Dark Matter interpretation of the IceCube diffuse neutrino flux

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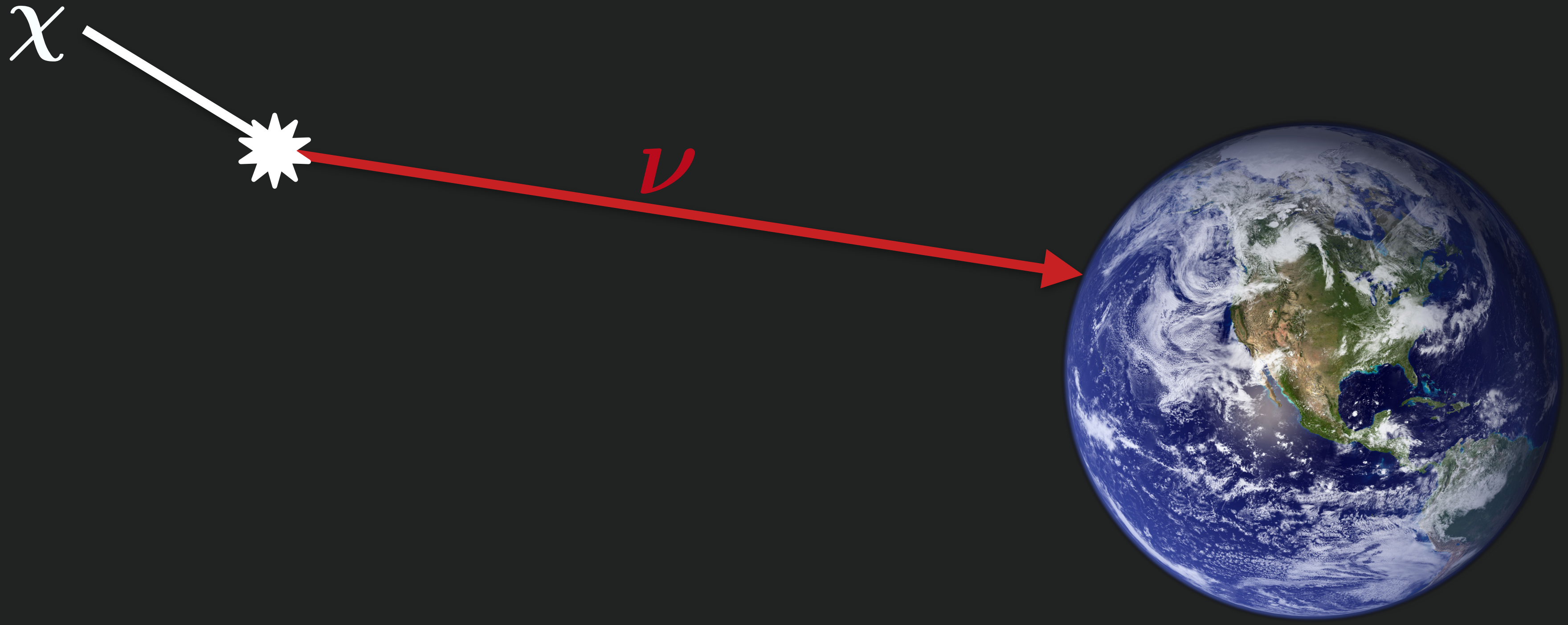
Dark Matter particles χ can decay or annihilate producing:

- **Neutrinos** travel in straight lines (**IceCube** and Antares/KM3NeT)



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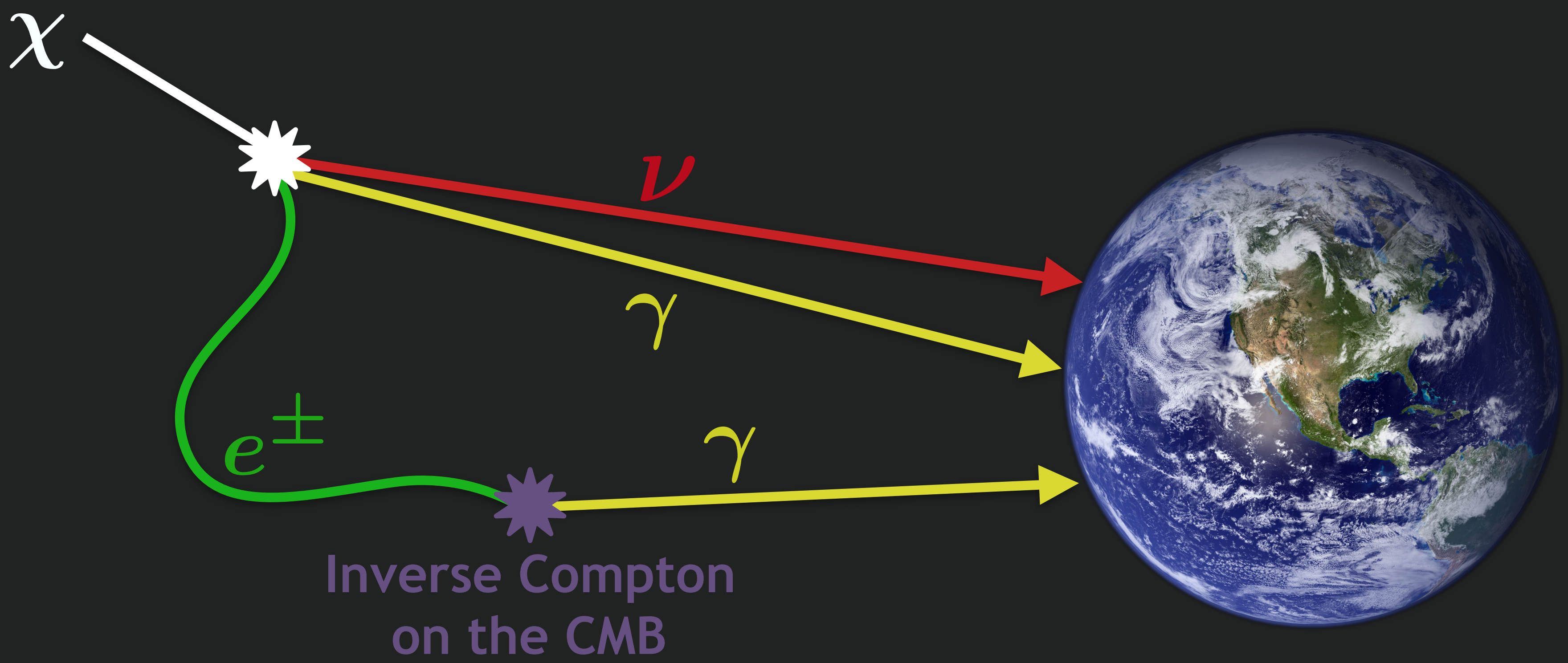

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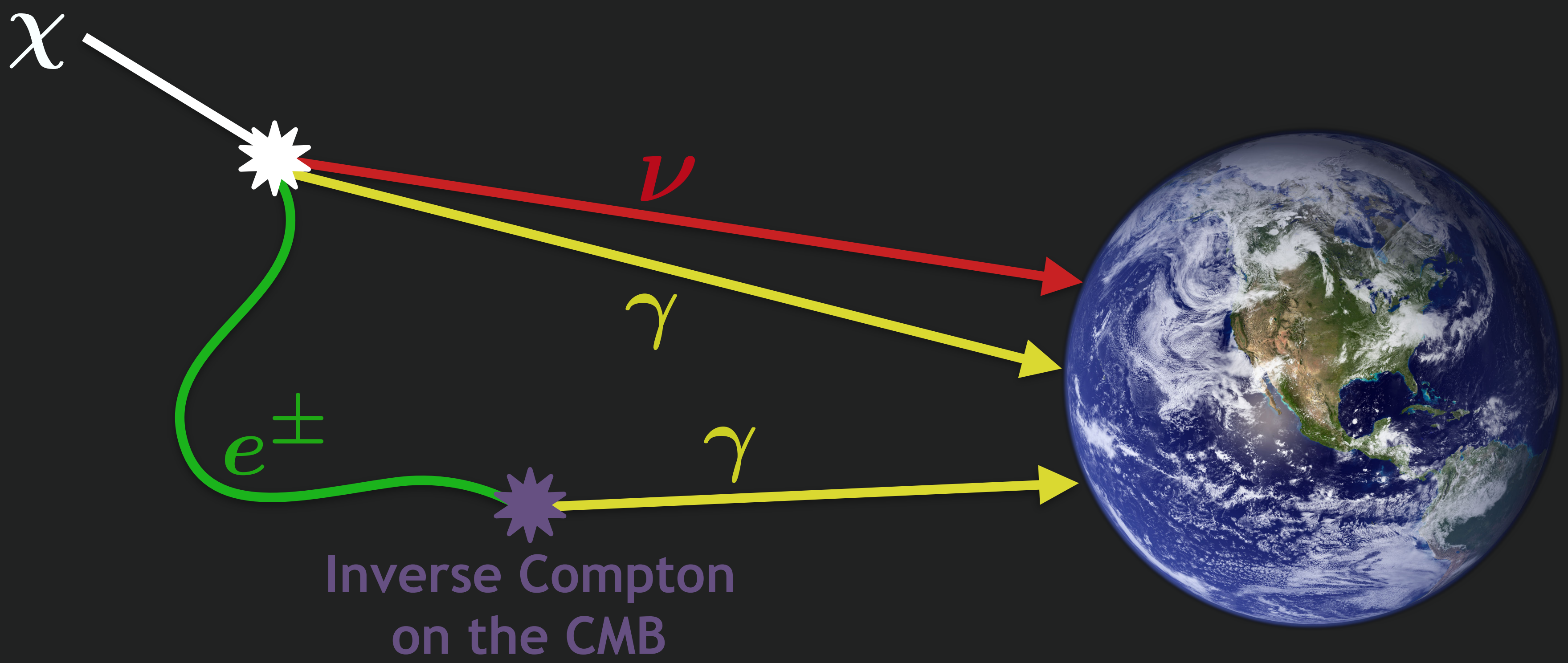
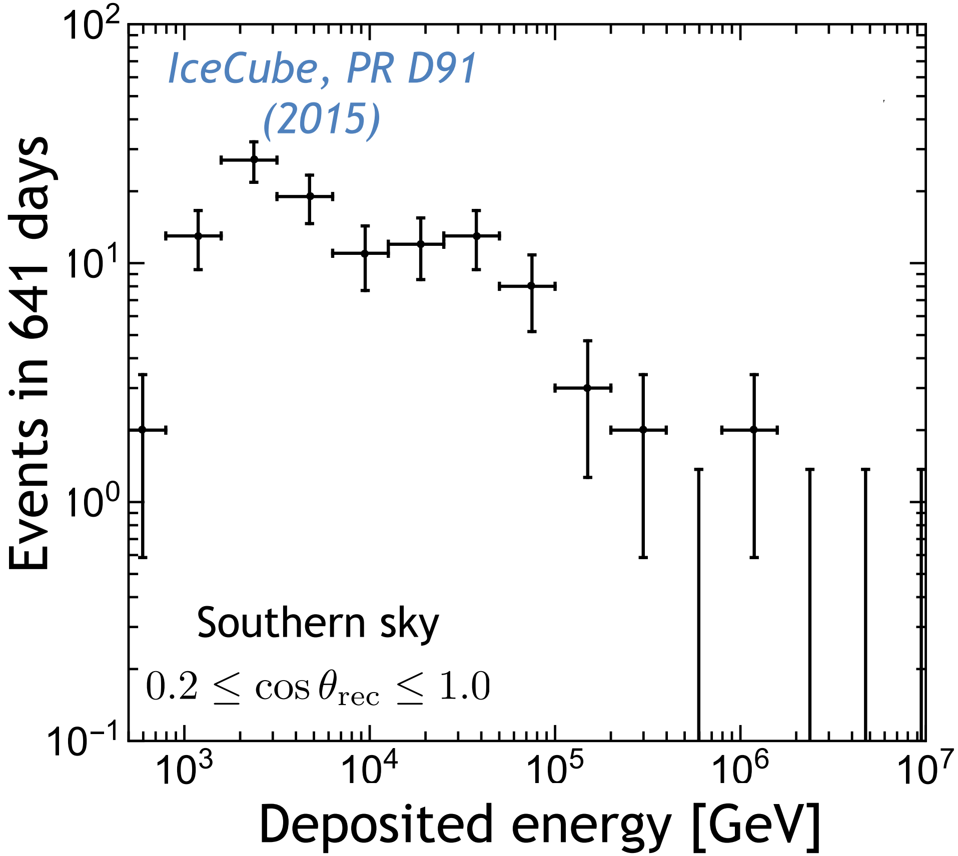
→ **Neutrino and Gamma-Ray Telescopes could provide important information about the nature of Dark Matter**

