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Search for an association between neutrinos and radio-selected blazars with ANTARES

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ICRC 2021, Berlin. July 12-23, 2021

Searching for sources of HE neutrinos

A lot of activity, as neutrino telescopes are gathering data:

Full sky searches

- IceCube 10yr PS sample
  (Aartsen et al. 2020) https://doi.org/10.1103/PhysRevLett.124.051103
- ANTARES 9 yr PS sample
  (Albert et al. 2017) https://doi.org/10.22323/1.358.0916

Examples of catalog-based searches

- IceCube 8yr up-going muons with 3FHL Fermi-LAT Blazars
  (IceCube ICRC 2019) https://doi.org/10.3847/1538-4357/abe53c
- IceCube HE neutrinos with γ-ray catalogs
  (Giommi et al. 2020) https://doi.org/10.1093/mnras/staa2082
- ANTARES 11 yr PS sample with Fermi 3LAC + other catalogs (Albert et al. 2021) https://doi.org/10.3847/1538-4357/abe53c

not even mentioning real-time alerts...

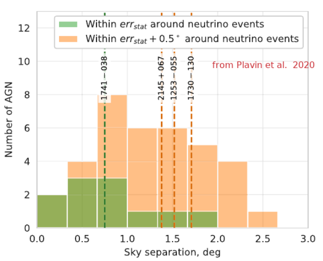
Radio Blazars

Recent evidence for Radio Blazars- IC neutrinos association

- Plavin et al. 2020 https://doi.org/10.3847/1538-4357/ab86bd
- Neutrinos: 56 IceCube tracks with E > 200 TeV (33 from EHEA + 23 from HESE, HESEA, MUONT)
- Blazars: 3388 objects selected in the 8 GHz band from VLBI observations (parsec-scale resolution of the AGN core http://astrogeo.org/rfc/

Spatial correlation study

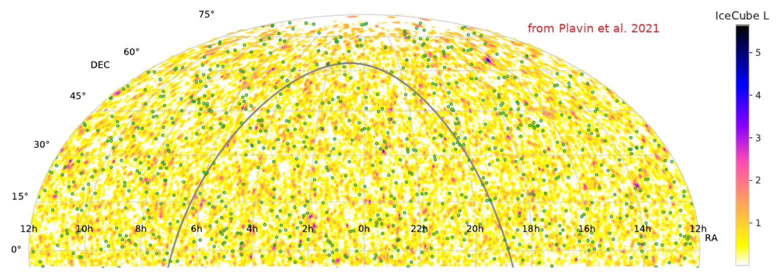
- Count the nb of pairs Blazar-Neutrino within IC angular error radius
- Best significance when adding $+0.5^{\circ}$ systematic
- Post-trial $P = 3.1\sigma$, driven by 4 bright sources



Radio Blazars

Confirmation with IC 7 yr public Point Source data

- Plavin et al. 2021 https://doi.org/10.3847/1538-4357/abceb8
- Use the IC published local p-value map (Northern sky $\delta > -5^\circ$)
- Compare the median p-value around blazars to random positions
- Highest excess for Blazars with $S_{8\,\mathrm{GHz}} > 0.33$ Jy ($3.0\,\sigma$ Post-trial)

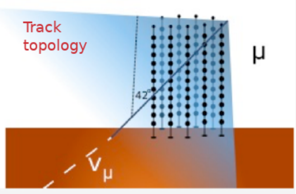


ANTARES neutrino data set

The ANTARES 13 yr Point Source Sample:

- Period: Jan 01, 2007 to Feb 28, 2020
- Livetime: 3845 days, updated calibration and reconstruction
- Track channel: 10162 events with angular uncert. $\beta < 1^\circ$
- Median angular resolution: $\sim 0.4^\circ$ above 10 TeV
- Energy range: from $\sim$ 100 GeV to $\sim$ 1PeV, resolution $\sim$ 0.3 in logE
- Field of view: $\delta \in [-90^\circ; +53^\circ]$

