Real-time astronomy with KM3NeT

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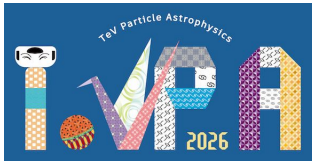
on behalf of the KM3NeT Collaboration



TeV Particle Astrophysics (TeVPA) Tendo, Japan 30 Aug - 4 Sept 2026

1. Istituto Nazionale di Fisica Nucleare (INFN) – Genova
2. Università di Genova – Dipartimento di Fisica

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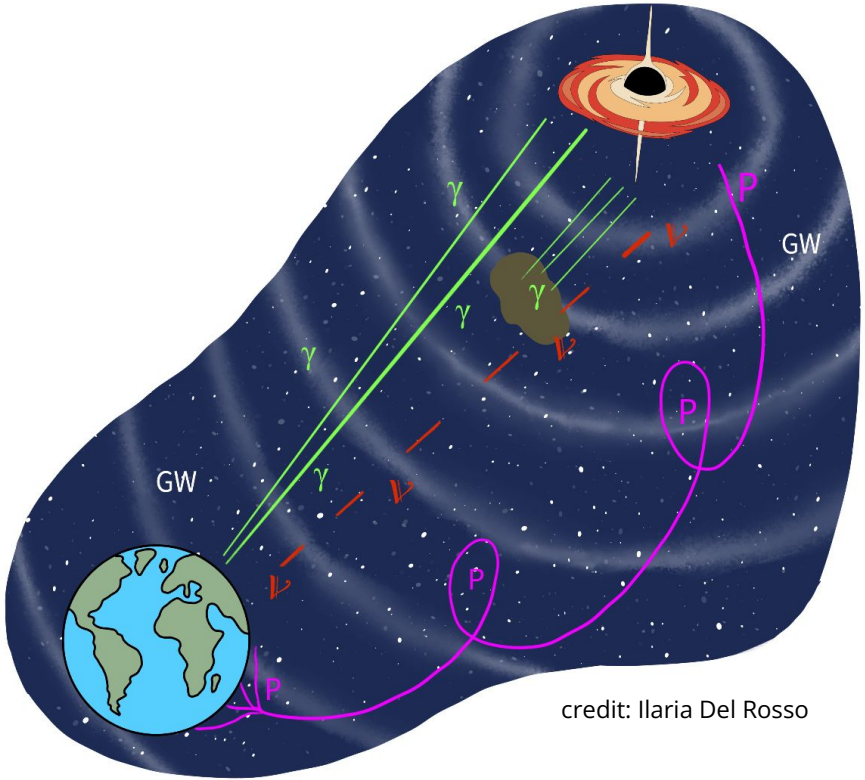
KM3NeT

Multi-messenger astronomy

- Each cosmic messenger gives a new insight on the astronomic phenomena
- Many sources are transient or fast-fading

Key requirements:

- Network of observatories:
  EM, CR, GW, neutrinos → e.g. **KM3NeT**
- Continuous monitoring
- Low-latency automated analyses
- Prompt alerts disseminations
- Prompt follow-up observations and joint interpretation



credit: Ilaria Del Rosso

KM3NeT

KM3NeT (Cubic Kilometre Neutrino Telescope) is an underwater **neutrino telescope** under construction in the Mediterranean Sea, already **taking data in partial configuration.**

It detects the **Cherenkov light** induced by charged particles produced by neutrino interactions in seawater using a 3D array of PMTs.

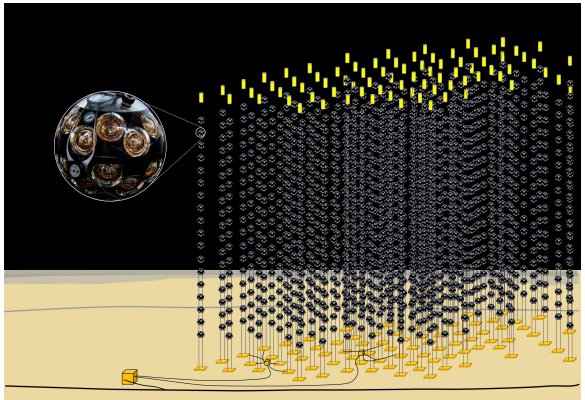
PMTs are hosted in Digital Optical Modules (DOM), each one containing 31 3” PMTs.
DOMs are organized in vertical lines anchored to the seabed, each one containing 18 DOMs.

