From ANTARES to KM3NeT online analysis platform

DAMIEN DORNIC (CPPM)
MATHIEU LAMOUREUX (CP3)

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Overview

1. Legacy of the ANTARES online analyses
2. The KM3NeT online system
3. First results of the online analyses performed with KM3NeT

Multi-messenger follow-ups

Given the current statistics-limited samples of astrophysical neutrinos, one of the most optimum analysis strategies is to:

- **Alerts to community upon detection of likely « astrophysical » neutrinos for rapid follow-ups**
- **Real-time searches for neutrino signals in response to transient events observed in other messengers**

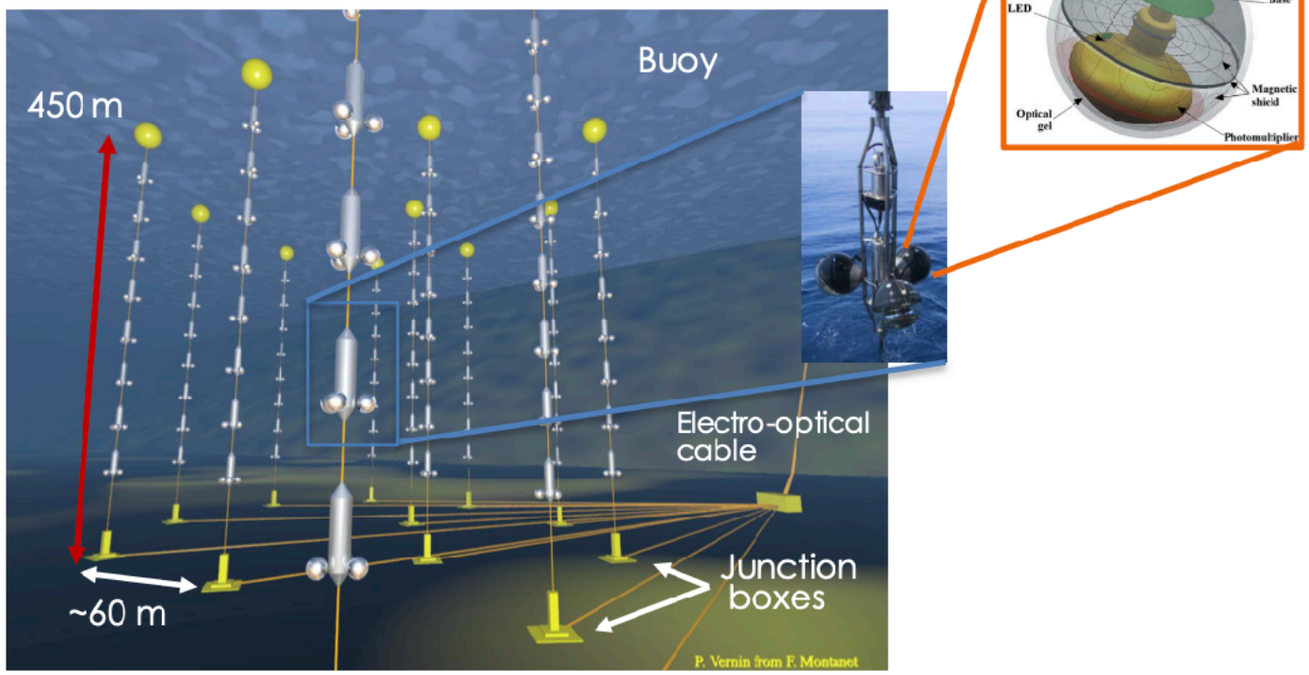
These observations can:

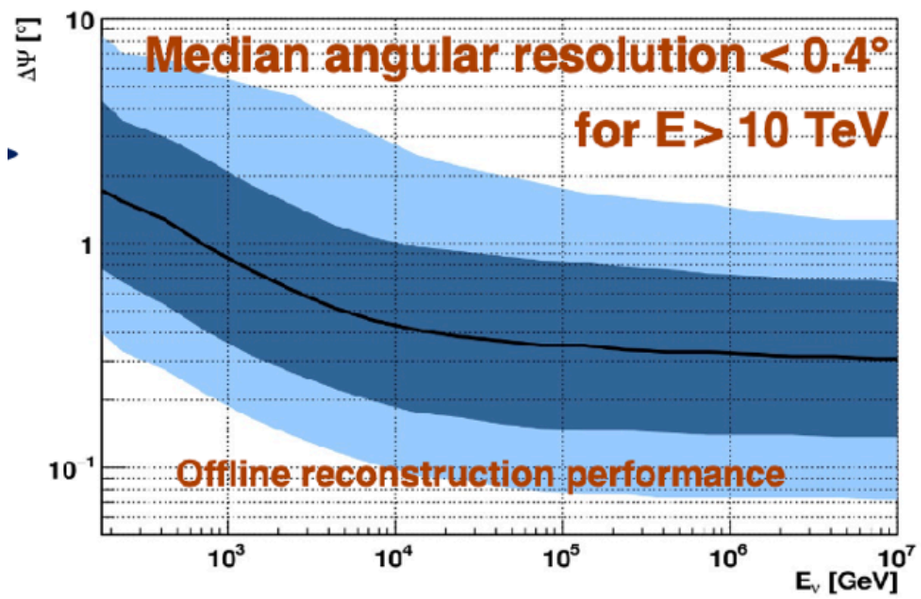
- **Strengthen or refine detections made in single messenger**
- **Probe source dynamics and populations, even in the absence of signal**
- **Identify the sources of the observed high-energy astrophysical neutrinos**

ANTARES neutrino telescope

- 2475m depth in the Mediterranean Sea
- 40 km offshore Toulon
- First detection line installed in early 2006
- **Completed in 2008**
- **Decommissioned in 2022**

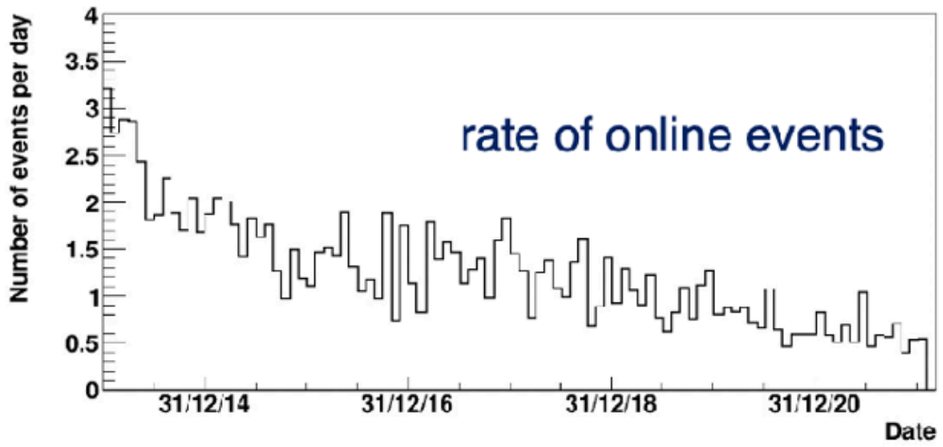
- 3D array of 885 PMTs (10”)
- 12 vertical lines
- Instrumented volume ~0.01 km^3



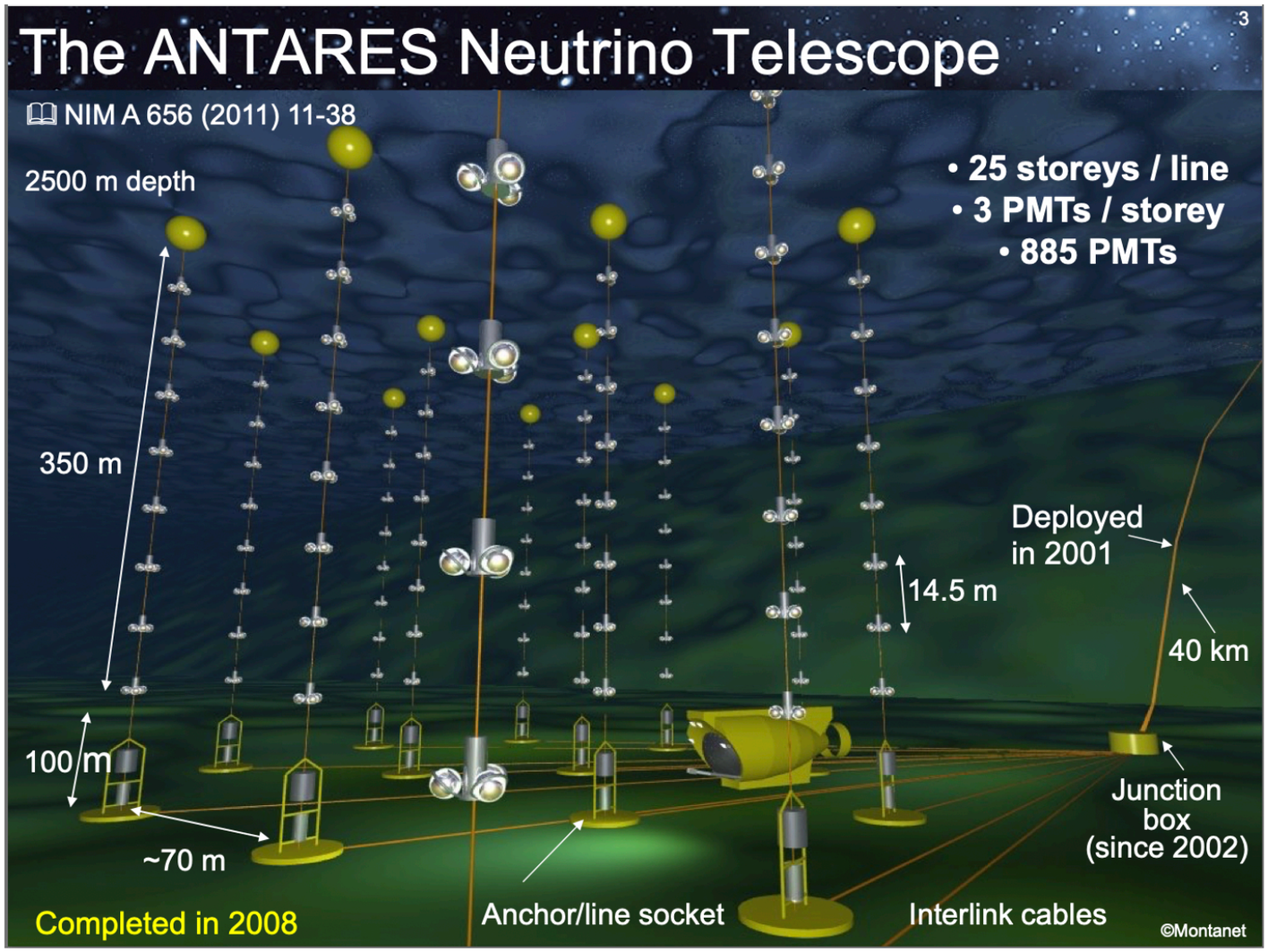


ANTARES sample for online analyses:

- Up-going tracks, good reconstruction quality
- → **0.5° median angular resolution**
- → **<10% muon contamination**



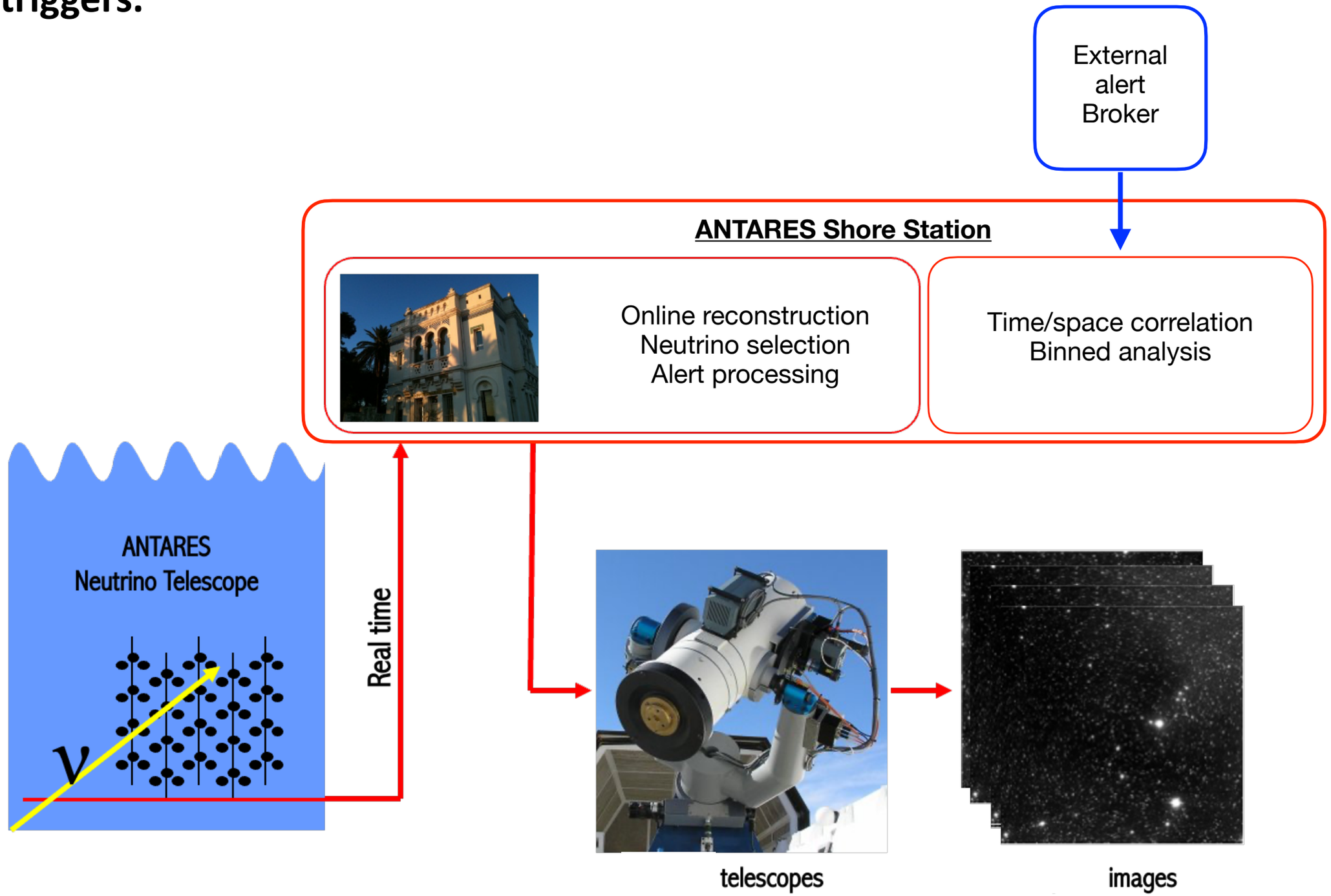
End of the ANTARES adventure



⟹ **ANTARES: continuous data-taking between 2007-2022 with very high efficiencies**
⟹ **ANTARES has been switch off in Feb 2022 and full recovery of the materials in June 2022.**
⟹ **Very competitive physics results. Legacy analyses still in progress. All the data will become public soon.**
⟹ **KM3NeT adventure**

Real-time analysis platforms

ANTARES and IceCube have implemented in 2008-9 a real-time analysis platform that triggers neutrino alerts and that performs time/space correlation analysis for external triggers.



Real-time analysis platforms

Online follow-up performed quickly after the reception of the external triggers using simple cut&count analysis method (pure-data driven):

- Follow-up of IceCube neutrino alerts

ANTARES has received 115 neutrino triggers from the IceCube alert system and has followed 37 alerts (7 HESE, 3 EHE, 10 gold and 17 bronze).

