Ten years of multi-wavelength follow-up observations of ANTARES neutrino alerts

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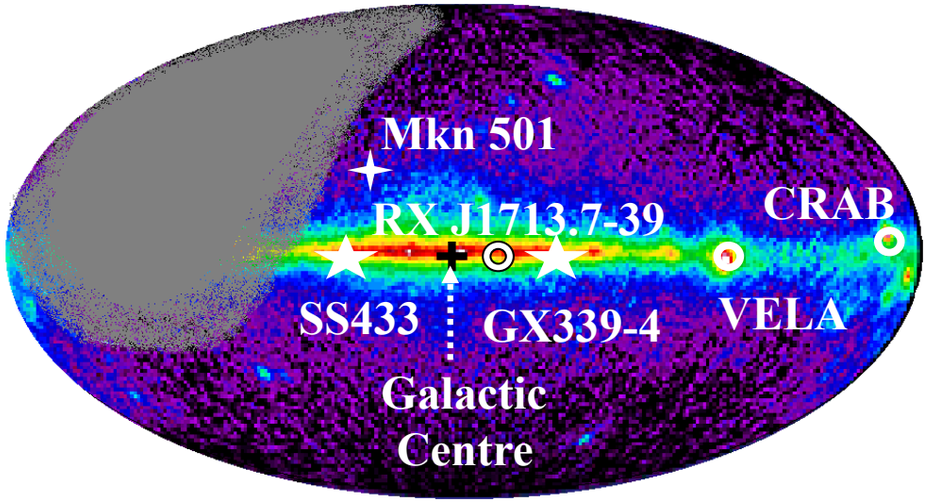
on behalf the ANTARES, MWA, ROTSE, MASTER, Swift, TAROT Collaborations

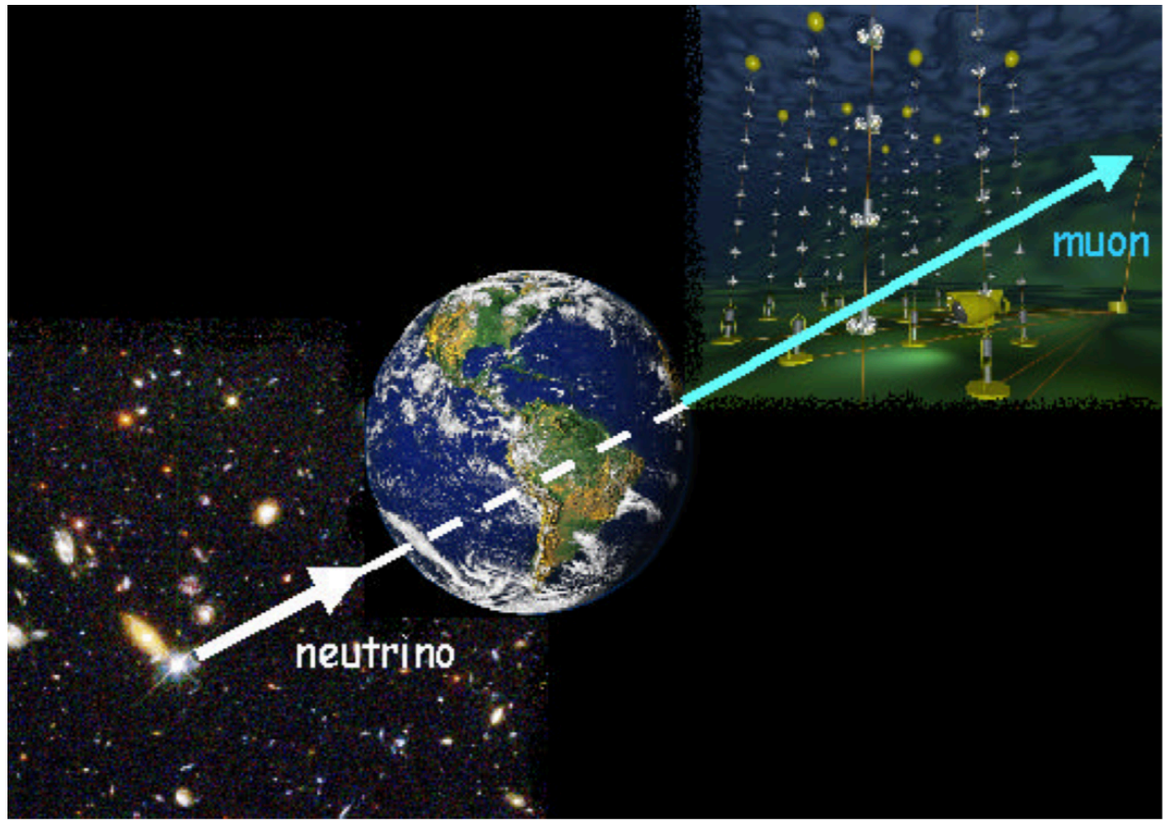
ICRC 2019 - Madison - 2019/07/30

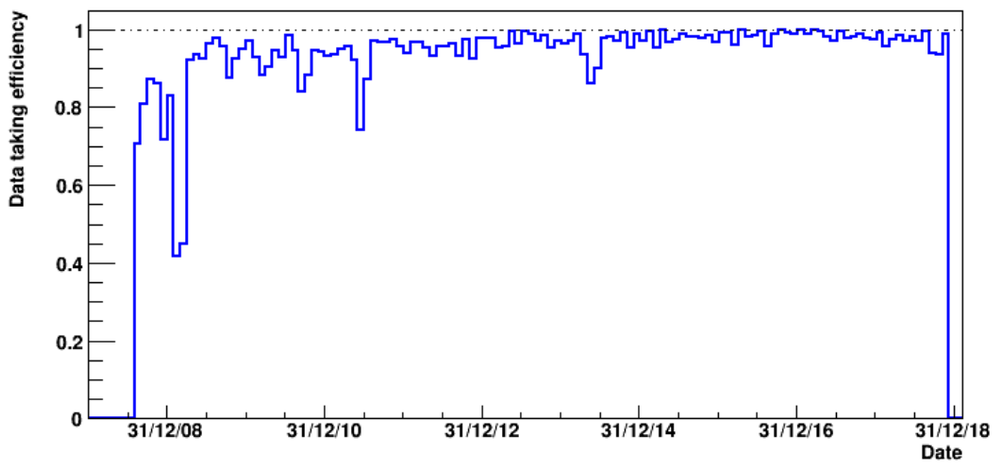
ANTARES

ANTARES in numbers:

