High-energy neutrino emission from the Seyfert galaxy NGC 7469

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Trapani, CRIS-MAC 2024

SFB1491

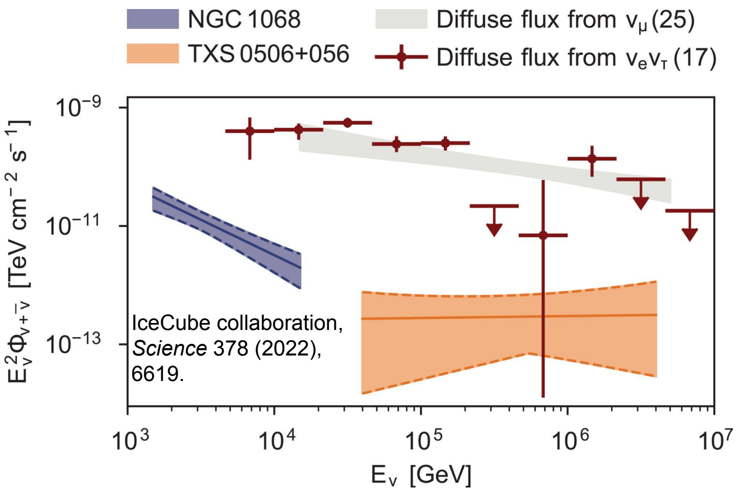
RUHR UNIVERSITÄT BOCHUM

RUB

Summary

- **Neutrinos from AGNs and Seyfert galaxies**
- **The Seyfert galaxy NGC 7469 inside the contours of two neutrinos**
- **Estimation of the chance probability**
- **Results**
- **A look at the SED**

Neutrinos from AGNs and Seyfert galaxies



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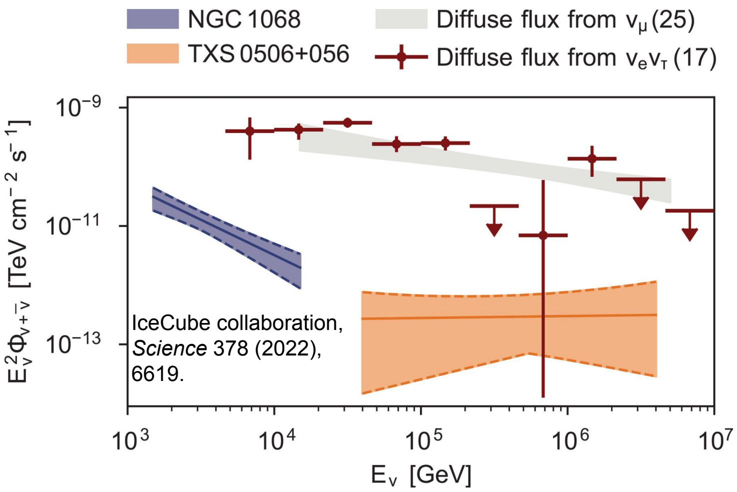

IceCube collaboration, *Science* 378 (2022), 6619.

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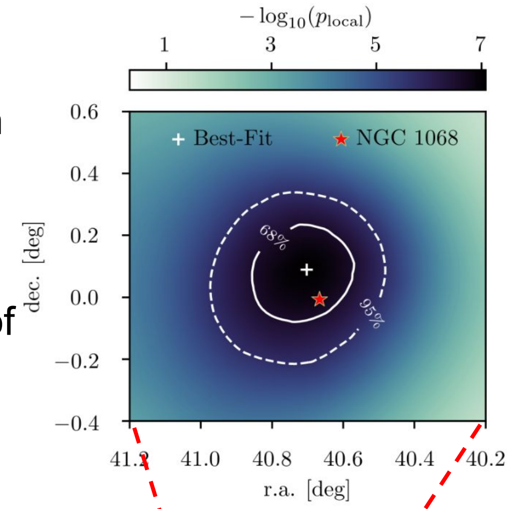
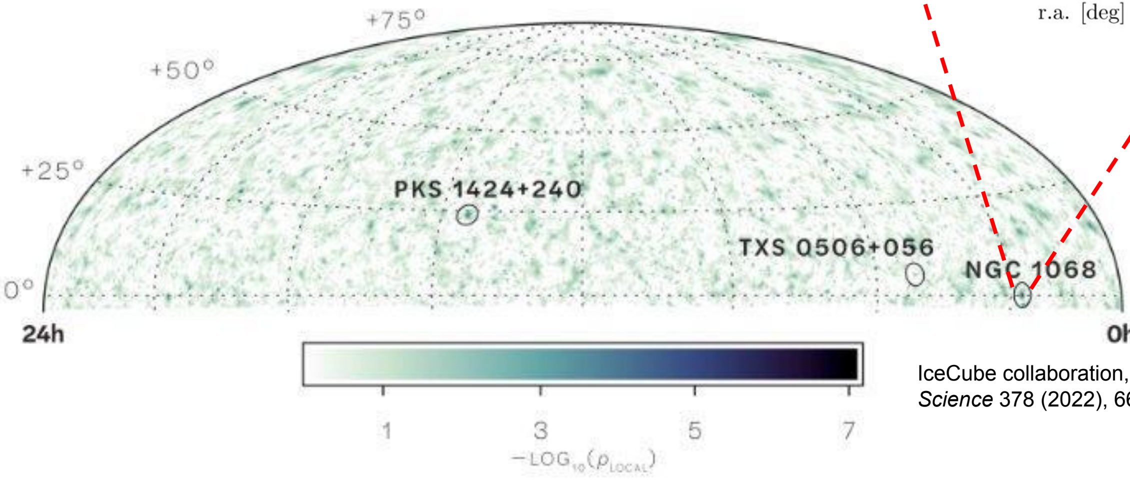
- In 2022, evidence of **4.2 σ** of neutrino emission from the **Seyfert galaxy NGC 1068**.





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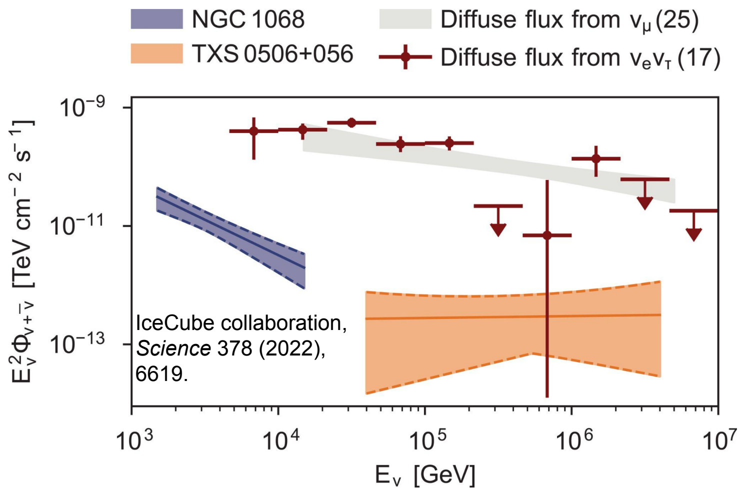

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physicsworld BREAKTHROUGH OF THE YEAR 2013

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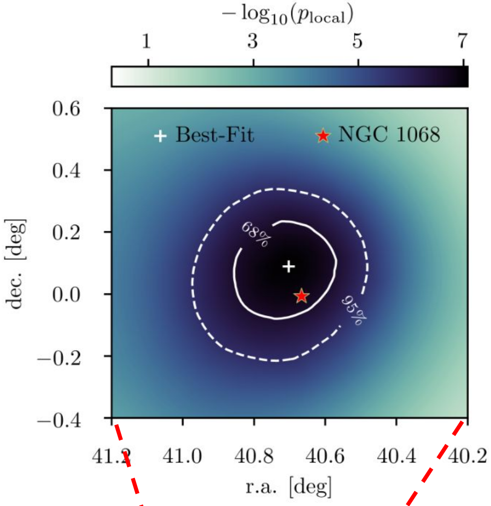
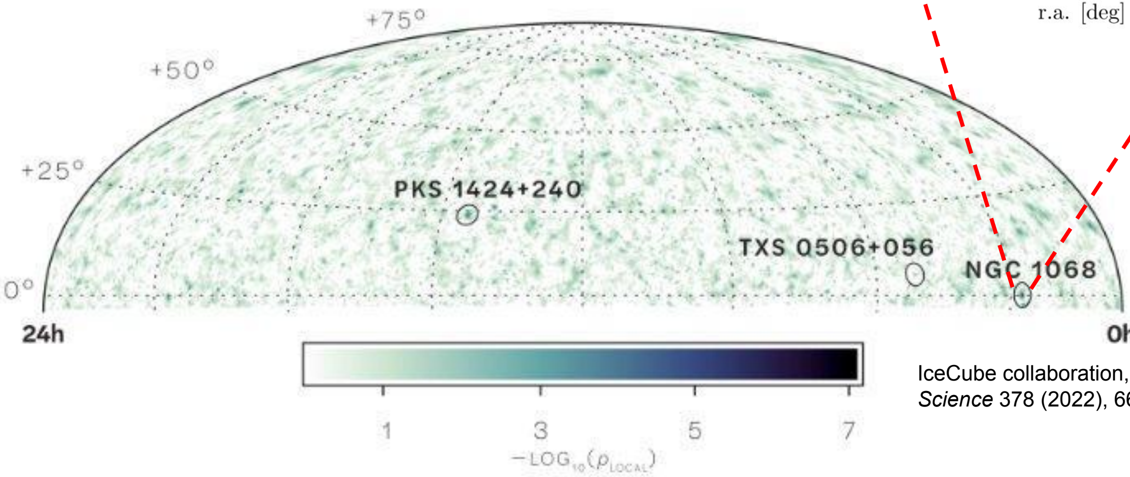


- Most of the astrophysical neutrino flux has a still unknown origin.



