High energy galactic neutrinos for different cosmic ray distributions

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Outline

- Expectations for high energy diffuse galactic neutrinos for different cosmic ray distributions

G. Pagliaroli (GSSI), C. Evoli (GSSI) and F.L. Villante - JCAP 1611 (2016) no.11, 004

- A multi-messenger determination of the total galactic (diff. + sources) neutrino component

G. Pagliaroli (GSSI) and F.L. Villante – In preparation
See poster of ***G.Pagliaroli*** *at this conference*

The HE galactic diffuse neutrino and gamma fluxes

The interaction of HE cosmic rays (CRs) with the gas contained in the galactic disk is a **guaranteed** source of **HE neutrinos** and **gammas**. The flux at Earth can be written as:

$$\varphi_{i,\mathrm{diff}}(E_i,\hat{n}_i) = A_i \left[\int_{E_i}^{\infty} dE \int_0^{\infty} dl \, \frac{d\sigma_i(E,E_i)}{dE} \times \varphi_{\mathrm{CR}}(E,\mathbf{r}_\odot + l\,\hat{n}_i) \times n_{\mathrm{H}}(\mathbf{r}_\odot + l\,\hat{n}_i)\right]$$

$$i = \nu, \gamma$$

where: $A_\gamma = 1$ $\quad$ $A_\nu = 1/3$

$$\frac{d\sigma_i(E,E_i)}{dE} = \frac{\sigma(E)}{E} F_i\left(\frac{E_i}{E}, E\right)$$

nucleon-nucleon cross section
[Kelner & Aharonian, PRD 2008, 2010]

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

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

N.B. We assume (ν_e: ν_μ: ν_τ) = (1:1:1) as expected due to flavour oscillations

The CR flux: local determination

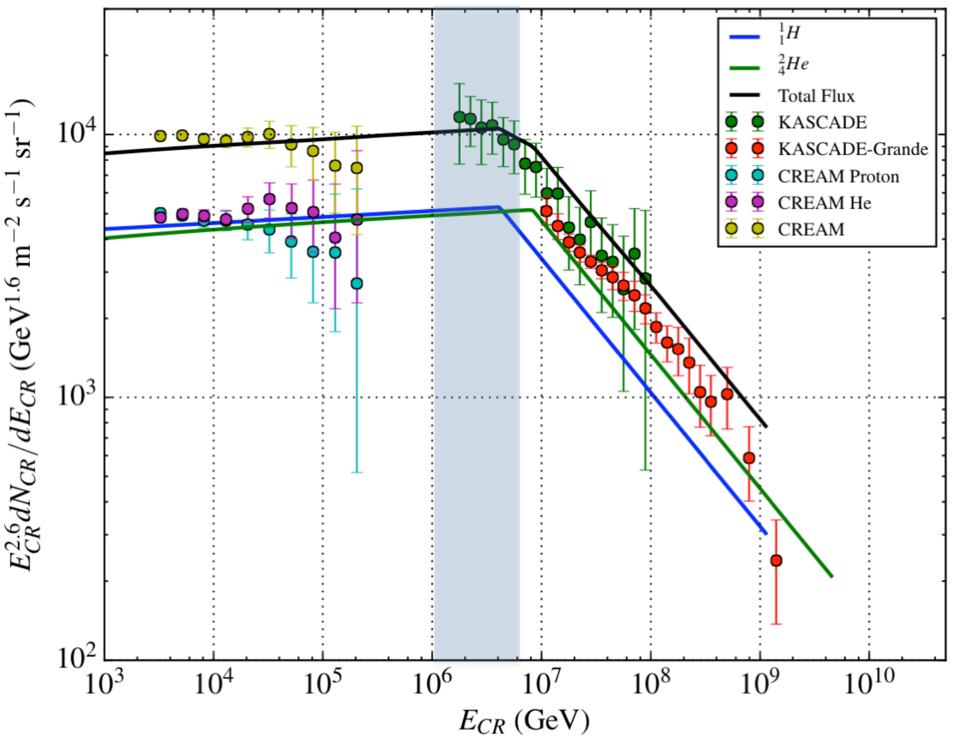
The neutrino flux at E_ν=100 TeV is determined by CR flux at:

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

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

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

Broken Power Law – Ahlers et al., PRD 2016



Note that: 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 CR flux in the Galaxy

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

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

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

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

$$g(\mathbf{r}) = \frac{n_{\rm S}(\mathbf{r})}{n_{\rm S}(\mathbf{r}_\odot)}$$

$n_{\rm S}(\mathbf{r}) = \text{source (SNRs, pulsars) density}$

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

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

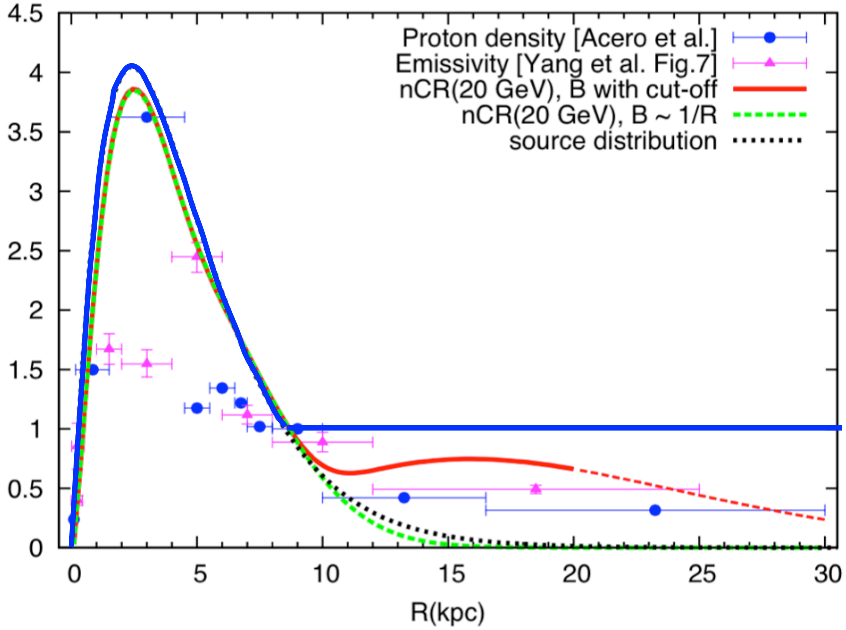
$$h(E, \mathbf{r}) = \left(\frac{E}{\overline{\overline{E}}}\right)^{\Delta(\mathbf{r})}$$

$\Delta(\mathbf{r}) =$ 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)

The CR flux in the Galaxy

CR density above 20 GeV
[re-adapted from Morlino et al, 2016]



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

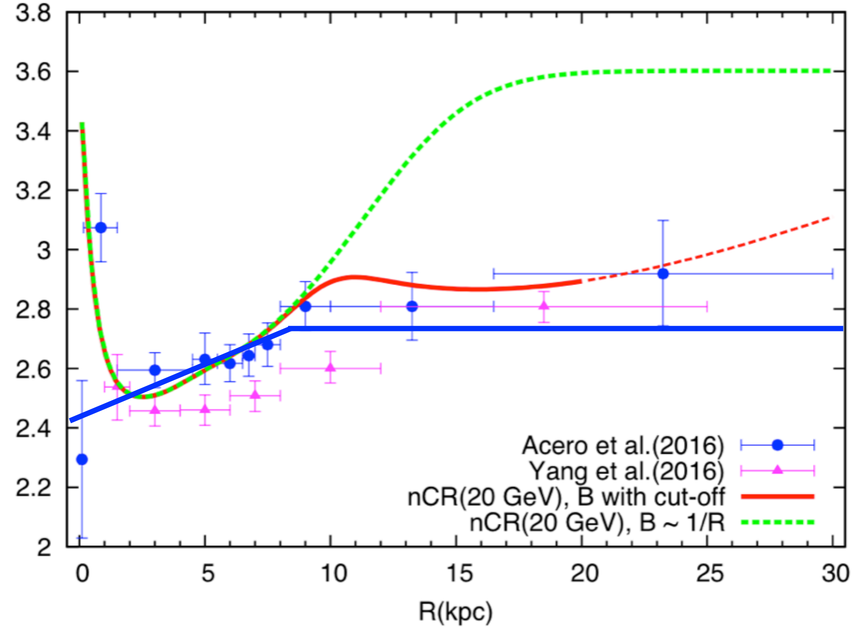
for $r \leq r_\odot$

with:

$$\begin{cases} \gamma = 1.09 \\ \beta = 3.87 \end{cases}$$

SNRs distribution
[Green, MNRAS 2015]

