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# Online Analysis Framework for Multi-Messenger Astronomy with KM3NeT

Vincent Cecchini - IFIC Valencia, KM3NeT-INFRADEV2 WP4  
On behalf of the KM3NeT collaboration.

2nd Astro-COLIBRI MM astrophysics workshop  
21/11/2023

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 **Funded by  
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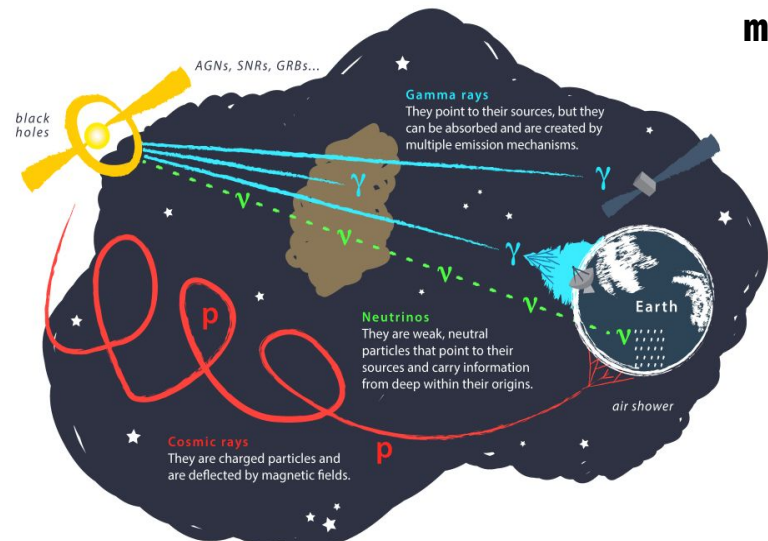
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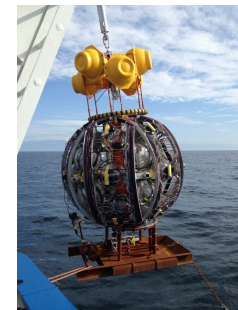
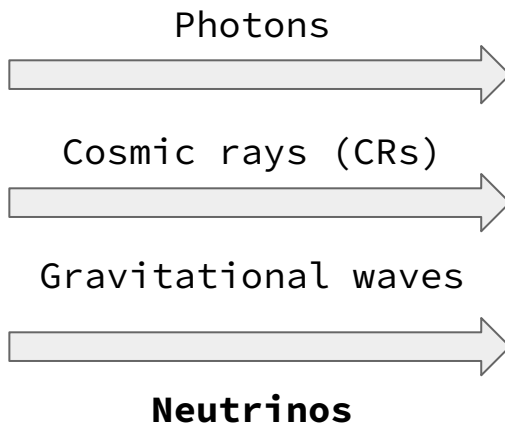
# Multi-messenger astronomy



Different nature of messengers  $\Rightarrow$  Different means of detection



Credit: Juan Antonio Aguilar and Jamie Yang, IceCube/WIPAC



MM Astronomy  $\Rightarrow$  Require to share the observations

CRs accelerated in astrophysical sources  $\rightarrow$  emits secondary neutrinos (and gammas) from pions decay.

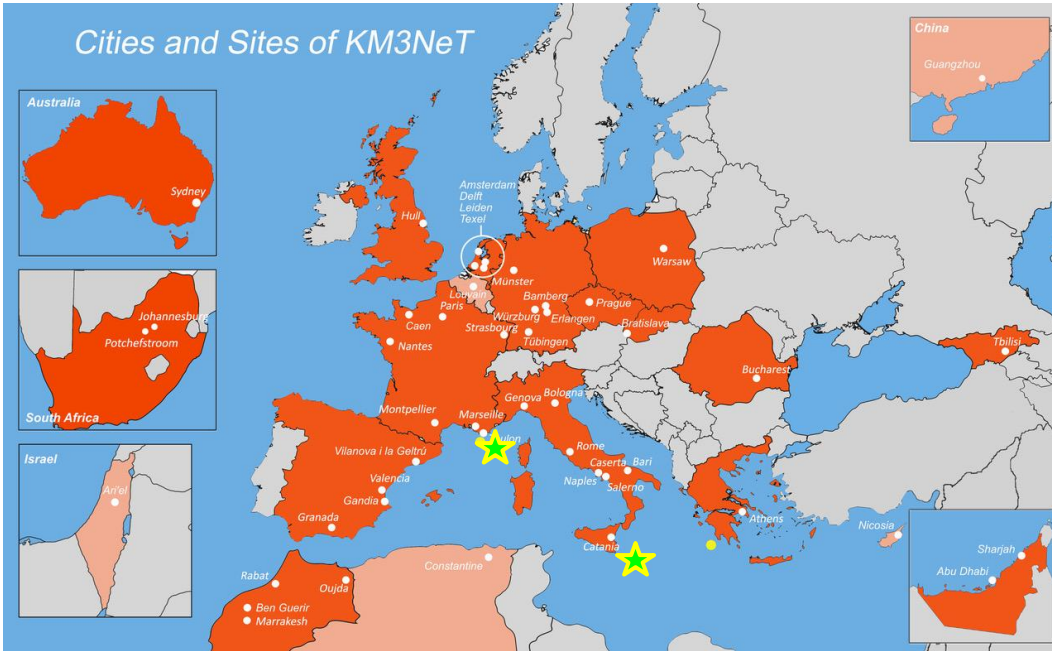
Neutrino advantages: No deflection, low absorption.

