Multi-messenger astronomy with KM3NeT: the real-time neutrino alert system

CPAN days - 20/11/2025 - Valencia
V. Cecchini, on behalf of the KM3NeT collaboration

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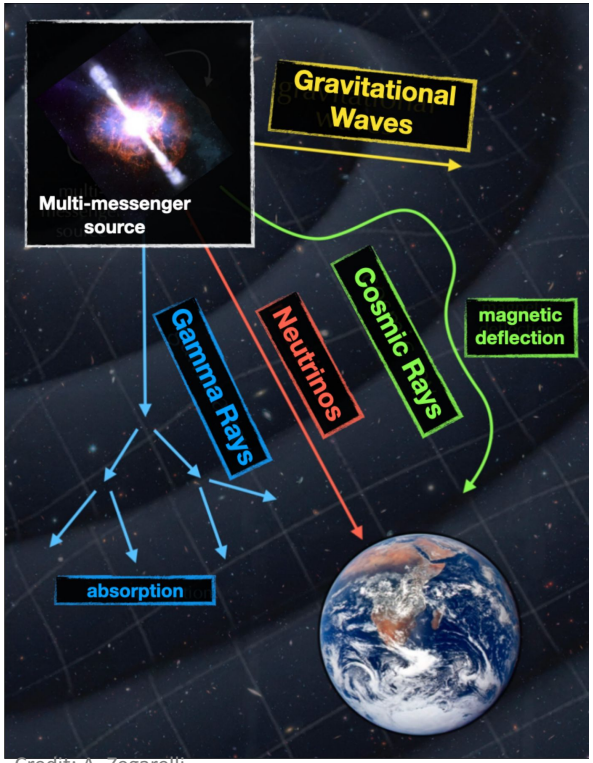
The Multi-Messenger landscape



Credit: A. Zegarelli

Various signatures from astrophysical sources, with complementary properties:

- **Gravitational Waves (GW)**: Travel far away, but detection techniques results in poor localisation and are sensitives to narrow wavelength, detecting only specific objects.

- **EM radiation and γ-rays**: **Straight line**, absorbed by dense medium, universe opaque at long range (> 100 kpc) for high energies (HE).

- **Cosmic Rays (CR)**: **Abundant** charged particles, subject to magnetic **deflection** and to GZK cut at ultra high energies (UHE).

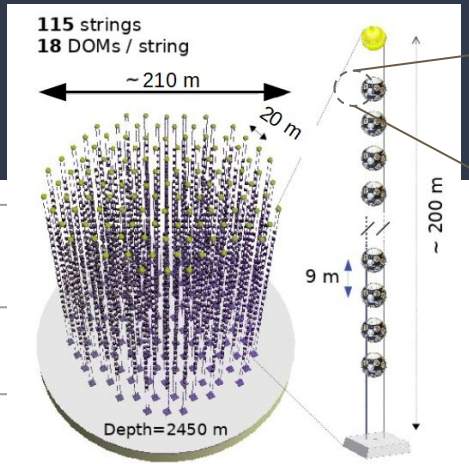
- **Neutrinos**: **No deflection** (q=0), **no opacity** (weakly interacting) but difficult to detect and mixed with a high background.

Common origin in the Hadronic process (pp/pγ) scenario.

The KM3NeT detectors

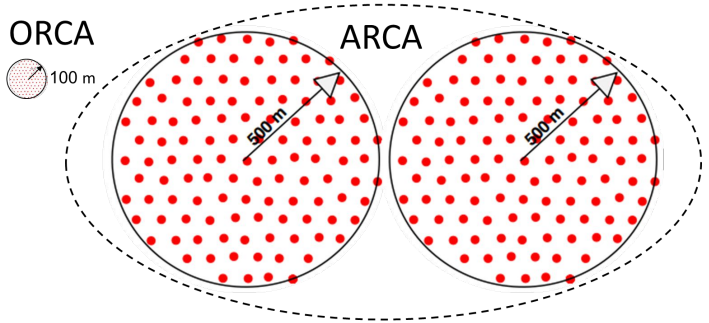
2 sites under construction → completion ~2030
Operational: ARCA51, ORCA33

