Diffuse high energy astrophysical neutrino flux and galactic contributions

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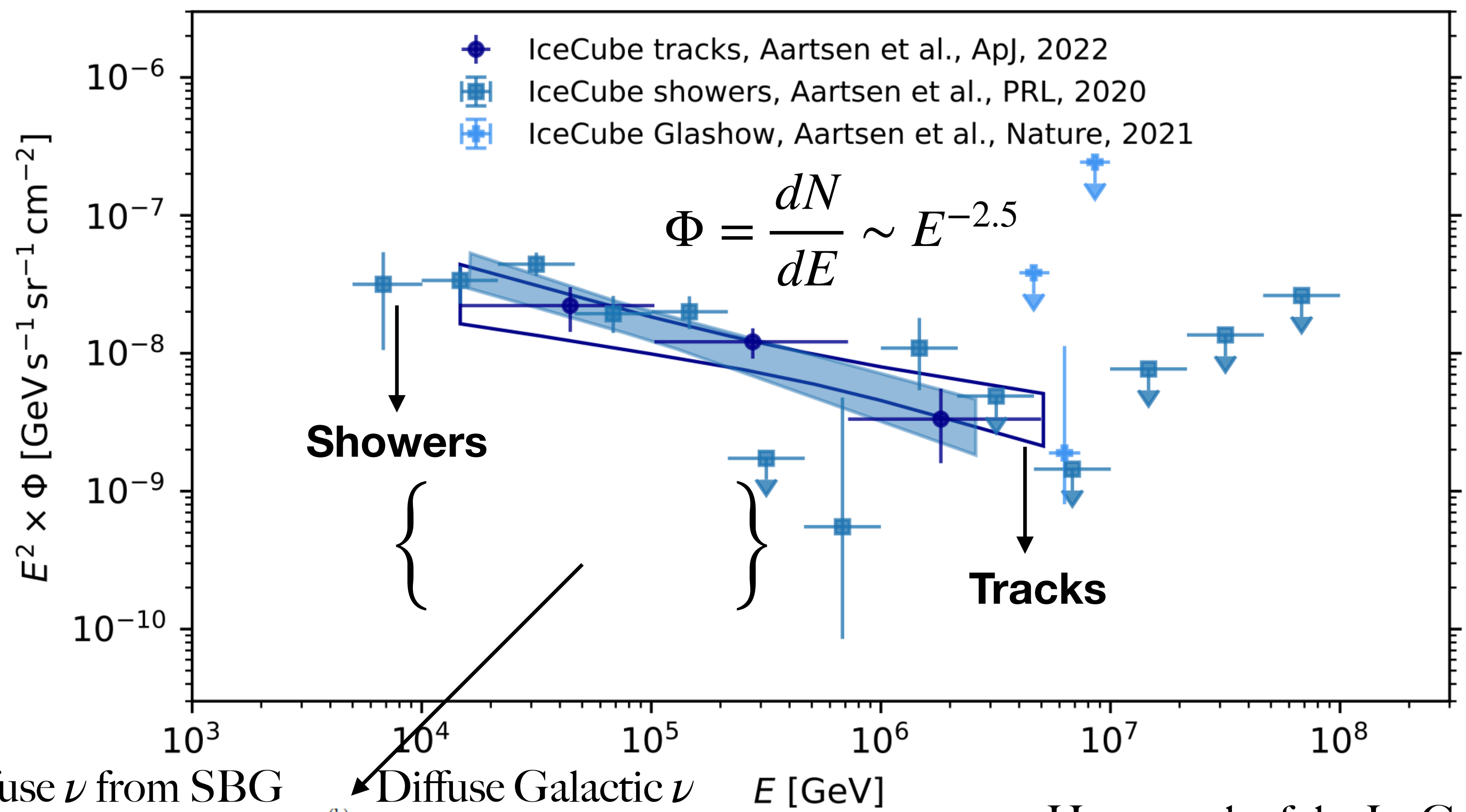
23-27/09/2024

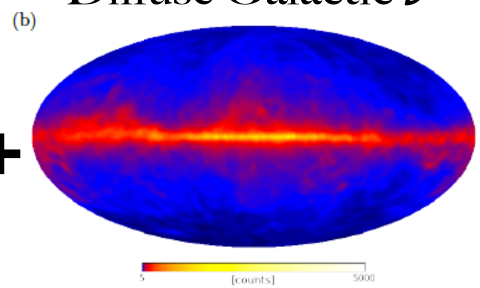
Setting the multicomponent energy ranges



Diffuse ν from SBG

Diffuse Galactic ν

+



How much of the IceCube neutrinos can be related to non-AGN-galaxy emission.
Is the Milky Way a real neutrino desert?

Hadronic production in the SBGs

p-p interaction is likely to occur when
density of gas higher than density of radiation
(for example in Starburst Galaxies)

The Starburst Galaxy M82

Credit:
NASA, ESA and the Hubble Heritage Team (STScI/AURA). Acknowledgment: J. Gallagher (University of Wisconsin), M. Mountain (STScI) and P. Puxley (NSF).

Properties of SBGs

- **~100 Myr phase** in the life of a Galaxy
- High Star Formation Rate **(10-100 times higher than Milky Way),** mainly concentrated into the nucleus
- They are abundant **(~10^4 — 10^5 Gpc^{-3})**
- Strong Magnetic field 10^2-10^3 μ**G** and high degree of magnetic turbulence which traps protons for ~ 10^5 years (**Reservoirs**)
- Not very brilliant in gamma-rays **(only a small portion currently observed)**

Starburst Galaxies properties

Interstellar gas as the target

$$p + p \rightarrow \pi^+ \pi^- \pi^0 \ldots$$

✦ **Neutrinos** and **γ-rays** from pions decays:

$$\pi^\pm \rightarrow e^\pm \nu_e \nu_\mu \overline{\nu}_\mu$$
$$\pi^0 \rightarrow \gamma\gamma$$

Leaky-box-like model for CR transport

$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)} + \frac{1}{\tau_{\rm adv}(p)} + \frac{1}{\tau_{\rm diff}(p)}\right) = Q(p)$$

injected CR from SN explosion

E.Peretti et al. MNRAS 2019

$$Q(p) \propto \left(\frac{p}{m_p}\right)^{-\alpha} \cdot e^{-p/p_{\rm max}}$$

CR acceleration up to the knee in Supernovae Remnants

- $$\tau_{\rm loss} \simeq \tau_{\rm pp} \propto \frac{1}{n_{\rm ISM}}$$

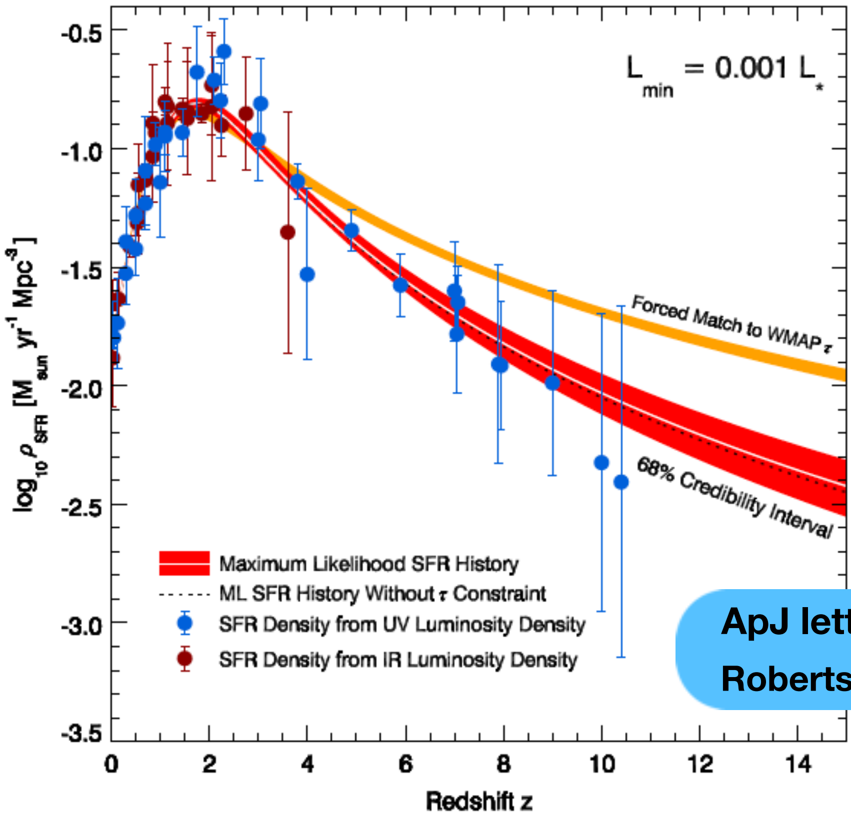
Tloss > Tesc in the core

- The denser the SBN, the more the energy losses affects the CR transport

- $\tau_{\rm adv} = R/v_{\rm wind}$
- $\tau_{\rm diff} = R^2/D$

$R_{\rm SBN} = 200\,{\rm pc}$ $v_{\rm wind} = 500\,{\rm km/s}$

Star formation rate can trace the ν emission



ApJ letter 2015
Robertson et al.

Important to estimate the diffuse ν emission of this galaxies population, we can follow the star formation density along the distance considered.

A proposed multimessenger fit

The Gamma-Ray Contributions:

1. SBGs
2. Blazar + Electromagnetic Cascades
3. Radio Galaxies

For Blazars and Radio Galaxies, we used the estimations given by Ajello et al. 2015 (ArXiv: 1501.05301)

The Neutrino Contributions:

1. SBGs
2. Blazars

For Blazars, we used the estimations given by Palladino et. Al 2019 (ArXiv:1806.04769)

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

Observational Samples Used

Extragalactic gamma-ray Background (EGB)

1. **7.5 years HESE**
2. **6 years Cascades**

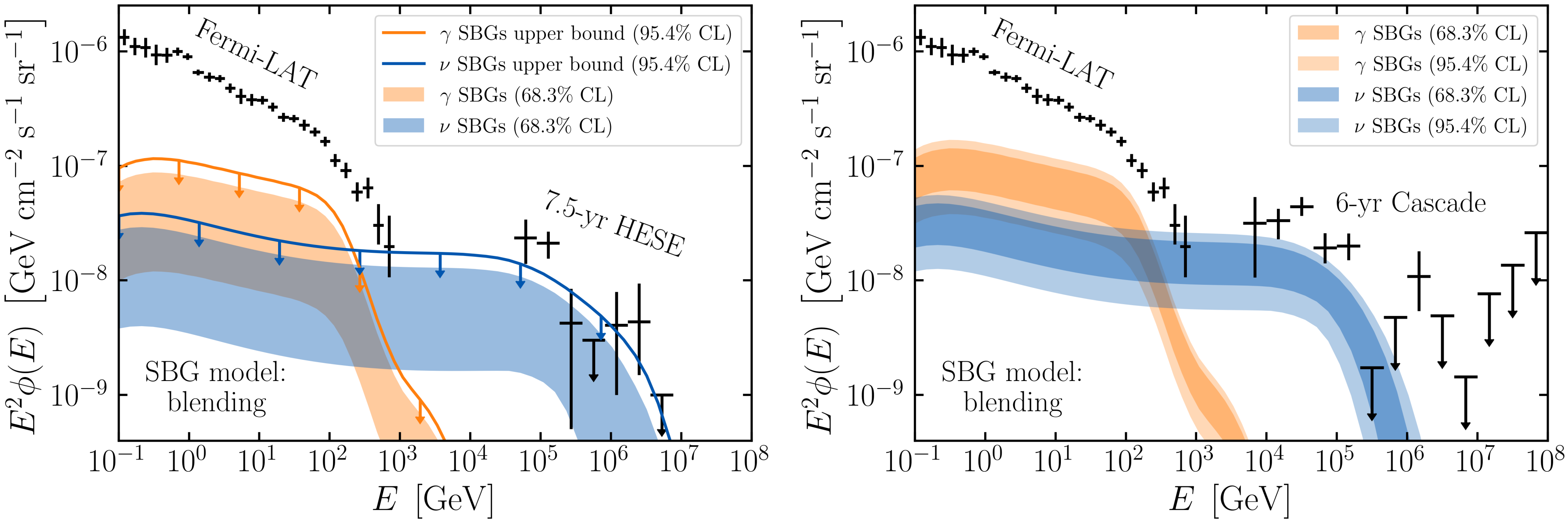
$$\chi^2_{\nu+\gamma}(N_{SBG}, N_{RG}, N_{Blazars}, p^{max}) = \chi^2_\nu + \chi^2_\gamma + \left(\frac{N_{Blazars}-1}{0.26}\right)^2 + \left(\frac{N_{RG}-1}{0.65}\right)^2 + \left(\frac{N_{Blazars}-0.80}{0.11}\right)^2$$

They come from uncertainties of the Non-SBG components

It comes from the positional limit of Point Sources above 50 GeV (Lisanti et al. 2016)

A proposed multimessenger fit

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti



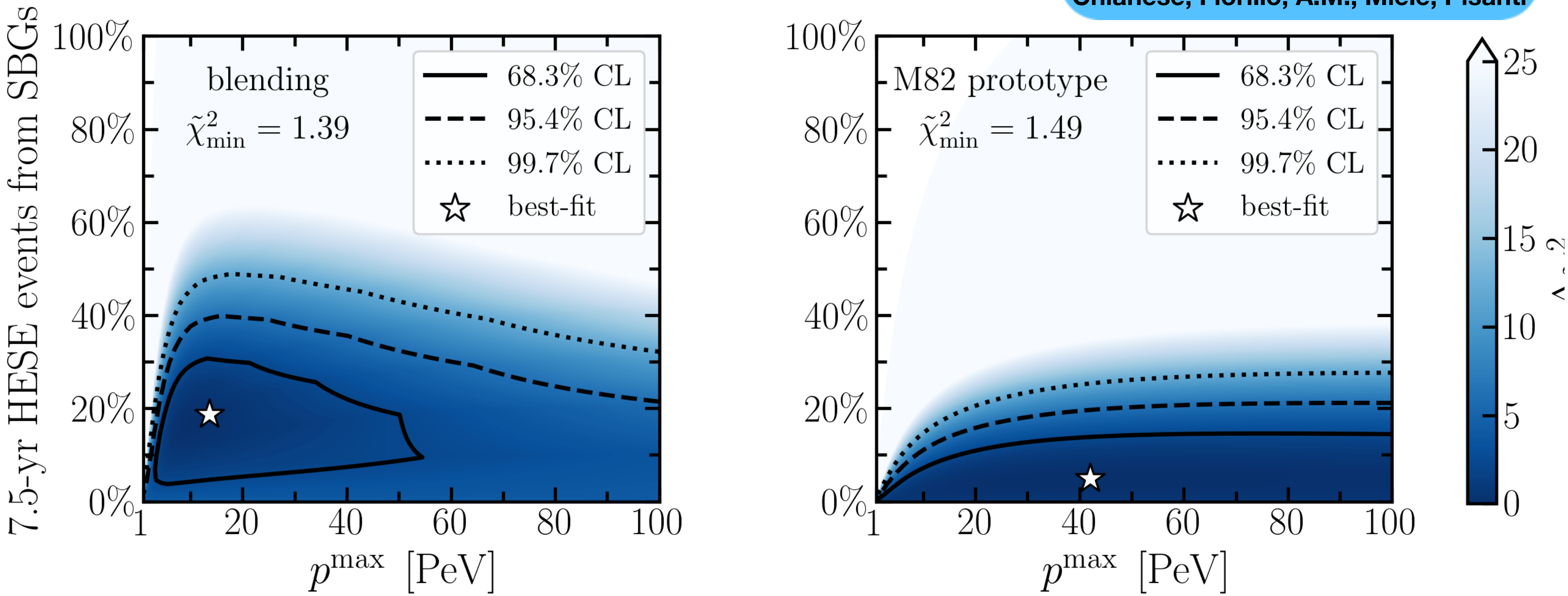
2 sigmas allowed SED considering Fermi-LAT EGB and IceCube HESE data

