Flavor ratio at IceCube

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"What is flavor ratio seen by IceCube",
Palladino-Pagliaroli-Villante-Vissani, PRL 114.171101, April 2015

Flavor ratio

In 3 years IceCube detected 37 High Energy Starting Events (HESE) with deposited energies above 30 TeV [1].

Total	μ background	ν background	Energy Range
37	8.4 ± 4.2	$6.6^{+2.2}_{-1.6}$	> 30 TeV
20	0.4	2.4	> 60 TeV

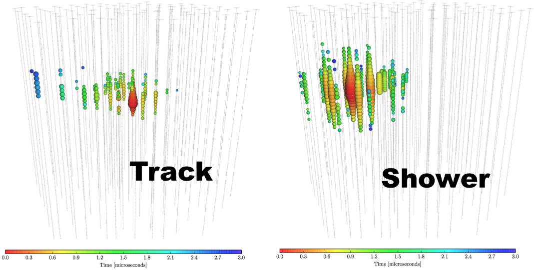
It is the first evidence for a high-energy neutrino flux of extraterrestrial origin.

Origin of neutrinos

Flavor ratio is the key to understand the origin of these neutrinos. The flavor identification is possibile studying the topology of events.

[1] M. G. Aartsen *et al.* [IceCube Collaboration], Phys. Rev. Lett. **113**, 101101 (2014)

Topology of events



- **Shower**: charge current (CC) interactions of ν_e and ν_τ and neutral current (NC) interactions of all neutrinos;
- **Track**: charge current interactions of ν_μ;

The crucial observable quantity is the track-to-shower ratio.

Analysis

Major statements discussed in our paper:

Subset of data

Analysis of events in the energy range $E_{dep} > 60\text{TeV}$, where the background is suppressed.

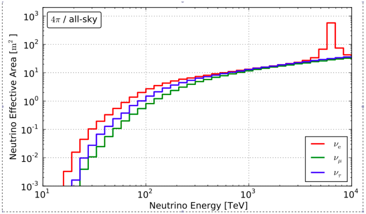
Uncertainties on parameters

Different mechanisms of production give different expectations of the track-to-shower ratio, even when the uncertainties due to neutrino oscillations are included.

Passing muons

Also the muon neutrinos passing through the Earth confirm the existence of an extraterrestrial component and we include this information into the analysis for the first time.

Effective areas



The effective areas are provided by the IceCube collaboration and include the effects of neutrino cross sections, partial neutrino absorption in the earth, detector efficiency and specific cuts of the HESE analysis.

Figure: IceCube effective areas

The expected number of events produced by an isotropic flux Φ_ℓ of neutrinos and antineutrinos with flavor ℓ is,

$$N_\ell = 4\pi \, T \int dE_\nu \, \frac{d\Phi_\ell}{dE_\nu} \, A_\ell(E_\nu)$$

where $\ell = e, \mu, \tau$ and $T = 3$ years is the exposure time.

Effective area of track events

In order to calculate the track-to-shower ratio, we must know the effective area for ν_μ CC interactions that produce tracks in the detector. It is given by:

$$A_\mu^{\mathrm{T}}(E) \equiv p_{\mathrm{T}}(E)\, A_\mu(E)$$

with $p_{\mathrm{T}}(E)$ given by:

$$p_{\mathrm{T}}(E) = \frac{\sigma_{\mathrm{CC}}(E)\, M_\mu^{\mathrm{CC}}(E)}{\sigma_{\mathrm{NC}}(E)\, M^{\mathrm{NC}}(E) + \sigma_{\mathrm{CC}}(E)\, M_\mu^{\mathrm{CC}}(E)} \simeq 0.8$$

where $\sigma_{\mathrm{CC}}(E)$ and $\sigma_{\mathrm{NC}}(E)$ are the cross section for CC and NC interactions of neutrinos while $M_\mu^{\mathrm{CC}}(E)$ and $M^{\mathrm{NC}}(E)$ are the effective detector mass for CC and NC interactions of ν_μ.

