Galactic emission of high-energy gamma rays and neutrinos

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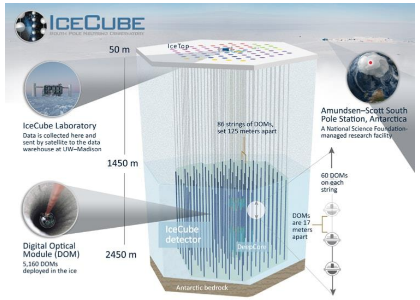
Presented by: Vittoria Vecchiotti

Outline:

1. Galactic gamma-ray sky;
2. Interpretation of gamma-ray data and unresolved sources;
3. Constrain the Galactic **diffuse** emission;



1. Galactic neutrino sky;
2. Neutrino measurements;
3. Future plans;

Total Galactic emission GeV-PeV:

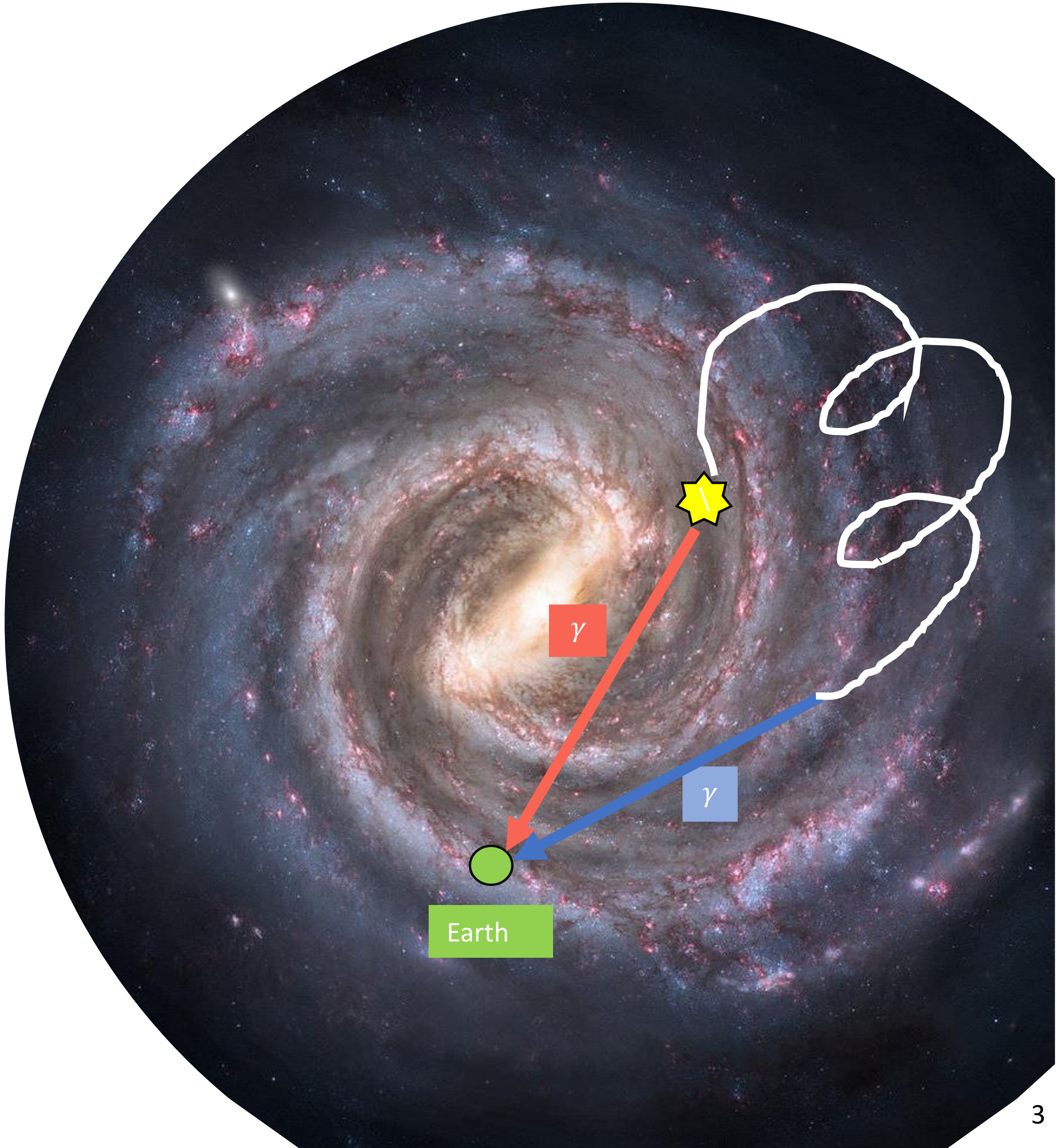
$$\phi_{\gamma,tot} = \boxed{\phi_{\gamma,s}} + \boxed{\phi_{\gamma,\text{diff}}} + \phi_{\gamma,IC}$$

Source component is due to the interaction of accelerated particles (hadrons or leptons) with the ambient within or close to an acceleration site (such as PWNe, SNRs).

Diffuse component is due to the interaction of Cosmic Rays (CRs) with the interstellar medium;

It encodes information about the CR spatial and energy distribution

Inverse Compton: is due to the interaction of accelerated leptons with the CMB ;



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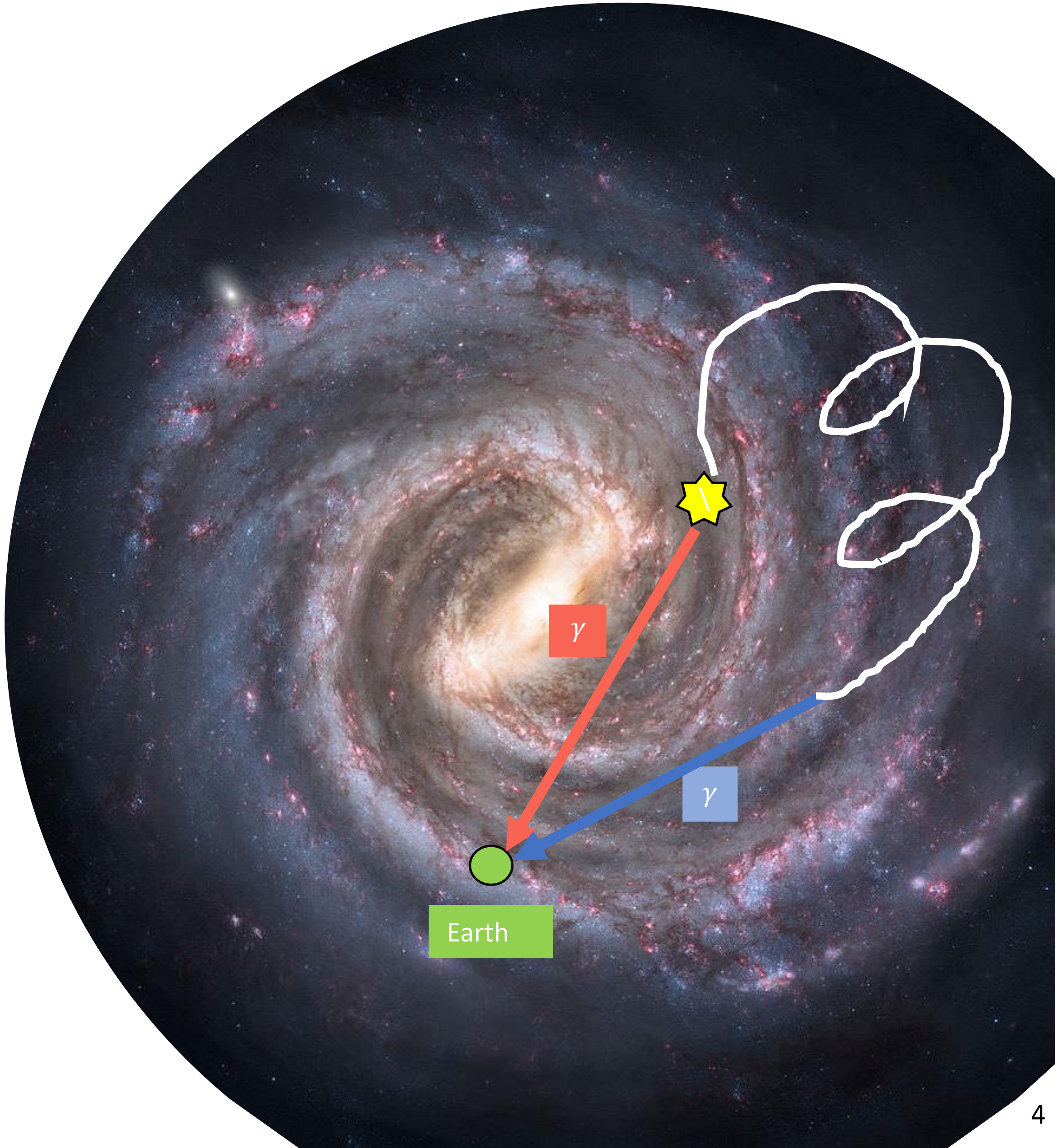
We want to constrain the diffuse emission

Diffuse c... tion of Cosmic Ra... um;

It encodes ... spatial and ...

