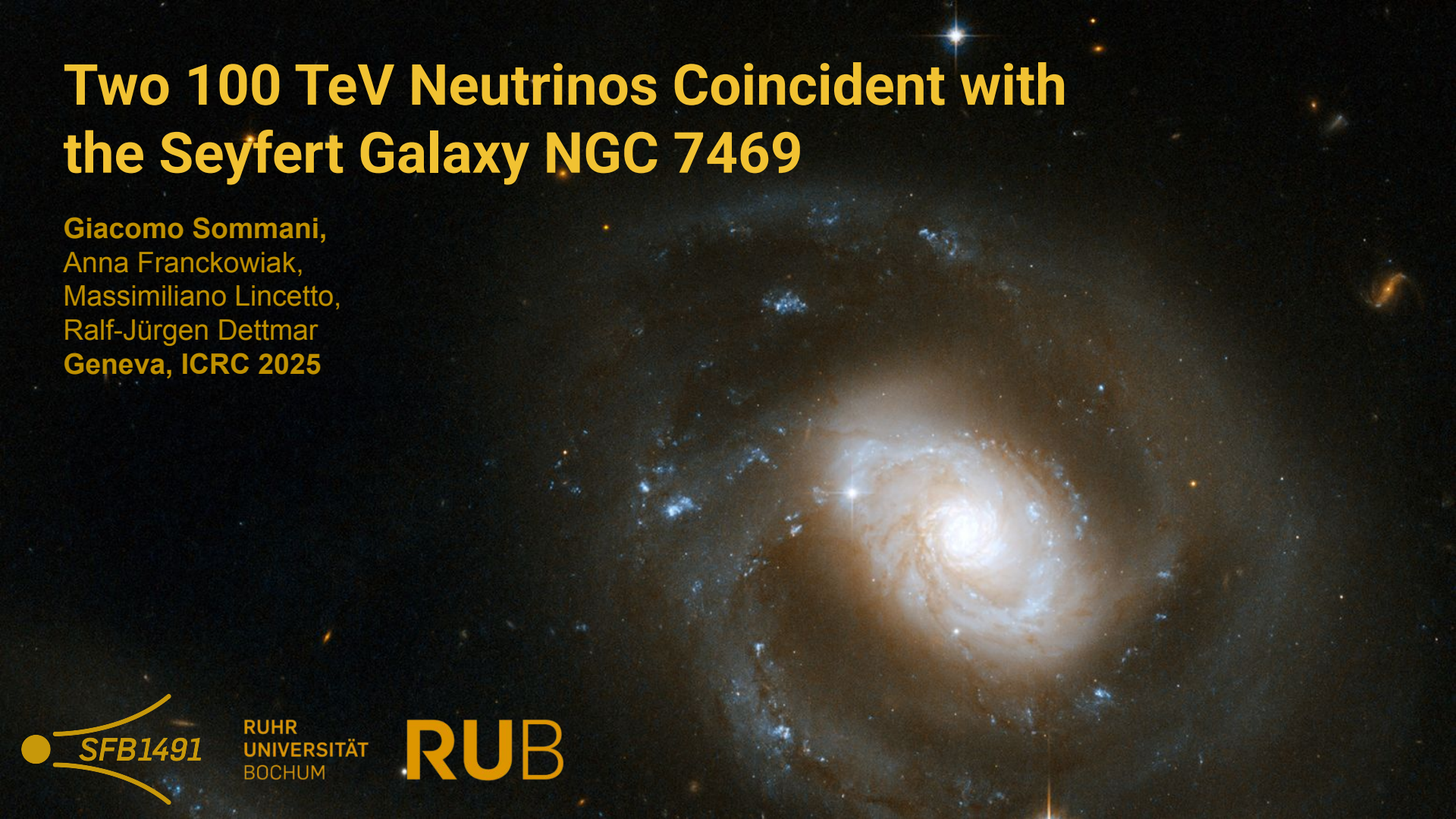
Two 100 TeV Neutrinos Coincident with the Seyfert Galaxy NGC 7469

Giacomo Sommani,
Anna Franckowiak,
Massimiliano Lincetto,
Ralf-Jürgen Dettmar
Geneva, ICRC 2025



SFB1491

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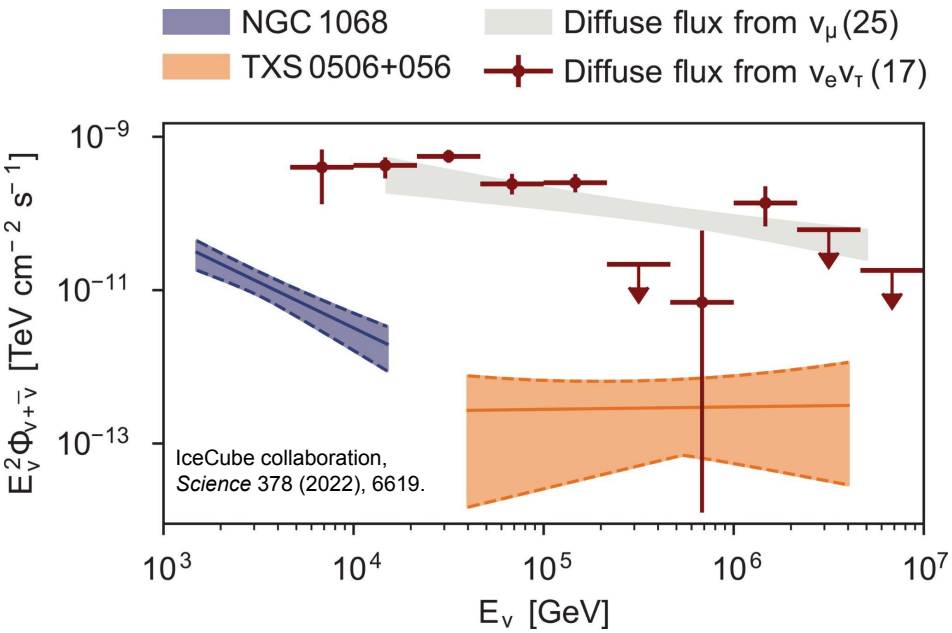
Outline

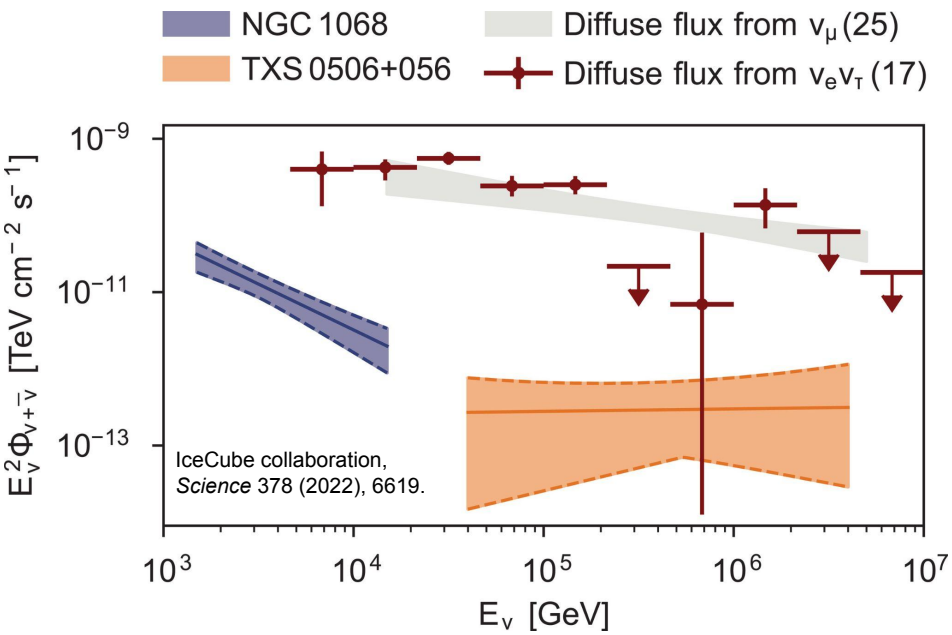
- Neutrinos from AGNs and Seyfert galaxies
- The Seyfert galaxy NGC 7469 inside the contours of two neutrinos
- Estimation of the chance probability
- Results
- A look at the SED

Neutrinos from AGNs and Seyfert galaxies



Detection of a diffuse astrophysical neutrino flux in 2013.

Neutrinos from AGNs and Seyfert galaxies



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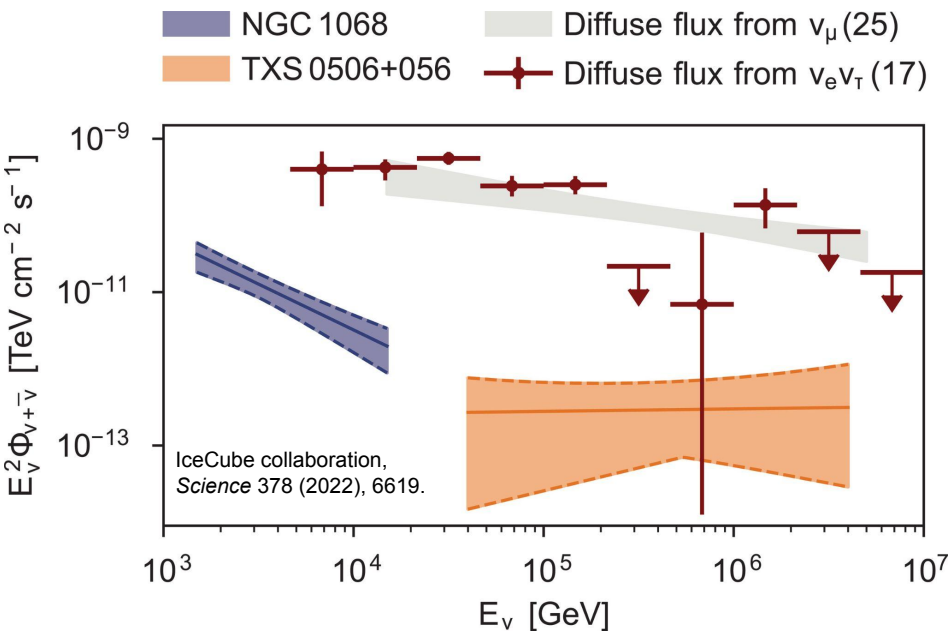

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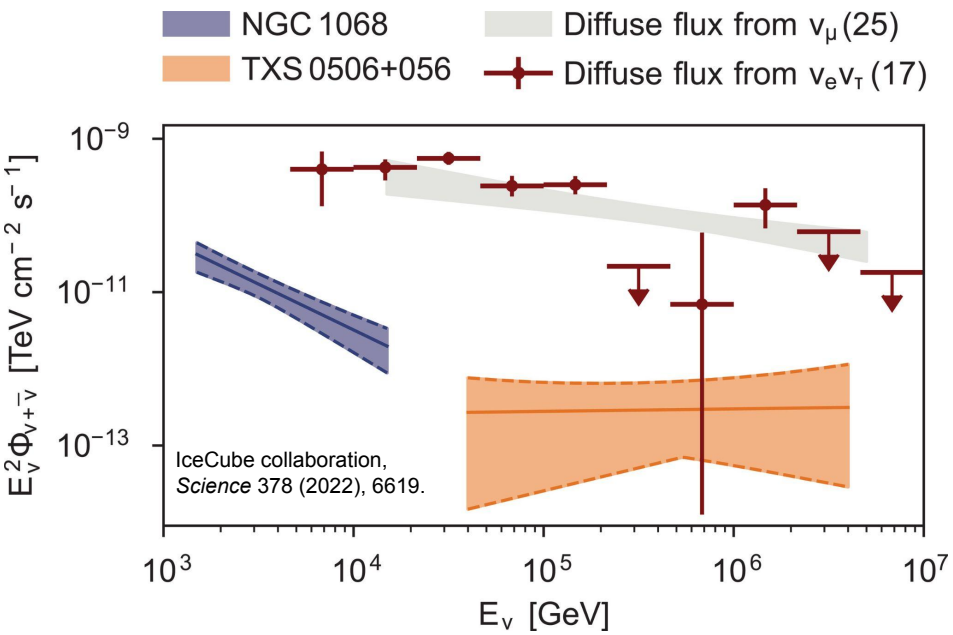

