Here, There & Everywhere
PhD Summer School on Neutrinos
July 17-21, 2023
Niels Bohr Institute, Copenhagen

INVESTIGATING HIGH-ENERGY NEUTRINOS FROM BLAZARS WITH A LIKELIHOOD ANALYSIS OF THE ICECUBE OBSERVATORY DATA

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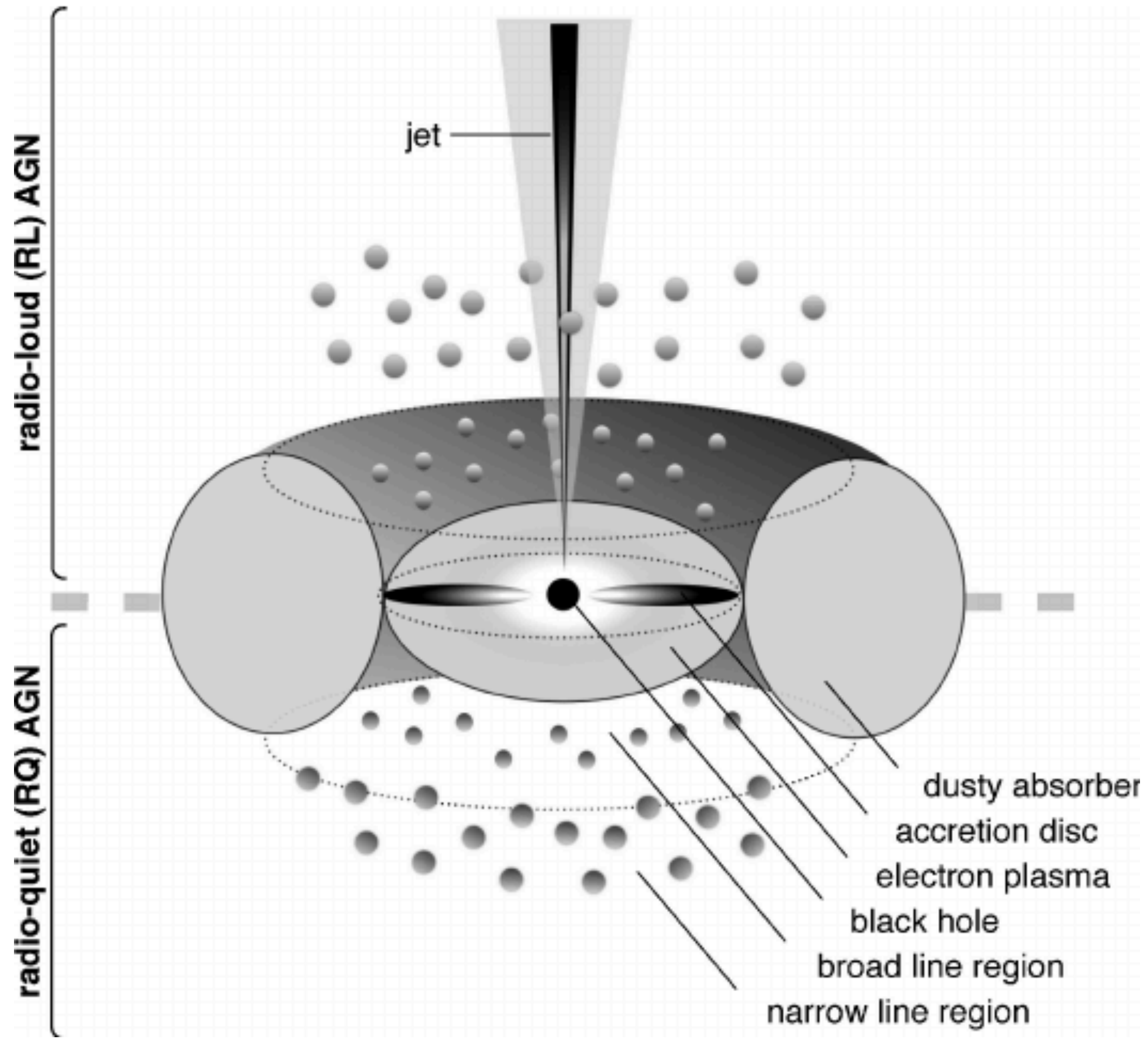
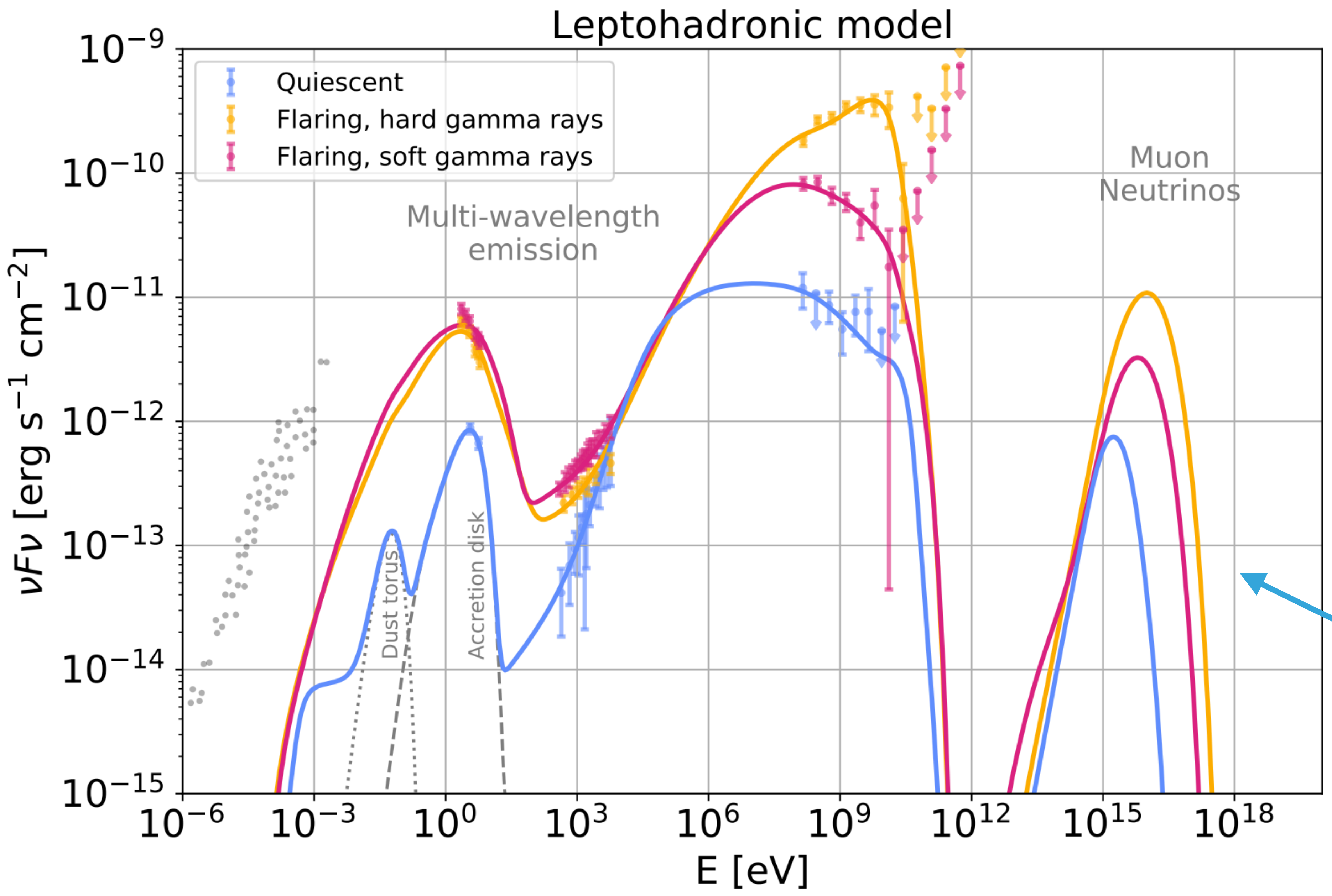
JULY 18, 2023

COPENHAGEN

ON BEHALF OF SARA BUSON, GAËTAN FICHET DE CLAIRFONTAINE, LENZ OSWALD, GIULIA ILLUMINATI, ANDREA TRAMACERE, ALESSANDRA AZZOLLINI, VARDAN BAGHMANYAN, LEONARD PFEIFFER

AGN (BLAZARS) AS CANDIDATE SOURCES FOR HIGH-ENERGY NEUTRINOS



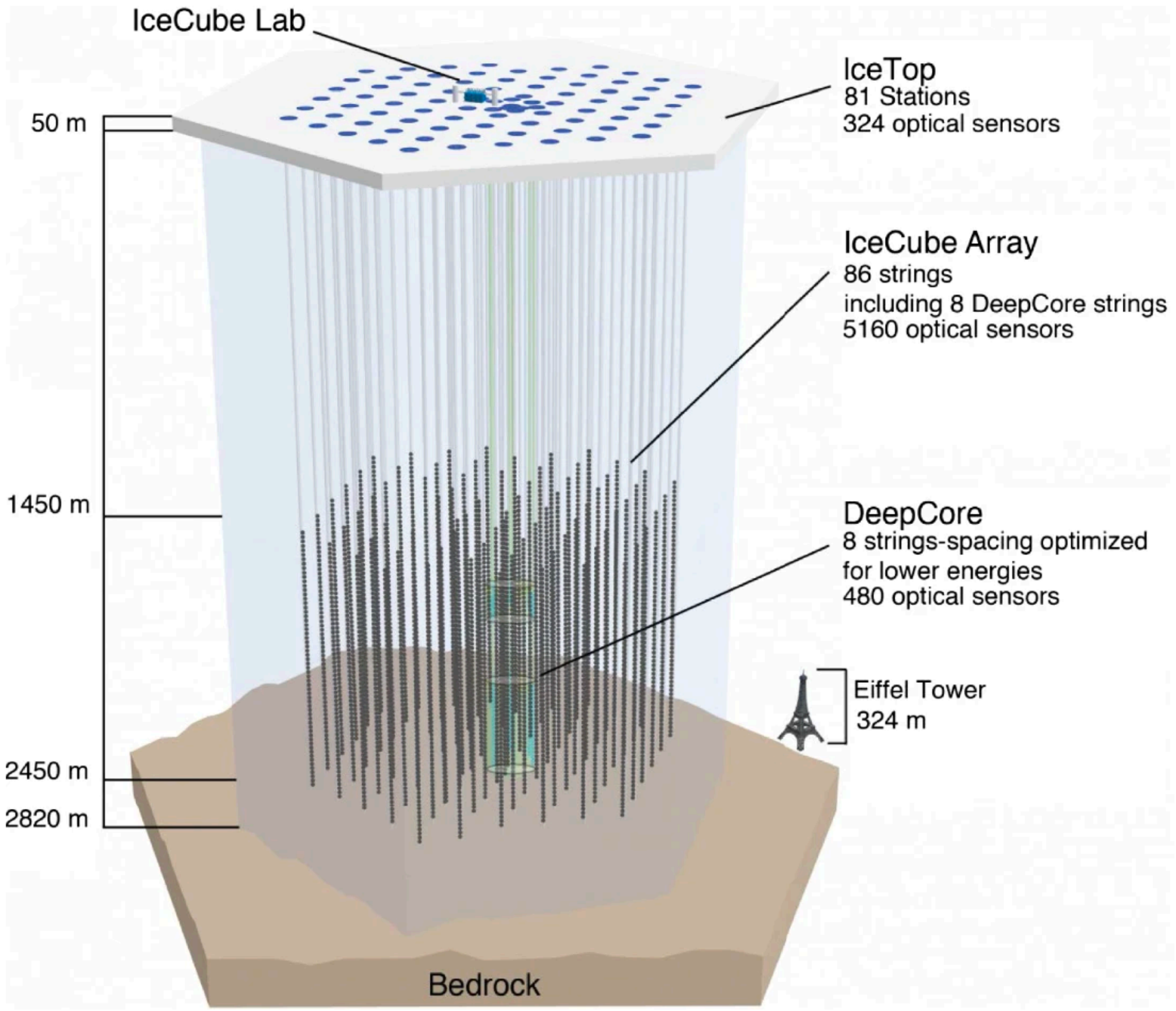


Neutrino production channels

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$$
$$\pi^0 \rightarrow \gamma + \gamma\,,$$
$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu\,,$$
$$n \rightarrow p + e^+ + \nu_e\,.$$