Inverse Compton... interaction of accelerated leptons with the CMB ;



Unresolved sources:

$$\phi_{\gamma,tot} = \boxed{\phi_{\gamma,s}} + \boxed{\phi_{\gamma,\mathrm{diff}}} + \cancel{\phi_{\gamma,IC}}$$

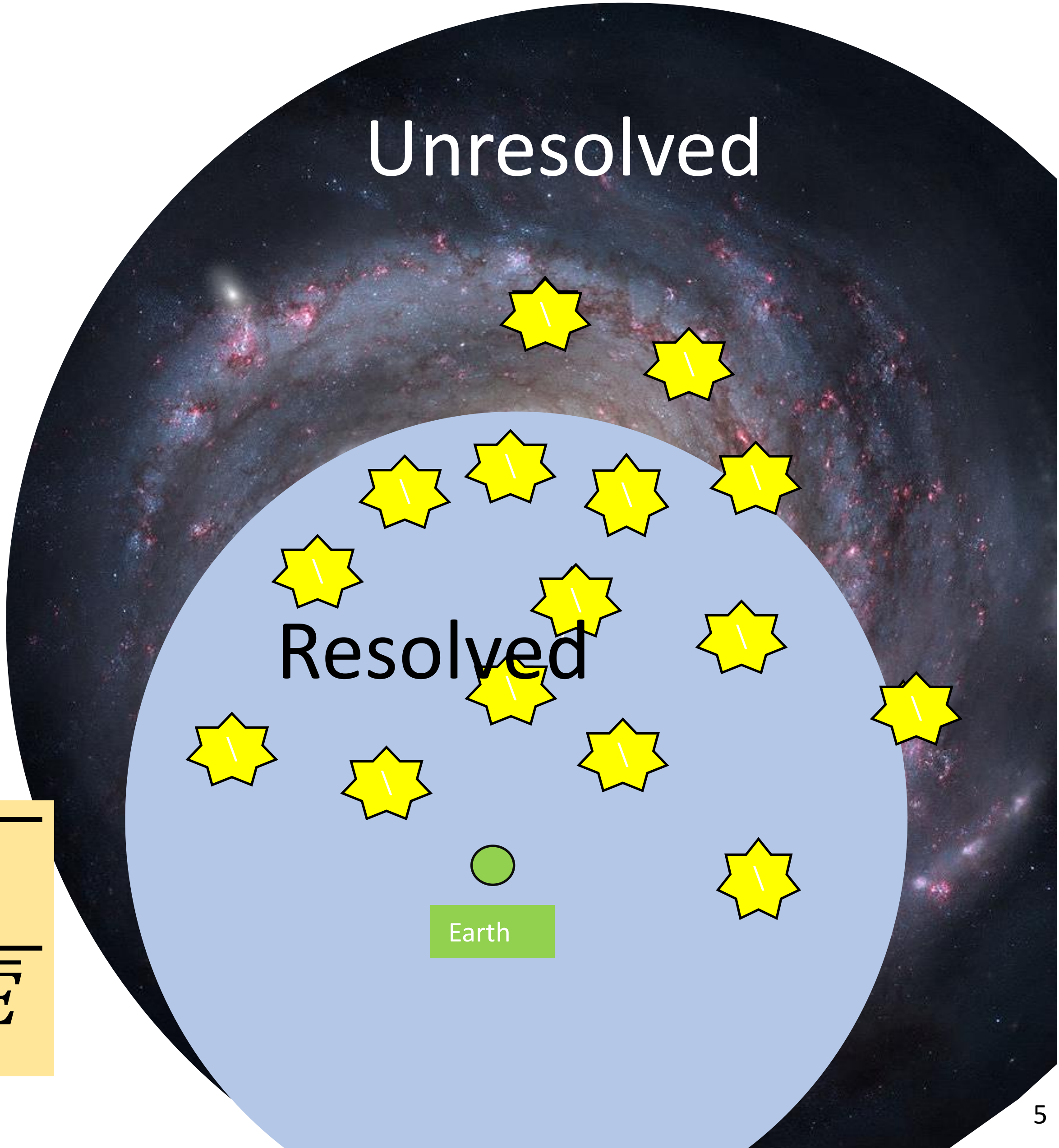
Measured

$$\phi_{\gamma,s}^{Res} \qquad \phi_{\gamma,s}^{UnRes}$$

Measured

The detectors have a limited sensitivity threshold and according to this they can resolve the sky up to a distance:

$$\overline{D} = \sqrt{\frac{L}{4\,\pi\phi_{th}\,\bar{E}}}$$



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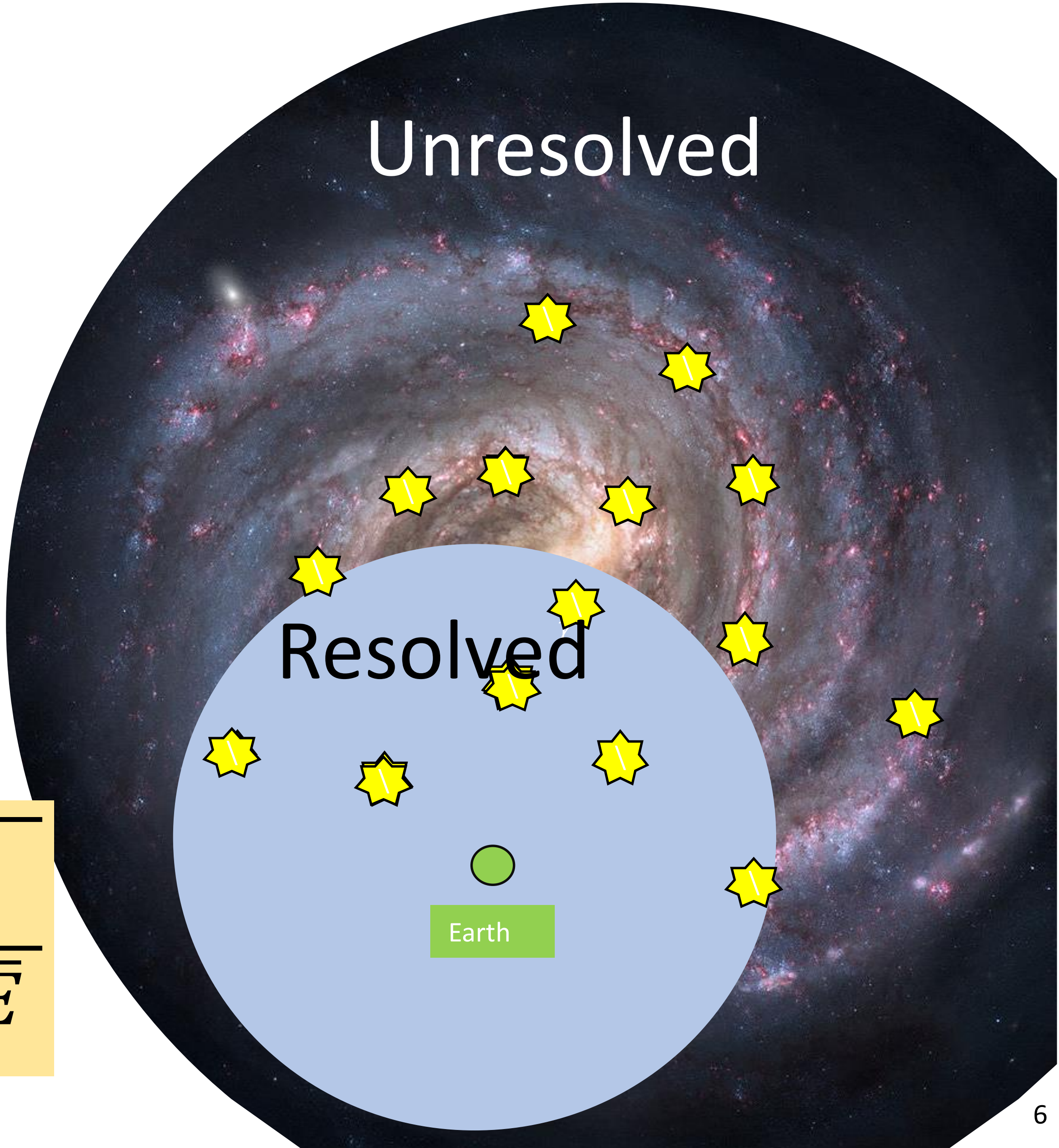

