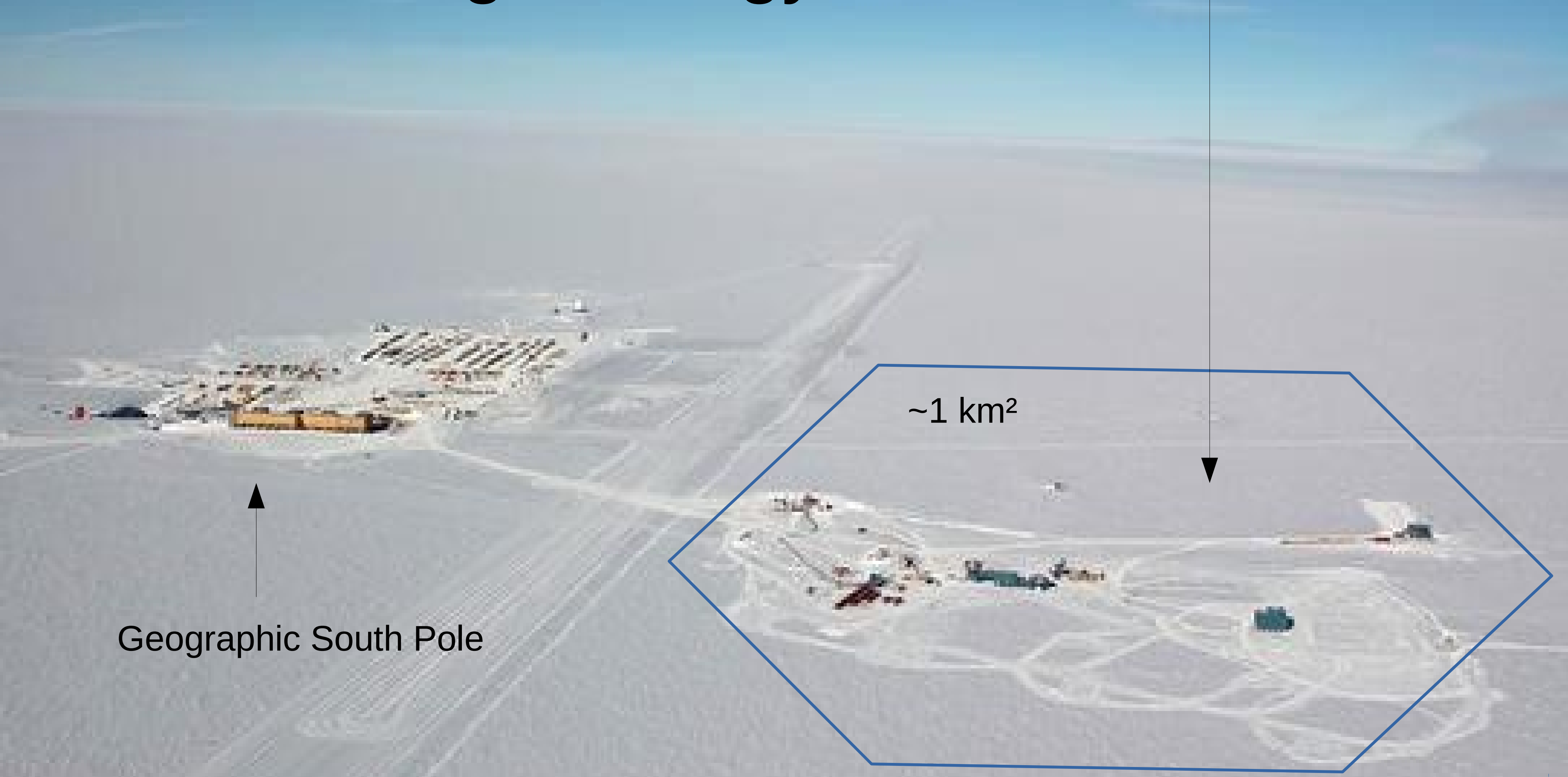
Possible Interpretations of IceCube High Energy Neutrinos



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Boris Panes, USP. January - 2016

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

III) Squeezing the information from IceCube
Events topology: showers and tracks
Neutrino versus anti-neutrino fractions

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

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

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- The main observable is the transition probability between different flavors

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

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*:

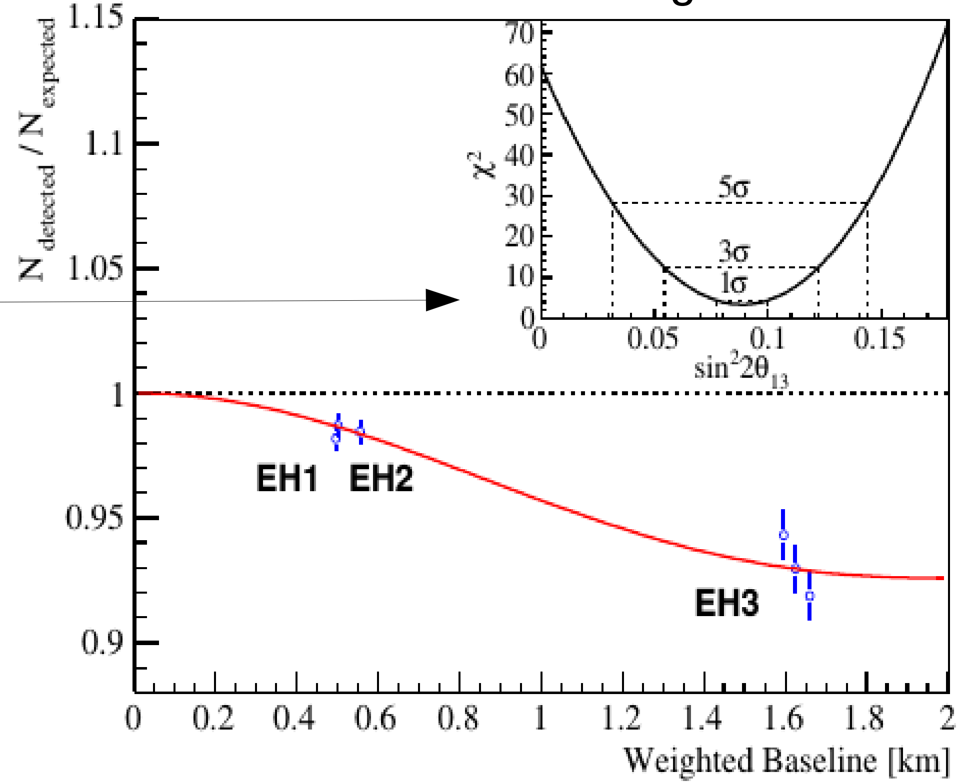
a) Angles

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

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 information, or neutrino physics precision:*

a) CP-Phases

b) Octant of θ_{23}

c) Dirac or Majorana

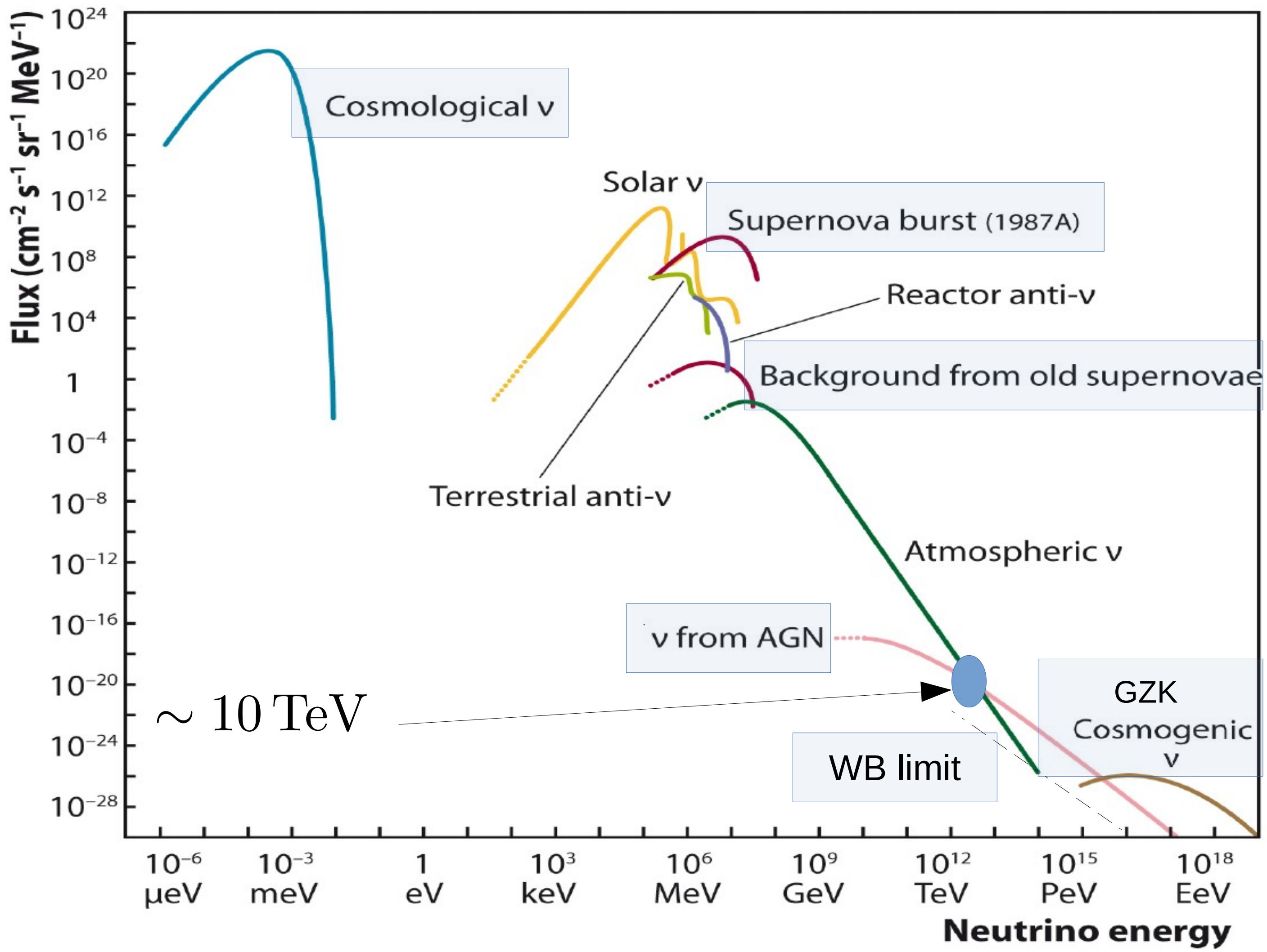
d) Absolute mass scale

e) Mass ordering or hierarchy

On the other hand, with the current information we are able to study with good accuracy

F) Very High Energy Neutrino Sources, Neutrino Astronomy

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.