J. Phys. G: Nucl. Part. Phys. 43 08400	ARCA	ORCA
Energie range	**> TeV**	**GeV - TeV**
Location	100 km off Sicily (It.)	40 km off Toulon (Fr.)
Max. Depth	3450 m	2450 m
DU Height	~ 700 m	~ 200 m
DUxDOM Spacing	90 m x 36 m	20 m x 9 m
# Building Block	2	1
Instrumented Volume	~ 1 Gton	~ 7 Mton



1 DOM = 31x3” PMTs
→ **Analysis @ MeV**

1 **DU** (Detection Unit) = 18 **DOMs** (Digital Optical Modules)
1 **BB** (Building Block) = 115 DUs



The KM3NeT Multi-Messenger Program

Context: Time-domain and multi-messenger astronomy requires combined observations → needs for a rapid communication of information.

KM3NeT Follow-up:
After reception of external alerts, look for space-time coincidence.

→ operational since early 2023

KM3NeT Alerts:
Identify interesting neutrino candidates and send alert.

→ Work in progress (2026 target)

→ Triggered Search: look for neutrino counterpart to external alerts.

→ Untriggered: Fast identification of interesting neutrino candidates.

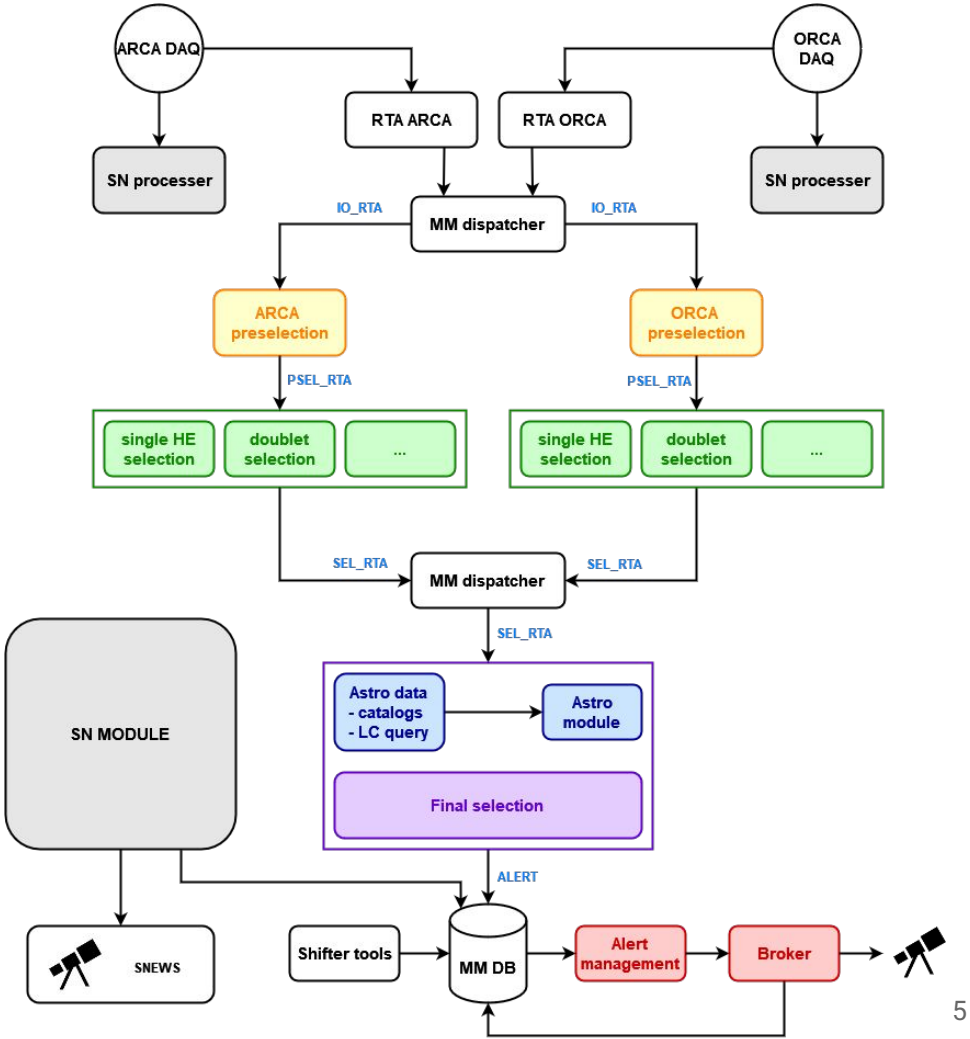
→ Sharing relevant information with the astronomy community for further follow-up.

