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► **To cite this version:**

Damien Dornic, Alexis Coleiro, M. Colomer Molla, Antoine Kouchner, Thierry Pradier. Real-time follow-up of multi-messenger alerts with the ANTARES neutrino telescope. 36th International Cosmic Ray Conference, Jul 2019, Madison, United States. pp.872, 10.22323/1.358.0872 . hal-02507601

HAL Id: hal-02507601

<https://hal.science/hal-02507601>

Submitted on 19 Mar 2020

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Real-time follow-up of multi-messenger alerts with the ANTARES neutrino telescope

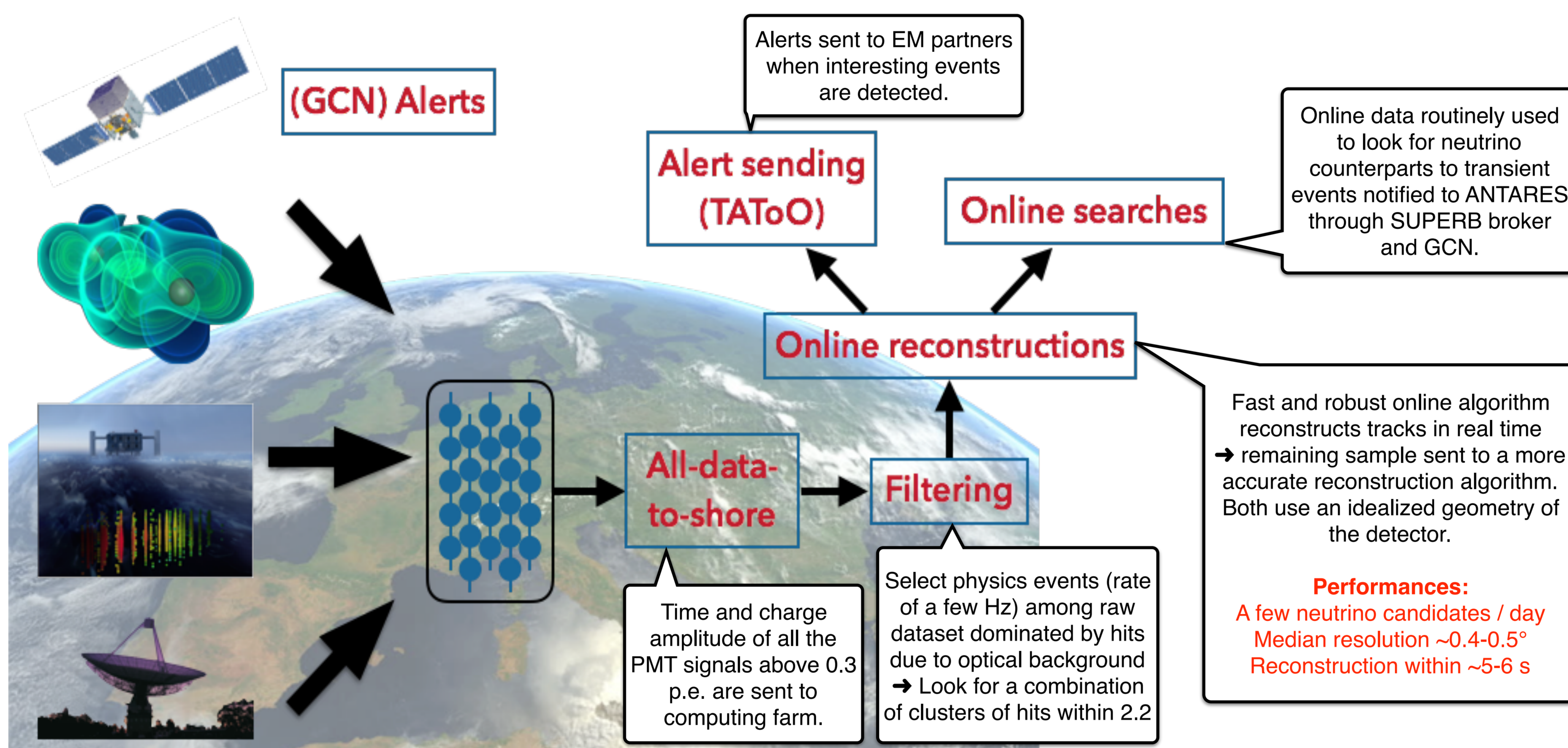
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on behalf of the ANTARES Collaboration



