KM3NeT Online Multi-Messenger Results

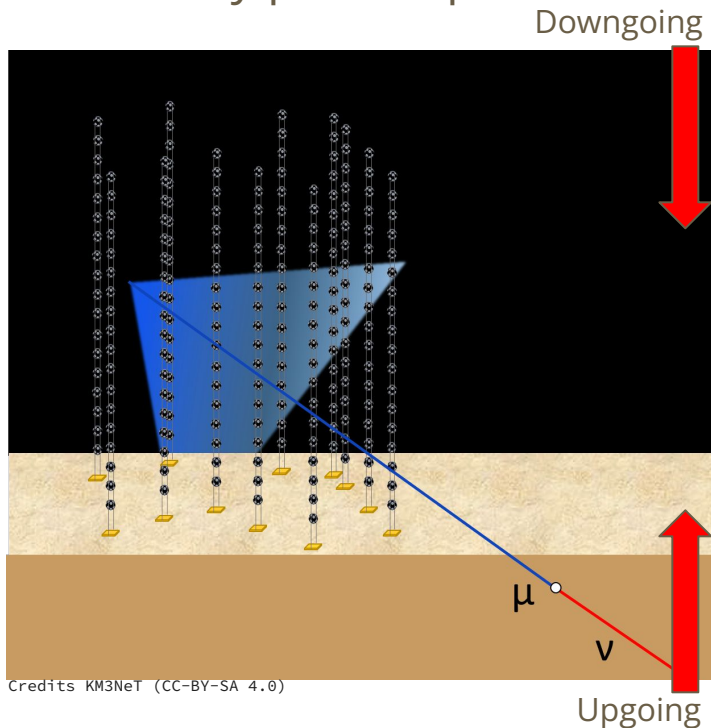September 24, 2024
Vincent Cecchini, IFIC Valencia (CSIC)
On behalf of the KM3NeT collaboration.
vcecchini@km3net.de

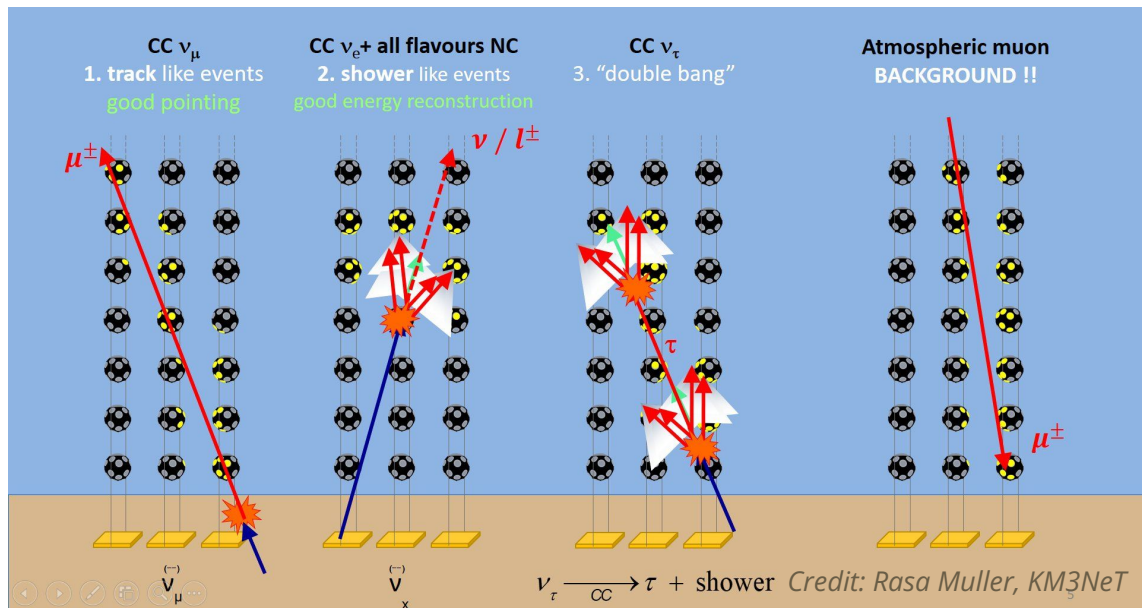**Vincent Cecchini**, IFIC Valencia (CSIC)
vcecchini@km3net.de

KM3NeT principles

PhotoMultiplier Tubes (PMTs) array: Detect the **Cherenkov radiation** from the secondary particle produced at neutrino interaction.

Downgoing

Upgoing

Credits KM3NeT (CC-BY-SA 4.0)

CC ν_μ
1. **track** like events
good pointing

CC ν_e + all flavours NC
2. **shower** like events
good energy reconstruction

CC ν_τ
3. "double bang"

Atmospheric muon
BACKGROUND !!

$\mu^\pm$

$\nu / l^\pm$

τ

$\mu^\pm$

$\overset{(-)}{\nu}_\mu$ ...

$\overset{(-)}{\nu}_x$

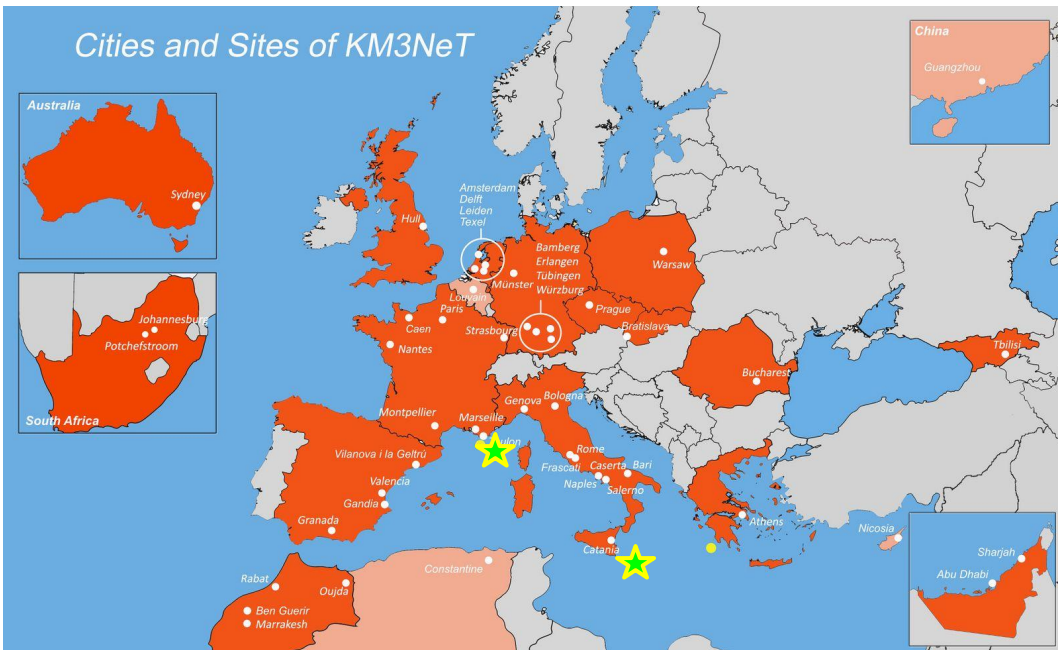$\nu_\tau \xrightarrow{CC} \tau + \text{shower}$ *Credit: Rasa Muller, KM3NeT*

