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# $\gamma$-Rays, $\nu$'s and Particle Astronomy as Messengers of the Universe

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**Abstract**

Observations of charged cosmic-rays, $\gamma$-rays and neutrino are possible thanks to the availability of new detectors coming from technologies typical of experimental particle physics. In conjunction with more traditional techniques used by astronomers, these multimessenger correlations of experimental data are opening a new scenario in astrophysics. We review some of the more recent developments in the field.

**Keywords:** cosmic-rays - $\gamma$-rays - neutrinos - satellites - ground-based experiments - neutrino telescopes.

## 1 Introduction

The multimessenger inter-correlation between Cosmic Rays (CRs), $\gamma$-rays and neutrinos is of fundamental importance for a deeper comprehension of high energy (HE) processes in astrophysical sources. One of the main questions in astrophysics is the origin and nature of CRs (§2), whose energy spectrum extends up to above $10^{20}$ eV. There are many indications of the galactic origin of the CR bulk (protons and other nuclei up to $\sim 10^{16}$ eV).

Due to the influence of galactic magnetic fields, charged particles detected on Earth do not point to the sources. Gamma-rays and neutrinos do not suffer the effect of magnetic fields: they represent the decay products of accelerated charged particles but cannot be directly accelerated. The possibility of *particle astronomy* rely on the detection of these neutral probes, or to the detection of the highest component of charged CRs (see Castellina, these proceedings).

Recent advances on GeV and TeV $\gamma$-ray astronomy by satellites and ground-based experiments (§3) have led to the discovery of different classes of galactic and extragalactic objects that can be shed light on the CR acceleration mechanisms.

Most objects observed in the $\gamma$-rays (see Fig. 1) are known sources from measurements of their electromagnetic emission at different wavelengths, in particular in the radio and in the X-rays.

Accelerated protons will interact in the surroundings of the CRs emitter with photons predominantly via the $\Delta^+$ resonance:

$$p + \gamma \to \Delta^+ \to \pi^o + p \quad \text{or} \quad \to \pi^+ + n \tag{1}$$

Protons will interact also with ambient matter (protons, neutrons and nuclei), giving rise to the production of charged and neutral mesons. The relationship between sources of $\gamma$-ray and neutrinos is the meson-decay channel. Neutral mesons decay in $\pi^o \to \gamma\gamma$ while charged mesons decay in neutrinos:

$$\begin{aligned} &\pi^+ \to \nu_\mu + \mu^+ \\ &\qquad\qquad \hookrightarrow \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+ \\ &\pi^- \to \overline{\nu}_\mu + \mu^- \\ &\qquad\qquad \hookrightarrow \mu^- \to \nu_\mu + \overline{\nu}_e + e^- \end{aligned} \tag{2}$$

In particular circumstances, the energy escaping from the source is distributed between CRs, $\gamma$-rays and neutrinos. Only the coincident measurement of neutrinos (§4) from the source would give a uncontroversial proof of the discovery of the galactic acceleration sites of protons and nuclei.

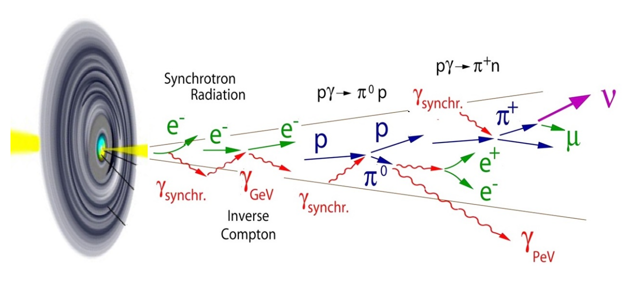


**Figure 1:** Sketch of the production of CRs, neutrinos, $\gamma$-rays and lower energy photons from an astrophysical jet.

The highest energy CRs are probably originated from extragalactic sources. If they are protons with $E > 5 \times 10^{19}$ eV, they could interact with the cosmic microwave background radiation. This process restricts the origin of highest energy protons seen on Earth to a small fraction of the Universe, a sphere of the order of

100 Mpc (the Greisen-Zatsepin-Kuzmin suppression).

The prediction of a diffuse flux of HE neutrino of extra-galactic origin is a direct consequence of the ultra HE CR observations. This connection between CRs, neutrinos and $\gamma$-rays was used to put upper bounds on the expected neutrino flux from extragalactic sources, since the neutrino energy generation rate will never exceed the generation rate of high energy protons.

