Possible Interpretations of IceCube High Energy Neutrinos

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Jun 23, 2015

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Outlook

I) Neutrino Oscillations
Spectrum and experiments
IceCube detector and the sources of VHE neutrinos

II) Interpretations of IceCube results after 988 days (37 VHE neutrinos)
Prove of existence of astrophysical neutrinos
Some hypotheses to explain the spectrum
Statistical analysis and results

III) Squeezing the information from IceCube
Astrophysical neutrino ratios

I Part

Introduction

Neutrinos: technical aspects

- Neutrinos are sometimes called quasi-particles because the interacting states, gauge or flavor eigenstates, do not coincide with the Hamiltonian or mass eigenstates. Then, the flavor nature of neutrinos is modified, oscillates, during their travel from the source to the target

PMNS Mixing Matrix

$$\nu_i = U_{i\alpha}\nu_\alpha$$

$$\begin{aligned}
U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}
\end{aligned}$$

- The main observable is the transition probability between different flavors

$$\begin{aligned}
P_{\alpha\to\beta} = \delta_{\alpha\beta} &- 4\sum_{i>j} Re(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij}L}{2E}\right) \\
&+2\sum_{i>j} Im(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)
\end{aligned}$$

For long distances, e.g. astrophysical sources, oscillations and CP-violating effects are average out. hep-ph/9711363

Important for Part III of this talk !!

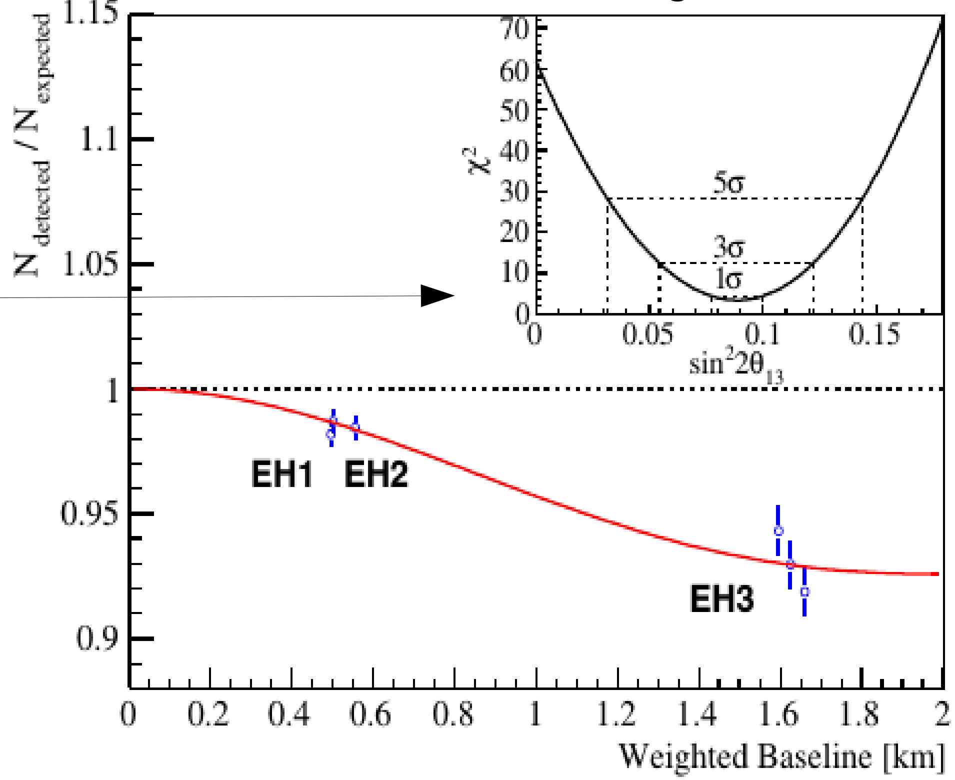
Neutrinos: observations

- Currently we are in the era of precision measurements but there are things that we still do not know

- *Known parameters*:

a) Angles

$$\theta_{23} \sim 45^\circ, \theta_{13} \sim 8^\circ, \theta_{12} \sim 33^\circ$$