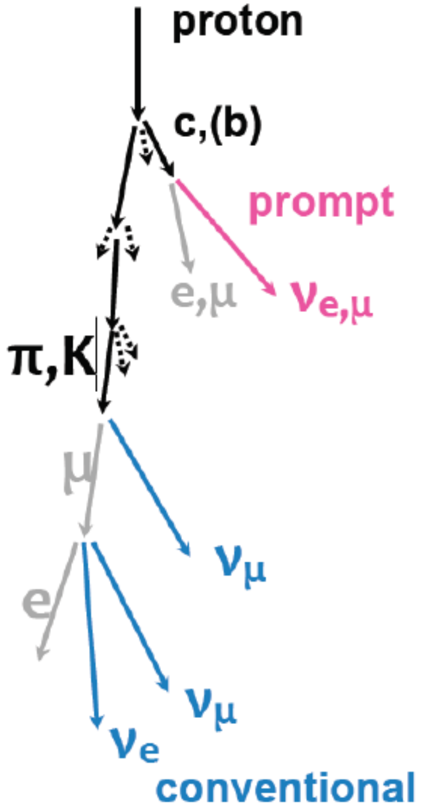


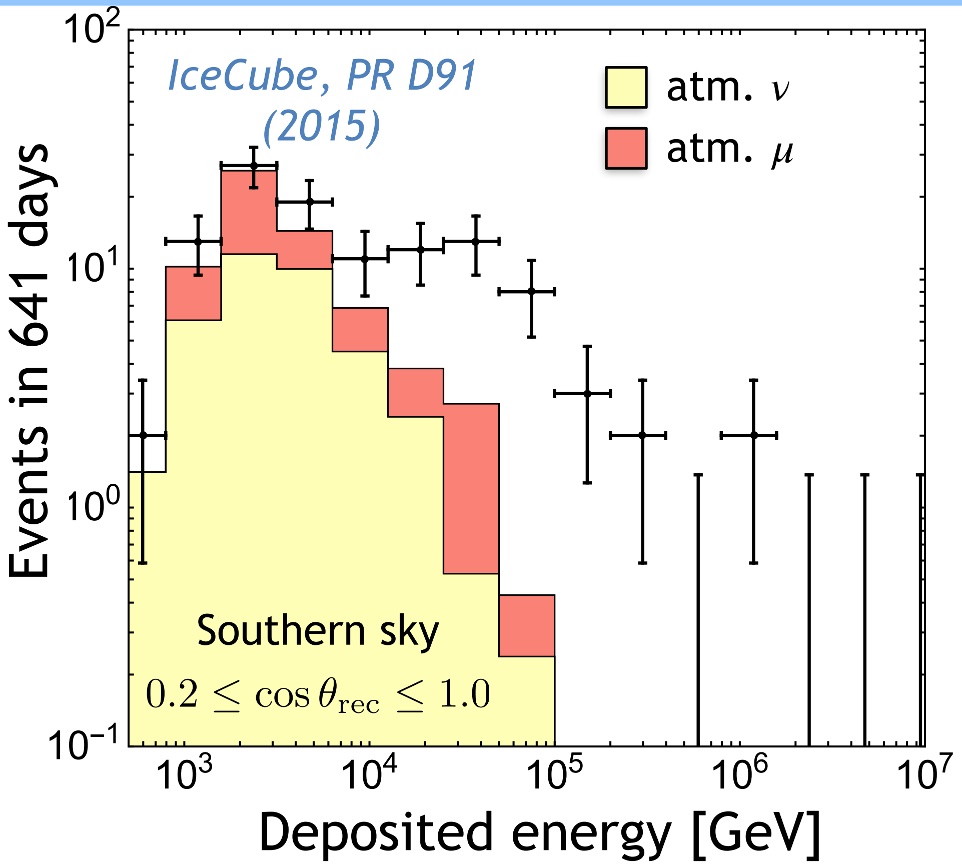
IceCube observations



IceCube observations

Atmospheric Background





Gaisser et al., PR D90 (2014)
Enberg et al., JHEP 1506
Gauld et ak., JHEP 1602
Halzen and Wille, PR D94 (2016)
Bhattacharya et al., arXiv:1607.00193

IceCube observations

Atmospheric Background

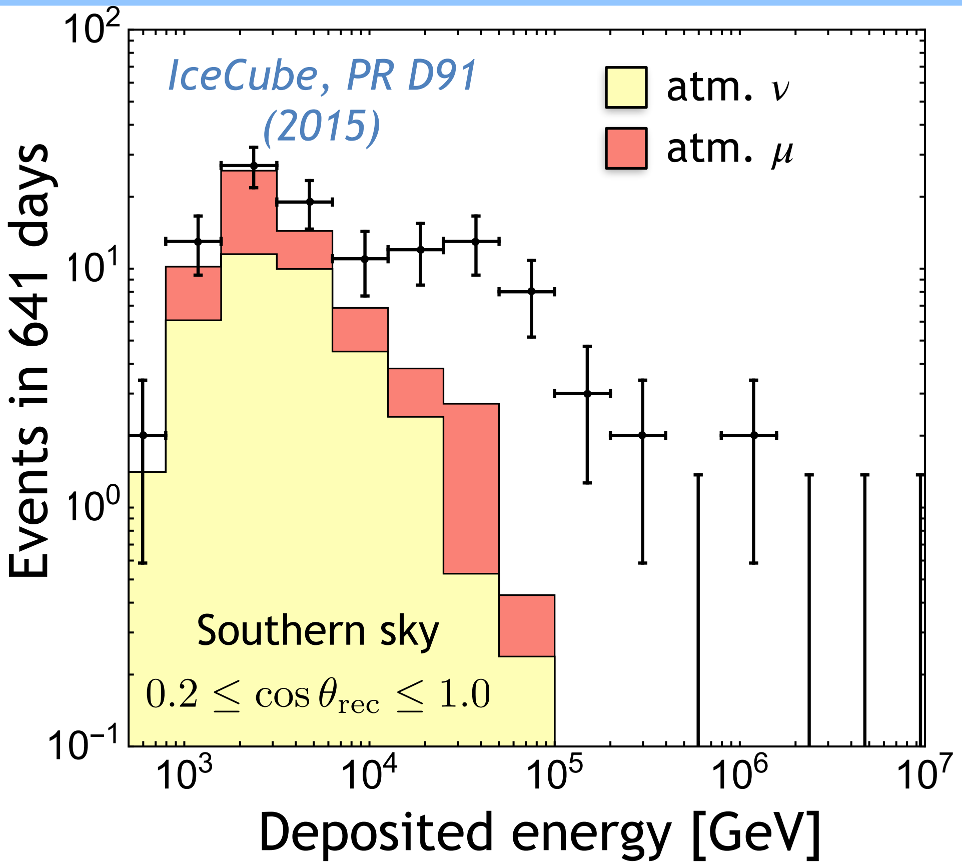
+

Astrophysical Component

Assuming a correlation with hadronic Cosmic-Ray, the astrophysical flux is parametrized by a **power-law**:

$$\frac{\mathrm{d}\phi^{\mathrm{Astro}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} = \phi_0 \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-\gamma}$$

Spectral index



Low-energy excess

Atmospheric Background

+

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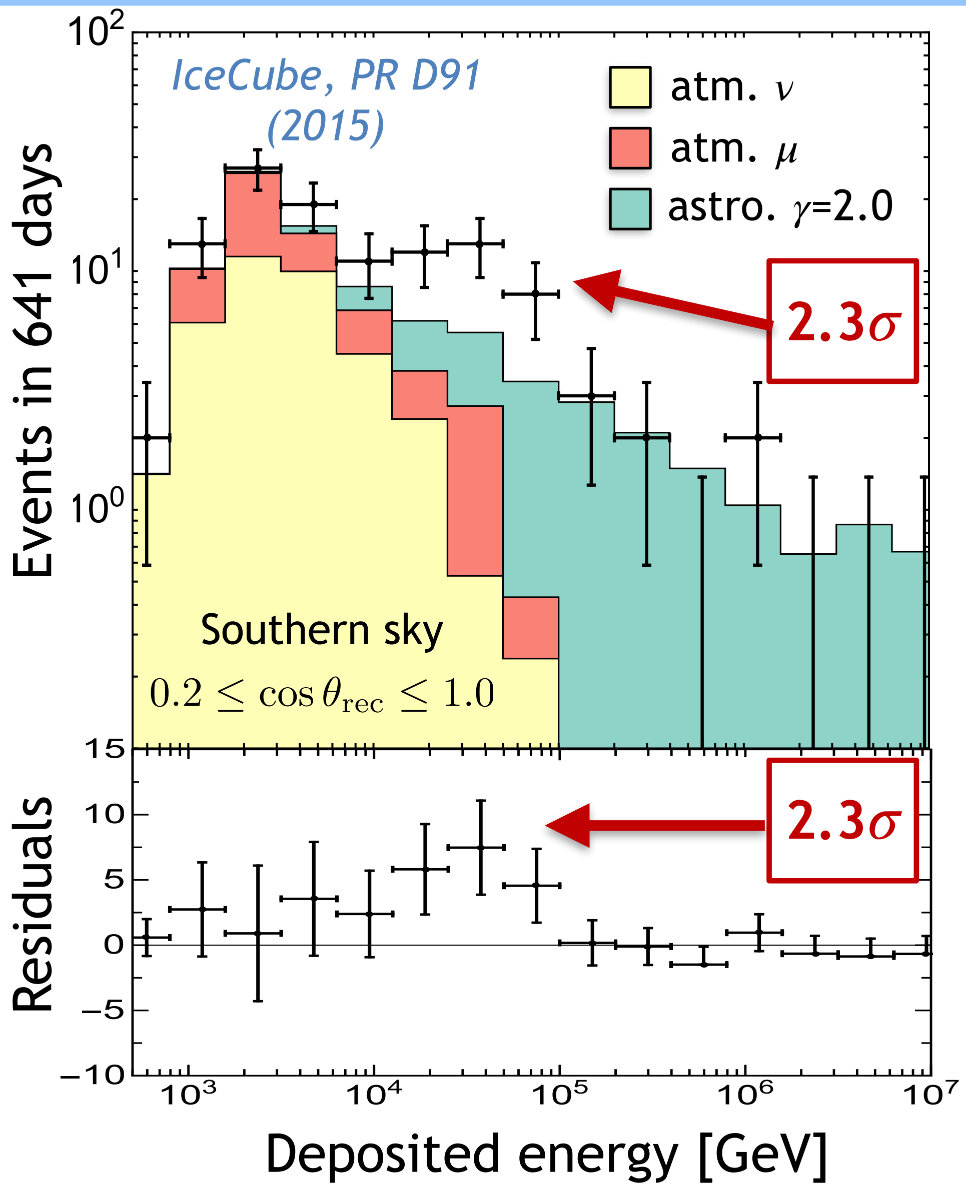
Fermi acceleration mechanism $\gamma \simeq 2.0$