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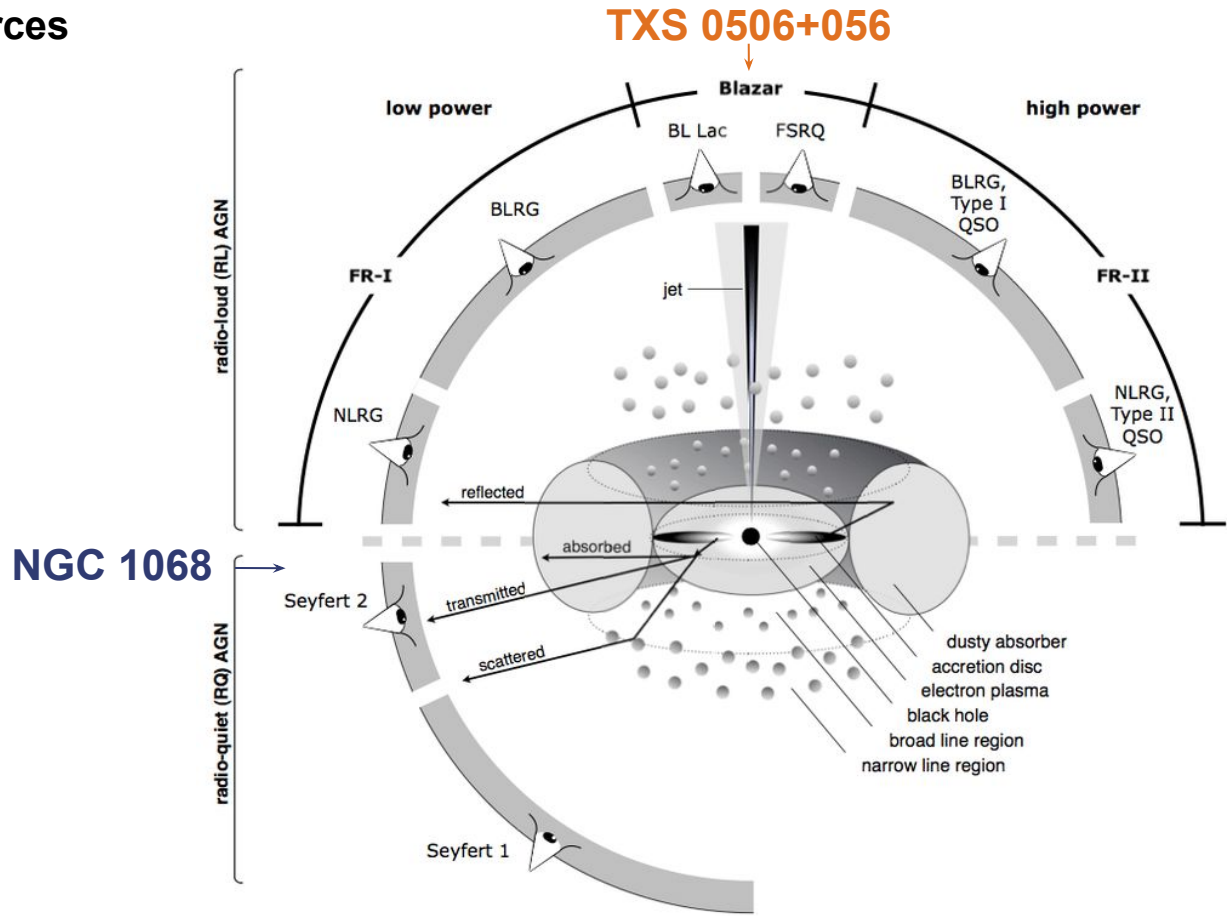
In 2017, neutrino alert coincident with the flaring **Blazar TXS 0506+056**.

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

Most of the astrophysical neutrino flux still has an unknown origin.

About AGNs and Seyfert galaxies

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



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

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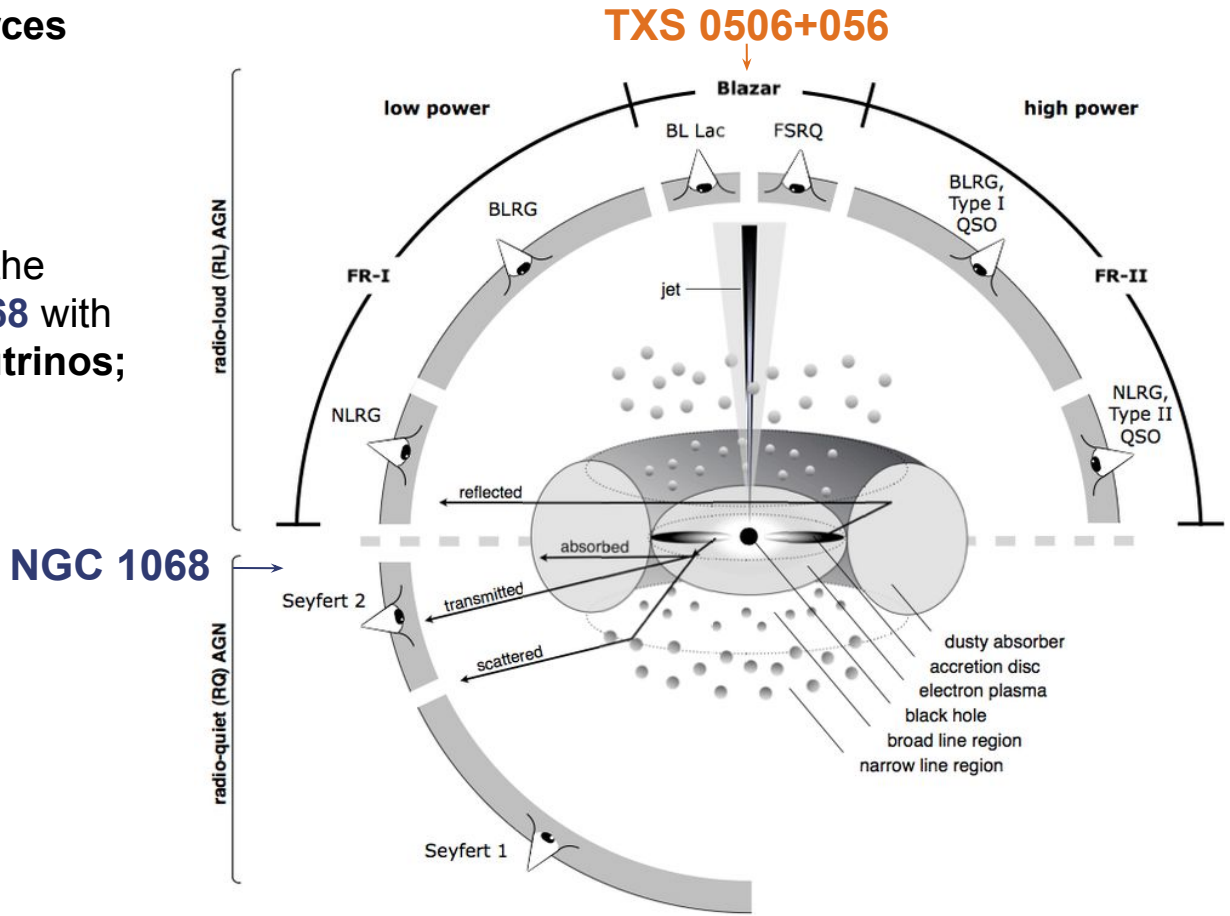

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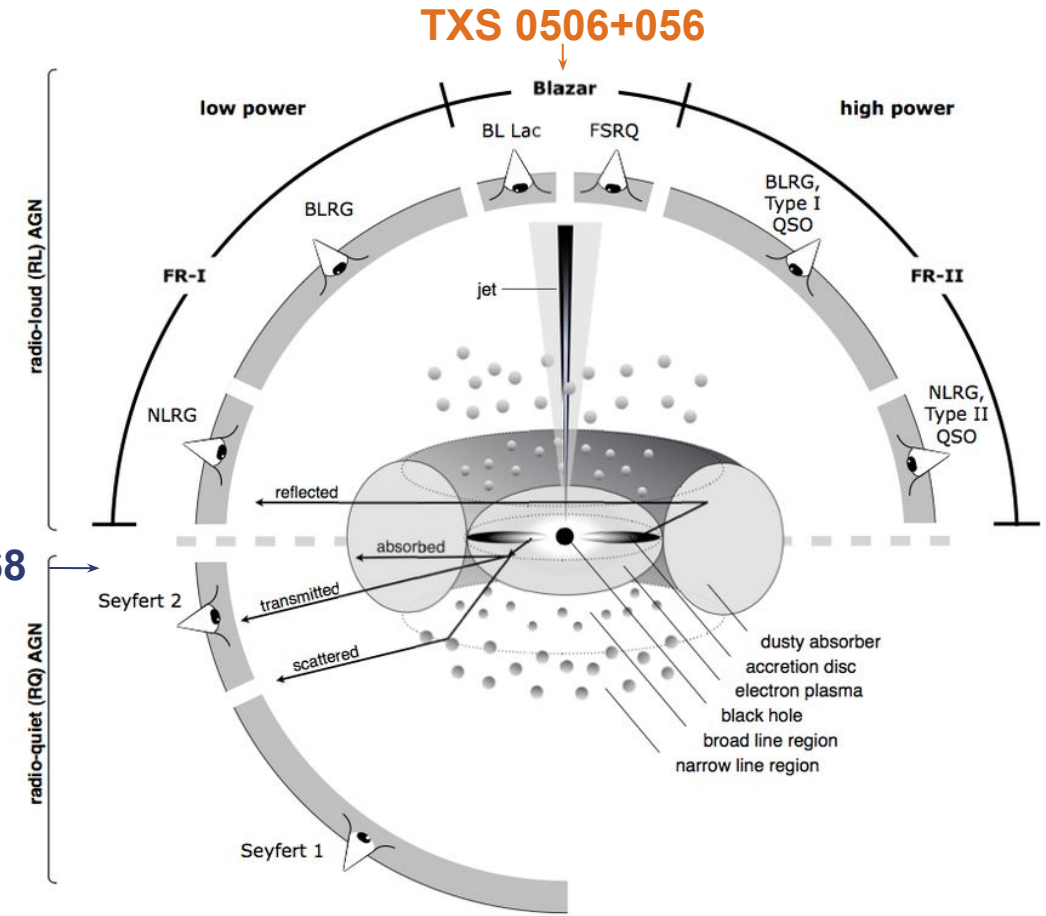

NGC 1068

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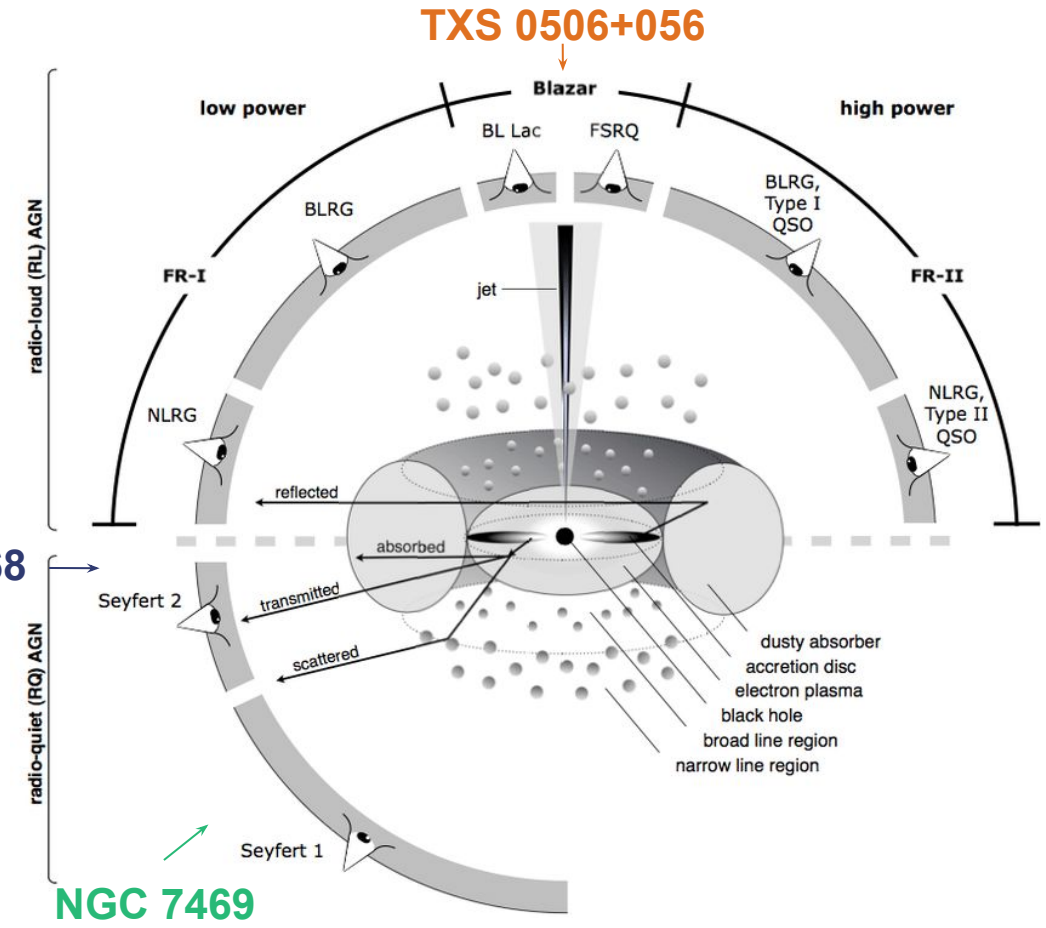
- The **Seyfert galaxy NGC 7469** inside the contours of **two neutrinos at ~100 TeV**;