KM3NeT-ARCA *Astroparticle Research with Cosmics in the Abyss (IT)*

- Optimized for the TeV to PeV energy range
- 51 deployed lines, 44 operational

KM3NeT-ORCA *Oscillation Research with Cosmics in the Abyss (FR)*

- Optimized for the GeV to TeV energy range
- 42 deployed lines, 41 operational



https://www.km3net.org/research/detector/

Real-time MM astronomy in KM3NeT

KM3NeT Follow-ups

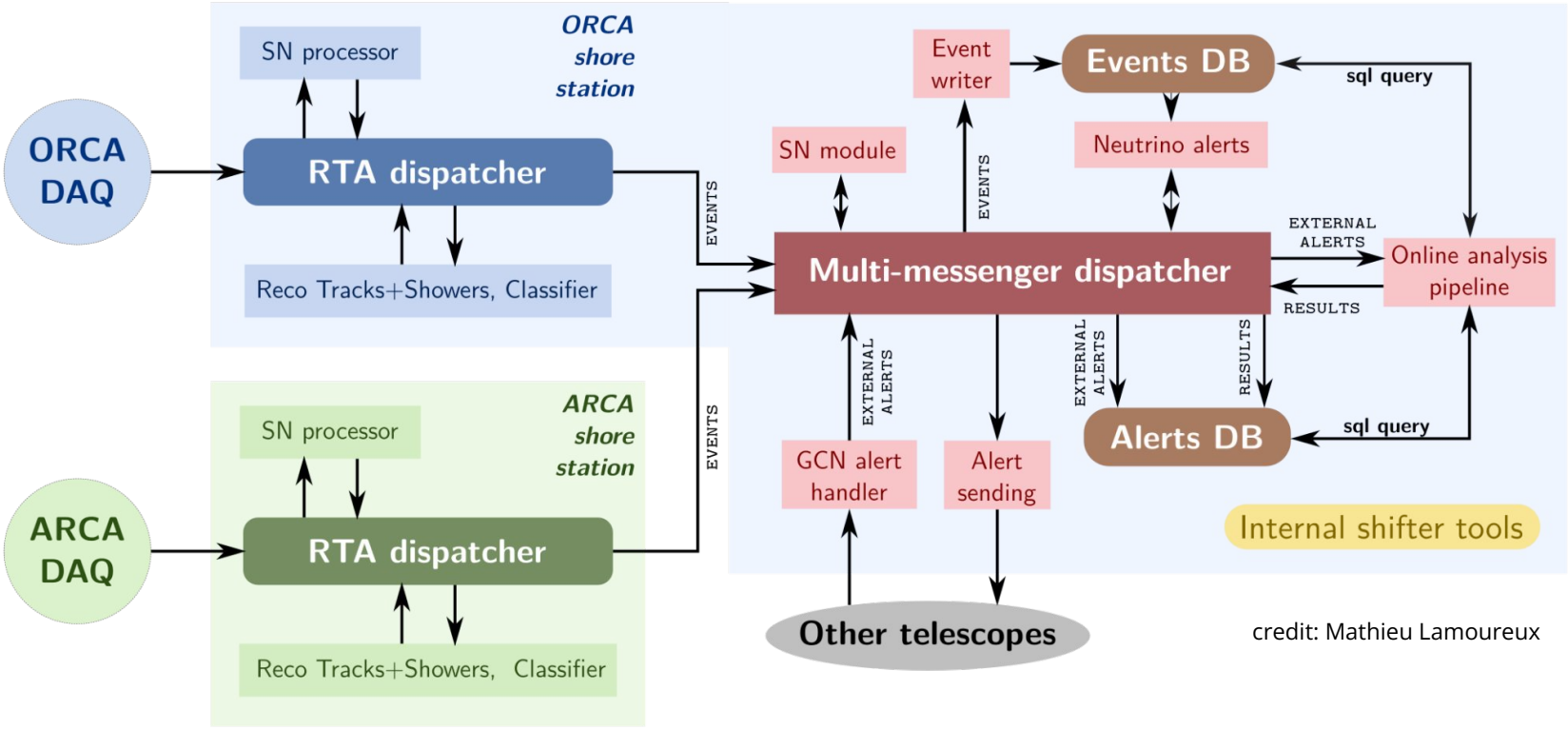
At reception of external alerts, look for space-time coincidence with KM3NeT events.
Operational since June 2023

KM3NeT Alerts

Identify interesting neutrinos and CCSN events and send alerts to the MM community.
Work in progress → ready for autumn 2026

