17th Marcel Grossmann Meeting - 11/07/2024 - Pescara

Searches for **Diffuse** and **Galactic** neutrino emissions with **ANTARES** telescope

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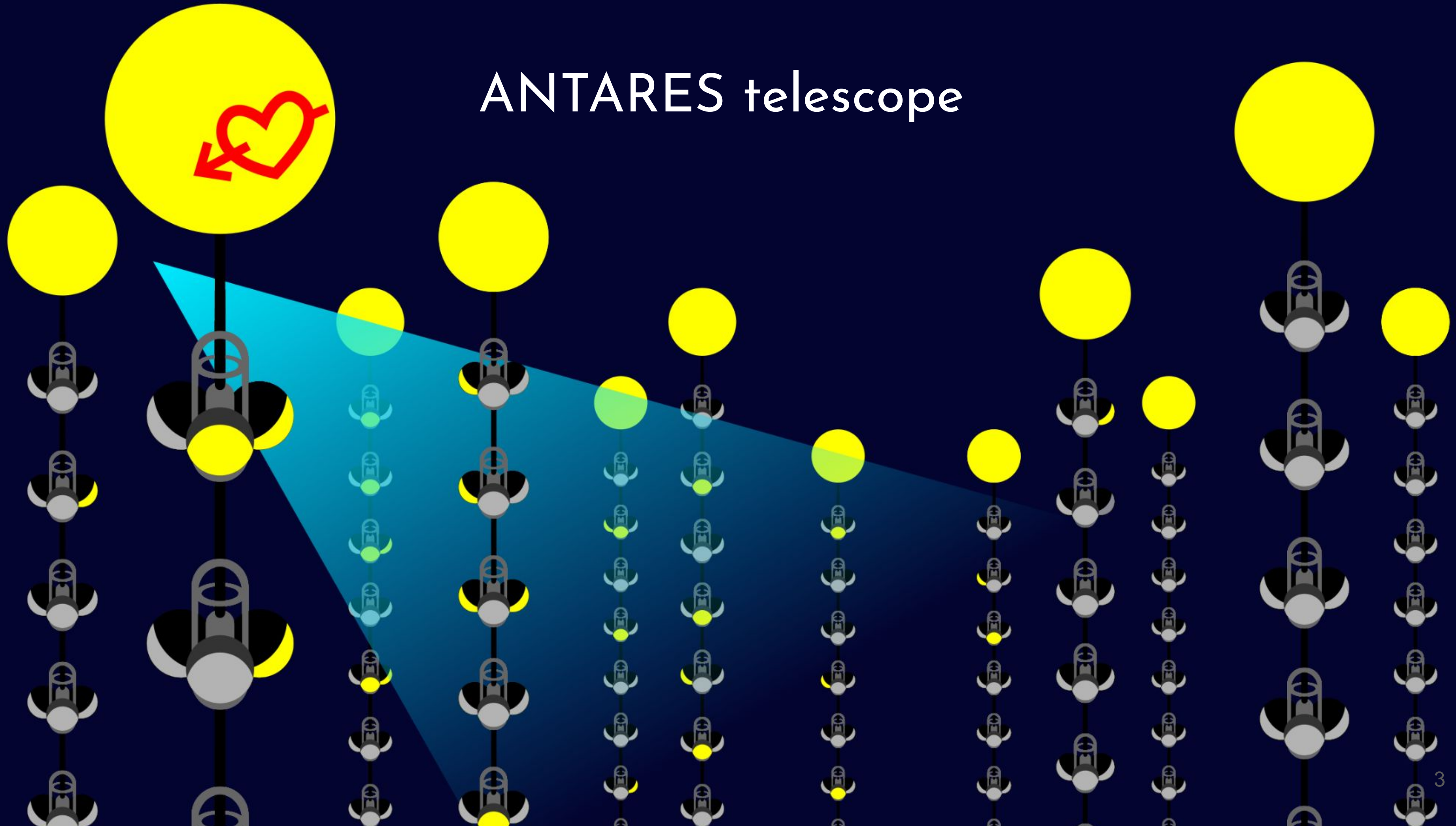
on behalf of ANTARES/KM3NeT collaboration

Plan

- ANTARES telescope and dataset
- Diffuse analysis:
  - final dataset (2007-2022)
  - ANTARES Collaboration, A. Albert et al. - astro-ph.HE: 2407.00328
- Galactic Ridge analysis:
  - dataset (2007-2020)
  - ANTARES Collaboration, A. Albert et al. - Phys.Lett.B 841 (2023)
- Galactic Template analysis
  - final dataset (2007-2022)
  - ANTARES Collaboration and KRAγ group, T. Cartraud et al. - PoS ICRC2023 (2023) 1084 *

* previously shown limits will be updated in a upcoming publication to include the full dataset and improvements in the method.

ANTARES telescope



ANTARES telescope

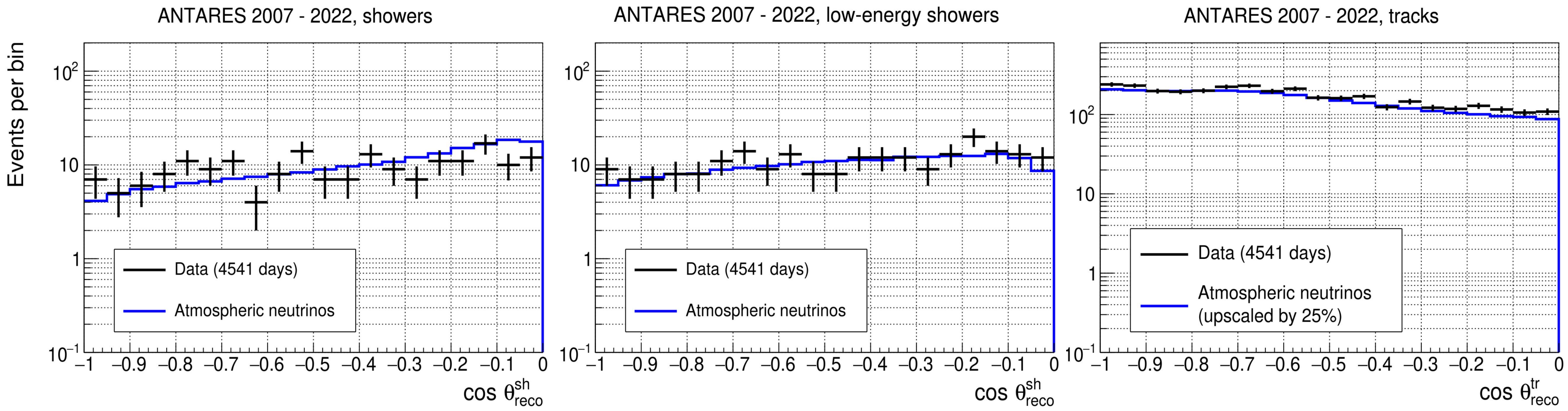
- 2007-2022.
- location: Mediterranean Sea, 40 km off-shore Toulon, France
- depth: 2475 m.
- 12 lines of 350m made of 25 triplets of optical modules.
- track and shower event topologies.

Final dataset

4541 days of effective livetime.

- Track channel
  - **3392** neutrino events
  - pure sample (0.3% of atm. muons)
- Shower channel
  - **187** events
  - above 1 TeV
  - pure sample (>95% neutrinos)
- Low-energy Shower channel
  - independent from the other channels
  - **219** events
  - pure sample (> 99% neutrinos)

Final datasets



showers

tracks

Diffuse analysis

Diffuse cosmic flux:

- from unresolved neutrino sources
- from high-energy CRs interacting while they propagate
- follows a power-law in energy of spectral index $\gamma \in [2.0, 2.4]$

Analysis method:

- bayesian analysis
- Poisson likelihood counting method
- Looking at the **energy spectrum**, independently from the direction.
- FoV in declination: from -90° to 53°
- Hypothesis: **Unbroken power-law**, scan $\gamma \in [1.5, 3.5]$

ANTARES Collaboration, A. Albert et al. - astro-ph.HE: 2407.00328

Statistical analyses

Same framework for **Diffuse** and **Galactic Ridge**

- bayesian analysis
- Poisson likelihood counting method

Other framework for **Galactic Templates**

- frequentist analysis
- unbinned maximum extended likelihood method

Bayesian framework: Poisson likelihood

spectral index

Poisson probability

$$\mathcal{L}\left(N_i; S_i^{(\gamma)}, B_i, \phi_0\right) = \prod_k \prod_{i=1}^{N_k} \mathcal{P}(N_i, B_i + \phi_0 S_i^{(\gamma)})$$

flux normalisation

observed number of events

Bayesian framework: Poisson likelihood

N_k bins in energy

expected background

$$\mathcal{L}\left(N_i; S_i^{(\gamma)}, B_i, \phi_0\right) = \prod_k \prod_{i=1}^{N_k} \mathcal{P}(N_i, B_i + \phi_0 S_i^{(\gamma)})$$

k channels (tracks, showers, showers at low energy)

expected signal (depends on the spectral index)

Bayesian framework

$$\mathcal{L}\left(N_i; S_i^{(\gamma)}, B_i, \phi_0\right) = \prod_k \prod_{i=1}^{N_k} \mathcal{P}(N_i, B_i + \phi_0 S_i^{(\gamma)})$$

