Multi-messenger observations with neutrinos

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Town Hall KM3NeT 2 - Sept 22, 2022

Requirements

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**

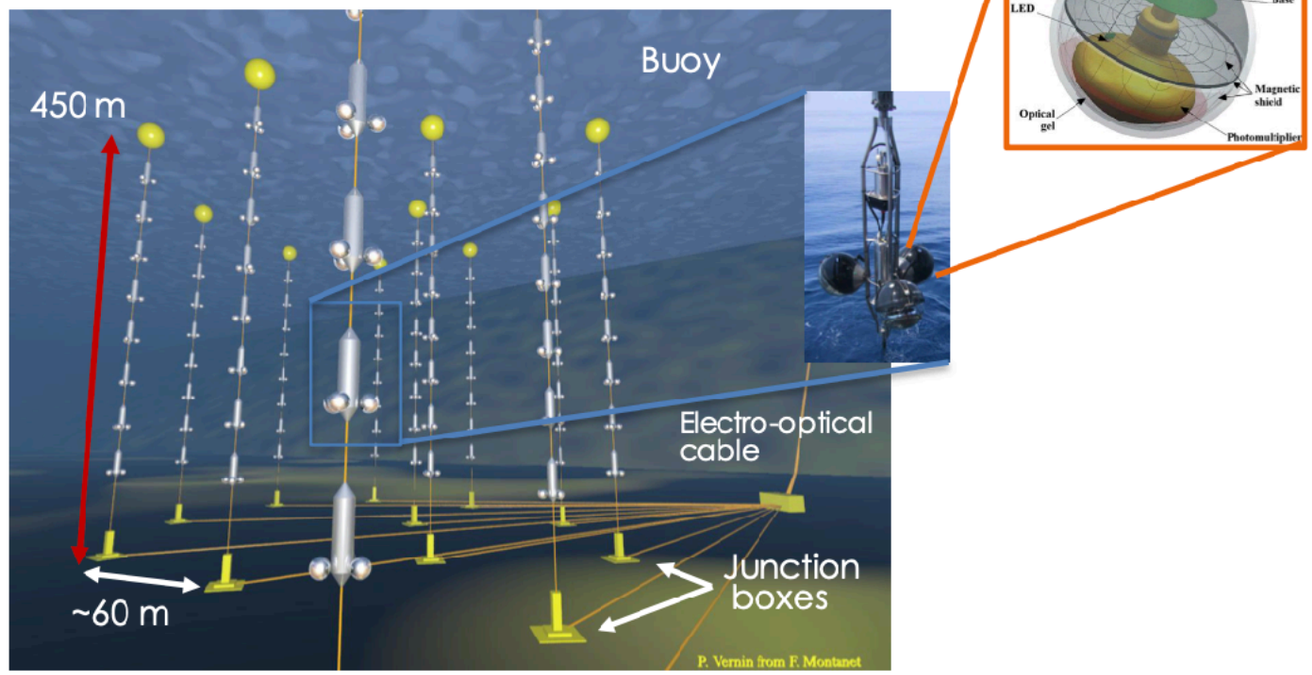
These observations can:

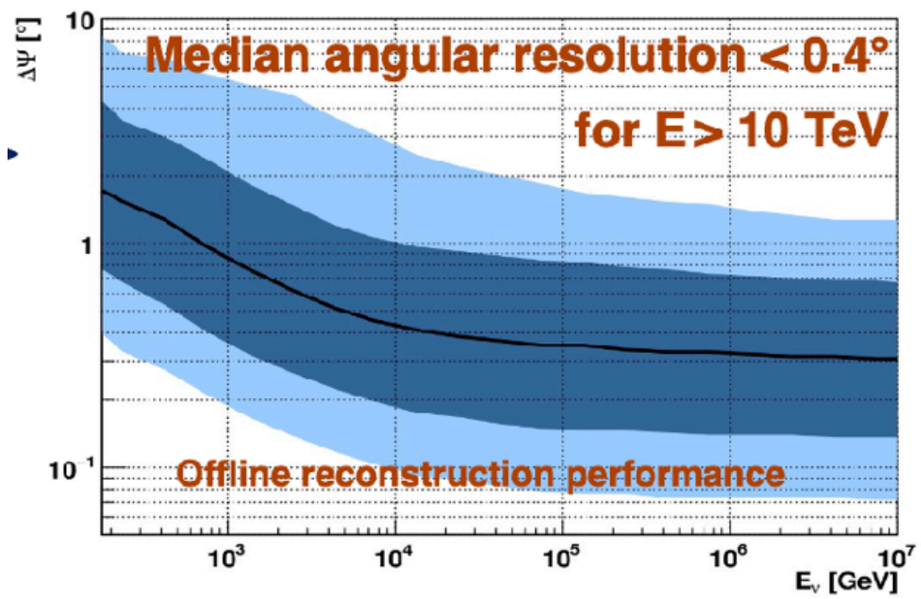
- **Strengthen or refine detections made in single messenger**
- **Probe source dynamics and populations, even in the absence of signal**
- **Identify the sources of the observed high-energy astrophysical neutrinos**

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**

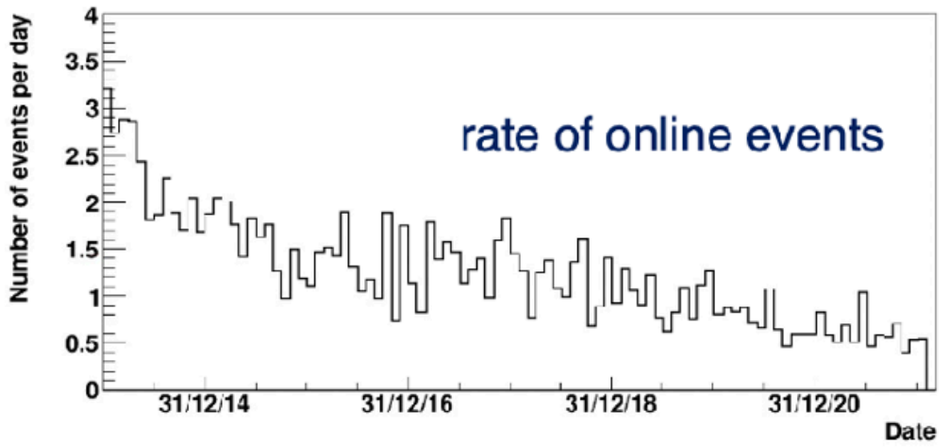
- 3D array of 885 PMTs (10”)
- 12 vertical lines
- Instrumented volume ~0.01 km^3





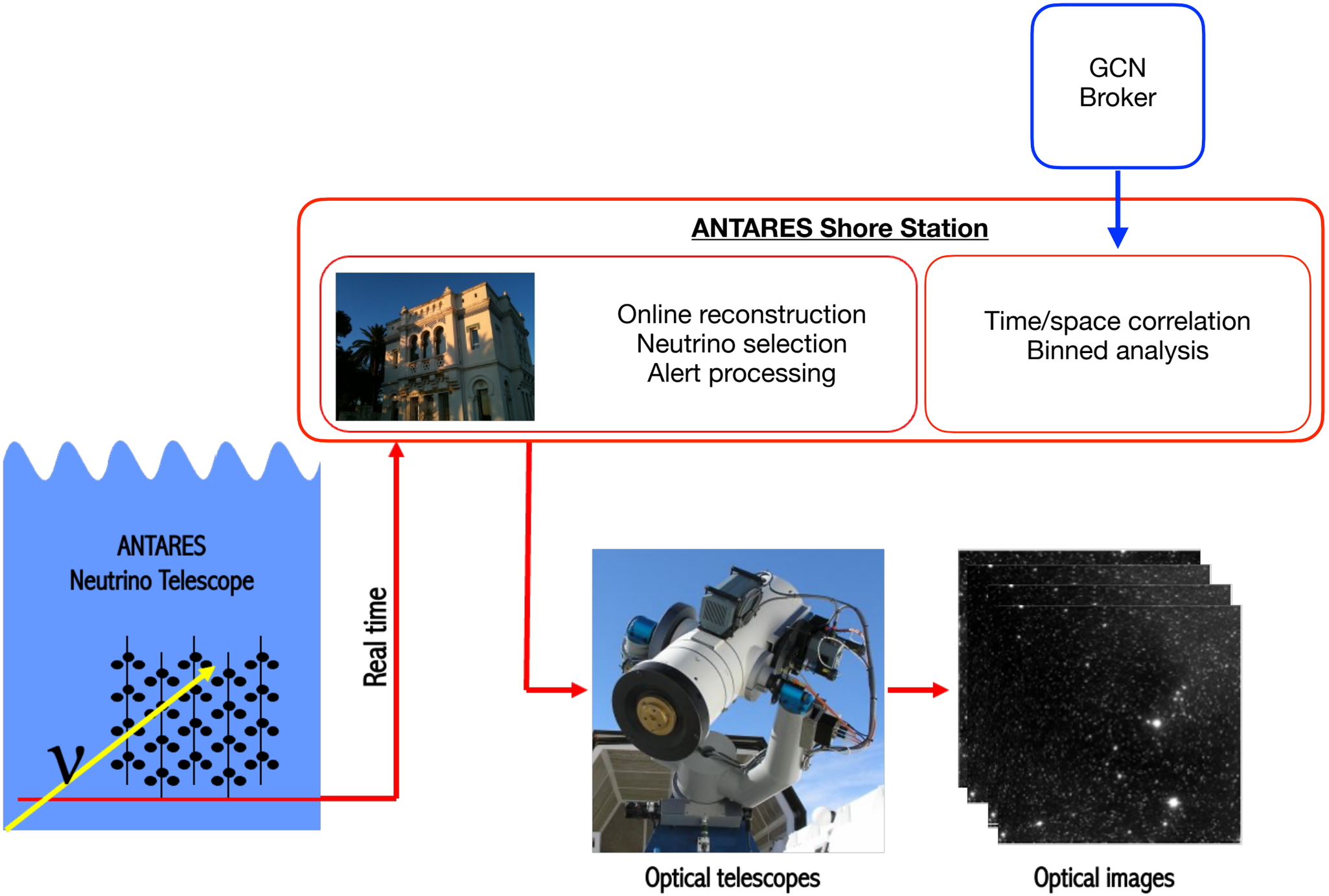
ANTARES sample for online analyses:

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



ANTARES real-time analysis platform

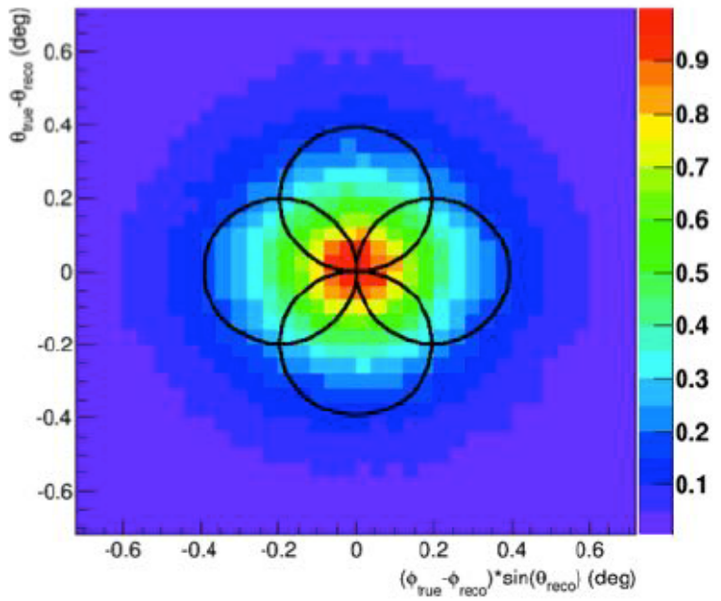
ANTARES have implemented in 2008-9 a real-time analysis platform that triggers neutrino alerts and that performs time/space correlation analysis for external triggers

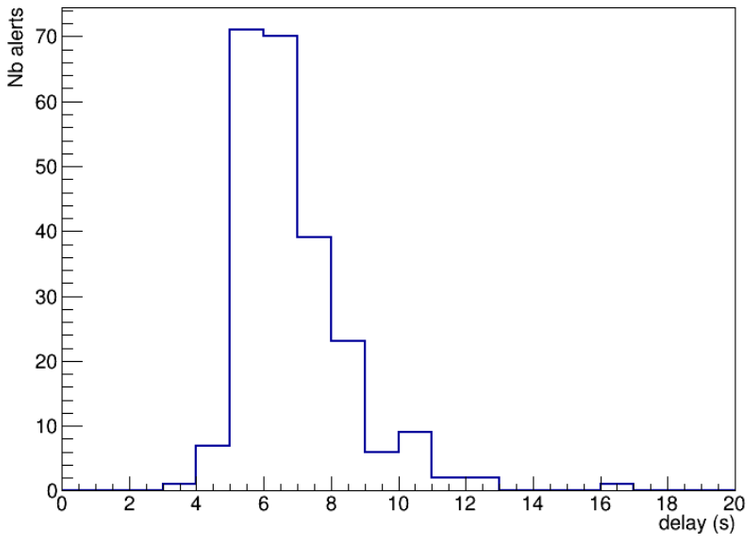


ANTARES neutrino alerts

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.

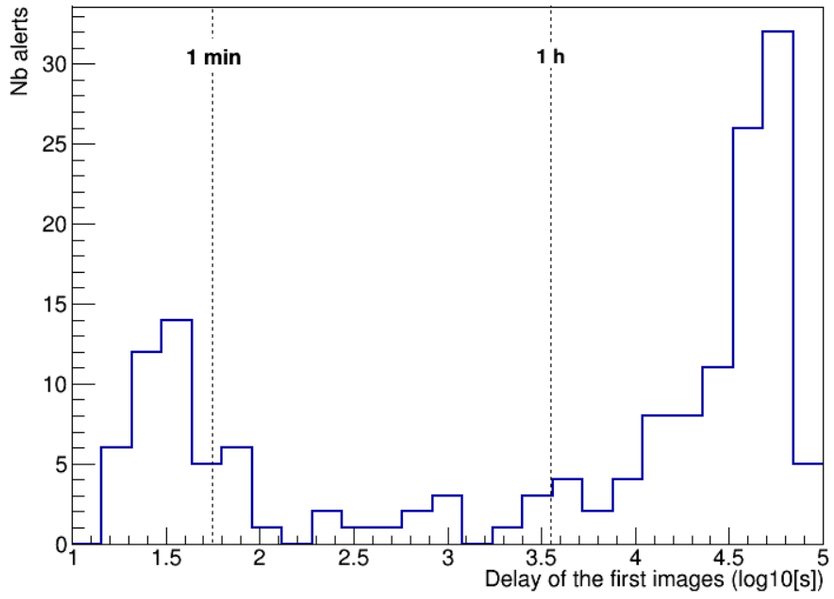
ANTARES PSF : ~0.4° (median)





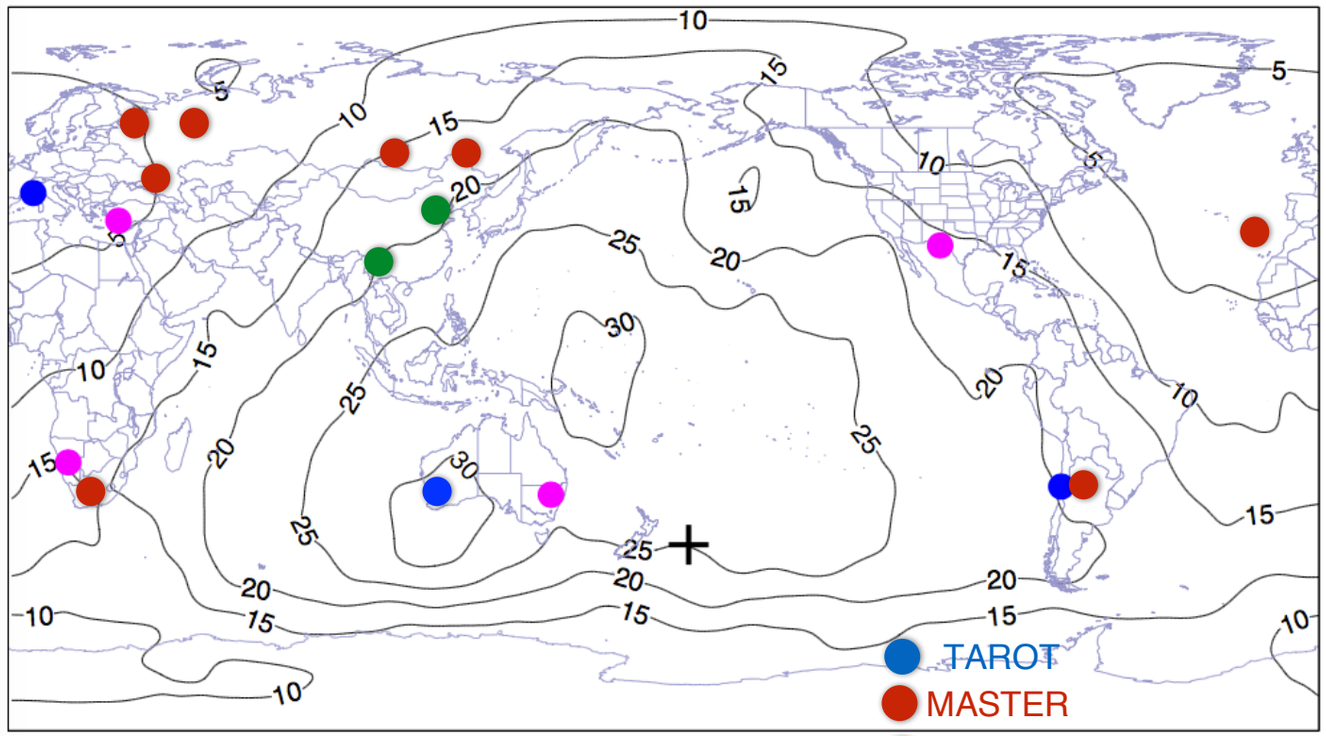
Alert message sent via the GCN using either GCN socket or VO Event
⟹ Average delay: ~6 s
(get data, trigger, online reconstructions, neutrino selection)