# The KM3NeT collaboration



20 countries, 47 institutes:

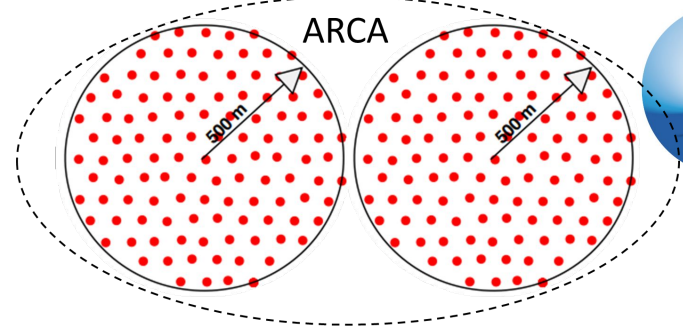
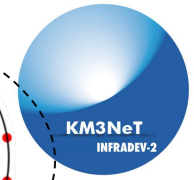
Cities and Sites of KM3NeT



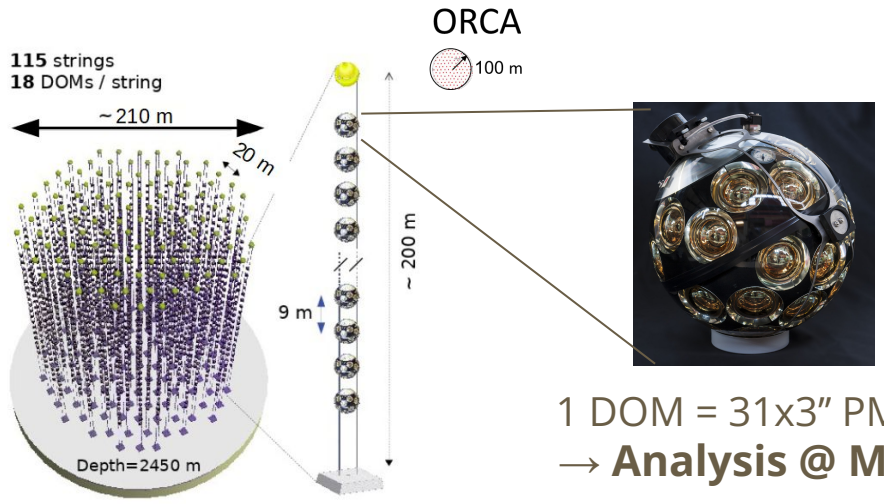
Two sites:

- **ARCA** (**A**stroparticle **R**esearch with **C**osmics in the **A**byss)  
→ Optimized for studies  $> \text{TeV}$ .
- **ORCA** (**O**scillation **R**esearch with **C**osmics in the **A**byss)  
→ Optimized for studies @  $\sim \text{GeV}$ .

# The KM3NeT detectors



	ARCA	ORCA
Location	100 km off Sicily (It.)	40 km off Toulon (Fr.)
Depth	3450 m	2450 m
Energie range	> TeV	GeV - TeV
DU Height	~ 800 m	~ 200 m
Number of Building Block	2	1
Instrumented Volume	~ 1 Gton	~ 7 Mton



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

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

# KM3NeT construction timeline



ORCA 18 muon event reco

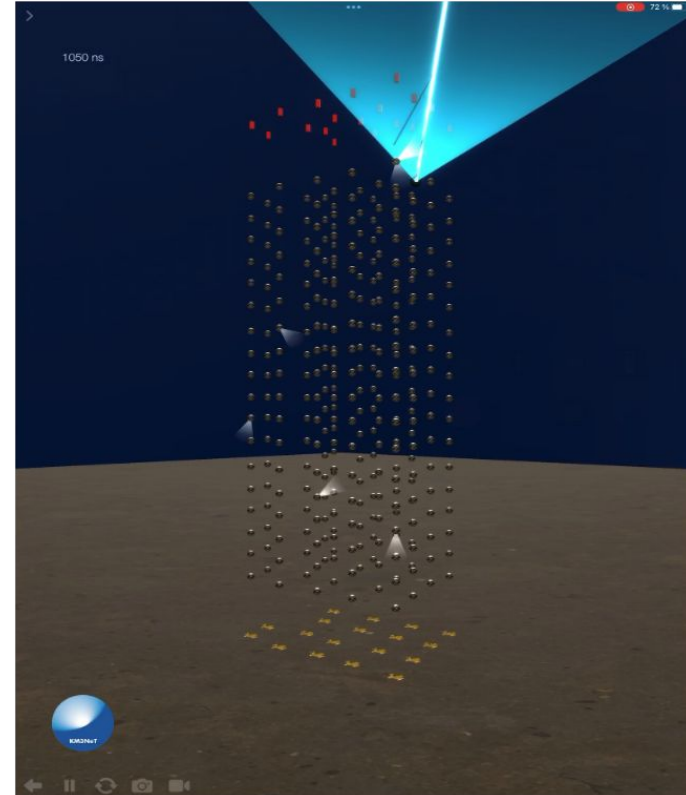
First lines of ARCA: 12/2015 ; ORCA 09/2017.

