

A look into

Experimental multi-messenger astronomy

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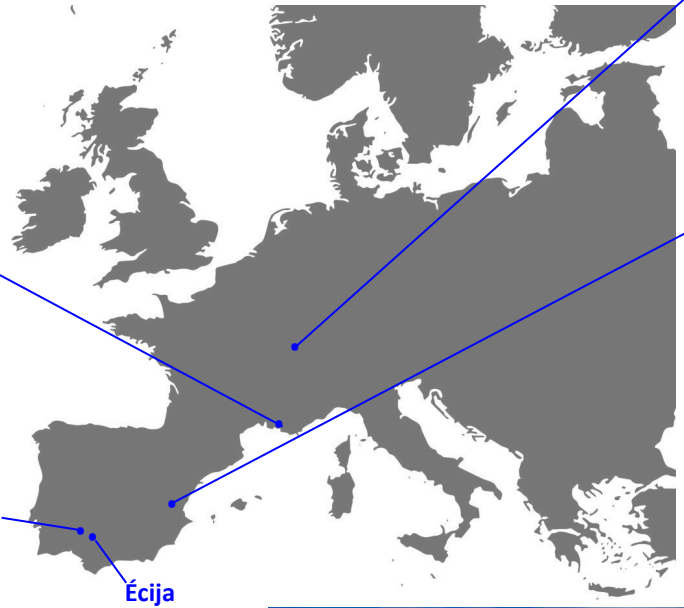
Our Future in Research: Physics, Collaboration and Careers Across Europe
Kraków, 30/10/2026

A personal journey





Geneva
First postdoc (2026-present)

CTAO

UNIVERSITÉ DE GENÈVE



Marseille
PhD fellowship stay (09/2023-12/2023)

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

Valencia
Master degree in Physics (2019-2020)
PhD (2020-2025)

IFIC

KM3NeT

Sevilla
Bachelor degree in Physics (2015-2019)

UNIVERSIDAD DE SEVILLA



Écija
Hometown



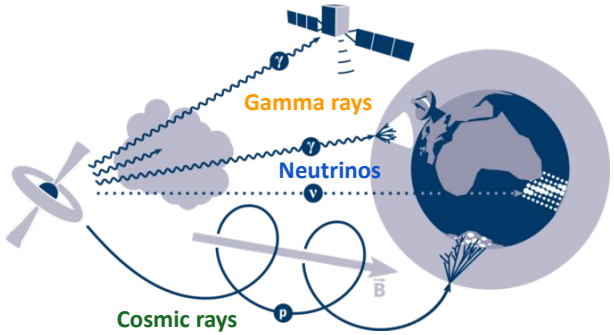


Multi-messenger Searches for Cosmic Neutrino Sources and Time Calibration with KM3NeT

Multi-messenger astronomy

Cosmic rays

- Energetic **charged particles reaching Earth** from all directions in space.
- **Deflected** by magnetic fields.



Gamma rays

- Neutral particles: they **point** directly to their sources of emission.
- > 100 TeV mainly **nearby** sources (i.e., Galactic) can be observed.
- Emitted in **both leptonic and hadronic** processes.

$$e^+ + e^- \rightarrow \gamma + \gamma$$

Example leptonic process

$$p + p \rightarrow p + p + \pi^0 \quad \hookrightarrow \quad \pi^0 \rightarrow \gamma + \gamma$$

Example hadronic process

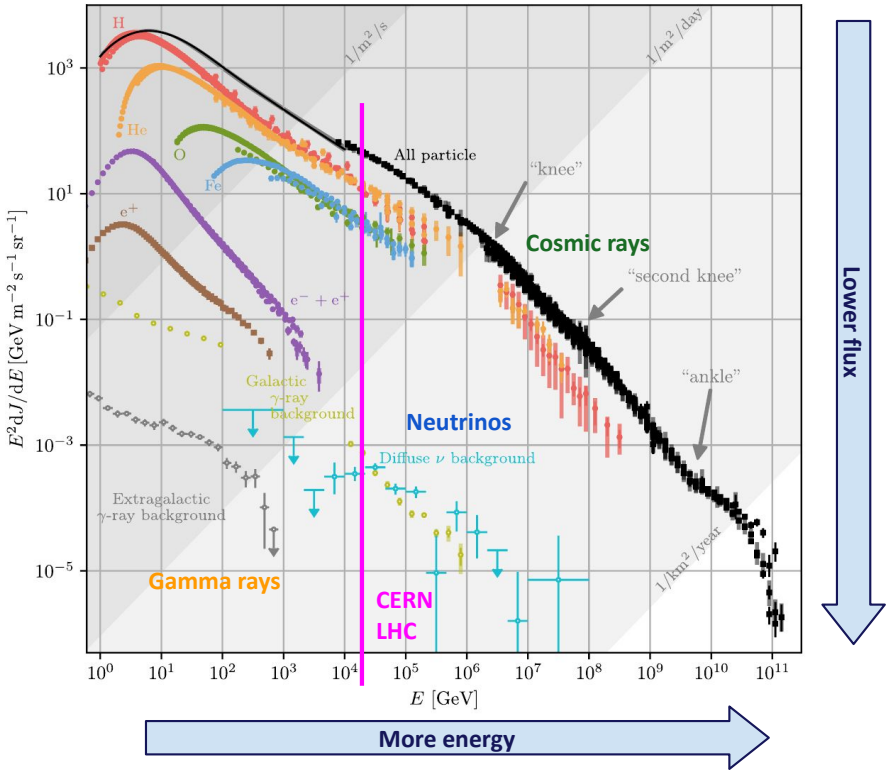
Neutrinos

- Stable, electrically neutral: can reach the Earth **undeflected**.
- Only weak interaction: can **escape dense environments** & are **not absorbed** during propagation to the Earth.
- Unambiguous evidence of **hadronic** acceleration.
- Main disadvantage: low fluxes & large atmospheric background.

Gravitational waves

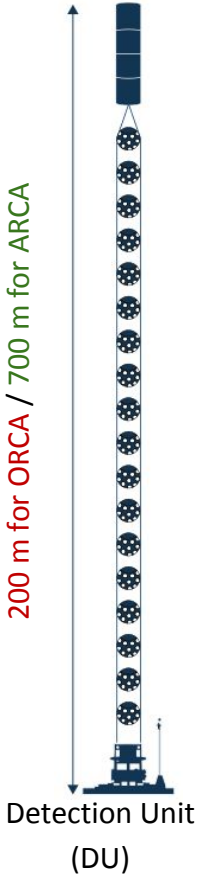
- Ripples in the space-time structure. Hints for the **merging** of compact objects.

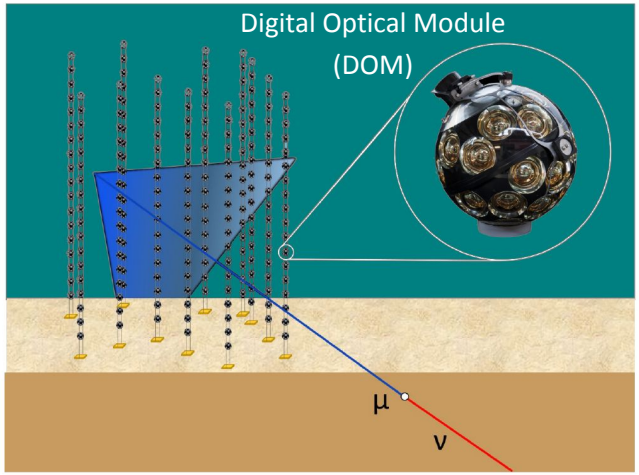
[Particle Data Group 2026]

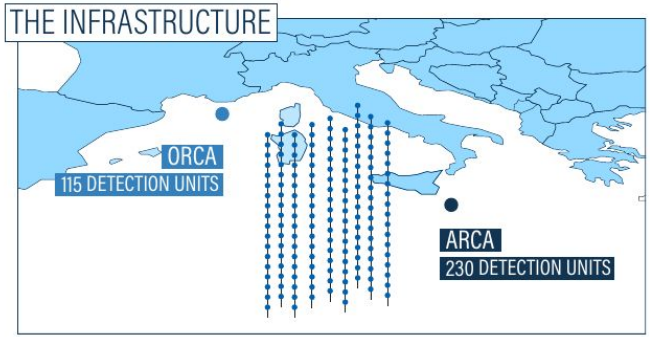


PhD: Cosmic neutrinos

KM3NeT



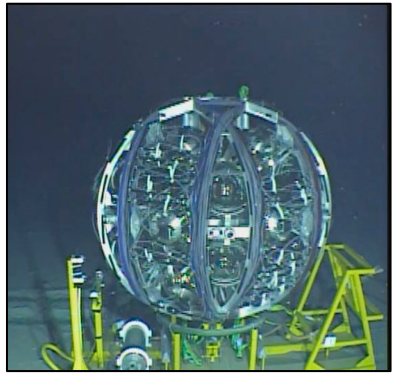




Submarine array of PMTs to detect the Cherenkov radiation induced by neutrino interactions.

