the search for HE cosmic neutrinos; expectations, synergies, results & prospects

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Expectations – astrophysical scenario; oscillations

Synergies – mostly gamma ray observations

Results – mainly IceCube data and their interpretations

Prospects – future data and experiments







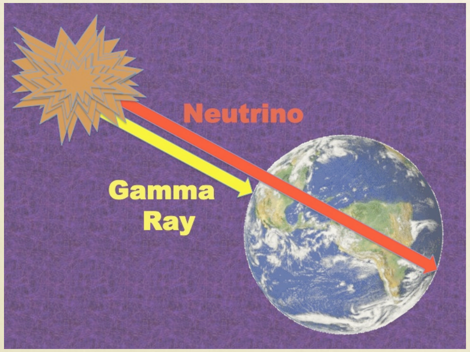



From the first idea to see cosmic muonic neutrinos/antineutrinos (1958) to IceCube results (2016); Fermi-LAT’s and of IceCube’s sky (2010)

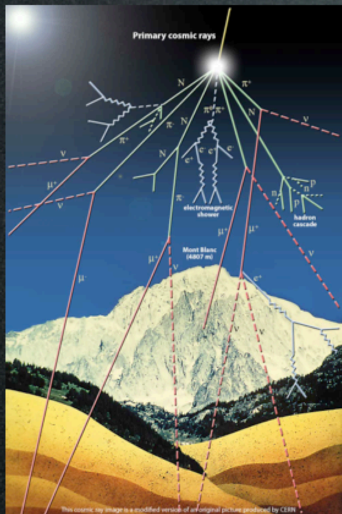
INTRODUCTION

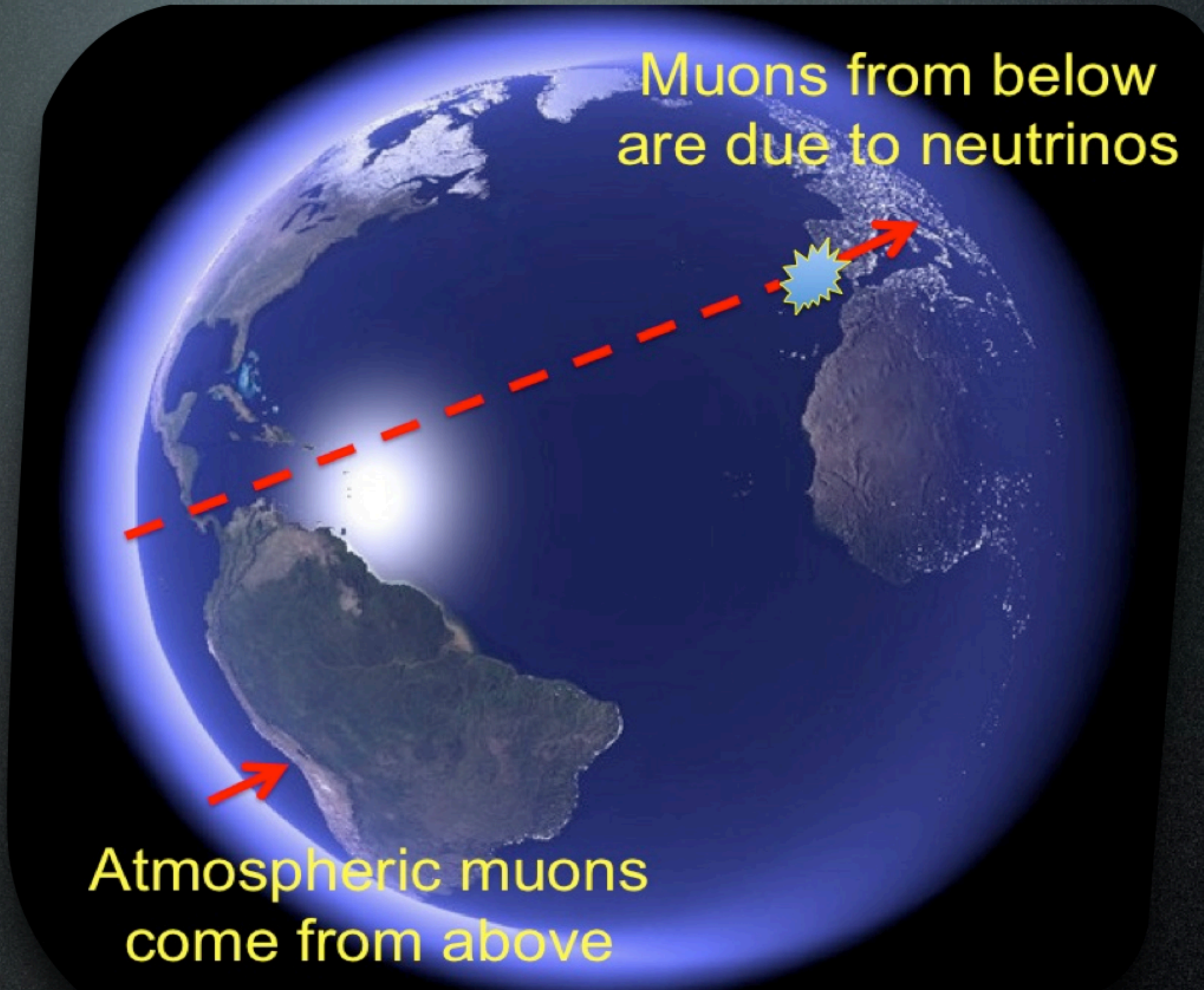
Cosmic neutrinos: how & why

In the master thesis of one student of Markov, Zheleznykh (1958), the key **technique** to observe the high-energy neutrinos was proposed for the 1st time.



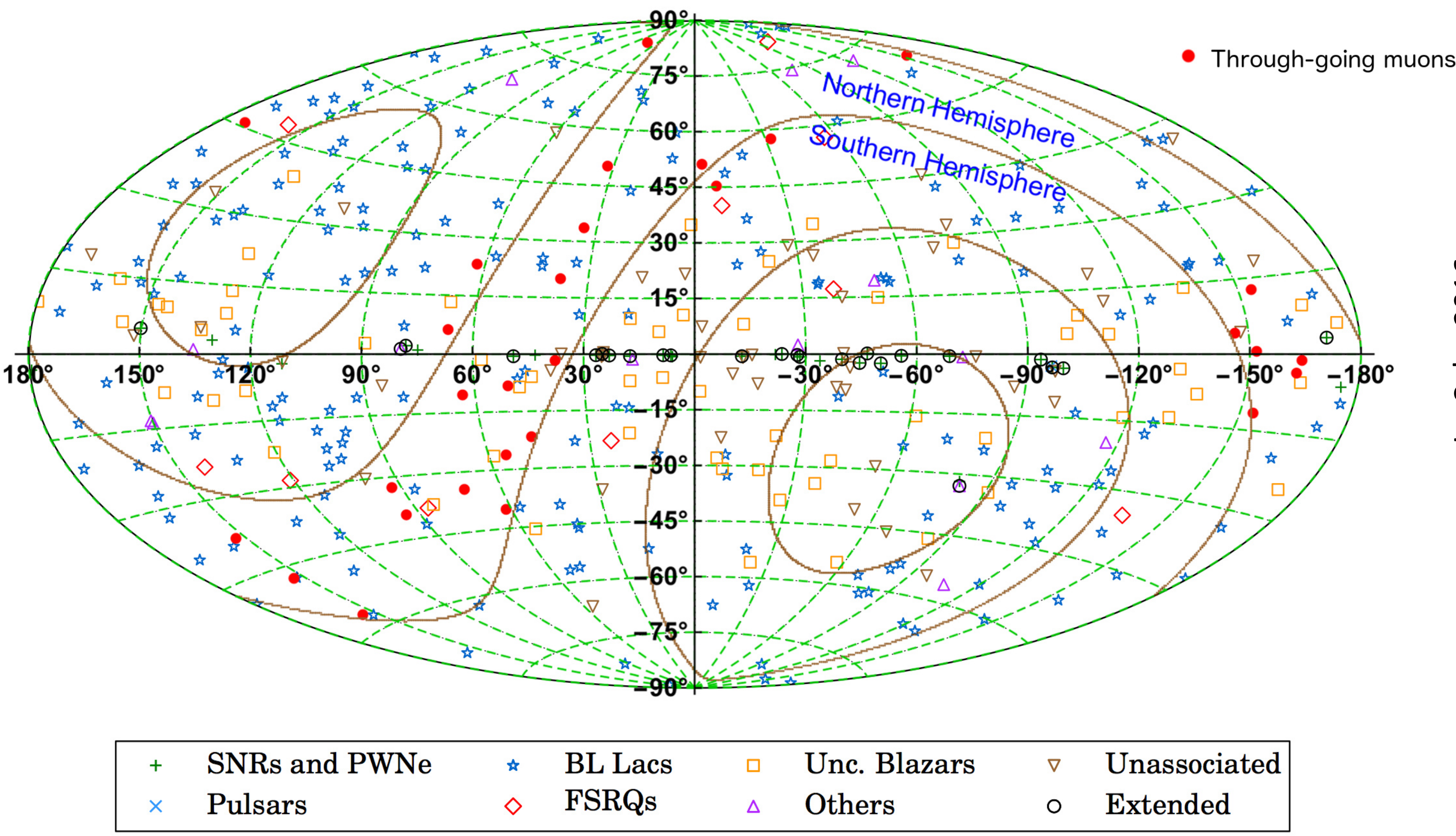
- *“γ quanta of 1 TeV favor existence of cosmic high-energy neutrinos”*
- *“worth searching especially if HE γ beyond atmosphere were found”*
- *from new star’s shell as Crab “the flux could equal the atmospheric one”*
- *from old CR population as GC “could be large if attenuation is essential”*