[1] Beckmann et al. (2012)
[2] Rodrigues et al. (2020)

ICECUBE NEUTRINO OBSERVATORY



Neutrino detection

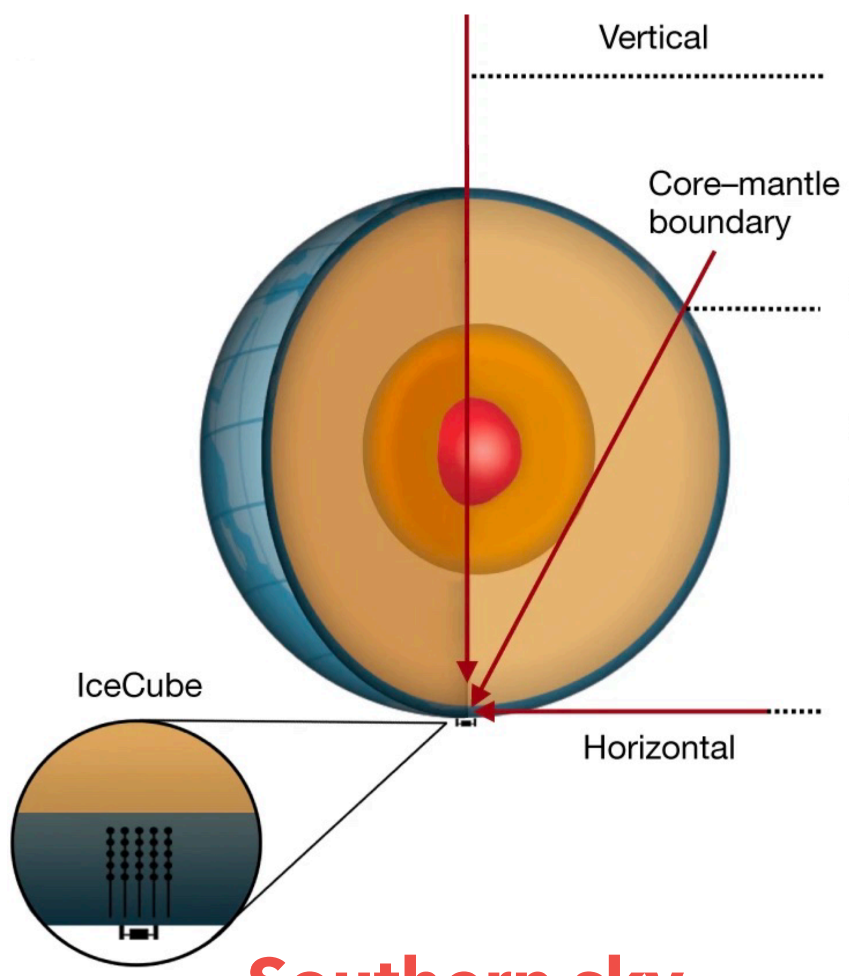
Charged-current interactions

$$\nu_e + X \xrightarrow{W^\pm} e^\pm + Y$$
$$\nu_\mu + X \xrightarrow{W^\pm} \mu^\pm + Y$$
$$\nu_\tau + X \xrightarrow{W^\pm} \tau^\pm + Y$$

Charged particles $v > \frac{c}{n}$ → Cherenkov light detected by PMTs by optical sensors

Neutrino data

Northern sky



Southern sky

Northern data:
ν interacts with Earth that shields the events ∝
- arrival angle
- energy

Southern data:
Large background rate

[3] Katori et al. (2021).
[4] IceCube Collaboration (2017).

NEUTRINO ANALYSIS FRAMEWORK

Maximization of the extended unbinned likelihood

f = probability density function

x_i = i-th of N event in the dataset collected

θ = parameters of the assumption

$$\mathscr{L}(\theta) = \prod_{i=1}^{N} f(x_i | \theta)$$

Maximization: The closer the parameters θ of the assumption are to the real ones θ^* the larger is $\mathscr{L}(\theta)$

Extended: the number of neutrinos detected by IceCube follows a Poisson distribution

$$\mathscr{L}(\theta) = \exp(-\lambda)\prod_{i=1}^{N} \lambda \cdot f(x_i | \theta)$$

λ = expected number of detected ν

Unbinned:

- limited amount of astrophysical neutrino events
- accurate estimation of model parameters

→ each event is weighted independently

NEUTRINO ANALYSIS FRAMEWORK

Maximization of the extended unbinned likelihood

$$\mathcal{L}(\theta) = \exp(-\lambda)\prod_{i=1}^{N} \lambda \cdot f(x_i|\theta)$$

Goal

We want to test in different position in the sky the validity of 2 possible hypothesis

$\mathcal{H}_0 ; \mathcal{H}_1$

For each of them we construct the correspondent likelihood function

1. Null hypothesis $\mathcal{H}_0$

In that region in the sky there is no astrophysical neutrino source

$$\mathcal{L}(\mathcal{H}_0(\theta)) = \exp(-N)\prod_{i=1}^{N} \mathcal{B}_i$$

2. Signal hypothesis $\mathcal{H}_1$

In the same region in the sky there are background + an astrophysical neutrino point-source

The source emits:

- a certain number of neutrinos of signal n_S
- according to a power-law with spectral index γ

$$\frac{d\phi}{dE_\nu} = E^{-\gamma}$$

For a large dataset $\lambda \to N = n_S + n_B$

$$\mathcal{L}(\mathcal{H}_1(\theta)) = \exp(-N)\prod_{i=1}^{N} N \cdot \frac{1}{N}\left(\frac{n_S}{N}\mathcal{S}_i + \frac{n_B}{N}\mathcal{B}_i\right)$$

NEUTRINO ANALYSIS FRAMEWORK: TEST STATISTIC AND P-VALUE

1)

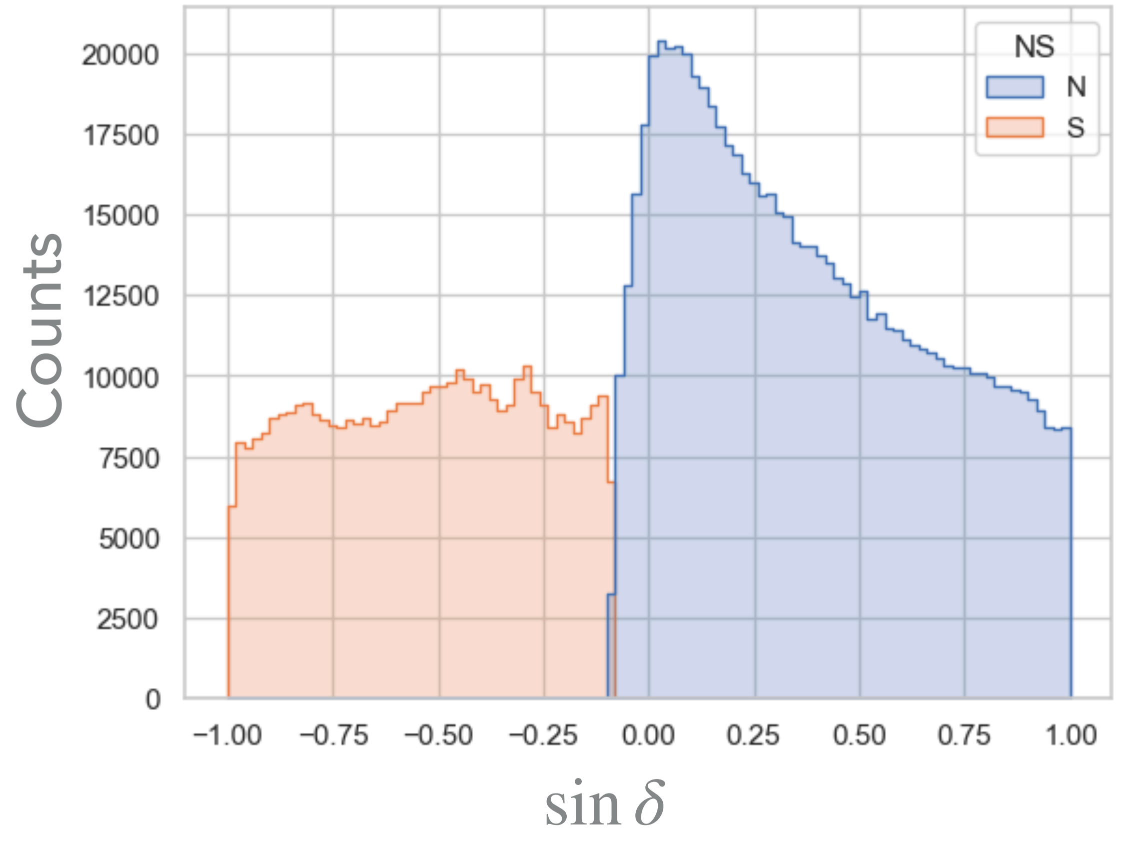
$$\mathcal{L}(\vec{x}_i, E_i | n_S = 0) = \exp(-N) \prod_{i=1}^{N} \mathcal{B}_i(\sin \delta_i, E_i)$$

$$\mathcal{L}(\vec{x}_i, E_i | n_S, \gamma) = \exp(-N) \prod_{i=1}^{N} \frac{n_S}{N} \mathcal{S}_i(|\vec{x}_i - \vec{x}_s|, E_i; \gamma) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i(\sin \delta_i, E_i)$$

$$TS = -2 \log \left(\frac{\mathcal{L}(\mathcal{H}_0)}{\mathcal{L}(\mathcal{H}_1)} \right) \in [0, +\inf]$$

2)

