UNIVERSITÀ DEGLI STUDI DI SALERNO
Dipartimento di
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INFN
Istituto Nazionale di Fisica Nucleare

High-energy emissions in the Milky Way

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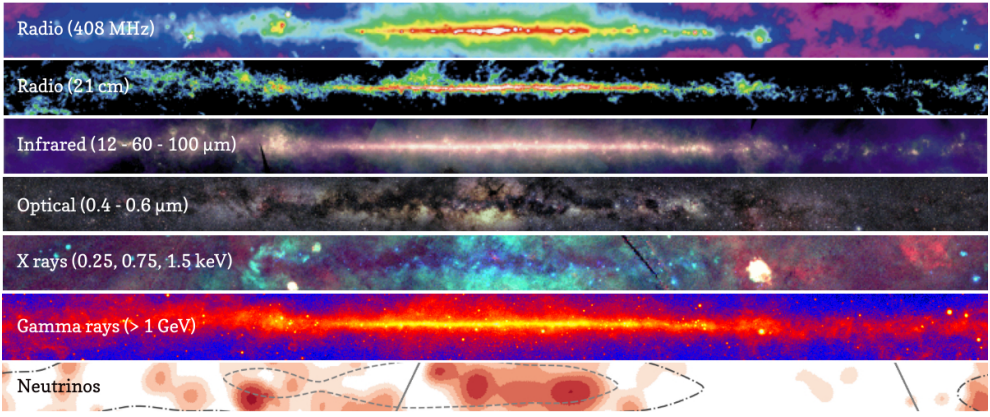
Outline

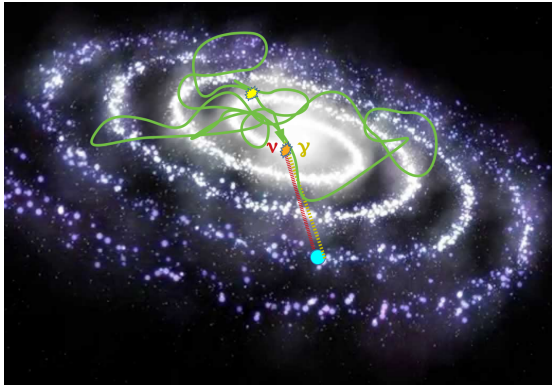
The multi-messenger Milky Way



Probes for Cosmic Rays

- Cosmic Rays fill the Galaxy
- Interstellar Medium fills the Galaxy

$\Rightarrow$ CR collisions will produce γs and νs (hadronic mechanism)[a]

