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

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On behalf the ANTARES/KM3NeT Collaboration

Toulouse — 2019/06/04

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

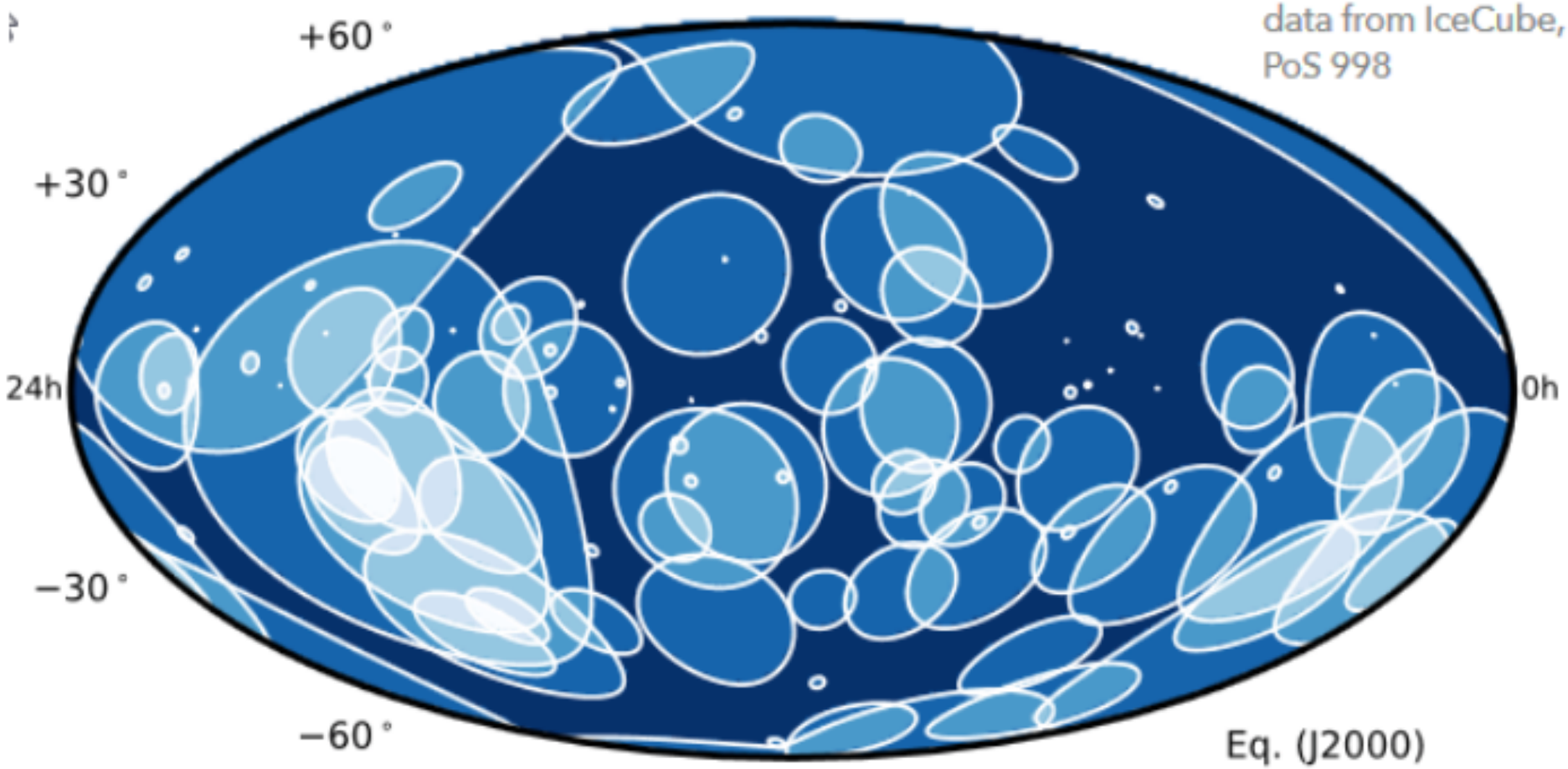
- Provide accurate positions (required for redshift, host measurements)

- 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

Neutrino sky



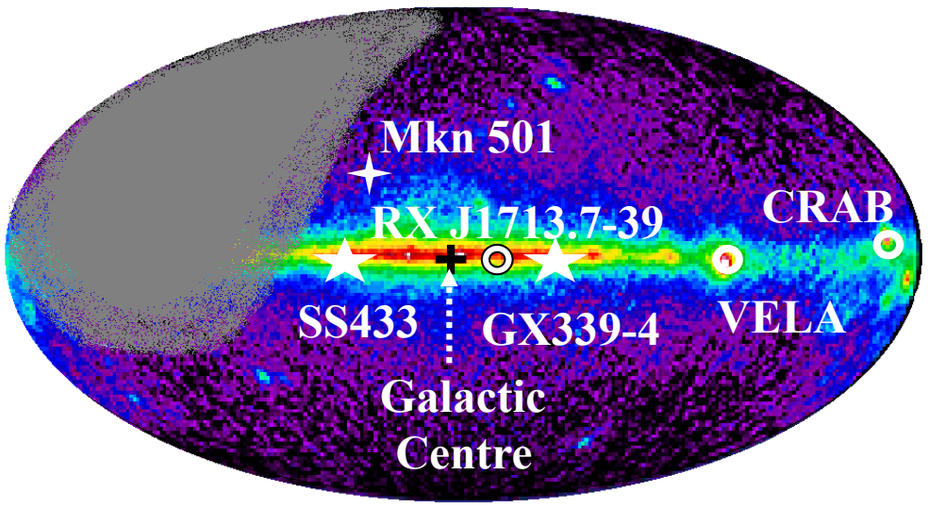
Resolution for ν_e	
ANTARES	○
KM3NeT	○

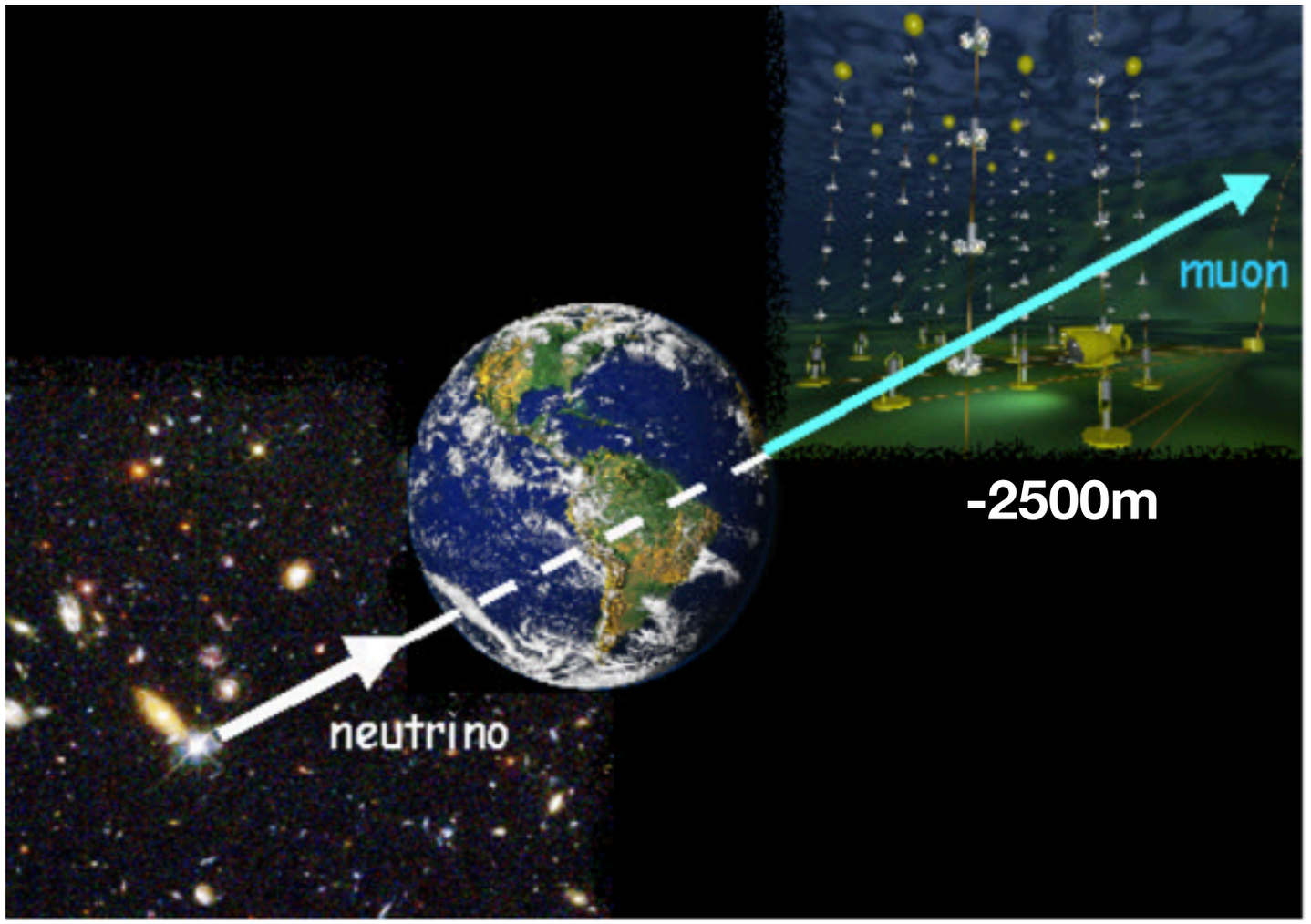
Up to now, only few evidences for blazars:
TXS0506+056, NGC1068…
But nothing yet significant