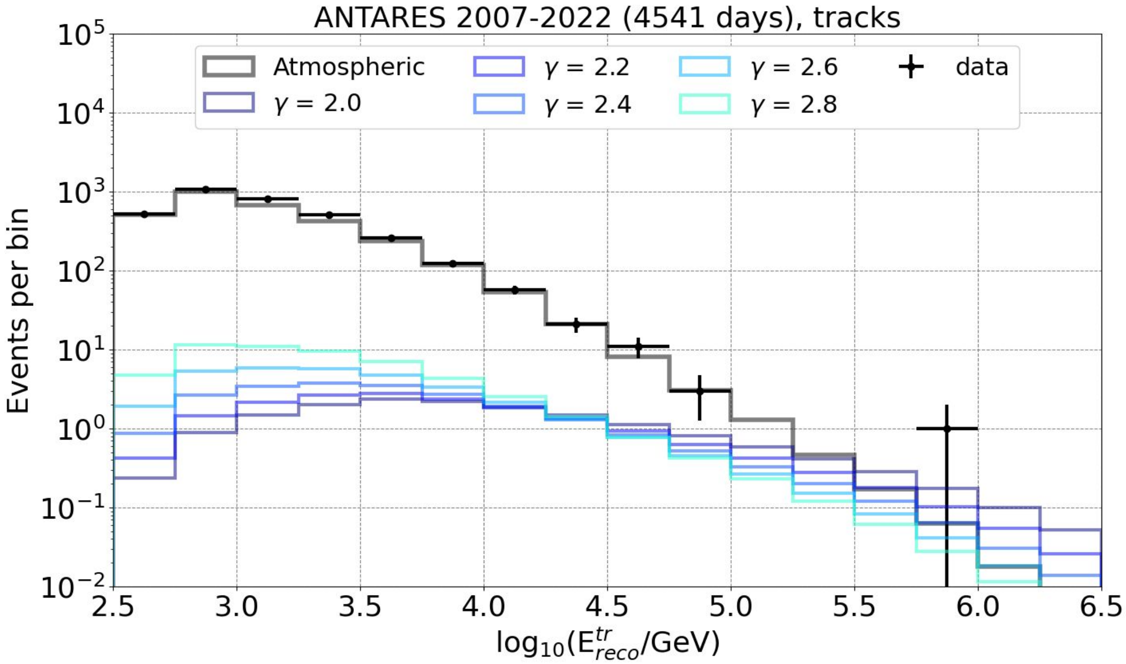
marginalized posterior distribution

stat. & syst. uncertainties

$$P\left(\gamma, \phi_0\right) = \int \mathcal{L}\left(N_i; S_i^{(\gamma)}, B_i, \phi_0\right) \times \boxed{\pi(B_i) \times \pi(S_i^{(\gamma)})} \times \boxed{\pi(\phi_0, \gamma)} \times \prod \mathrm{d}B_i \mathrm{d}S_i^{(\gamma)}$$

gaussian priors   flat priors

Energy distribution for tracks



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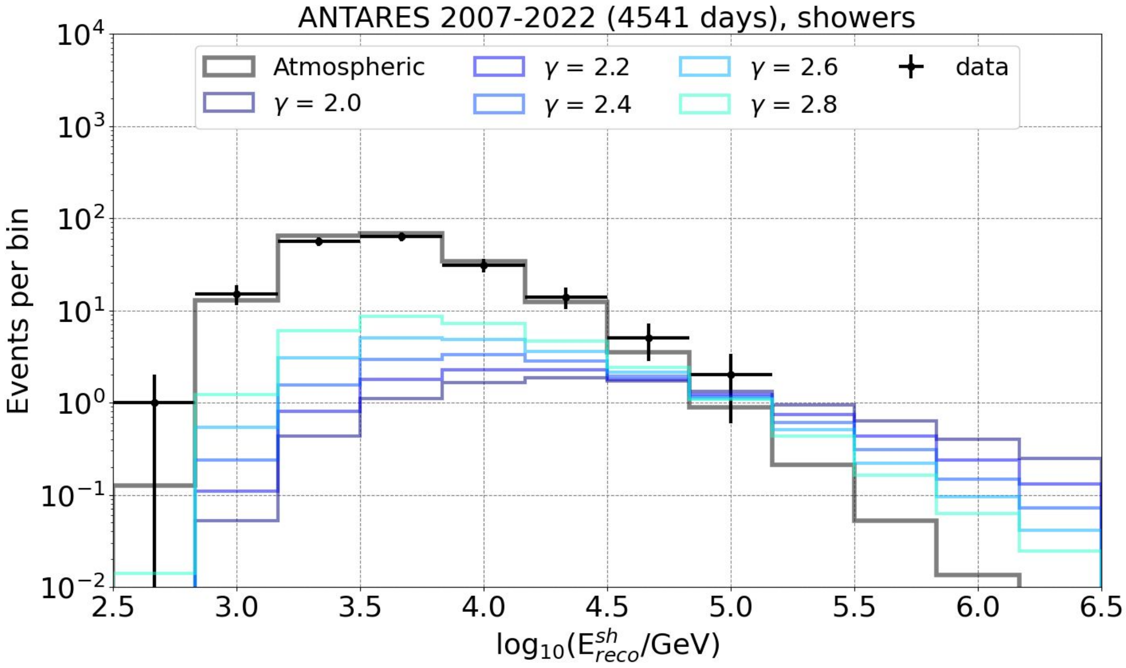
Energy distribution for showers



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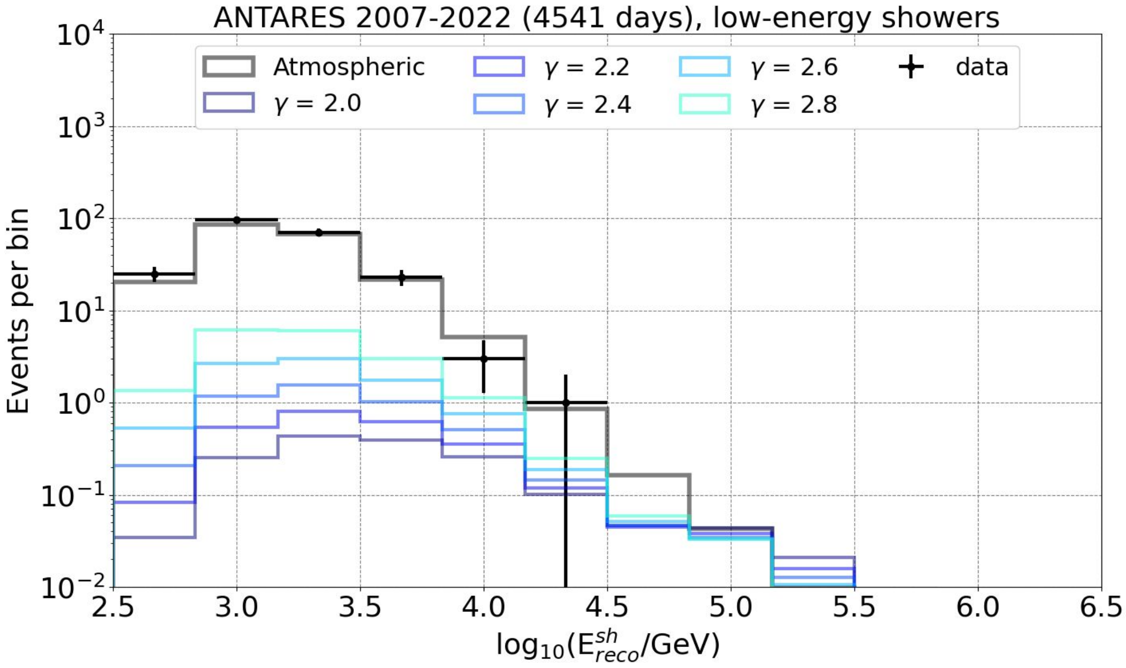
Energy distribution for low-energy showers



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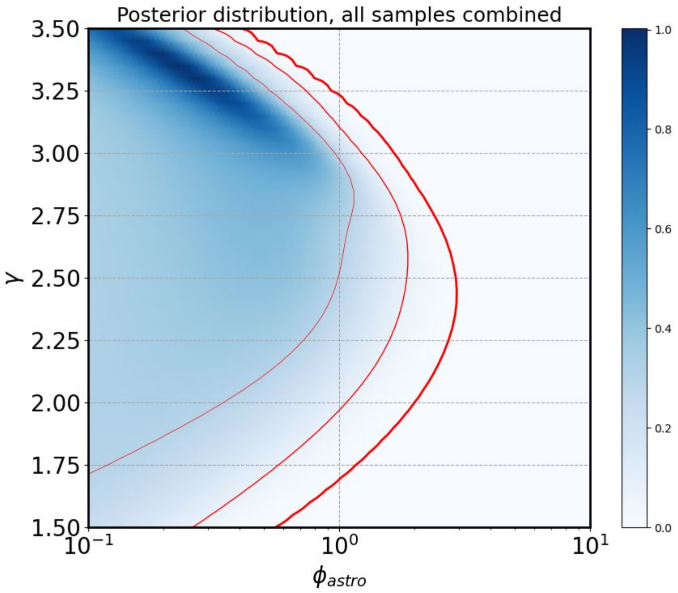
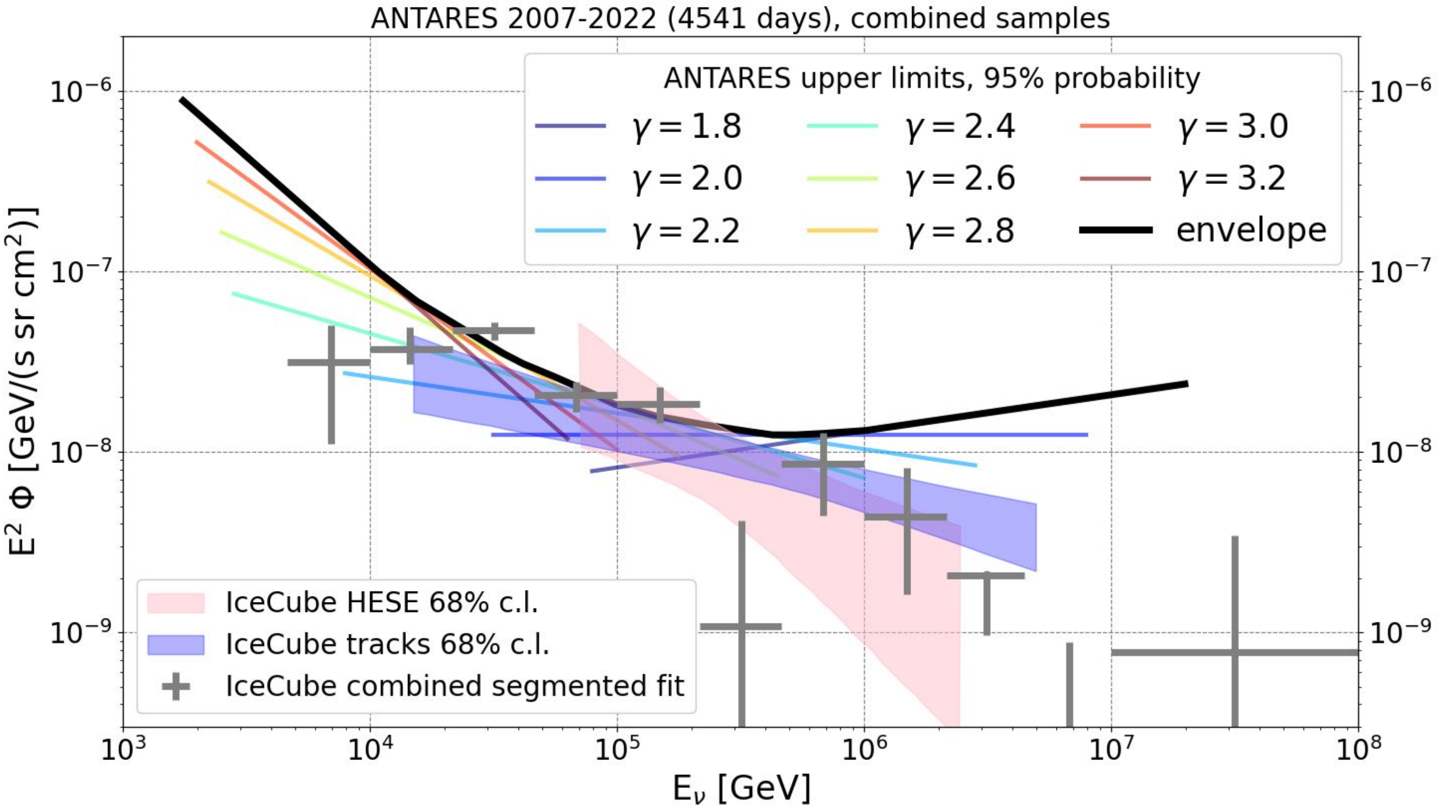
Posterior distribution



