Results of the follow-up of external triggers with KM3NeT

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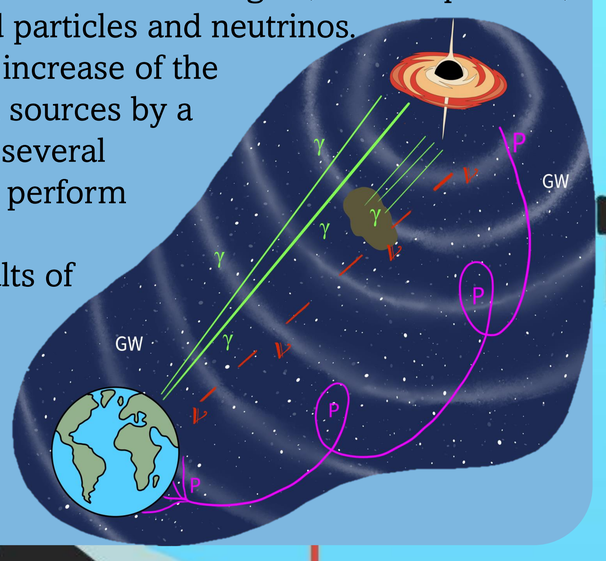
Motivations

Multi-messenger astronomy allows the sensitive investigation of the Universe by combining observations with diverse messengers, such as photons, gravitational waves, high-energy charged particles and neutrinos.
The strength of this approach lies on the increase of the chance of detection of new astrophysical sources by a **coincident detection**, which motivates several observatories to send external alerts and perform follow-ups.
This contribution presents the latest results of the **real-time search (follow-up) for neutrinos in coincidence with astrophysical sources** performed with the real-time multi-messenger analysis framework.

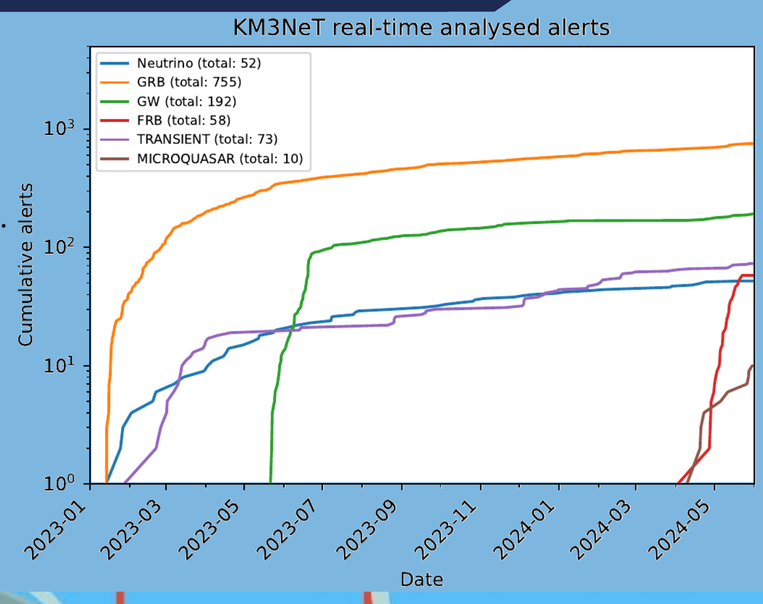


KM3NeT Detectors

- Telescope made by many Detection Units (DUs), each with 18 Digital Optical Modules (DOMs). Each DOM contains 31 small 3'' photomultipliers (PMTs).
- Detection of **Cherenkov light** induced in the medium by secondary particles.
- Two deep-sea telescopes [1]:
  - **ORCA** (40 km off-shore Toulon, France), 115 DUs (23 currently installed) with high DOM geometry density –> focused on **GeV-TeV ν**.
  - **ARCA** (100 km off-shore Sicily, Italy), 230 DUs (28 currently installed) with low DOM geometry density –> focused on **TeV-PeV ν.**