ANTARES

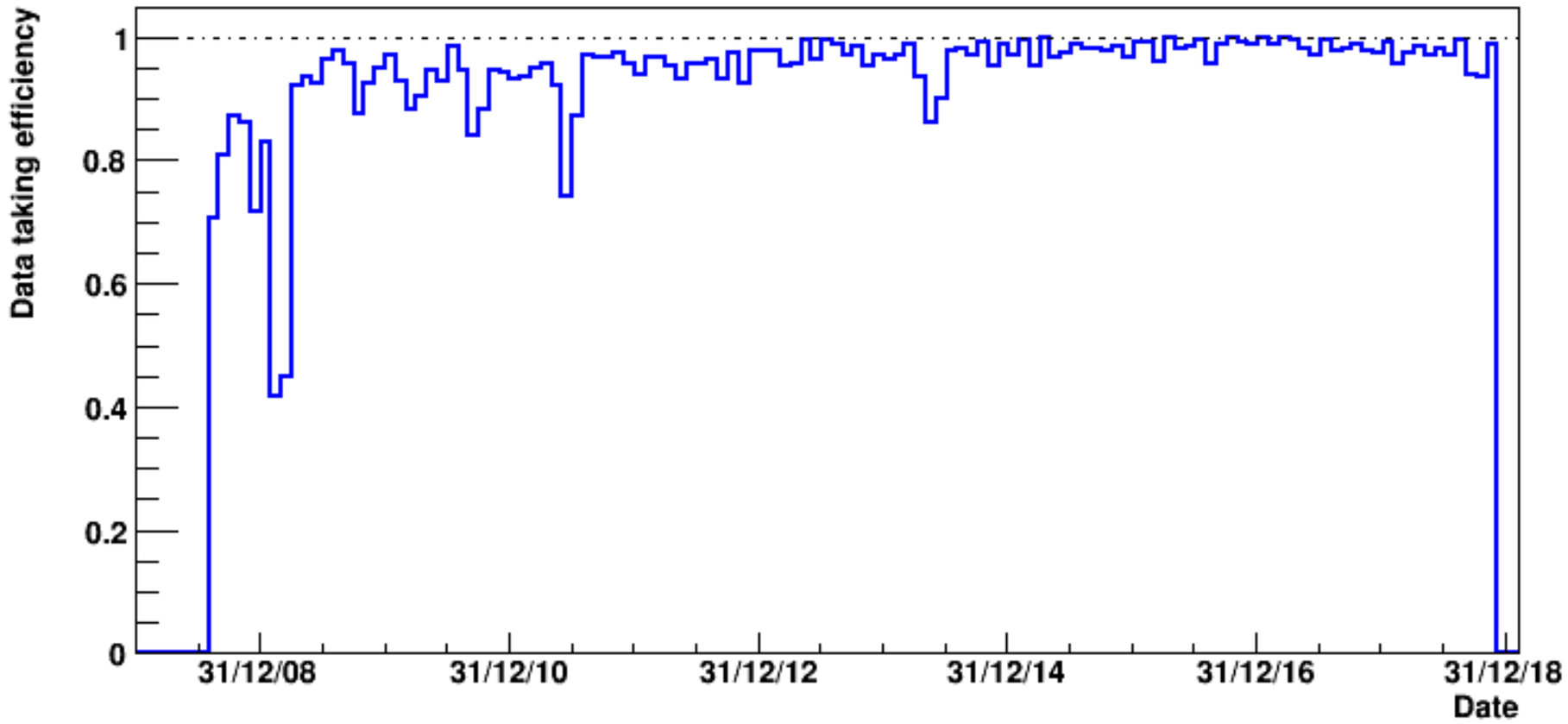
ANTARES in numbers:

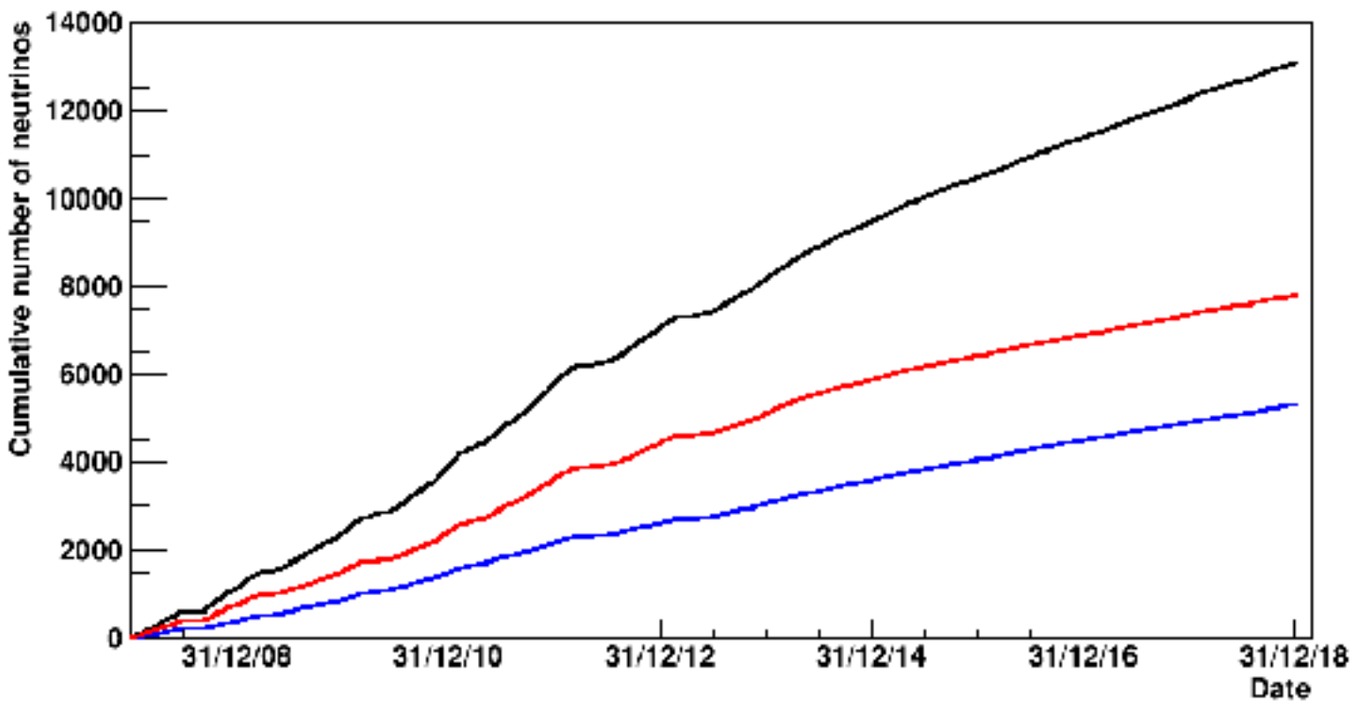
- Stable data taking since 2008 with high duty cycle (93-97% efficiency)
- Large field of view (2π instantaneously)
- Quite good angular resolution: 0.3-0.4° (median)
- But it is also small: effective area: ≈1m² @ 30 TeV (o(12000) detected neutrinos)





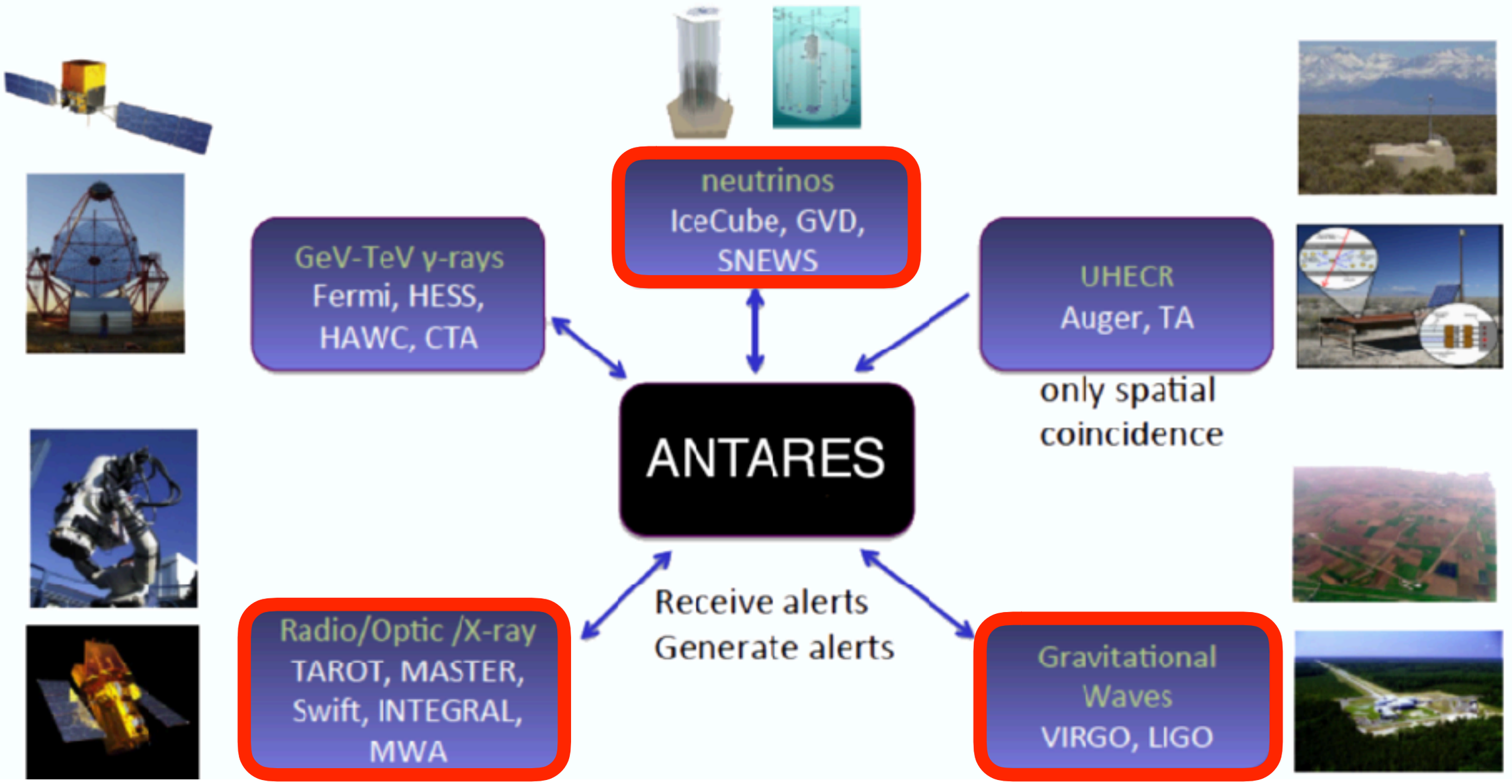
ANTARES





ANTARES complete construction in 2008:
Continuous data-taking during >11 years with a very high duty cycle ~94% since 2008 (>2012: ~97%).

