Galactic neutrinos with ANTARES/KM3NeT

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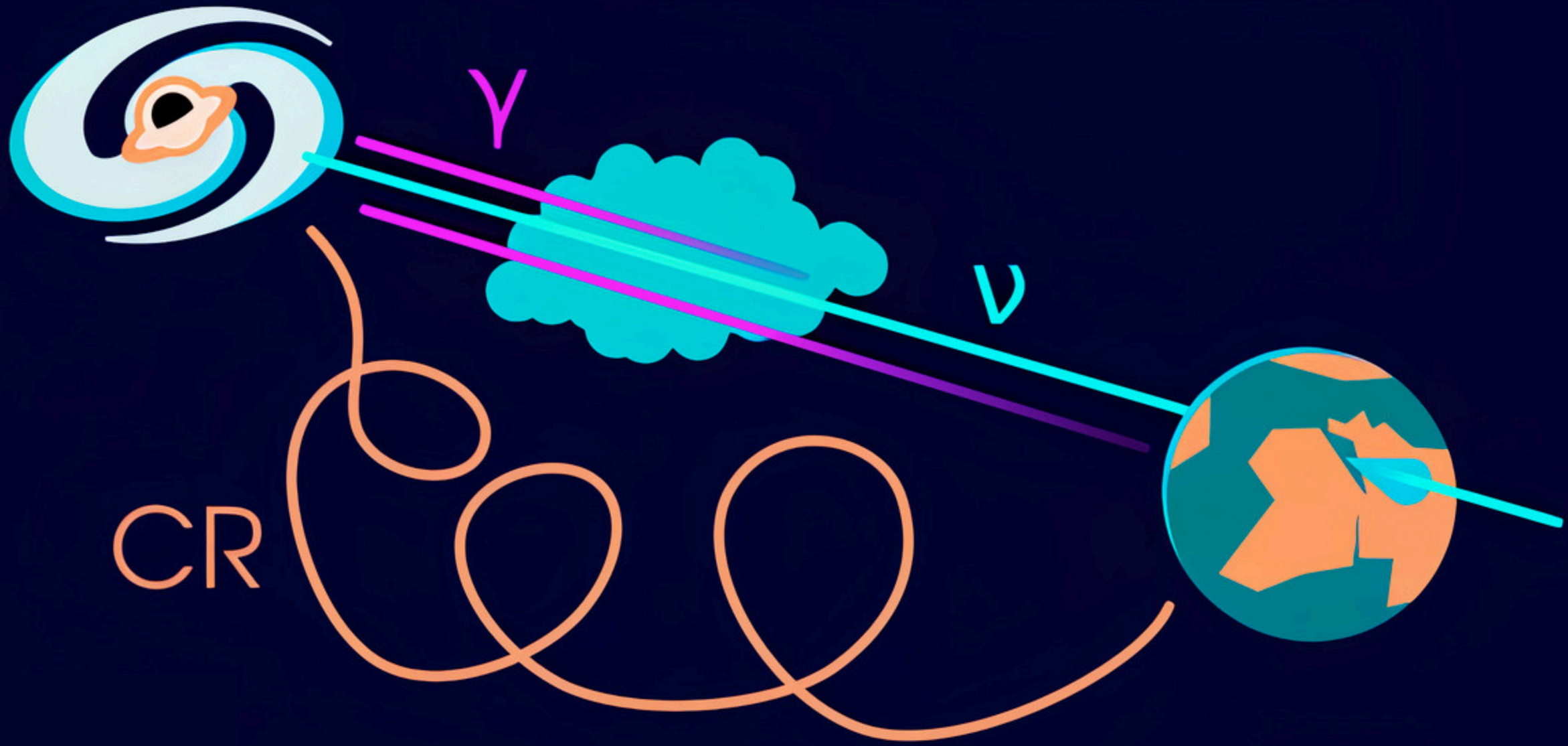

γ
ν
CR

KM3NeT

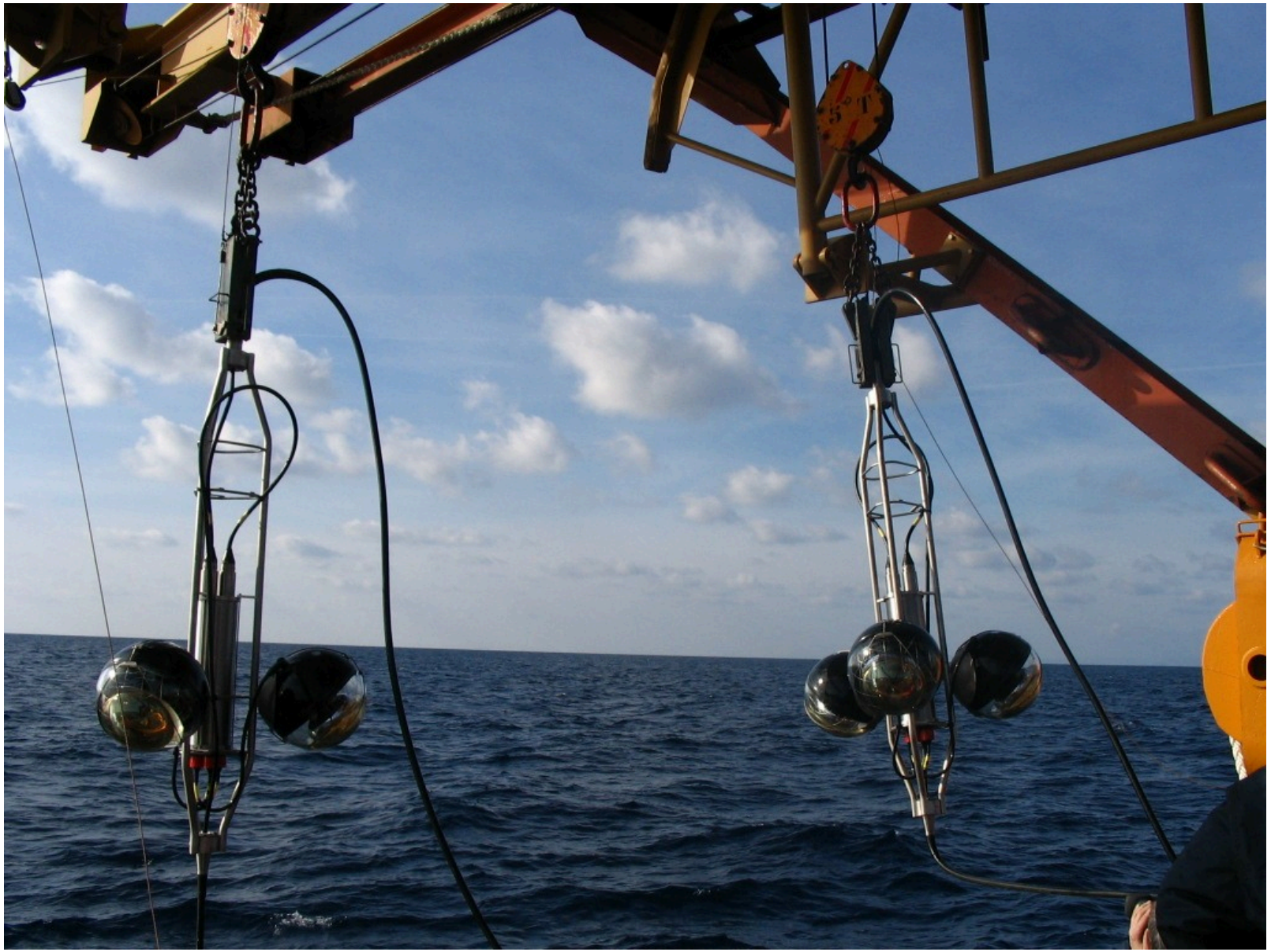
Location : Italy (ARCA) & France (ORCA) - Mediterranean sea

Depth : 2 500 m

Instrumented water volume : 1 km³

Current Status: ARCA28 & ORCA18

ANTARES



ANTARES status

Detector

- 12 detector lines in an octagonal arrangement
- 25 storeys (3 PMTs)

Finaly analysis:

- From February 2007 to its dismantlement in February 2022.
- Legacy ANTARES analysis $\rightarrow$ a full livetime of **4541** days.
- Previous ANTARES analysis: up to February 29th, 2020 $\rightarrow$ livetime of **3845** days. https://arxiv.org/pdf/2212.11876.pdf

1) Do we see neutrinos from the Galactic plane with ANTARES/KM3NeT ?

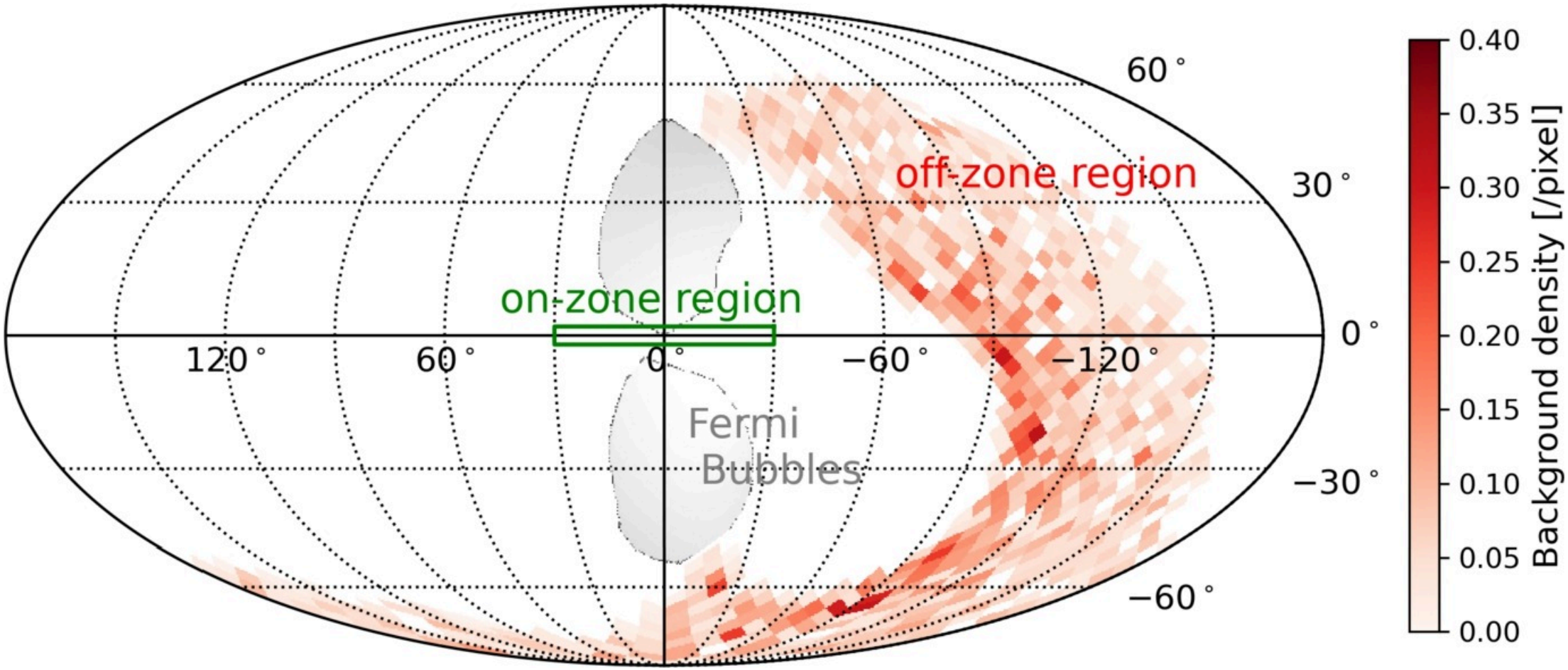
$\rightarrow$ Galactic Ridge Analysis

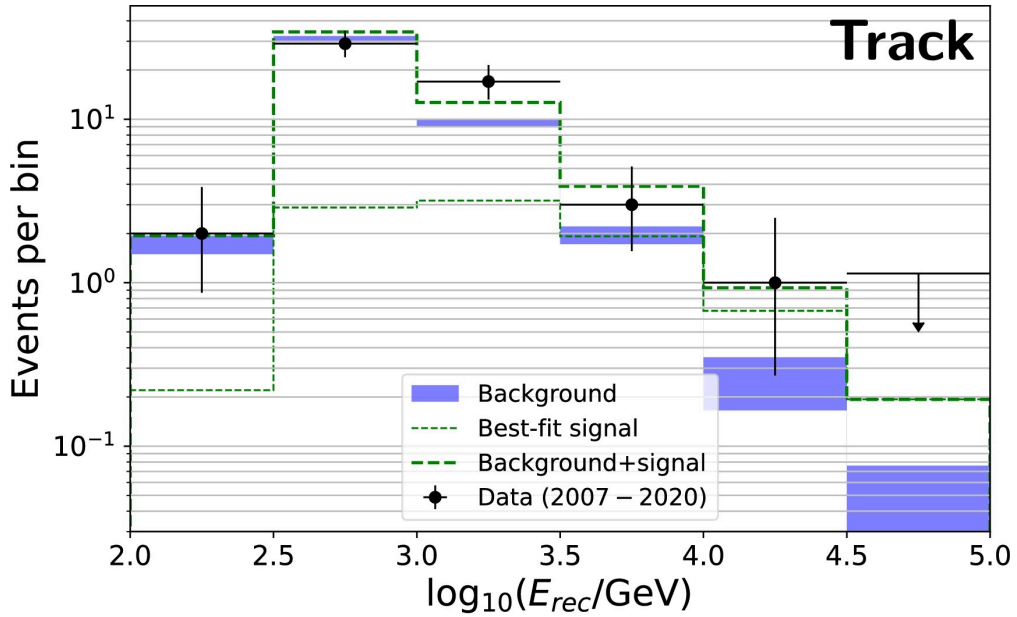
Hint for a TeV neutrino emission from the Galactic Ridge with ANTARES

