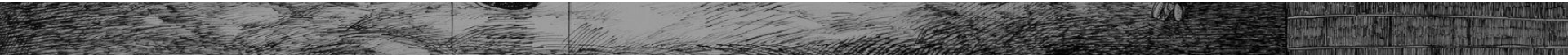
Neutrino real-time follow-ups with KM3NeT

M. Mastrodicasa on behalf of the KM3NeT Collaboration

17th Marcel Grossmann Meeting, Pescara
July 9, 2024

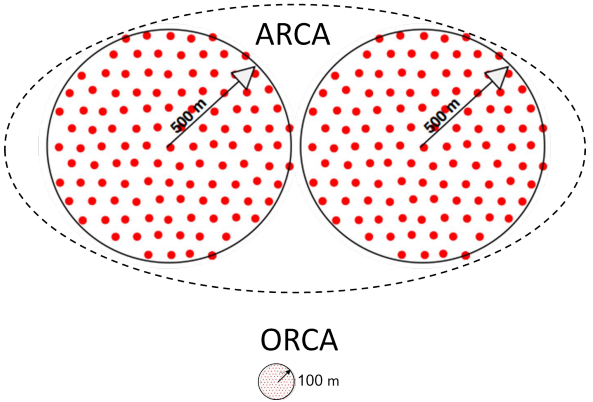


KM3NeT: a neutrino telescope in the Mediterranean Sea

Digital Optical Module (DOM): 31 x 3″ PMTs

Array of strings with 18 DOMs/string detecting Cherenkov light produced by secondary particles arising from neutrino interactions

Two detectors at two different sites



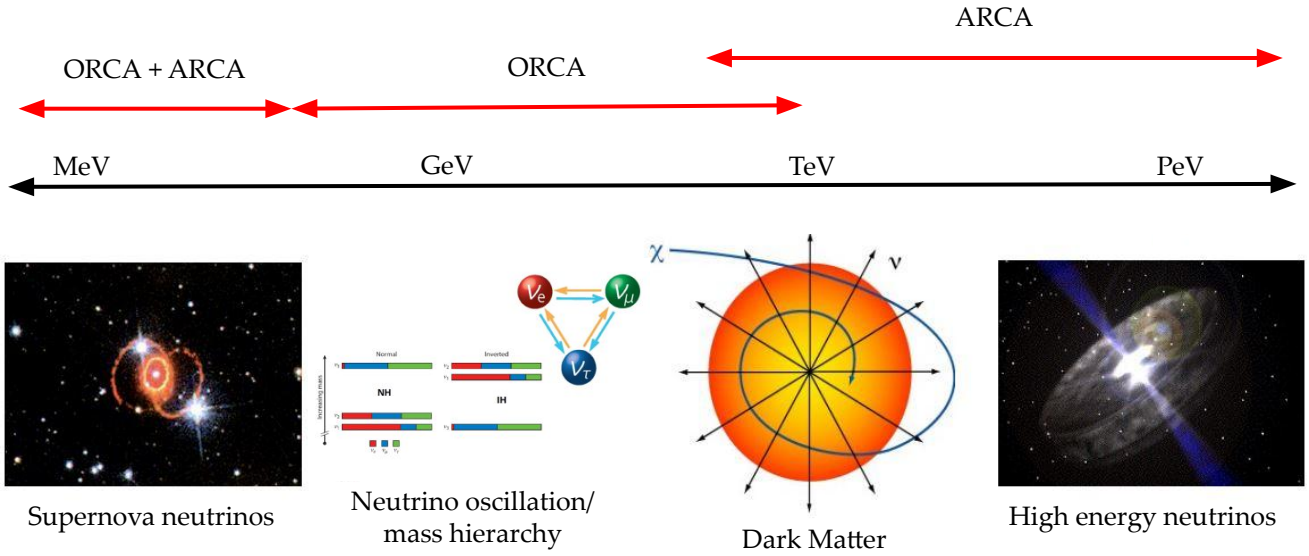
> 1 km^3 neutrino telescope under construction in the Mediterranean Sea

	Astroparticle Research with Cosmics in the Abyss (ARCA)	Oscillation Research with Cosmics in the Abyss (ORCA)
Location	Italy, 100 km offshore Sicily	France, 40 km offshore Toulon
Depth	3450 m	2450 m
String distance	90 m	20 m
DOM spacing	36 m	9 m
String height	800 m	200 m
Instrumented mass	~ 1 Gton	~ 7 Mton
No. strings	115 × 2	115

ARCA (ORCA) currently taking data with 28 (23) strings!

