Development of real-time systems for neutrino detection with KM3NeT in the context of multi-messenger astronomy

Soutenance de thèse

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Università di Genova

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

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↳ KM3NeT neutrino alerts

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Context of multi-messenger astronomy

Experimental setup of KM3NeT

Development of real-time systems

↳ **KM3NeT neutrino alerts**

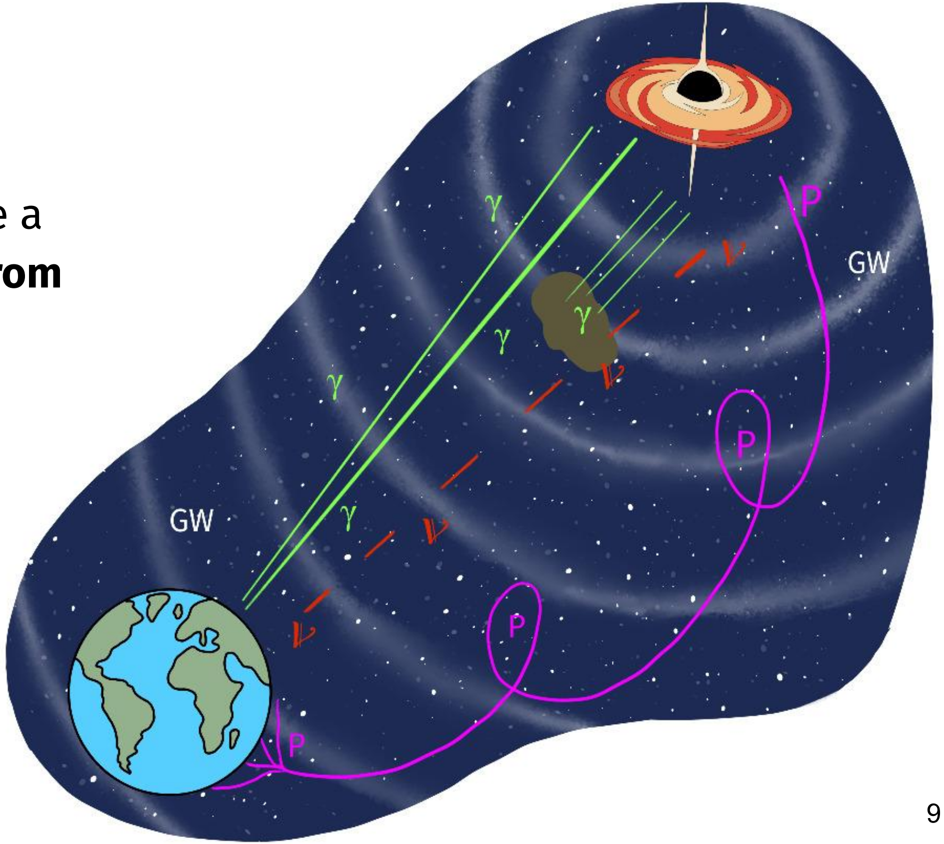
↳ **Core-Collapse Supernova real-time detection**

Multi-messenger astronomy

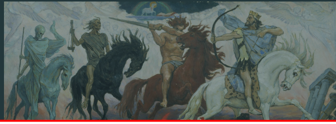
What is multi-messenger astronomy?

Multi-messenger astronomy aims to observe a **combination of signals of different nature from given sources**.

Each messenger brings a different kind of information.



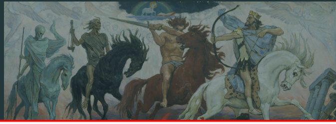
The four messengers of the Universe



Cosmic rays p

high energy charged particles, information from acceleration capabilities, composition, large scale anisotropy

The four messengers of the Universe



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Photons γ

EM radiation, each wavelength is associated to a specific physics mechanism

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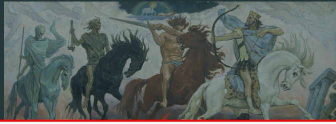

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spacetime deformation, knowledge on sources topologies and inner motions

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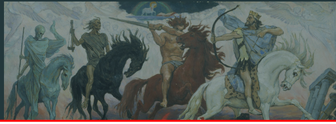

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Neutrinos ν

neutral, stable, weakly interacting particles, give access to cosmological distances and dense environments

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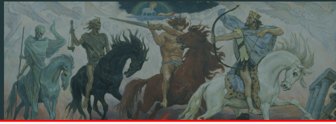

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MM

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Photons γ

EM radiation, each wavelength is associated to a specific physics mechanism

Connection between the different messengers

Hadronic models:
Accelerated CR interact with nucleons and radiation

$$p + p \longrightarrow \begin{array}{l} p + p + \pi^0 \\ p + n + \pi^+ \end{array} \qquad p + \gamma \longrightarrow \Delta^+ \longrightarrow \begin{array}{l} p + \pi^0 \\ n + \pi^+ \end{array}$$

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$$\pi^0 \longrightarrow \gamma + \gamma$$

$$\pi^\pm \longrightarrow \mu + \nu_\mu, \quad \mu \rightarrow e + \nu_\mu + \nu_e$$

Gammas produced either from pions or from leptonic process (accelerated electron population)

High-energy neutrinos are “smoking guns” of hadronic production

Connection between the different messengers

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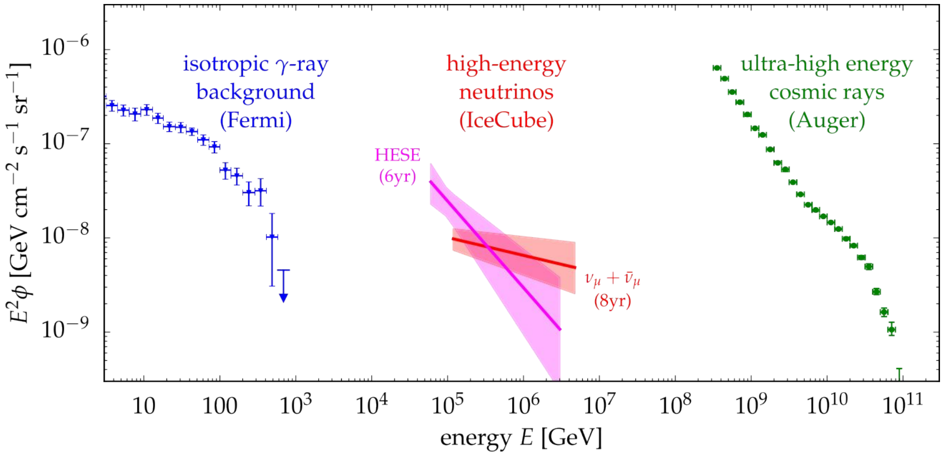
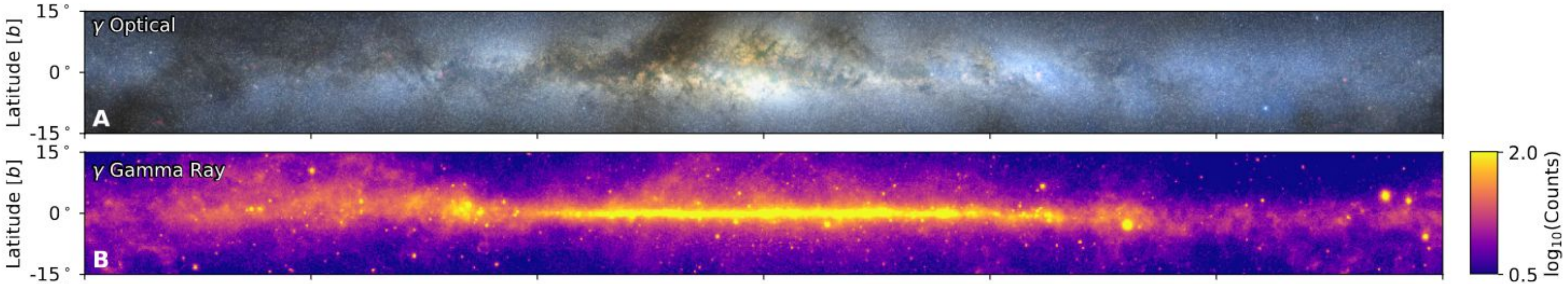


Diffuse fluxes for gamma, high-energy neutrino and ultra-high energy cosmic ray (Ahlers and Halzen 2018)

Similar energy densities in γ, ν and CR
→ hint of common origin?

Source candidates of neutrinos

Galactic



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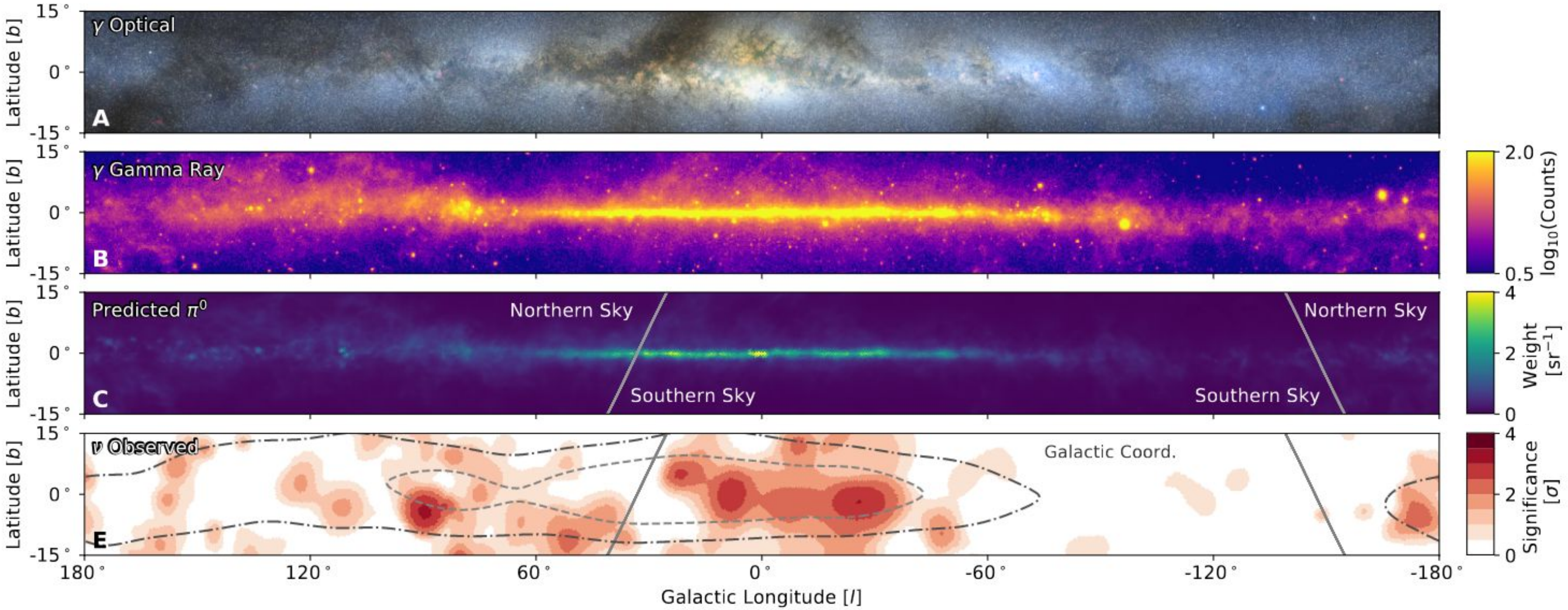
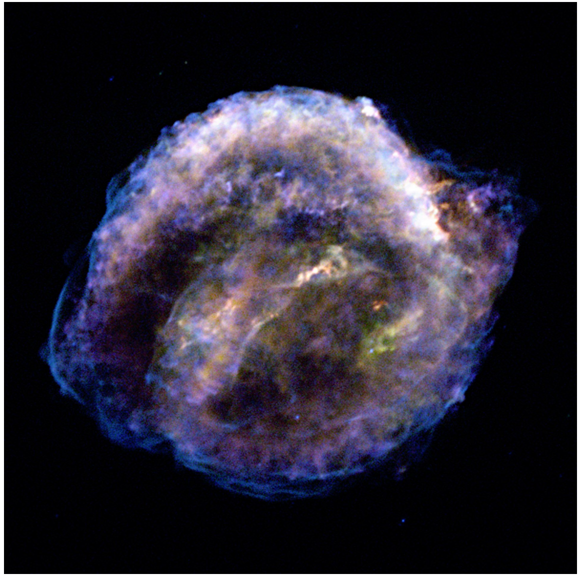


Observation of high-energy neutrinos from the Galactic plane (IceCube 2023)

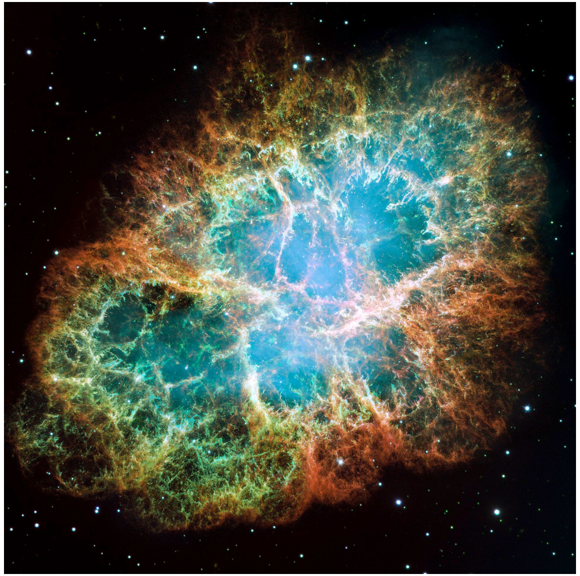
Source candidates of neutrinos

Galactic

Supernova remnants, pulsar wind nebulae, microquasars...



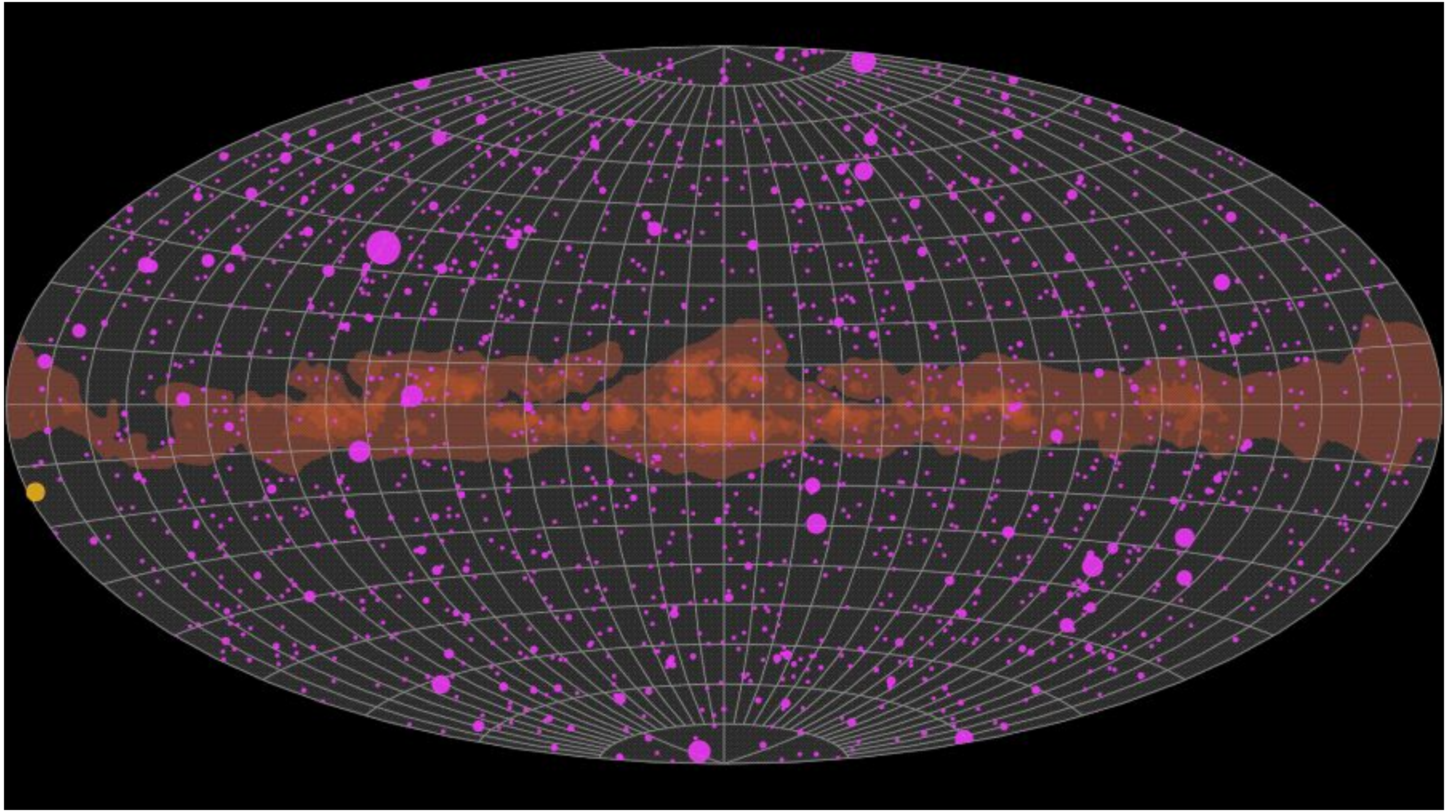
X-ray image of Kepler's SN (CXO)



Crab nebula (NASA/ESA)

Source candidates of neutrinos

Extragalactic



Transient gamma sky (Fermi-LAT 2023)

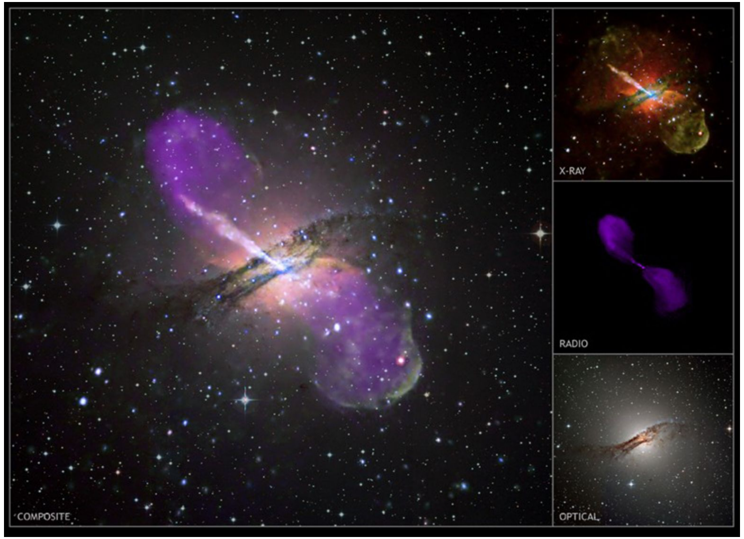
Source candidates of neutrinos

Extragalactic

Active galactic nuclei: Blazars, Seyfert,
Starburst galaxies

Observation from IceCube of flaring blazar (TXS 0506+056) and galaxy NGC 1068

Right: Centaurus A, the closest AGN from Earth (NASA, NSF, ESO)



