Neutrino Point Sources

Chad Finley
Oskar Klein Centre
Stockholm University

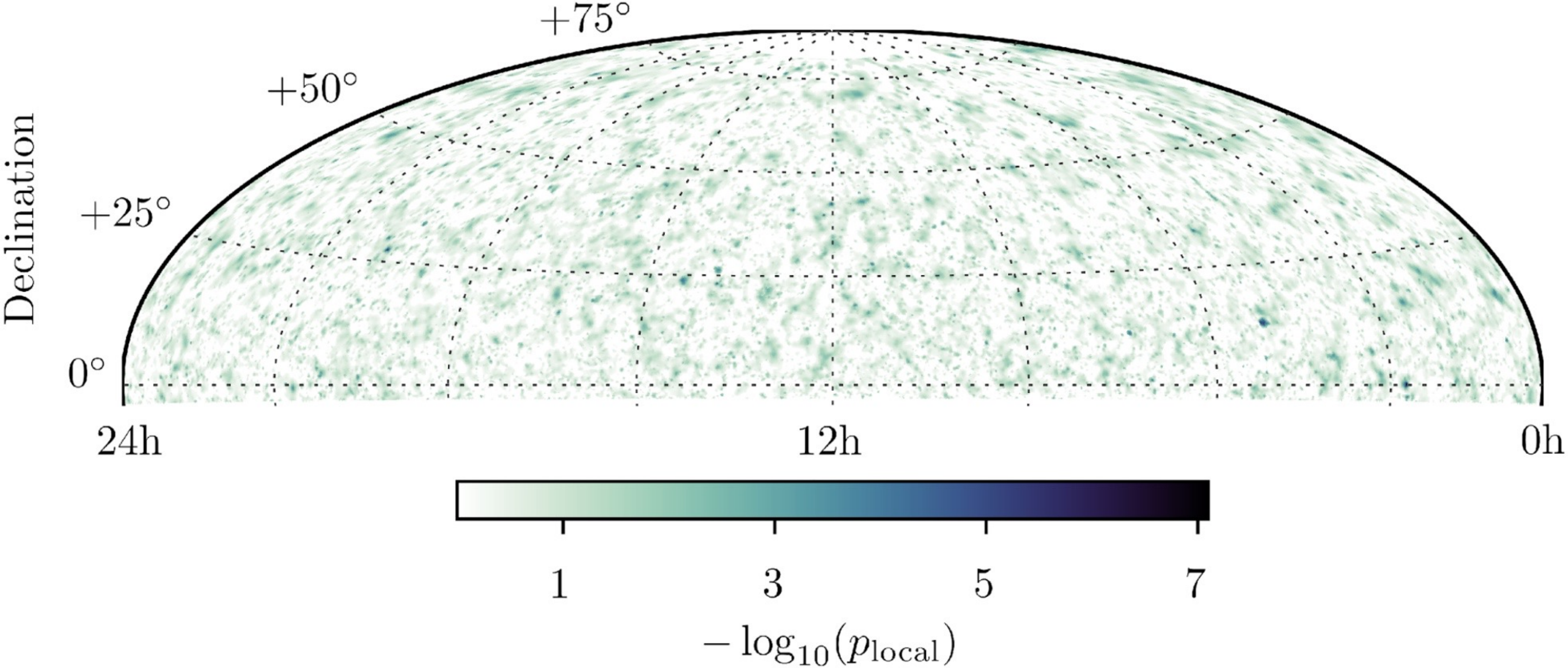
Neutrinos in the
Multi–Messenger Era

Louvain-la-Neuve
2022 December 1

Messier 77 / NGC 1068 (1780)

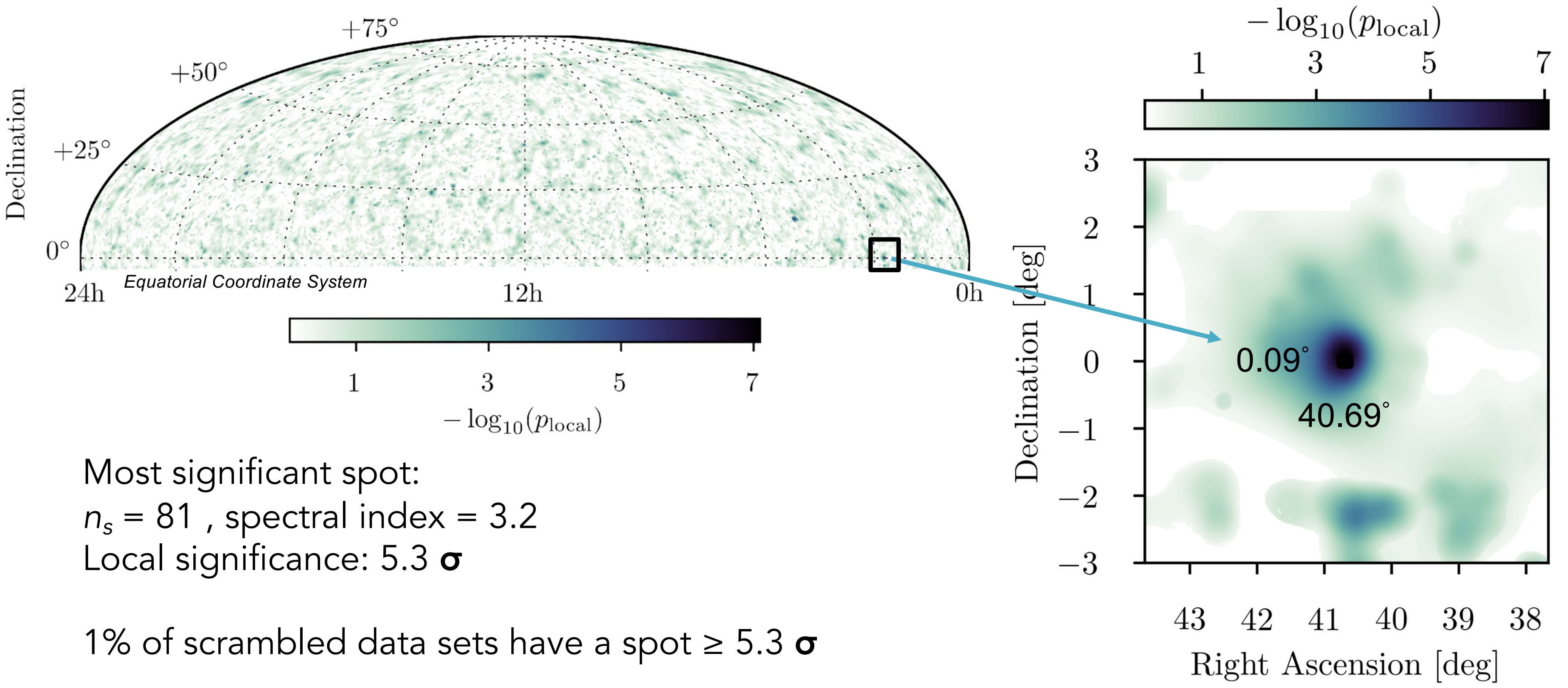
Ignace Gaston Pardies,
Globi coelestis in tabulas planas redacti descriptio,
Paris (1693)

IceCube 10 year (2011-2020) Northern Sky Neutrino Map



Fit number of astrophysical events (n_s) and spectral index at each spot in sky.

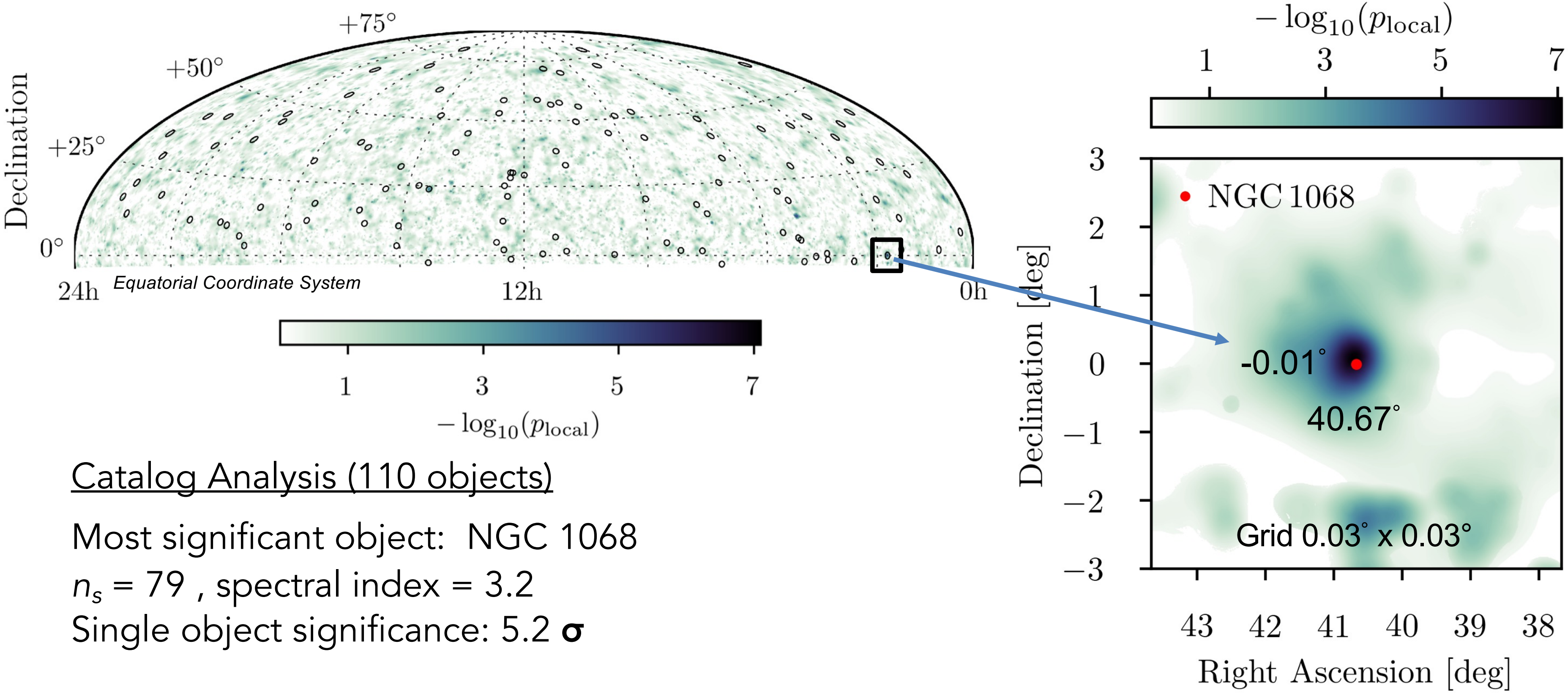
IceCube 10 year (2011-2020) Northern Sky Neutrino Map



Most significant spot:
n_s = 81 , spectral index = 3.2
Local significance: 5.3 **σ**