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

The KM3NeT collaboration

20 countries, 48 institutes:

Two sites, under construction:

- **ARCA** (**A**stroparticle **R**esearch with **C**osmics in the **A**byss)
→ First line: 12/2015; Phase 1: 24 lines.
→ ARCA 28 (12% ; 47 lines by end of 2024)

- **ORCA** (**O**scillation **R**esearch with **C**osmics in the **A**byss)
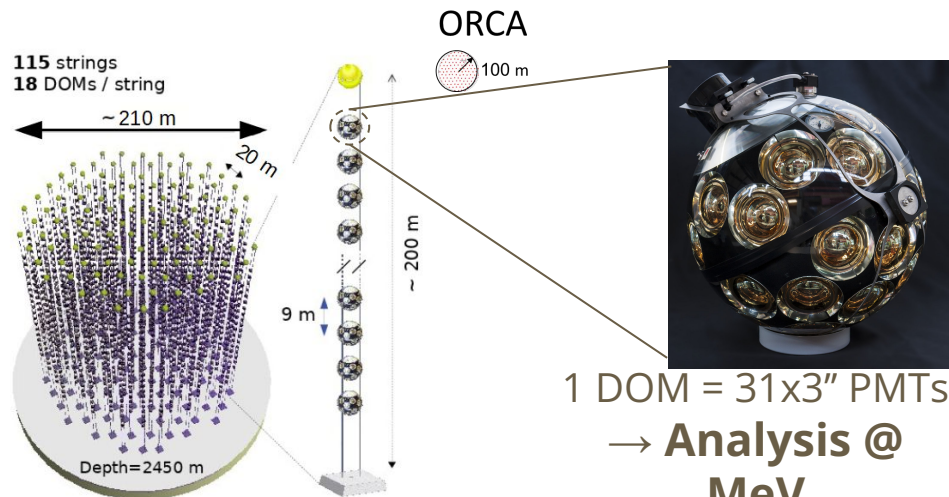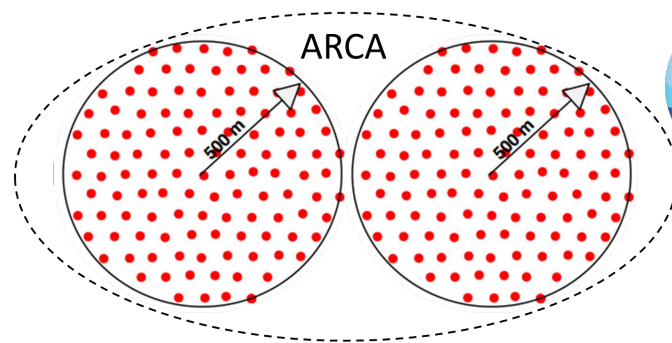→ First line: 09/2017; Phase 1: 6 lines.
→ ORCA 23 (20%)

Completion of the full detector ~ 2028.

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The KM3NeT detectors

	ARCA	ORCA
Location	100 km off Sicily (It.)	40 km off Toulon (Fr.)
Max. Depth	3450 m	2450 m
DU Height	~ 800 m	~ 200 m
DOM Spacing	90 m x 36 m	20 m x 9 m
# Building Block	2	1
Instrumented Volume	~ 1 Gton	~ 7 Mton
Energie range	**> TeV**	**GeV - TeV**

J. Phys. G: Nucl. Part. Phys. 43 08400

ARCA

ORCA

115 strings
18 DOMs / string

~210 m

20 m

~200 m

9 m

Depth=2450 m
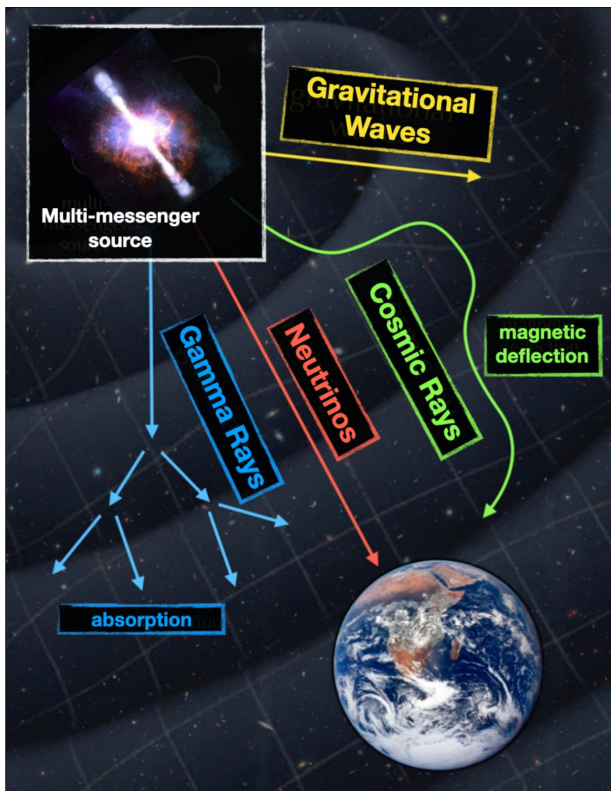
100 m

1 DOM = 31x3" PMTs

→ **Analysis @ MeV**

1 **BB** (Building Block) = 115 DUs (Detection Units)

1 **DU** = 18 **DOMs** (Digital Optical Modules)

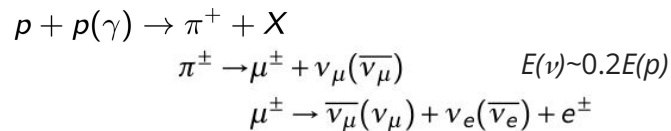# The multi-messenger (MM) astronomy context

Credit: A. Zegarelli

Various signatures from astrophysical sources, with complementary properties:

- **Gamma rays**: **Straight line**, opaque at long range for high-energies (> TeV)

- **Cosmic Rays (CR)**: **Abundant** charged particles, subject to magnetic **deflection**.

- **Gravitational Waves (GW)**: Bends space-time, poor localisation (+narrow wavelength).

