Neutrino alerts and follow-up challenges

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Neutrinos in the multi-messenger era - Louvain - 30/11/2022

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
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Multi-messenger alerts

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

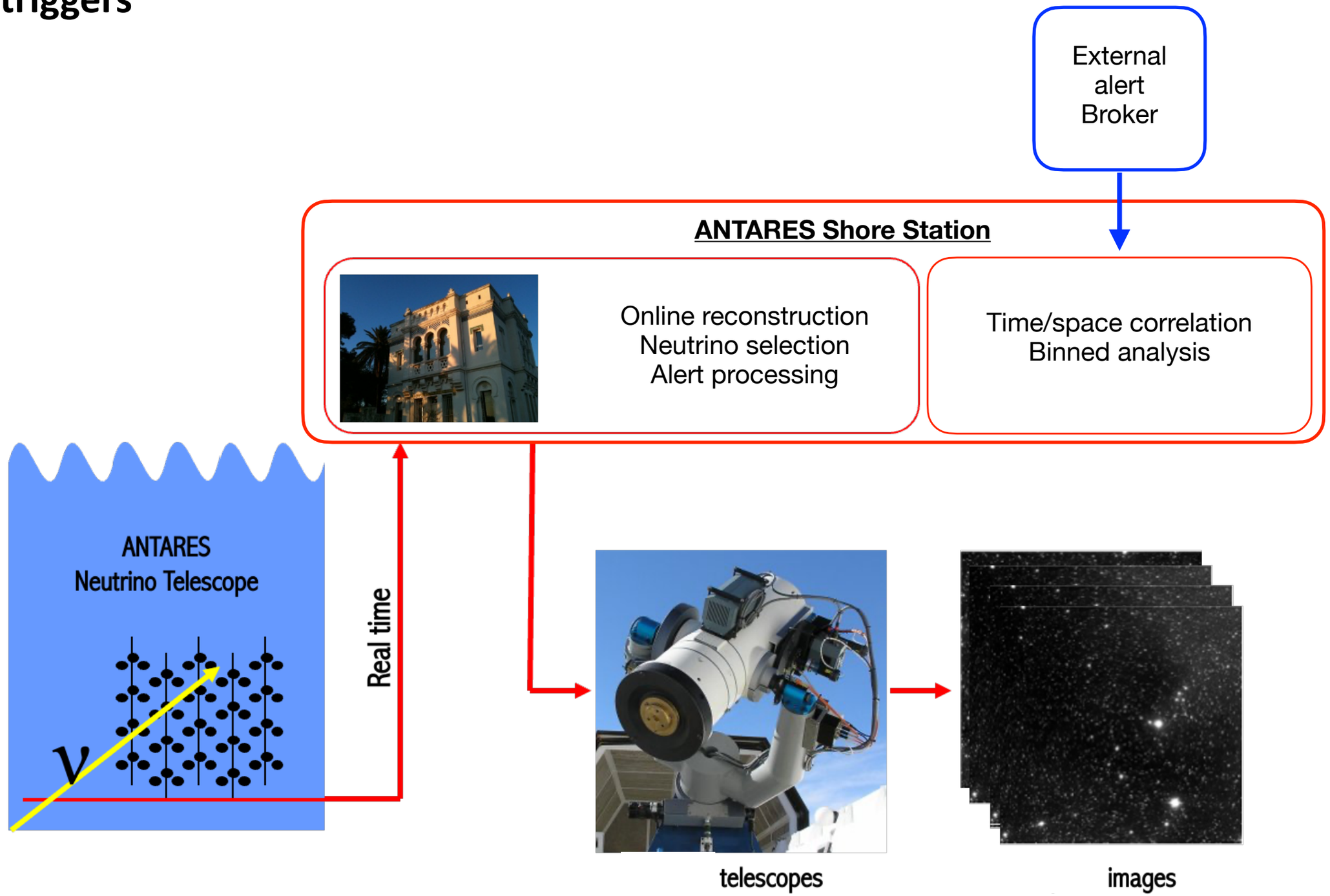
- **Alerts to community upon detection of likely « astrophysical » neutrinos for rapid follow-ups**
- **Real-time searches for neutrino signals in response to transient events observed in other messengers**

