High-energy diffuse emission from the Milky Way, a new multi-messenger perspective

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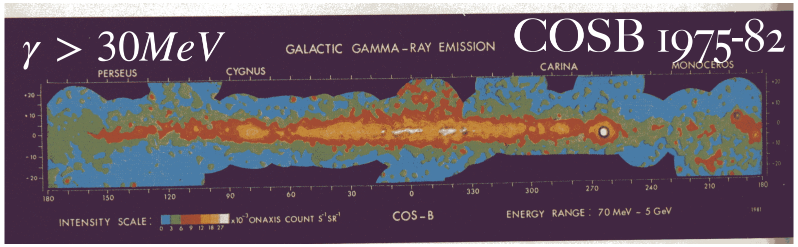
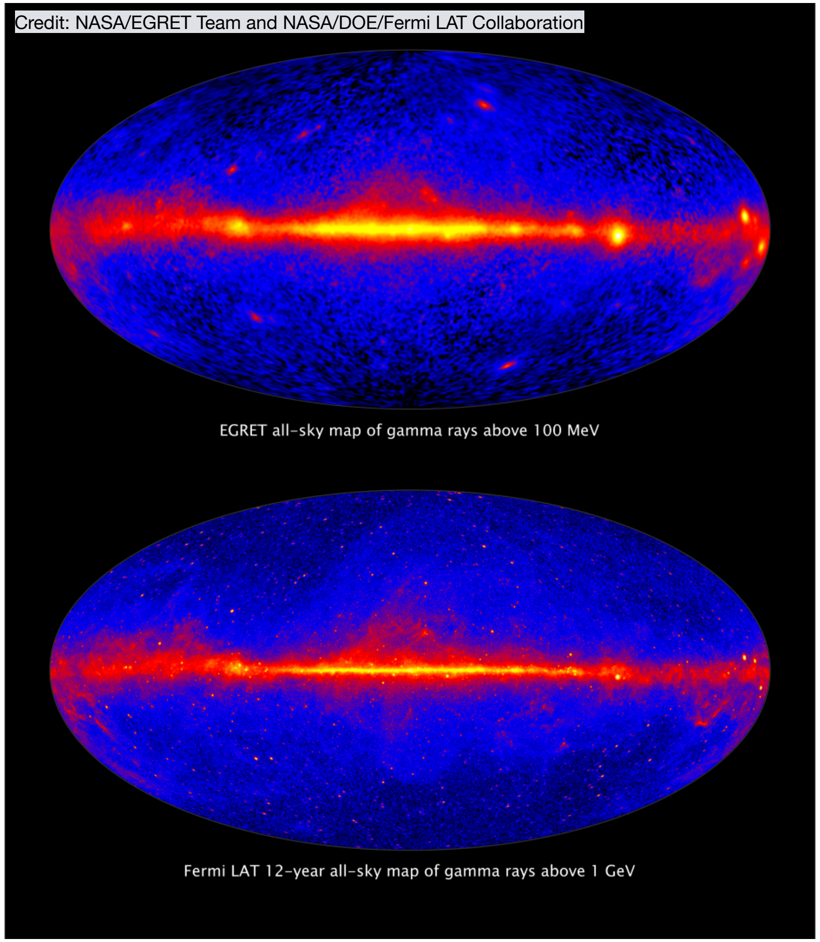
15/09/2023

Gamma-ray emission from the Milky Way

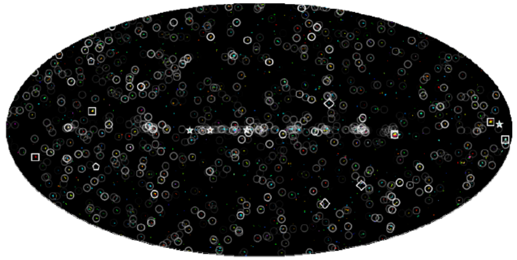




EGRET all-sky map of gamma rays above 100 MeV

Fermi LAT 12-year all-sky map of gamma rays above 1 GeV

Selig et al. A&A 2014

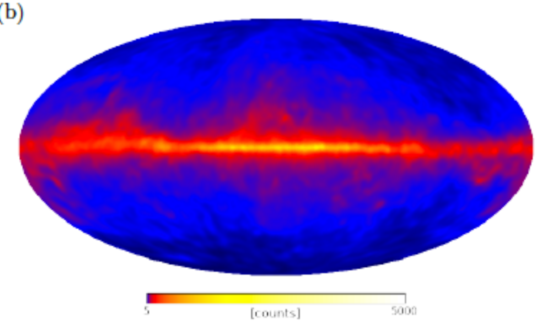


Resolved sources

Diffuse emission

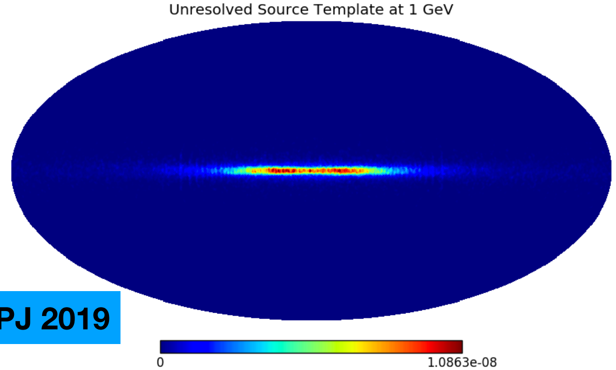
Selig et al. A&A 2014

(b)



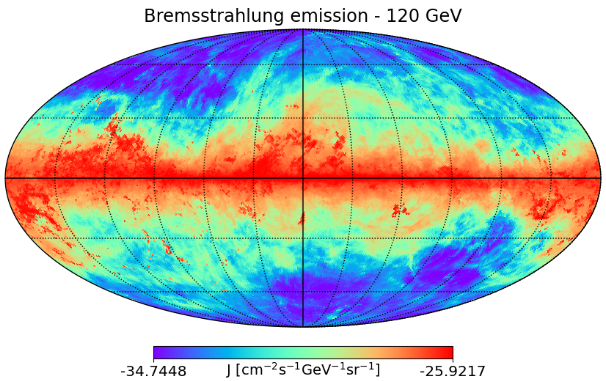
Unresolved sources

Unresolved Source Template at 1 GeV



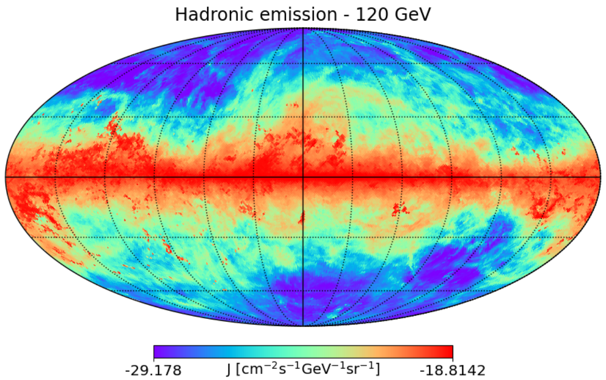
Fermi-LAT coll. APJ 2019

Galactic diffuse gamma-ray emission



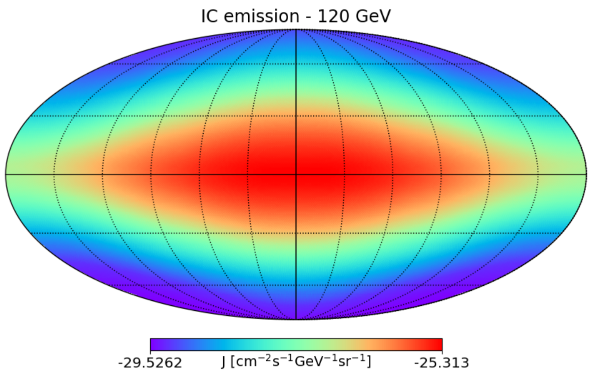
$$e + N \rightarrow e' + \gamma + N'$$

Bremsstrahlung emission follows the ISM gas distribution



$$p + p \rightarrow \pi_0 \pi_+ \pi_-$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

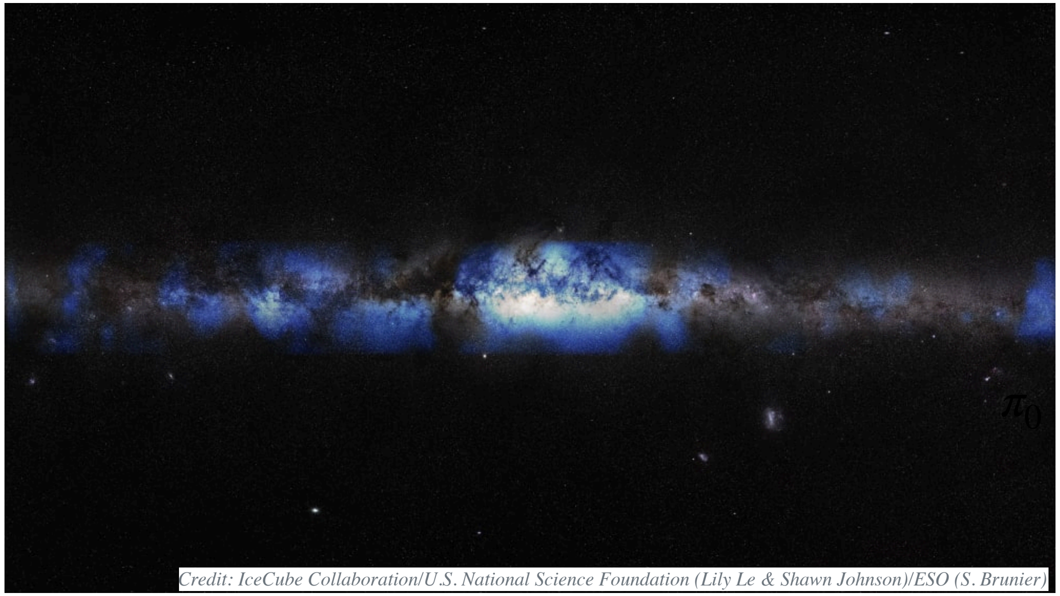
Diffuse emission totally correlated with the propagation of cosmic rays dominated by protons and He. Hadronic emission follows ISM gas distribution as well.



