Multi-messenger real-time analysis framework of the KM3NeT neutrino telescope

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On behalf the KM3NeT Collaboration

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Context

Open questions:

- Origin of high-energy cosmic rays: which sources? What acceleration mechanisms? Which source evolutions? (mysteries of UHECR ?)
- Origin of IceCube HE astrophysical neutrinos
- Disentangle astrophysical models with multi-messenger observations
- Study of galactic (and extra galactic) propagation of CR with neutrinos as tracers
- Test the neutrino sector of the SM and BSM physics

So far, GW170817, IC170922, ANT150901, etc have demonstrated the capabilities of doing real-time multi-messenger follow-ups:

- Most of the HE sources are time-dependent with the flux quickly varying

- Provide accurate positions (required for redshift, host measurements)

- Maximize the scientific return of this event having a larger and more complete follow-up.

- Achieve simultaneous observations of transient phenomena by pointing instruments (so important for the modelisation)

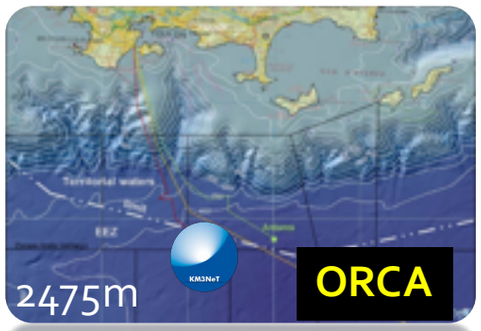
- Determine the nature of a single event

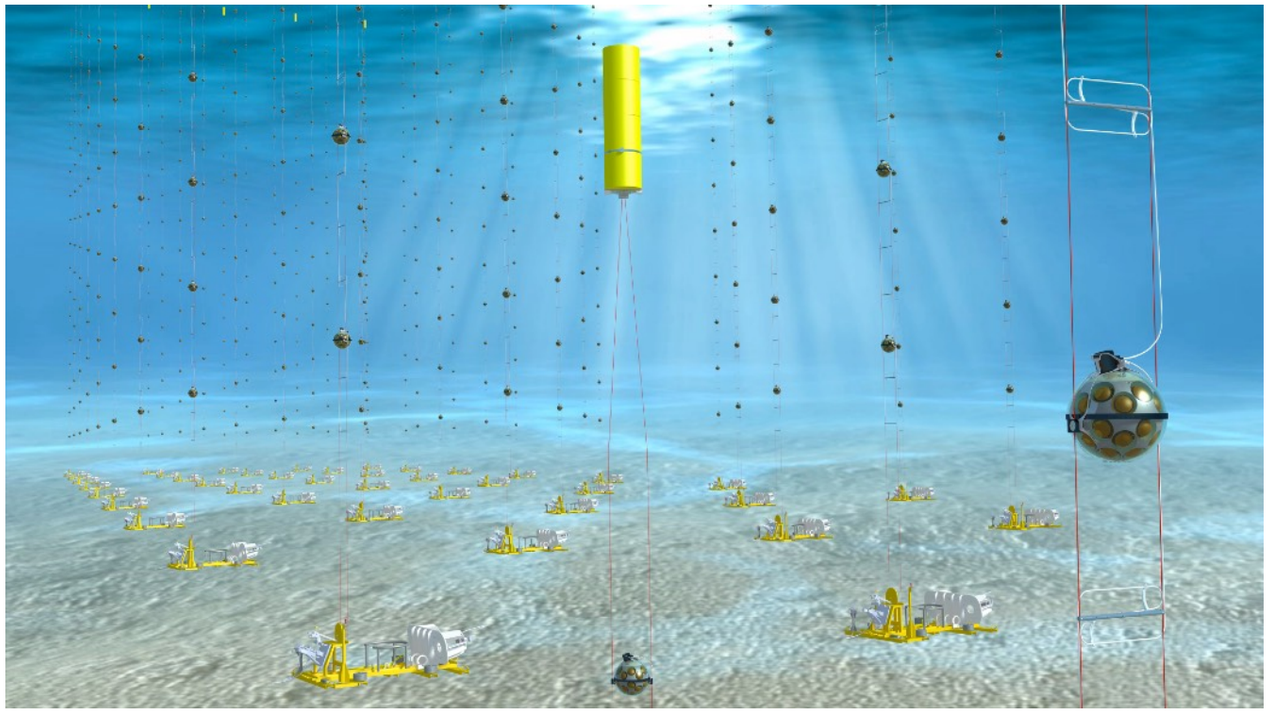
KM3NeT

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:

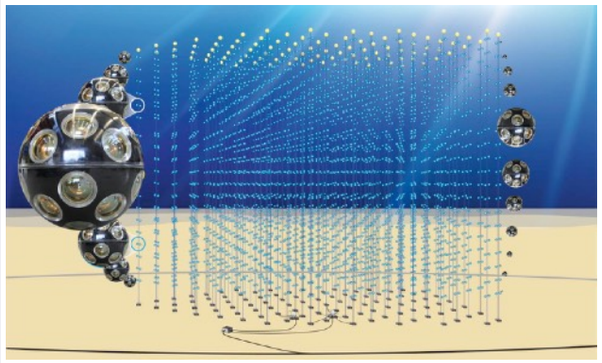
- Extended energy range: 3 GeV → 10 PeV (+ 10-40 MeV)
- Full sky coverage with the best sensitivity for the galactic sources
- High duty cycle (> 90-95%)
- All-flavour neutrino detection
- Good angular resolutions

⟹ Construction on-going: 1 DU working in ARCA & 4 DU in ORCA + 2 DUs ready for deployment in ORCA (+300 DOMs builded)

⟹ Mid 2020, better sensitivities than ANTARES in the whole energy range.