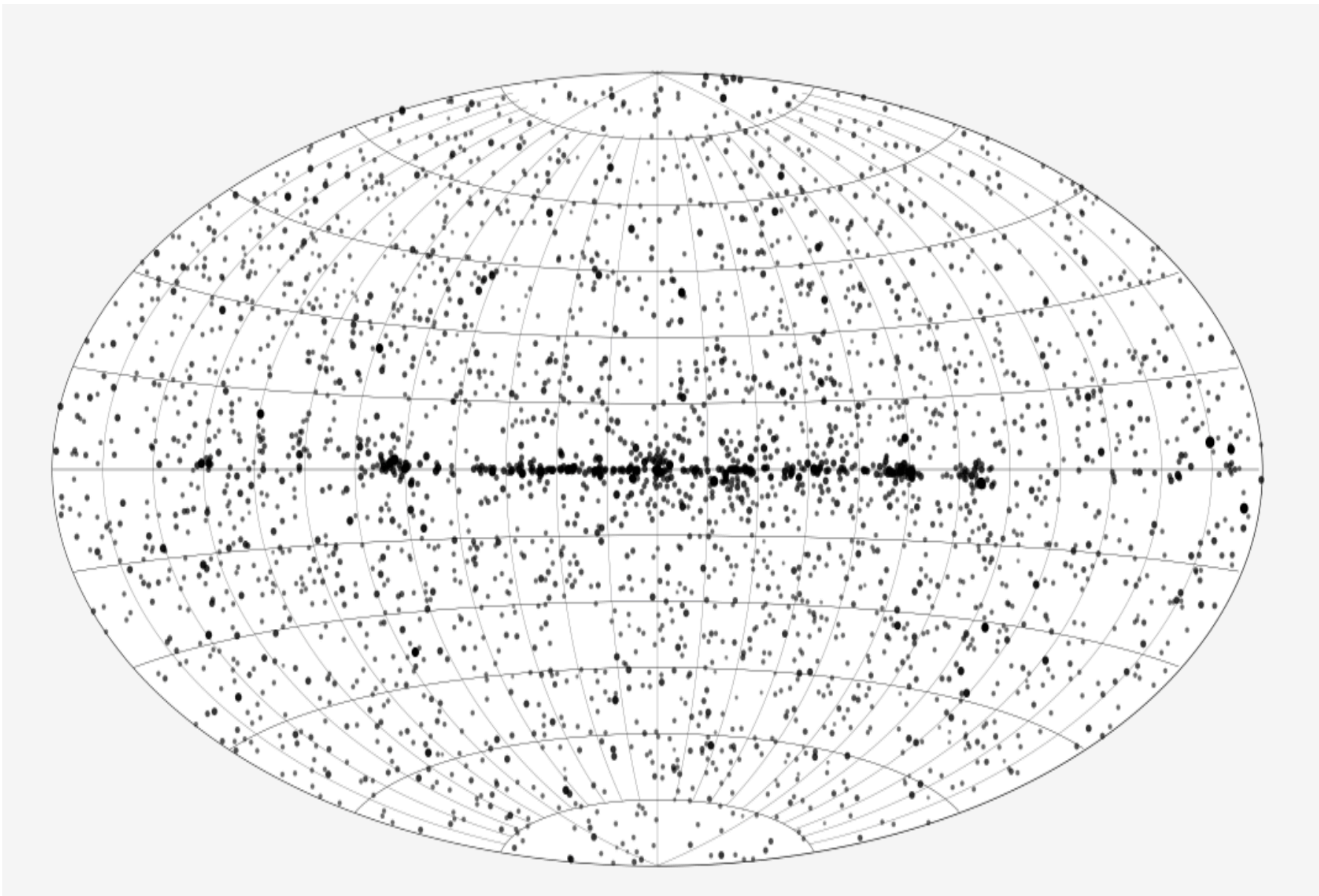
Muons as Spies of Neutrinos

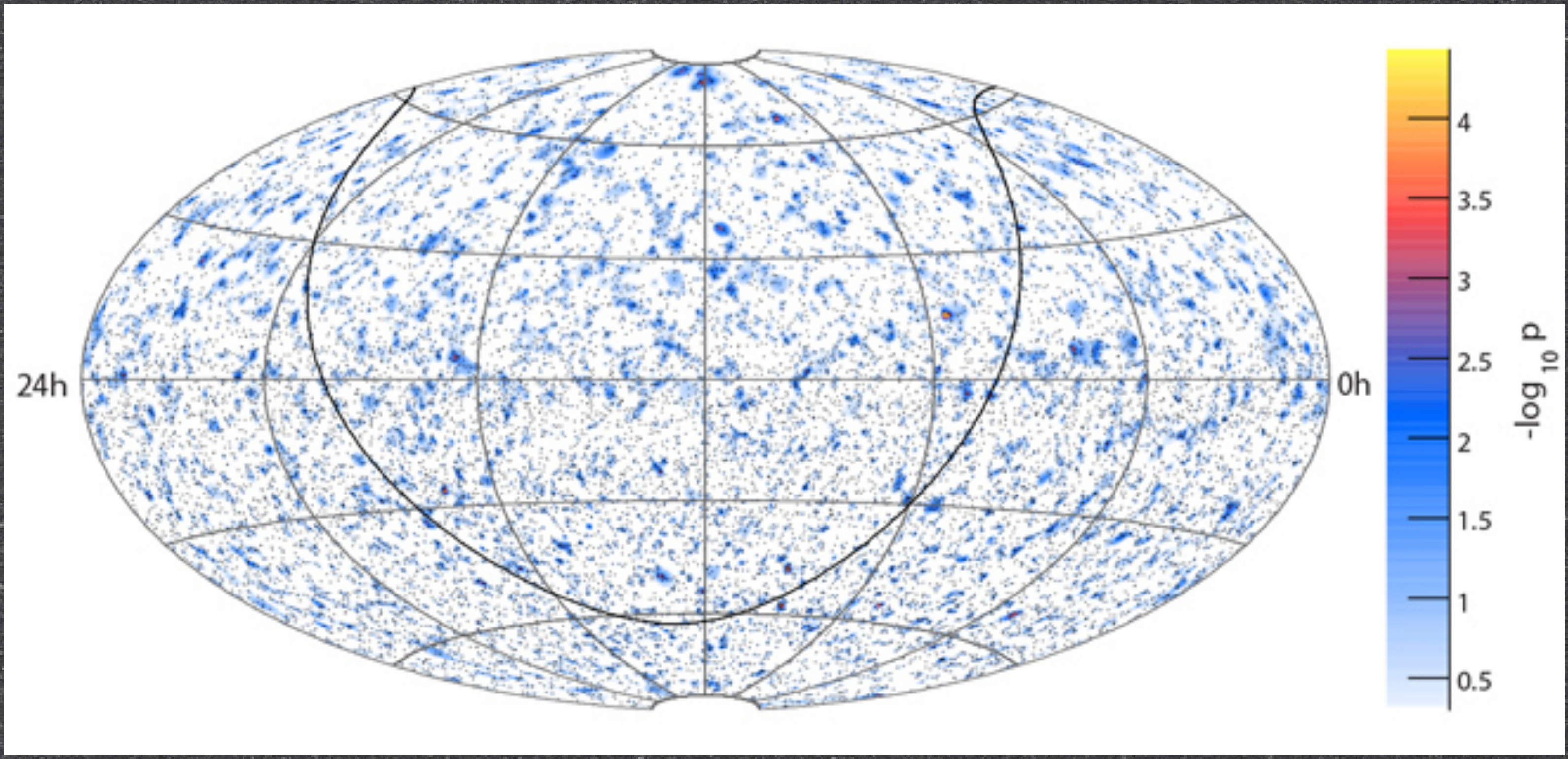
IceCube *did see such μ above 200 TeV*



IceCube 2016;
compiled by Palladino, FV 2017

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



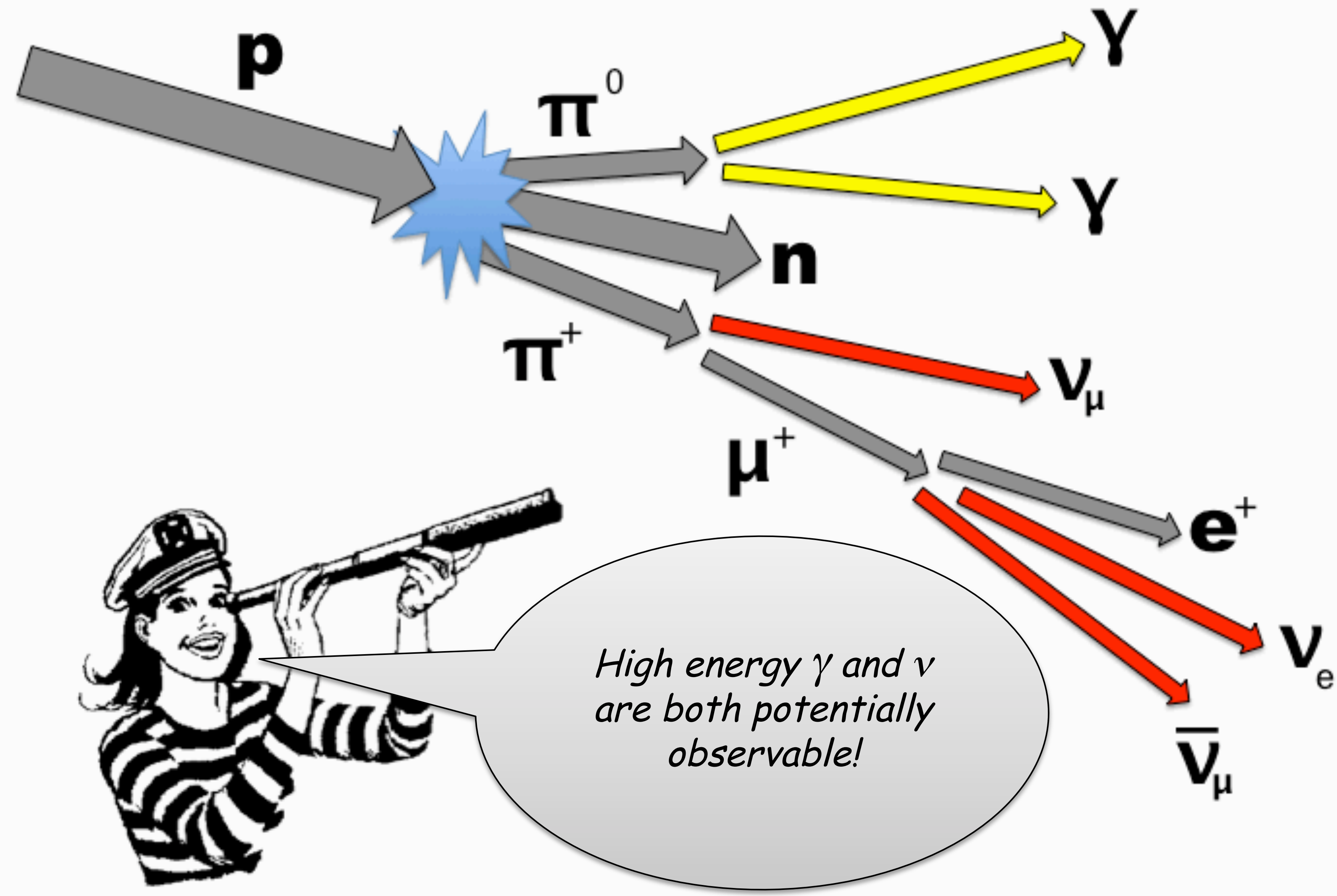


Skymap of IceCube (2010)

Milky Way and point sources unseen

Cosmic rays, γ and ν; fine prints of the multi-messenger assumption; spectrum of the high energy passing muons; atmospheric neutrinos

ASTROPHYSICAL CONNECTION



Thumb rules: $E_\pi = E_p/5$, $E_\gamma = E_\pi/2$ and $E_\nu = E_\pi/4$

cosmic ν in the astrophysical scenario (namely: assuming CR collisions)

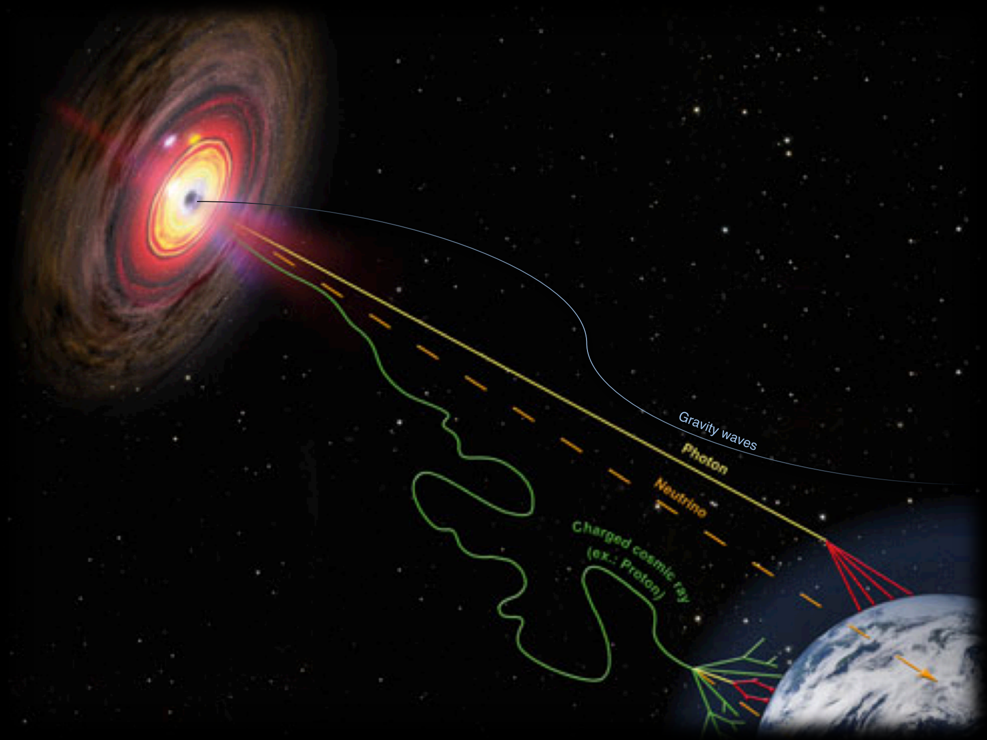
Cosmic ray density is larger near their **sources**

With sufficient **target,** secondary particles are produced at collisions

The neutral ones do not suffer deflection of **magnetic fields**

Neutrinos are produced only in this manner & are not absorbed

(But are difficult to be seen)



2 Potential neutrino sources and γ-rays

Potential neutrino sources are characterized by their hadronic γ-rays $\langle$`distributed as` $I_\gamma \propto E_\gamma^{-\alpha} \cdot e^{-\sqrt{E_\gamma/E_c}}$, `with` $\alpha = 1.8 - 2.2$ `and` $E_c =$ `TeV`$-$ `PeV`$\rangle$ for π^0 and $\pi^\pm$ are produced together.

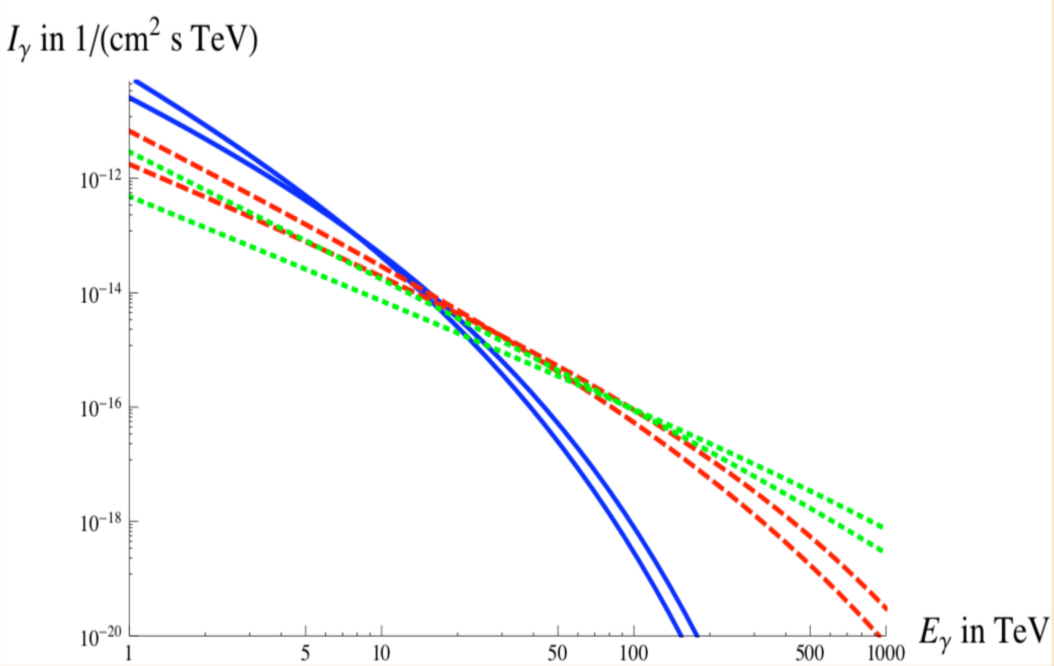


Figure 5: *γ-ray intensities corresponding to a signal of 1 muon/km^{2}yr above 1 TeV, evaluated assuming that the sources are transparent to their gamma rays.*

FV, Aharonian, Saakyan 2011

Calculating cosmic ν from γ

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

FV 2006;
Villante, FV 2008

Fine prints:

- γ-rays are produced also with electromagnetic mechanisms
- Could be absorbed – e.g., only γ-rays below 100 GeV may reach us from cosmological distances
- There could be ν from decay of DM -whatever it is- or topological defects. [This is bound by experiments.]
- ν could be messengers of `mirror world'
- etc etc

An interesting observation

- All IceCube data above 200 TeV agree well with

$$\Phi_\nu \sim E_\nu^{-2} \div E_\nu^{-2.2}$$

that fits the original expectation (maybe not "prediction")

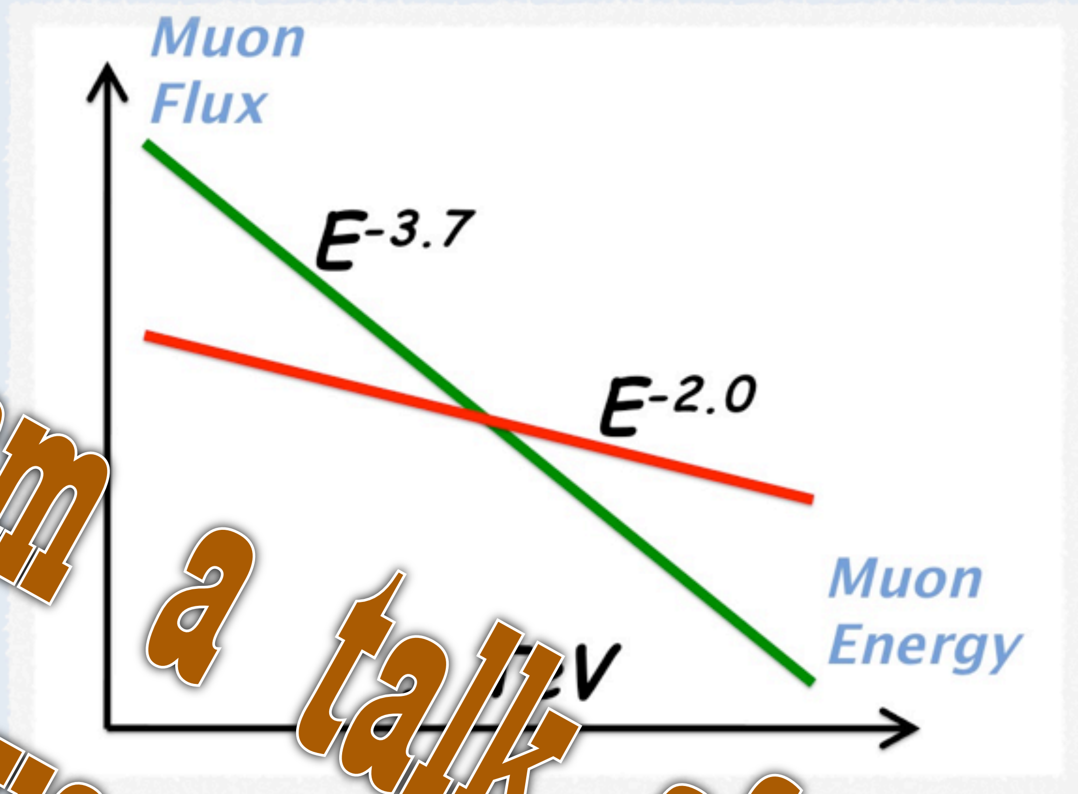
- The data collected mostly as "passing μ" are comparably clean & tested with other events

- They can be regarded as circumstantial argument in favor of **pp-collisions**, for,

$$\Phi_p \sim E_p^{-2} \rightarrow \Phi_\nu \sim E_\nu^{-2} \quad \text{i.e., "scaling"}$$

IceCube Collaboration, 2016

From a talk 10 years ago



the hope: some point source has a very hard spectrum above TeV.

recap on atmospheric ν

CR reaching the Earth behave as $E^{-2.7}$ till the knee
Interacting with atmosphere they produce secondaries, e.g.

$$\pi^+ \to \mu^+ + \nu_\mu \text{ then } \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

that initially maintain the shape of the primary distribution, $E^{-2.7}$.

Then, at about 10 GeV, interesting things happen

(1) :– the muon reaches the ground before decaying,

$$R_\mu^{\text{dec}} \approx 0.6 \text{ km } \times \left(\frac{E_\mu}{m_\mu}\right)$$

the neutrino beam gets depleted of ν_e.

(2) :– The interaction length of the pion becomes shorter than the decay length

$$R_\pi^{\text{int}} \approx 0.5 \text{ km} \quad \text{whereas } R_\pi^{\text{dec}} \approx 0.4 \text{ km } \times \left(\frac{E_\pi}{10\text{GeV}}\right)$$

the secondary are produced as $E^{-3.7}$

Thus at high energies above 100 TeV (corresponding to knee) the sky should be clearner but, somewhere there, we should have the D-meson decay product – **prompt neutrinos** – distributed as $\sim E^{-2.7}$

