High energy diffuse galactic neutrinos for different cosmic ray distributions

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The IceCube HESE events



The **energies** and **arrival directions** of High Energy Starting Events (HESE) in IceCube are compatible with an **isotropic population of HE cosmic neutrinos**.

The best fit (one-flavour) angle-integrated neutrino flux is (4yr data):

$$\mathcal{F}_{\rm iso}(E_{\nu}) = 8.72 \times 10^{-6} \left[\frac{E_{\nu}}{100 \,{\rm TeV}}\right]^{-2.58} \,{\rm GeV}^{-1} \,{\rm m}^{-2} \,{\rm y}^{-1}$$

IceCube collaboration, ICRC, PoS 2016

The IceCube HESE events



- No doubts that cosmic neutrinos have been detected (Obs. Events/Expt.Bkgd = 54/20).
 Sources are still unknown.
- No evidence for spatial clustering of the data or correlation with potential sources has been found up to now.
- Tension is emerging between the energy distribution of HESE events (lower energy, mostly from southern sky) and that of passing muons (higher energy, mostly from northern sky) → Hints for a break in the astrophysical neutrino spectrum ???

Hints for a Galactic contribution?

Neronov & Semikoz 2015 – The galactic latitude distribution of the 4y IceCube data with $E_{dep} > 100$ TeV is inconsistent at 3 σ with the assumption of an isotropic neutrino flux.

Palladino & Vissani 2016 – The data are better fitted by a two-component flux

$$\mathcal{F}_{\rm EG}(E_{\nu}) = 2.8 \times 10^{-6} \left[\frac{E_{\nu}}{100 \,{\rm TeV}}\right]^{-2} \,{\rm GeV^{-1} \,m^{-2} \,y^{-1}}$$

Extra-galactic = Isotropic

$$\mathcal{F}_{\rm G}(E_{\nu}) = 1.7 \times 10^{-6} \left[\frac{E_{\nu}}{100 \,{\rm TeV}} \right]^{-2.7} \,{\rm GeV^{-1} \,m^{-2} \,y^{-1}}$$

Galactic = uniform in the southern sky

The fraction f of the astrophysical neutrino signal due to galactic emission can be limited by event arrival direction distribution:

- Ahlers et al 2016: $f \le 50\%$ (at 90% CL)

[diffuse galactic neutrino emission assumed to follow the gas column depth]

Denton et al 2017: f ≈ 0.07^{+0.09}-0.06 (at 68% CL)
 [galactic neutrino production assumed to follow mass distribution in the disk (McMillan 2011)]



The HE galactic diffuse neutrino flux

The interaction of HE cosmic rays (CRs) with the gas contained in the galactic disk is a **guaranteed** source of HE neutrinos

The flux of HE neutrinos produced at Earth can be written as:

$$\varphi_{\nu}(E_{\nu},\hat{n}_{\nu}) = \frac{1}{3} \sum_{\ell=e,\mu,\tau} \left[\int_{E_{\nu}}^{\infty} dE \int_{0}^{\infty} dl \, \frac{d\sigma_{\ell}(E,E_{\nu})}{dE_{\nu}} \, \times \varphi_{\mathrm{CR}}(E,\mathbf{r}_{\odot}+l\,\hat{n}_{\nu}) \, \times \, n_{\mathrm{H}}(\mathbf{r}_{\odot}+l\,\hat{n}_{\nu}) \right]$$

where:

$$\sum_{\ell=e,\mu,\tau} \frac{d\sigma_{\ell}(E,E_{\nu})}{dE_{\nu}} = \frac{\sigma(E)}{E} \left[F_{\nu_{\mu}} \left(E_{\nu}/E, \ E \right) + F_{\nu_{e}} \left(E_{\nu}/E, \ E \right) \right]$$
nucleon-nucleon cross section
[Kelner & Aharonian, PRD 2008, 2010]

$$n_{\rm H}({f r})$$
 Gas density – same as Galprop
[http://galprop.stanford.edu]

 $\varphi_{\rm CR}(E,{f r})$ Differential CR flux - See next slides

<u>N.B.</u> We assume $(v_e: v_{\mu}: v_{\tau}) = (1:1:1)$ as expected due to flavour oscillations

The CR flux: local determination

The neutrino flux at $E_v = 100 \text{ TeV}$ is determined by CR flux at:

 $E \simeq 20 E_{\nu} = 2 \,\mathrm{PeV}$

At the Sun position the CR flux is constrained by observational data [CREAM, KASCADE, KASCADE-Grande]

$$\varphi_{\rm CR,\odot}(E) \equiv \sum_{A} A^2 \frac{d\phi_A}{dE_A d\Omega_A} (AE)$$



<u>Note that:</u> Other fits are possible [see e.g. Gaisser et al, Front. Phys. China 2013]. If we increase heavy element contribution at expenses of hydrogen, we obtain a smaller CR flux (since the flux decrease faster than E⁻²)

The local determination has to be related to the CR flux in all the regions of the Galaxy where the gas density is not negligible.