Multi-messenger analysis

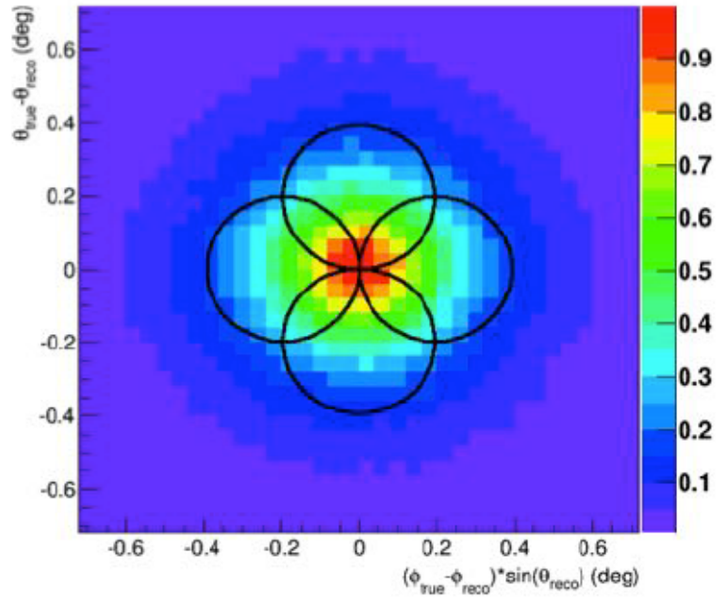


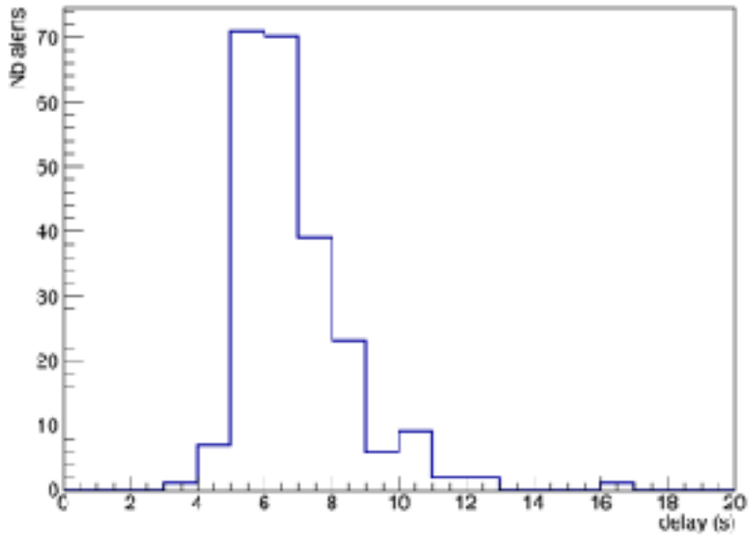
ANTARES neutrino alerts

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

$\Longrightarrow$ Average delay: ~6 s

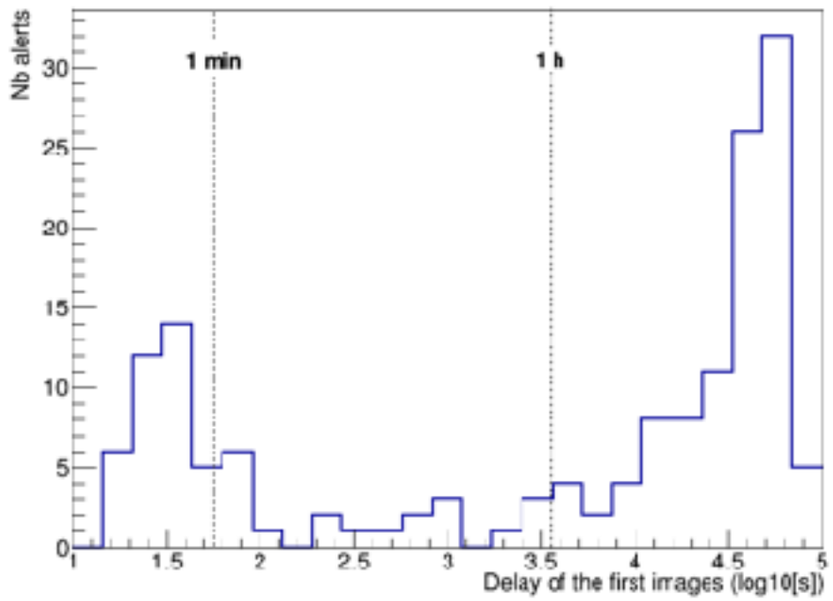
(get data, trigger, online reconstructions, neutrino selection)

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

$\Longrightarrow$ 192 alerts < 1 day

$\Longrightarrow$ 40 alerts < 1 min

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



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

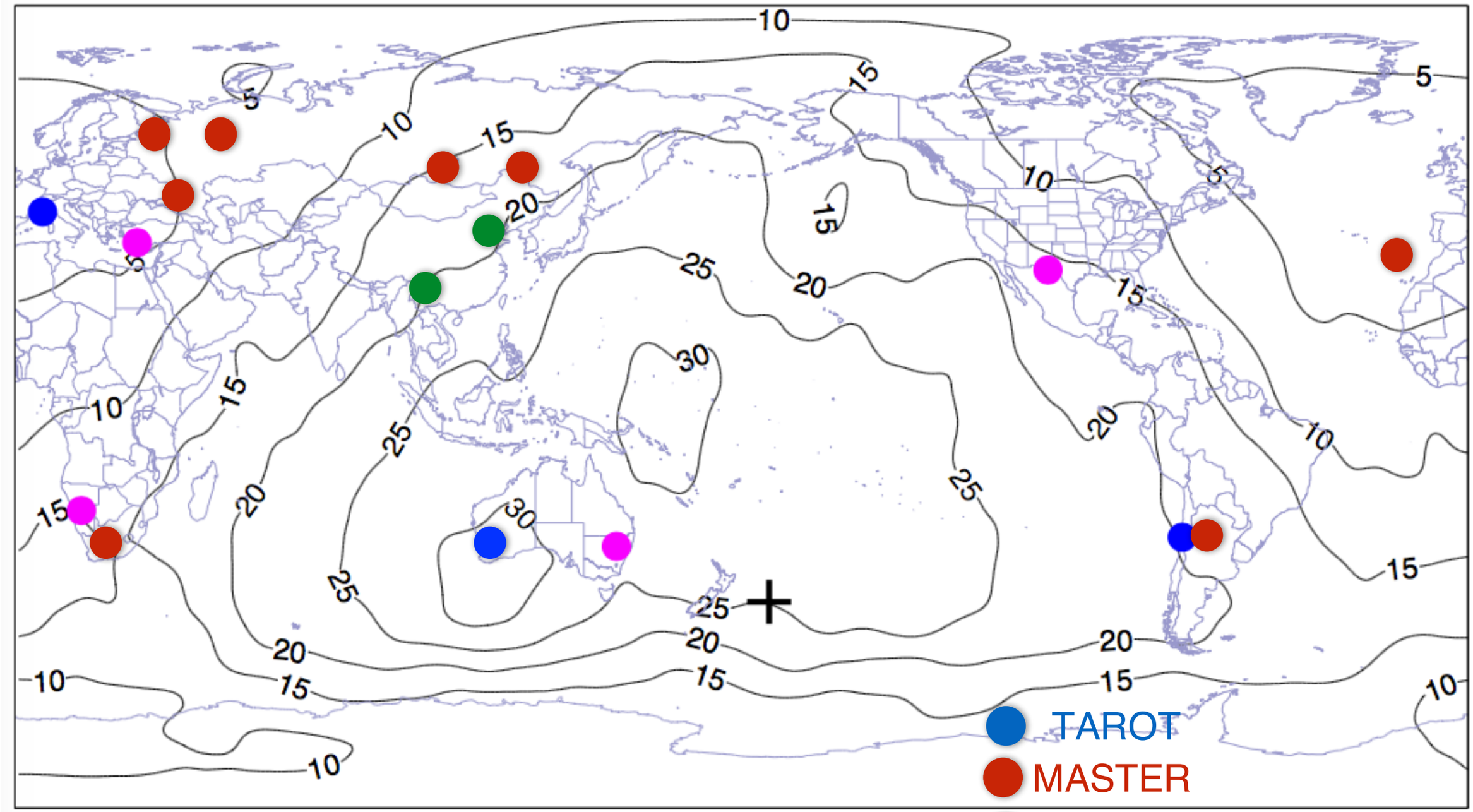
Real time

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

ANTARES

Efficiency of prompt observations vs location on the Earth



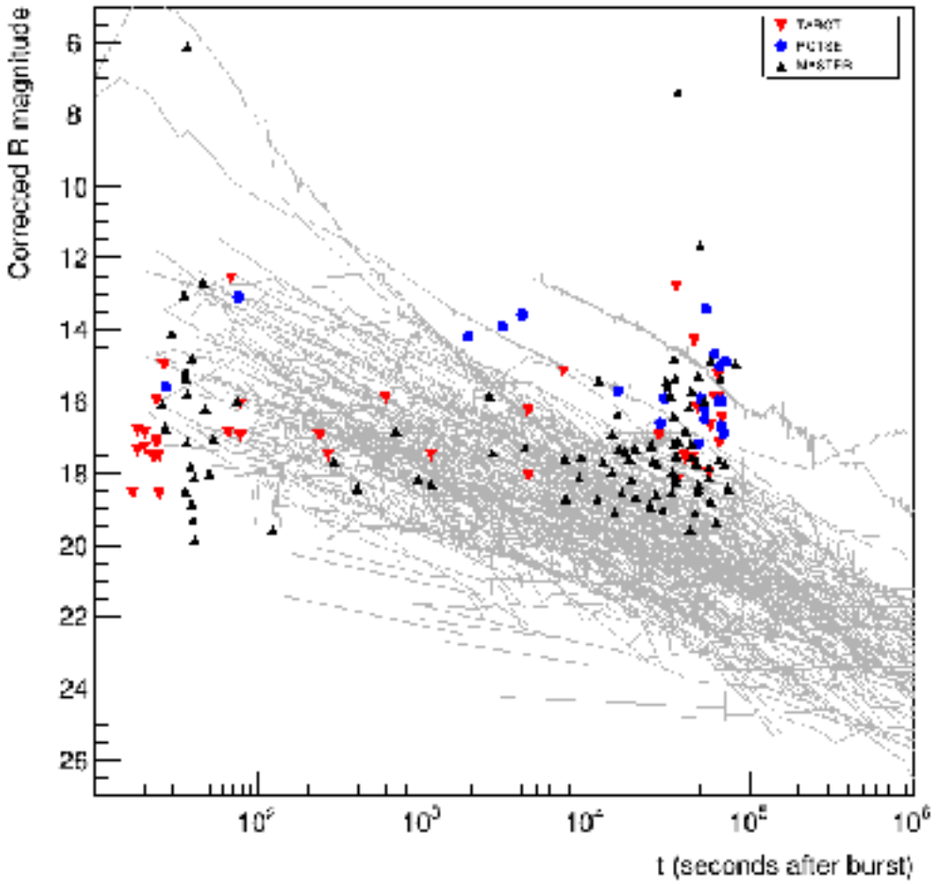
Early Vis+X-ray follow-up

Visible:

192 alerts analyzed 01/2010-12/2018 from TAROT, ROTSE, MASTER (67% of all alerts)

=> 40 alerts with delay <1min (best: 17s)

