HE neutrinos: expectations, inferences, prospects

Francesco Vissani, Andrea Palladino, Arman Esmaili

INFN L'Aquila - LNGS & GSSI

Purpose

IceCube has changed the rules of the game and continues to progress. Remarkably, the observations are compatible with the known neutrino oscillations. Moreover the topologies of the events have been used to probe ordinary and exotic physics, as we will discuss.

Still, we need independent confirmations; the connections of IceCube's neutrinos with astronomical/astrophysical facts heavily rely on speculations--excepting special cases, such as GRB; the amount of prompt events is not known precisely; double bang and/or Glashow resonance events are still to be seen.

In this talk, we select specific topics concerning expectations, inferences and prospects, in the hope to contribute to the impressive drive of this field or at least to the discussion in the 7th VLVνT workshop.

Let us begin with the expectations concerning atmospheric neutrinos. The most important facts are well-known to this audience and do not need to be recalled in details. We focus here on the most uncertain issue to date concerning atmospheric neutrinos, namely,

PROMPT NEUTRINOS

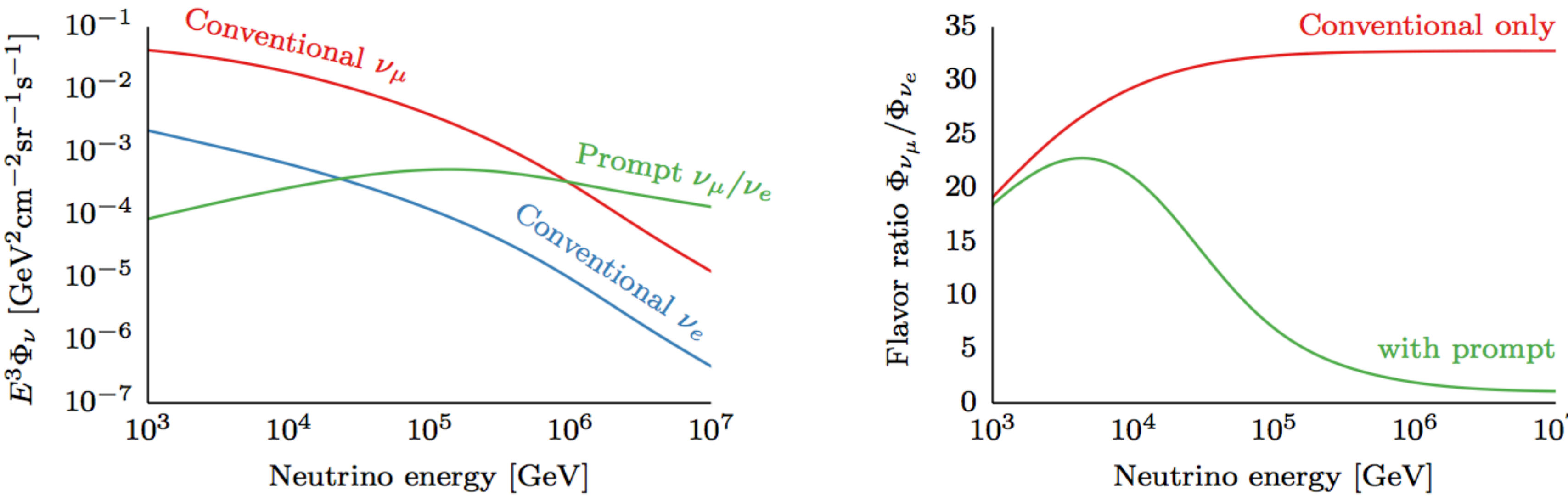
Charm decay in atmosphere

It is well-known that charm decay in atmosphere yield *prompt neutrinos*

- These make HE atm spectra harder, till $\gamma \sim 2.7$
- Normalization is not precisely predicted

- Peculiar flavor: $\nu_e \approx \nu_\mu$ and $\nu_\tau \approx 0$
- Signal from charm is rich in ν_e

- Charm contributes also to μ
- No time modulation, since charm decays promptly



Atmospheric background with emphasis on charm

Standard picture is illustrated well in this plot by J. van Santen (2015). Speculations on the role of (non-standard) charm distribution are in Lipari **1308.2086** and FV et al **JCAP 1309 (2013) 017.**

IceCube vs charm

- Data analyses deplete charm by $\nu - \mu$ correlation
  (Shoenert et al 2009)
- Testing predicted normalization but no hint of
  (IceCube 2015)

- Cosmic neutrino signal not far from $\gamma \sim 2.7$
- Charm does not swamp cosmic signal: good