1% of scrambled data sets have a spot ≥ 5.3 **σ**

IceCube 10 year (2011-2020) Northern Sky Neutrino Map



<u>Catalog Analysis (110 objects)</u>

Most significant object: NGC 1068

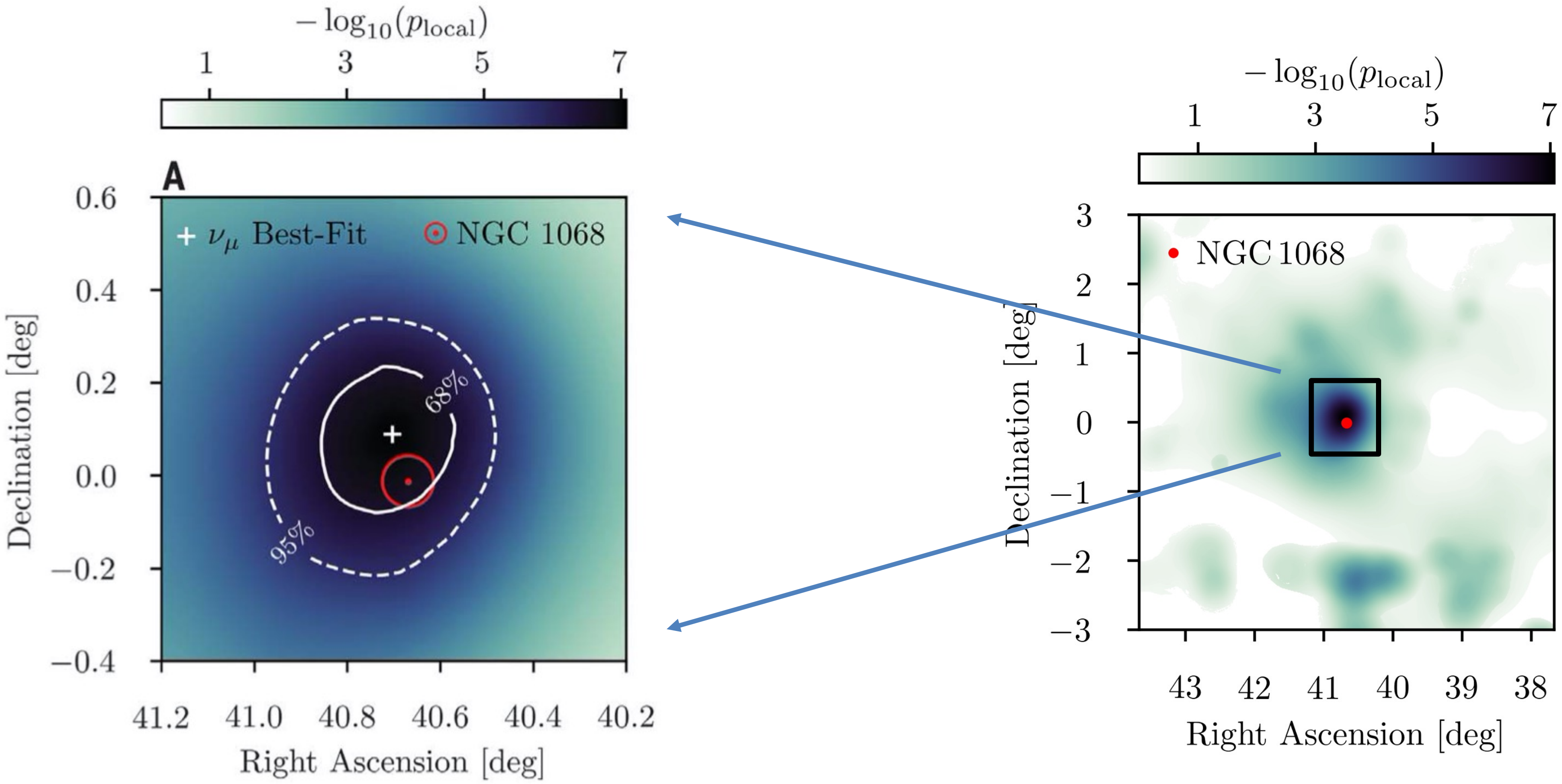
n_s = 79 , spectral index = 3.2

Single object significance: 5.2 **σ**

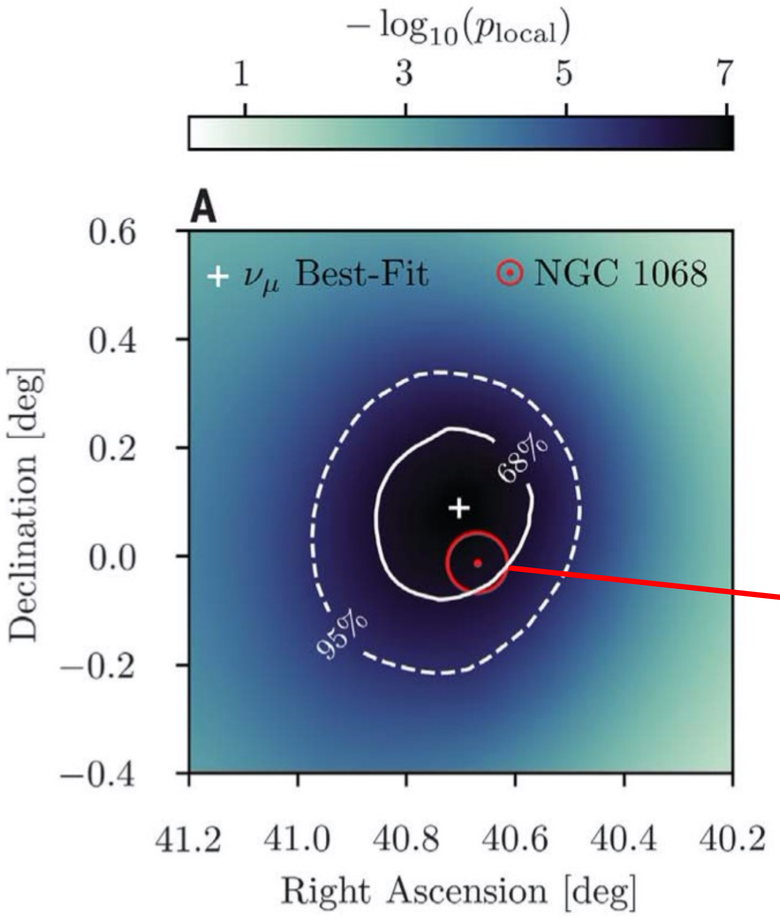
1 in 100,000 scrambled data sets have object ≥ 5.2 **σ**

= 4.2 **σ** evidence

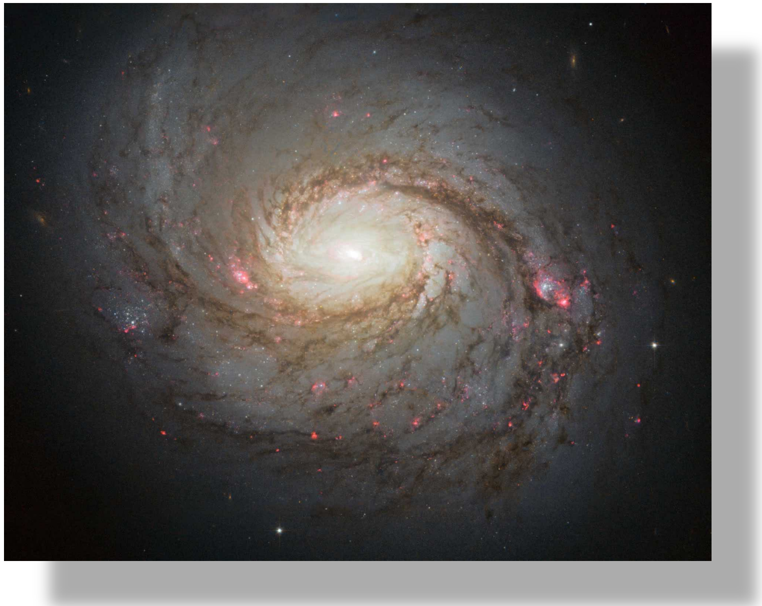
Location of Hottest Spot and NGC 1068



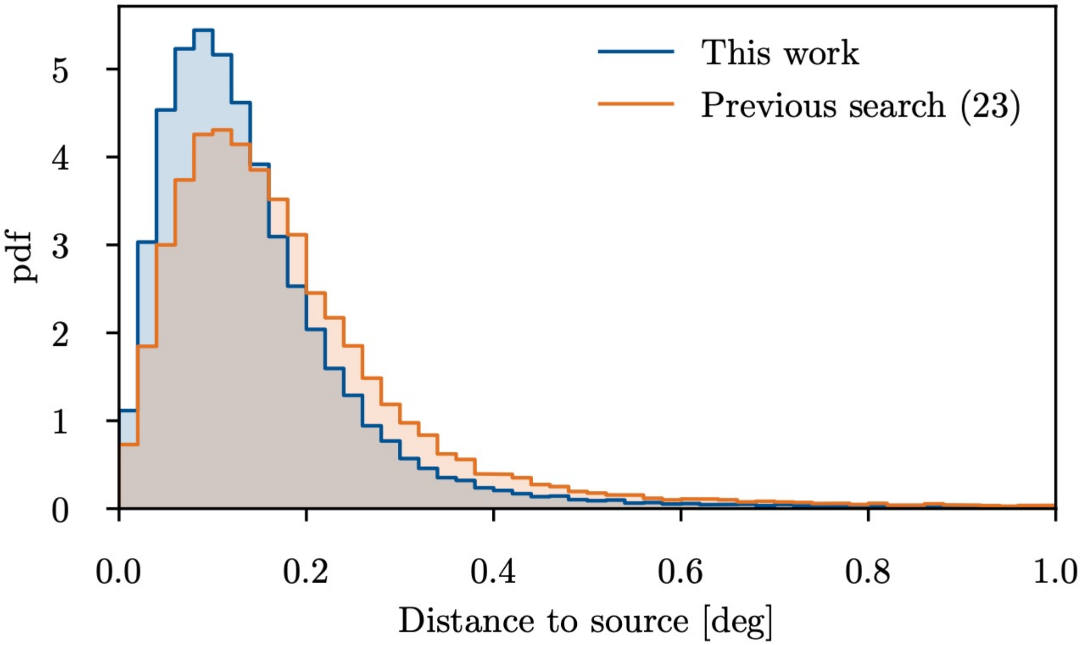
Location of Hottest Spot and NGC 1068



Hottest spot is 0.11° away from center of NGC 1068



Offset of Reconstructed hottest spot for Simulated Source



Localizing a source like NGC 1068: simulate with 80 events, $E^{-3.2}$ spectrum at dec=0°

Median offset of reconstructed hotspot from true source location: 0.12°

Catalog of 110 Objects

Based on 4th Fermi catalog of gamma-ray sources: 4FGL-2DR

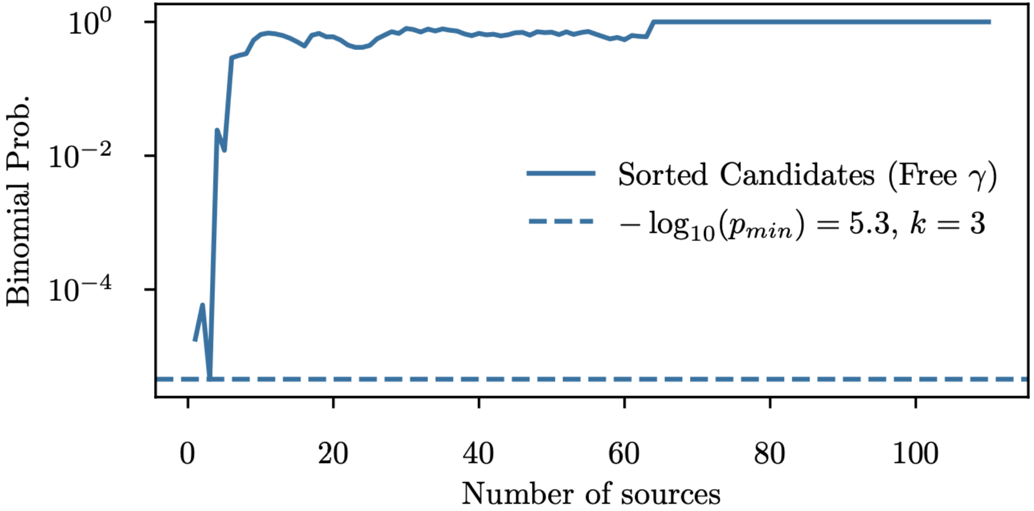
Selected a priori based on gamma-ray brightness and IceCube sensitivity at object's declination

95 are blazars
14 are AGN / other galaxies
1 Galactic source (MGRO J1908+06)