PoS(ICRC2025)920

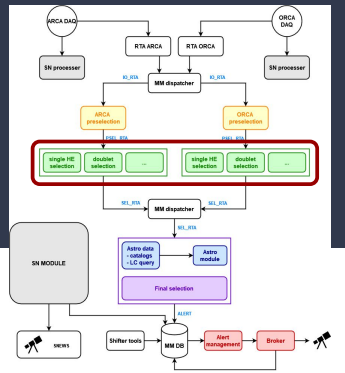
The Alert Sending System

Near to real-time (~1 min) trigger:

1. Acquire & process data (RTA ~20 Hz): **reconstruction and classification**
2. Data reduction: Fixed **preselection** ~500 events/month
3. **Analyses** selection ~1 event/day/analysis
4. Search for **astrophysical counterparts**
5. Alert **selection and broadcast**: ~1 events/month/analysis → Provide useful information (Time, Position, Energy, FAR, astrophysical counterparts, …)



Analysis methods for event selection



HE Analysis pipelines:

1. **Single Event selection**
2. **Multiplet selection**
   - *Long-duration excess (under investigation)*

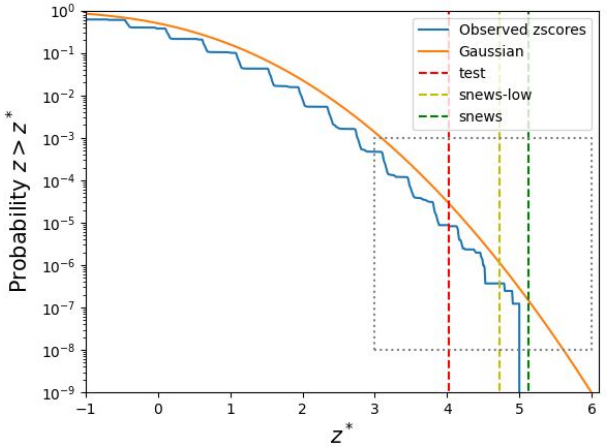
Run in // on all the pre-selected events.

Tuned to each detector ⇒ Distinct pipelines for ARCA / ORCA

Selection based on False Alarm Rate (FAR)

SN monitoring → At DAQ level, in 100ms timeslice:

1. Count # of DOMs with a given # of triggered PMTs.
2. Compare result to expected value from background → significance
3. Report directly to the SNEWS broker if result FAR < 1 in 8 days
   SNEWS2.0 work in progress
   + inclusion to the tools for HE alert sending on long term.



Single HE event selection

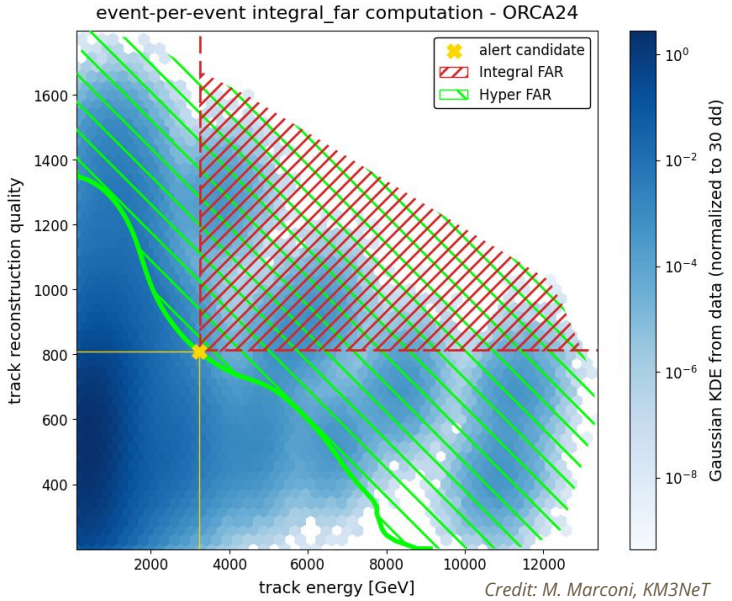
Look for high-energy cosmic neutrino candidate events.