$$e + \gamma \rightarrow e' + \gamma'$$

IC emission depends on the energy density of the **ISRFs**

High energy emission from Milky Way: a new piece of diffuse flux puzzle : VHE ν



Even if in gamma-ray (>1GeV) the Milky Way is the most prominent feature in the sky, in neutrino we reach a first observation (>4σ) only few months ago

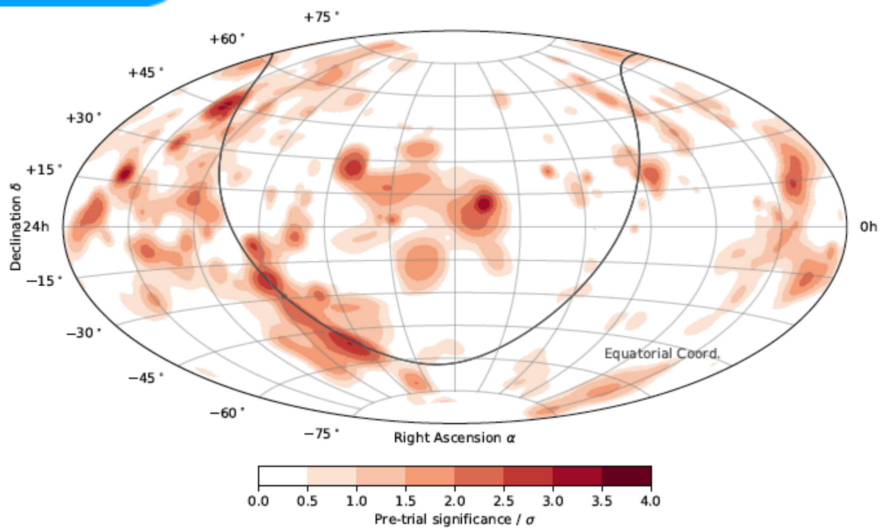
A total of 59592 cascade-like events with an energy above 500 GeV has been used to search for a signal with a spatial and energetic distribution similar to the reference templates:

Π_0 → A Fermi-LAT coll. template based on a homogeneous diffusion coefficient along the Milky Way longitude and a 2012 molecular gas map.

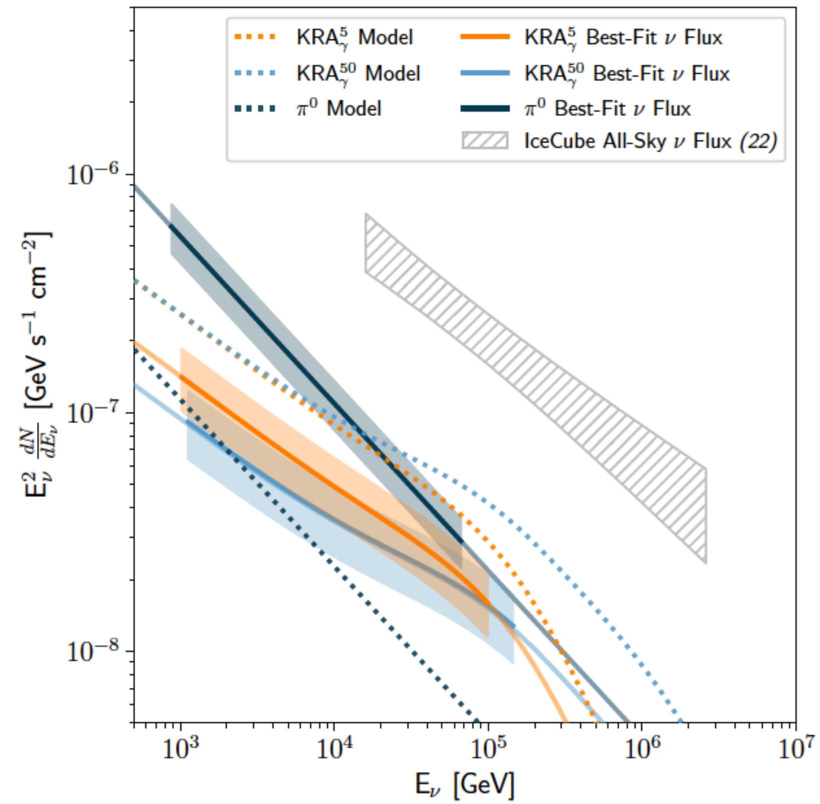
KRA-γ5 and KRA-γ50 → A template obtained with DRAGON and Gamma-sky codes based on a inhomogeneous diffusion coefficient and a CR spectral hardening toward the Milky Way center (radial dependent) and two different CR cutoffs at 5 and 50 PeV

IceCube observation of Galactic neutrinos

IceCube coll.
Science 2023



IceCube CASCADE best fit pre-trial significance distribution map



Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA$_\gamma^5$	0.16×MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}$×MF
KRA$_\gamma^{50}$	0.11×MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}$×MF

→ Considering the obtained best fit normalizations seems the more motivated case.

Galactic gamma-ray diffuse emission
Hardening towards the centre

The conventional picture of spatially-constant diffusion is not able to explain the data consistently

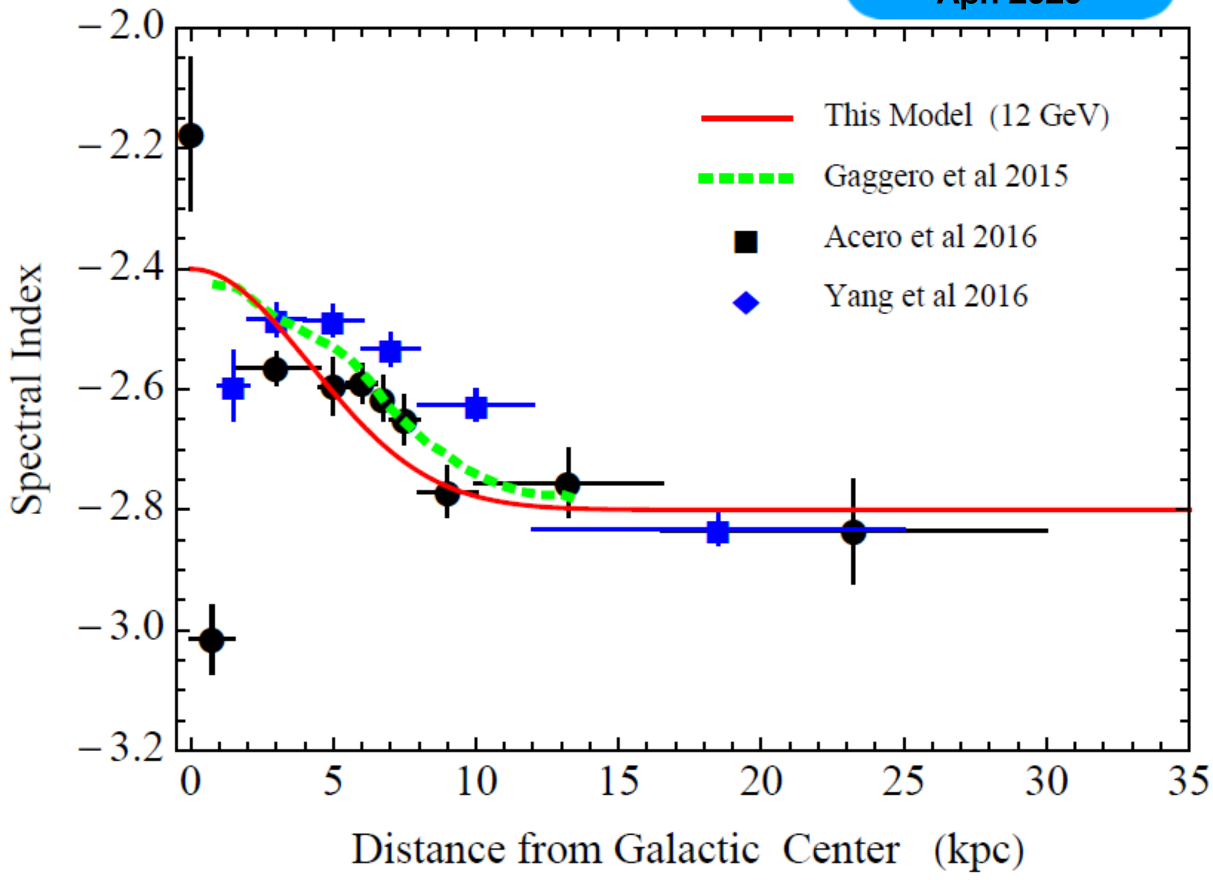
Progressive hardening of the gamma-ray diffuse spectrum towards the centre

Diffuse gamma-ray spectrum essentially follows the spectrum of CR protons:

Purely diffusive – $\phi \propto E^{-(\alpha + \delta)}$

Advection dominated – $\phi \propto E^{-\alpha}$

P.Lipari, S.Vernetto
Aph 2020



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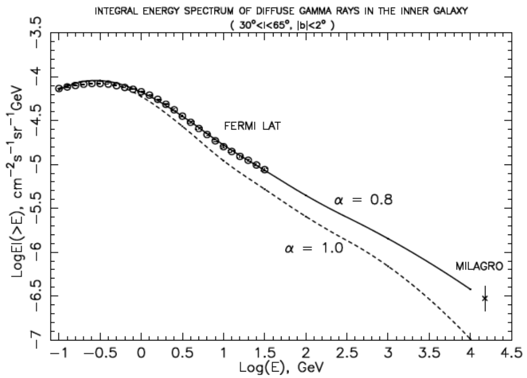
Inhomogenous diffusion model

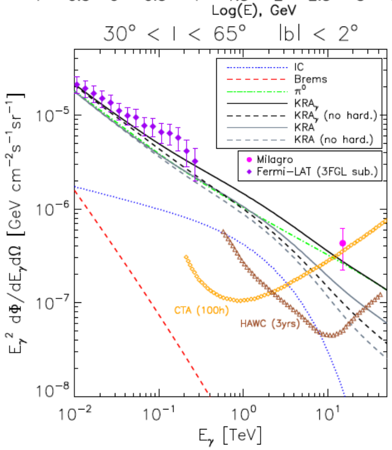
$D \propto E^{\delta(R)}$ with $\delta(R) = \delta_0 + \delta_a(R)$ Diffusion coefficient Change toward the Galactic center

- Erlykin & Wolfendale (APh 2012)