b) Square mass differences

$$\delta m^2 \sim 8 \times 10^{-5} eV^2$$

$$|\Delta m^2| \sim 2 \times 10^{-3} eV^2$$

- *Unknown parameters:*

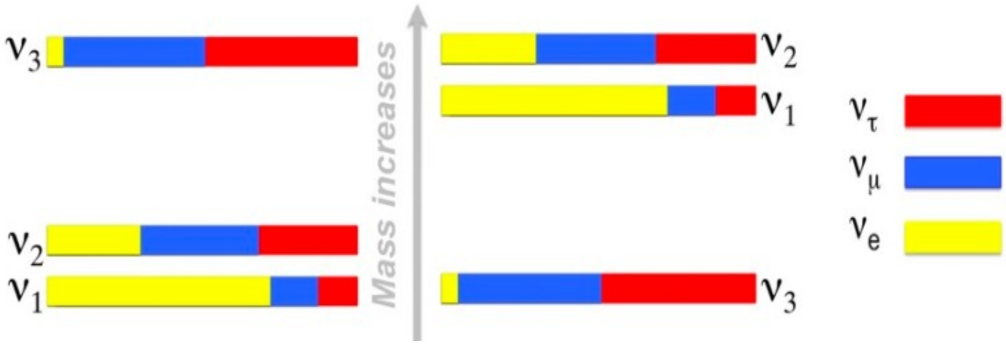
a) CP-Phases

b) Octant of θ_{23}

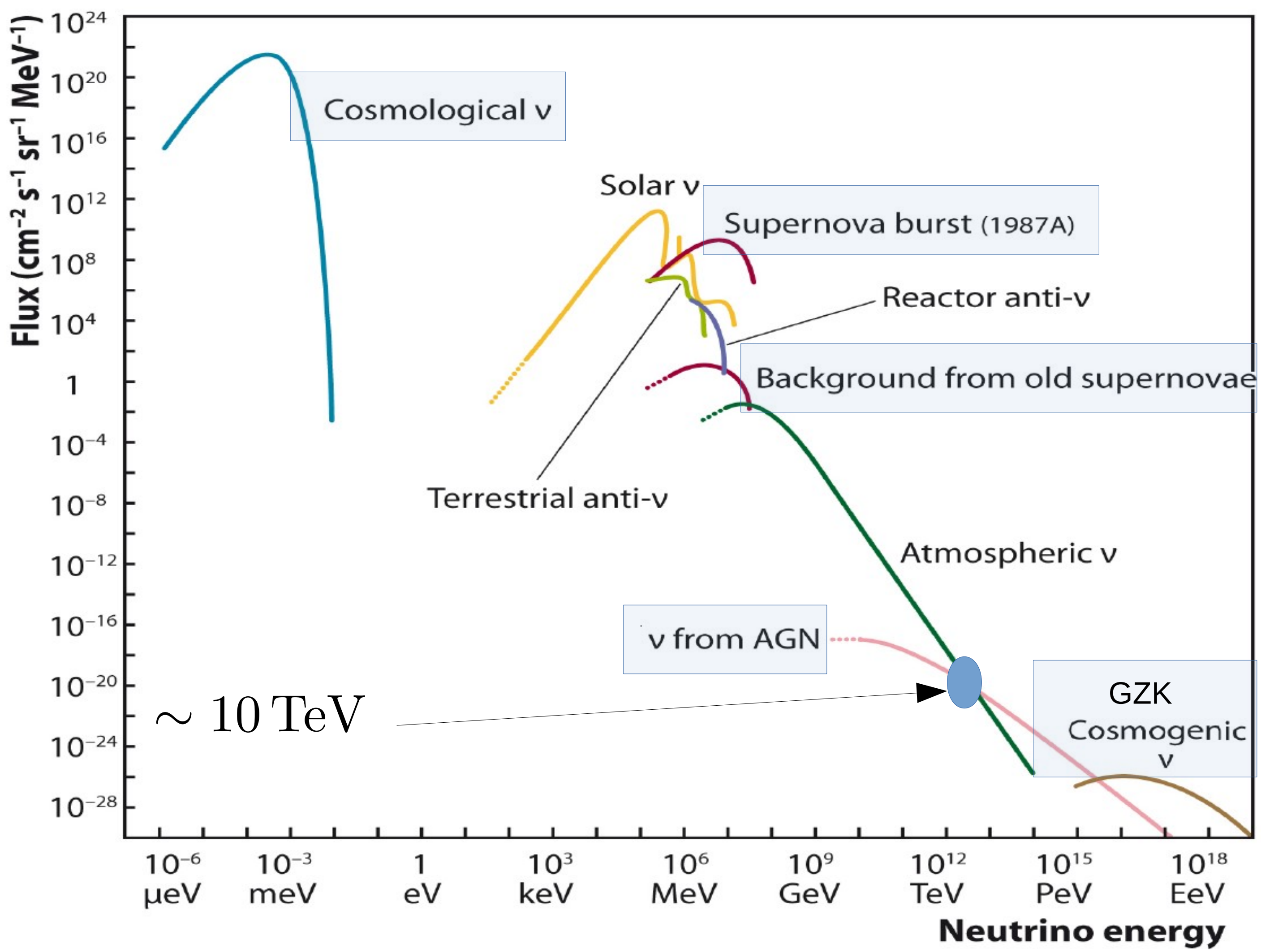
c) Dirac or Majorana

d) Absolute mass scale

d) Mass ordering or hierarchy



Neutrino spectrum and detection



- In general, in order to determine the experimental target dimensions it is necessary to consider the value of the cross section and the expected flux.

$$\frac{dN}{dE} \propto T \frac{d\phi}{dE} \sigma N_{\rm eff}$$

$$N_{\rm eff} = N_A V_{\rm eff}$$

$$V_{\rm eff} = M_{\rm eff}/\rho_{\rm m}$$

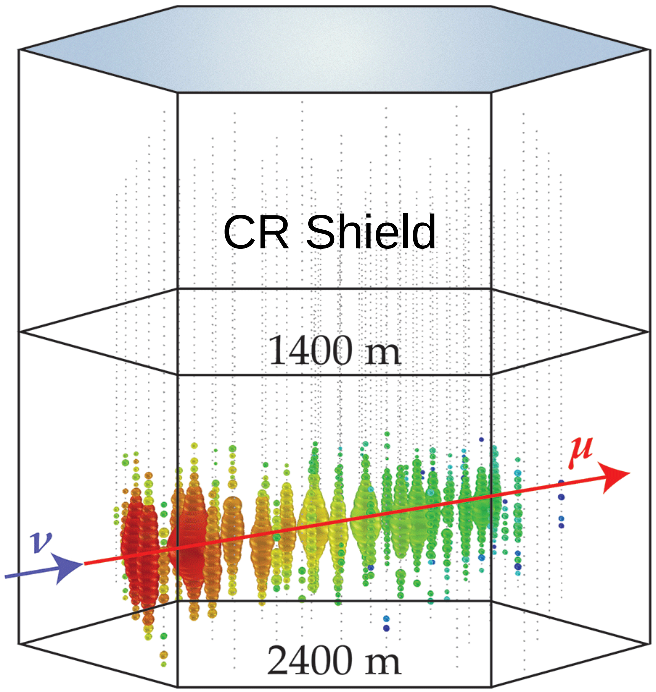
where the effective target mass includes the background rejection cuts and event containment criteria.

