KM3NeT & HAWC joint analysis of Galactic sources

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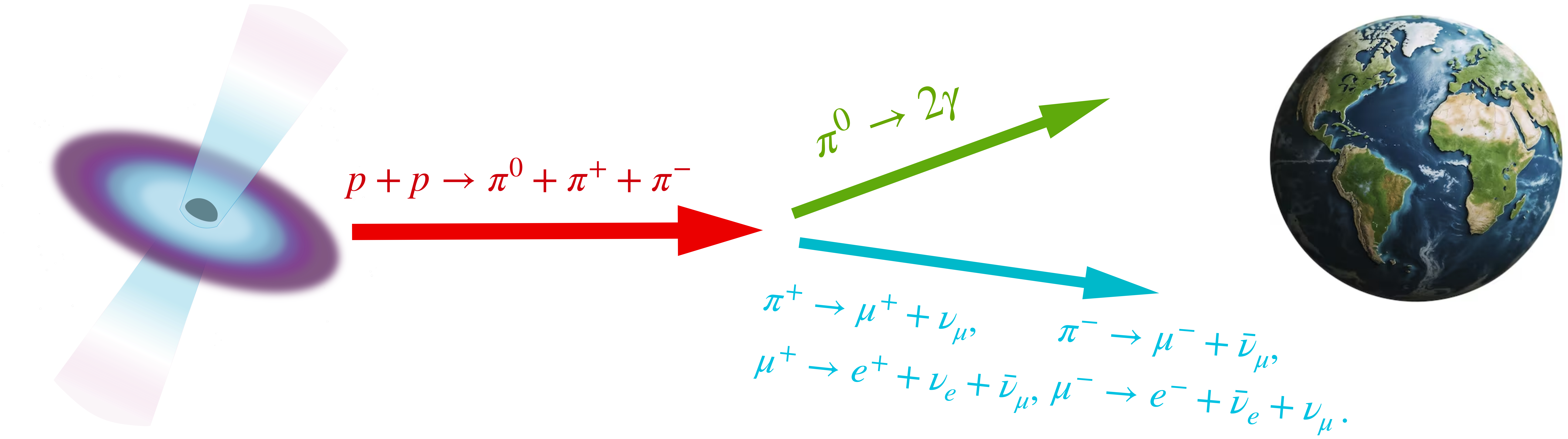
Introduction

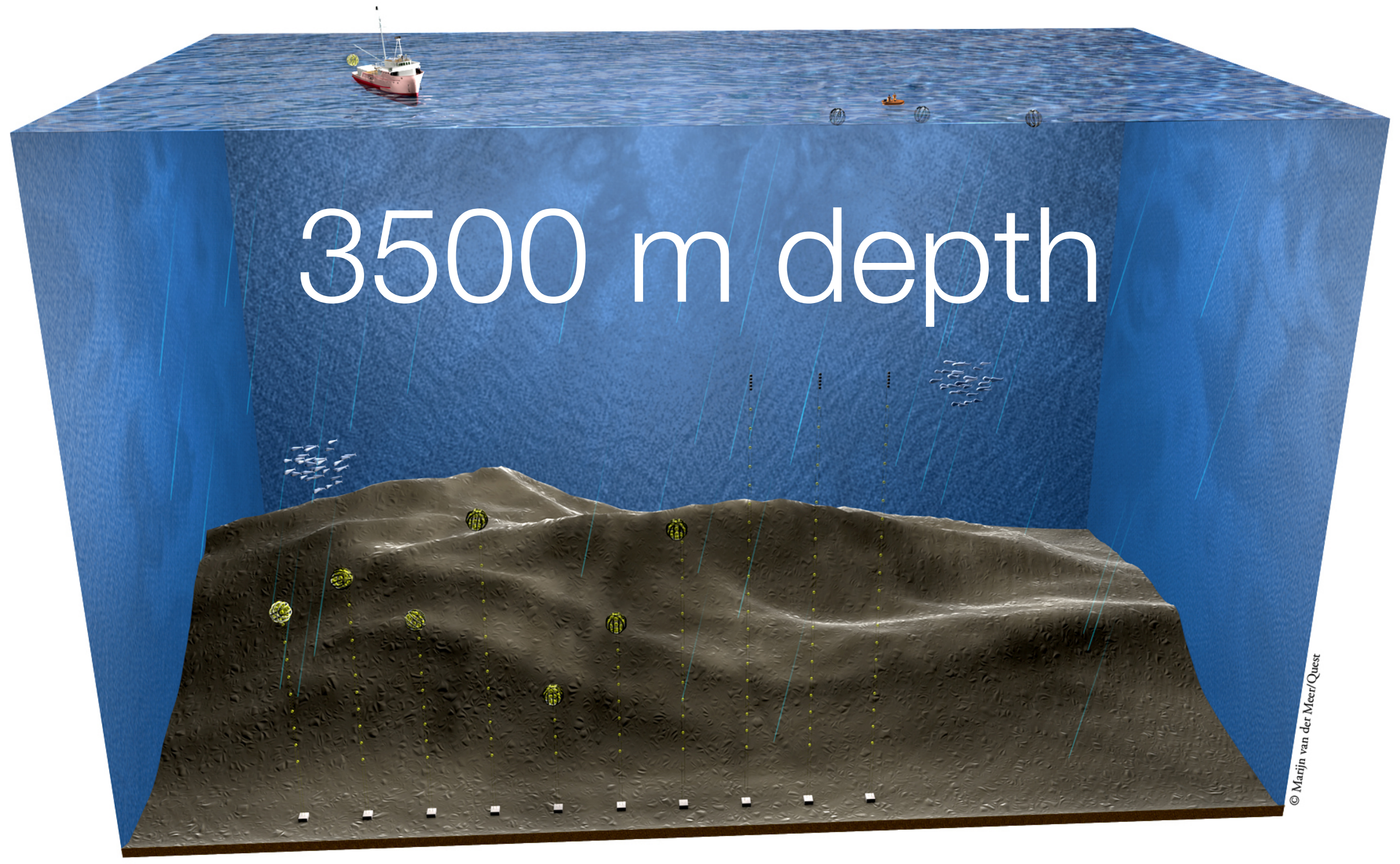
Multi-messenger astrophysics combines γ-ray and neutrino observations to study the most energetic phenomena in the Universe.