Case A: the CR flux is homogenous in the Galaxy

 $\varphi_{\rm CR}(E, \mathbf{r}) \equiv \varphi_{\rm CR, \odot}(E)$

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<u>Case B</u>: the CR flux follows the distribution of galactic CR sources (SNRs, Pulsars)

 $\varphi_{\rm CR}(E, \mathbf{r}) \equiv \varphi_{\rm CR, \odot}(E) g(\mathbf{r})$ $g(\mathbf{r}) = \frac{n_{\rm S}(\mathbf{r})}{n_{\rm S}(\mathbf{r}_{\odot})} \qquad n_{\rm S}(\mathbf{r}) = \text{source (SNRs, pulsars) density}$

CR density above 20 GeV [re-adapted from Morlino et al, 2016] 4.5 Proton density [Acero et al.] Emissivity [Yang et al. Fig.7] nCR(20 GeV), B with cut-off nCR(20 GeV), B ~ 1/R source distribution 4 3.5 3 2.5 2 1.5 1 0.5 0 20 25 30 0 5 10 15 R(kpc)

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$$g(r) \equiv \frac{n_{\rm S}(\mathbf{r})}{n_{\rm S}(\mathbf{r}_{\odot})} = \left(\frac{r}{r_{\odot}}\right)^{\gamma} \exp\left(-\beta \frac{r - r_{\odot}}{r_{\odot}}\right)$$

for $r \leq r_{\odot}$

with:

 $\begin{array}{ll} \gamma = 1.09 \\ \beta = 3.87 \end{array} \qquad \begin{array}{l} {\rm SNRs\ distribution} \\ {\rm [Green,\ MNRAS\ 2015]} \end{array}$

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Case B: the CR flux follows the distribution of galactic CR sources (SNRs, Pwne)

$$\begin{split} \varphi_{\rm CR}(E,\mathbf{r}) &\equiv \varphi_{\rm CR,\odot}(E) \, g(\mathbf{r}) \\ g(\mathbf{r}) &= \frac{n_{\rm S}(\mathbf{r})}{n_{\rm S}(\mathbf{r}_{\odot})} \qquad \qquad n_{\rm S}(\mathbf{r}) = \text{source (SNRs, pulsars) density} \end{split}$$

Case C: the CR flux has a spectral index that depends on the galactocentric distance.

 $\varphi_{\rm CB}(E,\mathbf{r}) \equiv \varphi_{\rm CB,\odot}(E) q(\mathbf{r}) h(E,\mathbf{r})$

 $\Delta(\mathbf{r}) = \text{position-dependent variation of the CR spectral index.}$ $h(E, \mathbf{r}) = \begin{pmatrix} E \\ \overline{E} \end{pmatrix}^{\Delta(\mathbf{r})} \qquad \Delta(\mathbf{r}) = \text{position-dependent variation of the CR spectral index.}$ Expected in prop.model with radially dependent transport properties (see e.g. Gaggero et al, ApJ 2015)





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 $\varphi_{\rm CR}(E,\mathbf{r}) \equiv \varphi_{\rm CR,\odot}(E)$

Case B: the CR flux follows the distribution of galactic CR sources (SNRs, Pwne)

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 $\varphi_{\rm CR}(E,\mathbf{r}) \equiv \varphi_{\rm CR,\odot}(E) g(\mathbf{r}) h(E,\mathbf{r}) \quad \to \quad \varphi_{\rm CR,\odot}(E) g(\mathbf{r}) \overline{h}(\mathbf{r})$

The CR density at few PeVs in the 3 different models



Case A: The neutrino angular distribution is determined by the gas column density