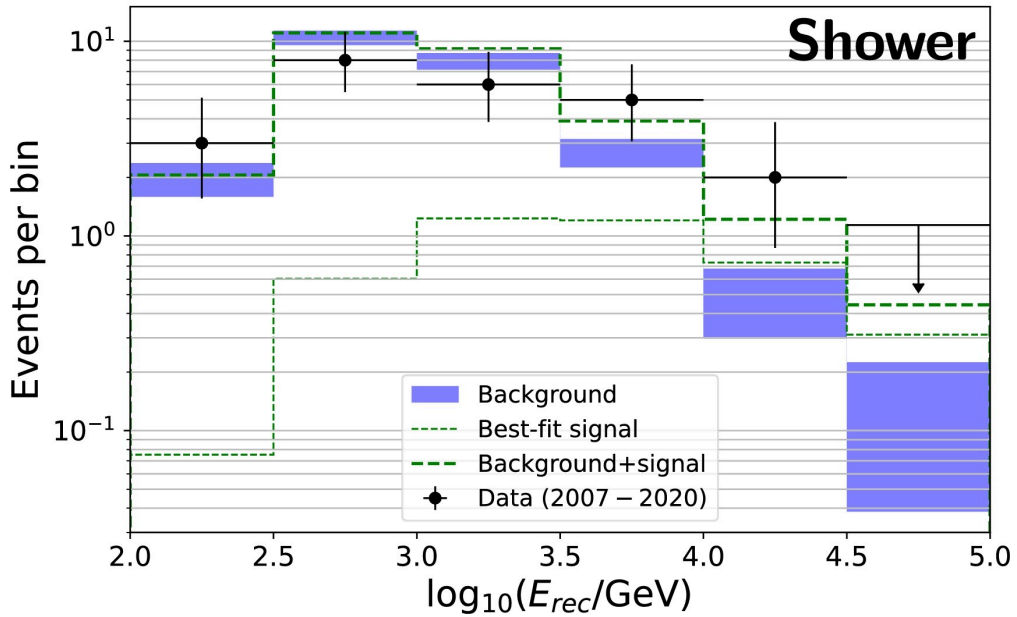
ANTARES Collaboration, Physics Letters B, Volume 841, 2023, 137951

https://arxiv.org/pdf/2212.11876.pdf

On-and-off analysis




Track
Events per bin
10^1
10^0
10^{-1}
Background
Best-fit signal
Background+signal
Data (2007 – 2020)
2.0
2.5
3.0
3.5
4.0
4.5
5.0
$\log_{10}(E_{rec}/\mathrm{GeV})$


Shower
Events per bin
10^1
10^0
10^{-1}
Background
Best-fit signal
Background+signal
Data (2007 – 2020)
2.0
2.5
3.0
3.5
4.0
4.5
5.0
$\log_{10}(E_{rec}/\mathrm{GeV})$

Bayesian analysis

Likelihood:

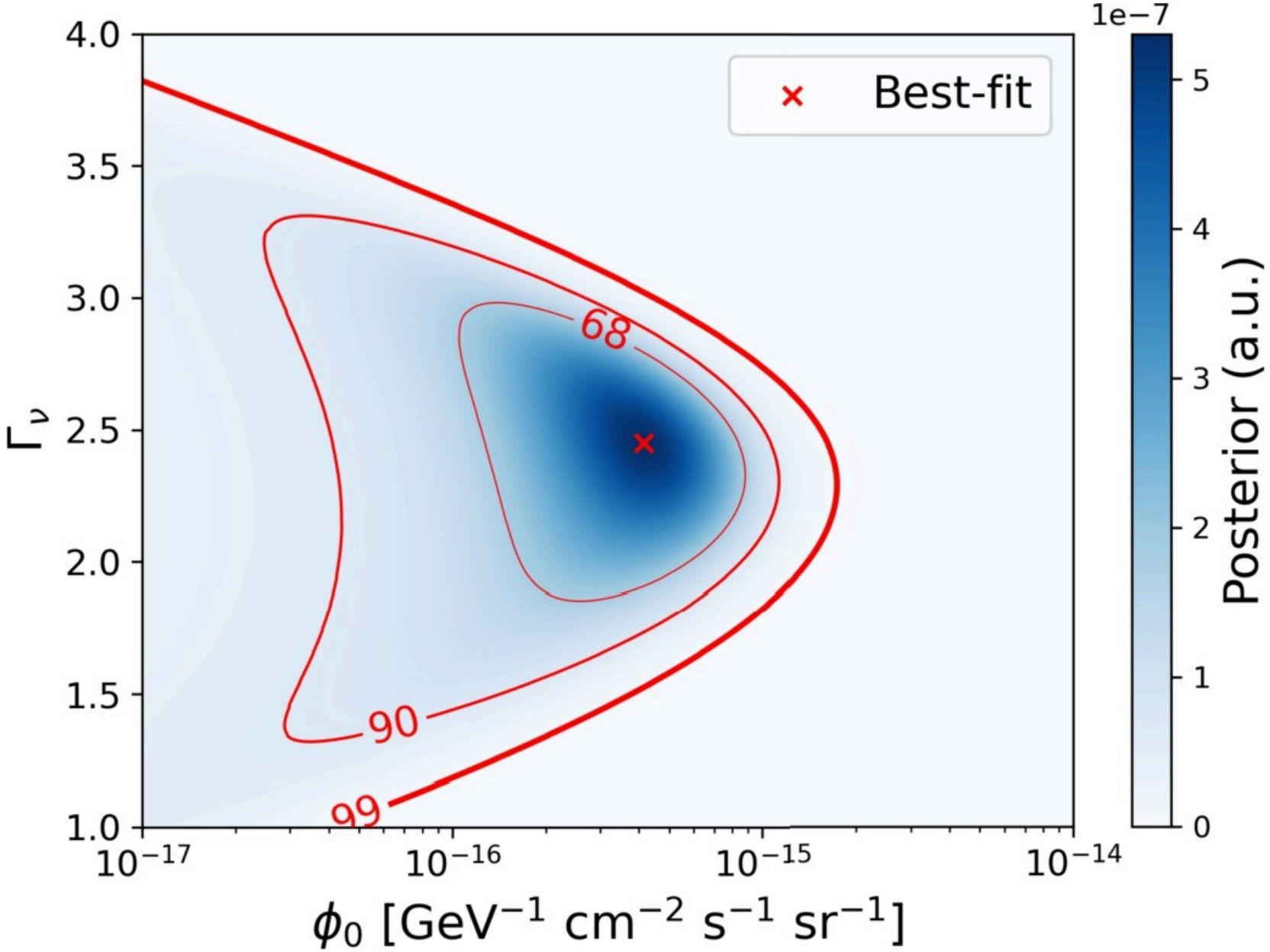
- N_i, $S_i^{(\Gamma_\nu)}$, B_i are respectively the observed number of events, the corresponding expected signal and background in the reconstructed energy bin i.

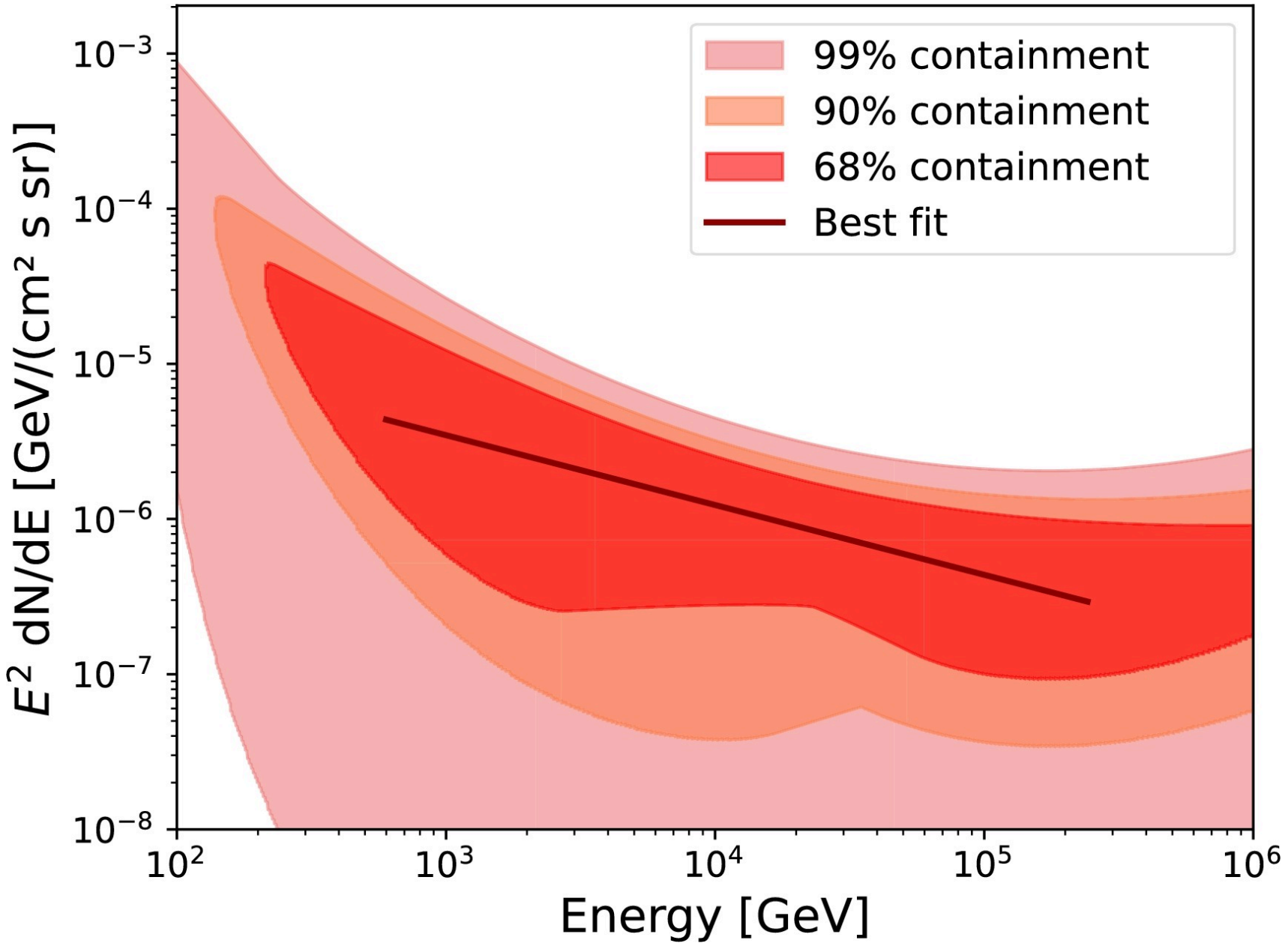
$$\mathcal{L}\left(\{N_i\};\{S_i^{(\Gamma_\nu)}\},\{B_i\},\Phi_0\right) = \prod_{i=1}^{12} \text{Poisson}\left(N_i, B_i + \Phi_0 S_i^{(\Gamma_\nu)}\right)$$

Bayesian analysis

The marginalized posterior distribution:

$$P(\Phi_0, \Gamma_\nu) = \int \mathcal{L}\left(\{N_i\}; \{S_i^{(\Gamma_\nu)}\}, \{B_i\}, \Phi_0\right) \times \pi(\{B_i\}) \times \pi(\{S_i^{(\Gamma_\nu)}\}) \times \pi(\Phi_0, \Gamma_\nu) \times \prod_i (\mathrm{d}B_i \mathrm{d}S_i^{(\Gamma_\nu)})$$


Best-fit
68
90
99
Γ_ν
ϕ_0 [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]
1e−7
Posterior (a.u.)


