Cosmic neutrino searches with the KM3NeT detectors: A multi-messenger approach

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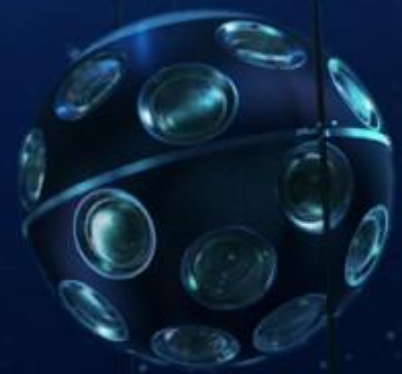
Juan.Palacios@ific.uv.es
20th November 2025



IFIC

VEGA Valencia Experimental Group of Astroparticles

GOBIERNO DE ESPAÑA MINISTERIO DE UNIVERSIDADES

CSIC

VNIVERSITAT DE VALÈNCIA

KM3NeT

CPAN Ingenio 2010

CPAN 2025

Cosmic messengers

Cosmic rays

- **Energetic particles from space**. Discovered in early 20th century.
- Abundant, mostly **charged** particles (~90 % protons).
- **Deflected** by magnetic fields.
- **Origin and acceleration mechanisms unknown**.

Electromagnetic radiation (gamma rays)

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

Gravitational waves

- **Ripples in the space-time structure**. Discovered in 2015.
- Hint for the **merging of compact objects**.

Neutrinos

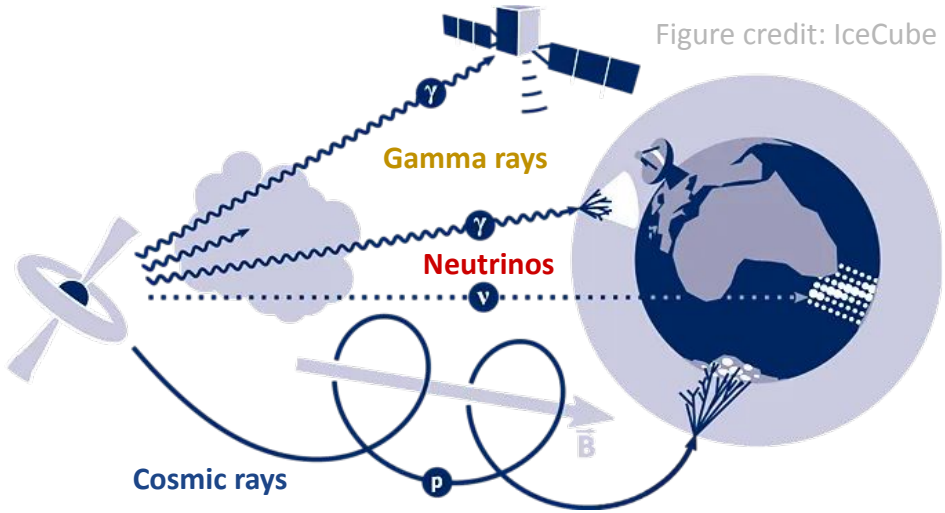
- Cosmic neutrinos (above GeV-TeV energies): discovered in 2013.
- **Stable, electrically neutral**: can reach the Earth undeflected.
- **Weak interaction**: they can escape dense environments and are not absorbed during propagation to the Earth.
- Unambiguous **evidence of hadronic acceleration**:

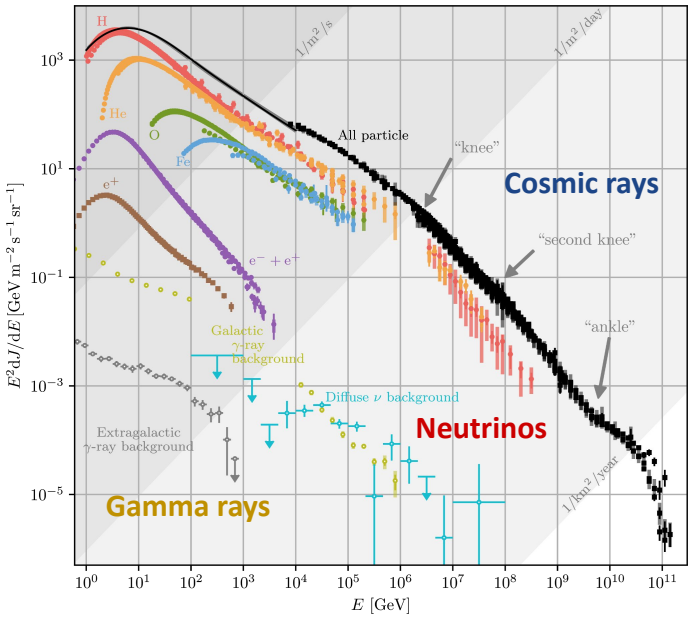
$$p + p(\gamma) \rightarrow \pi^+ + X \qquad \pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Multi-messenger astronomy

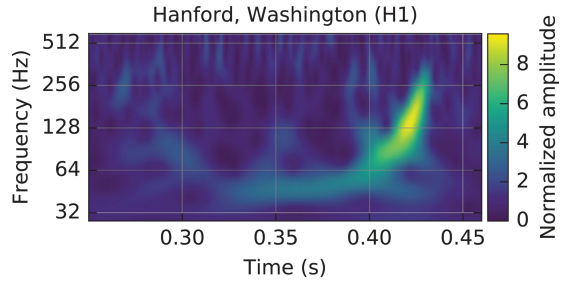
A coincident detection enhances the sensitivity for identifying astrophysical sources.

Figure credit: IceCube



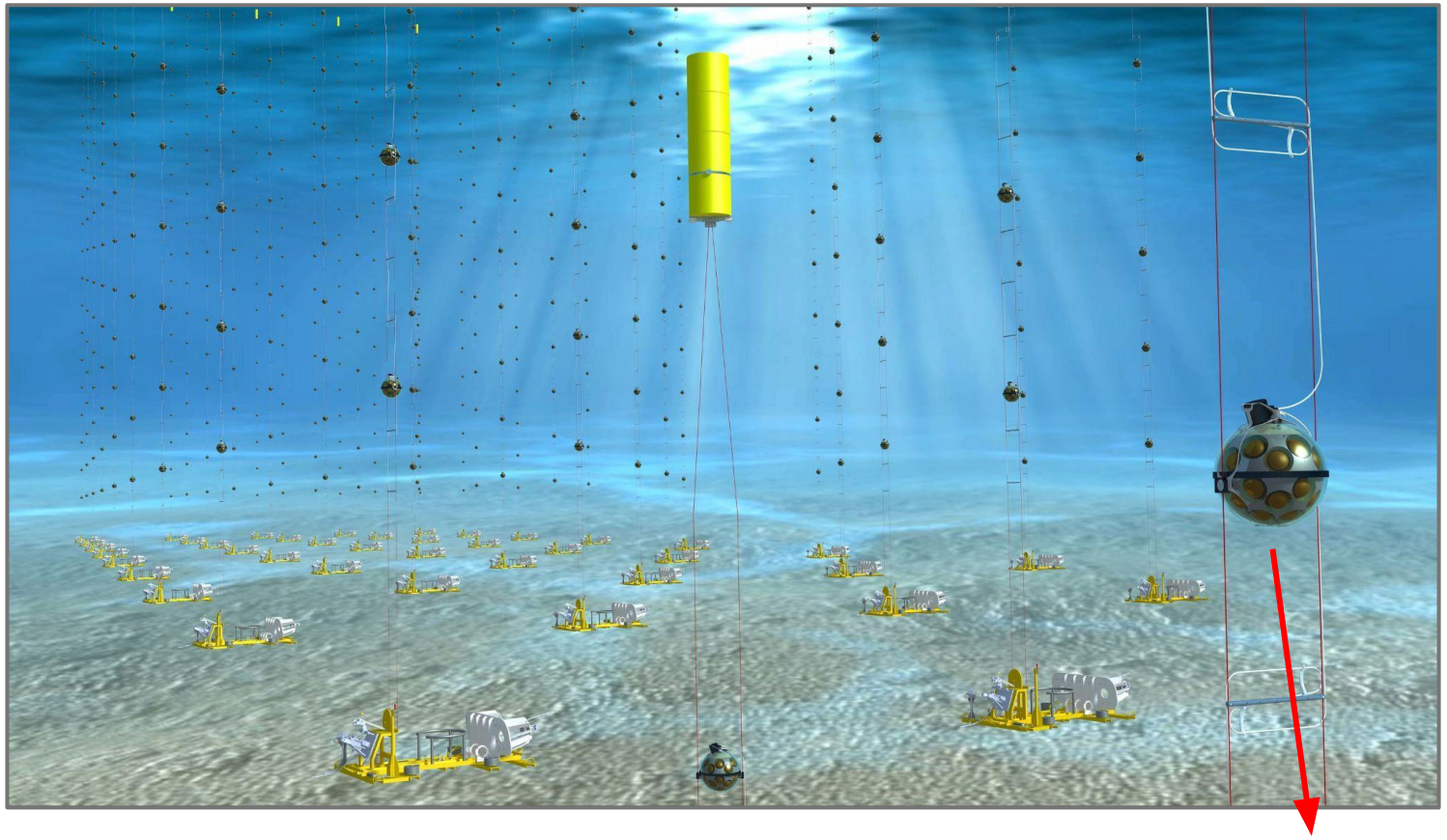


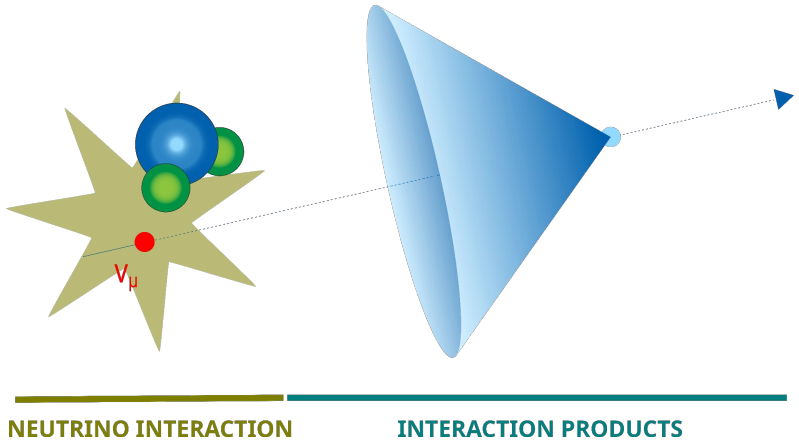
Gravitational waves



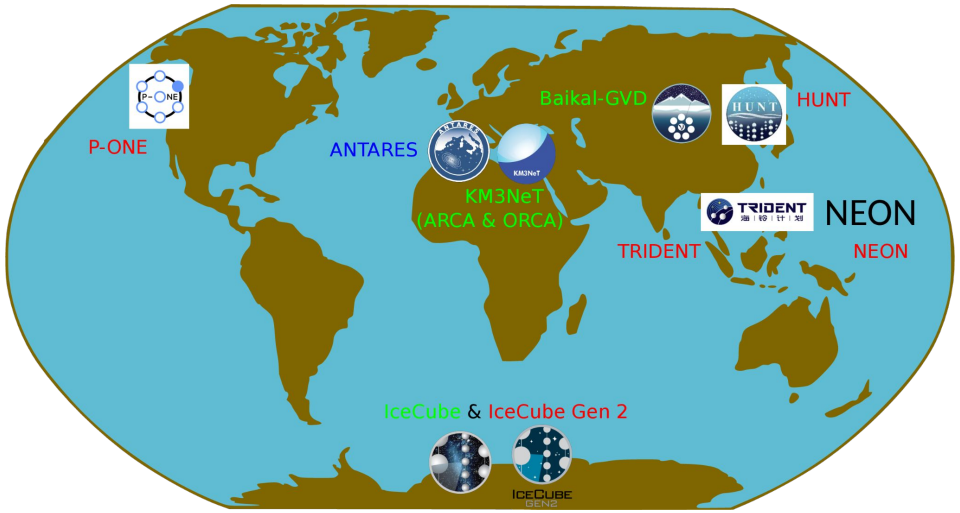
GW150914 Phys. Rev. Lett. 116, 061102

KM3NeT





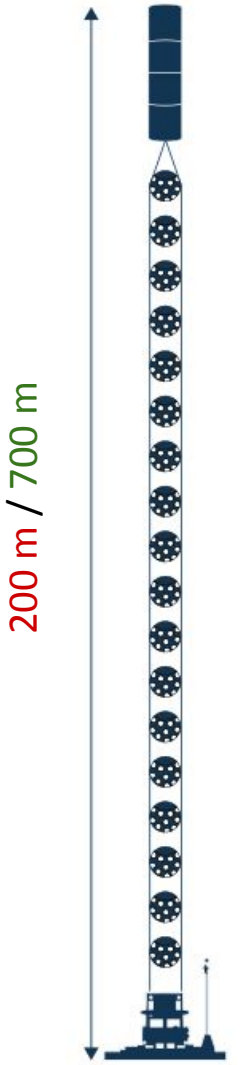
At present: several neutrino telescopes in operation & planned worldwide.



