High Energy Neutrino Astronomy

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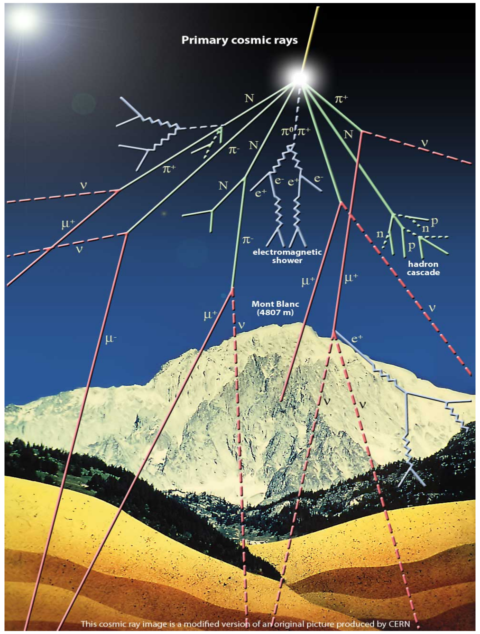
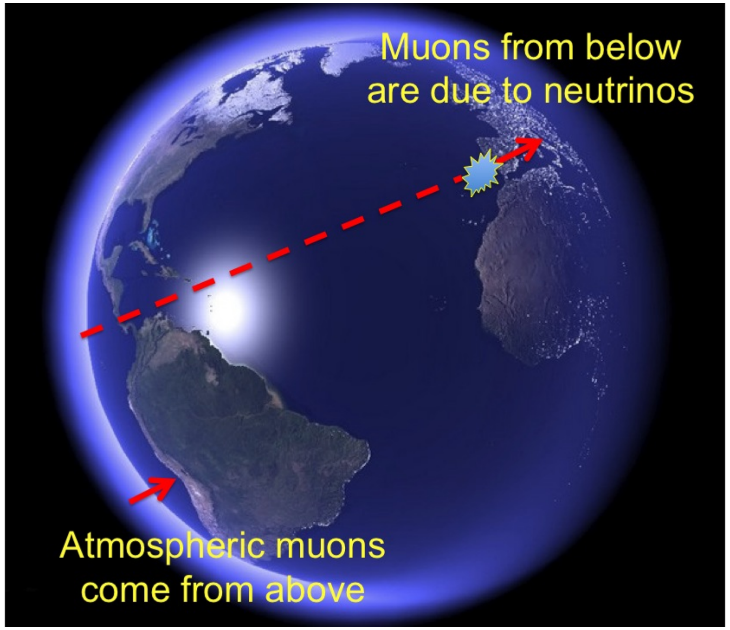
We discuss selected topics in high-energy neutrino-astronomy, in order to emphasize motivations, trends and open issues. We try to identify reliable connections, and, whenever possible, to offer quantitative statements.

High energy neutrinos telescopes – the beginning



Earth can shield atmospheric muons (continuous red lines) and convert muon-neutrinos (dashed) into observable muons, as understood by Markov in the late 50's.



We need to observe muons. Their range, dictated by e.m. interactions, is

$$R(E_\mu, E_{th}) \approx \textbf{2.5 km w.e.} \times \log \left[\frac{1 + \frac{E_\mu}{0.5\ \text{TeV}}}{1 + \frac{E_{th}}{0.5\ \text{TeV}}} \right]$$

already indicates the size of ~ 1 km of ideal HE neutrino detectors.

Again Markov's group raises the issue of additional contributions, i.e., concerning hypothetical COSMIC SOURCES OF HIGH ENERGY NEUTRINOS**.**

In the thesis of Zheleznykh (1958) we read,

1. *"γ quanta of 1 TeV favor existence of cosmic high-energy neutrinos"*
2. *"worth searching especially if HE γ beyond atmosphere were found"*
3. *from new star's shell as Crab* "the flux could equal the atmospheric one"
4. *from old CR population as GC* "could be large if attenuation is essential"

Most points are still qualitatively valid, In view of results on TeV γ, Fermi bubbles, theory. But today, the quantitative aspect does matter.

