Search for Gamma-Ray Counterparts of IceCube Neutrino Events in the AGILE Public Archive

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High Energy Astrophysical Neutrinos

High energy neutrinos production processes (E > TeV):

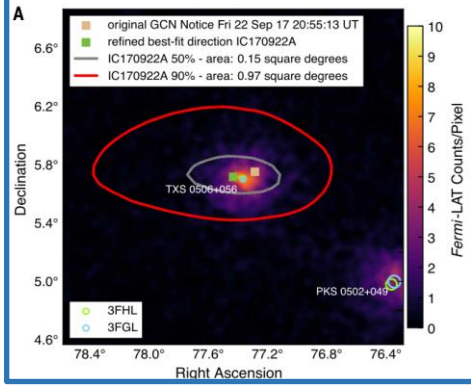
- pp interactions $p + N \rightarrow X + \text{many} \times (\pi^+ + \pi^- + \pi^0)$
- pγ interaction (photo-pion reaction, threshold process) $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$ $\rightarrow p + \pi^0$

Neutrino sources also gamma ray sources - Lepto-Hadronic Scenario vs Purely Leptonic Scenario (SSC or EIC)

Cosmic ray accelerators as producers of high energy neutrinos → Blazars (BL Lacertae + FSRQs) as best candidates

Eichler 1979, Stecker+ 1992, Mannheim 1995, Halzen&Zas 1997, Padovani&Resconi 2014, Ahlers&Halzen 2015, Tavecchio&Ghisellini 2015, Murase+ 2018, Giommi+ 2020, Giommi&Padovani 2021, Buson+ 2022, Bellenghi+ 2023, Buson+ 2023,…

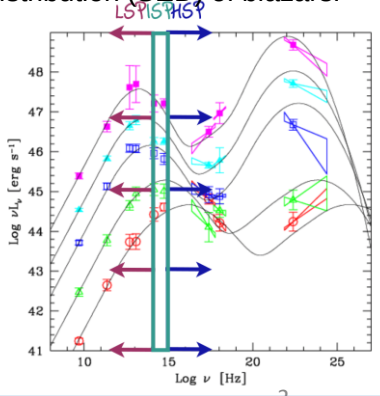
Blazar **TXS 0506+056** identified as EM counterpart of **IC-170922A** (*Aartsen+ 2018*)



Works about correlation with blazar catalogs and searches for EM counterparts of neutrino events

Lucarelli+ 2017, Lucarelli+ 2019, Krauss+ 2018, Aartsen+ 2019, Aartsen+ 2020, Franckowiak+ 2020, Kun + 2020, Plavin +2020, Plavin +2021, Abbasi+ 2022, Plavin +2023, Suray +2023, Abbasi +2023,…

Double humped Spectral Energy Distribution (SED) of blazars:



Searches on the contribution of the LBL/IBL/HBL subclasses: evidence accumulating for IHBLs

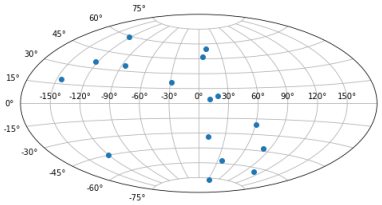
Padovani+ 2016, Giommi&Padovani 2021

Presentation Outline

- Search for candidate gamma-ray counterparts of a sample of IceCube neutrino events using the public data archive of the AGILE Mission
- Building of the light curves centered on the neutrino position using the AGILE-LV3 tool at the Space Science Data Center (SSDC) and multifrequency archival data
- Analysis of light curves over different time intervals around event T_0 (1 month, 1 year and full mission)
- Identification and classification of candidate blazar counterparts using the VOU-Blazars tool and ASI SED builder
- Estimation of contribution of different blazar subclasses

The IceCube neutrino sample (16 events)

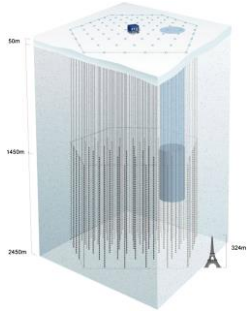
(September 2018 – March 2020)



Sample analized in my Master thesis (2022)
Advisors:
R. Poggiani, C. Pittori

IceCube Name	MJD	Event Type	RA (deg)	DEC (deg)	Error Radius* (arcmin)	Energy** ($\times 10^2$ TeV)	Signalness	l (deg)	b (deg)
IC-180908A	58369	EHE	$144.58^{+1.55}_{-1.45}$	$-2.13^{+0.9}_{-1.2}$	20.36	1.1998	0.34364	237.2	35.1
IC-181023A	58414	EHE	$270.18^{+2.00}_{-1.70}$	$-8.57^{+1.25}_{-1.30}$	17.50	1.1998	0.28016	19.4	7.2
IC-190503A	58606	EHE	$120.28^{+0.57}_{-0.77}$	$6.35^{+0.76}_{-0.70}$	14.99	1.0000	0.36266	215.2	18.4
IC-181014A	58405	HESE	$225.15^{+1.40}_{-2.85}$	$-34.80^{+1.15}_{-1.85}$	73.79	6037.47[pe]	0.10	331.0	20.9
IC-190104A	58487	HESE	$357.98^{+2.3}_{-2.1}$	$-26.65^{+2.2}_{-2.5}$	73.79	8584.32[pe]	0.35	31.6	-76.7
IC-190124A	58504	HESE	$307.40^{+0.8}_{-0.9}$	$-32.18^{+0.7}_{-0.7}$	73.79	13555.75[pe]	0.91	10.8	-33.8
IC-190221A	58535	HESE	$268.81^{+1.2}_{-1.8}$	$-17.04^{+1.3}_{-0.5}$	73.79	12264.54[pe]	0.37	11.4	4.2
IC-190331A	58573	HESE	$337.68^{+0.23}_{-0.34}$	$-20.70^{+0.30}_{-0.48}$	534.00	198736.44[pe]	0.57	36.6	-57.3
IC-190504A	58607	HESE	65.79	−37.44	73.79	7328.35[pe]	0.63	239.9	-44.7
IC-190619A	58653	GOLD	$343.26^{+4.08}_{-2.63}$	$10.73^{+1.51}_{-2.61}$	162.59	1.9870	0.54551	81.8	-42.5
IC-190730A	58694	GOLD	$225.79^{+1.28}_{-1.43}$	$10.47^{+1.14}_{-0.89}$	71.10	2.9881	0.67158	11.1	54.8
IC-190922A	58748	GOLD	$167.43^{+3.40}_{-2.63}$	$-22.39^{+2.88}_{-2.89}$	177.00	31.139	0.20165	274.1	34.7
IC-190922B	58748	GOLD	$5.76^{+1.19}_{-1.37}$	$-1.57^{+0.93}_{-0.82}$	64.80	1.8737	0.50501	106.8	-63.6
IC-191001A	58757	GOLD	$314.08^{+6.56}_{-2.26}$	$12.94^{+1.50}_{-1.47}$	177.00	2.1742	0.58898	60.2	20.3
IC-191119A	58806	GOLD	$230.10^{+4.76}_{-6.48}$	$3.17^{+3.36}_{-2.09}$	220.19	1.7648	0.44999	5.5	47.1
IC-200109A	58857	GOLD	$164.49^{+4.94}_{-4.19}$	$11.87^{+1.16}_{-1.36}$	174.60	3.7523	0.76931	237.2	59.3

*: 50% CL for EHE neutrinos, 90% CL for HESE, GOLD neutrinos
**: energy in photoelectrons for HESE neutrinos