- Stable data taking since 2008 with high duty cycle
- Large field of view (2π instantaneously)
- Quite good angular resolution: 0.3-0.5° (median)
- But it is also small: effective area: ≈1m² @ 30 TeV (O(12000) detected neutrinos)







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

ANTARES online framework

ANTARES Shore Station:

On-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

(Poster #872)

ANTARES
Neutrino Telescope

ν

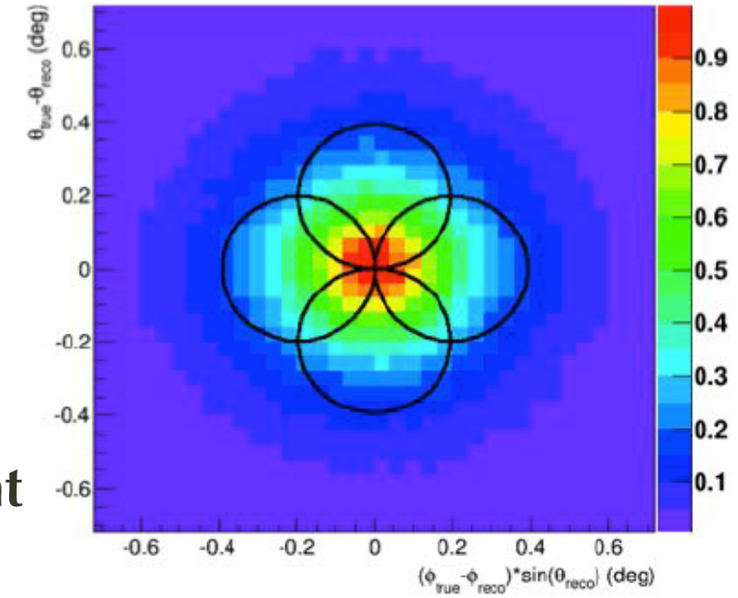
Real time

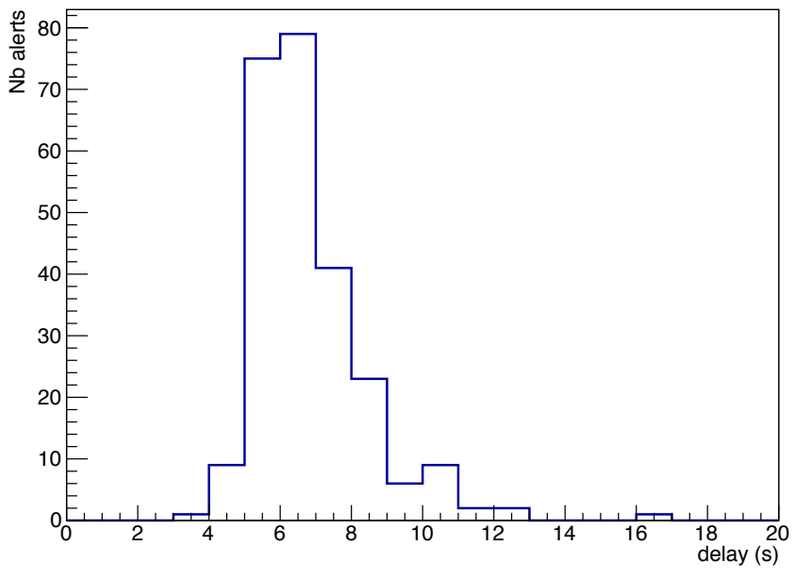
Neutrino alert selection

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)