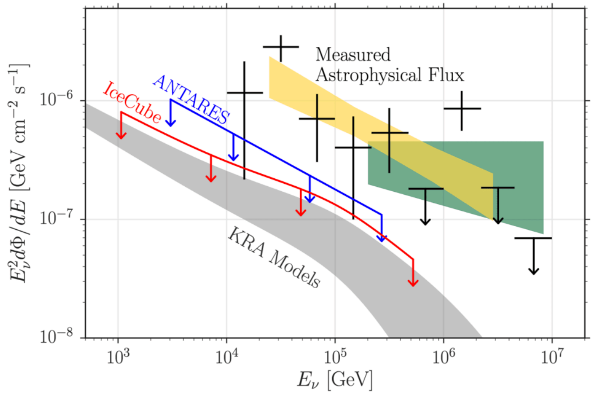


- Gaggero et al. (PRD 2015) ,
  Gaggero el al. (APJ letter 2015)

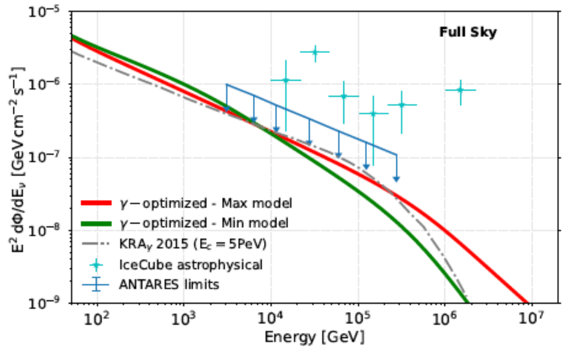
KRA-γ with CR cutoff at 5 and 50 PeV



maps produced for γ and ν



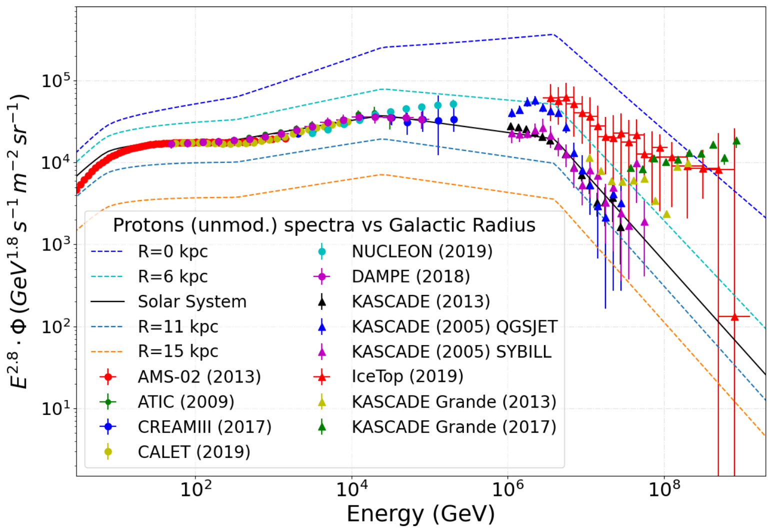
- De la Torre et al. (A&A 2023) , De la Torre et al. (Frontiers 2022)



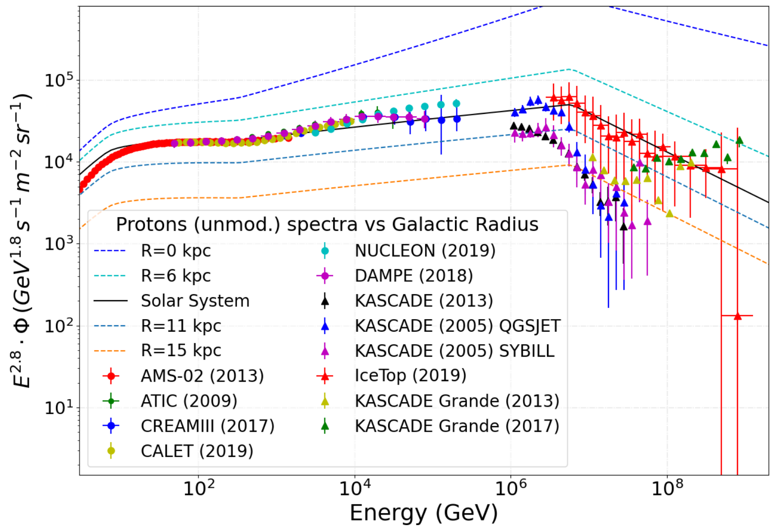
Updating the KRA-γ models - new version

De la Torre et al. A&A 2023

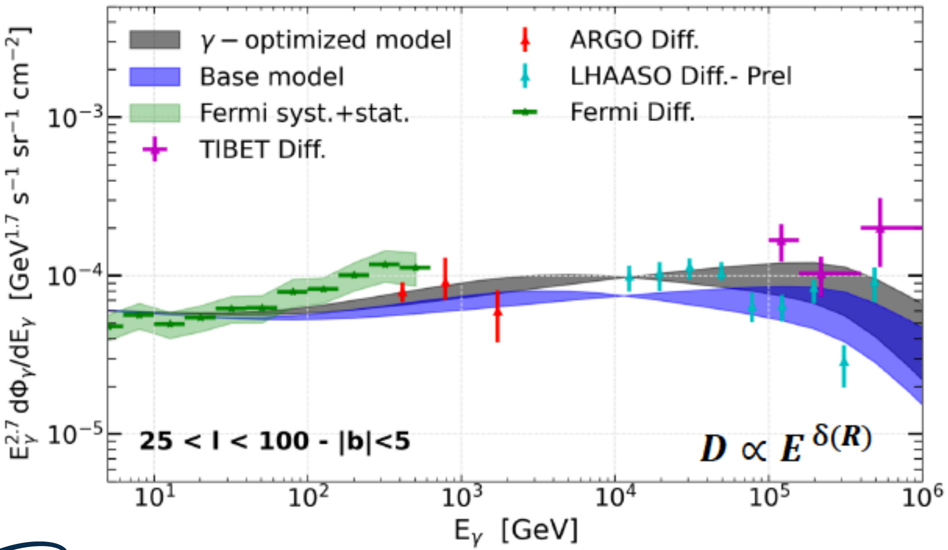
<u>MIN model</u> adopted to connect the DAMPE "bump" with KASCADE

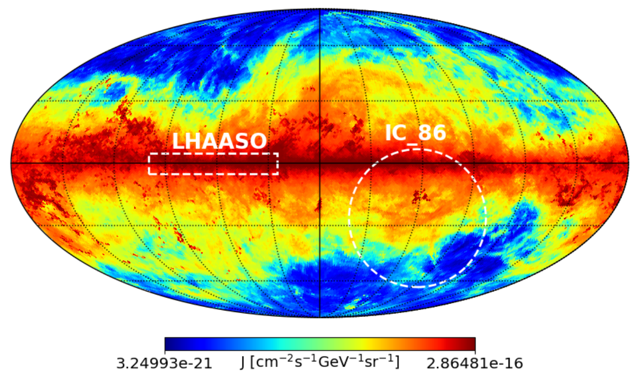


<u>MAX model</u> adopted connects AMS-02 data with IceTop



P.D.L. *et al* arXiv: 2203.15759



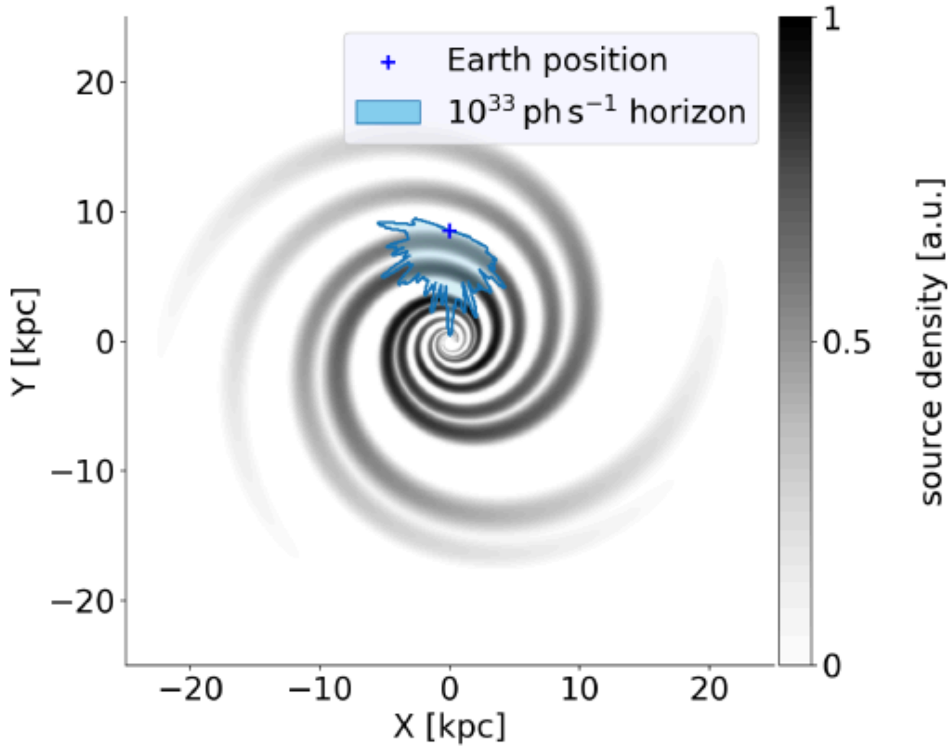


Gamma optimized model have good accordance also with VHE observations LHAASO and TIBET

