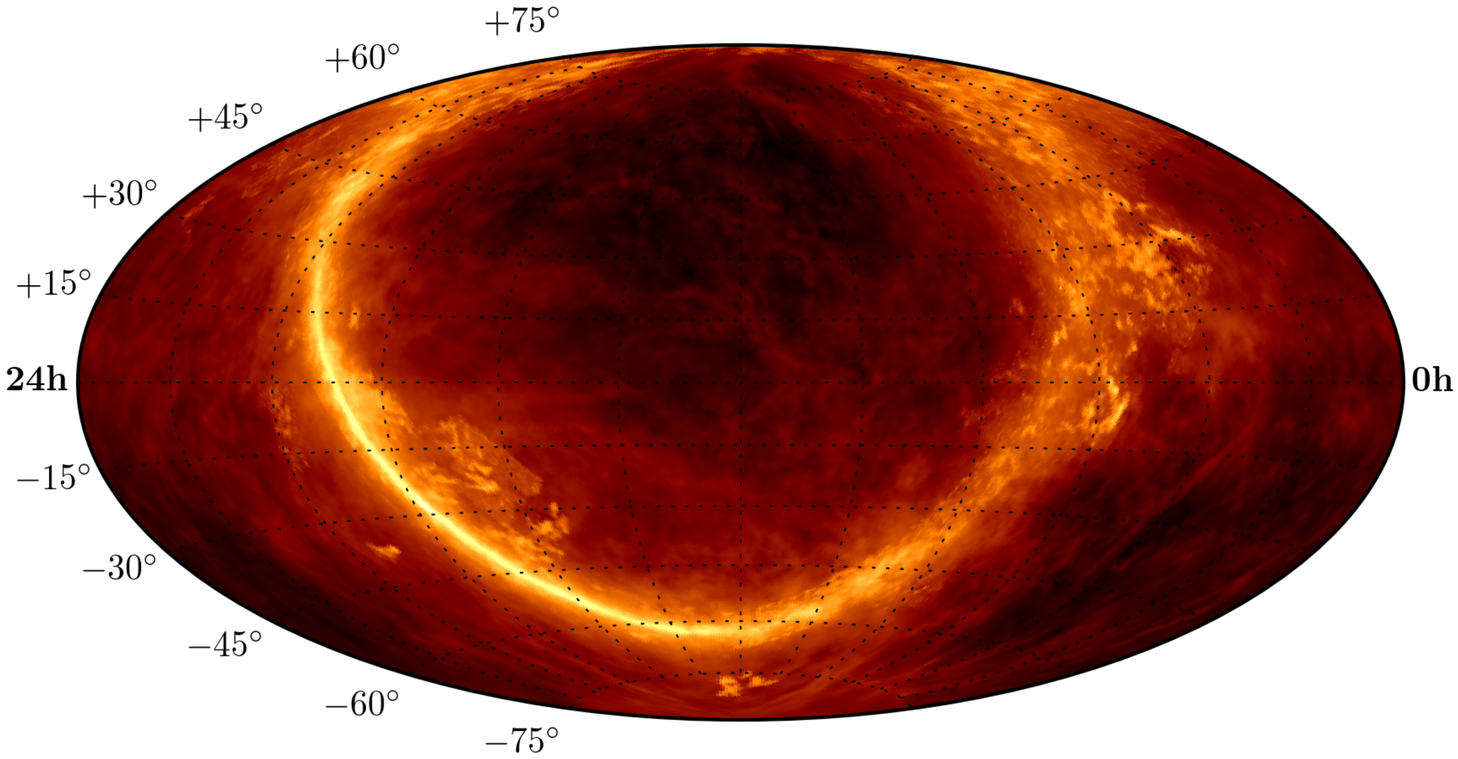


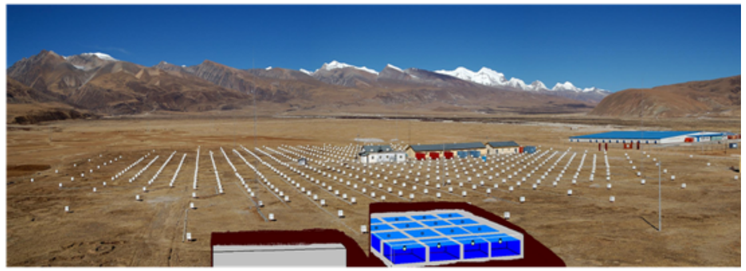
THE HIGH-ENERGY DIFFUSE GALACTIC EMISSION: REACHING THE PEV FRONTIER FOR NEUTRINOS AND GAMMA RAYS

Daniele Gaggero (IFIC, Valencia) with
P. De la Torre Luque, D. Grasso and A. Marinelli

KM3net Town Hall Meeting, Catania (Italy)

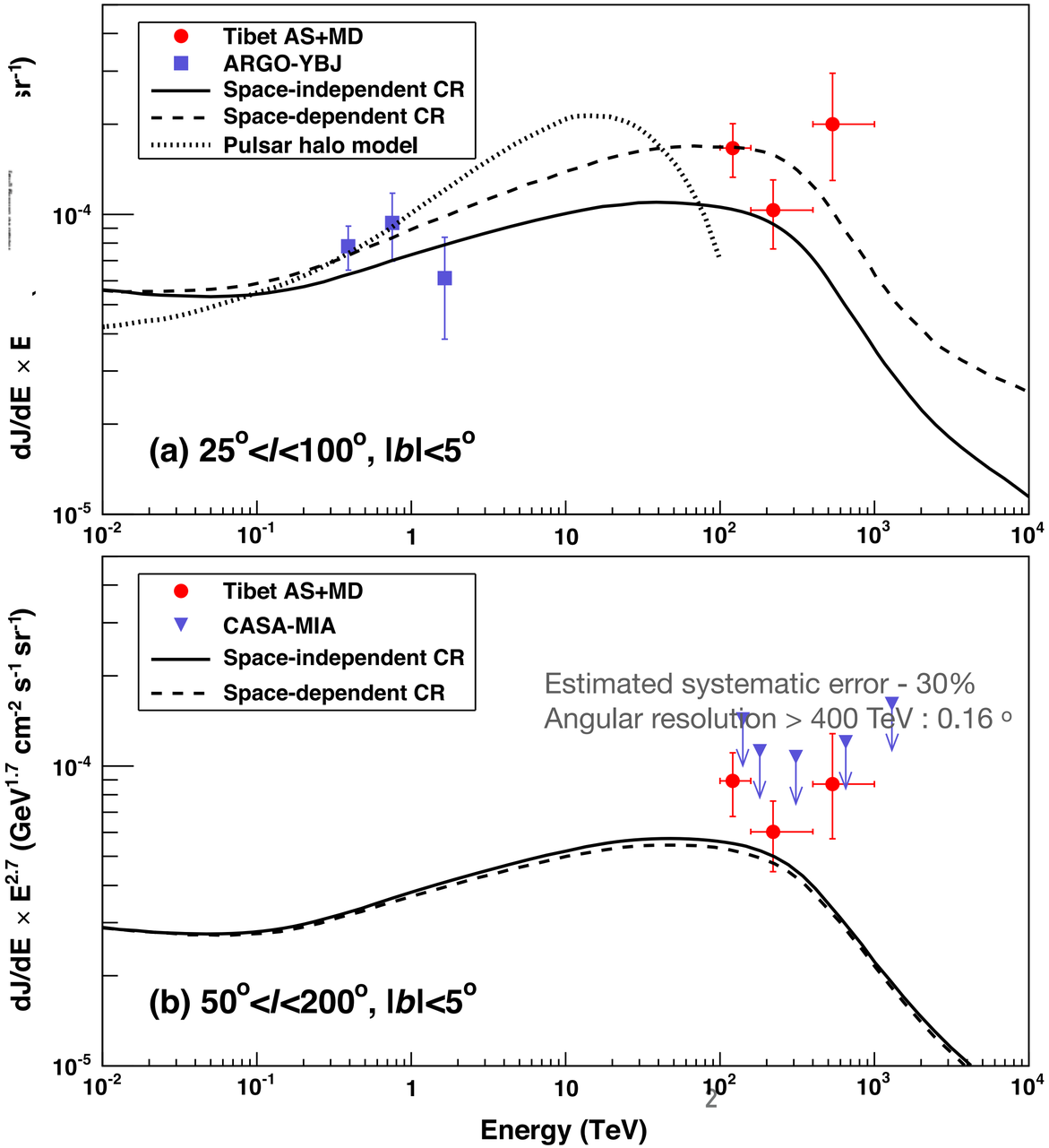
MOTIVATION: TIBET ASγ RESULTS

Tibet ASγ coll., PRL 2021



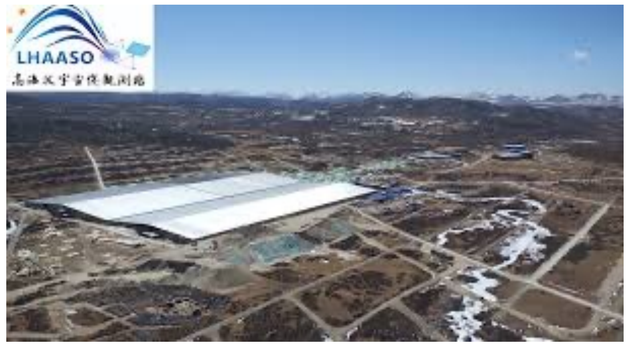
Air-Shower + muon detector at 4300 m a.s.l.

- **First detection of the γ-ray diffuse emission from the Galactic plane in the PeV domain.** 5.9σ significance (ON/OFF analysis. 23 events E > 398 TeV $|b|< 10^\circ$, 10 ev. $|b| > 20^\circ$)
- No events from known TeV sources above 398 TeV while above 100 TeV TeVCAT sources contribute a 13%
- 4 events (out of a total number of 10 above 398 TeV) from the Cygnus Cocoon ($l \simeq 80^\circ$)
- Under the hypothesis the emission is originated by CRs, a **good agreement with the predictions of a space-dependent CR transport scenario is claimed — as we will show in a while!**