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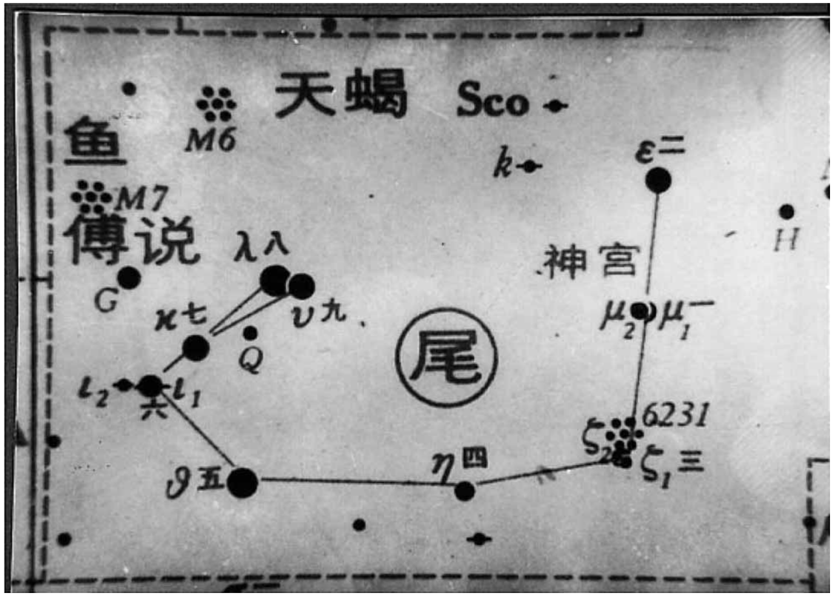
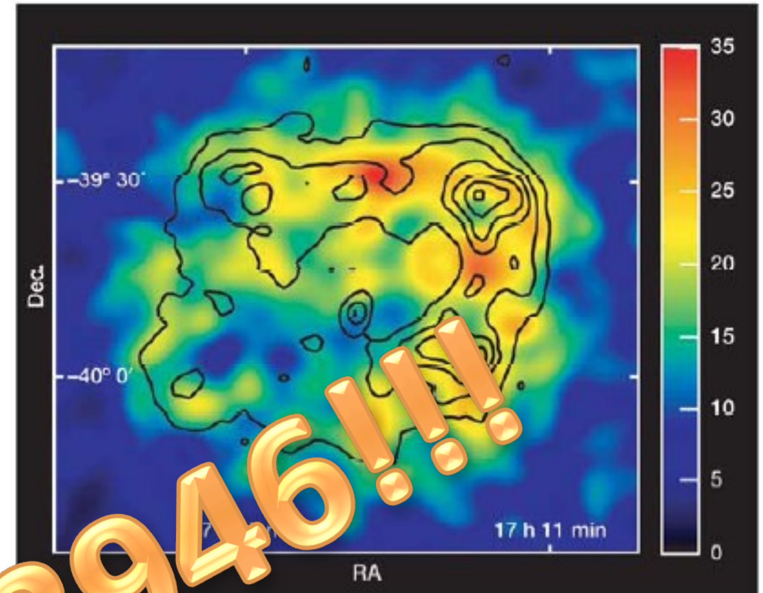
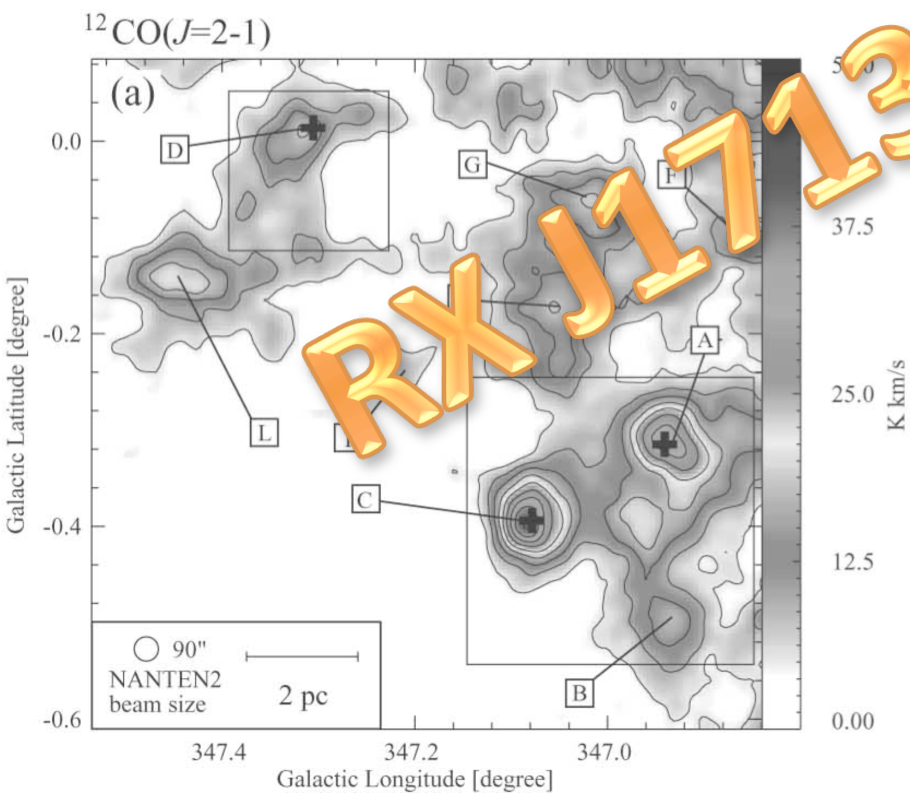
Objects characterized by the direction of arrival (=neutrino astronomy in proper sense); expected spectra; sporadic sources?

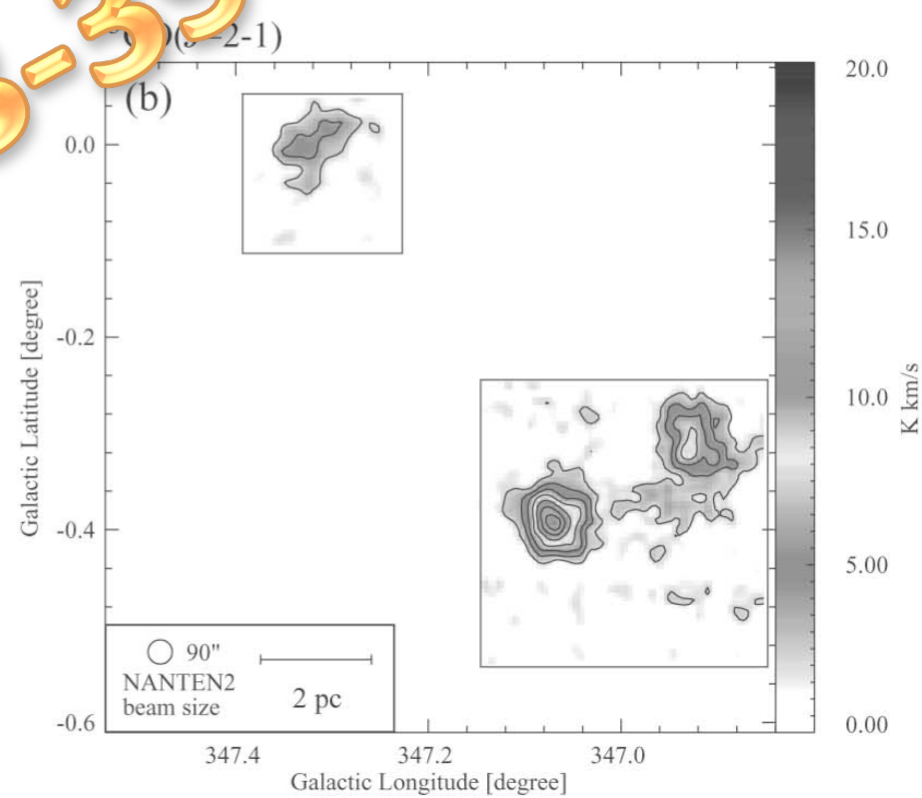
EXPECTATIONS ON THE SIGNAL

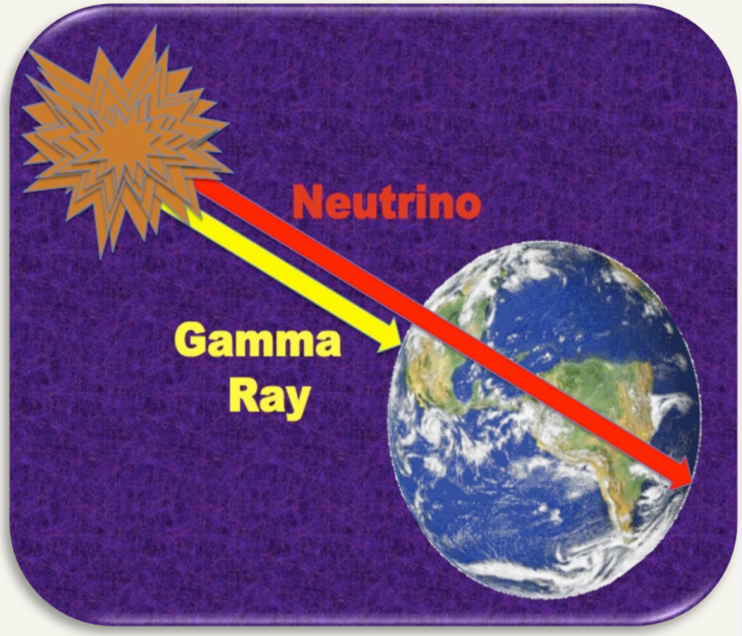




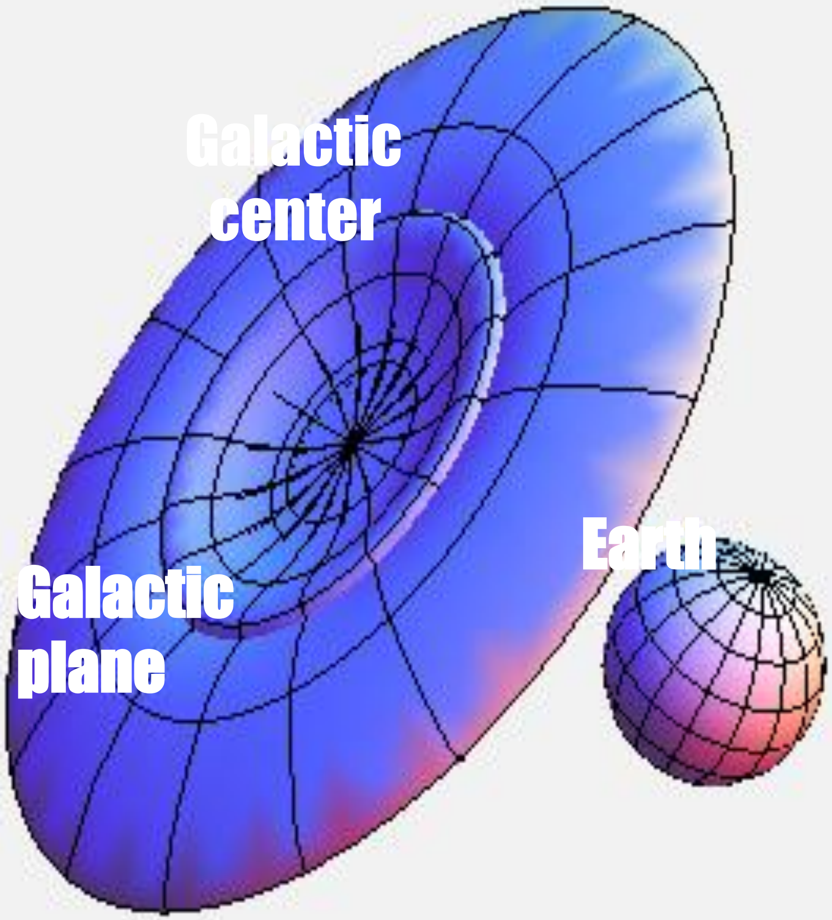
RX J1713-3946!!!







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]



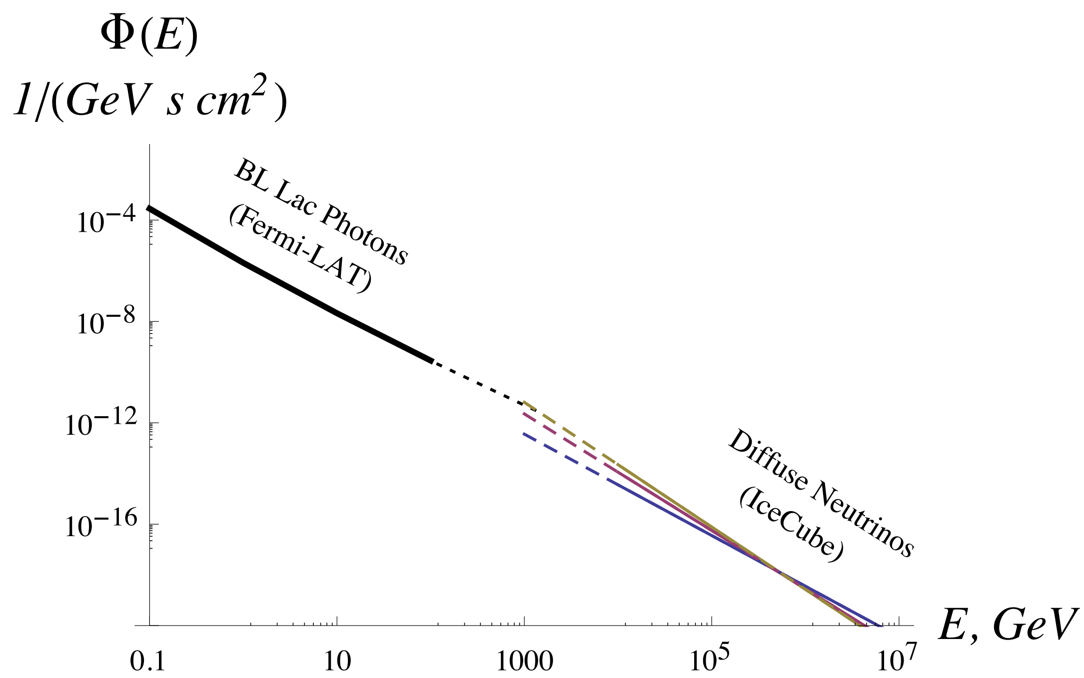
BL Lac γ-ray Flux *vs* IceCube Neutrino Flux

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%.)

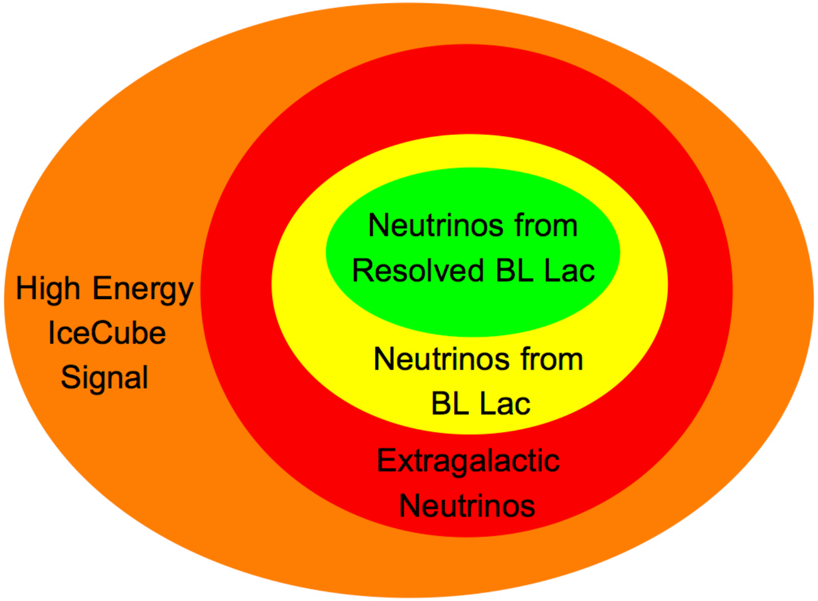
We expect a similar or smaller neutrino emission in the 0.1-100 GeV.

Thus, BL Lac could contribute, on general grounds.



Esmaili, Palladino, FV 2015

Trying the most luminous xgal sources of Fermi-LAT



- There are 29 passing muons, with resolution $\Delta\vartheta \sim 1°$

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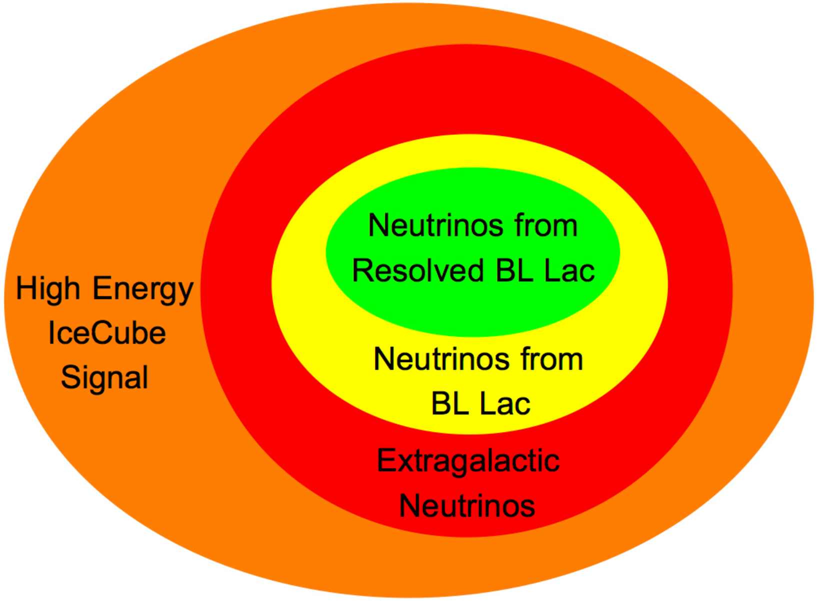

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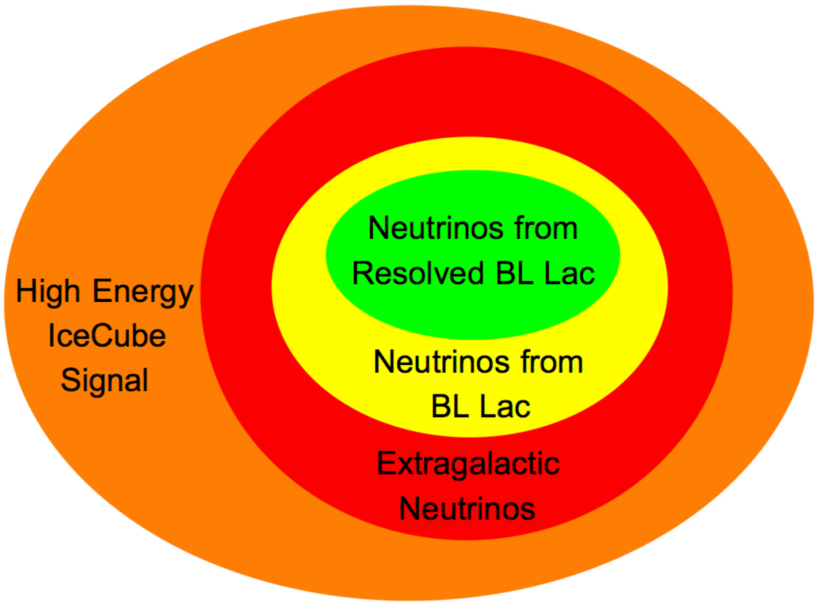

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- Calculate from Ajello'14 the fraction of those tagged=½

