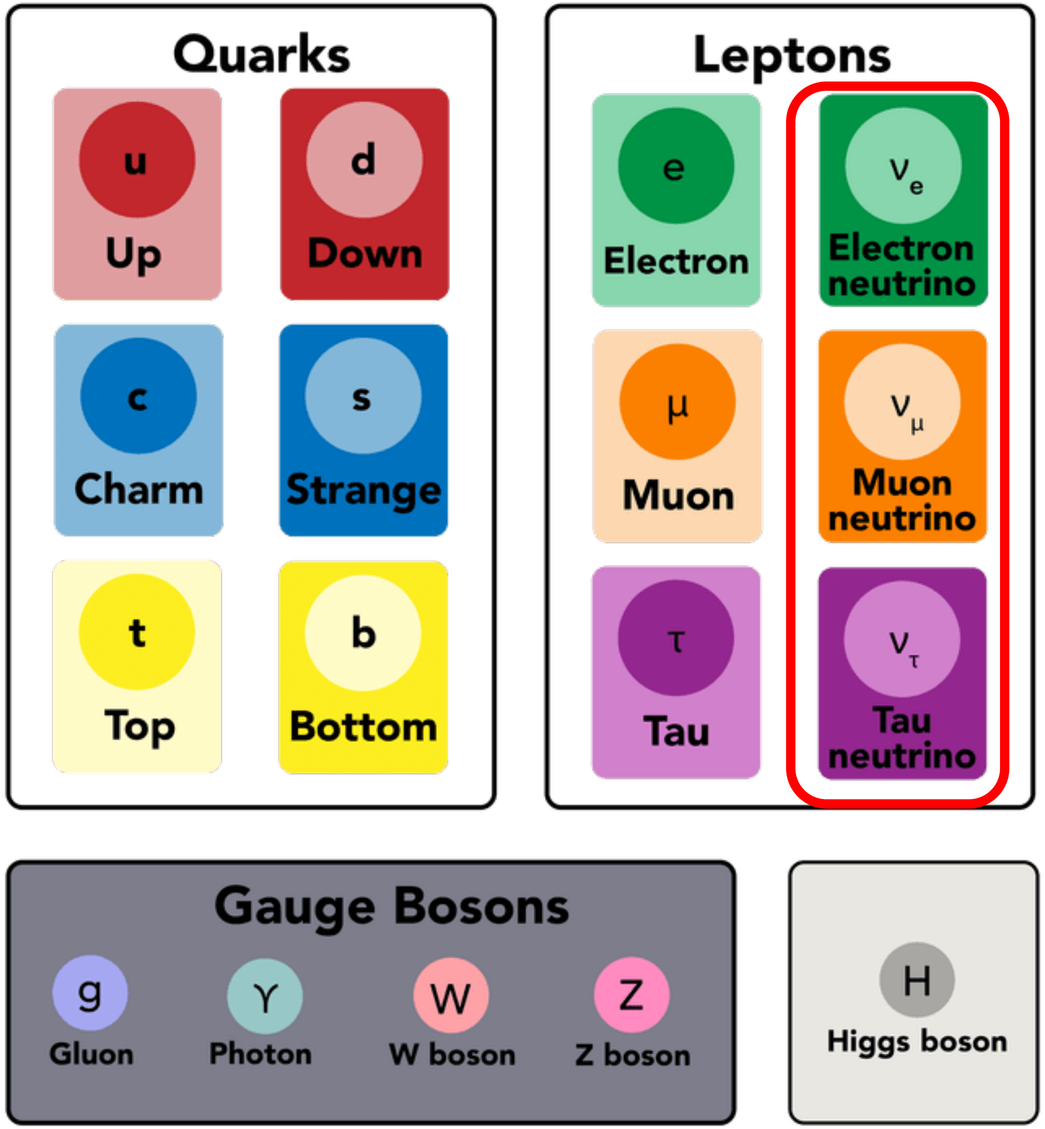
Viewing the neutrino sky: Latest results from the IceCube Neutrino Observatory

Erin O’Sullivan
Uppsala University

Astro seminar May 11, 2023

The neutrino sky

Shines with equal intensity day and night
You can look both above and below you
Views the furthest reaches of our Universe
But, is a very dark place unless you have a large and efficient telescope