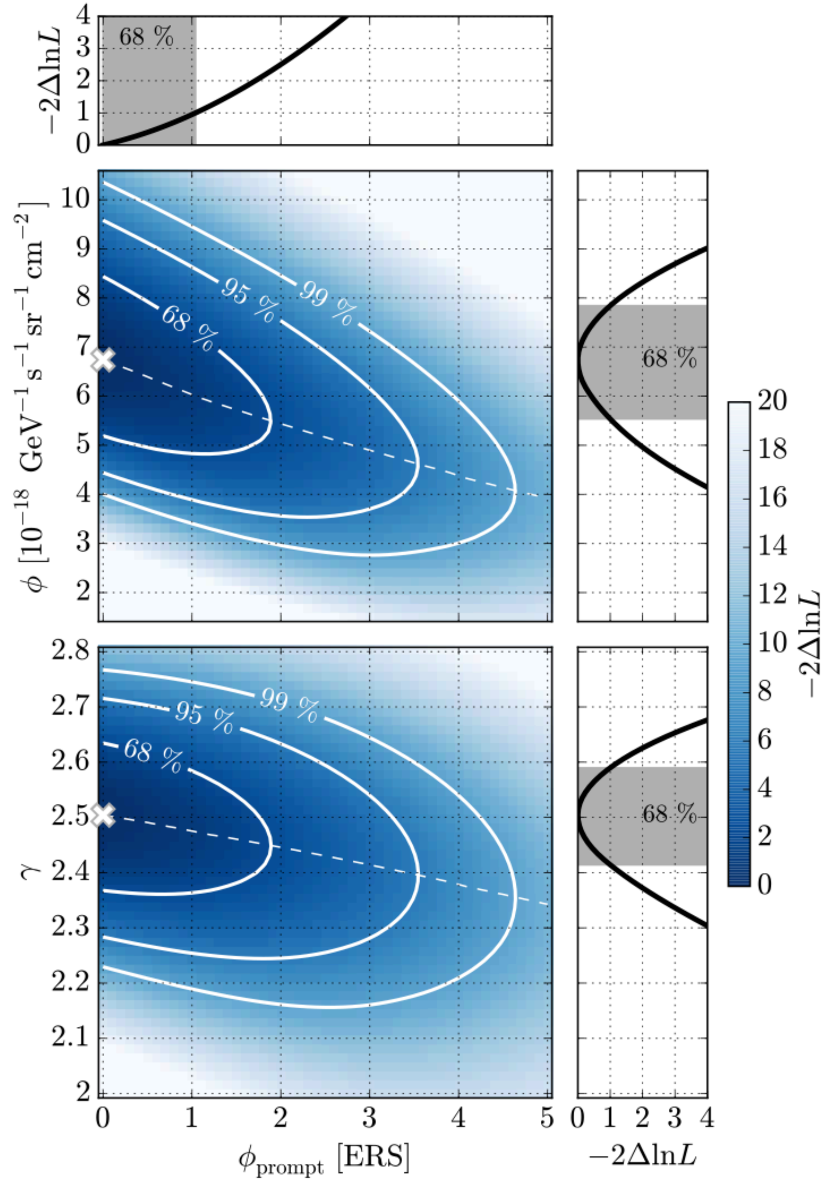
- Tasks left: finding prompt events, or to understand *"why IceCube lacks of charm"*

IceCube, ApJ 2015

Maximum-likelihood analysis of IceCube data. For prompt neutrinos, IceCube uses the predictions of Enberg et al. (2008) .

The best fit of the prompt flux is zero, or even slightly negative as we see from top panel.

Lower panel shows the mild correlation of the amount of (standard) prompt neutrino flux and spectral slope of the cosmic neutrinos.



Assume cosmic neutrinos seen. Ordinary 3 neutrinos oscillations modify their fluxes. Thanks to IceCube's capability to separate tracks from showers, these effects can be probed. We introduce and discuss two ways to compare with the data, discussing residual uncertainties.

OSCILLATIONS

Oscillations

- Cosmic neutrinos are supposedly produced in environments with small particle densities.
- During their propagation, they are subject to vacuum oscillations (Gribov-Pontecorvo regime).
- 3 flavor oscillations have been precisely measured in terrestrial laboratories and have an important impact on cosmic neutrinos (Learned & Pakvasa 95).
- Predictions and uncertainties can be treated easily by a suitable choice of parameters

we motivate and introduce the choice of the three natural parameters. The parameters P_0, P_1, P_2 are defined as follow,

$$P_0 = \frac{P_{ee} - \frac{1}{3}}{2} \ , \ P_1 = \frac{P_{e\mu} - P_{e\tau}}{2} \ , \ P_2 = \frac{P_{\mu\mu} + P_{\tau\tau} - 2P_{\mu\tau}}{4} \tag{2}$$

We can write in terms of P_0, P_1, P_2 the matrix that contains the probabilities of oscillations of cosmic neutrinos. This is the following symmetric matrix,

$$\mathcal{P} = \begin{pmatrix} \frac{1}{3} + 2P_0 & \frac{1}{3} - P_0 + P_1 & \frac{1}{3} - P_0 - P_1 \\ & \frac{1}{3} + \frac{P_0}{2} - P_1 + P_2 & \frac{1}{3} + \frac{P_0}{2} - P_2 \\ & & \frac{1}{3} + \frac{P_0}{2} + P_1 + P_2 \end{pmatrix} \tag{3}$$

It acts on the vector of fluxes before oscillations $F^0 = (F_e^0, F_\mu^0, F_\tau^0)$ just as $F = \mathcal{P}\ F^0$, giving the vector of fluxes observed after oscillations, $F = (F_e, F_\mu, F_\tau)$.

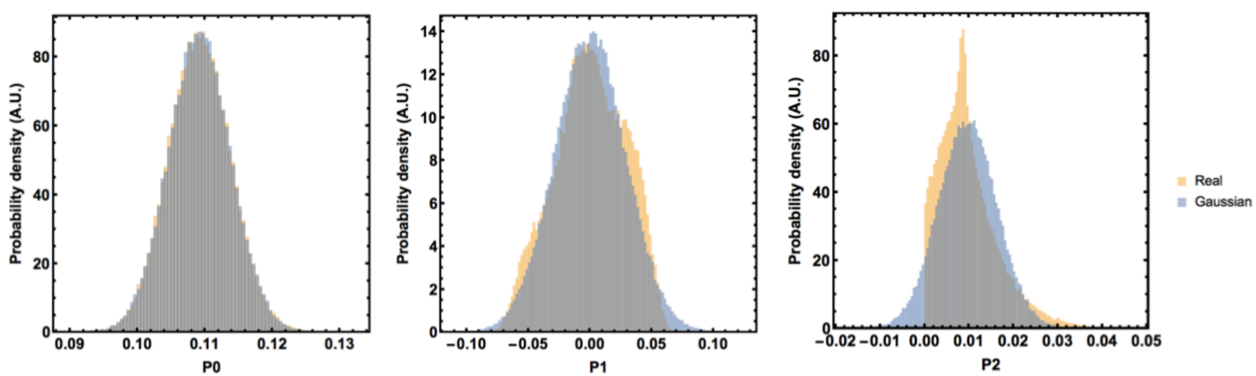


Figure 1: *Distribution of the natural parameters P_0, P_1 and P_2, due to the uncertainties in the mixing angles and the phase of leptonic CP violation.*