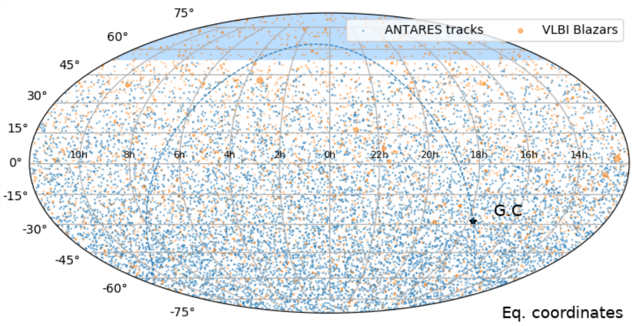
- Total nb of expected astrophysical ν: from $\sim$ 25 to $\sim$ 150 depending on the spectral index $\gamma \in [-2.; -2.5]$ and flux normalization $\Phi_{100\mathrm{TeV}} \in [1; 2]\, 10^{-18}$ GeV^{-1}.cm^{-2}.s^{-1}

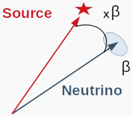


ANTARES-VLBI counting analysis

Simple counting analysis

- Count the nb of neutrino-blazar pairs at less than xβ
- Angular uncertainty estimate β is multiplied by x for possible systematics
- Scan on the values of x to search for the most significant excess





ANTARES-VLBI counting analysis

Simple counting analysis

- Count the nb of neutrino-blazar pairs at less than xβ
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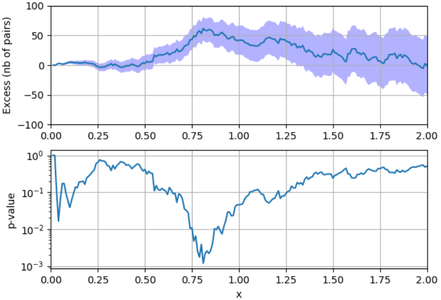
- Scan on the values of x to search for the most significant excess

Results

- Min. $p = 1.2\,10^{-3}$ ($3.2\,\sigma$) at $x = 0.81$
- Post-trial $P = 2.2\,10^{-2}$ ($2.3\,\sigma$)
- 451 pairs observed while 389 expected ($\sim$ 62 pairs in excess)



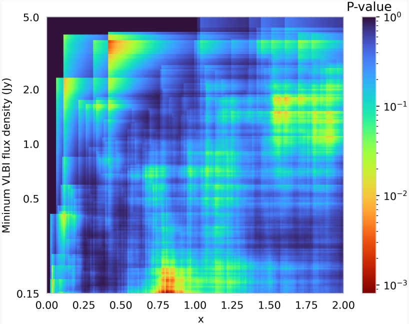
Selection in Radio Flux Density

Additional scan in radio flux density

- In Plavin et al. 2020, average flux density is higher for IC-associated blazars
- 2D Scan in ang. separation and flux density

Results

- $p \sim 1.2\,10^{-3}$ excess at $x \sim 0.8$ is observed for whole blazar sample
- Secondary minimum $p \sim 3.\,10^{-3}$ for $x \sim 0.4$ and very high flux $S_{8\mathrm{GHz}} > 3.7\mathrm{Jy}$.
- Inspect the 4 high flux blazars associations



Very high flux matches

Investigation of very high flux matches

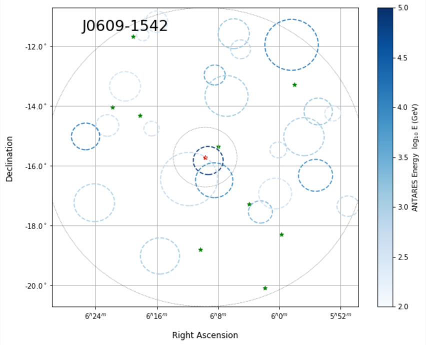
- For $S_{8GHz} > 3.7$ Jy, 4 observed pairs while 0.6 expected ($p \sim 3.10^{-3}$)
- Only ~ 20 blazars have $S_{8GHz} > 3.7$ Jy among the 3411 objects
- Angular separation for J1743-0350 is much smaller than the resolution, probability to find by chance such a close association $p \sim 0.14$.

