

# 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

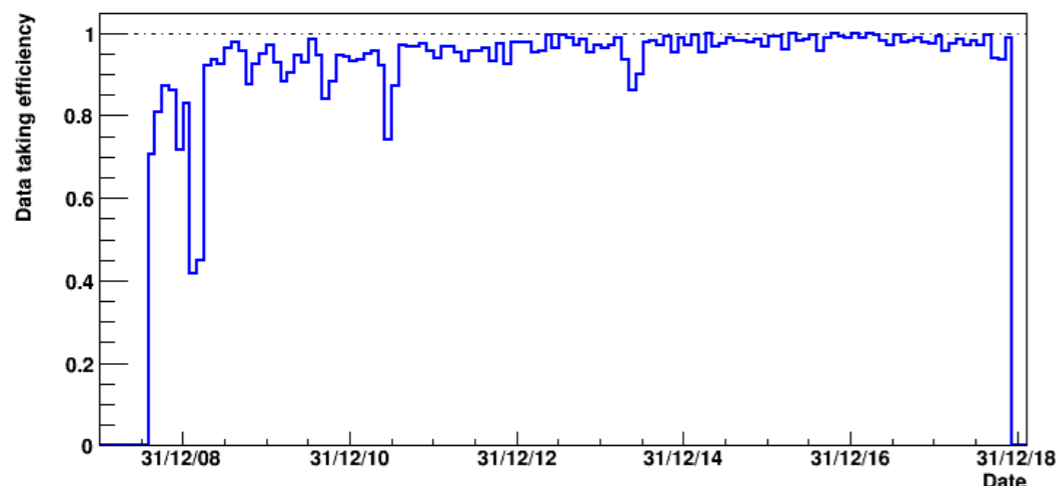
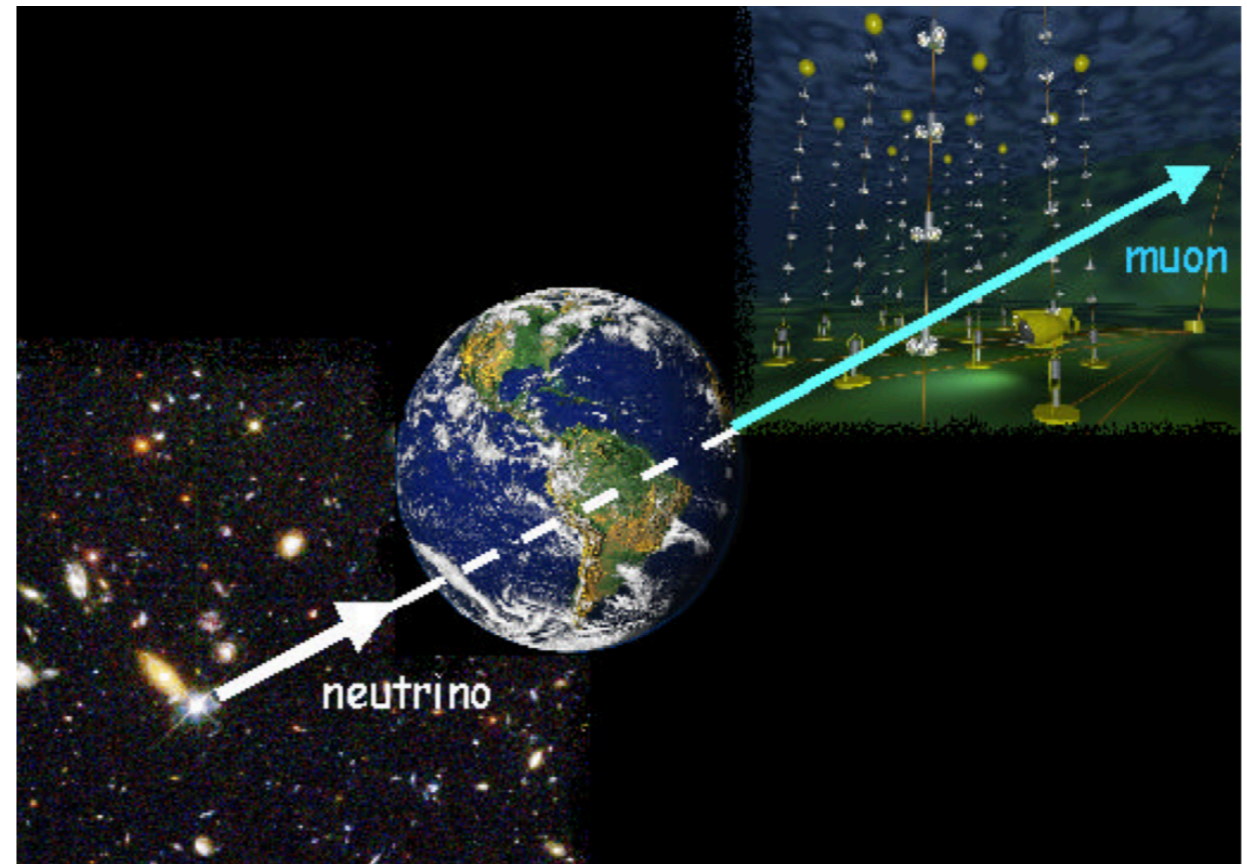
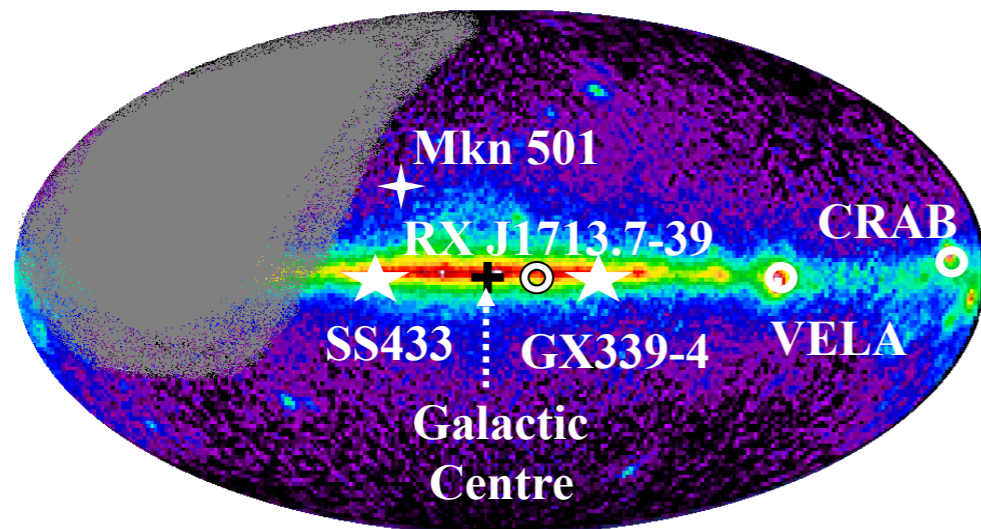