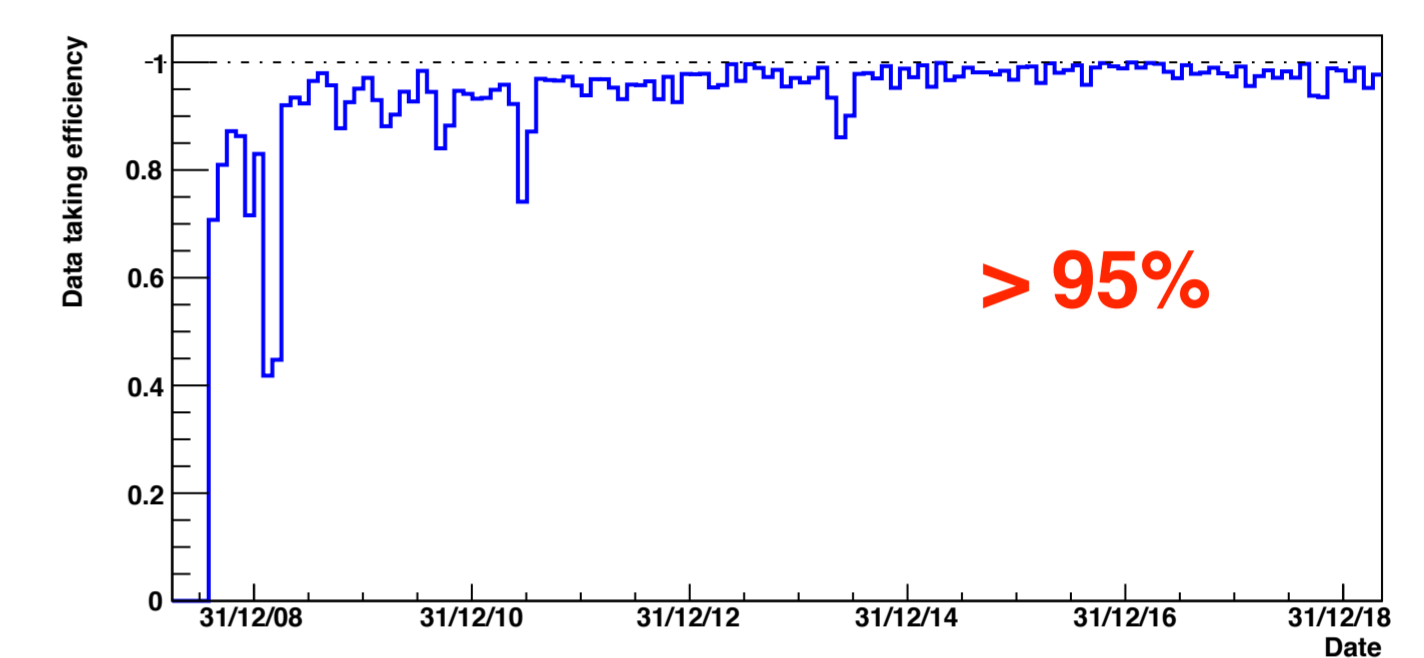
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By constantly monitoring at least one complete hemisphere of the sky, neutrino telescopes are well designed to detect neutrinos emitted by transient astrophysical events. **Real-time searches for ANTARES high-energy neutrino candidates coincident with Swift and Fermi gamma-ray bursts, Parkes, ASKAP fast radio bursts, IceCube high-energy neutrino events and gravitational wave (GW) candidates observed by LIGO/Virgo are performed with the ANTARES telescope.** By requiring temporal and spatial coincident detection, this approach increases the sensitivity and the significance of a potential discovery.

