TIME-DEPENDENT FLARE ANALYSIS WITH ANTARES AND KM3NeT/ARCA: GAMMA- RAY FOLLOW UP

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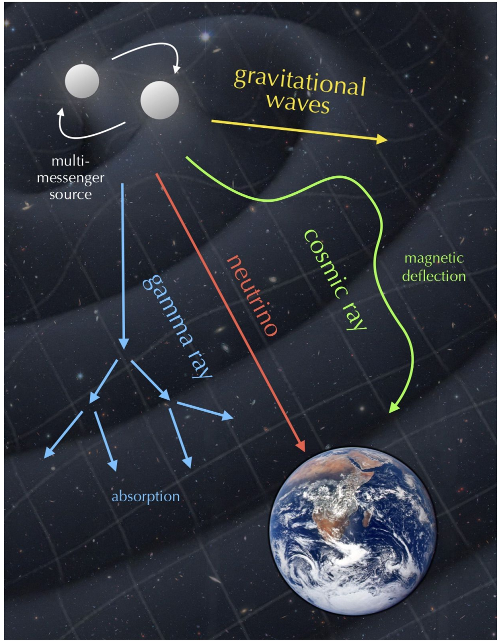
NEUTRINO EMISSION FROM GAMMA-RAY SOURCES

Photon and neutrino emission are expected to be correlated because both messengers can be produced through the same processes (Eq. 1).

$$
\begin{aligned}
&p + \gamma \rightarrow \pi^0(\pi^+) + p(n) \\
&\pi^0 \rightarrow \gamma\gamma \\
&\pi^+ \rightarrow \nu_\mu + \mu^+ \\
&\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+
\end{aligned}
$$

Eq 1: production chain of photons and neutrinos from cosmic rays

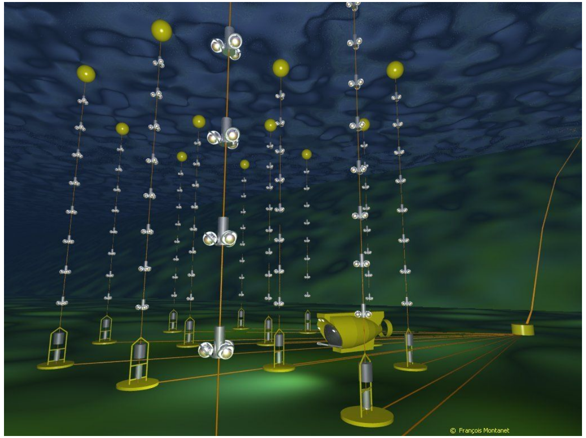


Credits to the Niels Bohr institute- Copenhagen

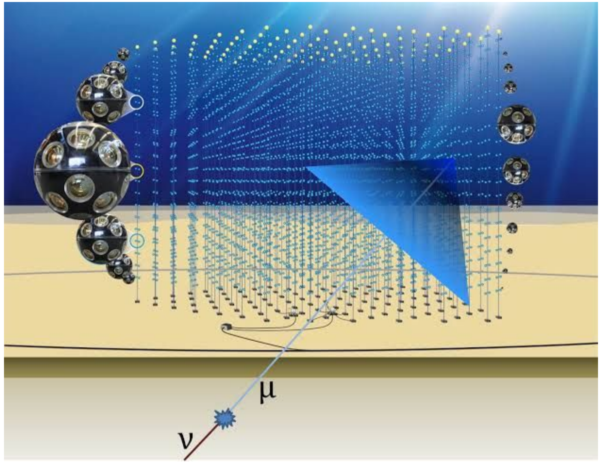
NEUTRINO TELESCOPES

Water cherenkov telescopes consist of a 3D array of optical modules that detect light produced by charged particles product of neutrino interactions.

ANTARES:
- Located at the coast of Toulon.
- 12 lines with 25 floors formed by optical modules (OMs).
- Operated for 15 years (2007-2022).



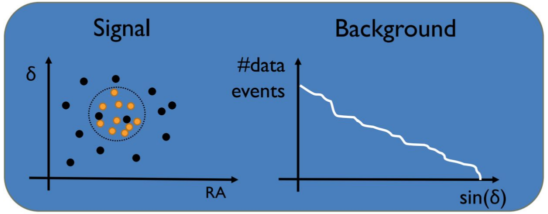
KM3NeT/ARCA:
- Located 100 km from the coast of Portopalo di Capo Passero (Sicily).
- This analysis uses the dataset obtained with 21 operating lines(ARCA21).

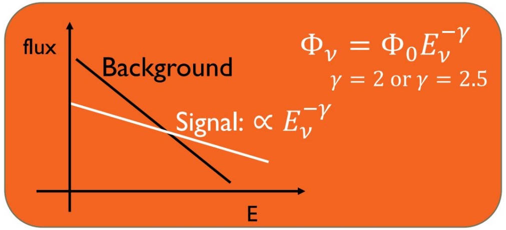


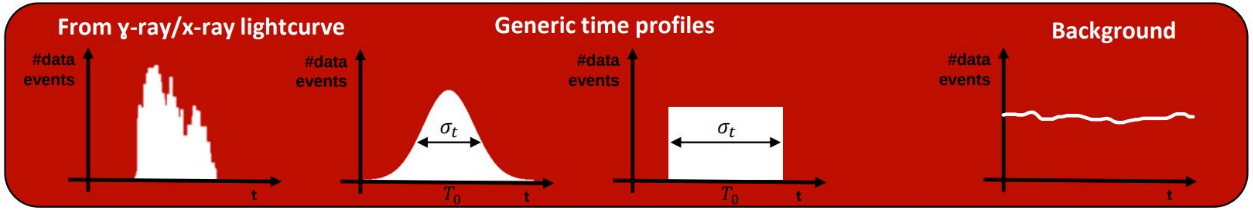
UNBINNED LIKELIHOOD ANALYSIS

Unbinned searches consider the contribution of each event within a given region of the sky and define a likelihood function based on the expected properties of signal and background events.

$$L(n_s) = \prod_{i=1}^{N} (\frac{n_s}{N}) \cdot S + (1 - \frac{n_s}{N}) \cdot B = \prod_{i=1}^{N} ((\frac{n_s}{N}) \cdot P_{sg}(\alpha|E) P_{sg}(E) P_{sg}(t) + (1 - \frac{n_s}{N}) P_{bkg}(\delta) P_{bkg}(E) P_{bkg}(t))$$

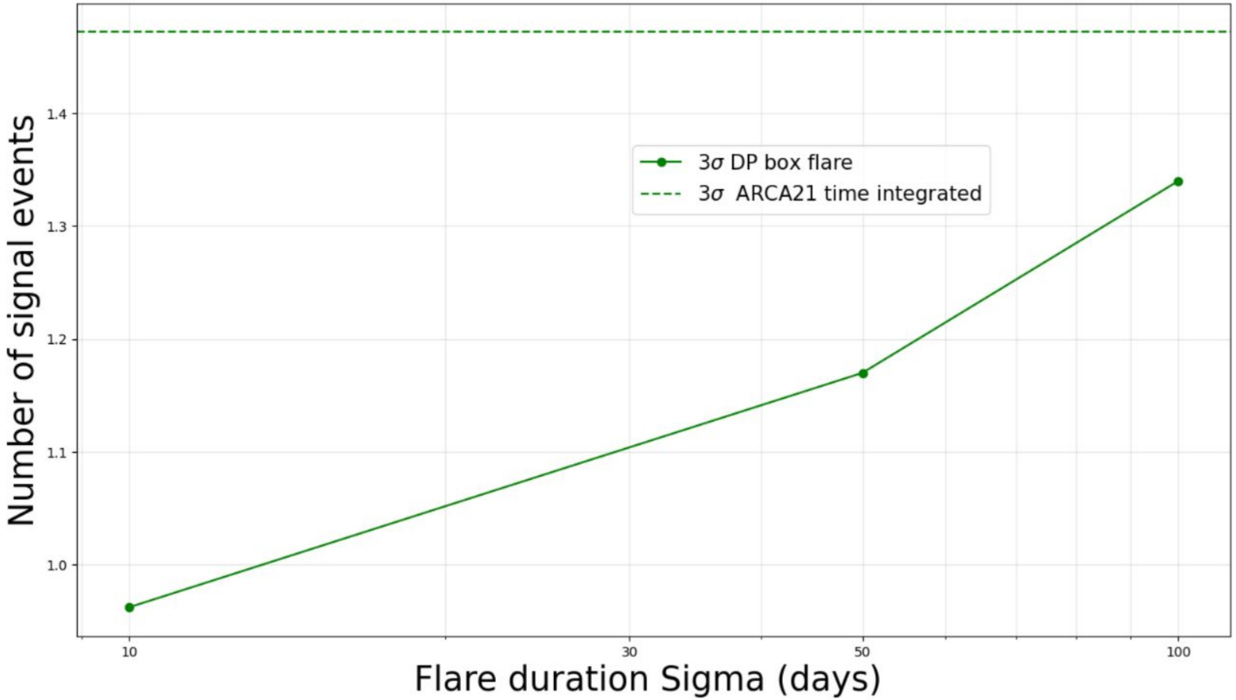






TIME-DEPENDENT ANALYSIS

Time-dependent analyses benefit of a more reduced background than time-integrated searches as the signal is expected only during well defined periods of time.



