ORIGIN OF THE HIGH-ENERGY NEUTRINO FLUX AT ICECUBE

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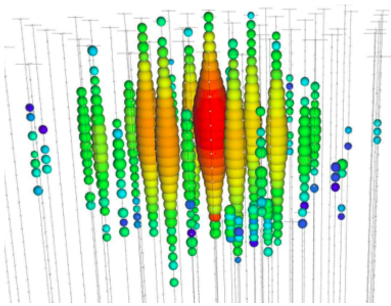
1. Atmospheric neutrinos
2. Diffuse flux of galactic neutrinos
3. Neutrinos from CR interactions with intergalactic matter
4. Fit of the IceCube data

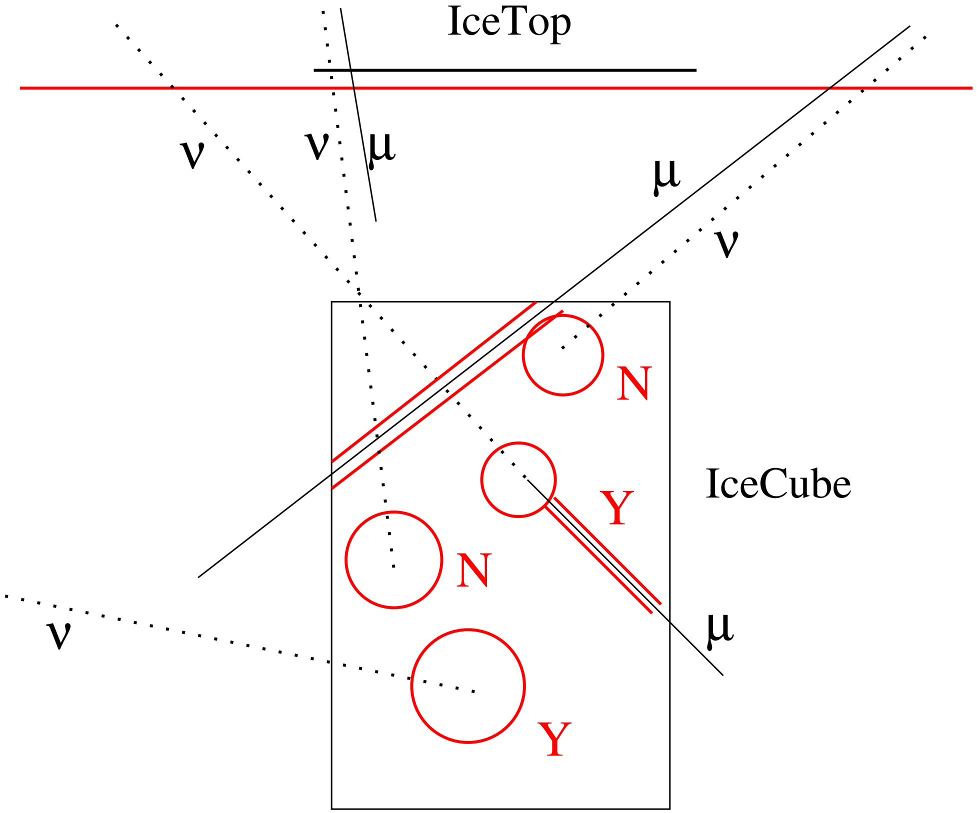
J.M. Carceller, M. Masip arXiv:1610.02552

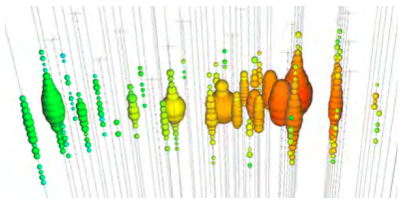
J.M. Carceller, J.I. Illana, M. Masip, D. Meloni in preparation

Lumley Castle MultiDark Multimessenger Approach for Dark Matter Detection November 2016

• IceCube can measure the energy ($E \geq 30$ TeV in this analysis), direction ($\pm 15^o$ for showers), time development (sinchronized with IceTop) and topology (shower or track) of an event: 54 events observed during a four year period







(some events may actually be atmospheric muons entering the detector)

- Atmospheric ν's from π/K decays:

(i) $(\nu_e : \nu_\mu : \nu_\tau) \approx (4 : 96 : 0)$

(ii) very steep flux, $\propto E^{-3.7}$

(iii) anisotropic, larger flux from horizontal directions (see plot)

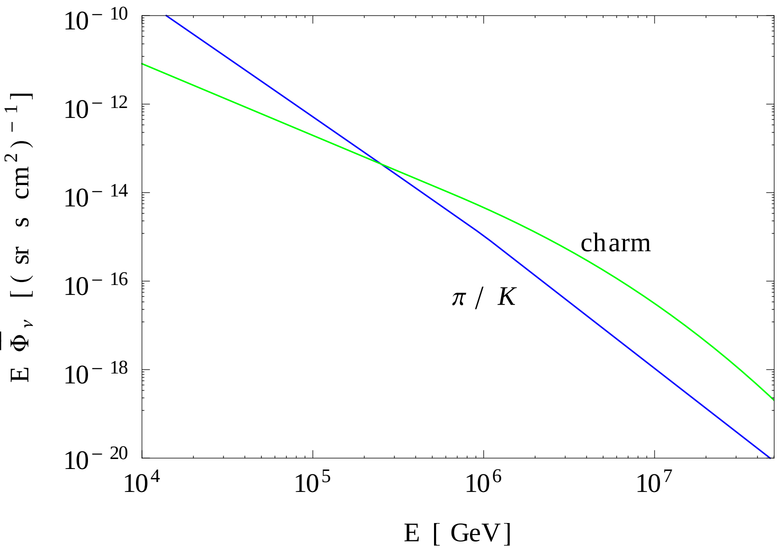
- Atmospheric ν's from charm decays:

