The Origin of the IceCube Neutrinos

Multimessenger hints from the diffuse ɣ-ray flux

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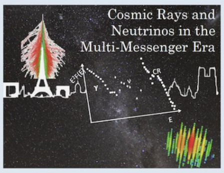
Based on the analysis and results from:
A. C., A. Esmaili, K. Murase, Phys. Rev. D 101 (2020) 103012
A. C., A. Esmaili, P. Serpico, arXiv:2007.07911 [hep-ph]



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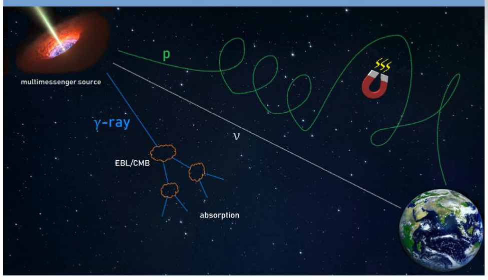
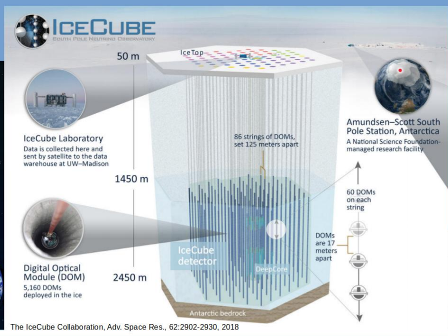
Neutrinos as cosmic messengers:

- **Neutral:** don't get deflected
- **Weakly interacting:** don't get absorbed

Perfect for probing the high energy Universe!



The IceCube Detector[1] @South Pole

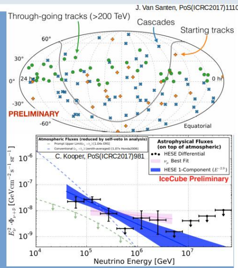


The IceCube Collaboration, Adv. Space Res., 62:2902-2930, 2018

- (Quasi-) isotropic neutrino flux
- Approximately equal flavor distribution at the Earth

⇩

Neutrinos are extragalactic!



Top: Astrophysical neutrino arrival directions.[2]
Bottom: IceCube's HESE 6-year data and fit.[3]

IceCube fit for the (per-flavor) astrophysical neutrino flux:

$$\frac{\mathrm{d}\phi_\nu}{\mathrm{d}E_\nu} = \Phi_{\rm astro} \times 10^{-18} \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-s_h}, \text{ for } E_\nu > E_{\rm th}$$

	HESE 7.5y	Cascades 6y	Through-going muons 9.5y
$\Phi_{\rm astro}$ [GeV^{-1} cm^{-2}s^{-1}sr^{-1}]	$2.15^{+0.49}_{-0.15}$	$1.66^{+0.25}_{-0.27}$	$1.44^{+0.25}_{-0.24}$
s_h	$2.89^{+0.2}_{-0.19}$	2.53 ± 0.07	$2.28^{+0.08}_{-0.09}$
$E_{\rm th}$ [TeV]	60	16	119

We assume the following ***minimal*** neutrino emission spectrum:

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}\varepsilon_\nu} = \begin{cases} A & \text{, for } \varepsilon_\nu < \varepsilon_{\rm br} \\ A\left(\frac{\varepsilon_\nu}{\varepsilon_{\rm br}}\right)^{-s_h} & \text{, for } \varepsilon_{\rm br} < \varepsilon_\nu < 10\ \mathrm{PeV} \\ 0 & \text{, for } \varepsilon_\nu > 10\ \mathrm{PeV} \end{cases}$$

These neutrinos are produced via accelerated protons interacting with ambient photons (or protons), leading ***unavoidably*** to γ-ray production!

$$p + p/\gamma \to \begin{cases} \pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow e^+ + \nu_e + \bar\nu_\mu + \nu_\mu \\ \pi^- \longrightarrow \mu^- + \bar\nu_\mu \longrightarrow e^- + \bar\nu_e + \nu_\mu + \bar\nu_\mu \\ \pi^0 \longrightarrow 2\gamma \end{cases}$$

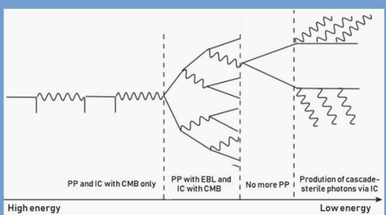
This implies a comparable γ-ray flux: $\varepsilon_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}\varepsilon_\gamma}(\varepsilon_\gamma) \simeq \frac{2}{3K_\pi} \varepsilon_\nu^2 \frac{\mathrm{d}N_\nu}{\mathrm{d}\varepsilon_\nu}(\varepsilon_\nu)\Big|_{\varepsilon_\nu = \varepsilon_\gamma/2}$

High energy ($\gtrsim$ TeV) γ-rays interact with CMB/EBL photons, γ_t.

Pair Production: $\gamma + \gamma_t \longrightarrow e^+ + e^-$

Inverse Compton Scattering: $e^\pm + \gamma_t \longrightarrow e^\pm + \gamma$

This chain process is known as an **Electromagnetic Cascade**.