EVENT SELECTION

To reduce the contamination of atmospheric muon and neutrino in the dataset the following selections are applied for each detector

ANTARES (TRACKS):

- Track-fit quality parameter(Λ) >-5.2.
- Reconstructed energy > 39.8 GeV.
- Angular resolution error < 1°.

ANTARES (SHOWERS):

- Shower Score > 0.3.
- Likelihood > 50.
- Upgoing/slightly horizontal.
- Angular resolution error <10°.

ARCA21 (TRACKS):

- Track length > 100 m.
- Reconstructed energy >100 GeV.
- Likelihood > 63.
- Track BDT score > 0.996.
- Angular resolution error< 0.005°.
- Upgoing/slightly horizontal.

SOURCES SELECTED

Sources were selected from the Fermi-LAT 16-year Source List filtering over the following criteria:

- Type of source: either BL Lac, Flat Spectrum Radio Quasars(FSRQ) blazars, or an active galaxy of an uncertain type.
- Declination below 40 degrees.
- Integral photon flux > 10^{-10} photons □ cm^2 □ s
- Variability > 41.42 for 12 intervals.
- Detection significance > 85σ.

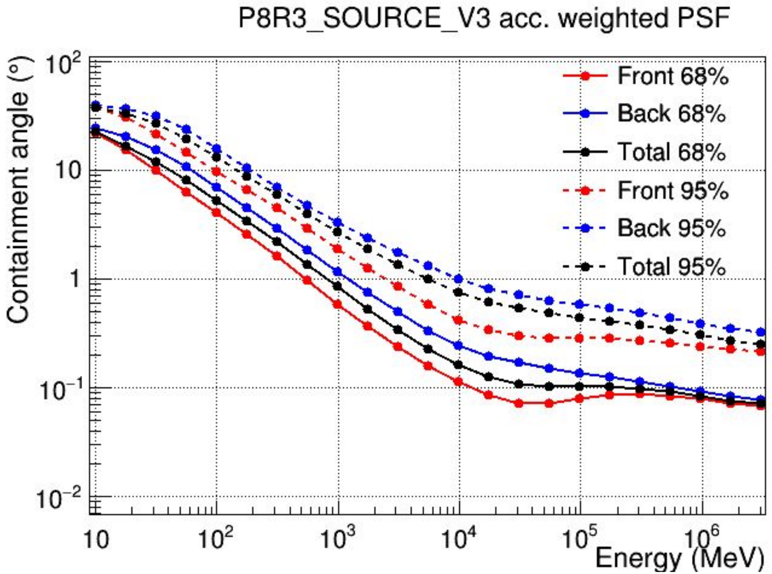
As a result: **50** sources selected.

TIME INTERVAL CONSIDERED

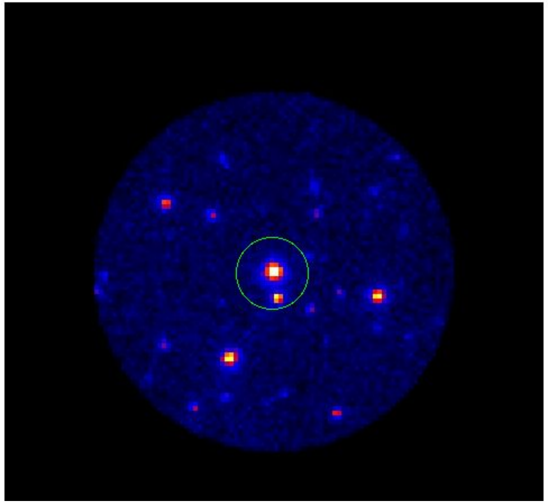
The analyzed data periods are:

- ANTARES: From 01/2007 to 02/2022: **40** sources with flares contained in the interval.
- ARCA21: From 09/2022 to 09/2023 : **14** sources with flares contained in the interval.

10 sources had their selected flares in days in which the detectors were not operational.



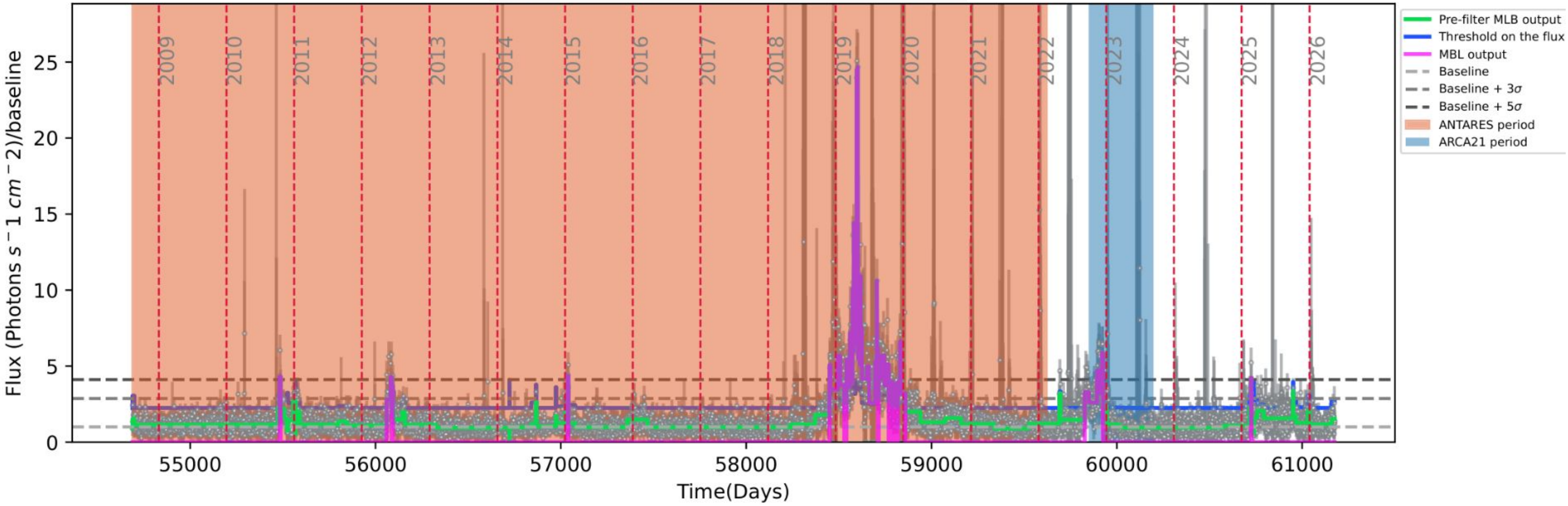
Source: Fermi-LAT Performance after 10 years of operation.



PKS 0208-512 as seen by Fermi LAT

Time signal hypothesis

The time signal distribution is built using maximum block likelihood (MBL) method (Scargle et al).



Light curve for PKS 1830-211

ANALYSIS METHODOLOGY

- A set of pseudo-experiments (PEXs), with signal events simulated during flaring periods, is generated.

- The unbinned likelihood is evaluated using a test statistic (TS) defined in terms of the likelihood ratio.

$$TS = -2\log\left[\frac{L(n_s = 0)}{L(\hat{n}_s)}\right]$$

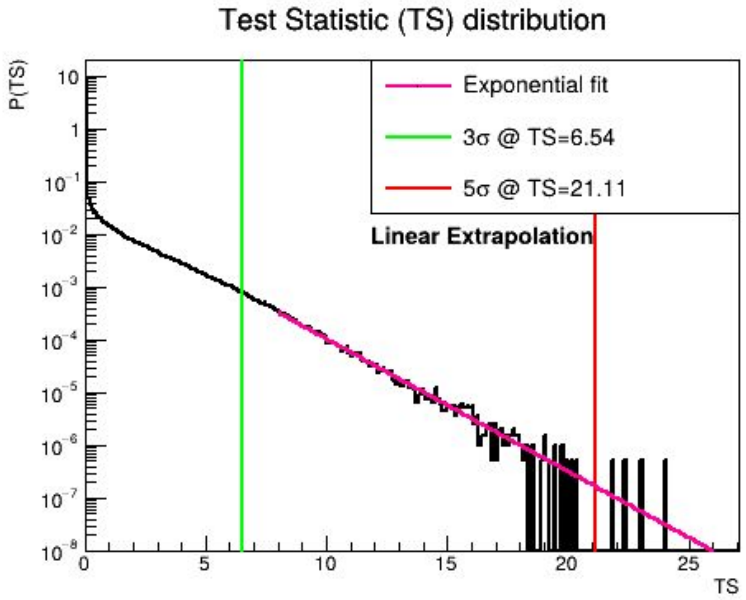
Likelihood under the background-only hypothesis