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**

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

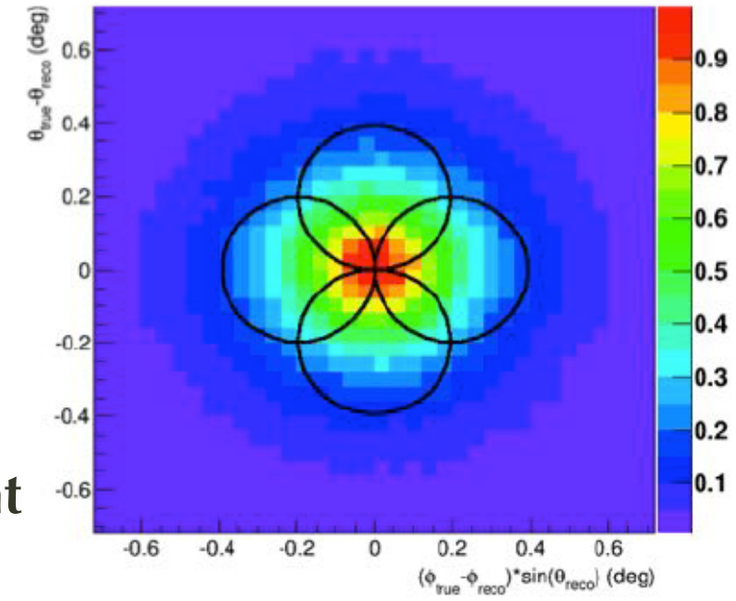


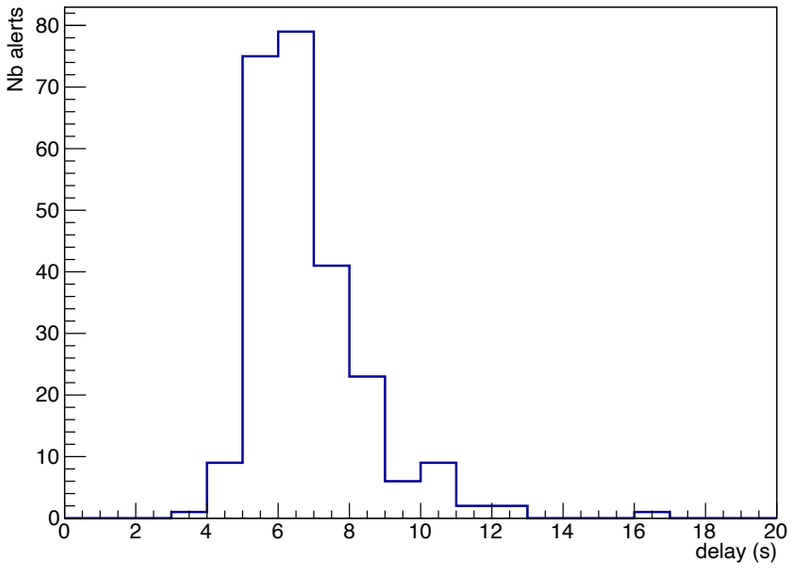
ANTARES neutrino alerts

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

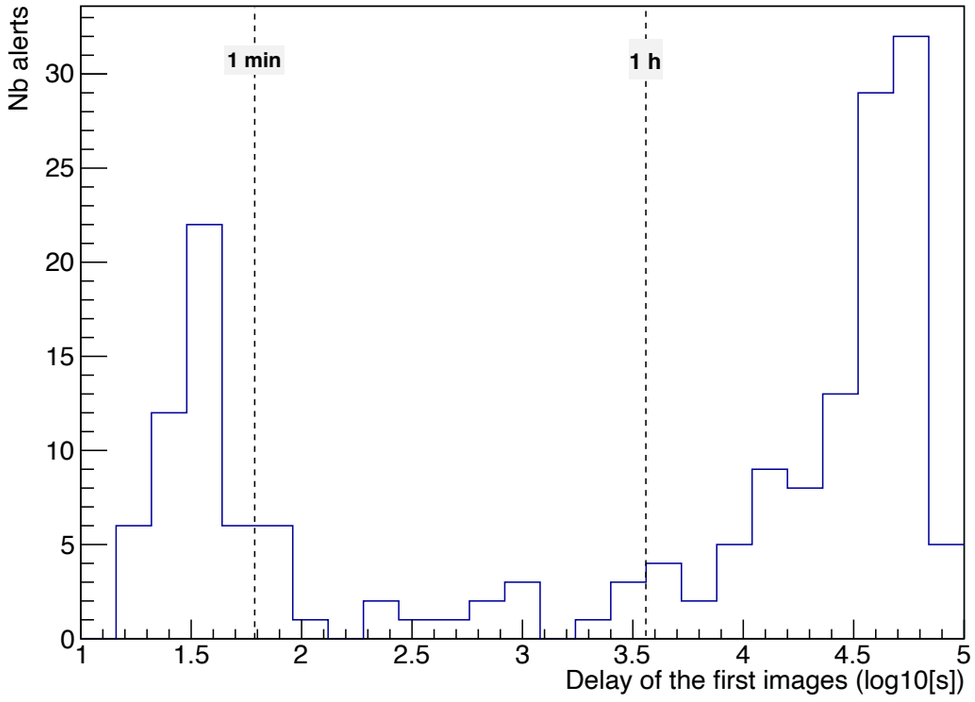
Private alert except if a potential counterpart is founded

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

⟹ 218 alerts < 1 day

⟹ 55 alerts < 1 min

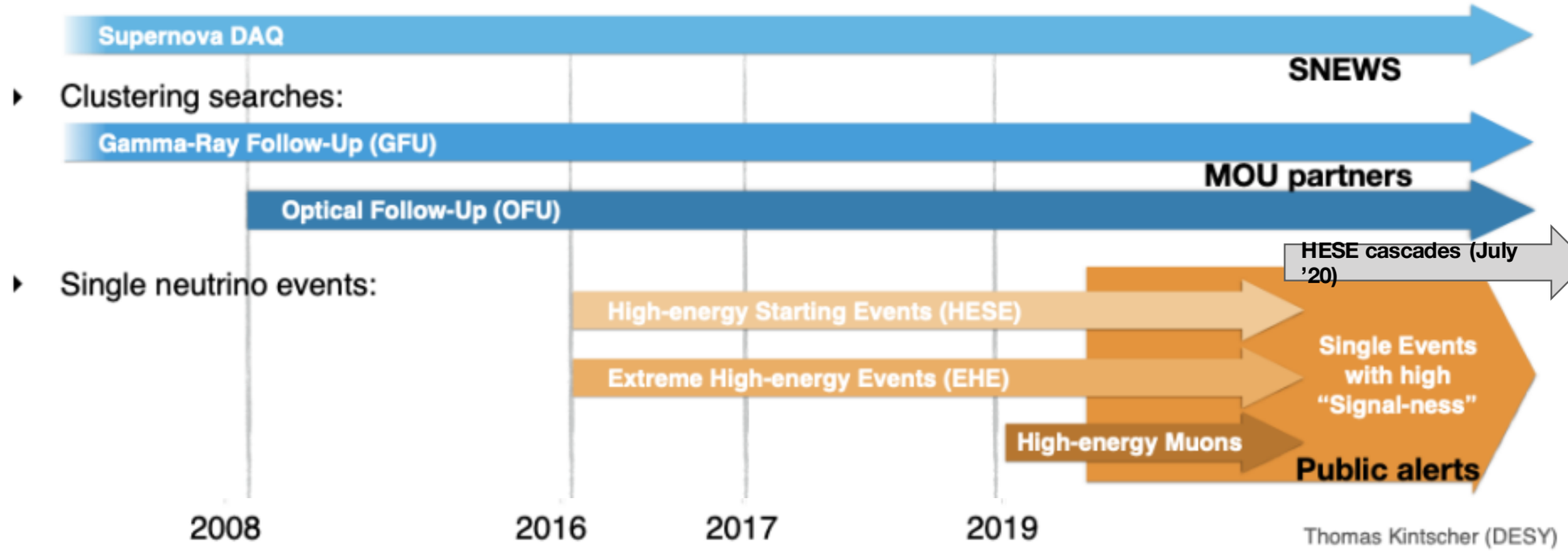
(wait for the alert visibility, stop previous acquisition, point the telescope, start the acquisition)