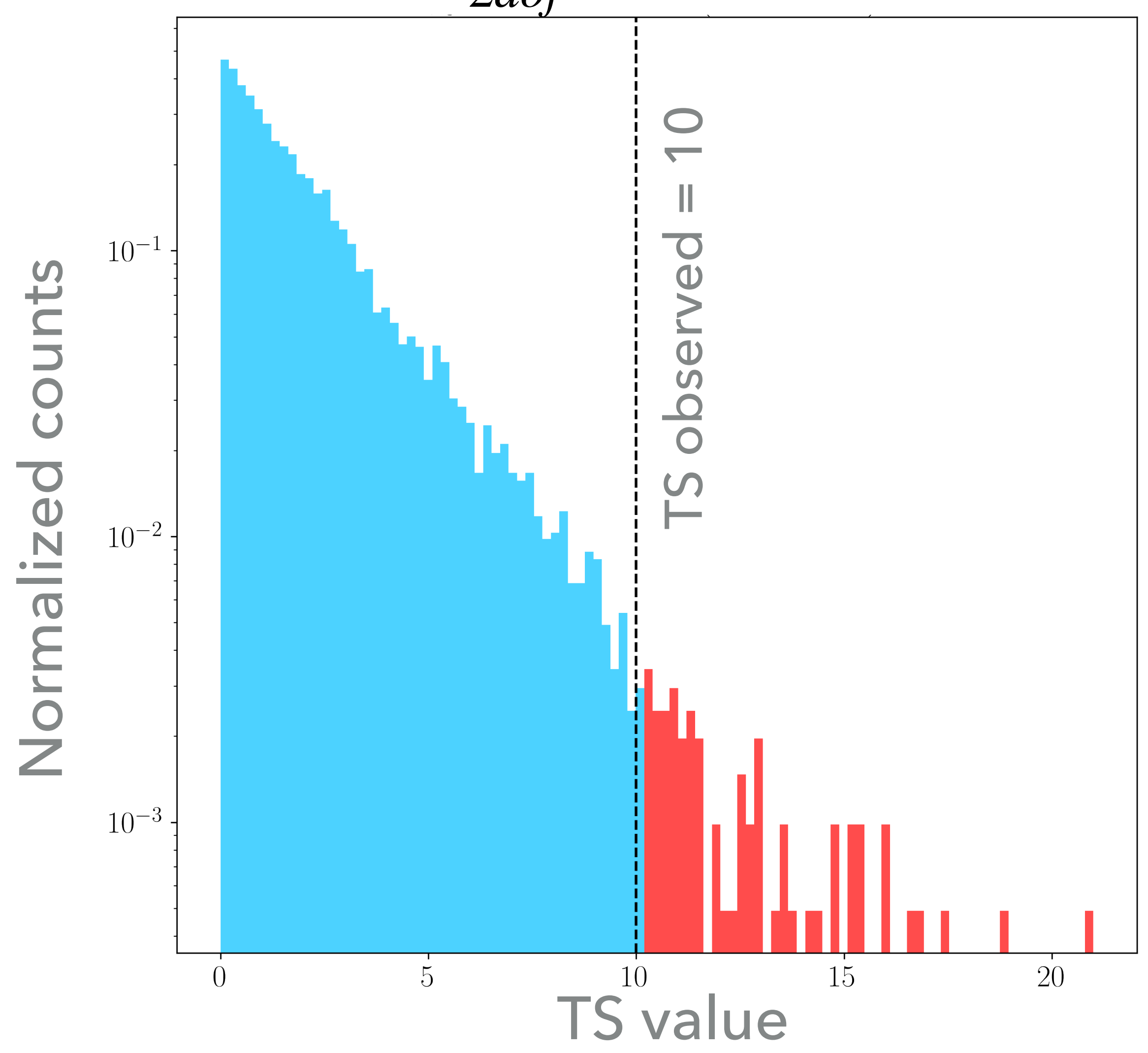
Data distribution in function of $\sin \delta$



Background strongly depends on declination

to mitigate the bias

χ^2_{2dof} distribution



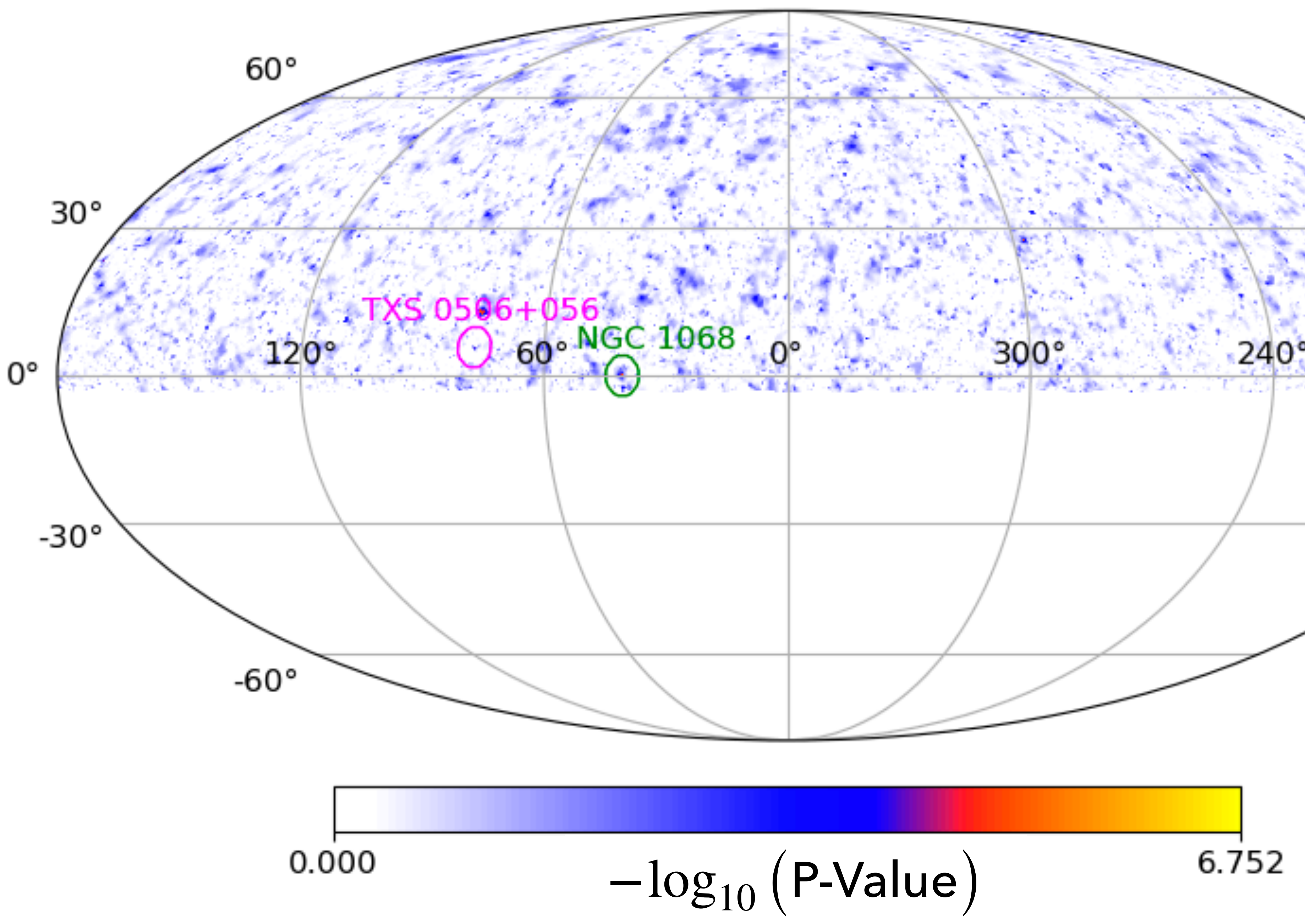
$$\text{P-Value} = \int_{TS_{obs}}^{\infty} g(TS | \mathcal{H}_0) dTS \in [0,1]$$

P-Value: **probability** of deviation from the background

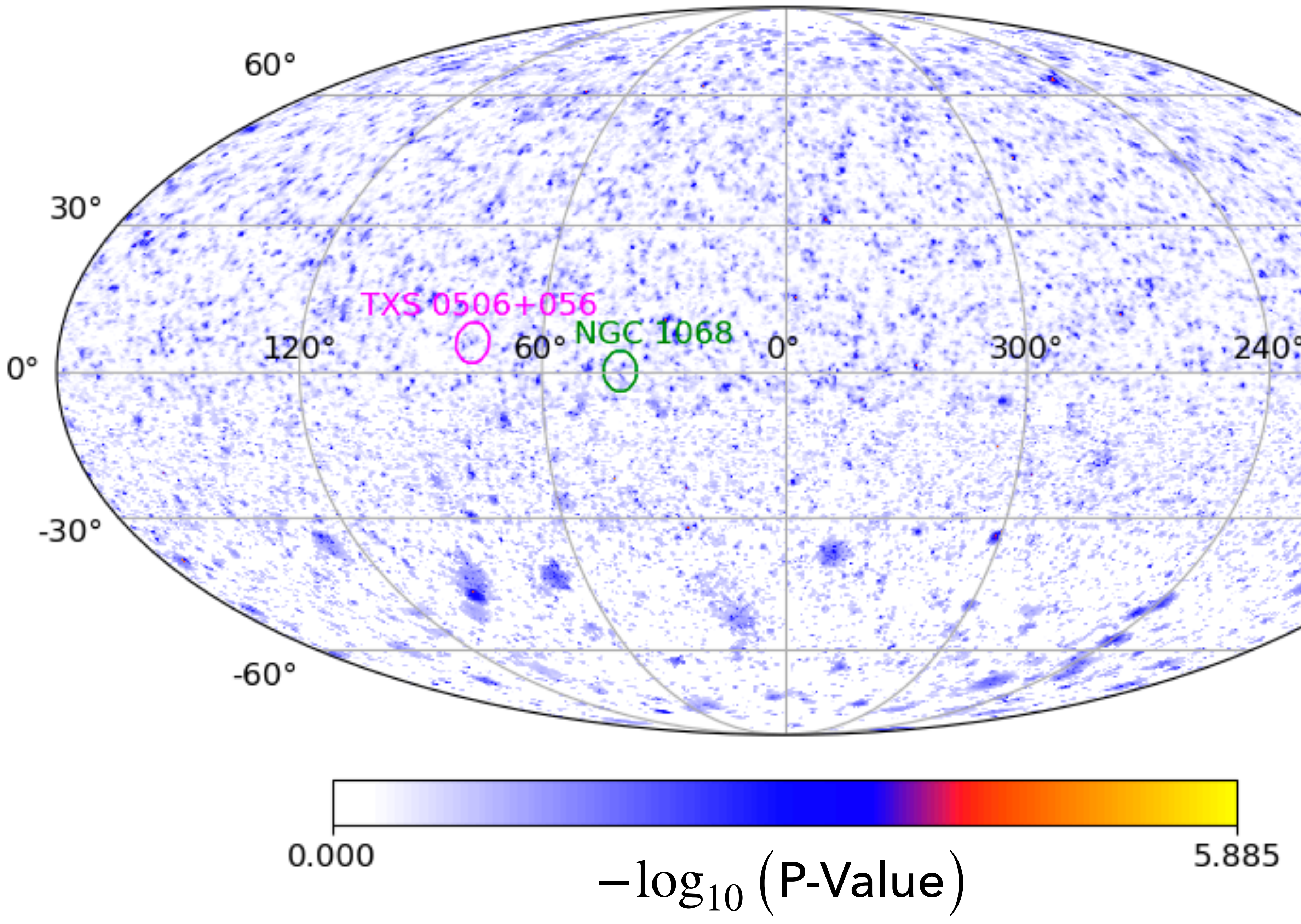
[5] IceCube Collaboration (2022).
[6] IceCube Collaboration (2017).