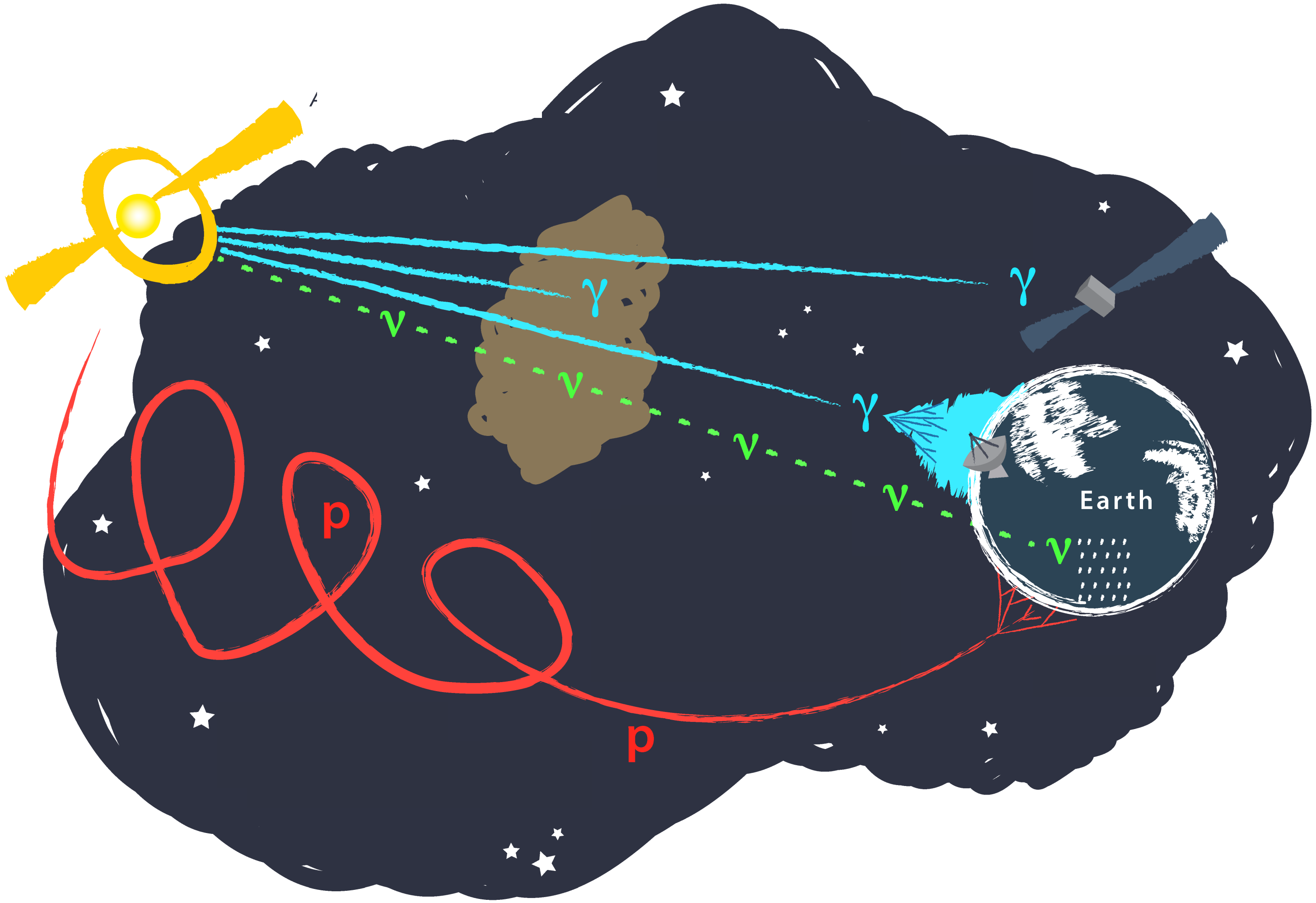


Neutrinos

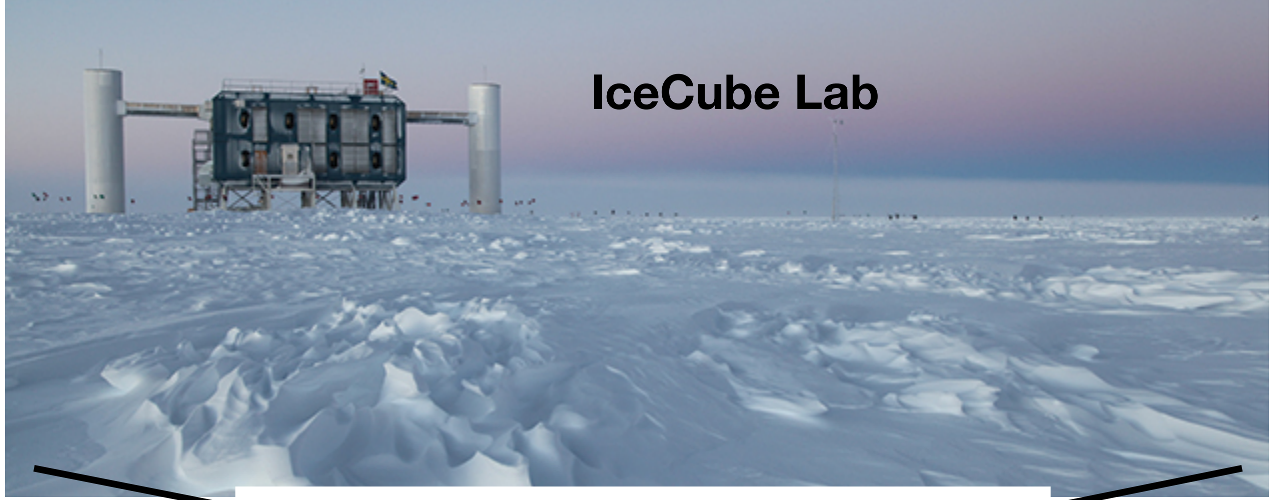
No charge

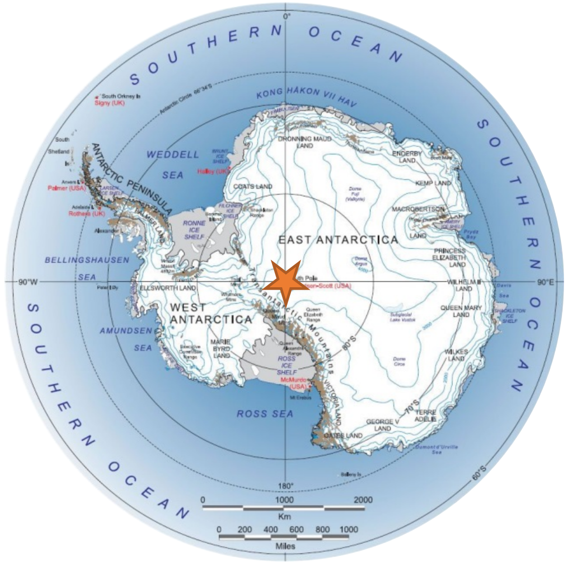
Nearly massless

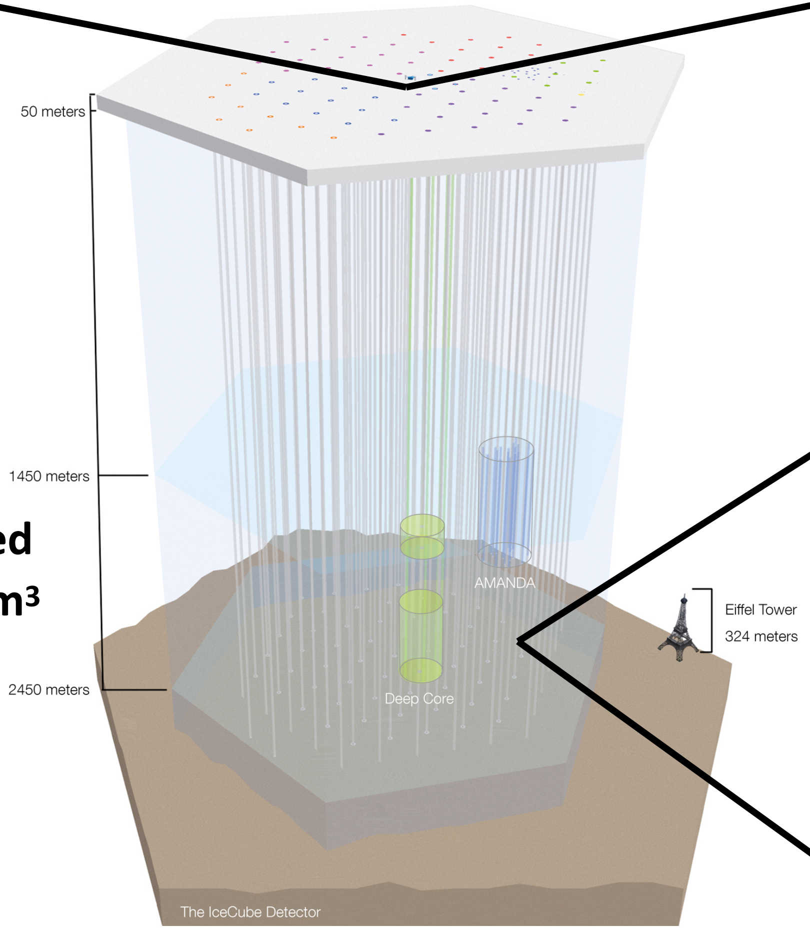
Three "flavours"