Still under investigation

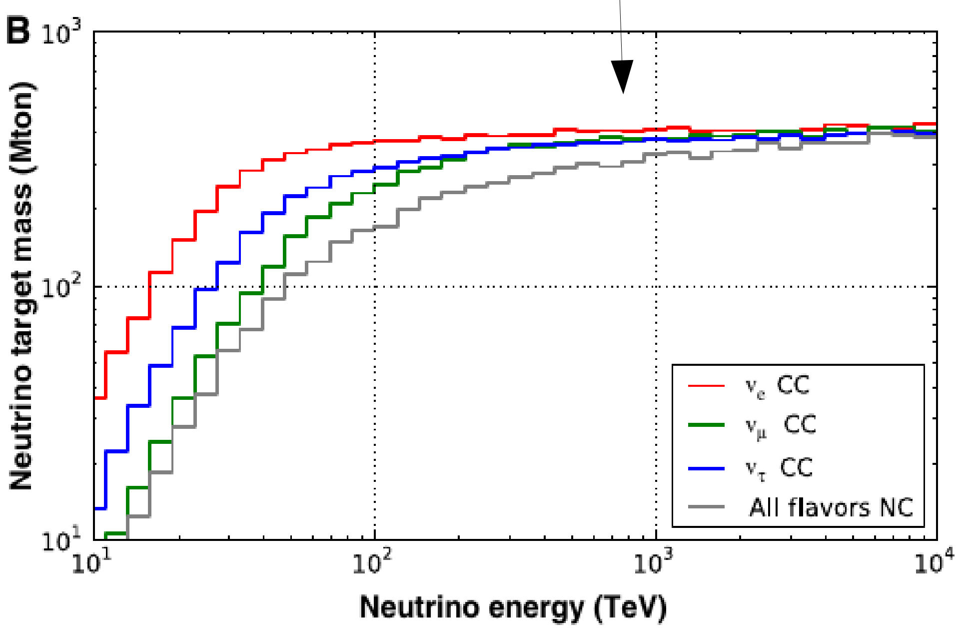
Kamiokande-II
Super-K
> 10-50 KTons

Lake Baikal
AMANDA
IceCube > 100 MTons

IceCube detector

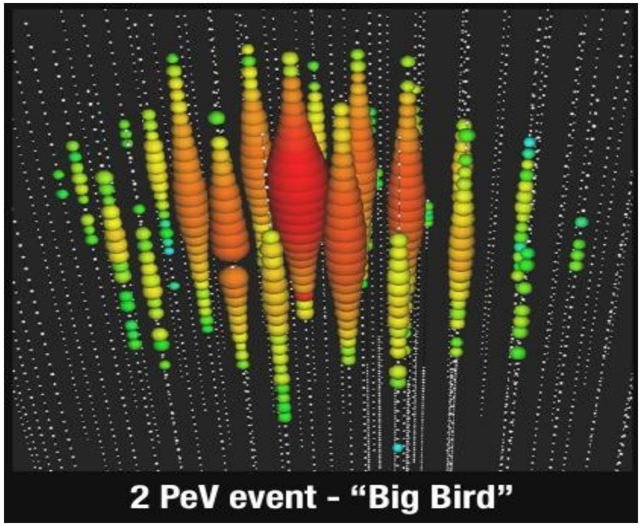


$0.44\,\mathrm{km}^3$ water equivalent volume



- The IceCube detector consists of 86 strings. Each string holds 60 Digital Optical Modules that transfer data up to the IceCube Lab once they sense energy from the Cherenkov radiation.

- Energy resolution is 15% above 10 TeV
- Direction resolution is ~1 degree for tracks and ~15 degrees for showers



True Picture of a Very High Energy (VHE) Neutrino Event.

Origin of IceCube VHE neutrinos

- *Signal*. Astrophysical sources. Products of the interaction of very high energy cosmic rays with the intergalactic media. Point and extended sources.

$$p + \gamma \to \pi^+ + n \to e + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n$$

In general, it has been observed that the flux of cosmic rays follows a power law distribution, with different spectral index depending on the energy. As the flux of neutrinos from CR interactions is proportional to the incoming flux of CRs, then the flux of neutrinos also should follow a power law distribution. The global normalization and the contribution of each flavor depends on the details of the interactions.

Power Law spectrum $$\left(\frac{d\phi}{dE}\right)_\nu \propto E^{-\gamma}$$

- *Background* Atmospheric neutrinos produced in interactions of very high energy cosmic ray showers with the atmosphere. The direction of the source is lost it. The mechanism of production is mainly via CR-Nucleon interactions (extensive literature with analytic computations). Atmospheric Muons.