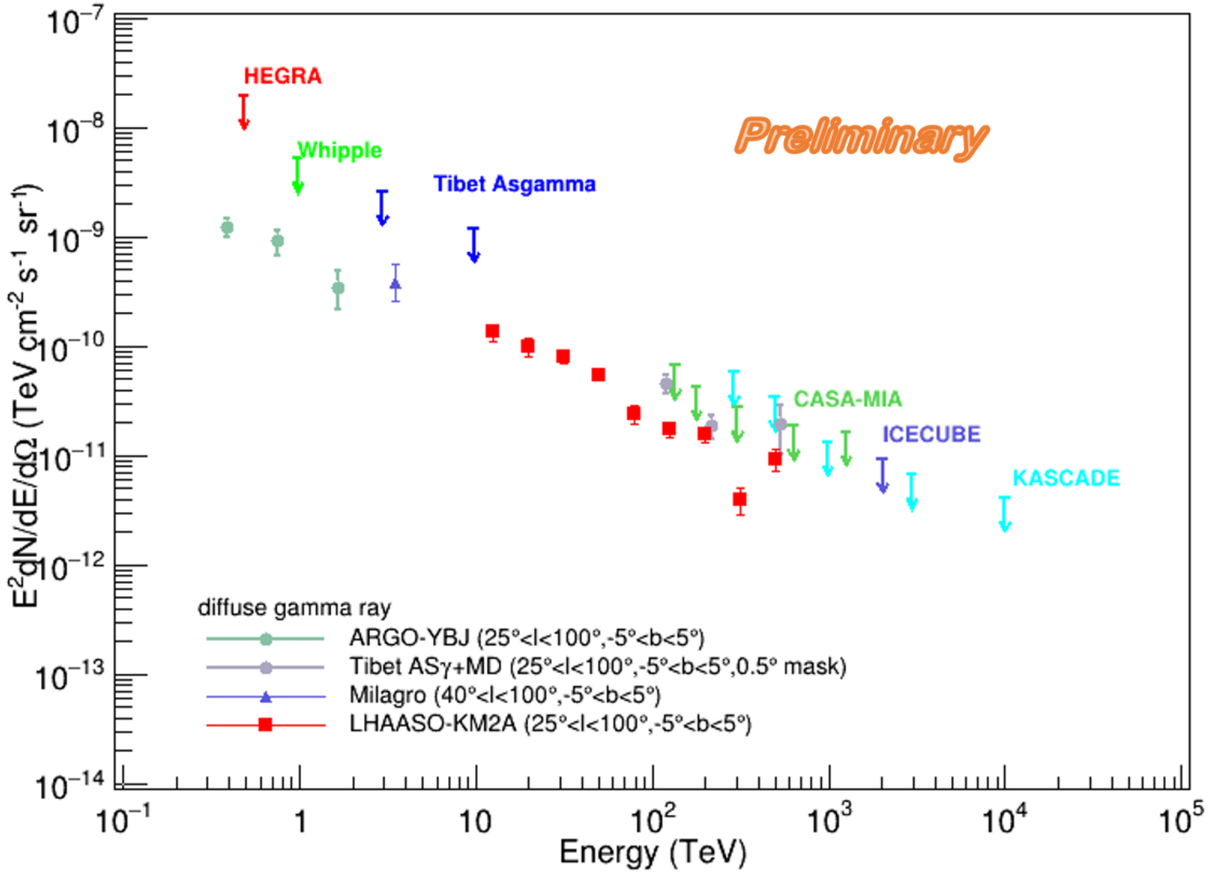
LHAASO (PRELIMINARY) RESULTS

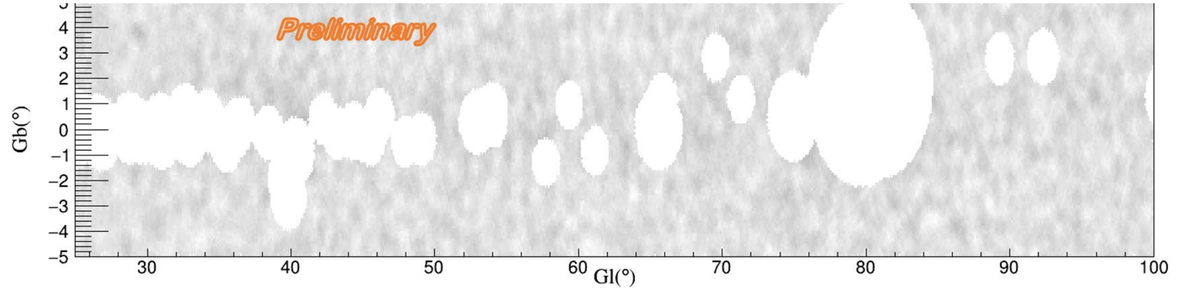
S.P. Zhao et al. - LHAASO coll., ICRC 2021



Air-Shower + muon detector at 4400 m a.s.l.

- Statistics is larger compared to Tibet results
- Energy threshold lower than Tibet
- TeVCAT sources were masked





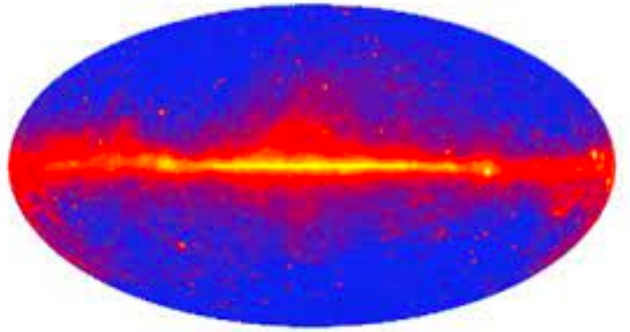
SCIENTIFIC QUESTIONS

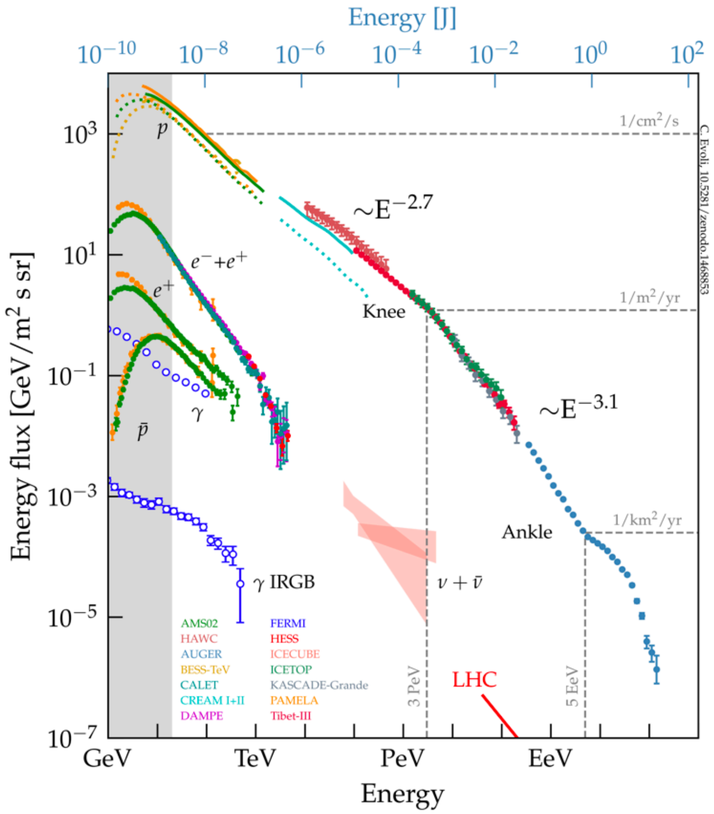
- Does this emission share the same nature of the ***"truly diffuse"*** interstellar emission (originated by the CR sea) as measured by Fermi-LAT? or it is the superposition of many *unresolved sources?*

- Is the spectral shape and normalization of the inferred primary CR population different from the local one?

- What is the CR spectrum and composition around the PeV ?

- *What are the **implications for the search of Galactic neutrinos** and **what would we learn** detecting the Galactic neutrino diffuse emission?*



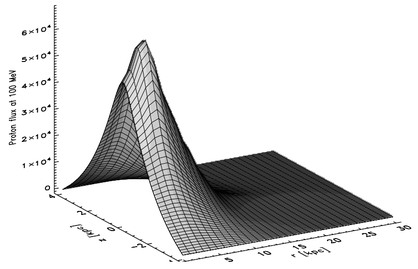


MODELLING THE INTERSTELLAR DIFFUSE EMISSION

The conventional scenario

https://github.com/cosmicrays/hermes

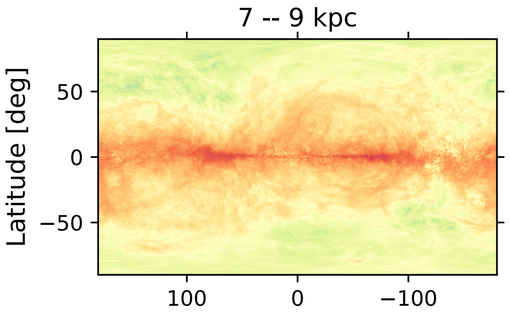
CR spatial/energy distribution from numerical codes (GALPROP/DRAGON)



(b) Propagated protons at 100 MeV

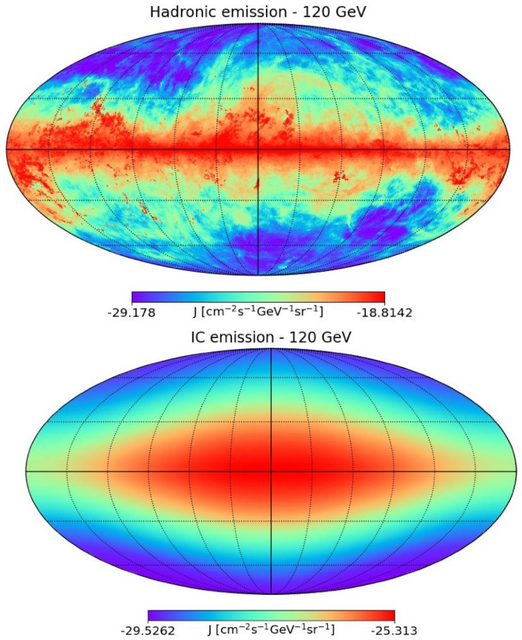
+

Astrophysical inputs : gas maps , interstellar radiation fields, magnetic fields



LOS integration

GALPROP/HERMES



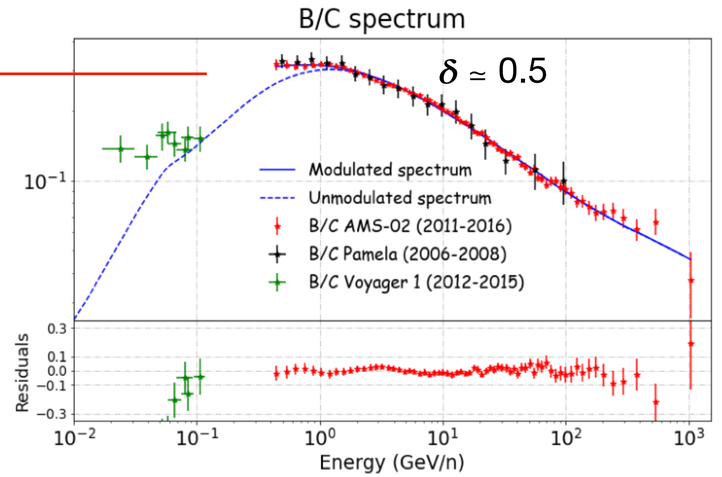
ρ : particle rigidity

Schematically, for CR nuclei

given a (uniform) source spectrum $J_S(\rho, \mathbf{x}) \propto n_S(\mathbf{x})\, \rho^{-\alpha}$

for a uniform diffusion coefficient $D(\rho, \mathbf{x}) \propto D_0\, \rho^{-\delta}$

$$J_{CR}(\rho, \mathbf{x}) \propto J_0(\mathbf{x})\, \rho^{-(\alpha+\delta)} \quad \text{in the whole Galaxy}$$