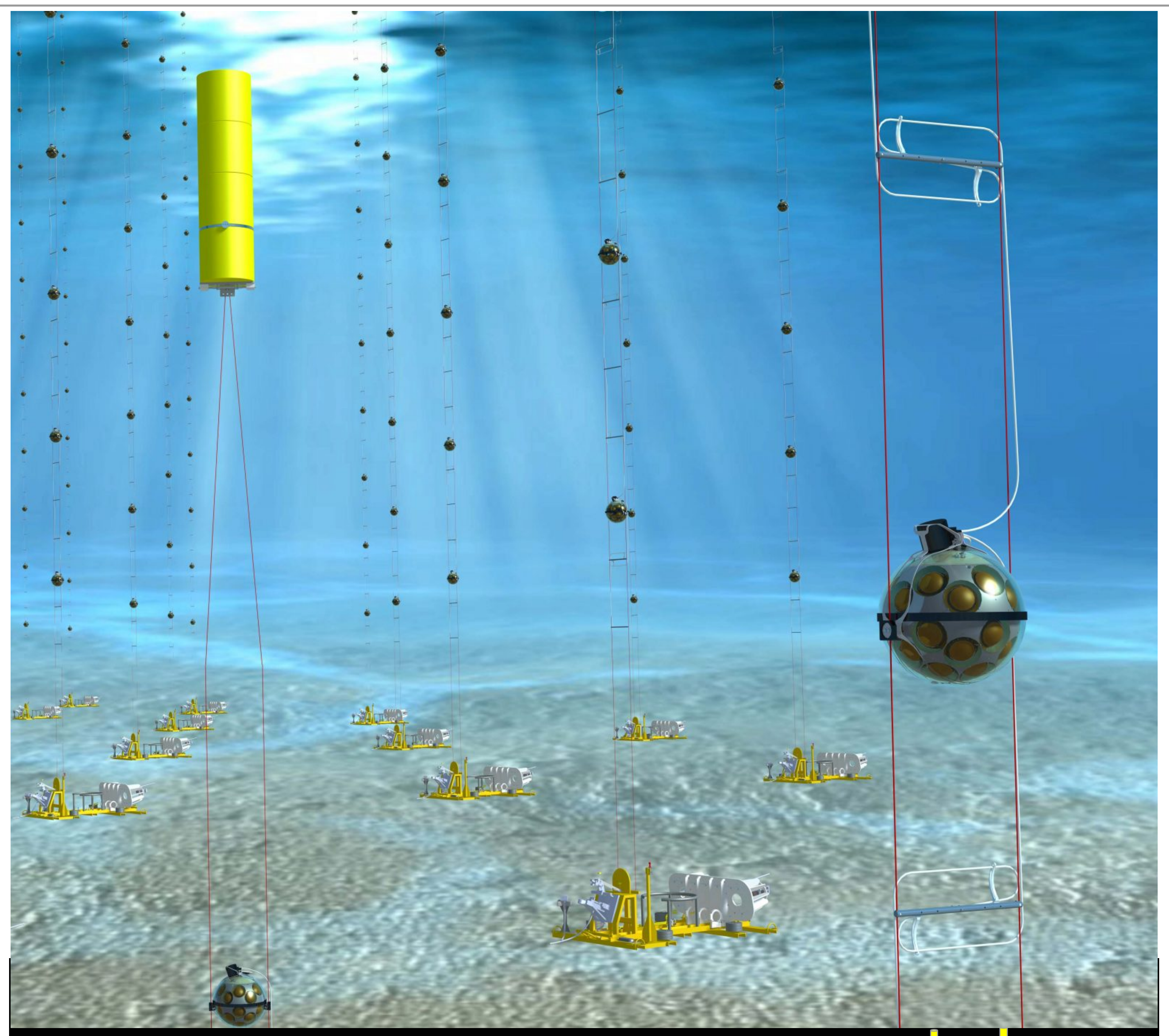


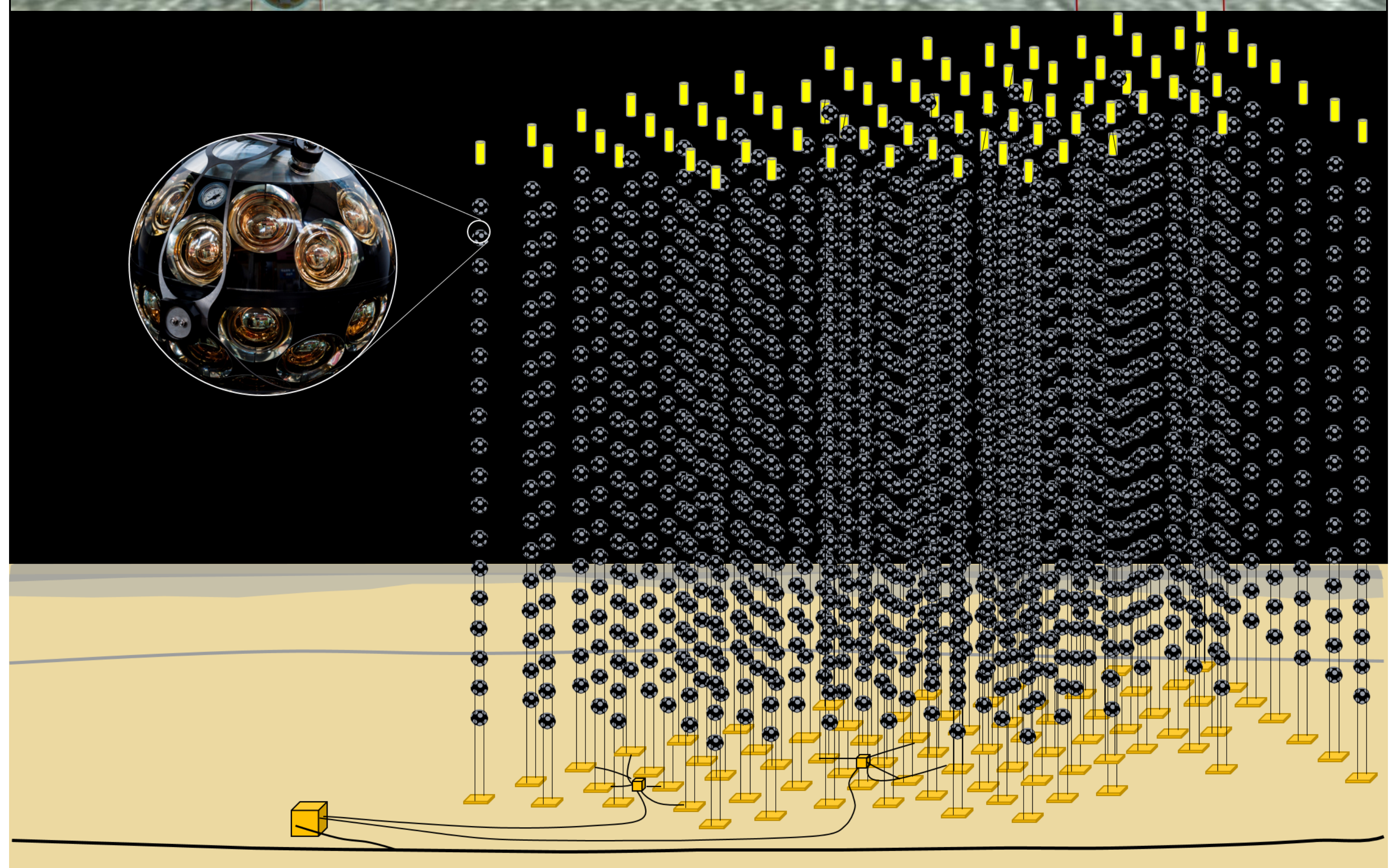
γ-rays and ν are produced in the decay of pions generated by hadronic interactions of cosmic rays. They are therefore direct indicators of proton acceleration.