**ICRC 2019 - Madison - 2019/07/30**

# ANTARES

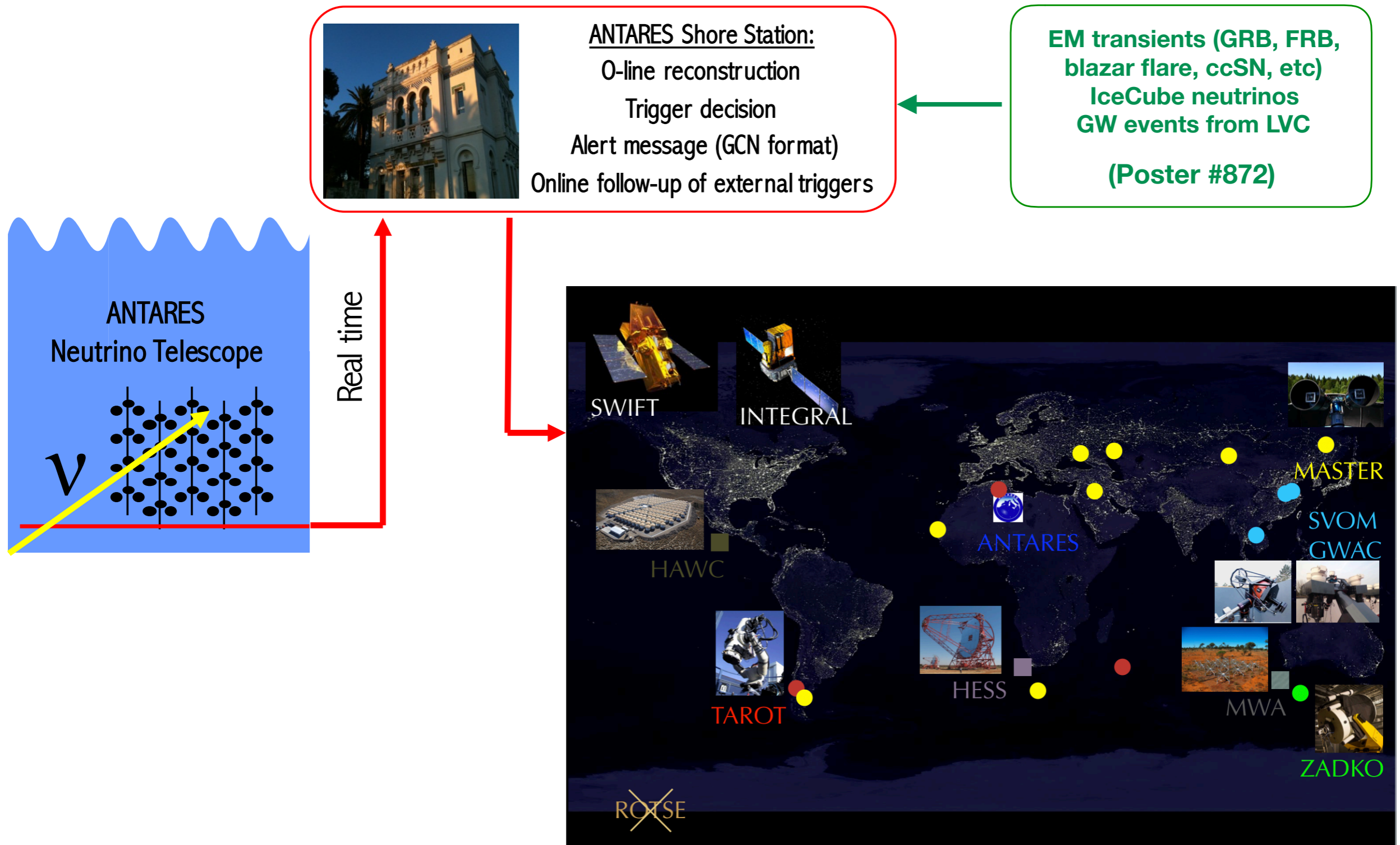
## ANTARES in numbers:

- Stable data taking since **2008** with high duty cycle
- Large field of view ( $2\pi$  instantaneously)
- Quite good angular resolution: **0.3-0.5°** (median)
- But it is also small: effective area:  $\approx 1\text{m}^2$  @ **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



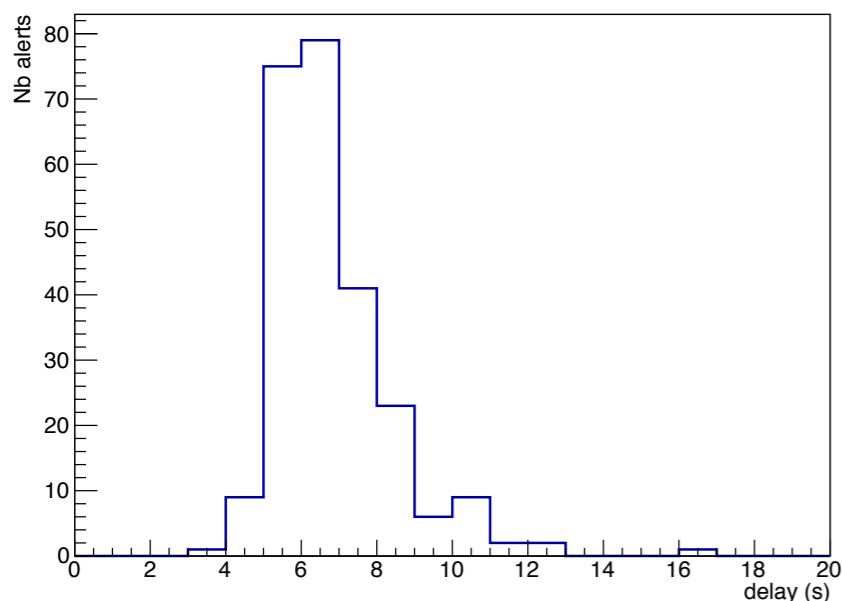
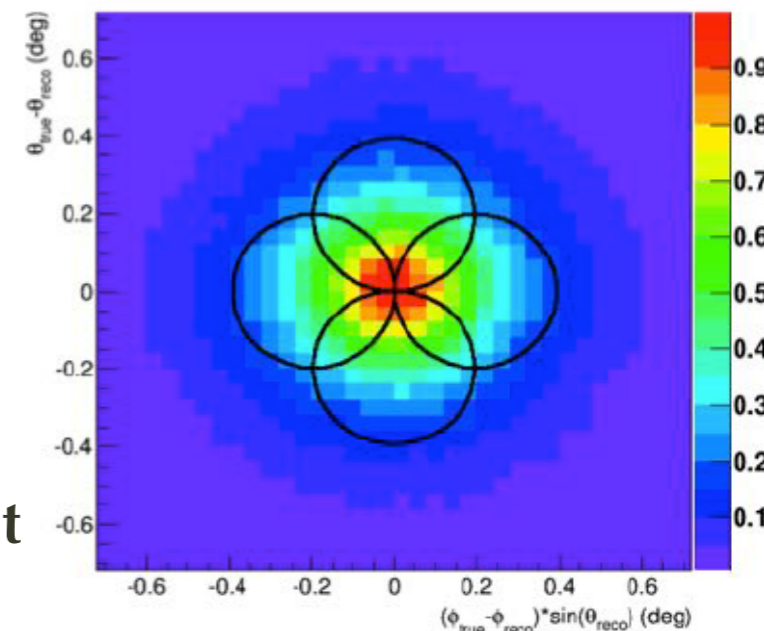