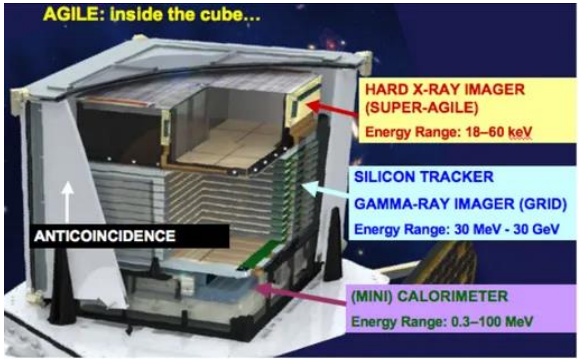
IceCube Alert System (> 2016)
EHE E = (500 TeV ÷ 10 PeV)
HESE E = (100 TeV ÷ 1 PeV)

GOLD (>2019)
signalness > 50%

$$Signalness(E,\delta) = \frac{N_{signal}(E,\delta)}{N_{signal}(E,\delta) + N_{background}(E,\delta)}$$

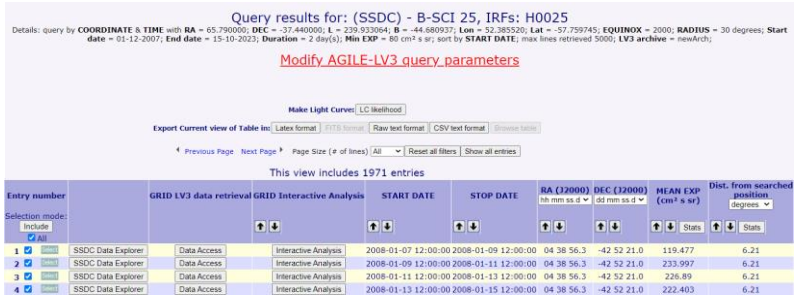
Search for Candidate Gamma-ray Counterparts in the AGILE-GRID public archive (SSDC AGILE-LV3 Analysis Tool)

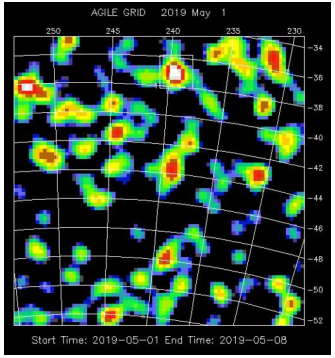
The AGILE Mission *Tavani+ 2008*



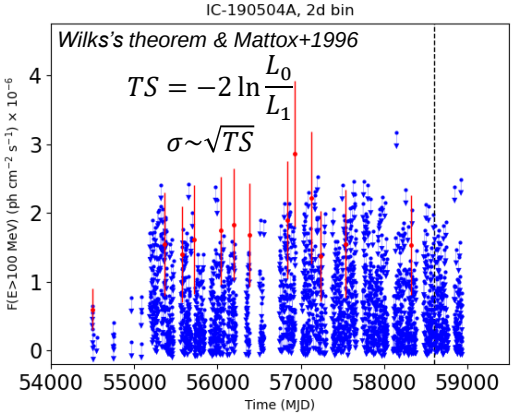
Full-mission (16 yrs) AGILE light curves using:

- Public data (AGILE-LV3 data archive, Energy > 100 MeV)
- AGILE-LV3 ASI SSDC tool: official on-line Maximum Likelihood analysis





Light curve of 2AGL J0429-3755 (PKS 0426-380)



Analysis Output

Light curves with bin duration: **2, 4, 7, 28 days**

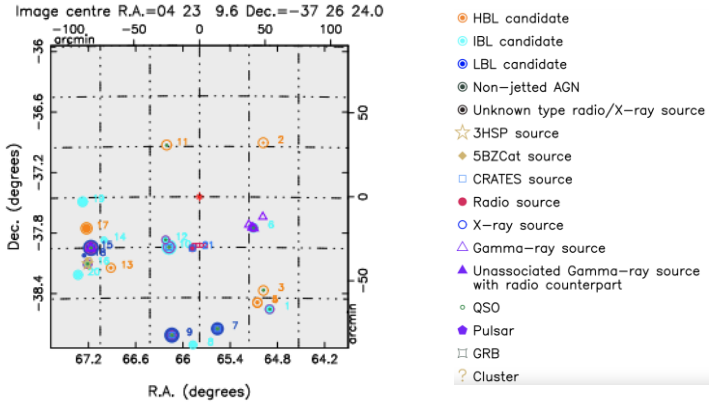
Significance ($\sqrt{TS}$) of a **Candidate Detections** (Maximum Likelihood results with $\sqrt{TS} > 3$)
Modified Julian Date **(MJD)**, **Flux** (ph/cm^2/s), Spectral Energy Distribution **(SED)** data

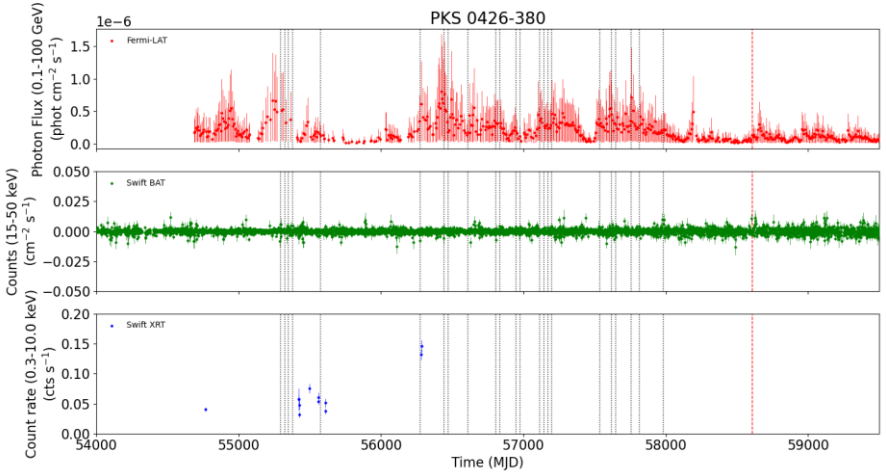
Example: the HESE neutrino event IC-190504A
MJD of neutrino event: T_0 (MJD)= 58607
Multiple candidate detections in all light curves
Closest candidate detection (ΔT ~ -9 months) in light curve with bin duration of 2 days:

- $\sqrt{TS} = 3.1$
- MJD of the Candidate Detection = 58324.5 ± 1.0
- Flux = (1.53 ± 0.72)e-6 ph/cm^2/s

Identification and Analysis of the Candidate EM Counterparts

VOU-BLAZARS Tool (Chang+ 2019)



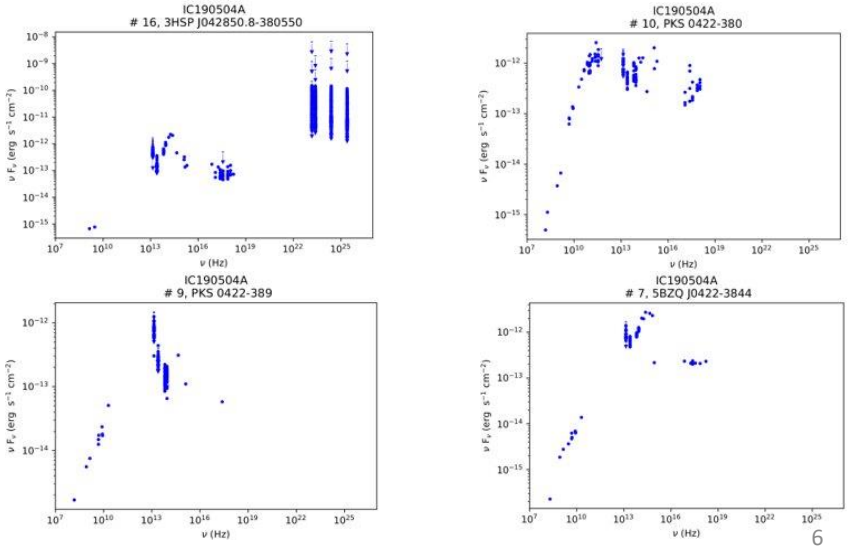


New candidate sources for all neutrino events

e.g.: IC-190504A (HESE)

