Latest multi-messenger results of the KM3NeT real-time analysis framework

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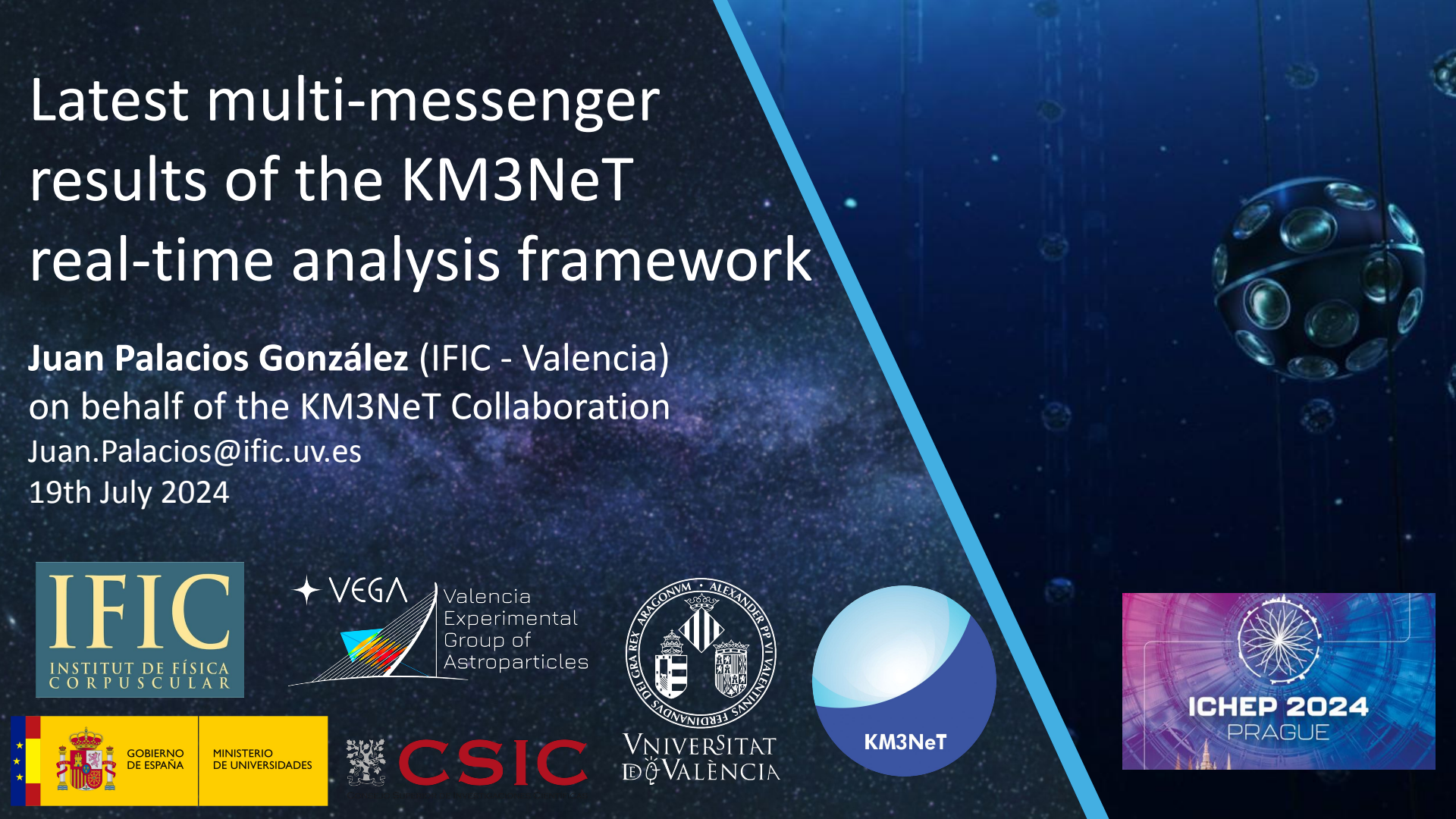
19th July 2024

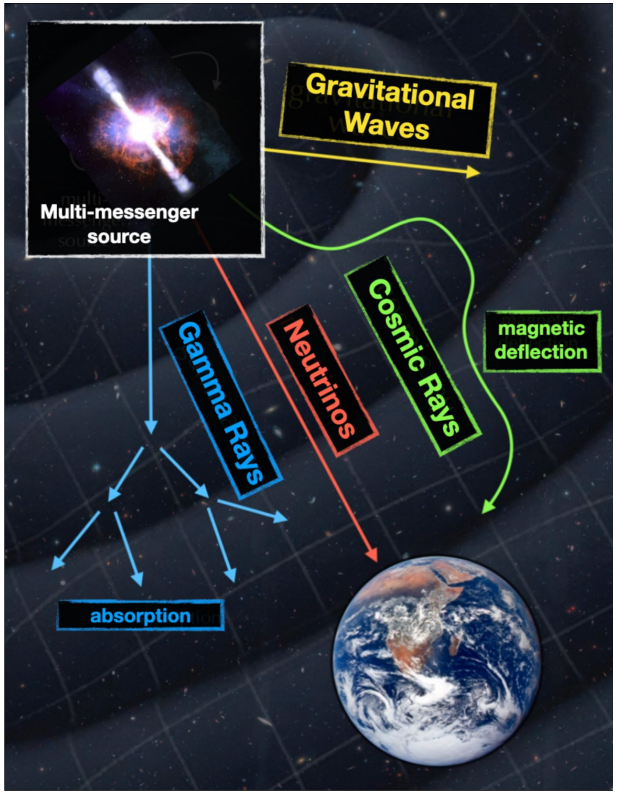


A multi-messenger context

- A **coincident detection** with multiple cosmic messengers enhances the sensitivity for identifying astrophysical sources.
- **Cosmic rays**
  - Abundant, mostly **charged** particles.
  - **Deflected** by magnetic fields.
- **Gamma-rays**
  - Emitted in **hadronic and leptonic** processes.
  - >100 TeV only **nearby sources** (i.e. Galactic) can be observed.
- **Gravitational waves**
  - Hint for the merging of **compact objects**.
- **… Neutrinos!**
  - Stable, electrically neutral: can reach the Earth **undeflected**.
  - Only **weak interaction**: can escape dense environments & not absorbed during the propagation to the Earth.
  - Unambiguous **evidence of hadronic** acceleration:

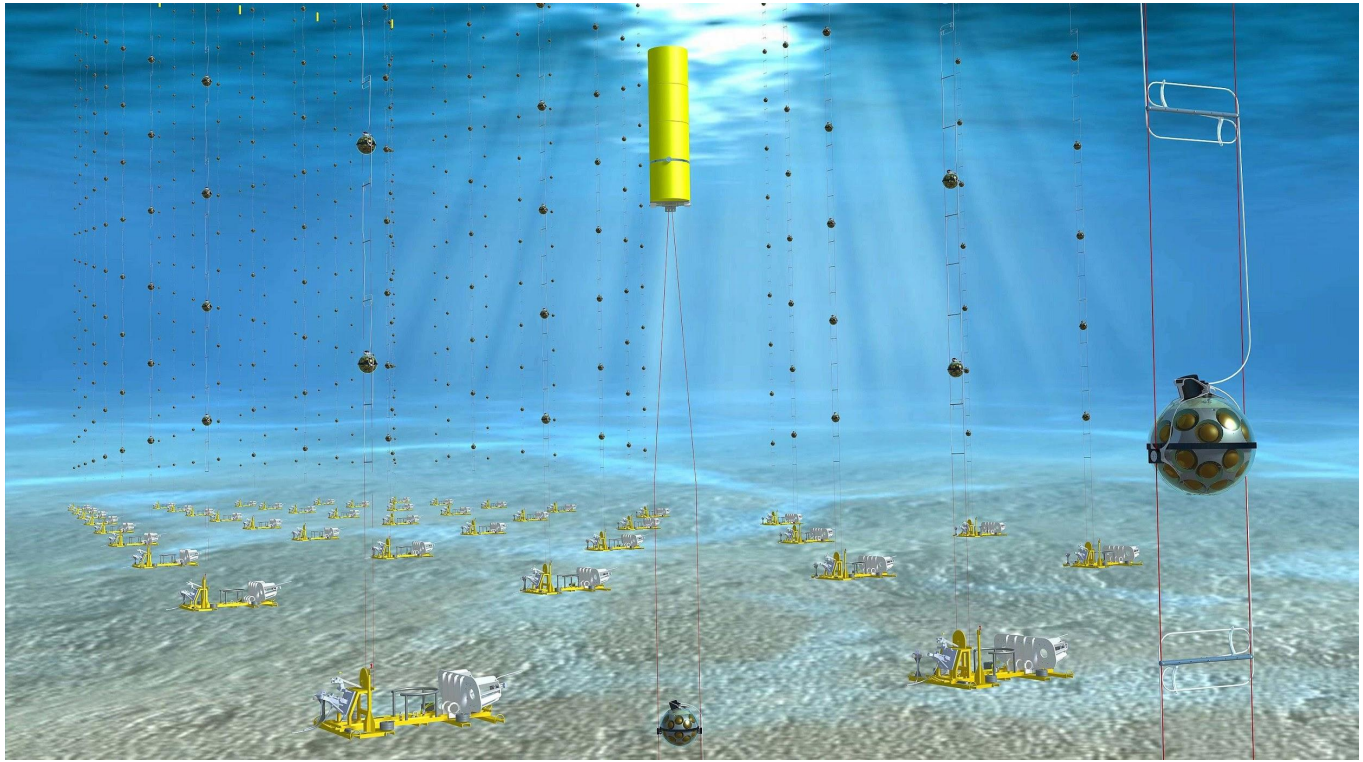
$$p + p(\gamma) \rightarrow \pi^+ + X \qquad \pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

  - Cons: low fluxes & large atmospheric background.



Credit: A. Zegarelli

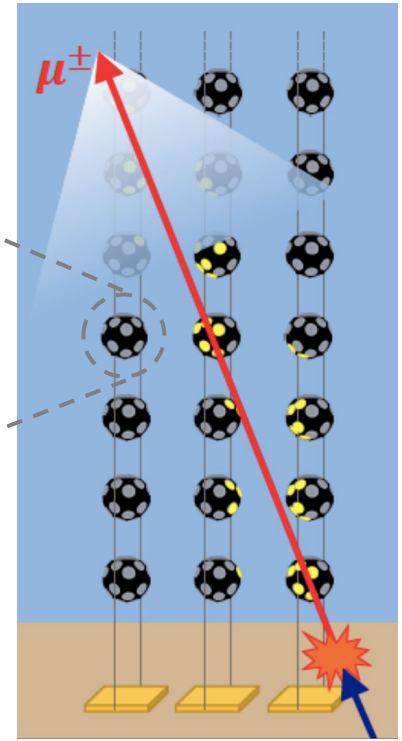
KM3NeT



How do we detect neutrinos? ⇒ Large-scale structures in **transparent media** (like the Mediterranean Sea).

KM3NeT

Digital Optical Module (DOM)



Credit: R. Muller

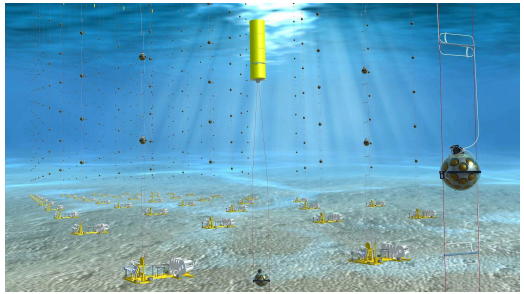
- Array of photomultipliers tubes (PMTs) to detect the **Cherenkov radiation** induced by neutrino interactions.
- **KM3NeT-ORCA:**
  - 40 km offshore Toulon (France), 2450 m depth.
  - DOM spacing: 20 m x 9 m.
  - Sensitive to the **GeV-TeV energy range**.
  - Currently taking data with 23 lines (20% of the full configuration).
- **KM3NeT-ARCA:**
  - 100 km offshore Sicily (Italy), 3450 m depth.
  - DOM spacing: 90 m x 36 m.
  - Sensitive to the **TeV-PeV energy range**.
  - Currently taking data with 28 lines (12% of the full configuration).
- Two main reconstruction event topologies: **tracks** and **cascades**.
- **MeV neutrinos** can also be detected through a global increase in the PMT coincide rate in single DOMs.

KM3NeT multi-messenger program

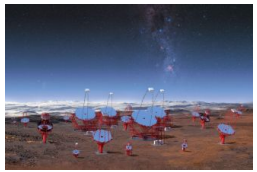
Follow-up of external alerts

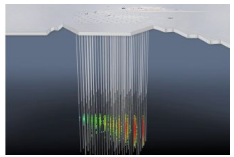
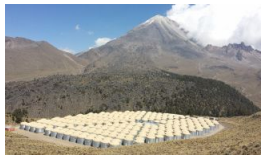
Search for spatial and time coincidences.

Ongoing. Currently reporting only interesting cases manually.