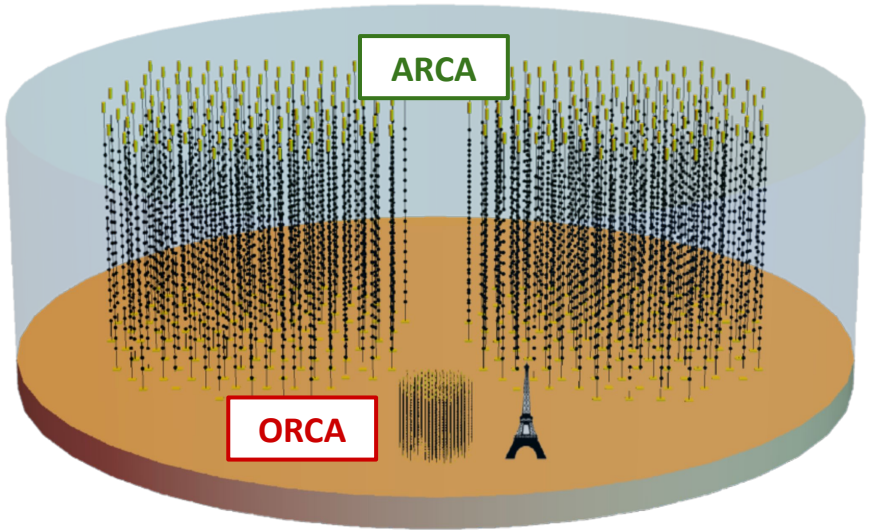
- Research infrastructure currently deploying **two deep-sea neutrino detectors** at the **bottom of the Mediterranean Sea**.
- **Three-dimensional array of PMTs** designed to detect the Cherenkov light emitted by charged particles originating from neutrino interactions.

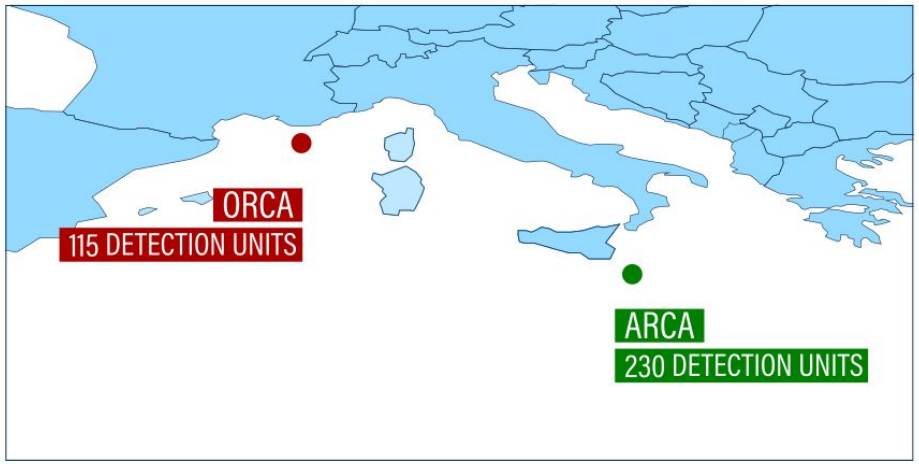
Digital Optical Module (DOM)

KM3NeT: ARCA and ORCA



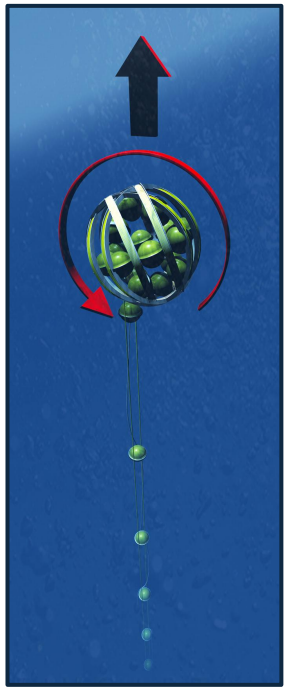
Detection Unit (DU)

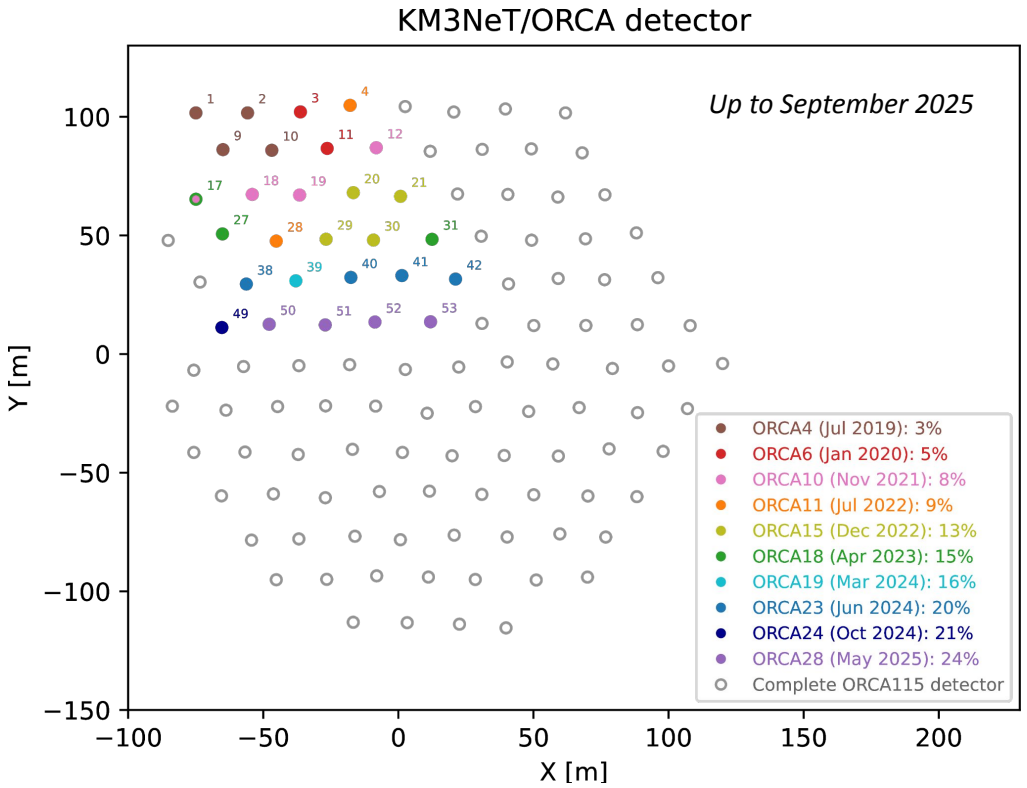


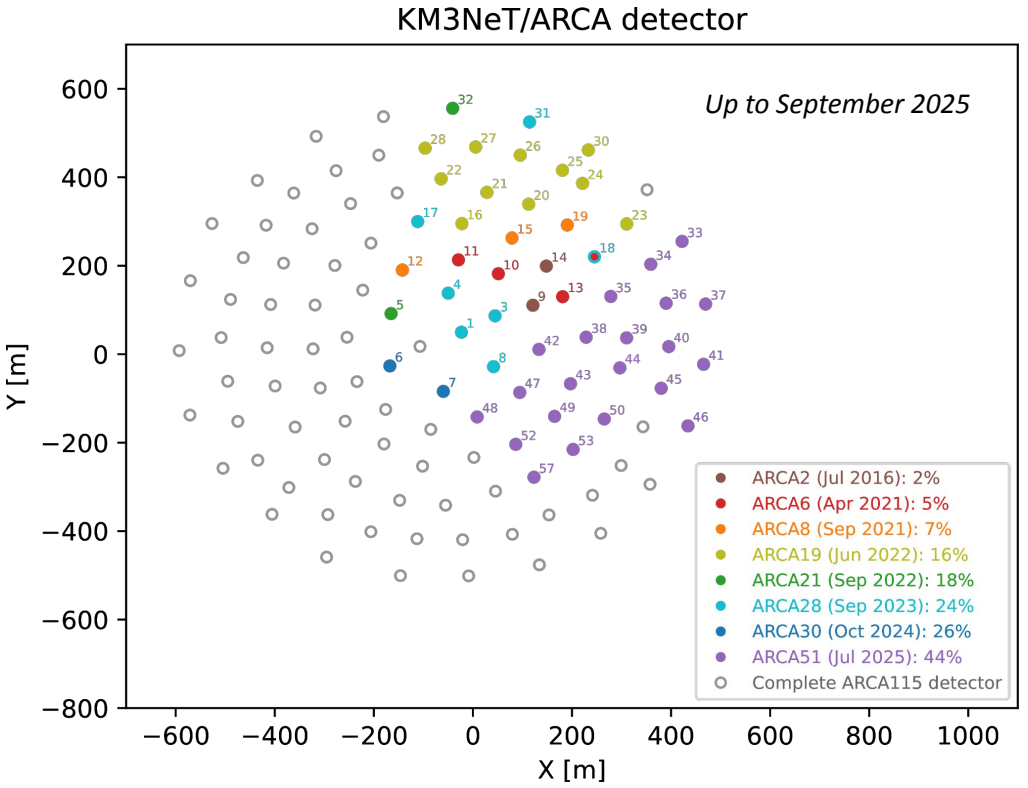


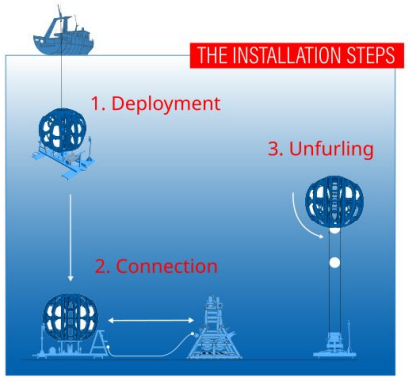
- **KM3NeT-ORCA** *Oscillation Research with Cosmic in the Abyss*
  - 40 km offshore Toulon (**France**), 2450 m depth.
  - DOM spacing: 20 m x 9 m.
  - Sensitive to the **GeV-TeV energy range**.
  - Complete future configuration: 115 DUs.
- **KM3NeT-ARCA** *Astroparticle Research with Cosmic in the Abyss*
  - 100 km offshore Sicily (**Italy**), 3450 m depth.
  - DOM spacing: 90 m x 36 m.
  - Sensitive to the **TeV-PeV energy range**.
  - Complete future configuration: 230 DUs.
- Two main reconstruction **event topologies**:
  - **Track-like events**: ν_μ CC and some ν_τ CC.
  - **Cascade-like events**: all NC, ν_e CC and some ν_τ CC.
- **Optical backgrounds:**
  - Bioluminescence. Radioactive isotopes decay (^{40}K).
  - Atmospheric muons: **upgoing sky vs downgoing sky**.

KM3NeT: construction









- The construction of the detector is **currently ongoing** in different phases.
- **Partial detector configurations** are already being used for the **acquisition of data.**
- ARCA8 (ARCA detector with 8 DUs installed), ARCA21, ARCA28, etc.
- At present, **ARCA counts with 51 DUs and ORCA with 33 DUs** already installed at the seabed.
- The completion of the detector is foreseen by the end of the decade.

The KM3NeT real-time platform

The multi-messenger community

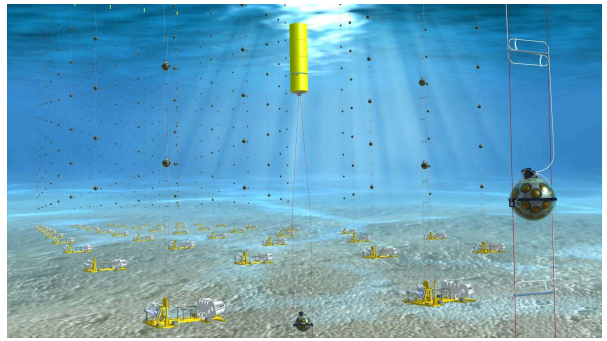
This talk!

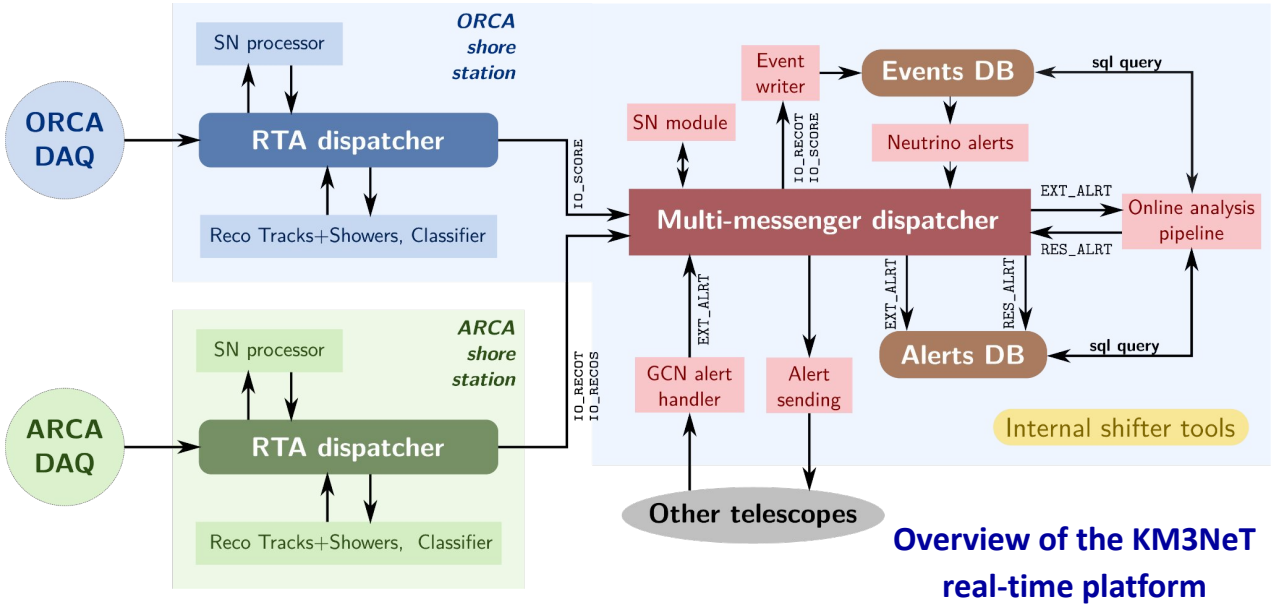
Follow-up of external triggers
Ongoing since early 2023.