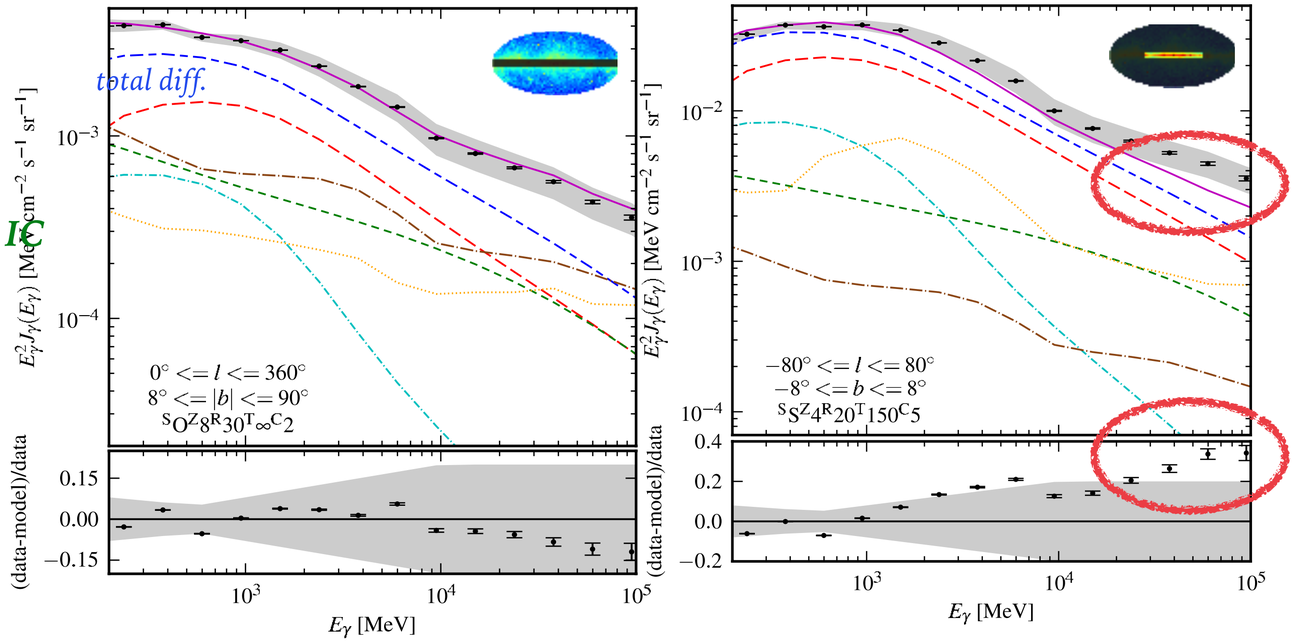


MODELLING THE INTERSTELLAR DIFFUSE EMISSION

The conventional approach - issues

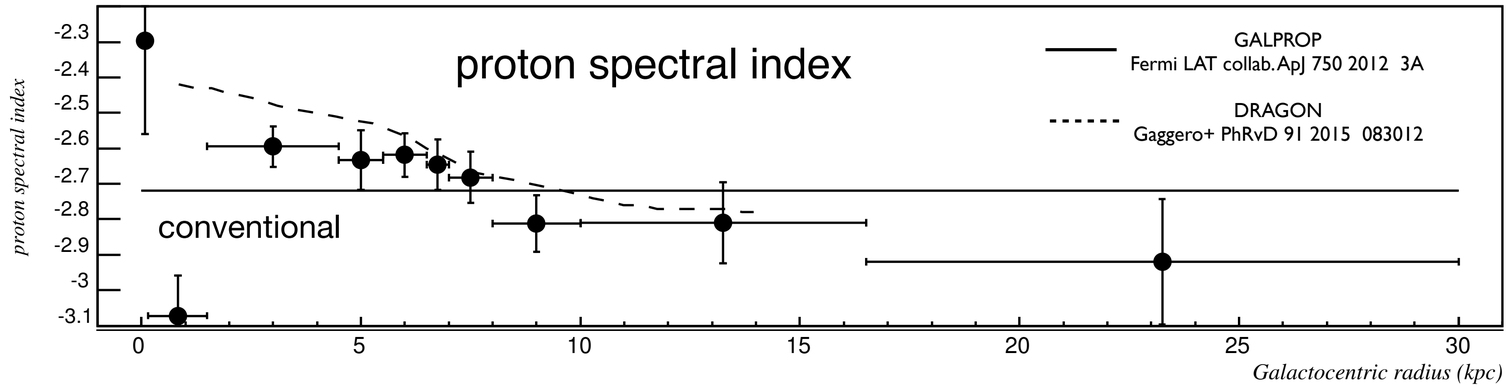
sources

IC



Fermi-LAT coll. 2012

Fermi-LAT coll. 2016



MODELLING THE INTERSTELLAR DIFFUSE EMISSION

The KRAγ or "gamma optimized" scenario

Schematically, for CR nuclei

given a (uniform) source spectrum $J_S(\rho, \mathbf{x}) \propto n_S(\mathbf{x})\, \rho^{-\alpha}$

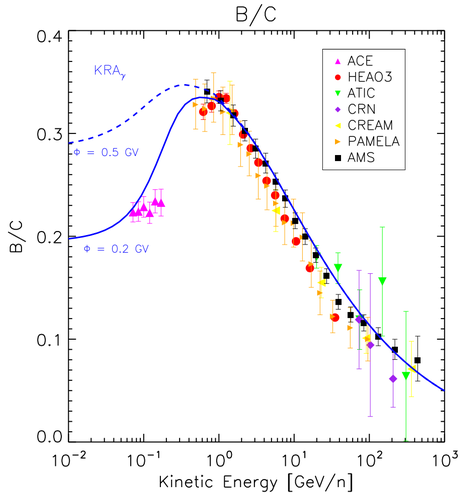
for **not** uniform diffusion coefficient $D(\rho, \mathbf{x}) \propto D_0\, \rho^{-\delta(\mathbf{x})}$

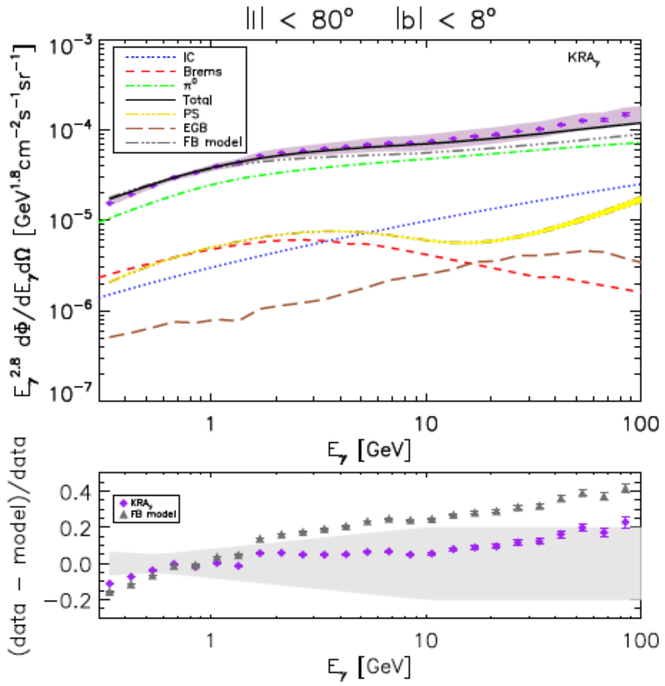
$$J_{CR}(\rho, \mathbf{x}) \propto J_0(\mathbf{x})\, \rho^{-(\alpha + \delta(\mathbf{x}))}$$

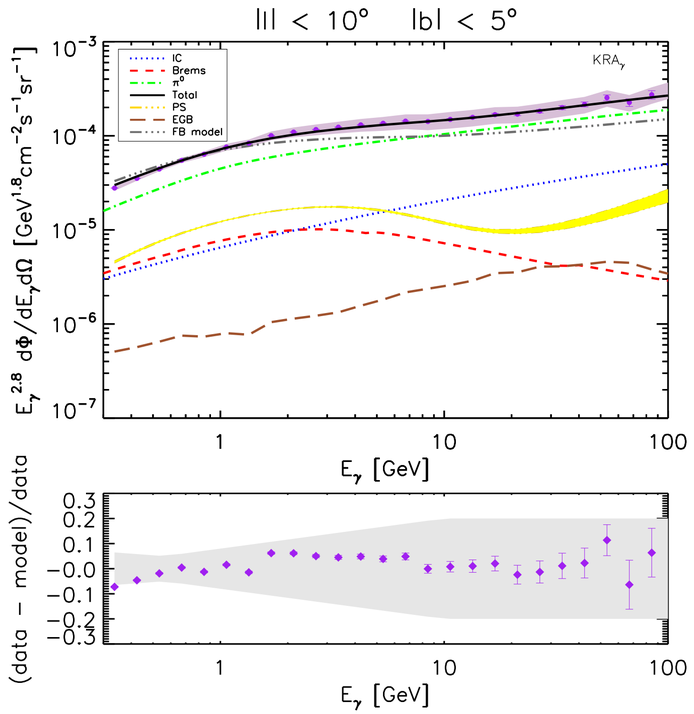
Unfactorized rigidity-position dependence

Gaggero, Urbano, Valli & Ullio, PRD 2015

$\delta(R) = A\,R + B$ for $r < 11$ kpc





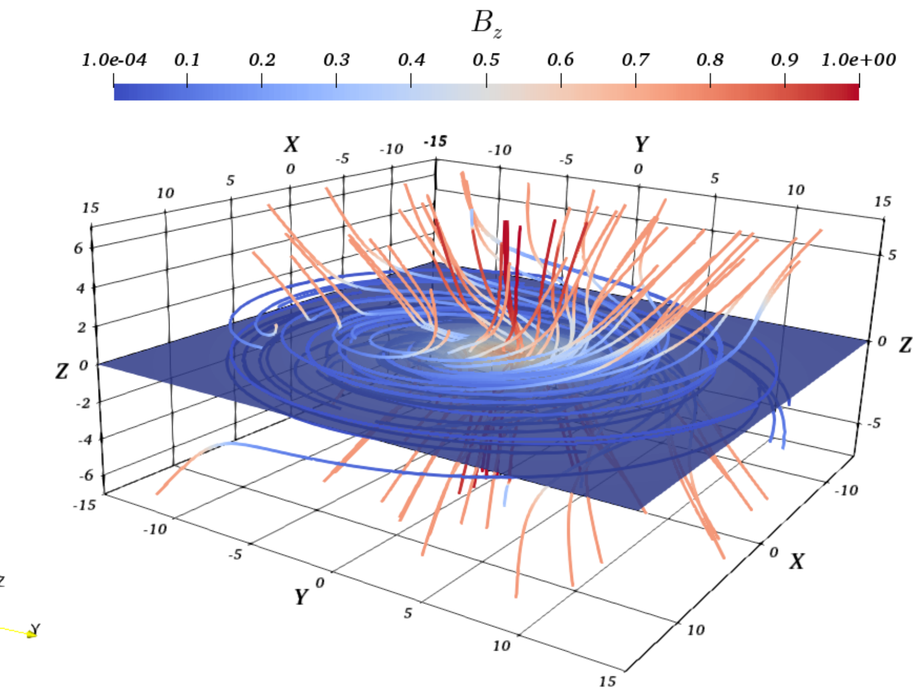


MODELLING THE INTERSTELLAR DIFFUSE EMISSION

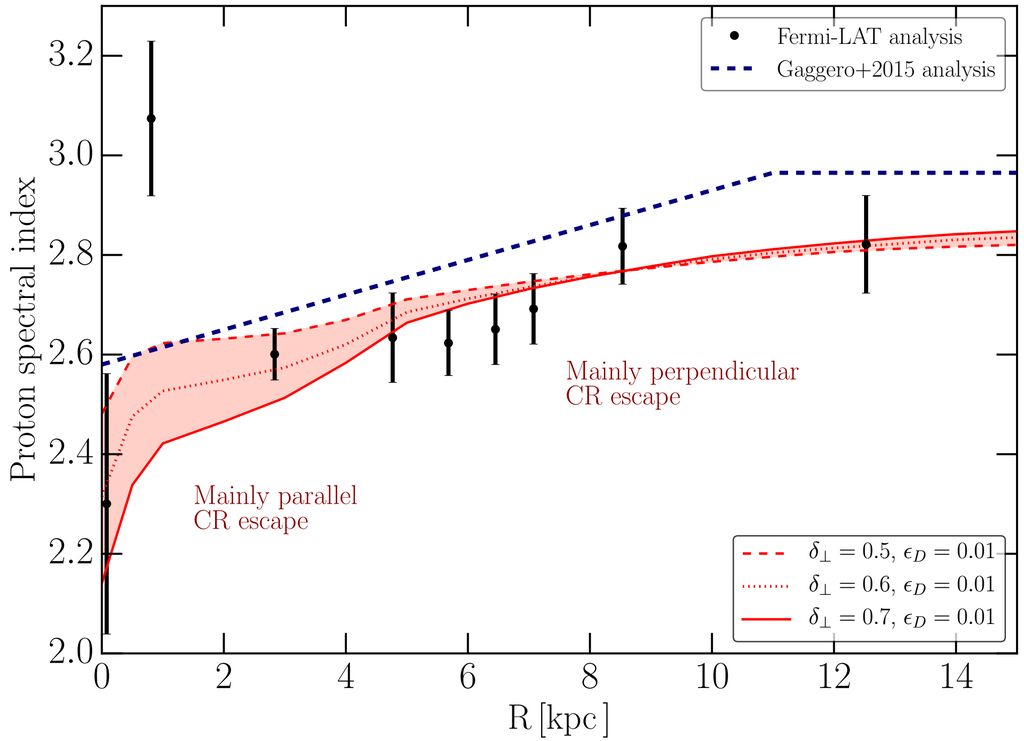
The KRAγ or "gamma optimized" scenario

Cerri, DG, Vittino, Evoli & Grasso, JCAP 2017

An interesting physical interpretation?