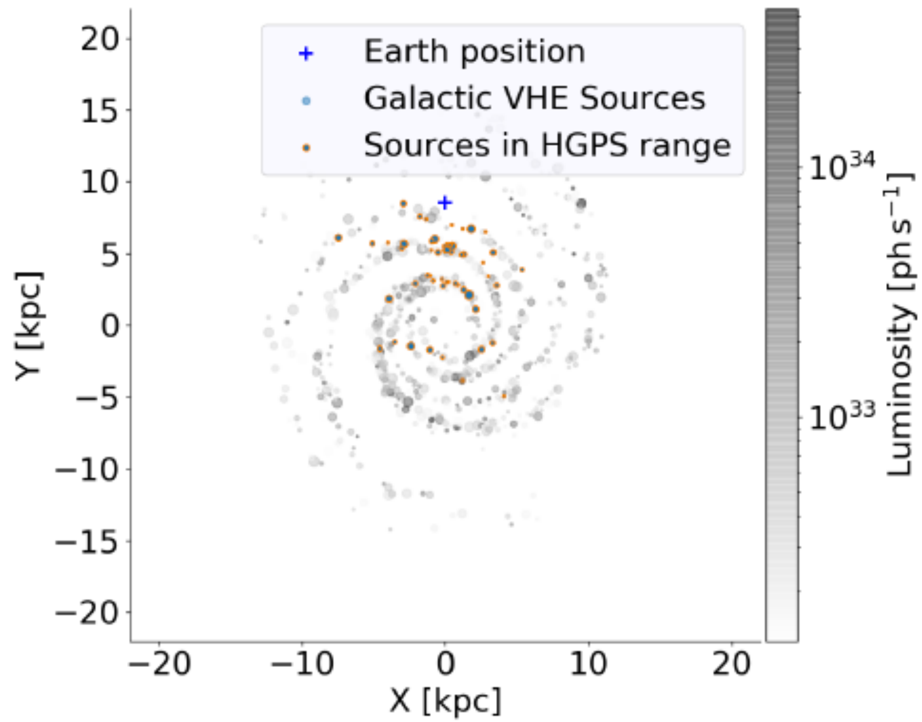
Considering unresolved source contribution

Steppa,Egbert
A&A 2023

Resolved source horizon for HESS



Realization of a synthetic population of VHE gamma-ray sources



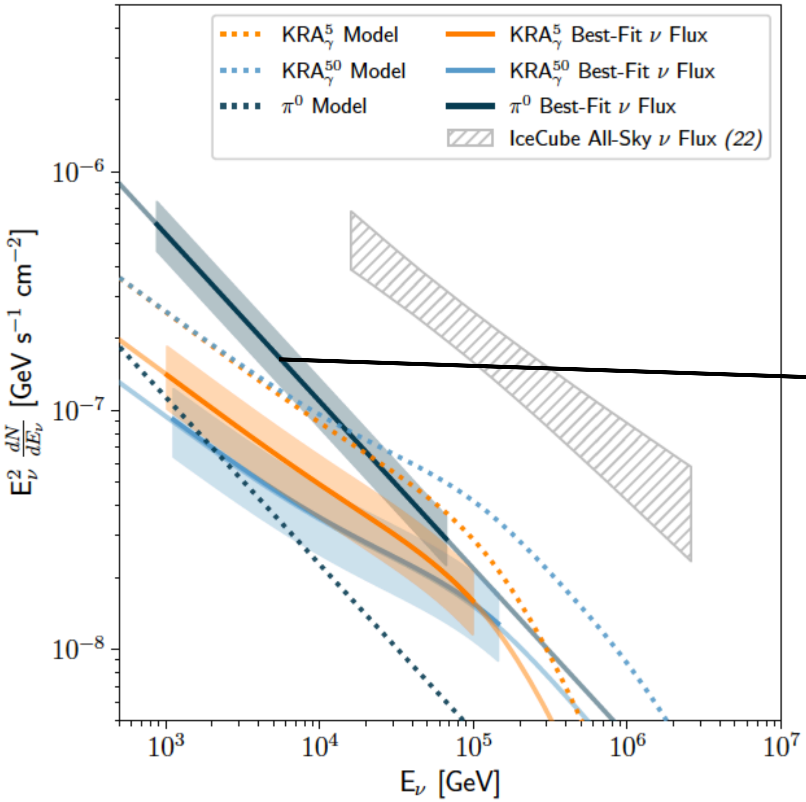
Depending on the model, the HGPS sample accounts for (68–87)% of the emission of the population in the scanned region. This suggests that unresolved sources represent a critical component of the diffuse emission measurable in the HGPS. This extra component is taken into account to tune the Min and Max diffuse models. Unresolved source component strongly dependent from the energy considered and from the experiment used.

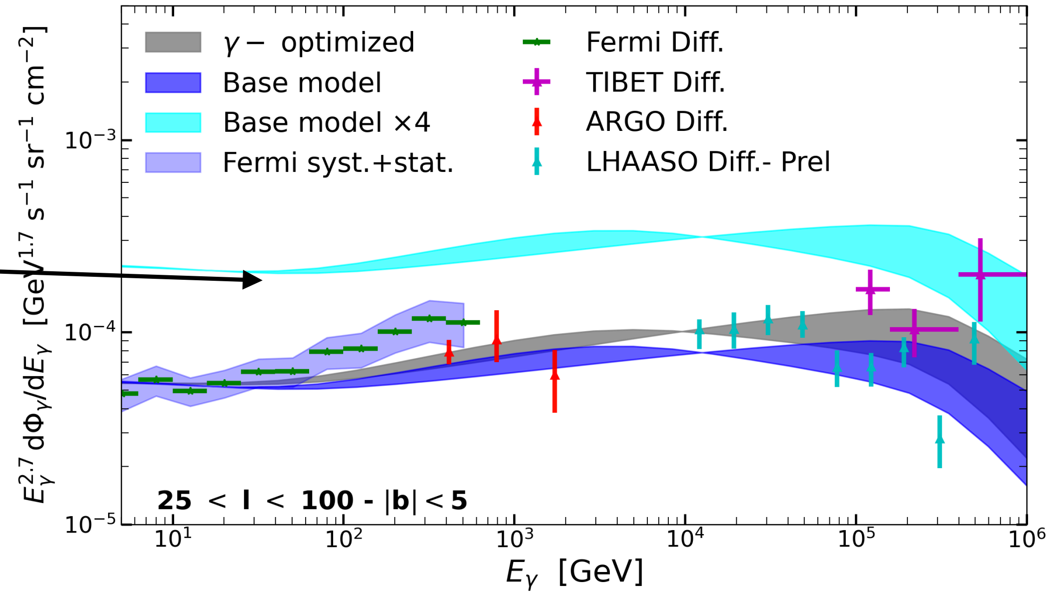
A better look to the IceCube results

IceCube coll. Science 2023

Base Model mostly equal to what is
is called π_0 model in the IceCube Science 2023

De la Torre et al. A&A 2023

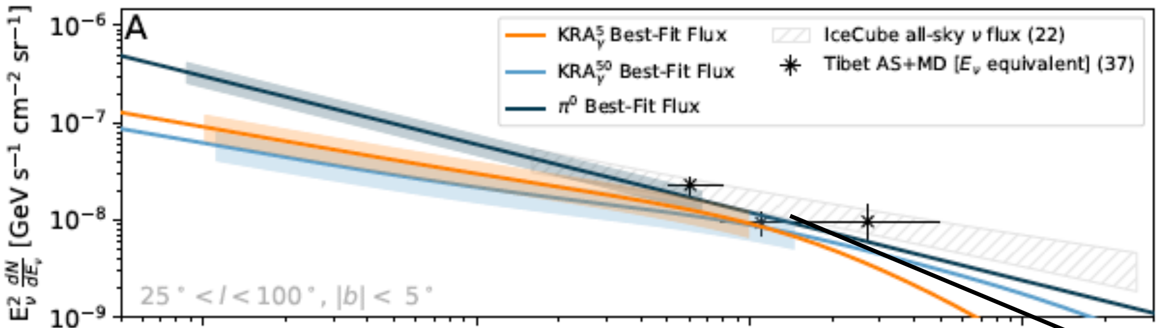




The best fit normalization of the π_0 model (4 times the expected value) strongly disagree with the Galactic diffuse Fermi-LAT observations.

A better look to the IceCube results

IceCube coll. Science 2023

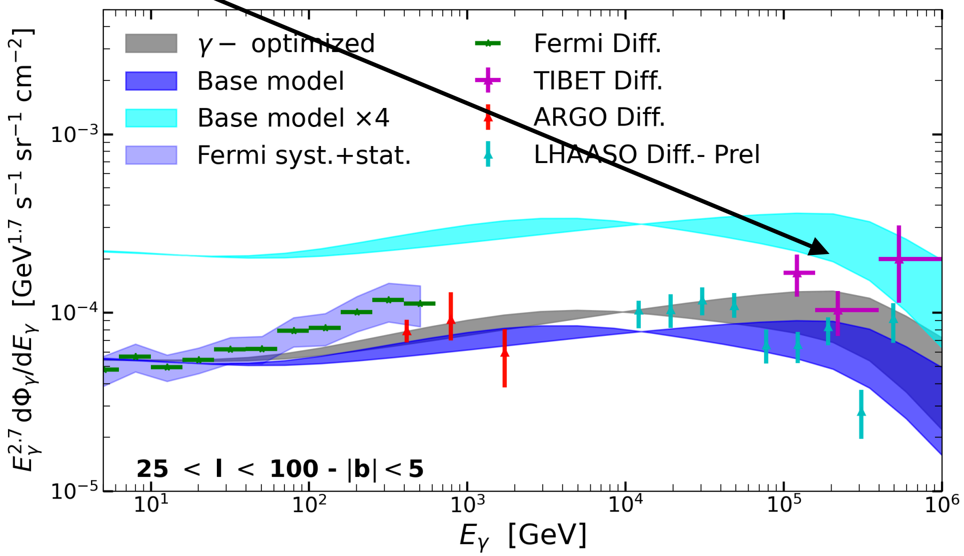


Caveat: the best-fit of observed ν is not obtained for the Tibet region, IceCube coll. rescaled of the measured flux

De la Torre et al. A&A 2023

Even though this extrapolation can partially fit the Tibet results, will completely miss the LHAASO observations in the same energy range.