- Follow-up of LIGO/Virgo gravitational wave alerts

ANTARES has followed all the LIGO/Virgo alerts in real time (15 GWs in o2 & 51 in o3)

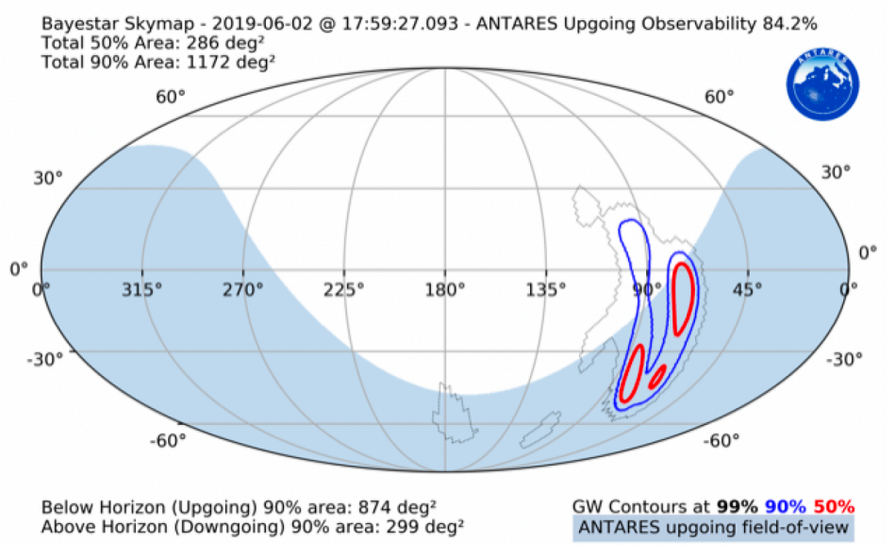
- Follow-up of gamma-ray bursts

ANTARES has followed 317 Swift and 770 Fermi-GBM between 2014 and 2022

- Follow-up of HAWC alerts for transient phenomena

ANTARES has followed 7/22 HAWC transient alerts

+ Development of combined HAWC+ANTARES searches within AMON

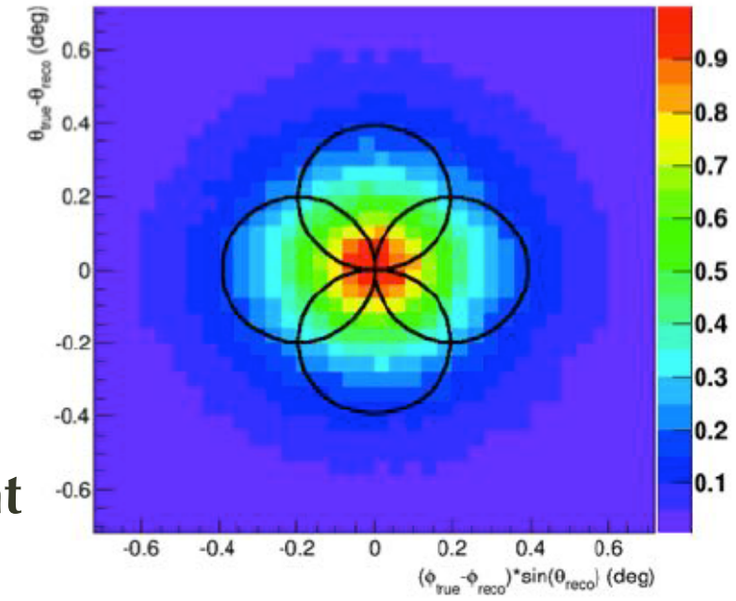


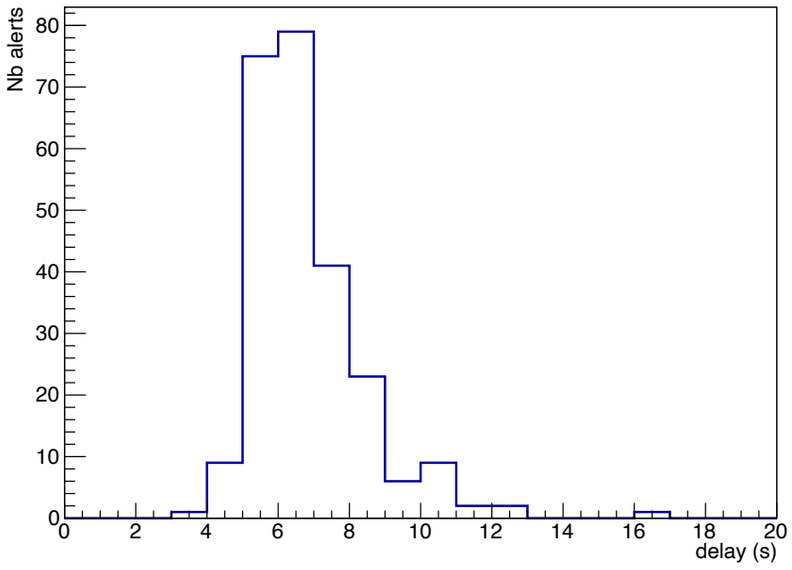
Legacy for ANTARES neutrino alerts

Triggers:

* Doublet of neutrinos: ~0.04 event / yr.
* Single neutrino with direction close to local galaxies: ~1 TeV, ~10 events / yr.
* Single HE neutrinos: ~7 TeV, ~15 event / yr
  - => Sub-sample HE neutrinos: ~5 TeV, 20 events / yr
  - => Sub-sample VHE neutrinos: ~30 TeV, ~3-4 events / yr.

ANTARES PSF : ~0.4° (median)





Alert message sent via the GCN using either GCN socket / VO Event

⟹ Average delay: ~6-7 s

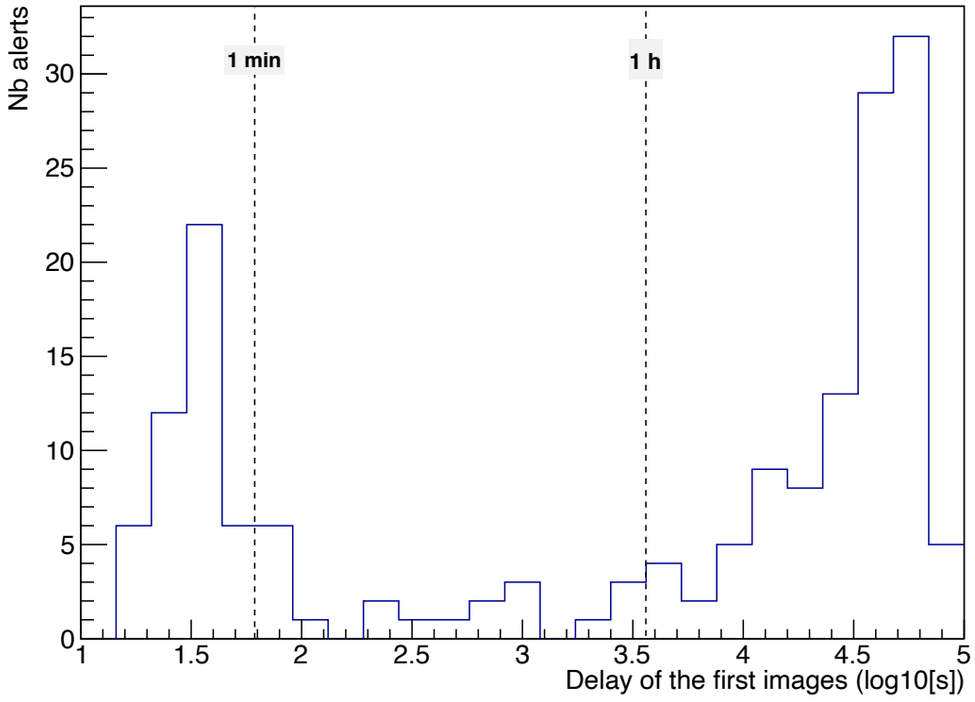
Private alert except if a potential counterpart is founded

Delays between the time of 1st image and the neutrino trigger

⟹ 218 alerts < 1 day

⟹ 55 alerts < 1 min

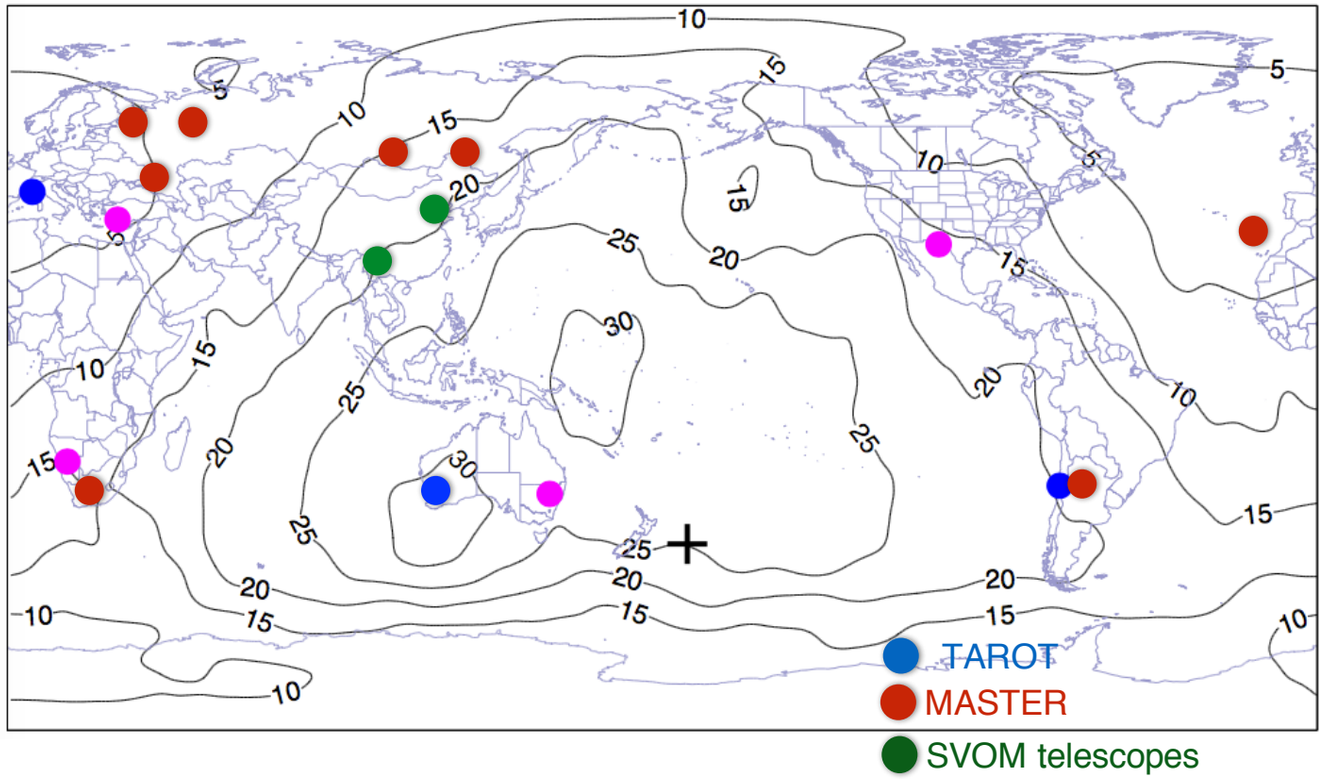
(wait for the alert visibility, stop previous acquisition, point the telescope, start the acquisition)



ANTARES, Astroparticle Physics, 2012, 35 (8)

ANTARES follow-up partners

Efficiency of prompt observations vs location on the Earth



ANTARES policy: all alerts are private (data exchange upon MoU). Only if a potential counterpart is found, the alert becomes public for further observations

Robotic telescopes: ~68% efficiency with observations within 24h [early] and ~70% for late follow-up [long]
=> Main limitations: weather, alert direction too close to the Sun/Moon/Galactic plane

Swift XRT: ~70% follow-up efficiency
=> Main limitations: alert direction too close to the Sun/Moon/Galactic plane, ToO not accepted

Lessons from the ANTARES follow-up

Key points to be improved:

- Important to have all-flavor neutrino reconstruction and classifier
- Reduce the systematics on the angular direction of the alerts (good control of the pointing accuracy)
- Private / public neutrino alerts (how to optimize the follow-up)
- Uniformise the alert format: only VO event

- Increase the scientific interest of the neutrino alerts (provide more astro content)
- Automatize the astro counterpart search directly at the alert level (crossmatch catalogs, LC…)

- Automatize the real-time correlation analyses as much as possible
- Have a real organized team to manage the online analyses, not only a few persons. Reinforce the MWL follow-up expertise in the collaboration. Provide some centralized tools for the shifters

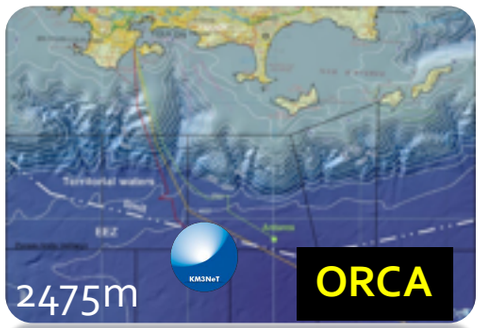
⇒ Based on this return of experience, we have built the KM3NeT online analysis platform.

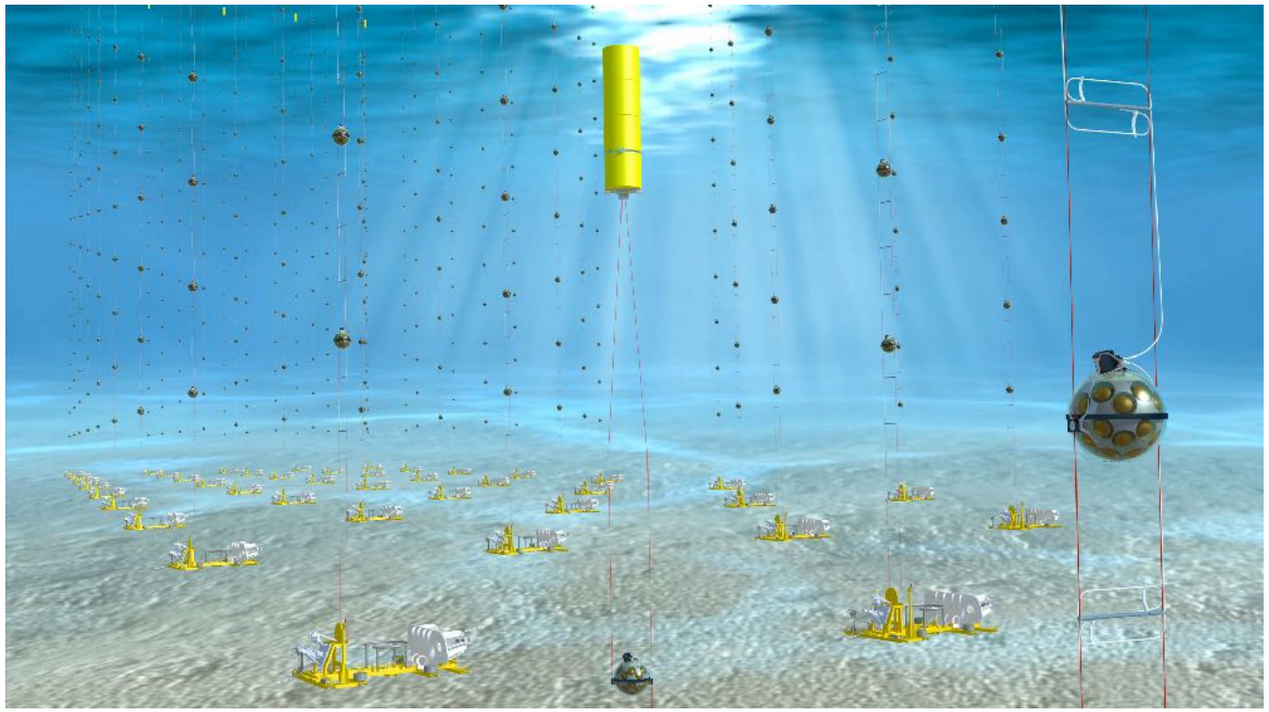
KM3NeT

KM3NeT is the neutrino research infrastructure in the deep Mediterranean Sea

Oscillation **R**esearch with **C**osmics In the **A**byss

ORCA: off shore Toulon, France



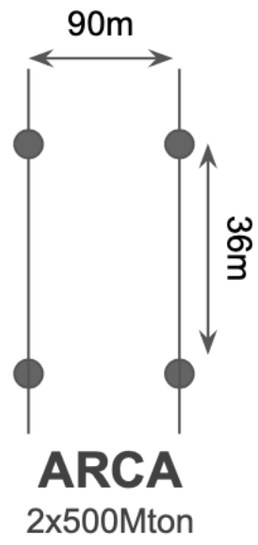


Astroparticle **R**esearch with **C**osmics In the **A**byss

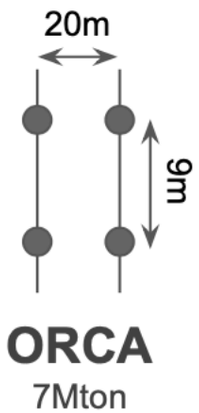
ARCA: off shore Capo Passero, Italy

Main characteristics:

- Extended energy range: 1 GeV → 10 PeV (+ 10-40 MeV)
- Full sky coverage with the best sensitivity for the galactic sources
- High duty cycle (> 95%)
- All-flavor neutrino detection
- Good angular resolutions



230 DUs, 128340 PMTs

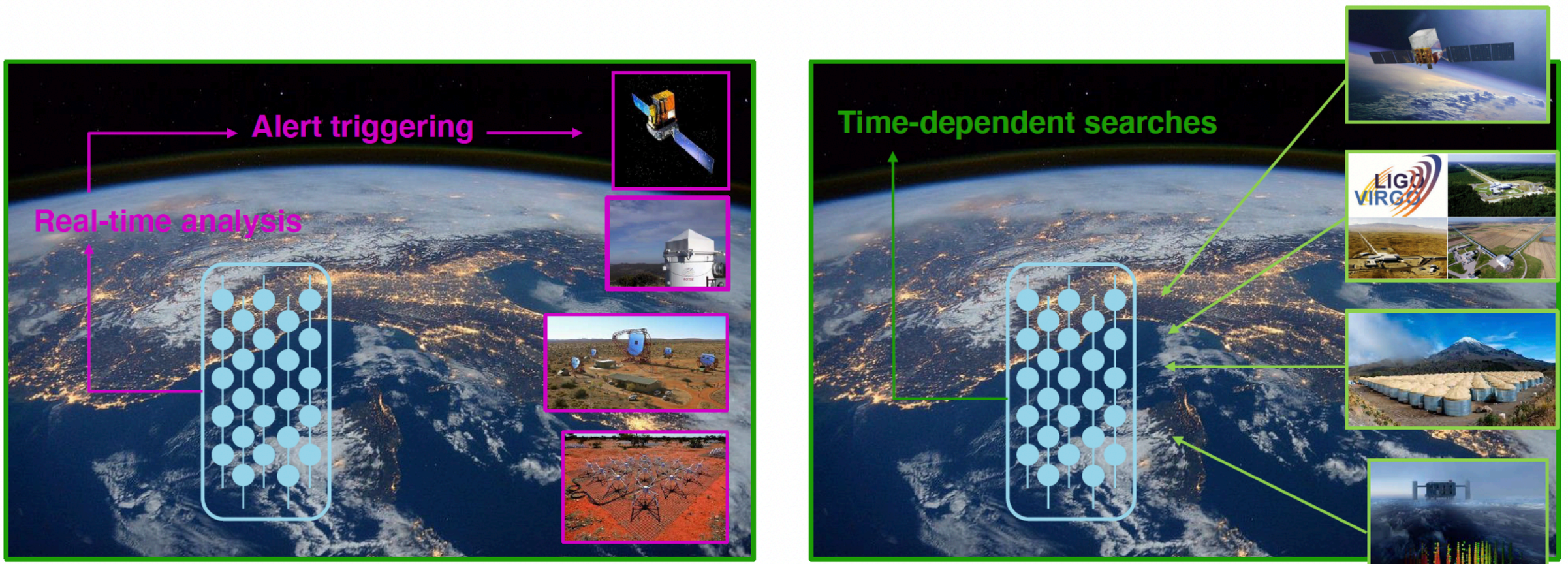


115 DUs, 64170 PMTs

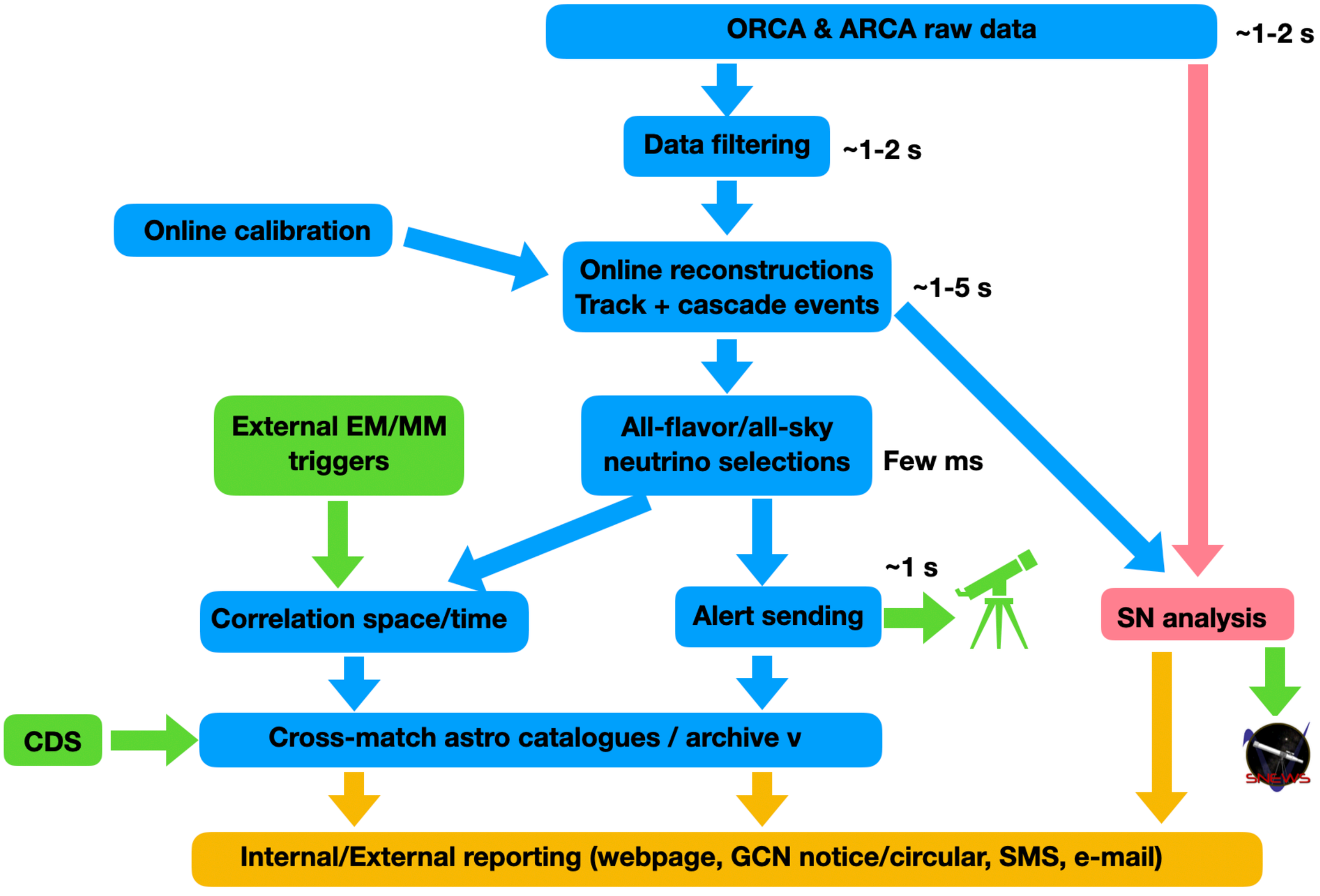
KM3NeT online physics framework

5 **main functionalities**:

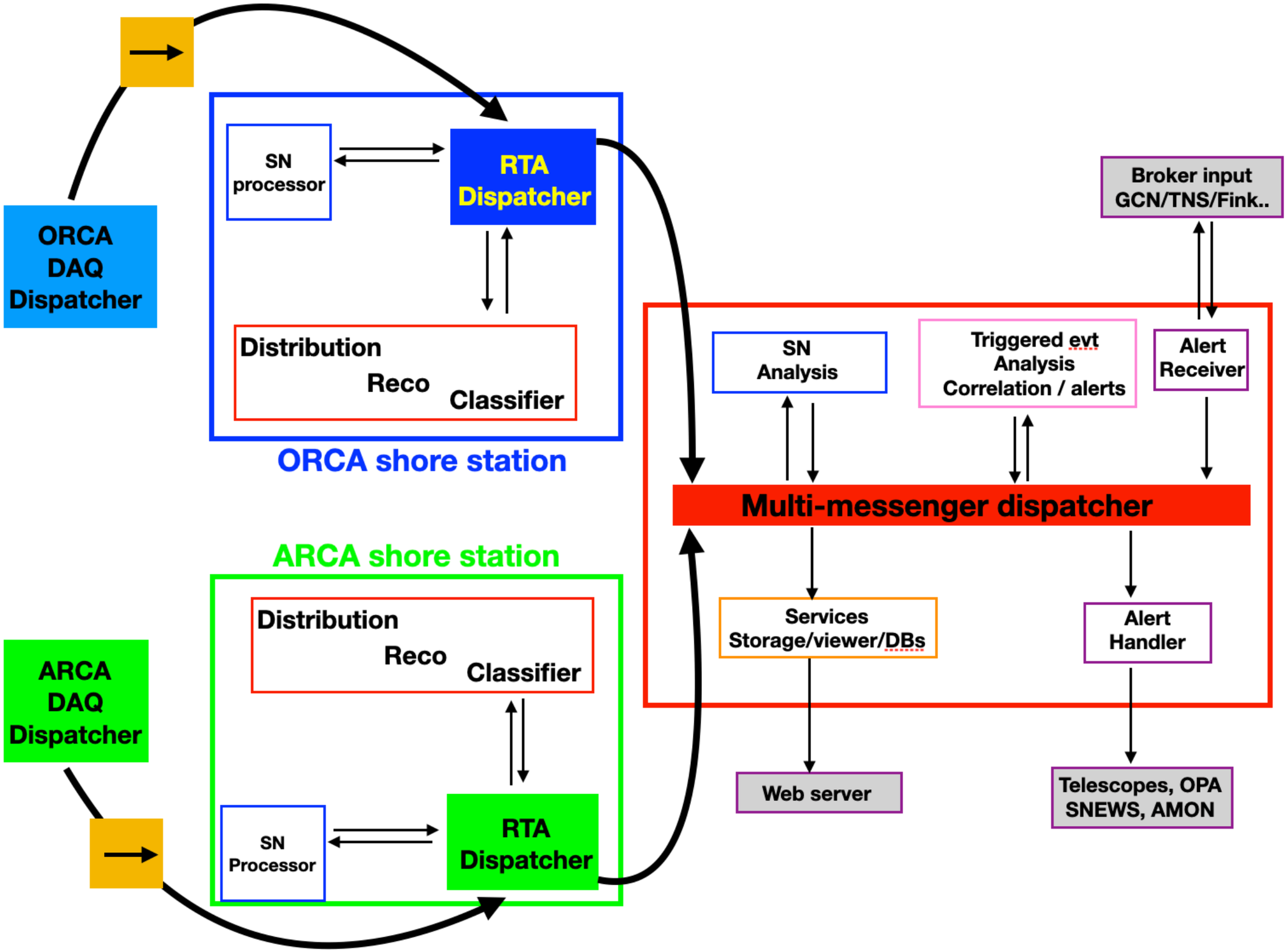
- CCSN real-time analysis pipeline
- Online analysis pipeline for track & shower triggered events
- Correlation analysis pipeline
- Alert sending program
- Incoming alert brokers (GCN, FINK, TNS…)
- Auxiliary tools and reporting tools: DBs, event display, storage, SMS/mail senders…



KM3NeT real-time analysis framework



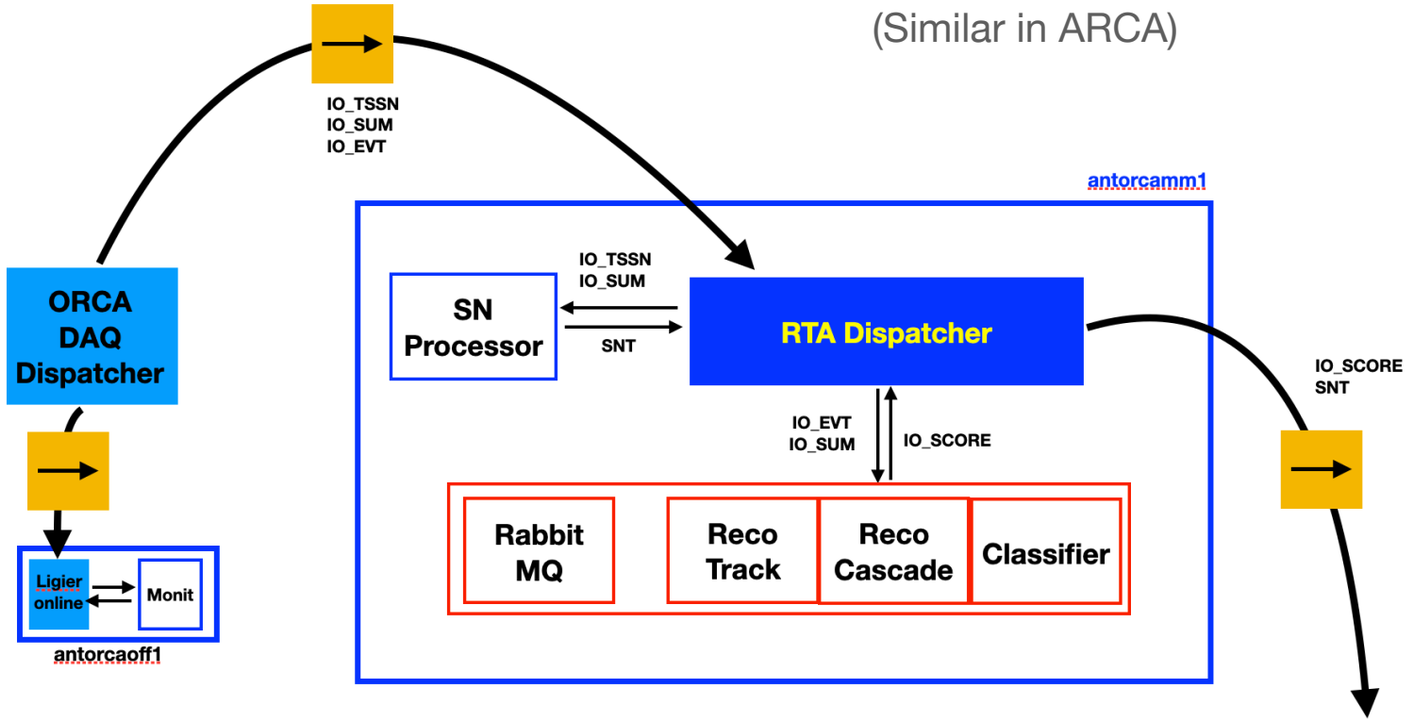
Real-time analysis framework

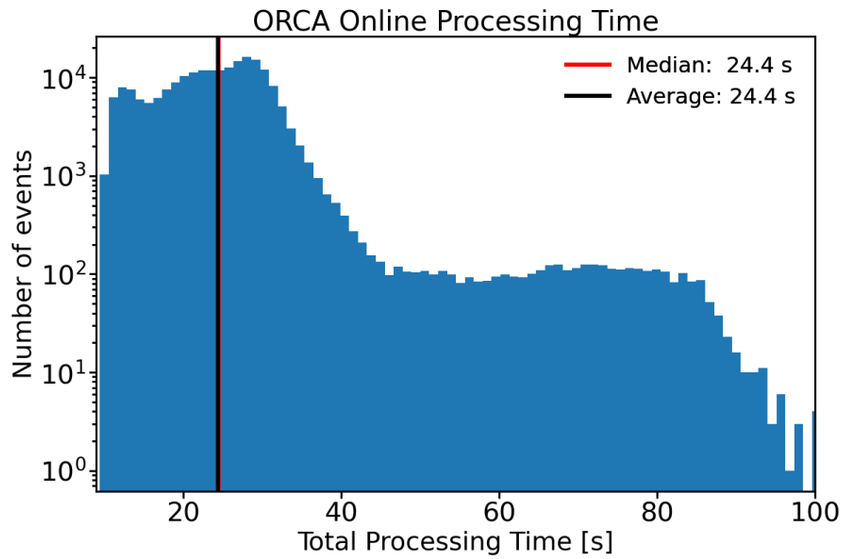


Real-time event processing

- **CCSN real-time analysis**
- **Triggered event processing**:
  - Calibration online (as close as possible as in offline including dynamical positioning)
  - Track & shower reconstructions (similar algorithms as offline)
  - Event classification (atmospheric muons-neutrinos, track-shower, atmospheric/cosmic neutrinos
  - Events from each detectors processed separately
  - Events are copied to a common event dispatcher and stored in a dedicated DB.