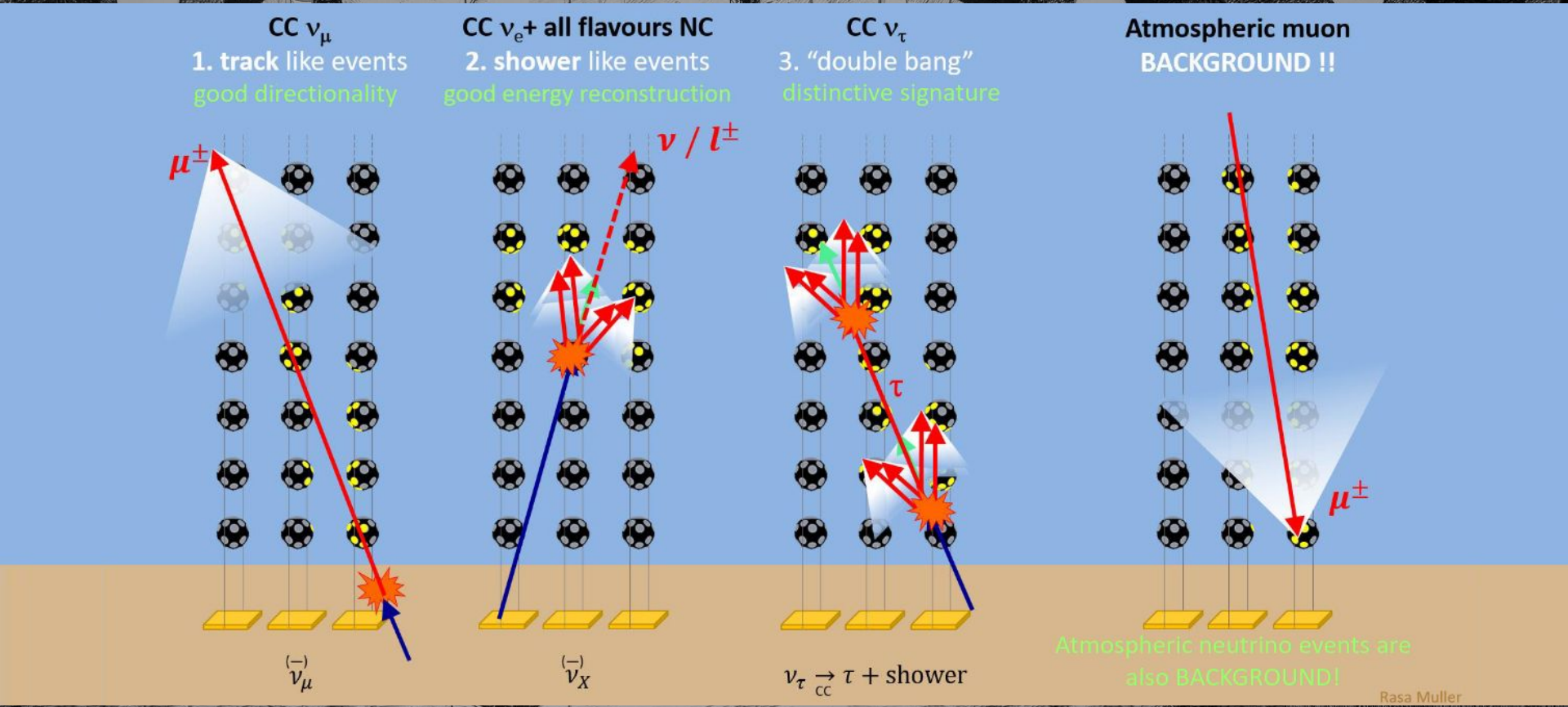
KM3NeT physics

- **ARCA**: optimised to identify and study TeV-PeV astrophysical neutrino sources
- **ORCA**: optimised to study the intrinsic properties of neutrinos in the few GeV range



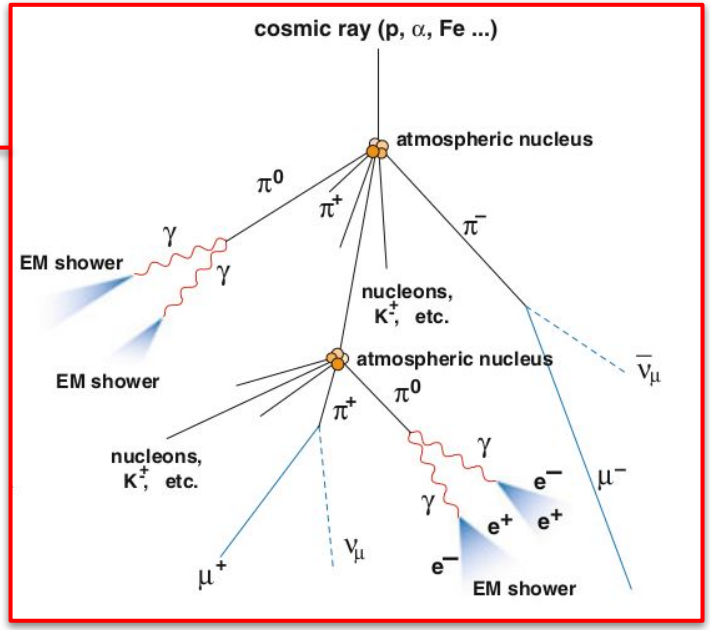
Different primary goals but both can be used for neutrino astronomy from few MeV to few PeV

Neutrino event topology



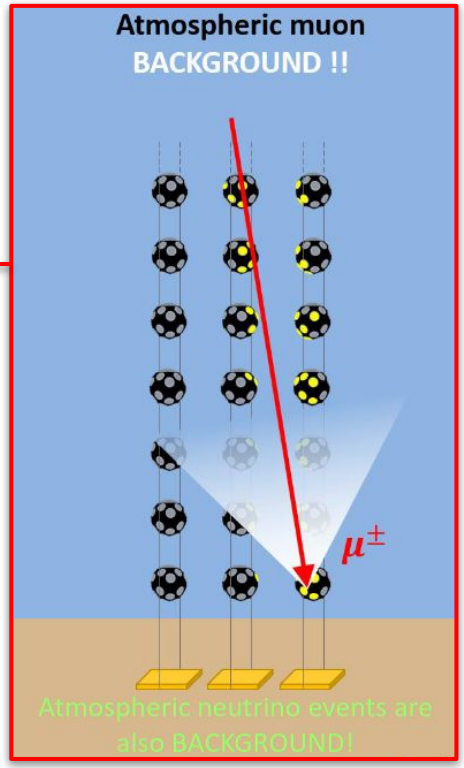
Atmospheric background

- Interactions of cosmic rays in the atmosphere generate atmospheric muons and neutrinos
- Atmospheric muons and neutrinos can reach the detector
- Earth can be used as a screen for all particles, except neutrinos
- Looking at high energies, cosmic neutrinos flux is higher than that of atmospheric neutrinos



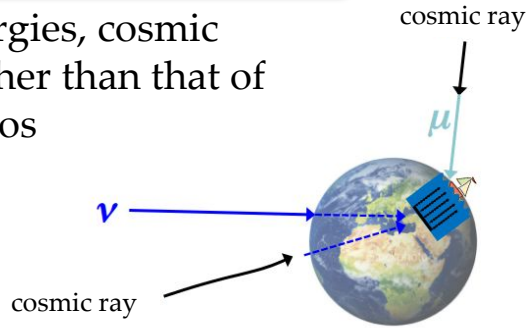
Atmospheric background

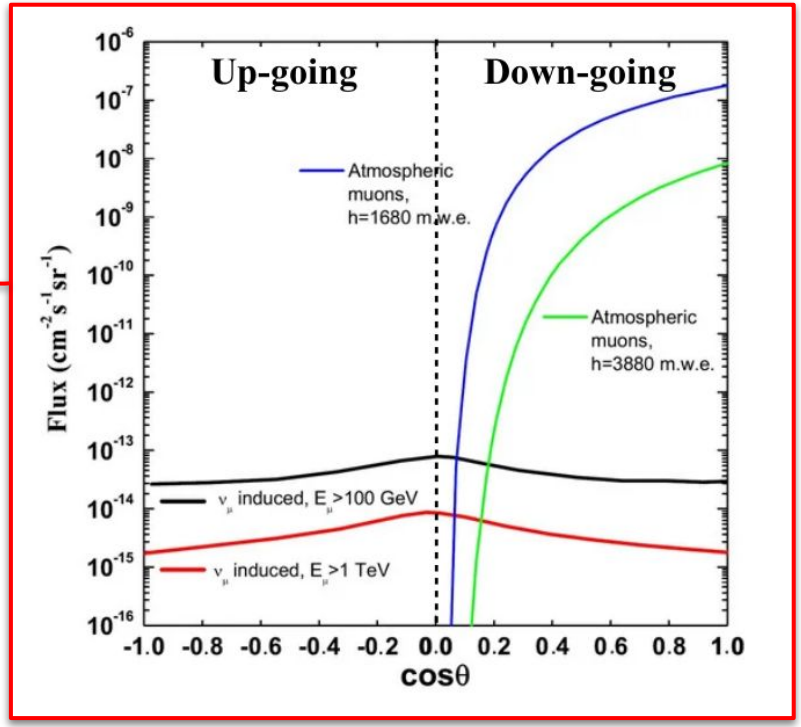
- Interactions of cosmic rays in the atmosphere generate atmospheric muons and neutrinos
- Atmospheric muons and neutrinos can reach the detector
- Earth can be used as a screen for all particles, except neutrinos
- Looking at high energies, cosmic neutrinos flux is higher than that of atmospheric neutrinos