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{local}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5
PKS 0019+058	BLL	5.64	6.13	1	2.4	0.4 (0.2 σ)	2.6
1ES 0033+595 (*)	BLL	8.98	59.83	0	4.3	0.0 (0.0 σ)	5.0
M 31	GAL	10.82	41.24	13	3.3	0.8 (1.0 σ)	6.2
4C +01.02	FSRQ	17.17	1.58	0	4.3	0.0 (0.0 σ)	2.1
S2 0109+22	BLL	18.03	22.75	10	2.8	0.7 (0.8 σ)	4.8
B3 0133+388	BLL	24.14	39.10	0	4.3	0.0 (0.0 σ)	3.8
TXS 0141+268	BLL	26.15	27.09	0	4.3	0.0 (0.0 σ)	3.2
MITG J021114+1051	BLL	32.81	10.86	0	4.3	0.0 (0.0 σ)	2.6
PKS 0215+015	FSRQ	34.46	1.73	2	3.9	0.2 (0.0 σ)	1.9
B2 0218+357	FSRQ	35.28	35.94	8	4.3	0.4 (0.2 σ)	4.1
3C 66A	BLL	35.67	43.04	0	4.3	0.0 (0.0 σ)	3.9
4C +28.07	FSRQ	39.47	28.80	3	2.9	0.3 (0.0 σ)	3.4
PKS 0235+164	BLL	39.67	16.62	5	3.9	0.3 (0.0 σ)	2.8
NGC 1275	RDG	49.96	41.51	8	3.0	0.5 (0.5 σ)	5.1
PKS 0336-01	FSRQ	54.88	-1.78	4	4.3	0.3 (0.1 σ)	2.1
PKS 0420-01	FSRQ	65.83	-1.33	0	4.3	0.0 (0.0 σ)	2.0
4C +41.11 (*)	BLL	65.98	41.83	0	4.3	0.0 (0.0 σ)	3.9
PKS 0422+00	BLL	66.19	0.60	0	4.3	0.0 (0.0 σ)	2.1
MG2 J043337+2905	BLL	68.41	29.10	0	4.3	0.0 (0.0 σ)	3.4
PKS 0440-00	FSRQ	70.66	-0.30	1	2.7	0.3 (0.0 σ)	2.0
S3 0458-02	FSRQ	75.30	-1.97	9	4.3	0.5 (0.4 σ)	2.4
PKS 0502+049	FSRQ	76.34	5.00	0	4.3	0.0 (0.0 σ)	2.3
PKS 0507+17 (*)	FSRQ	77.52	18.01	0	4.3	0.0 (0.0 σ)	2.9
TXS 0518+211	BLL	80.44	21.21	8	2.8	0.6 (0.6 σ)	4.1
OG 050	FSRQ	83.17	7.55	10	3.8	0.4 (0.2 σ)	2.6
TXS 0603+476 (*)	BLL	91.86	47.66	19	4.3	0.6 (0.7 σ)	5.9
B3 0609+413	BLL	93.22	41.37	5	2.1	1.1 (1.4 σ)	7.3
NGC 2146 (*)	SBG	94.53	78.33	0	3.0	0.0 (0.0 σ)	6.7
B2 0619+33 (*)	BCU	95.73	33.43	22	3.8	0.7 (0.9 σ)	5.5
1ES 0647+250	BLL	102.70	25.05	0	4.3	0.0 (0.0 σ)	3.2
PMN J0709-0255 (*)	FSRQ	107.45	-2.93	0	2.5	0.0 (0.0 σ)	2.0
S5 0716+71	BLL	110.49	71.34	0	4.3	0.0 (0.0 σ)	6.6
4C +14.23	FSRQ	111.32	14.42	6	4.3	0.3 (0.0 σ)	2.6
PKS 0735+17	BLL	114.54	17.71	9	4.3	0.3 (0.1 σ)	3.1
PKS 0736+01	FSRQ	114.82	1.62	8	4.3	0.3 (0.1 σ)	2.1
1ES 0806+524	BLL	122.46	52.31	0	4.3	0.0 (0.0 σ)	4.3
OJ 014	BLL	122.86	1.78	30	4.0	0.9 (1.1 σ)	3.5
S4 0814+42	BLL	124.56	42.38	0	2.9	0.0 (0.0 σ)	3.9
PKS 0829+046	BLL	127.97	4.49	0	3.0	0.0 (0.0 σ)	2.2
SBS 0846+513 (*)	NLSY1	132.51	51.14	6	3.3	0.4 (0.3 σ)	5.1
OJ 287	BLL	133.71	20.12	16	4.3	0.5 (0.4 σ)	3.7
S4 0917+44 (*)	FSRQ	140.23	44.70	0	4.3	0.0 (0.0 σ)	4.1
PMN J0948+0022	NLSY1	147.24	0.37	6	4.3	0.3 (0.1 σ)	2.3
M 82	SBG	148.95	69.67	0	4.3	0.0 (0.0 σ)	6.6
4C +55.17	FSRQ	149.42	55.38	9	3.1	0.6 (0.6 σ)	6.1
1H 1013+498	BLL	153.77	49.43	0	4.3	0.0 (0.0 σ)	4.1
GB6 J1037+5711 (*)	BLL	159.43	57.19	0	4.3	0.0 (0.0 σ)	4.8
S5 1044+71 (*)	FSRQ	162.11	71.73	45	4.3	1.3 (1.6 σ)	14.0
NGC 3424 (*)	SBG	162.91	32.89	0	4.3	0.0 (0.0 σ)	3.5
4C +01.28	BLL	164.62	1.56	0	4.3	0.0 (0.0 σ)	2.1
TXS 1055+567 (*)	BLL	164.67	56.46	8	4.3	0.4 (0.3 σ)	5.0
Mkn 421	BLL	166.12	38.21	4	4.3	0.3 (0.0 σ)	3.7
IC 678 (*)	GAL	168.56	6.63	22	3.1	0.9 (1.2 σ)	4.0
Arp 299	SBG	172.07	58.52	10	4.3	0.4 (0.4 σ)	5.7
PKS B1130+008	BLL	173.20	0.57	20	3.9	0.7 (0.8 σ)	3.0
Ton 599	FSRQ	179.88	29.24	2	4.3	0.2 (0.0 σ)	3.0
B2 1215+30	BLL	184.48	30.12	15	3.1	0.9 (1.1 σ)	5.7
PKS 1216-010	BLL	184.64	-1.33	0	3.7	0.0 (0.0 σ)	2.0
PG 1218+304	BLL	185.34	30.17	0	3.1	0.0 (0.0 σ)	3.4
W Comae	BLL	185.38	28.24	0	4.3	0.0 (0.0 σ)	3.3
4C +21.35	FSRQ	186.23	21.38	0	4.3	0.0 (0.0 σ)	3.2
3C 273	FSRQ	187.27	2.05	21	4.3	0.6 (0.7 σ)	3.0
ON 246	BLL	187.56	25.30	0	4.3	0.0 (0.0 σ)	3.2
M 87	RDG	187.71	12.39	0	0.6	0.0 (0.0 σ)	2.8
MITG J123931+0443	FSRQ	189.89	4.73	0	4.3	0.0 (0.0 σ)	2.4
PG 1246+586	BLL	192.08	58.34	0	4.3	0.0 (0.0 σ)	4.8
S4 1250+53	BLL	193.31	53.02	0	4.3	0.0 (0.0 σ)	4.0
B3 1343+451	FSRQ	206.39	44.88	5	2.9	0.4 (0.3 σ)	4.7
NGC 5380 (*)	GAL	209.33	37.50	4	2.4	0.9 (1.2 σ)	6.4
NVSS J141826-023336	BLL	214.61	-2.56	6	3.9	0.4 (0.4 σ)	2.3
PKS 1441+25	FSRQ	220.99	25.03	3	2.1	0.7 (0.9 σ)	5.0
TXS 1452+516 (*)	BLL	223.62	51.41	0	2.3	0.0 (0.0 σ)	4.4
PKS 1502+106	FSRQ	226.10	10.50	1	1.8	0.5 (0.5 σ)	3.4
PKS 1502+036	NLSY1	226.27	3.45	0	4.3	0.0 (0.0 σ)	2.1
B2 1520+31	FSRQ	230.55	31.74	35	4.3	1.0 (1.3 σ)	6.2
Arp 220 (*)	SBG	233.70	23.53	0	4.3	0.0 (0.0 σ)	3.1
GB6 J1542+6129	BLL	235.76	61.50	16	3.0	1.9 (2.2 σ)	13.0
PG 1553+113	BLL	238.93	11.19	2	4.3	0.2 (0.0 σ)	2.3
4C +15.54 (*)	BLL	241.77	15.84	0	4.3	0.0 (0.0 σ)	2.9
4C +38.41	FSRQ	248.82	38.14	4	2.3	0.9 (1.1 σ)	6.2
Mkn 501	BLL	253.47	39.76	15	4.3	0.5 (0.5 σ)	5.0
PKS 1717+177	BLL	259.81	17.75	34	4.3	1.0 (1.2 σ)	5.1
1H 1720+117	BLL	261.27	11.87	0	4.3	0.0 (0.0 σ)	2.7
S4 1749+70	BLL	267.16	70.10	0	4.3	0.0 (0.0 σ)	6.6
OT 081	BLL	267.88	9.65	0	2.9	0.0 (0.0 σ)	2.7
RX J1754.1+3212 (*)	BLL	268.55	32.20	0	4.3	0.0 (0.0 σ)	3.4
S5 1803+784 (*)	BLL	270.17	78.47	0	2.7	0.0 (0.0 σ)	7.5
NVSS J184425+154646 (*)	BLL	281.12	15.79	11	4.3	0.4 (0.2 σ)	3.1
LQAC 284+003 (*)	BCU	284.48	3.22	12	2.5	2.0 (2.3 σ)	5.2
TXS 1902+556	BLL	285.81	55.68	3	4.3	0.3 (0.0 σ)	4.6
MGRO J1908+06	UID	286.91	6.32	2	1.8	1.4 (1.7 σ)	4.8
RX J1931.1+0937	BLL	292.78	9.63	15	4.3	0.5 (0.4 σ)	3.1
87GB 194024.3+102612 (*)	BLL	295.70	10.56	0	4.3	0.0 (0.0 σ)	2.6
1ES 1959+650	BLL	300.01	65.15	8	3.4	0.5 (0.4 σ)	7.2
MITG J200112+4352	BLL	300.30	43.89	3	4.3	0.3 (0.0 σ)	3.6
7C 2010+4619 (*)	BLL	303.02	46.49	4	2.5	0.7 (0.9 σ)	6.4
MITG J201534+3710	FSRQ	303.89	37.18	19	3.6	0.7 (0.9 σ)	5.5
PKS 2032+107	FSRQ	308.85	10.94	0	4.3	0.0 (0.0 σ)	2.8
B2 2114+33	BLL	319.06	33.66	12	2.9	0.8 (0.9 σ)	5.7
OX 169	FSRQ	325.89	17.73	4	4.3	0.3 (0.0 σ)	2.7
BL Lac	BLL	330.69	42.28	11	4.3	0.4 (0.3 σ)	4.7
CTA 102	FSRQ	338.15	11.73	0	4.3	0.0 (0.0 σ)	2.6
B2 2234+28A (*)	FSRQ	339.10	28.48	8	3.2	0.4 (0.3 σ)	4.1
RGB J2243+203	BLL	340.99	20.36	5	3.6	0.3 (0.0 σ)	2.8
TXS 2241+406	FSRQ	341.06	40.96	0	4.3	0.0 (0.0 σ)	3.9
3C 454.3	FSRQ	343.50	16.15	1	1.5	1.2 (1.6 σ)	5.5
B2 2308+34 (*)	FSRQ	347.77	34.42	19	3.6	0.7 (0.9 σ)	5.6

Catalog of 110 Objects

Binomial Test



1 in 10,000 scrambled data sets have binomial test result $-\log_{10}(p_{min}) \geq 5.3$