CR spectral index
[re-adapted from Morlino et al, 2016]



$$\Delta(r) = 0.3\left(1 - \frac{r}{r_\odot}\right) \quad \text{for} \quad r \leq r_\odot$$

$$h(E, \mathbf{r}) \;\rightarrow\; \overline{h}(\mathbf{r}) = \left(\frac{E_{\rm CR}}{\overline{E}}\right)^{\Delta(\mathbf{r})} = 10^{\,5\times\Delta(\mathbf{r})}$$

$$\begin{cases} E_{\rm CR} = 2\,\mathrm{PeV} \\ \overline{E} = 20\,\mathrm{GeV} \end{cases}$$

HE diffuse galactic neutrinos – Integrated flux

The flux of HE neutrinos and antineutrinos of each flavour at Earth is (E_ν = 10 TeV – 1PeV):

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

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

where:

$$\mathcal{F}(E_\nu) = 4.76 \times 10^{-7} \left[\frac{E_\nu}{100\,\mathrm{TeV}}\right]^{-\alpha(E_\nu)} \mathrm{GeV}^{-1}\,\mathrm{m}^{-2}\,\mathrm{y}^{-1}$$

$$\alpha(E_\nu) = 2.65 + 0.13 \log_{10}\left(E_\nu/100\,\mathrm{TeV}\right).$$

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

Isotropic flux required to fit IceCube Hese (4 years)

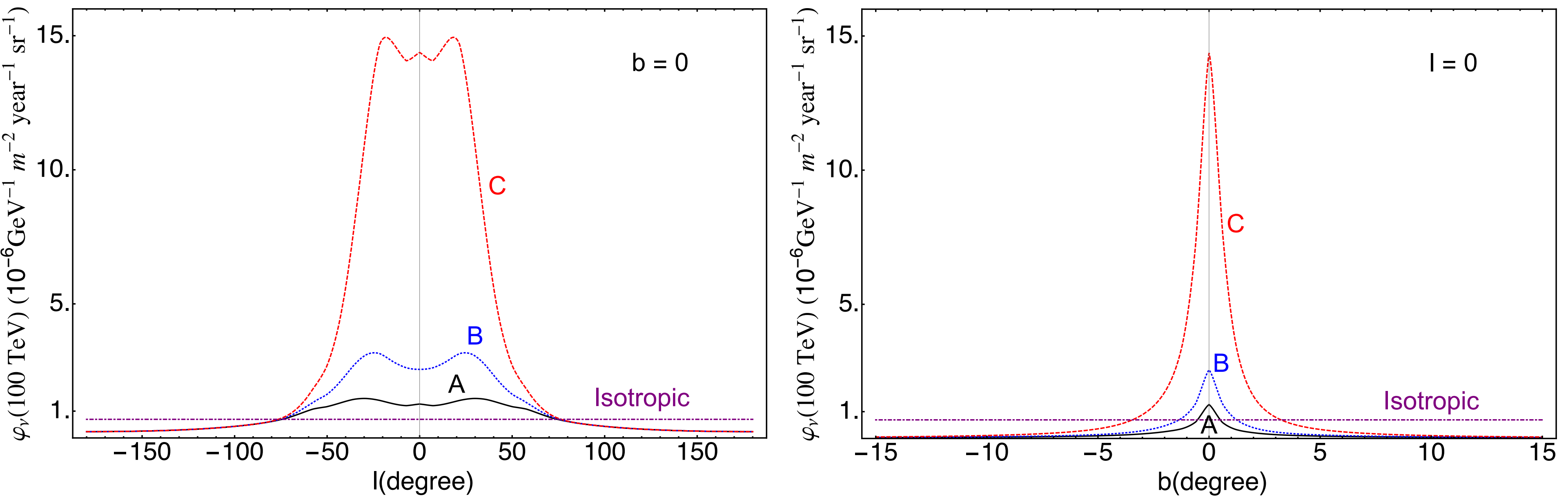
Case A: $\overline{\mathcal{A}} \equiv \int d\Omega\, \mathcal{A}(\hat{n}) = 1$ → $\dfrac{\mathcal{F}(E_\nu)}{\mathcal{F}_{\rm iso}(E_\nu)} = 5\%$

Case B: $\overline{\mathcal{B}} \equiv \int d\Omega\, \mathcal{B}(\hat{n}) = 1.23$ → $\dfrac{\mathcal{F}(E_\nu)}{\mathcal{F}_{\rm iso}(E_\nu)} = 7\%$ for $E_\nu = 100\,\mathrm{TeV}$

Case C: $\overline{\mathcal{C}} \equiv \int d\Omega\, \mathcal{C}(\hat{n}) = 2.34$ → $\dfrac{\mathcal{F}(E_\nu)}{\mathcal{F}_{\rm iso}(E_\nu)} = 13\%$

The integrated galactic diffuse ν flux is always subdominant with respect to the isotropic signal and well compatible with present bounds