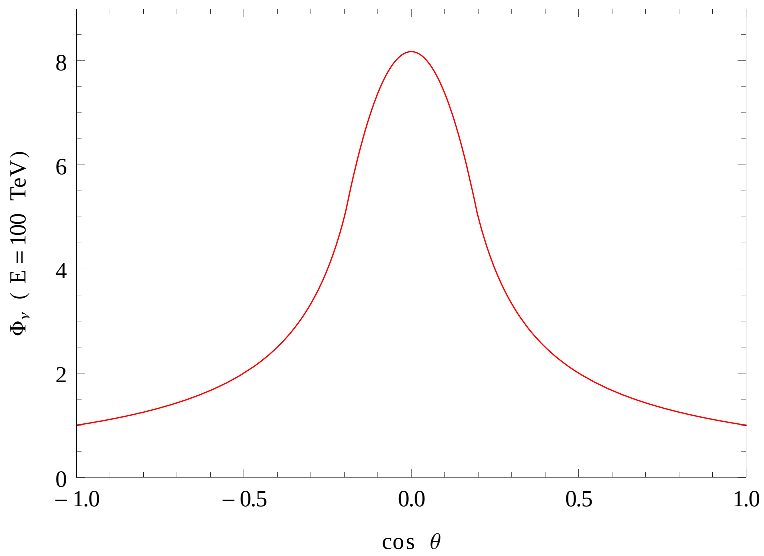
(i) $(\nu_e : \nu_\mu : \nu_\tau) \approx (48 : 48 : 2)$

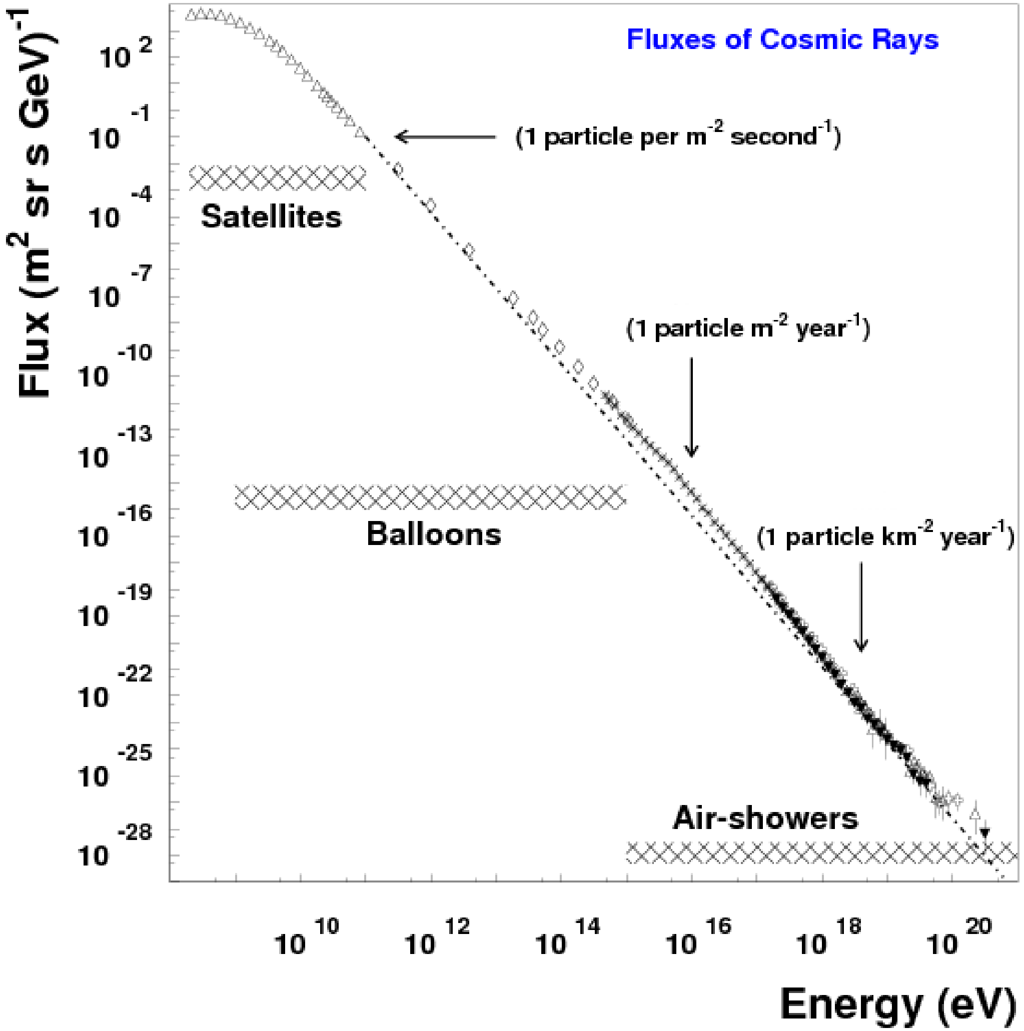
(ii) similar spectral index as cosmic rays, $\propto E^{-2.7}$