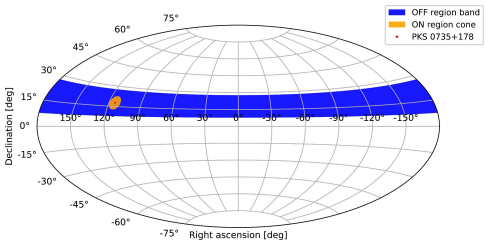
- **KM3NeT-ORCA:**
  - 40 km offshore Toulon (France), 2450 m depth.
  - DOM spacing: 20 m x 9 m.
  - Sensitive to the **GeV-TeV energy range**: Neutrino oscillation studies.
  - Currently 44 detection units deployed (38% of the full configuration).
  - During my PhD time: ORCA 6⇒10⇒11⇒15⇒18⇒19⇒23⇒24⇒28
- **KM3NeT-ARCA:**
  - 100 km offshore Sicily (Italy), 3450 m depth.
  - DOM spacing: 90 m x 36 m.
  - Sensitive to the **TeV-PeV energy range**: Cosmic neutrino searches.
  - Currently 62 detection units deployed (27% of the full configuration).
  - During my PhD time: ARCA 6⇒8⇒19⇒21⇒28⇒30⇒51





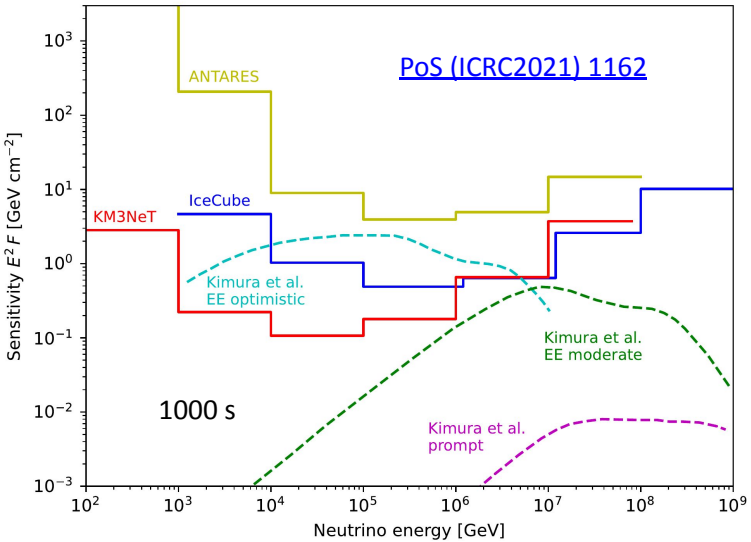


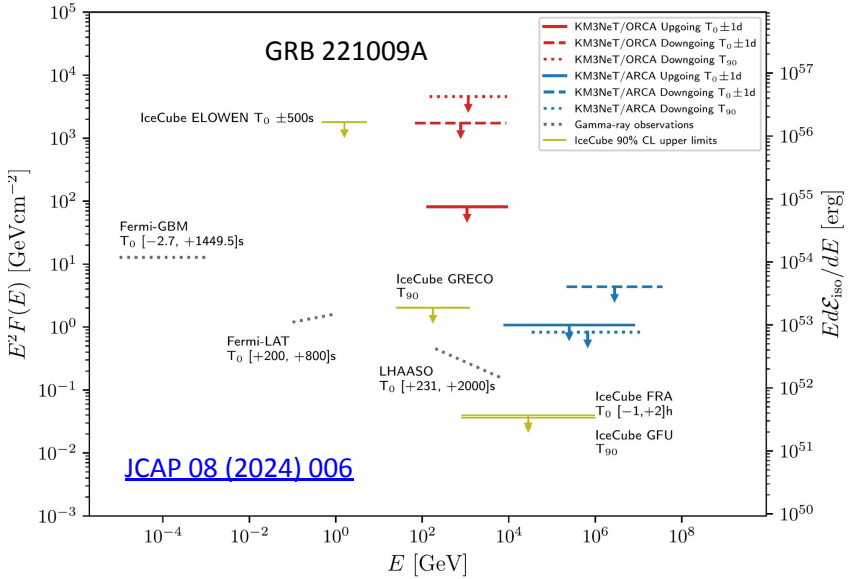
Transient neutrino astronomy



1. Sensitivity of the complete ARCA230 detector to transient neutrino sources.

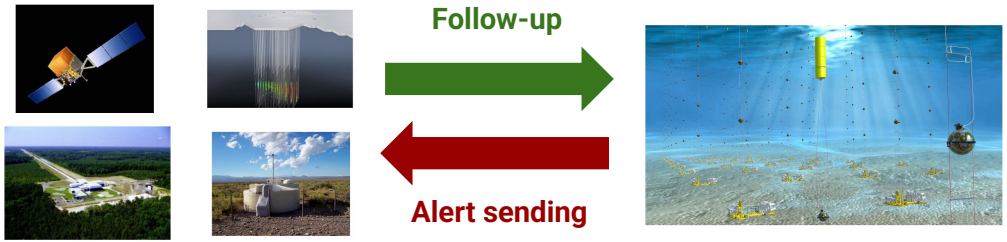
Expertise on “binned” ON/OFF techniques.





3. Contributions to the implementation of the real-time platform of KM3NeT.

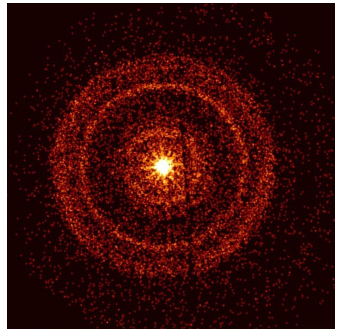
Follow-up analysis core: KOAP (KM3NeT Online Analysis Pipeline).



2. Follow-up of external triggers.

Follow-up of blazars with ARCA6-8 data.

GRB 221009A: the BOAT.
Search for neutrino counterparts with ARCA21 data. No correlation identified.
Setting upper limits on neutrino emission.



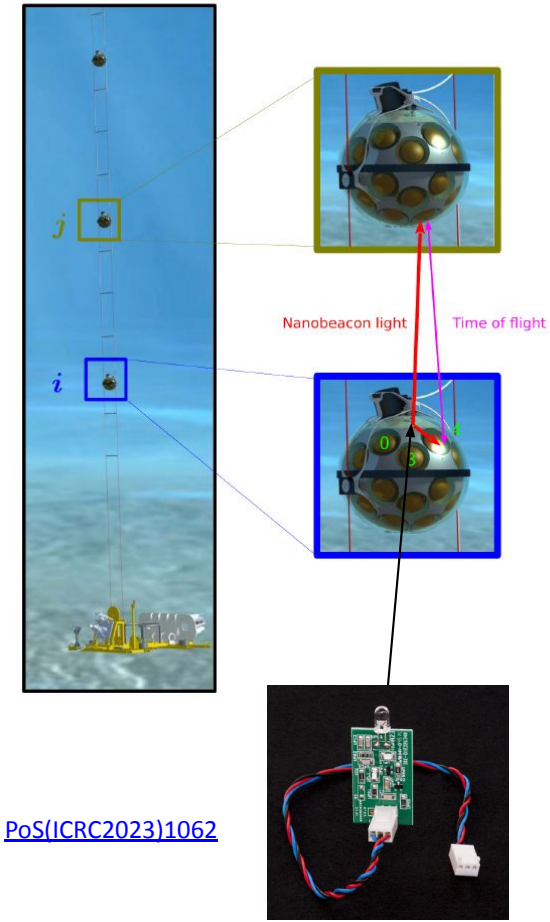
Time calibration with Nanobeacons

- Random effects may cause **time desynchronization** between the different elements of a neutrino telescope.
- Inter-DOM time calibration with **Nanobeacons** (LED flashers equipped in every DOM).

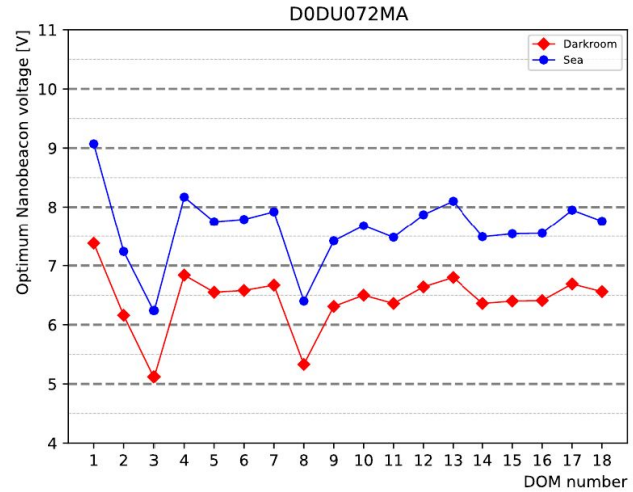
$$t^i_{\text{phys}} = t^i_{\text{raw}} + t^i_0$$

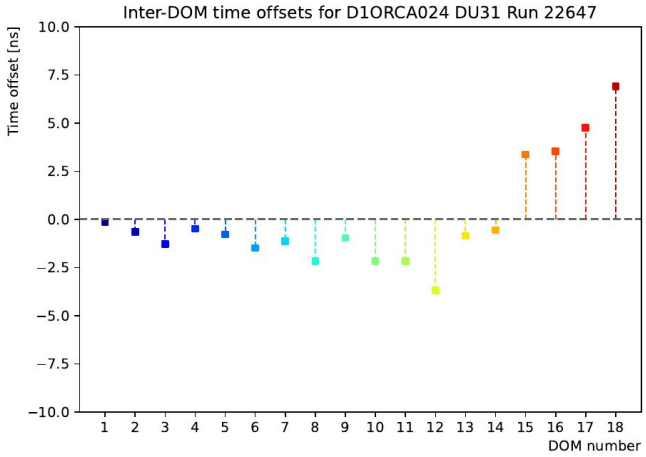
$$\Delta t_0(i,j) = \frac{d(i,j)}{c_w} - \Delta t_{\text{raw}}(i,j)$$

- Two main contributions:
  - Determination of the **optimal voltage** to flash each Nanobeacon from the data taken at the dark rooms.
  - **Automatization** of the **computation** of the **time offset** to be assigned to each DOM.
- Software development in **C++** and **python**.