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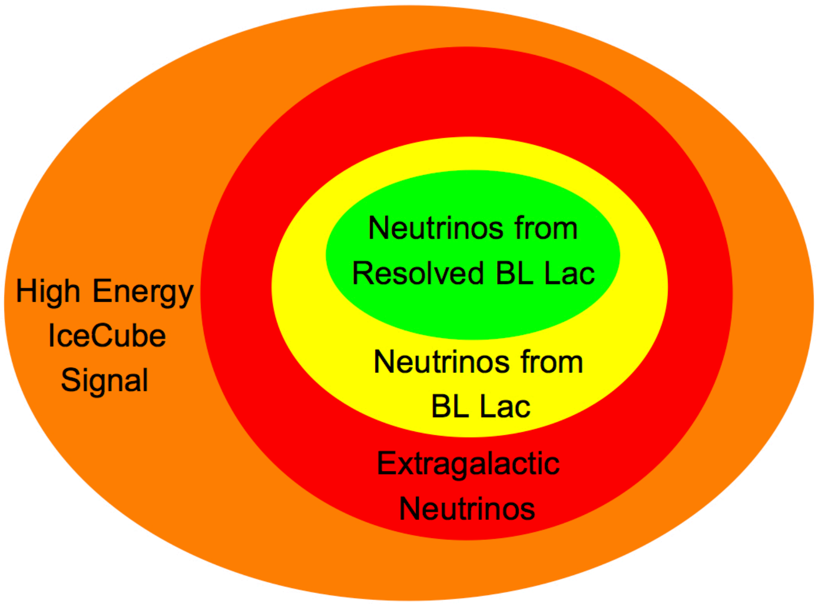

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- We expect 10 correlations

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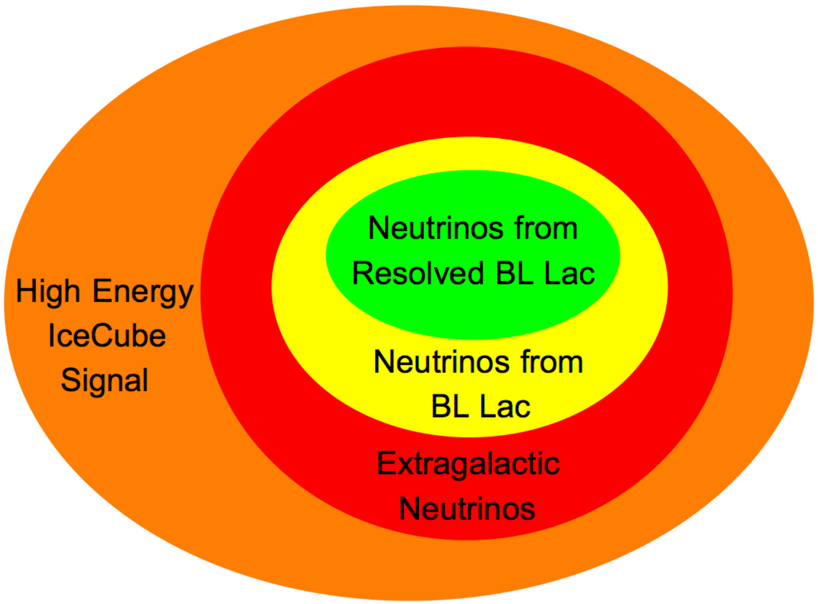

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- But we see just 1.

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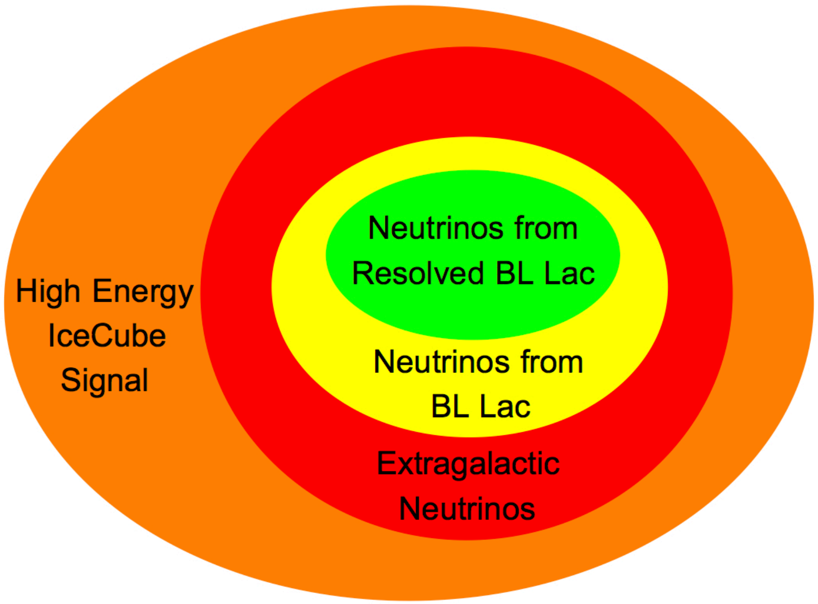

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- We expect 10 correlations
- But we see just 1.
- <u>And this one has $\Delta\vartheta \sim 10°$!</u>

Palladino, FV, A&A, 2017

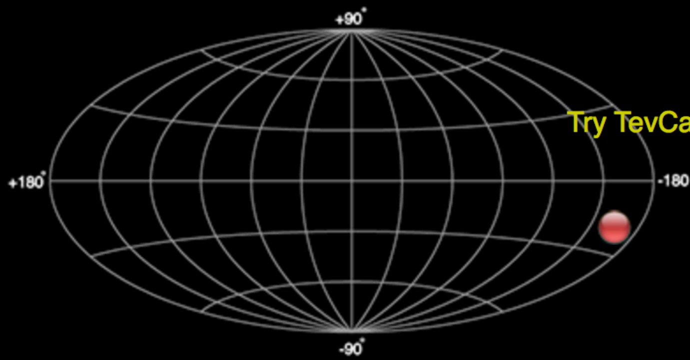
TXS 0506+056

SIMBAD

Canonical Name:	TXS 0506+056
TeVCat Name:	TeV J0509+056
Other Names:	EHE 170922A 3FGL J0509.4+0541 3FHL J0509.4+0542
Source Type:	Blazar
R.A.:	05 09 25.96370 (hh mm ss)
Dec.:	+05 41 35.3279 (dd mm ss)
Gal Long:	195.41 (deg)
Gal Lat:	-19.64 (deg)
Distance:	z=0.3365
Flux:	(Crab Units)
Energy Threshold:	100 GeV
Spectral Index:	
Extended:	No
Discovery Date:	2017-10
Discovered By:	MAGIC
TeVCat SubCat:	Newly Announced

Source Notes:

The blazar TXS 0506+056 lies within the error circle of IceCube-170922A, the IceCube high-energy neutrion candidate event whose detection was reported in GCN circular #21916.
Follow-up observations were performed by a number of GeV-TeV instruments with both Fermi-LAT and MAGIC reporting evidence for gamma-ray emission from positions consistent with the IceCube neutrino error circle which they thus associate with the blazar TXS 0506+056.
Upper limits on the gamma-ray emission from the region were reported by H.E.S.S, HAWC and VERITAS.



Try TevCat 2.0 Beta!

Observation Date (UT)

12-3-2018

Observation Lat

ARGO-YBJ (30.11)

Vis-Plot this Source!

Vis-Plot Full Year

TXS 0506+056

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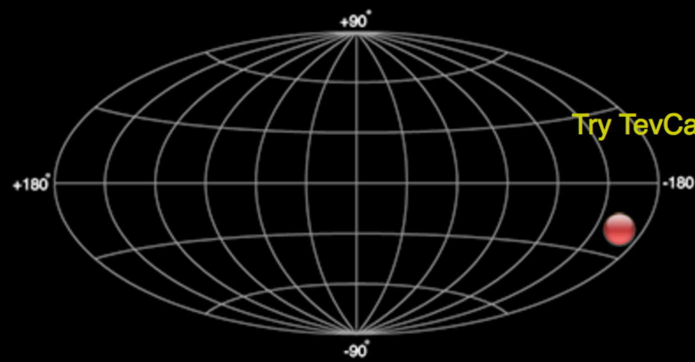

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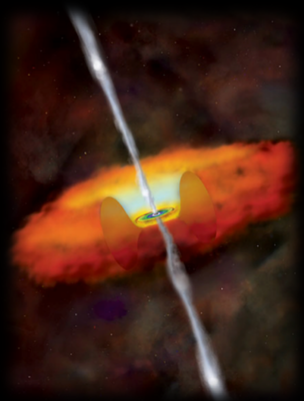
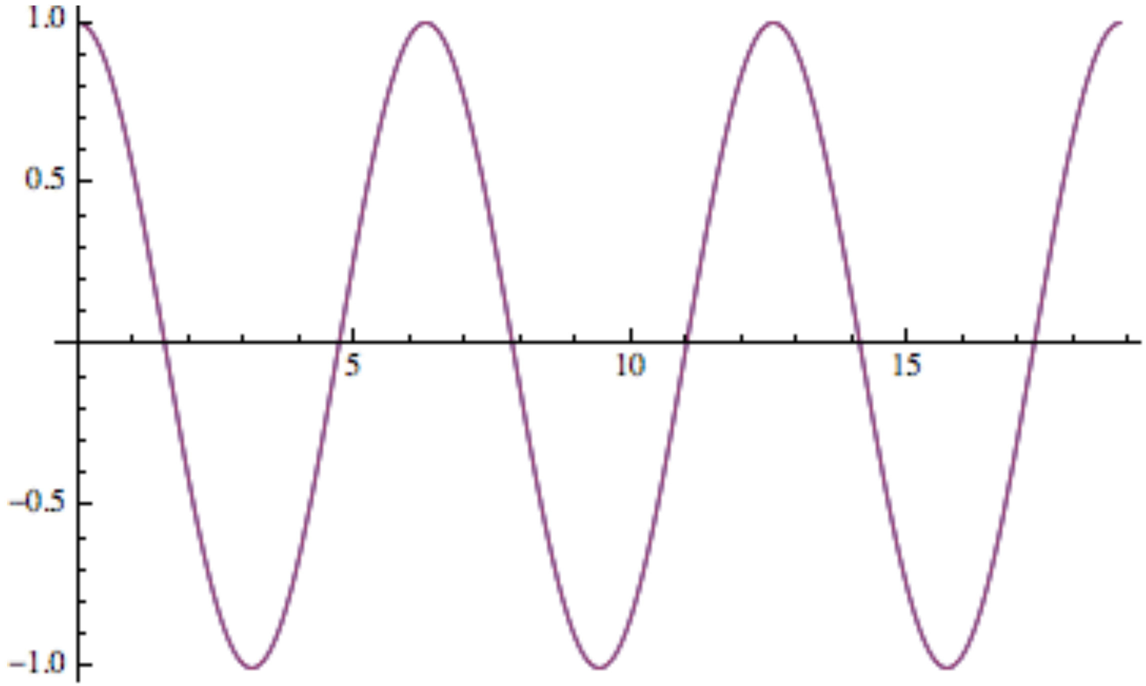


Sporadic encounters with / mergers of / big clumps of matter ?

Nature of neutrino oscillations; consistency with the available data of IceCube; a conclusive test of cosmic origin

NEUTRINO OSCILLATIONS

Electron, muon and tau ν are not mass eigenstates



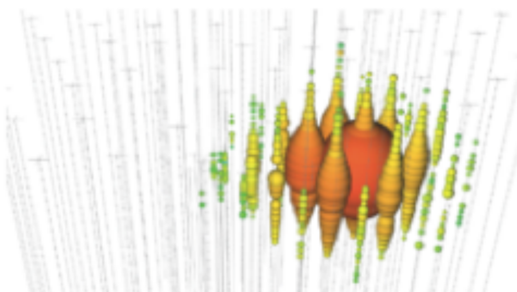
E.g., we begin with an electronic neutrino (in phase) and then we get a muonic one (counter-phase); then electronic again; and so on

(in reality, oscillations are not full and also tau neutrinos are involved—but these are details)

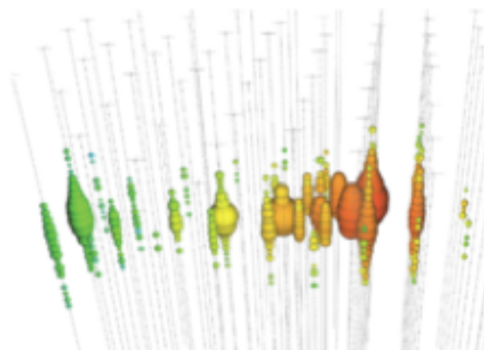
remarks on neutrino oscillations

- 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)
- Only "averaged" oscillations matter (Gribov Pontecorvo 1969) they depend upon 3 parameters only (Palladino Vissani 2015)

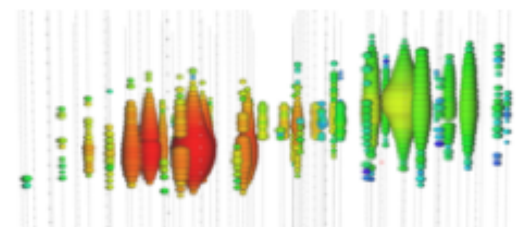
Not only passing muons!!!



cascade signature



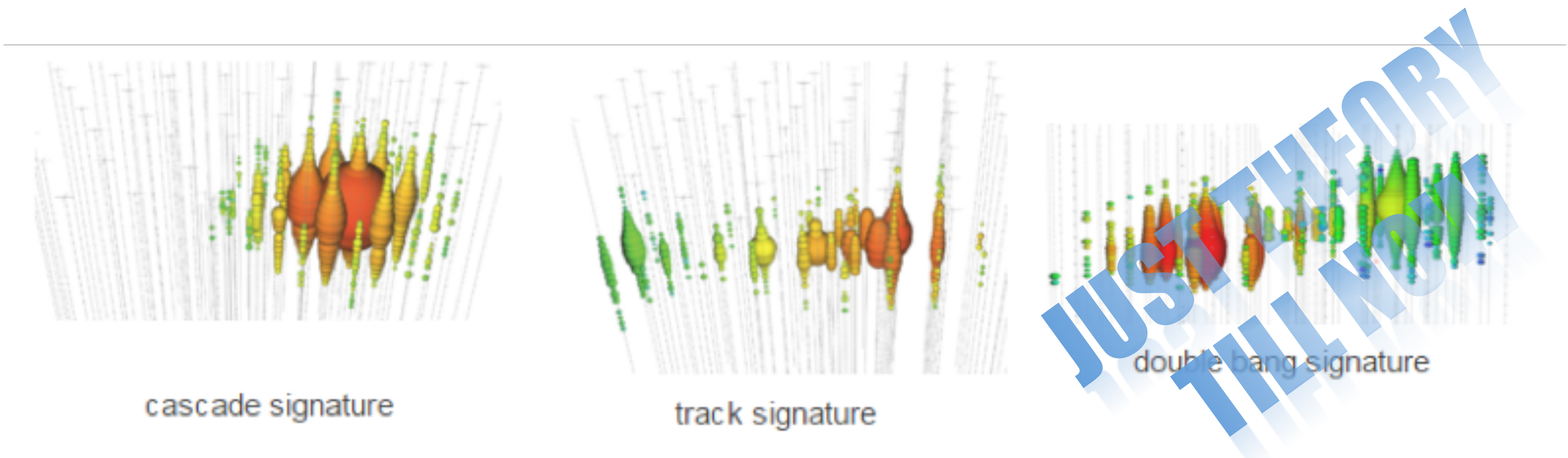
track signature



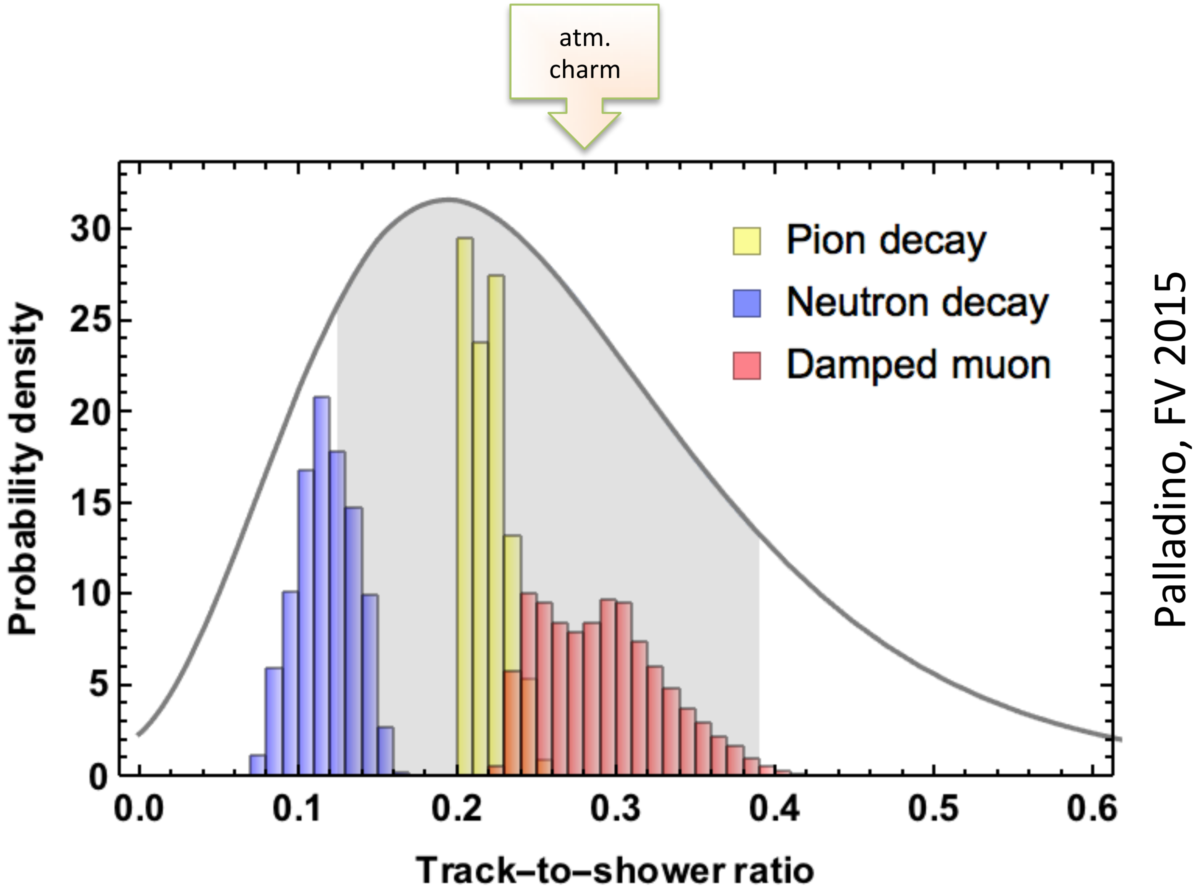
double bang signature

Mostly $\nu_{e,\tau}$ Mostly ν_{μ} Mostly ν_{τ}

Not only passing muons!!!