In this paper, we will review some of the recent updates in these fields.

## 2 CRs and Antimatter

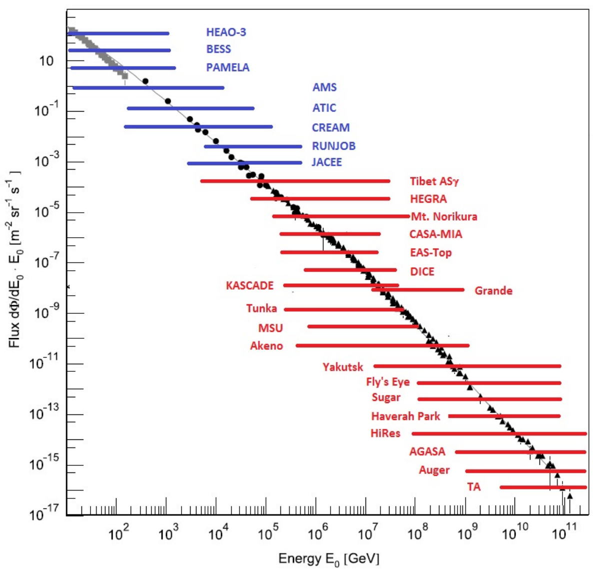


**Figure 2:** CR intensity as a function of the energy from $10^{10}$ to $10^{20}$ eV. Below few GeV, the contribution of particles coming from the Sun is not negligible. The energy range of the flux measured by direct experiments is reported as blue line; that measured by indirect experiments as red line

CRs are mainly protons (Fig. 2) and heavier nuclei which are constantly hitting the upper shells of the Earth's atmosphere (Blümer et al, 2009). Up to energies of $\sim 10^{14}$ eV, the CR spectrum is directly measured above the atmosphere. Stratospheric balloons and satellites have provided the most relevant information about the composition of CRs. Above $\sim 10^{14}$ eV, CR measurements are only accessible from ground-based large area arrays.

Recent observations of TeV photons seem to confirm the Diffusive Shock Acceleration (DSA) model, where the shocks powered by supernova explosions in our Galaxy provide the iterative scattering mechanism for CRs acceleration up to $\sim 10^{16}$ eV (see Hillas, 2005). The key feature of this process is that an energy power-law spectrum of the type $\sim E^{-2}$ is produced. The DSA model is consistent with the balance between the energy transferred to the accelerated particles and the energy loss due to the escape of CRs out of the Galaxy. The $E^{-2}$ emission at sources, when corrected for energy-dependent leakage from the Galaxy, is in agreement with the observed CR energy spectrum. The details of acceleration mechanism and propagation of cosmic rays at higher energies are not completely understood.

An important open item is the presence of antimatter in the radiation. Equal amounts of matter and antimatter should have been produced at the beginning of the universe. The fact that there seems to be only matter around us is one of the major open problems in cosmology and in particle physics. The antiprotons, as well as the positrons, are a component of the cosmic radiation being produced in the interaction between CRs and the interstellar matter. Being exactly the same as particles except for their opposite charge sign, antiparticles are readily distinguished as they bend in opposite directions in magnetic field. Magnetic spectrometers provide a clear and simple particle/antiparticle separation and probe the existence of antimatter in our Galaxy.

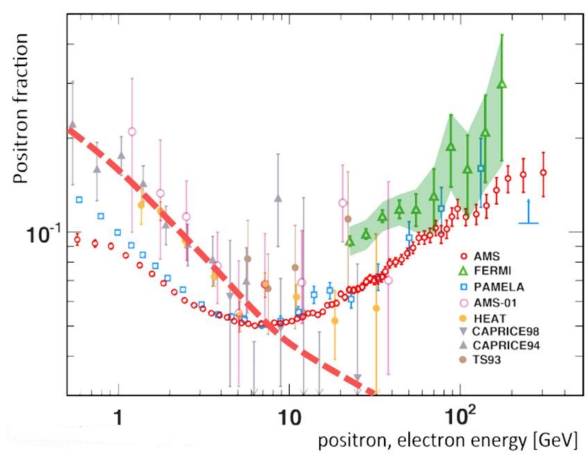


**Figure 3:** The positron ratio measured by the PAMELA, Fermi and AMS-02 as presented in the first public presentation of AMS-02 results. The expectation from the production of positrons as secondary particles is shown as dashed line. The discrepancy below 10 GeV is explained by different phases of solar activity when data were collected. From http://ams.cern.ch/

