A Review of 15 Years of Transient and Multi-Messenger Astronomy with the ANTARES Telescope

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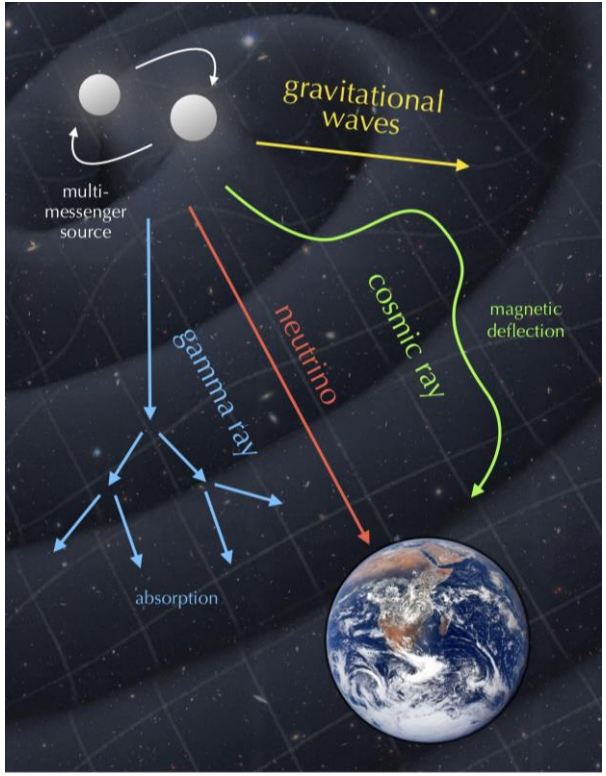
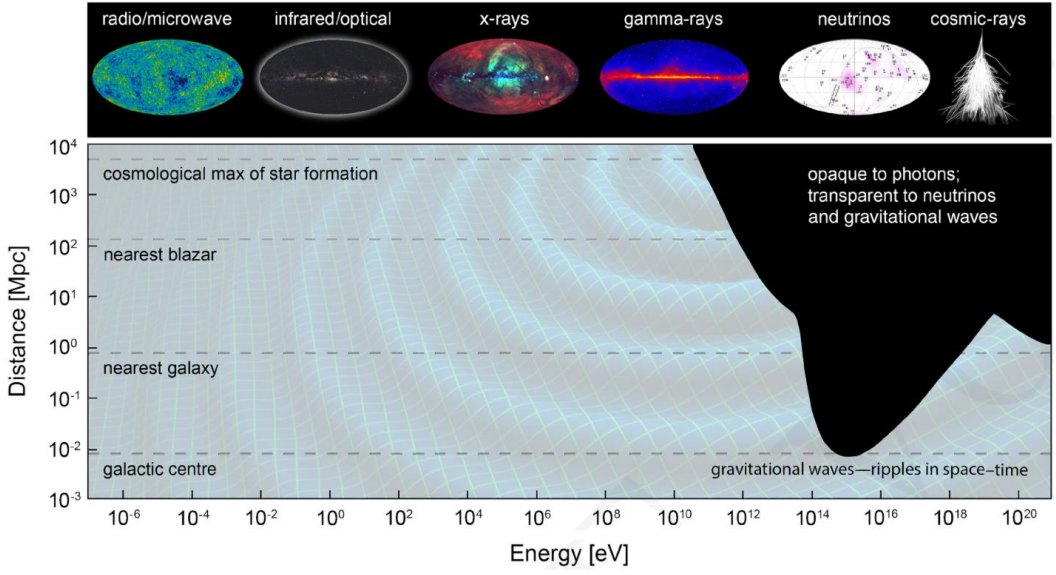
Invited talk for the ANTARES dedicated session @ 17th Marcel Grossmann conference, Pescara

The Multi-Messenger Paradigm



Multi-Messenger astronomy is not a single player game!
Associations of many messengers in space (**and time**) helps in understanding the puzzle of astroparticle physics!