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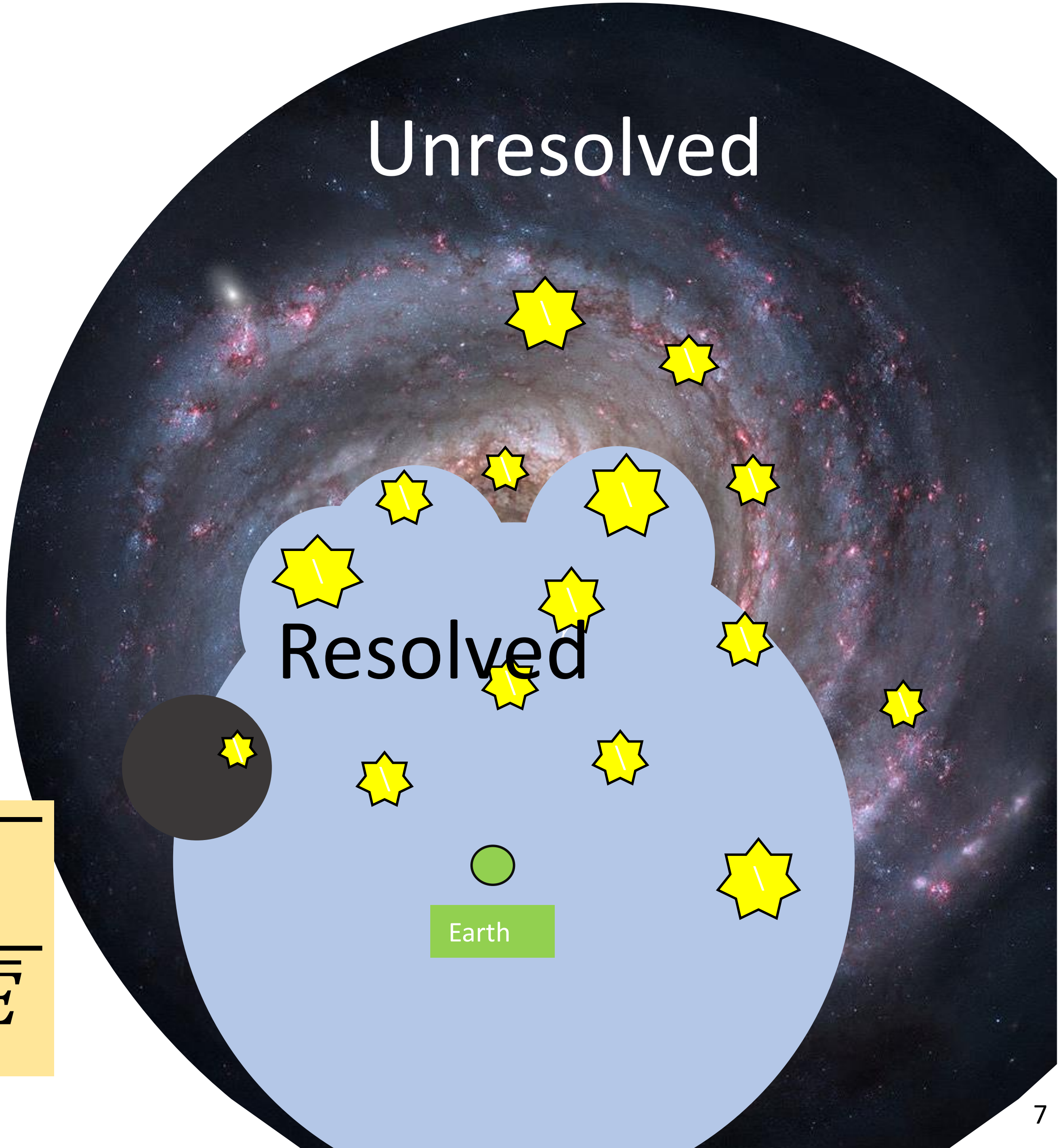

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Measured

$$\phi_{\gamma,S}^{Res} \qquad \phi_{\gamma,S}^{UnRes}$$

Measured

Total diffuse emission

We model the hadronic diffuse emission under different assumptions for the CR spatial and energy distributions;
We estimate the unresolved source component (this depends on the considered detector).

Diffuse Galactic gamma-ray emission:

$$\phi_{\gamma,S}^{UnRes} + \phi_{\gamma,\mathrm{diff}}$$

$$\varphi_\gamma^{diff}(E_\gamma, \hat{n}_\gamma) = \int_{E_\gamma}^{\infty} dE \frac{d\sigma(E, E_\gamma)}{dE_\gamma} \int_0^{\infty} dl\, \varphi_{CR}(E, \bar{r}_{Sun} + l\hat{n}_\gamma)\, n_H\, (\bar{r}_{Sun} + l\hat{n}_\gamma)$$

Interstellar gas distribution in the Galaxy *[Galprop]*

Differential inelastic cross section of pp interaction from the SYBILL code *[Kelner,Aharonian,Bugayov (2006)]*

Cosmic-ray energy and spatial distribution

Cosmic ray distribution:

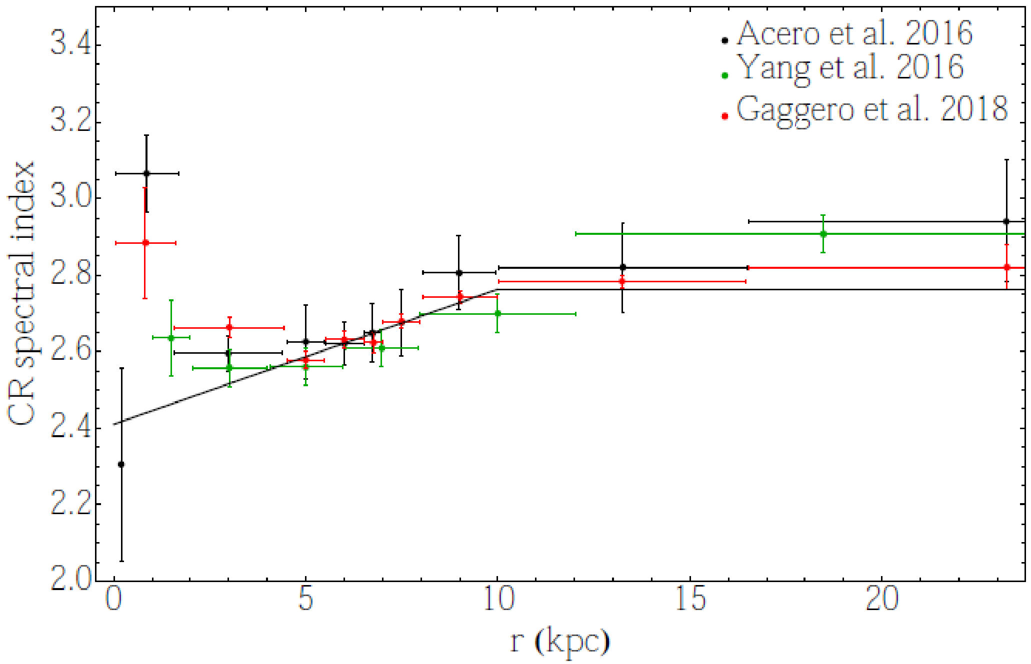
$$\varphi_{CR}(E,\vec{r}) = \boxed{\varphi_{CR,Sun}(E\ )}\boxed{g\ (\vec{r},R)}\ \boxed{h(E,\vec{r})}$$

Local spectrum

Spatial distribution

CR index that depends on the Galactocentric distance (hardening)

Spatially dependent CR spectral index
(from the analysis of the FermiLAT data at $\sim 20\ GeV$
[*Acero et al. (2016), Yang et al. (2016), Gaggero et al. (2018)*])



Sub PeV energy range

The Tibet ASγ collaboration has recently obtained a measurement of the Galactic diffuse γ-ray emission.