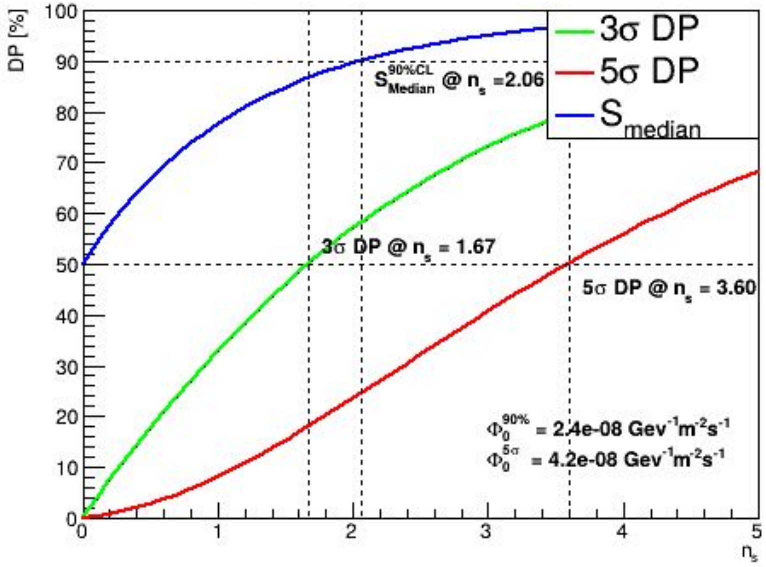
Likelihood under the background + signal hypothesis

- Background events are taken directly from data.

ANALYSIS METHODOLOGY

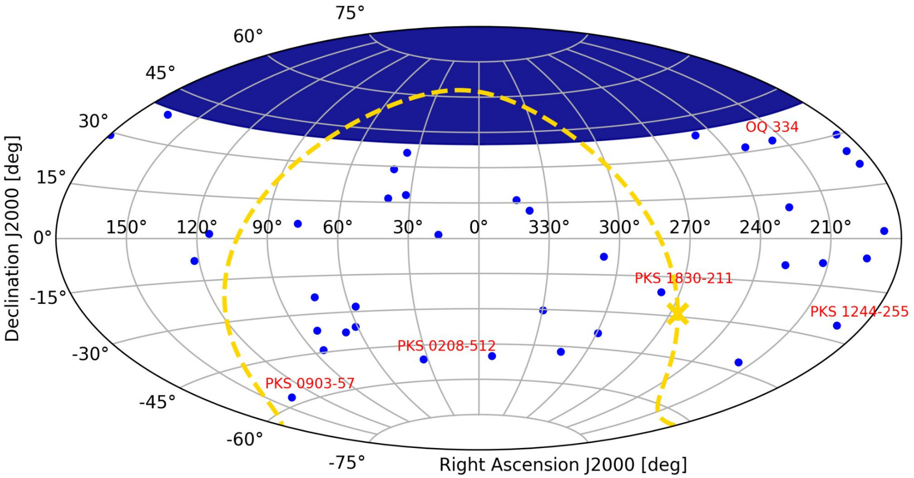
After PEX were performed for each of the sources studied, a fit for the Background TS was obtained on each case.





RESULTS

Collecting data during the selected flaring periods the p-trial value was calculated for each source.



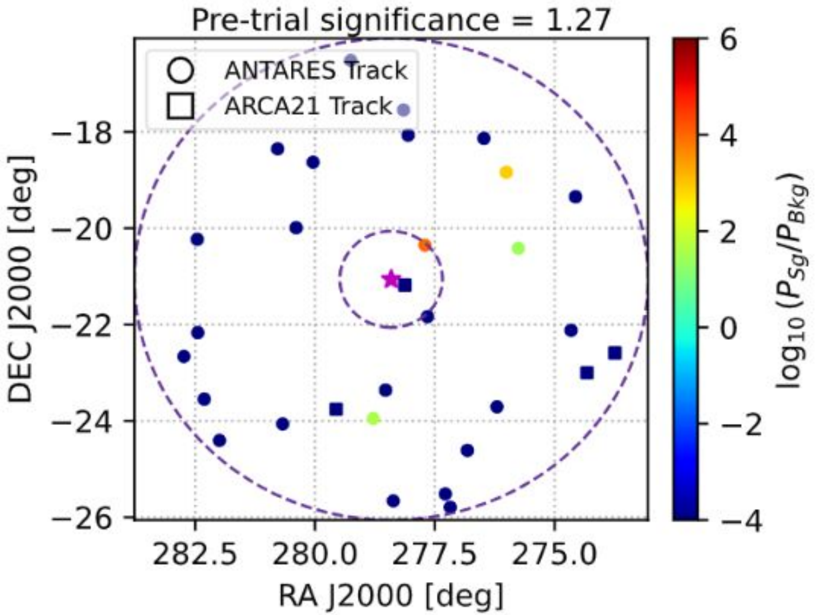
Source name	$\delta[°]$	$\alpha[°]$	Dur [d]	$\hat{\mu}_{\text{sig}}$	p-value (pre-trial)	$\mathcal{F}_\nu^{90\%\text{C.L.}}$
OQ 334	32.38	215.64	94	< 1	**0.0311**	3.27
PKS 1830-211	-21.06	278.41	432	< 1	**0.0411**	5.00
PKS 0903-57	-57.58	136.23	111	< 1	**0.0842**	2.18
PKS 0208-512	-51.02	32.70	184	< 1	**0.1017**	1.92
PKS 1244-255	-25.80	191.69	10	< 1	**0.1369**	6.79

RESULTS

For the sources with the lowest p-value on the pre-trial a sky map showing the data events within 5°of them is created.