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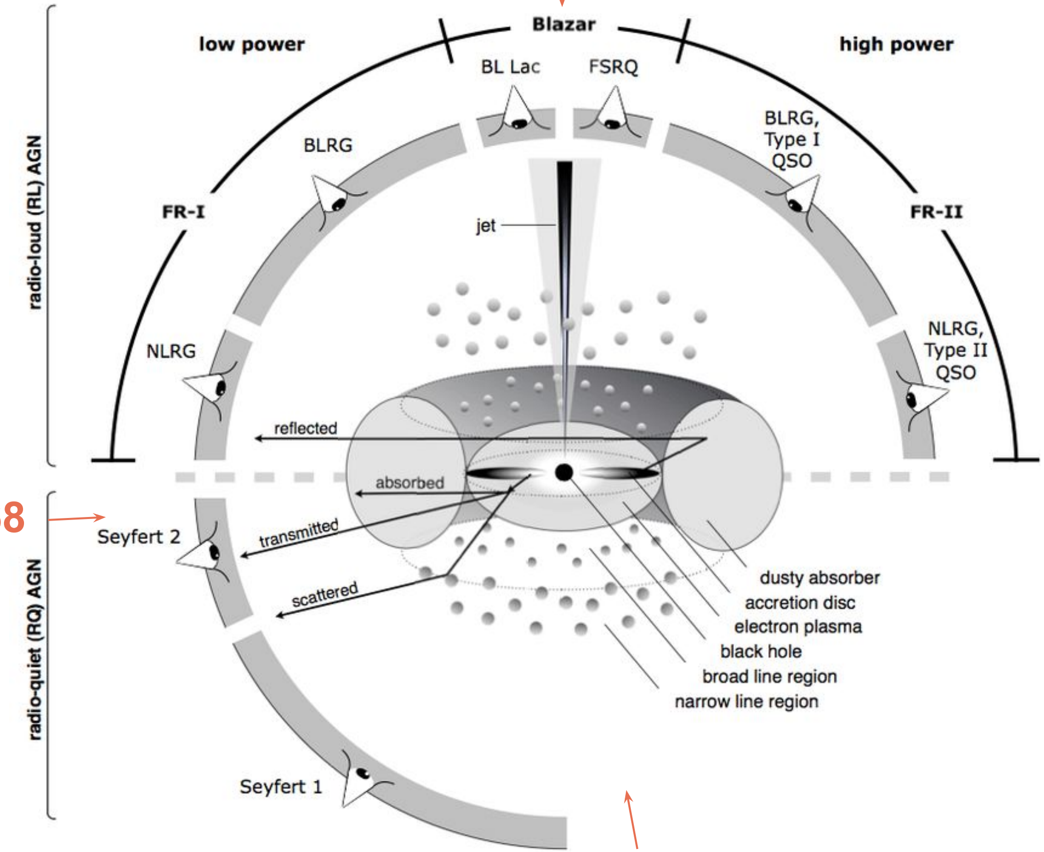
About AGNs and Seyfert galaxies

- **AGNs** are the main **sources** from which we expect **high-energy neutrino production**;



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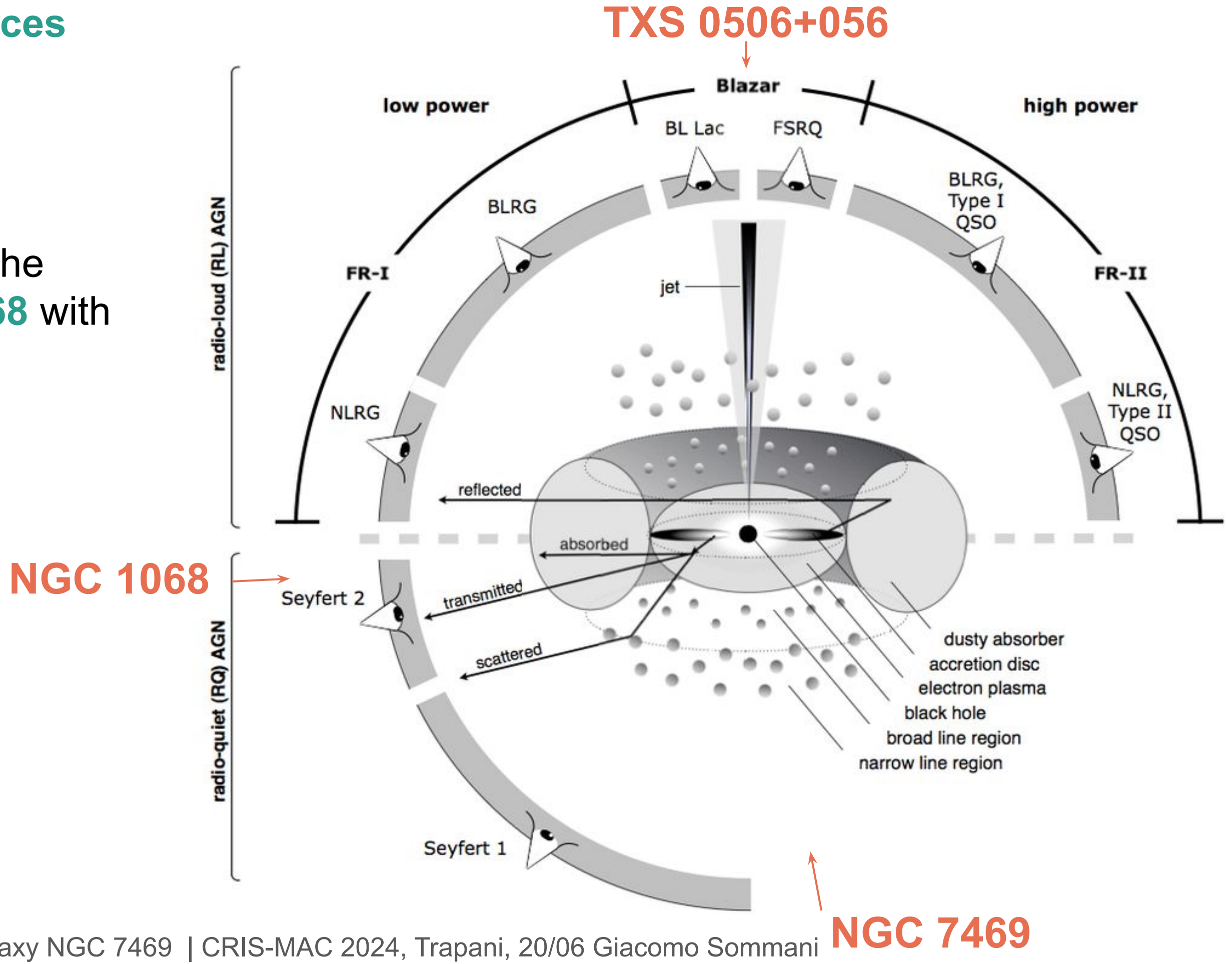

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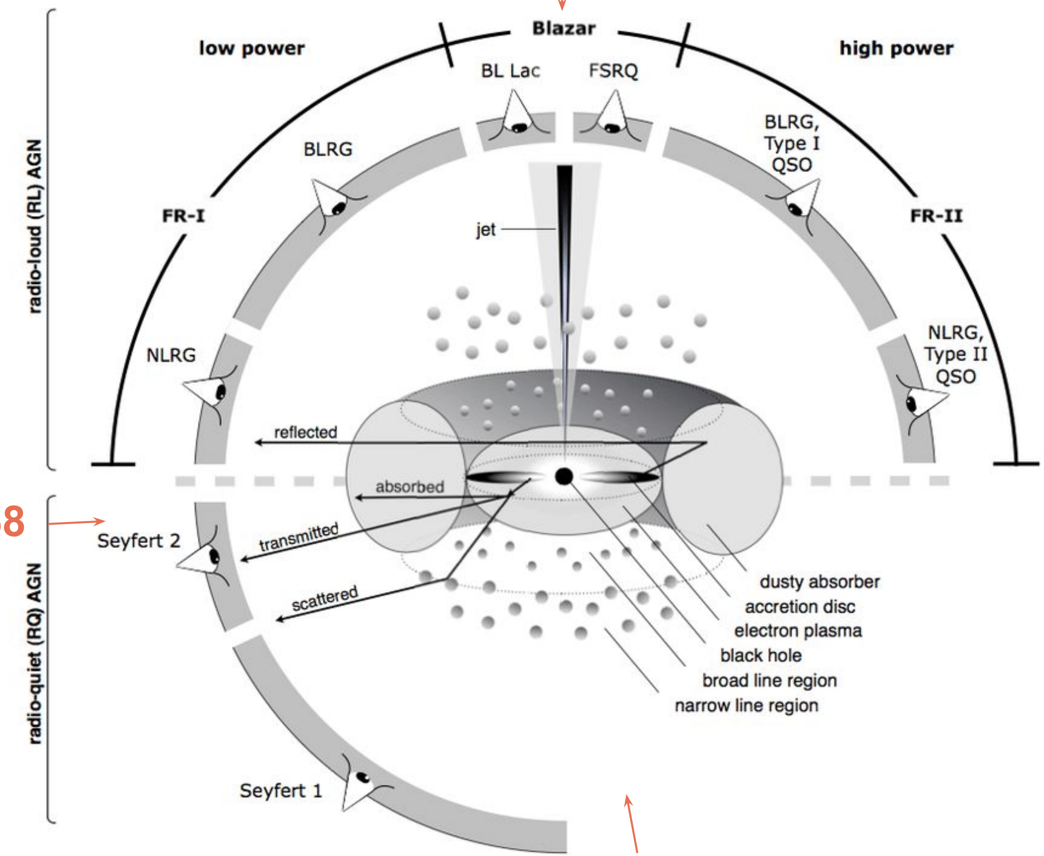
TXS 0506+056



NGC 1068

NGC 7469

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- The **Seyfert galaxy NGC 7469** inside the contours of **two IceCube realtime track alerts**;

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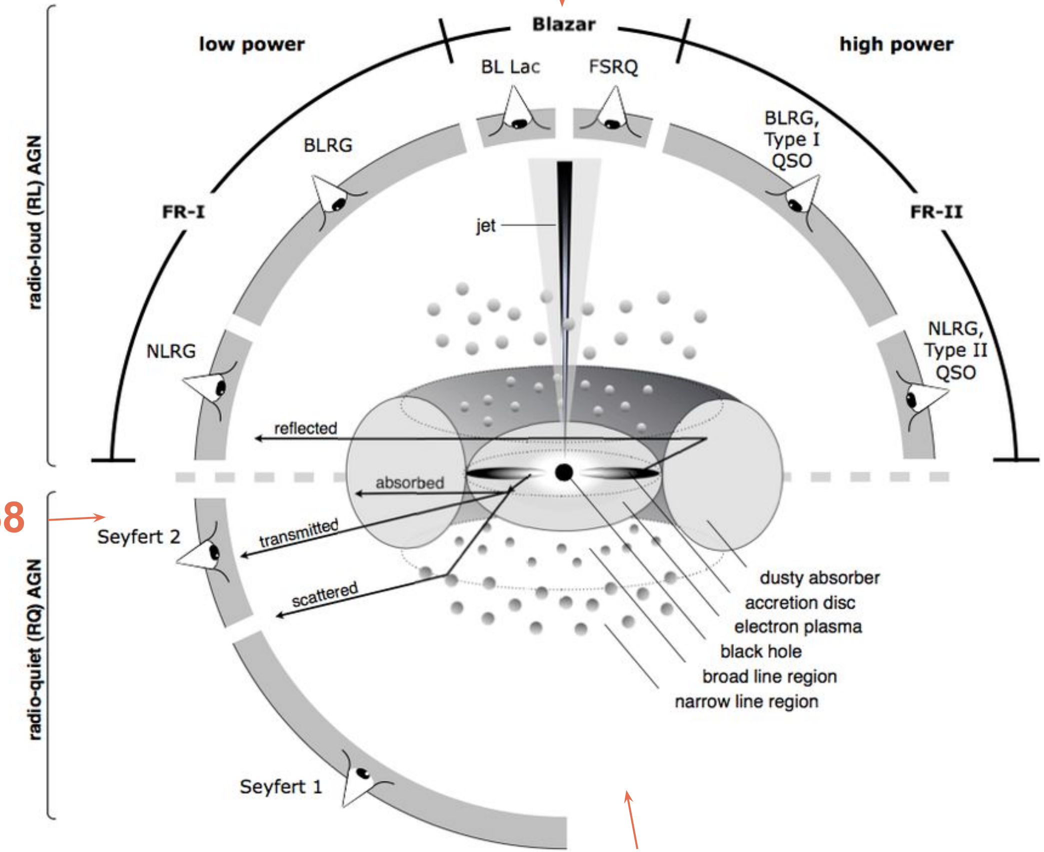

