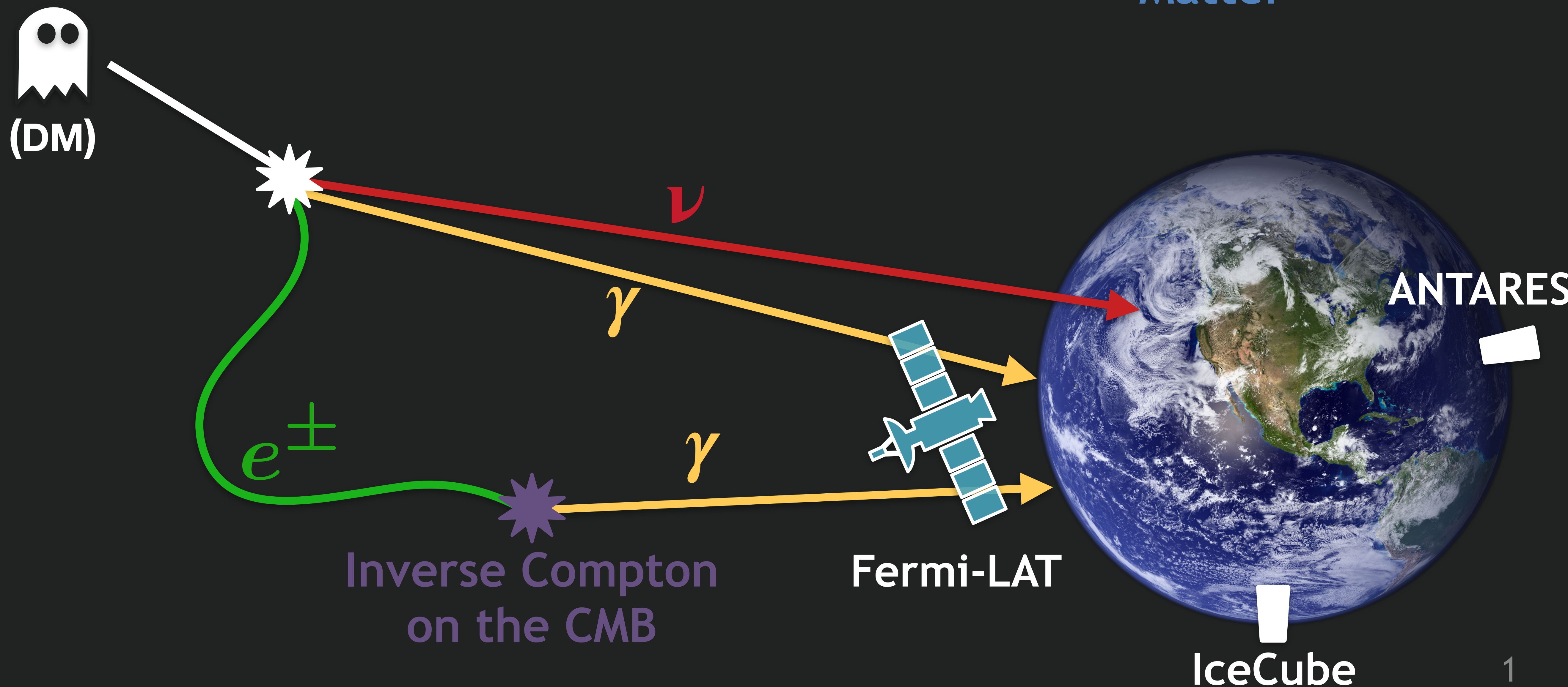
GRAPPA

GRavitation AstroParticle Physics Amsterdam

Dark Matter indirect detection: neutrinos and gamma-rays

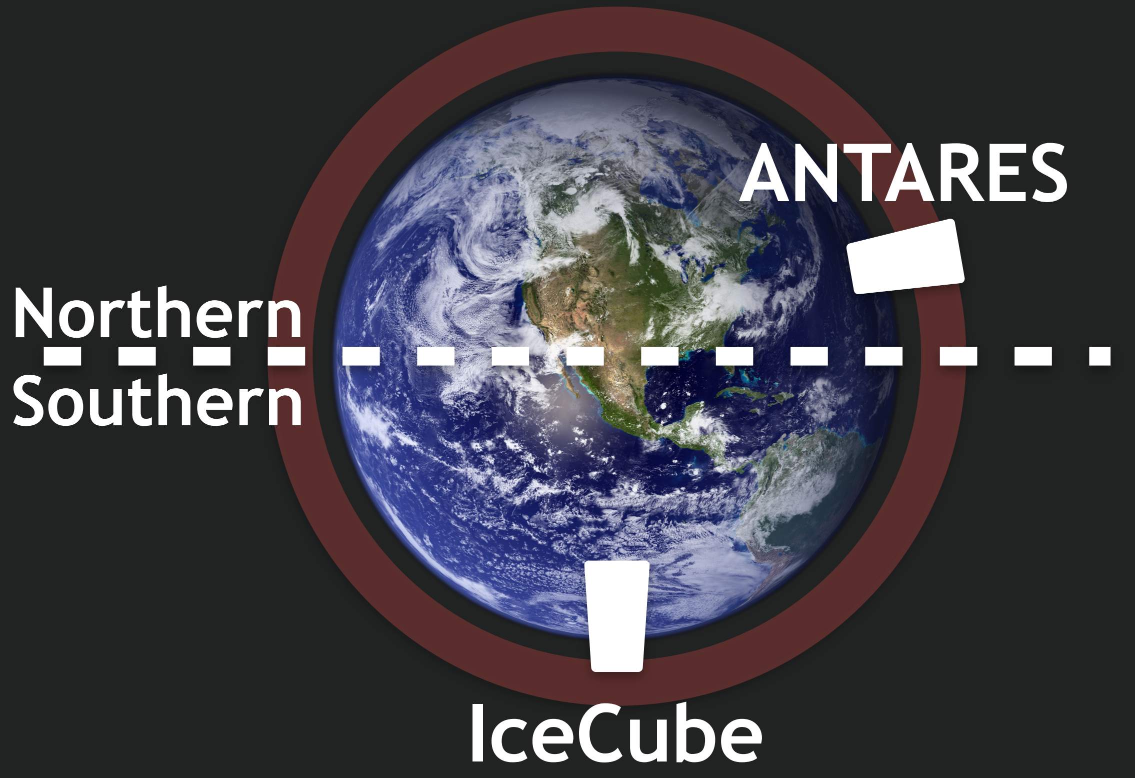
- **Dark Matter particles can decay/annihilate producing:**
  - **Neutrinos** travel in straight lines (**IceCube** and **ANTARES**/**KM3NET**)
  - **Gamma-Rays** are reprocessed (**Fermi-LAT**, H.E.S.S., CTA,…)

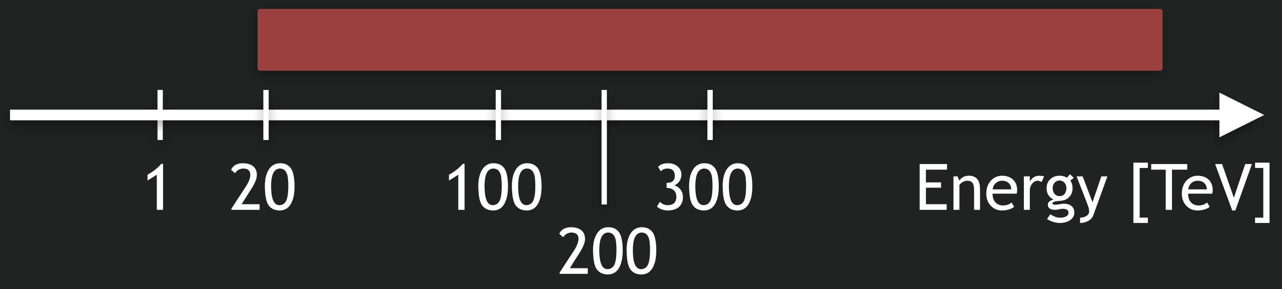
→ **Neutrino and Gamma-Ray Telescopes could provide important information about the nature of Dark Matter**



Neutrino Telescopes provide different data samples

- HESE - High Energy Starting Events
  - 82 events in 6 years
  - Full sky
  - High energy threshold





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- **MESE - Medium Energy Starting Events**
  - 388 events in 2 years
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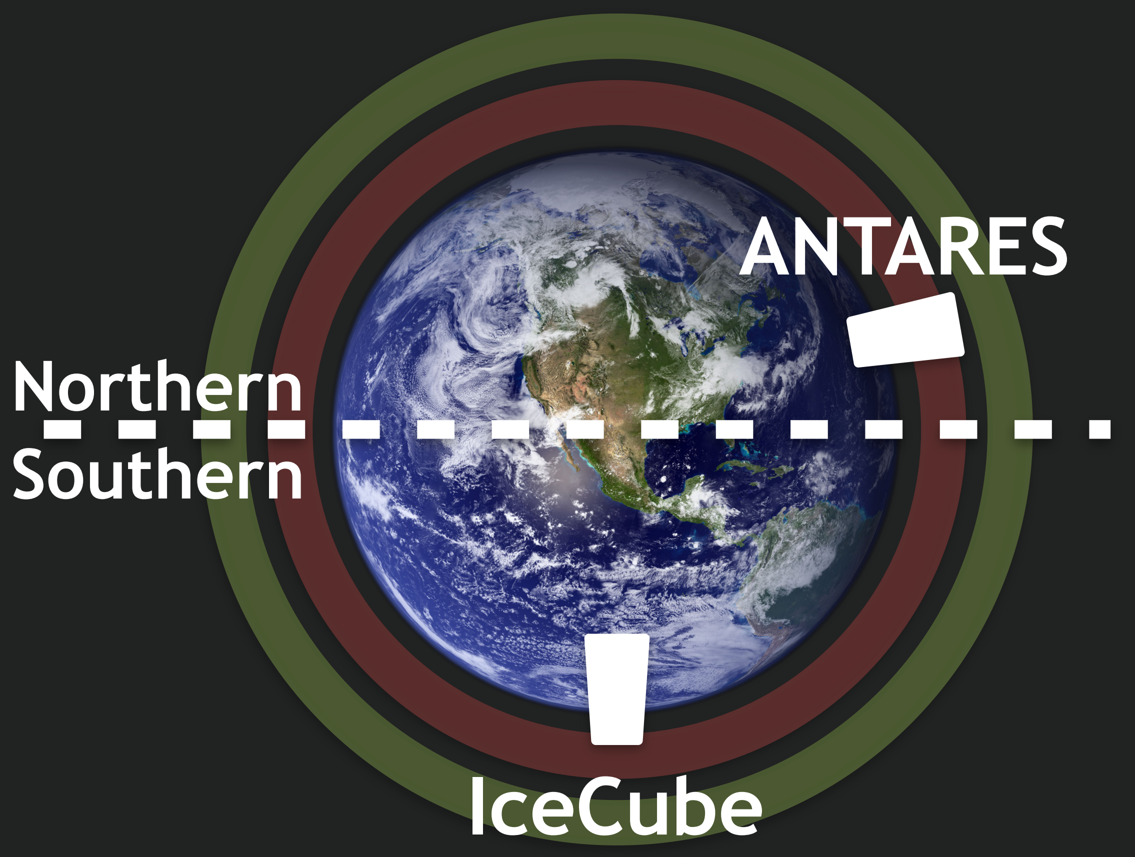
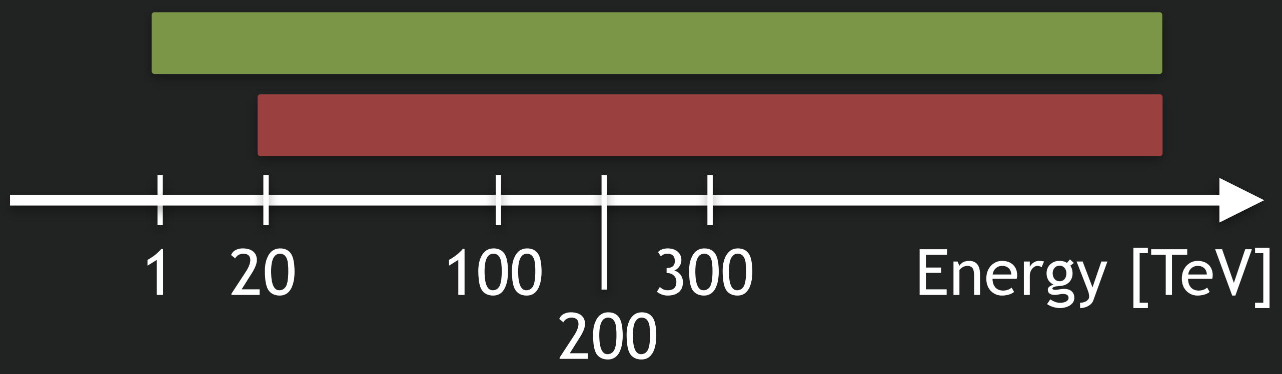
  - Low energy threshold