# Neutrino alert selection

## Triggers:

- \* Doublet of neutrinos:  $\sim 0.04$  event / yr.
- \* Single neutrino with direction close to local galaxies:  $\sim 1$  TeV,  $\sim 10$  events / yr.
- \* Single HE neutrinos:  $\sim 7$  TeV,  $\sim 15$  event / yr
  - => Sub-sample HE neutrinos:  $\sim 5$  TeV, 20 events / yr
  - => Sub-sample VHE neutrinos:  $\sim 30$  TeV,  $\sim 3-4$  events / yr.

ANTARES PSF :  $\sim 0.4^\circ$  (median)



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

⇒ **Average delay:  $\sim 6-7$  s**

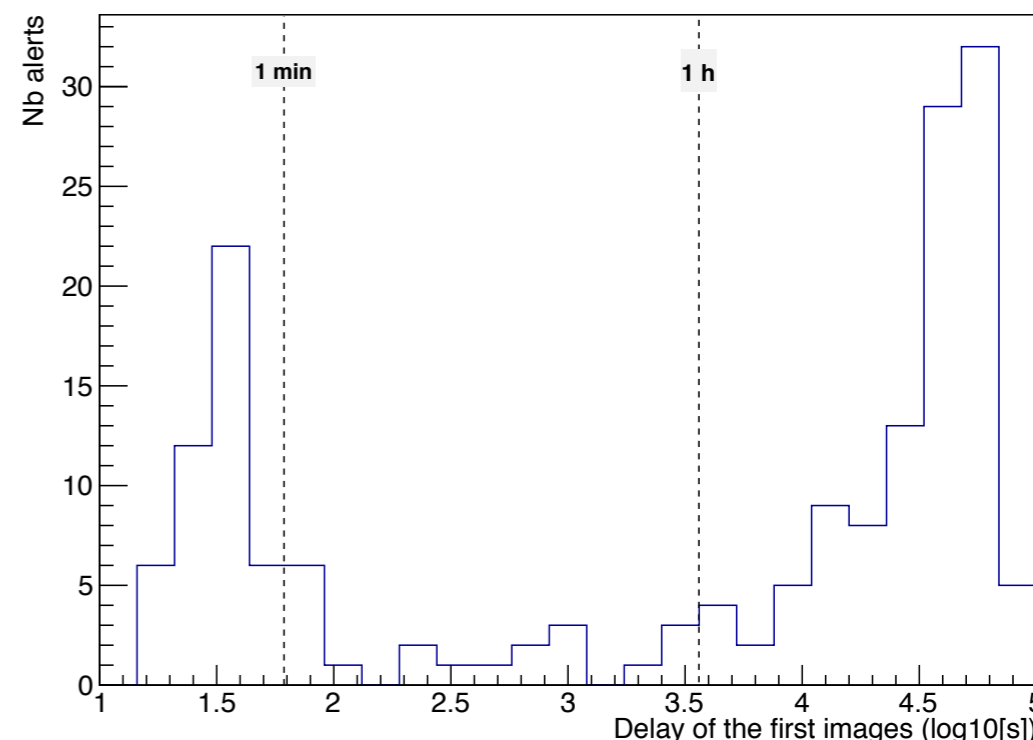
(get data, filtering, online reconstructions, neutrino selection, alert message)