γ	$\phi_{\text{astro}}^{68\%}$	$\phi_{\text{astro}}^{95\%}$	$\phi_{\text{astro}}^{99.7\%}$	Energy range [TeV]
3.2	0.51	0.68	0.94	1.8 – 63
3.0	0.82	1.03	1.49	2.0 – 100
2.8	0.98	1.49	2.06	2.2 – 180
2.6	0.98	1.80	2.61	2.5 – 450
2.4	0.94	1.80	2.86	2.8 – 1000
2.2	0.78	1.64	2.73	8 – 2800
2.0	0.59	1.24	2.17	30 – 8000
1.8	0.37	0.82	1.49	80 – 20000

Upper limits



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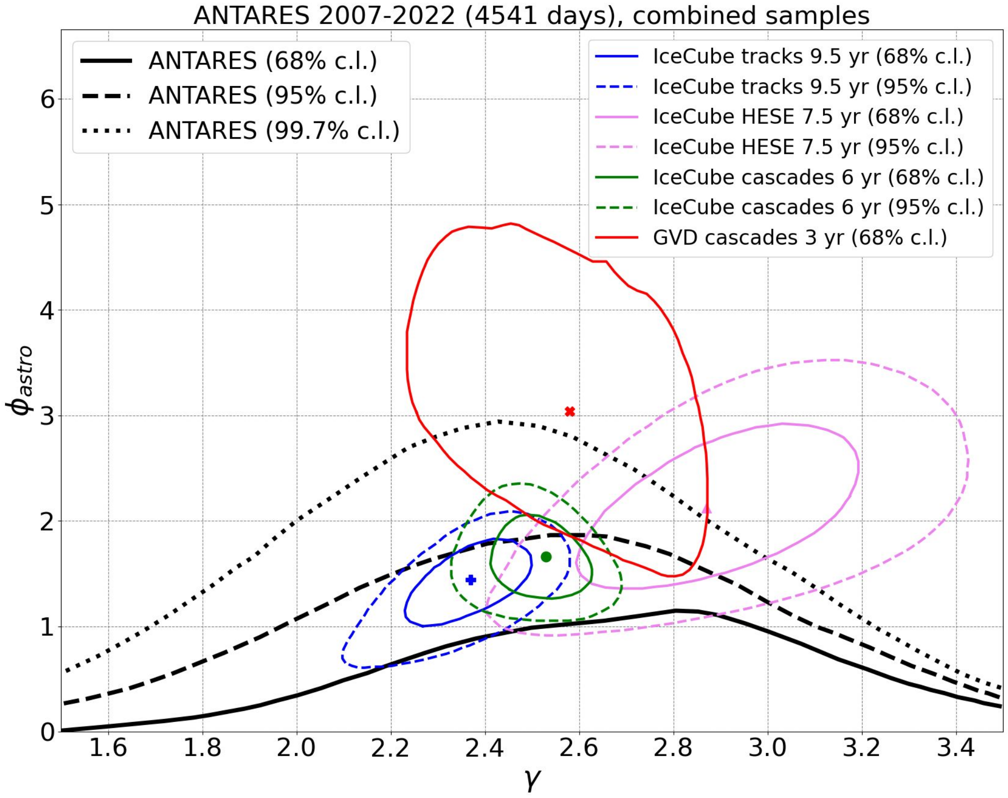
Posterior confidence intervals (CIs)

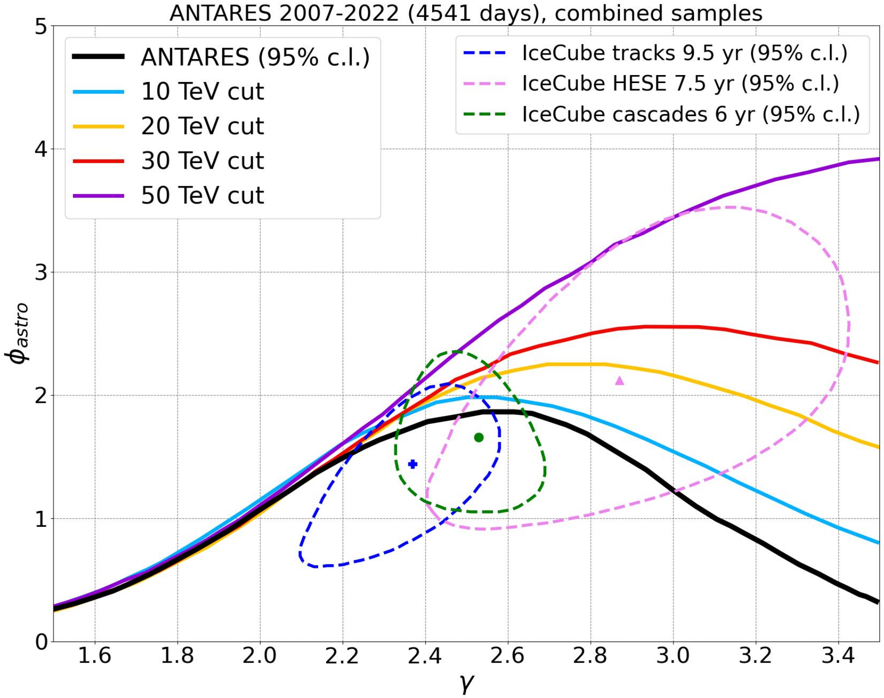


ANTARES Collaboration, A. Albert et al. - astro-ph.HE: 2407.00328

Posterior CIs with low-energy cuts

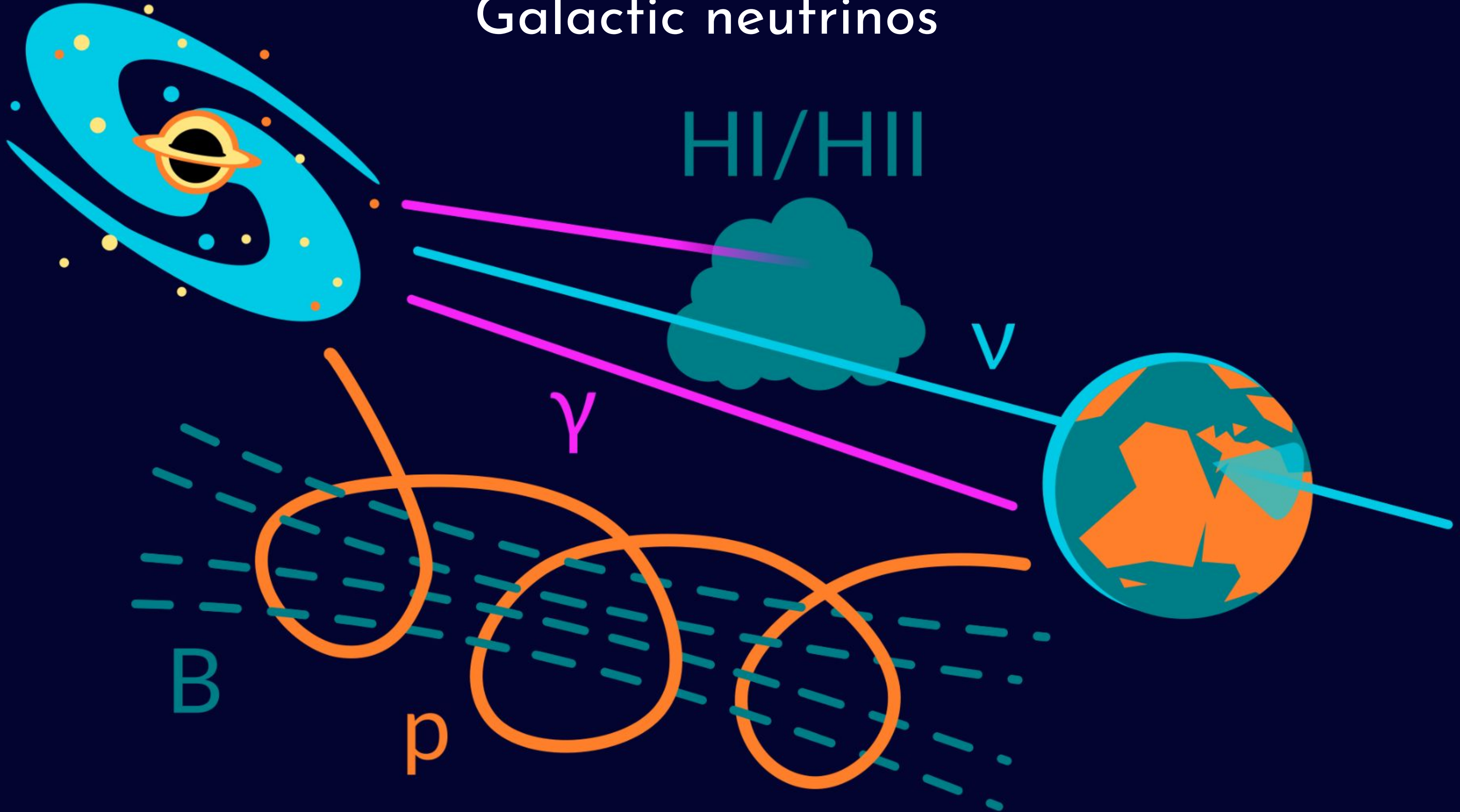
- absence of significant excess.
- extension of IceCube's spectra below 10 TeV excluded at 99.7%.
- cut-off needed in the 10 – 30 TeV region.