$N_{Candidate}$	Source name	Type	RA	DEC	Distance(arcmin)	γ-ray Counterpart
15	PKS 0426-380	LBL/IBL	67.17	-37.94	71.95	4FGL J0428.6-375
16	**3HSP J042850.8-380550**	IBL	67.21	-38.10	78.12	0
6	WISEA J042025.10-374445.0	IBL	65.11	-37.65	37.4	4LAC J0420.3-374
10	**PKS 0422-380**	LBL/IBL	66.17	-37.94	35.1	0
9	**PKS 0422-389**	LBL	66.14	-38.81	83.95	0
7	**5BZQ J0422-3844**	LBL/IBL	65.56	-38.75	79.2	0

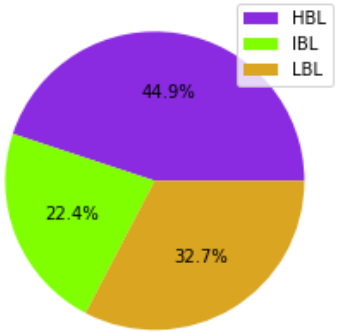
Previously reported candidates (*Giommi+ 2020*, *GCN 24401)*:
PKS 0426-380 (LBL) and 4LAC J0420.3-374 (IBL)



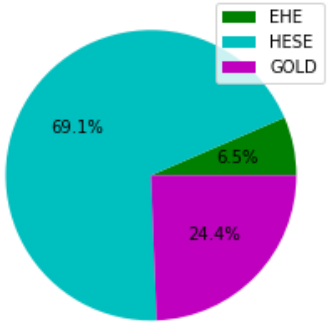
Conclusions

Analysis of 16 IceCube neutrino events from September 2018 to March 2020

- Full-mission (16 yrs) **AGILE light curves** using public data and **AGILE-LV3 SSDC tool**
- SED of identified candidates with VOU-Blazars tool: **new candidate EM counterparts for all neutrino events**
- **2/16 light curves with association to 2AGL catalog blazars** (IC-190504A and IC-190730A)
- **8/16 light curves show significant detections** ($\sqrt{TS} > 3$) **within T_0 ± 1 year**:
  - 2/3 EHE neutrinos (IC-180908A and IC-190503A)
  - 3/6 HESE neutrinos (IC-190104A, IC-190221A, IC-190504A)
  - 3/7 GOLD neutrinos (IC-190619A, IC-190922A, IC-191001A)



Classes of candidate blazars



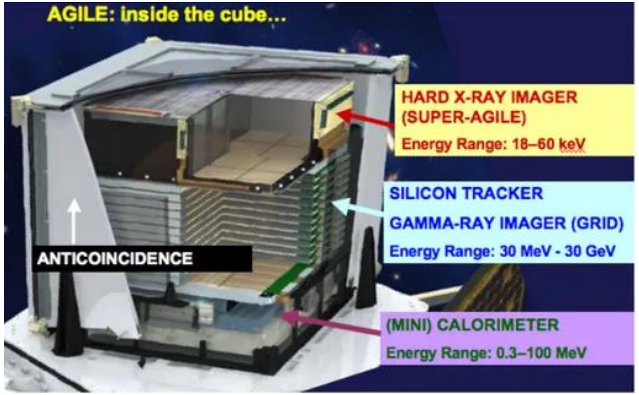
Candidate AGILE detections vs. neutrino event type

Post-trial Probability under evaluation

Paper in preparation

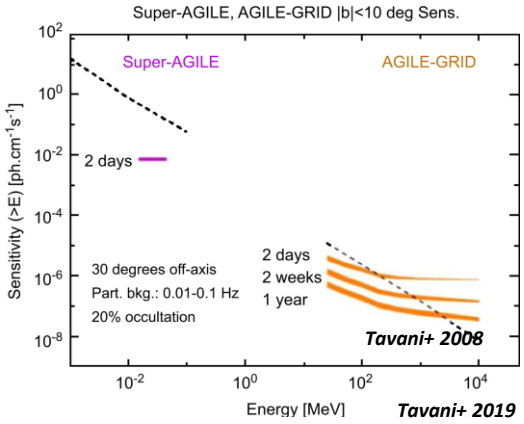
EXTRA SLIDES

The AGILE Mission



Tavani+ 2008

- Launch: 23/04/2007, more than 16 years activity
- Low Equatorial Orbit with 2.5° inclination
- Average altitudine: ~ 500 km
- Since 2009: "Spinning" observing mode
- Revolution period ~ 7 min: 80% sky coverage every day



Gamma-ray imaging detector (GRID)	
Energy range	30 MeV–50 GeV
Field of view	~ 2.5 sr
Flux sensitivity ($E > 100$ MeV, 5σ in 10^6 s)	3×10^{-7} (ph cm^{-2} s^{-1})
Angular resolution at 100 MeV (68% cont. radius)	3.5°
Angular resolution at 400 MeV (68% cont. radius)	1.2°
Source location accuracy (high Gal. lat., 90% C.L.))	~ 15 arcmin
Energy resolution (at 400 MeV)	$\Delta E/E \sim 1$
Absolute time resolution	~ 2 μs
Dead time	~ 100–200 μs
Hard X-ray imaging detector (Super-AGILE)	
Energy range	18–60 keV
Single (1-dim.) detector FOV (FW at zero sens.)	107° × 68°
Combined (2-dim.) detector FOV (FW at zero sens.)	68° × 68°
Sensitivity (18–60 keV, 5σ in 1 day)	~15 mCrab
Angular resolution (pixel size)	6 arcmin
Source location accuracy (S/N~10)	~1–2 arcmin
Energy resolution (FWHM)	$\Delta E \sim 8$ keV
Absolute time resolution	~ 2 μs
Mini-calorimeter	
Energy range	0.35–50 MeV
Energy resolution (at 1.3 MeV)	13% FWHM
Absolute time resolution	~ 3 μs
Dead time (for each of the 30 CsI bars)	~ 20 μs

AGILE-GRID:

- Silicon Tracker (ST): gamma-ray conversion into e+/e- pairs, charged particles track reconstruction
- Minicalorimeter (MCAL): measurement of charged particle energy (for estimation of incident photons energy); 30 CsI(Tl) bars with PIN photodiodes

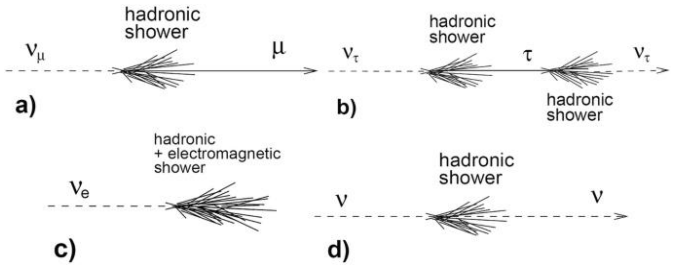
FOV ~ 2.5 sr

Angular resolution ~1.2° for E > 100 MeV (up to 30° off-axis)

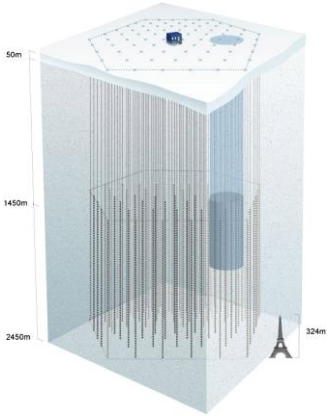
Sensitivity (10-20)x10^{-8} ph/cm^2/s (depending on sky region and exposure time)

IceCube

- Neutrino detection via Charged Current (CC) and Neutral Current (NC) ($\sigma \sim 10^{-38}$ cm^2 at 1 GeV):
  - Charged Current (CC) $\nu_l + N \rightarrow l + X$
  - Neutral Current (NC) $\nu_l + N \rightarrow \nu_l + X$



IceCube Alert System (> 2016)