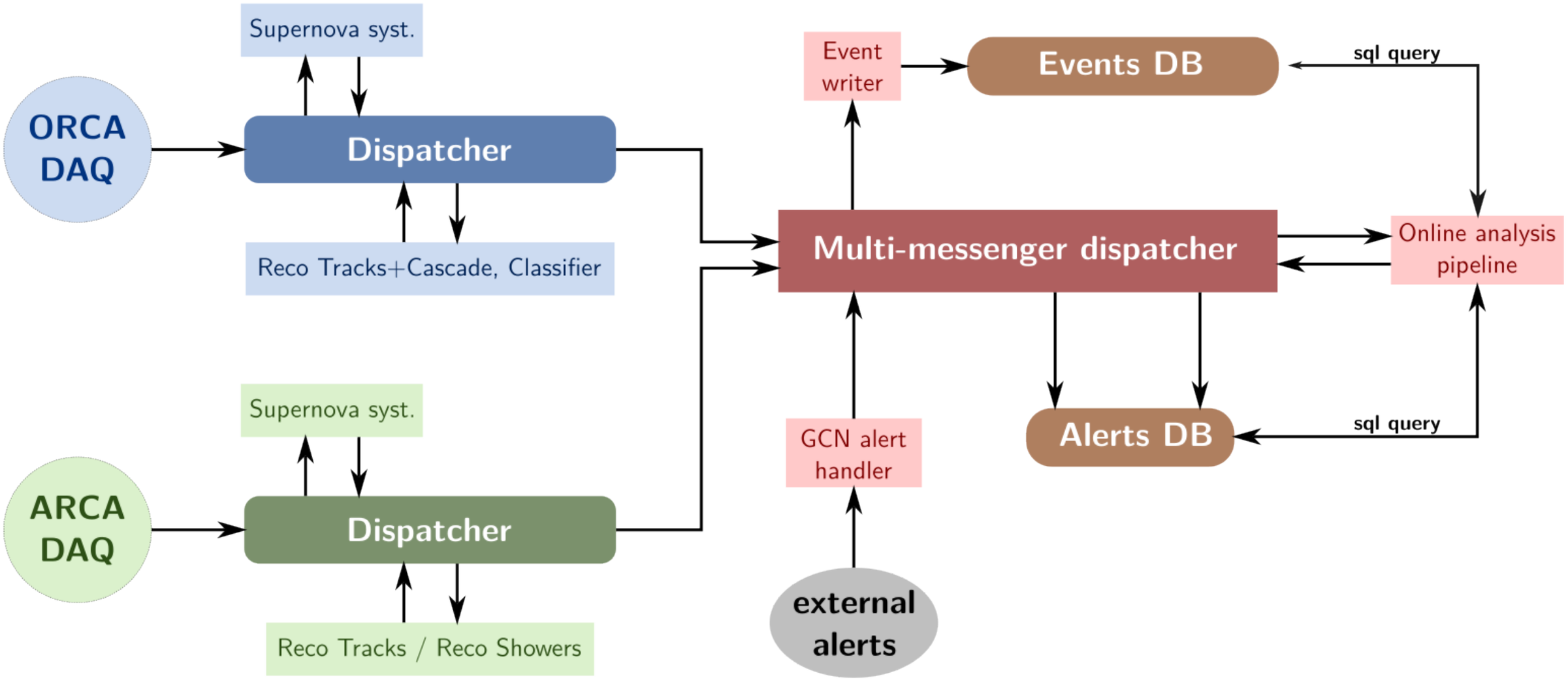
(Similar in ARCA)



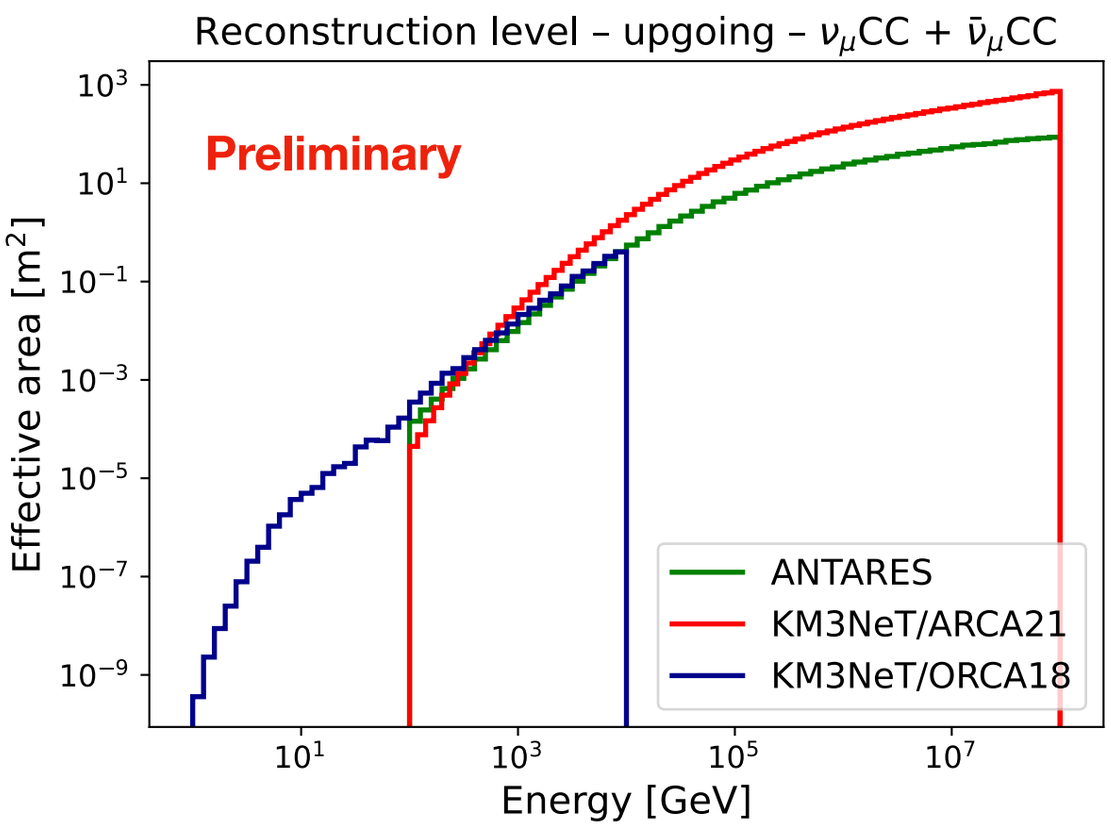


Real-time analysis processing

- **CCSN self/quasi-online/triggered analyses**
- **Reconstructed event processing**:
  - GCN broker connection + others brokers in dev (ZTF/VRO broker, TNS, …)
  - KOAP online analysis pipelines: for ORCA, ARCA, up/down-going, tracks/cascades searches
  - Reporting + communication tools + service applications (DBs, writers)



Actual KM3NeT detectors



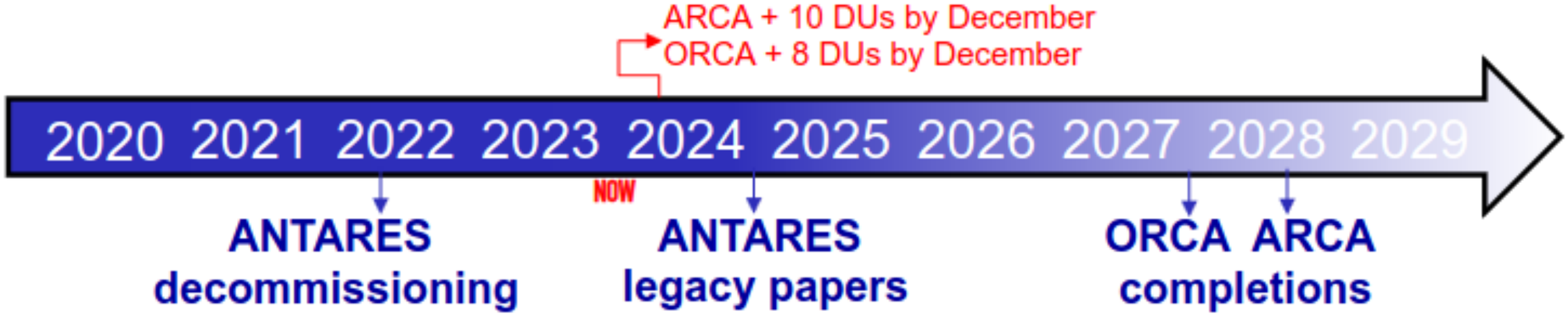
- **ORCA18 > ~10x ANTARES at LE**
- **ARCA21 > ~3x ANTARES at HE**

⇒ Continuous data flow since 1-2 years

⇒ Important work performed in the Collab to have reliable calibration, right now only available in offline after several months. Online calibration without dynamical positioning

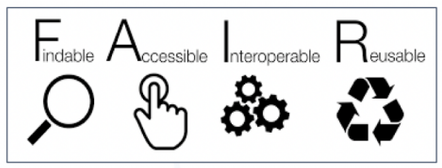
⇒ This yields to a limited angular accuracy ~1-2 deg at HE, ~2-5 deg at LE

⇒ Cascade channel being in operation

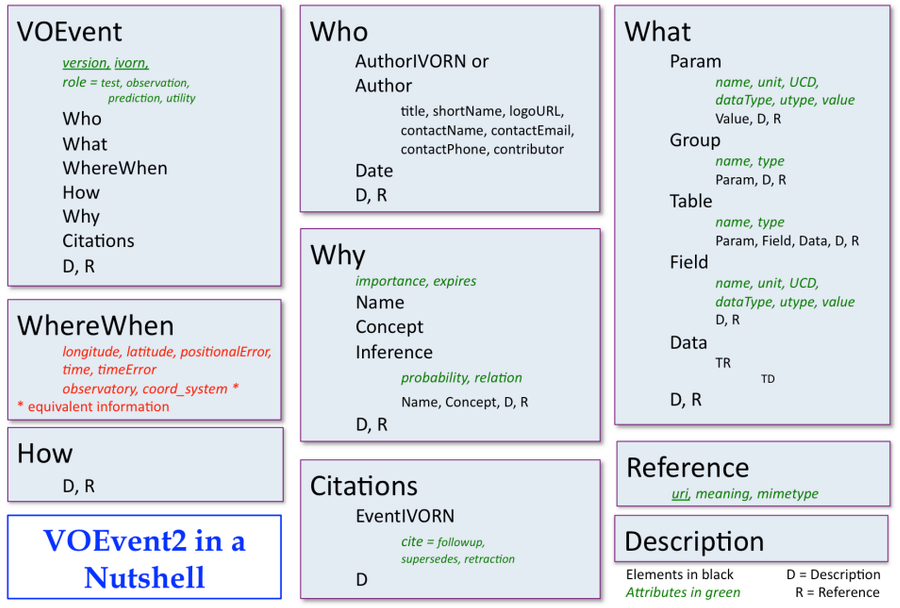


Standard neutrino alert format

- Definition of a **standard high-energy neutrino alert format** will help us as a community to have the best follow-up [VO Event format, Kafka ?]
- Important to add the **provenance information** for a better tracking of the information
- **Common definition of the scientific interest** (signalness, FAR, astro prob…) ⟹ criteria depending on the assumed source model. How to be model independent ?
- **Easy accessibility of all the alerts** [VO table] using common astro tools & services
- **Healpix skymap** to provide the detail error region of the neutrino
- How to provide the **neutrino alert catalog** (others neutrino catalogs) ? Need also to provide the IRFs. Gamma-py common format [GADF, VODF] https://gamma-astro-data-formats.readthedocs.io/en/v0.3/



Radio community has made this effort for the FRB triggers, as well as SNEWS for the CCSN triggers



Neutrino alert types

Selecting only 1-2 neutrinos per month from 5-6000 atmospheric neutrinos is not an easy task and depending on the selection procedure, we can find a different sample.
Alerts originate from track and cascade events (all-flavor)

Very high-energy single events
Selection of single neutrinos, the ones which reconstructed energy are the highest of the month
⟹ Well adapted to large volume telescope

Multiple events
In situations where multiple neutrinos are seen from the same direction within a limited time (a few sec to few days, months), an alert will be sent [sliding scan window]

Very low-energy signal
Mainly for MeV neutrino signal from CCSN

Alert form:
General template (VOEvent) filled automatically and checked before sending
Alert distributed publicly through a broker

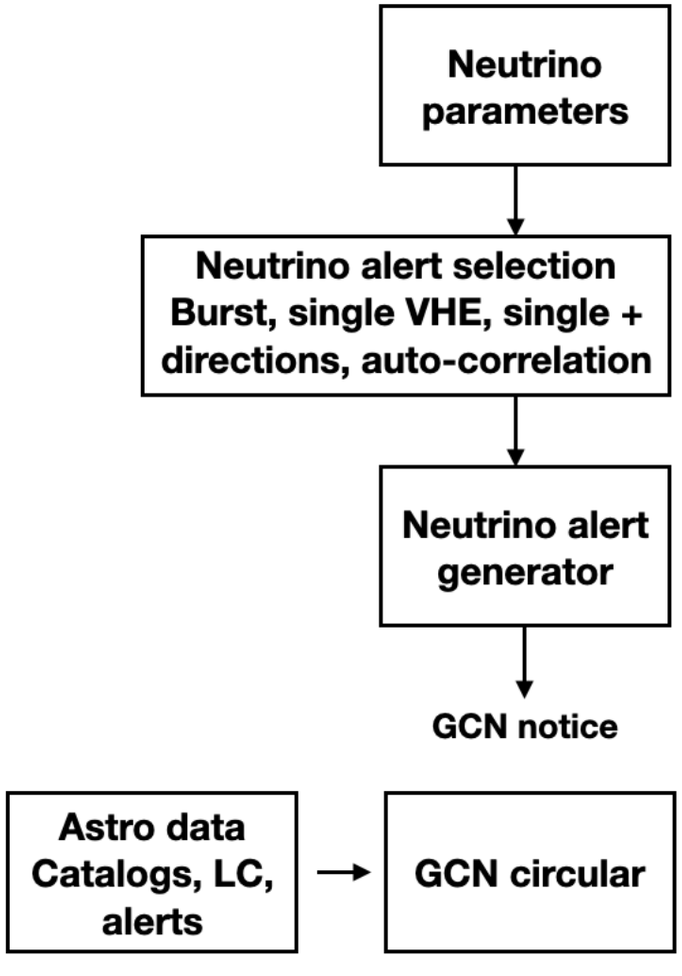
– ID
– Detector (ARCA/ORCA)
– Type of alerts triggers
– Number of events in given time and space widows
– Flavor
– Energy
– IsRealAlert
– FAR
– Time
– RA, Dec, Longitude, Latitude
– Error box 50% and 90%
– Reconstruction quality
– Probability of neutrino
– Probability of astrophysical neutrino
– Alert provenance data

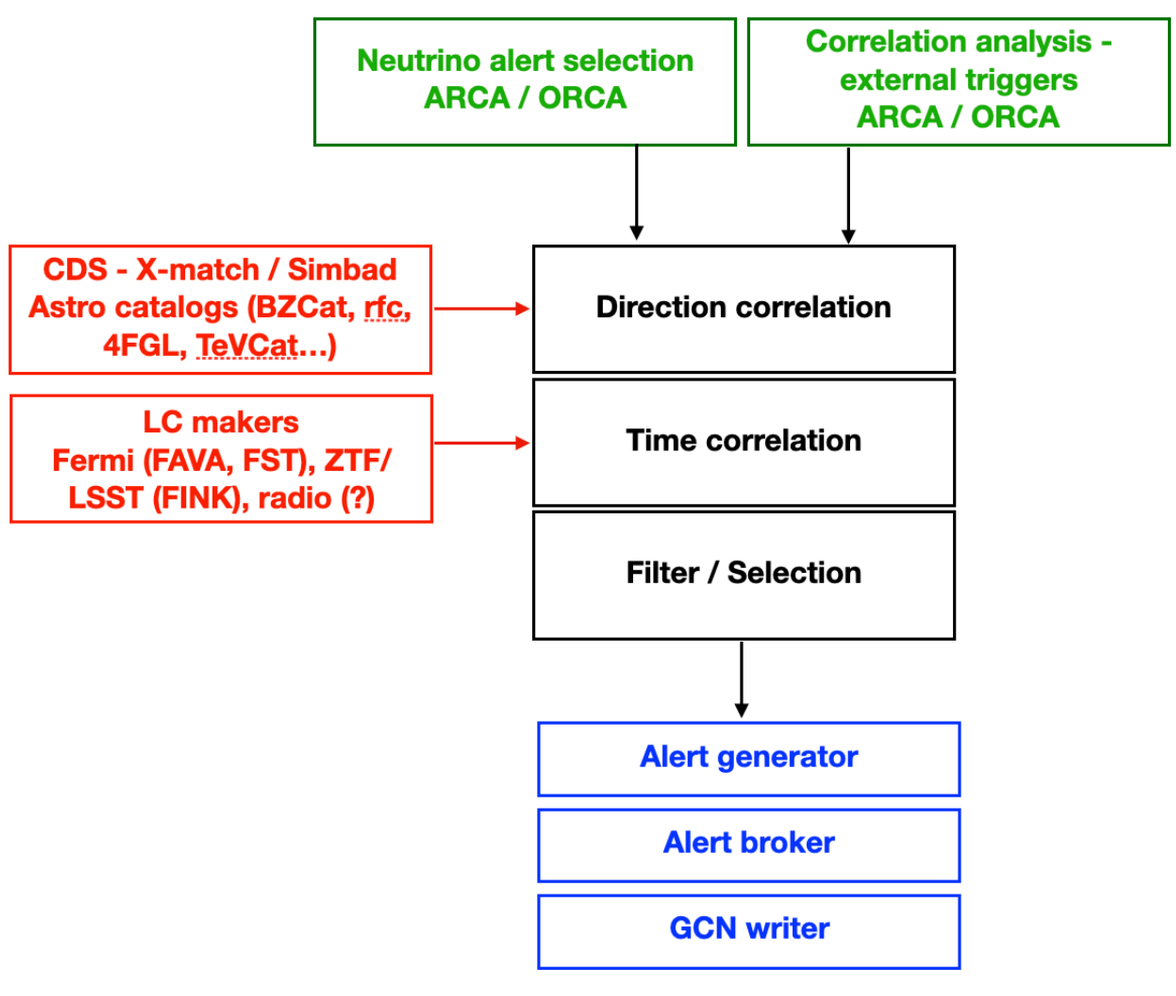
KM3NeT neutrino alert scheme

Selecting only 1-2 neutrinos per month from 5-6000 atmospheric neutrinos is not an easy task and depending on the selection procedure, we can find a different sample.