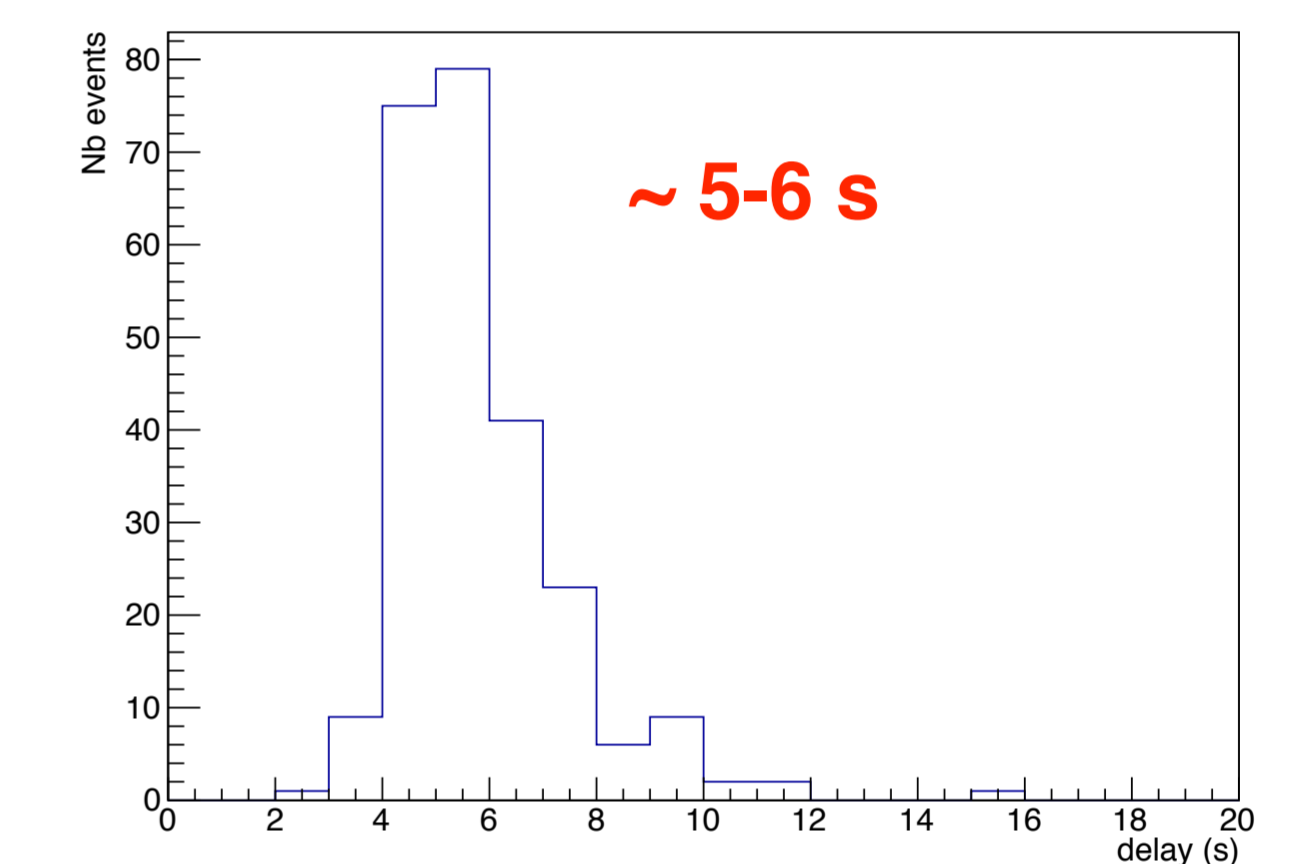
- **Time-domain astroparticle physics** enters an exciting period: development of wide-field-of-view instruments, communication strategies and low latency alert triggering of gravitational wave (GW) and high-energy neutrino (HEN) signals.
- **Multi-messenger / transient approaches:** best sensitivity to identify HEN sources and to understand acceleration mechanisms at play. HEN transient source is promising: short timescale of emission drastically reduces the background level.
- **Specific analysis strategies in nearly real-time:** search neutrino events in time/space coincident with transient astrophysical events or EM follow-up of the most interesting neutrinos (TAToO - D.Dornic et al, Pos(ICRC2019)871) .



Average data-taking efficiency of the ANTARES detector since 2008.



Typical delay between time of the neutrino and the end of the 2 track reconstructions.