Atmospheric background

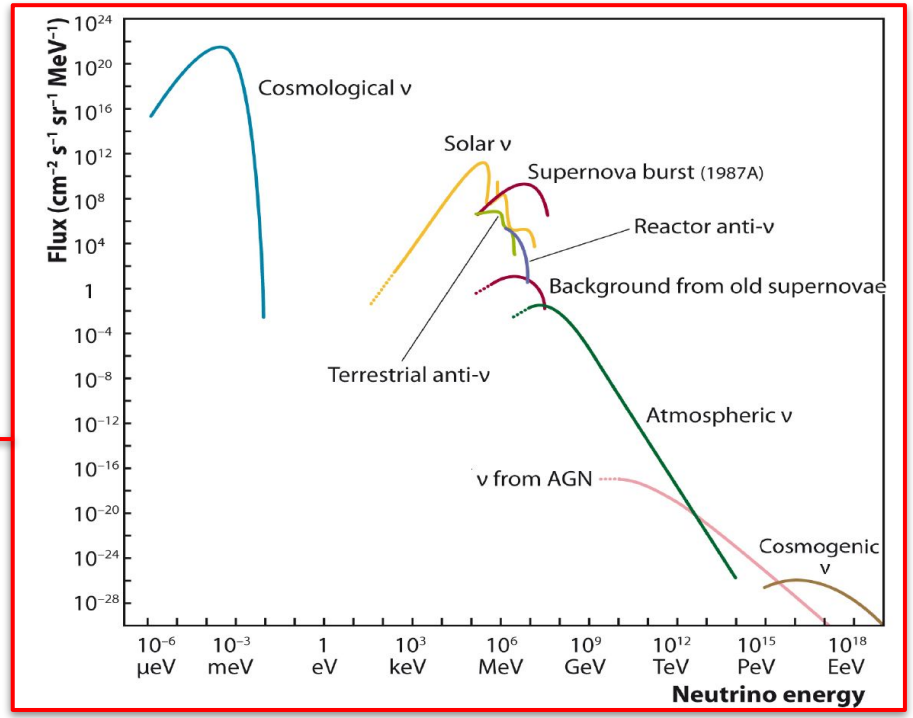
- Interactions of cosmic rays in the atmosphere generate atmospheric muons and neutrinos
- Atmospheric muons and neutrinos can reach the detector
- Earth can be used as a screen for all particles, except neutrinos
- Looking at high energies, cosmic neutrinos flux is higher than that of atmospheric neutrinos





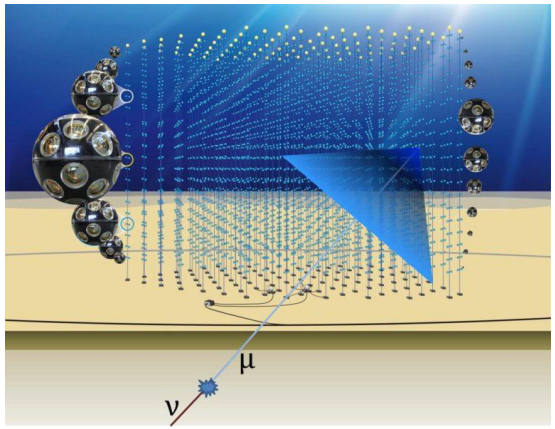
Atmospheric background

- Interactions of cosmic rays in the atmosphere generate atmospheric muons and neutrinos
- Atmospheric muons and neutrinos can reach the detector
- Earth can be used as a screen for all particles, except neutrinos
- Looking at high energies, cosmic neutrinos flux is higher than that of atmospheric neutrinos



The KM3NeT real-time multi-messenger program

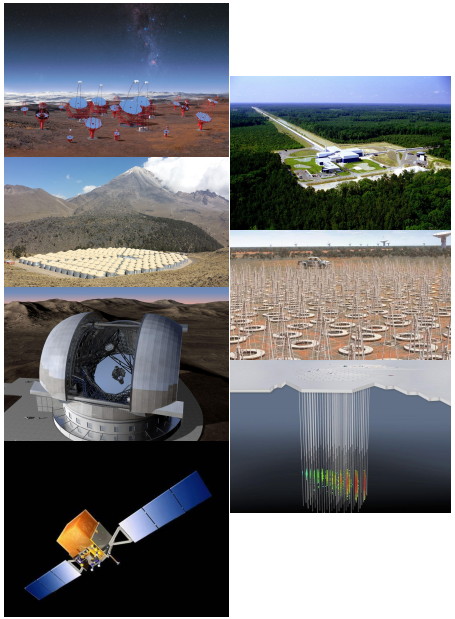
KM3NeT ORCA and ARCA



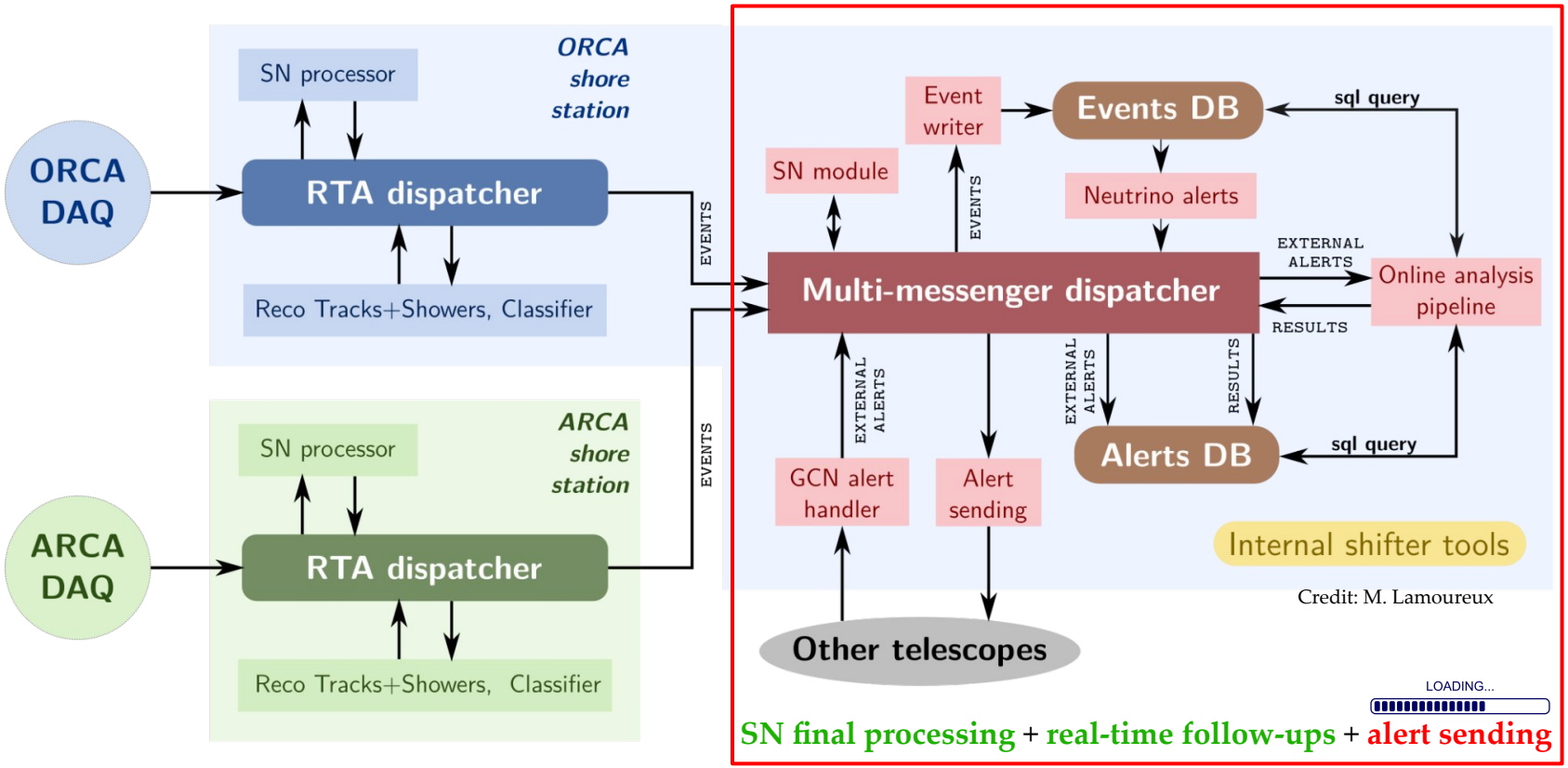
Follow-up of external alerts received from the multi-messenger community and search for spatial and temporal coincidences