(iii) isotropic

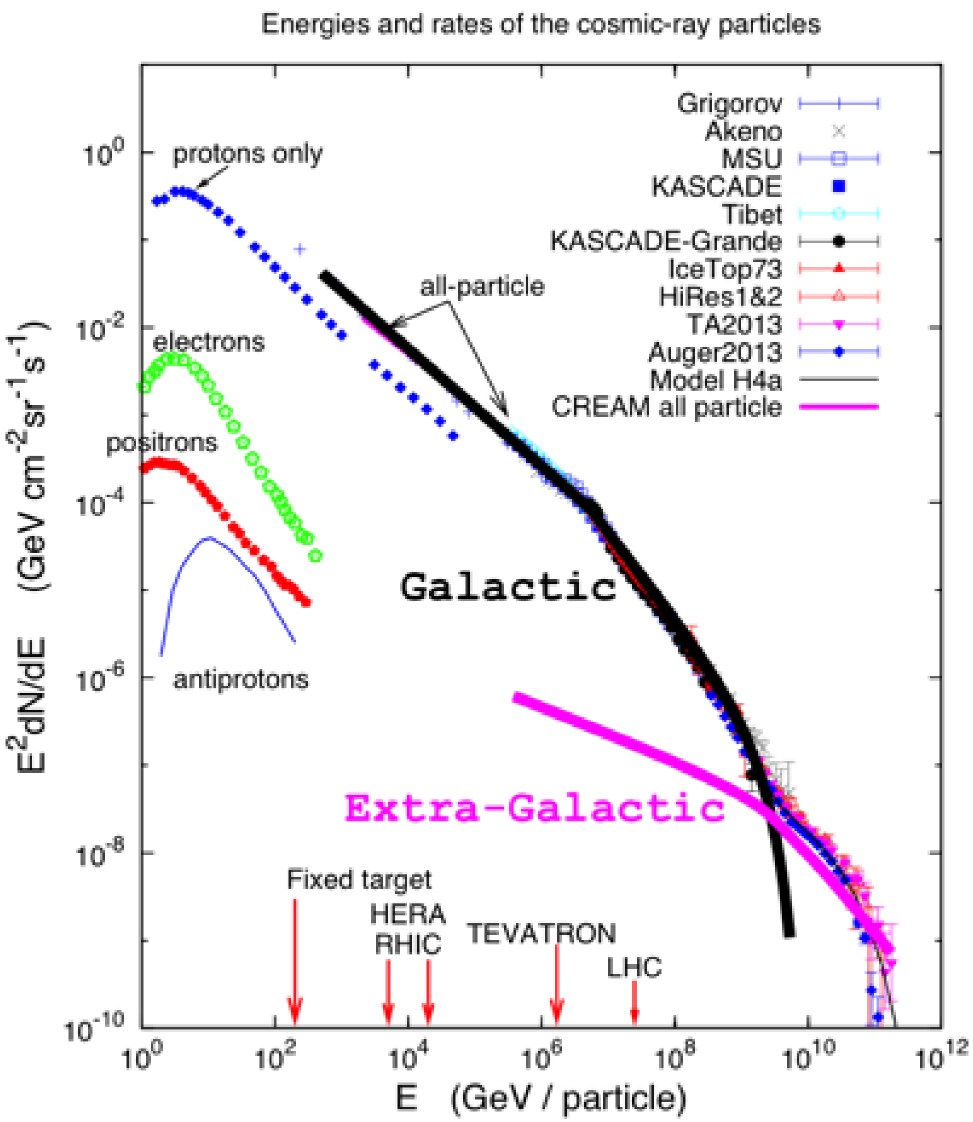
Charm neutrinos dominate at $E \gtrsim 250$ TeV ($E \gtrsim 10$ TeV for ν_e)







A single power law suggests an universal acceleration mechanism and universal propagation effects between the source and the Earth (both ends of the power law may be mere propagation effects)



(from an IceCube presentation)

- Up to $E_{\text{knee}} = 10^{6.7}$ GeV

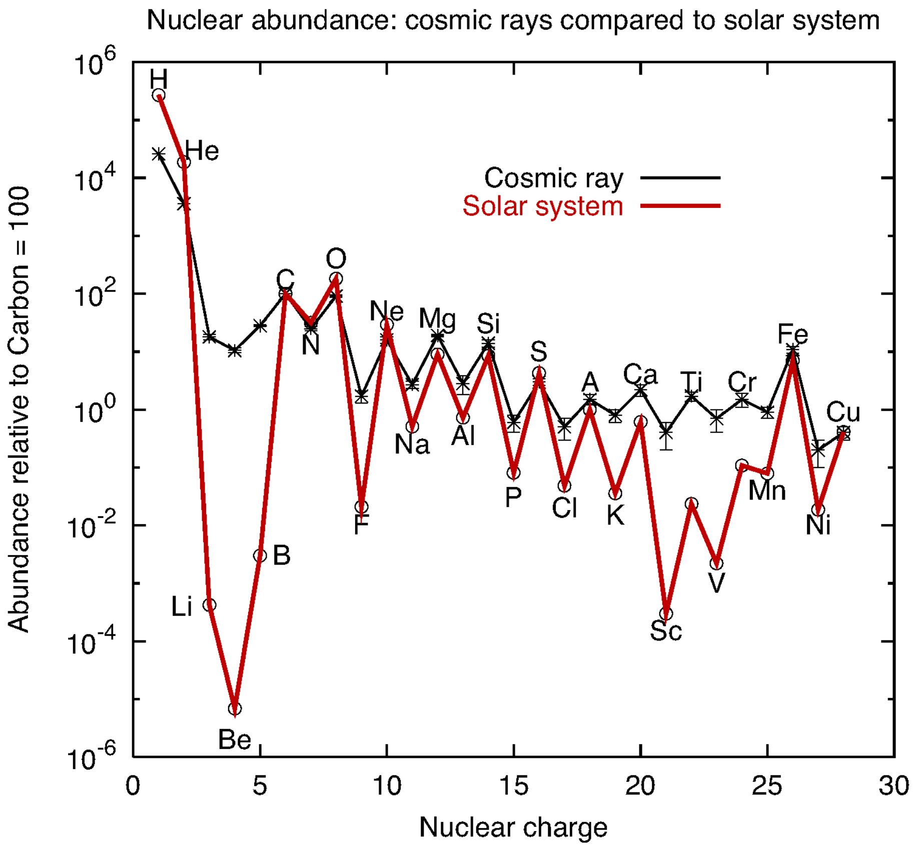
$$\Phi_p = 1.3 \left(\frac{E}{\text{GeV}}\right)^{-2.7} \quad \text{protons}/(\text{cm}^2\,\text{s}\,\text{sr}\,\text{GeV})$$