Neutrino search window: 1 TeV-few 100 TeV

1. $E_{th} > 1$ TeV: threshold to overcome atmospheric bkgr [e.g., Lipari 06].
2. $E_\nu \sim 10$ TeV: where $\sigma_{\nu N}$ starts to grow less $[2m_N E_\nu \sim M_W^2]$.
3. $E_\gamma^{max}/2 \sim 10$ TeV: typical extent of observed γ energies.
4. $E_p^{knee} x_{p\to\nu} \sim 150$ TeV: cutoff of Galactic CR $[x_{p\to\nu} \sim 1/20]$.
5. few 100 TeV: cut due to Earth absorption $[R_\oplus \sim m_N/(\rho_\oplus \sigma_{\nu N})]$.

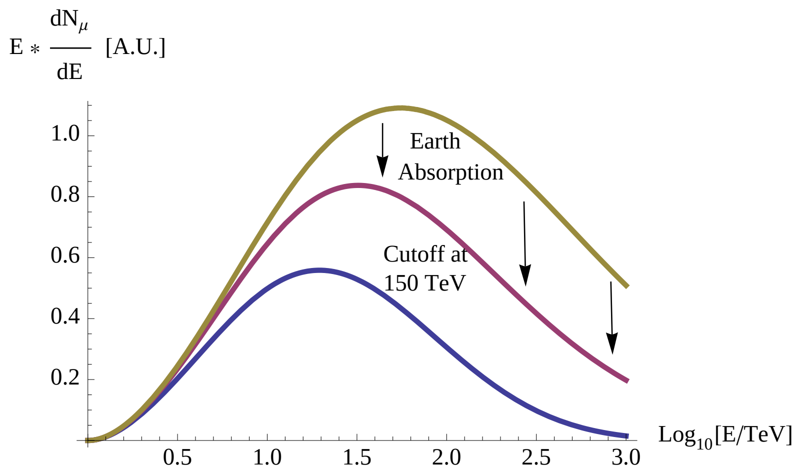
These considerations apply to search for induced μ signal, especially, from galactic sources. (Contained events, Earth skimming ones, extragalactic signals, may extend in energies.)

Standard calculation of the induced muon flux

$$P_{\nu_\mu \to \mu} = \int_{E_{th}}^{E} dE_\mu \frac{d\sigma_{cc}}{dE_\mu} R_\mu / m_n \qquad [\text{say, } 10^{-35}\ \text{cm}^2 \times N_A/\beta \sim 10^{-6}]$$

$$A_{\nu_\mu} = A_\mu(\theta) \times P_{\nu_\mu \to \mu}(E,\theta) \times e^{-\sigma\ z/m_n} \quad [\text{say, } 1\ \text{km}^2 \times 10^{-6} \sim 1\ \text{m}^2]$$

Distribution of ν_μ leading to muons, assuming E^{-2} primary spectrum (sienna); then, including Earth absorption, for a source at $\delta = -39°$ as seen from Antares (purple); then with a spectrum $E^{-2} e^{-\sqrt{E/150\ \text{TeV}}}$ (blue), i.e., with primaries cutoffed at $\sim$3 PeV.



The shape of the spectrum is based on the assumption that the primaries have an exponential cutoff (Ke'lner Aharonian 06; Kappes et al 07)

The effect of neutrino oscillations [1/2]

The emitted neutrino fluxes are reshuffled

$$F_{\nu_\ell}^{\text{osc.}} = \sum_{\ell'=e,\mu,\tau} P_{\ell\ell'}\ F_{\nu_{\ell'}}^{\text{no osc.}} \text{ where } \ell, \ell' = e, \mu, \tau$$

For HE neutrinos, Bilenky & Pontecorvo's 78 formulae usually apply;

$$P_{\ell\ell'} = \sum_{i=1}^{3} |U_{\ell i}^2||U_{\ell' i}^2|$$

They are just numbers and can be presented in a matrix

$$P = \begin{pmatrix} 0.54 & 0.26 & 0.20 \\ 0.26 & 0.37 & 0.37 \\ 0.20 & 0.37 & 0.43 \end{pmatrix}$$

See FV & Aharonian 2011 for a state-of-art discussion of these numbers and their errors.