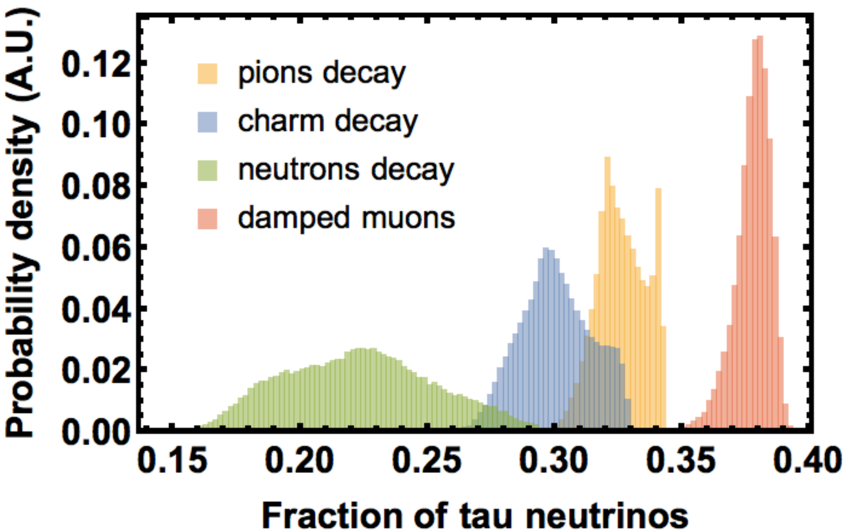
Mostly $\nu_{e,\tau}$ | Mostly ν_{μ} | Mostly ν_{τ}



TRACK-TO-SHOWER RATIO

Expectations including oscillations from three mechanisms (pions + a few speculative ones) as compared with the track-to-shower ratio obtained from 4 years IceCube data: 1 σ region in gray

Tau events - or “cosmic Opera”



* Cosmic ν_τ are unavoidable (Learned Pakvasa 1995)

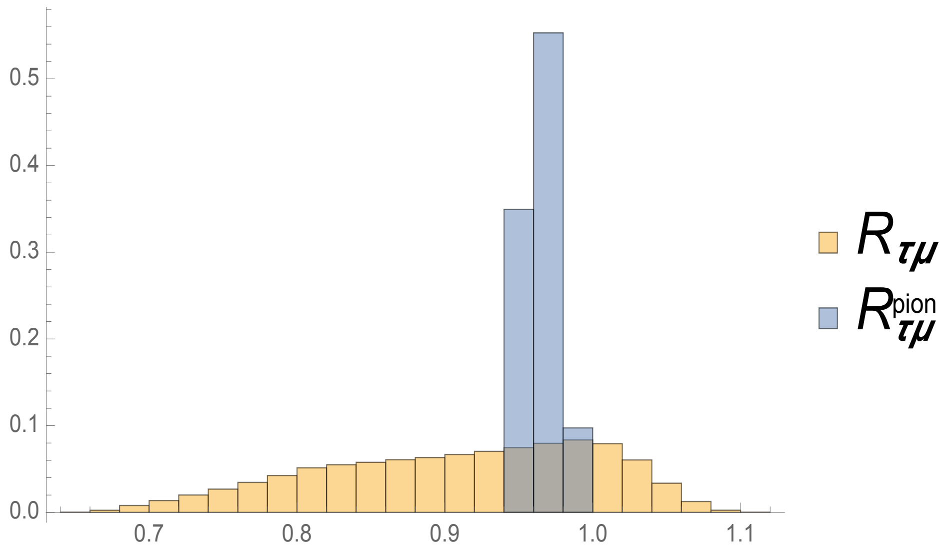
* At “low” energies, τ gives showers – just as electrons or NC

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

Tau neutrinos observed → Cosmic origin proved

tau-flux is firmly linked to the muon-flux

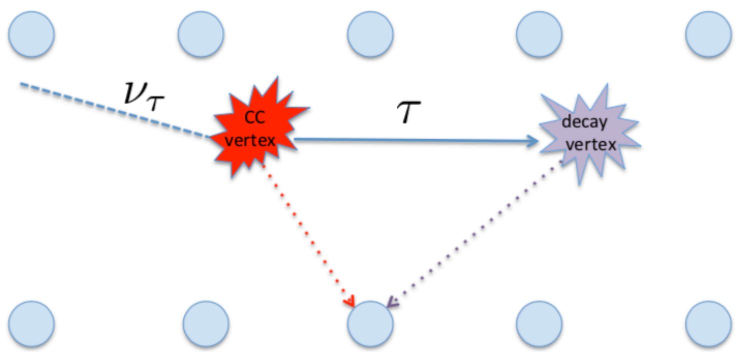
Mascaretti, Palladino FV 2017

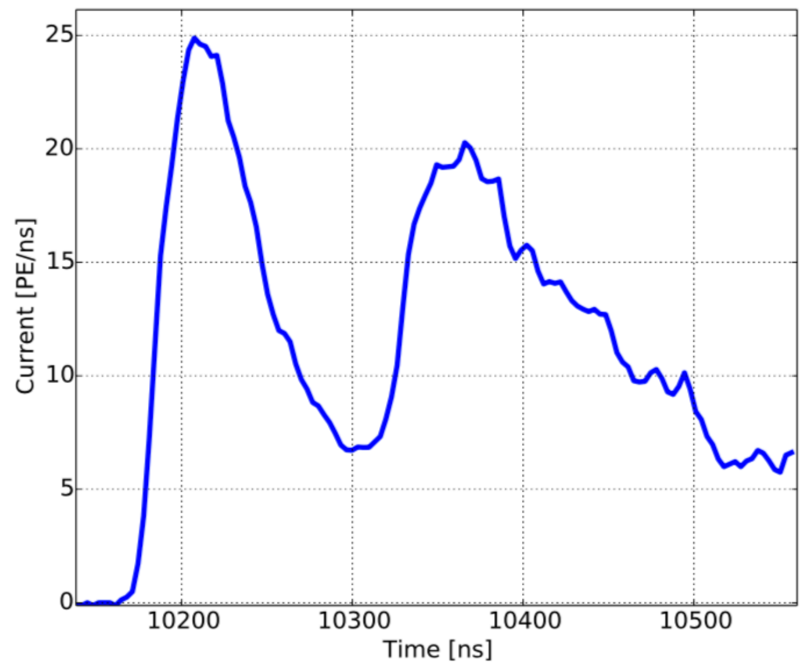


The cosmic neutrino flux of ν_τ is very constrained by the (observed) ν_μ flux, *simply due to the known oscillations.*

Residual uncertainties, due to production mechanism (and oscillations parameters), do not have a large impact.

the double pulse signal [1/2]





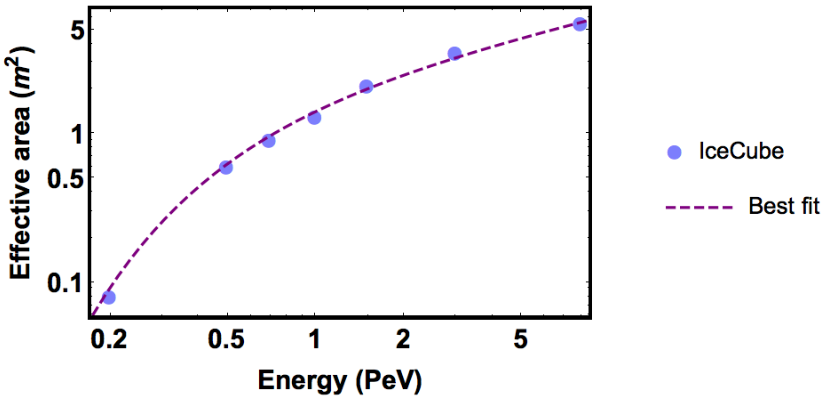
IceCube 2016

the double pulse signal [2/2]

Palladino, Pagliaroli, Villante FV 2016

$$A_\tau^{2\mathrm{P}} = \bar{A}_{2\mathrm{P}} \times \left(\frac{E_\nu}{\mathrm{PeV}}\right)^\beta \exp\left(-\frac{E_{\min}}{E_\nu}\right),$$

$$\text{with} \begin{cases} \bar{A}_{2\mathrm{P}} = 2.33\ \mathrm{m}^2 \\ \beta = 0.455 \\ E_{\min} = 0.5\ \mathrm{PeV} \end{cases}$$



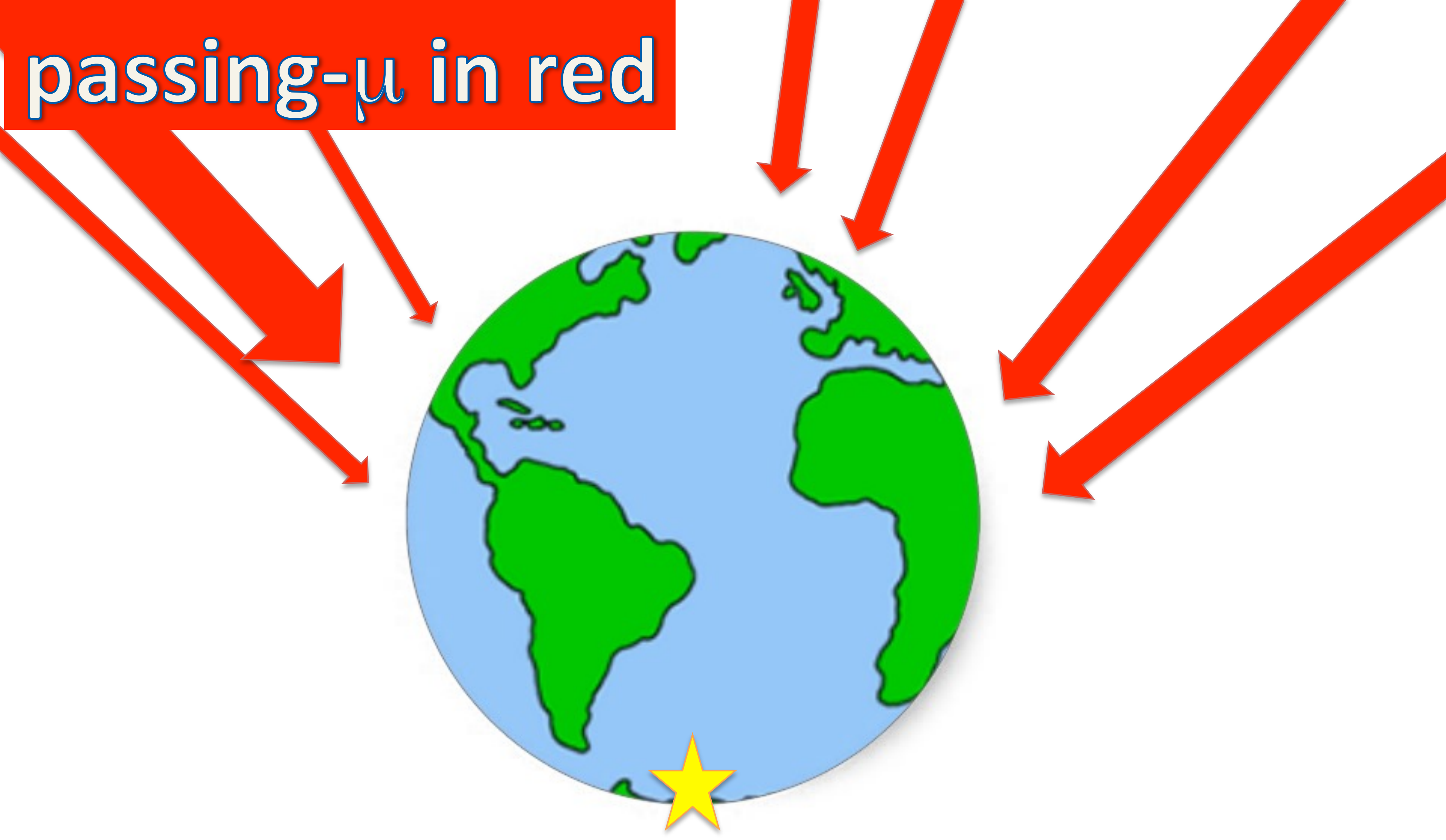
- The prediction is,
  0.1 double pulse/yr
- Error due to ν_μ-flux uncertainty is 30%
- Cutoff at 2, 5, 10 PeV cuts 45%, 30%, 15% of signal

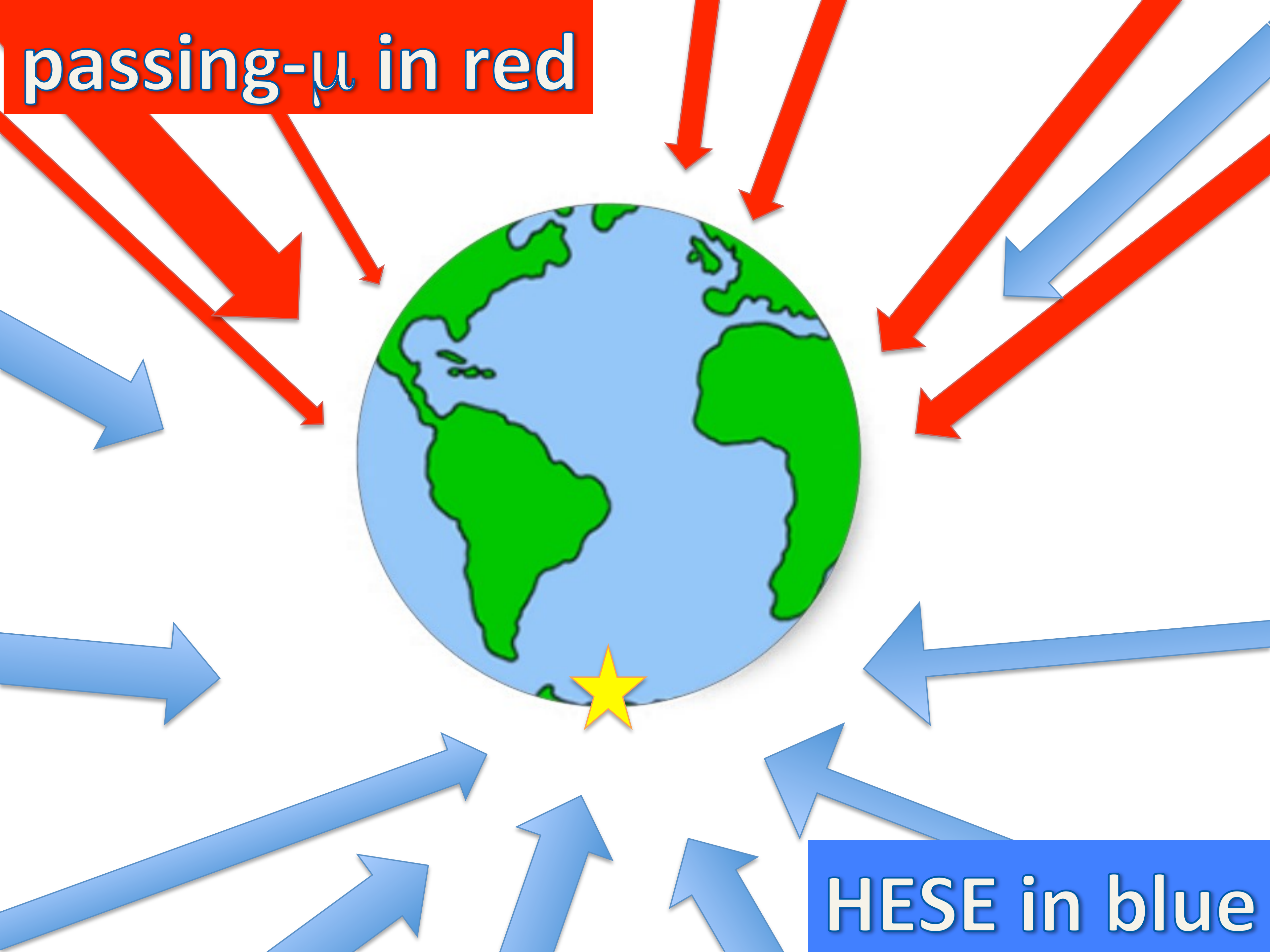
Mascaretti, Palladino FV 2017

Passing muons along with the other class of events (HESE); an obstruction / contradiction