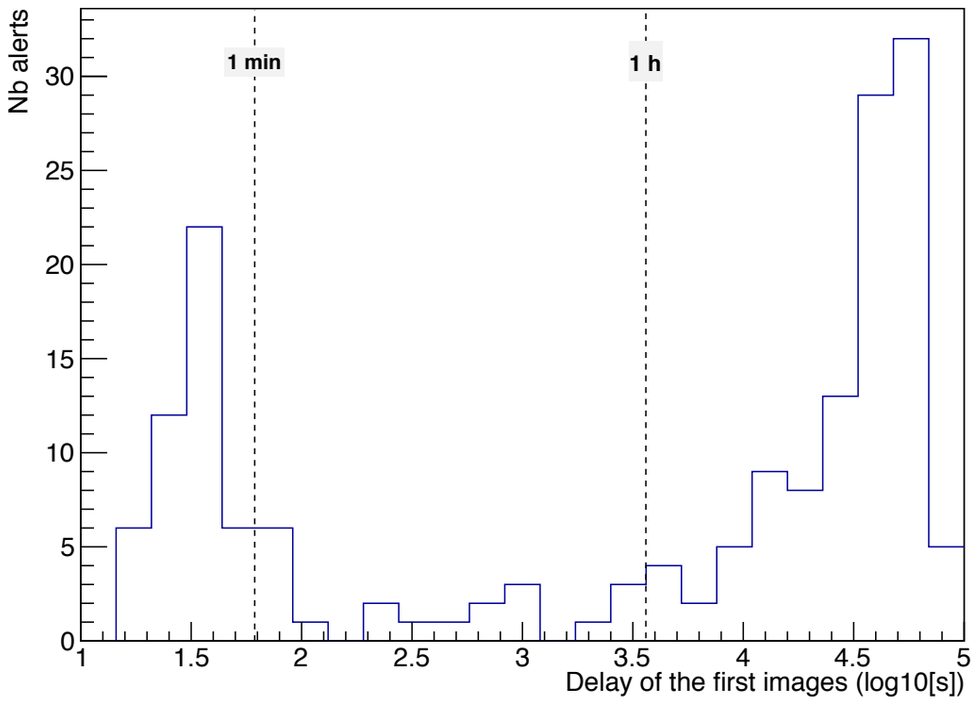




Alert message sent via the GCN using either GCN socket / VO Event

$\Longrightarrow$ Average delay: ~6-7 s

(get data, filtering, online reconstructions, neutrino selection, alert message)



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

$\Longrightarrow$ 208 alerts < 1 day

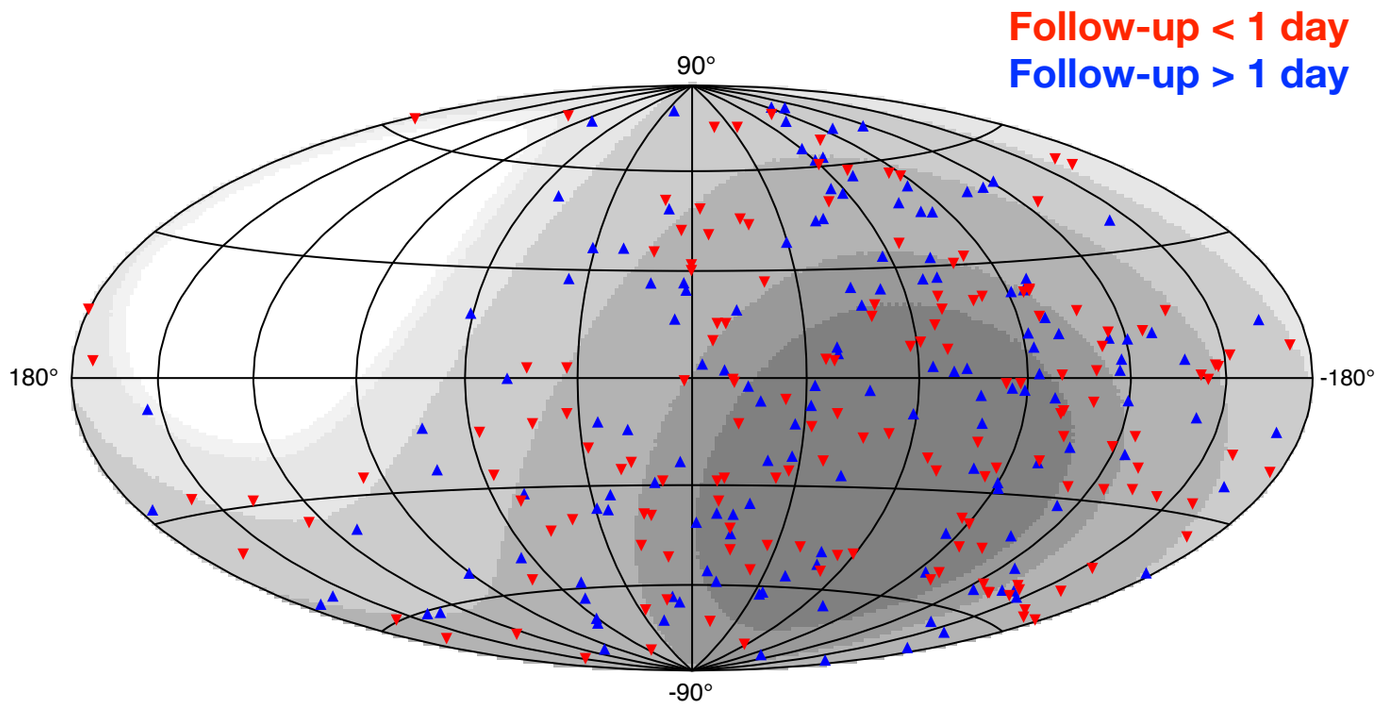
$\Longrightarrow$ 55 alerts < 1 min

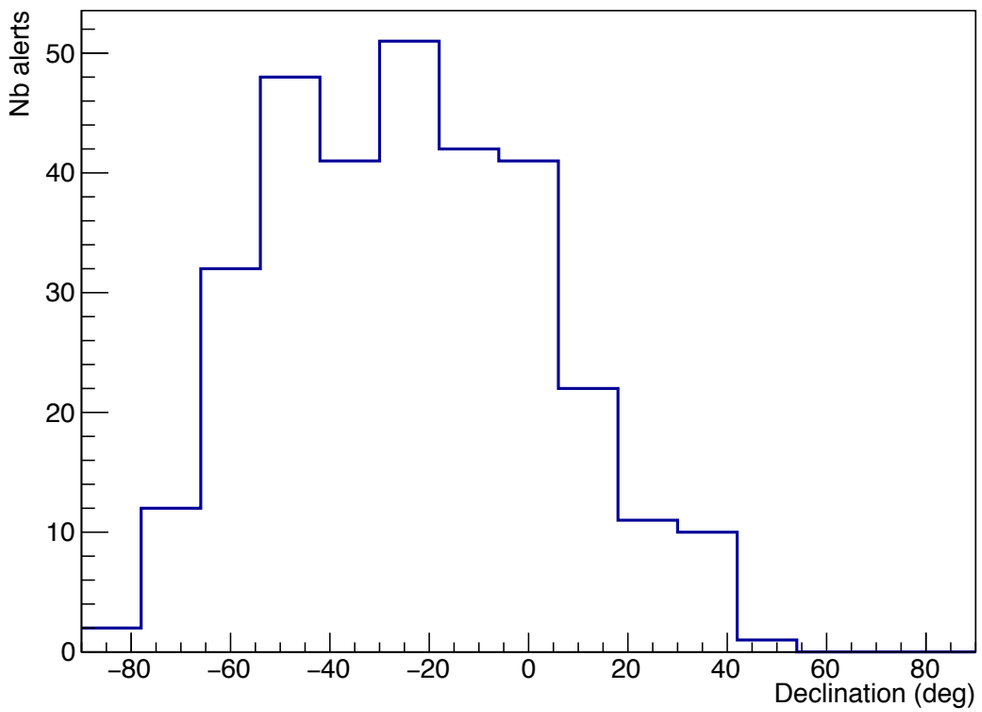
(wait for the alert visibility, stop previous acquisition, point the telescope, start the acquisition)