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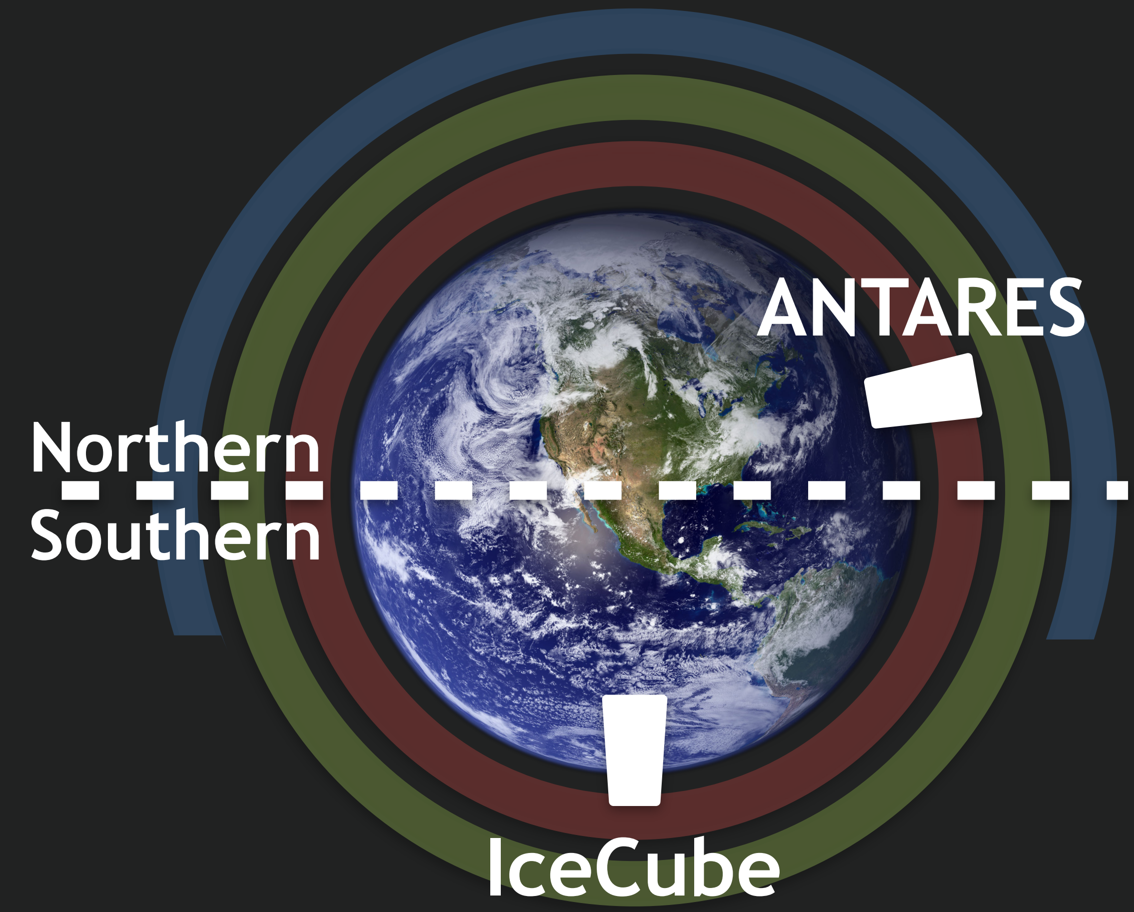
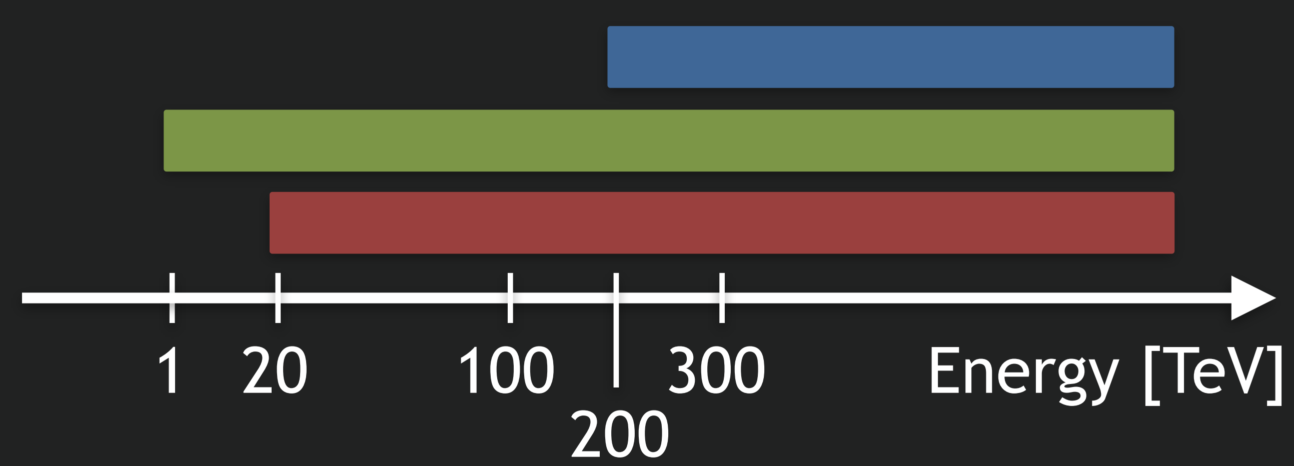
- **Up-going muon neutrinos**
  - 500 000 events in 8 years
  - Mainly Northern sky (up-going)
  - Very high energy threshold





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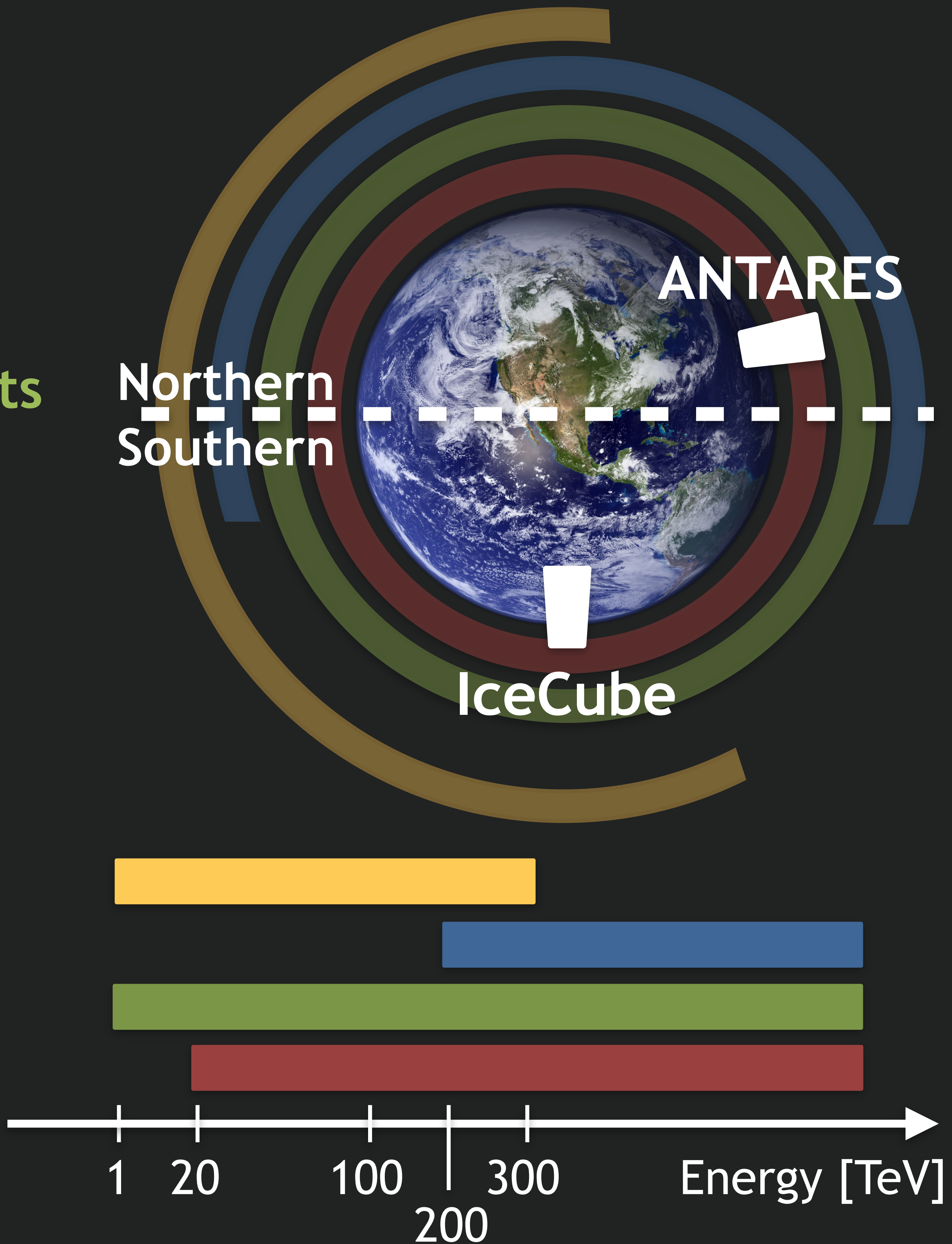
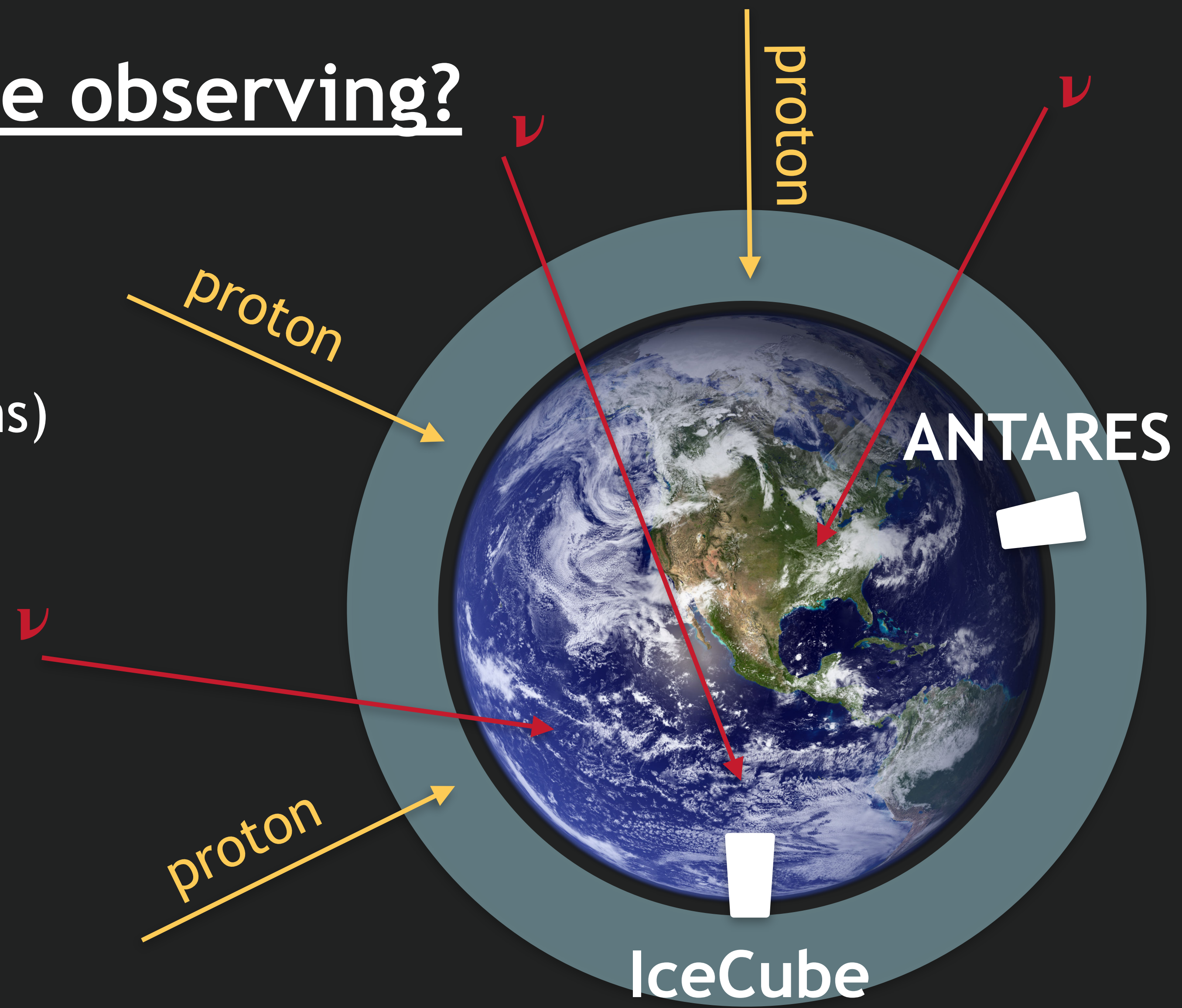
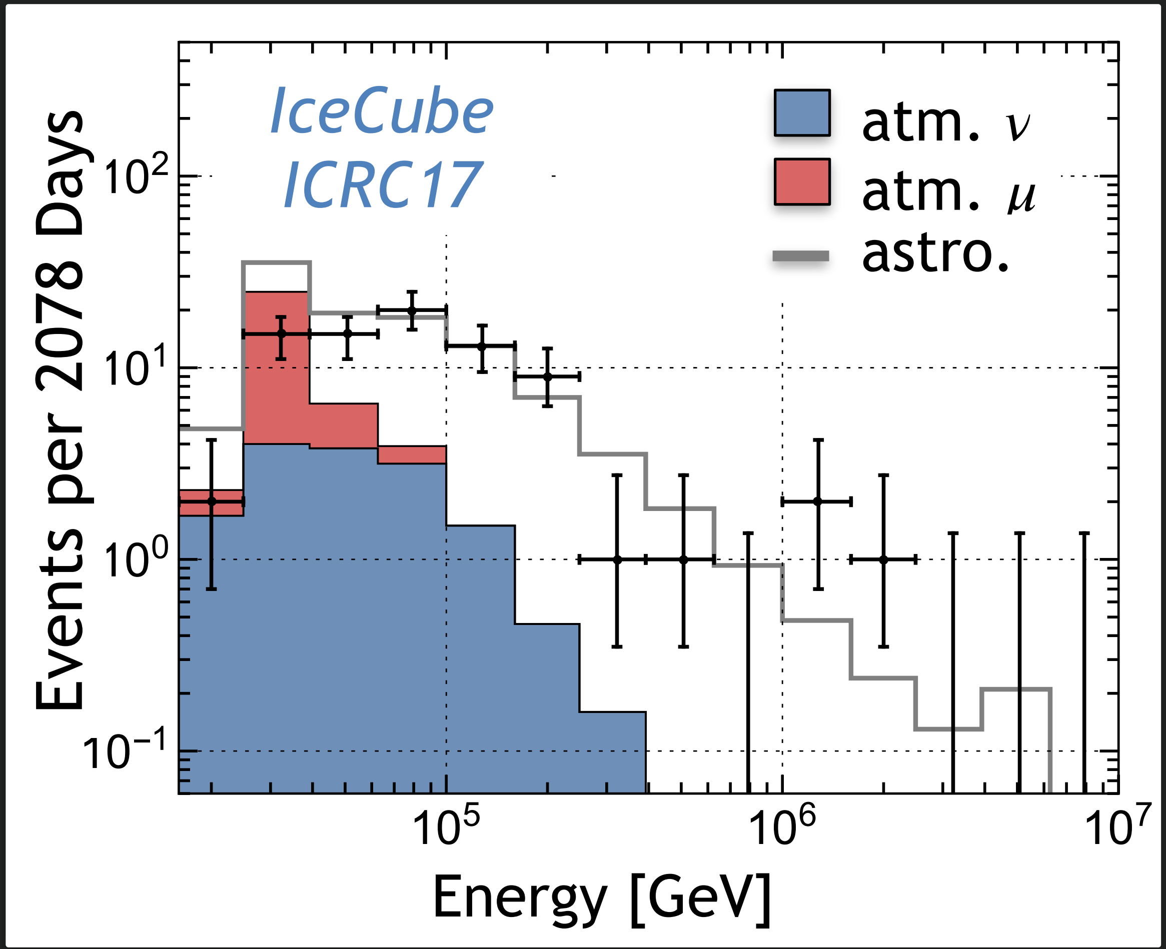
- **ANTARES**
  - 33 events in 9 years
  - Energy up to ~ 300 TeV