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

⇒ **208 alerts < 1 day**

⇒ **55 alerts < 1 min**

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

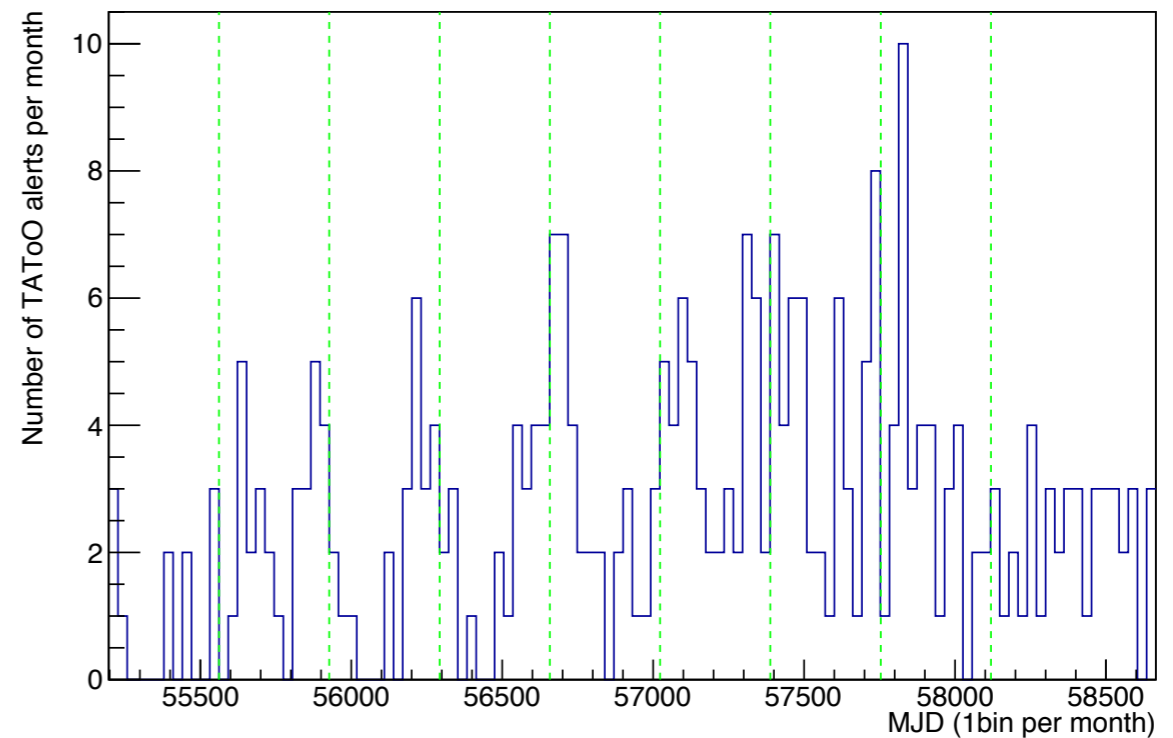
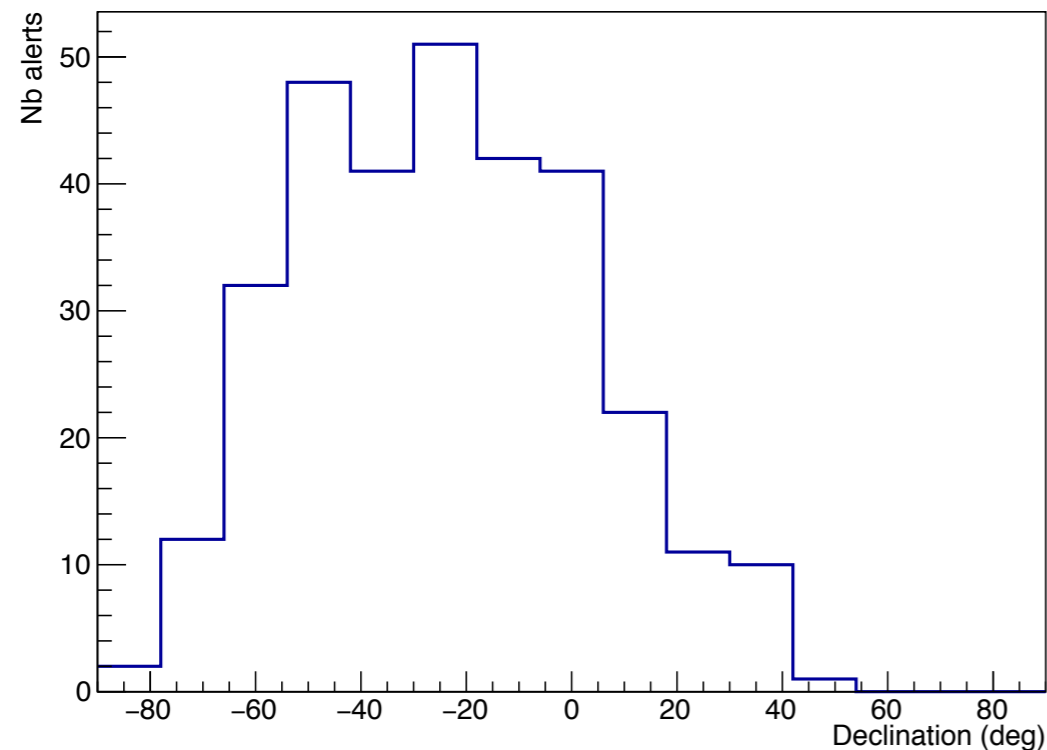
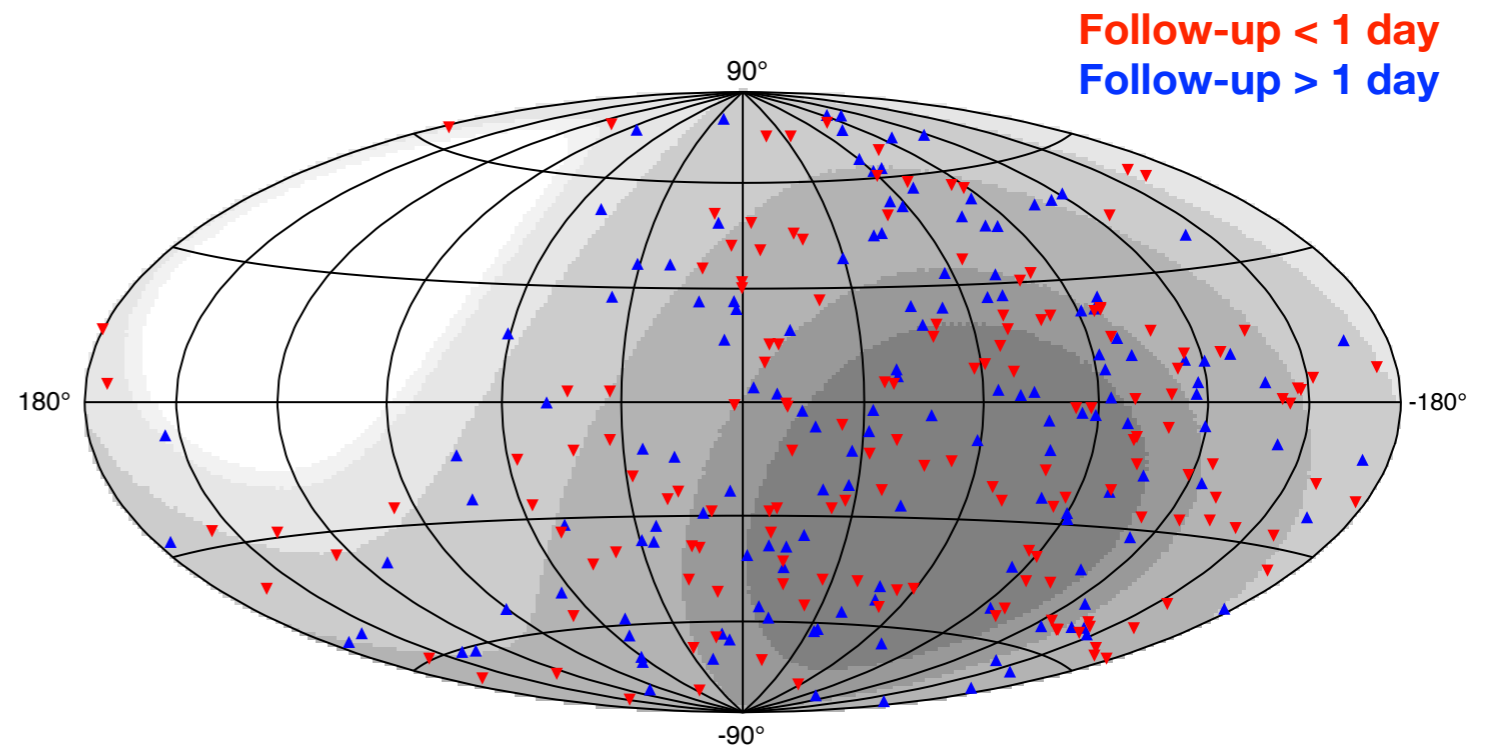