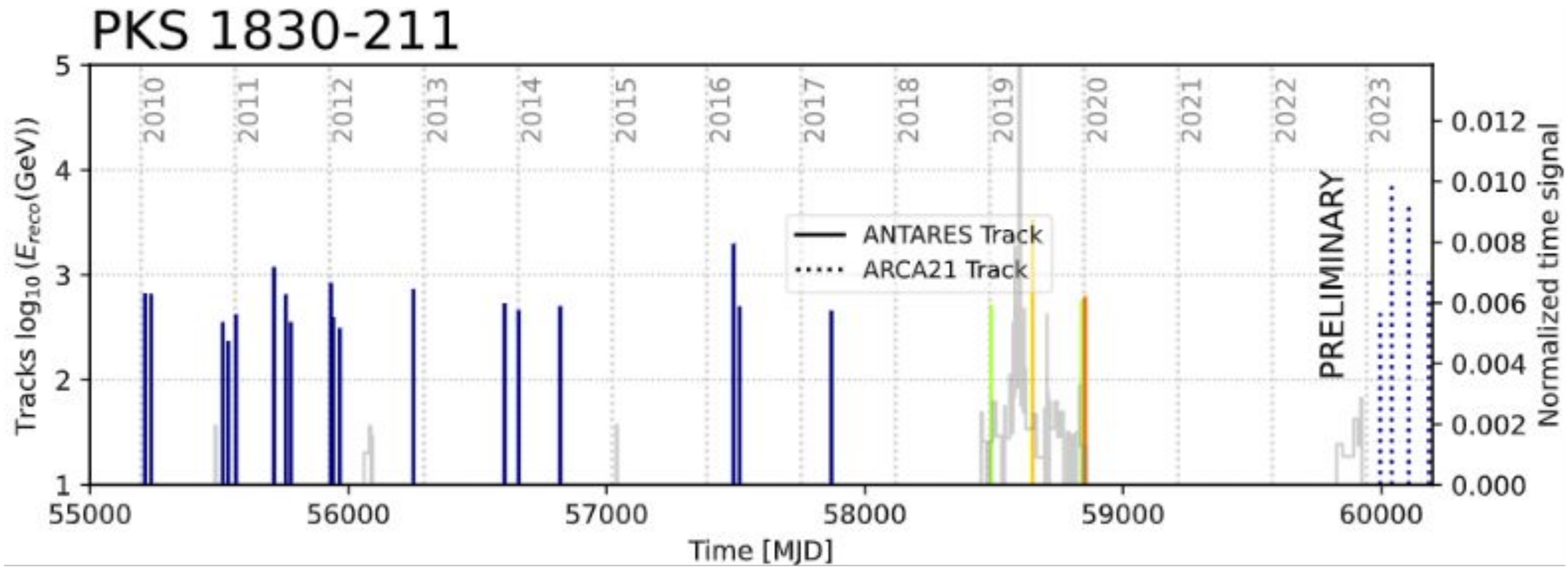
PKS 1830-211

PRELIMINARY

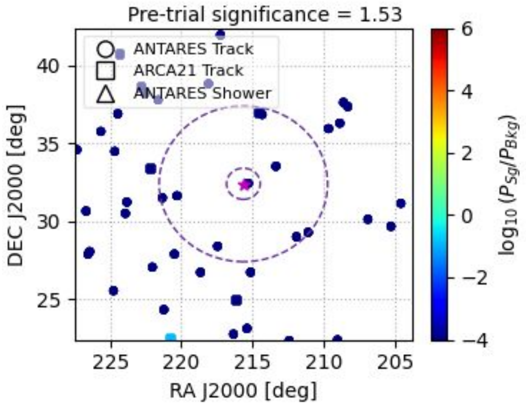


RESULTS

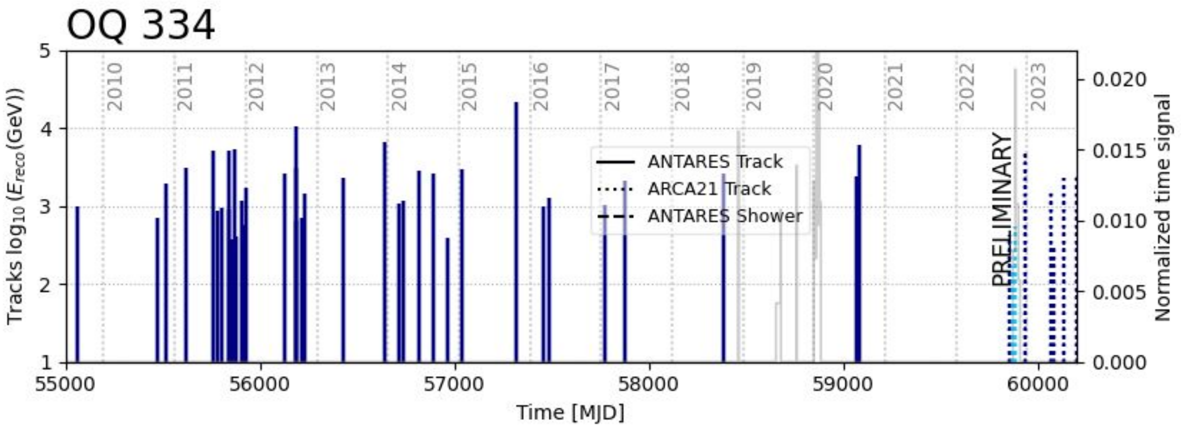
The detection time of the tracks is also displayed among the shape of the time signal hypothesis.



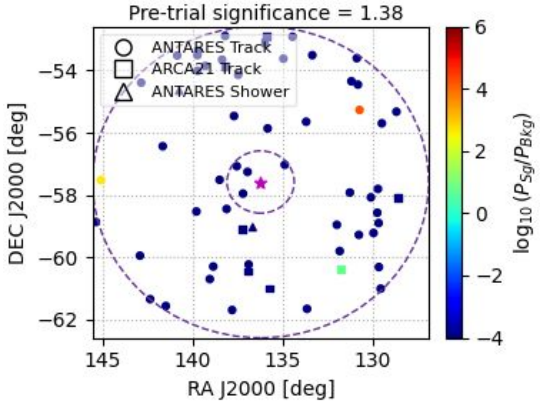
RESULTS



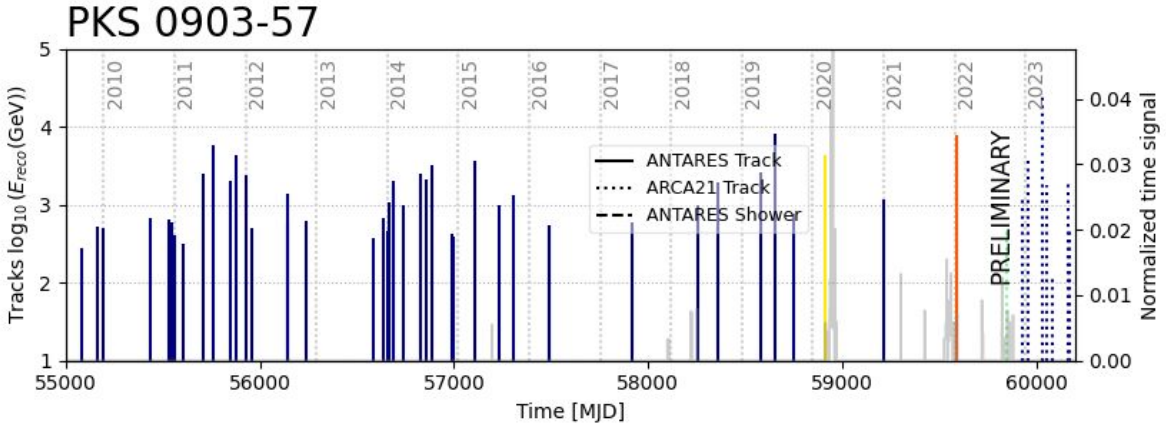
Pre-trial significance = 1.53
ANTARES Track
ARCA21 Track
ANTARES Shower
DEC J2000 [deg]
RA J2000 [deg]
$\log_{10}(P_{Sg}/P_{Bkg})$



OQ 334
Tracks $\log_{10}(E_{reco}(\mathrm{GeV}))$
Time [MJD]
Normalized time signal
ANTARES Track
ARCA21 Track
ANTARES Shower
PRELIMINARY

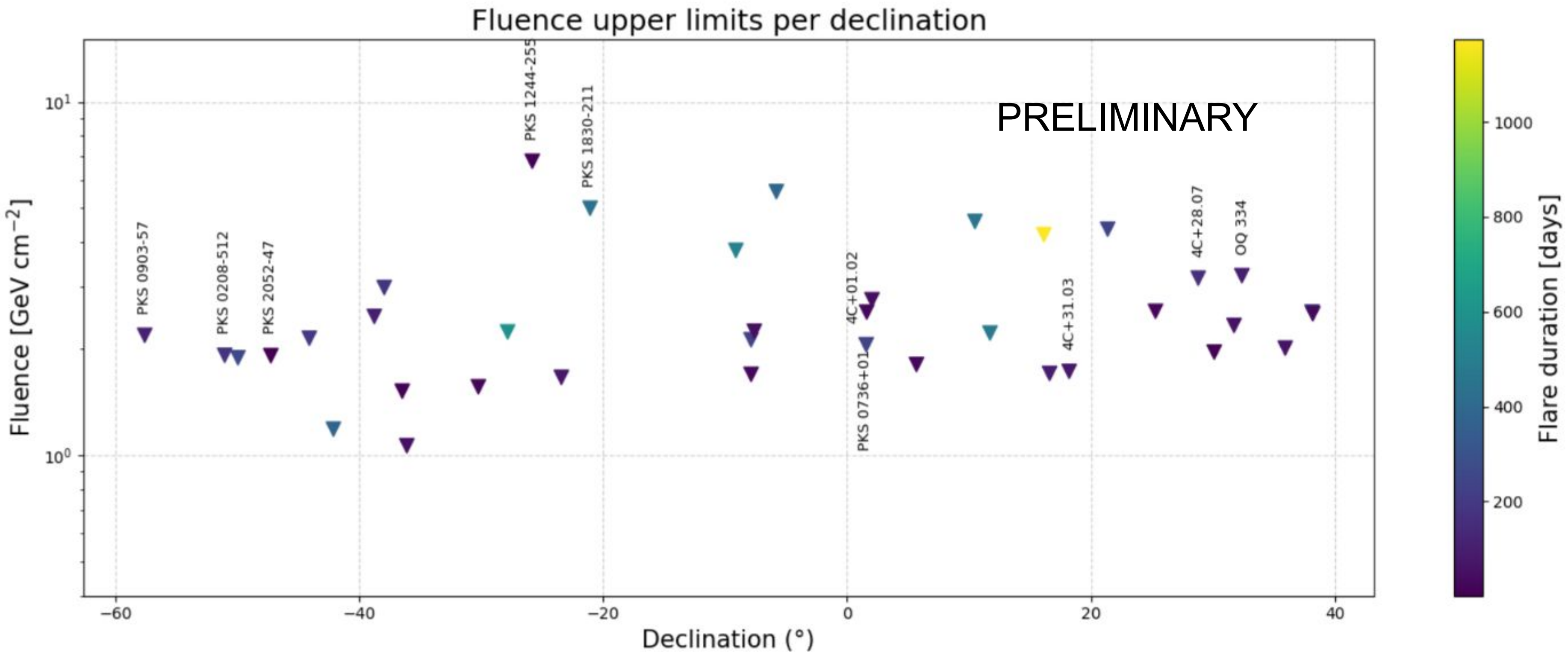


Pre-trial significance = 1.38
ANTARES Track
ARCA21 Track
ANTARES Shower
DEC J2000 [deg]
RA J2000 [deg]
$\log_{10}(P_{Sg}/P_{Bkg})$