Departure from the simple power-law



ANTARES Collaboration, A. Albert et al. - astro-ph.HE: 2407.00328

Galactic neutrinos



Galactic Ridge

Galactic Ridge

- ridge region: $|l| < 30^\circ$, $|b| < 2^\circ$ for tracks

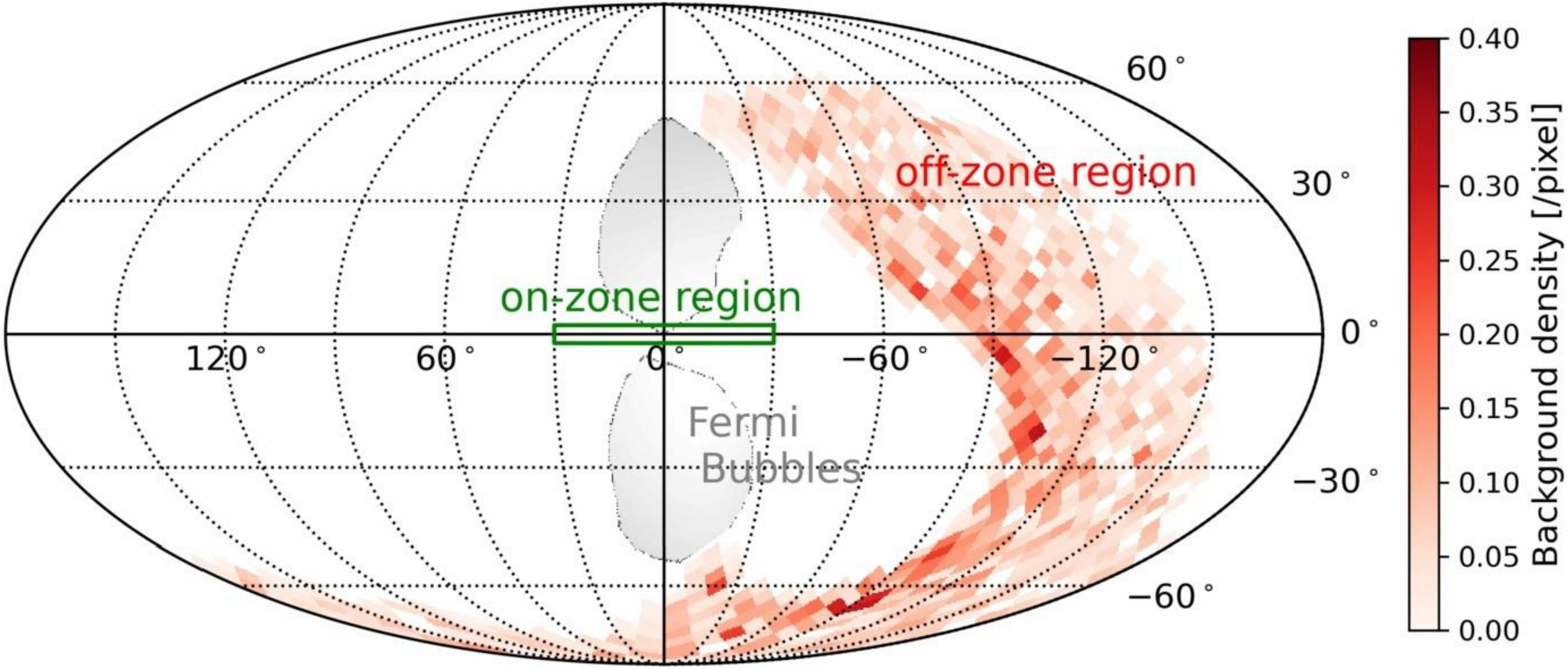
Analysis:

- same framework as for the diffuse analysis
- signal evaluated in an ON region
- background evaluated with data in an OFF region

Dataset:

- tracks and showers from 2007 to 2020

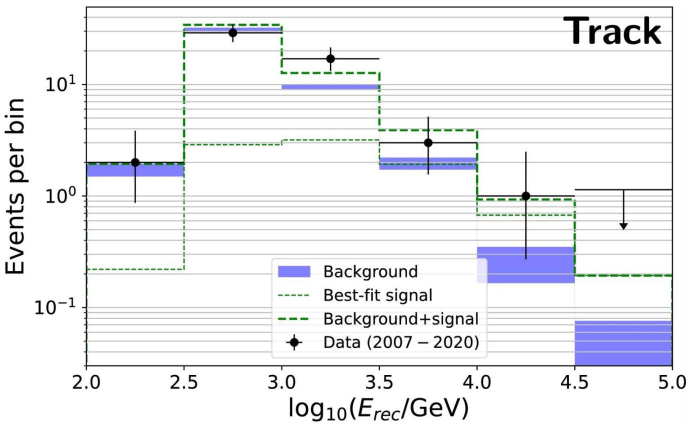
Galactic Ridge

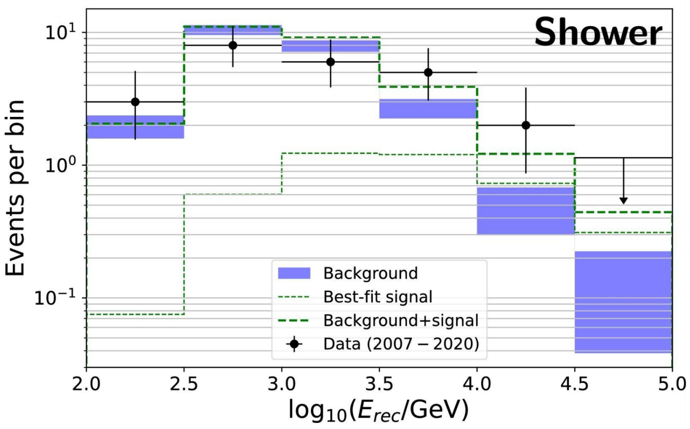


ANTARES Collaboration, A. Albert et al. - Phys.Lett.B 841 (2023)

Observed amount of events in the Galactic Ridge

	Track	Shower
Events observed	21	13
Expected Background	11.7 ± 0.6	11.2 ± 0.9
Background Rejection significance	98% (2.2σ)	56% (0.2σ)

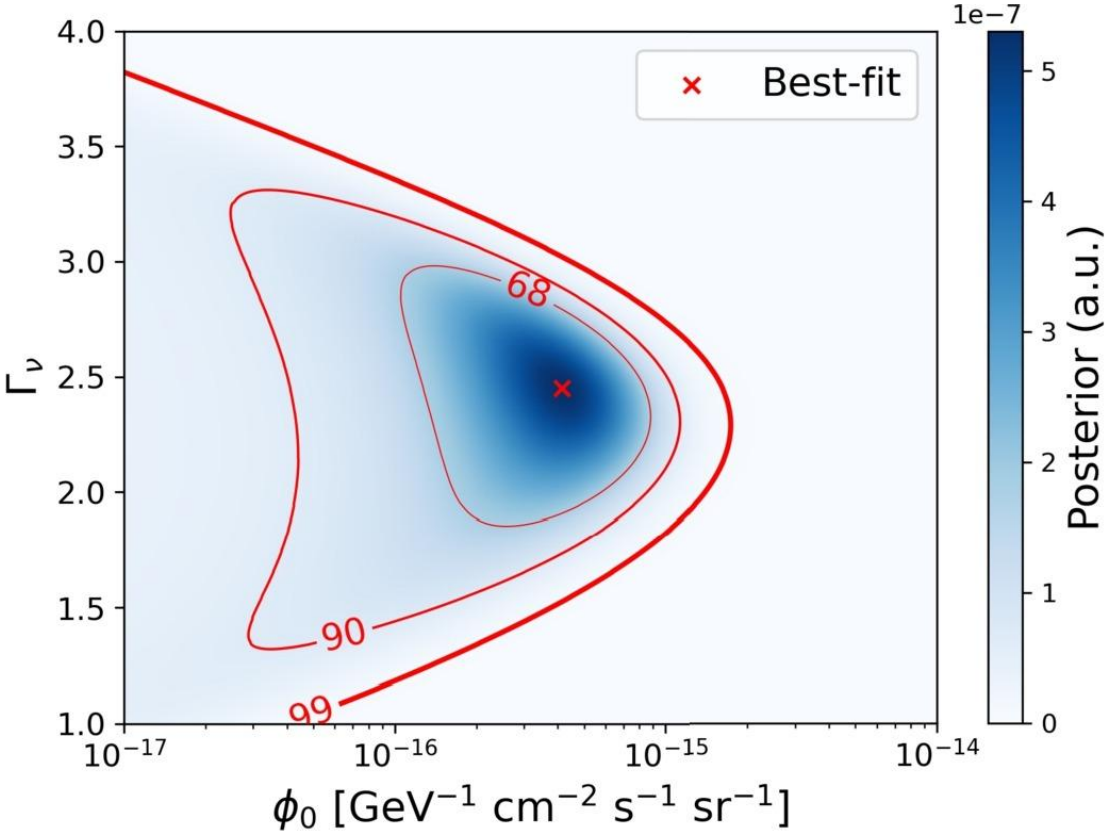




ANTARES Collaboration, A. Albert et al. - Phys.Lett.B 841 (2023)

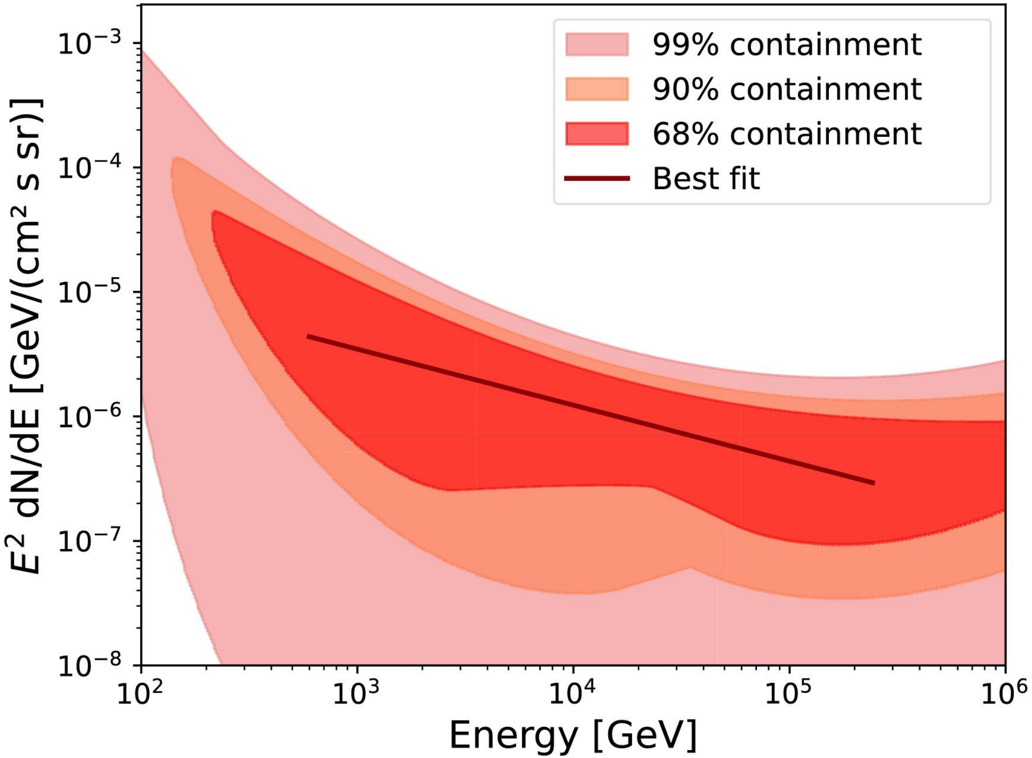
Posterior distribution

Background hypothesis rejected at a 96% confidence level.