99% containment
90% containment
68% containment
Best fit
E^2 dN/dE [GeV/(cm² s sr)]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^2
10^3
10^4
10^5
10^6
Energy [GeV]

Search for a diffuse astrophysical neutrino flux from the Galactic Ridge using KM3NeT/ARCA data

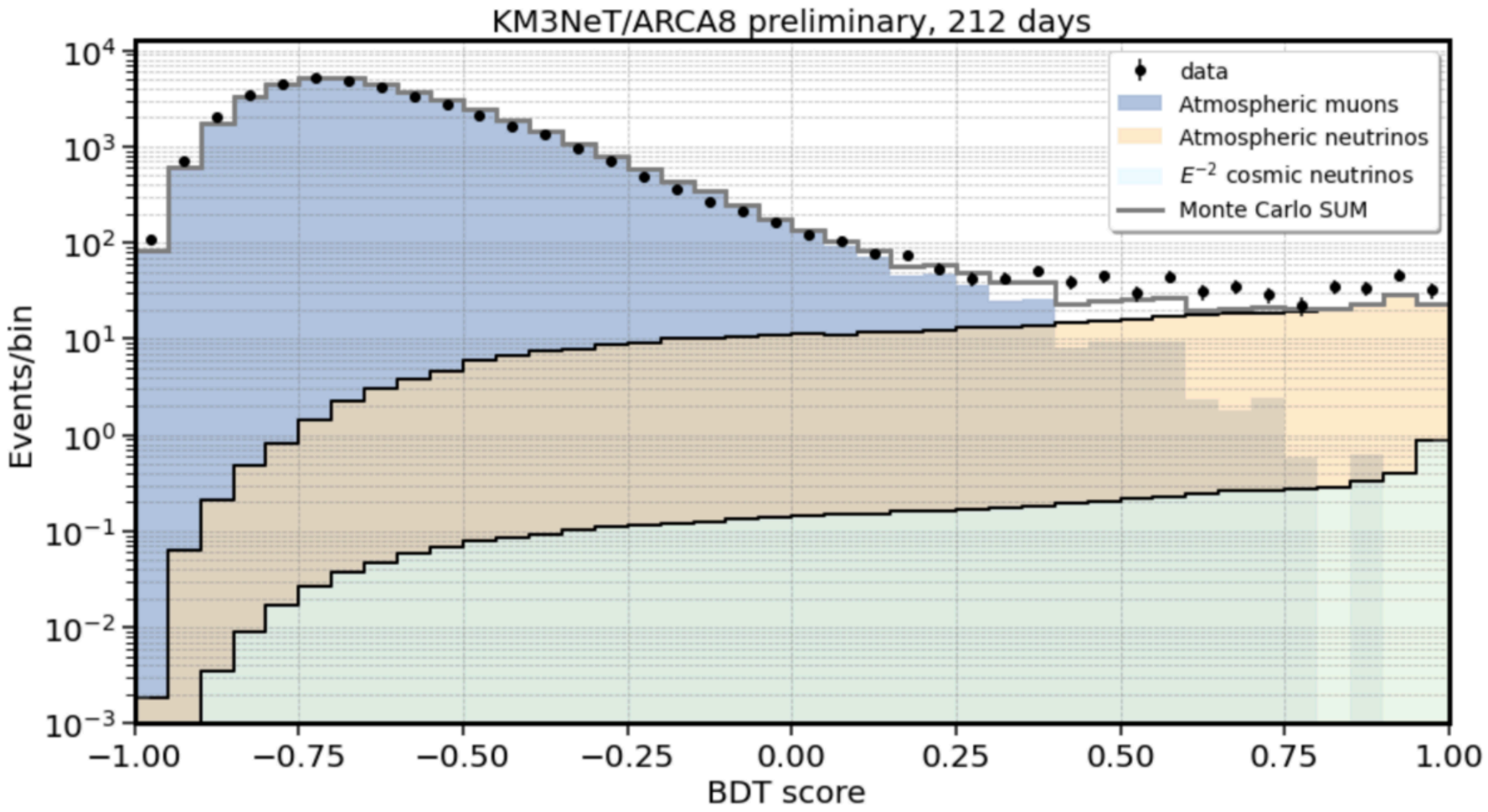
Francesco Filippini, ICRC2023

https://pos.sissa.it/444/1190/pdf

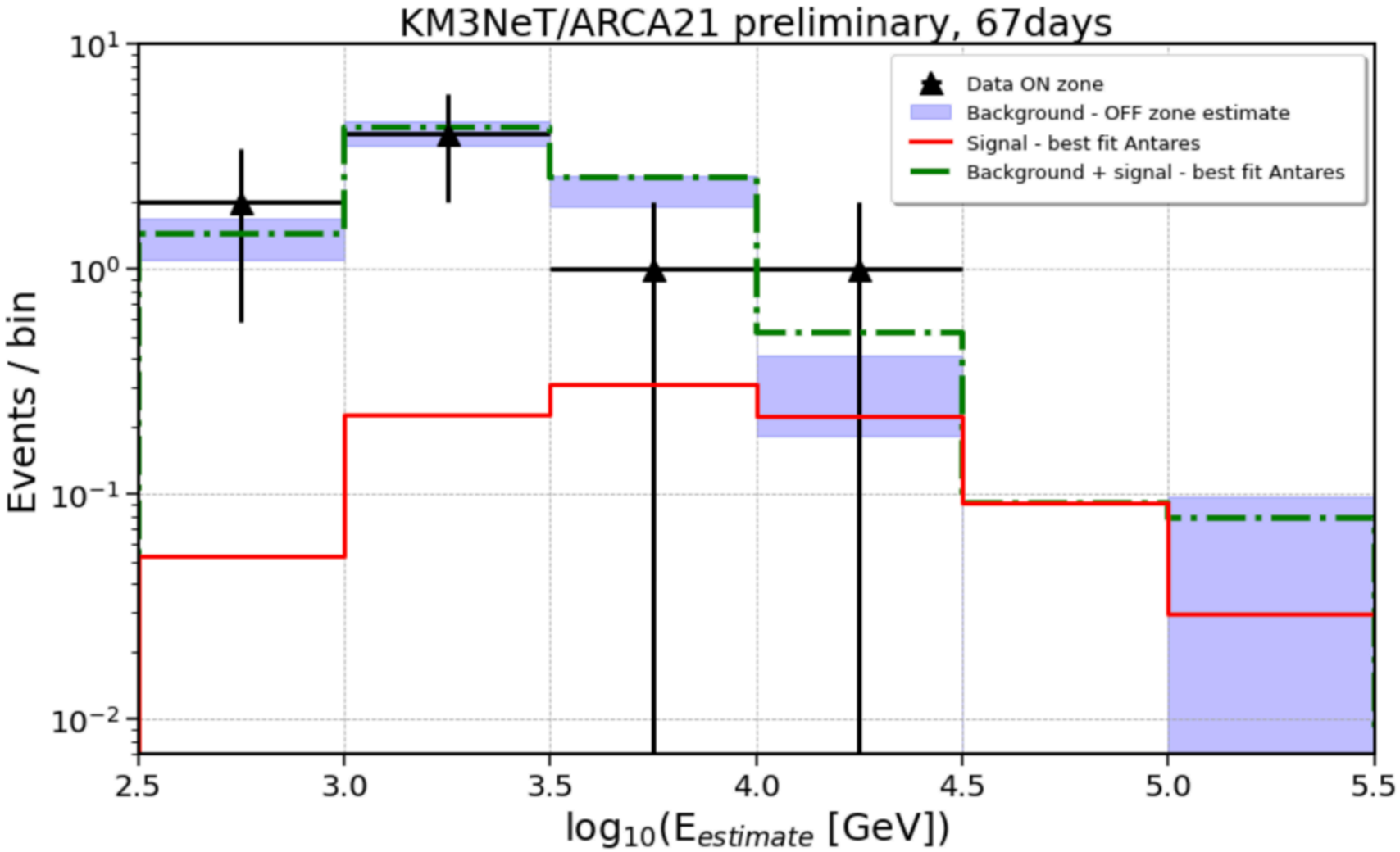
- Same analysis
- ARCA track channel only

BDT (Boosted Decision Tree) score

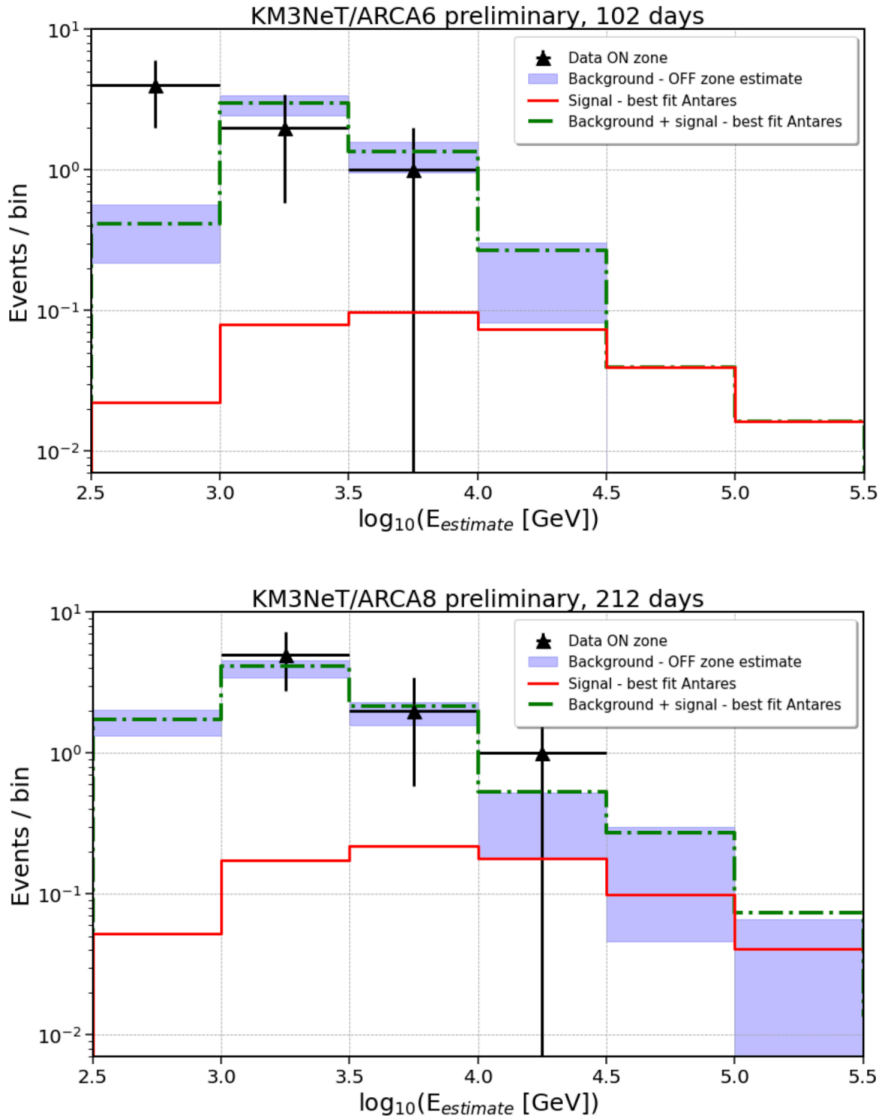
Atmospheric muons vs atmospheric neutrinos