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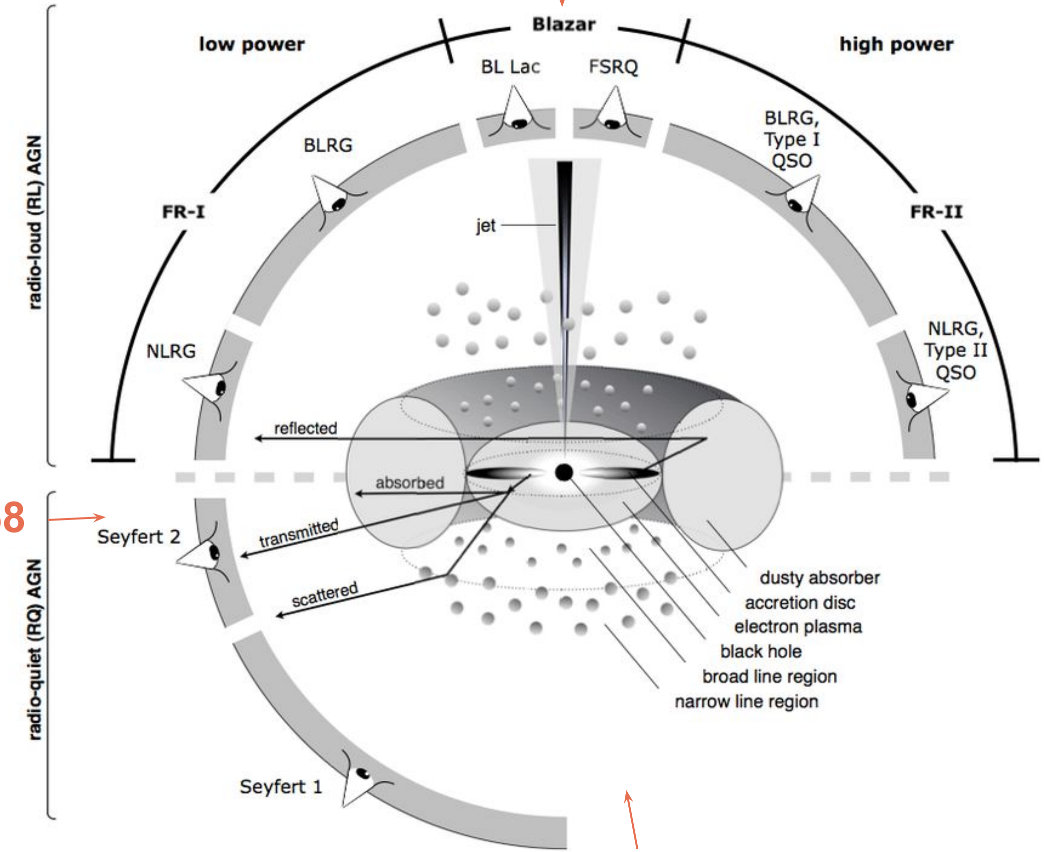
- The **Seyfert galaxy NGC 7469** inside the contours of **two IceCube realtime track alerts**;
- Is this **a new neutrino source**? Can this happen **by chance**?

TXS 0506+056

NGC 1068



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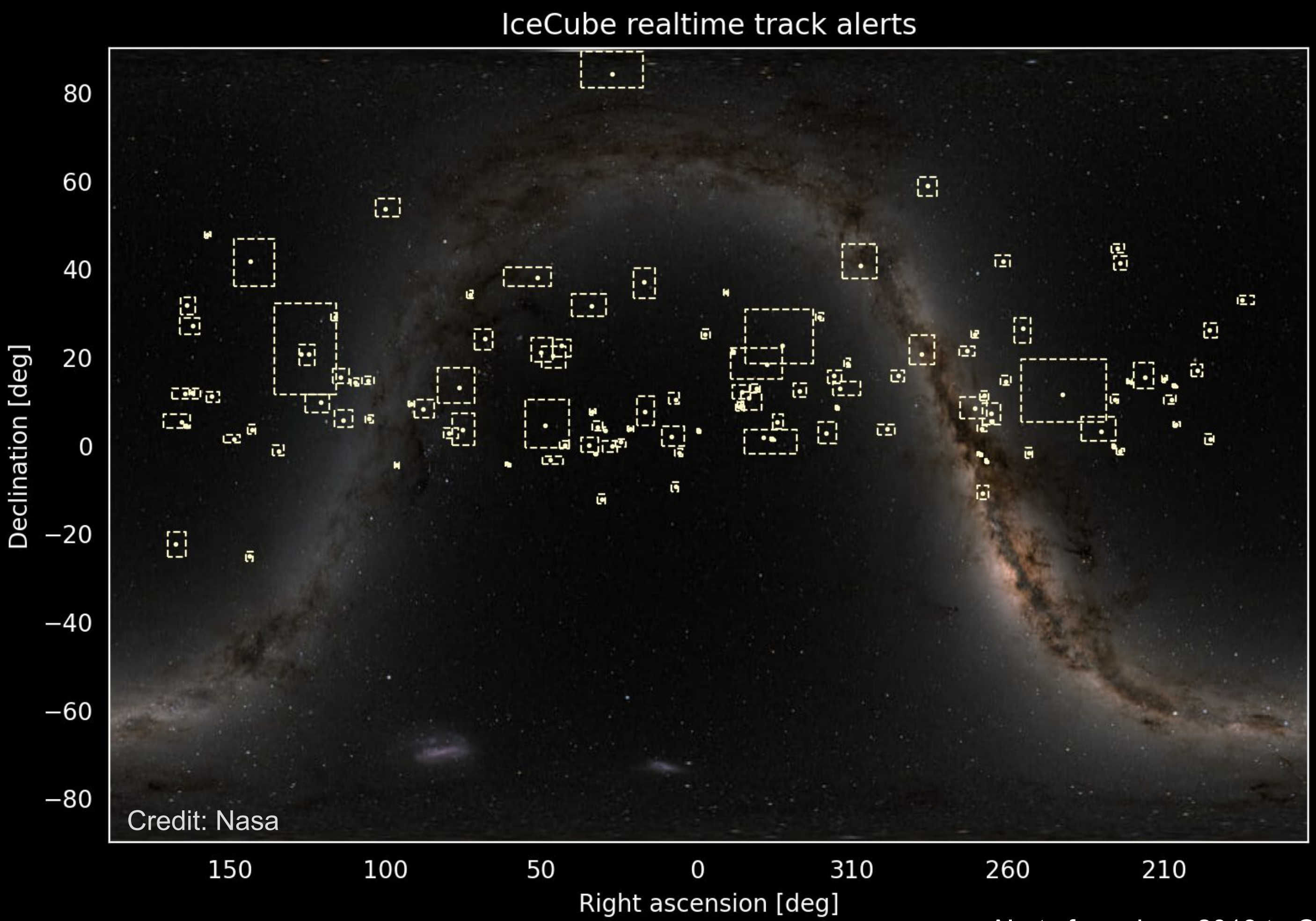
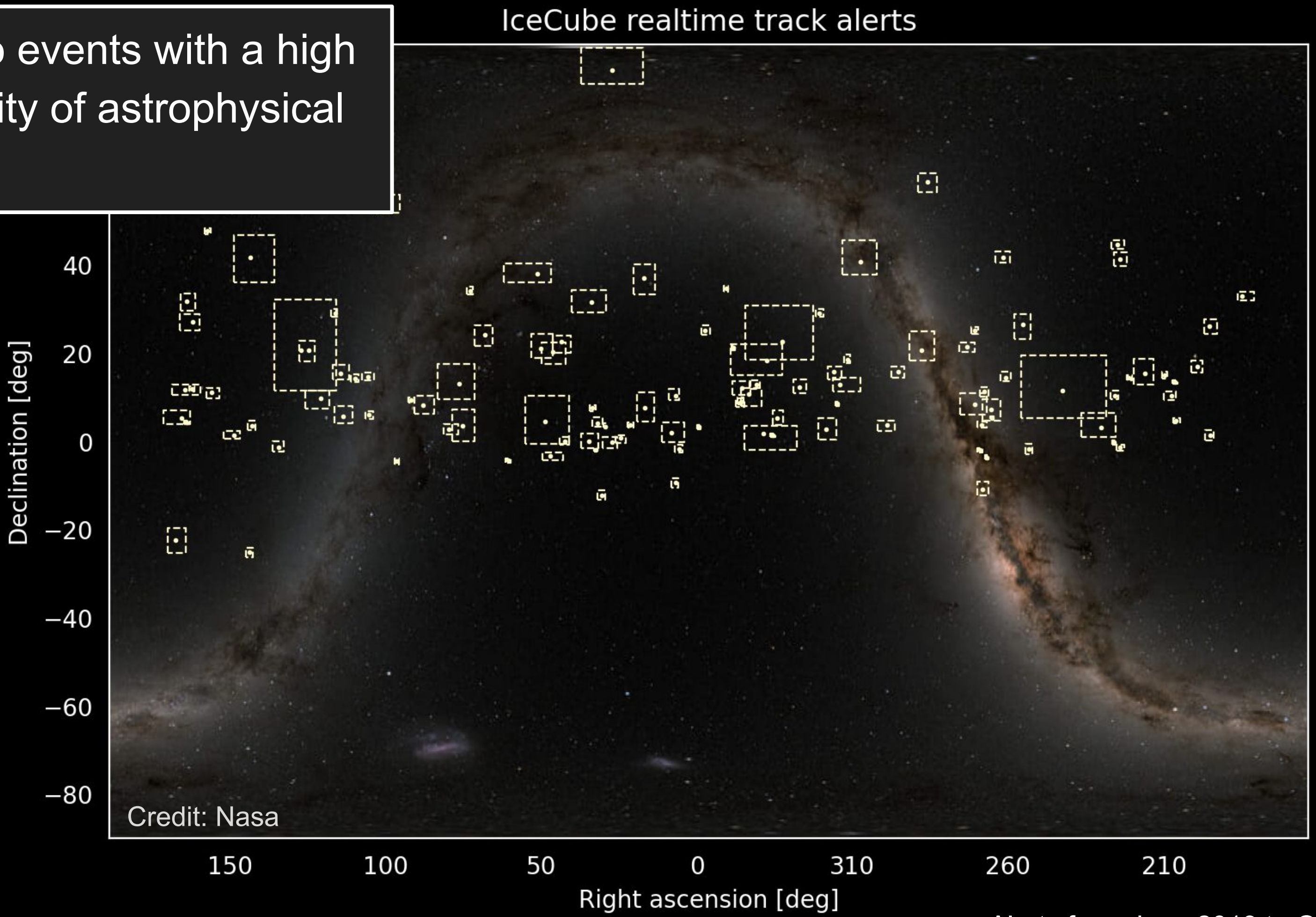