HE diff. galactic neutrinos – Angular distribution

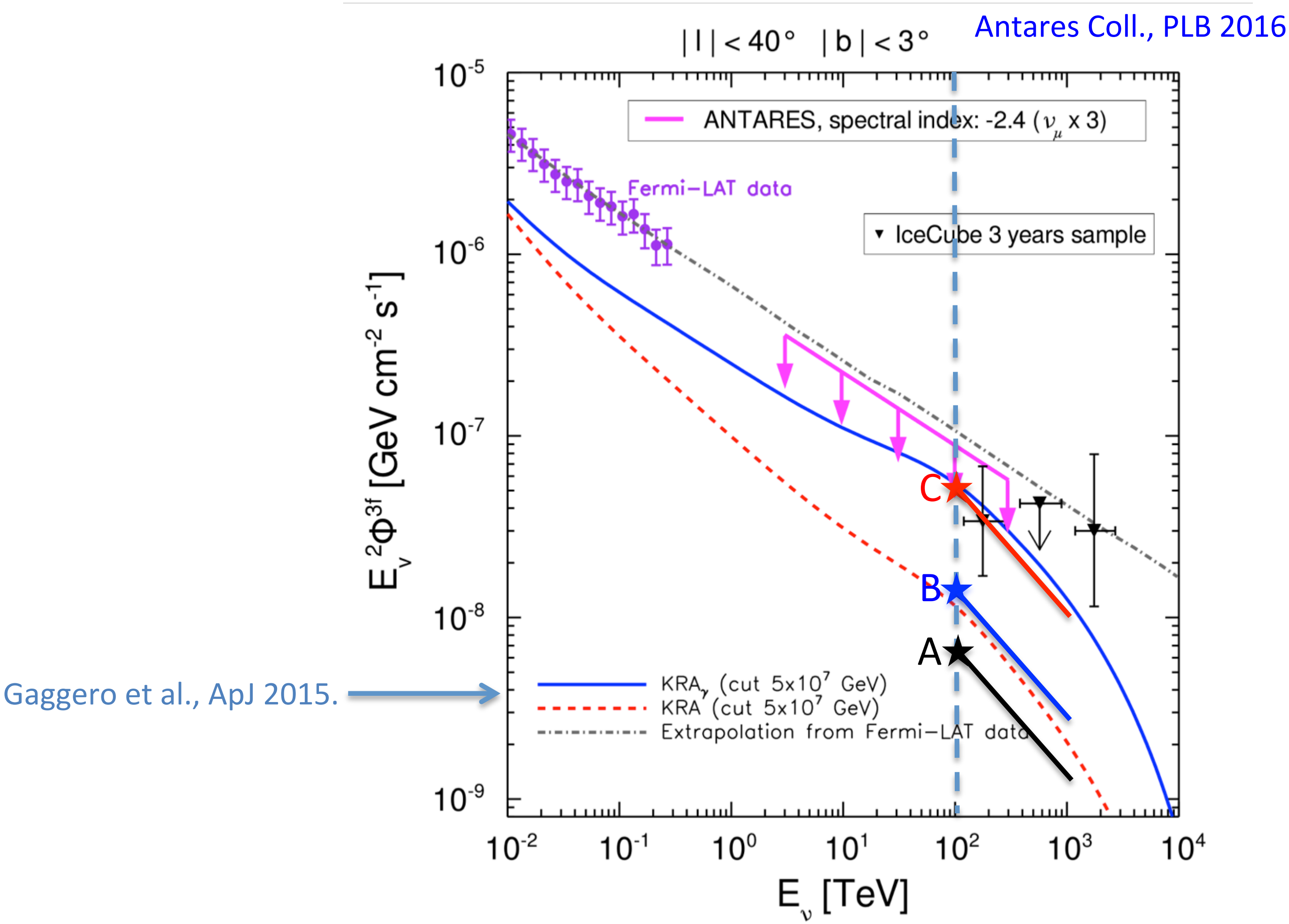


- It always exists a region where the galactic diffuse ν flux is comparable or larger than isotropic component.

- The region where galactic neutrinos dominate is quite narrow (e.g. |b|< 4° and |l|<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**)

Comparison with ANTARES



See also arXiv:1705.00497 for a more stringent (model-dependent) bound from Antares:

- $\phi_{gal} \leq 1.25\ \phi(\mathrm{KRA}\gamma)$ [all sky- nine years analysis tuned on Gaggero et al. predictions]

and preliminary IceCube results:

- $\phi_{gal} \leq 1.2\ \phi(\mathrm{KRA}\gamma)$ [galactic ν_μ analysis - presented at IPA 2017]

Events in IceCube – Integrated rates

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

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

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

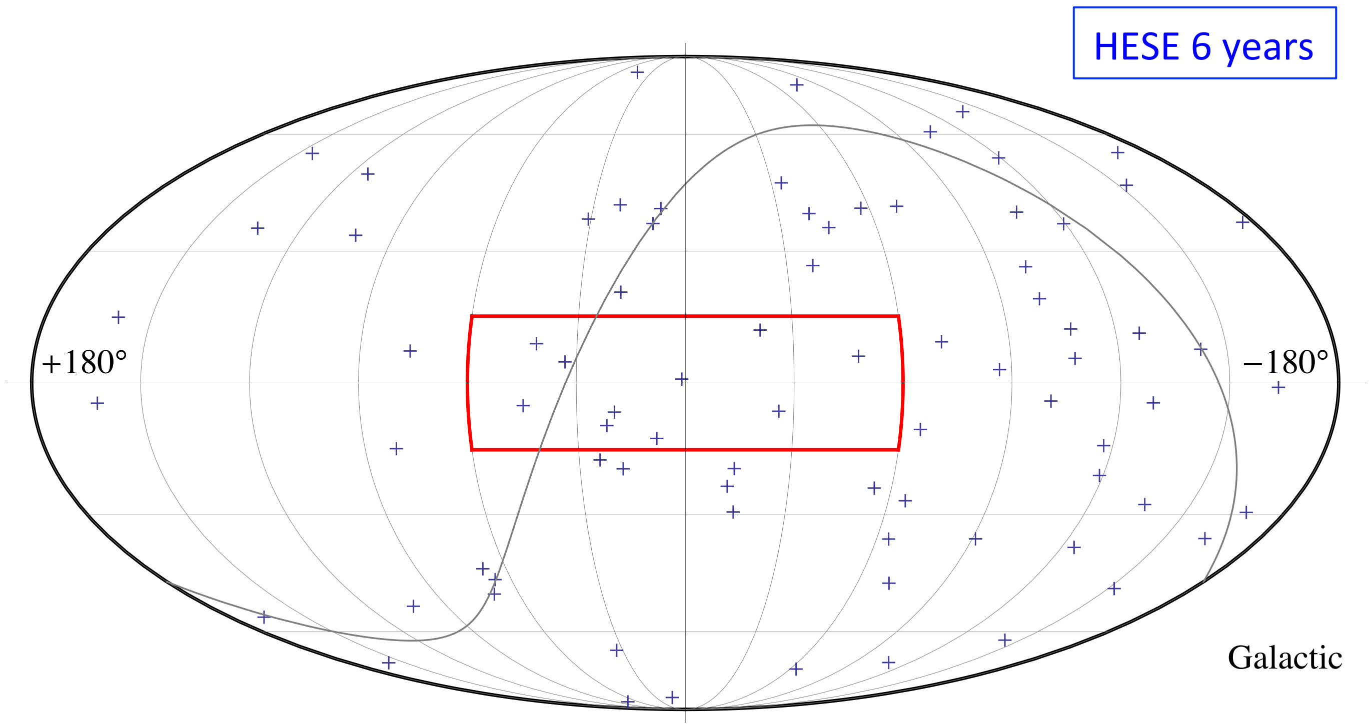
where: $A_\ell\left(E_\nu,\hat{n}_\nu\right)$ IceCube effective areas [http://icecube.wisc.edu/science/data/HE-nu-2010-2012]

$\eta \simeq 0.8$ Probability that ν_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 – counts $\cdot$ 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

Detectability in IceCube

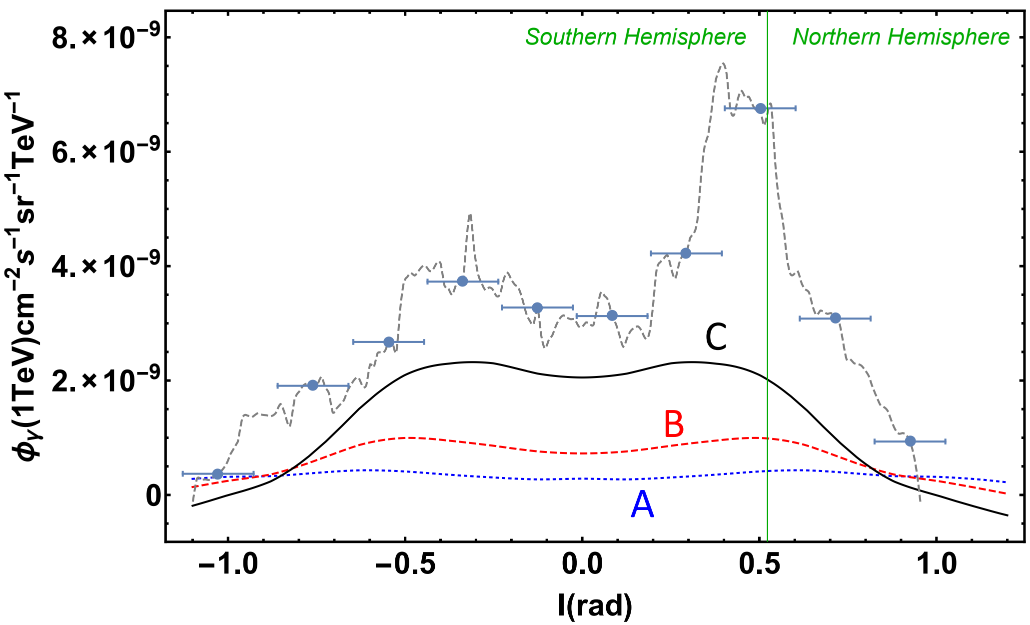


-15°<b<15°; -60°< l <60°
Optimal obs.window
for the search of diffuse component

According to **Case C**, **about 3.7 showers in the red box (out of 10)** may be of **galactic origin** (about 1 in **Case A** and **Case B** …)

HE diffuse gammas – Comparison with HESS

HESS provided in 2014 the first detailed observation of the large-scale γ-ray emission in the inner region of the galactic plane at Eγ ≃ 1 TeV [Abramowski et al., PRD 90 (2014) 122007].



