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Status of high-energy neutrino searches in the Galaxy

Luigi Antonio Fusco[a,*]

[a] *Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, Fisciano, 84084 Italy*

E-mail: lfusco@unisa.it

The presence of cosmic rays in our galaxy can be tracked with neutral messengers, such as photons and neutrinos. Photons are observed at various wavelengths, and gamma-ray observations from GeV to PeV scales have given an important insight on the behaviour of charged particles in the Milky Way. However, both leptonic – photon emission from processes involving electrons – and hadronic – emission coming from proton or nuclei interactions – mechanisms can be used to explain the observed gamma-ray flux in many different high-energy individual sources. On the other hand, neutrinos can only be produced in hadronic processes where protons or nuclei in the cosmic ray flux interact in the interstellar matter and radiation fields. For this reason, neutrinos are the ideal probe to test cosmic-ray physics at their sources. On top of the neutrino emission from individual sources, a guaranteed flux of cosmic neutrinos is expected from cosmic rays that reside, propagate, and interact in the Milky Way. This is already visible in high-energy photon surveys of the Galactic Plane, and such flux has been already clearly attributed to cosmic rays interacting in the denser inner regions of the galaxy. The observation of neutrinos from the same regions would provide an additional source of information on the properties of galactic cosmic rays, also allowing to study them far away from Earth, where measurements are currently done, since neutrinos can travel undeflected and unabsorbed over such large distances. In this contribution, a review of searches for cosmic neutrinos in the Milky Way is provided.

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1. Phenomenology of high-energy galactic emissions

Supernova Remnants (SNRs) with expanding shells of material in the Sedov-Taylor phase are usually proposed as sources and accelerators of galactic cosmic rays (GCRs) up to the CR *knee*, between 10^{15} and 10^{16} eV depending on the primary mass [1, 2]. Diffusive shock acceleration processes can happen in SNRs as the ejected shells of matter move though the interstellar medium (ISM): following the Fermi mechanisms [3, 4], power-law CR spectra are produced up to maximal energies which depend on the properties of the SNR, with a rigidity-dependent cut-off at some 10^{15}–10^{16} eV. CRs can interact near their acceleration sites with the dense matter and/or with the intense radiation fields. As the CR interacts, short-lived mesons (mainly pions) are produced, which will in turn decay into photons (as in the case of π^0) or into leptons (as in the case of $\pi^\pm$). The result of such CR interactions would then be visible as a flux of gamma-rays (up to hundreds of TeV) and neutrinos from those leptonic decays (with neutrinos carrying roughly half of the photon energy). Thus, the flux of neutrinos from high-energy gamma-ray sources can be estimated considering the abundance of produced mesons and the kinematics of these decays under certain conditions [5].

CRs exiting their acceleration site will instead be able to start their journey through the Galaxy, constantly being deflected by magnetic fields, until they interact with matter/radiation along their way, or they manage to exit the Galaxy. Similarly to GCRs at their sources, GCRs interacting in the ISM will produce meson that will generate a flux of high-energy photons and neutrinos. This high-energy photon flux is clearly visible in the Fermi-LAT sky [6] and the properties of CRs can be extracted from it, assuming a given distribution of sources, matter, radiation fields, and magnetic fields – all which contribute to the properties of the CR propagation. If these are modified, a different fit of Fermi-LAT data can be obtained, as in the KRA$_\gamma$ model [7], where the diffusion of CR is assumed to be dependent on the distance from the Galactic Centre: a harder and more intense flux is thus obtained in the inner Galactic Plane (GP). Consequently, also the neutrino flux can be estimated and will follow a similar behaviour as the photons flux. The ratio between the expected neutrino flux from the standard Fermi-LAT model, and that from the KRA$_\gamma$ model [8] is shown in figure 1.

2. Selected results from neutrino telescopes

Neutrino telescopes are large-volume 3D arrays of photodetectors placed at large depths in a transparent medium (water or ice). Cherenkov light induced by relativistic charged particles passing through the medium is detected in the array, and the recorded information can be used to reconstruct the direction and energy of the incoming neutrino by which those charged particles were produced. All-flavour neutrino interactions can be detected in neutrino telescopes which have already discovered the existence of cosmic fluxes [10]. Track-like events, induced by charged current muon neutrino interactions allow a precise directional reconstruction (typically better than 0.5° angular resolution), while all the other neutrino flavours will produce shower-like signature in which the direction is rather poorly reconstructed (2-10° uncertainties) but the energy can be obtained with quite good accuracy (up to ~15% uncertainties).