Alerts from June 2019 to October 2023

Neutrino events with a high probability of astrophysical origin



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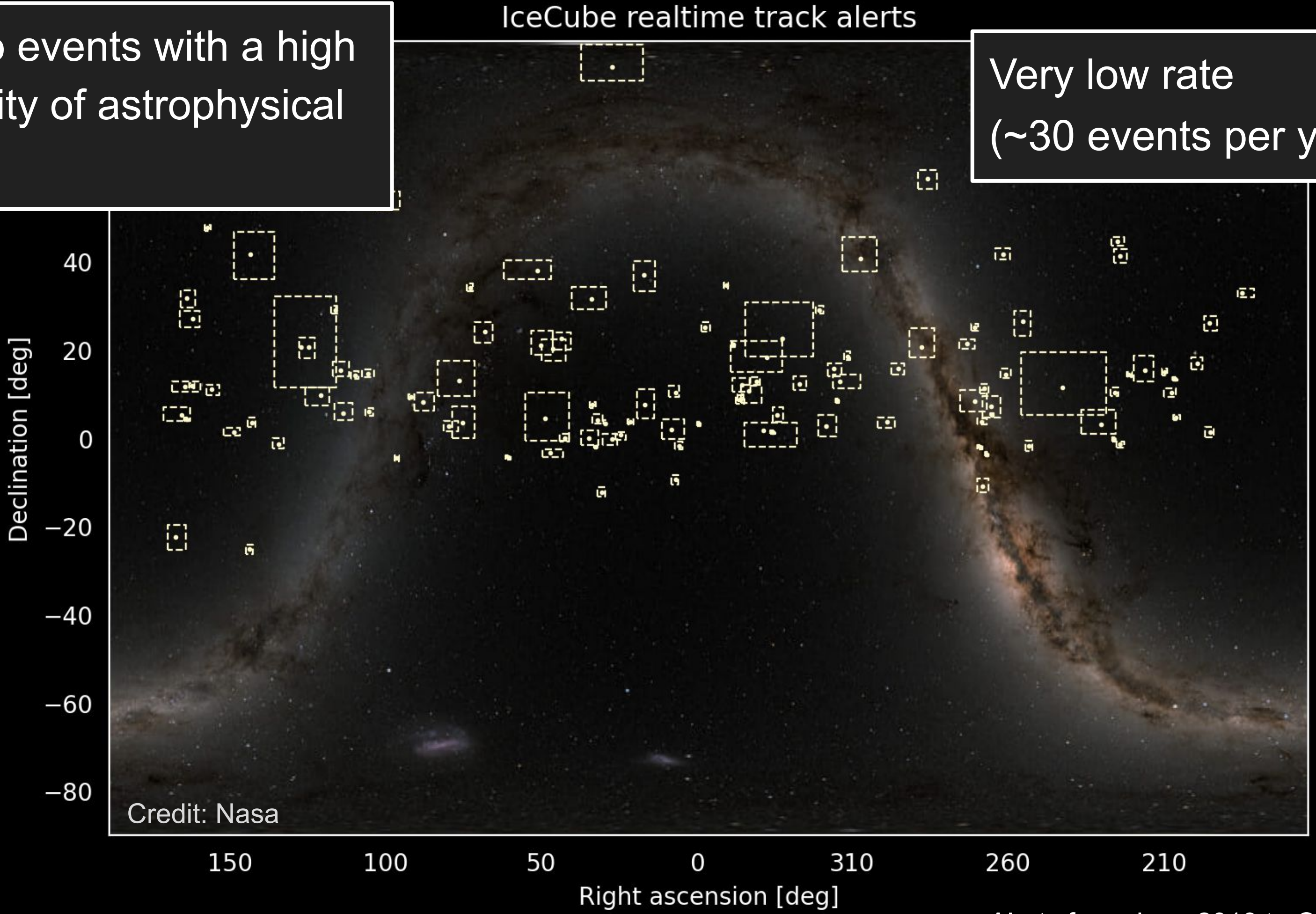
Very low rate (~30 events per year)



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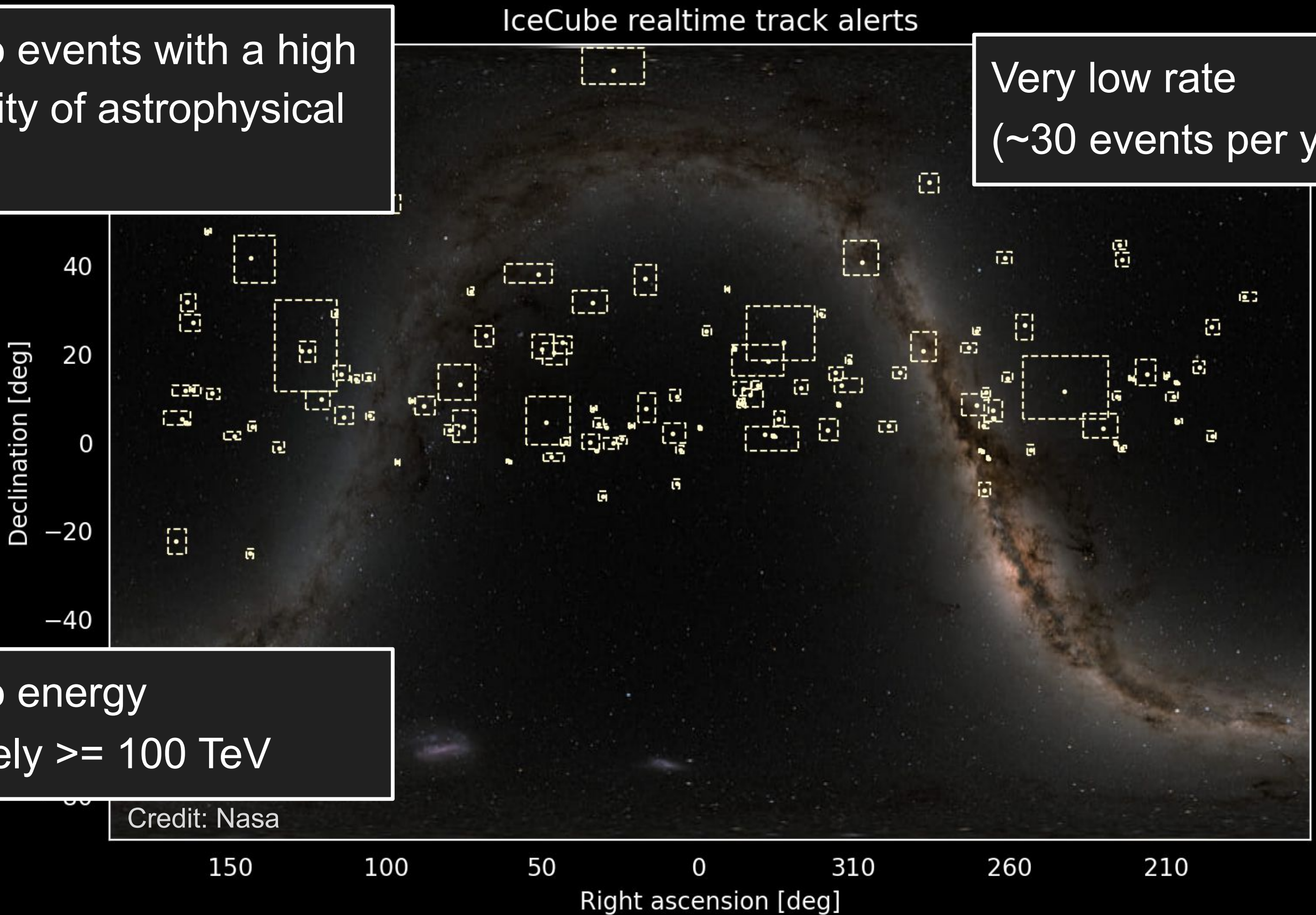