Palladino et al, , 1504.05238 EPJC

Analysis of tracks and showers

Palladino et al, **PRL 114 (2015) 171101**

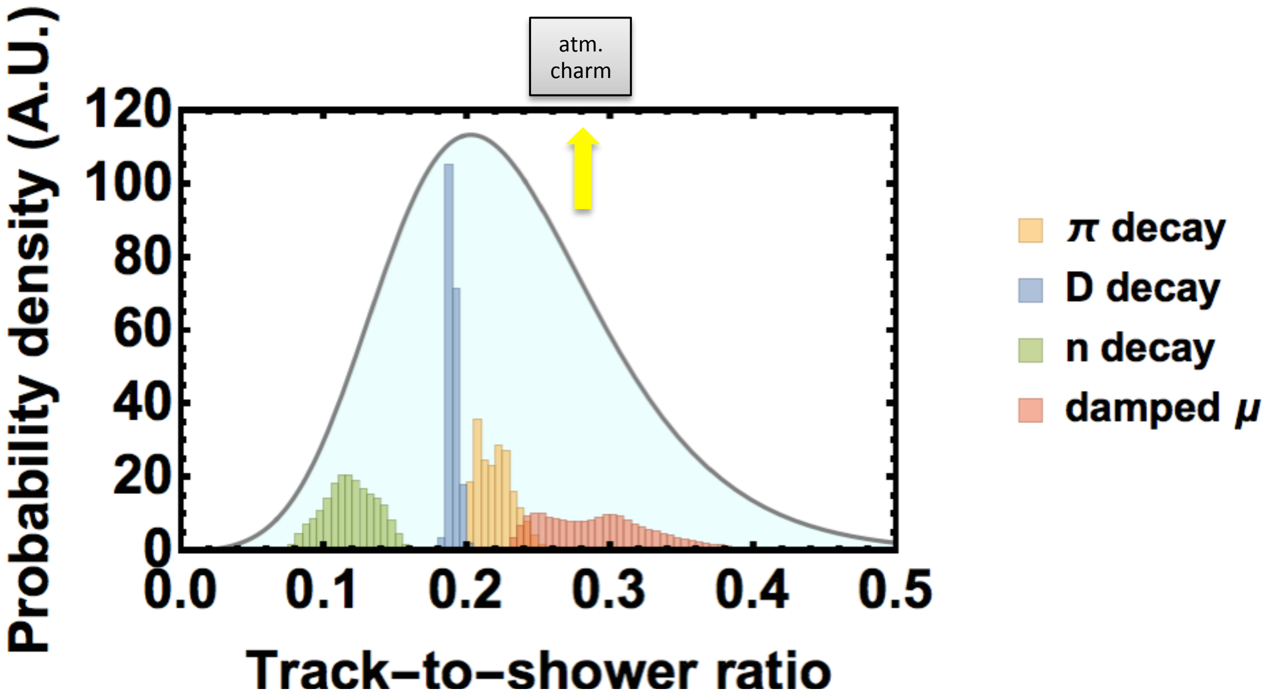
- N_T=track events due to CC ν_μ
- N_S=showers events to NC and to CC ν_e , ν_τ
- Other minor contributions neglected

- Assume power law fluxes F_e , F_μ , F_τ
- Use the effective areas and masses of IceCube
- Calculate dependence of N_T ,N_S from slope (mild) and from flux normalization (linear)

- Use Poisson statistics

Predictions and observations [1/2]

Palladino et al, **PRL 114 (2015) 171101**



- This presentation uses an observable quantity
- The predictions, however, *depend* upon the slope
- This is based on 3 yr data set and assumes α=2.3.

Alternative: display flavor fractions

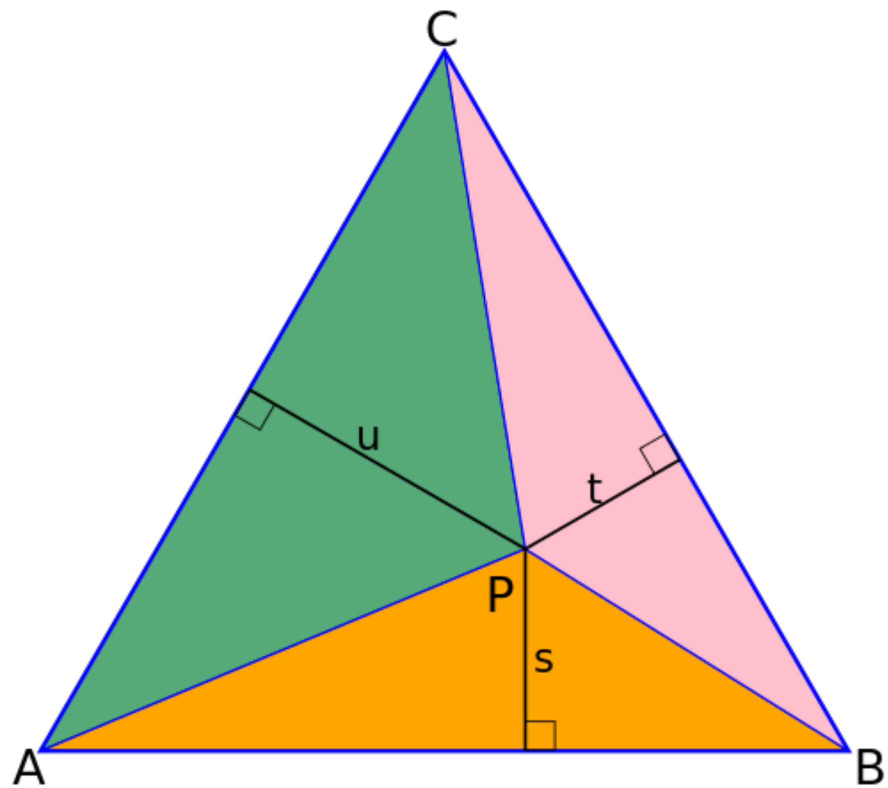
Consider the three fractions of flux (or flavor fractions) at Earth, e.g.,

electronic fraction= $F_e / (F_e + F_\mu + F_\tau)$

evidently, they sum to 1.

They can be represented as the distances from the sides of an equilateral triangle. This is called flavor triangle.