Neutrinos are a direct, unobscured tracers of hadronic acceleration



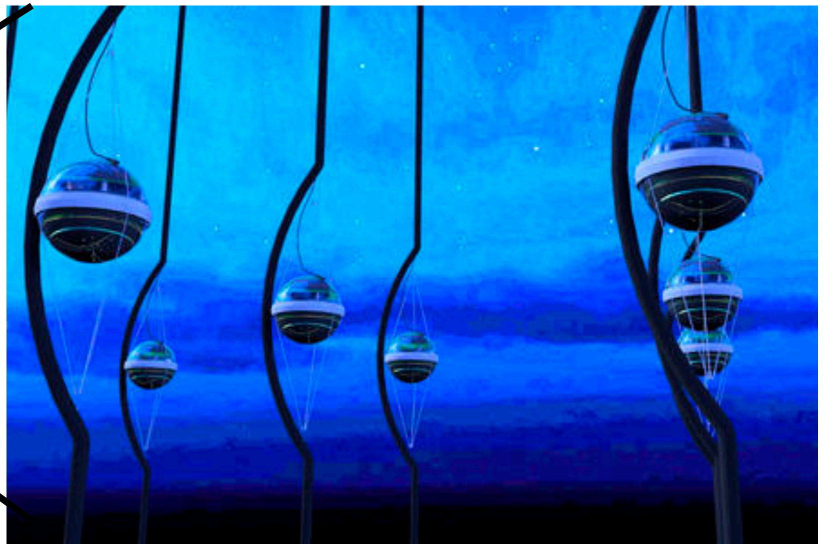




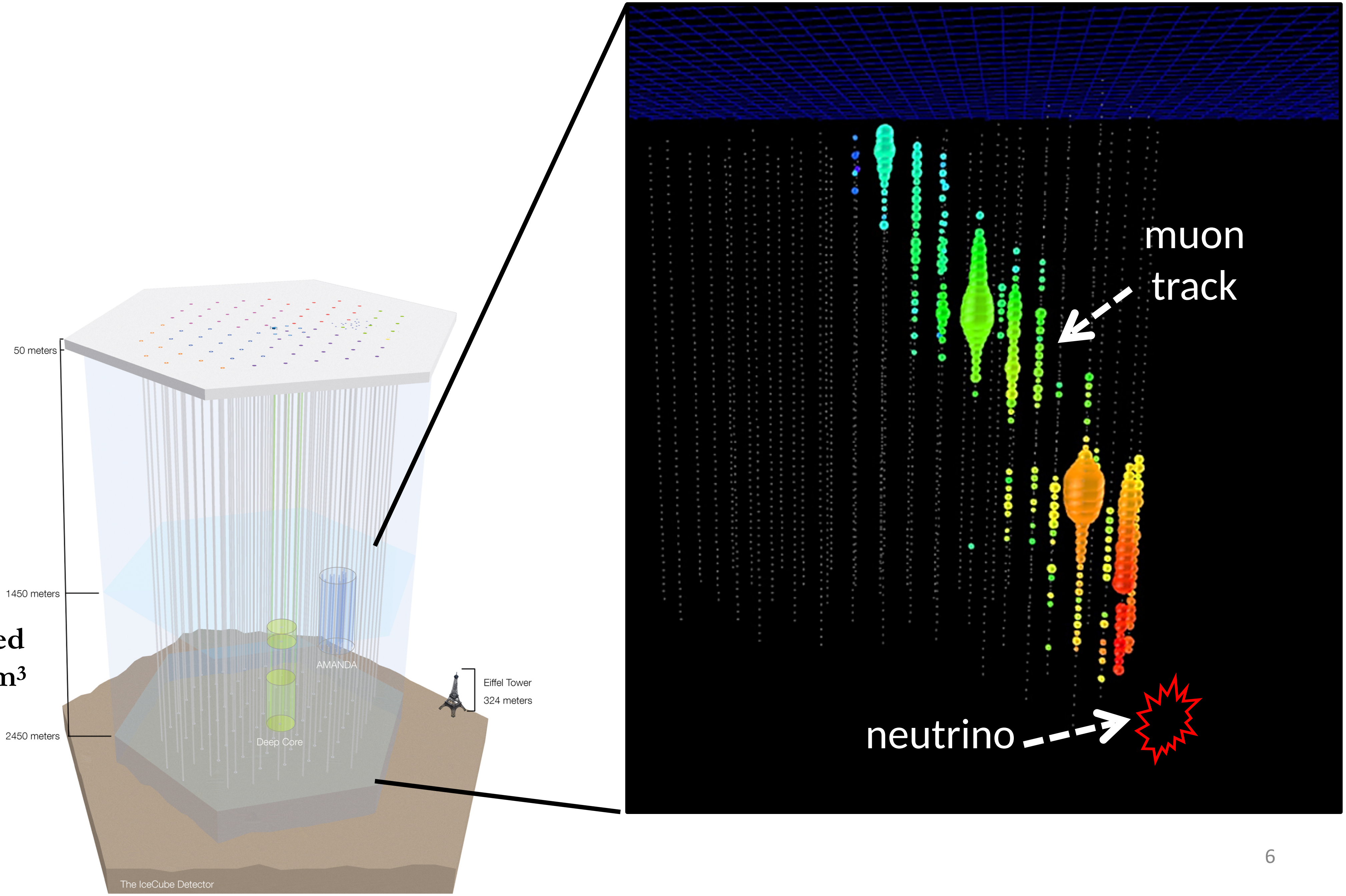
Instrumented volume: 1 km³

ICECUBE
completed 2011

86 Strings



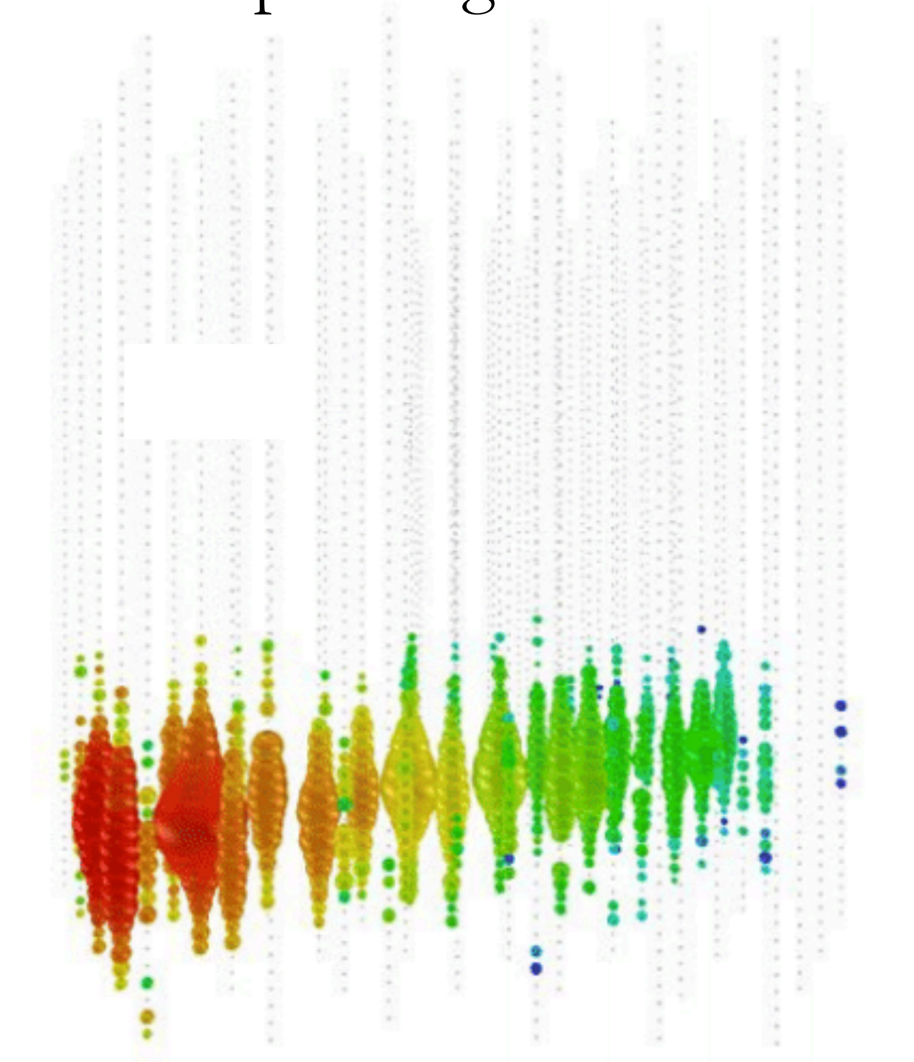
Instrumented volume: 1 km³



Tracks

Charged-current $\boldsymbol{\nu}_{\mu}$

Good pointing: 0.2° - 1°

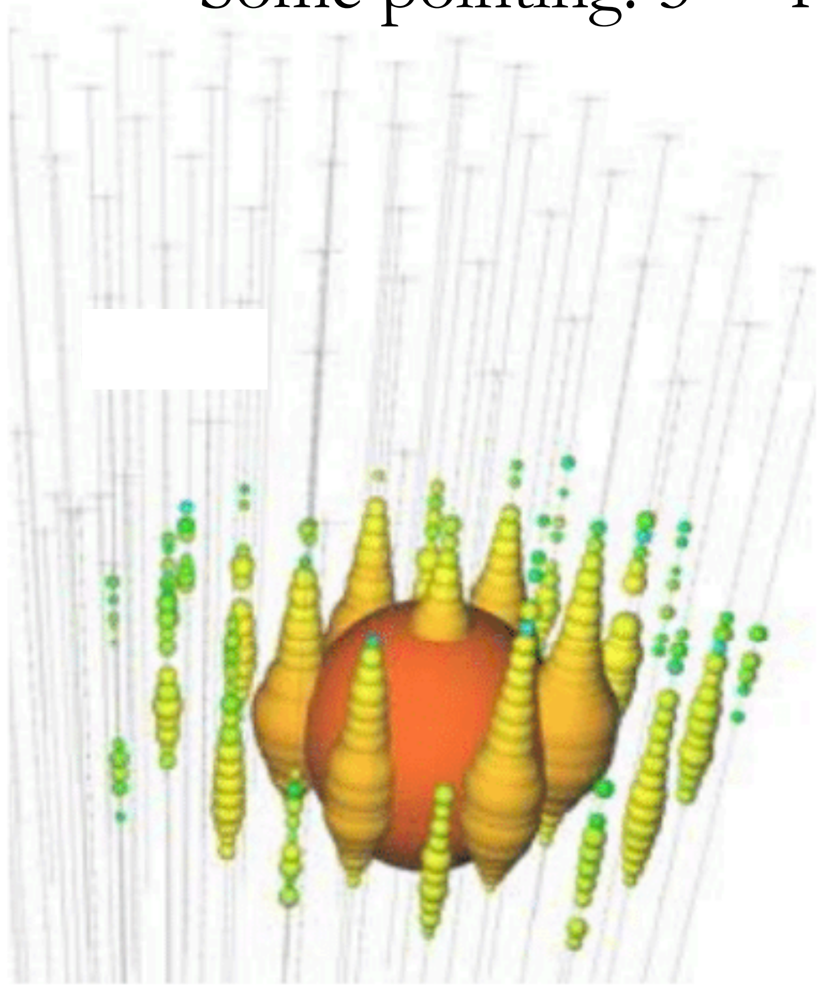


Cascades

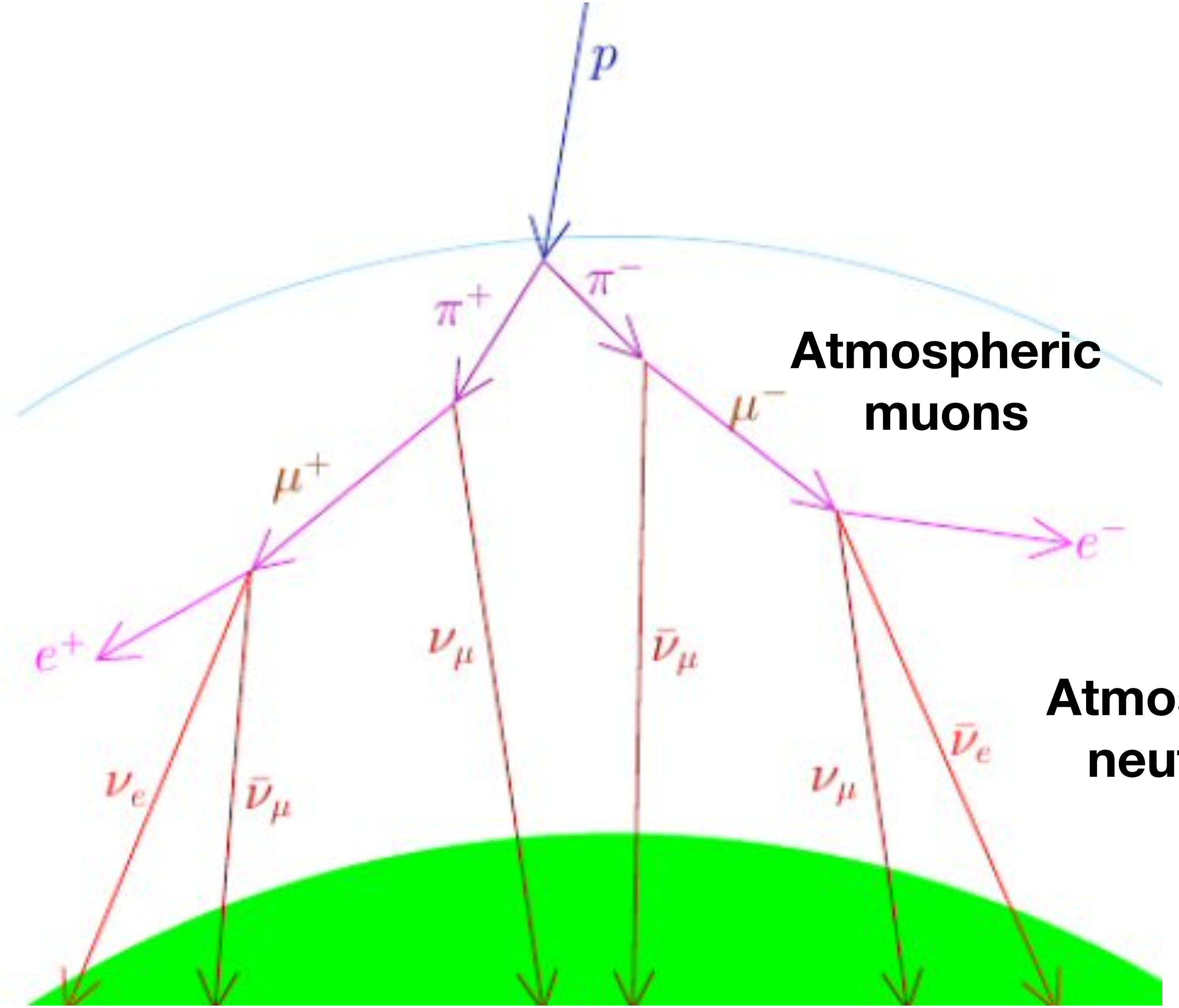
Charged-current $\boldsymbol{\nu}_e$ or $\boldsymbol{\nu}_{\tau}$ and neutral current

Good for energy reconstruction

Some pointing: 5° - 10°



What can mimic astrophysical neutrinos?



Atmospheric muons

Atmospheric neutrinos

Each year, IceCube records approximately:

100 000 000 000 events   (about 3000 events per second)

Almost all of these are muons from cosmic rays hitting the atmosphere above the detector

-> Atmospheric muons

100 000 neutrino events   (about 300 per day)

Almost all of these are nu's from cosmic rays hitting the atmosphere on other side of Earth

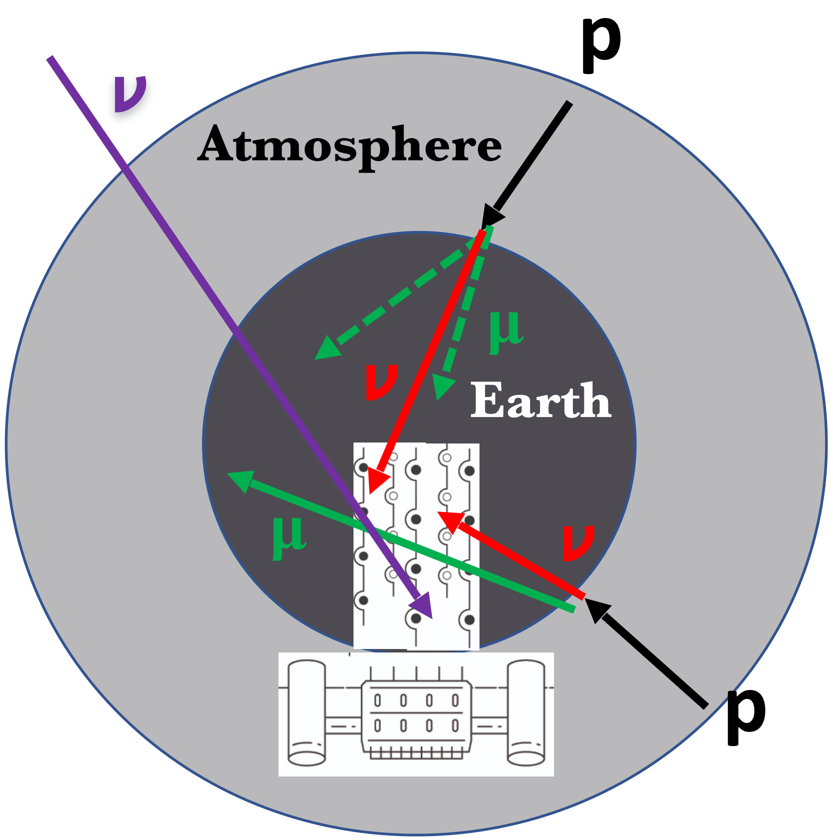
-> Atmospheric neutrinos

100s of astrophysical neutrinos (1 per day)

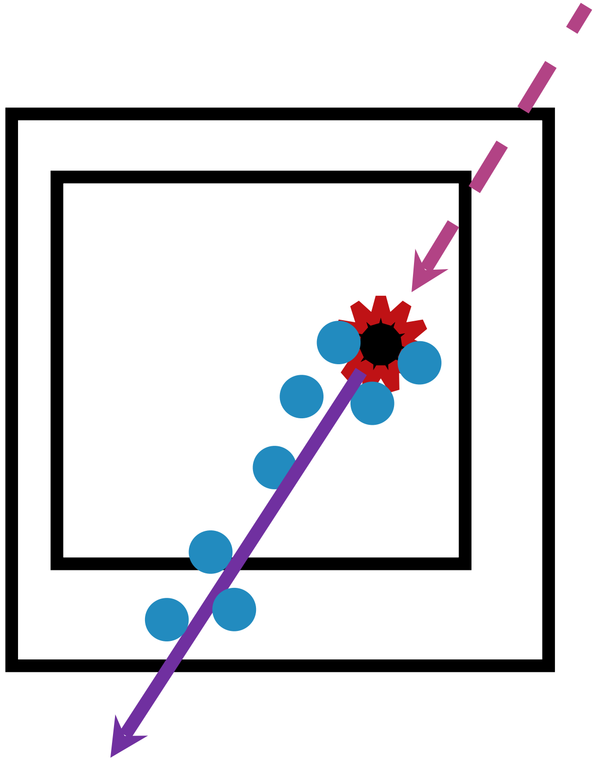
How to find astro. neutrinos (signal) in a background event rate 10^9 times higher?

How to pick out neutrinos from muons?