2 sigmas allowed SED considering Fermi-LAT EGB and IceCube CASCADE data

A proposed multimessenger fit

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

Redshift interval: $0 \leq z \leq 4.2$



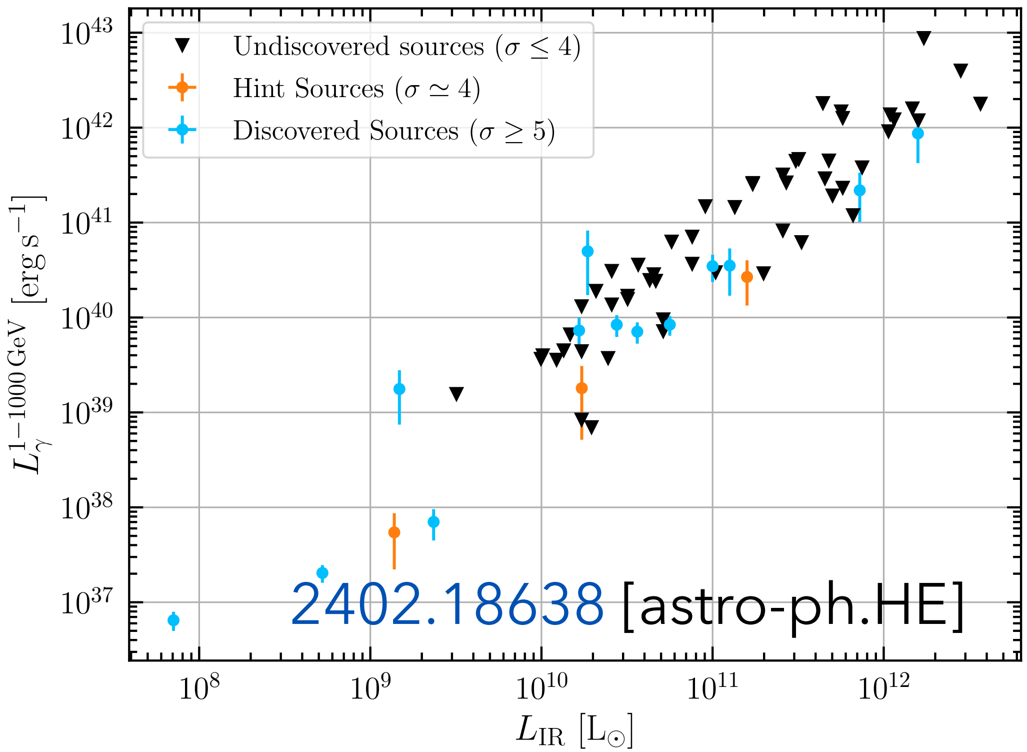
At 2 sigma level the "blending" scenario can account up to 40% of IceCube HESE measured flux, moreover at 1 sigma a Pmax up to 50 PeV is permitted, however a cutoff ~ 10 PeV is favored.

Relation star-formation and γ-rays luminosity

There is a tight correlation between the γ-ray luminosity and the Infrared (IR) Luminosity

Redshift interval: $0 \leq z \leq 8$

Analysing a catalogue of 70 sources with 15 years of Fermi-LAT data



A new analysis

The IR Luminosity is strictly connected to the Star Formation Rate (SFR)

$$\mathrm{SFR} = 1.36 \cdot 10^{-10} \left(\frac{\mathrm{L_{IR}}}{\mathrm{L}_\odot}\right)\left(1 + \sqrt{\frac{10^9 \mathrm{L}_\odot}{\mathrm{L_{IR}}}}\right) [\mathrm{M}_\odot\, \mathrm{yr}^{-1}]$$

- The higher the SFR, the more CRs get injected in SBG disk
- The higher the SFR, the more dense the system is and the CRs are trapped into the system **(Complete CR calorimetry)**

JCAP08(2024)040 Ambrosone, Chianese, + A.M.

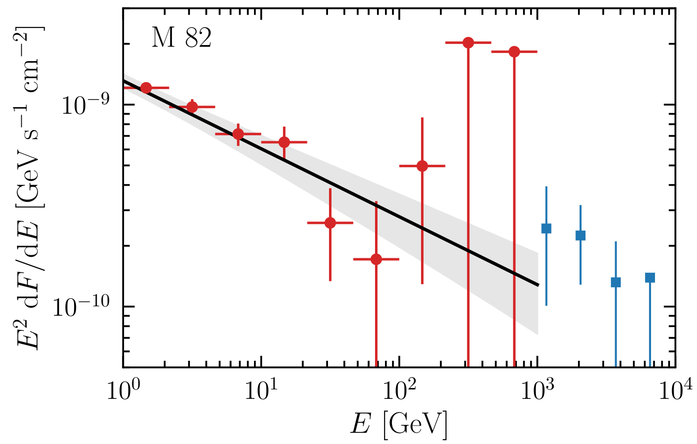
Properties of Discovered Sources

14 sources are discovered with more than 5σ (TS > 25)

$E_\gamma \in [1 - 1000]$ GeV

Take a look at 2402.18638 [astro-ph.HE]

Source	D_L [Mpc]	L_{IR} [10^{10} L$_\odot$]	$F_{1-1000\,\mathrm{GeV}}$ [10^{-10} ph cm^{-2} s^{-1}]	ϕ_0 [10^{-12} MeV^{-1} cm^{-2} s^{-1}]	γ	TS (σ)	TS$_{SM}$
M 82	3.53	5.6	9.8 ± 0.5	1.31 ± 0.10	2.34 ± 0.06	1104 (33)	0.35
NGC 253	3.56	3.6	8.1 ± 0.9	1.08 ± 0.10	2.33 ± 0.08	730 (27)	1.03
ARP 220	84.3	$1.7 \cdot 10^2$	1.6 ± 0.6	$(2.0 \pm 0.7) \cdot 10^{-1}$	2.2 ± 0.2	50 (7.1)	–
NGC 1068	10.1	10.0	4.5 ± 0.5	$(5.8 \pm 0.9) \cdot 10^{-1}$	2.28 ± 0.15	238 (15)	–
Circinus	4.21	1.7	5.1 ± 1.3	$(6.2 \pm 1.7) \cdot 10^{-1}$	2.23 ± 0.14	78 (8.8)	–
SMC	0.06	$7.1 \cdot 10^{-3}$	$(3.0 \pm 0.3) \cdot 10^1$	4.4 ± 0.3	2.44 ± 0.06	801 (28)	4.13
M 31	0.77	$2.3 \cdot 10^{-1}$	3.1 ± 0.8	$(6.3 \pm 1.3) \cdot 10^{-1}$	3.0 ± 0.3	74.6 (8.6)	0.22
NGC 2146	17.2	12.6	1.3 ± 0.5	$(1.5 \pm 0.5) \cdot 10^{-1}$	2.16 ± 0.18	41.5 (6.4)	–
ARP 299	48.6	72.6	1.3 ± 0.5	$(1.7 \cdot 0.6) \cdot 10^{-1}$	2.3 ± 0.2	46.4 (6.8)	–
NGC 4945	3.72	2.8	9.6 ± 1.3	1.34 ± 0.15	2.40 ± 0.08	412 (20)	–
NGC 2403	3.18	0.15	1.5 ± 0.5	$(10 \pm 4) \cdot 10^{-2}$	1.92 ± 0.17	52.8 (7.3)	–
NGC 3424	27.2	2.1	10 ± 5	$(1.3 \pm 0.5) \cdot 10^{-1}$	2.3 ± 0.3	28 (5.3)	–
LMC	0.05	$5.2 \cdot 10^{-2}$	$(1.38 \pm 0.07) \cdot 10^2$	$(1.85 \pm 0.08) \cdot 10^1$	2.41 ± 0.04	1493 (38)	0.24
M 33	0.91	0.14	$1.2 \pm 0.6^\dagger$	$(1.8 \pm 0.7) \cdot 10^{-1}$	2.5 ± 0.3	16 (4)	–



Two sources have a strong hint of γ-ray emissions($\sim 4\sigma$)

M83, NGC 1365

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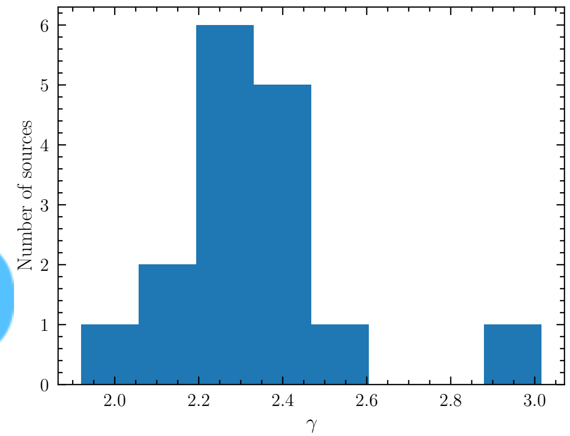


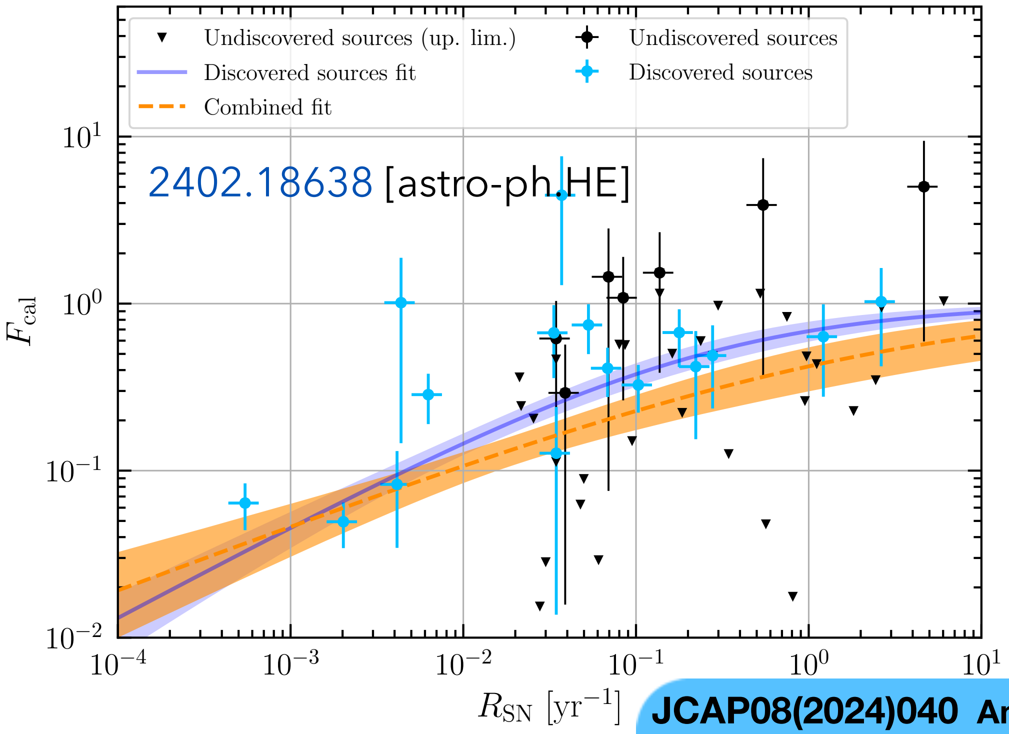
- All spectra are consistent with simple power-laws

Calorimetric Fraction and Star Formation Rate

$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)}+\frac{1}{\tau_{\rm adv}(p)}+\frac{1}{\tau_{\rm diff}(p)}\right)=Q(p) \;\Rightarrow\; f(p)\simeq Q(p)\tau_{pp}F_{\rm cal}$$

$F_{\rm cal}$: Fraction of CRs which actually interact and produce γ and ν

Average $F_{\rm cal}$ between $10-10^4\,{\rm GeV}$ for CRs



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$$R_{\rm SN}[{\rm yr}^{-1}]\simeq\frac{1}{83}{\rm SFR}[{\rm M}_\odot\,{\rm yr}^{-1}]$$

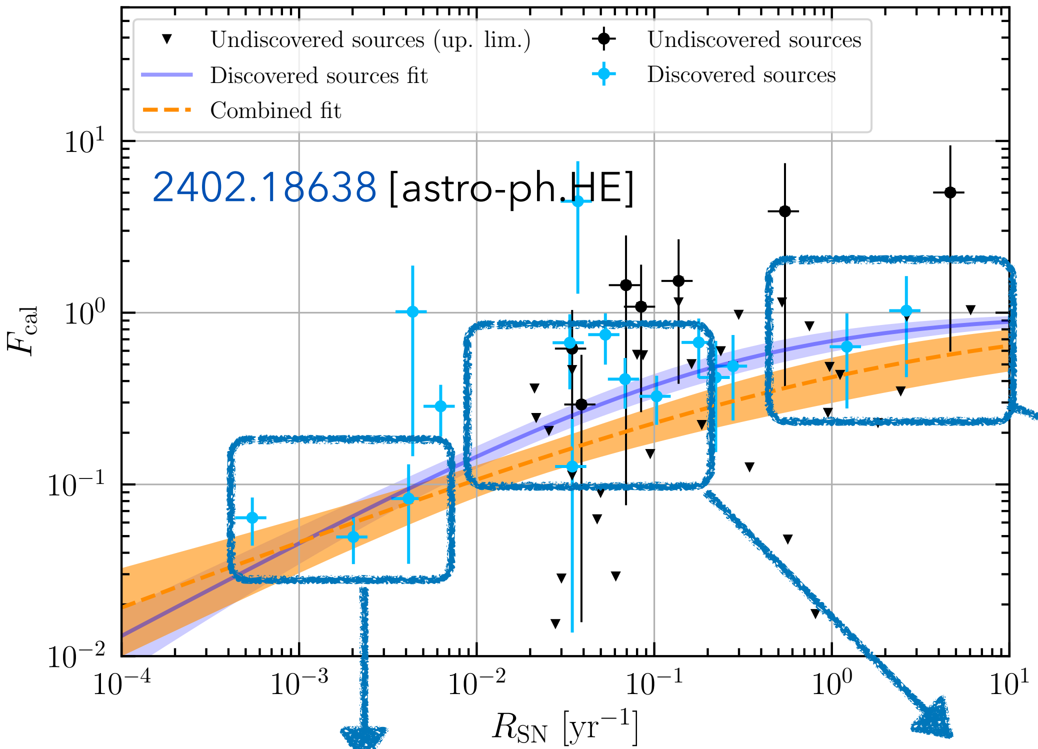
$F_{\rm cal}$ correlates with the SFR and the Supernovae explosion rate

$$F_{\rm cal}=A\left(\frac{R_{\rm SN}}{{\rm yr}^{-1}}\right)^{\beta}\left(1+A\left(\frac{R_{\rm SN}}{{\rm yr}^{-1}}\right)^{\beta}\right)^{-1}$$

$$A=0.7^{+0.3}_{-0.2}\quad\beta=0.39\pm0.07$$

Calorimetric Fraction and Star Formation Rate

Average $F_{\rm cal}$ between $10 - 10^4\,\mathrm{GeV}$ for CRs



$$F_{\rm cal} = A\left(\frac{R_{\rm SN}}{\mathrm{yr}^{-1}}\right)^{\beta}\left(1 + A\left(\frac{R_{\rm SN}}{\mathrm{yr}^{-1}}\right)^{\beta}\right)^{-1}$$

$$A = 0.7^{+0.3}_{-0.2} \quad \beta = 0.39 \pm 0.07$$

Powerful Starburst: ARP 299, ARP 220
$\mathrm{SFR} \sim 80 - 200\,\mathrm{M_\odot\,yr^{-1}}$