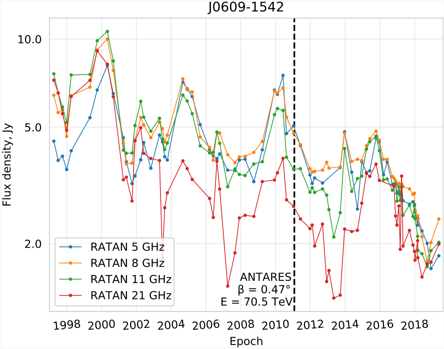
	J2000	flux_Jy	datetime	β°	separation°	energy_TeV
1	"J0609-1542"	3.76	2011-01-30T16:27:15.840	0.46936	0.1501	70.4872
2	"J0538-4405"	4.177	2011-08-09T11:21:33.120	0.92602	0.3875	45.0205
3	"J0538-4405"	4.177	2018-03-20T13:26:06.720	0.81888	0.3438	5.97943
4	"J1743-0350"	3.994	2019-03-08T21:15:41.760	0.42706	0.0475	2.32242

Interesting high flux sources (1/3)

Blazar J0609-1542

- One ANTARES event with E ~ 70 TeV (top 0.1% of E distribution)
- Arrival time close to a flaring period (but many flares...)

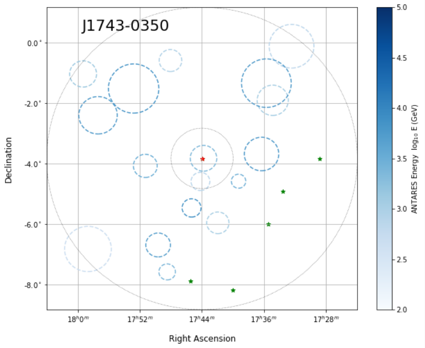


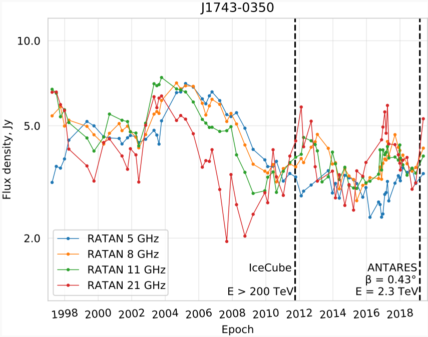


Interesting high flux sources (2/3)

Blazar J1743-0350

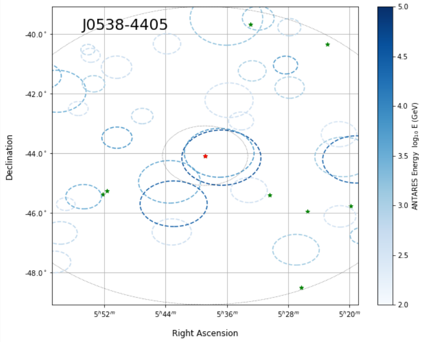
- One ANTARES event with E ∼ 2 TeV during high activity period
- Also in association with an EHEA IC event detected in Sep. 2011

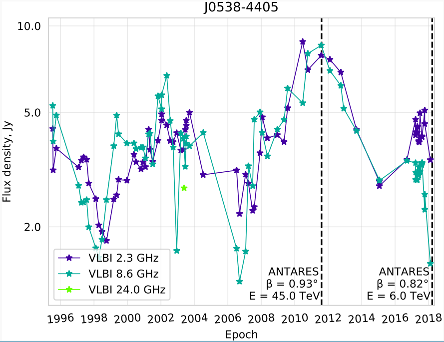




Blazar J0538-4405

- Two ANTARES event with E $\sim$ 45 and E $\sim$ 6 TeV
- Arrival times within high flux period
- However, poor reconstruction events ($\beta > 0.8$), more likely to be of atmospheric muon origin