# ANTARES neutrino alerts

## 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:

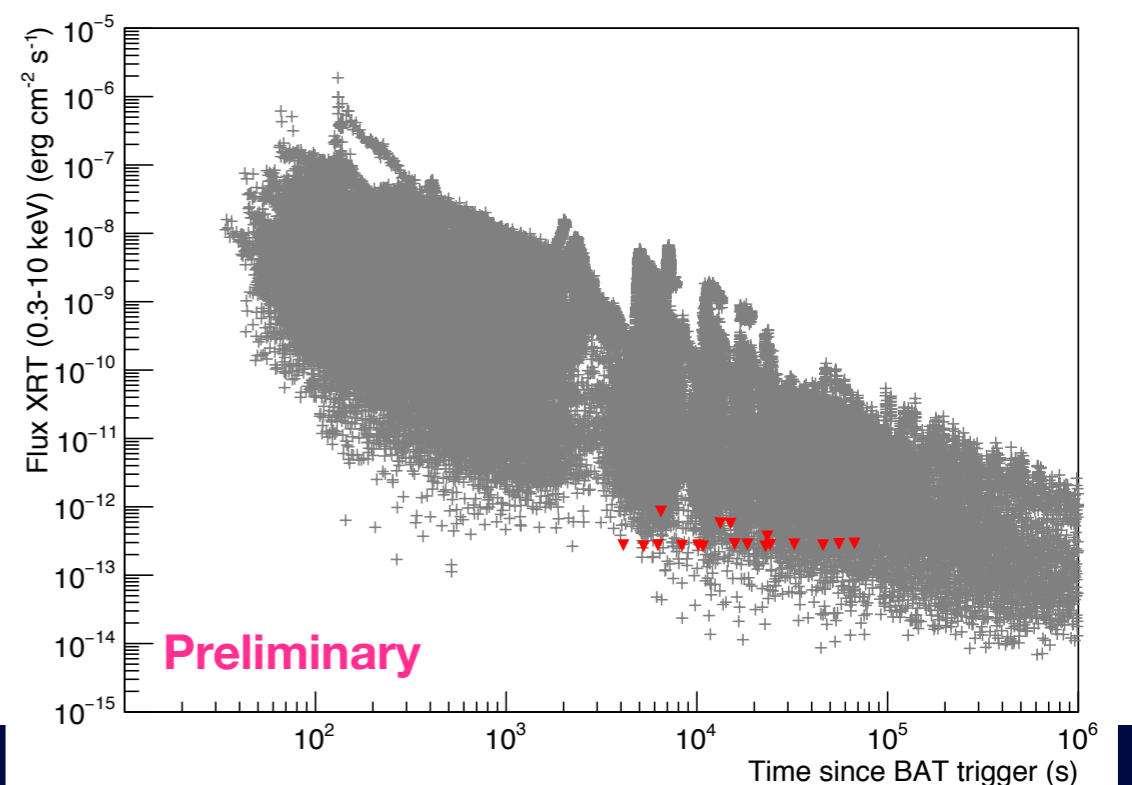
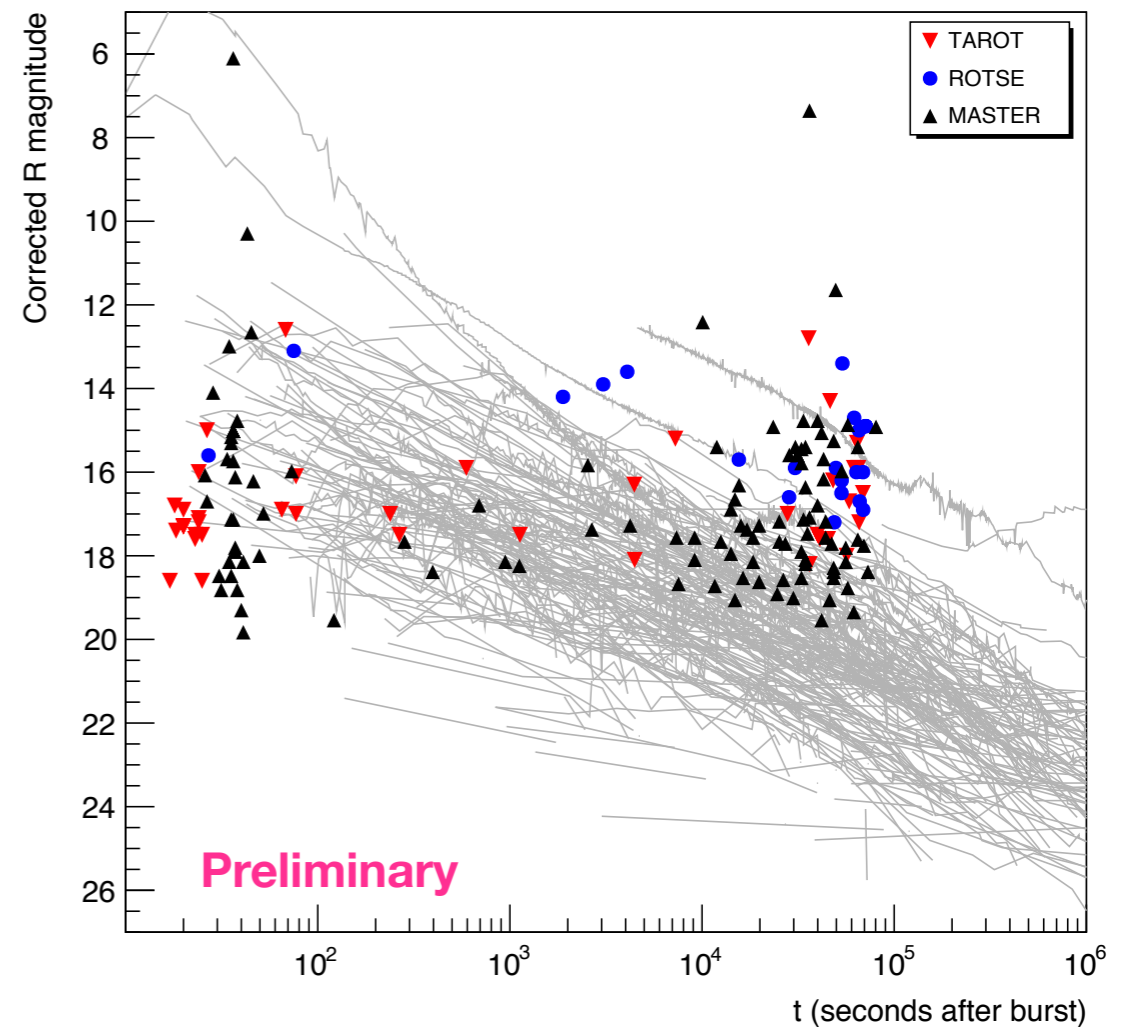
18/25 alerts followed 06/2013-07/2019 (72% of all alerts)