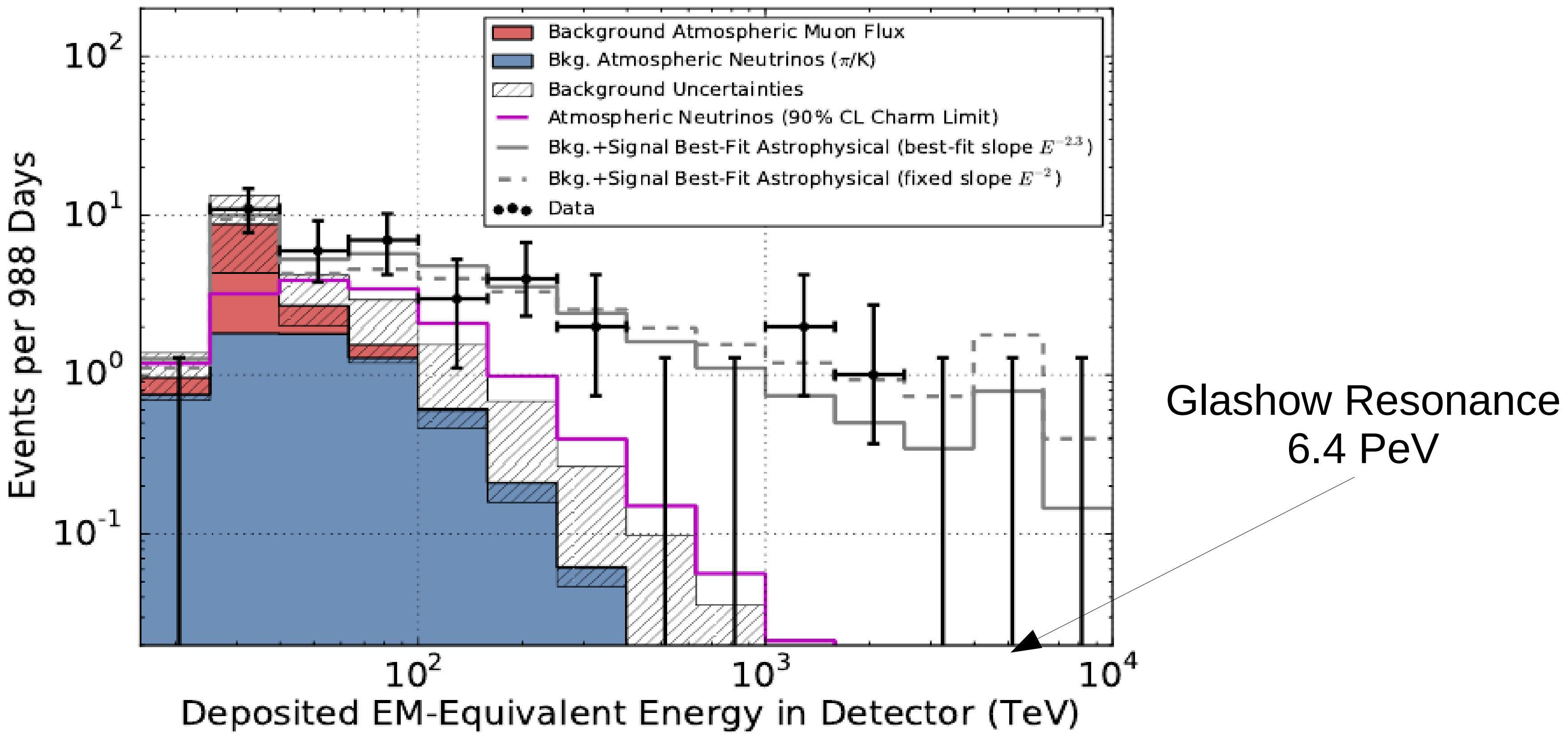
- *Exotic contributions*. Dark Matter, new interactions, etc. In this case both the shape of the flux and the specific contribution from each flavor depends on the hypothesis under study.

II Part

Interpretations of IceCube results
after 988 days (37 VHE neutrinos)
Based on hep-ph/1411.5318

Data Source: IceCube Collaboration
Science 342, (2013)

IceCube 3-Year Results



- 37 events (expect 8.4 cosmic ray muon events and 6.6 atmospheric neutrinos), purely atmospheric explanation rejected at 5.7 sigma.

- From the reconstructed direction of each neutrino is not possible to identify a significant preferred direction. Thus, the hypothesis of isotropy is consistent with the current data.

Number of events – Zero App.

- In this work we considered 3 different sources in order to explain IceCube events

  - Atmospheric neutrinos, conventional and prompt, and muons. Best fit from IceCube

  - Astrophysical neutrinos. Power law spectrum. Democratic contribution of flavors

$$\left(\frac{d\Phi_\nu}{dE_\nu}\right)_{\mathrm{pl},\alpha} = \frac{3C_0 f_\alpha}{10^8} \times \frac{1}{E_\nu^2} \times \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{2-s}$$

  - Neutrinos from heavy long lived particle decays, galactic and extragalactic

$$\left(\frac{d\Phi_\nu}{dE_\nu}\right)_{\mathrm{gl}} = \left(\frac{1.3\times 10^{-13}}{\mathrm{cm}^2\ \mathrm{sr\ s}}\right) \frac{10^{28}\,\mathrm{s}}{\tau_Y} \frac{1\,\mathrm{PeV}}{M_Y} \frac{1}{N} \frac{dN}{dE_\nu}$$

$$\left(\frac{d\Phi_\nu}{dE_\nu}\right)_{\mathrm{eg}} = \left(\frac{2.5\times 10^{-13}}{\mathrm{cm}^2\,\mathrm{sr\,s}}\right) \frac{10^{28}\,\mathrm{s}}{\tau_Y} \frac{1\,\mathrm{PeV}}{M_Y} \times \int_1^\infty dy \frac{dN}{N\, d(E_\nu y)} \frac{y^{-3/2}}{\sqrt{1+(\Omega_\Lambda/\Omega_M)\, y^{-3}}}$$