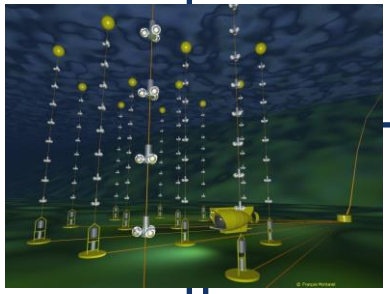


General Overview

Efforts can be divided in:

- **Online:** considers analysing of interesting received transient events and dispatch compelling neutrino events ourselves. Based on fast real-time algorithms.
- **Offline:** Revisit the promising cases with improved and refined algorithms and data. Can be updated as more data comes in.

ONLINE



Receive

Send

ROTSE

MASTER

OFFLINE

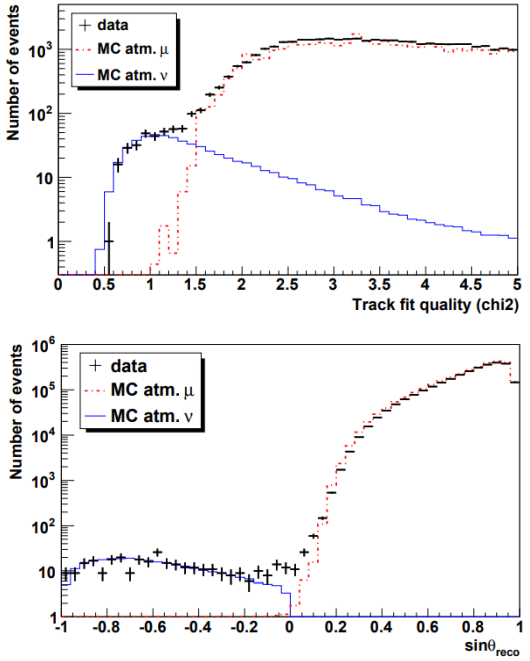
The ANTARES alert system: TAToO

A fast (almost real-time) **preliminary reconstruction** of events allowed for a preselection reducing the event rates from 3Hz to 0.01Hz.

Preselected events pass through a more accurate reconstruction (few second delay) reaching a **~0.5° angular resolution** for high energy events.

- *High Energy Trigger*: Single neutrino with $E > 5$ TeV. Rate of one event per month.
- *Very High Energy Trigger*: Single neutrino with $E > 30$ TeV. Rate of 3-5 per year.
- *Directional*: Single neutrino directionally coincident ($< 0.4°$) with a local galaxy (< 20 Mpc) from the GWGC.
- *Doublet*: Two neutrinos coincident in space ($< 3°$) and time (< 15 min).

Sent using the Gamma-ray burst Coordinate Network (***GCN***)

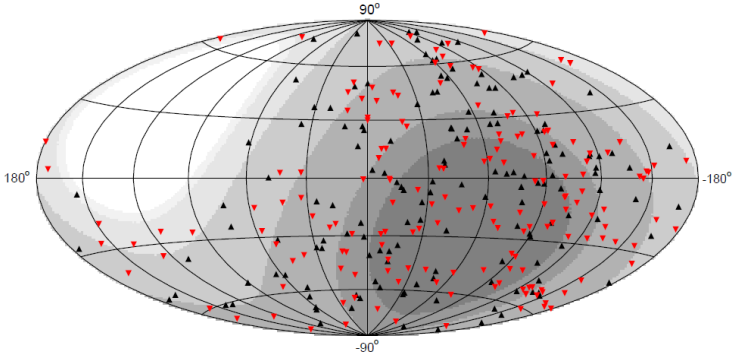


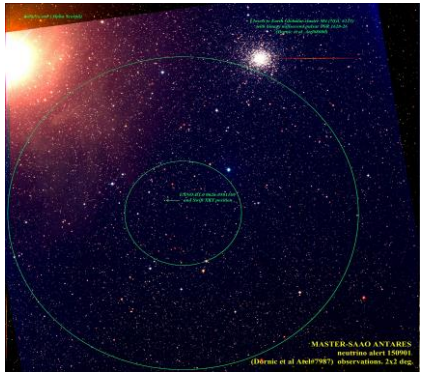
Ref: M. Ageron et al., "The ANTARES Telescope Neutrino Alert System," Astropart. Phys., vol. 35, pp. 530–536, 2012.