LATEST ICECUBE RESULTS

Latest IC release (2022)



7 years map (2017)



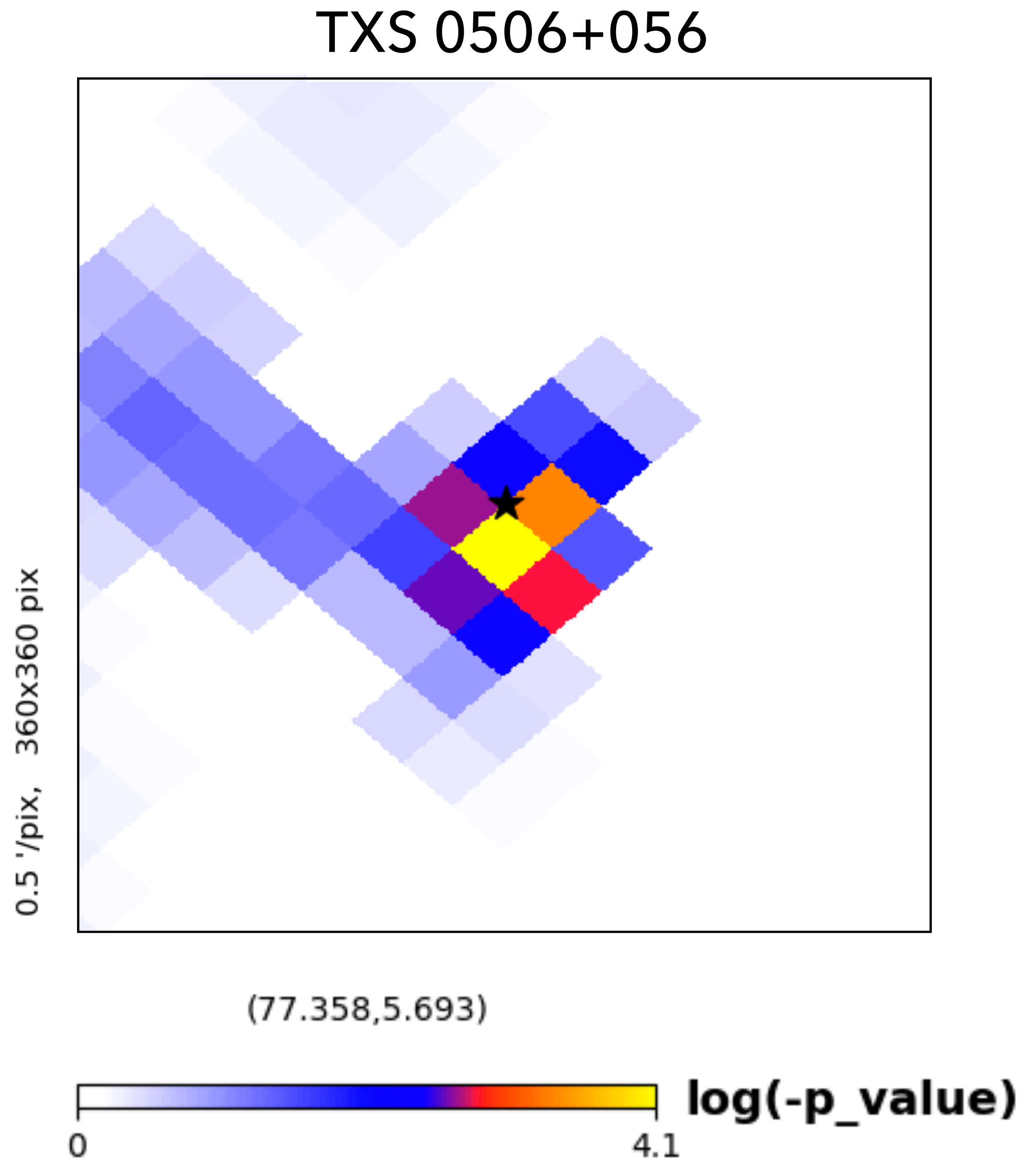
Tested positions ~ 400 000 (Area pixel ~ 0.05 [deg^2])	Tested positions ~ 3 000 000 (Area pixel ~ 0.01 [deg^2])
Data acquired between 2011 and 2020	Data acquired between 2008 and 2015
Only Northern sky published (dec >= -3°)	Both Northern and Southern sky published (horizon at -5°)
Dataset reprocessed and not published	First 7 years of the published "PSTracks v3" + ~1700 starting track at Southern Emisphere not published

LATEST ICECUBE RESULTS

"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A"

IceCube Collaboration (2018)

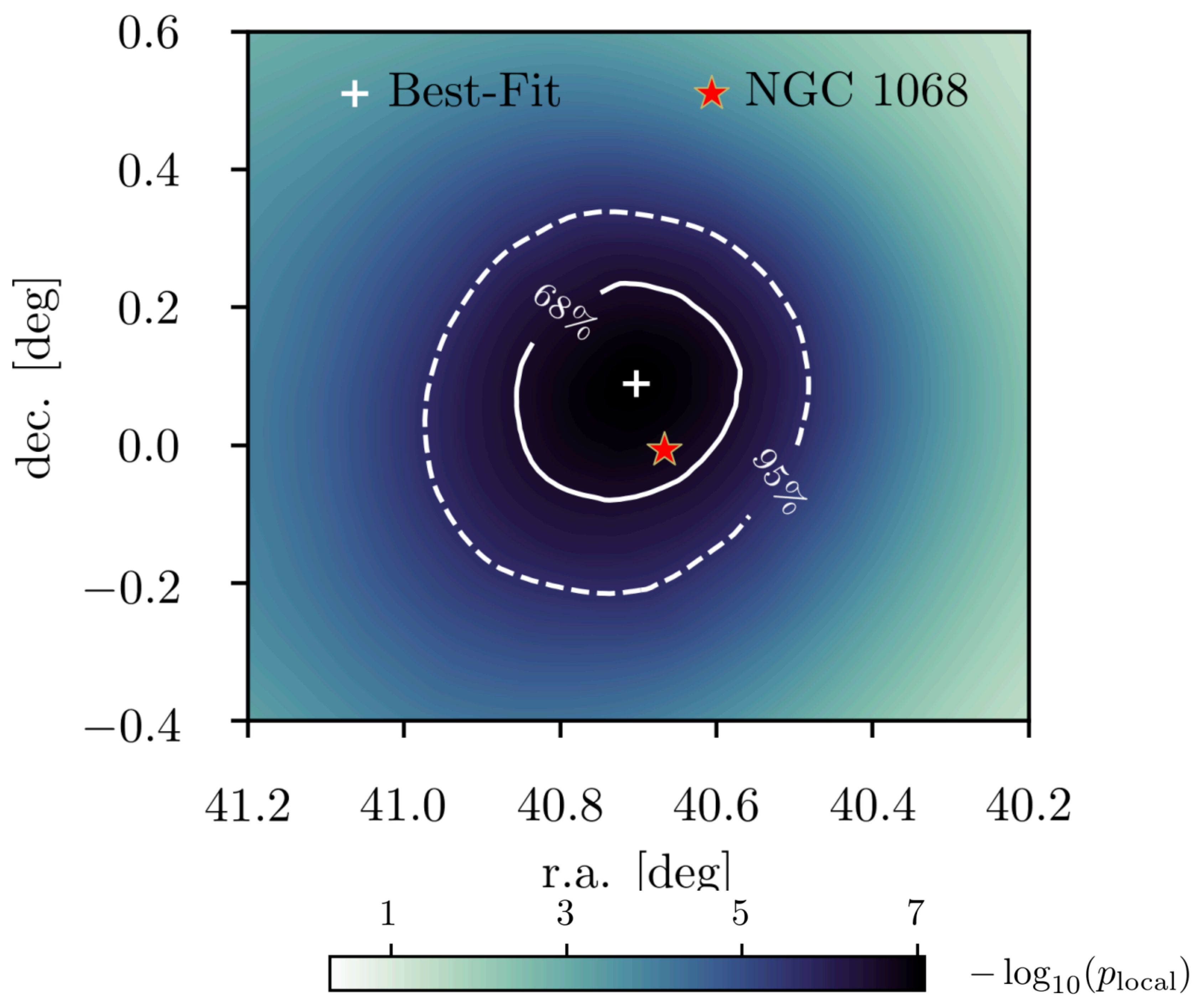
A chance correlation between a high-energy neutrino and the potential counterpart can be rejected at the 3σ level



"Evidence for neutrino emission from the nearby active galaxy NGC 1068"

IceCube Collaboration (2022)

Excess of 79^{+22}_{-20} neutrinos with a global significance of 4.2σ that they interpret as associated with NGC 1068



APPROACH

1. Driver: Public Data

✓ 10 years dataset released by IceCube collaboration in 2021

2. Tool

~ There are several tools enabling a similar analysis, they might have some limitations for our goals

⬇

Developement of a framework to analyze the IceCube 10 years public dataset

Motivations

- Aiming for an open-source and user-friendly framework
- Full reproducibility of results

Current step-stones

- Implementation of a software based on extended unbinned maximum likelihood
  - Models both spatial and energy pdfs

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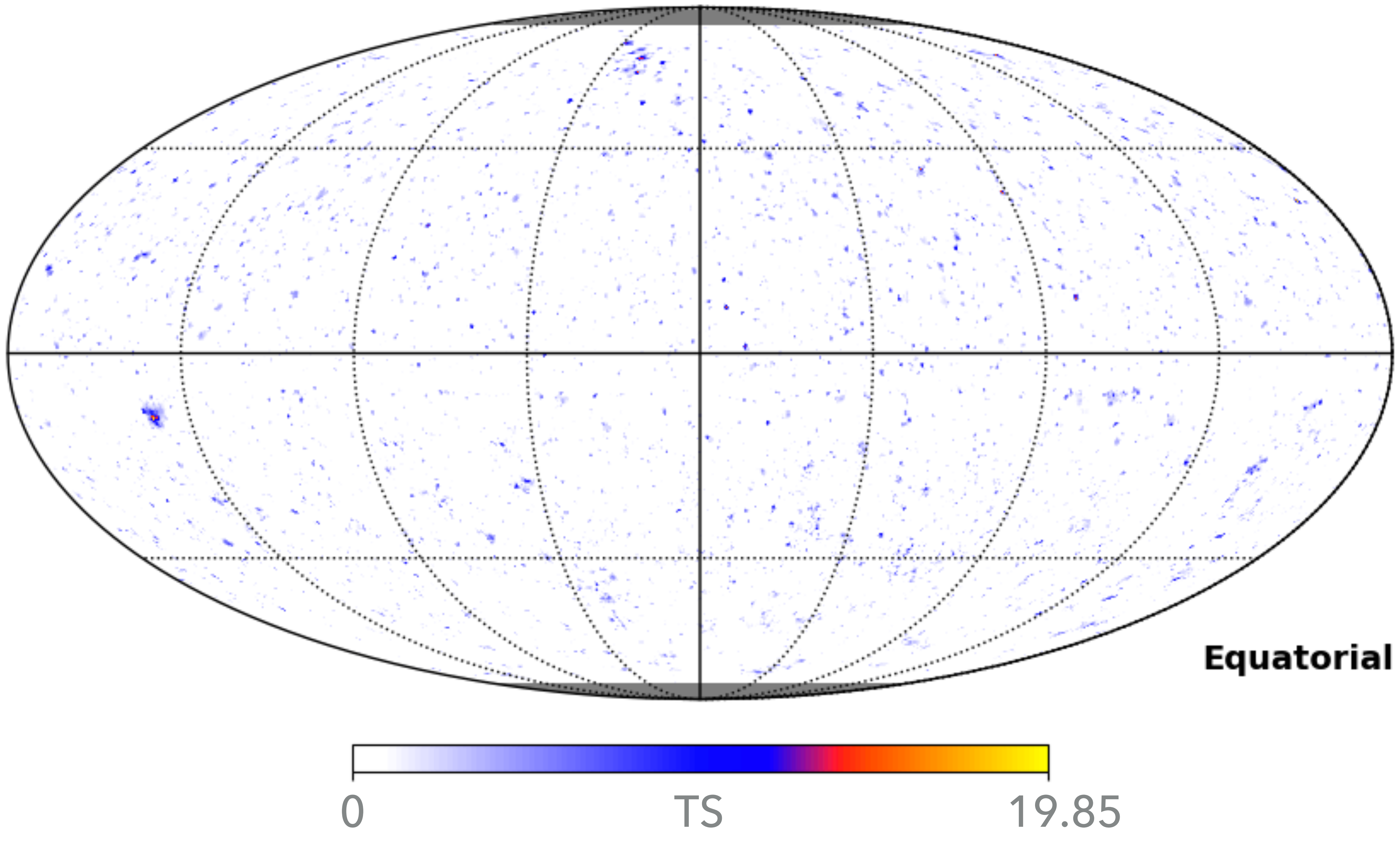
A BACKGROUND SKYMAP REALIZED

I developed a code that produces **sky maps**

Features:

- Create background maps by scrambling the data in right ascension
- Fixed spectral index γ for a power-law test source (preliminary test cariied out with γ = -2.0)
- Flexibility on the resolution of the map (or the pixel area, based on *Healpy* library)
- Choose the livetime of the experiment (1yr, 2yr, … 10yr)
- Simulation of power-law point source, for a given flux and index