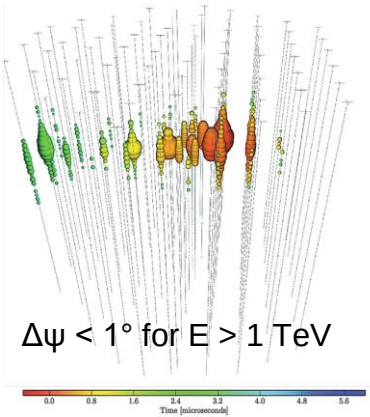


- **EHE** (Extremely High Energy event): E = 500 TeV – 10 PeV
- **HESE** (High Energy Starting Event): track-like events with interaction vertex inside detector, E = 100 TeV - 1PeV
- **GOLD (>2019):** signalness > 50%
- **BRONZE (>2019)**: signalness > 30%

$$Signalness(E,\delta) = \frac{N_{signal}(E,\delta)}{N_{signal}(E,\delta) + N_{background}(E,\delta)}$$

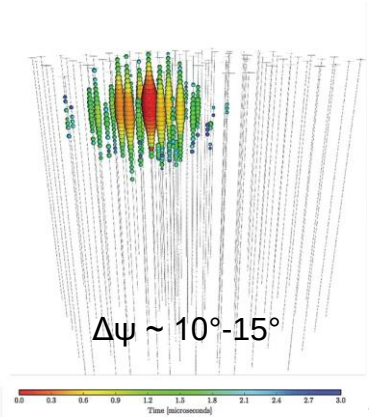
δ =declination

Track-like



Δψ < 1° for E > 1 TeV

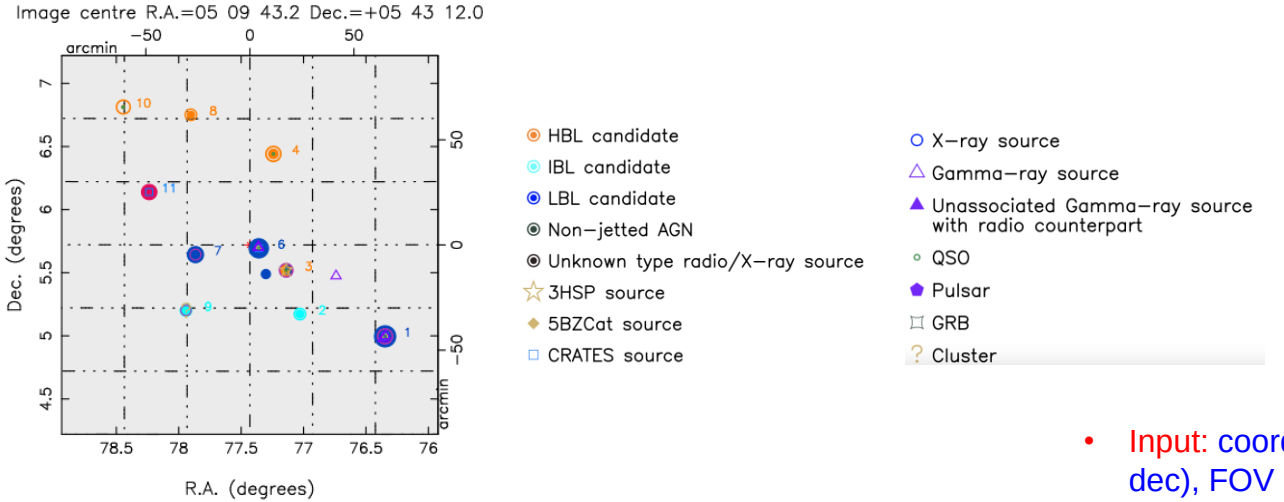
Cascade-like

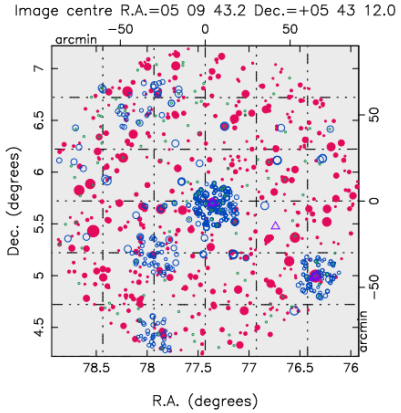


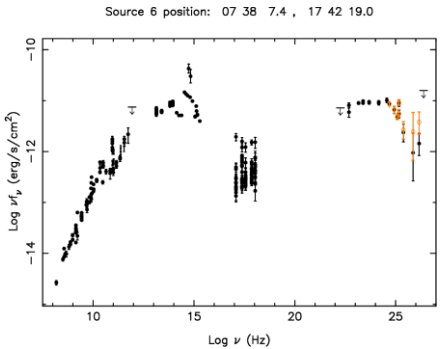
Δψ ~ 10°-15°

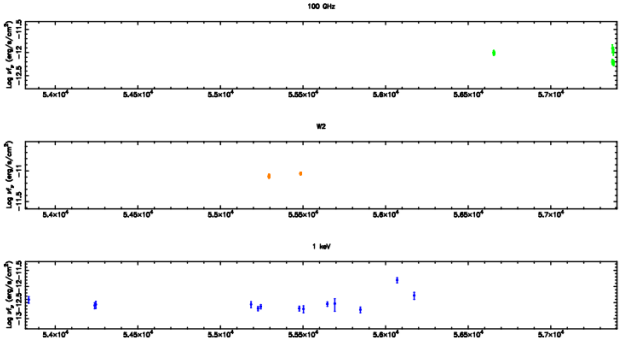
IceCube Collaboration

VOU-Blazars Tool *(Chang+ 2019)*



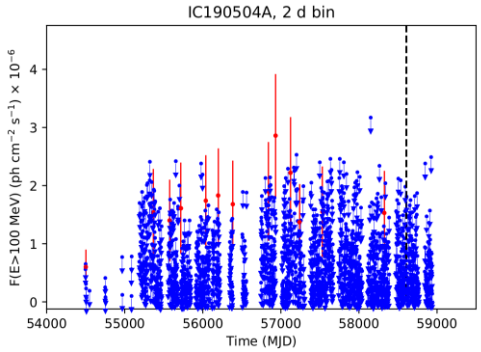


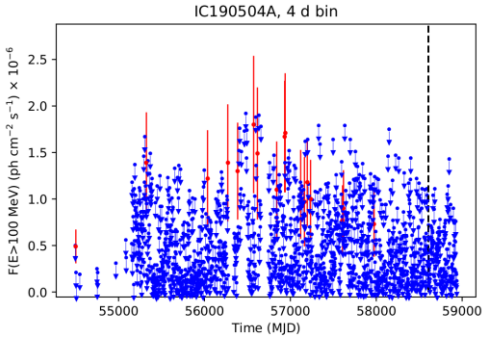


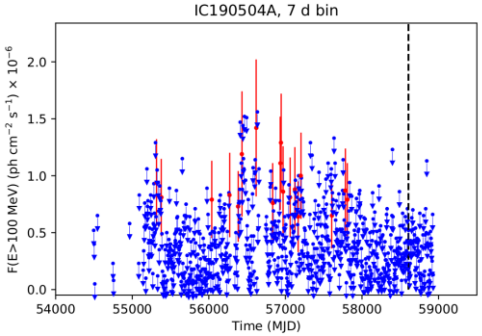


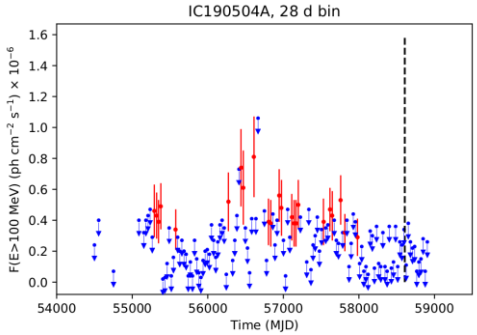
- Input: coordinates of center of search region (ra, dec), FOV
- Output Phase 1 (37 catalogs):
  - Sky Map with identified sources
  - Candidate list with: name, coordinates (ra, dec), angular distance from center, log(v_{peak}), classification as LBL/IBL/HBL
  - Gamma-ray counterparts from Fermi-LAT catalog
- Output Phase 2 (55 catalogs): analysis of specific sources with production of SED and light curves