$$\Phi_{\text{He}} = 0.54 \left(\frac{E}{\text{GeV}}\right)^{-2.6} \quad \text{nuclei}/(\text{cm}^2\,\text{s}\,\text{sr}\,\text{GeV})$$

- Between E_{knee} and $E_{\text{ankle}} = 10^{9.5}$ GeV

$$\Phi = 330 \left(\frac{E}{\text{GeV}}\right)^{-3.0} \quad \text{nuclei}/(\text{cm}^2\,\text{s}\,\text{sr}\,\text{GeV})\,.$$

(uncertain composition)



• Almost perfect isotropy (0.1% level). Very long trajectories that lose memory of the position of the sources (random walk, *CR gas*)

• The relative abundance of light (Li, Be, B) to medium (C, N, O) nuclei can be used to deduce the length of their trajectories: 3 Mpc, much larger than the 0.3 kpc thickness or the 30 kpc diameter of the galactic disk

• CRs are accelerated at supernova remnants during $\tau < 10^3$ years and stay trapped in the galaxy by magnetic fields during $T \approx 10^7$ years

• CRs are accelerated at the sources with with a spectrum $\propto E^{-\alpha_s}$, and then they stay trapped for a long time τ inside the galaxy.

• The time they stay trapped (and all magnetic effects on their trajectories) depend on the *rigidity* $R = E/(ZeB)$. Basic diffusion theory with a Kraichnan spectrum of magnetic turbulences gives a suppression $\tau \propto E^{-0.5}$

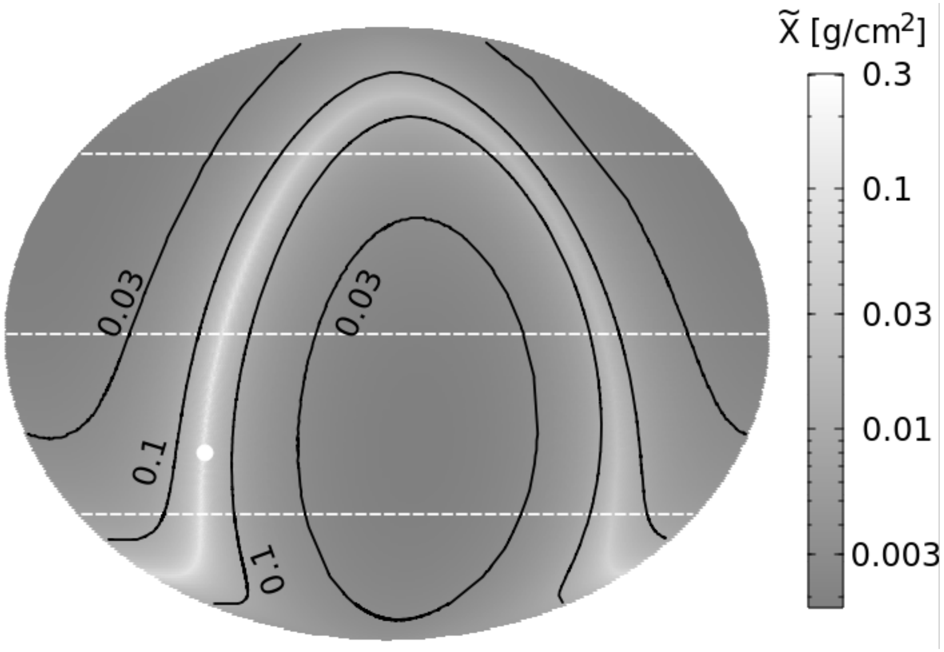
1. $E < E_{\text{knee}}$ $\quad \Phi_p \propto E^{-2.2} \times E^{-0.5} = E^{-2.7}$ $\quad \Phi_{\text{He}} \propto E^{-2.1} \times E^{-0.5} = E^{-2.6}$