=> no transient candidate associated to neutrinos

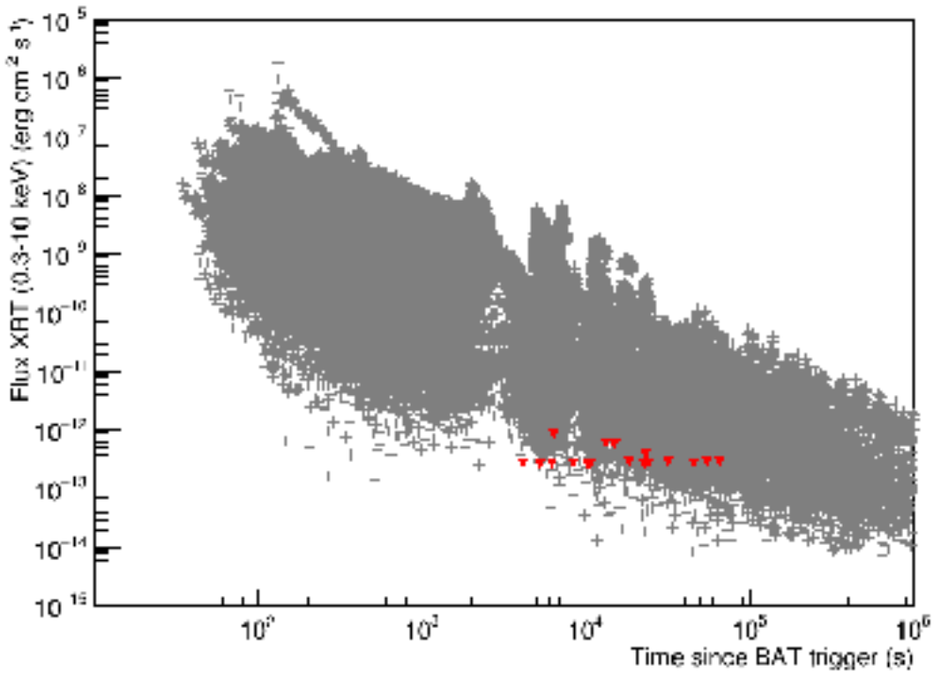


X-ray:

17 alerts analyzed 06/2013-12/2018

=> average delay ~5-6 hours

=> no transient candidate associated to neutrinos



=> Constrains on origin of individual neutrinos

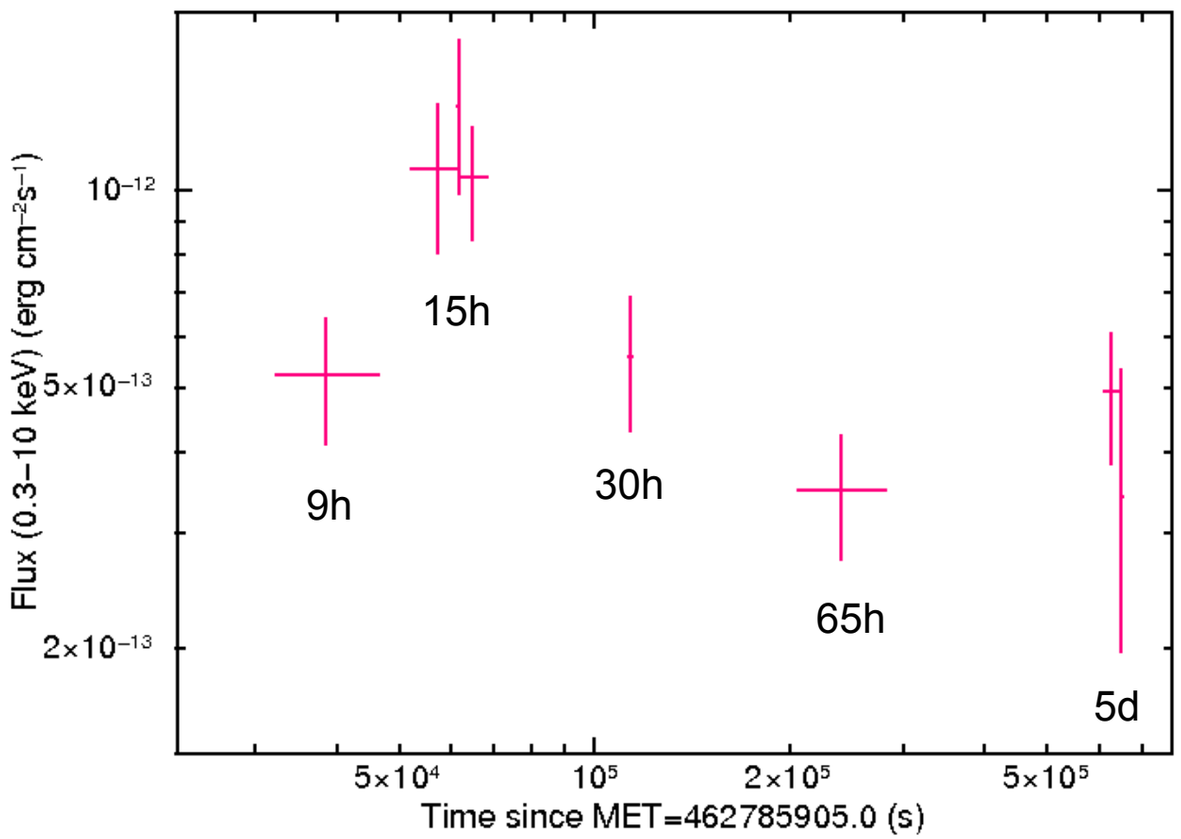
=> Interpretation of the UL in the case of GRB afterglow

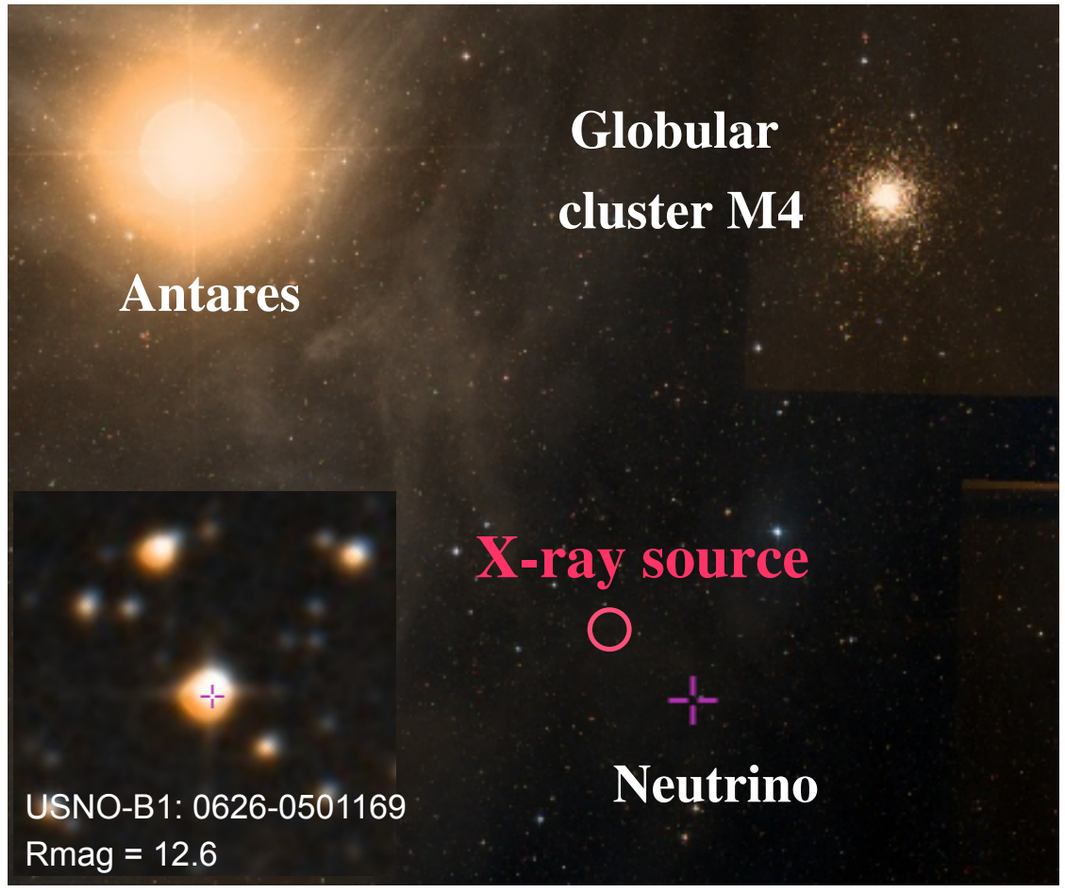
Adrián-Martínez et al, JCAP 02(2016) 062

ANT150901A

<u>Alert VHE (Sept. 1, 2015)</u>
(Nhit, Amp) = (127, 356), E ~ 50 TeV
RA=246.306°; dec=-27.468°

Sent after 10 s to MASTER, Swift-XRT
➡ **Follow-up with Swift-XRT after 9h**
➡ **Follow-up with MASTER after 10h**