Approach 1: Direction
Use the Earth as a muon filter

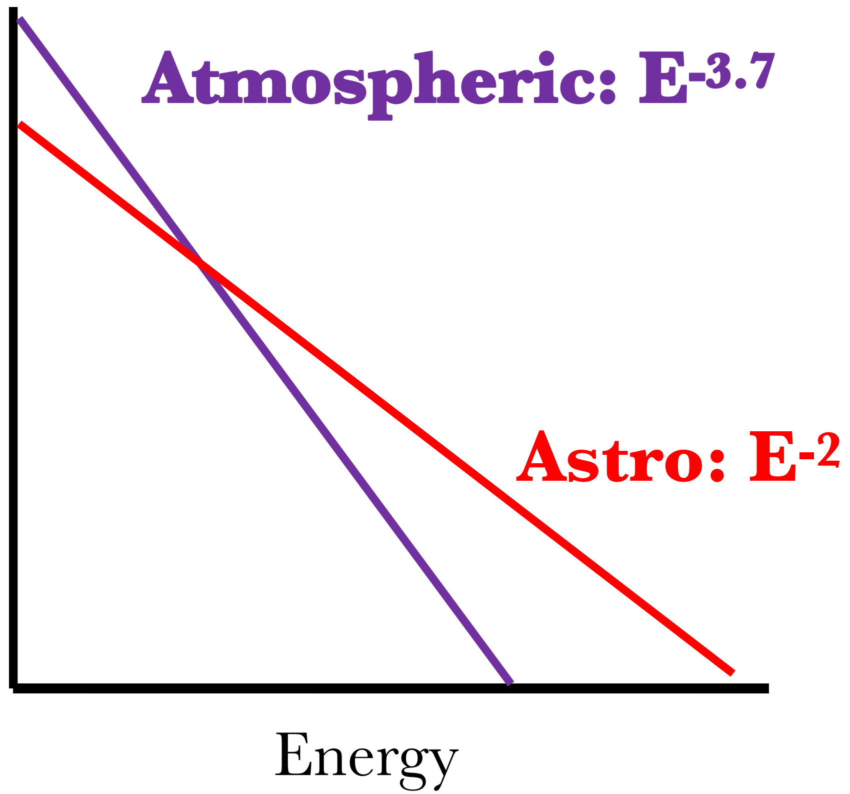


Approach 2: Veto
Require events to start in the detector

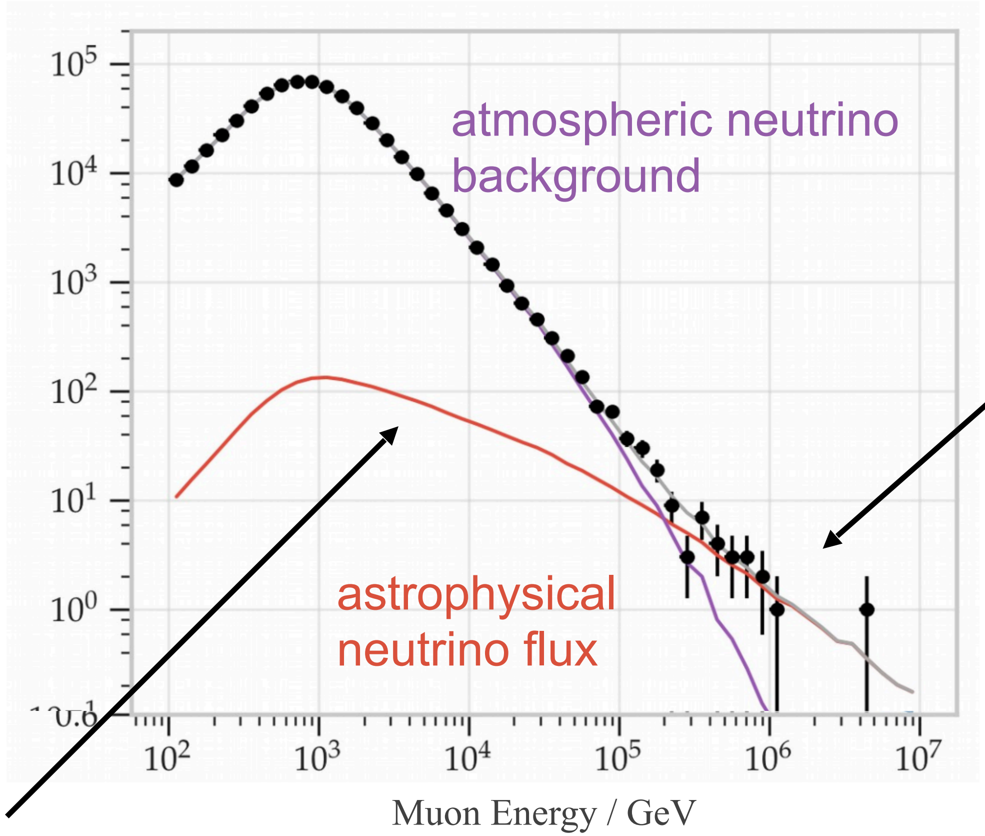


How to pick out astrophysical neutrinos from atmospheric neutrinos?

Energy:
Look for events with high energy

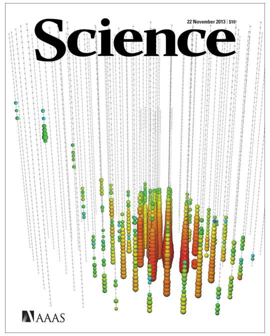


Muon Neutrino track events
2010-2018



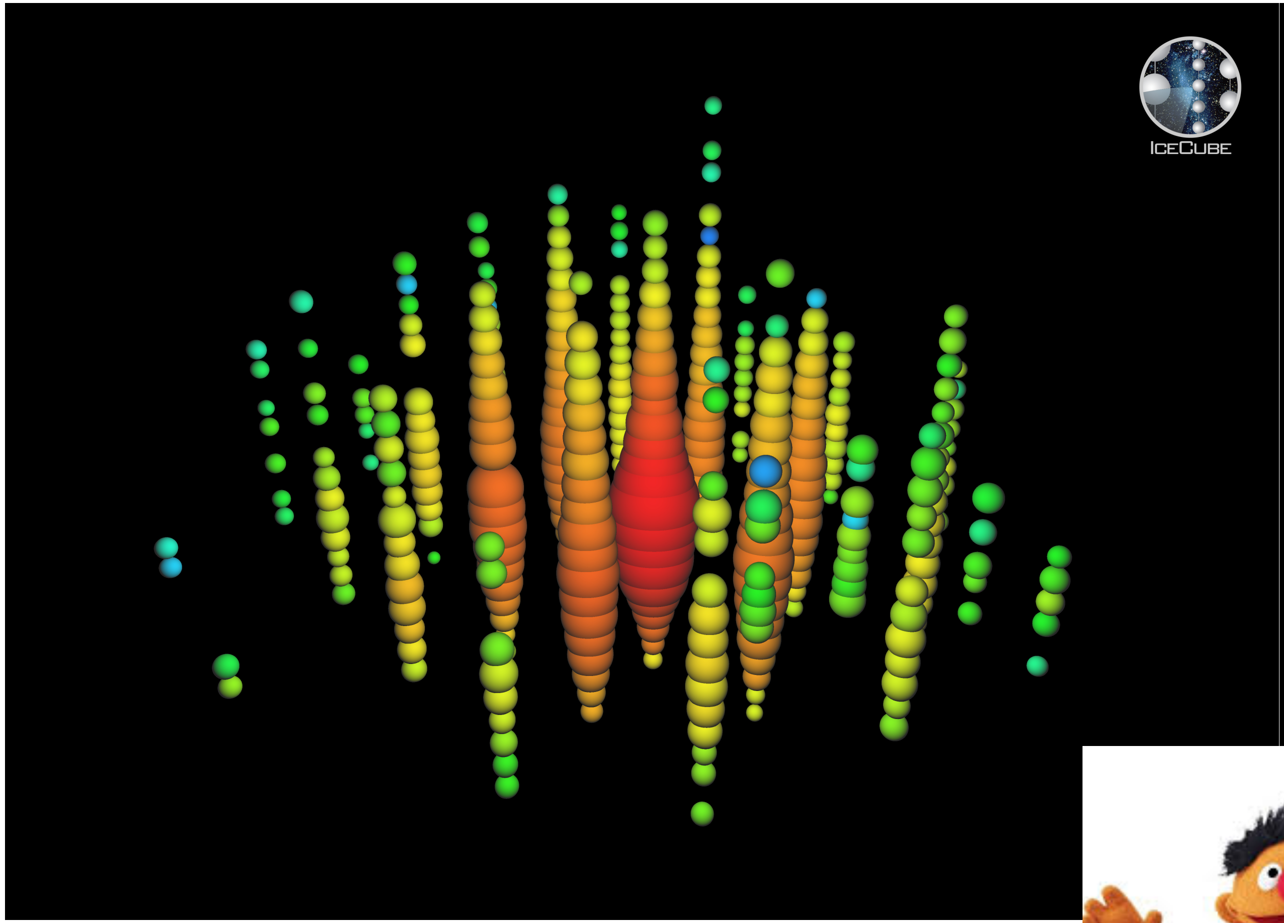
These events can be individually identified as astrophysical neutrinos

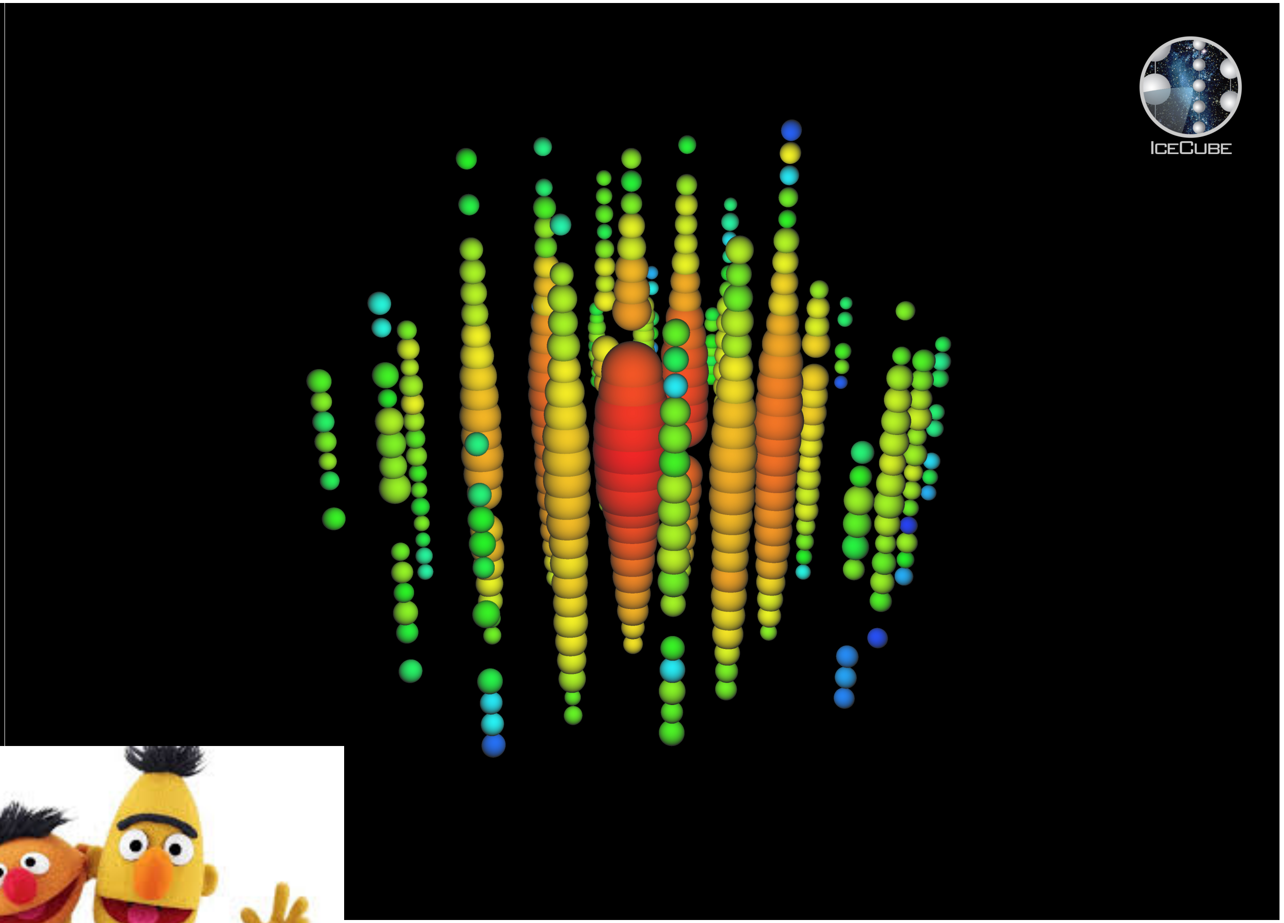
Requires spacial clustering of events to become significant: point sources