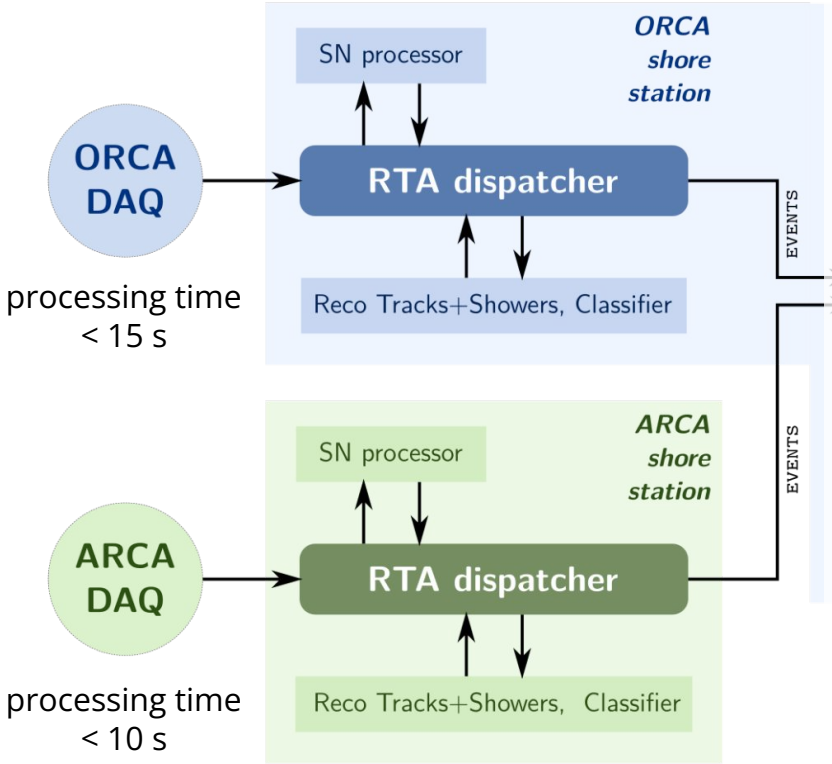
KM3NeT

KM3NeT real-time framework



credit: Mathieu Lamoureux

KM3NeT real-time framework



Real-time events processing

RTA dispatchers mirror data from DAQ and perform fast event processing:

- event reconstruction under track and shower assumptions
- ν/μ classification with ML algorithms

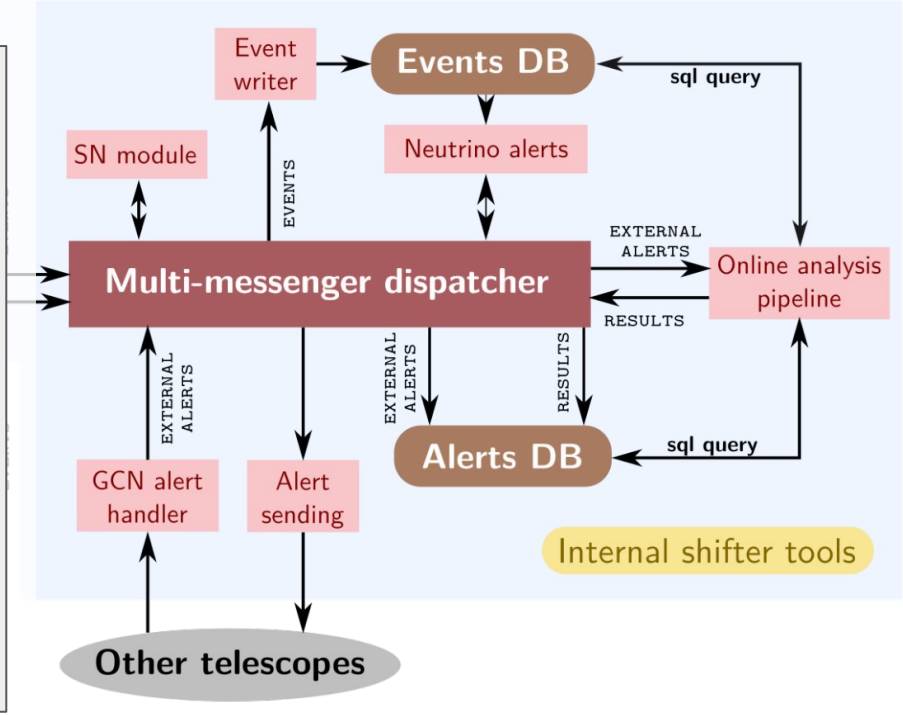
more info: PoS(ICRC2025)1115

KM3NeT real-time framework

Multi-messenger dispatcher

The MM dispatcher contains multiple modules that allow the system to:

- receive and follow-up external alerts triggers
- detect CCSN events
- select and send neutrinos alerts
- monitor the real-time framework performances



KM3NeT real-time follow-ups

Continuously receiving external alerts → **automatic space-time correlation analyses**