Description of extraterrestrial neutrinos

For extraterrestrial neutrinos we assume an isotropic flux described by a power law:

$$\Phi_\ell(E) = \frac{F_\ell \cdot 10^{-8}}{\text{cm}^2\ \text{s sr GeV}} \cdot \left(\frac{\text{GeV}}{E}\right)^\alpha$$

where $F_\ell \simeq 1$ are adimensional coefficients. In the case of $\alpha = 2$ we obtain:

$$\begin{aligned} N_{\rm S} &= 8.4 \times F_e + 0.9 \times F_\mu + 6.3 \times F_\tau \\ N_{\rm T} &= 3.7 \times F_\mu \end{aligned}$$

Calculation of track-to-shower ratio in PPVV

$$\frac{N_{\rm T}}{N_{\rm S}} = \frac{\xi_\mu}{2.3 - 2.0\,\xi_\mu - 0.6\,\xi_\tau}$$

$\xi_\ell \equiv F_\ell / F_{\rm tot}$ is the flavor fractions at the Earth

The effect of neutrino oscillations

For neutrinos traveling over cosmic distances, the simplest regime applies and the oscillation probabilities $P_{\ell\ell'}$ are energy independent[2]. The flavor fractions at Earth are thus given by

$$\xi_\ell = \sum_{\ell'} P_{\ell\ell'}\, \xi^0_{\ell'} \quad \text{with} \quad P_{\ell\ell'} = \sum_{i=1,3} |U^2_{\ell i}\; U^2_{\ell' i}|,$$

where U is the neutrino mixing matrix and ξ^0_ℓ are the *flavor fractions at the source* given by:

$$\xi^0_\ell \equiv F^0_\ell / F_{\rm tot}$$

where F^0_ℓ indicates the adimensional flux normalizations before oscillations.

[2] A distance of 0.1 parsec is sufficient to apply this regime.

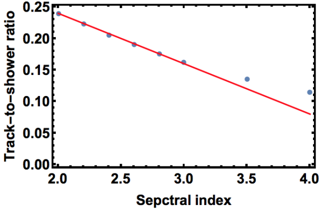
The case of pion

In the standard case of charge pions decay, there is a flavor ratio at source of $(\xi_e^0 : \xi_\mu^0 : \xi_\tau^0) \simeq (1:2:0)$ that, after oscillations, becomes:

$$(\xi_e : \xi_\mu : \xi_\tau) \simeq (1:1:1)$$

In this case the track to-shower ratio in IceCube is

$$\frac{N_T}{N_S} = 0.24 + 0.08(2-\alpha) \quad \text{in } 2 \leq \alpha \leq 3$$



Distributions of flavor ratio at source

4 cases

We consider four specific assumptions for the flavor composition at the source ($\xi_e^0 : \xi_\mu^0 : \xi_\tau^0$):
i) (1/3 : 2/3 : 0) for π decay;
ii) (1/2 : 1/2 : 0) for *charmed or K mesons* decay ;
iii) (1 : 0 : 0) for β decay of *neutrons* ;
iv) (0 : 1 : 0) for π decay with *damped muons*.

We determined the probability distributions of $N_{\rm T}/N_{\rm S}$ by MonteCarlo extraction of the oscillation parameters[3].

[3] M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, JHEP **1411**, 052 (2014)

Distributions of flavor ratio at the Earth

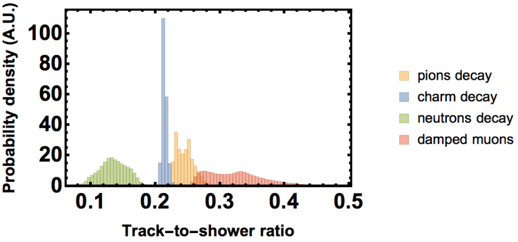


Figure: Track to shower ratio for $\alpha = 2$ and different mechanisms of production

Large contributions to N_T/N_S dispersions are provided by the δ and θ_{23} parameters. If we take the best fit oscillation parameters and assume a spectral index $\alpha = 2$, we obtain:

$$0.15 < \frac{N_T}{N_S} < 0.30$$

expected from extraterrestrial origin.

The track-to-shower ratio

The set of events observed by IceCube in three years of data, taking between 60 TeV and 3 PeV, consists in:

Table: IceCube 3 years data

	n_T	n_S
total	4	16
atm. ν	1.7	0.7
muon	0.4	0

In the above estimates, we assume that the prompt atmospheric neutrinos give negligible contributions, as it required by the spectral and arrival angles distributions of IceCube events.

The number of tracks N_T and showers N_S, which has to be ascribed to extraterrestrial sources, can be estimated from the Poisson likelihood functions:

$$\mathcal{L}(N_i) \propto (N_i + b_i)^{n_i} \times e^{-N_i}$$

where $i = T, S$ is used to refer to track and shower events and N_i, b_i to signal and background.

