High Energy Neutrinos

Expectations, Results & Questions After IceCube

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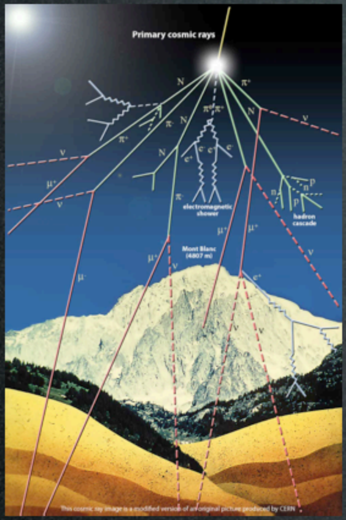
LNGS and GSSI

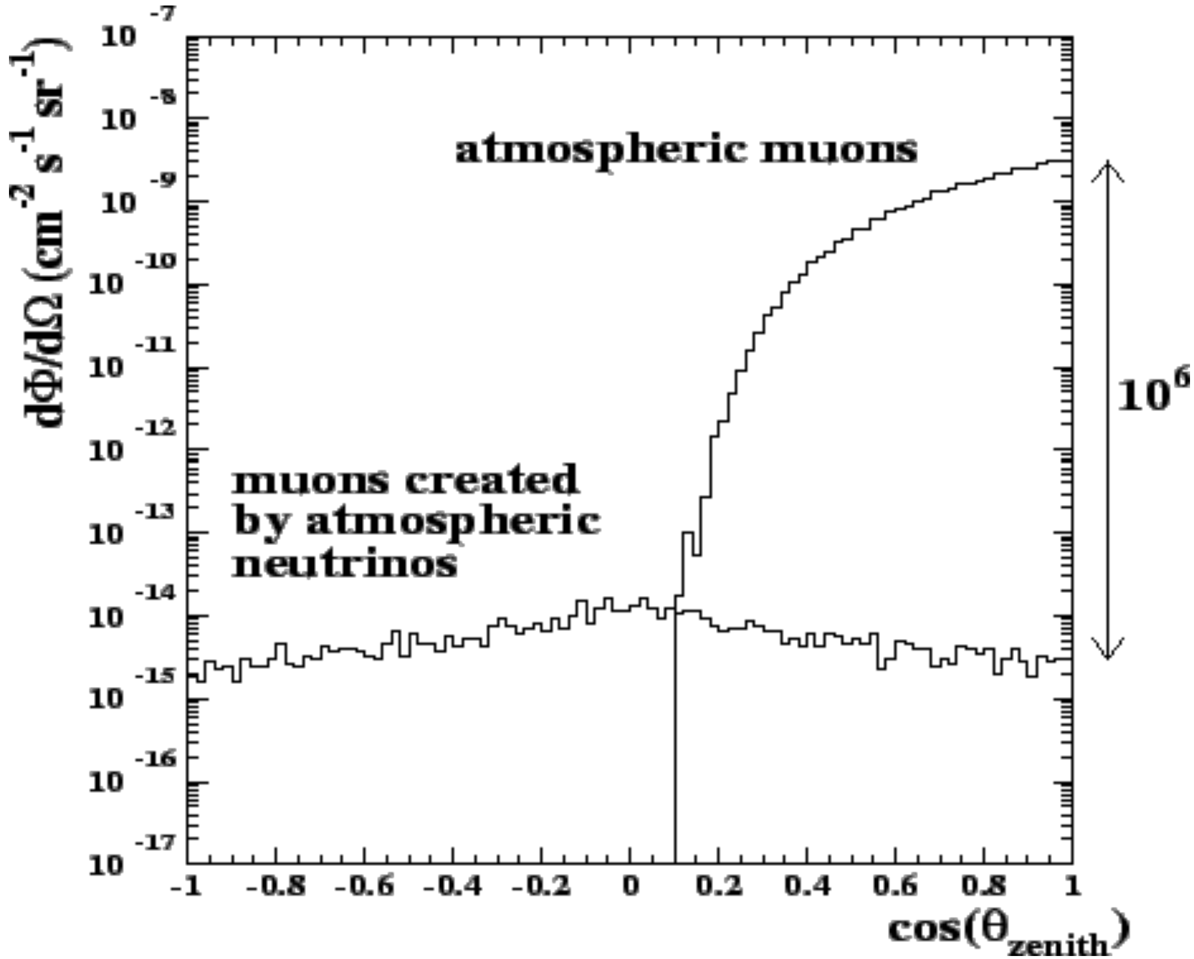
Here we discuss: local phenomena, concepts of high energy neutrino telescope, generic expectations for extraterrestrial neutrinos

INTRODUCTION



Muons as Spies of Neutrinos

Atmospheric muons and neutrinos



The first high energy ν telescopes

The idea: search for ν_μ by means of passing muons

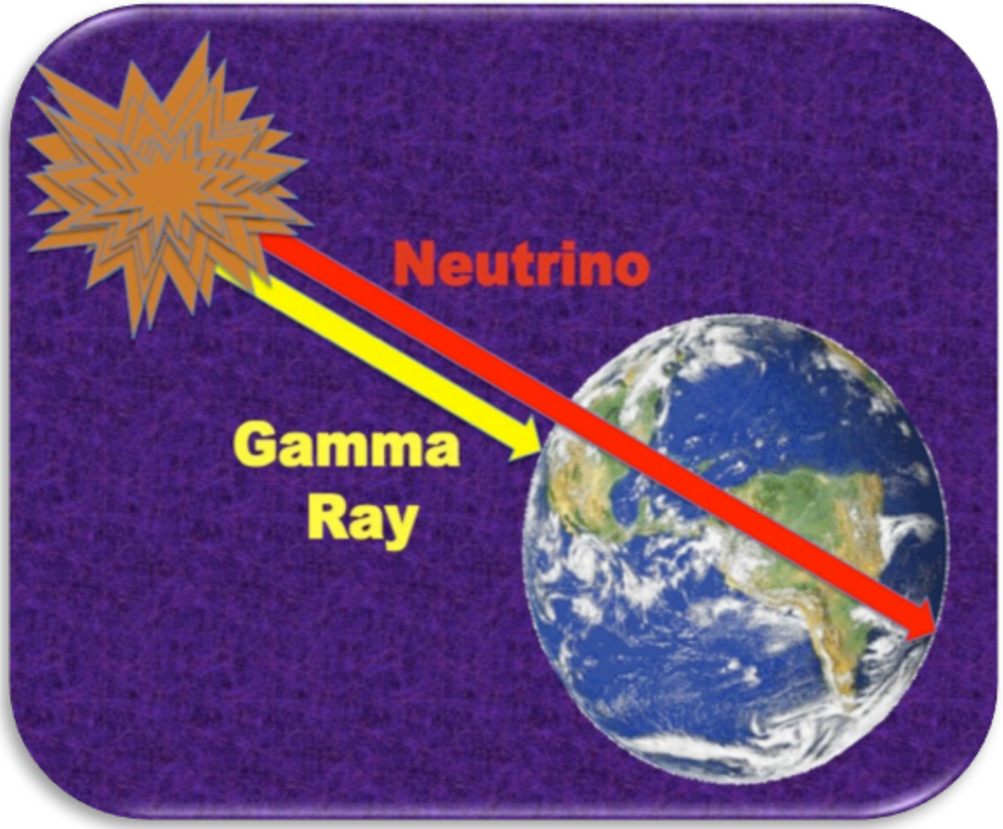
(aka: induced μ, throughgoing μ, upcoming μ, external μ, tracks)

Range of high energy muons is R_μ~km

(continuous energy loss below 0.5 TeV, then catastrophic losses)

The detectors had linear size L<< km, but,

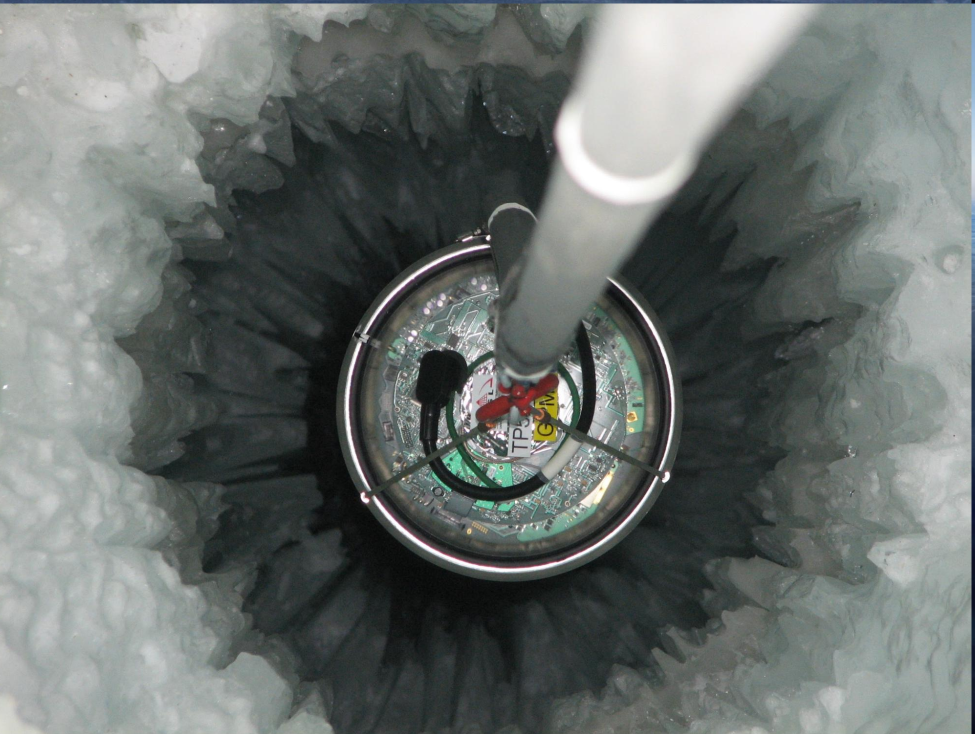
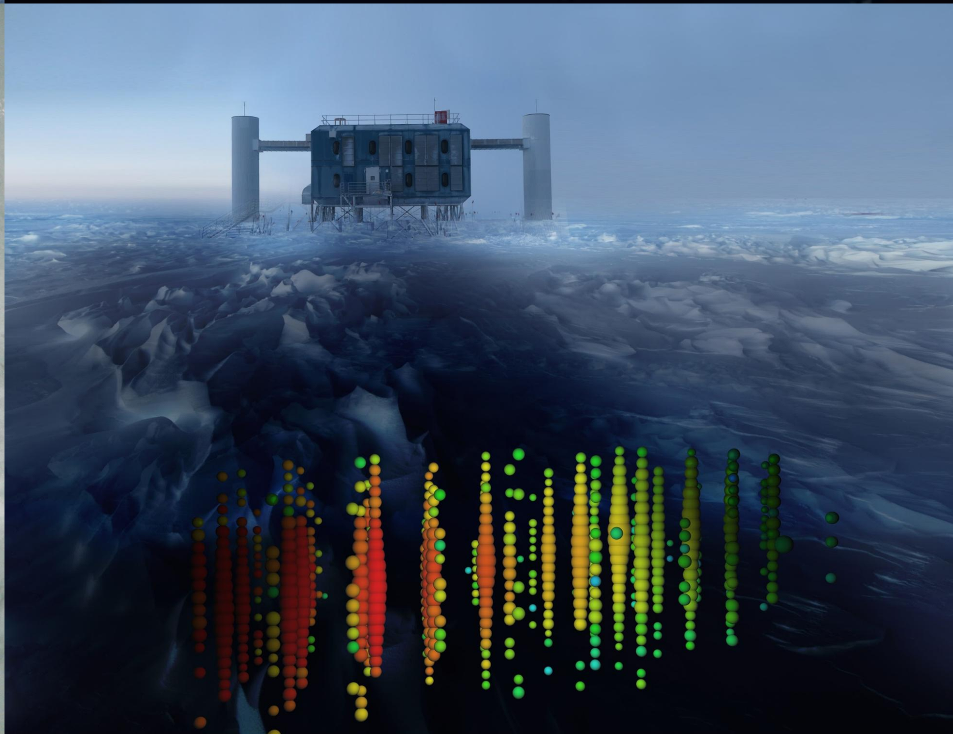
Volume for external muons is $\sim R_\mu \times L^2 >> L^3$



A funny consequence

The neutrino telescopes based on the observation of passing muon/track signal have a very curious and almost paradoxical feature: they observe the opposite part of the sky, that we observe with conventional astronomy. E.g., in IceCube, the passing muons/tracks, that have been observed, come from the Northern sky!