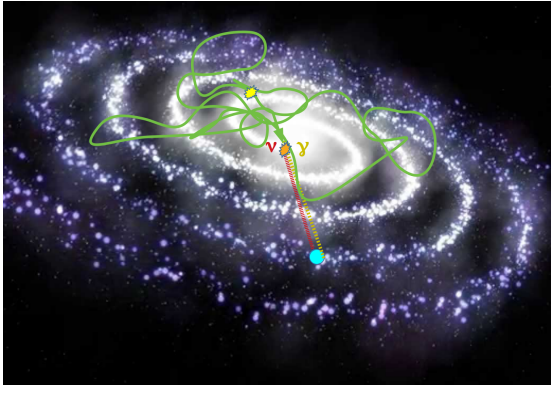


[a] Gamma rays may also come from leptonic processes

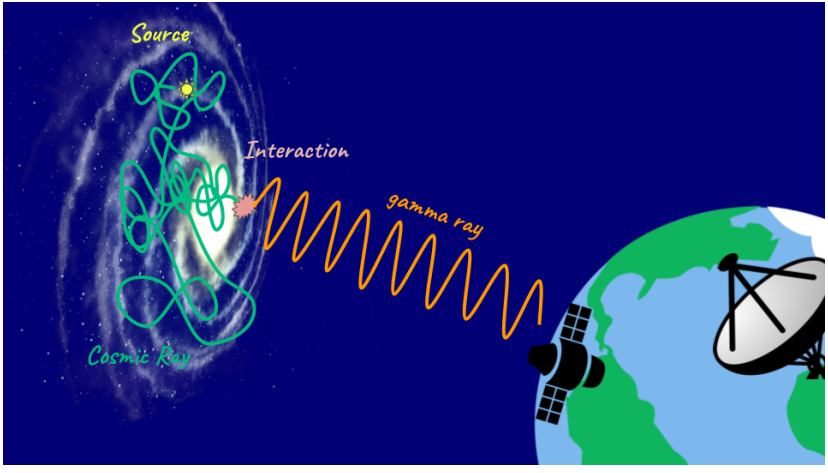
Galactic plane emissions

The main issue is: *we measure CRs at Earth; their behaviour in the rest of the Galaxy may be different*

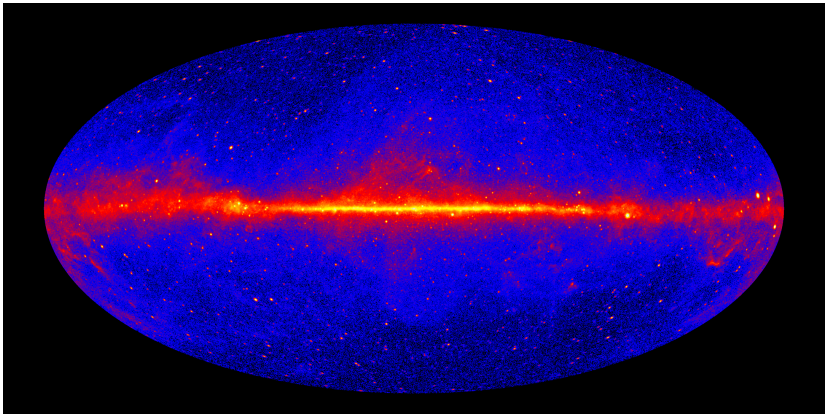
- Neutrinos and gamma-ray allow to map CRs along the line of sight
- Measure CR properties beyond the local environment



Gamma rays



Fermi-LAT

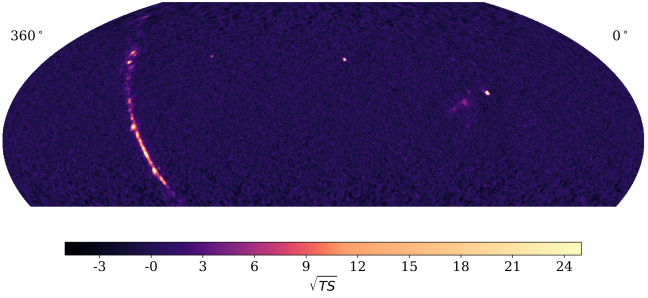


Credit: NASA/DOE/Fermi-LAT Collaboration, see [1]

HAWC

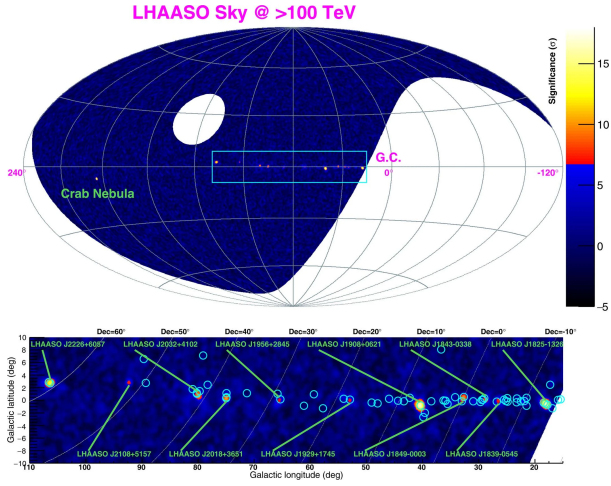
HAWC Cherenkov detector looks for TeV gamma rays producing showers in the atmosphere, with large FoV and high efficiency

- HAWC sky at TeV energies [2]
- Recent updates shown this summer with improved reconstruction [3]