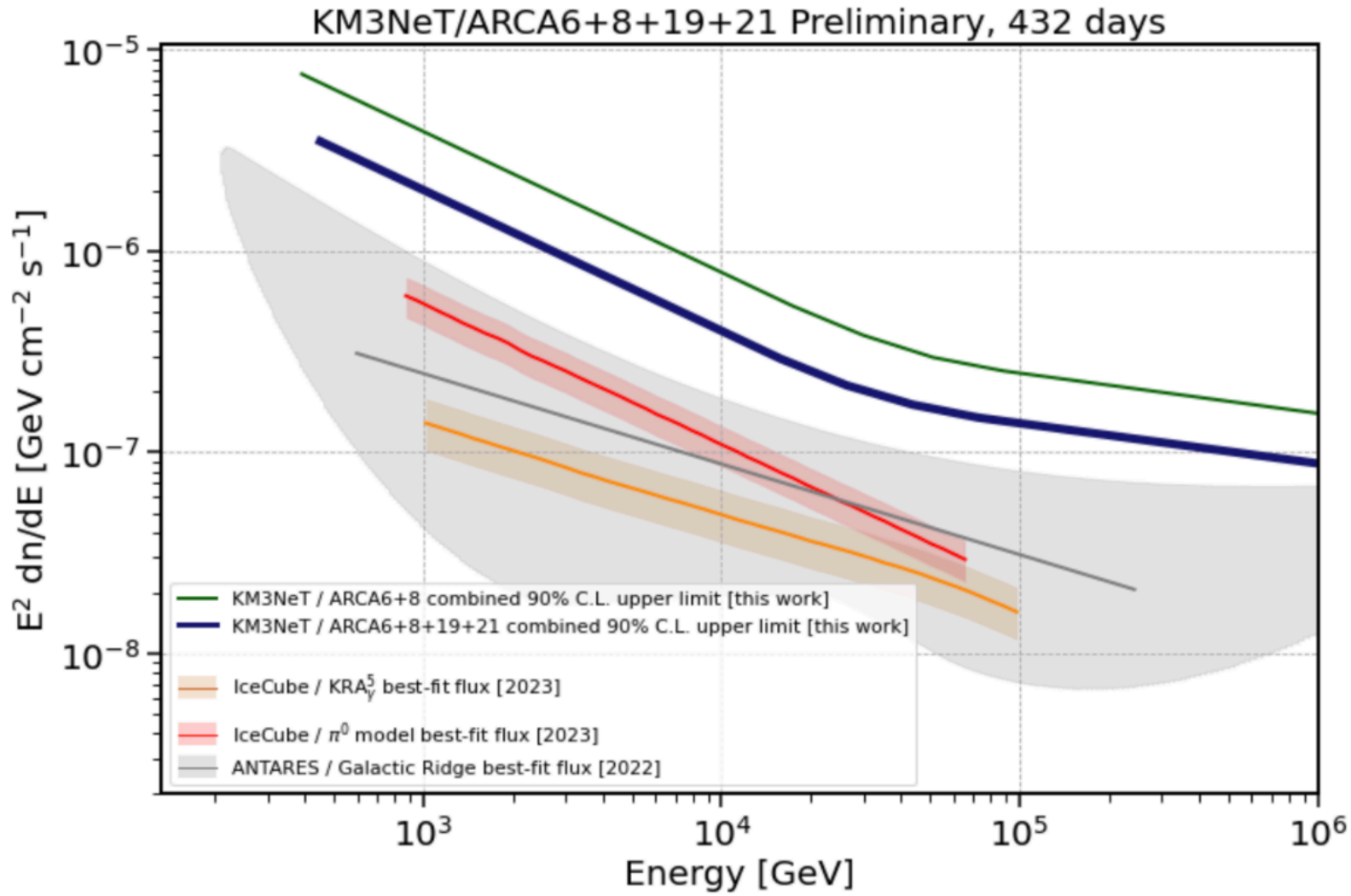
ARCA 21


KM3NeT/ARCA21 preliminary, 67days
Data ON zone
Background - OFF zone estimate
Signal - best fit Antares
Background + signal - best fit Antares
Events / bin
10^{1}
10^{0}
10^{-1}
10^{-2}
2.5
3.0
3.5
4.0
4.5
5.0
5.5
$\log_{10}(E_{estimate}$ [GeV])

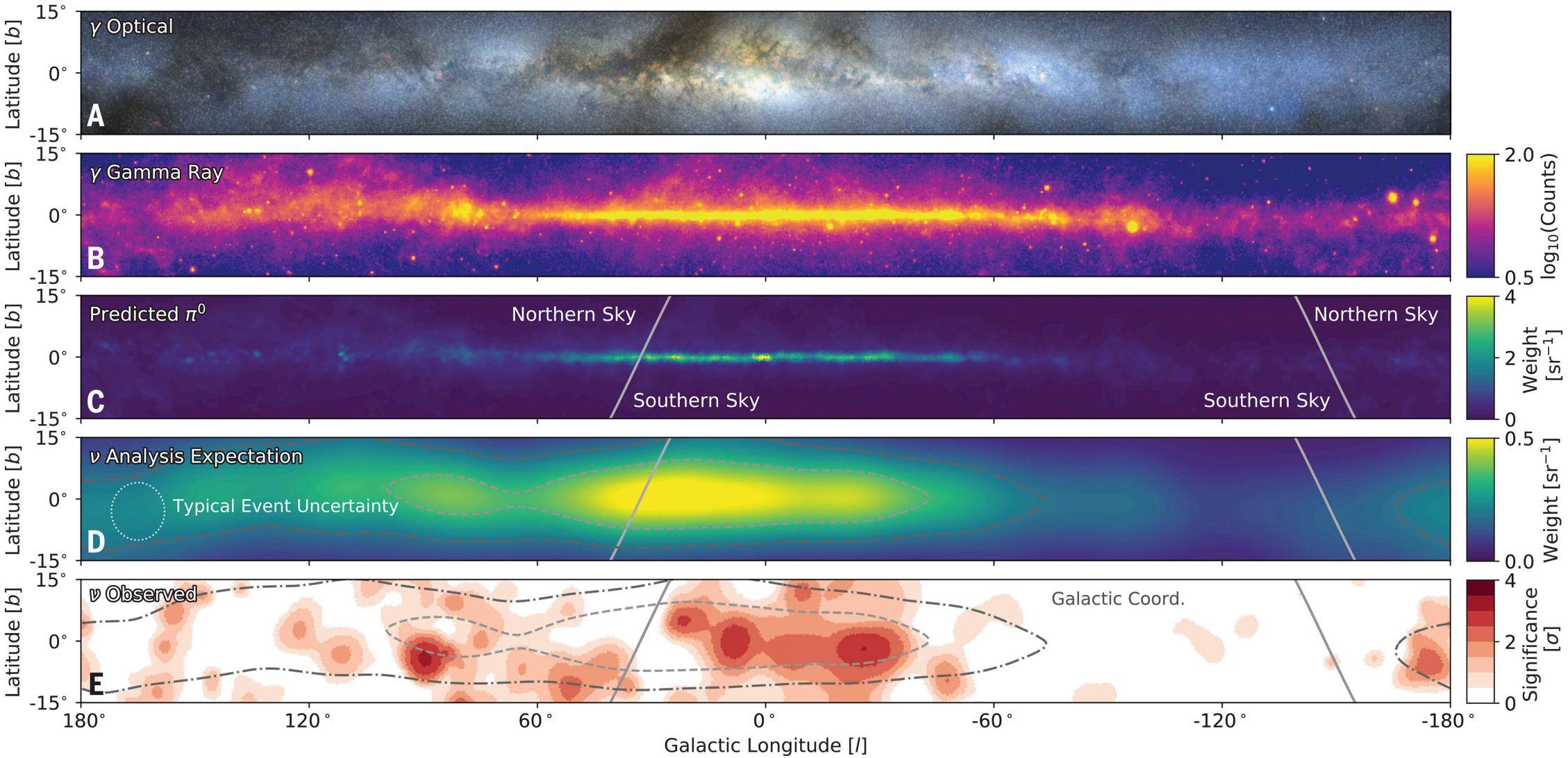
ARCA6 and ARCA8



UL(90%) of ARCA(6+8+19+21)



What about IceCube ?



2) Let's test the KRA-γ template with ANTARES !

Search for a diffuse neutrino emission from the Milky-Way with the ANTARES experiment.

Théophile Cartraud et al., ICRC2023

https://pos.sissa.it/444/1084/pdf

History

- Template framework $\neq$ on-and-off analysis.
- Previous analysis of this kind: **Joint constraints on Galactic diffuse neutrino emission from ANTARES and IceCube**
  https://doi.org/10.48550/arXiv.1808.03531
  $\rightarrow$ 2431 days of ANTARES data set + 7 years of IceCube

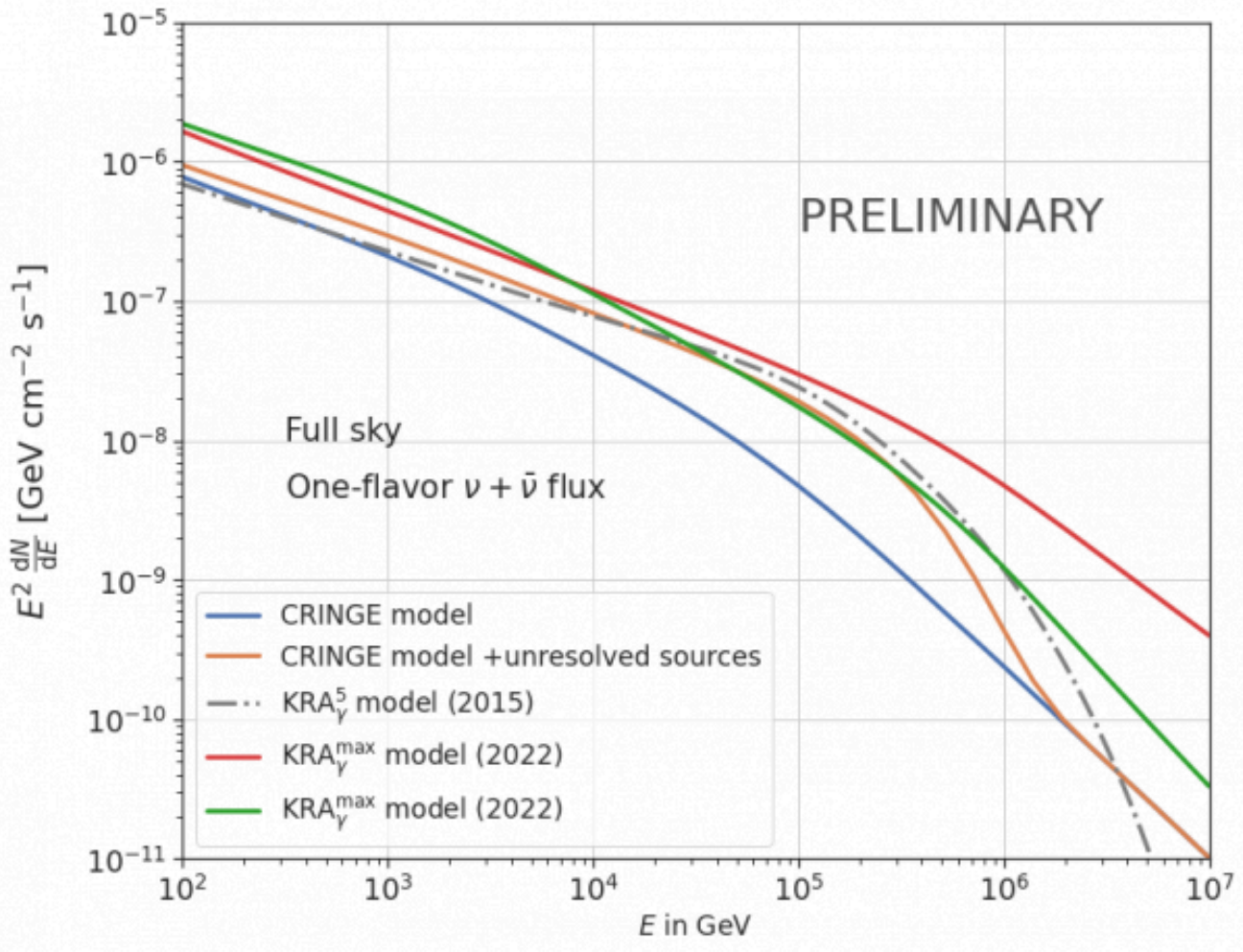
ICRC 2023

- track and shower channels
- 4541 days of ANTARES full data set
- only up to February 2020 for showers