PKS 0903-57
Tracks $\log_{10}(E_{reco}(\mathrm{GeV}))$
Time [MJD]
Normalized time signal
ANTARES Track
ARCA21 Track
ANTARES Shower
PRELIMINARY

SOURCES FLUENCES



CONCLUSIONS

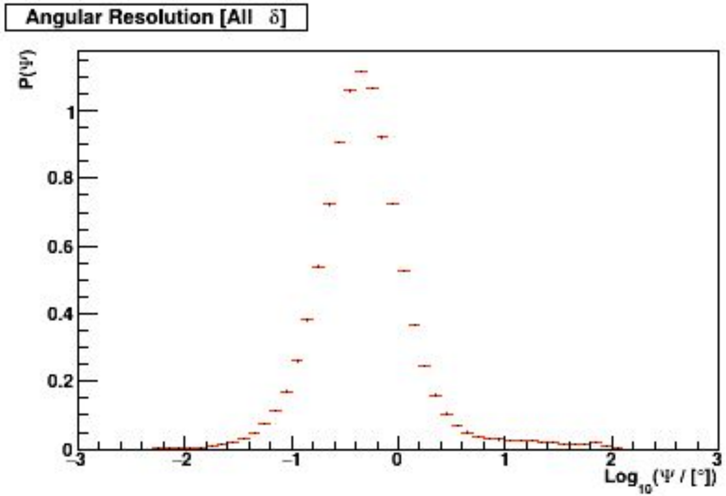
- An ANTARES-KM3NeT combined analysis assuming a time dependent signal hypothesis has been performed for the first time.

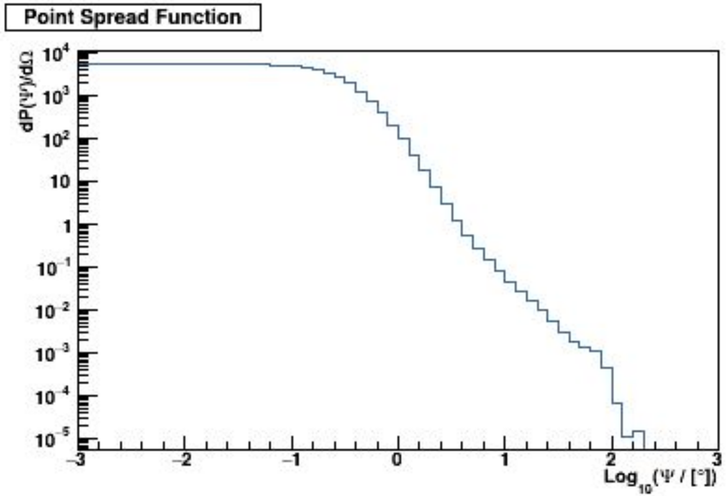
- No significant detection has been found in coincidence with the flaring periods selected for the study.

- Upper limits on the fluences for the studied sources were computed with the available data.

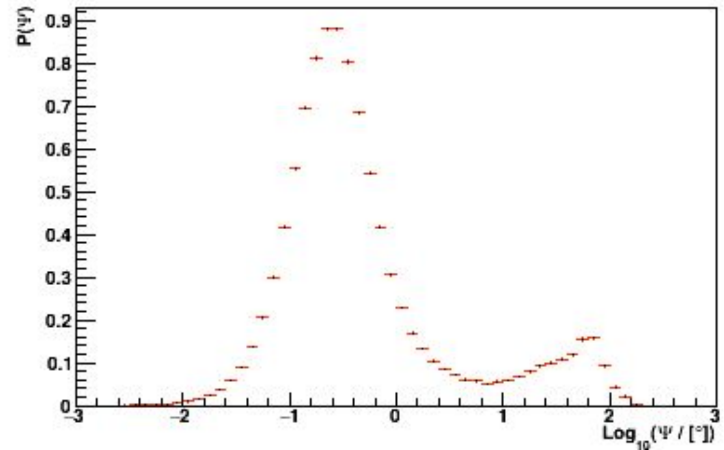
THANK YOU!