Goal: prioritize candidates according to their **level of exceptionality.**

For each event passing the pre-selection, compute:

1. "**IntegralFAR**": Compute the False Alarm Rate (FAR) by counting events with more extreme parameters in *reco_quality*, *energy* and *length*.
   ❗ Several points of the phase-space can have the same FAR ⇒ degeneracy problem

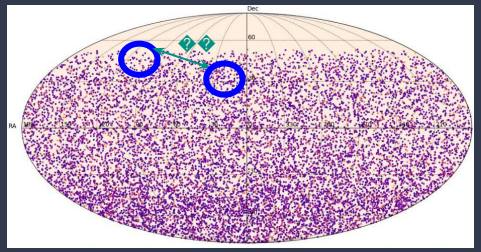
2. "**HyperFAR**": Sum of event satisfying Integral FAR ≤ integral FAR of the candidate (*count # background events with more extreme features than the alert candidate itself*).
   ⇒ Ensure the selection of a specific number of event each month



→ Alert significance is given by the IntegralFAR.

Multiplet selection

Look for events coming from **compatible sky locations in a given TW** (time window)
→ Use 2D map of time/space correlation

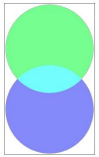


Time correlation (from Phys. Rev. D 103, 042003):

$P(\Delta t \leq \tau \mid \lambda) = 1 - e^{-2\lambda\tau}$

τ: Interval between two events
$\lambda = N/T * (1/D)$ weighted event rate
$D = N_{day} \times TW_{duration}$: dilution factor

Space correlation: $ploc = 1 - (\frac{N_\cap}{N_\cup} \times (1 - \frac{N_\cup}{N_{tot}}))$



$N_\cap$: Overlapping pixels (cyan)
$N_\cup$: Union pixels (green+cyan+blue)
N_{tot}: Number of pixels in the sky

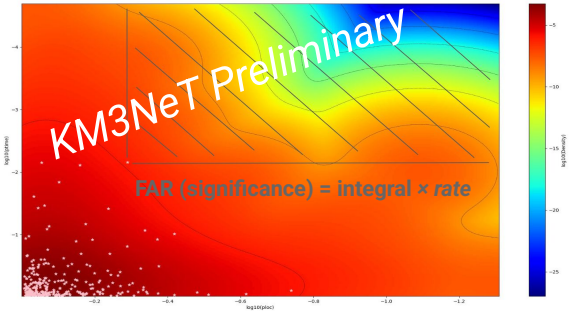
Combine direction and errors (from Astropart. Phys. 92 (2017) 30–41):

Weighted Arithmetic Mean → $X_{mean} = \frac{\Sigma_{i=1}^{N} X_i/\sigma_i^2}{\Sigma_{i=1}^{N} 1/\sigma_i^2} \quad \sigma_w = (\sum_{i=1}^{N} \sigma_i^{-2})^{-1/2}$

N: Multiplicity; ***i***: individual event; ***X***: cartesian coordinate; **σ**: direction uncertainty.

Give a significance: compare preselected events to a mock distribution

1. **OffSource sample**, once per day (~15min)
   a. Create a fake event list (~50000 evt) by fitting the true ones
   b. Compute *ploc* & *ptime* for all this fake events;
   c. Get the density by fitting the 2D distributions.
2. **OnSource sample**: all preselected events (~30/days) within the sliding TW.
3. Compute *ploc* & *ptime* of each new event against the OnSource list (~4s)
4. Get the FAR from integral of the density and TW rate.