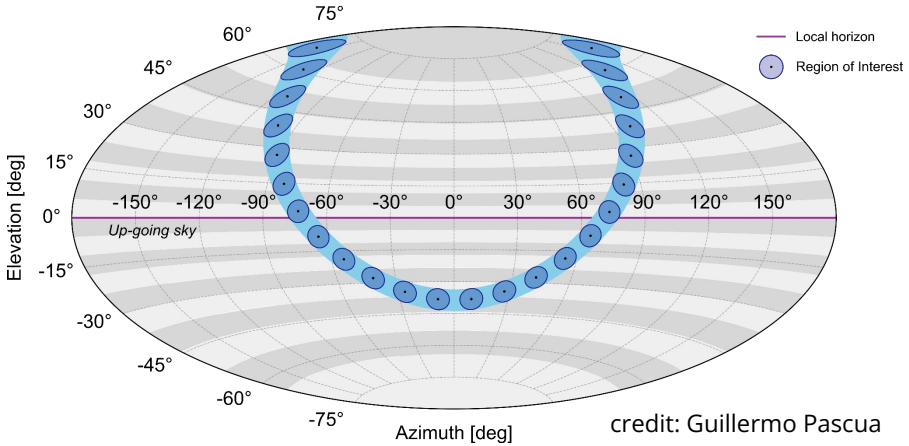
Search method: binned ON/OFF technique:

- compare the signal region data (ON) vs. past data from control regions (OFF) with similar background conditions, but no expected signal (i.e. elevation bands)
- multiple signal time windows are considered depending on the alert type

Event selection:

- fixed “precuts”
- elevation-dependent optimization: suppress background while keeping statistical uncertainties under control

Results: correlation significance (pre-trial *p*-value), optionally upper limits computation

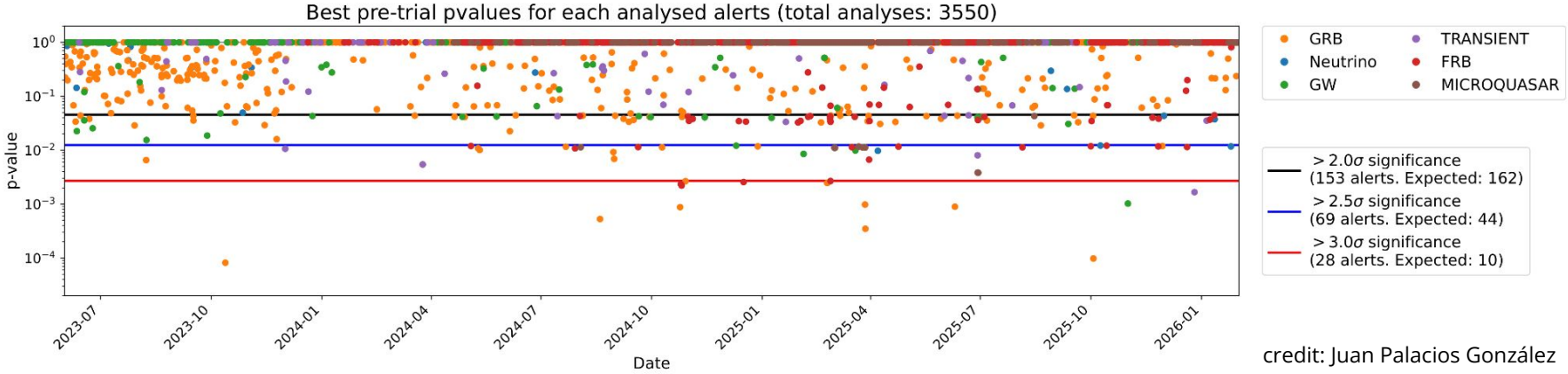


credit: Guillermo Pascua

KM3NeT real-time follow-ups

KM3NeT real-time follow-up activities ongoing since June 2023

- More than 3500 external alerts analysed successfully. More info: PoS(ICRC2025)1038
- Only track-like KM3NeT events are used. *Shower-like implementation is ongoing*
- No significant correlations observed so far → no results reported yet
- Providing results to the community is expected soon



credit: Juan Palacios González

MeV neutrinos with KM3NeT

KM3NeT is sensitive to MeV electron anti-neutrinos via inverse beta decay $\bar{\nu}_e + p \rightarrow n + e^+$

→ small track of ≈ 0.5 cm/MeV → single-event reconstruction impossible

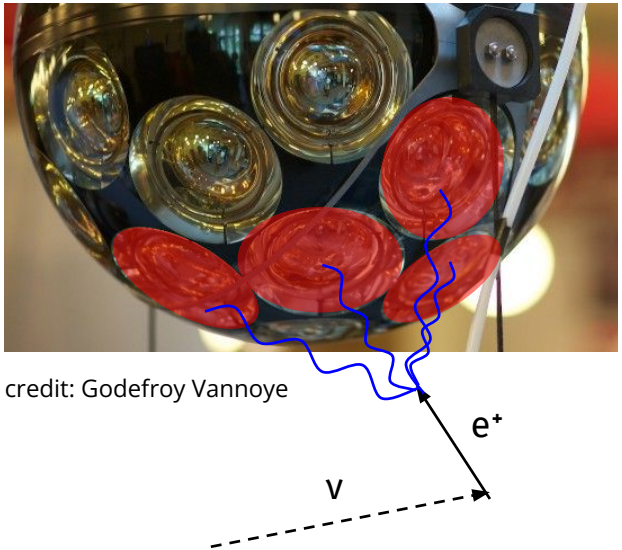
→ search for an excess of hit coincidences *hit = a PMT optical signal (time + time-over-threshold)*