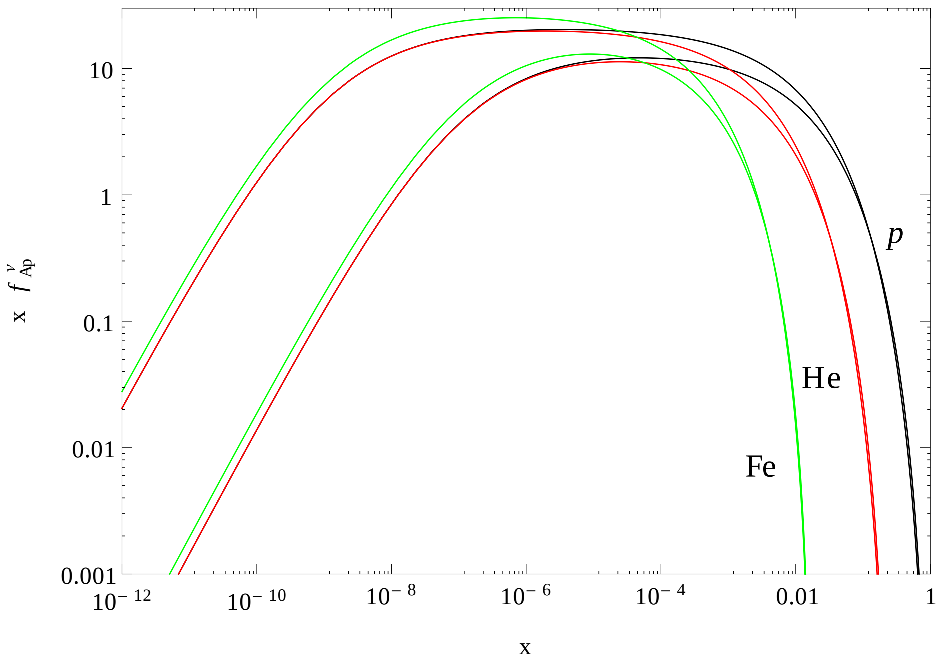
   $E > E_{\text{knee}}$ $\quad \Phi_A \propto E^{-2.5} \times E^{-0.5} = E^{-3}$

2. The density of CRs will be a factor of $(B/B_0)^{0.5}$ larger in regions of the galaxy where the average magnetic field strength is larger ($B_0 \approx 4\ \mu$G). In the galactic disk B changes radially in an e-fold every 8.5 kpc, while in the (60 kpc) halo it is 4 times smaller than here (GC: $\Phi = 1.6\,\Phi_0$; GH: $\Phi = 0.5\,\Phi_0$)

• These CRs are filling the galaxy, where they may collide with interstellar gas (hydrogen and helium) and produce a diffuse gas of galactic neutrinos

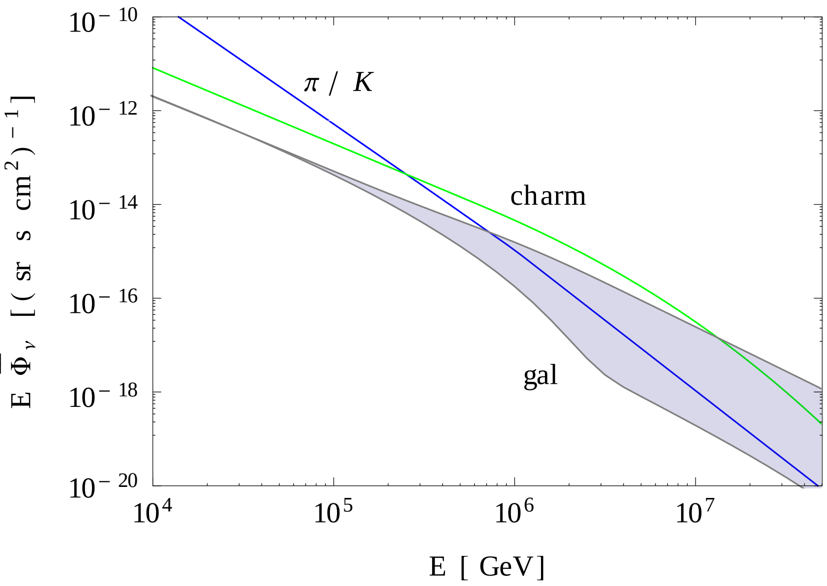
$$\Phi_\nu(E,\vec{u}_r) = \sum_A \frac{F_A}{m_p} \int_0^\infty \mathrm{d}r\, g(\vec{r})\, \rho_{IS}(\vec{r}) \int_0^1 \mathrm{d}x\, \sigma_{Ap}(E/x)\, \Phi_A^0(E/x)\, x^{-1} f_A^\nu(x,E/x)$$

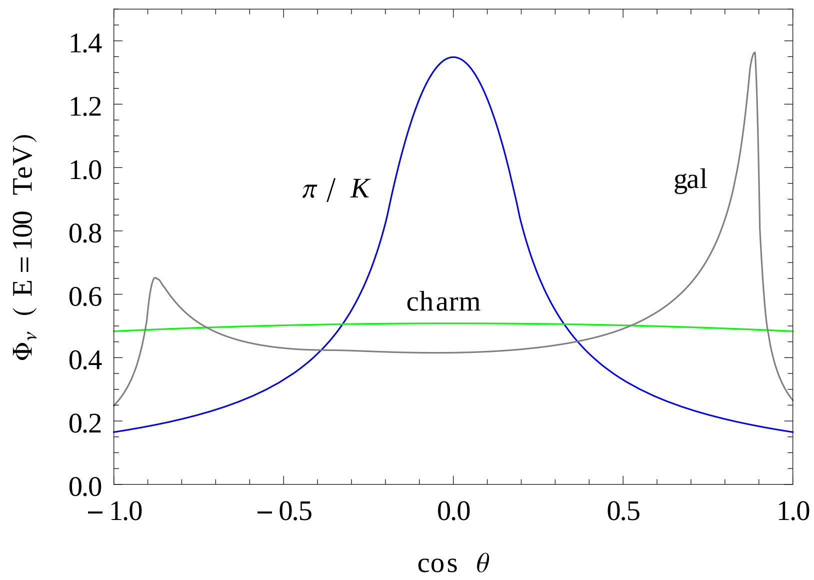




Effective depth for the gas distribution (thin disk, thick disk and halo) in Kalberla & Kerp (2007)

$f_A^\nu(x,E)$: number of ν's produced in Ap collisions carrying a fraction x of the incident energy ($E = 10^{6,8}$ GeV) for p, He, and Fe (EPOS-LHC)