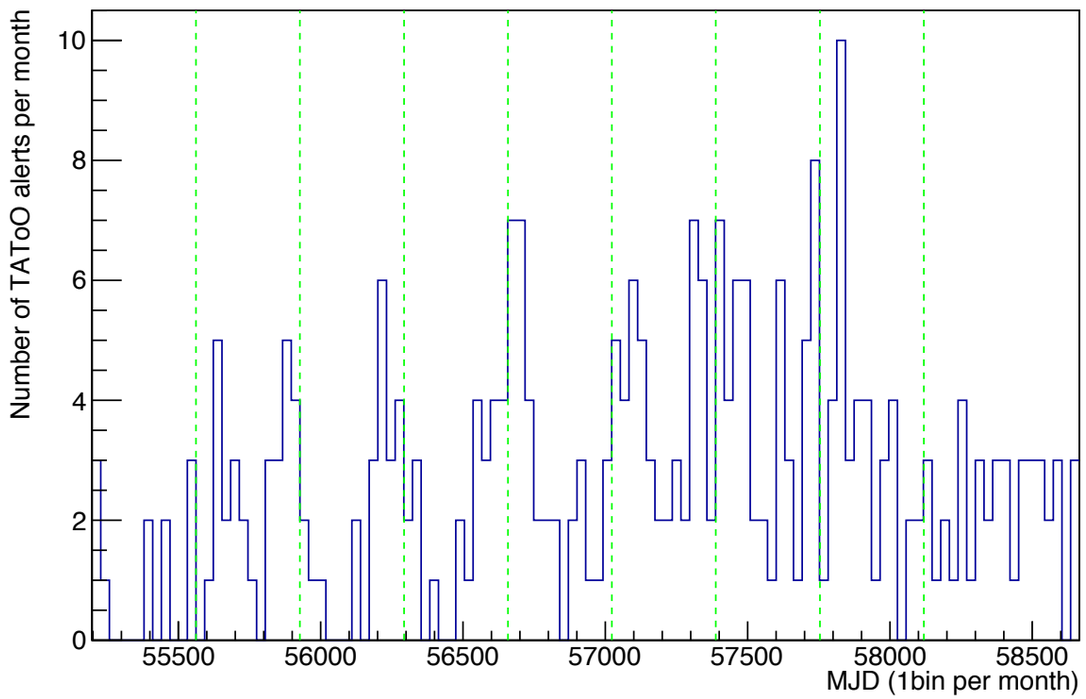
ANTARES neutrino alerts

Status ANTARES neutrino alerts (Oct 2009 - July 2019):

- 311 alerts sent to robotic telescopes
- 18/25 followed by Swift
- 4 followed by Integral
- 4 followed by MWA
- 2 followed by HESS







