XVIII International Conference on Topics in Astroparticle and Underground Physics
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Latest Results and Lessons Learned from the ANTARES Neutrino Telescope

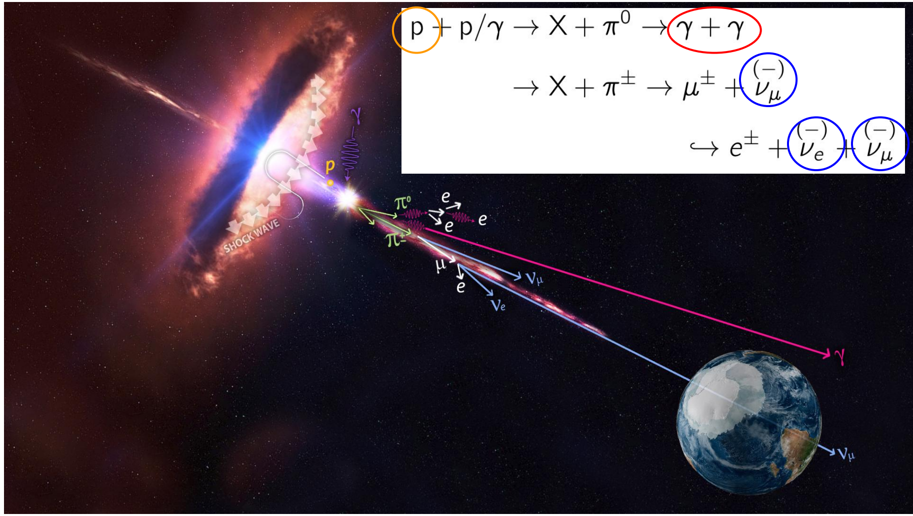
Francisco Salesa Greus
for the ANTARES collaboration

CSIC
IFIC INSTITUT DE FÍSICA CORPUSCULAR
VNIVERSITAT DE VALÈNCIA
GENERALITAT VALENCIANA
GenT
VEGA Valencia Experimental Group of Astroparticles
ANTARES

ANTARES Scientific Program

- **Astronomy & astrophysics** (main goal by design):
  - Neutrino astronomy: prove the existence of a cosmic neutrino flux and neutrino sources.
  - **Multi-messenger astronomy**: connects different cosmic messengers having a common origin.
  - High-energy cosmic rays origin. Study of the sources (particle acceleration and propagation).
- Dark matter & Particle physics:
  - Dark Matter origin.
  - Beyond Standard Model theories: magnetic monopoles, nuclearites.
- Neutrino oscillations & interactions.
- Not only physics: Environmental research (Earth & Sea Science).

Credit: IceCube/NASA



Cosmic accelerators can produce different *messengers*: **cosmic rays**, **gamma rays**, **neutrinos**, and **gravitational waves**.

Common origin: **cosmic rays** accelerators produce both γ and ν through hadronic processes, **pγ** and **pp** interactions.

Neutrino Telescopes: Detection Principle

- Primary neutrino interacts with the matter near the detector.
- A secondary lepton is produced inducing **Cherenkov light** collected by an **array of PMTs** embedded in optical transparent media, **water or ice**.
- Submerged to filter out the cosmic ray secondary backgrounds (mostly muons).
- “Gold” channel are upward-reconstructed events, to reject anything but neutrinos.
- **Cosmic neutrinos** are still **sub-dominant** compared to atmospheric neutrinos.

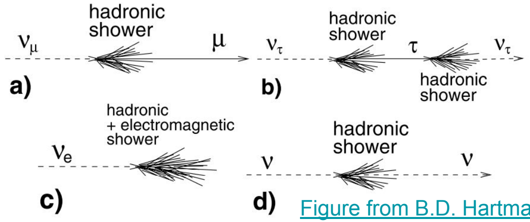
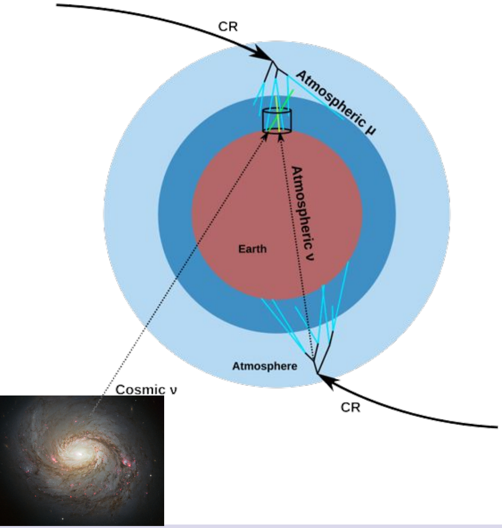
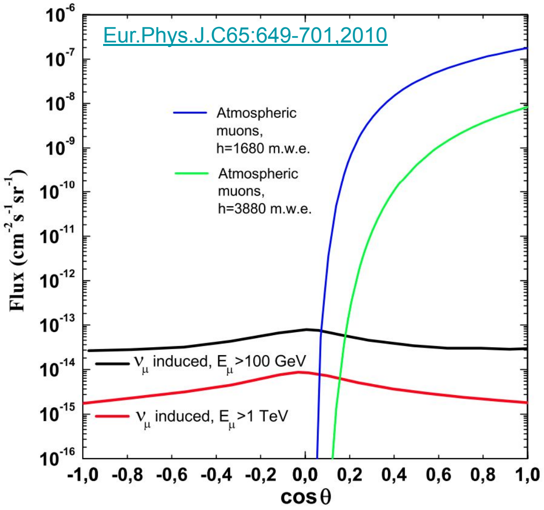
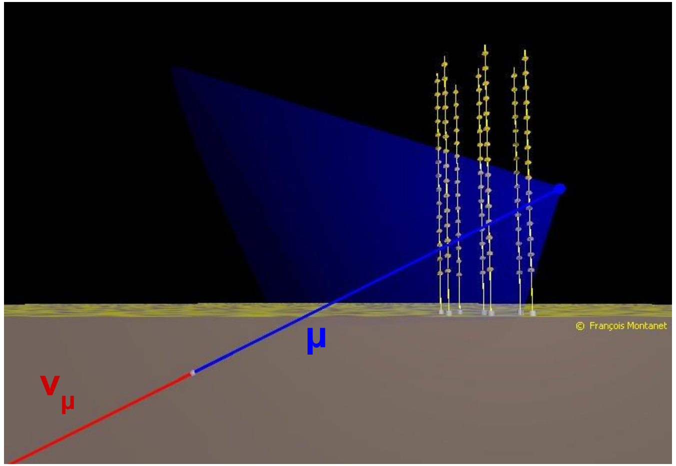


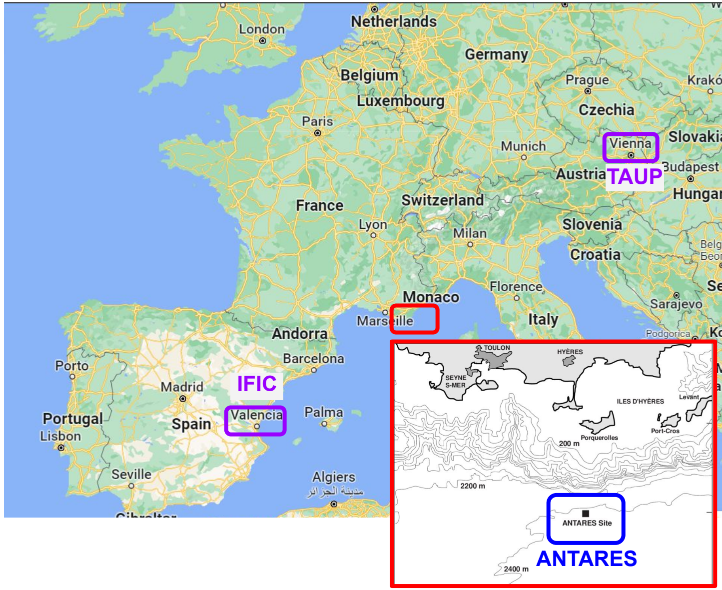
Figure from B.D. Hartmann PhD



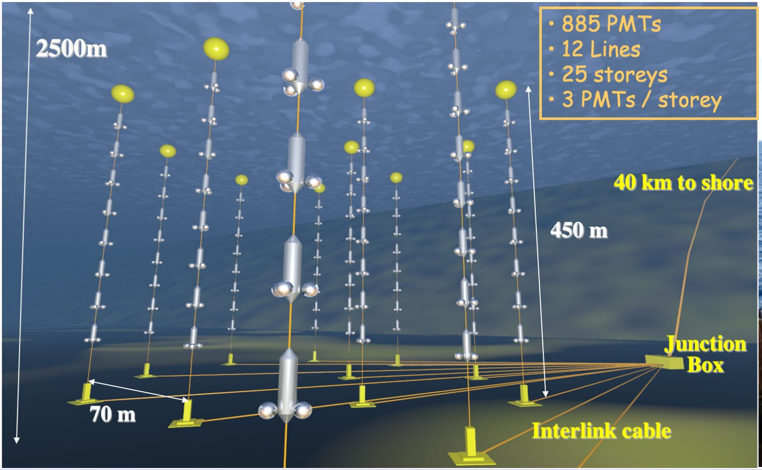


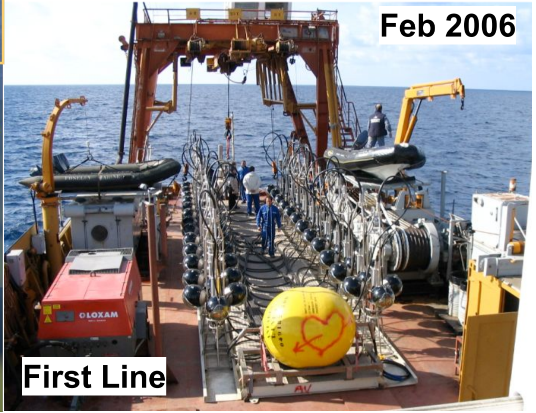


The ANTARES Neutrino Telescope



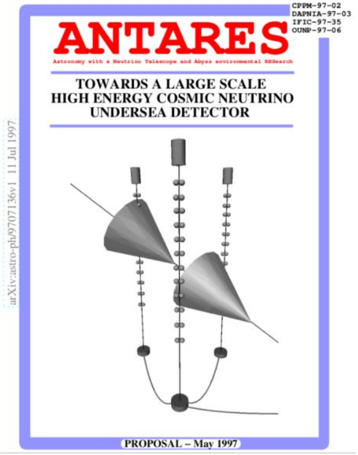
- [ANTARES](#) was an underwater neutrino telescope (2006 - 2022).
- Located at 2500 m depth, 40 km off the Toulon coast in France ([42°48'N](#)) [**good visibility of the Southern sky, inner Galaxy**].
- 3D array of 885 PMTs (10-inch) distributed in 12 lines of 25 storeys with an instrumented volume of ~0.01 km^3.
- Sensitive to energies from hundreds of GeV to PeV.
- Angular resolution (median) < 0.4° for E > 10 TeV (tracks).