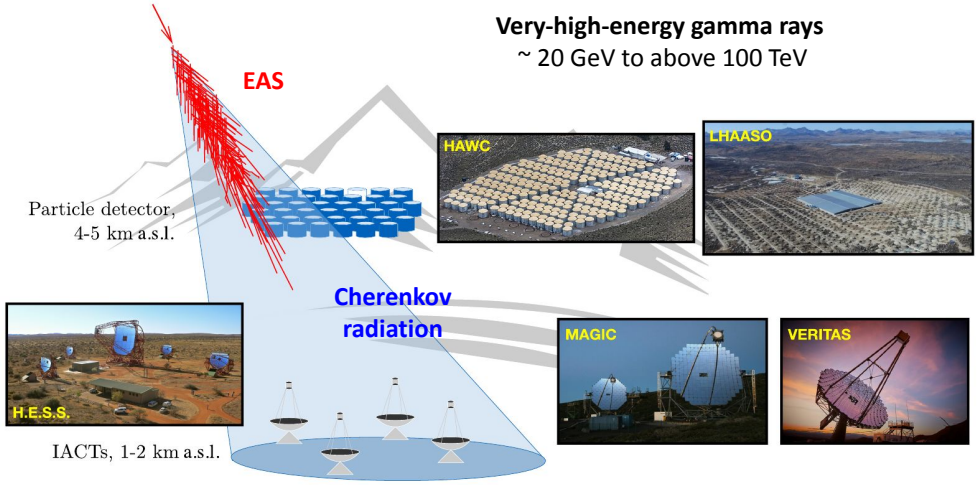
[PoS(ICRC2023)1062]





Postdoc: gamma rays

Ground-based gamma-ray detection

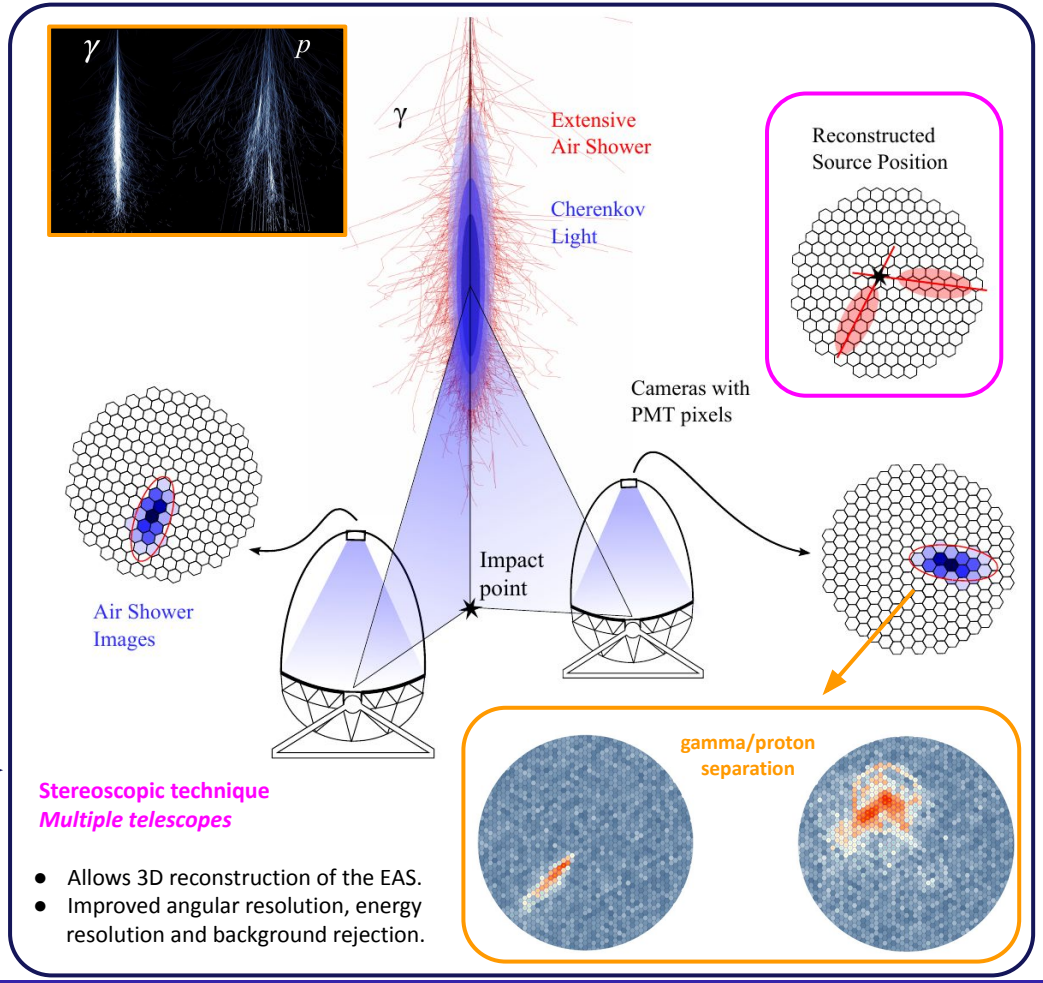


Particle detector arrays

- Large field-of-view (FoV): ~2 sr
- Energy resolution: ~40 %
- High duty cycle (~100%)
- Good angular resolution: 0.2°- 0.8°

Imaging Atmospheric Cherenkov Technique

- Pointing detectors: 5°- 10° FoV
- Energy resolution: ~15 %
- Better short time-scales sensitivity.
- Low duty cycle (~15 %, moonless)
- Excellent angular resolution: < 0.1°

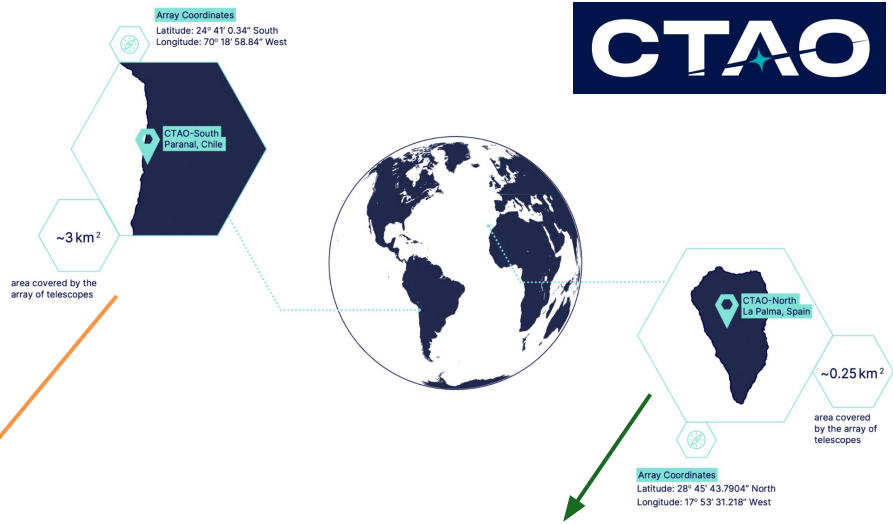


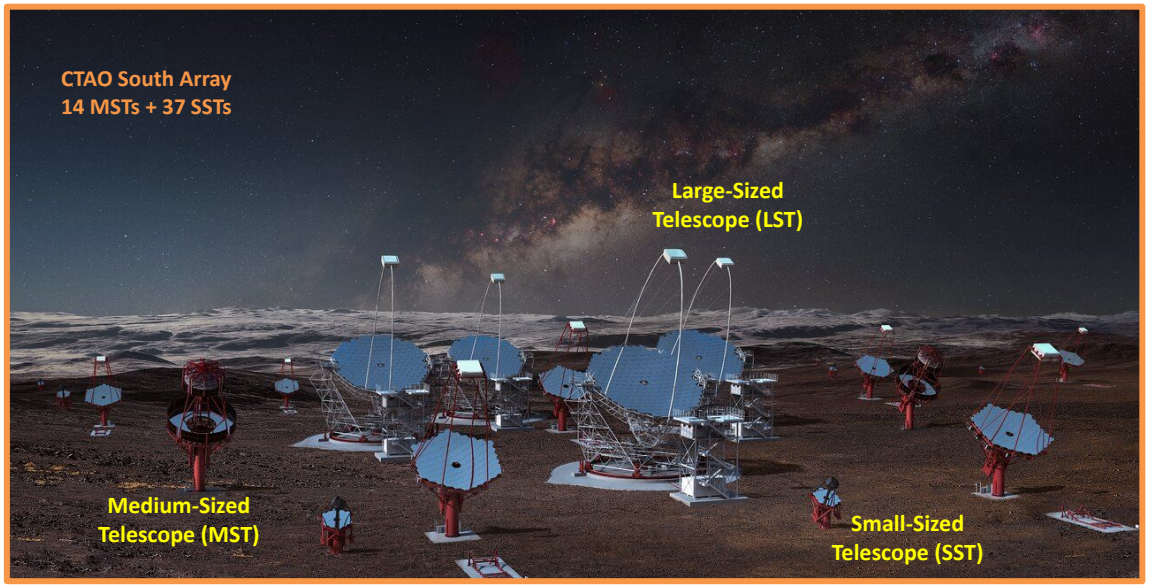
Stereoscopic technique
Multiple telescopes

- Allows 3D reconstruction of the EAS.
- Improved angular resolution, energy resolution and background rejection.