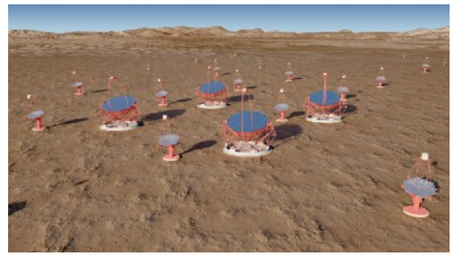
KM3NeT multi-messenger analyses

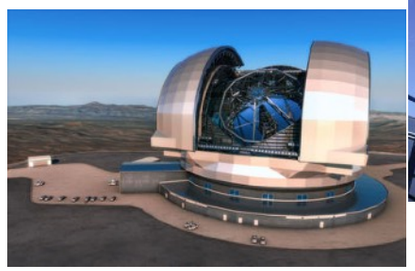
KM3NeT

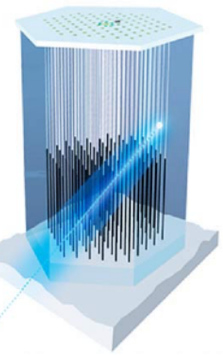


- **Follow-up of neutrino alerts**
- **Joint sub-threshold analysis**

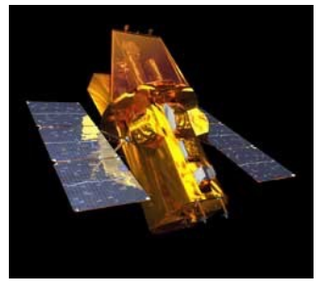
EM/MM external communities







- **Follow-up of EM/GW alerts**
- **Offline time/space correlation search with catalogues (GRB, AGN, XRB, SN, FRB…)**



- **ARCA dedicated to neutrino astronomy:**

  $\Longrightarrow$ Tracks (100 TeV - 10 PeV) with the excellent angular resolution (<0.2º)

  $\Longrightarrow$ Cascades (100 TeV - 10 PeV) thanks to the good angular resolution (1-2º) taking the advantage of the low atmospheric background contribution

- **ORCA can do also astronomy:**

  $\Longrightarrow$ Tracks & cascades at low energy (few GeV - 10 TeV), looking for time/space clusters

  $\Longrightarrow$ Example sources: winds of binaries, chocked GRBs, hidden jets in core-collapse SN

- **ORCA & ARCA:** detection of MeV neutrinos from core-collapse SN

ANTARES online framework

ANTARES Shore Station:
O-line reconstruction
Trigger decision
Alert message (GCN format)
Online follow-up of external triggers

EM transients (GRB, FRB, blazar flare, ccSN, etc)
IceCube neutrinos
GW events from LVC

ANTARES
Neutrino Telescope

Real time

Low latency alerts (<10 sec)

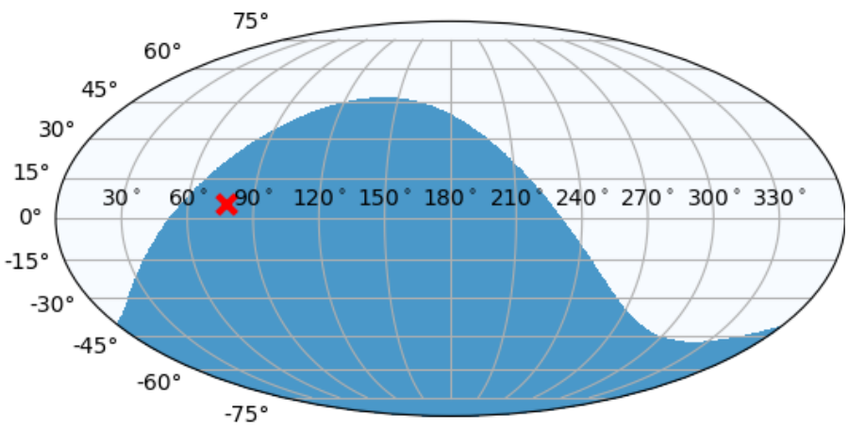
- 292 alerts sent to robotic telescopes [84 DIR + 208 HE]
- 17 sent to Swift
- 15 sent to Integral (3 followed)
- ~20 to MWA (4 followed)
- 2 to HESS