ICECUBE 2013

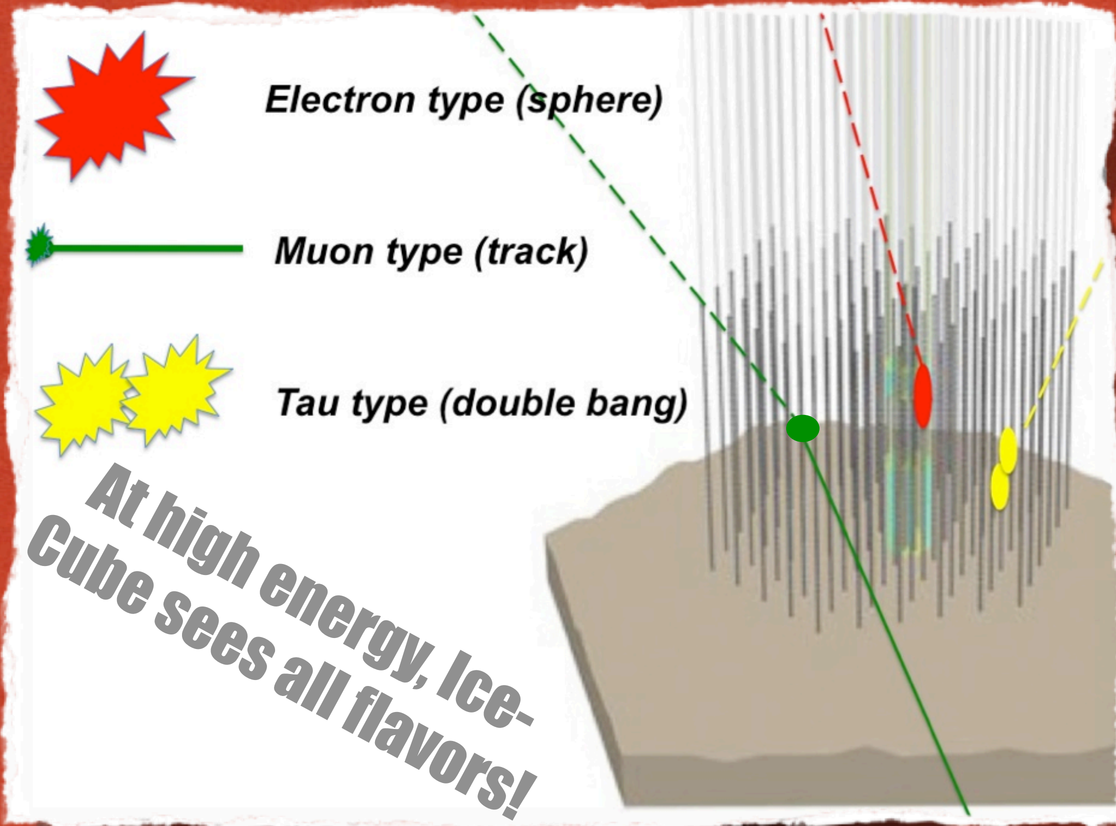
With increasing size, the concept of HE ν telescope changes

Suppose 1 ν interacts, and the detector has linear size L

- Volume for external muons is $\sim R_\mu \times L^2$
  (aka: induced μ, throughgoing μ, upcoming μ, external μ=tracks)

- Volume for internal events is $\sim L^3$
  (aka: contained vertex, starting events, high energy starting events=HESE)

When $L \sim$ km, as in Icecube, these rates become similar



THERE IS ANOTHER TECHNIQUE

THAT ALLOWS TO HUNT FOR UHE, NON-MUONIC NEUTRINOS

Summary of HE ν signals

TRACKS

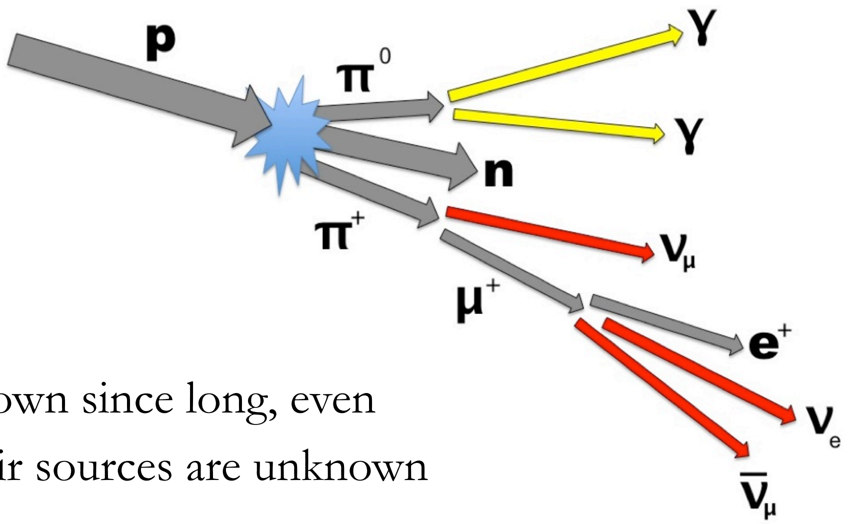
- Origin: external to the detector
- Direction: from below
- Flavor: only ν_μ

HESE

- Origin: internal to the detector
- Directions: above and below
- Flavor: all

Before looking at results and interpretations, let us spend a second on expectations

Expectations for neutrinos: The cosmic ray connection



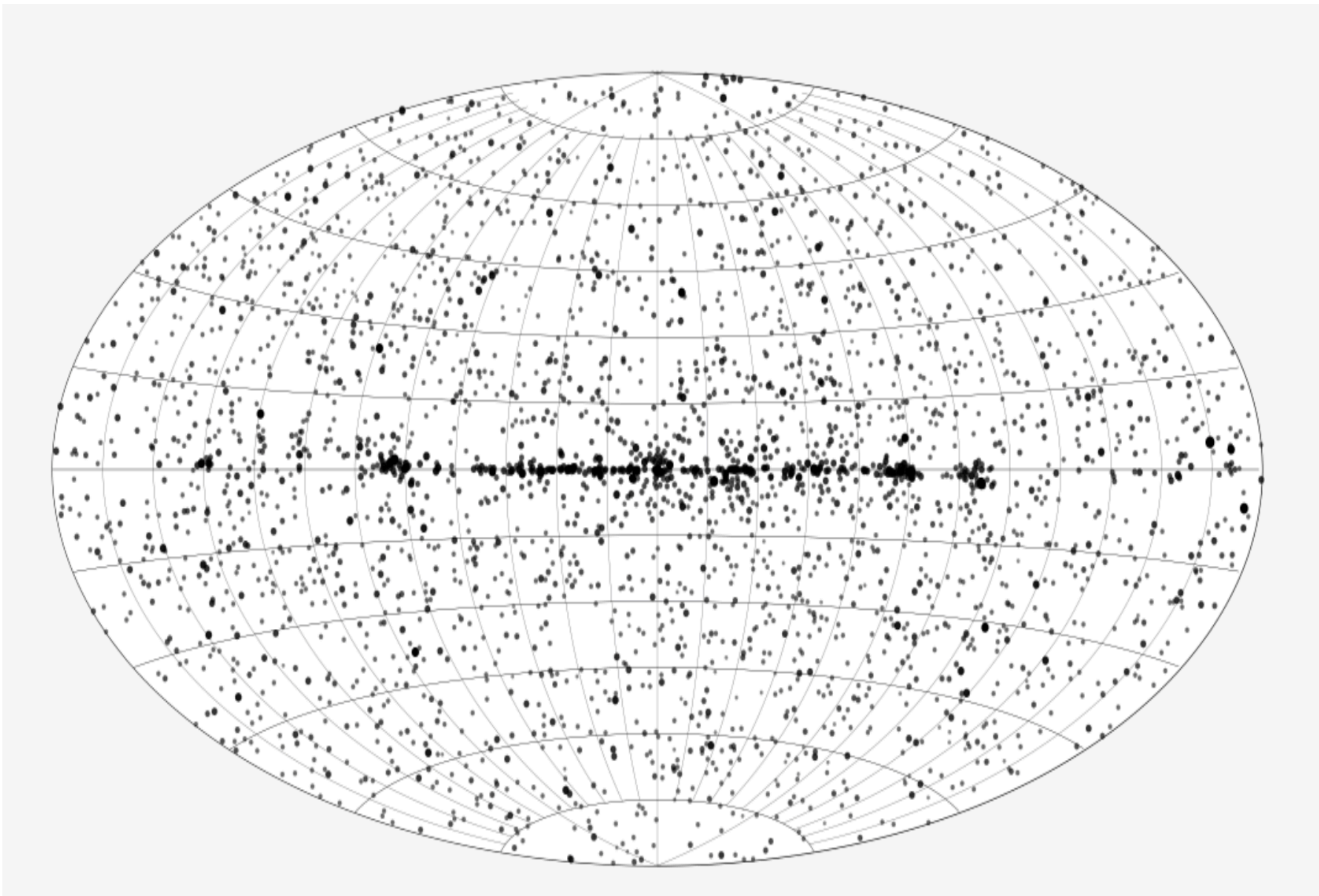
- Cosmic rays, galactic + extragalactic, are known since long, even if -- due to magnetic field deflections – their sources are unknown

- If their sources are surrounded by matter or γ-rays, collisions produce secondary particles. Neutral secondaries point to their sources and allow to make astronomy

- Neutrinos are hard to be observed, but neat. γ-rays are produced in similar amount, *plus* another contribution due to electromagnetic processes

- The γ-rays below 100 GeV can reach us also from extragalactic distances. Let us begin to have a look at the γ-rays sky in this energy region

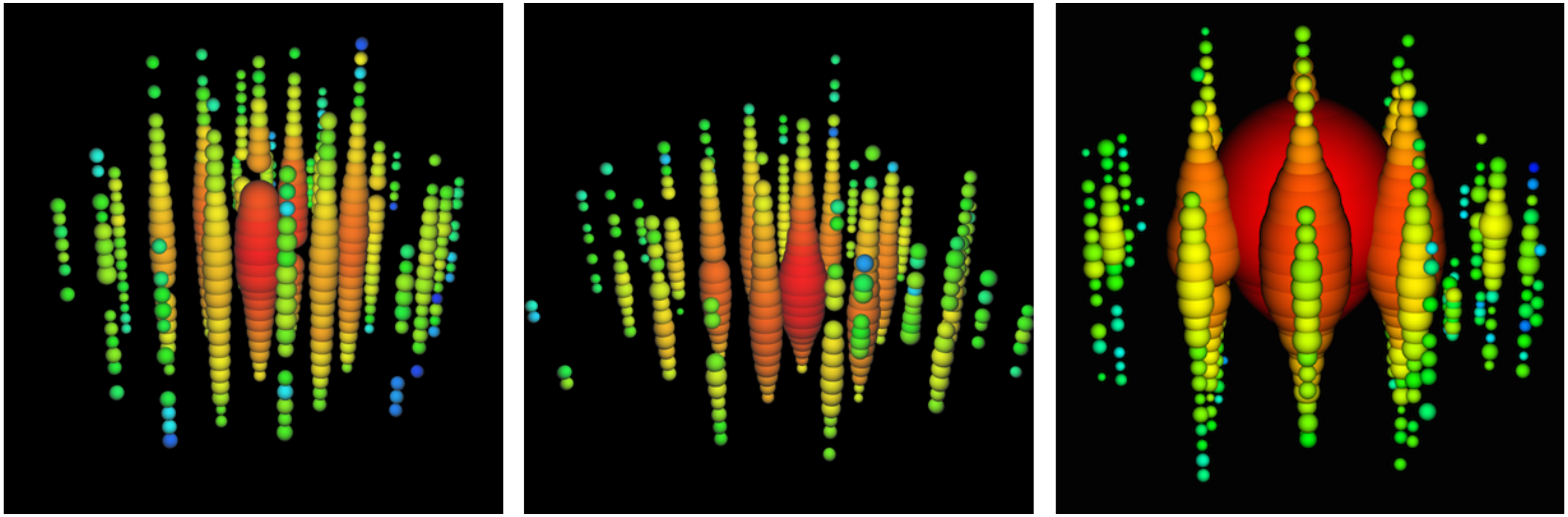
Gamma rays in 1-100 GeV energy region: 3rd catalogue of Fermi-LAT



Here we discuss: The population of the neutrinos seen by IceCube, its description as a power law, contrasting information, a new hypothesis

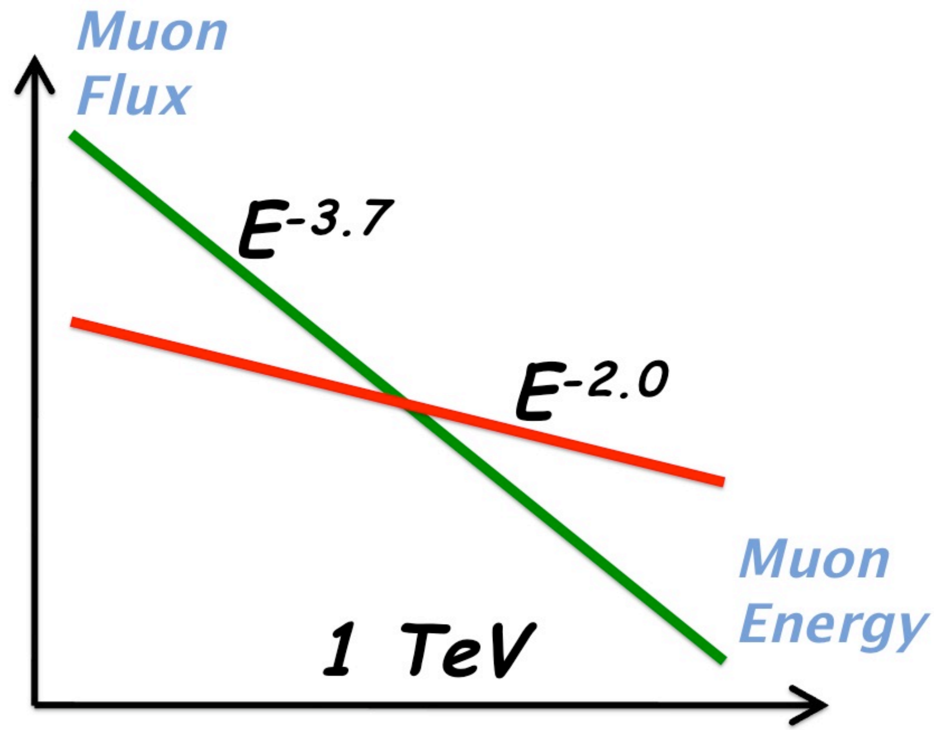
ENERGY SPECTRUM

The new population of neutrinos seen by IceCube by means of high energy starting events (HESE)



Dreams get almost true

The dream, illustrated in the figure was to find, above TeV and from some direction, µ-induced neutrinos with spectrum harder than the one of atmospheric neutrinos



It worked, but not exactly as expected,

- Excess conspicuous at very high energies
- Excess discovered with HESE not with muon neutrinos: What about compatibility?
- No preferential direction of arrival; namely in first approximation isotropic
- The distribution is not E^{-2}

Discussion of these (and other) points is needed!