Coincidence: ≥4 hits in 1 DOM, PMTs within 90°, Δt = 10 ns

Coincidence level: number of coincidences in 500 ms, evaluated every 100 ms independently for each detector

Optical background from bioluminescence, radioactive decays, muons

Detector combination → significance and False Alert Rate



<u>Sensitivity to MeV neutrinos:</u>

➔ GW event follow-ups with MeV neutrinos in ±2 s window

➔ Real-time detection of **Galactic Core Collapse Supernovae**

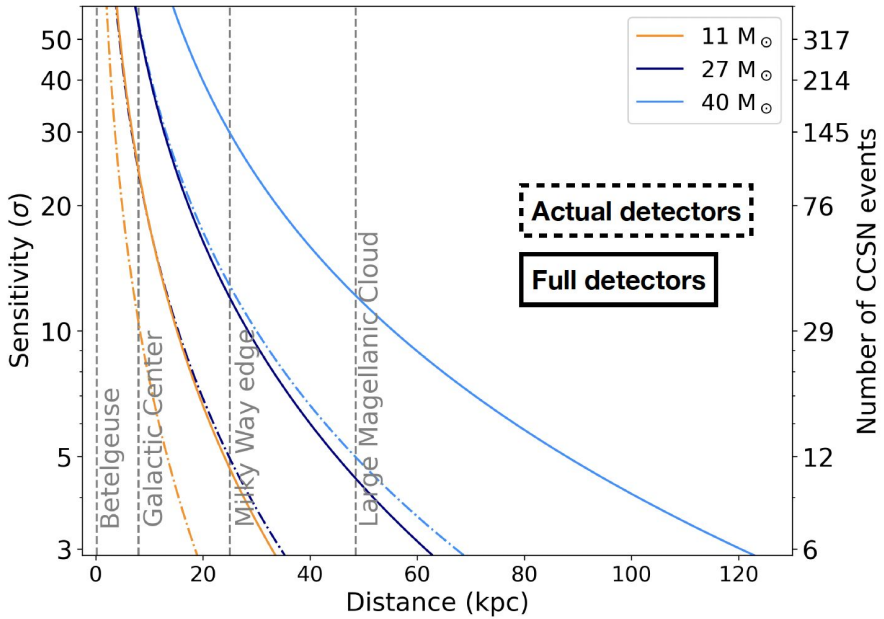
Core Collapse Supernovae detection

CCSN → enormous energy release, mostly as ~10 MeV neutrinos in < 0.5 s time window

Extremely rare + short duration
→ fast, automatic detection crucial

KM3NeT CCSN pipelines:

- **Real-time:** send alerts to SNEWS network if the coincidence level reaches a significant excess, with a given False Alert Rate
- **Quasi-online:** perform additional analyses with more statistics → time information
- **Triggered follow-up:** reanalyse past data following external triggers



KM3NeT ARCA + ORCA sensitivities as a function of the CCSN distance to Earth for three progenitor masses, for the current and full configuration detectors

KM3NeT alert sending system

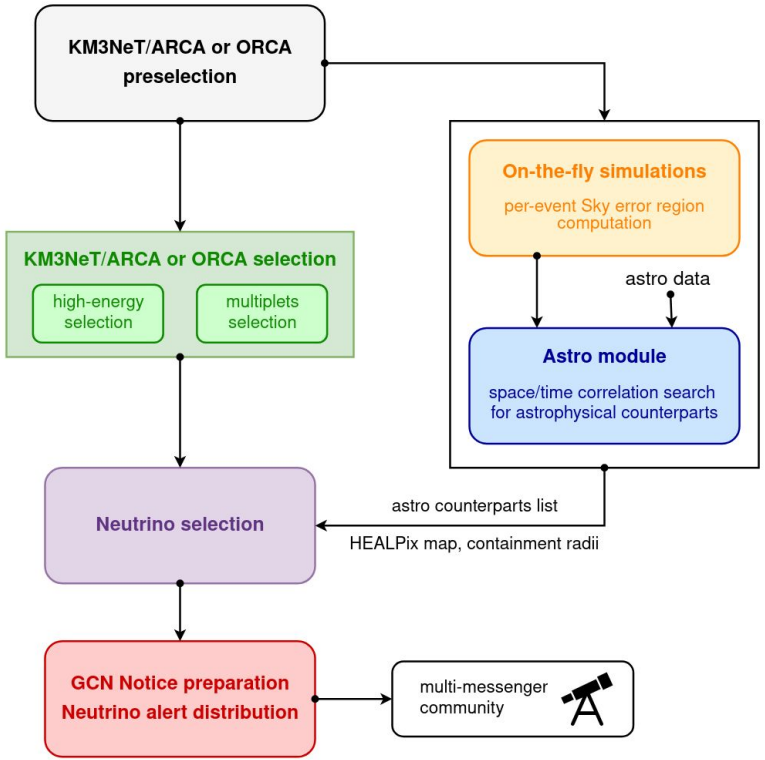
Thousands of events/day → only a few interesting