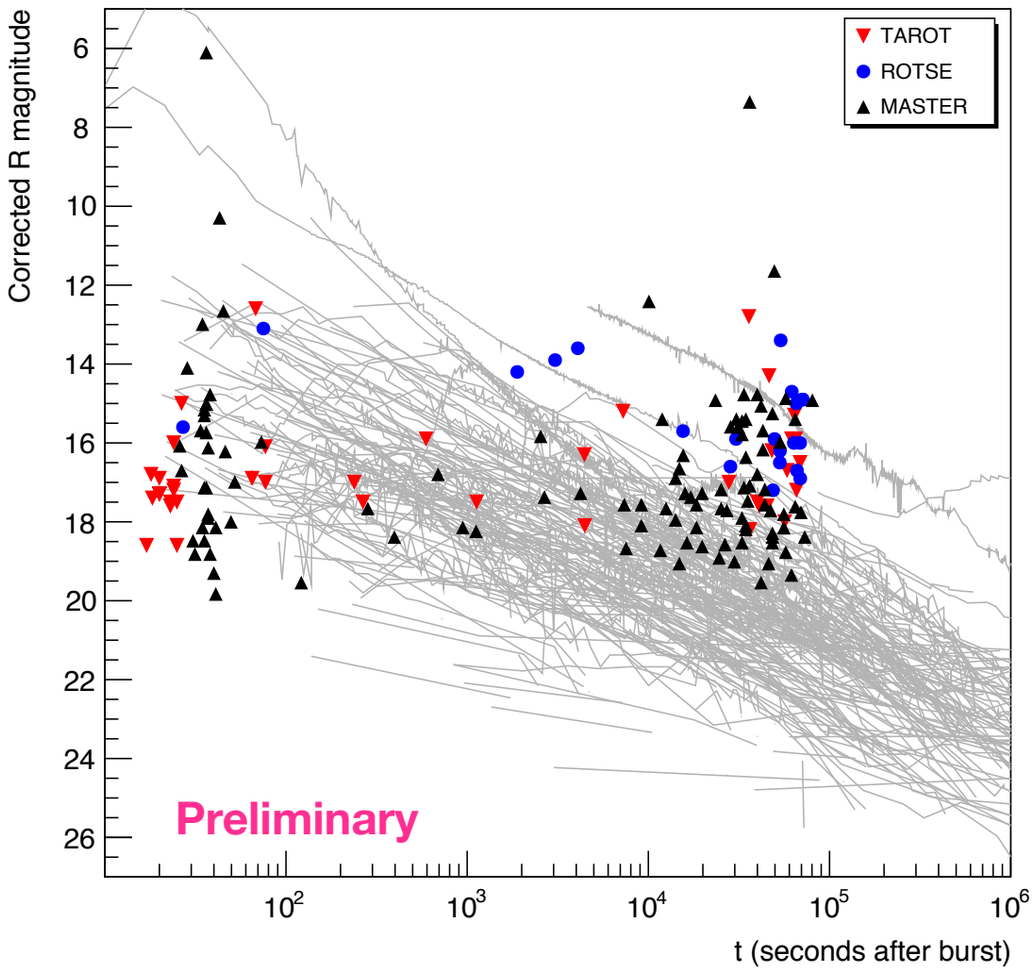
Optical & X-ray follow-up

Visible:

208/311 alerts followed 07/2009-07/2019 from TAROT, ROTSE, MASTER (67% of all alerts)

=> 55 alerts with delay <1min (best: 17s)

=> no transient candidate associated to neutrinos



X-ray:

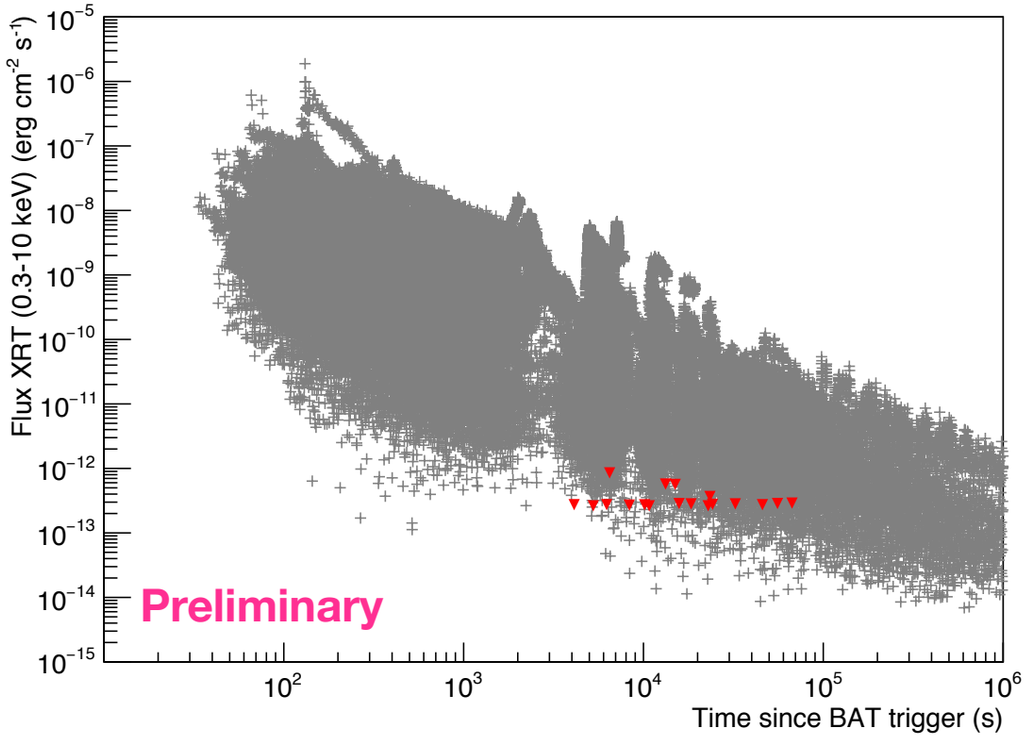
18/25 alerts followed 06/2013-07/2019 (72% of all alerts)

=> average delay ~6 h (best 1.1h)

=> no transient candidate associated to neutrinos

=> Constrains on origin of individual neutrinos

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



Optical & X-ray follow-up

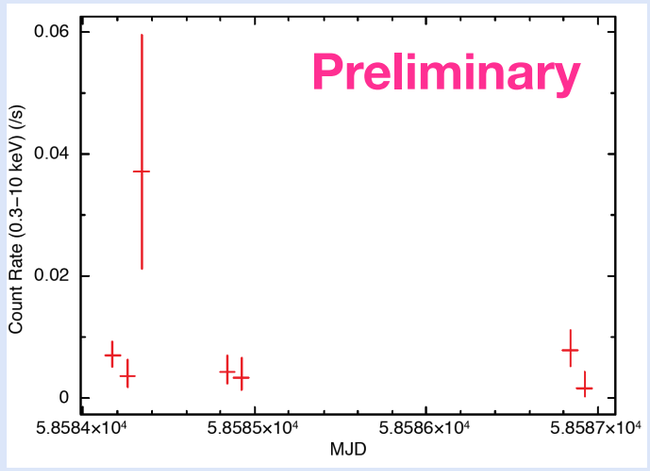
ANT190410A: VHE trigger

→ Follow-up Swift: +13.1h

→ Follow-up Master: +9.2h

- Swift discovered a bright transient (< 1day)
- Master found an optical source with no significant variation
- Probably also associated to a flaring star (prob~0.01)