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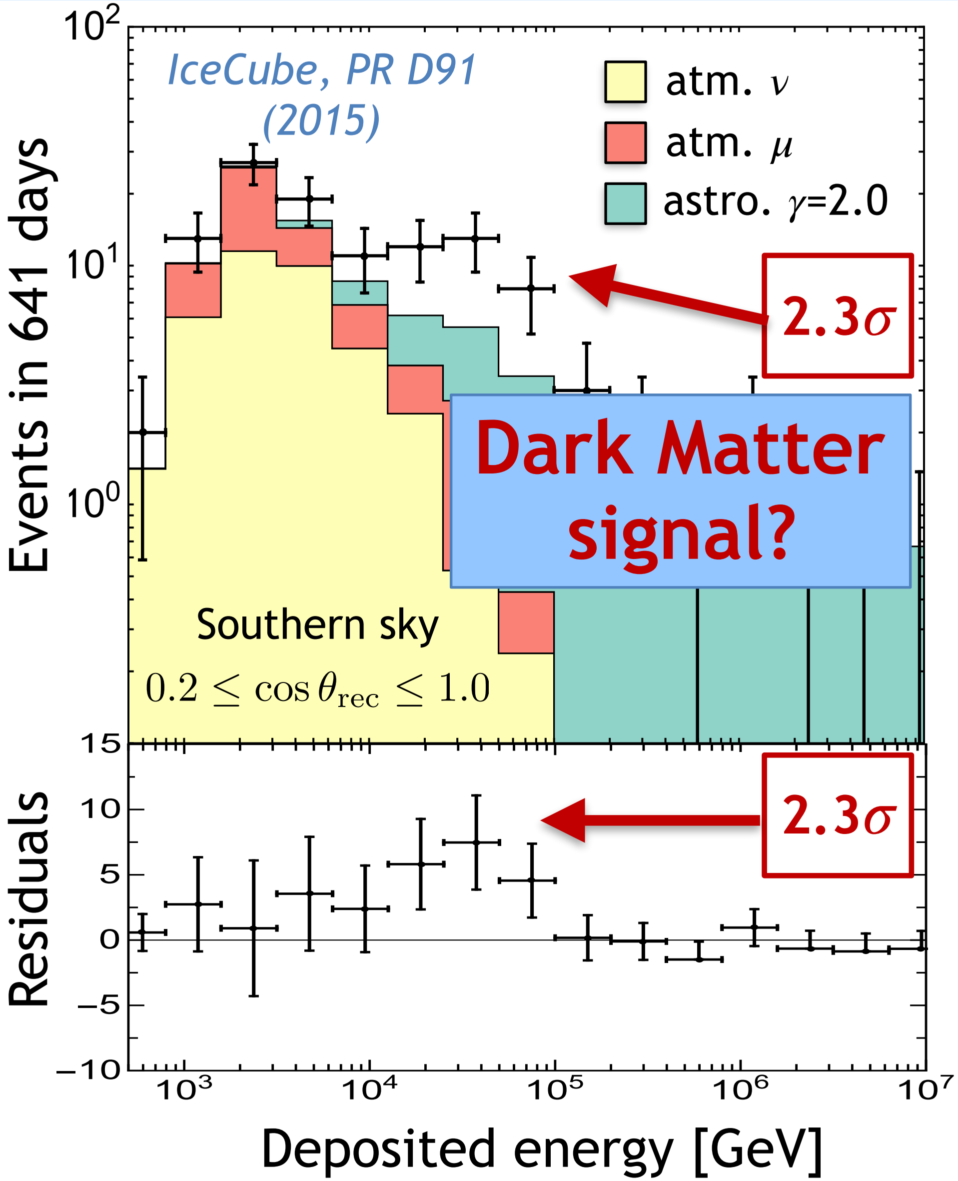


Neutrino flux: our assumption

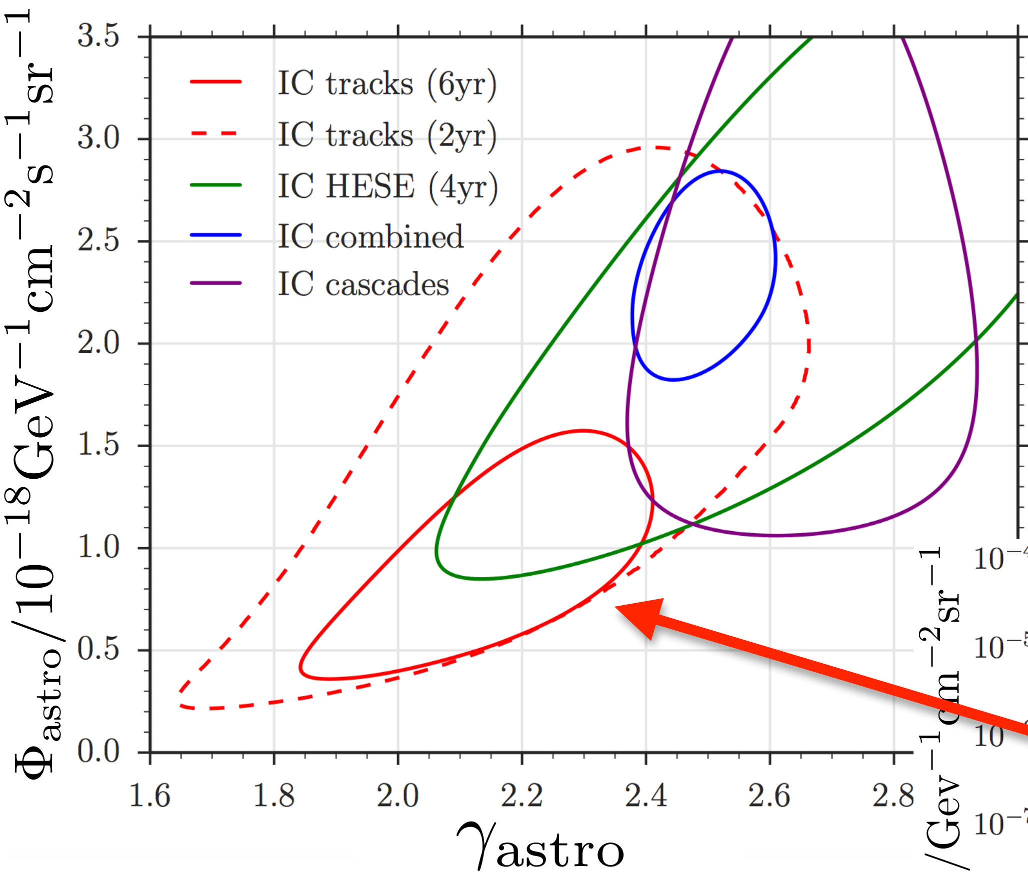
In addition to the atmospheric background, we assume **two-component flux**.

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

Astrophysical power-law

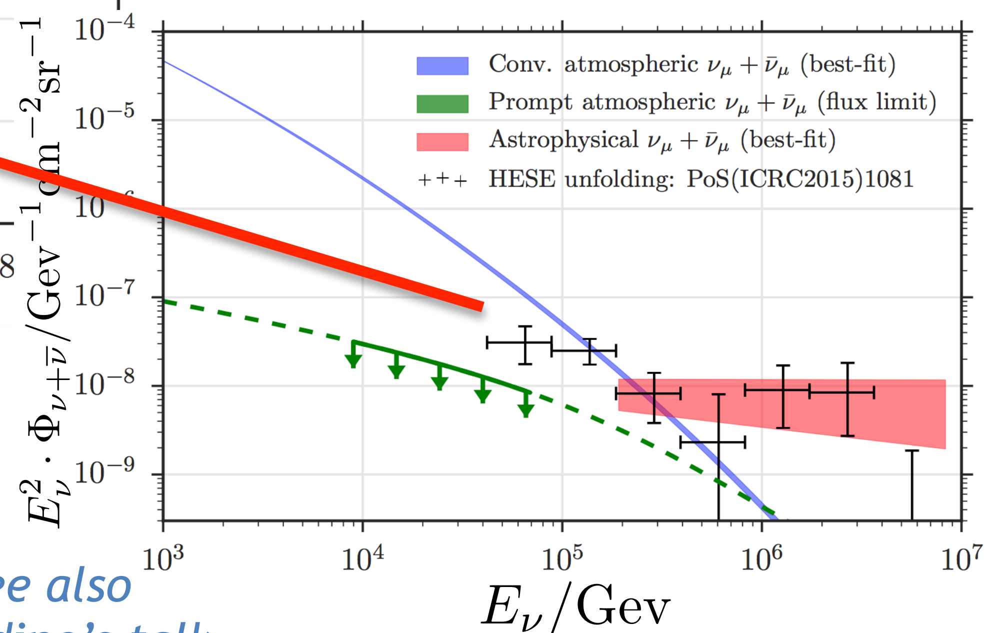
Dark Matter

Astrophysical flux: spectral index



The **6-years track** data sample (muon neutrinos from the Northern Sky) has some tension with the previous single unbroken power-law fits.