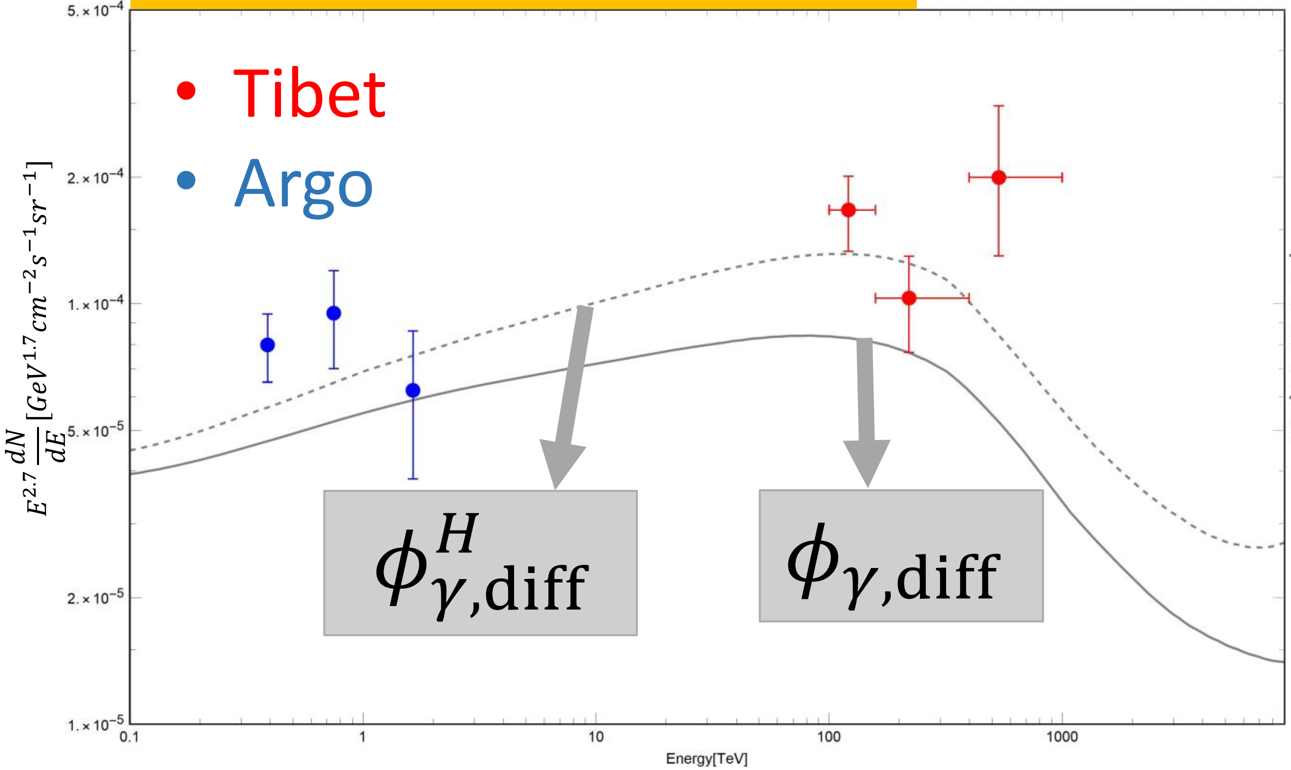
$\phi^{H}_{\gamma,\mathrm{diff}}$ Model **with** the hypothesis of CR spectral hardening.

$\phi_{\gamma,\mathrm{diff}}$ Model **without** the hypothesis of CR spectral hardening.

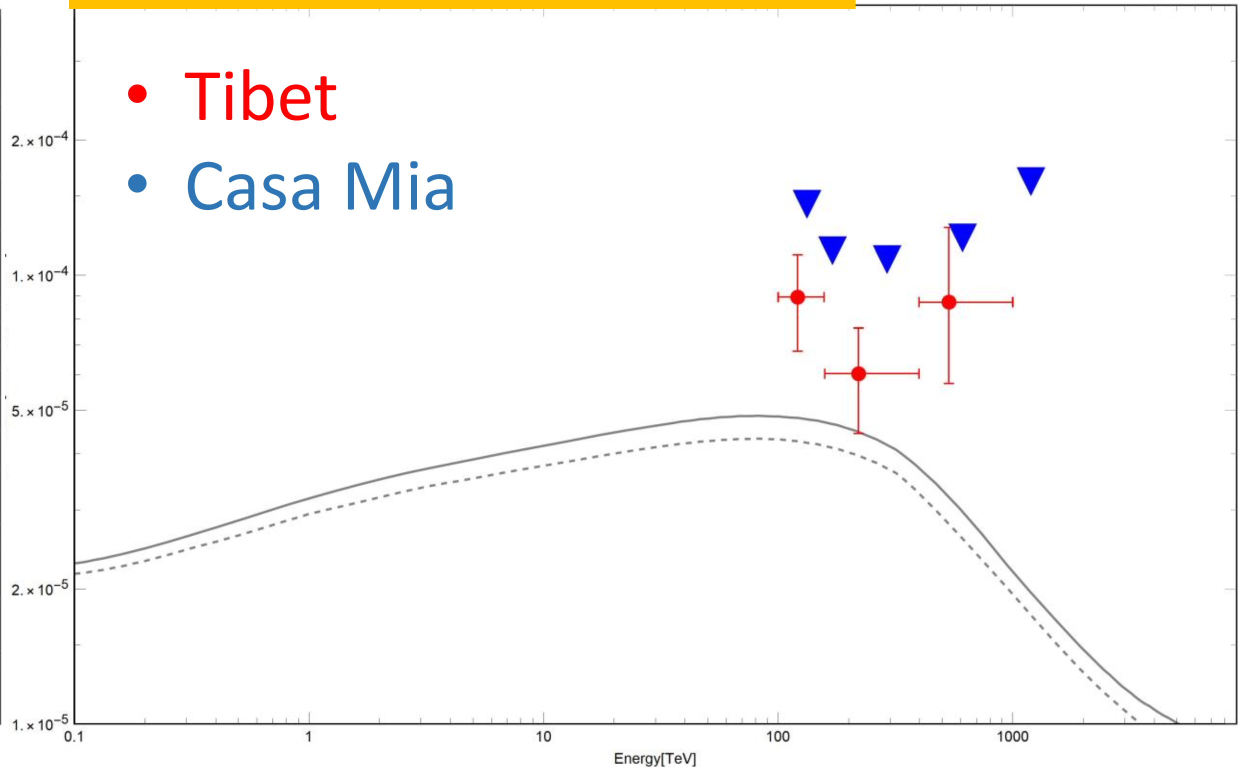
Diffuse Galactic gamma-ray emission:

Definition: Hardening ≡ spatially dependent CR spectral index

$25° < l < 100°, |b| < 5°$



$50° < l < 200°, |b| < 5°$



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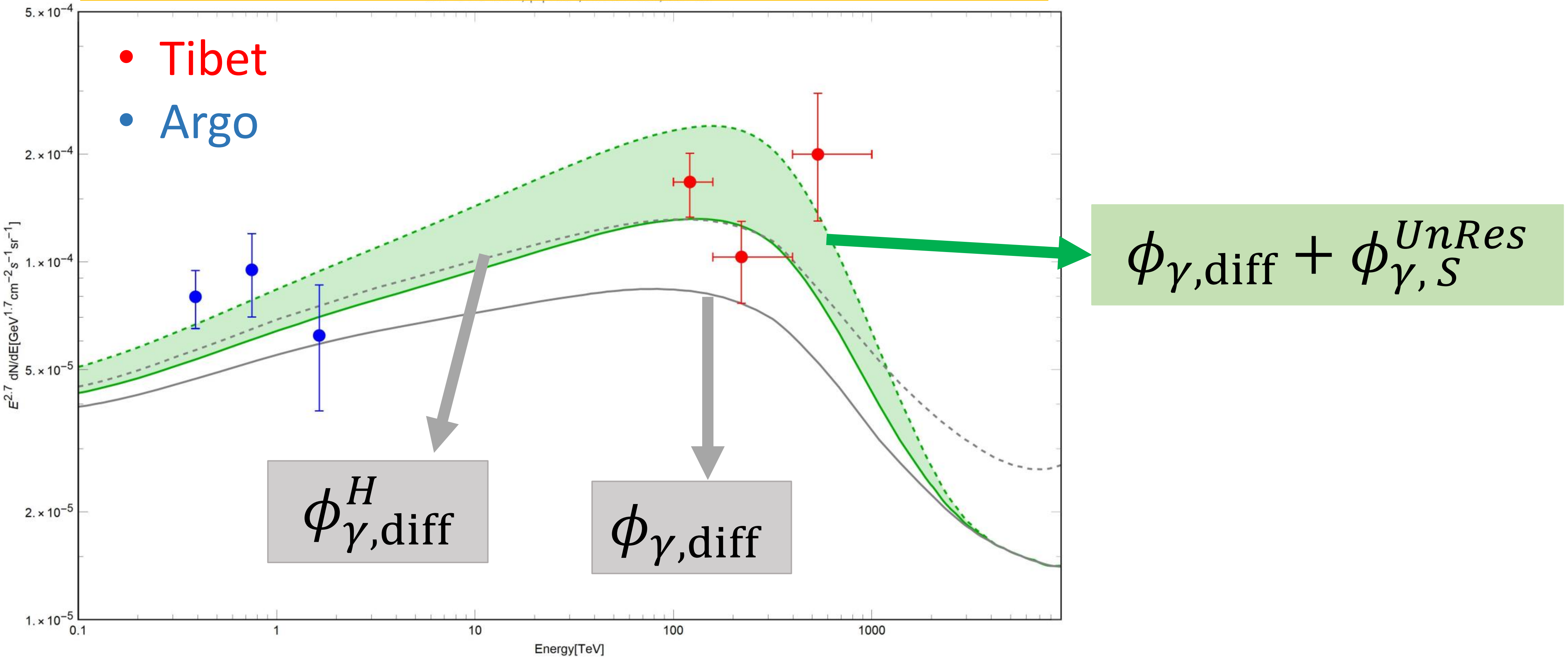