At low SFR, the local galaxies dominated (SMC,LMC, M31, M33)
$\mathrm{SFR} \sim 10^{-2} - 10^{-1}\,\mathrm{M_\odot\,yr^{-1}}$

Mild Starburst: M82, NGC 253, NGC 1068
$\mathrm{SFR} \sim 5 - 20\,\mathrm{M_\odot\,yr^{-1}}$

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Diffuse Fluxes and Neutrinos

The emission from all SBGs in the Universe

$$\phi^{\rm diff}_{\gamma,\nu} = \frac{c}{4\pi H_0}\int_0^{z_{\rm max}} \frac{{\rm d}z}{E(z)}\int_{10^6 L_\odot}^{\infty} \frac{{\rm d}L_{\rm IR}}{\ln(10)\, L_{\rm IR}} \mathcal{S}_{\rm SFR}(L_{\rm IR}, z) \times Q_{\gamma,\nu}\left(E(1+z), {\rm R_{SN}(L_{IR})}, {\rm F_{cal}(R_{SN}(L_{IR}))}\right)\; e^{-\tau_{\gamma,\nu}(E,z,L_{\rm IR})}$$

$E_{\rm max}$ assumed is $10\,{\rm PeV}$

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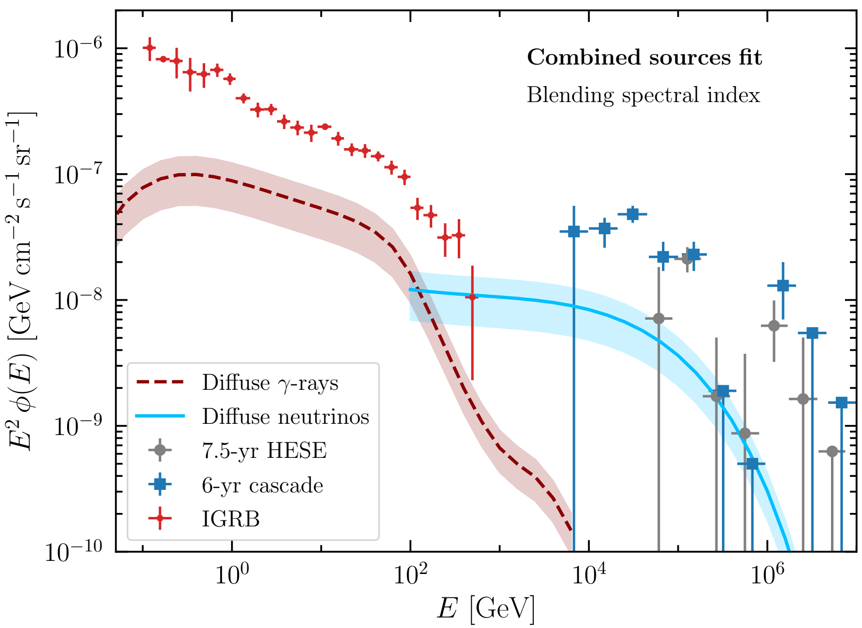
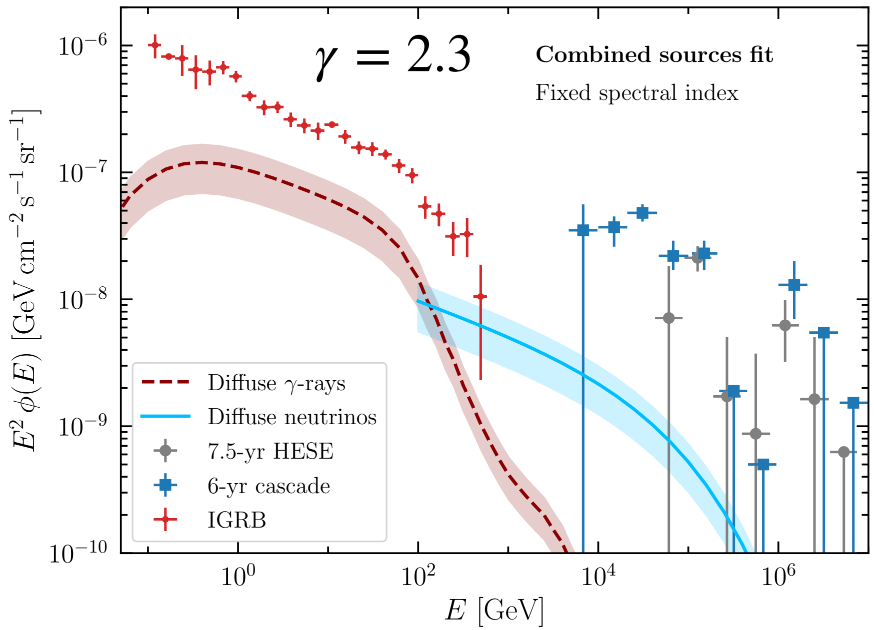


- The blending scenario increases the neutrino flux ($\sim 20\,\%$ of the IceCube measurements)



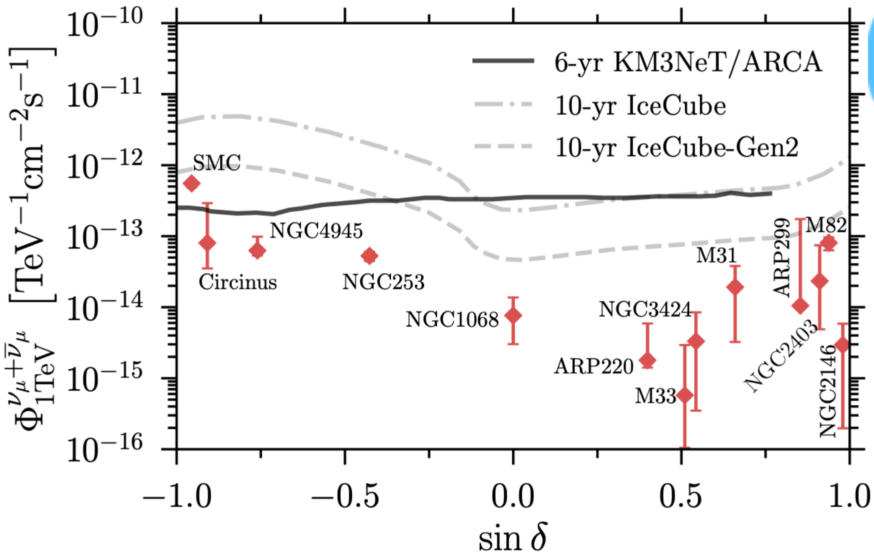
- The neutrino flux is constrained to be $\sim$ % of the IceCube diffuse Fluxes

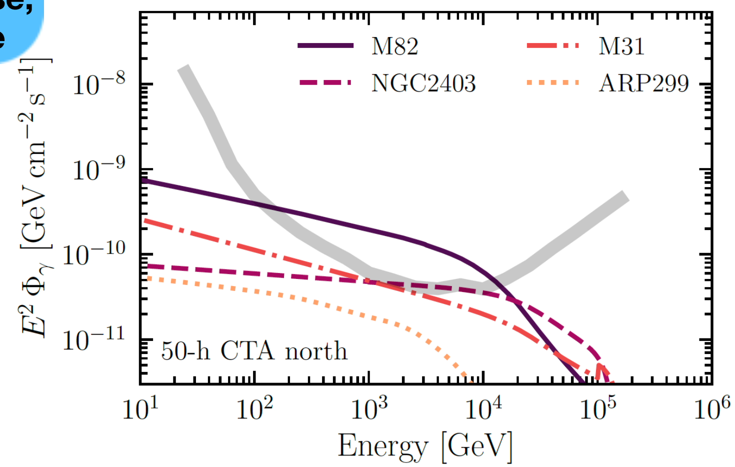
Probing the SBG Calorimetric Scenario

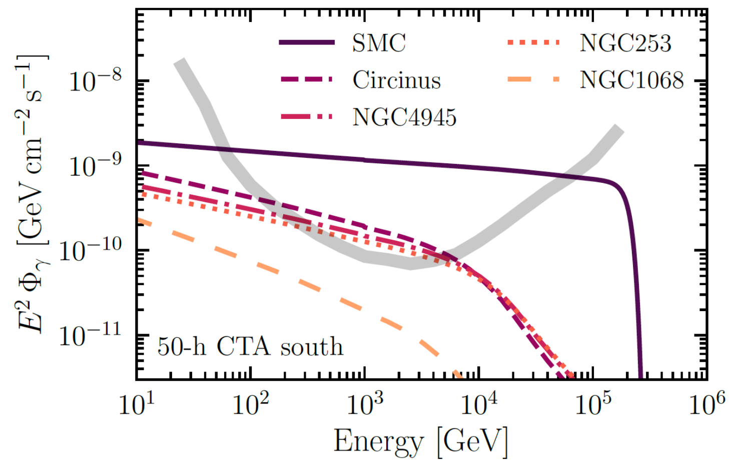
Tracing Neutrino Emission from Local resolved SFGs

Neutrino Expectations: KM3NeT Forecast Gamma-Rays Expectations. CTA Forecast

ApJL 919 2021
Ambrosone, Chianese, Fiorillo, A.M., Miele



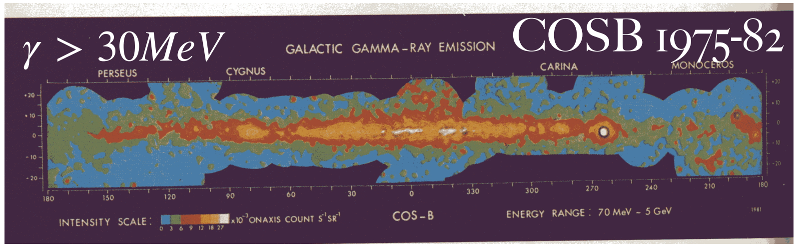


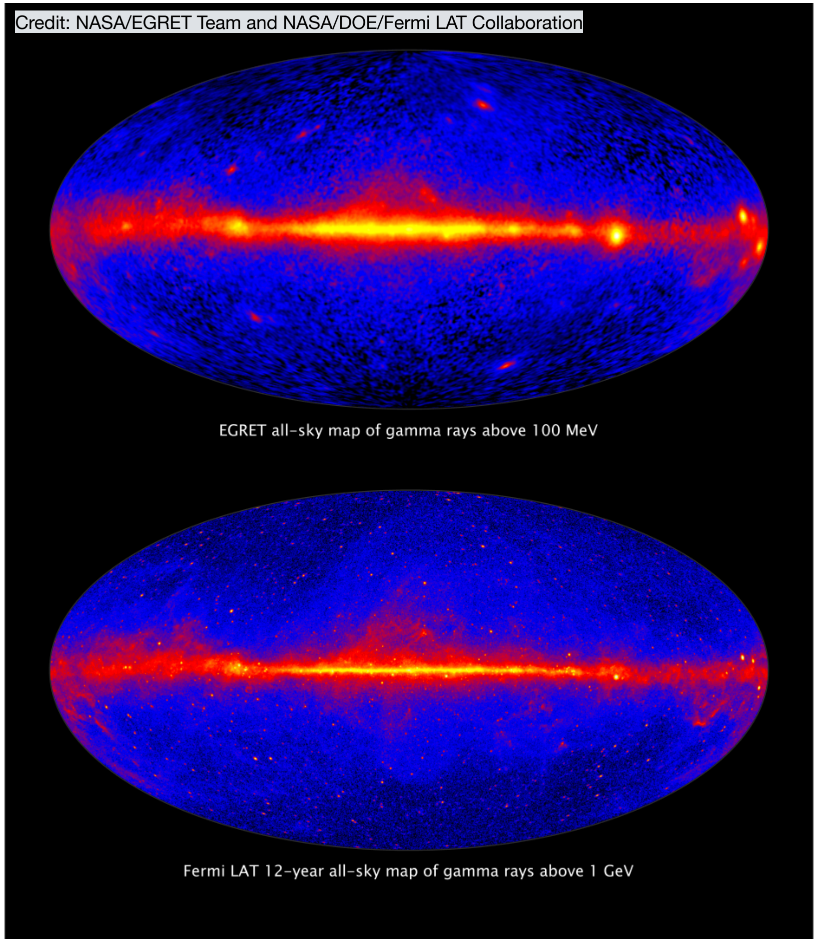


Future γ/ν observations will be fundamental to:

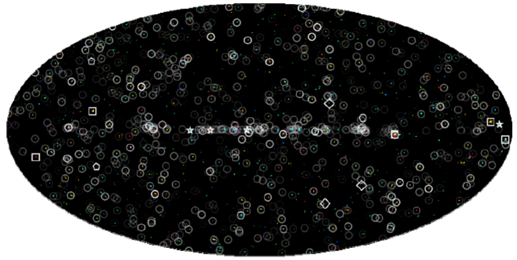
- ✦ Discover if Neutrino Astronomy is a tracer for star-forming activity
- ✦ Probe the calorimetric fraction inside SBG: If there will be no detection, nearby SBGs are dominated by diffusion and not by either p-p collisions or advection.