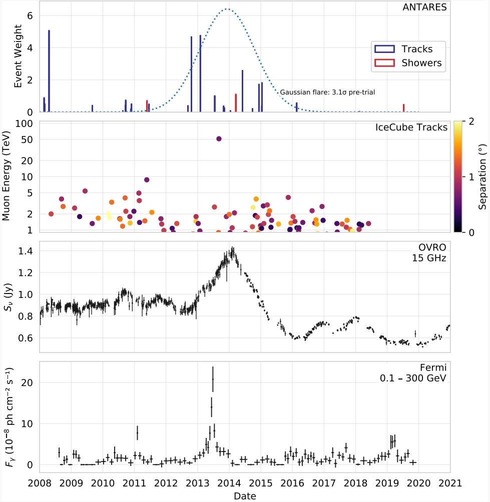




Potential radio - γ - ν association

Blazar J0242+1101

- Search for ANTARES untriggered neutrino flares using the same VLBI catalog
- Most significant source with 3.4σ pre-trial.
- Long flare in radio and few months flare in gamma-ray (Fermi)
- High energy IceCube track event also oberved in coincidence.
- See talk of G. Illuminati



Likelihood analysis

Extended maximum likelihood method:

- Similar method as in Albert et al. 2021 (see backup for details)
  https://doi.org/10.3847/1538-4357/abe53c
- Take into account the energy information in the PDFs.
- Weight sources with radio S_{8GHz} or use an equal weight.

		Equal weight			Flux weight		
Sample	Spectral index	n_s	λ	p-value	n_s	λ	p-value
Full VLBI	E^{-2}	57.	4.33	0.07	36.	3.64	0.05
	$E^{-2.25}$	112	7.26	0.08	64.	5.14	0.06
	$E^{-2.5}$	186	9.76	0.11	93	5.71	0.10
$S_{8GHz} > 3.7$ Jy	$E^{-2.}$	8	4.84	$2.3\ 10^{-3}$			
	$E^{-2.25}$	10.	5.16	$2.5\ 10^{-3}$			
	$E^{-2.5}$	11.	4.84	$4.5\ 10^{-3}$			

- Full sample: p-values are $\simeq 2.5 - 5$ higher than with the counting method, fitted n_s similar to the 62 pairs in excess found previously.
- High-flux sample: p-values are very similar to the counting results.
- A weight $\propto S_{8GHz}$ and E^{-2} spectrum give the lower p-values.

Summary & Conclusion

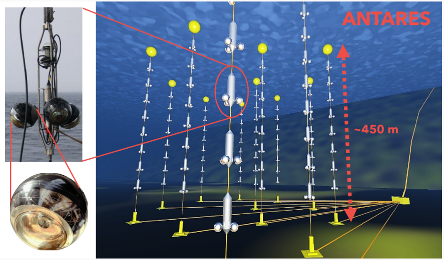
- A search for an association between radio-selected blazars and ANTARES neutrinos detected in 13 years of operation has been performed.
- Indication of a collective excess of neutrino-blazar pairs with the ANTARES 13yr PS sample with the counting method, with a $2.3\,\sigma$ post-trial p-value.
- A complementary likelihood analysis gives p-values $\in [1.6 - 2.0]\,\sigma$ for the full blazar sample.
- Possible associations with a few high flux blazars, with neutrino arrival times during intense radio activity have been shown.
- Work in progress to better understand this potential signal, and provide an estimation of the p-value of the neutrino-radio association.