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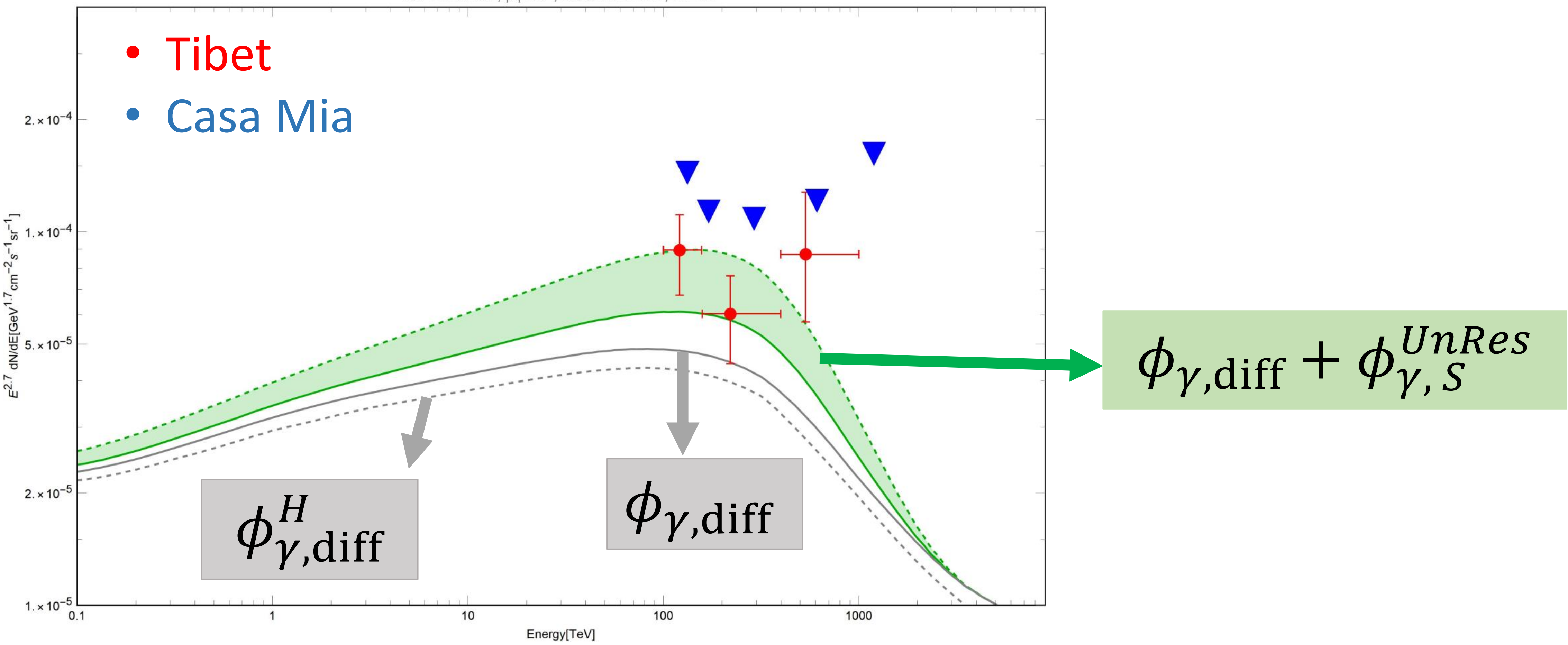

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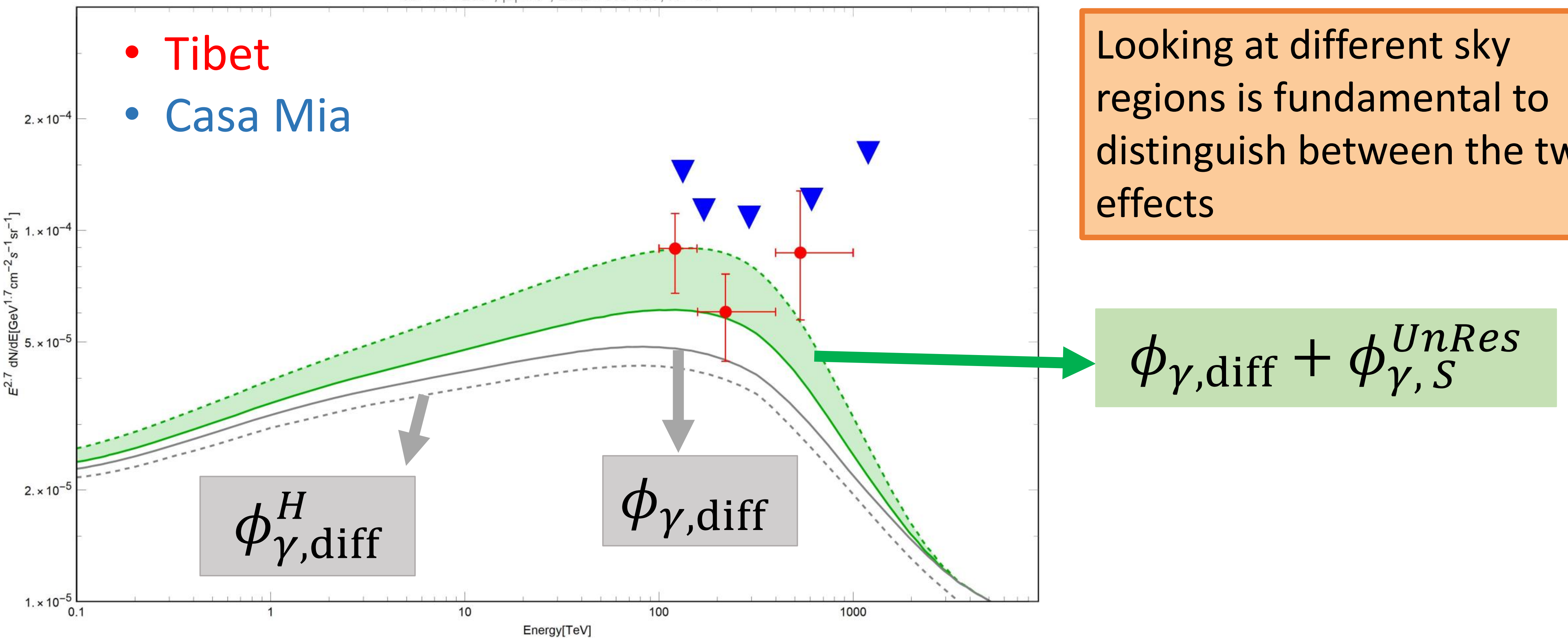
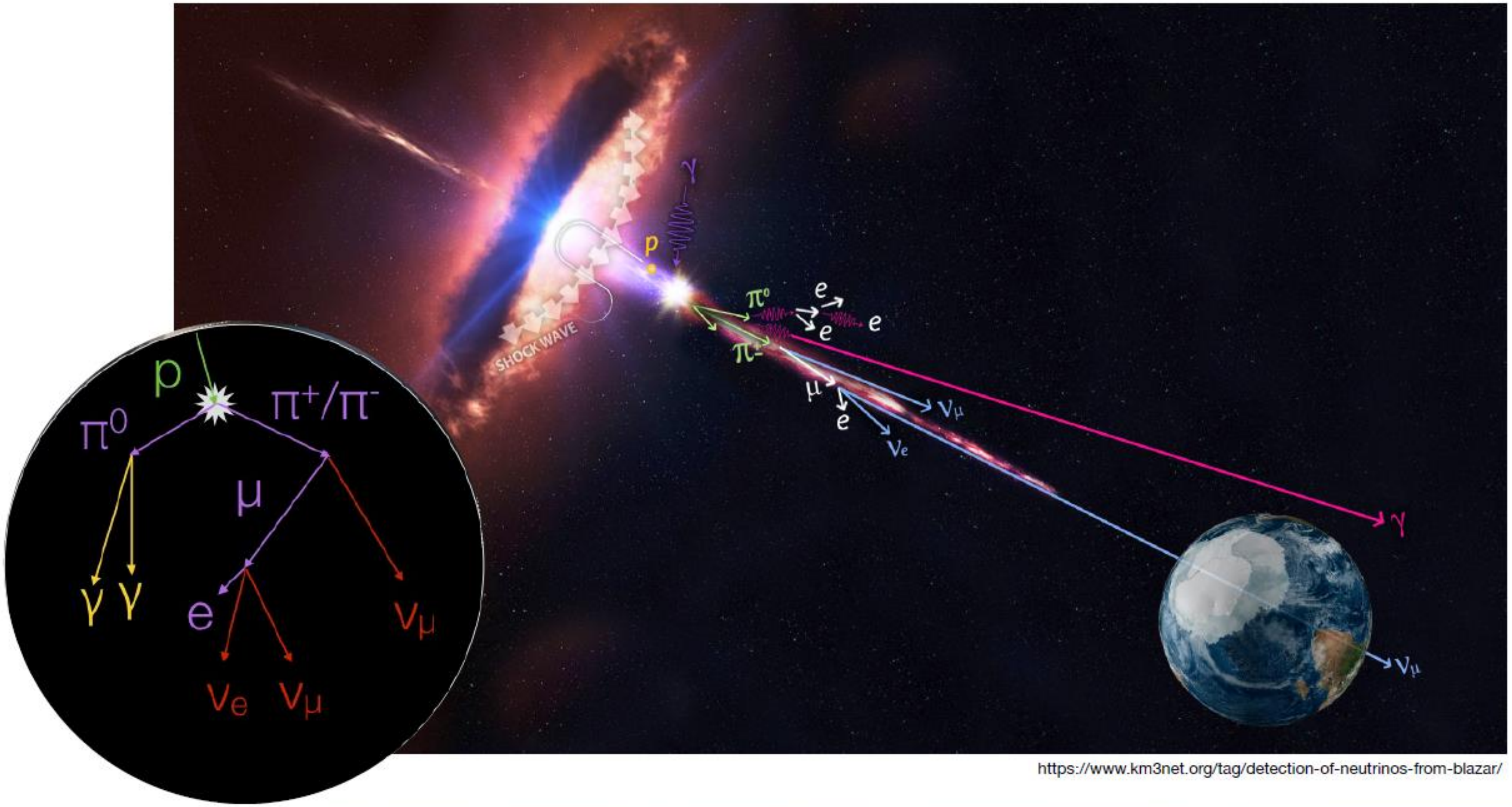