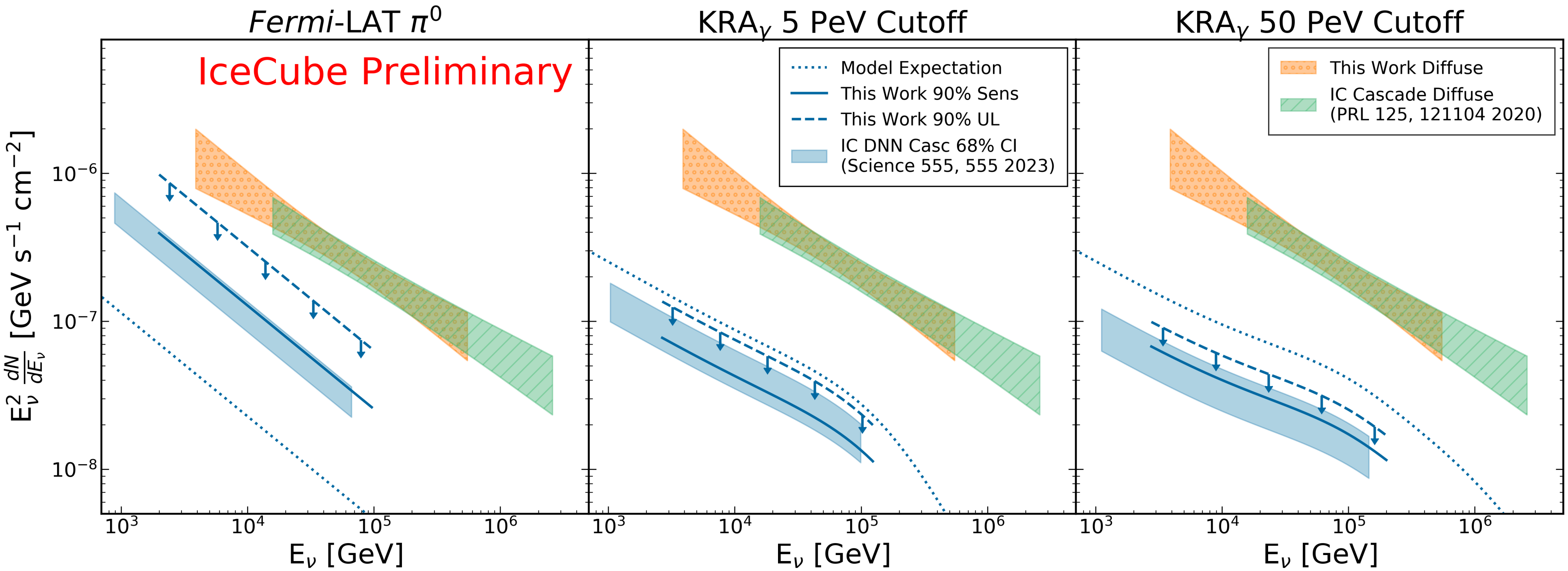
The best fit of the π_0 model is incompatible with gamma-ray observations at low and high energy



IceCube analysis with starting tracks 2008 -2018

Silva, Mancina
IceCube coll.
POS(ICRC2023) 1008

Mancina talk
TeVpa23

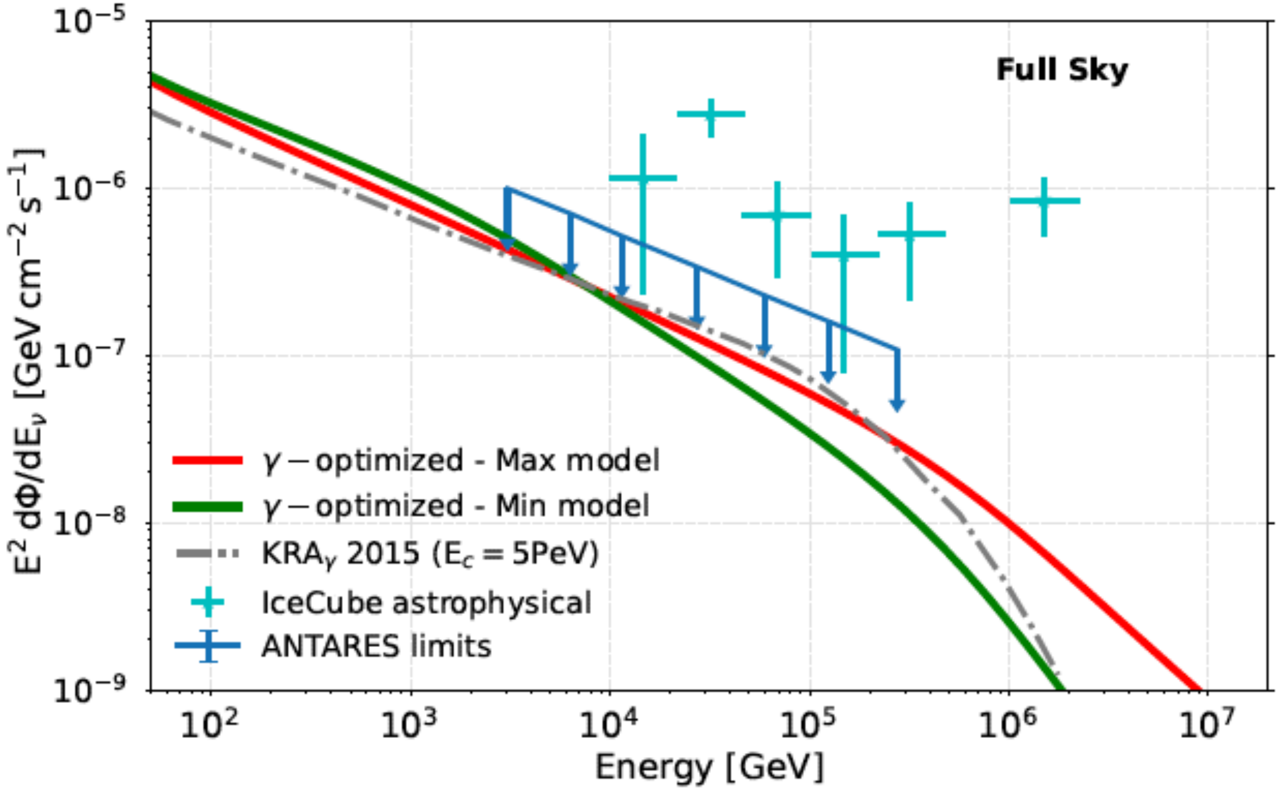


Starting track events IceCube analysis compatible with Cascade analysis, however any significant excess visible, KRA-γ with 50 PeV cutoff quite constrained.

ν expectations from the new KRA-γ models

De La Torre et al. Frontiers 2022

The expected new full sky ν SED in comparison with IceCube and ANTARES

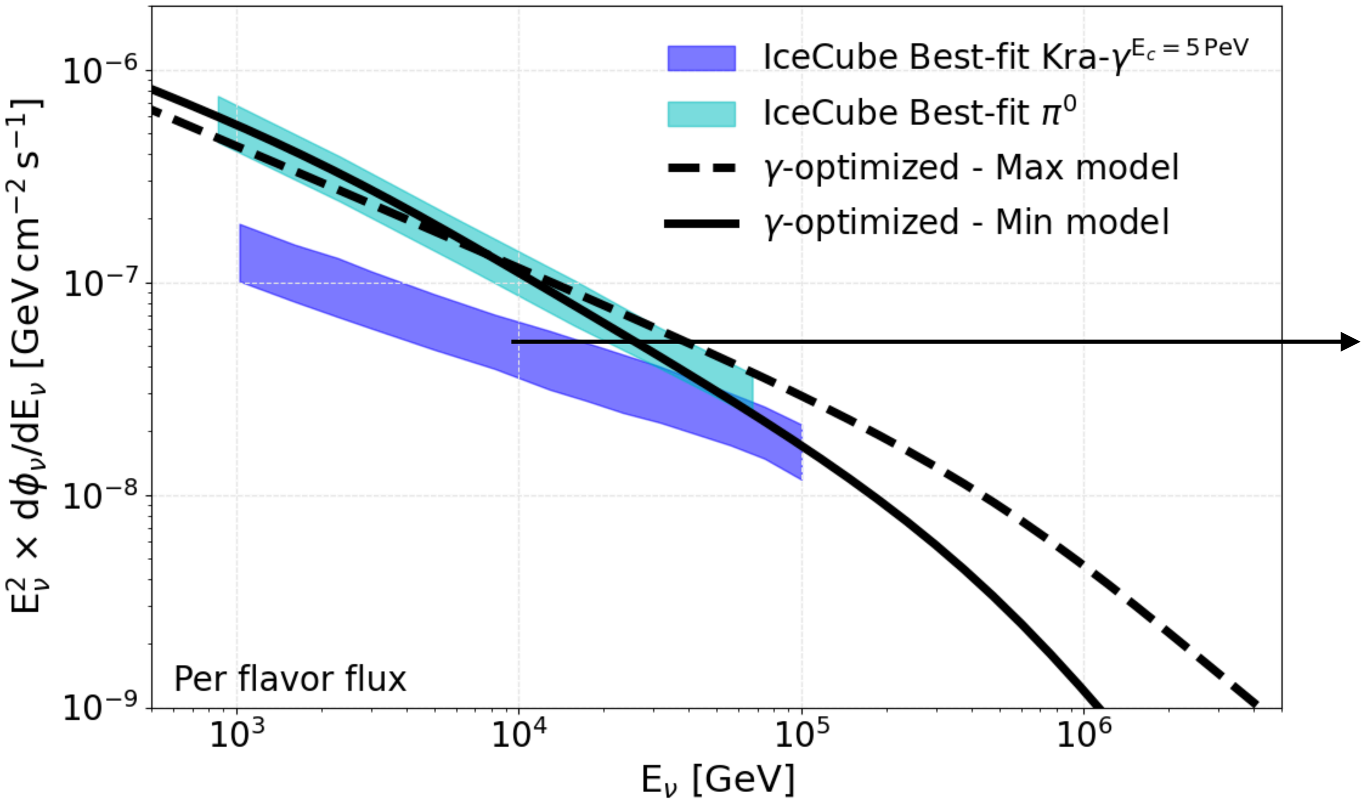


Still at the level of 10% of IceCube full sky observations and compatible with ANTARES model independent old upper limits

The updated KRA-gammas remain consistent with the previous KRA-gamma with CR cutoff at 5 PeV.