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

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

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

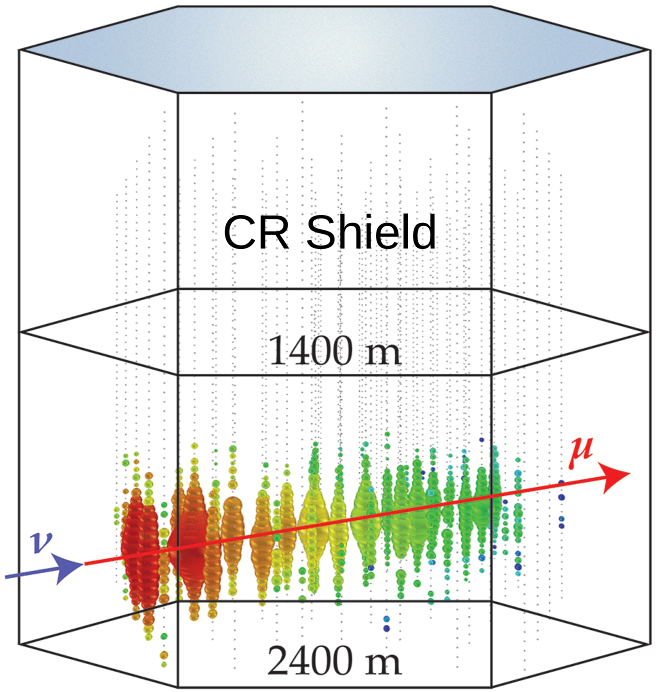
where the effective target mass includes the background rejection cuts and event containment criteria.