KM3NeT



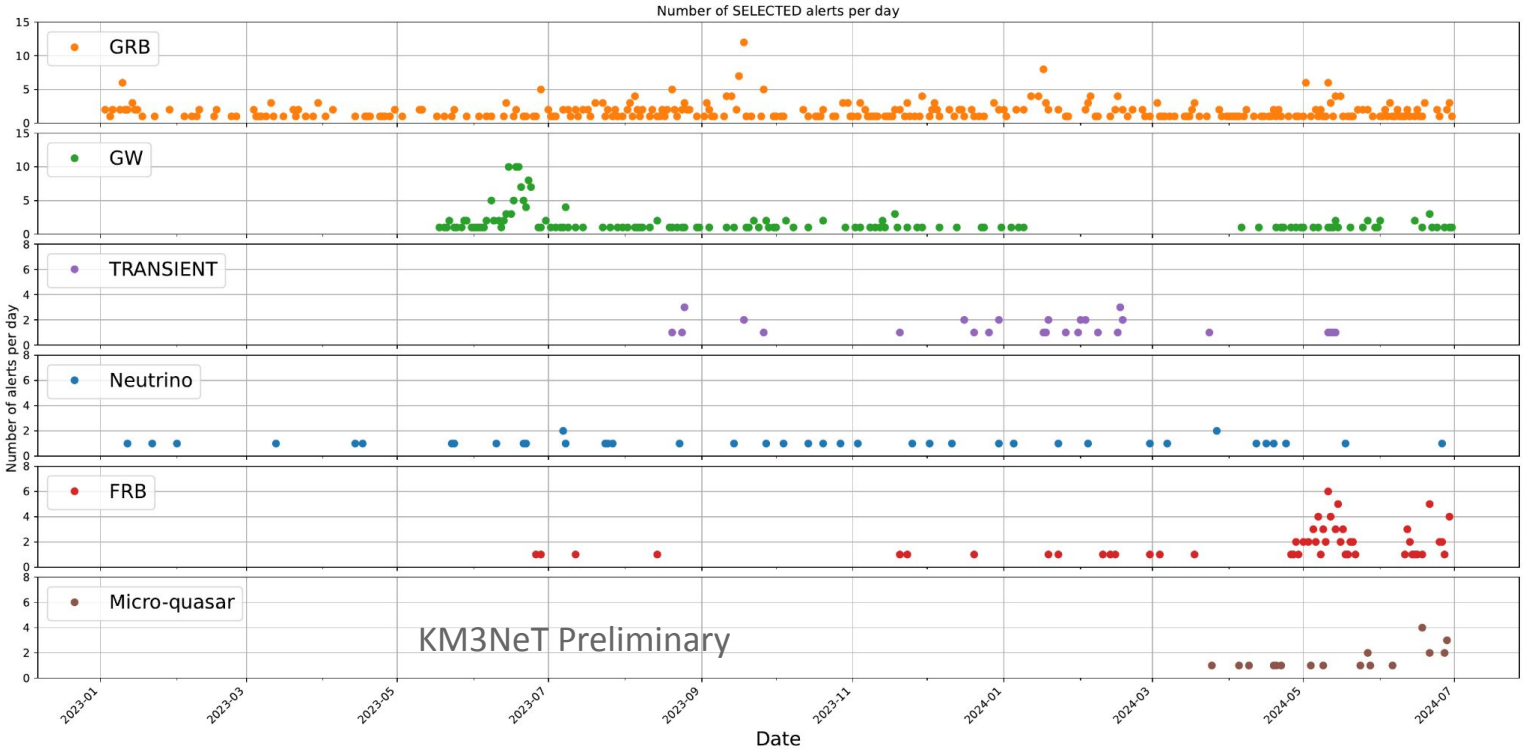
The multi-messenger community

Sending neutrino alerts

Identify potential interesting events to trigger external follow-ups.

Under development. Currently working on neutrino selection & alert sending program.

Incoming alerts



~1 per day

~1 every 2 days

~1 per week

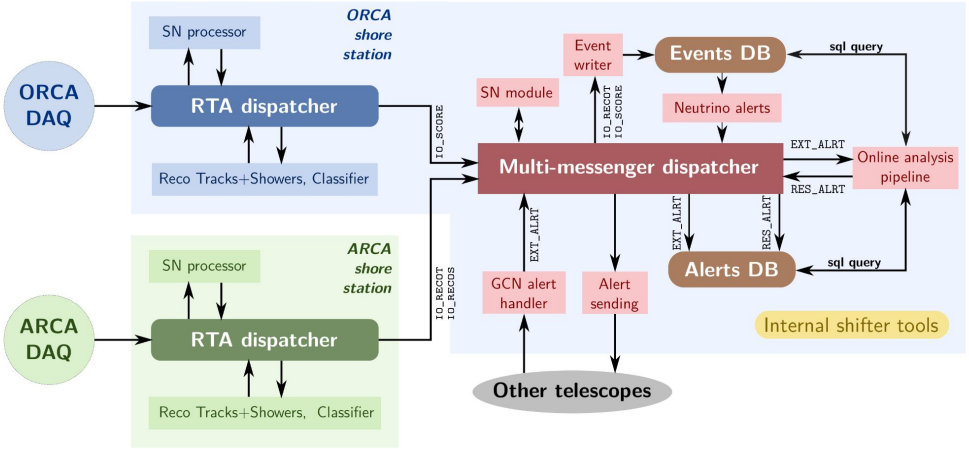
~1 every 2 weeks

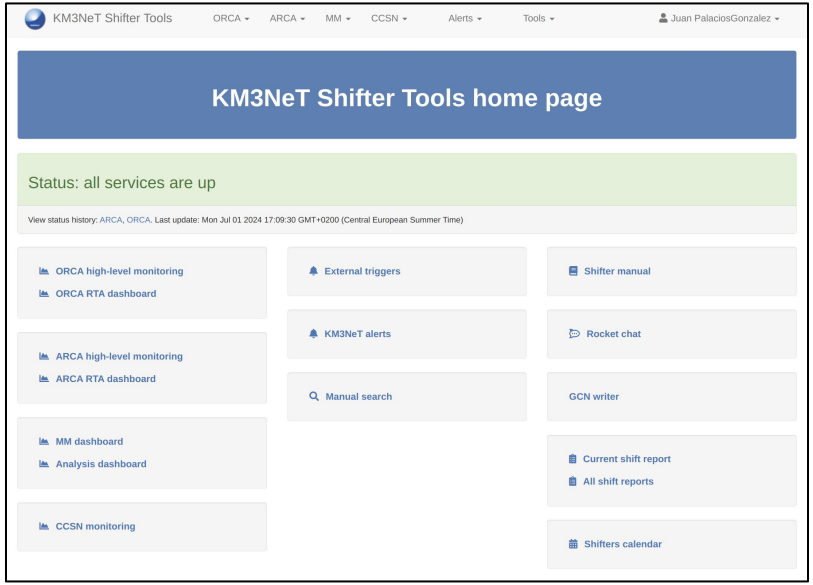
~1 every 5 days

~1 per week

Constantly receiving a stream of incoming external alerts triggers ⇒ Development of an **automatic system** to follow-up.

The real-time framework

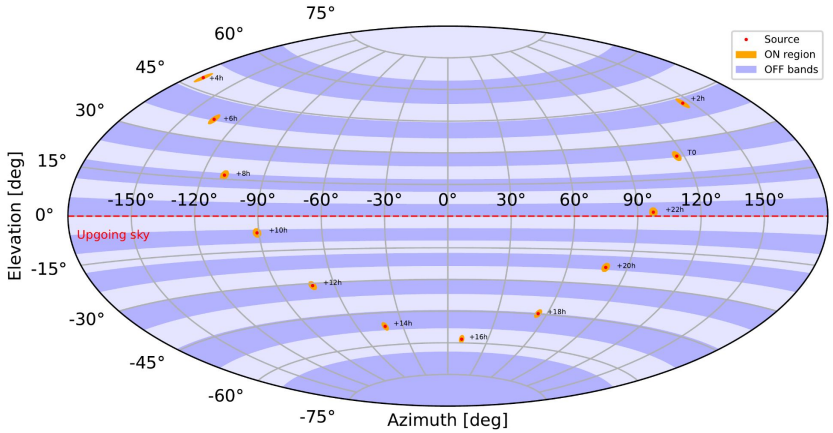




- **KM3NeT Online Platform**: real-time event reconstruction + MM dispatcher + Analysis module.
- Real-time processing of data with online calibration: **track** & **cascades** reconstruction + **classification**.
- Triggered events are processed in real-time in **less than 7 s** for both ARCA and ORCA.
- **Main analysis functionalities**: follow-up of external triggers (active), Core-Collapse Supernovae alert pipeline (active), sending high-energy neutrino alerts (work in progress).

Analysis technique

- **ON region:** where the **signal** is expected. Includes source location error + angular uncertainty.
- **OFF region**: local zenith bands to compute the **expected background**, spanning the ON region movement due to Earth's rotation.
- Multiple T_{ON} time windows are inspected depending on the alert type.
- T_{OFF}: up to two weeks of previously taken data.
- **Event selection** optimised to reduce the background to the level with the best achievable significance.
- **p-value** determined when comparing the number of events in the ON region with the expected background.