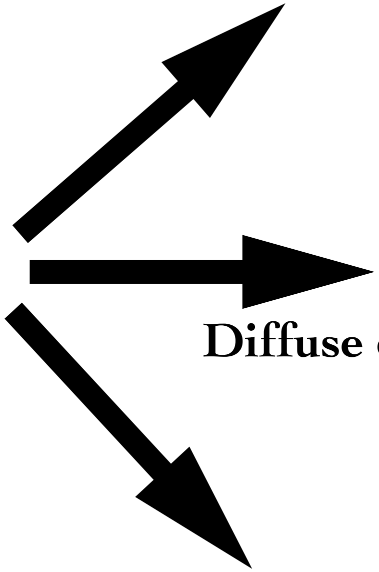
Gamma-ray emission from the Milky Way





Selig et al. A&A 2014



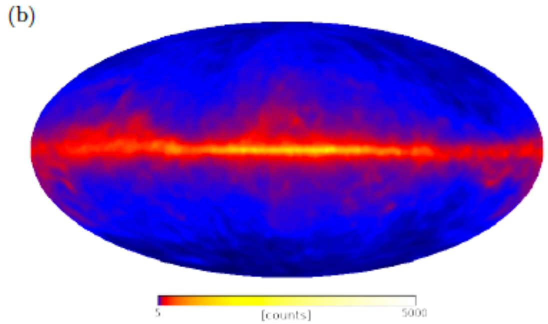


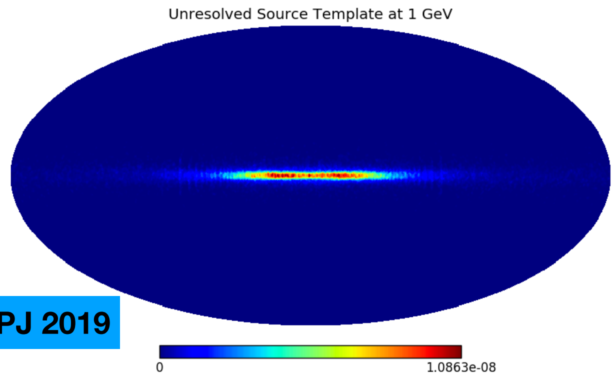
Resolved sources

Diffuse emission

Unresolved sources

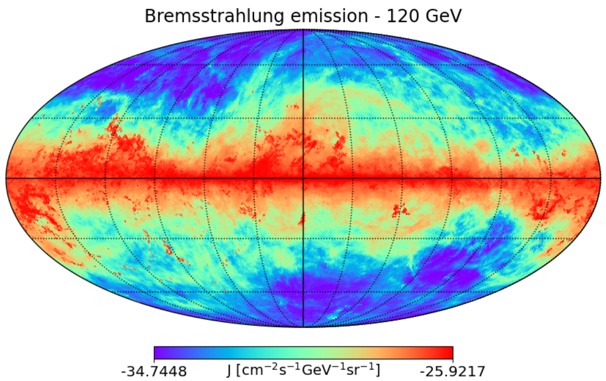
Selig et al. A&A 2014





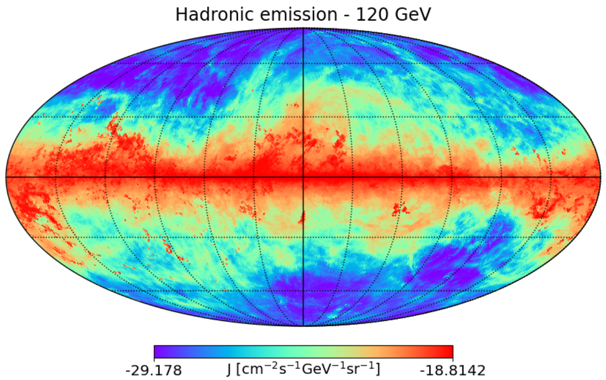
Fermi-LAT coll. APJ 2019

Galactic diffuse gamma-ray emission



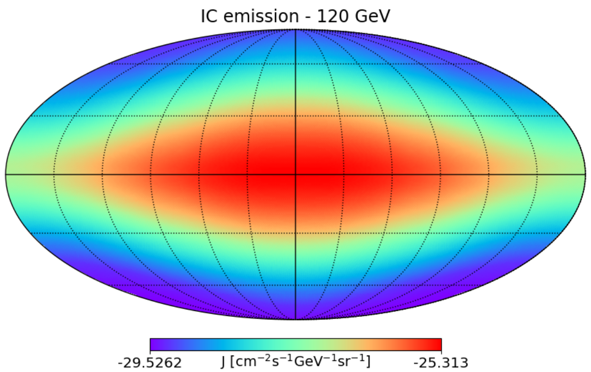
$$e + N \rightarrow e' + \gamma + N'$$

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.

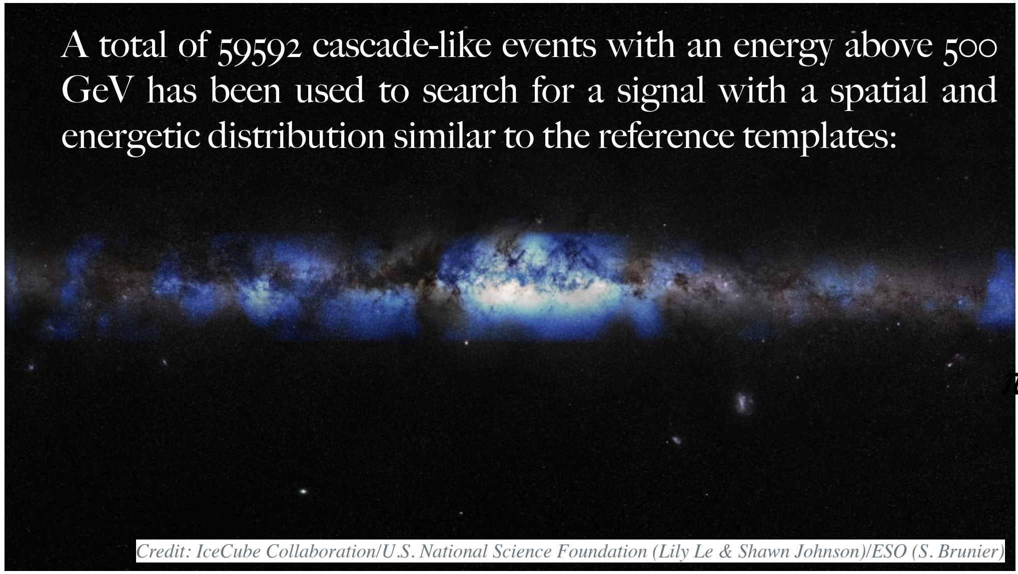


$$e + \gamma \rightarrow e' + \gamma'$$

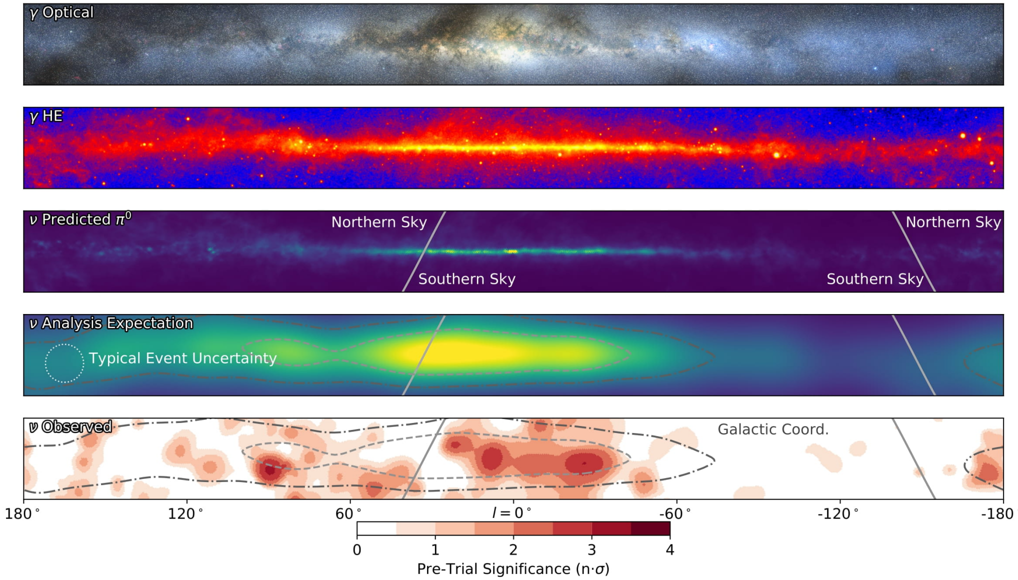
IC emission depends on the energy density of the **ISRFs**

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

IceCube Coll. Science 2023



π_0

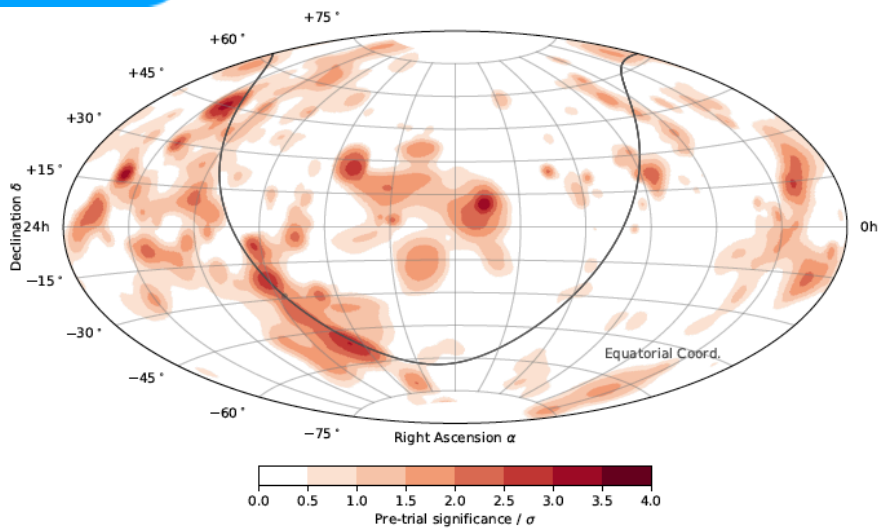


Π_0 → A Fermi-LAT coll. template based on a homogeneous diffusion coefficient along the Milky Way longitude and a 2012 molecular gas map.

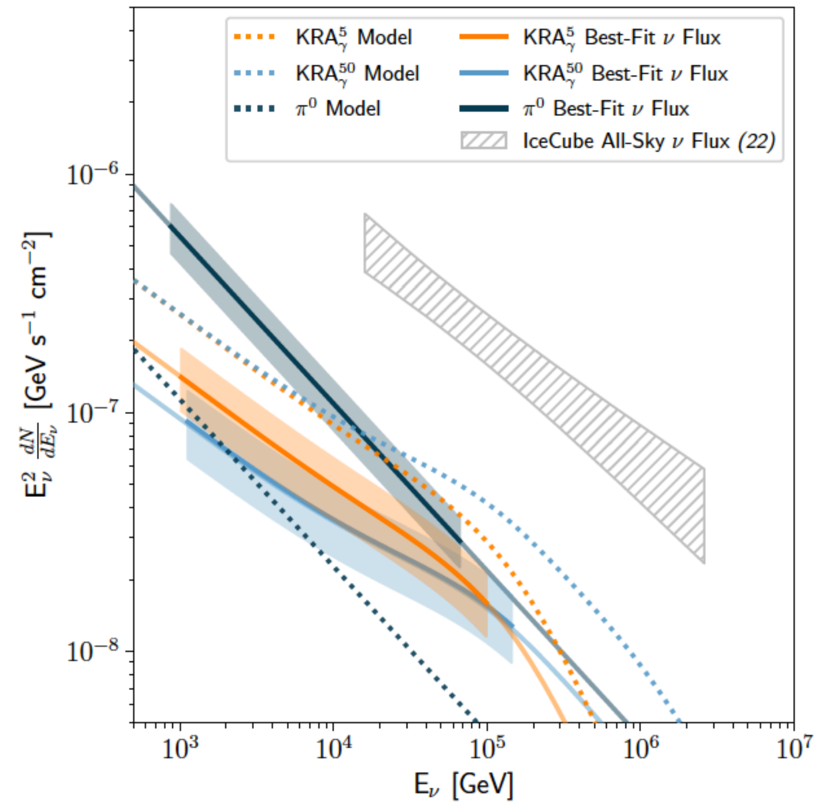
KRA-γ5 and KRA-γ50 → A template obtained with DRAGON and Gamma-sky codes based on a inhomogeneous diffusion coefficient and a CR spectral hardening toward the Milky Way center (radial dependent) and two different CR cutoffs at 5 and 50 PeV

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

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

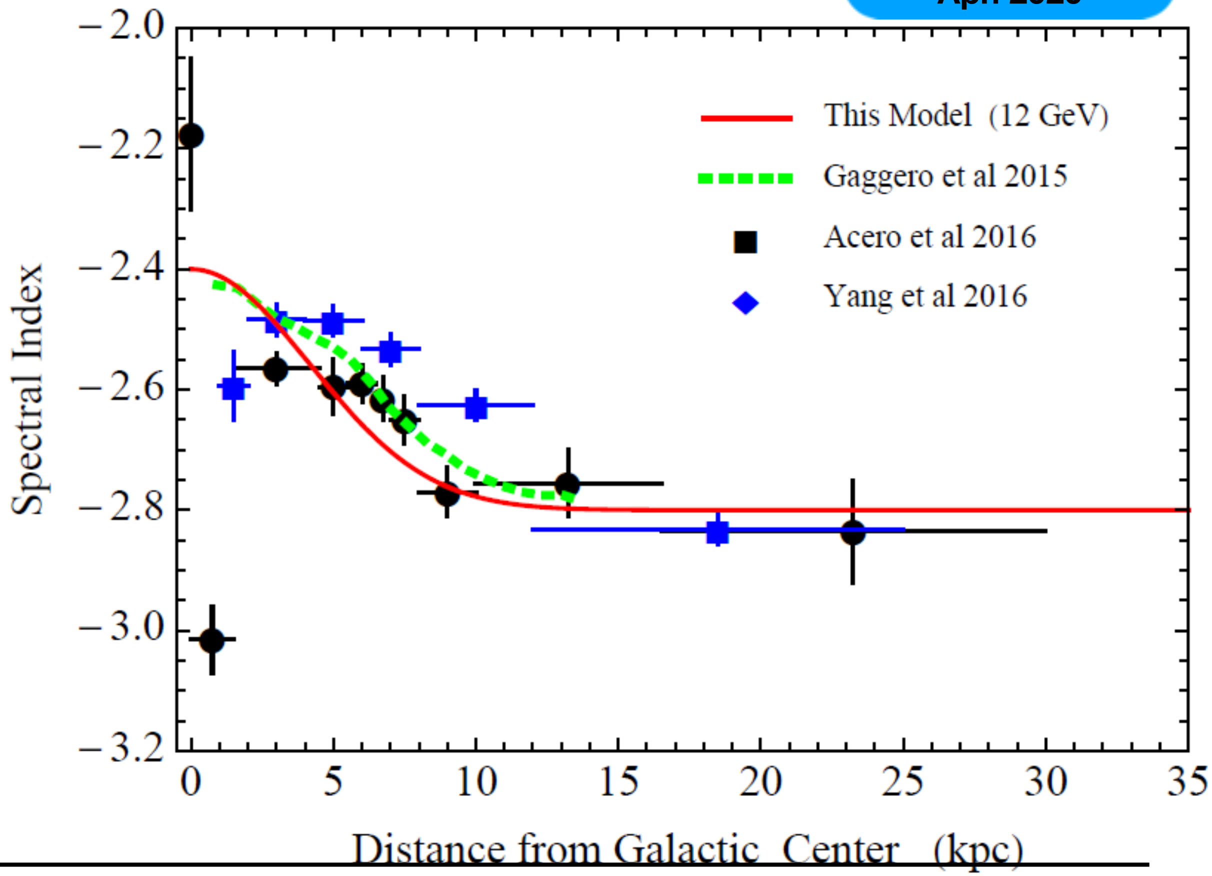
Diffuse gamma-ray spectrum essentially follows the spectrum of CR protons:

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

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

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

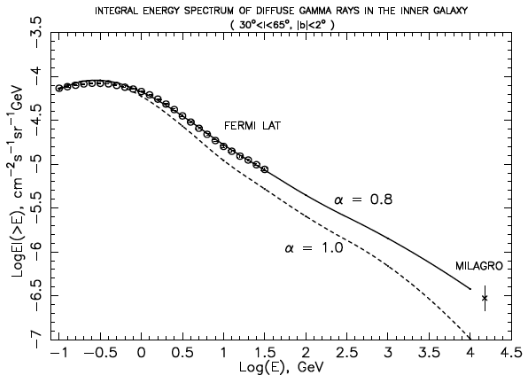
P.Lipari, S.Vernetto Aph 2020



Inhomogenous diffusion model

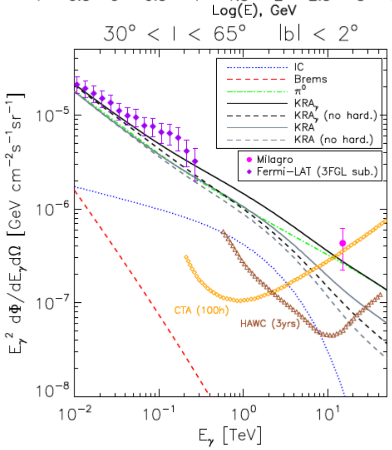
$D \propto E^{\delta(R)}$ with $\delta(R) = \delta_0 + \delta_a(R)$ Diffusion coefficient Change toward the Galactic center