- The number of neutrinos per bin observed by IceCube is given by

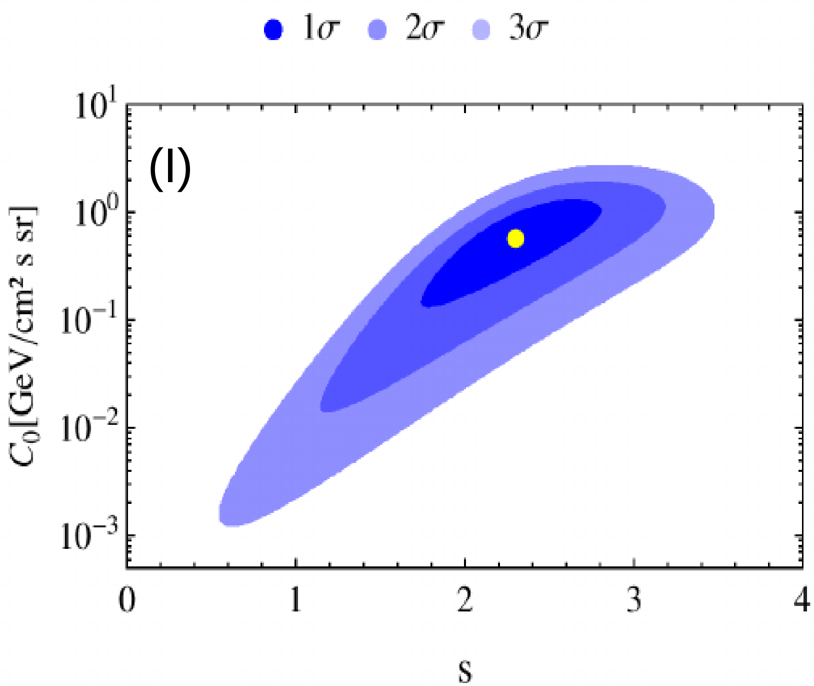
$$N(E_n) = T \times \Omega \times \sum_{j,\alpha} \int_{E_n}^{E_{n+1}} dE_\nu\, A_{\mathrm{eff}}^\alpha(E_\nu) \left(\frac{d\Phi_\nu}{dE_\nu}\right)_j^\alpha$$

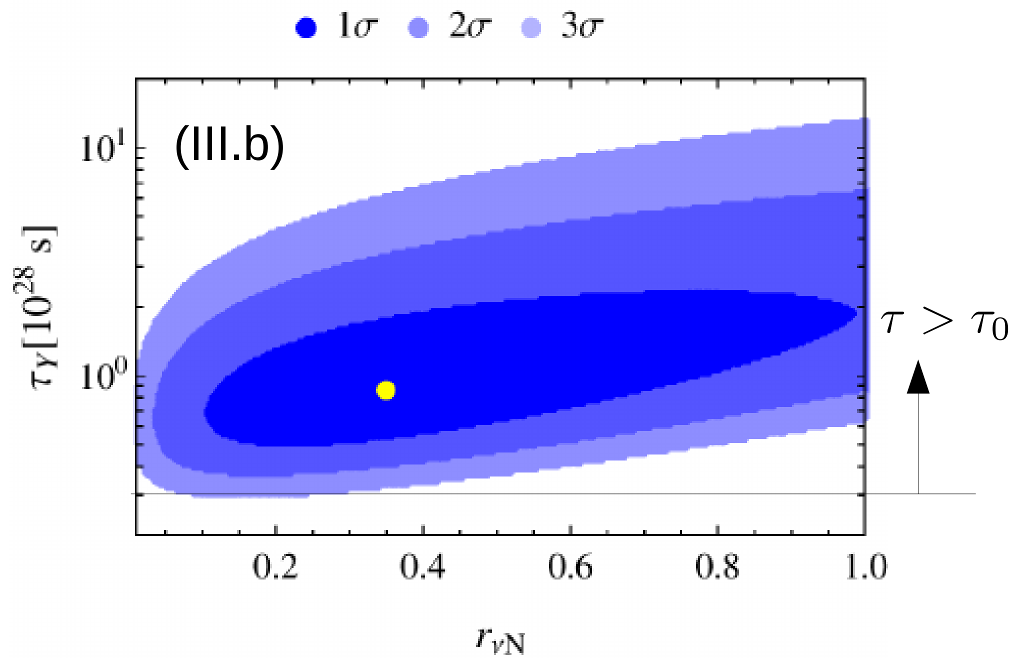
where Aeff = Neff x Cross Section.

Results with current data

- Best fit values and intervals of confidence

H_0	M_Y [PeV]	Scenario	s	C_0	τ_Y $\times 10^{28}$ [s]	$r_{\nu N}$	$\chi^2_{\rm min}$	p	
I	-	PL	2.3	0.6	-	-	39.41	0.5	
II.a	2.2	PL + νN	2.43	0.51	5.26	-	38.07	0.45	
II.b	4.0	PL + νN	2.76	0.52	2.72	-	36.67	0.58	
III.a	2.2	$\nu N + 4h$	-	-	0.73	0.14	42.53	0.06	
III.b	4.0	$\nu N + 4h$	-	-	0.88	0.35	36.6	0.56	
IV.a	2.2	$\nu N + 2h$	-	-	1.81	0.56	44.87	0.01	X
IV.b	4.0	$\nu N + 2h$	-	-	1.13	0.23	36.25	0.57	
V	4.0	νN	-	-	1.9	-	38.64	0.24	





III Part

Squeezing the information from IceCube
after 988 days

Based on hep-ph/1502.0337, 1502.02649, 150X

Signal is assumed to follow a power law distribution

Data Source: IceCube Collaboration
hep-ph/1502.0337 and Science 342, (2013)

Motivation

- With IceCube it is possible to obtain information about the ratio of neutrinos at Earth. In order to use this information to know the ratios at Source it is necessary to consider that neutrinos oscillate in their way to the Earth.

$$f_{\alpha,S} = \frac{N_{\alpha,S}}{N_T} \rightarrow f_{\alpha,E} = \frac{N_{\alpha,E}}{N_T}$$

$$N_{\beta,E} = \sum_{\alpha} N_{\alpha,S} \langle P_{\alpha\rightarrow\beta} \rangle$$

$$\langle P_{\alpha\rightarrow\beta} \rangle = \delta_{\alpha\beta} - 2\sum_{i>j} Re(U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j})$$

In principle, neutrino ratios at earth could be used to study the unknown components of Upmns, or even exotic physics in the neutrino sector.