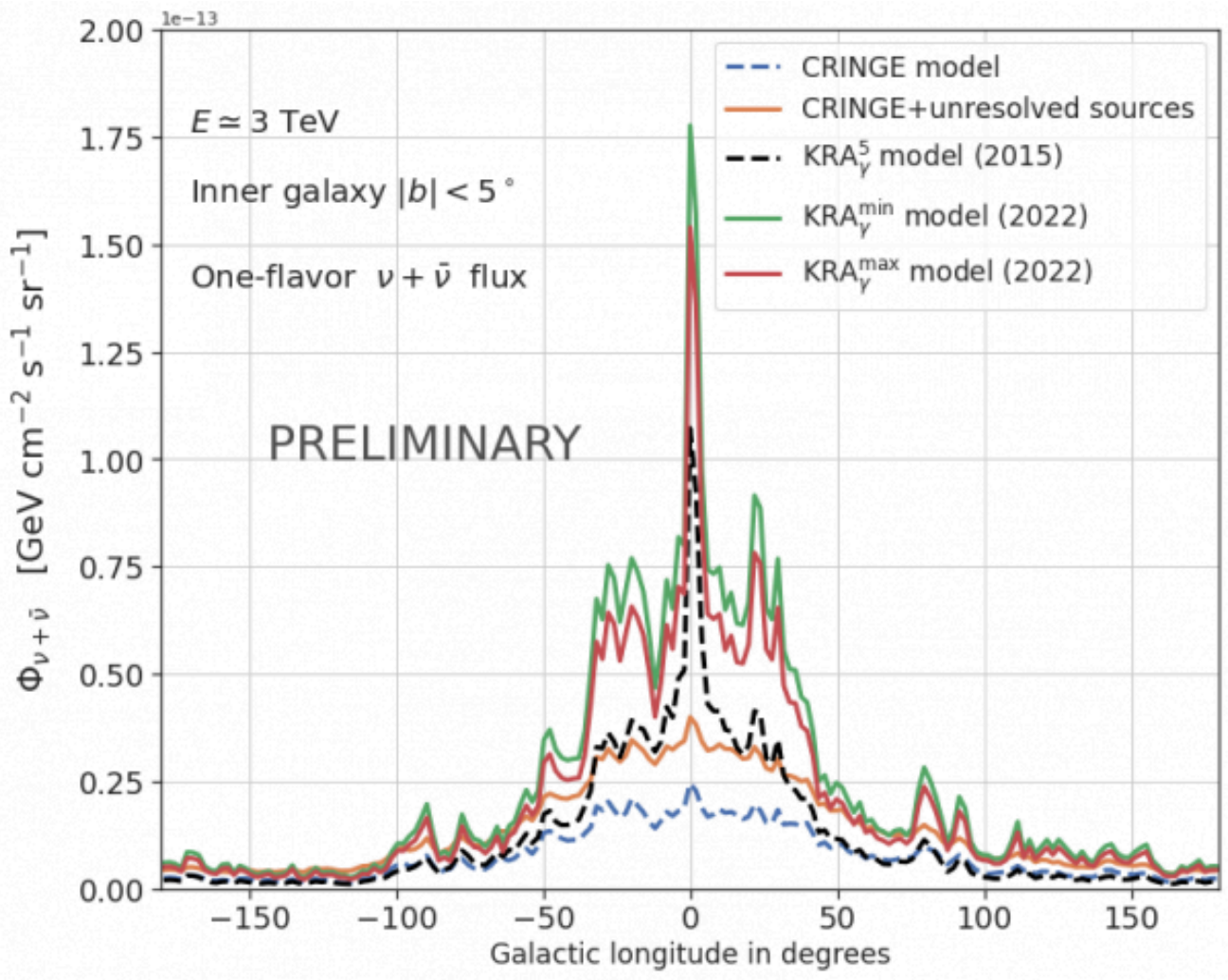
Legacy analysis

- full dataset
- new models tested
- new data cuts (similar to the astrophysical diffuse analysis)
- improved signal PDFs

Model comparison (ICRC 2023)



$\rightarrow$ focus on testing KRA-γ(2023) min/max models.



Flux along the the galactic plane $\rightarrow$ KRA-γ models are more peaked toward the center.

Fine detailed structure.

Likelihood method

- $\mu_s^i = r \times \mu_{\text{model}}^i$ number of signal events in the channel i
- r: flux ratio
- μ_{model}^i: expected number of signal events for the model in the channel i
- μ_b^i: expected number of background events in the channel i

We define a **signed test statistic**:

$$TS = \text{sign}(\hat{r}) \times \left\{ \mathcal{L}_{H_1}(\hat{r}, \hat{\boldsymbol{\mu}}_{\boldsymbol{b}}) - \mathcal{L}_{H_0}(\hat{\boldsymbol{\mu}}_{\boldsymbol{b}}) \right\}$$

Definition of the log-likelihood

$$\mathcal{L}_{H_1}(r, \boldsymbol{\mu_b}) = \sum_{i=1}^{m} \left\{ \sum_{j=1}^{n_i} \log \left[r \times \mu^i_{\text{model}}\, f^i_s(\alpha^i_j, \delta^i_j, E^i_j) + \mu^i_b\, f^i_b(\alpha^i_j, \delta^i_j, E^i_j) \right] - r \times \mu^i_{\text{model}} - \mu^i_b \right\}$$

$$\mathcal{L}_{H_0}(\boldsymbol{\mu_b}) = \sum_{i=1}^{m} \left\{ \sum_{j=1}^{n_i} \log \left[\mu^i_b\, f^i_b(\alpha^i_j, \delta^i_j, E^i_j) \right] - \mu^i_b \right\}$$

- for the signal likelihood, only m+1 parameters are minimized (can be reduced to 1 in case of hard convergence cases ($r < 0$)) by applying $\mu^i_s + \mu^i_b = n_i$.
- for the background likelihood, m parameters are minimized.

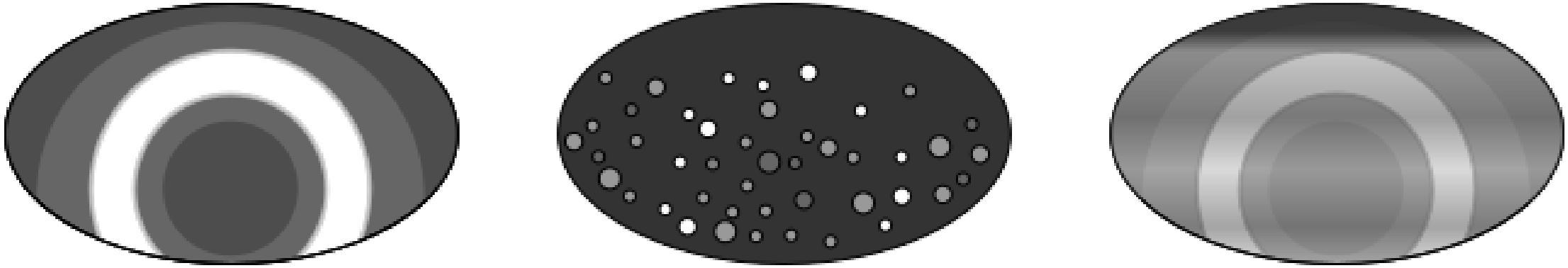
Definition of the log-likelihood

$$\mathcal{L}_{H_1}(r, \boldsymbol{\mu_b}) = \sum_{i=1}^{m} \left\{ \sum_{j=1}^{n_i} \log \left[r \times \mu^i_{\text{model}}\, f^i_s(\alpha^i_j, \delta^i_j, E^i_j) + \mu^i_b\, f^i_b(\alpha^i_j, \delta^i_j, E^i_j) \right] - r \times \mu^i_{\text{model}} - \mu^i_b \right\}$$

$$\mathcal{L}_{H_0}(\boldsymbol{\mu_b}) = \sum_{i=1}^{m} \left\{ \sum_{j=1}^{n_i} \log \left[\mu^i_b\, f^i_b(\alpha^i_j, \delta^i_j, E^i_j) \right] - \mu^i_b \right\}$$

- The PDF is NOT a product of $f(E)$ and $g(\alpha, \delta)$ as $g(\alpha, \delta)$ clearly depends of the energy.
- Hence the PDF is built as a piecewise function of energy

Signal PDFs: diffuse templates

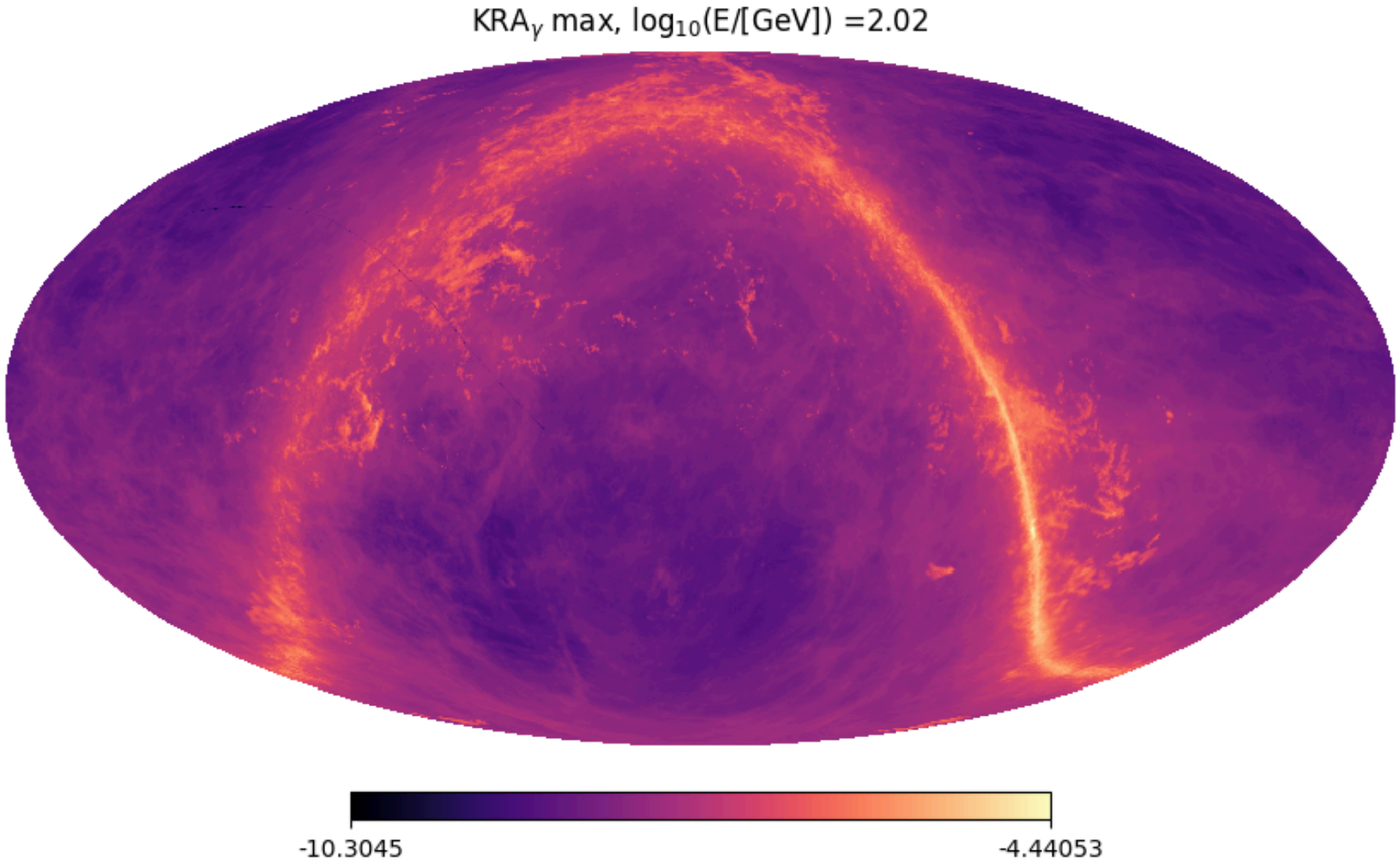


left: full-sky diffuse template. Ex: KRA-γ or Fermi-LAT model

middle: MC events are evaluated within the template

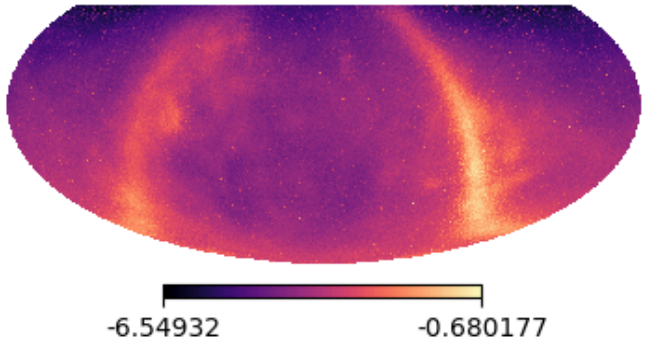
right: PDF that naturally convolves ANTARES response (MC events) and template.

