High energy ν and γ from the galactic disk

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Based on work done in collaboration with:

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JCAP 1611 (2016) no.11, 004; JCAP 1808 (2018) no.08, 035

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

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

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 $(\nu_e : \nu_\mu : \nu_\tau) = (1:1:1)$ as expected due to flavour oscillations

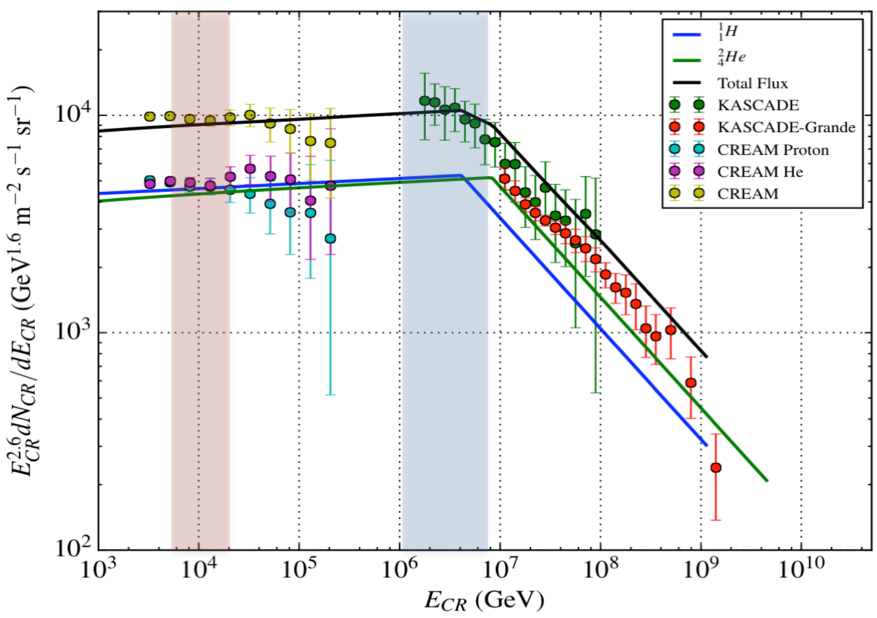
The CR flux: local determination

The neutrino (gamma) flux at E_ν=100 TeV (E_γ=1 TeV) is determined by CR flux at:

$$20\,E_\nu \simeq 2\,\mathrm{PeV}$$
$$10\,E_\gamma \simeq 10\,\mathrm{TeV}$$

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

Broken Power Law – Ahlers et al., PRD 2016



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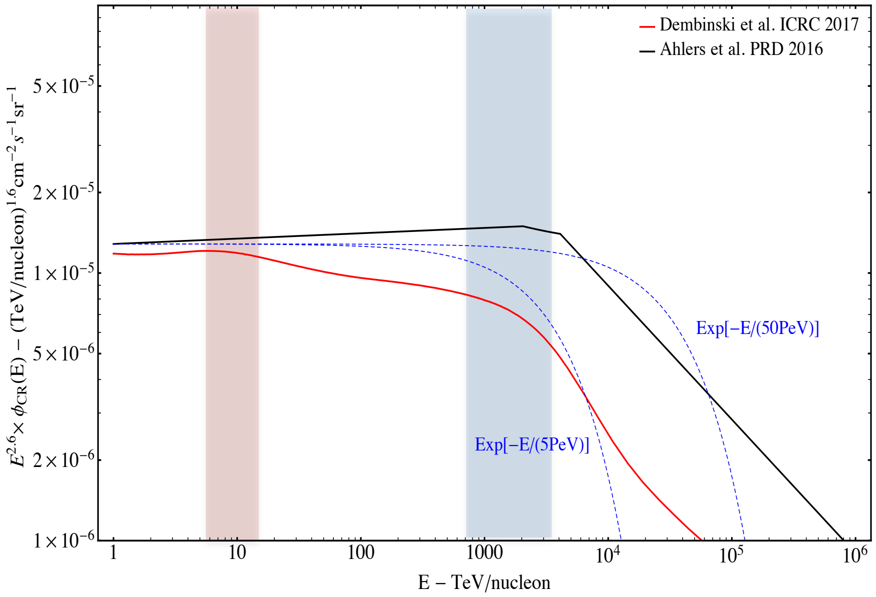
$$\varphi_{\mathrm{CR},\odot}(E) \equiv \sum_A A^2 \frac{d\phi_A}{dE_A d\Omega_A}(AE)$$

The CR flux between 1 Tev and 1 EeV



Note that: Other fits are possible [see e.g. GSF from Dembinski et al, ICRC 2017]. 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.

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

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

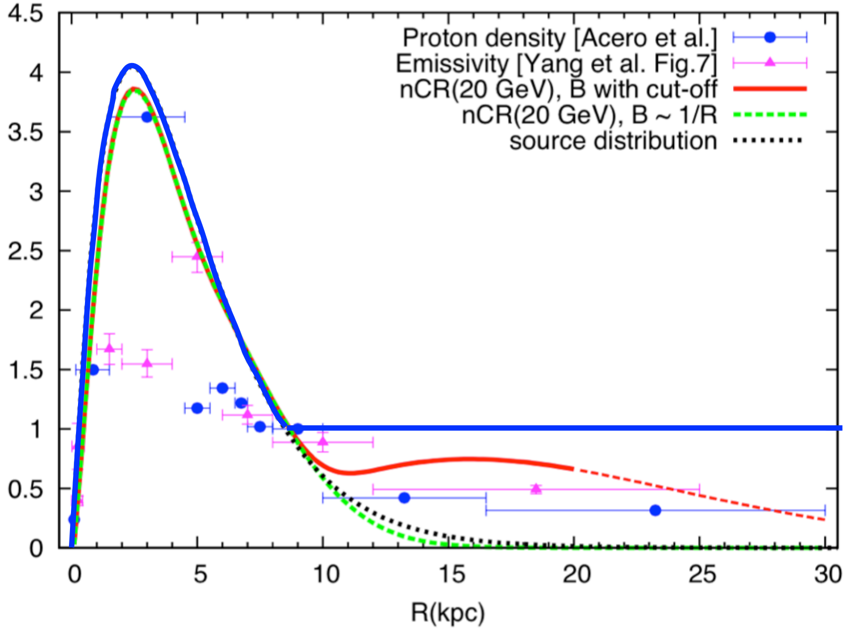
$\Delta(\mathbf{r}) =$ position-dependent variation of the CR spectral index.

Expected in prop.model with radially dependent transport properties (see e.g. Gaggero et al, ApJ 2015)

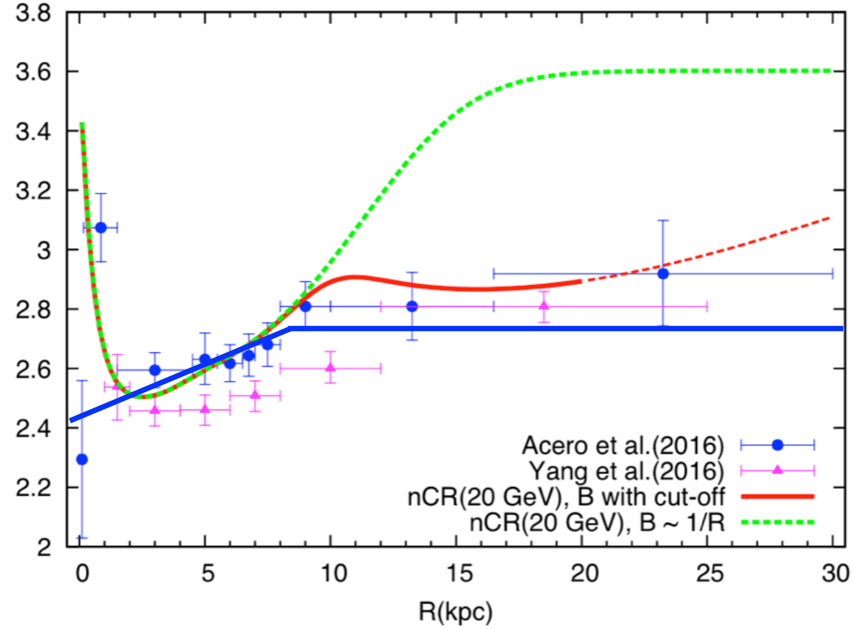
[Similar approach recently used by Lipari & Vernetto, PRD 2018]

The CR flux in the Galaxy

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



CR spectral index
[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]

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

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

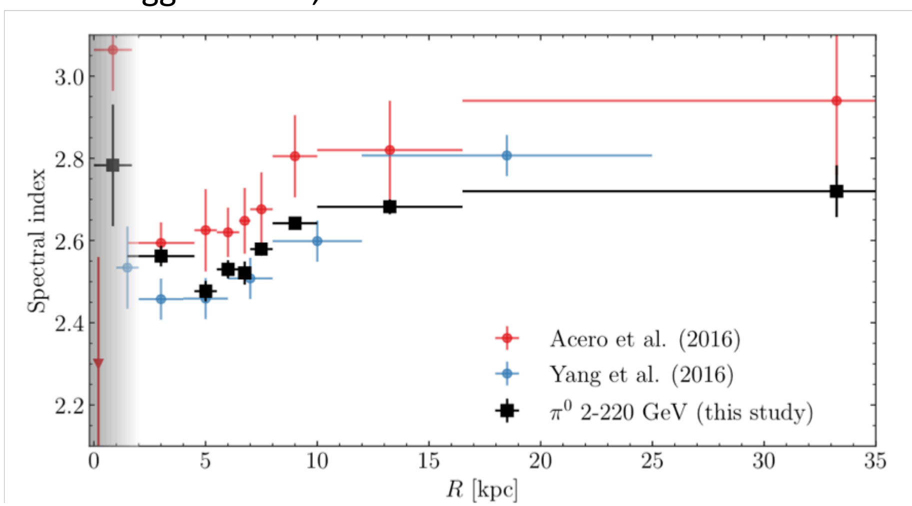
$$\begin{cases} E_{\rm CR} = 2\,\mathrm{PeV} \\ \overline{E} = 20\,\mathrm{GeV} \end{cases}$$

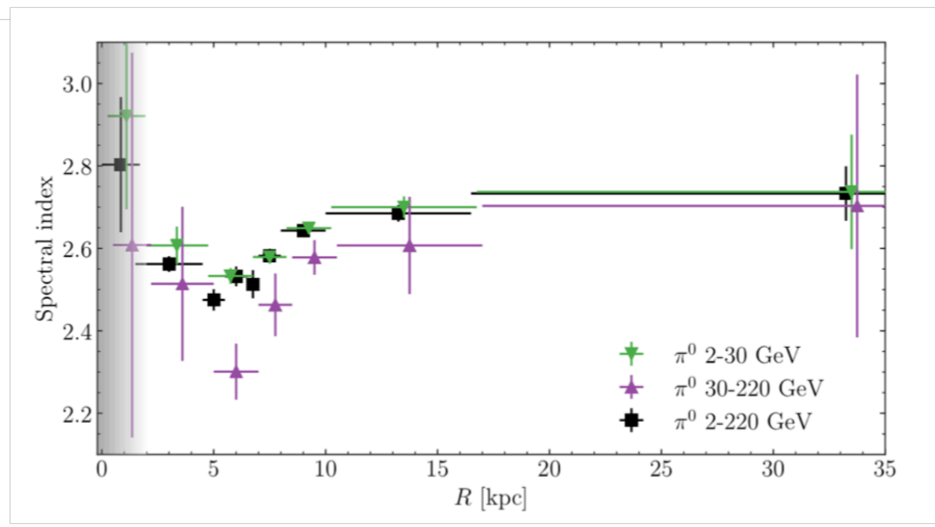
The CR flux in the Galaxy

Spectral hardening suggested by Gaggero et al. 2015 and then reported by two different model-independent analyses of (Acero et al. 2016) and (Yang et al. 2016) of Fermi-LAT data. Very recent analysis (Gaggero et al. 2018) reports the same behavior.