The neutrino flux: what are we observing?

- **Atmospheric background**
  - Penetrating muons
  - *Conventional* neutrinos (pions and Kaons)
  - *Prompt* neutrinos (charmed mesons)
- **Astrophysical neutrinos**
  - Extragalactic sources (isotropic)
  - Neutrino flavour ratio (1:1:1)





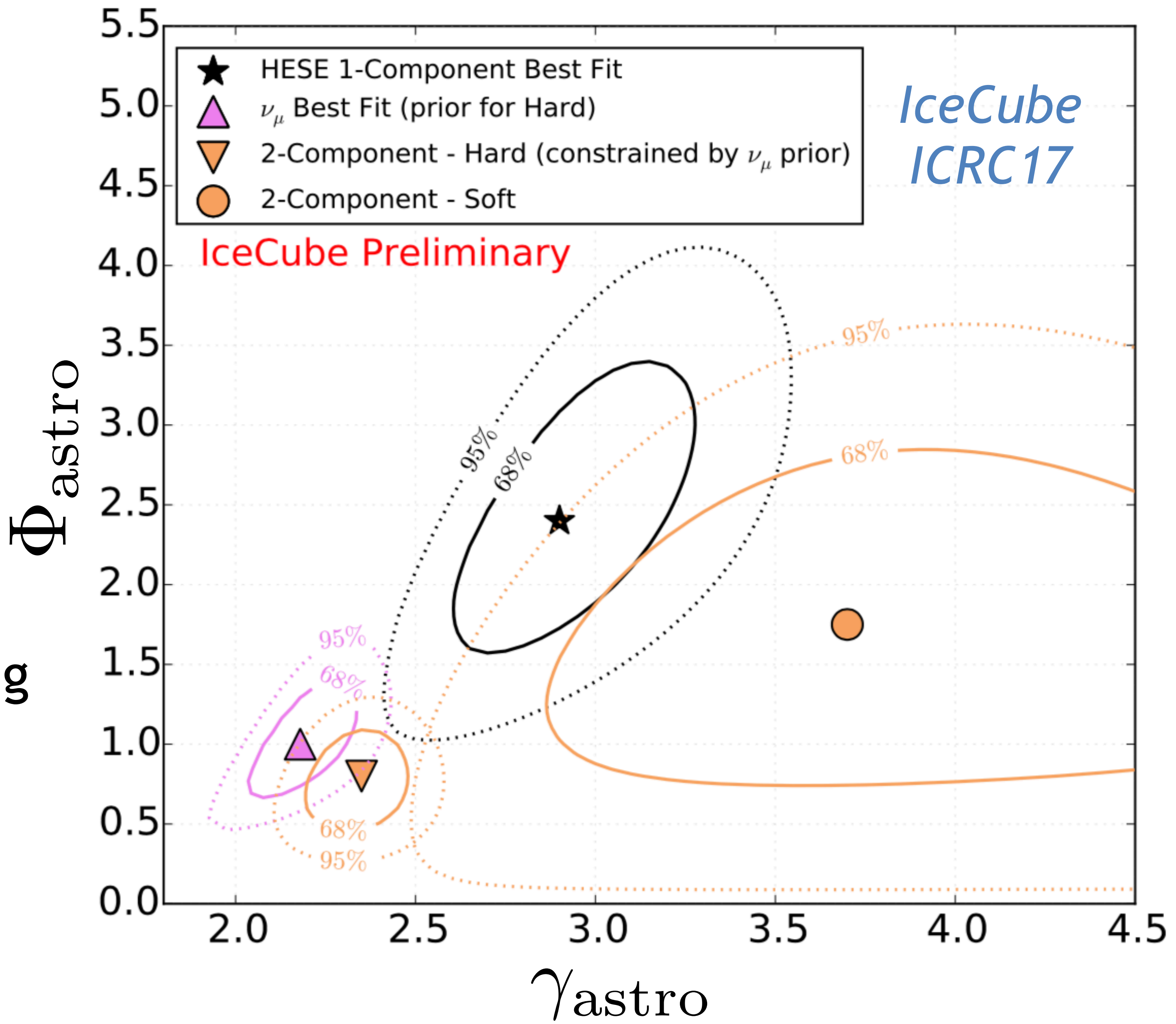
The astrophysical neutrino flux is parametrized by a power-law

$$\frac{d\phi^{\text{astro}}}{dE_\nu d\Omega} = \phi_0 \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma}$$

The Fermi acceleration mechanism predicts a spectral index equal to 2.0

Tension with single power-law

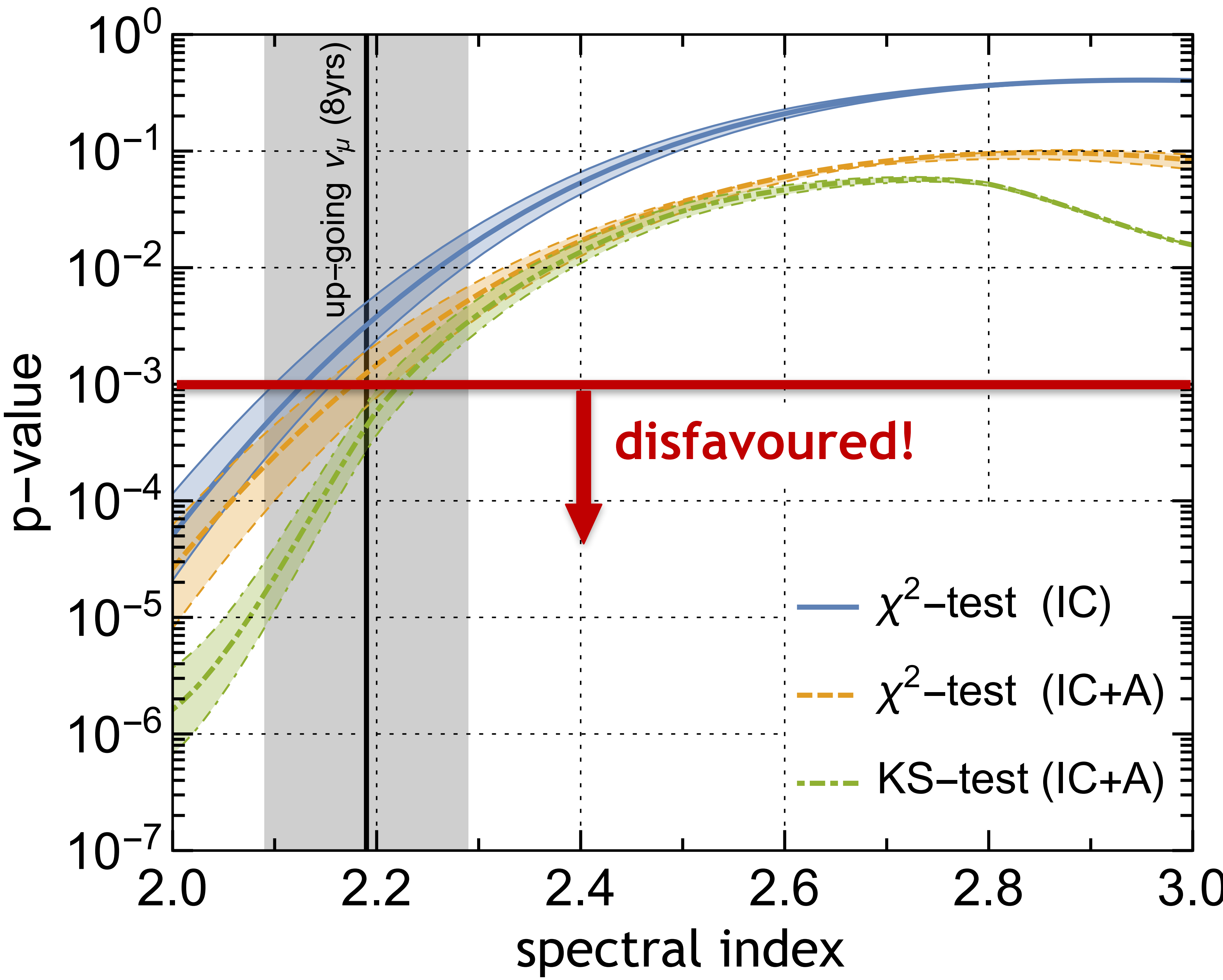
Data sample	Spectral index
HESE (6yrs)	$2.92^{+0.29}_{-0.33}$
MESE (2yrs)	$2.46^{+0.12}_{-0.12}$
Up-going muon neutrinos (8yrs)	$2.19^{+0.10}_{-0.10}$
TXS 0506+056	$2.10^{+0.20}_{-0.20}$



- Discrepancy (3σ) between the up-going muon neutrinos and the other data
- More neutrinos at $E_\nu \leq 200$ TeV
- Asymmetry between North and South

Tension with the simplest assumption of a single power-law: the observed neutrino flux is given by **two contributions** dominating at low (100 TeV) and high energies (PeV), respectively.