ANTARES, Astroparticle Physics, 2012, 35 (8)

IceCube neutrino alerts

IceCube is sending a broad list of alerts mainly centered in muon neutrino tracks

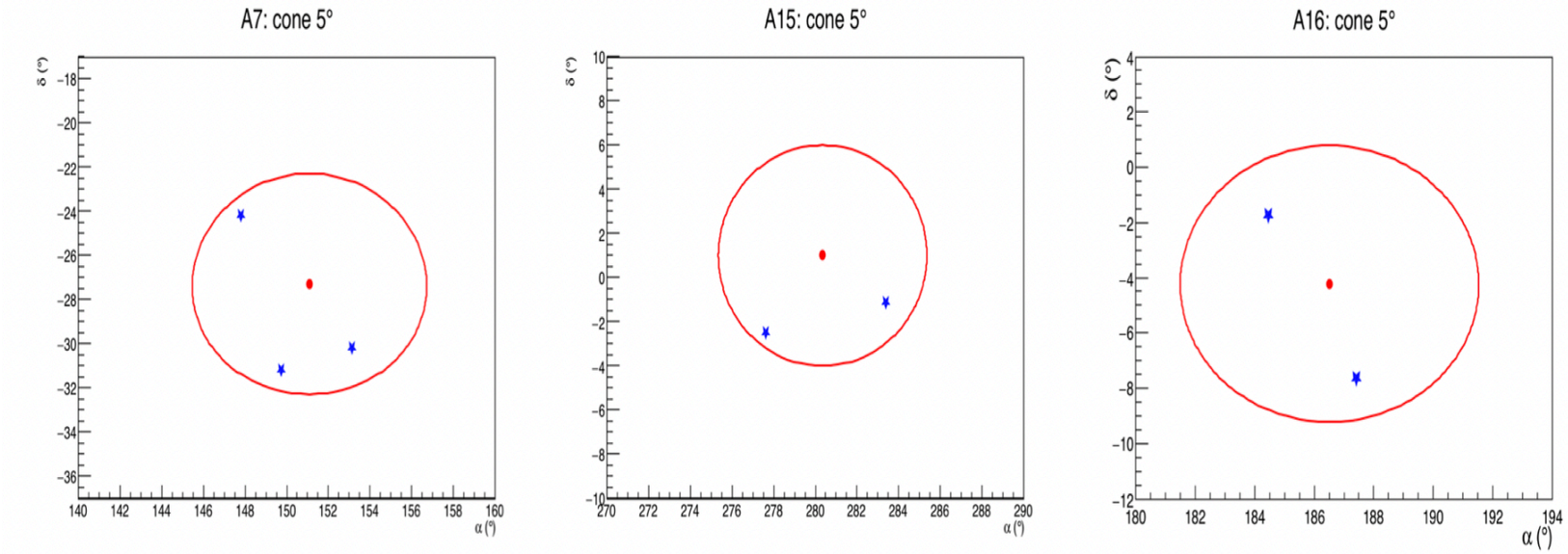


Updated selection: GOLD / BRONZE single events

- Improved background rejections
- Added through-going track selections
- "Signalness" = N_{Signal} / (N_{Signal} + $N_{Background}$)
- 2 classifications:
  - GOLD : > 50% signalness
  - BRONZE : > 30% signalness

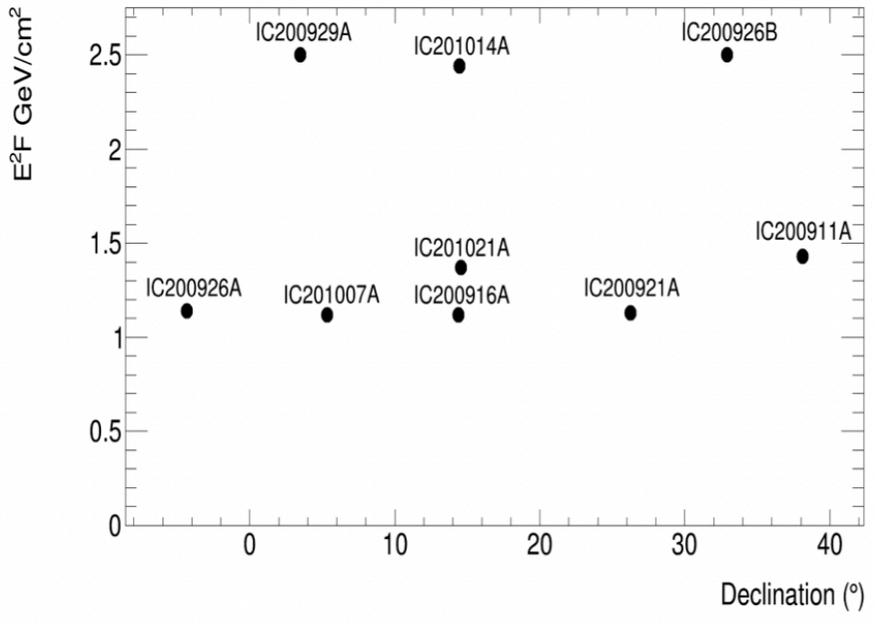
GVD

So far, GVD has not sent any neutrino alerts, but they have participates to several fast follow-ups of transient events or neutrino alerts