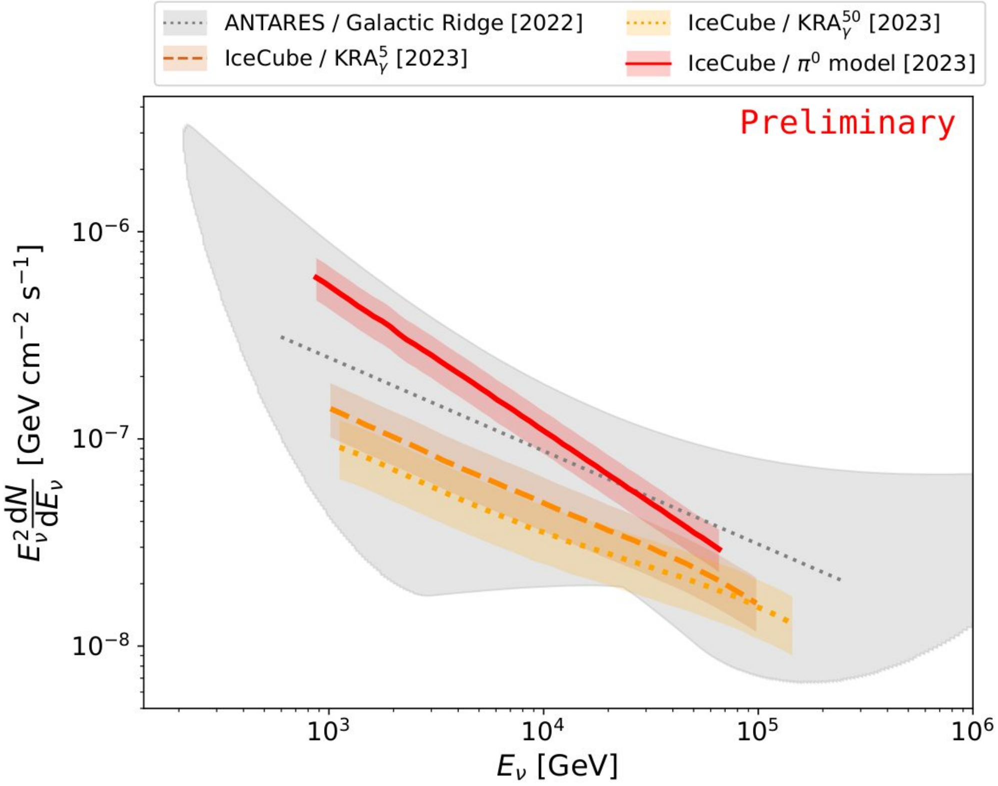
ANTARES Collaboration, A. Albert et al. - Phys.Lett.B 841 (2023)

Results



ANTARES Collaboration, A. Albert et al. - Phys.Lett.B 841 (2023)

Comparison with IceCube



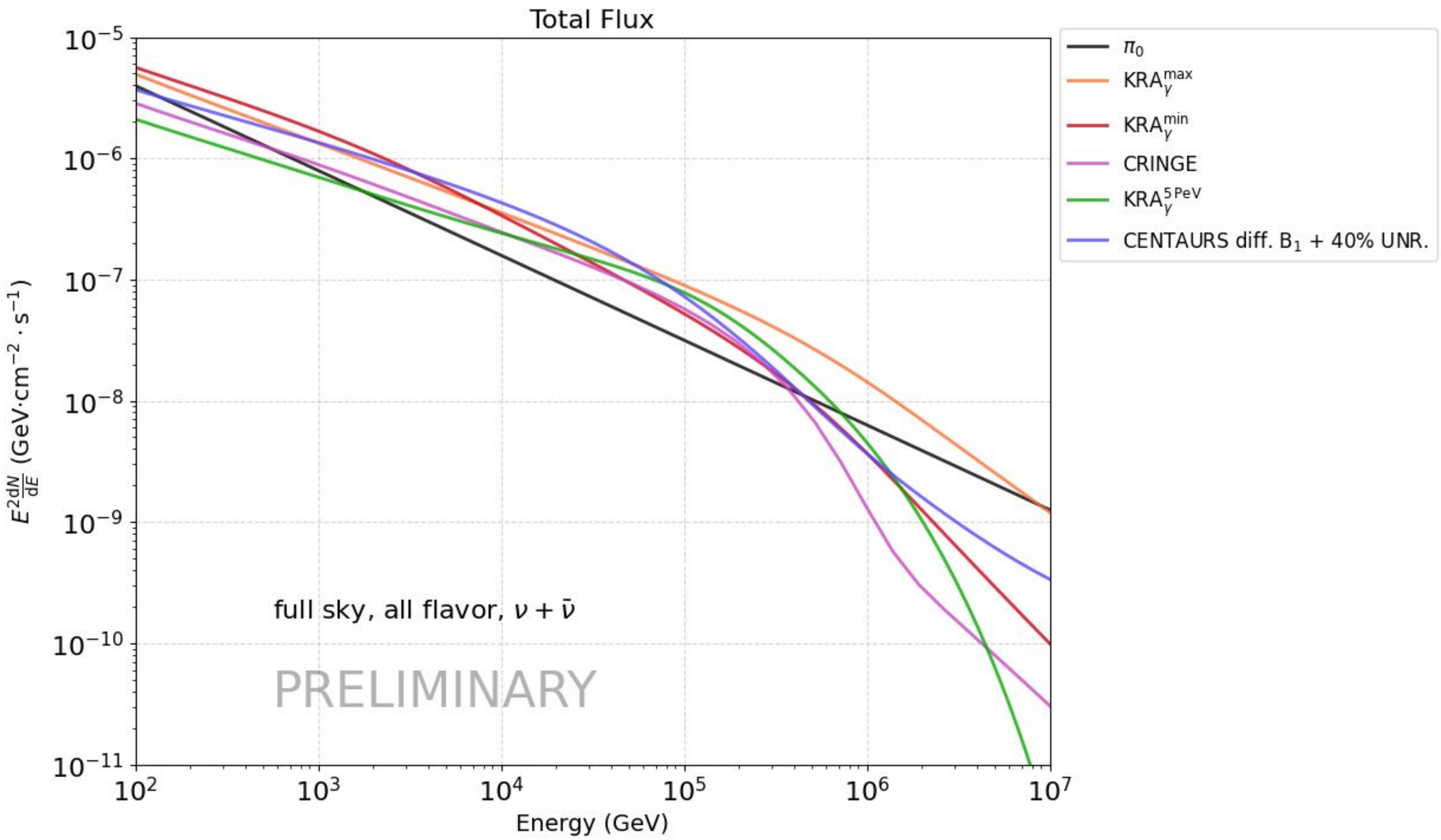
ANTARES Collaboration, M. Lamoureux et al. - PoS ICRC2023 (2023) 1103

Template Analysis

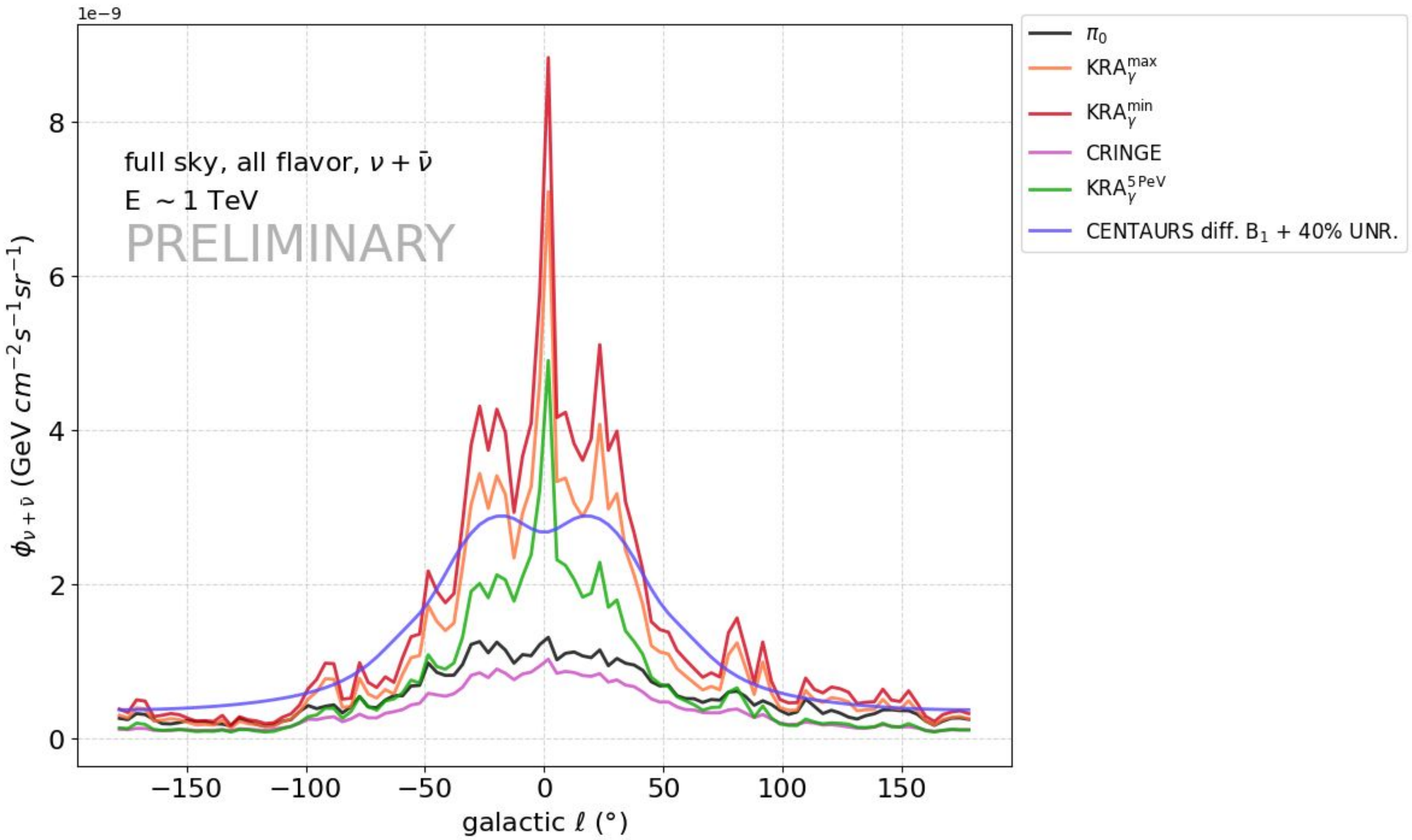
- likelihood analysis with a frequentist framework
- Fit the flux predicted by several models of galactic neutrino emissions
- test different models
  - Fermi-LAT Galprop π^0 [1]
  - KRAγ 5PeV (2015) [2]
  - KRAγ max and min (2023) [3]
  - CENTAURS diff. B1 + 40% of unresolved contribution) [4]
  - CRINGE (diff. + unresolved contribution) [5]

[1] Ackermann, M. et al. ApJ 750, 3 (2012).
[2] Gaggero, D. et al. ApJL 815, L25 (2015).
[3] De La Torre Luque, P. et al. Front. Astron. Space Sci. 9 (2022).
[4] Vecchiotti, V. et al. ApJL 956 L44 (2023).
[5] Schwefer, G. et al. ApJ 949, 16 (2023).