Neutrino alert sending.
Under final development. Expected in 2026.

Next talk by V. Cecchini

KM3NeT

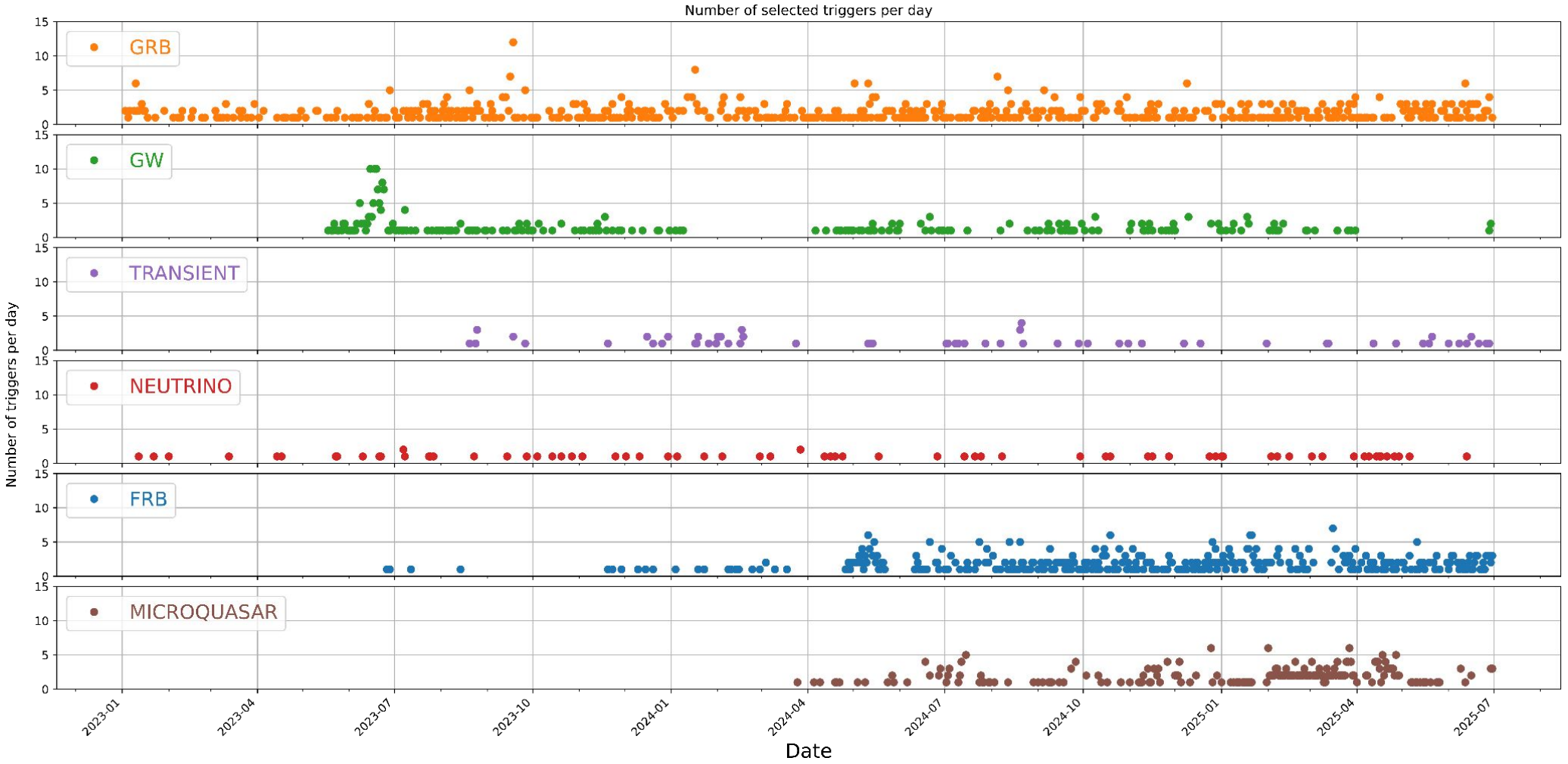




Overview of the KM3NeT real-time platform

- **MM real-time activities:** the follow-up of triggers reported by external observatories and the dispatch of neutrino alerts.
- **KM3NeT real-time platform:** collection of software modules to perform these tasks in a quasi-automatic way.
  - Real-time processing of the ARCA and ORCA events.
  - Reception of incoming triggers.
  - Multi-messenger dispatcher (coordinates the system).
  - Core-Collapse Supernovae pipeline.
  - Follow-up analysis pipeline. Alert sending pipeline.
  - Monitoring tools for internal usage.

Incoming external triggers



INTEGRAL, Fermi, Swift, SVOM
~ 1 per day

LVK
~ 1 per 2 day

INTEGRAL, Fermi, Swift, MAXI, HAWC, SVOM
~ 1 every 9 days

IceCube
~ 1 every 2 weeks

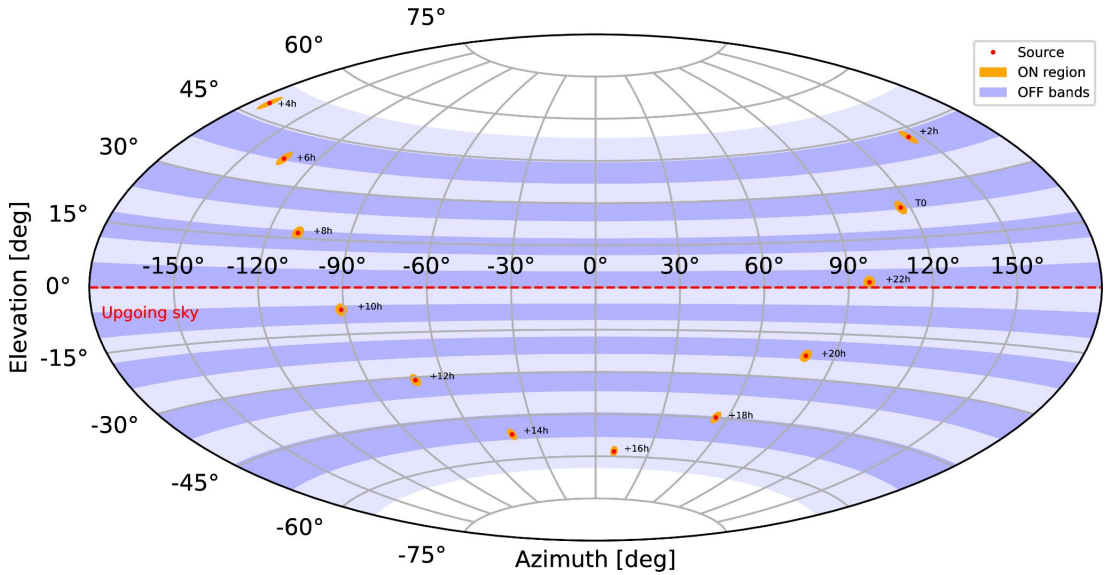
CHIME, TNS
~ 1 per day

Internal microquasar broker
~ 1 every 2 days

Constantly receiving a stream of incoming external alerts triggers ⇒ It is necessary to develop an **automatic system** for the follow-up

KOAP: KM3NeT Online Analysis Pipeline

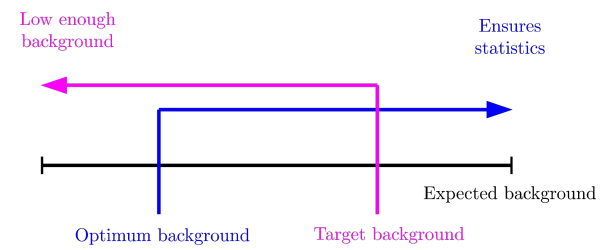
- **ON region**: where the signal is expected. It includes the alert location error + angular uncertainty of the detector:
  - Currently (conservatively): 2° for ARCA, 4° for ORCA.
- **OFF region**: local zenith bands to determine the expected background, spanning the ON region movement due to Earth's rotation.
- **T_{ON}**: multiple time windows inspected depending on alert type.
  - GRB and FRB: $T_0 \pm 500$ s, $T_0 \pm 1$ h, $T_0 \pm 1$ d
  - NEUTRINO: $T_0 \pm 1$ h, $T_0 \pm 1$ d
  - GW: $T_0 \pm 500$ s, [T_0 - 500 s, T_0 + 6 h]
  - TRANSIENT: trigger duration (min 500 s), $T_0 \pm 1$ day.
  - MICROQUASAR: trigger duration (min 500 s)
- **T_{OFF}**: up to two weeks of previously taken data.
- **Event selection optimization**:
  - Fixed "precuts" + elevation-dependent selection in a concrete reconstruction variable.
  - "*n*sigmas-*m*events" procedure: reduce as much as possible the expected background, without large statistical uncertainties.
- **Main final result**: p-value (pre-trial). Also possibility to compute ULs.



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

$$n_{\text{bckg}} \leq \alpha \qquad \sigma(n_{\text{bckg}})/n_{\text{bckg}} < 30\%$$

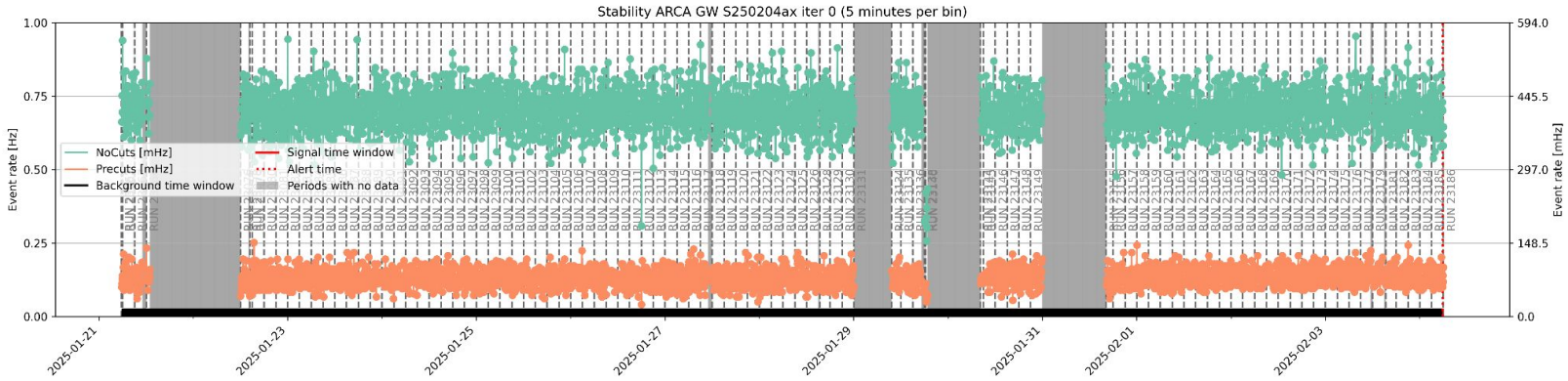
$$\sigma(N^i_{\text{OFF}})/N^i_{\text{OFF}} < 50\%$$