IceCube, PoS (ICRC2015) 1079

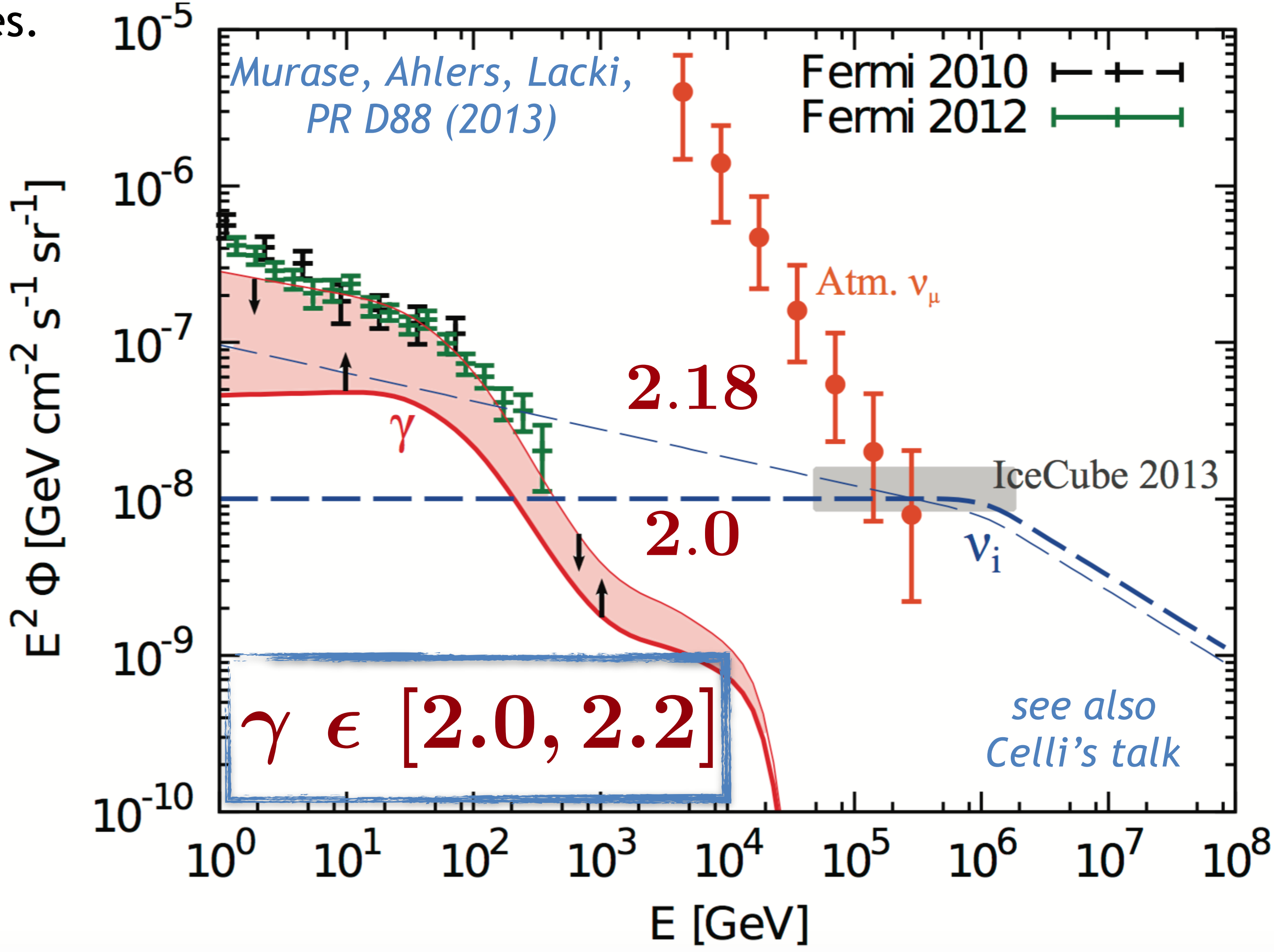


The latest IceCube data suggest a small value for the spectral index

see also Palladino's talk

Neutrino *VS* Gamma-Rays

Multi-messenger approaches provide very strong constraints to astrophysical sources.



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Astrophysical power-law

Dark Matter

- Prior on the spectral index

$$\gamma \, \epsilon \, [2.0, 2.2]$$

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$$\frac{d\phi}{dE_\nu d\Omega} = \frac{d\phi^{\rm bkg}}{dE_\nu d\Omega} + \frac{d\phi^{\rm Astro}}{dE_\nu d\Omega} + \frac{d\phi^{\rm DM}}{dE_\nu d\Omega}$$

Astrophysical power-law

- Prior on the spectral index

$$\gamma \in [2.0, 2.2]$$

M.C., Miele, Morisi, Vitagliano, PL B757 (2016)

M.C., Miele, Morisi, JCAP 1701

Dark Matter

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

decay	annihihalion
$\frac{\rho_{\rm DM}}{m_{\rm DM}}$	$\left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^2$

- decay/annihilation *into* **leptonic/hadronic** final-states

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

Neutrino flux: our assumption

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

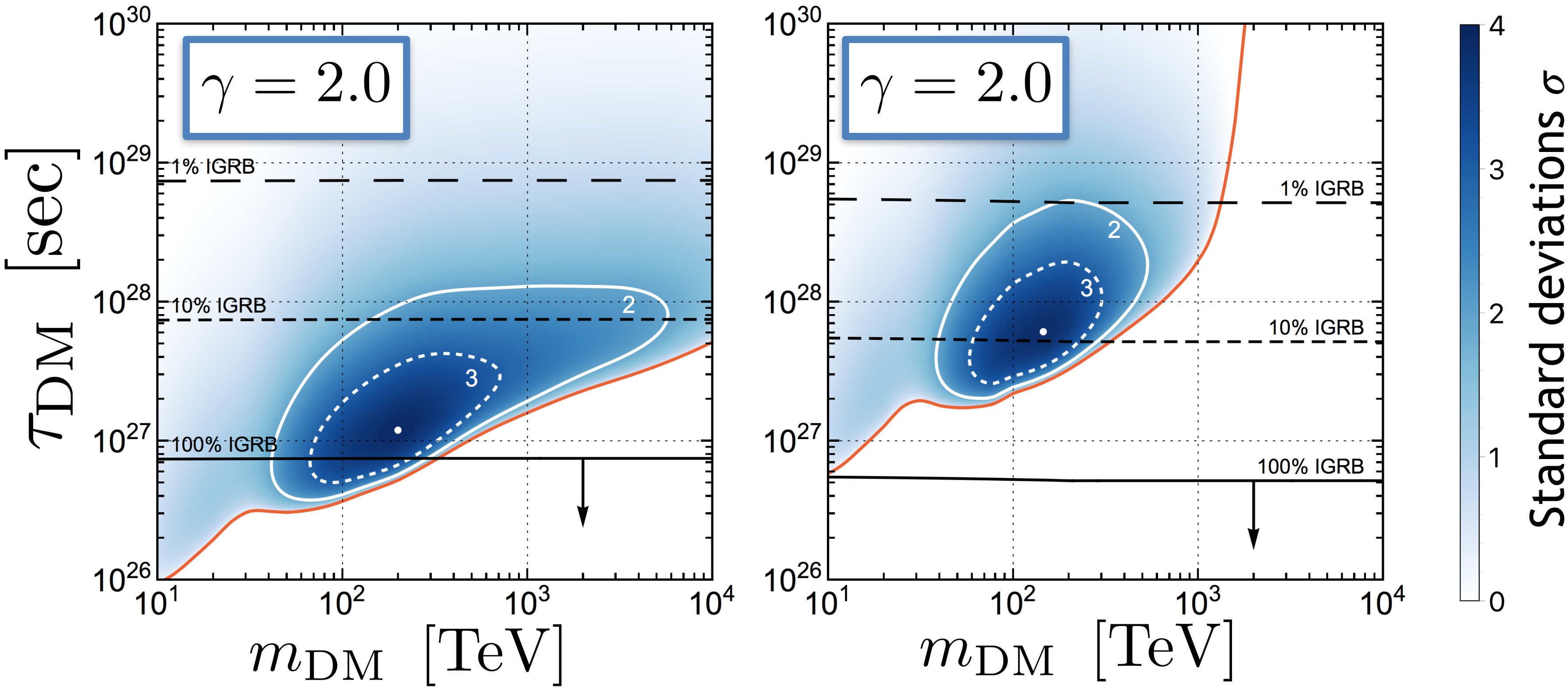
$$\frac{\mathrm{d}\phi}{\mathrm{d}E_\nu \mathrm{d}\Omega} = \frac{\mathrm{d}\phi^{\mathrm{bkg}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} + \frac{\mathrm{d}\phi^{\mathrm{Astro}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} + \frac{\mathrm{d}\phi^{\mathrm{DM}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}$$

Astrophysical power-law | **Dark Matter**

Likelihood-Ratio Statistical Test

$$\mathrm{TS} = 2 \ln \frac{\mathcal{L}\,(\mathrm{Astro} + \mathrm{DM})}{\mathcal{L}\,(\mathrm{Astro})} \quad \xRightarrow{\text{Chernoff theorem}} \quad \sqrt{\mathrm{TS}} = \text{significance in } \sigma$$