- **Neutrinos**: **No deflection** (q=0), weakly interacting (**no opacity**).
Hadronic production only:

$$p + p(\gamma) \rightarrow \pi^+ + X$$
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\overline{\nu_\mu}) \qquad E(\nu) \sim 0.2 E(p)$$
$$\mu^\pm \rightarrow \overline{\nu_\mu}(\nu_\mu) + \nu_e(\overline{\nu_e}) + e^\pm$$

High background + low flux

# Neutrino astronomy in MM context

→ Coincident detection increases probability of astrophysical origin.

Science cases:

- Identify ν Point Sources.
- Probe gamma-rays production mechanism and associated fluxes.
- Probe source opacity (*cf.* coincident detection with TXS 0506+056 X-ray).

⇒ Prompt sharing of observations is primordial.

NB: Universe opaque to EM at PeV/EeV
⇒ need ν to do astronomy at UHE.
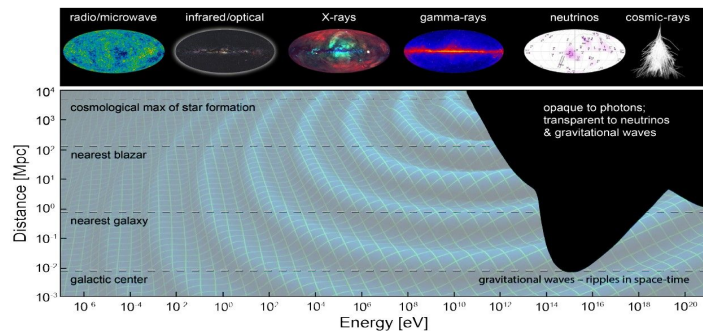
KM3NeT Multi-Messenger Program

Follow-up of external alerts:
Look for space-time coincidence.

→ operational since early 2023

Broadcast alert for significant observation of
HE neutrino candidates.

→ work in progress

Follow-up policy 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:

WiP: If a **HE neutrino candidate is identified** → Send a **notice** (GCN / SNEWS2 through Kafka)
→ Various event selections (exceptional event ; multiplet ; MM enhanced)
→ Early 2025

⇒ share events like the VHE event candidate identified before summer (see R. Coniglione talk tomorrow)

The online analysis framework (more in *M. Mastrodicasa* talk)
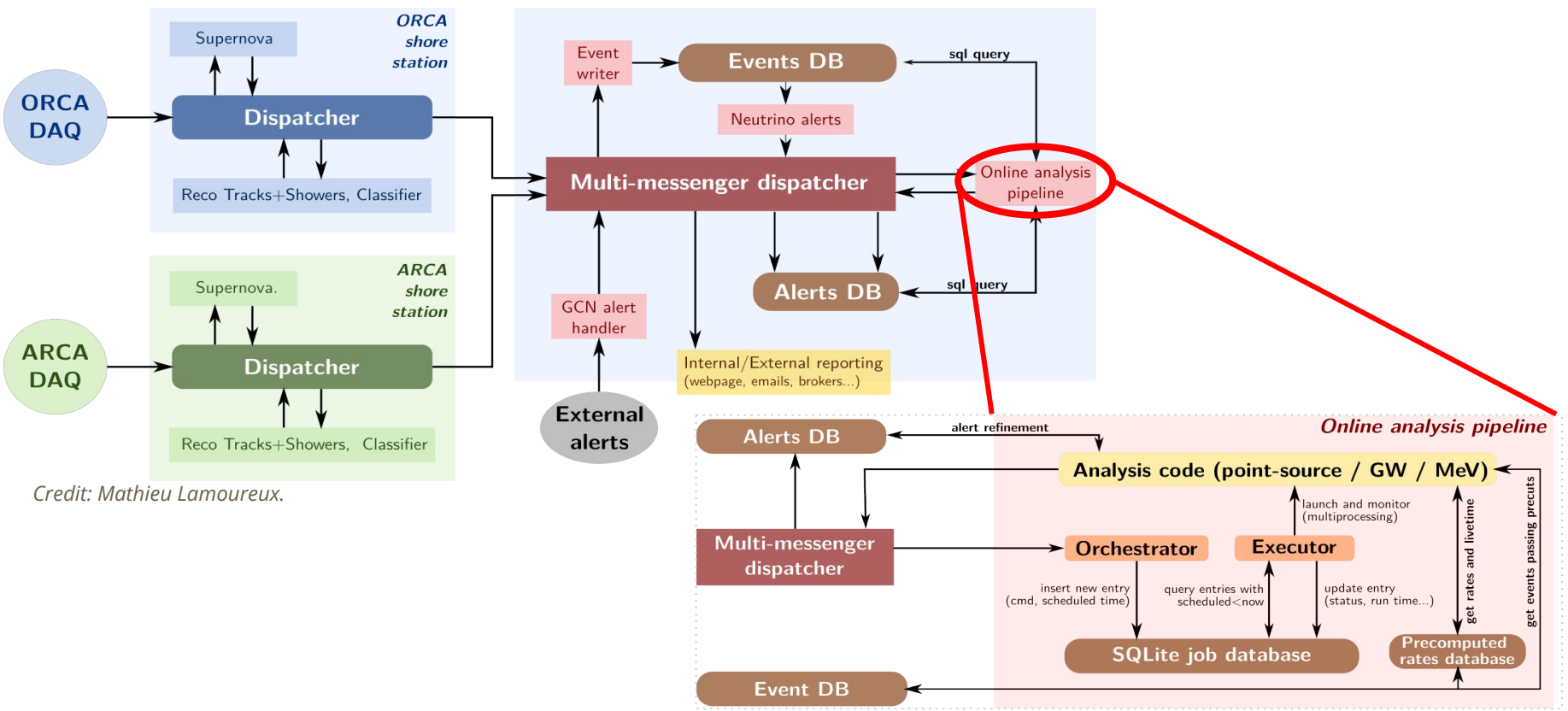
Credit: Mathieu Lamoureux.

Analysed alerts

Commissioning period: 2023 Jan.→June.