Phase 1: 24 DUs ARCA ; 6 DUs ORCA.

Construction phase, currently:

- ARCA 28 (9 lines deployed this summer)
- ORCA 18 (sea operation foreseen by the end of the year)

Completion of the full detector ~ 2028.

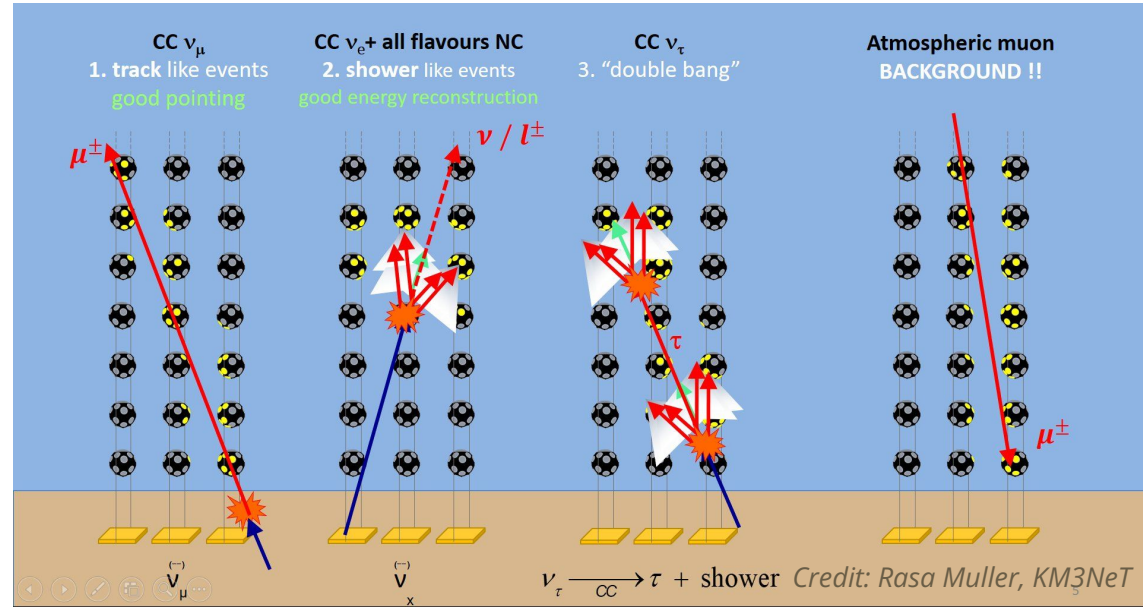
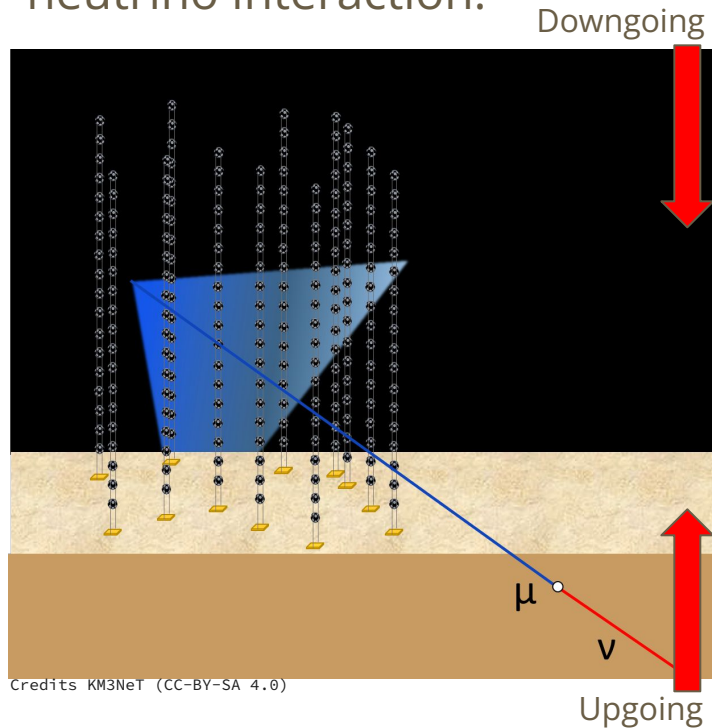


Credits: [R. Coniglione, NeuTel23](#)



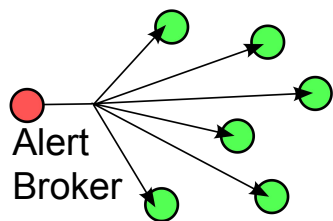
# Detections principle and event topologies

Detect the **Cherenkov light cone** from the secondary particle produce at neutrino interaction.



High Energies studies: use earth as target.