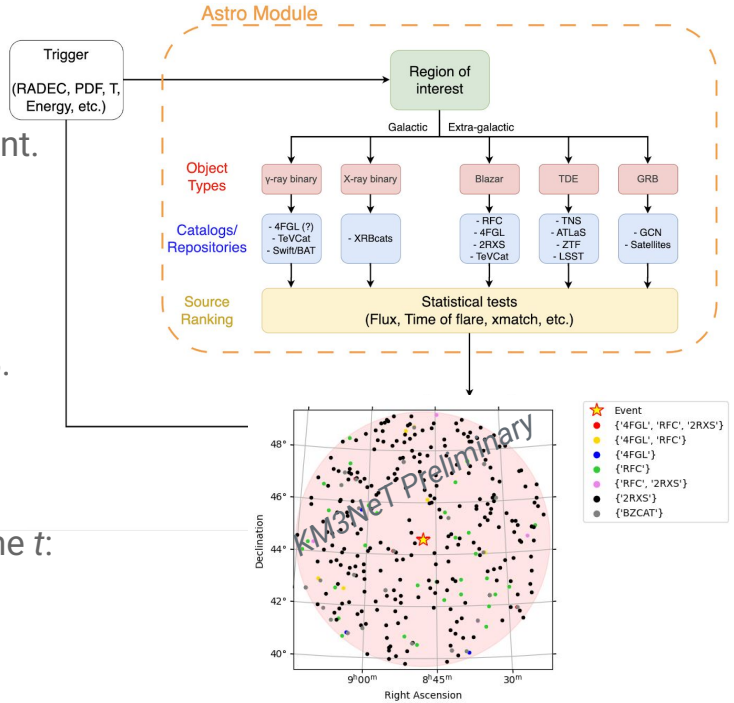


Astro module

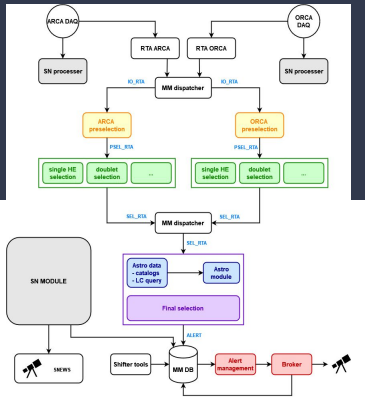
Look for **astrophysical counterparts** to each event selected as neutrino candidate.

→ provide additional information to increase the interest of external collaborations in follow-up.
→ Complement the "pure neutrino" alerts by alerts with a MM component.

1. A focus on Blazars, GRBs, TDEs and μQuasars.
2. Two search samples:
   - Galactic (|b|<10º): 4FGL, TeVCat, XRB.
   - Extragalactic: ROSAT , 4FGL, RFC.
3. Xmatch to avoid source appearing in >1 catalog.
4. Rank the source from its flux *f*, the distance to our event *r* and time *t*:
   → Compute a probability $P_{Tot} = P(P_f, P_r, P_t)$
5. Return Names, RA, Dec, pval, info (flux, type, z, etc.)

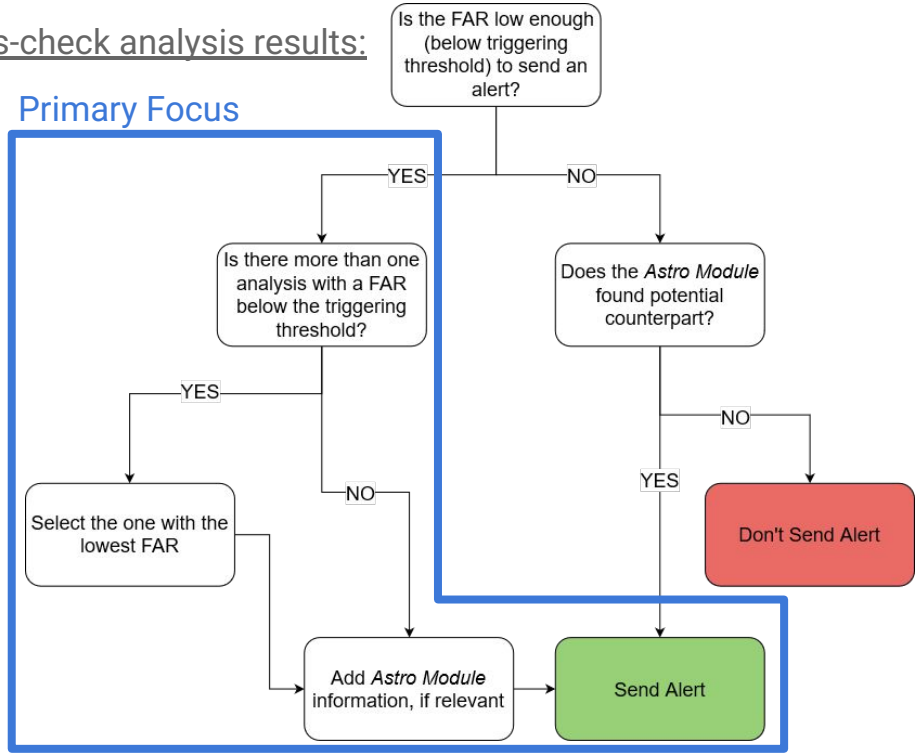


Final selection module



Cross-check analysis results:

Primary Focus



1. Prepare additional info:
   - Event name
   - HEALPix skymap
   - Error region

2. Store Event, Selection, Information, *etc*.into our database (*MM_DB*)

3. Orchestrate further checks (e.g. verify the presence of the identified singleHE events into the Multiplet list, or insert them if missing).