The ANTARES Collaboration

- The ANTARES collaboration includes about 150 engineers, technicians, and physicists from institutes mainly in Europe.
- The collaboration was established in 1997 when the detector proposal was published. It is still presently active, even though the detector was decommissioned in 2022.
- The final results by the collaboration are being produced, some will be presented today.
- The ANTARES legacy: papers with the whole dataset are already being published. Hoping to have all publications ready by 2024.



ANTARES'97

https://arxiv.org/abs/astro-ph/9707136

Review of the online analyses of multi-messenger alerts and electromagnetic transient events with the ANTARES neutrino telescope

A. Albert[1,2] S. Alves[3] M. André[4] M. Ardid[5] S. Ardid[5] J.-J. Aubert[6] J. Aublin[7] B. Baret[7] S. Basa[8] B. Belhorma[9] M. Bendahman[7,10] F. Benfenati[11,12] V. Bertin[6] S. Biagi[13] M. Bissinger[14] J. Boumaaza[10] M. Bouta[15] M.C. Bouwhuis[16] H. Brânzaş[17] R. Bruijn[16,18] J. Brunner[6] J. Busto[6] B. Caiffi[19] D. Calvo[3] S. Campion[20,21] A. Capone[20,21] L. Caramete[17] J. Carr[6] V. Carretero[3] S. Celli[20,21] M. Chabab[22] T. N. Chau[7] R. Cherkaoui El Moursli[10] T. Chiarusi[11] M. Circella[23] J.A.B. Coelho[7] A. Coleiro[7] R. Coniglione[13] P. Coyle[6] A. Creusot[7] A. F. Díaz[24] B. De Martino[6] C. Distefano[13] I. Di Palma[20,21] A. Domi[16,18] C. Donzaud[7,25] D. Dornic[6] D. Drouhin[1,2] T. Eberl[14] T. van Eeden[16] D. van Eijk[16] N. El Khayati[10] A. Enzenhöfer[6] M. Fasano[20,21] P. Fermani[20,21] G. Ferrara[13] F. Filippini[11,12] L. Fusco[26] S. Gagliardini[20,21] J. García[5] P. Gay[27,7] N. Geißelbrecht[14] H. Glotin[28] R. Gozzini[3] R. Gracia Ruiz[14] K. Graf[14] C. Guidi[19,29] L. Haegel[7] S. Hallmann[14] H. van Haren[30] A.J. Heijboer[16] Y. Hello[31] J.J. Hernández-Rey[3] J. Hößl[14] J. Hofestädt[14] F. Huang[6] G. Illuminati[11,12] C. W. James[32] B. Jisse-Jung[16] M. de Jong[16,33] P. de Jong[16,18] M. Kadler[34] O. Kalekin[14] U. Katz[14] A. Kouchner[7] I. Kreykenbohm[35] V. Kulikovskiy[19] R. Lahmann[14] M. Lamoureux[7] D. Lefèvre[36] E. Leonora[37] G. Levi[11,12] S. Le Stum[6] D. Lopez-Coto[38] S. Loucatos[39,7] L. Maderer[7] J. Manczak[3] M. Marcelin[8] A. Margiotta[11,12] A. Marinelli[40] J.A. Martínez-Mora[5] K. Melis[16,18] P. Migliozzi[40] A. Moussa[15] R. Muller[16] L. Nauta[16] S. Navas[38] E. Nezri[8] B. Ó Fearraigh[16] A. Păun[17] G.E. Păvălaş[17] C. Pellegrino[11,41,42] M. Perrin-Terrin[6] V. Pestel[16] P. Piattelli[13] C. Pieterse[3] C. Poirè[5] V. Popa[17] T. Pradier[1] N. Randazzo[37] D. Real[3] S. Reck[14] G. Riccobene[13] A. Romanov[19,29] A. Saina[3] A. Sánchez-Losa[3,23] F. Salesa Greus[3] D. F. E. Samtleben[16,33] M. Sanguineti[19,29] P. Sapienza[13] J. Schnabel[14] J. Schumann[14] F. Schüssler[39] J. Seneca[16] M. Spurio[11,12] Th. Stolarczyk[39] M. Taiuti[19,29] Y. Tayalati[10] S.J. Tingay[32] B. Vallage[29,7] V. Van Elewyck[7,43] F. Versari[11,12,7] S. Viola[13] D. Vivolo[40,44] J. Wilms[35] S. Zavatarelli[19] A. Zegarelli[20,21] J.D. Zornoza[3] J. Zúñiga[3]

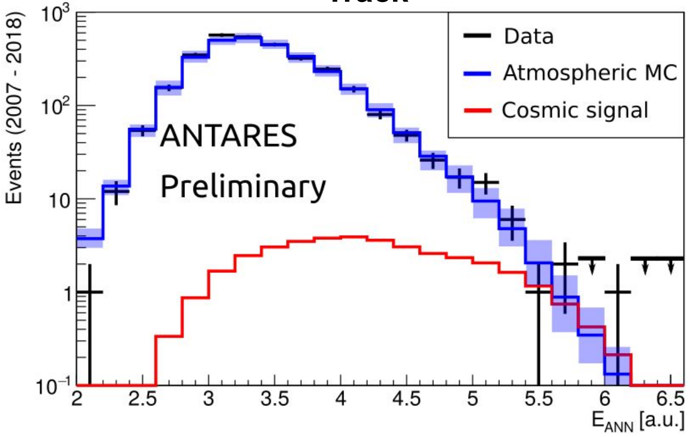
Legacy paper accepted for publication in JCAP

Results

Cosmic Diffuse Emission

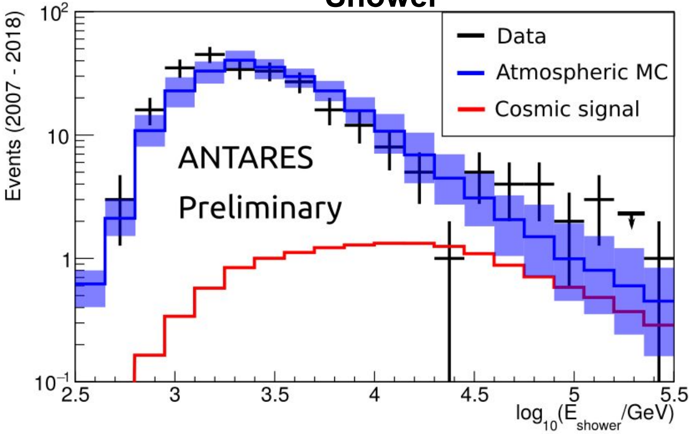
- High-energy cosmic neutrinos were confirmed by the IceCube collaboration in 2013.
- ANTARES has observed a mild 1.8 σ excess with data from 2007-2018 (3330 days).
- 50 events (27 tracks & 23 showers) observed while 36.1 ± 8.7 (19.9 tracks & 16.2 showers) expected from background.
- The last ~4 years of data will be added soon with analysis improvements (e.g. new shower selection, improved energy estimation).

Track

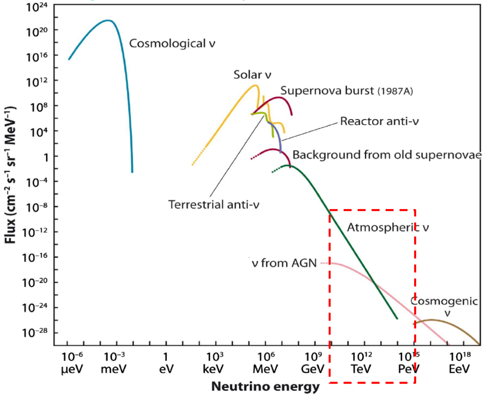


PoS ICRC2021 (891)