- *Obs. reg.: -75° < l < 60° ; -2° < b < 2°*
- *Galactic signal obtained as the excess relative to γ-ray emission at |b| ≥ 1.2°*
- *To avoid fluctuations and compare with predictions, we re-binned the data → Δl =15°*

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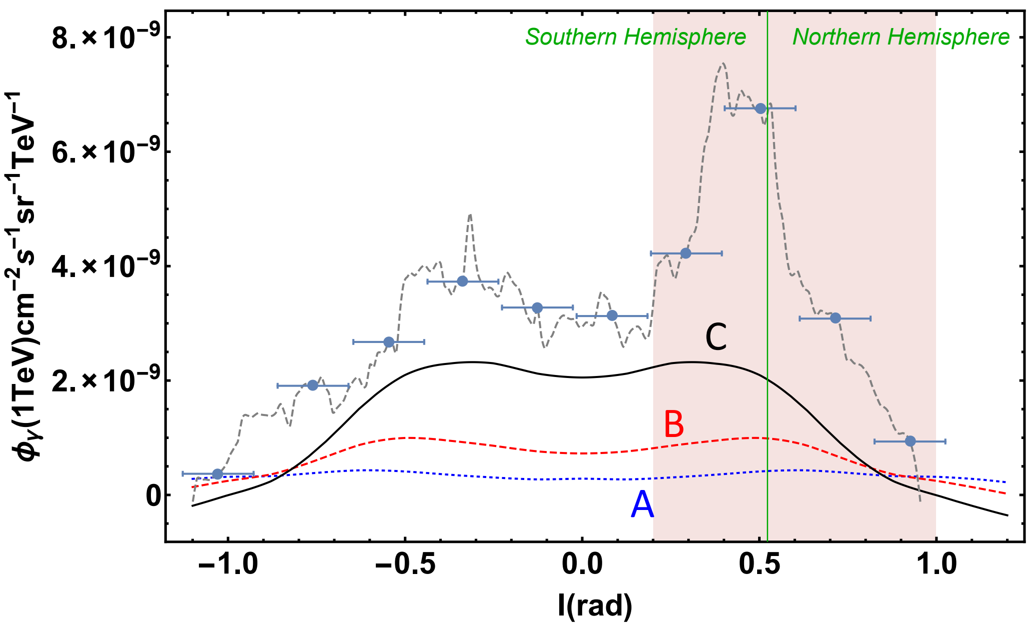
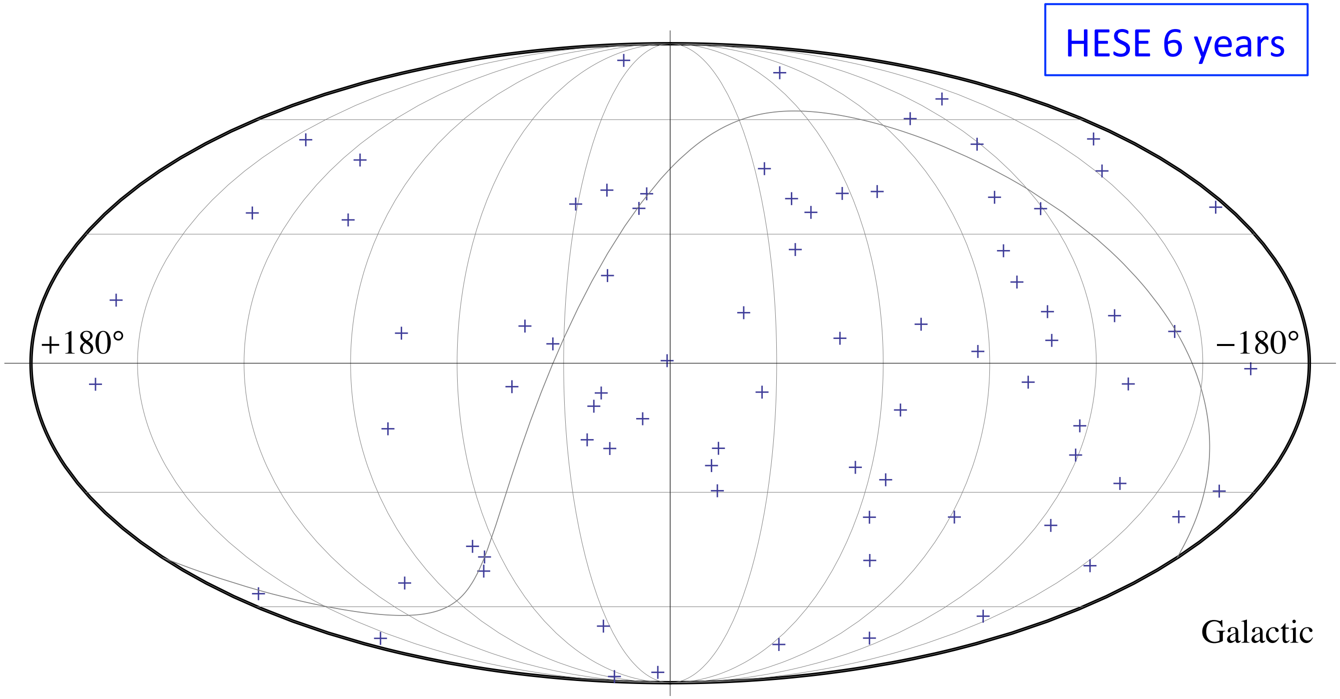


11°< l <57°
Extended "Hot" region (EHR)

- *Obs. reg.: -75° < l < 60° ; -2° < b < 2°*
- *Galactic signal obtained as the excess relative to γ-ray emission at |b| ≥ 1.2°*
- *To avoid fluctuations and compare with predictions, we re-binned the data → Δl =15°*

- The three considered models are **consistent with HESS data**;
- Superimposed to diffuse emission, there is an additional component (sources?, IC?) that has **a peculiar angular distribution**
- The **cumulative flux** associated to this component **dominates certain portions of the sky**.

Has EHR a counterpart in neutrino sky?