Neutrino energy most likely >= 100 TeV

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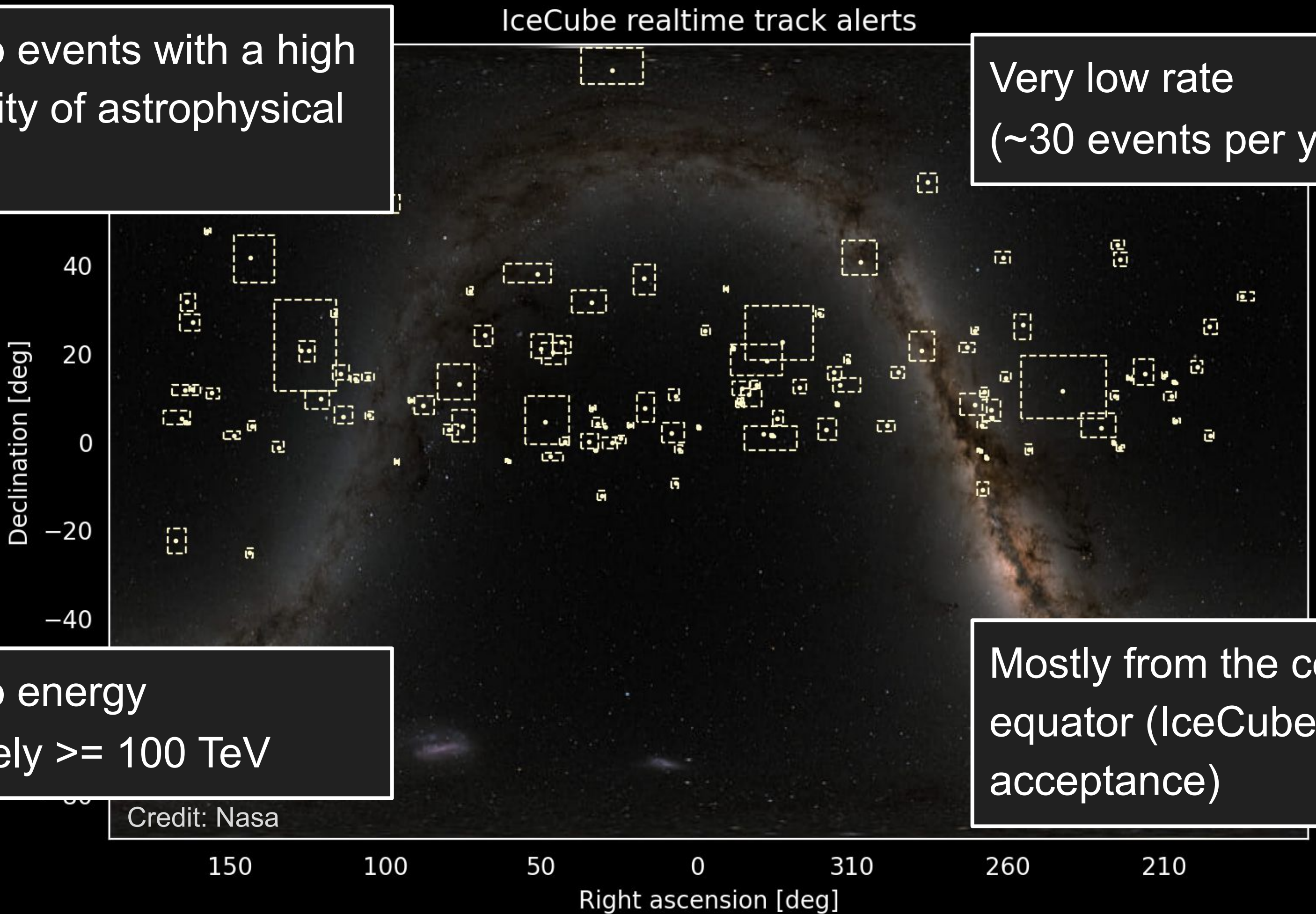

Neutrino energy most likely >= 100 TeV

Mostly from the celestial equator (IceCube acceptance)

Alerts from June 2019 to October 2023

General Coordinate Network (GCN) Notices and Circulars

From: The IceCube realtime program, TeVPA 2023, Napoli, Giacomo Sommani.

Gamma-ray Coordinate Network (GCN) Notices and Circulars

From: The IceCube realtime program, TeVPA 2023, Napoli, Giacomo Sommani.

GCN Notice (Rev0)

- ➢ Processed at South Pole.
- ➢ With a first, fast reconstruction (**SplineMPE**).

Abbasi et al. 2021, JINST, 16, P08034

Gamma-ray Coordinate Network (GCN) Notices and Circulars

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GCN Notice (Rev0)

- Processed at South Pole.
- With a first, fast reconstruction (**SplineMPE**).

Abbasi et al. 2021, JINST, 16, P08034

GCN Circular

- Processed at north.
- More sophisticated algorithm (**Millipede**).

Aartsen et al. 2014, JINST, 9, P03009

- Refined direction and angular coordinates (rectangular error region).

First GCN Notice or updated GCN Circular?

GCN Circular -> Millipede

GCN Notice -> SplineMPE

From monte carlo study in “Sommani et al., *PoS ICRC2023* (2023), 1186”, SplineMPE very precise:

- **92% of the simulated events** have true direction within **0.5 deg** from best fit.

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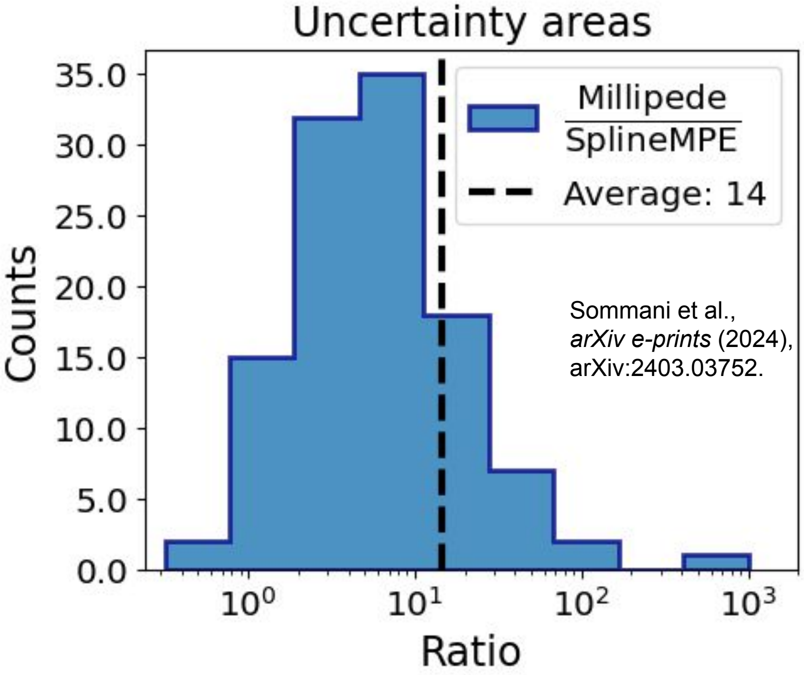
Moreover, The GCN Notices' area is way smaller than the GCN Circular area

GCN Notice (SplineMPE) error smaller and precise



Sommani et al., *arXiv e-prints* (2024), arXiv:2403.03752.

The neutrino doublet

Two IceCube realtime alerts:

- **IC 220424A**,
  most-likely neutrino energ
  184 TeV;
  GCN Notice run 136565 evt 2186969 (v1), 24/04/22.
- **IC 230416A**,
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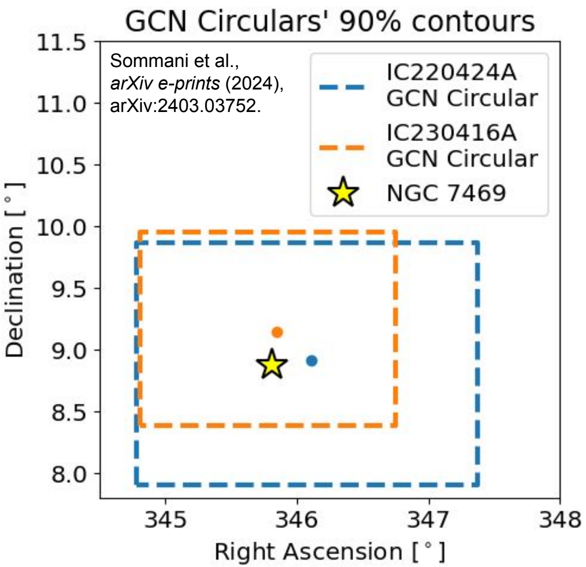

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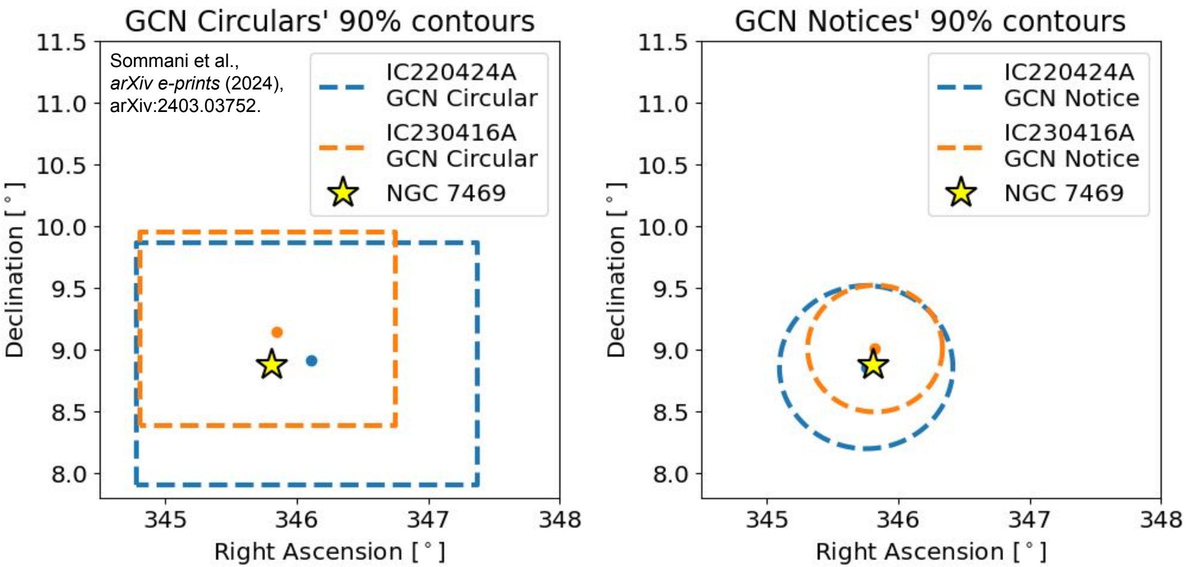

GCN Notice with smaller contours -> We use them to estimate **the chance probability**!

Estimation of the chance probability

I repeat the IceCube experiment N times (with N very big)

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↓

I always detect only background

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In how many cases do I get an equally or more significant coincidence?

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In how many cases do I get an equally or more significant coincidence?

What does this mean??

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In how many cases do I get an equally or more significant coincidence?

What is a coincidence?

What is the significance of a coincidence?

What is a **coincidence**?

A **coincidence** is made of **any two neutrinos** related to an **interesting source**

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We made use of two **catalogs**:

- All the **AGN** in the **Milliquas** catalog (**50757 sources**);
- **Turin-SyCAT** catalog (**351 sources**):
    - **Seyfert galaxies** selected on multifrequency observations.