Case B and Case C: More pronounced emission from the inner galactic region

HE galactic neutrinos – Integrated flux

The flux of HE neutrinos and antineutrinos of each flavour at Earth is ($E_v = 10 \text{ TeV} - 1 \text{PeV}$):

$$\varphi_{\nu}(E_{\nu}, \hat{n}_{\nu}) = \mathcal{F}(E_{\nu}) \,\mathcal{I}(\hat{n}_{\nu})$$

where: $\mathcal{F}(E_{\nu}) = 4.76 \times 10^{-7} \left[\frac{E_{\nu}}{100 \text{ TeV}} \right]^{-\alpha(E_{\nu})} \text{GeV}^{-1} \text{m}^{-2} \text{y}^{-1}$ $\alpha(E_{\nu}) = 2.65 + 0.13 \log_{10} \left(E_{\nu} / 100 \text{ TeV} \right).$

 $\mathcal{I} = \mathcal{A}, \, \mathcal{B}, \mathcal{C}$ depending on the considered scenario.

 $\underline{Case \ A:} \qquad \overline{\mathcal{A}} \equiv \int d\Omega \ \mathcal{A}(\hat{n}) = 1 \qquad \longrightarrow \qquad \frac{\mathcal{F}(E_{\nu})}{\mathcal{F}_{iso}(E_{\nu})} = 5\%$ $\underline{Case \ B:} \qquad \overline{\mathcal{B}} \equiv \int d\Omega \ \mathcal{B}(\hat{n}) = 1.23 \qquad \longrightarrow \qquad \frac{\mathcal{F}(E_{\nu})}{\mathcal{F}_{iso}(E_{\nu})} = 7\% \quad \text{for} \quad E_{\nu} = 100 \text{ TeV}$ $\overline{\mathcal{F}}(E_{\nu}) = 7\% \quad \text{for} \quad E_{\nu} = 100 \text{ TeV}$

<u>Case C:</u> $\overline{\mathcal{C}} \equiv \int d\Omega \, \mathcal{C}(\hat{n}) = 2.34 \longrightarrow \frac{\mathcal{F}(E_{\nu})}{\mathcal{F}_{\rm iso}(E_{\nu})} = 13\%$

The integrated galactic diffuse v flux is always subdominant with respect to the isotropic signal and well compatible with present bounds [even Case C is lower than what advocated by Semikoz & Neronov 2016 and Palladino and Vissani 2016]

Comparison with ANTARES



Comparison with ANTARES



See also arXiv:1705.00497 for a more stringent (model-dependent) bound from Antares: $-\phi_{gal} \le 1.25 \phi(KRA\gamma)$ [all sky- nine years analysis tuned on Gaggero et al. predictions]

and preliminary IceCube results:

- $φ_{gal}$ ≤ 1.2 φ(KRAγ) [galactic $ν_μ$ analysis - presented at IPA 2017]

HE galactic neutrinos – Angular distribution



- It always exists a region where the galactic diffuse v flux is comparable or larger than isotropic component.
- The region where galactic neutrinos dominate is quite narrow (e.g. |b|< 4° and ||<70° for Case C). The optimal detector should have a good pointing capability (or a large counting rate) in order to avoid diluting the signal below the isotropic background.
- The angular distributions are quite different in the three considered scenarios (e.g. the flux from galactic center is factor ≈10 larger in Case C than in Case A)

Events in IceCube – Integrated rates

The number of HESE events in IceCube is calculated according to:

$$N_{\rm S} = T \int dE_{\nu} \int d\Omega_{\nu} \varphi_{\nu}(E_{\nu}, \hat{n}_{\nu}) \left[A_e \left(E_{\nu}, \hat{n}_{\nu} \right) + A_{\mu} \left(E_{\nu}, \hat{n}_{\nu} \right) \left(1 - \eta \right) + A_{\tau} \left(E_{\nu}, \hat{n}_{\nu} \right) \right]$$

$$N_{\rm T} = \eta T \int dE_{\nu} \int d\Omega_{\nu} \varphi_{\nu}(E_{\nu}, \hat{n}_{\nu}) A_{\mu} \left(E_{\nu}, \hat{n}_{\nu} \right)$$

where: $A_{\ell} (E_{\nu}, \hat{n}_{\nu})$ IceCube effective areas [http://icecube.wisc.edu/science/data/HE-nu-2010-2012] $\eta \simeq 0.8$ Probability that v_{μ} produce track events [Palladino et al. PRL 2015]

Table 1: The track and shower HESE rates expected in IceCube for the three different models and for the isotropic flux observed by IceCube. The separate contributions from Northern and Southern hemisphere are also shown.