The ANTARES [11] and IceCube [12] neutrino telescopes have combined their datasets in order to perform the most sensitive search for individual sources of neutrinos from the Milky

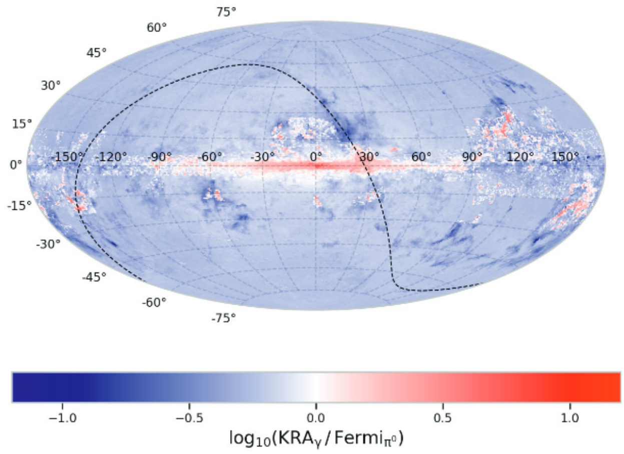

Figure 1: Ratio between the expected flux of neutrinos from GCR propagation in the Milky Way standard model from the Fermi-LAT and the KRA$_\gamma$ model described in text [8] in galactic coordinates. This figure is taken from ref. [9]. The Fermi model is more intense than the KRA$_\gamma$ model in the regions in blue; on the contrary, the KRA$_\gamma$-flux is generally more intense in the inner GP (red regions).

Way [13]. Clusters of events were searched for in the Southern Sky, also towards known TeV gamma-ray sources that are plausible CR accelerators. No evidence for any directional excess has been found and upper limits on the neutrino flux have been obtained, as reported in figure 2 - left. With a similar combined dataset, the two Collaborations have also searched for neutrinos following a spatial and energy template of the emission from the KRA$_\gamma$ model. In this case, a non-significant excess of neutrino events over the background has been detected, compatible with the expectations from the model. The corresponding upper limits are reported in figure 2 - right, with the expected neutrino flux from the GP. Such flux can account for, at most, 10% of the overall diffuse neutrino flux detected by IceCube (described in ref. [10]).

3. Outlook

The sensitivities of both the ANTARES and IceCube neutrino telescopes are now very close to the expected diffuse GP neutrino flux. The final push towards discovery can be probably made by including shower-like events into these searches. Some indication has already been presented, for example in ref. [14], where some additional excess of events has been spotted in the shower-like sample. A further boost in sensitivity is expected when including machine-learning-based analyses that should significantly enhance the IceCube sensitivity in this channel [15] and which could lead to a more significant statement on the detection of this flux. Similarly, ANTARES updated analyses are in sight. On the other hand, the discovery of GCR accelerators using neutrinos from hadronic mechanisms will require data from the next generation neutrino telescope KM3NeT [16] which is currently being built in the Mediterranean Sea and has been specifically optmised for this task [17].

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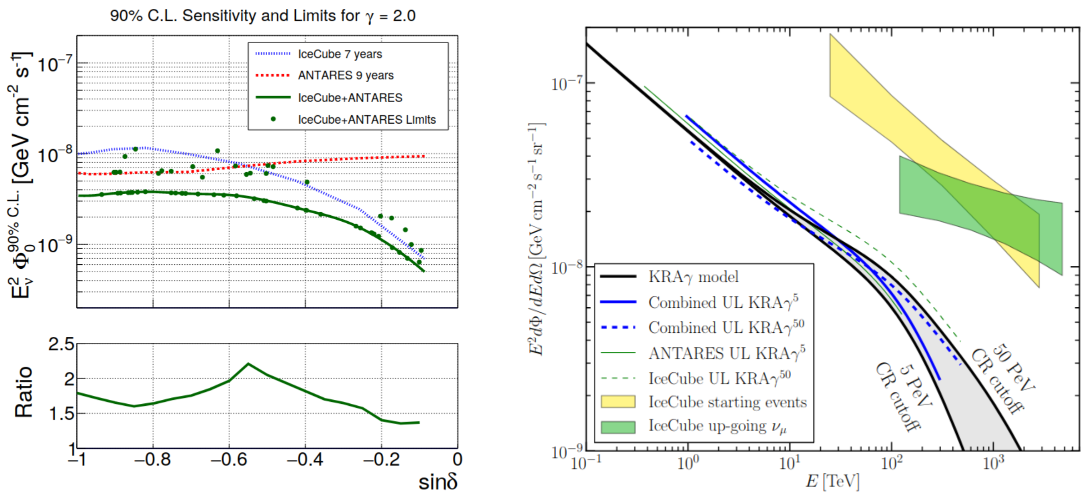

Figure 2: Left: Upper limits at 90% confidence level on the one-flavour neutrino flux normalization from the combined ANTARES and IceCube data (green dots) as a function of the source declination for an E^{-2} power-law spectrum. The green line indicates the sensitivity of the combined analysis. The dashed curves indicate the sensitivities for the IceCube (blue) and ANTARES (red) individual analyses, with the ratio in the bottom panel. Right: Combined ANTARES and IceCube upper limits on the neutrino emission from the GP, compared with the model from ref. [8], and the all-sky diffuse flux measured in IceCube [10].

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