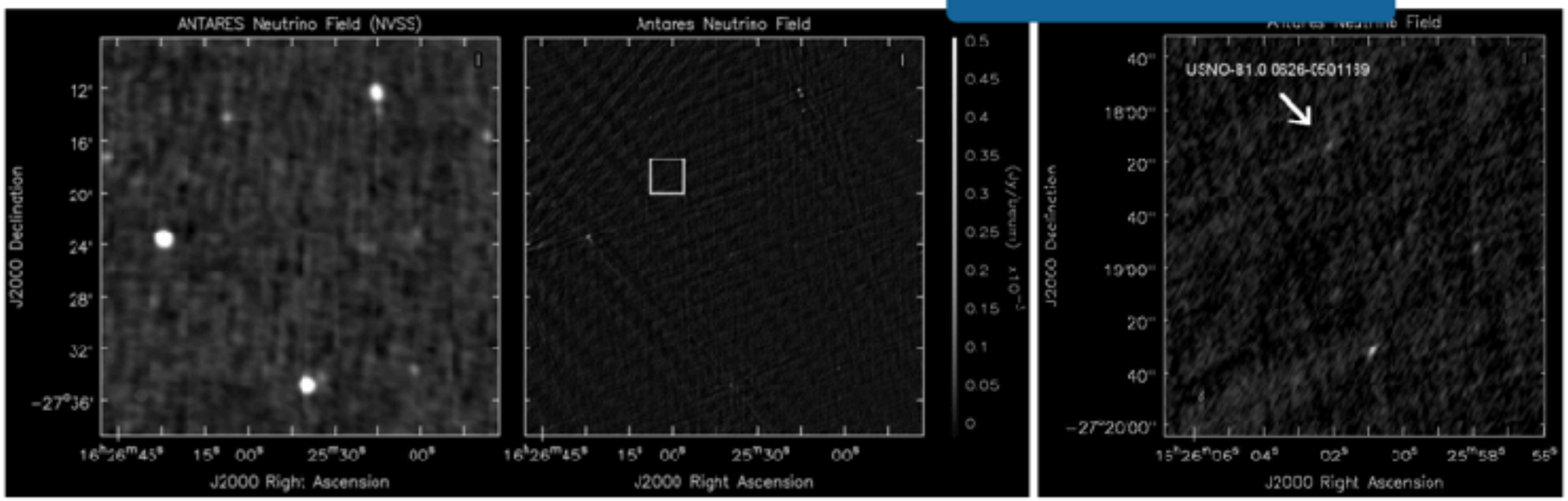


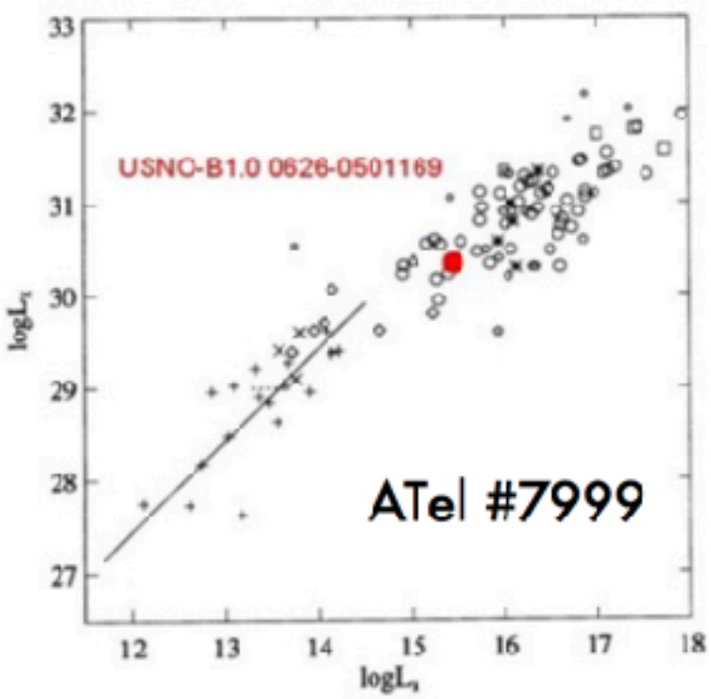
➡ Emission of a GCN notice (#18231) and an ATEL (#7987) after ~24h to require more follow-up to identify the X-ray flare

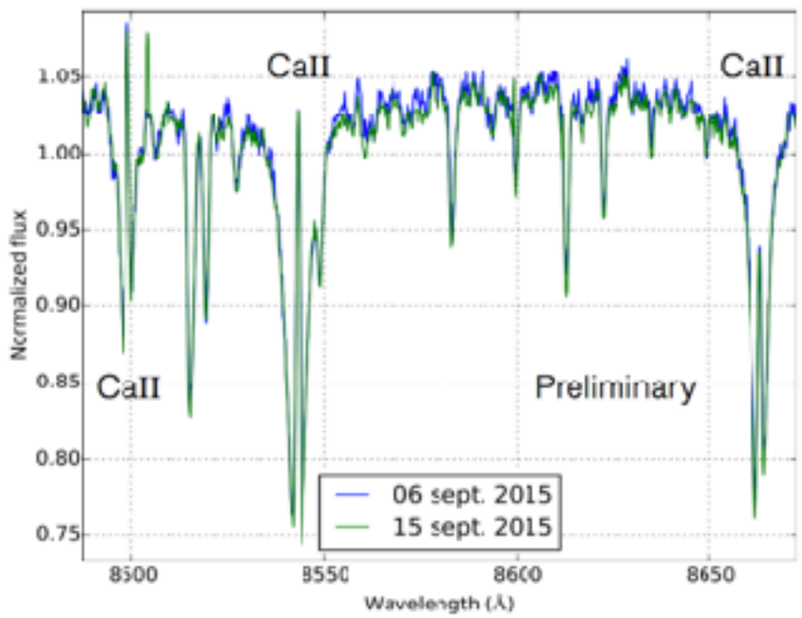
ANT150901A

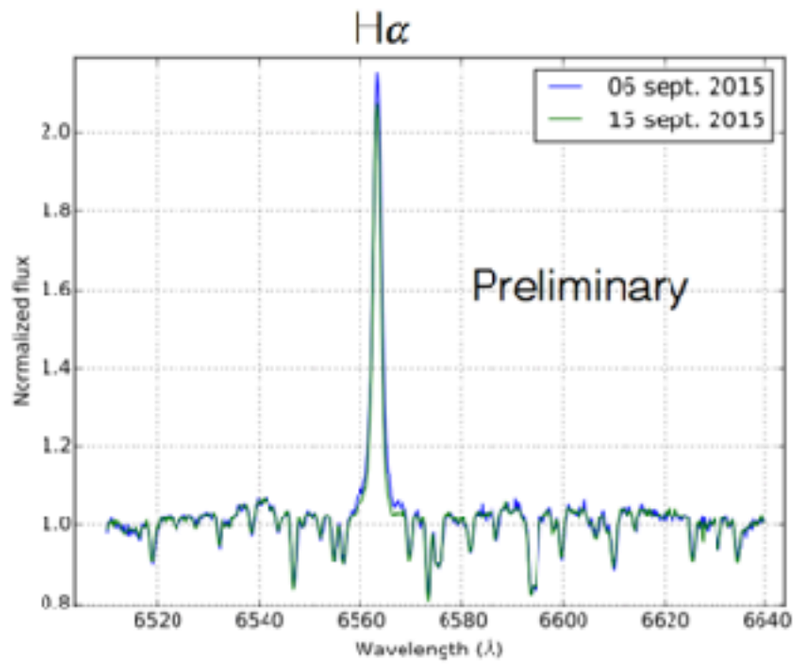
TATOO: ANT150109A ALERT

Active X-ray star





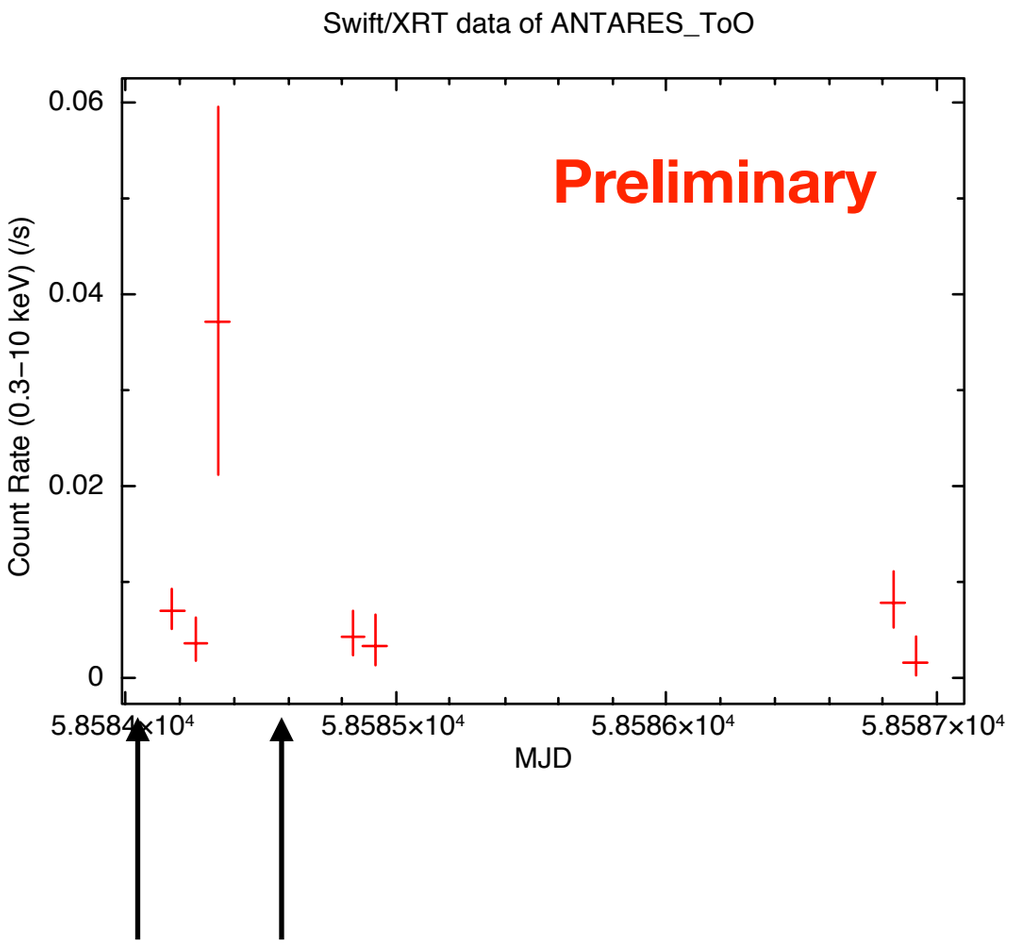




ANT190410A

-- Sent alert [Master He Mwa Swift Hess Amon]
2019-04-10 13:52:04
ra= 50.351 [3h 21m 24s] dec= -48.082 [-48° 4' 55"]

RN 87154 FI 175399
Nb_hit 82 Ampl 400 lambda -4.15 Nlines 9 costh 0.01
Qly 1 pval 0.030



MASTER-OAFA and MASTER-SAAO observed this ANTARES alert.

in 2.9" there is a star with unfiltered m~20+-0.5 in MASTER images both on 10th of April and in archive data on
2019-03-25 01:17:09 (mlim=20.8)
2018-12-07 05:43:57UT (mlim=20.8)
2018-10-18 23:36:16UT (mlim=20.1)
2016-03-05 19:19:02UT (mlim=20.4)
2016-11-19 21:17:17UT (mlim=20.7)

MASTER coordinates RA,Dec(2000)=$03^h\ 20^m\ 57.31^s$, $-48^d\ 8^m\ 35.07^s$ +-2"

In 1.2" from MASTER star there is USNO-B1 source with blue bmag=20.5, red rmag=20.7
(MASTER W=0.2B+0.8R by USNO B1 thousands field stars)