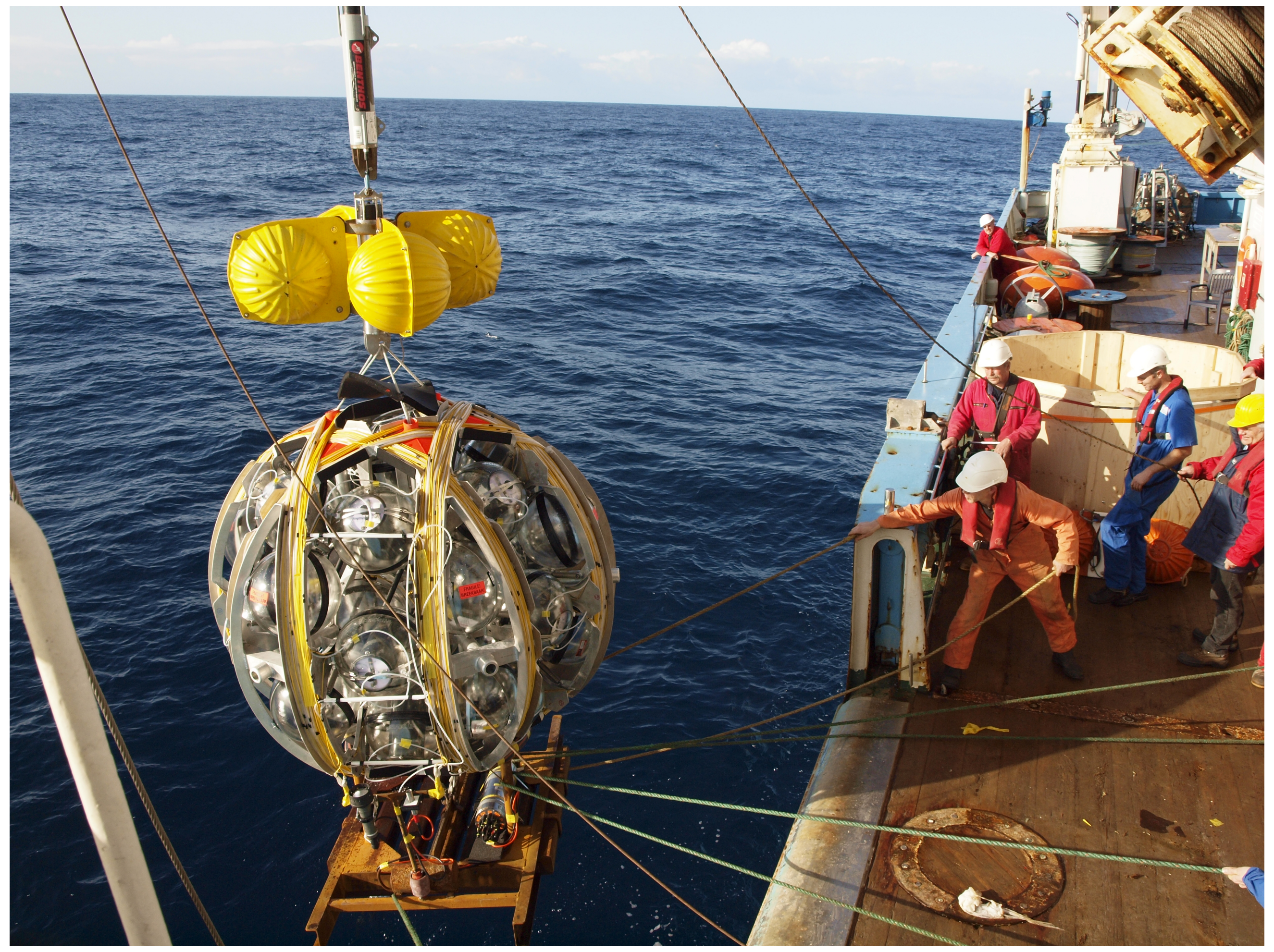
KM3NeT / ARCA

Latitude 36°16’N, longitude 16°06’W





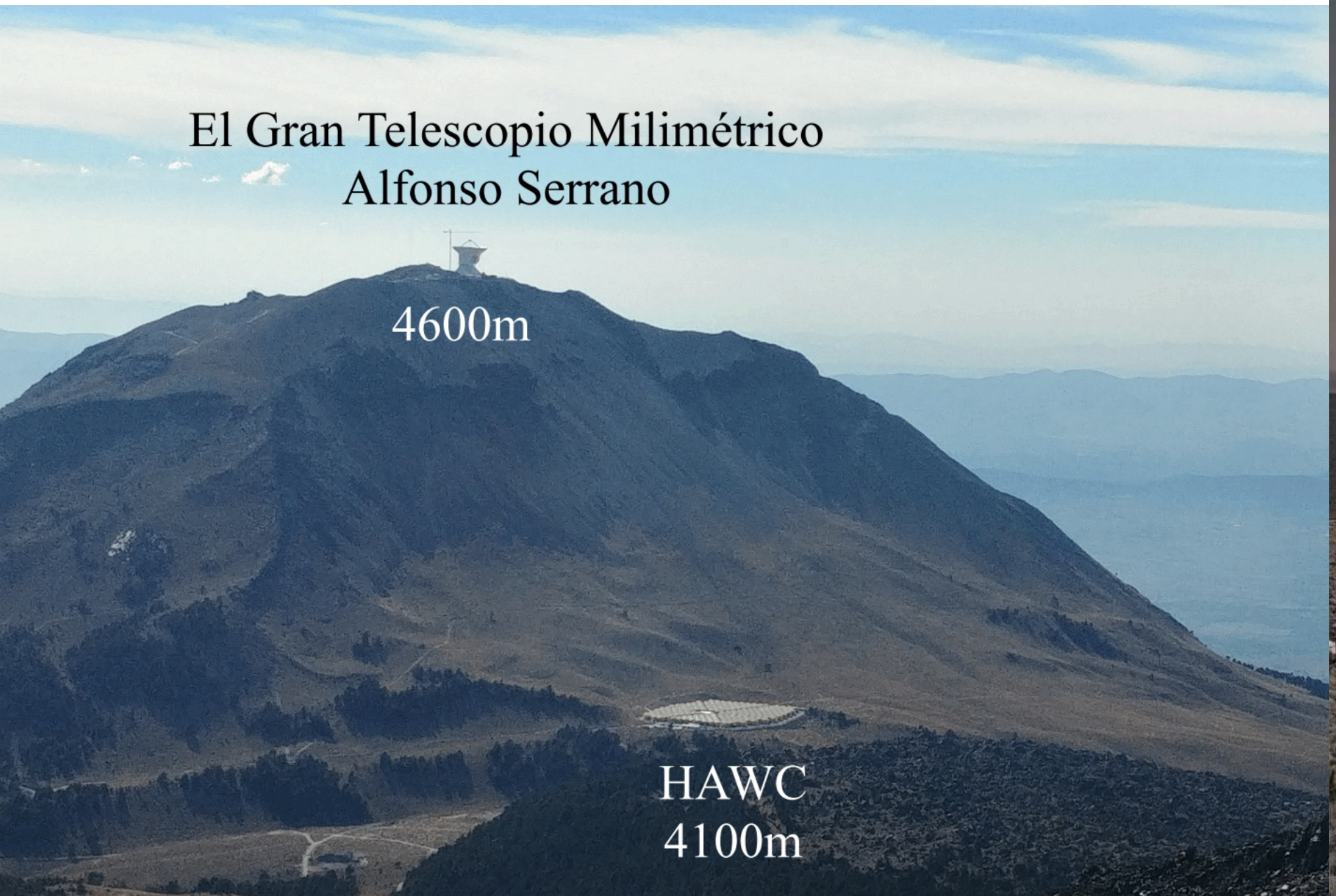


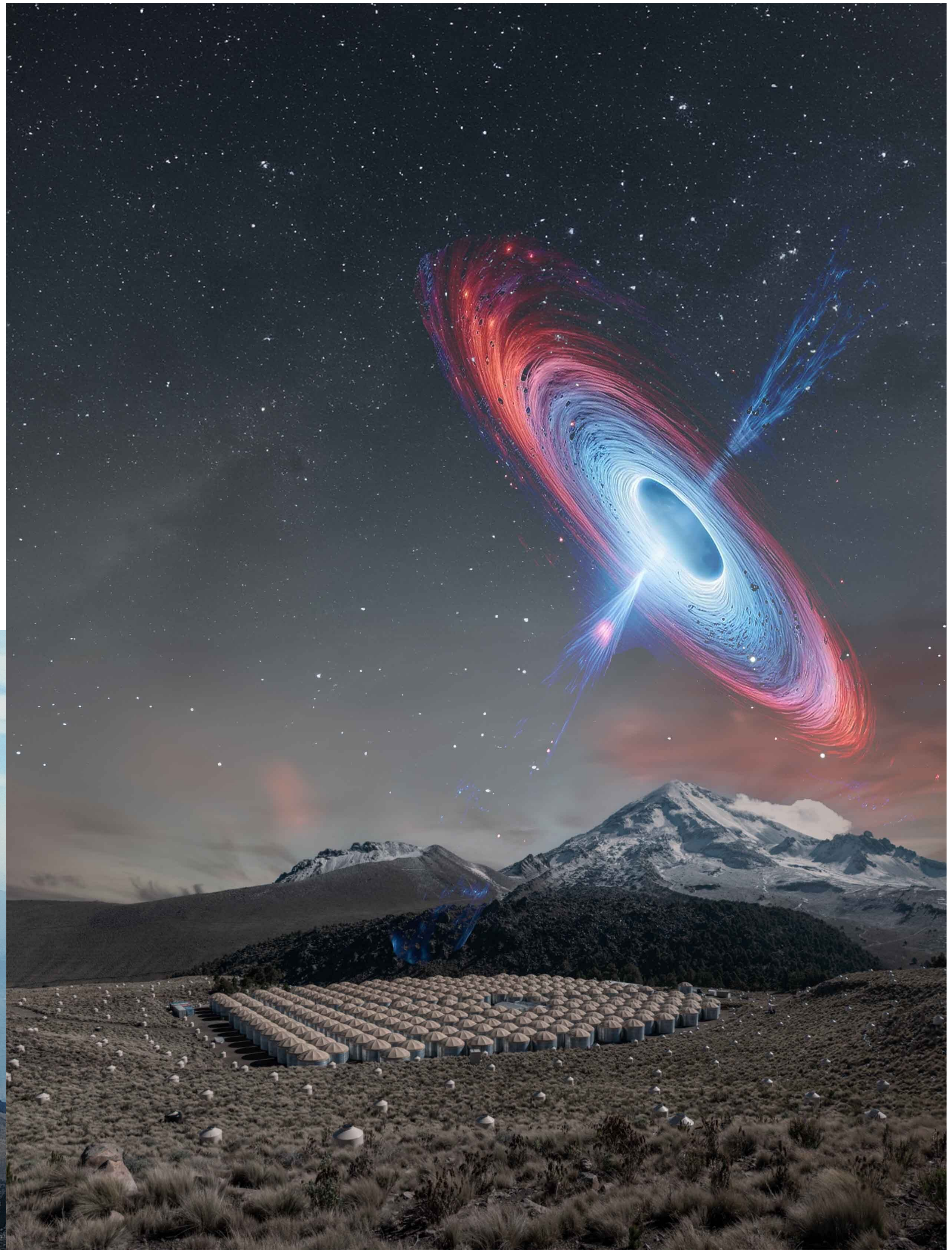


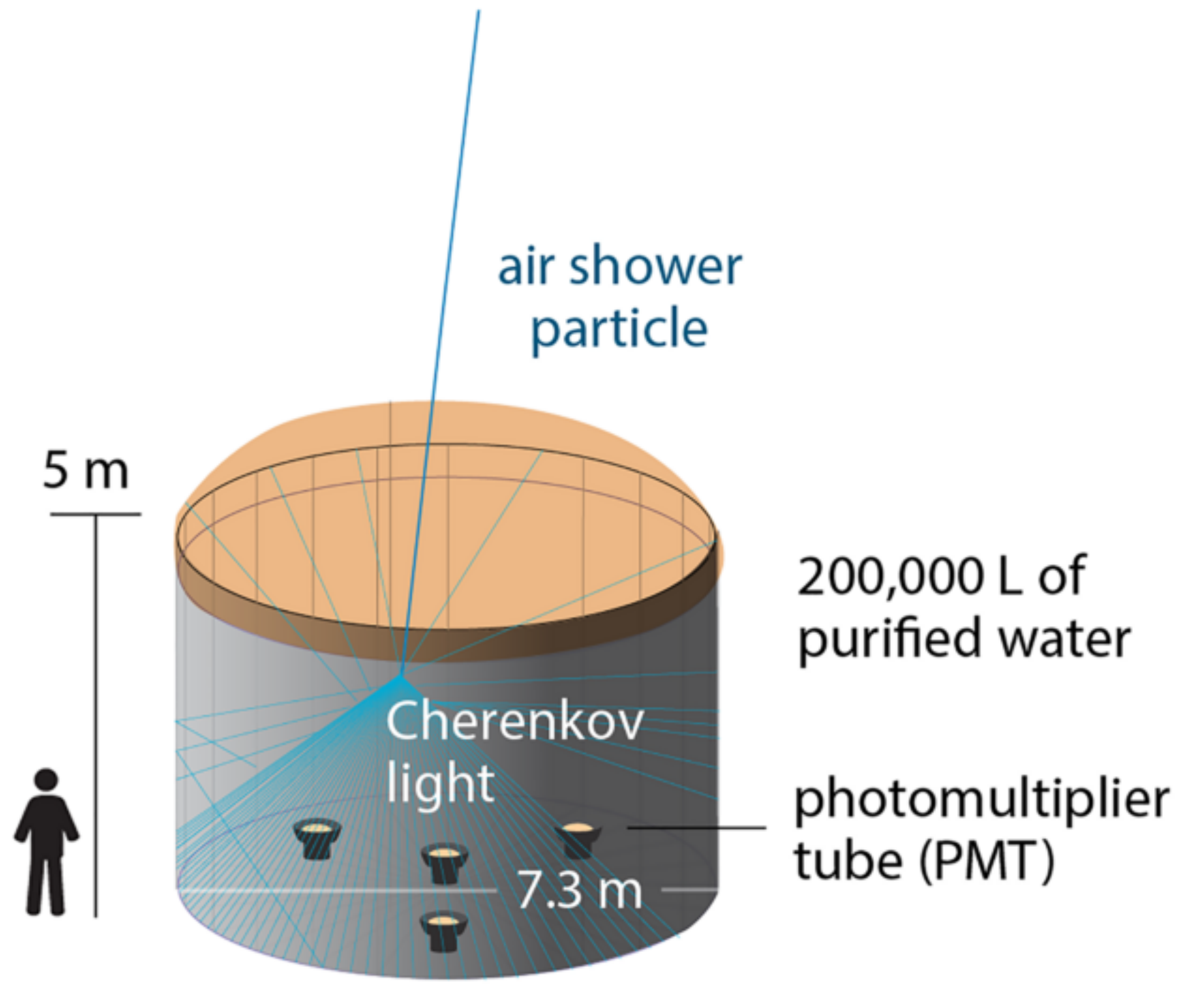
- Planned 230 detection units.
- Each detection unit has 18 digital optical modules (DOMs)
- Each DOM has 31 PMTs.
- Currently, taking data with partial configuration with 51 deployed detection units.

High Altitude Water Cherenkov (HAWC) gamma-ray observatory

Latitude 19ºN, longitude 97ºW







- 300 water Cherenkov detectors (+300 outriggers)
- 95% duty-cycle.
- ~2 sr instant coverage.
- Full array inaugurated in March 2015.

Introduction

- HAWC: continuous monitoring of the sky in the TeV γ-ray energy range.