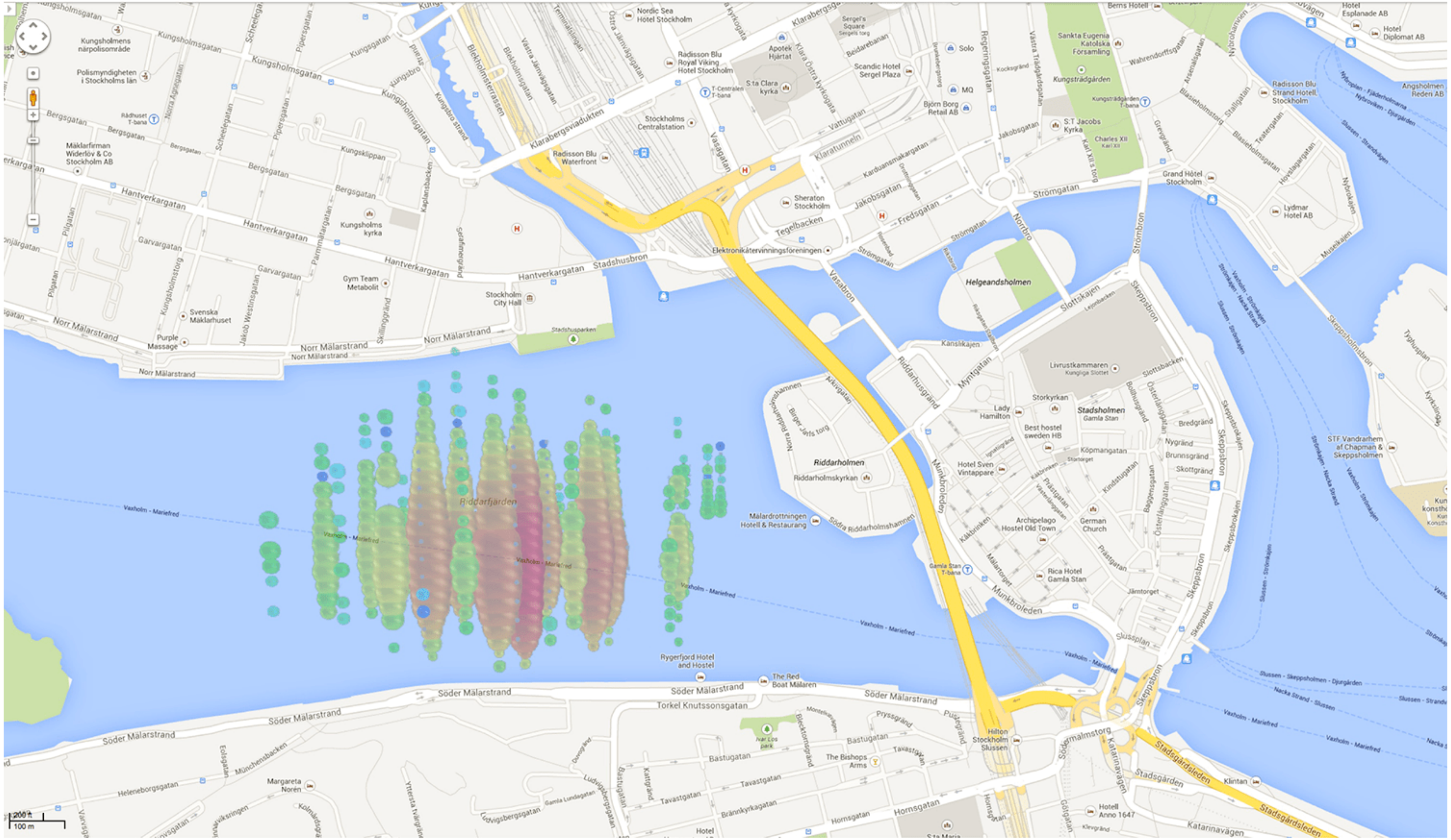


2013
IceCube discovers the
high energy astrophysical
neutrino flux

The first high energy (PeV) events

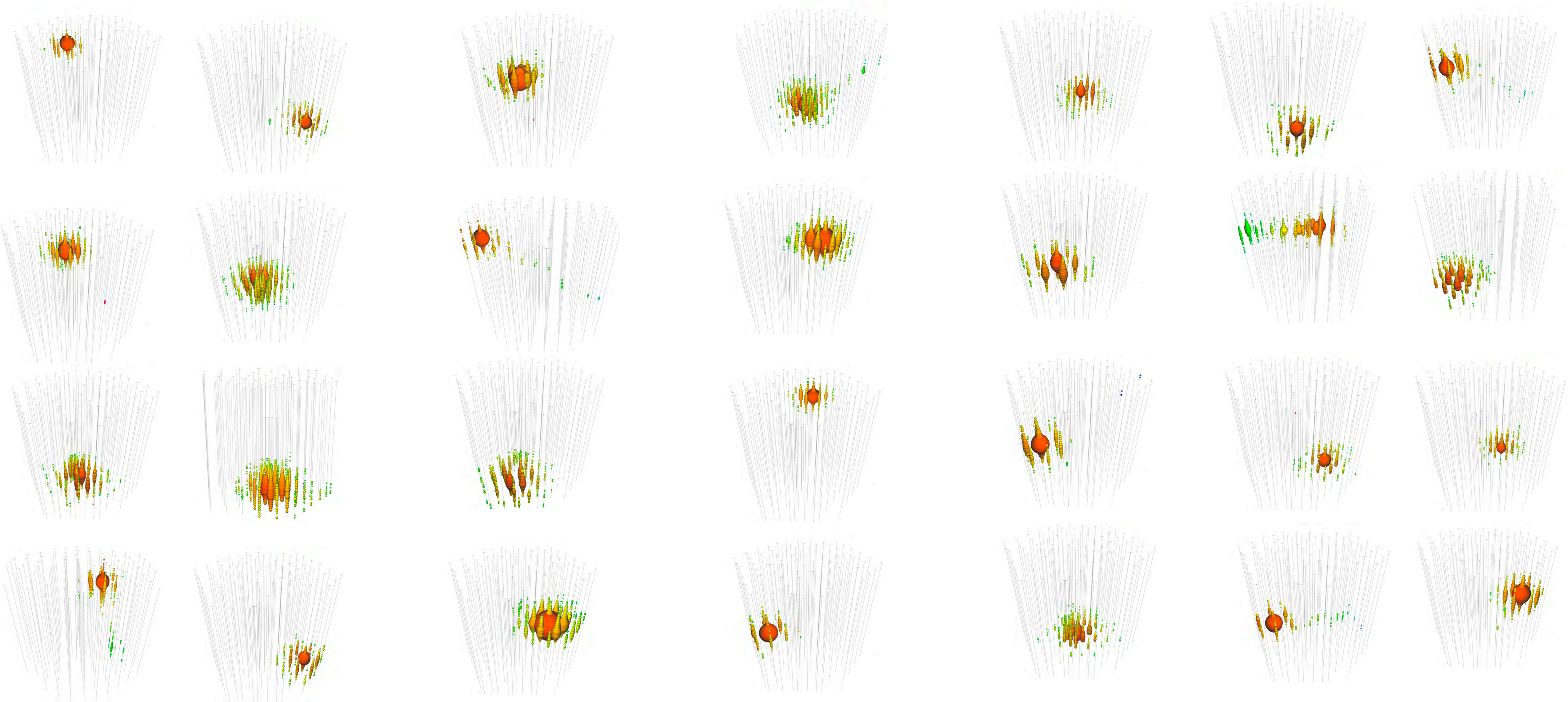


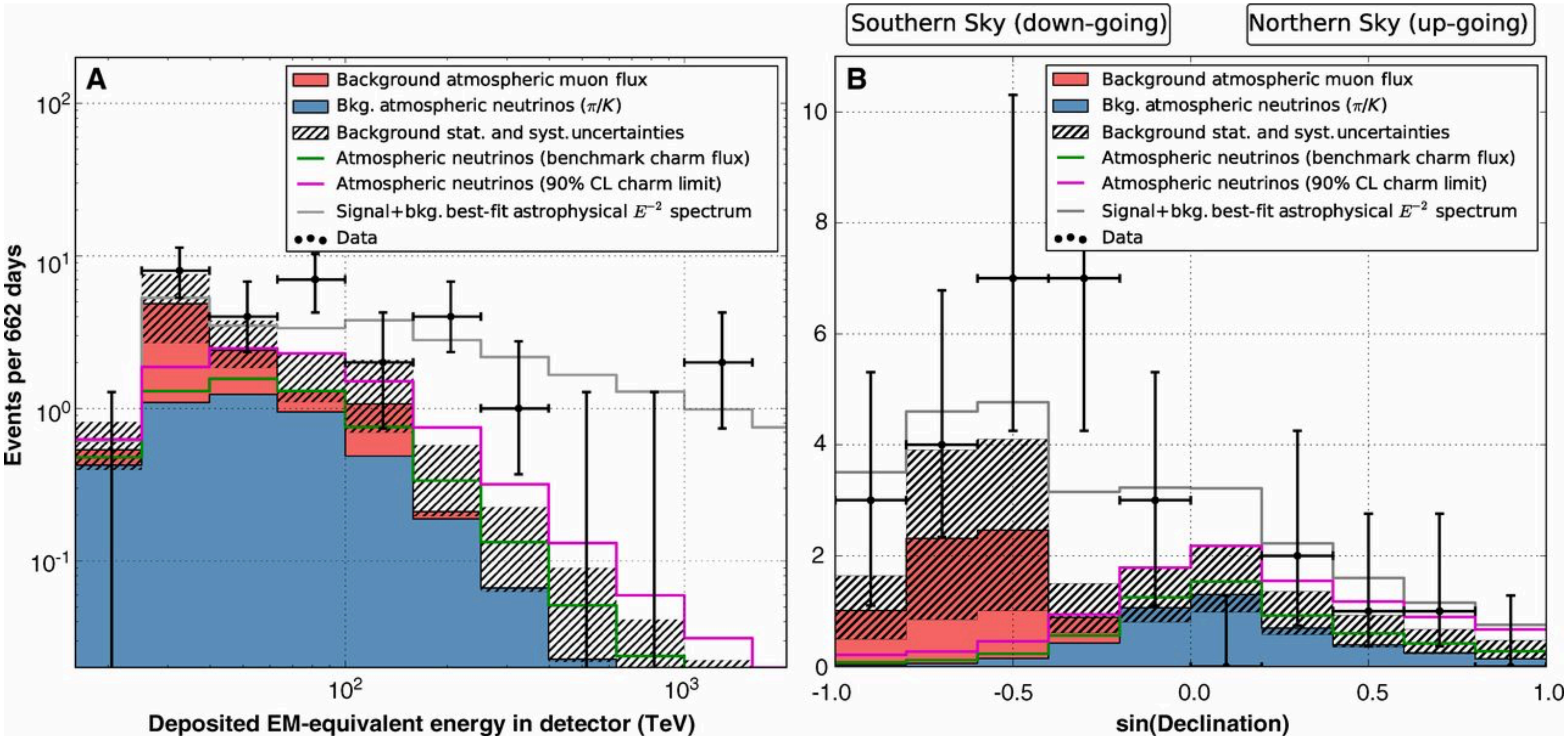




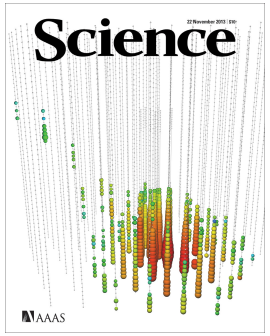
Riddarfjärden
Riddarholmen
Helgeandsholmen
Stadsholmen
Norr Mälarstrand
Söder Mälarstrand
Vaxholm - Mariefred