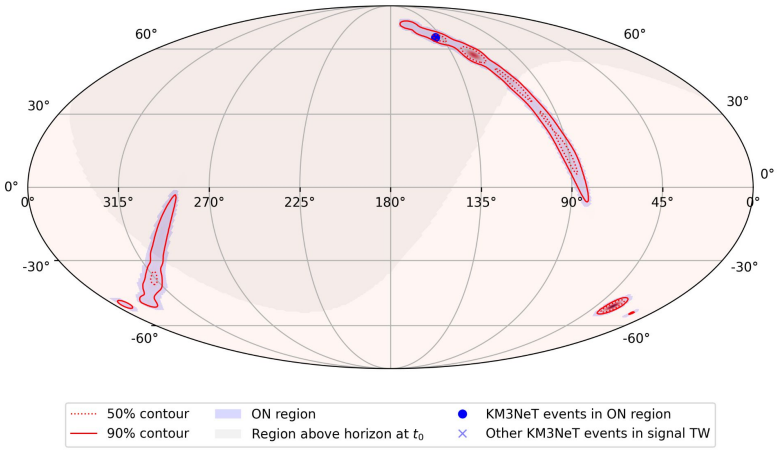


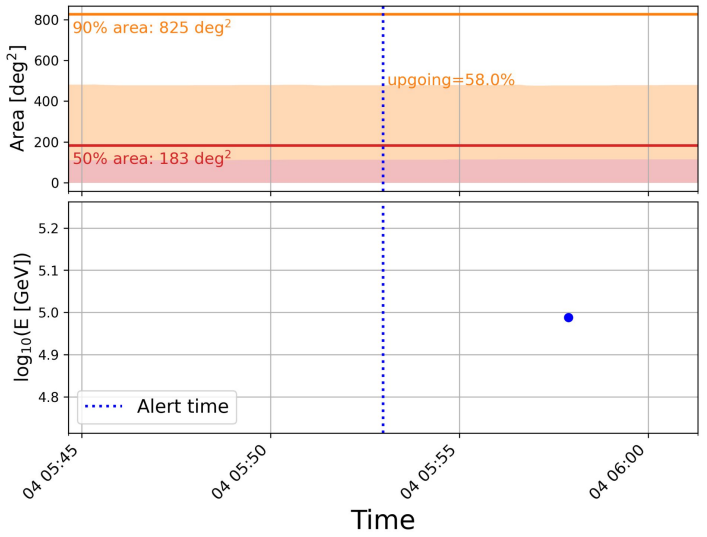
KOAP: an example

Analysis ARCA - v0	
ID_Event	S250204ax
Date_Event	2025-02-04T05:52:59.004
Detector	ARCA
Pipeline	ARCA_GW
Iteration	0
Date_Analysis	2025-02-04T06:06:40.841
Search time window	t_alert-500.0 s TO t_alert+500.0 s
Livetime[sig] (seconds)	1000.0
Livetime[bkg] (days)	4.471
Remaining fraction after rate cuts (%)	39.893
nON	1
nOFF	0,3,9,16,16,16,17
Expected Background	0.00856
Err(Expected Background)	0.00101
Bkg Target	2.5sigma/1events
Cuts on RecoQuality	inf,85,85,91.112,101.9,123.29,144.92
p-value	0.009

S250204ax GW trigger on 4th February 2025

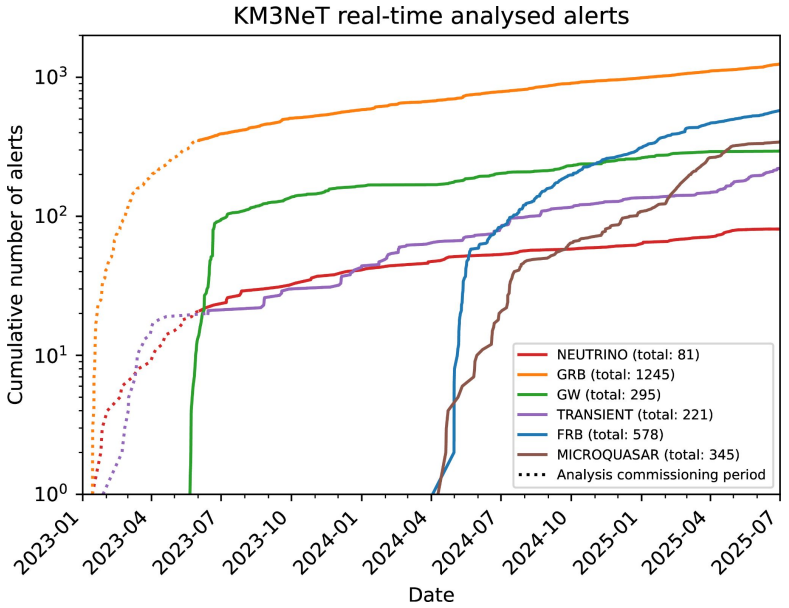


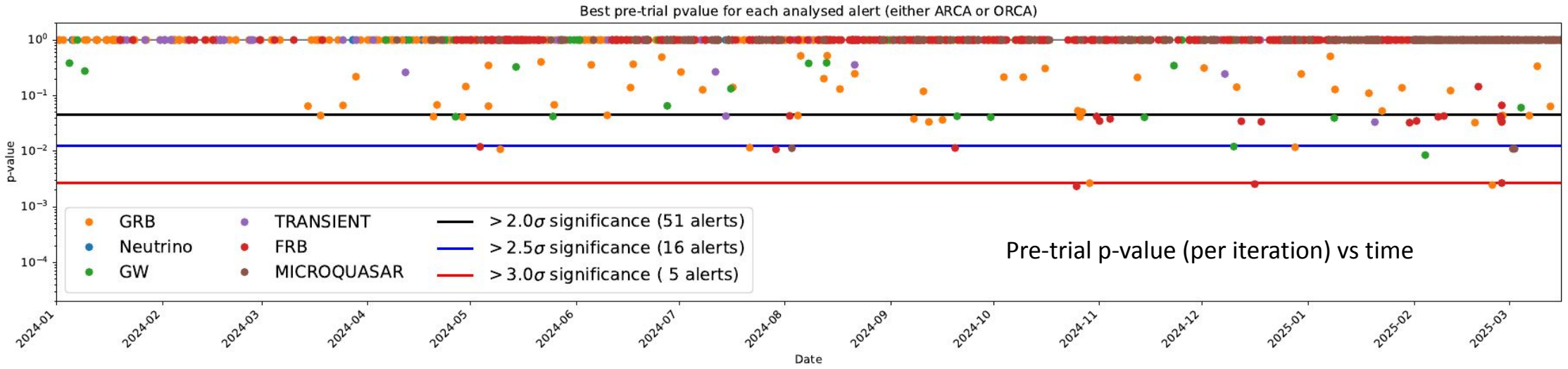




Summary: follow-up activities

- KM3NeT online follow-up of external triggers is ongoing **since early January 2023**.
- **Cumulative number of analysed alerts** (from any iteration of ARCA or ORCA, or from both):
  - More than **2700 alerts** have been successfully followed up in real time during this period.
- At present analyses use only **track-like events**. Implementation of cascade-like events ongoing.
- So far, **no significant correlations have been observed.**
  - There has not been a report of results from the real-time platform yet.
- **The system continues the monitoring,** searching for future potential correlations in real time**.**

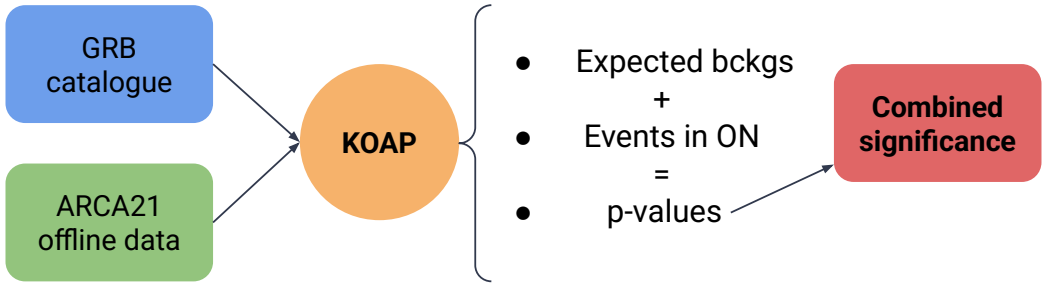


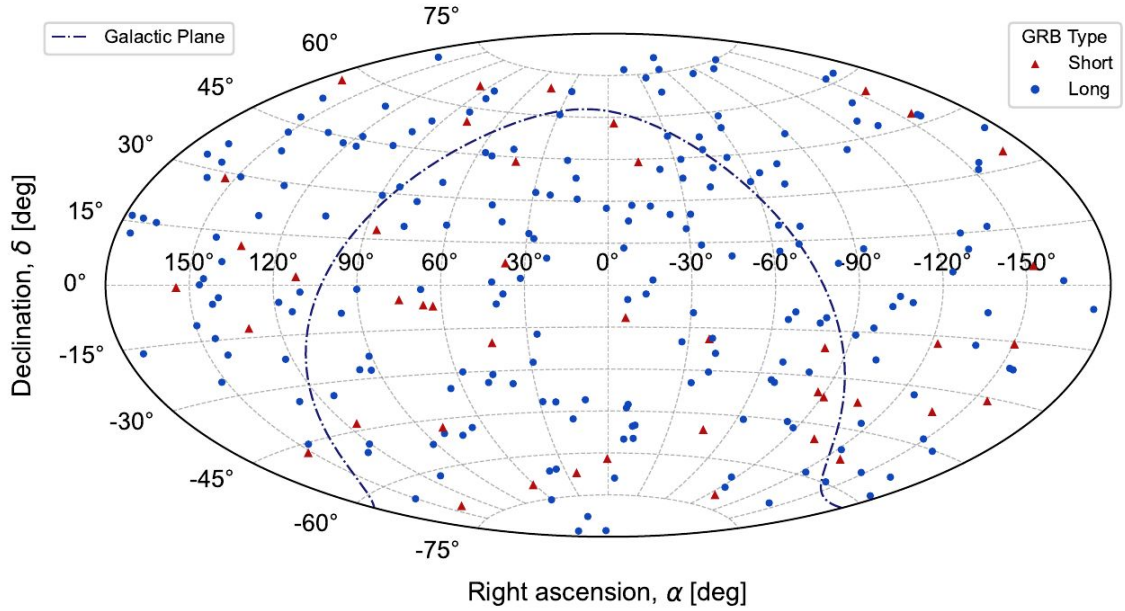


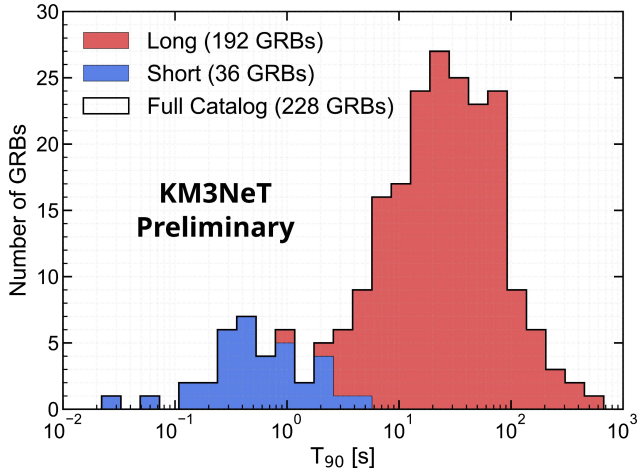
Stacking of GRBs

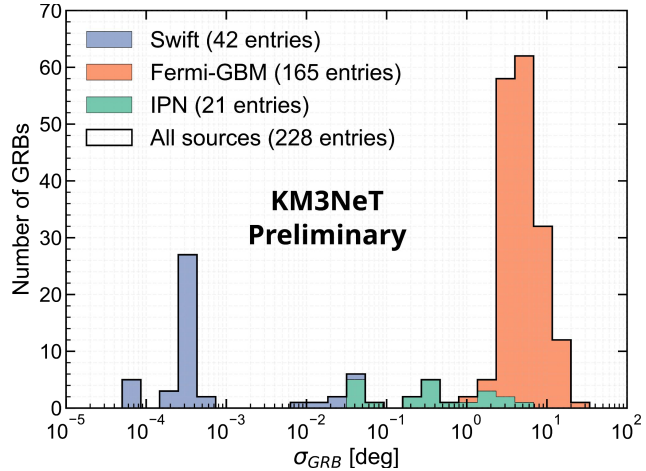
- **Objective:** Perform a stacking search for neutrinos in correlation with GRBs during the ARCA21 period.
- **Novelty:** First time that dedicated real-time tools are used with data including refined (e.g., dynamic positioning) calibrations.
- **GRB catalog:** constructed based on the data-taking period of ARCA21.
  - Livetime: 292.2 days (from 25/09/2022 to 11/09/2023).
  - Long/short selection based on duration and GCN information.
- **Search method:** binned ON/OFF technique (using KOAP).