Combining IceCube and ANTARES



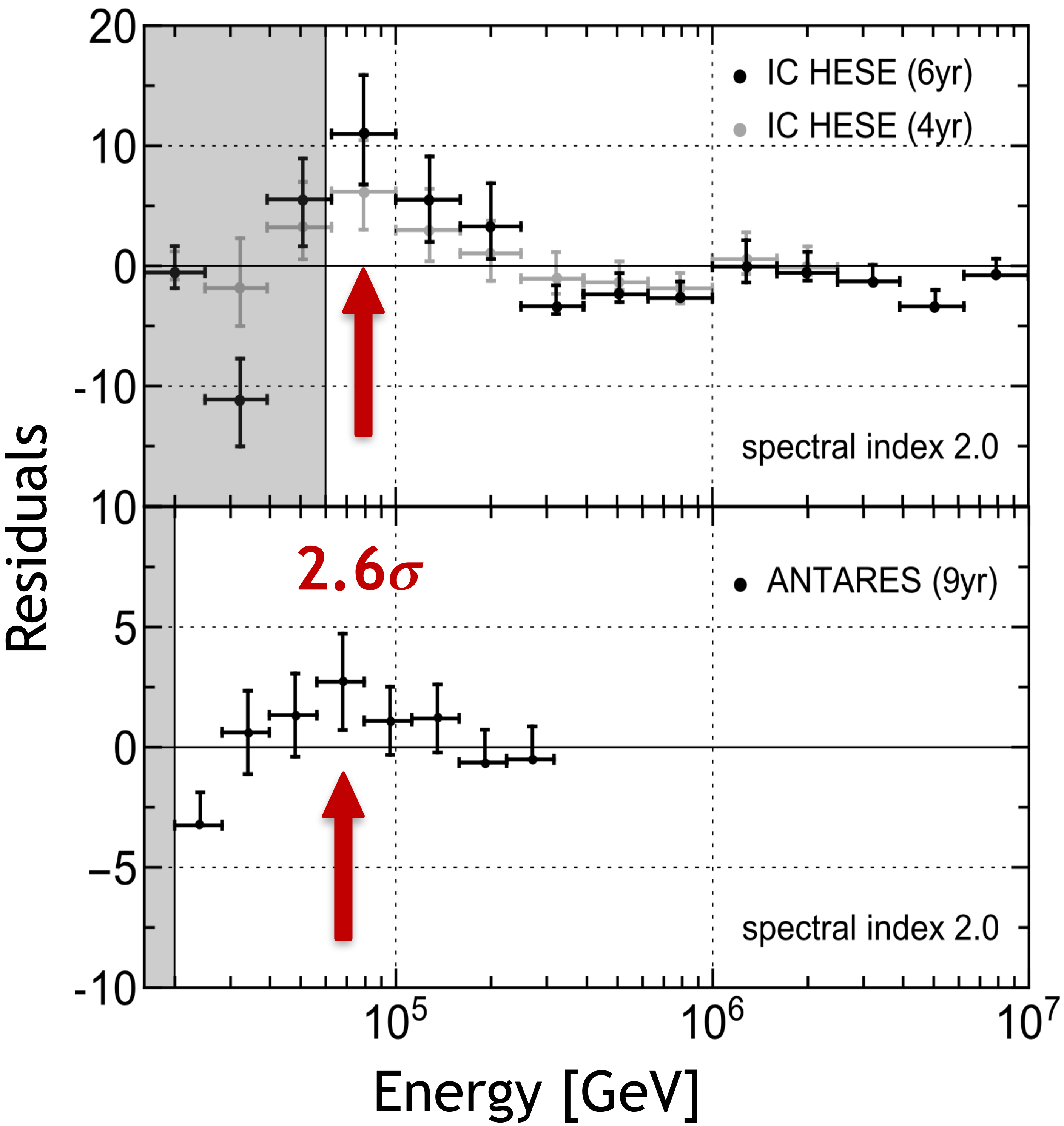
We performed a goodness-of-fit test to scrutinize the *null hypothesis* of a single power-law neutrino flux:

- The smaller the p-value, the less probable is the null hypothesis;
- The two data samples are combined by using the Fisher's method;
- The ANTARES data reduce the p-value by a factor of 2-3.

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

The addition of the ANTARES data further strengthens the tension with the up-going muon neutrino fit

The low-energy excess



We assume as benchmark a spectral index equal to 2.0. Such a value is compatible with:

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

low-energy excess!

Dark Matter at 100 TeV?

Neutrino flux: our assumption

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

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

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**

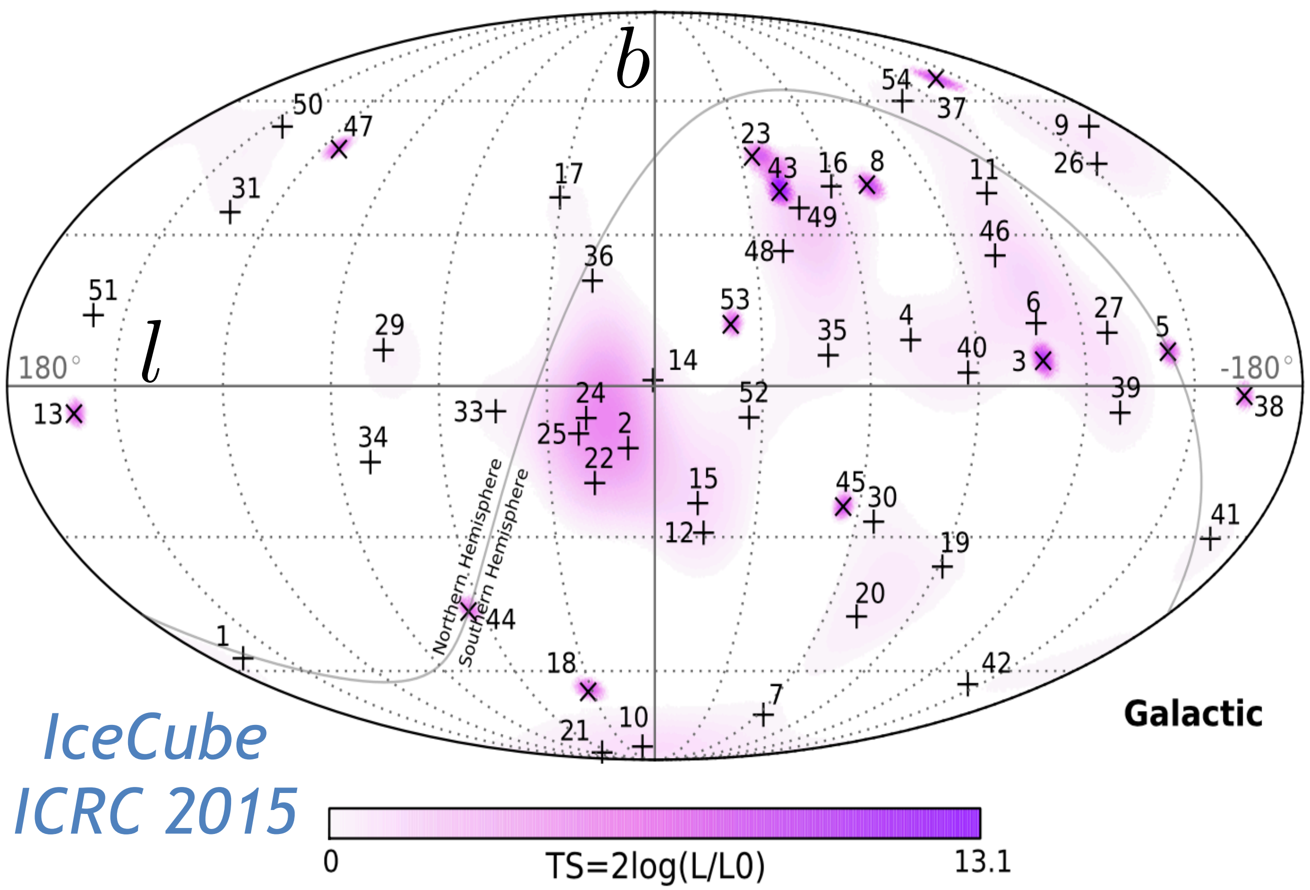
- Leptonic/hadronic final states

$$\chi \to \tau^+\tau^- \;/\; \chi \to t\bar{t}$$

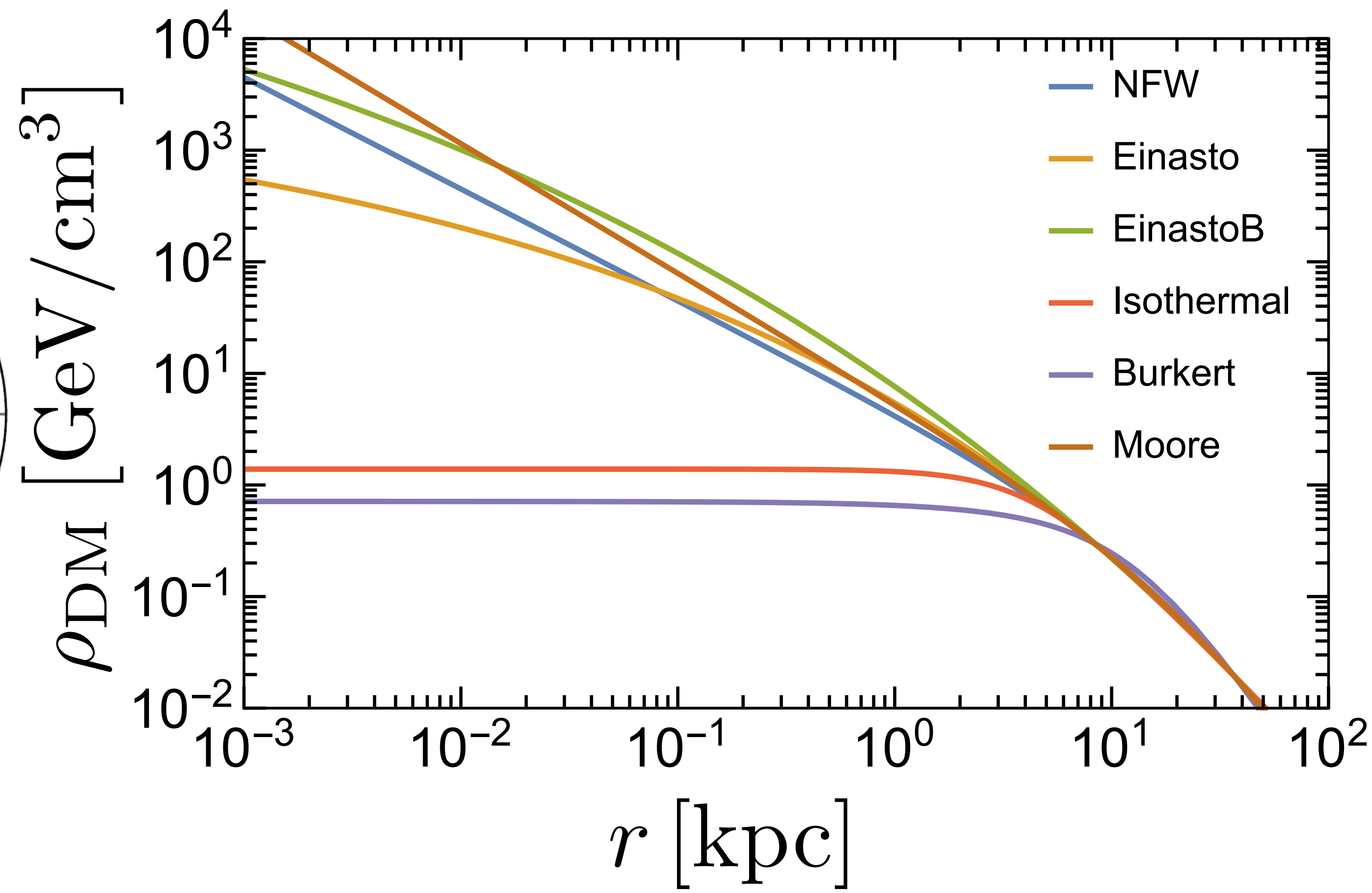
→ **Analysis on energy spectrum**

Analysis on Angular Distribution

Observable: sky map



Theory: density profile



$$\left(r = \sqrt{s^2 + r_\odot^2 - 2\, r_\odot\, s \cos b \cos l} \right)$$

Decaying or Annihilating Dark Matter?