Preliminary

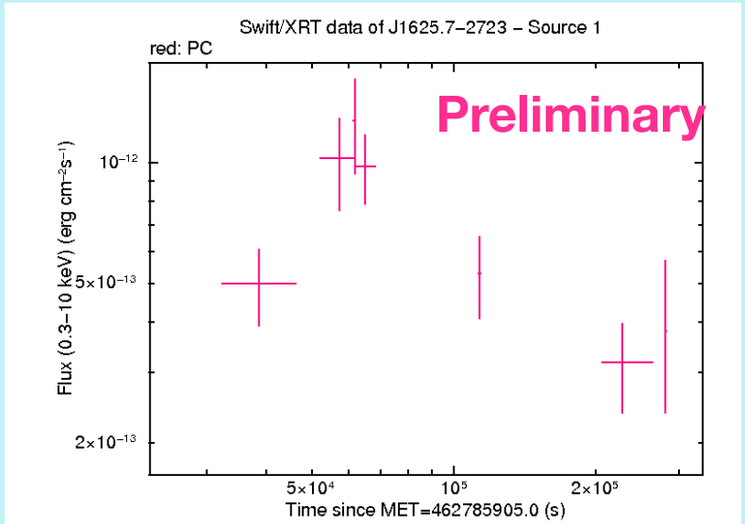


ANT150901A: VHE trigger (GCN 18231 and ATeL 7987)

→ Follow-up Swift: +9h

→ Follow-up Master: +10h

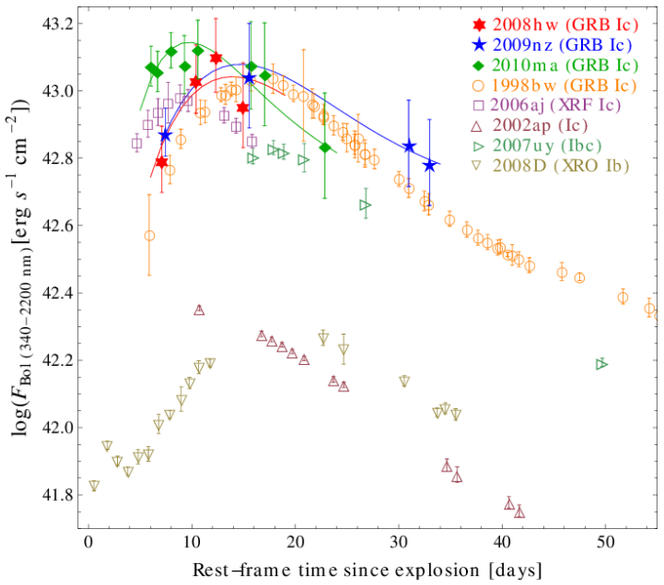
- Swift discovered a bright transient (~2 days)
- Master found a bright optical source but with no significant variation
- Large MWL follow-up permits to characterize the source as a young accreting G-K star or a RS CVn (prob=0.03)



Others candidates: Pulsar, PWN, AGN, ccSN, GC… but no EM flux variation

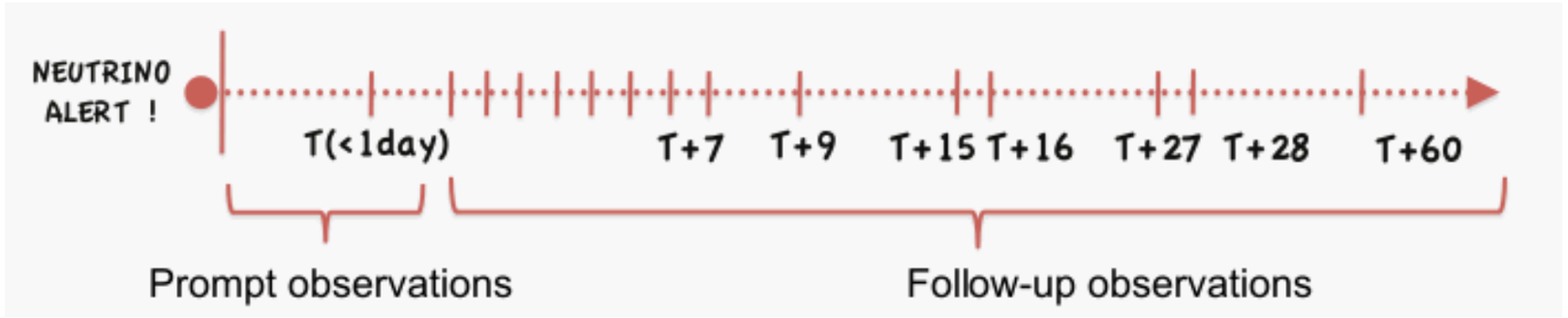
Name	Date	Ra, Dec	Nhit	Amplitude (pe)	p-value
ANT150901A	2015-09-01 07:38:25	246.31°, -27.47°	127	356	0.002
ANT190410A	2019-04-10 13:52:04	50.35°, -48.08°	82	400	0.030

Long-term optical follow-up



Olivares et al, A&A 577, A44 (2015)

Observing strategies of TAROT/ROTSE :



MASTER: T-T+1, T+7, T+15, T+21 days

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

- ➡ Alert types: 74 DIRECTIONAL + 141 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
- ➡ $N_{exp}(SN) = 0.4$ 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…)