- Each neutrino flavor is able to produce shower or track topologies with different probability.

  - Electron neutrinos only produce showers. Glashow Resonance at 6.4 PeV predicts a peaked amount of showers if the flux is not negligible at these energies.

  - Muon neutrinos are able to produce showers and tracks. Indeed, as CC interactions are three times bigger than NC ones, it is expected that most of the muon neutrinos are going to produce track signals. This is applicable to signal and background.

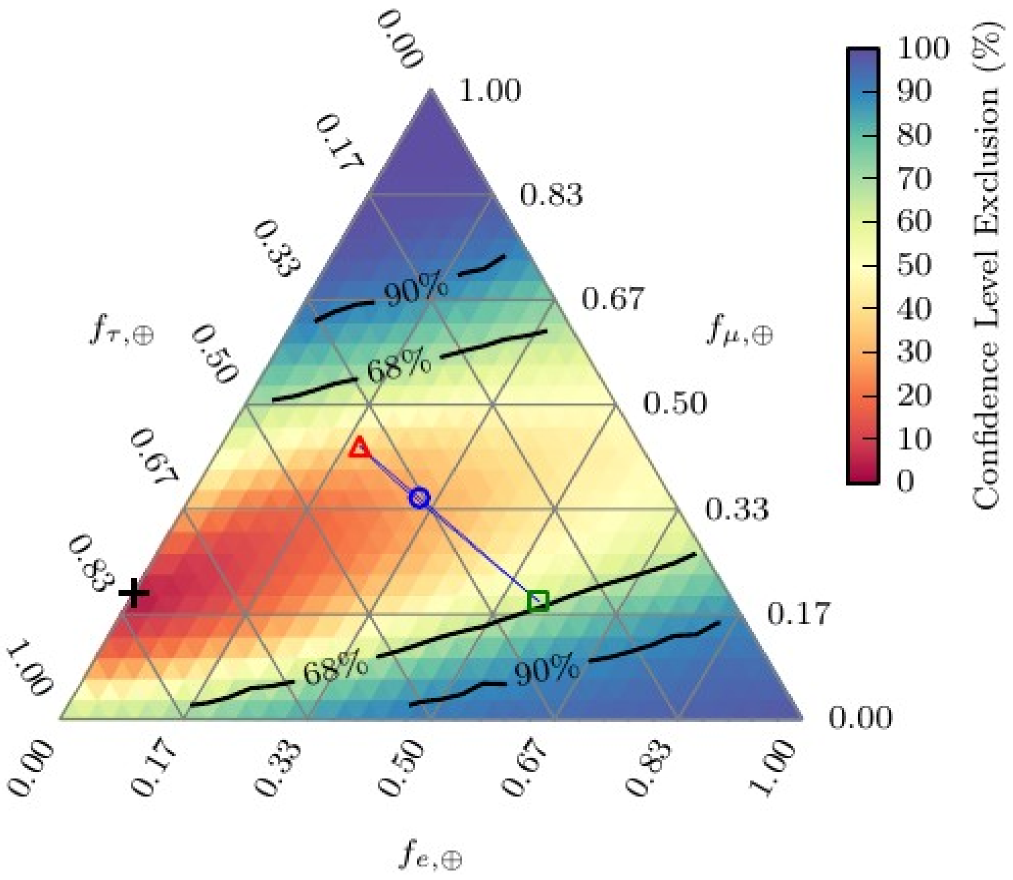
  - Tau neutrinos produce mostly showers, as electron neutrinos, however some tracks are expected because tau final states can decay into muons giving a track signal.

IC Results For Neutrino Ratios

- In order to interpret the IceCube results in terms of flavor ratios it is necessary to consider the contributions of each flavor by separate. Also, some assumptions must be specified in order to clarify the scope of the results.

$$\left(\frac{dN}{dE}\right)_{\nu_l}^{t,c} = \mathcal{L} \times \left(\frac{d\Phi_{\nu_l}}{dE}\right) \times \text{Earth} \times \sigma_{\nu_l}^{t,c} \times \text{Detector}$$

- Current results from IceCube: IceCube paper *1502.0337*, Feb 2015



- The best fit point is indicated by a black cross.

- The diagonal line represents the predicted ratios from standard assumptions at the source. For example (1,2,0)_S, (0,1,0)_S and (1,0,0)_S.

- Extreme regions, as (0,1,0)_E or (1,0,0)_E are excluded at 3.3 and 2.3 sigma.