Waxman-Bahcall bound as an example [2/2]

The ultra-high energy cosmic rays interact $p\gamma \to \pi^+ X$; their measured energy suggests the bound for all neutrinos from $\pi^+ \to \nu_\mu \bar{\nu}_\mu \nu_e e^+$

$$E^2 F(E) < 1.9 \times \frac{10^{-8}\ \text{GeV}}{\text{cm}^2\ \text{s sr}}$$

After oscillations the antineutrino flux consists of $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

$$E^2 F(E) < (0.5, 0.7, 0.7) \times \frac{10^{-8}\ \text{GeV}}{\text{cm}^2\ \text{s sr}}$$

and similarly it happens to ν_e, ν_μ, ν_τ

$$E^2 F(E) < (1.5, 1.2, 1.1) \times \frac{10^{-8}\ \text{GeV}}{\text{cm}^2\ \text{s sr}}$$

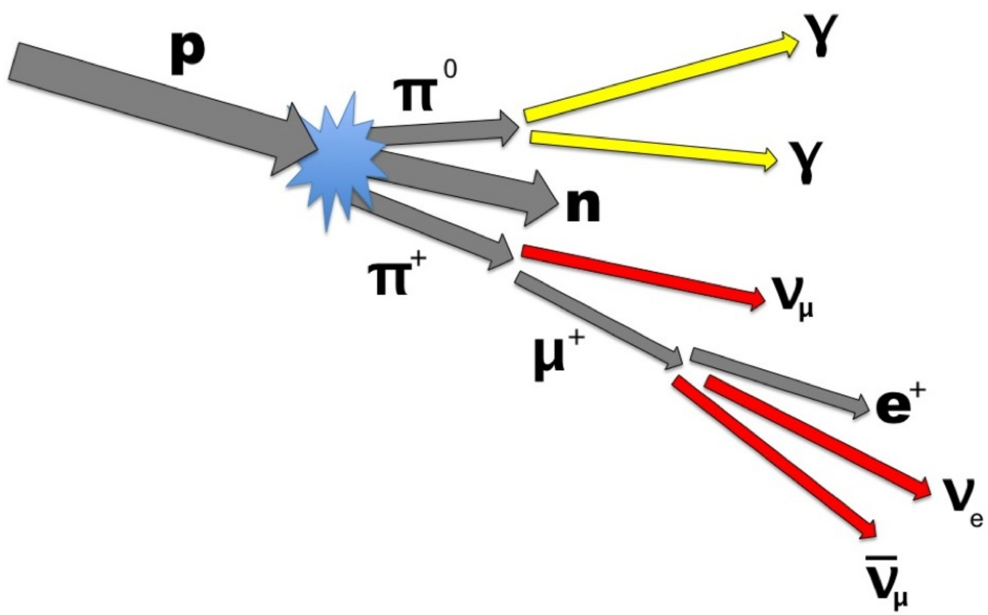
All type of neutrinos appear, with similar fluxes.

NEUTRINOS AND GAMMA RAYS

Let us **quantify** the relation between photons and neutrinos, assuming that:

(1) the sources are transparent to the gamma rays;

(2) the CR collide with protons.



These hypotheses apply for important galactic sources, as SNR.

Neutrinos and hadronic contribution to gamma are both linear functions of the cosmic ray intensity. They are linked as,

$$\Phi_{\nu_\mu}(E) = 0.380\ \Phi_\gamma\left(\frac{E}{1-r_\pi}\right) + 0.013\ \Phi_\gamma\left(\frac{E}{1-r_K}\right) + \int_0^1 \frac{dx}{x} K_\mu(x)\Phi_\gamma\left(\frac{E}{x}\right)$$

$$\Phi_{\bar\nu_\mu}(E) = 0.278\ \Phi_\gamma\left(\frac{E}{1-r_\pi}\right) + 0.009\ \Phi_\gamma\left(\frac{E}{1-r_K}\right) + \int_0^1 \frac{dx}{x} K_{\bar\mu}(x)\Phi_\gamma\left(\frac{E}{x}\right)$$

The first and second contributions are due to direct mesons decay into neutrinos, $r_x = (m_\mu/m_x)^2$ **with** $x = \pi, K$ **and the third to** μ **decay, e.g.:**

$$K_\mu(x) = \begin{cases} x^2(15.34 - 28.93x) & 0 < x < r_K \\ 0.0165 + 0.1193x + 3.747x^2 - 3.981x^3 & r_K < x < r_\pi \\ (1-x)^2(-0.6698 + 6.588x) & r_\pi < x < 1 \end{cases}$$

and similarly for antineutrinos; oscillations included FV'06; Villante & FV'08.