Delays between the time of 1st image and the neutrino trigger
⟹ 192 alerts < 1 day
⟹ 40 alerts < 1 min
(wait for the alert visibility, stop previous acquisition, point the telescope, start the acquisition)



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

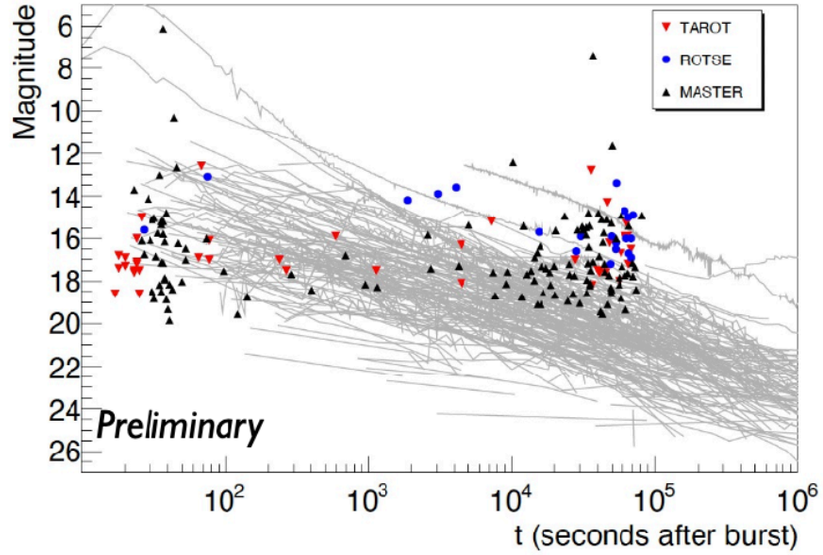
Swift XRT: ~70% follow-up efficiency
=> Main limitations: alert direction too close to the Sun/Moon/Galactic plane, ToO not accepted

Main results of the follow-ups (Mid 2009-End 2021)

- 322 alerts sent to robotic telescopes
- 26 sent to Swift
- 15 sent to INTEGRAL
- 20 sent to MWA
- 2 sent to H.E.S.S.

Prompt follow-ups

No clear optical transient counterparts found → upper limits on the magnitude of a transient astrophysical source derived



Long-term follow-ups

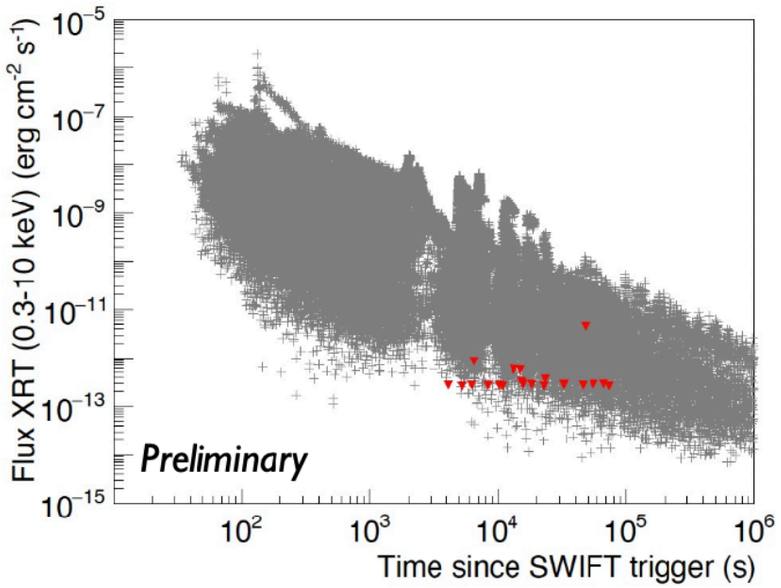
224 alerts allowed for good optical follow-ups for 2/3 nights

No significant slowly varying optical counterpart found

Radio follow-up

2 alerts followed by M.W.A.

No strongly varying radio counterpart identified



H.E.S.S. follow-up

2 alerts followed shortly after ν detection

No VHE candidates associated

Search for correlation with sources

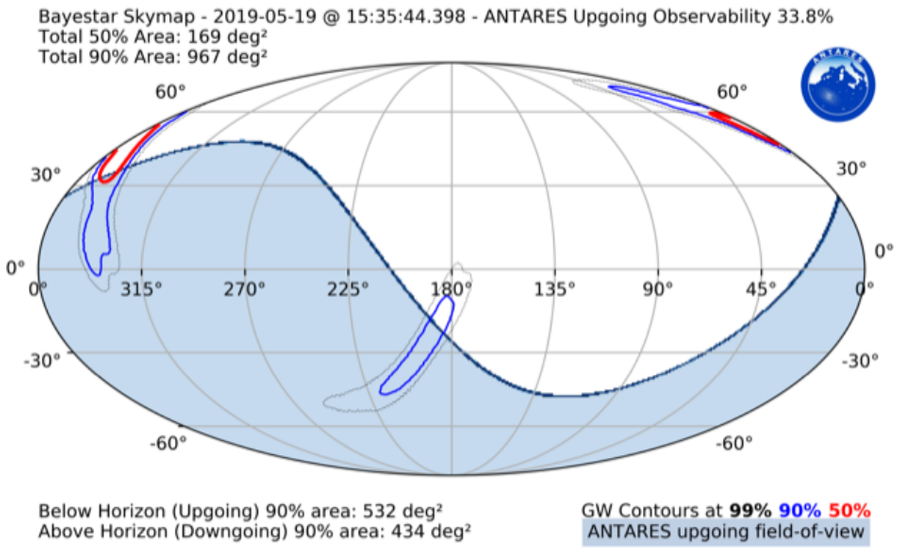
No significant correlation with GRBs/CCSNs/blazars found