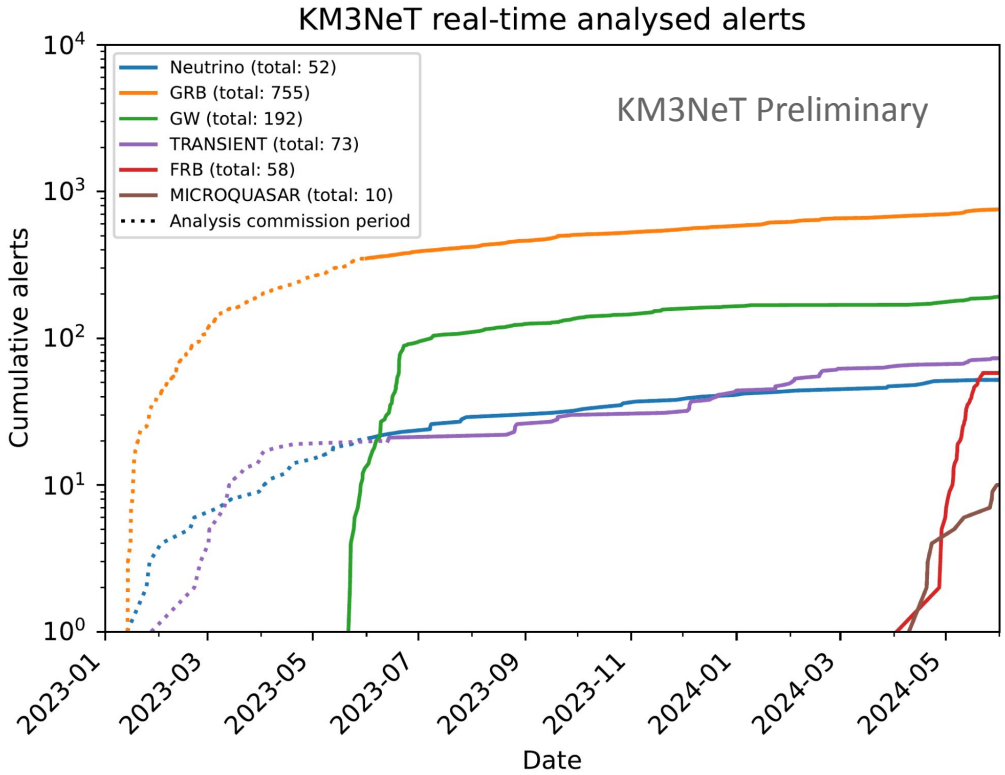


$$n_{bkg} = \sum_{i \in bands} \frac{T_{ON}}{T_{OFF}} \frac{\Omega^i_{ON}}{\Omega^i_{OFF}} N^i_{OFF}$$

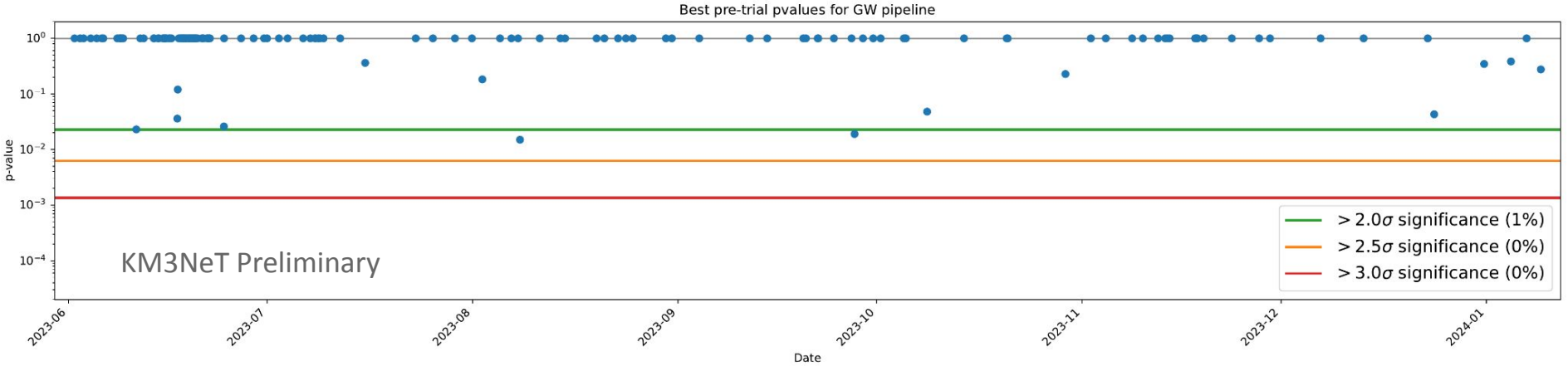
T_{ON} : search time window, depending on the source type
T_{OFF} : 2 weeks
Ω^i_{ON}: overlap between ON region and OFF region band
Ω^i_{OFF}: size of OFF region band
N^i_{OFF} : number of events in OFF region band after selection

Analysed alerts

- Since the beginning of 2023 we are **continuously analysing** incoming alerts in real-time.
- The **analyses features** are defined depending on the alert type:
  - Dedicated time windows.
  - Source location uncertainties (point-sources vs. GWs)
  - Optimized event selection based on local sky position.
- So far, analyses only use **track-like events** (better angular resolution).
  - ARCA: Median below 2°.
  - ORCA: Median below 4°.
  - Implementation of cascades-like events ongoing.
- **No significant neutrino counterpart** has been found so far.



Follow-up: GWs

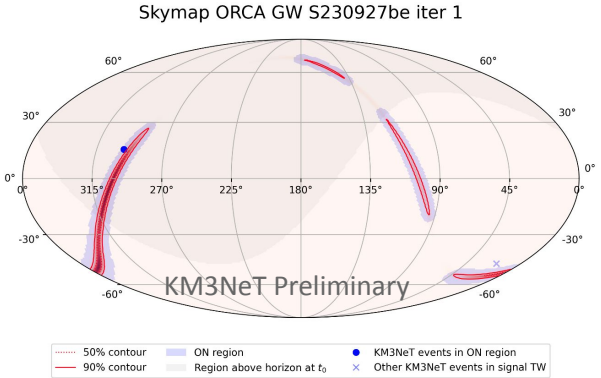


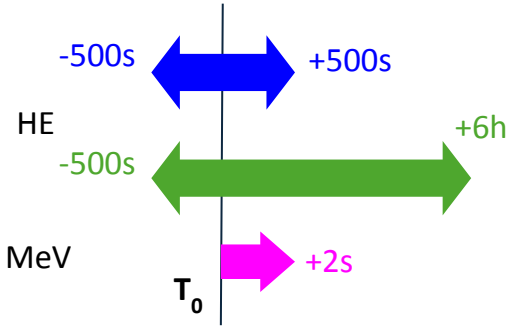
- **Full run O4a covered**. Currently ongoing the follow-up of run O4b.
- No **significant correlation** found.
- Example of typical interesting case:

  S230927be (BBH merger)

  Expected background: 0.018 events

  1 event in ON ⇒ 2.1σ significance





Time windows covered

Follow-up: GRBs, transients

GRB pipeline

- Example of typical interesting case:

  722864655 (28-Nov-2023)

  Alert trigger by Fermi-GBM.

