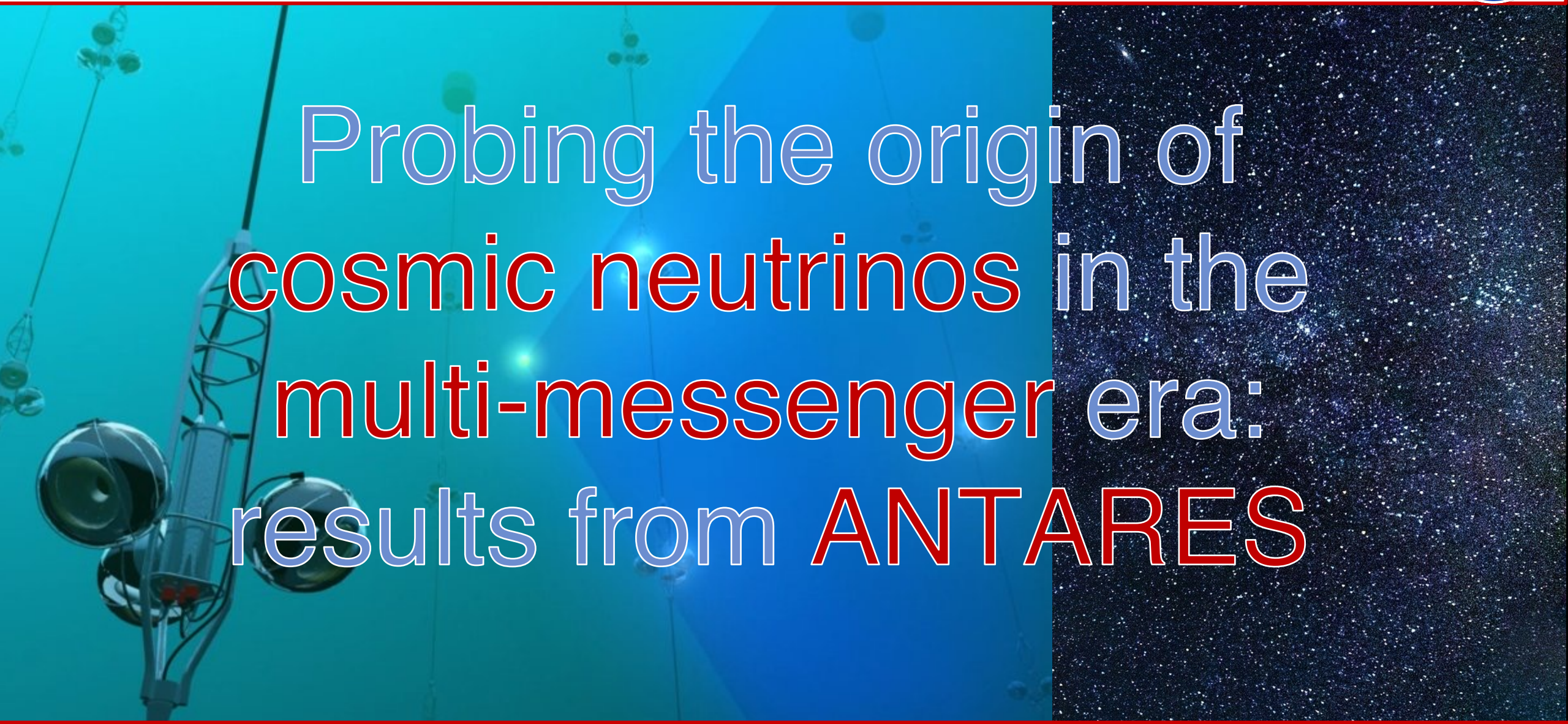


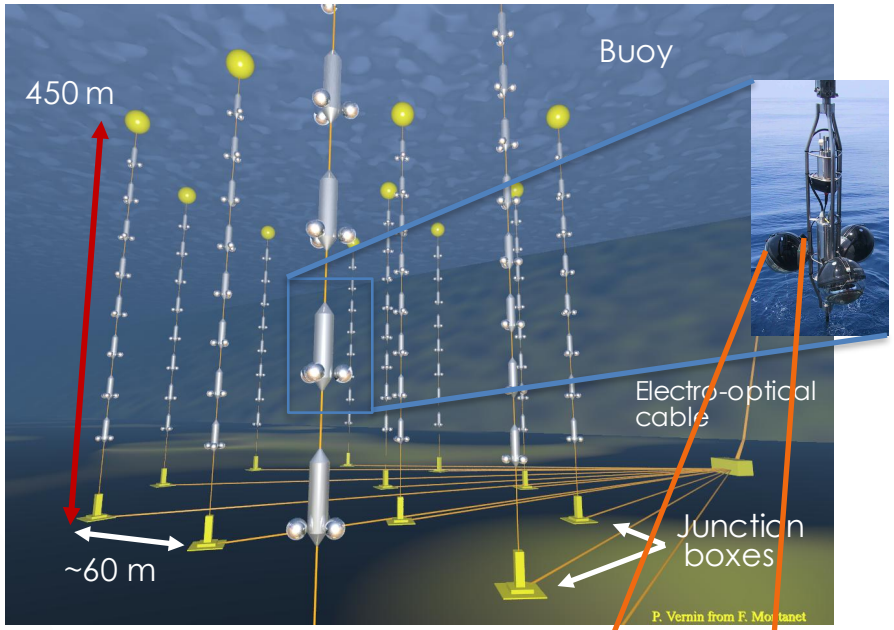
Probing the origin of cosmic neutrinos in the multi-messenger era: results from ANTARES

Giulia Illuminati on behalf of the **ANTARES** Collaboration

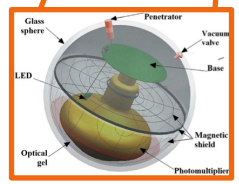
Marcel Grossmann Meeting, Pescara, 2024

ANTARES telescope

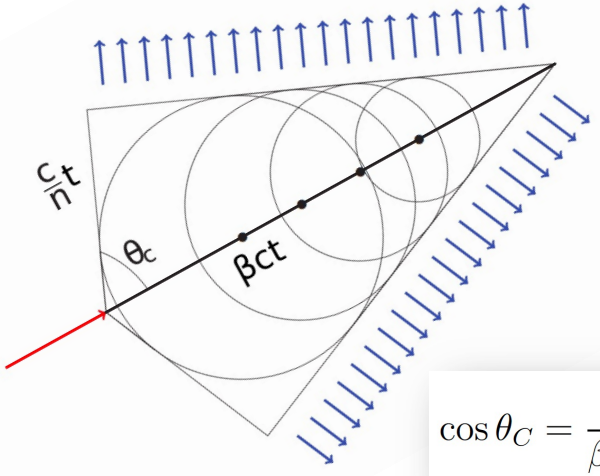
- Designed to detect ν **with E > few GeV**
- First detection line installed in early 2006
- **Completed in 2008, decommissioned in 2022**
- **2475 m depth** in the Mediterranean Sea
- 40 km offshore from Toulon



- Matrix of **885 PMTs**
- **12 vertical lines**, 25 storeys



Cherenkov radiation detected by PMTs



$$\cos\theta_C = \frac{1}{\beta n}$$

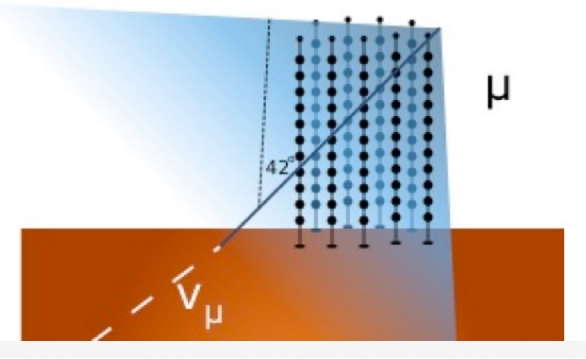
Position, time and charge used to reconstruct **direction and energy of the parent ν**

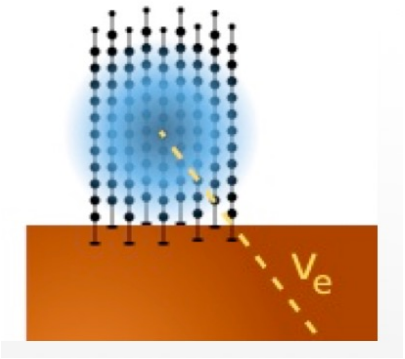
Either **CC** or **NC interaction** with a nucleon N of a nucleus