+ANT150901: only public alert with a complete MWL follow-up

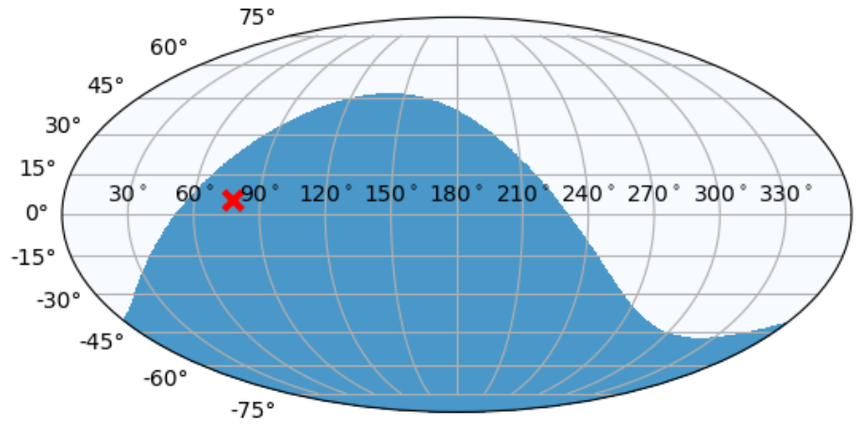
Examples of online ANTARES analyses

Follow-up of EM/MM triggers in real time: IceCube, LVC, GRBs, FRBs

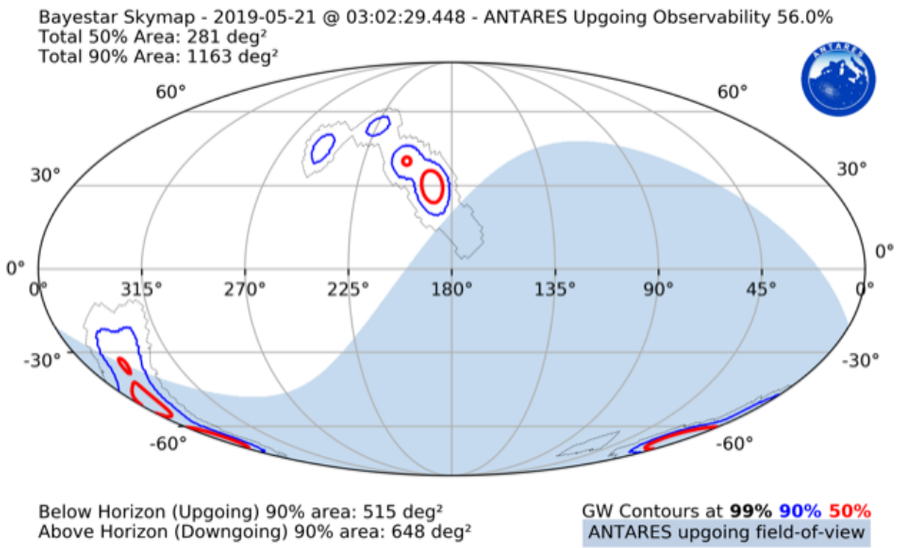
(±500 s & ±1 h)

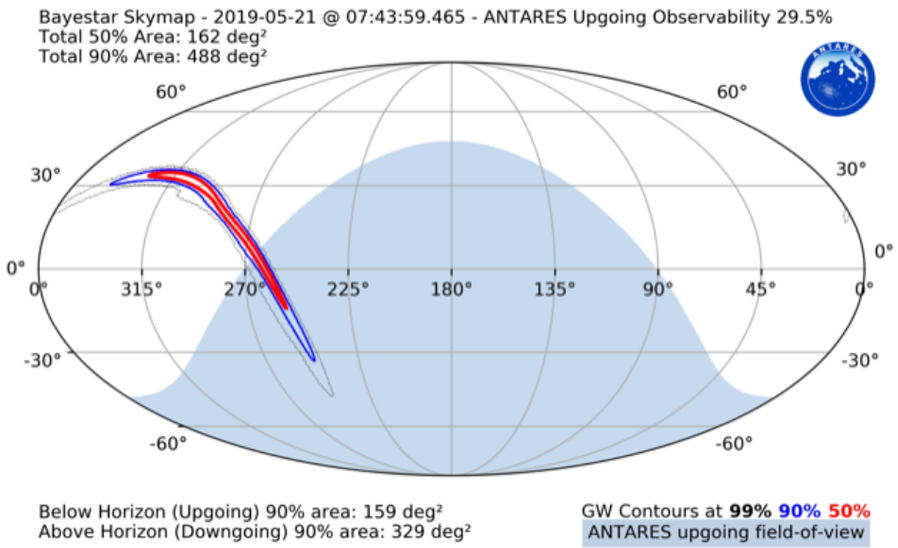


IC170922



The last 3 GW candidates by LVC S190519bj, S190521g and S190521r





Lessons from the ANTARES follow-up

Online processing:

- Quite large difference between the online calibrations used for the reconstruction and the offline ones used in the offline analyses (no dynamical positioning)
- No online shower reconstruction => need to implement it (important discovery channel)
- Reduce the systematics on the angular direction of the alerts (good control of the pointing accuracy)

Neutrino alert selection:

- As the results were not so good, better neutrino selections
- 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…)
- Private / public neutrino alerts (how to optimize the follow-up)
- Uniformise the alert format: only VO event

Real-time correlation analysis:

- Automatize the analyses as much as possible

Organisation:

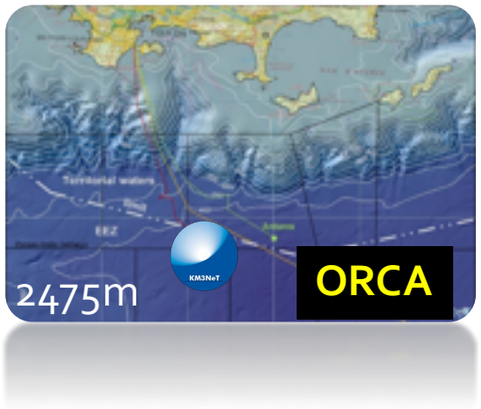
- Have a real organized team to manage the online analyses, not only a few persons. Reinforce the MWL follow-up expertise in the collaboration. Provide some centralized tools for the shifters