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

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

Results

Scenario		KS	AD
Astrophysics	Gal. plane	0.007 - 0.008	not defined
	Iso. dist.	0.20 - 0.55	0.17 - 0.54
DM decay	NFW	0.06 - 0.16	0.03 - 0.14
	Isoth.	0.08 - 0.22	0.05 - 0.19
DM annih. $\Delta_0^2 = 10^4$	NFW	$(0.3 - 0.9) \times 10^{-4}$	$(0.3 - 3.8) \times 10^{-4}$
	Isoth.	$(0.9 - 2.8) \times 10^{-3}$	$(1.0 - 5.0) \times 10^{-3}$
DM annih. $\Delta_0^2 = 10^6$	NFW	0.02 - 0.05	0.02 - 0.07
	Isoth.	0.10 - 0.28	0.08 - 0.29
DM annih. $\Delta_0^2 = 10^8$	NFW	0.19 - 0.54	0.17 - 0.53
	Isoth.	0.20 - 0.55	0.17 - 0.54

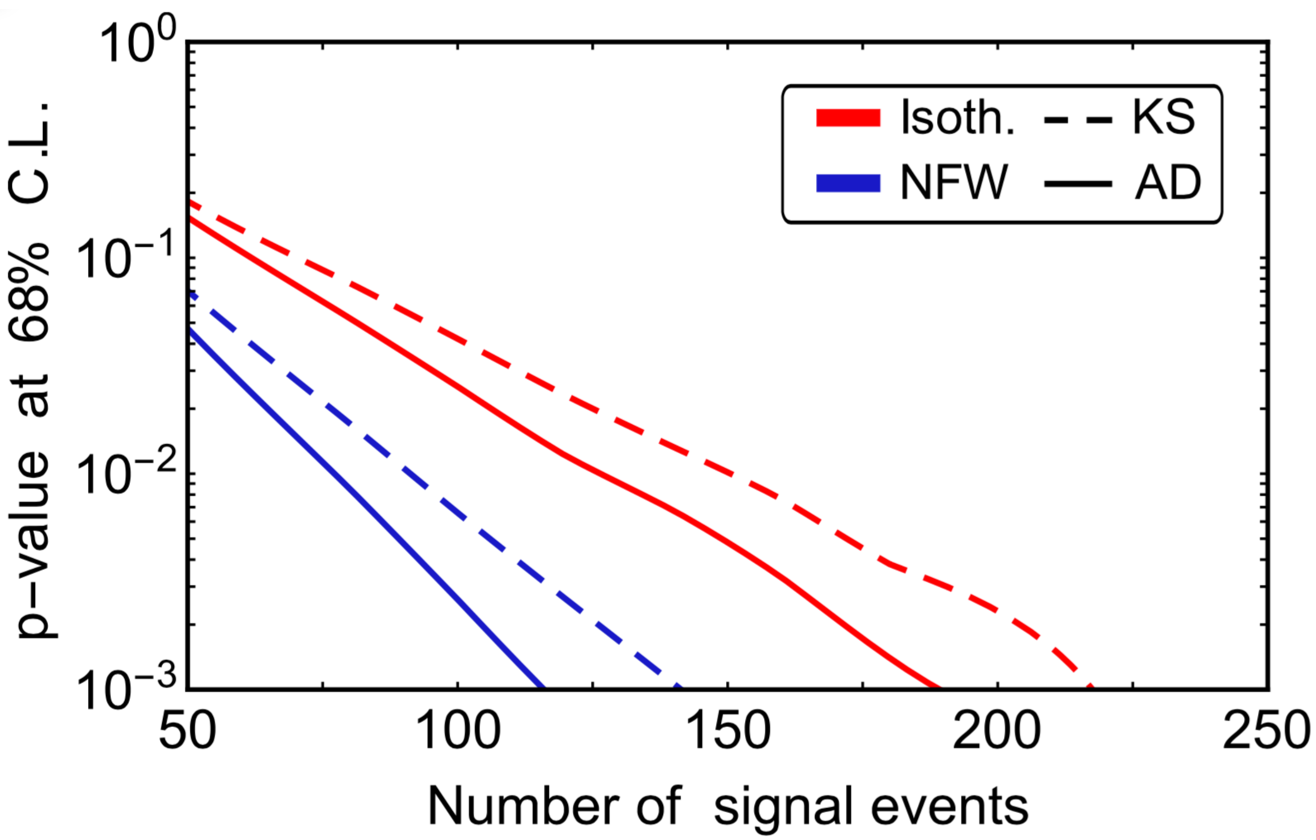
The main results of the analysis are:

- **Disfavor** the correlation with the Galactic Plane;
- Annihilating Dark Matter **excluded** for some choices of parameters.

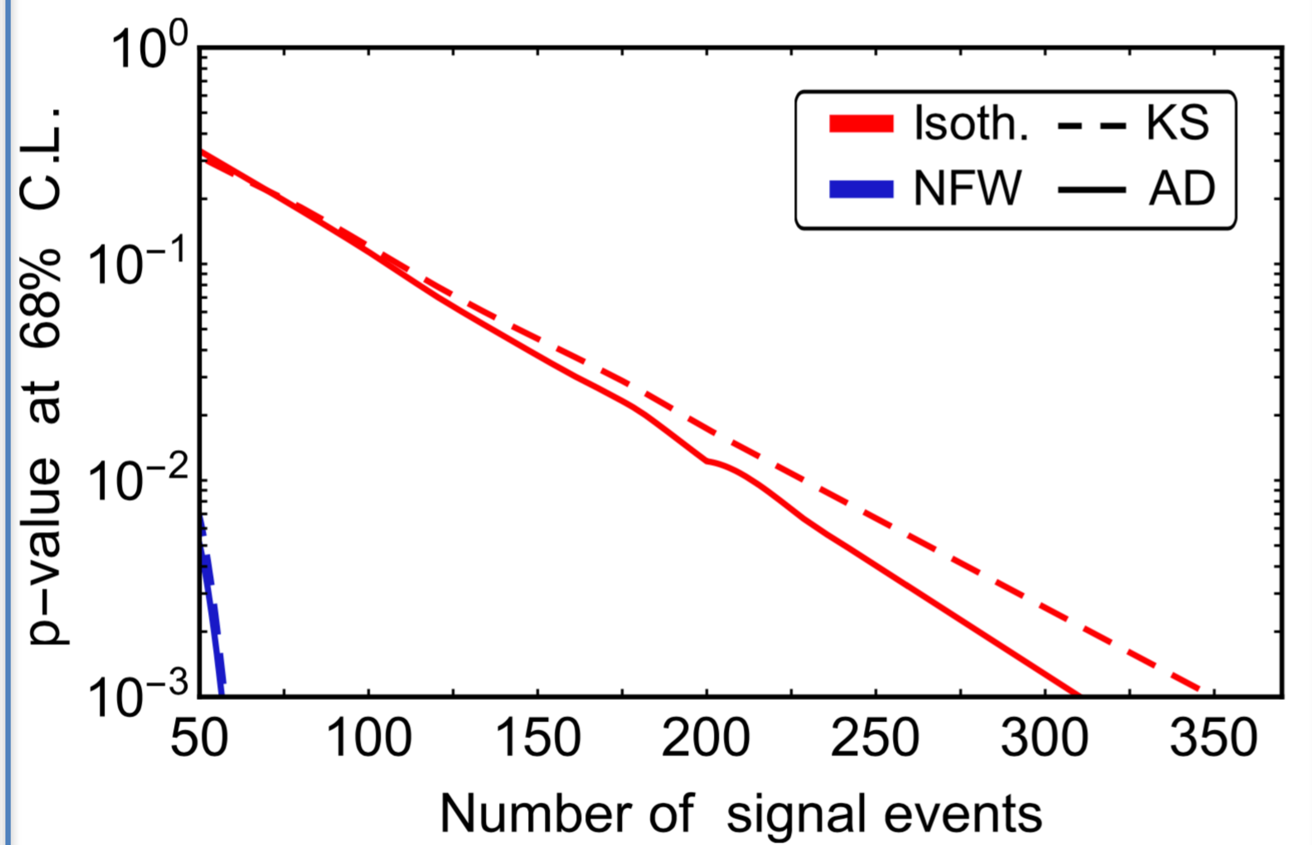
MC, Miele, Morisi, Vitagliano, PLB 757 (2016)

Forecast

Few hundreds neutrino events are required to exclude a Dark Matter explanation of the low-energy excess.



Decaying DM

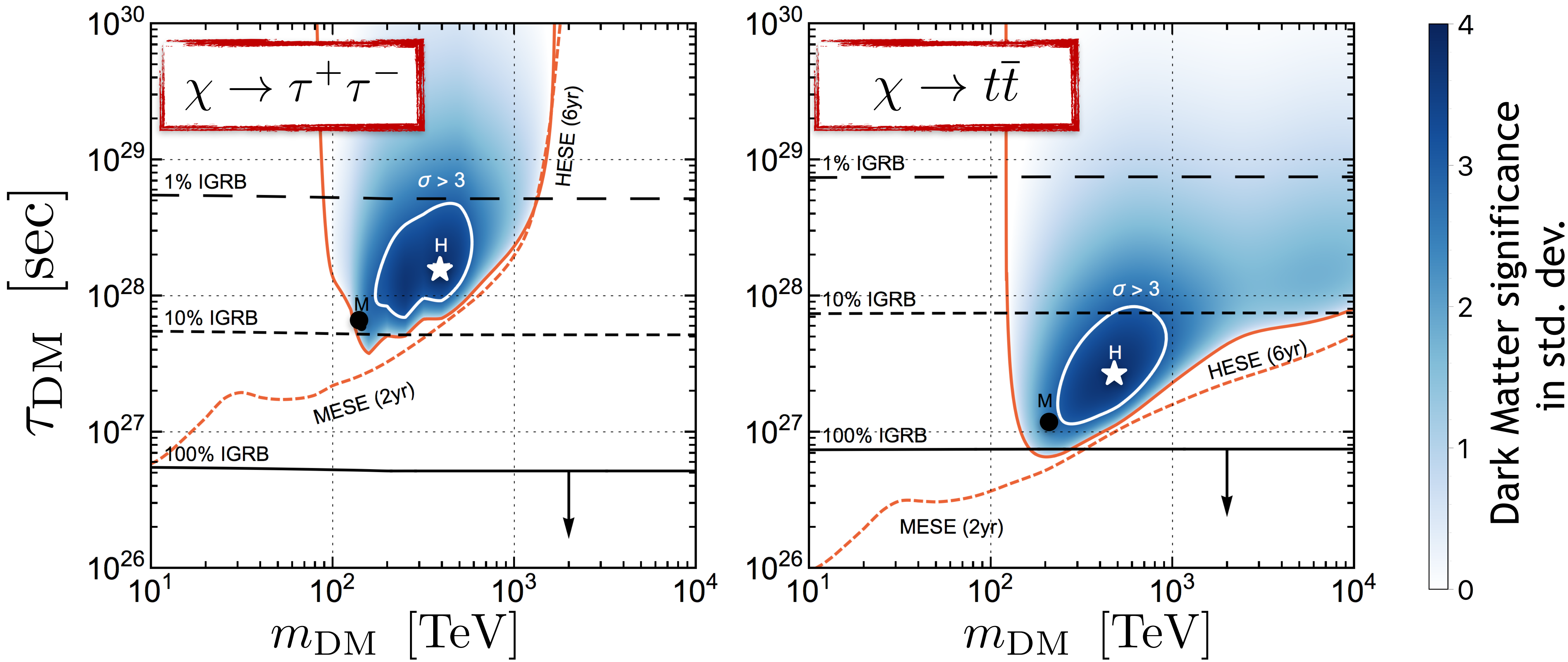


Annihilating DM

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

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

Decaying Dark Matter



Dark Matter Flux

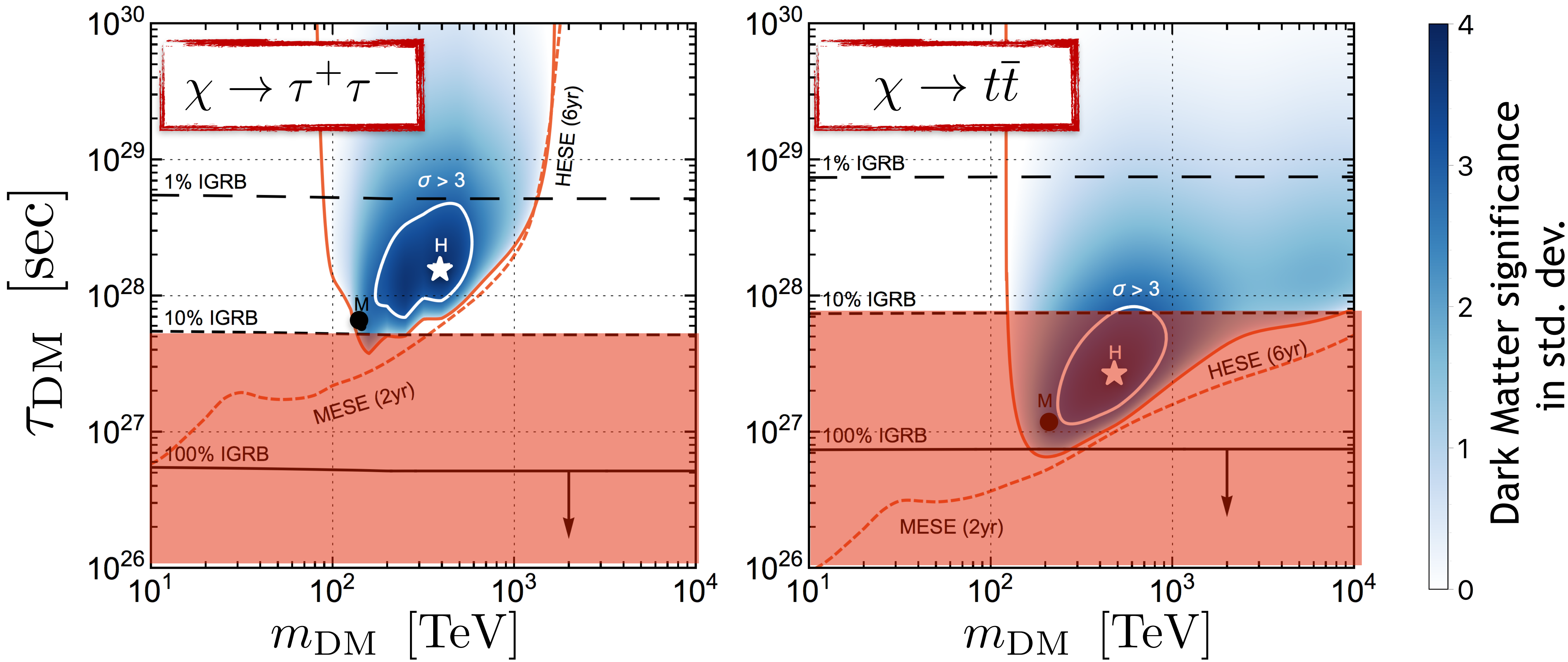
$$\frac{d\phi^{\rm DM}_{\rm dec.}}{dE_\nu d\Omega} \propto \frac{1}{\tau_{\rm DM}\, m_{\rm DM}}$$

Gamma-Rays Constraints

The Fermi-LAT measurements of the Isotropic Gamma-Rays Background (**IGRB**) provide strong constraints to Dark Matter models.