Cherenkov Telescope Array Observatory

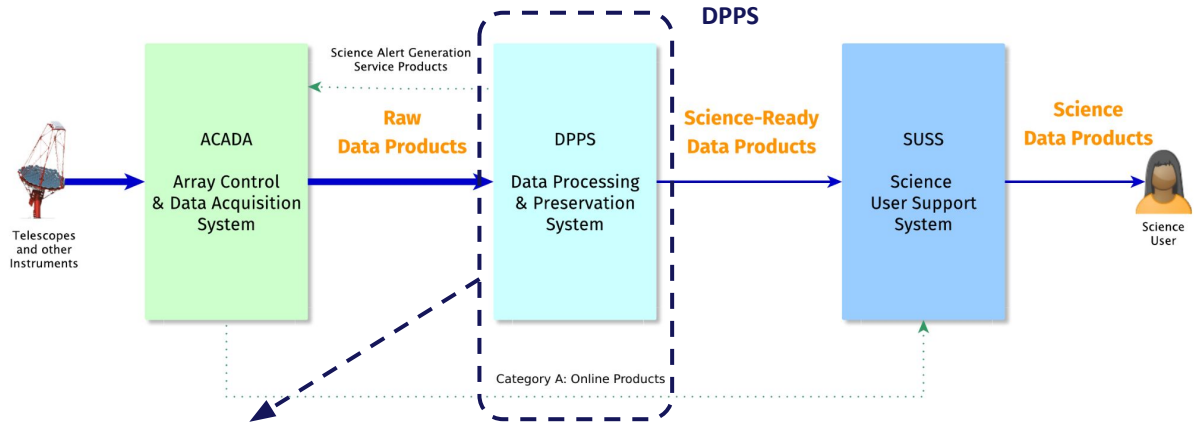
- **Next-generation IACT gamma-ray observatory**, unifying the worldwide research groups in this field into a common strategy for realising an observatory.
- It is expected to be **one order of magnitude more sensitive** to VHE gamma-ray fluxes than the current IACT generation (MAGIC, VERITAS, H.E.S.S.).
- **Wide scientific programme** to probe particle accelerator in the Universe: nearby pulsars, micro-quasars, stellar winds, supernova, AGNs, gamma-ray bursts, clusters of galaxies, etc.
- It will comprise **two arrays** of more than 60 telescopes with three different designs.

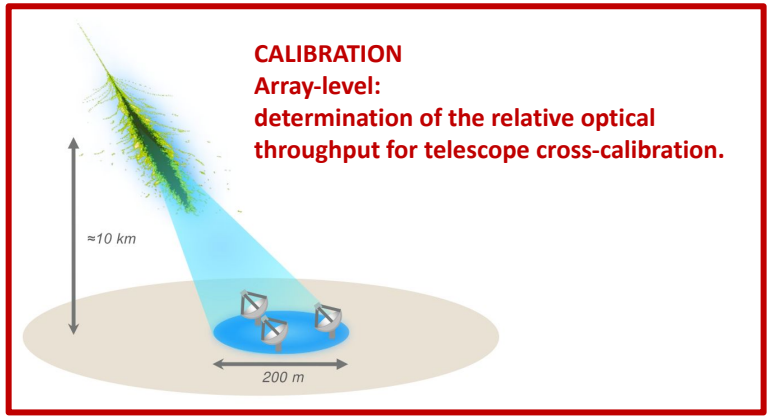




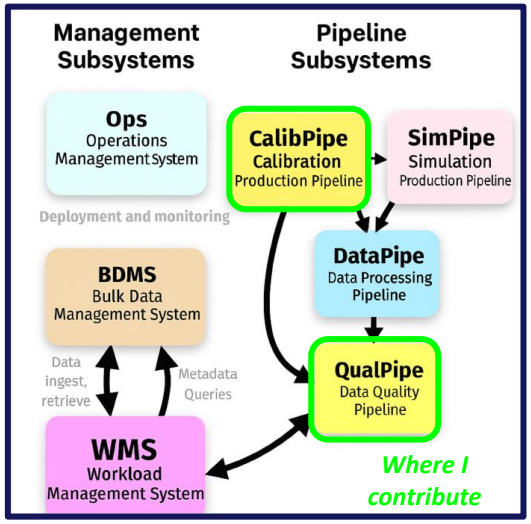


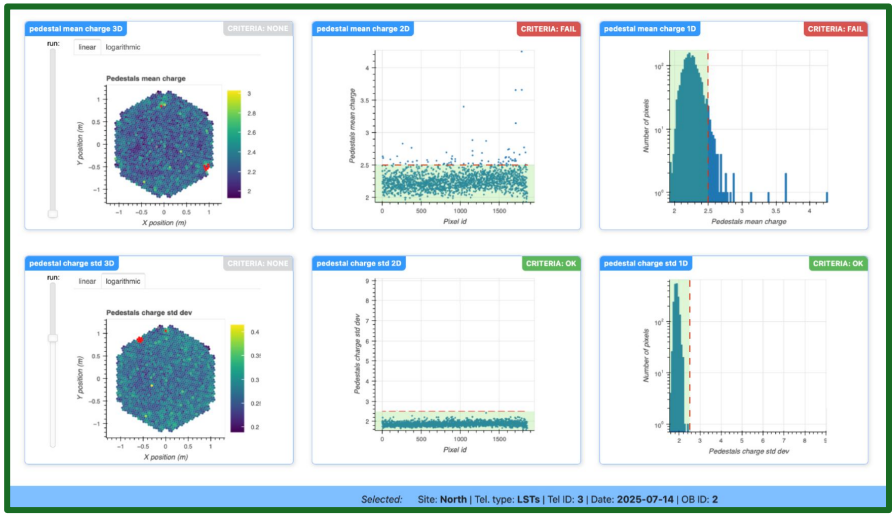
DPPS: Calibration & data quality





CALIBRATION
Array-level:
determination of the relative optical throughput for telescope cross-calibration.





DATA QUALITY
Implementation of DQ monitoring and production of automatic DQ reports.

Data quality report example

Metric Reports

Flatfield charge mean

- Descriptor used: PlainAggregator

Metric Results

Criterion	Outcome	Passing condition
Telescope Range	FAIL	Variable should be within range 7.0e+01 to 8.5e+01 for LST*

Flatfield charge std

- Descriptor used: PlainAggregator

Metric Results

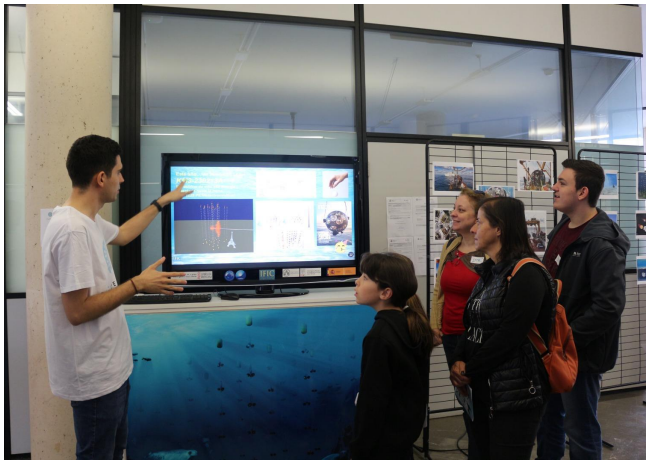
Criterion	Outcome	Passing condition
Telescope Threshold	PASS	Variable should be below threshold 1.0e+01 for LST*

Outlook

Some personal advices for PhD students:

- The PhD learning & results generation curves are **exponential**. Take your time!
- Perform (if possible) an **international research fellowship**.
- Get involved (if possible) in **outreach** activities!
- Get involved (if possible) in **teaching**: lab courses and problem-solving sessions.
- Always improve you **software skills** (AI agents are just a helping tool!).







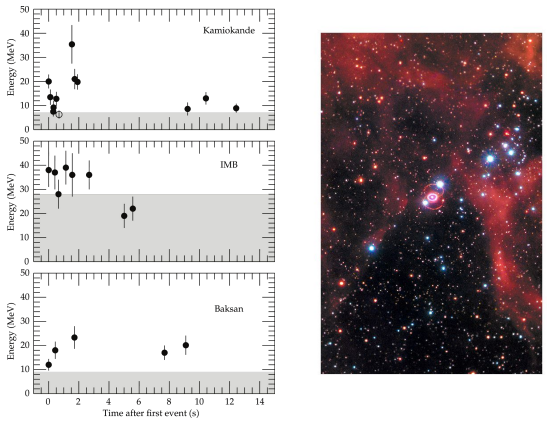




Backup

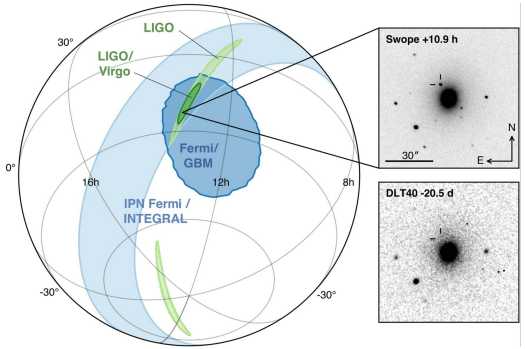
Multi-messenger milestones

The supernova explosion SN1987A (February 1987)



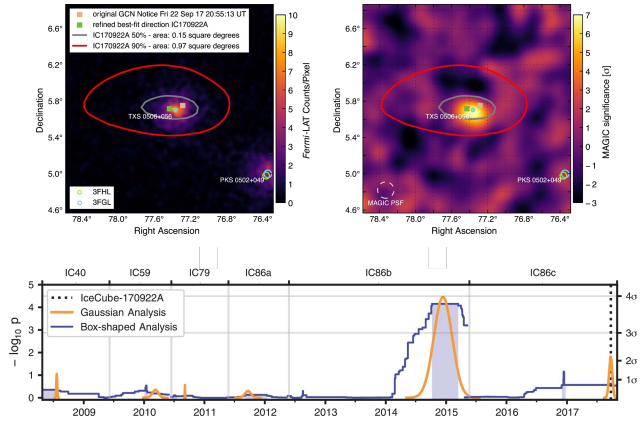
Neutrino detection (~10 MeV) prior to the **electromagnetic signal** observed.