Various analysis pipelines:
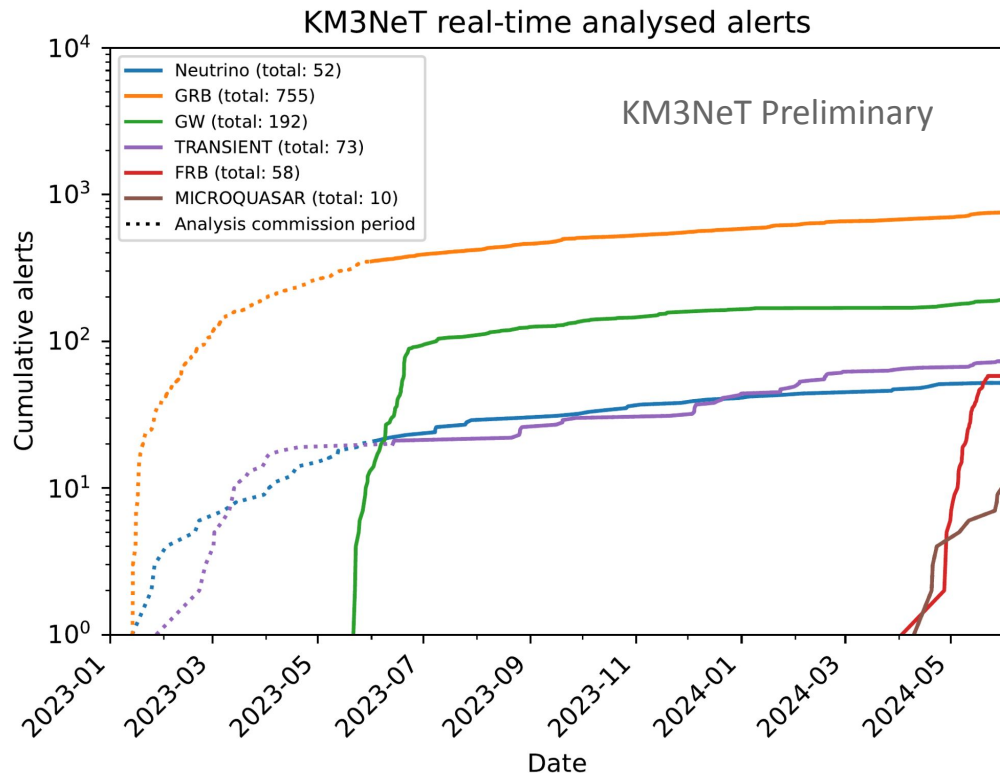- Core Collapse Super Novae ($[T_{evt}, T_{evt}+2s]$,

Coincidence in single DOM)
- Point-like Source
- GW (extended source)
→ dedicated Time-Windows

Analyses use **only track-like events**
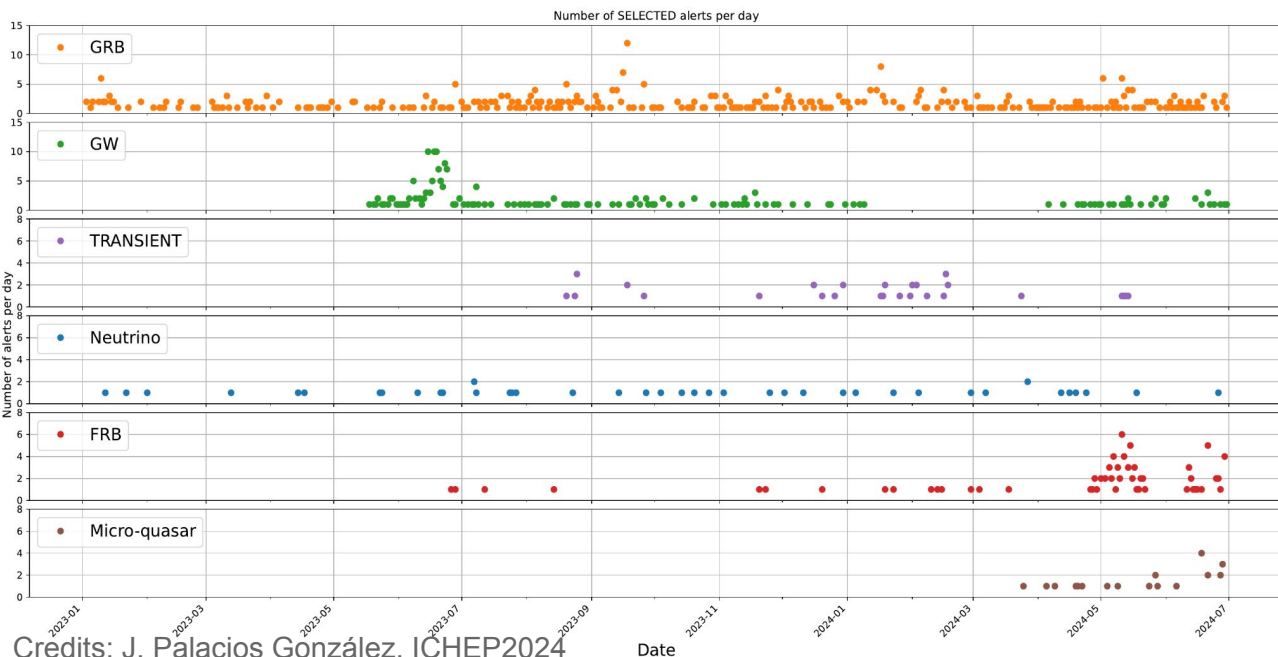(better angular resolution)
- ARCA < 2°
- ORCA < 4°
→ include showers in progress.

KM3NeT real-time analysed alerts

KM3NeT Preliminary

Neutrino (total: 52)
GRB (total: 755)
GW (total: 192)
TRANSIENT (total: 73)
FRB (total: 58)
MICROQUASAR (total: 10)
Analysis commission period

Cumulative alerts

Date

Credits: J. Palacios Gonzalez, ICHEP2024

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Source Follow-up: incoming alerts

Credits: J. Palacios González, ICHEP2024

ON/OFF region, data driven analysis
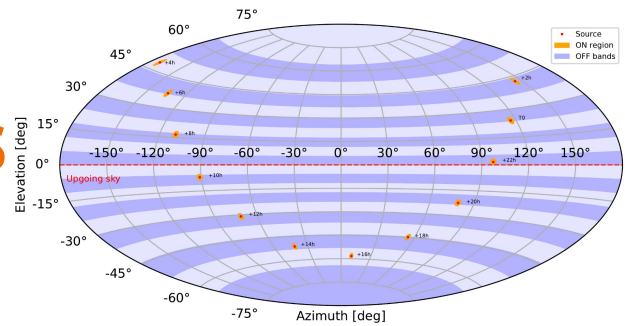
Binned: compare data in ON region (signal awaited here) with expected number of events, estimated from an OFF region (background):

1. **ON region** = <u>search time window</u> + Ω_{ON} <u>RoI</u> (cone in source direction, with aperture accounting for position uncertainty).
2. **OFF region** = <u>2 weeks life-time (LT)</u> data before the alert + <u>Bands</u> at elevation of the source (Ω_{OFF}).
3. Adjust the number of events in OFF bands N_{OFF} with **cuts** to achieve a targeted N_{bkg} → selection to optimise the achievable significance.

$$N_{bkg} = \sum_{i \in \text{ bands}} N_{OFF,i} \times \frac{LT(sig)}{LT(bkg)} \times \frac{\Omega_{ON,i}}{\Omega_{OFF,i}}$$