Models: predicted neutrino energy spectrum



Models: flux in along galactic longitude



The challenge

Frequentist framework

number of events per channel

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

number of channels: tracks, showers, etc.

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

Frequentist framework

signal PDF

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

background PDF

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

Frequentist framework

number of background events for each channel

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

number of background events

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

Frequentist framework

flux ratio

number of signal events

number of events predicted by the model

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

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

The PDFs

factorized PDFs

$$s_j^i = f_s^i(\alpha_j^i, \delta_j^i) \cdot g_s^i(E_j^i)$$

$$b_j^i = f_b^i(\delta_j^i) \cdot g_b^i(E_j^i)$$

non-factorized PDFs

$$s_j^i = f_s^i(\alpha_j^i, \delta_j^i, E_j^i)$$

$$b_j^i = f_b^i(\delta_j^i, E_j^i)$$

The PDFs

factorization:

- disentangle the degrees of freedom.
- require less statistics to build the PDF
- remove energy-position correlations

$$s_j^i = f_s^i(\alpha_j^i, \delta_j^i) \cdot g_s^i(E_j^i)$$

$$b_j^i = f_b^i(\delta_j^i) \cdot g_b^i(E_j^i)$$

non-factorization:

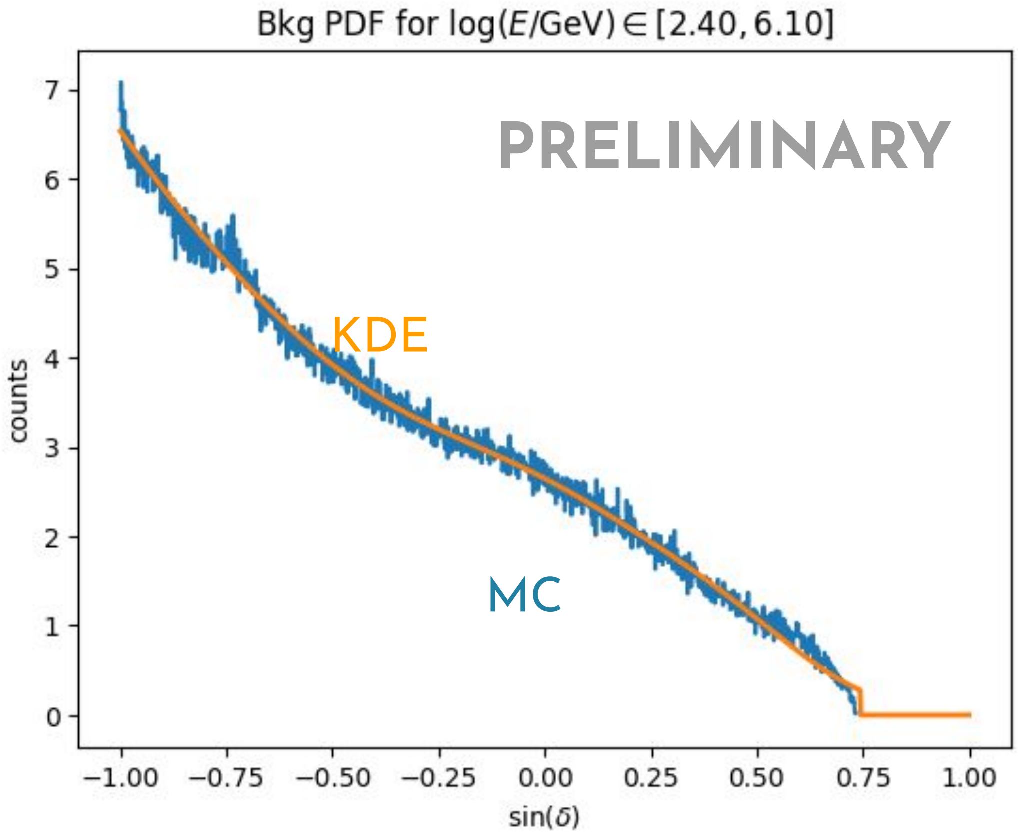
- entangled degrees of freedom.
- phase space with low-statistics
- more precise detector response

$$s_j^i = f_s^i(\alpha_j^i, \delta_j^i, E_j^i)$$

$$b_j^i = f_b^i(\delta_j^i, E_j^i)$$

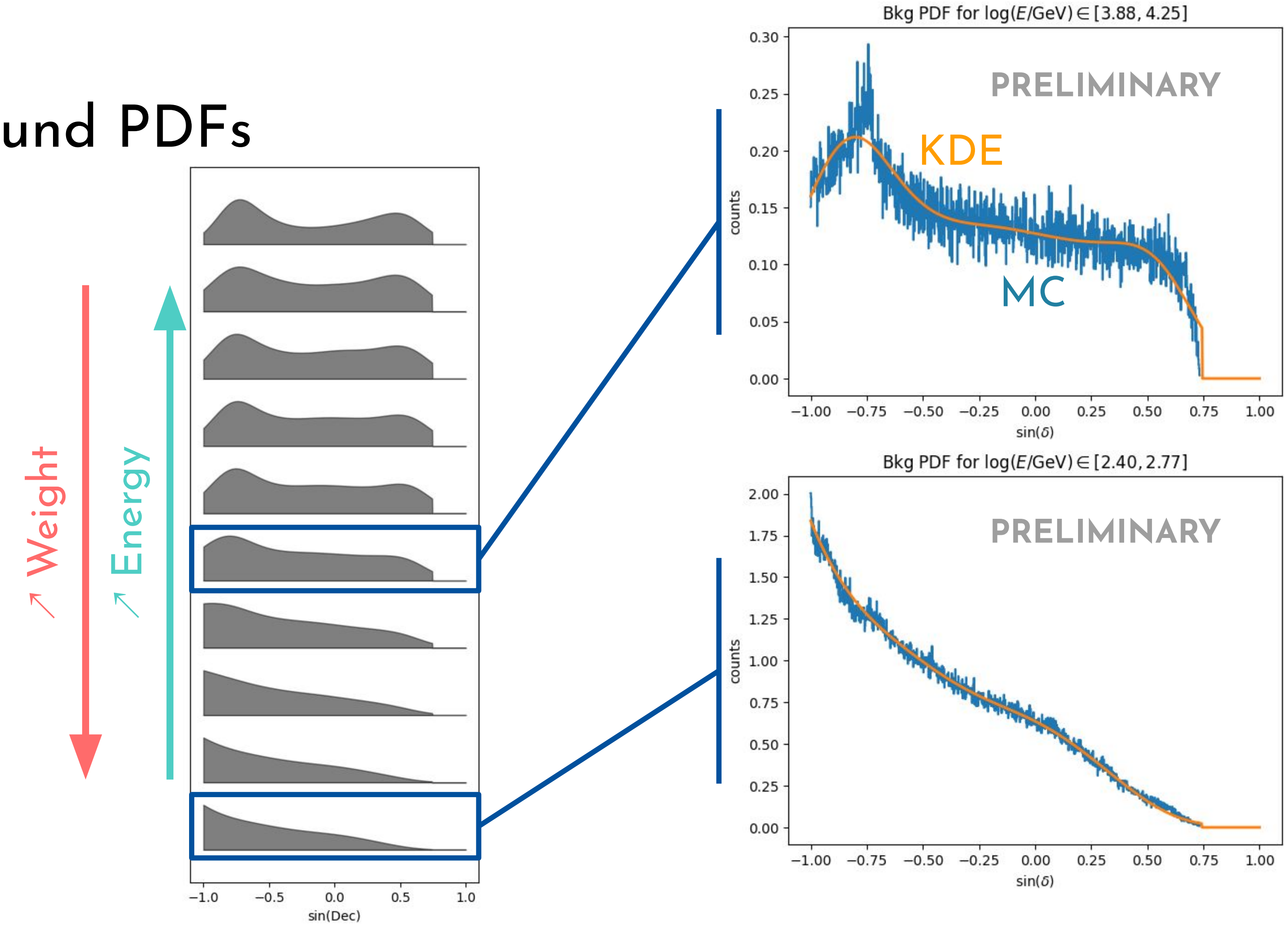
Background PDFs*

- Uniform in α because of Earth's rotation.
- Integrated on the full range of energy.



* all following plots and examples have been obtained with the final ANTARES MC of the track-like selection

Background PDFs



Background PDFs

- use of KDE (Kernel Density Estimation)
- more statistics in every bin of energy: data $\longrightarrow$ MC
- spatial shape vary highly energy
- **cumulated spatial shape dominated by low energy events**