Looking at different sky regions is fundamental to distinguish between the two effects

Galactic Neutrino sky

Multimessenger astronomy at TeV:

Neutrinos are produced in the same hadronic interactions as gamma rays →
gamma-ray observations can be used to constrain the neutrino signal and vice versa



https://www.km3net.org/tag/detection-of-neutrinos-from-blazar/

Total Galactic neutrino emission:

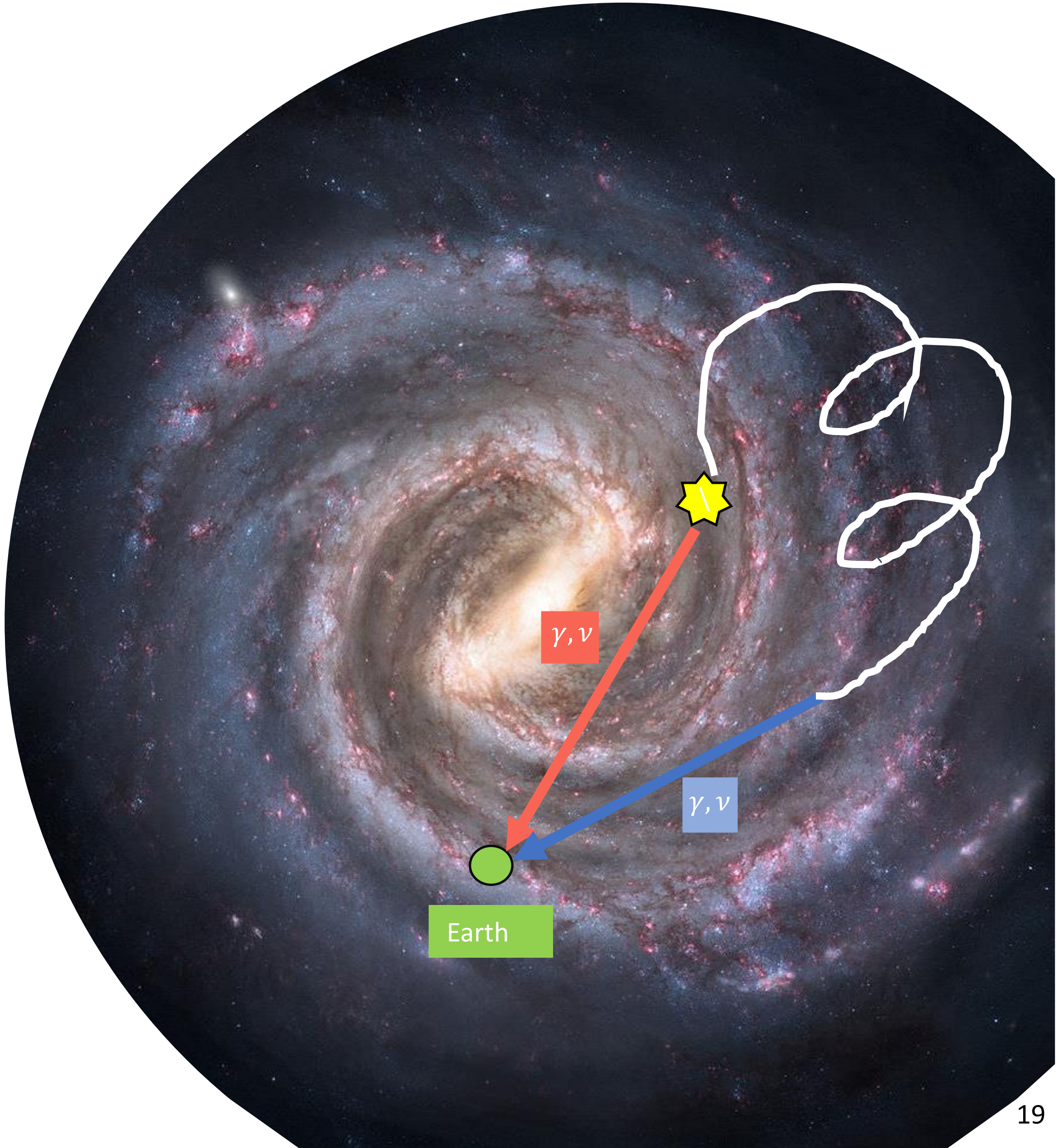
$$\phi_{\nu,tot} = \phi_{\nu,s} + \phi_{\nu,\mathrm{diff}}$$

?

$$\phi_{\gamma,tot} = \phi_{\gamma,s} + \phi_{\gamma,\mathrm{diff}}$$

The neutrino diffuse emission can be constrained using gamma-ray observations

Galactic sources of neutrinos: SNRs, Starclusters (PWNe?)

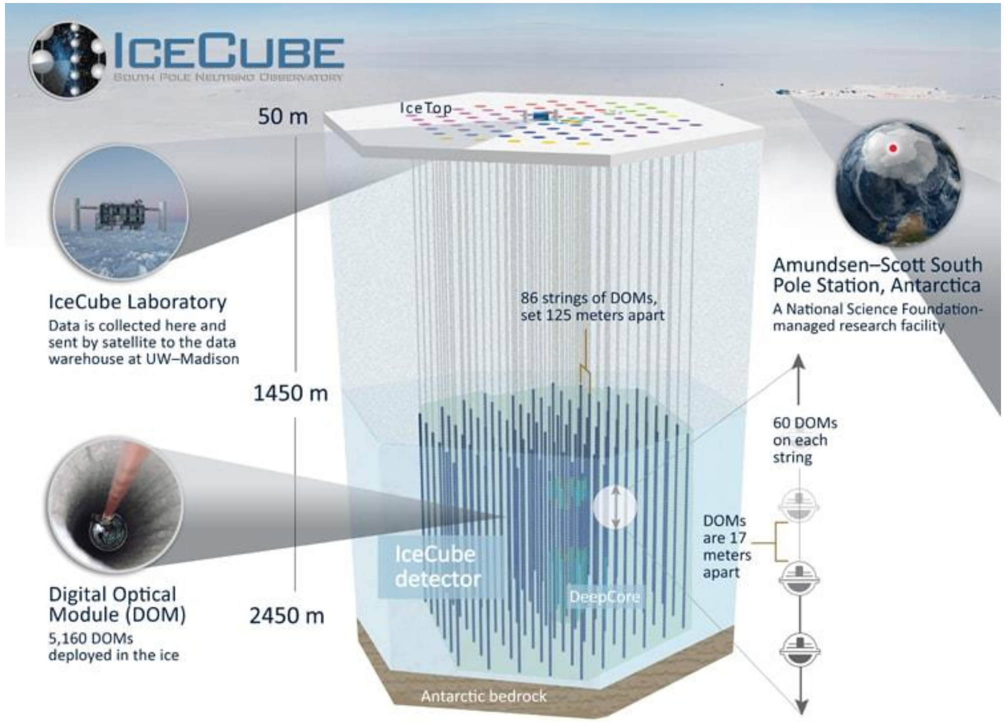


Neutrino and Gamma-ray Sky:

IceCube: Isotropic high-energy neutrino signal around 100 TeV.

The majority of the signal is expected to be of extragalactic origin.

A Galactic component cannot be excluded.