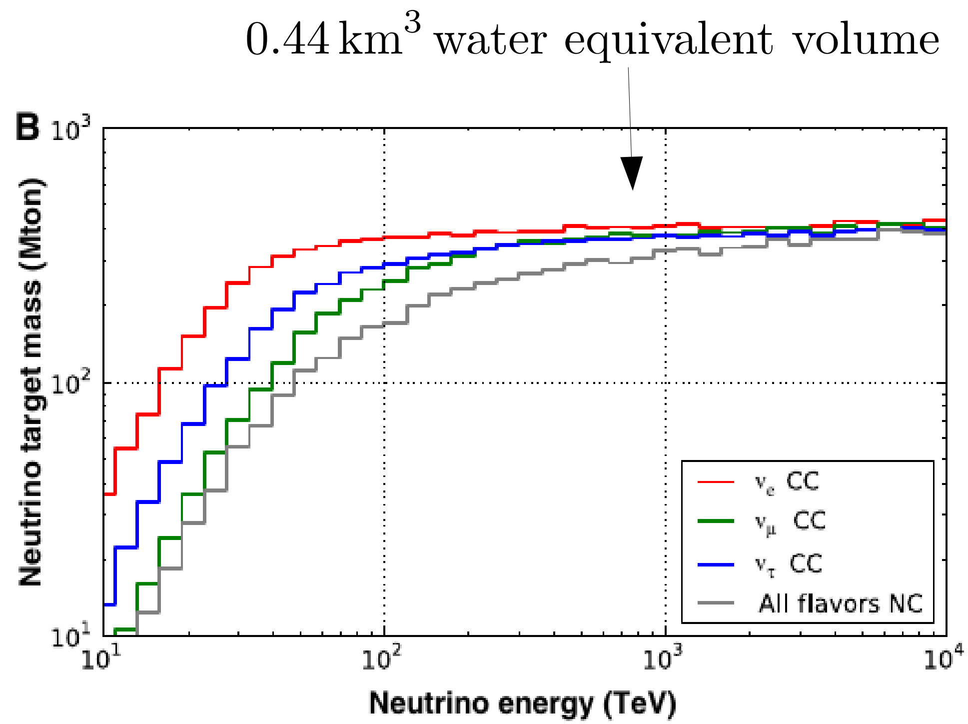
Still under investigation

Kamiokande-II
Super-K
> 10-50 KTons

Lake Baikal
AMANDA
IceCube > 100 MTons

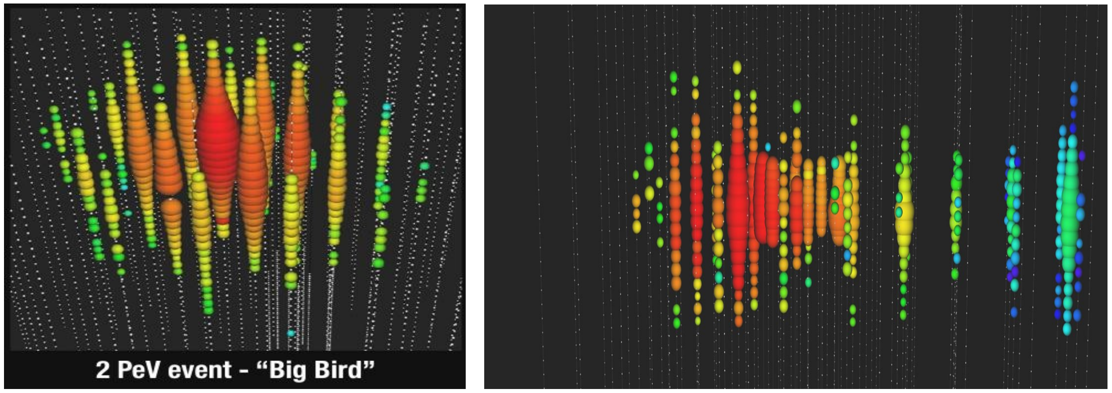
IceCube detector





- 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 Cerenkov radiation.

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



Shower and Track like events

Origin of IceCube VHE neutrinos

- *Signal*. Astrophysical sources, e.g GRBs, AGNs. Products of the interaction of very high energy cosmic rays with the intergalactic media. Point and extended sources. At first order neutrino spectrum follows a power-law distribution.

$$p + \gamma \to \pi^+ + n \to e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu + n$$
$$p + p \to \pi^\pm + X \to e^\pm + \bar{\nu}_\mu + \nu_e(\bar{\nu}_e) + \nu_\mu$$

$$\phi_\nu(E) \sim E^{-\gamma}$$

- *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.

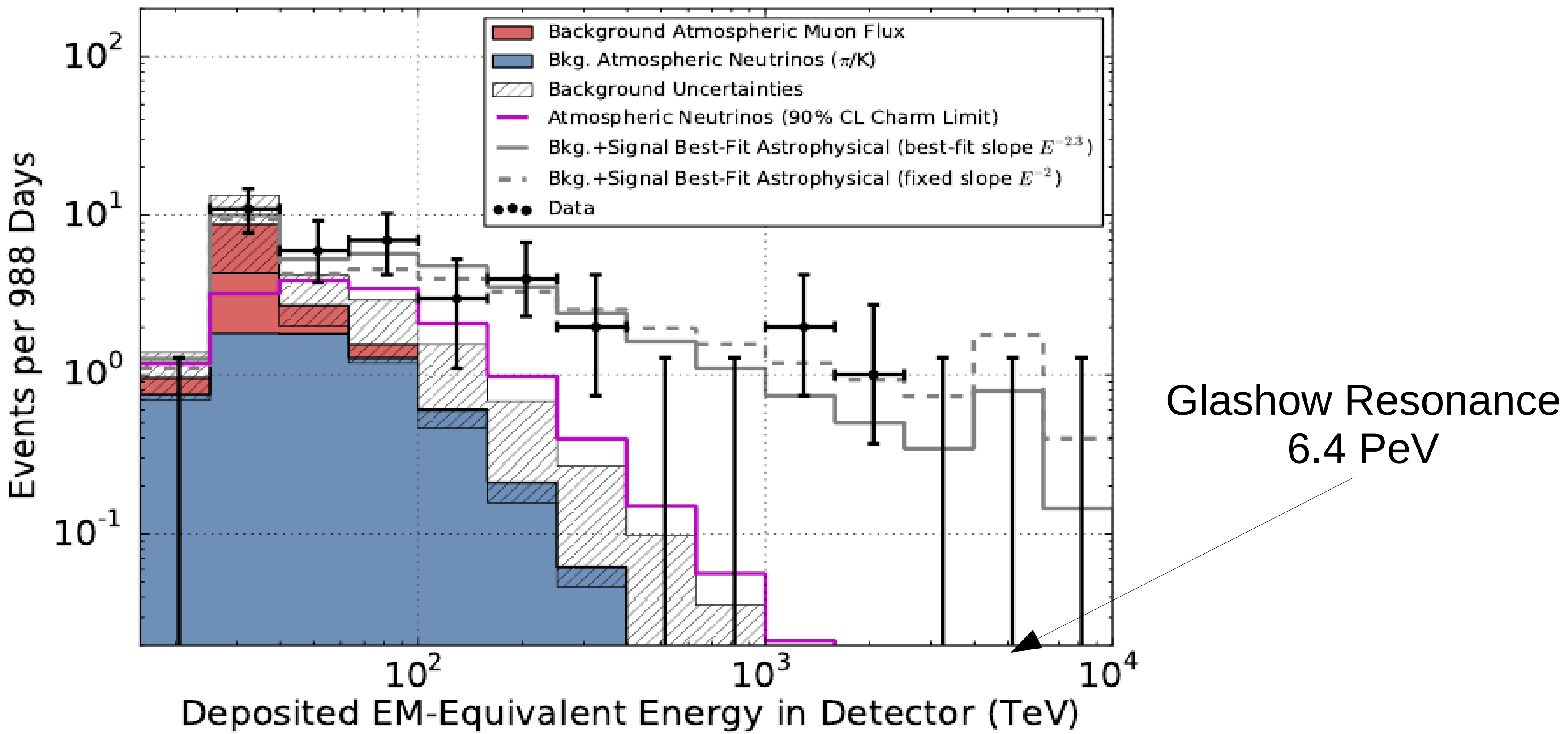
II Part

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.