MC, Miele, Morisi, PLB 773 (2017)

Decaying Dark Matter



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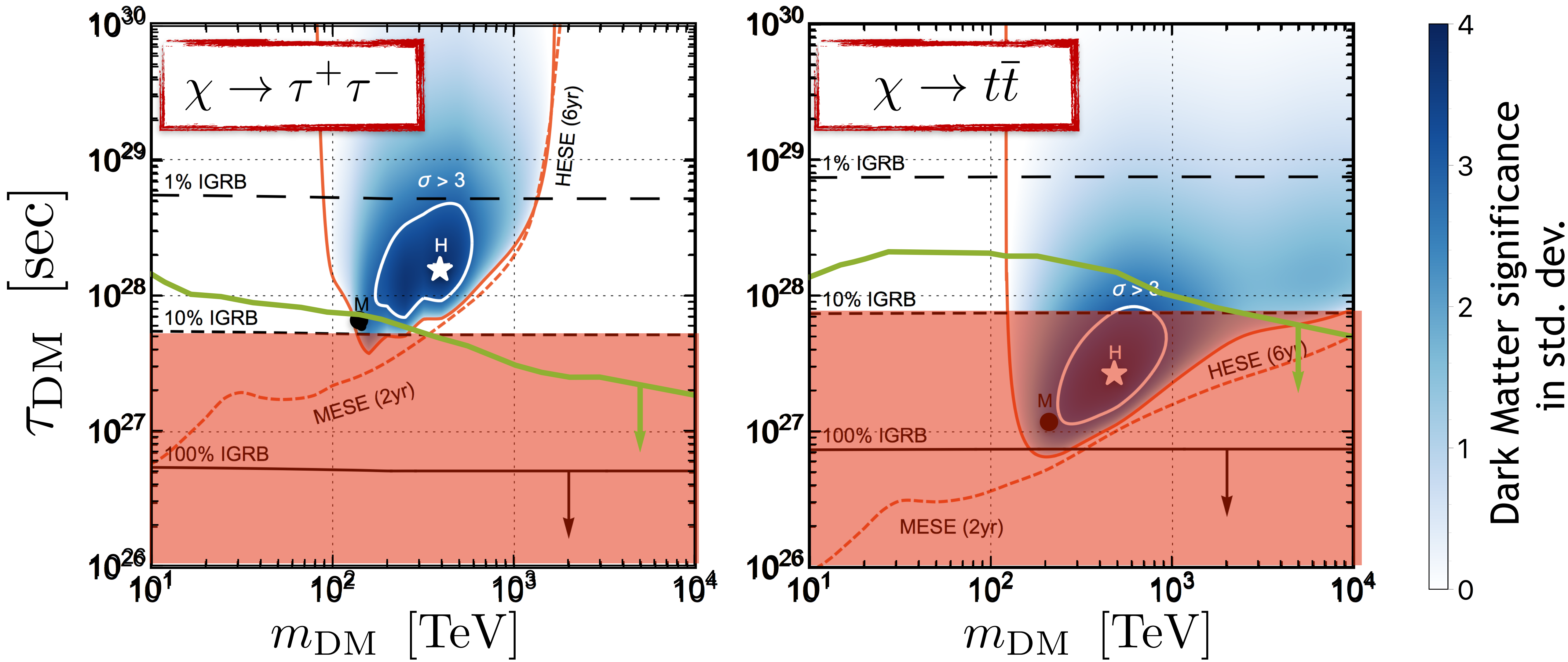

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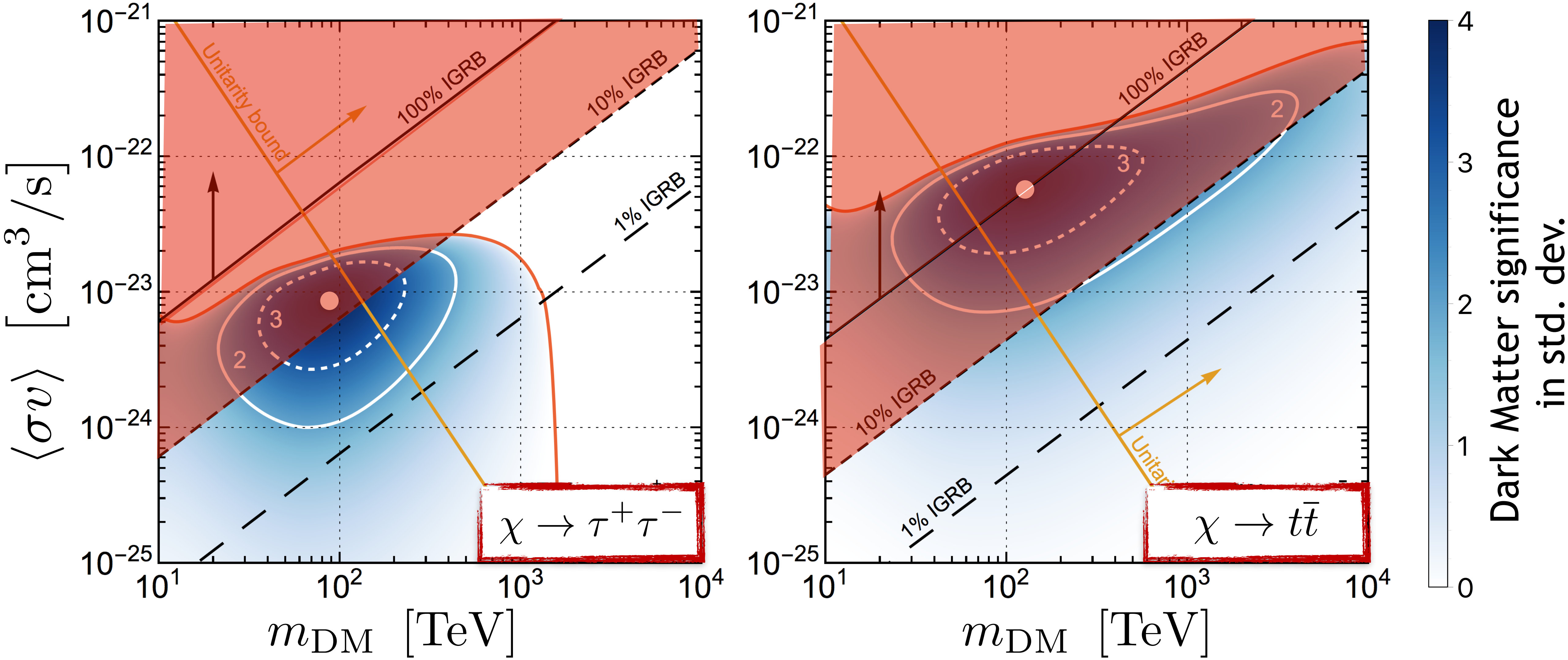
STRONGEST LIMITS: *Cohen et al., PRL17*

MC, Miele, Morisi, PLB 773 (2017)

Annihilating Dark Matter



Dark Matter Flux

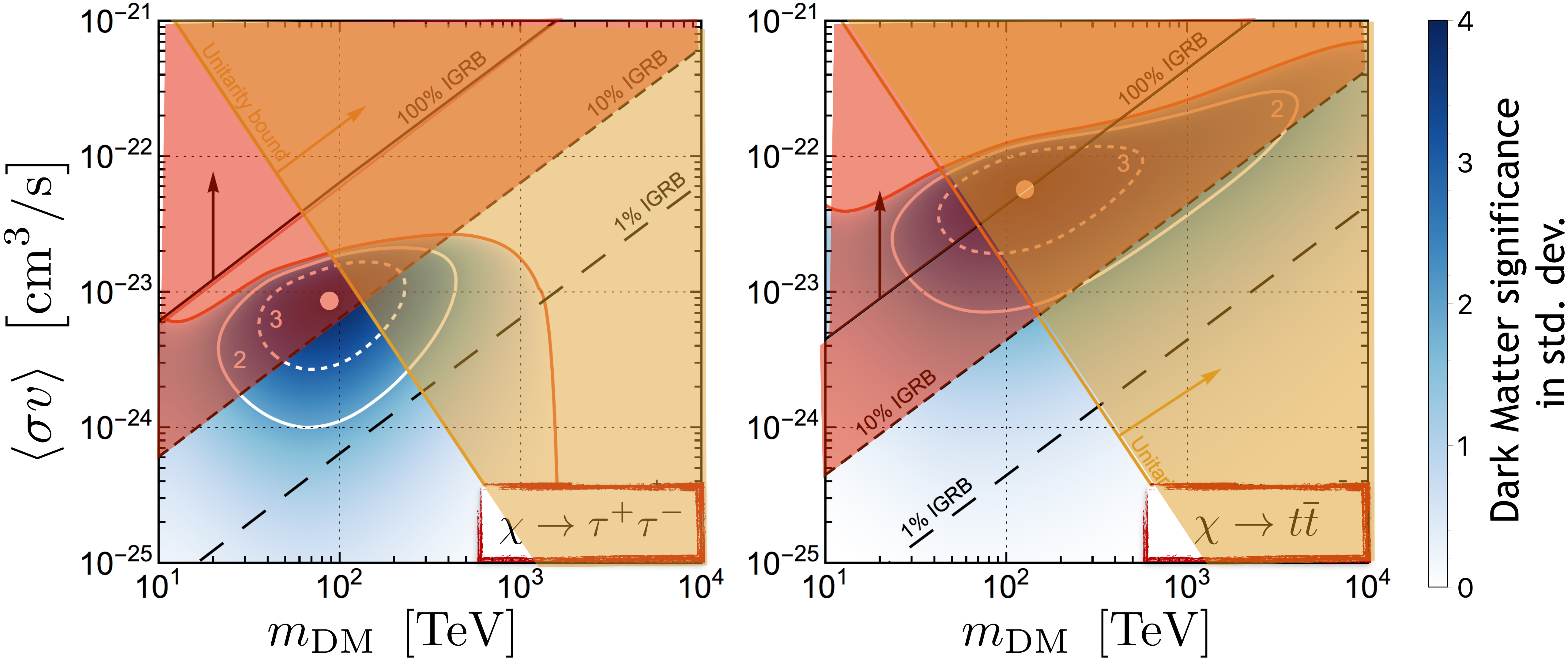
$$\frac{d\phi^{DM}_{ann.}}{dE_\nu d\Omega} \propto \frac{\langle \sigma v \rangle}{m^2_{DM}}$$