The binary neutron star merger GW170817 (August 2017)



GW detection coincident with the **electromagnetic signal** from a short GRB.

The blazar TXS 0506+506 (September 2017)



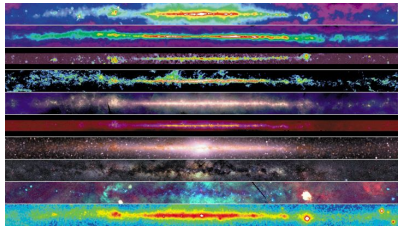
Gamma-rays (Fermi, MAGIC) in coincidence with a cosmic **neutrino** alert (~290 TeV) from IceCube.

1. **More events like these are necessary for a complete characterization** of the physical phenomena that produce them.
2. There are **some correlations of interest still not observed**:
   - Neutrinos + GWs (probably also with an electromagnetic counterpart).
   - Neutrinos in spatial and time coincidence with a GRB event, etc.

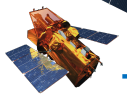
The multi-messenger era



Galileo
Optical telescope
17th century







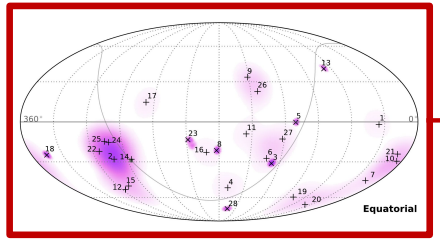


Present

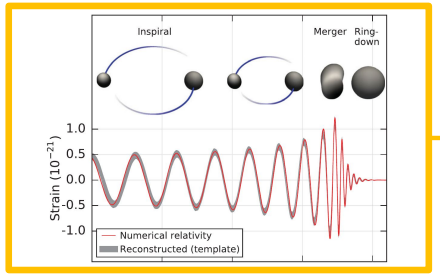
XVII … XX XXI XXII

Centuries timeline

Cosmic neutrinos
2013

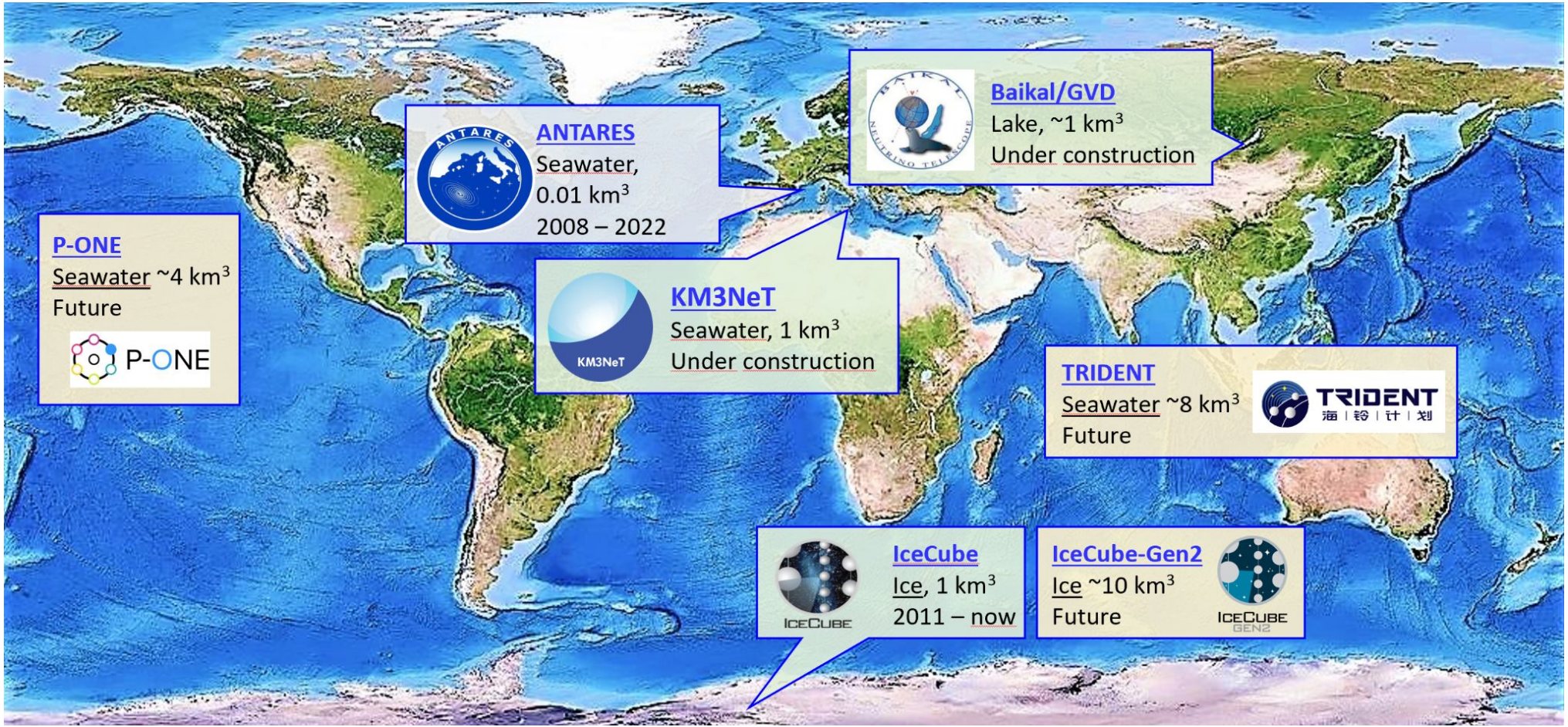


Gravitational waves
2016

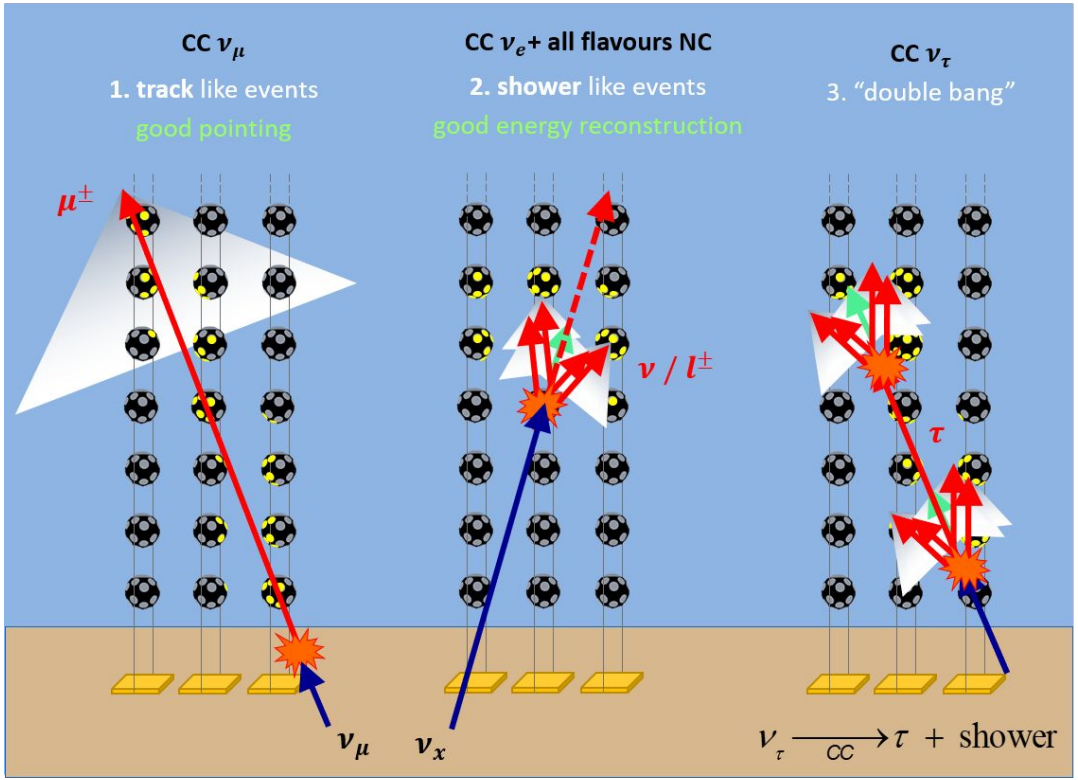




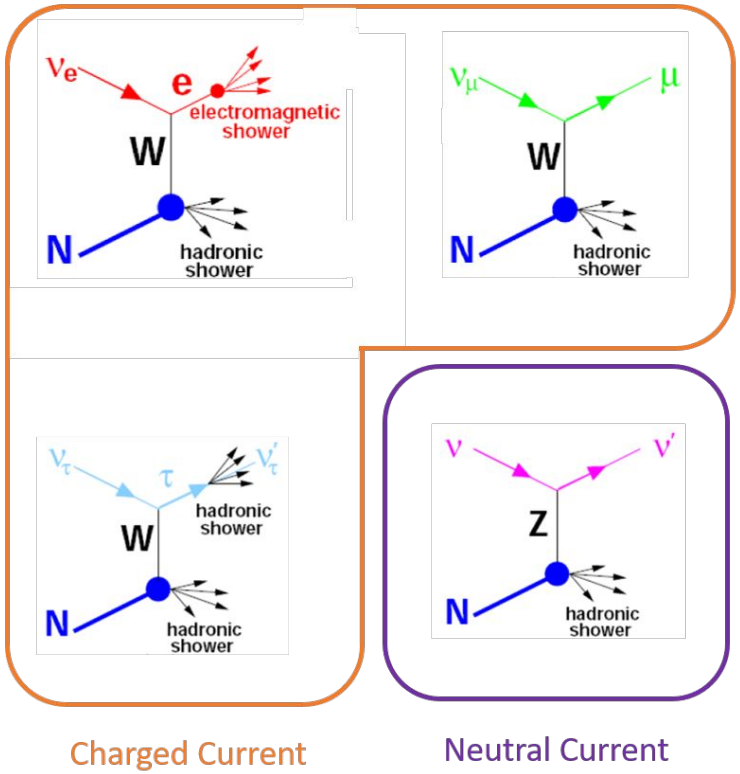
Neutrino telescopes worldwide



Event topology

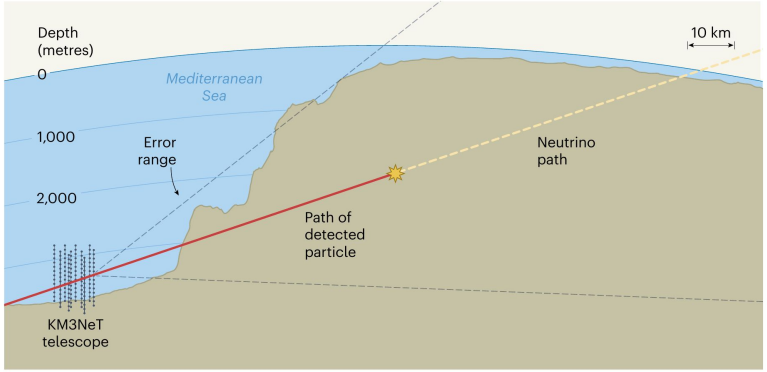


NEUTRINO INTERACTIONS



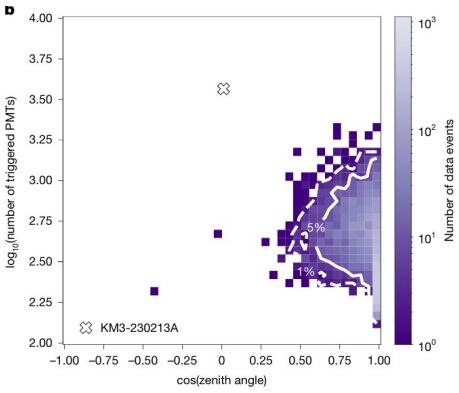
An ultra-high-energy neutrino

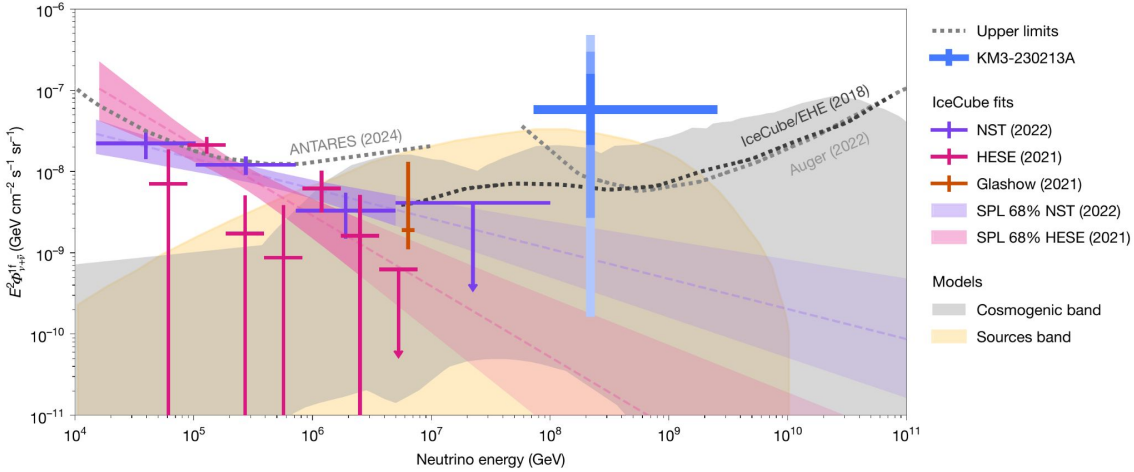
- KM3-230213A by ARCA21.
- Muon: ~120 PeV ⇒ ~220 PeV.
- 0.6 deg above the local horizon.
- No counterpart source observed.
- May be the first hint of a cosmogenic neutrino.



Extended Data Table 2 | Results of the searches for a cosmic point-like neutrino source in the direction of KM3-230213A