# KM3NeT in MM astronomy



Perform HE follow-up

ALERTS

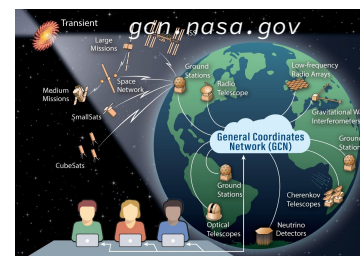
- ◆ Triggered by external alerts
- ◆ Search for  $\nu$  counterpart / Refine alert position (GW)



Send HE neutrino candidates

ALERTS

- ◆ Continuously running
- ◆ Work in progress: neutrino selection, alert sending program



# KM3NeT MM programm



Combination of:

- RTA: **Real-Time Analysis** framework (reconstruction of events from data)
- KOAP: **KM3NeT Online Analysis Pipeline** (run the physics analysis)

Aims at:

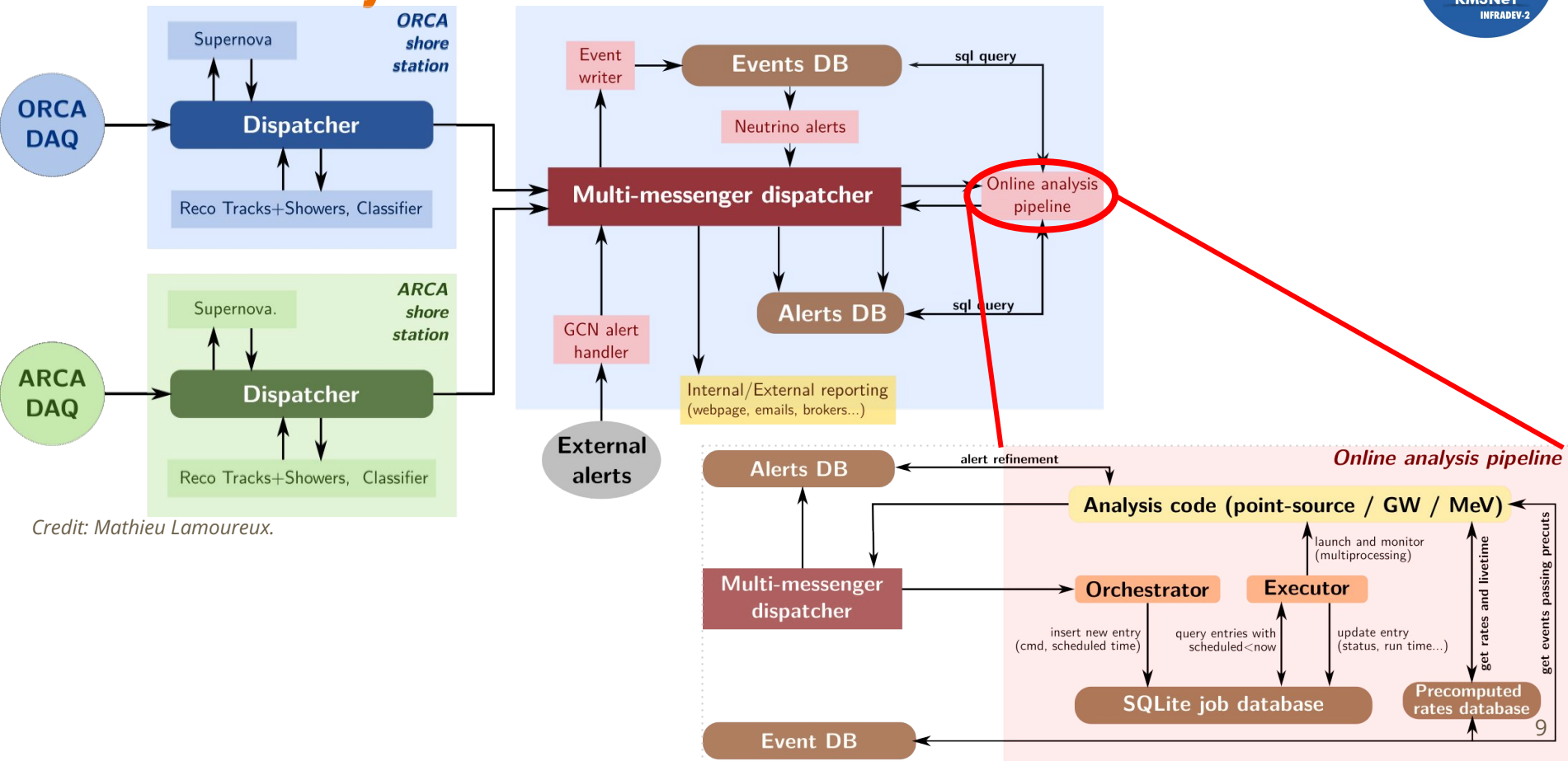
- Looking for spatial and temporal coincidences of KM3NeT reconstructed events with active astrophysical sources.

High-energy analysis: ON/OFF regions searches, with event selections depending on the trigger type

+ MeV Pipeline for Core-Collapse SuperNovae (CCSN).