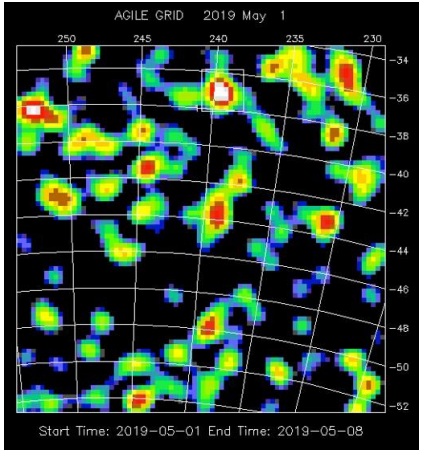
IC-190504A (HESE)



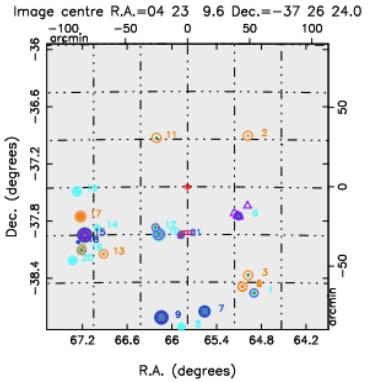








IC-190504A (HESE)



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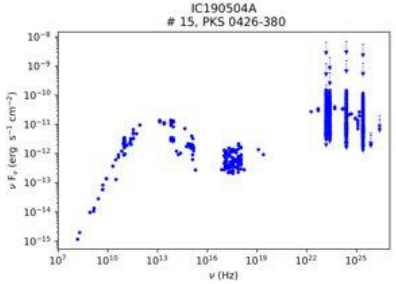
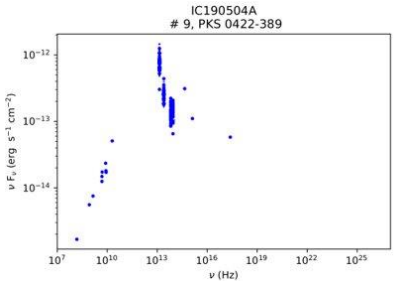
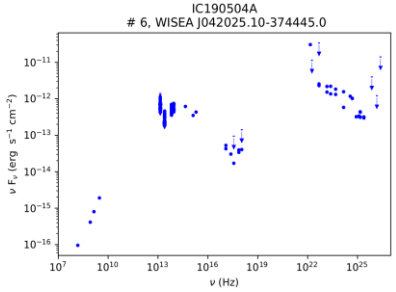
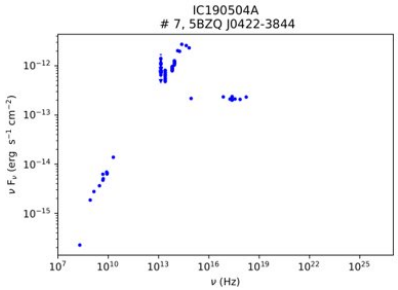
6	WISEA J042025.10-374445.0	IBL	65.11	-37.65	37.4	4LAC J0420.3-374
10	**PKS 0422-380**	LBL/IBL	66.17	-37.94	35.1	0
9	**PKS 0422-389**	LBL	66.14	-38.81	83.95	0
7	**5BZQ J0422-3844**	LBL/IBL	65.56	-38.75	79.2	0

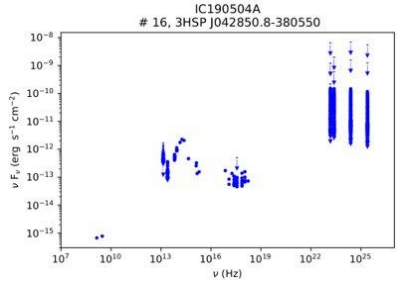
Previously reported candidates (*Giommi+ 2020*, *GCN 24401)*: PKS 0426-380 (LBL) and 4LAC J0420.3-374 (IBL)

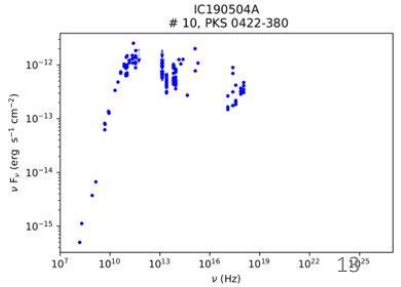




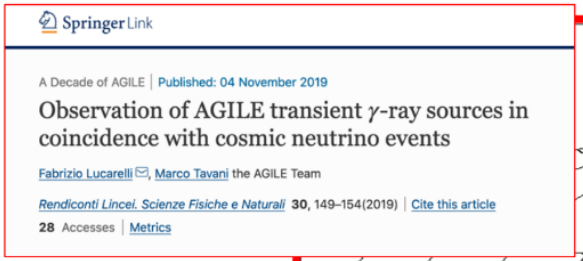


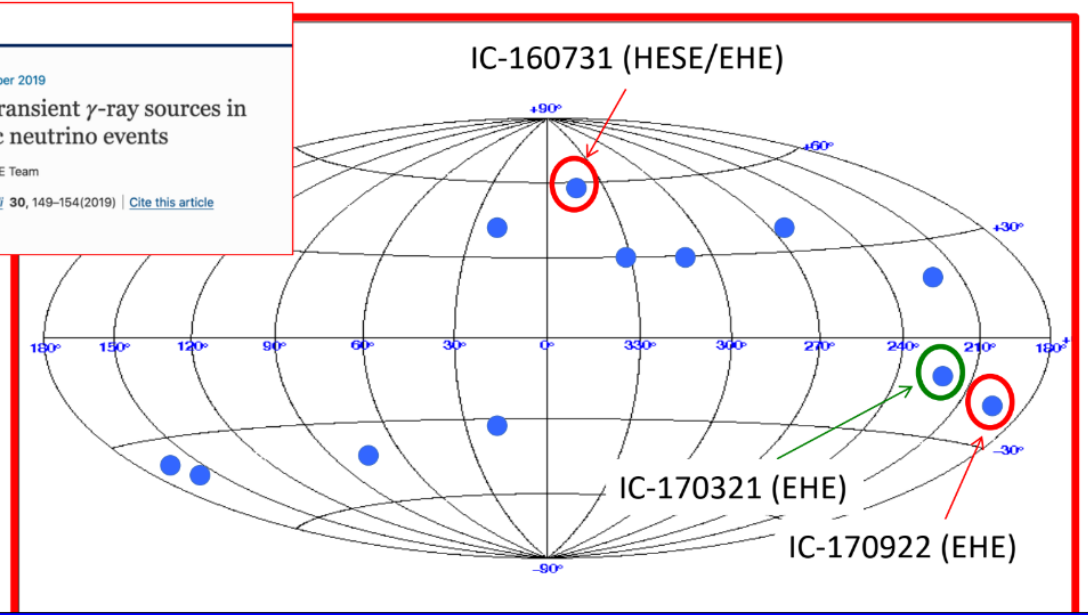






AGILE detections of IceCube Neutrino Events
(F. Lucarelli et al, ApJ 870, 2019)

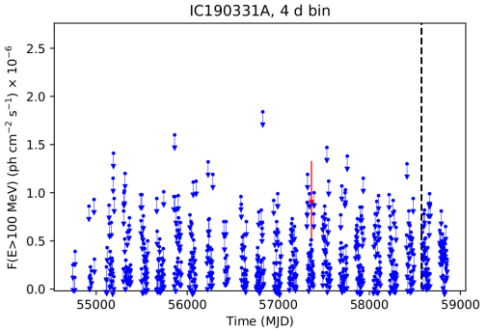




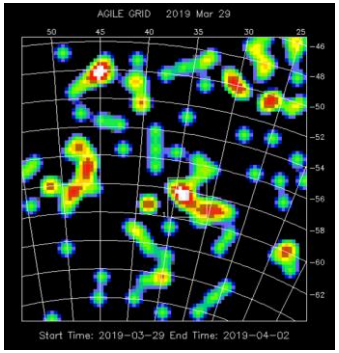
Three AGILE detections (~4σ each) from the automatic QL system consistent with time/position of 3 IC events out of 10!