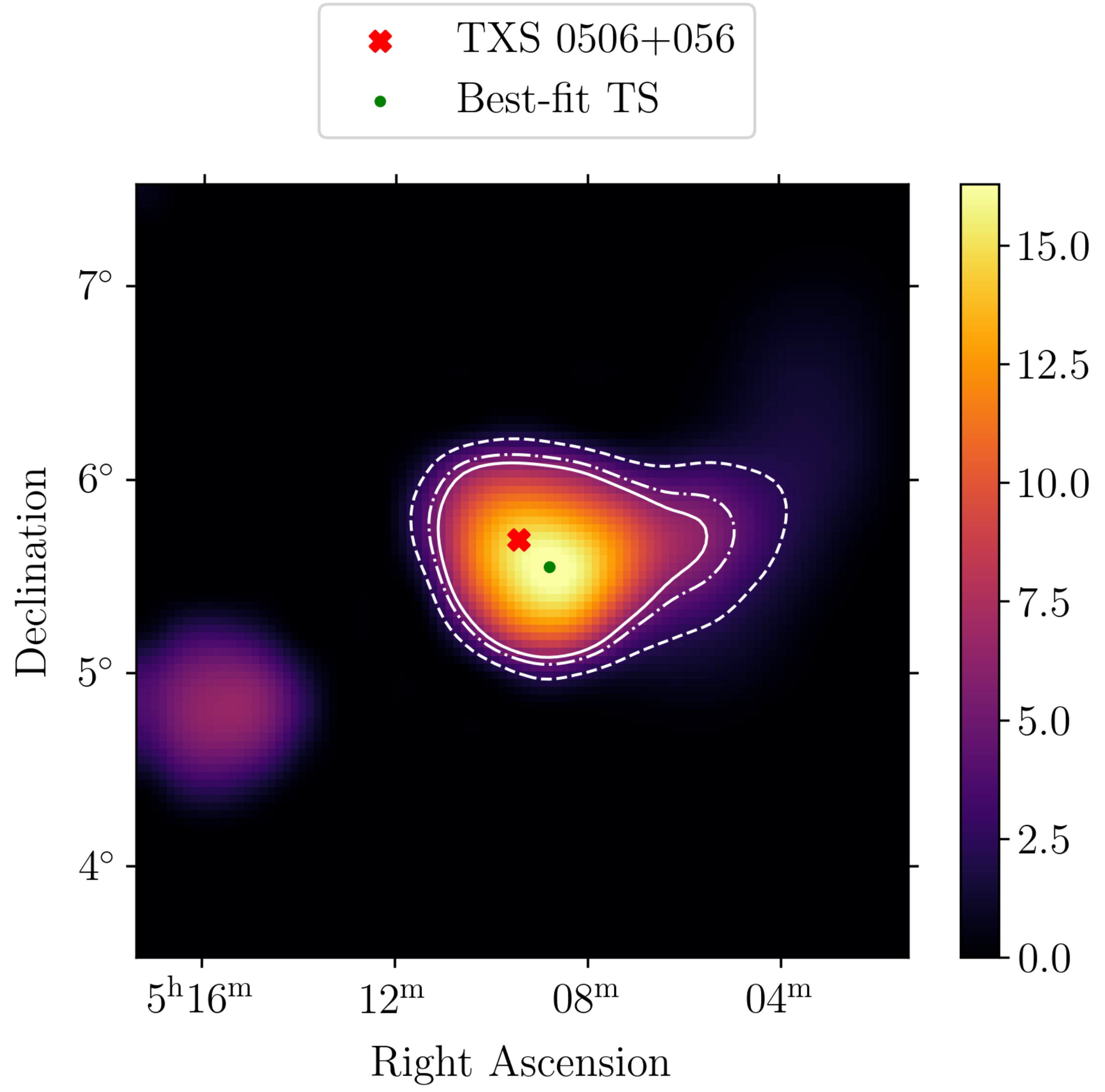
Resolution	NSIDE = 256 Area pixel ~ 0.02 [deg^2]
Tested positions	776632 (dec < |81°|)
Livetime	2011 - 2018 IC86I - IC86VII
Execution time	~ 4 hours

STUDY OF DEDICATED REGIONS OF INTEREST

TS sky maps for close-up view of a region

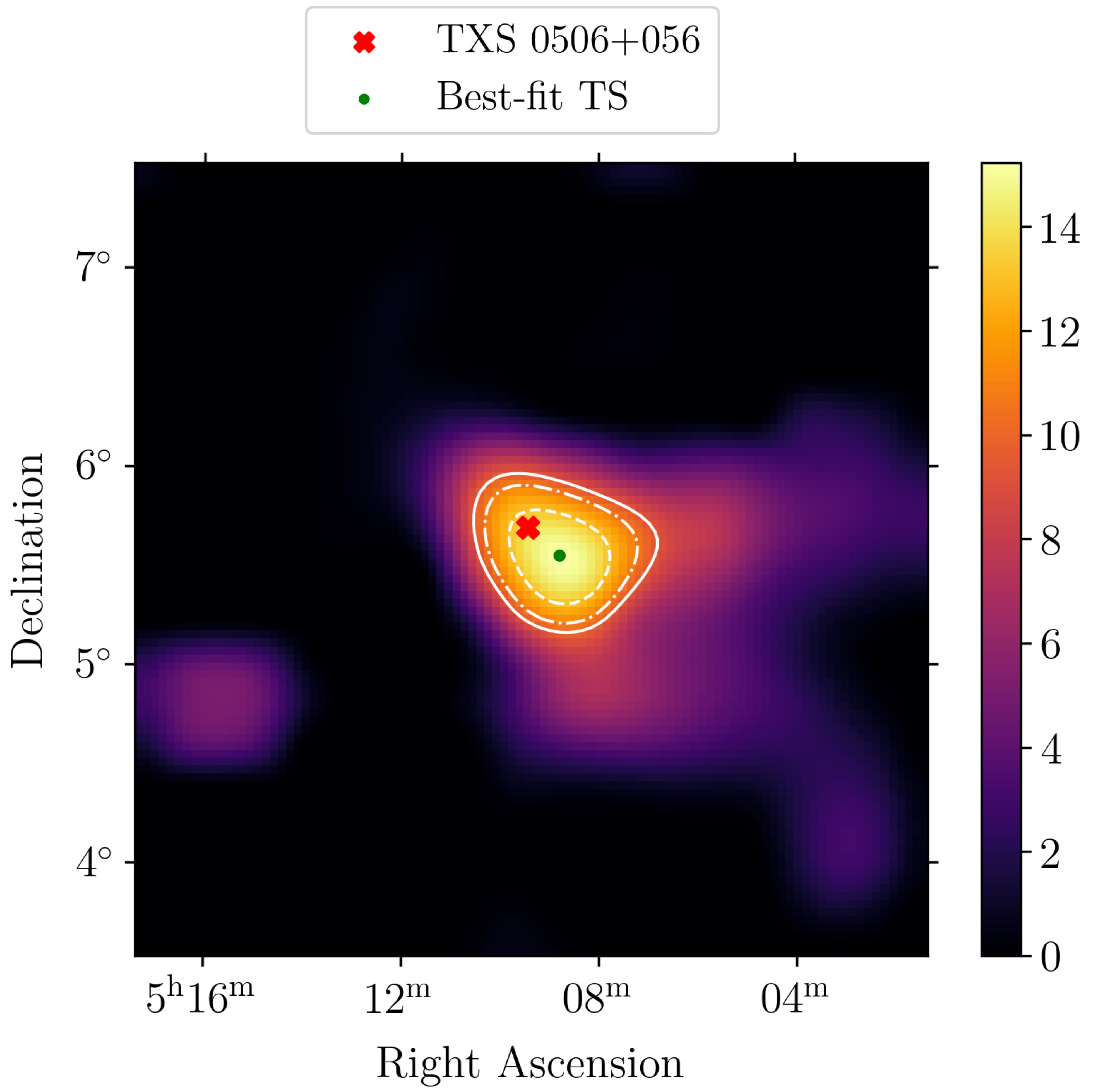
Features:

- Analyze (real) sky maps
- Fixed spectral index γ for a power-law test source
- (preliminary test cariied out with γ = -2.0)
- Flexibility on the resolution of the map (or the pixel area, based on *WCS* library)
- Choose the livetime of the experiment
- (1yr, 2yr, … 10yr)
- Simulation of power-law point source, for a given flux and index



Resolution	Area pixel ~ 0.2 [deg^2]
Tested positions	20 x 20 = 400
Livetime	2011 - 2018 IC86I - IC86VII
Execution time	~ 13 s

VALIDATION OF THE CODE THROUGH THE OPEN-SOURCE SKYLLH FRAMEWORK



SkyLLH

It is an open-source Python3-based tool available at the IceCube Neutrino Observatory GitHub repository (https://github.com/icecube/skyllh) customized for the analysis of the 10 years IC public dataset through the "extended unbinned likelihood maximization" method

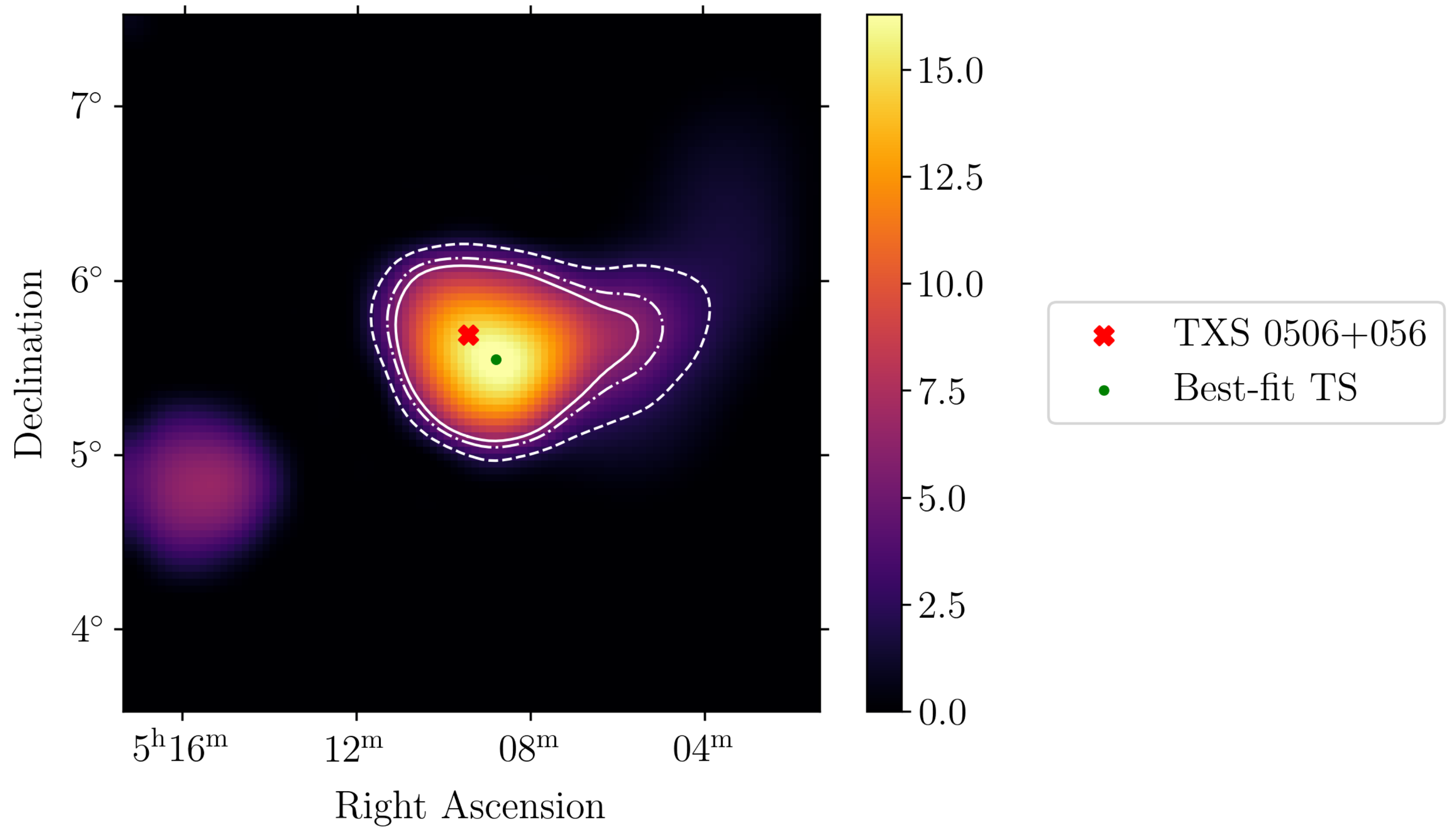
What it can be used for, following the tutorial

