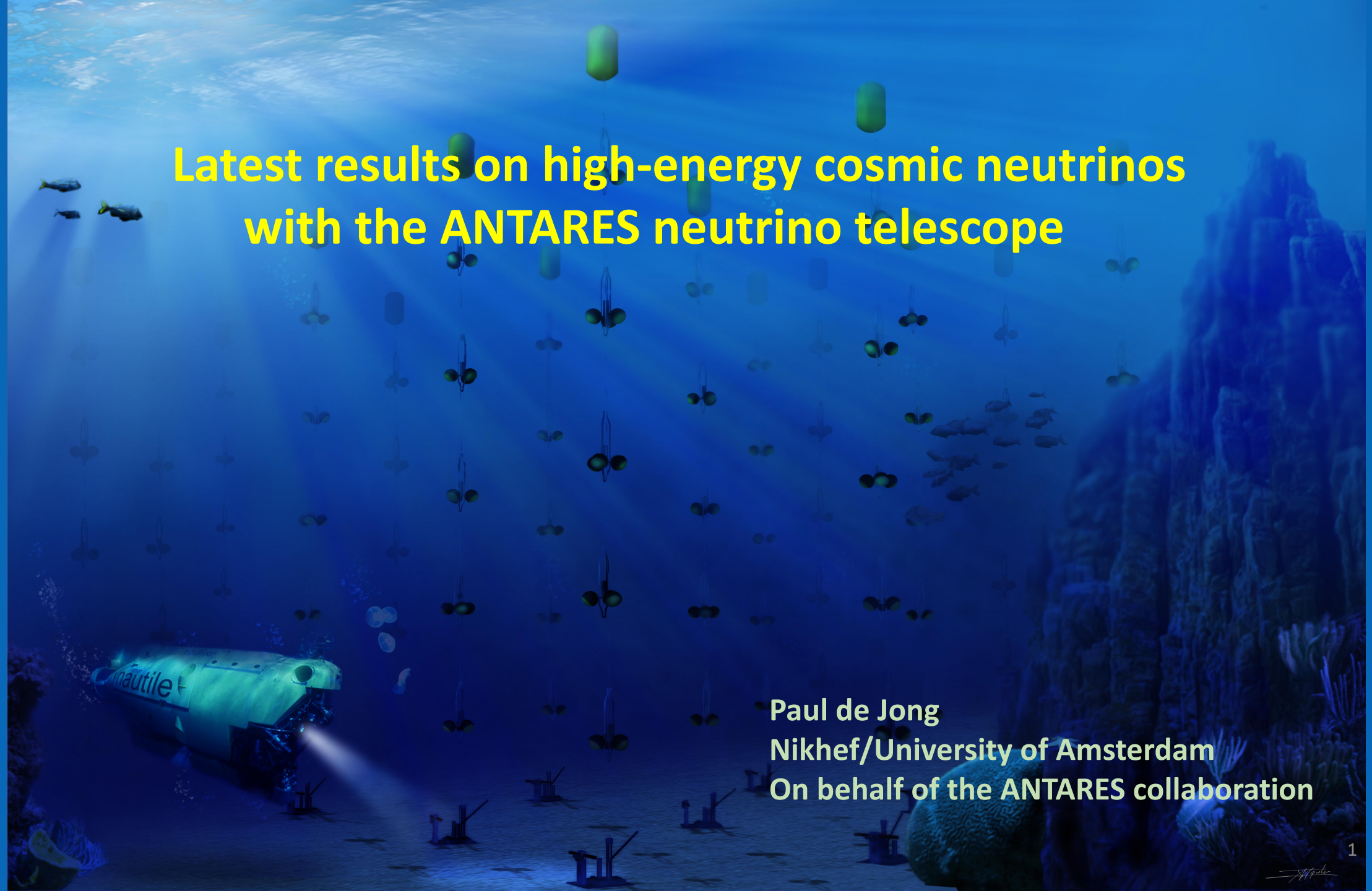
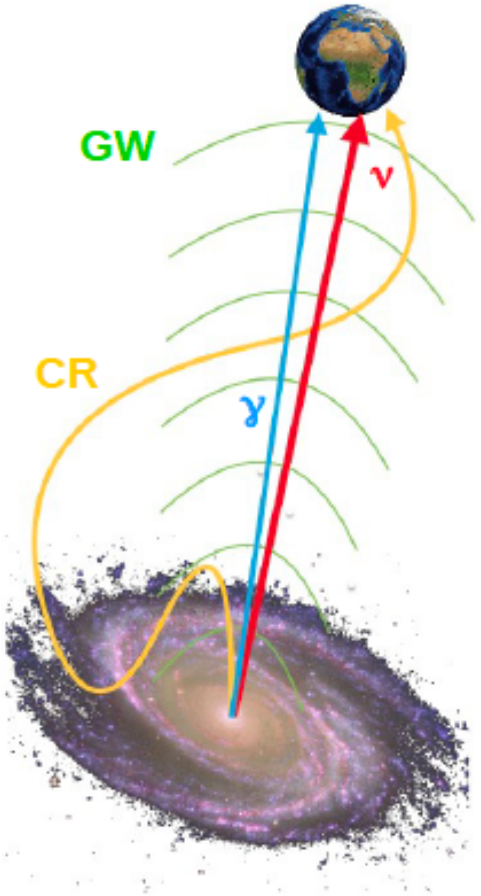
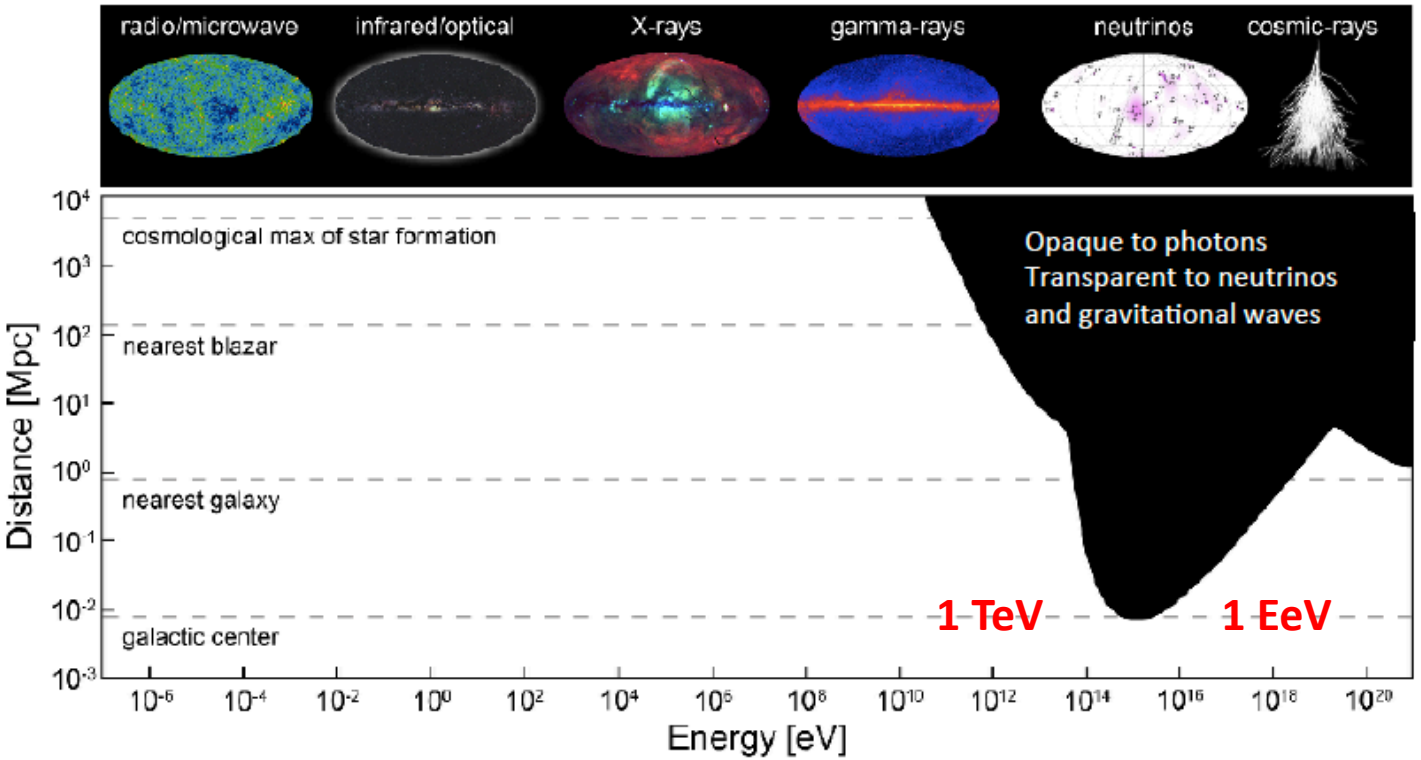


Latest results on high-energy cosmic neutrinos with the ANTARES neutrino telescope

Paul de Jong
Nikhef/University of Amsterdam
On behalf of the ANTARES collaboration

Astrophysical neutrinos





$$p+\gamma \rightarrow \Delta^{+} \begin{cases} \rightarrow p+\pi^{0} \\ \rightarrow n+\pi^{+} \end{cases}$$

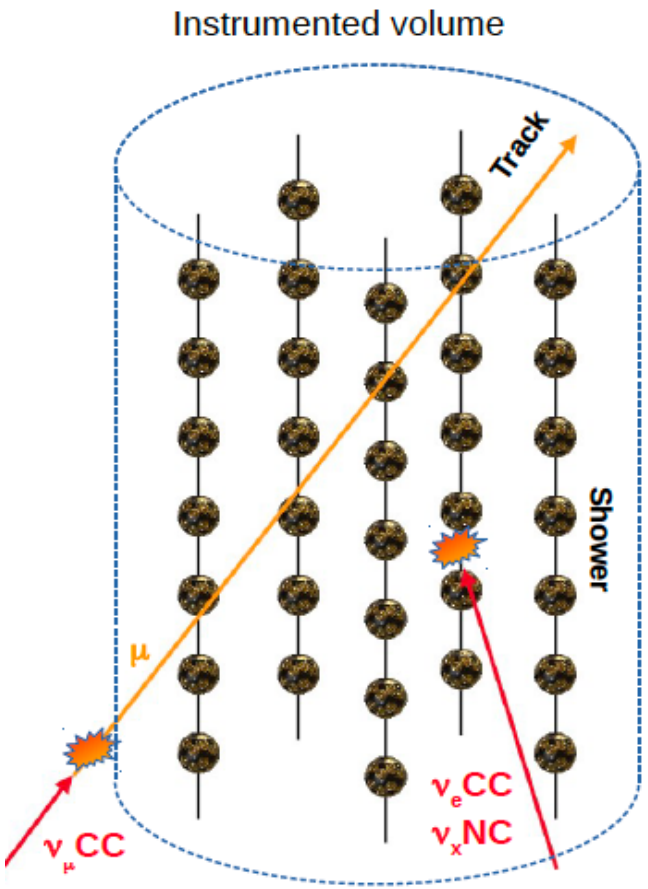
$\pi^{0} \rightarrow \gamma\gamma$ ← Observable as TeV photons