C. Pittori talk @20MAGIC

IC-190331A (HESE)



ATel #12623, Lucarelli+ (2019): new identified source AGL J2233-2212 spatially and temporally coincident with the neutrino event

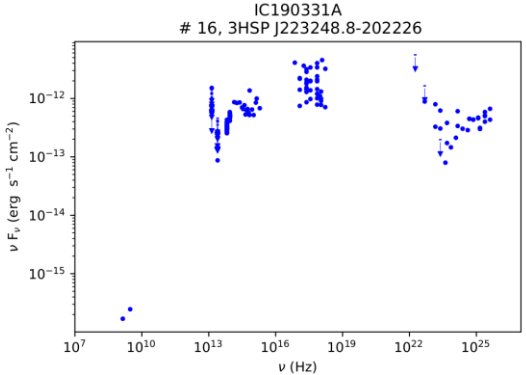


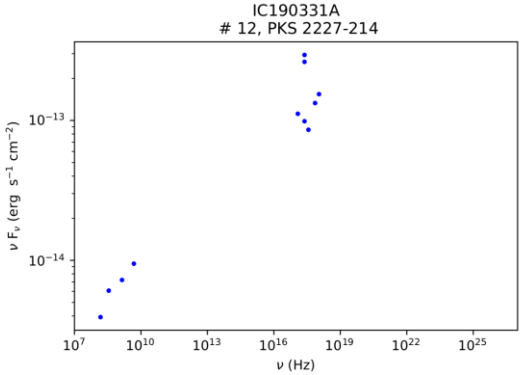
Some candidates not previously reported

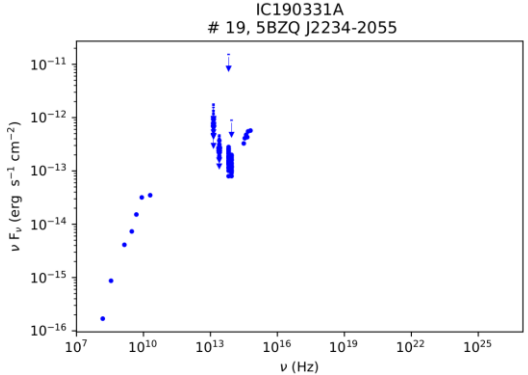
$N_{Candidate}$	Source name	Type	RA	DEC	Distance(arcmin)	γ-ray Counterpart
	AGL J2233-2212					
16	**3HSP J223248.8-202226**	HBL	338.20	-20.37	35.3	4FGL J2232.6-2023
12	**PKS 2227-214**	LBL	337.65	-21.21	30.8	-
19	**5BZQ J2234-2055**	LBL	338.73	-20.92	60.83	-

Lightcurve centered on arrival direction of neutrino:
T_0 = 58573 MJD
Bin duration: 4 days
ΔT = -3.3 years
MJD Detection = 57365.5 ± 2.0 (09-12-2015)
Flux = (0.91 ± 0.42)e-6 ph/cm^2/s (sqrt(TS)=3.0)

SEDs of the sources

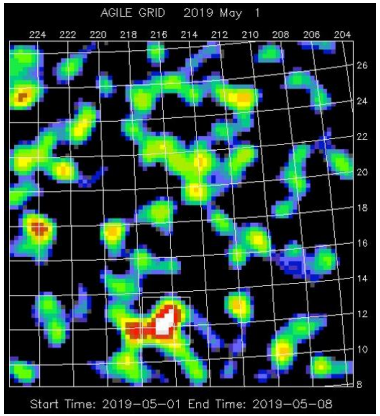


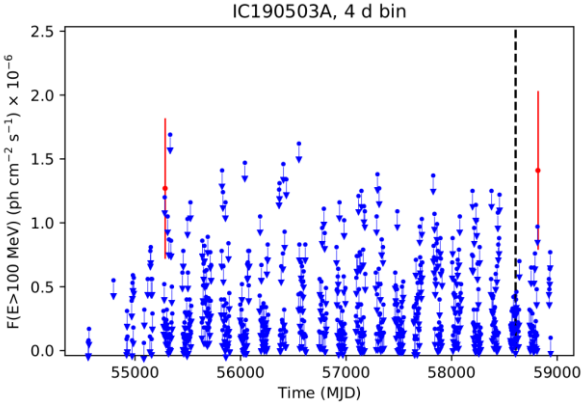


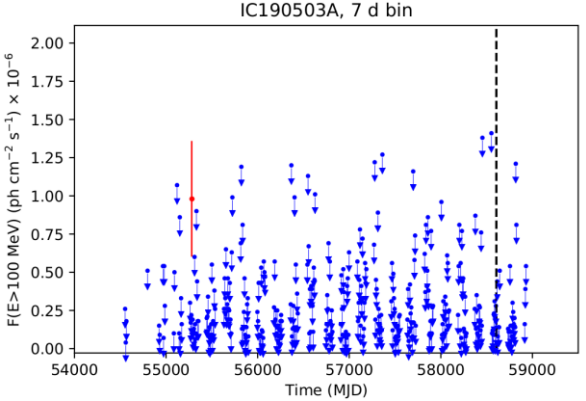


IC-190503A (EHE)

Map at time T_0 and time bin 7 days







Candidate Associated sources

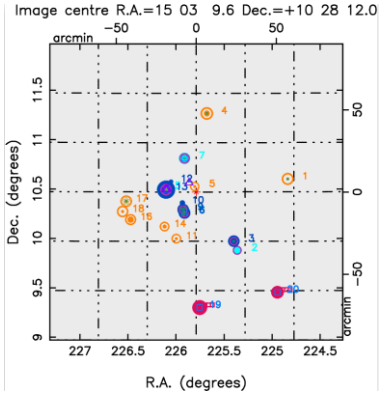
$N_{Candidate}$	Source name	Type	RA	DEC	Distance(arcmin)	γ-ray Counterpart
1	3HSP J080056.5+073235	HBL	124.24	7.54	71.1	4FGL J0800.9+0733
6	**MRK 1210**	Sy2	121.02	5.11	86.37	-
7	**WISEA J080406.36+064843.3**	HBL	121.03	6.81	51.23	-
4	**SDSS J080352.97+061704.3**	IBL	120.97	6.28	40.27	-

One previously reported candidate (*GCN 24378*): 3HSP J080056.5+073235 (HBL, 4FGL J0800.9+0733)

Lightcurve centered on arrival direction of neutrino:
T_0 = 58606 MJD
Detections for 4, 7 days binning

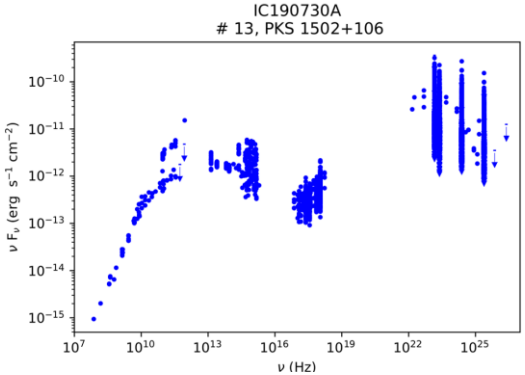
Closest Detection:
sqrt(TS) = 3.4
MJD = 58817.5 ± 2.0 (30-11-2019)
ΔT = +7 months
Flux = (1.41±0.62)e-6 ph/cm^2/s