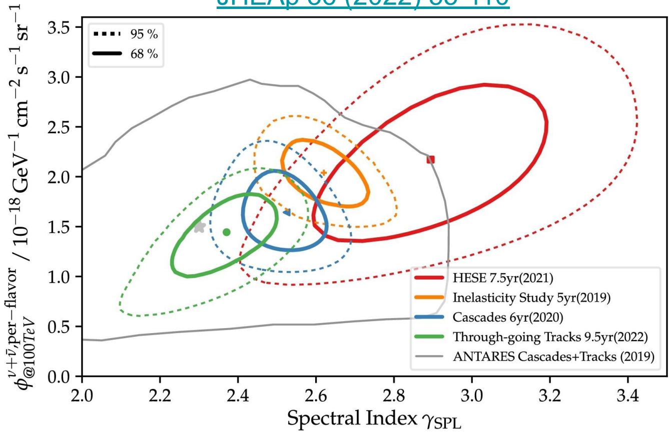
Shower



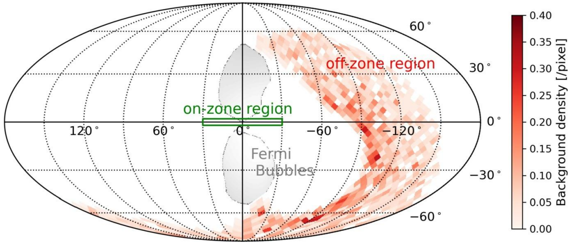
Prog.Part.Nucl.Phys. 67 (2012) 651-704



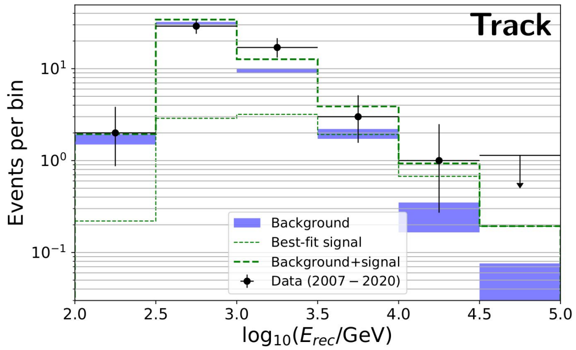
JHEAp 36 (2022) 55-110

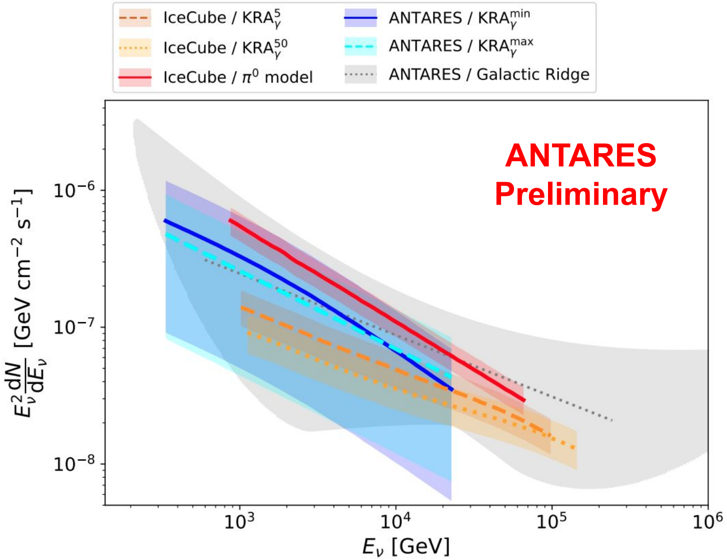


Galactic Diffuse Emission

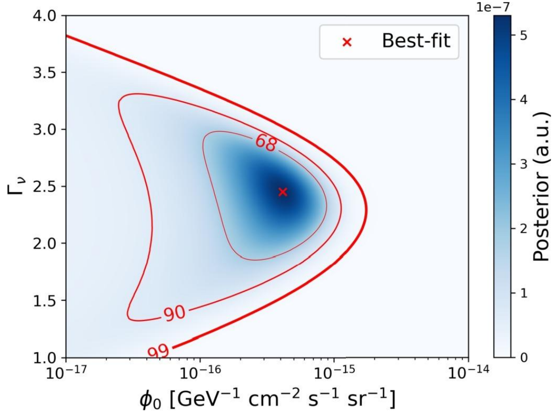


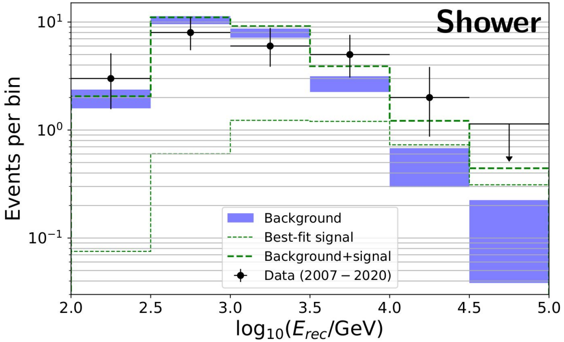
- A Galactic component contributing to the cosmic neutrino diffuse flux was announced this year by ANTARES (~2 σ) and IceCube (~4.5 σ).
- ANTARES ON/OFF analysis at E>1 TeV detects 21 (13) track (shower) events while 11.7 ± 0.6 (11.2 ± 0.9) track (shower) events are expected, 2.2 (0.2) σ excess.
- ANTARES template analysis using the most recent KRAγ models shows a 1.5-1.8 σ excess.





Phys.Lett.B 841 (2023) 137951 &
PoS ICRC 2023 (1084)

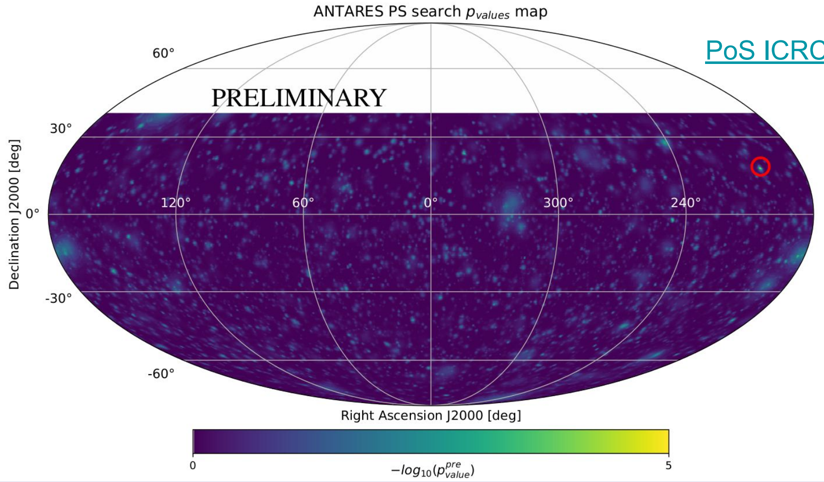




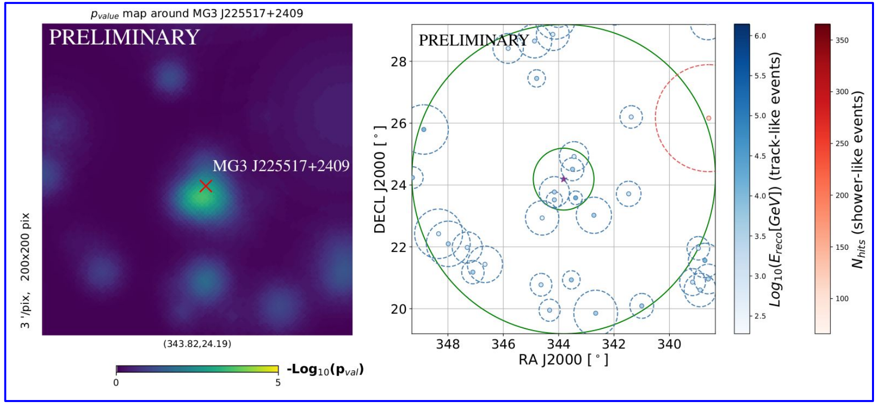
Search for Neutrino Sources

- Several types of searches performed: time-dependent, time-integrated, all-sky search, candidate list search, catalog-stacked, etc.
- In an **all-sky time-integrated** search the **most significant spot**, (RA, dec) = (200.5, 17.7)°, has a pre(post)-trial significance of 4.0(1.2) σ, with **no evident association** (closest source is 1° away).
- A list of 163 candidate sources was tested to reduce the trial factor. No significant excess observed but some sources show **interesting upper fluctuations**.
- Best candidates are **MG3 J225517+2409** and 3C403 with 3.4(1.7) σ pre(post)-trial significance.

Source	n_signal	pre-trial sign (σ)
MG3 J225517+2409	**4.4**	**3.4**
3C 403	3.2	3.4
J0242+1101	4.4	2.6
J2136+0041	2.8	2.4
TXS 0506+056	**2.5**	**2.4**
J0609-1542	1.2	2.3
PKS 1741-038	2.7	2.0
Galactic Center	2.0	2.0



PoS ICRC 2023 (1128)

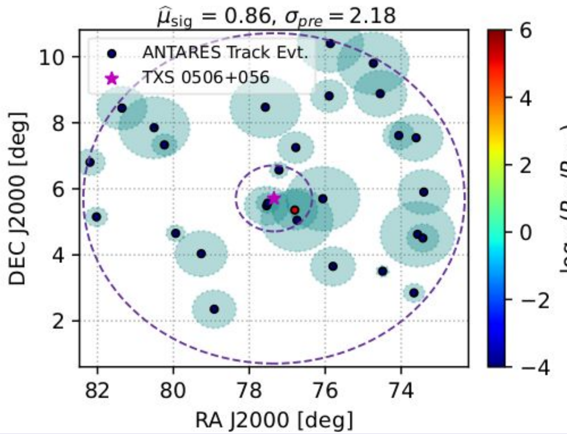


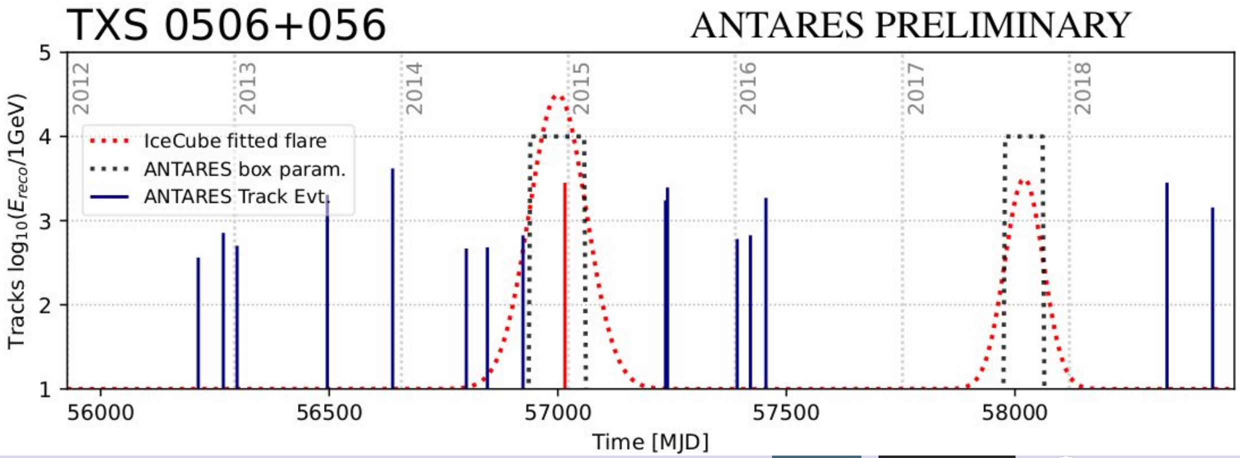
Time-dependent Source Searches

PoS ICRC 2023 (1480)

- Search for neutrinos using the temporal information from external observatories (triggered).
- Tested potential neutrino flares by IceCube [ApJL 920 L45 (2021)] with ANTARES data.
- Out of 36 sources, 4 have fitted signal (~2 σ upper-fluctuations).
- TXS 0506 has **1 event compatible** with the “**orphan” neutrino flare** (2014-2015).
  Overall significance comparable to time-integrated search, with 3 times less signal.
- Searches based on EM observatories ongoing.

Source	n_signal	pre-trial sign (σ)
NGC 598	0.86	2.2
TXS 0506+056	**0.86**	**2.2**
PKS 1502+106	1.31	2.1
B3 0609+413	0.40	1.7