Examples of online ANTARES analyses

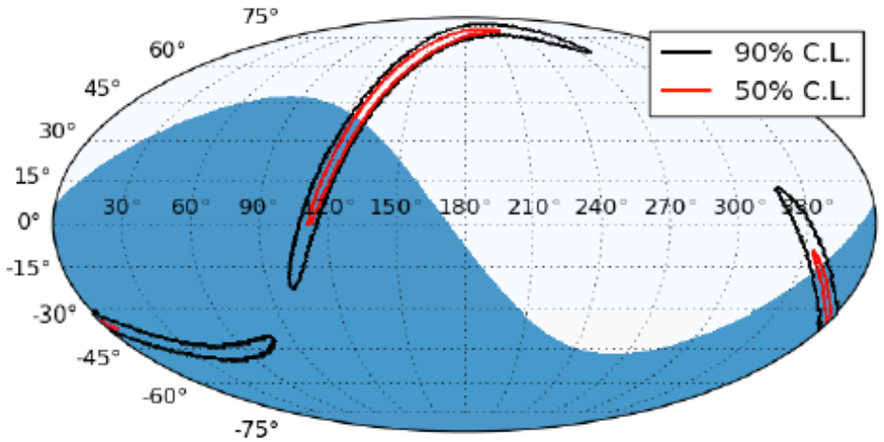
Follow-up of EM/MM triggers: IceCube, LVC + GRBs, FRBs

(±500 s & ±1 h)