Discovering high energy astro neutrinos–the first 28 events





A
Background atmospheric muon flux
Bkg. atmospheric neutrinos (π/K)
Background stat. and syst. uncertainties
Atmospheric neutrinos (benchmark charm flux)
Atmospheric neutrinos (90% CL charm limit)
Signal+bkg. best-fit astrophysical E^{-2} spectrum
Data
Events per 662 days
Deposited EM-equivalent energy in detector (TeV)
Southern Sky (down-going)
Northern Sky (up-going)
B
sin(Declination)



2013
Discovery of the
high energy astrophysical
neutrino flux

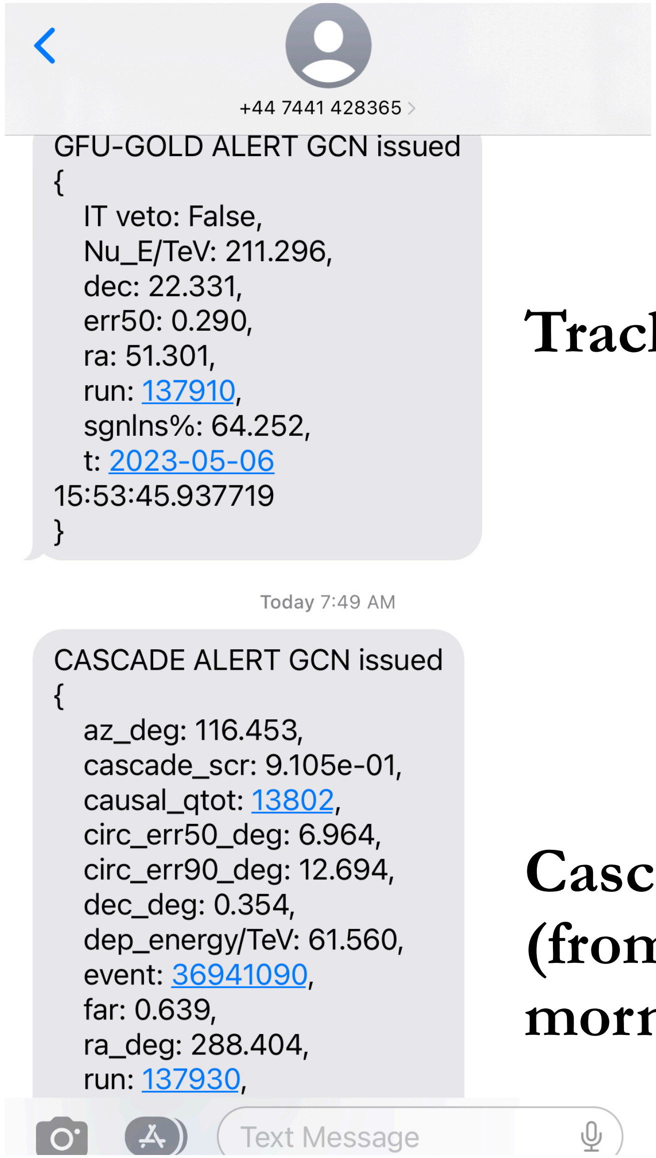
2018
Observation of the first
source of high energy
neutrinos

Real time alerts of high energy events started in 2016

Tracks: ~10 alerts/year in the gold channel (half from background)

Cascades: ~8 alerts/year in the gold channel (half from background)

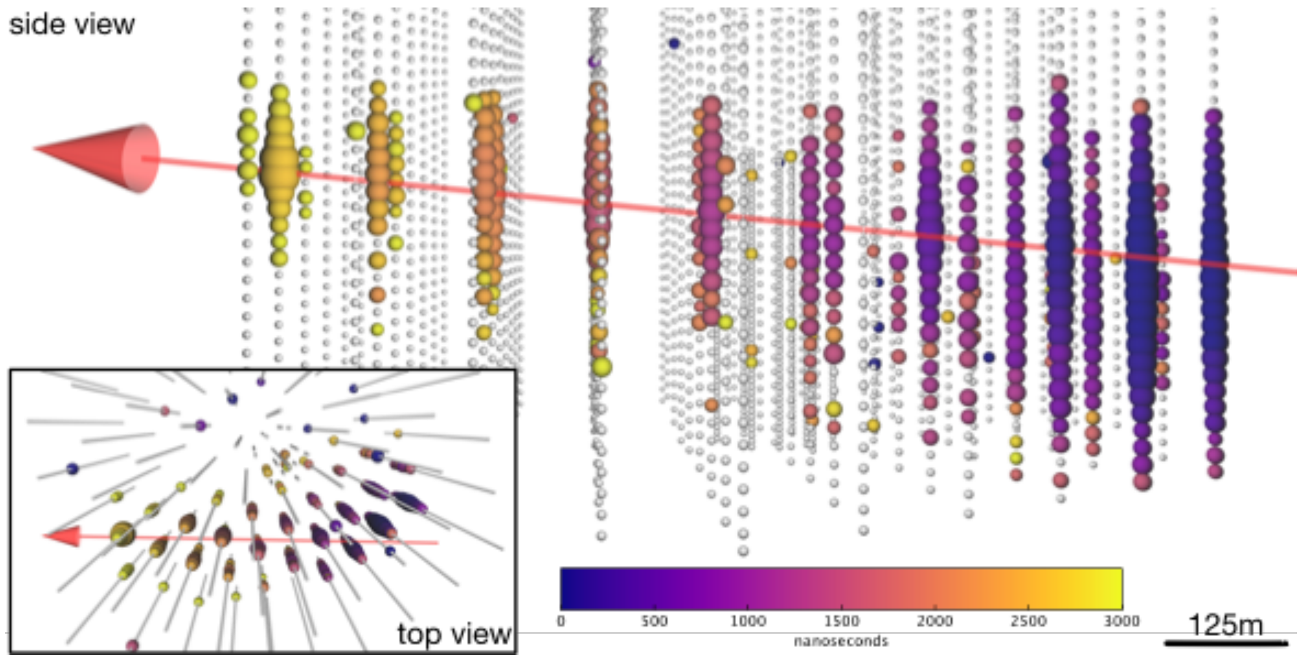
Typical latency of < 3 minutes



Track

Cascade (from this morning!)