	$N/T - \mathrm{counts} \cdot \mathrm{y}^{-1}$			
	Showers	Tracks	North	South
Case A	0.40	0.07	0.18	0.29
Case B	0.50	0.09	0.20	0.39
$Case \ C$	1.01	0.19	0.27	0.92
Isotropic	8.33	1.61	4.13	5.80

Events in IceCube – Angular distribution

The angular distribution of HESE events is estimated by:

$$\frac{dN_{\rm S}(\hat{n})}{d\Omega} = T \int dE_{\nu} \int d\Omega_{\nu} G_{\rm S}(\hat{n}, \hat{n}_{\nu}) \varphi_{\nu}(E_{\nu}, \hat{n}_{\nu}) \left[A_e(E_{\nu}, \hat{n}_{\nu}) + A_{\mu}(E_{\nu}, \hat{n}_{\nu})(1-\eta) + A_{\tau}(E_{\nu}, \hat{n}_{\nu})\right]$$

$$\frac{dN_{\rm T}(\hat{n})}{d\Omega} = \eta T \int dE_{\nu} \int d\Omega_{\nu} G_{\rm T}(\hat{n}, \hat{n}_{\nu}) \varphi_{\nu}(E_{\nu}, \hat{n}_{\nu}) A_{\mu}(E_{\nu}, \hat{n}_{\nu})$$

The IceCube angular resolution is described as:

$$G_{\rm I}(\hat{n}, \hat{n}_{\nu}) = \frac{m}{2\pi\delta n_{\rm I}^2} \exp\left(-\frac{1-c}{\delta n_{\rm I}^2}\right)$$

where :

- $\mathrm{I}=\mathrm{S},\,\mathrm{T}$
- \boldsymbol{m} is a normalization factor
- $c \equiv \cos \theta = \hat{n} \, \hat{n}_{\nu}$
- $\delta n_{\rm S}$ ($\delta n_{\rm T}$) fixed by requiring $\theta \leq 15^{\circ}$ ($\theta \leq 1^{\circ}$) for showers (tracks) at 68.3% C.L.

Events in IceCube – Angular distribution



Events in IceCube – Angular distribution



• The track rate is generally too small to obtain a non negligible detection probability.

• Due to the **poor pointing accuracy**, the **showers** produced by diffuse galactic neutrinos are diluted below the isotropic component everywhere in the sky except for Case C.

Detectability in IceCube

The fractional uncertainty δN_{I} in the determination of a galactic signal N_{I} over the isotropic background $N_{I,iso}$ is estimated as:

$$\delta N_{\rm I} \simeq \sqrt{\frac{1+\rho}{N_{\rm I}}}$$
 - I = S, T
- $\rho = N_{\rm I,iso}/N_{\rm I}$

For the most favorable Case C:

Optimal Obs. Window for Showers:

$$\begin{aligned} |l| &\leq 60^{\circ} \\ |b| &\leq 15^{\circ} \end{aligned} \longrightarrow \begin{aligned} N_{\rm S}/T &= 0.65 \text{ y}^{-1} \\ \rho &= 1.3 \end{aligned} \longrightarrow \qquad T \geq 4 \text{ y for } 1\sigma \text{ extraction} \end{aligned}$$

Optimal Obs. Window for Tracks:

$$|l| \le 80^{\circ}$$

 $|b| \le 3^{\circ}$ \longrightarrow $N_{\rm T}/T = 0.12 \ {\rm y}^{-1}$ \longrightarrow
 $\rho = 0.25$

 $T \ge 11 \,\mathrm{y}$ for 1σ extraction

Detectability in IceCube



According to Case C, about 2.5 showers in the red box may be of galactic origin (less than 1 in Case A and Case B ...)

Summary and Conclusions

- The diffuse HE galactic neutrino flux is expected to be subdominant but not necessarily negligible (up to 13% of the total astrophysical signal in our calculations).
- IceCube (and ANTARES) are approaching the sensitivity level to probe at least some CR model (see e.g. our Case C).
- A statistically significant excess of events from galactic plane in present or next future IceCube HESE data (or ANTARES) would favour models in which the CR density in the inner galactic region is much larger than its local value.

Possible future improvements:

- Increase the statistics (at the level ≈ few y⁻¹ at least) by lowering the detection threshold in IceCube.
- KM3NeT → will observe the inner galactic region with a relatively large exposure by using up-going passing muons (good pointing accuracy).

Diffuse galactic neutrinos are not completely out-of-reach of present and future experiments.