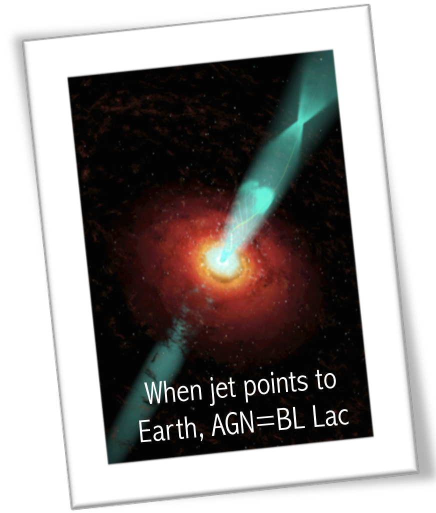
The power law hypothesis

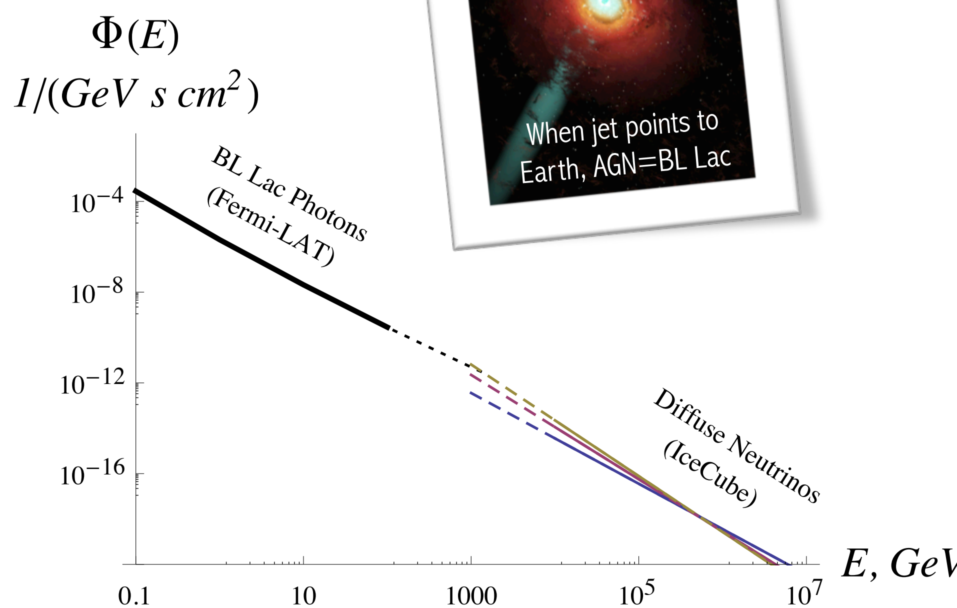
It is generally <u>assumed</u> that the observations of IceCube can be summarized by power laws. Here we use those of Gaisser 2015

Compare with *integrated* BL Lac emission, that dominate the γ ray sky at several GeV.

The common origin (pions) implies that the the neutrino flux cannot exceed the γ-ray flux. This constrains the distributions

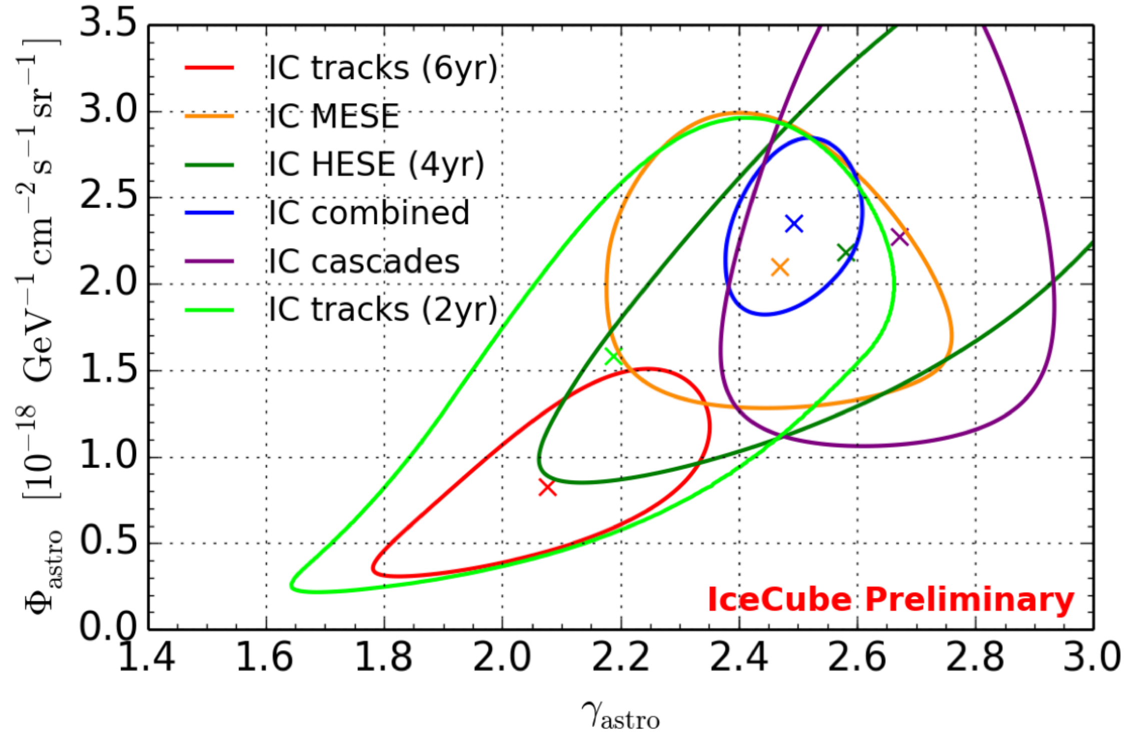
We conclude that, if neutrino spectra are power law, their slope cannot be too steep at all energies. A power law $E^{-2.0}$ is OK, whereas a power law as $E^{-2.5}$ is not



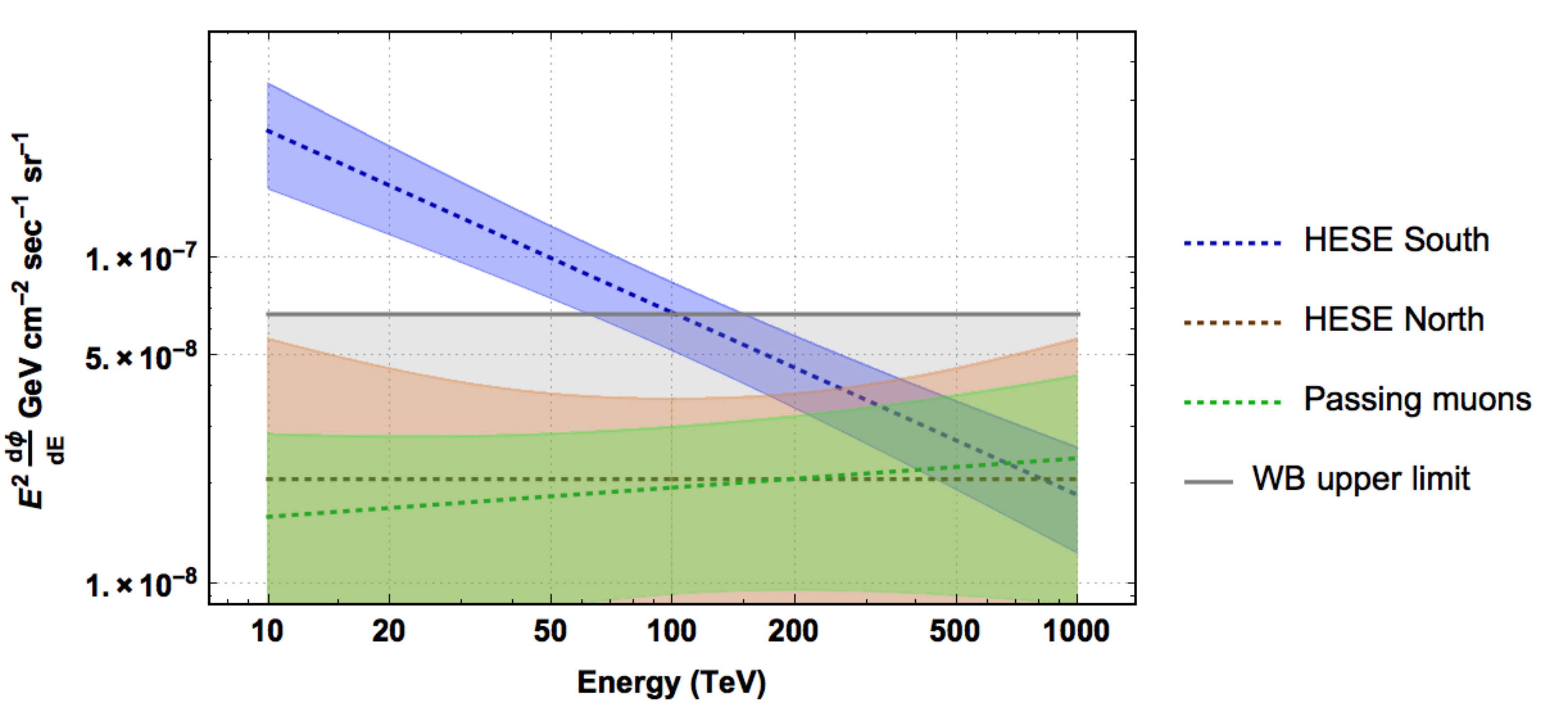


Esmaili, Palladino & FV, 2015

Are ***tracks*** inconsistent with HESE? Or maybe we use an oversimplified interpretation?

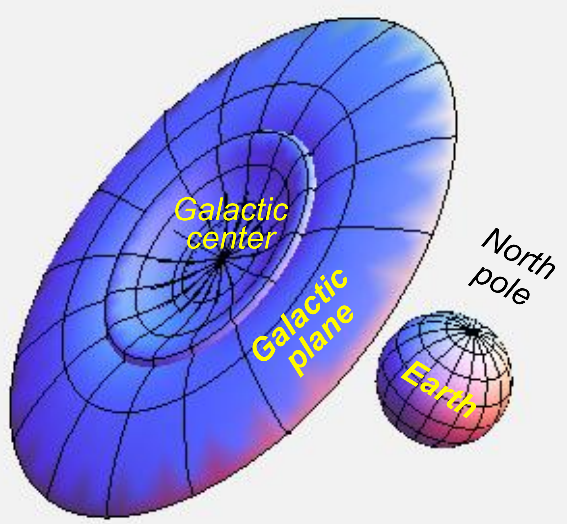


Waxman-Bahcall bound violated by cosmic neutrinos from Southern sky?



Palladino & FV, 2016

A different hypothesis for the HE ν



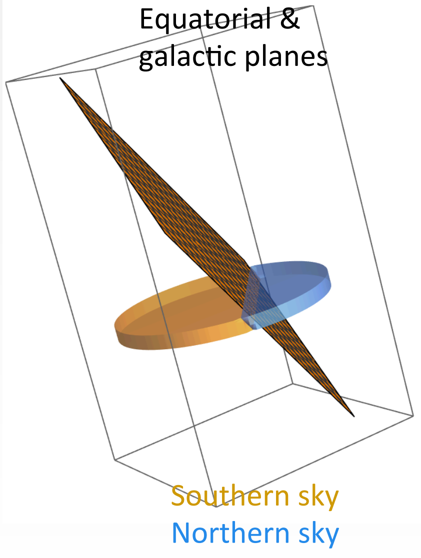
<u>There is an extragalactic component with E^{-2} spectrum as initially expected</u>

<u>But there is also a galactic component, that is seen in Southern sky</u>

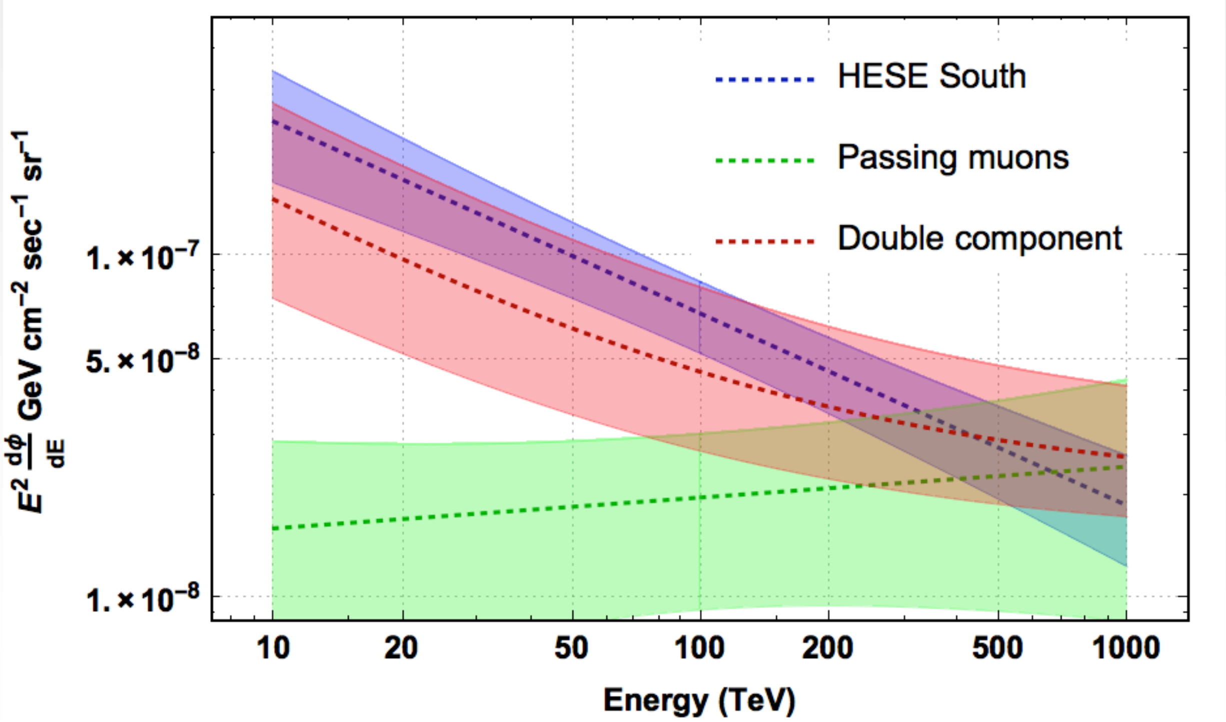
=> Tracks see the extragalactic component