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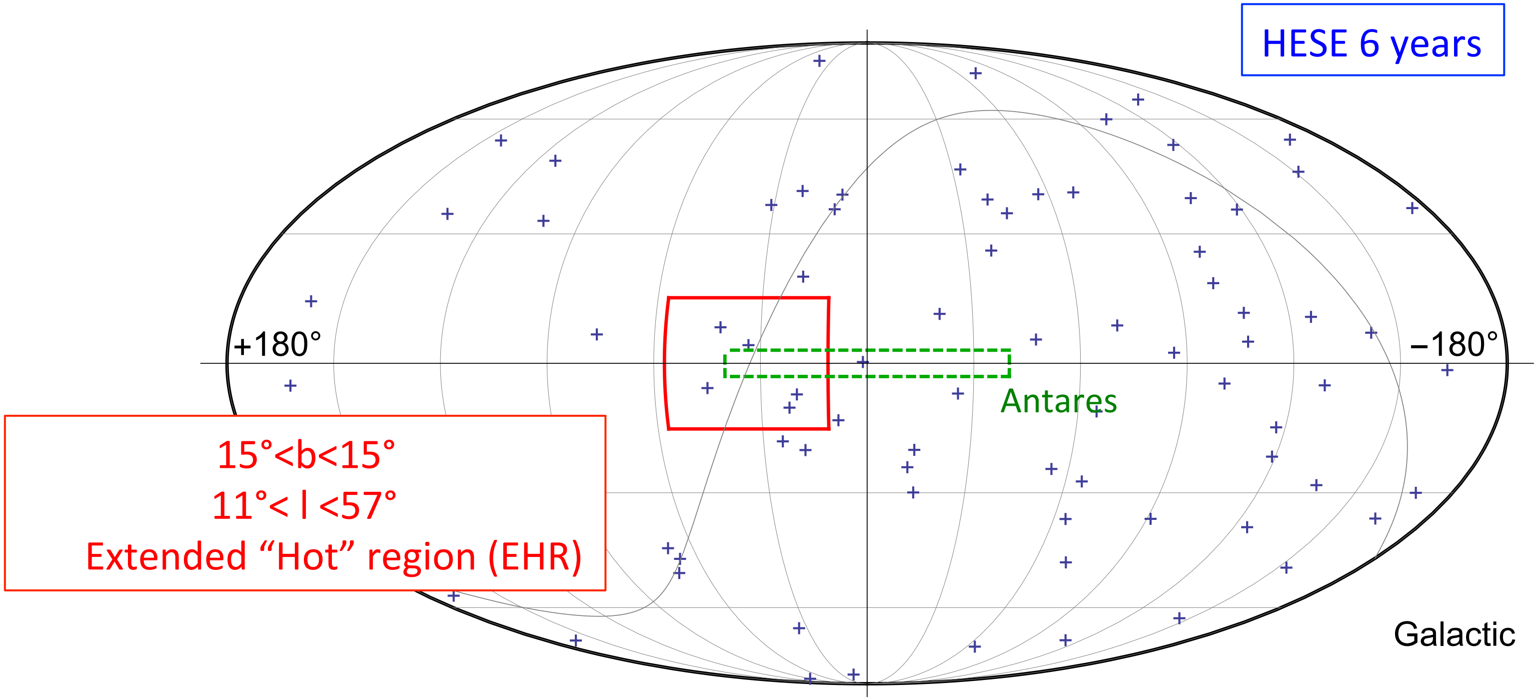

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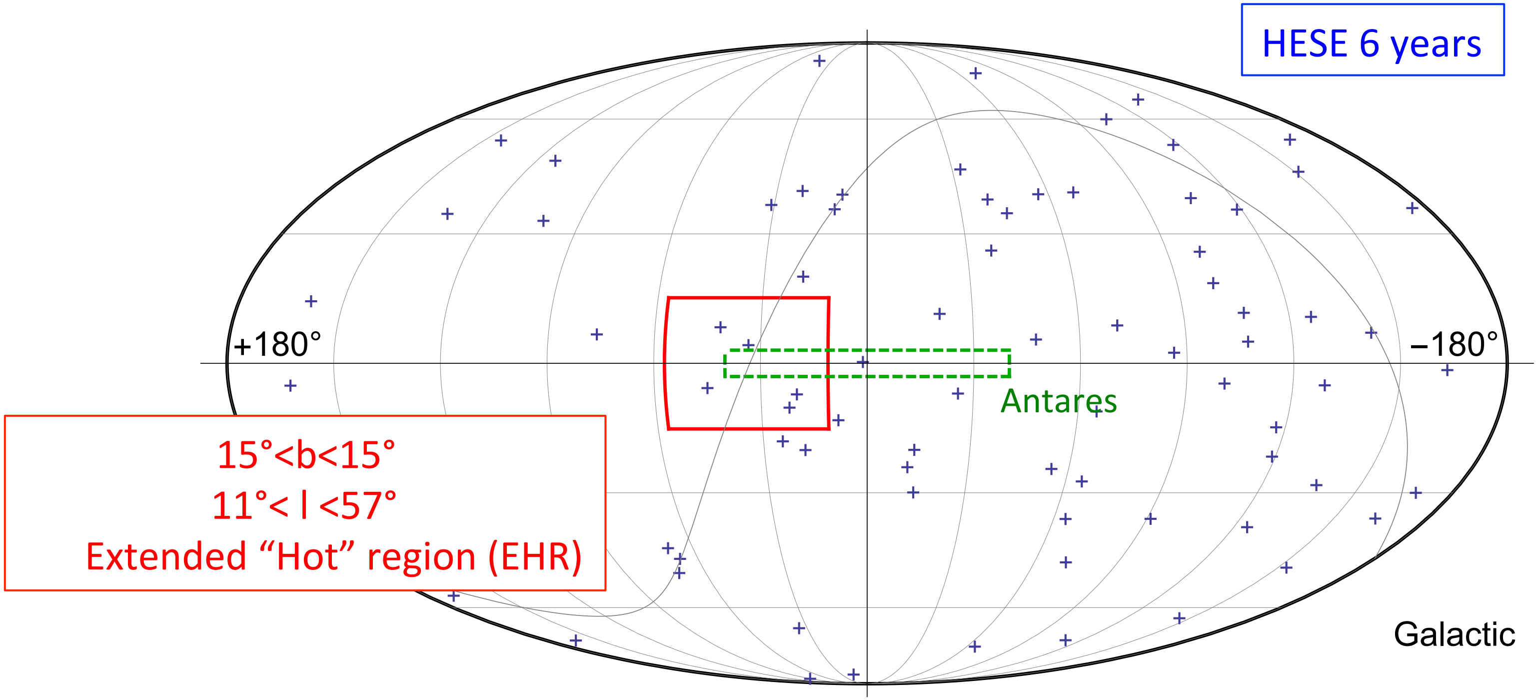

In the selected observation window:

- $N_{Sh,obs} = 5$

$\Delta N_{Sh,obs} = 3.3$
(1.5σ excess over predictions)

to be compared with:

- $N_{Sh,iso} = 1.4$ (isotropic flux)
- $N_{Sh,atmo} = 0.3$ (atmo ν back.)

Could be a (preliminary) indication in favour of a galactic component?

A multi-messanger study of total galactic emission

The total fluxes of HE neutrinos and gammas produced in our Galaxy can be written as:

$$
\begin{aligned}
\varphi_{\gamma,\mathrm{tot}} &= \varphi_{\gamma,\mathrm{diff}} + \varphi_{\gamma,\mathrm{S}} + \varphi_{\gamma,\mathrm{IC}} \\
\varphi_{\nu,\mathrm{tot}} &= \varphi_{\nu,\mathrm{diff}} + \varphi_{\nu,\mathrm{S}}
\end{aligned}
$$

where: $\varphi_{i,\mathrm{diff}}$ → diffuse γ and ν flux

$\varphi_{i,\mathrm{S}}$ → γ and ν fluxes produced by resolved and unresolved sources

$\varphi_{\gamma,\mathrm{IC}}$ → γ flux produced through inverse compton by diffuse HE electrons

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\end{aligned}
$$

95% reduction of "standard" IC signal due to background cuts [Abramowski et al., 2014]

where: $\varphi_{i,\mathrm{diff}}$ → diffuse γ and ν flux *(calculable)*

$\varphi_{i,\mathrm{S}}$ → γ and ν fluxes produced by resolved and unresolved sources

$\varphi_{\gamma,\mathrm{IC}}$ → γ flux produced through inverse compton by diffuse HE electrons *(Hp: negligible in the obs. signal)*

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$\varphi_{\gamma,\mathrm{IC}}$ → γ flux produced through inverse compton by diffuse HE electrons *(Hp: negligible in the obs. signal)*