Search time windows $T_{\mathrm{ON}} = \begin{cases} \text{Short GRBs:} & T_0 \pm 500 \text{ seconds} \\ \text{Long GRBs:} & T_0 \pm 1 \text{ day} \end{cases}$









Stacking of GRBs: results

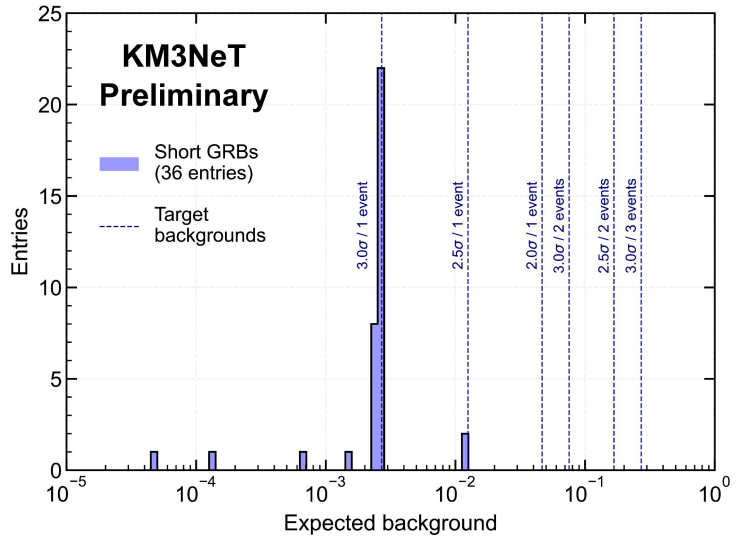
- **Stacking method:** background-rejection procedure.
- **Test Statistic** defined as the combination of p-values for each individual search by the Fisher's method:

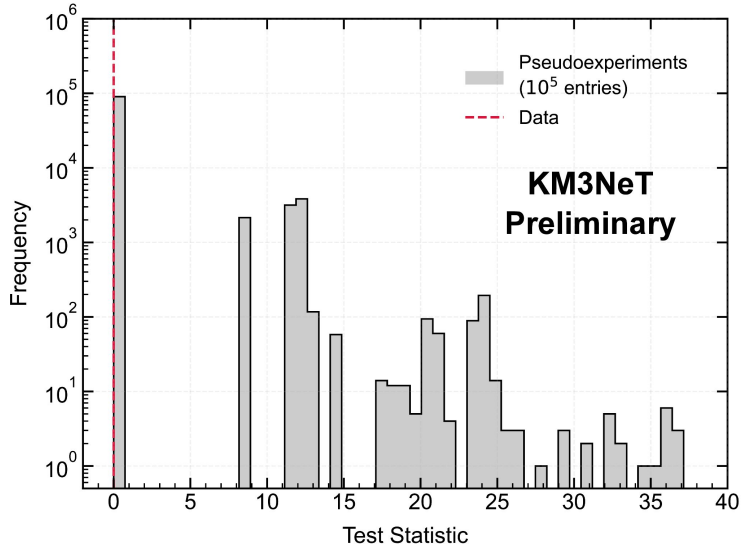
$$\mathrm{TS} = -2\sum_i \log(p_i)$$

- **Background compatible distributions** are determined from pseudo-experiments using random Poisson trials.
- **Final result:** significance of the observed data to deviate from the background-only hypothesis.
- **No significant excess** of candidate neutrino events has been observed coming from the populations of GRBs inspected.
- Check [Pos ICRC2025 1139]

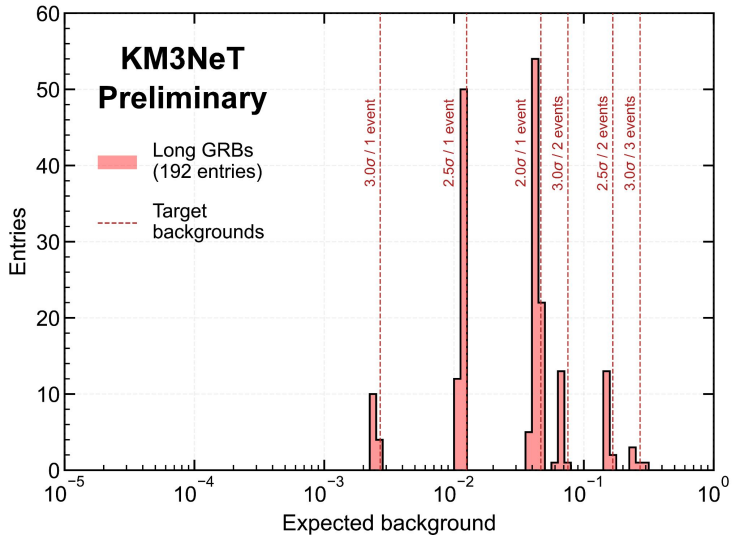
	TS	p-value	Most significant	Expected background	ON events	Pre-trial p-value	Post-trial p-value
SHORT	0.0	1.00	-	-	-	-	-
LONG	47.6	0.48	GRB230718A	0.29	2	0.034	0.68

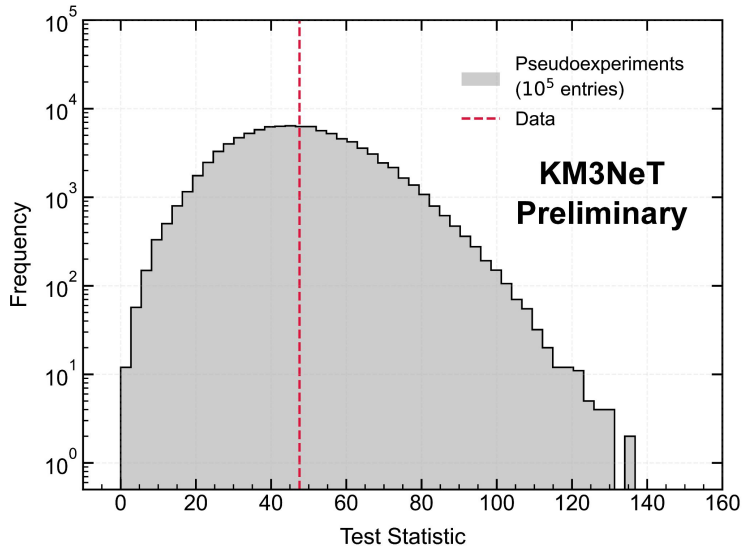
Short GRBs





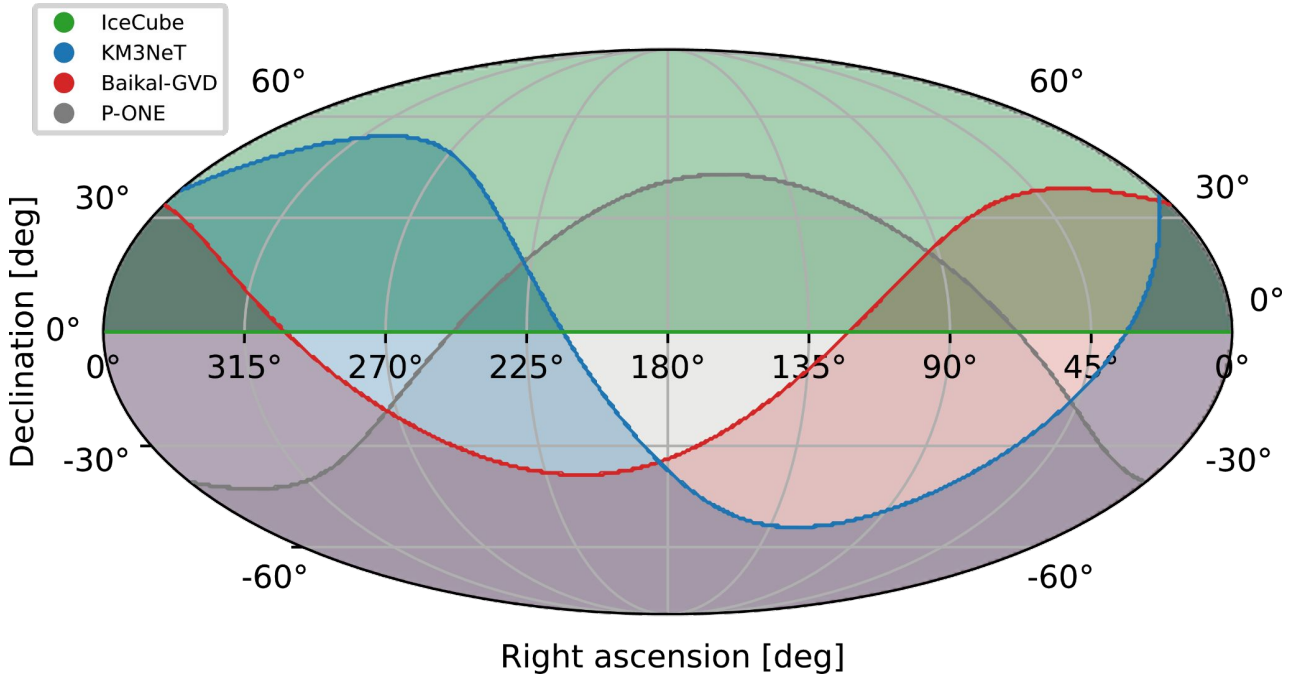
Long GRBs





Conclusions

- The **KM3NeT online platform is currently operational**, reconstructing ARCA and ORCA events in real time for multi-messenger activities.
- **Follow-up of external triggers**:
  - Based on a binned ON/OFF technique.
  - No significant candidate neutrino event has been found so far in coincidence with the external alerts received.
- **Stacking of GRBs during the ARCA21 period**:
  - First time that dedicated real-time tools are used including “offline” features.
  - No significant excess of candidate neutrino events has been observed.
- **The searches continue** while the size of the detectors increases.
- A **world-wide array of neutrino telescopes** doing real-time activities is crucial for a full-sky coverage.



Backup

KOAP: KM3NeT Online Analysis Pipeline

KM3NeT **O**nline **A**nalysis **P**ipeline

- Framework (python-package format) to run follow-up searches in spatial and time coincidence with the incoming alerts, and evaluate the significance of a detection based on the expected background.
- Modular: different time windows and event selections are inspected.

Orchestrator

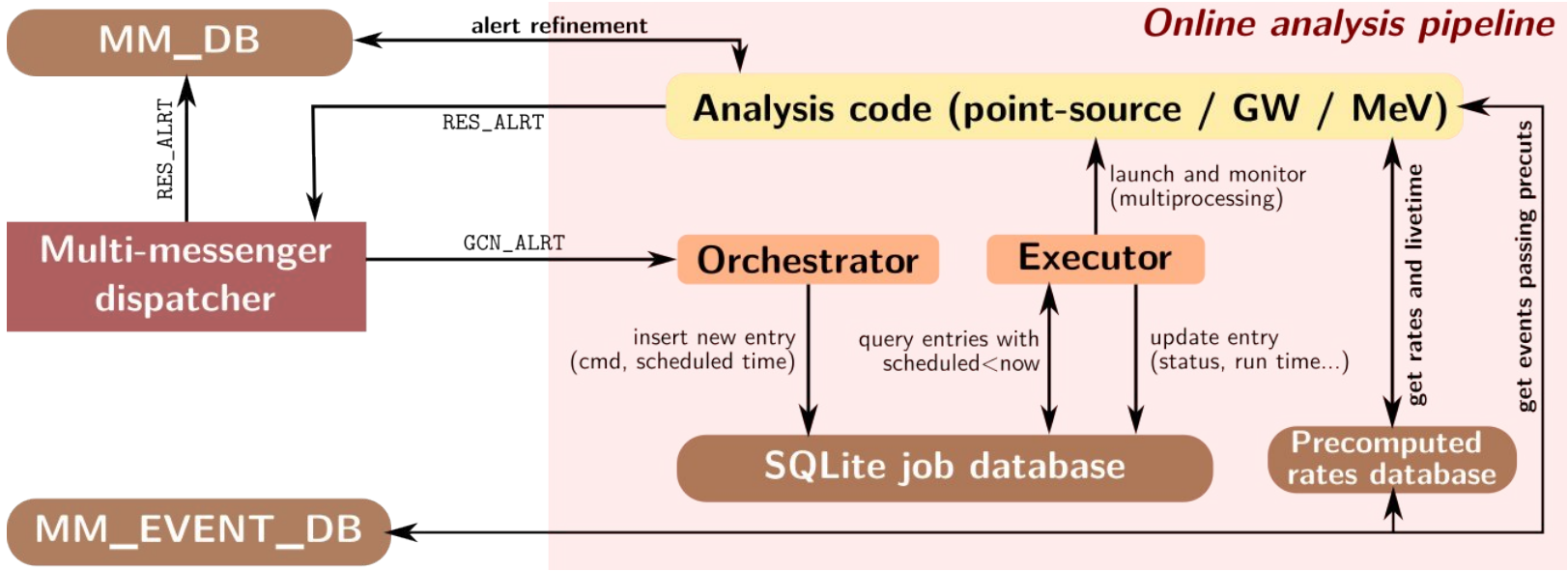
- Receives alerts.
- Check the analyses that should be triggered.
- Schedule the execution.