With the growing number of MM/MWL alerts in the future, it is important to increase the scientific content of the alert. We are trying to implement new type of alerts based on their astro content.

- **Reduce the threshold for the selection to a few per day and investigate the potential neutrino counterpart. If a potential interesting cosmic source is found, release an alert.**
- **Keep the pure-based neutrino selection with a very high threshold (> gold)**



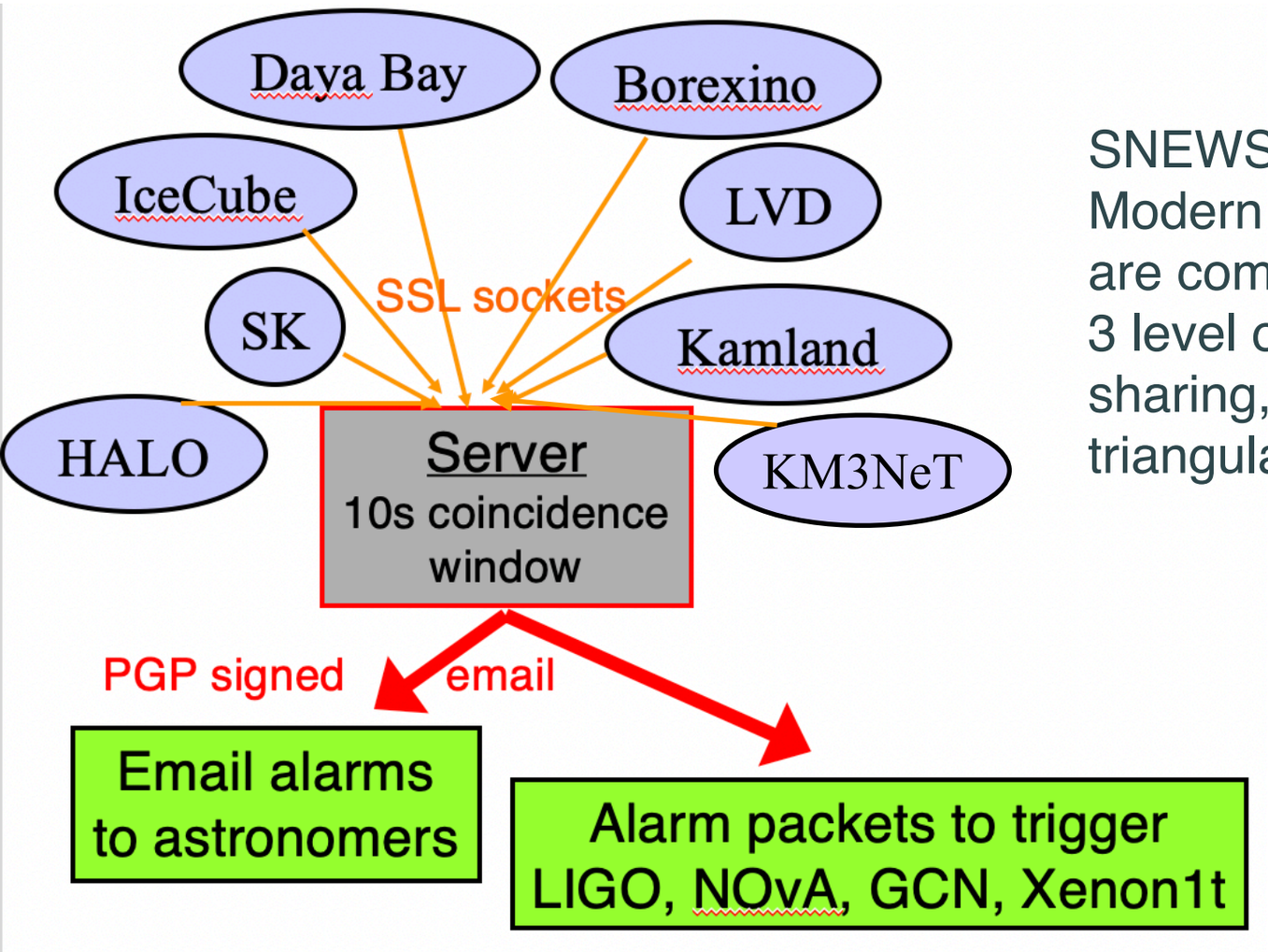


SNEWS

- SNEWS: Supernova Neutrino Early Warning System (started in 1998, fully operational in 2005)
- Neutrino detectors send alerts with FAR < 1 / week.
- 10 second coincidence time window.

=> A public alert is produced if coincidence is found. Prompt and positive alerts. Less than one false alert per century.

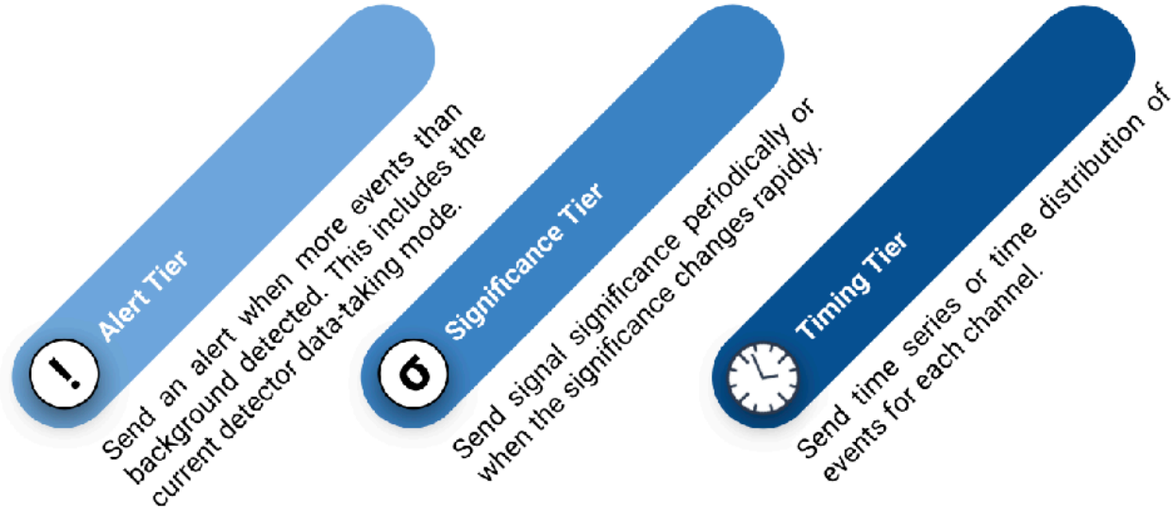
=> No SNEWS alert has been ever sent



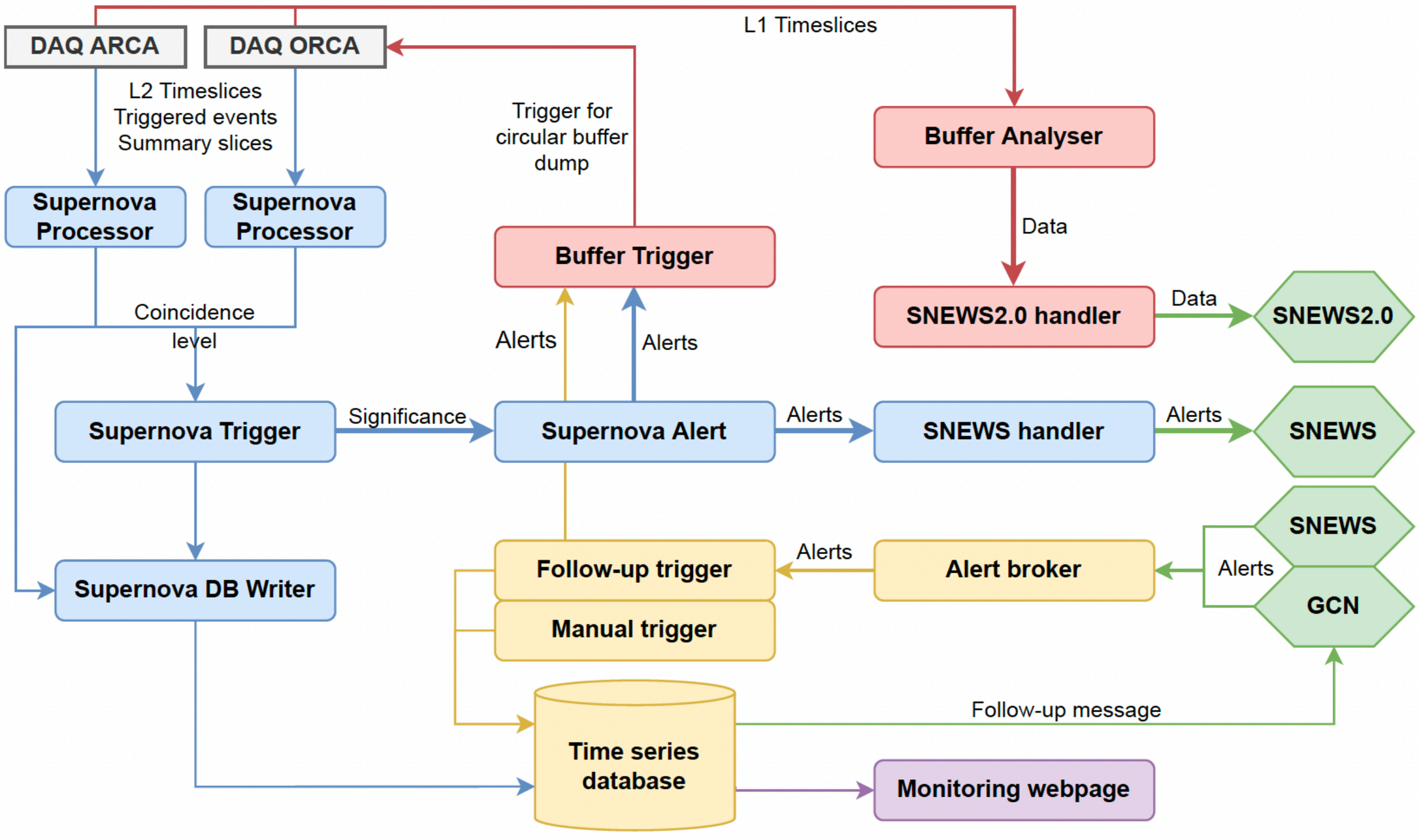
SNEWS 2.0 (in development)

Modern multi-messenger scenario, low-threshold alerts are common => Richer multi-messenger program.

3 level of alerts: Significance-based alerts, time-series sharing, real-time analysis capabilities (e.g. triangulation).



CCSN KM3NeT pipelines



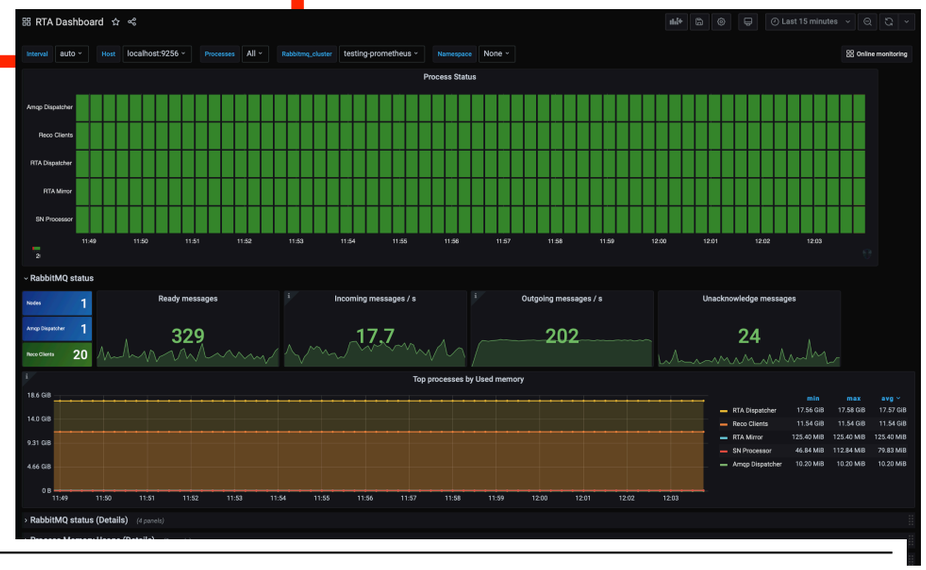
Online shifter organization

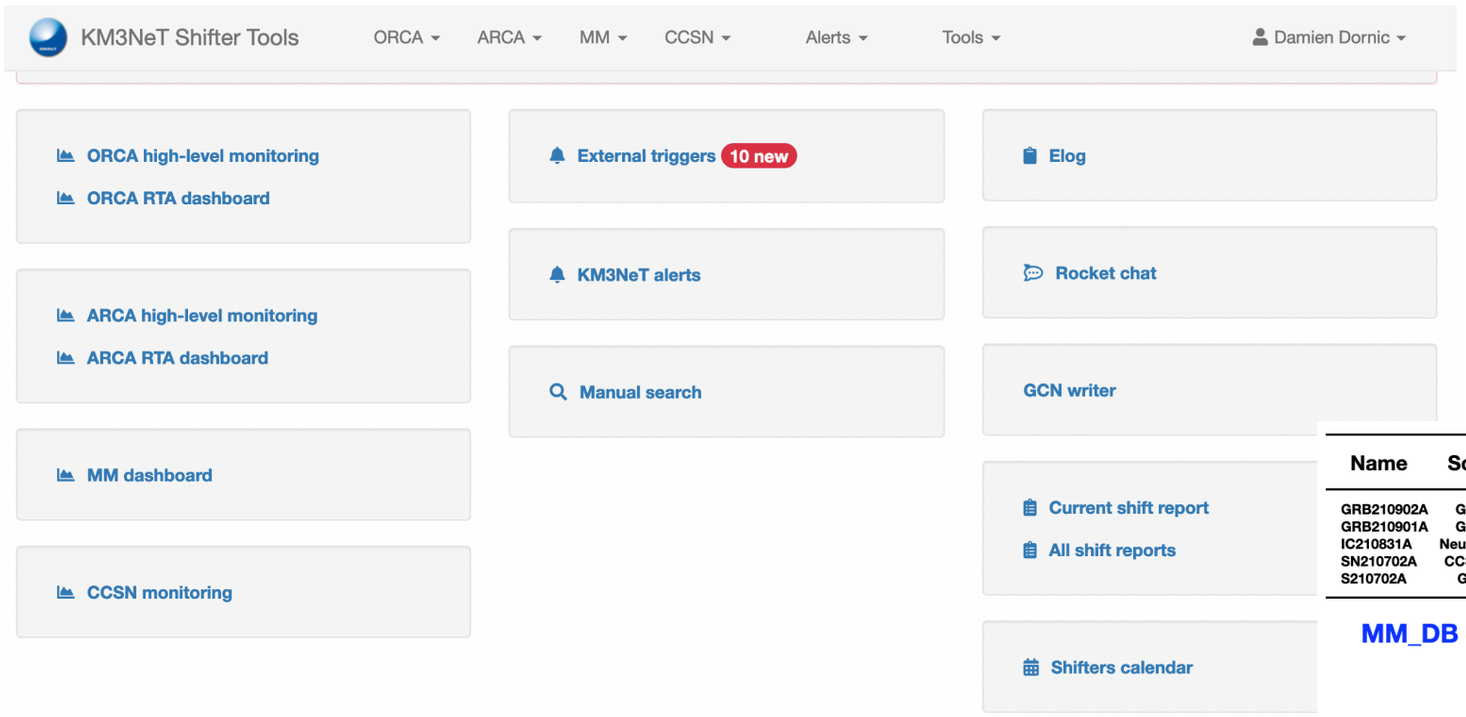
<u>Goal</u>: build an online analysis group that will take care of the real-time follow-up of the KM3NeT internal alerts and EM/MM external triggers.