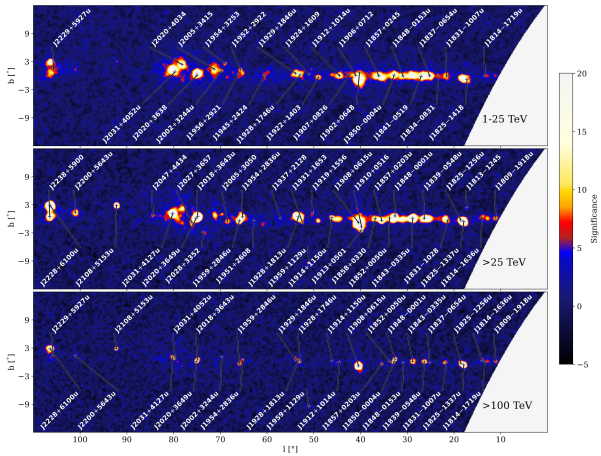
LHAASO

- The LHAASO array observes large parts of the sky up to (potentially) PeV energies [4]
- Pushing observations to the highest energies ever



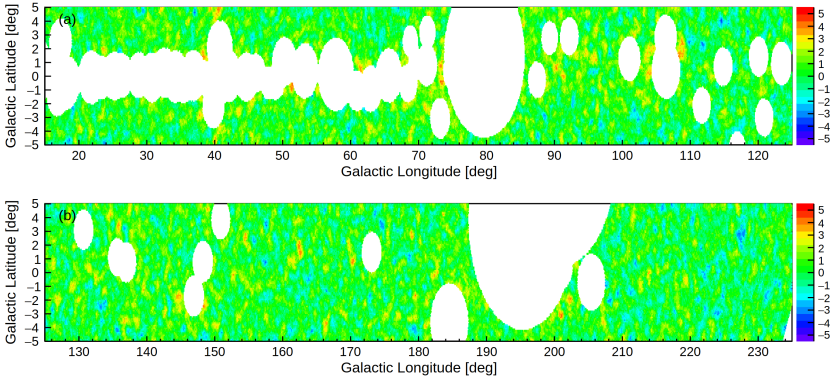
LHAASO

- Sources are clearly visible above 100 TeV [5]
- Hints for PeVatrons for some of those



LHAASO

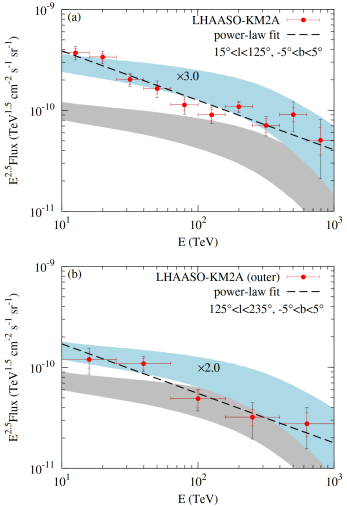
- Once sources (LHAASO and TeVCat) are removed, a diffuse component survives [6]
- High-significance observation



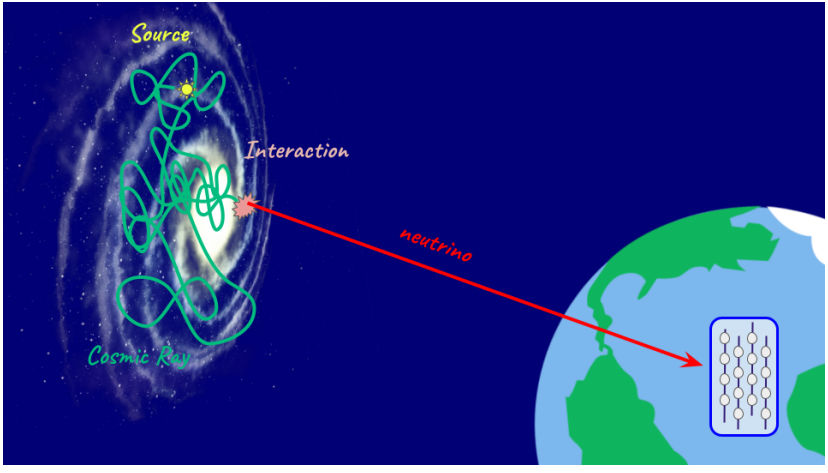
LHAASO

- A rather large flux is measured [6] both in the inner and outer plane
- About a factor 2-3 higher than the baseline expectations

$\Rightarrow$ Some unresolved source in there?