→ The spectral hardening is observed in different energy ranges and resilient wrt different prescriptions in the analysis

Gaggero et al., arXiv:1807.04554v1





Before presenting results ….

The results that I will present for HE photon and neutrino fluxes are from:
- JCAP 1611 (2016) no.11, 004
- JCAP 1808 (2018) no.08, 035

A similar approach to ours was used by Lipari and Vernetto, PRD 2018 with different prescriptions for CR space and energy distribution.
- Factorized fluxes → analogous to our Case A, B
- Non-factorized → analogous to our Case C

KRAγ - CR Propagation model with radially dependent transport properties
see e.g. Gaggero et al., APJ 2015

Updated calculations of HE photon and neutrino fluxes are currently in progress and will be presented soon (Cataldo, Pagliaroli, Villante, Vecchiotti, in preparation)

ν

HE diffuse galactic neutrinos – Integrated flux

The angle-integrated HE neutrino flux at Earth is (E_ν = 10 TeV – 1PeV):

$$\varphi_\nu(E\nu) = \mathcal{F}(E_\nu)\,\overline{\mathcal{I}}$$

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

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

$$\alpha_{\mathcal{A},\mathcal{B}}(E_\nu) \simeq 2.65 + 0.13\log_{10}(E_\nu/100\,\mathrm{TeV})$$

HE diffuse galactic neutrinos – Integrated flux

The integrated HE neutrino flux at Earth is (E_ν = 10 TeV – 1PeV):

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

Isotropic flux required to fit IceCube Hese (4 years)

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Isotropic flux required to fit IceCube Hese (4 years)

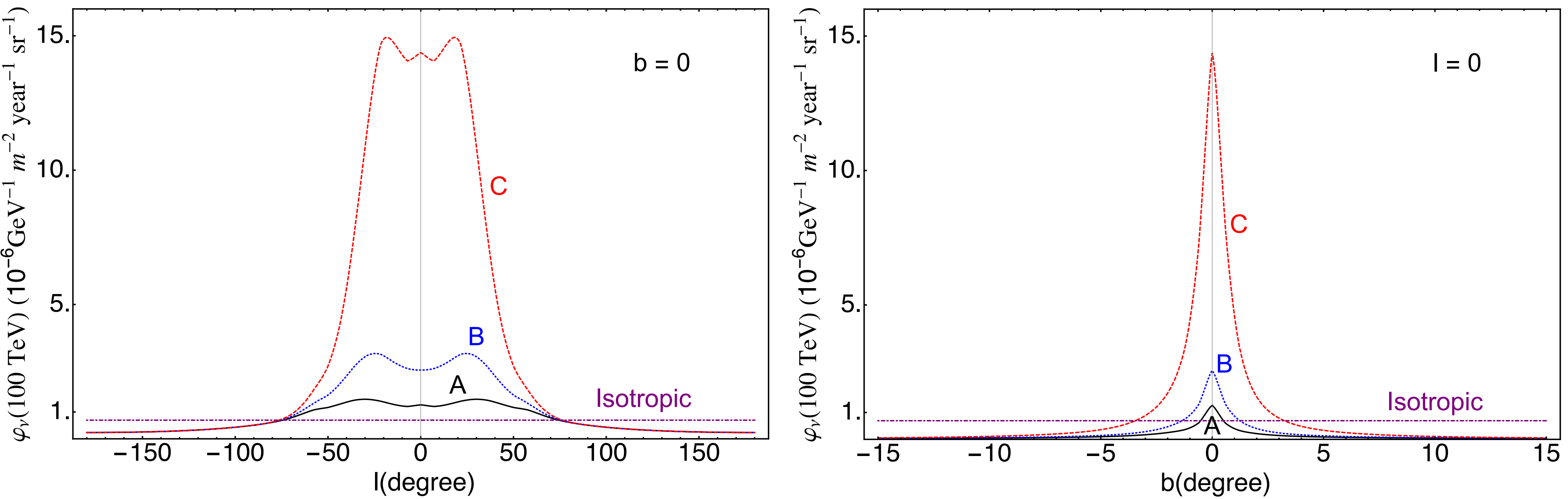
Case A: $\overline{\mathcal{A}} \equiv \int d\Omega\, \mathcal{A}(\hat{n}) = 1 \longrightarrow \dfrac{\mathcal{F}(E_\nu)}{\mathcal{F}_{\rm iso}(E_\nu)} = 5\%$

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

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

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

HE diff. galactic neutrinos – Angular distribution

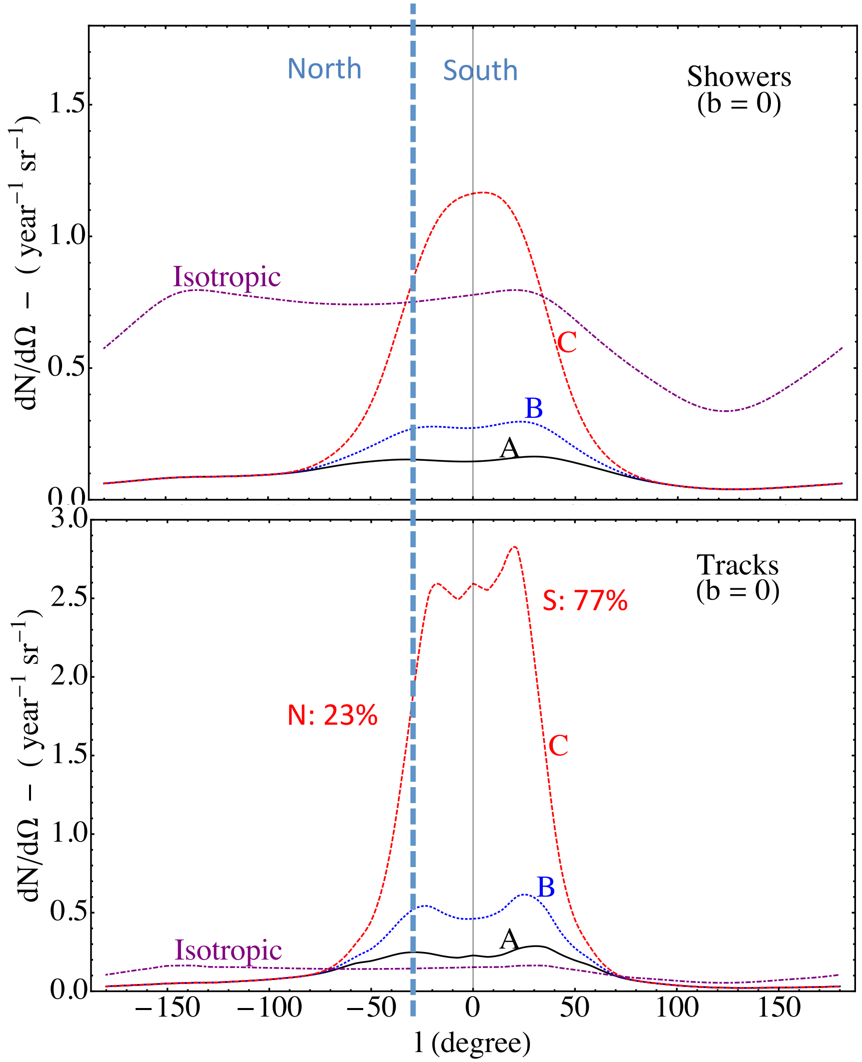


- It always exists a region where the galactic diffuse ν flux is comparable or larger than isotropic component.

- 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**)

HESE events in IceCube

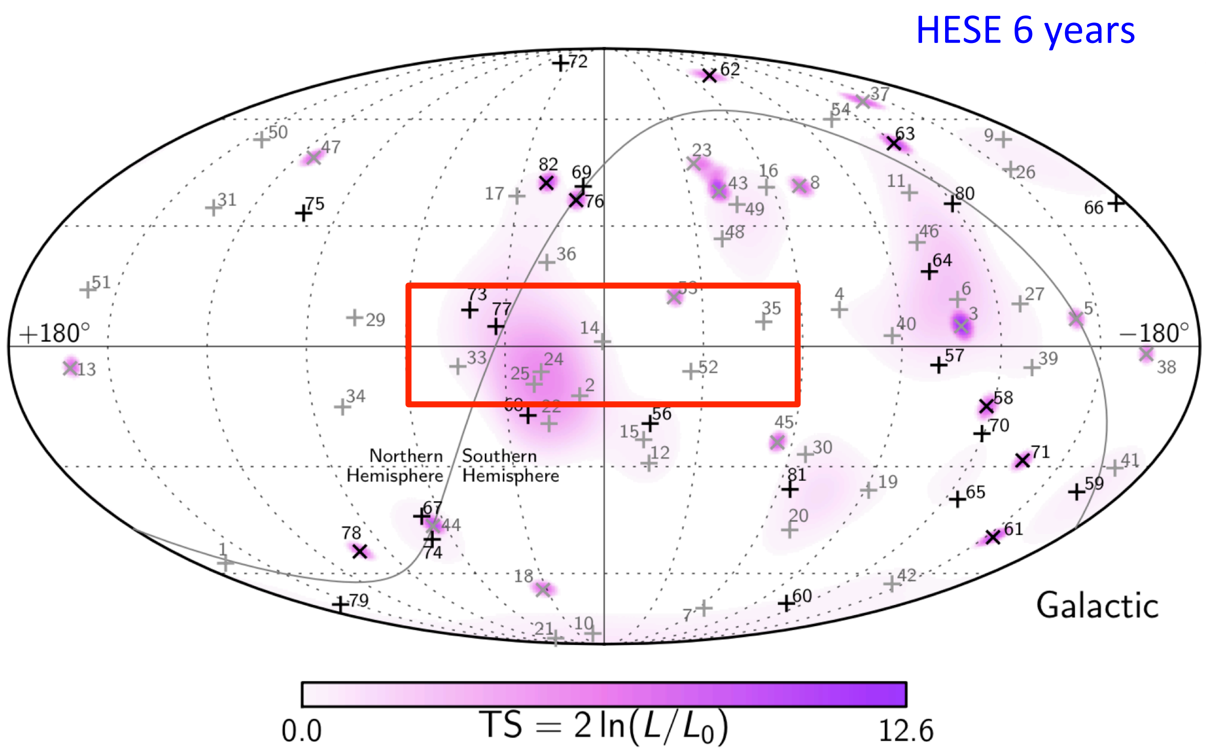


Expected HESE event rates

	N/T – counts · 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

- The **track rate** is **too small (0.2 counts/y^{-1} at most)** 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



-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** …)

[Recent analysis of IceCube data: Palladino and Winter 2018]

[Hints for galactic contribution: Neronov & Semikoz 2015, Palladino & Vissani 2016, Palladino, Spurio, Vissani 2016] γ