- Erlykin & Wolfendale (APh 2012)

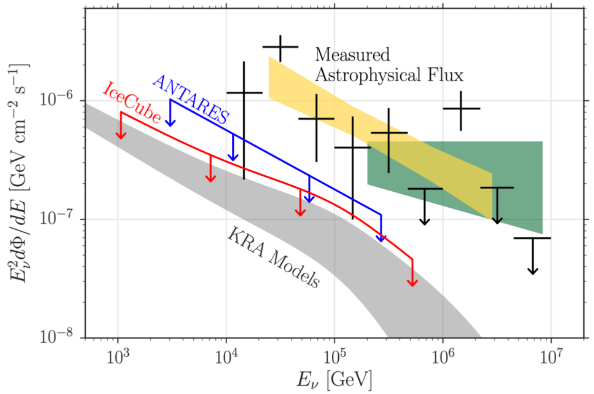


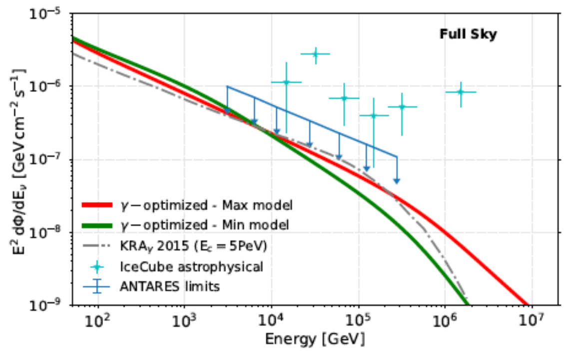
- Gaggero et al. (PRD 2015) ,
  Gaggero el al. (APJ letter 2015)

KRA-γ with CR cutoff at 5 and 50 PeV



maps produced for γ and ν

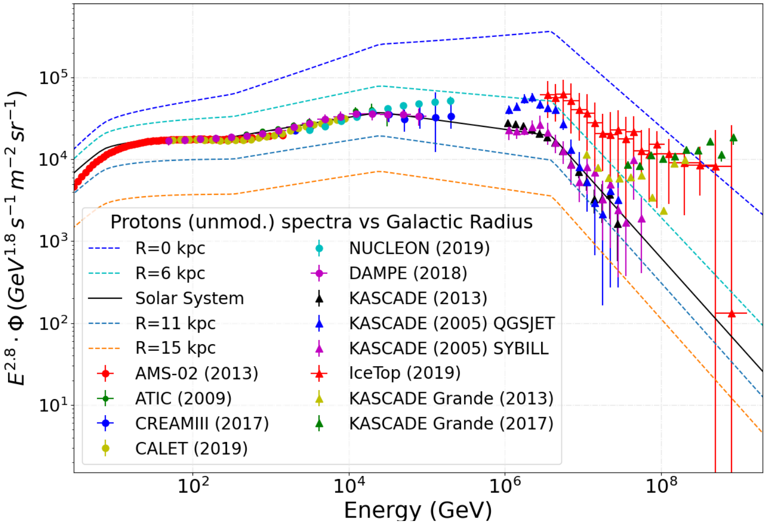




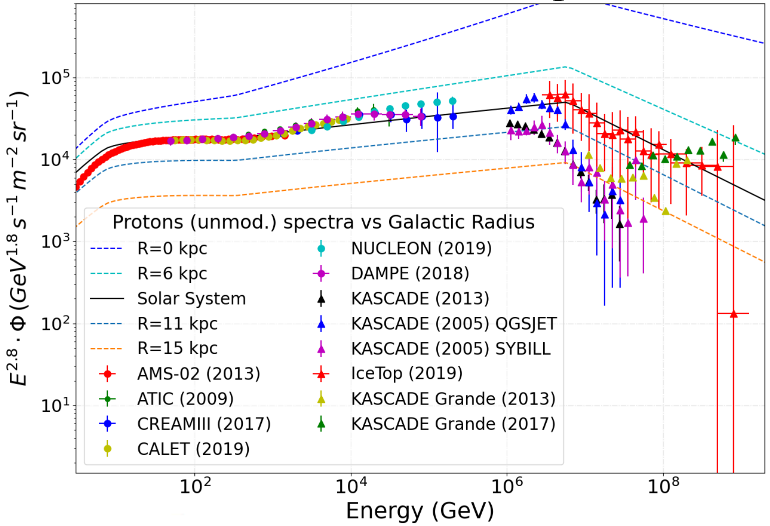
- De la Torre et al. (A&A 2021) , De la Torre et al. (Frontiers 2022)

Updating the KRA-γ models - new version

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

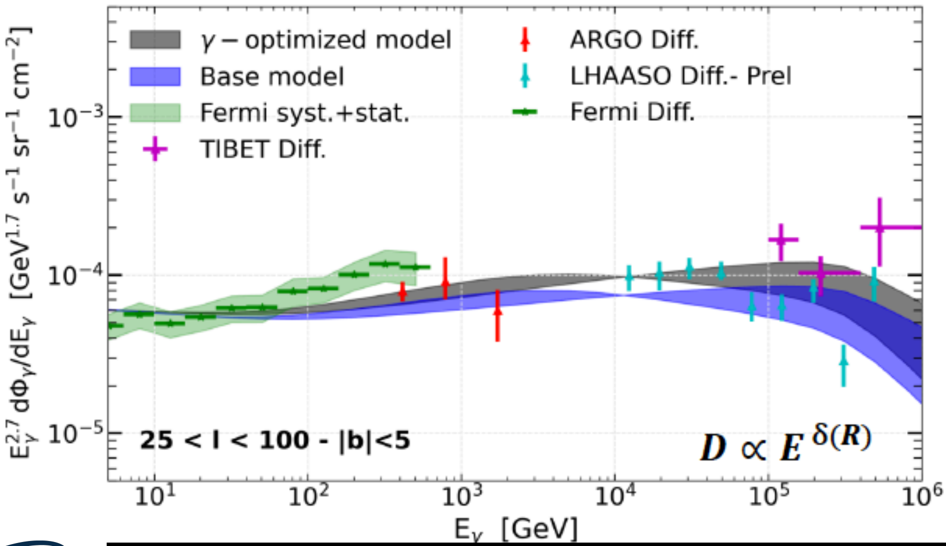


<u>MAX model</u> adopted connects AMS-02 data with IceTop

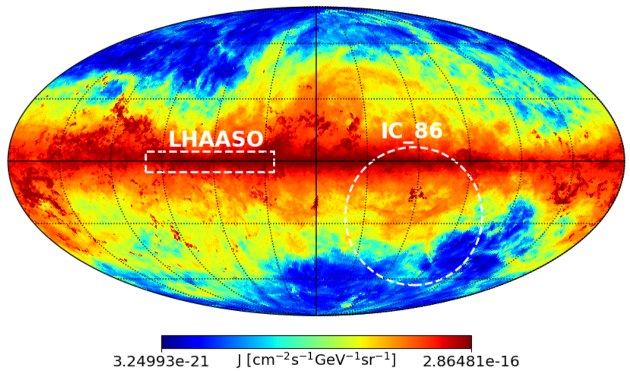


Look at the D. Gaggero talk

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



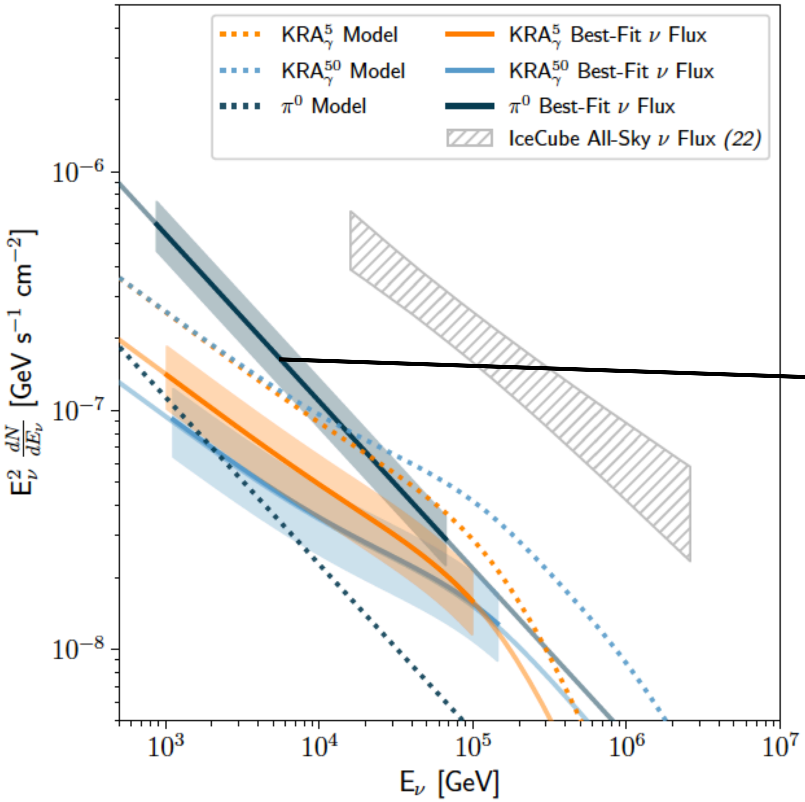
De la Torre et al. A&A 2023



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

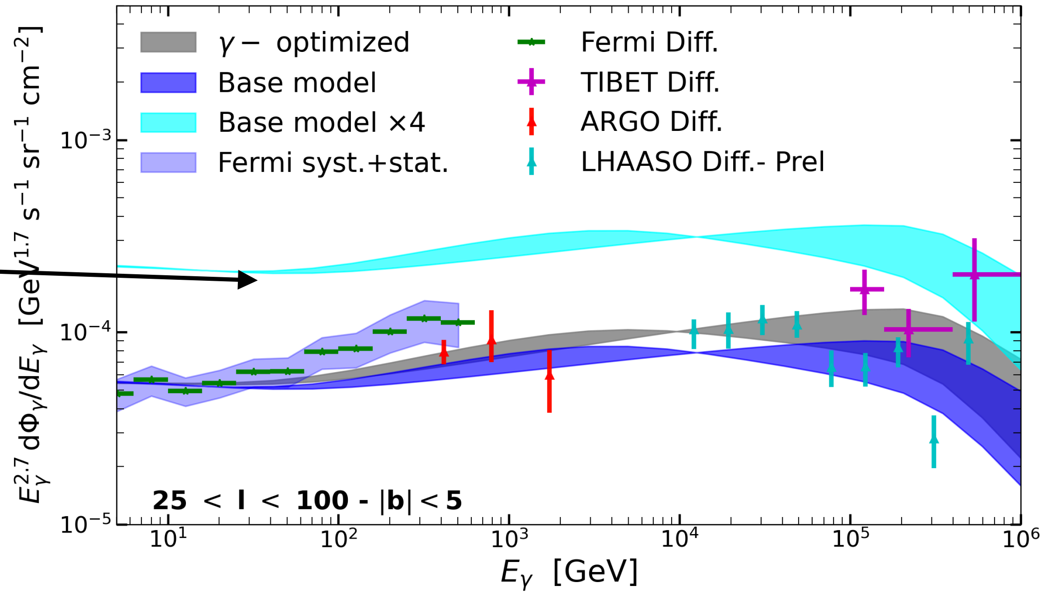
A better look to the IceCube results

IceCube coll.
Science 2023



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

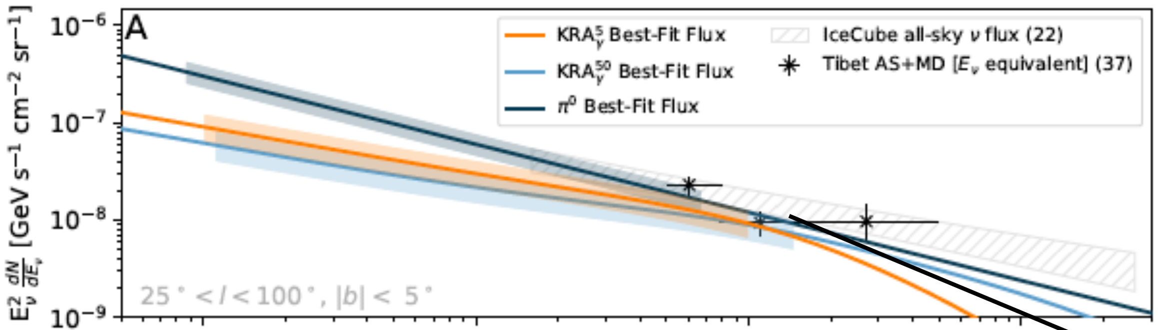
De la Torre et al.
A&A 2023



The best fit normalization of the π_0 model (4 times the expected value) present a strong tension with Galactic diffuse Fermi-LAT observations.

A better look to the IceCube results

IceCube coll.
Science 2023

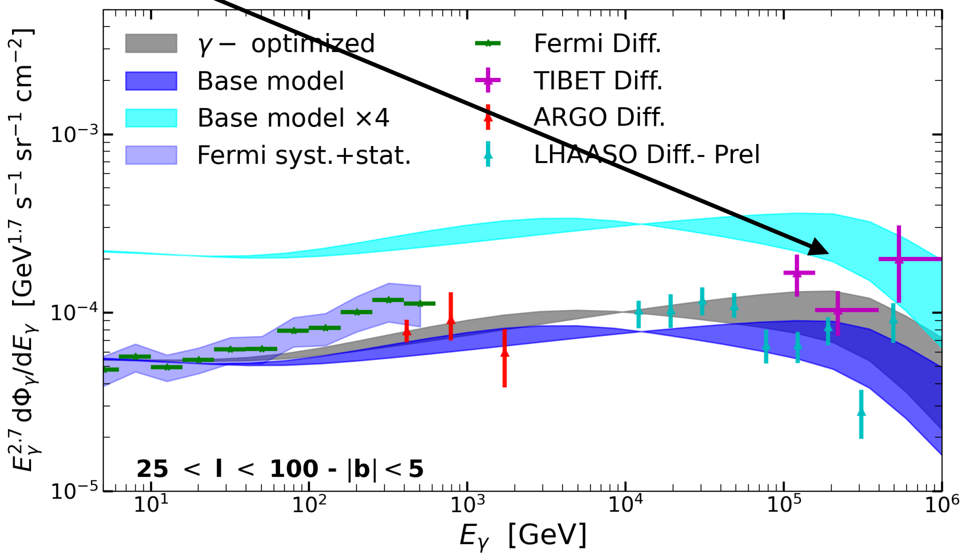


Caveat: the best-fit of observed ν is not obtained for the Tibet region, IceCube coll. rescaled of the measured flux

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.