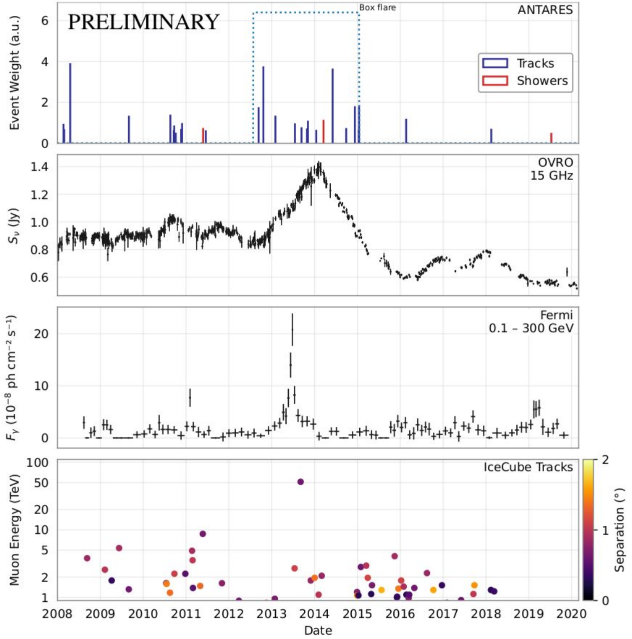


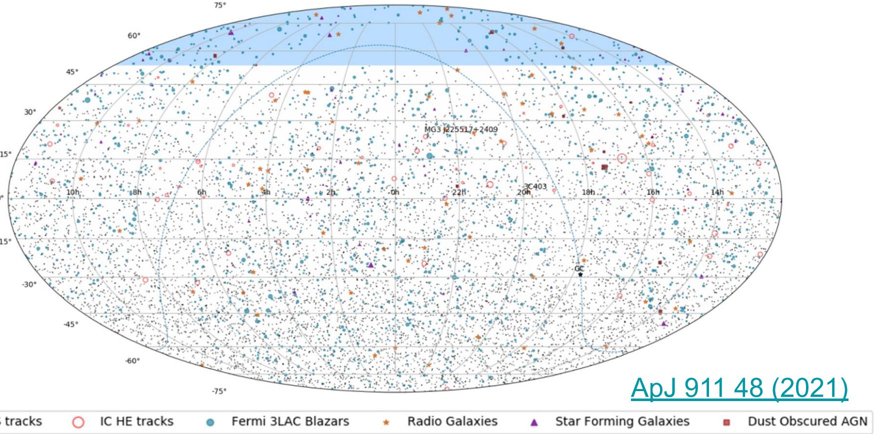


Catalog-based Searches

- Different catalogs tested with 11 yr ANTARES data. Radio Galaxies the most significant with a pre(post)-trial 2.8 (1.6) σ excess ApJ 911 48 (2021).
- **New analysis:** updated radio-bright (VLBI) blazars catalog +2 yr data. Counting analysis and likelihood analysis consistent showing a 2.2 σ excess.
- Additional search for **neutrino flares** (untriggered) show **18 sources** (out of 2744 tested) with pre-trial significance **>3 σ pre-trial. Background probability 1.4%** (2.5 σ).
- Both time-integrated and time-dependent analyses hint that some blazars might emit neutrinos.
- Interesting case of **J0242+1101**, showing temporal coincidence with gamma and radio flares and also coincident with a high-energy IceCube track. **Chance** coincidence **probability 0.5%** (caveat: coincidence **found a posteriori**, assumptions made in this estimation).

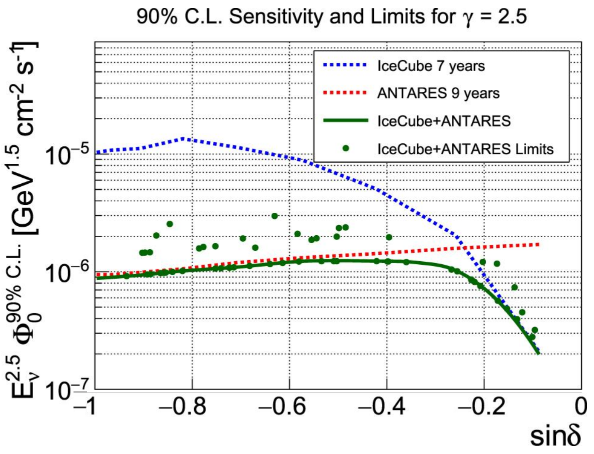
PoS ICRC 2023 (1567)





ApJ 911 48 (2021)

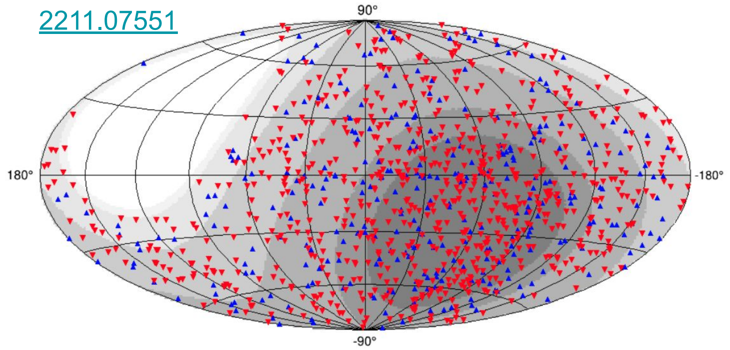
ApJ 892 92 (2020)

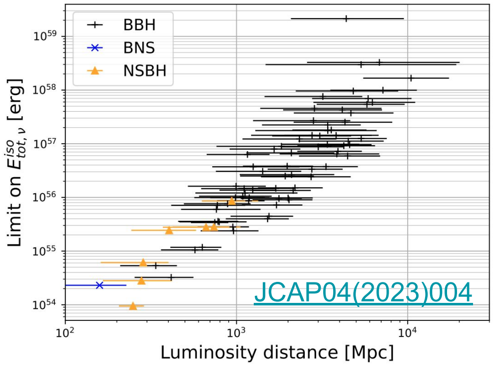


Other Astrophysics Analyses

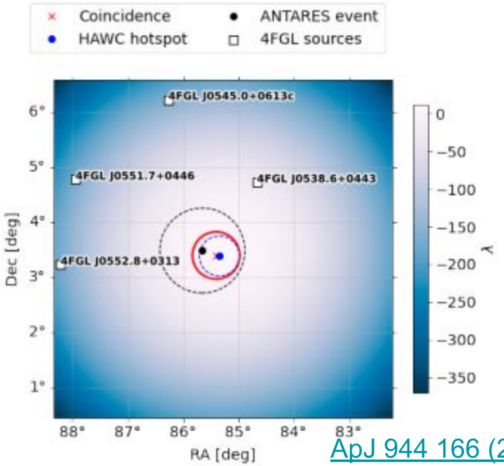
- ANTARES has a rich **multi-messenger program** with **MoUs** with different observatories.
- Combined analyses with IceCube (Southern sky): searches for sources, Galactic diffuse emission, dark matter, gravitational waves, etc.
- Multi-messenger searches with HAWC through AMON [ApJ 944 166 (2023)].
- Correlations of neutrinos (ANTARES & IceCube) with UHE Cosmic Rays (Auger & Telescope Array) [ApJ 934 164 (2022)].
- Search for neutrinos from transients (offline): GWs [JCAP04(2023)004], GRBs [JCAP03(2021)092].
- Legacy of all the ANTARES **follow-up online searches** (alerts & transients): 2211.07551

2211.07551





JCAP04(2023)004



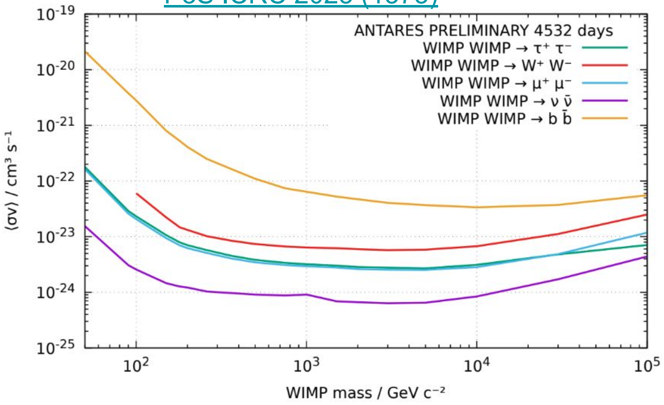
ApJ 944 166 (2023)

Full list of publications (>100):
https://antares.in2p3.fr/publications/

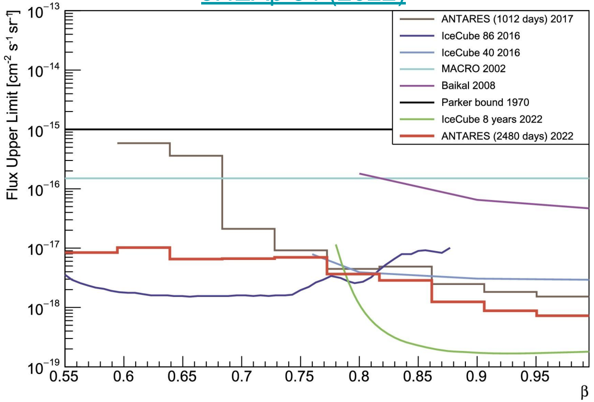
Other Analyses & Publications

- Dark Matter searches: JCAP06(2022)028 (from Gal. Cen.), PoS ICRC 2023 (1406) (from Sun), Phys Dark Universe 16, 41 (2017) (from Earth).
- Exotics: Limits on the nuclearite flux [JCAP01(2023)012], search for magnetic monopoles [JHEAp 34 (2022)]
- Cosmic-Ray Physics: Measurement of the atmospheric ν_e and ν_μ energy spectra with the ANTARES [Phys.Lett.B 816 (2021) 136228], Shadow of the Moon [Eur.Phys.J.C 78 (2018) 12, 1006] and Sun [Phys. Rev. D 102, 122007 (2020)], solar atmospheric neutrinos [JCAP06(2022)018].
- Neutrino physics: Neutrino oscillations [JHEP 06 (2019) 113], Non-standard Interactions [JHEP 07 (2022) 048] [**tomorrow by A. Lazo** (link)].
- Several technical papers and not only Physics! Multi-disciplinary facility, e.g. "Sperm whale long-range echolocation sounds revealed by ANTARES, a deep-sea neutrino telescope" [Sci Rep . 2017 Apr 12;7:45517].

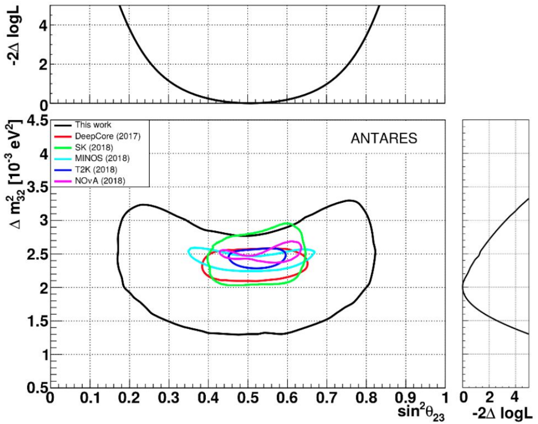
PoS ICRC 2023 (1375)



JHEAp 34 (2022)

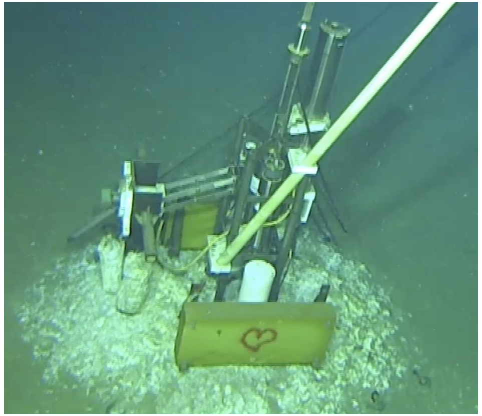


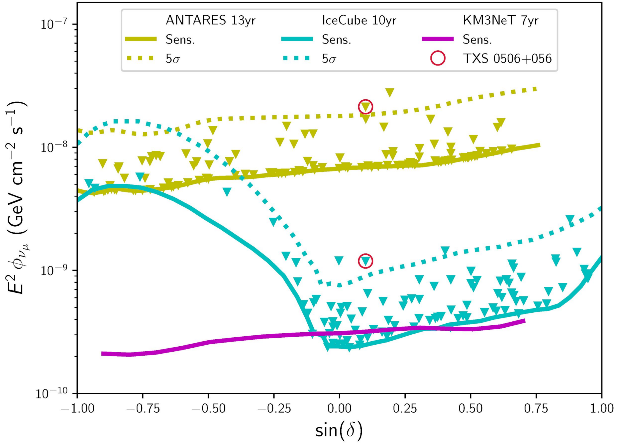
JHEP 06 (2019) 113

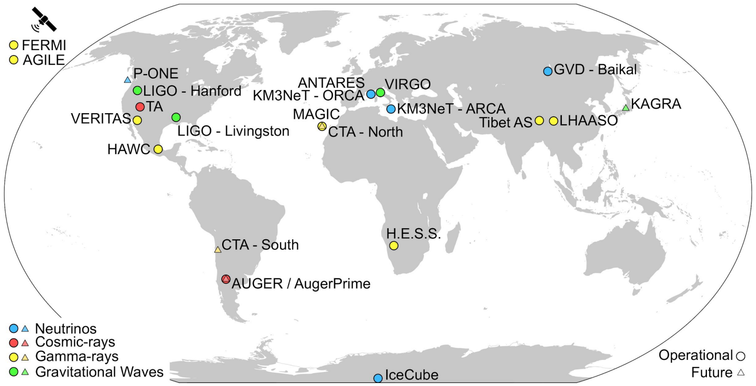


What did we learn?