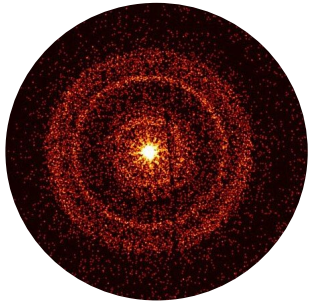
Dataset	n_{sig}	$-\log_{10}(p\text{-value})$	Flux Upper Limit [$GeV^{-1}cm^{-2}s^{-1}$]	(RA, Dec) [deg, deg]	Distance [deg]	P-value
ARCA6-21	0.4	0.044	1.8×10^{-8}	(94.3, −7.8)	0.0	-
	1.3	1.308	1.9×10^{-8}	(96.7, −6.8)	2.6	0.44
ORCA6-18	0	-	2.1×10^{-7}	-	-	-
ORCA18-23	0	-	2.3×10^{-6}	-	-	-
ORCA-combined	-	-	2.0×10^{-7}	-	-	-
ANTARES	0	-	1.1×10^{-8}	(94.3, −7.8)	0.0	-
	1.9	1.936	1.7×10^{-8}	(94.4, −5.3)	2.5	0.53
IceCube	1.4	0.327	1.2×10^{-9}	(94.3, −7.8)	0.0	-
	15.1	3.782	6.3×10^{-9}	(93.9, −10.1)	2.4	0.07



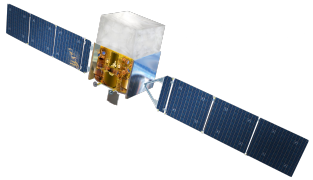




GRB 221009A

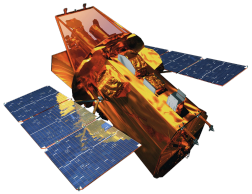


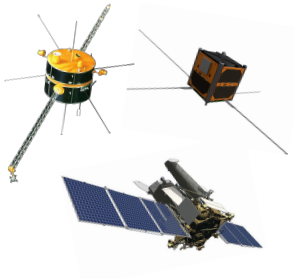
GRB 221009A by Swift



Fermi-GBM
9th October 2022
13:16:59.0 UT

Swift-BAT
9th October 2022
14:10:17.0 UT



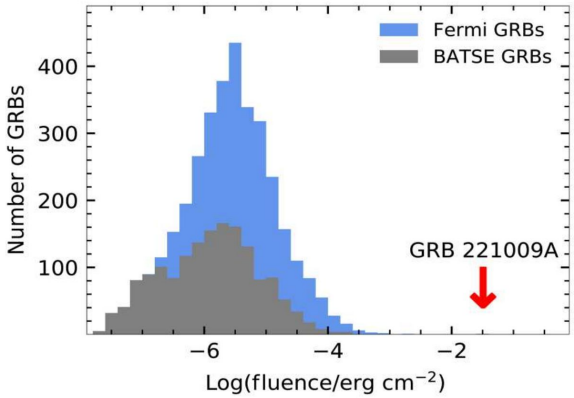


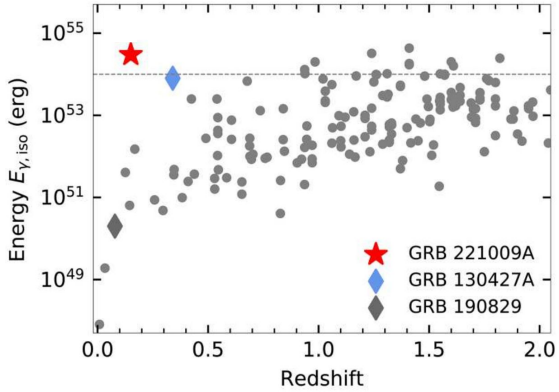
Detection by other multiple satellites (Konus-Wind, SRG, GRBAlpha, etc).

Highest energy observed from a GRB by LHAASO



- The **BOAT**: 'Brighest of All Time'.
- Isotropic equivalent energy around $3 \cdot 10^{54}$ erg (among the highest ever detected).
- Observation by **LHAASO** of photons up to around 13 TeV: the highest energy ever detected from a GRB.
- Also highest energy detection by Fermi-LAT from a GRB: photons up to about 99 GeV (instrument saturation).
- Redshift z=0.151 →relatively close event.
- **A GRB as extraordinary as GRB 221009A is expected to occur only once every ten thousand years.**
- One of the most **extensive follow-up campaigns** ever!