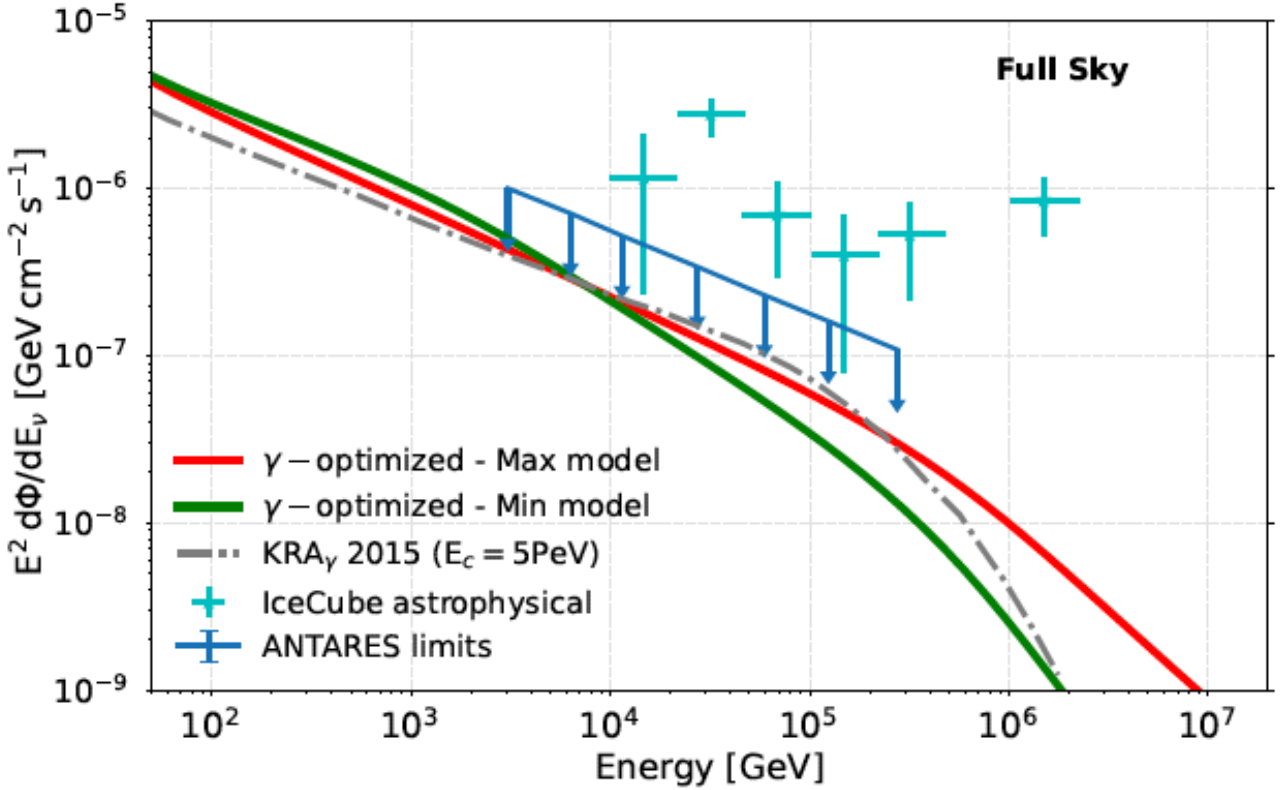
The best fit of the π_0 model is incompatible with gamma-ray observations at low and high energy



ν expectations from the new KRA-γ models

De La Torre, Gaggero, Grasso, A.M.
Frontiers 2022

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

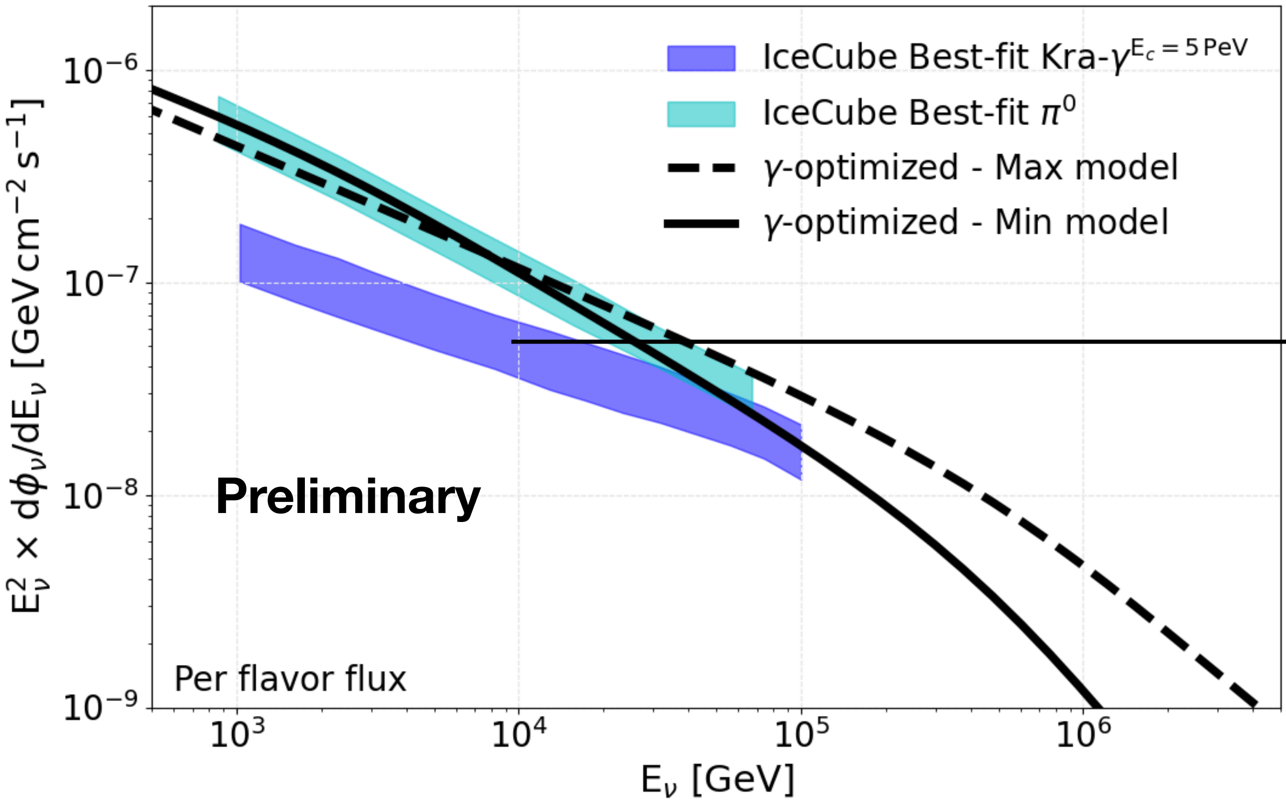


Still at the level of 10% of IceCube full sky observations and compatible with ANTARES model independent old upper limits

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



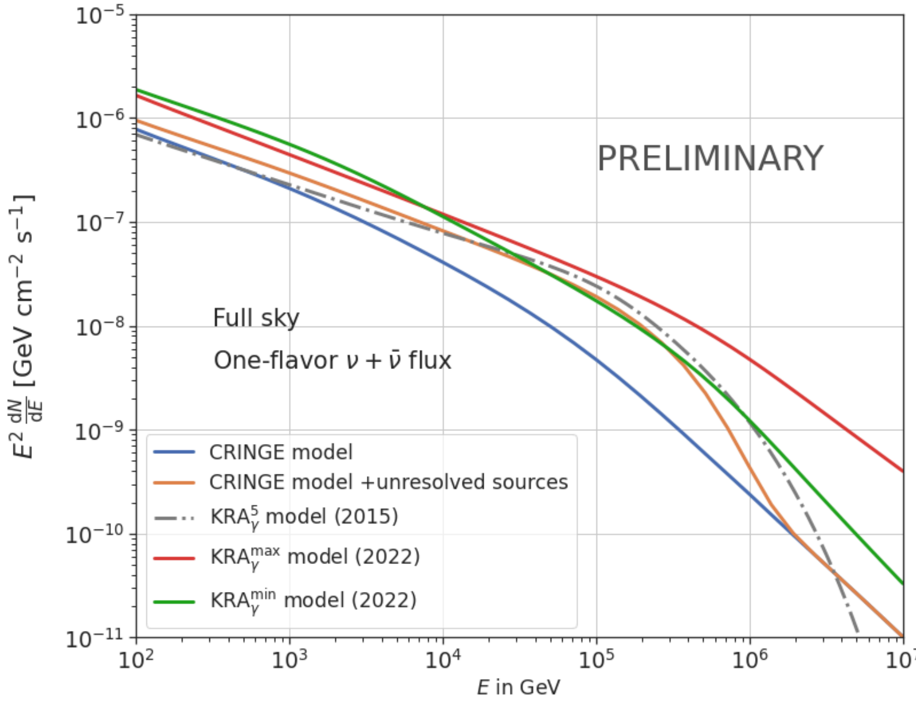
Remember that the KRA-γ 5 best-fit is 0.55 the model expectations

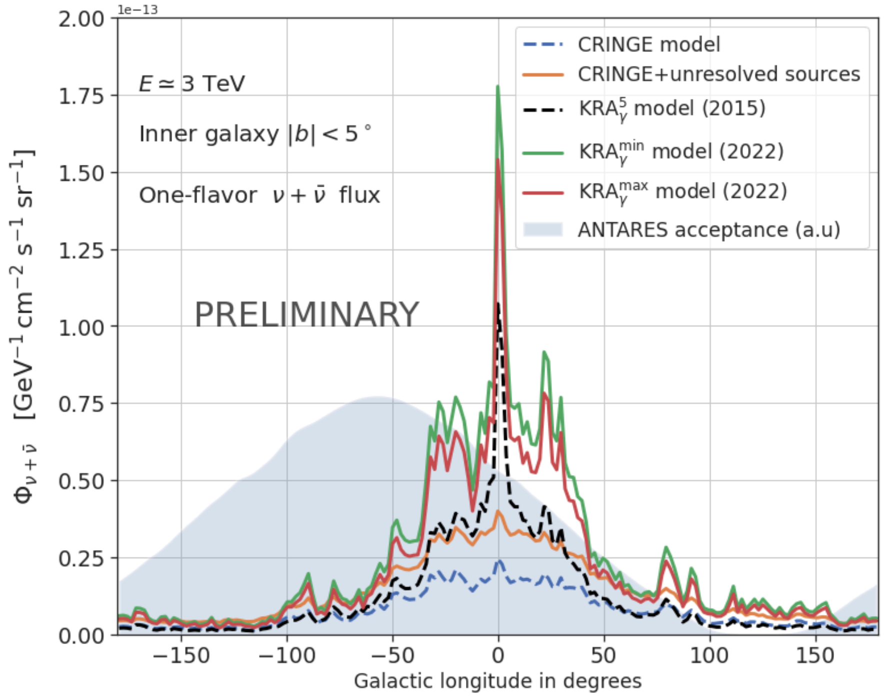
π_0 neutrino best fit and the new expectations from MIN and MAX models suggest that the Fermi-LAT spatial template can agree with diffuse γ-ray and ν observations only if an hardening of the CR toward the Galactic center is assumed ($D \propto E^{\delta(R)}$).

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. For the Antares coll. ICRC 2023

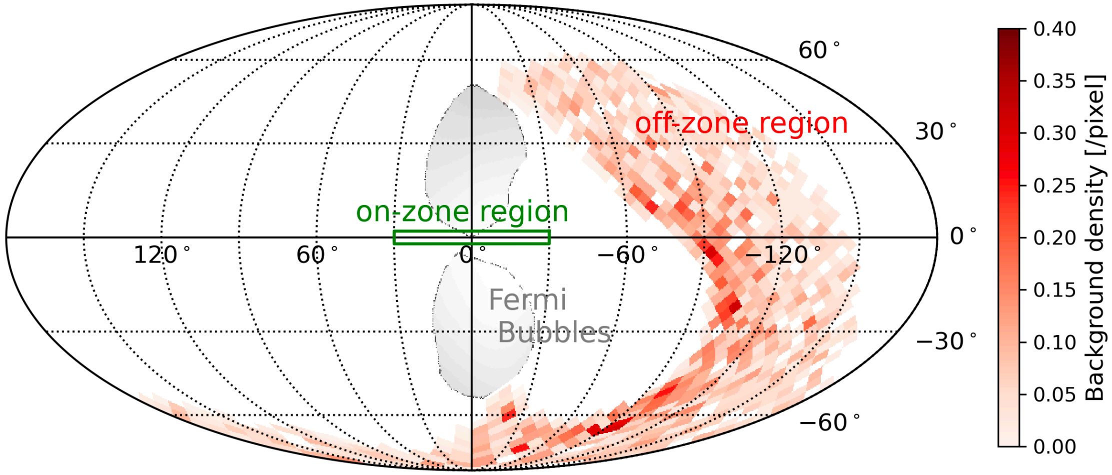


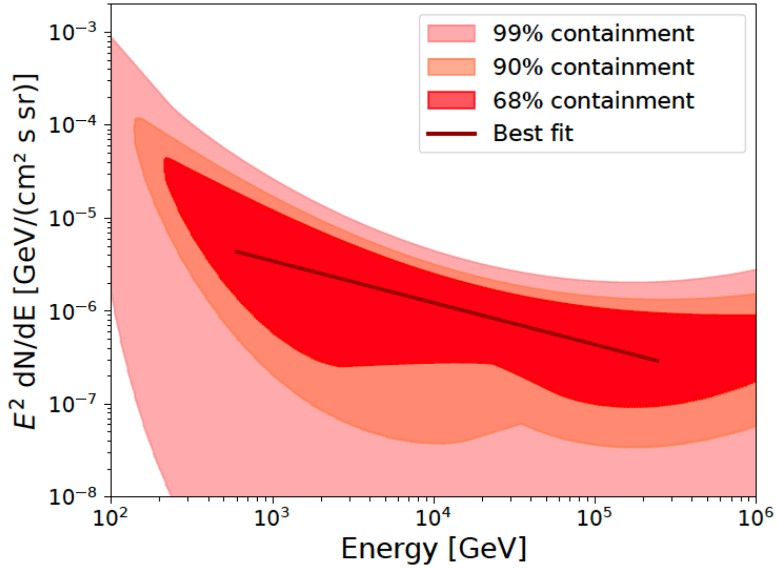


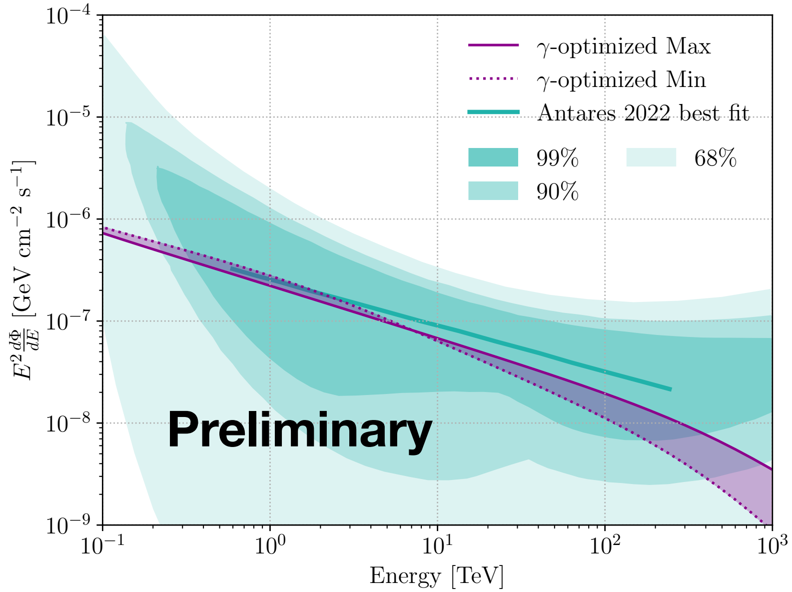
The good acceptance of ANTARES experiment for the central part of our Galaxy, makes is answer a crucial probe of the neutrino flux arriving for this region of the sky.