Magnetic field model
Jansson & Farrar ApJ 2012
Terral & Ferriere 2016



- **Poloidal** magnetic field become more relevant toward the GC
- CR escape via **parallel diffusion** (irrelevant at large radii) becomes dominant at small R
- Parallel diffusion seems to exhibit a harder scaling with rigidity *Casse+ 2001, De Marco+ 2007 , Snodin + 2015]*

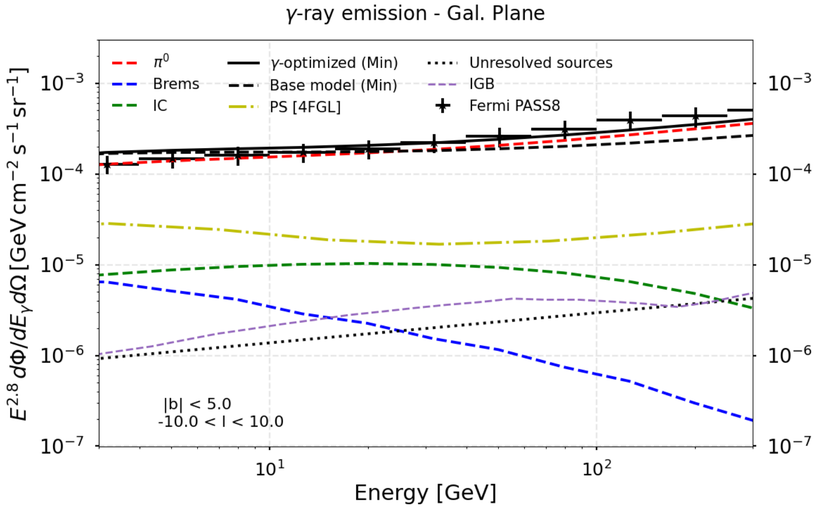
$D_{||} \propto \rho^{1/3}$ $D_\perp \propto \rho^{1/2}$

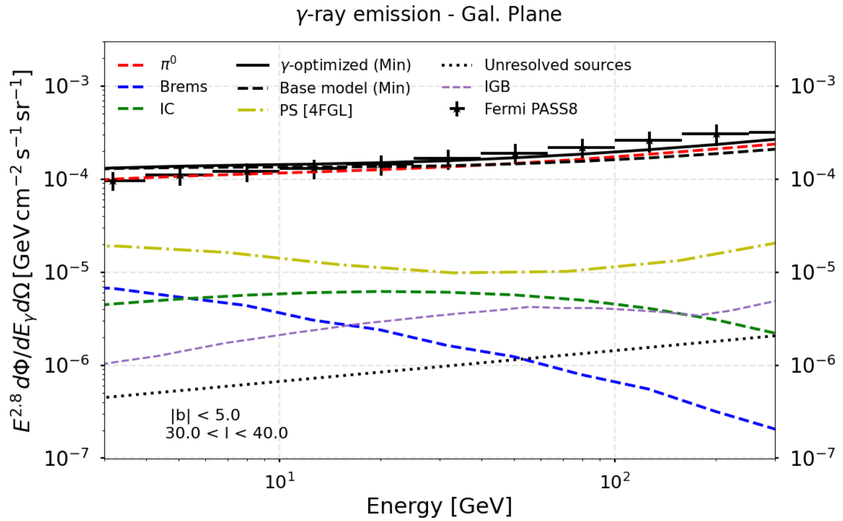
➜ **CR spectrum becomes harder** for R ➜ 0 (same effect at all relevant energies)

THE UPDATED "GAMMA-OPTIMIZED" MODELS

Updated models compared to Fermi-LAT data

P. De La Torre Luque, D. Gaggero, DG, O. Fornieri, K. Hegberts, C. Steppa, C. Evoli, 2203.15759

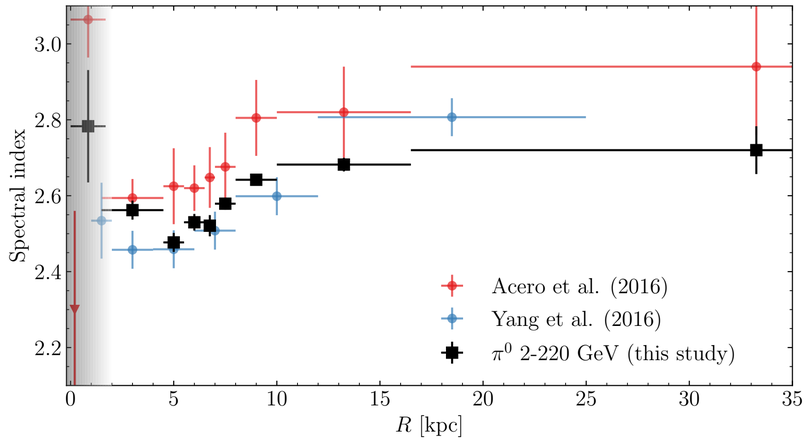




The model was retuned on most recent Fermi-LAT data, taking into account more recent analyses of the hardening trend

The model adopts a hardening of the source spectrum at 300 GeV to reproduce AMS-02 data

CR (proton) spectral index as inferred from several analysis of *Fermi*-LAT γ-ray data

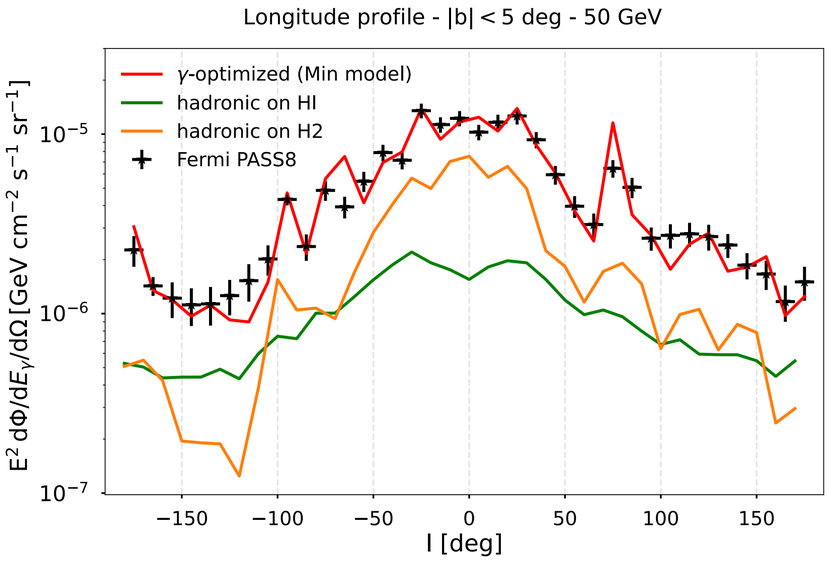


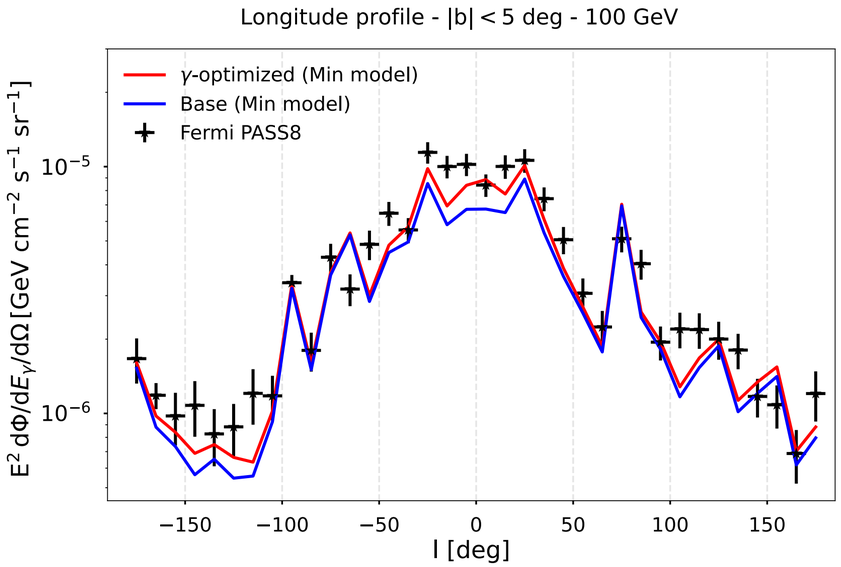
We include an unresolved source model based on the H.E.S.S. galactic plane survey
[Steppa & Egberts A&A 2022]