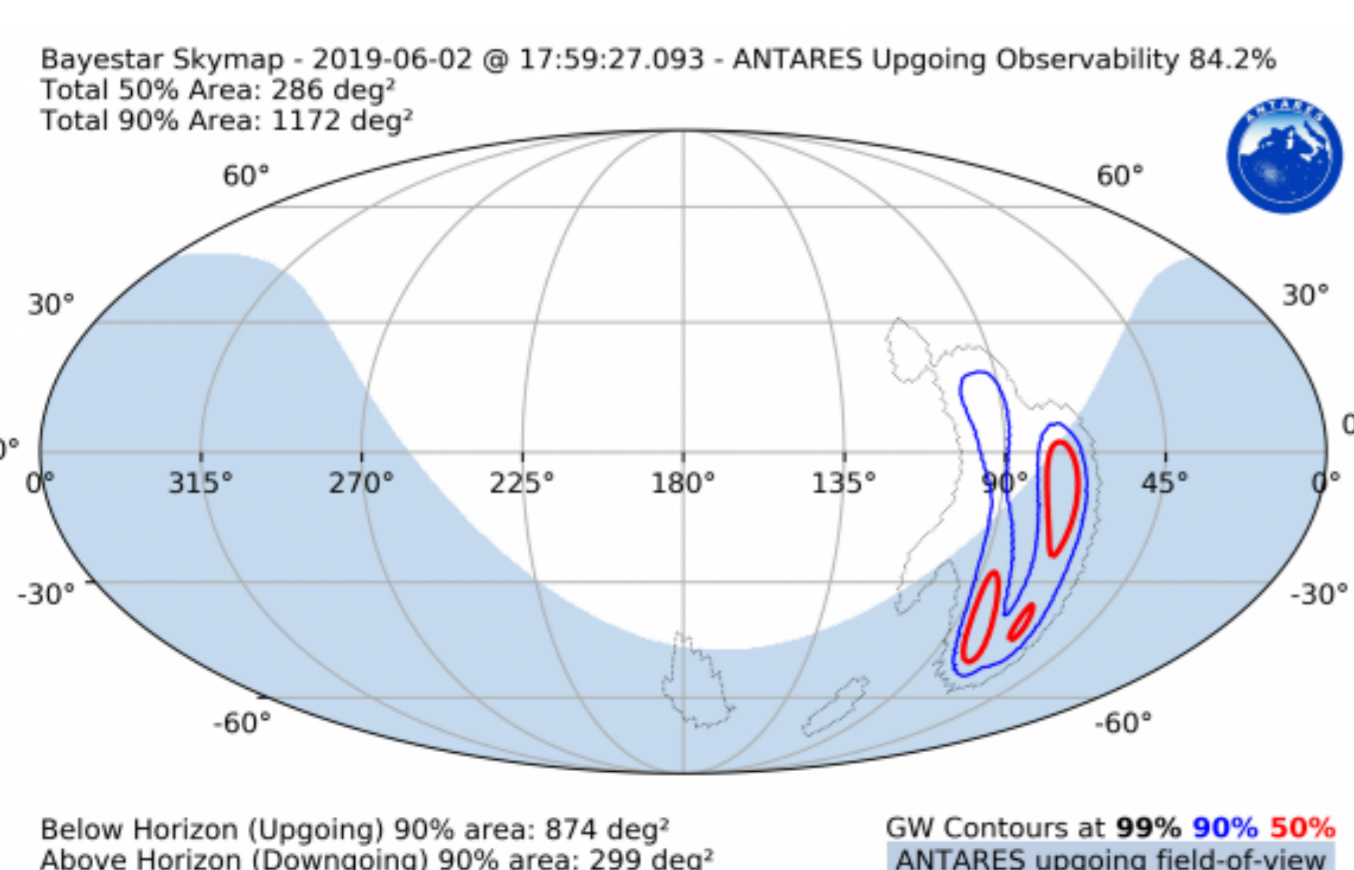


Follow-up of gravitational wave events

- Since run O2, ANTARES is receiving and processing GW alerts in real-time.
- During run O2 (20161130 → 20170825), ANTARES has triggered on 15 alerts selected with a false-alarm rate of 1/ month: 7 BBHs (+3 found in offline) and 1 BNS merger has been identified. Only for the last one, GW170817, an EM counterpart has been identified.
⇒ No ongoing muon track neutrino found in coincidence (cf GCN circulars)
⇒ Followed by more optimised all-sky/all-flavor offline analyses.
See M. Colomer Molla et al, Pos(ICRC2019)856.
- During run O3 (20190401 →), 18 alerts distributed publicly, 15 confirmed astrophysical events, 3 retracted by LVC after further investigations: 12 BBHs, 1 NSBH and 1 BNS (S190510g is now classified as terrestrial). Update 20190630.
⇒ ANTARES has performed real-time analysis on 13 GW triggers.
⇒ Up to now, no ongoing muon track neutrino found in coincidence.
(results published in GCN circulars shortly after the GW notices)