Policy for follow-up reporting and alert sending.

If a **follow-up** shows interesting results or an **astro event is notable enough**:

- ➔ Send a **GCN circular** or an **Astronomer's Telegram** (written by shifters/online coordinator and approved within 12h by the decision group)
- ➔ Set up an **offline analysis** with refined detector knowledge (MC, calibration, reco, analysis methods …), if needed.

Alert Broadcasting: If a **HE neutrino candidate is identified** → Send a public **notice** (GCN / SNEWS2 through Kafka)

⇒ share events like the UHE event candidate KM3-230213A identified in 2023.

Alert content

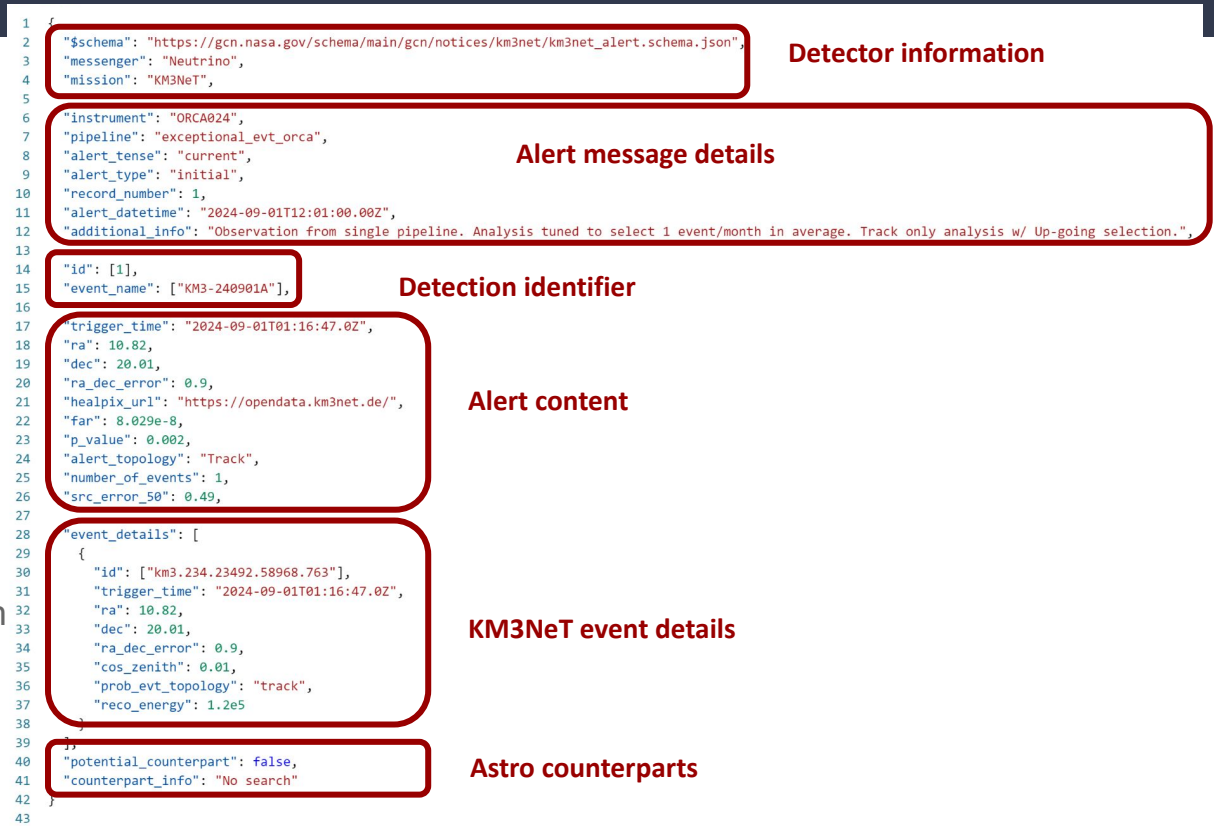
JSON Notice example

Common core for Neutrino Telescopes
→ defined with IceCube

- Notice related information:
  Analysis, time, identifier
- Alert related information:
  Time, Coordinates, Error,
  Statistics, Topology

KM3NeT specific:

- Neutrino related information:
  Event details with energy, direction
- Selection of Counterparts.