= 3.7 **σ** evidence

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{local}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5
PKS 0019+058	BLL	5.64	6.13	1	2.4	0.4 (0.2 σ)	2.6
1ES 0033+595 (*)	BLL	8.98	59.83	0	4.3	0.0 (0.0 σ)	5.0
M 31	GAL	10.82	41.24	13	3.3	0.8 (1.0 σ)	6.2
4C +01.02	FSRQ	17.17	1.58	0	4.3	0.0 (0.0 σ)	2.1
S2 0109+22	BLL	18.03	22.75	10	2.8	0.7 (0.8 σ)	4.8
B3 0133+388	BLL	24.14	39.10	0	4.3	0.0 (0.0 σ)	3.8
TXS 0141+268	BLL	26.15	27.09	0	4.3	0.0 (0.0 σ)	3.2
MITG J021114+1051	BLL	32.81	10.86	0	4.3	0.0 (0.0 σ)	2.6
				2	3.9	0.2 (0.0 σ)	1.9
				8	4.3	0.4 (0.2 σ)	4.1
				0	4.3	0.0 (0.0 σ)	3.9
				3	2.9	0.3 (0.0 σ)	3.4
				5	3.9	0.3 (0.0 σ)	2.8
				8	3.0	0.5 (0.5 σ)	5.1
				4	4.3	0.3 (0.1 σ)	2.1
				0	4.3	0.0 (0.0 σ)	2.0
				0	4.3	0.0 (0.0 σ)	3.9
				0	4.3	0.0 (0.0 σ)	2.1
				0	4.3	0.0 (0.0 σ)	3.4
				1	2.7	0.3 (0.0 σ)	2.0
				9	4.3	0.5 (0.4 σ)	2.4
				0	4.3	0.0 (0.0 σ)	2.3
				0	4.3	0.0 (0.0 σ)	2.9
				8	2.8	0.6 (0.6 σ)	4.1
				10	3.8	0.4 (0.2 σ)	2.6
				19	4.3	0.6 (0.7 σ)	5.9
				5	2.1	1.1 (1.4 σ)	7.3
				0	3.0	0.0 (0.0 σ)	6.7
				22	3.8	0.7 (0.9 σ)	5.5
				0	4.3	0.0 (0.0 σ)	3.2
				0	2.5	0.0 (0.0 σ)	2.0
				0	4.3	0.0 (0.0 σ)	6.6
				6	4.3	0.3 (0.0 σ)	2.6
				9	4.3	0.3 (0.1 σ)	3.1
				8	4.3	0.3 (0.1 σ)	2.1
				0	4.3	0.0 (0.0 σ)	4.3
				30	4.0	0.9 (1.1 σ)	3.5
				0	2.9	0.0 (0.0 σ)	3.9
				0	3.0	0.0 (0.0 σ)	2.2
				6	3.3	0.4 (0.3 σ)	5.1
OJ 287	BLL	133.71	20.12	16	4.3	0.5 (0.4 σ)	3.7
S4 0917+44 (*)	FSRQ	140.23	44.70	0	4.3	0.0 (0.0 σ)	4.1
PMN J0948+0022	NLSY1	147.24	0.37	6	4.3	0.3 (0.1 σ)	2.3
	SBG	148.95	69.67	0	4.3	0.0 (0.0 σ)	6.6
	SRQ	149.42	55.38	9	3.1	0.6 (0.6 σ)	6.1
	BLL	153.77	49.43	0	4.3	0.0 (0.0 σ)	4.1
	BLL	159.43	57.19	0	4.3	0.0 (0.0 σ)	4.8
	SRQ	162.11	71.73	45	4.3	1.3 (1.6 σ)	14.0
	SBG	162.91	32.89	0	4.3	0.0 (0.0 σ)	3.5
	BLL	164.62	1.56	0	4.3	0.0 (0.0 σ)	2.1
	BLL	164.67	56.46	8	4.3	0.4 (0.3 σ)	5.0
	BLL	166.12	38.21	4	4.3	0.3 (0.0 σ)	3.7
	GAL	168.56	6.63	22	3.1	0.9 (1.2 σ)	4.0
	SBG	172.07	58.52	10	4.3	0.4 (0.4 σ)	5.7
	BLL	173.20	0.57	20	3.9	0.7 (0.8 σ)	3.0
	SRQ	179.88	29.24	2	4.3	0.2 (0.0 σ)	3.0
B2 1215+30	BLL	184.48	30.12	15	3.1	0.9 (1.1 σ)	5.7
PKS 1216-010	BLL	184.64	-1.33	0	3.7	0.0 (0.0 σ)	2.0

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{local}$	$\Phi_{90\%}$
PG 1218+304	BLL	185.34	30.17	0	3.1	0.0 (0.0 σ)	3.4
W Comae	BLL	185.38	28.24	0	4.3	0.0 (0.0 σ)	3.3
4C +21.35	FSRQ	186.23	21.38	0	4.3	0.0 (0.0 σ)	3.2
3C 273	FSRQ	187.27	2.05	21	4.3	0.6 (0.7 σ)	3.0
ON 246	BLL	187.56	25.30	0	4.3	0.0 (0.0 σ)	3.2
M 87	RDG	187.71	12.39	0	0.6	0.0 (0.0 σ)	2.8
MITG J123931+0443	FSRQ	189.89	4.73	0	4.3	0.0 (0.0 σ)	2.4
PG 1246+586	BLL	192.08	58.34	0	4.3	0.0 (0.0 σ)	4.8
S4 1250+53	BLL	193.31	53.02	0	4.3	0.0 (0.0 σ)	4.0
B3 1343+451	FSRQ	206.39	44.88	5	2.9	0.4 (0.3 σ)	4.7
NGC 5380 (*)	GAL	209.33	37.50	4	2.4	0.9 (1.2 σ)	6.4
NVSS J141826-023336	BLL	214.61	-2.56	6	3.9	0.4 (0.4 σ)	2.3
PKS 1441+25	FSRQ	220.99	25.03	3	2.1	0.7 (0.9 σ)	5.0
TXS 1452+516 (*)	BLL	223.62	51.41	0	2.3	0.0 (0.0 σ)	4.4
PKS 1502+106	FSRQ	226.10	10.50	1	1.8	0.5 (0.5 σ)	3.4
PKS 1502+036	NLSY1	226.27	3.45	0	4.3	0.0 (0.0 σ)	2.1
B2 1520+31	FSRQ	230.55	31.74	35	4.3	1.0 (1.3 σ)	6.2
Arp 220 (*)	SBG	233.70	23.53	0	4.3	0.0 (0.0 σ)	3.1
GB6 J1542+6129	BLL	235.76	61.50	16	3.0	1.9 (2.2 σ)	13.0
PG 1553+113	BLL	238.93	11.19	2	4.3	0.2 (0.0 σ)	2.3
4C +15.54 (*)	BLL	241.77	15.84	0	4.3	0.0 (0.0 σ)	2.9
4C +38.41	FSRQ	248.82	38.14	4	2.3	0.9 (1.1 σ)	6.2
Mkn 501	BLL	253.47	39.76	15	4.3	0.5 (0.5 σ)	5.0
PKS 1717+177	BLL	259.81	17.75	34	4.3	1.0 (1.2 σ)	5.1
1H 1720+117	BLL	261.27	11.87	0	4.3	0.0 (0.0 σ)	2.7
S4 1749+70	BLL	267.16	70.10	0	4.3	0.0 (0.0 σ)	6.6
OT 081	BLL	267.88	9.65	0	2.9	0.0 (0.0 σ)	2.7
RX J1754.1+3212 (*)	BLL	268.55	32.20	0	4.3	0.0 (0.0 σ)	3.4
S5 1803+784 (*)	BLL	270.17	78.47	0	2.7	0.0 (0.0 σ)	7.5
NVSS J184425+154646 (*)	BLL	281.12	15.79	11	4.3	0.4 (0.2 σ)	3.1
LQAC 284+003 (*)	BCU	284.48	3.22	12	2.5	2.0 (2.3 σ)	5.2
TXS 1902+556	BLL	285.81	55.68	3	4.3	0.3 (0.0 σ)	4.6
MGRO J1908+06	UID	286.91	6.32	2	1.8	1.4 (1.7 σ)	4.8
RX J1931.1+0937	BLL	292.78	9.63	15	4.3	0.5 (0.4 σ)	3.1
87GB 194024.3+102612 (*)	BLL	295.70	10.56	0	4.3	0.0 (0.0 σ)	2.6
1ES 1959+650	BLL	300.01	65.15	8	3.4	0.5 (0.4 σ)	7.2
MITG J200112+4352	BLL	300.30	43.89	3	4.3	0.3 (0.0 σ)	3.6
7C 2010+4619 (*)	BLL	303.02	46.49	4	2.5	0.7 (0.9 σ)	6.4
MITG J201534+3710	FSRQ	303.89	37.18	19	3.6	0.7 (0.9 σ)	5.5
PKS 2032+107	FSRQ	308.85	10.94	0	4.3	0.0 (0.0 σ)	2.8
B2 2114+33	BLL	319.06	33.66	12	2.9	0.8 (0.9 σ)	5.7
OX 169	FSRQ	325.89	17.73	4	4.3	0.3 (0.0 σ)	2.7
BL Lac	BLL	330.69	42.28	11	4.3	0.4 (0.3 σ)	4.7
CTA 102	FSRQ	338.15	11.73	0	4.3	0.0 (0.0 σ)	2.6
B2 2234+28A (*)	FSRQ	339.10	28.48	8	3.2	0.4 (0.3 σ)	4.1
RGB J2243+203	BLL	340.99	20.36	5	3.6	0.3 (0.0 σ)	2.8
TXS 2241+406	FSRQ	341.06	40.96	0	4.3	0.0 (0.0 σ)	3.9
3C 454.3	FSRQ	343.50	16.15	1	1.5	1.2 (1.6 σ)	5.5
B2 2308+34 (*)	FSRQ	347.77	34.42	19	3.6	0.7 (0.9 σ)	5.6

Catalog of 110 Objects

Binomial Test

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{local}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{local}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5