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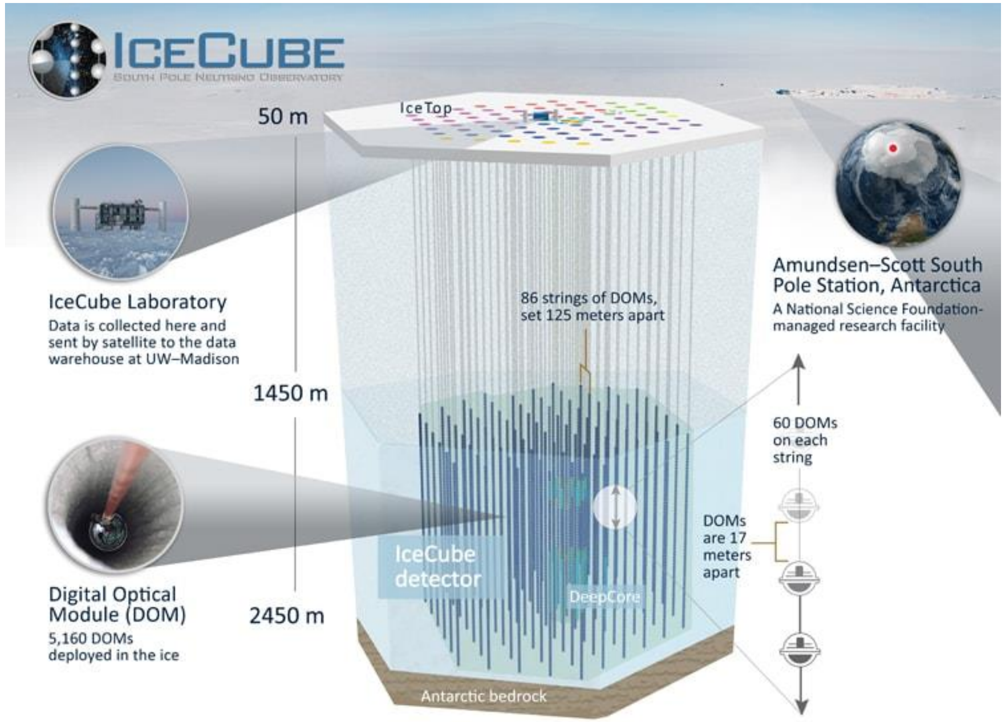


ANTARES: Hint for a TeV neutrino emission from the Galactic Ridge

Sources or diffuse emission?

Summary:

- Constraining the diffuse emission brings information on the CR spatial and energy distribution in our Galaxy;
- It is fundamental to estimate the **unresolved source** component in order to correctly interpret the large scale diffuse emission data.

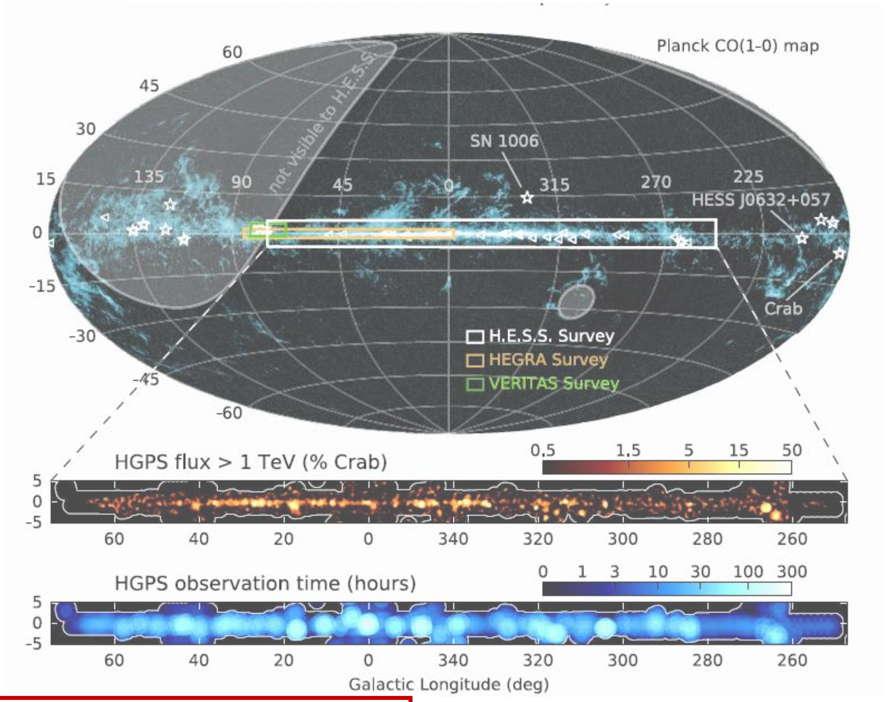
What's next?

- Prediction for future experiments.
- Disentangle CR spectral hardening from unresolved source contribution.
- Galactic neutrino diffuse and source component;

Backup slides

Study of the Pulsar wind nebulae population in the TeV range:

Abdalla et al, *A&A*, 612, A1 (2018)



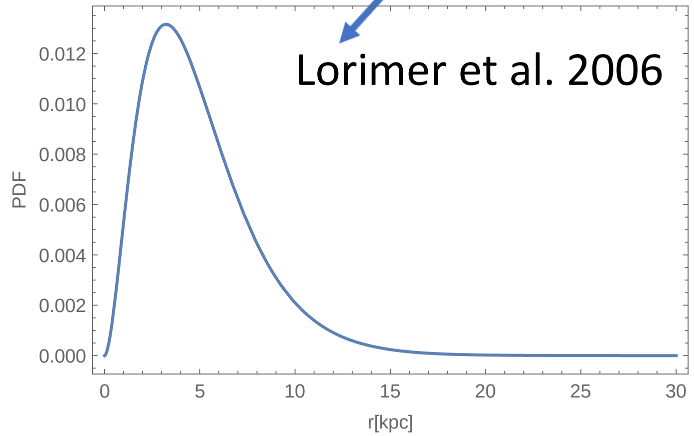
Cataldo et al. *Astrophys.J.* 904 (2020)

- The HGPS catalogue ($\phi > 0.1\phi_{Crab}$);
- Model for TeV source population:

we assume the spatial distribution and the luminosity distribution of the sources;

$$\frac{dN}{d^3r\,dL} = \rho(r)\,Y(L)$$

$$\boxed{Y(L) = \frac{R\tau(\alpha-1)}{L_{\max}}\left(\frac{L}{L_{\max}}\right)^{-\alpha}}$$



$$\alpha = 1/\gamma + 1$$

$$R = 0.019\,\mathrm{yr}^{-1}$$

For pulsar-powered sources:

$$L(t) = L_{\max}\left(1 + \frac{t}{\tau}\right)^{-\gamma}$$

We assume a **power-law** energy spectrum with index $\boldsymbol{\beta_{TeV} = 2.3}$ that is the average index for all the sources in the HGPS catalogue.

Study of the Pulsar wind nebulae population in the TeV range:

We fit the H.E.S.S. observational results with an unbinned likelihood

$$L_{max} = L^{BF}$$
$$\tau = \tau^{BF}$$

$$\Phi_{\mathrm{PWN}}$$

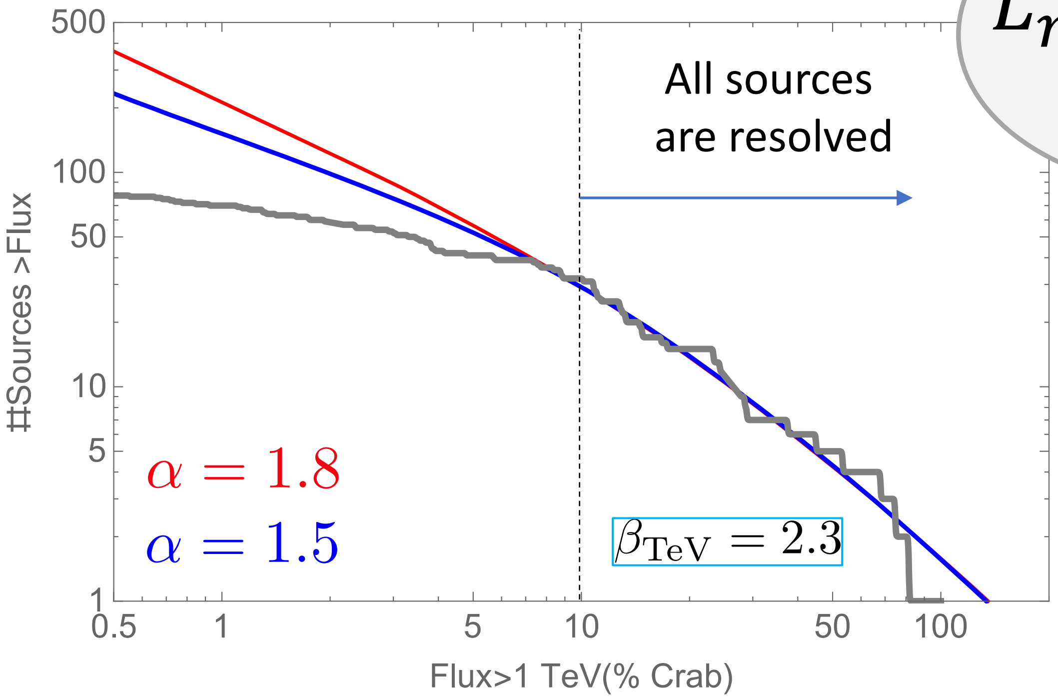
Cataldo et al. *Astrophys.J.* 904 (2020)

$\alpha = 1.8$

$$L_{max} = 6.8 \times 10^{35}\ erg\ s^{-1}$$
$$\tau = 0.5\ kyr$$

$\alpha = 1.5$

$$L_{max} = 5.0 \times 10^{35}\ erg\ s^{-1}$$
$$\tau = 1.7\ kyr$$



Total flux due to PWNe in the FERMI energy range (1-100 GeV)?