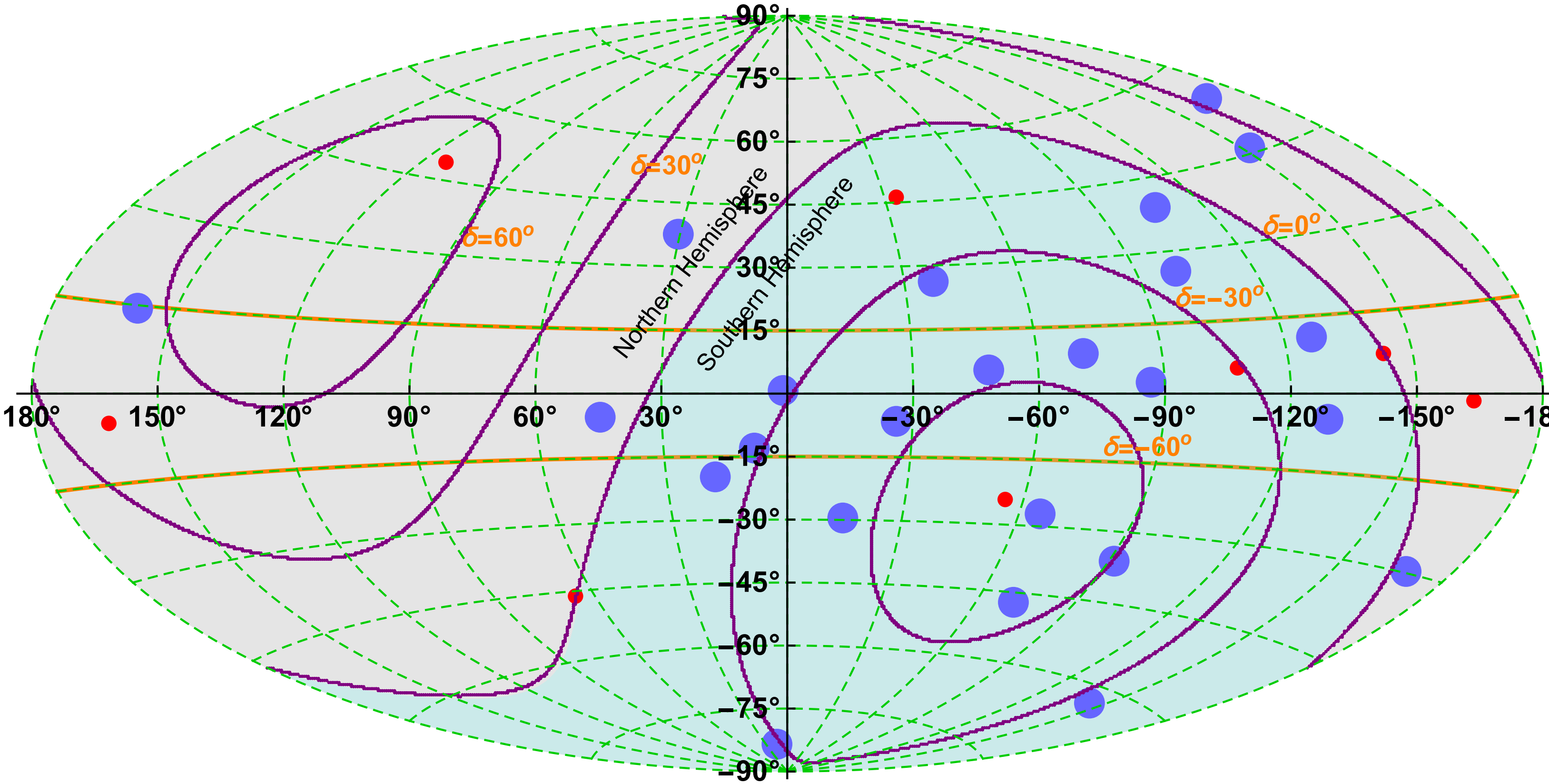
GLOBAL INTERPRETATION?

passing-μ in red



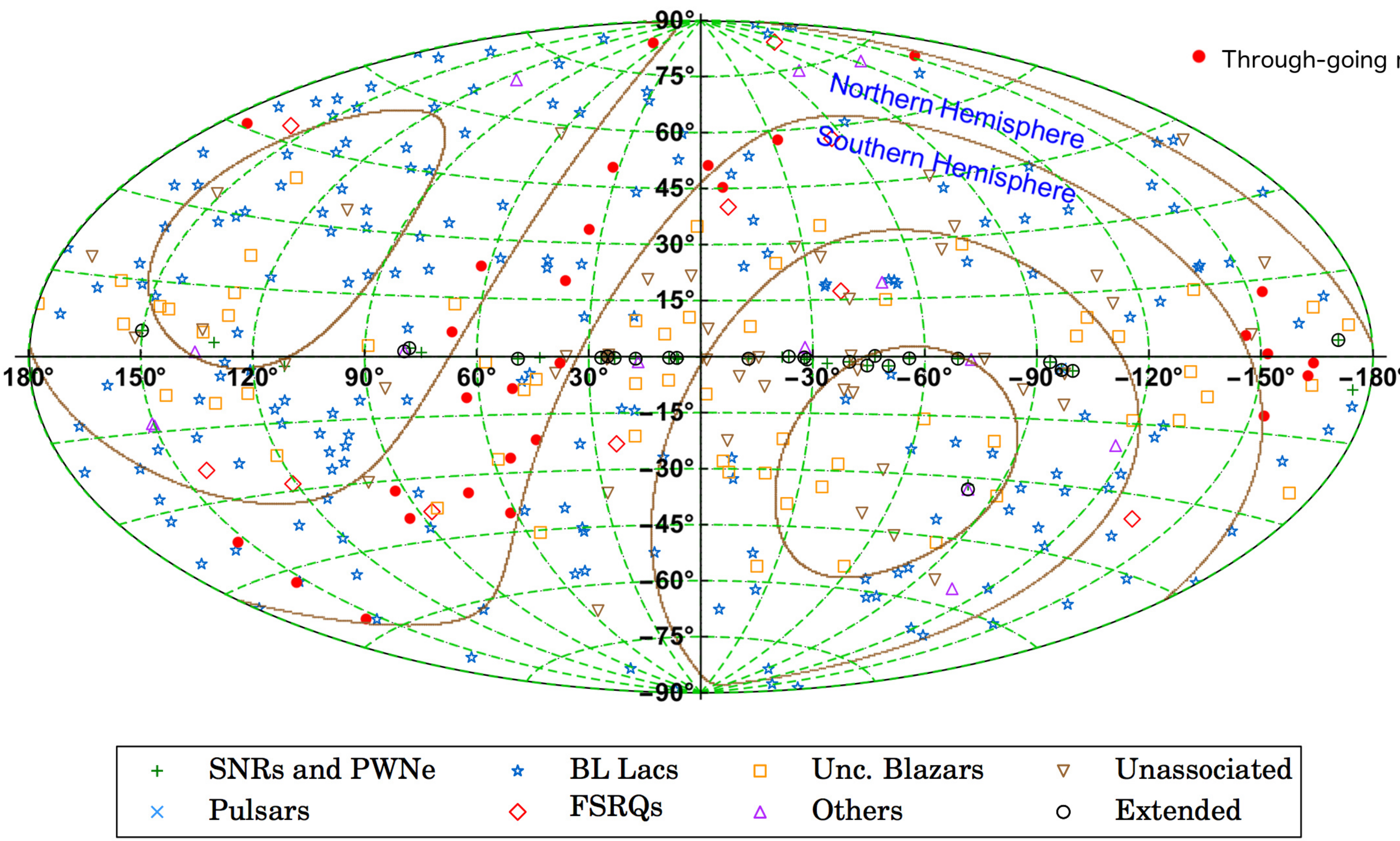

passing-μ in red
HESE in blue

HESE above 60 TeV, showers in blue

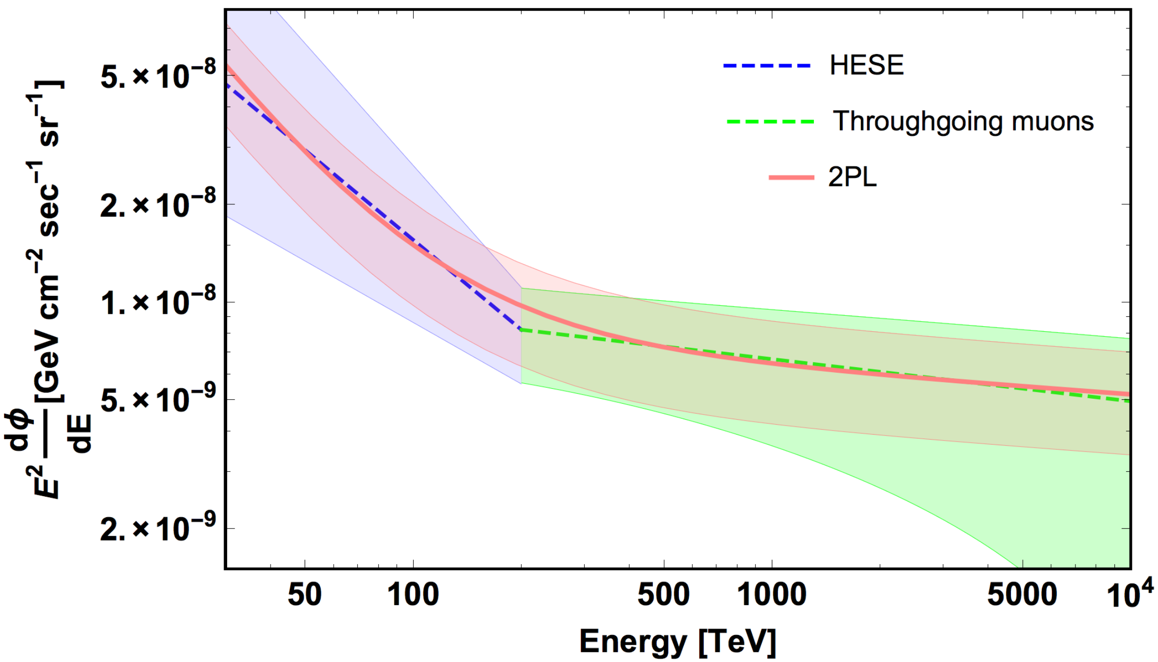


IceCube 2015 compiled by
Palladino, Spurio FV 2016

passing-μ above 200 PeV, in red



IceCube 2016;
compiled by Palladino, FV 2017



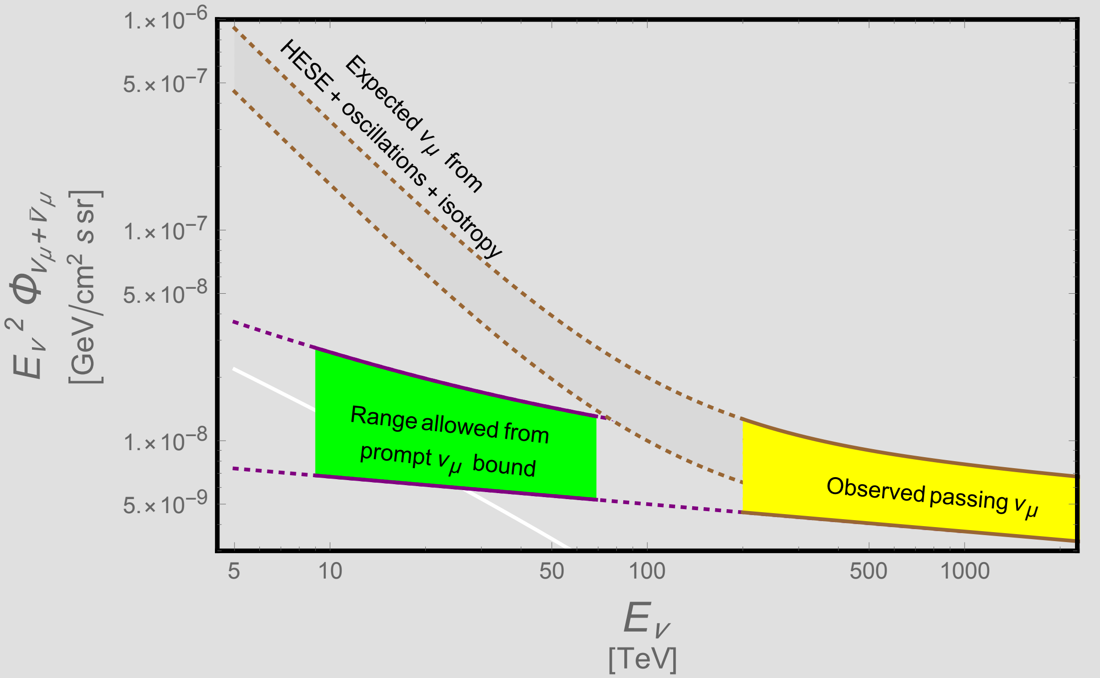
Mascaretti, Palladino, FV 2017

A single isotropic cosmic ν-flux for HESE & tracks

Join interpretation of HESE and tracks based on 1) conventional astrophysics, 2) conventional oscillations, 3) current hypothesis on the background.

If we want to cover both datasets, two-power-law cosmic neutrino spectrum is at least necessary.

an obstruction to this interpretation



Palladino, Spurio FV 2016;
Mascaretti, Palladino FV 2017

- No large ν_μ component distributed as $E^{-2.7}$ or similar in north sky – prompt events searched in the track data, as excess over astrophysical signal extrapolated at low energies *but have not been found.*
- Isotropy implies the same for south sky: No large ν_μ component distributed as $E^{-2.7}$ or similar.
- Then neutrino oscillations imply that large ν_e and ν_τ component should not be in south sky!

SUMMARY AND DISCUSSION

- CR and γ-ray motivate the search for cosmic ν
- Something very similar to the expected μ-signal has been seen; has IceCube seen cosmic ν_μ ? ! ? !
- Some flavor tests have been passed; what about ν_τ ?
- What is the meaning of the low energy IceCube spectrum? isotropy called into question?
- Which are the sources??? Notice that :-- pointing is (will be) much better in water than in ice,
- A lot of efforts on theoretical elaborations, but more data and independent tests seem necessary
- Increasing motivations for one km^3 size telescope in north hemisphere
- Neutrinos are intrinsically multimessenger (due to flavor); however, γ-rays were and remain essential for further planning and proper interpretation

main references used

Expected neutrino signal from supernova remnant RX J1713.7-3946 and flavor oscillations
Maria Laura Costantini, Francesco Vissani
Astropart.Phys. 23 (2005) 477-485

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Galactic Sources of High-Energy Neutrinos: Highlights
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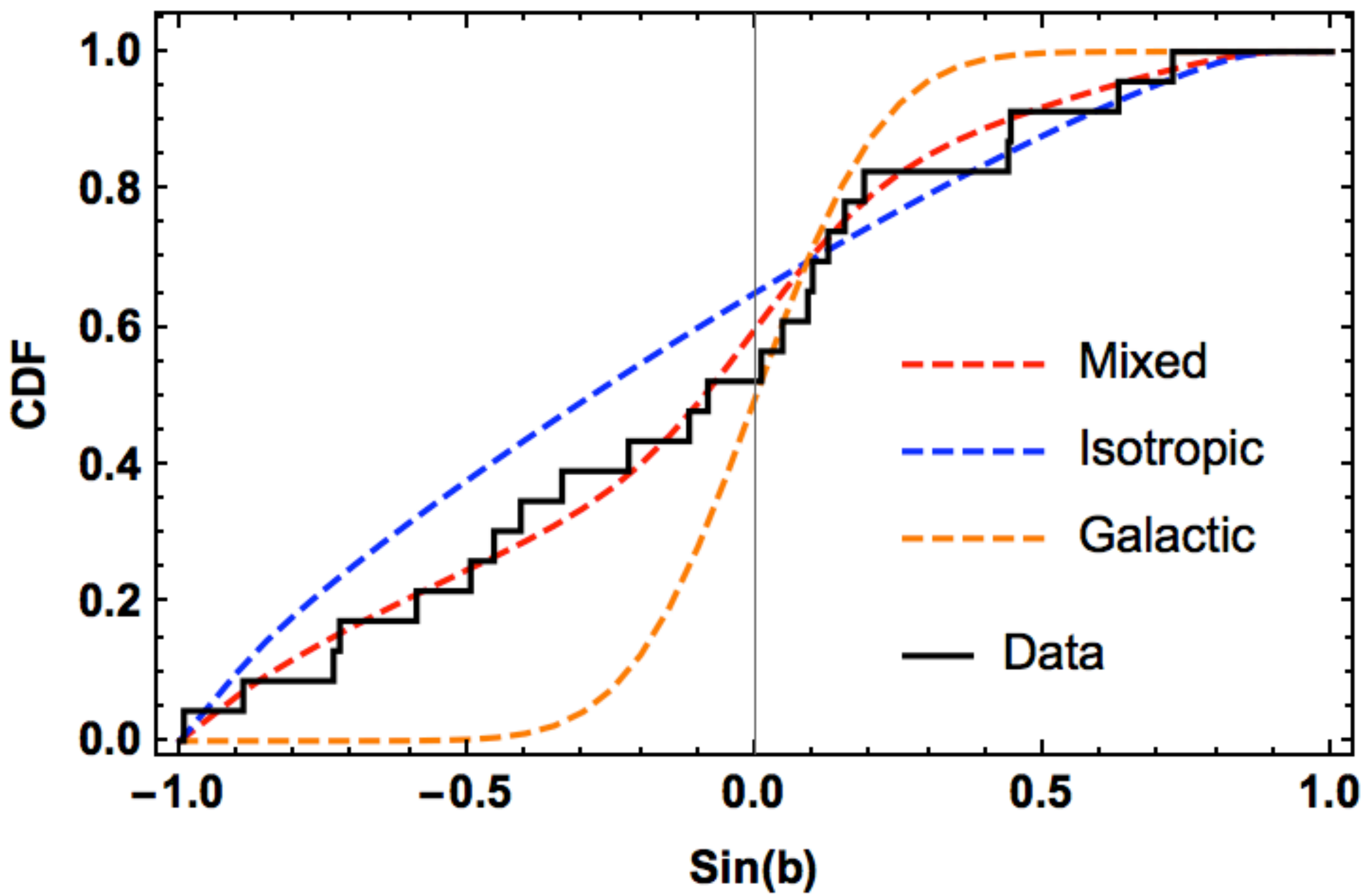
Multiple messengers and challenges in astroparticle physics
R. Aloisio, E. Coccia, F. Vissani
Springer (2018)

Tests of three hypotheses



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* !!!