- At 100 TeV $\Phi_{\rm Gal} \approx 0.28\,\Phi_{\rm charm}$ and $\Phi_{\rm charm} \approx 0.30\,\Phi_{\pi/K}$

$$(\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau) = \frac{1}{6}(1.13 : 1.07 : 0.99 : 0.91 : 0.99 : 0.91) \quad \text{proton}$$

$$(\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau) = \frac{1}{6}(1.04 : 1.06 : 0.97 : 1.00 : 1.00 : 0.93) \quad \text{He, Fe}$$

- $\Phi_{\rm Gal}$ has similar spectrum as $\Phi_{\rm charm}$ (subleading at all IceCube energies but with a different angular distribution)

- Large uncertainty related to the possible CR composion at $E \geq E_{\rm knee}$ (left)

- Data is not reproduced by atmospheric contributions, galactic neutrinos are a small correction

	Data	Atm	Gal	Data	Atm	Gal	Data	Atm	Gal	
Tracks	2	1.0+0.1	0	1	0.1+0	0	0	0+0	0	UPGOING
Showers	6	0.4+0.5	0.1	1	0+0.2	0.1	0	0+0.1	0	$(+20^\circ < \delta < +90^\circ)$
Tracks	3	3+3.9+0.2	0	1	0.7+0.1	0	0	0.1+0	0	HORIZONTAL
Showers	8	1+1.8+0.6	0.2	2	0.3+0.3	0.1	1	0.1+0.1	0	$(-20^\circ < \delta < +20^\circ)$
Tracks	7	6+0.3+0	0.1	0	0.1+0	0	1	0+0	0	DOWNGOING
Showers	9	1+0.1+0.2	0.3	9	0+0.1	0.1	3	0+0	0.1	$(-90^\circ < \delta < -20^\circ)$
Total	35	11+7.5+1.6	0.7	14	1.2+0.6	0.3	5	0.2+0.2	0.1	
	30–100 TeV			100–300 TeV			300–3000 TeV			

• The spectrum I_A at the source is corrected by the propagation, that introduces a suppression proportional to $(E/Z)^{-0.5}$:

$$\Phi_p = c \times I_p \times E^{-0.5}\ ;\ \ \Phi_{\rm He} = c \times I_{\rm He} \times (E/2)^{-0.5} \qquad E < E_{\rm knee}$$

$$\Phi_A = c \times I_A \times (E/Z)^{-0.5} \qquad E > E_{\rm knee}$$

• Therefore, we can deduce the relative production of each species by the sources (E in GeV):

$$I_p + I_{\rm He} = c' \ \left(E^{-2.2} + 0.29\ E^{-2.1}\right) \qquad E < E_{\rm knee}$$

$$I_A = c' \ \frac{254}{\sqrt{Z}}\ E^{-2.5} \qquad E > E_{\rm knee}$$

• The CR flux we see is stationary: the rate of CRs leaving the galaxy into the intergalactic space coincides with the number of CR produced at the sources. Our galaxy is emitting a CR flux with this spectrum and relative composition

• If the acceleration mechanism is universal (all galaxies have same type of sources: SN remnants, pulsars, etc...) then you expect this CR spectrum is filling the intergalactic space

In addition to the atmospheric ν's, we may then distinguish 3 other components:

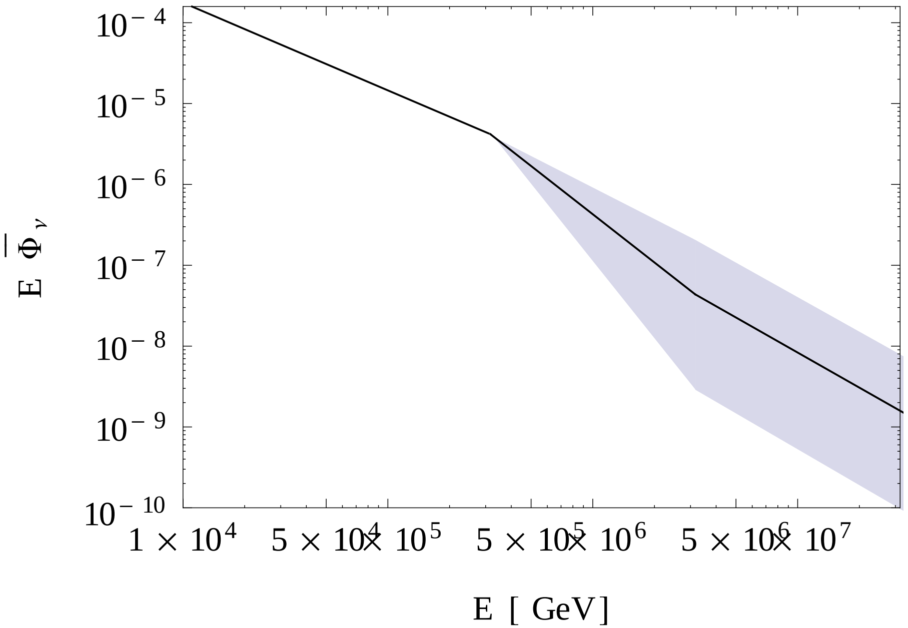
• Galactic neutrinos from collisions of CRs trapped in our galaxy with IS matter. This component is way too low to account for the number of events at IceCube and it is concentrated near the galactic plane.