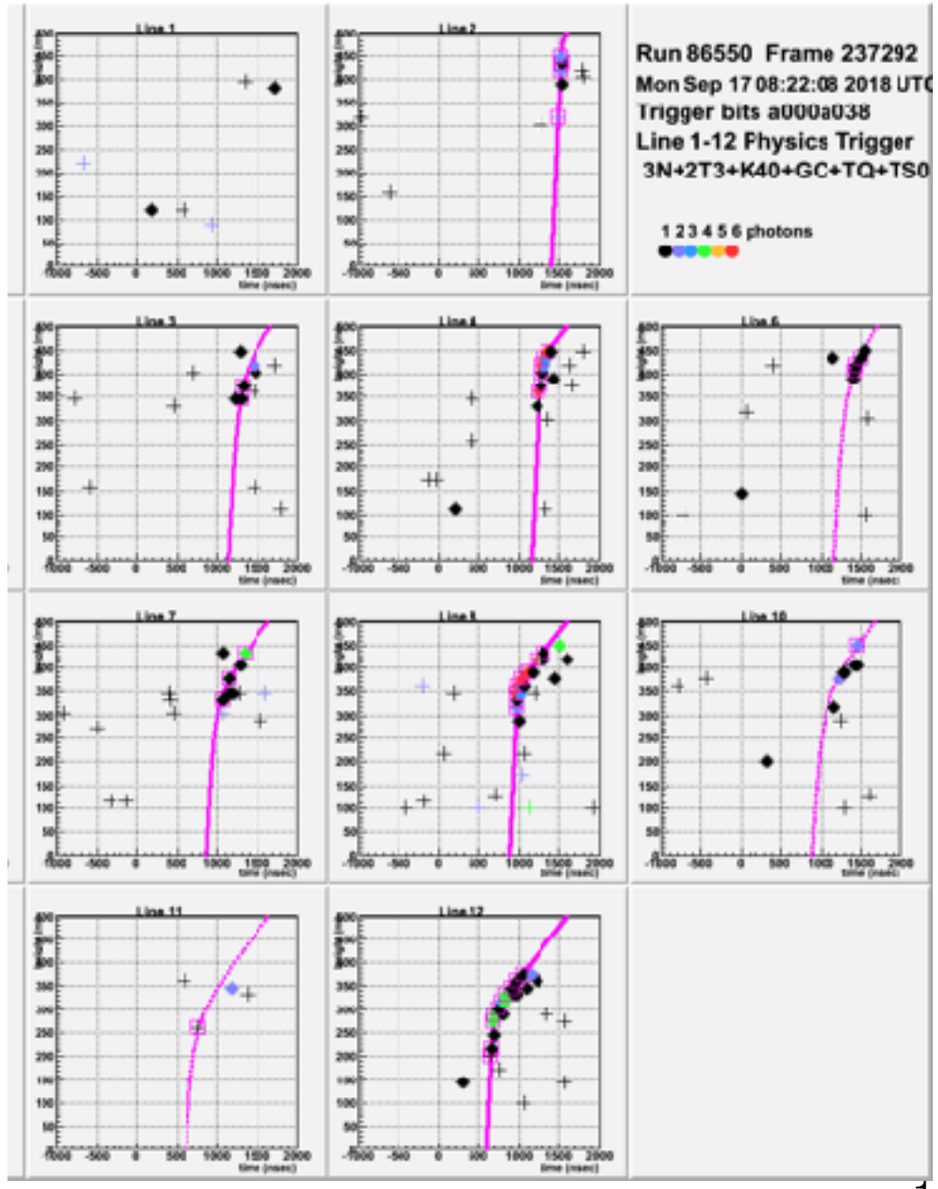
ANT180917A

2018-09-17 08:22:08
ra= 17.122° [1h 8m 29s] dec= -68.069° [-68° 4' 8 »]. Err=0.3° (median)
Nb_hit=87 & Ampl=294 , Lambda=-4.54 Rank 1 pval=0.0234742

Preliminary

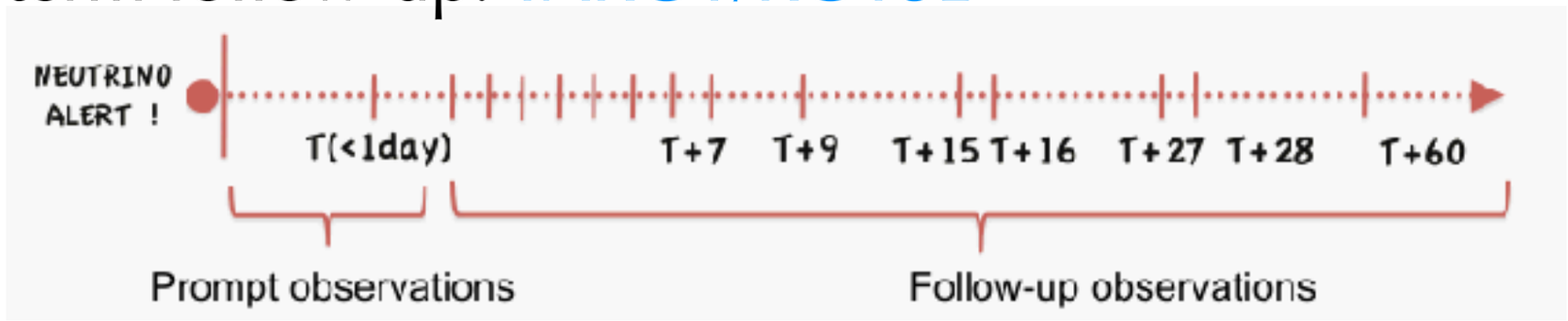
MASTER found one interesting transient: cc-SN, originally detected by MASTER on 2017-11-09 and also by OGLE (SN OGLE17ory, Type II, z=0.02, 90 Mpc),
$\Longrightarrow$ 377.34 days before Antares Alert20180917.
Swift observations ~4h after the alerts $\Longrightarrow$ 3 new sources but not so bright/variable.

$\Longrightarrow$ We need to think about a physical mechanism to produce high energy neutrinos. In general, we may expect neutrinos emitted closed to T0 (chocked jets in the shell of the star) or very late (few 100 years) in the SN remnant shocks.



Long-term visible follow-up

Long-term follow-up: TAROT/ROTSE



MASTER: 3 observations T+7, T+15, T+21 days

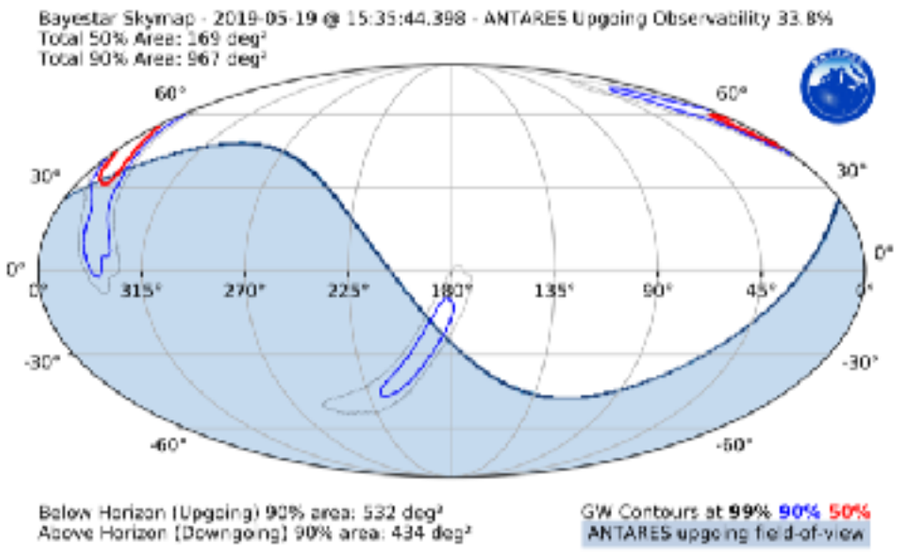
197 alerts with a "rather good" long-term follow-up (> 3 nights for TAROT+ROTSE+ > 2 nights for MASTER)

- ➡ Alert types: 65 DIRECTIONAL + 132 HE trigger
- ➡ Dedicated analysis pipeline for TAROT/ROTSE images (stacking night-by-night + subtraction). MASTER used its standard online transient pipeline
- ➡ No SN (and no interesting transient) associated with the neutrinos
- ➡ $N_{exp}(SN) = 0.3\text{-}0.4$ for the full follow-up [SN rate=2.4 10^{-4} $yr^{-1}Mpc^{-3}$]
- ➡ Other types of hadronic sources not looked up to now (CV…)

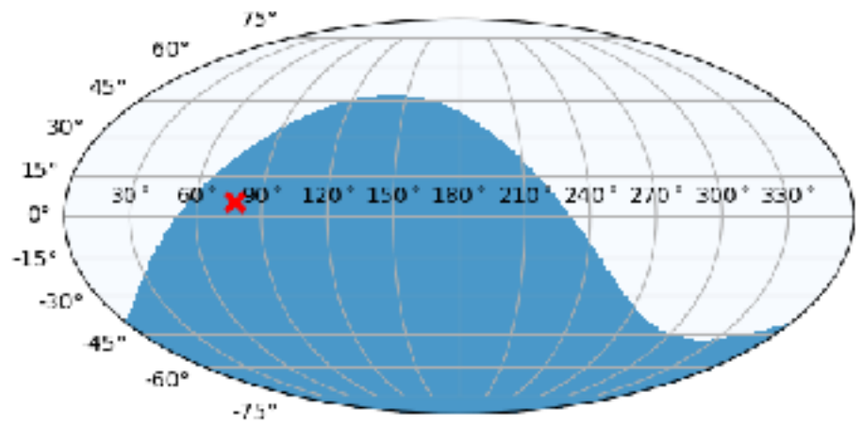
Examples of online ANTARES analyses

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

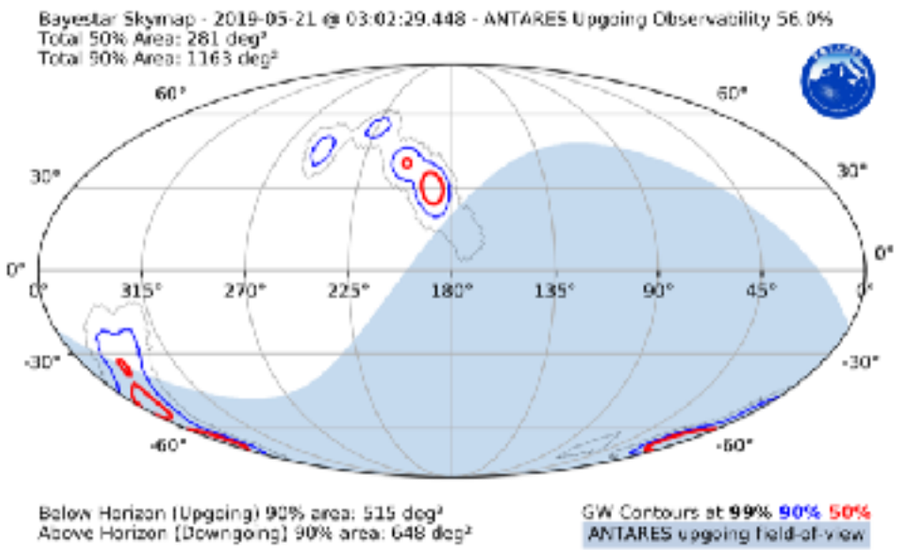
(±500 s & ±1 h)