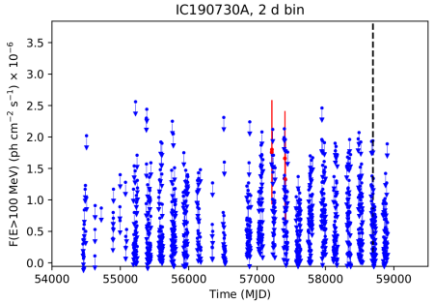
IC-190730A (GOLD)

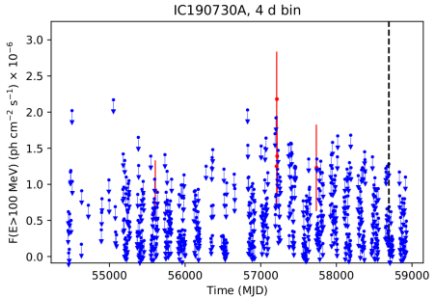


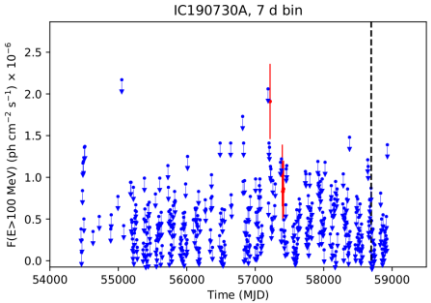
$N_{Candidate}$	Source name	Type	RA	DEC	Distance(arcmin)	γ-ray Counterpart
13	PKS 1502+106	LBL	226.10	10.49	18.59	2AGLJ1507+1019
17	3HSP J150604.4+102233	HBL	226.52	10.38	43.35	-
6	**SDSS J150340.61+101429.4**	LBL	225.91	10.25	15.12	-
8	**1WGA J1503.7+1018**	LBL	225.91	10.27	14.21	-
7	**CRATES J150339+104836**	IBL	225.91	10.81	21.69	-
9	**SDSS J150339.35+101820.7**	LBL	22.93	10.29	13.63	-
1	**SDSS J145920.92+103603.3**	HBL	224.84	10.60	56.87	-
3	**SDSS J150135.83+095818.6**	LBL	225.40	9.97	37.75	-
4	**SDSS J150243.09+111557.3**	HBL	225.68	11.27	48.16	-

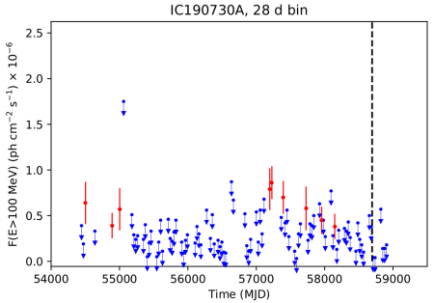
Previously reported candidates:
PKS 1502+106 (LBL) and 3HSP J150604.4+102233 (HBL)
(*GCN 25225, Giommi+ 2020,* Rodrigues+ 2021, Oikonomou+ 2021)





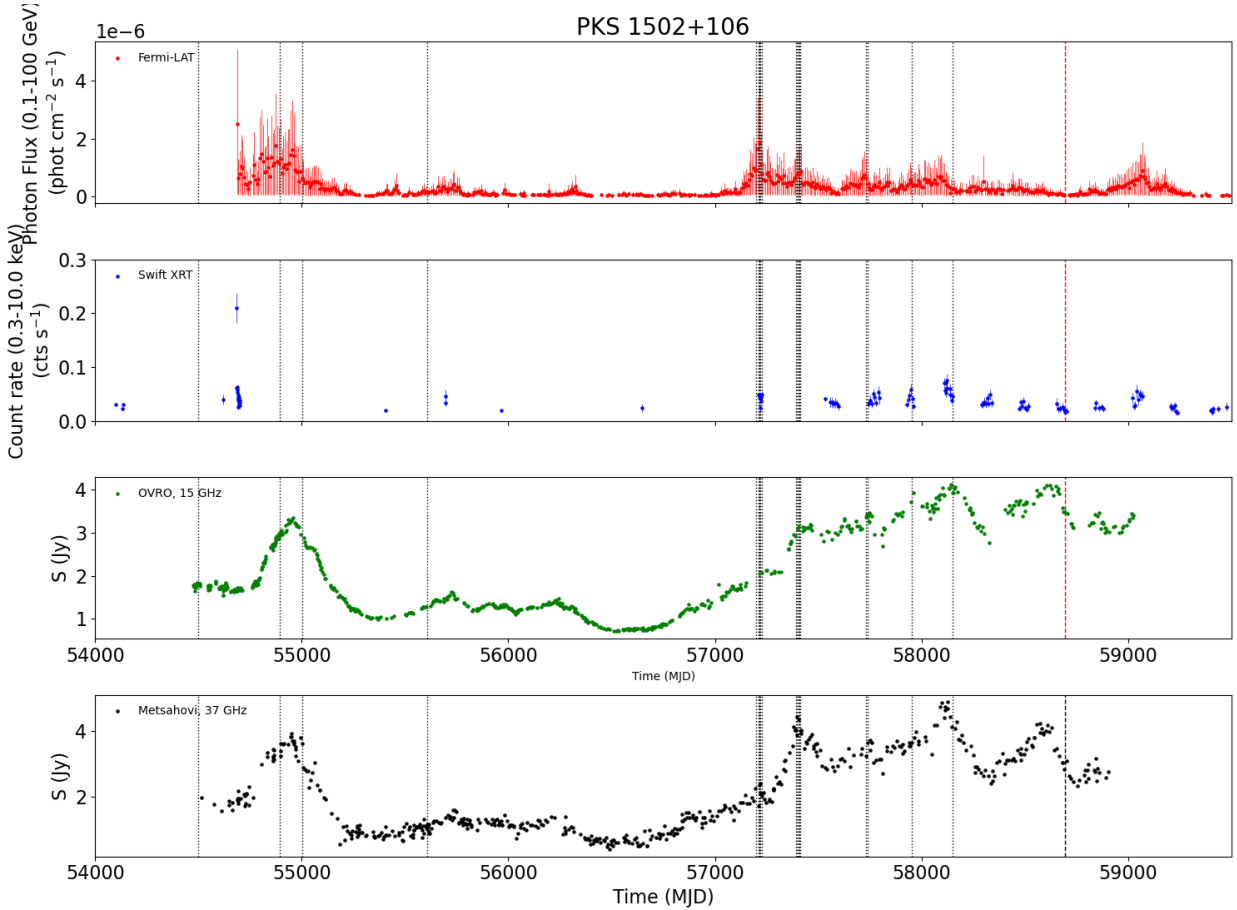






Light curves of 2AGLJ 1507+1019:
T_0 = 58694 MJD
Bin duration: 28 days
ΔT = -1.5 yr
MJD Detection= 58149.5 ± 14.0 d (31-01-2018)
Flux = (0.38 ± 0.14)e-6 ph/cm^2/s, sqrt(TS)=3.4

IC-190730A (GOLD)



Results: EHE neutrinos

IceCube Name	T_0 (MJD)	Event Type	F_γ(E > 100 MeV) $\times 10^{-6}$(ph cm^{-2} s^{-1})	Δt (yr)	$\sqrt{TS}$	Bin (days)	Associated Sources
IC-180908A	58369	EHE	2.18 ± 0.95	+0.66	3.5	2	3HSP J093938.5-031503 (HBL)
							MQ J093826.55-004244.5 (LBL)
IC-181023A	58414	EHE	-	-	-	-	4FGL J1804.5-0852 (BCU)
							4FGL J1805.8-0803 (UNK)
IC-190503A	58606	EHE	1.41 ± 0.62	+0.66	3.4	4	3HSP J080056.5+073235 (HBL)
			1.27 ± 0.55	−9.2	3.4	4	**Mrk 1210 (Sy2)**
			0.98 ± 0.38	−9.2	3.5	7	**WISEA J080406.36+064843.3 (HBL)**
							SDSS J080352.97+061704.3 (IBL)