Comparison with ANTARES ridge observation

Phys Letter B 2023
Antares Coll.





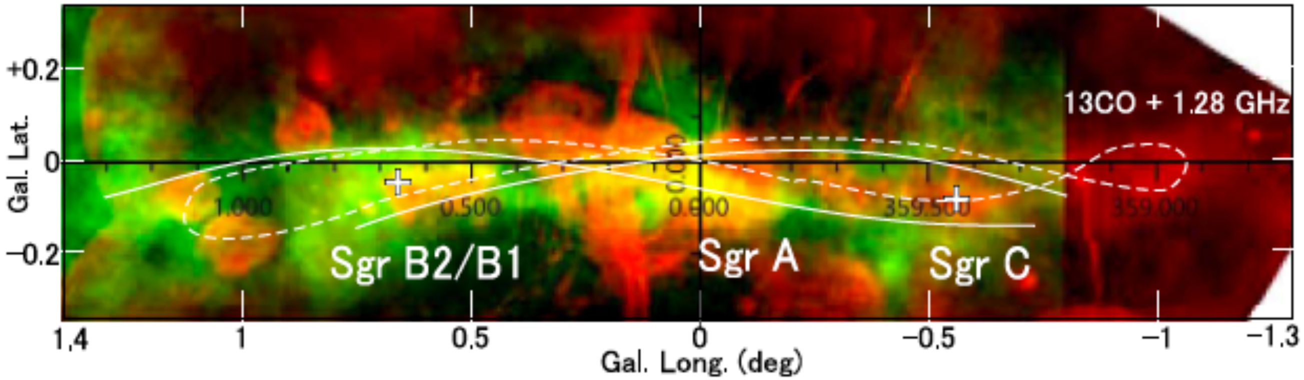


The Updated KRA_γ model expectations for the Galactic ridge (l< 30°, b<2°) results to be in agreement with the Antares confidence regions

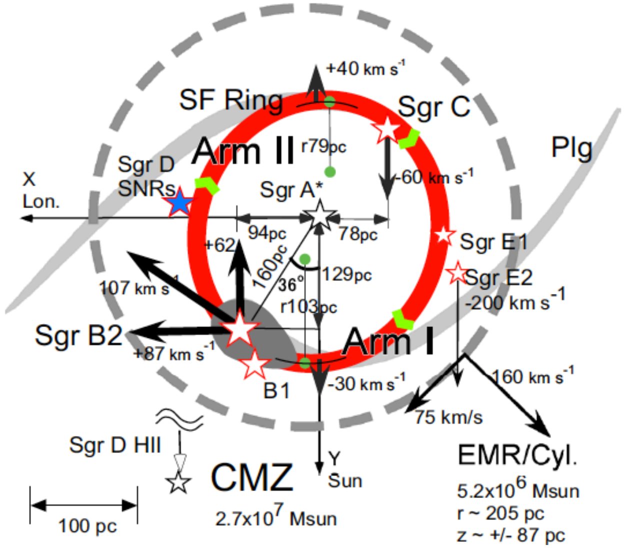
The central molecular zone

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



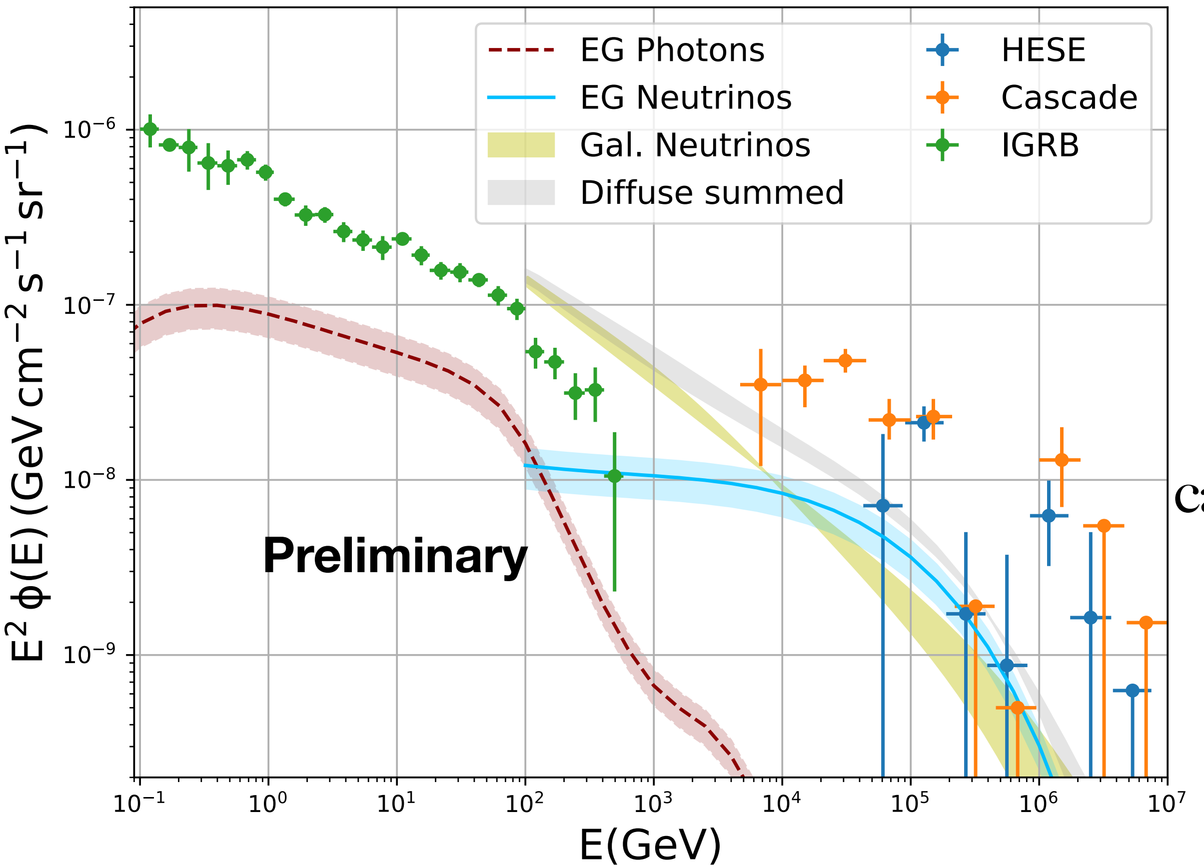
The Central Molecular Zone will be the Gold region to test the cosmic-ray sea physics through neutrinos, already done in the past with HE (Fermi_LAT) and VHE gamma rays (HESS) (Gaggero et al. PRL 2017)

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

With the incoming KM3NeT telescope, can this extended region solve the puzzle diffuse + unresolved sources ?

A diffuse emission associated to non AGNs

Milky Way diffuse ν emission spatially related to Galactic disk while the SBG diffuse emission is a isotropic component



EG neutrino = Diffuse SFG component

Gal Neutrino = Diffuse Galactic from the updated KRA_γ model

The sum of these two components can account for a non negligible part of the flux measured by IceCube

The absence of a AGN for the SFG population does not prevent a accountable diffuse neutrino emission when integrating over high redshifts.

SUMMARY

- Galaxies who don't host a AGN can still be a important astrophysical component to explain the IceCube diffuse observations.

- Star forming abundance can be a tracer of neutrino emission.

- Single Starburst galaxies are hardly resolved as a point like ν emitters however the ν diffuse component becomes important when integrating up to high redshifts.

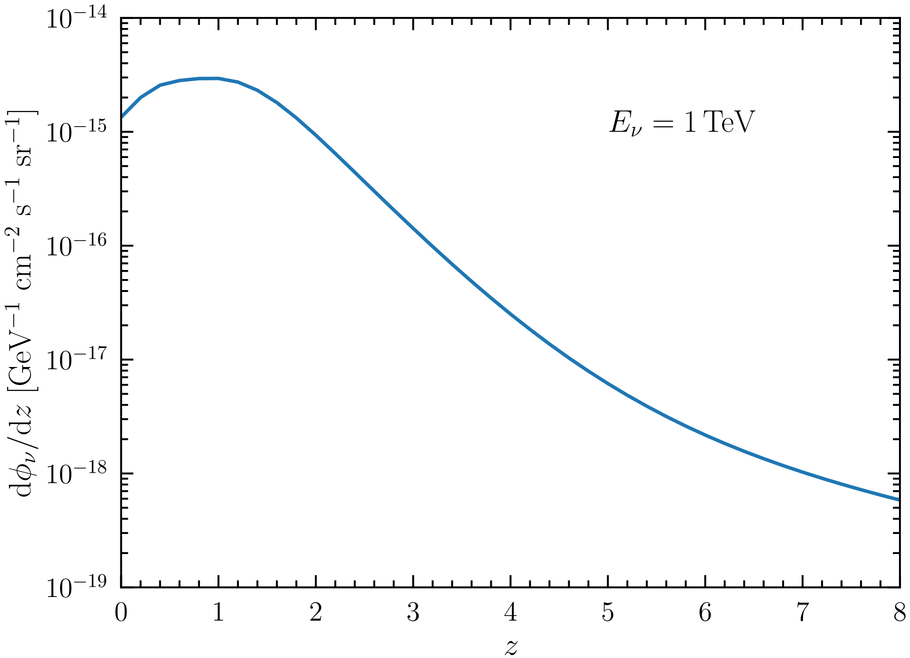
- IceCube and Antares start to characterize the Galactic neutrino emission (still nice questions to go through).

- Galactic emission seems not properly a neutrino desert and some oasis (CMZ….) can appears soon with the incoming KM3NeT telescope.

BACK UP SLIDES

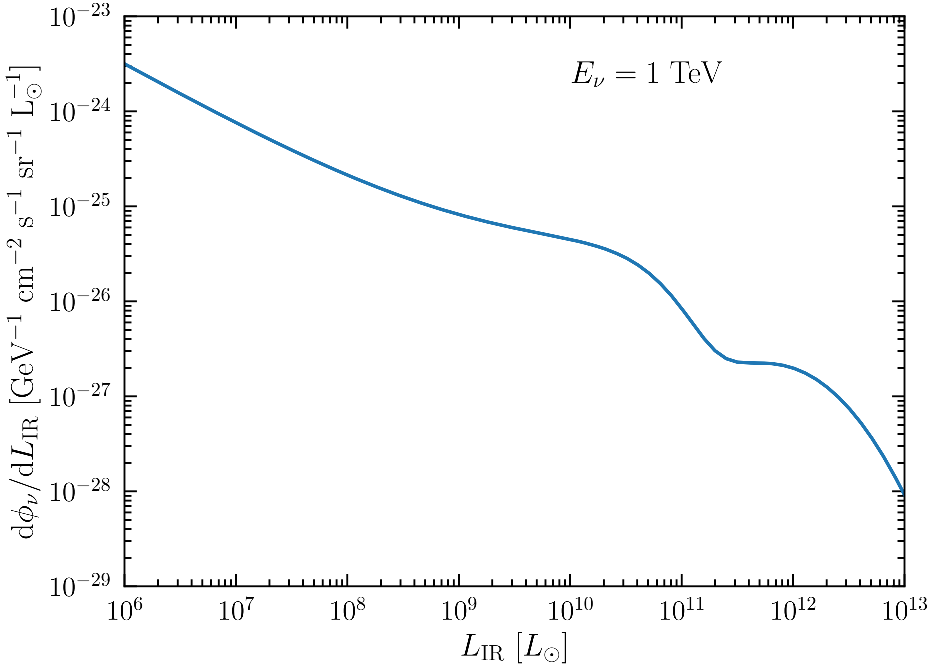
Properties of the Neutrino Flux

Redshift Distribution of the Neutrino Flux



Distant sources dominate the emission (peaking at $z \simeq 1$)

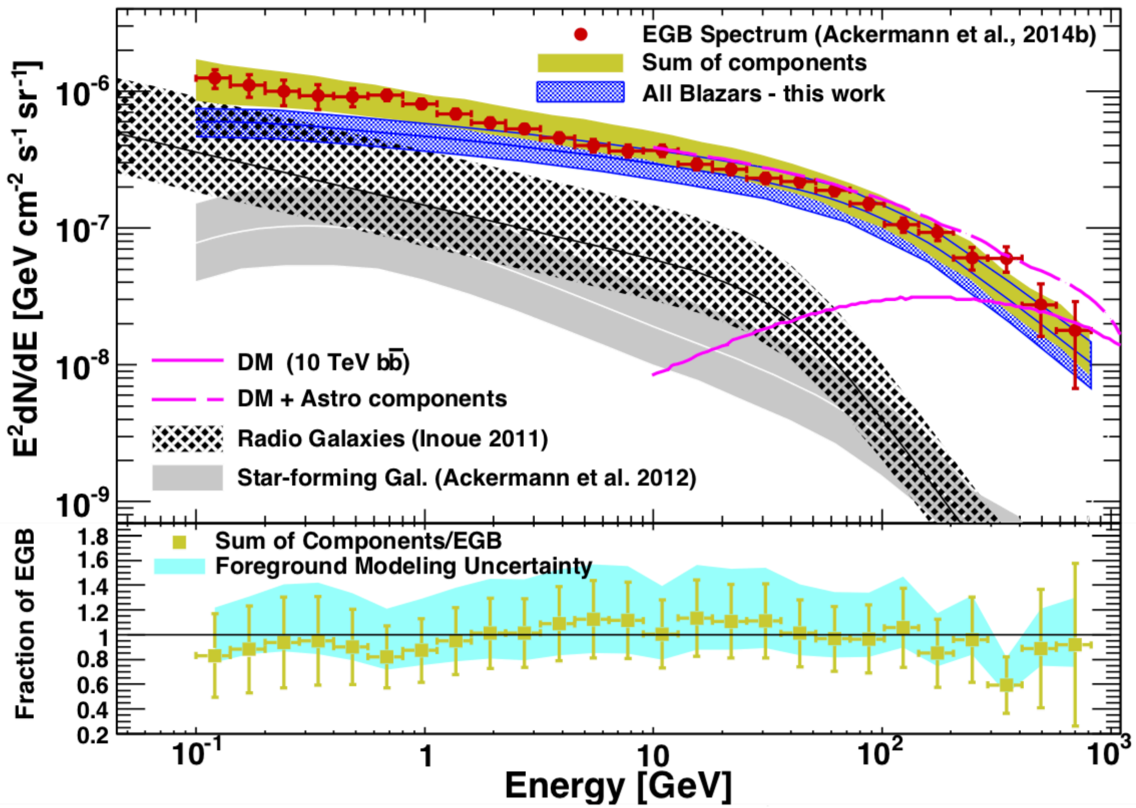
IR Luminosity Distribution of the Neutrin



Powerful SBGs $(\mathrm{SFR} > 100\,\mathrm{M}_\odot\,\mathrm{yr}^{-1})$ dominate the emission (> 50% of the emission)

extragalactic gamma-ray background

Ajello et al., APJL 800 (2015)