THE UPDATED MODELS

Updated models compared to Fermi-LAT data

De La Torre Luque, DG, Gaggero, Marinelli, accepted by Frontiers



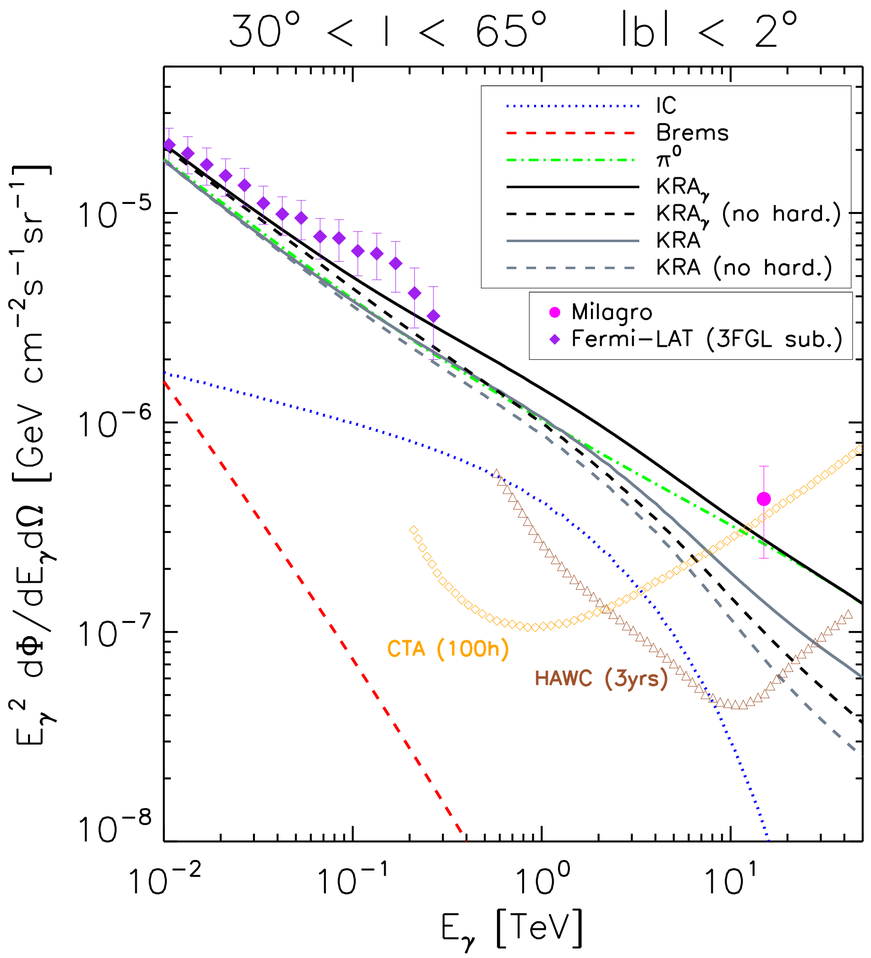


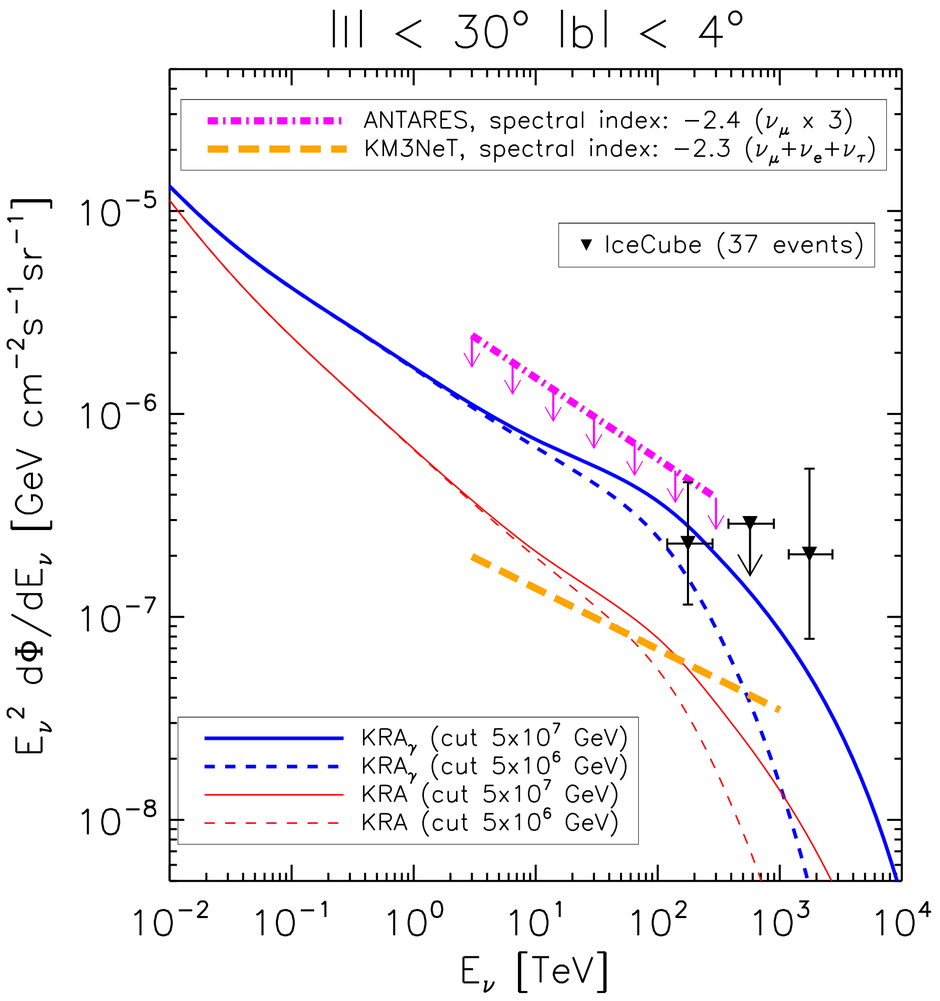
Performed with HERMES

https://github.com/cosmicrays/hermes

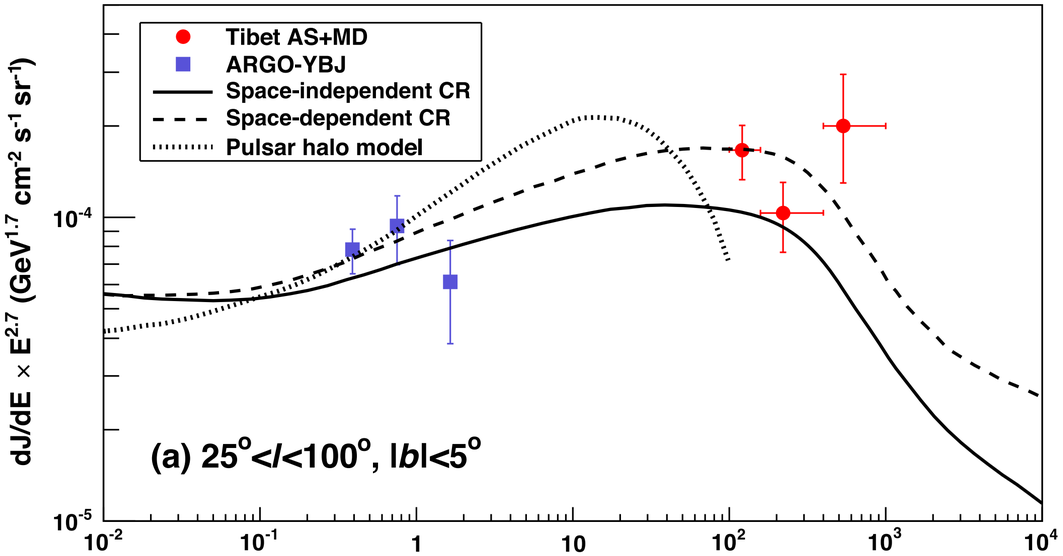
TOWARDS THE PEV DOMAIN: GAMMA RAYS AND NEUTRINO PREDICTIONS IN 2015

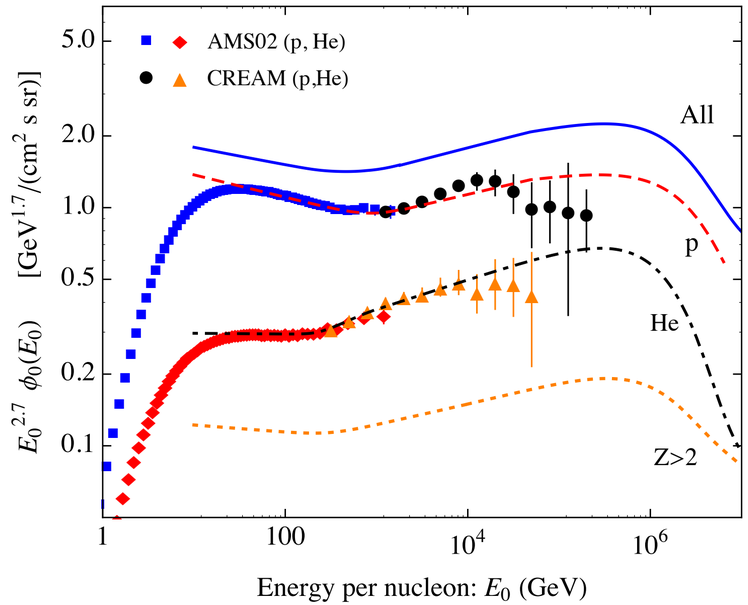
Gaggero, D.G., A. Marinelli, Urbano, Valli ApJ L 2015



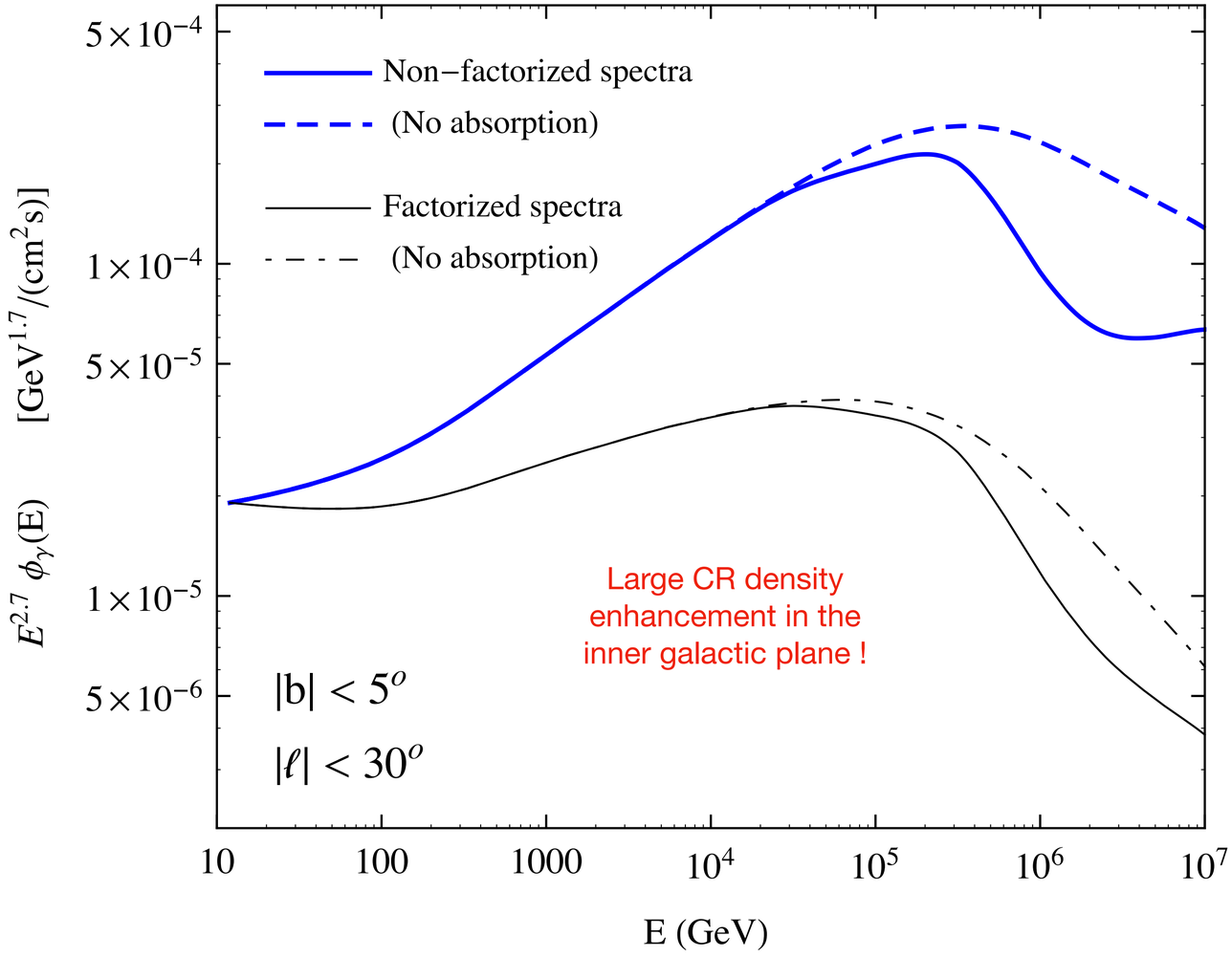


TOWARDS THE PEV DOMAIN: SEMI-ANALYTICAL RESULTS



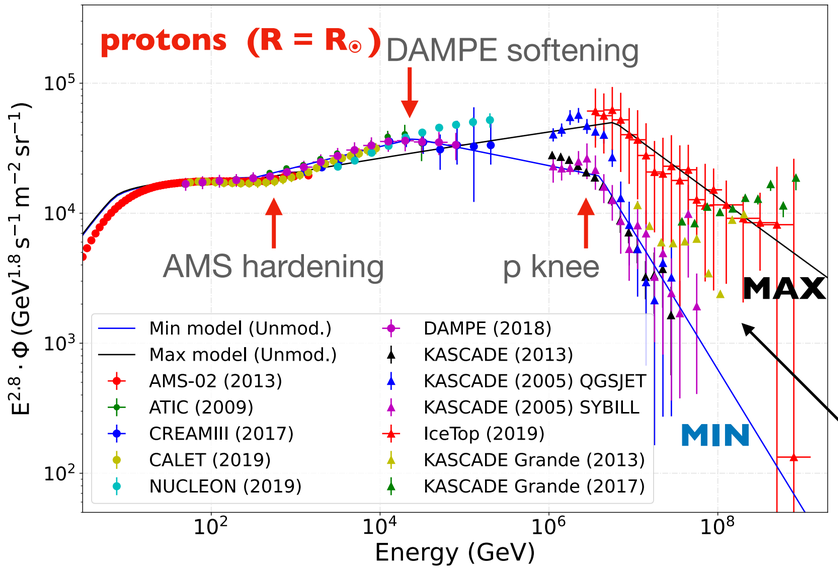


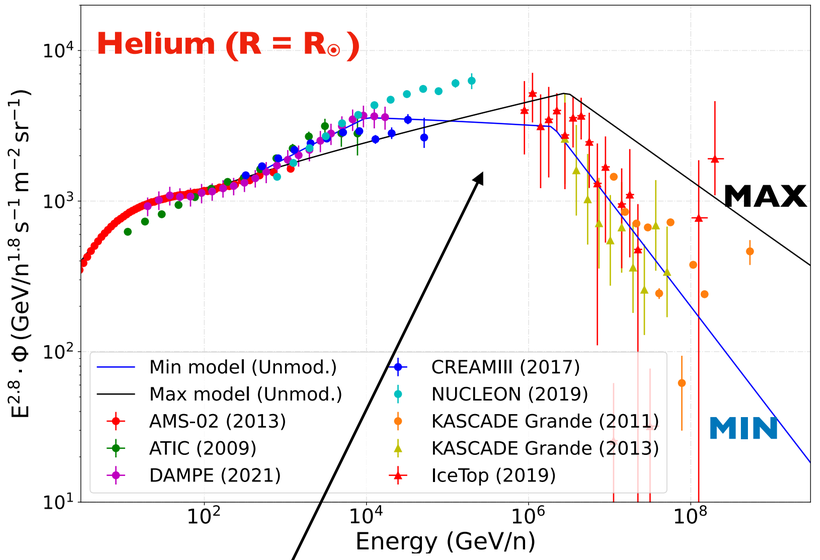
Lipari & Vernetto, 2018

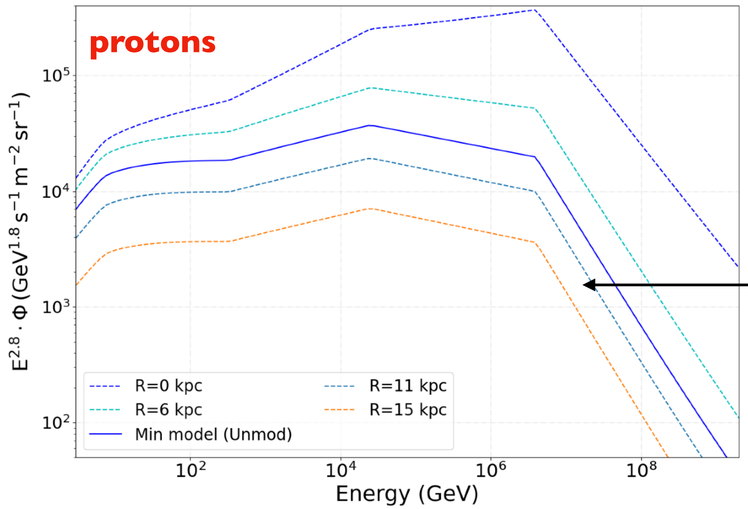


OUR NEW RESULTS: DIFFERENT FITTING STRATEGIES OF PRIMARY CR SPECTRA ABOVE 100 TEV

P. De La Torre Luque at al., 2203.15759







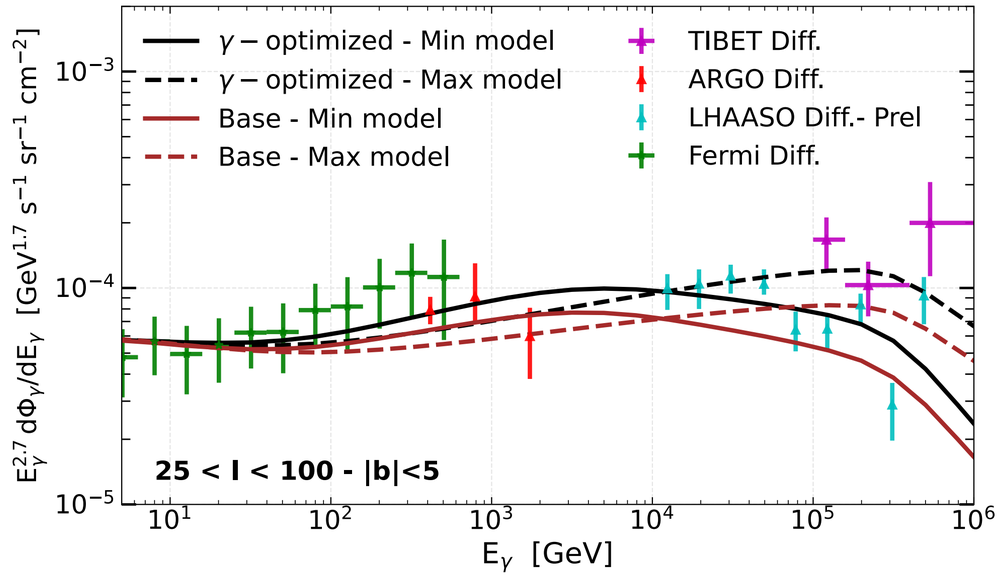
Different lines represent **local** propagated spectra that **bracket the uncertainty** in the very-high energy domain due to different results of different data analyses.