ν expectations from the updated KRA-gamma

The expected new full sky ν SED in comparison with IceCube



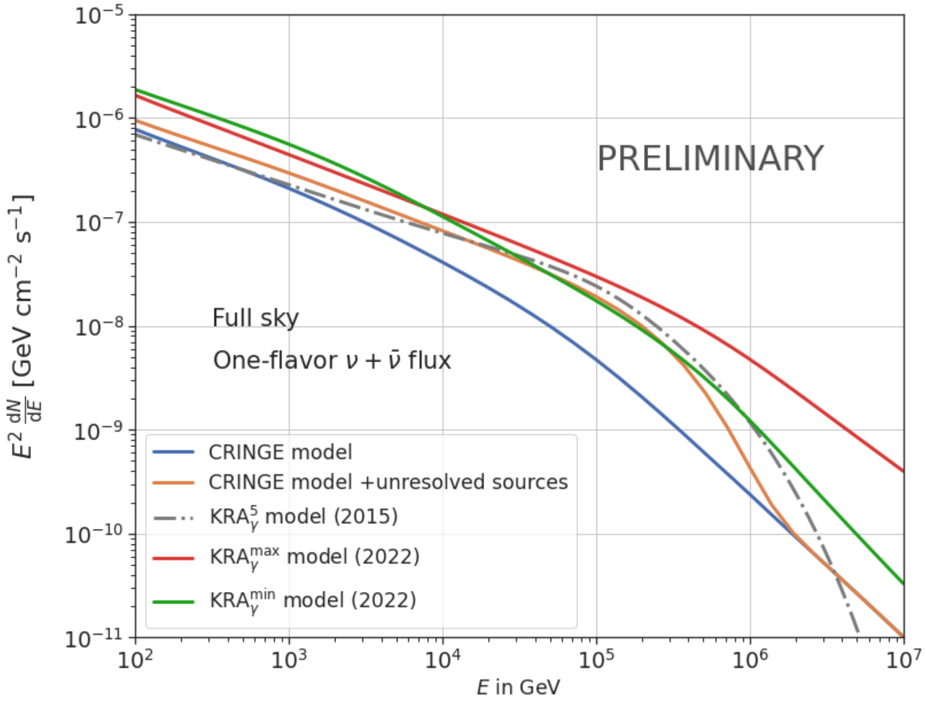
Remember that the KRA-γ 5 best-fit is 0.55 the model expectations

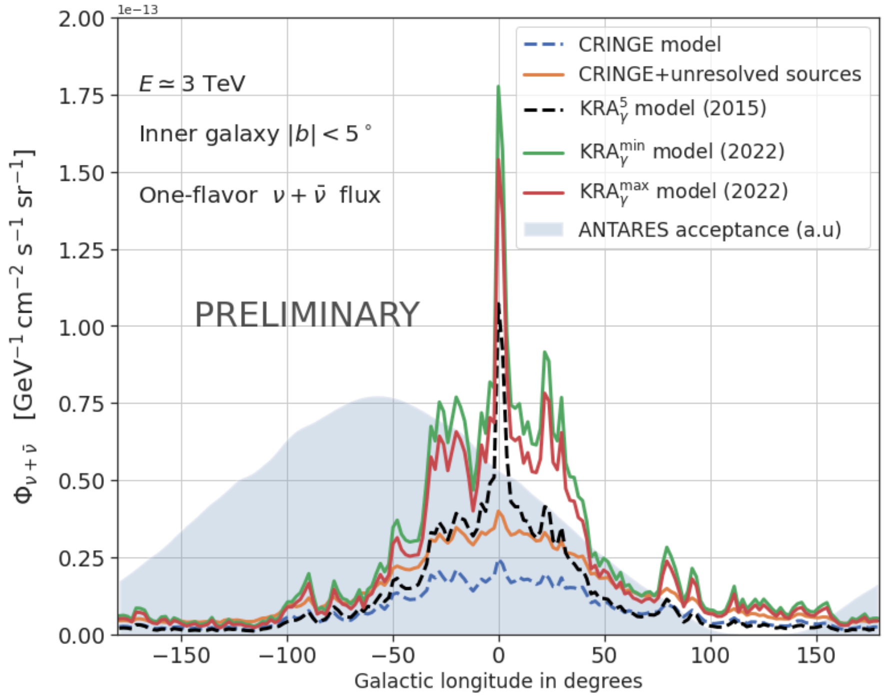
The agreement between the π_0 neutrino best fit and the new expectations from MIN and MAX models certify that the Fermi-LAT spatial template can agree with diffuse γ-ray and ν observations only if an hardening of the CR toward the Galactic center is assumed ($D \propto E^{\delta(R)}$).

Template fitting of the new KRA-γ with ANTARES

The new template fitting of ANTARES using track-like and shower-like events from 2007 to 2022, 4541 days of live time

Cartraud T. et al. ICRC 2023

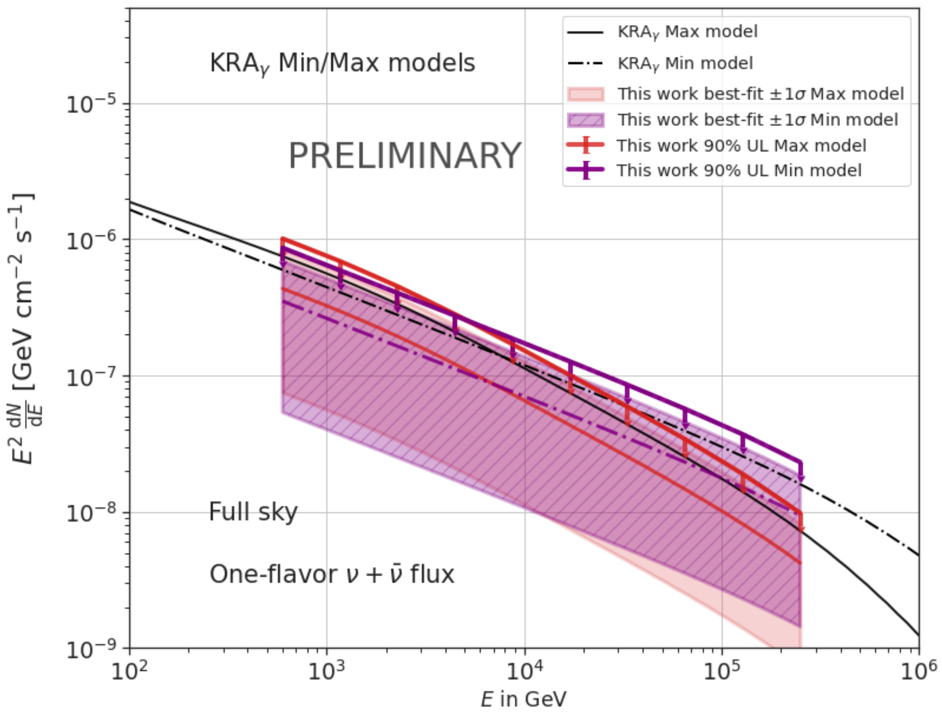




The good acceptance of ANTARES experiment for the central part of our Galaxy, makes is answer a crucial probe of the neutrino flux arriving for this region of the sky.

Template fitting of the new KRA-γ with ANTARES

Cartraud T. et al. ICRC 2023



The updated KRA-gamma template cannot be constrained at the moment with the ANTARES data. However the analysis show already hints of a preference for the a template with a hardening of CR toward the center of the Galaxy respect to a homogeneous CR transport assumption (CRINGE)

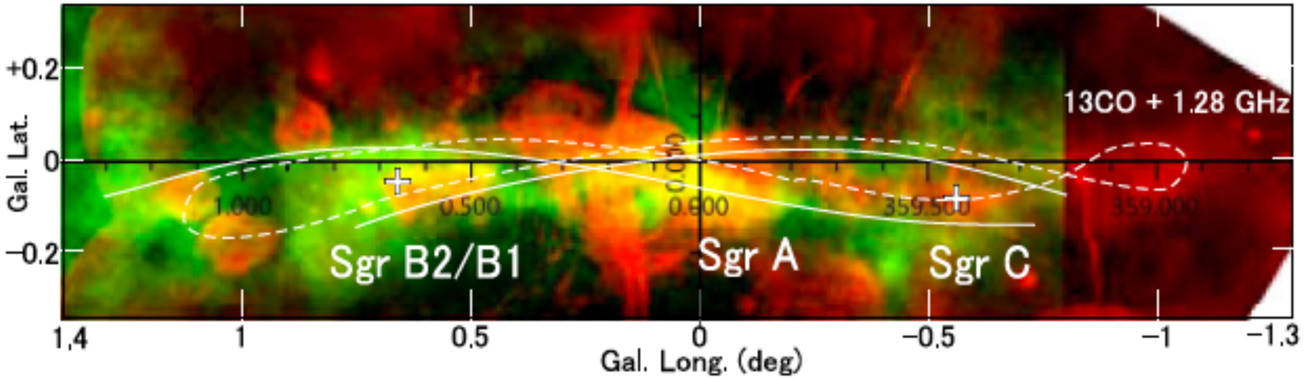
Higher significance for KRA-γ with CR cutoff at 5 PeV

Model	r^{fit}	μ_s^{fit} (tr/sh)	TS	pre-trial p-value	post-trial p-value	UL90(r)
KRA$_\gamma^{\mathrm{max}}$	$0.58^{+0.55}_{-0.48}$	9.6/6.7	0.77	$9.80 \cdot 10^{-2}$ (1.65σ)	$1.19 \cdot 10^{-1}$ (1.56σ)	1.35
KRA$_\gamma^{\mathrm{min}}$	$0.59^{+0.57}_{-0.50}$	9.3/7.2	0.73	$1.06 \cdot 10^{-1}$ (1.62σ)	$1.30 \cdot 10^{-1}$ (1.51σ)	1.45
KRA$_\gamma^{5}$	$0.93^{+0.81}_{-0.70}$	10.2/6.8	0.95	$7.40 \cdot 10^{-2}$ (1.79σ)	$8.92 \cdot 10^{-2}$ (1.70σ)	1.99
CRINGE+Unresolved	$1.08^{+1.18}_{-1.07}$	11.6/8.4	0.50	$1.47 \cdot 10^{-1}$ (1.45σ)	$1.79 \cdot 10^{-1}$ (1.34σ)	2.64
CRINGE	$1.58^{+2.46}_{-1.58}$	8.5/6.8	0.24	$2.35 \cdot 10^{-1}$ (1.19σ)	$2.74 \cdot 10^{-1}$ (1.09σ)	4.57

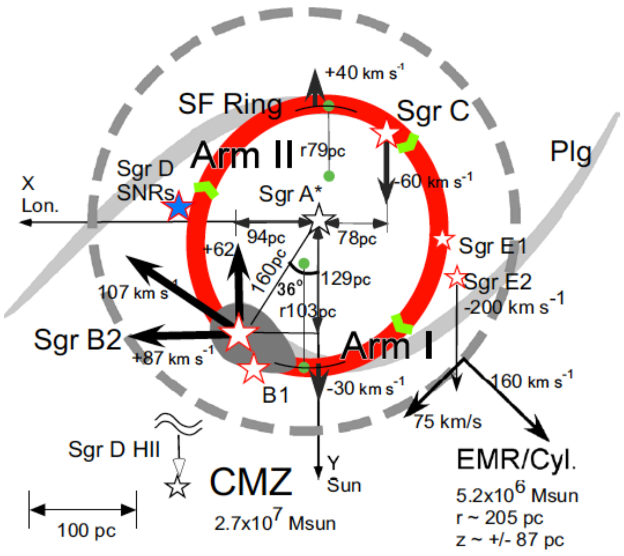
The central molecular zone

Contain 5% of the total mass of Milky Way

MNRAS 2022
Yoshiaki S.