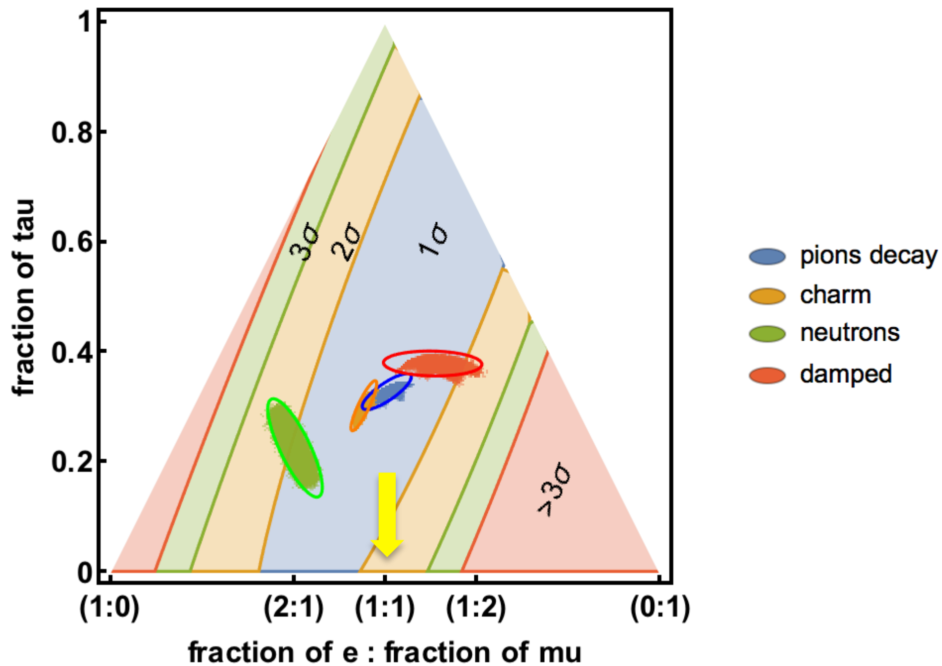
Note however that the flavor fraction at Earth is not directly observable; what we observe are event topologies.



[From Wiki: Equilateral triangle's area, a h/2, equals the sum of the areas of the 3 colored triangles, a u/2+a t/2+a s/2=a (u+t+2)/2=a h/2 and we conclude: u+t+s=h. In math, this is called *Vivani's theorem*, after the name of one student of Galileo]

Predictions and observations [2/2]

Palladino et al, 1504.05238 EPJC



- The presentation *does not* use observable quantities
- But the predictions are independent from the slope
- This is based on 3 yr data set and assumes α=2.3.

Summary

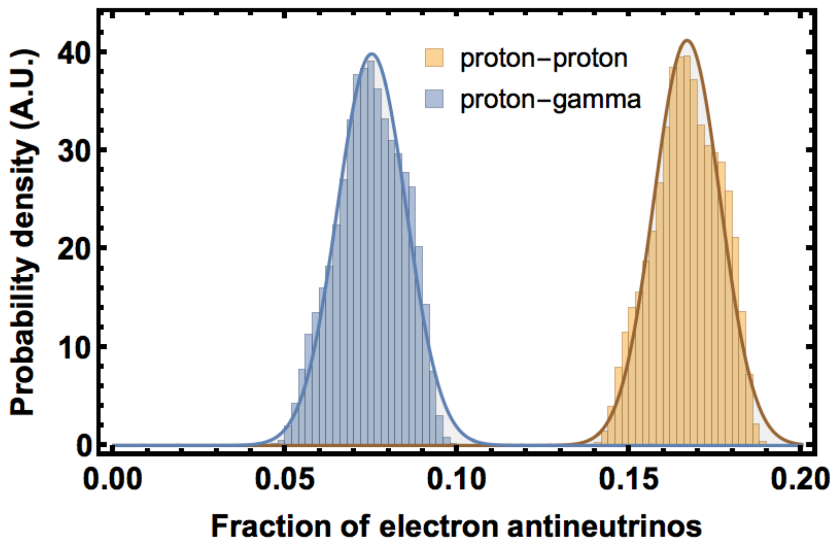
- Expectations from vacuum oscillations (+power law distribution) are well understood and seem to be sound.
- The observations agree with all production models.
- Electron neutrinos at source slightly disfavored, a feature more prominent analyzing the 4 yr dataset.

Palladino et al., **PRL 114 (2015) 171101**
IceCube coll., **PRL 114 (2015) 171102**
IceCube coll., **ApJ. 809 (2015) 98**
Palladino et al. 1504.05238 **EPJC**

If the spectrum is not too soft, other topologies of events exist, whose amount depends on the type of cosmic source. Oscillations imply that cosmic neutrinos should include taus in large amount. Finally, we can begin to explore exotic possibilities such as neutrino decay.

INFERENCES ON COSMIC NEUTRINOS

Glashow resonance: dependence on sources



Palladino et al, PRL 114 (2015) 171101

There is a difference between *pp* and $p\gamma$ sources and uncertainties are small:

Decay of π^+ from $p\gamma$ sources don't produce anti-ν_e; oscillations do it

(Berezinsky Gazizov 1981; Anchordoqui et al 2005)

No event observed around Glashow resonance. Why?