  Expected background: 0.13 events

  1 event in ON ⇒ 1.2σ significance

Transients pipeline

- Example of typical interesting case:

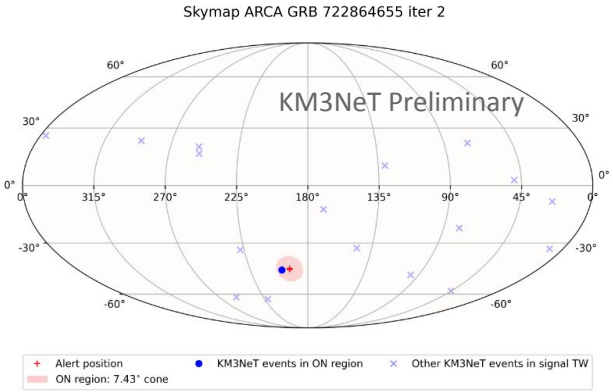
  1186296 (20-Aug-2023)

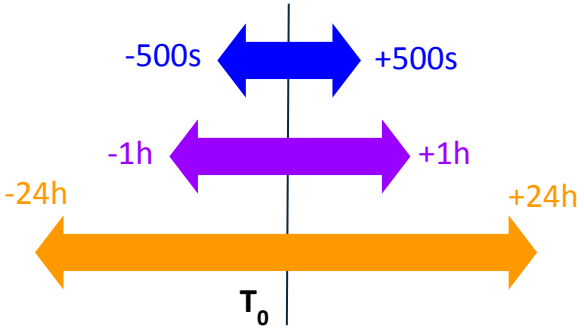
  Alert trigger by Swift-BAT

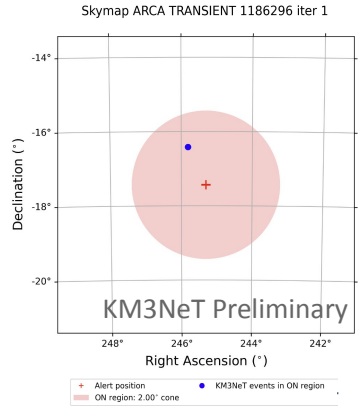
  Expected background: 0.14 events

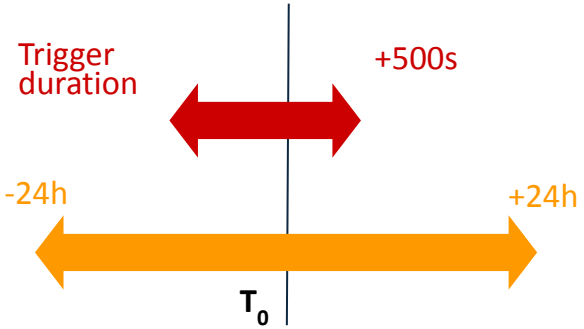
  1 event in ON ⇒ 1.2σ significance

- **No significant correlations** found so far.
- **Follow-ups ongoing**.









Follow-up: Neutrinos, FRBs, μQuasars, CCSNe

Neutrino pipeline (IceCube alerts)

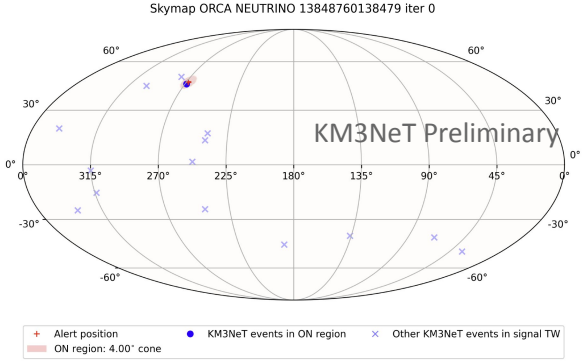
- Example of typical interesting case:

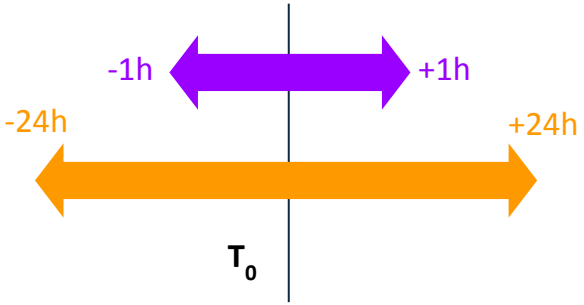
  IC 231027A (27-Oct-2023)

  IceCube gold alert.

  Expected background: 0.07 events

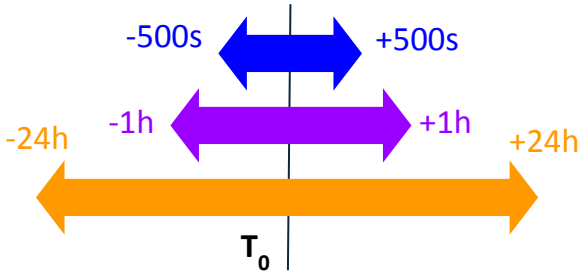
  1 event in ON ⇒ 1.8σ significance





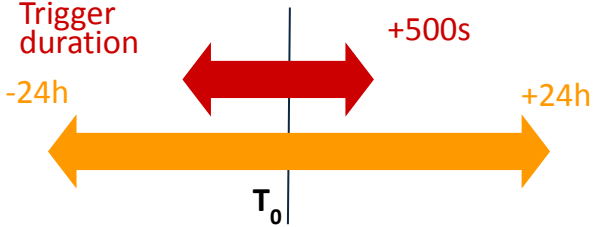
FRB pipeline

- Chime and TNS brokers implemented.



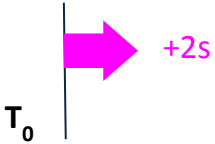
μQuasar pipeline

- Internal broker for detecting luminosity increases in the light curves of selected sources.



CCSNe pipeline

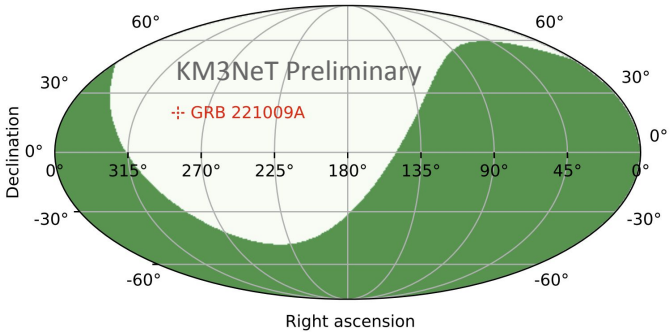
- Search for MeV anti-electron neutrino excess in single DOMs.
- Part of the SNEWS global network.

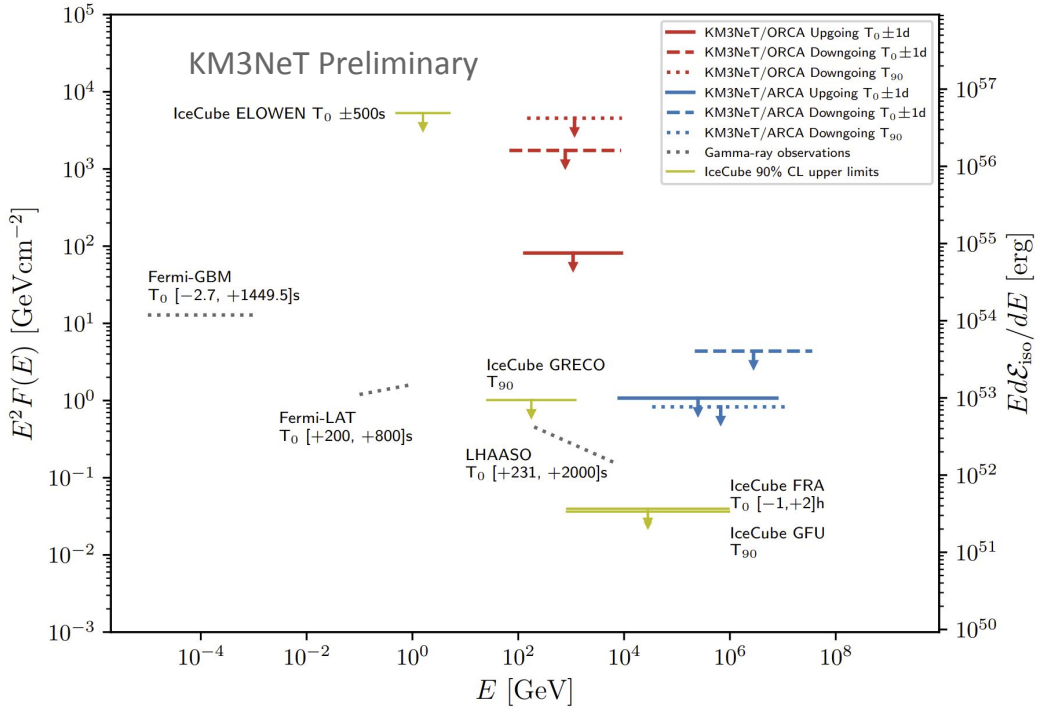


No significant neutrino excess found in any of these pipelines so far. The search continues!