=> HESE South sees both components

Palladino & FV, 2016



A double power law reproduces the observations rather well

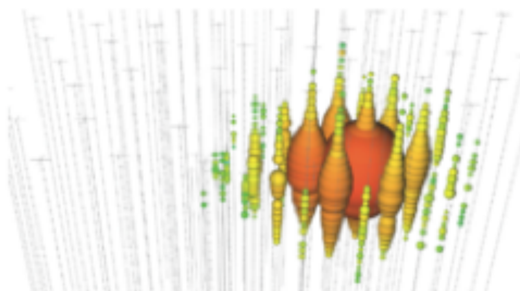


Palladino & FV, 2016

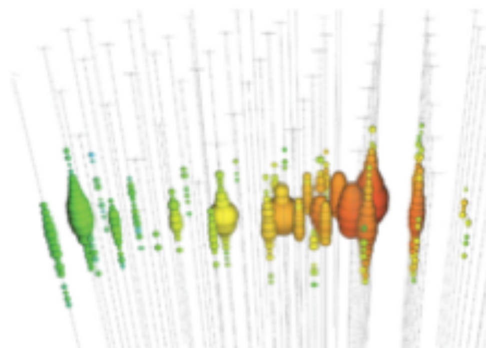
Here we discuss: Event topologies, oscillations, expectations for cosmic neutrinos, comparison with data, future tests -- tau & Glashow

NEUTRINO FLAVOR

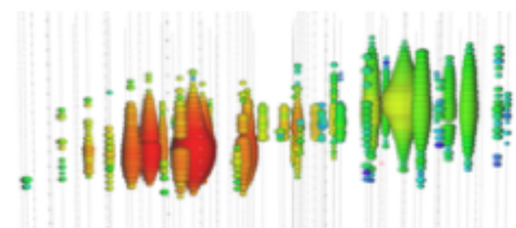
Various types of observable events



cascade signature

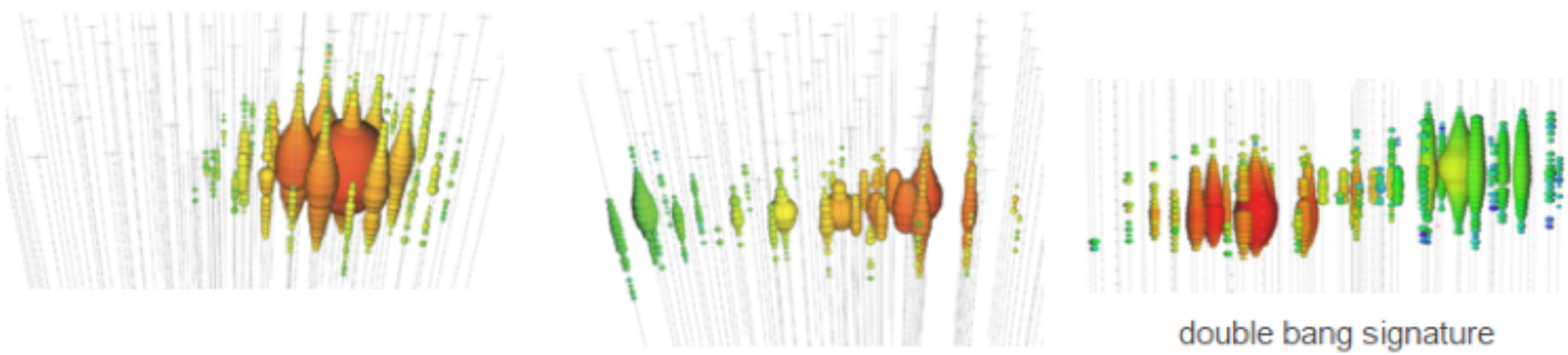


track signature



double bang signature

Various types of observable events

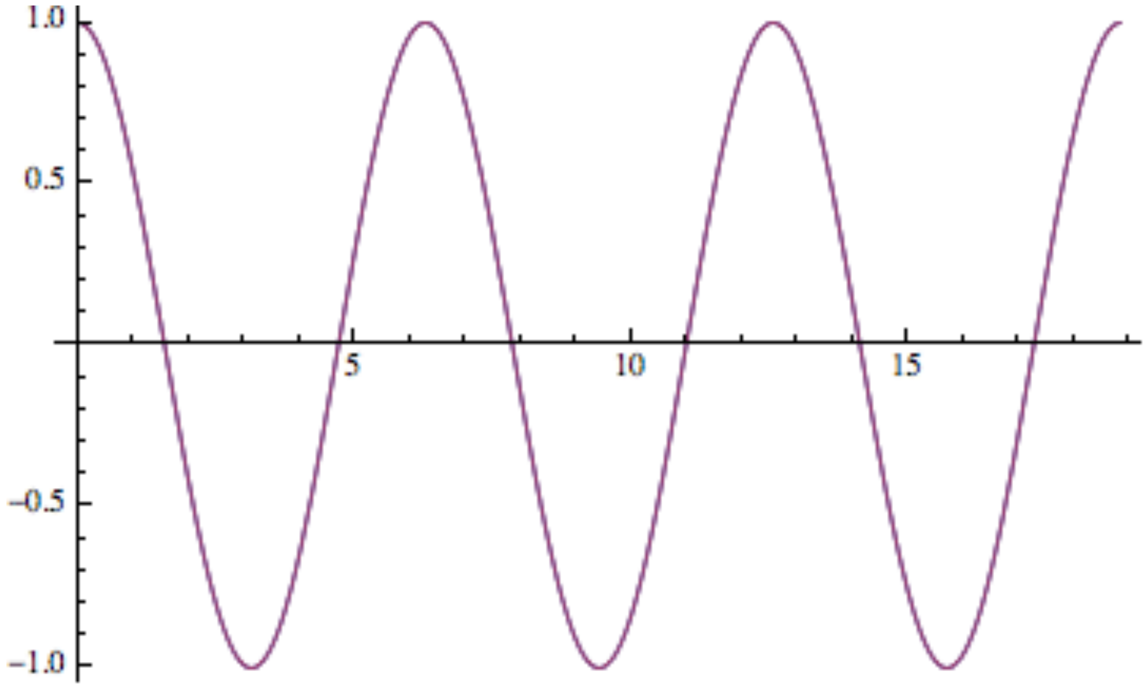


cascade signature — track signature — double bang signature

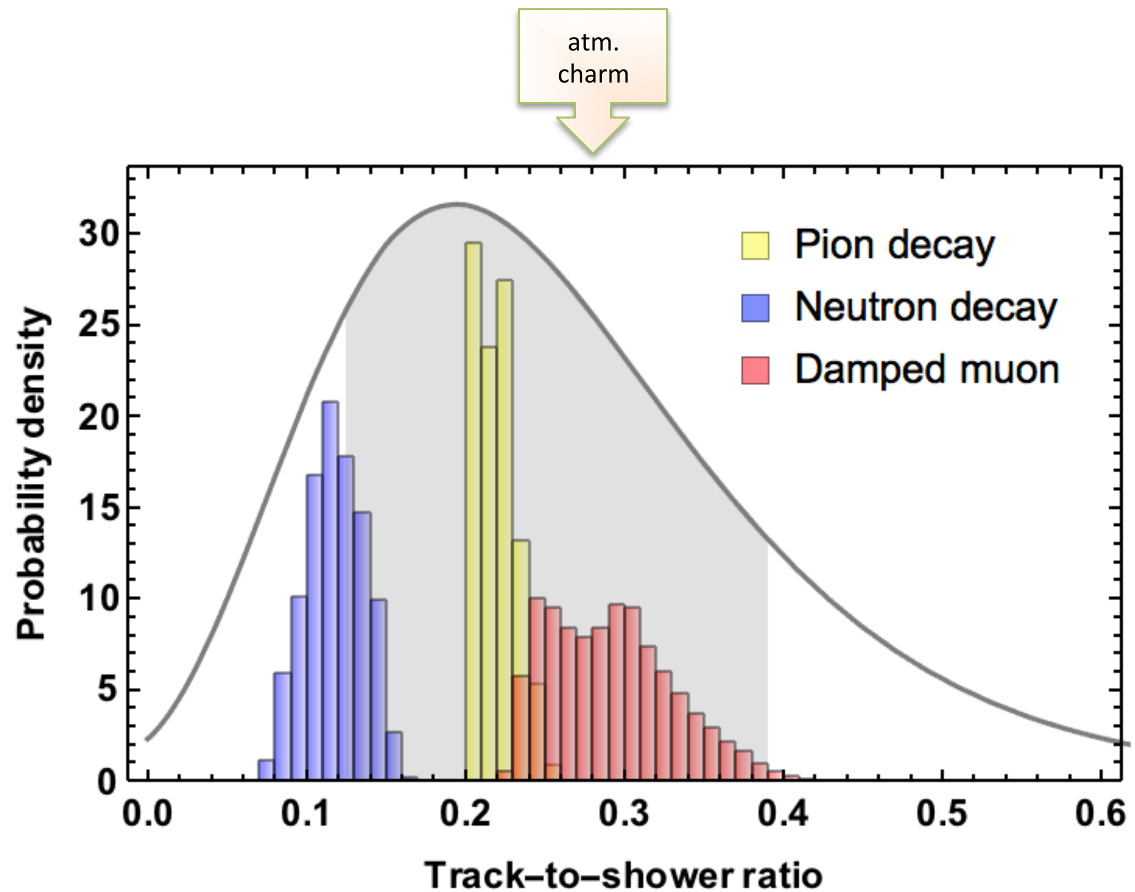
Mostly ν_e — Mostly ν_μ — Mostly ν_τ

Neutrino oscillations

- Relevant and proved (Pontecorvo 57-67; Nobel in Physics, 2015)
- The parameters: 2 differences of mass squared, 3 mixing angles, 1 phase (Capozzi et al 2016)
- For us "averaged" oscillations apply (Gribov Pontecorvo 1969) that depend upon 3 parameters only (Palladino Vissani 2015)



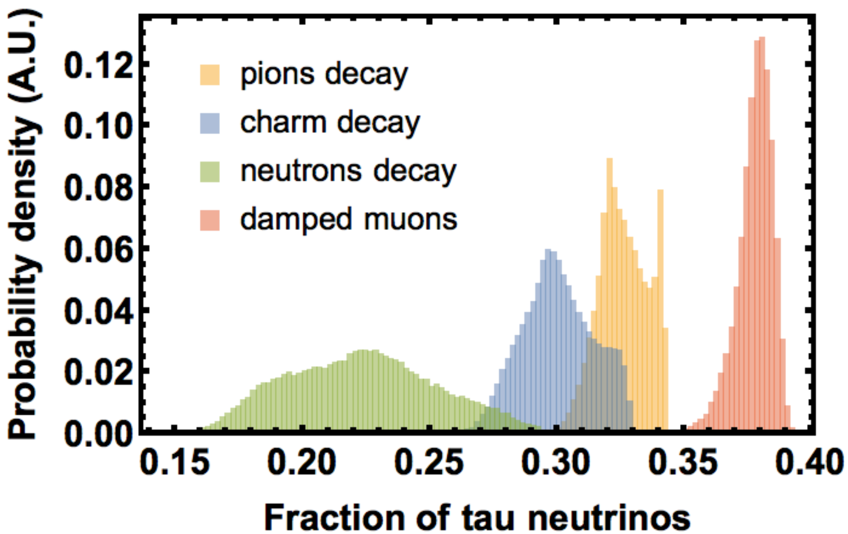
Suppose $|\nu_\mu>$ is a superposition of two waves with different mass and thus different velocities. They are initially in phase. During the time they will go counter-phase, then again in phase, etc. It can be interpreted saying: initially we have $|\nu_\mu>$; then we have $|\nu_\tau>$; then again $|\nu_\mu>$…. The averaged regime is when we are very far from the production site.



TRACK-TO-SHOWER RATIO

Expectations including oscillations from 3 mechanisms (pions + 2 speculative ones) as compared with 4 years data: 1 σ region in gray

Tau events - or "cosmic Opera"



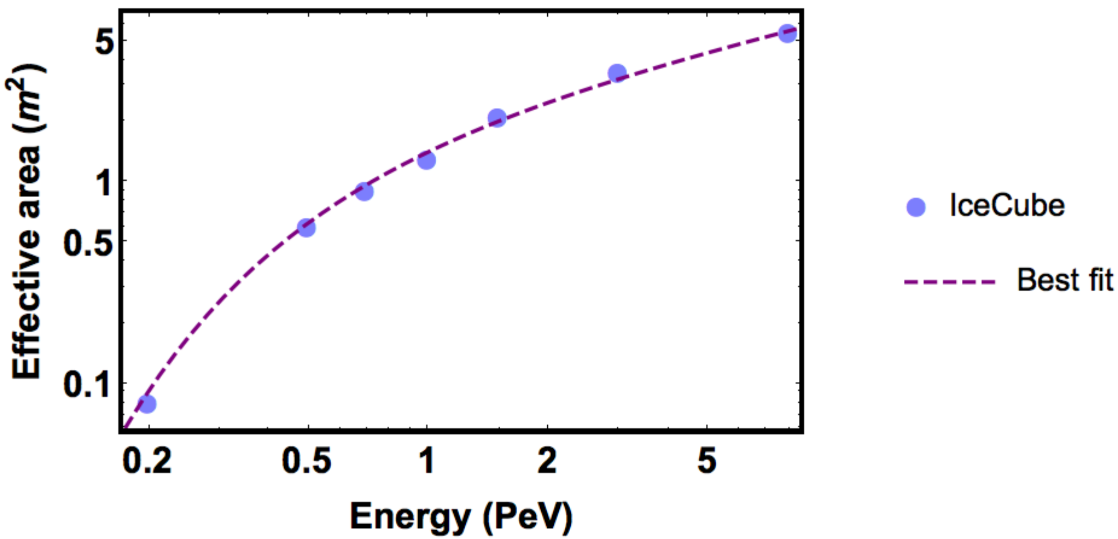
* Cosmic tau neutrinos are unavoidable (Learned Pakvasa 1995)

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

* At HE, tau yields a unique topology: double-bang (pulse) event.