=> 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

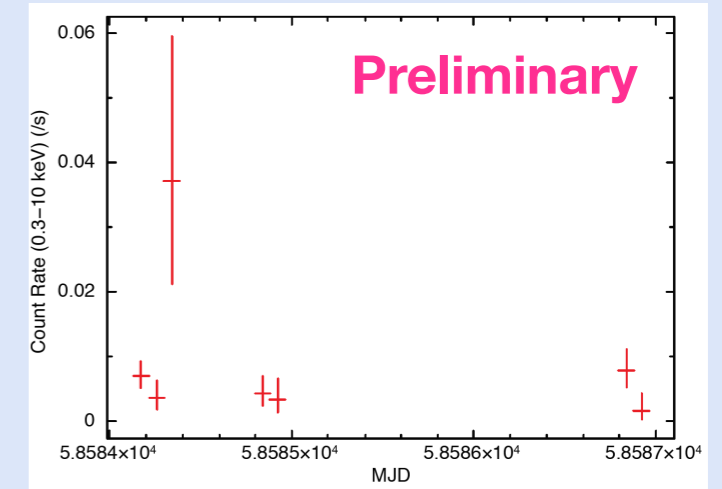


# Optical & X-ray follow-up

## ANT190410A: VHE trigger

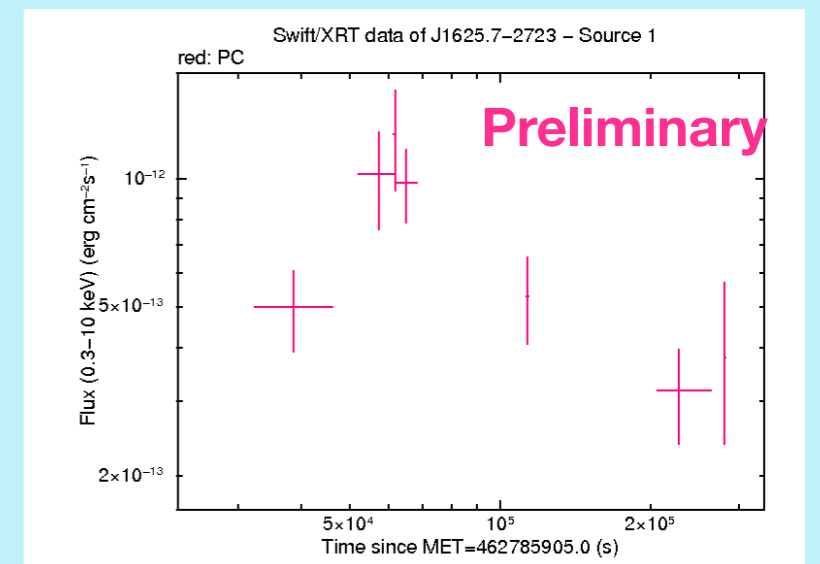
- Follow-up Swift: +13.1h
- Follow-up Master: +9.2h
- Swift discovered a bright transient (< 1day)
- Master found an optical source with no significant variation
- Probably also associated to a flaring star (prob~0.01)

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)