Decaying Dark Matter



Leptonic states

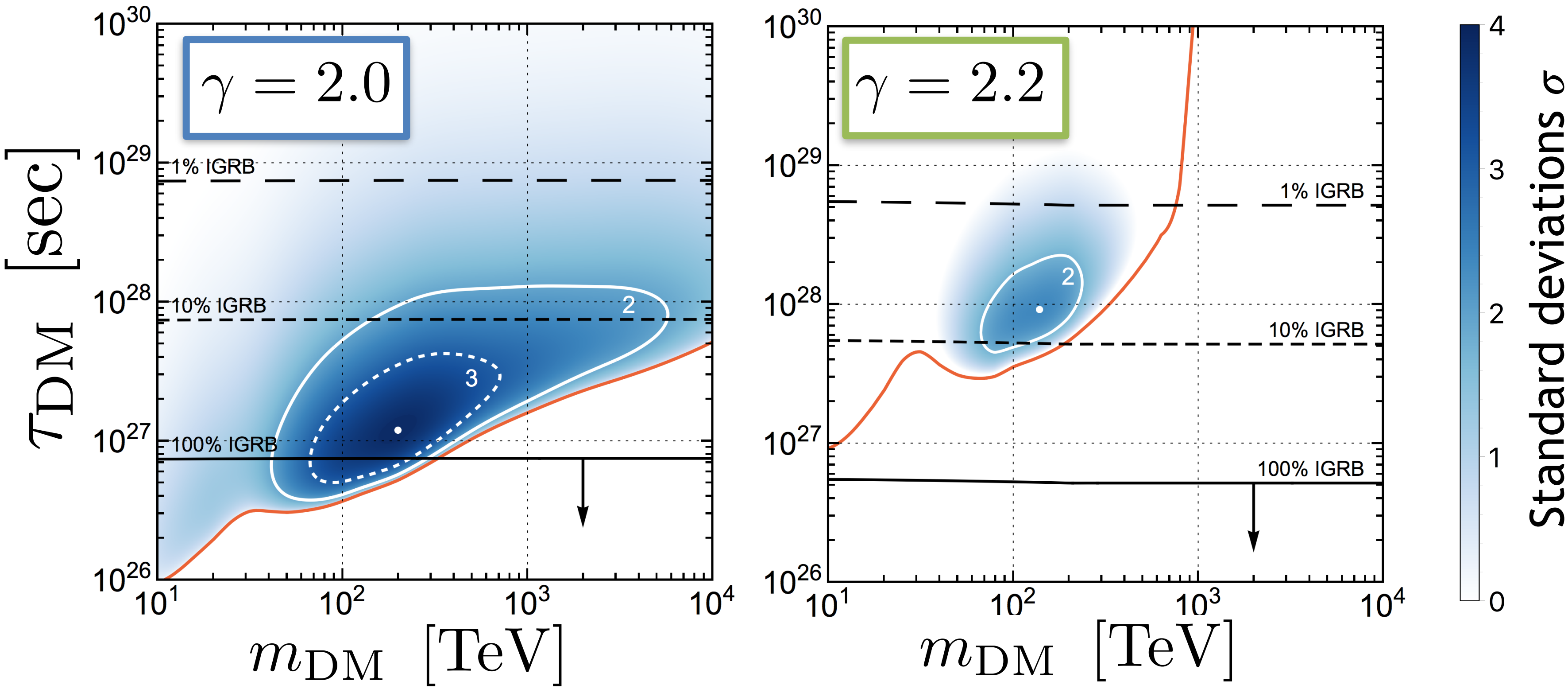
$$\chi \to \tau^+\tau^-$$

Hadronic states

$$\chi \to t\bar{t}$$

M.C., Miele, Morisi, JCAP 1701

Decaying Dark Matter



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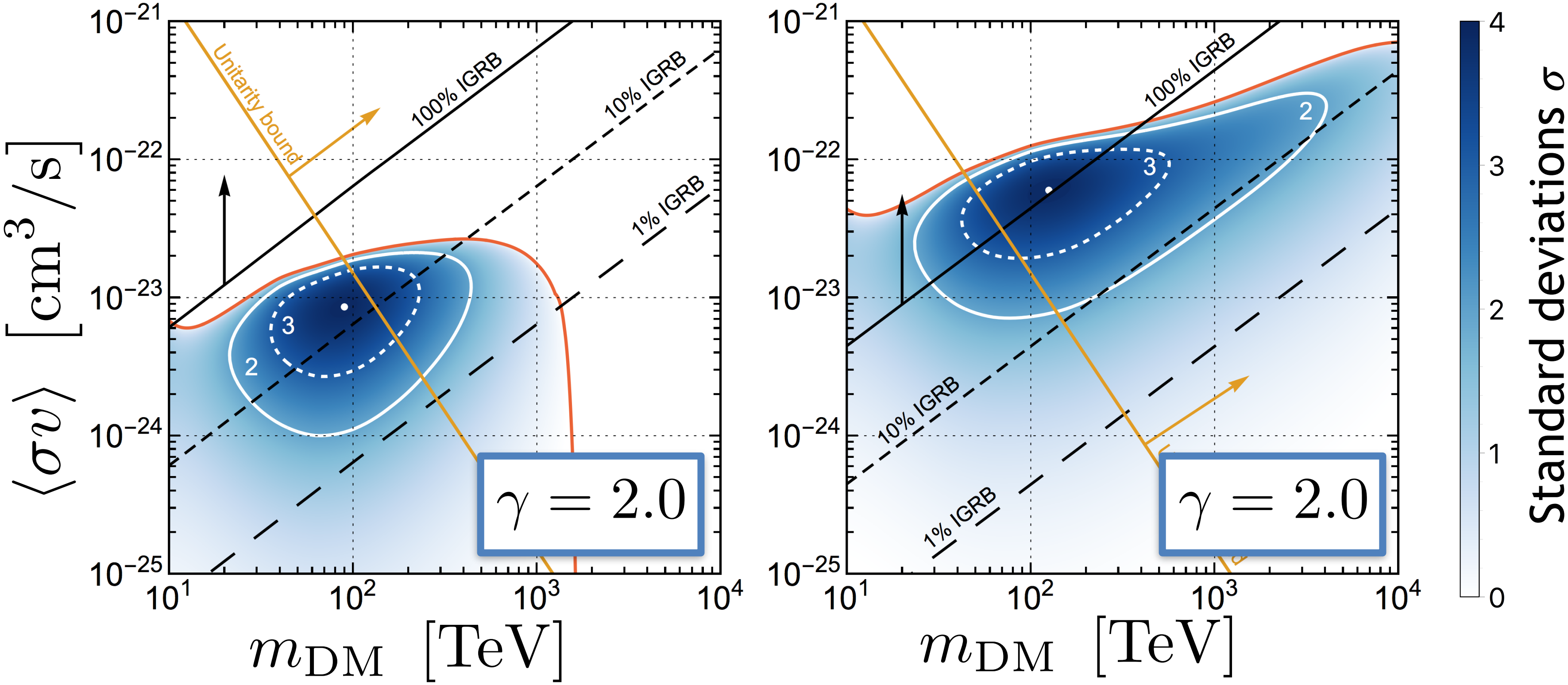
M.C., Miele, Morisi, JCAP 1701