KRAγ max template

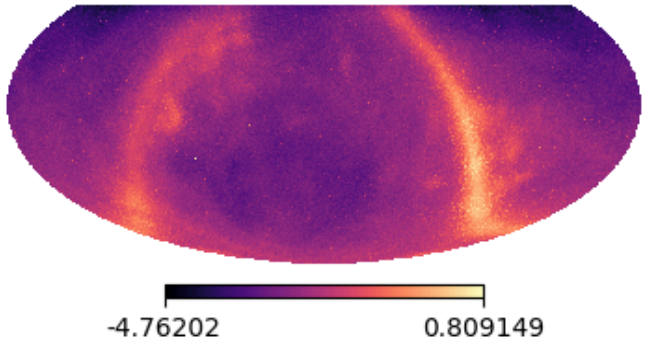


Shower Signal PDFs: KRAγ max

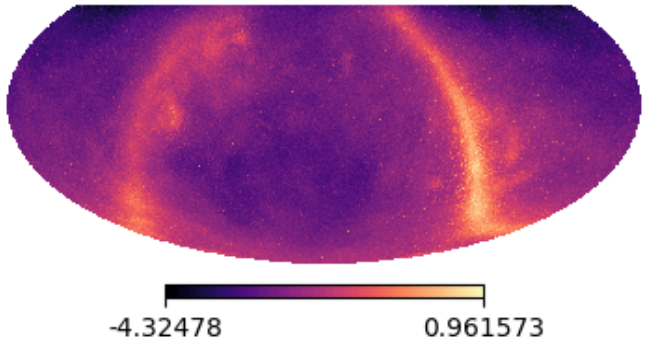
$\log_{10}$E/[GeV] = [2.50, 3.08[



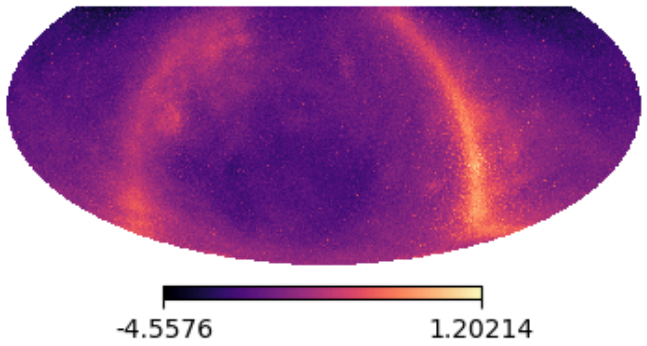
$\log_{10}$E/[GeV] = [3.08, 3.67[



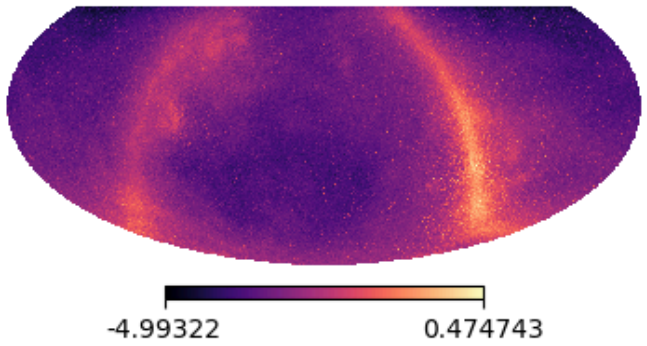
$\log_{10}$E/[GeV] = [3.67, 4.25[



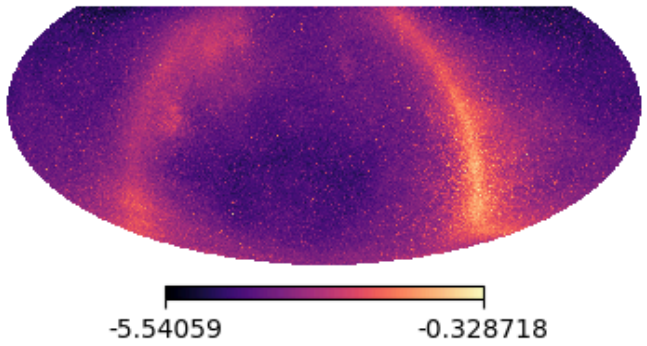
$\log_{10}$E/[GeV] = [4.25, 4.83[



$\log_{10}$E/[GeV] = [4.83, 5.42[

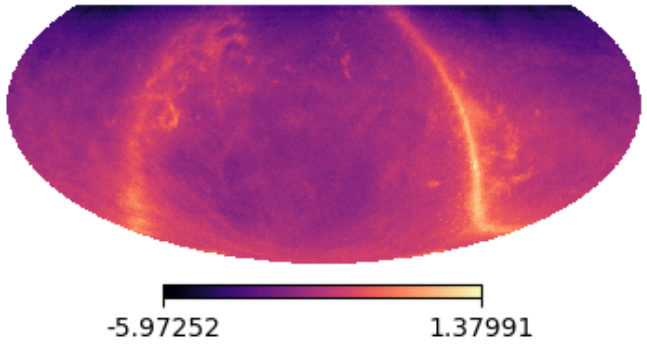


$\log_{10}$E/[GeV] = [5.42, 6.00[

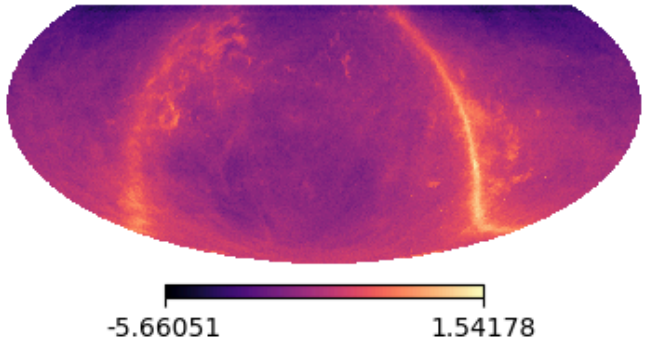


Track signal PDFs (KRAγ max)