Tau neutrinos observed → Cosmic origin proved

No such events observed in 3 years dataset.



A. Palladino et al, 2015

Expectations for IceCube

The "effective area" can be fit by product of the effective area to produce a tau times the probability that the two "bangs" are far enough. We expect about 0.1 events/year, half of them from the same region of energy where IceCube has collected events already (see next slide)

Glashow resonance

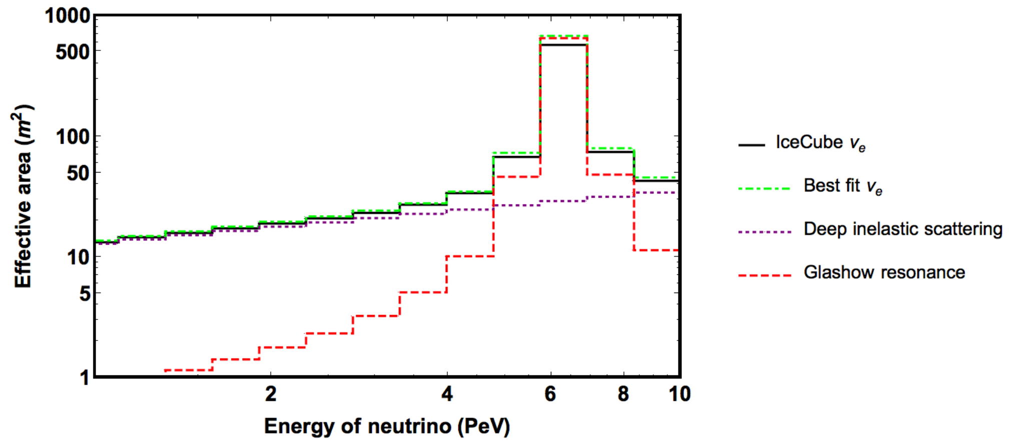
One of the first signals of the W boson, considered by Glashow in 1960, is

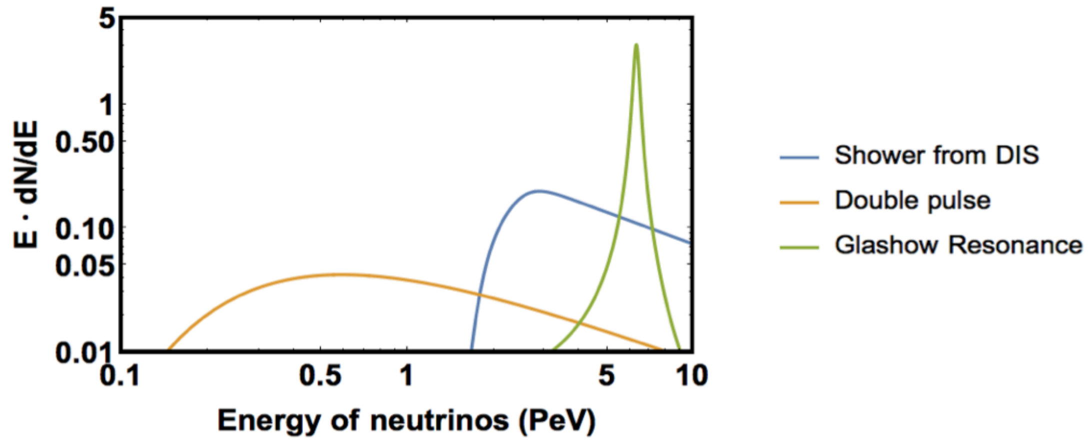
$$\text{anti } \nu_e + e^- \rightarrow \text{hadrons}$$

We know today that this produces a signal at 6.3 PeV, not that far from the highest energy event seen by IceCube

Thanks to oscillations, the signal exists *whatever* the production mechanism

Unless spectrum is depleted at 6.3 PeV we are going to see it in 10 yr or so

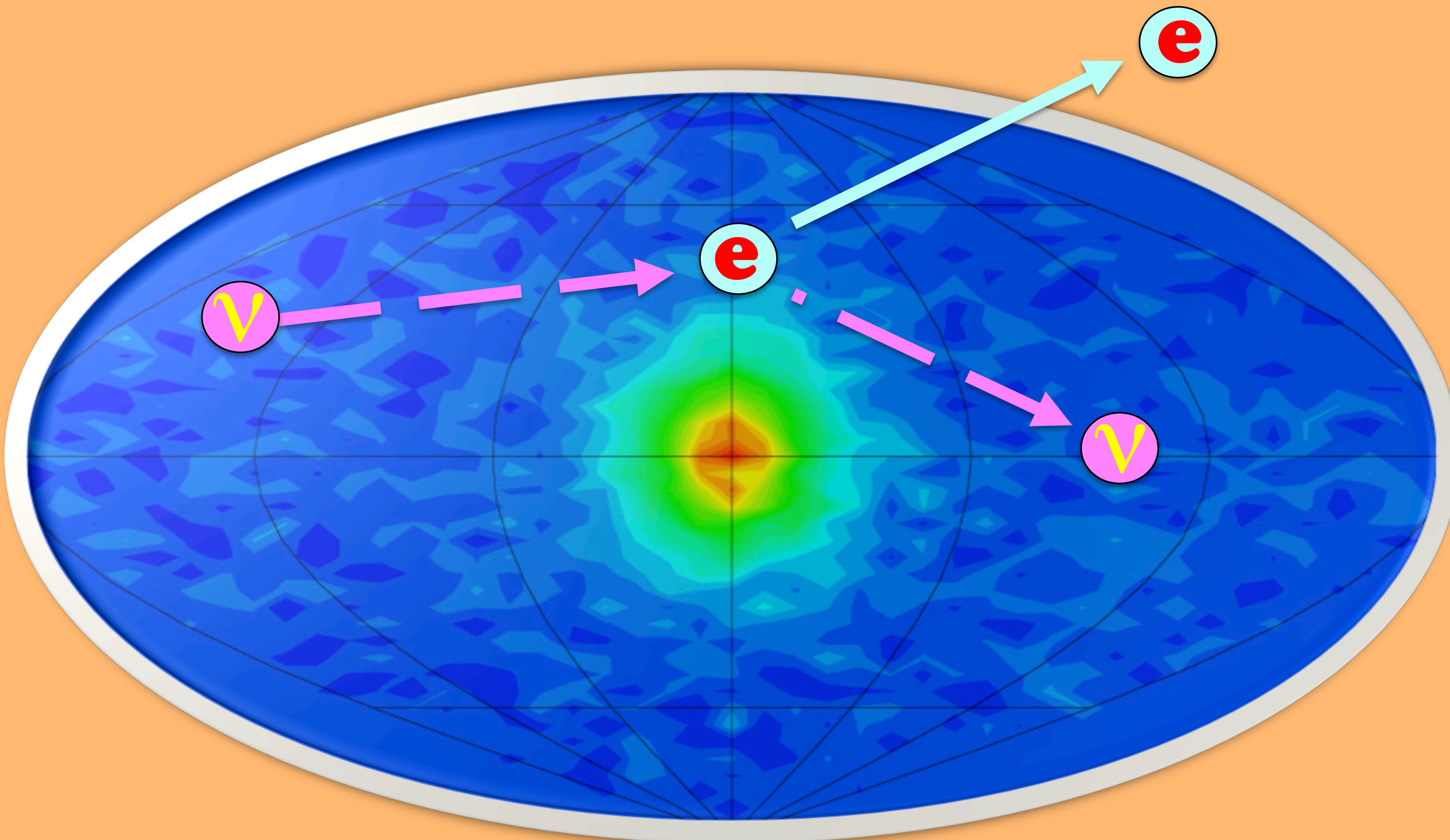




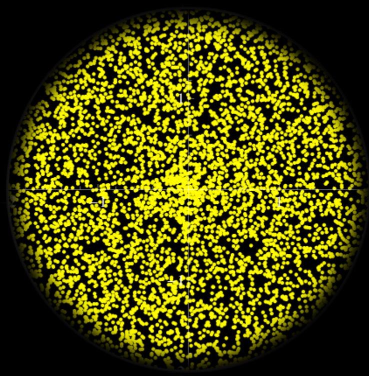
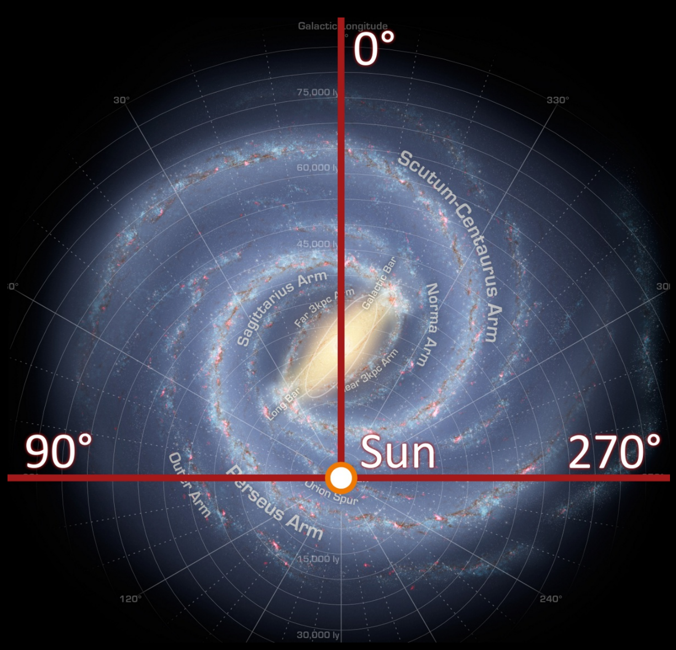
Here we discuss: Principles of neutrino astronomy, isotropic distribution (or maybe not) of IceCube sky map, what do we expect from Sgr A*?