Between the interpretations we have...

Isotropic power-law spectrum,
viable astrophysical sources, connections to dark matter,
leptoquark resonances, decays of massive neutrinos,
decays of a very heavy long lived particles,
exotic interactions between active neutrinos and the cosmic neutrino background,
etc. *References in the paper*.

In particular, we consider in hep-ph/1411.5318

- Power Law spectrum,

$$\gamma = 2.0 - 2.6$$

$$C_0 \sim 10^{-8} \mathrm{GeV}/\mathrm{cm}^2 \mathrm{sr\ sec}$$

- Heavy dark matter decaying to Nnu, 2h, 4h, 2h+Nnu, 4h+Nnu

$$m_{dm} = 4\,\mathrm{PeV}$$

$$\tau_{dm} \sim 10^{27} - 10^{28}\,\mathrm{sec}$$

- Power-law plus heavy decaying dark matter

Projections: with the current data many hipothesis are viable, but there are some particular features that could allow us to distinguish between different scenarios when more luminosity is accumulated. See for example our analysis in hep-ph/1411.5318.

III Part

Squeezing the information from IceCube

Based on hep-ph/1502.0337, 1502.02649

Signal is assumed to follow a power-law distribution

Data Source: IceCube Collaboration

hep-ph/1502.0337 and Science 342, (2013)

Motivation

- Astrop. sources: different production mechanisms at source produce particular fluxes of neutrinos in flavor space, $f_{a,S}$, e.g. pion decays (1,2,0), muon damped (0,1,0) or neutron decays (1,0,0).

- Detector at earth: each neutrino flavor produce particular topologies at the detector

  - Electron neutrinos only produce showers plus Glashow resonance at 6.4 PeV.

  - Muon neutrinos produce mostly tracks. CC interactions are three 3x NC ones

  - 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.

- Caveat and opportunity: neutrinos oscilate between flavors in their way from the source 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.

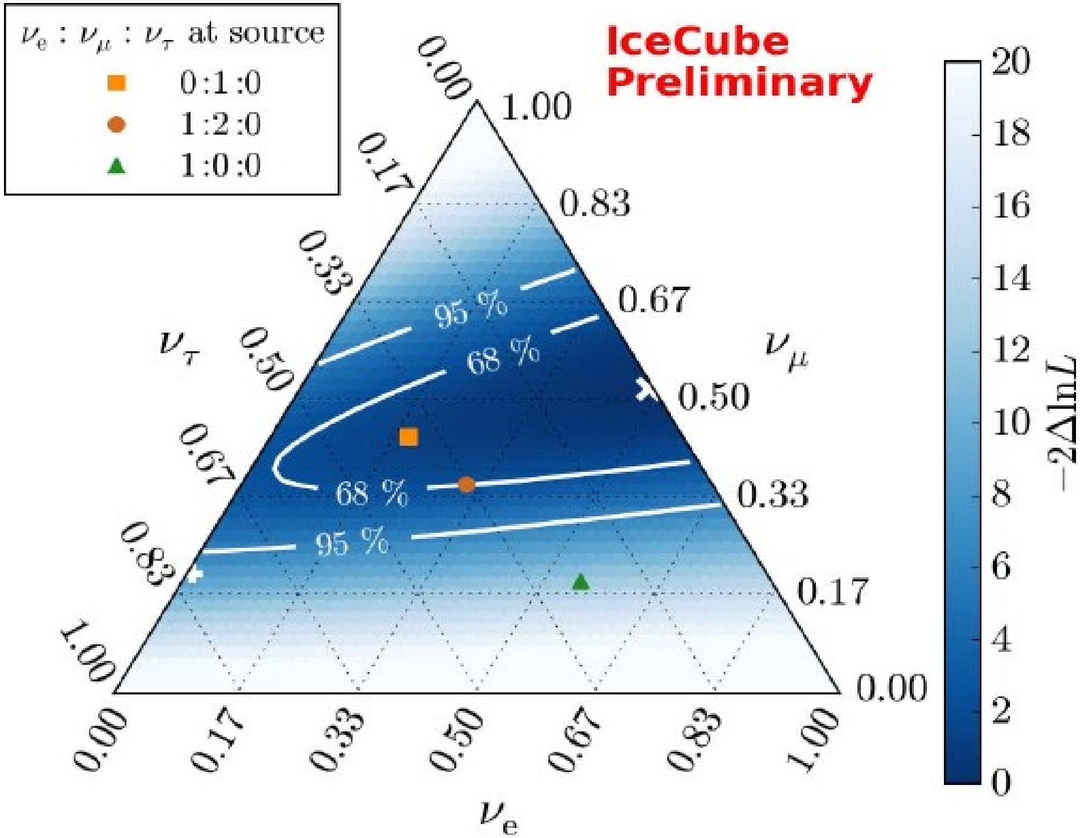
Notice that the sum of fractions must add to 1

IceCube 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 (particle and antiparticle in principle) by separate. Also, some assumptions must be specified in order to clarify the scope of the results.