Annihilating Dark Matter



Leptonic states

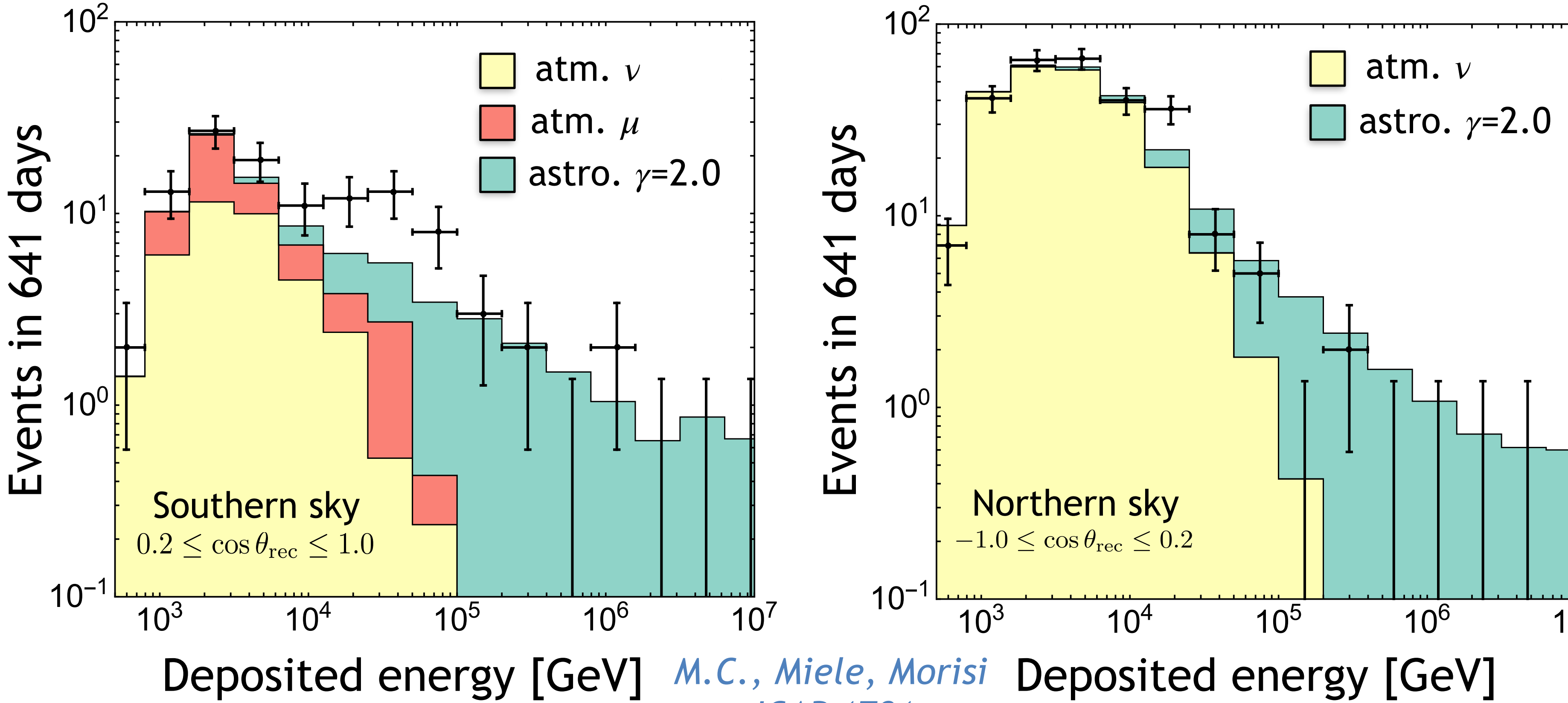
$$\chi \rightarrow \tau^+ \tau^-$$

Hadronic states

$$\chi \rightarrow t\bar{t}$$

M.C., Miele, Morisi, JCAP 1701

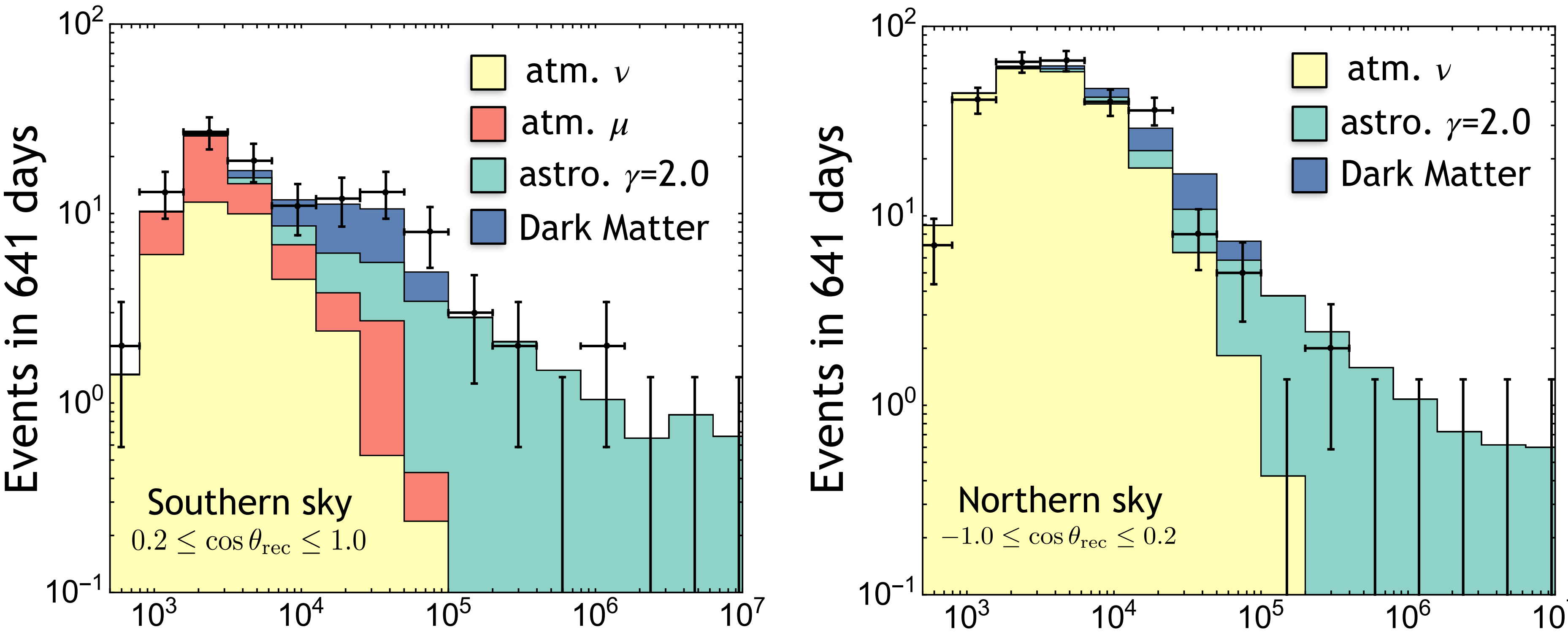
Dark Matter at 100 TeV



M.C., Miele, Morisi
JCAP 1701

⟹ Astrophysical power-law with **spectral index 2.0**

Dark Matter at 100 TeV



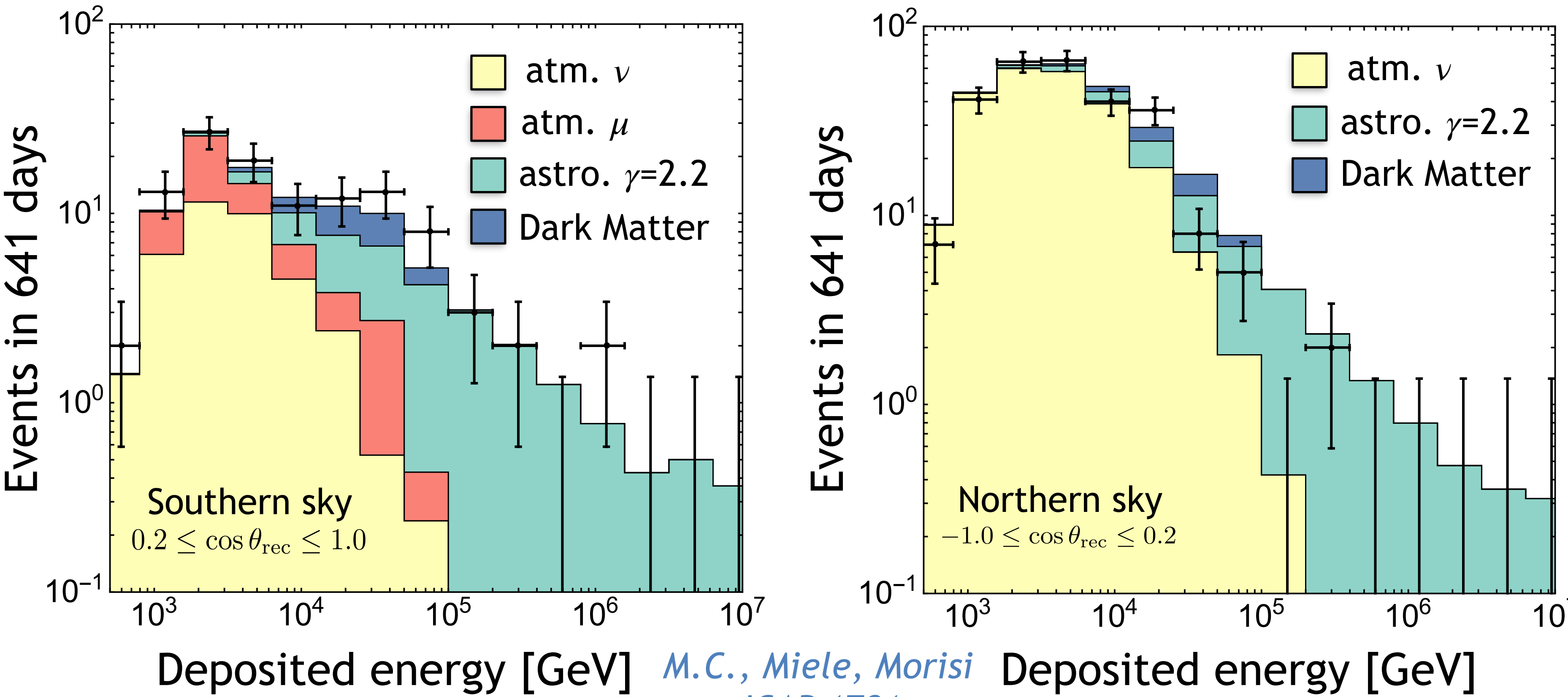
M.C., Miele, Morisi JCAP 1701

⟹ Astrophysical power-law with **spectral index 2.0**

⟹ Decaying Dark Matter component with $M_{\rm DM} = 140\ \mathrm{TeV}$

$$\chi \to \tau^+\tau^-$$

Dark Matter at 100 TeV



M.C., Miele, Morisi
JCAP 1701

⟹ Astrophysical power-law with **spectral index 2.2**

⟹ Decaying Dark Matter component with $M_{\rm DM} = 140\ \mathrm{TeV}$

$$\chi \to \tau^+\tau^-$$

Conclusions

Neutrino and Gamma-Ray Telescopes could potentially shed light on the nature of Dark Matter.

The tension among different IceCube data samples could indicate the presence of a **multi-component** diffuse neutrino flux.

The **low-energy excess** (100 TeV) can be explained in terms of **Dark Matter**:

- the statistical relevance of two-component flux (with Dark Matter) ranges between about 2σ—4σ;
- decaying DM models (leptonic final states) are favored with respect to the annihilating ones (hadronic ones).

The need of **more statistics** at low and high energies emphasizes the importance of future Neutrino Telescopes (IceCube-2gen and KM3NeT).

Workshop: Perspective in Astroparticle physics from High Energy Neutrinos — PAHEN'17

Naples, 25—26 September 2017

Napoli dal Mare

https://agenda.infn.it/conferenceDisplay.py?confId=12121

About 30 talks divided into four sessions:

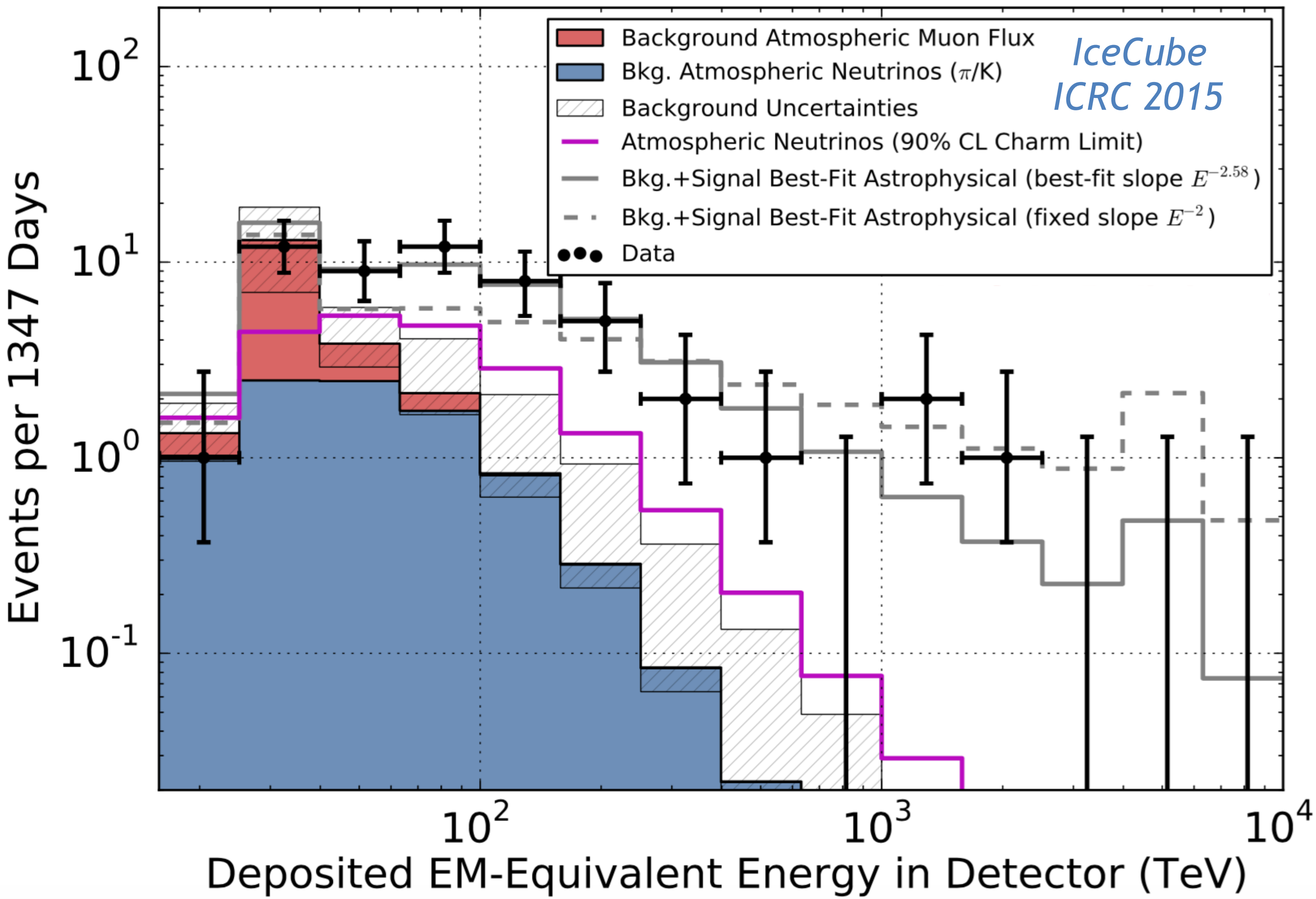
1. **High-energy neutrino observations and perspectives**
2. **Astrophysical sources and backgrounds**
3. **Multi-messenger physics**
4. **New physics at high-energy neutrino telescopes**

You are very welcome to attend

Confirmed Speakers: M. Ackerman, M. Ahlers, R. Aloisio, A. Cuoco, P. Di Bari, R. Enberg, A. Esmaili, M. Gustafsson, F. L. Halzen, C. Perez de los Heros, P. Lipari, T. Moroi, A. Morselli, V. Niro, E. Resconi, G. Riccobene, D. Samtleben, D. Semikoz, G. Di Sciascio, M. Spurio, F. Villante, F. Vissani, E. Waxman, W. Winter, E. Zas.

Backup Slides

High Energy Starting Events



Astrophysical sources

Different astrophysical sources are potential candidates for the IceCube observations:

- SuperNova and HyperNova Remnants
- Active Galactic Nuclei
- Gamma-Rays Bursts

p-p sources

expected for CR reservoirs, where CR escaping from their accelerators are confined in magnetized environments for a long time

p-gamma sources

mostly cosmogenic interactions of CR in the intergalactic space

Power-law spectrum

Assuming a correlation with hadronic Cosmic-Ray, the neutrino flux is

Unbroken Power-Law

$$\frac{d\phi^{\mathrm{Astro}}}{dE_\nu d\Omega} = \phi_0 \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma} \exp\left(-\frac{E_\nu}{E_0}\right)$$

Broken Power-Law

The spectral index is given by:

- at first order
- at second order

$$\gamma \simeq 2.0$$

Fermi acceleration mechanism

p-p sources

$$\gamma \lesssim 2.2$$

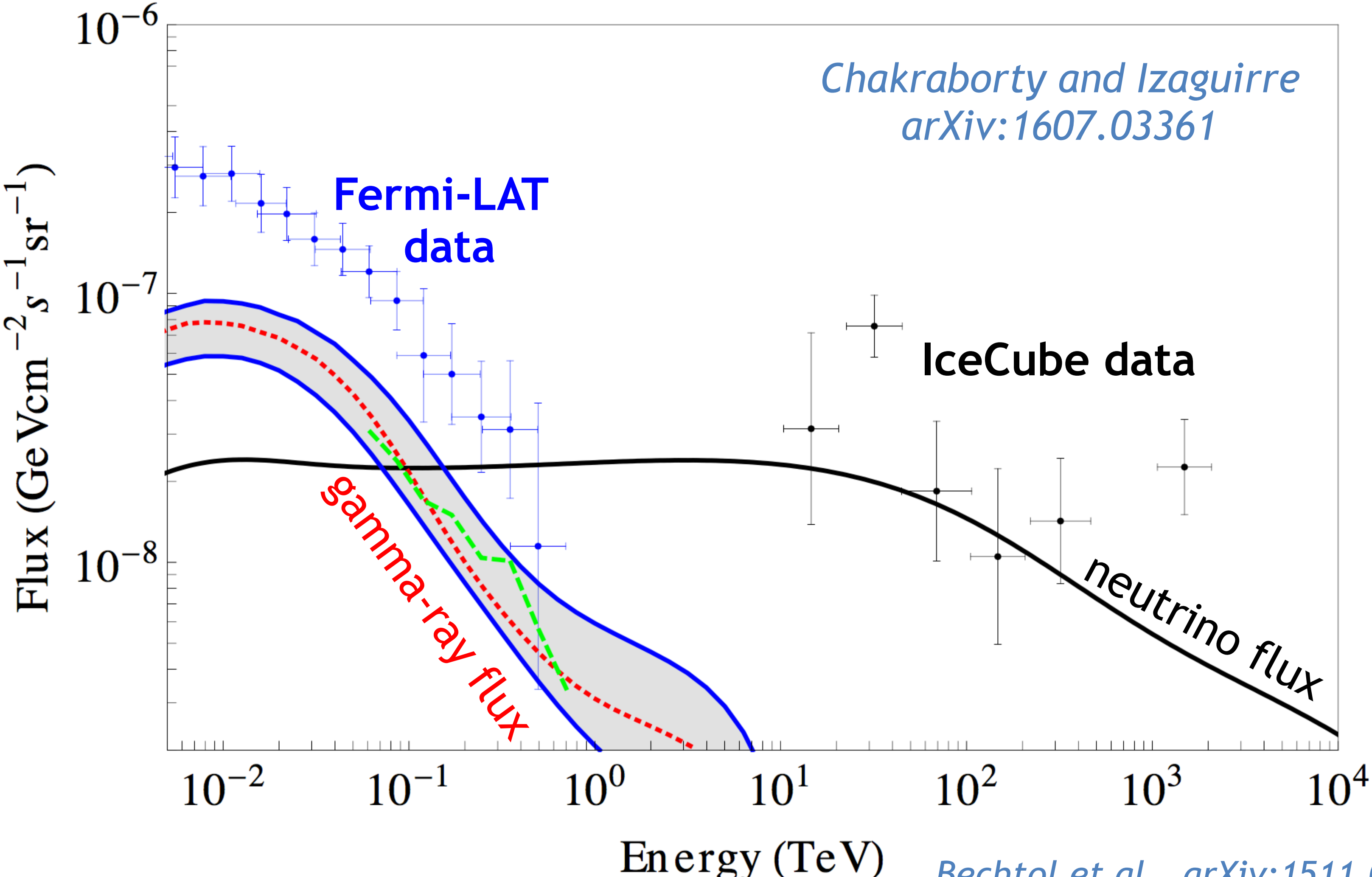
Loeb, Waxman, JCAP 0605

p-gamma sources

$$\gamma \gtrsim 2.3$$

Winter, PR D88 (2013)

Multi-messenger: p-p sources



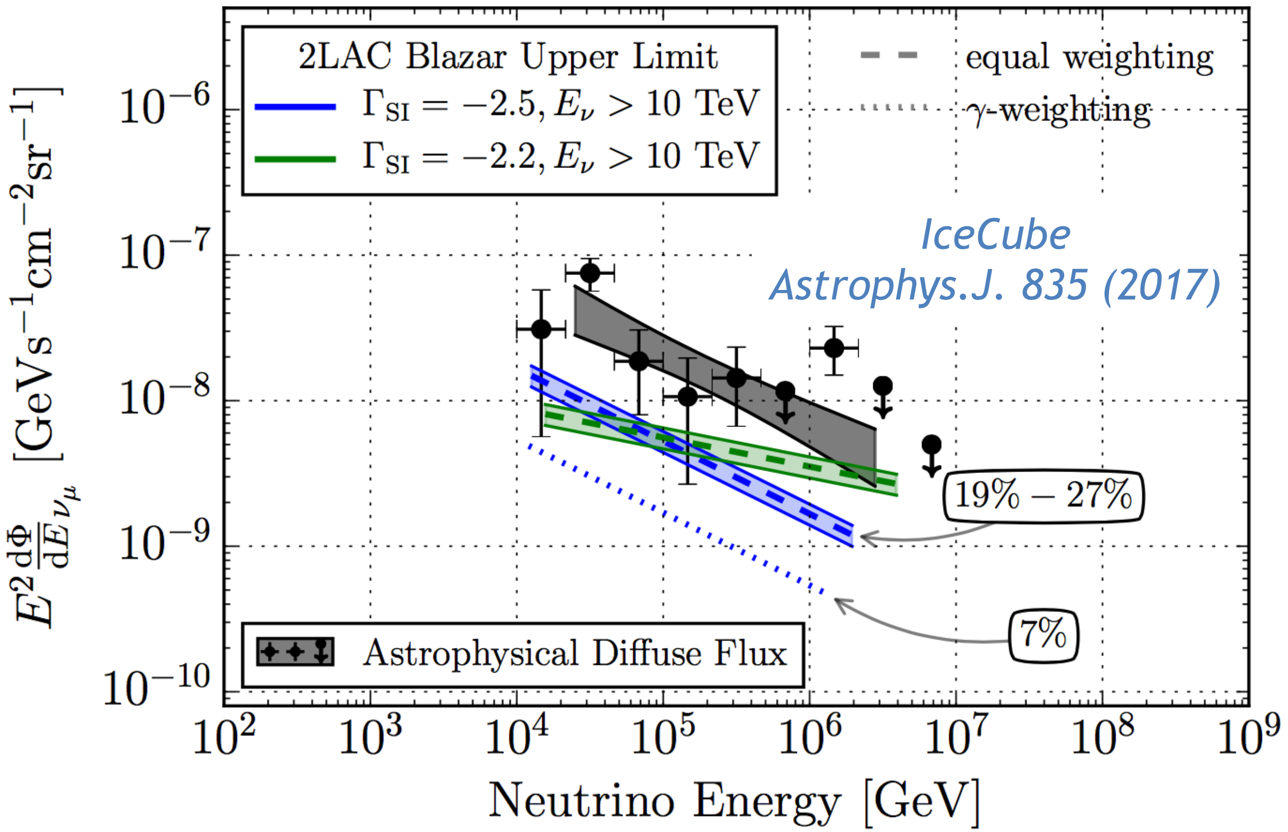
Bechtol et al., arXiv:1511.00688

SNRs contribute to the neutrino flux ~30% at 100 TeV and ~60% at 1 PeV.

Multi-messenger: p-gamma sources

Spatial and temporal correlations with the Fermi-LAT observations point out that the contribution of p-gamma sources to the diffuse neutrino flux is:

- Gamma-Ray Bursts — ~1% *IceCube, Astrophys.J. 805 (2015)*
- Blazars (AGN) — ~20% *IceCube, arXiv:1502.03104 and arXiv:1509.02980*



Dark Matter signal

The differential neutrino flux provided by Dark Matter models is given by

- **Decay**

$$\left.\frac{\mathrm{d}\phi^{\mathrm{G}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{dec.}} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N}{\mathrm{d}E_\nu} \int_0^\infty ds\, \rho_h \left[r\left(s, \ell, b\right)\right]$$

$$\left.\frac{\mathrm{d}\phi^{\mathrm{EG}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{dec.}} = \frac{\Omega_{\mathrm{DM}}\rho_c}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty dz\, \frac{1}{H\left(z\right)} \left.\frac{\mathrm{d}N}{\mathrm{d}E_\nu}\right|_{E'=E(1+z)}$$

- **Annihilation**

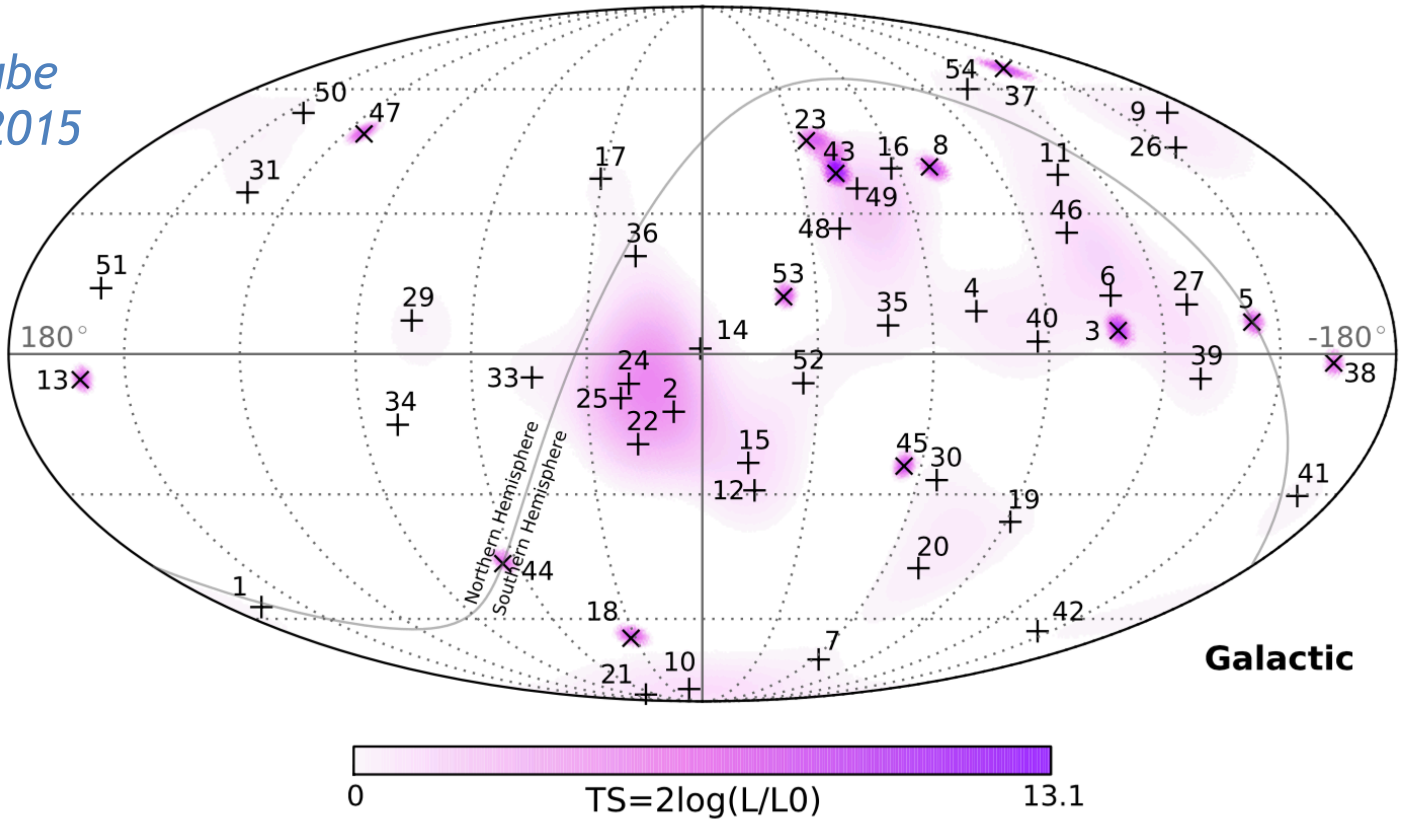
$$\left.\frac{\mathrm{d}J^{\mathrm{G}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{ann.}} = \frac{1}{2} \frac{\langle\sigma v\rangle}{4\pi\, m_{\mathrm{DM}}^2} \frac{\mathrm{d}N}{\mathrm{d}E_\nu} \int_0^\infty ds\, \rho_h^2 \left[r\left(s, \ell, b\right)\right]$$

$$\left.\frac{\mathrm{d}J^{\mathrm{EG}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{ann.}} = \frac{1}{2} \frac{\langle\sigma v\rangle\, \left(\Omega_{\mathrm{DM}}\rho_c\right)^2}{4\pi\, m_{\mathrm{DM}}^2} \int_0^\infty dz\, \frac{B\left(z\right)\left(1+z\right)^3}{H\left(z\right)} \left.\frac{\mathrm{d}N}{\mathrm{d}E_\nu}\right|_{E'=E(1+z)}$$