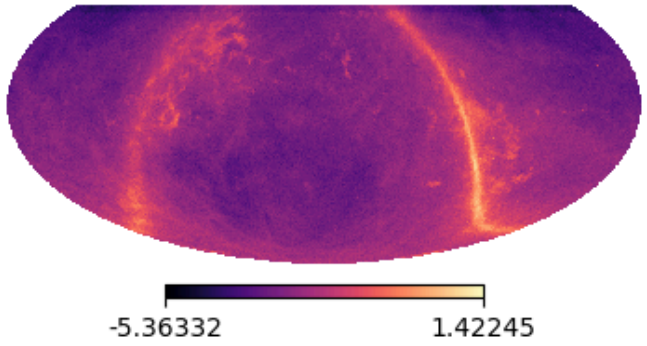
$\log_{10}$E/[GeV] = [2.50, 3.08[



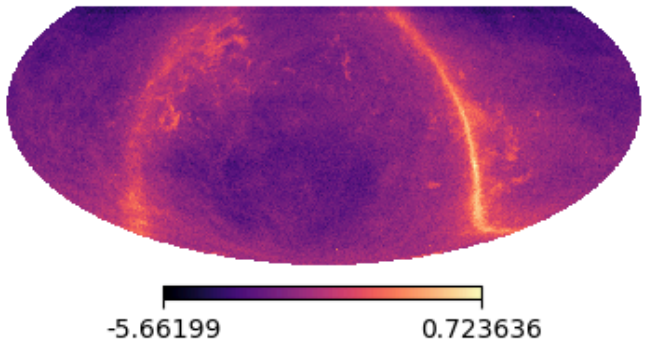
$\log_{10}$E/[GeV] = [3.08, 3.67[



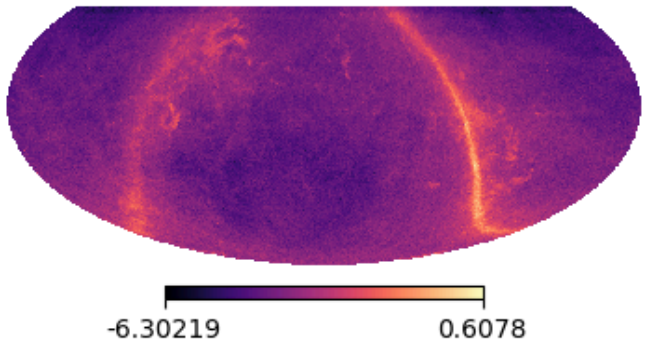
$\log_{10}$E/[GeV] = [3.67, 4.25[



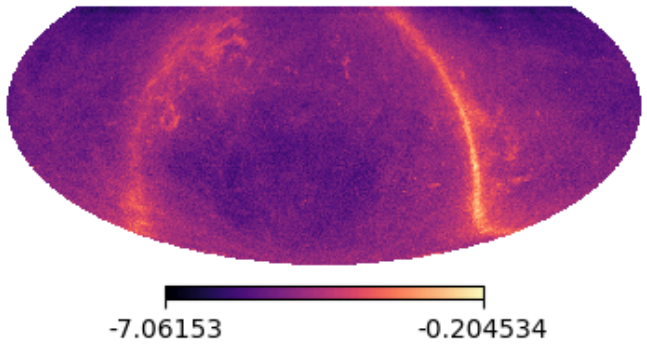
$\log_{10}$E/[GeV] = [4.25, 4.83[



$\log_{10}$E/[GeV] = [4.83, 5.42[



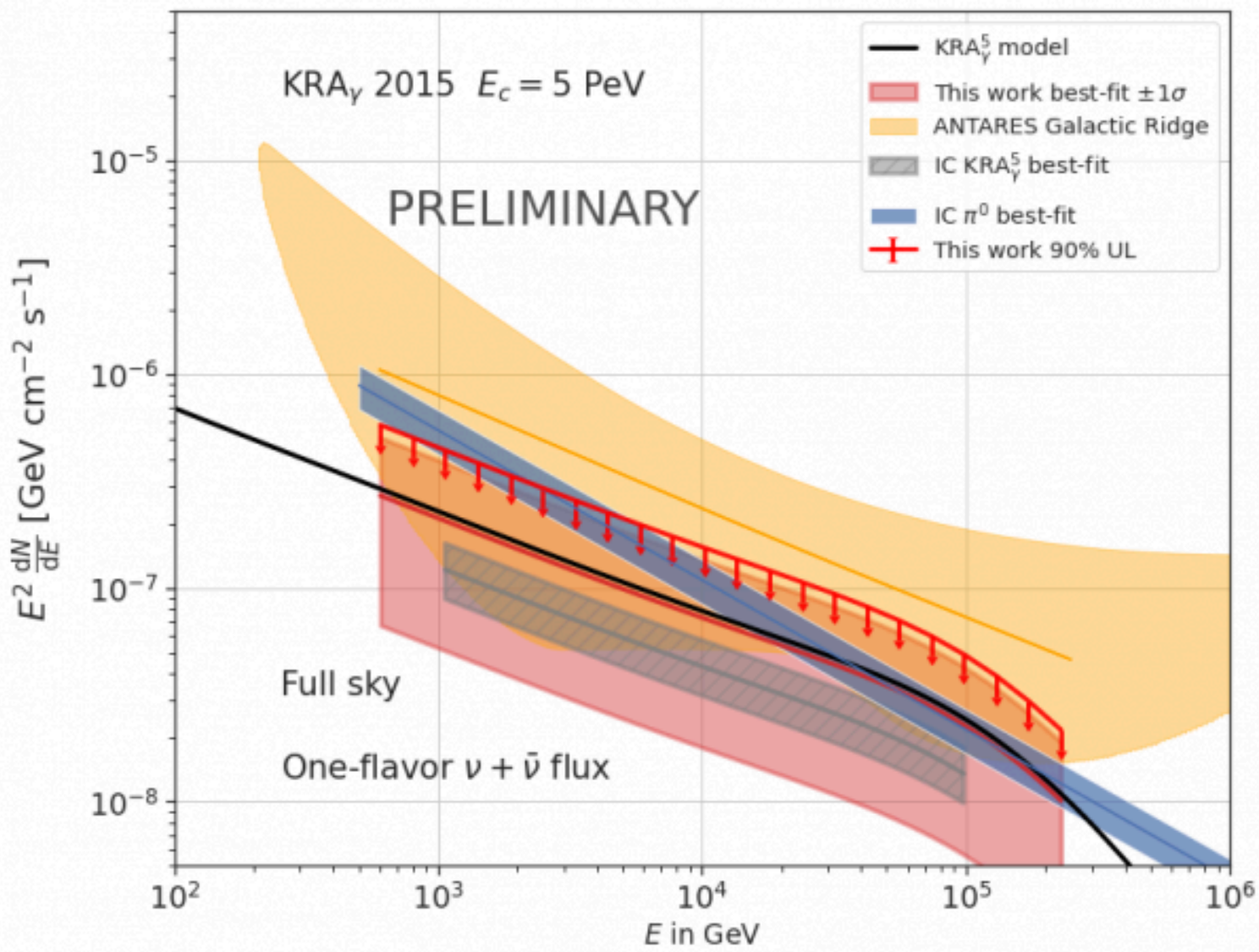
$\log_{10}$E/[GeV] = [5.42, 6.00[



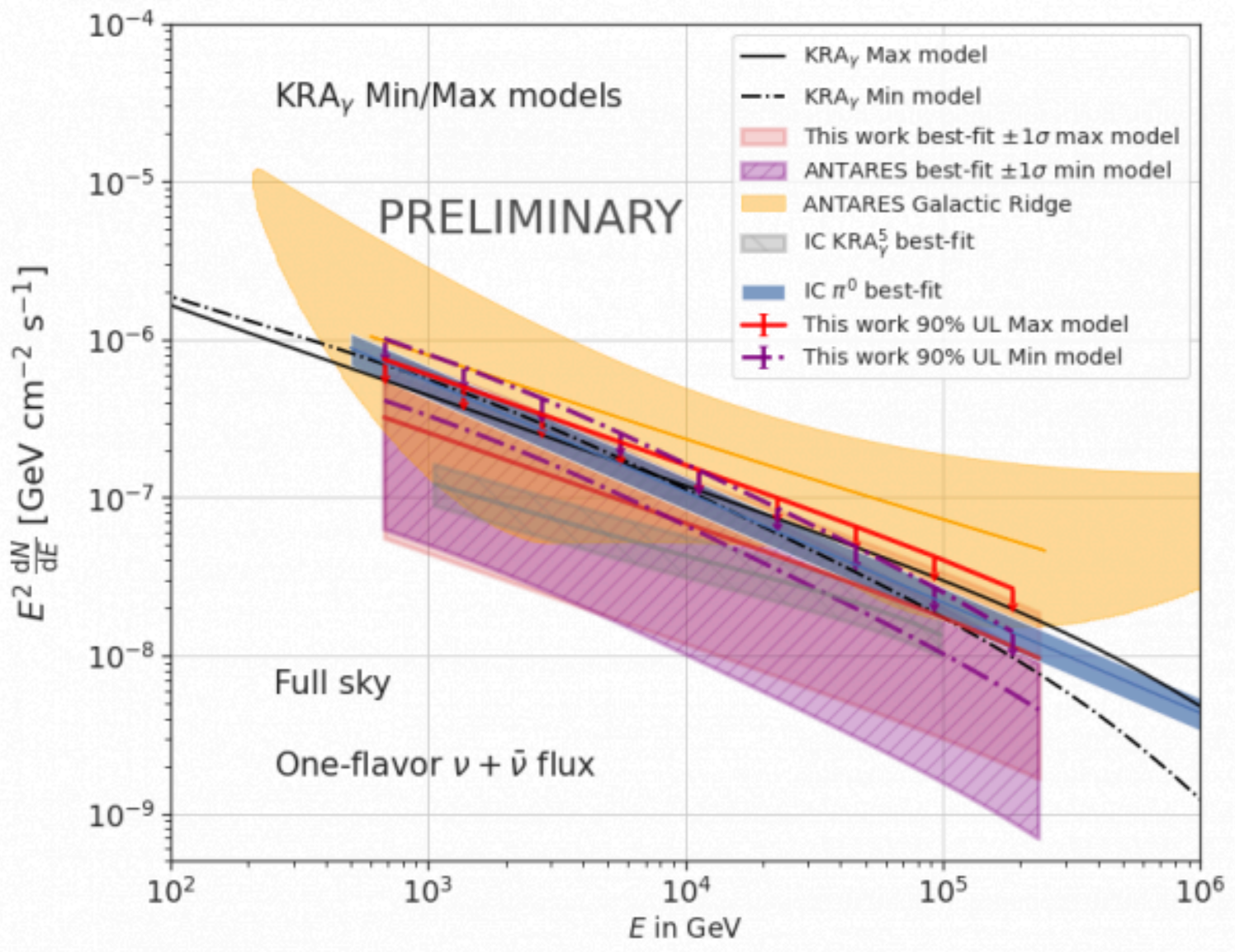
ICRC 2023 results

Model	r^{fit}	μ_s^{fit} (tr/sh)	TS	p-value	z-score (post-trial)	UL $90(r)$
KRA$_\gamma$ max	$0.58^{+0.55}_{-0.48}$	9.6/6.7	0.77	$9.80 \cdot 10^{-2}$	1.65σ (1.56σ)	1.35
KRA$_\gamma$ min	$0.59^{+0.57}_{-0.50}$	9.3/7.2	0.73	$1.06 \cdot 10^{-1}$	1.62σ (1.51σ)	1.45
KRA$_\gamma$ old	$0.93^{+0.81}_{-0.70}$	10.2/6.8	0.95	$7.40 \cdot 10^{-2}$	1.79σ (1.70σ)	1.99
CRINGE+UR	$1.08^{+1.18}_{-1.07}$	11.6/8.4	0.50	$1.47 \cdot 10^{-1}$	1.45σ (1.34σ)	2.64
CRINGE	$1.58^{+2.46}_{-1.58}$	8.5/6.8	0.24	$2.35 \cdot 10^{-1}$	1.19σ (1.09σ)	4.57

KRAγ (2015, cutoff at 5 PeV)



KRAγ Min and Max



3) Let's try new models...

Unresolved contribution to the Galactic flux

Aim: to better understand unresolved contribution to the galactic flux

- CRINGE (ICRC2023)
- CENTAURS (*Cosmic Emission of Neutrinos at TeV Arriving from UnResolved Sources*) - Vecchiotti et al. (Legacy)
  Probing galactic cosmic ray distribution with TeV gamma-ray sky
  https://doi.org/10.48550/arXiv.1904.03894

Different diffuse fluxes but same unresolved contribution.

Comparison with ANTARES

Vittoria Vecchiotti et al., ICRC2023 https://pos.sissa.it/444/1089

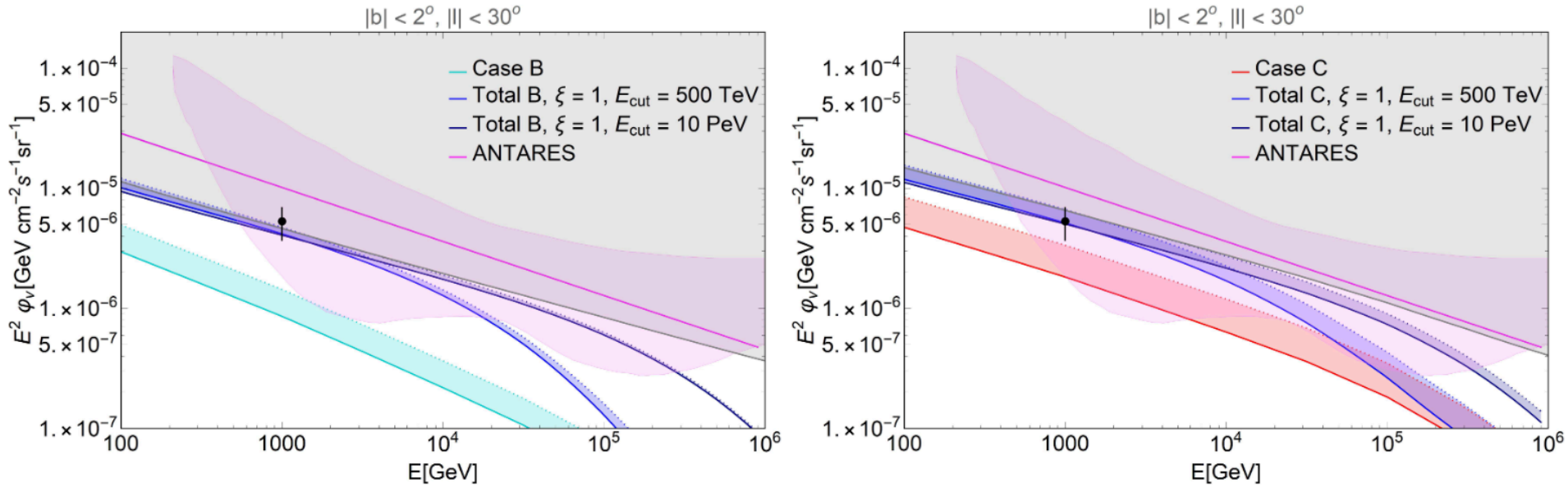


Figure 1: *Differential energy spectra of diffuse neutrino from the Galactic plane in the angular regions probed by ANTARES. See text for details.*

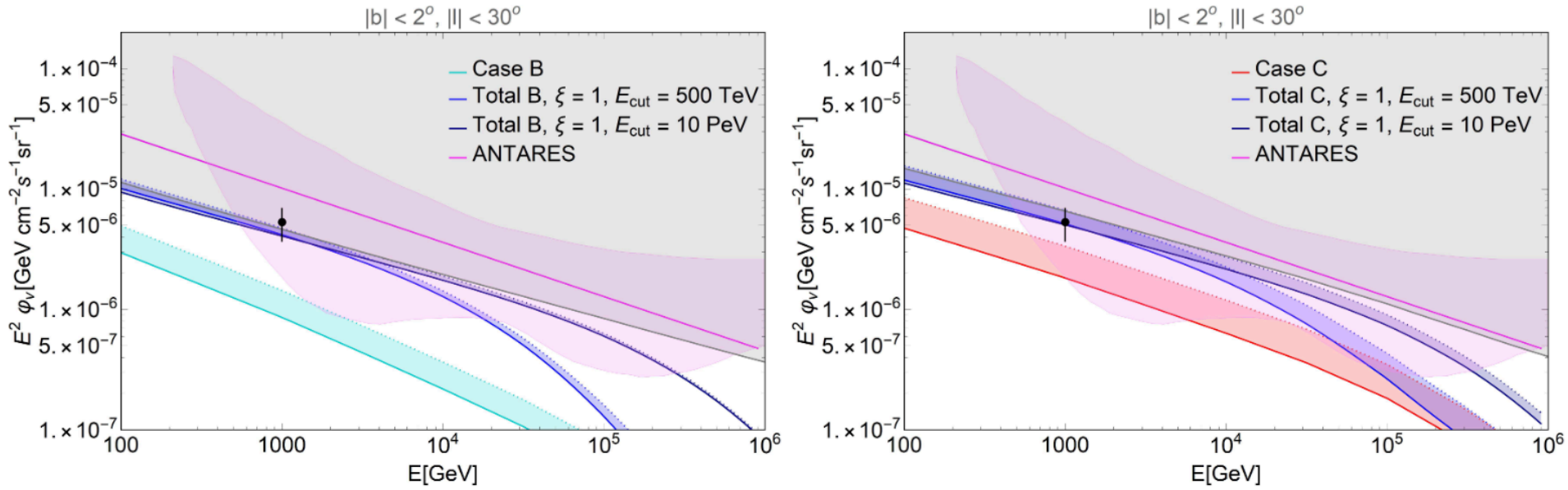


Figure 1: *Differential energy spectra of diffuse neutrino from the Galactic plane in the angular regions probed by ANTARES. See text for details.*

- Case B: homogeneous CR spectral index. Even with unresolved contribution $\rightarrow$ bellow ANTARES best fit.
- Case C: saturates IC without UR source contribution.

Comparison with other analysis

Compare with ANTARES

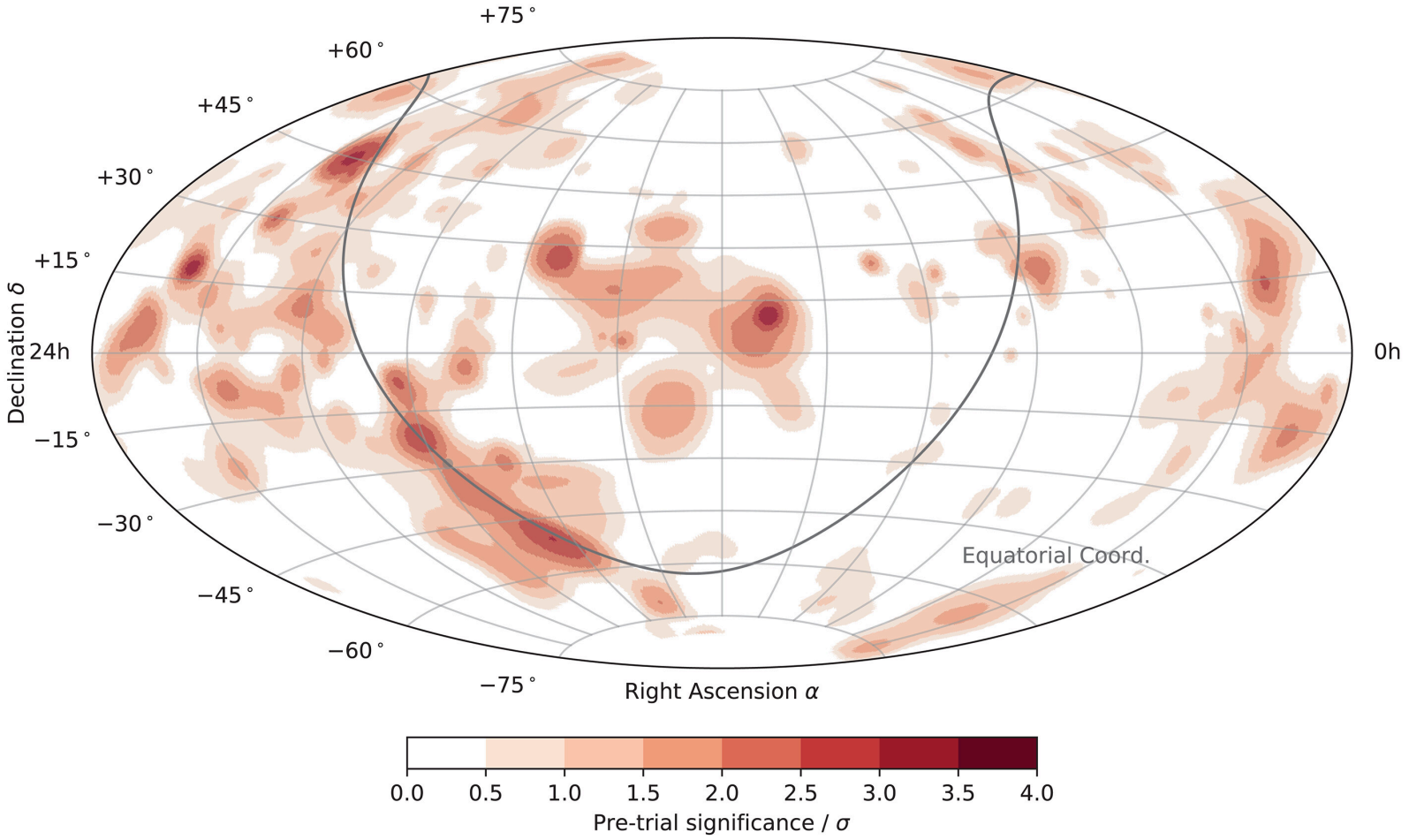
- Galactic Ridge "template" analysis.