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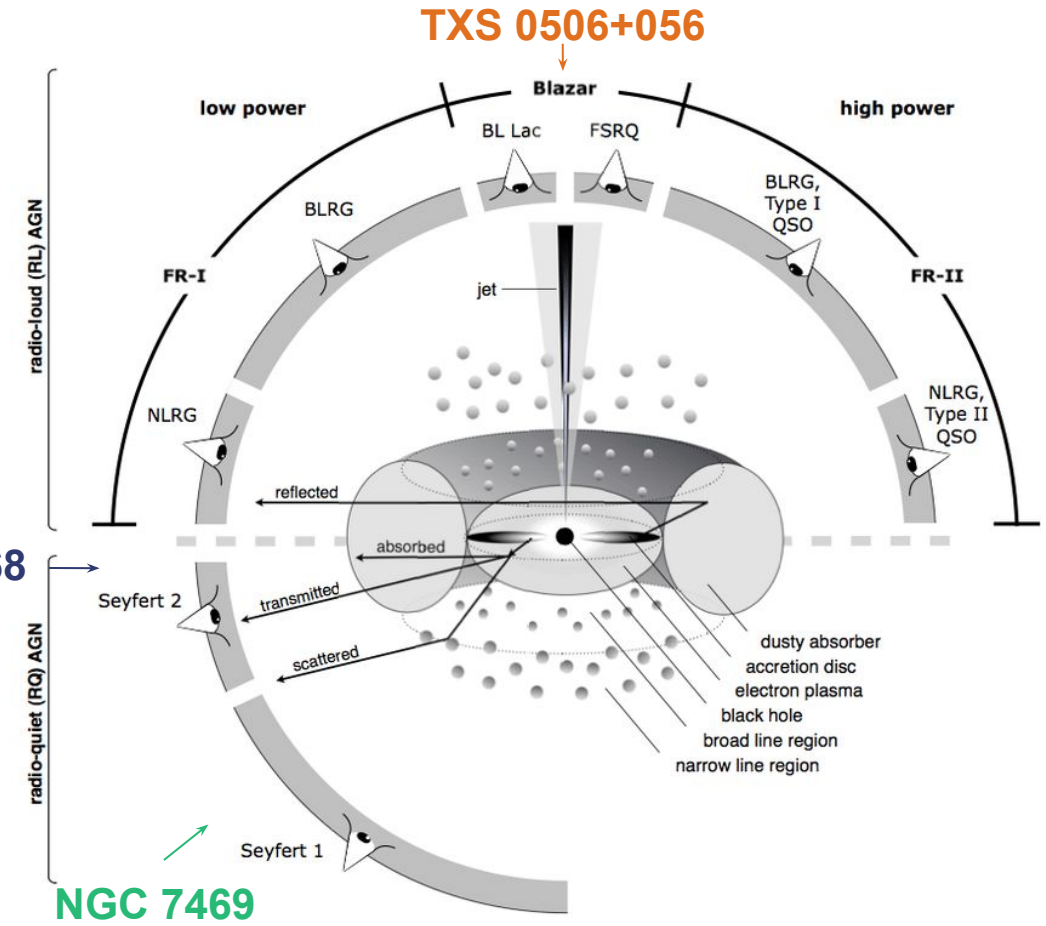
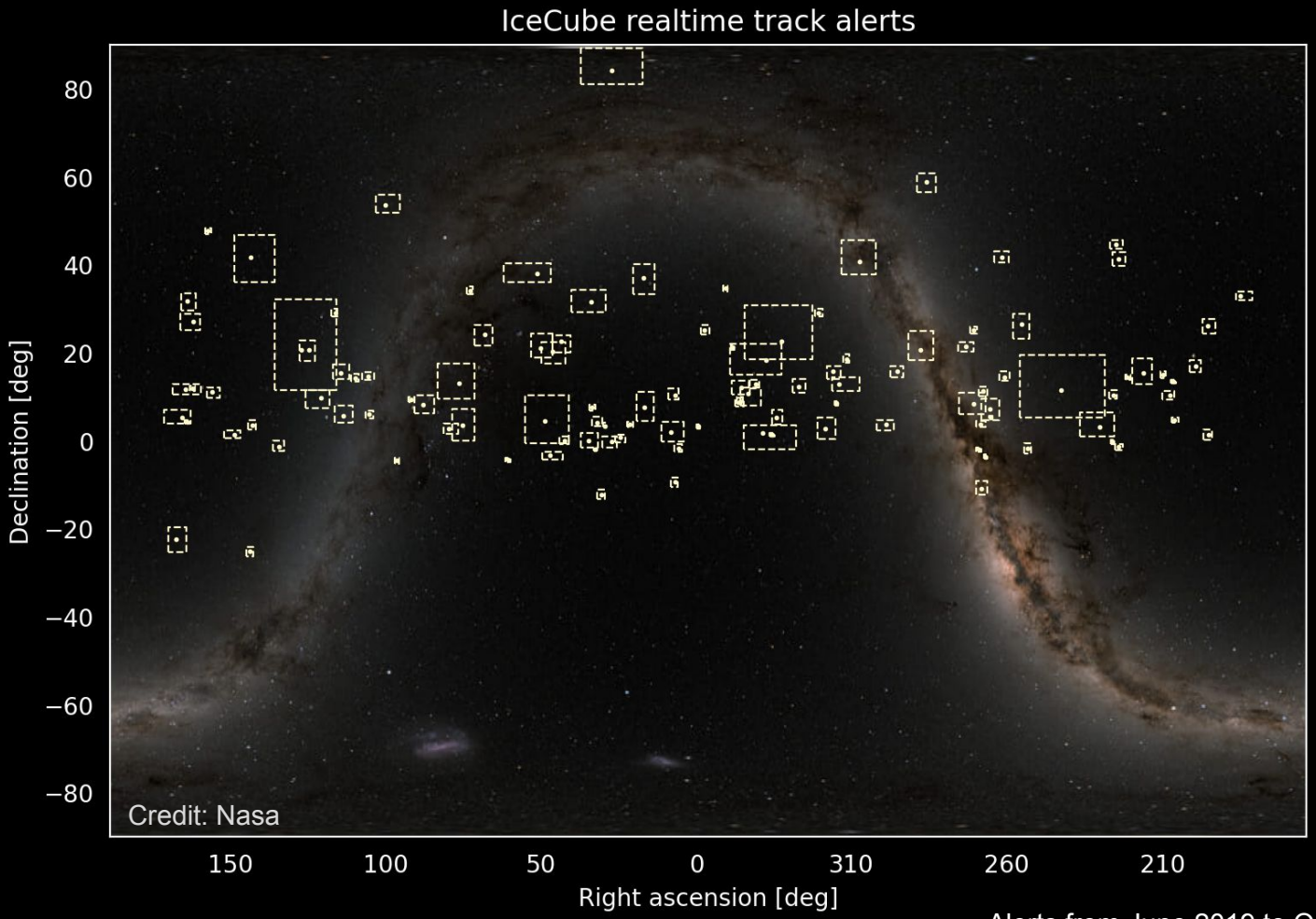
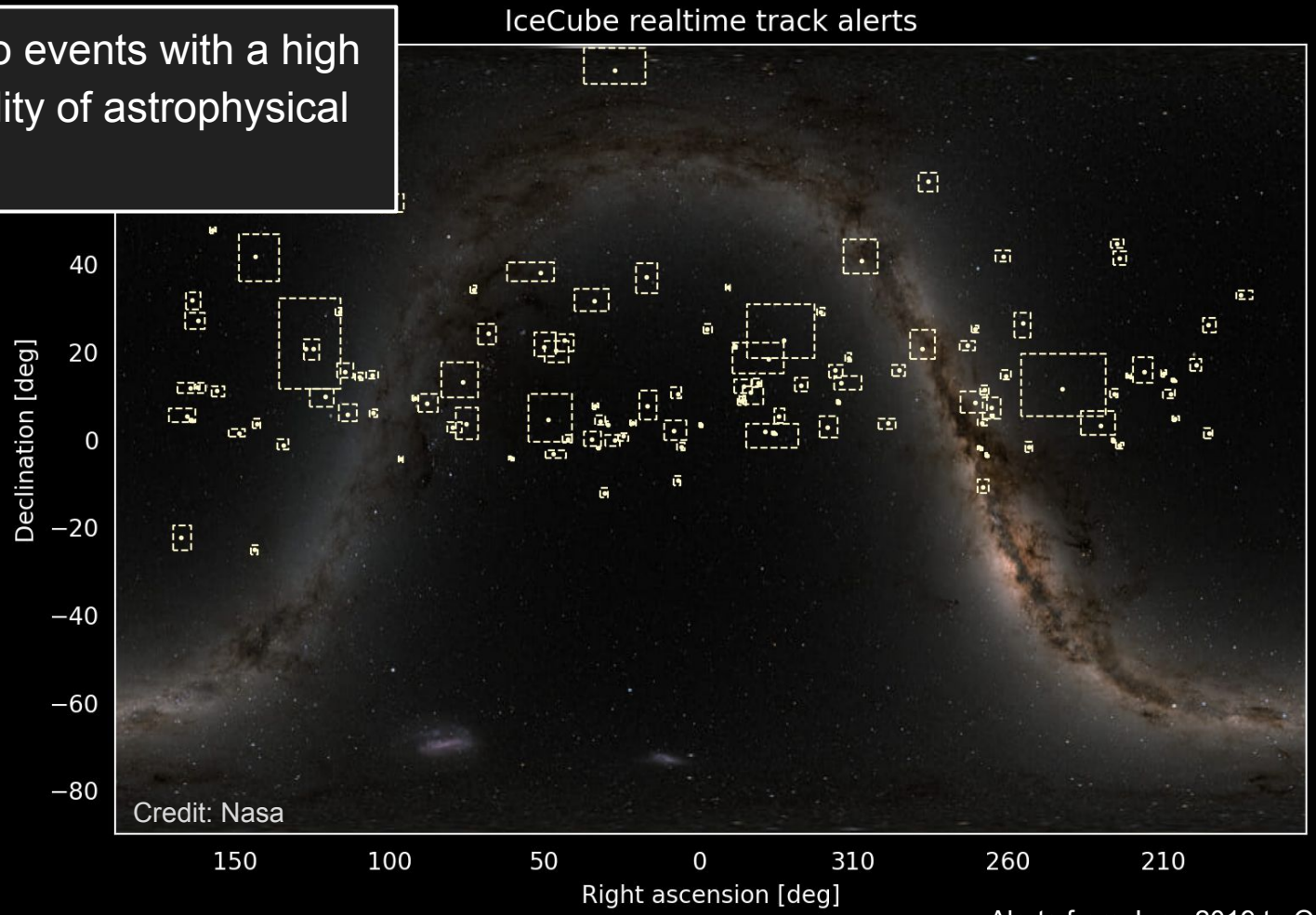
- Is this **a new neutrino source**? Can this happen **by chance**?