GW name	Type	Latency (min)	Error box (deg ²)	FAR (yr ⁻¹)	Coverage (%)	GCN number
S190405ar	Retracted					
S190408an	BBH	34.5	381	1/1.12e-10	/	no analysis
S190412m	BBH	60.9	156	1/1.89e19	9	24105
S190421ar	BBH	1247.5	1444	1/2.13	52	24156
S190425z	BNS	42.8	7461	1/69384	/	no analysis
S190426c	NSBH	25.3	1131	1/1.63	45	24271
S190503bf	BBH	36.2	448	1/19.37	98	24387
S190510g	Terrestrial	82.3	1166	1/3.59	55	24446
S190512at	BBH	51.8	252	1/16.67	83	24516
S190513bm	BBH	27.4	691	1/84864	55	24539
S190517h	BBH	35.8	939	1/13.35	83	24581
S190518bb	Retracted	6.5				
S190519bj	BBH	85.9	967	1/5.56	34	24602
S190521g	BBH	6.3	765	1/8.34	56	24628
S190521r	BBH	6.5	488	1/100.04	30	24634
S190524q	Retracted	6.5				
S190602aq	BBH	6.6	1172	1/16.67	84	24719

- Real-time analysis: binned analysis to look for:
 - temporal coincidences within ± 500 s and ± 1 h centered in the GW time,
 - spatial overlap between the 90% GW probability counter and the ANTARES visibility region at the time of the GW event.