Compare with IceCube

IceCube: Observation of high-energy neutrinos https://doi.org/10.1126/science.adc9818 from the Galactic plane.

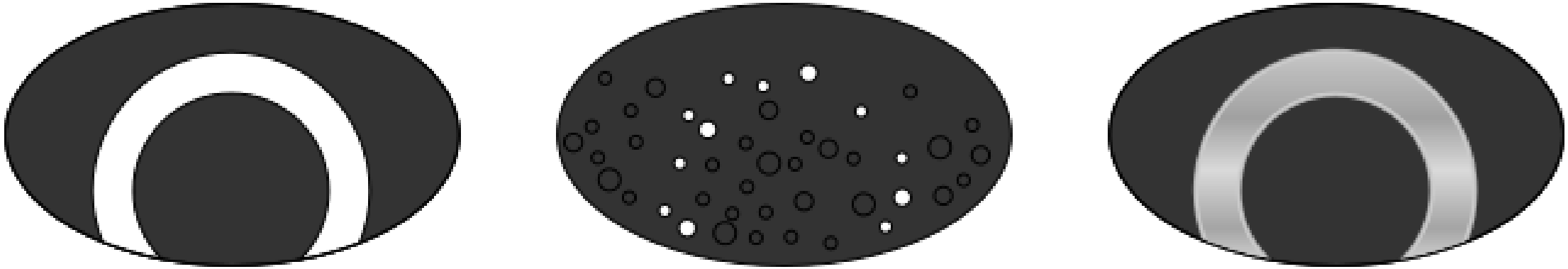
- Fermi-LAT π_0, to compare with IC best fit of 4.71σ.
- IC significance map.

Use public IceCube's significance map as a mask



Warning: convolve it with a galactic band mask to exclude extra-galactic significance.

How to use a mask to build PDFs ?

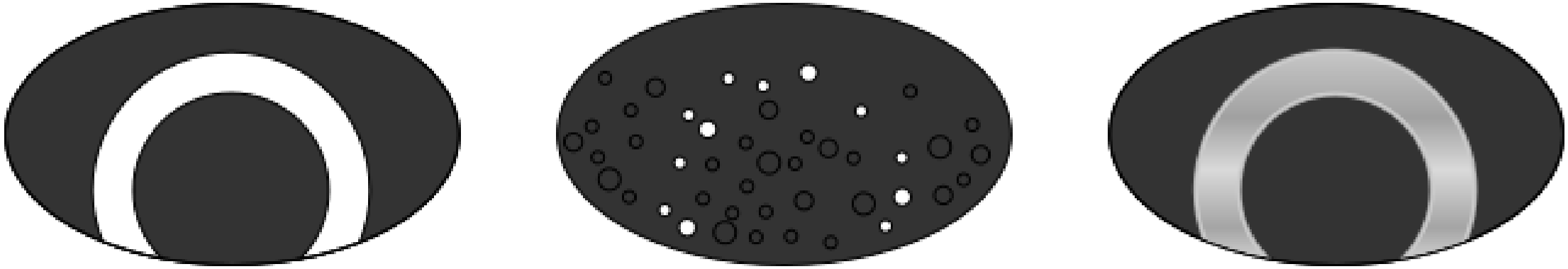


left: mask along the galactic plane.

middle: MC events are evaluated within the template

right: PDF that naturally convolves ANTARES response (MC events) and template.

Masked Signal PDFs

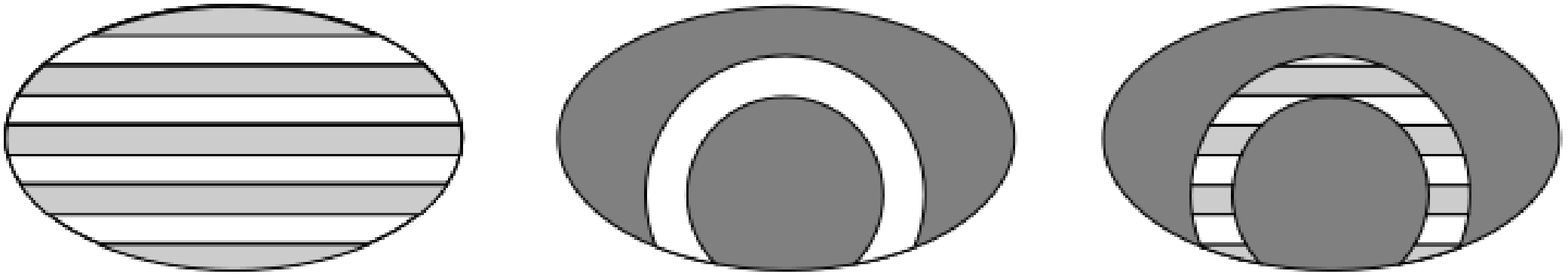


PROBLEM Not enough MC events !!!

- We need a method to increase the amount of MC events.

Step 1: Splitting of masks

Masks allow to look at a specific region of the sky.

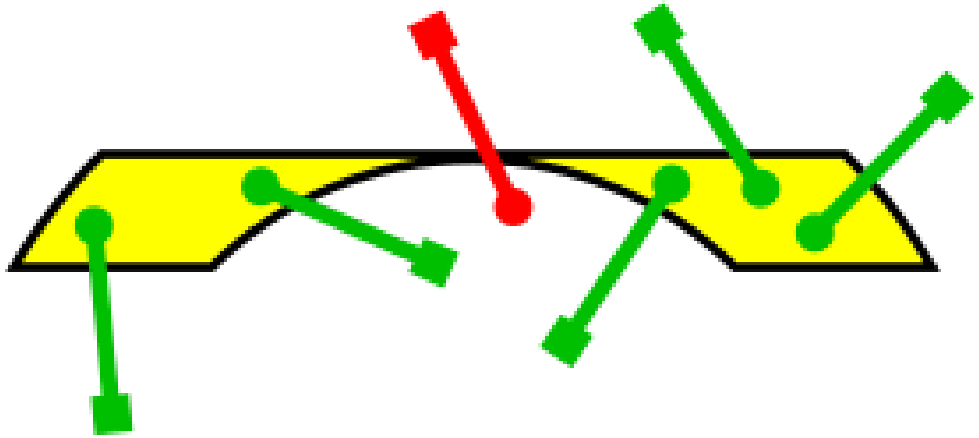


left: the sky in equatorial coordinates is divided into uniform bins according to $\sin(\delta)$ as ANTARES response is uniform in α.

middle: a galactic mask in equatorial coordinates

right: the mask is splitted in bins of declination

Step 2: Resampling - Bootstrap method



- Circle: true coordinates, Square: reconstructed coordinates
- In *red*: the original MC event. Its true declination lies within a bin of declination.
- In *green* : artificial MC event. Its true position is choosen inside the mask *yellow*
- The angular distance between true and reconstructed coordinates is preserved.

Current state of the Legacy analysis

- Legacy ANTARES analysis will use diffuse astrophysical track + shower selection.
- fixes in the building of the PDFs.

  $\rightarrow$ New discovery potentials

Discovery potential at 3σ for Tracks+Shower for KRAγ max

Analysis	ICRC2023	Legacy (Preliminary)
$r_{3\sigma}^{\mathrm{fit}}$	1.28 ± 0.3	0.77 ± 0.5

$\sim 40\%$ decrease of the flux ratio at 3σ.

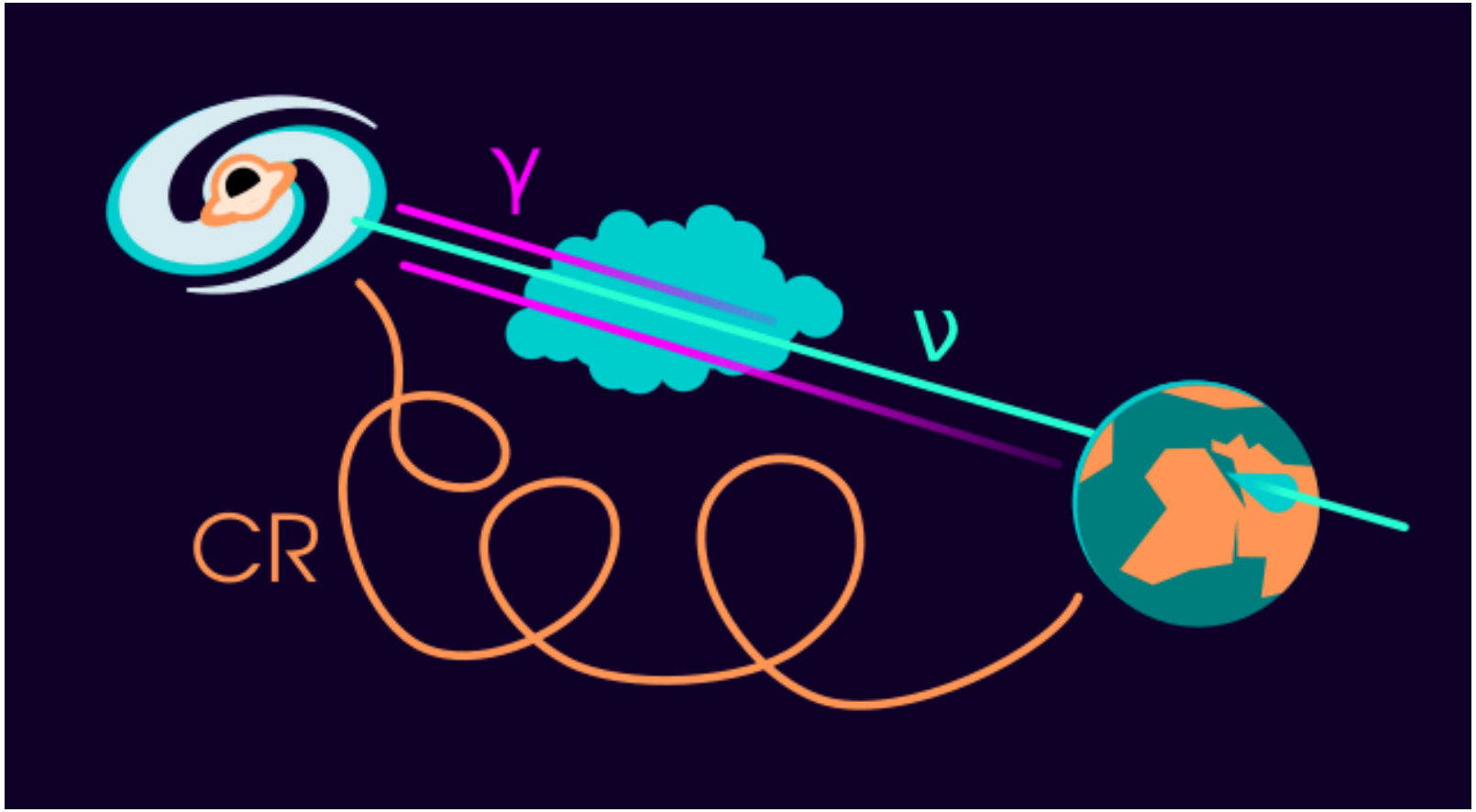
Next results:

- Paper in preparation
- Discovery Potentials and Sensitivity @ **Moriond 2024**
- Unblinding @ **Neutrino 2024**

See you there !

If you want to contact me: cartraud@apc.in2p3.fr

Thanks to all of you !



And my deepest thanks to Gwenhaël and UCL for welcoming me.

Annexes

masked vs unmasked PDFs