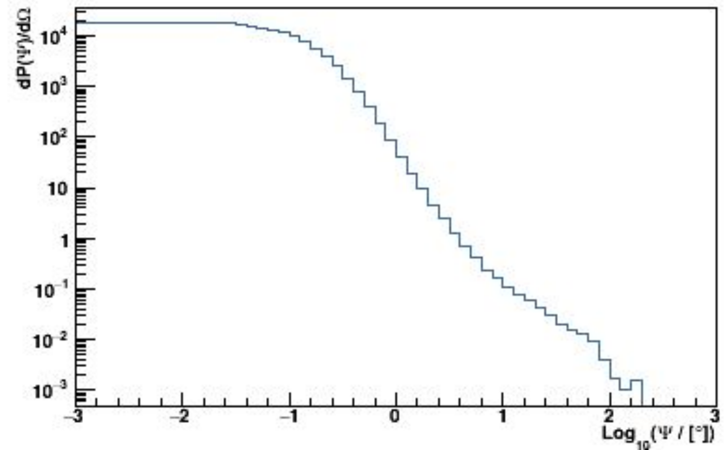
SPACE DISTRIBUTIONS





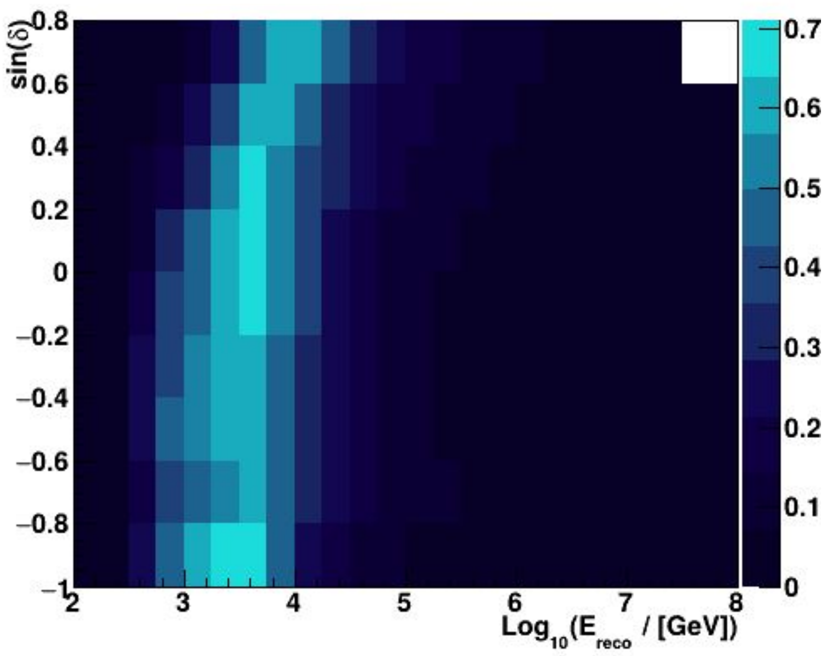
ANTARES



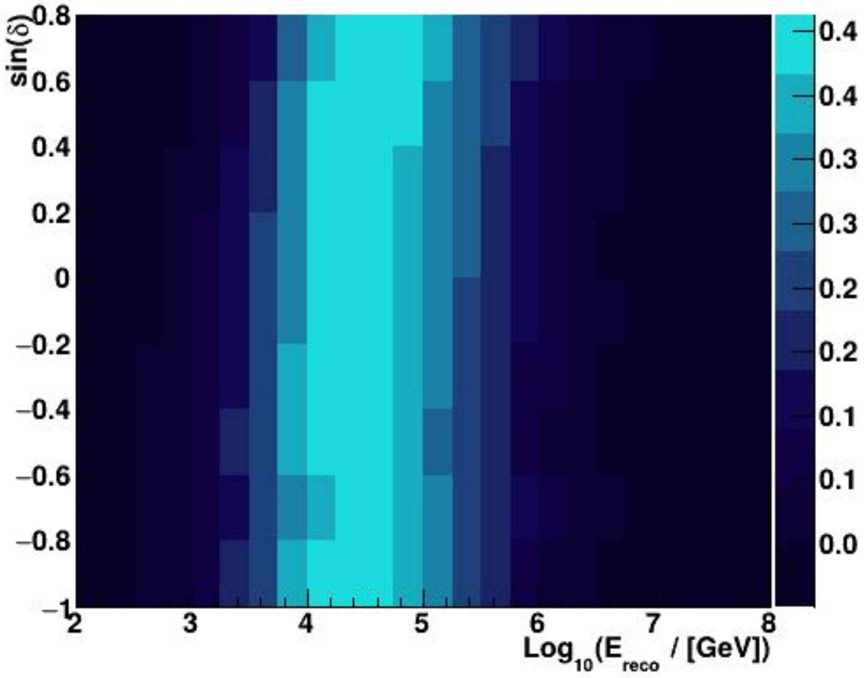


ARCA21

ENERGY DISTRIBUTIONS

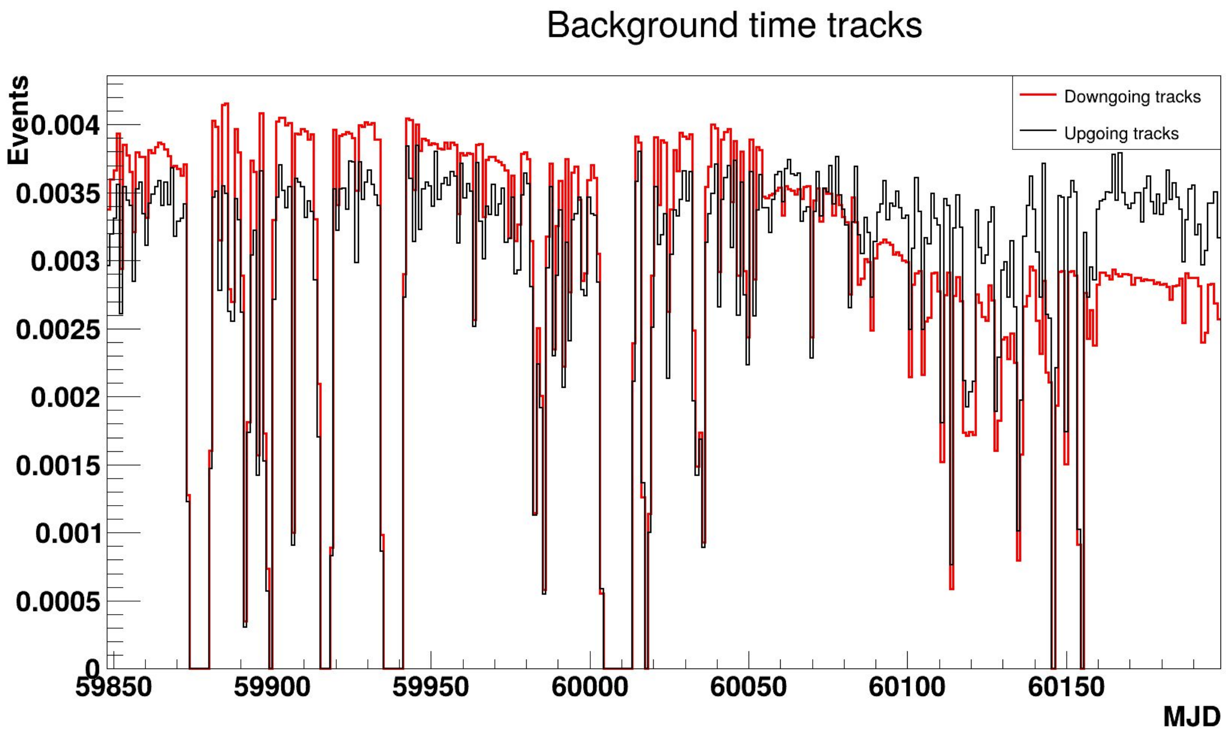


dE/dX estimator for
ANTARES



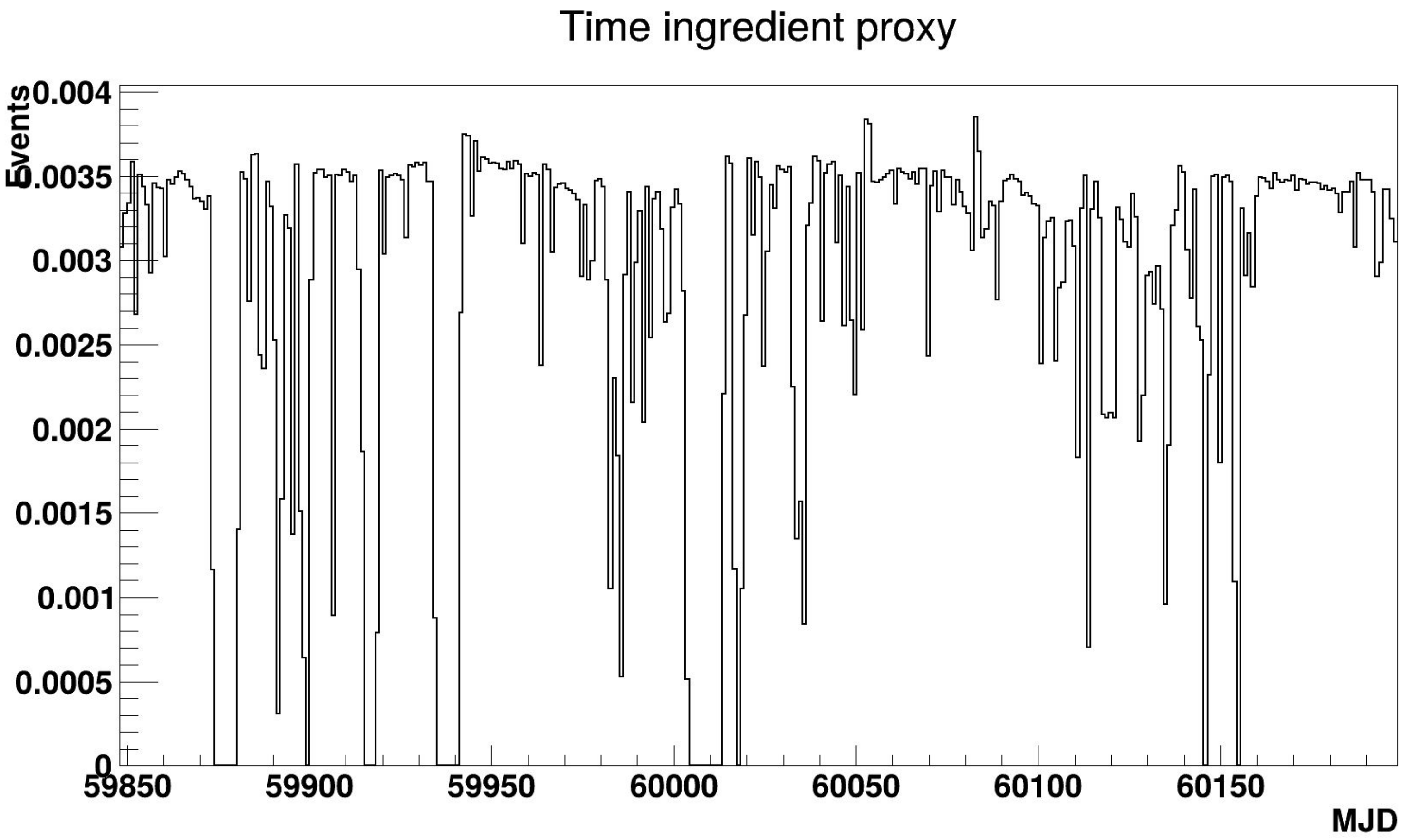
Ereco estimator for
ARCA21

BKG TIME DISTRIBUTION



Background time upgoing and downgoing tracks PDF for ARCA 21. It is possible to see that there is a discrepancy between the rate of upgoing and downgoing tracks towards the end of the detection period