- Cut-off in neutrino spectrum below 6 PeV;
- Spectral index much larger than 2;
- Or simply, a bigger exposure is required

Rates for resonant events

Anchordoqui, Goldberg, Halzen, Weiler:

Rate *pp* = 4.6 per year

Rate $p\gamma$ = 0.8 per year

This assumes *same CR flux*. The difference is due to

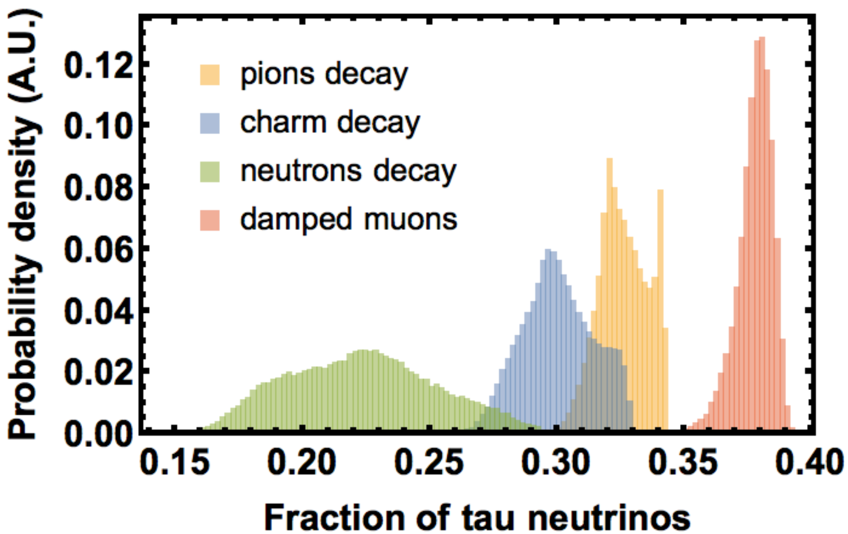
- Oscillations
- Energy distribution of secondary particles

Barger, Fu, Learned, Marfatia, Pakvasa, Weiler:

Glashow / non resonant events ratio, for E_ν>2 PeV, is 0.5 for *pp* and 0.25 for $p\gamma$.

Thus: deep inelastic scattering is an important background for Glashow resonance events

Tau neutrinos



* Tau neutrinos are unavoidable (Learned Pakvasa 1995)

* At “low” energies, tau is same as showers -- electrons or NC

* At HE, tau yields a unique topology: double bang event.

Double bang observed ⟶ Cosmic origin proved

No double bang events observed in 4 years.

Neutrino decay

The idea that neutrinos are unstable is old (1972).

Assume decay into a lighter neutrino and an invisible particle (non-radiative decay). The probability to survive is,

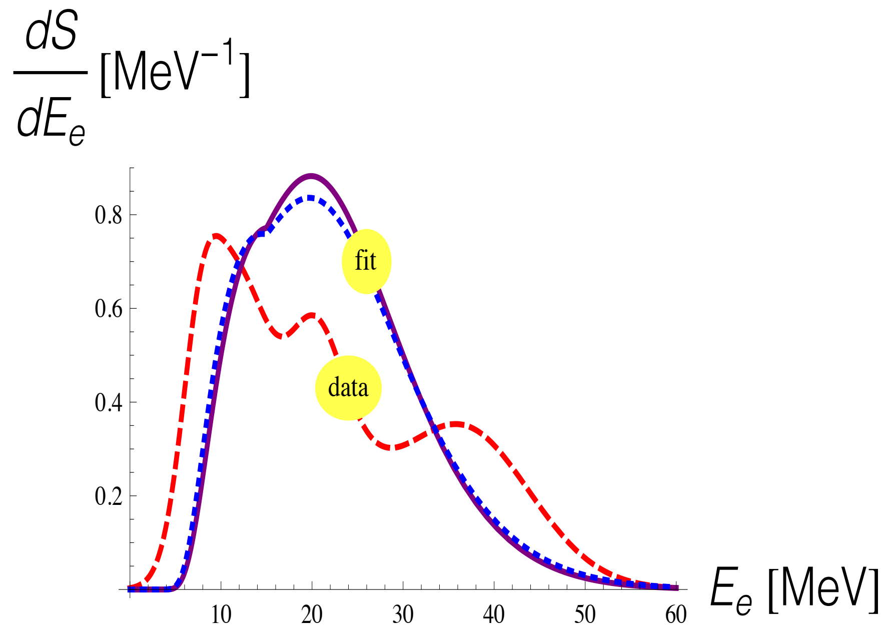
$\exp(-T/t\ \ m c^2/E)$

Assume: only lighter neutrino is stable.

For inverse mass hierarchy, we'd receive mostly μ and τ neutrinos. This is ruled out by SN1987A.

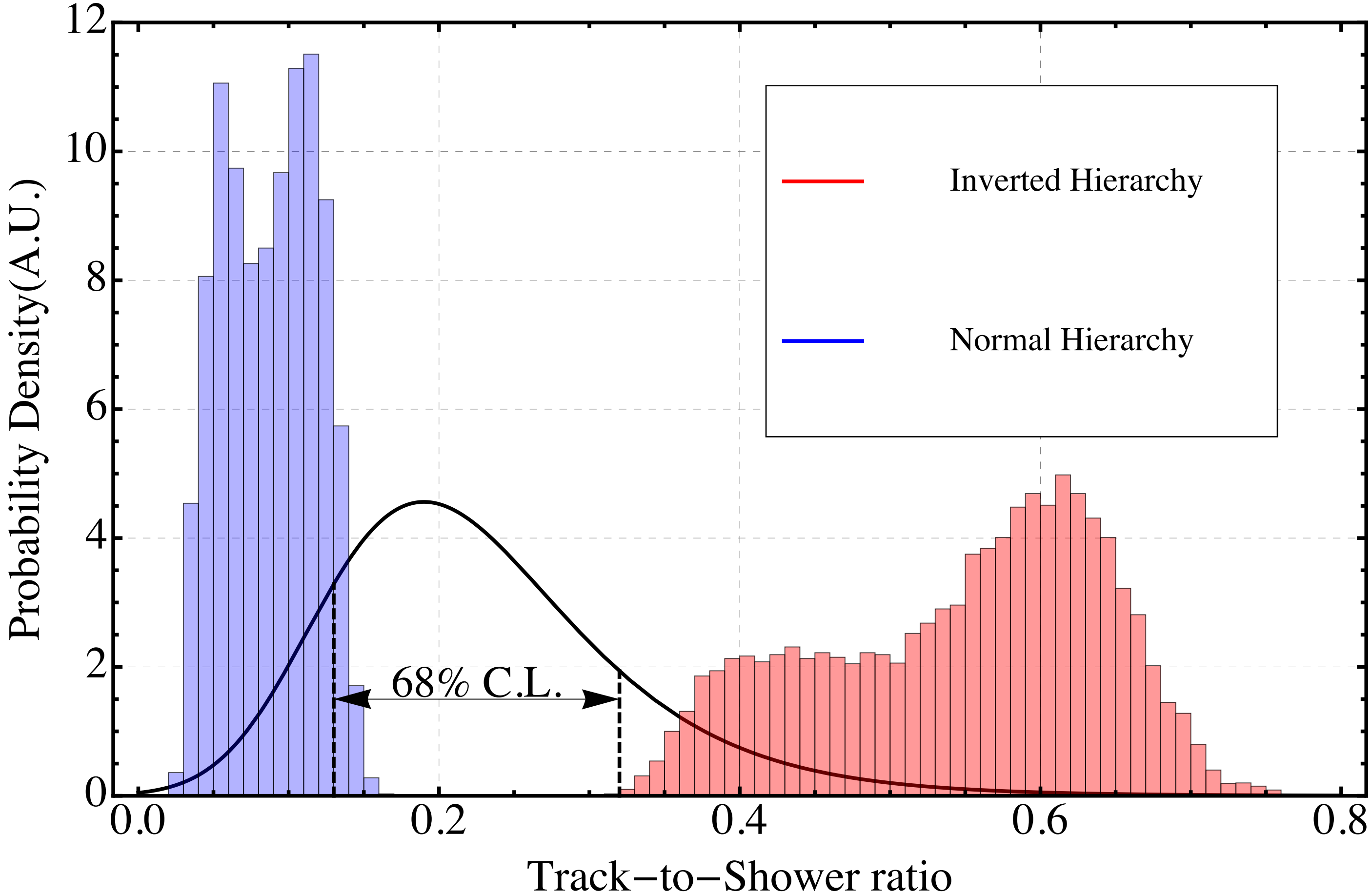
The case of normal hierarchy instead is not probed significantly by SN1987A: the expected energy spectrum is almost identical to the standard case.