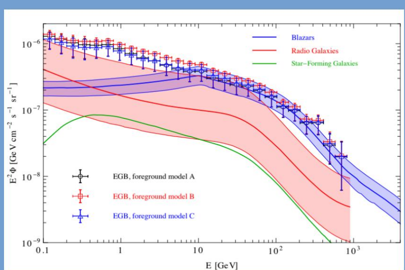


At the Earth, we are left with a γ-ray flux at sub-TeV energies, contributing to the **Extragalactic Gamma-ray Background** (EGB) measured by the *Fermi* Collaboration.[4]

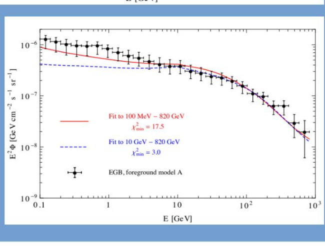
Other "Conventional" EGB contributions:

- Blazars
- Radio Galaxies
- Star-Forming Galaxies

The low-energy (< TeV) emission from these objects provides a good fit to the EGB data, leaving small room for any extra contribution.



Assuming a free normalization for each of these conventional contributions, we fit the Fermi data at all energies (> 100 MeV) and at high energies (> 10 GeV) exclusively.



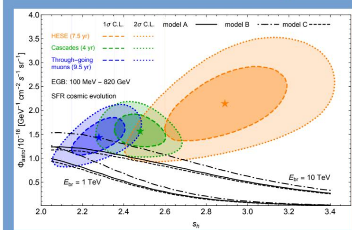
Left: fit to the EGB data with only the conventional contributions.

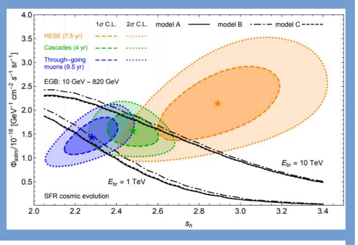
$$\chi^2(A, s_h, \varepsilon_{\rm br}) = \min_{\{\alpha_j\}} \left\{ \left[\sum_i \frac{(F_i^{\rm EGB} - \sum_j \alpha_j F_i^j)^2}{\sigma_i^2} \right] + \text{pullterms} \right\}$$

- $F_i^{\rm EGB}$ is the EGB intensity in the i'th bin with uncertainty σ_i^2
- j indexes the different contributions to the EGB ("conventional" contributions + cascaded IceCube γ-ray counterpart), with intensities F_i^j
- α_j is the nuisance parameter renormalizing the j'th contribution

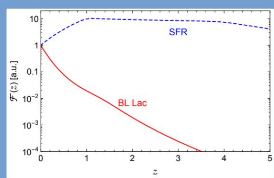
Constraints in the $(s_h, \Phi_{\rm astro})$ plane: SFR & BL Lac cosmic evolution

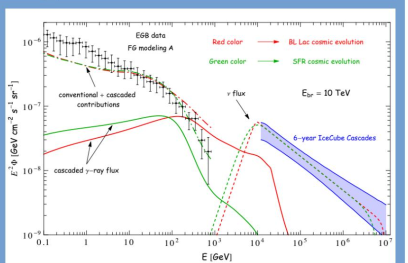
- Black Lines: Upper limits coming from the EGB data (2σ C.L.)
- Colored lines: IceCube allowed regions for each dataset



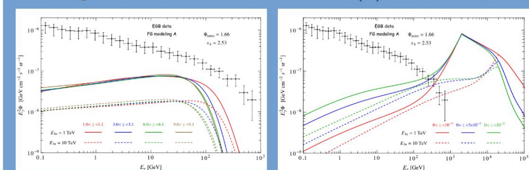


We find similar results for sources following the distribution of BL Lacs. However, the tension arises from last few Fermi data points.





High-z and low-z sources: $\mathcal{F}(z) = \text{const.}, \ z_{\rm min} < z < z_{\rm max}$



- High-z: energy budget required is too large
- Low-z: unfeasible source population and likely excluded by EGB at higher energies

$\Delta\chi^2$ values for different distributions

$4.61 \to 1\sigma$
$6.18 \to 2\sigma$
$11.83 \to 3\sigma$

		SFR	BL Lac	$z \gtrsim 3$	$0 \leq z \leq 10^{-2}$	$0 \leq z \leq 10^{-3}$
$E_{\rm br} = 1$ TeV	EGB > 100 MeV	47	137	35	232	110
	EGB > 10 GeV	37	113	29	211	103
$E_{\rm br} = 10$ TeV	EGB > 100 MeV	19	39	4.5	49	5.1
	EGB > 10 GeV	6	26	3.5	40	4.1

Possible solutions:

- "γ-ray opaque" sources (e.g. choked-jet GRBs, AGN cores)
- BSM processes (e.g. DM decay/annihilation)

References:

1 – M. G. Aartsen et al. [The IceCube Collaboration], Adv. Space Res., **62**:2902-2930, 2018.
2 – J. Van Santen, PoS (ICRC2017) **1110** (2017).
3 – C. Kooper, PoS (ICRC2017) **981** (2017).
4 – M. Ackermann et al. [Fermi-LAT Collaboration], Astrophys. J. **799**, 86 (2015).