Conclusion

Alerts are key in multi-messenger astronomy to allow for wide follow-up observations of transient phenomena.

KM3NeT is building a multi-messenger program.

Its follow-up part has been running for more than a year.

The alert sending system for supernova as well.

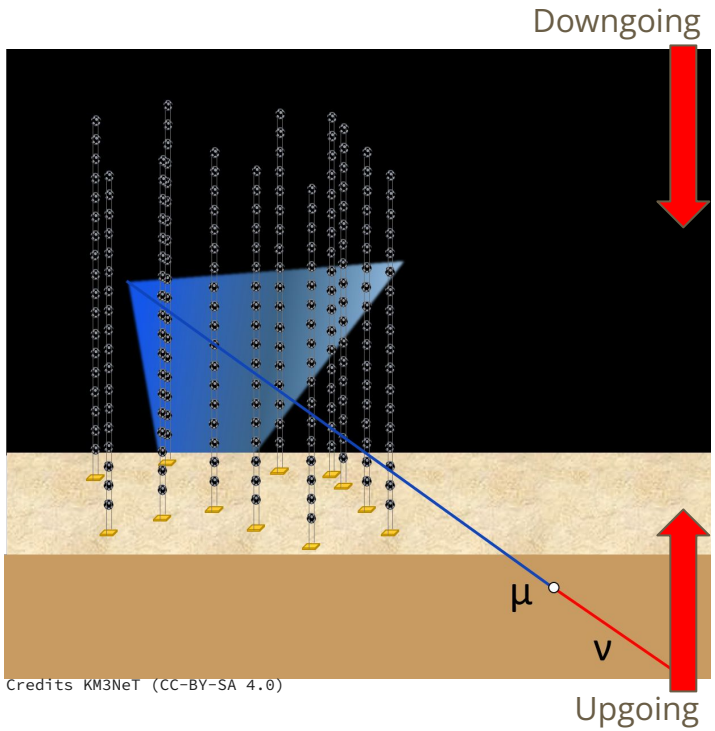
The alert sending system for HE events is under construction, with final development on the error region.

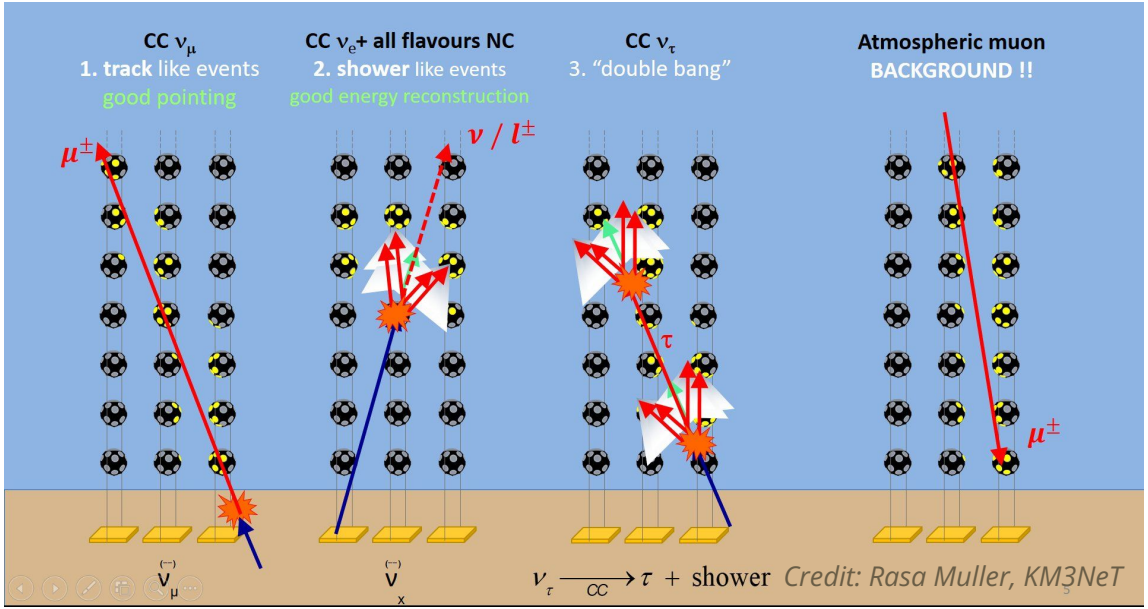
The commissioning phase is expected to start by the end of the year.