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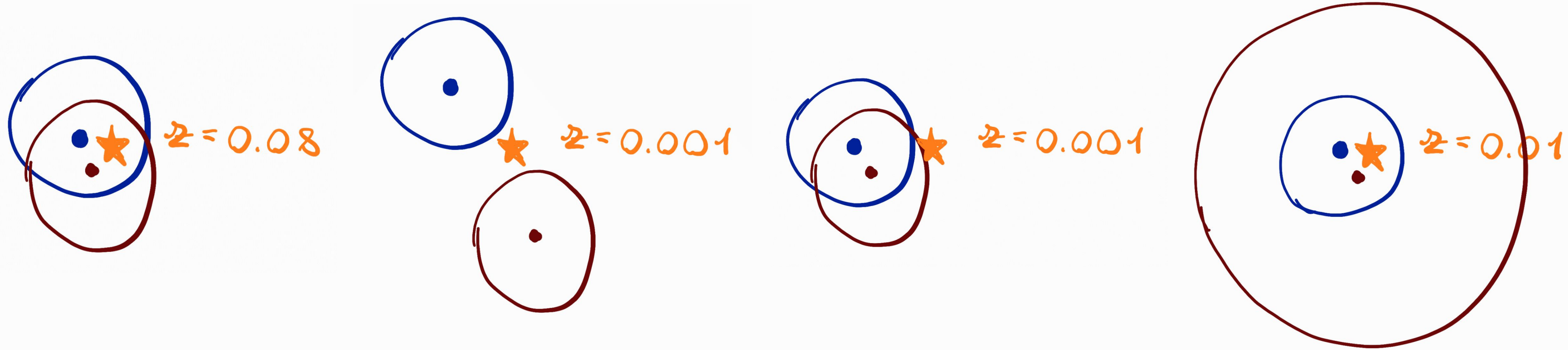
Example:
we have **N** neutrinos -> **N***(**N**-1)/2 **doublets**,
with **S** sources -> **S***N***(**N**-1)/2 **coincidences**.
We need a **significance** so distinguish among them.

Significance of a coincidence



Which **coincidence** is the most **significant**?

We need a system to distinguish among various **coincidences**:
Log-likelihood ratio

Log-likelihood ratio

- ***B*** -> Background Hypothesis:

  the two neutrinos are background

- ***A*** -> Alternative Hypothesis:

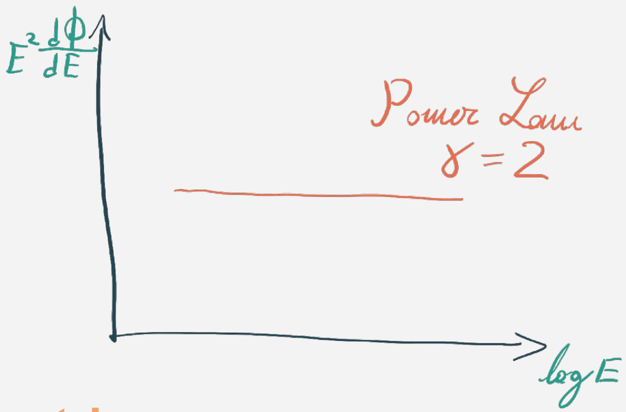
  the two neutrinos are emitted by a source ***S***

$$\lambda(\mathrm{Doublet}|\mathrm{S}) = 2\log\frac{p_A(\mathrm{Doublet}|S)}{p_B(\mathrm{Doublet})}$$

$p_A(\mathrm{Doublet}|S)$

Takes into account:

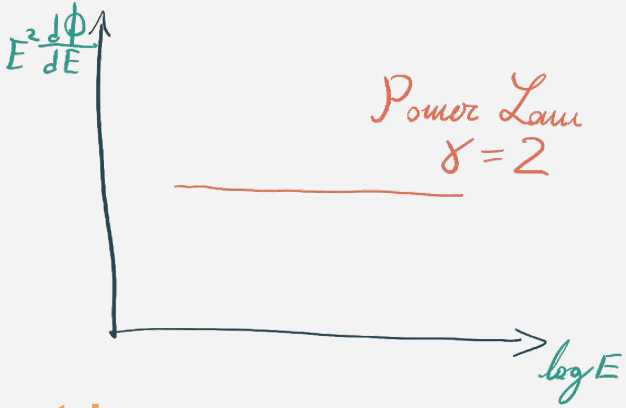
$p_A(\mathrm{Doublet}|S)$



Takes into account:

- Probability for the source ***S*** to emit *at least* **2 neutrinos**.
  - All **sources** as standard candles (emission scales with redshift)
  - Power-law spectrum with spectral index = 2 ↦ Fermi shock acceleration scenario

$p_A(\text{Doublet}|S)$



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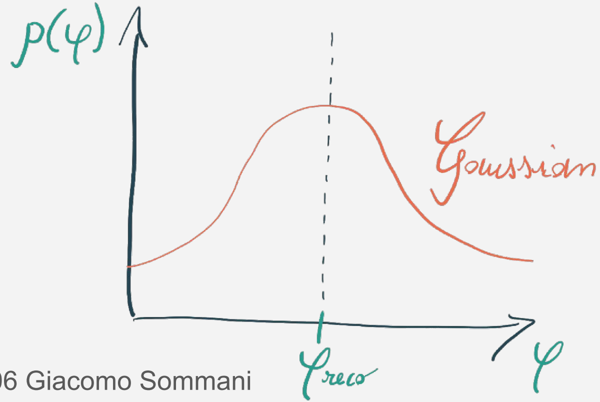
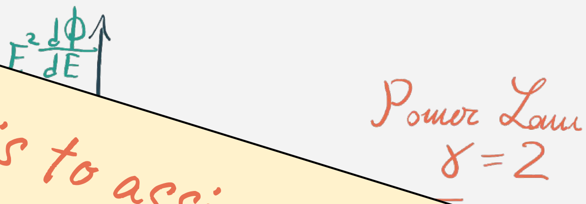


- Distance of the **neutrinos** from the **source *S***
  - We assume gaussian neutrino psf

$p_A(\text{Doublet}|S)$

We need this to assign a significance to the several coincidences, not to describe realistically the sources



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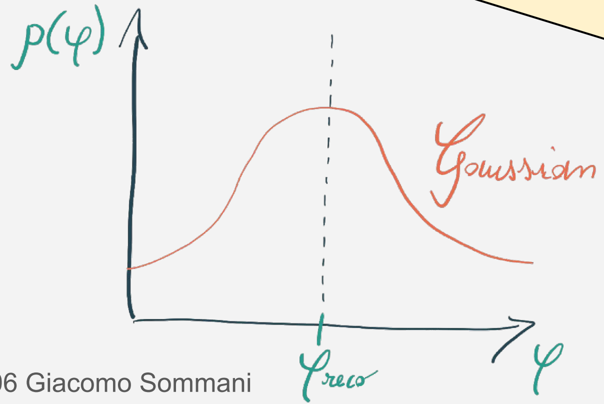

Per-doublet source selection

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Per-**doublet** **source** selection

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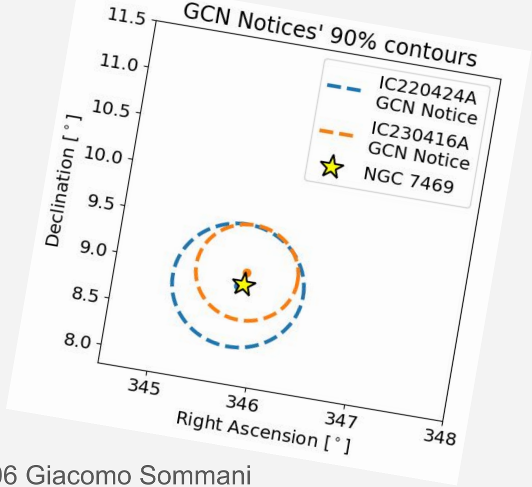
Which using all realtime alerts is our doublet!



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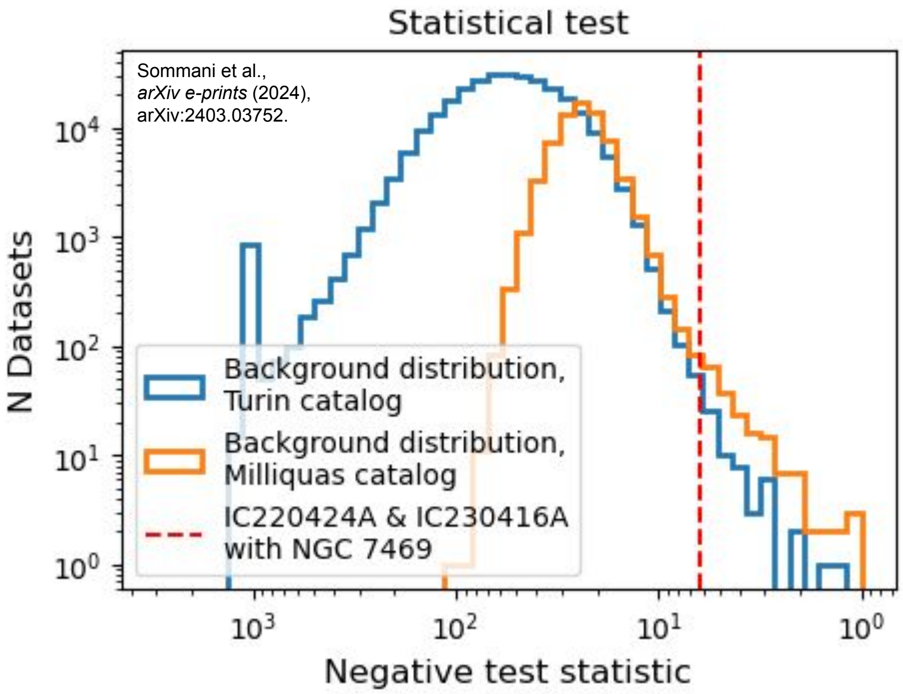
In how many cases do I get an equally or more significant coincidence?