4. Apply **cuts** to ON region → **count N_{ON}** and compare to N_{bkg} (P-value)

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Follow-up: GW

Iteration 0
Iteration 1

+ CCSN search: [T_{evt}, T_{evt}+2s]
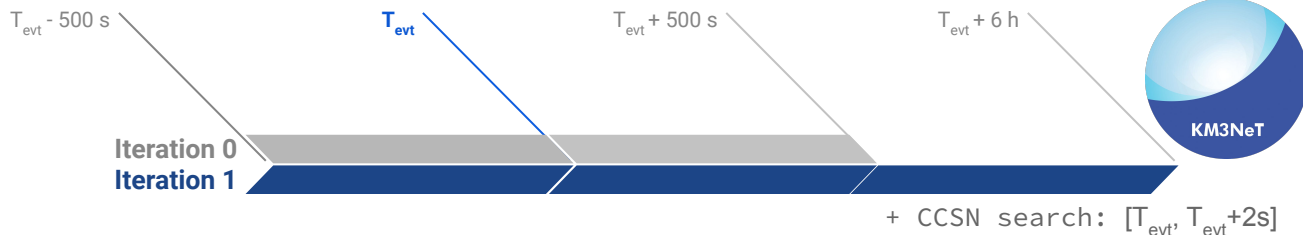
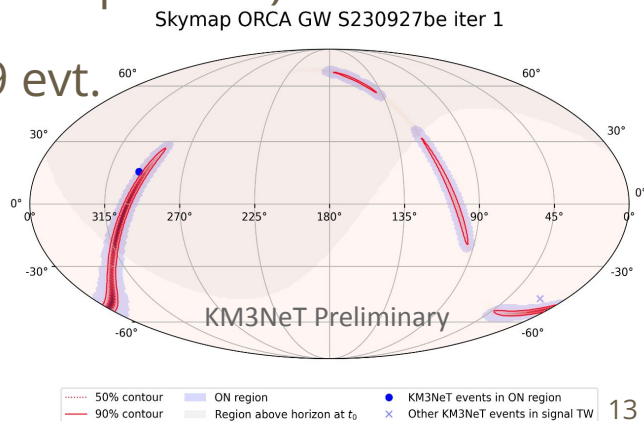→ LIGO-Virgo-KAGRA alerts (*via* GCN): run **O4a fully covered** (O4b ongoing)

→ **No significant correlation** found yet.

Example: S230927be (BBH merger @ ~1060 Mpc). (27-Sept-2023).

→ Expected KM3NeT background (-500s, +6h): 0.019 evt.

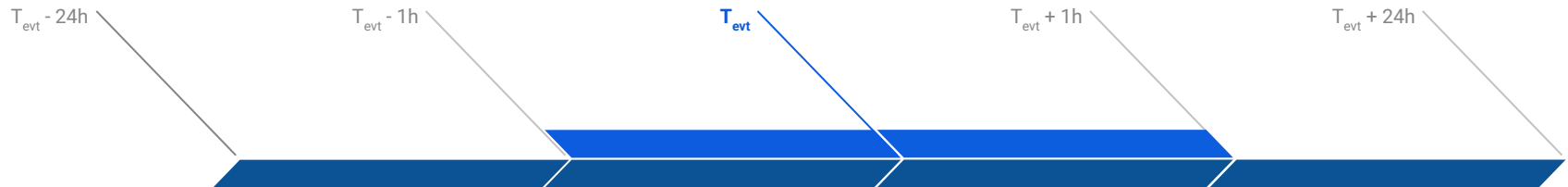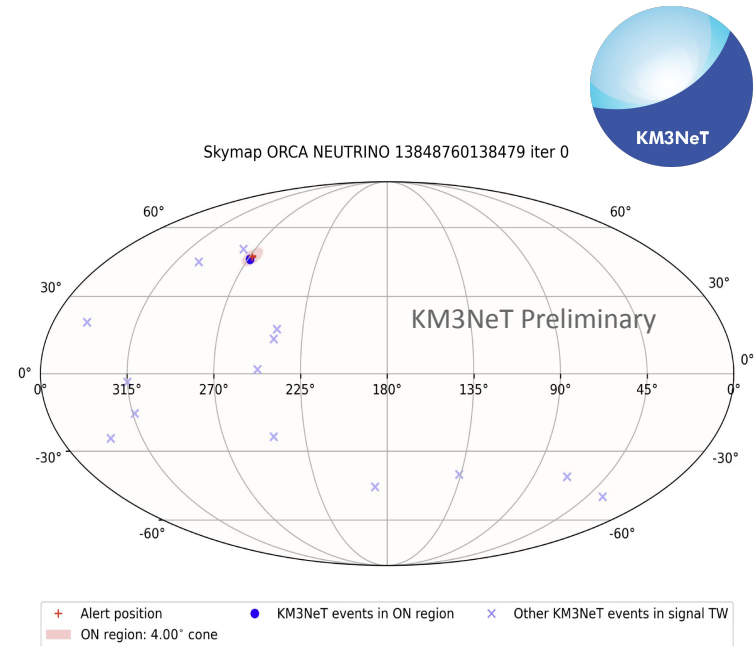→ 1 KM3NeT/ORCA event in ON region.

⇒ 2.35 σ upper-fluctuation.

Skymap ORCA GW S230927be iter 1

KM3NeT Preliminary

| 50% contour | ON region | KM3NeT events in ON region |
| 90% contour | Region above horizon at t_0 | Other KM3NeT events in signal TW |

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Follow-up: HE Neutrino

→ IceCube Gold & Bronze alerts (*via* GCN).

→ **No significant correlation** found yet.

Example: <u>**IC 231027A**</u> Gold alert (27-Oct-2023)

→ Expected KM3NeT background (±1h): 0.071 evt.

1 KM3NeT/ORCA event (downgoing sky) ⇒ 1.82 σ upper-fluctuation.

Skymap ORCA NEUTRINO 13848760138479 iter 0

KM3NeT Preliminary

+ Alert position   ● KM3NeT events in ON region   × Other KM3NeT events in signal TW
ON region: 4.00° cone

T_{evt} - 24h T_{evt} - 1h   **T_{evt}** T_{evt} + 1h T_{evt} + 24h

Follow-up: Gamma Ray Bursts

→ Fermi, Swift & Integral (*via* GCN). Dominated by Fermi.

→ **No significant correlation** found yet.

Skymap ARCA GRB 722864655 iter 2

KM3NeT Preliminary

Example: 722864655 Fermi alert (28-Nov-2023)

→ Expected KM3NeT background (±24h): 0.13 evt.