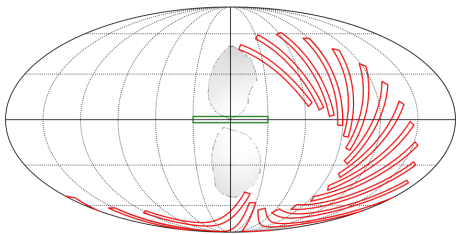
Neutrinos



Searches for neutrinos - I

ON/OFF searches
("Galactic Ridge")

- **Background** from data, from analogous regions as the **signal** – thanks to the rotation of the Earth
- Limited dependency on models
- Provide a "general" limit on the integrated neutrino flux

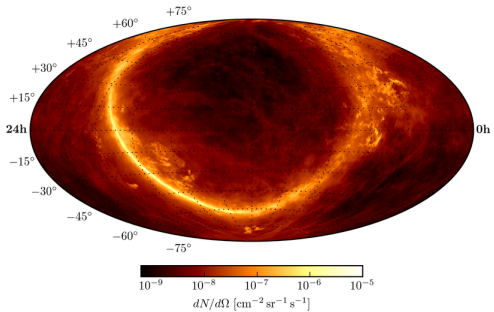


Searches for neutrinos - II

Template search
("likelihood analysis")

- **Sky-map from models** (accounting for CRs and the properties of the Galaxy)
- Spatial and spectral information
- Model-dependent results
- Whole sky is contributing

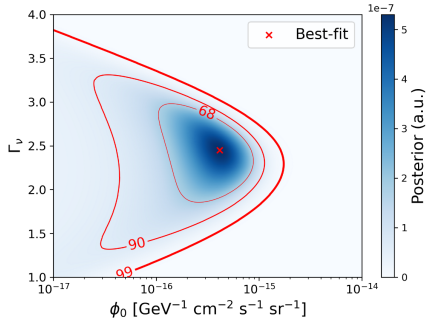
KRA$_\gamma$ model [7]



ANTARES Galactic Ridge

ON/OFF analysis [8] with 2007-2020 data

- Mild excess ($> 2\sigma$)
- Excess of data can be fitted with power-law spectrum
- Best fit $\gamma \simeq 2.5$
- Falls on top of the extrapolation of diffuse gamma rays from Fermi-LAT



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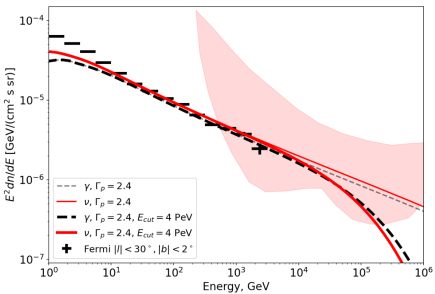
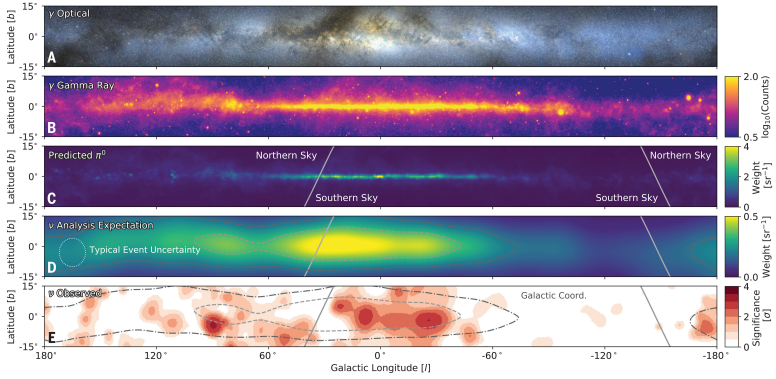