Alerts from June 2019 to October 2023

Neutrino events with a high probability of astrophysical origin



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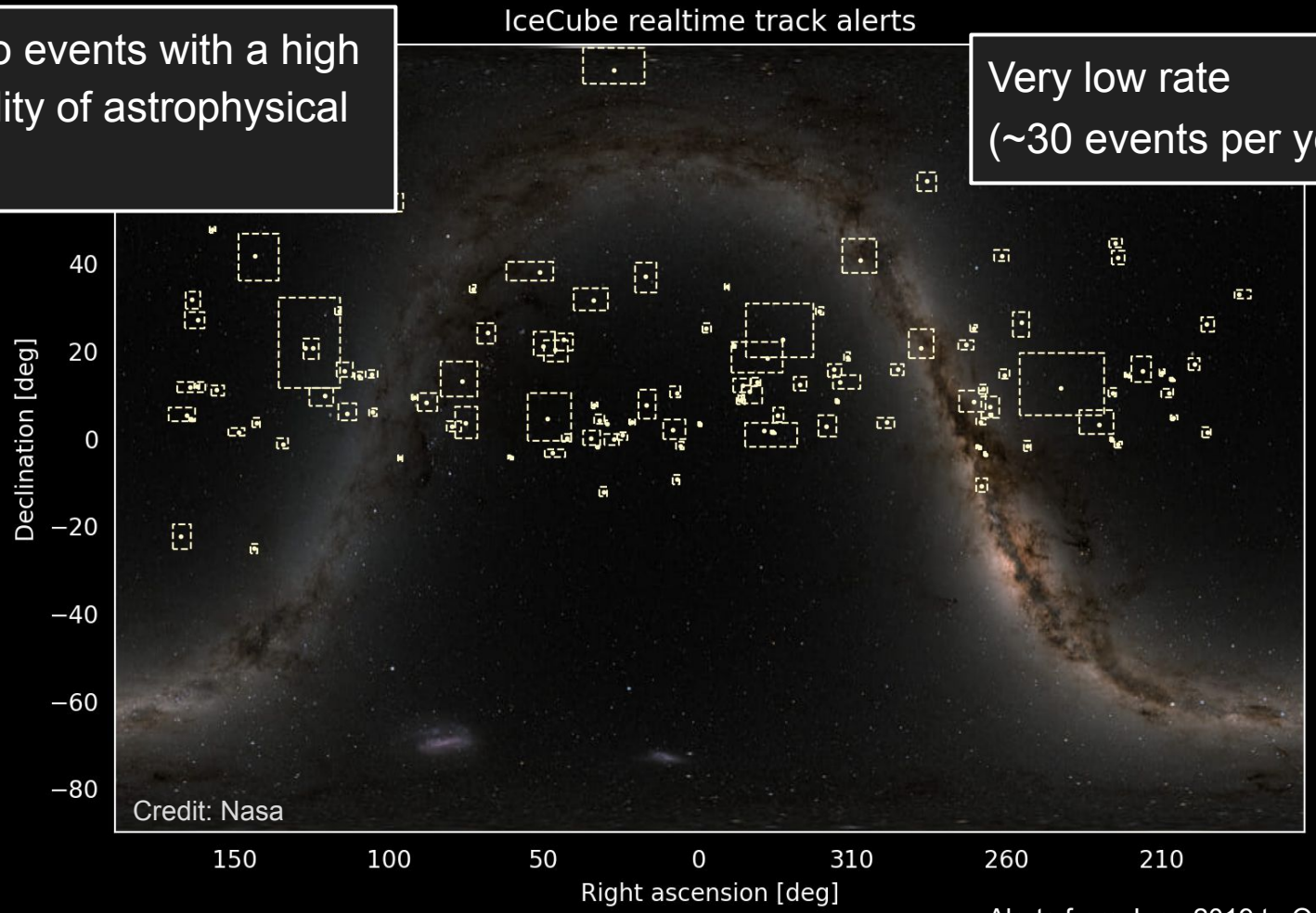

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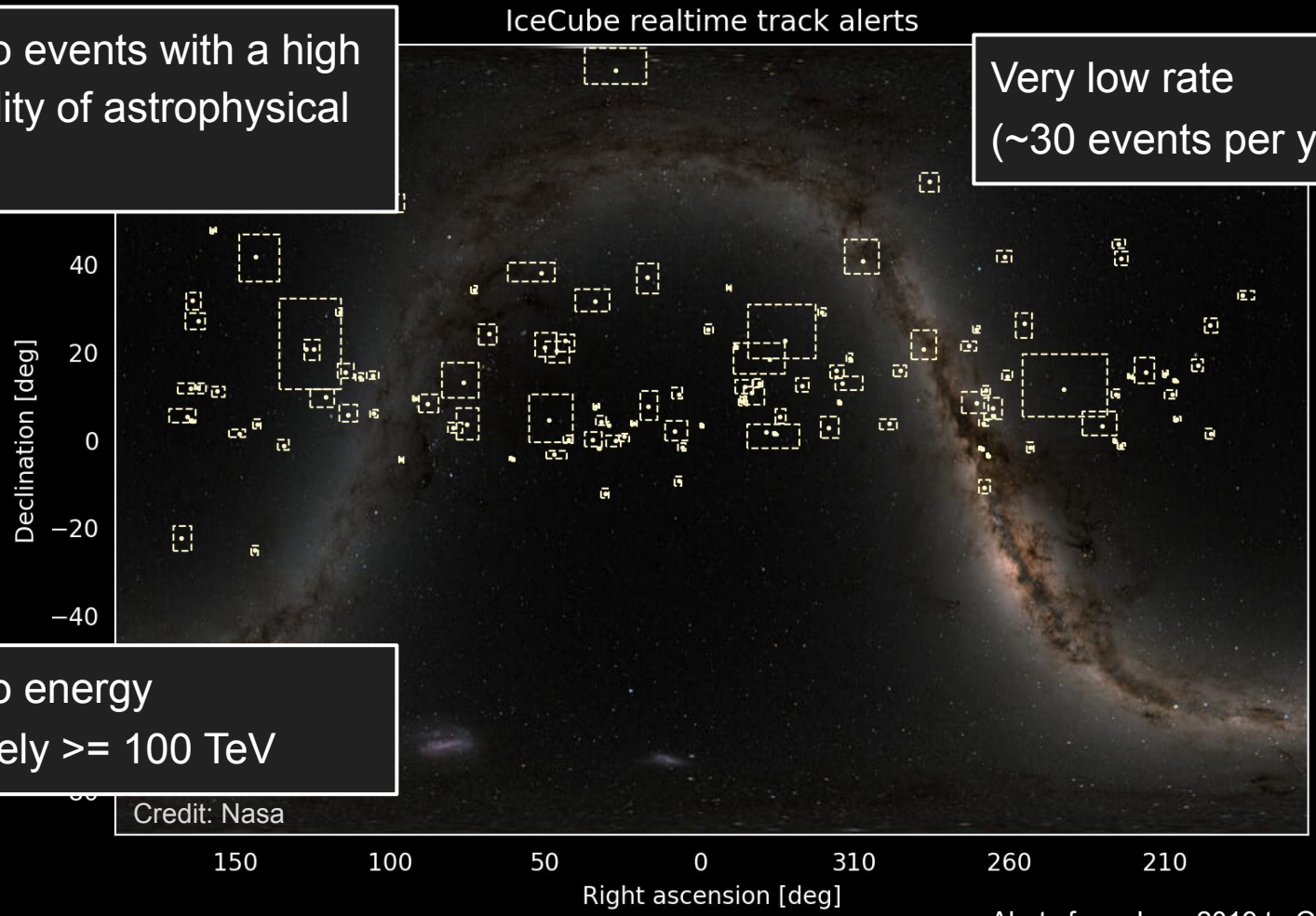

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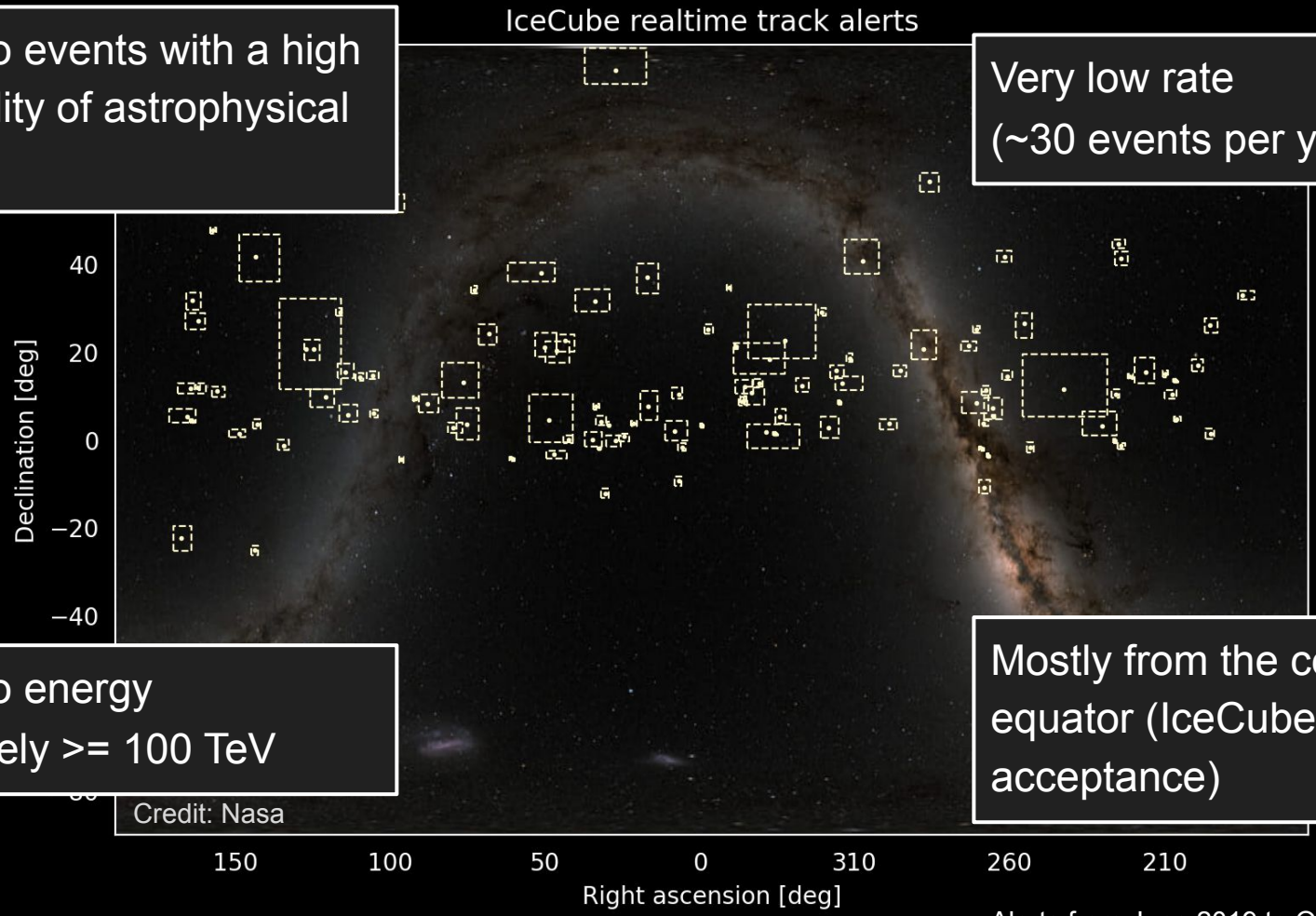

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Mostly from the celestial equator (IceCube acceptance)

Alerts from June 2019 to October 2023

Gamma-ray Coordinate Network (GCN) Notices and Circulars

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

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GCN Notice (Rev0)

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Abbasi et al. 2021, JINST, 16, P08034

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  Abbasi et al. 2021, JINST, 16, P08034

GCN Circular

- More sophisticated algorithm (**Millipede**).
  Aartsen et al. 2014, JINST, 9, P03009
- Refined direction (rectangular error region).

First GCN Notice or updated GCN Circular?