- **Feasibility & reliability** of operating a neutrino telescope **underwater** (ANTARES operated for +15 years!)
- ANTARES was relatively small, although relevant results were produced including **hints compatible with the IceCube discoveries** (cosmic & Galactic diffuse flux, TXS 0506).
- We need **more neutrino telescopes**: complete sky coverage, trial factor reduction, cross-checks.
- Cooperation with other observatories, **multi-messenger astronomy**, is key.

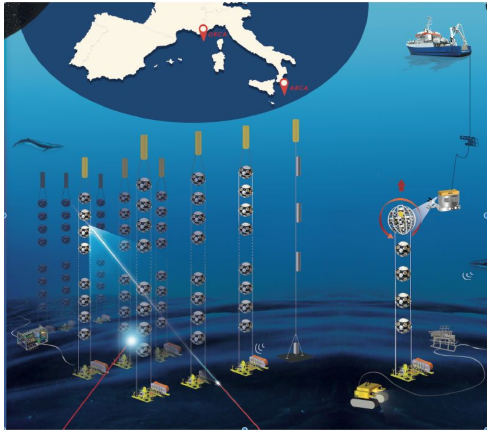


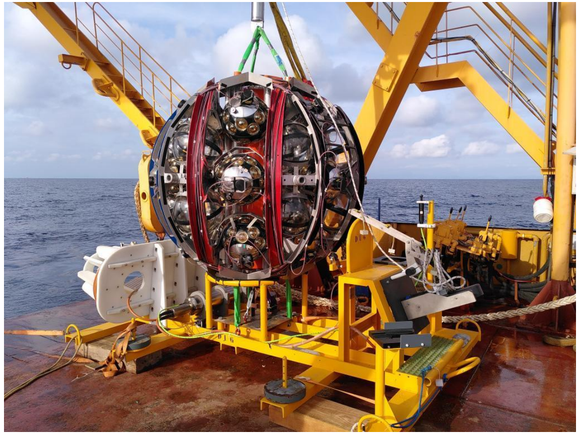


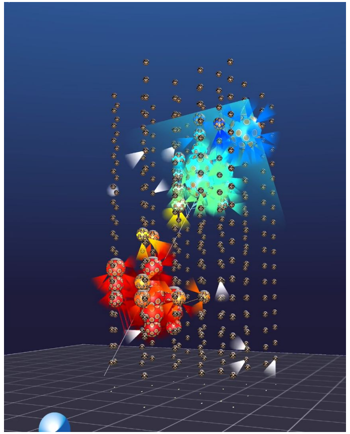


What is next?

- ANTARES **legacy papers** are being produced, expected to be published by 2024.
- The next generation neutrino telescope **KM3NeT** is already taking data with a partial configuration whose **size already exceeds** that of **ANTARES**. Overview **tomorrow by R. Gozzini** [link].
- KM3NeT has an **improved design**, with two detectors (ARCA & ORCA) sensitive from MeV to PeV energies.
- Expected to become fully operational by 2028, KM3NeT will be a **discovery instrument.**



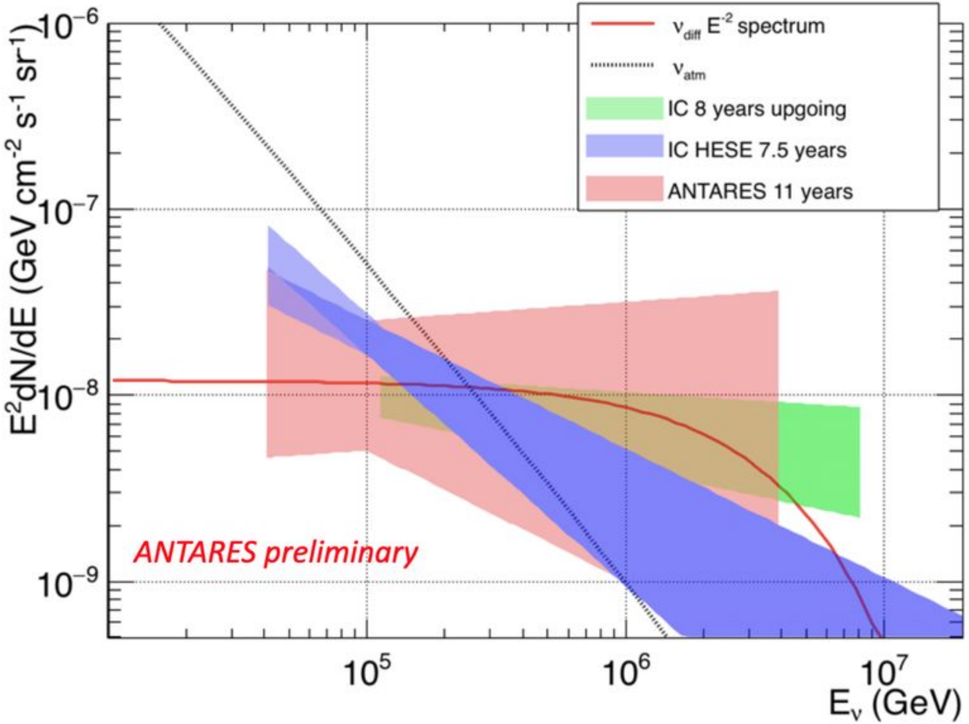




Thanks for your attention!

Backup slides

Diffuse flux



MG3 J225517+2409

https://www.astronomerstelegram.org/?read=13202

Spectroscopic lower limit to the redshift (z>0.863) of the BL Lac object 4FGL J2255.1+2411, a possible neutrino source

ATel #13202; *Simona Paiano (Universita' dell'Insubria, INAF-OAPD), Paolo Padovani (ESO), Renato Falomo (INAF-OAPD), Paolo Giommi (ASI), Riccardo Scarpa (IAC, Universidad de la Laguna), Aldo Treves (Universita' dell'Insubria, INAF-OABrera)*

on ***19 Oct 2019; 09:41 UT***

Credential Certification: Simona Paiano (simona.paiano@inaf.it)

Subjects: Optical, Gamma Ray, Neutrinos, Blazar

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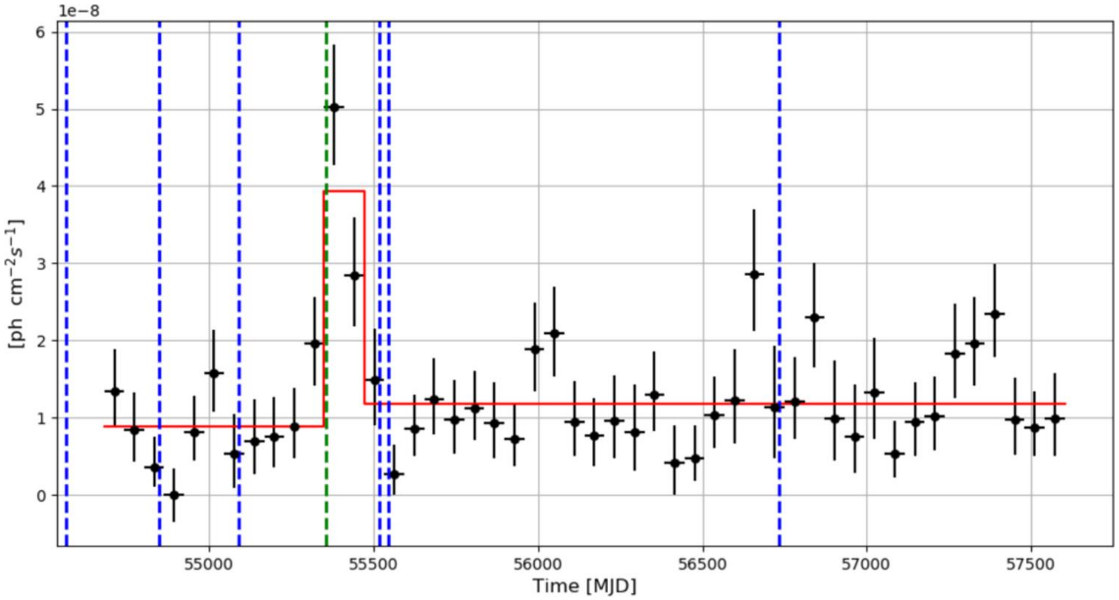
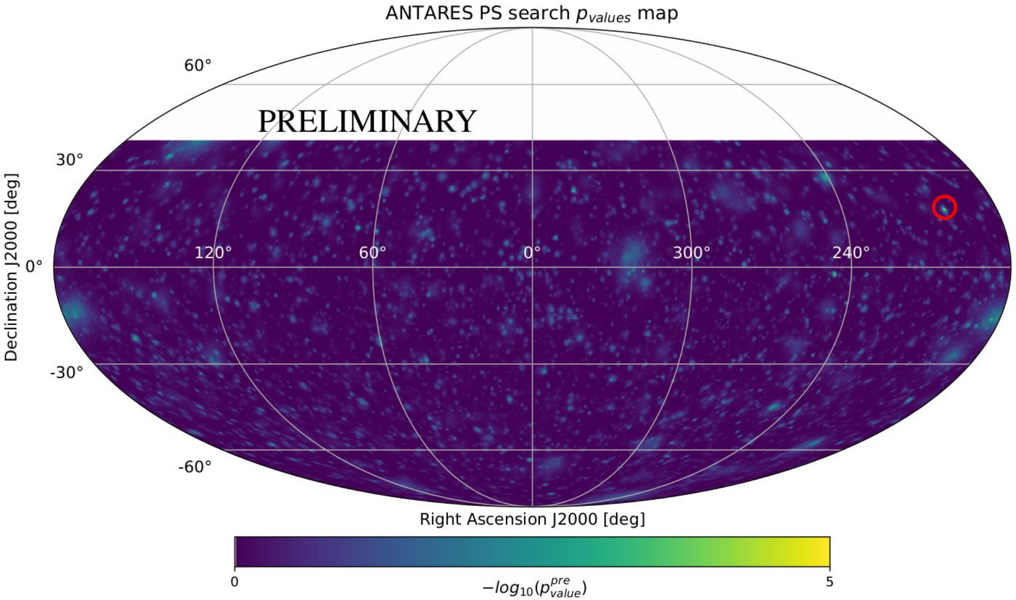
The most significant possible neutrino source found by the ANTARES collaboration is the BL Lac object MG3J225517+2409 associated to the gamma-ray source 4FGLJ2255.1+2411, and also associated with an IceCube high-energy track (Antares collaboration, 2019ICRC,36,840A). A SDSS spectrum obtained in 2013 is dominated by a non thermal continuum with no significant features. The redshift is therefore unknown. In October 2019, we obtained optical spectroscopy of the object (g = 17.5, r = 17.1) in the 4100-7700 Ang band at the 10.4m GTC+OSIRIS. The spectrum has a S/N ~ 500 and shows the continuum typical of a BL Lac objects and it is available in the database ZBLLAC http://archive.oapd.inaf.it/zbllac/. We found an absorption doublet identified as MgII 2800 intervening system (the two features are at 5209.8 Ang, EW = 0.37 Ang and at 5223.1 Ang, EW = 0.25 Ang). We searched for possible intrinsic emission lines (e.g. MgII 2800 and CIV 1540) of the source . No lines are found with an upper limit of EW > 0.1 Ang. We conclude that the source is at z >= 0.8633. At this redshift limit, the absolute magnitude M(UV) < -26.5, and the gamma-ray luminosity L(100MeV-100GeV)> 4x10^46 erg s-1. From our high quality spectrum, we estimated an emission line luminosity upper limit of 1.5x10^41 erg s-1. These values are close to the ones reported for the neutrino source TX0506+056.