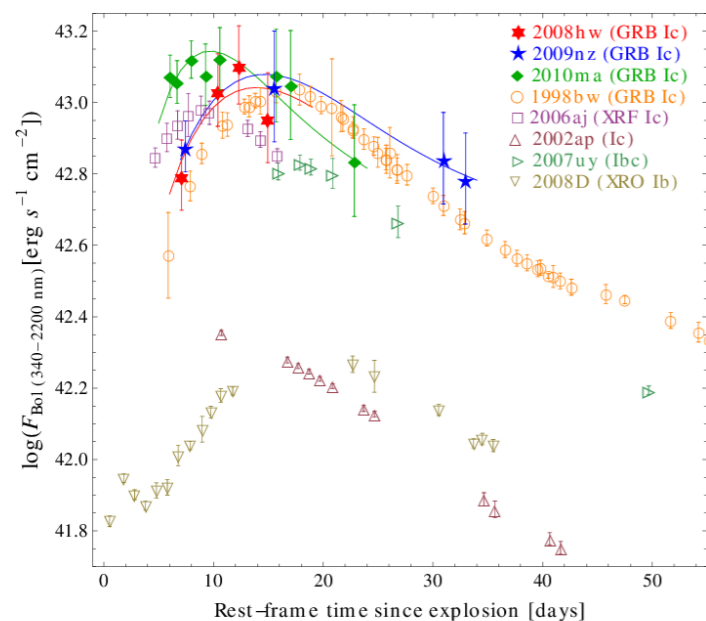


**Others candidates: Pulsar, PWN, AGN, ccSN, GC... but no EM flux variation**

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

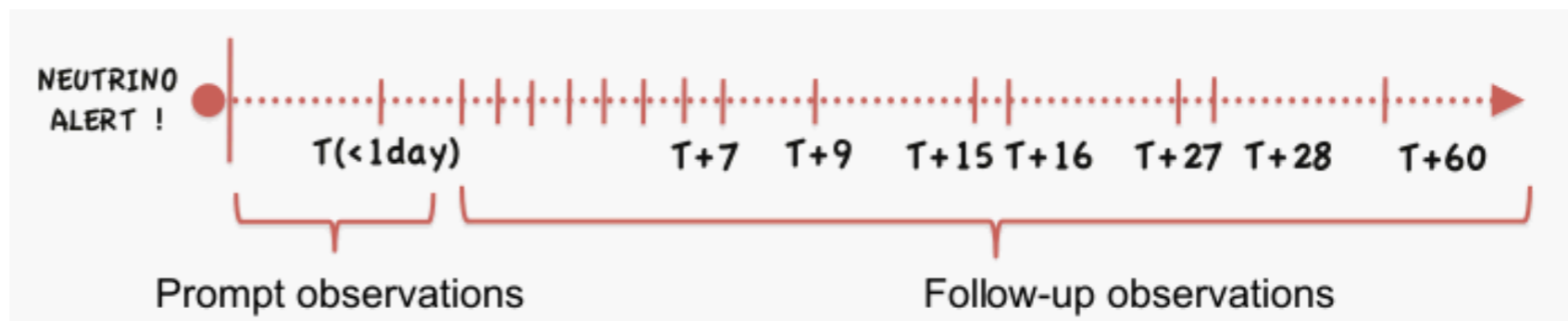


# Long-term optical follow-up



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**
- ➔  **$N_{\text{exp}}(\text{SN}) = 0.4$**  for the full follow-up [SN rate= $2.4 \cdot 10^{-4} \text{ yr}^{-1} \text{ Mpc}^{-3}$ ]
- ➔ **Other types of hadronic sources not looked up to now (CV...)**

# Radio & VHE $\gamma$ -ray follow-up

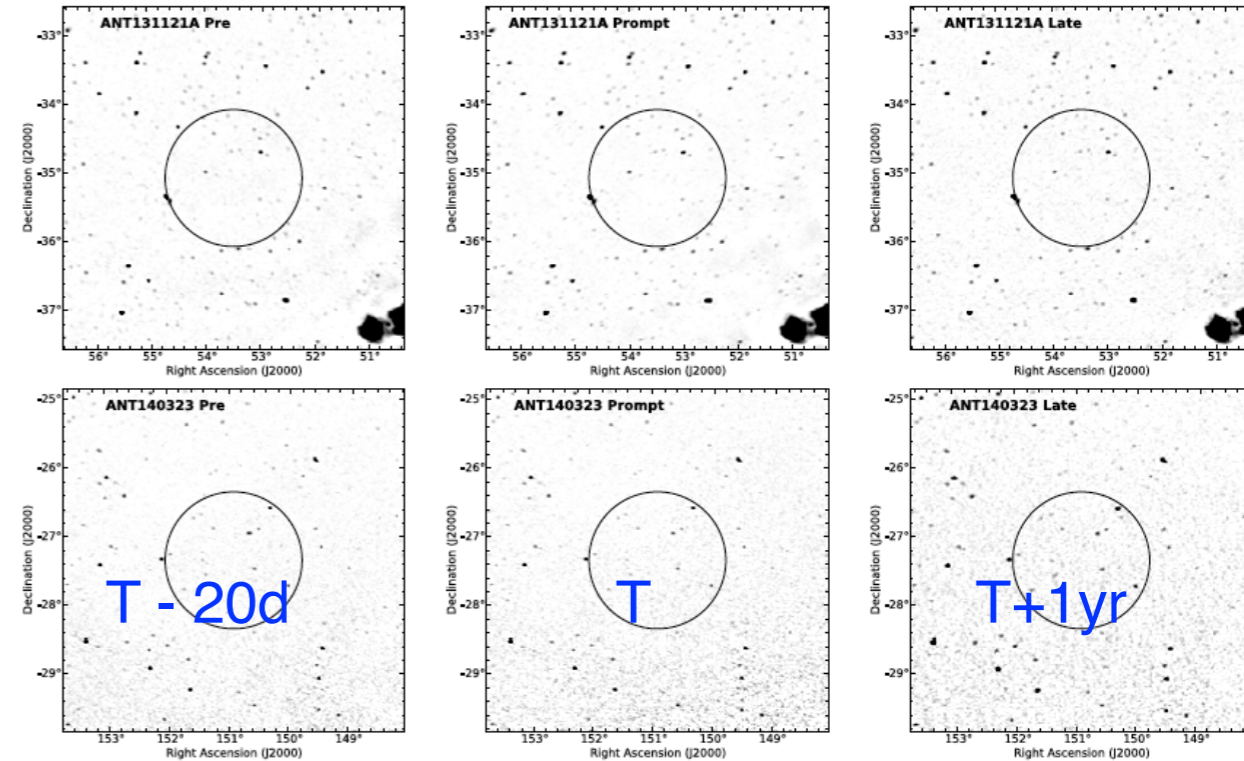
## Radio follow-up:

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

- ➔ No interesting transient associated with the neutrinos
- ➔ If source at 20 Mpc,  $UL(5\sigma) = 90\text{--}340$  mJy  
—>  $L_{150\text{ MHz}} < 10^{29}$  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



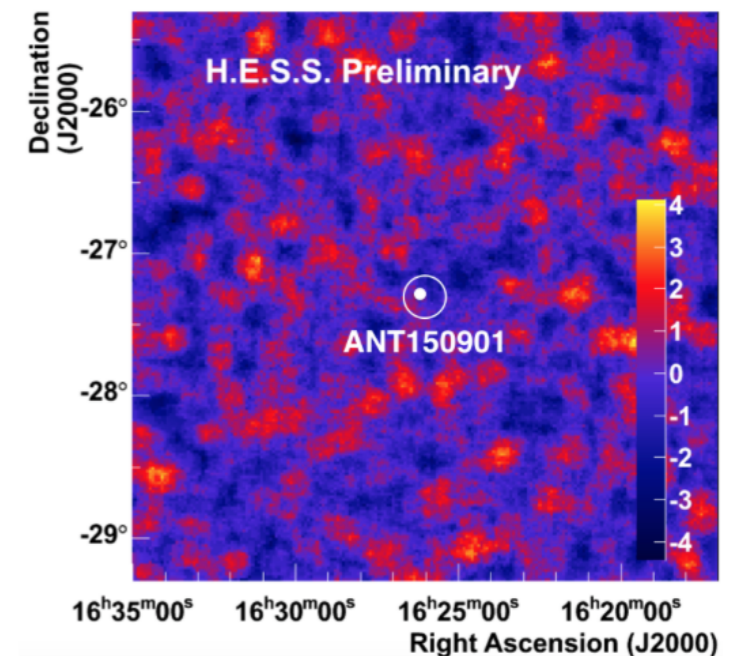
Croft S. et al (MWA & ANTARES Collaboration), ApJ 823 (2016) 24.