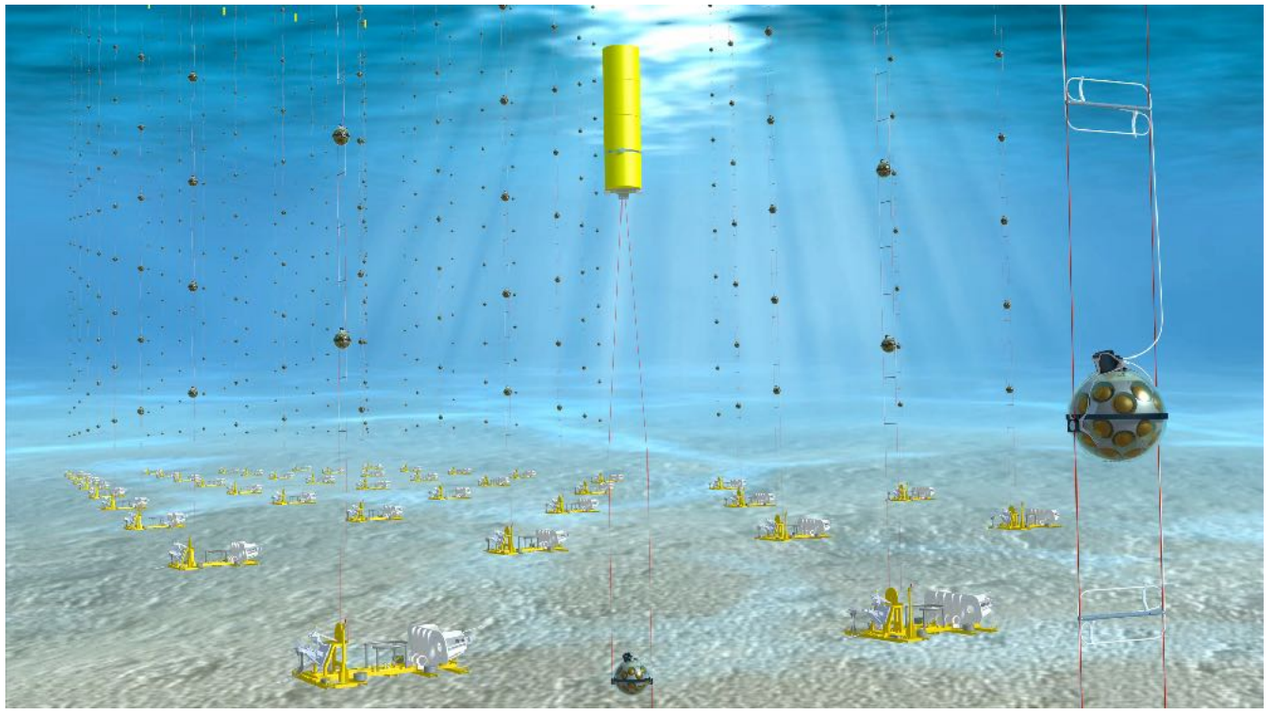
KM3NeT

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



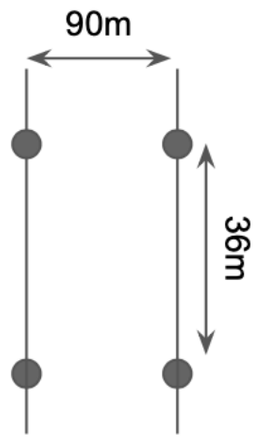


Astroparticle **R**esearch with **C**osmics In the **A**byss

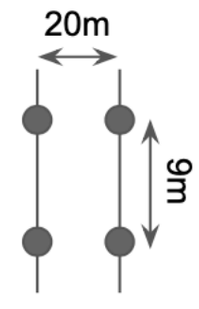
ARCA: off shore Capo Passero, Italy

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

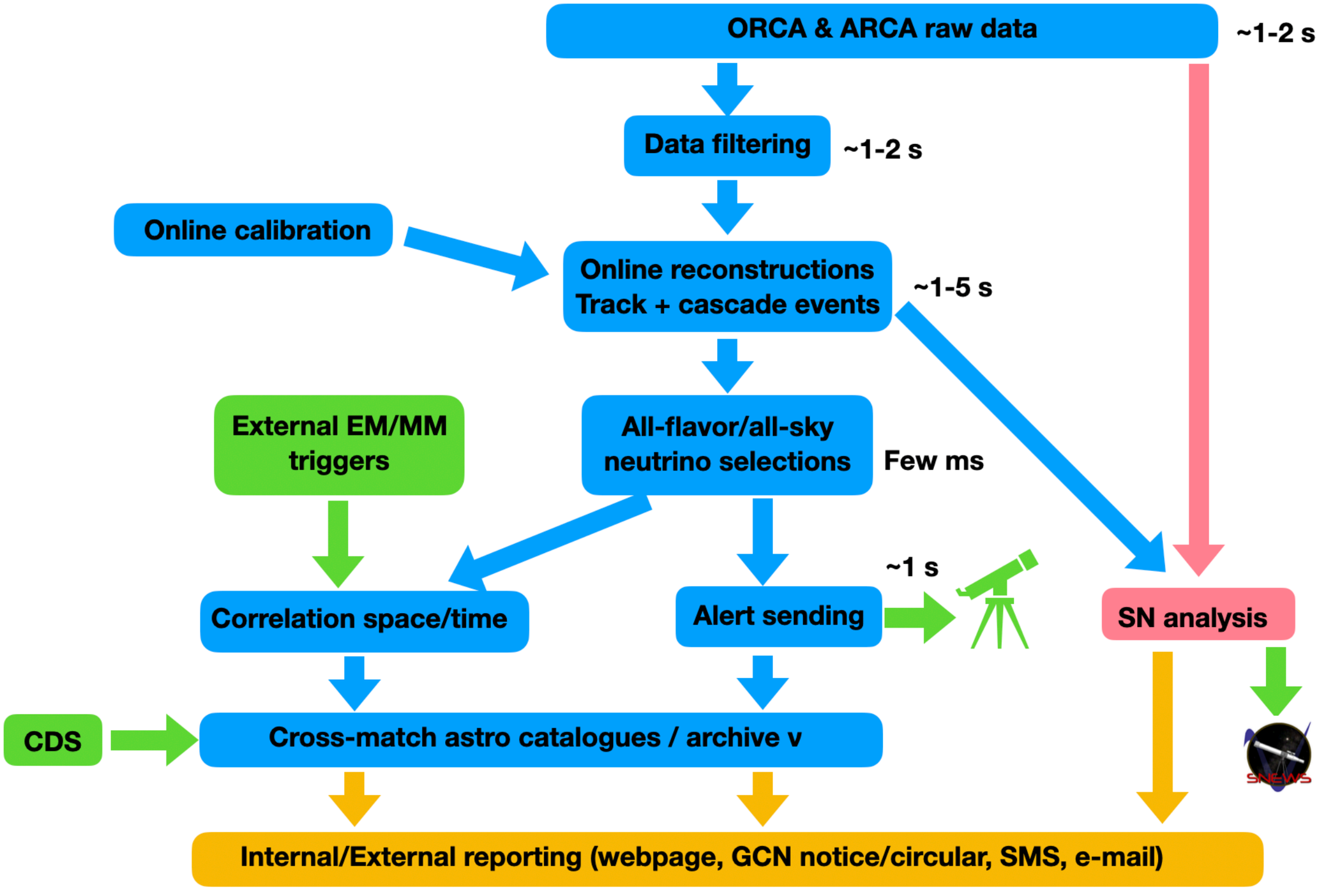


230 DUs, 128340 PMTs



115 DUs, 64170 PMTs

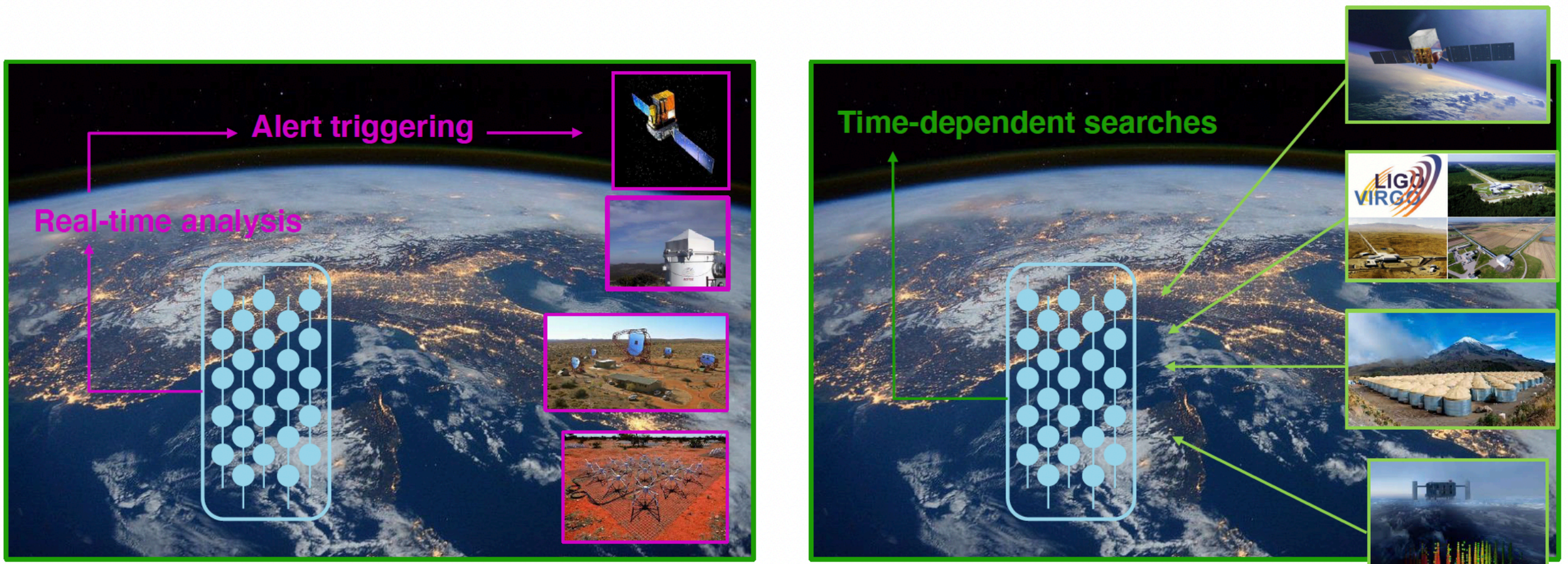
Real-time analysis framework



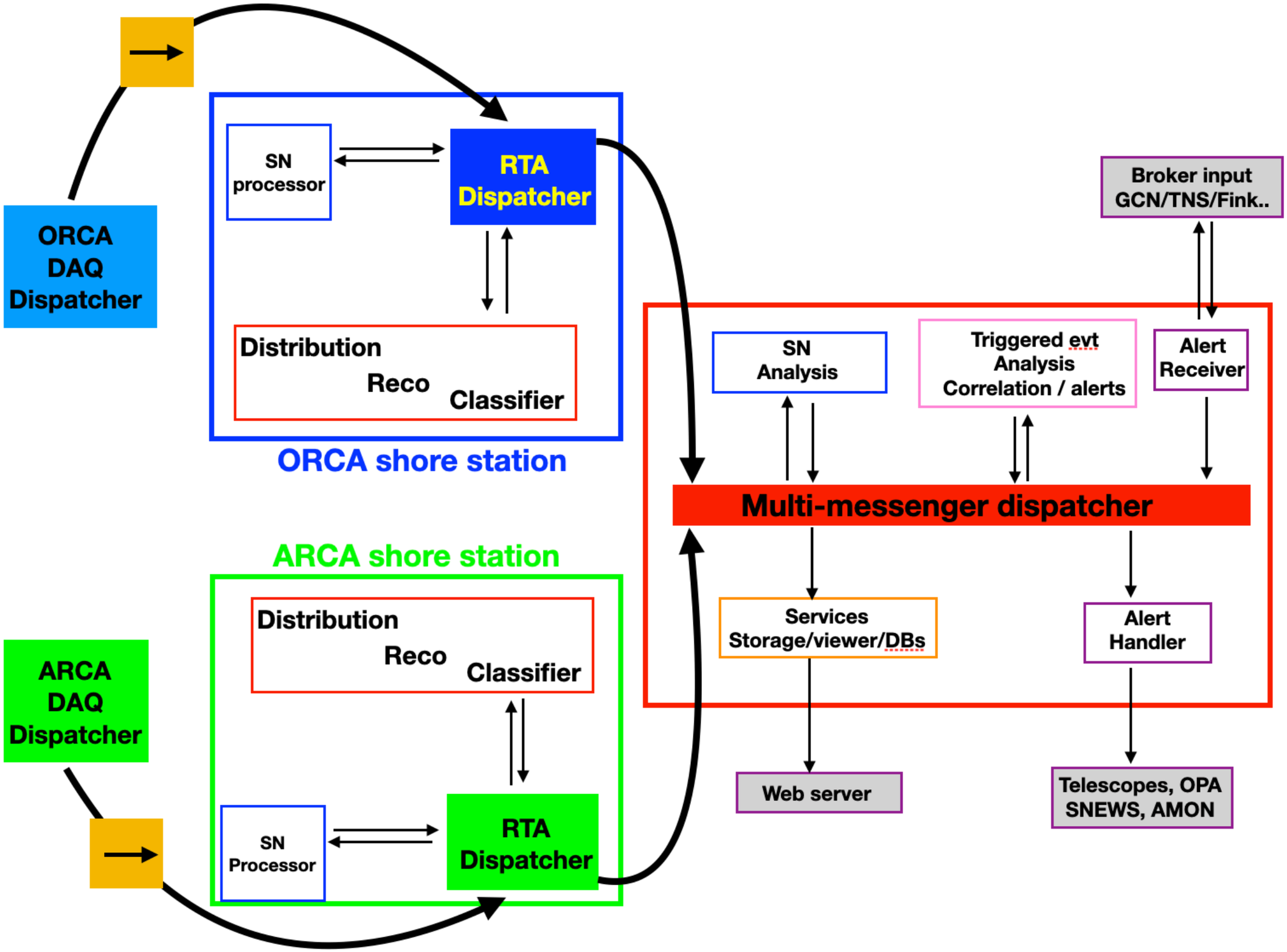
KM3NeT online physics framework

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…



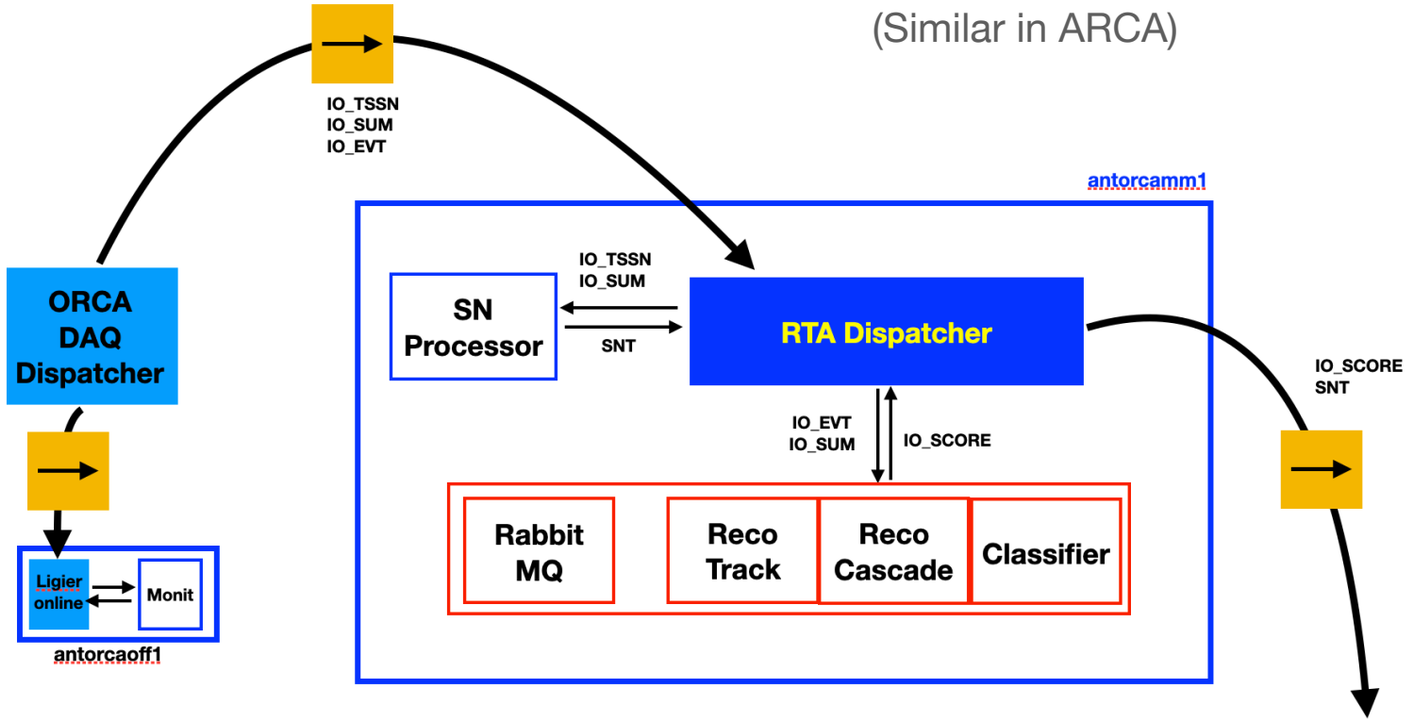
Real-time analysis framework

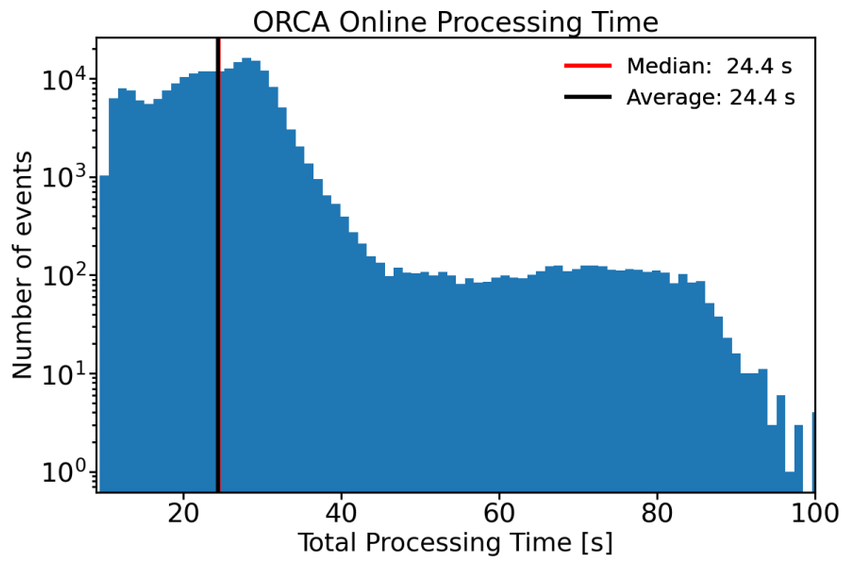


Real-time event processing