CC: $\nu_l + N \rightarrow l + X$

NC: $\nu_l + N \rightarrow \nu_l + X$

ANTARES telescope





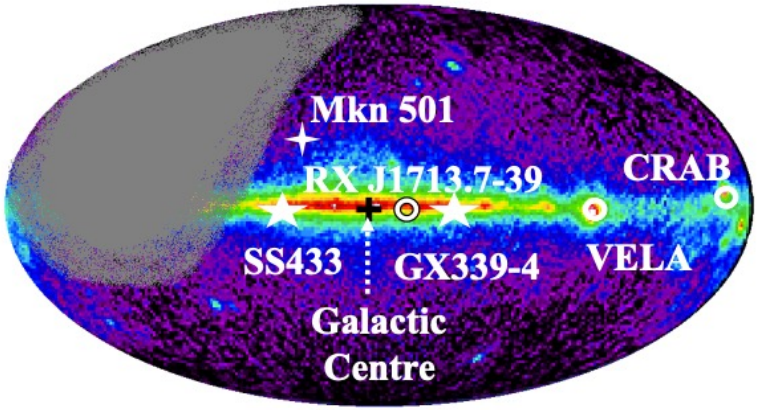
Track-like events:

$\nu_\mu(\nu_\tau)$ neutrino
CC interaction near the detector

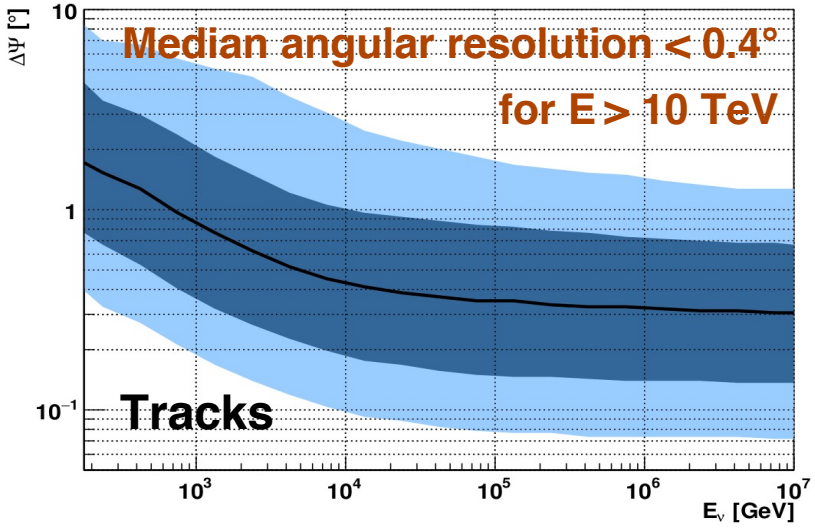
Shower-like events:

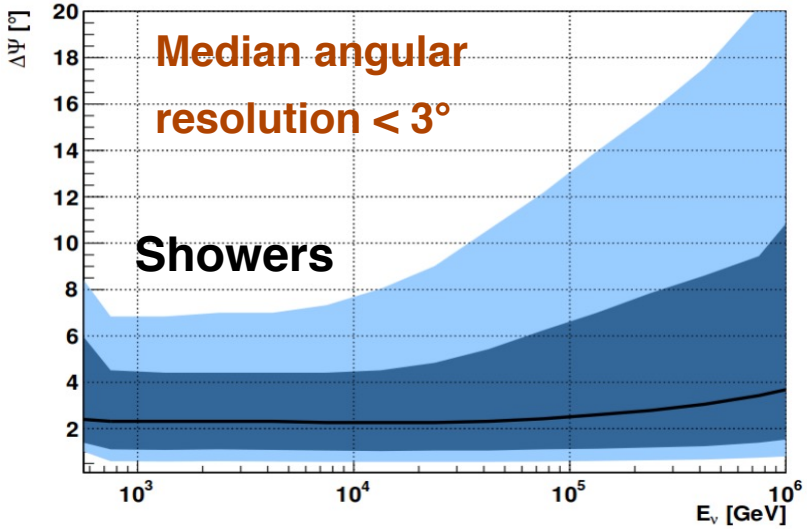
all neutrinos NC, ν_e, ν_τ CC interaction
inside or very close to the detector

Earth used as shield against up-going atmospheric muons



Visibility for up-going events: ¾ of the sky, most of the Galactic plane
~95% duty cycle



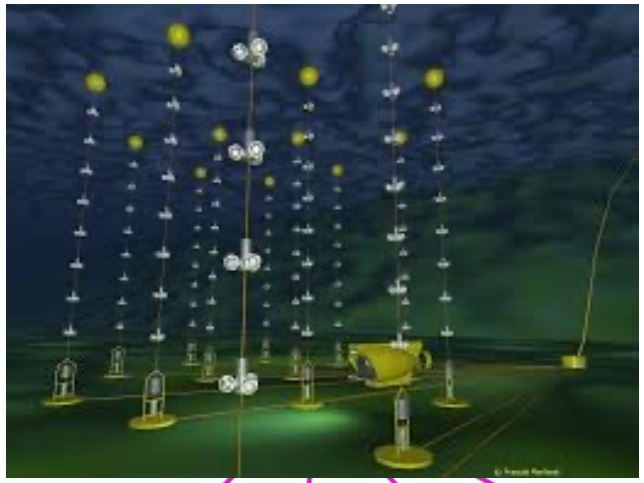


IL NUOVO CIMENTO 41 C (2018) 134

Multi-messenger analyses: 3 approaches

Cross-correlation between archival events and multi-messenger catalogs

Multi-messenger real-time alerts triggering immediate neutrino follow-up



Real-time neutrino alerts triggering immediate multi-messenger follow-up

Multi-messenger analyses: 3 approaches

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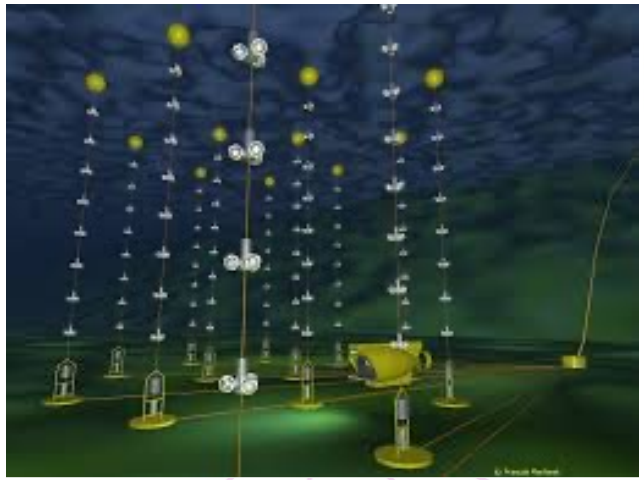


Real-time neutrino alerts triggering immediate multi-messenger follow-up

Stacking search

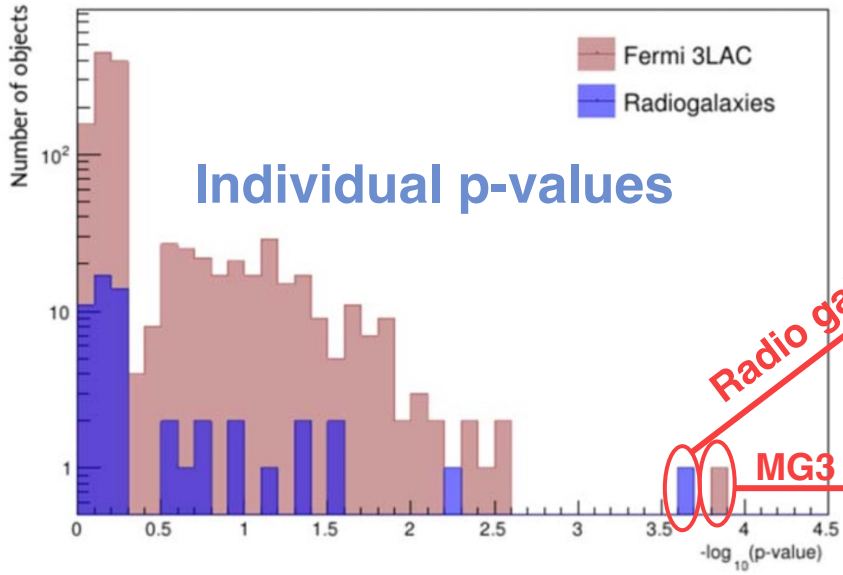
Astrophys.J. 911 (2021) 1, 48

FIVE CATALOGS

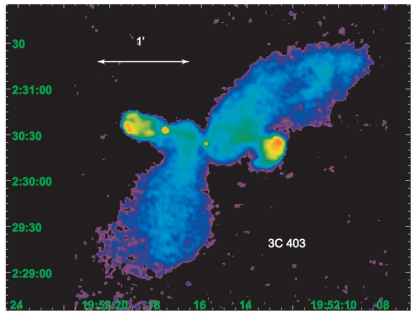
IC HE tracks | Fermi 3LAC Blazars | Radio Galaxies | Star Forming Galaxies | Dust Obscured AGN