In September 2017, IceCube sends out an alert of IC170922A

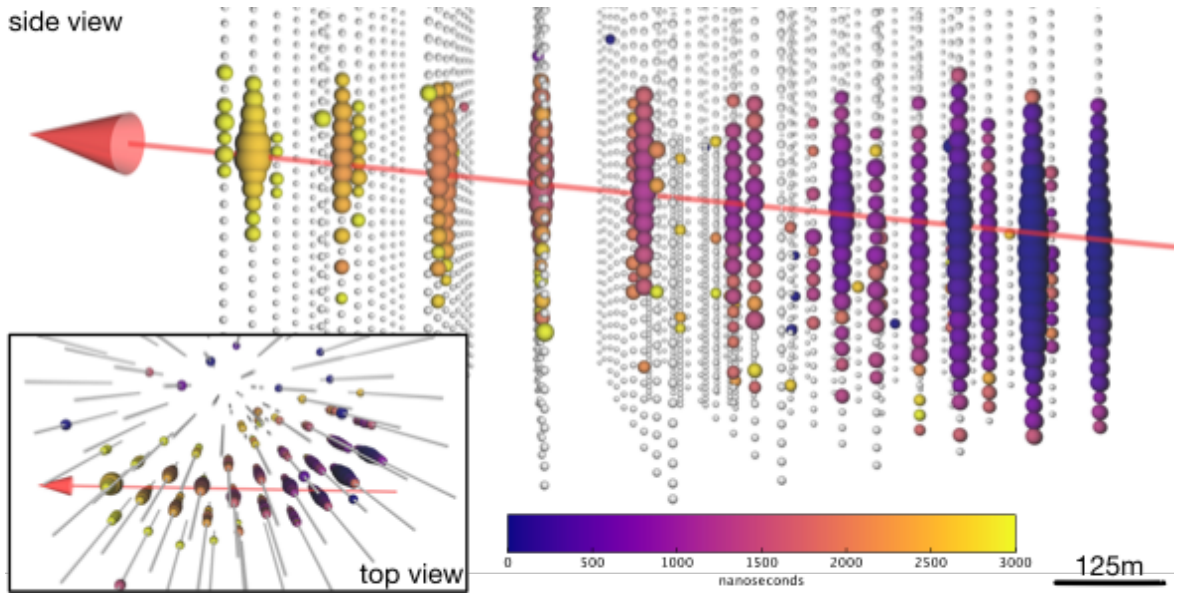


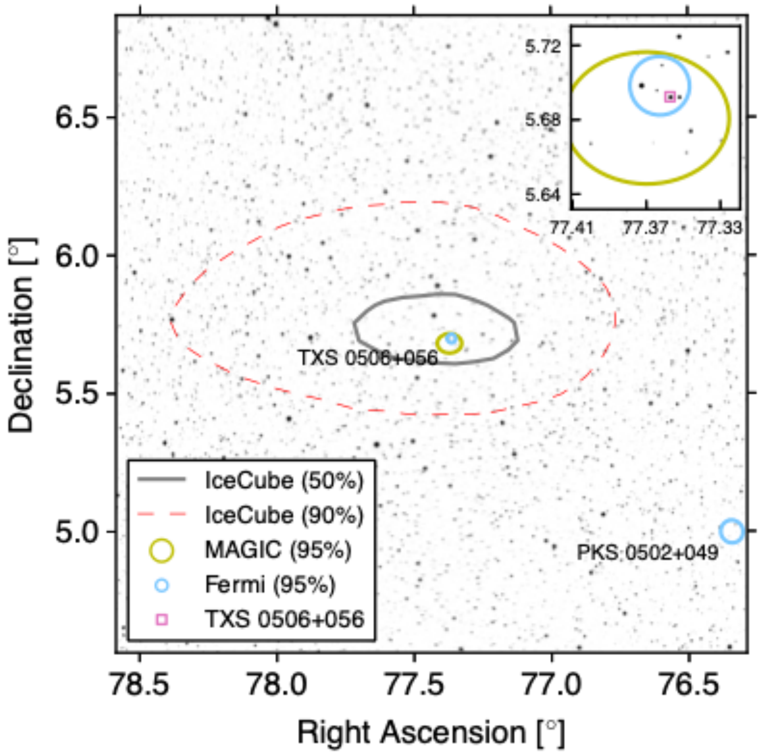

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy
neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube
<blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss
(University of  Maryland) report on behalf of the IceCube
Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy
event with a high probability of being of astrophysical origin.
The event was identified by the  Extremely High Energy (EHE)
track event selection. The IceCube detector was in a normal
operating state. EHE events typically have a neutrino
interaction vertex that is outside the detector, produce a muon
```

Mean angular resolution: 0.25°
Best fit neutrino energy 290 TeV

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†





IC170922A

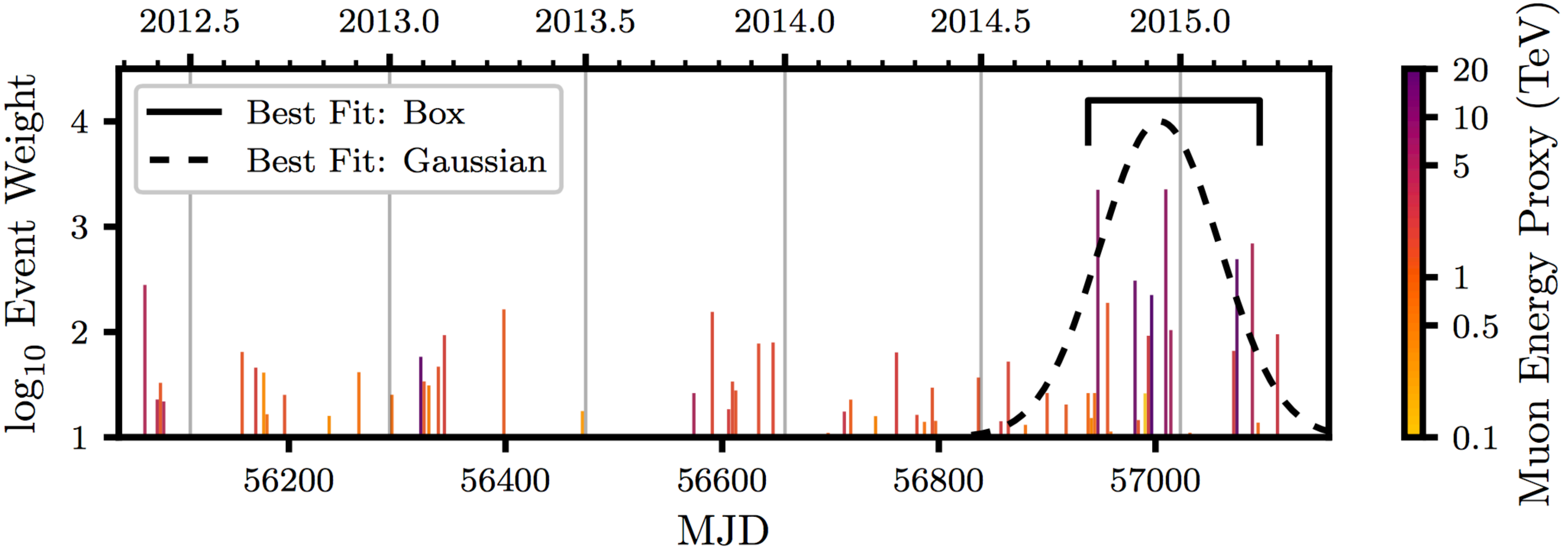
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

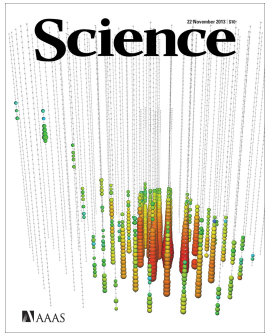
IceCube Collaboration*†

Science 361, 147-151 (2018)

13 neutrinos over 4-5 months

~ 3.5 σ





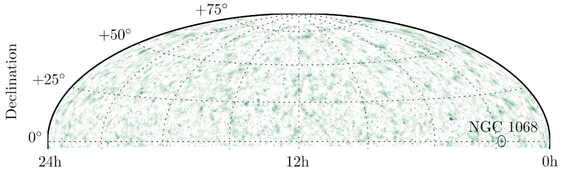
RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†



2013
Discovery of the high energy astrophysical neutrino flux

2018
Observation of the first source of high energy neutrinos

2022
Observation of the second source of high energy neutrinos

Science — Nov. 4, 2022

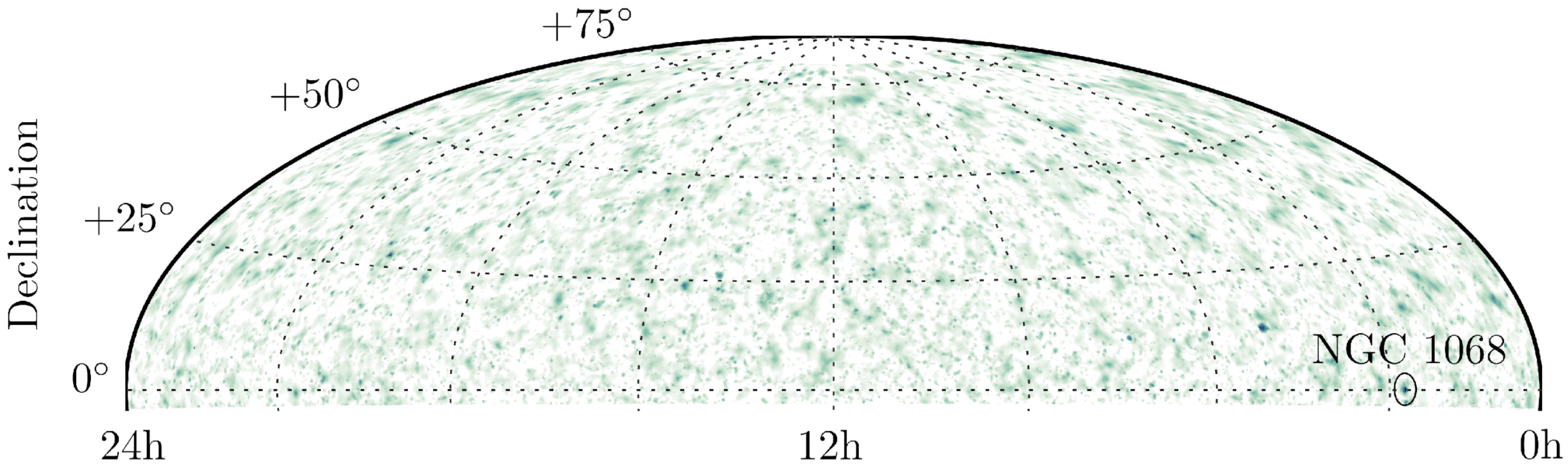
RESEARCH

RESEARCH ARTICLE

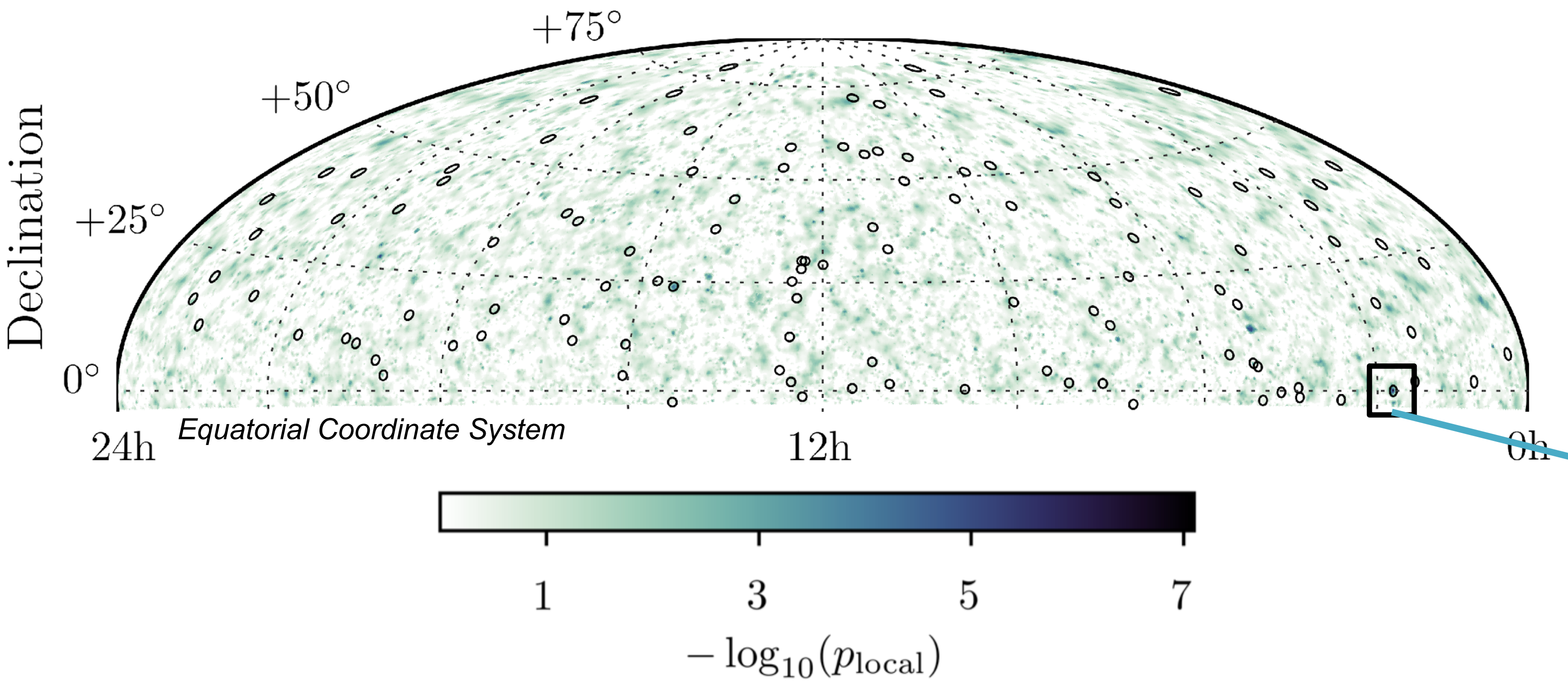
NEUTRINO ASTROPHYSICS

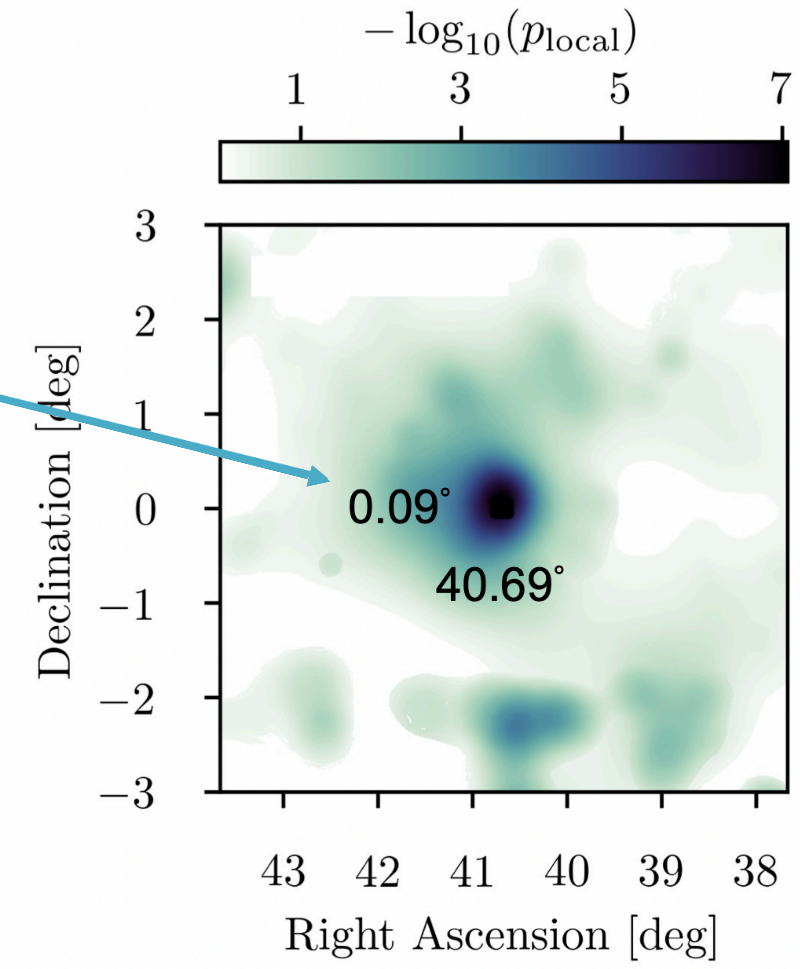
Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†



Northern-sky scan for neutrino emission





Northern sky scan hottest spot:
Astrophysical neutrino events =
81 Spectral index = 3.2 ± 0.2
Local significance of 5.3 σ

1 in 100 scrambled data sets have a spot ≤ 5.3 σ

Northern sky scan

	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 $\boldsymbol{\gamma}$					
#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

Northern sky scan

	α [°]	δ [°]	$\hat{\mu}_{ns}$	$\hat{\gamma}$	$-\log_{10}(p_{local})$
$\boldsymbol{\gamma = 2.0}$					
#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 (NGC 1068)
#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 (NGC 1068)