E.g., the HESS data of 2007 on RX J1713.7-3946 permit us to evaluate a precise upper bound on the observable neutrino flux:

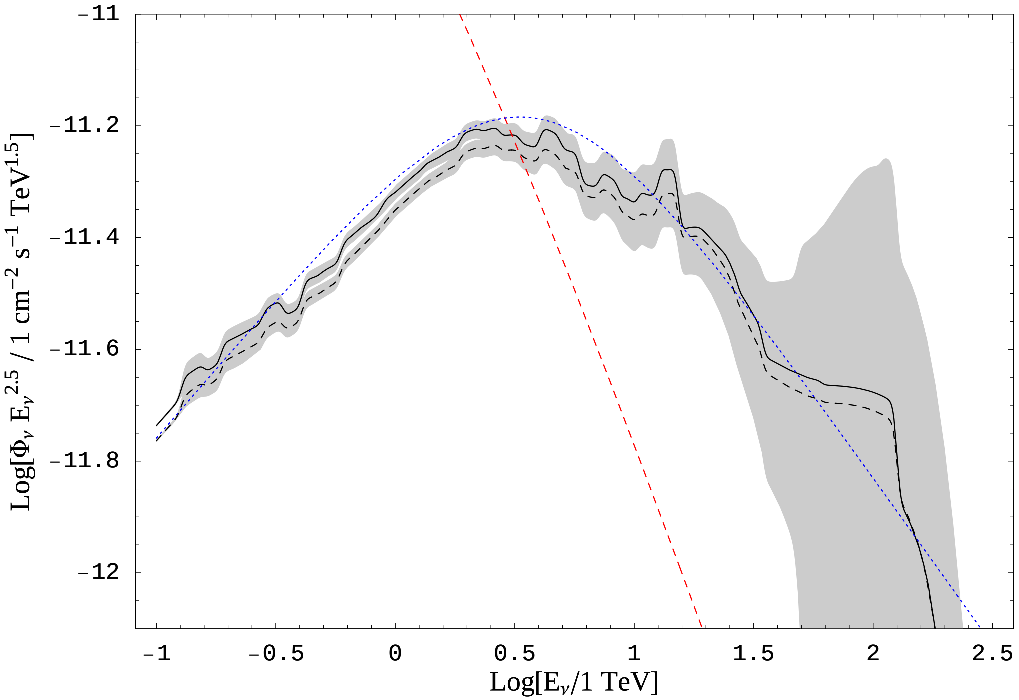


Figure 1: *ν_μ and $\bar{\nu}_\mu$ fluxes under the hypothesis of a hadronic γ-ray emission. The corresponding number of events above 1 TeV* (Villante & FV '08) *is:*

$I_{\mu+\bar{\mu}} = 2.4 \pm 0.3 \pm 0.5/km^2\ yr$

Application to other galactic souces of gamma rays

Source	Type	Challenge	$N(\mu+\bar{\mu})$
Vela Junior	SNR	Fermi	4
MGRO 2019+37	Star Form.+?	Argo, Veritas	1.5
MGRO 1908+06	Star Form.+?	HESS	2.5
Galactic Center	CR reservoire?	*wide source*	100

Approximate number of througoing muon events per km^2 above 1 TeV.

PREDICTIONS REQUIRE AN EXTRAPOLATIONS AT HIGH ENERGY.

Crocker, Aharonian, PRL106 (2011) 101102.
Aharonian & FV, NIM A692 (2012) 5 and ref.s therein;
Km3NeT Coll., http://arxiv.org/pdf/1208.1226v1.pdf.

Which γ-ray sources are potential neutrino sources?

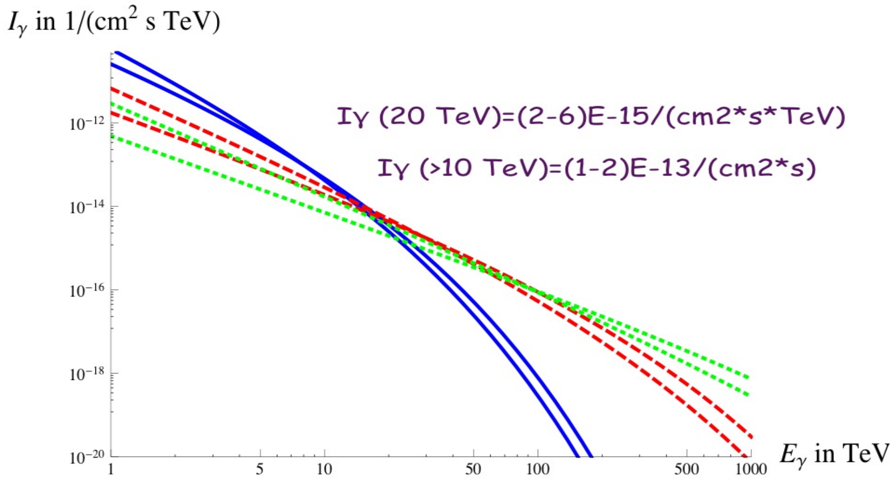
They should be characterized by hadronic γ-rays distributed as