Best catalog
2.8σ pre-trial
1.6σ post-trial

Catalog	Equal Weighting λ	p	P	$\Phi_{90\%}^{UL}$	Flux Weighting λ	p	P	$\Phi_{90\%}^{UL}$
Fermi 3LAC All Blazars	6.1	0.19	0.83	4.3	0.21	0.85	1.0	2.1
Fermi 3LAC FSRQs	0.83	0.57	0.97	2.2	~0	~1	1.0	1.8
Fermi 3LAC BL Lacs	8.3	0.088	0.64	4.8	0.84	0.56	0.96	2.0
Radio Galaxies	3.4	4.8×10^{-3}	0.10	4.2	5.1	6.9×10^{-3}	0.13	4.7
Star-forming Galaxies	0.030	0.37	0.93	2.0	~0	~1	1.0	1.7
Dust-obscured AGNs	1.0×10^{-3}	0.73	0.98	1.5	~0	~1	1.0	1.4
IceCube High-energy Tracks	0.77	0.05	0.49	5.2	…	…	…	…



Radio galaxy 3C403



p-value: 2.3 x 10^{-4} → **3.7σ**
chance probability ($N_{sources}$ = 56) = **1.3%**
→ **2.5σ**

BLLac
MG3 J225517+2409

p-value: 1.4 x 10^{-4} → **3.8σ**
chance probability ($N_{sources}$ = 1255) = **15%**
→ **1.4σ**

Search from radio-bright blazars

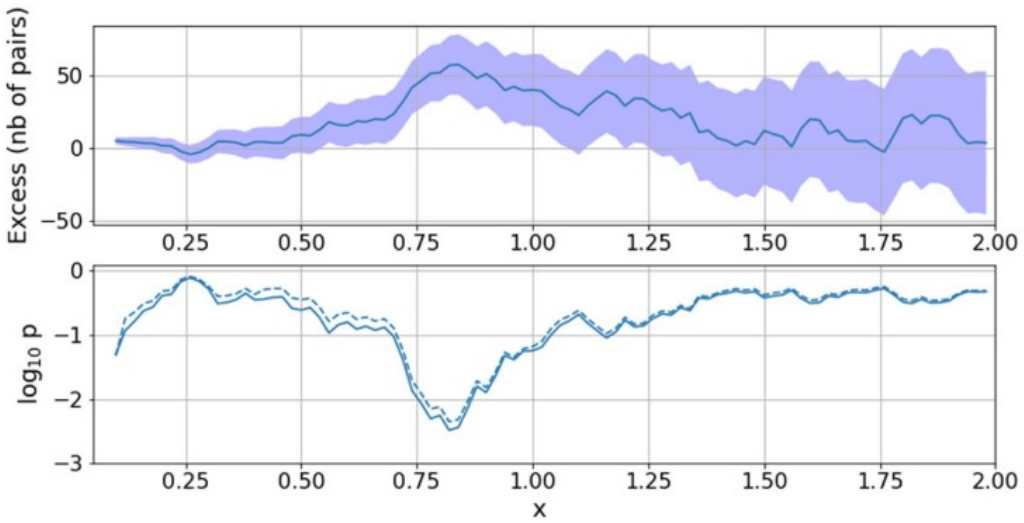
Steady emission

Astrophys.J. 964 (2024) 1, 3

CATALOG

- **3051 blazars** selected on the basis of VLBI **radio flux**
- **promising correlation with IceCube events (Plavin et al 2020, 2021, 2023)**

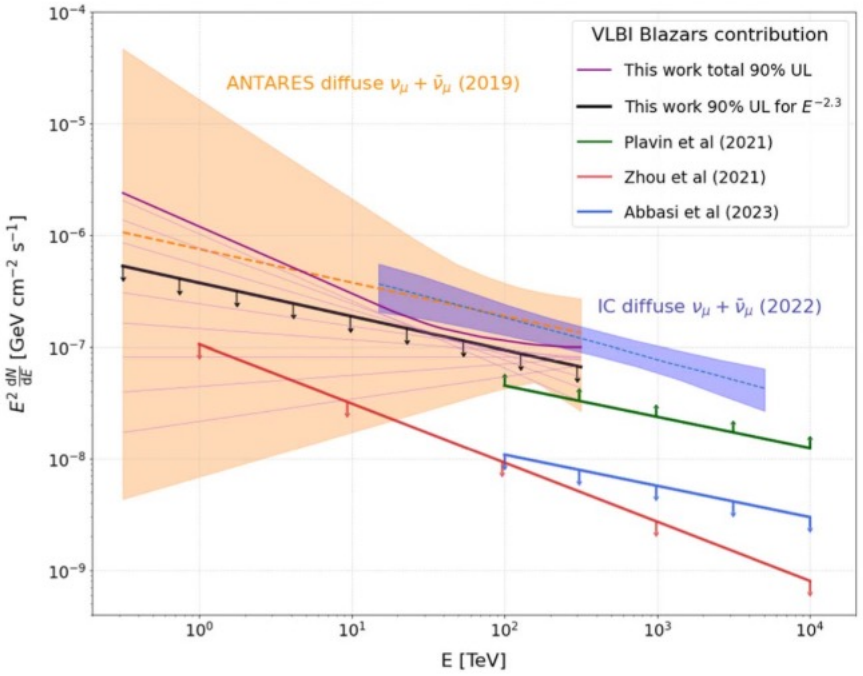
1) Count how many ν-blazar pairs are found with a ν-blazar angular separation < $x \cdot \beta$



Results ($x = 0.82$):
# of observed (expected) pairs: 469 (410.4)
→ 59 pairs in excess
→ 3σ pre-trial significance
→ 2.2σ post-trial significance

2) Stacking analysis based on maximum likelihood method

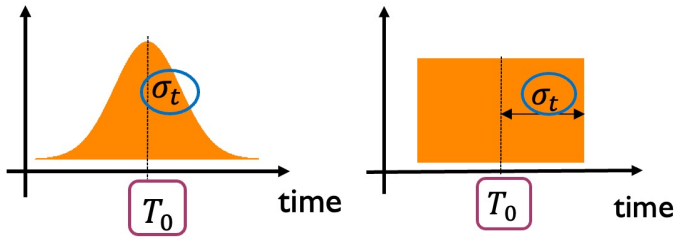
Results: highest significance found for $E^{-2.3}$ and with radio-weight hypothesis
→ 2.2σ significance



Search from radio-bright blazars

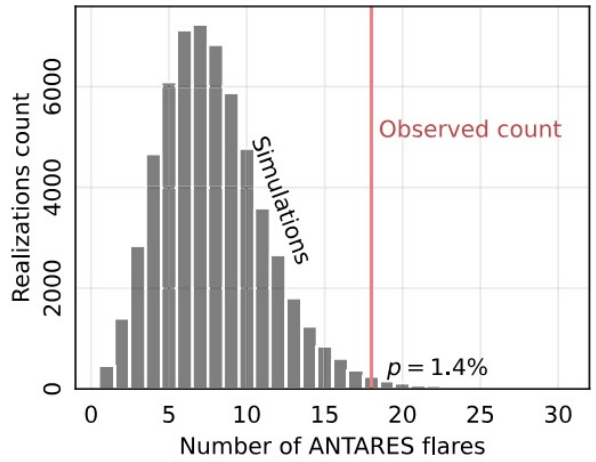
Astrophys.J. 964 (2024) 1, 3

Flaring emission

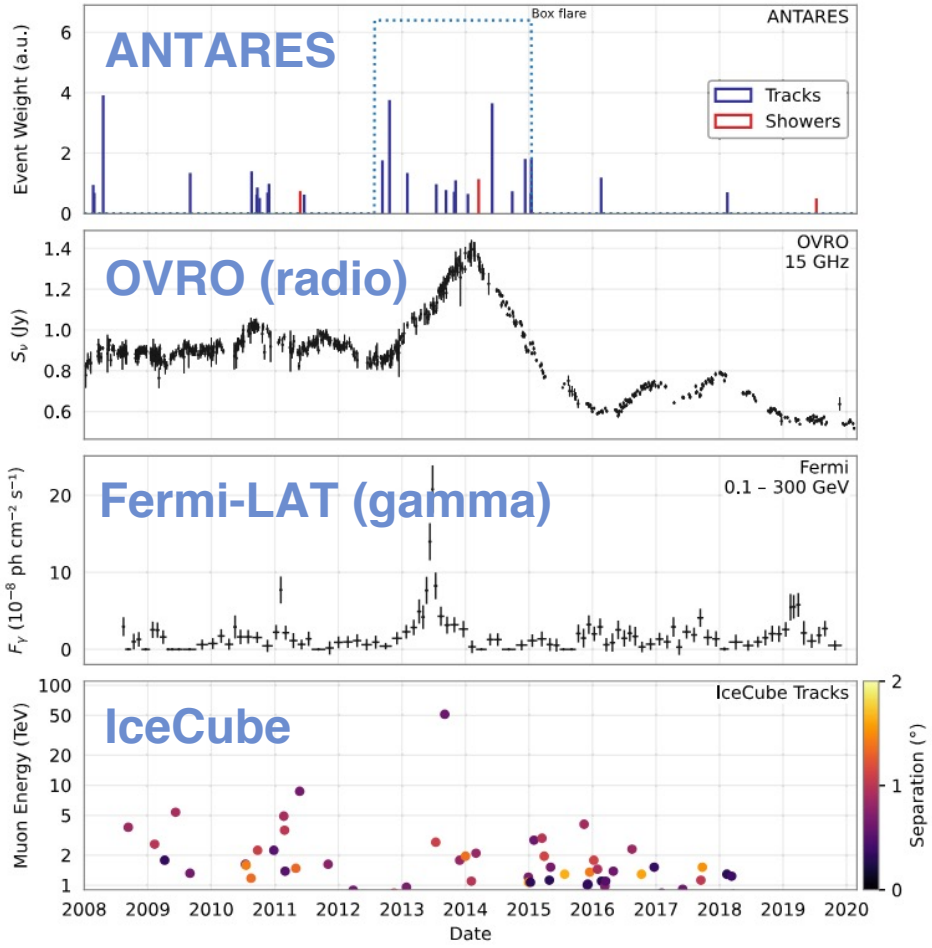


Result: 18 flares with over 3σ pre-trial significance

Chance probability: 1.4% (2.5σ)