Radio & VHE γ-ray follow-up

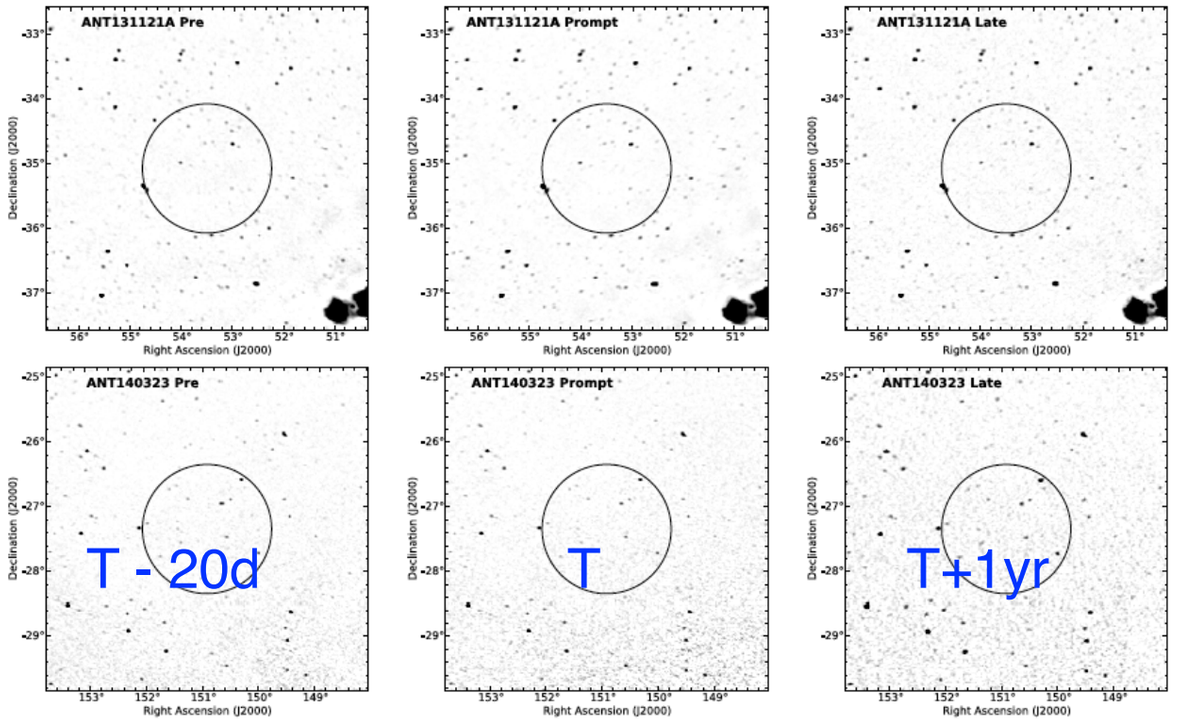
Radio follow-up:

2 directional alerts followed over a year with MWA (ANT131121A & ANT140323A)

- ➡ No interesting transient associated with the neutrinos
- ➡ If source at 20 Mpc, UL(5σ) = 90–340 mJy —> $L_{150\ MHz} < 10^{29}$ erg/s/Hz ($<10^{37}$ erg/s). If NS-NS coalescence limit at $z > 0.2$

Other alerts followed in real-time with MWA (2017-19)

- ➡ Analysis still in progress

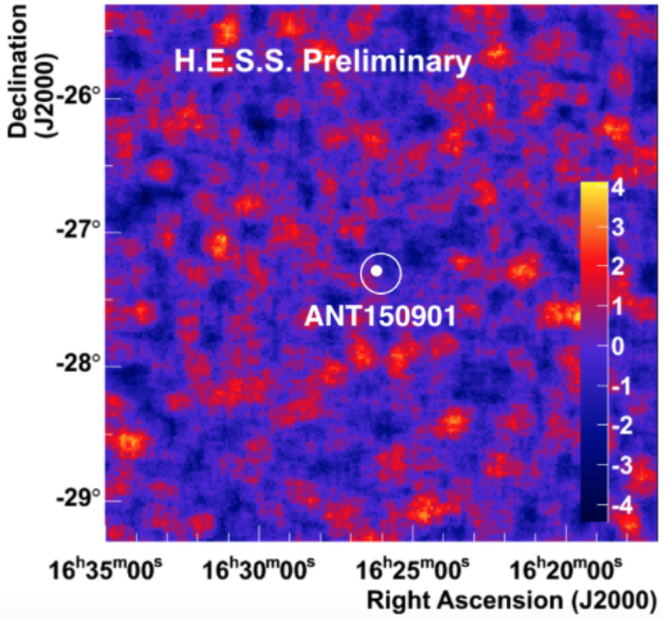


Croft S. et al (MWA & ANTARES Collaboration), ApJ 823 (2016) 24.

H.E.S.S. follow-up:

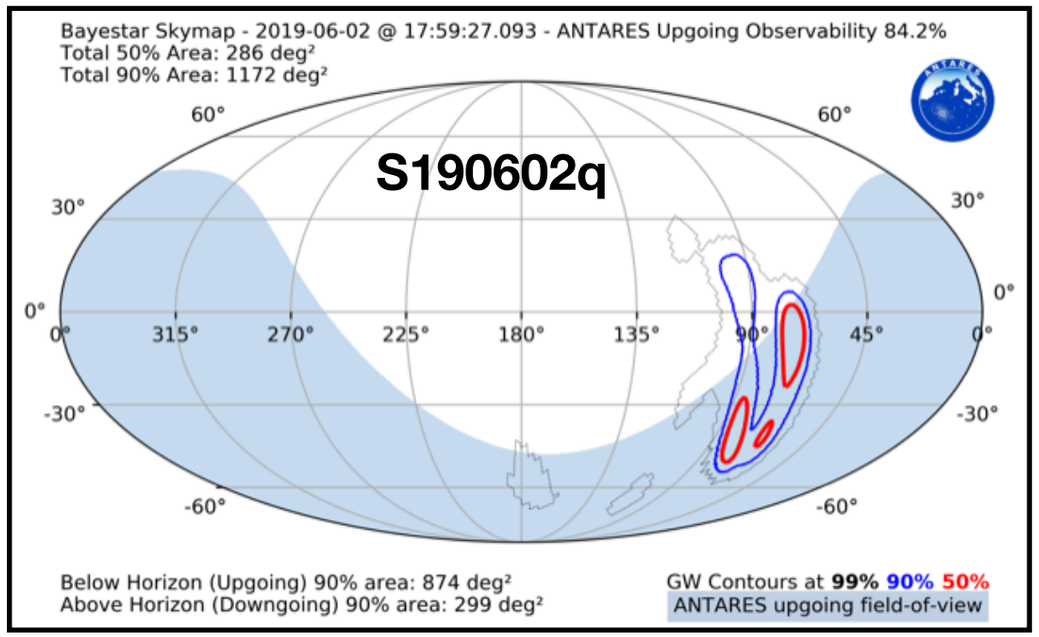
2 alerts followed with very small delay (2015-2017)

- ➡ ANT150901(+2.5d), ANT170130 (+32s): No VHE candidates associated with the neutrinos



Schüssler F. et al, arXiv:1705.08258 & Pos(ICRC2017)253.