Source candidates of neutrinos

Extragalactic

Active galactic nuclei: Blazars, Seyfert, Starburst galaxies

Tidal disruption events

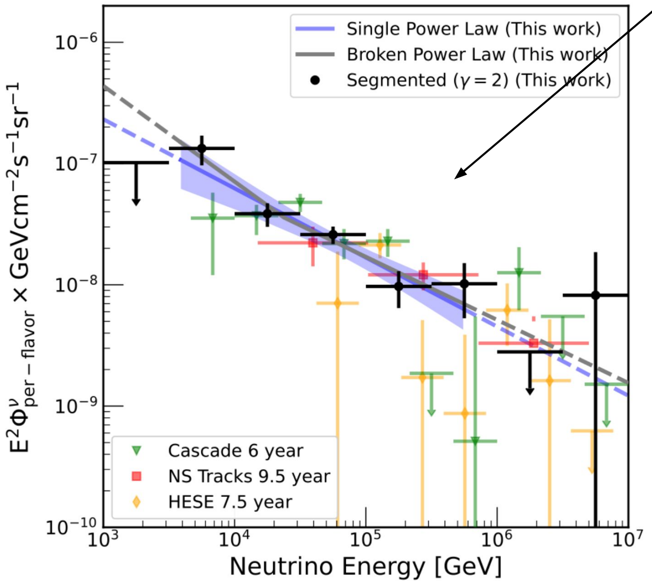
Neutrino arrival potentially around 100 days after the tidal disruption flare

Right: artistic illustration of a TDE

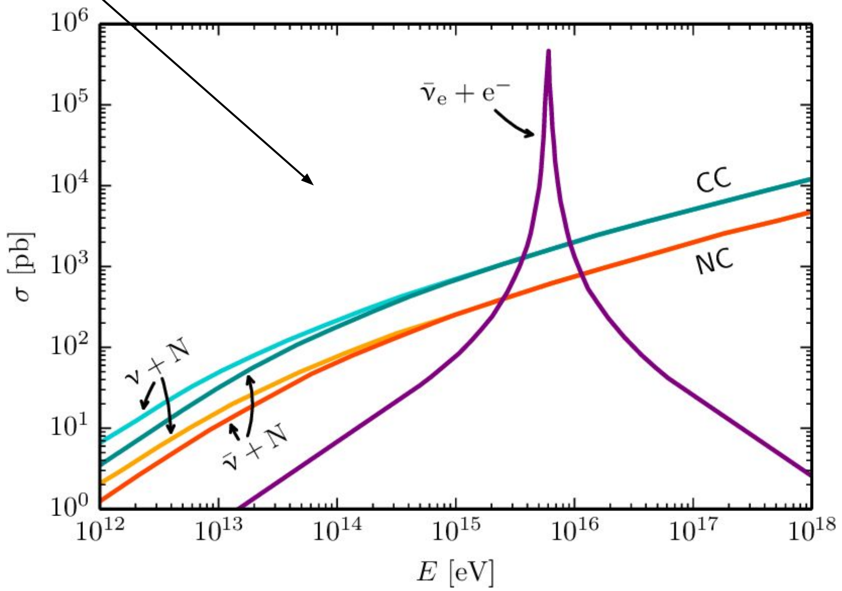
How to detect cosmic neutrinos?

Number of cosmic neutrinos interacting per volume

$$\Phi \times \sigma \times \rho$$



Cosmic neutrino flux (IceCube 2024)



Neutrino cross section (Mohrmann 2025)

How to detect cosmic neutrinos?

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$\Phi \times \sigma \times \rho \approx 800$ per year per km^3 in water

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Markov, 1960:

"We propose to install detectors in an underground lake or deep in an ocean and determine the direction of charged particles with the help of Cherenkov radiation"

KM3NeT: a neutrino telescope in the deep Mediterranean Sea

Principle of water Cherenkov detectors

Neutrinos interact only weakly
→ detection of the induced secondary particles

Charged current: $\nu_l + N \rightarrow l + X$

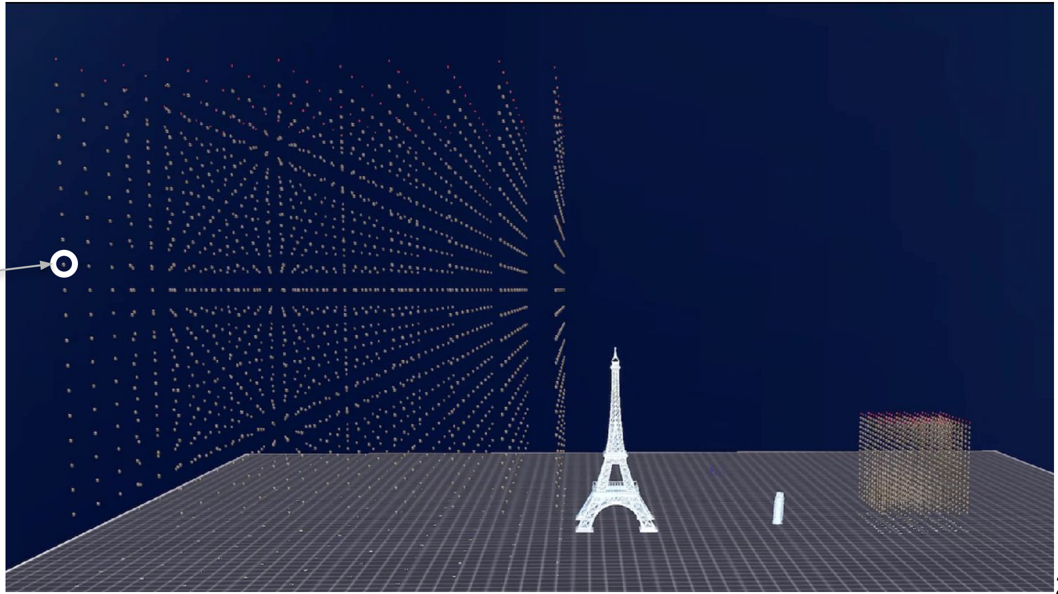
Neutral current: $\nu_l + N \rightarrow \nu_l + X$

Illustration of Cherenkov radiation (public domain)

Experimental setup of KM3NeT

KM3NeT
Water Cherenkov neutrino detector currently in construction at the bottom of the Mediterranean Sea

Detector design
DOM (digital optical module): sphere hosting 31 PMTs
Multiple lines of 18 DOMs, with different spacing for different energy ranges

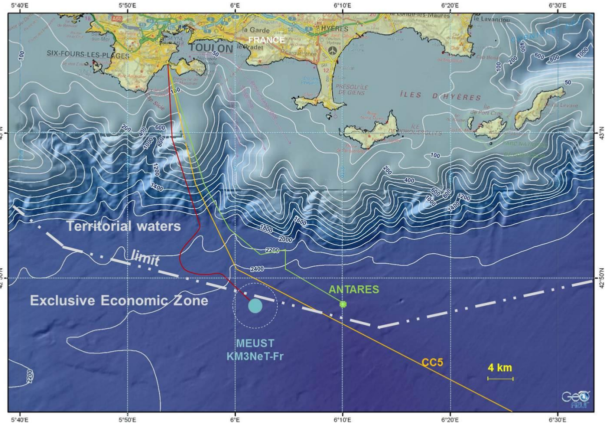


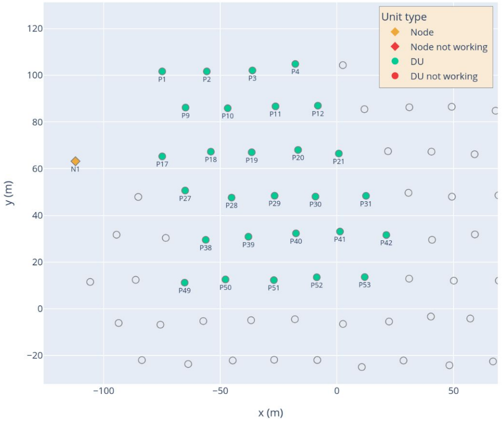
The two KM3NeT detectors

ORCA

Denser array, volume 7Mt, optimized for detection of neutrinos in the tens of GeV, offshore Toulon (FR)

28 lines deployed, 24 operational

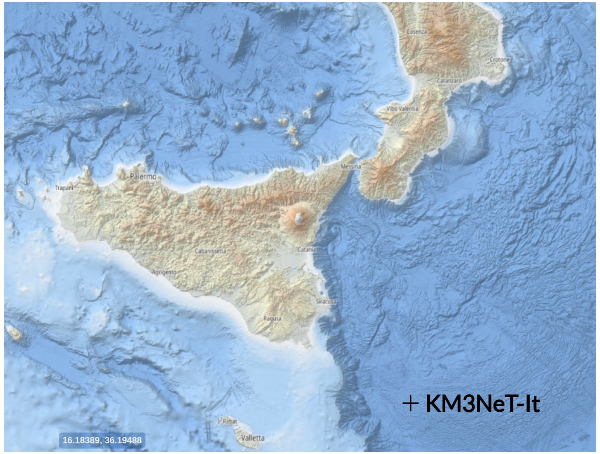


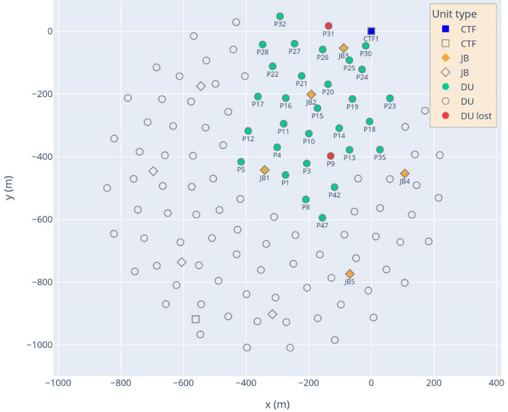


ARCA

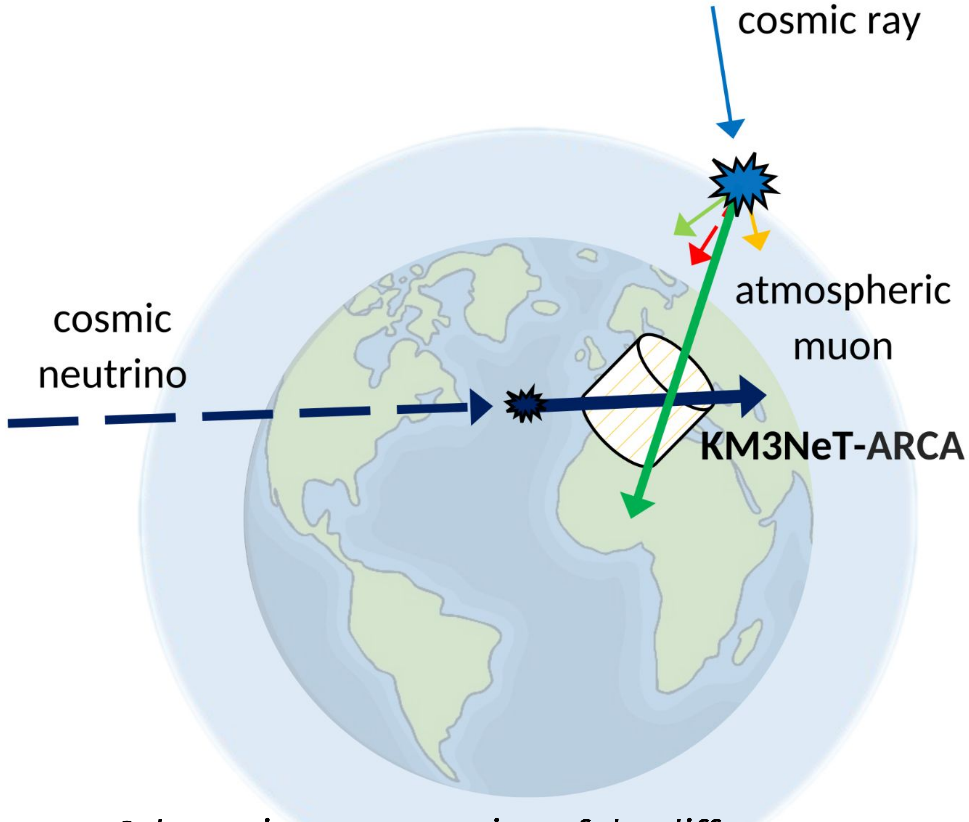
Volume of > 1Gt, optimized for the detection of neutrinos in the TeV to PeV energy range, offshore Sicily

33 lines deployed, 3 operational





Events seen with KM3NeT

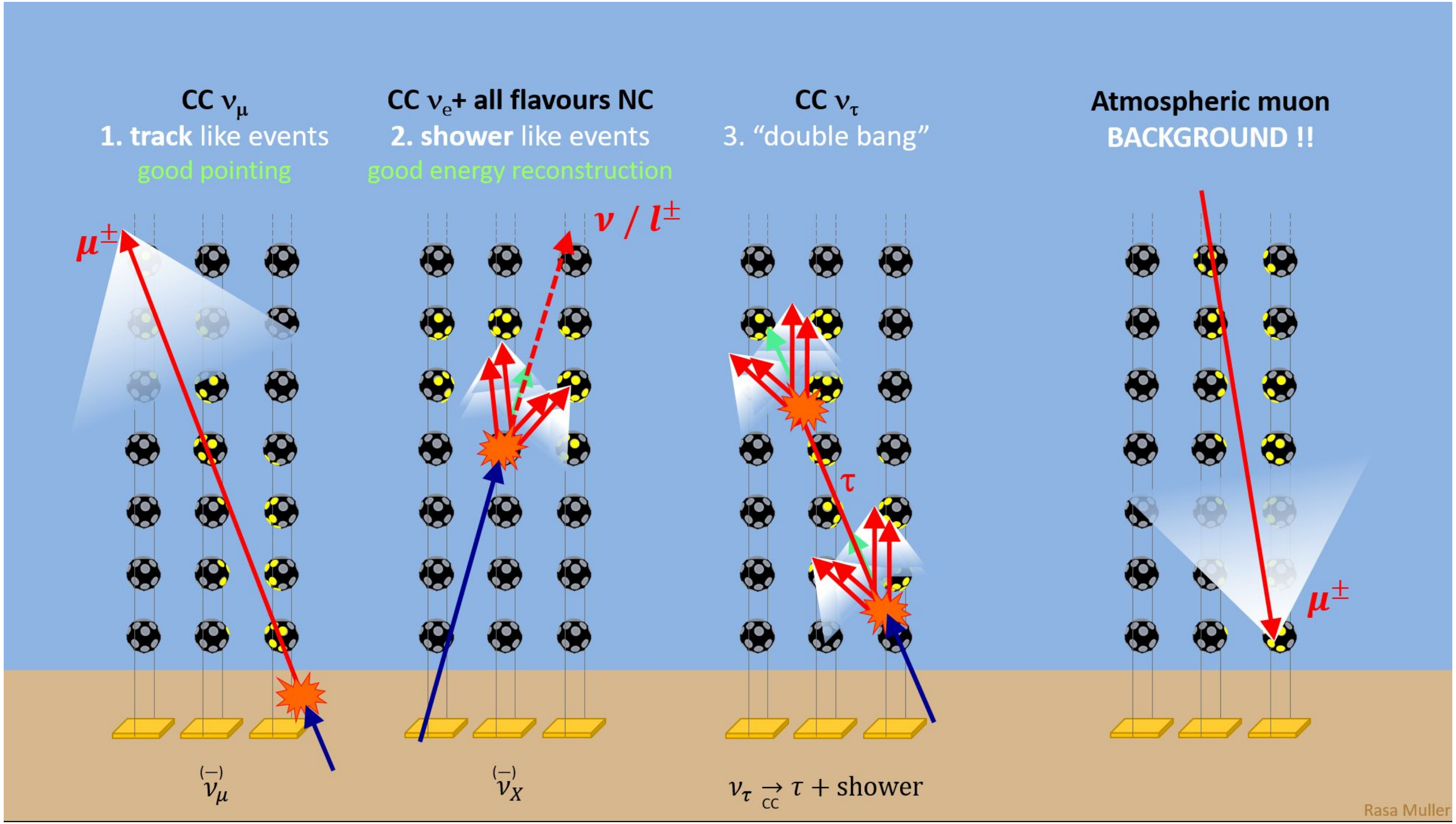


Schematic representation of the different events seen with KM3NeT (Marconi 2023)

	Trigger level	Upgoing events
Atmospheric muons	8.1×10^7	5.3×10^5
Atmospheric neutrinos	1.9×10^5	1.2×10^5
Cosmic Neutrinos	730	420

Number of events per year for ARCA (KM3NeT 2024)

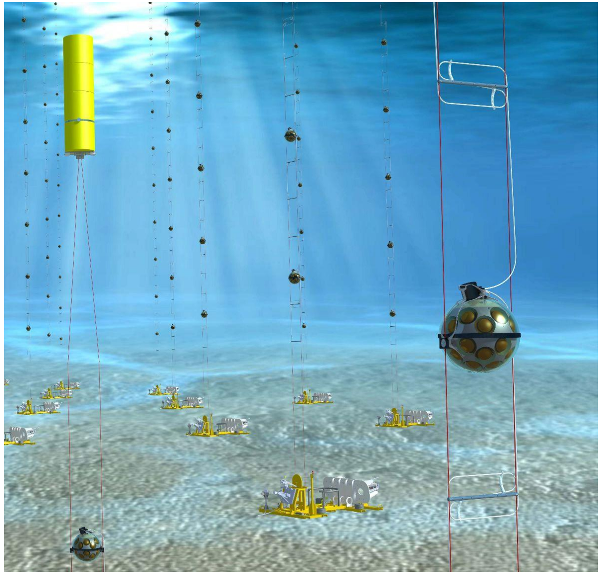
Topology of KM3NeT events



The KM3NeT online program

The two goals of the online pipeline

Current statistics-limited samples of astrophysical neutrinos, optimum strategies are:



Neutrino alert sending

Follow-up of external triggers

Why real-time analysis?