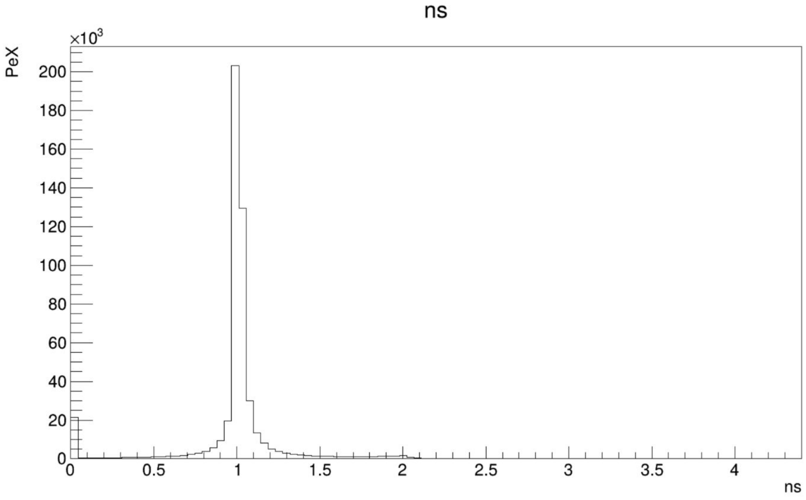
BKG TIME DISTRIBUTION

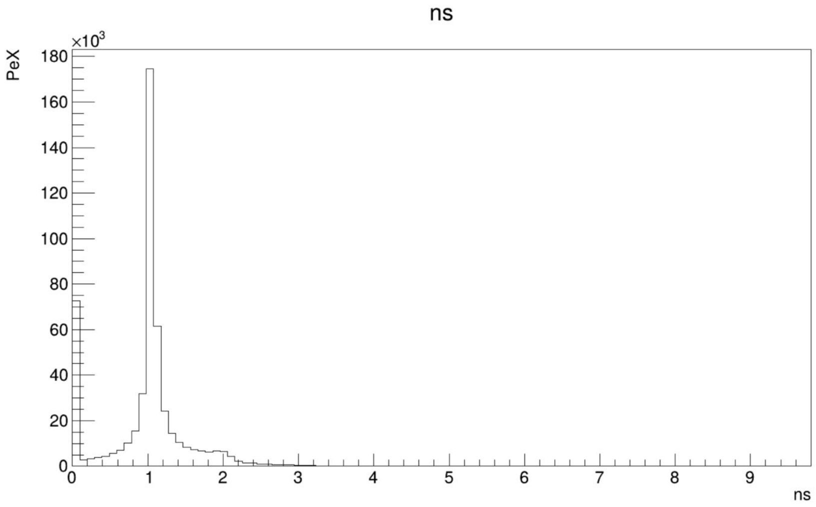


PSEUDOEXPERIMENTS

Using the ingredients for signal and background a set of 500k pseudoexperiments (PeX) was done for each type of source studied for the flares (box and PS).

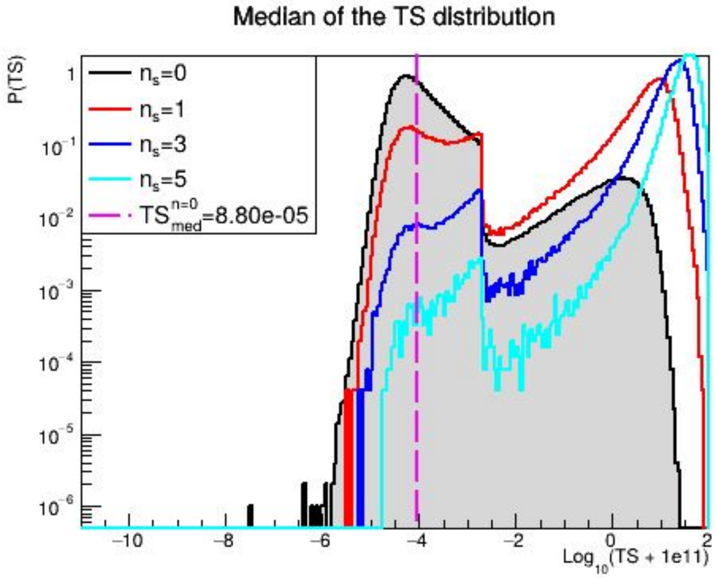
From these, a test statistic and fitted signal was obtained for each set of Pex for each given source.

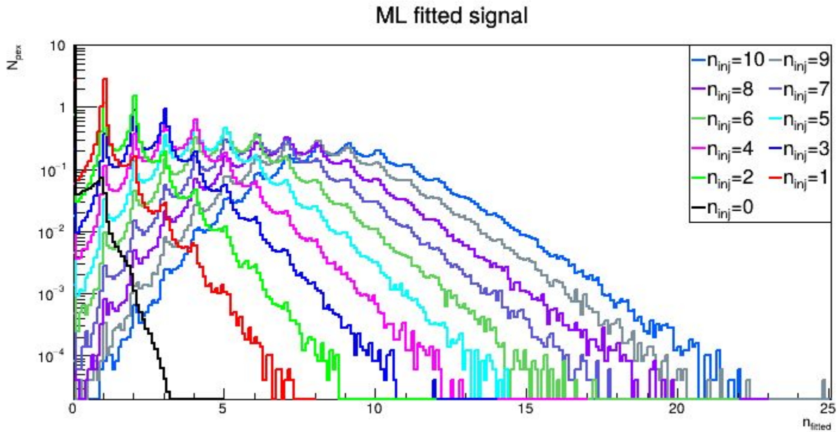




Example of fitted signal for n=1 injected signal over 500k PeX for a 30 days box flare (left) and for CTA102 (right). Both cases correspond to ANTARES and ARCA21 joint.

FITTED SIGNAL





TS distributions for all the cases of injected signal for PKS 1830-211.

Median of the distribution of the Log10(TS) for N=0, 1, 3 and 5 (Left), on the N=0 curve the median is indicated by a vertical line.

DENOISING: MAXIMUM BLOCK LIKELIHOOD(MLB)

The likelihood is assumed as a normal distribution of the flux measurements with their errors as a variance; so each point contributes as:

$$L_i = \frac{1}{\sqrt{(2\pi)}\sigma_i} e^{\frac{-(x_i-\lambda_b)^2}{2\delta_i^2}}$$

Where λ_B is the actual flux during that block, so a given block n_b has a contribution to the likelihood of the form:

$$ln(L_{nb}) = \sum_{i \in n_b} \rho_i (x_i - \lambda_b)^2$$

DENOISING: MAXIMUM BLOCK LIKELIHOOD(MLB)

The likelihood is maximized in each block by setting to 0 the derivative of the logarithm with respect to the flux, giving:

$$\lambda_B^{max} = \sum_{i \in n_b} \rho_i x_i / \sum_{i \in n_b} \rho_i$$

Which after substituting the expression for λ_B into the log likelihood function and summing over all blocks gives:

$$ln(L) = \sum_{n_b}^{N_B} \frac{\sum_{i \in n_b} (\rho_i x_i)^2}{\sum_{i \in n_b} \rho_i}$$

DENOISING: MAXIMUM BLOCK LIKELIHOOD(MLB)

To determine the number of blocks that are associated with the change points of the curve a prior function is needed, so far the one selected is based on a work by scargle (2013) in which an empirical expression for the number of blocks is found:

$$ncp_{prior} = 4 - log(73.53 p_0 N^{-0.478})$$

This search for change points and prior function is implemented in an astropy library called bayesian blocks.

DENOISING: BASELINE FIT

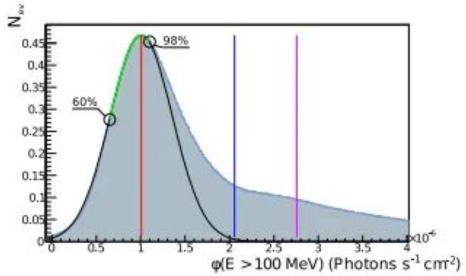
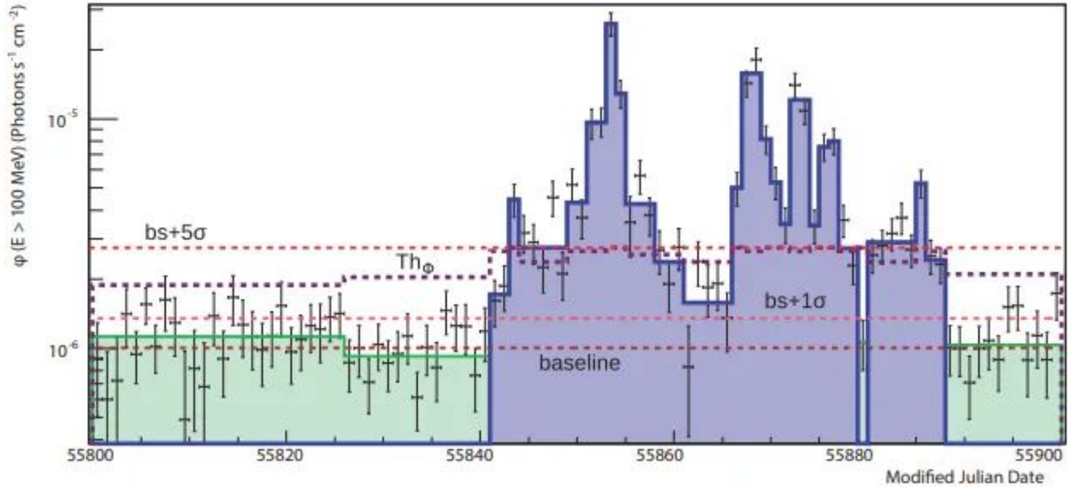
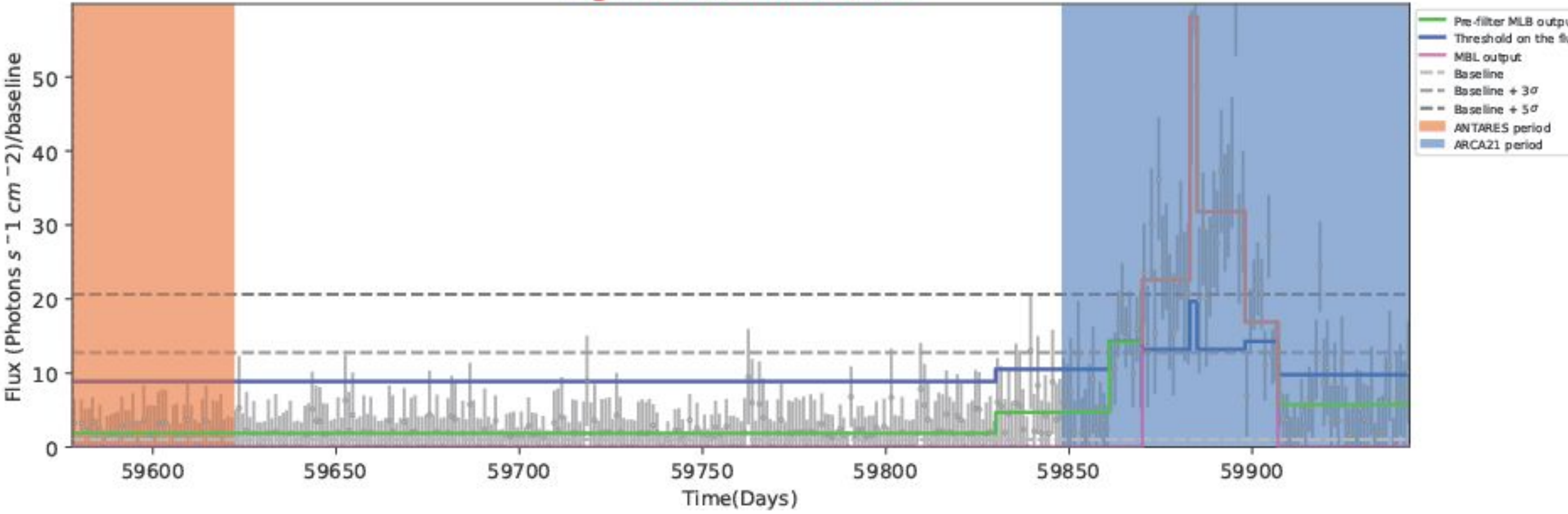