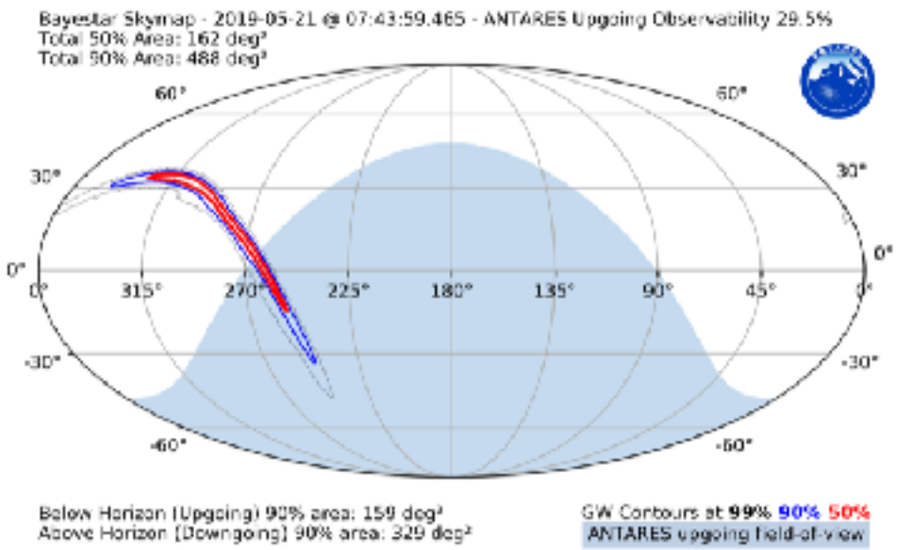


IC170922



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



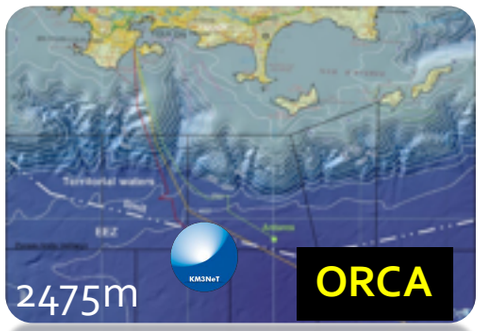


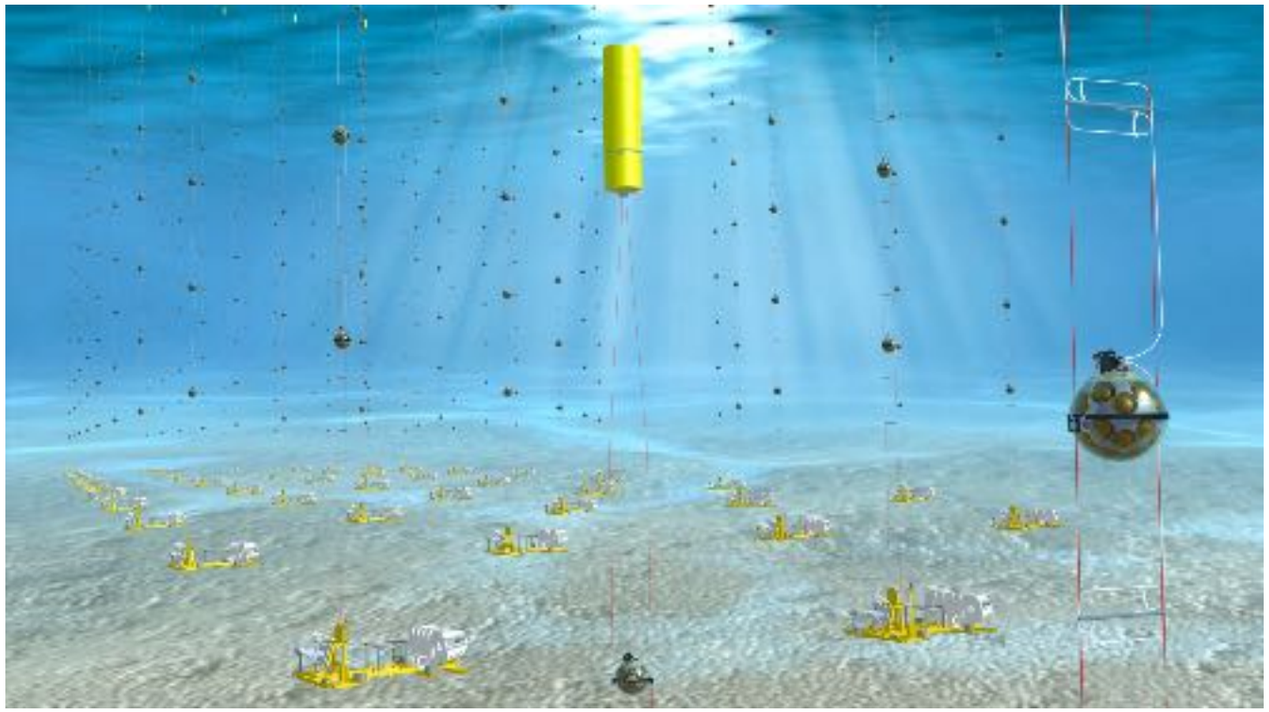
KM3NeT

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:

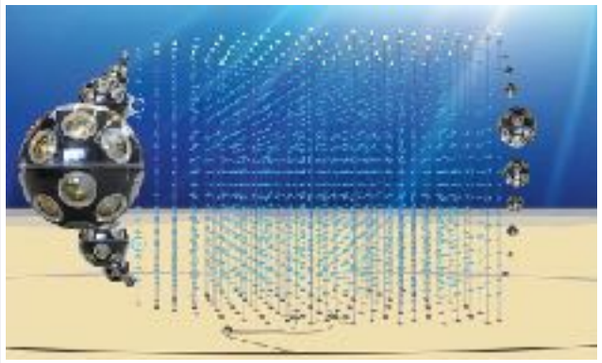
- Extended energy range: 1 GeV → >10 PeV (+ 10-40 MeV)
- Full sky coverage with the best sensitivity for the galactic sources
- High duty cycle (> 90-95%)
- All-flavour neutrino detection
- Good angular resolutions