Independent ARCA & ORCA selections:
- high-energy neutrinos
- neutrino multiplets (doublets for now)

Per-event Sky error region computation
➔ HEALPix prob density skymap
➔ containment radii (50%, 90% CL)
➔ 50% and 90% probability contour footprints

Search for potential astrophysical counterparts to list in the notice

Final selection and alerts reporting
➔ **1-2 alerts per month from KM3NeT**
➔ **Latency time: ~ 4 min (p90). Goal 2 min**



Selection modules

Selection of high-energy track-like events

→ properly reconstructed events
→ good angular resolution
→ likely cosmic neutrinos, i.e. high-energy

1. Partial high-energy selection
   reconstructed muon energy, reconstructed track length and track reconstruction quality
2. Computation of False Alert Rates:
   - INTEGRAL FAR (track_energy, track_length, track_quality)
   - HYPER FAR
3. Selection on HYPER FAR

Selection of multiplets (doublets for now)

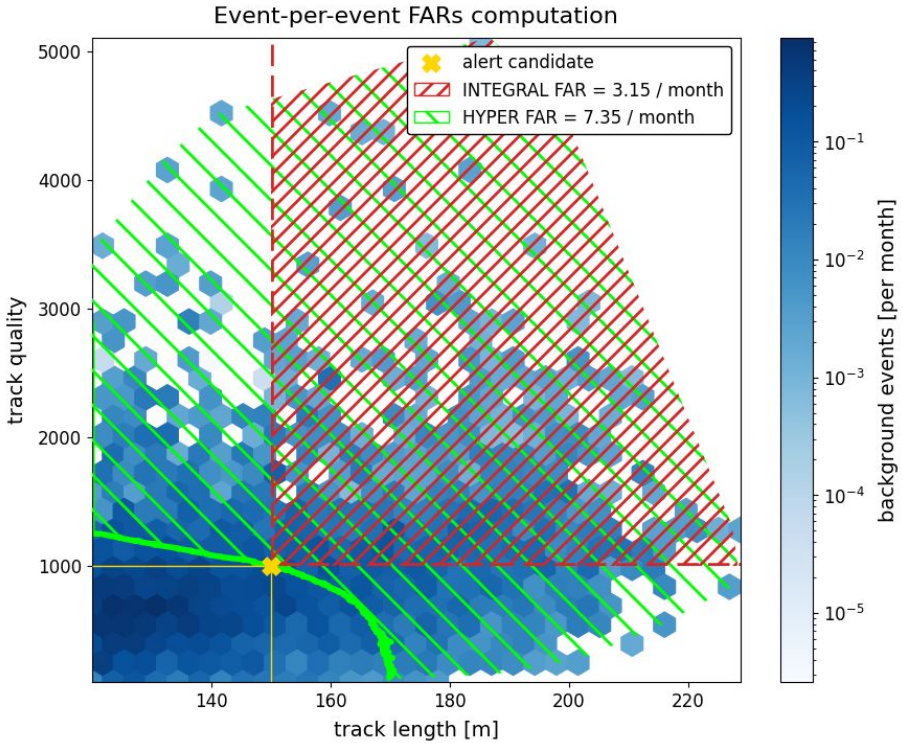
→ multiple events coming from compatible Sky locations in a given time window

1. onsource / offsource events lists
   - onsource: true events within the sliding time window
   - offsource: fake events reproducing true events
2. Time and space correlation probabilities computed for every duet of the onsource and offsource events lists
3. Computation of False Alert Rates:
   - INTEGRAL FAR (from space and time correlation probs)
   - HYPER FAR
4. HYPER FAR selection + convolved Sky localisation

Event-per-event False Alert Rate

Event-per-event False Alert Rate (FAR) used to identify cosmic neutrino candidates in high-background conditions