Thanks! Now, question time!

Detection principles

3D PhotoMultiplier Tubes (PMTs) array: Detect the **Cherenkov radiation** from the secondary particle produced by neutrino (weak) interaction.





High Energies (HE) studies: use Earth as target.

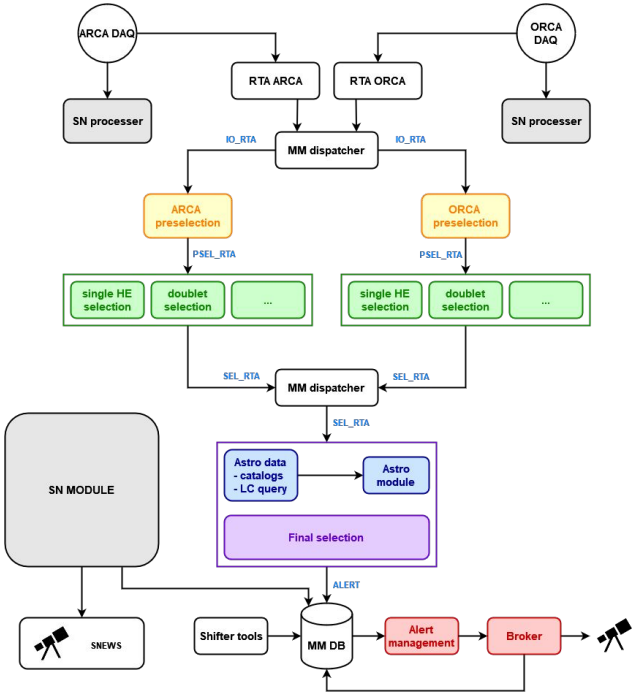
Data management

Data exchanges between standalone modules → various protocols:

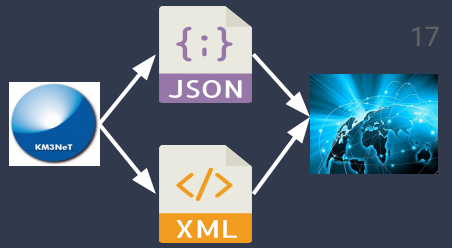
- **JLigier** instances: IO_RTA (all events reconstructed online) and SEL_RTA (to make the final selection)
- **RabbitMQ** server: PSEL_RTA (listened to by each analysis module)
- **PostgreSQL notification** (on new insertion in DB): trigger the alert sending module

Dedicated tables in MM_DB to archive event and alert information (selection type, FAR, notice, …)

	Module	Rates
PSEL_RTA	Pre-selection	~500 events/month/detector
	Analysis	~20 events/month/analysis
SEL_RTA	Final selection	1 event/month/analysis



Alert Reporting



External Broker:

GCN Notices (Standard in MM community)

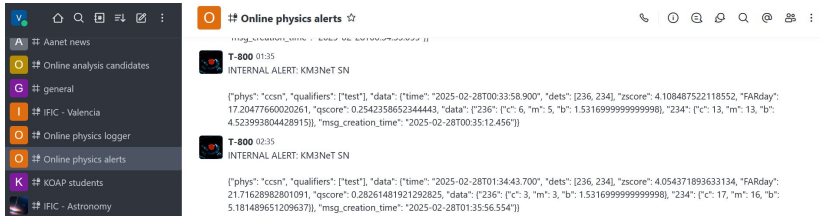
- JSON (see slide 33)
- VOEvent (IVOA historic XML standard)

→ Both via the Kafka protocol (decentralized creation and reception of messages through a central server)

Can be disabled through command line
`<set-alrt-sender-veto ON>`

Internals:

- Dedicated ROCKET.CHAT channel



- Mail list (could be used for subthreshold events)

→ Always active