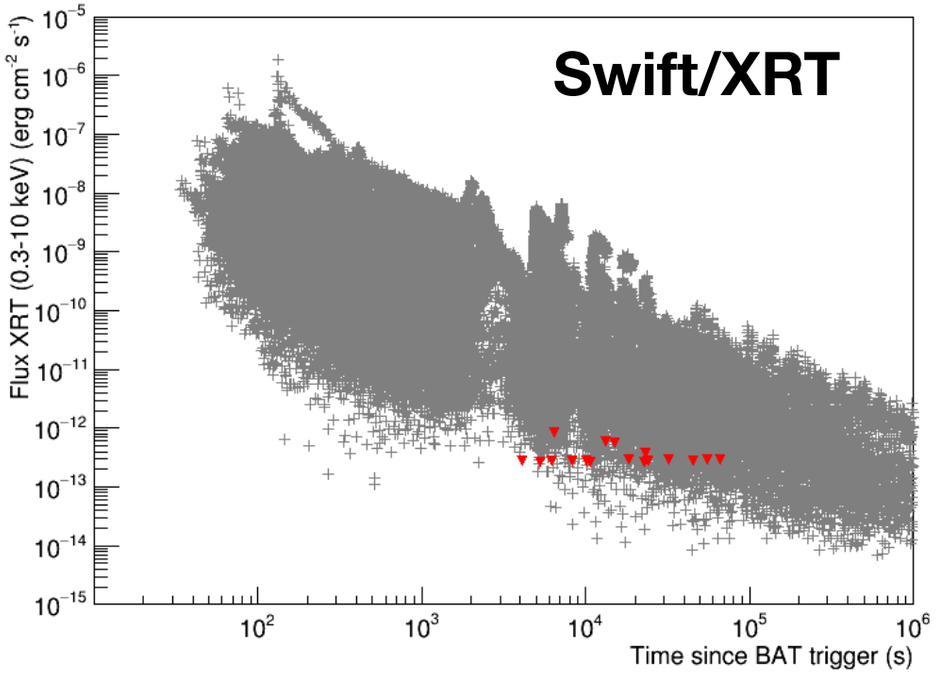
IC170922

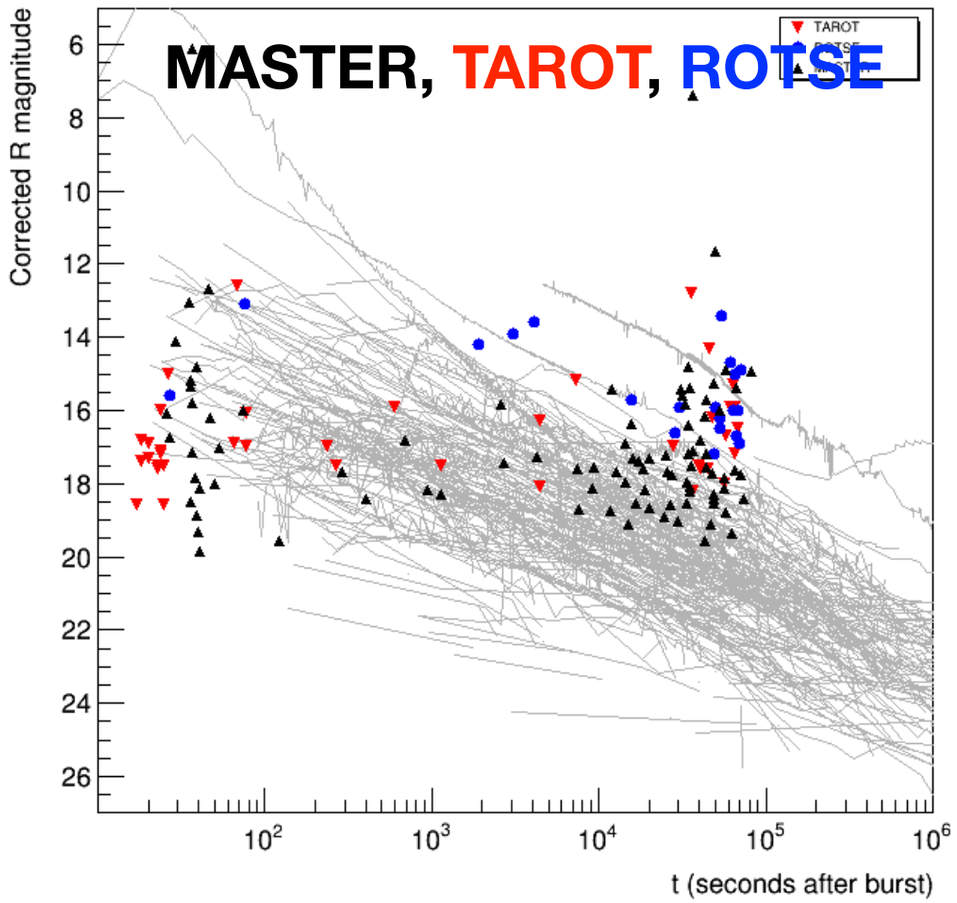


GW170104

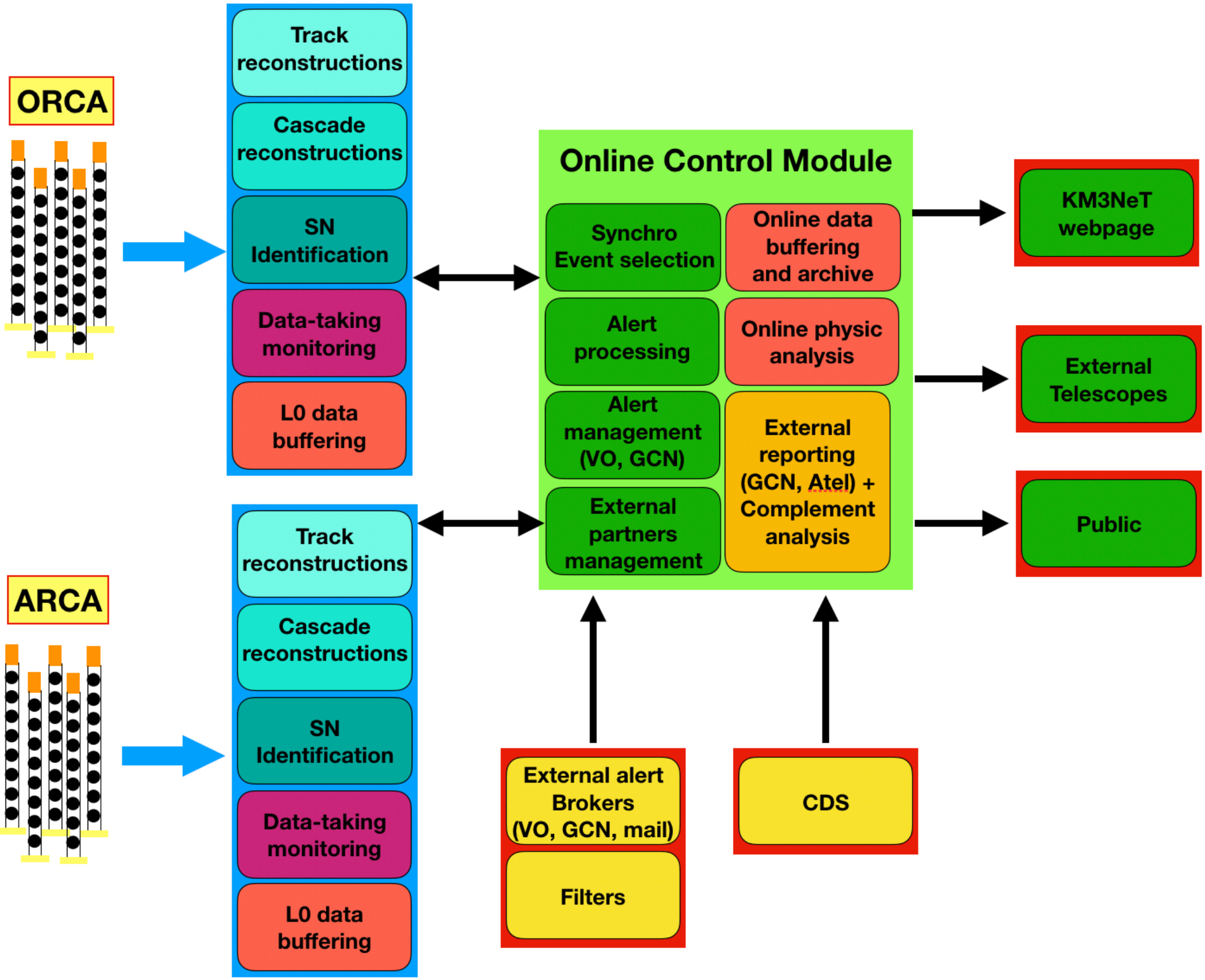