$$I_\gamma \propto E_\gamma^{-\alpha} \ \exp[-\sqrt{E_\gamma/E_c}]$$

with $\alpha = 1.8 - 2.2$ and $E_c =$ TeV– PeV. Aharonian et al., Astrophys.J. 656 (2007) 870.

γ-ray intensities corresponding to a signal of *1 muon/km^{2}yr above 1 TeV**, evaluated assuming that the sources are transparent to their gamma rays.*

Aharonian et al., *Astropart.P34 (2011) 77*



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The γ-ray flux above 10 TeV is almost universal!

All potential neutrinos sources have

$$I_\gamma(> 10\ \text{TeV}) = (1-2) \times 10^{-13}/(\text{cm}^2\ \text{s})$$

To collect $\geq 100\ \gamma$**'s in a reasonable time, km^2 area is needed:**

$$\textbf{Exposure} = L^2 \times T \sim 2 \times\ \text{km}^2 \times 10\ \text{h}$$

e.g., a 10×10 Cherenkov telescopes array, or one dedicated EAS array.

∴ A large area γ apparatus, such as the high energy array in CTA or a custom instrument, would be invaluable for ν community.

THE NEUTRINO SKY TODAY

Point sources

The neutrino sky is ‘cloudy’: At the moment we do not see anything else than atmospheric neutrinos – that should be very well understood for the next steps anyway, and that are all but uninteresting (e.g., large scale anisotropies revealed; charm contribution still searched).

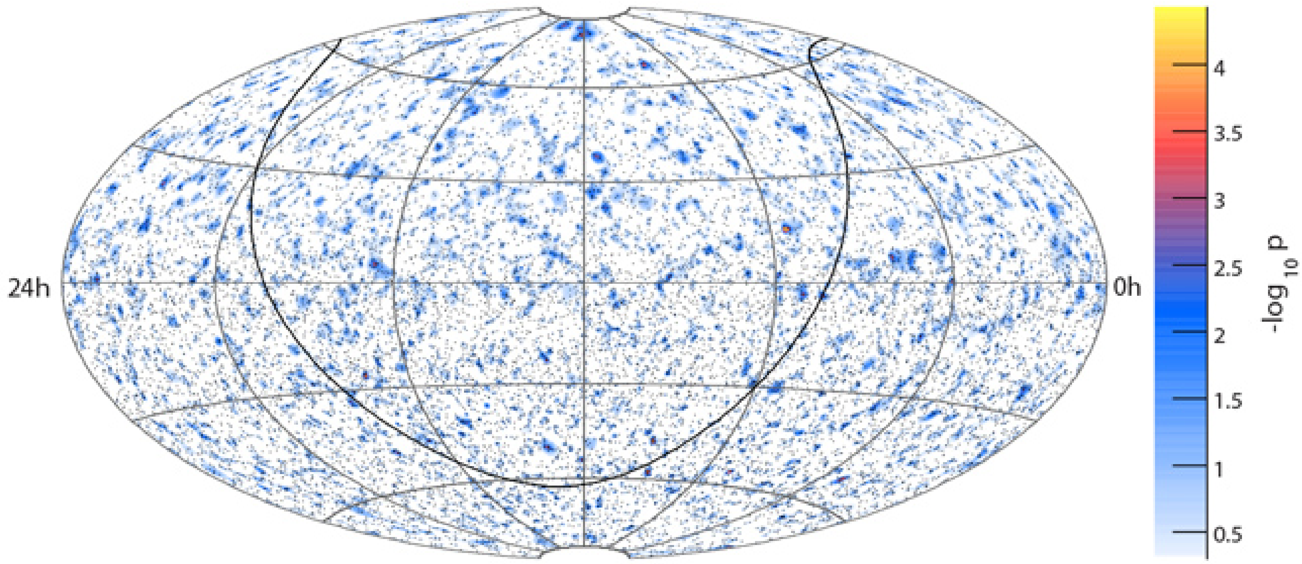


Figure 2: *A significance skymap of IceCube (from high energy muon events) in Galactic coordinates, assuming that the spectra of the neutrino sources is* E^{-2}*.*