The IceCube results

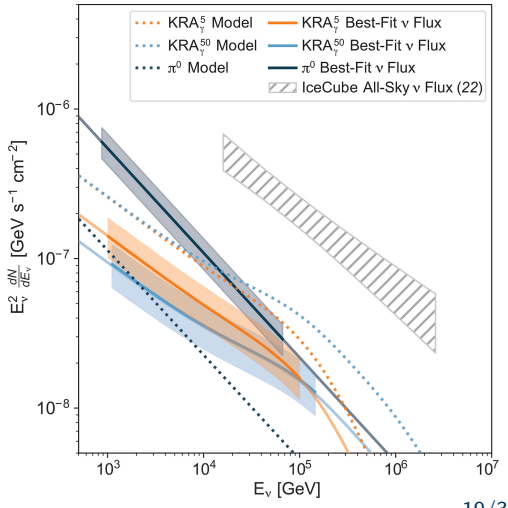
- June 29$^{\text{th}}$ 2023: IceCube announced the detection of Milky Way neutrinos [9]
- Selected cascade events using machine learning techniques to improve the purity



The IceCube results

Template search

- One using Fermi-LAT reference
- 2 from the "old" KRA_γ model [a] (tuned to reproduce Fermi data, and CRs)

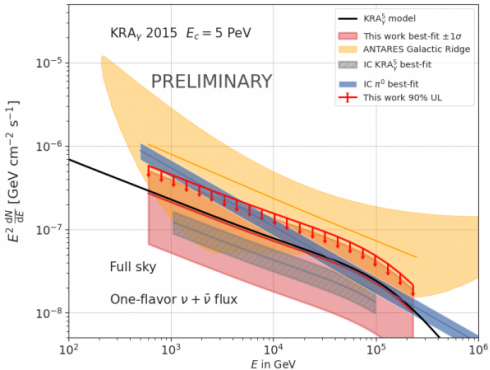


[a] See next talk by A. Marinelli

ANTARES, again

Updated template search presented at ICRC2023 [10]

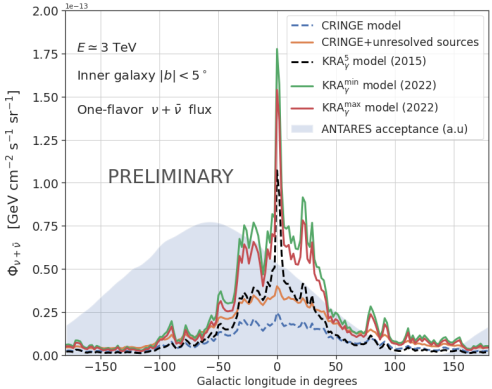
- No significant excess observed
- Resulting best fit is compatible within uncertainties with other ANTARES measurements and IceCube observations



Something on templates

Comparison done in the ANTARES proceedings at ICRC23 [10]

- CRINGE models [11]
- Updated KRA models [12]
- Mainly differing in the CR diffusion properties



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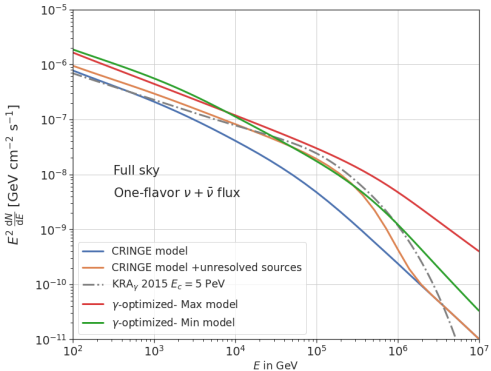

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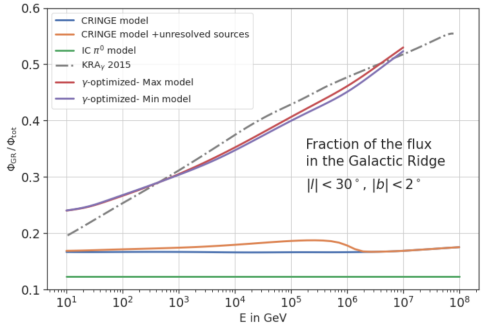