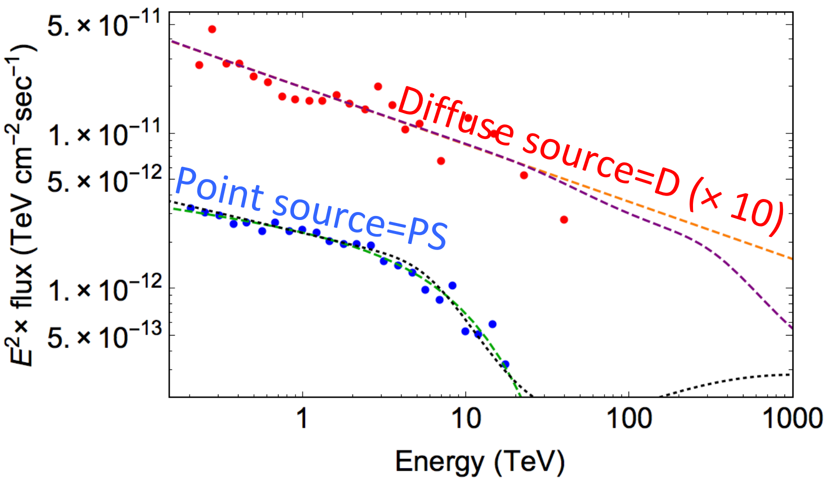
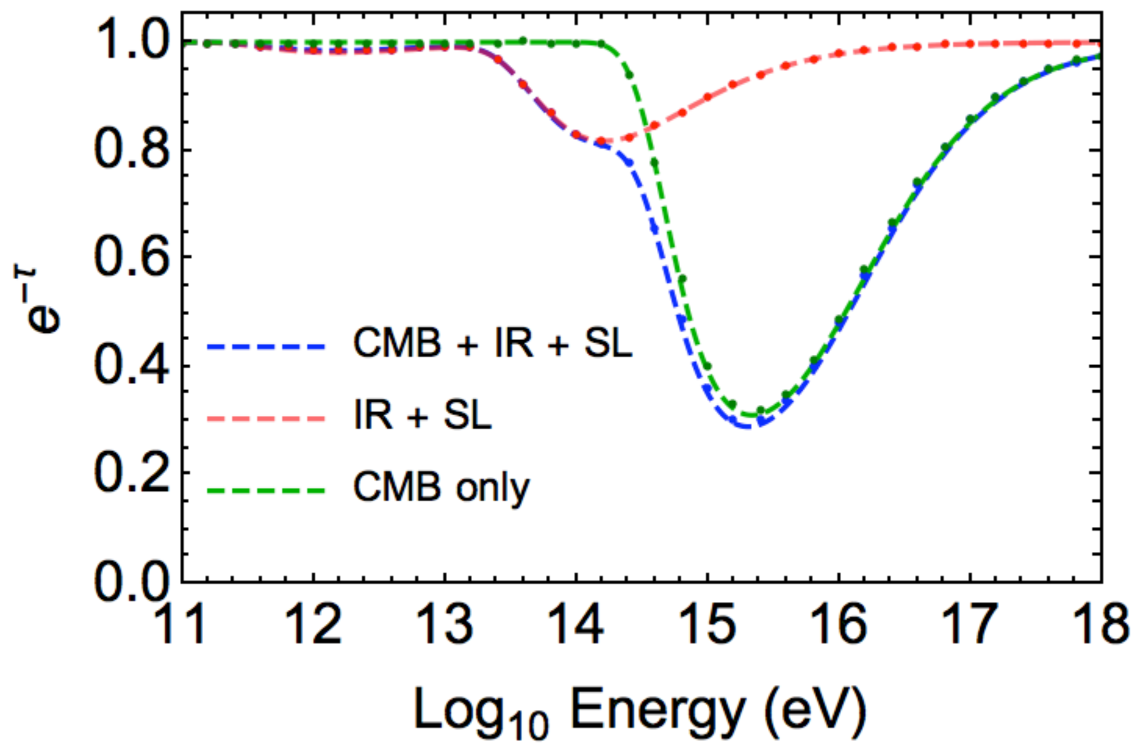


Table II. Spectral parameters from γ-ray HESS data: the search region (Point Source or Diffuse), the spectral index Γ, the flux normalization ϕ_0 in units of 10^{-12} TeV^{-1} cm^{-2} s^{-1} and the energy cut-off E_{cut} in TeV. Then the expected number of neutrinos per year from current neutrino detectors.

	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



Photon absorption

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

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:

$V_{cr} = \text{pi}\, R^2\, H$
(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

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, $F = (F_e, F_\mu, F_\tau)$.

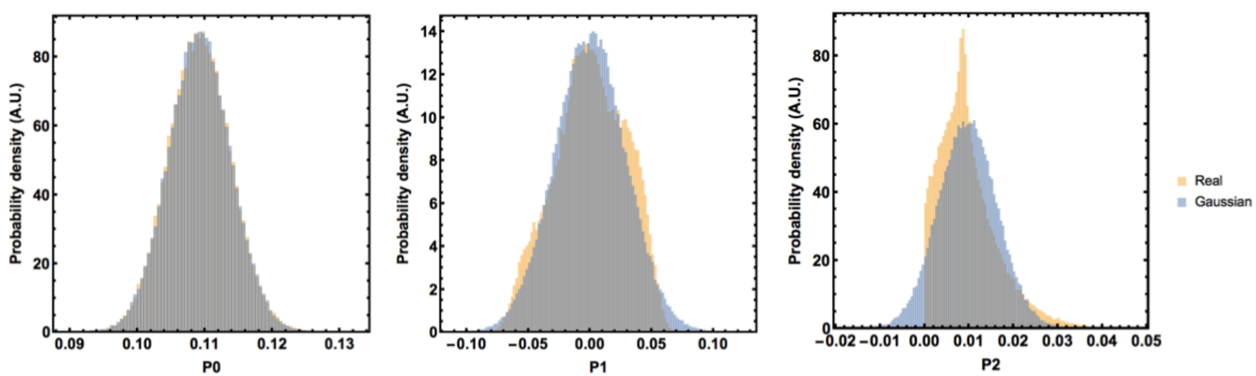


Figure 1: *Distribution of the natural parameters P_0, P_1 and P_2, due to the uncertainties in the mixing angles and the phase of leptonic CP violation.*

Palladino et al, , 1504.05238 EPJC

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

Alternative: display flavor fractions

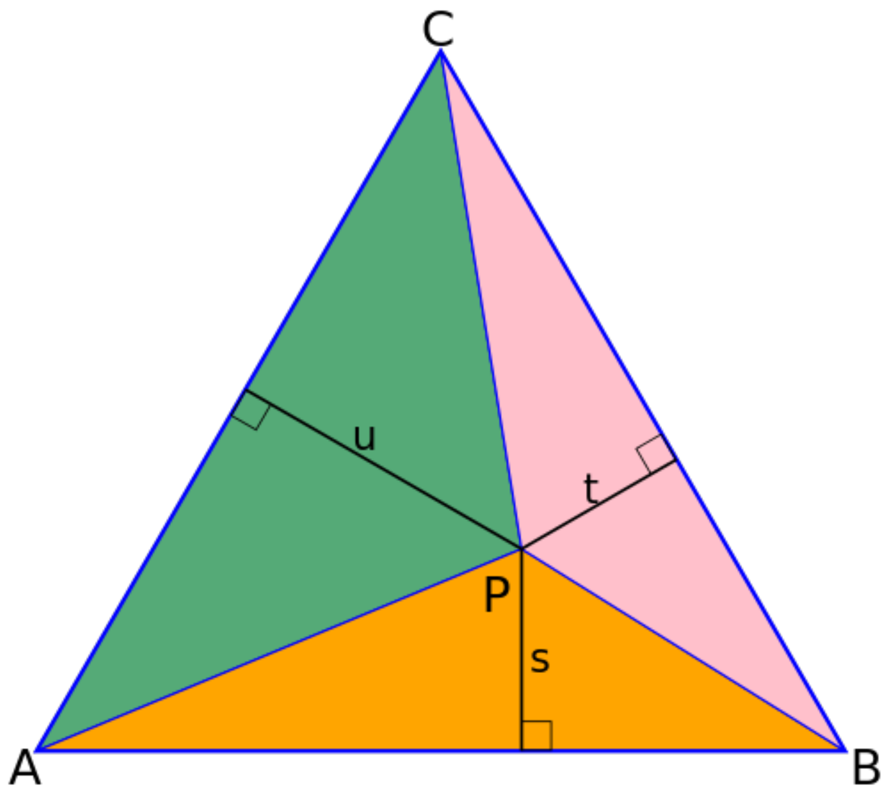
Consider the three fractions of flux (or flavor fractions) at Earth, e.g.,

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.

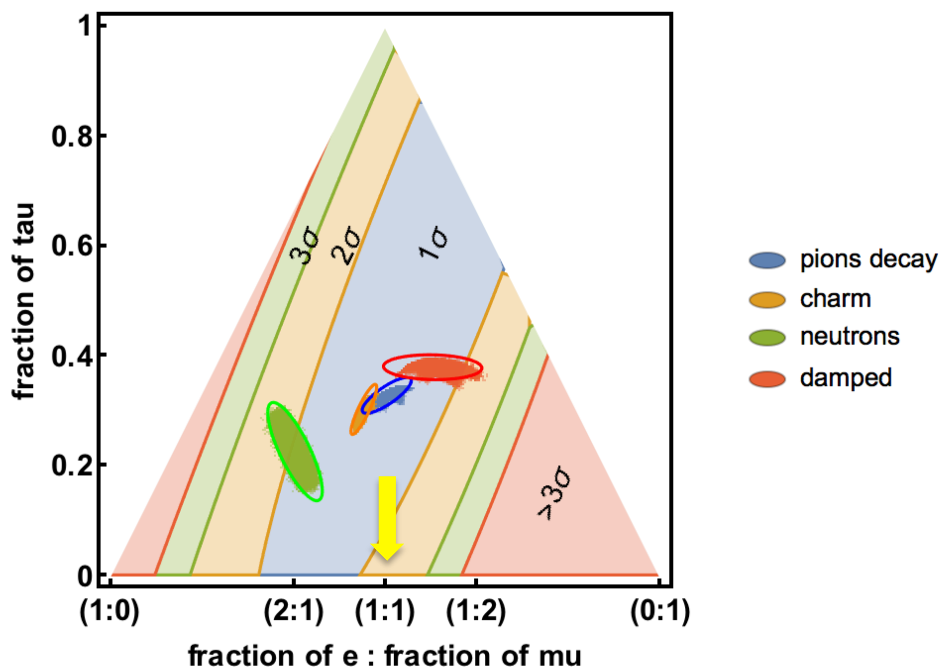
Note however that the flavor fraction at Earth is not directly observable; what we observe are event topologies.



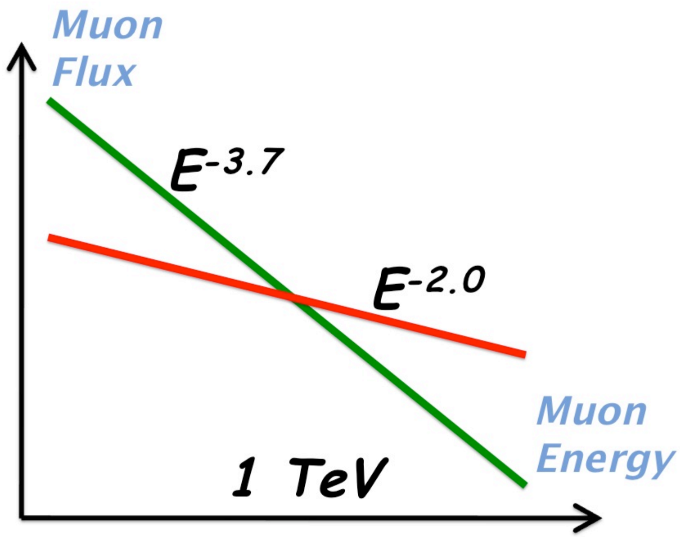
[From Wiki: Equilateral triangle's area, a h/2, equals the sum of the areas of the 3 colored triangles, a u/2+a t/2+a s/2=a (u+t+2)/2=a h/2 and we conclude: u+t+s=h. In math, this is called *Vivani's theorem*, after the name of one pupil of Galileo]

Predictions and observations

Palladino et al, 1504.05238 EPJC

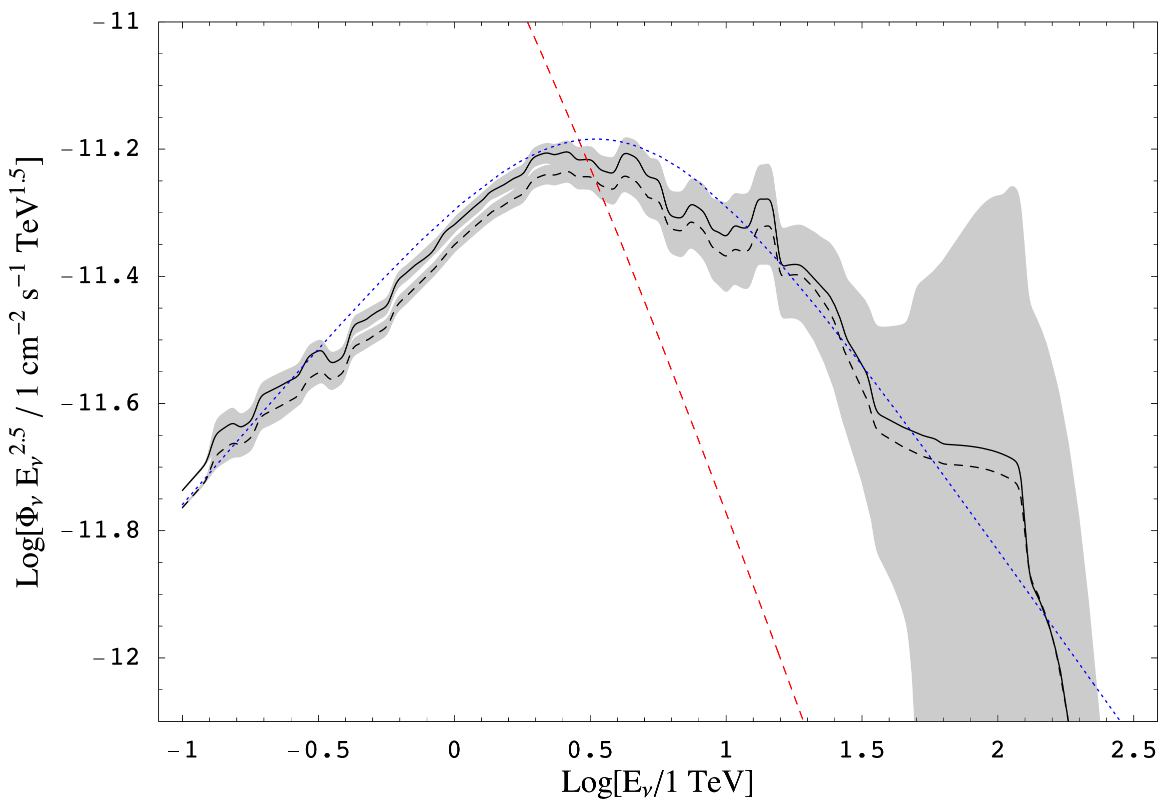


- The presentation *does not* use observable quantities
- But the predictions are independent from the slope
- This is based on 3 yr data set and assumes α=2.3.