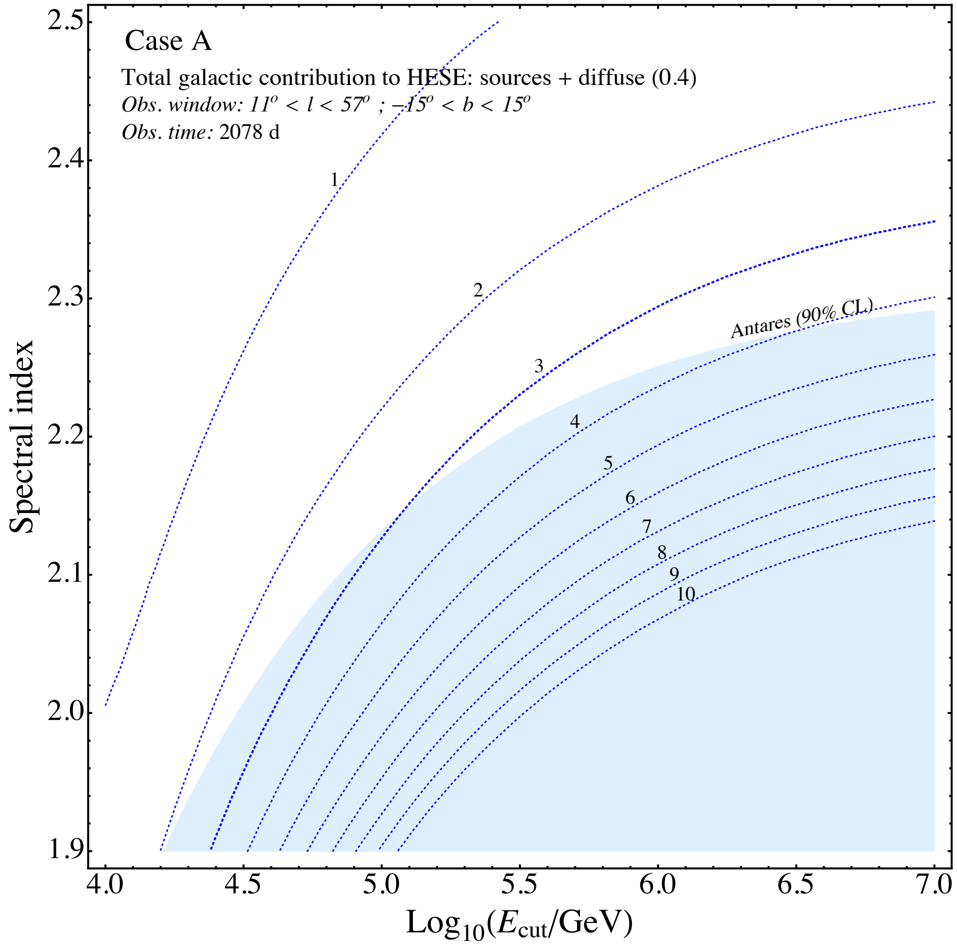
The **cumulative ν source contribution** is estimated by assuming that the **observed** γ are produced by **hadronic mechanisms** (and not absorbed)

[Kappes et al., ApJ 2007]

$$
\begin{aligned}
\varphi_{\gamma,\mathrm{S}}(E_\gamma,\, \hat{n}_\gamma) &= k_\gamma(\mathbf{n}_\gamma) \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{-\alpha_\gamma} \exp\left(-\sqrt{\frac{E_\gamma}{E_{\mathrm{cut},\gamma}}}\right) \\
\varphi_{\nu,\mathrm{S}}(E_\nu,\, \hat{n}_\nu) &= k_\nu(\mathbf{n}_\nu) \left(\frac{E_\nu}{\mathrm{TeV}}\right)^{-\alpha_\nu} \exp\left(-\sqrt{\frac{E_\nu}{E_{\mathrm{cut},\nu}}}\right)
\end{aligned}
$$

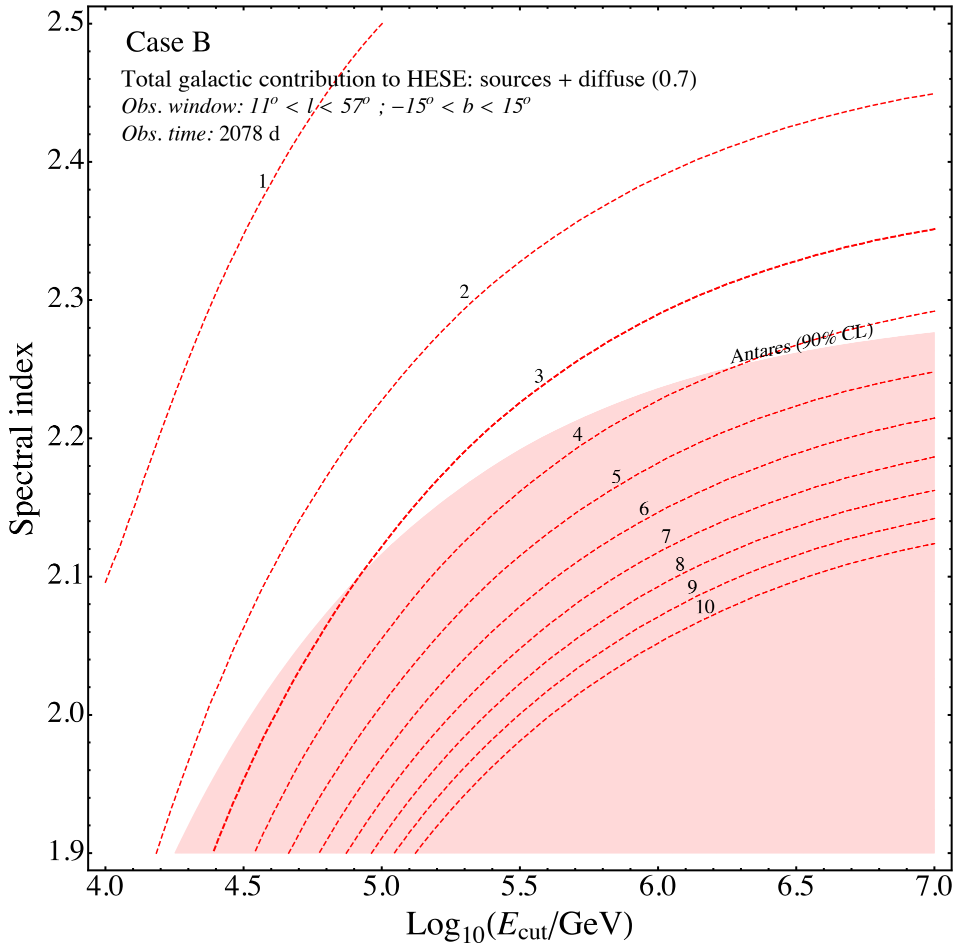
$$
\begin{aligned}
k_\nu &= (0.694 - 0.16\alpha_\gamma)\; k_\gamma \\
\alpha_\nu &= \alpha_\gamma \\
E_{\mathrm{cut},\nu} &= 0.59\, E_{\mathrm{cut},\gamma}
\end{aligned}
$$

The total (diffuse+source) galactic signal in EHR (Case A)