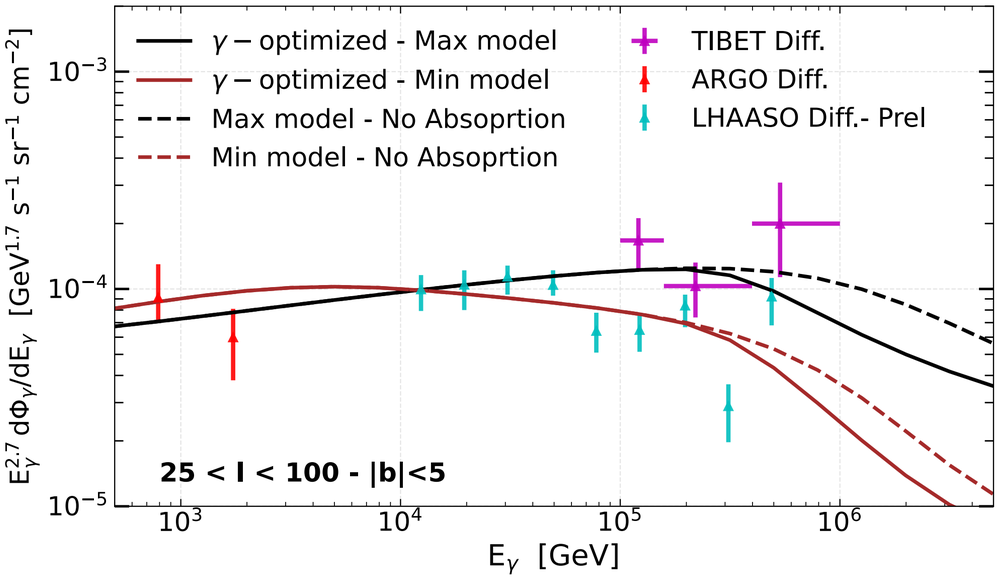
Propagated spectra at **several Galacto-centric radii** for the γ-optimized scenario

The source spectra is assumed to be the same in the whole Galaxy

OUR NEW RESULTS

Compared with Tibet and LHAASO data



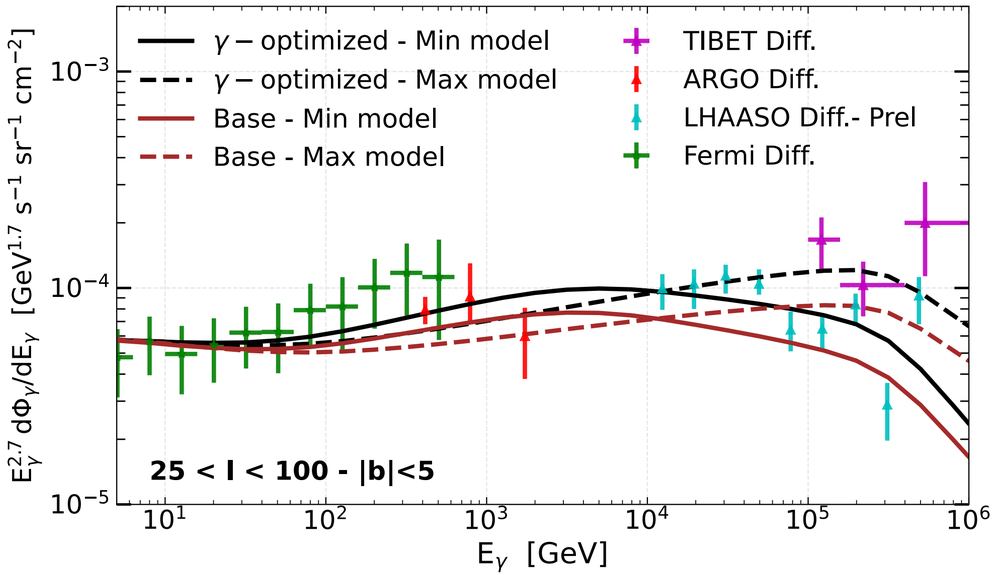


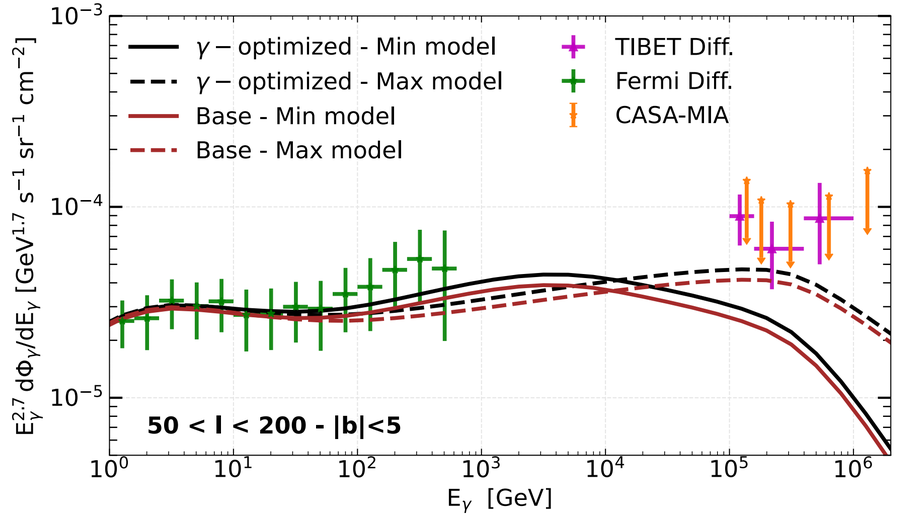
P. De La Torre Luque at al., 2203.15759

- Strong degeneracy between the CR transport scenario and the CR high-energy fit.
- LHAASO + ARGO + Fermi seems to favor the γ-optimized scenario? More accurate data certainly needed.
- γ-ray opacity due to γ-γ_{CMB} significant only for E > 100 TeV. ISRF plays negligible role.
- At large longitudes the observed spectrum is not sensitive to the details of the inner Galaxy hardening. Low-longitude data are crucial!

NEW RESULTS

Compared with Tibet and LHAASO data





P. De La Torre Luque at al., 2203.15759

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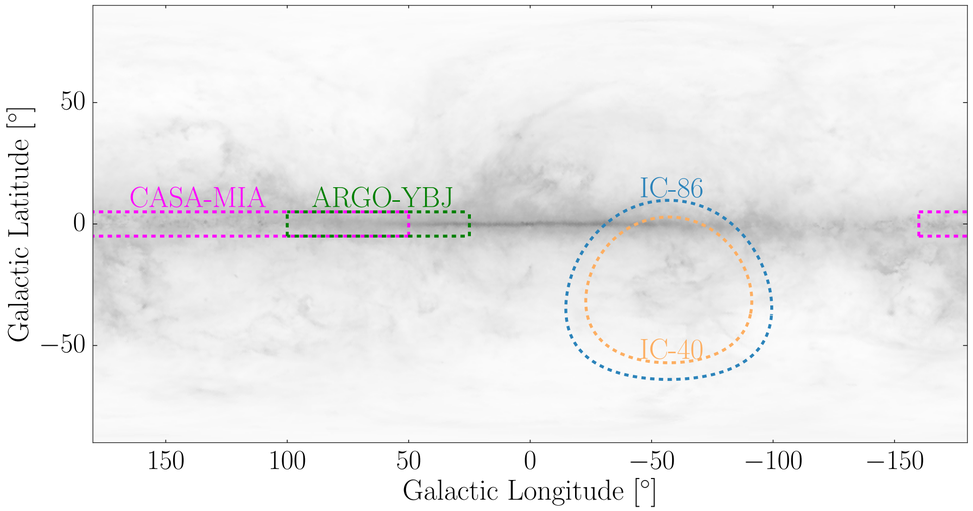
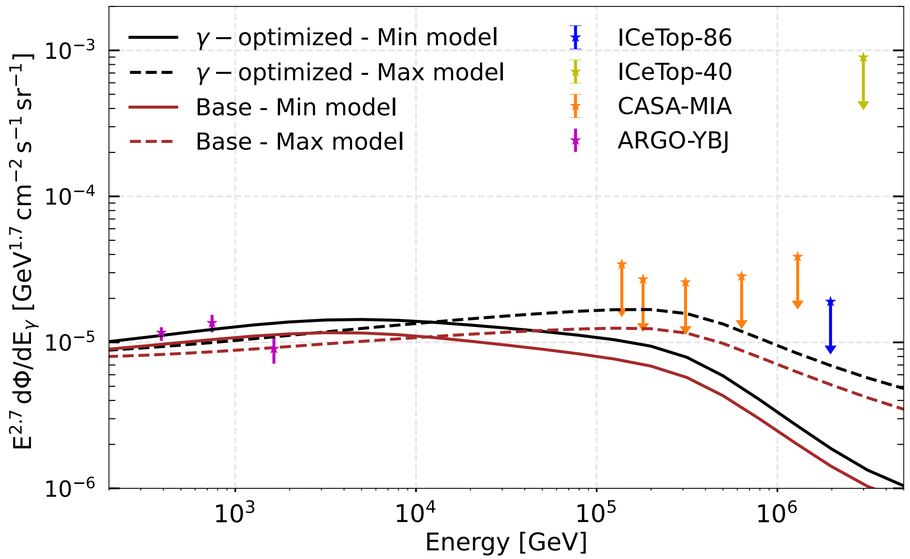
NEW RESULTS