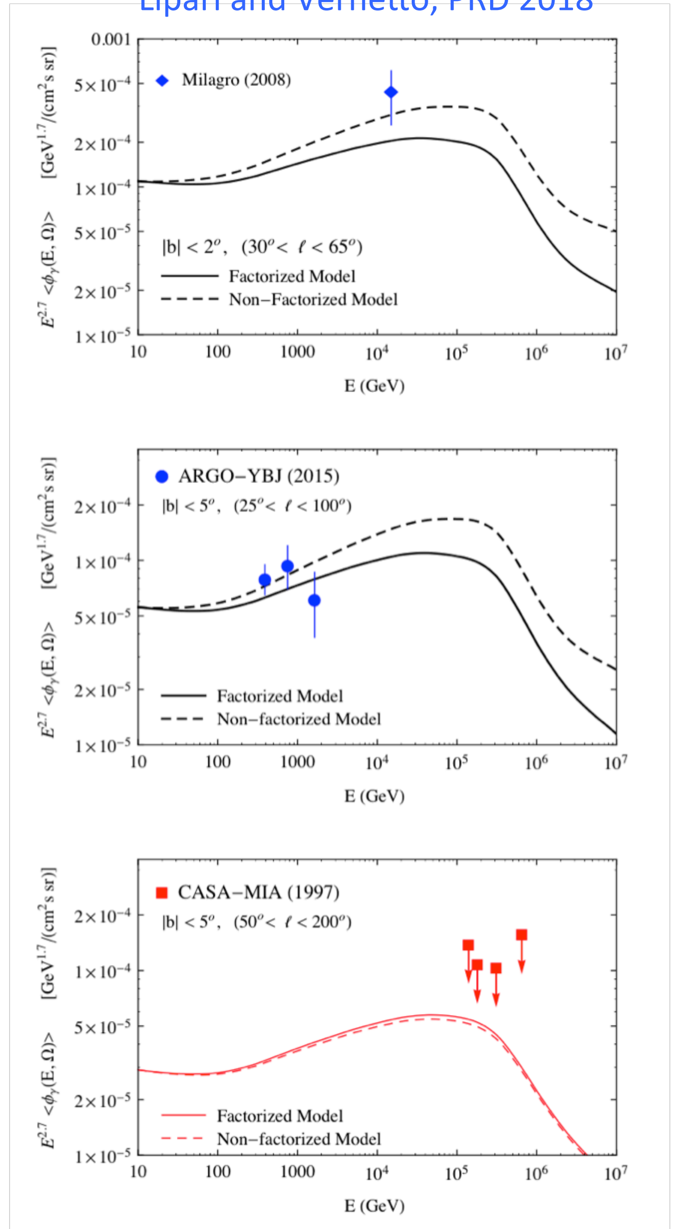
The galactic plane in gammas

- The HE diffuse γ emission can be probed by Milagro (15 TeV) and Argo-YBJ (≈1 TeV)
- Milagro and Argo-YBJ only partially cover the region of most intense emission (-40° < l < 40°) where differences between the various models are more relevant
- Lipari and Vernetto, PRD 2018:

Factorized = No hardening (Case B)

Non-factorized = Hardening (Case C)

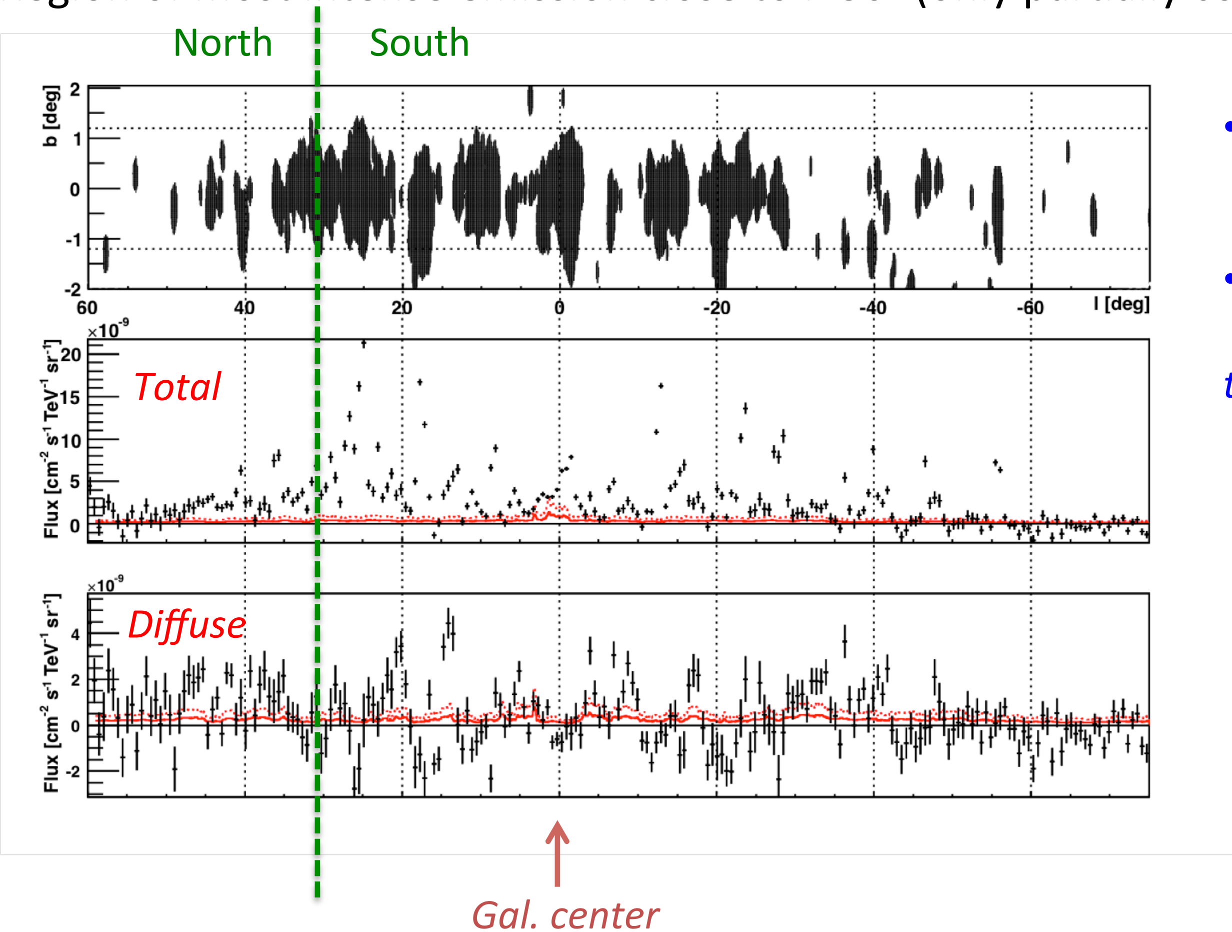
Lipari and Vernetto, PRD 2018



The galactic plane in gammas

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

- Region of most intense emission close to l=30° (only partially contained in the northern sky)



- *Observed region:* *-75° < l < 60° ; -2° < b < 2°*
- *Galactic signal:* *obtained as the excess relative to γ-ray emission at |b| ≥ 1.2°*

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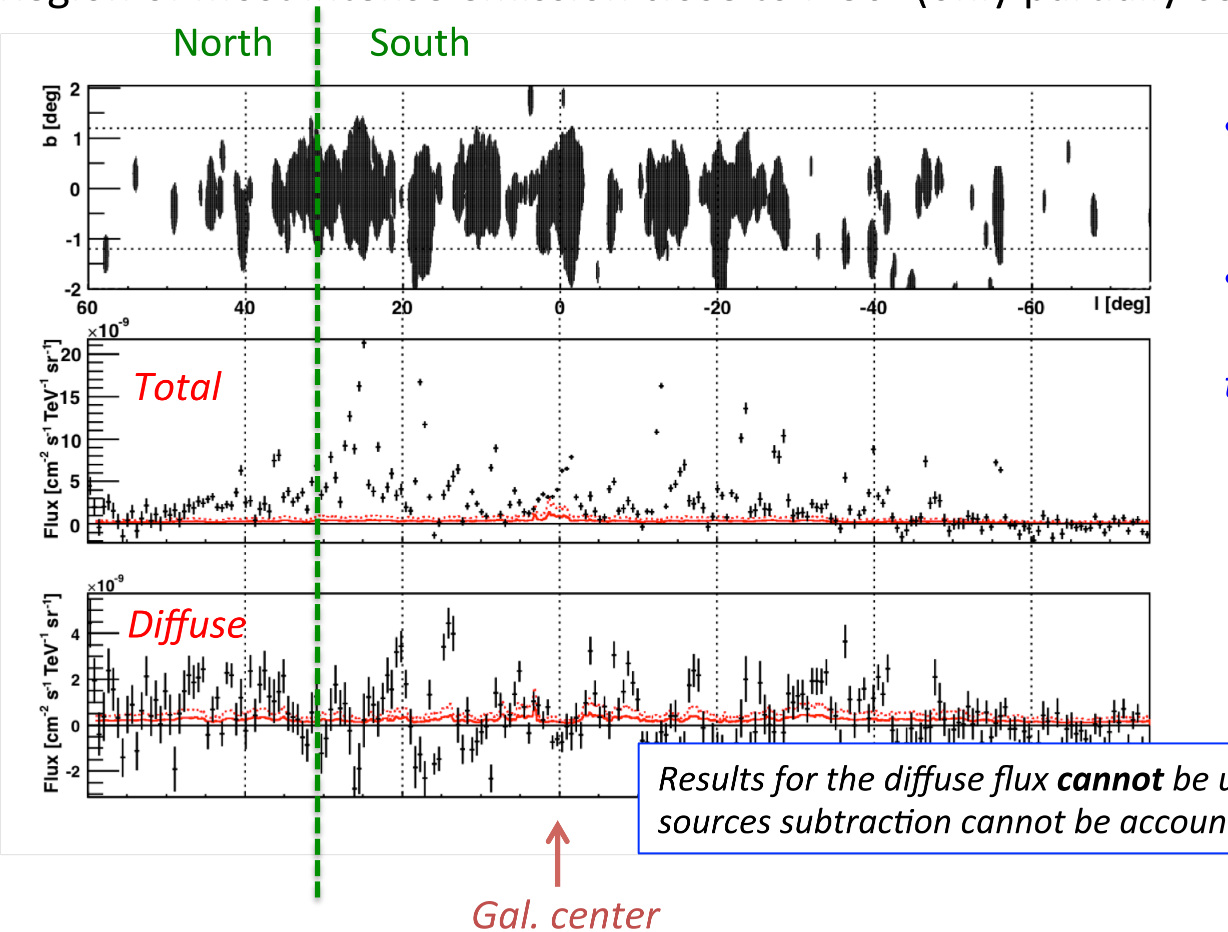
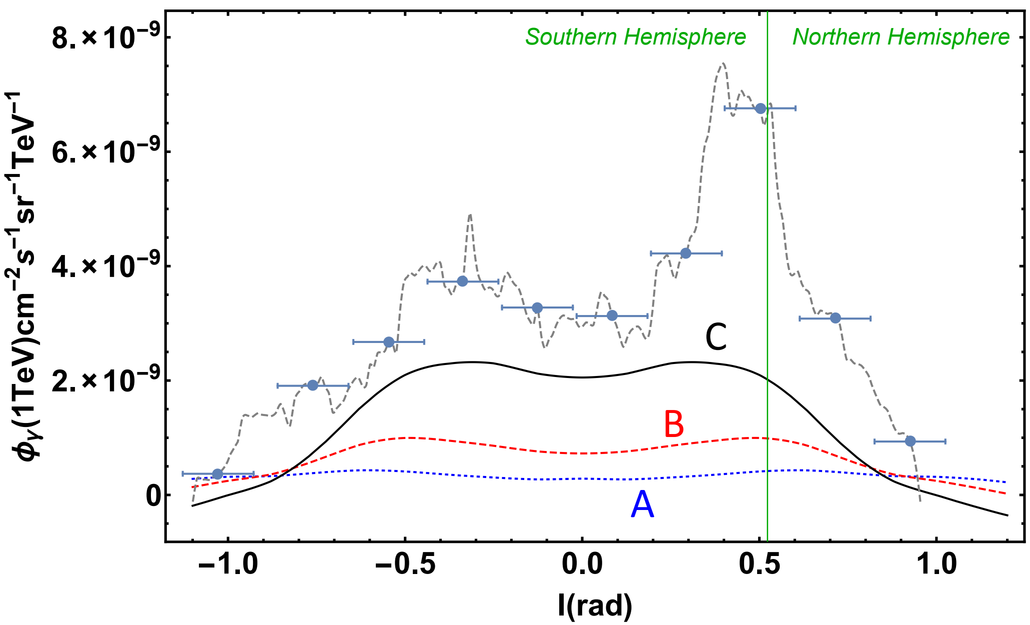