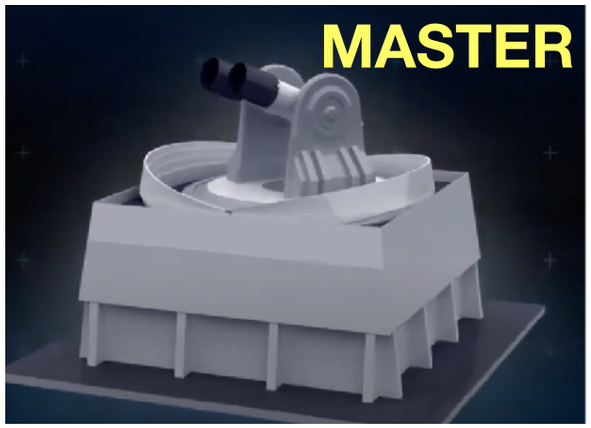


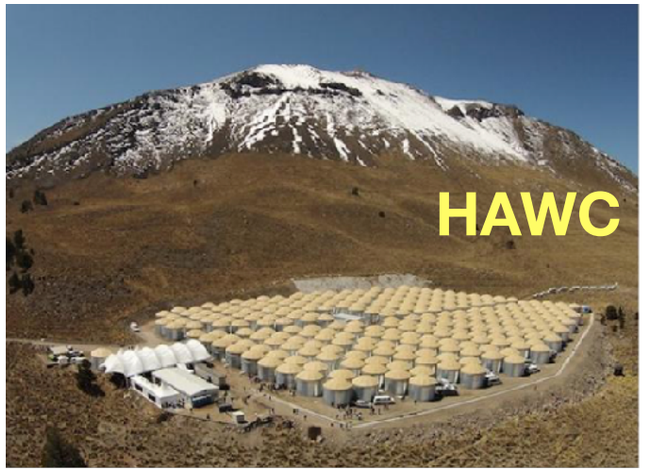
Follow-up of ANTARES alerts

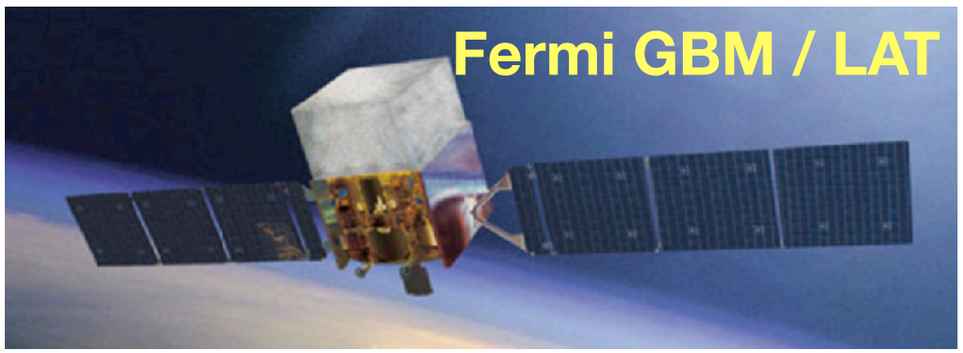
Follow-up of IceCube alerts



Main followers of neutrino alerts







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…)

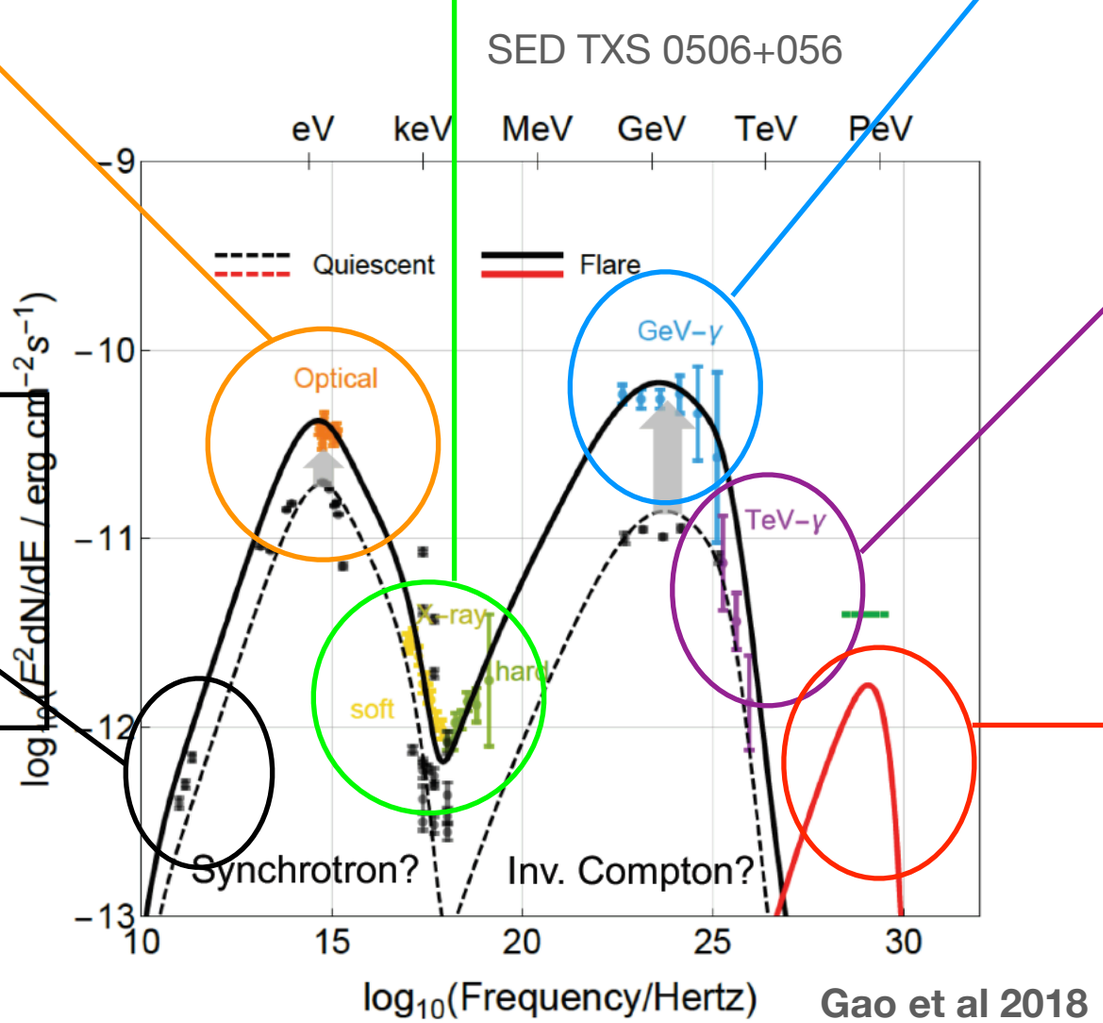
VHE γ-ray telescopes: HESS, MAGIC, CTA…
- Most natural common science case
- Follow-up (not easy access)