ApJ 911 48 (2021)

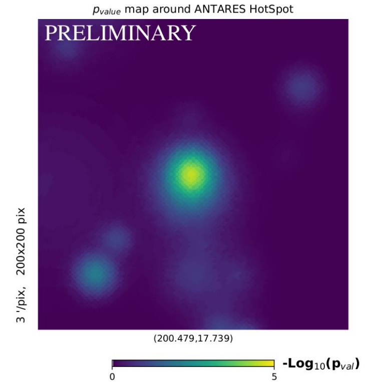


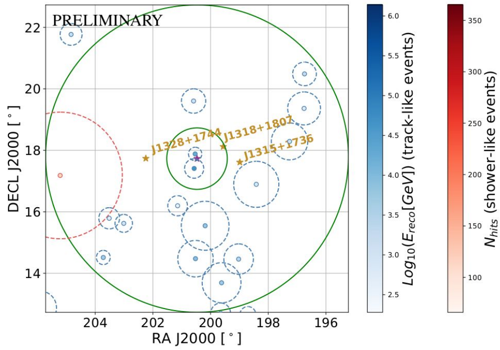
Search for Neutrino Sources

- Several types of searches performed: time-dependent, time-integrated, all-sky search, candidate list search, catalog-stacked, etc.
- In the **all-sky search** we divided the sky in a grid with 0.11° spacing between pixel centres (HEALPix, Nside=512).
- The **most significant spot**, (RA, dec) = (200.5, 17.7)°, has a pre(post)-trial significance of 4.0 (1.2) σ, with **no evident association** as the nearest source (J1318+1807) is 1° away.



PoS ICRC 2023 (1128)

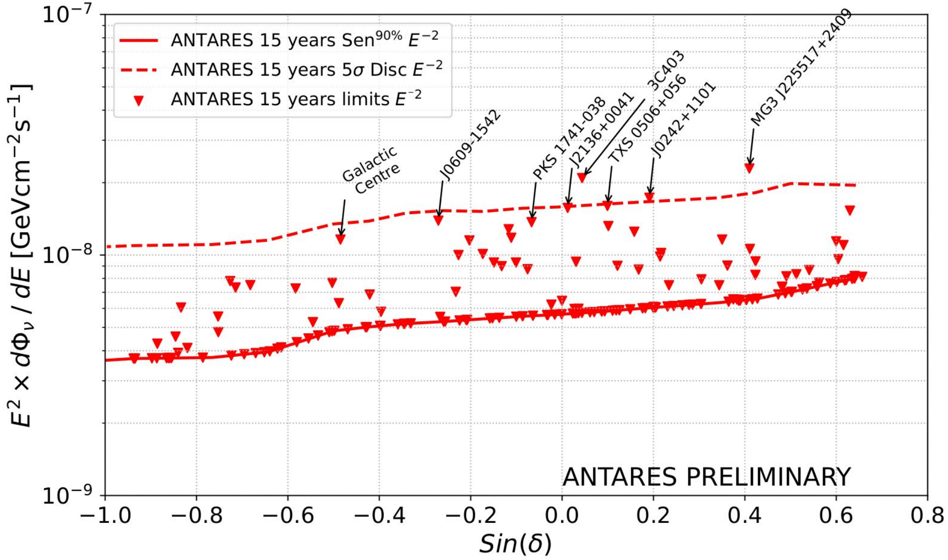




Candidate Sources Search

- To reduce the search trials of the all-sky search, a list of 163 candidate sources was tested.
- No significant excess observed but some sources show **interesting upper fluctuations**.
- Best candidates are MG3 J225517+2409 and 3C403 (radio-blazars) with 3.4(1.7) σ pre(post)-trial significance.

Source	n_signal	pre-trial sign (σ)
MG3 J225517+2409	**4.4**	**3.4**
3C403	**3.2**	**3.4**
J0242+1101	4.4	2.6
J2136+0041	2.8	2.4
TXS 0506+056	**2.5**	**2.4**
J0609-1542	1.2	2.3
PKS 1741-038	2.7	2.0
Galactic Center	2.0	2.0



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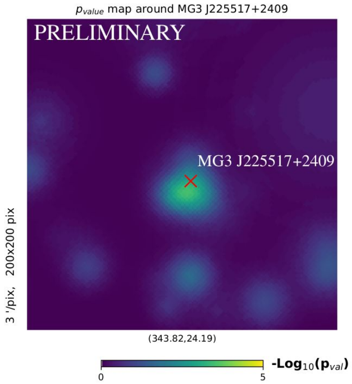
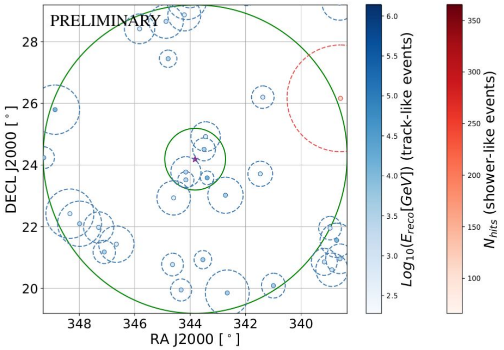
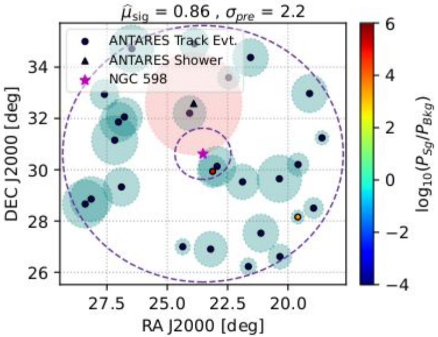
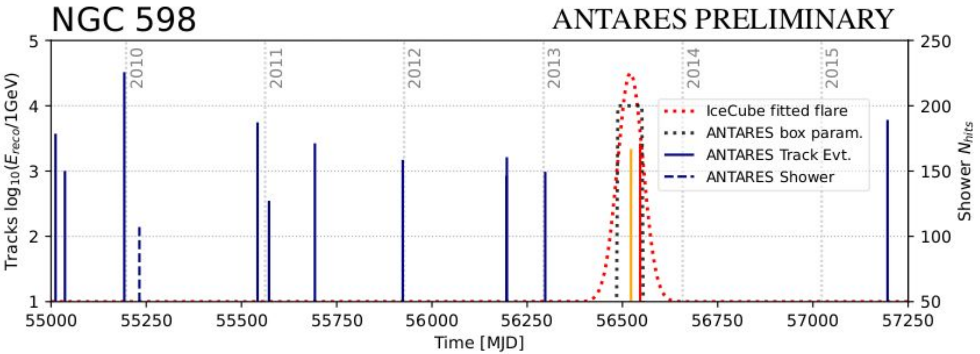
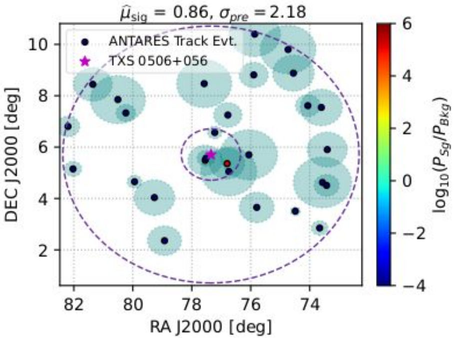