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

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All of this is true only for the alerts before September 2024 (update in the realtime-alerts reconstruction)

-> See poster at PO-2 Session, PoS(ICRC2025)1184 Improvements in the Reconstruction of IceCube Realtime Alerts G. Sommani, T. Yuan, on behalf of IceCube Collaboration

The neutrino doublet

Two IceCube realtime alerts:

- **IC 220424A**,
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  GCN Notice run 136565 evt 2186969 (v1), 24/04/22.
- **IC 230416A**,
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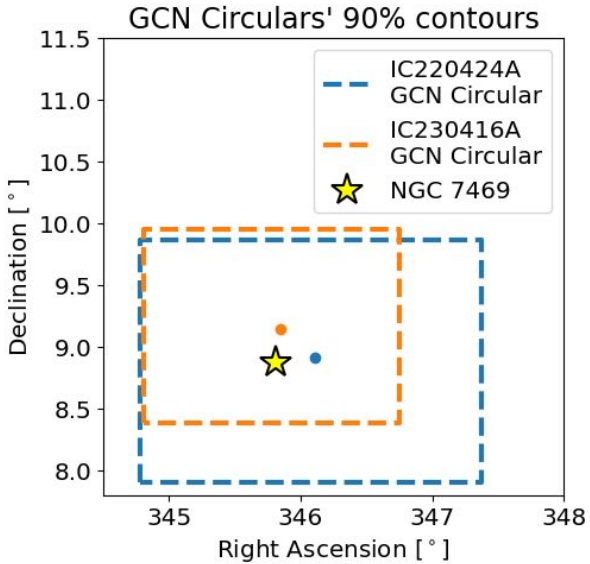

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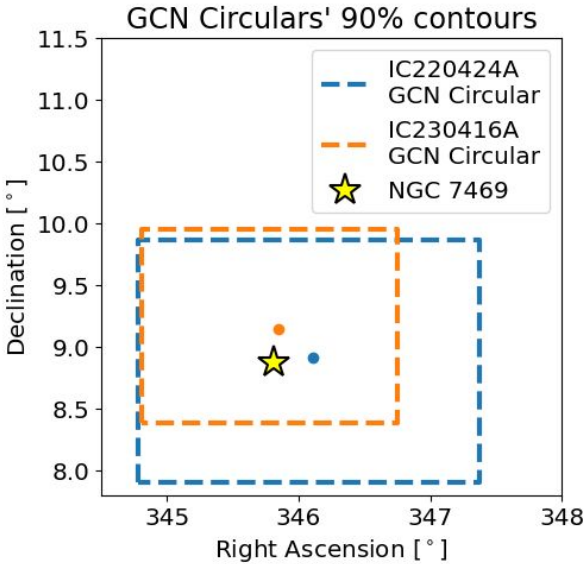

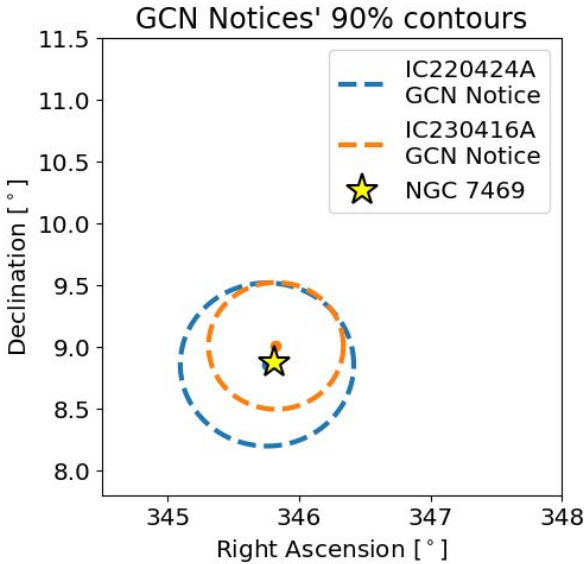

GCN Notice with smaller contours -> We use them to estimate **the chance probability**!

Estimation of the chance probability

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

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↓

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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?

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Any source in a pre-defined catalog.

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We made use of two catalogs:

- All the AGN in the Milliquas catalog (71,345 sources);
- Turin-SyCAT catalog (351 sources):
    - Seyfert galaxies selected on multifrequency observations.

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Example:

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

Significance of a coincidence

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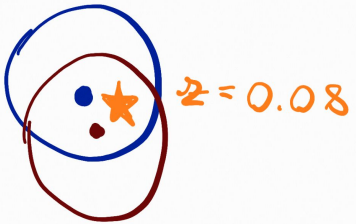

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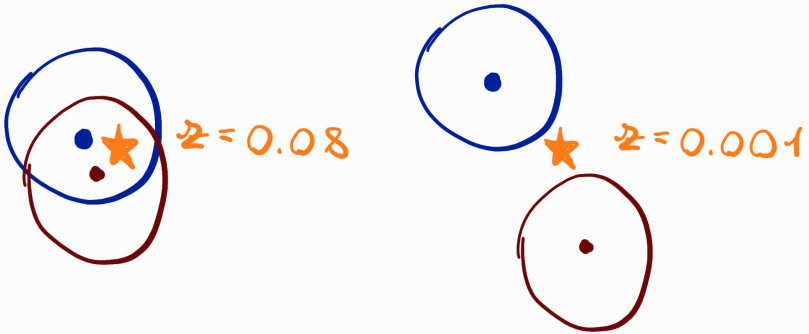

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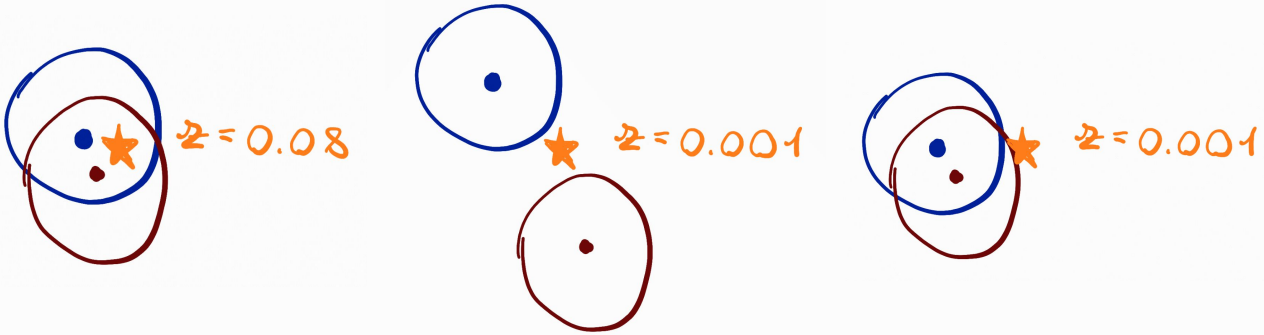

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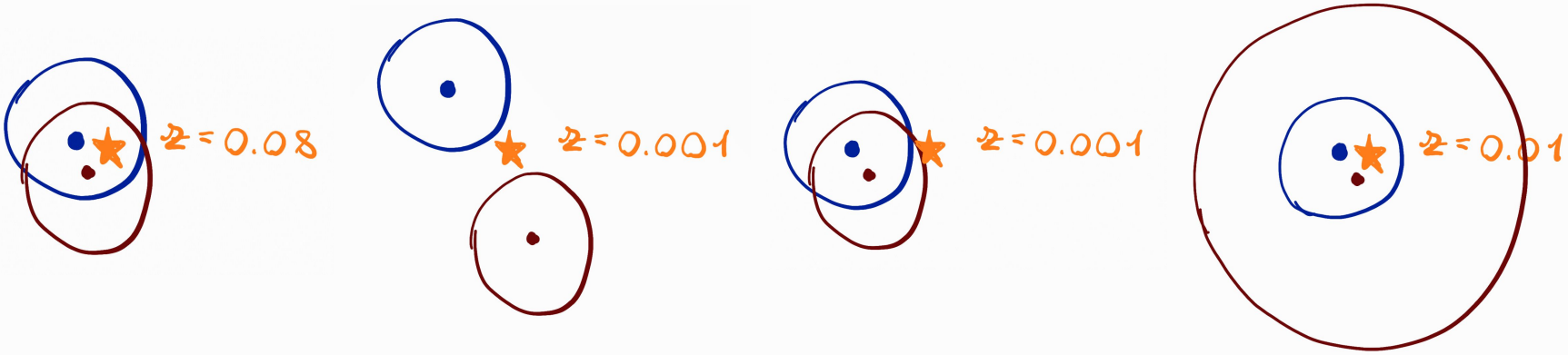

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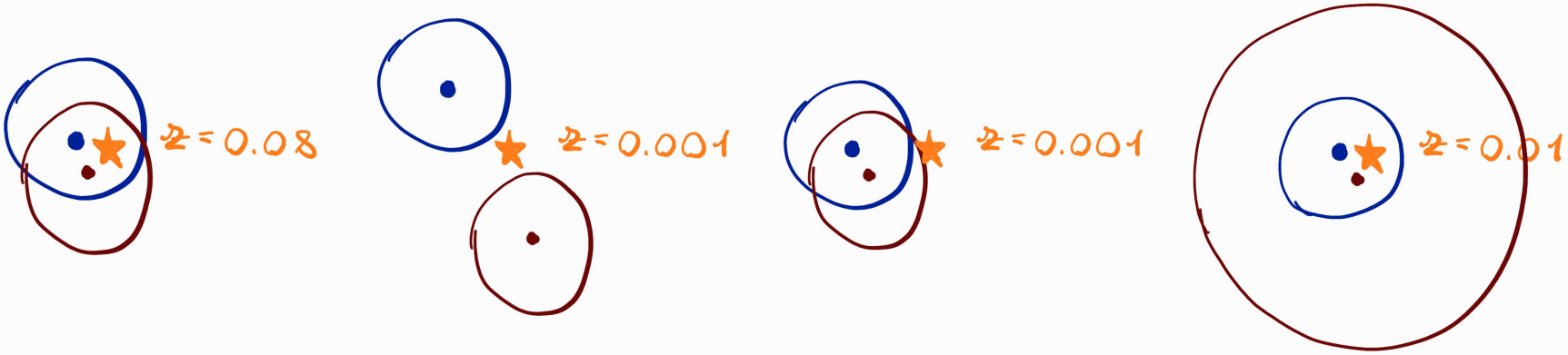

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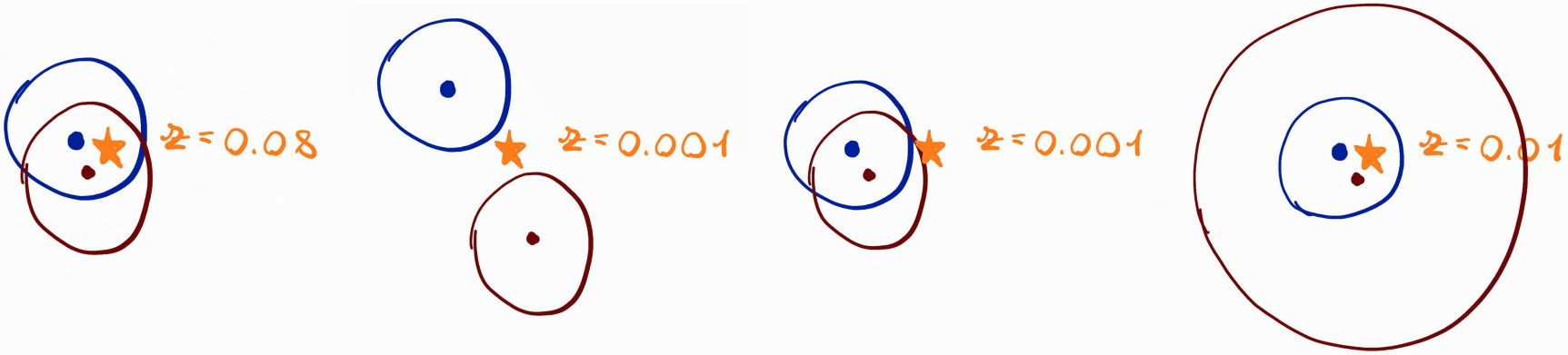

Which coincidence is the most significant?