$\pi^{+} \rightarrow \mu^{+}+\nu_{\mu}$

$\hookrightarrow e^{+}+\bar{\nu}_{\mu}+\nu_{e}$ ← High energy neutrinos

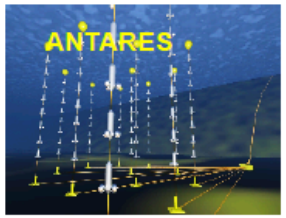
Messengers of some of the most violent processes in the Universe

Neutrino telescopes

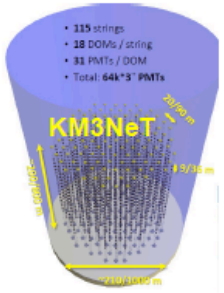


Water or ice

Running since 2007



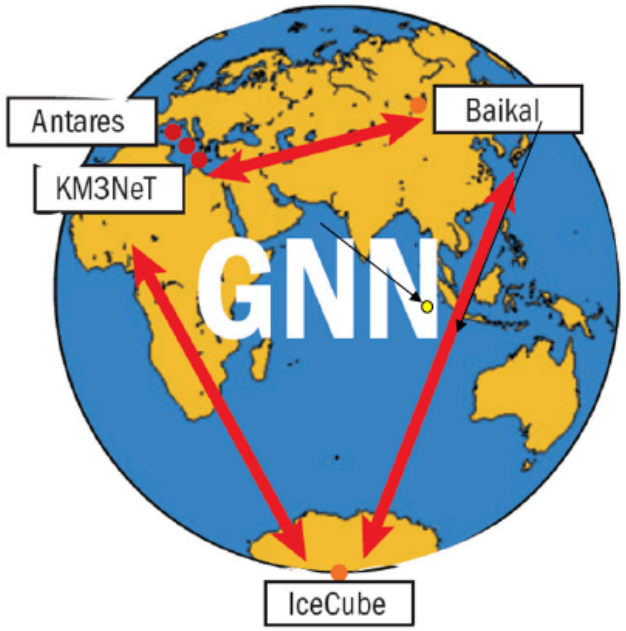
0.01 km^3



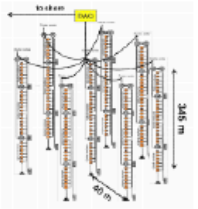
1 + 0.008 km^3

GNN

The Global Neutrino Network



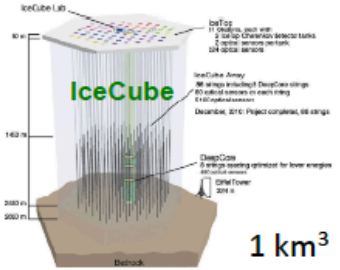
GVD (Baikal)



1 km^3

5 of 8 clusters installed
2015- 2019
(to be finished 2021)