An important feature in the $e^+$ spectrum was observed by the PAMELA satellite and confirmed with the high precision measurement of AMS-02. Launched in 2011, the AMS-02 experiment started immediately to take date on the International Space Station (ISS). It is the largest particle physics detector never carried outside the Earth atmosphere. The first results were presented in April, 2013 and refer to the measurement of positron in the CRs. The $e^+$ fraction in the $e^- + e^+$ flux found in the cosmic radiation increases steadily between 10 GeV to $\sim$ 250 GeV, see Fig. 3. At energies above 250 GeV, the spectrum appears to flatten but to study the behavior at higher energy more statistics is required. The positron fraction spectrum exhibits no spatial anisotropy, structures or time dependence.

These measurements have stimulated a large debate, as they cannot in fact be understood by models describing the production of secondary CRs during propagation in the Galaxy (see dashed line in Fig. 3). Several explanations have been proposed to interpret the observed excess: an astrophysical origin, such as nearby pulsars or microquasars, or exotic sources, as for instance the annihilation of Dark Matter particles in our Galaxy.

The $\bar{p}/p$ ratio ($\sim 10^{-5} \div 10^{-4}$) shows that the antiproton flux is in overall agreement with a pure secondary component: antiparticles are produced during the interaction of CRs with the interstellar matter. On the contrary, the ratio $e^+/e^- \sim 0.1$ seems indicate that most of the detected electrons are of primary origin.

Due to energy loss processes, the majority of HE electrons must be originated by sources closer than a few hundred pc. HE electrons really probe CR production and propagation in the nearby region of our Galaxy. In the next years, the AMS-02 experiment will undoubtedly be the leading experiment for a systematic study of the CRs through direct measurements, for the searches of antimatter in space, and for the searches for particles originated by Dark Matter annihilations.

## 3 High Energy $\gamma$-Rays

HE astrophysical processes producing relativistic particles are in most cases associated with the production of $\gamma$-rays in a wide range of energies. Starting from the EGRET satellites in the '90th, a new window has been opened in the observation of photons above $\sim$ 100 MeV [1].

The EGRET catalog consists of about 270 galactic and extragalactic objects. The present generation of space-based gamma ray telescopes, AGILE and LAT, has opened a new era with thousands of galactic and extragalactic sources. The large number of sources and the high data quality are producing a deeper insight into the understanding of the processes of acceleration and radiation of non-thermal particles in the Universe at sub-TeV energies. As the flux of $\gamma$-rays decreases with increasing energy, space-based observations of most sources are limited to less than 100 GeV.

Gamma-rays above 100 GeV [2] are detected on ground, using extensive air shower (EAS) particle detectors or the Imaging Atmospheric-Cherenkov Technique (IACT). TeV $\gamma$-rays are absorbed when reaching the Earth atmosphere, and the absorption process proceeds by creation of a cascade of secondary particles. These emit Cherenkov radiation, at a characteristic angle in the visible and UV range, which passes through the atmosphere. As a result of Cherenkov light collection by a suitable mirror in a camera, the showers can be observed on the surface of the Earth. The comparisons between the main features of space-based, IACTs, EAS and neutrino telescopes (§4) are presented in Table 1.

**Table 1:** Characteristic of space-based, IACTs, EAS and neutrino telescopes. From the top raw: energy range; effective area; the background rejection power; the angular and energy resolutions; the characteristic aperture of the telescopes; the duty cycle.

| | Space | IACT | EAS | $\nu$-Tel |
|---|---|---|---|---|
| Energy (TeV) | $10^{-4}$-0.3 | 0.5-100 | 0.5-50 | 1-1000 |
| Area (m$^2$) | 1 | $10^4$ | $10^4$ | 0.1-300 |
| Bck Rejec. | $>$ 99% | $>$ 99% | 95% | 99% |
| Angular Resol. | 0.5° | 0.05° | 0.7° | 0.5° |
| $\Delta E/E$ | 10% | 15% | 50% | 40% |
| Aperture (sr) | 2.7 | 0.003 | 1.8 | $2\pi$ |
| Duty cycle | 85% | 10% | 95% | 95% |

### 3.1 HE $\gamma$-rays on satellites

The Large Area Telescope (LAT) on the Fermi satellite (launched in June 2008) is a $\gamma$-ray detector designed to distinguish photons in the energy range 20 MeV to more than 300 GeV from the high background of energetic charged particles.