We need a system to distinguish among various coincidences:

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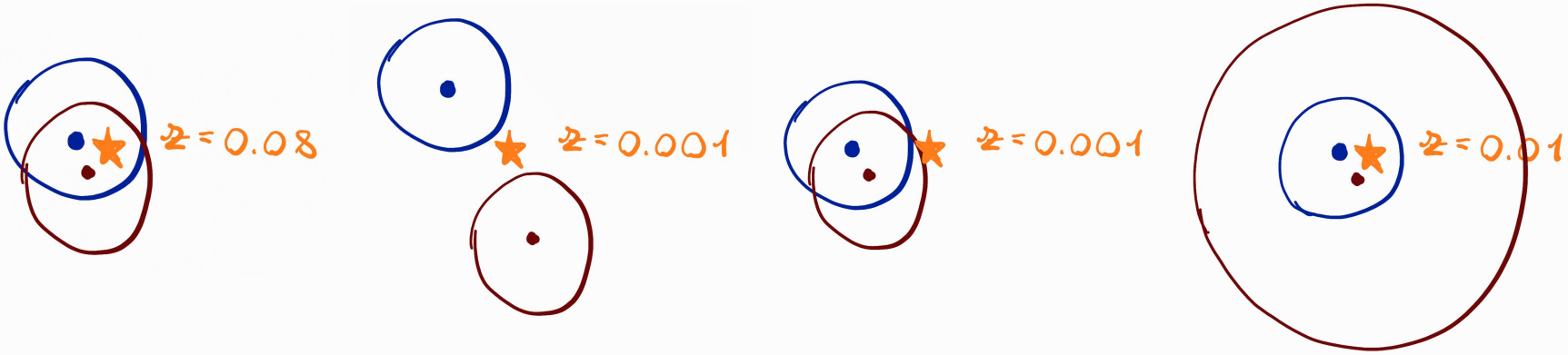

Which coincidence is the most significant?

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Log-likelihood ratio

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- ***B*** -> Null Hypothesis:

  the two neutrinos were not produced by any source in the catalog

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

  the two neutrinos are emitted by a source *S*

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

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

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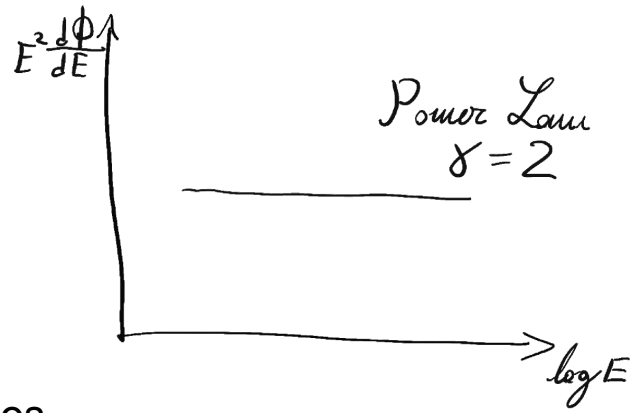
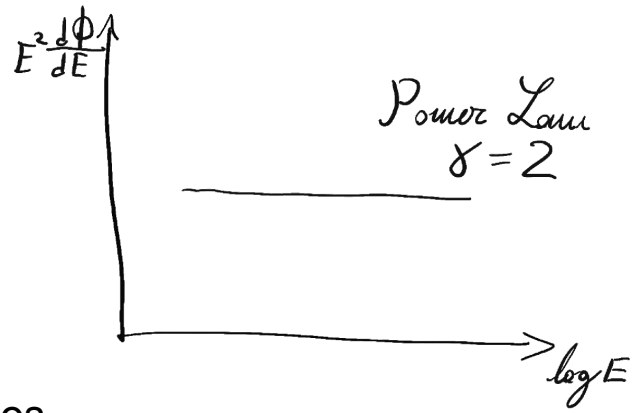


Takes into account:

- 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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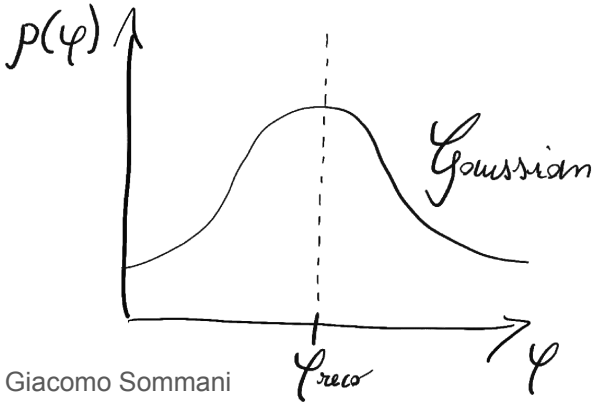
- Distance of the neutrinos from the source *S*
  - We assume gaussian neutrino point spread function



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

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

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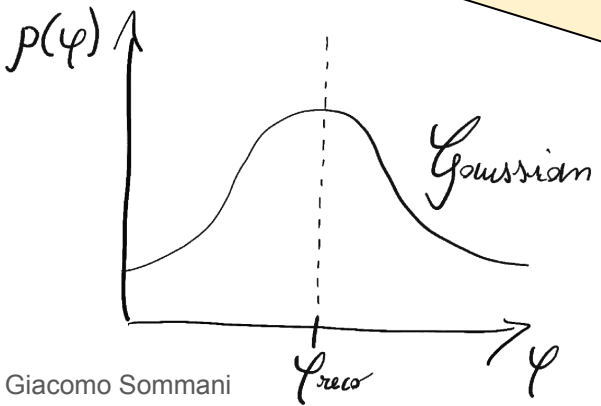

Per-doublet source selection

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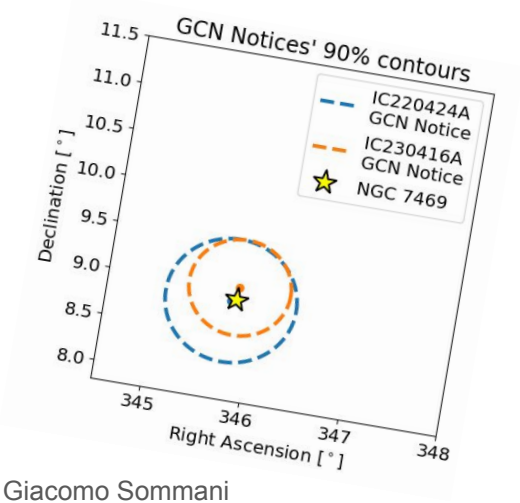
Which using all realtime alerts is our doublet!



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1. Scramble the alerts (generate random right ascensions)

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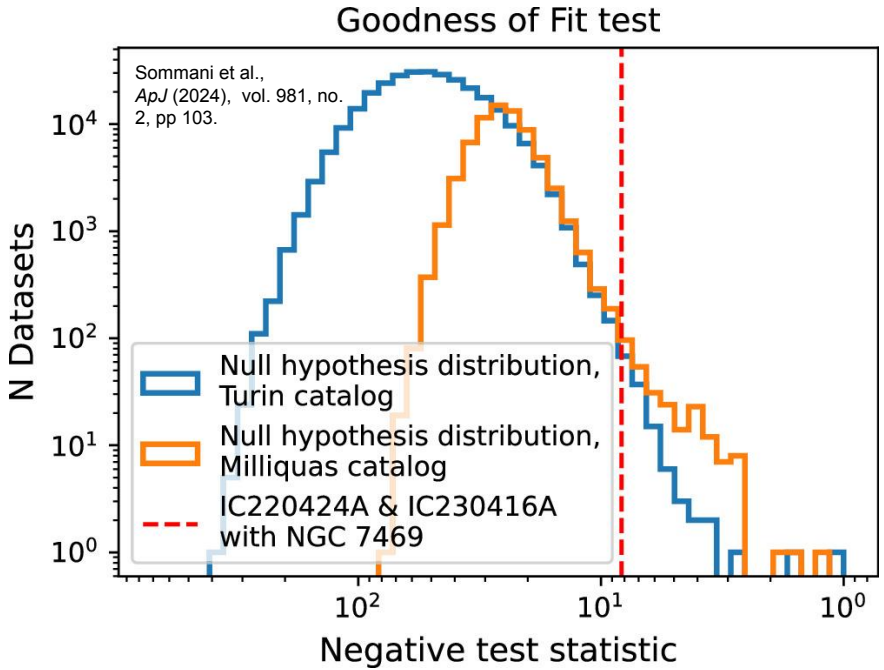
1. Scramble the alerts (generate random right ascensions)
2. Take the highest log-likelihood ratio for each scramble