- Point-source analysis
- Maximizing the log-likelihood ratio to find the best TS value
- Calculating the flux ϕ at the point-source position
- Calculating the significance (local p-value)

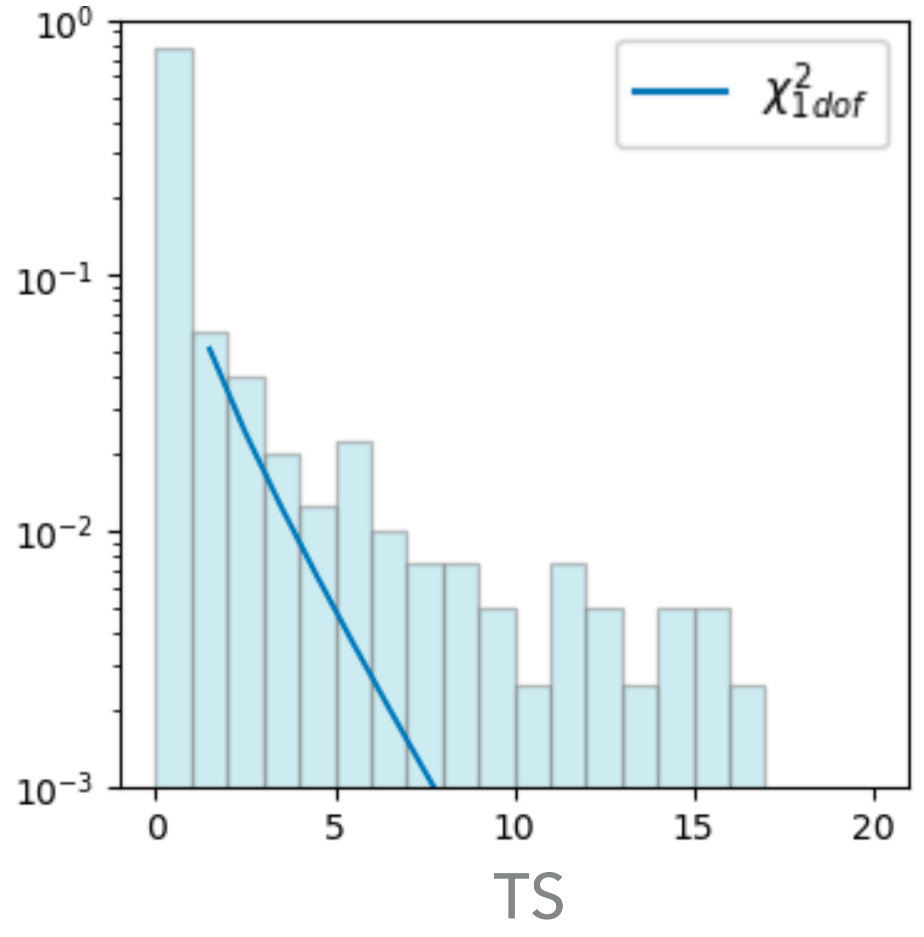
[7] IceCube Collaboration (2019).