GRB 221009A

- The **BOAT**: the brightest GRB up to date.
- A **real-time search** was conducted by KM3NeT, reported three days after the event: GCN 32741
- **Later refined search** with improved calibrations and selections.
- **No candidate neutrino events** found in spatial and time coincidence.
  - Multiple time windows and event selections were inspected.

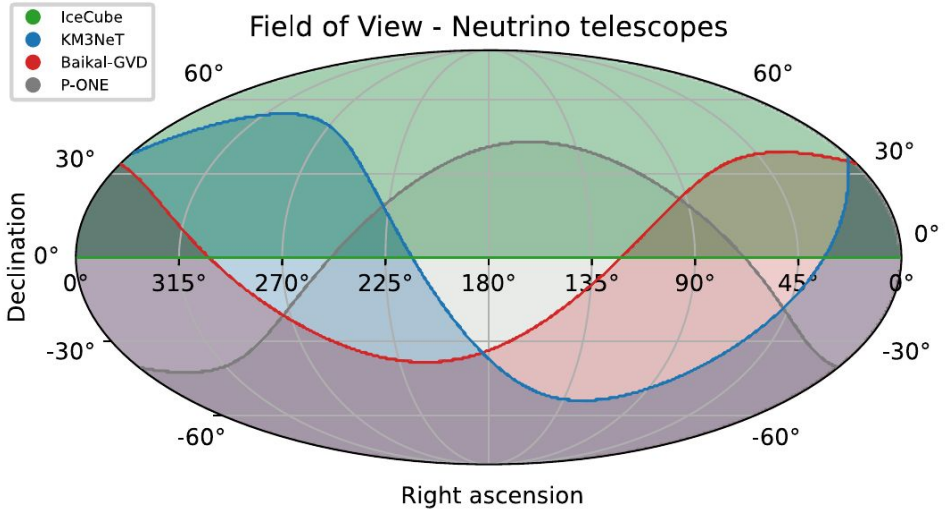




Palacios et al. arXiv: 2404.05354

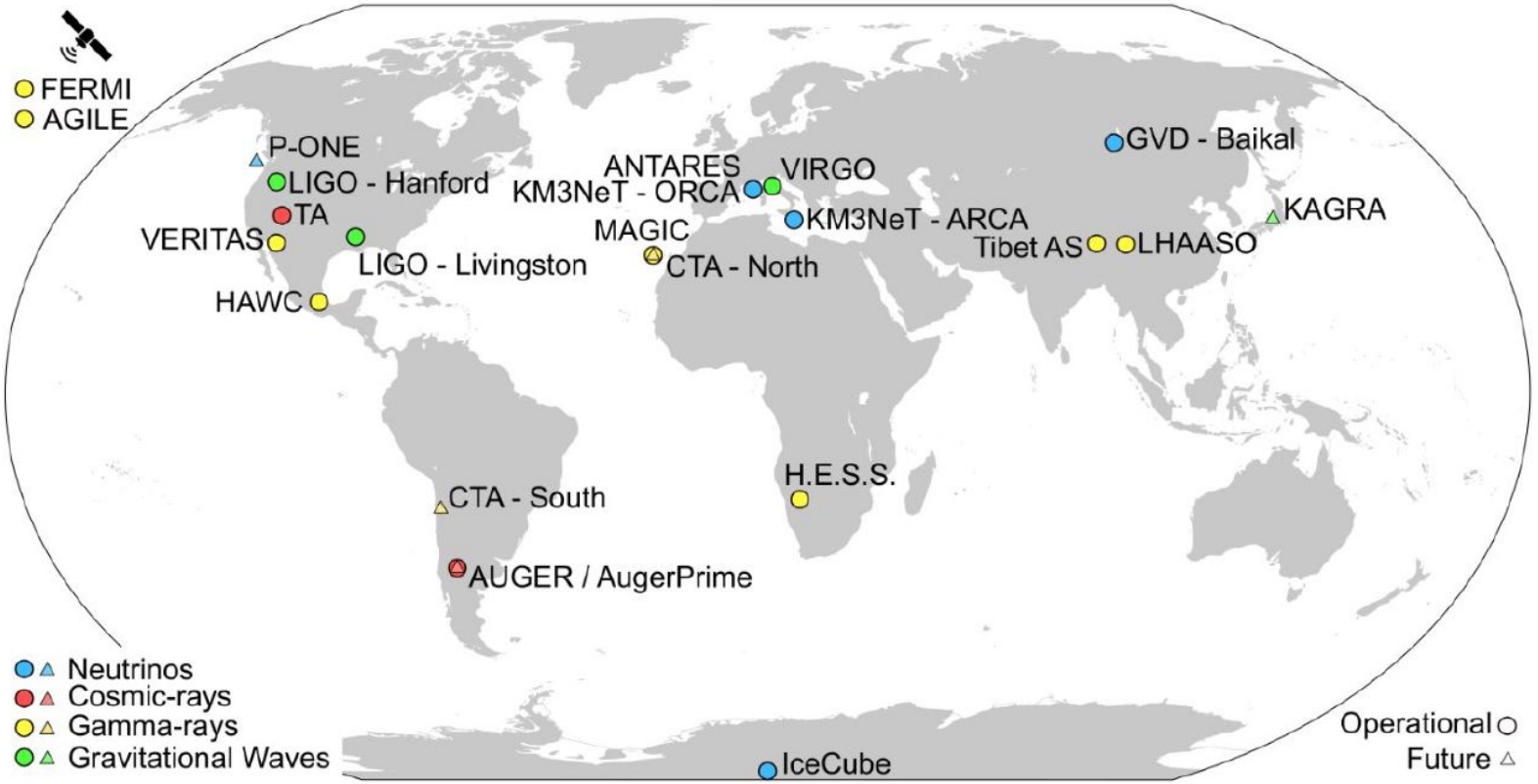
Conclusions

- The **KM3NeT online platform is currently working**, reconstructing ARCA and ORCA events in real-time for multi-messenger activities.
- A crew of two shifters takes care every week of supervising the **correct functioning of the system** and potential interesting results to report.
- **Different analyses** are performed depending on the nature of the source being followed.
- **No candidate neutrino events have been found** so far in coincidence with the external alerts received.
- **The searches continues** while the detectors size grow, increasing the sensitivity to cosmic neutrinos.
- A **world-wide array** of neutrino telescopes doing real-time activities is crucial for a full-sky coverage.