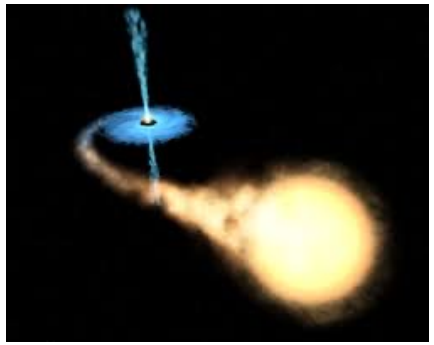
A posteriori study finds multi-messenger flare overlap for J0242+1101(PKS 0239+108)



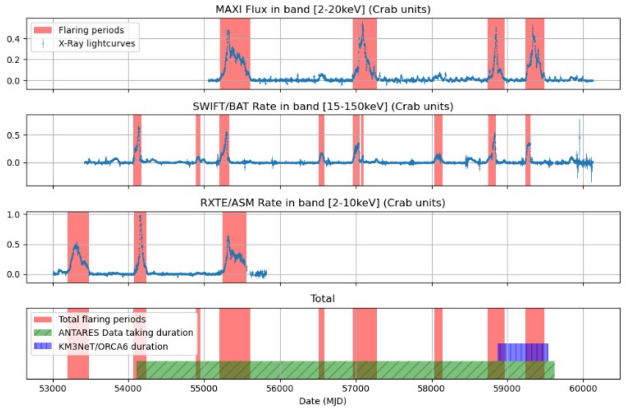
0.5% (2.9σ) chance probability of ν+radio+γ correlation

More on multi-messenger searches

Searching for neutrinos from microquasar flares

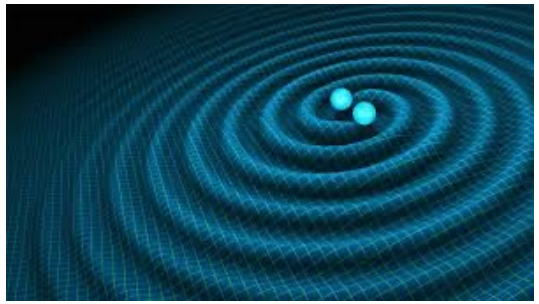


➡️ PoS(ICRC2023)1505



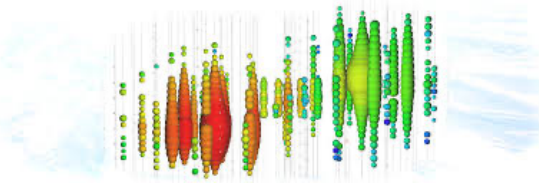
Searching for neutrinos coincident with GW events

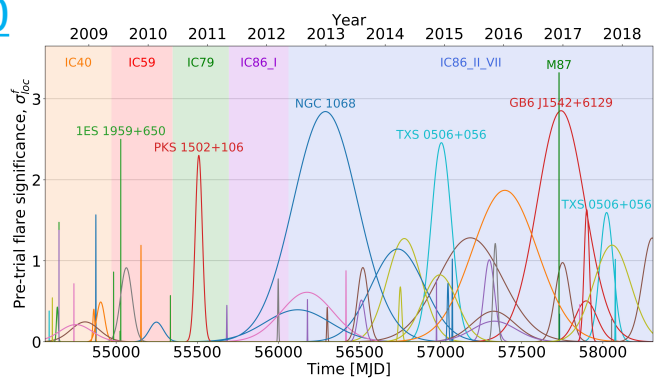
➡️ JCAP 04 (2023) 004



Searching for neutrinos compatible with IceCube neutrino flares

➡️ PoS(ICRC2023)1480





Details later this week in the ANTARES session

ANTARES: 15 years of cosmic neutrino source searches

ANTARES, an observatory for high-energy neutrinos located below the surface of the Mediterranean Sea, finished its observational mission in February 2022 after operating for 15 years. Positioned strategically in the Northern

17:00 - 17:20
(The 'Gabriele d'Annunzio' University, ICRANet and Aurum)
Pescara, Italy

Presenter Giulia Illuminati

15 Years of Transient and Multi-Messenger Astronomy with the ANTARES Neutrino Telescope

The water Cherenkov neutrino telescope ANTARES was a 0.01 km3 volume detector located in the Mediterranean Sea which aimed at the detection of high-energy cosmic neutrinos, specially those of Galactic

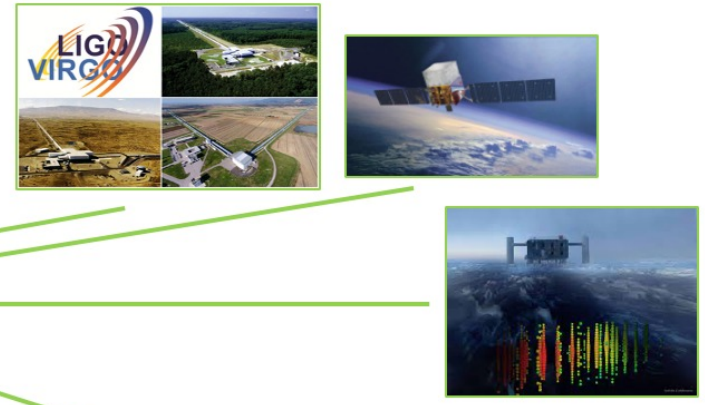
17:20 - 17:40
(The 'Gabriele d'Annunzio' University, ICRANet and Aurum)
Pescara, Italy

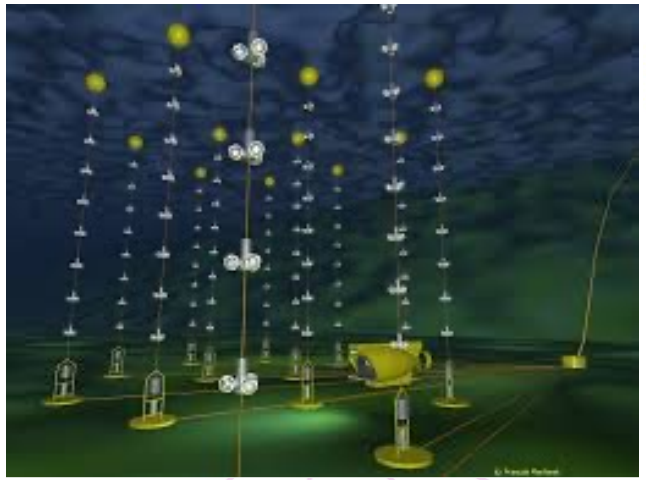
Presenter Sergio Alves Garre

Multi-messenger analyses: 3 approaches

Cross-correlation between archival events and multi-messenger catalogs

Multi-messenger real-time alerts triggering immediate neutrino follow-up

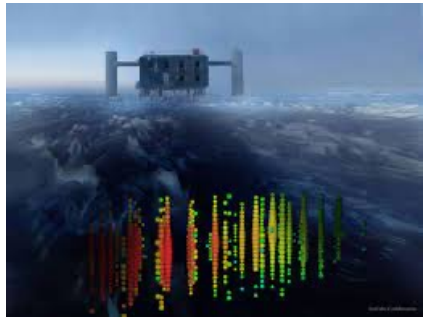


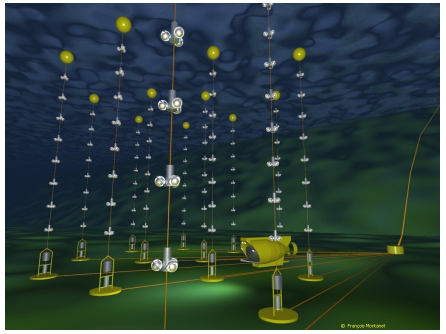


JCAP 08 (2023) 072

Real-time neutrino alerts triggering immediate multi-messenger follow-up

Follow-up of IceCube neutrinos





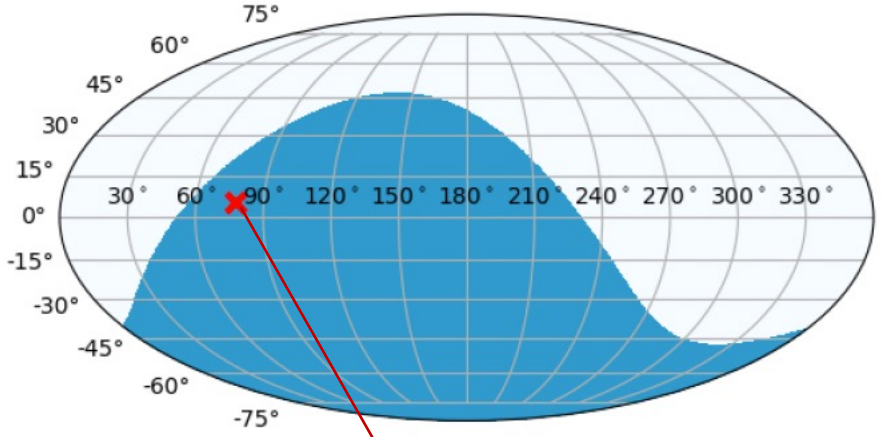
→ 115 neutrino IceCube triggers received, **37 analysed**
(7 HESE, 3 EHE, 10 gold and 17 bronze)
→ **No neutrino candidates found compatible** with any of the alerts
→ 90% confidence level **upper limits on the neutrino fluence**:

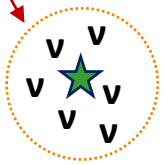
~15 GeV/cm^2 in [2.8 TeV, 3.3 PeV] for E^{-2}
~30 GeV/cm^2 in [0.4 TeV, 280 TeV] for $E^{-2.5}$

IceCube event	Elevation	Fluence U.L. (GeV cm^{-2}) at 90 % C.L. $dN/dE \propto E^{-2}$	Fluence U.L. (GeV cm^{-2}) at 90 % C.L. $dN/dE \propto E^{-2.5}$	GCN Id	ATels Id
IC160731A (EHE/HESE)	-28°	14 (2.8 TeV - 3.1 PeV)	27 (0.4 - 280 TeV)	/	9324
IC160814A (HESE)	-26°	16 (2.9 TeV - 3.3 PeV)	43 (0.5 - 250 TeV)	19885	9440
IC161103A (HESE)	-26°	13 (3.8 TeV - 3.8 PeV)	22 (0.7 - 370 TeV)	20134	9715
IC170321A (EHE)	-57°	16 (2.5 TeV - 2.5 PeV)	26 (0.5 - 220 TeV)	20926	10189
⋮					
IC211216A (bronze)	-8°	16 (5.0 TeV - 5/0 PeV)	49 (1 - 450 TeV)	31252	15121
IC211216B (bronze)	-4°	17 (5.0 TeV - 5.0 PeV)	40 (1 - 450 TeV)	31262	15127
IC220205B (gold)	-51°	16 (3.0 TeV - 3.3 PeV)	30 (0.6 - 300 TeV)	31556	15207

Published in **GCN circulars** and **Astronomer's Telegrams**

ANTARES visibility sky-map for IC170922 (TXS 0506+056)



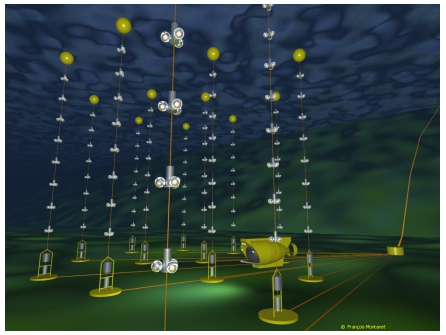


Search in
3° cone
±1 hour and **±1 day**

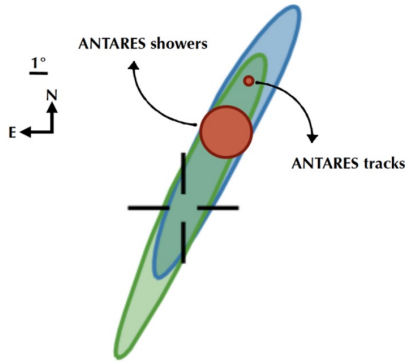
Dedicated offline follow-up:

- **TXS0506+056**
  → *Astrophys.J.Lett.* 863 (2018) 2, L30
- **AT2019dsg and AT2019fdr**
  → *Astrophys.J.* 920 (2021) 1, 50
- **HESE and EHE events**
  → *Astrophys.J. 879 (2019) no.2, 108*

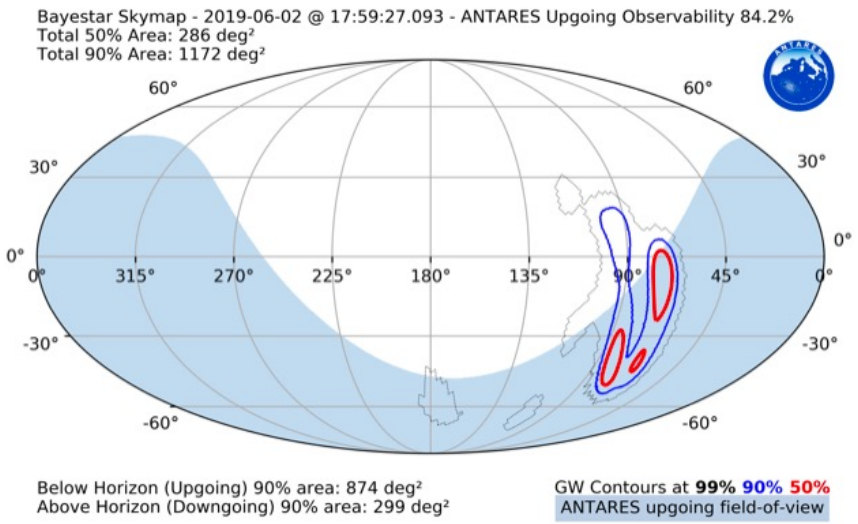
Follow-up of LIGO/Virgo GWs



Neutrinos would
- help **understand physics** of the merger, jets
- significantly **constrain the location** of the source

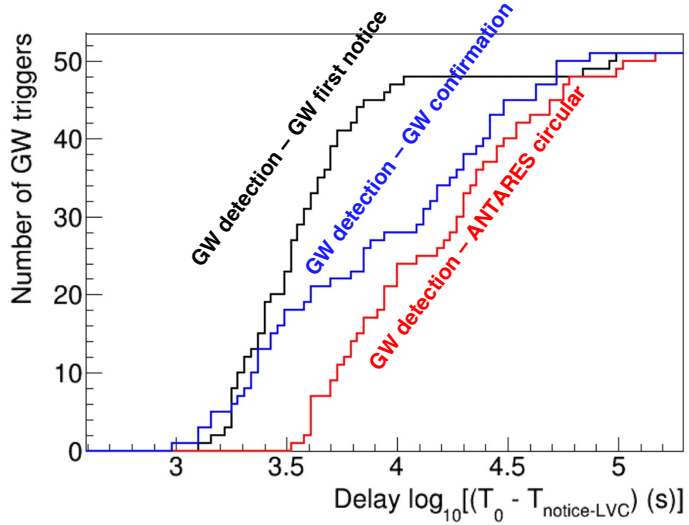


- RunO1 (2015): **3 GW events** detected, all followed **offline (online analysis not ready)**
- RunO2 (2016-2017): **15 GW alerts**, all followed **online (manually)**
- RunO3 (2019-2020): **78 GW alerts** (22 retracted, 3 terrestrial noise, 2 non visible) → **51 followed online (fully automatised)**



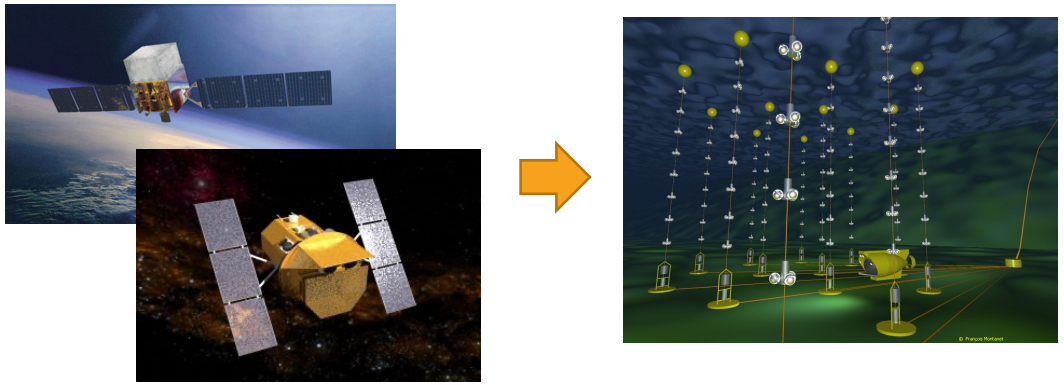
Search in
Spatial overlap between 90% GW contour and ANTARES visibility region
±500 s and **±1 hour**

- **No** time&space **coincidence found**
- Results communicated through **GCN circular**
- **~4.5h from GW detection**



Refined offline analyses:
→ Phys.Rev. D93 (2016) no.12, 122010, → Phys.Rev. D96 (2017) no.2, 022005
→ Eur.Phys.J. C77 (2017) no.12, 911, → Astrophys.J. 850 (2017) no.2, L35
→ JCAP 04 (2023) 004