1 KM3NeT/ARCA event (upgoing sky, ~8h before event) ⇒ 1.55 σ deviation.

T_{evt} - 24h T_{evt} - 1h T_{evt} - 500s   **T_{evt}** T_{evt} + 500s T_{evt} + 1h T_{evt} + 24h
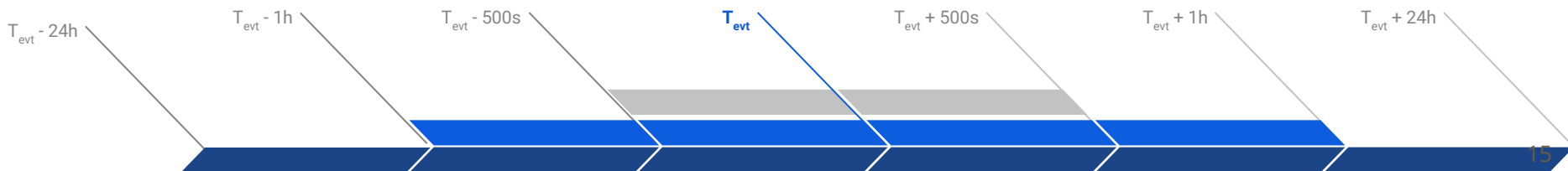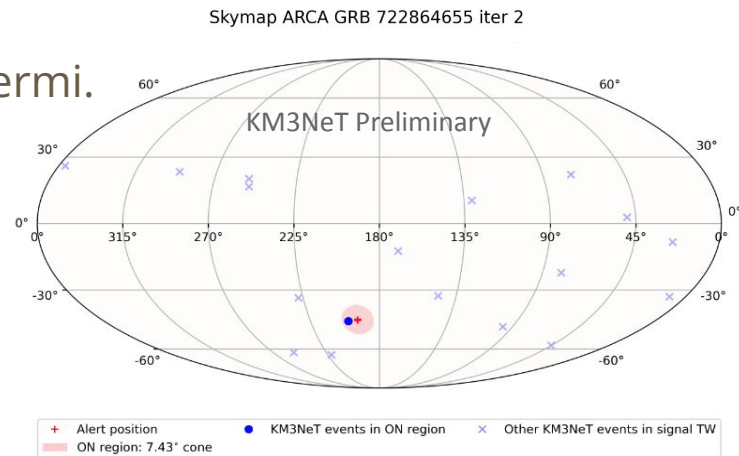
GRB 221009A (Brightest of all time)

2022, 9 Oct. at 13:16.59 UT: Long GRB at RA, Dec = (288.3, 19.8) deg detected at z~0.15 (2.4e9 light-years away)
→ GRB with **highest energy** ever detected by Fermi LAT (99 GeV, ATel #15656).
→ **LHAASO detected photons of the order of ~10 TeV** (among highest energies for a GRB, GCN #32677).
→ One of the largest **worldwide follow-up campaigns** ever (among which KM3NeT).

KM3NeT Preliminary

PoS (ICRC2023) 1503

+ Alert position   ▨ Region above horizon at t_{alert}
▬ Error radius   ▬ Galactic plane
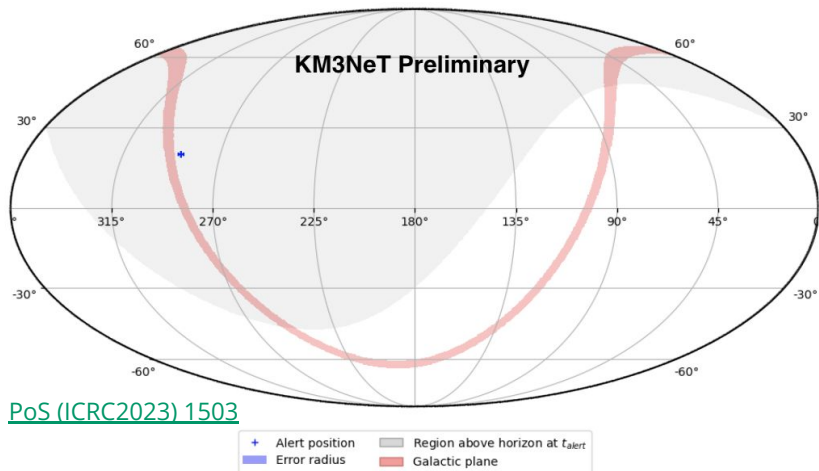
Circular 32741

```
TITLE:    GCN CIRCULAR
NUMBER:   32741
SUBJECT:  GRB 221009A: search for neutrinos with KM3NeT
DATE:     22/10/13 18:57:37 GMT
FROM:     Damien Dornic at CPPM,France  <dornic@cppm.in2p3.fr>

The KM3NeT Collaboration (https://www.km3net.org/) reports:<br><br>

Using the data from the online fast processing chain, the KM3NeT Collaboration has performed a
dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A
(Dichiara et al. GCN 32632 (Swift);  Veres et al. GCN 32636 (Fermi-GBM)). The search covers the
time range of [T0-50s, T0+5000s], with T0 being the trigger time reported by Fermi-GBM
(T0=2022-10-09 13:16:59.00 UTC), during which both KM3NeT detectors were collecting good quality
data. However, the GRB location was above the KM3NeT horizon (mean elevation of about ~40deg)
during the search time window, significantly reducing the point-like source sensitivity. In both
detectors, zero events were observed in the search window, while o(0.1) were expected from the
background. The online fast processing uses preliminary calibrations and detector alignment,
which will be superseded in a future elaborated analysis.<br><br>

A parallel search has been performed in the MeV range (Eur.Phys.J.C 82 (2022) 4, 317) without any
significant neutrino coincidence.<br><br>

KM3NeT is a large undersea (Mediterranean Sea) infrastructure hosting two neutrino detectors,
sensitive to burst of supernova neutrinos in the MeV range and to astrophysical neutrinos in the
GeV-PeV energy range: ARCA at high energy and ORCA at low energy. A total of 21 and 11 detection
lines are currently in operation in ARCA and ORCA, respectively.
```

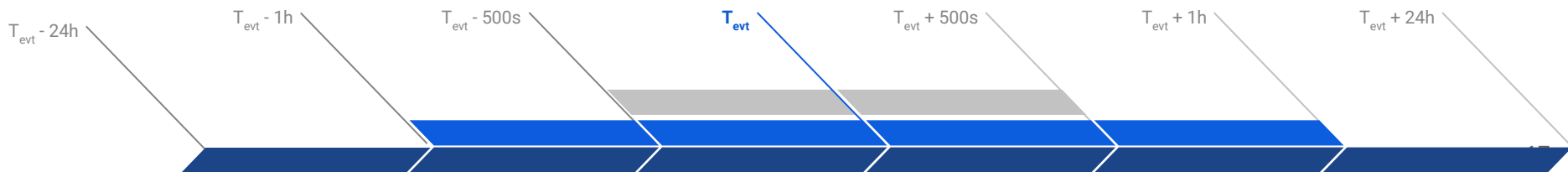KM3NeT ARCA21, ORCA10 → No event found in signal region. Offline refinement, see J. Palacios Gonzalez talk!