- *Observed region:* *-75° < l < 60° ; -2° < b < 2°*
- *Galactic signal:* *obtained as the excess relative to γ-ray emission at |b| ≥ 1.2°*

*Results for the diffuse flux **cannot** be used because the effect of sources subtraction cannot be accounted in our calculation*

HE diffuse gammas – Comparison with HESS

To avoid large fluctuations and compare with diffuse flux predictions predictions, we re-binned the data → Δl =15° (angular accuracy of shower events in IceCube)



- *Observed region:* *$-75° < l < 60°$; $-2° < b < 2°$*

- *Galactic signal:* *obtained as the excess relative to γ-ray emission at $|b| \geq 1.2°$*

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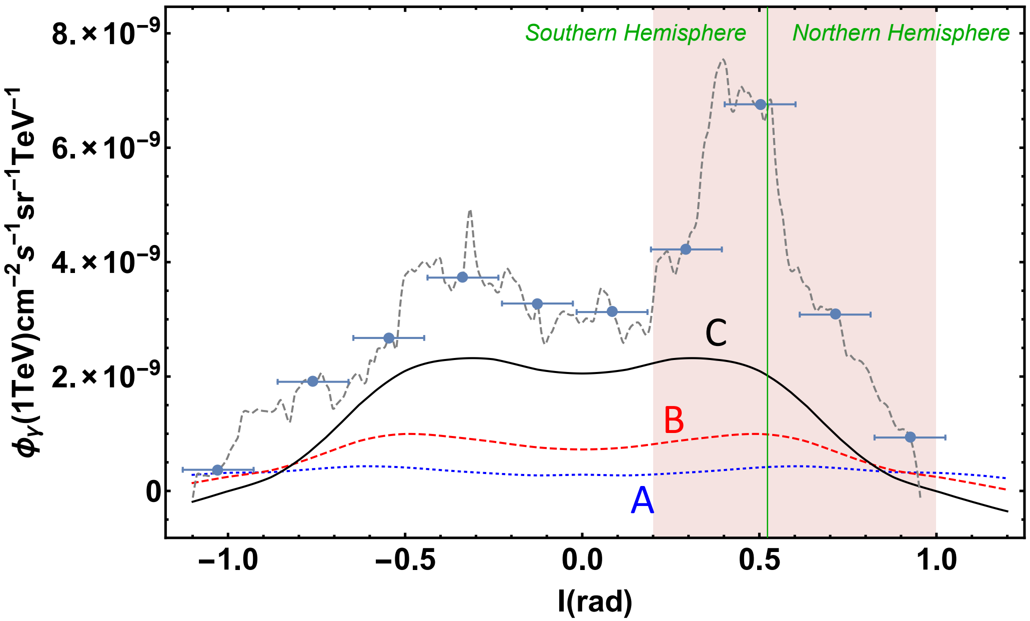


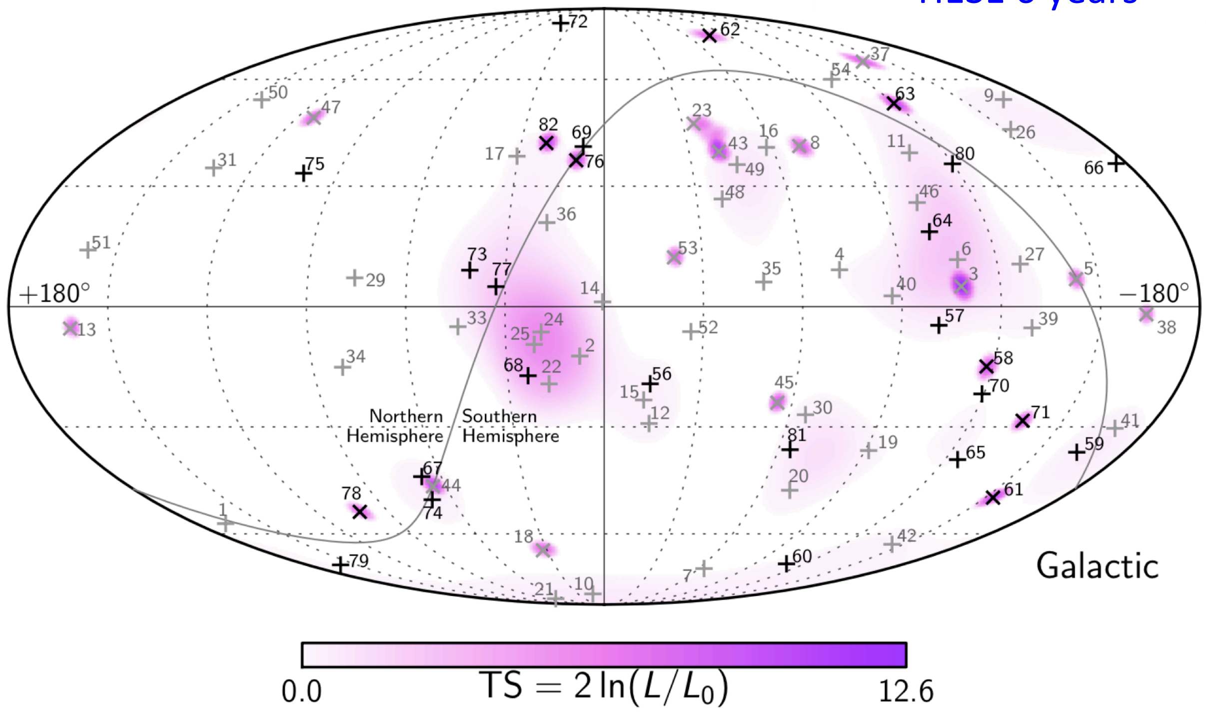
11°< l <57°
Extended "Hot" region (EHR)

- *Observed region:*
  -75° < l < 60° ; -2° < b < 2°
- *Galactic signal:*
  obtained as the excess relative to γ-ray emission at |b| ≥ 1.2°

- 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?

HESE 6 years

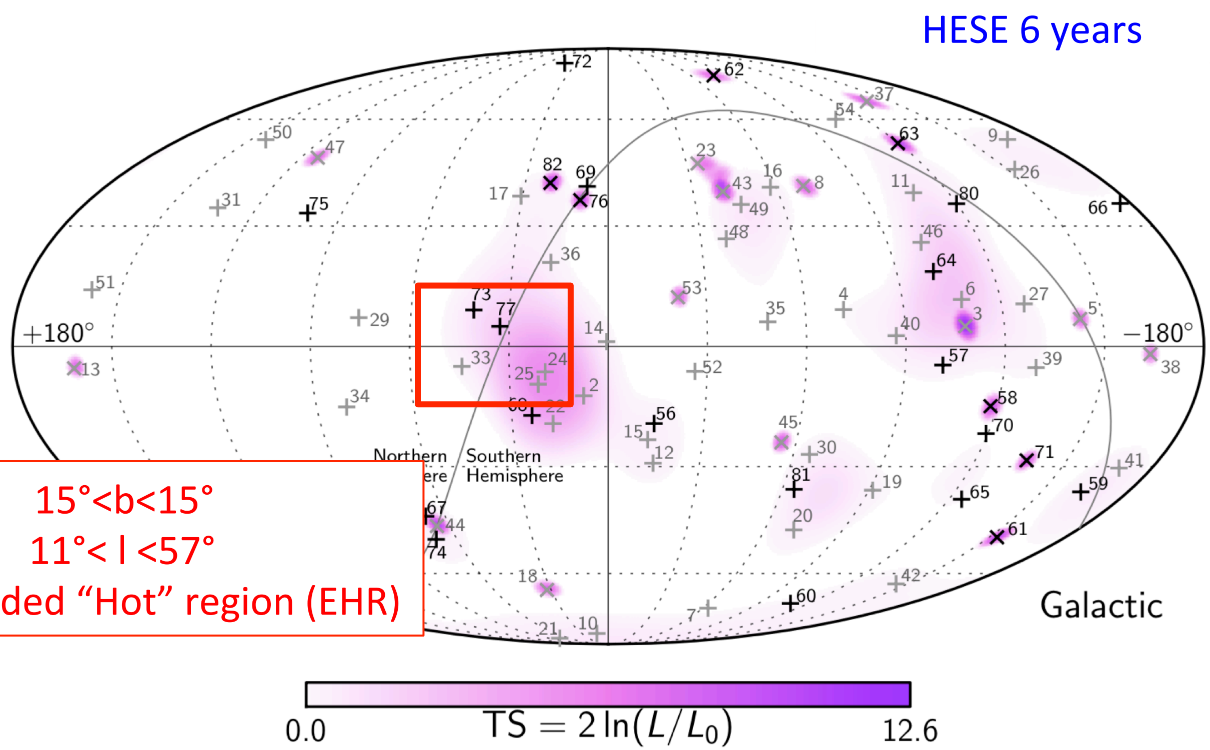


*If the **observed gammas** are due to hadronic mechanism, **neutrinos** are also produced*

↓

***EHR** has to be considered as a **preferential target** for the search of a galactic neutrino component*

Has EHR a counterpart in neutrino sky?