Follow-up of Fermi-GBM and Swift GRBs

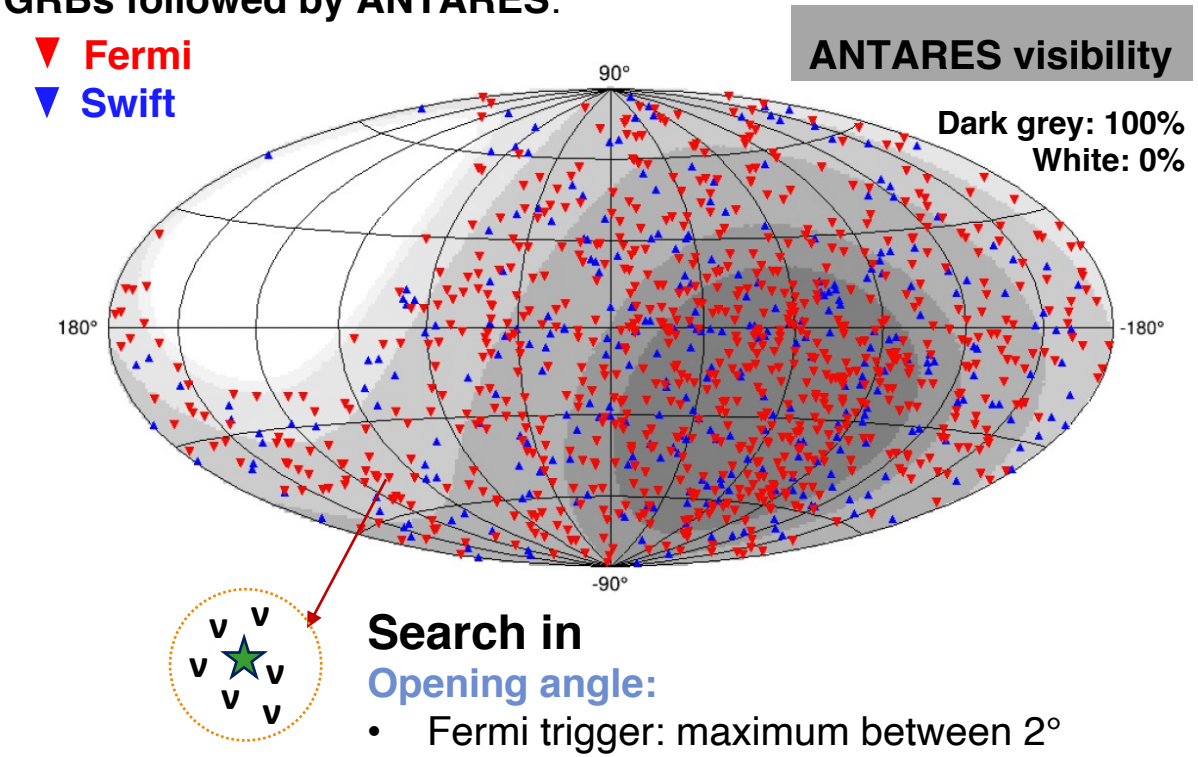


Fermi/Swift alert message sent via the **GCN** within a **few tens of seconds** after GRB detection

- **Automatic** analysis of ANTARES online data
- Run for **8 years** (01/2014–02/2022)
- **317** Swift and **230** Fermi-GBM bursts followed
- **No** significant **coincidences** detected

Offline analyses:
→ Eur. Phys. J. C 77.1 (2017)
→ Mon. Not. Roy. Astron. Soc. 469 (2017)
→ MNRAS 500 (2021) 5614

Skymap in Galactic coordinates with the positions of the **GRBs followed by ANTARES**:



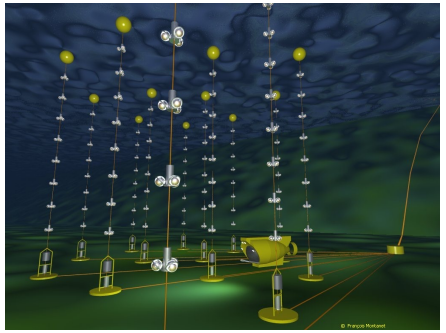
Search in

Opening angle:
- Fermi trigger: maximum between 2° and size of the GRB error box
- Swift trigger: 2°

Time window:
[–250 s; +750 s] around the GRB time

→ **One coincidence event = p-value of 2-5×10^{-5}**

Follow-up of HAWC alerts

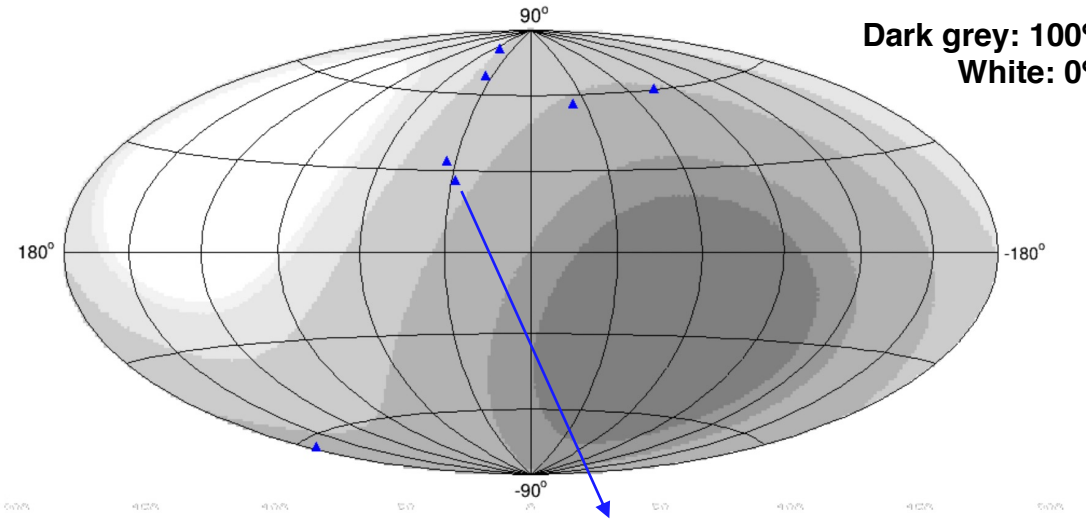


- Alerts of **short (0.2 to 100 s) TeV transients** sent by the **HAWC** Collaboration since mid 2019 (→ link to alert list)
- Targeting in particular GRBs
- Alerts channeled via the **AMON** framework and then distributed by the **GCN**
- Up to Feb. 2022, 22 triggers sent, **7 followed by ANTARES (in FoV)**
- No coincidences found

Skymap in Galactic coordinates with the positions of the **HAWC alerts**:

ANTARES visibility

Dark grey: 100%
White: 0%



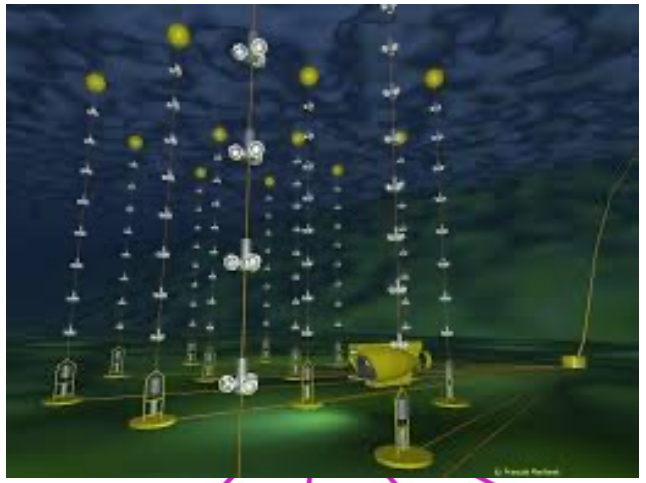
Search in
3° cone
±1 hour and **±1 day**

- Additional follow-up of **the IceCube + HAWC coincidences** (NuEM) provided by AMON (→ link to alert list)
- No coincidence found

Multi-messenger analyses: 3 approaches

Cross-correlation between archival events and multi-messenger catalogs

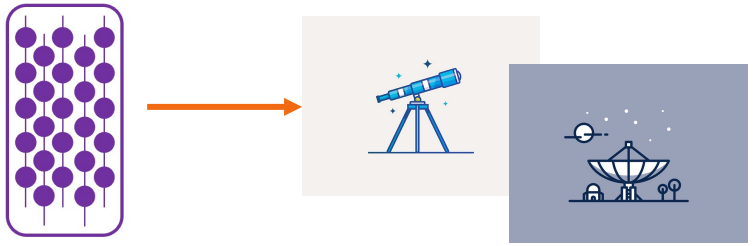
Multi-messenger real-time alerts triggering immediate neutrino follow-up



Real-time neutrino alerts triggering immediate multi-messenger follow-up

arXiv:2402.16498 **[astro-ph.HE]**

ANTARES alerts



Alert system (**TAToO: Telescopes and Antares Target of Opportunity**) operating since 2009