Running since 2009

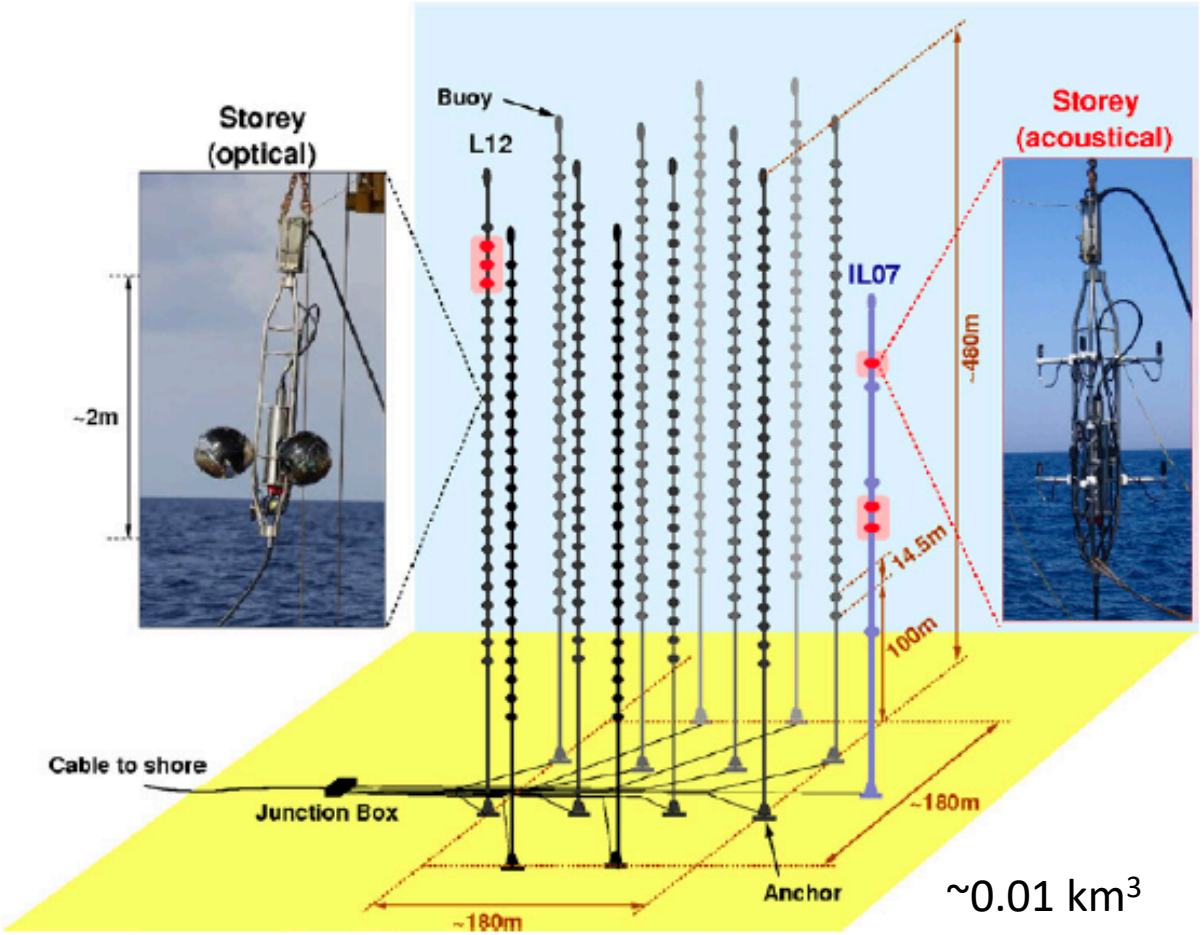


1 km^3

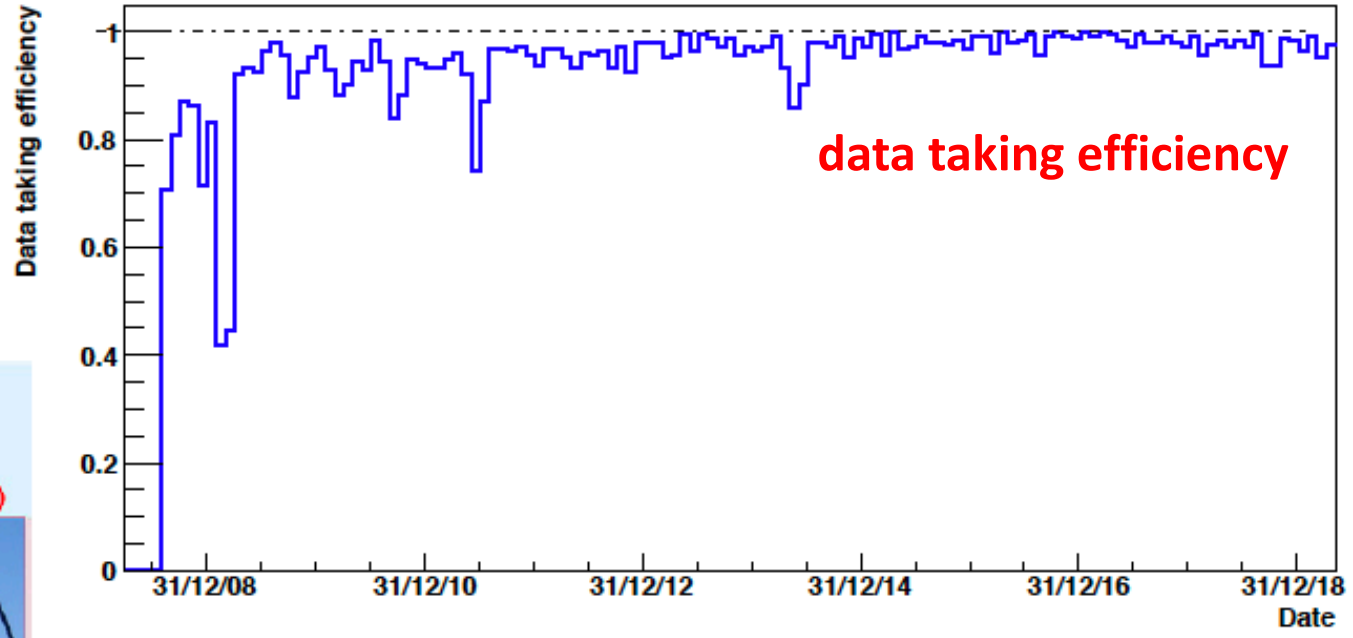
ANTARES

40 km south of Toulon, 2475 m depth

12 lines, each with 25 storeys, each with 3 OM



~0.01 km^3



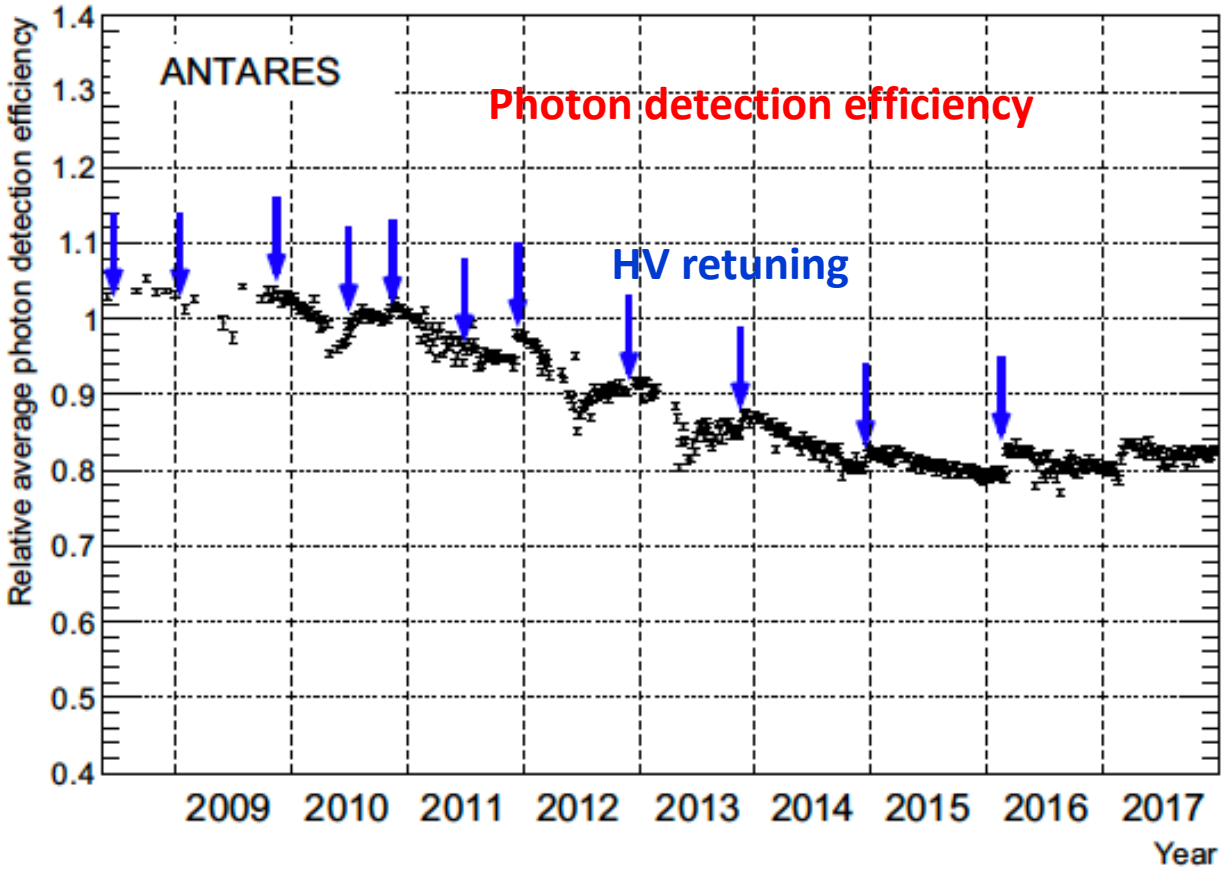
data taking efficiency

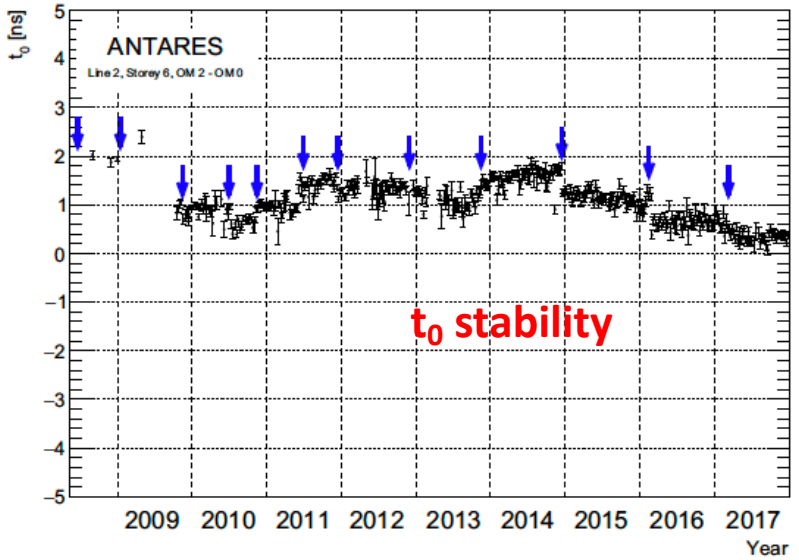
storey

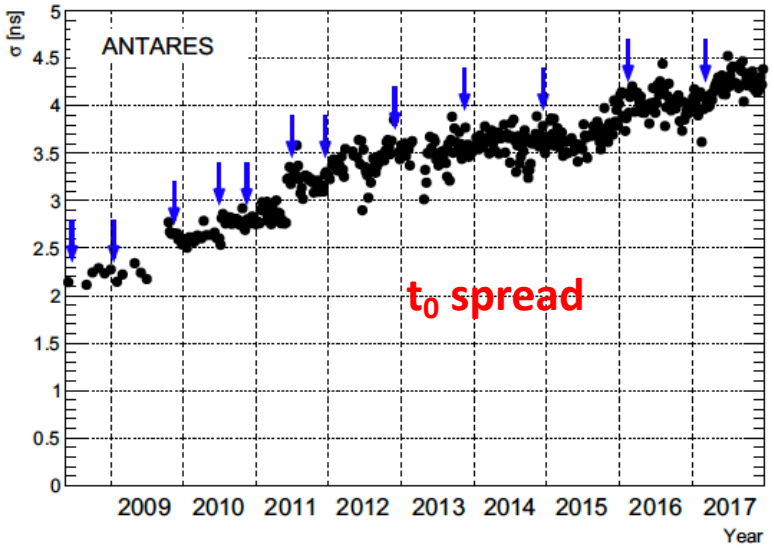
optical module

ANTARES stability (using ^{40}K decays)

Eur. Phys. J. C78 (2018) 669







Loss of photon detection efficiency over the years has affected physics results in only a limited way.

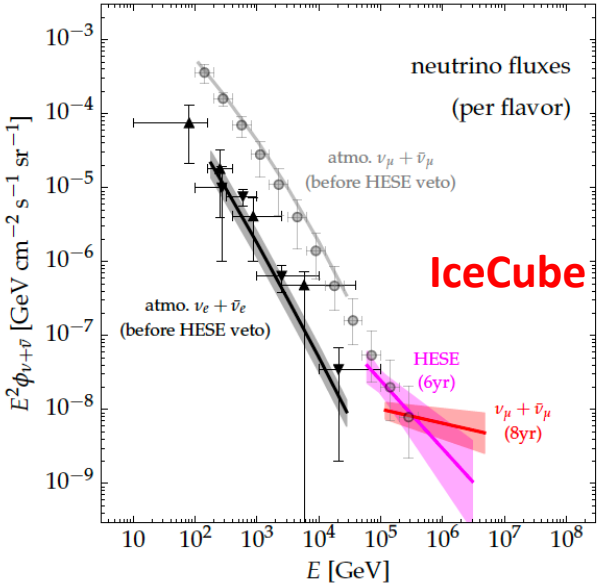
(15% loss of efficiency for astrophysical all-sky E^{-2} signal)

Diffuse Cosmic Neutrino Flux

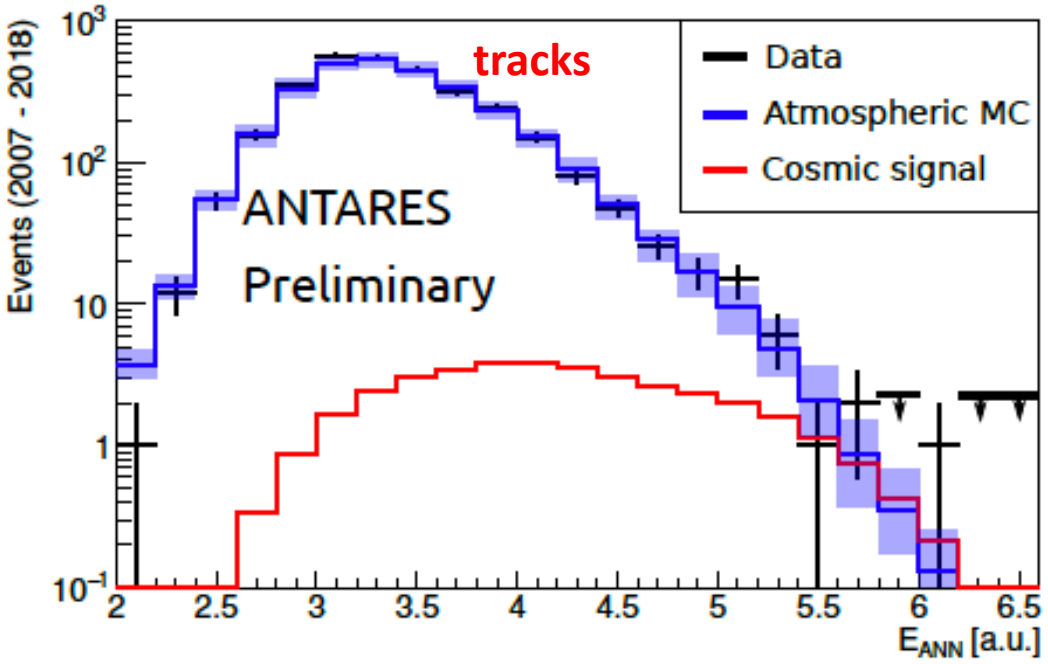
Diffuse cosmic neutrino flux

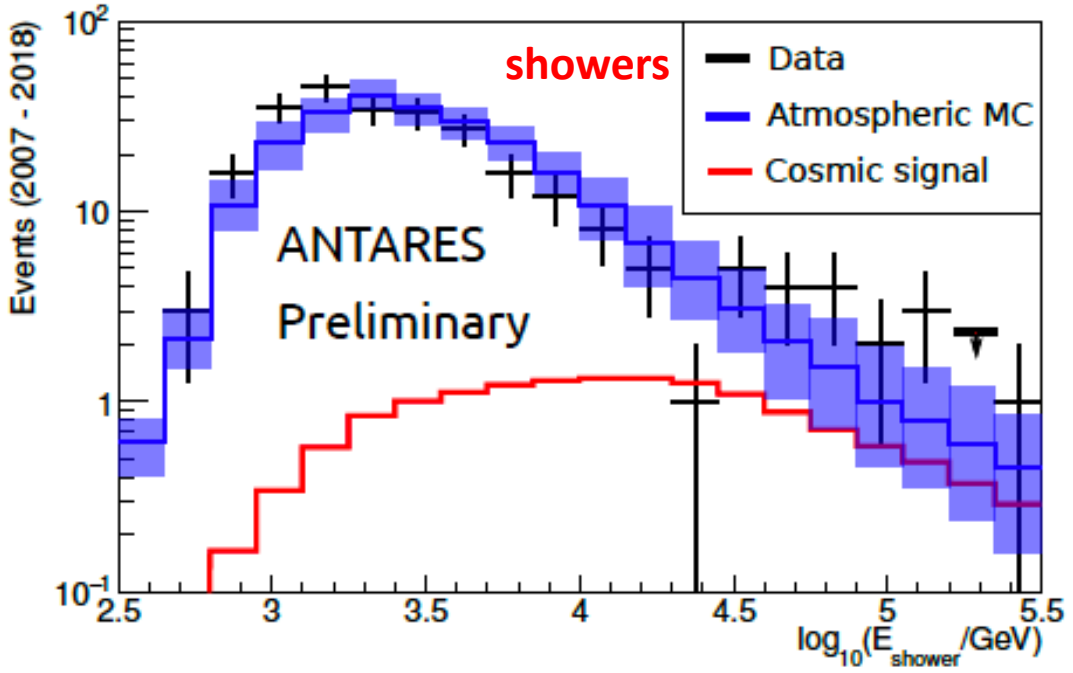
Data corresponding to 3330 days, 2007-2018
(+880 days of data since publication ApJL 853 (2018) L7)
All-flavor search: tracks and showers (showers E-resolution < 10%)