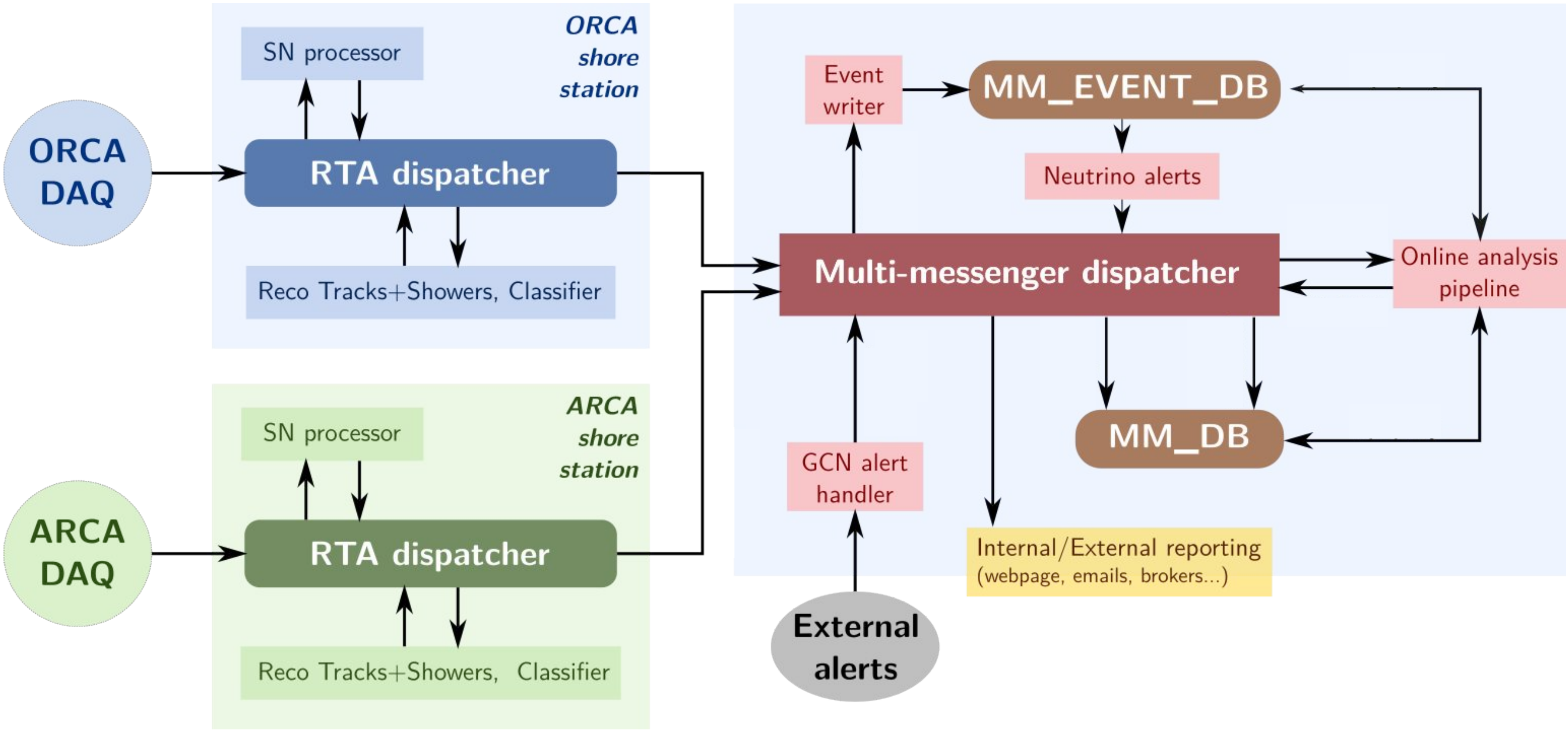
Current statistics-limited samples of astrophysical neutrinos, optimum strategies are:

– Neutrino alerts for rapid follow-ups
– Real-time searches for neutrino signals in response to transient observations

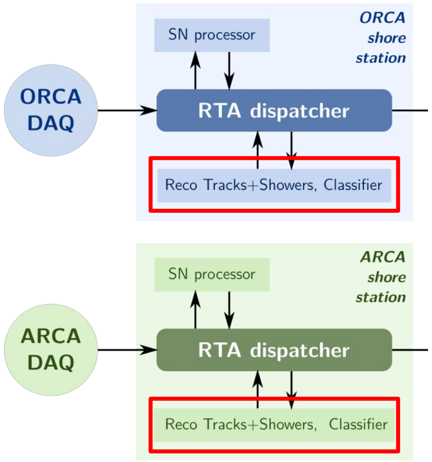
The observations:

– Strengthen or refine detections made in single messenger
– Probe source dynamics and populations, even in the absence of signal
– Identify the sources of the observed high-energy astrophysical neutrinos

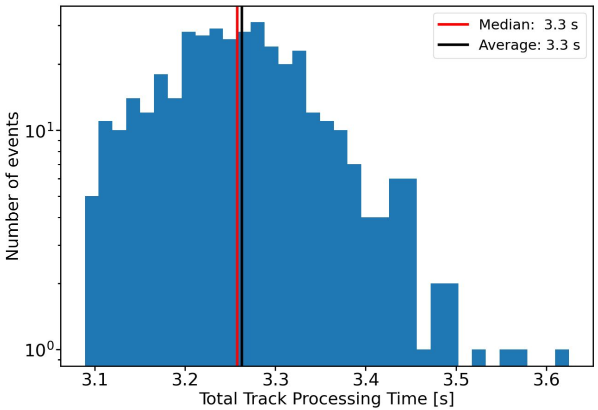
Diagram of the KM3NeT online pipeline dataflow

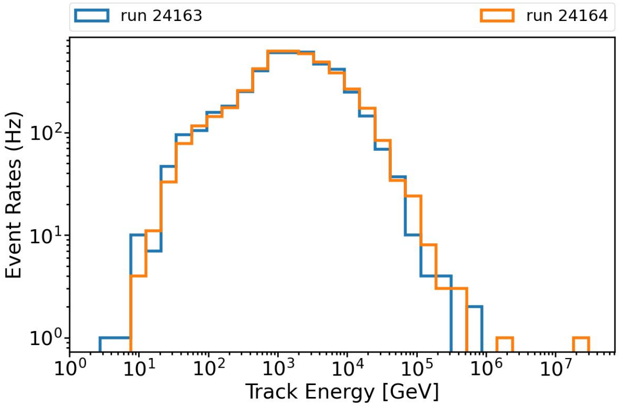


Real-time event processing



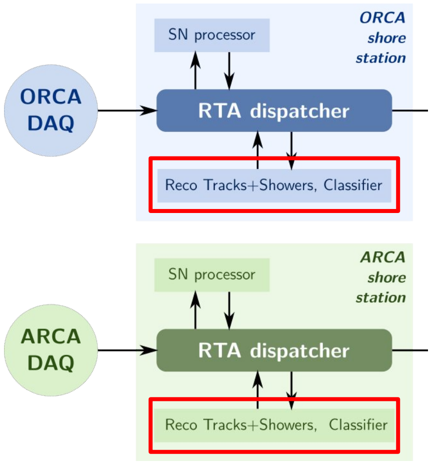
ARCA





Less than one minute
→ results of the track and shower reconstruction (direction, quality, energy) and classification for the event topology

Real-time event processing



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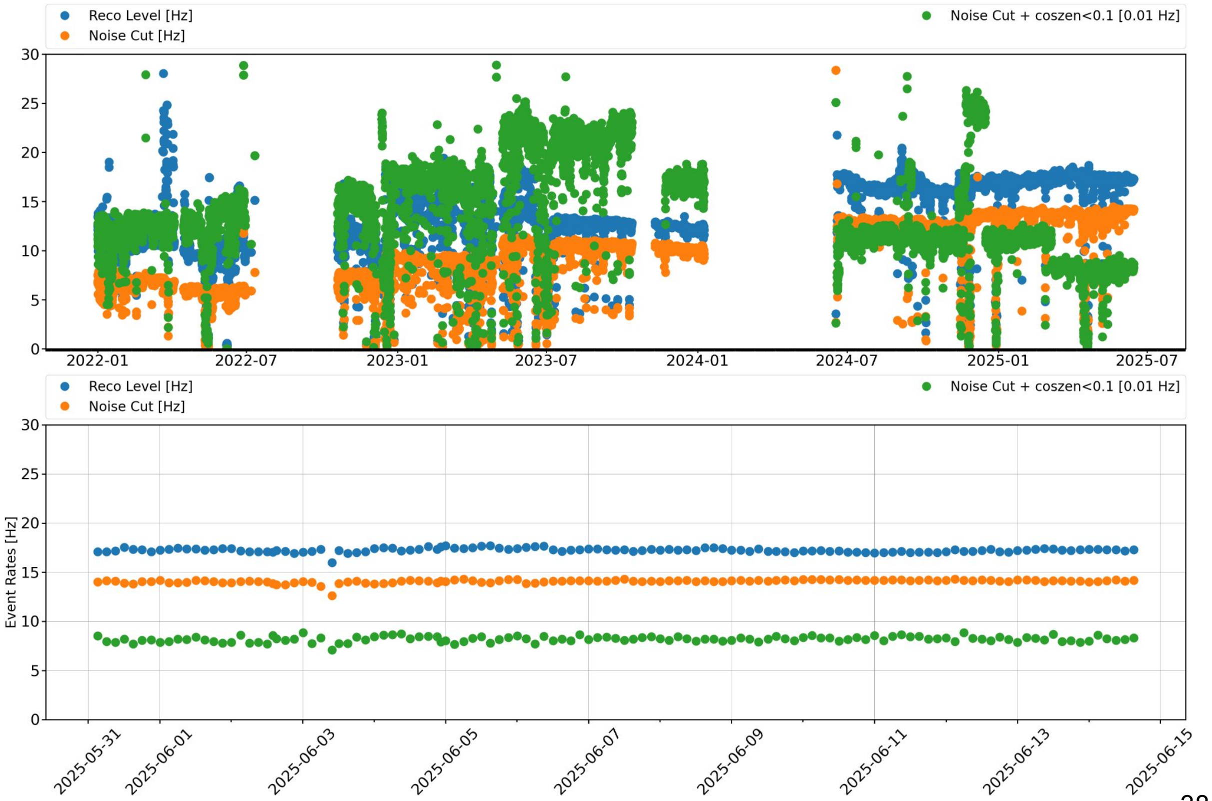

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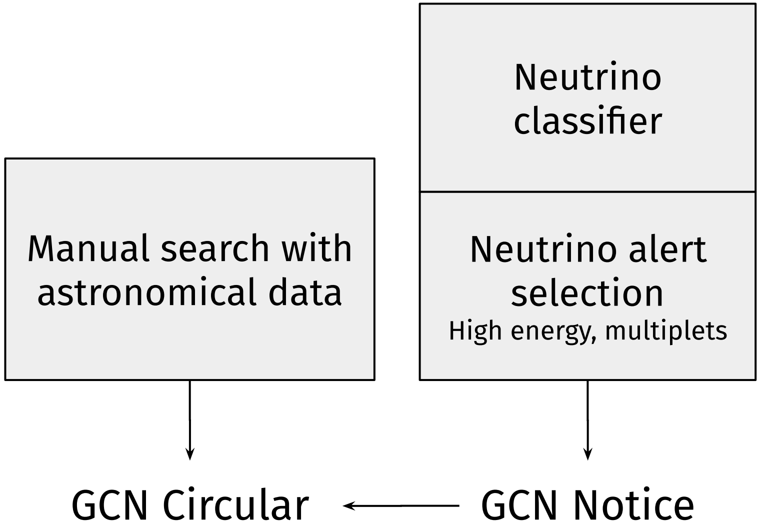
KM3NeT neutrino alerts

KM3NeT neutrino alert scheme

Selecting 1-2 neutrinos per month from thousands of events is not easy, and different selections lead to different samples

“Classic” selection on neutrino properties



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Selecting 1-2 neutrinos per month from thousands of events is not easy, and different selections lead to different samples
→ two selections method, one based only on ν properties, one based on ν-astro mix

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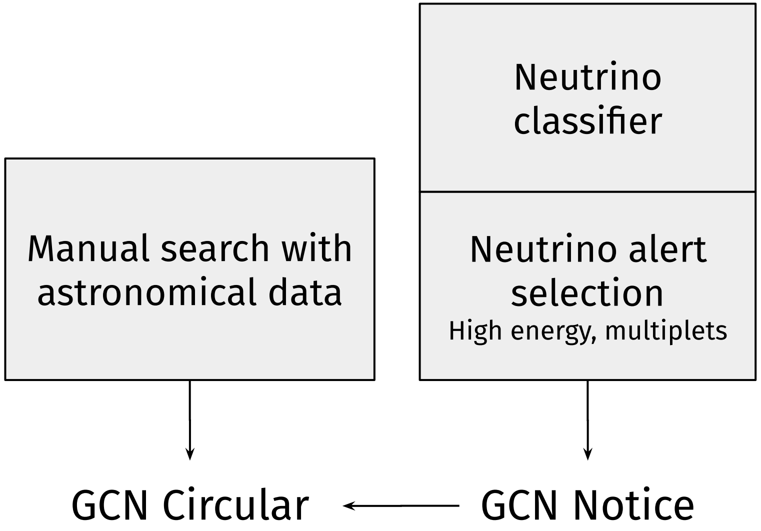
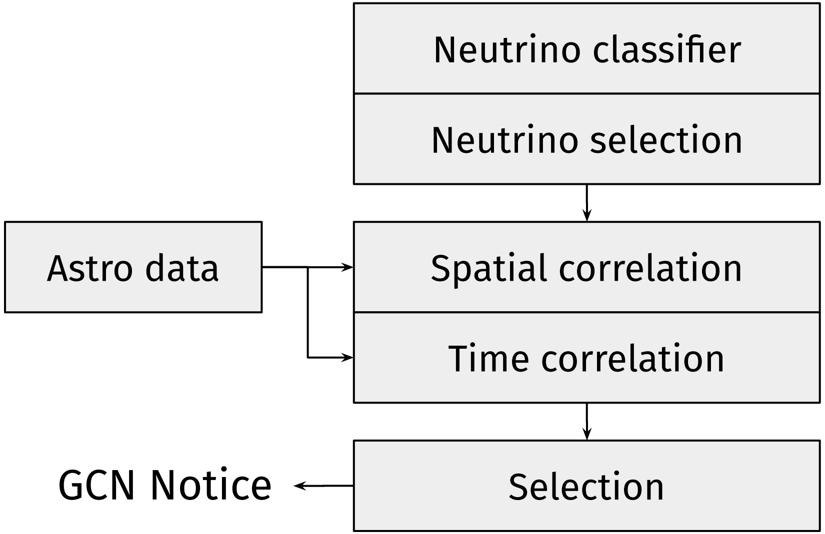


Selection on a mix of neutrino properties and properties of the potential source



The KM3NeT neutrino alerts

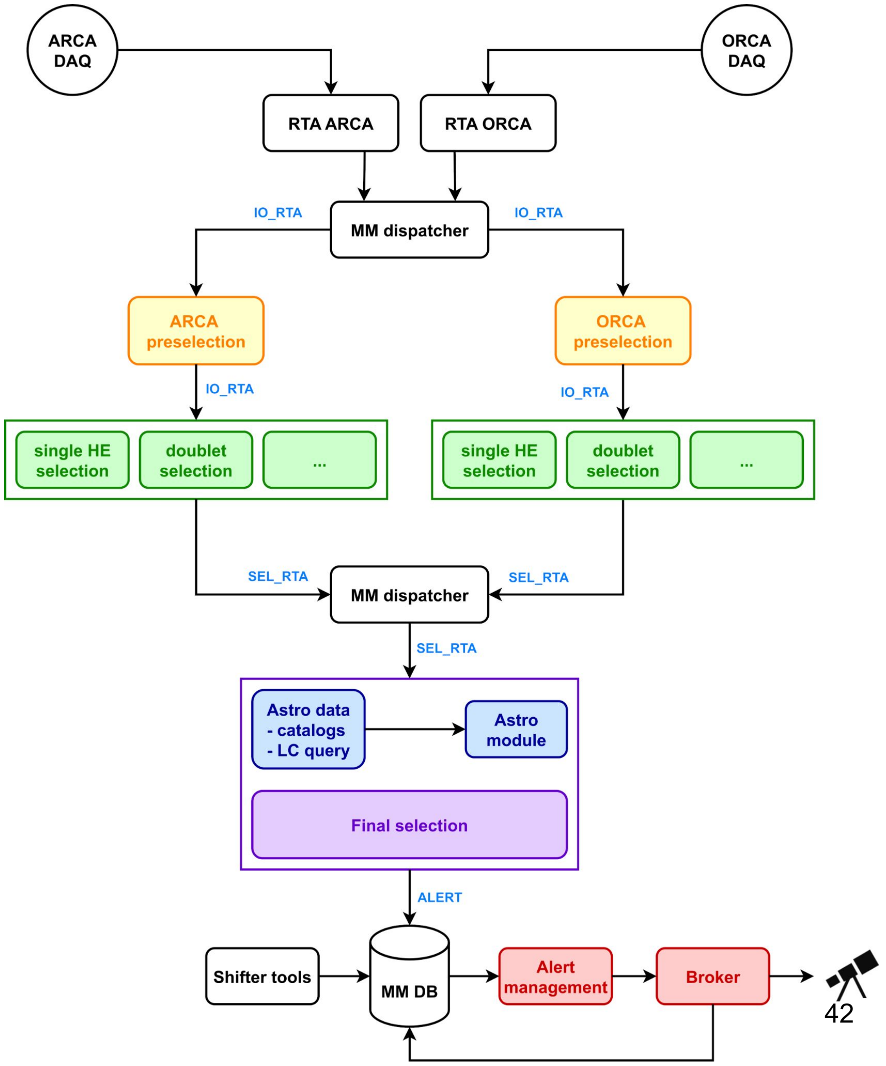
1. Fixed preselection, o(1000) events per month

2. Selection pipelines, o(100) events per month

    High energy neutrinos;
    Multiplets;
    ...