The track-to-shower ratio (HESE)

By using the three years data, we obtain:

$$\begin{aligned} N_T &= 3.1 \pm 2.1 \\ N_S &= 16.4 \pm 4.1 \end{aligned}$$

Marginalizing over the total number of events, we reconstruct the track-to-shower ratio of comsic neutrino obtaining:

$$\frac{N_T}{N_S} = 0.11^{+0.23}_{-0.05} \quad \text{[HESE only]}$$

where the error was obtained by integrating out symmetrically (1-CL)/2 on both sides of the N_T/N_S distribution using a confidence level CL $= 68.3\%$.

The track-to-shower ratio (HESE+passing muons)

Recently IceCube data on passing muons have appeared[4]. About 12 events with visible energy above 60 TeV have been observed and they cannot be explained by atmospheric neutrinos and muons.

Passing muons

In the assumption of E^{-2} neutrino spectrum, this corresponds to a flux normalization:

$$F_\mu = 1.01 \pm 0.35 \to N_T = 3.7 \pm 1.3$$

It is compatible with the value $N_T = 3.1 \pm 2.1$ obtained from the HESE analysis

Taking into account those events we obtain:

$$\frac{N_T}{N_S} = 0.18^{+0.13}_{-0.05} \quad \text{[all data]}$$

[4] C. Weaver, Spring APS Meeting, Savannah, Georgia (2014)

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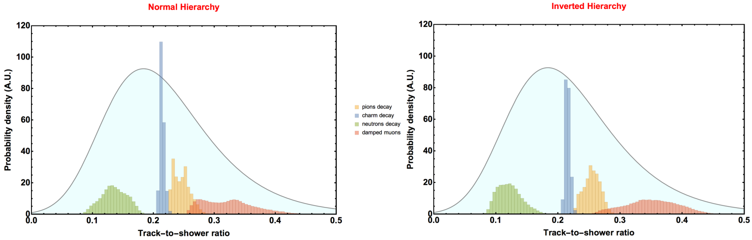
Data and prediction



- Despite other recent claims, [5] the present observational agrees with extraterrestrial neutrinos produced by standard scenarios;
- there is no clear preference **yet** for a specific neutrino production mechanism.

$$(1:0:0) \quad \text{purely } \nu_e \text{ at the Earth disfavored at} \simeq 3\ \sigma$$
$$(0:1:0) \quad \text{purely } \nu_\mu \text{ at the Earth disfavored at} \simeq 4.5\ \sigma$$

[5] O. Mena, S. Palomares-Ruiz and A. C. Vincent, Phys. Rev. Lett. **113**, no. 9, 091103 (2014)

Triangle of flavor ratio

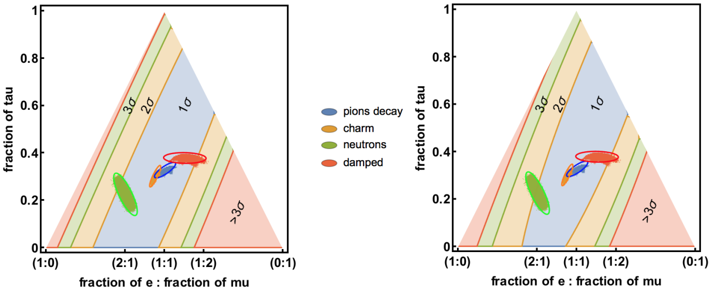


Figure: IceCube data analysis with spectral index 2 (on the left) and 2.3 (on the right)

The elliptic regions are intervals inside the 99 % confidence level, obtained with a gaussian treatment of oscillation parameters[6].

[6] A new parametrization of cosmic neutrino oscillations, Palladino-Vissani, arXiv:1504.05238

What next ?

In two new papers appeared today it is shown that exotic models can be tested.

- **Testing neutrino decay scenarios with IceCube data**, Pagliaroli, Palladino, Villante, Vissani, arXiv:1506.02624
- **Theoretically palatable flavor combinations of astrophysical neutrinos**, Bustamante, Beacom, Winter, arXiv:1506.026245

Conclusion

We showed that:

- flavor ratio remains separate despite the uncertainties;
- passing muons help us to improve analysis, reducing the uncertainties on the track-to-shower ratio;
- the analysis of the present data gives a track-to-shower ratio that agrees with that expected for an extraterrestrial population;
- the initial neutrino flavor cannot be yet probed but we are not so far. Present exposure has to increase by a factor of few.

Thank you for your attention !