<u>Duties</u>:

- Monitor the health of the online processes (reco, classifiers, SN processes), the network and the high-level neutrino performances.
- Monitor the outgoing broker
- Organize follow-up for our alerts
- Monitor the EM/MM trigger receptions and the online analyses
- Report the results

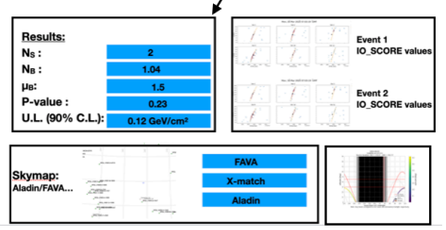
Website with all the required tools





Name	Source	Parameters	Inputs	Results
GRB210902A	GRB	1071488, 20210902T040507, 122.278 -32.388, 0.12, Swift	Links_GCN	Link_res_ana1 / Link_res_ana2
GRB210901A	GRB	652326622, 20210901T140407, 160.238 +2.398, 5.20, Fermi	Links_GCN	Link_res_ana1 / Link_res_ana2
IC210831A	Neutrino	13591_36044887, 20213108T063657, 58.788 +34.576, 0.38, IceCube	Links_GCN	Link_res_ana1
SN210702A	CCSN	210702_040507, 20210702T040507, , SNEWS	Links_SNEWS	Link_res_ana3
S210702A	GW	S200316bj, 20210701T101507, skymap_GW, LVKC	Links_GCN	Link_res_ana1 / Link_res_ana2

MM_DB **GCNALRT** **VO Event** **Online analysis**



Challenges for the neutrino follow-up (1)

Need to increase the follow-up capabilities, probably not increasing the number of instruments but more by increasing the access to existing/planned facilities.

For this we should **increase the scientific interest of the astro community**
$\Longrightarrow$ This will help us to have more observing proposals to be accepted by the TACs.

Sending **public alerts** is clearly the way to go.

Having the best angular accuracy for the neutrino alerts is the best but with a **good control of the systematics (absolute pointing)**.

The GW/GRB communities have made this effort to have better organized analysis groups [ENGRAVE, STARGATE…].

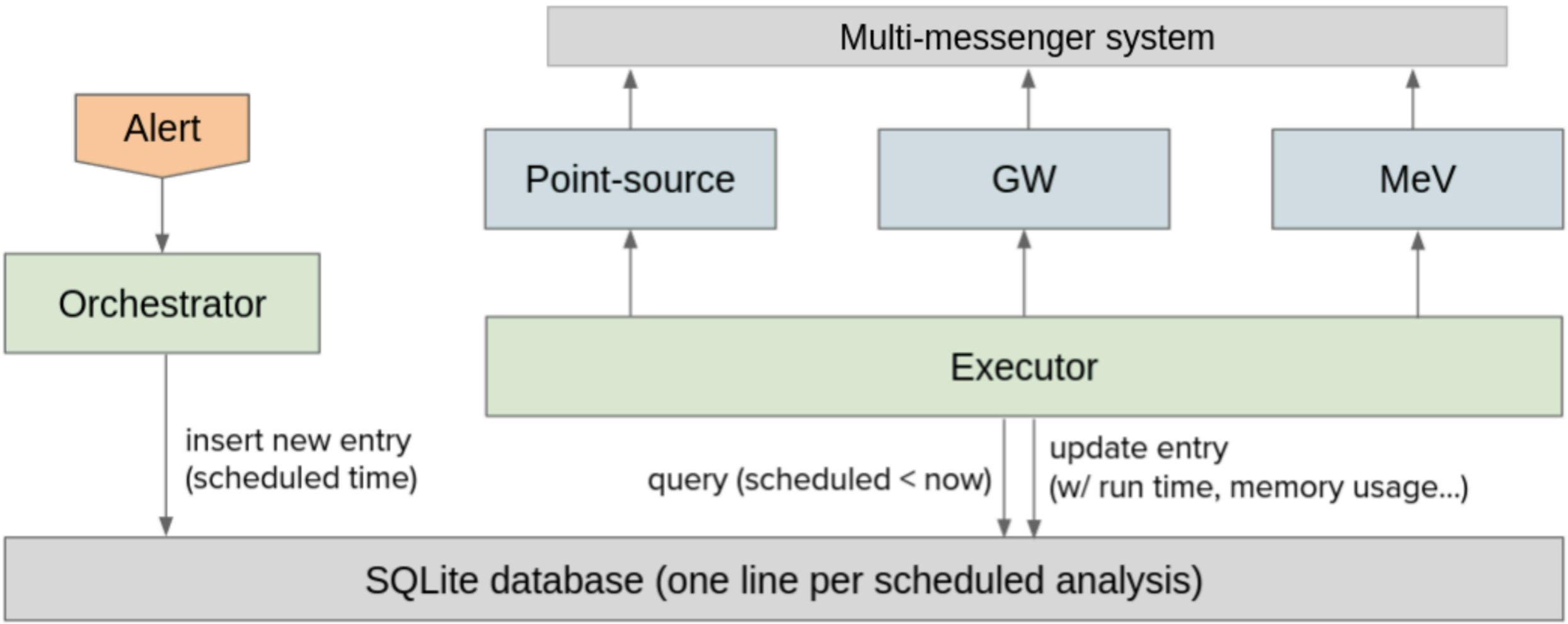
Challenges for the neutrino follow-up (2)

- **Wide-field (ideally all sky) EM counterpart discovery obs.** [ZTF, MASTER, GRANDMA… in visible, Fermi-LAT at high energies]. Rapid dissemination of the information.
- **Complete MWL follow-up from radio to gamma-rays to identify features** [VLBI, X-ray satellites, CTA…]
- **Easy access to large surveys** [ATLAS, Rubin, Euclid, Desi, eRosita…]. In quite a lot of cases, the potential counterpart has already been characterized, without spending new observing time…
- In relatively large error box, **multiple interesting sources** [source confusion, different redshift horizons].
- **Better knowledge of the origin of the different EM/MM components inside the sources**. Going beyond the 3**σ**.
- **Standard way to infer a correlation probability** [need to understand the correlation of the MWL emissions in the sources]
- **Multi-messenger search automatization following FAIR principles** (tools for joint neutrino searches, tools to access to archive observing data)

First results from the online system

KM3NeT Online Analysis Pipeline

- Alerts received by an orchestrator scheduling some analysis.
- At due time (end of search time window), analyses are launched.



Running analyses

- GRB alerts from Fermi, Swift, INTEGRAL → track searches with ARCA/ORCA
  - 4 time windows: [T_0 - 1 day, T_0], …, [T_0 - 1 day, T_0 + 1 day]
  - soon to be adapted with more physics-driven windows

- IceCube high-energy ν and other transient alerts (HAWC, Fermi-LAT, MAXI)
  - 2 time windows: [T_0 - 1 hour, T_0 + 1 hour], [T_0 - 1 day, T_0 + 1 day]

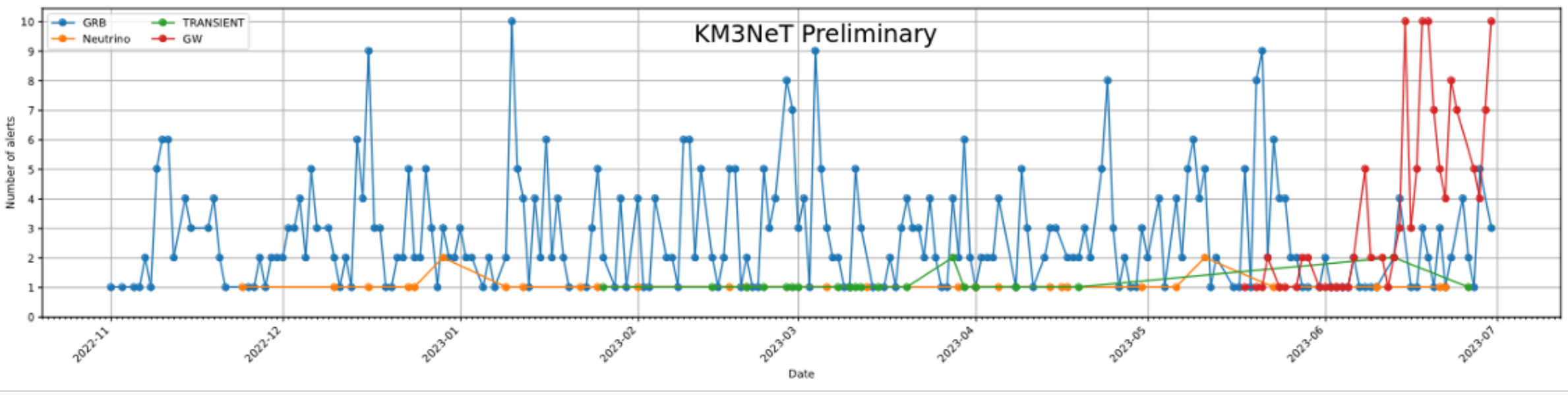
- Gravitational waves alerts from LIGO/Virgo/KAGRA
  - Track searches with ARCA/ORCA: [T_0 - 500 s, T_0 + 500 s], [T_0 - 500 s, T_0 + 6 hour]
  - MeV neutrino search with ARCA+ORCA: [T_0, T_0 + 2 s]

- After summer: add shower and full-sky

Online follow-ups performed with KM3NeT

❖From October 2022 to June 2023:

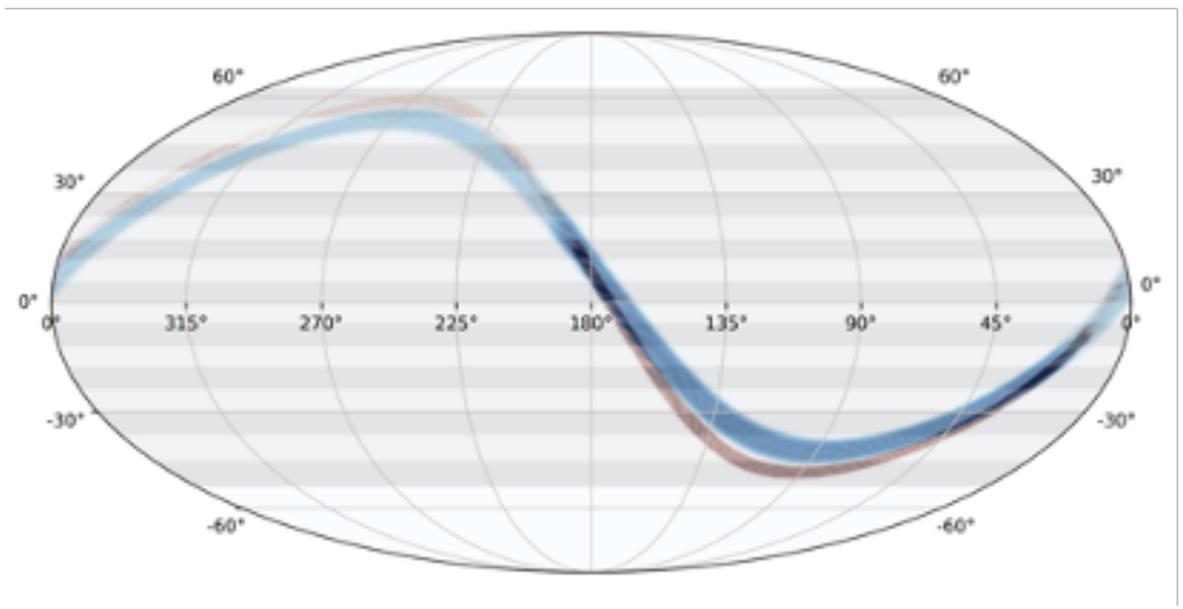
- ➢ 300 alerts have been followed up…
- ➢ … **~60%** of these are gamma-ray bursts
- ➢ … **50** IceCube high-energy neutrinos
- ➢ … **> 100 GW** alerts:
  - ■ including low-significance ones up to mid-June
  - ■ now restricted to significant ones (15 in total)



Online PS analysis method principle

ON-OFF analysis using upgoing track events

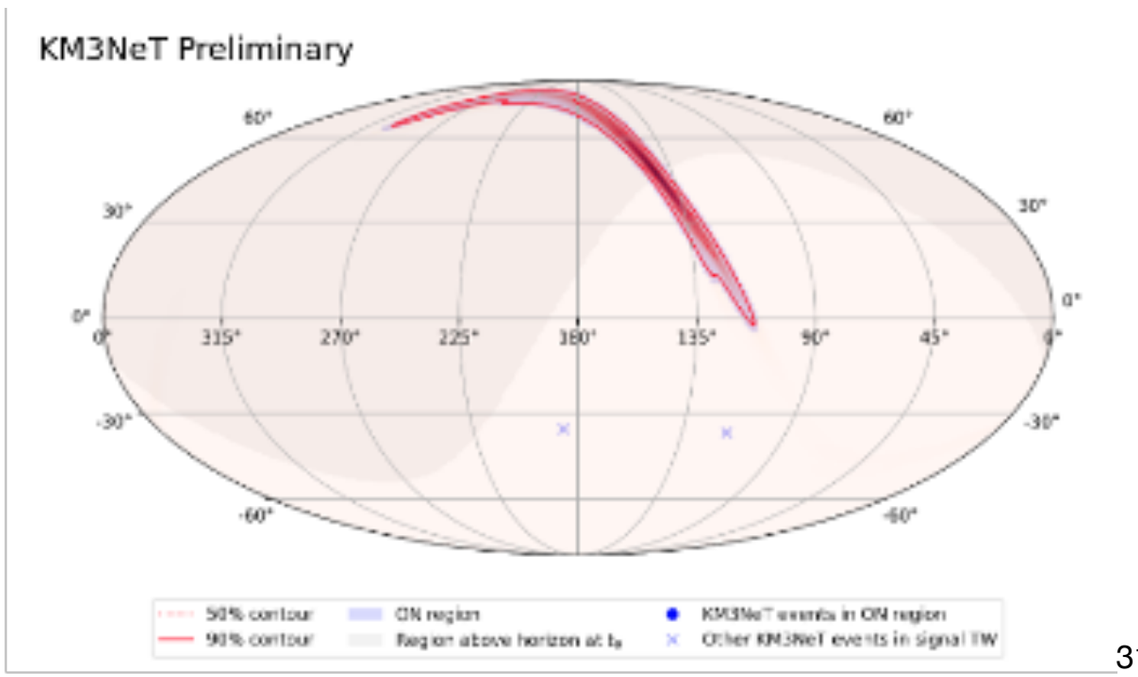
- ❖ **Search time window:** centered on T_0.
- ❖ **Region of interest:** cone centered on source with radius = max[Source error, 2º (ARCA) / 4º (ORCA)].
- ❖ **Background:** estimated with one week of data prior to the search window and events spanning same local coordinates as the region of interest.
- ❖ **Fixed event selection**
- ❖ Count N_{ON} and compare to expected background.
- ❖ Convert to **constraints on the neutrino flux**.