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

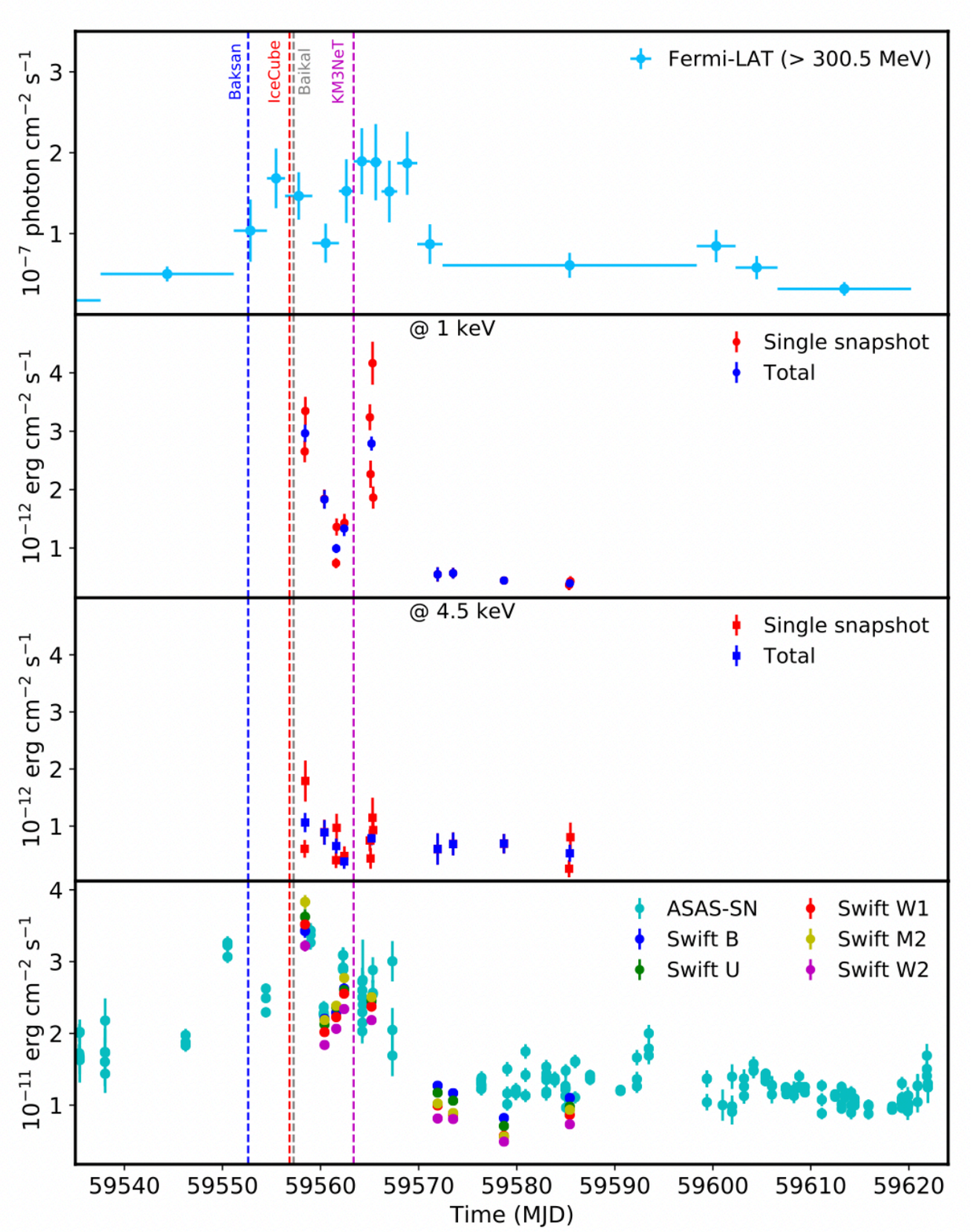
Neutrino telescopes: ANTARES, IceCube, KM3NeT, GVD…
- Mutual follow-up
- Confirmation of sources, improve significance

+ 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]