Executor

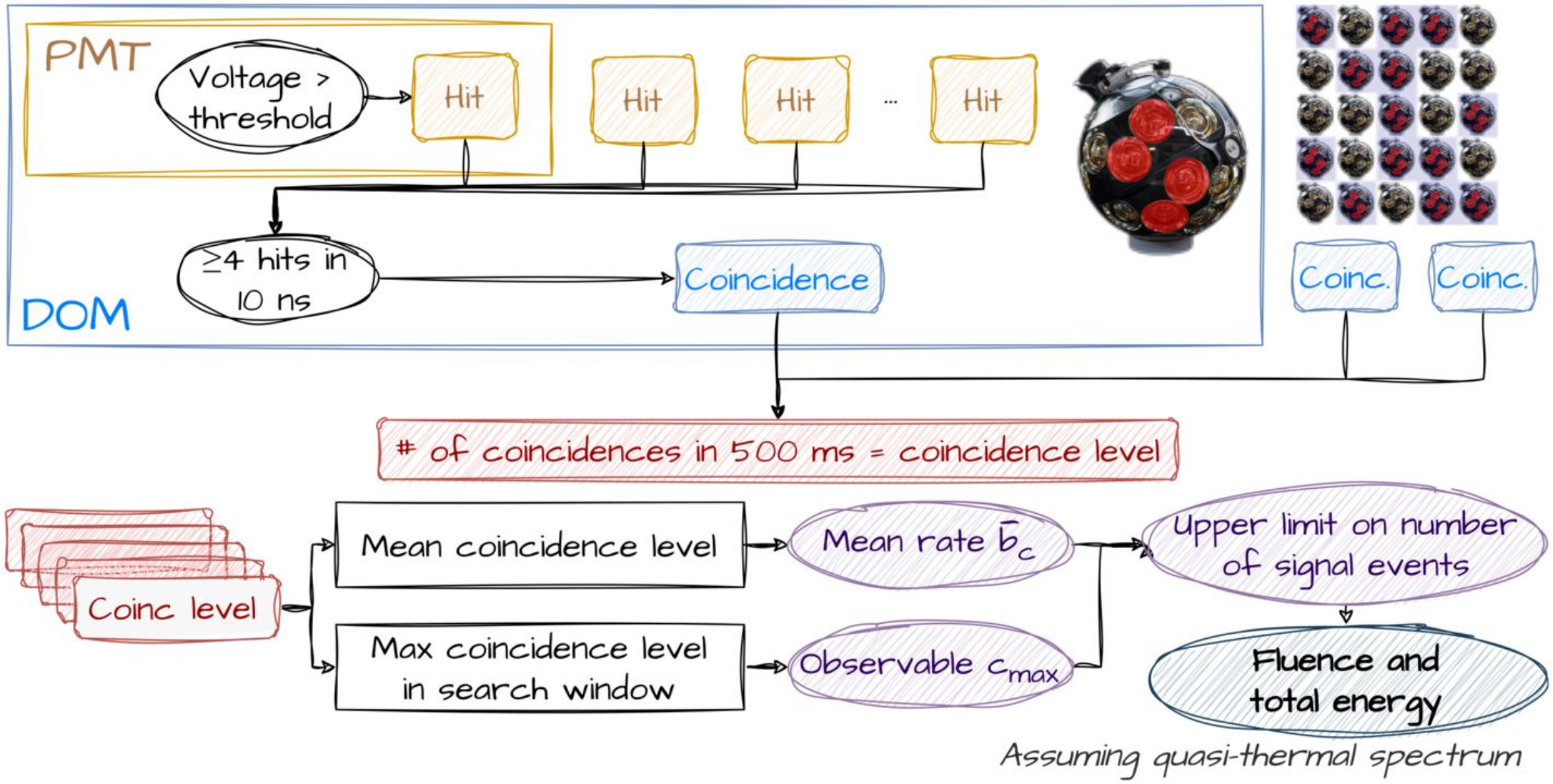
- Launch the analysis.
- Check the status.

Correlation analysis code

- Point-source (reco data)
  - GRB
  - Transient
  - Neutrino
  - FRB
  - µQuasar
- Extended search (reco data):
  - GW
  -
- MeV search (L0 data):
  - CCSN
  - GW

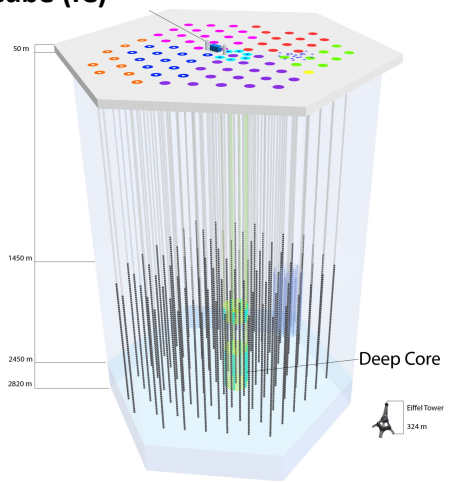


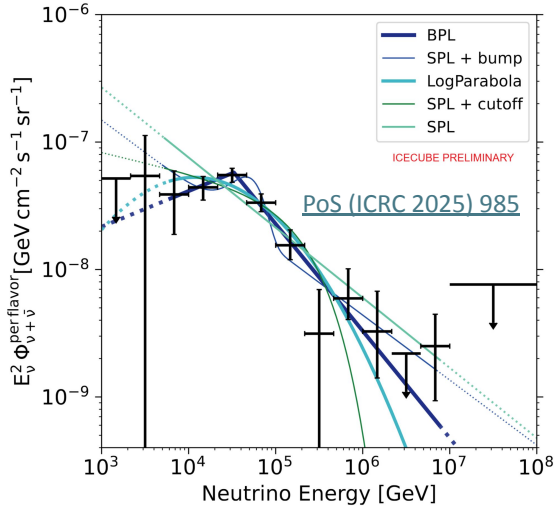
MeV searches

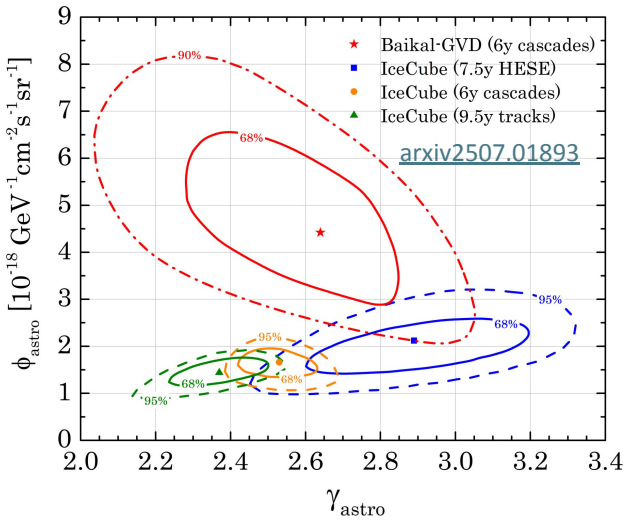


Neutrino astronomy

IceCube (IC)







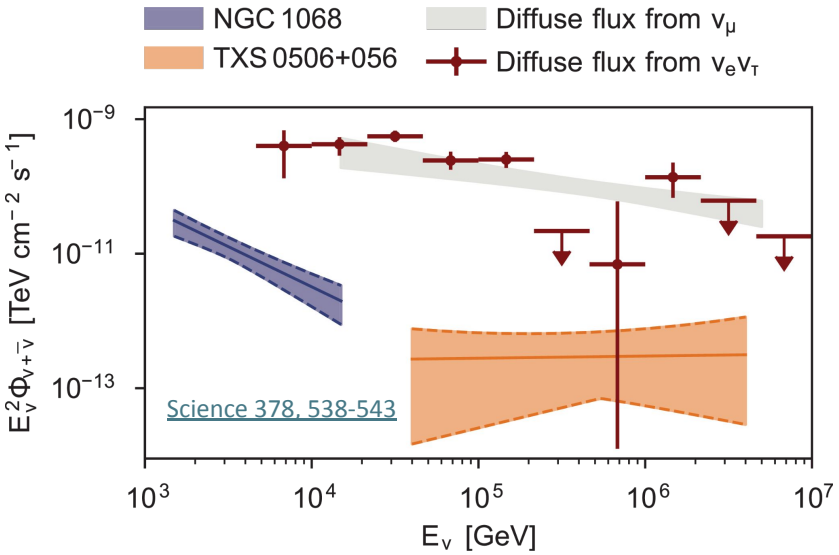
IC: Diffuse cosmic neutrino flux

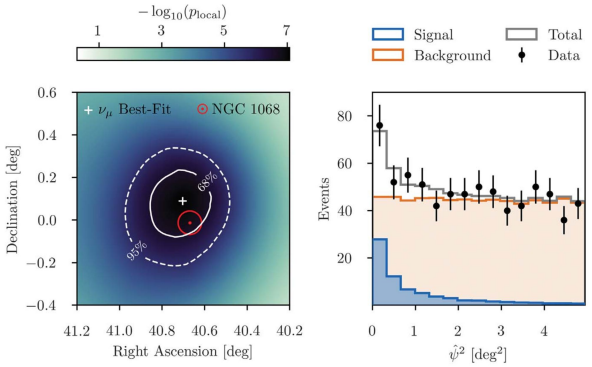
2013: *4σ*. Energy: 30 TeV - 1.2 PeV.

Tension between different datasets

Single power law excluded at *4σ*

Baikal-GVD: Hint for diffuse cosmic neutrino flux 2025





IC: First potential neutrino point sources

2017, real time

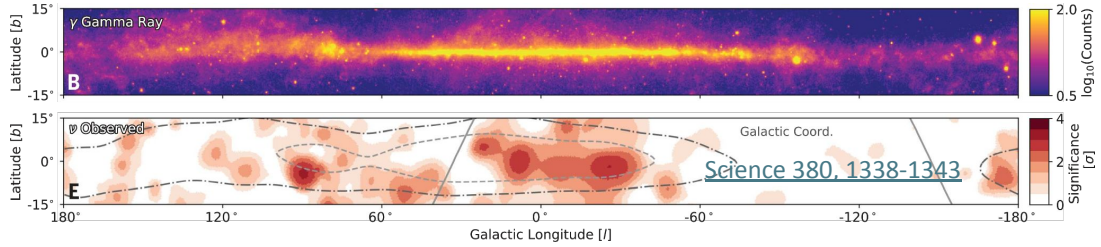
TXS 0506+056: *3.5σ*

2022, time integrated

NGC 1068: *4.2σ*

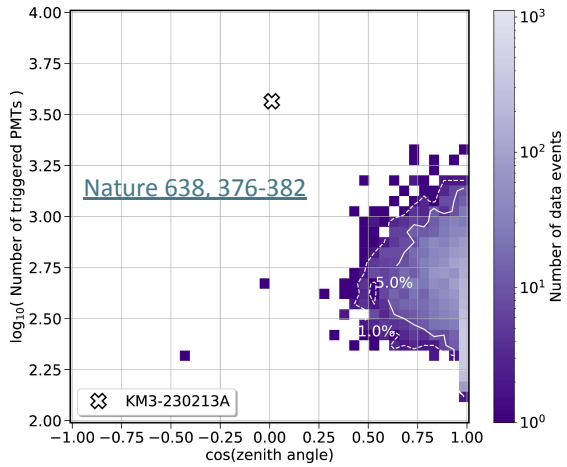
IC: Neutrinos from the GP

2022: *4.5σ*



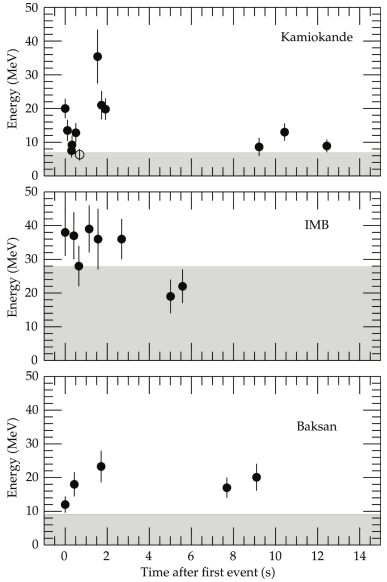
KM3NeT/ARCA: Observed a UHE neutrino event. 2023. Unknown origin. Cosmogenic?

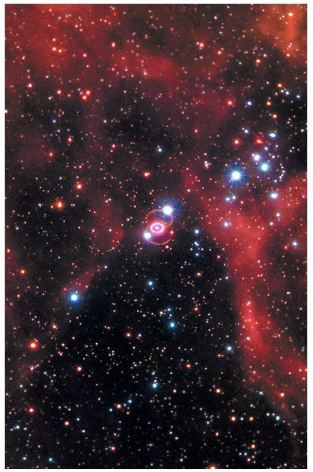
72 PeV - 2.6 EeV 90% CL



Multi-messenger milestones

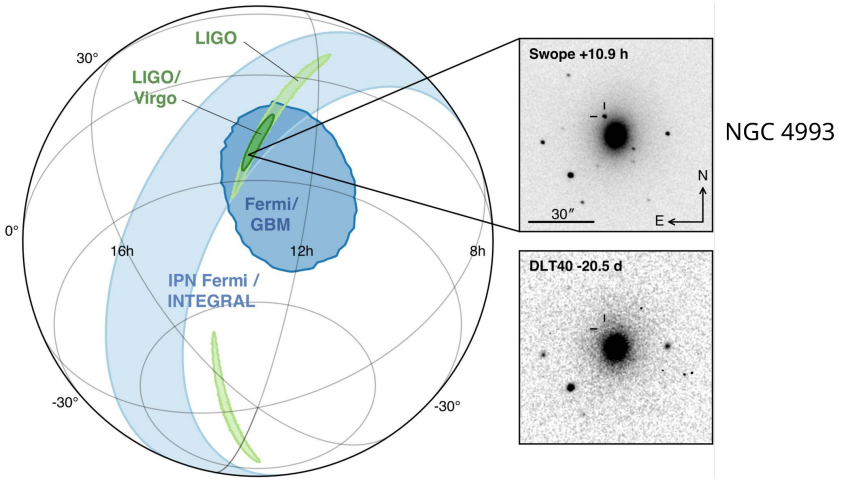
The supernova explosion SN1987A (February 1987)





- **Neutrino** detection (~10 MeV) prior to the **electromagnetic signal** observed.
- **Implications**: exact time for SN explosion; energy release estimations and time distributions in well agreement with theory.
- **Open questions:** compact object remnant not yet observed; blue supergiant precursor; formation of the hourglass-shape nebula.