Online GW analysis method principle

ON-OFF analysis using upgoing+downgoing track events

- ❖ **Search time window:** [-500 s, +500 s], [-500 s, +6 h]
- ❖ **Region of interest:** GW 90% contour extended by 2°/4° for ARCA/ORCA
- ❖ **Background:** estimated with two weeks of data prior to the search window and events spanning same local coordinates as the region of interest.
- ❖ Event selection **optimized** to achieve $2.7 \cdot 10^{-3}$ background
- ❖ Count N_{ON} and compare to expected background.
- ❖ Convert to **constraints on the neutrino flux**.



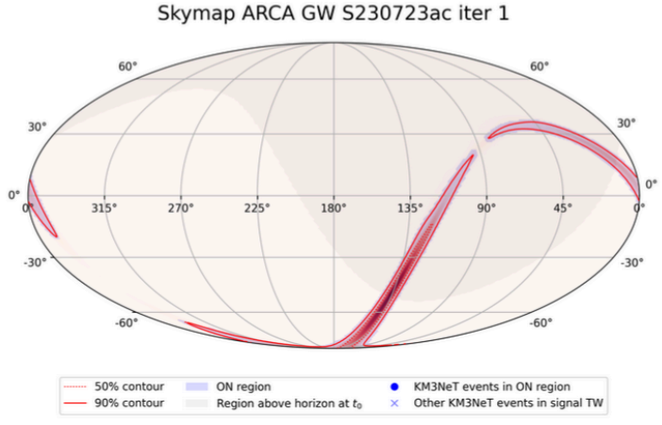
First results

❖ No significant excess observed in any of the searches.

❖ Results are not yet sent through GCN, but will be (with the corresponding constraints on the neutrino emission) in the next months.

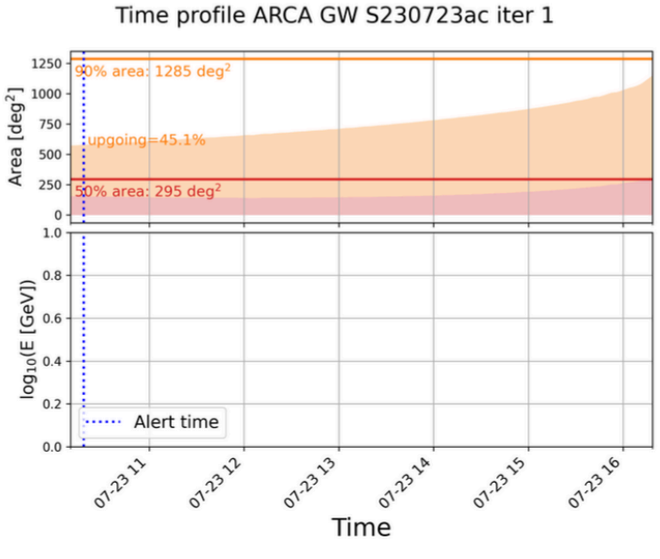
Analysis ARCA - v1	
TAG	RES_ALRT
Notice_Name	LVC_INITIAL
ID_Event	S230723ac
Date_Event	2023-07-23T10:18:34.000
Detector	ARCA
Pipeline	ARCA_GW
Iteration	1
Date_Analysis	2023-07-23T16:21:49.744
Code_Version	0.3.2
Search time window	t_alert-500 second TO t_alert+6 hour
Livetime[sig] (seconds)	21980.0
Livetime[bkg] (days)	8.749
Remaining fraction after rate cuts (%)	74.226
nON	0
nOFF	2,2,2,2,2,2,2,2
Expected Background	0.02486
Cuts on RecoQuality	1.30367863e+02,1.66133206e+02,1.41113980e+
p-value	1.0
Comments	-
IOSCORE_Stream	[]

Analysis skymap
Click to enlarge



Stability
Click to enlarge

Time profile
Click to enlarge



Analysis improvements

❖ **Selection optimization:** optimize the search region and the cuts for point-source follow-ups

❖ **Samples:** adding downgoing tracks for point-source follow-ups and cascades for all follow-ups.

❖ **Online data:** assess quality for each event and apply dynamic positioning calibration to get more precise reconstruction.

❖ **Statistical method:** on longer term, switch from ON-OFF counting method to full likelihood analysis with PSF.

❖ Follow-up results for GRBs / binary mergers / other potential transient sources will be reported through GCNs.

➢ scheduled for end of 2023

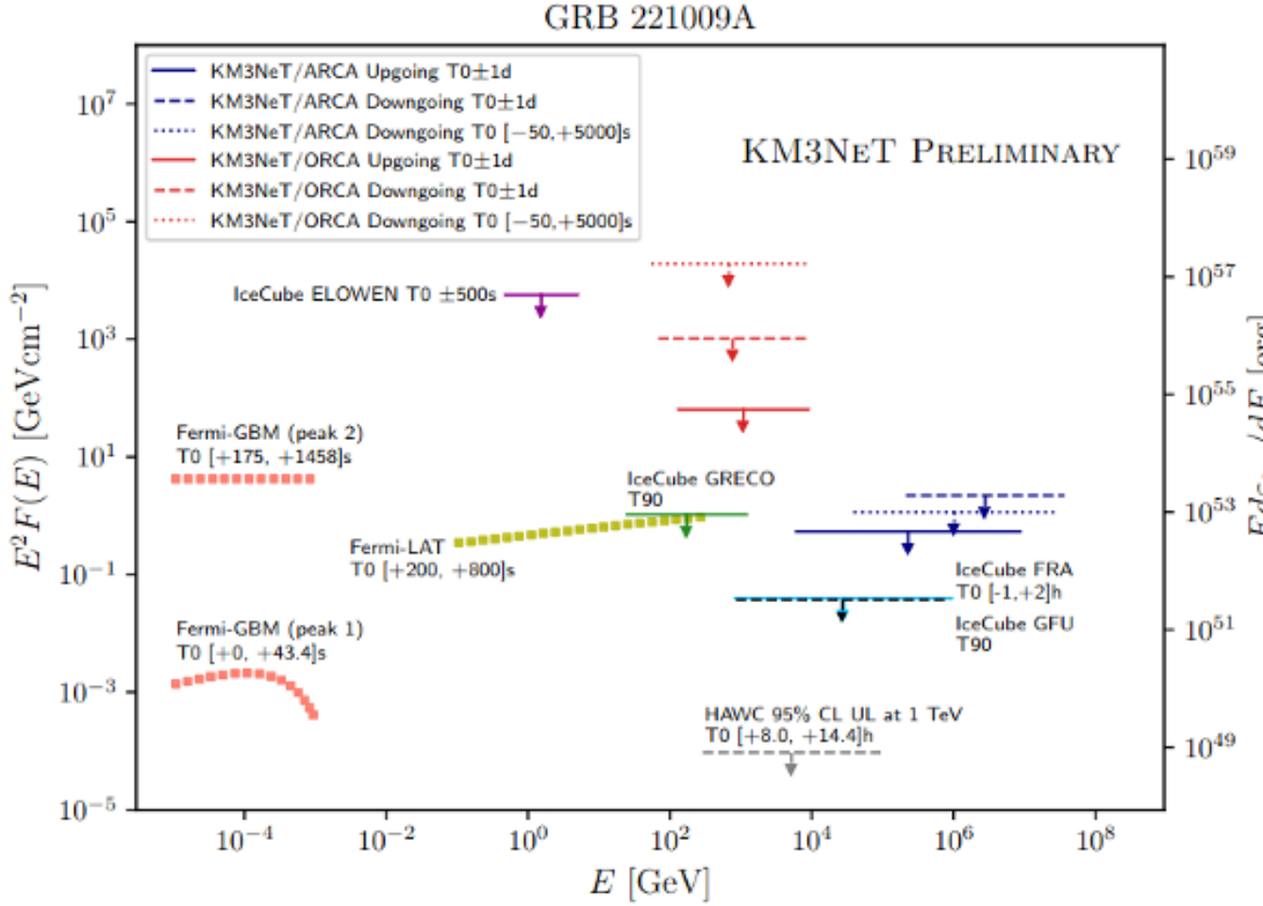
Offline analyses for GRB221009A

❖ At T_0=2022-10-09T13:16:59, an extraordinarily bright gamma-ray burst was detected by Fermi-GBM, confirmed by Swift, LHAASO, and others…
❖ Neutrino follow-ups have been performed by IceCube and KM3NeT.

⇒ Available in offline searches: better detector calibration, dynamical positioning + detailed MC production

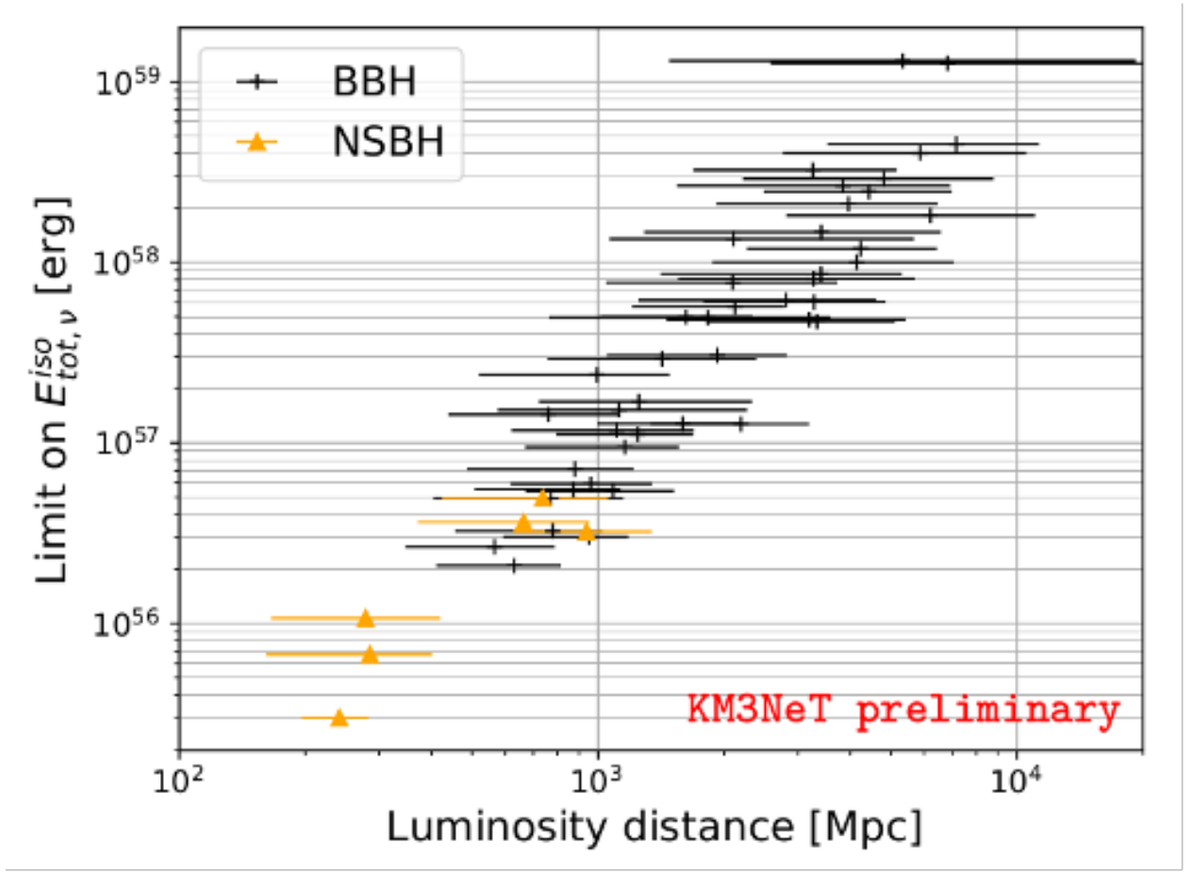
❖Two search time windows:
- ➢$[T_0 - 50\ \text{s}, T_0 + 5000\ \text{s}]$: source above horizon, only **downgoing** track selection
- ➢T0 ±1 d, **upgoing+downgoing** track selections

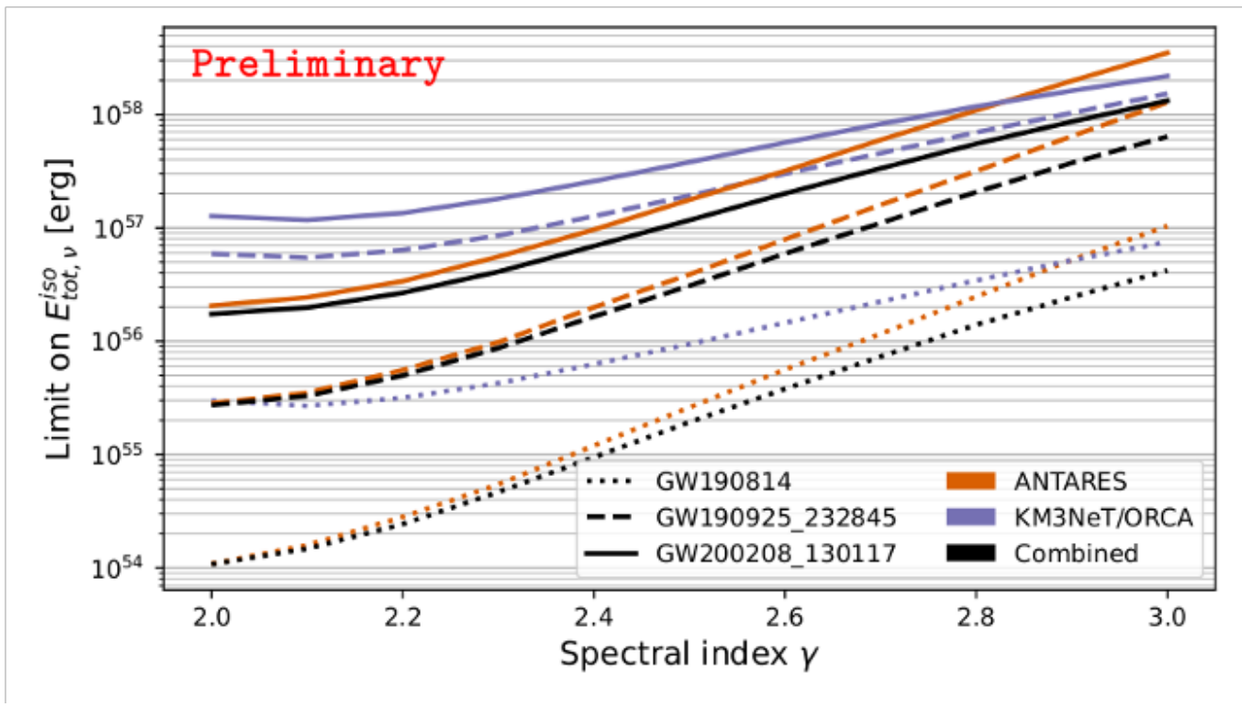
❖ON/OFF technique, selection optimized to ensure 3σ excess if $N_{ON}>0$.
❖No excess observed in either detectors.
❖Upper limits on the corresponding ν flux.



Offline follow-up for o3 GW events with ORCA

- ❖ Same strategy as for ANTARES.
- ❖ Using ORCA4+6 data and 2019–2020 GW data (GWTC-2/2.1, GWTC-3).
- ❖ Upgoing track events (GeV–TeV) and MeV searches.
- ❖ **ON-OFF search** in region = 90% GW contour + 30° extension.

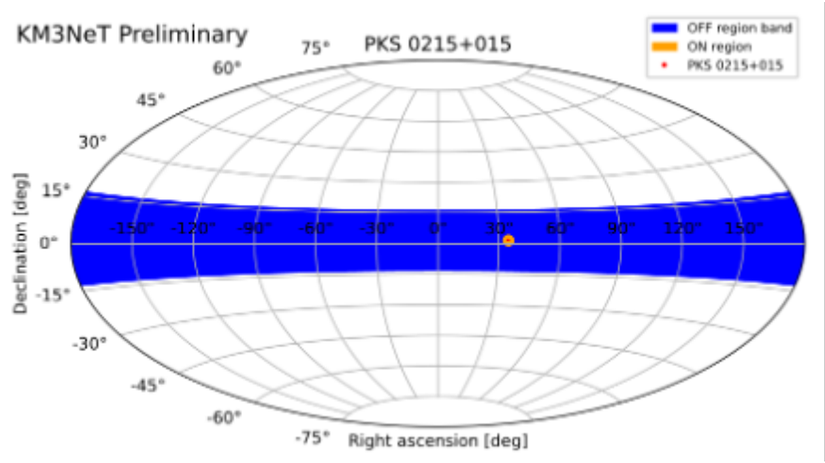




Offline follow-up for IC neutrino alerts

±1 day time window. ON/OFF analysis technique:

- ON region = cone around source position with radius optimized with MDP technique.
- OFF region: declination band around source.
- Independent searches for ARCA and ORCA.