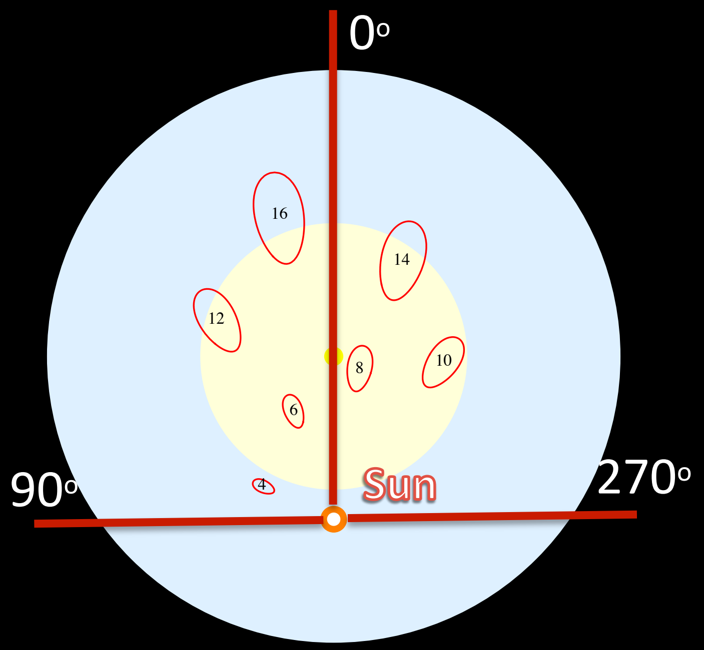
NEUTRINO ASTRONOMY

Solar neutrino astronomy

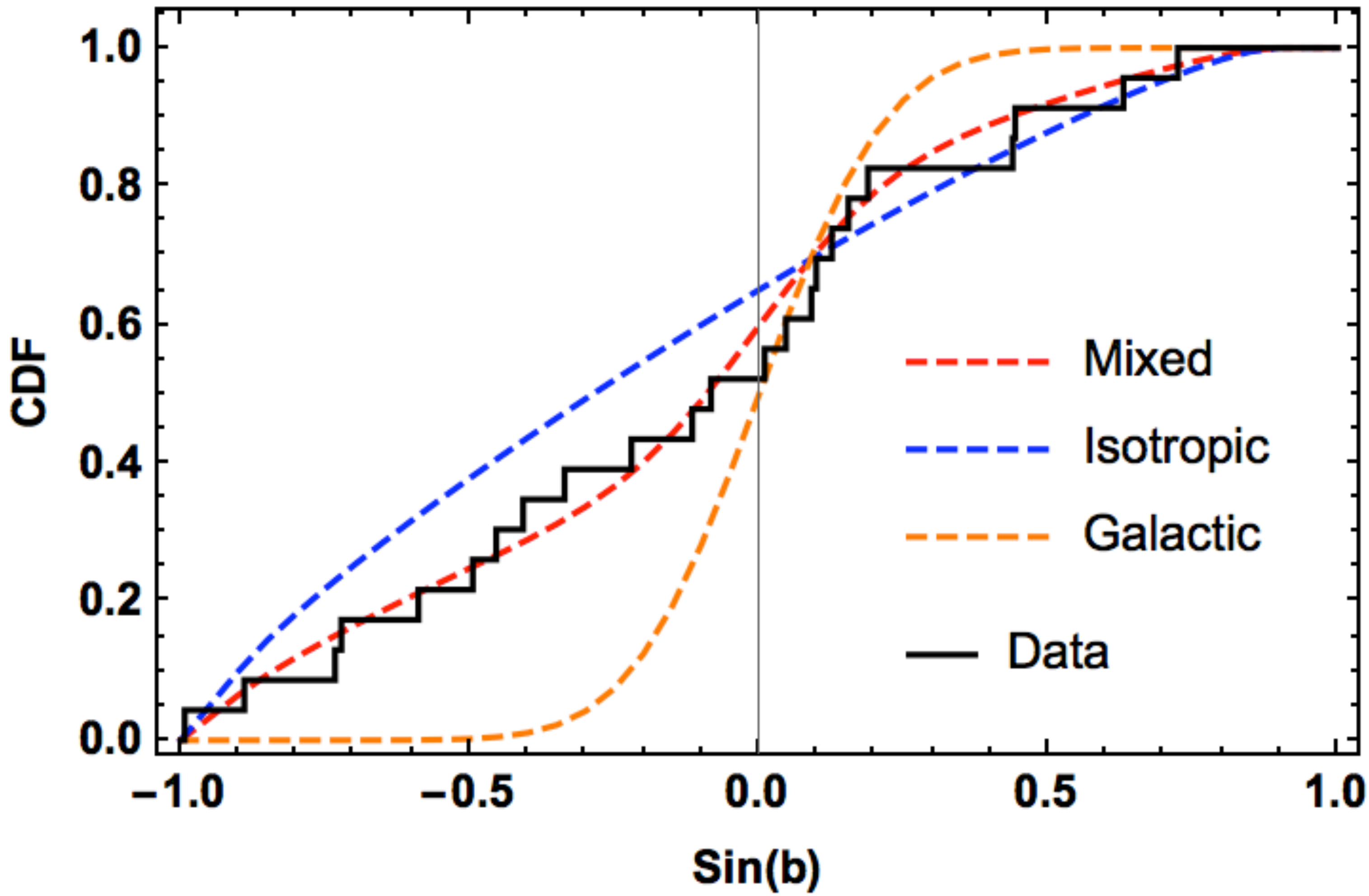


Supernova neutrino astronomy

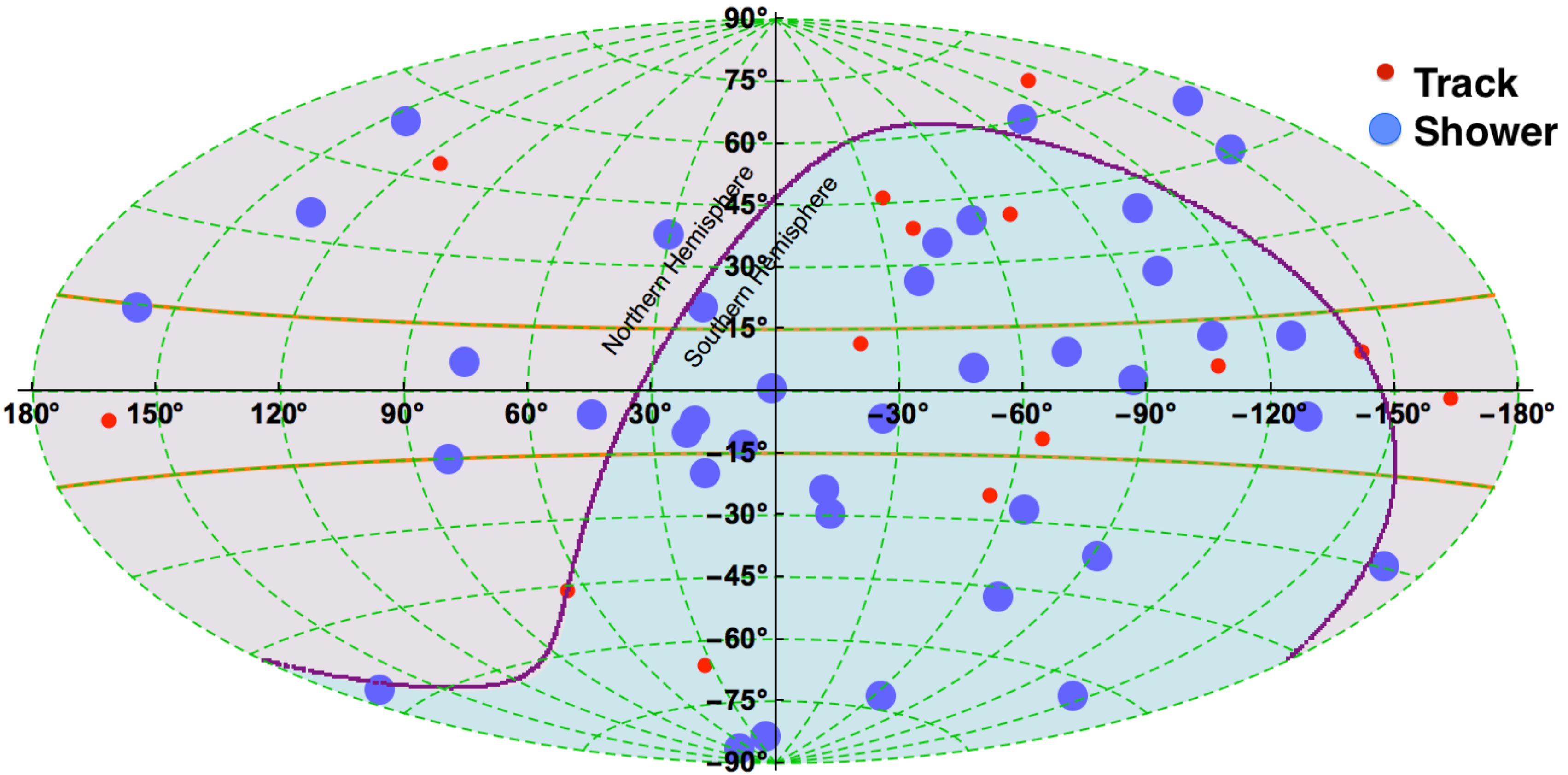


Tests of three hypotheses



Palladino and FV, 2016

HESE Events in the Galaxy



Palladino and FV, 2016

Sgr A* after HESS

(beware, this last slide is purely theory)

HESS gamma ray detector has measured an intense emission from Sgr A* and its surrounding.

It was shown that this emission is compatible with *unbroken* power law emission.

Assuming the hadronic origin, high energy neutrinos could be observable from Sgr A* !!!

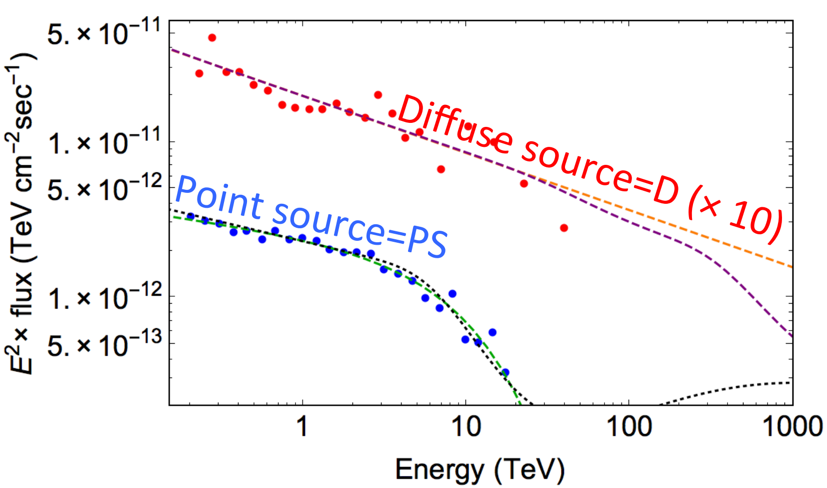


Table II. Spectral parameters from γ-ray HESS data: the search region (Point Source or Diffuse), the spectral index Γ, the flux normalization ϕ_0 in units of 10^{-12} TeV^{-1} cm^{-2} s^{-1} and the energy cut-off E_{cut} in TeV. Then the expected number of neutrinos per year from current neutrino detectors.

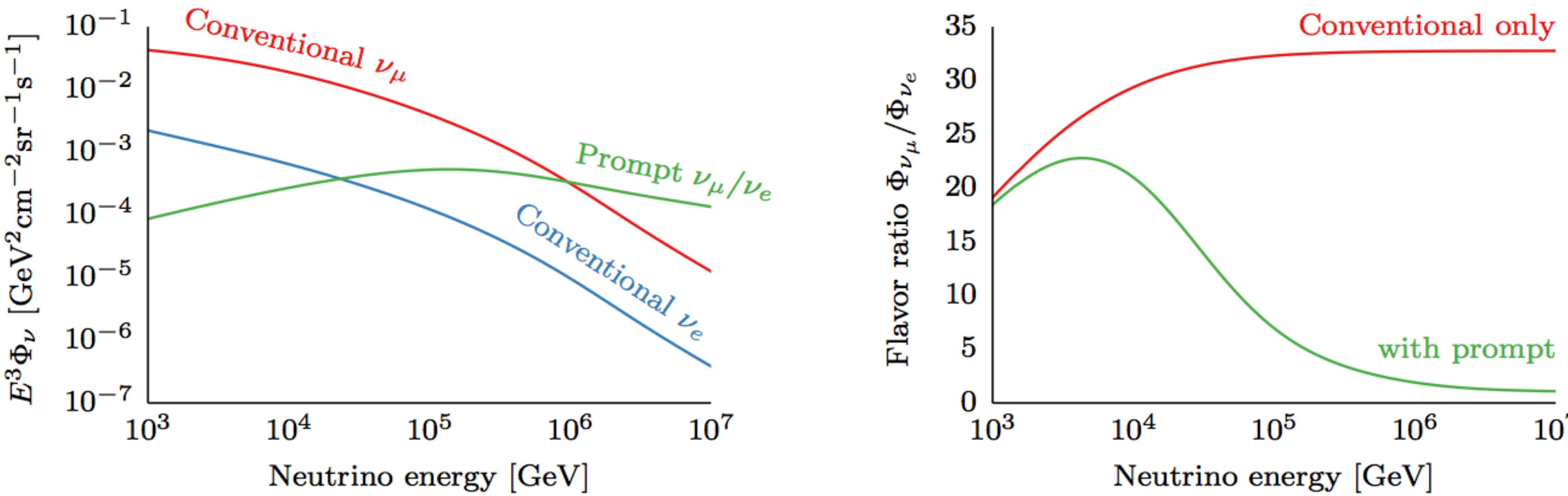
	γ-rays			$\nu_\mu + \bar{\nu}_\mu$		
	Γ	ϕ_0	E_{cut}	$R^{ANTARES}$	R^{ARCA}	$R^{IceCube}$
PS	2.14	2.55	10.7	6.56×10^{-3}	1.45	1.50×10^{-6}
PS	2.04	2.92	13.6	1.01×10^{-2}	2.05	6.68×10^{-6}
PS	2.24	2.18	7.8	4.14×10^{-3}	1.00	2.03×10^{-7}
D	2.32	1.92	-	1.31×10^{-2}	1.96	2.39×10^{-3}
D	2.20	2.21	-	2.23×10^{-2}	2.97	5.96×10^{-3}
D	2.44	1.63	-	7.93×10^{-3}	1.34	9.53×10^{-4}
DC	2.32	1.92	400	1.10×10^{-2}	1.80	7.41×10^{-4}
DC	2.32	1.92	600	1.15×10^{-2}	1.84	9.64×10^{-4}
DC	2.32	1.92	2900	1.26×10^{-2}	1.93	1.77×10^{-3}

Celli, Palladino & FV, 2016

Overview

- The first signal of HE neutrinos has been seen. The era of HE neutrino astronomy is beginning
- Still we want to understand better spectrum, angular distribution, flavor
- Many tests are possible and will be done. A lot of progress will come still from IceCube
- Growing interest (or even need) for an independent experiments

Thanks!