CMZ	CHZ
207 pc radius	320 pc radius
28 pc high	70 pc high



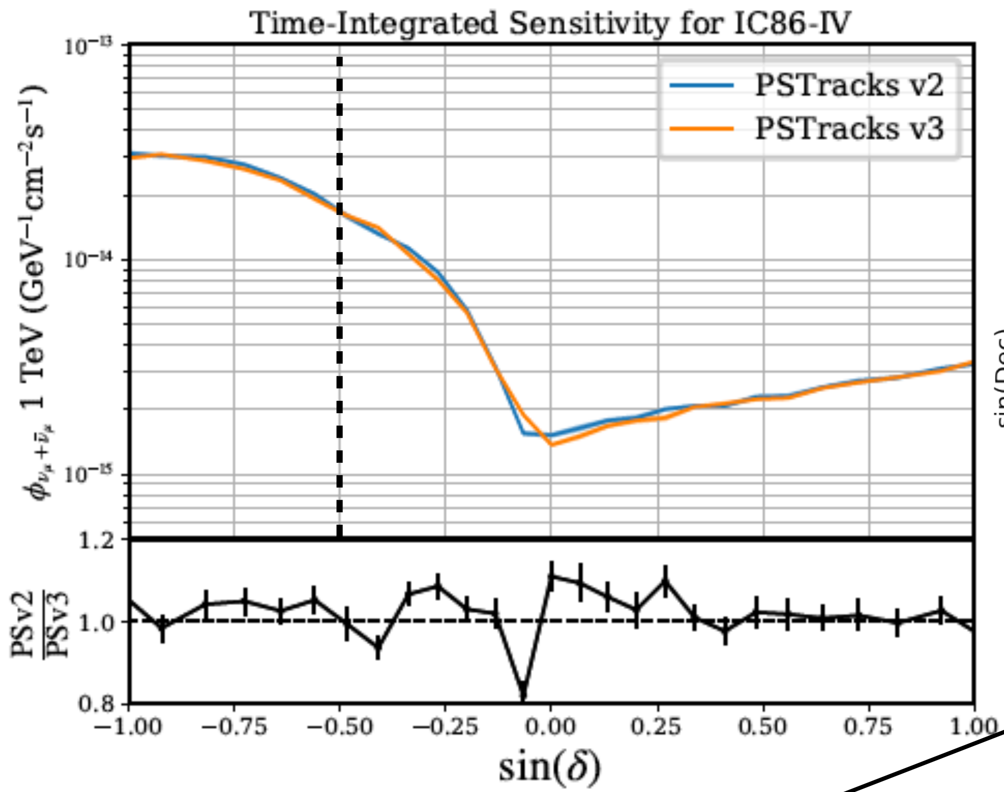
The Central Molecular Zone will be the Gold region to test the cosmic-ray sea physics through neutrinos, already done in the past with HE (Fermi_LAT) and VHE gamma rays (HESS) (Gaggero et al. PRL 2017)

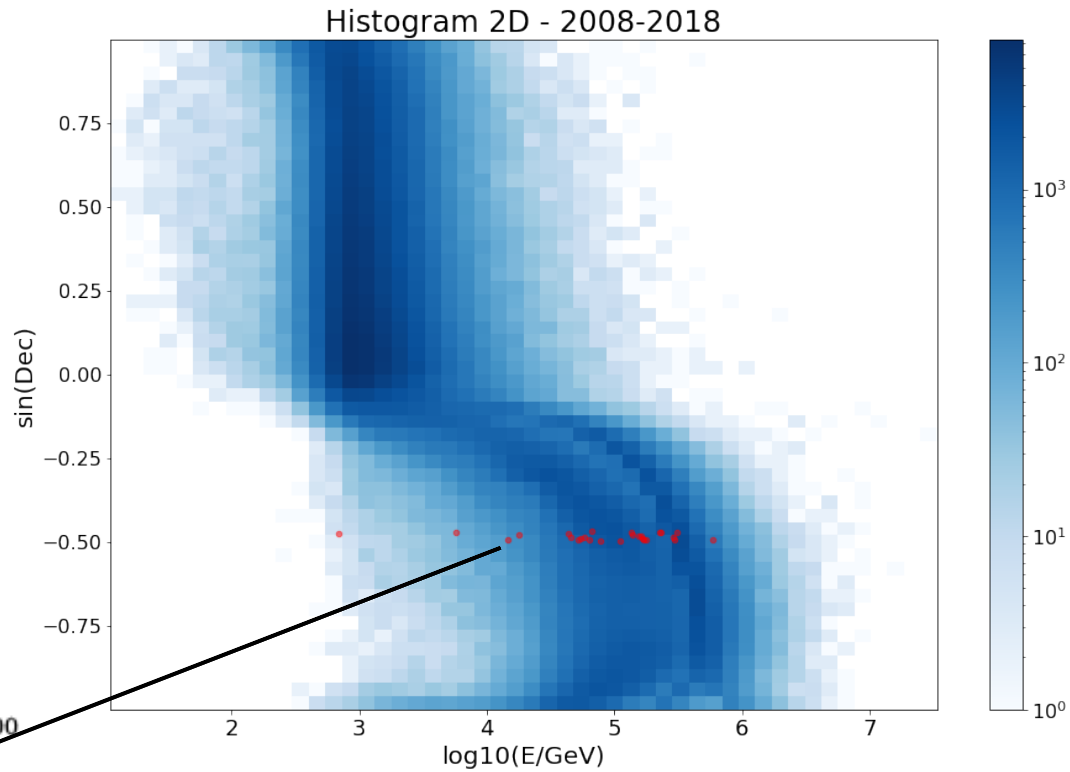
The region where more gas is concentrated and where the spectral assumptions of different models have the large discrepancy.

Search for ν in the central molecular zone

IceCube coll. data release 2021

Looking to the last release of track-like events collected by IceCube between 2008 and 2018, through-going tracks, primarily due to muon neutrino candidates, that reach the detector from all directions, as well as neutrino track events that start within the instrumented volume





24 through-going track potentially correlated with the CMZ ν emission

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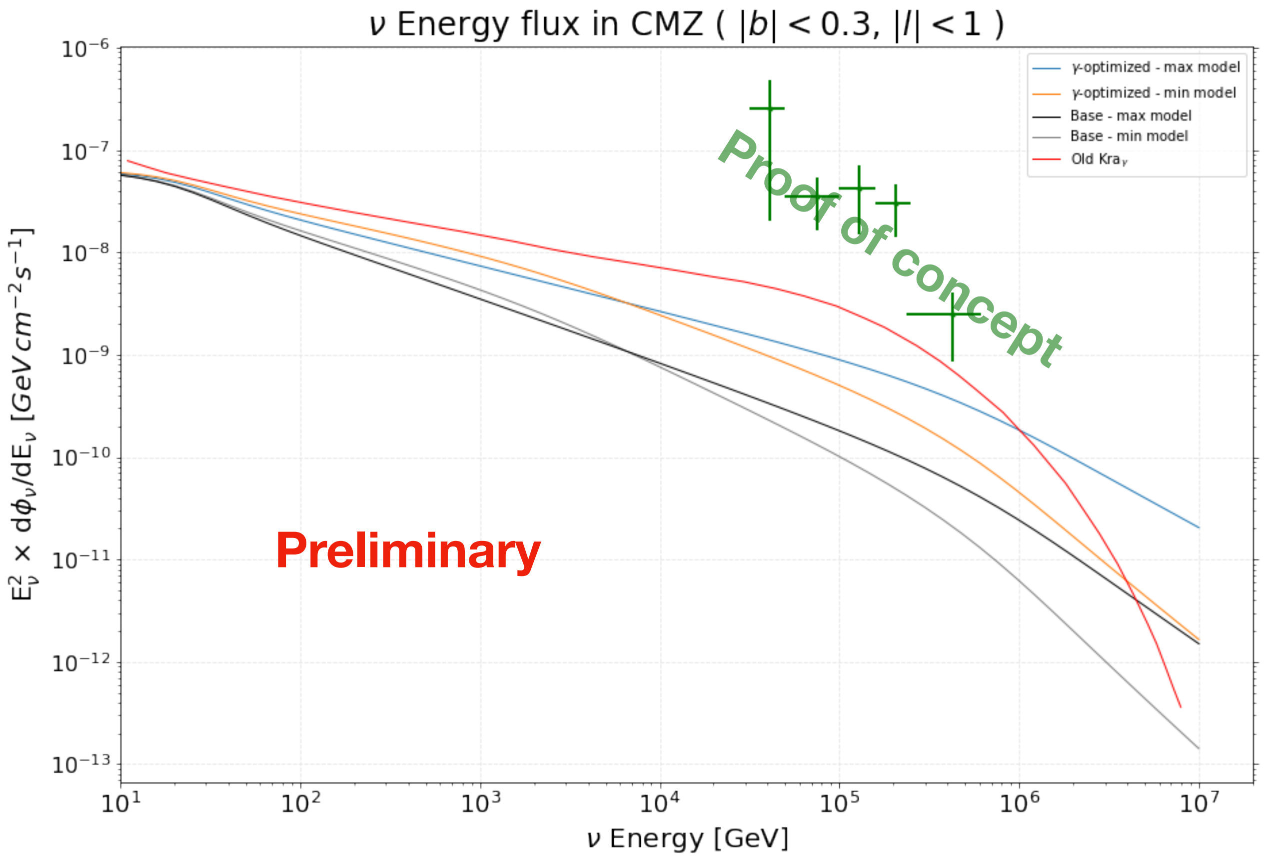
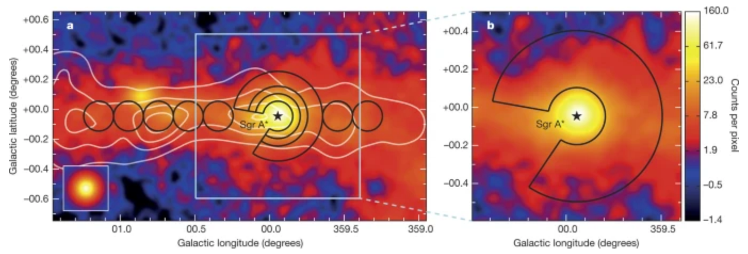
Search for ν in the central molecular zone