FV, J.Phys. G42 (2015) 013001



But now we have also cosmic neutrinos!

With 3 yr (here shown), normal hierarchy gone @ 1.8 σ
With 4 yr, inference strenghtens



Pagliaroli et al, 1506.02624

Finally we discuss briefly the astronomical connection, emphasizing the importance of independent measurements and of angular resolution better than 1^o. We offer few comments on the hot case of the BL Lac.

PROSPECTS

NEXT STEPS?

- Diffuse angular distribution *or* many weak sources?
- Need to identify astronomical counterparts (optical, radio, X, gamma, etc)
- Tracks and passing μ-events particularly valuable. Statistics still rather limited
- Need to confirm these results by independent observations.

Note: telescopes deployed in the water have typical angular resolution of 0.2^{o}, so they identify regions of the sky that are 25 times smaller

BL Lac as a case study

Fermi observed have hard spectra. Likely to dominate the diffuse gamma background at 10-100 GeV. Interesting candidates as neutrino emitters.

- Padovani & Resconi, MNRAS 2014, *plausible astronomical correlation*
- Kowalski, ICRC 2015 (but cfr Lipari PRD 2008), *energy OK but constrained from multiplets*
- Giommi et al, MNRAS 2015 (and next talk), *perhaps at high energy*

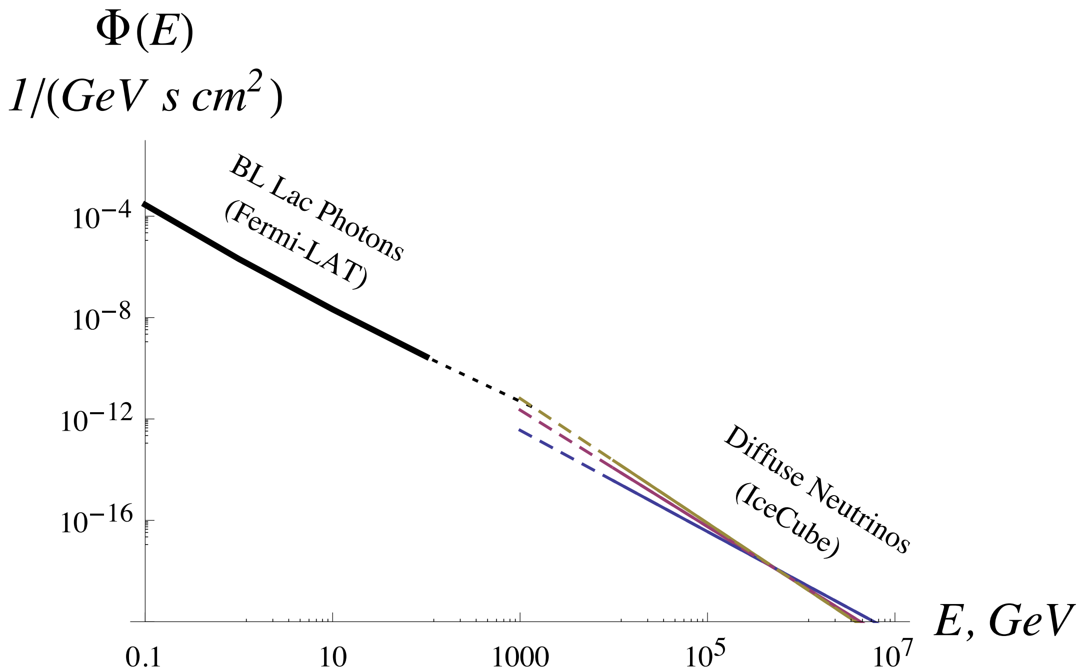
Comparison with BL Lac Photon Flux

BL Lac model by Fermi LAT (Ajello 2014) describes quite reliably the total emission from BL Lac in 0.1-100 GeV region.

(5 BL Lac have more than 1% of the total photon flux each; the brightest has 2%.)

We expect a similar or smaller neutrino emission in the 0.1-100 GeV.

Thus, BL Lac could contribute, but space to explain the whole neutrino flux is restricted: see the plot.