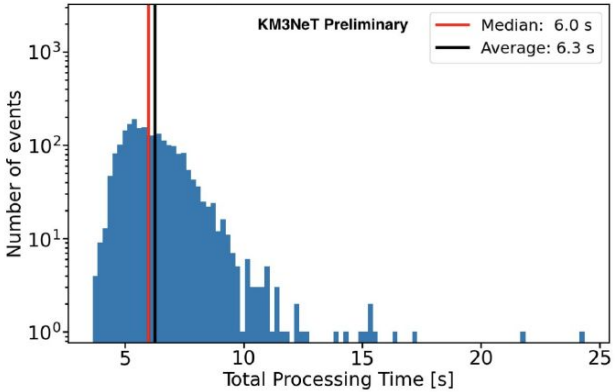
Backup

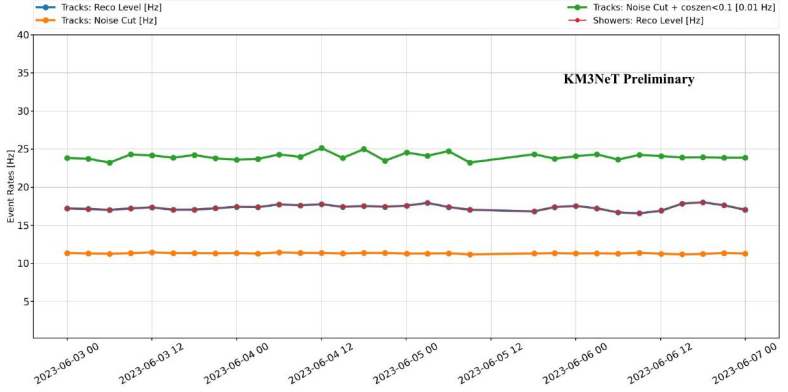
The multi-messenger community



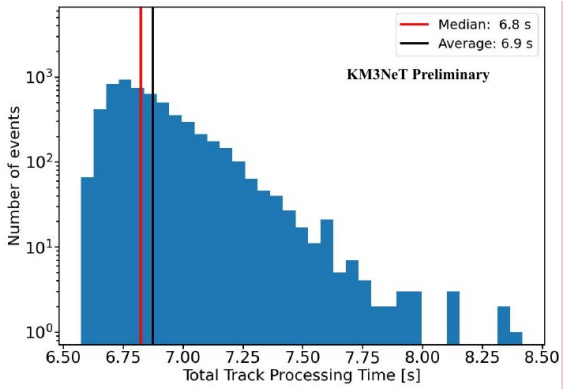
RTA processing times and rates

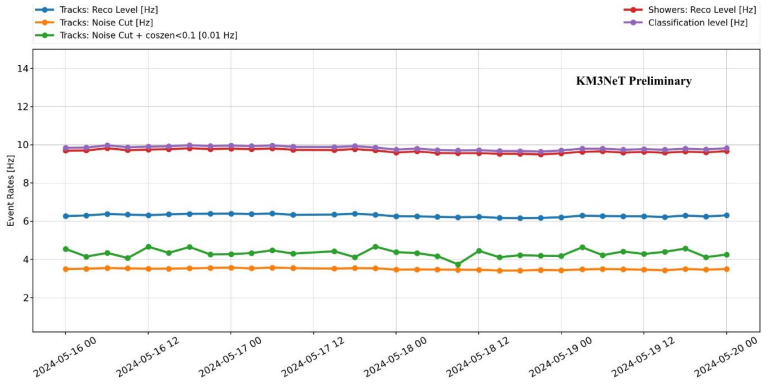
ORCA18