Spectrum fit: atmospheric contribution (π,K + prompt) + cosmic signal
Normalization signal and bg, and spectral index of signal left free



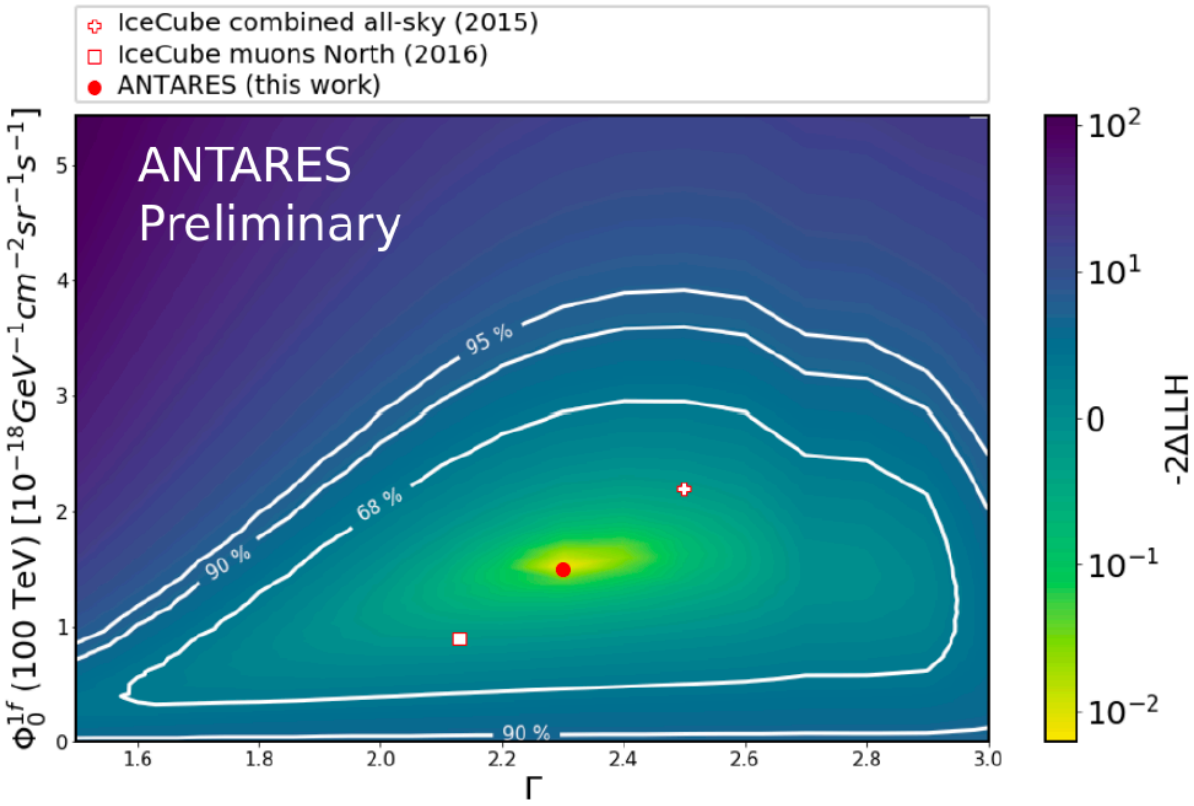
PoS (ICRC2019) 891





Diffuse cosmic neutrino flux

PoS (ICRC2019) 891



Null hypothesis excluded at 1.8σ

Tracks only:

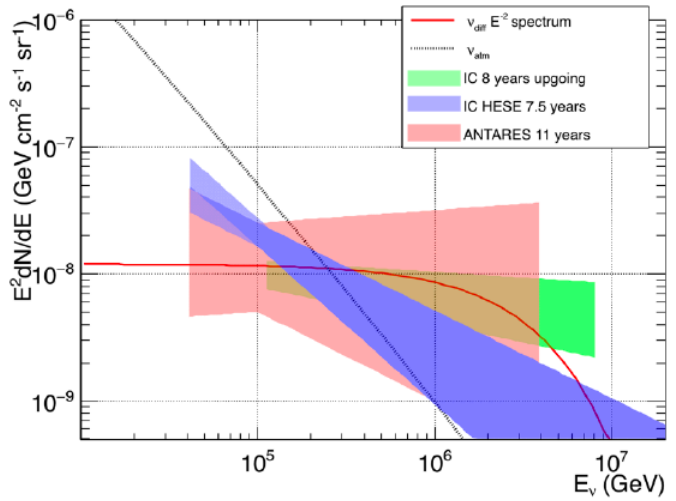
$$\Phi_{0,tr}(100\ \text{TeV}) = (0.8^{+0.5}_{-0.6}) \times 10^{-18}\ [\text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}]$$
$$\Gamma_{tr} = 2.0^{+0.8}_{-0.4}$$

Showers only:

$$\Phi_{0,sh}(100\ \text{TeV}) = (2.1 \pm 0.8) \times 10^{-18}\ [\text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}]$$
$$\Gamma_{sh} = 2.4^{+0.4}_{-0.4}$$

Combined:

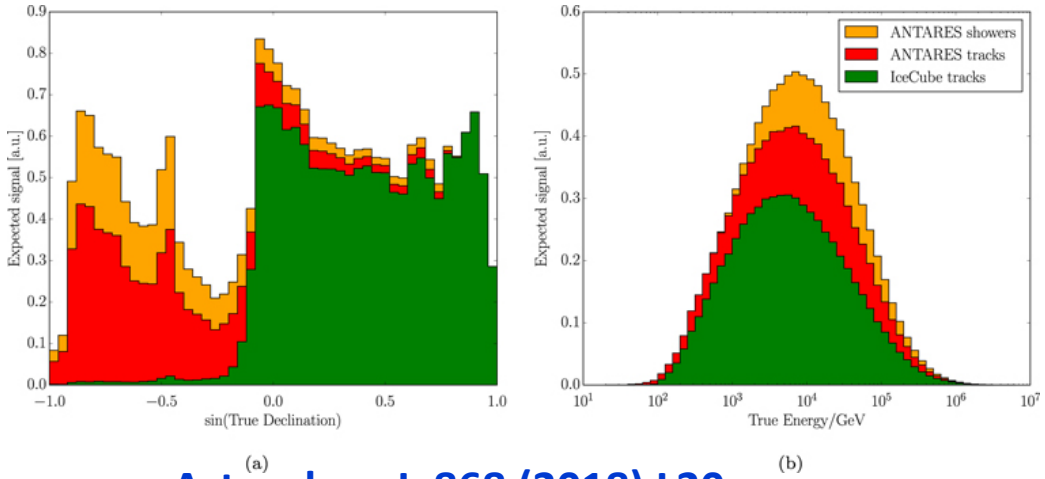
$$\Phi_0(100\ \text{TeV}) = (1.5 \pm 1.0) \times 10^{-18}\ [\text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}]$$
$$\Gamma = 2.3^{+0.4}_{-0.4}$$



Compatible with IceCube

Galactic Diffuse Neutrino Flux

ANTARES and IceCube complement each other, in particular in the southern sky

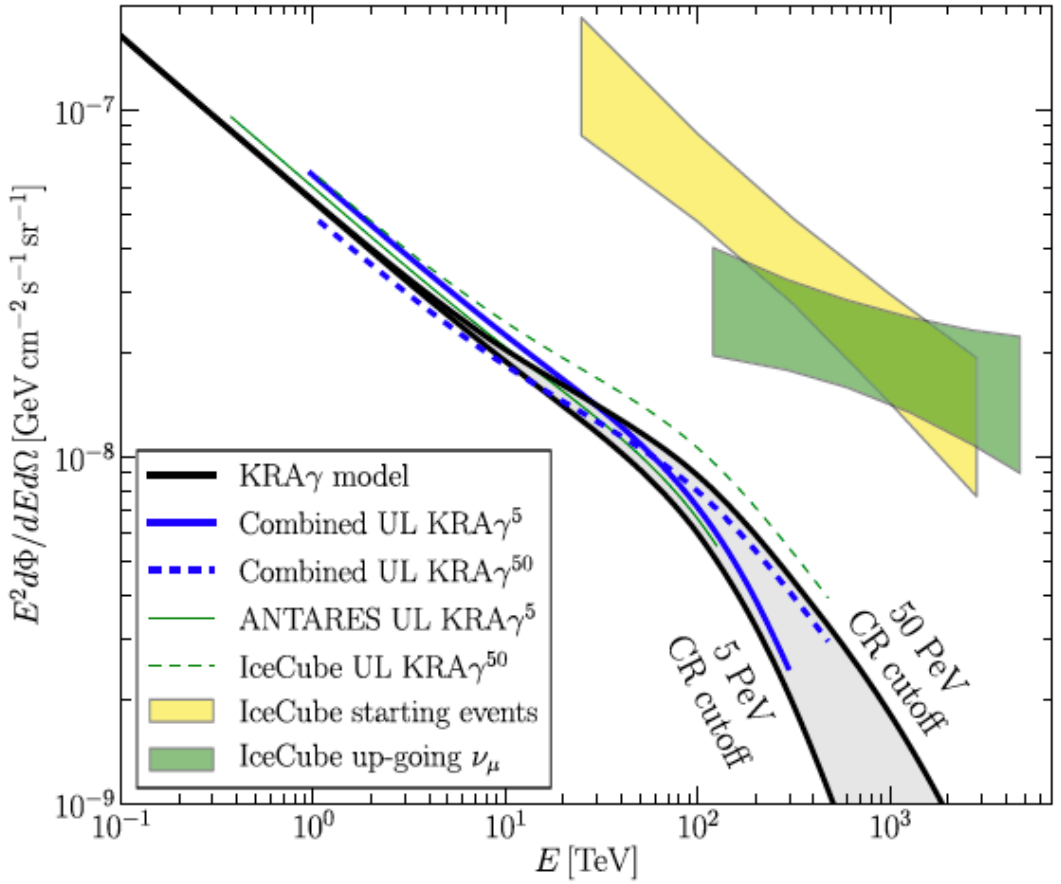


Using KRA$_\gamma$ model with cutoffs of 5 PeV or 50 PeV per nucleon.
(Gaggero et al, ApJL 815 (2015) L25, PRD91 (2015) 083012, PRL119 (2017) 031101)

ANTARES + IceCube combination:
Flux < 0.9 Φ(KRA$_\gamma^{50}$) @90%CL

Assuming KRA$_\gamma^{5}$: no more than 8.5% of observed diffuse cosmic neutrino flux is from galactic origin.