TAToO: 12 years of monitoring

Between mid 2009 and December 2020:

- 322 alerts to **robotic telescopes**, 218 triggers with an early optical follow-up analysed (< 24h), 244 with long-term follow up (> 2 days). No counterpart found.
- 26 ToO to **Swift** since mid 2013. Follow-up 19 ANTARES alerts:
  > **ANT150901A**: 90TeV (8% signalness) associated with and uncatalogued X-ray counterpart eventually identified as a young accreting G-K star (3% of chance association).
- Matching alerts with the **Roma-BZCAT**, and **MASTER+Gaia** data, show few possible associations, but not enough optical variability to explain the neutrino emission.
- **MWA** did long (days) radio monitoring of two ANTARES alerts coincident with nearby galaxies. Followed 5 alerts in real-time (30 min). No counterpart.
- **HESS** followed up two HE ANTARES alerts looking for High Energy gamma-rays. No counterpart found.





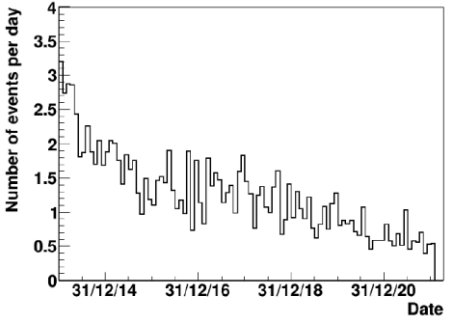
Ref: *Albert, A., et al. "Results of the follow-up of ANTARES neutrino alerts." arXiv preprint arXiv:2402.16498 (2024).*

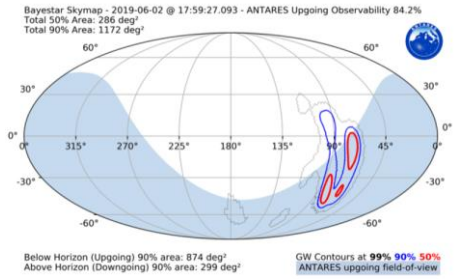
ANTARES Real-Time Follow-up

Real time analysis pipeline implemented with a strict event selection (same as point-source searches). Allowed for a clean sample with good angular resolution. In operation since 2014.

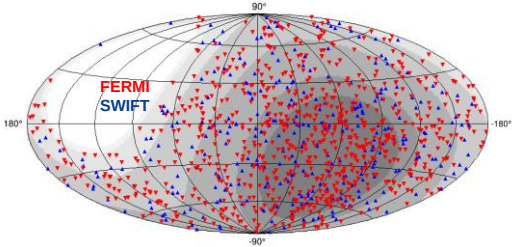
- Followed 37 of 115 ***IceCube*** alerts (7HESE, 3EHE, 10 Gold & 17 Bronce). Region of $3°$ in times of $\pm 1\mathrm{h}$ and $\pm 1\mathrm{day}$.
- Analysed ***Ligo/Virgo*** alerts from O2 (15/15) and O3 (51/56). Looked for temporal ($\pm 500\mathrm{s}, \pm 1\mathrm{h}$) and spatial ($\in 90\%$ cont.) coincidence.
- Received a total of 317 ***Swift*** & 770 ***FERMI*** GRB alerts below the ANTARES horizon. Searches in $-250s$ to $+750s$ with a region of interest depending on the apparatus.
- Answered 7 of the 22 TeV transients from ***HAWC*** and 9 IceCube + HAWC ***NuEM*** coincidences with same strategy as the IceCube neutrino events.