- KM3NeT: Sensitive to TeV-PeV neutrinos, probing hadronic interaction directly.
- Combined analysis enables:
  - Disentangling hadronic vs. leptonic emission.
  - Testing cosmic-ray acceleration models.
- We define the hadronic fraction f as:

$f = \dfrac{\phi_\gamma^{\text{hadronic}}}{\phi_\gamma^{\text{total}}}$, where f quantifies the contribution of hadronic emission to the total γ-ray flux.

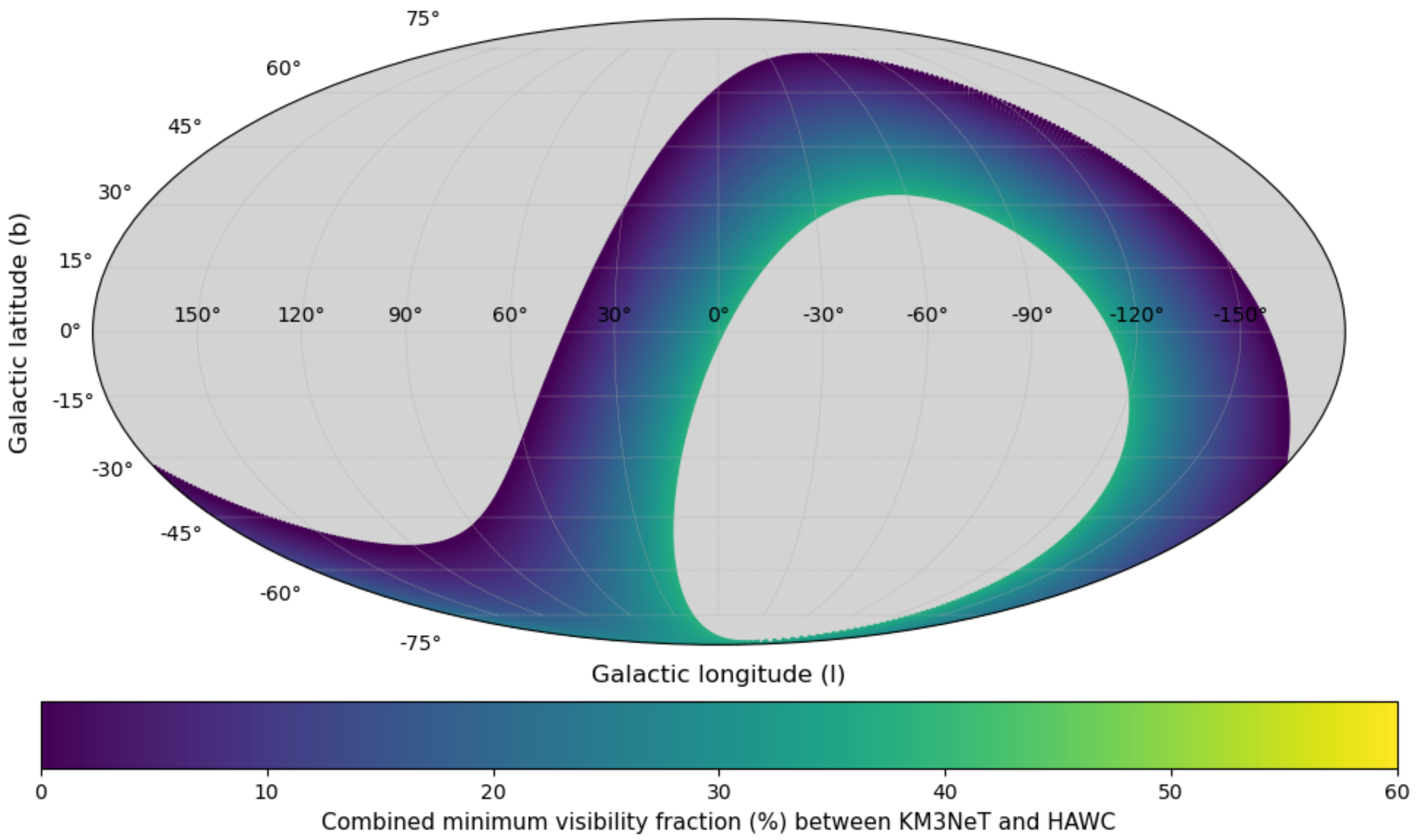
In this work, we present first estimations of the capabilities of a **joint KM3NeT and HAWC analysis** to constrain the hadronic contribution to the emission processes of selected Galactic sources, using **KM3NeT Monte Carlo simulations** and **HAWC observational data**.