Four ANTARES alert triggers:

- **High energy (HE) trigger:** single neutrino with an **energy ≥ 5 TeV**. → **Rate: ~1/month**
- **Very high energy (VHE) trigger:** single neutrino with an **energy ≥ 30 TeV**. → **Rate: ~3-5/year**
- **Directional trigger:** single neutrino from the **direction (≤ 0.4°) of a local galaxy (≤ 20 Mpc)** of the Gravitational Wave Galaxy Catalogue (GWGC). This trigger was mainly introduced to enhance the chance to detect a local CCSN. → **Rate: ~1/month**
- **Doublet trigger: at least two neutrinos** coming from **close directions (≤ 3°) within** a predefined **time window (15 min).** → No doublet trigger ever been issued

- **Signal p-value** associated to alert: probability to find higher energy events in online data
- Alerts sent a **few seconds (~6 s) after ν detection**

- All alerts sent **privately** using the **Gamma-ray bursts Coordinates Network (GCN) normalised format and the standard VO Event format**

ANTARES partner followers

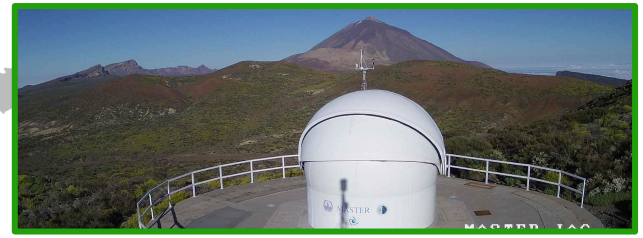
2009 (TAToO starts) 2014 2015 2017 2022

TAROT

ROTSE

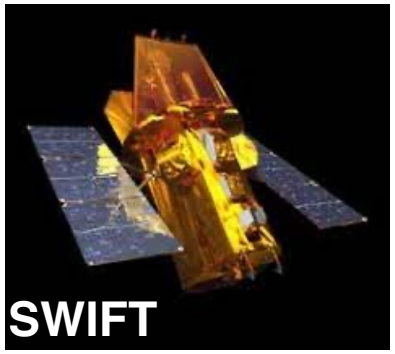
MASTER

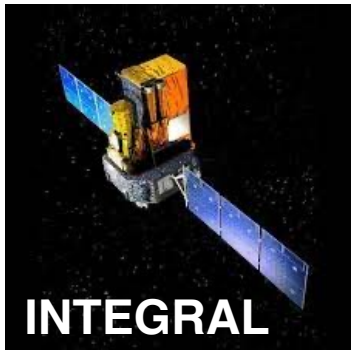
SVOM/GWAC



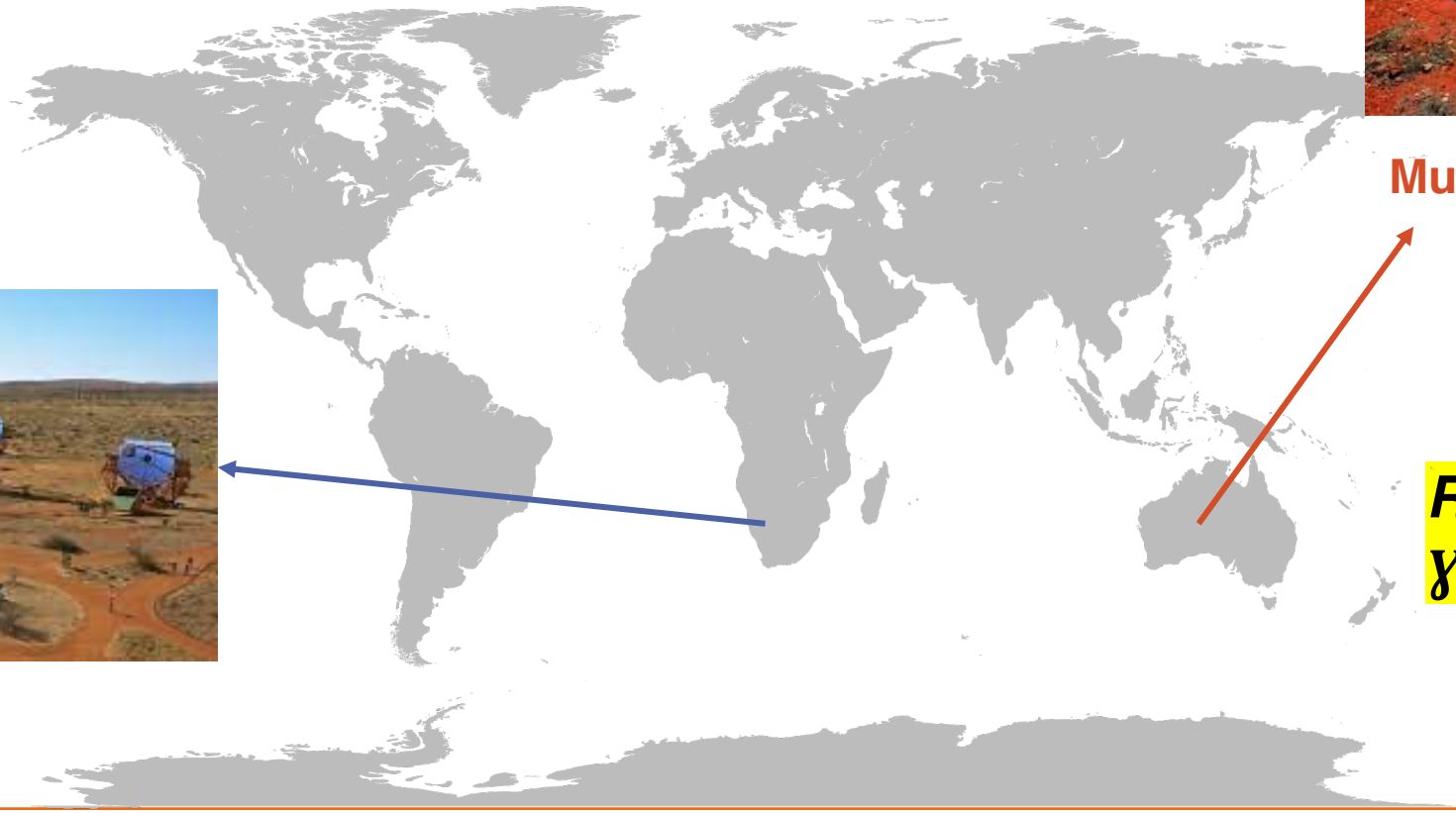
Optical telescopes

ANTARES partner followers





Murchinson Wide Field Array (MWA)

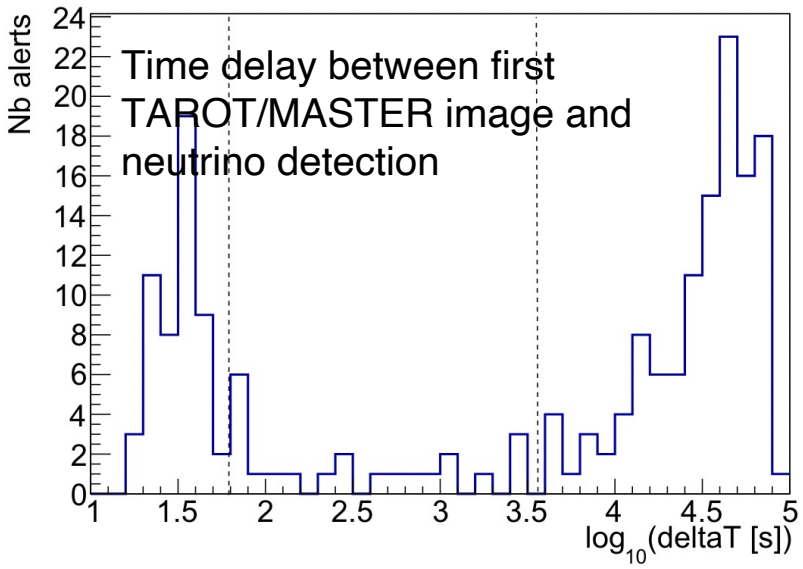


H.E.S.S.