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

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



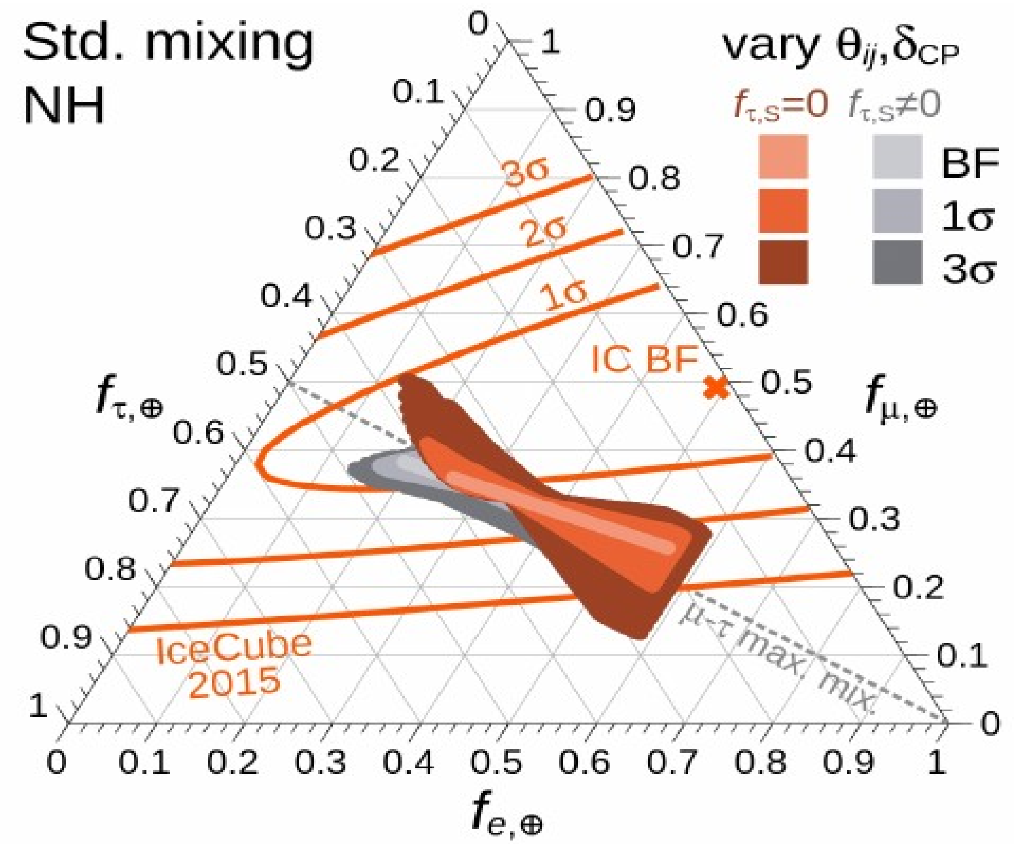
- The best fit point is indicated by a white cross.
- Neutrino and Anti-neutrino fractions are assumed to be equal.
- The diagonal line represents the predicted ratios from standard assumptions at the source. For example (1,2,0)_S, (0,1,0)_S and (1,0,0)_S.
- Extreme regions, as (0,1,0)_E or (1,0,0)_E are excluded at 3.3 and 2.3 sigma.

IceCube 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 (particle and antiparticle in principle) by separate. Also, some assumptions must be specified in order to clarify the scope of the results.