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.**

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

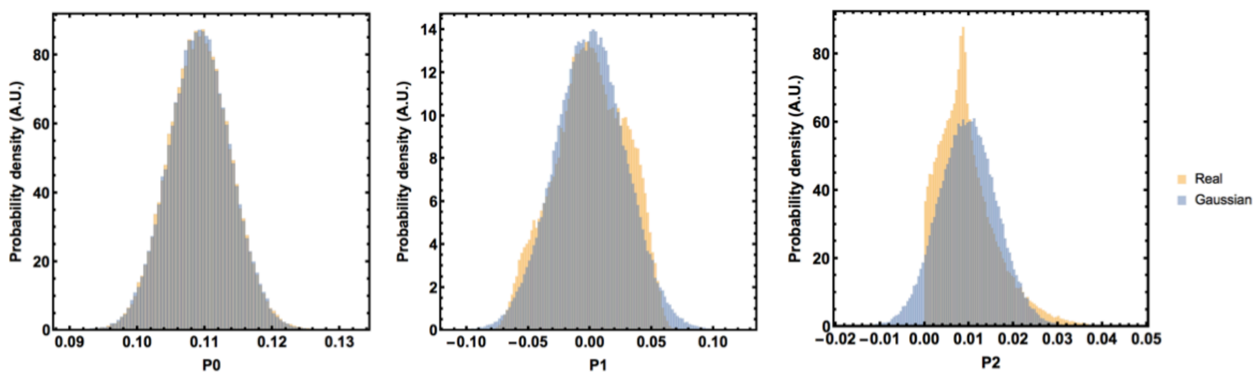
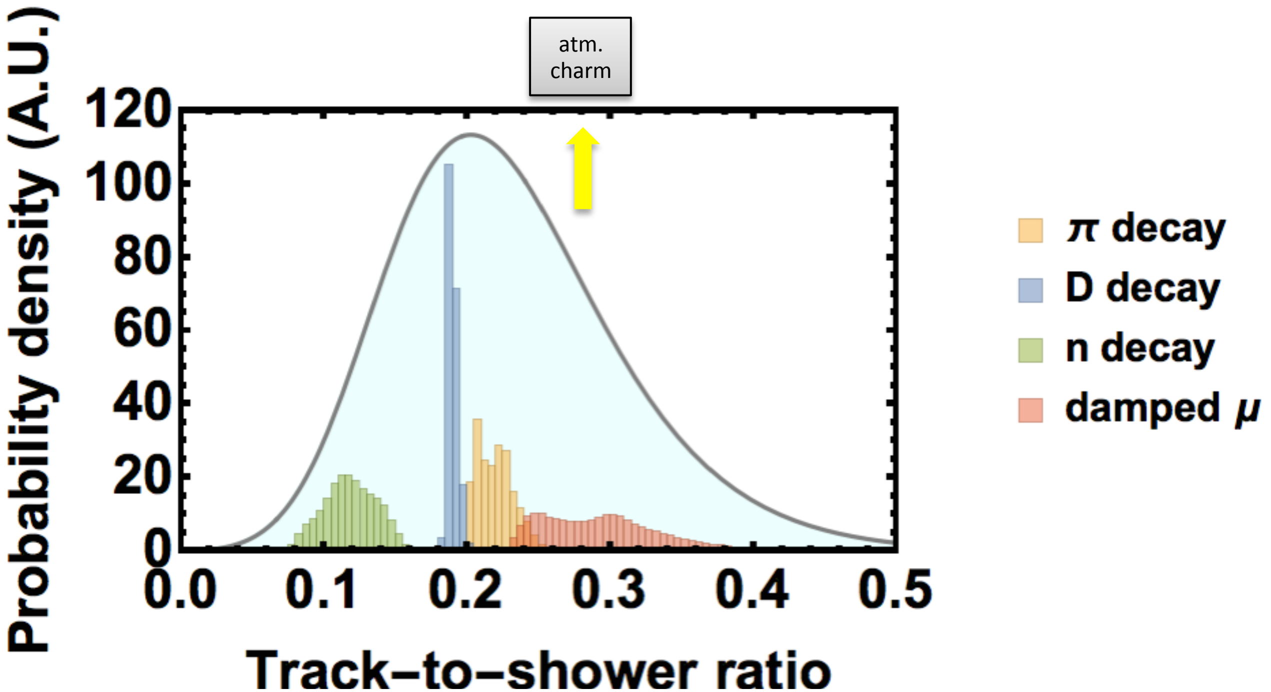


Figure 1: *Distribution of the natural parameters P_0, P_1 and P_2, due to the uncertainties in the mixing angles and the phase of leptonic CP violation.*

Palladino et al, , 1504.05238 **EPJC**

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

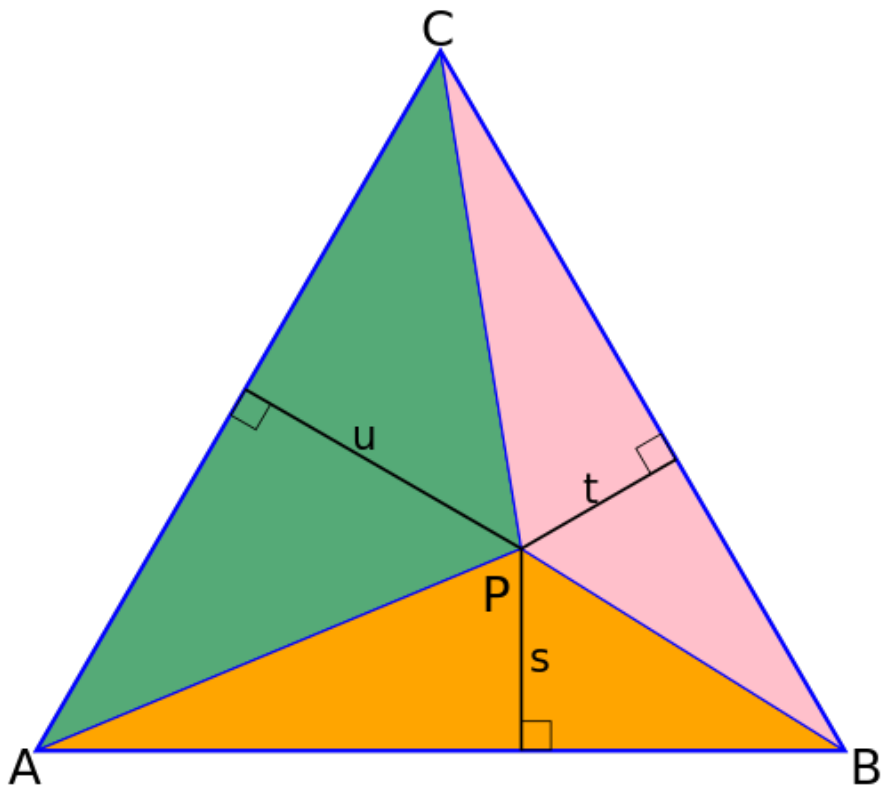
Consider the three fractions of flux (or flavor fractions) at Earth, e.g.,

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.

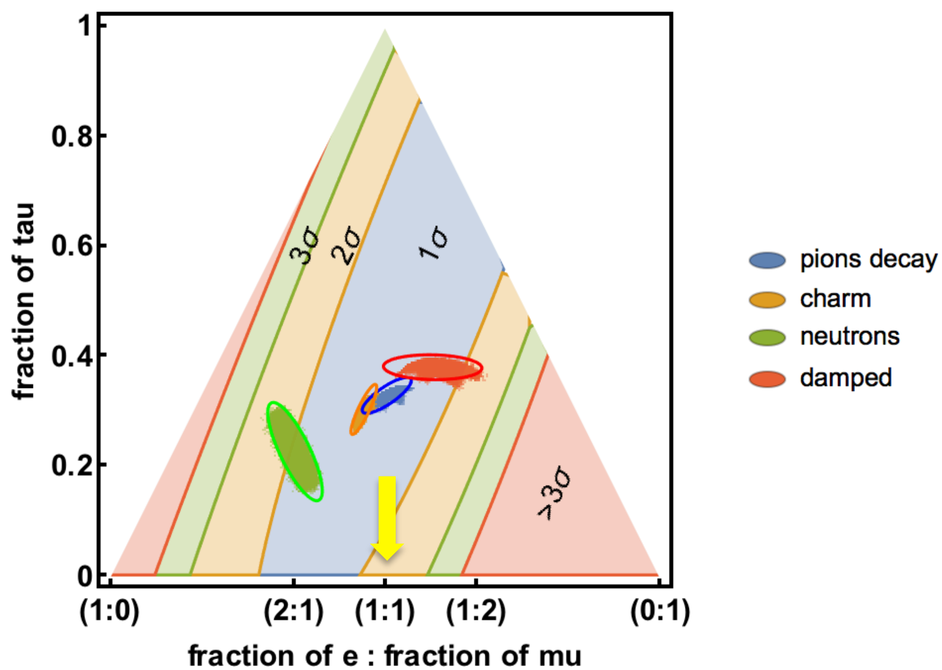
Note however that the flavor fraction at Earth is not directly observable; what we observe are event topologies.



[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 pupil of Galileo]

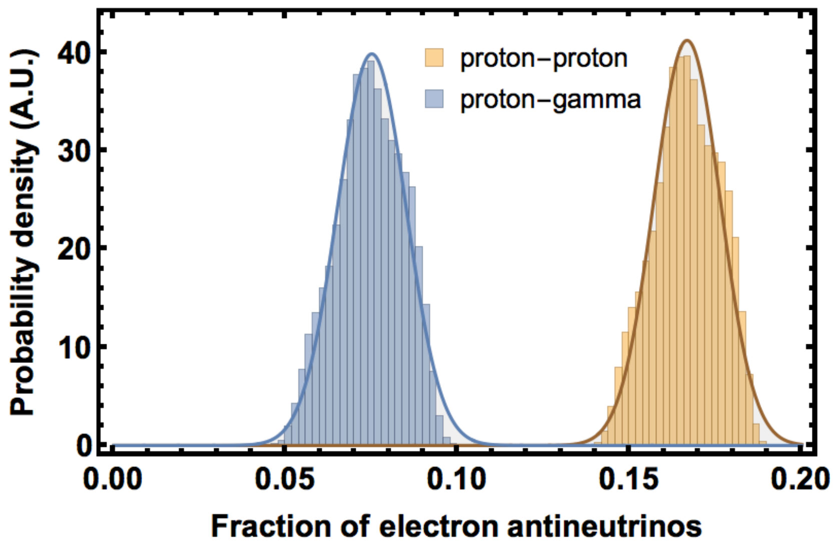
Predictions and observations [2/2]

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.

Glashow signal depends on sources



Palladino et al, PRL 114 (2015) 171101

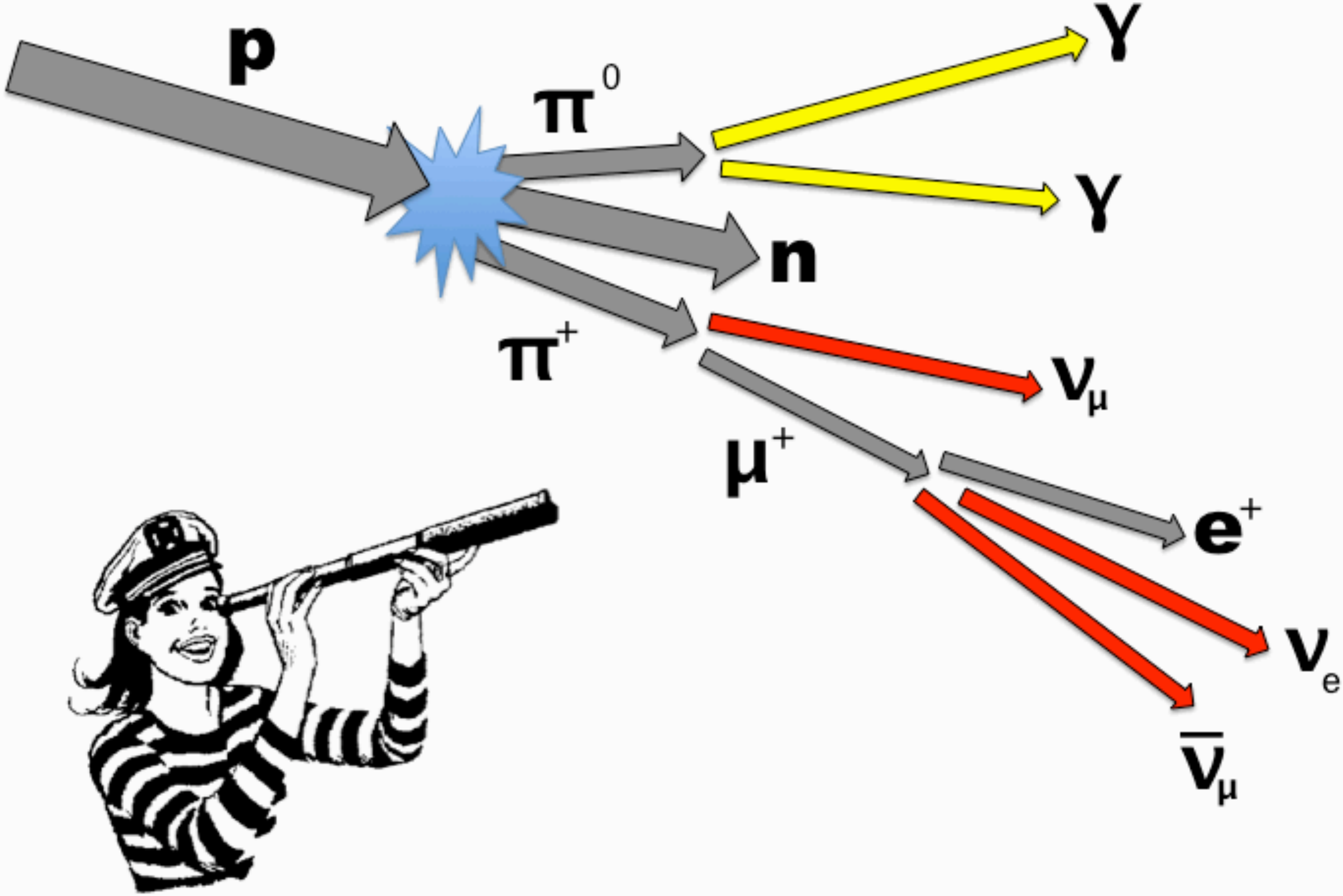
There is a difference between *pp* and $p\gamma$ sources:

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

(Berezinsky Gazizov 1977; 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



Thumb rules: $E(\pi)=E(p)/5$, $E(\gamma)=E(\pi)/2$ and $E(\nu)=E(\pi)/4$

Conversion $\gamma-\nu$

- 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 $1\pi^+$

The calculation of neutrinos is *easy*

Neutrinos and hadronic gamma are linear functions of the cosmic ray intensity, thus they are linked by a linear relation:

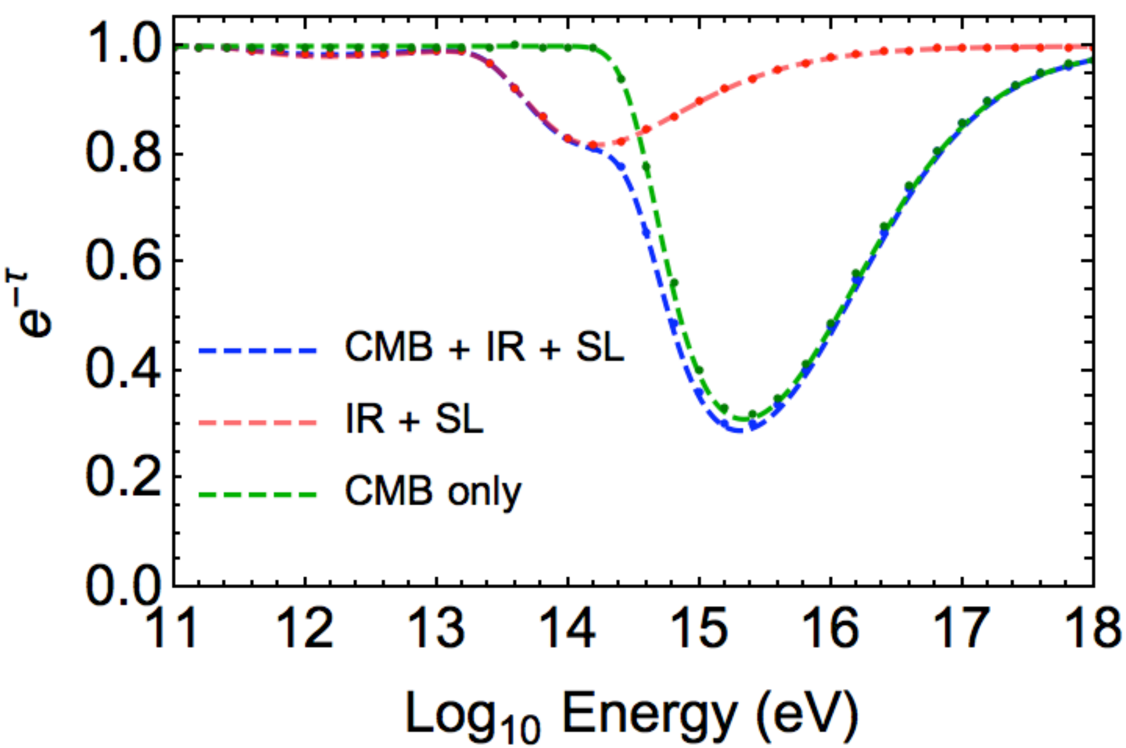
$$\Phi_{\nu_\mu}(E) = 0.380\,\Phi_\gamma\left(\frac{E}{1-r_\pi}\right) + 0.013\,\Phi_\gamma\left(\frac{E}{1-r_K}\right) + \int_0^1 \frac{dx}{x} K_\mu(x)\Phi_\gamma\left(\frac{E}{x}\right)$$

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

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

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

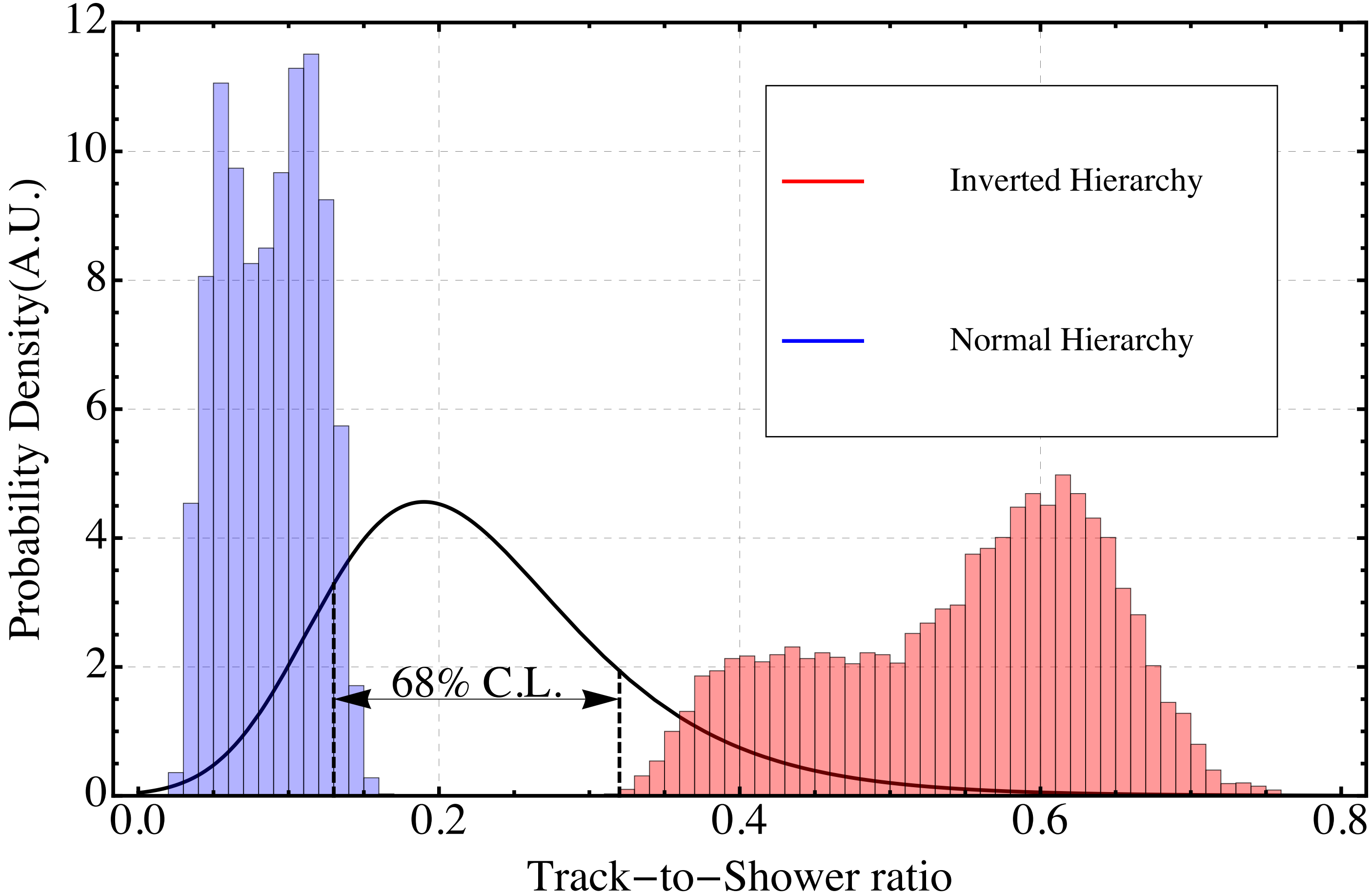
and similarly for antineutrinos; 3 flavor oscillations included Villante FV '08.



Photon absorption

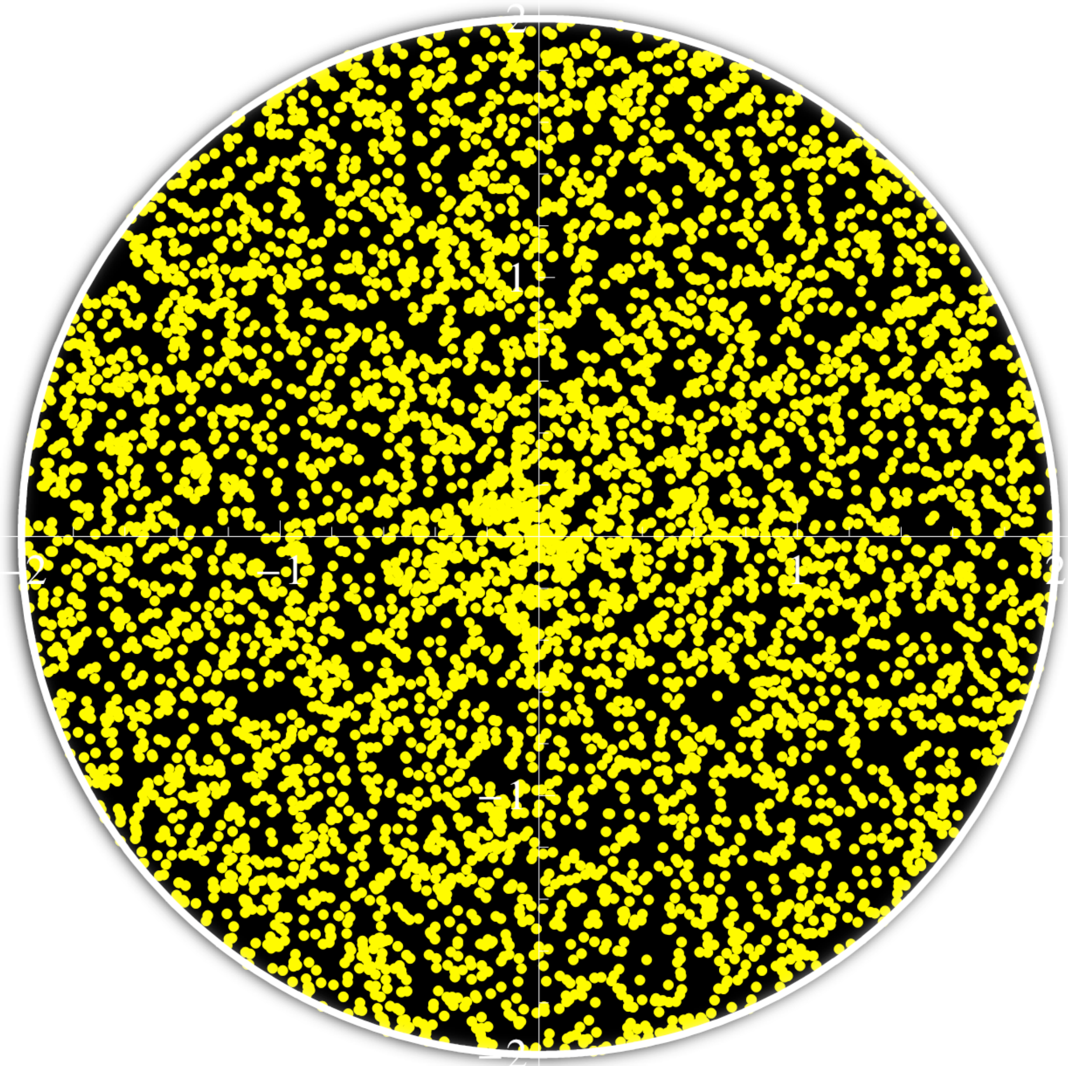
In this plot, we consider absorption of photons from the Galactic center due to standard contributions. For a very easy and efficient description of this phenomenon, see https://arxiv.org/abs/1604.08791

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



Pagliaroli et al, [1506.02624]

Direction of the events from a future supernova (simulation)



Origin of galactic CR

- *A fraction of SNR's kinetic energy can compensate the galactic CR loss.*
- *A Hp consistent with Fermi-LAT observations of W44 and W28.*
- *(even if a full theory of CR acceleration is still missing).*

$$V_{cr}\, n_{cr} / T_{cr} = 0.1 \times E_{sn} / T_{sn}$$

as we plug typical values:

V_{cr} =pi R^2 H
(R=15kpc, H=5kpc)
n_{cr} =1 eV/cc
T_{cr} =50 Myr

E_{sn} =10^{51} erg
T_{sn}=30 yr

(Ginzburg–Syrovatskii)

Something alike for the extragalactic CR

- 1,000 GRB per Gpc^3 per year injecting 10^{51} erg
- 150 AGN per Gpc^3 releasing $2x10^{44}$ erg/s
- (i.e., as many CR as the e.m. energy output)

$$n_{uhecr} / T_H = 10^{45} \text{ erg/Mpc}^3\text{/yr}$$

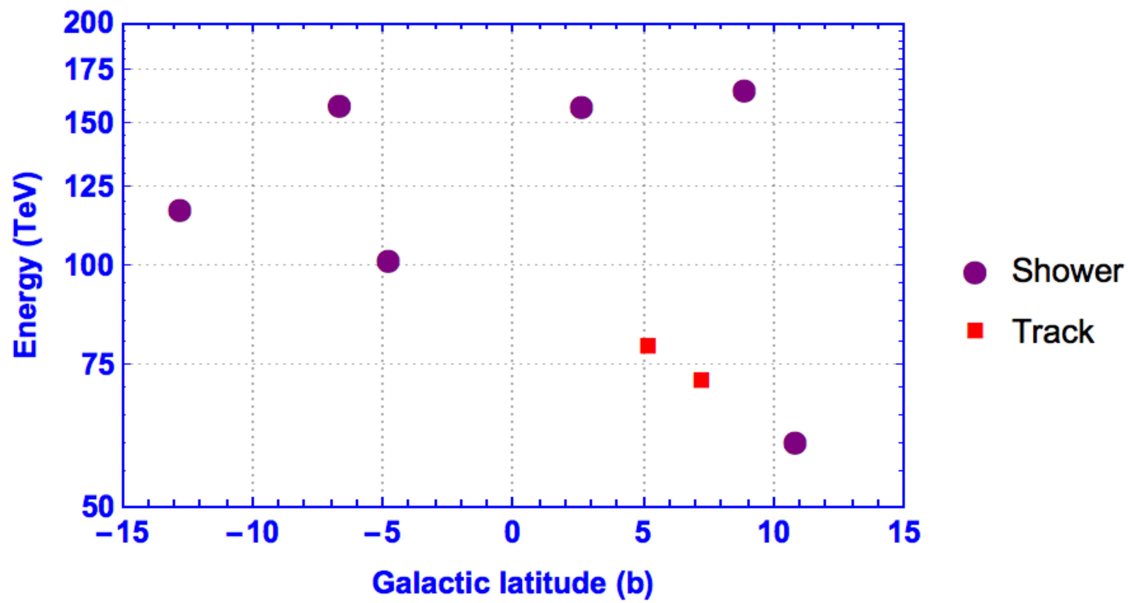
where

$n_{uhecr} = 3x10^{-19}$ erg/cm^3

is the UHECR density with energy above EeV, and

T_H=15 Myr

is the Hubble time



More on the events seen by IceCube

Distribution of the cosmic neutrino events, with lowest energy, that have been seen by IceCube close to the galactic plane

$$T_{\oplus} \doteq 100 \times \mathrm{Exp}[\,-\rho_{\oplus} \times R_{\oplus} \times \sigma_{\nu}(\mathrm{E})]$$