No neutrinos were found. Results (upper limits) were distributed through GCN and the Astronomer Telegram. **Dedicated offline analysis** were performed for interesting cases.





Example of GW provenience region



Locations of all analysed GRBs

Ref: [Albert, A., et al. "Review of the online analyses of multi-messenger alerts and electromagnetic transient events with the ANTARES neutrino telescope." Journal of Cosmology and Astroparticle Physics 2023.08 (2023): 072.]

The Offline side of MM and Transient Efforts

Offline analyses use more refined data**: improved time and charge calibrations** plus more **precise description of the detector and data taking conditions**. Analyses benefit from case-by-case optimization, Montecarlo simulations and more time-consuming algorithms.

Data is modelled by **PDFs** (probability density functions):

1. Angular distribution (Point Spread Function)
2. Energy distribution
3. Time distribution

Each analysis method uses this information on different manners:

BINNED METHOD

It is based on a **cut-&-count** method. Compare data with MC expectations, and compute the **significance of the excess**, if any.

- Fast and easy
- Loss of information
- Requires constant optimization

UNBINNED METHOD

Data is modelled as a **two-component mixture**, and it is fitted to estimate the relative contribution of each component. A **likelihood** is defined:

$$L(n_s) = \prod_{i=1}^{N} \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right]$$

Summary of binned analyses.

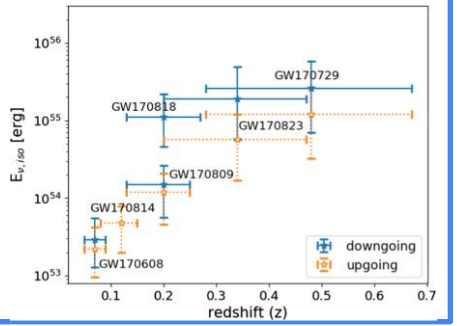
The criteria of optimization in binned searches aims for a 3σ detection (Poisson) for the case of a single neutrino over the cuts

Ligo/Virgo O2

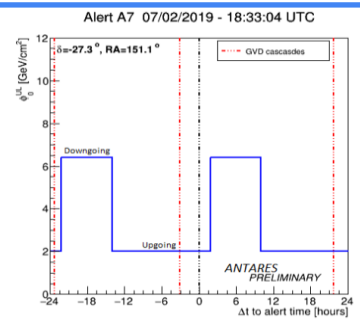
Data from Dec-2016 to Aug-2017 analysed. Total of 6 GW from coalescences of binary black-hole systems.

Search in ± 500s in the 90% containment region. No neutrinos. Upper limits set.

Ref: Marta Colomer et. al.



ANT-GVD Alerts



Three ANTARES alerts with GVD cascades nearby (< 4.5°).

Dedicated analysis around alert direction with ANTARES data. Search in ± 1day and optimized region of interest. No further events found.

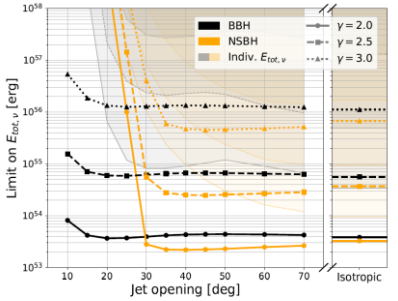
Ref: Sergio Alves et. al.

Ligo/Virgo O3

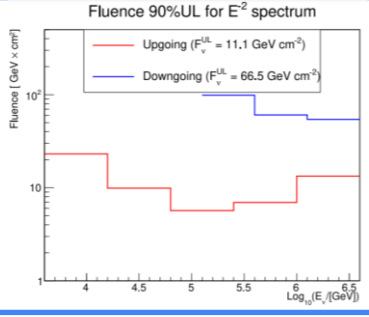
Data from Apr-2-Sep 2019 and Nov19-2-Mar20. Total of 83 GW events.