The $\gamma$-ray sky (unlike at other wavelengths) is strongly dominated by diffuse radiation originating in our Galaxy by CR interactions with the interstellar gas and photon fields through the processes of inelastic nucleon scattering, bremsstrahlung, and inverse Compton scattering. The LAT mapping of the galactic $\gamma$-rays offers a way to derive information about the spatial distribution of CRs and matter.

The second catalog of high-energy $\gamma$-ray sources (2FGL) detected by the LAT (Nolan P.L. et al., 2012) derives from data taken during the first 24 months of the science phase of the mission, which began on 2008 August 4. The 2FGL catalog contains 1873 sources detected and characterized in the 100 MeV to 100 GeV. It includes source location regions, energy dependence of the flux in terms of a power-law with an exponentially cutoff and light curves on monthly intervals for each source. Among the 1873 sources, 127 are firmly identified and 1171 reliably associated with counter-

[1] We indicate with HE $\gamma$-rays the photons between 0.02-100 GeV

[2] We indicate with VHE $\gamma$-rays the photons between 100 GeV-100 TeV

parts of known or likely $\gamma$-ray producing source classes, see Fig. 4.

AGN, and in particular blazars, are the most prominent class of associated sources: 917 sources are associated, of which 894 are blazars, 9 are radio galaxies, 5 Seyfert galaxies. Normal galaxies are now established as a class of $\gamma$-ray emitters and 7 2FGL sources are associated with such objects.

Pulsars have been traditionally studied through radio astronomy methods, with about 1800 pulsars found beaming radio waves. However, most of their radiation (a few percent of their spin-down power) is emitted at high-energies. In the last few years, the number of pulsars detected in the $\gamma$-ray has increased from half a dozen to more than 150 thanks to the AGILE satellite and the Fermi-LAT. Among the pulsar, the Crab plays a fundamental role, as it is the strongest $\gamma$-ray source in our field of view. The Crab was since recently thought to be a steady source of radiation, from optical to TeV energies. AGILE unexpected has discovered in 2010 (Tavani et al., 2011) strong and rapid $\gamma$-ray flares from the Crab Nebula over daily timescales. This observation have changed the understanding of this cosmic object, and challenged emission models of pulsar wind and particle acceleration processes. Pulsed $\gamma$-ray emission above 100 GeV and up to 400 GeV was recently detected from the Crab with the VERITAS and MAGIC IACTs.

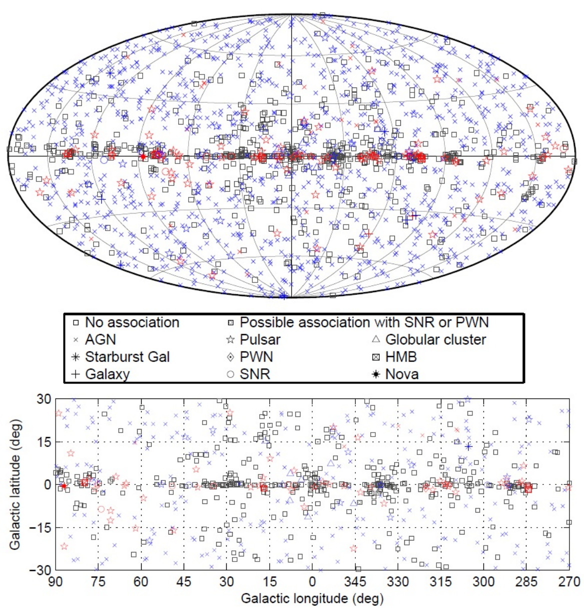


**Figure 4:** Fermi-LAT 2FGL full sky map (top) and blow-up of the inner Galactic region (bottom) showing sources by source class. Identified sources are shown with a red symbol, associated sources in blue.