3. Search for interesting astrophysical counterparts

4. Select either only on the event properties or on a neutrino-astro max, o(1) event per month



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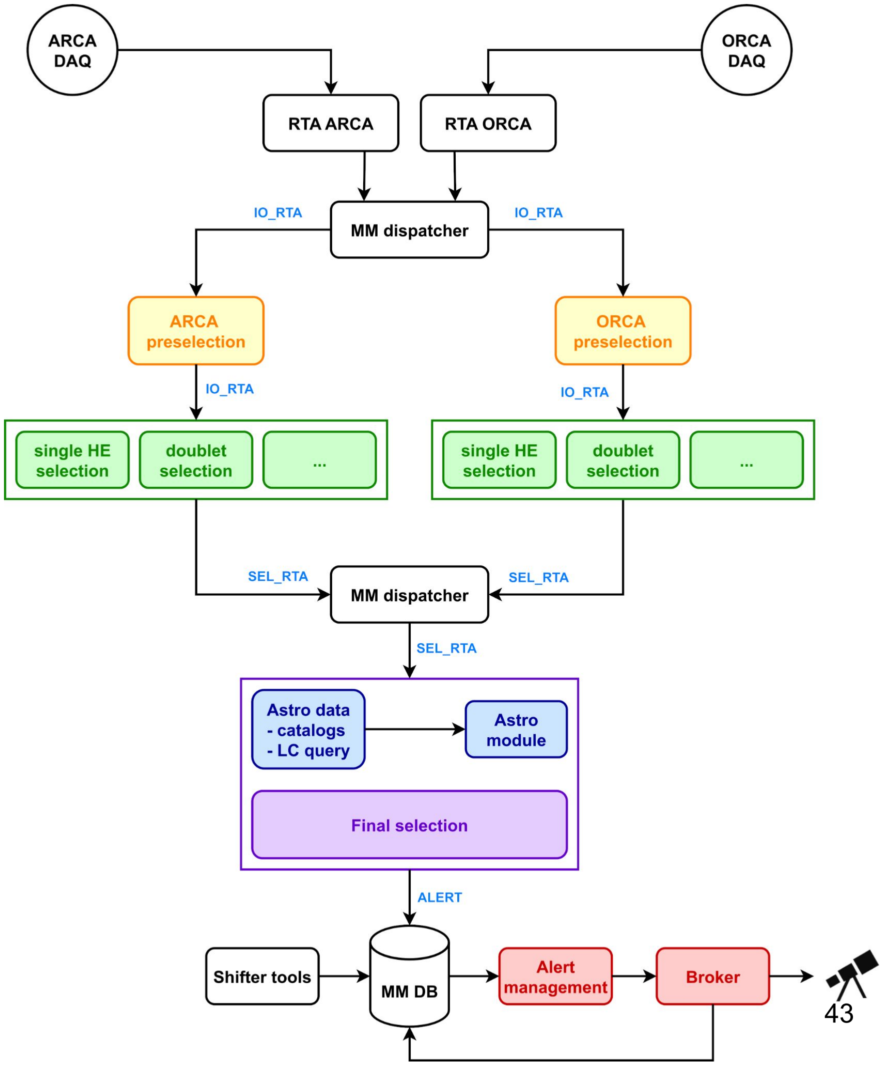
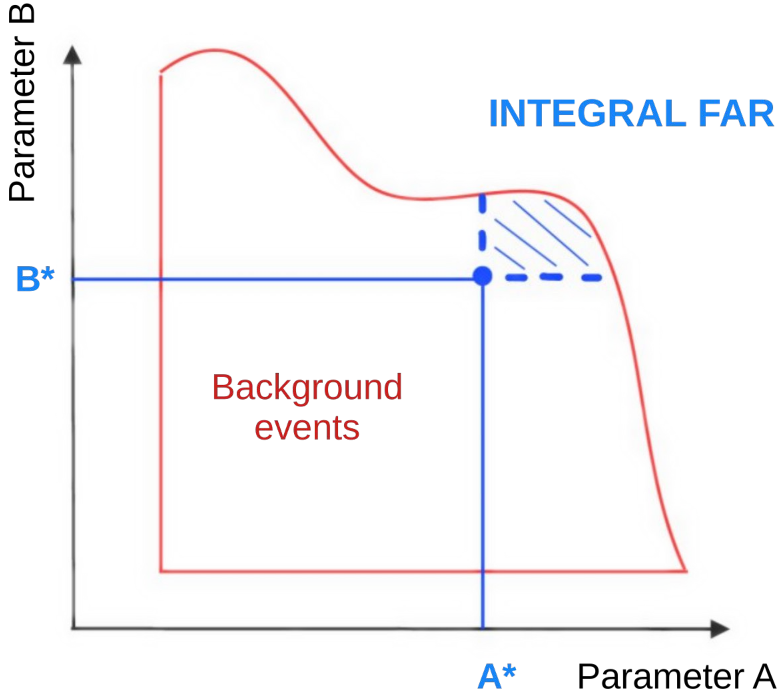


Selection method

High background when searching for cosmic neutrinos → define for every event a False Alarm Rate (FAR) and select on it

Generalization of one-dimensional FAR: $\mathrm{FAR}(\mathrm{A}^*,\mathrm{B}^*) = \text{rate of events} \times \int_{\mathrm{A}^*}^{+\infty} \int_{\mathrm{B}^*}^{+\infty} \mathrm{N}(\mathrm{A},\mathrm{B})\mathrm{d}\mathrm{A}\mathrm{d}\mathrm{B},$



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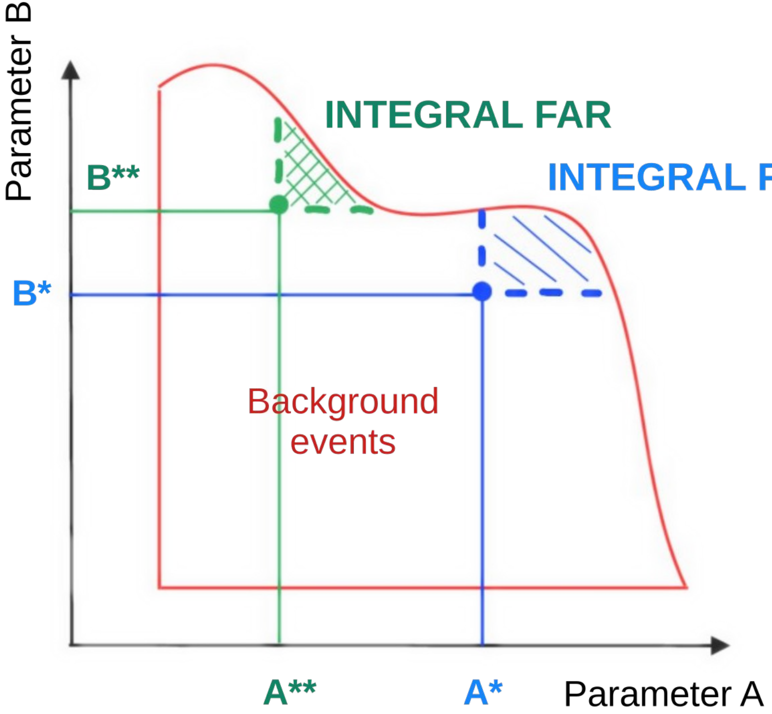

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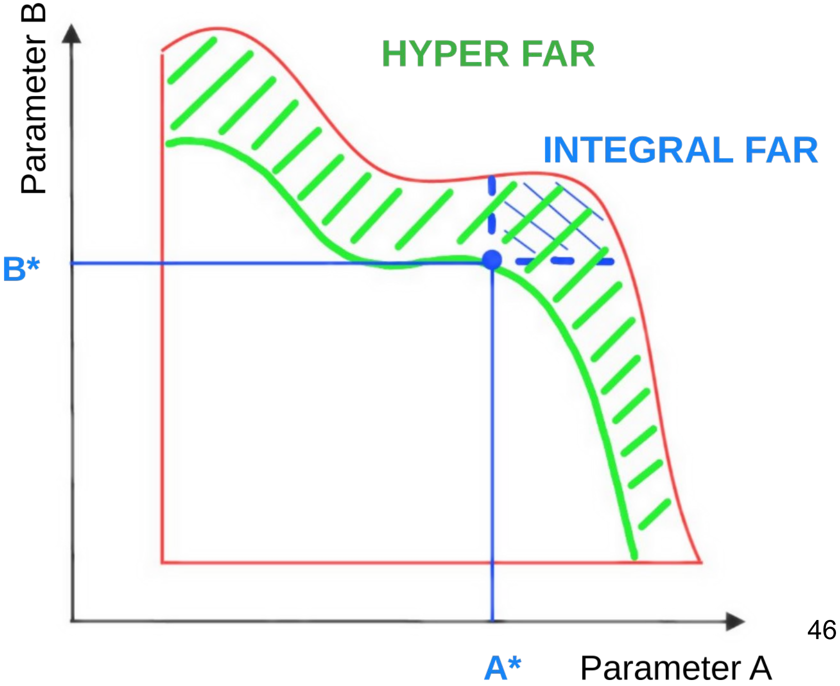
New hyperFAR method to compute the expected number of background events for a given FAR selection

$$\mathrm{hyperFAR}(\mathrm{A}^*, \mathrm{B}^*) = \iint_{\mathrm{FAR(A,B)<FAR(A^*,B^*)}} \mathrm{N}(\mathrm{A}, \mathrm{B}) \mathrm{dAdB}.$$



Unbiased method (based on background events only), generalizable with N dimensions

High energy selection

Selection on three parameters:

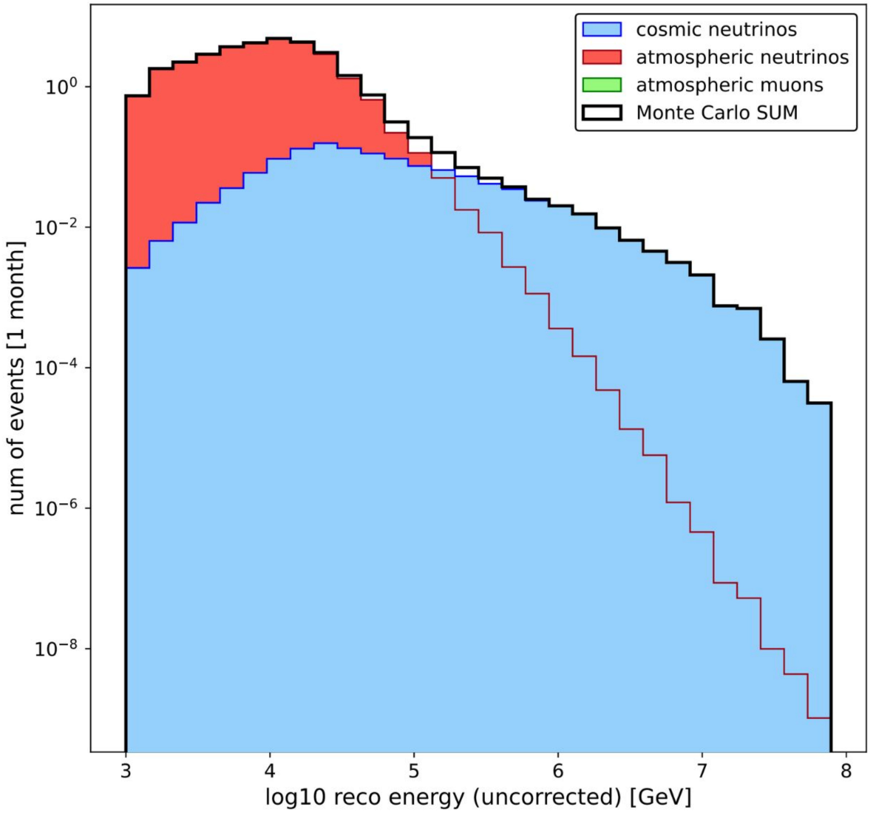
– reco quality for properly reconstructed events
– track length for low angular error
– energy for selection of cosmic neutrinos

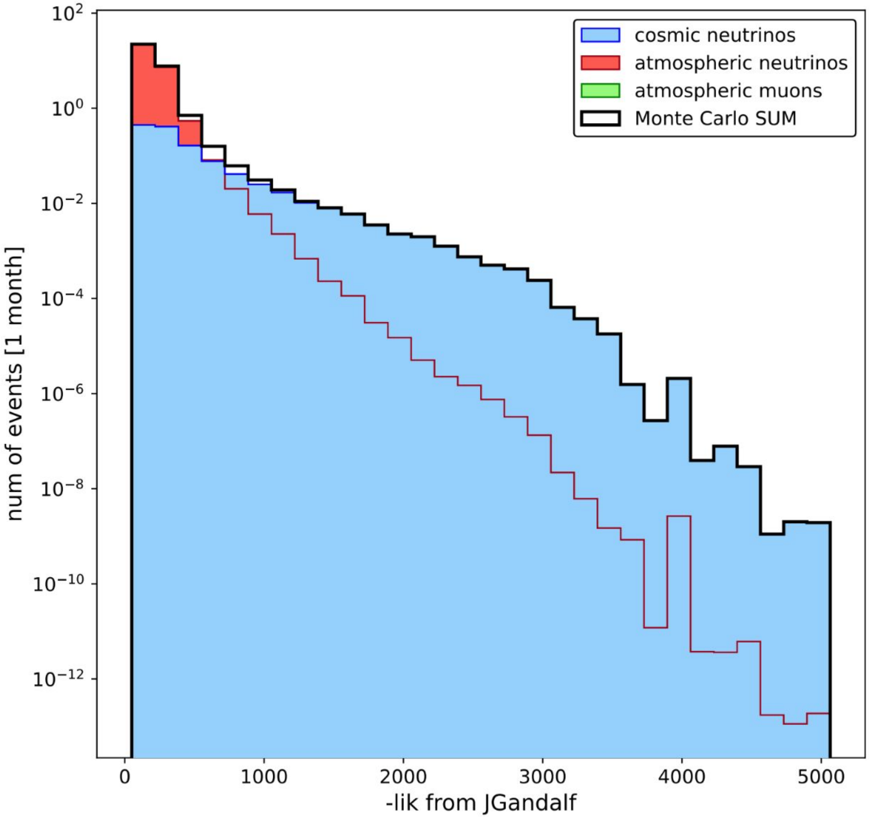
From few hundred events per month after preselection to 30 per month (for ν-astro mix) or 1 per month (pure ν selection)

	HE selection	Pure HE selection
Atmospheric muons	--	--
Atmospheric neutrinos	30	0.98
Cosmic Neutrinos	1.2	0.42

Results of the high energy selection applied on simulated events, rate per month

Results of the HE selection: energy and reco quality

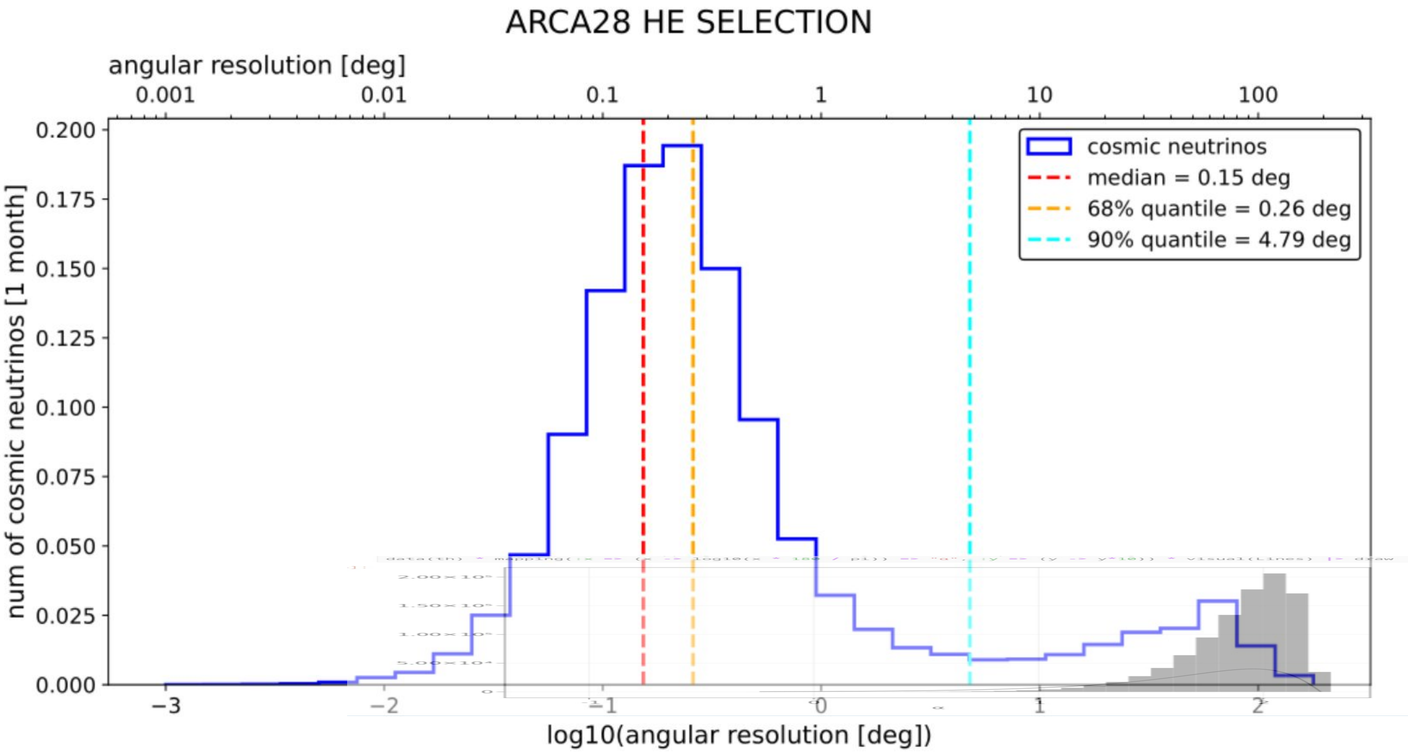




→ further cuts to be considered

Results of the HE selection: angular error on cosmic ν

For a given selected event, there is a 68% probability of the angular error being less than 0.26° (without considering systematics)



The KM3NeT neutrino alerts

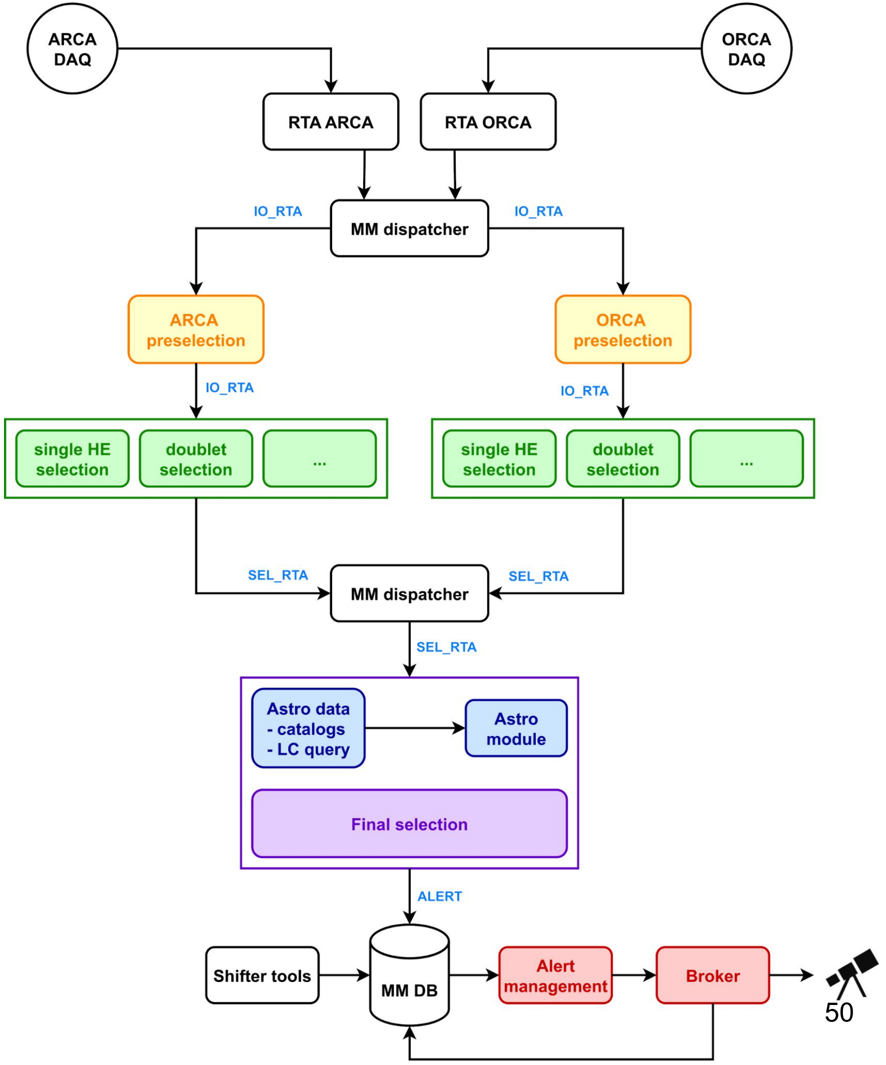
1. Fixed preselection, o(1000) events per month

2. Selection pipelines, o(100) events per month

    High energy neutrinos;
    Multiplets;
    ...