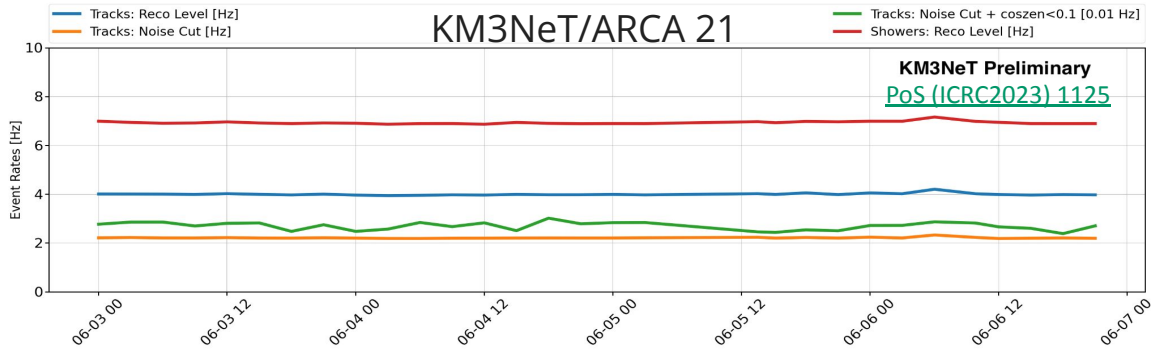


# Online analysis framework

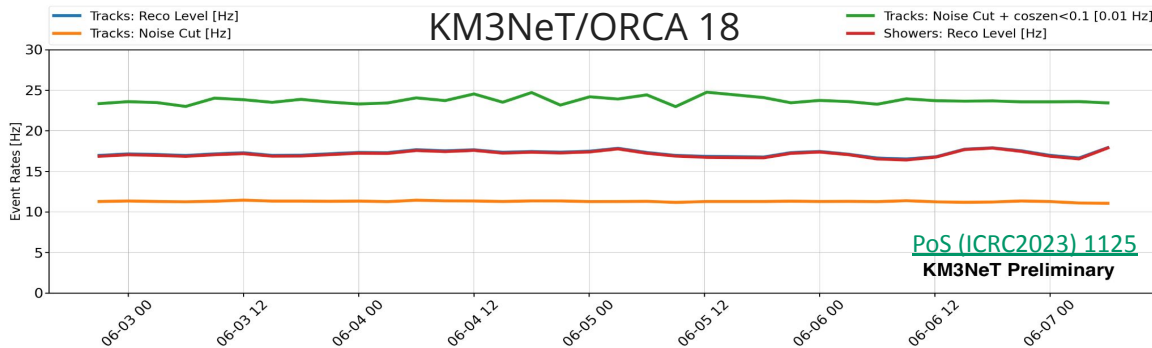


Credit: Mathieu Lamoureux.

# Real-Time Analysis: events rate and processing time



- Track reco. ( $\sim 4$ s)
- Shower reco. ( $\sim 4$ s)
- Classifier  $\mu / \nu$  ( $\sim 4$ s)

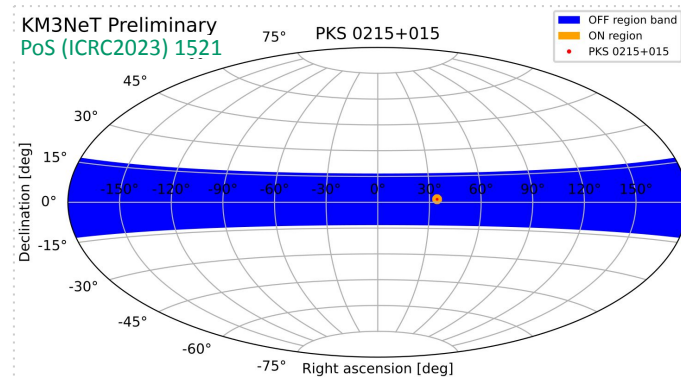


- Track reconstruction + Shower reconstruction + Classifier →  $\sim 6$ s

Expect  $\sim 100$  Hz rate for full detector

# MM follow-up analysis method: ON/OFF technique

1. **Signal (ON) region** = Roi (Region of Interest, source direction with its uncertainty + extension\*) + search time window. →  $N_{on}$
2. **Background region** = OFF band defined in local coordinates + 1-2 weeks data before the alert.
3. Estimate the expected background of Roi: 
$$N_{bkg} = \sum_{i \in \text{bands}} N_{OFF,i} \times \frac{LT(sig)}{LT(bkg)} \times \frac{\Omega_{ON,i}}{\Omega_{OFF,i}}$$
4. P-value: compare  $N_{on}$  with  $N_{bkg}$

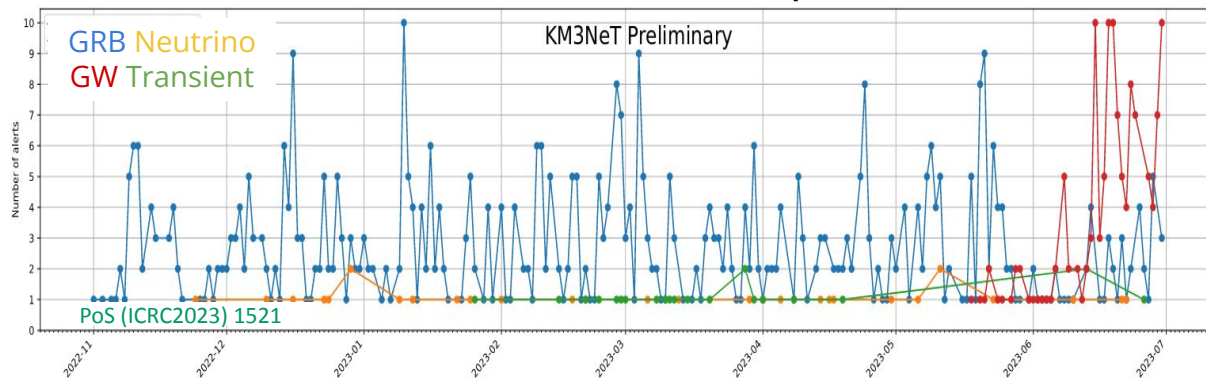


\*to cover for detector angular resolution  
 → analyses performed using **only track-like events** (include showers still in progress).