Sending of alerts when potentially interesting events are detected to trigger follow-ups

Multi-messenger community

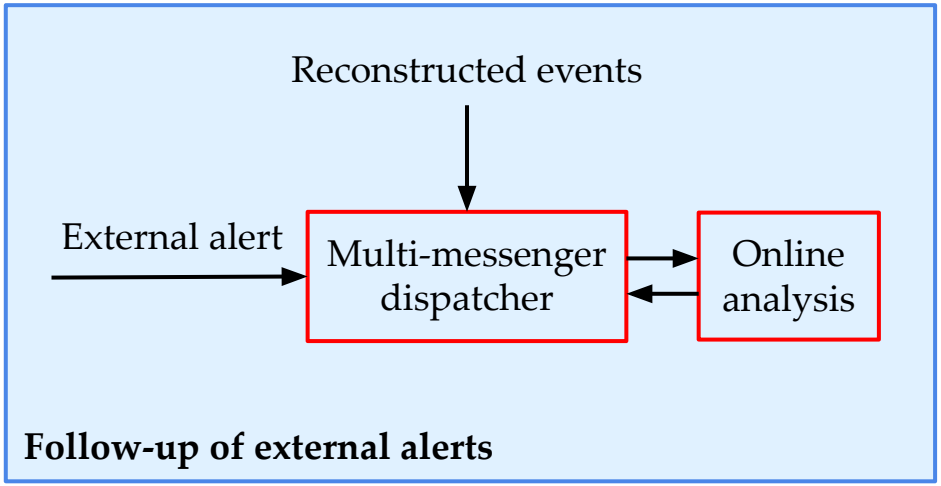


The KM3NeT real-time analysis framework



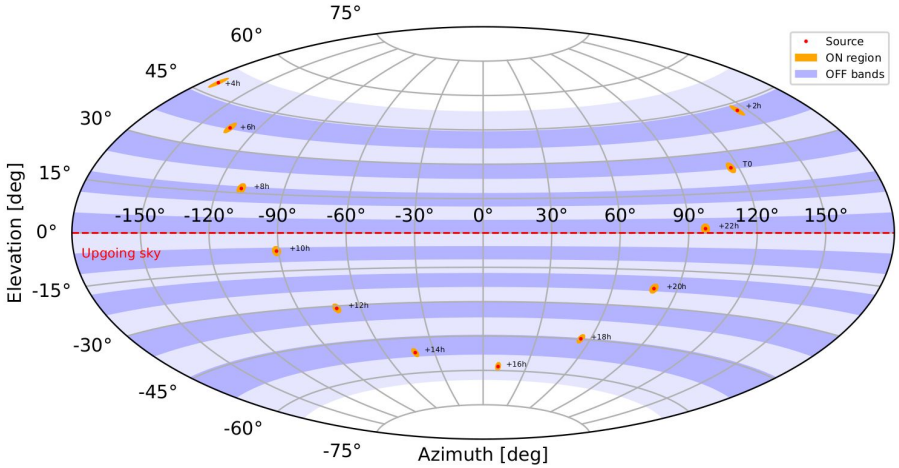
KM3NeT real-time follow-ups in a nutshell

- So far, only track-like events used for follow-ups (inclusion of shower-like events still in progress)
- Alerts received from 3 external brokers (GCN, Chime, TNS) + 1 internal broker (μQuasar) + SNEWS
- Each alert triggers an all-sky analysis for both ARCA and ORCA
- Binned ON/OFF analysis technique
- Follow-ups in place:
  - ➔ Gamma Ray Bursts (GRBs)
  - ➔ General transients
  - ➔ IceCube neutrinos
  - ➔ Core Collapse Supernovae (CCSNe)
  - ➔ Gravitational Waves (GWs)
  - ➔ Fast Radio Bursts (FRBs)
  - ➔ μQuasars



A binned ON/OFF analysis technique

- **ON region**: region where signal is expected, during a time window T_{ON}. It is defined taking into account the source error and the current detector angular resolution (2° for ARCA and 4° for ORCA)
- **OFF region**: elevation bands in local coordinates where only background is expected during a time window T_{OFF}, covering the local movement of the ON region during T_{ON}
- Search time window defined depending on the source type
- Background computed in a time window of 2 weeks before the alert
- Event selection optimised for each alert to have a small enough background (10^{-3} - 10^{-1} events)
- P-value computed comparing the number of events in ON region with that from background