3. **Search for interesting astrophysical counterparts**

4. Select either only on the event properties or on a neutrino-astro max, o(1) event per month

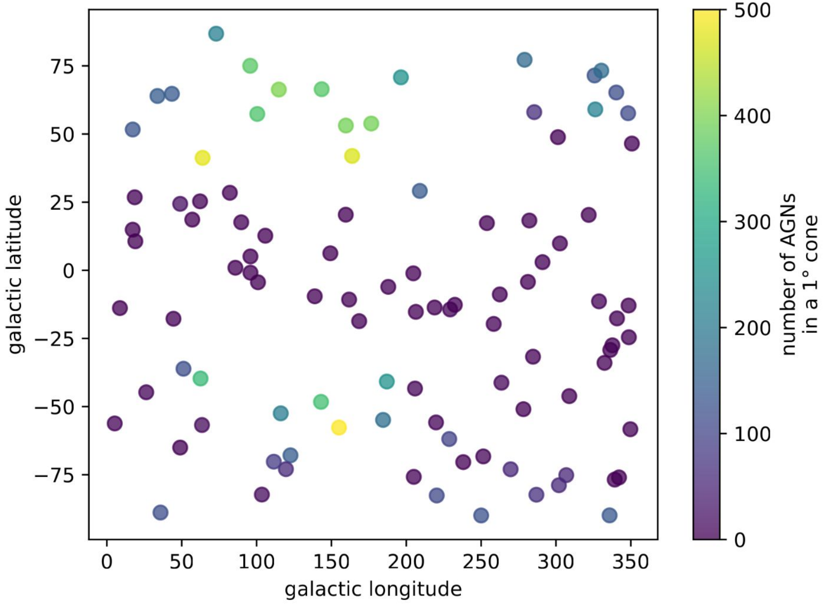


Why search for astronomical counterparts?

Association between neutrino and source → promotion of a “non exceptional” neutrino event to an alert

Provide astronomers with clearer and more complete information to maximize follow-up opportunities

Especially needed from the high number of objects within neutrino uncertainty cone



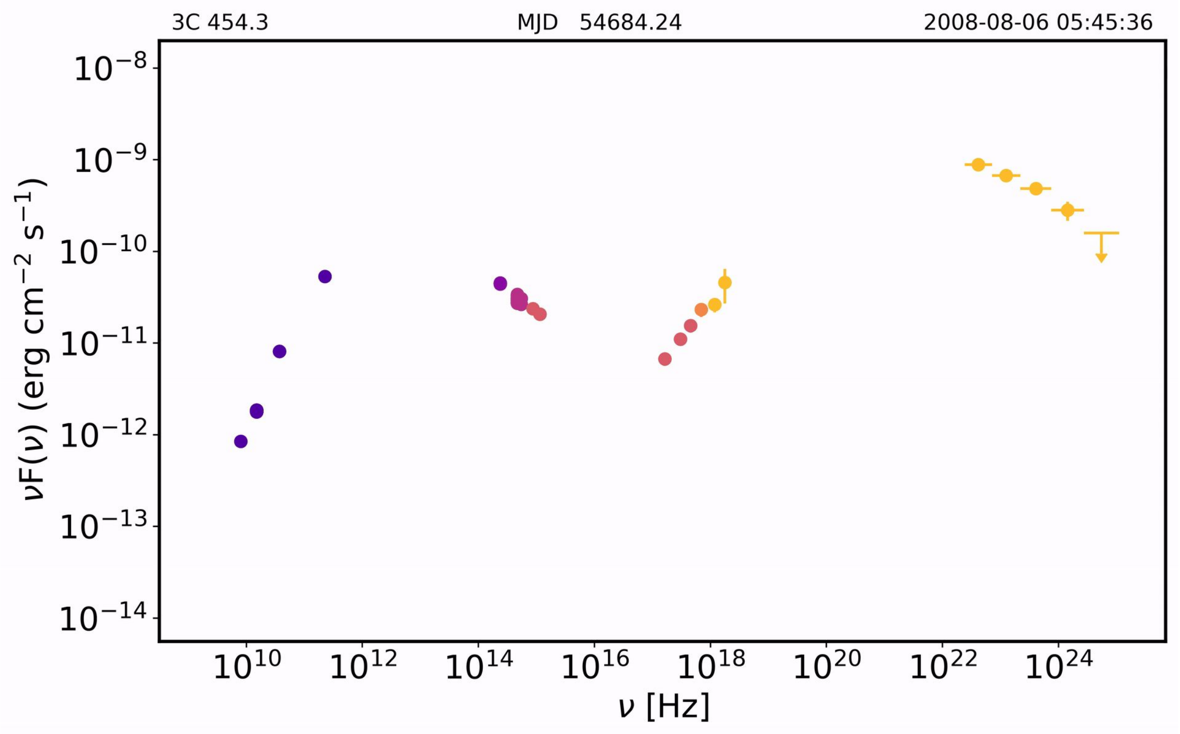
Number of AGN within a 1° search cone for a search in all wavelengths

Astronomical information to retrieve

Average flux at different wavelengths

Brightness compared to other objects in multiple wavelengths

Flaring state at the time of neutrino detection



Temporal evolution of the spectral distribution of the 3C 454.3 blazar (Markarian Multiwavelength Data Center)

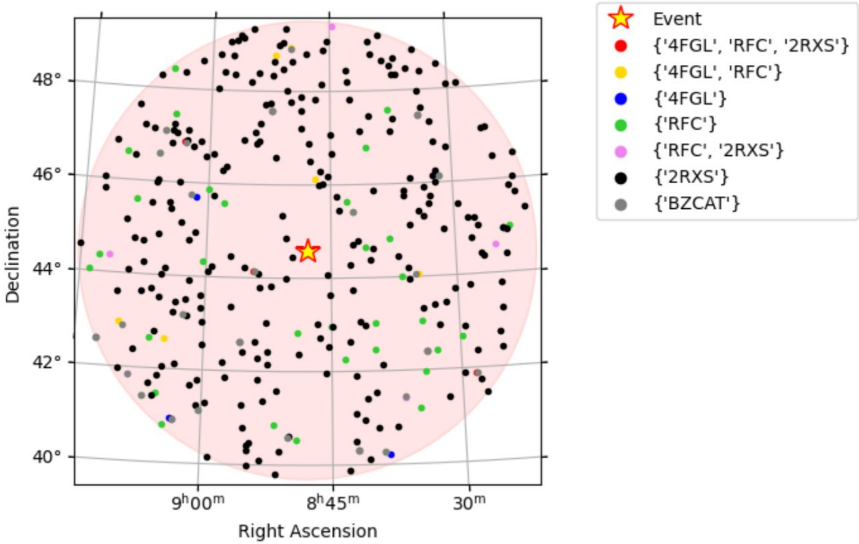
Astro correlation module

Current implementation of the astro module:

Search for within 4FGL, RFC, 2RXS, BZCAT

Cross-match for sources in multiple catalogs

Ranking from flux, distance to event, activity at the time of the event



Method focused on AGN, different strategies to be applied for other sources (TDE with ATel and ZTF/VRO, GRBs with GCN...)

Final selection and alert reporting

Final selection:

Does the event reach a low enough threshold in one of the analysis?

YES → Alert published with lowest FAR

NO → Did the astro module find a good association?

YES → Alert published

NO → Nothing happens

Alert reporting as a GCN notice (VOEvent or JSON)


```json
{
  "$schema": "https://gcn.nasa.gov/schema/main/gcn/notices/km3net/km3net_alert.schema.json",
  "messenger": "Neutrino",
  "mission": "KM3NeT",

  "instrument": "ORCA024",
  "pipeline": "exceptional_evt_orca",
  "alert_tense": "current",
  "alert_type": "initial",
  "record_number": 1,
  "alert_datetime": "2024-09-01T12:01:00.00Z",
  "additional_info": "Observation from single pipeline. Analysis tuned to select 1 event/month in average. Track only analysis w/ Up-going selection.",

  "id": [1],
  "event_name": ["KM3-240901A"],

  "trigger_time": "2024-09-01T01:16:47.0Z",
  "ra": 10.82,
  "dec": 20.01,
  "ra_dec_error": 0.9,
  "healpix_url": "https://opendata.km3net.de/",
  "far": 8.029e-8,
  "p_value": 0.002,
  "alert_topology": "Track",
  "number_of_events": 1,
  "src_error_50": 0.49,

  "event_details": [
    {
      "id": ["km3.234.23492.58968.763"],
      "trigger_time": "2024-09-01T01:16:47.0Z",
      "ra": 10.82,
      "dec": 20.01,
      "ra_dec_error": 0.9,
      "cos_zenith": 0.01,
      "prob_evt_topology": "track",
      "reco_energy": 1.2e5
    }
  ],
  "potential_counterpart": false,
  "counterpart_info": "No search"
}
```


Detector information

Alert message details

Detection identifier

Alert content

KM3NeT event details

Astro counterparts

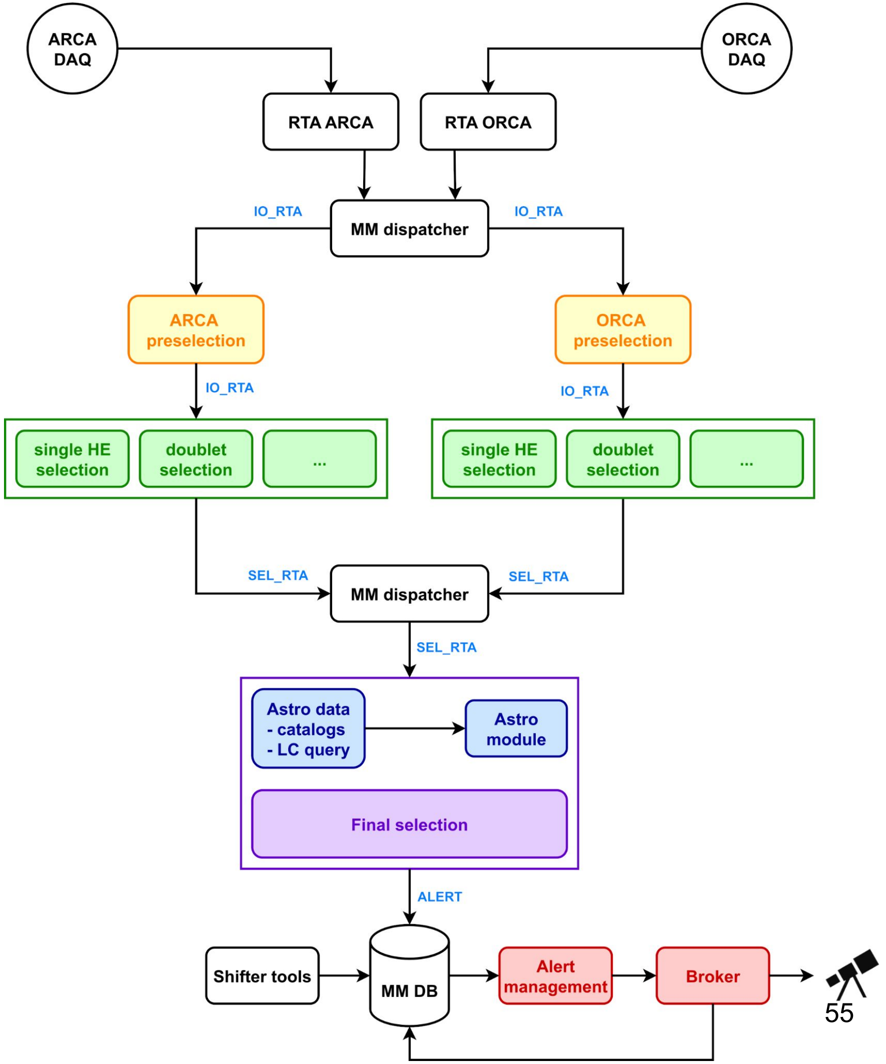
Current status of ν alerts

Two analysis methods are defined and implemented: single HE selection for ARCA and ORCA and multiplet search for ORCA

A first version of the astro module is implemented

The alert format and broker is ready

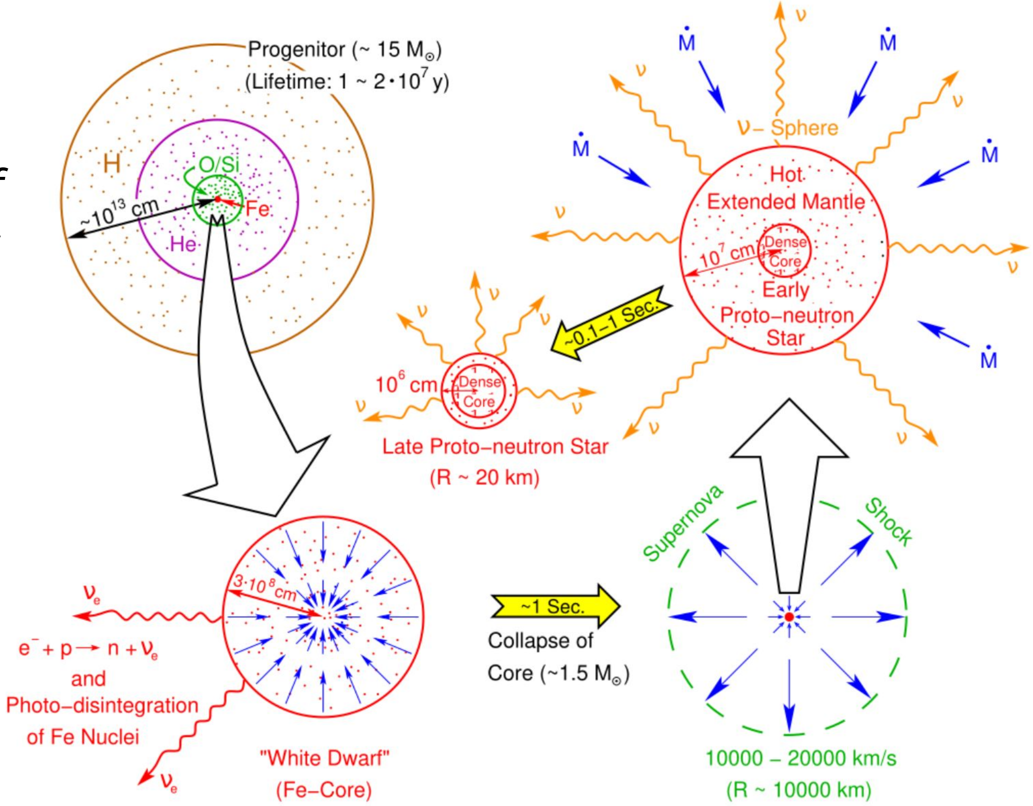
Tests are being conducted on ORCA real time data



Alert system for CCSN MeV neutrinos

Core-collapse supernovae
Explosive phenomena ending the life of massive stars with an enormous energy release (≈ 3×10^{53} erg)

Physics of the core-collapse
Iron photo-dissociation and electron capture → diminution of the electron degeneracy pressure → collapse of the core until bounce and shockwave propagation



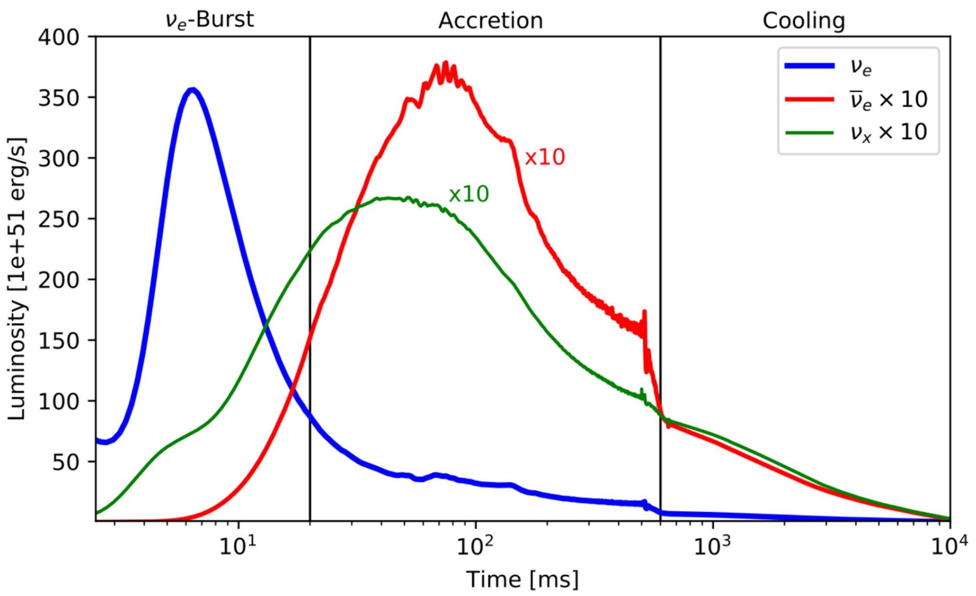
Neutrino emission from CCSN

Three phases of neutrino emission

– Prompt ν_e emission when trapped neutrinos are release

– Charged current and thermal production of neutrinos during accretion

– Neutrino cooling to dissipate gravitational energy



99% of the gravitational energy is released as low energy neutrinos (≈ 10 MeV) in less than 0.5 s

Electromagnetic and gravitational wave emission

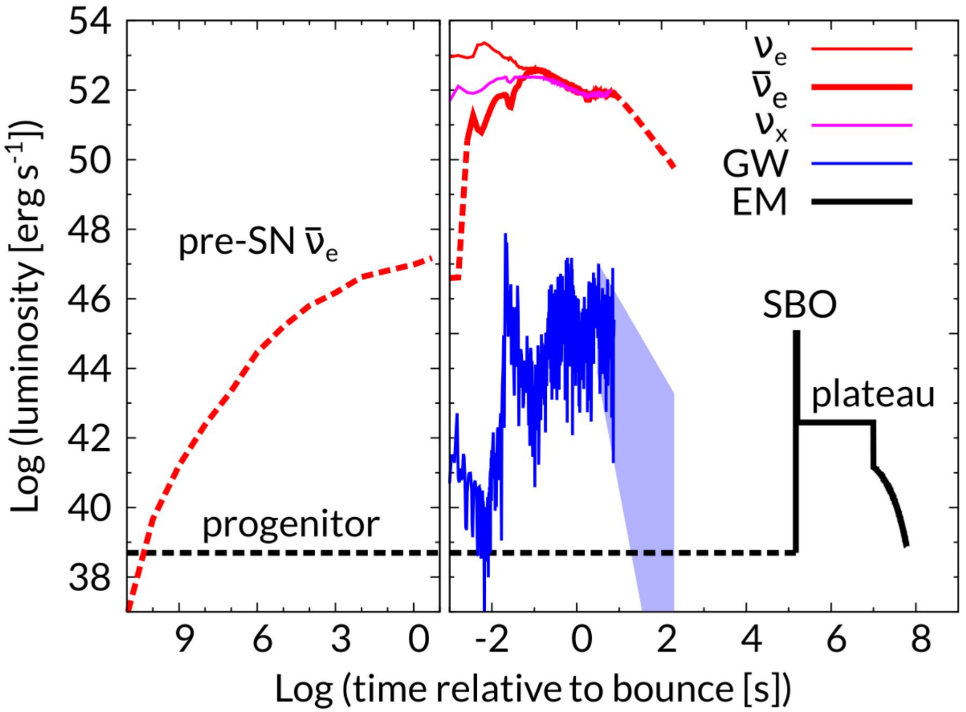
Electromagnetic emissions in two phases

– Shock breakout, when the medium becomes transparent (UV and X-ray flash)

– Optical plateau or linear decrease

Gravitational waves
Caused by asymmetric motions of matter

Neutrinos are emitted few minutes to few hours before photons → can be used as an alarm signal

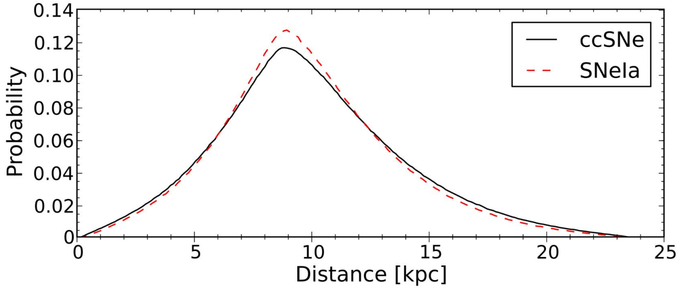


Why the need for real-time detection of CCSN neutrinos?