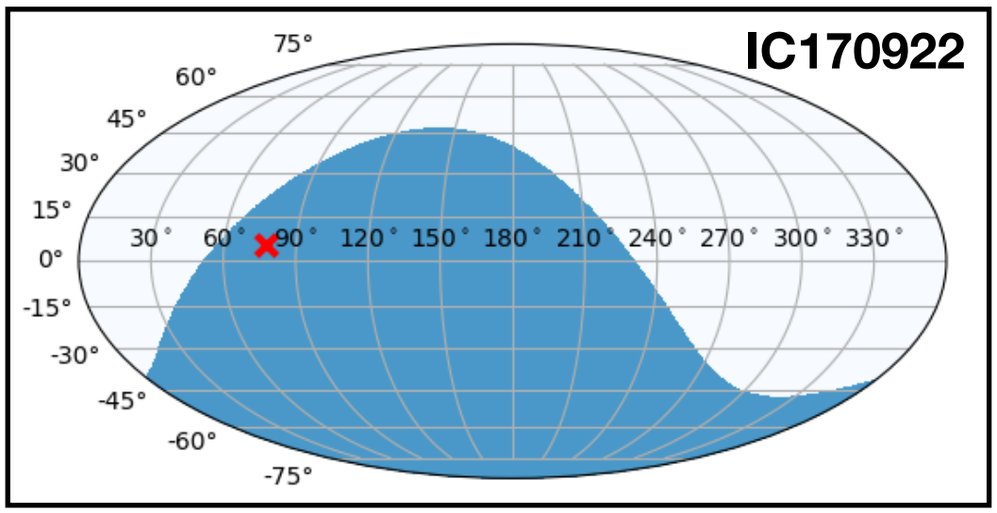
Real-time follow-ups of external triggers



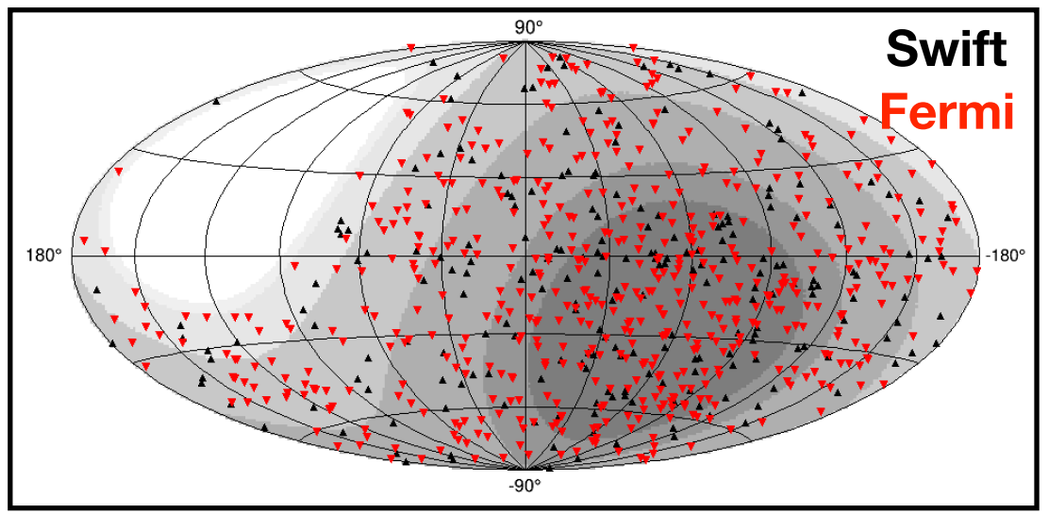
- ANTARES is performing real-time follow-up for all IceCube/GW/GRB/FRB events (+exceptional events, AT2018cow, V407cyg…) whose positions are below its horizon at the time of the events.
- Fully automatized analysis on different time windows: +/-500s, +/-1h, +/-1d

➡ Up to now, no significant associations

➡ For IC/GW, we report the results in GCN circulars or Atels.



IceCube HESE/EHE (gold/bronze) neutrinos



Swift/Fermi GRBs
Parkes FRBs

Dornic et al, Poster, Pos(ICRC2019)872

Summary

- Since 2007, ANTARES is taking good data with a very high duty cycle (~95%). Very rich real-time multi-messenger programs with more than ten years of data including an alert sending program (TAToO) and an EM/MM transient follow-up (Poster #872).

- Very performant & efficient alert sending system:
  => Able to emit alerts within ~6-7 s with a precision of 0.4-0.5^{o} (only ν_{μ}).
  => Full multi-wavelength follow-up covering the whole EM spectrum.
  => 311 alerts sent to robotic telescopes, 25 to Swift, a few to Integral, M.W.A. & H.E.S.S..
  => Up to now, no significant transient associated to neutrinos. Set constraints on nature of individual neutrinos .

- On-going implementation of the on-line framework in KM3NeT (see R. Coniglione's talk) with the goal to send alerts in 2020.

The ANTARES Collaboration would like to warmly thank the EM teams for their huge and constant effort on following its neutrino alerts and on having constructive discussions.