# Alert follow-up



Follow-up from 11/2022 to 06/2023



GRBs	302
Transient	22
IC Neutrinos	57
GWs	154

→ Alerts received from the GCN (General Coordinate Network) broker through the Apache Kafka protocol.

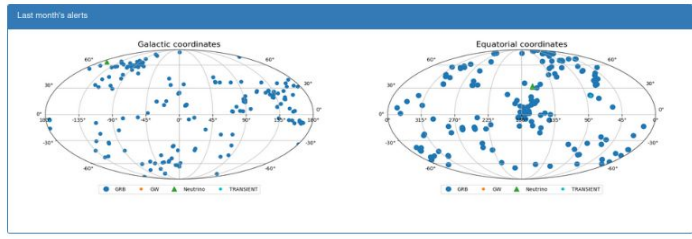
→ Ongoing implementation of additional brokers (TNS,  $\mu$ Quasar, FlaapLUC).

→ Each alert trigger all sky analysis for both ARCA and ORCA, as well as the MeV analysis pipelines.

Information returned: Versioning, search parameters, expected background, observed number of events, p-value, and flux upper limits.

# Internal online monitoring: shifter tools

## External triggers



Filter

Name-Tag ID:  Status:  Event type:

RA:  DEC:  Radius:

Between:  And:

Alerts [Make an alert](#) [Download CSV](#)

Showing alerts 1 to 20 of 3254 in total.

Entries per page:

...   >

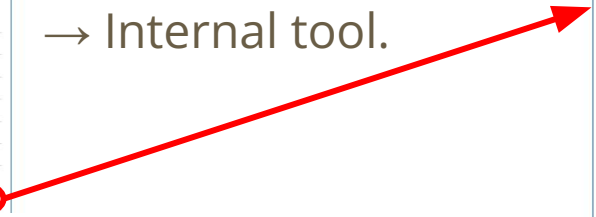
Event ID	Type	Event date (UTC)	Validity	RA (deg)	Dec (deg)	Links
<a href="#">new</a> 717313591	GRB	2023-09-25 05:46:26	Excluded	64.2	-60.3833	<a href="#">GCN_n</a> <a href="#">Details</a> <a href="#">-</a>
<a href="#">new</a> 717305385	GRB	2023-09-25 03:29:40	Excluded	157.8333	30.65	<a href="#">GCN_n</a> <a href="#">Details</a> <a href="#">-</a>
<a href="#">new</a> S230925k	GW	2023-09-25 02:26:25	Excluded	-	-	<a href="#">GCN_n Link</a> <a href="#">Details</a> <a href="#">-</a>
<a href="#">new</a> 717299390	GRB	2023-09-25 01:49:45	Selected	6.88	-57.33	<a href="#">GCN_n</a> <a href="#">Details</a> <a href="#">Analysis</a>
<a href="#">new</a> S230924bl	GW	2023-09-24 23:29:19	Excluded	-	-	<a href="#">GCN_n Link</a> <a href="#">Details</a> <a href="#">-</a>
<a href="#">new</a> S230924ao	GW	2023-09-24 13:04:17	Excluded	-	-	<a href="#">GCN_n Link</a> <a href="#">Details</a> <a href="#">-</a>
<a href="#">new</a> S230924an	GW	2023-09-24 12:44:53	Selected	-	-	<a href="#">GCN_n Link</a> <a href="#">Details</a> <a href="#">Analysis</a>

**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.



Available analysis for event S230919bj

Details for this alert

Detector: ORCA

Analysis ORCA - v1

TAG	RES_ALERT
Notice_Name	LVC_INITIAL
ID_Event	S230919bj
Date_Event	2023-09-19T21:57:12.000
Detector	ORCA
Pipeline	ORCA_GW
Iteration	1
Date_Analysis	2023-09-20T04:01:04.981
Code_Version	0.3.4.dev0-g8fb1fbc-d20230915
Search time window	1 alert:500 second TD 1 alert:6 hour
Livetime[μs]	20360.0
Livetime[hk]	11.045
Remaining fraction after rate cuts (%)	81.584
nON	0
nOFF	2,2,2,2,2,2,2
Expected Background	0.02053
Cuts on ClassificationScore	9.95969750e-01, 9.9596930e-01, 9.9596833e-01, 9.9596743e-01, 9.95966473e-01, 9.95965519e-01, 9.9596456e-01, 9.95884819e-01
p-value	1.0
Limits on Flux [GeV <sup>-1</sup> cm <sup>-2</sup> ]	-
Comments	-
IOSCORE_Stream	[]

Analysis skymap  
Click to enlarge



Skymap GW S230919bj iter 1

Stability  
Click to enlarge



Time profile  
Click to enlarge



Time profile ORCA GW S230919bj iter 1

# Broadcasting 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** (write by shifters/online coordinator and approved within 12h by the decision group)
- Set-up an **offline analysis** with refined detectors knowledge (MC, calibration, reco, analysis methods ...), if needed.