Follow-up of ANTARES alerts





KM3NeT real-time framework



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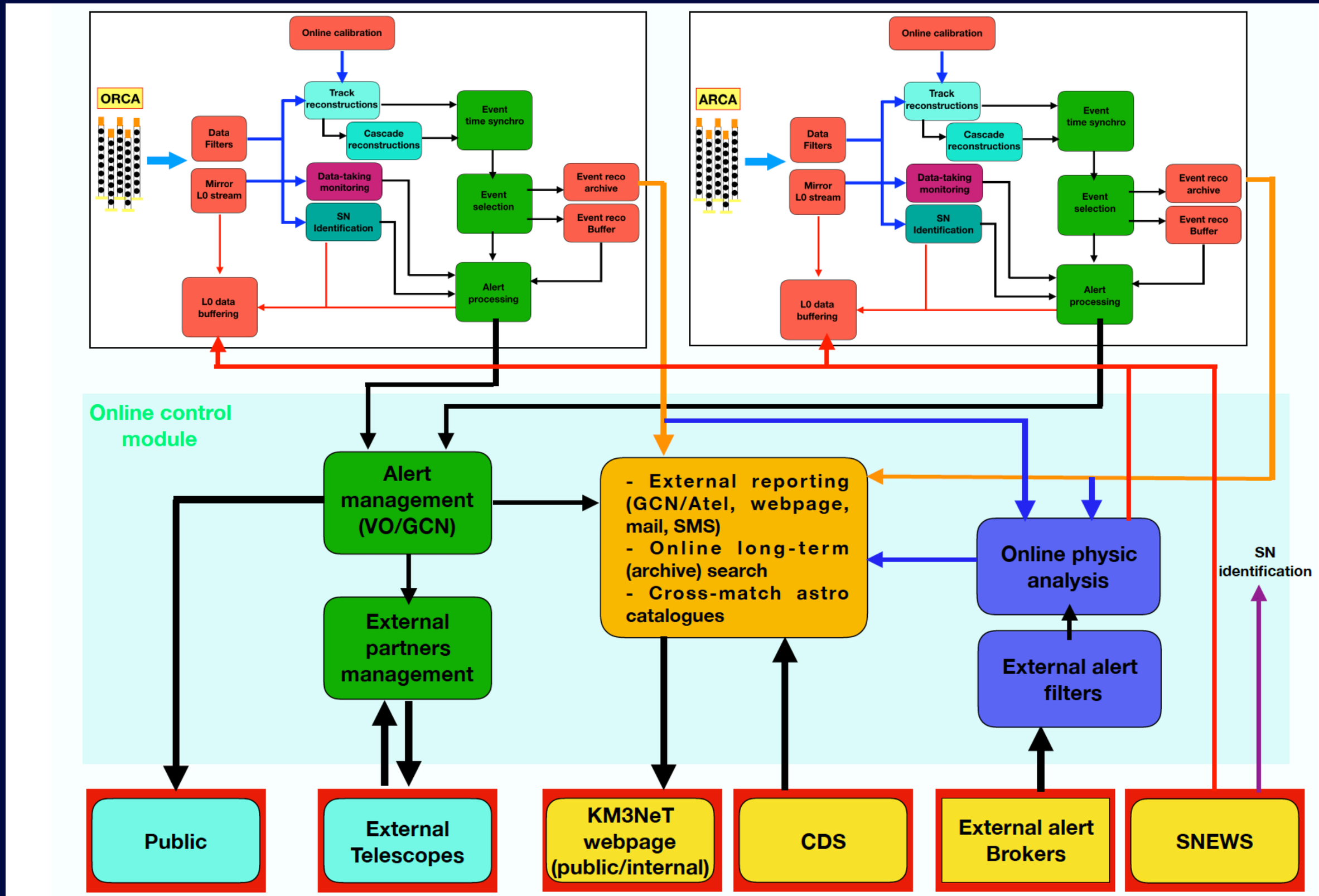
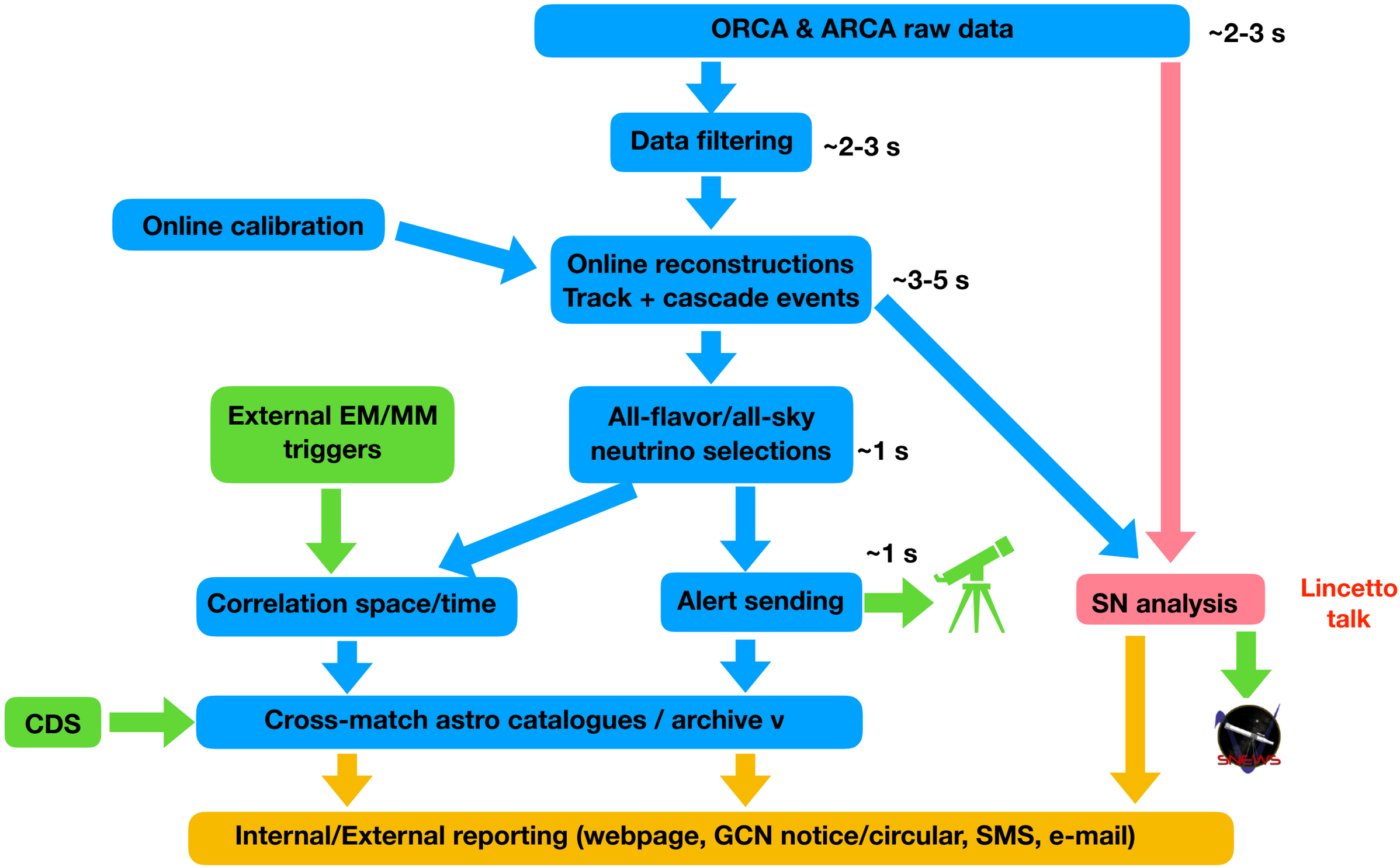
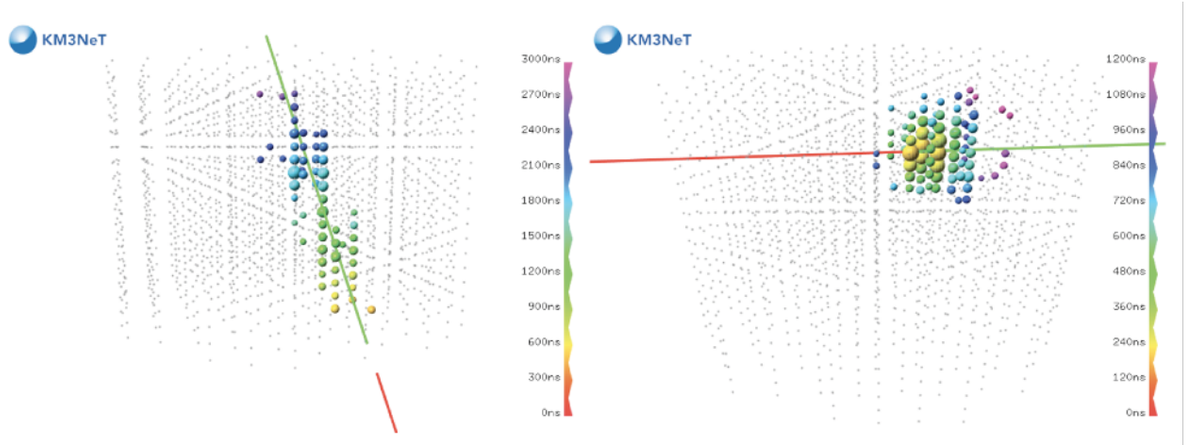