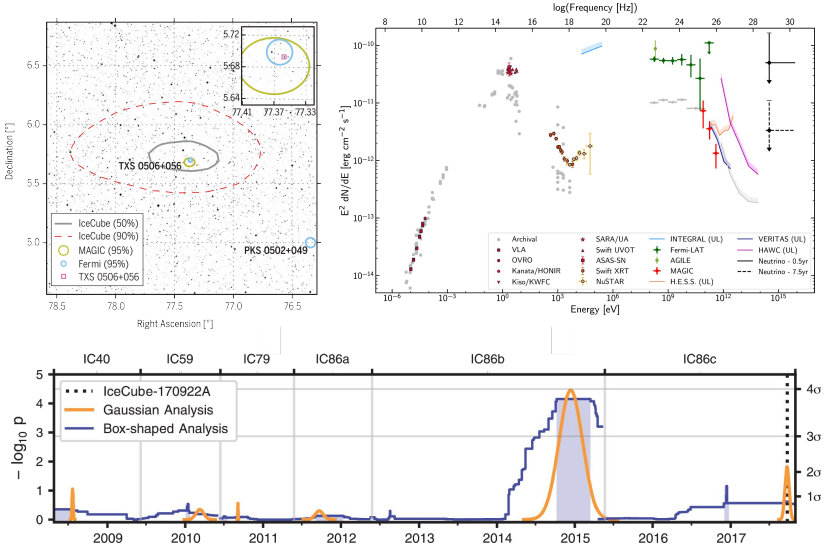
The binary neutron star merger GW170817 (August 2017)



NGC 4993

- **GW** detection coincident with the **electromagnetic signal** from a short GRB.
- **Implications**: first direct observation of a kilonova; heavy elements nucleosynthesis confirmed; first direct relation between the merger of compact objects and short GRBs.
- **Open questions:** no neutrinos detected; nature of the remnant; jets from neutron star mergers.

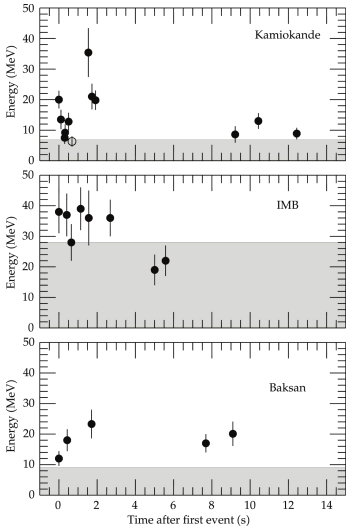
The blazar TXS 0506+506 (September 2017)

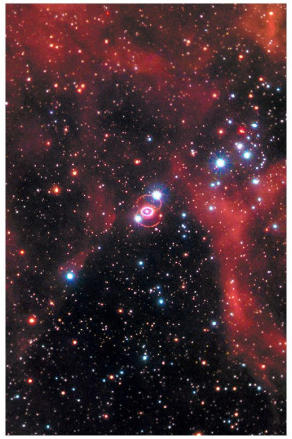


- **Gamma-ray emission** (Fermi, MAGIC) observed in coincidence with a cosmic **neutrino** alert (~290 TeV) from IceCube.
- **Implications**: identification of a prior neutrino excess in the same direction; first potential neutrino source identified.
- **Open questions:** blazars as potential neutrino sources; neutrino emission mechanism in AGNs: jet vs corona.

Multi-messenger milestones

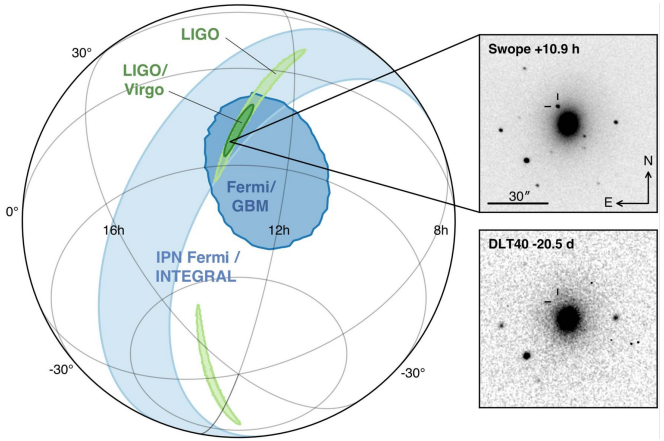
The supernova explosion SN1987A (February 1987)





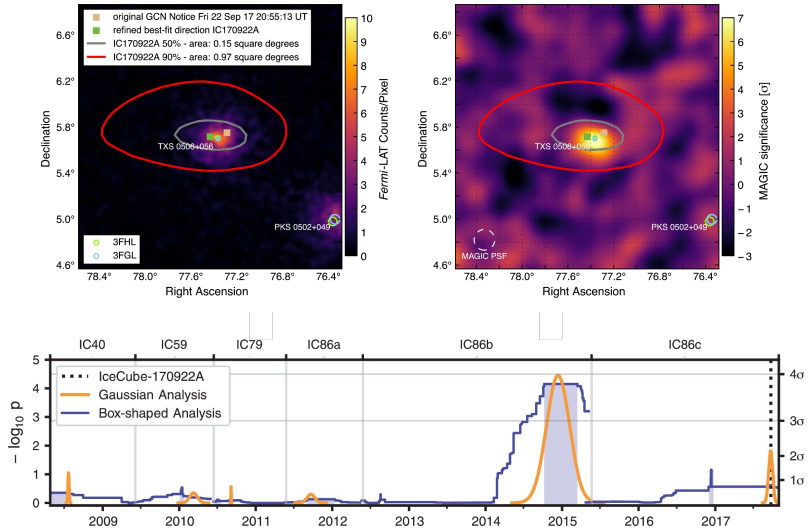
Neutrino detection (~10 MeV) prior to the **electromagnetic signal** observed.

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.

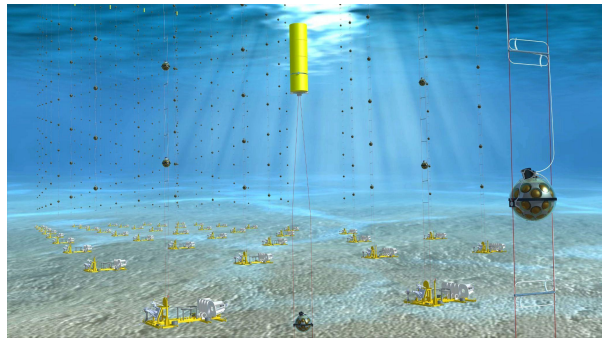
An online context

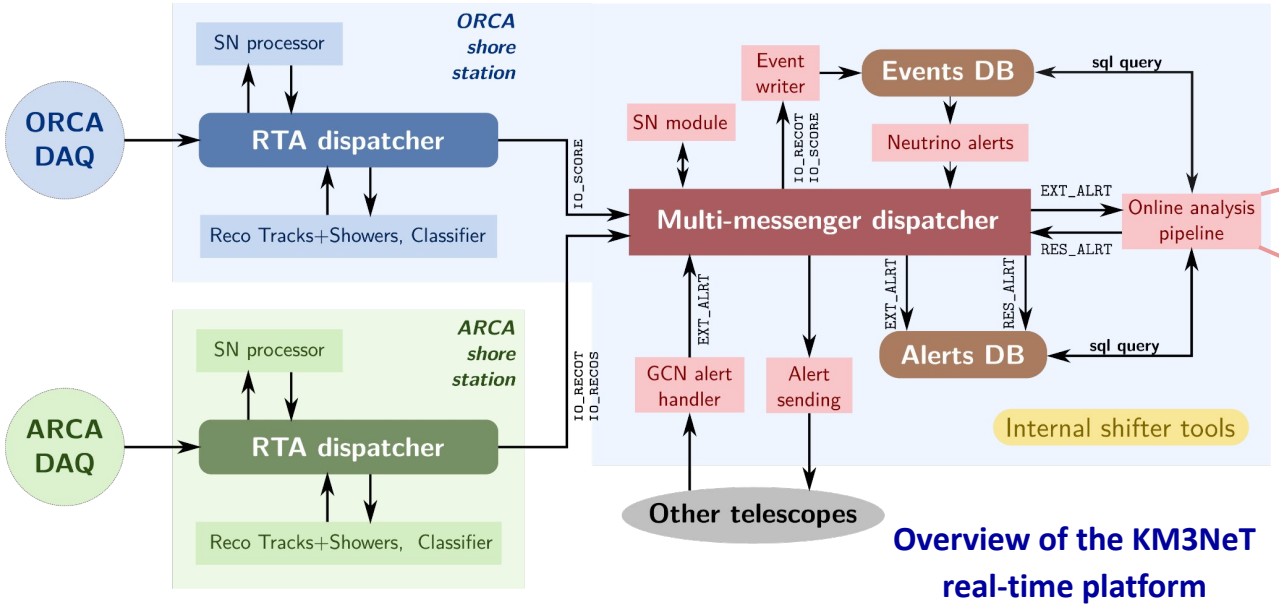
The multi-messenger community

Follow-up of external triggers
Ongoing since early 2023.

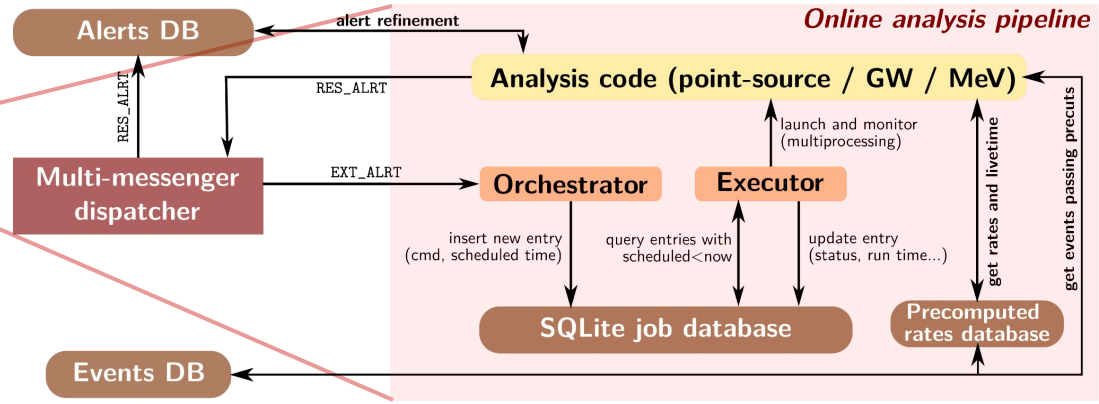
Neutrino alert sending.
Under final development. Expected in 2026.

KM3NeT



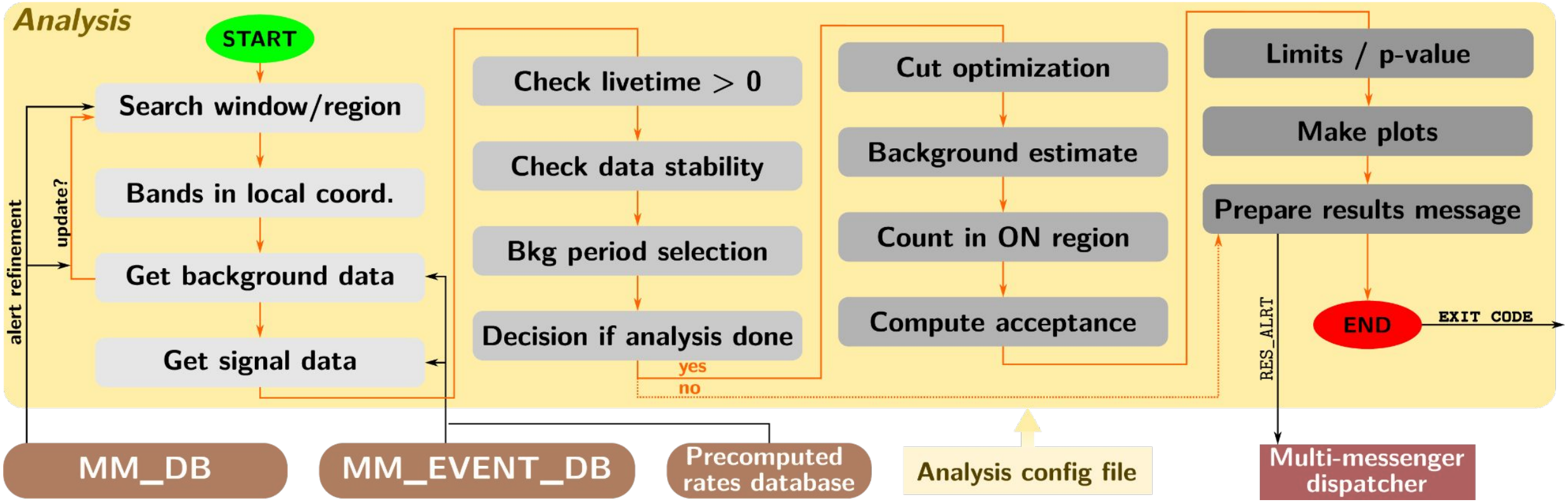


Overview of the KM3NeT real-time platform



KOAP: KM3NeT Online Analysis Pipeline

KOAP in detail



Thesis Figure 6.9

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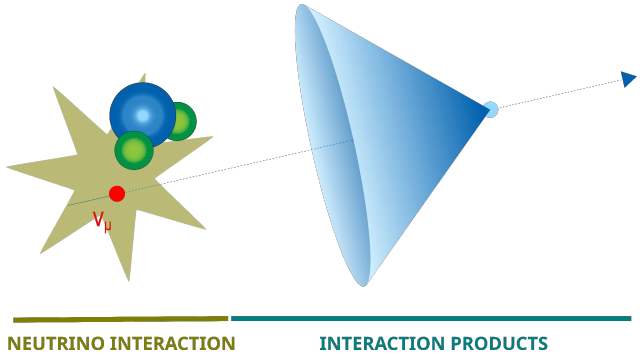
High-energy neutrino detection

⇒ Neutrinos interact with matter via the **weak fundamental force**.