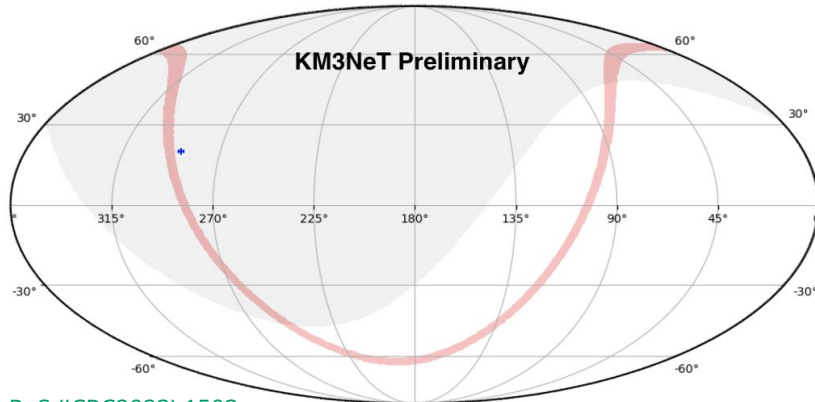
Future: If a **HE neutrino candidate is identified** → Send a **notice** (GCN with VOEvent format, SNEWS through Kafka)



# Example: The online follow-up of GRB 221009A

**2022, 9 Oct. at 13:16.59 UT: Long GRB** at RA, Dec = (288.3, 19.8) deg detected at  $z \sim 0.15$  (2.4 billion light-years away)

- GRB with **highest energy** ever detected by Fermi LAT (99 GeV, [ATel #15656](#)).
- **LHAASO detected photons of the order of  $\sim 10$  TeV** (among highest energies for a GRB, [GCN #32677](#)).
- One of the largest **worldwide follow-up campaigns** ever (among which KM3NeT).



[PoS \(ICRC2023\) 1503](#)



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>

[Circular 32741](#)

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

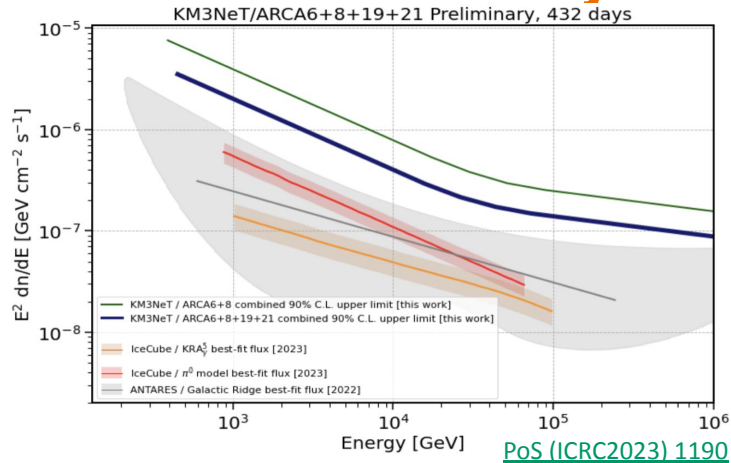
Using the data from the online fast processing chain, the KM3NeT Collaboration has performed a dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A (Dichiara et al. GCN 32632 (Swift); Veres et al. GCN 32636 (Fermi-GBM)). The search covers the time range of  $[T_0 - 50s, T_0 + 5000s]$ , with  $T_0$  being the trigger time reported by Fermi-GBM ( $T_0 = 2022-10-09 13:16:59.00$  UTC), during which both KM3NeT detectors were collecting good quality data. However, the GRB location was above the KM3NeT horizon (mean elevation of about  $-40$ deg) during the search time window, significantly reducing the point-like source sensitivity. In both detectors, zero events were observed in the search window, while  $0(0.1)$  were expected from the background. The online fast processing uses preliminary calibrations and detector alignment, which will be superseded in a future elaborated analysis.

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

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, see [PoS \(ICRC2023\) 1503](#) for refined offline analysis.

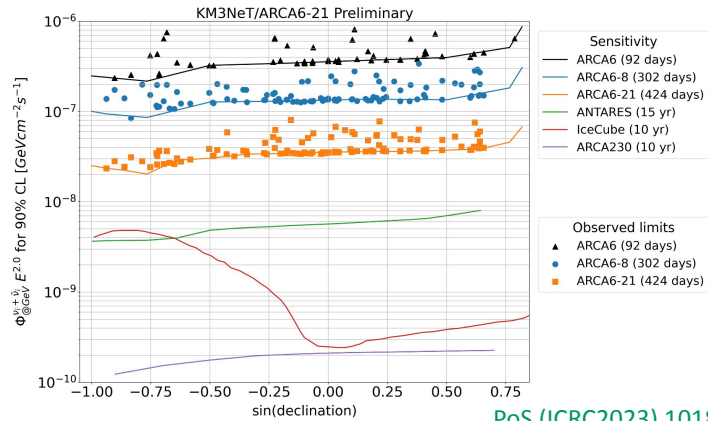
# Recent astronomy results from KM3NeT



Diffuse neutrino emission from Galactic Ridge, 90% upper limits (KM3NeT/ARCA6+8 and 6-21), compared to ANTARES and IceCube best fitting fluxes.