About 70 sources of the 2FGL catalog are associated with Pulsar Wind Nebulae. Supernova remnants are a special class because a substantial number of the known objects are sufficiently extended to be potentially resolved with the LAT. These objects are particularly interesting because they can represent regions of CR acceleration. In total, twelve sources in the catalog are modeled as spatially extended.

## 3.2 VHE $\gamma$-rays at ground

One of the most recent and remarkable achievements in astrophysics is the discovery of more than 110 galactic and extragalactic sources of VHE radiation (see for a review Rieger et al., 2013). At present, seven shell-type SNRs have been firmly identify as VHE $\gamma$-ray emitters

The pioneering ground based $\gamma$-ray experiment was built by the Whipple collaboration. During the last decade, several ground-based $\gamma$-ray detectors were developed, both in the North and South Earth hemisphere. At present, the new generation apparatus are the H.E.S.S. and VERITAS telescope arrays and the MAGIC telescopes. These IACTs have produced a catalogue of TeV $\gamma$-ray sources which is continuously updated and available at http://tevcat.uchicago.edu/.

Electron can produce HE $\gamma$-rays through the so-called *leptonic model*. Synchrotron radiation from radio to the X-ray band is originated by accelerated electrons moving in the source magnetic fields. These particles can also produce GeV-TeV $\gamma$-rays through inverse Compton scattering on the produced radiation field, or on external radiation fields. Therefore, measurements of the synchrotron X-ray flux from a source can constrain the predictions on the accompanying $\gamma$-rays produced in leptonic processes.

Accelerated hadrons could either produce $\gamma$-rays via interaction with ambient matter or photon fields with sufficient high density. In this case, $\gamma$-rays are produced by the decay of neutral mesons while $\nu$'s are produced by the decay of charged mesons. This $\gamma$-rays and neutrino production refer to a so-called *astrophysical hadronic model*. In this framework, the energy spectrum of secondary $\gamma$ and $\nu$ particles follows the same power law of the progenitor CRs.

Both the leptonic and the hadronic models, or a combination of them, could provide an adequate description of the present experimental situation. If high energy photons are produced in the hadronic models, high energy neutrinos will be produced as well. Most of observed TeV $\gamma$-ray galactic sources have a power law energy spectrum $E^{-\alpha_\gamma}$, where $\alpha_\gamma \sim 2.0 \div 2.5$. The values of the spectral index are very close to the expected spectral index of CR sources, $\alpha_{CR}$. This lead to the conclusion that sources of TeV $\gamma$-rays can also be the sources of galactic CRs.

## 4 Neutrino Astrophysics

The main detection signatures for neutrinos in a Neutrino Telescope (see Chiarusi & Spurio, 2010) are long, straight tracks and approximately spherical cascades. The former are created by neutrino-induced muons while the latter are produced by neutrino-induced electromagnetic and/or hadronic showers. Charged particles emit Cherenkov light. From the measured arrival time of the Cherenkov light, the direction of the neutrino can be derived. The accurate measurement of the $\nu_\mu$ direction (up to $0.3^o$ in water) could allows the association with (known) sources. Because the mechanisms that produce CRs can produce also neutrinos and $\gamma$-ray, potential neutrino sources are in general also $\gamma$-ray emitters. Due to the production mechanism (Eq. 2), the flavor ratio at sources is $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, which is changed by the neutrino oscillations to $1 : 1 : 1$ on Earth.

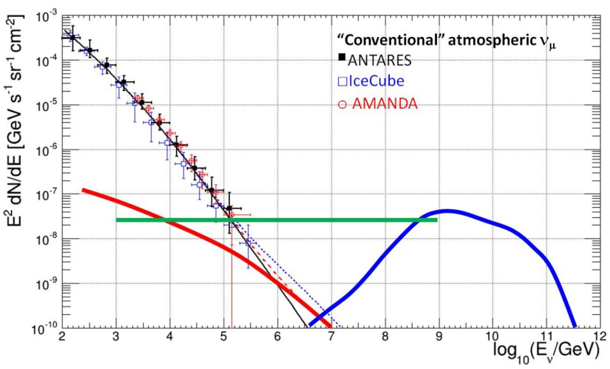


**Figure 5:** Neutrino telescopes searches for an excess of events over the irreducible background of atmospheric neutrinos. The points represent the measurements of atmospheric $\nu_\mu$ spectrum by three telescopes. The red curve represent the still unmeasured contribution of *prompt* neutrinos from charmed mesons decay. The green lines are the Waxman& Bahcall (1999) upper bound from diffuse flux of neutrinos from extragalactic sources. The blue line the possible contribution of $\nu$ from the GZK effect.