WORKING PRINCIPLE OF A NEUTRINO TELESCOPE

1. **Neutrino interaction**
2. **Cherenkov radiation**
3. **Light propagation**
4. **Event reconstruction**



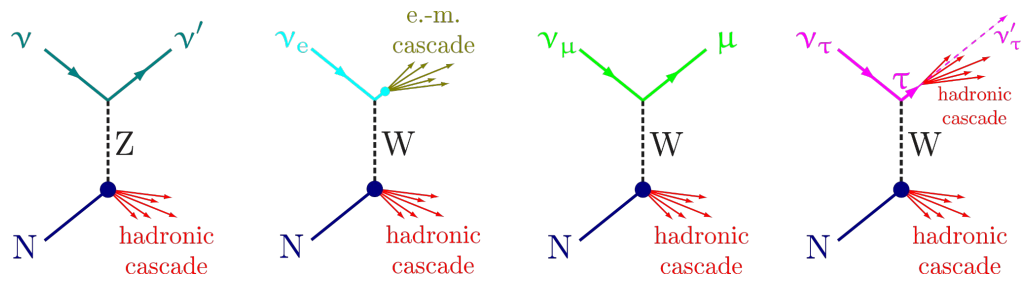
1. Neutrino interaction

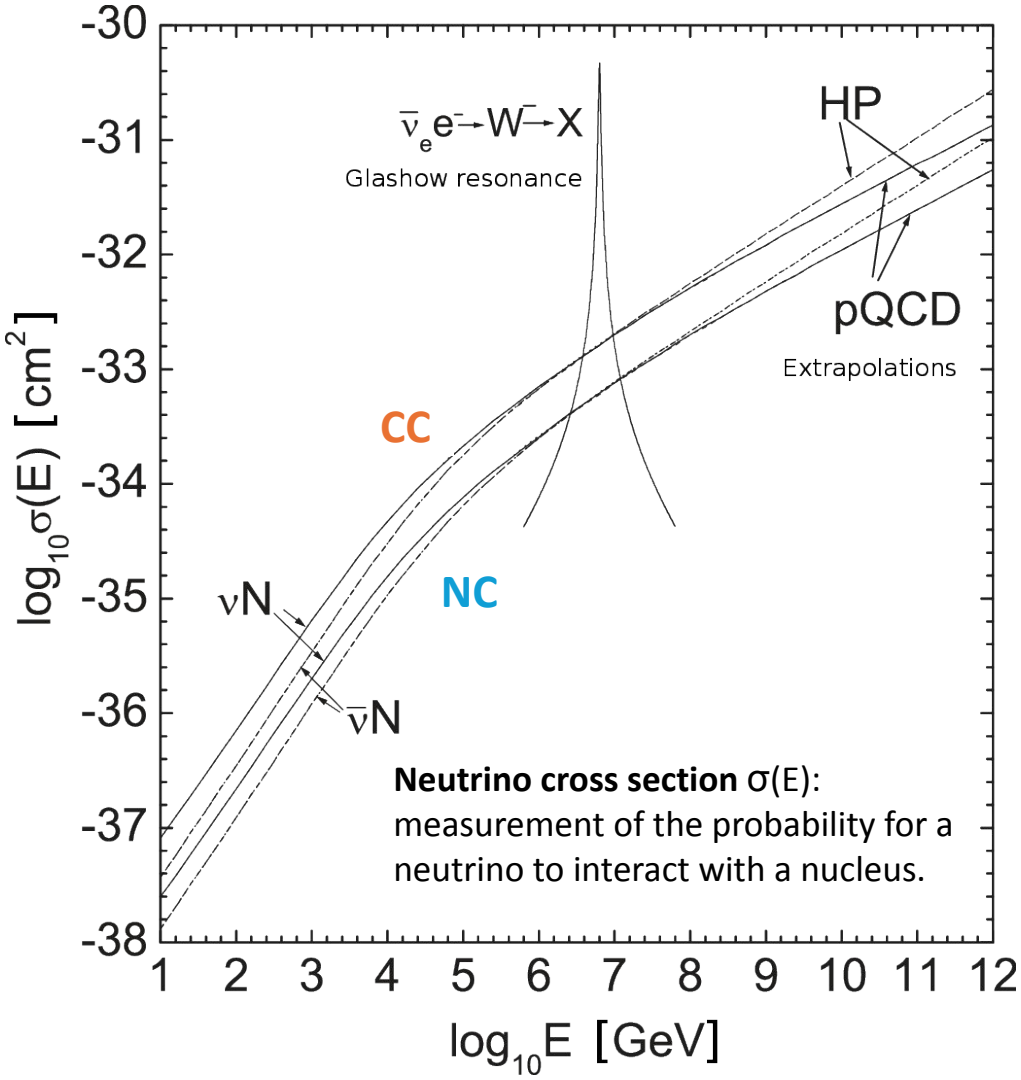
- **Charged-current interactions (CC)**:

$$\nu_l + N \rightarrow W^- \rightarrow l^- + X \qquad \bar{\nu}_l + N \rightarrow W^+ \rightarrow l^+ + X$$

- **Neutral-current interactions (NC)**:

$$\nu_l + N \rightarrow Z^0 \rightarrow \nu_l + X \qquad \bar{\nu}_l + N \rightarrow Z^0 \rightarrow \bar{\nu}_l + X$$





Neutrino cross section σ(E): measurement of the probability for a neutrino to interact with a nucleus.

High-energy neutrino detection

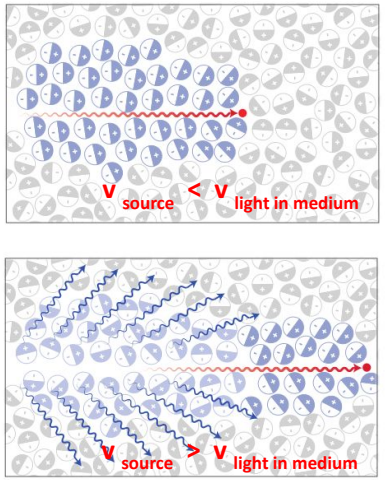
⇒ Neutrinos interact with matter via the **weak fundamental force**.

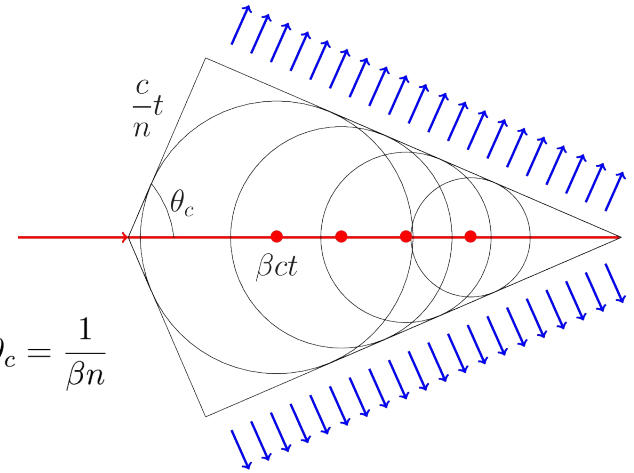
WORKING PRINCIPLE OF A NEUTRINO TELESCOPE

1. **Neutrino interaction**
2. **Cherenkov radiation**
3. **Light propagation**
4. **Event reconstruction**

2. Cherenkov radiation

Charged particle traversing a dielectric medium with **velocity larger than the speed of the light in that medium: Constructive interference** of the light emitted by the displaced electrons.





$$\cos\theta_c = \frac{1}{\beta n}$$

3. Detection of the light after its propagation

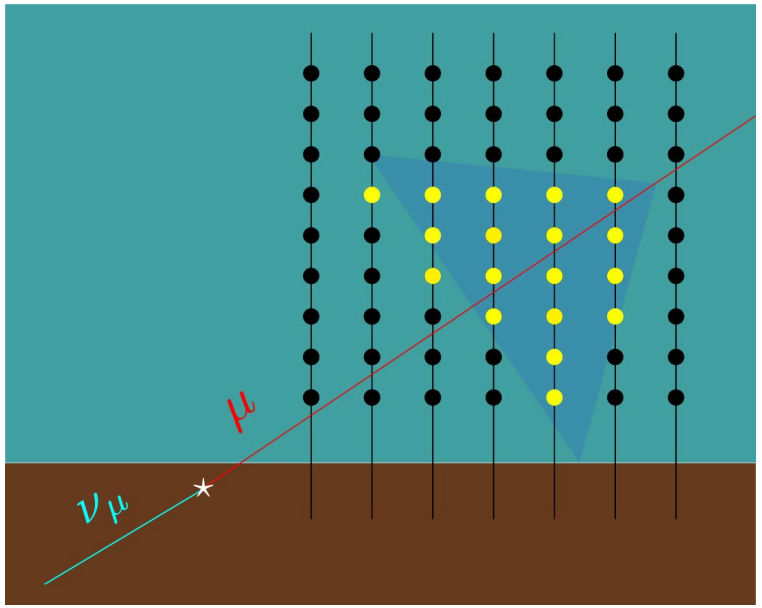
Requires to use a **large transparent medium**.

Unique feasible choice: **natural media**.

Photomultiplier tubes (PMTs)

31 PMTs in each DOM

Digital Optical Module (DOM)



4. Event reconstruction

"Neutrino event"

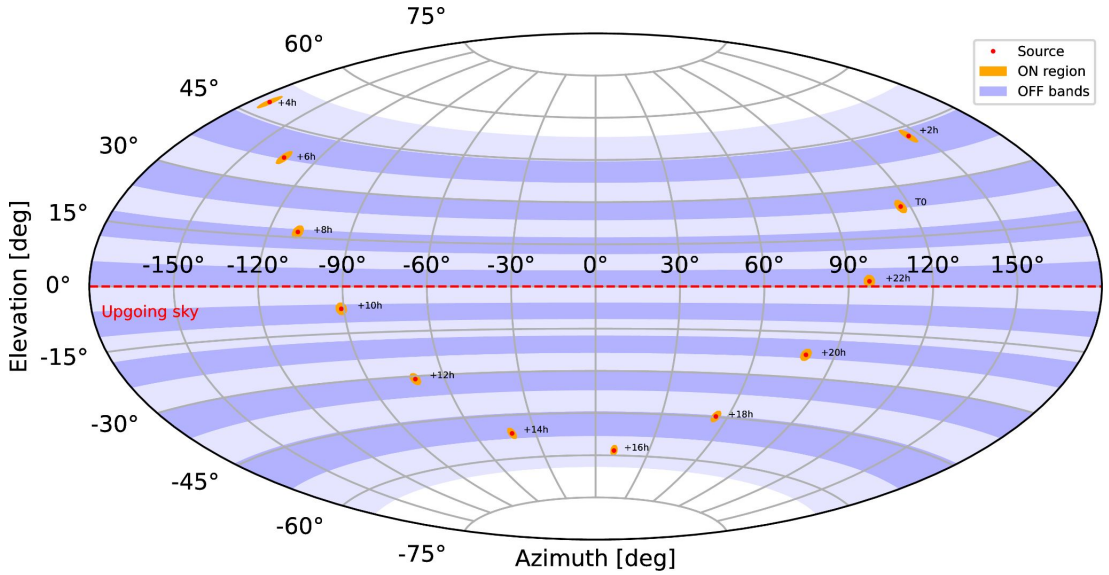
- Arrival time.
- Incoming direction.
- Estimated energy.
- Neutrino flavour.

etc.

Procedure to infer the physical properties of an event based on the **light pattern** observed in the detector.

KOAP: KM3NeT Online Analysis Pipeline

- **ON region**: where the signal is expected. It includes the alert location error + angular uncertainty of the detector:
  - Currently (conservatively): 2° for ARCA, 4° for ORCA.
- **OFF region**: local zenith bands to determine the expected background, spanning the ON region movement due to Earth's rotation.
- **T_{ON}**: multiple time windows inspected depending on alert type.
  - GRB and FRB: $T_0 \pm 500$ s, $T_0 \pm 1$ h, $T_0 \pm 1$ d
  - NEUTRINO: $T_0 \pm 1$ h, $T_0 \pm 1$ d
  - GW: $T_0 \pm 500$ s, [T_0 - 500 s, T_0 + 6 h]
  - TRANSIENT: trigger duration (min 500 s), $T_0 \pm 1$ day.
  - MICROQUASAR: trigger duration (min 500 s)
- **T_{OFF}**: up to two weeks of previously taken data.
- **Event selection optimization**:
  - Fixed "precuts" + elevation-dependent selection in a concrete reconstruction variable.
  - "*n*sigmas-*m*events" procedure: reduce as much as possible the expected background, without large statistical uncertainties.
- **Main final result**: p-value (pre-trial). Also possibility to compute ULs.



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

$$n_{\text{bckg}} \leq \alpha \qquad \sigma(n_{\text{bckg}})/n_{\text{bckg}} < 30\%$$

$$\sigma(N^i_{\text{OFF}})/N^i_{\text{OFF}} < 50\%$$