Observation of a CCSN can inform on:
– SN formation mechanisms;
– Nucleosynthesis;
– Neutrino mass...

Neutrinos play a key role in the collapse mechanism

Current gen neutrinos detector are sensitive up to a few 100 kpc



Left: distance distributions of possible Galactic SNe from the Sun

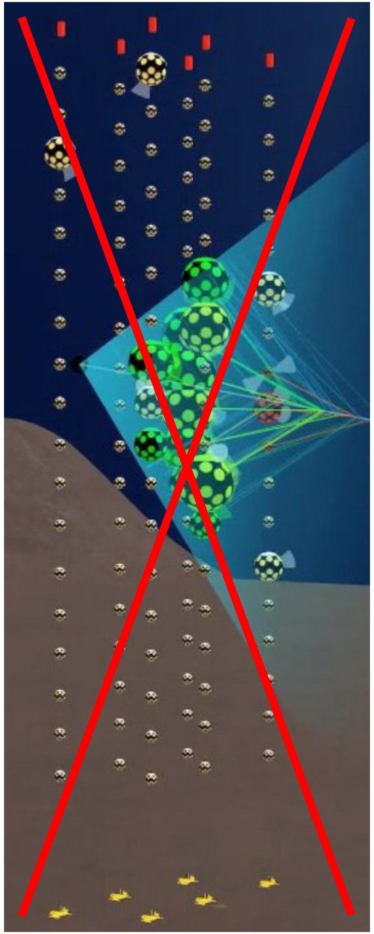
Estimated Galactic rate of ≈ 1.6 per Century

Extremely rare event + short duration of neutrino event + scientific potential → need for fast, reliable and automatic detection system

How do we detect CCSN neutrinos with KM3NeT?

KM3NeT is only sensitive to electron anti-neutrinos *via* inverse beta decay $\bar{\nu}_e + p \longrightarrow n + e^+$

Small tracks of ~ 0.5 cm per MeV
→ reconstruction of individual events using multiple DOMs impossible



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Small tracks of ~ 0.5 cm per MeV
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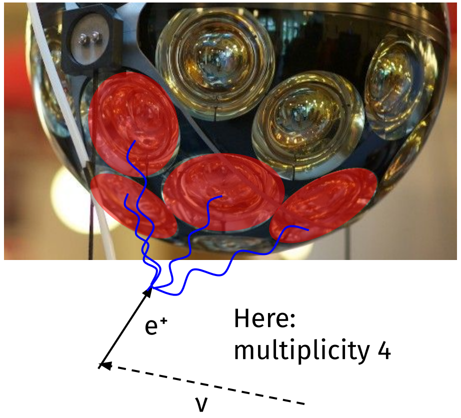
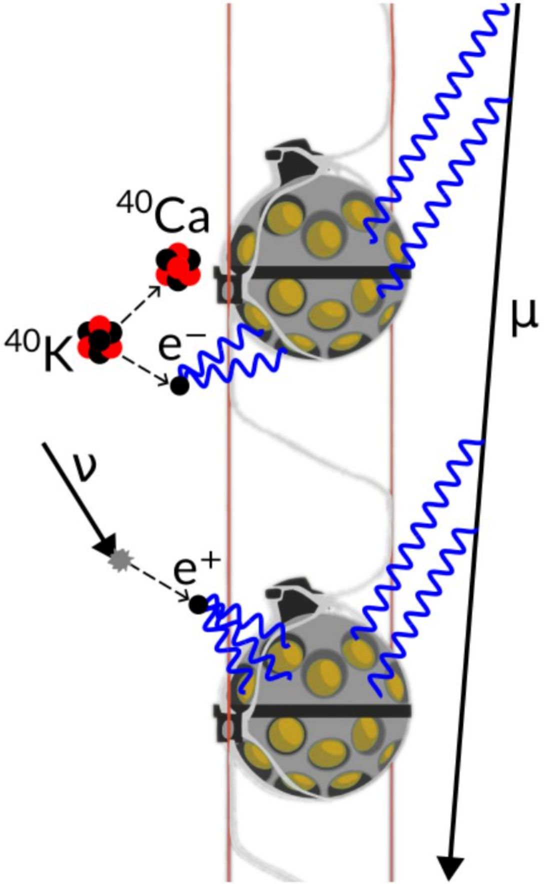
Analysis principle: **search for an excess of hit coincidences above the optical background**

Coincidence: **at least four hits** (PMT voltage above a given threshold) **within one DOM** and **with PMT direction within 90 degrees** of each other, in a **time window of 10 ns**



Background sources in KM3NeT and PMT high-rate veto



Sources of optical background

– **Radioactive decays**: mostly ^{40}K in seawater

– **Muons**: reconstructed and associated hits removed

– **Bioluminescence**: non-coherent light emitted by living organisms; localized increase of the hit rates up to the MHz range

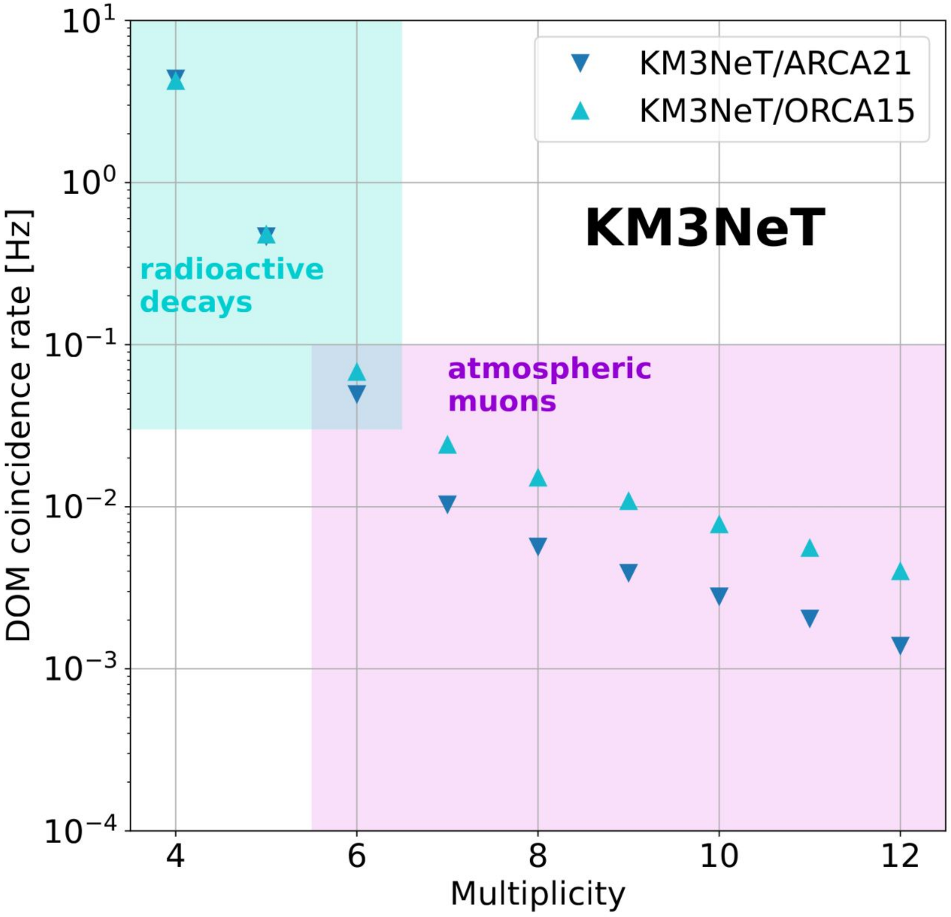
High-rate veto

PMT with rates above 20 kHz automatically deactivated by the DOM electronics

Background rates in KM3NeT

Multiplicity: number of unique PMTs involved in a coincidence

Lower atmospheric muons rate with higher depth



Signal rates in KM3NeT

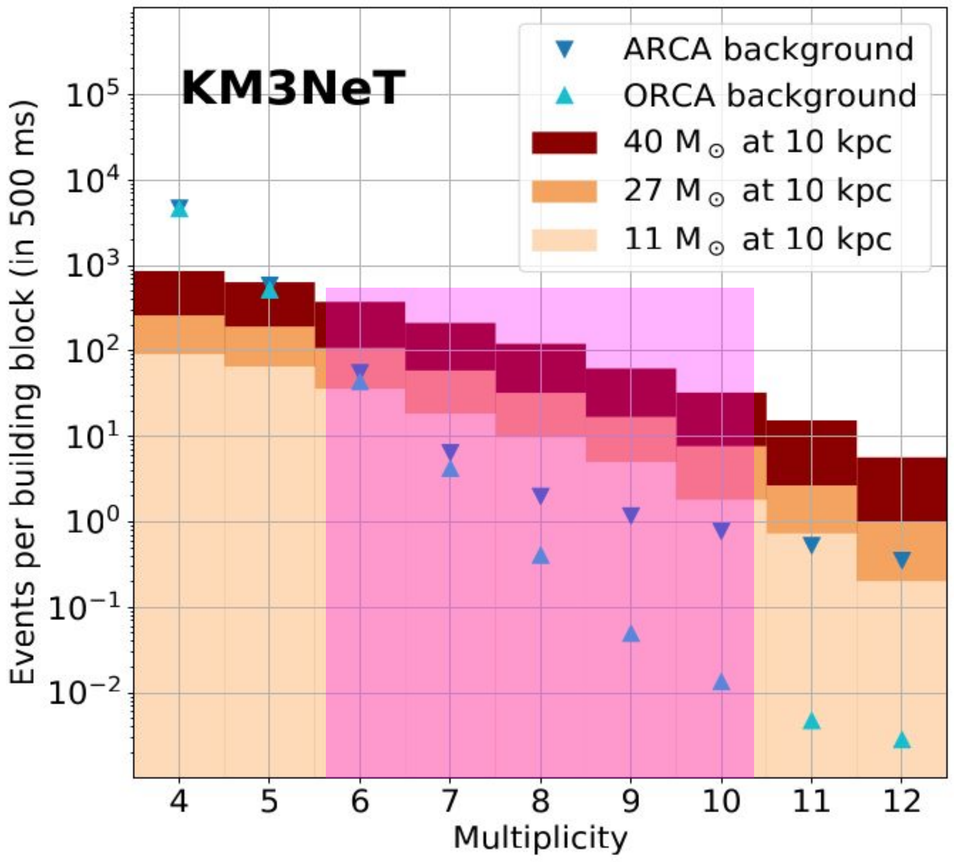
Different CCSN models: 11, 27 and 40 solar masses (Garching 3D simulations)

Optimized discovery sensitivity for:

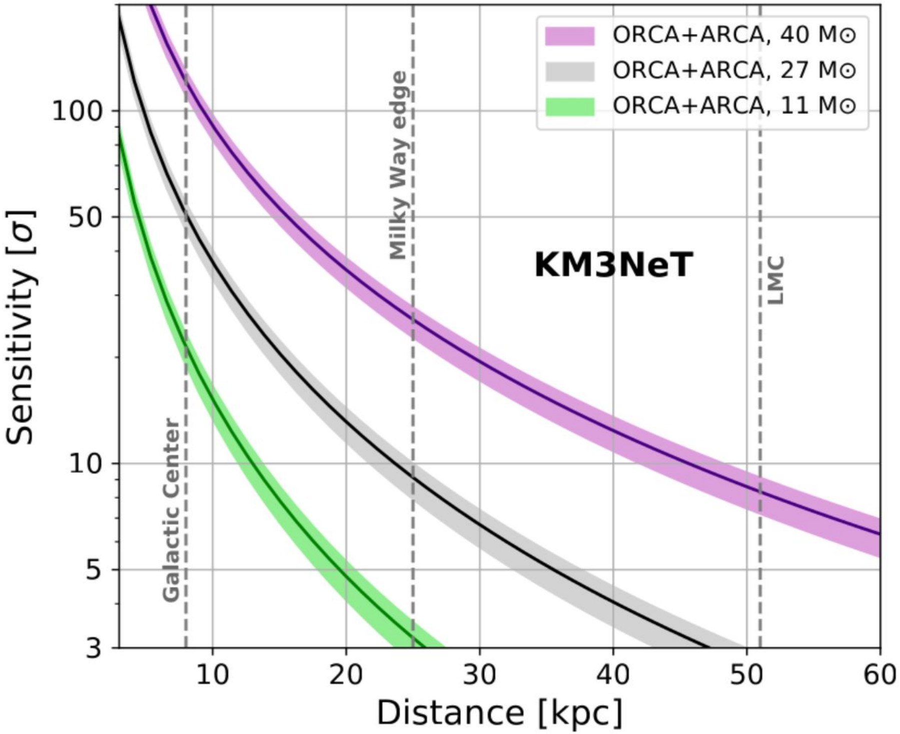
– windows of 500 ms (duration of electron anti-neutrinos emission);

– multiplicity between 6 and 10.

Lower ORCA background because of better muon trigger



KM3NeT sensitivity to a Galactic CCSN



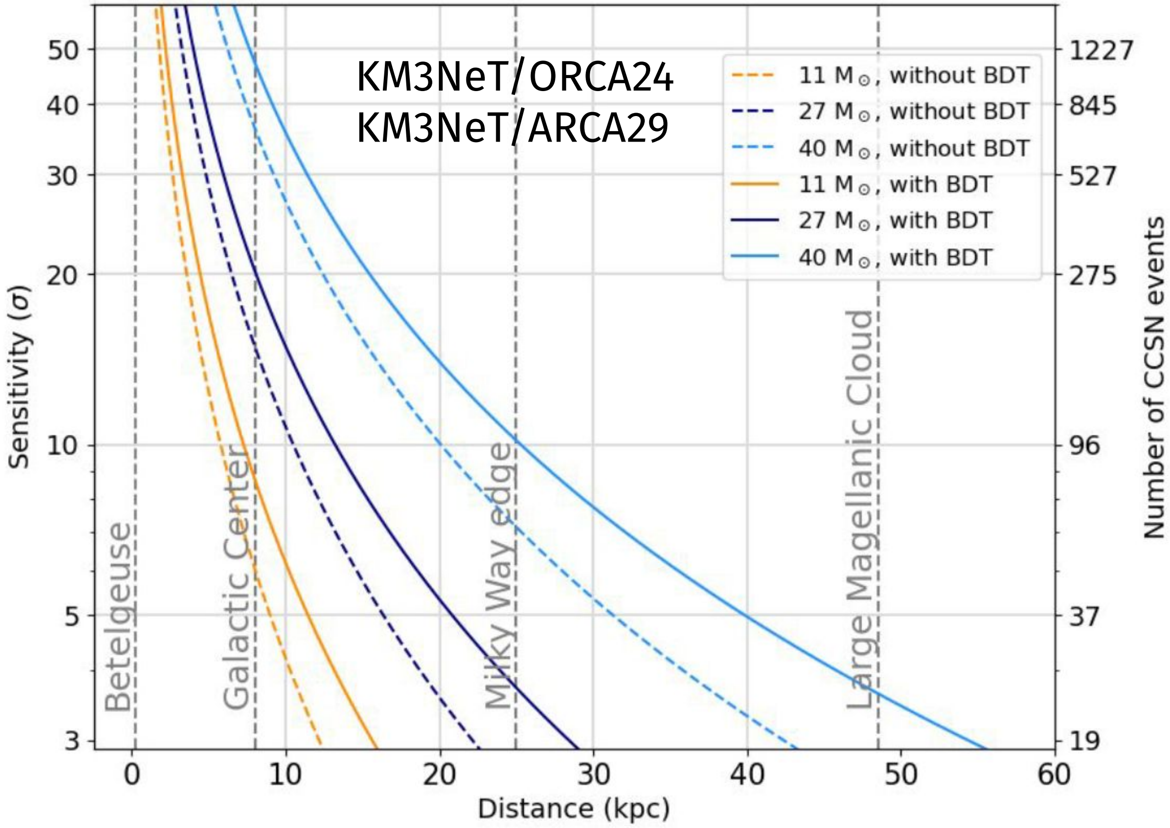
Full KM3NeT detection sensitivity

Expected number of signal events for the three progenitors at 10 kpc

Model	Multiplicity 2	3	4	5	6
$11\ M_\odot$ (340 ms)	1119 ± 3	258 ± 1	100.4 ± 0.8	48.9 ± 0.5	25.8 ± 0.4
$27\ M_\odot$ (543 ms)	4806 ± 9	1120 ± 5	442 ± 3	218 ± 2	116.0 ± 1.5
$40\ M_\odot$ (572 ms)	15240 ± 30	3650 ± 10	1449 ± 8	723 ± 6	399 ± 4