Astrophys. J. 868 (2018) L20



Searching for sources

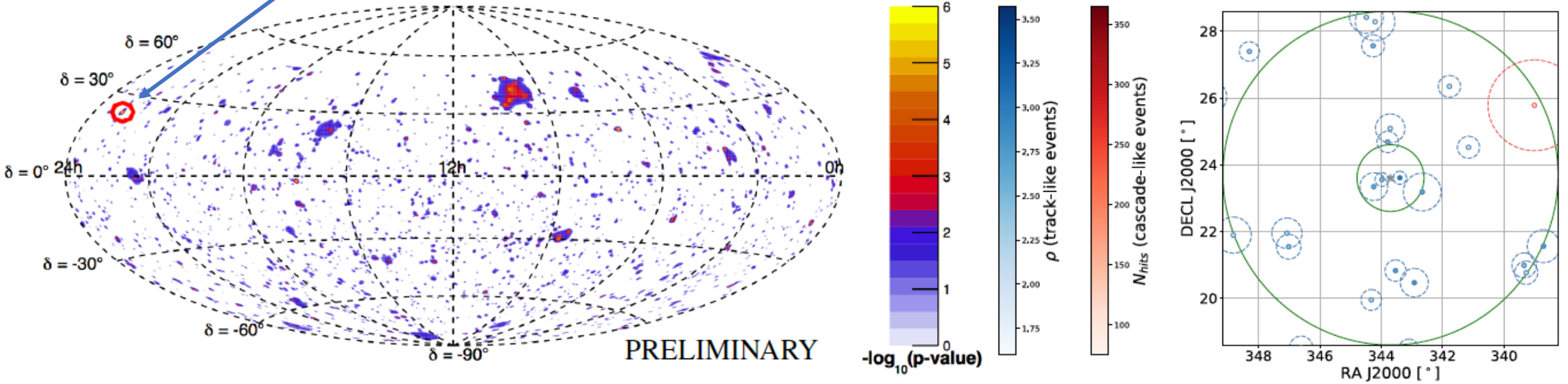
ANTARES point source search

11 years of data, 3125 days

Selection optimized for 5σ discovery of $E^{-2.0}$ spectrum source
8754 tracks, 195 showers selected
Angular resolution >100 TeV: 0.4° for tracks, 3° for showers

Full sky search: most significant point pre-trial p-value 1.5×10^{-6} , post-trial 23%

blue: tracks
red: showers

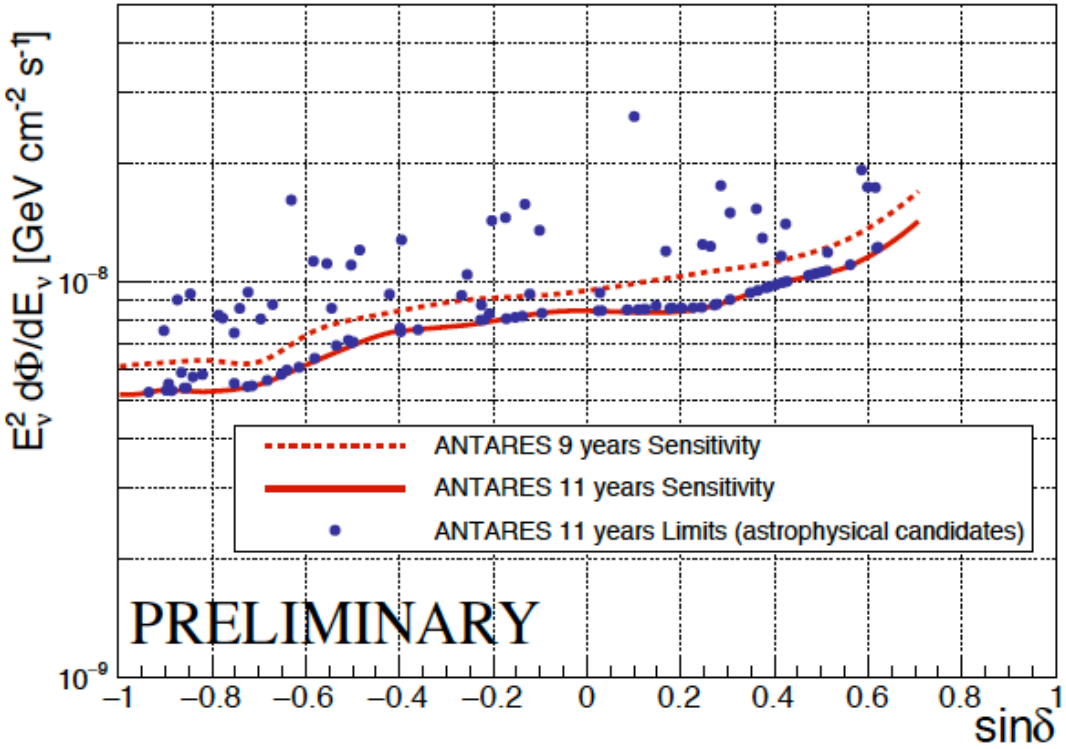


PoS (ICRC2019) 920

Catalog-based searches

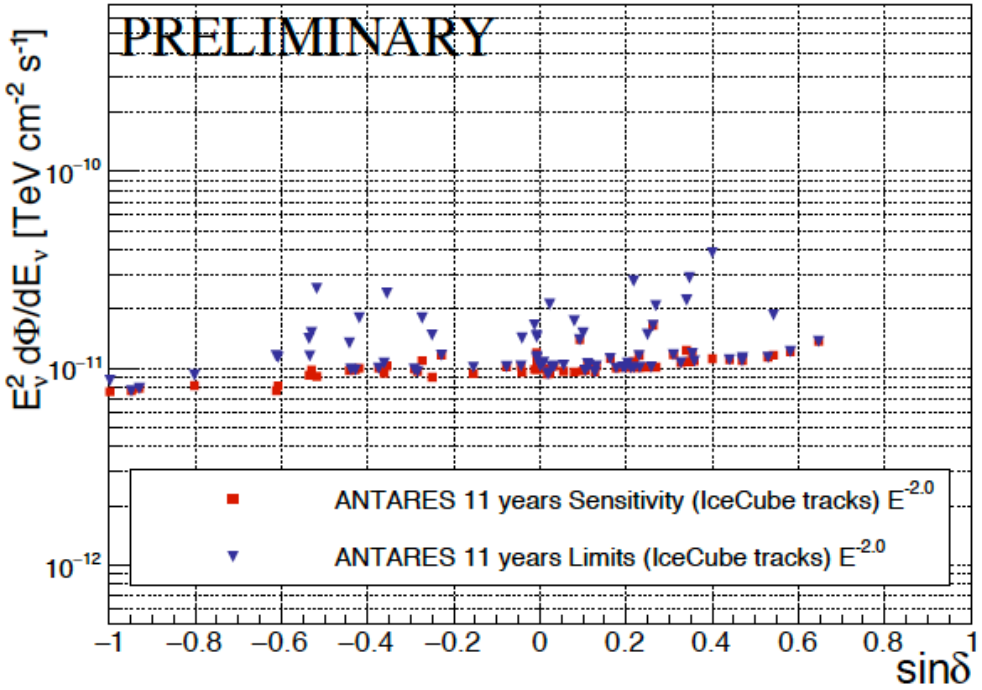
Catalog of 112 possible galactic and extra-galactic sources.

Largest excess: HESSJ0632+057
Pre-trial p-value 0.15%, post-trial significance 1.4σ



PoS (ICRC2019) 920

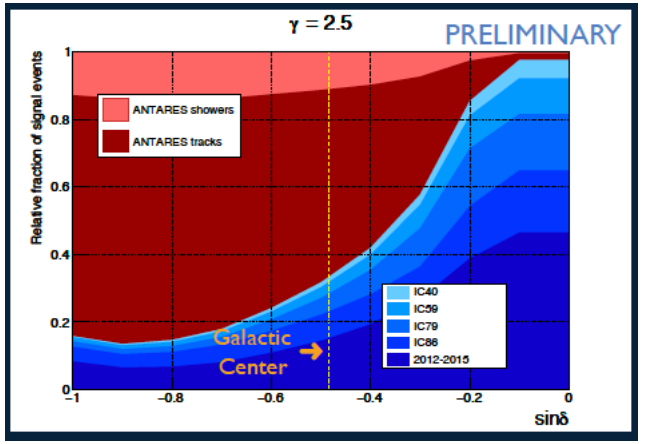
PoS (ICRC2019) 920



Catalog of 75 IceCube events
20 HESE + 34 EHE + 21 AMON alerts

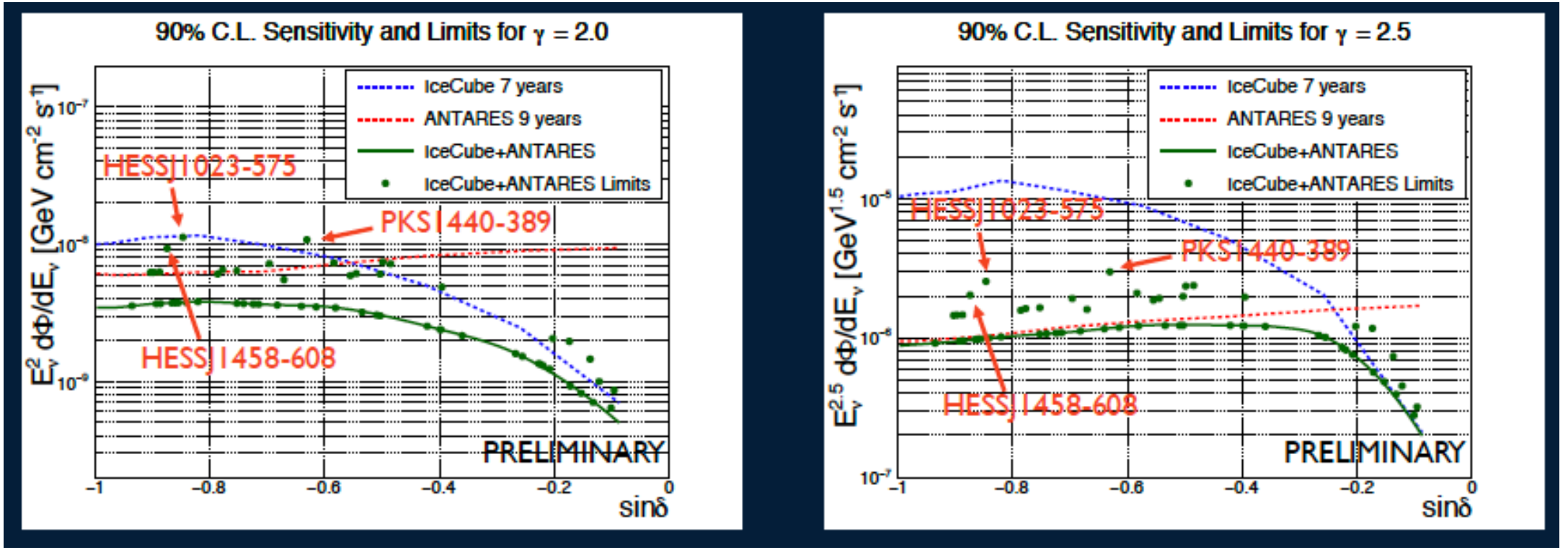
Largest excess: EHE ID3
Post-trial significance 2.4σ