Plot by J.Aublin, and the KRA$_\gamma$ group

Galactic neutrinos

So, Milky Way neutrinos are there

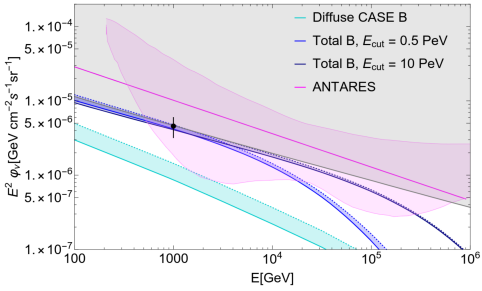
- Interestingly, the best fit from ANTARES is above the CR propagation models – even though its uncertainties are rather large
  - And it's above the IceCube best fit
- On the contrary, the IceCube results are a factor $\sim$2 below the CR models for KRA-models, while above the π^0 model

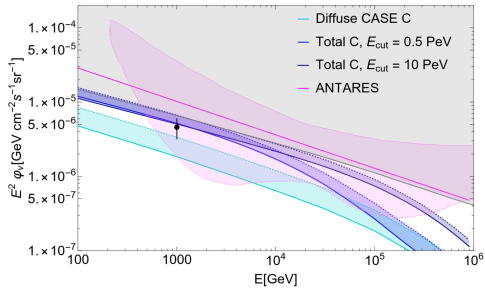
This has triggered some further investigations (see References III for a few of such studies).

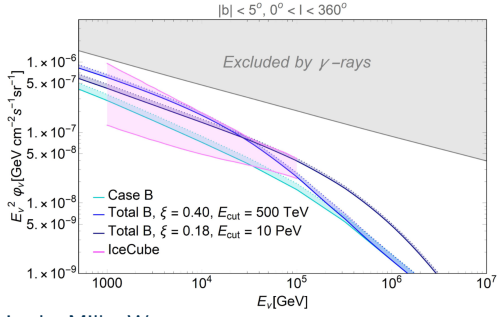
Diffuse and sources

Just one example (V. Vecchiotti, G. Pagliaroli, F. Villante, 2023)

- They estimate the neutrino flux from diffuse (i.e. CR propagation) and CR sources
- Compare it to ANTARES (Galactic Ridge)
- And to IceCube (Templates)


Diffuse CASE B
Total B, E_{cut} = 0.5 PeV
Total B, E_{cut} = 10 PeV
ANTARES
$E^2\,\varphi_\nu$[GeV cm^{-2}s^{-1}sr^{-1}]
E[GeV]

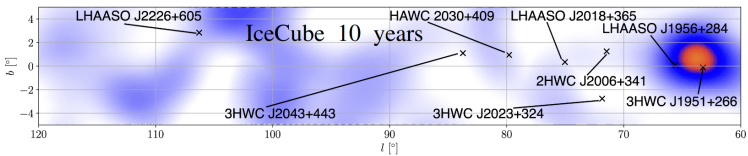

Diffuse CASE C
Total C, E_{cut} = 0.5 PeV
Total C, E_{cut} = 10 PeV
ANTARES
$E^2\,\varphi_\nu$[GeV cm^{-2}s^{-1}sr^{-1}]
E[GeV]


|b| < 5°, 0° < l < 360°
Excluded by γ−rays
Case B
Total B, ξ = 0.40, E_{cut} = 500 TeV
Total B, ξ = 0.18, E_{cut} = 10 PeV
IceCube
$E_\nu^2\,\varphi_\nu$[GeV cm^{-2}s^{-1}sr^{-1}]
E_ν[GeV]

Galactic neutrinos

What about neutrino sources?

- Not yet observed by either ANTARES [13] or IceCube [14]
- Main target for KM3NeT in the next years



Outlook

- IceCube finally found Galactic neutrinos!
- LHAASO and HAWC are already studying possible PeVatrons!

There is a lot we can get to know from this

- How do CRs behave away from Earth?
- How much do we not (still) see?
- Which sources?