Figure 5.15: An example of the baseline estimation for the same 100-day sample of PKS 1510−08 as in previous figures. The vertical red line is the baseline, determined by a fit (green curve) over the Gaussian convolved data within the limits shown. The other vertical lines represent the bs + 3σ (blue line) and 5σ (magenta line).



Light curve for OQ334



Zoom over the year 2022 for OQ334. Showing the bayesian blocks and their filtering over the threshold.

Source name	$\delta[°]$	$\alpha[°]$	Dur [d]	$\hat{\mu}_{sig}$	p-value	$\mathcal{F}_{\nu}^{90\%C.L.}$
OQ 334	32.38	215.64	94	< 1	**0.0311**	3.27
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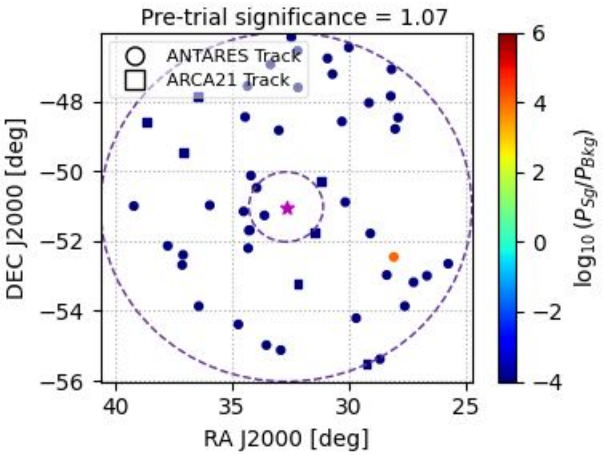
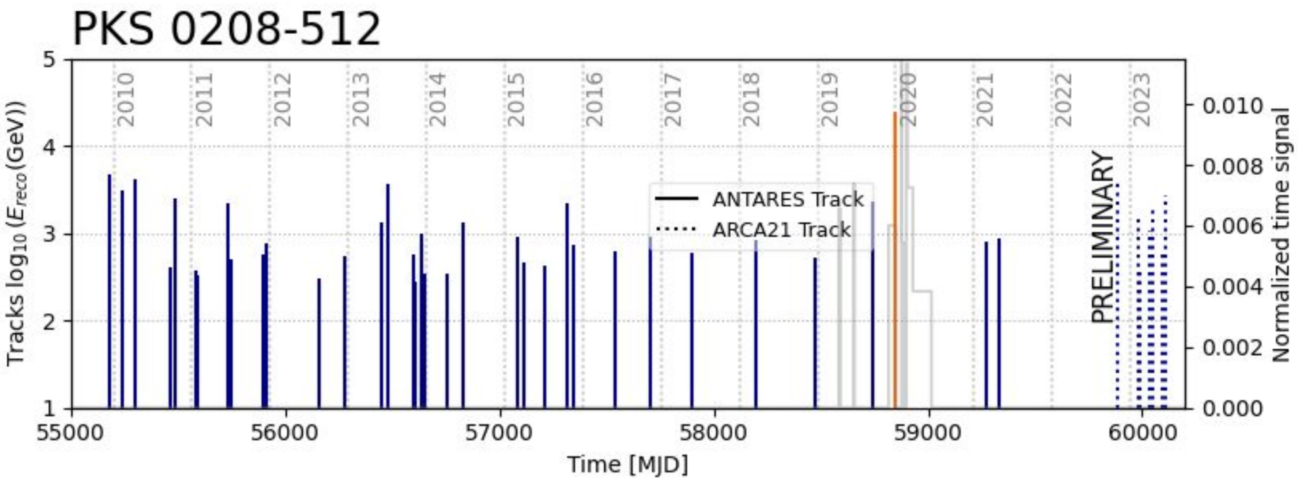
PKS 1244-255	-25.80	191.69	10	< 1	**0.1369**	6.79
4C+01.02	1.58	17.17	236	< 1	0.1849	2.05
PKS 2052-47	-47.24	314.07	3	< 1	0.1872	1.91
4C+28.07	28.80	39.47	159	< 1	0.2223	3.17
4C+31.03	18.22	32.14	77	< 1	0.2443	1.73
PKS 0736+01	1.62	114.82	28	< 1	0.3073	2.54
PKS 0805-07	-7.86	122.07	28	< 1	0.3384	1.69
PKS 1424-41	-42.11	216.99	373	< 1	0.3677	1.18
3C 279	-5.79	194.04	390	< 1	0.3780	5.57
PKS 0346-27	-27.82	57.15	594	< 1	0.3925	2.23
3C 273	2.05	187.27	39	< 1	0.4070	2.75
PKS 2155-304	-30.23	329.71	23	< 1	0.4543	1.56
PKS 2023-07	-7.59	306.42	52	< 1	0.4624	2.24
PKS 0454-234	-23.41	74.26	79	< 1	0.4826	1.66
PKS 1502+106	10.50	226.10	456	< 1	0.5223	4.58
CTA 102	11.73	338.15	482	< 1	0.5368	2.21
PKS 0402-362	-36.09	60.98	56	< 1	0.5395	1.06
ON 246	25.30	187.56	24	< 1	0.5654	2.55
PKS 1954-388	-38.76	299.50	103	< 1	0.5663	2.47
3C 454.3	16.15	343.50	1173	< 1	0.5844	4.21
4C+38.41	38.14	248.82	238	< 1	0.6375	2.54
4C+21.35	21.38	186.23	243	< 1	0.6457	4.36
PKS 0426-380	-37.94	67.17	180	< 1	0.7808	2.98
PKS 0537-441	-44.09	84.71	196	< 1	0.7810	2.14
PKS 2326-502	-49.93	352.33	266	< 1	0.7851	1.89
B2 1215+30	30.12	184.48	2	< 1	0.8244	1.96
PKS 0235+164	16.62	39.67	95	< 1	0.8264	1.70
B2 0218+35	35.94	35.28	65	< 1	0.8275	2.01
PKS 0521-36	-36.46	80.74	8	< 1	0.8404	1.52
Mkn 421	38.20	166.12	32	< 1	0.8924	2.51
TON 599	29.25	179.88	421	< 1	0.9196	2.09
TXS 0506+056	5.70	77.36	26	< 1	0.9336	1.80
B2 1520+31	31.74	230.55	58	< 1	0.9370	2.33
PKS B1406-076	-7.86	212.23	232	< 1	0.9631	2.12
PKS 1510-089	-9.11	228.22	520	< 1	0.9781	3.80

SKYMAP: PKS 0208-512





SKYMAP: TXS0506 +056