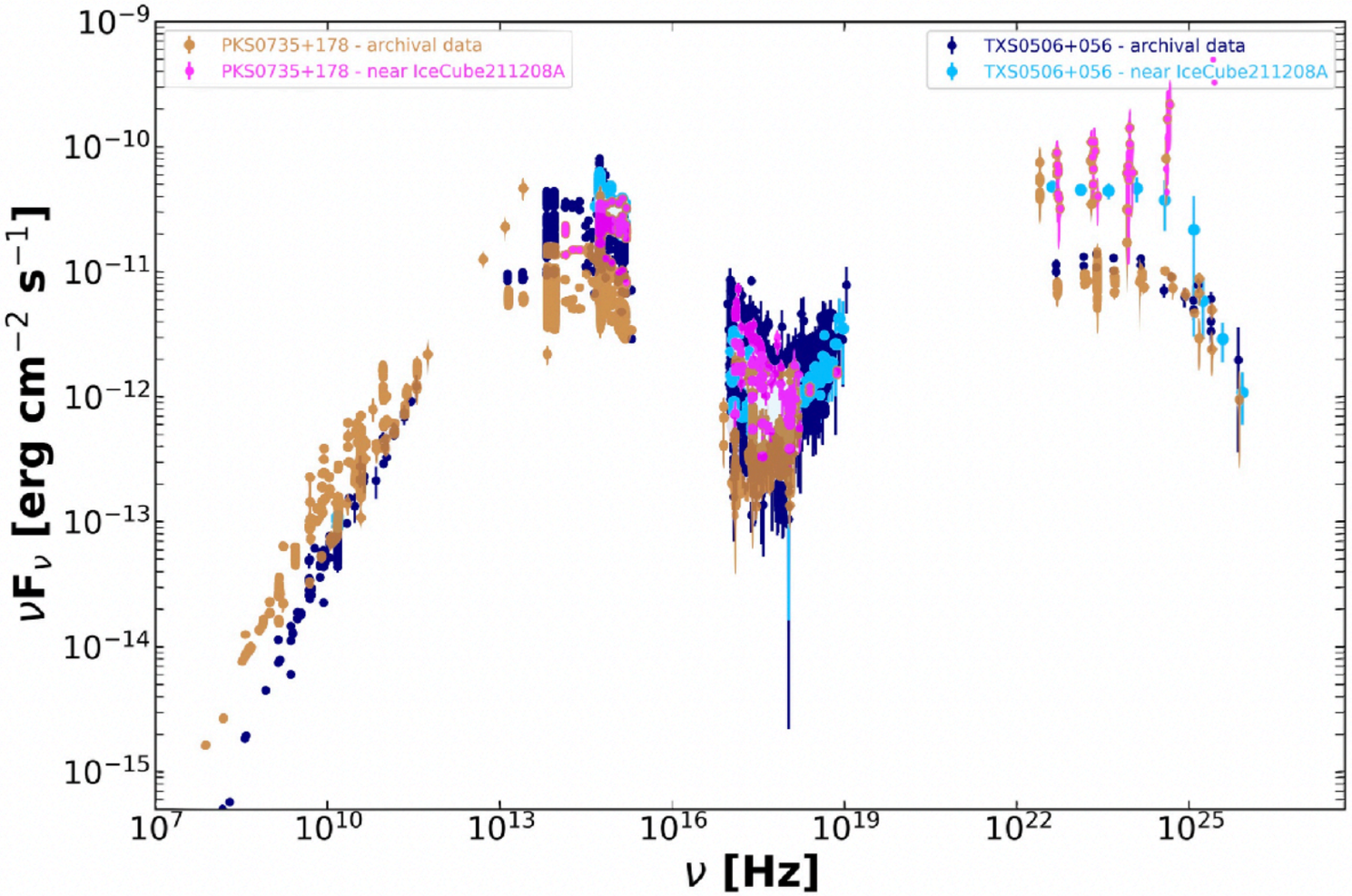
GVD-Baikal: 1 cascade event (~43 TeV), ~4h after the IC neutrino, ~5deg from the blazar direction (2.85 σ) [ATel #15112]

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**

Lessons from the ANTARES follow-up

Key points to be improved:

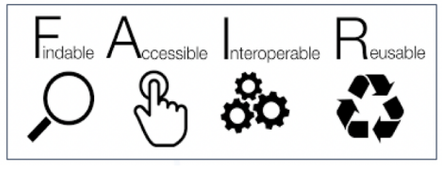
- Important to have all-flavor neutrino reconstruction and classifier
- Reduce the systematics on the angular direction of the alerts (good control of the pointing accuracy)
- Private / public neutrino alerts (how to optimize the follow-up)
- Uniformise the alert format: only VO event

- 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…)

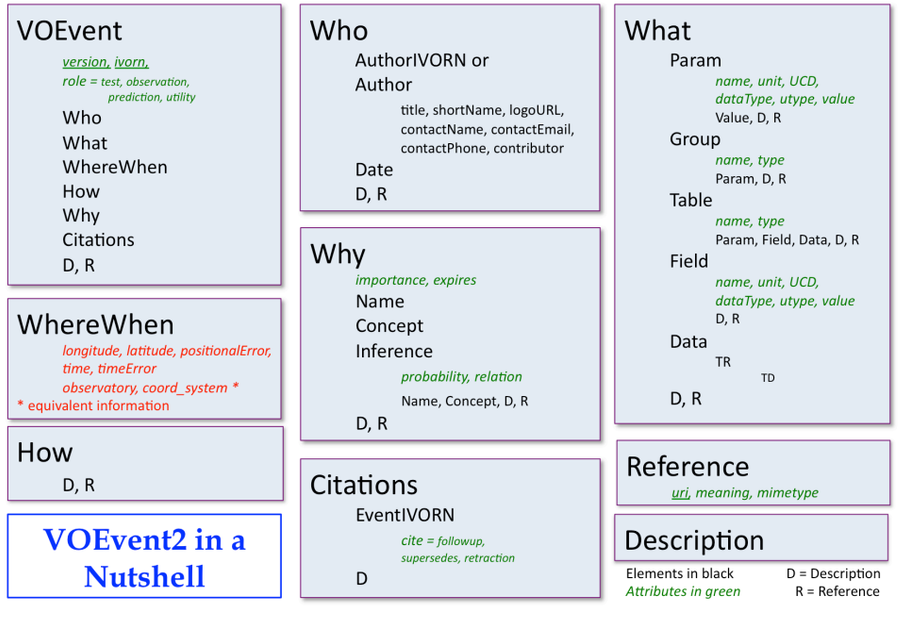
- Automatize the real-time correlation analyses as much as possible
- Have a real organized team to manage the online analyses, not only a few persons. Reinforce the MWL follow-up expertise in the collaboration. Provide some centralized tools for the shifters

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 ?]
- 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, an alert will be sent