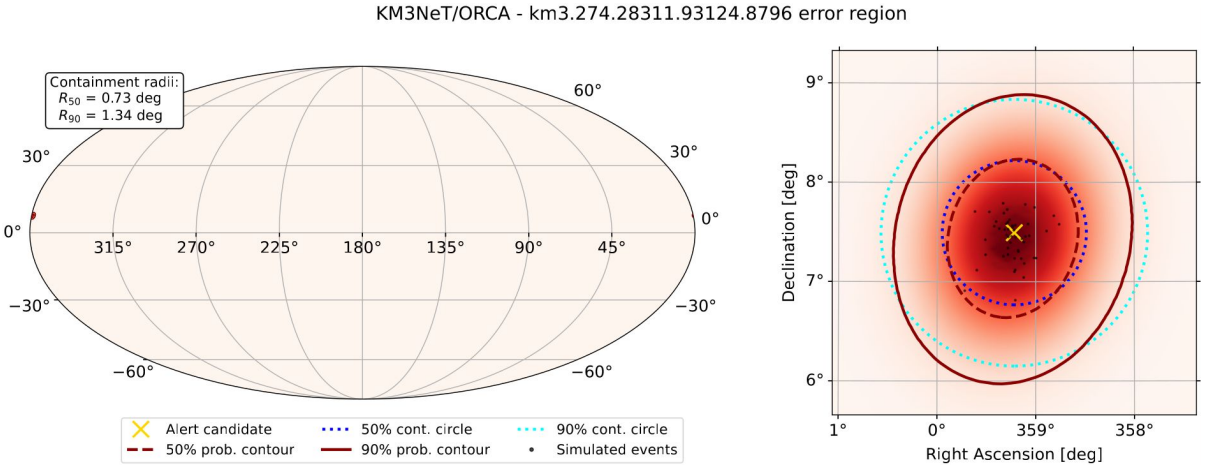
- **INTEGRAL FAR**: derived from the multidimensional background distribution obtained through MC simulations
- Multi-dimensionality leads to degeneracies → a fixed INTEGRAL FAR threshold would select too many alerts
- **HYPER FAR** - physical false alert rate
  - Accounts for multidimensionality
  - Defines the actual alert emission rate → used as final selection metric
  - Reported in the public alert notice



Sky error region estimation

"On-the-fly simulations" to produce N copies of the event → per-event Sky error region accounting for per-event fluctuations, reconstruction effects, detector systematics, neutrino-muon kinematics

➔ Latency time: 4 min (p90). Goal: 2 min

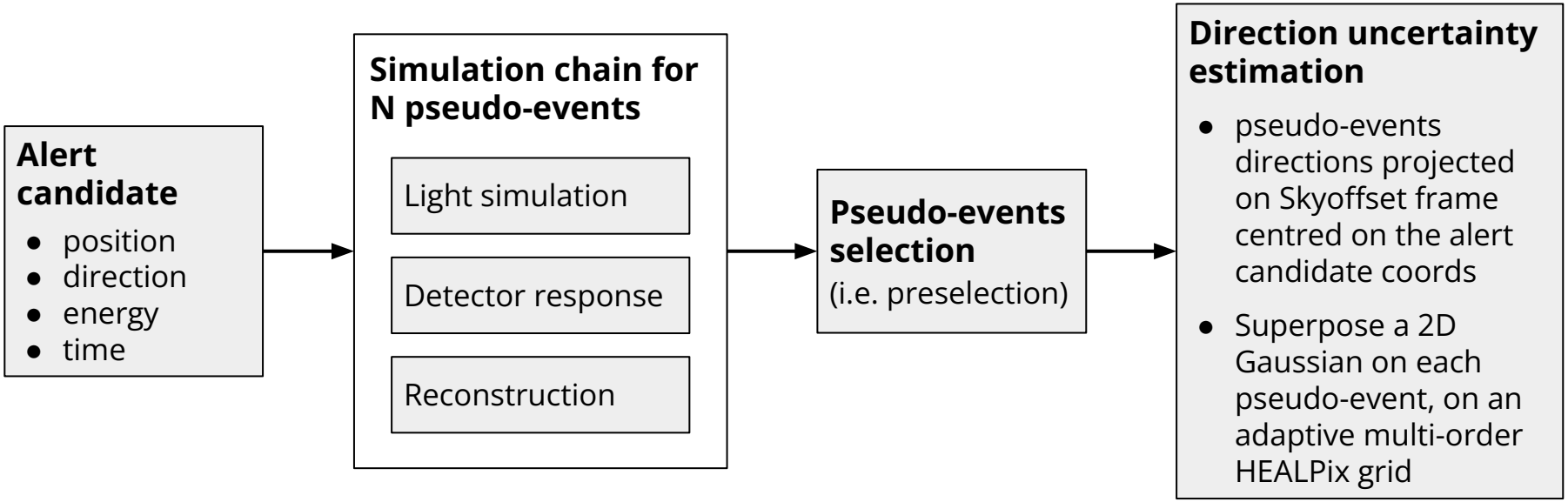


Outputs:

- multiorder HEALPix probability map
- 50% and 90% probability contours footprints
- 50% and 90% circular containment radii

Accessible via GCN notice

Sky error region estimation



In the case of doublets → HEALPix maps Bayesian combination:

$P(\Theta \mid \text{event 1, event 2}) \propto P(\text{event 1} \mid \Theta) \cdot P(\text{event 2} \mid \Theta) \cdot P(\Theta) \propto P(\text{event 1} \mid \Theta) \cdot P(\text{event 2} \mid \Theta)$ = per-pixel product

with Θ the direction of an hypothetical source, flat prior $P(\Theta) = const$, $P(\text{event 1} \mid \Theta)$ the individual skymaps