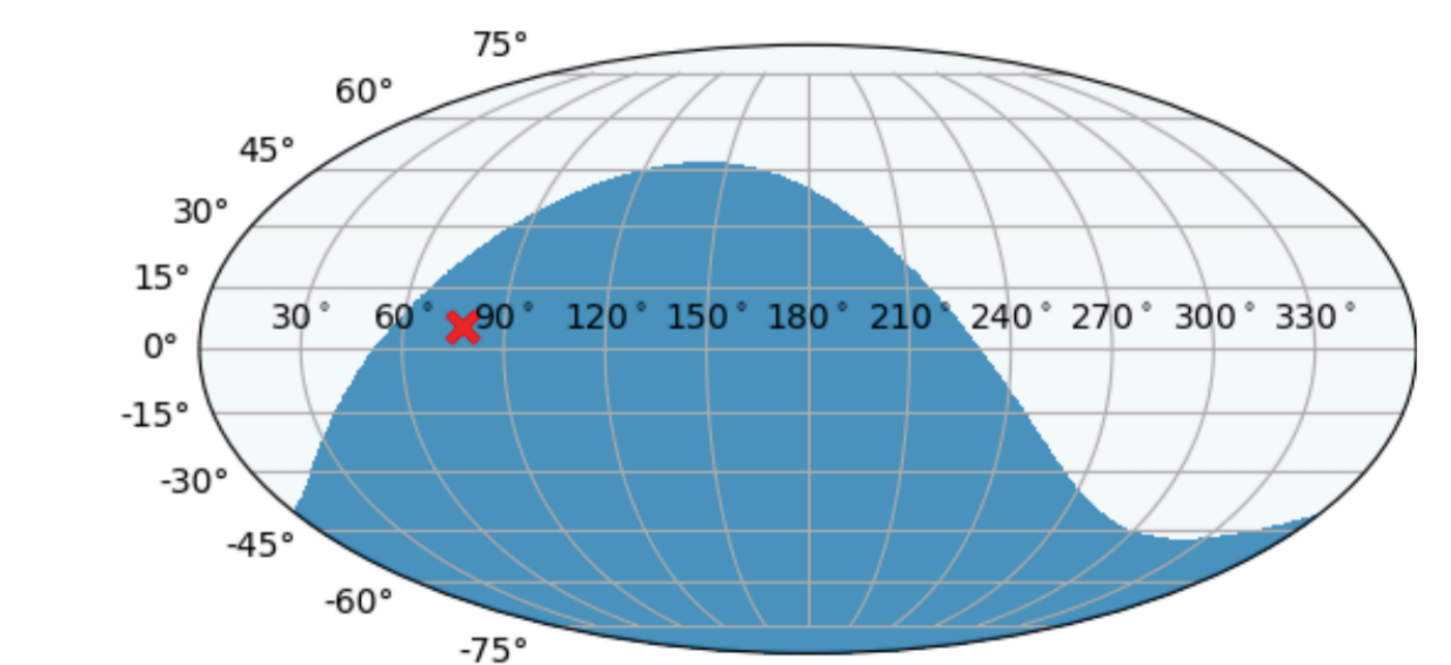


Skymap in equatorial coordinates showing the probability contours of S190602q together with the ANTARES field of view at the GW time (blue area)

Follow-up of IceCube neutrino alerts

- Since 2016, IceCube is sending high-energy starting events (HESE) and extremely high-energy events (EHE) by the AMON network via the GCN. In 2019, IceCube provides in replacement 2 new very high-energy track event categories: gold / bronze samples.
- ANTARES is performing real-time follow-up for each IceCube event whose position is below its horizon at the time of the event. ANTARES has received 27 neutrino triggers and has followed 11 alerts (7 HESE, 3 EHE and 1 gold).
- No neutrino candidates were found within a cone of 3° and a time window of ± 1 h (an extended time window of ± 1 d is also investigated). Preliminary 90% C.L. upper limits on the radiant neutrino fluency are derived: ~ 15 (30) GeV.cm^{-2} for $E^{-2(2.5)}$ spectral models. Results published in GCN circulars and ATels.