BackUp

The ANTARES detector:

- Water Cherenkov detector operating since 2007
- Located 40 km offshore Toulon, France
- 2475 m depth in the Mediterranean sea

- Array of 885 PMT
- 12 detection lines, each with 25 storeys
- 3 PMT (10“) per storey, facing 45° downwards



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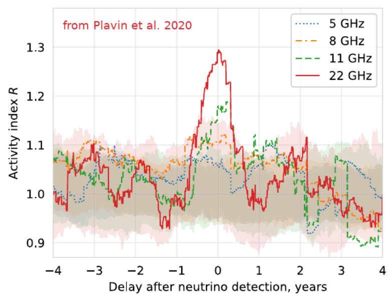
Time correlation study

- Use RATAN-600 AGN monitoring data 2009-2019
- Higher radio activity observed @11 GHz and 22 GHz for ~ months around neutrino detection



Test statistic

Define the test statistic $\lambda = \ln\left(\frac{\max(\mathcal{L}(H_1))}{\max(\mathcal{L}(H_0))}\right)$ with

$$\ln\mathcal{L}(H_0) = \sum_i^N \ln\left(\mu_b B_i\right) - \mu_b$$

$$\ln\mathcal{L}(H_1) = \sum_i^N \ln\left(\mu_s S_i + \mu_b B_i\right) - \mu_s - \mu_b\,,$$

where

- S and B are the signal and background pdfs
- (μ_s, μ_b) are the number of signal and background events (free parameters).

Signal and background PDFs

PDFs are written as a product of a spatial $f(\alpha, \delta)$ and an energy part $g(E)$:

$$S_i = f_s(\alpha_i, \delta_i) \cdot g_s(E_i) \quad \text{and} \quad B_i = f_b(\delta_i) \cdot g_b(E_i), \tag{1}$$

The spatial part of the signal PDFs is a weighted sum of all the sources contributions:

$$f_s(\alpha_i, \delta_i) = \frac{1}{\sum w_j} \sum_{j=1}^{N_{sources}} w_j \, \mathcal{F}_j(\alpha_i, \delta_i), \qquad w_j = w_j^{model} \, \mathcal{A}(\delta_j), \tag{2}$$

where $\mathcal{F}(\alpha, \delta)$ is the ANTARES Point Spread Function, that depends on energy, declination and angular uncertainty β.

Weights of each source written as:

$$w_j = w_{model} \times \mathcal{A}(\delta_j) \quad \text{with} \quad \mathcal{A} \rightarrow \text{ANTARES acceptance}$$

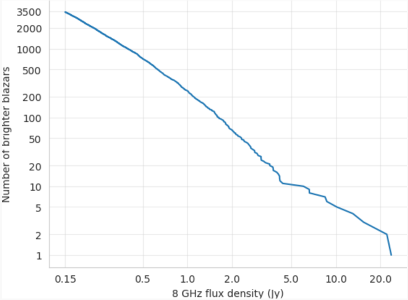
Assumptions for w_{model}:

- Flux weight:

$$w_{model} \propto S_{8GHz}$$

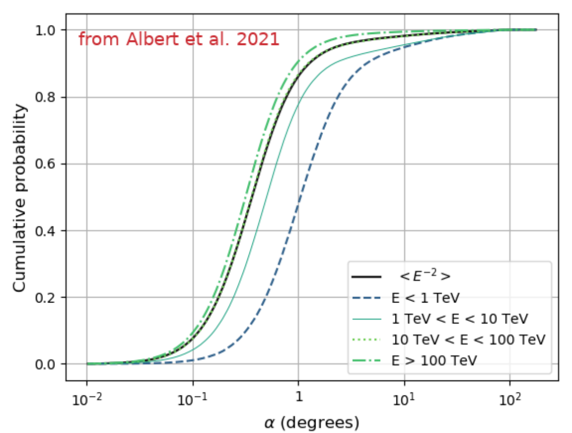
- Equal weight:

$$w_{model} = 1$$



Cumulative distribution of the VLBI blazars according to their radio flux density.

ANTARES Point Spread Function



ANTARES Background PDF

Spatial part of the background PDF

The real data RA distribution is compatible with a constant. The declination distribution is fitted by a polynomial function that is used in the likelihood.