Complementarity ANTARES – IceCube in southern sky



For IceCube neutrinos in southern sky are downgoing: large bg for lower energies.
ANTARES + IceCube combination helps, especially for softer spectrum.
(Original results: APJ 835(2017) 151 (IceCube), PRD96 (2017) 082001 (ANTARES))

PoS (ICRC2019) 919



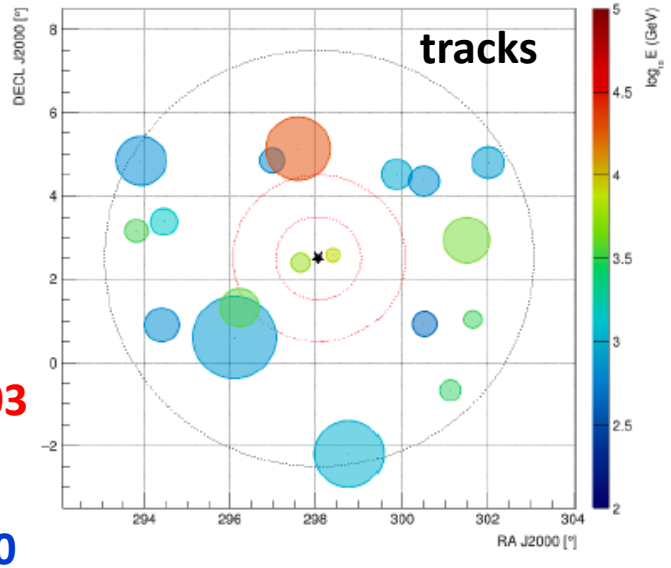
HESSJ1023-575
0.2σ post-trial
significance

G. Illuminati, ICRC2019

Stacking analysis

Likelihood stacking using track-like events and catalogs of:

- Fermi 3LAC Blazars
- Star forming galaxies
- Giant radio-galaxies
- Jet-obscured AGNs



Radio-galaxy 3C403

PoS (ICRC2019) 840

	Equal weighting				Flux weighting			
Catalog	TS	p	P	$\Phi^{UL}_{90\%}$	TS	p	P	$\Phi^{UL}_{90\%}$
Fermi 3LAC All Blazars	6.15	0.19	0.83	4.1	0.21	0.85	1.	2.0
Fermi 3LAC FSRQ	0.83	0.57	0.97	2.1	~ 0	~ 1	1.	1.7
Fermi 3LAC BL Lacs	8.3	0.088	0.64	4.6	0.84	0.56	0.96	1.9
Radio-galaxies	3.4	$4.8\ 10^{-3}$	0.10	3.3	5.1	$6.9\ 10^{-3}$	0.13	3.7
Star Forming Galaxies	0.030	0.37	0.93	1.9	~ 0	~ 1	1.	1.6
Obscured AGN	$1.0\,10^{-3}$	0.73	0.98	1.4	~ 0	~ 1	1.	1.3
IC HE Tracks	0.77	0.05	0.49	0.96	-	-	-	-

ANTARES analysis of HE IceCube events/sources

Sources identified by IceCube as promising are included in our catalog.
No excess observed by ANTARES, flux limits set, compatible with IceCube results.

Interesting individual events:

IC 191119A (HE track-like, gold alert, possible FERMI gamma ray source J1511+0550 reported recently):
No neutrino found by ANTARES in on-line analysis (track-like, +-1 hour window, 3^o cone)

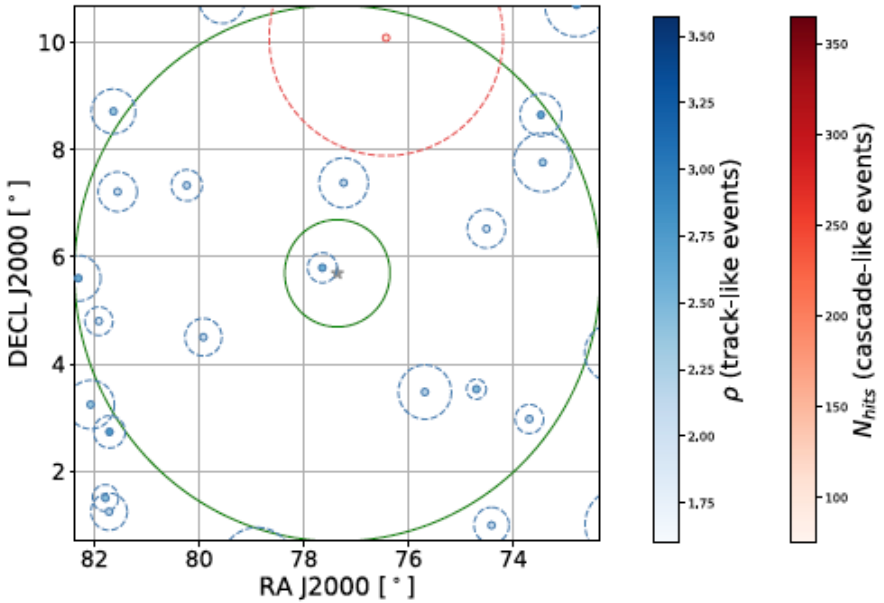
blue: tracks
red: showers

PoS (ICRC2019) 920

IC 170922A, EHE track
found to correlate with blazar TXS0506+056

ANTARES time-integrated search:
3rd most significant source, μ_{sig} = 1 event,
Pre-trial p-value 3.4%

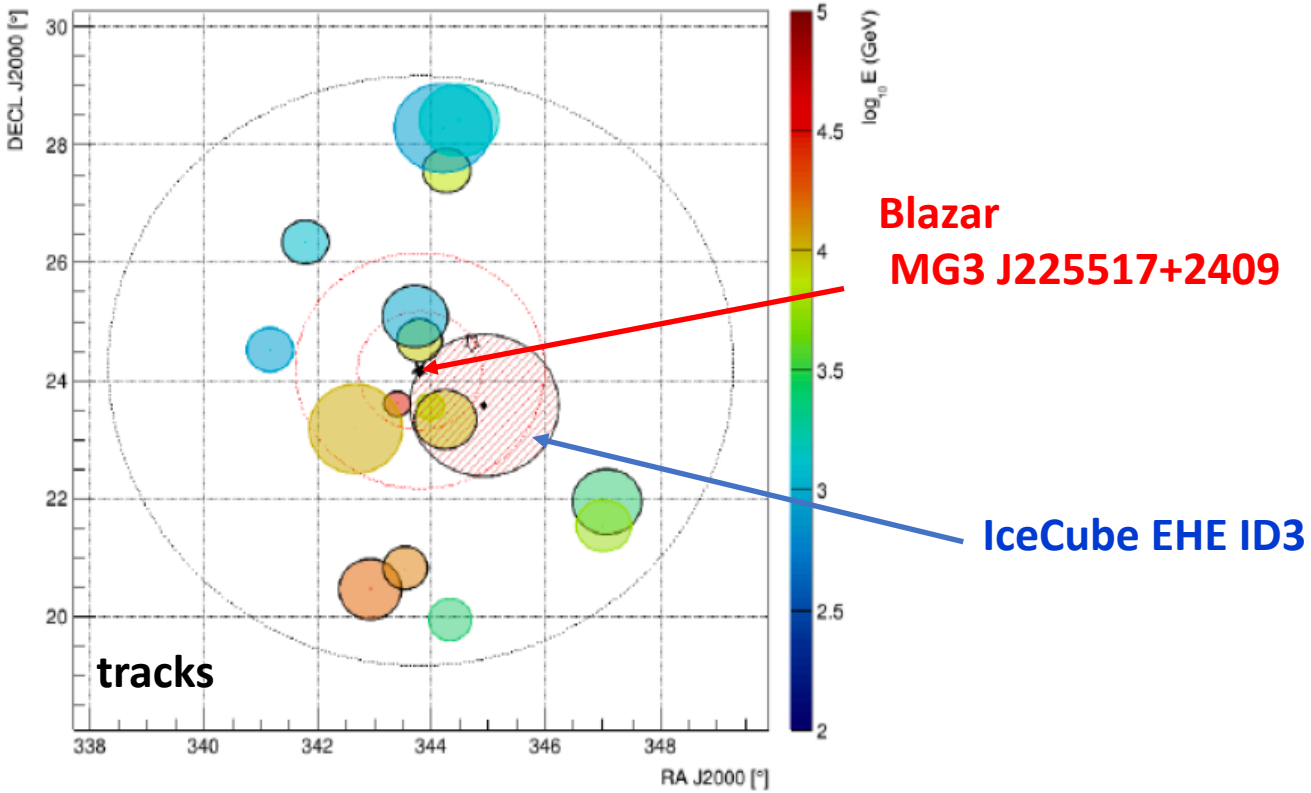
ANTARES time-dependent search:
no correlation with flaring periods



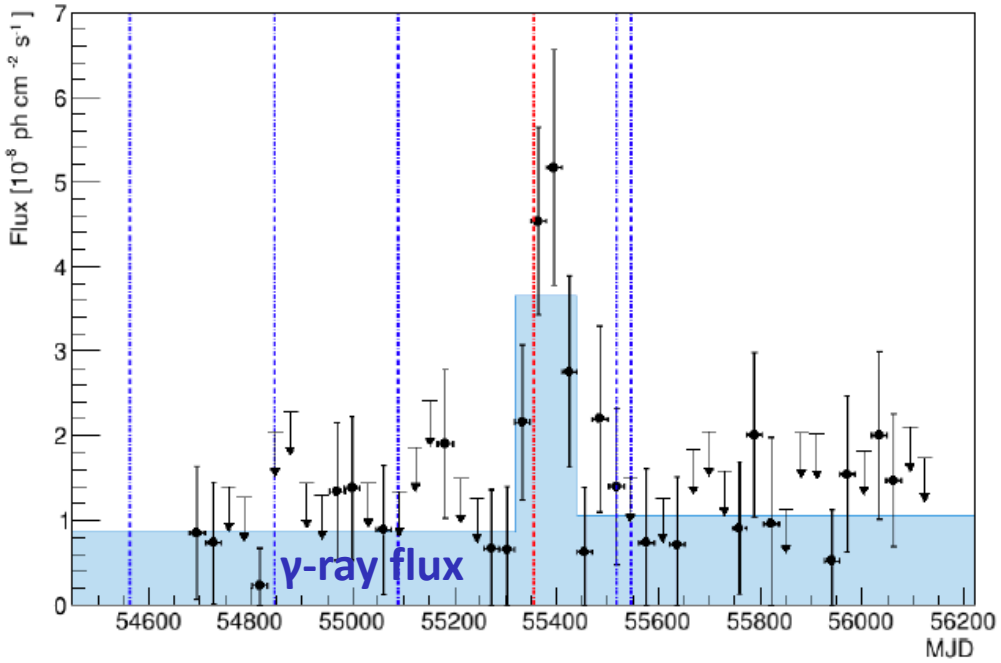
ANTARES analysis of HE IceCube events

ANTARES largest excess in IceCube catalog (EHE ID3) coincides with ANTARES most significant all-sky excess and with Fermi source 3FG J2255.1+24311 (3LAC catalog blazar MG3 J225517+2409).
Blazar association: pre-trial significance 3.8σ, post-trial significance 1.4σ.