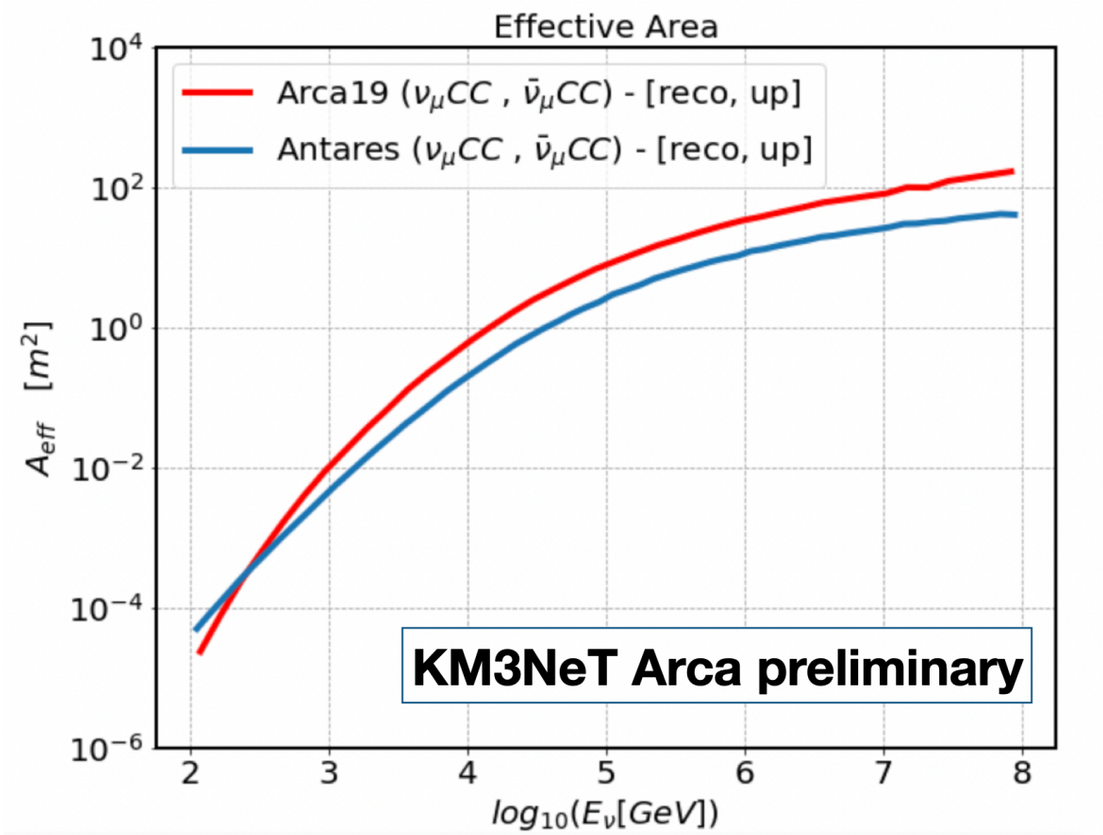
- **CCSN real-time analysis** (cf Talk I. Goos)
- **Triggered event processing**:
  - Calibration online (as close as possible as in offline including dynamical positioning)
  - Track & shower reconstructions (similar algorithms as offline)
  - Event classification (atmospheric muons-neutrinos, track-shower, 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)





Actual KM3NeT detectors



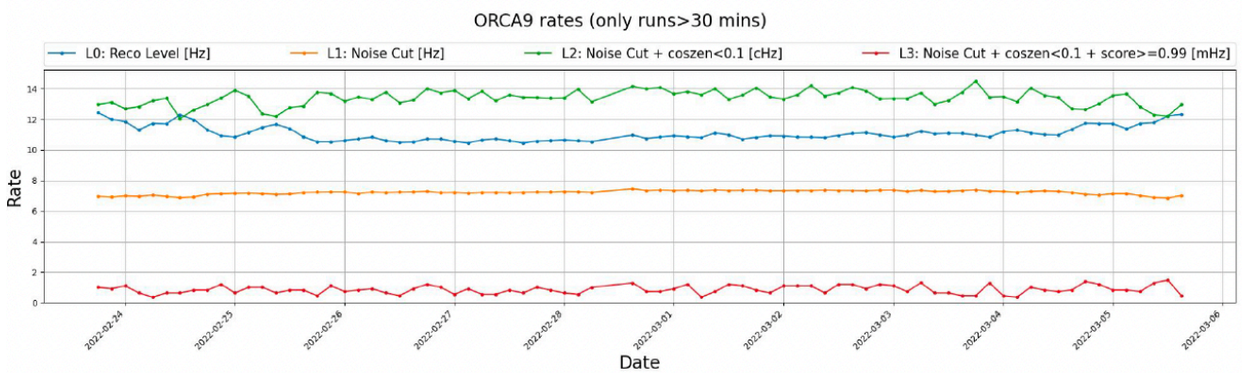
- **ORCA11 > ANTARES at LE**
- **ARCA21 > ~3x ANTARES at HE**

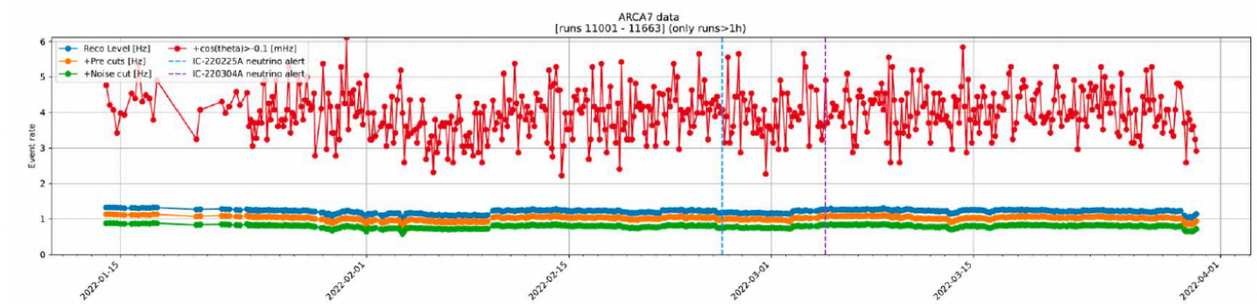
⇒ Continuous data flow since 1-2 years

⇒ 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

⇒ Not yet the cascade channel in operation





When it will be operational ?

- **What is working now ?**
  - Calibration online (without dynamical positioning)
  - CCSN analysis pipeline operational
  - Track & shower reconstructions on both detectors ARCA21 & ORCA11
  - Preliminary neutrino selections on both detectors
  - Transient correlation pipelines fully set. We will start the real-time analyses in October with the IC neutrino alert follow-up.
  - Most of the auxiliary tools are in place including shifter tools
  - Online physics analysis shifts starting Oct 2022 to test the system

=> <u>1st Atel issued by KM3NeT: Atel #15290</u>

<u>Still in progress:</u>

- Improving the control of the angular pointing of the neutrinos
- Implementation of the neutrino selection (multiple, VHE) for the alert sending
- Alert sending programs [ETA: Spring 2023]