Some of the most promising candidate neutrino sources in our Galaxy are extremely interesting, due to the recent results from TeV $\gamma$-ray detectors. A neutrino telescope in the Mediterranean sea is looking at the same Southern field-of-view as the H.E.S.S. including the galactic center.

The small interaction cross section of neutrinos allows them to come from far away, but it is also a drawback, as their detection requires a large target mass. Assuming the present boundaries arising from $\gamma$-rays sources, the challenge to detect galactic neutrinos is open for a multi kilometer-scale apparatus, see Fig. 5. Also the extragalactic CRs-neutrinos connection sets the scale of the detectors to 1 km$^3$.

IceCube (http://icecube.wisc.edu/) is a 1 km$^3$-scale neutrino detector buried in the Antarctic ice. It comprise 86 strings, with 5160 photomultiplier tubes (PMT). Each string includes 60 digital optical modules. The DeepCore infill array to IceCube reduces the energy threshold of IceCube to energies as low as 10 GeV. In water the ANTARES collaboration (Ageron et al, 2011) has completed in 2008 the construction of the largest neutrino telescope ($\sim 0.1$ km$^2$) in the Northern hemisphere.

**Galactic sources.** Although much smaller than IceCube, ANTARES is advantaged by its geographical location for the study of galactic sources. To give a figure of merit, the TeV photon flux from a possible neutrino candidate source as RX J1713.7-3946 is $E_\gamma^2 \Phi_\gamma \simeq 10^{-11}$ TeV cm$^{-2}$ s$^{-1}$. Assuming the same flux from neutrinos and no HE cutoff, few events/year are expected in a 1 km$^3$ telescope over the background of atmospheric neutrinos in a $\sim 1^\circ$ search cone. The sensitivity of ANTARES for 1000 days of livetime is $\sim E_{\nu_\mu}^2 \Phi_{\nu_\mu}^{sens} \simeq (3-8) \times 10^{-11}$ TeV cm$^{-2}$ s$^{-1}$ in the declination range from $\delta = -90^\circ$ to $+43^\circ$. In total 51 possible neutrino sources have been studied. None of them shows a significantly excess of TeV events over the expected background.

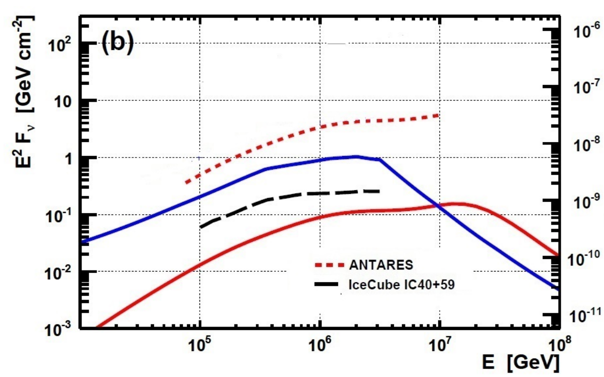


**Figure 6:** Expected neutrino spectra from full numerical NeuCosmA (red) and simply analytic Guetta (blue) models. Limits on these predictions are shown in the energy ranges where 90% of the flux (dashed lines) is expected. The IceCube limit on the neutrino emission (black dashed) is based from 300 GRBs. The ANTARES limit on 296 GRBs (red dashed) takes into account the neutrino oscillation effect.

**$\nu$ from GRBs.** Gamma-ray bursts (GRBs) are short and very intense flashes of HE $\gamma$-rays, which occur unpredictably and isotropically over the sky. In model describing the $\gamma$-ray emission, protons can also be shock-accelerated, yielding secondary emission of HE $\nu$'s accompanying the electromagnetic signal. The detection of neutrinos in coincidence with a GRB would be unambiguous proof for hadronic acceleration in cosmic sources.