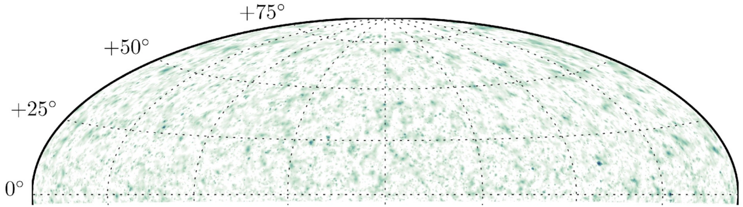
Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{local}$	$\Phi_{90\%}$
PKS 0019+058	BLL	5.64	6.13	1	2.4	0.4 (0.2 σ)	2.6
1ES 0033+595 (*)	BLL	8.98	59.83	0	4.3	0.0 (0.0 σ)	5.0
M 31	GAL	10.82	41.24	13	3.3	0.8 (1.0 σ)	6.2
4C +01.02	FSRQ	17.17	1.58	0	4.3	0.0 (0.0 σ)	2.1
S2 0109+22	BLL	18.03	22.75	10	2.8	0.7 (0.8 σ)	4.8
B3 0133+388	BLL	24.14	39.10	0	4.3	0.0 (0.0 σ)	3.8
TXS 0141+268	BLL	26.15	27.09	0	4.3	0.0 (0.0 σ)	3.2
MITG J021114+1051	BLL	32.81	10.86	0	4.3	0.0 (0.0 σ)	2.6
PKS 0215+015	FSRQ	34.46	1.73	2	3.9	0.2 (0.0 σ)	1.9
B2 0218+357	FSRQ	35.28	35.94	8	4.3	0.4 (0.2 σ)	4.1
3C 66A	BLL	35.67	43.04	0	4.3	0.0 (0.0 σ)	3.9
4C +28.07	FSRQ	39.47	28.80	3	2.9	0.3 (0.0 σ)	3.4
PKS 0235+164	BLL	39.67	16.62	5	3.9	0.3 (0.0 σ)	2.8
NGC 1275	RDG	49.96	41.51	8	3.0	0.5 (0.5 σ)	5.1
PKS 0336-01	FSRQ	54.88	-1.78	4	4.3	0.3 (0.1 σ)	2.1
PKS 0420-01	FSRQ	65.83	-1.33	0	4.3	0.0 (0.0 σ)	2.0
4C +41.11 (*)	BLL	65.98	41.83	0	4.3	0.0 (0.0 σ)	3.9
PMN J0709-0255 (*)	FSRQ	107.43	-2.93	0	2.5	0.0 (0.0 σ)	2.0
S5 0716+71	BLL	110.49	71.34	0	4.3	0.0 (0.0 σ)	6.6
4C +14.23	FSRQ	111.32	14.42	6	4.3	0.3 (0.0 σ)	2.6
PKS 0735+17	BLL	114.54	17.71	9	4.3	0.3 (0.1 σ)	3.1
PKS 0736+01	FSRQ	114.82	1.62	8	4.3	0.3 (0.1 σ)	2.1
1ES 0806+524	BLL	122.46	52.31	0	4.3	0.0 (0.0 σ)	4.3
OJ 014	BLL	122.86	1.78	30	4.0	0.9 (1.1 σ)	3.5
S4 0814+42	BLL	124.56	42.38	0	2.9	0.0 (0.0 σ)	3.9
PKS 0829+046	BLL	127.97	4.49	0	3.0	0.0 (0.0 σ)	2.2
SBS 0846+513 (*)	NLSY1	132.51	51.14	6	3.3	0.4 (0.3 σ)	5.1
OJ 287	BLL	133.71	20.12	16	4.3	0.5 (0.4 σ)	3.7
S4 0917+44 (*)	FSRQ	140.23	44.70	0	4.3	0.0 (0.0 σ)	4.1
PMN J0948+0022	NLSY1	147.24	0.37	6	4.3	0.3 (0.1 σ)	2.3
	SBG	148.95	69.67	0	4.3	0.0 (0.0 σ)	6.6
	SRQ	149.42	55.38	9	3.1	0.6 (0.6 σ)	6.1
	BLL	153.77	49.43	0	4.3	0.0 (0.0 σ)	4.1
	BLL	159.43	57.19	0	4.3	0.0 (0.0 σ)	4.8
	SRQ	162.11	71.73	45	4.3	1.3 (1.6 σ)	14.0
	SBG	162.91	32.89	0	4.3	0.0 (0.0 σ)	3.5
	BLL	164.62	1.56	0	4.3	0.0 (0.0 σ)	2.1
	BLL	164.67	56.46	8	4.3	0.4 (0.3 σ)	5.0
	BLL	166.12	38.21	4	4.3	0.3 (0.0 σ)	3.7
	GAL	168.56	6.63	22	3.1	0.9 (1.2 σ)	4.0
	SBG	172.07	58.52	10	4.3	0.4 (0.4 σ)	5.7
	BLL	173.20	0.57	20	3.9	0.7 (0.8 σ)	3.0
	SRQ	179.88	29.24	2	4.3	0.2 (0.0 σ)	3.0
B2 1215+30	BLL	184.48	30.12	15	3.1	0.9 (1.1 σ)	5.7
PKS 1216-010	BLL	184.64	-1.33	0	3.7	0.0 (0.0 σ)	2.0
PG 1218+304	BLL	185.34	30.17	0	3.1	0.0 (0.0 σ)	3.4
W Comae	BLL	185.38	28.24	0	4.3	0.0 (0.0 σ)	3.3
4C +21.35	FSRQ	186.23	21.38	0	4.3	0.0 (0.0 σ)	3.2
3C 273	FSRQ	187.27	2.05	21	4.3	0.6 (0.7 σ)	3.0
ON 246	BLL	187.56	25.30	0	4.3	0.0 (0.0 σ)	3.2
M 87	RDG	187.71	12.39	0	0.6	0.0 (0.0 σ)	2.8
MITG J123931+0443	FSRQ	189.89	4.73	0	4.3	0.0 (0.0 σ)	2.4
PG 1246+586	BLL	192.08	58.34	0	4.3	0.0 (0.0 σ)	4.8
S4 1250+53	BLL	193.31	53.02	0	4.3	0.0 (0.0 σ)	4.0
B3 1343+451	FSRQ	206.39	44.88	5	2.9	0.4 (0.3 σ)	4.7
NGC 5380 (*)	GAL	209.33	37.50	4	2.4	0.9 (1.2 σ)	6.4
NVSS J141826-023336	BLL	214.61	-2.56	6	3.9	0.4 (0.4 σ)	2.3
PKS 1441+25	FSRQ	220.99	25.03	3	2.1	0.7 (0.9 σ)	5.0
TXS 1452+516 (*)	BLL	223.62	51.41	0	2.3	0.0 (0.0 σ)	4.4
PKS 1502+106	FSRQ	226.10	10.50	1	1.8	0.5 (0.5 σ)	3.4
PKS 1502+036	NLSY1	226.27	3.45	0	4.3	0.0 (0.0 σ)	2.1
B2 1520+31	FSRQ	230.55	31.74	35	4.3	1.0 (1.3 σ)	6.2
Arp 220 (*)	SBG	233.70	23.53	0	4.3	0.0 (0.0 σ)	3.1
GB6 J1542+6129	BLL	235.76	61.50	16	3.0	1.9 (2.2 σ)	13.0
PG 1553+113	BLL	238.93	11.19	2	4.3	0.2 (0.0 σ)	2.3
4C +15.54 (*)	BLL	241.77	15.84	0	4.3	0.0 (0.0 σ)	2.9
	SRQ	248.82	38.14	4	2.3	0.9 (1.1 σ)	6.2
	LL	253.47	39.76	15	4.3	0.5 (0.5 σ)	5.0
	LL	259.81	17.75	34	4.3	1.0 (1.2 σ)	5.1
	LL	261.27	11.87	0	4.3	0.0 (0.0 σ)	2.7
	LL	267.16	70.10	0	4.3	0.0 (0.0 σ)	6.6
	LL	267.88	9.65	0	2.9	0.0 (0.0 σ)	2.7
	LL	268.55	32.20	0	4.3	0.0 (0.0 σ)	3.4
	LL	270.17	78.47	0	2.7	0.0 (0.0 σ)	7.5
	LL	281.12	15.79	11	4.3	0.4 (0.2 σ)	3.1
	CU	284.48	3.22	12	2.5	2.0 (2.3 σ)	5.2
	LL	285.81	55.68	3	4.3	0.3 (0.0 σ)	4.6
	ID	286.91	6.32	2	1.8	1.4 (1.7 σ)	4.8
	LL	292.78	9.63	15	4.3	0.5 (0.4 σ)	3.1
	LL	295.70	10.56	0	4.3	0.0 (0.0 σ)	2.6
1ES 1959+650	BLL	300.01	65.15	8	3.4	0.5 (0.4 σ)	7.2
MITG J200112+4352	BLL	300.30	43.89	3	4.3	0.3 (0.0 σ)	3.6
7C 2010+4619 (*)	BLL	303.02	46.49	4	2.5	0.7 (0.9 σ)	6.4
MITG J201534+3710	FSRQ	303.89	37.18	19	3.6	0.7 (0.9 σ)	5.5
PKS 2032+107	FSRQ	308.85	10.94	0	4.3	0.0 (0.0 σ)	2.8
B2 2114+33	BLL	319.06	33.66	12	2.9	0.8 (0.9 σ)	5.7
OX 169	FSRQ	325.89	17.73	4	4.3	0.3 (0.0 σ)	2.7
BL Lac	BLL	330.69	42.28	11	4.3	0.4 (0.3 σ)	4.7
CTA 102	FSRQ	338.15	11.73	0	4.3	0.0 (0.0 σ)	2.6
B2 2234+28A (*)	FSRQ	339.10	28.48	8	3.2	0.4 (0.3 σ)	4.1
RGB J2243+203	BLL	340.99	20.36	5	3.6	0.3 (0.0 σ)	2.8
TXS 2241+406	FSRQ	341.06	40.96	0	4.3	0.0 (0.0 σ)	3.9
3C 454.3	FSRQ	343.50	16.15	1	1.5	1.2 (1.6 σ)	5.5
B2 2308+34 (*)	FSRQ	347.77	34.42	19	3.6	0.7 (0.9 σ)	5.6

1 in 10,000 scrambled data sets have binomial test result $-\log_{10}(p_{min}) \geq 5.3$

= 3.7 **σ** evidence

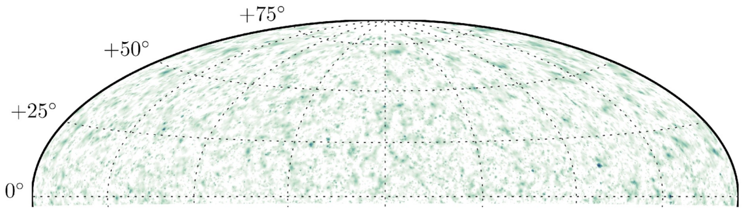
Hottest SpotS in Northern Sky Neutrino Map

	α [°]	δ [°]	$\hat{\mu}_{\rm ns}$	$\hat{\gamma}$	$-\log_{10}(p_{local})$
$\boldsymbol{\gamma = 2.0}$					
#1	76.93	12.90	13.4	2.00	6.08
#2	9.76	7.50	4.9	2.00	5.04
#3	77.37	5.57	6.2	2.00	4.88
#4	179.25	52.44	5.5	2.00	4.87
#5	202.63	33.89	7.1	2.00	4.74
$\boldsymbol{\gamma = 2.5}$					
#1	40.65	0.09	36.8	2.50	5.84
#2	177.91	23.24	21.4	2.50	5.45
#3	105.78	1.03	23.6	2.50	5.17
#4	182.46	39.52	22.2	2.50	4.91
#5	180.16	42.21	26.0	2.50	4.86
Free γ					
#1	40.69	0.09	80.7	3.20	7.30
#2	297.27	27.45	69.8	3.24	5.51
#3	76.93	12.90	11.2	1.81	5.37
#4	180.20	42.19	47.8	3.03	4.80
#5	208.15	23.16	55.5	3.19	4.60



Hottest SpotS in Northern Sky Neutrino Map

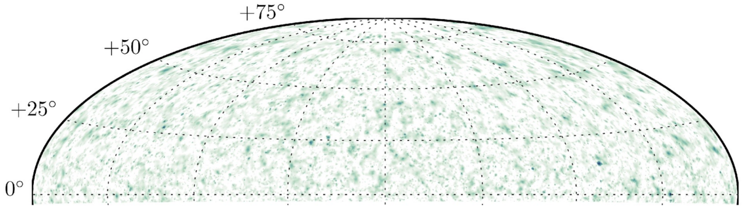
	α [°]	δ [°]	$\hat{\mu}_{\text{ns}}$	$\hat{\gamma}$	$-\log_{10}(p_{local})$
$\boldsymbol{\gamma = 2.0}$					
#1	76.93	12.90	13.4	2.00	6.08
#2	9.76	7.50	4.9	2.00	5.04
#3	77.37	5.57	6.2	2.00	4.88
#4	179.25	52.44	5.5	2.00	4.87
#5	202.63	33.89	7.1	2.00	4.74
$\boldsymbol{\gamma = 2.5}$					
#1	40.65	0.09	36.8	2.50	5.84
#2	177.91	23.24	21.4	2.50	5.45
#3	105.78	1.03	23.6	2.50	5.17
#4	182.46	39.52	22.2	2.50	4.91
#5	180.16	42.21	26.0	2.50	4.86
Free γ					
#1	40.69	0.09	80.7	3.20	7.30
#2	297.27	27.45	69.8	3.24	5.51
#3	76.93	12.90	11.2	1.81	5.37
#4	180.20	42.19	47.8	3.03	4.80
#5	208.15	23.16	55.5	3.19	4.60



NGC 1068

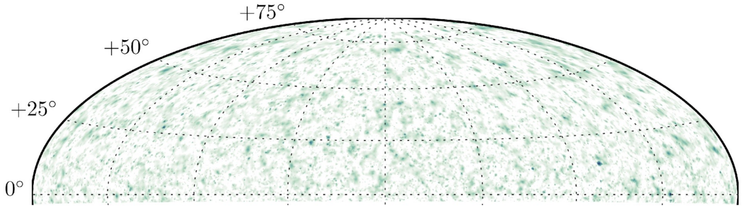
Hottest SpotS in Northern Sky Neutrino Map

	α [°]	δ [°]	$\hat{\mu}_{\rm ns}$	$\hat{\gamma}$	$-\log_{10}(p_{local})$
$\gamma = \mathbf{2.0}$					
#1	76.93	12.90	13.4	2.00	6.08
#2	9.76	7.50	4.9	2.00	5.04
#3	77.37	5.57	6.2	2.00	4.88
#4	179.25	52.44	5.5	2.00	4.87
#5	202.63	33.89	7.1	2.00	4.74
$\gamma = \mathbf{2.5}$					
#1	40.65	0.09	36.8	2.50	5.84
#2	177.91	23.24	21.4	2.50	5.45
#3	105.78	1.03	23.6	2.50	5.17
#4	182.46	39.52	22.2	2.50	4.91
#5	180.16	42.21	26.0	2.50	4.86
Free γ					
#1	40.69	0.09	80.7	3.20	7.30
#2	297.27	27.45	69.8	3.24	5.51
#3	76.93	12.90	11.2	1.81	5.37
#4	180.20	42.19	47.8	3.03	4.80
#5	208.15	23.16	55.5	3.19	4.60