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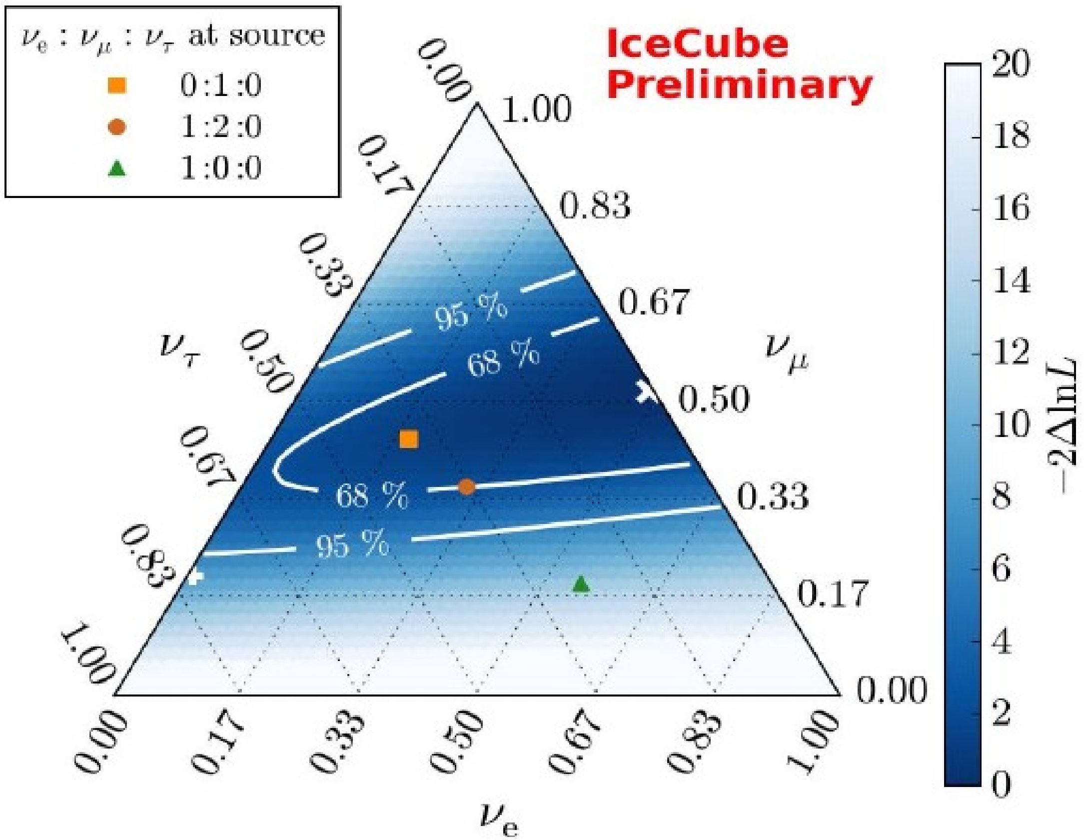
- Current results from IceCube : Yañez talk at Moriond, March 2015



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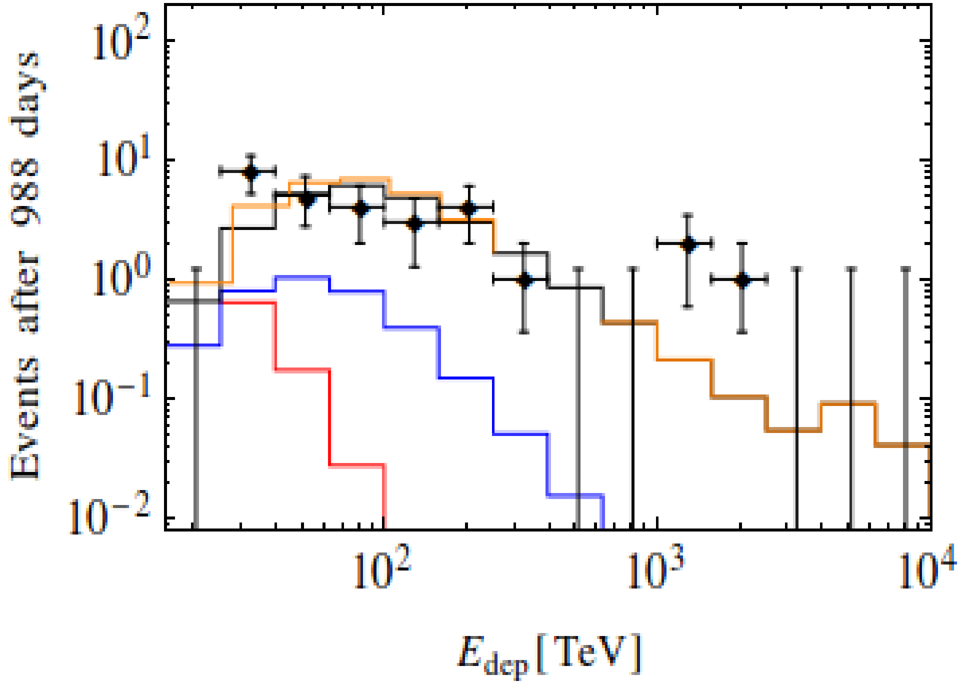
Numerical results including ratios

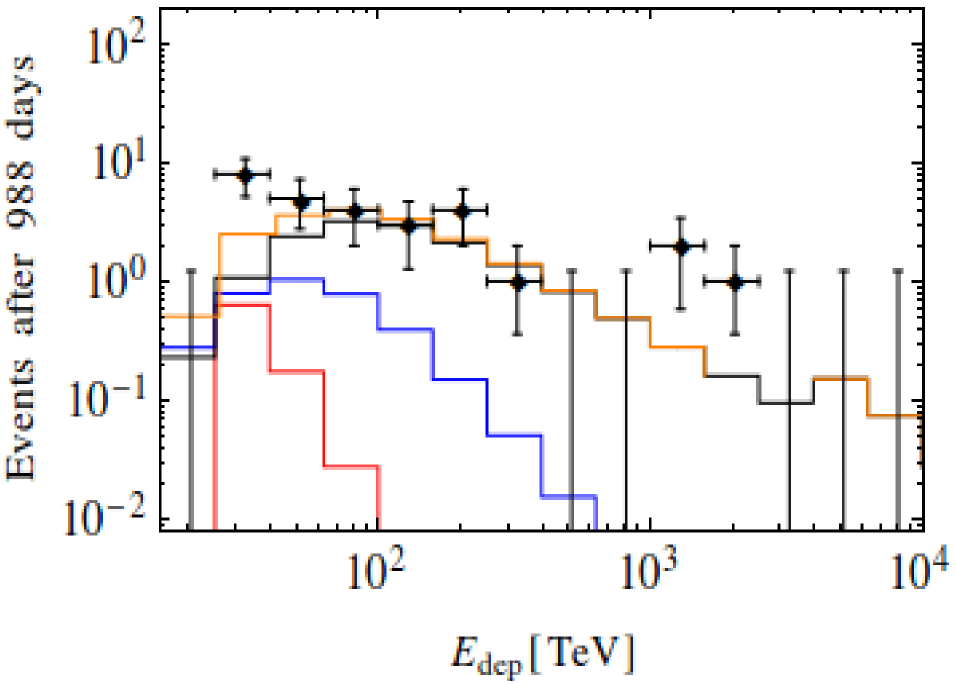
- Based on 1502.02649 we have implemented our own code to compute the number of showers and tracks depending on the values of the spectral index, ratios and normalizations.