Search in ± 500s in the 90% containment region + stacking analysis. No significant excess

Ref: M. Lamoureux, et al



PKS 0735+17



Follow-up of interesting case of blazar PKS 0735+17 coincident with alert IC211208A.

Dedicated ± 1day binned analysis and 1 month unbinned search. No excess found. Upper limits set on the neutrino fluence.

Ref: S. Alves, G. Illuminati et. al.

Summary of Unbinned Analysis

A likelihood is implemented with space and energy information. Time information can be added to constrain the expected background (not in the likelihood) or to parametrized the signal hypothesis (added as a likelihood term).

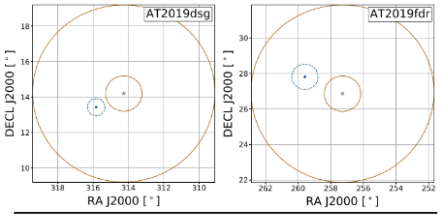
TDE Analysis

Follow-up of two TDE – IC neutrino spatially coincident.

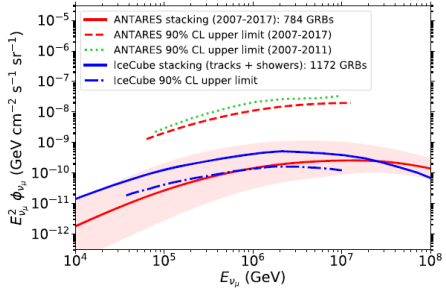
- AT2019dgs (309 days)
- AT2019fdr (151 days)

One event found near each of the TDEs, not significant in both cases. Upper limits in the flux normalization.

Ref: Giulia Illuminati, et al.



GRB Analysis



Sample of 784 GRBs analysed (FERMI + Swift + Konus Wind).

Likelihood based selection optimization for each GRB is done. Finally, a stacking analysis is performed with the whole set.
No neutrino pass the selection.

Ref: A. Zegarelli, S Celli et al.

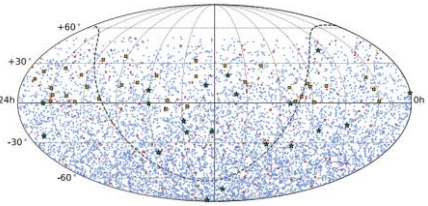
IceCube HE Events

Total of 54 neutrinos from the HESE and Muon sample (up to 2017) analyzed.

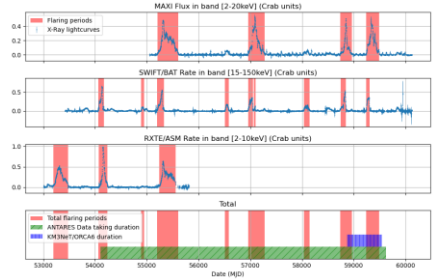
Gaussian time profile assumed centred around the event time and fitted length σ_T.

No significant excess

Ref: Giulia Illuminati, et al.



μQuasar Analysis

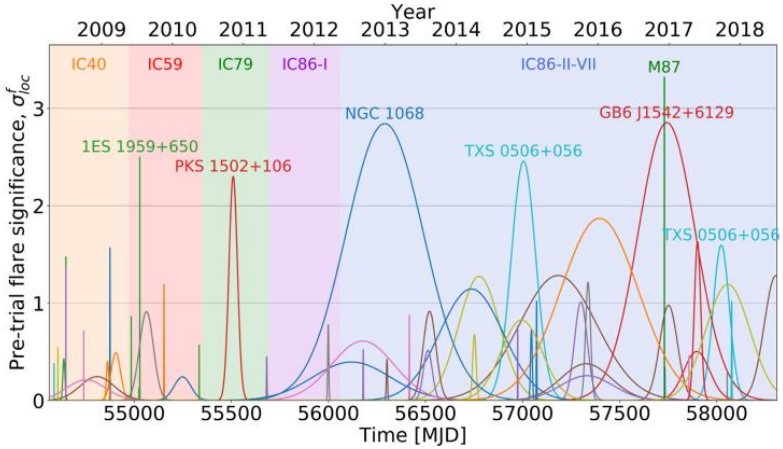


Search for correlation of neutrinos with X-ray flares from 13 μQuasars.
(RXTE/ASM + MAXI/GSC + Swift/BAT).