NGC 1068

Hottest SpotS in Northern Sky Neutrino Map



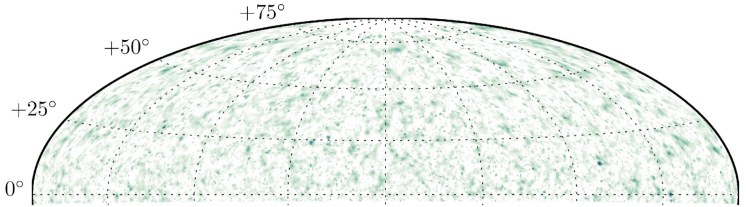
	α [°]	δ [°]	$\hat{\mu}_{ns}$	$\hat{\gamma}$	$-\log_{10}(p_{local})$
$\gamma = 2.0$					
#1	76.93	12.90	13.4	2.00	6.08
#2	9.76	7.50	4.9	2.00	5.04
#3	77.37	5.57	6.2	2.00	4.88
#4	179.25	52.44	5.5	2.00	4.87
#5	202.63	33.89	7.1	2.00	4.74
$\gamma = 2.5$					
#1	40.65	0.09	36.8	2.50	5.84
#2	177.91	23.24	21.4	2.50	5.45
#3	105.78	1.03	23.6	2.50	5.17
#4	182.46	39.52	22.2	2.50	4.91
#5	180.16	42.21	26.0	2.50	4.86
Free γ					
#1	40.69	0.09	80.7	3.20	7.30
#2	297.27	27.45	69.8	3.24	5.51
#3	76.93	12.90	11.2	1.81	5.37
#4	180.20	42.19	47.8	3.03	4.80
#5	208.15	23.16	55.5	3.19	4.60

TXS 0506+056 ($\gamma = 2.0$, #3)

NGC 1068 ($\gamma = 2.5$, #1; Free γ, #1)

Hottest SpotS in Northern Sky Neutrino Map

	α [°]	δ [°]	$\hat{\mu}_{ns}$	$\hat{\gamma}$	$-\log_{10}(p_{local})$
$\gamma = 2.0$					
#1	76.93	12.90	13.4	2.00	6.08
#2	9.76	7.50	4.9	2.00	5.04
#3	77.37	5.57	6.2	2.00	4.88
#4	179.25	52.44	5.5	2.00	4.87
#5	202.63	33.89	7.1	2.00	4.74
$\gamma = 2.5$					
#1	40.65	0.09	36.8	2.50	5.84
#2	177.91	23.24	21.4	2.50	5.45
#3	105.78	1.03	23.6	2.50	5.17
#4	182.46	39.52	22.2	2.50	4.91
#5	180.16	42.21	26.0	2.50	4.86
Free γ					
#1	40.69	0.09	80.7	3.20	7.30
#2	297.27	27.45	69.8	3.24	5.51
#3	76.93	12.90	11.2	1.81	5.37
#4	180.20	42.19	47.8	3.03	4.80
#5	208.15	23.16	55.5	3.19	4.60



TXS 0506+056 (γ = 2.0 #3)

NGC 4151 (0.18° offset) (γ = 2.5 #4)

NGC 1068 (γ = 2.5 #1; Free γ #1)

NGC 1068 & NGC 4151: Original Seyfert Galaxies

NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

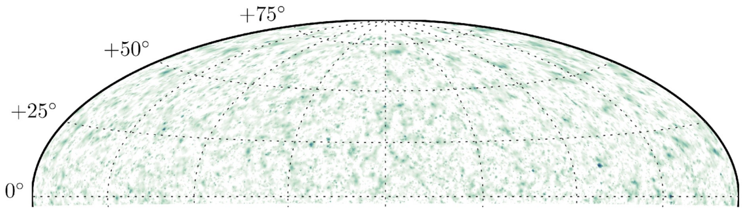
Astrophysical Journal, vol. 97, p.28 (1943)

We conclude that active galactic nuclei are powerful sources for accelerating particles to cosmic ray energies. The bulk of metagalactic cosmic rays is likely to originate in the AGN. In particular, in the Virgo supercluster, the two Seyfert galaxies NGC 4151 and NGC 1068 are likely to be the sources of most of the "local" metagalactic cosmic rays, including those that generate the ultra-high energy ($E \geqslant 10^{19}$ eV) air showers. The energy

R. Silberberg and M. M. Shapiro (1982)

Hottest SpotS in Northern Sky Neutrino Map

	α [°]	δ [°]	$\hat{\mu}_{\text{ns}}$	$\hat{\gamma}$	$-\log_{10}(p_{local})$
$\gamma = 2.0$					
#1	76.93	12.90	13.4	2.00	6.08
#2	9.76	7.50	4.9	2.00	5.04
#3	77.37	5.57	6.2	2.00	4.88
#4	179.25	52.44	5.5	2.00	4.87
#5	202.63	33.89	7.1	2.00	4.74
$\gamma = 2.5$					
#1	40.65	0.09	36.8	2.50	5.84
#2	177.91	23.24	21.4	2.50	5.45
#3	105.78	1.03	23.6	2.50	5.17
#4	182.46	39.52	22.2	2.50	4.91
#5	180.16	42.21	26.0	2.50	4.86
Free γ					
#1	40.69	0.09	80.7	3.20	7.30
#2	297.27	27.45	69.8	3.24	5.51
#3	76.93	12.90	11.2	1.81	5.37
#4	180.20	42.19	47.8	3.03	4.80
#5	208.15	23.16	55.5	3.19	4.60

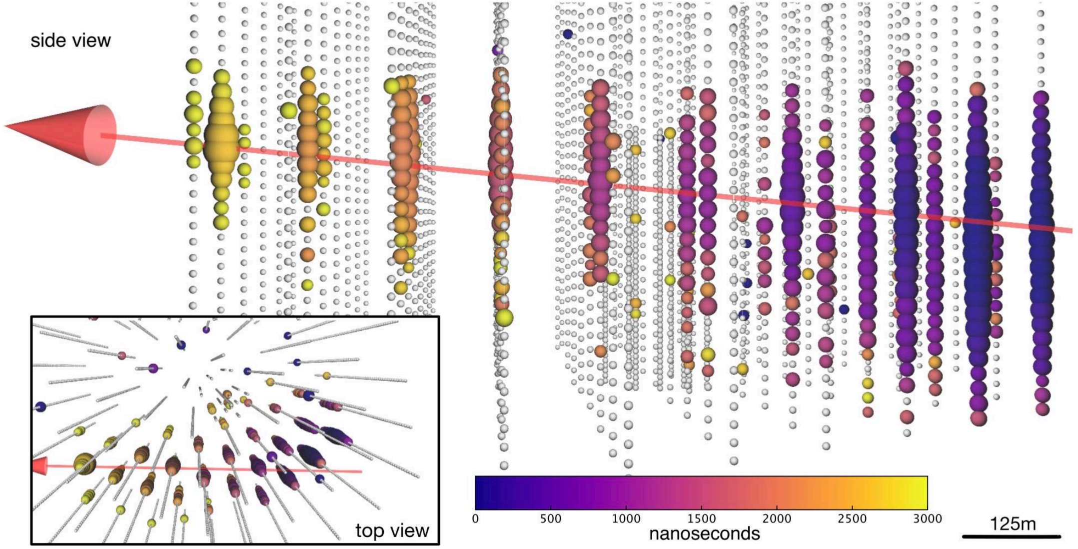


TXS 0506+056

NGC 4151
(0.18° offset)

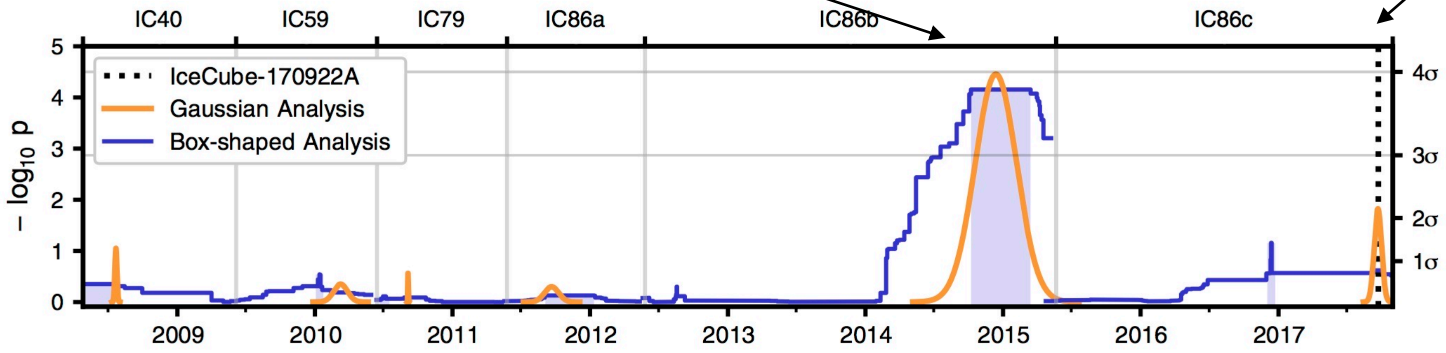
NGC 1068

TXS 0506+056



3.5 **σ**
"untriggered"
flare analysis

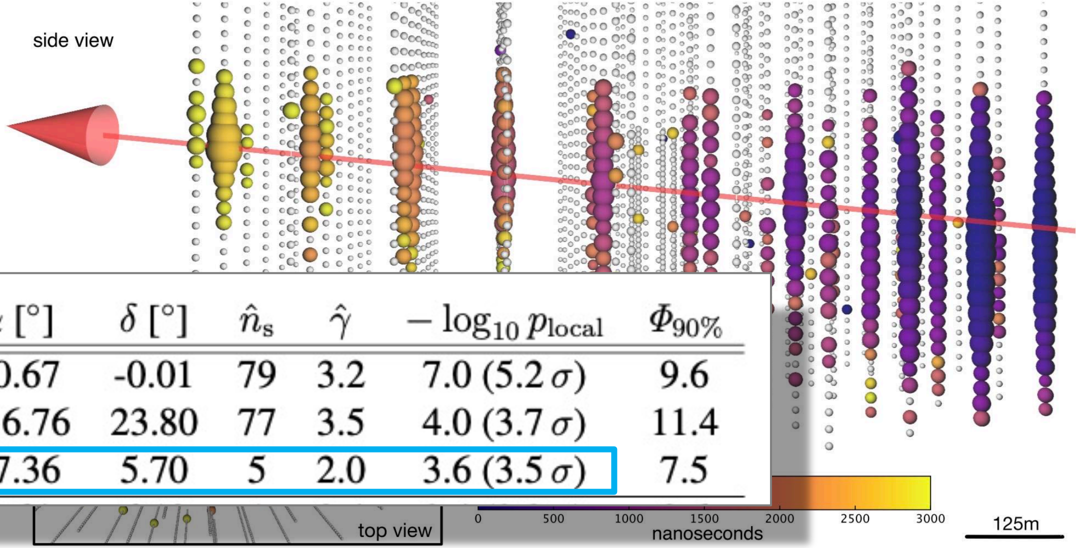
Science 361, 6398, (2018) 147



Science 361, 6398, (2018) eaat1378

3 **σ** coincidence with gamma-ray flare

TXS 0506+056



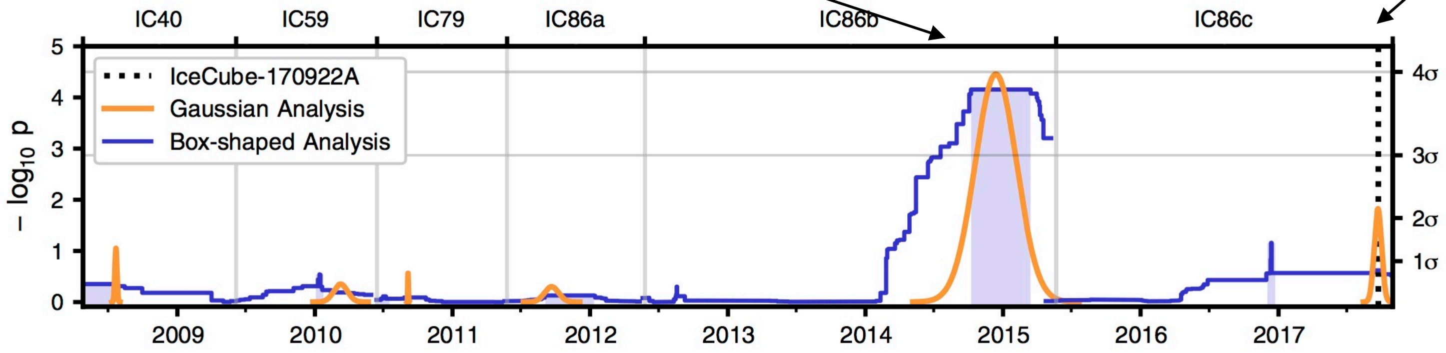
Most recent analysis, steady search:

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\mathrm{local}}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5

"untriggered" flare analysis

Science 361, 6398, (2018) 147

Science 361, 6398, (2018) eaat1378



3 **σ** coincidence with gamma-ray flare

"Untriggered" Time-Dependent Likelihood

Braun et al. Astropart. 33, 175 (2010)