Results

Results

test statistic = log-likelihood ratio

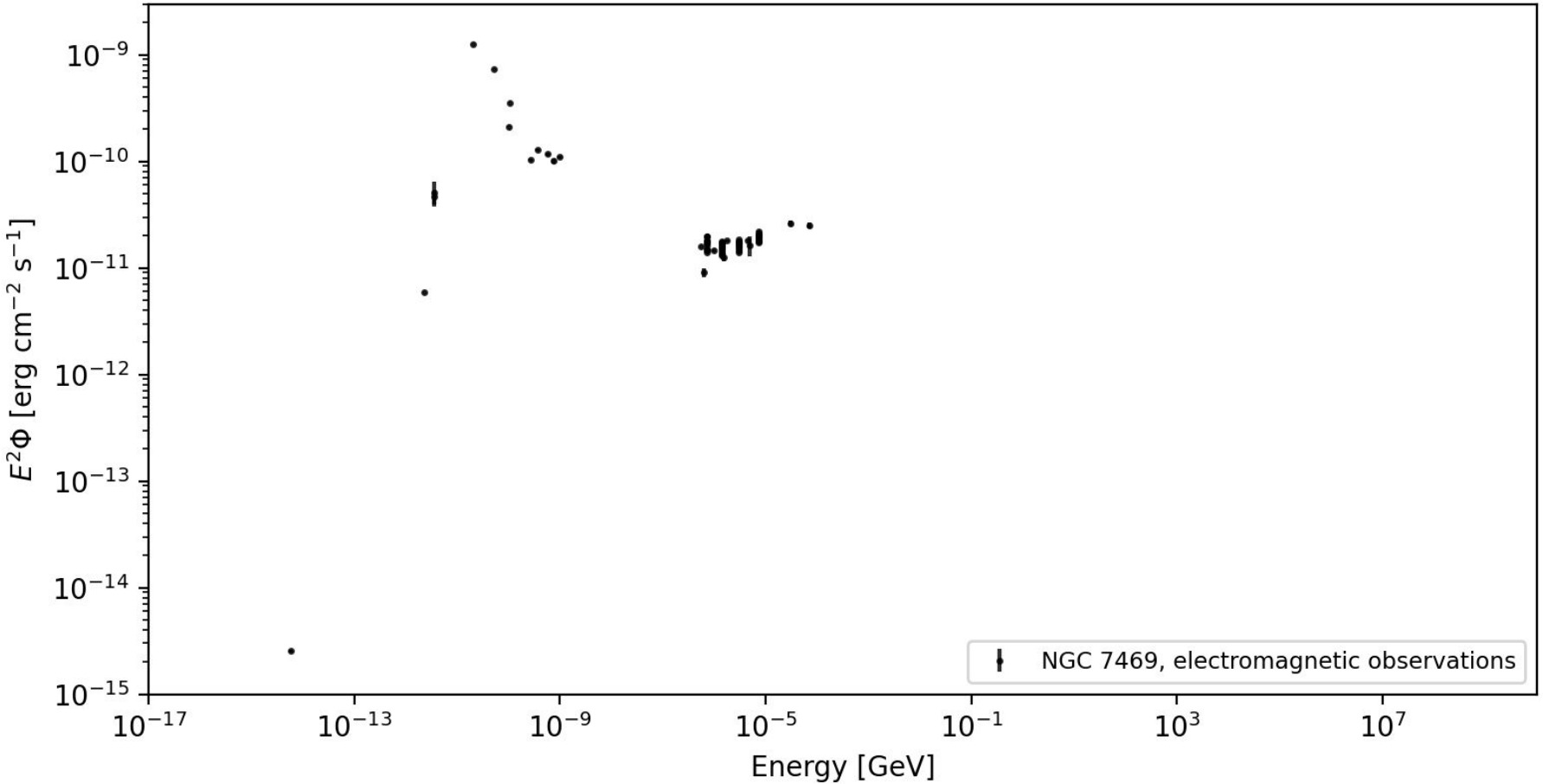


Turin (Seyferts): 3 × 10^5 scrambles
Milliquas (AGNs): 7 × 10^4 scrambles

Catalog	p-value	p-value (in σ)
Turin	4.0×10^{-4}	3.35
Milliquas	4.5×10^{-3}	2.61

Post-trial p-value: 3.16 σ

A look at the SED



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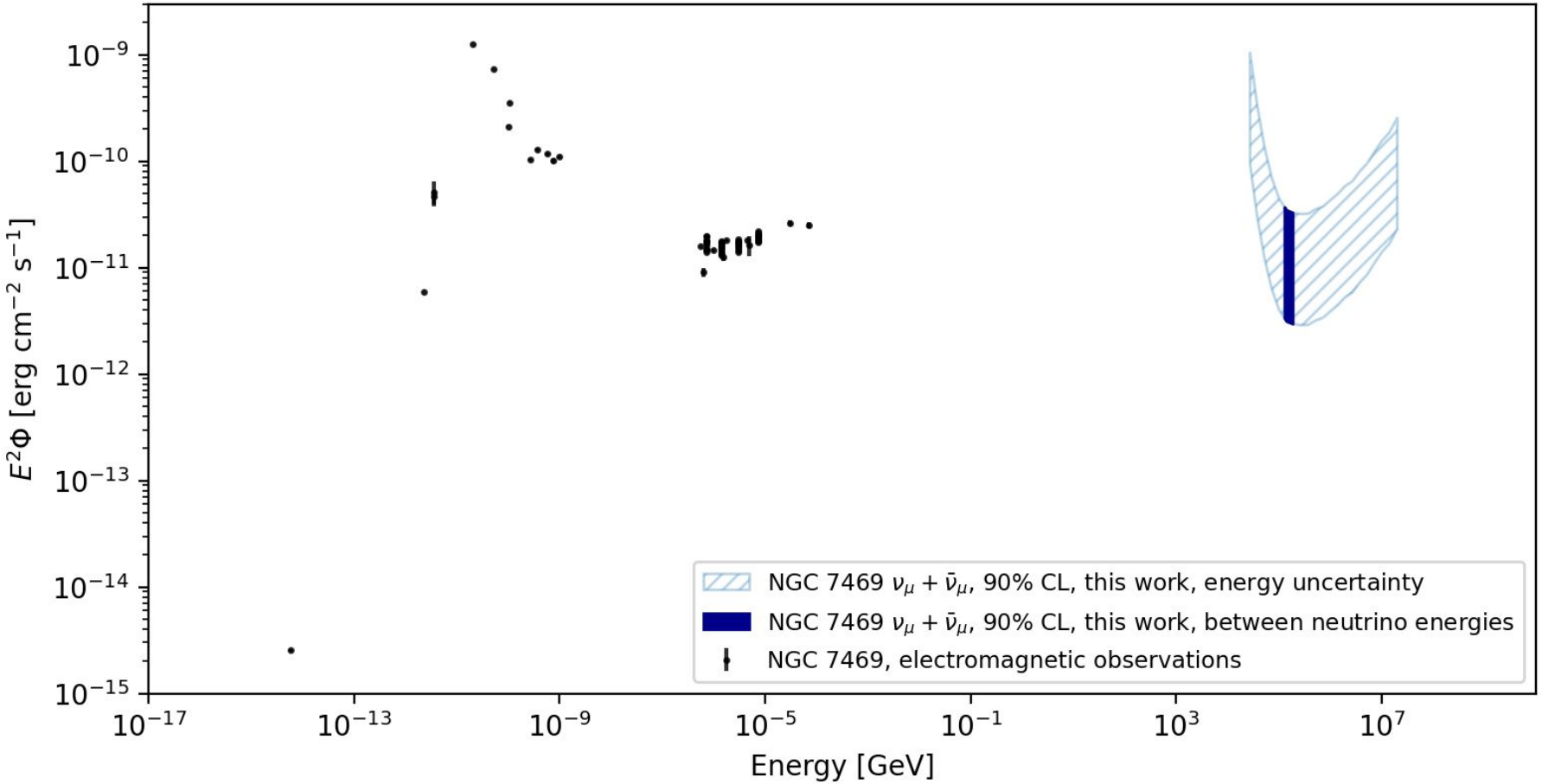
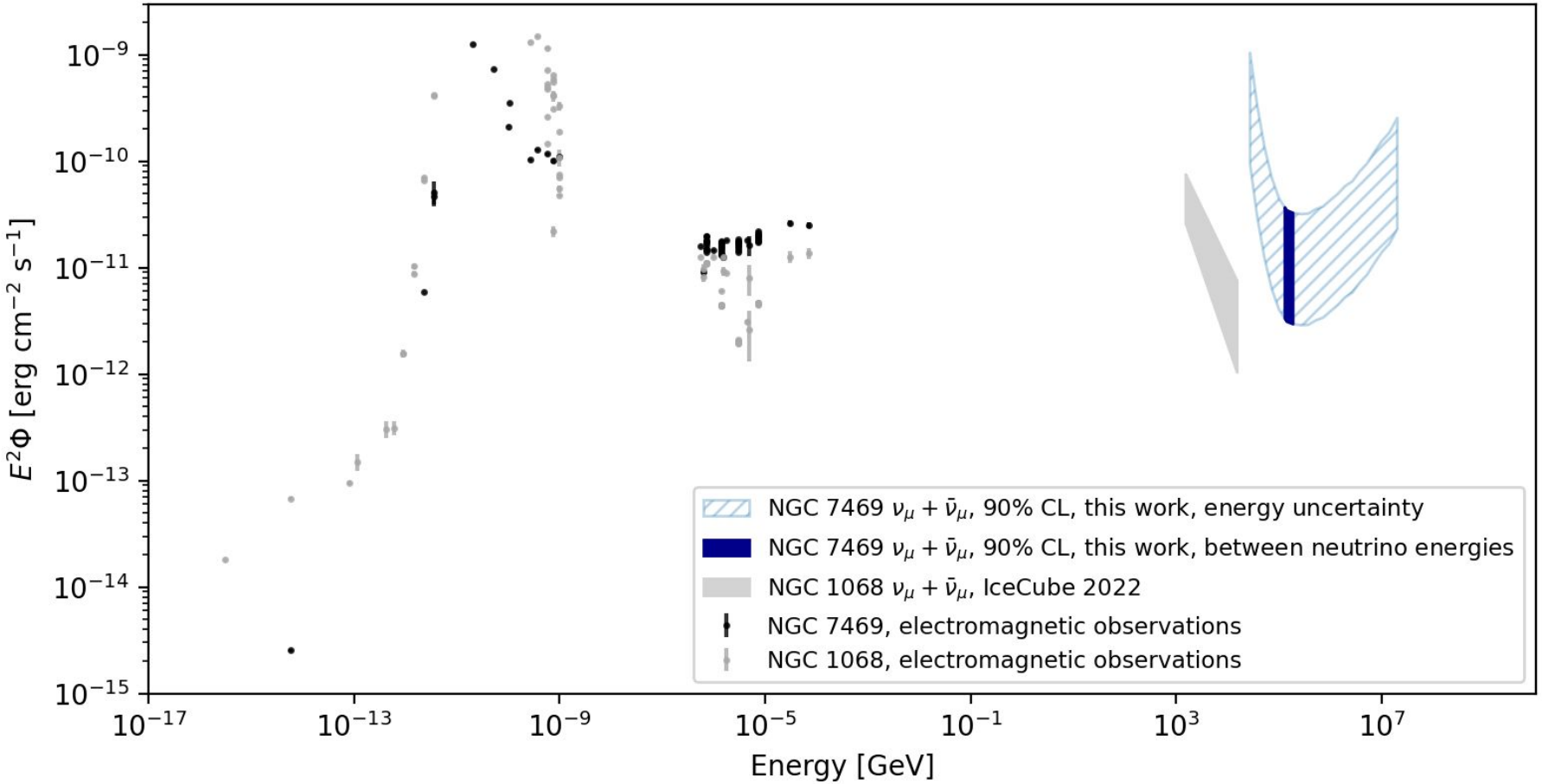
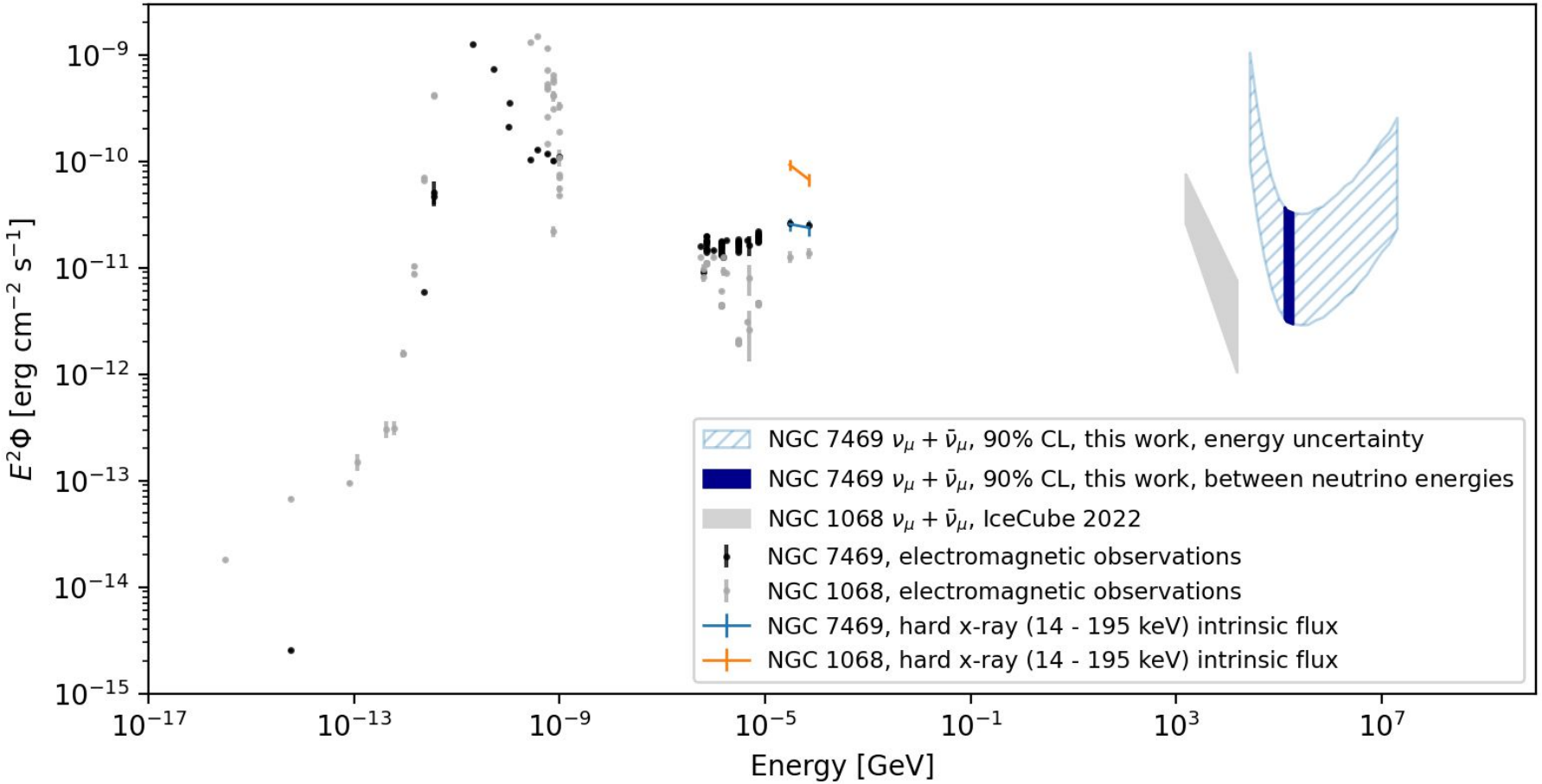