Flaring periods introduce as *boxes* in the likelihood (On/Off flag).
No signal fitted for all cases.

Ref: S. Le Stum, D. Dornic, S. Alves, et al.

Follow up of IceCube Untriggered Flares



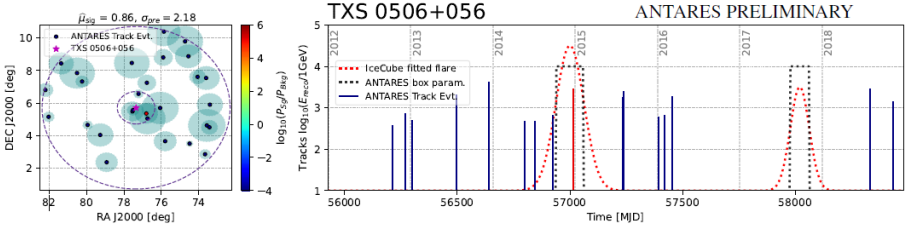
Only 4 sources with some fitted signal and mild pretrial significance:

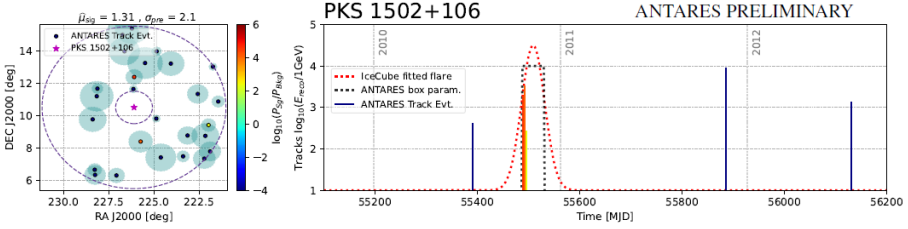
- NGC 598: $\mu_{fitted} = 0.86,\ \sigma_{pre} = 2.2$
- TXS 0506+056: $\mu_{fitted} = 0.86,\ \sigma_{pre} = 2.18$
- PKS 1502+106: $\mu_{fitted} = 1.31,\ \sigma_{pre} = 2.1$
- B3 0609+413: $\mu_{fitted} = 0.4,\ \sigma_{pre} = 1.7$

Very interesting analysis for future detectors with rich statistics.

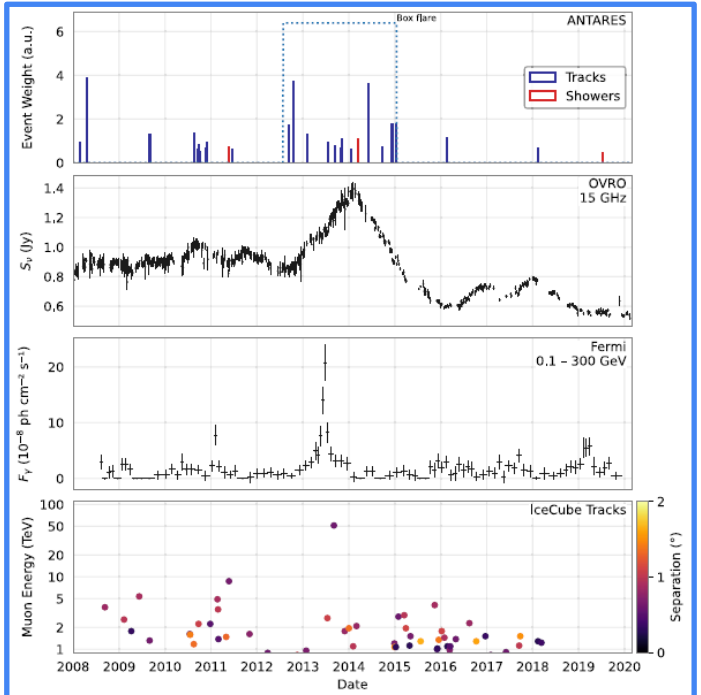
Ref: S. Alves, F. Salesa, A. Sanchez, et al.