Model	Multiplicity 7	8	9	10	11
$11\ M_\odot$ (340 ms)	13.3 ± 0.3	7.2 ± 0.2	3.4 ± 0.1	1.29 ± 0.08	0.50 ± 0.05
$27\ M_\odot$ (543 ms)	64 ± 1	35.2 ± 0.8	19.4 ± 0.6	8.0 ± 0.4	1.9 ± 0.2
$40\ M_\odot$ (572 ms)	226 ± 3	127 ± 2	69.5 ± 1.8	36.6 ± 1.3	15.0 ± 0.8

Current KM3NeT sensitivity



For a realistic model, sensitive to 90% of the Milky Way

Real-time detection of CCSN

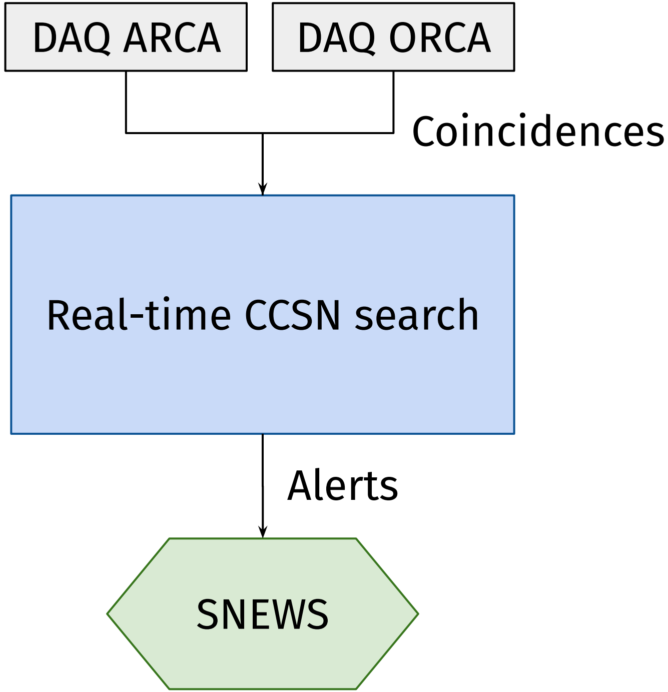
Every 100 ms, real-time computation of coincidences aggregated over 500 ms for each detector

“Smart” combination of the two detectors

Quality score to reject detector anomalies

FAR/significance computation

Filter to communicate 1 alert per 8 days



False Alert Rate computation

Assuming constant background, simple Poisson significance

$$p(n) = 1 - \sum_{0 \le i < n} \mathrm{P}_{\text{Poisson}}^{\text{exp bkg}=b}(\mathrm{X} = i) = \mathrm{P}(\mathrm{X} \ge n).$$

FAR = observation frequency × *p*

Zscore: easier representation of the FAR
≈ “significance” (higher means less likely to come from background)

False Alert Rate computation

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FAR = observation frequency × *p*

Zscore: easier representation of the FAR

≈ “significance” (higher means less likely to come from background)

BUT bioluminescence and high rate veto → variation of background level $\pi(\lambda)$ as a function of number of PMTs

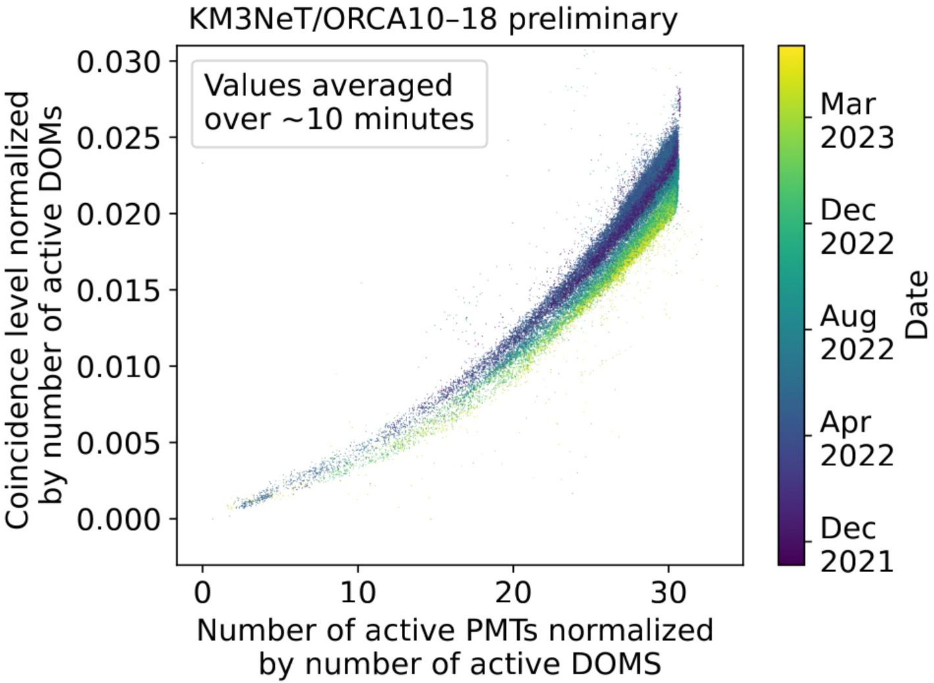
Mixed Poisson distribution

$$\mathrm{P}(X = k) = \int_0^\infty \frac{\lambda^k}{k!} e^{-\lambda} \, \pi(\lambda) \, \mathrm{d}\lambda.$$

Need to properly characterize the background distribution as a function of the number of active PMTs

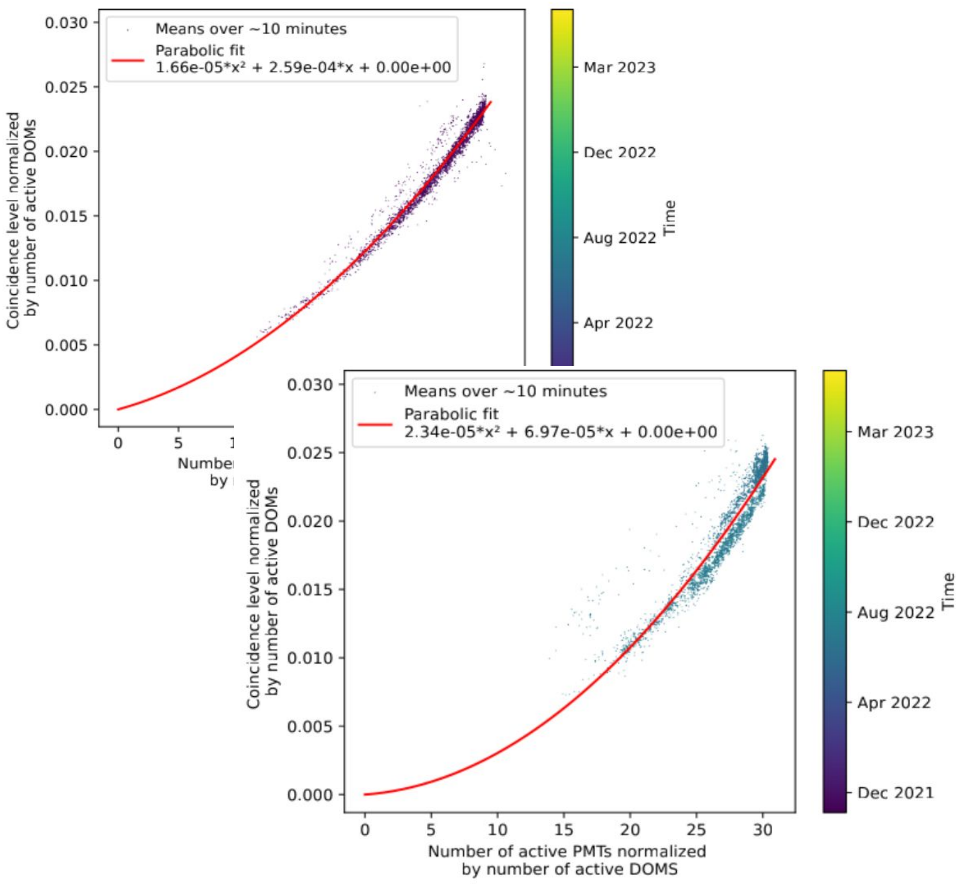
Adaptive background expectation

Analysis on 1.5 year of ORCA data
(December 2021 to June 2023)



Quadratic relation which changes over time (might be due to variations in PMTs quantum efficiency, water mass...)

Adaptive background expectation



Quadratic relation which changes over time (might be due to variations in PMTs quantum efficiency, water mass...)

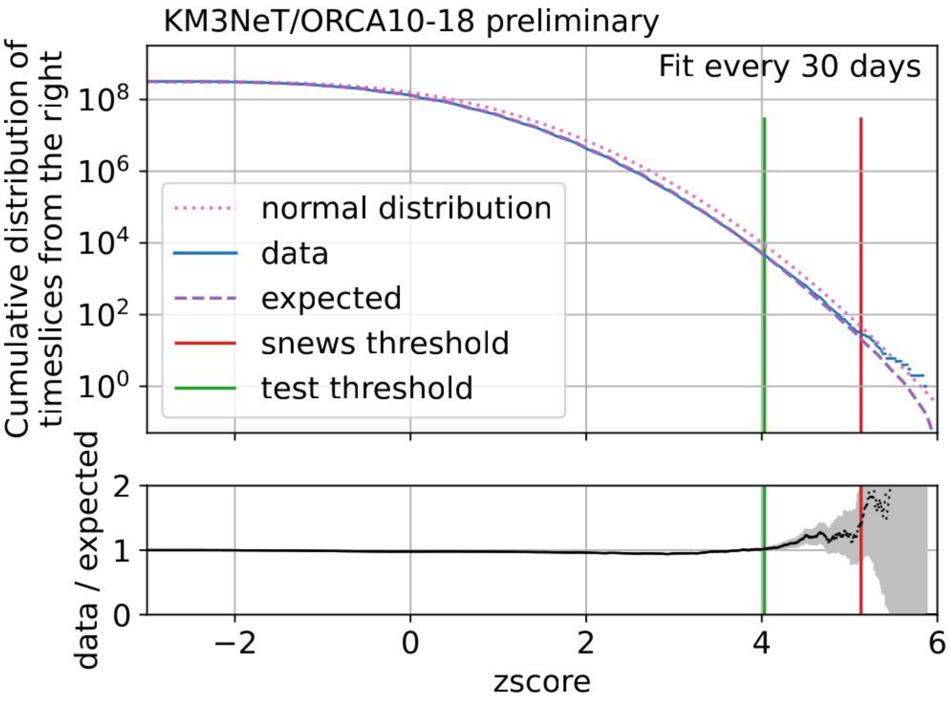
Monthly fit (compromise between variability and amount of statistics)

Effect on the FAR distribution

Right plot: number of alert candidates reaching a zscore threshold

test: FAR = 1 per hour, zscore ≈ 4
SNEWS: FAR = 1 per 8 days, zscore ≈ 5

FAR [d^{-1}] (number of alerts)	goal	expected	obtained
test	24 (45.91)	12.36 (4539.54)	12.62 (4633)
SNEWS	0.125 (8814.11)	0.06 (20.79)	0.08 (29)



Good agreement, able to tweak zscore threshold to reach goal of 1 per 8 day

The SNEWS network

SuperNova Early Warning System

Alert from at least two detectors within ten seconds
→ alert to astronomers

Current detectors: Super-K, IceCube, LVD, KamLAND, Borexino, SNO+, NOvA, Baksan, HALO, MicroBooNe, SBND

BUT further capabilities for KM3NeT and other neutrino telescopes → SNEWS2.0

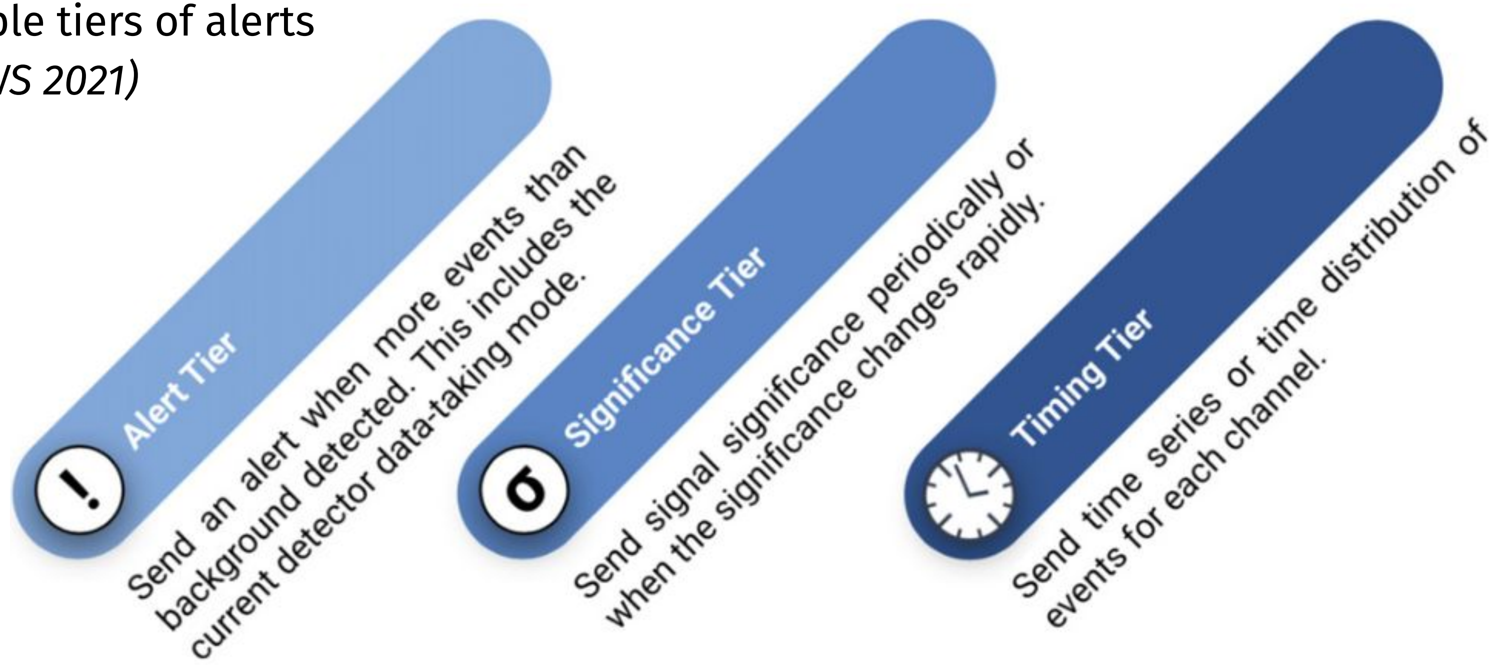
SNEWS2.0

Upgrade from SNEWS:

– reduce alert threshold to gain sensitivity;
– reduce alert latency;
– combine pointing information *via* triangulation;
– implement pre-supernova alerts;
– develop a follow-up strategy.

SNEWS2.0

Multiple tiers of alerts
(SNEWS 2021)



Real-time CCSN search

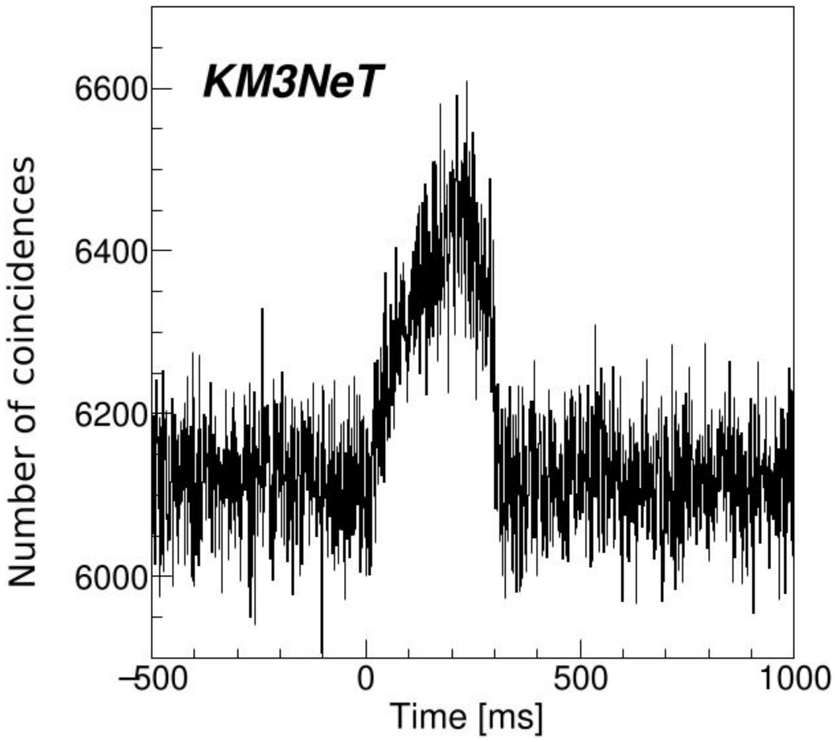
Quasi-online pipeline

Goals of the quasi-online pipeline

Real-time CCSN search pipeline optimized for detection taking into account high optical background

Quasi-online pipeline: retrieve more statistics (multiplicity 2 and above) to perform physics analysis on the neutrino signal time-profile (“neutrino light curve”)

Can provide the neutrino light curve to feed the timing tier of SNEWS



Light-curve obtained from pseudo-experiments for the full ARCA detector considering a 20 $M_\odot$ progenitor at 5 kpc

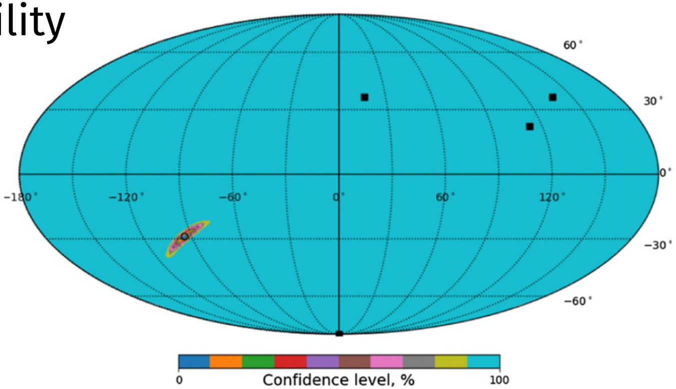
Physics opportunities from a neutrino light curve