1. Scramble the alerts (generate random right ascensions)
2. Take the highest log-likelihood ratio for each scramble

Results

Results

test statistic = log-likelihood ratio



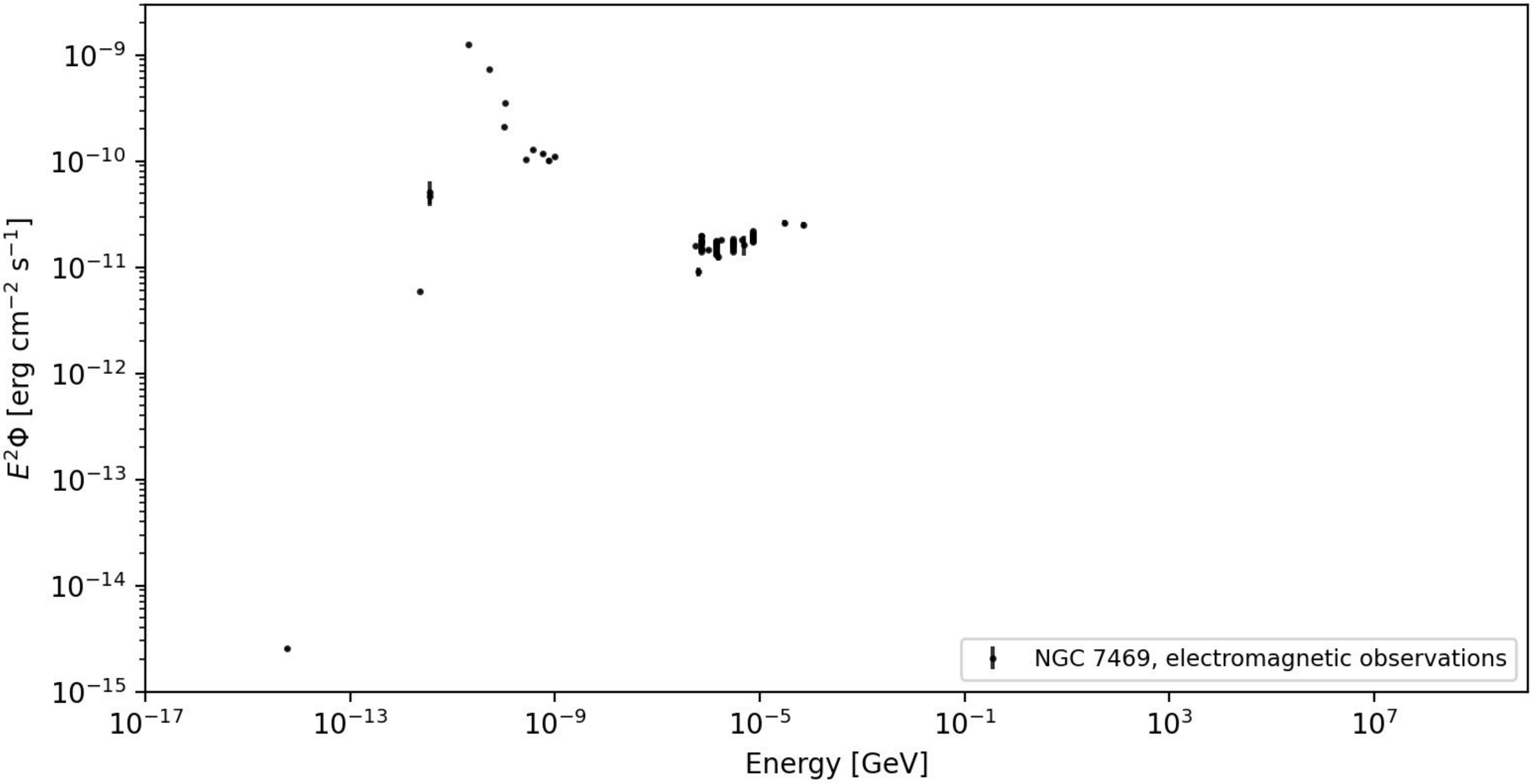
"Bump" at -10^3 due to scrambles where all coincidences were very insignificant (acceleration of the algorithm)

Turin (Seyferts): 3 × 10^5 scrambles
Milliquas (AGNs): 7 × 10^4 scrambles

Catalog	p-value	p-value (in σ)
Milliquas	3.2×10^{-3}	2.73
Turin	2.2×10^{-4}	3.51

Post-trial p-value: 3.33 $\boldsymbol{\sigma}$

A look at the SED



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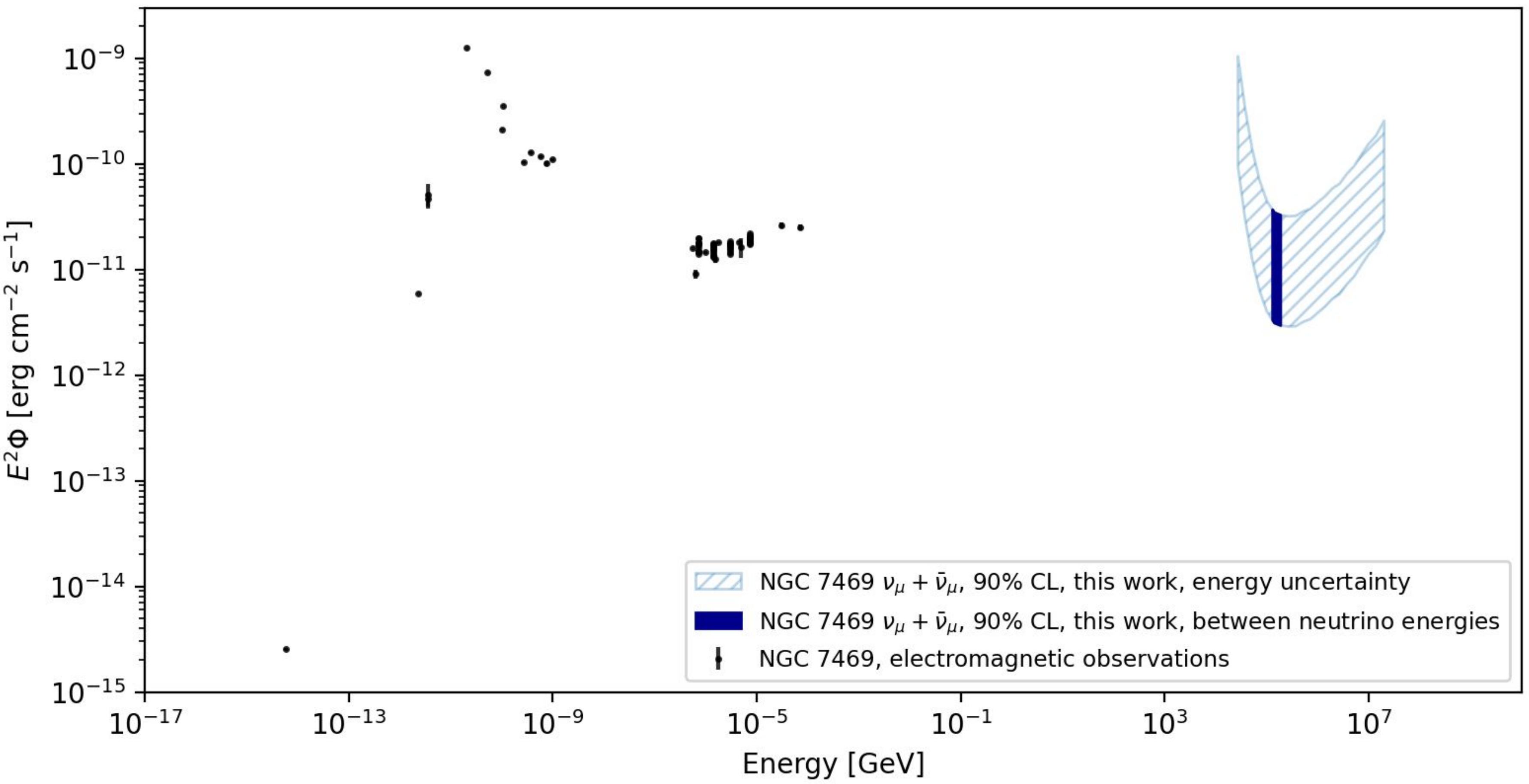

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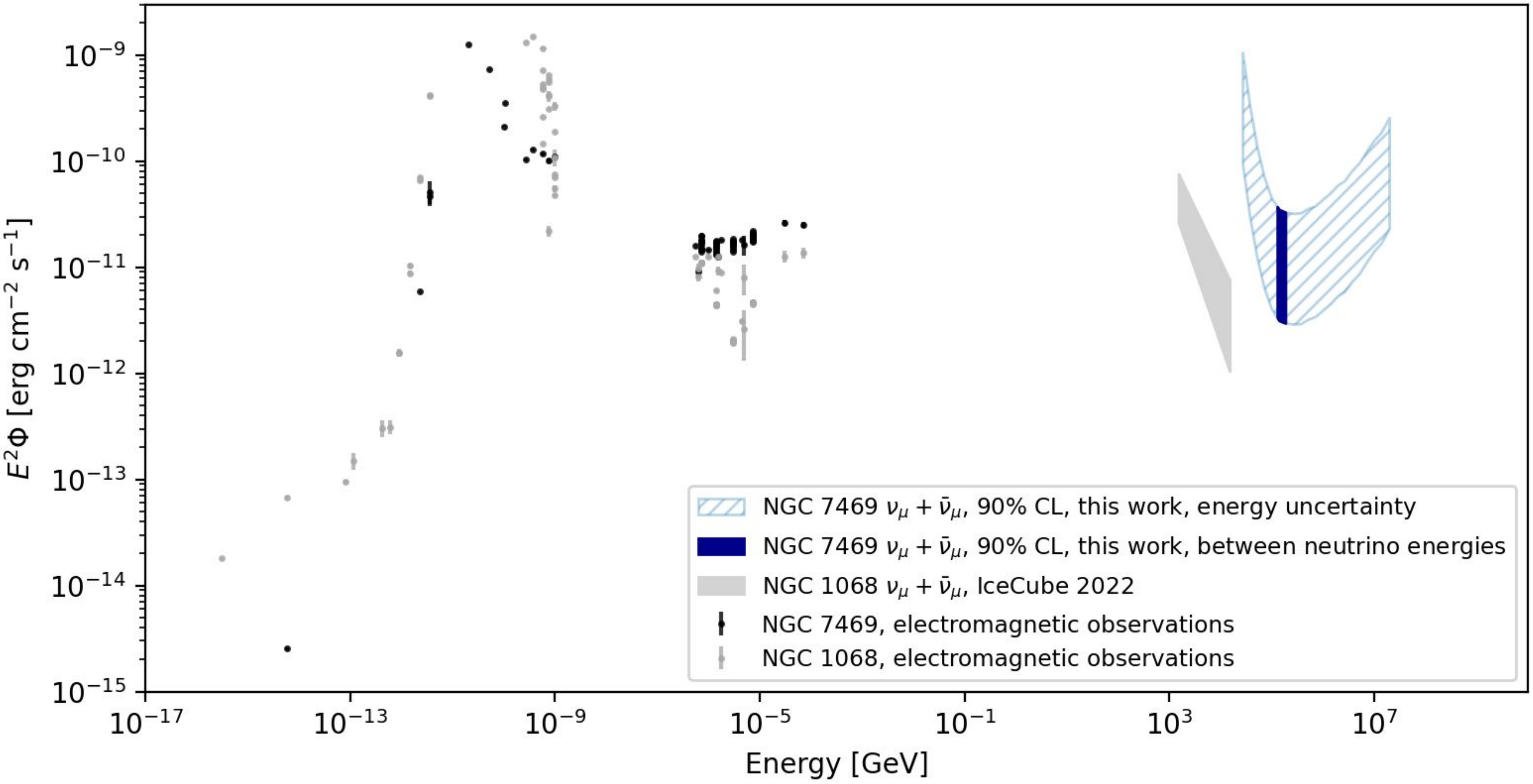