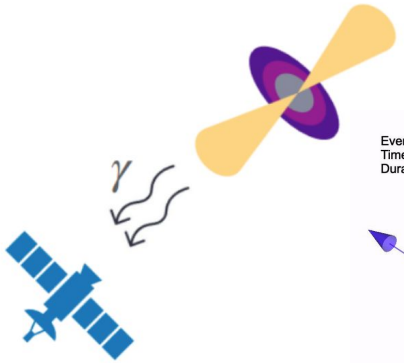
Credit: J. Palacios Gonzalez

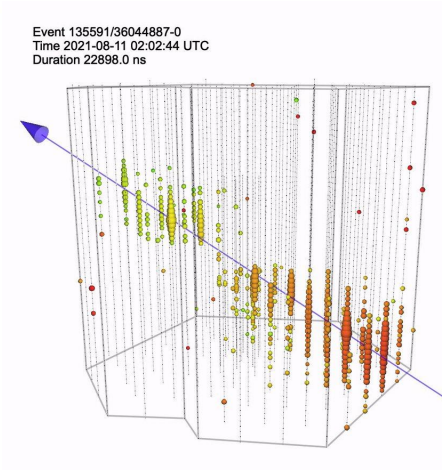
$$n_{bkg} = \sum_{i \in bands} \frac{T_{ON}}{T_{OFF}} \frac{\Omega^i_{ON}}{\Omega^i_{OFF}} N^i_{OFF}$$

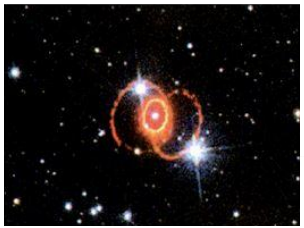
T_{ON} : search time window, depending on the source type
T_{OFF} : 2 weeks
Ω^i_{ON}: overlap between ON region and OFF region band
Ω^i_{OFF}: size of OFF region band
N^i_{OFF} : number of events in OFF region band after selection

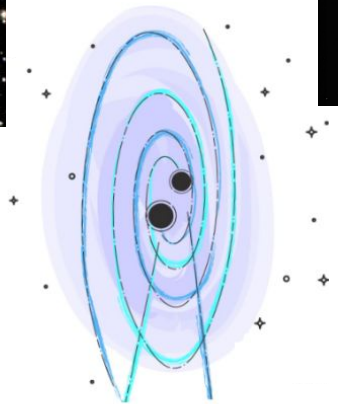
KM3NeT follow-up analyses

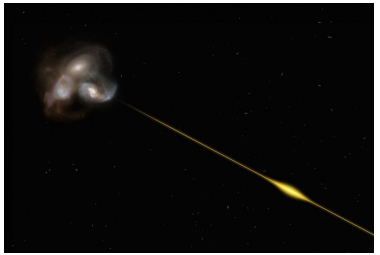
GRBs and transients	Neutrinos	CCSNe	GWs	FRBs and μQuasars

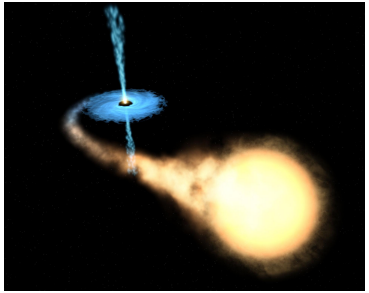






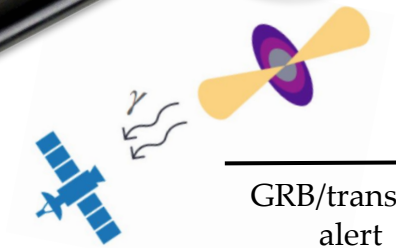






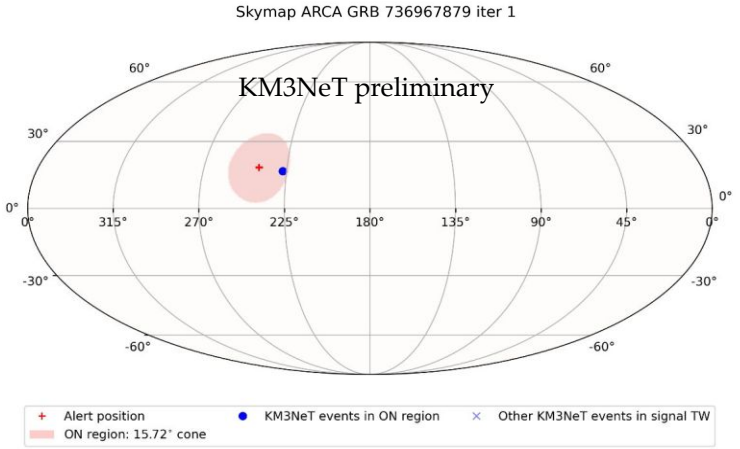
GRBs and transients follow-ups

Neutrinos | CCSNe | GWs | FRBs and μQuasars

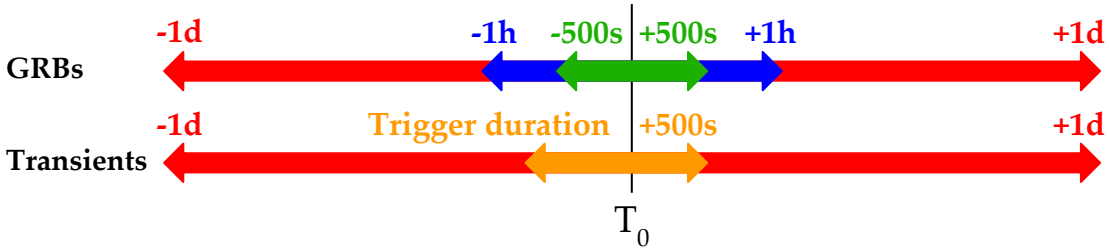


Reconstructed events

GRB/transient alert → Multi-messenger dispatcher ↔ Online analysis



Search time windows (T_{ON})

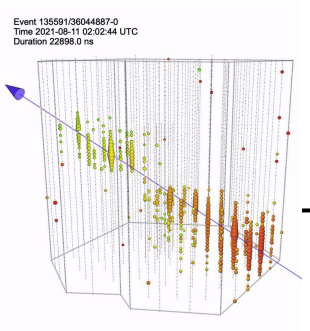


$n_{bkg} = 0.011$
$N_{ON} = 1$
p-value = 0.011

→ Not significant, but interesting example

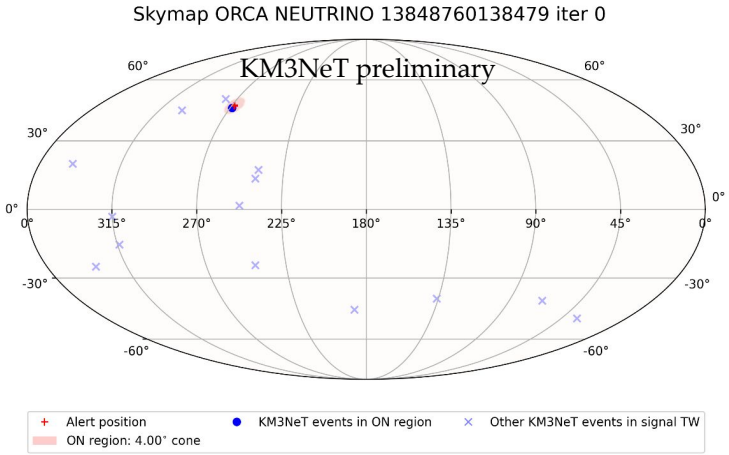
IceCube neutrinos follow-ups

GRBs and transients | Neutrinos | CCSNe | GWs | FRBs and μQuasars

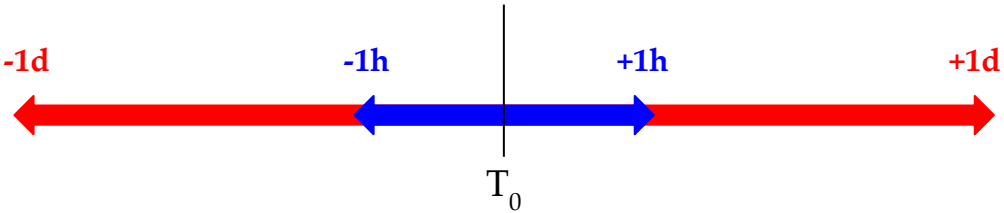


Reconstructed events

Neutrino alert → Multi-messenger dispatcher ↔ Online analysis



Search time windows (T_{ON})