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

- Current results from IceCube : astro-ph/1506-02645



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

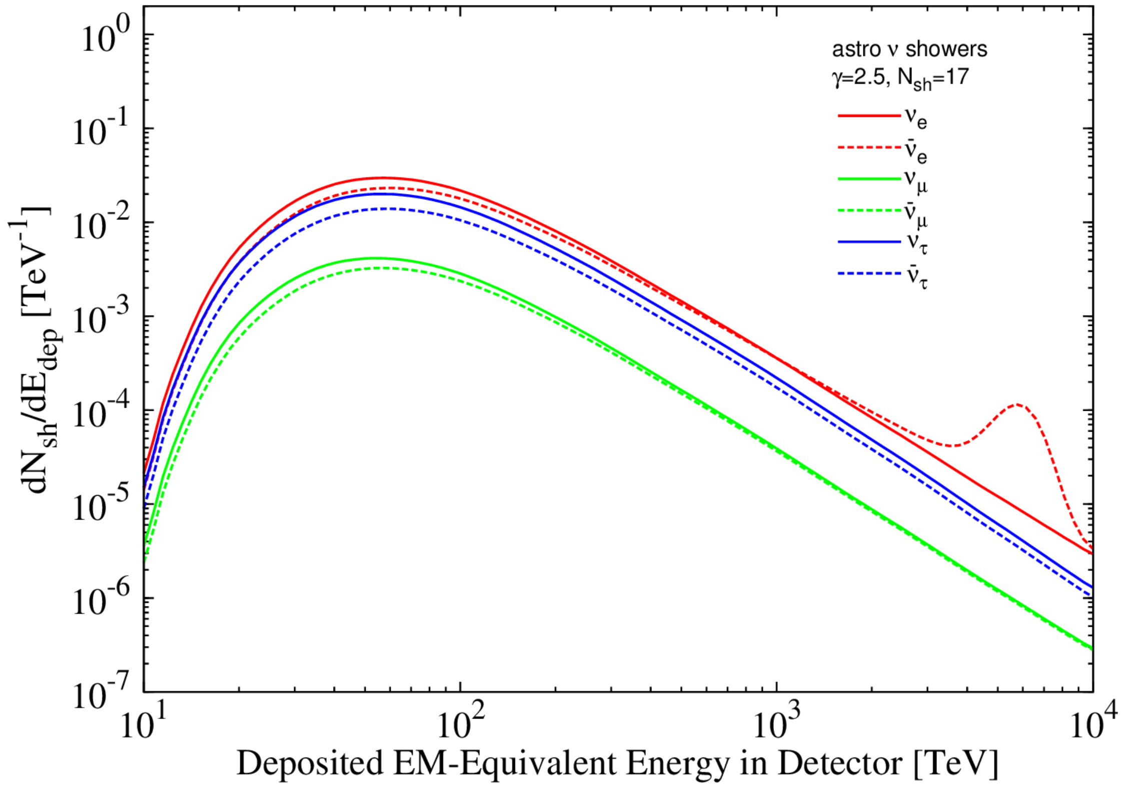
- Neutrino and Anti-neutrino fractions are assumed to be equal.

- 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.

Neutrino and Anti-Neutrino Shapes

- As a first step on the task of including the flavor dependent features of neutrino interactions at IceCube we have compiled and systematized the expressions shown in 1502.02649. These computations include effects such as earth attenuation and regeneration, energy resolution, transformation of neutrino energy into EM-Deposited energy, tau decays, etc. All these effects give as result plots like the following,



Highlights:

Glashow resonance in the electron-anti-neutrino spectrum.

Contribution of muon neutrinos to showers is negligible (but they are the dominant contributor to tracks)

Tau-neutrinos and electron-neutrino spectra are quite similar.

- Similarly we have simulations for astrophysical neutrino tracks for several values of gamma, and atmospheric neutrino and muon showers and tracks (background).

Recasting Results for Flavor Ratios

Assuming that particle and anti-particle neutrino ratios are independent degrees of freedom, we can try to interpret the IceCube best fit in terms of standard neutrino physics.

For instance, and as a preliminary result, we have found that a composition at source of the type (0,0.3,0) for neutrinos, and (0.4,0.3,0) for anti-neutrinos is able to generate a triangle plot in the space Neutrino+Anti-Neutrino that mimic the results of IceCube.

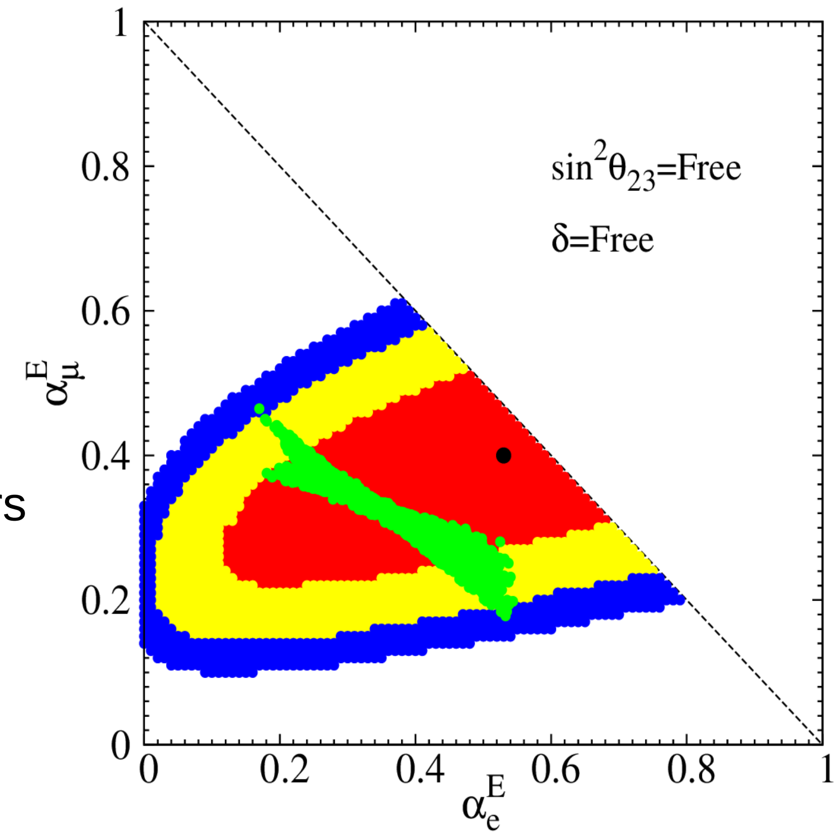
Algorithm:

a) Assume a particular composition at source with different fractions of neutrinos and anti-neutrinos.

b) Apply the neutrino transmutation probabilities to neutrinos and anti-neutrinos independently.

c) Compute the corresponding number of showers and tracks detected by IceCube (for 370 events)

d) Find the best fit of the data assuming that Neutrinos and anti-neutrinos fractions are equal (as usual).