References I

- 12-years Fermi-LAT results: S. Abdollahi et al. [Fermi-LAT], Astrophys. Journ. S **260**: 53 (2022)
- A. Albert et al. [HAWC], Astrophys. Journ. **905**: 76 (2020)
- K. Malone et al. [HAWC], PoS(**ICRC2023**)698
- LHAASO Skymap: Z. Cao et al. [LHAASO], Nature **594**: 33-39 (2021)
- First LHAASO Catalog: Z. Cao et al. [LHAASO], https://doi.org/10.48550/arXiv.2305.17030
- LHAASO Diffuse Emission: Z. Cao et al. [LHAASO], https://doi.org/10.48550/arXiv.2305.05372
- KRA models: D. Gaggero et al., Astrophys. Journ. Lett. **815**: L25 (2015)
- ANTARES Galactic Ridge: A. Albert et al [ANTARES], Phys. Lett. B **841**, 137951 (2023)

References II

- IceCube Galactic Plane: R. Abbasi et al. [IceCube], Science **380**, 6652 (2023)
- ANTARES template: T. Cartraud et al. [ANTARES], PoS(**ICRC2023**)1084
- CRINGE: G. Schwefer et al., Astrophys. Journ. **949**: 16
- KRA: P. De La Torre Luque et al., Front. Astron. Space Sci 9 (2022) and P. De La Torre Luque et al., Astron. & Astrophys. **672**: A58 (2023)
- ANTARES point sources: G. Illuminati et al. [ANTARES], PoS(**ICRC2023**)1128
- IceCube point sources: R. Abbasi et al. [IceCube], Phys. Rev. Lett. **124**: 051103 (2020) and R. Abbasi et al. [IceCube], https://doi.org/10.48550/arXiv.2307.07576
- KM3NeT Galactic Ridge: F. Filippini [KM3NeT], PoS(**IRC2023**)1190

References III

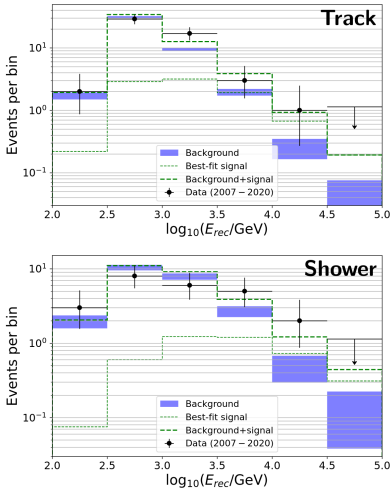
- V. Vecchiotti et al., https://doi.org/10.48550/arXiv.2306.16305 and https://doi.org/10.48550/arXiv.2307.07451
- A. Ambrosone et al., https://doi.org/10.48550/arXiv.2306.17285
- K. Fang et al., https://doi.org/10.48550/arXiv.2307.02905
- K. Yan et al., https://doi.org/10.48550/arXiv.2307.12363
- A. Neronov et al., https://doi.org/10.48550/arXiv.2307.07978

Backup slides

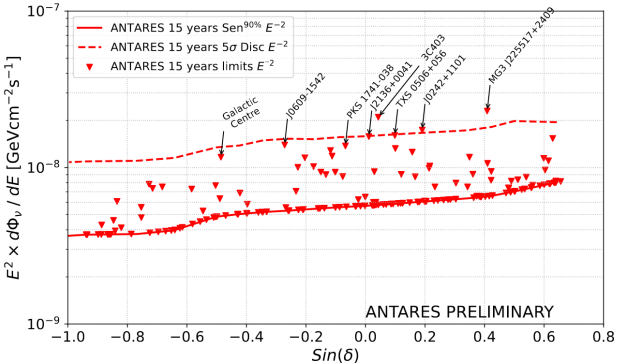
ANTARES Galactic Ridge

ON/OFF analysis [8]

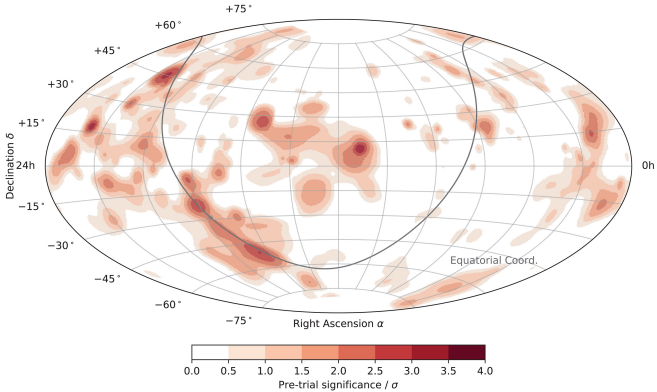
- 2007-2020 data
- Tracks and shower combined
- Excess of data above the average off-region $> 2\sigma$