Source contribution to Sub-PeV energy range:

- Spectral assumption: power-law with an exponential cut off.

$$\varphi(E) = \left(\frac{E}{1\,TeV}\right)^{-\beta_{TeV}} Exp\left(-\frac{E}{E_{cut}}\right)$$

$\beta_{TeV} = 2.3$ from the HGPS catalogue;

$E_{cut} = 500\ TeV$ still not well constrained but justified by recent observations of Tibet, HAWC and LHAASO;

Amenomori, M., Bao, Y. W., Bi, X. J., et al. 2019, Phys.323Rev. Lett., 123, 051101

Abeysekara, A., Albert, A., Alfaro, R., et al. 2020, Physical316Review Letters, 124

Cao, Z., Aharonian, F. A., An, Q., et al. 2021, Nature, 594,33033

- Absorption from CMB.

We introduce a flux detection threshold based on the performance of H.E.S.S.
$\phi_{th} = 0.01\phi_{crab} - 0.1\phi_{crab}$

We calculate the unresolved source contribution.

Model:

The power-law for the luminosity distribution can be automatically obtained assuming a fading source population (like PWNe, TeV Halos) create at a constant rate $\bar{r}$.

The spin-down power is described by: $\dot{E}\,(t) = \dot{E}_0 \left(1+\frac{t}{\tau}\right)^{-2}$

Considering that a fraction $\boldsymbol{\lambda(t)}$ of the spin-down power is converted into gamma-rays then the intrinsic luminosity decreases according to:

$$L(t) = \lambda(t)\dot{E}(t) = \underbrace{\lambda\dot{E}_0}_{L_{max}}\left(1+\frac{t}{\tau}\right)^{-\gamma} \text{ where } \gamma = 2(\delta+1);$$

$$\lambda(t) = \lambda\left(\frac{\dot{E}(t)}{\dot{E}_0}\right)^{\delta}$$

Abdalla et al, *A&A*, 612, A2 (2018)

Then:

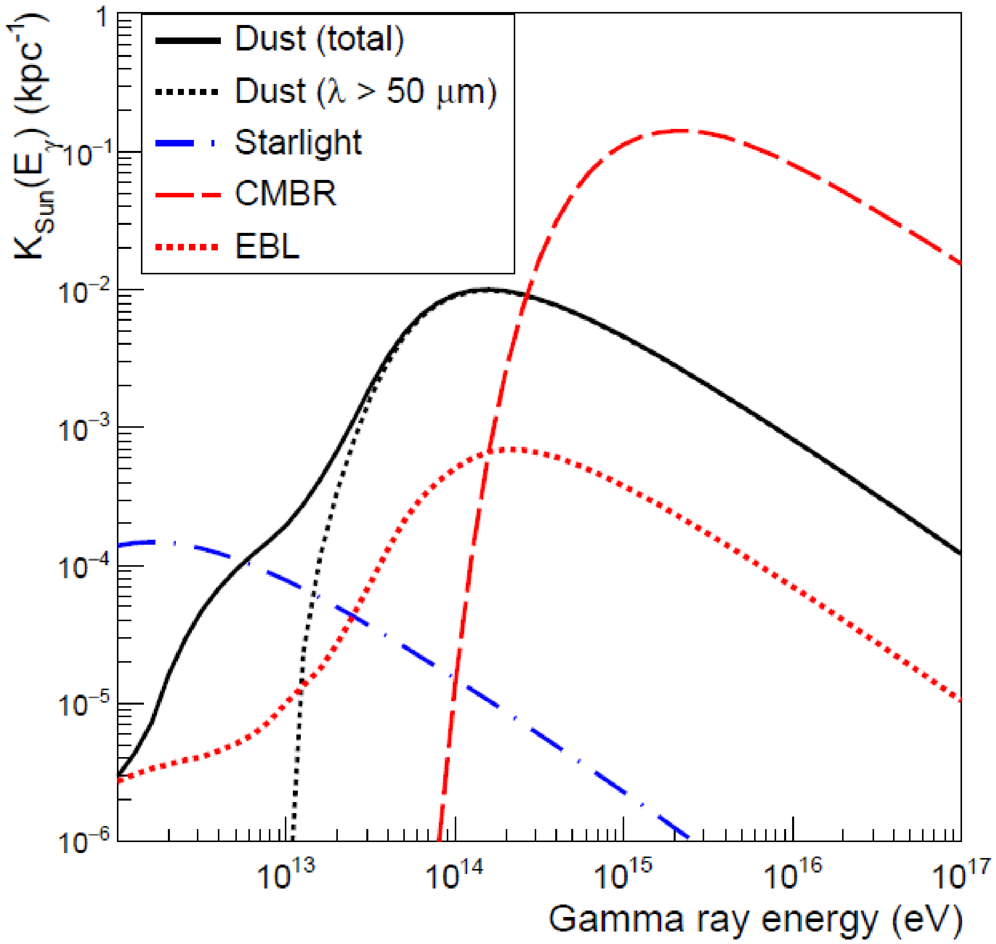
$$\boxed{Y(L) = \frac{\bar{r}\,\tau\,(\alpha-1)}{L_{\max}}\left(\frac{L}{L_{\max}}\right)^{-\alpha}}$$

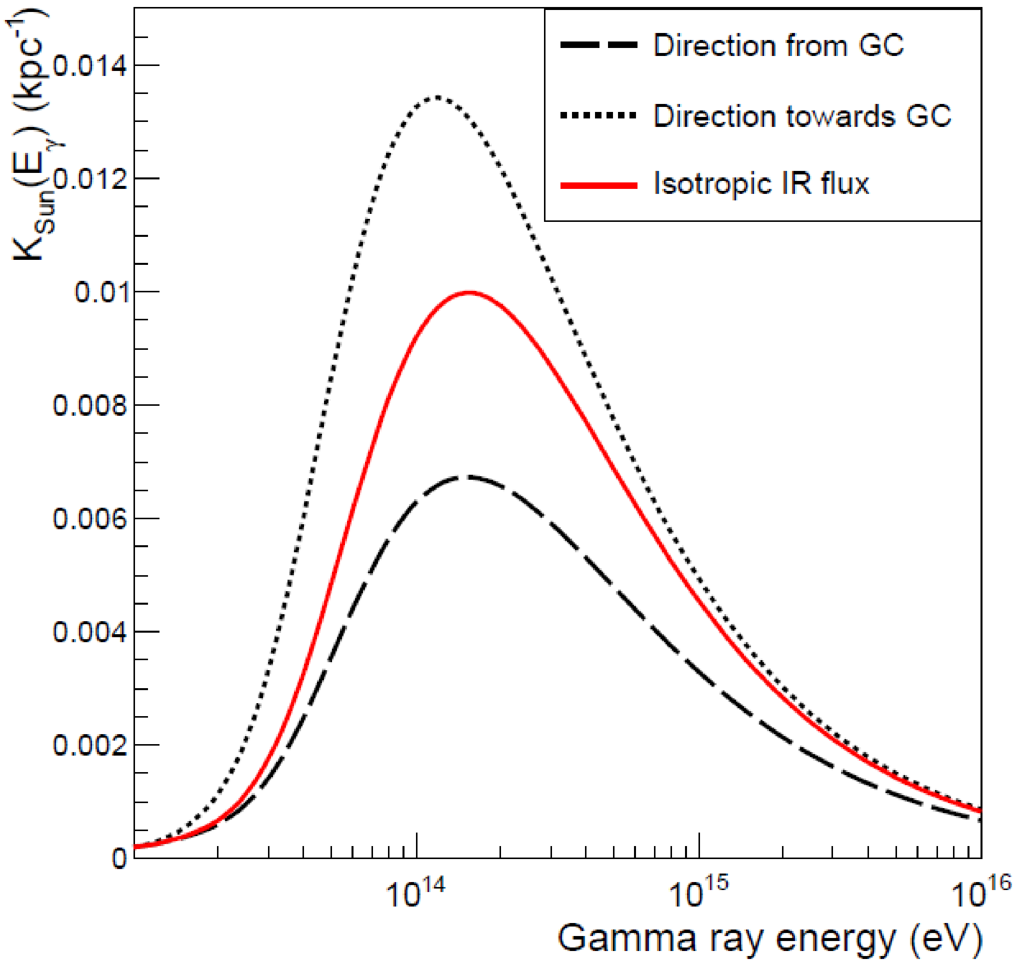
Where $\bar{r} = 0.019\ yr^{-1}$ is the SN's rate and $\alpha = \left(\frac{1}{\gamma}+1\right)$ therefore for $\gamma = 2$ we have $\alpha = 1.5$.

And instead of the parameter $\mathcal{N}$ we have the spin-down timescale of the Pulsar τ.

GSSI

Absorption in the Sub PeV energy range:





Vernetto and Lipari, Phys. Rev. D 94, 063009 – Published 19 September 2016