2 events out of 3 show a candidate detection within ± 1 year around T_0 of neutrino event

New candidate counterparts (not previously reported in literature) in bold

Results: HESE neutrinos

IceCube Name	T_0 (MJD)	Event Type	F_γ(E > 100 MeV) $\times 10^{-6}$(ph cm^{-2} s^{-1})	Δt (yr)	$\sqrt{TS}$	Bin (days)	Associated Sources
IC-181014A	58405	HESE	1.07 ± 0.48	−7.3	3.1	4	2AGL J1459-3542/PKS 1454-354 (LBL)
			0.32 ± 0.11	−9.7	3.4	28	PMN J1505-3432 (LBL)
IC-190104A	58487	HESE	1.60 ± 0.71	0.84	3.0	4	IC 5362 (BCG)
			1.43 ± 0.61	−2.7	3.3	4	VOU J235815-285341 (HBL)
			0.72 ± 0.31	−3.0	3.3	7	3HSP J235034.3-300604 (HBL)
			0.33 ± 0.13	−3.0	3.2	28	3HSP J235023.3-243602 (HBL)
							1WGA J2350.5-2620 (Sy2)
							5BZQ J2353-2743 (IBL)
							MCXC J2351.6-2605 (CoG)
IC-190124A	58504	HESE	1.26 ± 0.56	−2.6	3.2	7	**5BZQ J2024-3253/PKS 2021-330 (LBL)**
			0.94 ± 0.40	−10.9	3.3	2	**WISEA J202151.77-324420.6 (LBL)**
			0.85 ± 0.39	−5.3	3.0	7	**Abell 3681 (CoG)**
			0.61 ± 0.19	−5.3	4.2	28	**PMN J2028-3154 (LBL)**
IC-190221A	58535	HESE	1.12 ± 0.45	+0.07	3.1	7	4FGL J1758.6-1622 (Radio source)
							4FGL J1750.4-1723 (Gamma source)
							4FGL J1751.6-1750 (BCU)
IC-190331A	58573	HESE	0.91 ± 0.42	−3.3	3.0	4	AGL J2233-2212 (HBL)
							3HSP J223248.8-202226 (HBL)
							PKS 2227-214 (LBL)
							5BZQ J2234-2055 (LBL)
IC-190504A	58607	HESE	1.53 ± 0.72	−0.78	3.1	2	2AGL J0429-3755/PKS 0426-380 (LBL/IBL)
			0.73 ± 0.35	−1.7	3.2	4	4LAC J0420.3-3745 (IBL)
			0.79 ± 0.32	−2.2	3.4	7	**3HSP J042850.8-380550 (IBL)**
			0.29 ± 0.12	−1.7	3.0	28	**PKS 0422-380 (LBL)**
							PKS 0422-389 (LBL)
							5BZQ J0422-3844 (LBL/IBL)

2AGL associated source

Multiple detections in all light curves, only those closest to T_0 reported here

3 events out of 6 show a candidate detection within ± 1 year around T_0 of neutrino event

Results: GOLD neutrinos

2AGL associated source

3 events out of 7 show a candidate detection within ± 1 year around T_0 of neutrino event

IceCube Name	T_0 (MJD)	Event Type	F_γ(E > 100 MeV) $\times 10^{-6}$(ph cm^{-2} s^{-1})	Δt (yr)	$\sqrt{TS}$	Bin (days)	Associated Sources
IC-190619A	58653	GOLD	1.61 ± 0.75	−0.47	3.2	2	4FGL J2252.6+1245 (Gamma-ray source)
			1.18 ± 0.49	−0.47	3.2	4	**PKS 2251+11 (BLRG)**
			1.14 ± 0.52	−5.1	3.3	4	**WISEA J224854.73+111427.3 (HBL)**
							UGC 12237 (Sy2)
							UGC 12243 (Sy1)
							MCXC J2250.3+1054 (CoG)
							3C 454.3 (FSRQ, within a few deg)
IC-190730A	58694	GOLD	1.33 ± 0.65	−3.5	3.1	2	2AGL J1507+1019/PKS 1502+106 (LBL)
			1.23 ± 0.60	−2.6	3.1	4	3HSP J150604.4+102233 (HBL)
			0.86 ± 0.34	−3.5	3.3	7	**SDSS J150340.61+101429.4 (LBL)**
			0.38 ± 0.14	−1.5	3.4	28	**1WGA J1503.7+1018 (LBL)**
							CRATES J150339+104836 (IBL)
							SDSS J150339.35+101820.7 (LBL)
							SDSS J145920.92+103603.3 (HBL)
							SDSS J150135.83+095818.6 (LBL)
							SDSS J150243.09+111557.3 (HBL)
IC-190922A	58748	GOLD	0.83 ± 0.33	−0.25	3.5	7	4FGL J1103.6-2329 (BL Lac)
			2.01 ± 0.84	−3.8	3.2	2	4FGL J1120.0-2204 (Gamma ray source)
							4FGL J1100.0-2044 (BCU)
							HE 1106-2321 (HBL)
							MQ J111552.48-215640.7 (IBL)
IC-190922B	58748	GOLD	1.53 ± 0.68	−3.8	3.0	4	4FGL J0022.0+0006 (BL Lac, within a few deg)
			0.79 ± 0.36	−4.8	3.0	7	**LBQS 0020-0202 (HBL)**
			0.41 ± 0.16	−4.8	3.0	28	**Mrk 947 (Sy2)**
							PGC 1077256 (HBL)
							MQ J002002.35-002122.9 (HBL)
							SDSS J001920.37-003532.9 (LBL)
IC-191001A	58757	GOLD	2.10 ± 0.90	−0.82	3.7	2	4FGL J2115.2+1218 (BL Lac)
							4FGL J2052.7+1218 (Millisecond pulsar)
IC-191119A	58806	GOLD	1.81 ± 0.86	−7.2	3.1	2	**MQ J151757.77+021544.2 (HBL)**
			1.39 ± 0.70	−9.8	3.0	2	**ZW 20733 (IBL)**
							WISEA J152506.63+022425.1 (HBL)
							CRATES J152122+042021 (Radio galaxy)
							4FGL J1518.8+0203 (Pulsar)
IC-200109A	58857	GOLD	1.18 ± 0.53	−1.6	3.0	4	TXS 1100+122 (IBL)
			1.19 ± 0.53	−4.6	3.0	4	**PGC 1403648 (HBL)**
							ZW 11570 (HBL)
							SDSS J110108.25+111635.3 (IBL)
							PKS 1058+110 (Sy1)
							Mkn 728 (Sy1)
							Abell 1142 (CoG)
							DRCG 22-46 (CoG)

Multiple detections in all light curves, only those closest to T_0 reported here

Post-trial significance of identified detections

For each candidate detection we estimated *(Bulgarelli+2012, Lucarelli+2017)*:

- The *p-value* (or *pre-trial probability, p*): the probability for a candidate detection to be a false detection;
- The *Post-trial probability* (*P*) to have *k* or more random detections in non-overlapping time intervals out of *N* trials (i.e., the number of generates maps with exposure above 80 cm^2/s/sr centered on arrival direction neutrinos coordinates);

$$P(N, X \geq k) = 1 - \left(\sum_{j=0}^{k-1} \binom{N}{j} p^j (1-p)^{N-j} \right)$$

- The *Combined post-trial probability* (P_{cpt}) to have a spatial coincidence of an AGILE-GRID detection with the IceCube error region inside the 10 deg *Region of Interest* (ROI);

$$P_{cpt} = P \times P_{ROI} \quad \text{where } P_{ROI} = 10^{-2}$$

- The *Joint post-trial probability* (P_{joint}) is the probability to have a number *n* of neutrinos with a false candidate detection over a year from T_0 out of *N* trials given by the product of the total number of the neutrino events analysed and the number of optimization of search radius (equal 1 in our work).

$$P_{joint}(\text{post-trial}) = 1 - \left(1 - \prod_{i=1}^{n} P_i \right)^N$$