Unitarity of cross-section

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

MC, Miele, Morisi, JCAP 1701

Annihilating Dark Matter



Dark Matter Flux

Unitarity of cross-section

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

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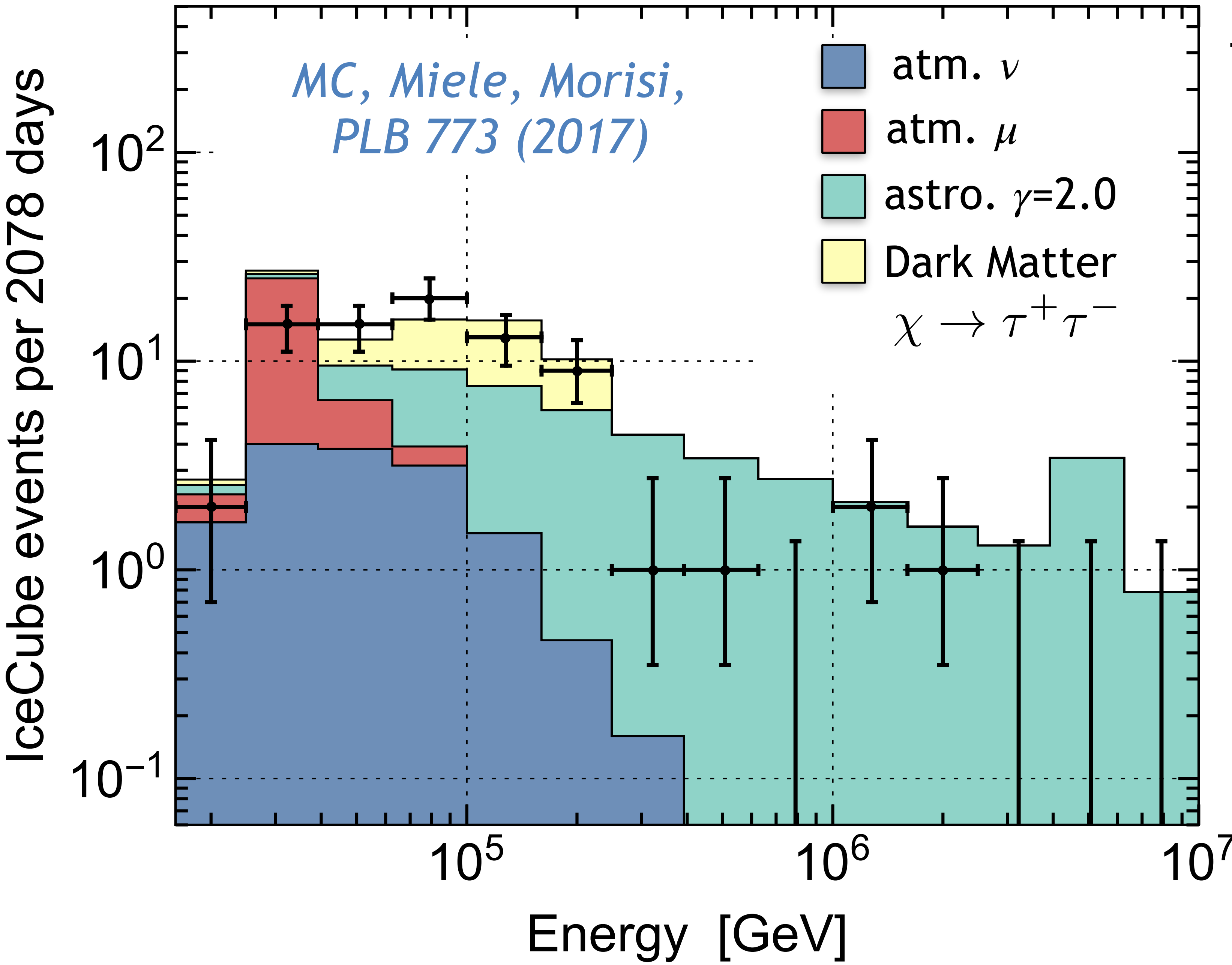
MC, Miele, Morisi, JCAP 1701

Main results



The main results are:

- annihilating Dark Matter is almost excluded.
- hadronic final states highly disfavoured.

↓

Decaying leptophilic Dark Matter

The low-energy excess can be explained by Dark Matter: we have investigated a consistent model allocating a neutrinophilic decaying Dark Matter candidate.

Neutrinophilic Dark Matter

The main features of the studied model allowing only for Dark Matter decays into a neutrino line 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)

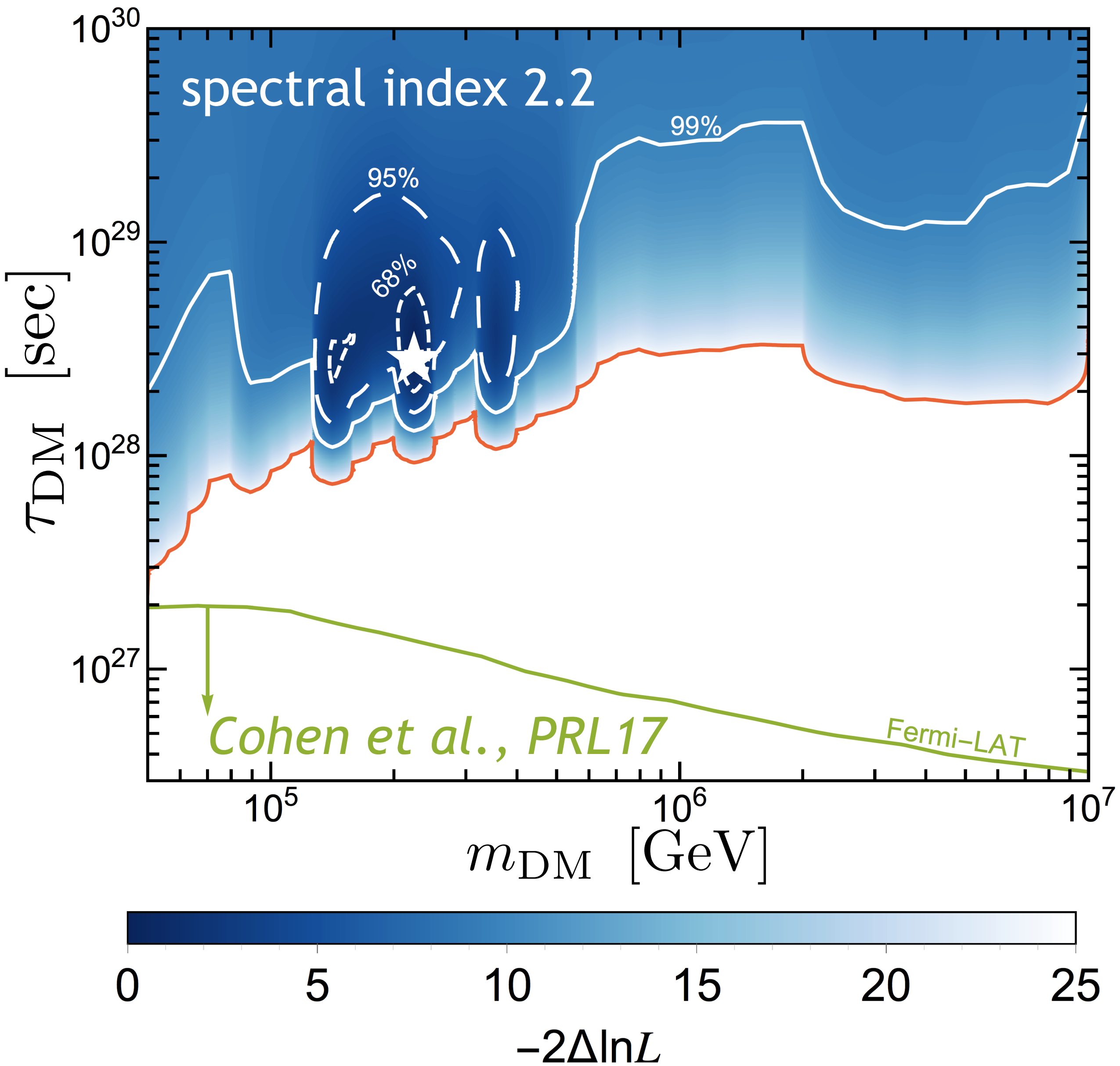
→

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

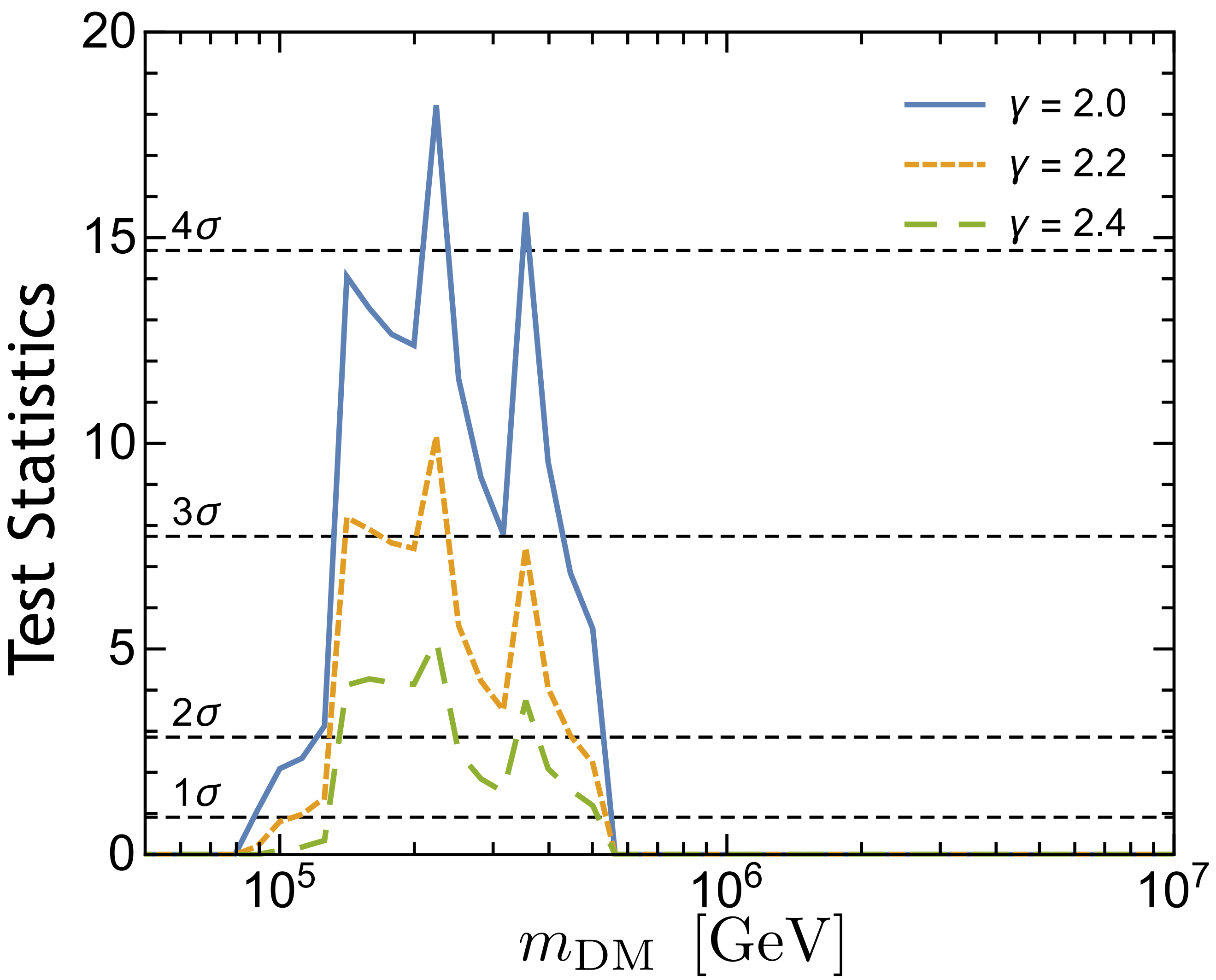
additional long-lived unstable particles

Neutrinophilic Dark Matter

Likelihood Profile



Likelihood-Ratio



The significance of the Dark Matter signal ranges from 2σ to 4σ, depending on the value of the spectral index of the astrophysical power-law.

MC, Miele, Morisi, Peinado, arXiv:1808.02486

Conclusions

The tension among different data samples strongly suggest a **two-component neutrino flux**.

First combined analysis of the latest IceCube and ANTARES data:

- the tension with the single power-law hypothesis is strengthened;
- both experiments show a **2.6σ excess** in the energy range 40–200 TeV.

The **low-energy excess** can be explained in terms of **dark matter**:

- decaying leptophilic Dark Matter models are still viable;
- a consistent neutrinophilic dark matter model is not easy to realize in a minimal framework.

More statistics (IceCube-Gen2 and KM3NeT) and **multi-messenger observations/analyses** are crucial.