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

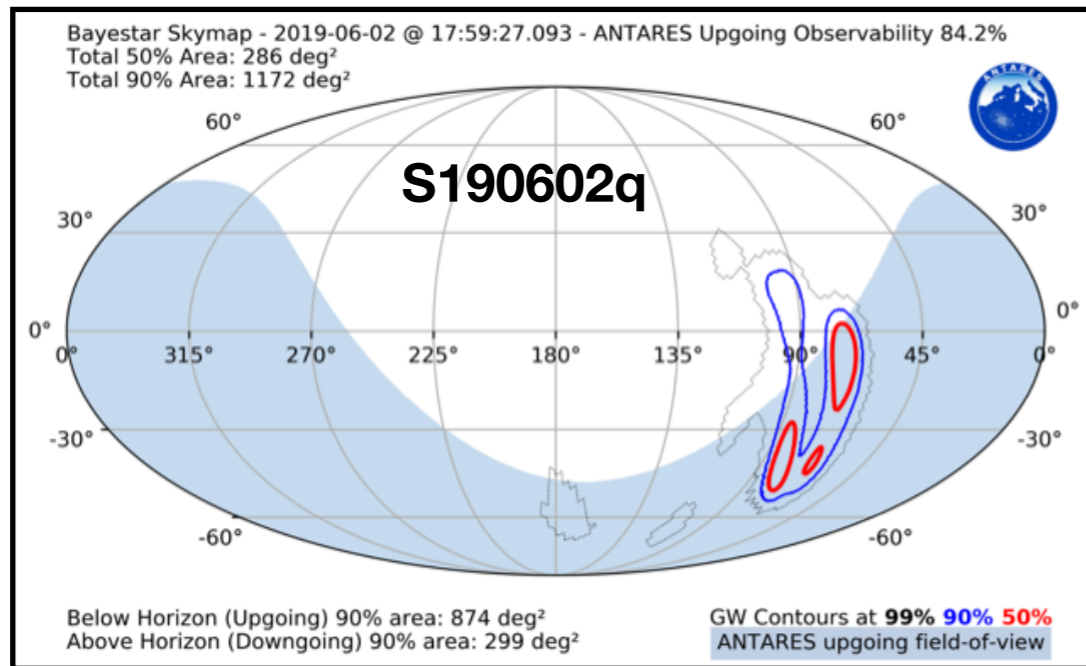
2 alerts followed with very small delay (2015-2017)

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

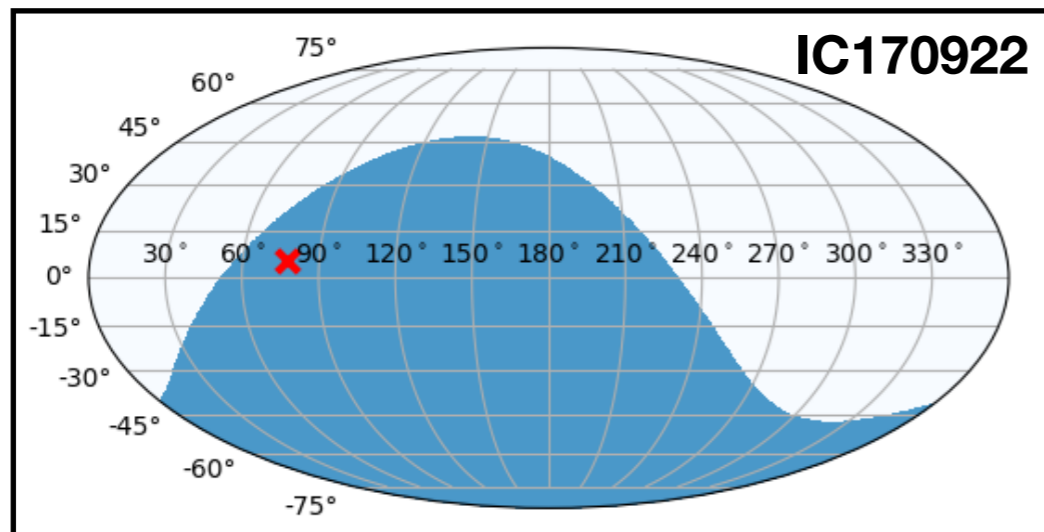
Schüssler F. et al, arXiv:1705.08258 & Pos(ICRC2017)253.



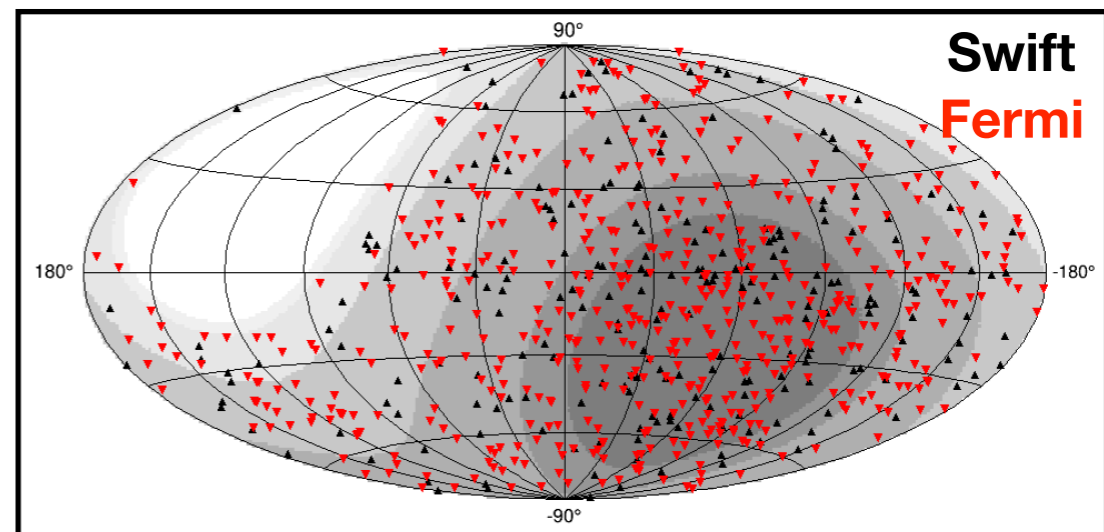
# Real-time follow-ups of external triggers



- 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° (only  $\nu_\mu$ ).
  - => 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.**