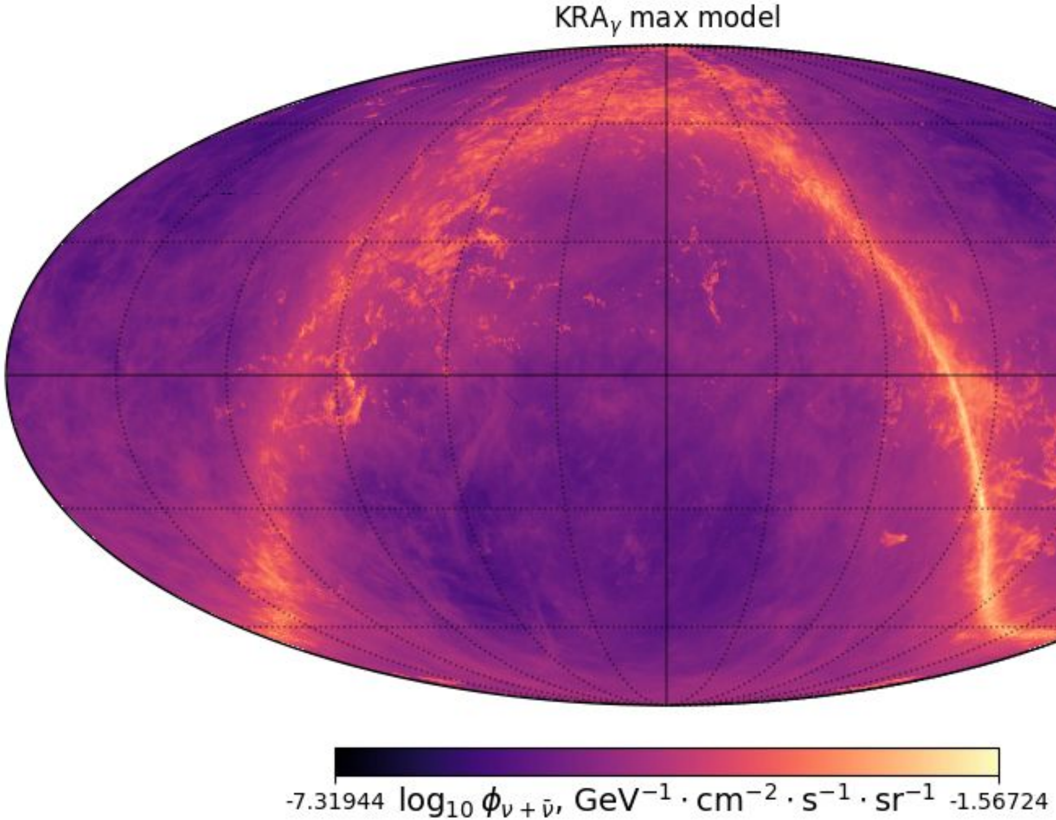
$$s_j^i = f_s^i(\alpha_j^i, \delta_j^i) \cdot g_s^i(E_j^i)$$
$$b_j^i = f_b^i(\delta_j^i) \cdot g_b^i(E_j^i)$$

✗

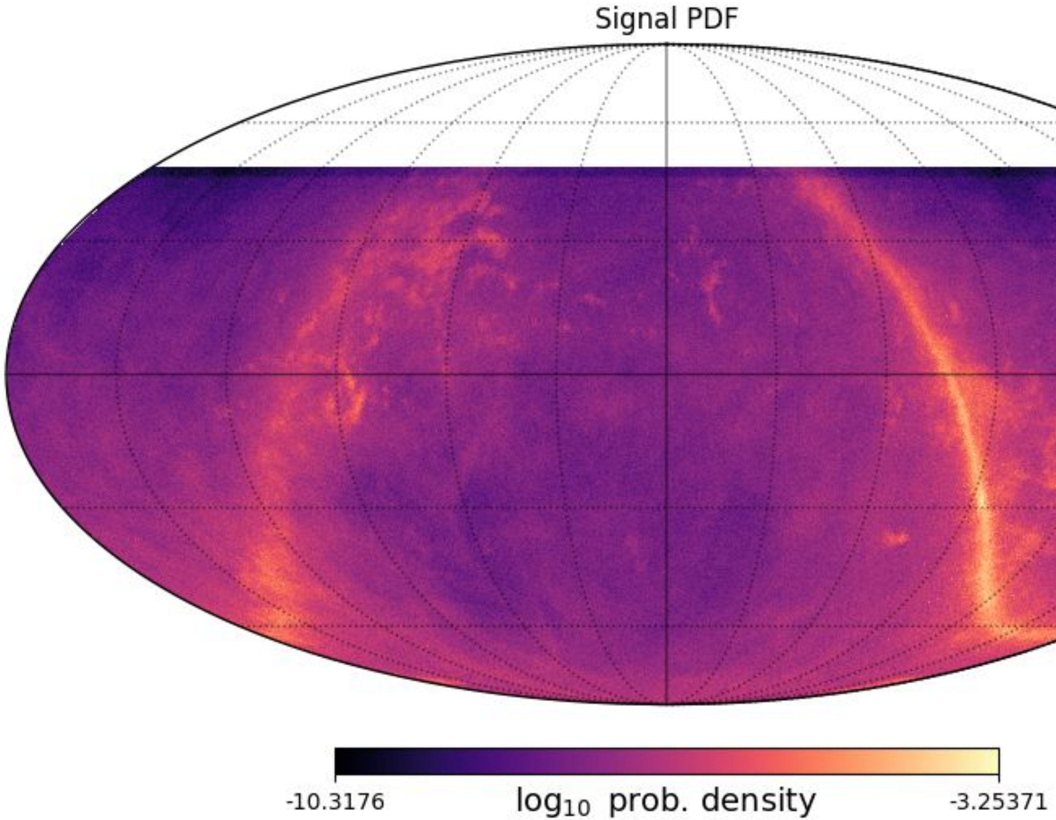
$$s_j^i = f_s^i(\alpha_j^i, \delta_j^i, E_j^i)$$
$$b_j^i = f_b^i(\delta_j^i, E_j^i)$$

✓

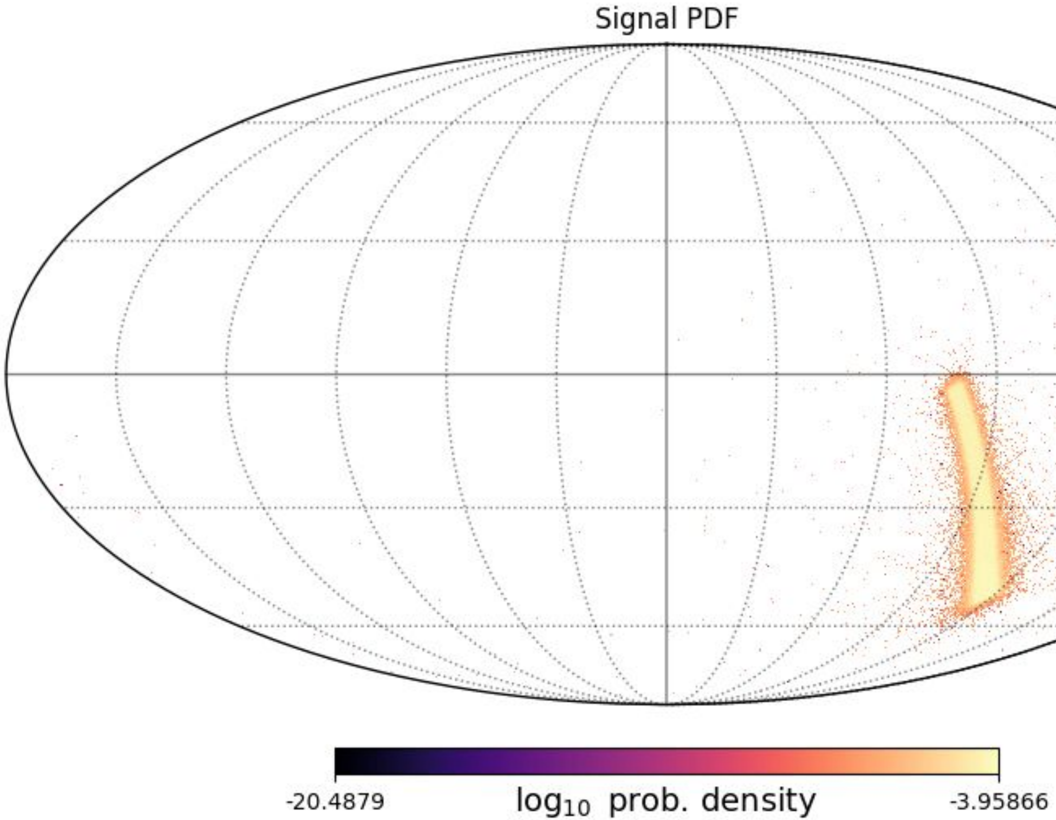
From the galactic template…



…to the signal PDF

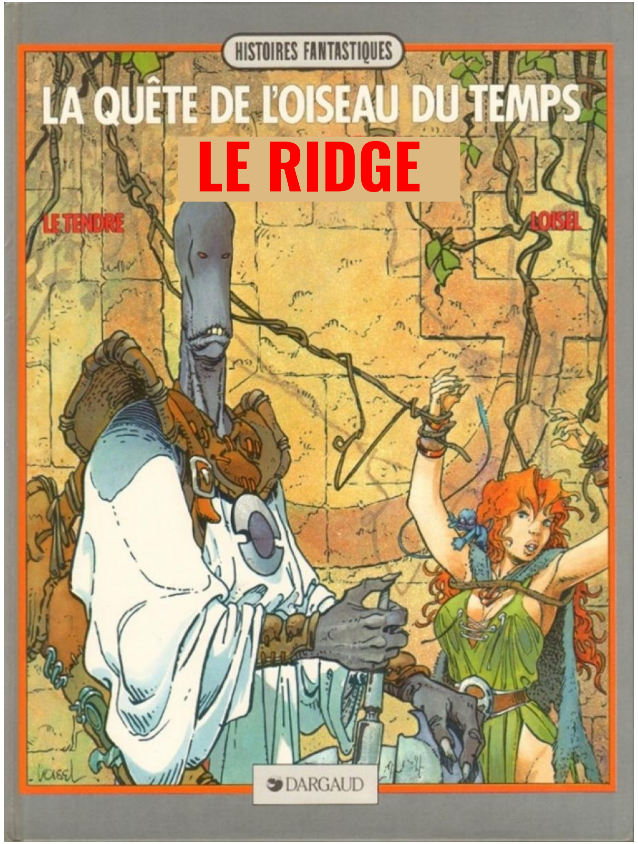


to the signal PDF



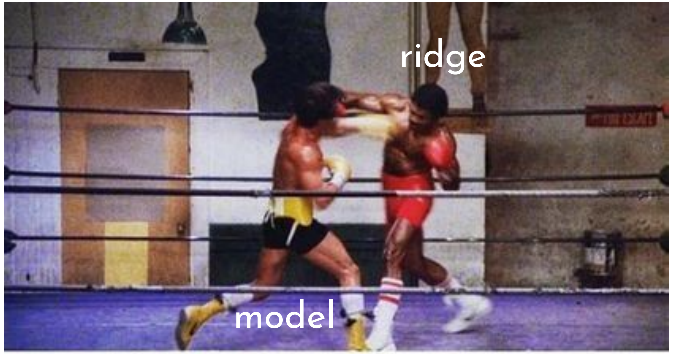
The Ridge is back !

- frequentist framework
- flux following a power-law in a masked region of the sky
- different modeling of signal/background compared to bayesian framework.