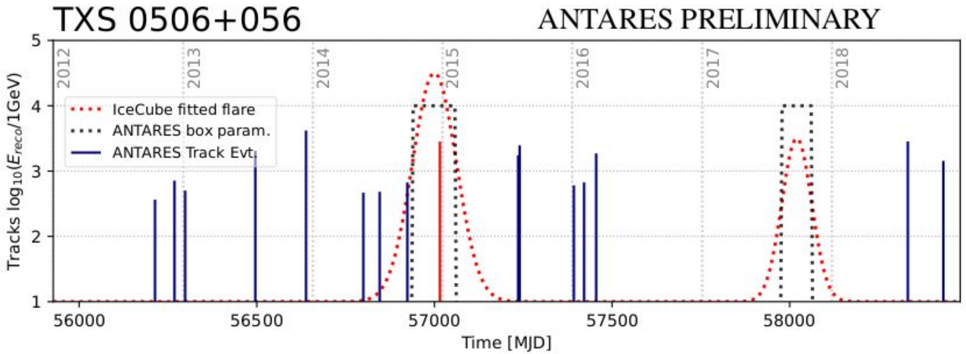


Time dependent (triggered) search

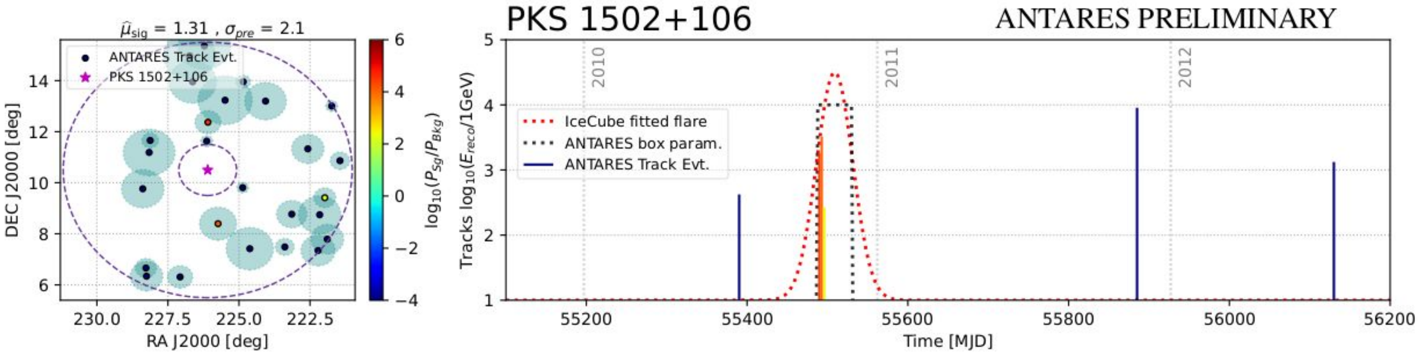


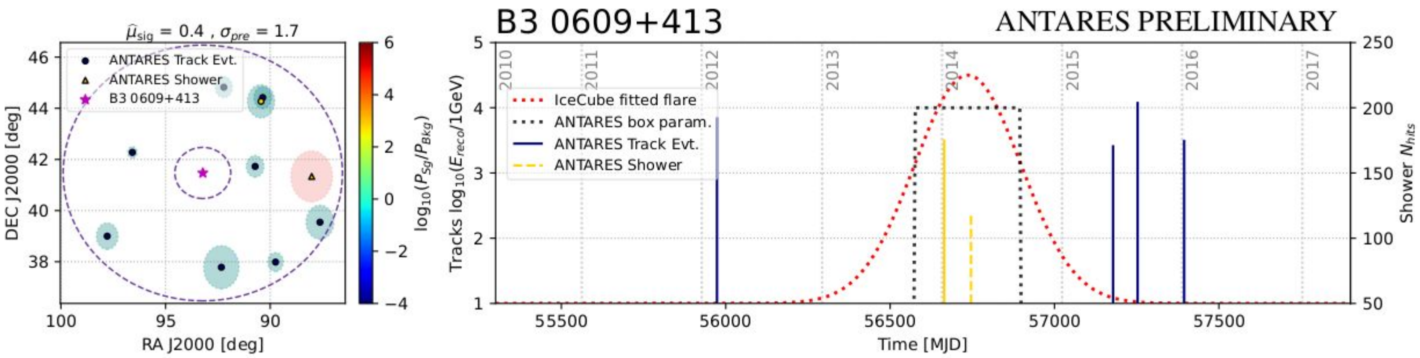






Time dependent (triggered) search





Radio-blazar flares

Source			Results									
Name	δ	α	Gaussian-shaped time profile					box-shaped time profile				
	[deg]	[deg]	$\hat{T}_0$ [MJD]	$\hat{\sigma}_t$ [days]	$\hat{\mu}_s$	$\hat{\gamma}$	p-value	$\hat{T}_0$ [MJD]	$\hat{\sigma}_t$ [days]	$\hat{\mu}_s$	$\hat{\gamma}$	p-value
J0112-6634	-66.6	18.1	58215	304	4.5	2.7	0.0026	58154	305	3.8	2.7	0.0097
J1355-6326	**-63.4**	**208.9**	**56524**	**1041**	**7.9**	**2.8**	**0.00018**	56091	905	6.0	2.9	0.0048
J0359-6154	-61.9	59.7	56316	78	5.4	3.5	0.0022	56321	112	5.7	3.5	0.0013
J0522-6107	-61.1	80.6	56221	42	4.6	3.4	0.0034	56232	59	4.9	3.4	0.0023
J1220-5604	-56.1	185.1	58406	18	2.8	2.6	0.00029	58413	22	0.4	2.2	0.0032
J1825-5230	-52.5	276.3	57265	600	5.4	2.7	0.0031	57188	959	5.5	2.7	0.0027
J0641-3554	-35.9	100.3	58084	16	2.9	3.0	0.0021	58081	19	3.0	3.0	0.0018
J1418-3509	-35.2	214.7	58120	11	3.3	2.9	0.0018	58121	14	2.9	2.8	0.0021
J1500-2358	-24.0	225.2	55846	4	3.7	2.3	0.0016	55847	6	3.7	2.2	0.0015
J0521-1737	-17.6	80.3	57332	1	2.0	1.9	0.0011	57333	1	2.0	1.9	0.0023
J2345-1555	-15.9	356.3	57653	460	3.2	2.6	0.0011	57784	404	2.4	2.7	0.0030
J1537-1259	-13.0	234.3	58201	46	2.6	2.0	0.0019	58201	55	2.7	2.0	0.0016
J0933-0819	-8.3	143.3	57411	533	3.1	2.0	0.0014	57128	697	2.9	2.0	0.0017
J0732+0150	1.8	113.1	55794	82	5.0	3.5	0.0010	55854	61	2.7	3.4	0.033
J0242+1101	11.0	40.6	56676	311	5.4	2.2	0.0060	56586	451	6.6	2.6	0.0021
J1826+1831	**18.5**	**276.6**	57672	151	2.9	2.5	0.0015	**57636**	**178**	**3.0**	**2.5**	**0.0010**
J1606+2717	27.3	241.7	58793	1	1.0	1.0	0.00076	58793	1	1.0	1.0	0.0017
J1800+3848	38.8	270.1	56590	3	1.7	2.4	0.0024	56590	3	1.9	2.6	0.0021

Targeted sources list

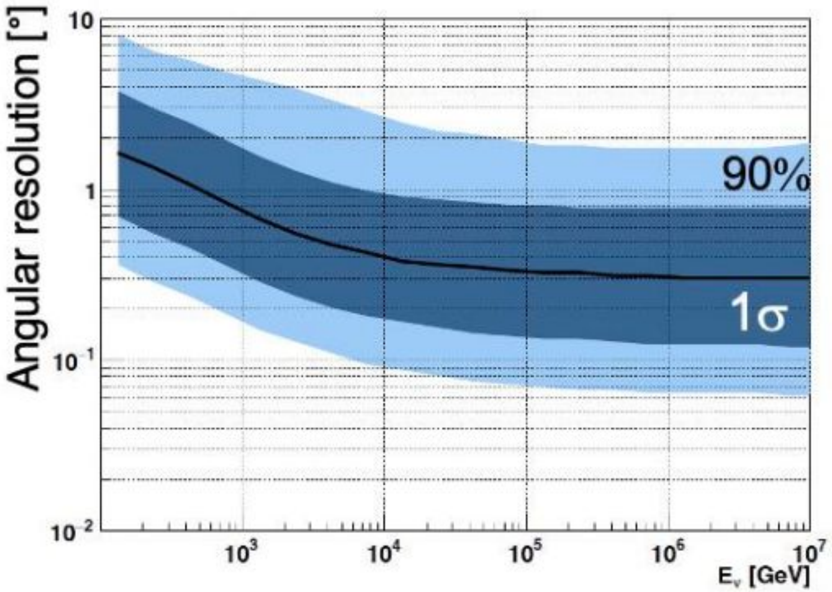
Name	$\delta[°]$	$\alpha[°]$	$\hat{\mu}_{sig}$	p-value	$\Phi_0^{90\%C.L.}$
LMCN N132D	-69.5	81.2	–	–	0.37
LHA 120-N-157B	-69.16	84.43	–	–	0.37
PSRB1259-63	-63.83	195.70	–	–	0.37
RCW86	-62.48	220.68	–	–	0.37
HESS J1507-622	-62.34	226.72	–	–	0.43
ESO 139-G12	-59.94	264.41	–	–	0.37
SNR G318.2+00.1	-59.46	224.42	–	–	0.37
MSH 15-52	-59.16	228.53	–	–	0.37
HESS J1503-582	-58.74	226.46	–	–	0.37
HESS J1023-575	-57.76	155.83	–	–	0.46
CirX-1	-57.17	230.17	–	–	0.37
$IC_{hotspot}$ South	-56.5	350.2	0.4	0.19	0.61
SNR G327.1-01.1	-55.08	238.65	–	–	0.41
HESSJ1614-518	-51.82	243.58	–	–	0.37
PKS 2005-489	-48.82	302.37	0.25	0.25	0.55
GX339-4	-48.79	255.70	–	–	0.48
HESS J1641-463	-46.30	250.26	2.26	0.067	0.78
RX J0852.0-4622	-46.37	133.00	–	–	0.38
Vela X	-45.60	128.75	1.9	0.094	0.73
PKS0537-441	-44.08	84.71	–	–	0.39
CentaurusA	-43.02	201.36	1.05	0.085	0.75
PKS1424-418	-42.10	216.98	–	–	0.38
1ES2322-409	-40.66	351.20	–	–	0.38
RXJ1713.7-3946	-39.75	258.25	–	–	0.40
CTB 37A	-38.52	258.56	–	–	0.40
PKS0426-380	-37.93	67.17	–	–	0.40

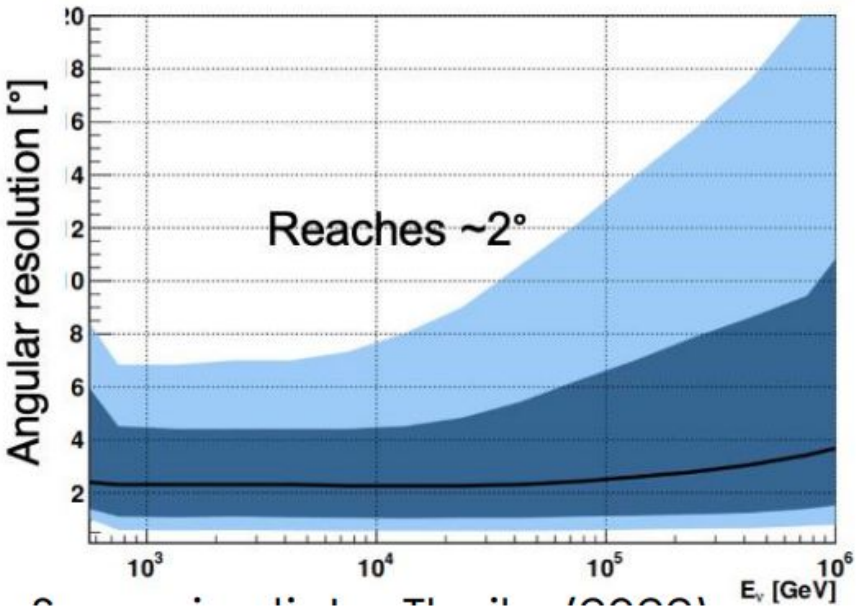
Name	$\delta[°]$	$\alpha[°]$	$\hat{\mu}_{sig}$	p-value	$\Phi_0^{90\%C.L.}$
RGBJ0152+017	1.79	28.17	–	–	0.57
J1229+0203	2.05	187.5	–	–	0.60
HESS J1858+020	2.06	284.57	–	–	0.57
3C403	**2.51**	**298.07**	**3.21**	**0.000337**	**2.09**
1LHAASO J1858+0330	3.51	284.59	–	–	0.57
CGCG 420-015	4.03	73.38	–	–	0.58
SS433	4.98	287.96	–	–	0.58
J0433+0521	5.35	68.30	–	–	0.58
TXS 0506+056	**5.7**	**77.35**	**2.5**	**0.0083**	**1.6**
HESS J0632+057	5.81	98.24	1.66	0.036	1.32
LHAASO J1908+0621	6.35	287.05	–	–	0.58
1LHAASO J1902+0648	6.8	285.58	–	–	0.59
PKS 2145+067	6.96	327.02	0.29	0.21	0.92
B1030-074	7.19	158.39	–	–	5.9
1LHAASO J906+0712	7.2	286.56	–	–	0.59
3HWC J1914+118	8.57	286.79	–	–	0.59
W 498	9.09	287.78	1.00	0.052	1.25
OT 081	9.65	267.89	0.09	0.72	0.87
HESS J1921+101	10.15	288.21	–	–	0.6
PKS 1502+106	10.49	226.1	–	–	0.6
J0242+1101	**11.02**	**40.6**	**4.43**	**0.00526**	**1.73**
1LHAASO J1959+1129u	11.49	299.82	–	–	0.6
RBS 0723	11.56	131.8	–	–	0.61
3HWC J1914+118	11.72	288.68	–	–	0.6
J2232+1143	11.73	338.15	–	–	0.61
J0121+1149	11.83	20.42	–	–	0.61