Sporadic point sources

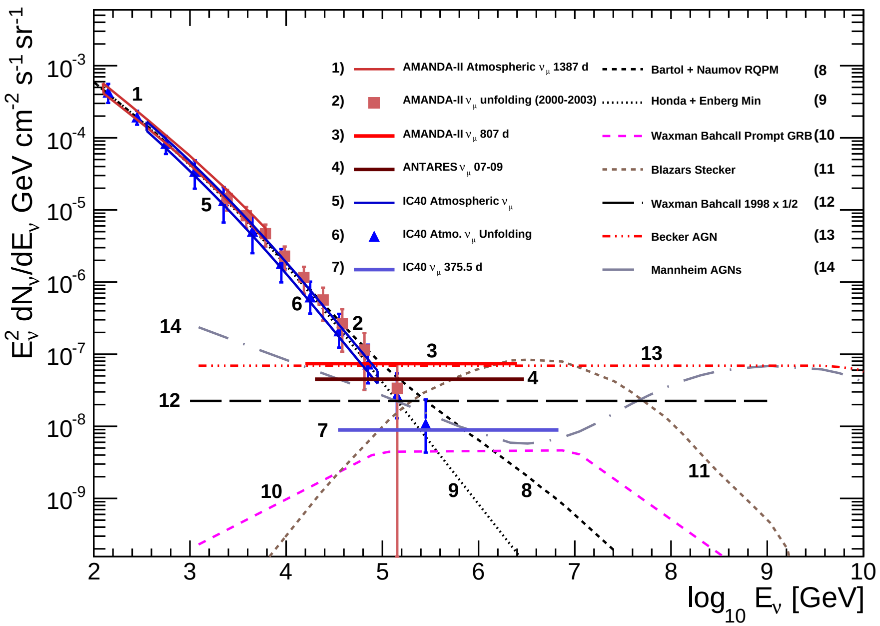
The hypothesis that GRB's are UHECR accelerators permits to estimate neutrino emission (Waxman '95, WB '97).

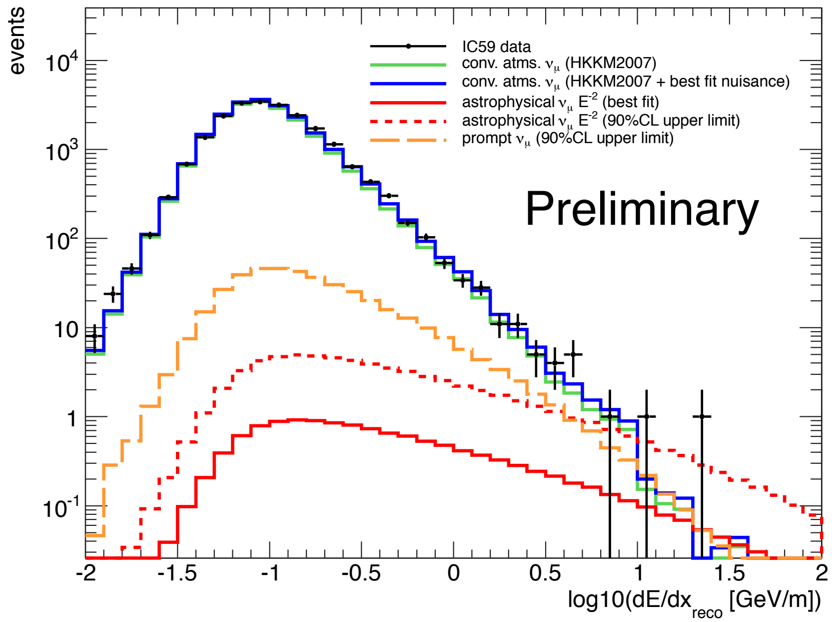
IceCube monitored about 100 GRB in the window of time when neutrinos were expected. Expected 0.1 background plus 3 signal events, saw none – that leaves a wide margin for further searching.

Theoretical uncertainties have been estimated to be a factor of 2 (Guetta 04) but are presumably much larger (Asano & Meszaros 12).