PoS (ICRC2019) 840



PoS (ICRC2019) 840



Time analysis: ANTARES events, IceCube EHE ID3
Assuming continuous neutrino production,
pre-trial significance 5.2σ

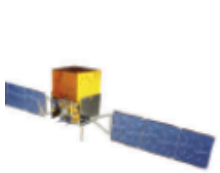
Summary of source searches:

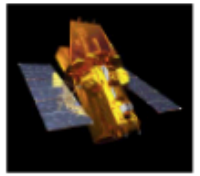
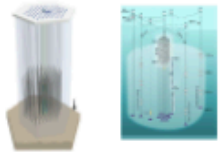
PoS (ICRC2019) 006

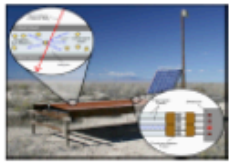
Analysis	Source	α [°]	δ [°]	pre-trial (σ)	post-trial (σ)
full sky		343.5	+23.6	$1.5\ 10^{-6}$ (4.8)	0.23 (1.2)
candidate list	HESSJ0632+057	98.24	+5.81	$1.5\ 10^{-2}$ (2.4)	0.16 (1.4)
IceCube tracks	EHE ID3	343.5	+23.6	$1.5\ 10^{-6}$ (4.8)	0.015 (2.4)
TXS0506+056		77.36	+5.69	$3.4\ 10^{-2}$(2.1)	0.87 (0.16)
ANT-IceCube Southern sky		213.2	-40.8	$1.3\ 10^{-5}$ (4.3)	0.18 (1.3)
ANT-IceCube RXJ1713		258.25	-39.75	$4.0\ 10^{-1}$ (0.84)	
stacking Radio-galaxies		-	-	$4.8\ 10^{-3}$ (2.8)	0.10 (1.6)
stacking Radio-galaxies	3C403	298.06	+2.5	$2.3\ 10^{-4}$ (3.7)	0.013* (2.5)
stacking 3LAC BL Lacs		-	-	$8.8\ 10^{-2}$ (1.7)	0.64 (0.5)
stacking 3LAC BL Lacs	MG3J225517+2409	343.78	+24.19	$1.4\ 10^{-4}$ (3.8)	0.16* (1.4)
Time Analysis	MG3J225517+2409	343.78	+24.19	$1.4\ 10^{-4}$ (3.7)	0.16* (1.4)
Time Analysis ANT-IceCube	MG3J225517+2409	343.78	+24.19	$2.2\ 10^{-7}$ (5.2)	-

Multimessenger astronomy

Multimessenger network





neutrinos
IceCube, GVD, SNEWS

GeV-TeV γ-rays
Fermi, HESS, HAWC, CTA

UHECR
Auger, TA

only spatial coincidence

ANTARES, KM3NET

Receive alerts
Generate alerts

Radio/Optic /X-ray
TAROT, MASTER, Swift, INTEGRAL, MWA

Gravitational Waves
VIRGO, LIGO

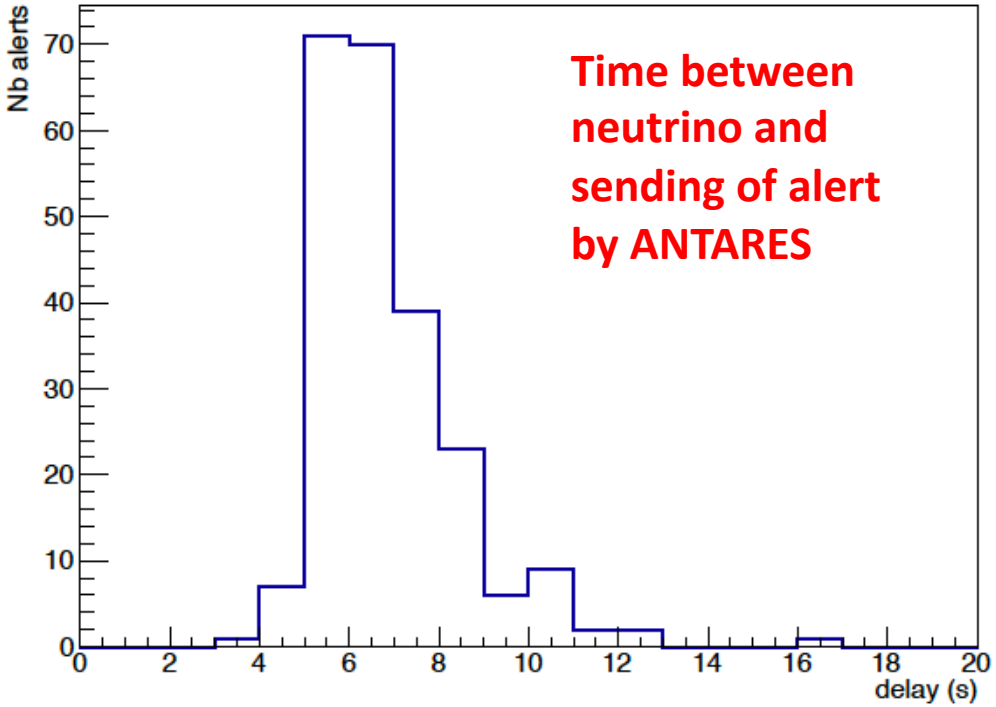
Transient events and time correlations: reduction of background, more insight in physics of sources

Alerts generated by ANTARES (TAToO)

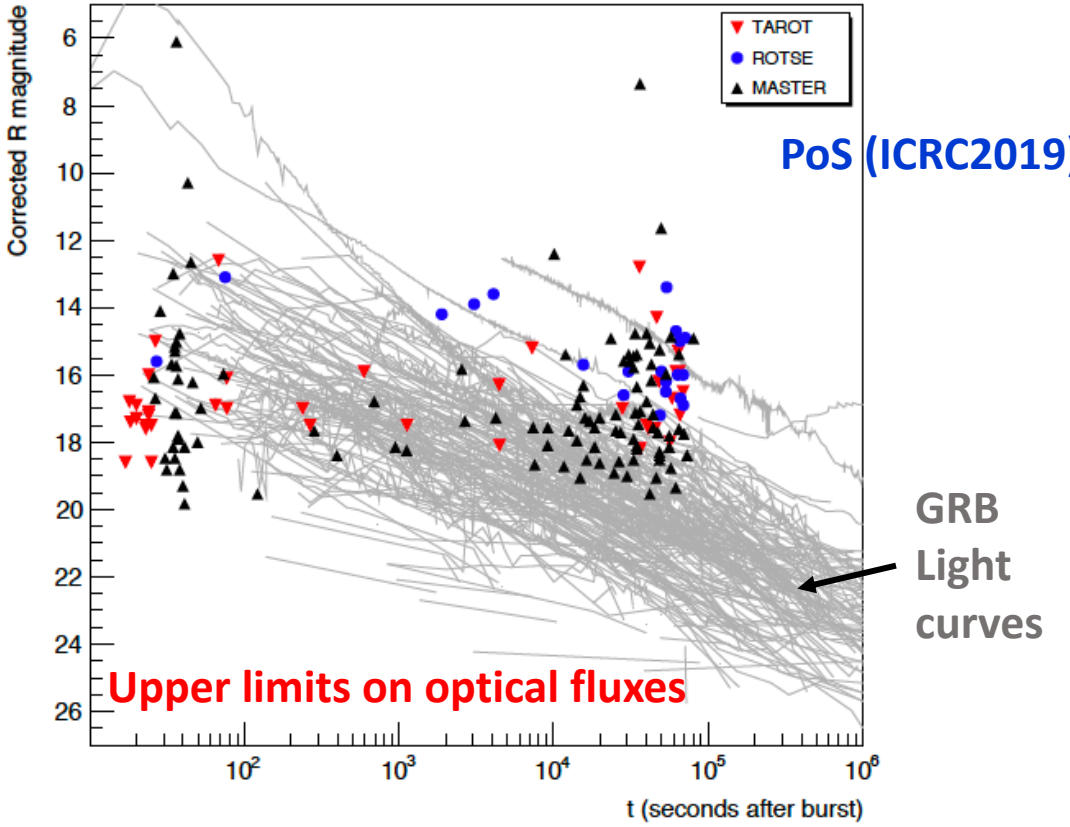
Neutrino telescopes observe a large part of the sky, 24/7
Alerts after HE neutrino can be generated within O(10) s

311 alerts 2009-2019 to optical telescopes
6 to SWIFT, 4 to MWA, 2 to H.E.S.S.

PoS (ICRC2019) 871



No significant counterpart observed



PoS (ICRC2019) 871

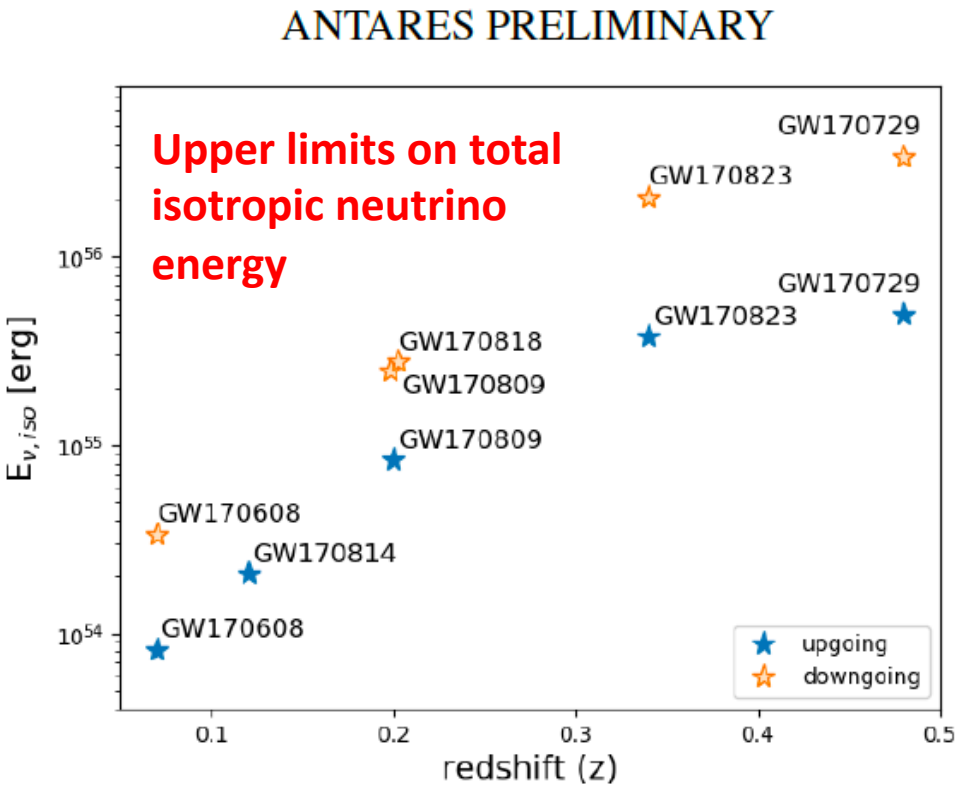
Alerts: HE neutrino (>5 TeV), VHE neutrino (>30 TeV), directional (local galaxies catalog), doublet