VALIDATION OF THE CODE THROUGH THE OPEN-SOURCE SKYLLH FRAMEWORK

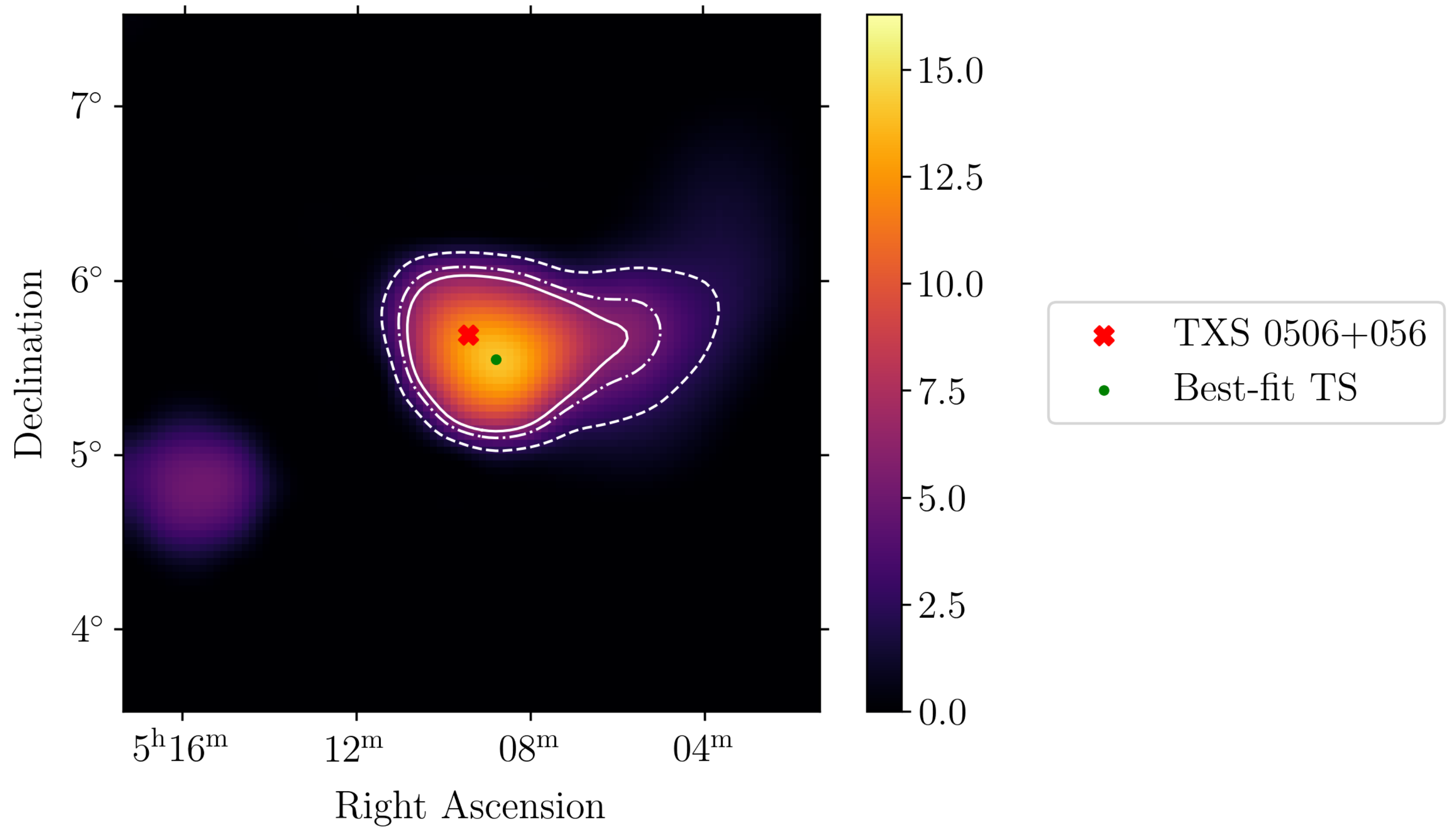
Code developed



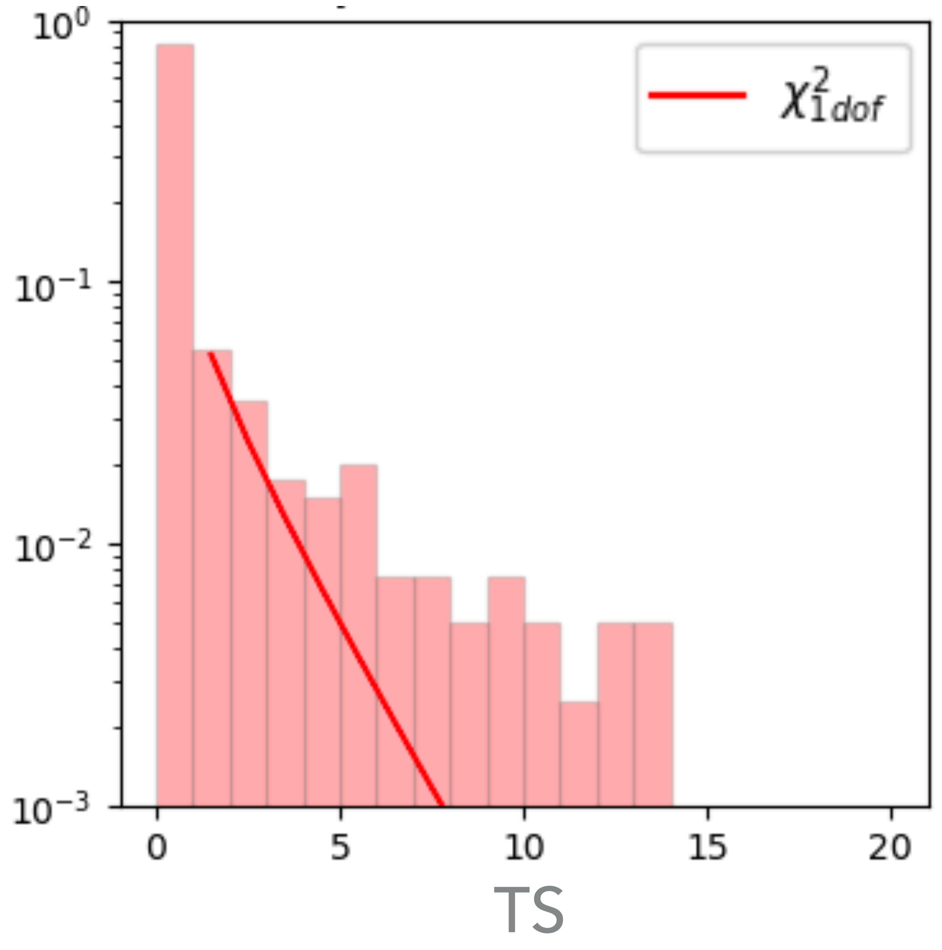
TS distribution with code developed



SkyLLH



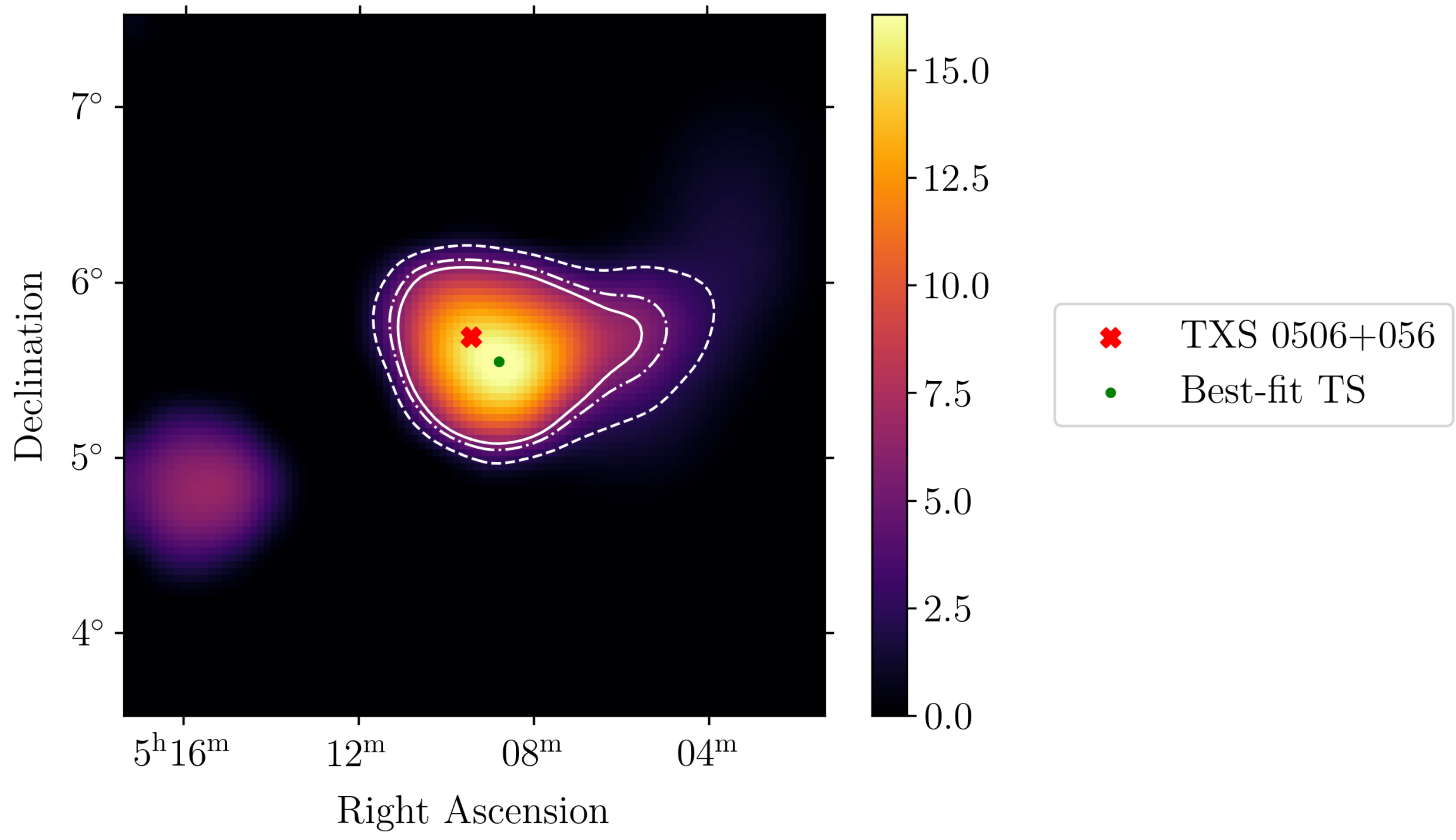
TS distribution for TXS with SkyLLH



- Both the codes reconstruct the TS best-fit in the same position
- Blazar and TS best-fit position are compatibles in the error of the resolution of the maps (angular distance = 0.21°)
- The TS values distributions follow a χ^2_{1dof} with a clear deviation from the background at the tail
  → presence of an astrophysical signal

VALIDATION OF THE CODE THROUGH THE OPEN-SOURCE SKYLLH FRAMEWORK

Code developed



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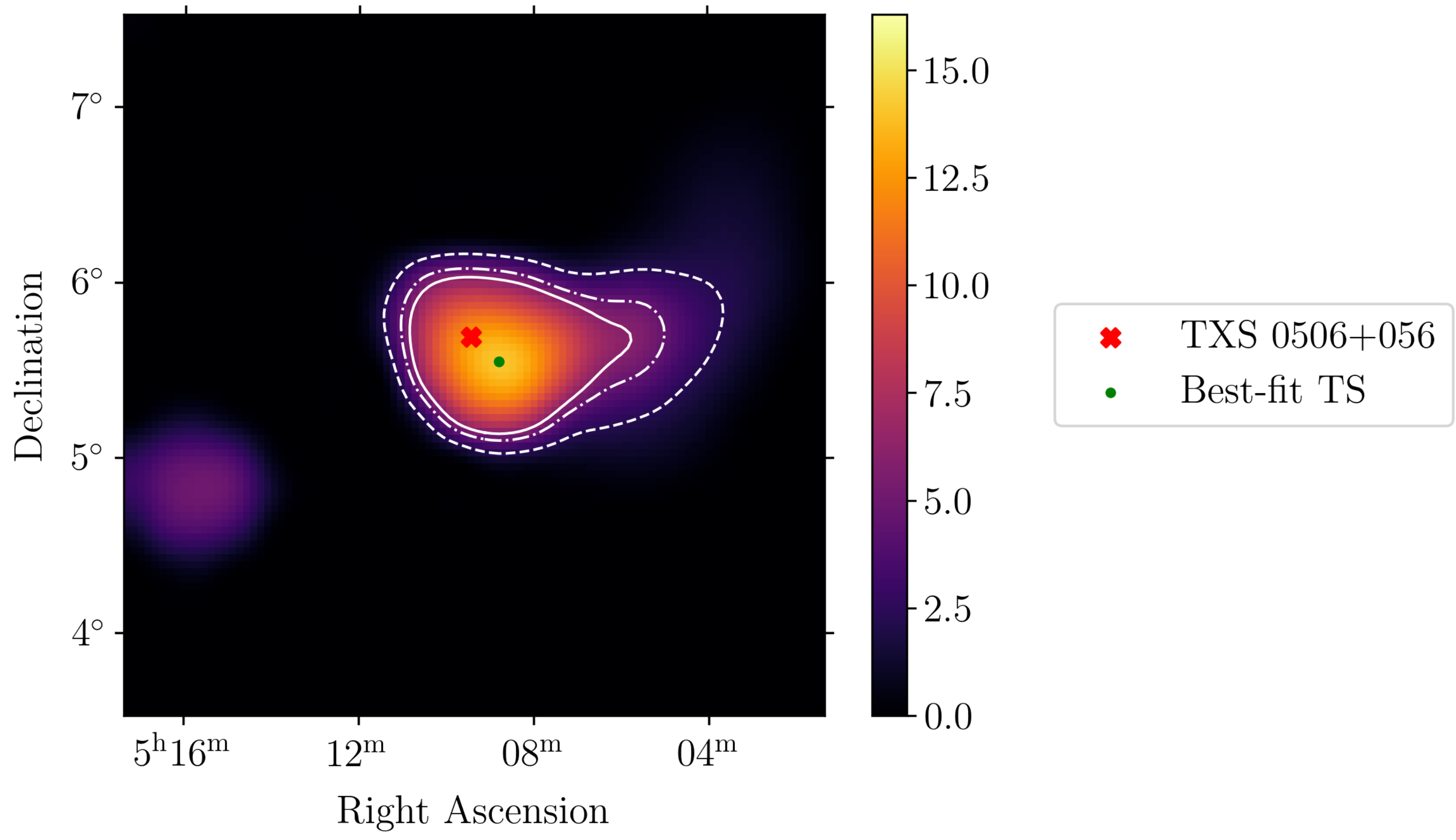

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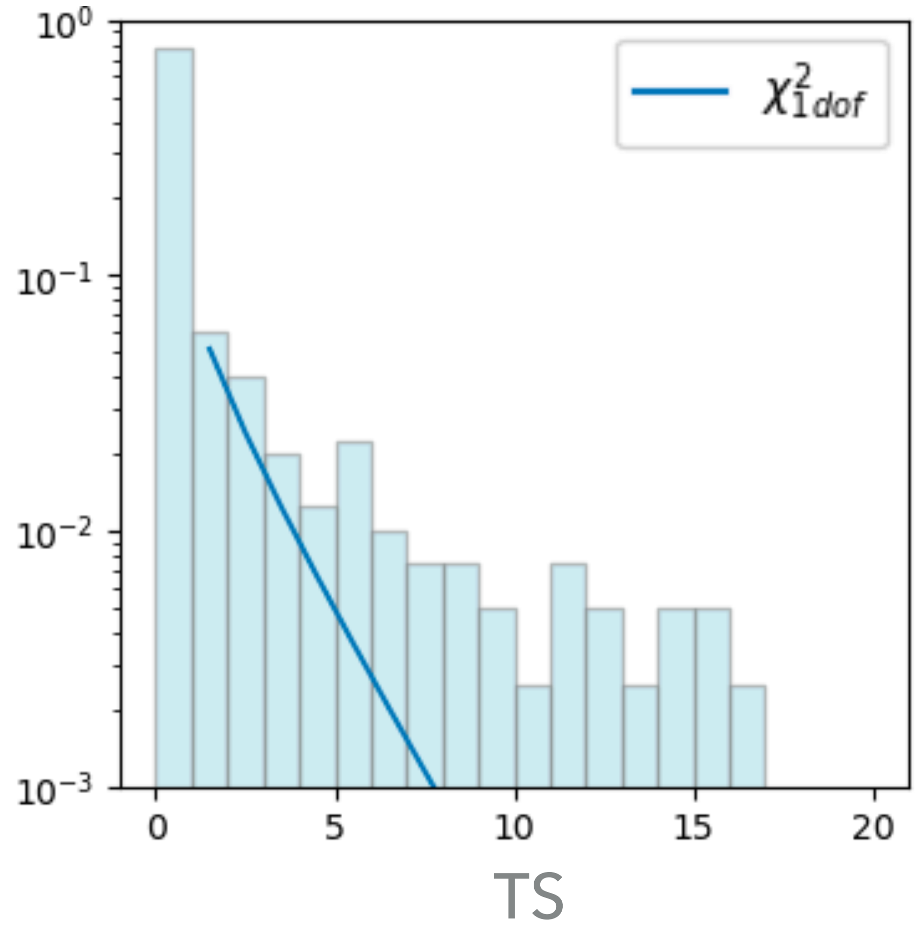