Fig. 6 shows the result from these searches. The stringent IceCube limit (black dashed line, Abbasi et al., 2012) was a factor of 3.7 below the predictions made using the Guetta et al. (2004) model (blue line in Fig. 6), creating tension between the non-observation of a signal and the prevailing models for neutrino emission from GRBs. This could either indicate the need for rejection of these models or for more detailed modeling of the neutrino emission. The $\nu$ prediction from an advanced numerical calculation of GRB (NeuCosmA- Hümmer et al., 2012), including the full photohadronic interaction cross-section, independent losses of secondary particles, and flavor mixing, is shown as read line. The new predicted flux is about an order of magnitude below than the previous analytic approach, and thus it is still compatible with the limit as published by IceCube.

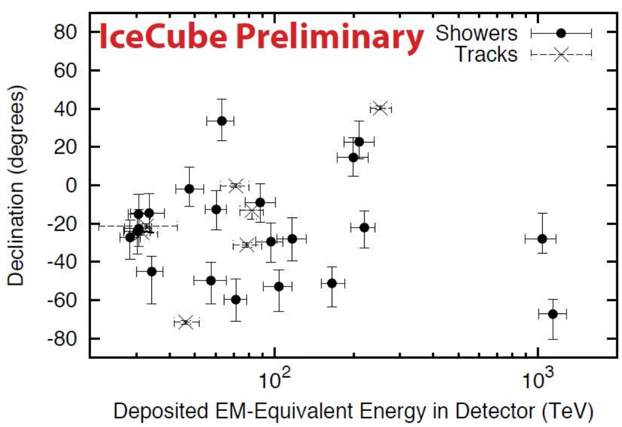


**Figure 7:** Declination vs reconstructed energy of the HE cosmic neutrino candidates in the IceCube detector (Whitehorn at WIPAC 2013)

**Diffuse HE neutrinos.** Recently IceCube reported on the observation of two HE particle shower events discovered in a search for PeV neutrinos (Aartsen et al., 2013). These events (reconstructed as downward going) are of much higher energy than expected from the background of atmospheric neutrinos, Fig. 5. Stimulated by these two events, almost during the same time of this Frascati workshop, the IceCube announced the results of a dedicated search for downward going neutrino-induced events in a restricted fiducial volume. Here, 28 events (7 muon-like and 21 shower-like) were discovered, with an expected background of 12.1 events (from atmospheric and prompt neutrinos, and atmospheric muons). The distribution of the declination and deposited energy for these events is shown in Fig. 7. The collaboration asserts that the events *seems* to be neutrinos, with flavor ratios consistent with the expected 1 : 1 : 1 and compatible with an isotropic flux.

## 5 Conclusions

Multimessenger astrophysics becomes more and more important to obtain a complete picture of non-thermal processes in the Universe. This program can be achieved by combining pieces of information from all three messengers: photons, charged CRs and $\nu$'s. The implications extend from the origin of CRs to the origin of Dark Matter, from processes of acceleration of particles by strong shock waves to the magnetohydrodynamics of relativistic jets, from distribution of matter in the Interstellar Medium to the intergalactic radiation and magnetic field distributions.

The strong impact of HE and VHE $\gamma$-rays discoveries on several topical areas of modern astrophysics and cosmology are recognized and of fundamental importance for the astronomical communities. In the near future, the role of AMS-02 is of overwhelming importance for direct measurement of CRs. Finally, the recent multi-TeV excess of neutrino events may be a first hint of an astrophysical HE neutrino flux, opening the field of neutrino astronomy for the next decade.

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## DISCUSSION

**ARNON DAR:** Concerning the IceCube events, the quoted error on the atmospheric neutrino background seems to be very small.

**MAURIZIO SPURIO:** In my opinion the main uncertainty could arise not from atmospheric neutrinos, but from the vetoing efficiency estimate for surviving atmospheric muons. There are some peculiarity of the events which are intriguing and only a detailed publication can clarify. For instance, the fact that (after background subtraction) the muon neutrinos are fewer than the expected from the quoted 1 : 1 : 1 ratio; that a cutoff energy at ∼1 PeV should be present; that the upgoing signal (4 events) is compatible with the background (3 events). For these reasons, if there is no underestimated contamination from atmospheric muons, the signal seems to be more likely of galactic origin than diffuse extragalactic.