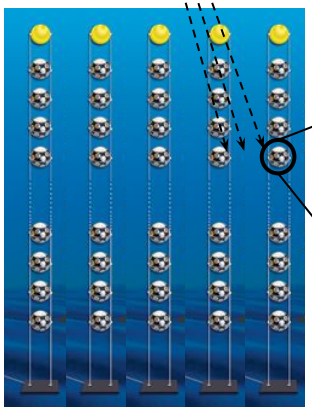
$n_{bkg} = 0.071$
$N_{ON} = 1$
p-value = 0.068

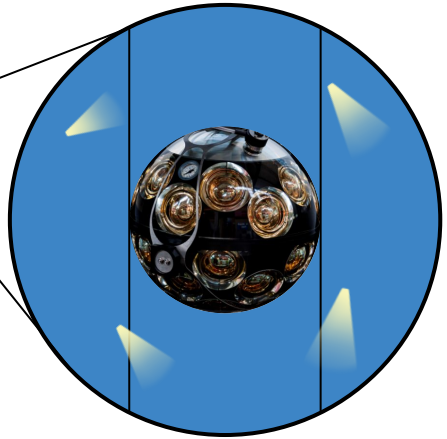
→ Again, an interesting example

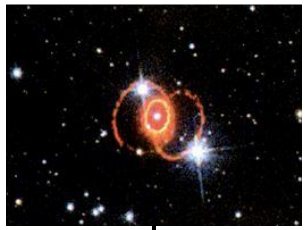
CCSNe follow-ups

GRBs and transients | Neutrinos | CCSNe | GWs | FRBs and μQuasars

$\bar{\nu}_e, \nu_e, \nu_x$

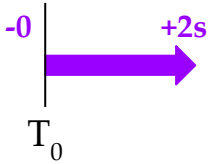






MeV $\bar{\nu}_e$ interact via inverse-beta decay
→ short tracks visible in single DOMs
→ **search for excess of coincidences between PMTs in single DOMs**

Search time window

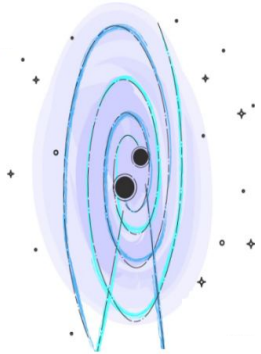


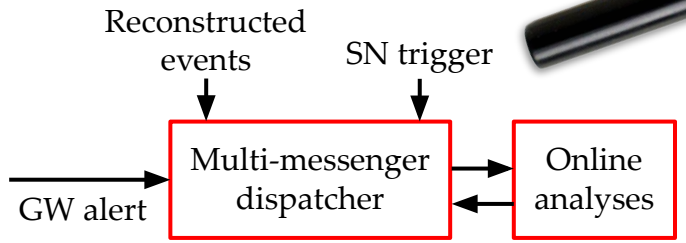
Different strategy from ON/OFF approach

Online analysis ← Multi-messenger dispatcher ← CCSN alert

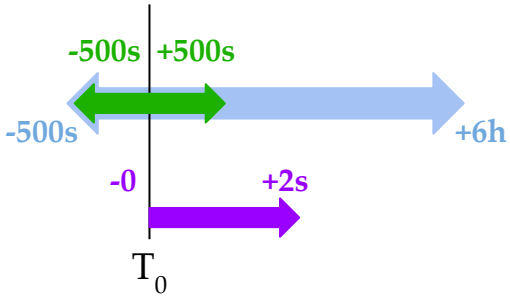
GWs follow-ups

GRBs and transients | Neutrinos | CCSNe | **GWs** | FRBs and μQuasars



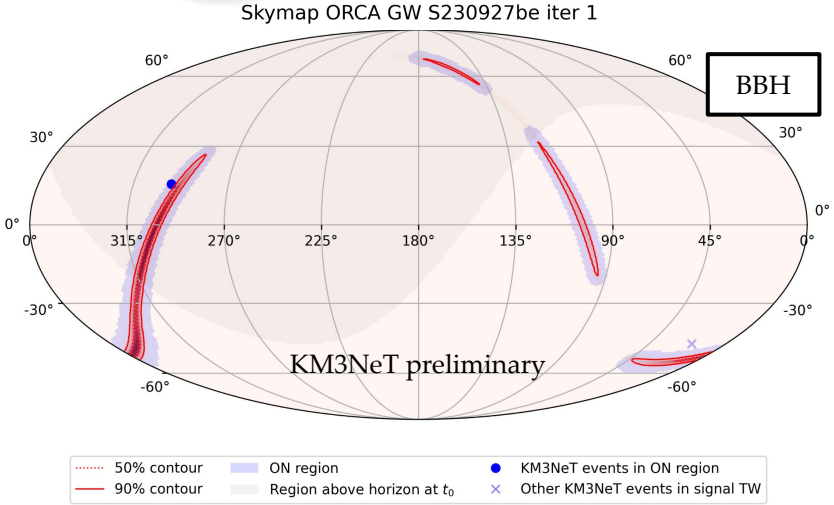


Search time windows



High energy analysis (ON/OFF technique)

MeV analysis (same approach as CCSNe)

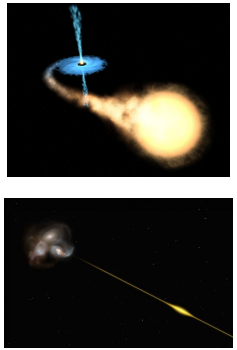


n_{bkg} = 0.019, N_{ON} = 1, p-value = 0.019
(no ARCA counterpart)