We report the expected CMZ diffuse emission (KRA-gamma models and Base models) in comparison with extrapolated spectral points from the 2008-2018 IceCube track-like sample



Caveat: errors of data SED should be properly reproduced (systematic unc.)
Sample can suffer of sizeable atmospheric contamination

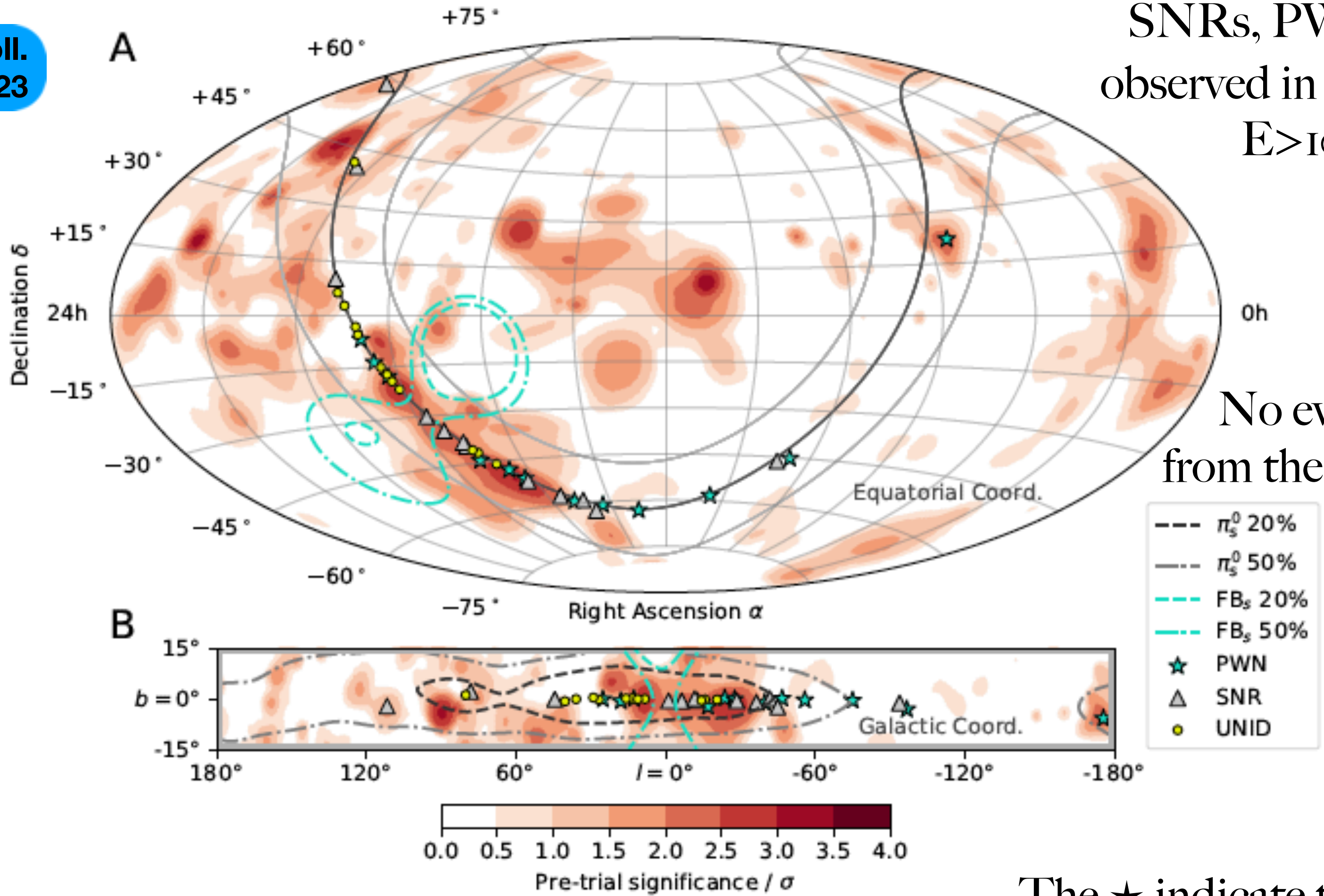
HESS coll Nature 2016



If this would be the case KRA-gamma models will still leave a room for: Sag $A^\star$, HESS 1745 290, young stellar clusters, gas overdensity effects from Sag A,B,C,D and presence of Dark Matter

Search for possible known Galactic ν sources

IceCube coll. Science 2023



SNRs, PWNs, UNIDs observed in γ with energies E>100 GeV

No evidence of ν excess from the selected populations

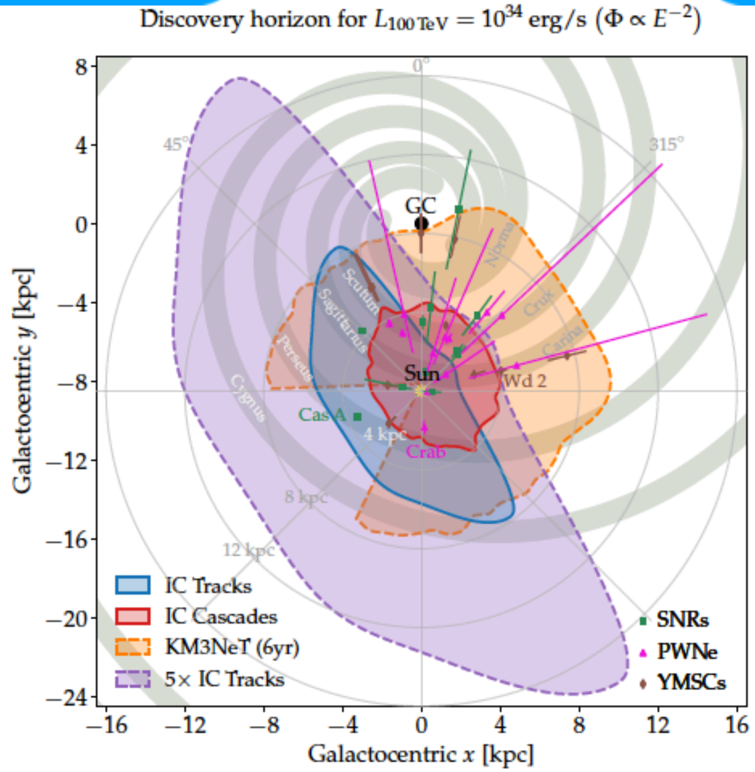
Catalog stacking analyses	p-value
SNR	5.90×10^{-4} (3.24σ)*
PWN	5.93×10^{-4} (3.24σ)*
UNID	3.39×10^{-4} (3.40σ)*

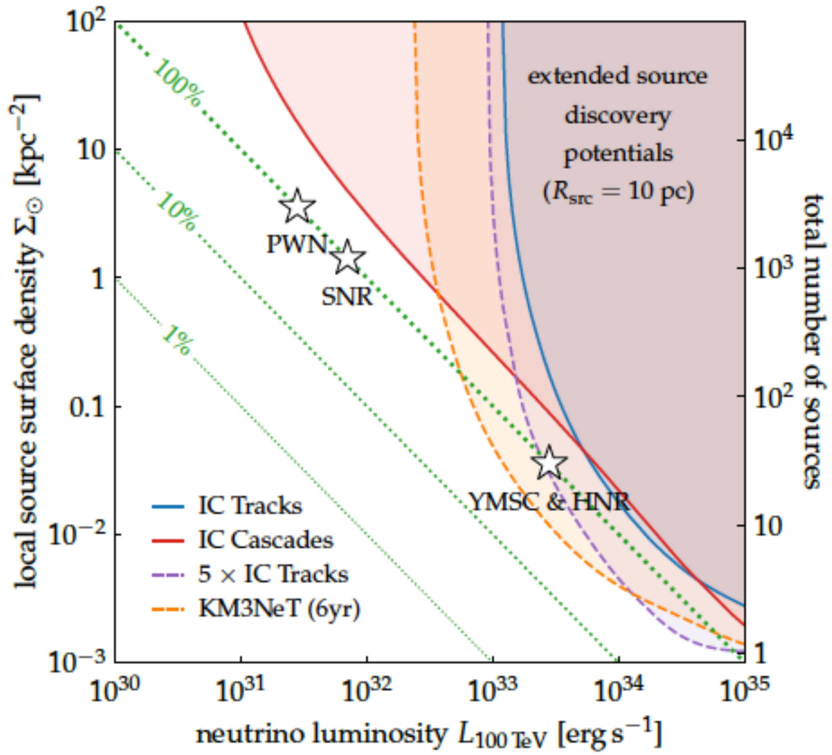
The ★ indicate that the significance is consistent with the diffuse emission template searches

Possible unresolved Galactic ν sources

Ambrosone et al. arXiv 2306.17285

TEVpa talk of Kathrine Groth





As showed in this work the actual ν telescopes and the incoming ones have a limited capabilities to resolve the known neutrino point-like populations, pointing to a possible additional quasi diffuse ν flux. However we don't know the amount hadronic production still associated to the position of these sources.

SUMMARY

- Galactic diffuse neutrino has finally been detected, indicating a preference to a CR hardening toward the GC and a cutoff ~ 5 PeV

- A updated version of the KRA-gamma template has been produced for γ and ν taking into account the new data of DAMPE, KASCADE, AMS02, IceTop, and the last Fermi-LAT release.

- The predictions from the γ-optimized model (modeled from GeV Fermi data) explain perfectly both, LHAASO and IceCube observations

- The CMZ is a preferential region to test the different available phenomenological models of the diffuse sea non only with γ but also with ν

- A more detailed answer on Galactic ν will be possible with KM3NeT and IceCube Gen2