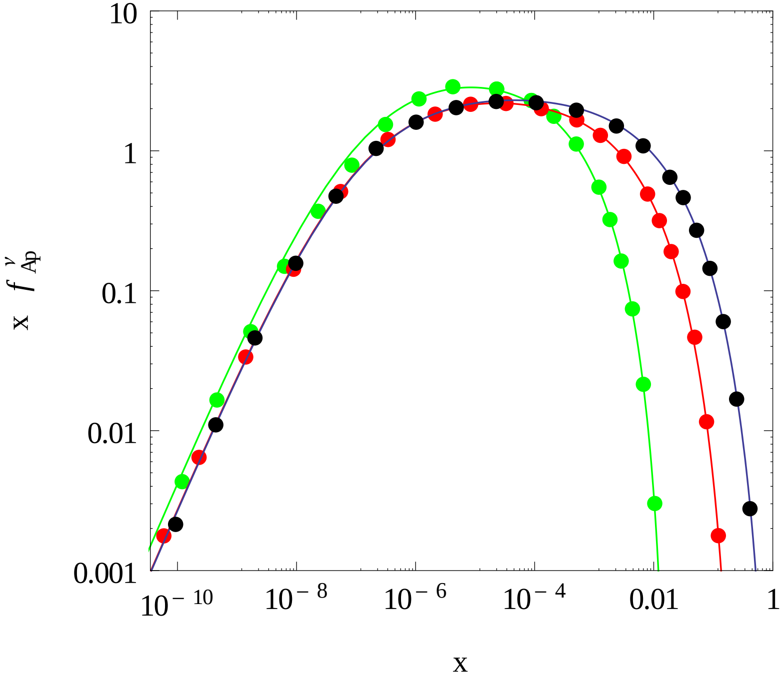
• Neutrinos emitted by other galaxies (produced in collisions of CRs trapped inside other galaxies). Since both the CR sources (SN remnants, pulsars, ...) and the magnetic turbulences that trap them are universal, we expect a spectrum similar to the previous one. This ν flux, from the ensamble of all galaxies, would be more isotropic than the diffuse galactic one, but its $E^{-2.6}$ spectrum seems too steep to account for the IceCube events ($E^{-2.0}$–$E^{-2.5}$).

• Neutrinos produced in collisions of CRs emitted (not trapped!) by all galaxies (including ours) with intergalactic matter. These collisions provide a diffuse ν flux with a $E^{-2.1}$ spectrum below the knee that may explain the IceCube data

We can calculate it up to an overall normalization

$$\bar{\Phi}_\nu(E) \approx R\,\bar{\rho}_{IG} \sum_A \frac{F_A\,\sigma^0_{Ap}\,C_A}{m_p}\,E^{-(\alpha_A-\beta_A)} Z^\nu_A \quad \text{with} \quad Z^\nu_A = \int_0^1 \mathrm{d}x\, x^{\alpha_A-\beta_A-1} f^\nu_A(x)$$



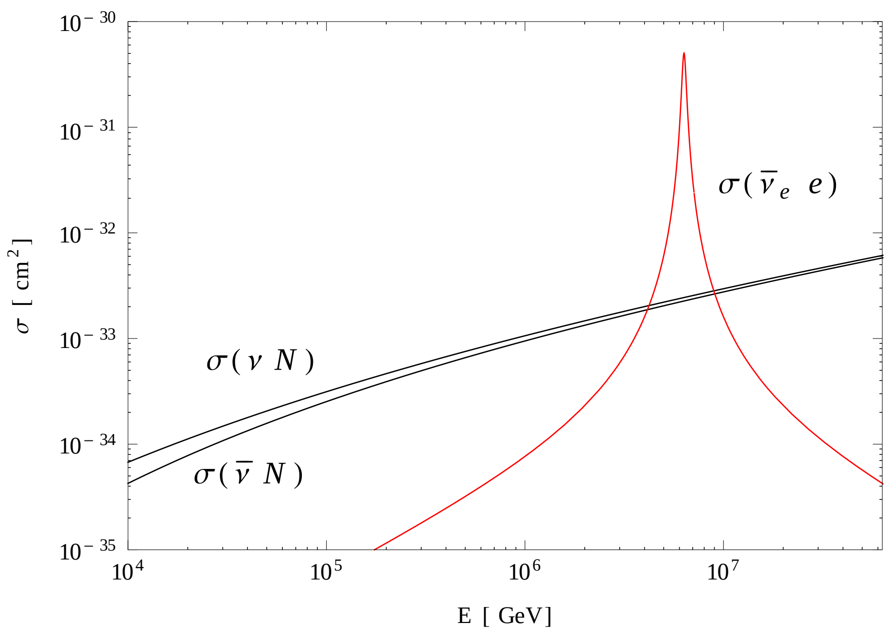


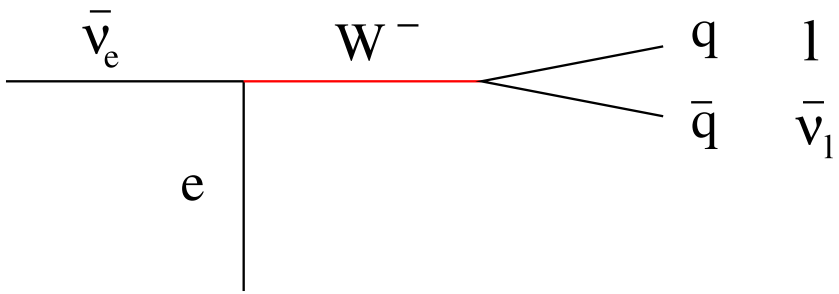
$$\bar{\Phi}^{IG}_\nu = N\left(3.2\,E^{-2.12} + 1.0\,E^{-2.04}\right) \qquad E < 10^{5.5}\ \text{GeV}$$

$$\bar{\Phi}^{IG}_\nu = N \times \begin{cases} 350\,E^{-2.42} & \text{(proton)} \\ 110\,E^{-2.44} & \text{(helium)} \\ 11\,E^{-2.47} & \text{(iron)} \end{cases} \qquad E > 10^{6.5}\ \text{GeV}$$