KM3NeT real-time framework



Online event reconstructions

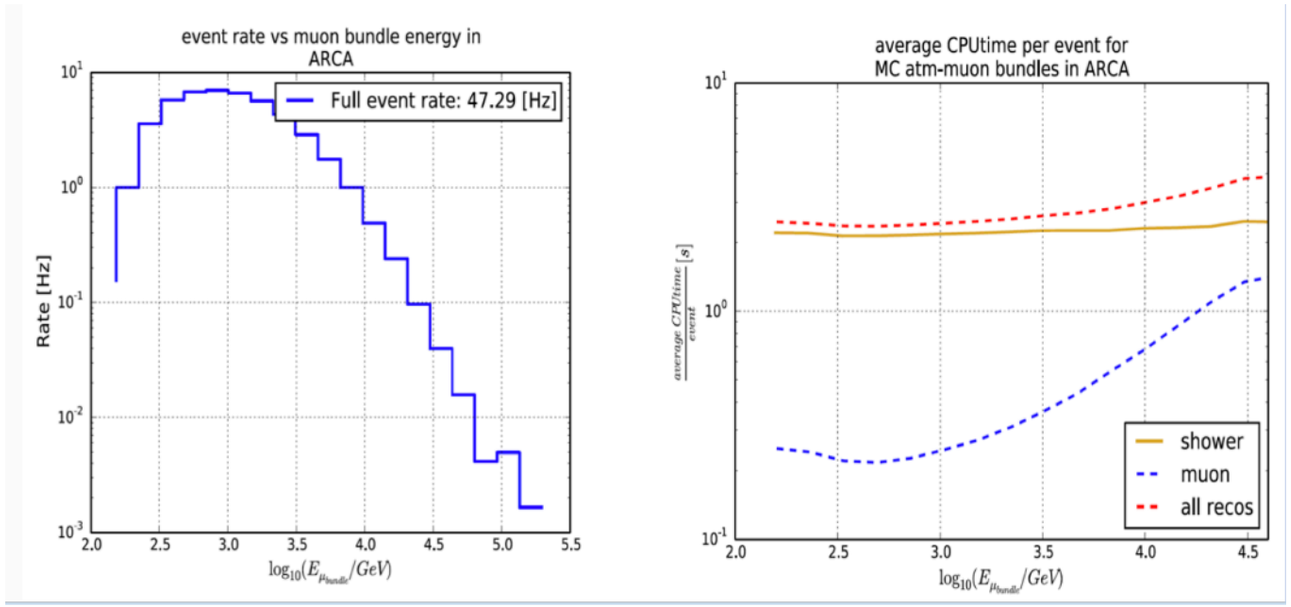
*** All-flavor (track+cascade) event reconstructions: same framework and the same reconstruction tools as in offline**



Tracks:
ARCA: < 0.2º (>10 TeV)
ORCA: 1 - 2º (100 GeV - 1 TeV)

Cascades:
ARCA: 1.5 - 2º (>10 TeV)
ORCA: ~4 - 5º (100 GeV - 1 TeV)

*** Time to reconstruct all events: Trigger rate: ~100 Hz ⟹ Neutrino rate: 1-2 mHz**



SHOWER;	
90TeV < E_ν < 110TeV	2.30 sec/event
900TeV < E_ν < 1100TeV	2.80 sec/event
TRACKS	
90TeV < E_ν < 110TeV	0.85 sec/event
900TeV < E_ν < 1100TeV	1.95 sec/event

⟹ Need 2 farms of 200 CPUs

Sending alert system

Alert sending policy:

➡ Typical alert rate: few per month

➡ Standard alerts will be distributed through private channel to observing teams upon MoU agreements like ANTARES.

➡ After a commissioning phase, notable events will trigger alerts that will be distributed publicly to the astro community [**Open Public Alert program**]

Alert distribution:

➡ Distribution via the GCN network

➡ Message: VO event (XML file)

➡ Tool used: Comet

➡ Several brokers for public and private alerts for both KM3NeT detectors

Reporting:

➡ SMS/e-mail to alert KM3NeT shifters

➡ Automatic GCN notices in case of very interesting neutrino signals

➡ KM3NeT subgroup shifters (check detector stability, update reconstructions, etc)

➡ GCN circular sent for refined information or identified counterpart (+ retraction).

➡ Results displayed in public/internal webpages

KM3NeT online - VO

Online Demands:

1- Standardize KM3NeT VO Event and transport protocol
2- Archiving VO Event
3- Search for potential interesting EM sources in catalogues
4- Cross-correlation between astrophysical + neutrino catalogs