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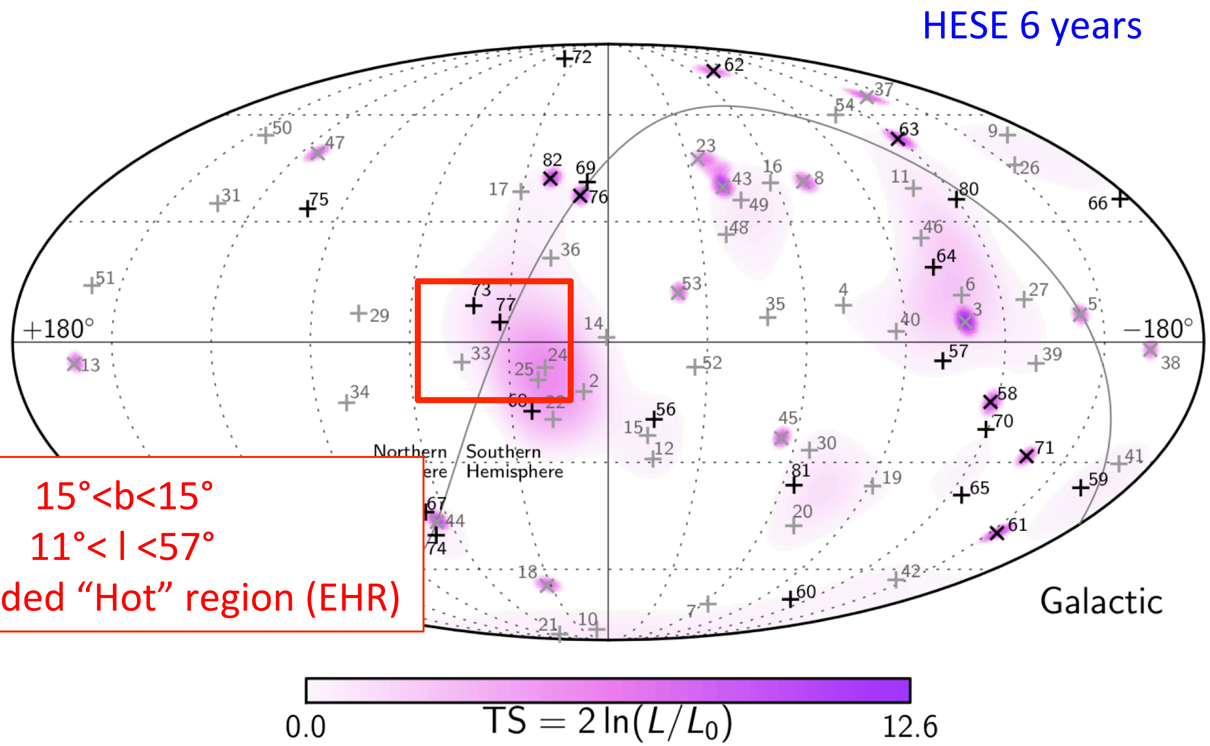

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↓

***EHR** has to be considered as a **preferential target** for the search of a galactic neutrino component*

In the selected observation window:

- $N_{Sh,obs} = 5$

to be compared with:

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

Excess wrt predictions: $\Delta N_{Sh,obs} = 3.3$

ν/γ

A multi-messenger study of total galactic emission

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

$$\varphi_{\gamma,\mathrm{tot}} - \varphi_{\gamma,\mathrm{diff}} = \varphi_{\gamma,\mathrm{S}} + \cancel{\varphi_{\gamma,\mathrm{IC}}}$$
$$\varphi_{\nu,\mathrm{tot}} = \varphi_{\nu,\mathrm{diff}} + \varphi_{\nu,\mathrm{S}}$$

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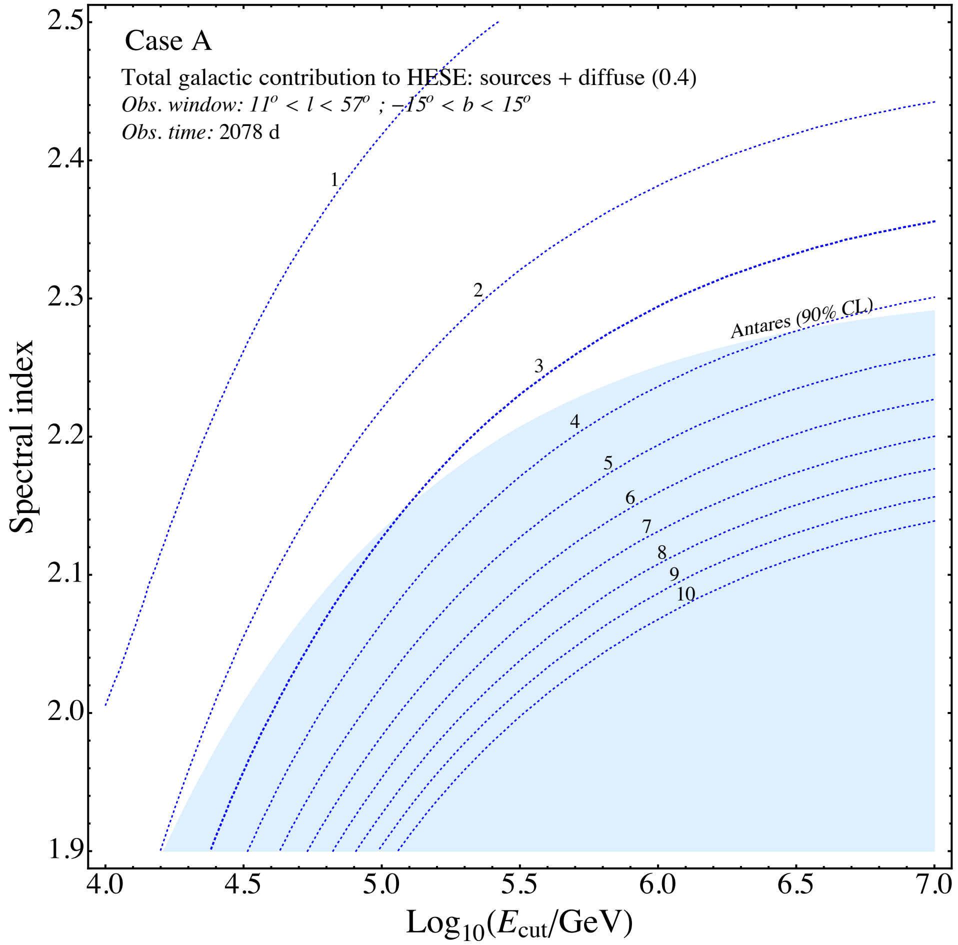
The **cumulative ν source contribution** is estimated by assuming that the **observed** γ are produced by **hadronic mechanisms** (and not absorbed)

[Kappes et al., ApJ 2007]

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

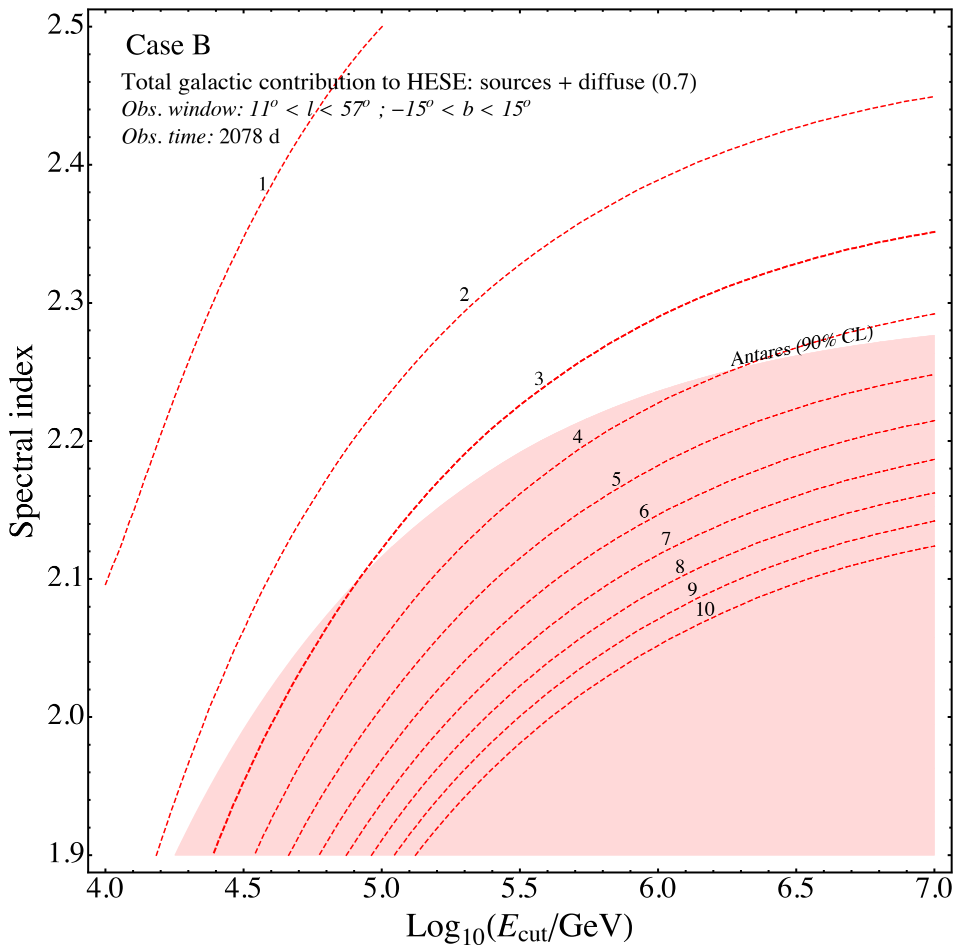
$$\begin{aligned} k_\nu &= (0.694 - 0.16\alpha_\gamma)\;k_\gamma \\ \alpha_\nu &= \alpha_\gamma \\ E_{\mathrm{cut},\nu} &= 0.59\,E_{\mathrm{cut},\gamma} \end{aligned}$$

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)



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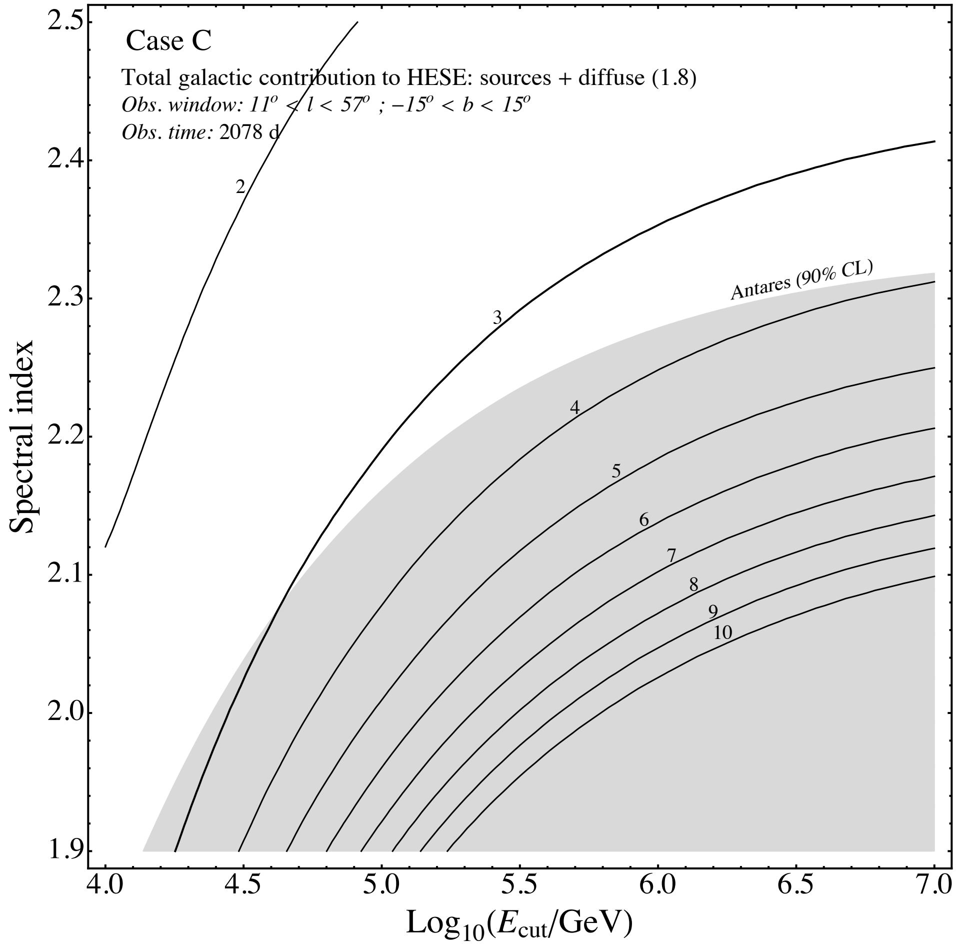
The total (diffuse+source) galactic signal in EHR (Case C)



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Summary and conclusions

- ✓ The diffuse gamma and neutrino fluxes are a tool to study CR in different regions of the Galaxy
- ✓ 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).
- ✓ Search strategies of galactic HE ν component should be optimized by using ν/γ connection
- ✓ IceCube and ANTARES are approaching the sensitivity level to probe the total galactic component.