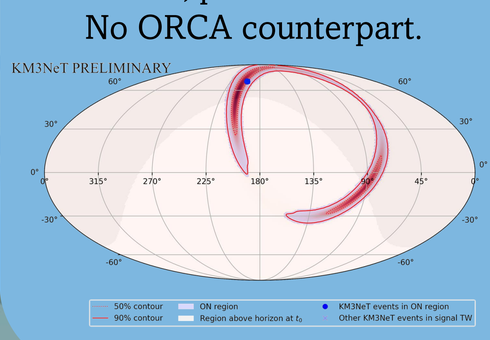
Analysis approach

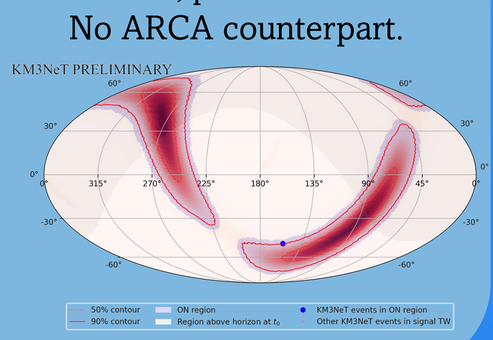
- Real-time analyses performed using the KM3NeT Online Platform (for details see [2]).
- Events reconstructed as **tracks** selected.
- Full-sky coverage of the current analyses, for all the pipelines.
- **Binned ON/OFF technique:**
  - **ON region**: area where the signal is expected to dominate over the background, in a time window T_{ON}.
  - **OFF region**: bands in local coordinates, where only background is expected.
  - **Background** computed in a time window of 2 weeks (T_{OFF}) as: $n_{bkg} = \sum_i \frac{T_{ON}}{T_{OFF}} \frac{\Omega^i_{ON}}{\Omega^i_{OFF}} N^i_{OFF}$,
    where $\frac{\Omega^i_{ON}}{\Omega^i_{OFF}}$ is the ratio between the ON and OFF region sizes.
  - Event selection optimized for each alert and in each OFF band to achieve small enough n_{bkg} ($\sim 10^{-3} - 10^{-1}$).



Gravitational waves

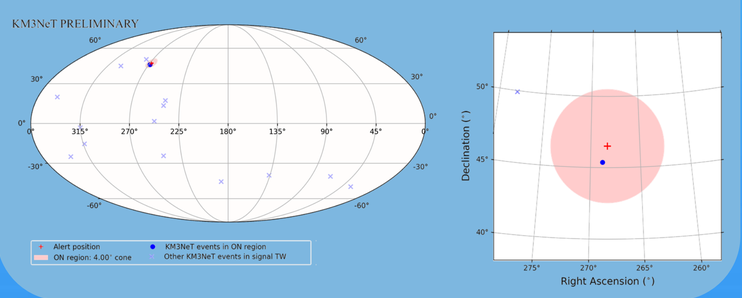
- The LIGO-VIRGO-KAGRA Collaborations started the run O4 on May 24th 2023 -> 192 alerts followed-up since then up to May 2024.
- This **real-time analysis** is the first search for ν coincidences performed by KM3NeT/ARCA, while an offline GW/ν search was already performed with KM3NeT/ORCA during the O3 run [4].
- Low energy analysis:
  - Search for an excess of coincidences between PMTs in a single DOM above the optical background.
  - Short time window of **2 s** after the GW alert.
  - Results available in ~ **5-10 s**.
- High energy analysis:
  - ON region: **GW 90% CL contour** in equatorial coordinates + angular extension of 2° in ARCA and 4° in ORCA.
  - Two time windows: T_0±500s and [T_0-500s, T_0+6 h].
  - Results available in ~ **15 minutes**.
- Interesting alerts:
  - On April 22nd 2024, a NS-BH merger (the only one during the O4 run) was detected. No significant ν excess.
  - **S2306111**
    ARCA analysis: expected background ~ 0.022, N_{ON}=1, p-value=0.023. No ORCA counterpart.
  - **S230808i**
    ORCA analysis: expected background ~ 0.2, N_{ON} =1, p-value=0.015. No ARCA counterpart.





IceCube alerts

- 52 alerts followed-up from January 2023 to May 2024.
- ON region: Region of Interest (RoI) defined as a **circular region** around the alert position.
- Two time windows: T_0±1hour and T_0±1day.
- **13848760138479** (IceCube gold event): lowest p-value found in the T_0±1hour time window with ORCA on 2023, October 27th:
  - expected background ~ 0.071, N_{ON}=1, p-value=0.068.



Transients and GRB

- 755 Gamma Ray Bursts and 73 Transients followed-up from January 2023 to May 2024.
- ON region: **circular error region** of the alert with a minimum of 2° (ARCA) and 4° (ORCA) radius taken into account for the angular resolution.
- Three time windows for GRB: T_0±500s, T_0±1hour and T_0±1day.
- Transients time window: T_0±1d.
- Offline analyses will be performed as for GRB 221009A [3].

Fast Radio Bursts and Microquasars

- 58 FRB alerts and 10 microquasars followed-up since March 2024.
- Microquasar dedicated pipeline search for X-rays flares from known sources in a time window of [T_0-1d, T_0].
- FRBs time windows: T_0±500s, T_0±1hour and T_0±1day.
- ON region: **circular region** considering the error region of the alert.

Conclusions

- No significant neutrino candidate associated with an external alert has been found.
- The KM3NeT Online Platform will continue monitoring the alerts performing full-sky follow-ups with the dedicated pipelines implemented and optimized for each kind of alert.
- Works ongoing for the implementation of a module to send KM3NeT neutrino alerts.
- Ongoing work to include shower-like events.

References

[1] KM3NeT Collaboration. "*Letter of intent for KM3NeT 2.0*". In: Journal of Physics G Nuclear Physics 43.8 (Aug. 2016), p. 084001.
[2]: M. Mastrodicasa et al. PoS TAUP2023 (2024), 273.
[3]: J. Palacios, S. Le Stum, G. Vannoye. "*Search for Neutrino Emission from GRB 221009A using the KM3NeT ARCA and ORCA detectors*". arXiv preprint arXiv:2404.05354 (2024).
[4]: KM3NeT Collaboration. " *Searches for neutrino counterparts of gravitational waves from the LIGO/Virgo third observing run with KM3NeT*". In JCAP04(2024)026.

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