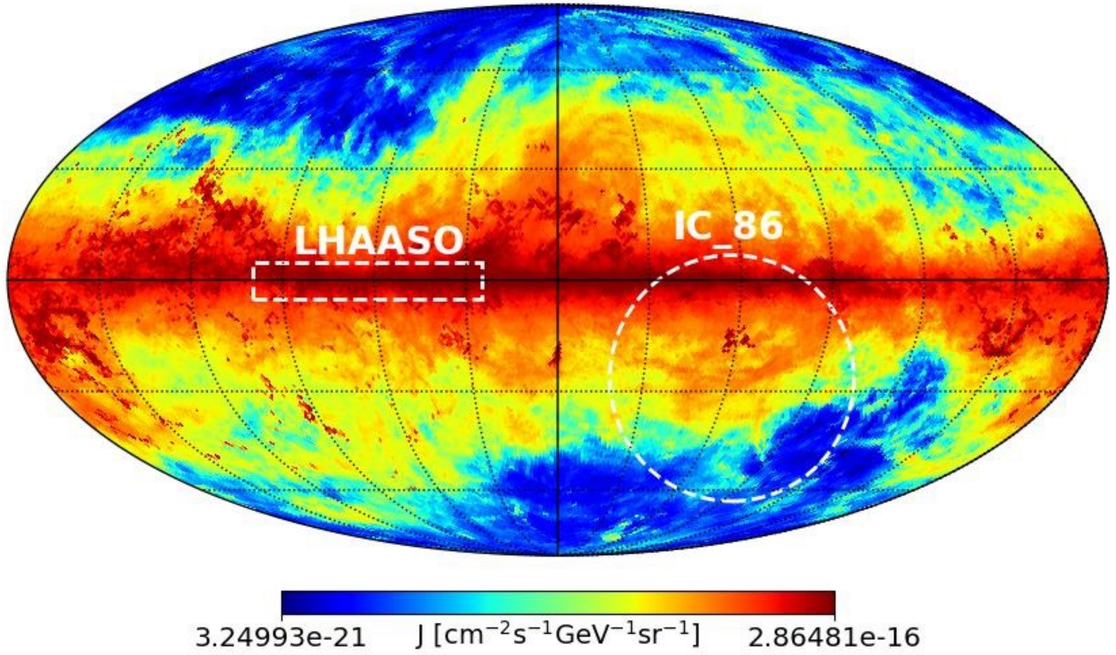
Compared with IceTop data

IceCube coll., Astrophys.J. 891 (2019) 9





100 TeV γ-ray sky simulated with HERMES



Performed with HERMES

https://github.com/cosmicrays/hermes

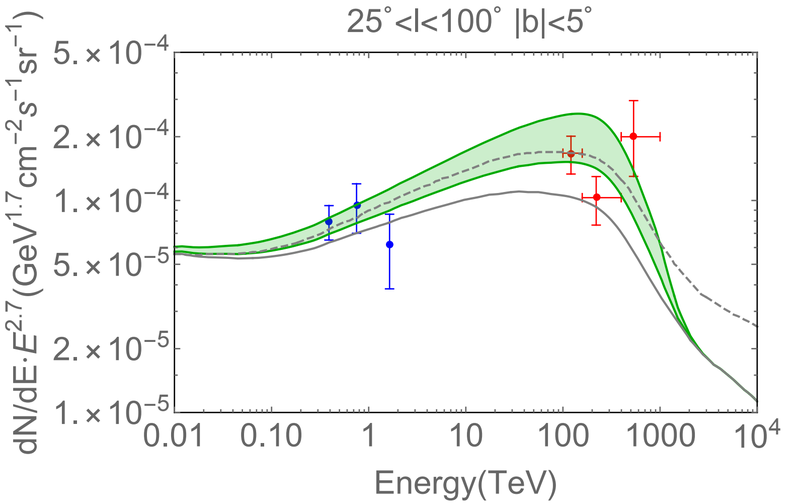
A LARGER CONTRIBUTION FROM UNRESOLVED SOURCES ?

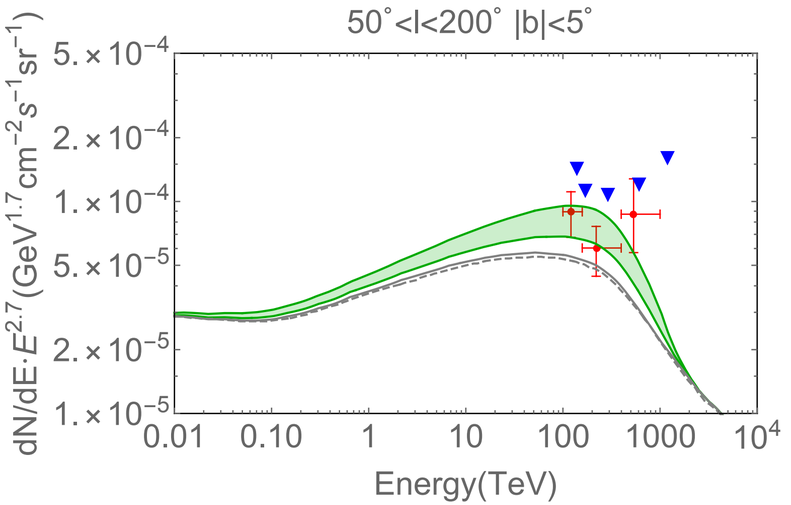
Vecchiotti et al., 2107.14584

Although unlikely (no emission from TeVCAT above 400 TeV was found) an interpretation of Tibet and LHAASO results is these terms cannot be excluded

It assumes leptonic accelerators (PWNe, TeV halos) as the main unresolved sources

It might provide a better agreement with Tibet results for $50 < l < 200$ °

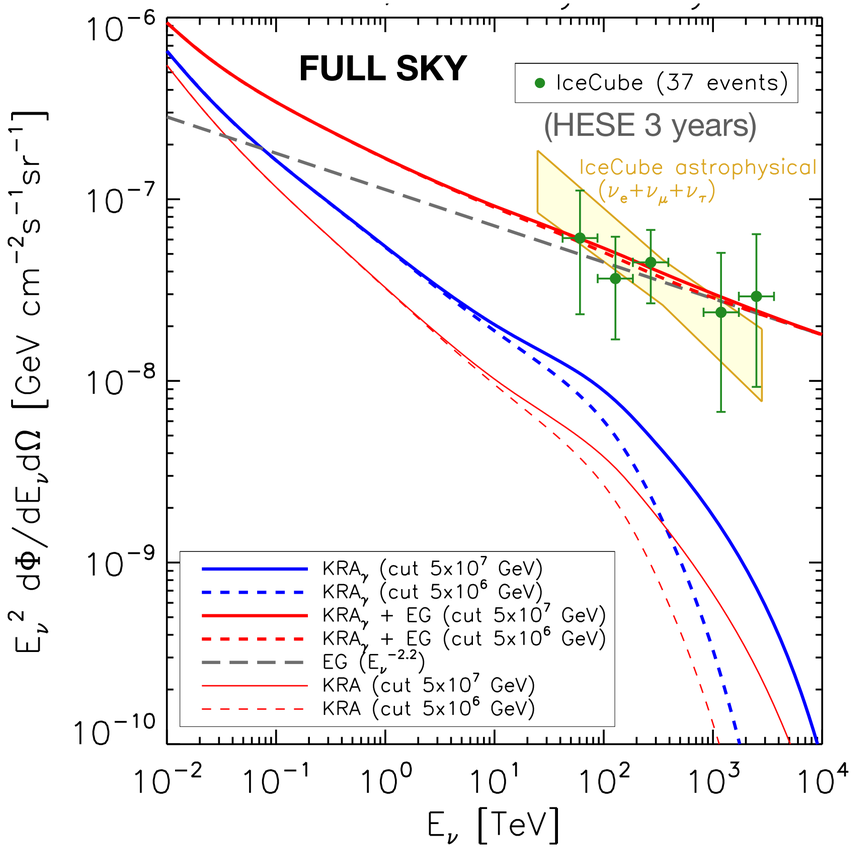


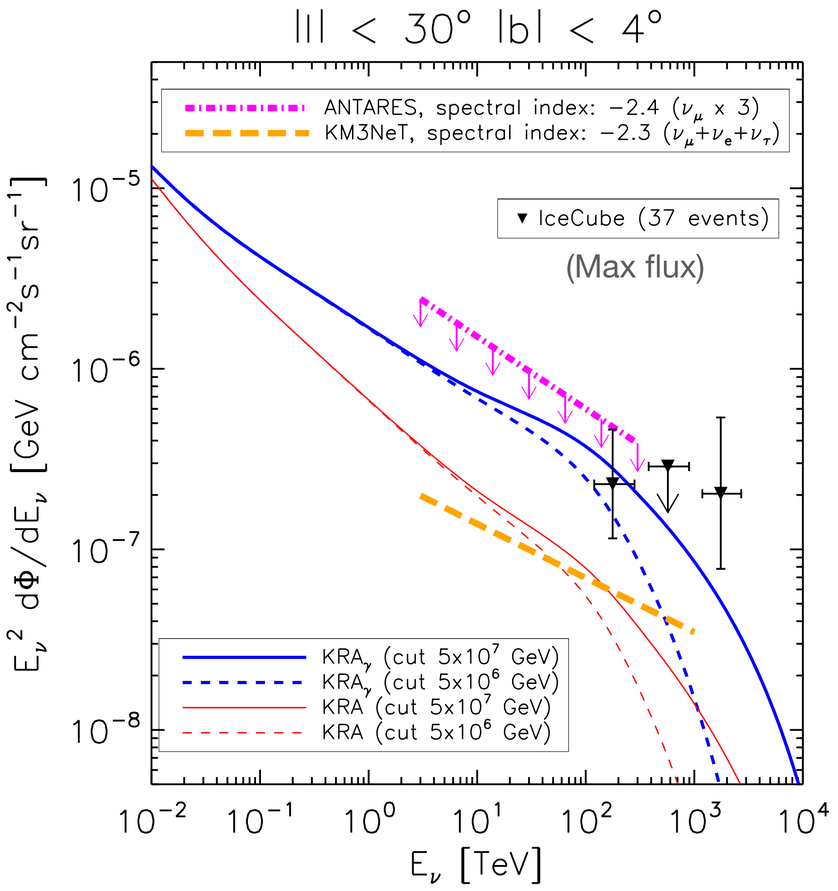


NEUTRINO DIFFUSE EMISSION FROM THE GALAXY

Gaggero, D.G., A. Marinelli, Urbano, Valli ApJ L 2015

The enhancement of the hadronic γ-ray emission predicted by the γ-optimized models must have a corresponding effect for neutrinos.
Here we show the prediction obtained with the KRAγ models in 2015.





NEUTRINOS FROM THE GP

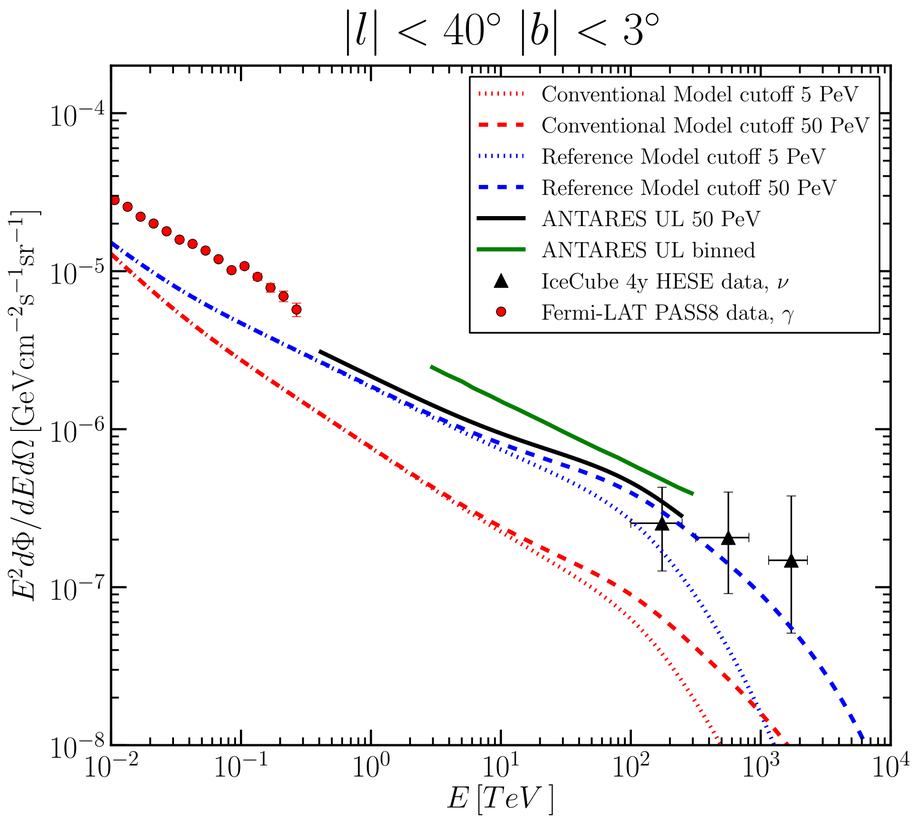
IceCube + ANTARES constraints

ANTARES coll. + DG & D.Grasso PRD 2017

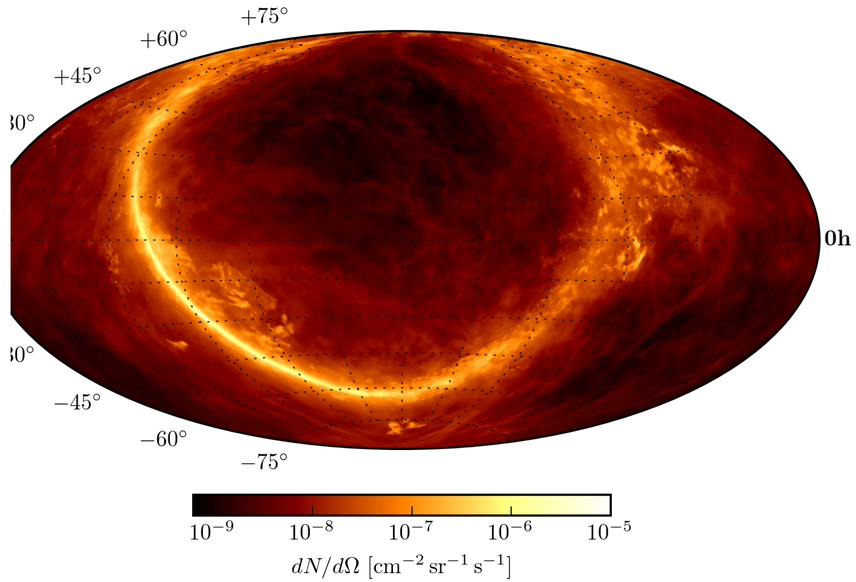
*"New Constraints on all flavour Galactic diffuse neutrino emission with the **ANTARES** telescope"* [arXiv:1705.00497]