Diffuse sources – conventional muon events

WB bound: UHECR observed energy should exceed the one of secondary particles: i.e., the accelerators should not be *too* hidden.



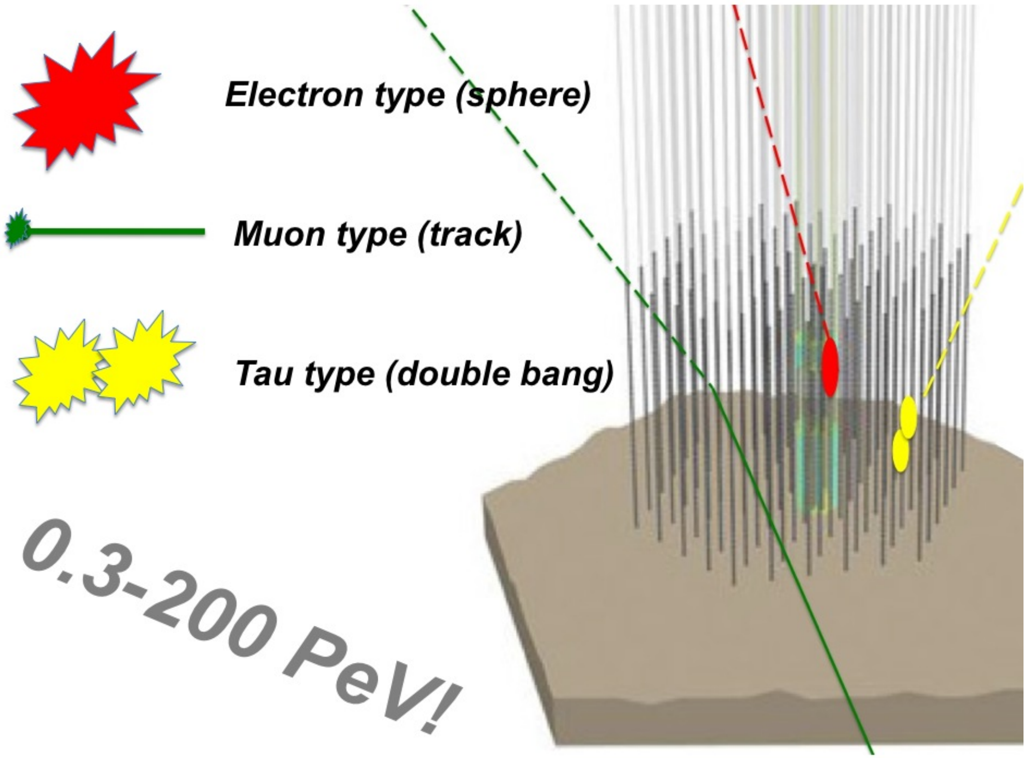


Left: results on the diffuse flux of IC40, Abbasi, 2011 are below the WB bound – blue line. Right: preliminary analysis of IC59 (348d) with 2 σ a hint for something.

Now, the exposure is increased by 672/348 80/59=2.5 times!!

Diffuse sources – contained events [1/3]

At PeV, the atmospheric neutrinos fade out. One could search for downward travelling events, contained in the detector.



At IC22 (200d) of PRD86 (2012) background was $0.60 \pm 0.19^{+0.56}_{-0.58}$, larger than claimed at IC86 (672d) A. Ishihara, Neutrino 2012.

Diffuse sources – contained events [2/3]

An important question is: which signal we could possibly expect?

The prompt (charm decay) events should be rare, but in any case yield

$$\Phi_e^{prompt} \approx \Phi_\mu^{prompt}, \quad \Phi_\tau^{prompt} \approx 0$$

A cosmic (extragalactic) neutrino source should have tau neutrinos as well, due to oscillations

$$\Phi_e^{cosmic} \approx \Phi_\mu^{cosmic} \approx \Phi_\tau^{cosmic}$$

The tau events could be <u>the</u> signature of a cosmic source.

The new data of IC86 (672d) have an exposure of about 2 km^3 yr.
Consider a common flux for neutrinos/antineutrinos

$$E^2 F < \frac{10^{-9} \text{ GeV}}{\text{cm}^2 \text{ s sr}}$$

It gives ~ 50 througoing muons events above 1 TeV in $\Omega = 2\pi$; the higher tail could be observable. The contained events with cuts as in IC22 paper on tau neutrinos are well characterized but also much less

$$N_e = 1.8,\ N_\mu = 0.7,\ N_\tau = 1.1$$

A. Ishihara at Neutrino 2012 showed 2 events at PeV possibily compatible with electron type **in my knowledge still unpublished.**

Of course, next questions are: What is the background? How many taus? How many muons? Are them downward? Wait and see!