Clumpiness Factor

Angular analys

IceCube
ICRC 2015



Decaying or Annihilating Dark Matter?

$$\text{Flux} \propto \begin{cases} (\rho_{\rm DM}/m_{\rm DM}) & \text{decay} \\ (\rho_{\rm DM}/m_{\rm DM})^2 & \text{annihilation} \end{cases}$$

Angular analysis

Scenario		KS	AD
Astrophysics	Gal. plane		
	Iso. dist.		
DM decay	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^4$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^6$	NFW		
	Isoth.		
DM annih. $\Delta_0^2 = 10^8$	NFW		
	Isoth.		

We consider only events in the energy range 60—100 TeV and perform two *one-dimensional* statistical tests:

- Kolmogorov-Smirnov (**KS**)
- Anderson-Darling (**AD**)

M.C., Miele, Morisi, Vitagliano, PL B757 (2016)

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Astrophysics	Gal. plane		
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DM annih. $\Delta_0^2 = 10^8$	NFW		
	Isoth.		

galactic sources: galactic plane

$$p^{\rm gal}(\sin b, l) = \frac{\Theta(\sin b + \sin b_{\rm gal}) - \Theta(\sin b - \sin b_{\rm gal})}{4\pi \sin b_{\rm gal}}$$

extragalactic sources: isotropic distribution

$$p^{\rm iso}(\sin b, l) = \frac{1}{4\pi}$$

M.C., Miele, Morisi, Vitagliano, PL B757 (2016)

Angular analysis

Scenario		KS	AD
Astrophysics	Gal. plane		
	Iso. dist.		
DM decay	NFW		
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DM annih. $\Delta_0^2 = 10^4$	NFW		
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DM annih. $\Delta_0^2 = 10^8$	NFW		
	Isoth.		

Decaying Dark Matter

$$p^{\rm dec}(\cos\theta) \propto \int_0^\infty \rho_h[r(s,\cos\theta)]\mathrm{d}s + \Omega_{\rm DM}\rho_c\,\beta$$

Annihilating Dark Matter

$$p^{\rm ann}(\cos\theta) \propto \int_0^\infty \rho_h^2[r(s,\cos\theta)]\mathrm{d}s + (\Omega_{\rm DM}\rho_c)^2\,\Delta_0^2\,\beta$$

clumpiness factor

Hooper, Serpico, JCAP 0706
Cirelli et al., JCAP 1103

$$\beta = \int_0^{\frac{100}{60}-1} \frac{\mathrm{d}z}{H(z)} = \frac{0.56}{H_0}$$

M.C., Miele, Morisi, Vitagliano, PL B757 (2016)

Angular analysis

Scenario		KS	AD
Astrophysics	Gal. plane		
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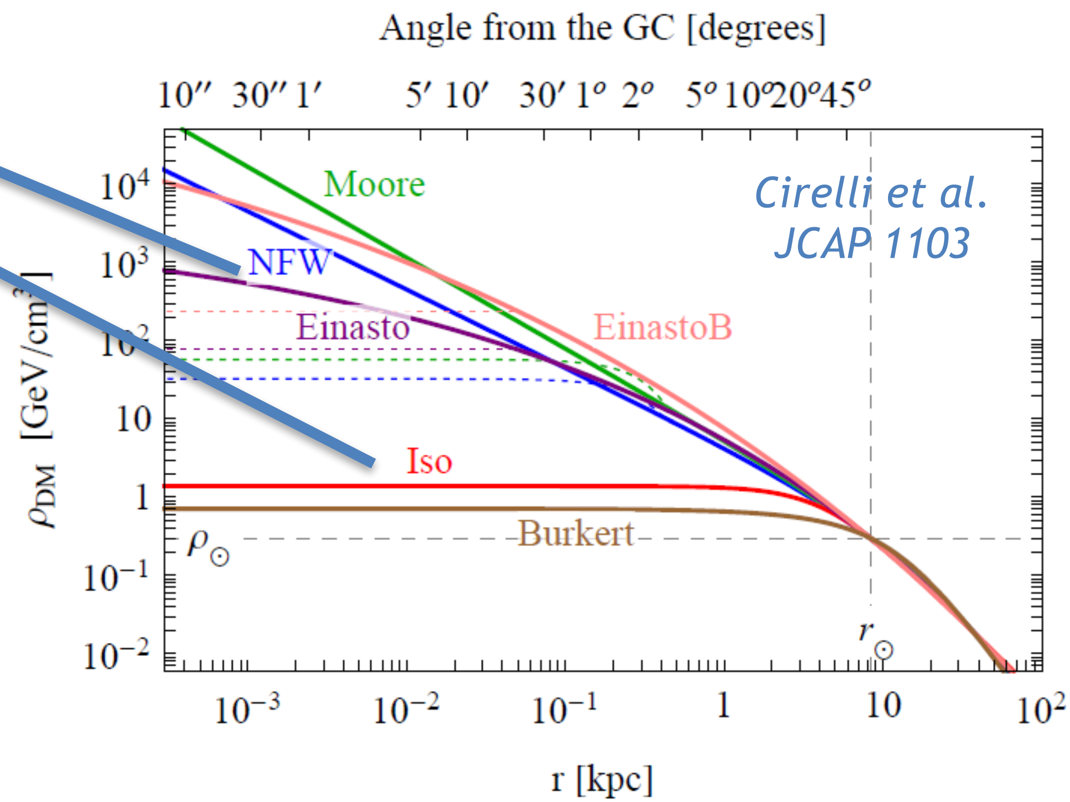
	Isoth.		



M.C., Miele, Morisi, Vitagliano, PL B757 (2016)

Angular analysis

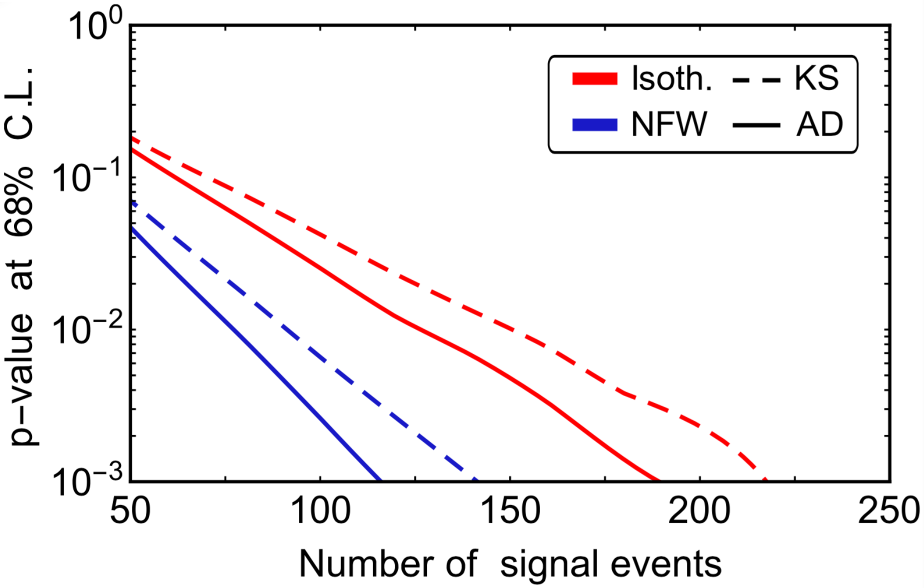
Scenario		KS	AD
Astrophysics	Gal. plane	0.007 - 0.008	not defined
	Iso. dist.	0.20 - 0.55	0.17 - 0.54
DM decay	NFW	0.06 - 0.16	0.03 - 0.14
	Isoth.	0.08 - 0.22	0.05 - 0.19
DM annih. $\Delta_0^2 = 10^4$	NFW	$(0.3 - 0.9) \times 10^{-4}$	$(0.3 - 3.8) \times 10^{-4}$
	Isoth.	$(0.9 - 2.8) \times 10^{-3}$	$(1.0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

- **Disfavor** the correlation with the Galactic Plane
- Annihilating DM **excluded** for small clumpiness factor

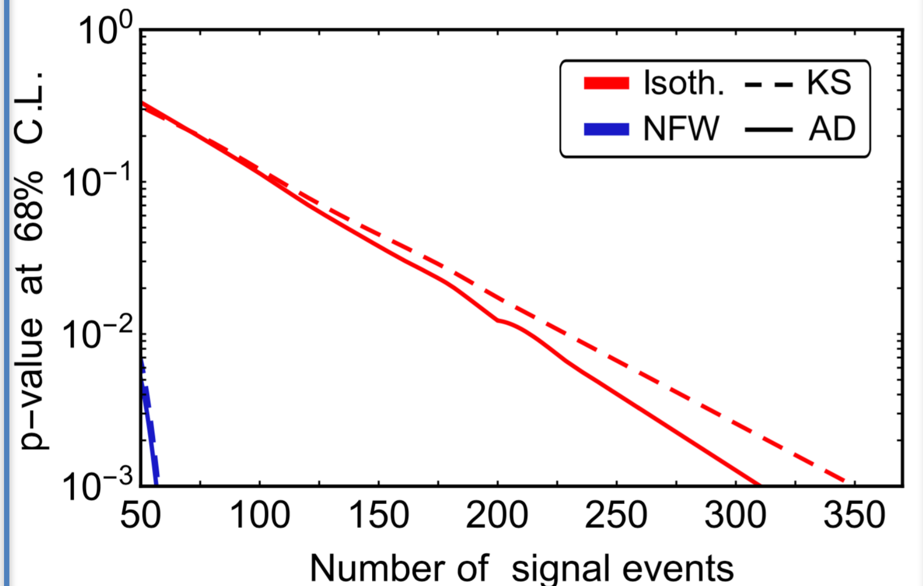
M.C., Miele, Morisi, Vitagliano, PL B757 (2016)

Forecast

We generate 10^5 sets of data according to the isotropic distribution, and then we perform the statistical tests under the DM null hypotheses.



Decaying DM



Annihilating DM

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

M.C., Miele, Morisi, Vitagliano, PL B757 (2016)