The KM3NeT alert sending system

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1. Motivations: Multi-messenger astronomy

Combines observations from neutrinos, photons, charged particles, and gravitational waves to study transient astrophysical phenomena.

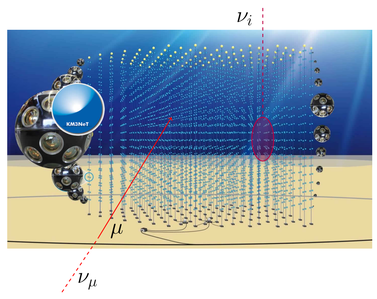
- Probe the theoretical models,
- Unveil the acceleration mechanisms responsible for gamma-ray emission,
- Neutrinos travel undeflected through space, which may help identify the sources of the highest-energy cosmic rays.

Near **real-time sharing of observations** allows for prompt follow-up:

- Ensure data collection if pointing is required,
- Enhance the likelihood of source identification from coincident neutrino detections.

2. The KM3NeT detectors

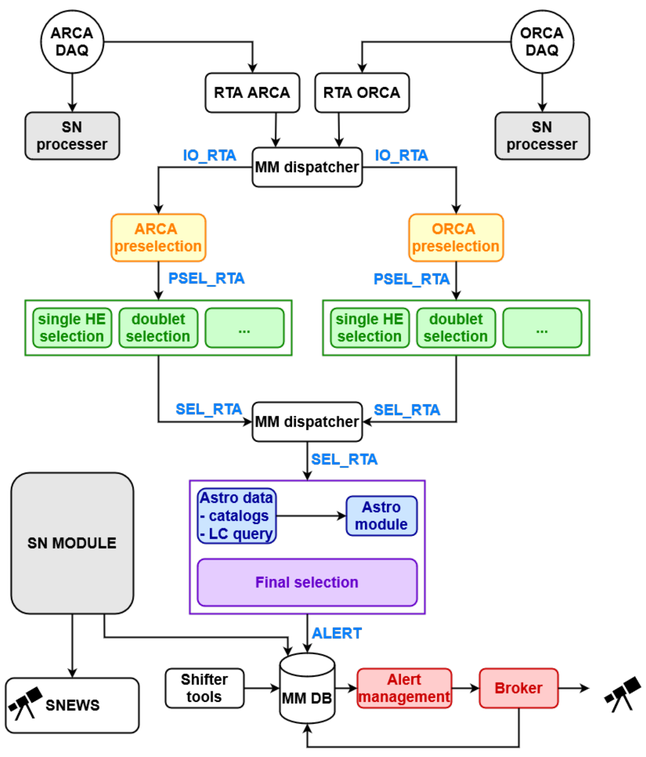
Undersea Cherenkov neutrino telescopes: KM3NeT/ARCA and KM3NeT/ORCA, in the Mediterranean Sea.
Shared hardware design: 18 (multi-PMTs) Digital Optical Modules (DOMs) forms a Detection Unit (DU). DUs are deployed on the seabed as 3D array.



	KM3NeT/ARCA	**KM3NeT/ORCA**
Location	100 km S. Sicily (It.)	40 km S. Toulon (Fr.)
Depth (m)	∼3450	∼2450
Opt. energy range	> TeV	[GeV, TeV]
Instrumented vol.	∼1 Gton	∼7 Mton
Number of DUs	230	115
DU heights (m)	800	200

Individuals DOMs ⇒ Sensitivity to MeV neutrinos.

3. Workflow



After real-time reconstruction of the data, a common pre-selection is applied before running the analysis.

To remain model agnostic, **analysis selections are based on False Alarm Rate** (FAR = number of events with more extreme features than the one investigated, in a given period of time).

Potential neutrino candidates trigger the alert creation and subsequent broadcast.

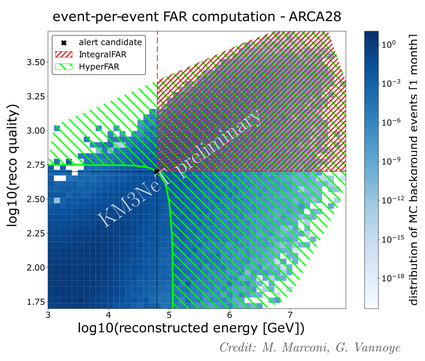
From data acquisition to alert sending. Credit: M. Marconi.

4.1 Analysis Pipeline: Single event selection

High-energy (HE) **pipeline** - Identify individual events:

1. Derive a HE selection from MC: select $\mathcal{O}(1)$ event/day.
2. Compute its (*integral-* and *hyper-*) FARs.
3. Apply the HE selection (TrackLength, Energy, hits Nb).
4. Forward selected events to the *Final selection module.*

Integral-FAR: nb. bkg events with more extreme features than the alert. Use it to **quantify the alert significance**. → red area.
Hyper-FAR: FAR of the FAR, *ie* bkg events with IntegralFAR ≤ integral-FAR(alert). → green area.