Thank you

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

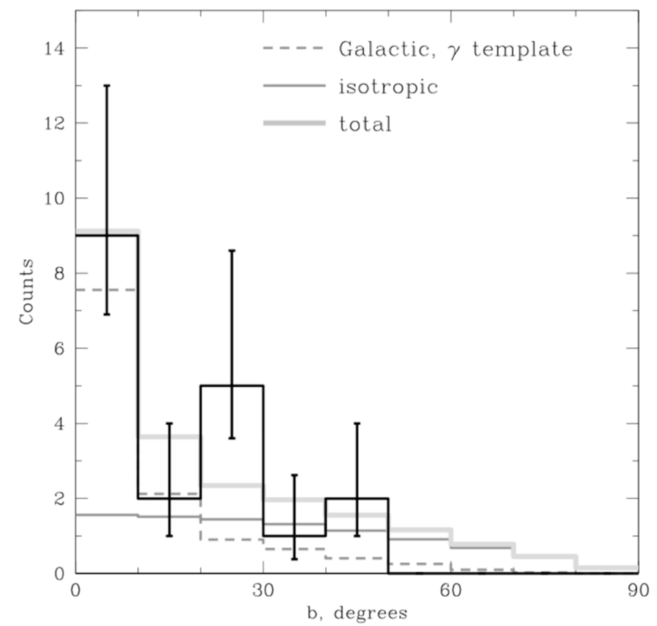
$$\mathcal{F}_{\rm EG}(E_\nu) = 2.8 \times 10^{-6} \left[\frac{E_\nu}{100\,\mathrm{TeV}}\right]^{-2} \mathrm{GeV}^{-1}\,\mathrm{m}^{-2}\,\mathrm{y}^{-1}$$

Extra-galactic = Isotropic

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

Galactic = uniform in the southern sky

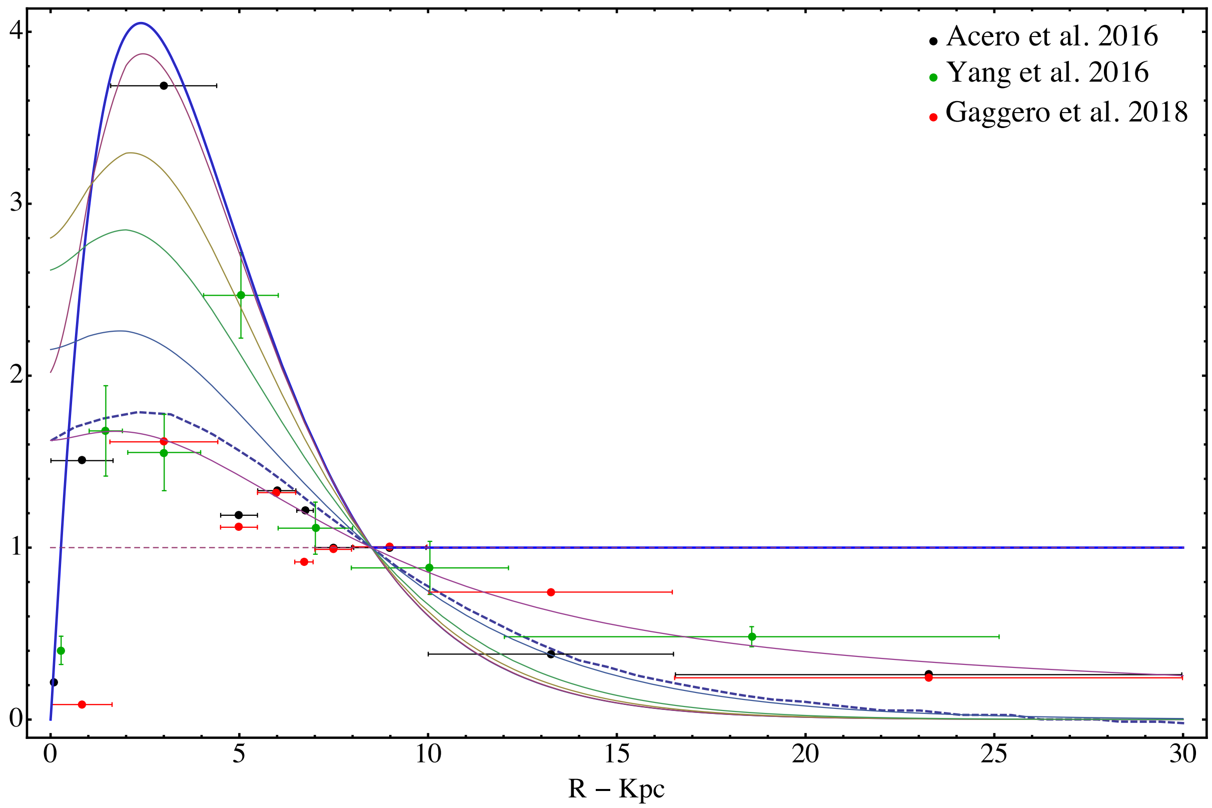
Neronov & Semikoz 2015



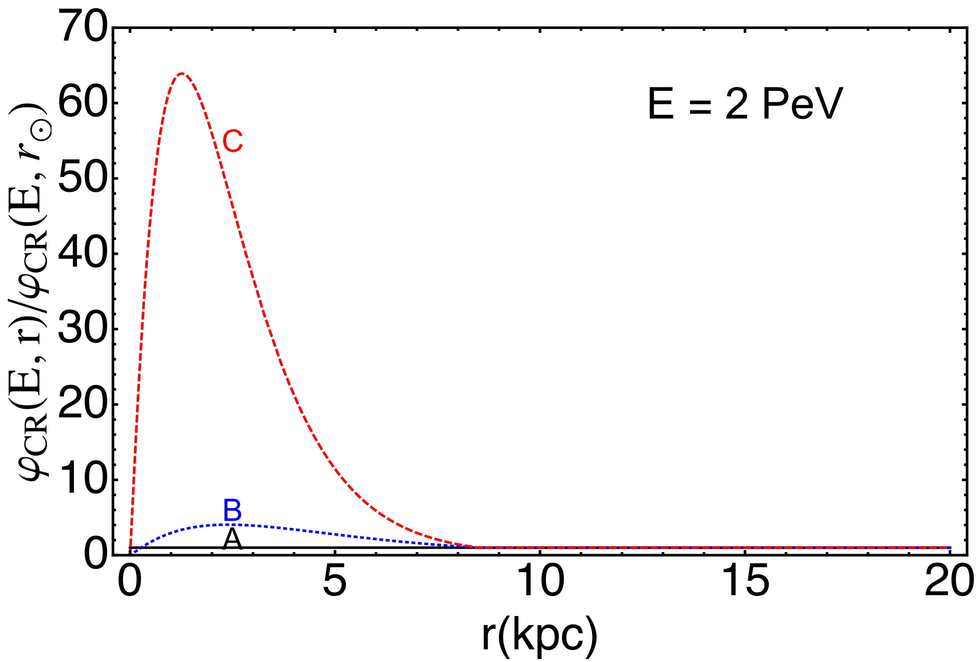
The fraction f of the astrophysical neutrino signal due to galactic emission can be limited by event arrival direction distribution:

- 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)]

The CR distribution



The CR density at few PeVs in the 3 different models



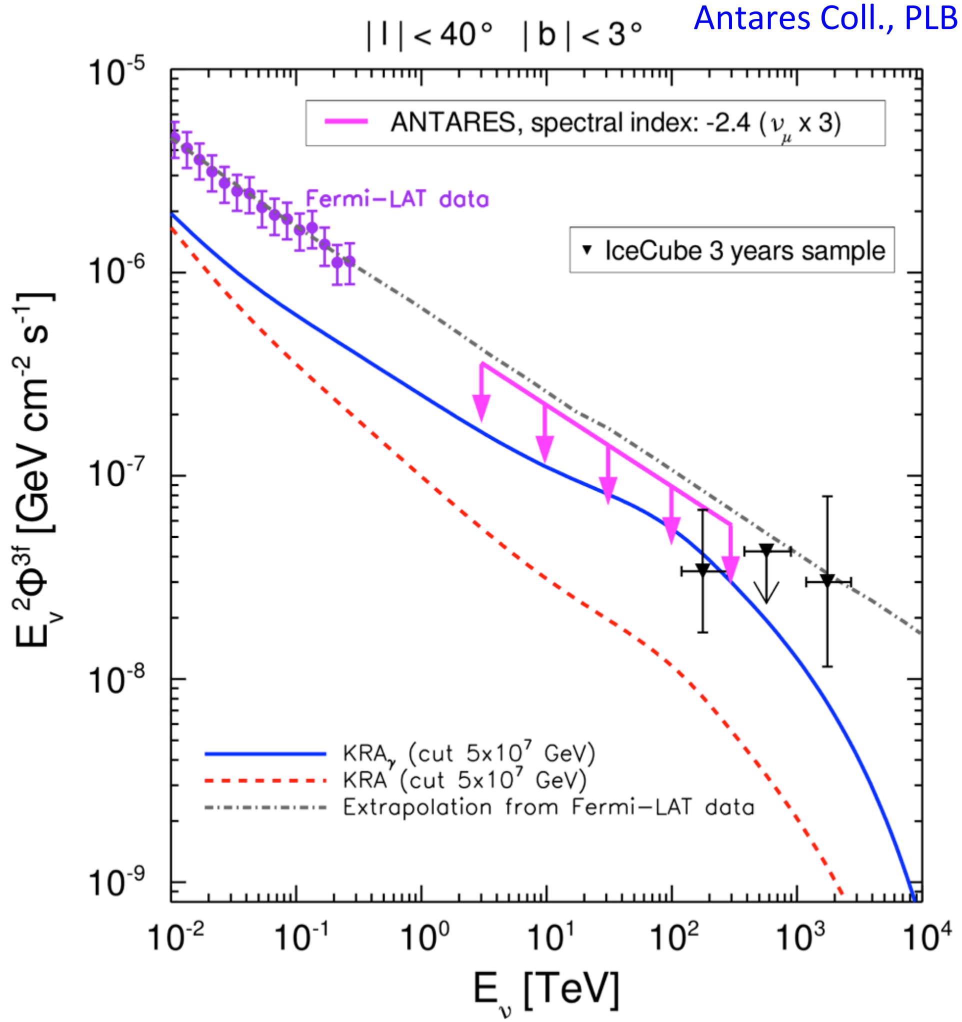
$$\varphi_\nu(E_\nu, \hat{n}_\nu) = \frac{1}{3} \sum_{\ell=e,\mu,\tau} \left[\int_{E_\nu}^{\infty} dE \int_0^{\infty} dl \, \frac{d\sigma_\ell(E, E_\nu)}{dE_\nu} \times \varphi_{\rm CR}(E, \mathbf{r}_\odot + l\,\hat{n}_\nu) \times n_{\rm H}(\mathbf{r}_\odot + l\,\hat{n}_\nu) \right]$$