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

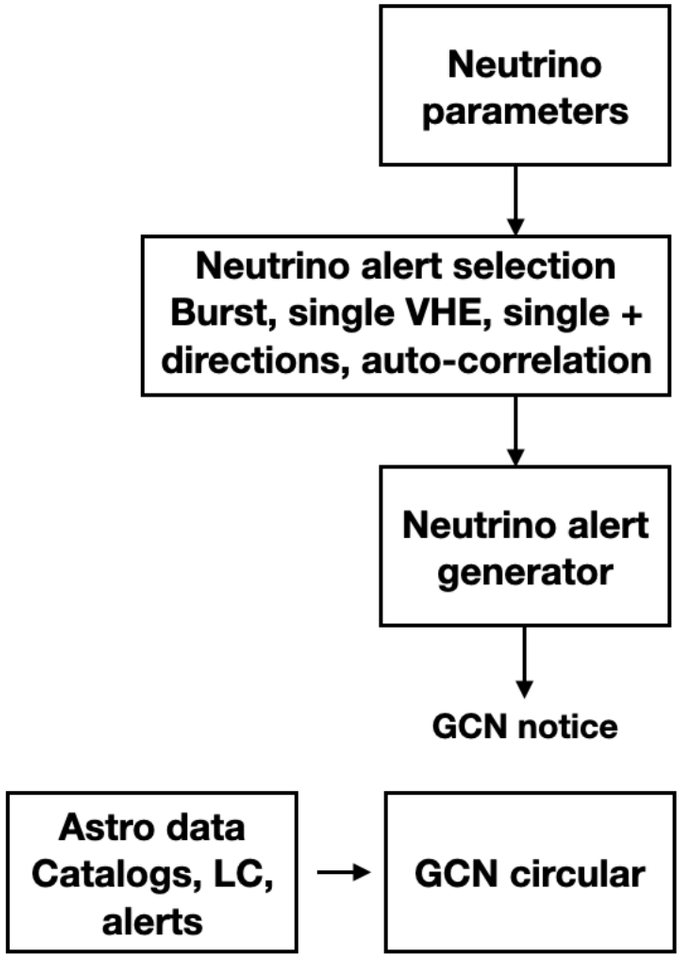
– ID
– Detector (ARCA/ORCA)
– Type of alerts triggers
– Number of events in given time and space widows
– Flavor
– Energy
– IsRealAlert
– FAR
– Time
– RA, Dec, Longitude, Latitude
– Error box 50% and 90%
– Reconstruction quality
– Probability of neutrino
– Probability of astrophysical neutrino
– Alert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