Name	$\delta[°]$	$\alpha[°]$	$\hat{\mu}_{sig}$	p-value	$\Phi_0^{90\%C.L.}$
PKS1454-354	-35.67	224.36	1.46	0.12	0.73
PKS0625-35	-35.49	96.78	–	–	0.40
TXS1714-336	-33.70	259.40	–	–	0.40
SwiftJ1656.3-3302	-33.04	254.07	–	–	0.53
PKS0548-322	-32.27	87.67	–	–	0.40
H2356-309	-30.63	359.78	–	–	0.40
PKS2155-304	-30.22	329.72	–	–	0.40
HESSJ1741-302	-30.20	265.25	1.2	0.095	0.77
PKS1622-297	-29.90	246.50	–	–	0.48
J1924-2914	-29.24	291.21	–	–	0.63
Galactic Centre	**-29.01**	**266.43**	**2.01**	**0.024**	**1.16**
J2258-2758	-27.97	344.52	–	–	0.48
J1625-2527	-25.46	246.45	–	–	0.50
NGC 253	-25.29	11.8	–	–	0.50
Terzan5	-24.90	266.95	–	–	0.69
1ES1101-232	-23.49	165.91	–	–	0.51
J0457-2324	-23.24	270.43	–	–	0.51
W28	-23.34	270.43	–	–	0.58
J1833-210A	-21.06	278.42	–	–	0.52
J0836-2016	-20.28	129.16	–	–	0.52
J1911-2006	-20.12	287.79	–	–	0.52
eHWCJ1809-193	-19.34	272.46	–	–	0.53
J0609-1542	**-20.12**	**287.79**	**1.23**	**0.015**	**1.39**
SNR G015.4+00.1	-15.47	274.52	–	–	0.55
j2158-1501	-15.02	329.53	–	–	0.52
LS5039	-14.83	276.56	–	–	0.52
LHAASOJ1825-1326	-13.45	276.45	–	–	0.70
QSO1730-130	-13.10	263.30	1.41	0.104	1.00
J1337-1257	-12.96	204.42	–	–	0.53
J2246-1206	-12.11	241-58	–	–	0.53
1ES0347-121	-11.99	57.35	–	–	0.53
PKS0727-11	-11.70	112.58	1.52	0.051	1.15
HESSJ1828-099	-9.99	277.24	0.87	0.11	1.01
J1512-0905	-9.10	228.21	–	–	0.55
HESSJ1834-087	-8.76	278.69	–	–	0.55
J0607-0834	-8.58	-92	0.61	0.152	0.93
PKS1406-076	-7.90	212.20	–	–	0.55
QSO2022-077	-7.60	306.40	0.59	0.17	0.89
RS Ophiuchi	-6.71	267.55	1.67	0.027	1.28
J0006m0623	-6.39	1.56	1.57	0.047	1.18
3C279	-5.79	194.05	0.88	0.152	0.93
LHAASO J1839-0545	-5.75	279.95	–	–	0.55
J2225-0457	-4.95	336.45	–	–	0.56
PKS 1741-038	**-3.38**	**266**	**2.71**	**0.021**	**1.37**
LHAASO J1843-0338	-3.65	280.75	–	–	0.56
HESS J1848-018	-1.89	282.12	–	–	0.56
J0339-0416	-1.78	54.88	–	–	0.56
J0423-0120	-1.34	65.82	–	–	0.62
J0725-0054	-0.92	111.46	–	–	0.56
LHAASOJ1849-0003	-0.05	282.35	–	–	0.56
NGC1068	-0.01	40.67	–	–	0.65
J2136+0041	**0.70**	**324.16**	**2.82**	**0.0079**	**1.57**
3HWC J1852+013	1.34	283.05	–	–	0.57
J1058+0133	1.57	164.62	–	–	0.60
J0108+0135	1.58	17.16	–	–	0.57
PKS 0736+017	1.79	28.17	–	–	0.57

Name	$\delta[°]$	$\alpha[°]$	$\hat{\mu}_{sig}$	p-value	$\Phi_0^{90\%C.L.}$
J1230+1223	12.39	187.71	0.48	0.173	0.98
J0750+1231	12.52	117.72	0.91	0.151	1.02
PKS 1413+135	13.35	214.03	–	–	0.61
J0530+1331	13.53	82.74	–	–	0.75
W 51	14.14	290.75	–	–	0.61
VER J0648+152	15.27	102.2	–	–	0.62
J2253+1608	16.15	343.49	–	–	0.62
PKS 0235+164	16.17	39.66	–	–	0.62
PKS 0735+178	17.71	114.53	–	–	0.62
LHAASO J1929+1745	17.75	292.25	–	–	0.79
J0854+2006	20.11	133.70	–	–	0.75
RGB J2243+203	20.5	340.98	0.82	0.109	1.16
VER J0521+211	21.21	80.40	–	–	0.90
4C+21.35	21.38	186.23	–	–	0.64
Crab	22.01	83.63	–	–	0.65
IC 443	22.5	94.21	–	–	0.65
S20109+22	22.74	18.02	–	–	0.65
B1422+231	22.93	216.76	–	–	0.65
3HWC J1940+237	23.77	295.05	–	–	0.65
PKS 1424+240	23.8	21.76	–	–	0.65
MG3 J225517+2409	**24.19**	**343.82**	**4.39**	**0.00034**	**2.29**
3HWC J1950+242	24.26	297.69	–	–	0.66
MS1221.8+2452	24.614	186.1	–	–	0.65
PKS 1441+25	25.03	220.99	–	–	0.83
1ES0647+250	25.05	102.69	–	–	0.65
S31227+25	25.3	187.56	–	–	0.66
W Comae	28.23	185.38	–	–	0.69
LHAASO J1956+2864u	28.75	299.78	–	–	0.74
J0237+2848	28.8	39.47	–	–	0.74
TON0599	29.24	179.88	–	–	0.69
1LHAASO J1219+2915	29.25	184.98	–	–	0.69
3HWC J1951+2915	29.4	297.99	–	–	0.82
1ES1215+303	30.1	184.45	–	–	0.70
1ES1218+304	30.19	185.36	–	–	0.70
HESS J1746-308	30.84	266.57	–	–	0.83
B21811+31	31.74	273.4	–	-	0.72
J1310+3220	32.25	197.62	–	–	0.73
B21420+32	32.39	215.63	–	–	0.72
1LHAASO J2002+3244u	32.74	300.64	–	–	0.86
1LHAASO J2028+3352	33.88	307.21	–	–	0.74
3HWC J2006+340	34.0	301.73	–	–	0.74
J1613+3412	34.21	243.42	–	–	0.86
S30218+35	35.94	35.27	–	–	0.76
LHAASO J2018+3651	36.85	304.75	–	–	1.14
1LHAASO J2027+3657	36.95	306.88	–	–	0.77
J2015+3710	37.18	303.87	–	–	0.96
Milagro Diffuse	38	305	0.45	0.195	1.1
Mkn 421	38.21	166.11	–	–	0.78
B32247+381	38.43	342.53	–	–	0.78
J0927+3902	39.04	141.76	0.98	0.043	1.53
NGC 4151	39.41	182.63	–	–	0.80
Mkn 501	39.76	253.47	–	–	0.80
J1642+3948	39.81	250.75	–	–	0.82
J0555+3948	39.81	88.88	–	–	0.80
LHAASO J2032+4102	41.05	308.05	–	–	0.81

Angular Resolution (tracks & showers)

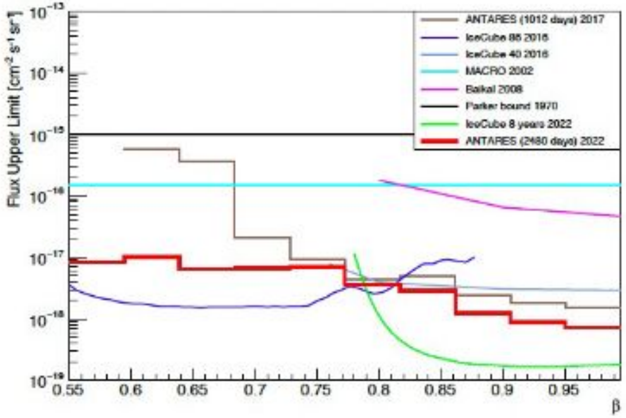




Search for Exotic Physics

Monopoles

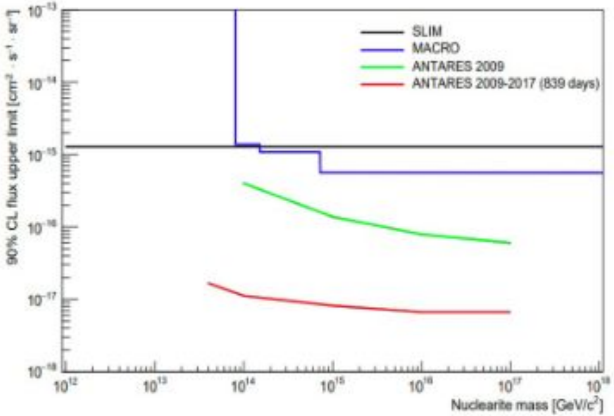
Magnetic monopoles
Kasama, Yang and Goldhaber model
Adapted reco for slow moving particles



JHEAp, Volume 34, 2022, Pages 1-8

Nuclearites

Nuclearites of strange quark matter
Down going flux with Galactic velocities according to de Rújula & Glashow model



JCAP 01 (2023) 012