Multimessenger diffuse emission from the Galactic plane

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Multimessenger astronomy

Multimessenger astronomy relies on the observation of several "messengers" (usually photons, neutrinos and gravitational waves which are not deflected by magnetic fields). Observing of them from the same source gives us a better understanding of the physical processes involved.

It could help us determine if γ-ray production processes are **hadronic** or **leptonic**:

- γ-rays can be accelerated to similar energy with both *pp* interaction and inverse Compton scattering
- neutrinos are only produced in the first case

γ-rays and neutrinos emission

Pion photo-production:

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

Hadronic collisions:

$$p + p \rightarrow p + p + \pi^0$$
$$\rightarrow p + n + \pi^+$$
$$p + n \rightarrow p + n + \pi^0$$
$$\rightarrow p + p + \pi^-$$

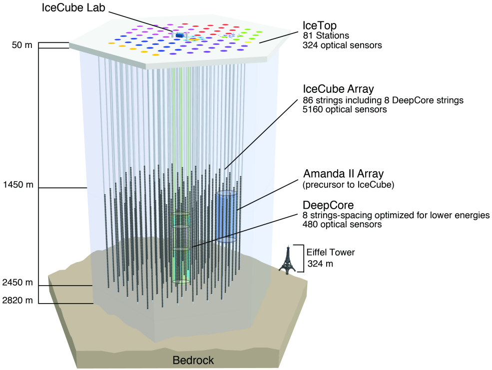
π decay:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$
$$\pi^0 \rightarrow \gamma + \gamma$$

IceCube

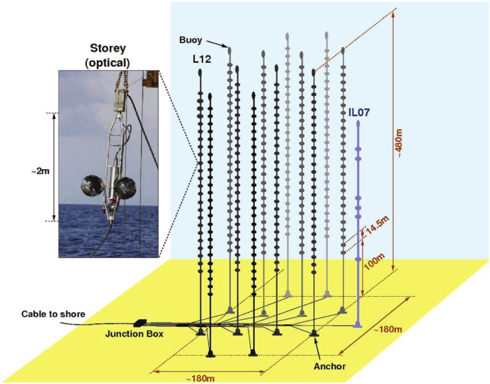
- Located under the Antarctic ice
- Ice gives a good energy resolution
- Currently the most sensitive neutrino telescope

Discovered astrophysical neutrinos in 2013



ANTARES

- Located in Mediterranean sea
- Sea water gives a good angular resolution
- Most sensitive neutrino telescope in northern hemisphere



Astrophysical neutrinos

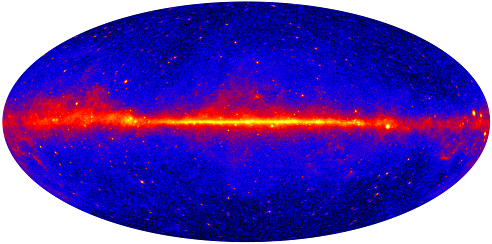
Features

- Energy: from ~ 40 TeV to 10 PeV
- Spectral index ~ 2.5

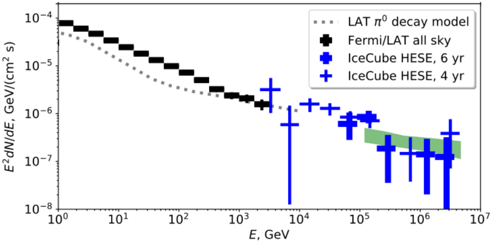
Galactic versus extra-Galactic origin

- Angular distribution suggests extra-galactic origin at first sight [PoS(ICRC2017)981]
- Recently began to observe an anisotropy around the Galactic plane with significance between 2 and 3σ [A.Neronov, D.Semikoz, Astropart.Phys. 75,60 (2015)] & [IceCube Collab. arXiv:1907.06714]

GeV-PeV sky



γ-ray diffuse emission from Fermi-LAT



Diffuse emission spectrum for γ-rays and neutrinos [Phys. Rev. D **98**, 023004 (2018)]

Diffuse VHE ν and γ-ray

Galactic CR interaction with the ISM

At energies $E \lesssim 10^{15}$ eV, cosmic rays mostly come from the Galaxy and produce neutrinos of energy $\lesssim 30$ TeV.

Extra-galactic CR interaction emission with the ISM

At energies $E \gtrsim 10^{18}$ eV, the sources are no longer in the Galaxy and produce neutrinos with energy $\gtrsim 10$ PeV.

Neutrino origin

We know the origin of most neutrinos at a given energy:

$$\begin{cases} E_{Galactic} \lesssim 30 \text{ TeV} \\ E_{extra-galactic} \gtrsim 10 \text{ PeV} \end{cases}$$

IceCube observe this astrophysical flux from 60 TeV up to the PeV scale.

$\Rightarrow$ Need to find a model working between 30 TeV and 10 PeV.

The most natural way to determine the energy of these neutrinos through multimessenger astronomy is first to understand the Galactic γ-ray physics in the PeV range (not observed yet, should be soon with VHE γ-ray observatory such as LHAASO).