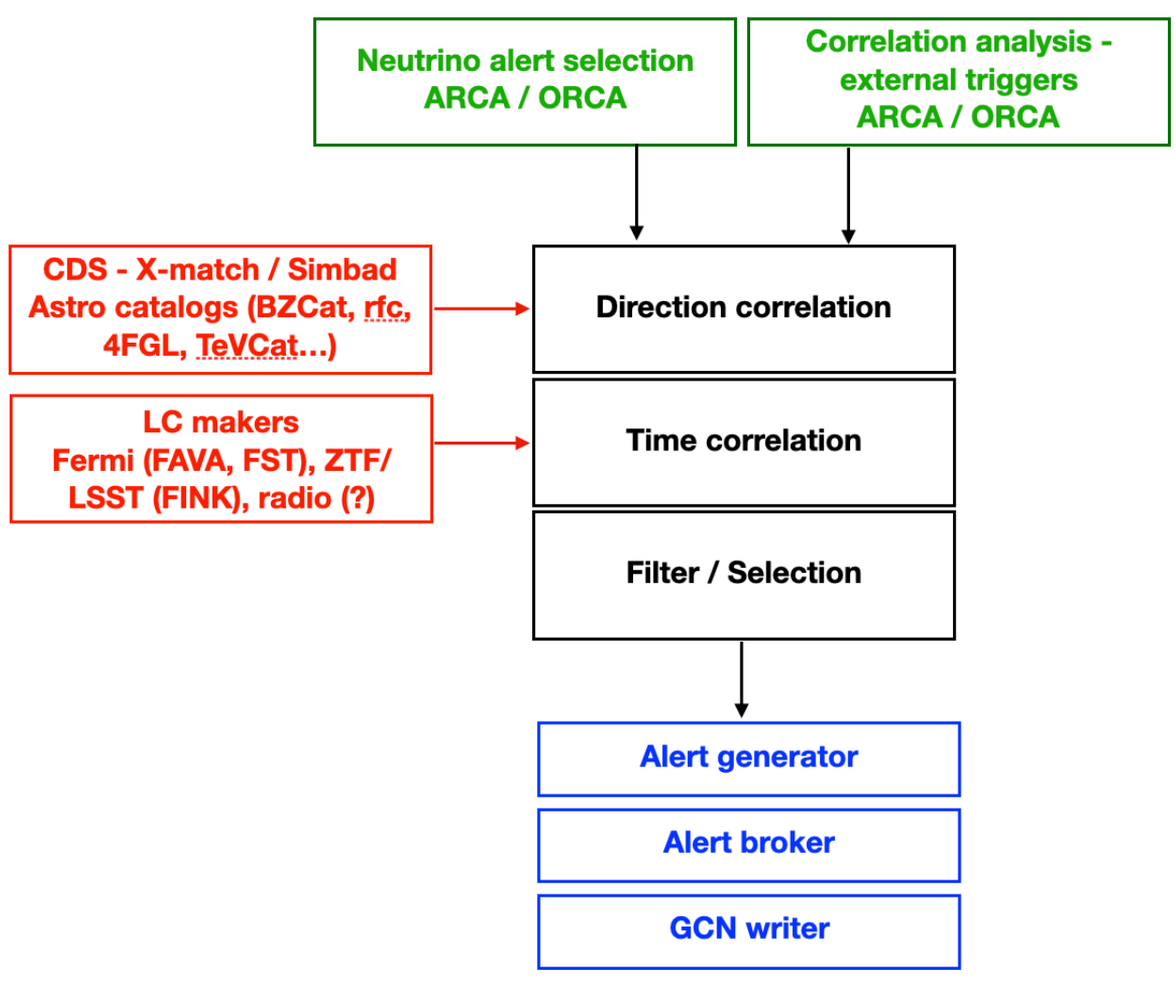
KM3NeT neutrino alert scheme

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)**



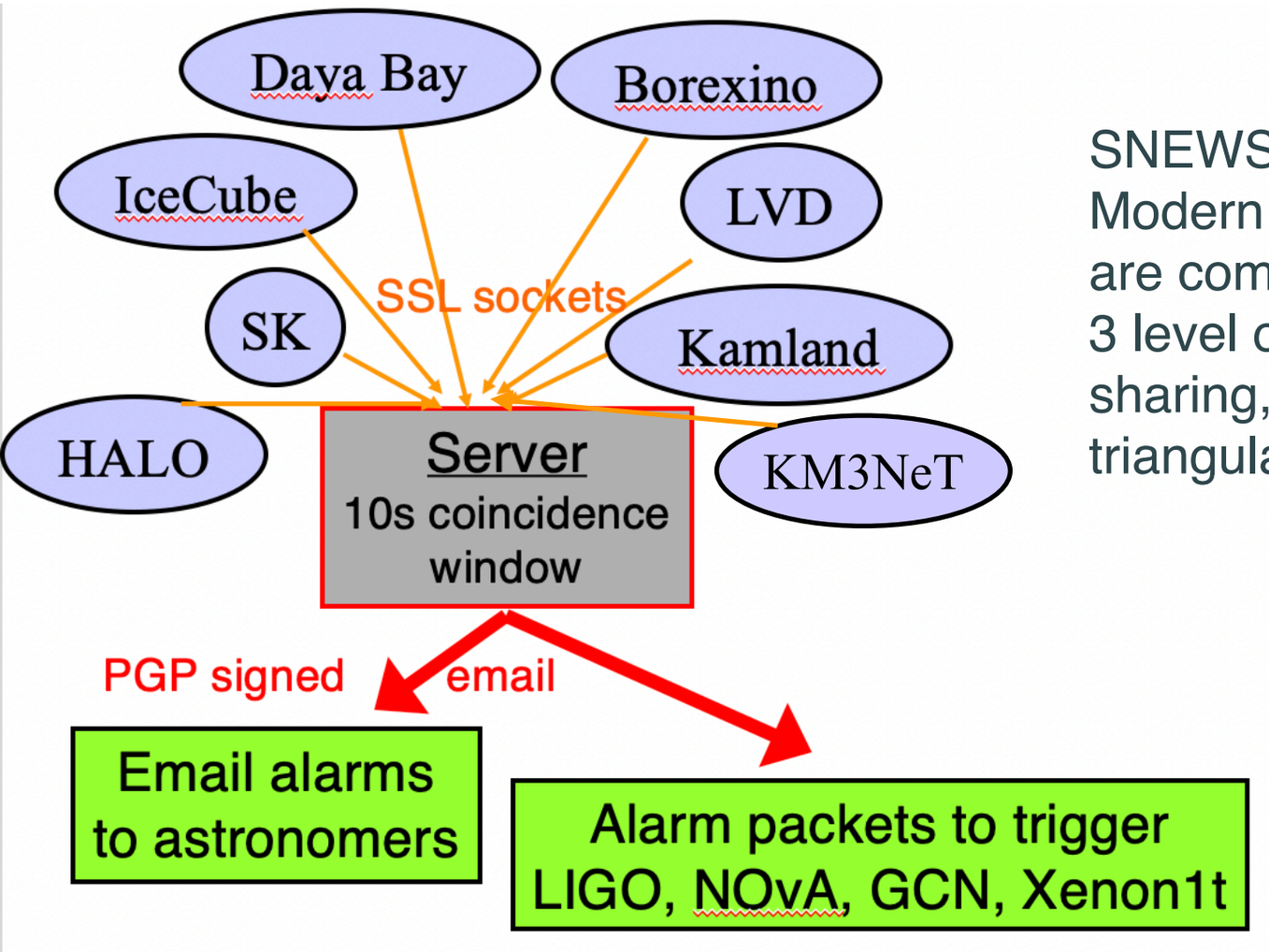


SNEWS

- 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.

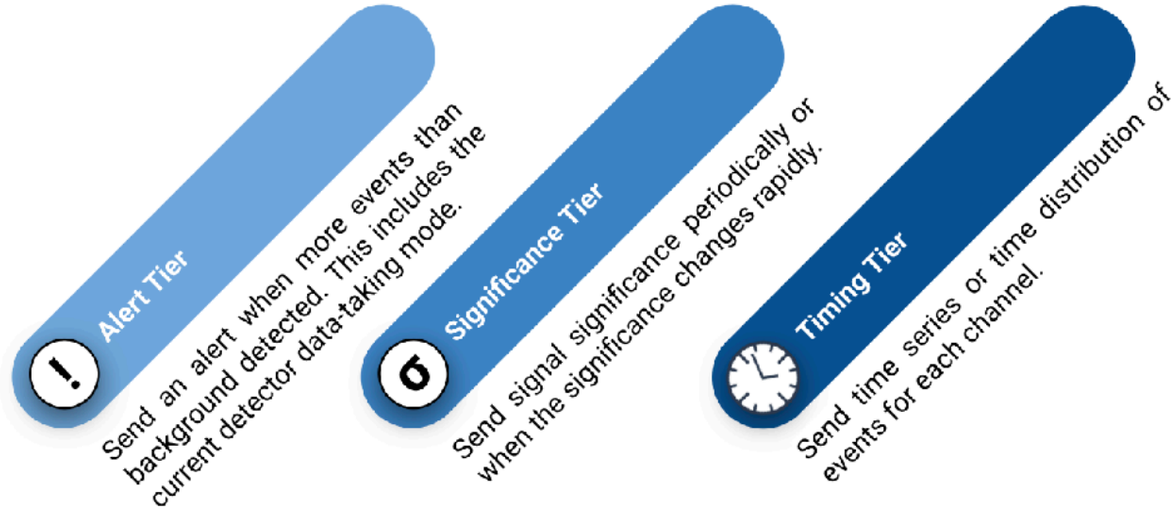
=> No SNEWS alert has been ever sent



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).



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 3σ.
- **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)

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 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 my 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.