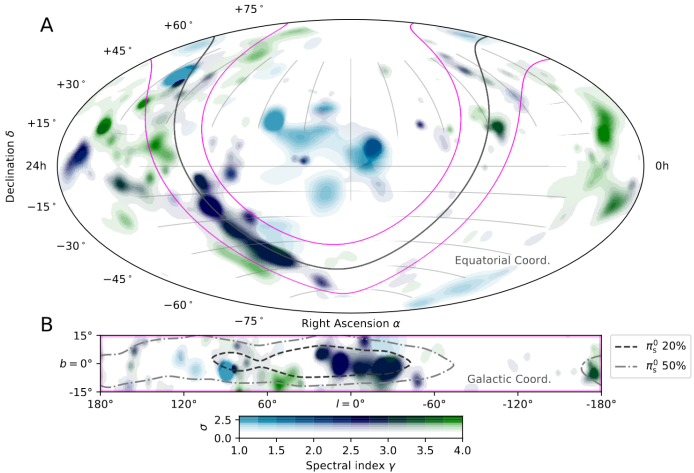
ANTARES 15 years point sources



The IceCube results



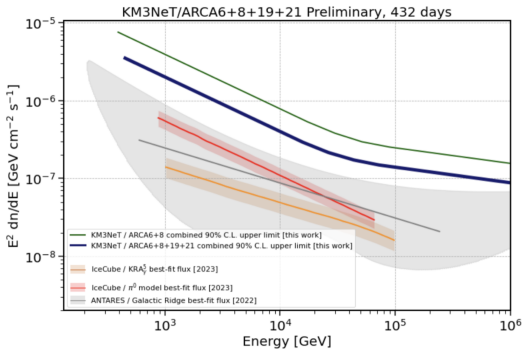
The IceCube results



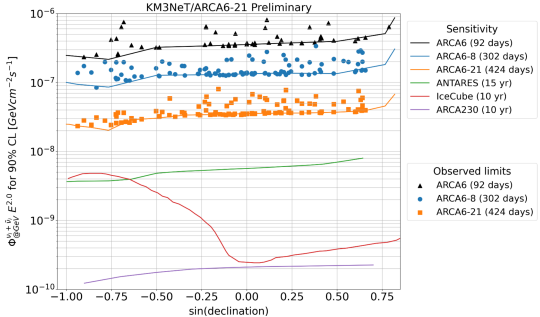
KM3NeT, first results

Search for neutrinos from the Galactic Ridge with the first data from ARCA [15]

- No excess yet
- Short livetime, but already promising results for ARCA21

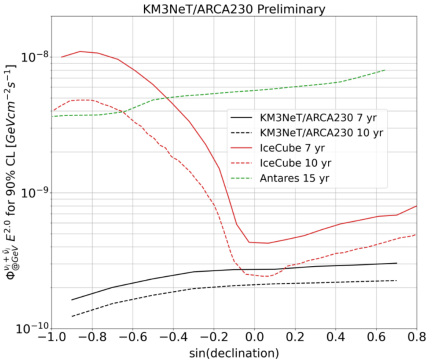


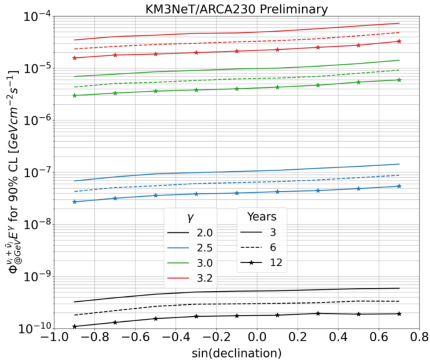
KM3NeT, first results



R. Muller et al. [KM3NeT], PoS(ICRC2023)1018

KM3NeT, expected results





T.J. van Eeden [KM3NeT], PoS(ICRC2023)1075