Credit: M. Marconi, G. Vannoye

4.2 Analysis Pipeline: Multiplet selection

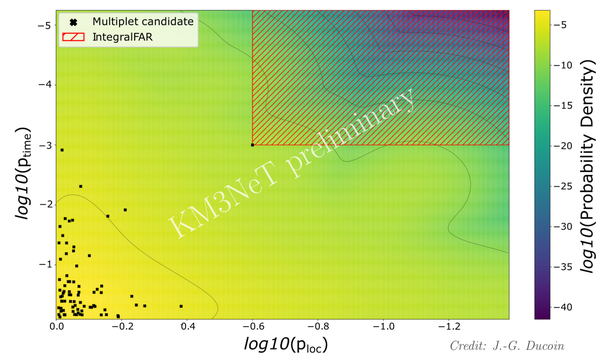
Multiplet pipeline - Look for events compatible in position and time[1]:

1. Add the pre-selected events to the *OnSource* list.
2. Compute the time (p_{time}) and space (p_{loc}) correlation probabilities against all the *OnSource* list events of the sliding time-window.
3. Extrapolate a 50000 events mock sample by fitting the *OnSource* events parameters.
4. Compare the *OnSource* p_{time} and p_{loc} to the mock distribution and compute the FAR.
5. Select the events if the FAR of this probability is low enough.

$$p_{loc} = 1 - \left(\frac{N_\cap}{N_\cup} \times (1 - \frac{N_\cup}{N_{tot}})\right)$$
$$p_{time} = P(\Delta t \leq \tau|\lambda) = 1 - e^{-2\lambda\tau}$$

Combine individual positions and errors[2]:

$$X_{mean} = \frac{\sum_{i=1}^{N} X/\sigma_i^2}{\sum_{i=1}^{N} 1/\sigma_i^2} \quad ; \quad \sigma_w = \left(\sum_{i=1}^{N} \sigma_i^{-2}\right)$$



Credit: J.-G. Ducoin

5. Multi-messenger counterpart search

Astro module - search for astronomical counterpart to the neutrino event.

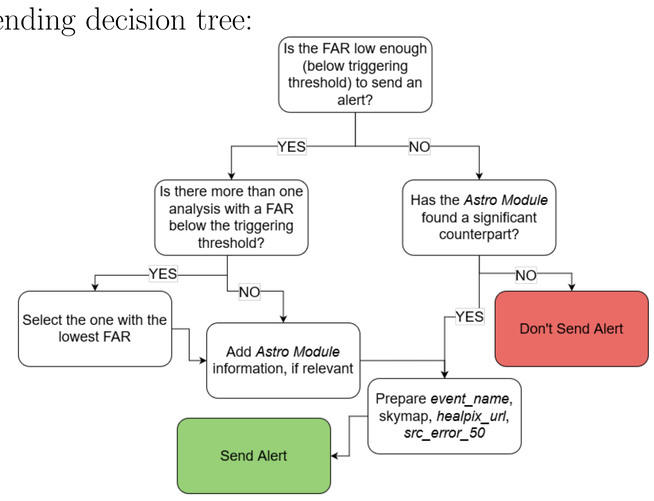
1. Explore different catalogues according to the event directionality and cross-match their results to avoid duplicates:
   - *Extra-galactic event* ($|b| \geq 10°$): 2RXSC (Rosat), 4FGL (Fermi-LAT), RFC + Use BZcat and TeVcat to cross-match.
   - *Ambiguous origin* ($|b| < 10°$): 4FGL, TeVcat and XRB (in H and L masses).
2. Assert a p-value from the source flux, its distance to the neutrino event and eventual real-time information on the source evolution: $p_{val} = \mathcal{P}(\phi_\gamma, \phi_X, \phi_{radio}, dist., time)$.
3. For each source, evaluate the FAR by comparing with a large source sample and select below a given threshold.

6. Final selection: To send or not to send?

Final module - Merge Analyses and Astro module information, produce alert metadata, apply selection to desired rate ($\mathcal{O}(5)$ event/month), store alert information and orchestrate additional analysis if required. Alert sending decision tree:

→ "Pure neutrino alert", *i.e* event significant enough on its own to trigger an alert.

→ "MM-component alert", *i.e* in case of Astro module outstanding information, "upgrade" an event which does not reach the significance threshold.



7. Alert content and dissemination

KM3NeT Broker - share the detection with the community.
Minimal requirements: time and space coordinates of the event, error region and systematics, statistics information (FAR) and alert identifier.
Additionally includes information related to the triggering, details on the neutrino(s) candidate(s) and information about counterparts if available.

When a new alert is triggered, its information is retrieved from our internal MM_DB and

1. Wrap it in **JSON** (GCN unified standard) and **VOEvent** (IVOA historic standard) files.
2. Broadcast via the **GCN's Kafka** servers with topic *gcn.notices.km3net(.voevent).*

The JSON notice is based on the "Neutrino template" developed in collaboration with IceCube.

References:
1. "A coincidence null test for Poisson-distributed events", Phys. Rev. D 103, 042003
2. "Multiwavelength follow-up of a rare IceCube neutrino multiplet", A&A 607 (2017) A115.

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