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

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

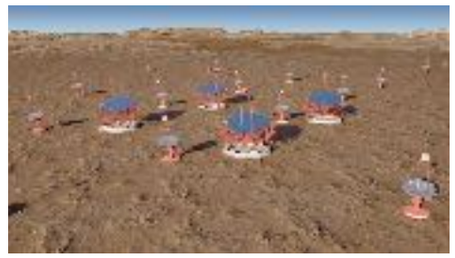
KM3NeT multi-messenger analyses

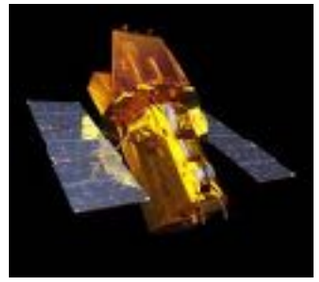
KM3NeT

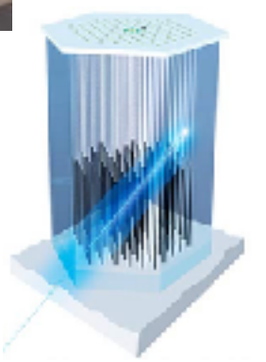


- **Follow-up of neutrino alerts**
- **Joint sub-threshold analysis**

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

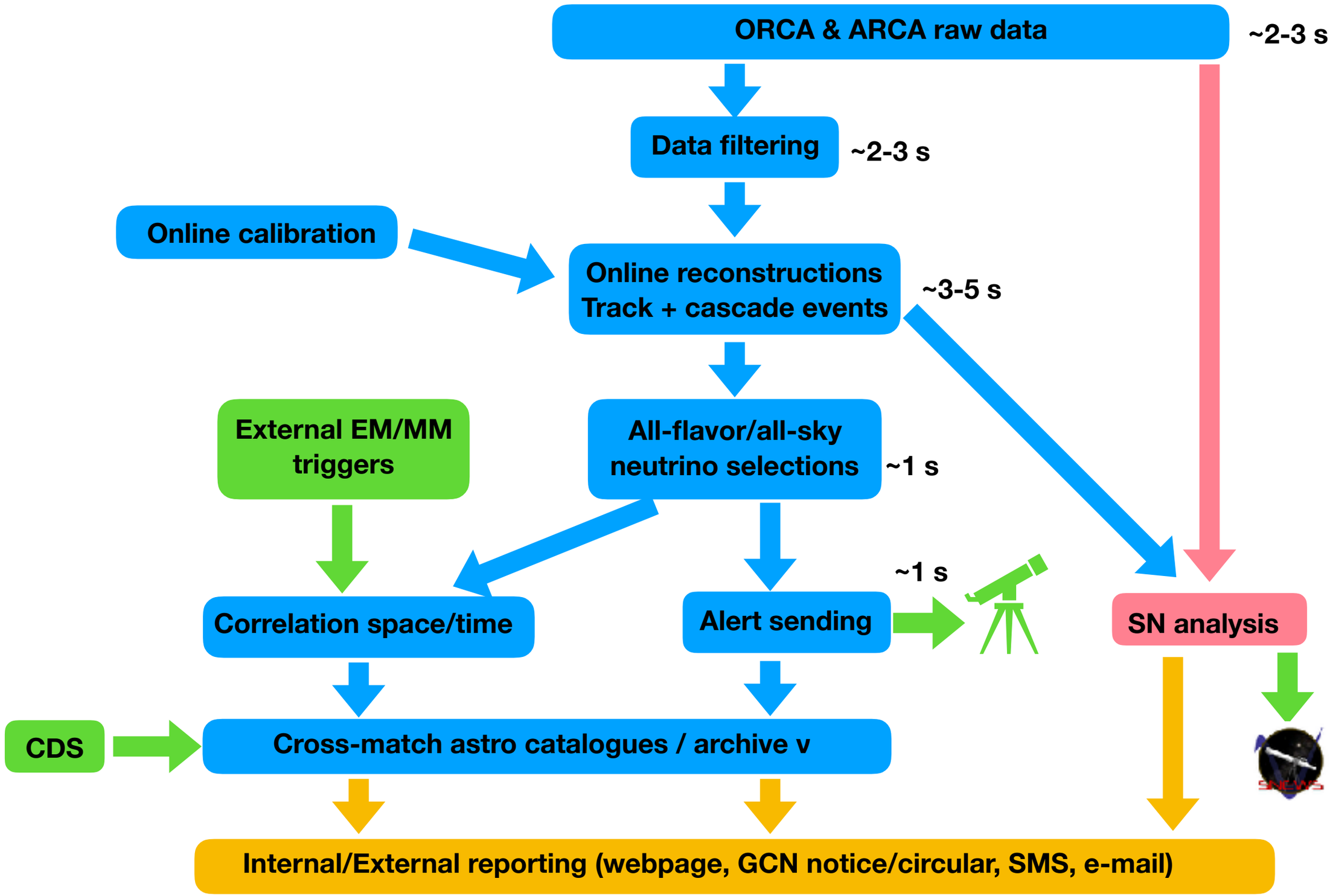
- **ORCA can do also astronomy:**

  $\Longrightarrow$ 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

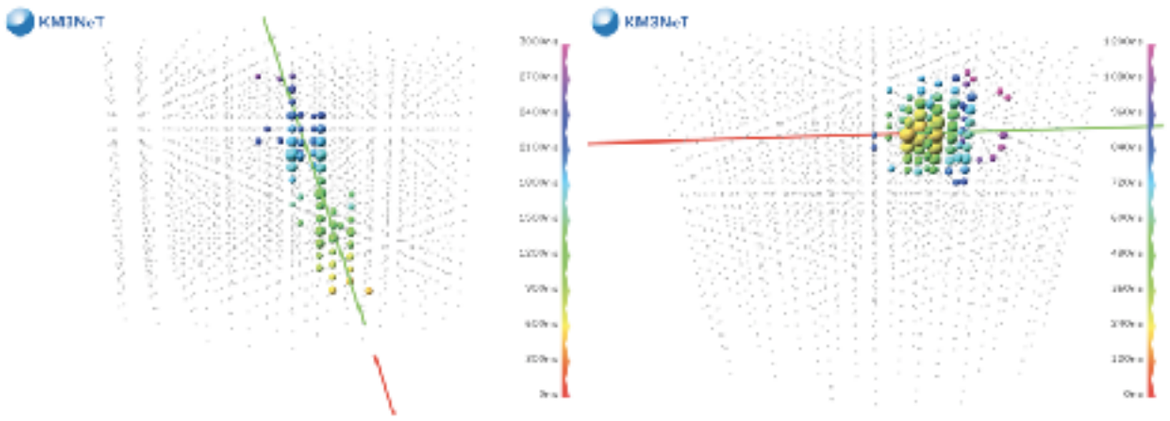
- **ORCA & ARCA:** detection of MeV neutrinos from core-collapse SN

KM3NeT real-time framework



Online event reconstructions

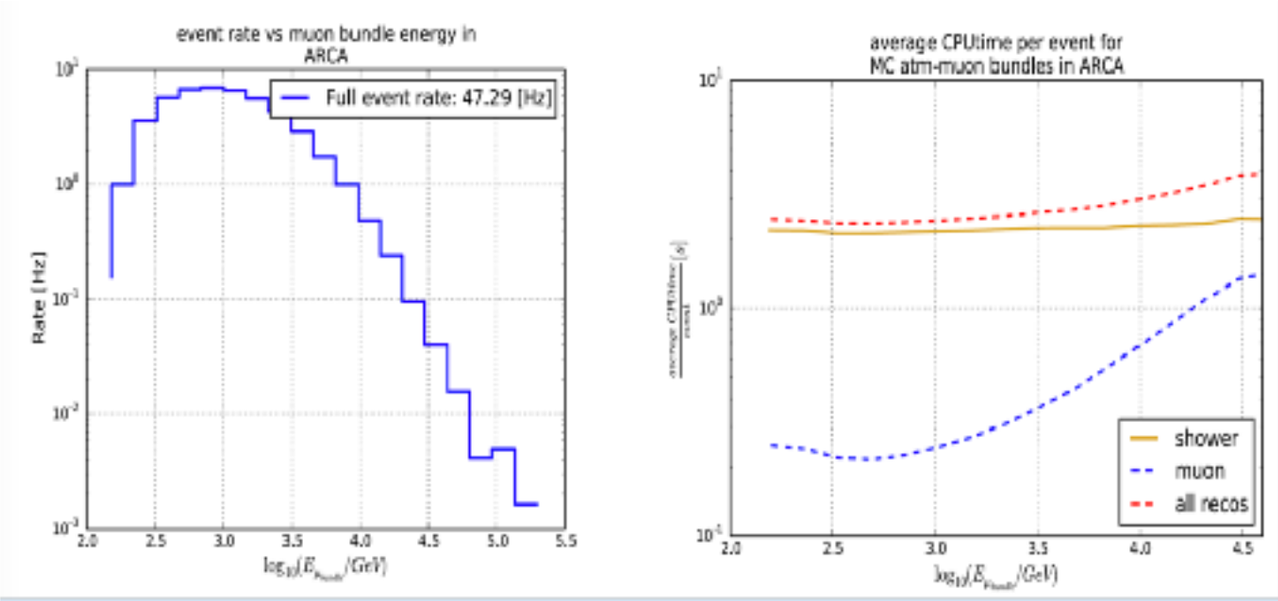
*** All-flavor (track+cascade) event reconstructions: same framework and the same reconstruction tools as in offline**



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)

➡ Only 2 brokers for public and private alerts for both KM3NeT detectors

Reporting:

➡ SMS/e-mail to alert KM3NeT shifters

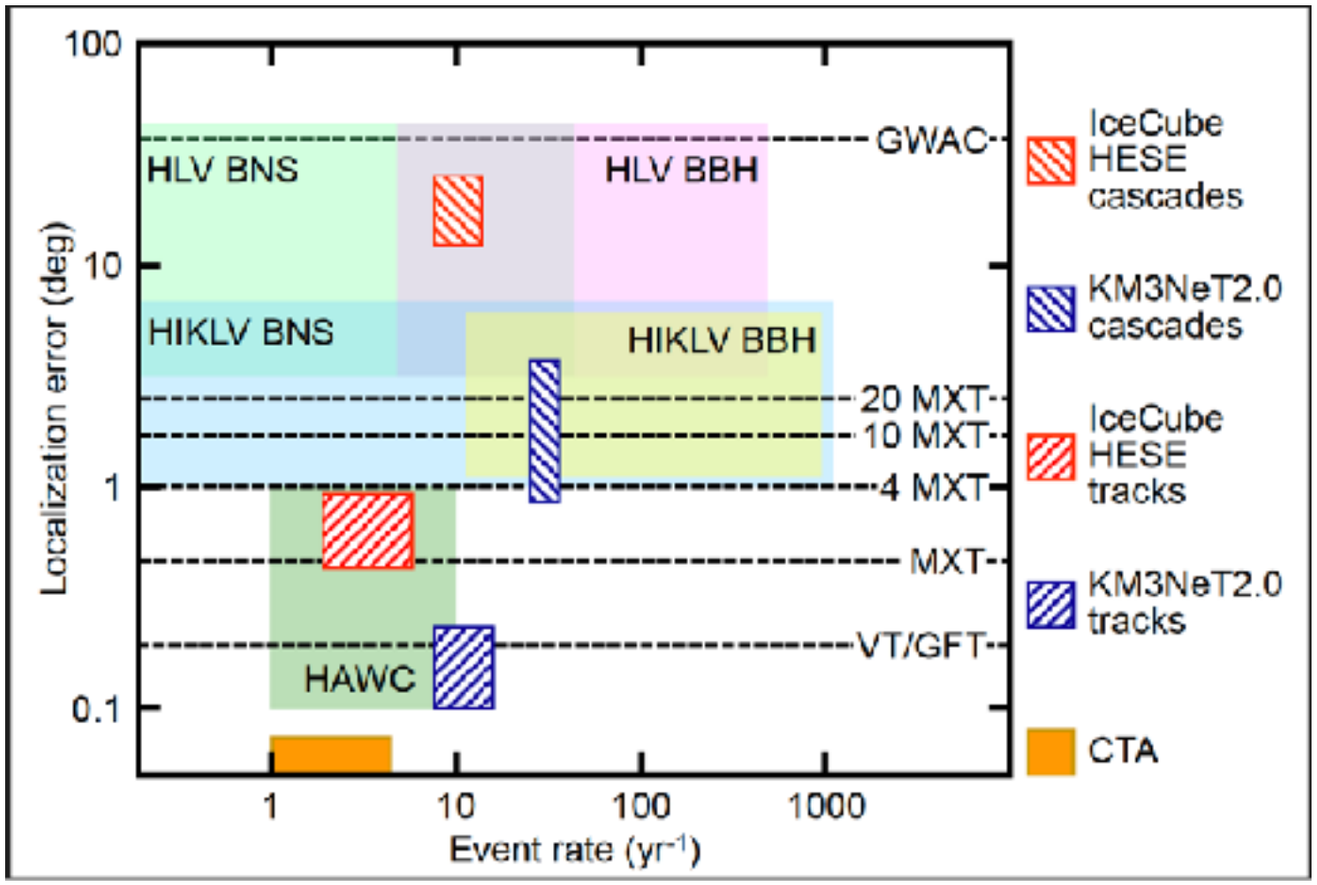
➡ Automatic GCN notices in case of very interesting neutrino signals

➡ 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 / SVOM



* **ToO MM with MXT and VT**

$\Longrightarrow$ Large FoV of MXT covers most of the error boxes of the KM3NeT track neutrino alerts, even for cascades, only few tiles necessary (quite competitive compare to Swift)

* **Ground follow-up with telescopes with large FoV and deep searches**

MoU between ANTARES-SVOM signed summer 2017

• 29% of the ANTARES neutrino triggers visible at Xinglong, 20% have been followed with mini-GWAC + 30 cm telescope [in agreement with the location of the telescopes in Xinglong and the weather constrains]

⇒ Delay: [0, 50min] for mini-GWAC (auto), [40, 1h40] for 30cm (manual)

⇒ No counterpart identified [mag<12 for mini-GWAC, mag<≈18 for 30cm]

KM3NeT / COLIBRI

In the OCEVU proposal, we have identified since the beginning the important role of COLIBRI for the follow-up of multi-messenger alerts.

COLIBRI telescope may followed KM3NeT neutrino alerts:

- Real-time follow-up of neutrinos: ~15% common visibility. Needed photometry clear filter
- Characterization of potential candidates (GRB counterpart, supernova, AGN, flaring star). Needed multi-filter photometry/spectrum

Process MM alerts as GRB, use pre-defined observing strategies + automatic image analysis to look for the counterpart.

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.

- **Great synergy between KM3NeT / SVOM / COLIBRI**