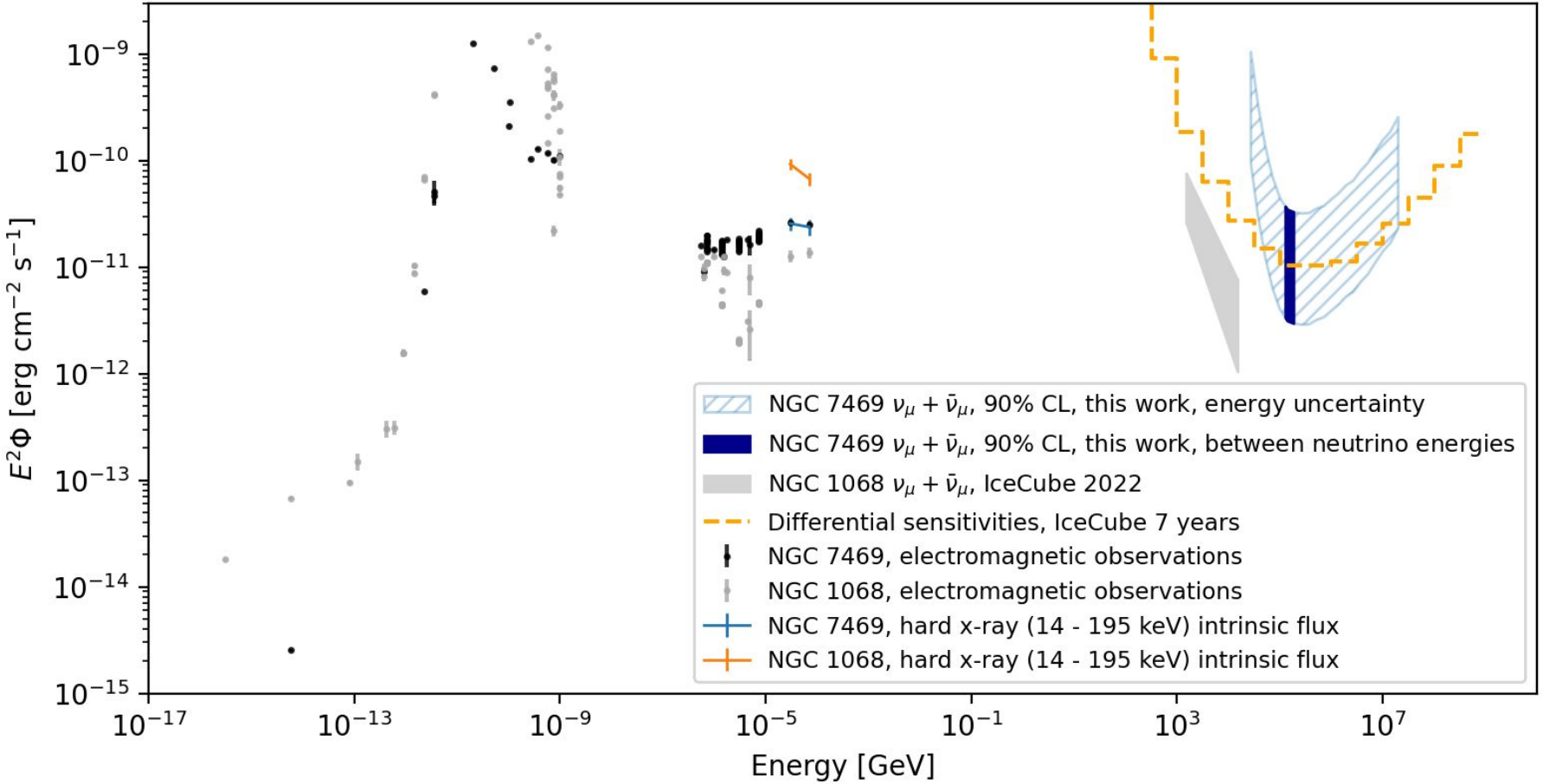
A look at the SED



A look at the SED



A look at the SED



Conclusions

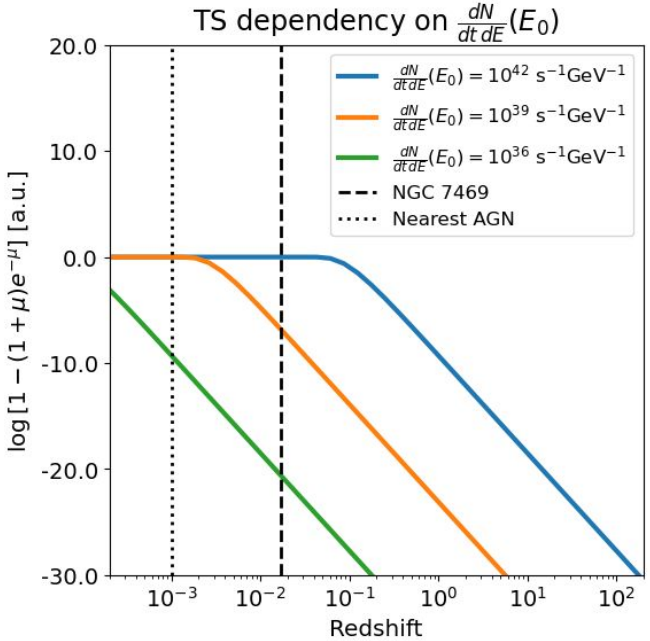
- **NGC 7469** inside the contours of **IC220424A** and **IC230416A**;
- Null hypothesis rejected with **3.2 σ**;
- **NGC 7469**'s neutrino flux at higher energies than **NGC 1068**;.
- Source never "observed" before in precedent IceCube analyses -> **emission must be peaked at high energies**
- Theoretical study requires a strongly non-uniform corona to explain neutrino emission (Talk today at **17:05 in GWMS by S. Salvatore** et al., PoS ICRC2025, 961)

Thank you for listening!

Backup slides

Intrinsic flux of sources choice

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



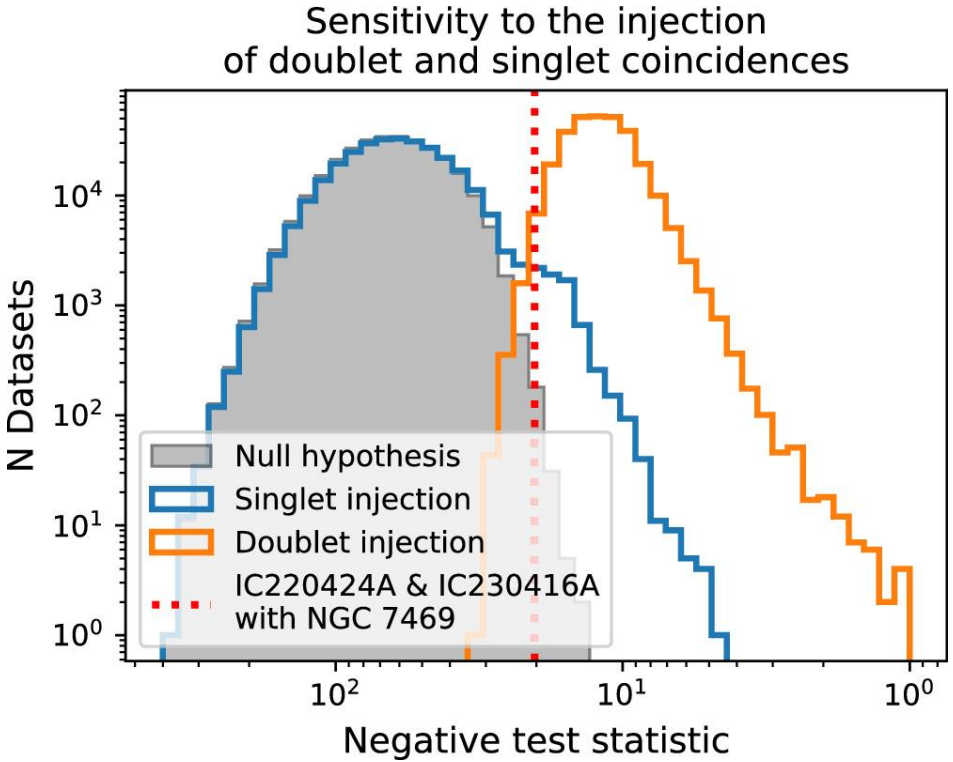
In the small-intrinsic-flux regime the outcome of the test is independent on the specific choice.

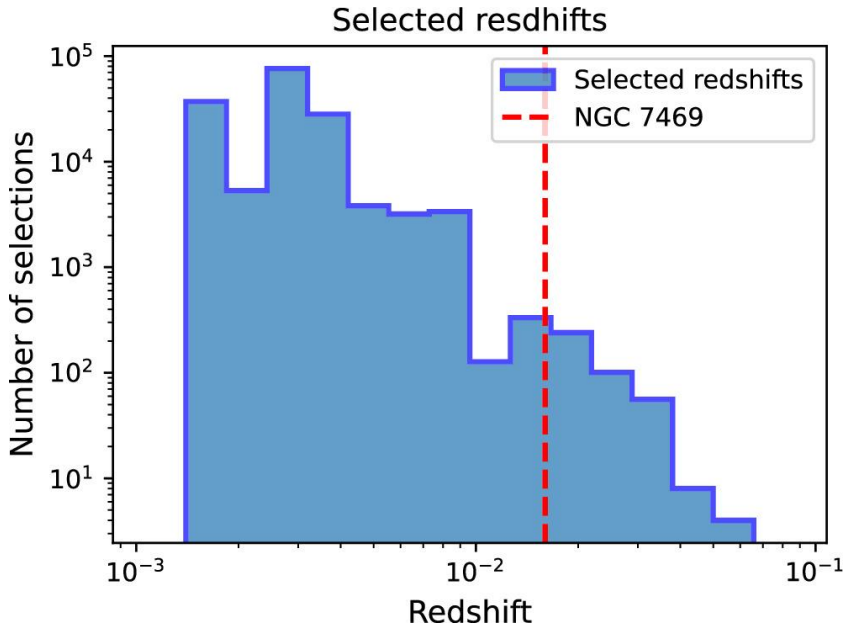
Complete test statistic

$$TS(A_i, A_j) = \max_S \left\{ \log\left[1 - (1 + \mu_S)e^{-\mu S}\right] - \left(\frac{\Omega_{Si}^2}{2\sigma_i^2} + \frac{\Omega_{Sj}^2}{2\sigma_j^2} \right) \right\} -$$

$$- 2\log(\sigma_i \sigma_j) - \log[\cos\theta_i \cos\theta_j] + 2\log(E_i E_j) - \log[\xi_k \zeta_k r_k(\theta_i, E_i) \xi_l \zeta_l r_l(\theta_k, E_k)].$$

Test: injecting doublets and singlets from sources





Redshift of the sources selected for the injection

Test: using X-ray fluxes as weight

Use intrinsic X-ray fluxes in the 14–195 keV energy band estimated by Ricci et al. ApJS (2017), V. 233, pp. 38.
Used only Turin catalog, 67 sources do not have a flux in that band (excluded).
Not consider in the main test of the analysis.

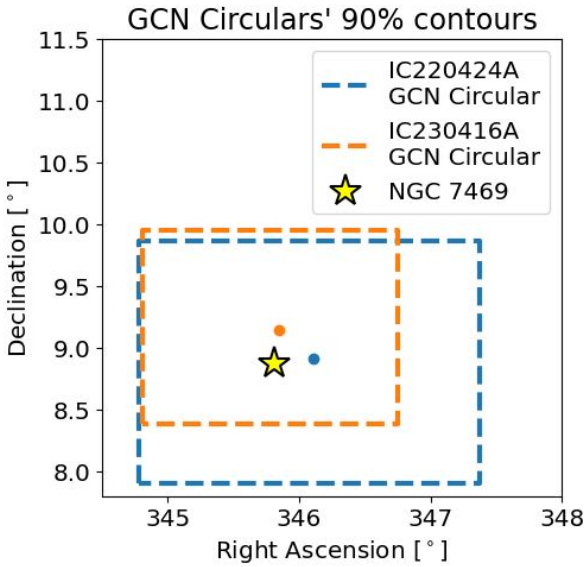
p-value	p-value (in σ)
2.4×10^{-4}	3.49

Test: using equal weights among all sources

Used only Turin catalog, the Milliquas catalog has a too high density of sources in the sky
Not consider in the main test of the analysis.

p-value	p-value (in σ)
5.9×10^{-4}	3.24

Test: using GCN Circulars' errors



Catalog	p-value	p-value (in σ)
Turin	3.7×10^{-2}	1.79
Turin (X-ray weight)	1.4×10^{-2}	2.20
Turin (equal weights)	2.3×10^{-2}	1.99
Milliquas	0.26	0.64

Test: varying the declination in the scrambles

Per-source shift sampled from uniform distribution between -x and x
Results not strongly affected

x [deg]	p-value	p-value (in σ)
0 (original)	4.0×10^{-4}	3.35
1	5.3×10^{-4}	3.27
2	7.6×10^{-4}	3.17
3	7.9×10^{-4}	3.16

Using IceCat-1 to estimate the neutrino flux

IceCat-1 has the reconstruction only from the GCN Circulars (Millipede). Therefore it could not be used in this analysis. However, we used it to check if in the past there were any further neutrinos coincident with NGC 7469.

A third neutrino is coincident, IC 190619A, but for this event the GCN Notice is available and not coincident with NGC 7469, therefore we have not taken it into account.

We re-estimated the flux taking into account 12 years of steady emission instead of 4.