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

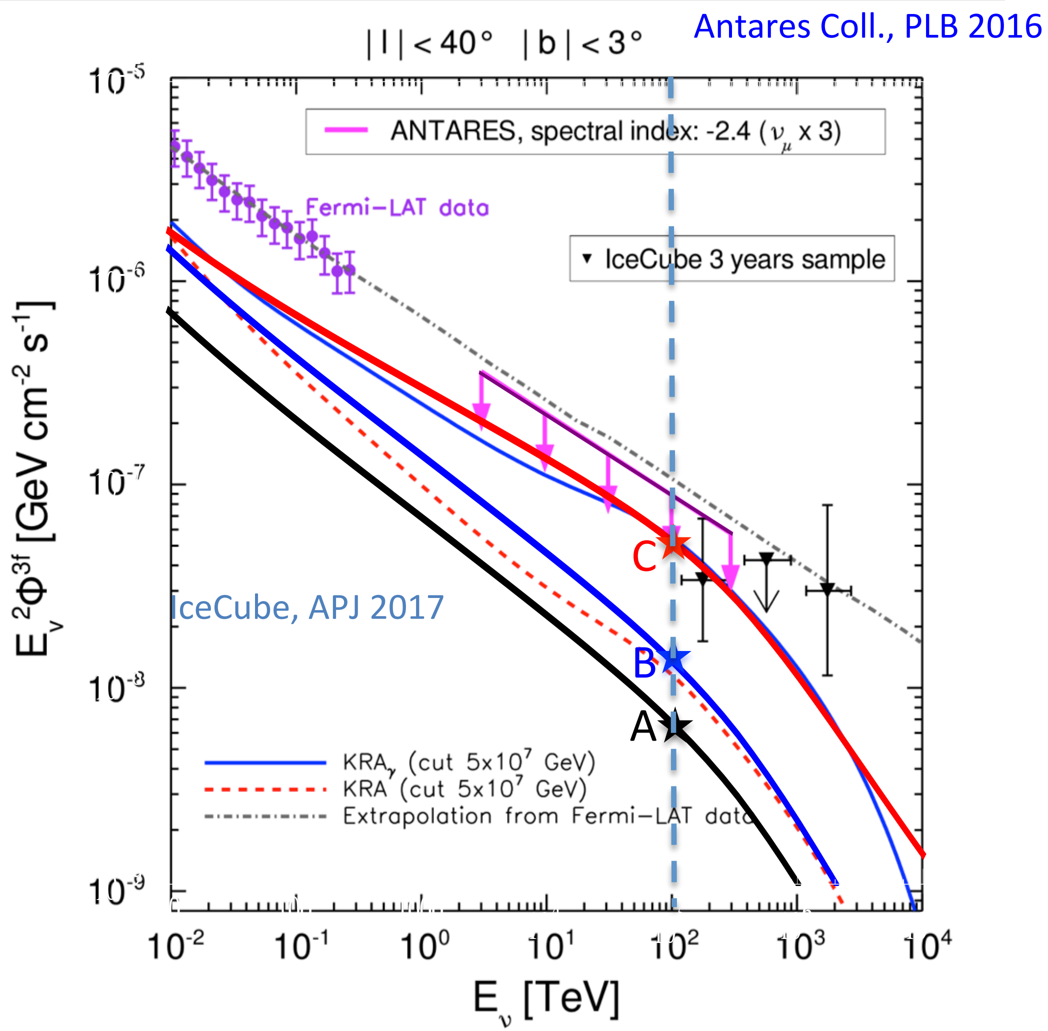
Case B and Case C : More pronounced emission from the inner galactic region

Comparison with KRAγ and ANTARES

Antares Coll., PLB 2016



Comparison with KRAγ and ANTARES



Latest (combined) analyses from **Antares** (PRD 2017) and **IceCube** (ApJ 2017) adopt **templates** for galactic emissions:

Galactic component < 10% - 20% of the isotropic contribution

Events in IceCube – Integrated rates

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

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

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

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 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

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:

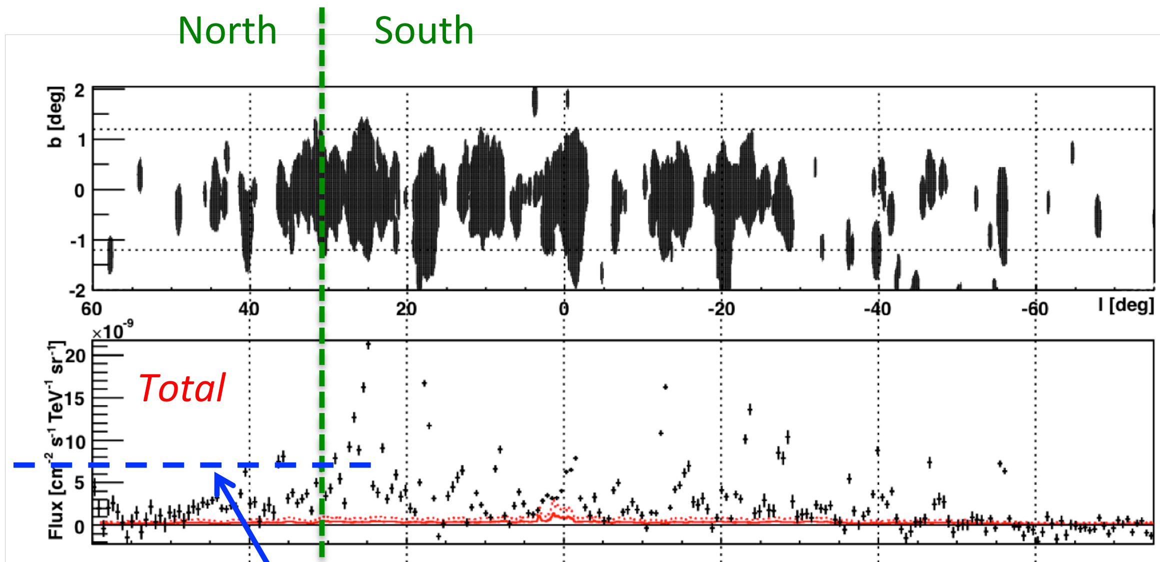
$$G_{\rm I}(\hat{n},\hat{n}_\nu) = \frac{m}{2\pi\delta n_{\rm I}^2}\exp\left(-\frac{1-c}{\delta n_{\rm I}^2}\right)$$

where :

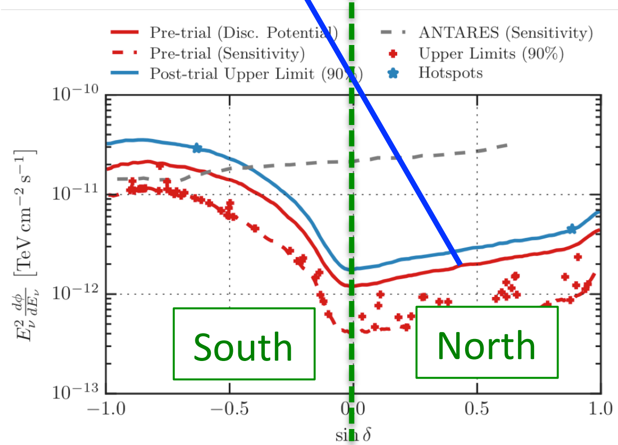
- $\rm I = S,\ T$
- m is a normalization factor
- $c \equiv \cos\theta = \hat{n}\,\hat{n}_\nu$
- $\delta n_{\rm S}$ $(\delta n_{\rm T})$ fixed by requiring $\theta \leq 15^\circ$ $(\theta \leq 1^\circ)$ for showers (tracks) at 68.3% C.L.

The galactic plane in gammas

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



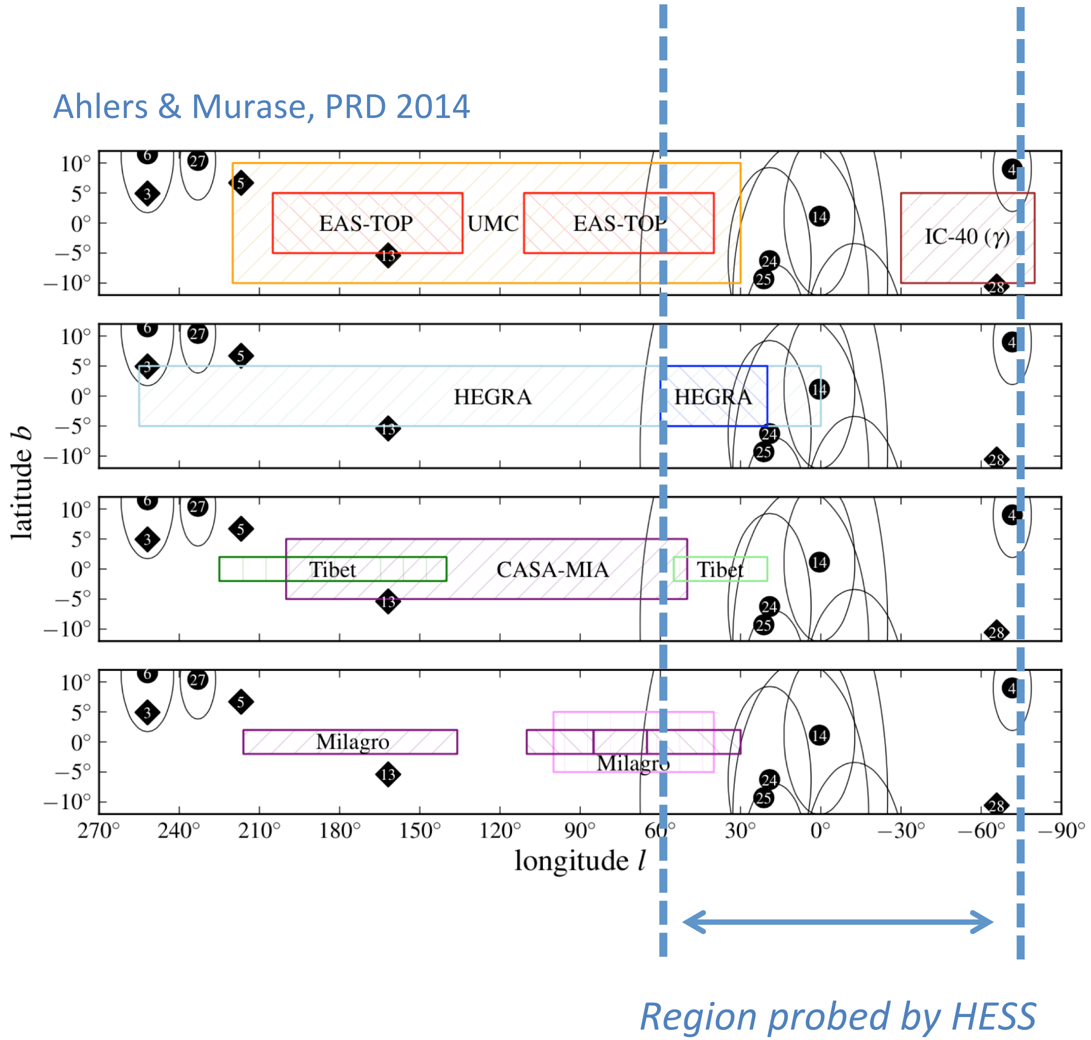
- *Observed region:* *-75° < l < 60° ; -2° < b < 2°*
- *Galactic signal:* *obtained as the excess relative to γ-ray emission at |b| ≥ 1.2°*