Ways to fill this gap:

- Extrapolation of known lower energy emission models
- Unknown sources

Fill the gap with new sources

Hypotheses:

- Local sources of VHE CR [M. Bouyahiaoui *et al.* JCAP01(2019)046]
- Heavy dark matter decay [Phys. Rev. D **98**, 083016 & arXiv:1903.12623]

$$\frac{\mathrm{d}N}{\mathrm{d}E}(E) \propto \frac{1}{\tau M_X}$$

with $M_X \gtrsim 1$ PeV and τ the mass and lifetime of the DM particle

- Fermi Bubble or extended Galactic halo [arXiv:1403.3206]

$$\frac{N_\nu^h}{N_\nu^d} \simeq 5 \times 10^{-2} \left(\frac{n_{p,-3}^h}{n_{p,0}^d}\right) \left(\frac{L_1^h}{L_1^d}\right) \left(\frac{\Omega^d}{0.1}\right)^{-1}$$

KRA$_\gamma$ model

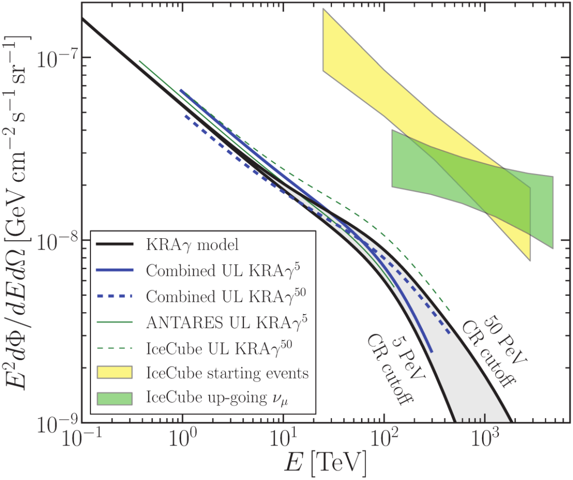
Relaxed relax the assumption that the local CR transport property can be extended to the entire Galaxy to describe the γ-ray diffuse emission. Chose radially dependent diffusion coefficient:

$$D(\rho) = \left(\frac{\rho}{\rho_0}\right)^\delta$$

with $\delta = ar + b$ instead of a constant.
Fit Fermi-LAT data around 1 GeV $\Rightarrow$ reproduce better the high energy γ-ray properties (in particular in the inner Galactic region).

Limitation: radial dependence doesn't match the Galaxy geometry.

Previous results



KRA_γ^{50} rejected with $>$ 90% CL.

Upper limit on KRA_γ^{5}: 110% of the expected flux with ANTARES only.

[T. Grégoire thesis, 2018 & arXiv:1808.03531]

Current work

ANTARES data analysis: preliminary work for a combined analysis with IceCube: Monte Carlo simulation to extract the sensitivity, upper limit or discovery potential from this detector with a simple model from a likelihood:

$$\mathcal{L}(n_S|\{E,\alpha,\delta,\theta\}) = \prod_{i=1}^{N} \mathcal{L}_i(n_S|E_i,\alpha_i,\delta_i,\theta_i)$$

with:

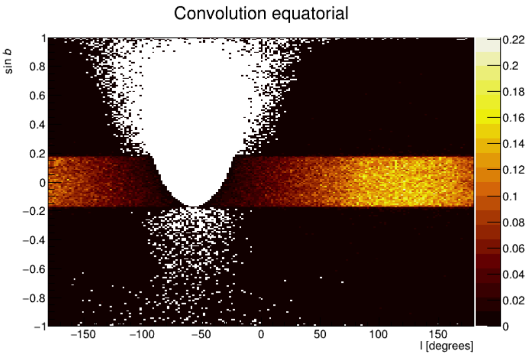
$$\mathcal{L}_i(n_S|E_i,\alpha_i,\delta_i,\theta_i) = \frac{n_S}{N} \times \mathcal{S}(E_i,\alpha_i,\delta_i) + \frac{n_B}{N} \times \mathcal{B}(E_i,\theta_i)$$

Need to study the diffuse γ-ray diffuse emission in detail to produce a robust model for the neutrino signal $\mathcal{S}$.

Toy model

Flux described by a single power law with Galactic latitude cut:

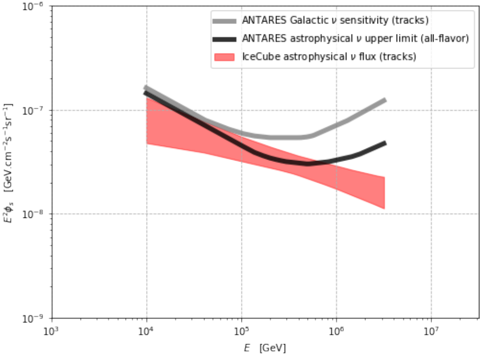
$$\frac{d\phi}{\mathrm{d}\Omega} = \frac{\mathrm{d}N}{\mathrm{d}E\,\mathrm{d}t\,\mathrm{d}S\,\mathrm{d}\Omega} = \begin{cases} \phi_0 \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-\gamma} & \text{if } |b| < b_0 = 10^\circ \\ 0 & \text{otherwise} \end{cases}$$



Signal flux for track events after convolution with the PSF.

Preliminary results

Results for tracks events selected for point source, with toy model flux and background model based on the real data.



- Better sensitivity will be achieved by combination with IceCube data
- Better models will be tested

ANTARES upper limit obtained from scanning the 90% confidence level of a contour plot [Fig. 2, APJ Letters, Volume 853, Number 1]

Conclusion

- Unkown origin of astrophysical neutrinos
- Need a better understanding of γ-rays diffuse emission between 30 TeV and 10 PeV
- A likelihood analysis with ANTARES and IceCube combined data is under development