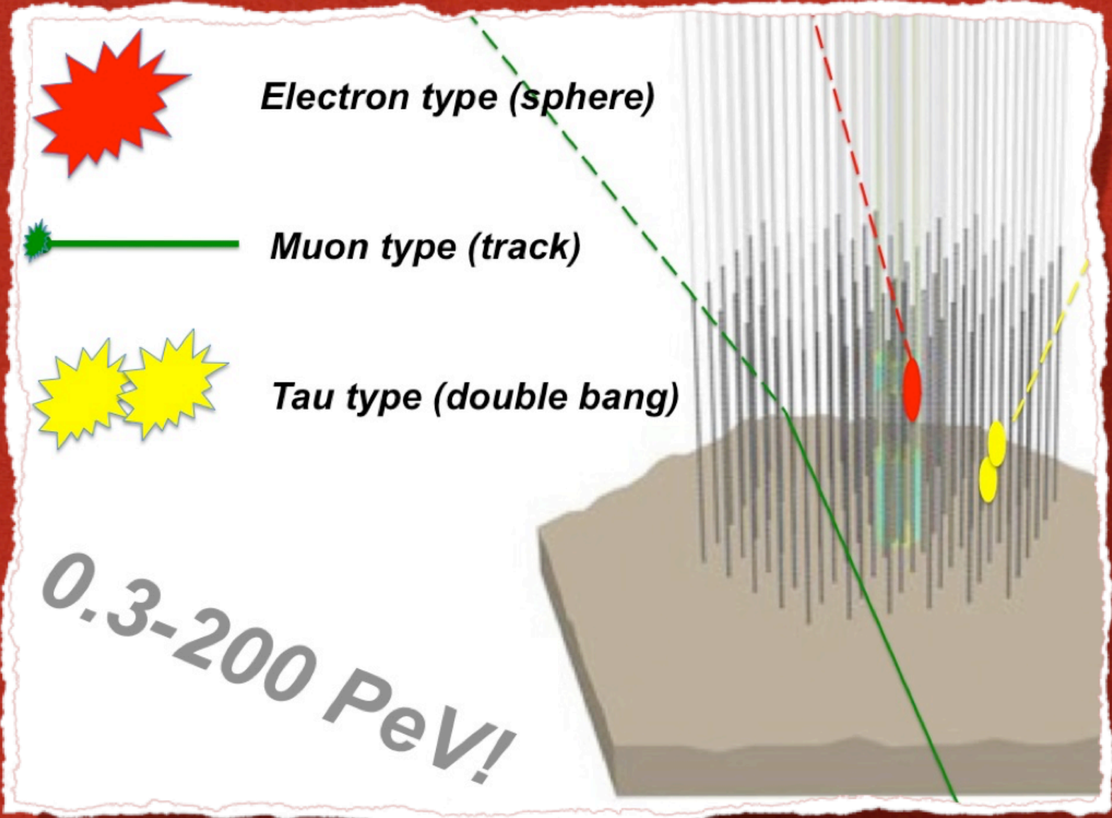


Left: our hope concerning the intensity of neutrino (point) sources as compared with the atmospheric one.

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



Villante & FV 08



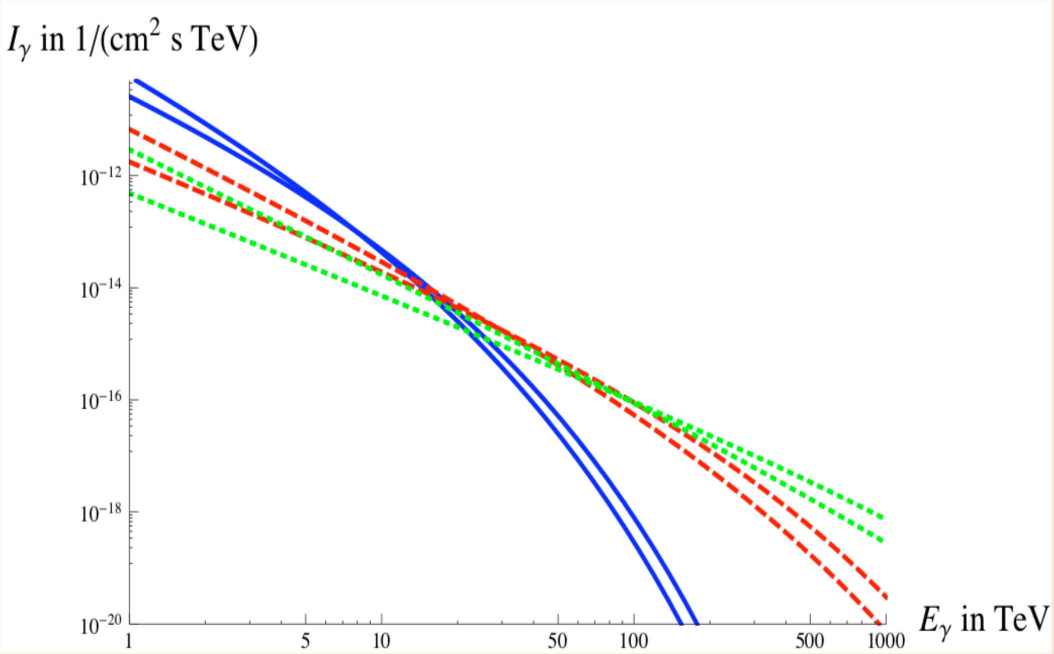
THERE IS ANOTHER TECHNIQUE

THAT ALLOWS TO HUNT FOR UHE, NON-MUONIC NEUTRINOS

2 Potential neutrino sources and γ-rays

Potential neutrino sources are characterized by their hadronic γ-rays $\langle$`distributed as` $I_\gamma \propto E_\gamma^{-\alpha} \cdot e^{-\sqrt{E_\gamma/E_c}}$, `with` $\alpha = 1.8 - 2.2$ `and` $E_c =$ `TeV`$-$ `PeV`$\rangle$ for π^0 and $\pi^\pm$ are produced together.

Figure 5: *γ-ray intensities corresponding to a signal of 1 muon/km^{2}yr above 1 TeV, evaluated assuming that the sources are transparent to their gamma rays.*



Note that:

Similar intensities $10 - 50$ TeV; all fluxes are in a narrow range:

$$I_\gamma(> 10 \text{ TeV}) = (1 - 2) \times 10^{-13}/(\text{cm}^2 \text{ s})$$

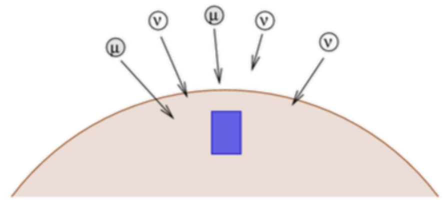
To collect $\geq 100\gamma$'s in a reasonable time, km^2 area needed:

$$\textbf{Exposure} = L^2 \times T \sim 2 \times \text{ km}^2 \times 10 \text{ h}$$

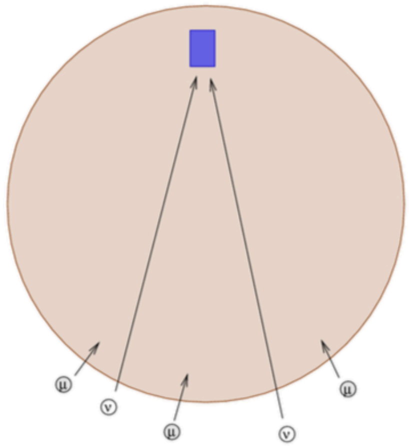
e.g., a 10×10 Cherenkov telescopes array, or one dedicated EAS array.

A large area γ apparatus, such as CTA or a custom instrument, would be invaluable for ν community and would cost $\sim 10\%$ of a ν-telescopes.

High energy neutrinos telescopes – the beginning



Induced μ's are the main practical way to cope with atmospheric μ's and probe high energy neutrinos, as understood by Markov end of 50's.

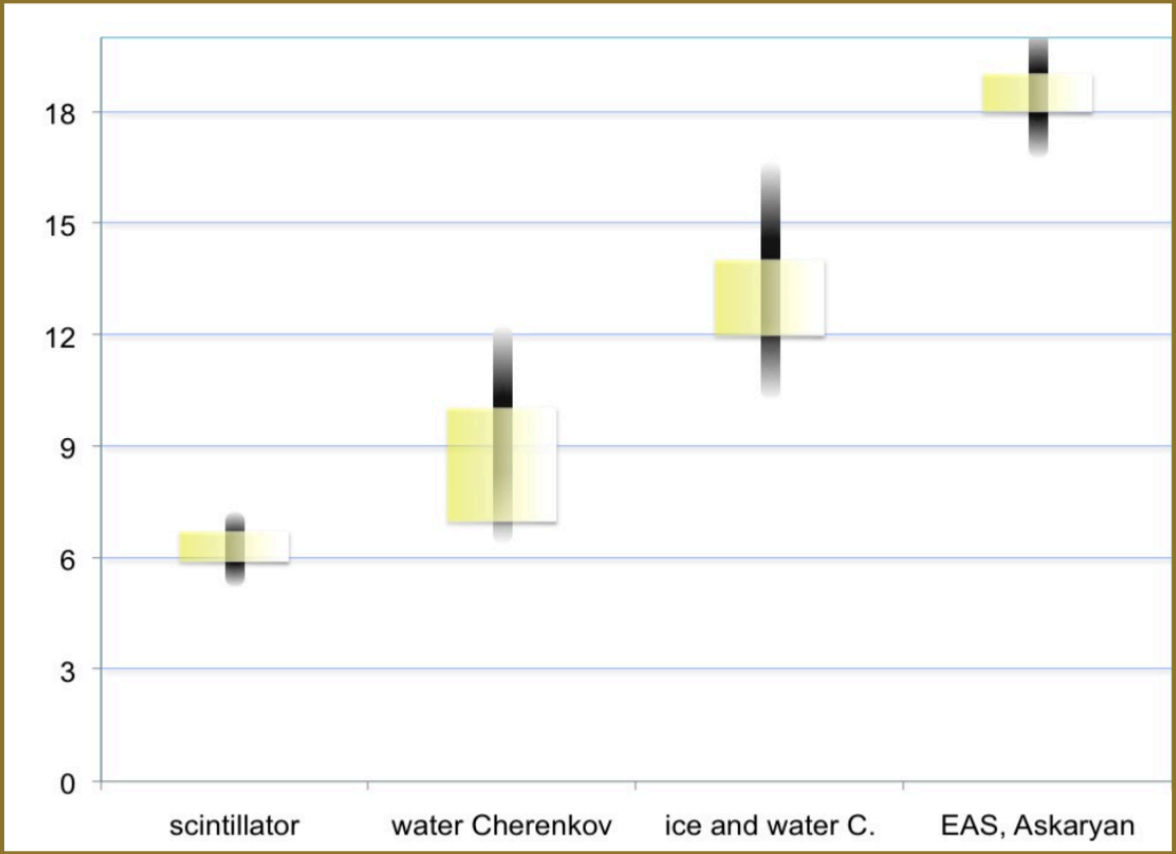


The muon range, dictated by e.m. interactions

$$R(E_\mu, E_{th}) \approx \mathbf{2.5\ km\ w.e.} \times \log \left[\frac{1 + \frac{E_\mu}{0.5\ \text{TeV}}}{1 + \frac{E_{th}}{0.5\ \text{TeV}}} \right]$$

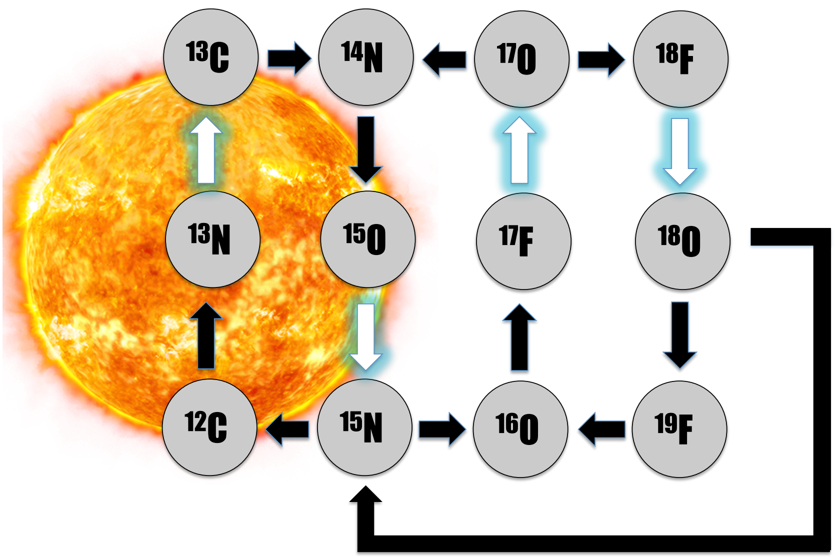
already indicates the size of ~ 1 km of ideal HE neutrino detectors.

We are now monitoring a huge range of energies



WHY NU-ASTRONOMY?

To study cosmic reactors: e.g., the CNO cycle of the Sun



To study cosmic accelerator: e.g., Supernova remnants

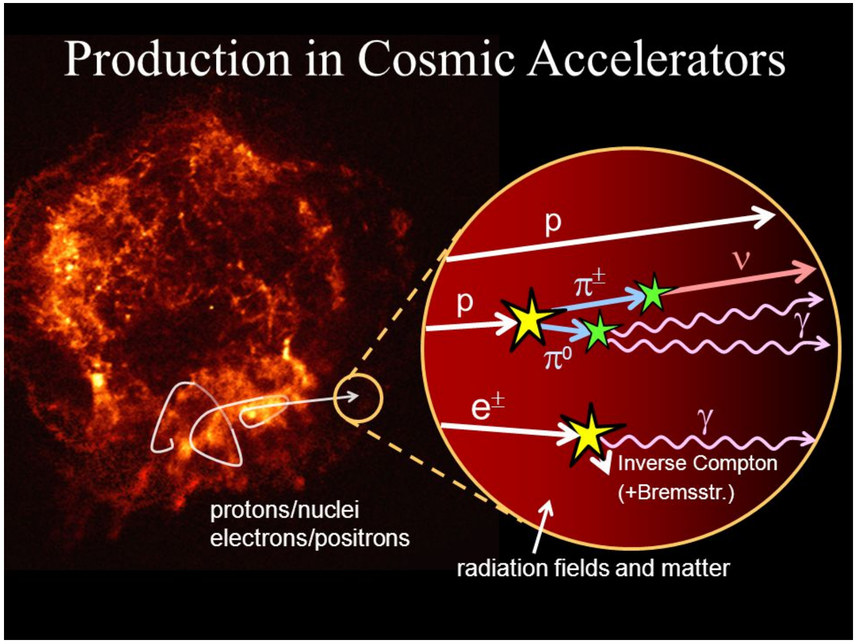
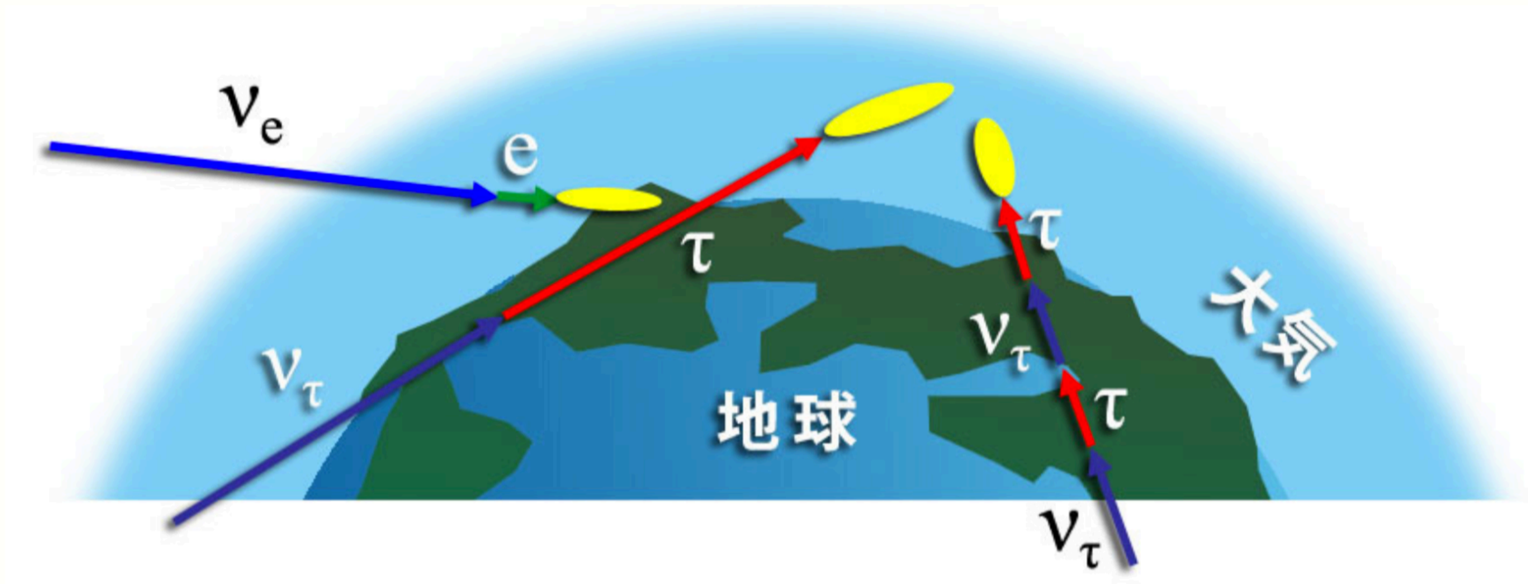


Figure 31: *Moreover, at UHE also tau (not only muon or electron) neutrinos propagate for long distances and can lead to an observable signal.*



But which are the sources: AGN, GRB, or what? The (even larger) uncertainty in the predictions would require more theoretical efforts.

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