__Back-of-the-envelope estimate:__

Obtained by converting the point source limit for ν_μ flux $[E_\nu^2 f_\nu(E_\nu) = 2 \cdot 10^{-12}$ TeV cm^{-2} s$^{-1}]$ in the associated photon flux (α=2 is assumed) and dividing by the solid angle of HESS bins (Δb=4°; Δl=0.6°)

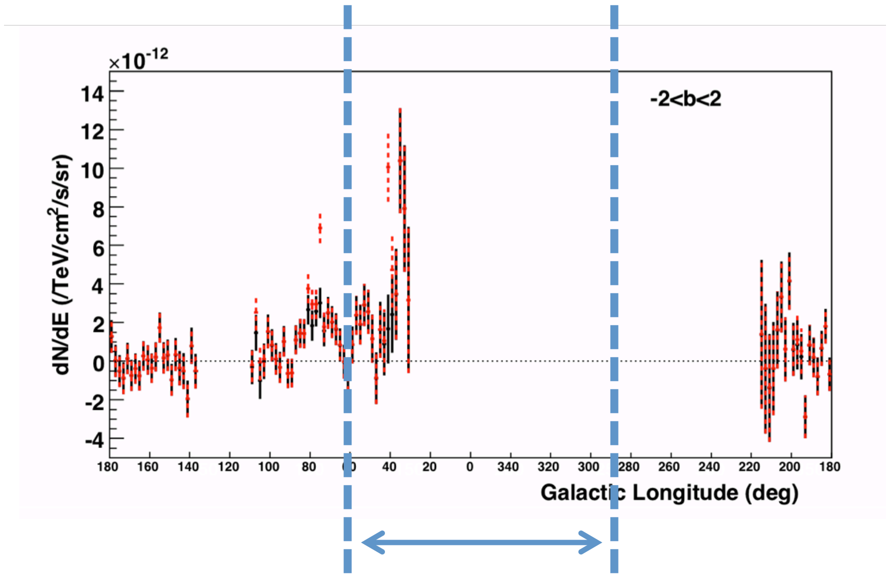
The galactic plane in gammas



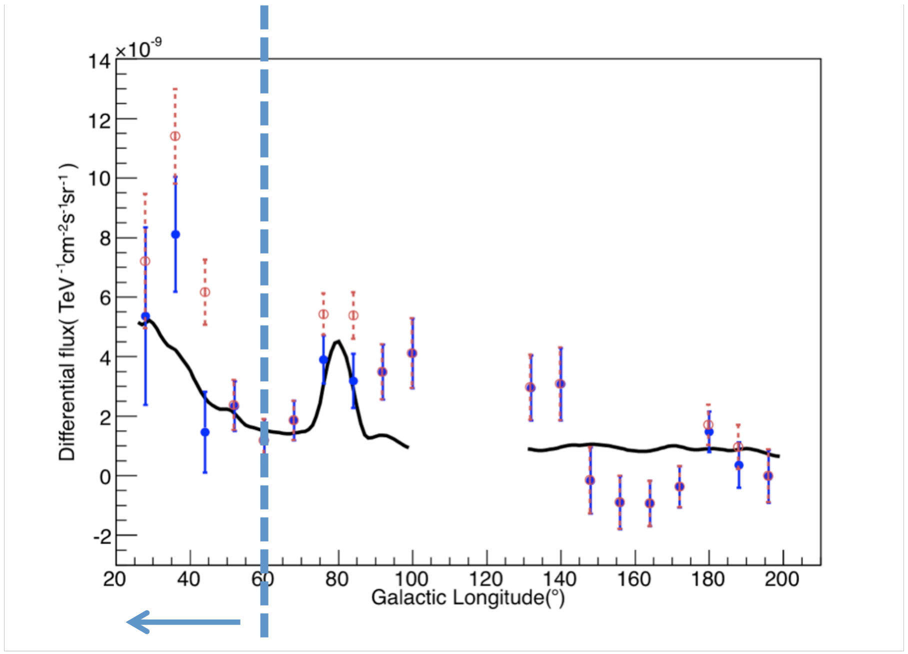
Milagro and Argo-YBJ

Milagro and Argo-YBJ overlap only partially with HESS

Milagro (E=15 TeV, l > 30°, |b|<2°)

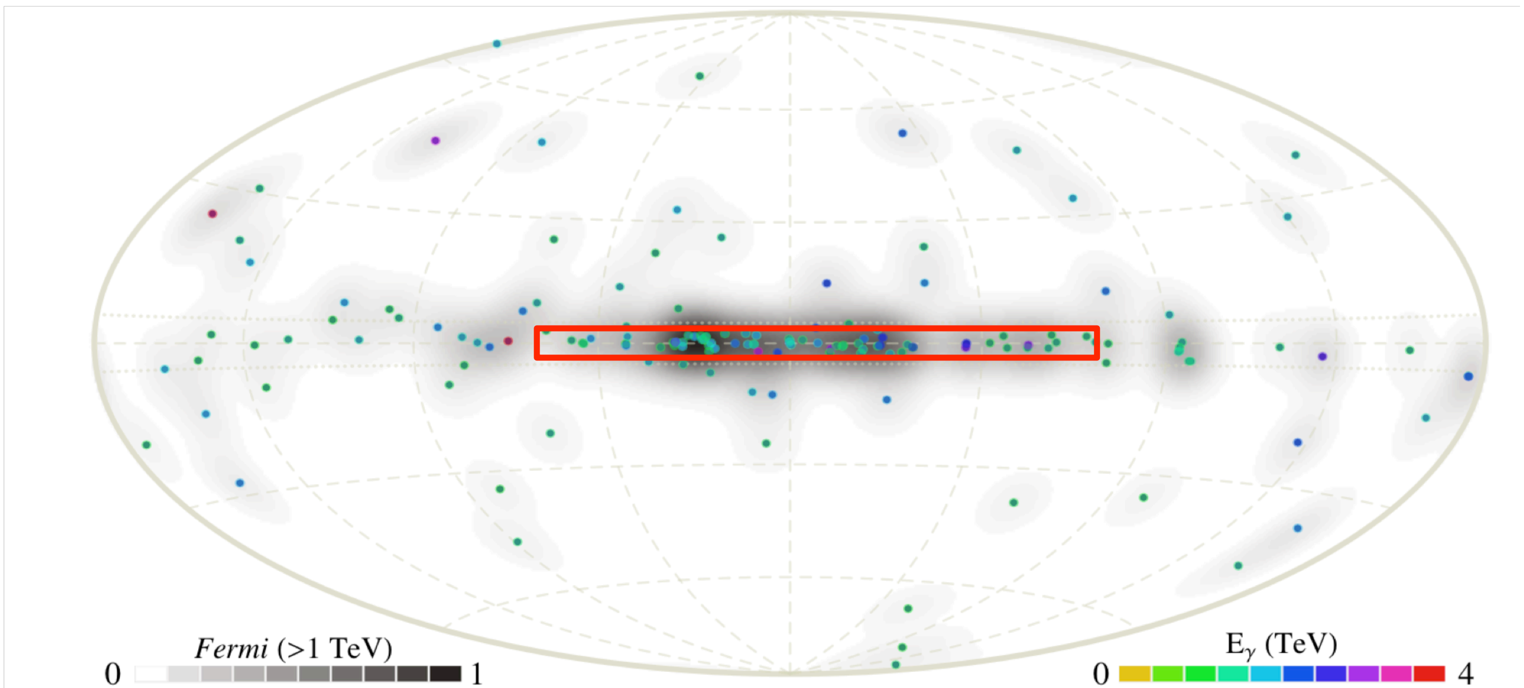


Argo-YBJ (E=0.6 TeV, l > 25°, |b|<5°)



Fermi-LAT above 1 TeV

By using the Fermi-LAT Pass8 data, Kistler [arXiv:1511.0599] selected 97 events with $E_\gamma \geq 1$TeV and latitude $|b| \leq 5°$ in about 7 years data



The galactic plane in gammas

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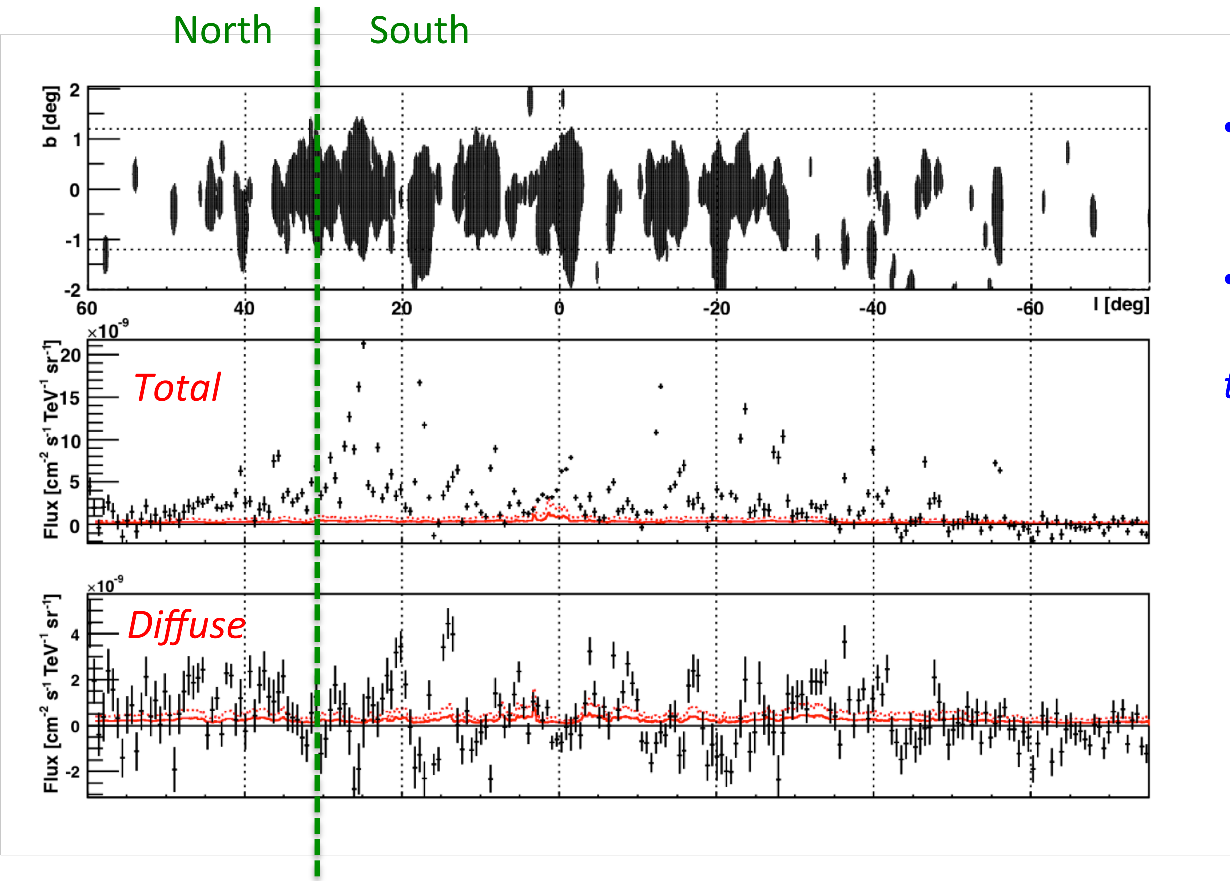

- *Observed region:*
  -75° < l < 60° ; -2° < b < 2°

- *Galactic signal:*
  obtained as the excess relative to γ-ray emission at |b| ≥ 1.2°