→ Not significant, but interesting case

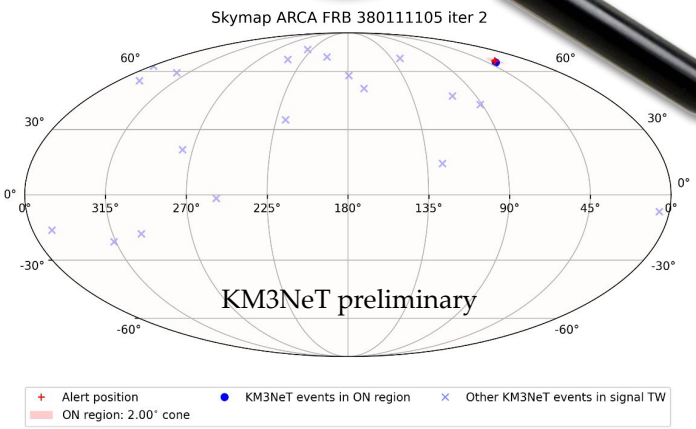
FRBs and μQuasars follow-ups

GRBs and transients | Neutrinos | CCSNe | GWs | FRBs and μQuasars

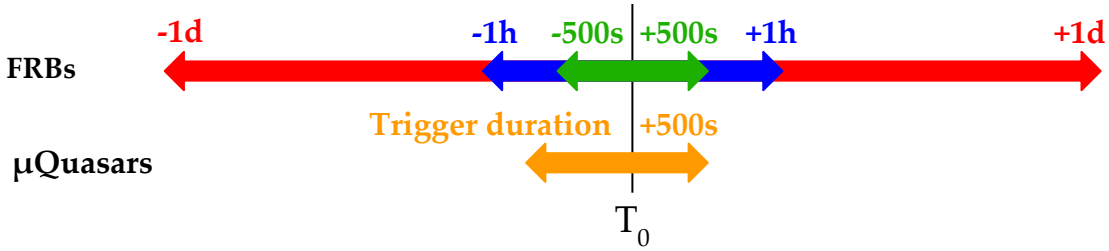


Reconstructed events

FRB or μQuasar FRB alert → Multi-messenger dispatcher ↔ Online analysis



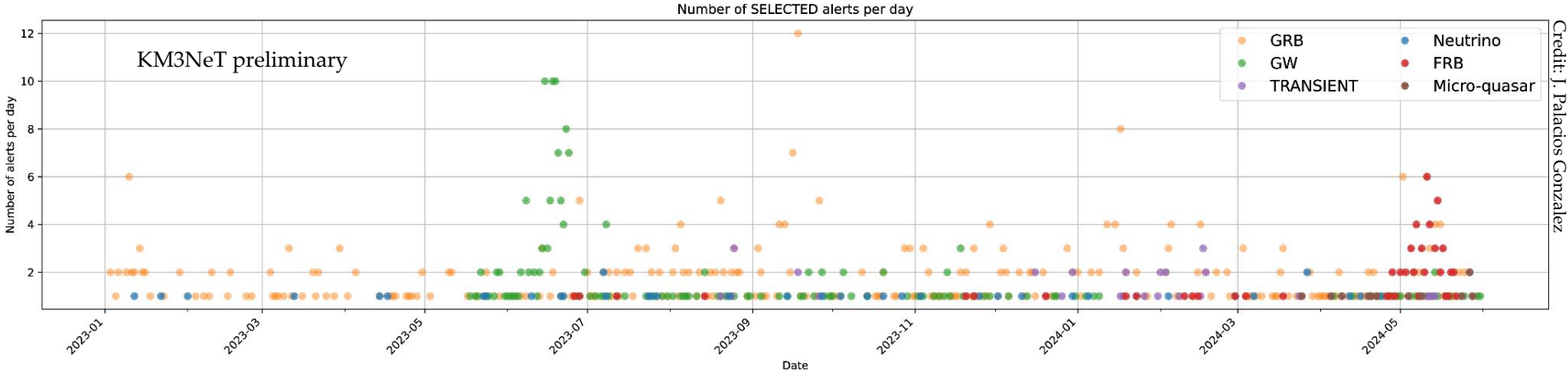
Search time windows (T_{ON})



$n_{bkg} = 0.012$
$N_{ON} = 1$
p-value = 0.012

Interesting example of a FRB follow-up

How many alerts did we analyse?

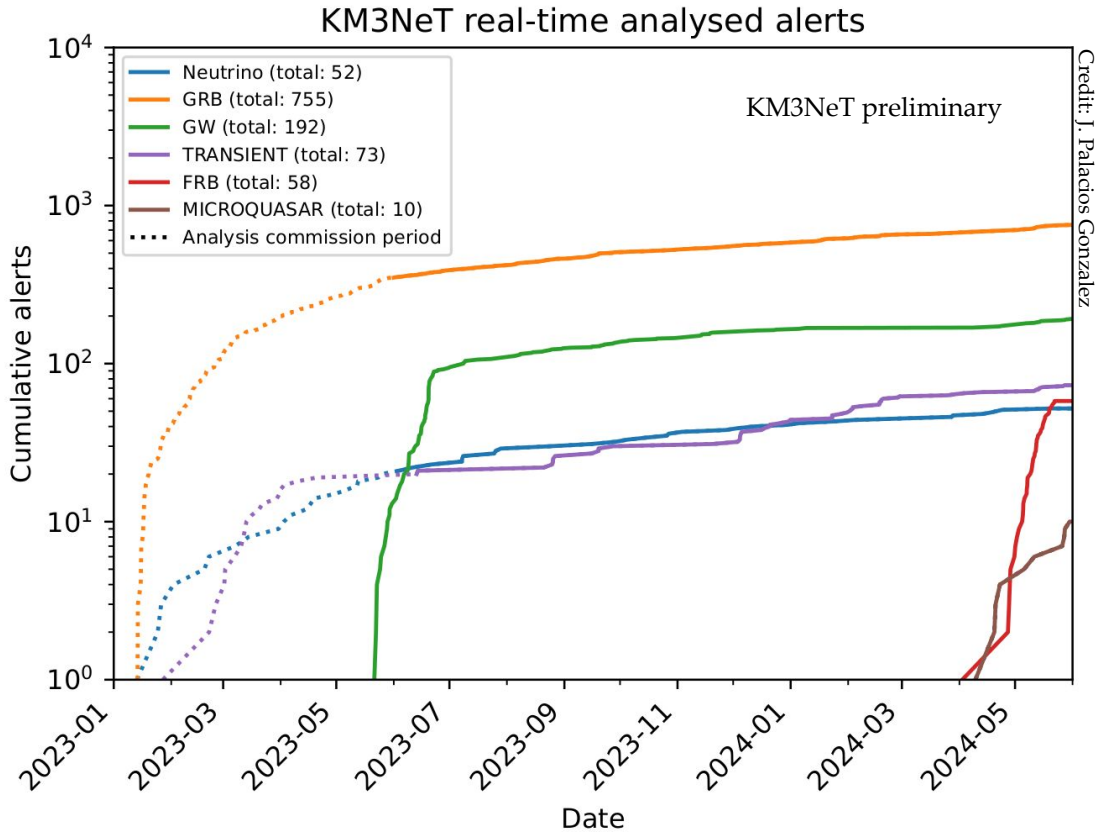


Credit: J. Palacios Gonzalez

Rate of triggered real-time follow-ups

- GRBs: ~ 1 per day
- GWs: ~ 1 per 2 days
- Transients: ~ 1 per week
- Neutrinos: ~ 1 per 2 weeks
- FRBs: ~ 1 per 5 days
- μQuasar: ~ 1 per week

Results of KM3Net real-time follow-ups



So far, many alerts have been analysed but **no significant candidate event has been found**

KM3NeT keeps growing and real-time follow-ups are continuously performed. Also, selection to send alerts to the external community is in preparation → **most exciting time has to come yet!**

STAY TUNED!