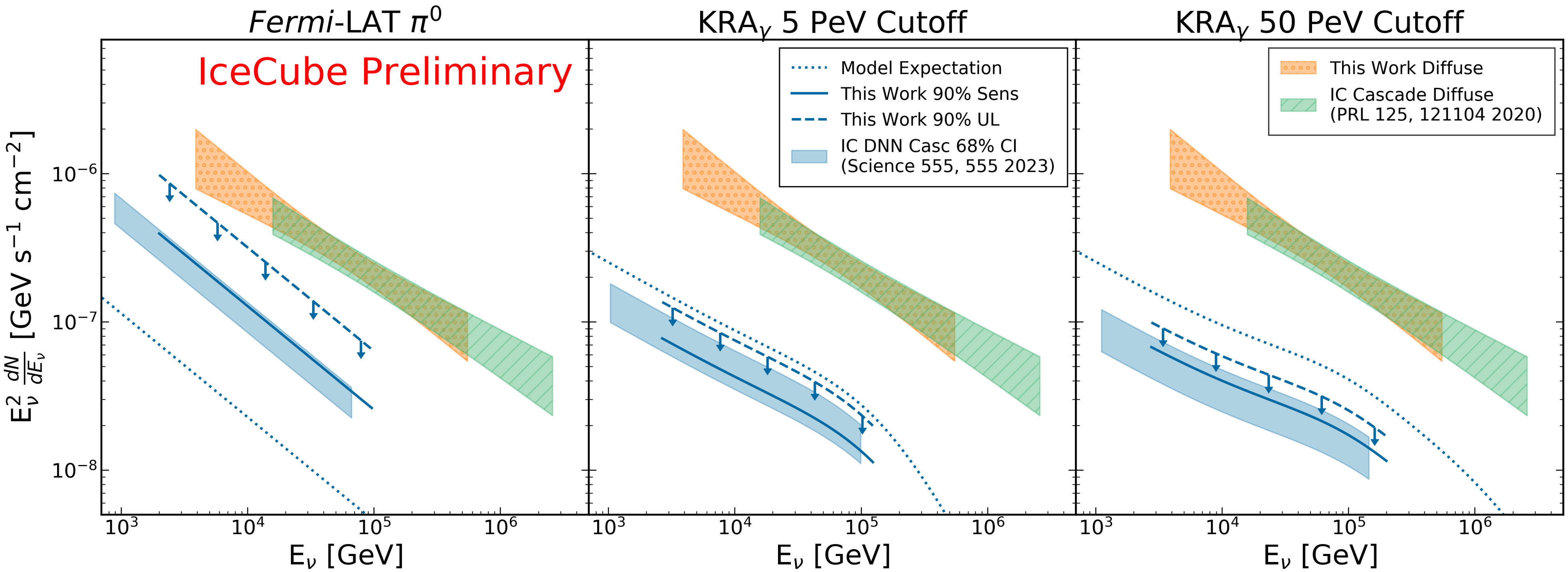
- Fermi-LAT resolved many individual sources belonging to different classes, Blazars dominates the EG samples.
- Limit on PS above 50 GeV varies from 68% (Lisanti et al. 2016) to 86% (Ackermann et al. 2016) of the EGB

Starforming and Starburst galaxies gamma-ray component needs a better definition due to the small number of resolved ones at HE

IceCube analysis with starting tracks 2008 -2018

Silva, Mancina IceCube coll. POS(ICRC2023) 1008

Mancina talk TeVpa23

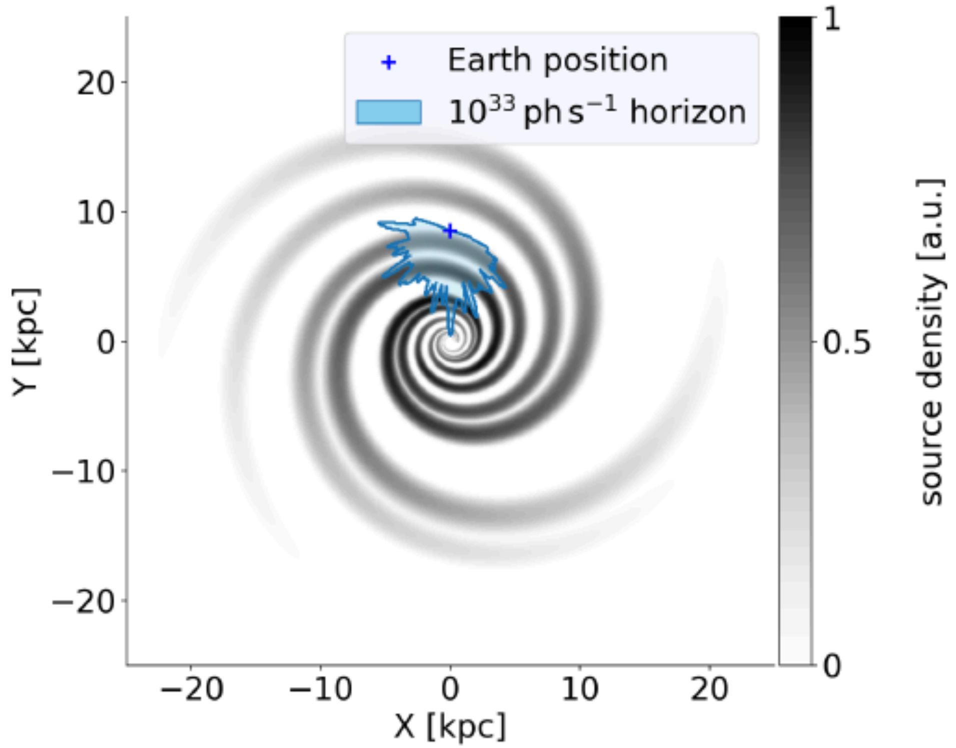


Starting track events IceCube analysis compatible with Cascade analysis, however any significant excess visible, KRA-γ with 50 PeV cutoff quite constrained.

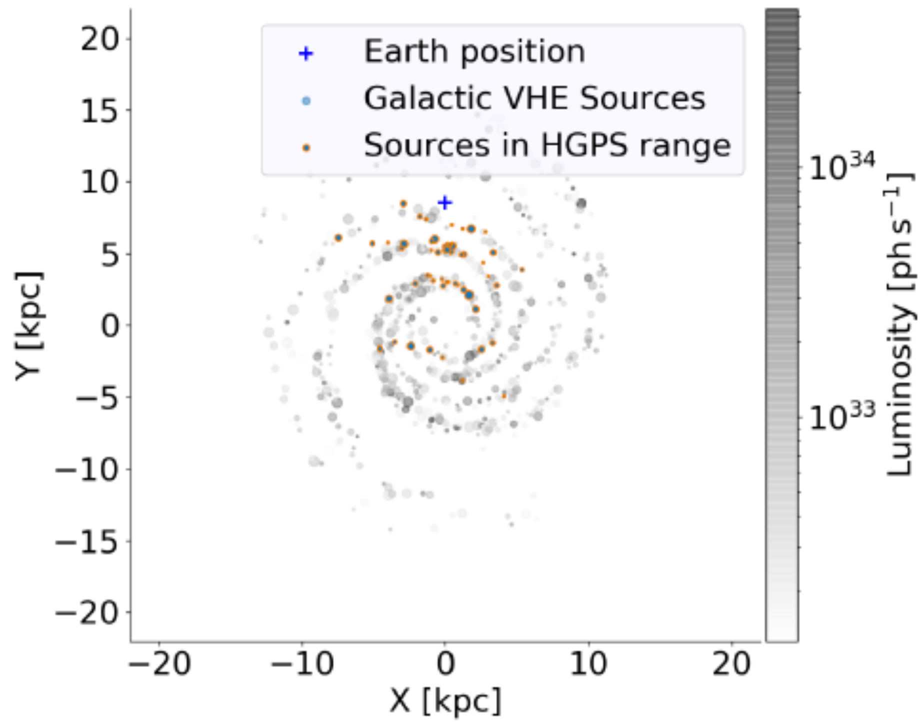
Considering unresolved source contribution

Steppa,Egbert
A&A 2023

Resolved source horizon for HESS



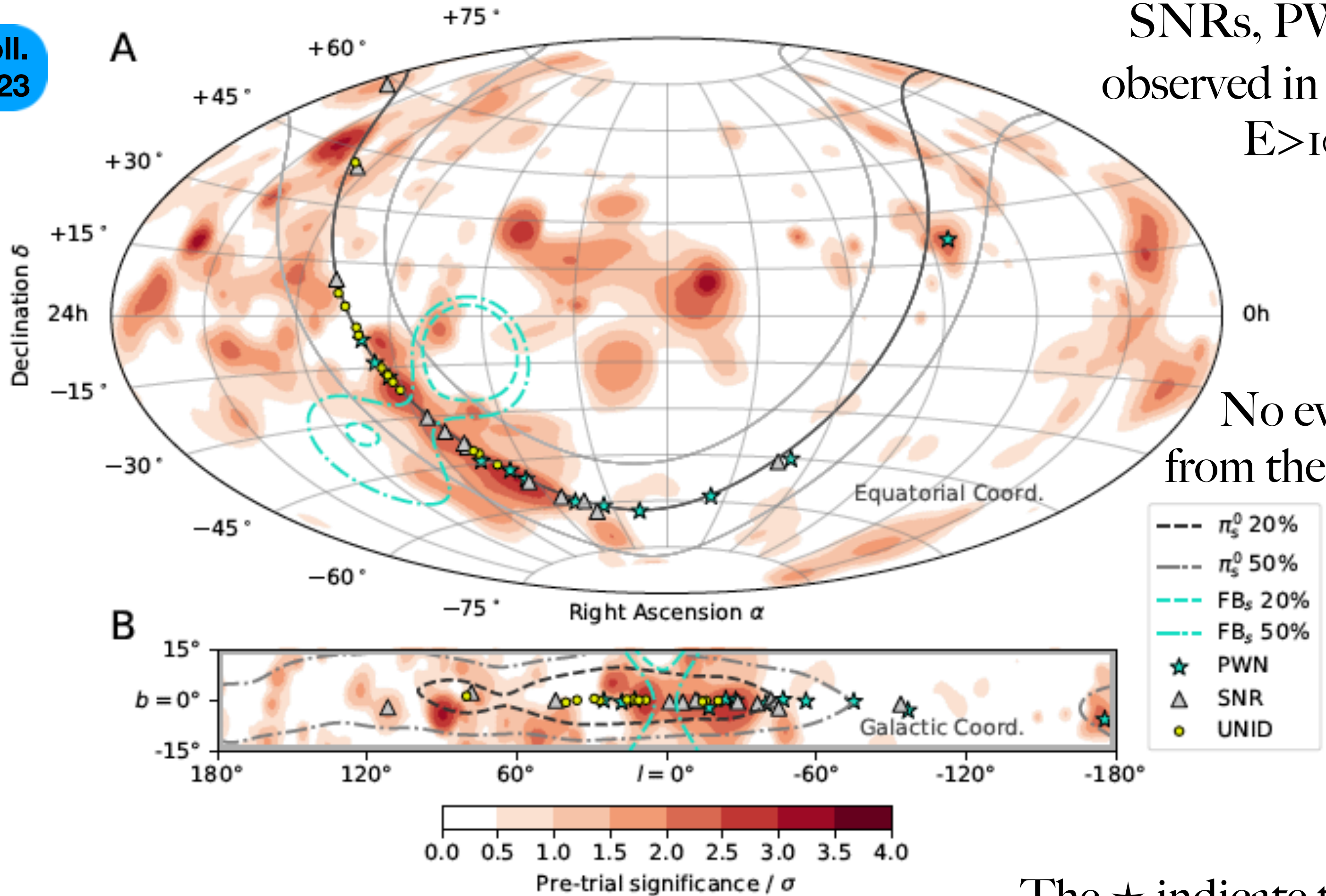
Realization of a synthetic population of VHE gamma-ray sources



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. <u>Unresolved source component strongly dependent from the energy considered and from the experiment used.</u>

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

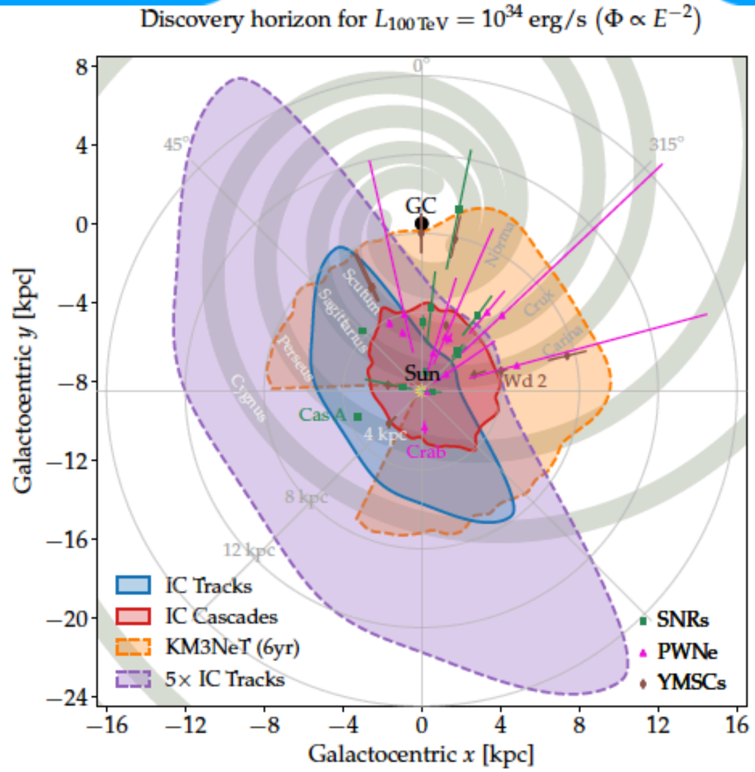
Catalog stacking analyses	p-value
SNR	5.90×10^{-4} (3.24σ)*
PWN	5.93×10^{-4} (3.24σ)*
UNID	3.39×10^{-4} (3.40σ)*

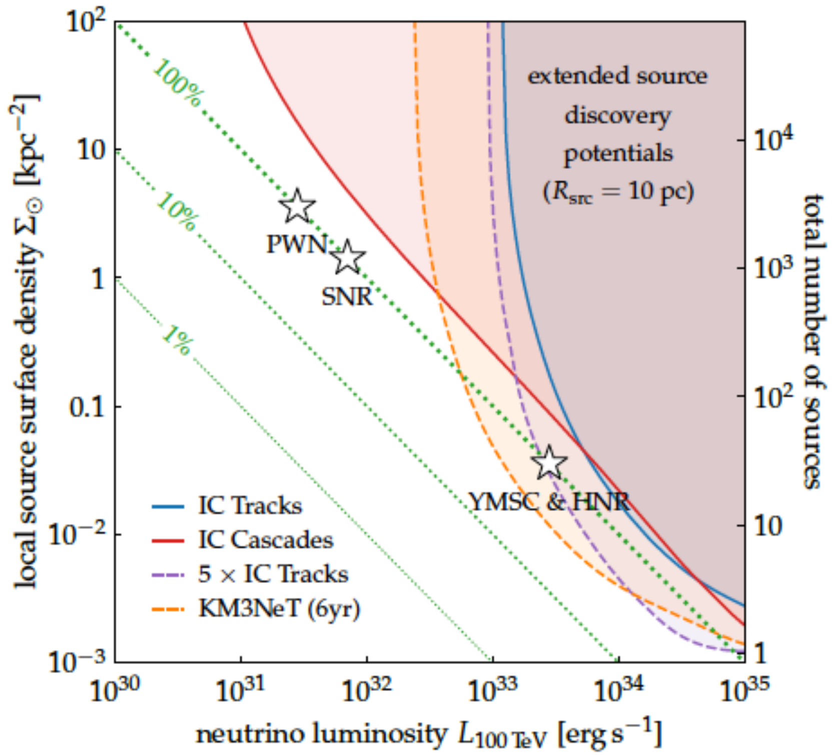
The ★ indicate that the significance is consistent with the diffuse emission template searches

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.