Follow-up: Fast Radio Bursts

2 alert sources:

1) Chime VOEvent broker (Comet) → ~ Real-time
2) TNS catalog (API) → publication delay (days to months).

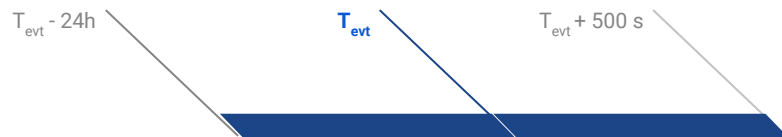5 months operation → **No significant correlation** found yet.

T_{evt} - 24h T_{evt} - 1h T_{evt} - 500s   **T_{evt}** T_{evt} + 500s T_{evt} + 1h T_{evt} + 24h

Transient and MicroQuasar

Transient sources from Fermi, Swift, MAXI, HAWC, EP_wxt
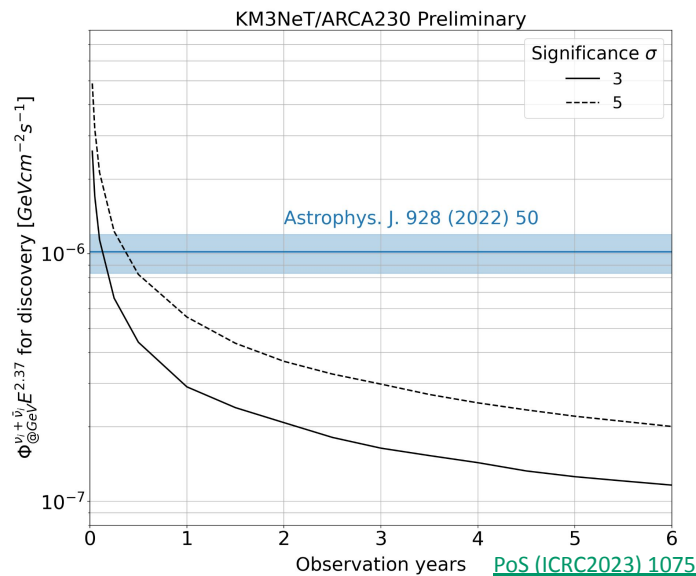→ **No significant correlation** found yet.

μQasars: Analysis of Light Curves provided by MAXI and Swift-BAT for a list of μQuasars. If >2σ deviation from baseline → trigger KM3NeT analysis.

→ **No significant correlation** found yet.

Astronomy potential for KM3NeT/ARCA 230

KM3NeT/ARCA230 Preliminary

Astrophys. J. 928 (2022) 50

PoS (ICRC2023) 1075

KM3NeT/ARCA230 Preliminary

- KM3NeT/ARCA230 7 yr
- KM3NeT/ARCA230 10 yr
- IceCube 7 yr
- IceCube 10 yr
- Antares 15 yr

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3 and 5 σ discovery values for a diffuse neutrino flux from galactic ridge, with spectral index of 2.37 (as reported by IceCube, blue line).
→ detection (5 σ) of the all-sky diffuse neutrino flux in ½ year.
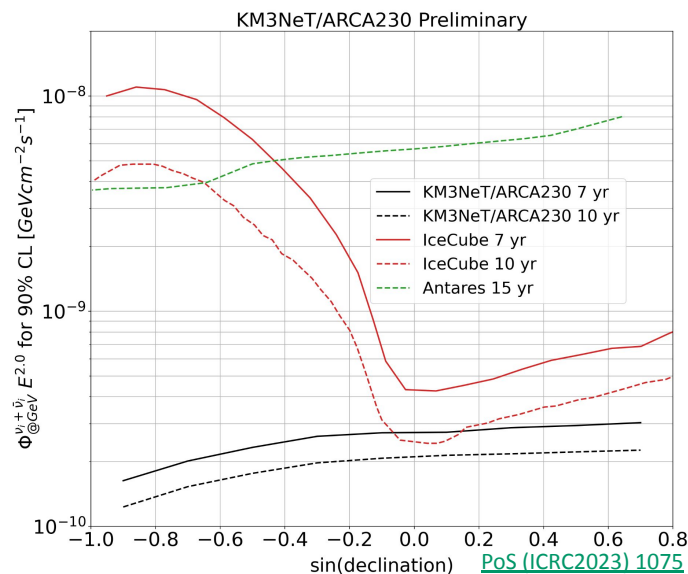
Point source sensitivity for spectral index of 2 (black) compared with 15 years of ANTARES and 7 years of IceCube.
→ Improvement of current limits over the full sky
→ Unprecedented sensitivity in the Southern Sky

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Conclusion

➔ KM3NeT online follow-up pipelines are in nominal production mode.

➔ Various alert brokers for different messengers and astrophysical sources are followed.

➔ No significant correlation has been observed so far.
3 GCN Circulars (26249, 26751, 32741) + 1 ATeL (15290) submitted.

➔ Alert sending ready early next year.

➔ The detector growth will bring exciting detection capabilities.

BACKUP

Detectors timelines

ARCA

2021
Start of the implementation of the ARCA online framework

ARCA1   ARCA2   **2017** TXS 0506+056 & IC-120922A   ARCA6   ARCA9   ARCA21   ARCA28

2016   2017   2019   2021   2022   2023   2024

ORCA

2016 IceCube alert system implemented

ORCA4   ORCA6   ORCA10   ORCA15   ORCA18   ORCA23

2019
Start of the implementation of the ORCA online framework

Credit: A. Veutro

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Effective area

KM3NeT/ARCA Preliminary

Effective area [m²] vs E_ν [GeV]

$\nu_\mu CC + \bar{\nu}_\mu CC$
- ARCA21
- ARCA19
- ARCA8
- ARCA6
- Antares

PoS (ICRC2023) 1018

Steady sources searches:
ANTARES > KM3NeT
→ Matter of time for KM3Net.

Transient searches:
KM3NeT > ANTARES (since
KM3NeT/ARCA19, now 28).