SHOWERS

Symbology: **Atmospheric μ**, **Atmospheric ν**, **Astrophysical ν** and **Total**



Showers obtained from the best fit of *1502.02649* with 0.63:0.27:0.1 ratios



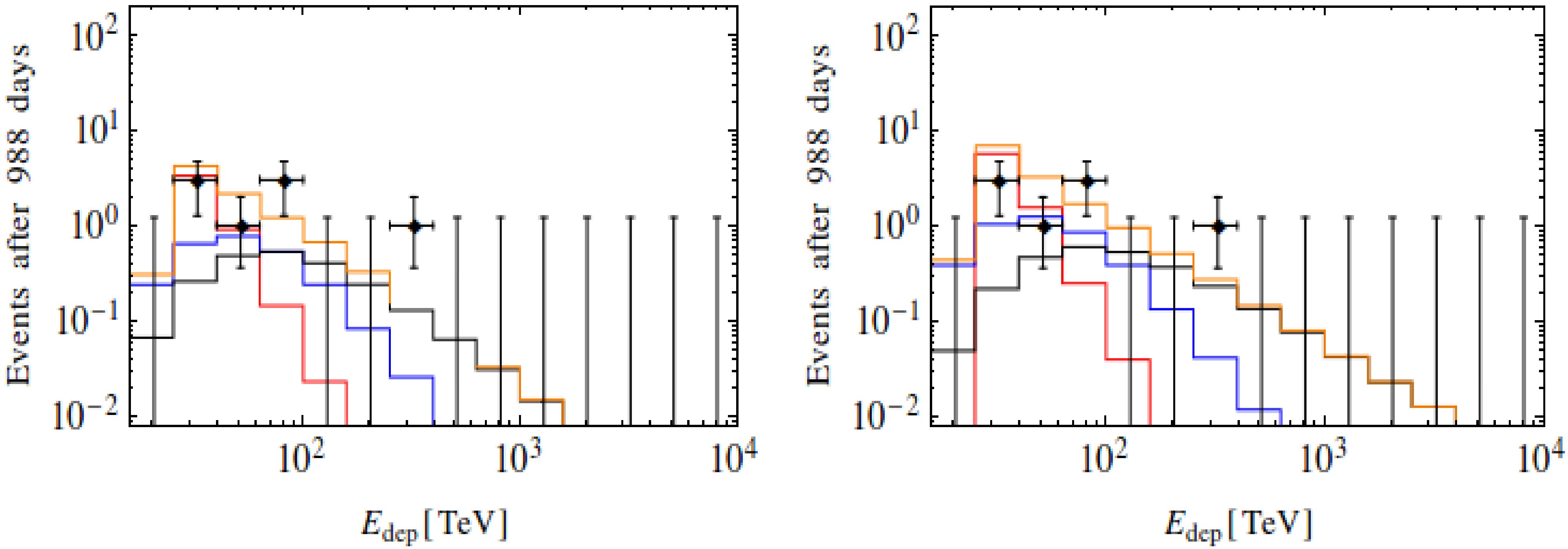
Showers predicted from *1411.5318* with 0.33:0.33:0.33 ratios

Now we have shower and track events as a function of Edep. We found consistency with *1502.02649* results. We see that the democratic assumption shows a similar behavior.

Numerical results including ratios

TRACKS

Symbology: **Atmospheric μ**, **Atmospheric ν**, **Astrophysical ν** and **Total**



Tracks obtained from the best fit of *1502.02649* with 0.63:0.27:0.1 ratios

Tracks predicted from *1411.5318*
With 0.33:0.33:0.33 ratios

- in a forthcoming work we are going to use these tools in order to analize the real potential of IceCube (Gen2) in order to learn much more about neutrino physics and...

Conclusions

- The neutrino sector of the SM is reaching the era of precision measurements for most of the relevant parameters. However, there are still important questions and parameters that need to be clarified.

- VHE neutrinos could be used to improve our knowledge of the neutrino sector, but also as a tool to understand the properties of astrophysical sources of cosmic rays. The main obstacle for these studies was the required size of the detectors, reaching the km^3 dimensions.

- Thus, the IceCube experiment has come on the scene in order to asses these issues. After 3-years of time exposure, this experiment has detected astrophysical neutrinos at a 5.7 sigma level and a systematic path to study neutrino astronomy has been opened.

- Currently, the small number of detected events does not allow us to accurately determine the properties of astrophysical neutrino sources. Or in other words, several models are able to explain the observed excess of neutrinos.

- More events and ideas are required in order to exploit this corner of neutrino physics. The experiment is preparing for getting more data with an even bigger instrumented volume and accordingly we are preparing our phenomenological tools to interpret this data.