Discussion

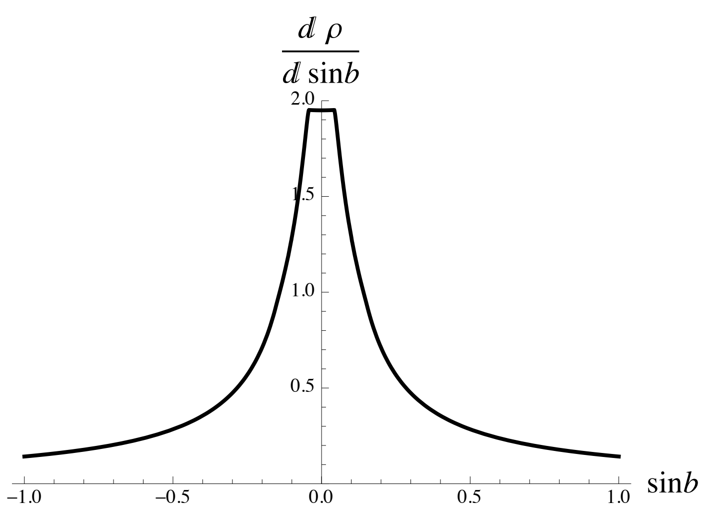
- The case made by IceCube for a new population of very high energy neutrinos, on top of conventional atm neutrinos (but charm?), is very convincing

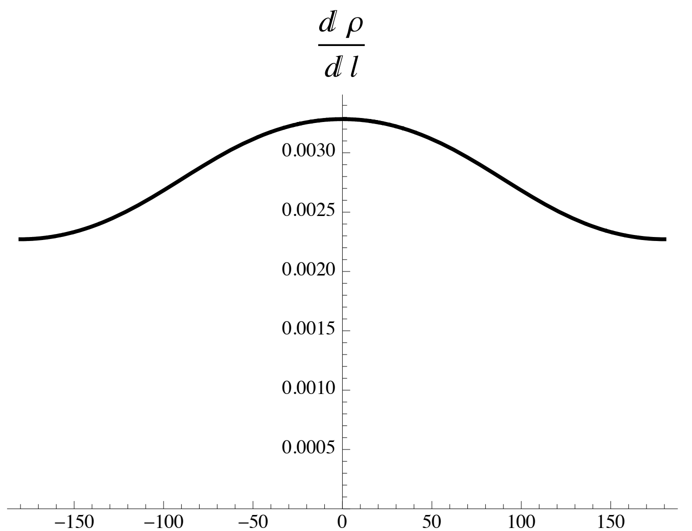
- It can be attributed to cosmic neutrinos. It is consistent with ordinary vacuum oscillations

- Definitive proofs of this hypothesis could come from tau (double bang) and/or Glashow resonance

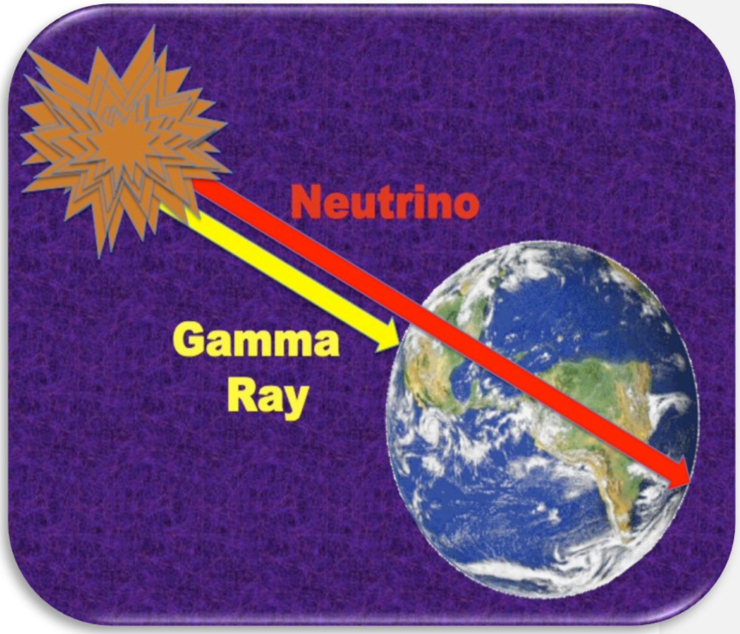
- Needs: confirm this case independently; search deviations from uniform distribution; locate its source(s); remind that this could be just the beginning