Generic Time Window can be Gaussian (here) or Box ("Top Hat")

$$\mathcal{S}_i = \frac{1}{2\pi\sigma_i^2} e^{-|\vec{x}_i - \vec{x}_s|^2/2\sigma_i^2} \cdot P(E_i|\gamma) \cdot \boxed{\frac{1}{\sqrt{2\pi}\sigma_\mathrm{T}} e^{-(t_i - T_0)^2/2\sigma_\mathrm{T}^2}}$$

$$\mathcal{L}(n_s, \gamma, \underline{\sigma_\mathrm{T}, T_0}) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma, \underline{\sigma_\mathrm{T}, T_0}) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

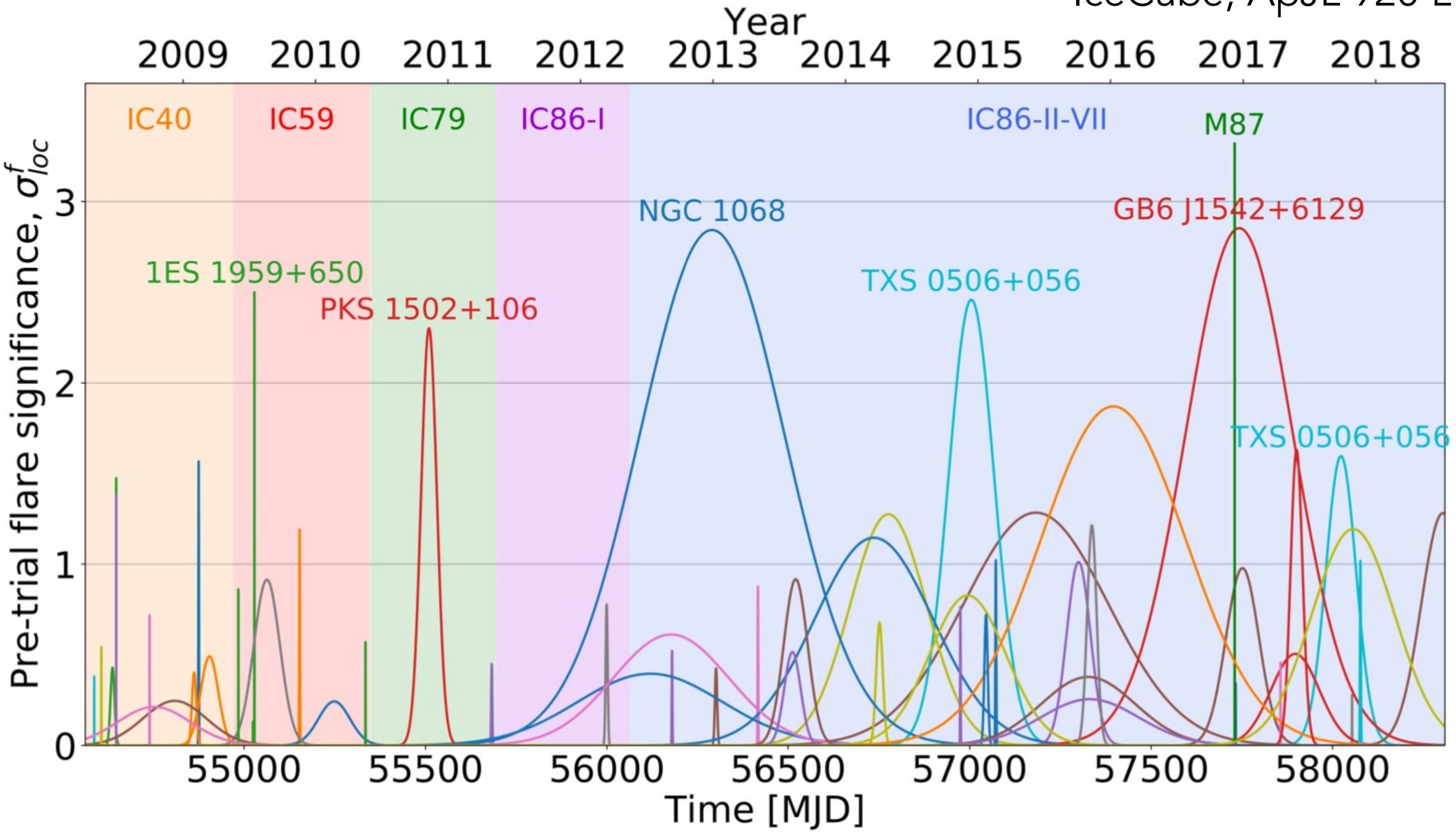
For "untriggered" search, consider **all** possible time windows and durations:

$$TS = 2\log\left(\boxed{\frac{\hat{\sigma}_T}{T_\mathrm{tot}}} \times \frac{\mathcal{L}(\hat{n}_s, \hat{\gamma}, \hat{\sigma}_T, \hat{T}_0)}{\mathcal{L}(n_s = 0)} \right)$$

Penalty for choosing a short-time window duration σ_T
(corresponds to the fact that there are many more short than long windows)

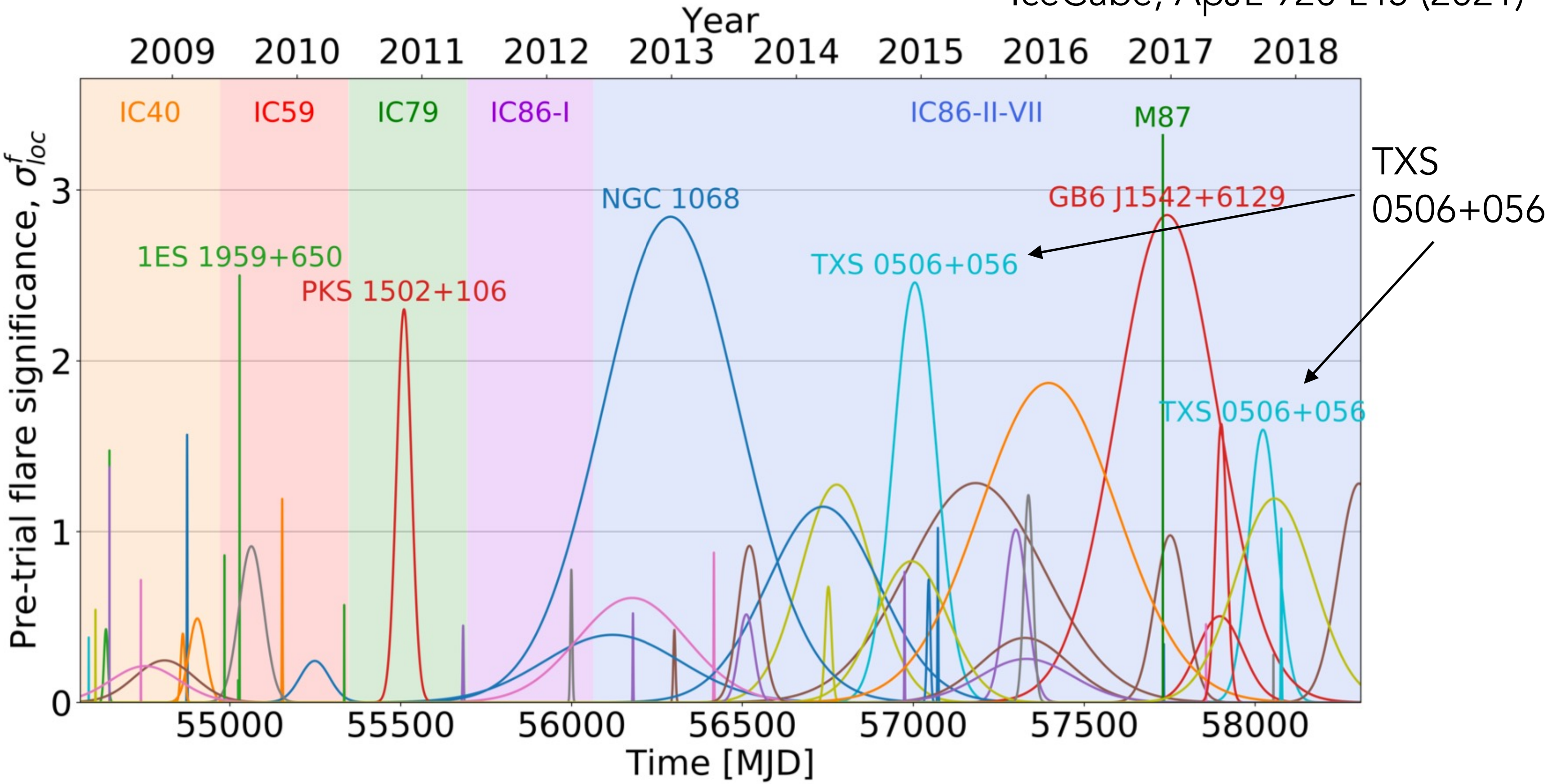
Multi-flare Analysis

IceCube, ApJL 920 L45 (2021)



Multi-flare Analysis

IceCube, ApJL 920 L45 (2021)



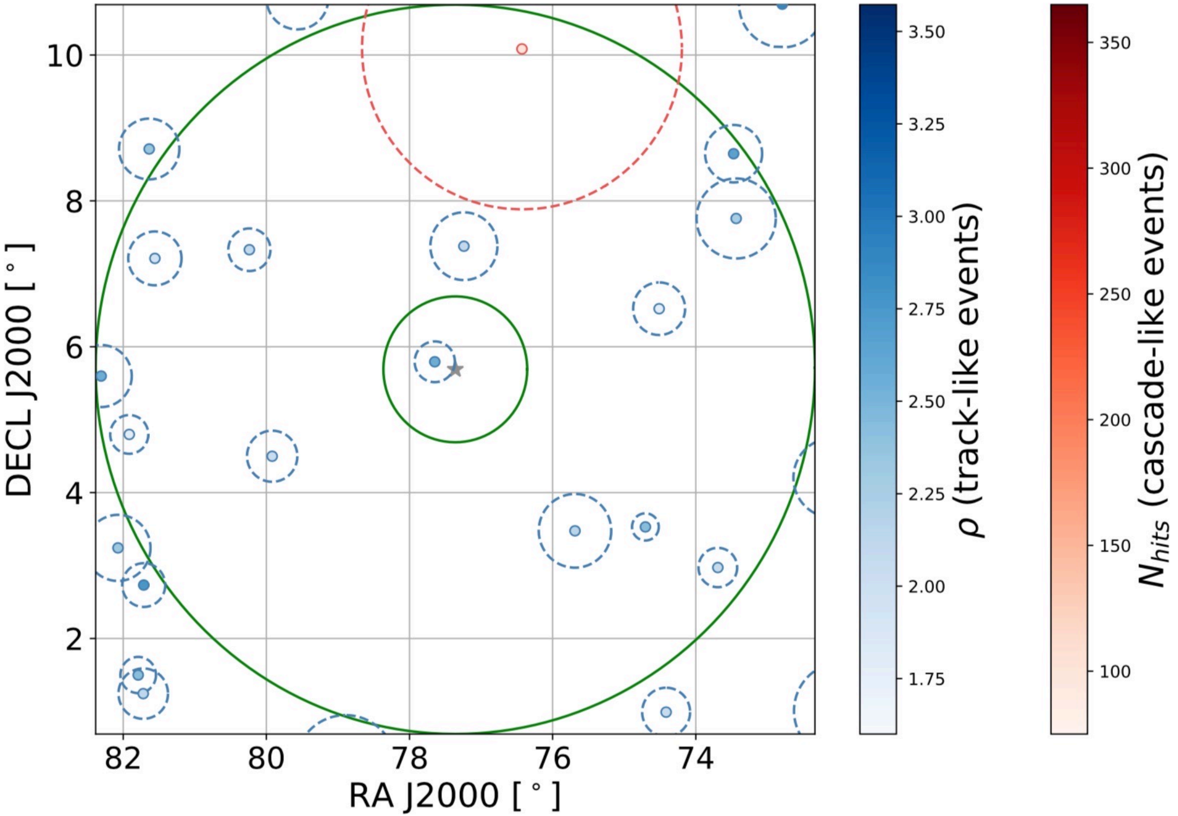
TXS 0506+056 only source (out of 110) where fit prefers 2 separate emission episodes