RTA operation

KM3NeT/ARCA 21

- Tracks: Reco Level [Hz]
- Tracks: Noise Cut [Hz]
- Tracks: Noise Cut + coszen<0.1 [0.01 Hz]
- Showers: Reco Level [Hz]

KM3NeT Preliminary
PoS (ICRC2023) 1125

KM3NeT/ORCA 18

- Tracks: Reco Level [Hz]
- Tracks: Noise Cut [Hz]
- Tracks: Noise Cut + coszen<0.1 [0.01 Hz]
- Showers: Reco Level [Hz]

PoS (ICRC2023) 1125
KM3NeT Preliminary
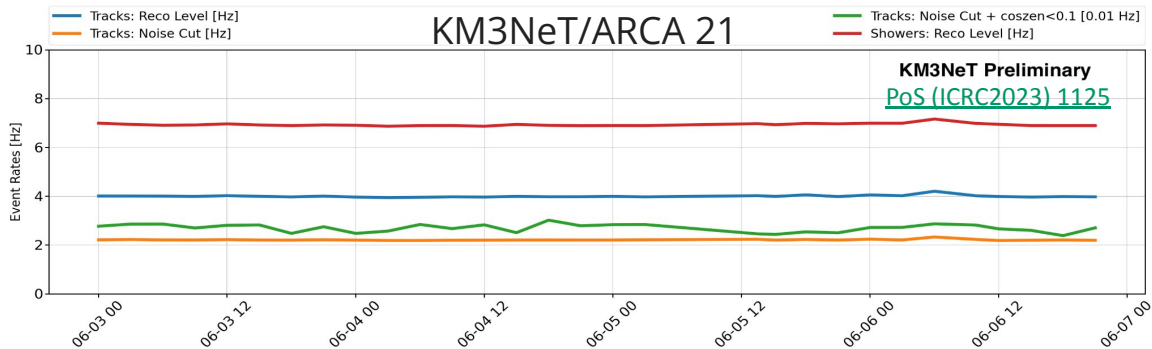
➔ Track reconstruction (~ 4s)
➔ Shower reco. (~ 4s)
➔ Classifier μ / ν (~ 4s)
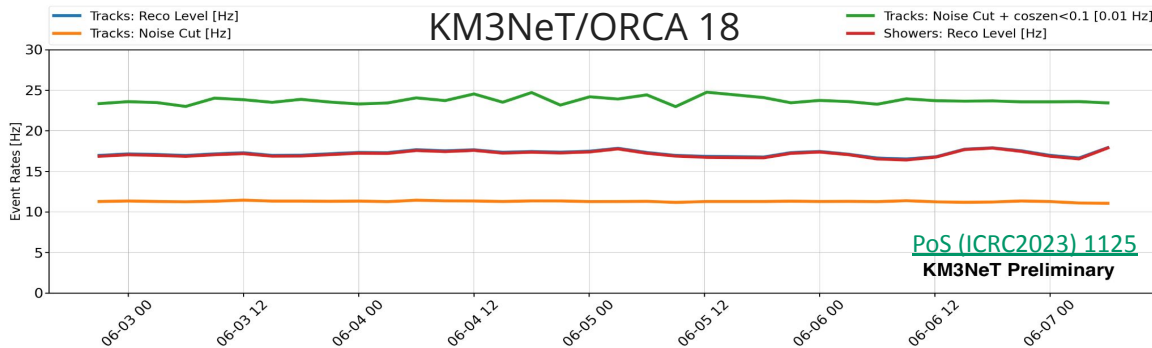
➔ Track reconstruction +
   Shower reconstruction +
   Classifier → ~ 6s

Expect ~ 100 Hz rate for full detector

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Internal monitoring: Shifter-tool

RTA monitoring for both ARCA and ORCA (Event rates, Processing time, Physics variables)

MM follow-up monitoring:

➢ Alerts ID, type, trigger status
➢ Details of the alerts and link to GCN notices
➢ Plots and results of the online analyses

→ Internal tool.

VHE event candidate
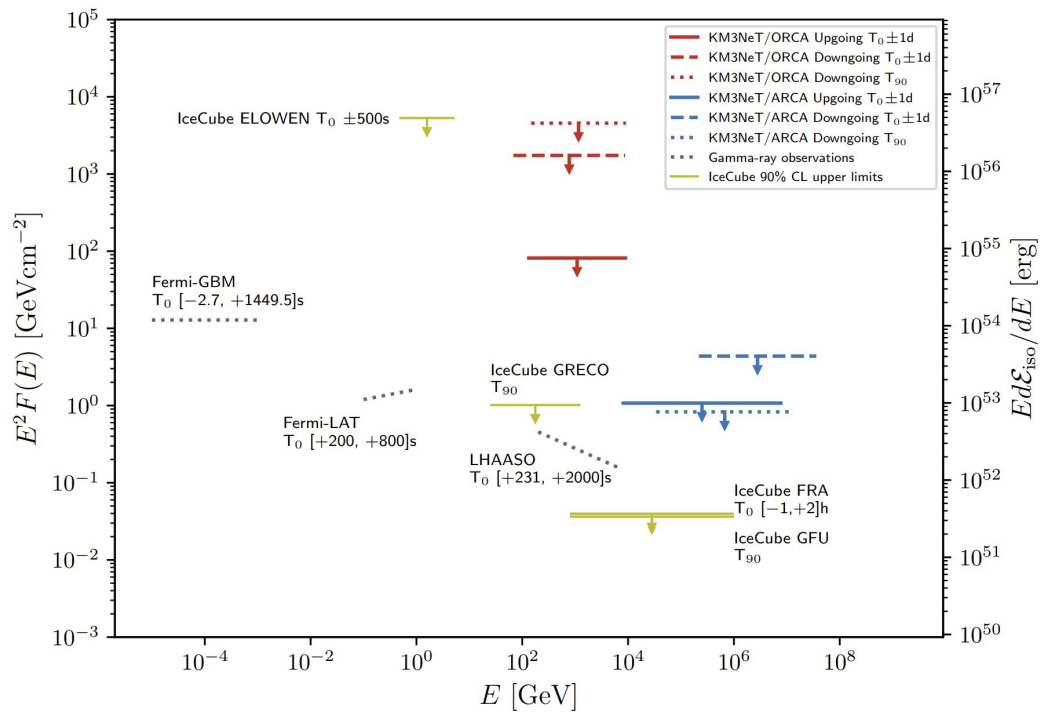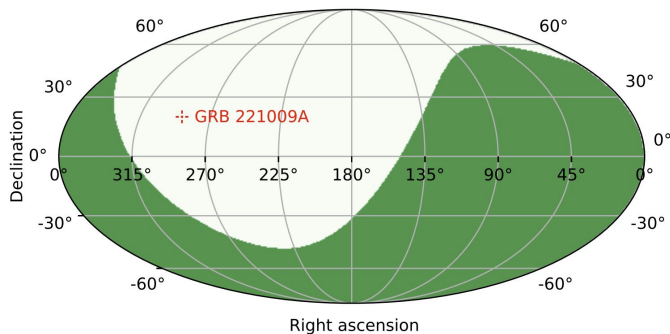

Horizontal event (~1º above horizon) with energy > 10 PeV.

GRB 221009A: offline refinement

Use <u>refined detector calibration</u>

<u>Various selections</u>: time and direction

No candidate neutrino found → Set <u>flux limits</u>

Palacios et al. arXiv: 2404.05354