Radio, x-ray and γ-ray telescopes

Statistics of ANTARES alerts

- **322 alerts sent to robotic telescopes**
  - 68% followed within 24h
  - Late follow-up due to bad weather or direction under horizon/close to Sun/Moon
- **26 sent to Swift**
- **15 sent to Integral**
- **20 sent to MWA**
- **2 sent to H.E.S.S.**



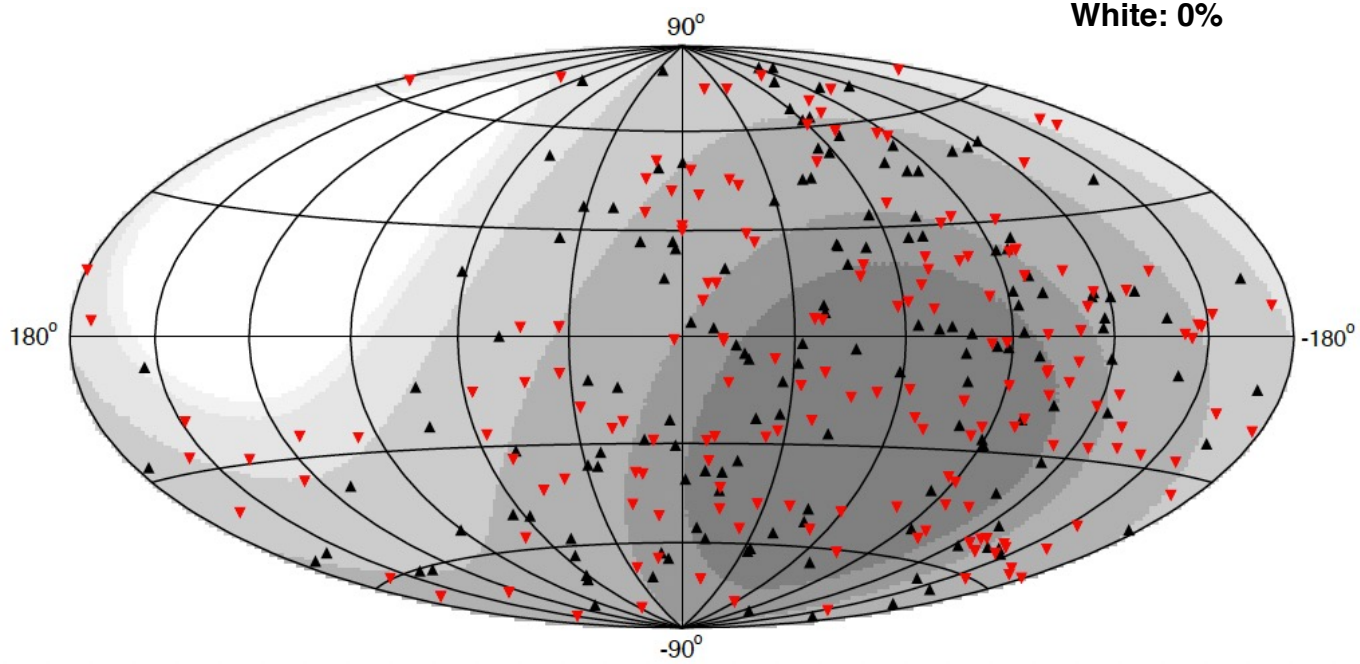
Skymap in Galactic coordinates with the positions of the **directions of all the TAToO alerts sent by ANTARES**

▼ **early follow-up (<24 h)**

▼ **late follow-up**

ANTARES visibility

Dark grey: 100%
White: 0%



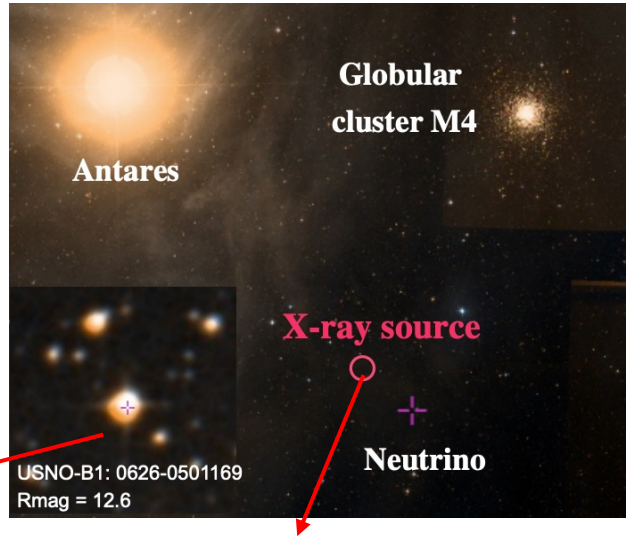
No significant multi-messenger counterpart found

ANT150901A: multi-wavelength follow-up

VHE trigger (E ~ 87 TeV)
Sept. 1, 2015
RA=246.31°; dec=-27.47°

Follow-up by partner telescopes
- **Swift-XRT (after 9h)**
- **MASTER (after 10h)**
- **H.E.S.S. (after 11h)**

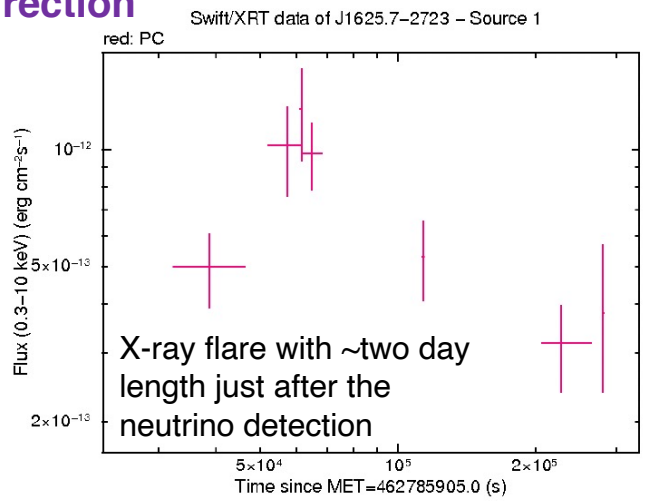
H.E.S.S.:
No VHE transient source
Flux U.L. F(E > 320GeV) < 2.4×10^{-7} m^{-2}s^{-1}



bright star (USNO-B1.0 0626-0501169) identified by MASTER

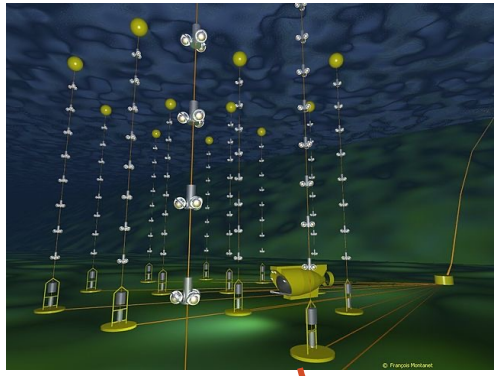
Uncatalogued, relatively bright and variable X-ray source
$(0.5\text{-}1.4)\times10^{-13}$ erg cm^{-2} s^{-1} detected by Swift-XRT
0.11° from neutrino direction

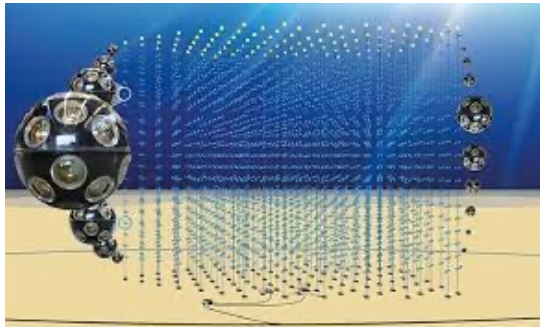
Analysis of **optical and IR archival data** point to **USNO-B1.0 0626-0501169** being a young accreting G-K star or a binary system of chromospheric active stars (RS CVn), undergoing a flaring episode that produced the X-ray emission → **unlikely (3% chance association) to be the origin of ANT150901A**



Great interest in the community (15ATels+6 GCN)
A total of 20 observatories answered to this trigger: one **radio**, 11 **optical/IR**, four **X-ray** satellites, four **VHE gamma-ray** and one **neutrino** observatory

Summary and outlook

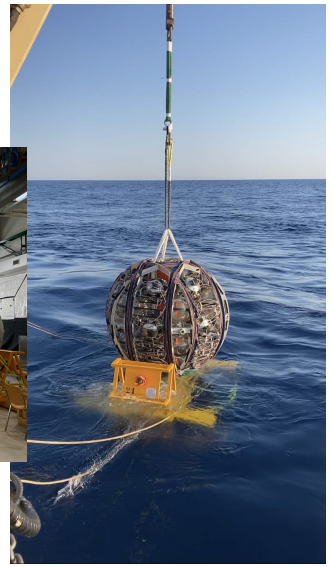




ANTARES

- Run for 15 years with high duty cycle (~95%)
- **Rich multi-messenger archival and real-time program**
- **Over 300 ANTARES alerts were followed** by multi-wavelength observatories
- **Over 500 alerts** received by multi-wavelength observatories were **followed by ANTARES**
- **No significant correlation found, but important return of experience for KM3NeT**

➡️ **Overview on ANTARES results in dedicated session this Thursday**



FUTURE: KM3NeT

- Next generation neutrino telescope in the Mediterranean Sea
- Under construction: currently running with 28 DUs (ARCA) and 23 DUs (ORCA)
- Has **already reached a comparable instantaneous sensitivity** to cosmic neutrinos **as ANTARES**
- Better **median angular resolution (~0.1° @1 PeV) and x100 ANTARES instrumented volume** (ARCA)
- Will allow **multi-flavour neutrino detection in real-time** over an **extended energy range** (ARCA+ORCA)

➡️ **More on construction status, first results, and real-time framework of KM3NeT in next three talks**