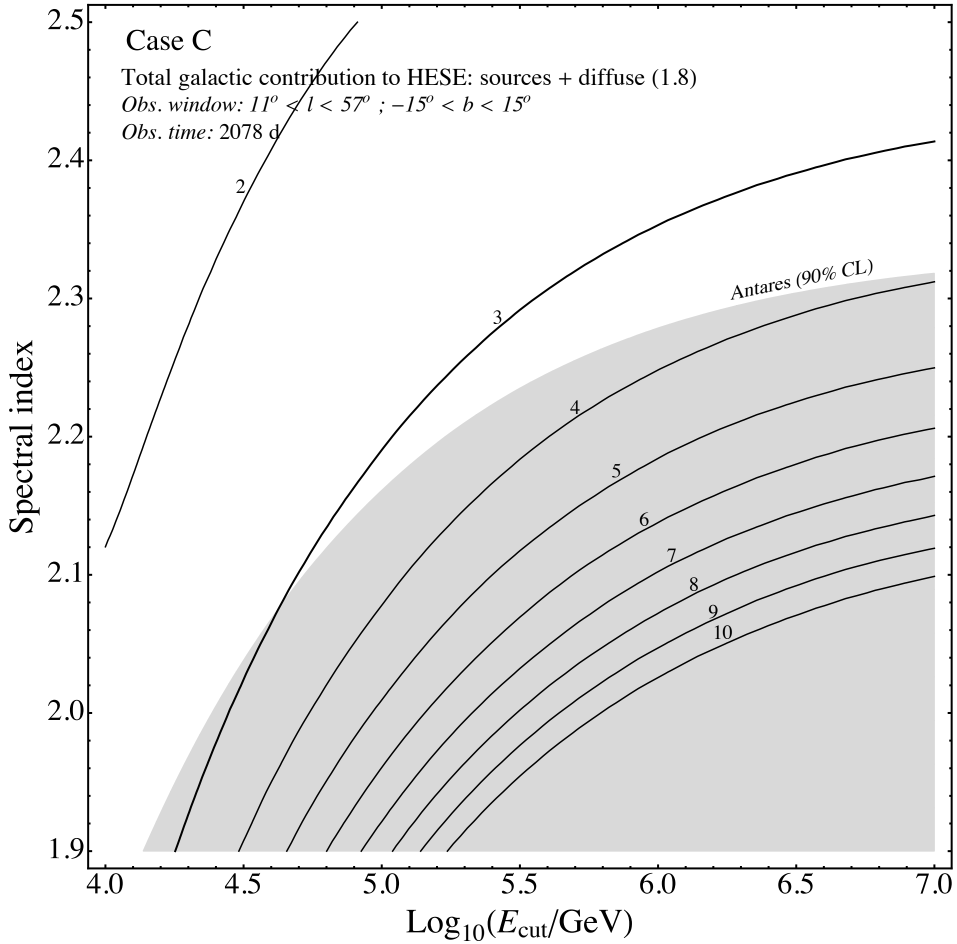
- The shaded area describes the regions excluded by **Antares upper limit** *[90% CL - PLB 2016]*;
- Relevant bounds are obtained for spectral index $\alpha_\nu < 2.3$
- Still exists a region, compatible with Antares, that provides **relevant contribution** to IceCube HESE shower rate
- Dedicated analysis may exclude this region or prove/disprove the **hadronic emission assumption**

The total (diffuse+source) galactic signal in EHR (Case B)



- The shaded area describes the regions excluded by **Antares upper limit** *[90% CL - PLB 2016]*;
- Relevant bounds are obtained for spectral index $\alpha_\nu < 2.3$
- Still exists a region, compatible with Antares, that provides **relevant contribution** to IceCube HESE shower rate
- Dedicated analysis may exclude this region or prove/disprove the **hadronic emission assumption**

The total (diffuse+source) galactic signal in EHR (Case C)



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- Relevant bounds are obtained for spectral index $\alpha_\nu < 2.3$
- Still exists a region, compatible with Antares, that provides **relevant contribution** to IceCube HESE shower rate
- Dedicated analysis may exclude this region or prove/disprove the **hadronic emission assumption**

Summary and conclusions

- ✓ The HE diffuse galactic neutrino flux is expected to be subdominant but not necessarily negligible.

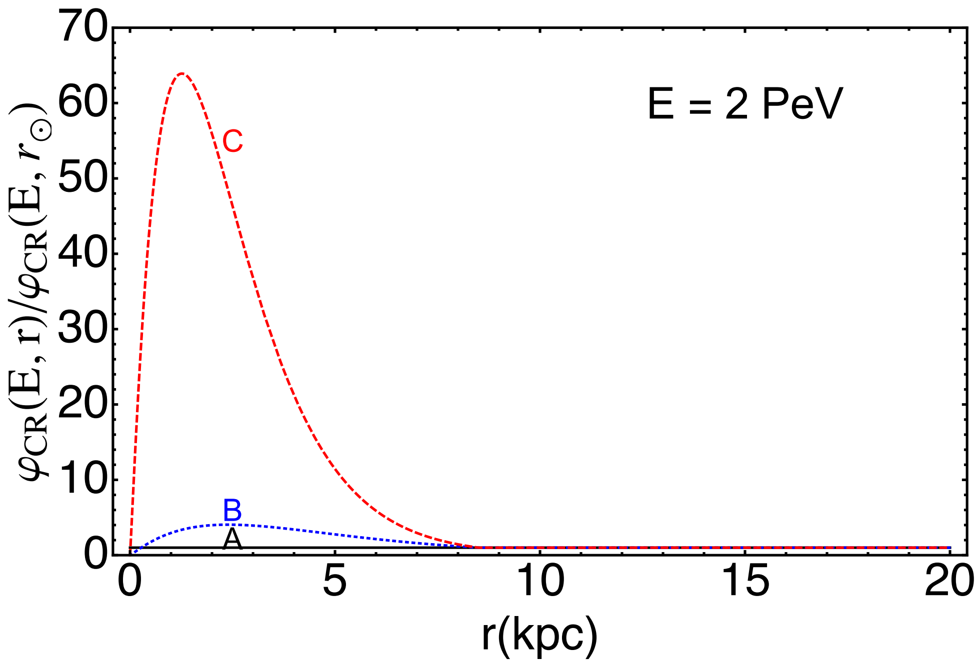
- ✓ Superimposed to diffuse emission, there is an additional component that has a peculiar angular distribution and dominates certain portions of the γ sky (at E_γ =1 Tev).

- ✓ IceCube and ANTARES are approaching the sensitivity level to probe the total galactic component.

- ✓ Search strategies could be optimized by using ν/γ connection

Thank you

The CR density at few PeVs in the 3 different models



$$\varphi_\nu(E_\nu, \hat{n}_\nu) = \frac{1}{3} \sum_{\ell=e,\mu,\tau} \left[\int_{E_\nu}^{\infty} dE \int_0^{\infty} dl \, \frac{d\sigma_\ell(E, E_\nu)}{dE_\nu} \times \varphi_{\rm CR}(E, \mathbf{r}_\odot + l\,\hat{n}_\nu) \times n_{\rm H}(\mathbf{r}_\odot + l\,\hat{n}_\nu) \right]$$

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

Events in IceCube – Angular distribution

The **angular distribution** of HESE events is estimated by:

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

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

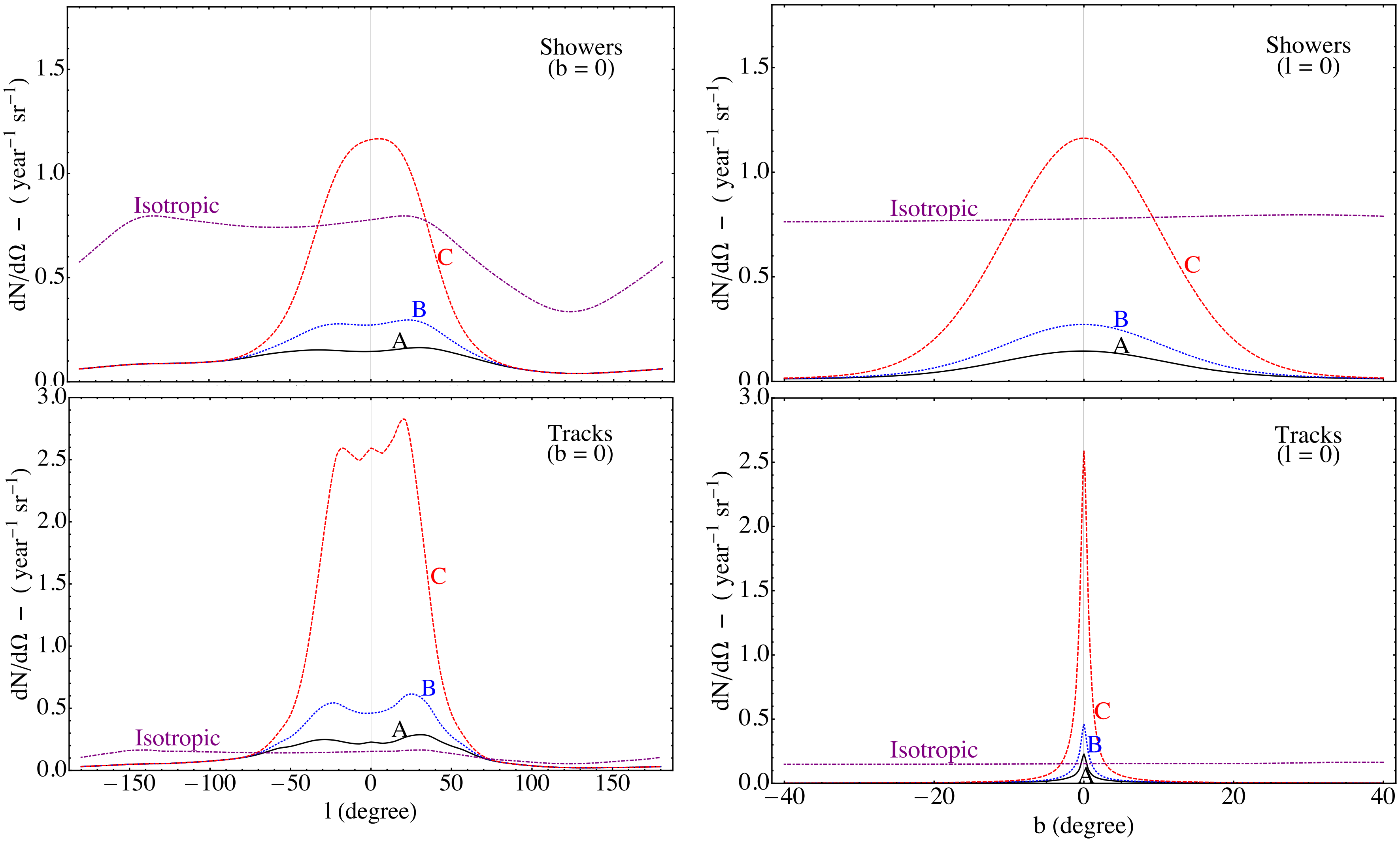
The IceCube **angular resolution** is described as:

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

where :

- $\rm I = S,\ T$
- 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



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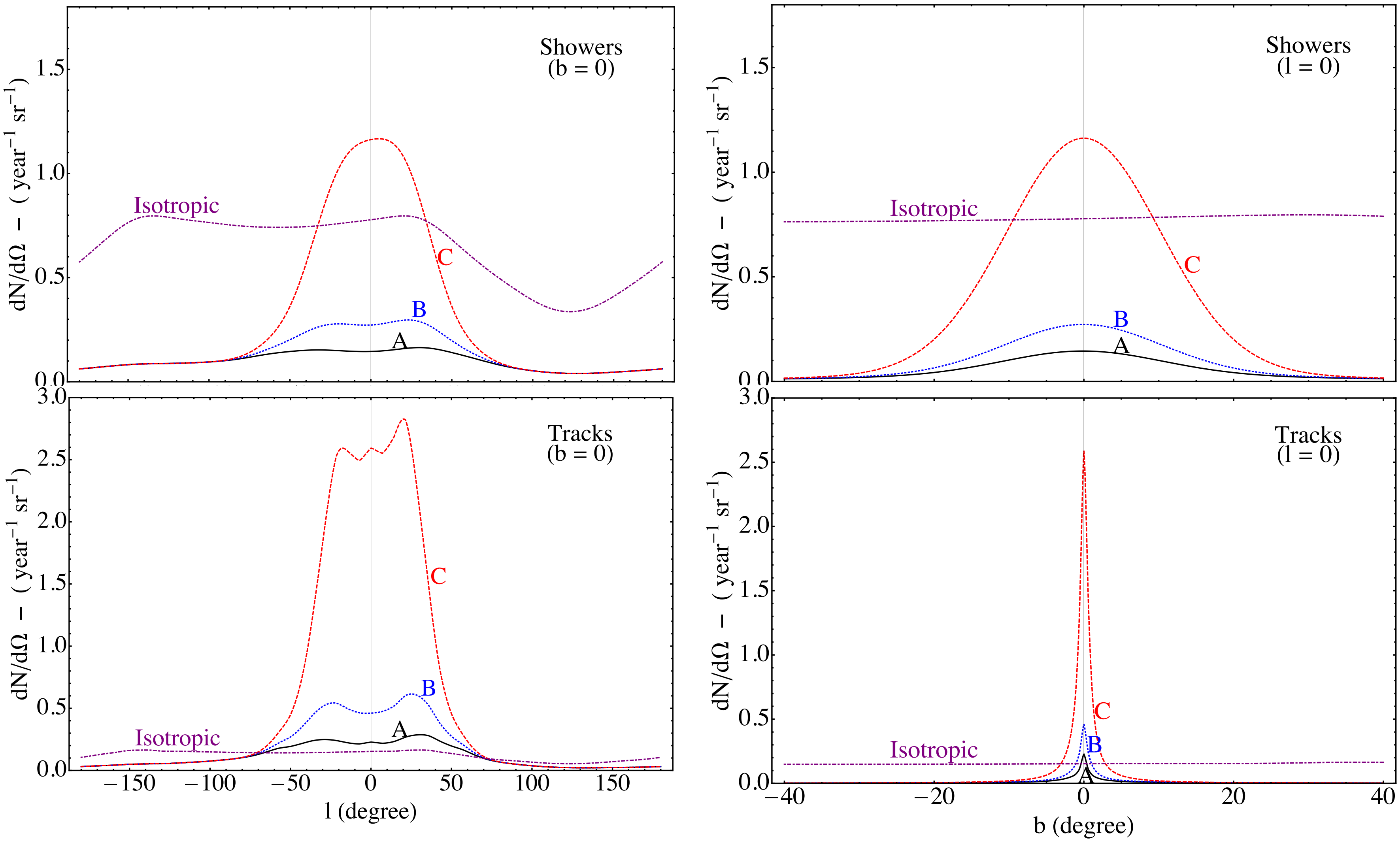


- The **track rate** is generally **too small** to obtain a non negligible detection probability.
- Due to the **poor pointing accuracy**, the **showers** produced by diffuse galactic neutrinos are diluted below the isotropic component everywhere in the sky except for Case C.

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 3σ with the assumption of an isotropic neutrino flux.

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

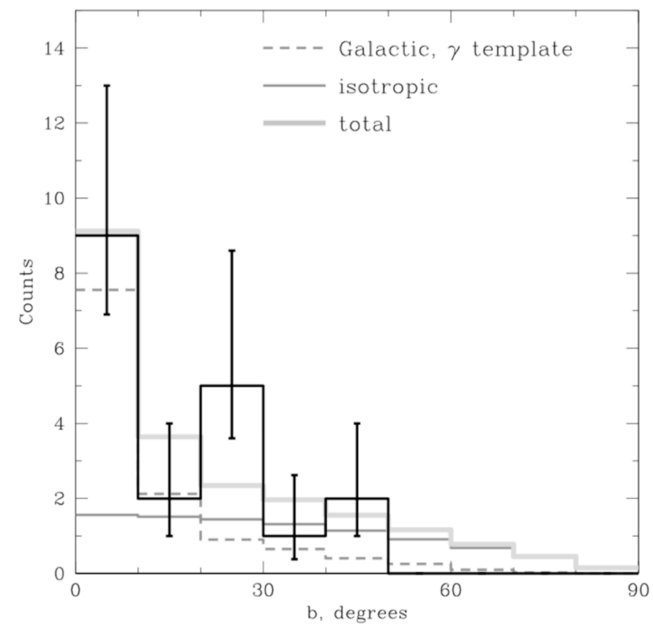
$$\mathcal{F}_{\rm EG}(E_\nu) = 2.8 \times 10^{-6} \left[\frac{E_\nu}{100\,\rm TeV}\right]^{-2} \rm GeV^{-1}\, m^{-2}\, y^{-1}$$

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

Neronov & Semikoz 2015



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

- Ahlers et al 2016: $f \leq 50\%$ (at 90% CL)
  [diffuse galactic neutrino emission assumed to follow the gas column depth]
- Denton et al 2017: $f \approx 0.07^{+0.09}_{-0.06}$ (at 68% CL)
  [galactic neutrino production assumed to follow mass distribution in the disk (McMillan 2011)]