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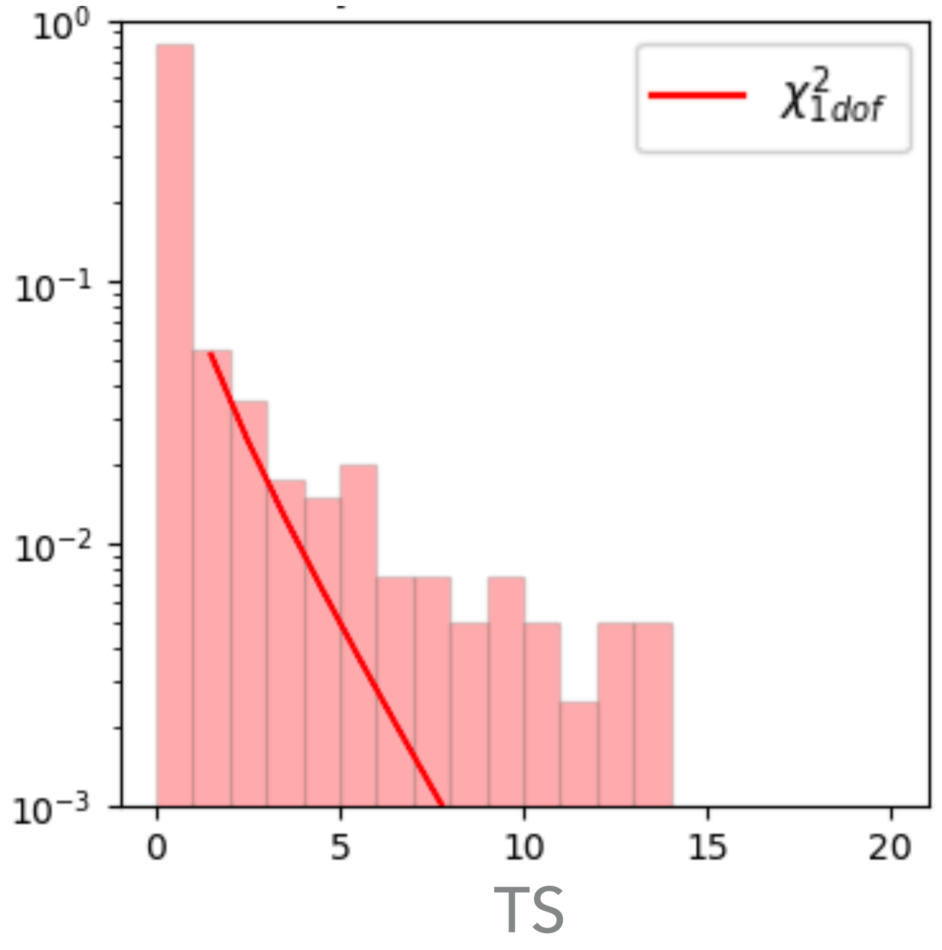
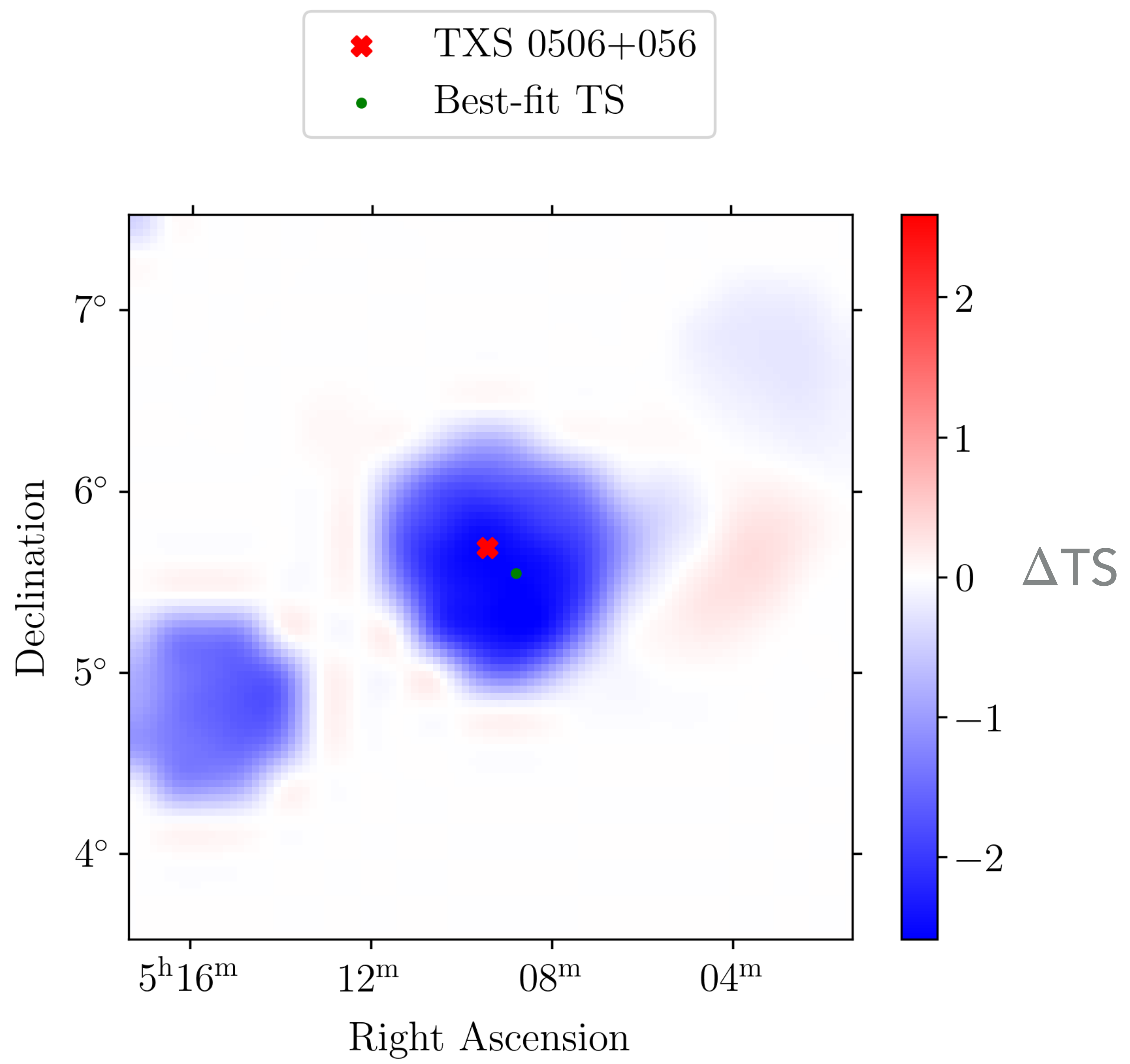
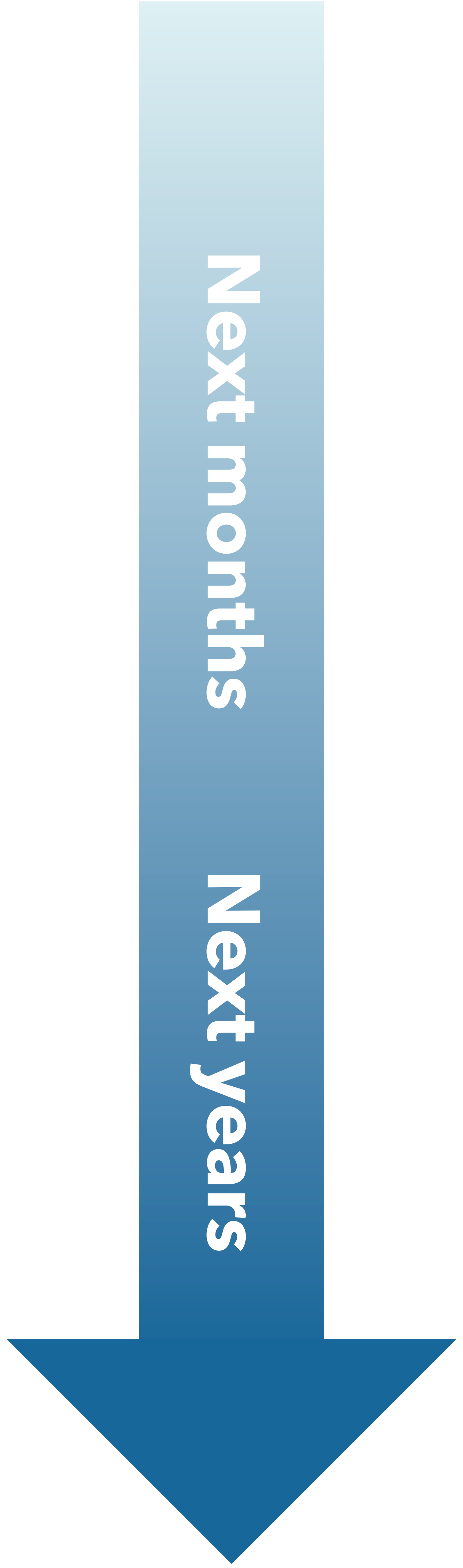


ΔTS **= SkyLLH map - Code developed**



CONCLUSIONS AND PROSPECTIVES

1. Further validation of the code
2. Code improvements, e.g. free spectral index, further optimization
3. Employing it to investigate compelling matter:
    - study a (possible) population(s) of astrophysical neutrino sources
4. Employ Machine Learning techniques for data selection / analysis
5. Release of the open-source code along with a user-friendly tutorial



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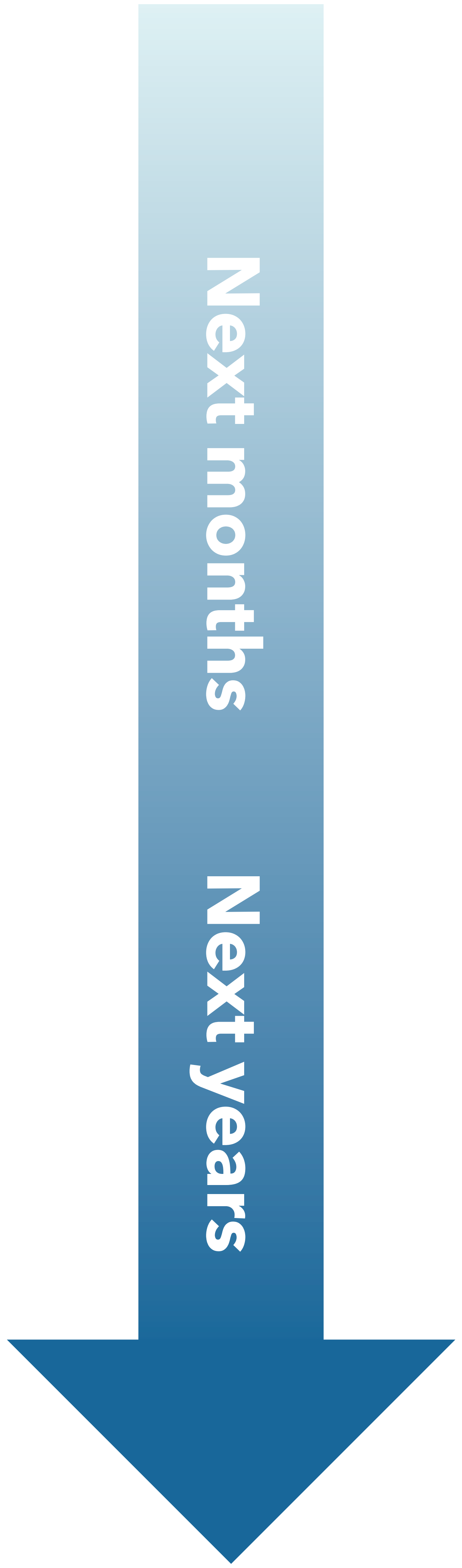

THANKS FOR YOUR ATTENTION!

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BACKUP SLIDES

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NEUTRINO ANALYSIS FRAMEWORK: EXPLICIT THE PARAMETERS

$$\mathscr{L}(\mathscr{H}_0(\theta)) = \exp(-N)\prod_{i=1}^{N}\mathscr{B}_i$$

$$\mathscr{L}(\mathscr{H}_1(\theta)) = \exp(-N)\prod_{i=1}^{N} N\cdot\frac{1}{N}\left(\frac{n_S}{N}\mathscr{S}_i + \frac{n_B}{N}\mathscr{B}_i\right)$$

Factorization of the spatial and energetic component of the Signal and Background pdfs:

$$\mathscr{S}_i = S_i \times \mathscr{E}_{\mathscr{S}_i} = \frac{1}{2\pi\sigma_i^2}\exp\left(-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}\right) \times \mathscr{E}_{\mathscr{S}_i}(\sin\delta_i, E_i; \gamma)$$

$$\mathscr{B}_i = B_i \times \mathscr{E}_{\mathscr{B}_i} = \frac{1}{N}\cdot\frac{N_\nu}{\Omega} \times \mathscr{E}_{\mathscr{B}_i}(\sin\delta_i, E_i)$$

$$\mathscr{L}(\vec{x}_i, E_i \,|\, n_S = 0) = \exp(-N)\prod_{i=1}^{N}\mathscr{B}_i(\sin\delta_i, E_i)$$

$$\mathscr{L}(\vec{x}_i, E_i \,|\, n_S, \gamma) = \exp(-N)\prod_{i=1}^{N}\frac{n_S}{N}\mathscr{S}_i(|\vec{x}_i - \vec{x}_s|, E_i; \gamma) + \left(1 - \frac{n_s}{N}\right)\mathscr{B}_i(\sin\delta_i, E_i)$$