Source selection: Common field of view (FoV)

- Declination range: **-29.8º to 9.8º**

- **Exposure:** fraction of a sidereal day each source is observable above the detector horizon.

- **Combined visibility:** minimum exposure of HAWC and KM3NeT at each sky position.



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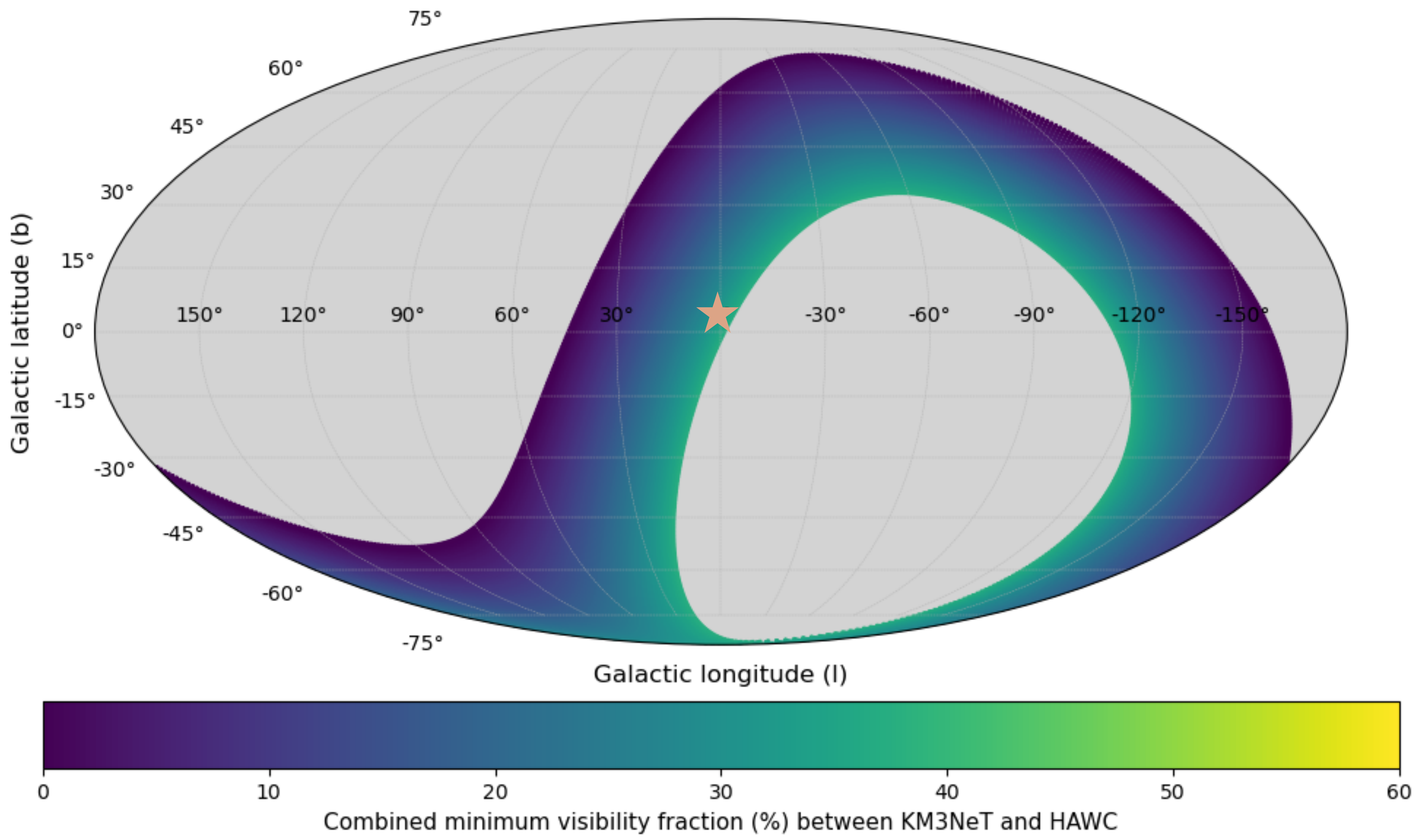
- **Combined visibility:** minimum exposure of HAWC and KM3NeT at each sky position.
- The source with the largest visbility is the Galactic Center, reported as a point-like PeVatron candidate.



Methodology

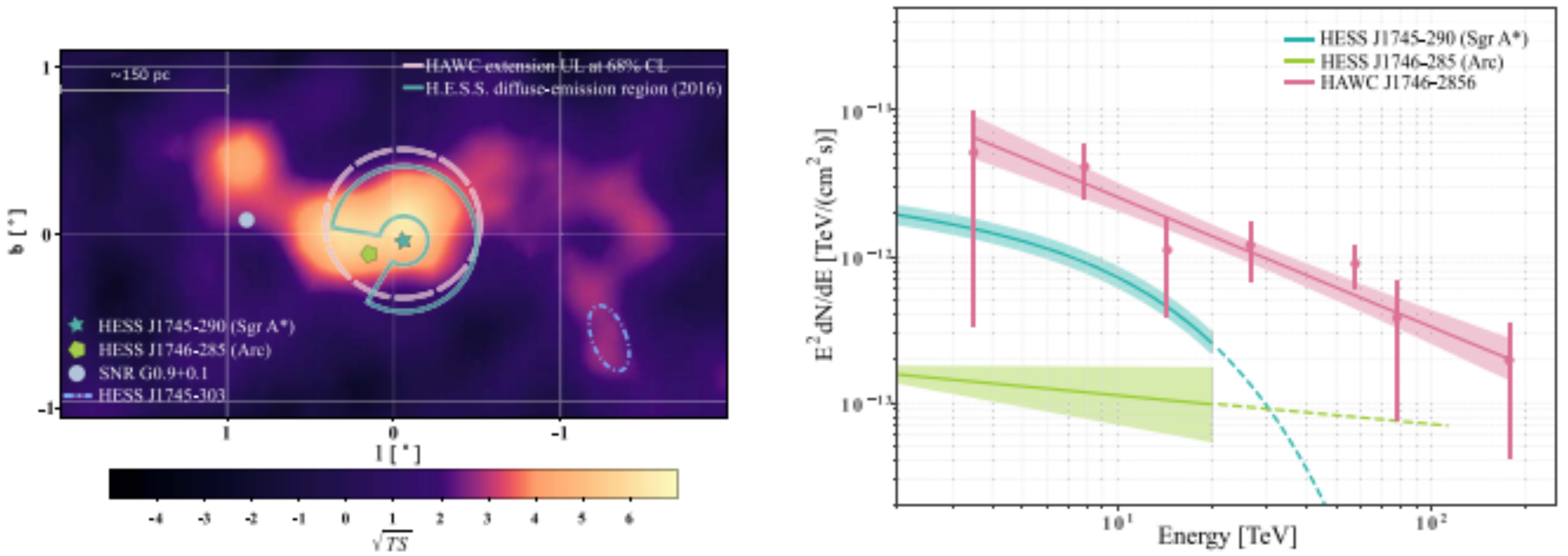
1. Use HAWC measurements to get the best-fit hadronic model, to use a prior information for the joint analysis.