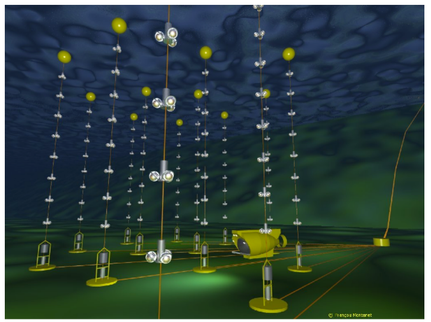
- Upper limits at 90% CL on the three flavour neutrino flux based on 9 years of ANTARES data (2007 - 2015)
- Limits are compared to *reference models* for the expected diffuse emission

Energy cut-off	μ^*	σ^*	$\mu^{\rm sh}_{\rm data}$	$\mu^{\rm tr}_{\rm data}$	p-valu
5 PeV	11.6	13	1.9	2×10^{-3}	0.67
50 PeV	13.7	12	2.6	7×10^{-4}	0.54



Maximum-liklihood analyses based on the KRAγ templates (hadronic component)





NEUTRINOS FROM THE GP

IceCube + ANTARES constraints

ANTARES + IceCube + DG & D.Gaggero ,APJ 2018

*"Joint constraints on Galactic diffuse neutrino emission from the **ANTARES** and **IceCube** neutrino telescopes"* [arXiv:1808.03531]

- Combined ULs at 90% confidence level on the three-flavor ν flux of the reference Galactic models.
- **10 years of ANTARES showers and tracks** (218 showers, 2.6 should come from KRAγ Galactic model),
- **7 years of IceCube tracks** (730130 events with 191 events expected from the optimistic Galactic model)

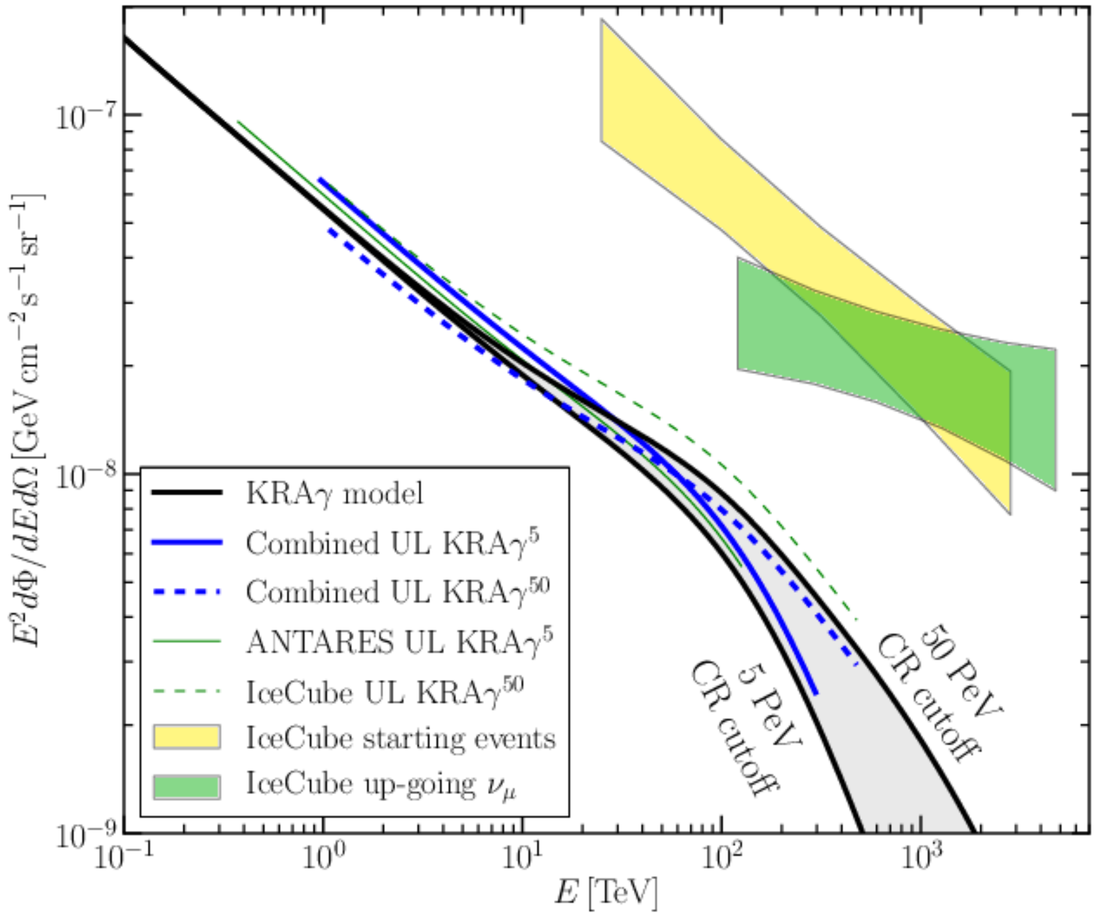


Table 1. Sensitivities and results of the analysis on the KRA$_\gamma$ models with the 5 and 50 PeV cutoffs.

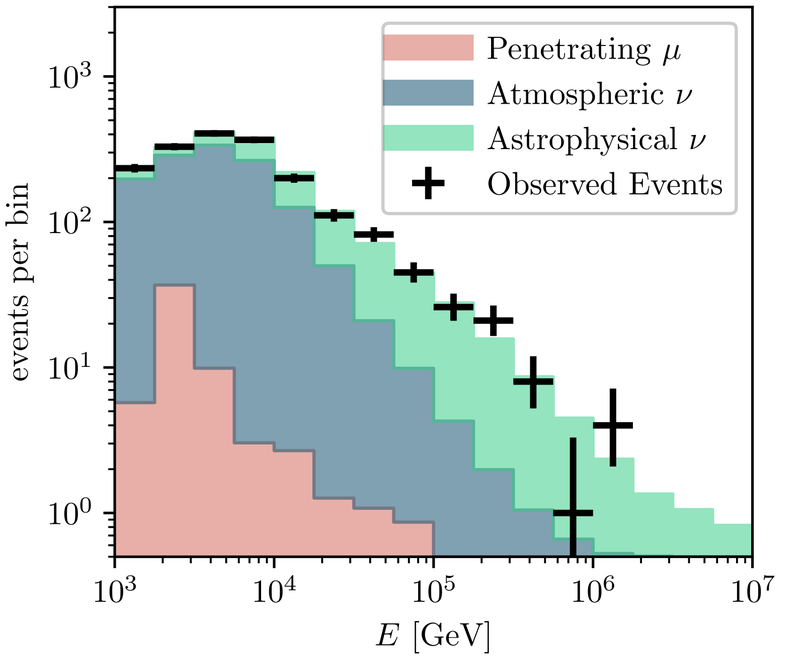
Energy cutoff	Sensitivity [$\Phi_{\mathrm{KRA}_\gamma}$]			Fitted flux	p-value	UL at 90% CL
	Combined	ANTARES	IceCube	[$\Phi_{\mathrm{KRA}_\gamma}$]	[%]	[$\Phi_{\mathrm{KRA}_\gamma}$]
5 PeV	0.81	1.21	1.14	0.47	29	1.19
50 PeV	0.57	0.94	0.82	0.37	26	0.90

NEUTRINOS FROM THE GP

IceCube + ANTARES constraints

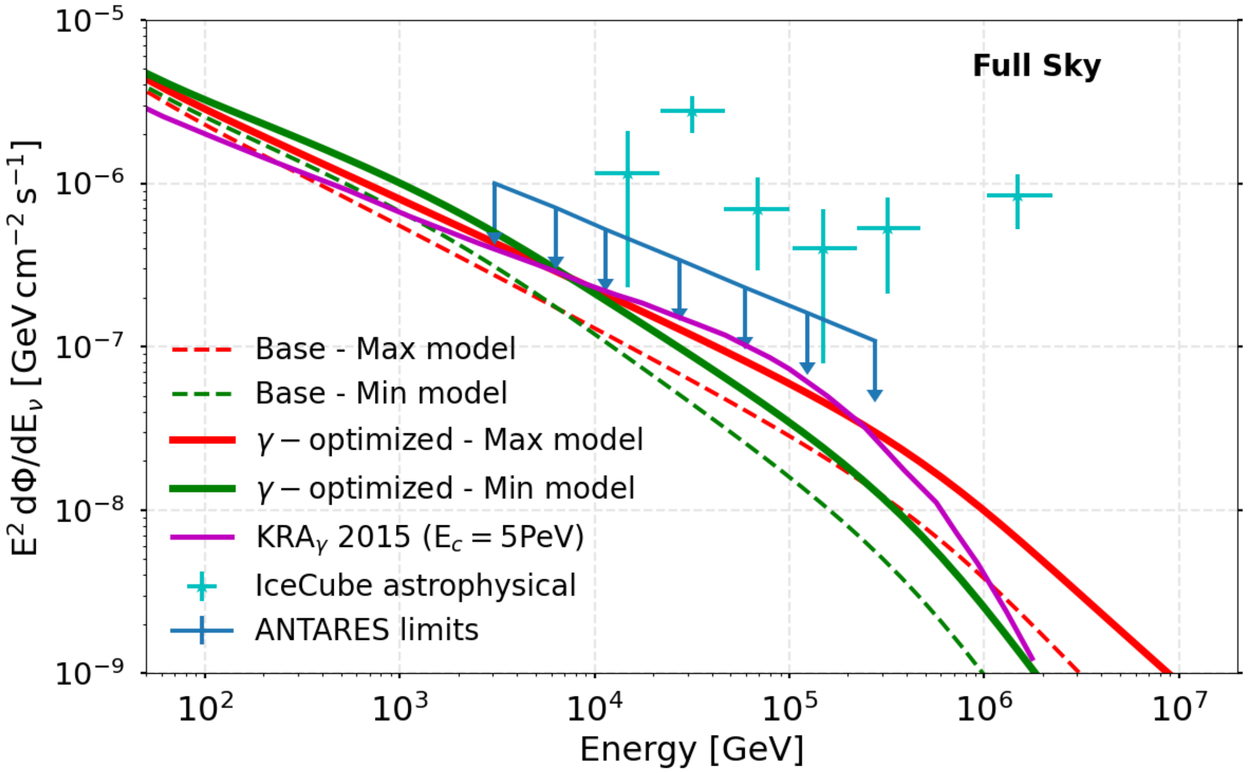
*"Search for Sources of Astrophysical Neutrinos Using Seven Years of **IceCube Cascade** Events"* [arXiv:1907.06714]

- Analysis of **seven years** of IceCube *cascade* data (interaction vertex inside the detector) in order to search for high energy neutrino emission from a number of Galactic astrophysical source candidates
- No detection confirmed, however some relevant hints
- The most significant source was RX J1713.7-3946, a well-known SNR. Post-trial p-value = 0.28
- **2σ hint for a Galactic component** consistent with the optimistic "Gamma" models
- Compare with another **2σ hint for a Galactic component in the HESE data above 100 TeV** [IceCube ICRC contributions, 1710.01191]



PREDICTIONS WITH THE UPDATED MODELS

De La Torre Luque, DG, Gaggero, Marinelli, accepted by Frontiers



- The predictions of the old KRAγ^5 are very close to those of the γ-optimized Max.
- If IceCube were to detect evidence for GP emission compatible with those models, the spatial-dependent propagation models would be favoured.

CONCLUSIONS

- Tibet ASγ and LHAASO (if confirmed) provided the first evidence of γ-ray diffuse emission from the Galactic plane up to the PeV.
- We showed that their results are naturally consistent with Fermi-LAT and ARGO-YBJ if the emission is originated by the galactic CR population
- Our results seems to favour a space-dependent CR transport scenario though, due to the uncertainties in the source spectrum above the 100 TeV, a solid confirmation requires more data especially at low Galactic longitudes.
- IceCube and KM3Net may soon provide stronger and complementary pieces of evidence of that scenario with strong implications for CR physics