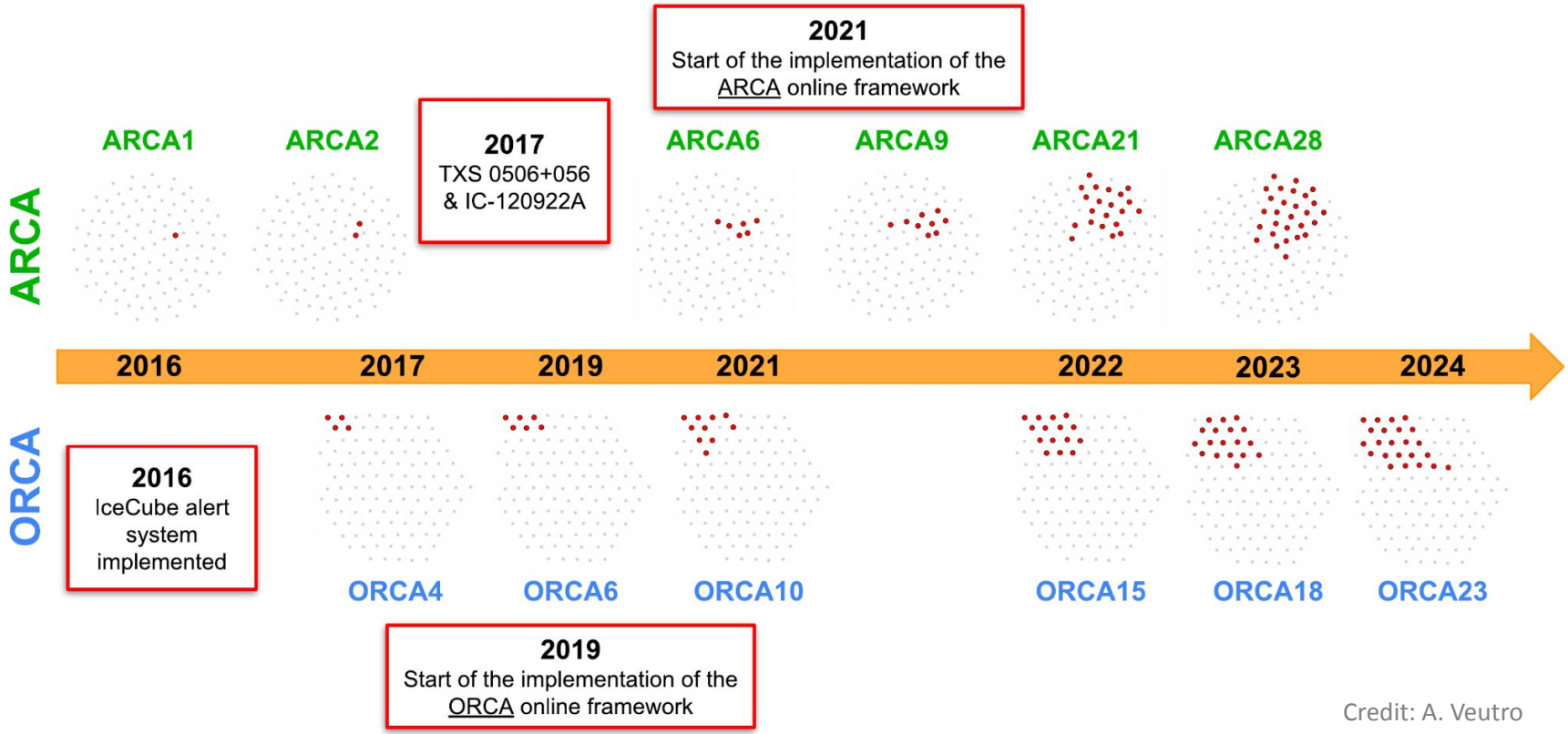
ARCA28





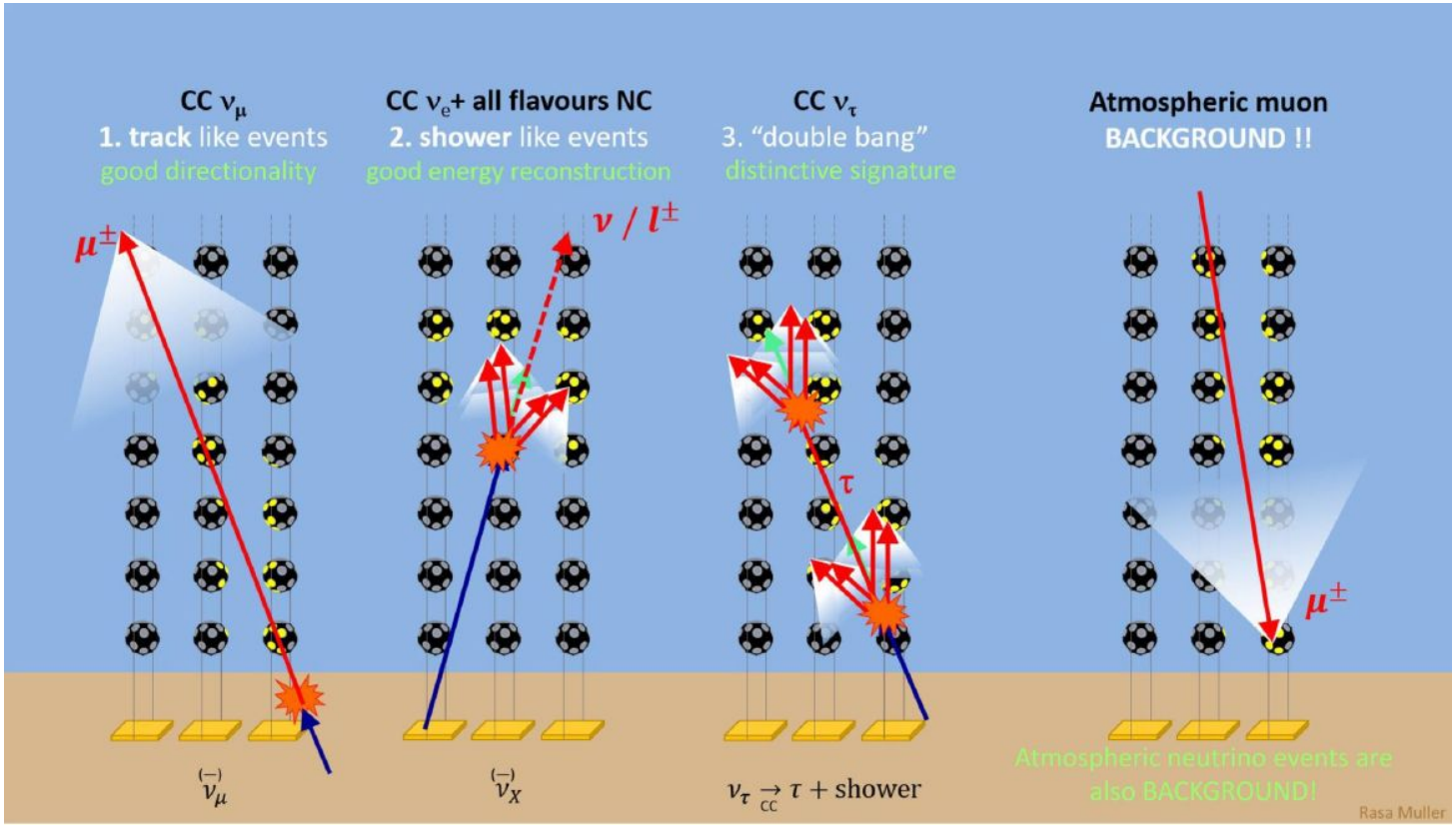
Mastrodicasa et al. Neutrino 2024 poster

Detector construction

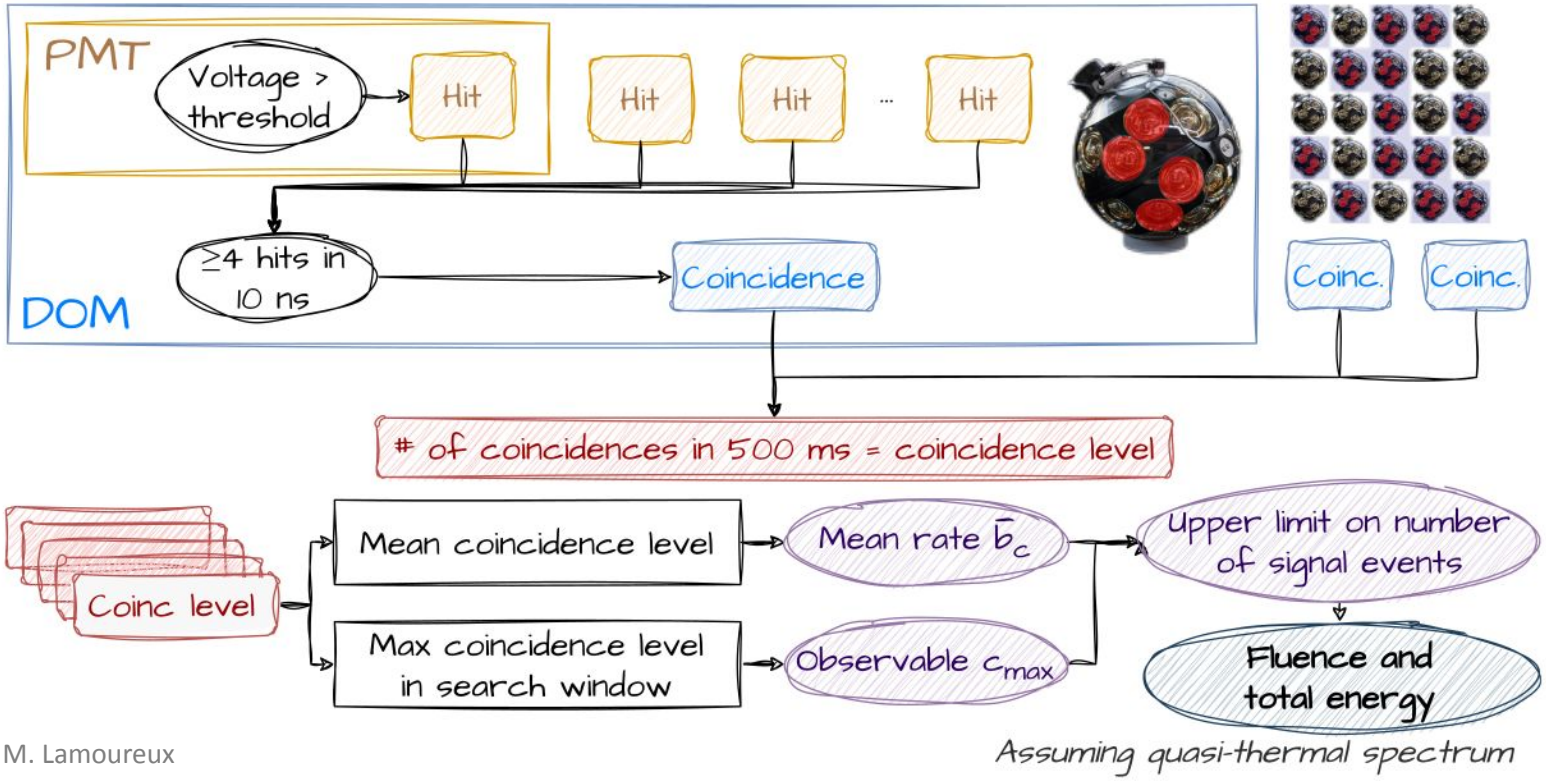


Credit: A. Veutro

Event topologies



MeV analysis scheme



Credit: M. Lamoureux