2. Convolve the KM3NeT instrument response functions with these HAWC priors to create a pseudo-dataset equivalent to 10 years of exposure, with the complete full configuration.

3. Perform a likelihood scan over f to illustrate how the fit statistic responds to changes in the hadronic contribution, providing a validation and sensitivity check.

Spectral modeling of proton distribution

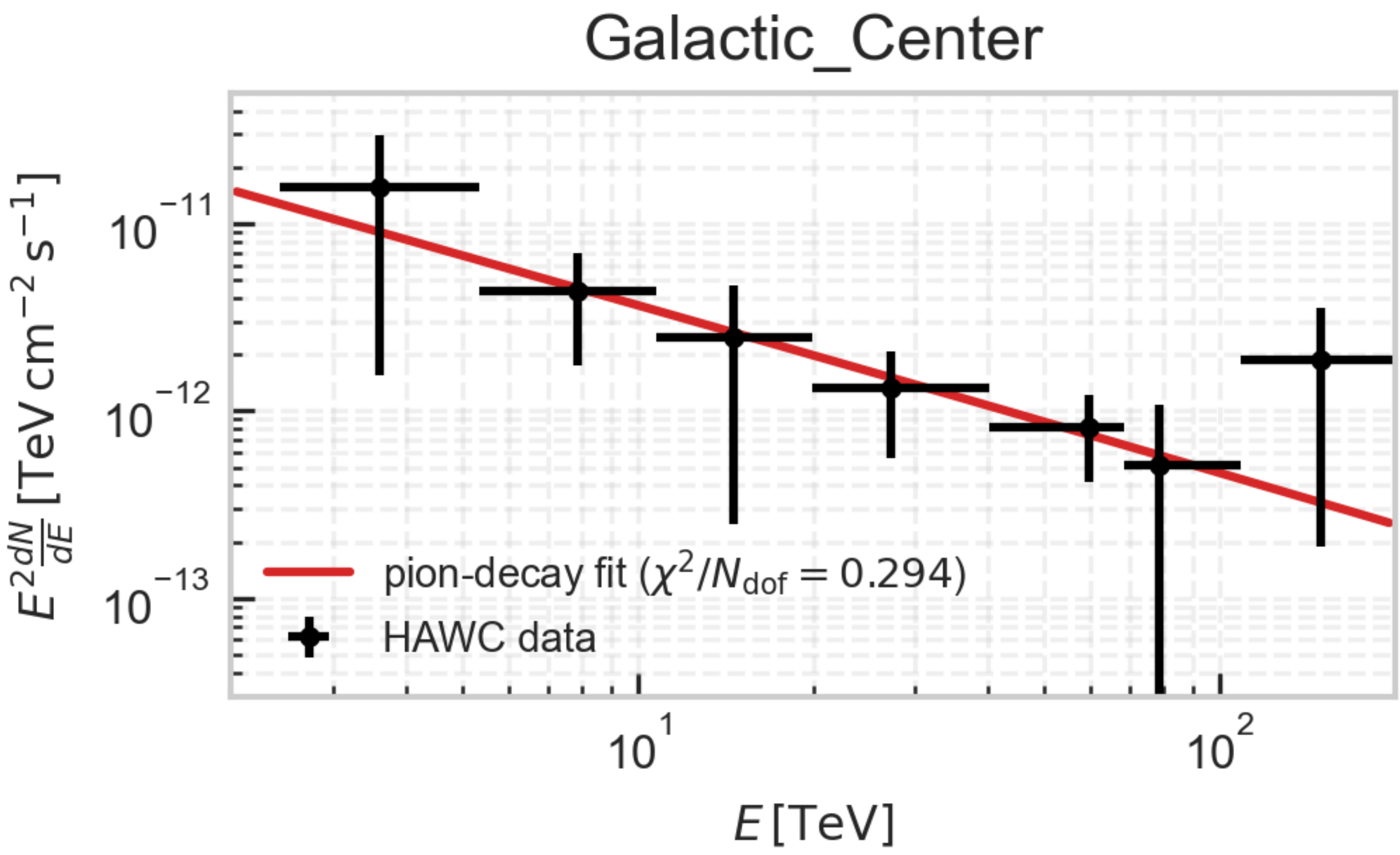
The γ-ray spectrum is well fitted to a power-law with an spectral index of -2.88 (Albert et al., 2024).



We define the proton spectrum to also follow a power law:

$$\phi_p(E) = A \cdot \left(\frac{E}{80\ \mathrm{TeV}}\right)^{-\alpha}.$$

A pion-decay model is used to generate an expected γ-ray flux, which is fitted to the HAWC data.

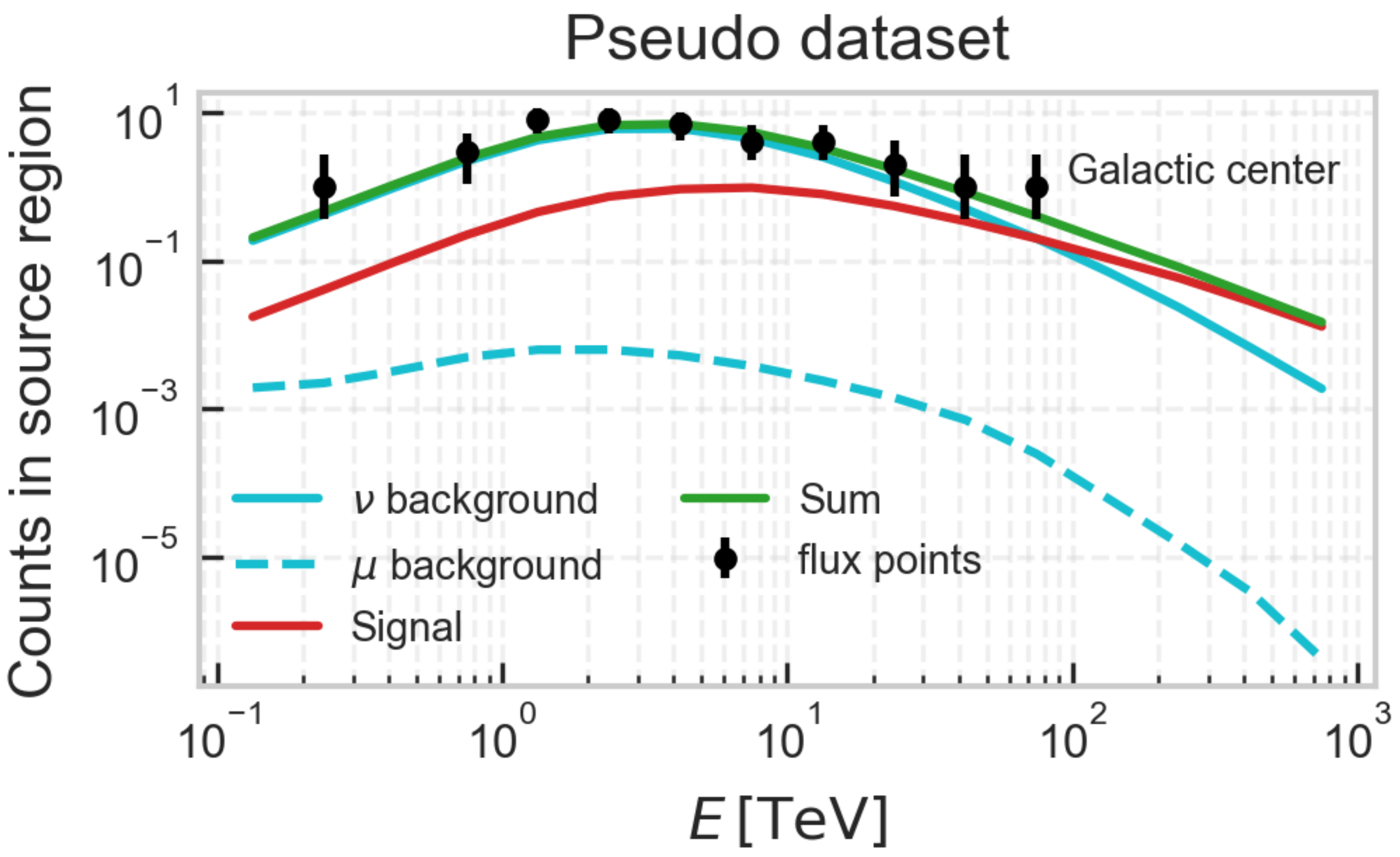


Pseudo-dataset creation

Using Kelner et al. (2006) model and the proton spectrum, the ν flux is calculated (spectral model)

Source model = ν spectral model + ν spatial model

The total expected signal from this source model is **convolved** with the KM3NeT IRFs -> observed counts in the pseudo dataset



KM3NeT WORK IN PROGRESS

Next step: compute the hadronic fraction f

- **Pseudo-dataset** uses a spectrum from a **100% hadronic** (pion-decay) model.
- Real sources are a mix of hadronic and leptonic processes; the true hadronic fraction is unknown.
- The simulated data is used for validation and sensitivity checks.
- **Goal:** Determine if the pipeline can correctly **recover the input hadronic fraction**.
- Varying the hadronic fraction parameter in the fit tests the detector's **sensitivity** to a mixed composition, indicating the **precision of future measurements**.