			ARCA				ORCA			
IceCube alert	Potential blazar	Sky location (RA, DEC)	Optimum RoI	Expected background	Expected signal	Events in ON region	Optimal RoI	Expected background	Expected signal	Events in ON region
IC211208A	PKS 0735+17	$(114.5°, +17.7°)$	1.4°	$(4.7 \pm 0.7) \cdot 10^{-2}$	$8.9 \cdot 10^{-3}$	0	4.2°	$(9 \pm 2) \cdot 10^{-2}$	$8.6 \cdot 10^{-4}$	0
IC220205B	PKS 1741-03	$(266.1°, -3.9°)$	1.9°	$(4.9 \pm 0.9) \cdot 10^{-2}$	$9.7 \cdot 10^{-3}$	0	3.6°	$(9 \pm 1) \cdot 10^{-2}$	$6.7 \cdot 10^{-4}$	0
IC220225A	PKS 0215+15	$(34.5°, +1.7°)$	3.0°	$(2.9 \pm 0.4) \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	0	4.0°	$(8 \pm 1) \cdot 10^{-2}$	$6.5 \cdot 10^{-4}$	0
IC220304A	TXS 0310+022	$(48.3°, +2.5°)$	2.9°	$(2.6 \pm 0.4) \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	0	4.0°	$(9 \pm 1) \cdot 10^{-2}$	$6.3 \cdot 10^{-4}$	0

No significant excess for any of the searches.

Summary

IceCube and ANTARES have proven the high interest of the alert sending with 14-15 years of operation.

- **Alerts to community upon detection of likely « astrophysical » neutrinos for rapid follow-ups and fast multi-messenger follow-ups of external events are at the basis of almost all the neutrino discoveries**

But, the concurrence of alerts will increase significantly in the coming years with the arrival of new instruments (LSST, SKA, CTA, LVKC…) and even new neutrino telescopes (KM3NeT, GVD…).

From our point of view, we should go to a global effort of the neutrino community to have more standard alerts with easy criteria to judge the pertinence of the alerts, more complete astro information already present in the alert, to interest more the MWL followers.

The new online framework is ready and already running internally.

- Follow-up results will be released publicly through **GCN** in the next months.
- High-energy neutrino alerts will also be sent in **real-time** by end of 2024.

Back-ups

Multi-messenger synergies

Optical telescopes: TAROT, GRANDMA, MASTER, LCOGT, ZTF, LSST…
- Easy access follow-up of large error box
- Characteristation of the potential counterpart with spectroscopy (nature, redshift…)

X-ray telescopes: Swift, INTEGRAL, SVOM, ATHENA…
- Very clean sky
- Provide transient triggers (GRB, AGN, Novae…)
- ToO program (not so easy access)

γ-ray telescopes: Fermi-LAT
- All-sky complete monitoring
- Provide transient triggers (GRB, AGN…)

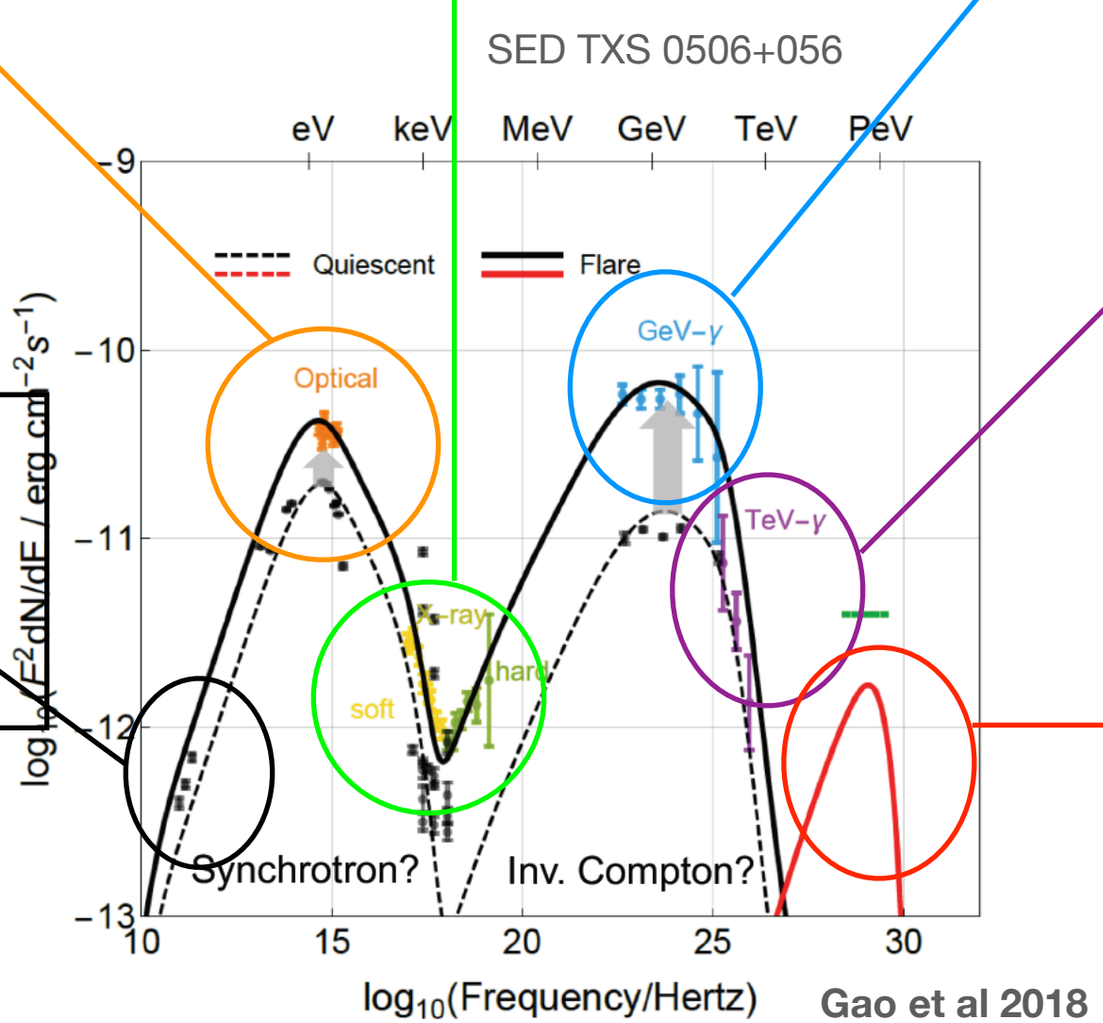
VHE γ-ray telescopes: HESS, MAGIC, CTA…
- Most natural common science case
- Follow-up (not easy access)

VHE γ-ray telescopes: HAWC, LHAASO…
- All-sky monitoring
- Provide triggers

Radio telescopes: Parkes, MWA, Lofar, Nenufar, ASKAP, SKA, VLBI…
- Provide triggers (FRB…)
- Follow-up

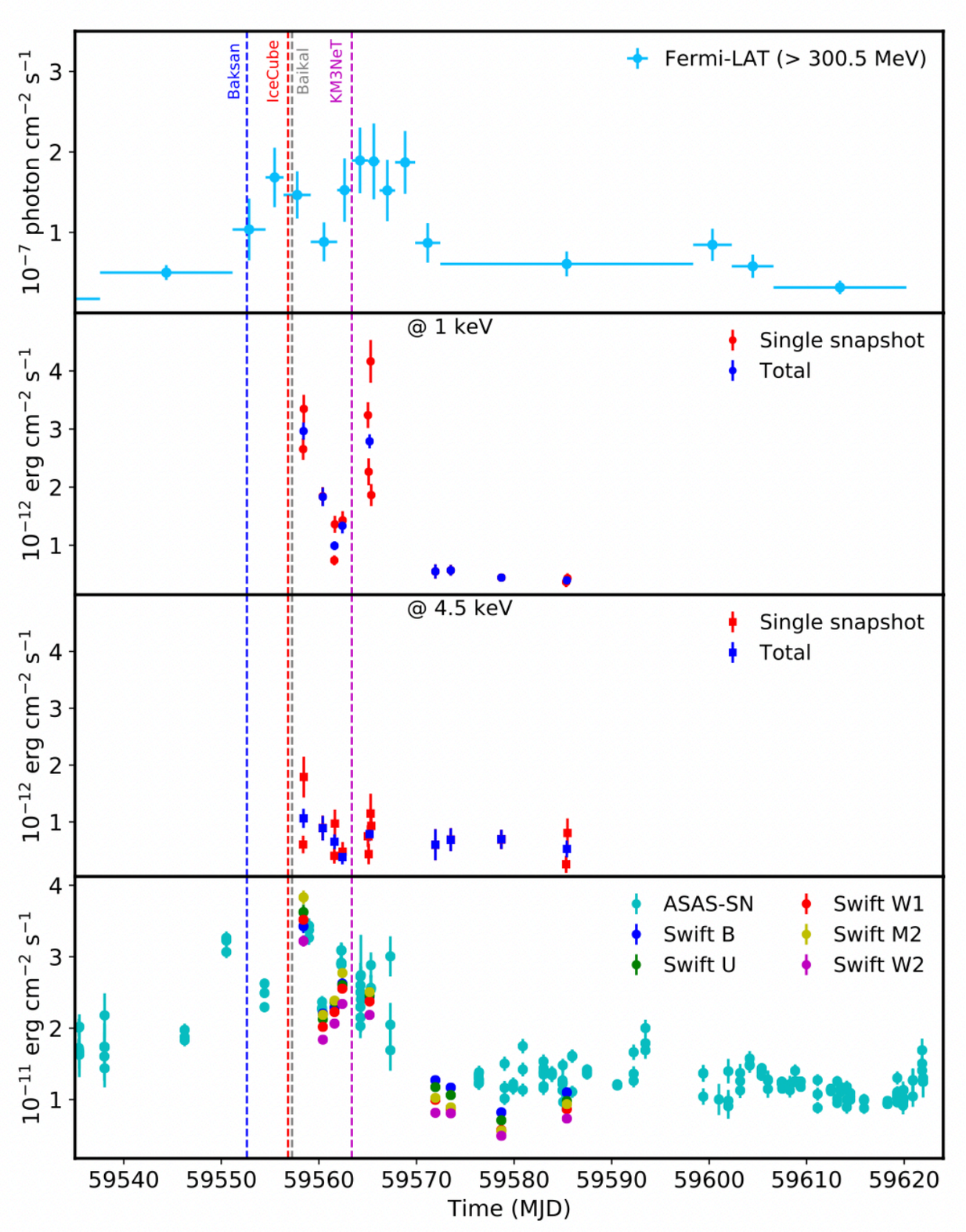
Neutrino telescopes: ANTARES, IceCube, KM3NeT, GVD…
- Mutual follow-up
- Confirmation of sources, improve significance

+ link with LIGO/VIRGO
+ SK, SNEWS



Gao et al 2018

Example: association with PKS0735+178



Sahakyan et al (arXiv:2204.05060)

IceCube: 1 bronze alert (~172 TeV) [GCN #31191]

ANTARES: no coincidence [ATel #15106]

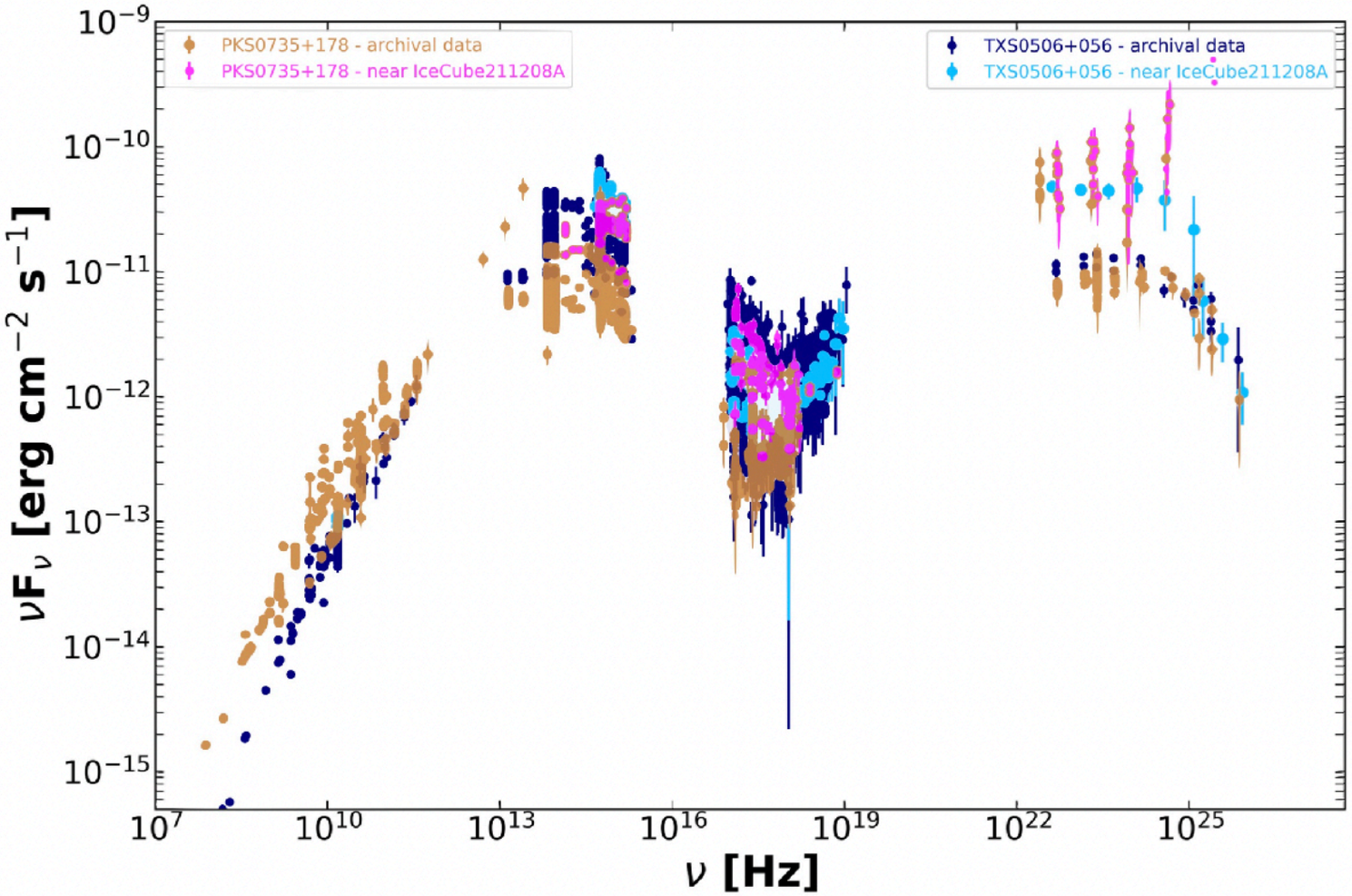
GVD-Baikal: 1 cascade event (~43 TeV), ~4h after the IC neutrino, ~5deg from the blazar direction (2.85 σ) [ATel #15112]

KM3NeT: 1 track neutrino candidate (~18 TeV) in ARCA, 1.8 deg from the blazar (p=0.14). No coincidence in ORCA [ATel #15290]

Baksan: 1 track neutrino (1 GeV), 2.2 deg from the blazar (~3 σ) [ATel #15143]

The blazar was found to experience a strong flare in gamma rays (ATel #15099, ATel #15129), X-rays (ATel #15102, ATel #15108, ATel #15109, ATel #15113, ATel #15130), optical (ATel #15098, ATel #15100, ATel #15132, ATel #15136, ATel #15148) and radio (ATel #15105) bands.

Example: association with PKS0735



Sahakyan et al (arXiv:2204.05060)

- **PKS 0735+178 (IHBL object) is one of the brightest BL Lac objects in the sky both in radio and gamma**
- **Similar spectral energy distributions, very high radio and γ-ray powers, and parsec scale jet properties as TXS0506**
- **Redshift unknown z ≥ 0.424**

Main followers of neutrino alerts