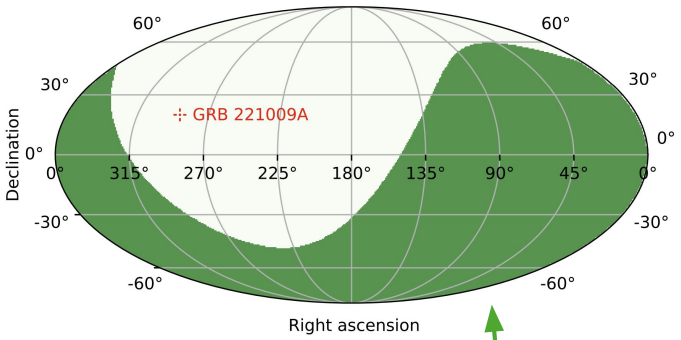




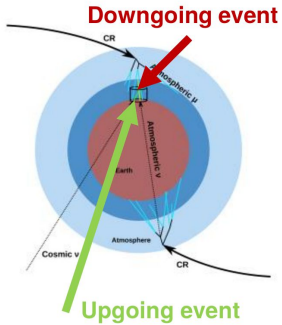
O'Connor et al 2023

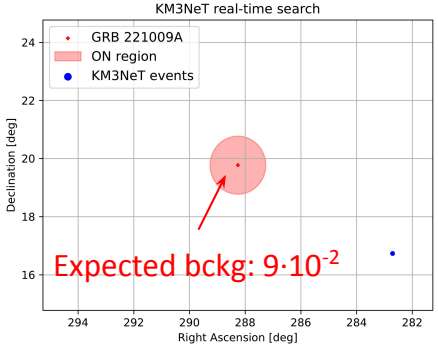
GRB 221009A: online neutrino search

- When GRB 221009A took place, ARCA21 and ORCA10 were taking data.
- The event was **above the local horizon of KM3NeT** (a.k.a. downgoing) at T_0.
- KM3NeT reported **results in real-time,** just four days after the event: GCN #32741
- Search time window: [T_0 - 50 s, T_0 + 5000 s].
- **No track-like candidate neutrino event found.**
- A MeV search was also conducted in real-time with no significant detection.
- IceCube also reported real-time results (GCN #32665) with no candidate neutrino event.



Visibility below the horizon (a.k.a. upgoing)





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:

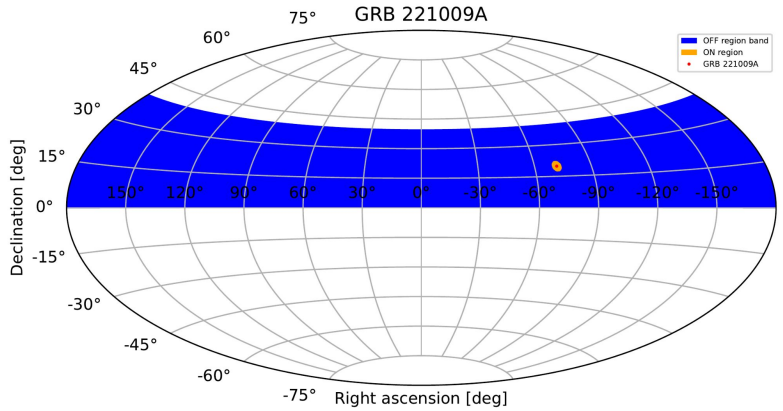
Using the data from the online fast processing chain, the KM3NeT Collaboration has performed a dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A (Dichiara et al. GCN 32632 (Swift); Veres et al. GCN 32636 (Fermi-GBM)). The search covers the time range of [T0-50s, 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.

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

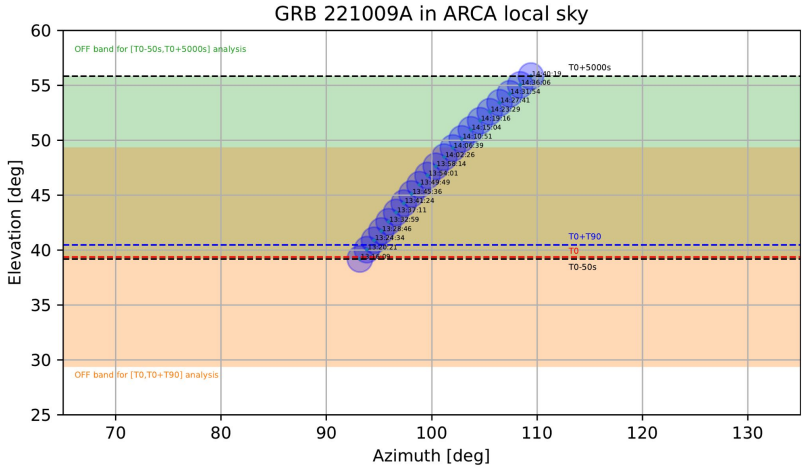
KM3NeT is a large undersea (Mediterranean Sea) infrastructure hosting two neutrino detectors, sensitive to burst of supernova neutrinos in the MeV range and to astrophysical neutrinos in the GeV-PeV energy range: ARCA at high energy and ORCA at low energy. A total of 21 and 11 detection lines are currently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

GRB 221009A: search method

Equatorial coordinates



Local coordinates



- **ON region:** where the **signal** is expected.
  Circular area region optimized for each analysis.

- **OFF region**: band in the local/equatorial sky used to compute the **expected background**:

$$n_{\text{bckg}} = \frac{T_{\text{ON}}}{T_{\text{OFF}}} \times \frac{\Omega_{\text{ON}}}{\Omega_{\text{OFF}}} \times N_{\text{OFF}}$$

- **Time windows** analysed (both ARCA and ORCA):

  a. <u>Above</u> the day range (equatorial coordinates):

  - $T_0 \pm 1$ day upgoing selection.
    (the integrated visibility in one day is 45%).
  - $T_0 \pm 1$ day downgoing selection.

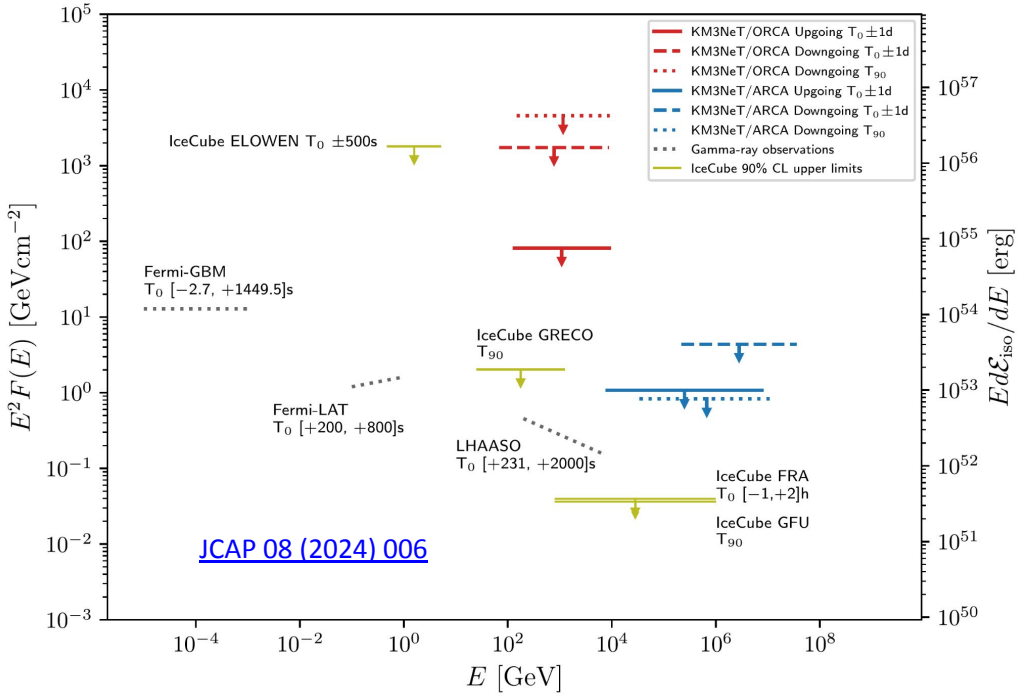
  b. <u>Below</u> the day range (local coordinates):

  - $[T_0 - 50\ \text{s}, T_0 + 5000\ \text{s}]$ downgoing selection.
  - $[T_0, T_0 + T_{90}]$ downgoing selection.

- **Optimization procedure:**
  1. Reduce expected bckg so that one event in the ON region is enough to reach a 3σ significance.
  2. Maximize the expected signal from MC simulations.