Workflow

The hadronic model (derived from HAWC observations) is defined by an amplitude A

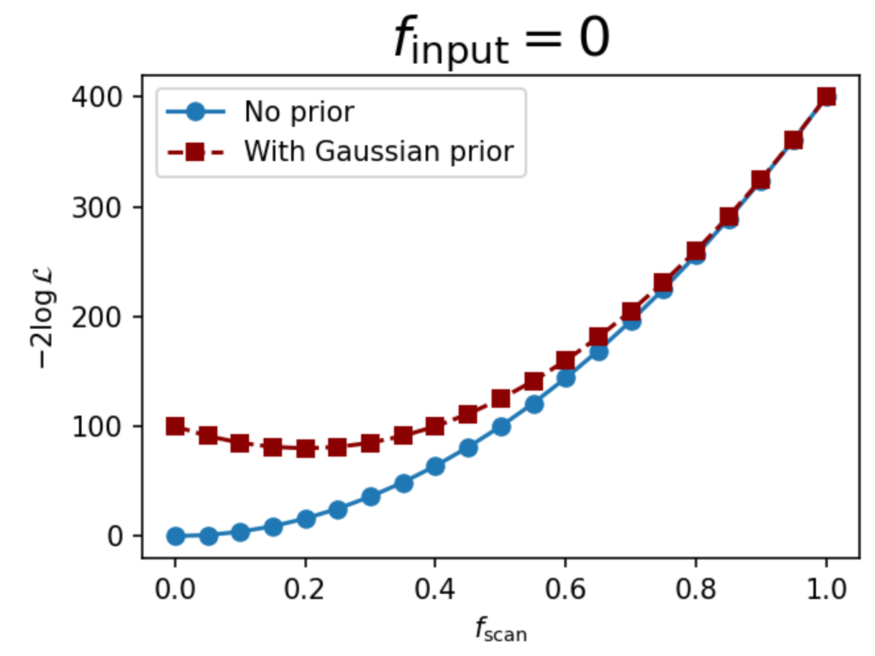
Injected KM3NeT pseudo-data
$$A_d = A \times f_{\text{input}}$$

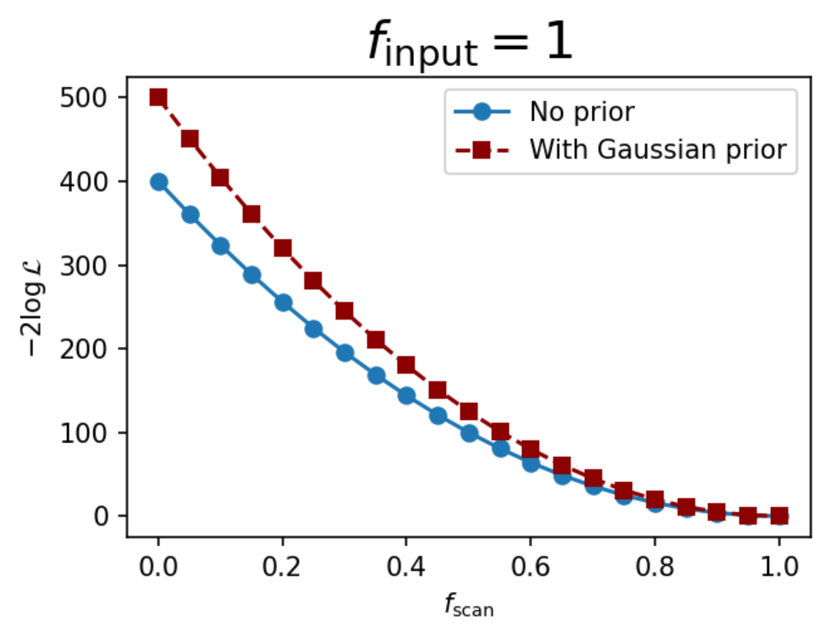
Model tested:
$$A_m = A \times f,$$
$$f \in [0,1]$$

Fit model to pseudo data
-> Cash statistic
$$-2\log \mathscr{L}(\text{data}\,|\,\text{model})$$

With and without priors

Minimum at $f \sim f_{\text{input}}$
-> best match to simulated data





ΔTS

In order to quantify the confidence intervals, we analyze ΔTS:

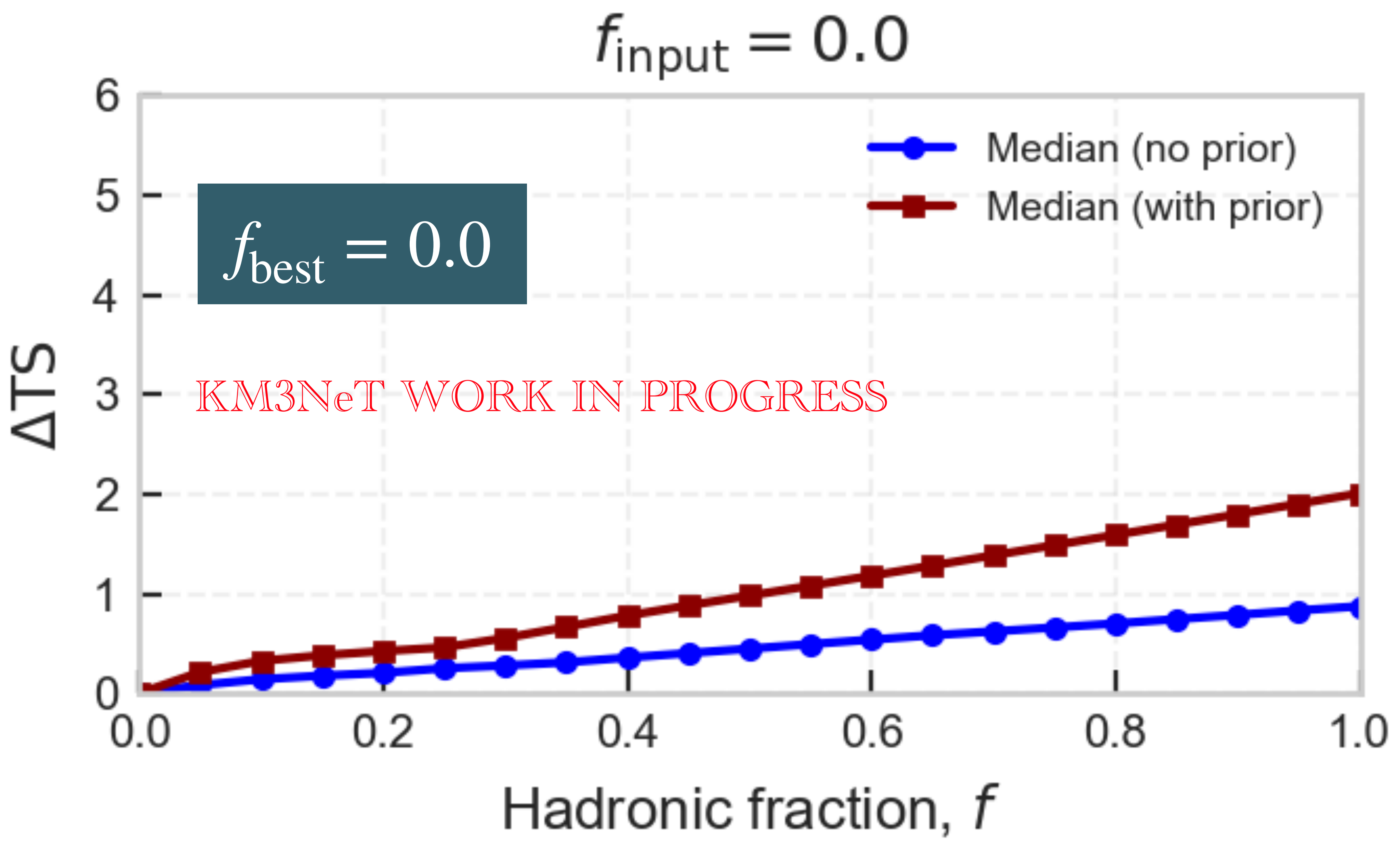
$$\Delta\text{TS} = -2\log\mathscr{L}(f) + 2\log\mathscr{L}_{\text{max}},$$