- Follow-up of IceCube untriggered flares. Search for "*neutrino to neutrino*" space-time correlation.
- Sources selected based on flare duration, significance and position ($\delta < 45°$). Total of 36 sources analysed.
- Flares parametrized as boxes for the likelihood. "On/Off" approach.
- Per flare selection optimization based on MDP to a $\phi_E \propto E^{-2}$.





Untriggered Neutrino Flares from Radio-Blazars



Comparison of the fitted flare with other messenger time profiles. Only source J0242+1101 shows a notable overlap with radio, gama-ray and even an IceCube neutrino!

Analysis conducted together with other types of searches in *G. Illuminati, A. Plavin et al, 2024*.

- Search for clustering of neutrinos in space and time in the ANTARES dataset coming from the direction of radio-bright blazars.
- A total of 2774 blazars investigated drafted from catalogues of VLBI observations.
- Two different time profiles explored: box and gaussian

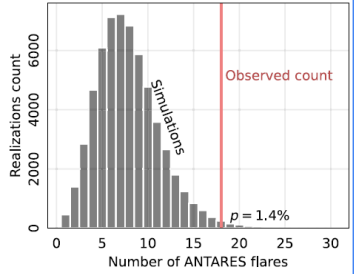
$$S(t) = \left({}^{1}/_{\sqrt{2\pi}\sigma_t}\right) e^{-(t_i - T_0)^2/2\sigma_t^2}$$

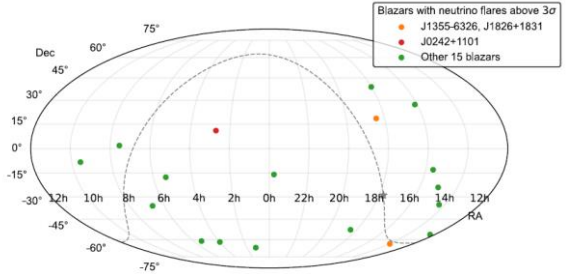
$$S(t) = {}^{1}/_{2\sigma_t} \quad \text{if } [T_0 - \sigma_t] \leq t_i \leq [T_0 + \sigma_t], \qquad 0 \text{ otherwise}$$

The search result in 18 sources showing a flare with pretrial significance above 3σ for one of the tested profiles. Best:

- J1355-6326 with Gaussian fit with 3.7σ, $\mathrm{p_{pos}} = 29\%$.
- J1826+1831 with box fit with 3.3σ, $\mathrm{p_{pos}} = 84\%$.

Chance of findings 18 sources over 3σ is 1.4% Potential hint for emission?





Summary

- The ANTARES Neutrino Telescope took for almost **15 years high-quality data** of neutrinos from the Southern Sky Hemisphere.

- A **rich online program** was developed with many partners all over the globe for:
  -> **Sending alerts** of interesting HE neutrino events too many observatories
  -> Running **automatized analyses in response** to alerts coming from other facilities.
  No coincidences found but path cleared for future KM3NeT MM alert system.

- **Refined analyses** performed with **different methodologies** (cut-&-count, stacking, likelihood maximization, etc…) for **different physics cases** (GWs, GRBs, Gamma-Ray flares, X-ray flares, TDEs, neutrino events, Radio-blazars…) **using data from many other observatories** (FERMI, Swift, OVRO…)

- Transient searches **reduce the discovery threshold** of neutrino sources, a great help for smaller detectors as ANTARES (or detectors in construction). **Many constrains have been set**. In the latest years even hints of neutrino emission could be spotted!