Milky Way as a cylinder (H=1 kpc, R=15 kpc) of uniform neutrino luminosity

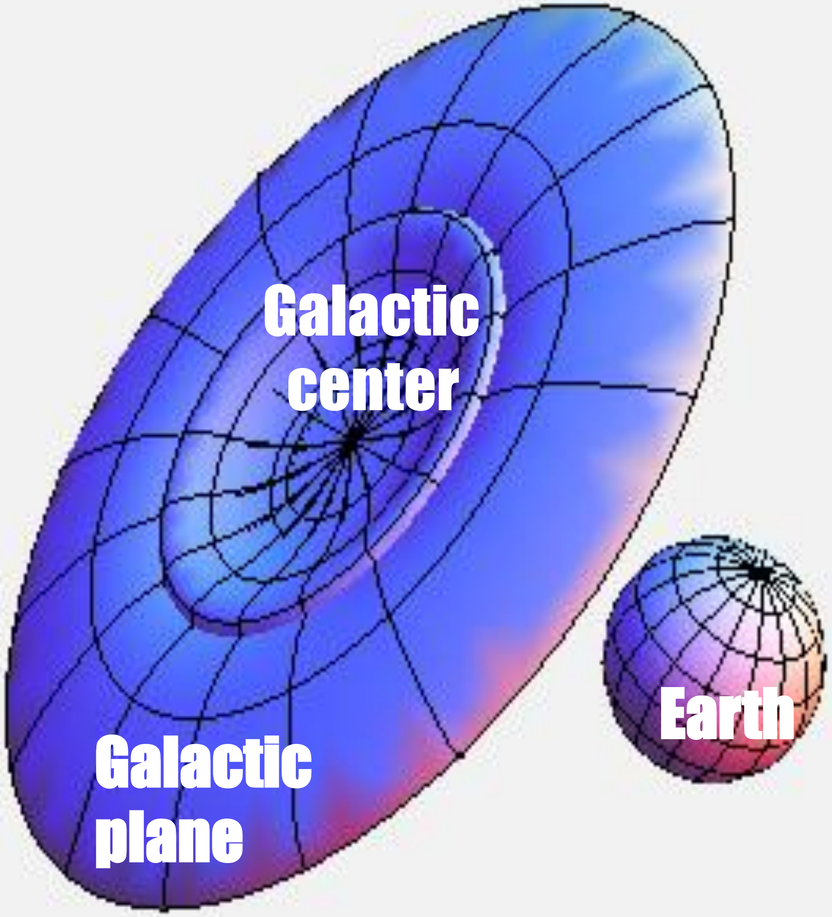


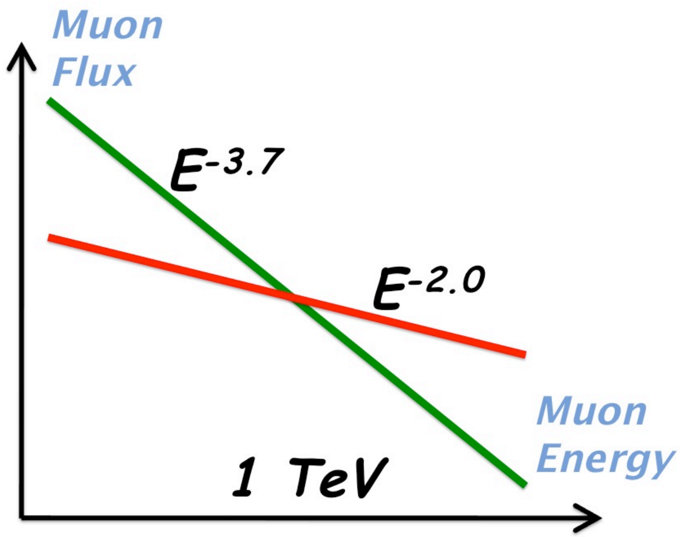


Quite different from what it is seen. But the events could be from the halo (Taylor, Gabici, Aharonian 2014)



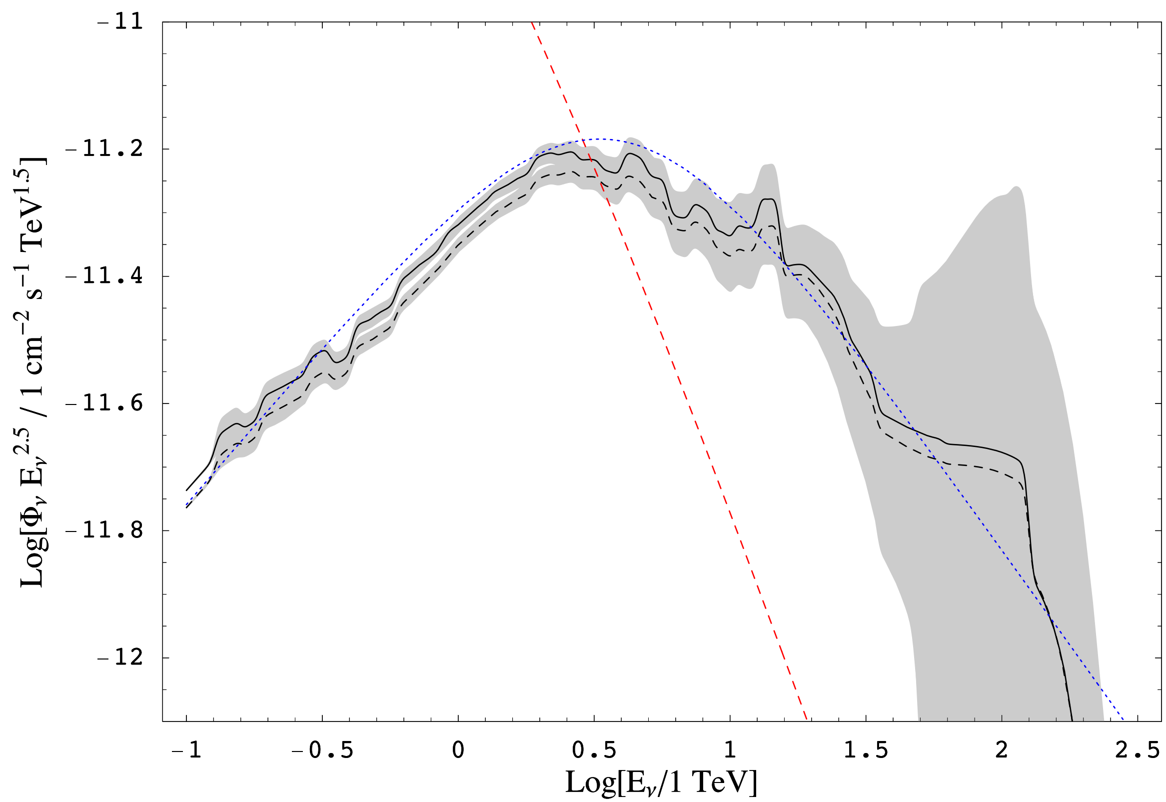
Where we can see the Milky Way?
Southers hemisphere for γ-rays [e.g. Hess];
Northern hemisphere for (through-going) muon neutrinos [e.g. Antares]





Left: our hope concerning the intensity of neutrino (point) sources as compared with the atmospheric one.

Right (below): the upper bound on neutrino flux from one of the most luminous supernova remnant, RX J1713.7-3946.



Villante & FV 08

Conversion γ–ν

- If γ-ray are "hadronic" and from *pp* thin source, use Villante FV 2008 to calculate ν-flux.

- When γ-ray are power law distributed, also ν-flux is such. Typically, neutrino flux (6 species) is close in size to observed photon flux.

- If we have $p\gamma$, neutrinos go down by a factor ≈4 due to isospin. In fact, *pp* makes $\pi^+ \pi^- \pi^0$ while $p\gamma$ makes $2\pi^0$ and $1\pi^+$