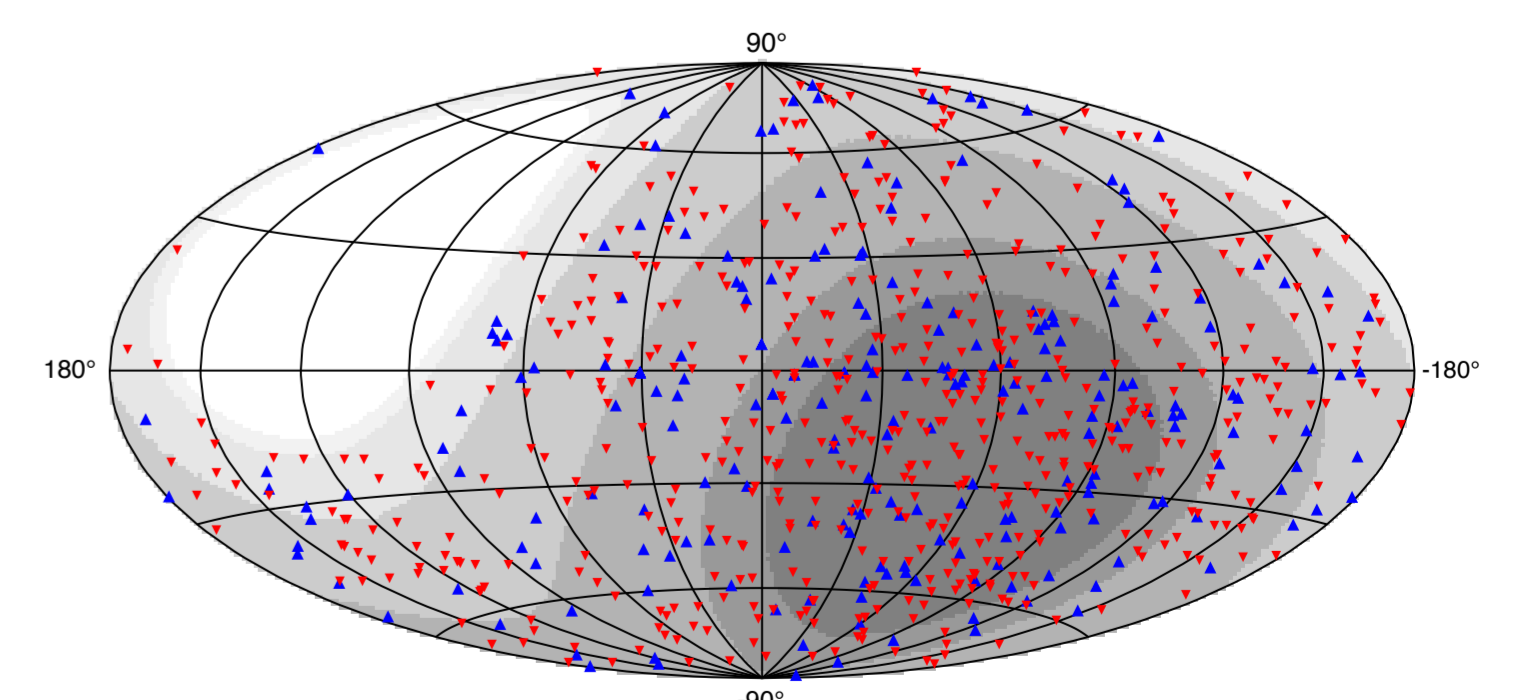
IceCube event	Elevation (deg)	Fluence U.L. (GeV cm^{-2})	
		$dN/dE \propto E^{-2}$	$dN/dE \propto E^{-2.5}$
IC160731A (EHE/HESE)	-28°	14 (2.8 TeV - 3.1 PeV)	27 (0.4 - 280 TeV)
IC160814A (HESE)	-26°	16 (2.9 TeV - 3.3 PeV)	43 (0.5 - 250 TeV)
IC161103A (HESE)	-26°	13 (3.8 TeV - 3.8 PeV)	22 (0.7 - 370 TeV)
IC170321A (EHE)	-57°	16 (2.5 TeV - 2.5 PeV)	26 (0.5 - 220 TeV)
IC170922A (EHE)	-14°	15 (3.3 TeV - 3.4 PeV)	34 (0.5 - 280 TeV)
IC171015A (HESE)	-45°	14 (2.7 TeV - 2.9 PeV)	27 (0.4 - 240 TeV)
IC180908A (EHE)	-41°	18 (2.4 TeV - 2.6 PeV)	36 (0.4 - 250 TeV)
IC190104A (HESE)	-39°	16 (3.2 TeV - 3.5 PeV)	30 (0.6 - 315 TeV)
IC190124A (HESE)	-44°	15 (3.1 TeV - 3.6 PeV)	25 (0.6 - 316 TeV)
IC190504A (HESE)	-18°	16 (3.1 TeV - 3.5 PeV)	32 (0.6 - 316 TeV)
IC190619A (gold)	-19°	13 (3.9 TeV - 3.9 PeV)	33 (0.7 - 320 TeV)



Skymap (equatorial coordinates) showing the position of IC270922 and the ANTARES field of view at the GW time.

Follow-up of GRB triggers

- ANTARES is performing real-time follow-up for each GRB detected by Swift and Fermi satellites whose positions are below its horizon at the time of the burst. Each trigger is transmitted via GCN.
- ANTARES analysis consists in looking for muon-track neutrino counterparts in a time window $[-250$ s; $+750$ s] around the trigger time and in a cone of max $[2^\circ, \text{error box Fermi}]$ radius.
- Analysis is operational since 2014 and up to now $\sim 98\%$ of the triggers have been processed: 226 Swift and 536 Fermi GRBs.
⇒ No neutrino associated to GRBs.
- Dedicated all-sky and all-flavor offline analysis for the most interesting bursts (GRB190114C and GRB180720B) and for stacking analysis of the GRB population in progress.
- Similar analyses performed for FRB triggered by Parkes and ASKAP radio telescopes.



Skymap (galactic coordinates) showing the positions of Fermi (red) and Swift (blue) GRBs followed by ANTARES.