Early results

	predicted number of sig/bkg events	
Model	track	shower
KRAγ max (2023)	9.2/3392	5.6/196
Ridge*	8.8/3392	5.3/196



* best-fits as in ANTARES Collaboration, A. Albert et al. - Phys.Lett.B 841 (2023)

Conclusion

Legacy analyses from ANTARES:

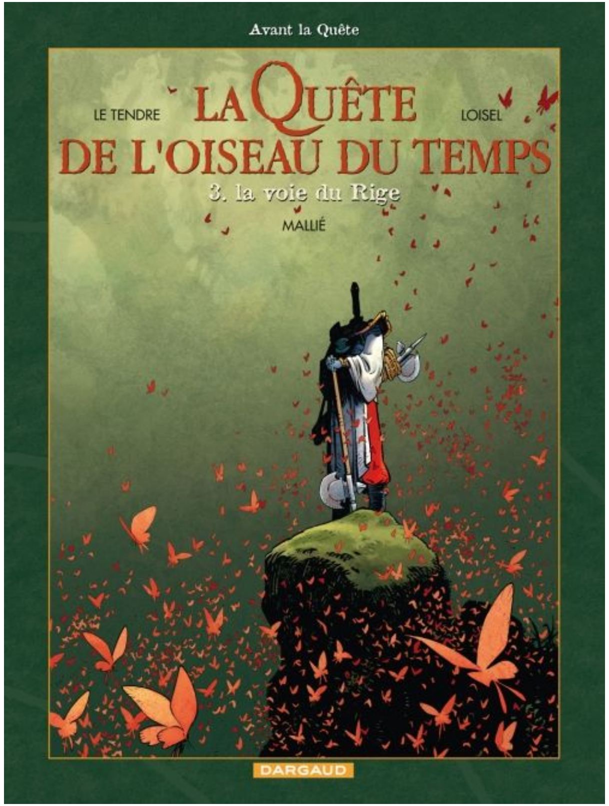
diffuse analysis:

- absence of significant excess.
- extension of IceCube's spectra below 10 TeV excluded at 99.7%.
- cut-off needed in the 10 – 30 TeV region.

  ⟶ discrepancy from the no-break single-term power law.

galactic analysis:

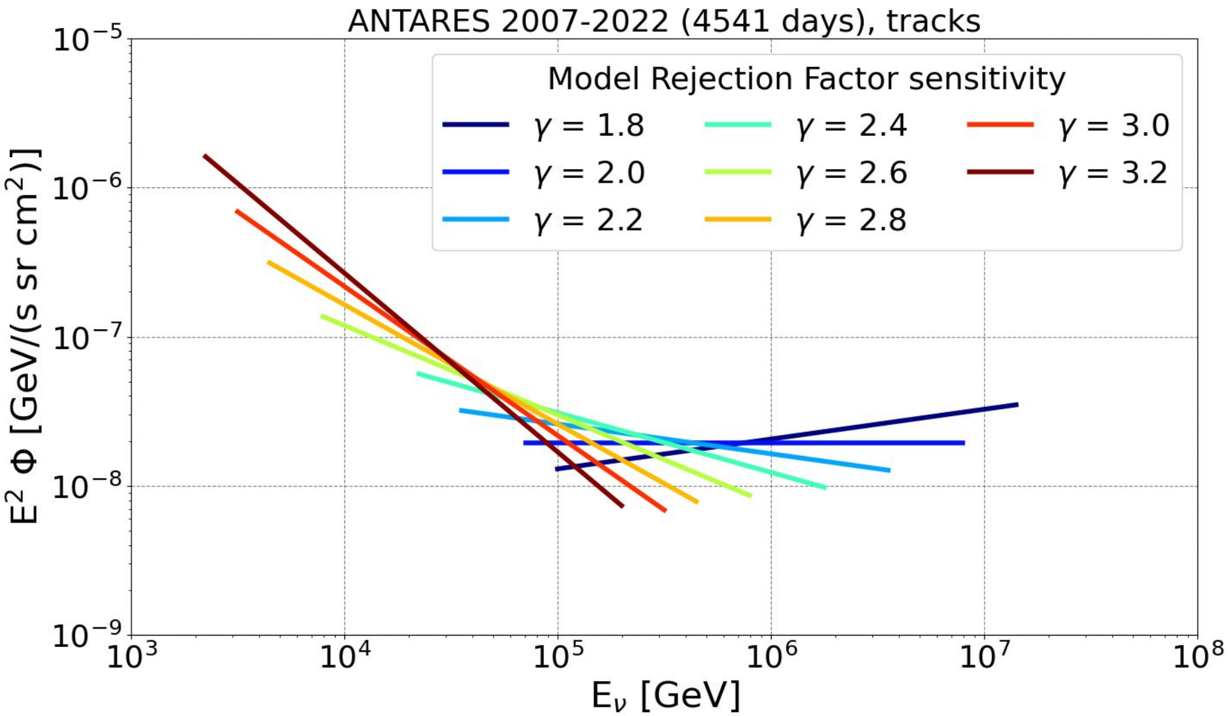
- MC-driven frequentist framework able to precisely test the **ridge** and **galactic** models.
- Results will arrive soon: stay tuned !



Thanks to all of you !

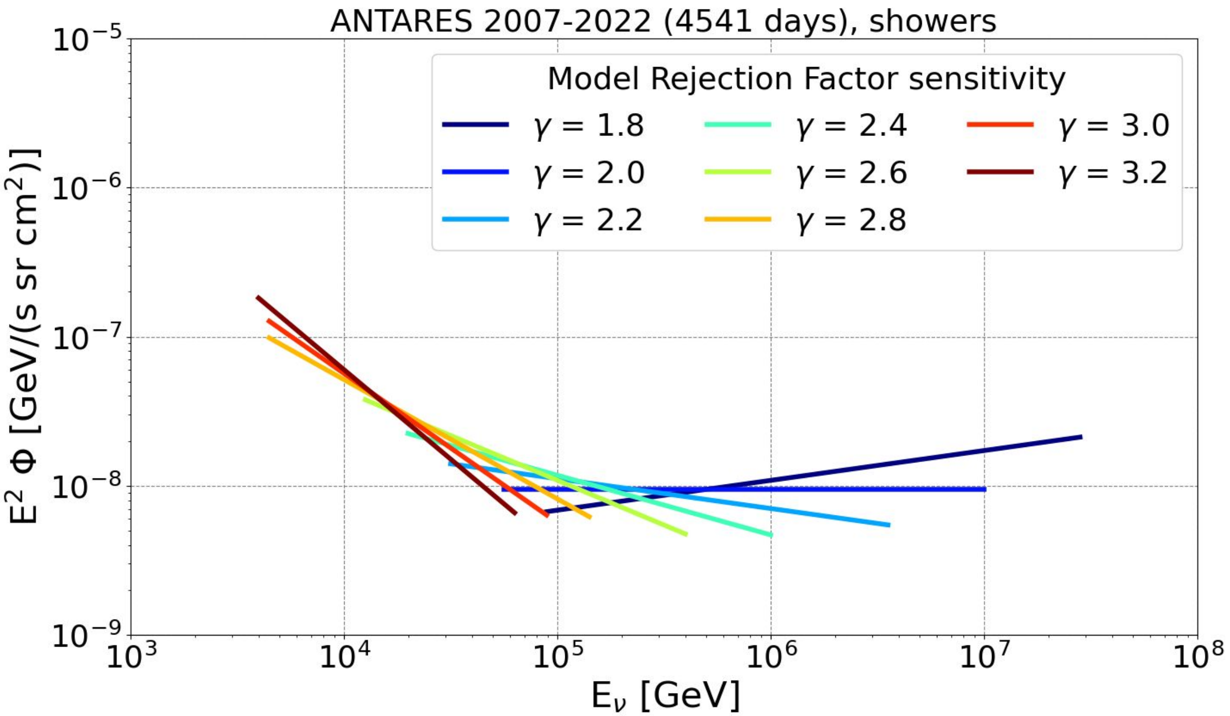
To contact me: cartraud@apc.in2p3.fr

Sensitivity for tracks: diffuse analysis



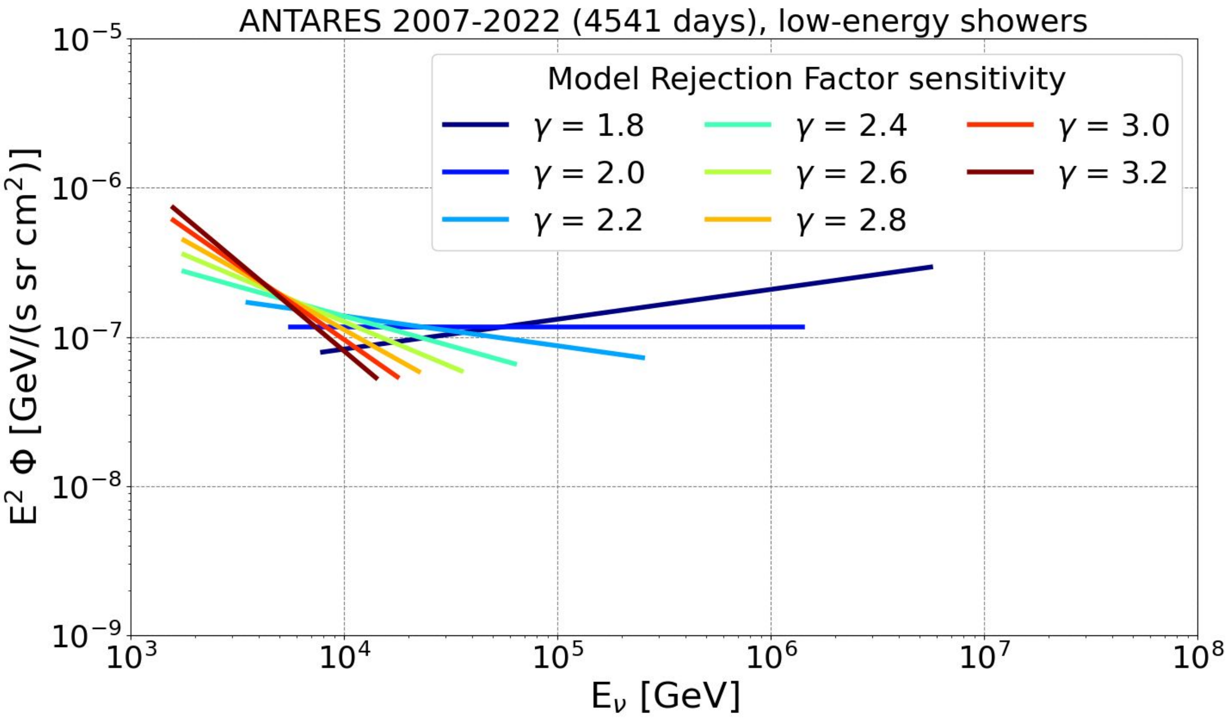
ANTARES Collaboration, A. Albert et al. - astro-ph.HE: 2407.00328

Sensitivity for showers: diffuse analysis



ANTARES Collaboration, A. Albert et al. - astro-ph.HE: 2407.00328

Sensitivity for low-energy showers: diffuse analysis



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