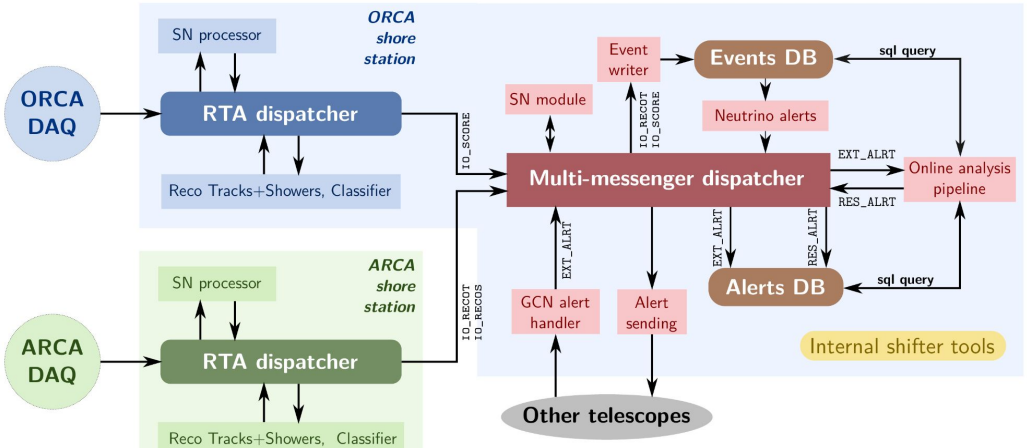
GRB 221009A: results

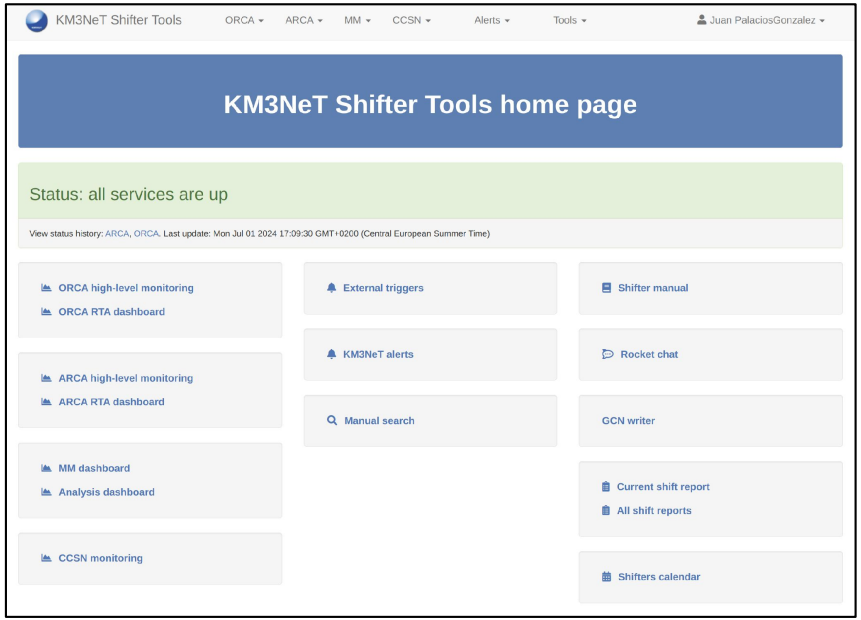
- No candidate neutrino events found within the ON region for any of the searches performed.
- Upper limits derived on the neutrino emission.
- The most restrictive results were found for the upgoing search:
  - ARCA21: Φ_0 UL = $6.2 \cdot 10^{-6}$ GeV^{-1}cm^{-2}s^{-1}
  - ORCA10: Φ_0 UL = $4.7 \cdot 10^{-4}$ GeV^{-1}cm^{-2}s^{-1}
- **$E^2F(E)$**: per-flavour energy-scaled time-integrated neutrino flux.
- **Multi-messenger plot:** KM3NeT limits + IceCube limits + some gamma-ray measurements for comparison.
- For KM3NeT, GRB 221009A happened in the non-visible region, unlike IceCube.
- About a 15% improvement in sensitivity is expected upon detector completion. Cascade-like events will be added also in the future in similar analyses.



$$\Phi_0^{\mathrm{UL}} = \frac{\mu_{90}^{\mathrm{FC}}(n_b)}{\int dt \int dE \cdot (E/E_0)^{-\gamma} \cdot A_{\mathrm{eff}}^{\delta}(E)} \qquad E^2F(E) = \Delta T \cdot \Phi_0^{UL} \cdot E_0^2$$

The KM3NeT real-time framework



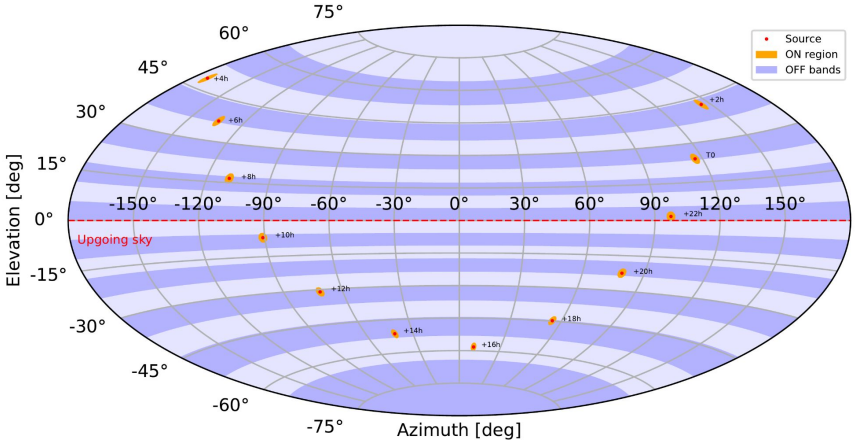


- **KM3NeT Online Platform**: real-time event reconstruction + MM dispatcher + Analysis module.
- Real-time processing of data with online calibration: **track** & **cascades** reconstruction + **classification**.
- Triggered events are processed in real-time in **less than 7 s** for both ARCA and ORCA.
- **Main analysis functionalities**: follow-up of external triggers (active), Core-Collapse Supernovae alert pipeline (active), sending high-energy neutrino alerts (work in progress).



Analysis technique

- **ON region:** where the **signal** is expected. Includes source location error + angular uncertainty.
- **OFF region**: local zenith bands to compute the **expected background**, spanning the ON region movement due to Earth's rotation.
- **p-value** determined when comparing the number of events in the ON region with the expected background.
- Multiple T_{ON} time windows are inspected depending on the alert type.
- T_{OFF}: up to <u>two weeks</u> of previously taken data.
- **Event selection**: fixed "precuts" + optimization of a given reco variable per zenith band.
    - RecoQuality in ARCA.
      ClassificationScore (BDT) in ORCA.
    - Optimised to reduce the background to the level with the best achievable significance.
    - Different selections in each zenith band.



Optimization criteria: *m-sigma/n-events*

1. $n_{\mathrm{BKG}} \leq \alpha$
1. $\sigma(n_{\mathrm{BKG}})/n_{\mathrm{BKG}} < 30\%$
1. $\sigma(n^i_{\mathrm{OFF}})/n^i_{\mathrm{OFF}} < 50\%$

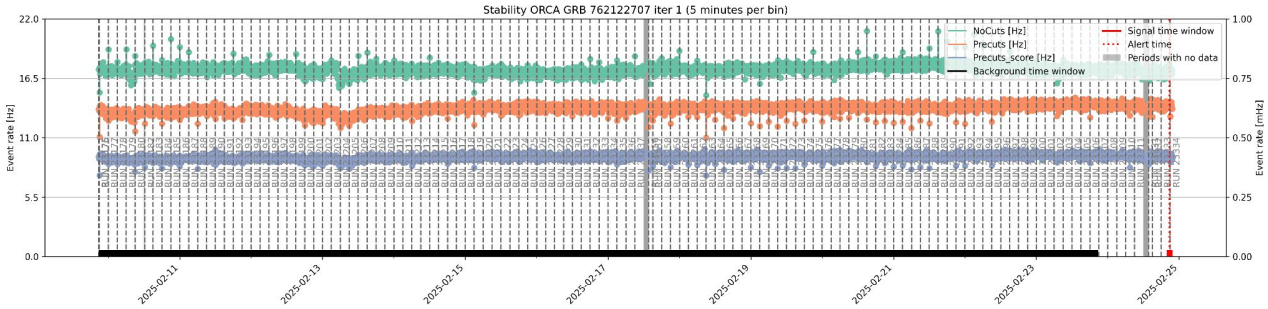
$$n_{\mathrm{BKG}} = \sum_i \frac{T_{\mathrm{ON}}}{T_{\mathrm{OFF}}} \frac{\Omega^i_{\mathrm{ON}}}{\Omega^i_{\mathrm{OFF}}} N^i_{\mathrm{OFF}}$$

Low, but robust, background

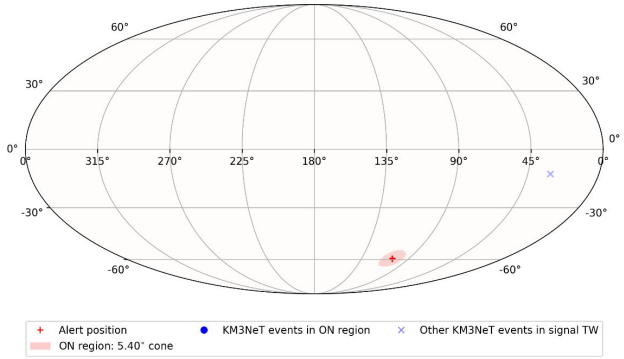
Real-time result example

Analysis ORCA - v1	
TAG	RES_ALRT
Notice_Name	FERMI_GBM_FLT_POS
Alert_Source	FERMI
ID_Event	762122707
Date_Event	2025-02-24T20:45:02.690
Detector	ORCA
Pipeline	ORCA_GRB
Iteration	1
Date_Analysis	2025-02-24T21:49:56.374
Code_Version	0.4.18
Search time window	t_alert-1.0 h TO t_alert+1.0 h
Livetime[sig] (hours)	1.983
Livetime[bkg] (days)	13.519
Remaining fraction after rate cuts (%)	97.713
RA (deg)	105.6833
DEC (deg)	-59.4833
RoI (deg)	5.4
nON	0
nOFF	10,9,10
Expected Background	0.0026019
Err(Expected Background)	0.0005969
Bkg Target	3.0sigma/1events
Cuts on ClassificationScore	0.99991,0.99987,0.99981
p-value	1.0

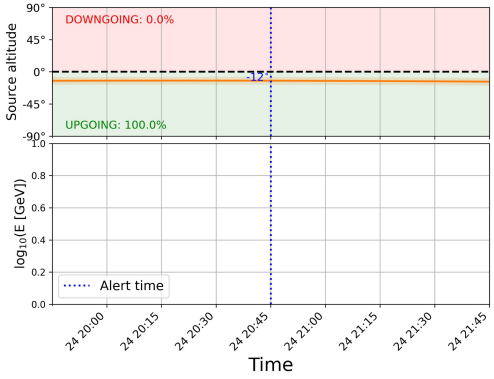
GRB 762122707 trigger on 24th February 2025



Skymap ORCA GRB 762122707 iter 1



Time profile ORCA GRB 762122707 iter 1



CTAO Key Science Projects