Summary

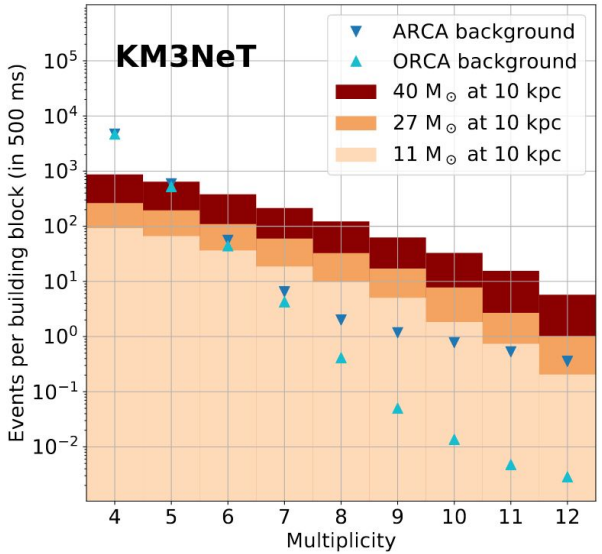
- KM3NeT is currently taking data in a partial detector configuration
- Real-time multi-messenger searches are a key component of the KM3NeT program
- Events reconstructed within the KM3NeT real-time analysis framework are used to perform follow-ups of external alerts received from other multi-messenger instruments
- Different analyses are triggered depending on the source type
- No candidate neutrino events have been found so far in spatial and temporal coincidence with received alerts
- KM3NeT size is growing and follow-ups of external alerts keep being automatically triggered
- The definition of an event selection to start sending alerts to the external multi-messenger community is ongoing

Art by Floris Tilanus

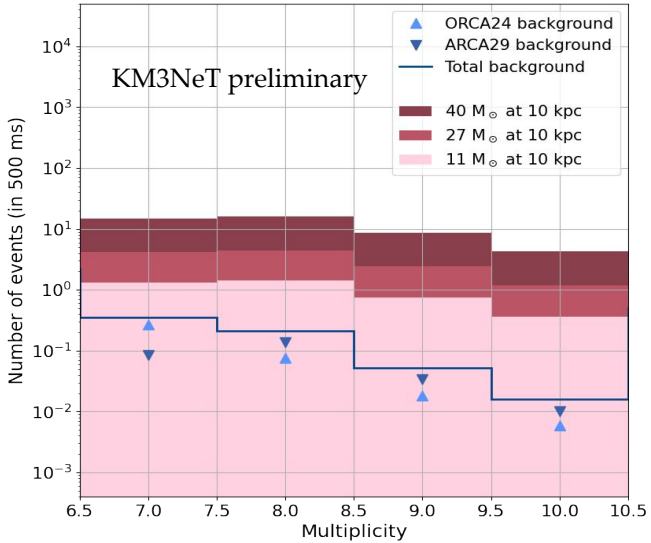
Backup

Expected number of events for CCSNe

KM3NeT 115 strings

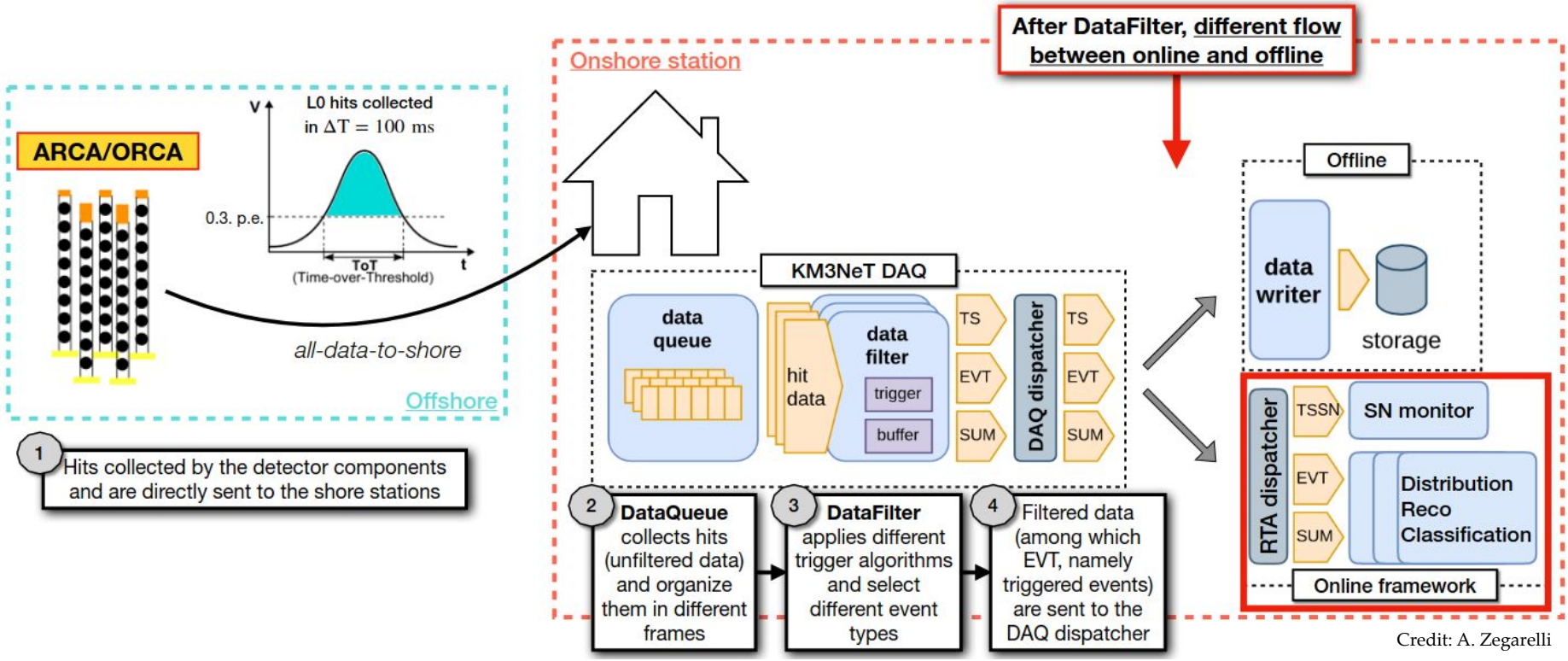


ARCA 29 strings + ORCA 24 strings



Multiplicity: number of unique PMTs involved in a coincidence

KM3NeT data flow



Credit: A. Zegarelli