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Thank you for your attention

Backup Slides

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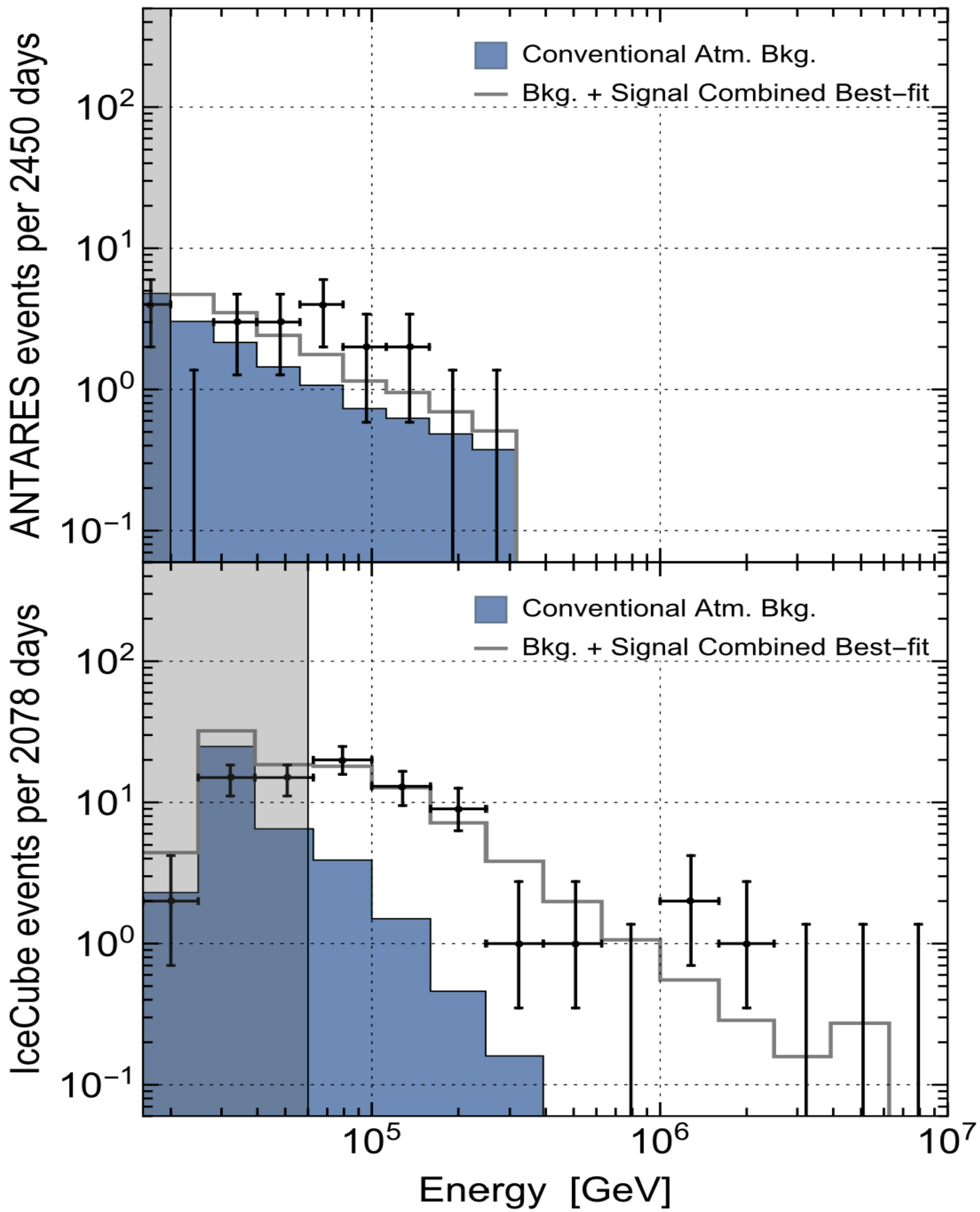
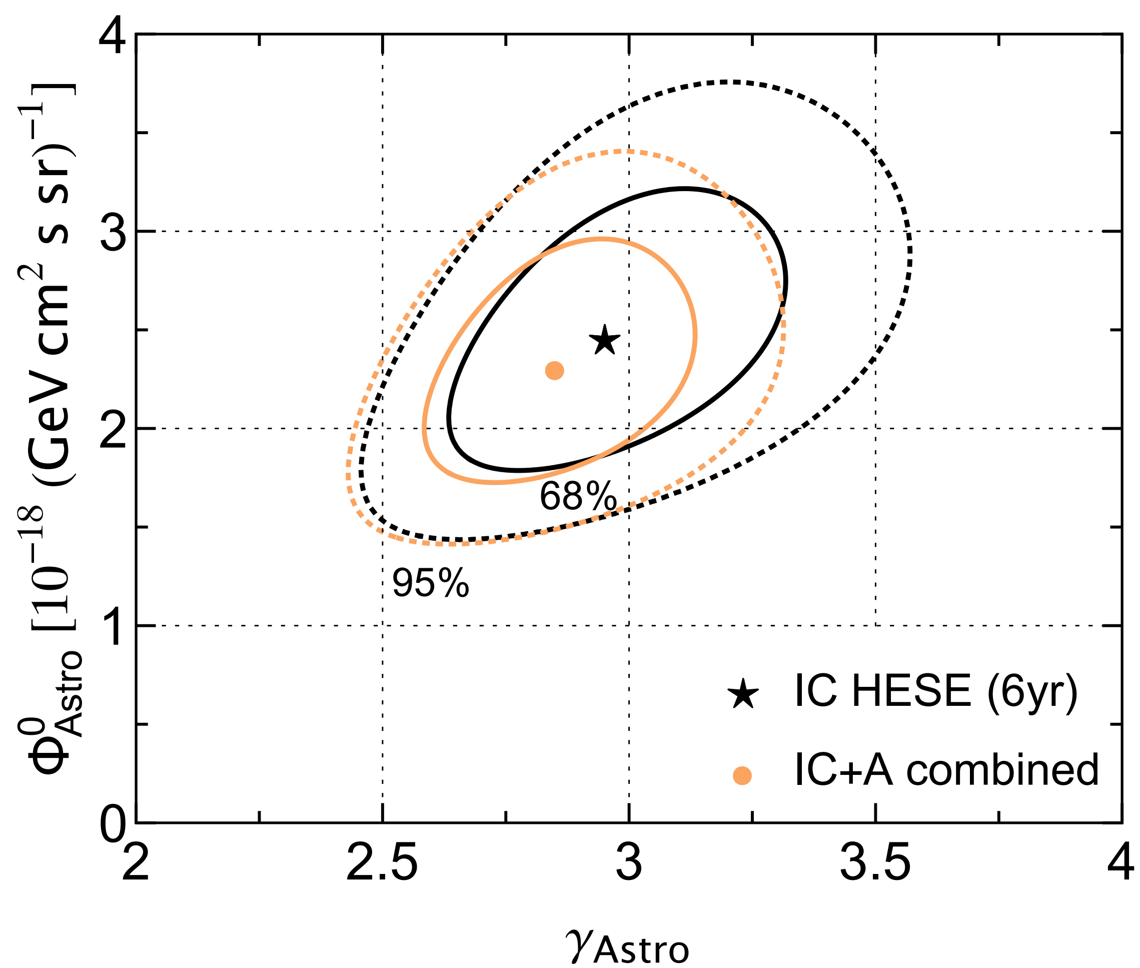
Combined analysis: IC + ANTARES

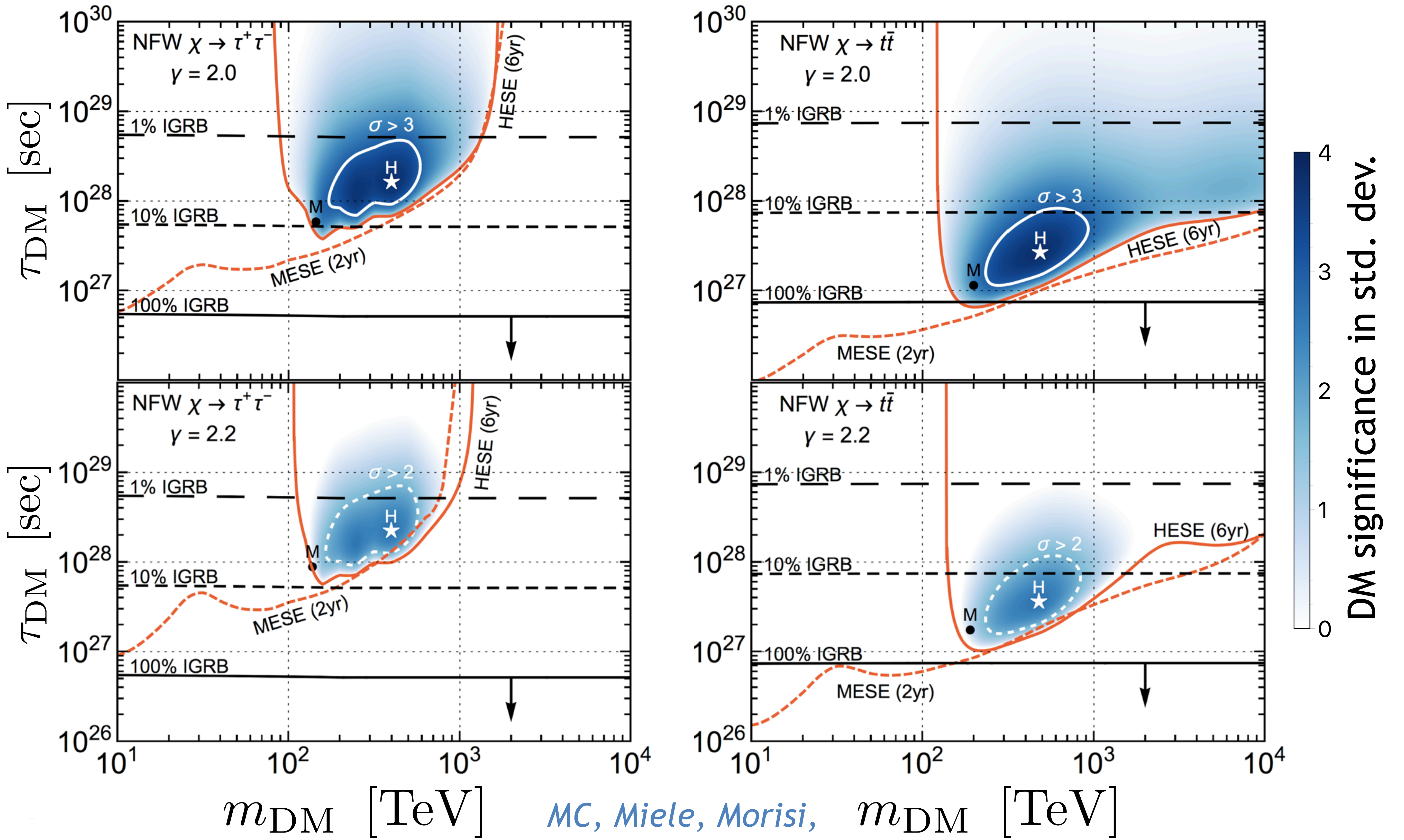




Data sample	Spectral index
HESE (6y)	$2.92^{+0.29}_{-0.33}$
IC + ANTARES	$2.85^{+0.38}_{-0.33}$

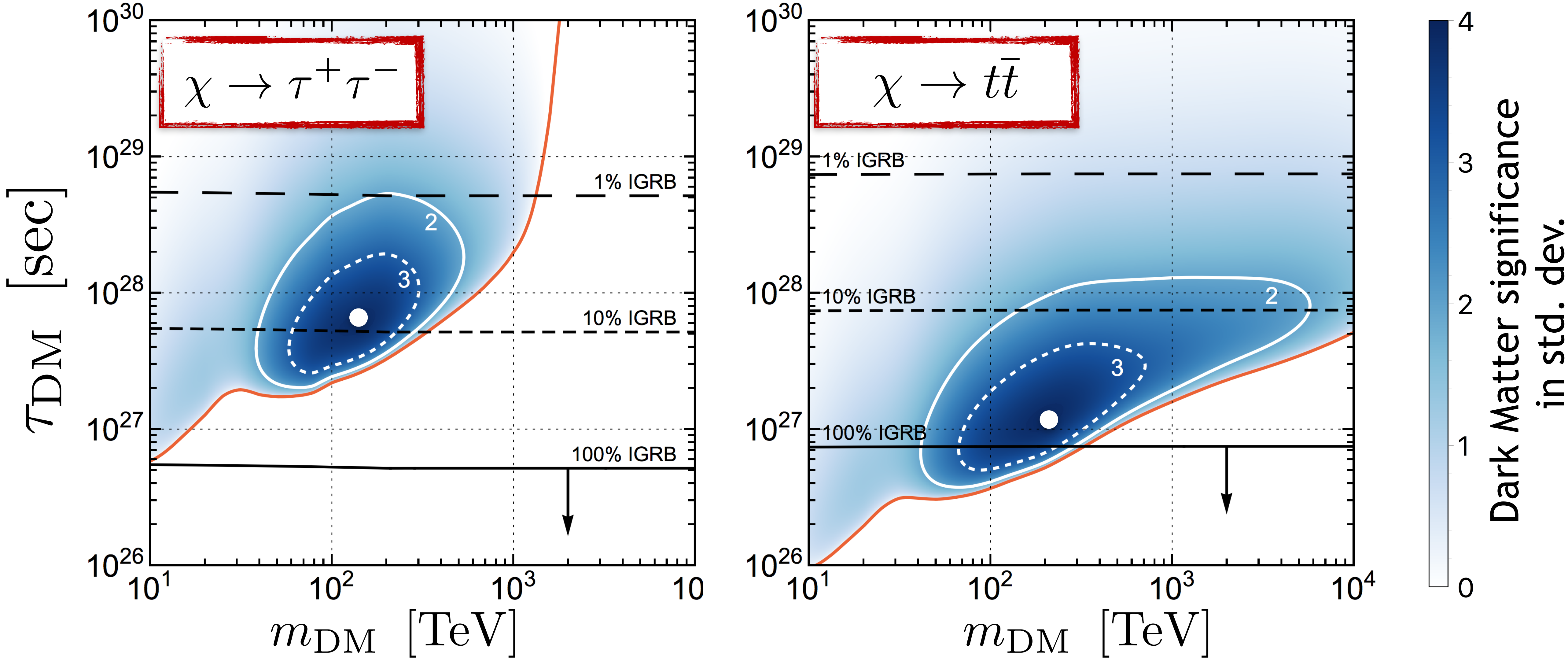
MC, Mele, Miele, Migliozzi, Morisi, ApJ 851 (2017)

Decaying Dark Matter



MC, Miele, Morisi, PLB 773 (2017)

Decaying Dark Matter (MESE)



MC, Miele, Morisi, JCAP 1701