KM3NeT VO Event and transport protocol

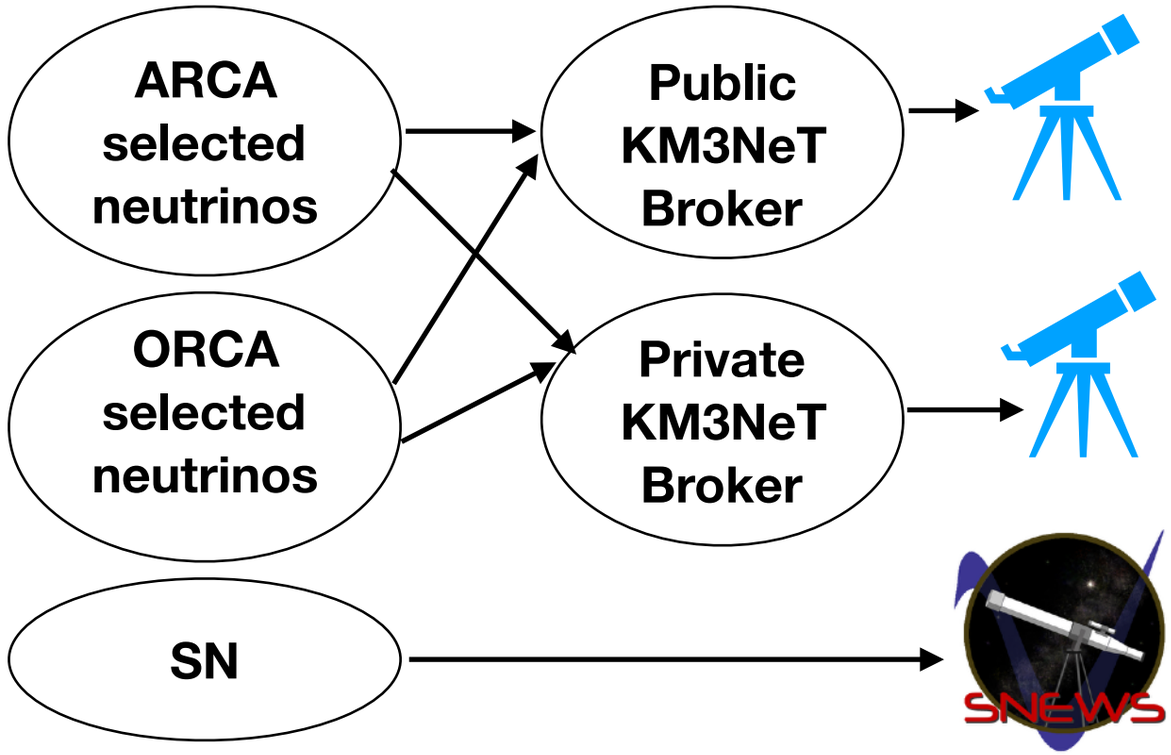
ANTARES alert distributions:
* GCN socket: TAROT, ZADKO, MASTER, INTEGRAL
* VO Event: MWA, HESS, SVOM, AMON
* Mail: Swift

For ANTARES, neutrino information is private. Need MoU with external partners.

Alert Message: Only one real-time message
* ID
* Time,
* RA, DEC, error 50%
* Energy proxy
* Reconstruction quality
* probability neutrino
* Multiplicity, type of trigger

For KM3NeT: define a standard VO event:
* ID
* Detector (ORCA/ARCA)
* Time
* RA, DEC, error 50%, 90% (TBC)
* Energy estimate
* Reconstruction quality
* Probability neutrino
* Type of neutrino
* Multiplicity
* Type of trigger

KM3NeT VO Event transport protocol



*** Up to now, we are using Comet to transport our alert.**
*** Do we need to separate more the brokers for the different alert streams: public/private, different of trigger types, sites, neutrinos, etc.**

Archiving online VO Events

Up to now, we are archiving the messages of the alerts in ascii logbook files.

For KM3NeT, we want to find a better way of archiving directly the VO events (link to KM3NeT DB) and have the possibility to import these alert catalogues in the standard astronomical tools (same format as the KM3NeT public event release).

Search for potential interesting EM sources in catalogues

Answer in real-time to the question: are there some potential interesting sources in the neutrino fields ?

For ANTARES, I am using manually Aladin and Simbad to look for catalogued sources + Fermi catalogues (4FGL, FAVA) and TeVcat for the VHE gamma-rays. Then, I am writing a report and distribute to the online group.

$\Longrightarrow$ For KM3NeT, we want to do this task in real-time automatically. Start with X-ray and (VHE) gamma-ray catalogues

$\Longrightarrow$ Automatize Aladin/TopCat and add results in an API ?

$\Longrightarrow$ What about adding the timing information (flaring sources ?). A kind of TAP for Fermi, X-ray flaring sources ?

Also, this can help to provide tiles for the small FoV telescopes for the follow-up of cascade neutrinos (~10 sq deg error box).

Summary

- **Despite its small size, ANTARES has performed plenty of multi-messenger analyses with more than 10 years of data, some really competitive with IceCube. Existing experiences for setting KM3NeT multi-messenger program.**

- **By observing astrophysical neutrinos with an unprecedented angular resolution, an extended energy range and a full sky coverage, KM3NeT will play a key role.**

- **The construction of ORCA and ARCA is on-going. First data looks good and first data analysed to validate the detector performance.**

  $\Longrightarrow$ Setting the data acquisition using standard tools (IVOA, ASTERICS, CDS) and prepare the multi-messenger analyses.