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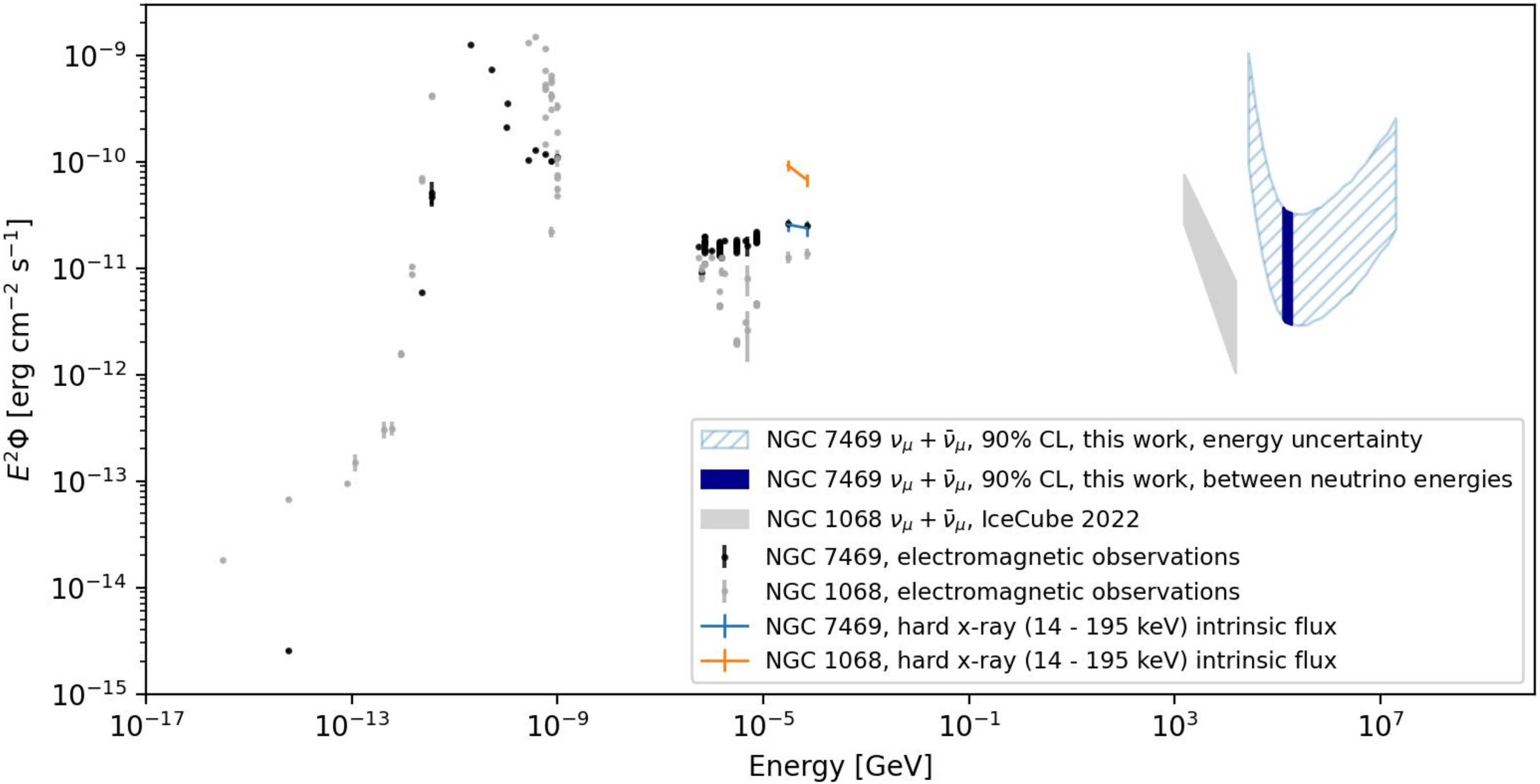

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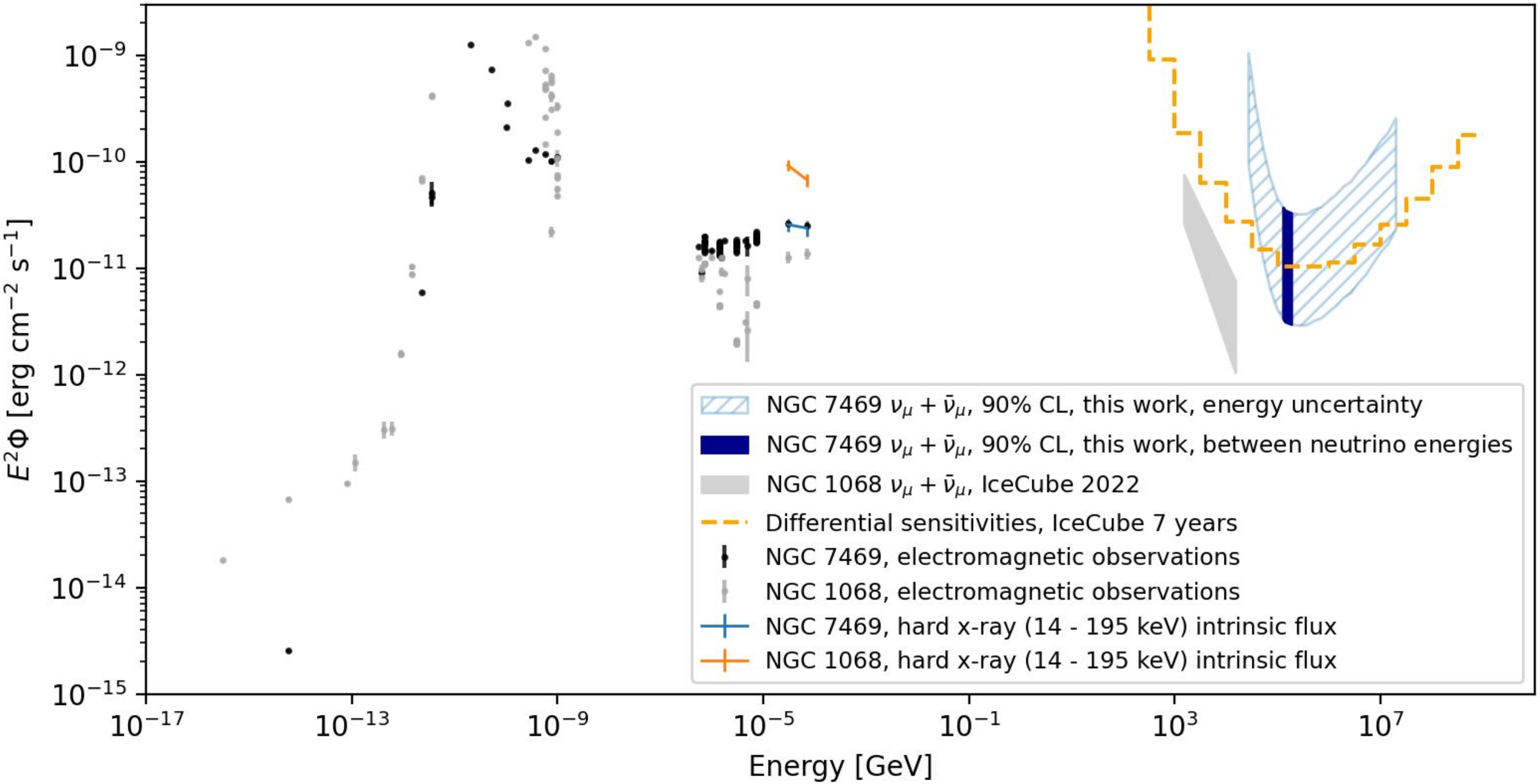


Conclusions

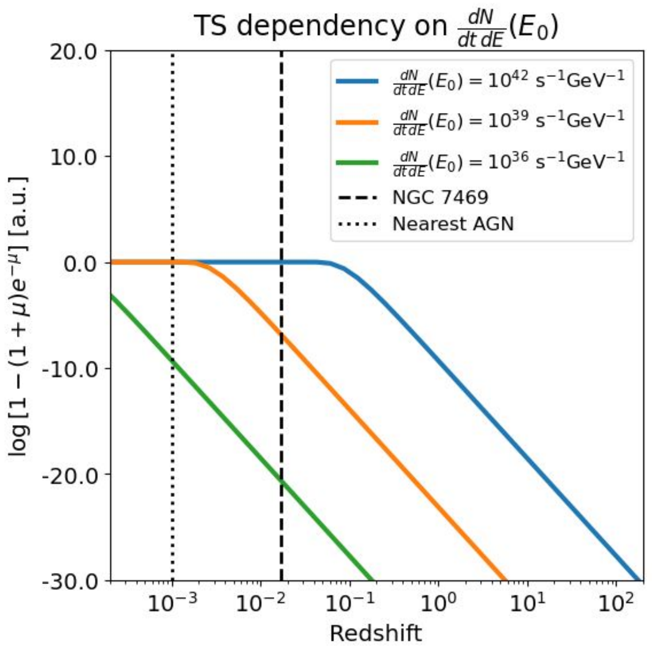
- **NGC 7469** inside the contours of **IC220424A** and **IC230416A**;
- Background scenario rejected with **3.3 σ**;
- **NGC 7469**’s neutrino flux at higher energies than **NGC 1068**;
- Source never “observed” before in precedent IceCube analyses -> **necessity of hard spectral index**.

Thank you for listening!

Backup slides

Intrinsic flux of sources choice

The choice of the **intrinsic flux** influences the outcome of the test.



In the small-intrinsic-flux regime the outcome of the test is independent on the specific choice.

Complete test statistic

$$\max_k \left\{ \log\left[1 - (1+\mu_k)\, e^{-\mu_k}\right] - \frac{1}{2}\left(\frac{\Phi_{ik}^2}{\sigma_i^2} + \frac{\Phi_{jk}^2}{\sigma_j^2}\right)\right\}$$

$$- 2\log(\sigma_i \sigma_j) - \log\left[\cos\theta_i \cos\theta_j\, A_{\text{eff}}(\theta_i, E_i)\, A_{\text{eff}}(\theta_j, E_j)\right]$$

Test: injecting doublets from sources