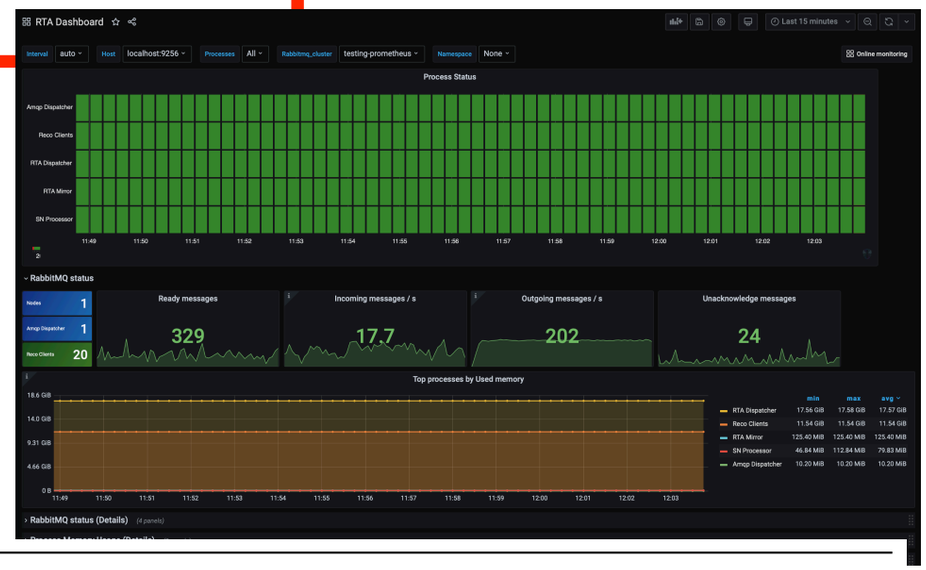
Online shifter organization

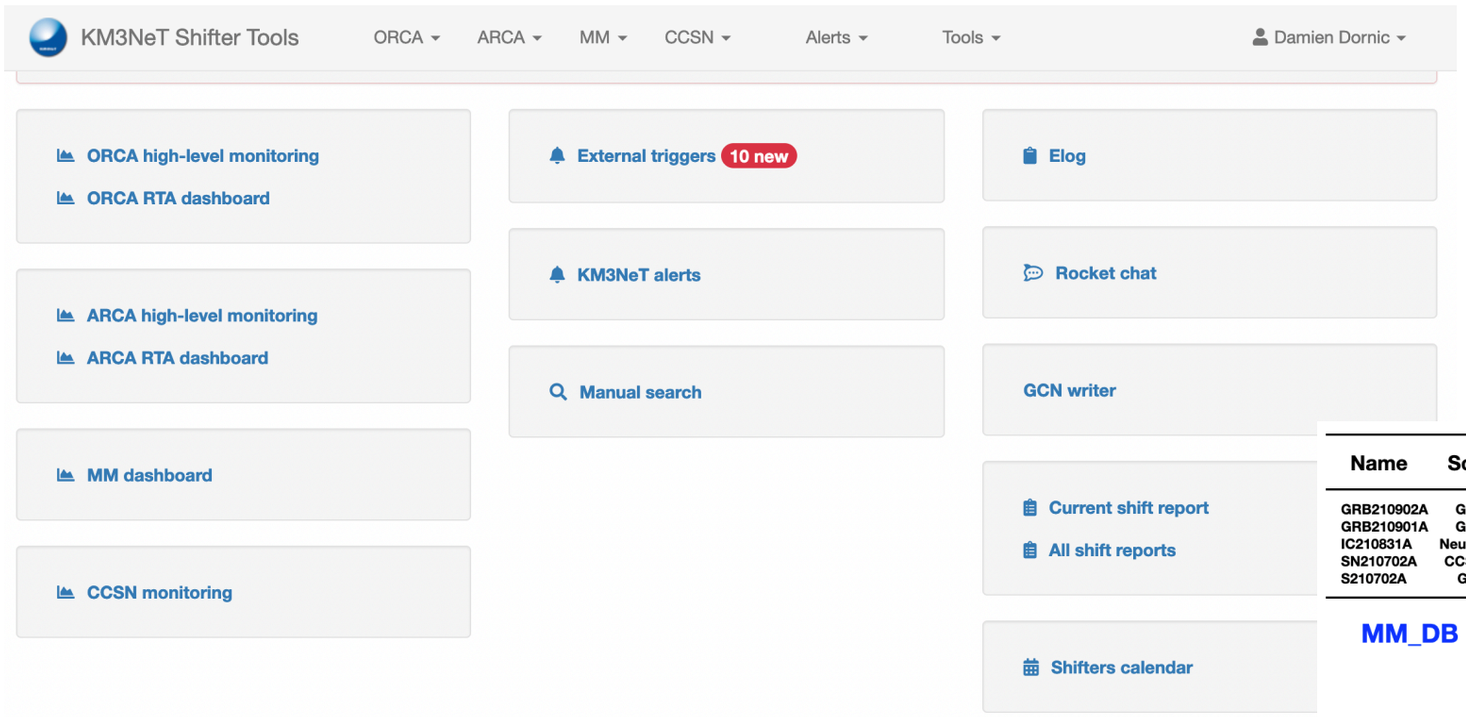
<u>Goal</u>: build an online analysis group that will take care of the real-time follow-up of the KM3NeT internal alerts and EM/MM external triggers.

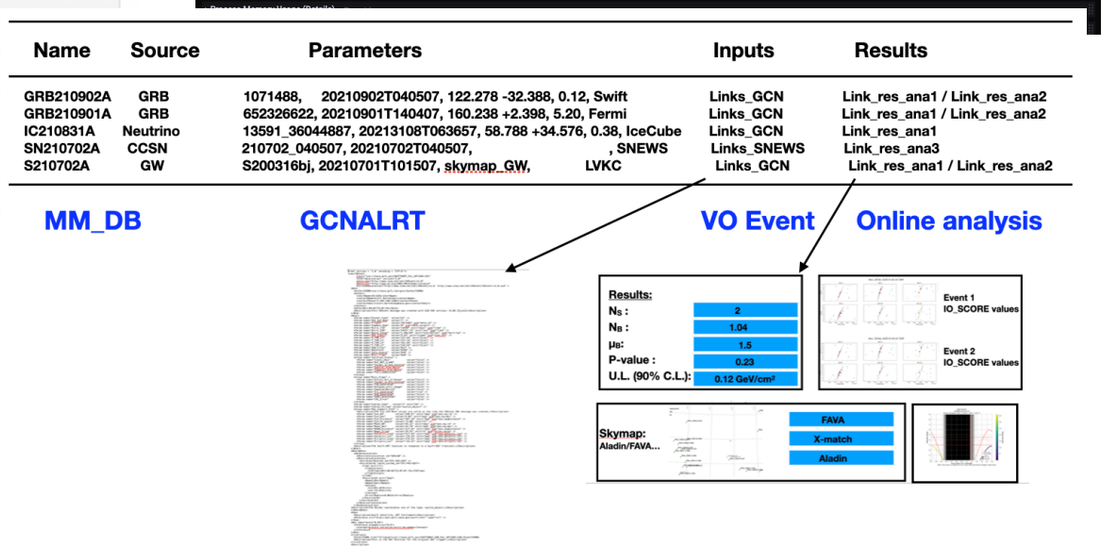
<u>Duties</u>:

- 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







Summary

→ Simultaneous MWL/MM follow-up is the key to resolve the neutrino sources (too few statistic in the neutrino side)

→ ANTARES online framework has been used the last 14 years to either send neutrino alerts (~300 alerts) and to perform space/time correlation analysis of external triggers (GW, IC nu, GRB…)

→ Based on this experience, we are building the KM3NeT real-time architecture with the same functionalities but more automatisation. The details of this architecture will be presented in S. Le Stum and G. Vannoye talks)

→ The work is well advanced and so far, we will online correlation analysis in October 2022 and the alert sending in Spring 2023.

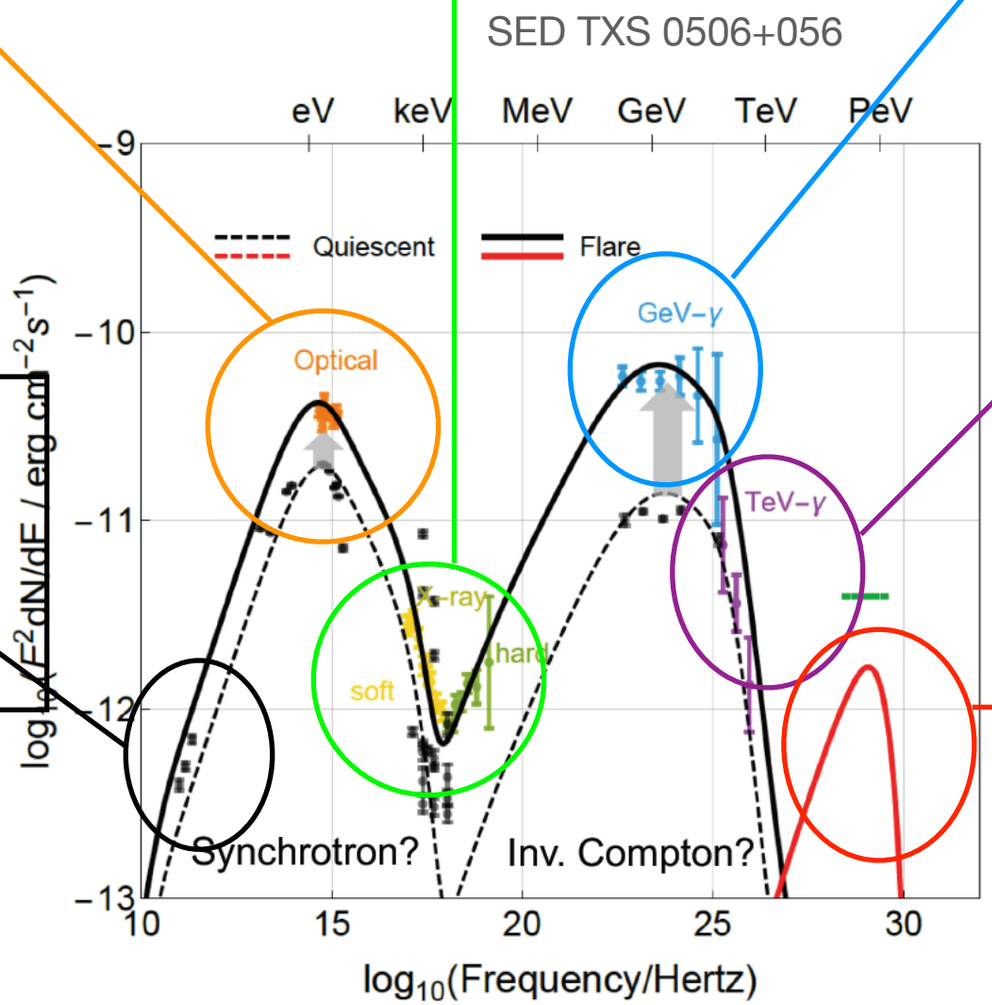
Multi-messenger synergies

Optical telescopes: TAROT, 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