LIGO/VIRGO GW alerts followup

Since O2, LIGO/VIRGO alerts are followed up in on-line analysis: upgoing tracks only, +-500 s and +- 1 hour windows

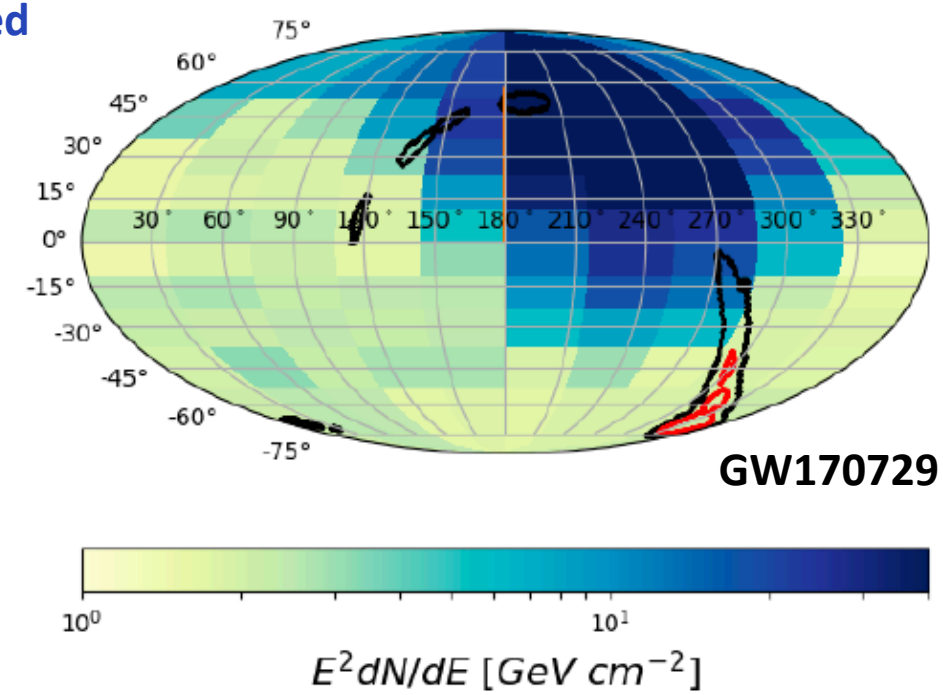
Offline followup of O2 catalog (BBH) events:
Up-going AND down-going tracks, background from data
Cuts such that 1 observed event would correspond to 3σ significance

No event observed



PoS (ICRC2019) 872

Upper limits on neutrino flux assuming E^{-2} spectrum



GW170729

LIGO/VIRGO O3 GW alerts on-line followup

PoS (ICRC2019) 872

As of November 2019:
36 alerts

End of June 2019: 14 alerts,
12 followed up by ANTARES
on-line

Tracks, +- 500 s and +- 1 hour
Overlap with 90% contour and
ANTARES visibility map

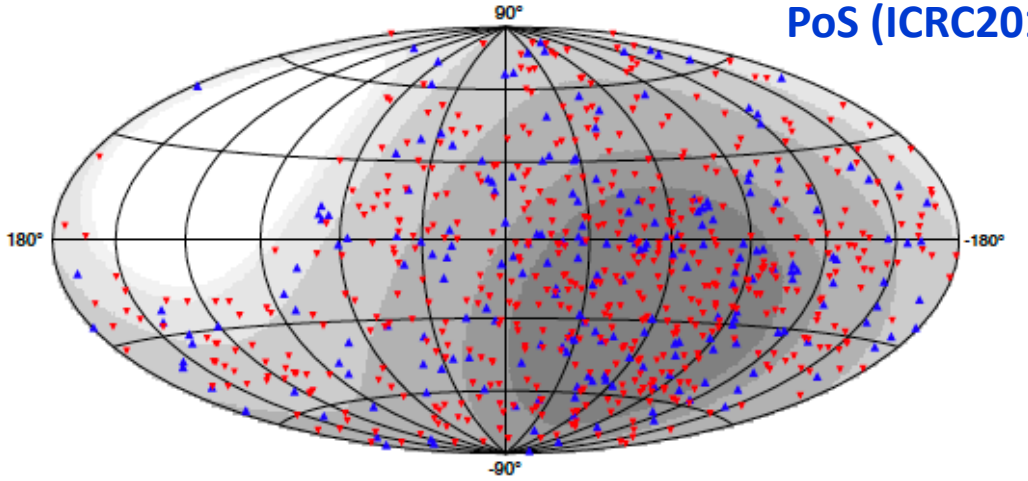
No candidates observed

Off-line analysis will follow
at end of O3

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

Gamma Ray Bursts followup

PoS (ICRC2019) 872



GRBs observed by SWIFT or Fermi, alert via GCN
Analyzed on-line by ANTARES if in field-of-view
Window -250 s < t_0 < 750 s
Within cone max[2°, Fermi error cone]

Up to June 2019: 226 SWIFT (blue), 536 Fermi (red) alerts followed. **No neutrino assigned to GRB**.

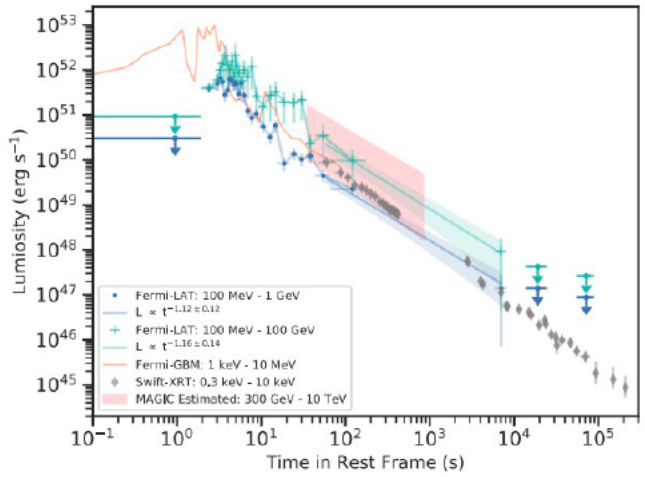
Interesting GRB events with earth-based TeV gamma ray observations:

GRB 180720B H.E.S.S. reported observation of VHE gamma rays in afterglow
no real-time followup was performed by ANTARES

GRB 190829A observed by H.E.S.S., on-line track reco found no neutrino in 3 degrees, +- 1 hour
offline all-flavor analysis in progress

Gamma Ray Bursts followup

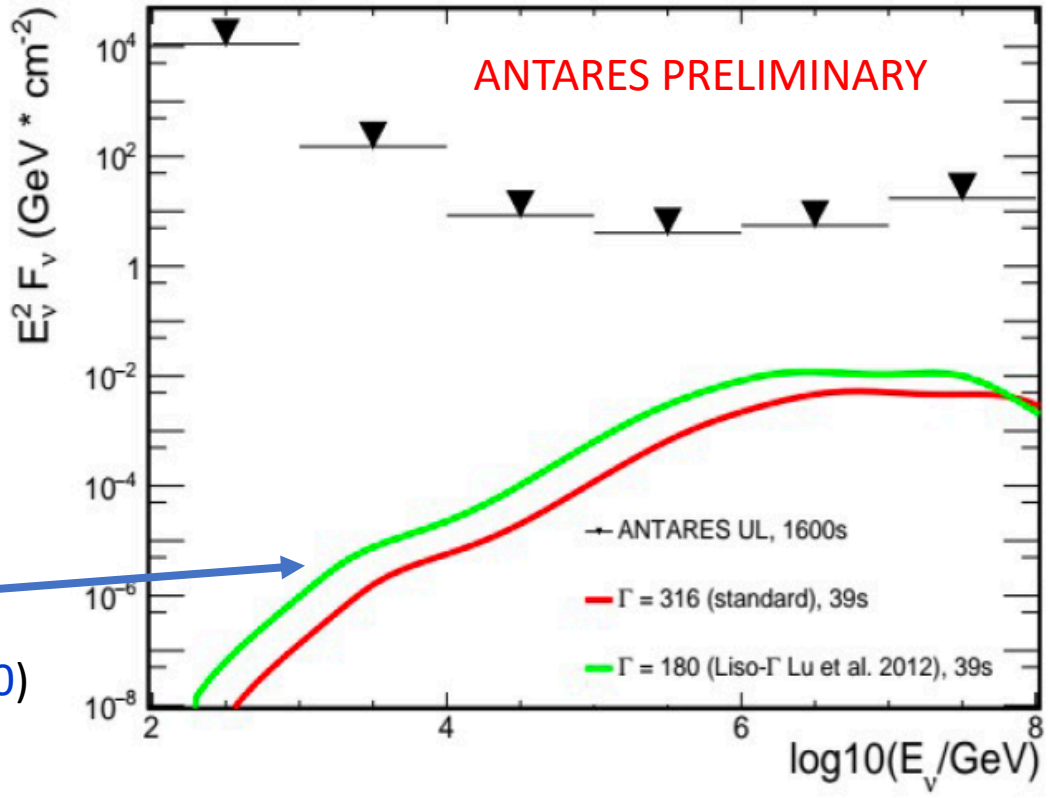
GRB 190114C TeV emission observed by MAGIC



All-flavor search by ANTARES
$-350 < t_0 < 1250$ s
Background estimated from data
Cone 2° for tracks, 22° for showers
Cuts optimized such that 1 event observed would correspond to 3σ significance

No candidate found

Flux limits set, compared to model of internal shock neutrino emission.
(NEUCOSMA, Huemmer et al, ApJ 721 (2010) 630)



Summary and Conclusion

- 11 years of ANTARES prove the principle of an underwater neutrino telescope and its excellent angular resolution, and the value of having one in the Northern Hemisphere.

- Diffuse cosmic flux seen: absence excluded at more than 90% CL.

Upper limits set on galactic contribution.

- No significant point source seen in all-sky or catalog search.

However, most significant all-sky excess coincides with IceCube EHE ID3 and Fermi blazar.

- Active multimessenger program, both in generating alerts and responding to them.

ANTARES will remain operational at least until end of LIGO/VIRGO O3.