TXS 0506+056 in ANTARES analysis

2007-2017 Time-integrated analysis

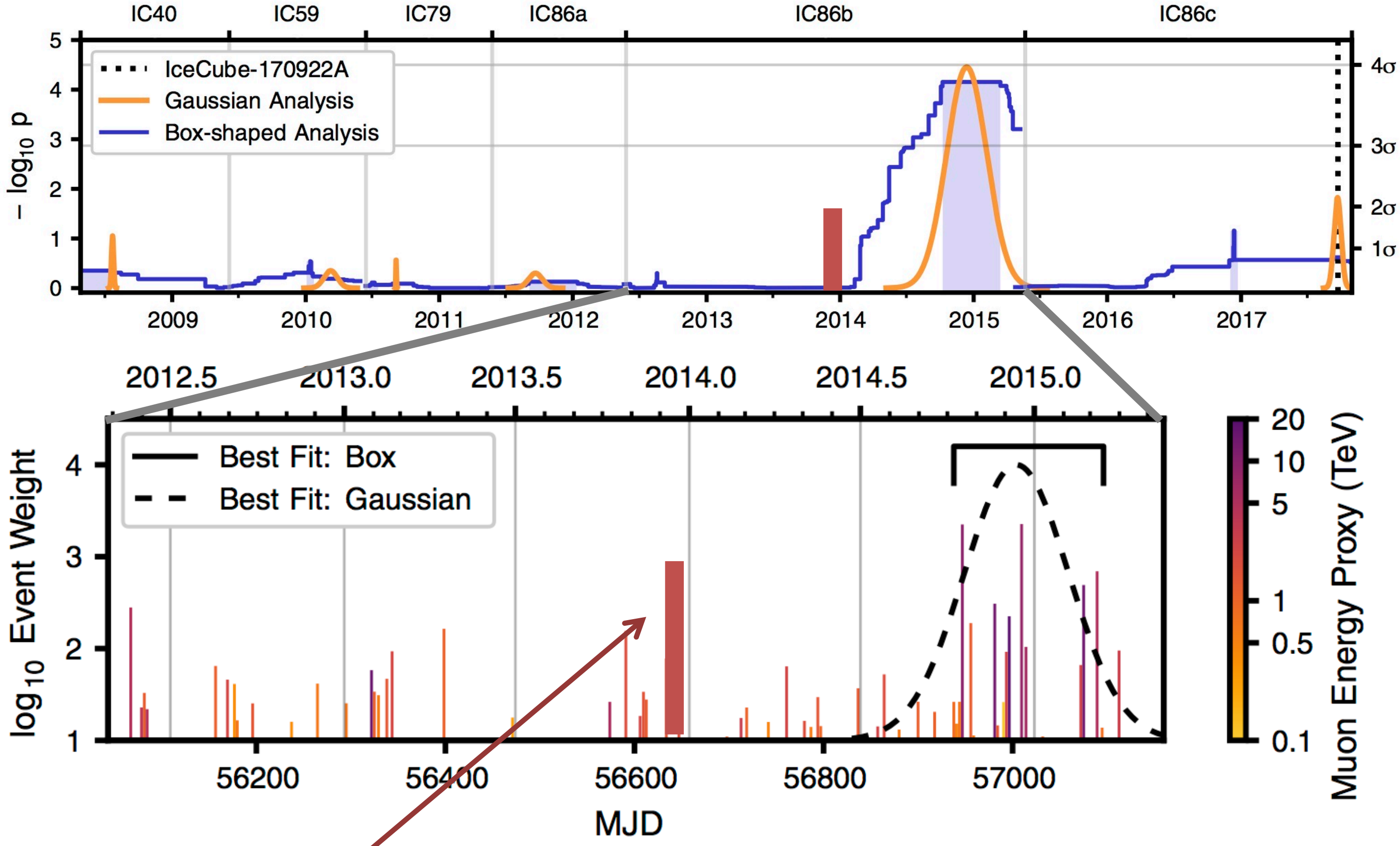
Best-fit number of signal events: 1.03

Local Significance (p-value): 3.4%



ANTARES, ApJ 863 (2018) 2, L30

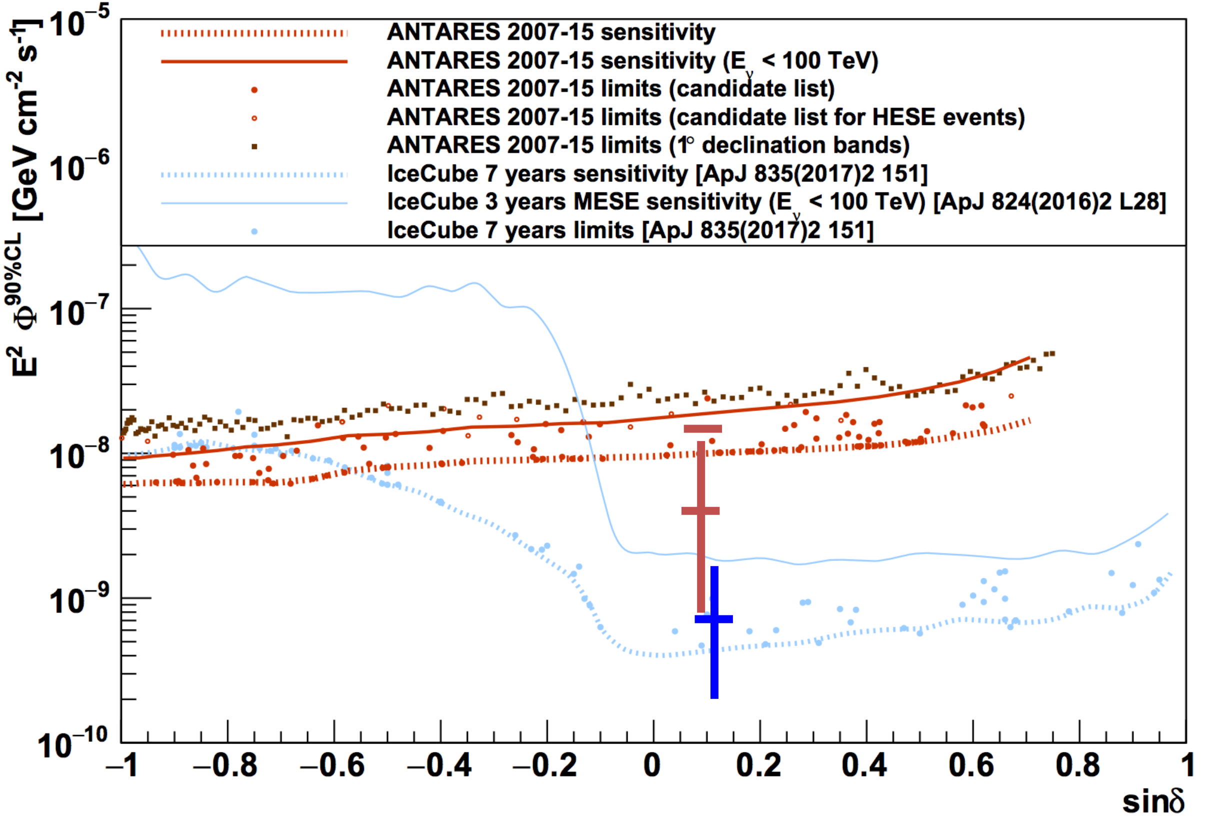
TXS 0506+056



ANTARES event 2013.12.12 1 year earlier … so, not related to flare?

TXS 0506+056

ANTARES, Phys. Rev. D 96, 082001 (2017)



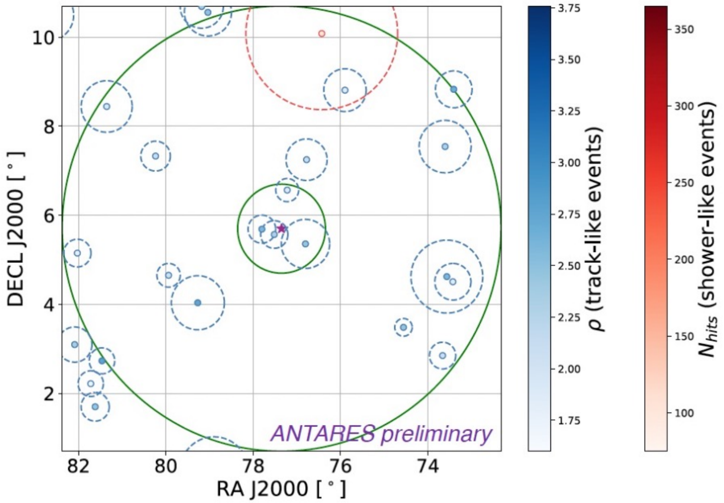
For time-integrated (steady source) analysis:

ANTARES best-fit flux (my estimate) is within 1-σ of IceCube best-fit flux

Search for neutrinos from TXS 0506+056

ANTARES Time integrated search

- Same method as PS study 2007-2017
  - Expected background (3136 days) :
    - 0.23/deg^2 for track-like
    - 0.005/deg^2 for shower-like events
  - \# of events fitted the likelihood signal function for the source: μ_{sig} **= 1.03**
  - **Pre-trial p-value of 3.4%** (post-trial 87%)



- Updated 2007-2020, recalibrated
  - 4 events within 1° μ_{sig} = 2. 9
  - Pre-trial: 2.9σ (1-sided)

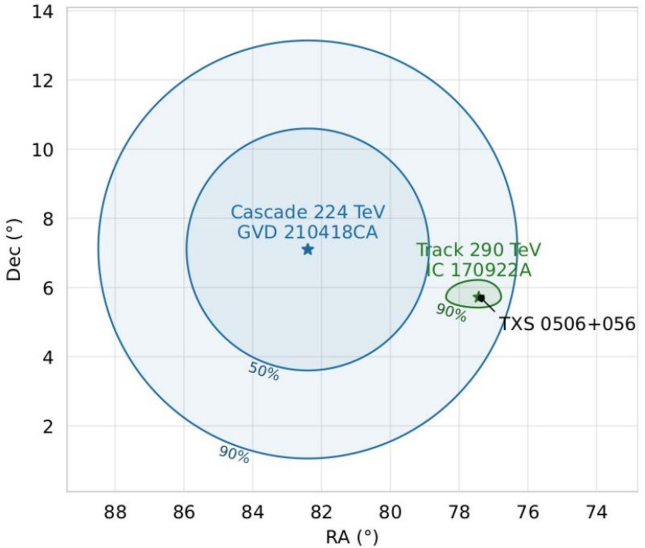
- Soon, yet another update
- Time sequence under investigation

ApJL 863, L2 (2018) update at ICRC 2021

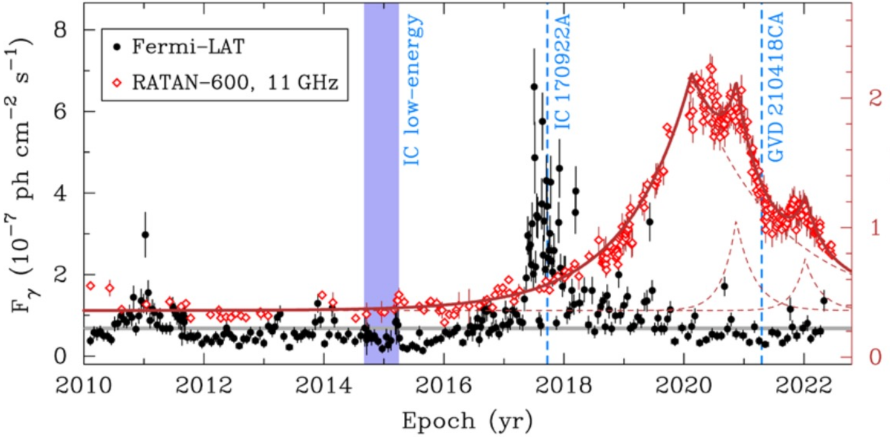
Antoine's talk yesterday

A high energy neutrino from the direction of TXS 0506+056

GVD210418CA (97% signalness) lies within 90% error circle from TXS 0506+056



Radio and gamma-ray light curves of TXS 0506+056.



The chance probability for such an association to occur randomly due to the background is p = 0.0074

Analysis of RATAN-600 radiotelescope data (11GHz) showed increased activity

- IC event registered during γ flare and radio activity
- Baikal-GVD event during radio activity
- Probability of IC non-observation: 11%

arXiv:2210.01650

Zhan's talk yesterday


Triangulum
Andromeda
Olor
Aquarius
Sagittarius