- No excess over background founded
- Not yet competitive limits

Perspectives: 6 more month of data with KM3NeT/ARCA21 + detector growth

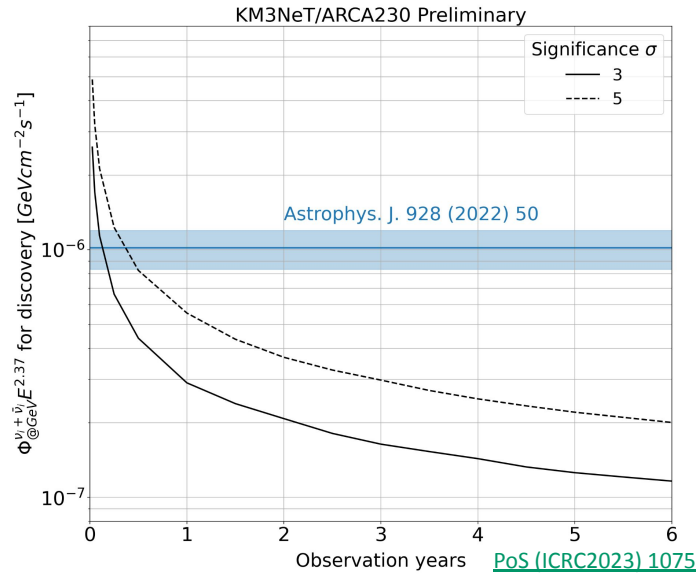


Point Source sensitivity and observed limits (KM3NeT/ARCA6-21 424 days) for 101 sources.

- Not significant neutrino excess observed.
- Sensitivity factor 4 from ANTARES (1.5 vs 13 y live-times).
- Astronomy potential rises fast with growing detector.

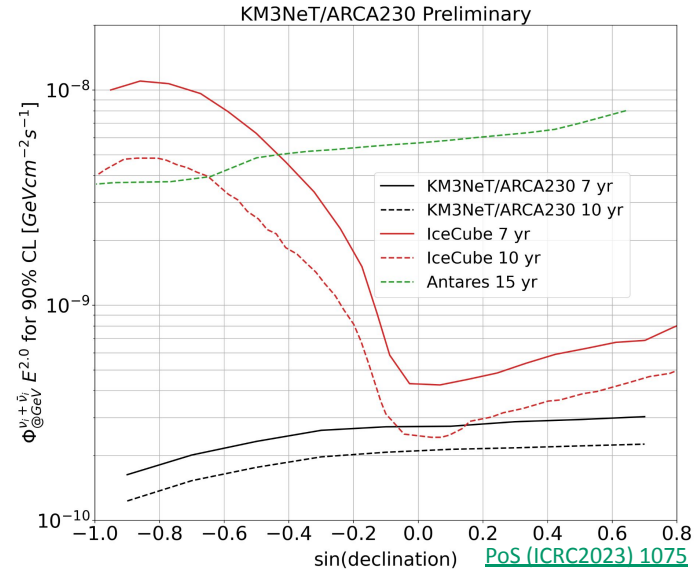
NB: KM3NeT already better than ANTARES for transient sources.

# Astronomy potential for KM3NeT/ARCA 230



3 and 5  $\sigma$  discovery values for a neutrino flux with spectral index of 2.37 (as reported by IceCube, blue line).

→ detection (5  $\sigma$ ) of the all-sky diffuse neutrino 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

# Conclusion



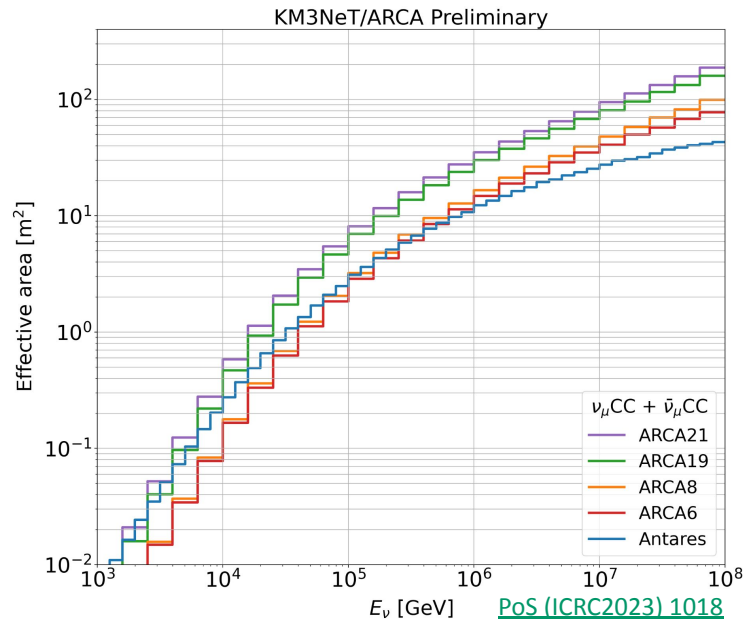
- KM3NeT RTA for online event reconstruction and classification is functional, current rate of tens of Hz.
- Analysis pipelines for follow-up are in nominal production mode.  
3 GCN Circulars + 1 ATeL already submitted.
- Alert sending status is work in progress.
- The detector growth will bring exciting detection capabilities.

Thanks for  
listening



Questions ?

# Effective area comparison KM3NeT/ANTARES



ANTARES better than KM3NeT when looking at steady sources due to live-time.

But KM3NeT better than ANTARES for Transients sources detection thanks to an higher effective area (reached since KM3NeT/ARCA19, now KM3NeT/ARCA28).