Astro module

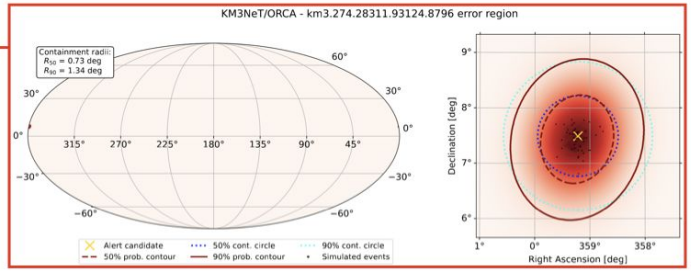
Goal: provide a list of candidate sources of interest

- Why?
  - help the multi-messenger community to select interesting event
  - give a list of candidate sources to observe with electromagnetic follow-ups
- **How sources are selected?** Try to infer statistical grades based on several criteria
  - distance of the source to the alert → G_{pos}
  - brightness of the source in several energy bands/catalogs → G_{det}

  } combination → G_{tot}
  - variability of the source (is it flaring at the neutrino detection time) → `True/False`
- For now, investigating AGNs and X-ray & γ-ray binaries. In the future: GRBs and TDEs
- Takes HEALPix probability map
  → **return two candidate source lists: one extragalactic and one galactic**

Astro module

Input
Mandatory : Healpix Map (single or multi order)
Optional : error radius 90%



Read catalogs :
RFC, 2RXS, 4FGL, HMXB, LMXB

Concatenate and separate galactic / extragalactic sources (based on source type)

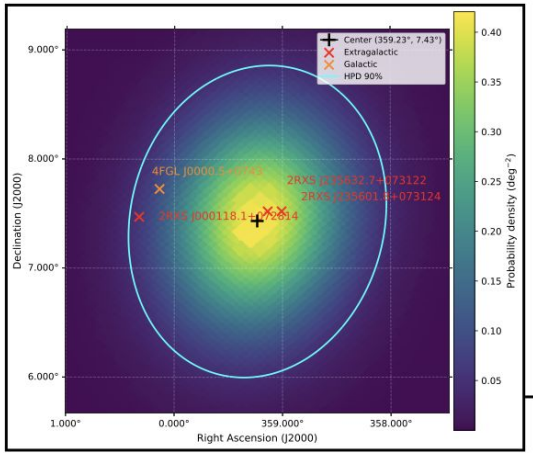
Searching sources :
Extragalactic catalogs → AGNs
Galactic catalogs → XRBs
GCN → GRBs (1day window)
TNS + ZTF/VRO → TDEs (1 year window)

Cross-match

Compute statistical grades :
1) Based on the probability of the healpix map at the source position → g_{pos}
2) Based on the source brightness in the catalog → g_{det}

Ranking based on the total statistical grade

3 lists :
- extragalactic candidate sources
- galactic candidate sources
- GRBs and TDEs from GCN and TNS



Timing : Flaring state (True/ False) at the alert time detection
1) γ-rays via Fermi-FAVA
2) optical via ZTF and LSST (potentially radio/X-ray)

Output : total source ranking
Galactic sources : …
Extragalactic sources : …

Given infos :
- Source names
- Coordinates
- Statistical values (g_{pos}, g_{det}, g_{tot})
- Distance to the center of the alert
- Flaring state in optical
- Flaring state in γ-ray

credit: Antoine Foisseau

Already implemented

Not yet implemented

Final selection and reporting

Final selection:

- incorporate results from multiple neutrino alert pipelines
- add lists of candidate sources found from the astro module
- select 1-2 neutrino alerts per month

Reporting:

- build and share a GCN notice
- Total latency time: 3-4 min
  Goal: 1-2 min


```
{
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"counterpart_info": "No search"
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```


Detector information

Alert message details

Event identifier

Alert content

Event details

Astro counterparts

KM3NeT GCN notice schema

- Common with IceCube
  - notice related info
  - alert related info
- KM3NeT specific
  - neutrino features
  - astro counterparts

credit: Vincent Cecchini

Conclusions

KM3NeT is already actively contributing in the field of real-time MM astronomy

- **KM3NeT real-time platform is operating on a constant basis**
  → events reconstruction and classification
- A shift crew provides continuous monitoring to ensure the system functions correctly and to identify potentially interesting results for reporting
- **External alerts follow-ups**
  continuously performing automatic analyses, no significant correlations observed
  Soon: reporting results to the MM community
- **CCSN detection**
  real-time detection pipeline in place, tests for the quasi-online pipeline
- **Alert sending system**
  - system ready end-to-end, commissioning ongoing
  - private alerts sent to partner experiments ~ autumn 2026

Thank you!