UHE neutrinos

Scattering of neutrinos above EeV causes impulsive radio emission, due to Cherenkov radiation from the subsequent bunch of negative particles (Askaryan effect).

ANITA experiment expected 1 background plus 0.3-30 signal events and saw 1 – thus proceeding much farther won't be easy.

The key hypothesis, that UHE cosmic rays are protons (Berezinsky, Zatsepin) is however called into cause by the recent studies of composition of Pierre Auger Observatory.

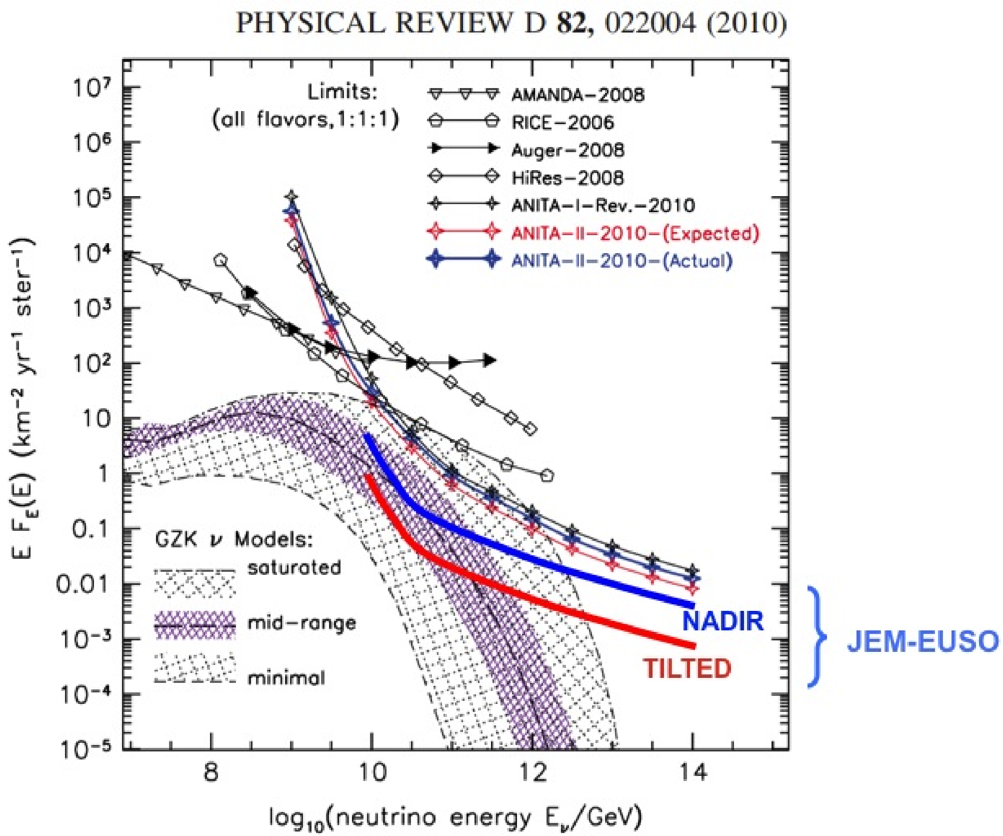


Figure 3: *Limits obtained by ANITA and RICE, by Amanda and by the UHECR observatories. The theoretical curves assume that UHECR are protons. In the future, JEM-EUSO could contribute to the search (curves drawn by Medina-Tanco).*

After a long phase of preparation, we are close to know the answers.

Cosmic rays, gamma rays and all that.

A lot of relevant information is being and will be collected. It will surely help us to proceed greatly in the understanding HE neutrinos.

Theory.

Aims are getting clearer; upper bounds are known; imaginative works are frequent. More predictions with errorbars and input from astronomers are desirable.

IceCube, Antares, KM3NeT; Rice, Anita, ARA; Auger, Jem-Euso...

This generation of experiments has chances of discovery. Galactic neutrinos are of great interest and still unexplored. Extragalactic diffuse flux could be seen.

Thanks a lot for the attention!