– Fit of the neutrinos arrival time → signal triangulation with multiple detectors

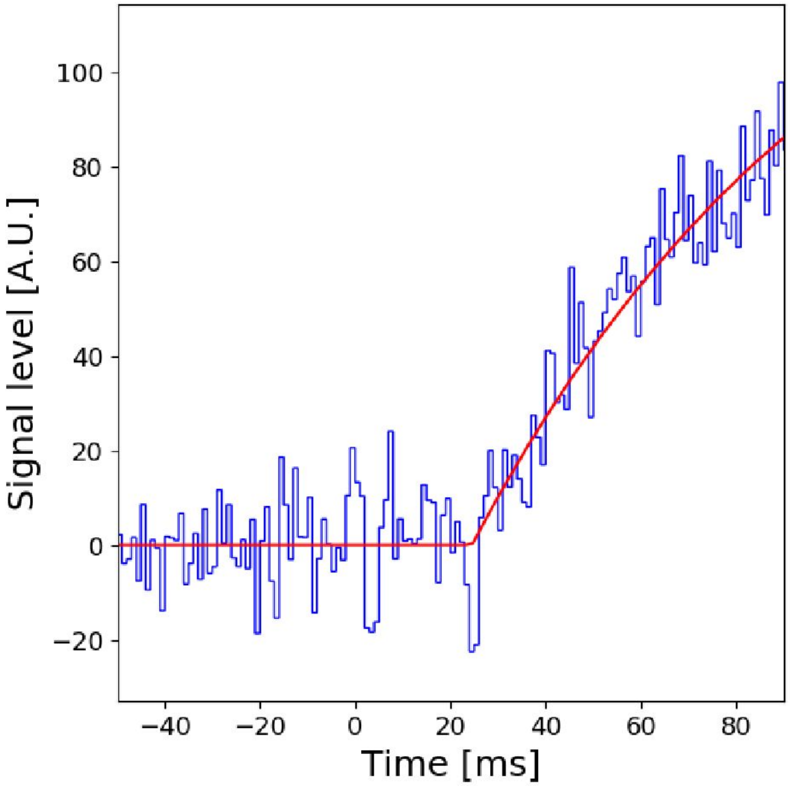
– Refined estimation of the CCSN parameters (distance, mass, mean neutrino energy)

– Information on black hole formation

– Detection of the standing accretion shock instability



Right: triangulation map with IceCube, ARCA, HK and JUNO (Coleiro et al 2020)

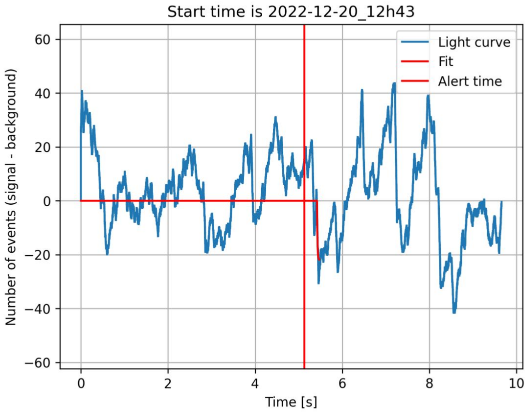


Top: Fit of the light-curve obtained from pseudo-experiments for the full ARCA detector considering a 20 $M_\odot$ progenitor at 5 kpc

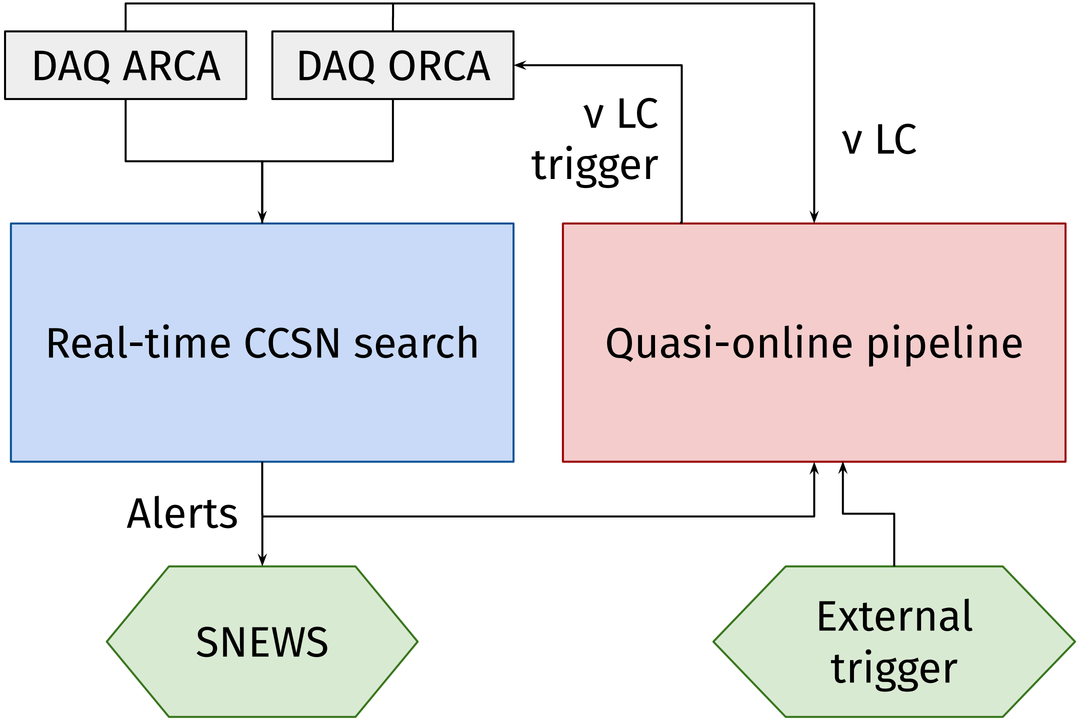
Implementation of the quasi-online pipeline

KM3NeT cannot store all low-level coincidences → need to retrieve the data for specific triggers

Every time the detector reaches the SNEWS threshold, 10 minutes (5 past + 5 future) of all coincidences are written to disk



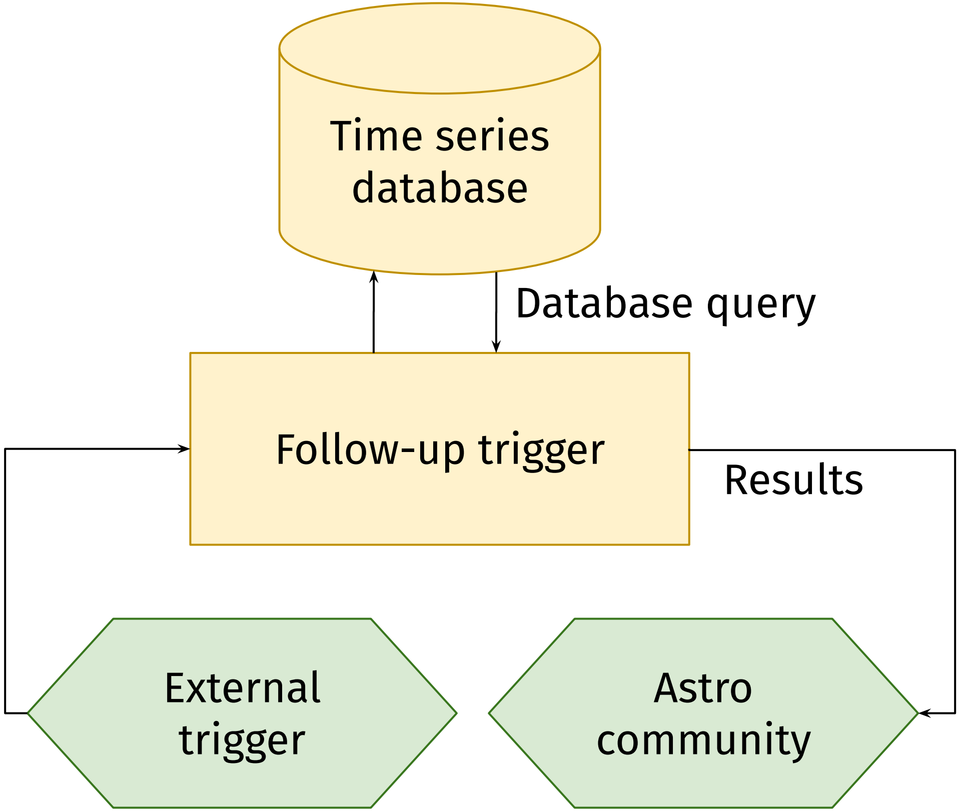
Fit example on background data



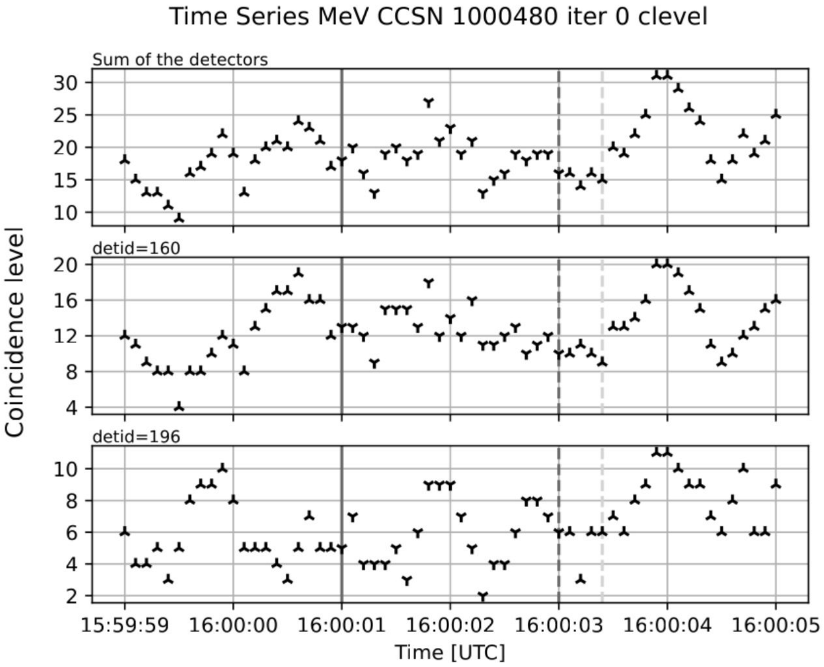
Follow-up trigger

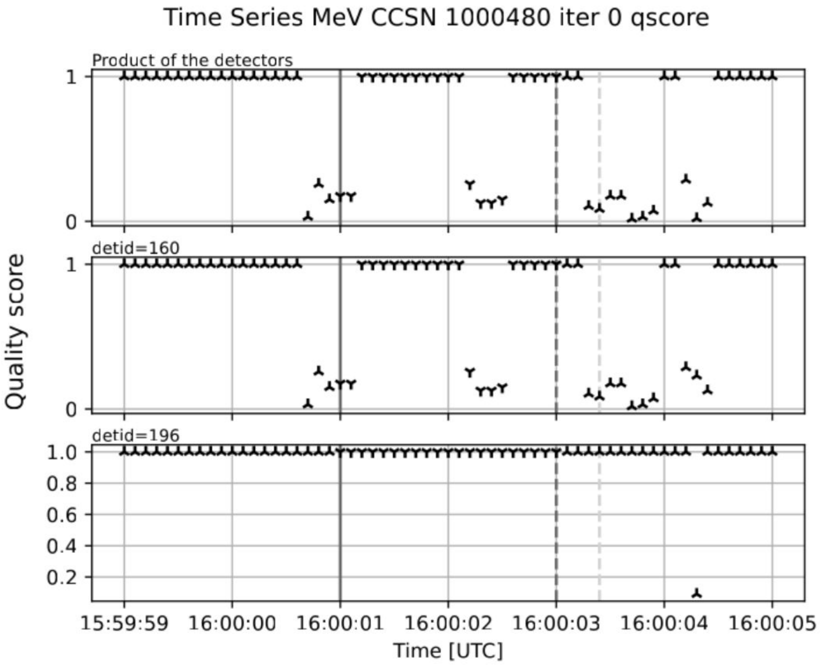
Following external triggers (GW with NS, SK or SNEWS alerts), maximum coincidence searched over 2 s window

Results reported in an internal KM3NeT website

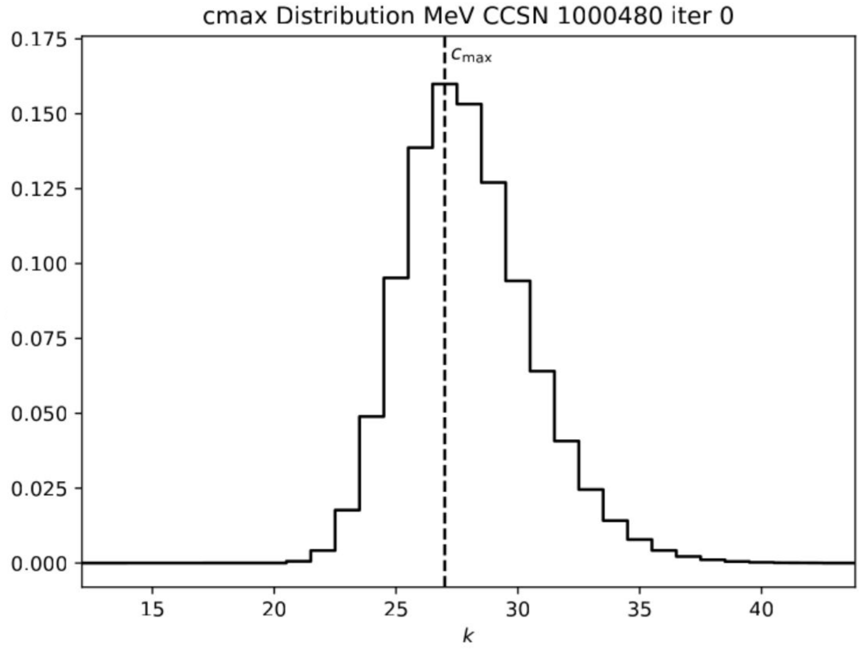


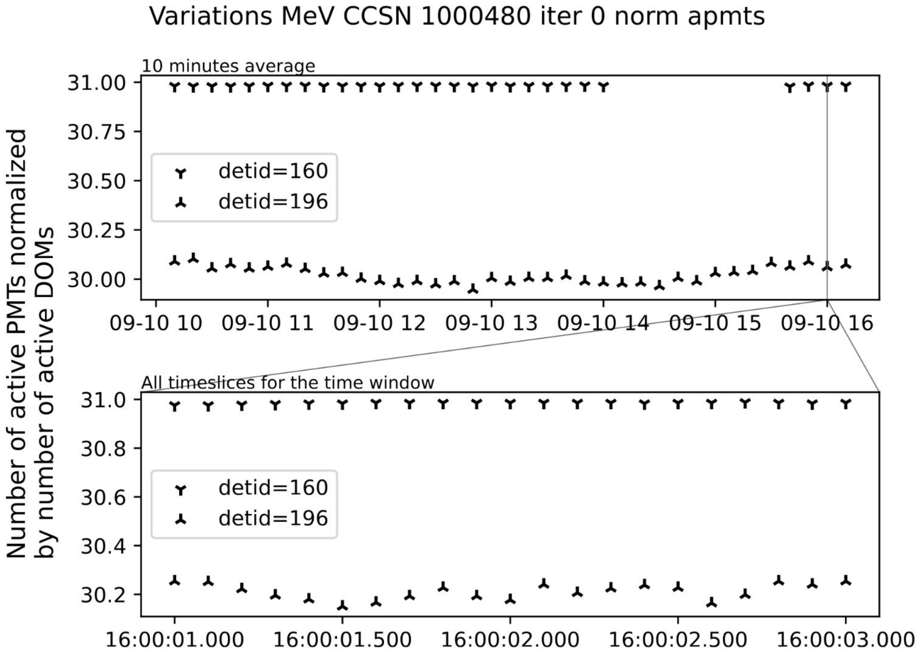
Results of the follow-up trigger





Results of the follow-up trigger



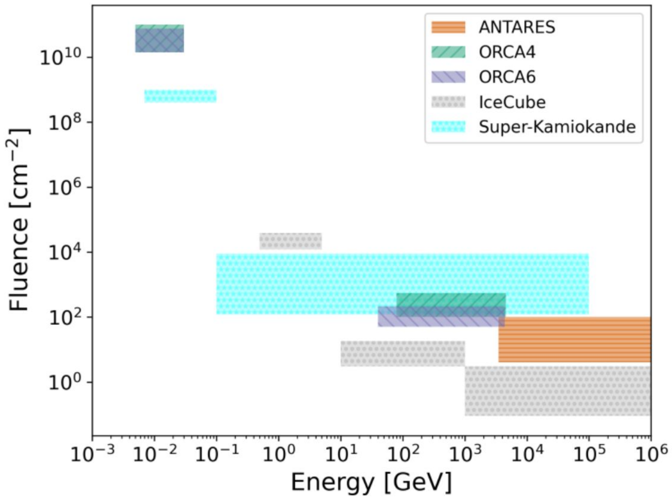


Offline searches for MeV neutrino burst counterparts

GW from O3

Search within 2 s after GW detection for 55 events, including 5 NSBH

Upper limits on fluence and energy released as MeV neutrinos



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S. Aiello *et al.* [KM3NeT], "Searches for neutrino counterparts of gravitational waves from the LIGO/Virgo third observing run with KM3NeT," JCAP **04** (2024), 026

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Upper limits on fluence and energy released as MeV neutrinos

GRB 221009A, the brightest γ-ray burst of all times

Search within the 90% gamma central emission time window and $[T_0 - 50\text{ s}, T_0 + 5000\text{ s}]$

Similar method

Time window	Maximum coincidence level	Expected background	p-value	Total $\bar{\nu}_e$ flux [cm^{-2}]	$E_{tot,\nu}^{iso,90\%}$ [erg]
T_{90}	27	29	0.99	2.5×10^9	5.1×10^{62}
T_0 [−50 s, 5000 s]	32	33	0.79	4.8×10^9	9.7×10^{62}

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S. Aiello *et al.* [KM3NeT], "Search for Neutrino Emission from GRB 221009A using the KM3NeT ARCA and ORCA detectors," JCAP **08** (2024), 006

Conclusion and prospects

The KM3NeT online program is (almost) ready

KM3NeT CCSN online program

Current sensitivity to our Galaxy and running real-time search and quasi-online processing → ready for the event of the century

In particular I:
– was responsible for the development and maintenance of the full CCSN pipeline and the monitoring tools for the shifters;
– devised a new method to properly characterize the optical background for the different detectors configurations;
– performed the first published follow-up analyses.

KM3NeT online program

From real-time processing prototype to the actual running system

First iteration for the KM3NeT alerts ready and being tested

In particular I:
– participated to the global development of the program and co-developed the shift system;
– co-devised the multi-variables FAR selection method;
– implemented the first prototype of the astro module, able to search for sources and retrieve optical light-curves.