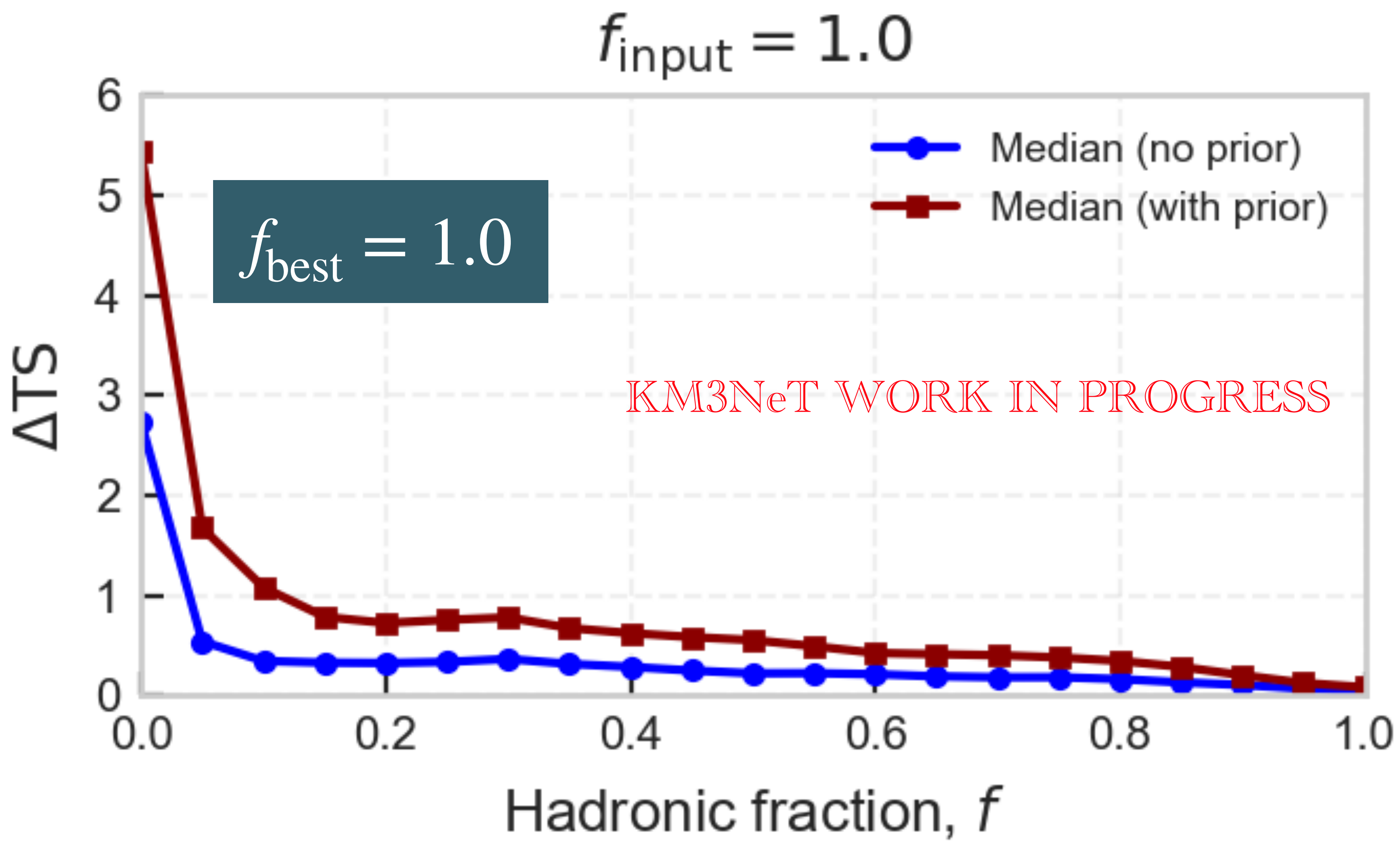
where $\mathscr{L}(f)$ = likelihood evaluated at f, and $\mathscr{L}_{\text{max}}$ is the maximum likelihood (minimum $-2\log\mathscr{L}$).

The minimum, at $\Delta\text{TS} = 0$, occurs at the best-fit f.

If we want to understand the expected statistical uncertainty of our method, we must look at the median behavior. So we created many experiments by applying Poisson fluctuations with random seeds.

Results: Galactic center for a simulated 10-year observation dataset





The model **correctly reproduces a null detection** when no hadronic component is injected.

The model with $f = 1$ is not strongly disfavored by the data

A purely leptonic model is **strongly disfavored** (at ~2.3σ), when taking into account the HAWC priors.

In both scenarios, incorporating the HAWC priors **yields a slightly more constrained result** compared to the analysis without priors.

Overall conclusion

- The pipeline works as expected:
  - Recovers true f_{input} values
  - $\Delta\mathrm{TS}$ curves behave as likelihood-based statistics
  - Confidence intervals are sensible
- For $f_{\text{input}} = 0$, the data **cannot strongly reject** $f > 0$, reflecting realistic statistical limits.
- For $f_{\text{input}} = 1$, the data **significantly reject** $f = 0$, showing the pipeline can quantify model exclusion.

Thank you

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Backup slides

Background Model Creation in the KM3NeT Pseudo-Dataset

- The simulation includes two types of atmospheric background, modeled using pre-computed **Instrument Response Functions (IRFs).**
- The total observation time is broken down into small **time steps** and a loop runs through each step.
- At each time step, the **zenith angle** (θ) is calculated for every map pixel, as the background rates depend strongly on θ.
- The ν and μ background IRFs are used to determine the **differential event rate** (counts/s/solid angle) for the current θ and energy bin.
- The differential rate is multiplied by the solid angle and the time step duration, and the resulting counts are **accumulated** into background maps based on their corresponding zenith bin.
- The average rate is then scaled by the total effective **livetime** for that bin to yield the final predicted counts.
- The ν and μ background maps are **summed** to create the final total background prediction, which is assigned to each KM3NeT dataset.

Kelner et al. (2006) model

- It computes the resulting fluxes of secondary particles: neutrinos (ν), gamma rays (γ), and electron/positron pairs ($e^{\pm}$).
- The model uses inclusive cross-sections and spectra (based on accelerator data and theoretical models) to describe the energy distribution of secondary particles (pions, kaons, etc.).
- These secondary particles decay rapidly (e.g.,$\pi^+ \rightarrow \mu^+ + \nu_\mu$,$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$), producing the final neutrino flux.
- It provides ready-to-use analytical formulas for the differential neutrino flux ($\mathrm{d}N_\nu/\mathrm{d}E_\nu$) given an input proton spectrum ($\mathrm{d}N_p/\mathrm{d}E_p$).
- It is essential for modeling $\nu$and γ production in sources where protons interact with ambient matter

Spectral modeling and prior parameters

- The priors are implemented as Gaussian penalties in the likelihood framework:

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{KM3NeT}} \times \mathcal{L}_{\text{prior}}, \quad \mathcal{L}_{\text{prior}} \propto \exp\left[-\frac{(p - p_0)^2}{2\sigma_p^2} \right],$$

- where p_0 is the parameter value derived from HAWC and σ_p its uncertainty.

- This constrains the hadronic parameters to remain consistent with gamma-ray observations while still allowing the neutrino data to modify the fit.