• A change in the CR composition at E_{knee} may produce a dip at ≈ 1 PeV in the IG neutrino flux that *disconnects* the low and the high energy power laws

• This could improve the fit of the IceCube data at $E \approx 6.3$ PeV: the Glashow resonance has not been observed yet. *Flatter* spectra ($\propto E^{-2}$) are currently (after the fourth year of data at IceCube) disfavoured respect to the steeper ones ($\propto E^{-2.5}$)



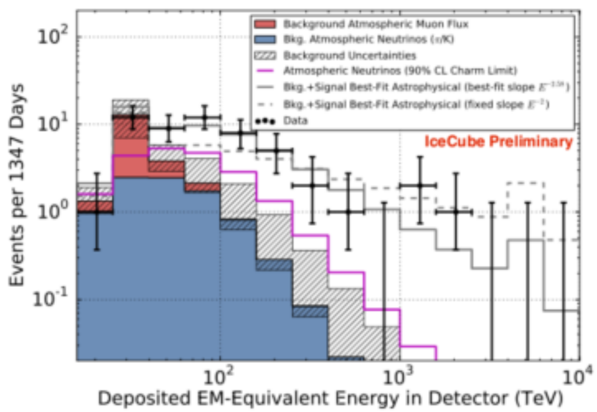


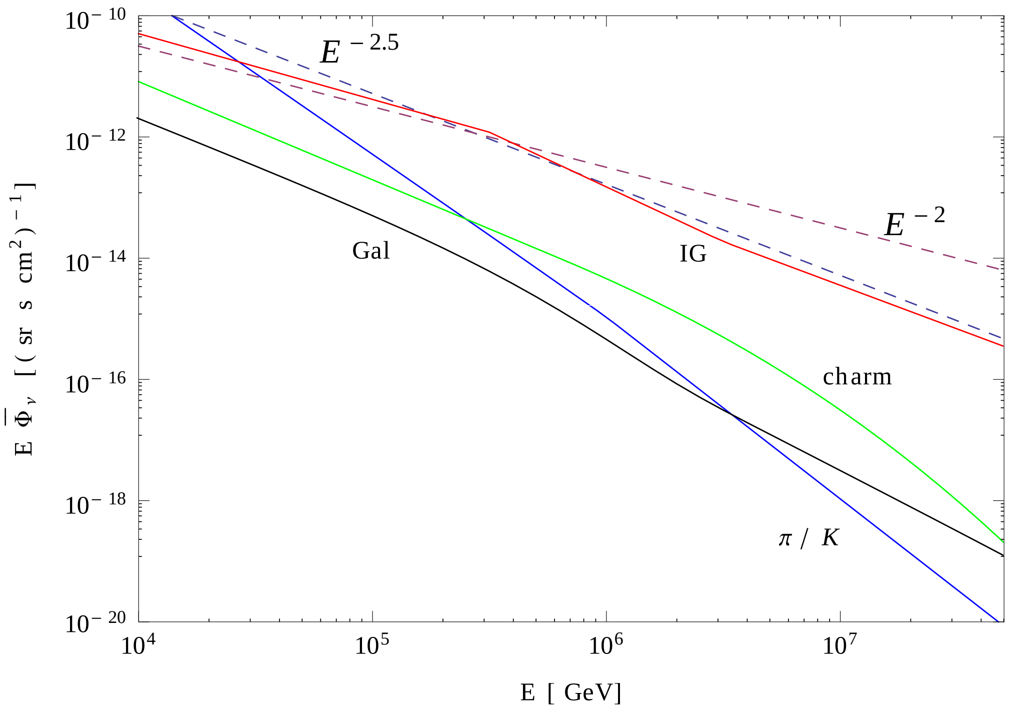
Its discovery will be essential to calibrate de detector at PeV energies

	Excess	E^{-2} $E^{-2.5}$	IG	Excess	E^{-2} $E^{-2.5}$	IG	Excess	E^{-2} $E^{-2.5}$	IG	
Tracks	0.9	0.4 1.0	0.6	0.9	0.3 0.4	0.4	0	0.1 0.1	0.1	UG
Showers	5.0	1.7 4.1	2.6	0.7	1.1 1.5	1.5	-0.1	0.6 0.4	0.5	
Tracks	-4.1	0.7 1.6	1.0	0.2	0.6 0.8	0.8	-0.1	0.7 0.4	0.4	NH
Showers	4.4	2.8 6.6	4.2	1.3	2.6 3.5	3.5	0.8	2.8 1.9	1.9	
Tracks	0.6	0.7 1.6	1.0	-0.1	0.7 0.9	0.9	1	0.8 0.5	0.5	DG
Showers	7.4	2.9 6.7	4.2	8.8	2.8 3.7	3.7	2.9	3.2 2.1	2.1	
Total	14.2	9.3 21.6	13.6	11.8	8.1 10.8	10.9	4.5	8.2 5.5	5.4	
	30–100 TeV			100–300 TeV			0.3–3 PeV			

Events at 3–10 PeV (Glashow resonance):

E^{-2}: 3.2 $E^{-2.5}$: 0.7 IG: 0.4





• Neutrinos come from CR collisions. We should not expect an unbroken power law at PeV energies since there is a change in the CR spectral index at $E_{\rm knee} \approx 5$ PeV

• A drop in the astrophysical neutrino flux could be due to a change in the CR composition at $E_{\rm knee}$

• Let us wait for higher statistics at IceCube and the discovery (or not) of the Glashow resonance