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.

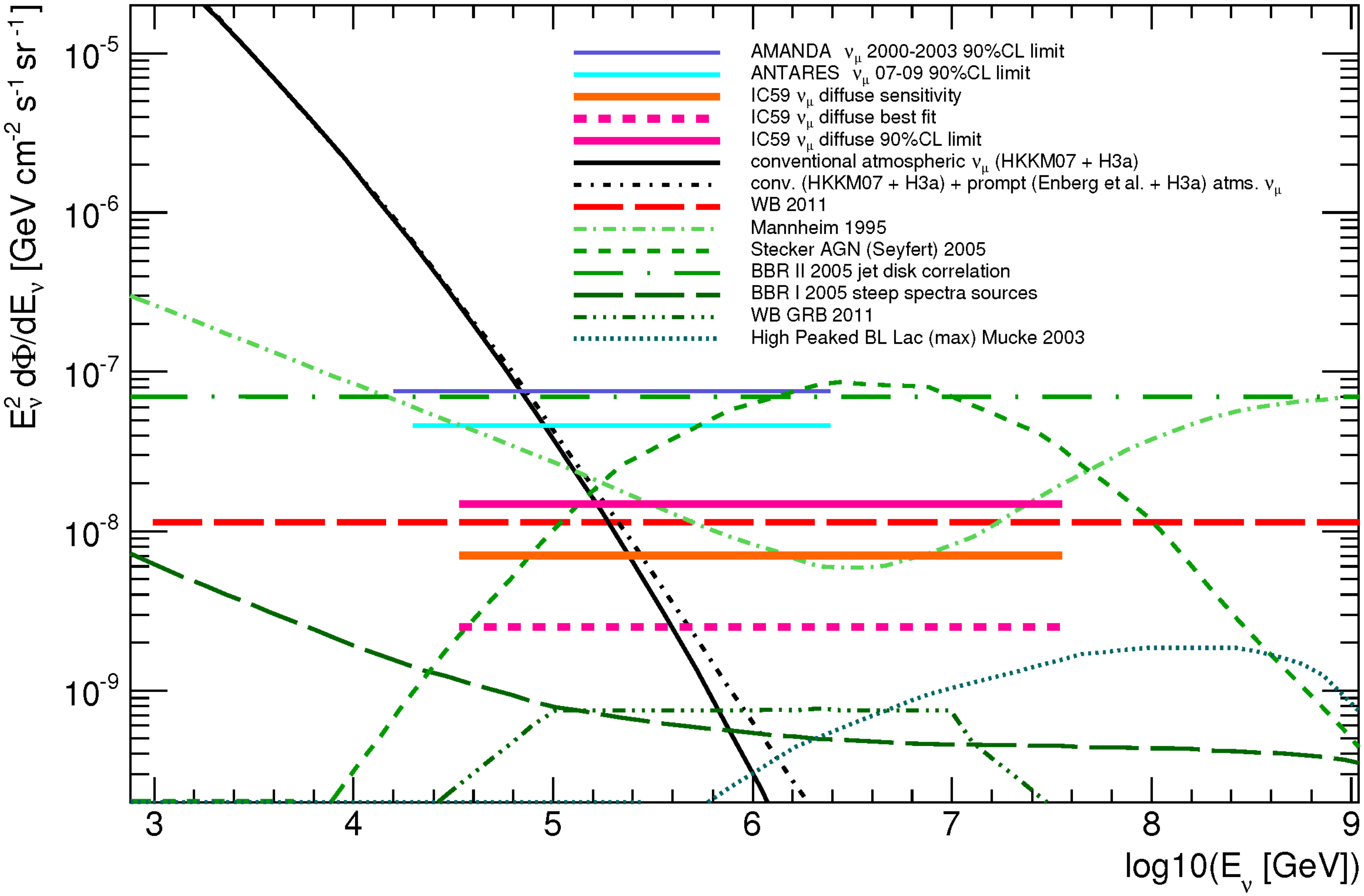
- Currently, the small number of detected events does not allow us to accurately determine the properties of astrophysical neutrino sources. Or in other words, several models are able to explain the observed excess of neutrinos.

- Neutrino ratios at earth give important information about the source mechanisms but also they are useful for neutrino physics. In particular, our preliminary results show that it would be convenient to consider neutrino and anti-neutrino ratios indpendently.

Backup

Origin of IceCube VHE neutrinos

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.



Number of events – Vanilla 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

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

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

- 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. Deposited energy equals to neutrino energy.

Results with current data

- Best fit values and intervals of confidence

H_0	M_Y [PeV]	Scenario	s	C_0	$\tau_Y \times 10^{28}$ [s]	$r_{\nu N}$	χ^2_{min}	p
I	-	PL	2.3	0.6	-	-	39.41	0.5
II.a	2.2	$PL + \nu N$	2.43	0.51	5.26	-	38.07	0.45
II.b	4.0	$PL + \nu N$	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
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

X