#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

Northern sky scan

	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

Northern sky scan

	α [°]	δ [°]	$\hat{\mu}_{\mathrm{ns}}$	$\hat{\gamma}$	$-\log_{10}(p_{local})$
$\boldsymbol{\gamma = 2.0}$					
#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 $\boldsymbol{\gamma}$					
#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 4151
(0.18 degrees away)

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)

Catalog search

110 objects chosen a priori

Sources from Fermi catalog 4FGL-2DR

Selection based on gamma flux and IceCube's declination-dependent sensitivity

95 blazars, 14 AGN/other galaxies, 1 galactic source

NGC 1068 and TXS 0506+056 were in catalog, NGC 4151 was not

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
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

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
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

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

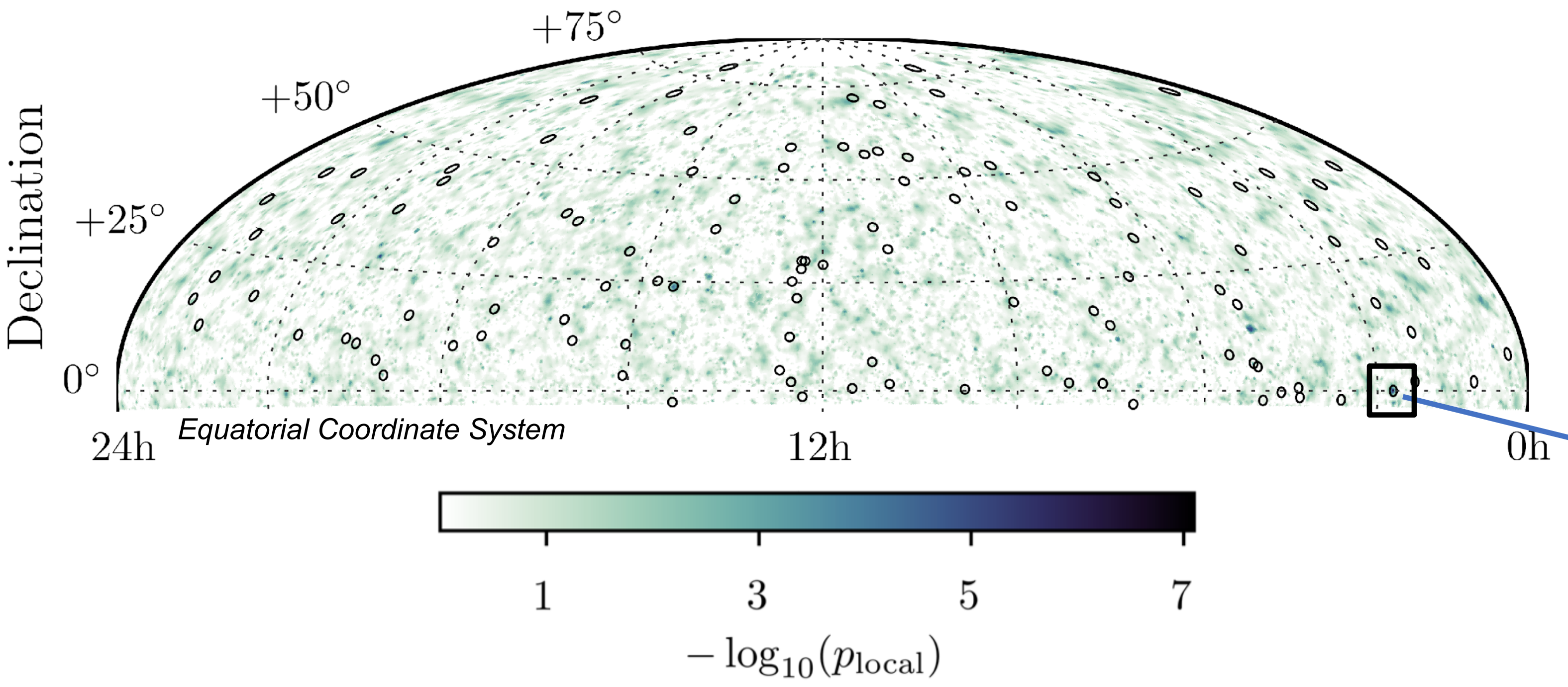
PKS 0507+17 (*)	FSRQ	77.52	18.01	0	4.3	0.0 (0.0 σ)	2.9
TXS 0518+211	BLL	80.44	21.21	8	2.8	0.6 (0.6 σ)	4.1
OG 050	FSRQ	83.17	7.55	10	3.8	0.4 (0.2 σ)	2.6
TXS 0603+476 (*)	BLL	91.86	47.66	19	4.3	0.6 (0.7 σ)	5.9
B3 0609+413	BLL	93.22	41.37	5	2.1	1.1 (1.4 σ)	7.3
NGC 2146 (*)	SBG	94.53	78.33	0	3.0	0.0 (0.0 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

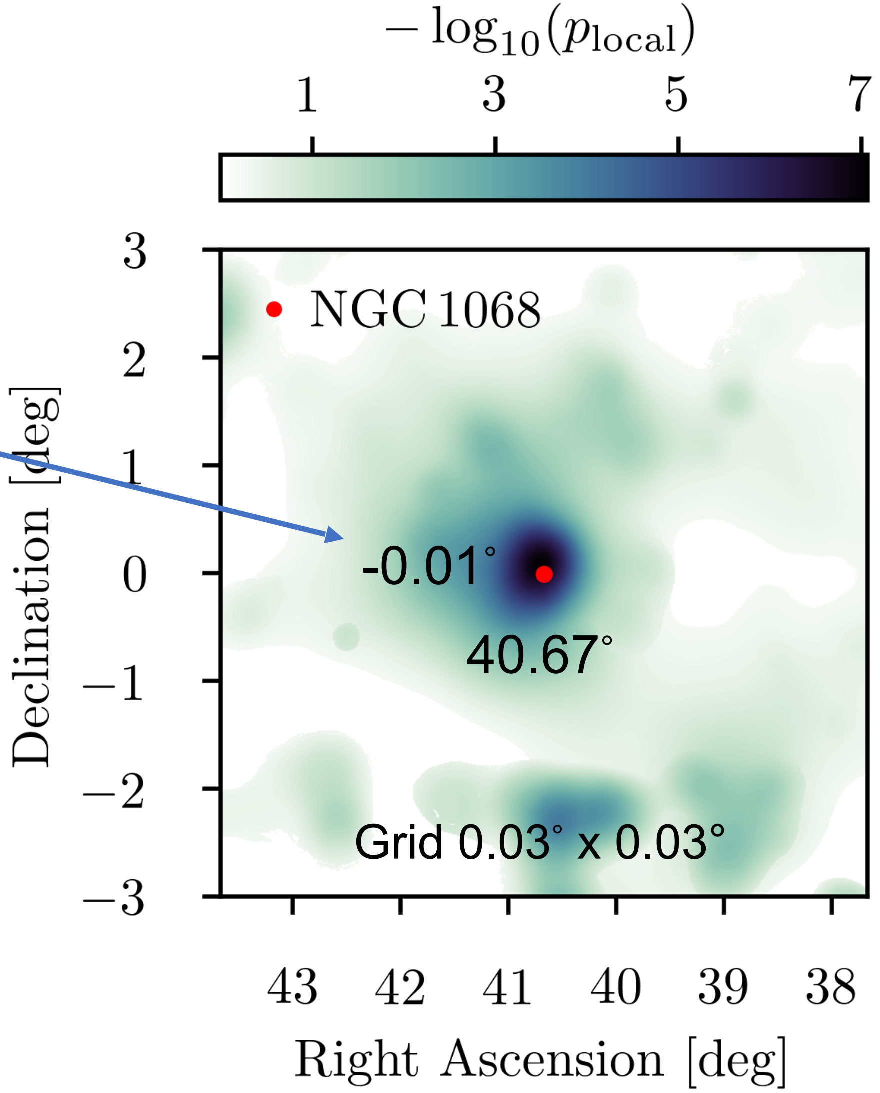
Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\mathrm{local}}$	$\Phi_{90\%}$
PG 1218+304	BLL	185.34	30.17	0	3.1	0.0 (0.0 σ)	3.4
W Comae	BLL	185.38	28.24	0	4.3	0.0 (0.0 σ)	3.3
4C +21.35	FSRQ	186.23	21.38	0	4.3	0.0 (0.0 σ)	3.2
3C 273	FSRQ	187.27	2.05	21	4.3	0.6 (0.7 σ)	3.0
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
KS 1502+106	FSRQ	226.10	10.50	1	1.8	0.5 (0.5 σ)	3.4
KS 1502+036	NLSY1	226.27	3.45	0	4.3	0.0 (0.0 σ)	2.1
2 1520+31	FSRQ	230.55	31.74	35	4.3	1.0 (1.3 σ)	6.2
rp 220 (*)	SBG	233.70	23.53	0	4.3	0.0 (0.0 σ)	3.1
B6 J1542+6129	BLL	235.76	61.50	16	3.0	1.9 (2.2 σ)	13.0
G 1553+113	BLL	238.93	11.19	2	4.3	0.2 (0.0 σ)	2.3
C +15.54 (*)	BLL	241.77	15.84	0	4.3	0.0 (0.0 σ)	2.9
C +38.41	FSRQ	248.82	38.14	4	2.3	0.9 (1.1 σ)	6.2
kn 501	BLL	253.47	39.76	15	4.3	0.5 (0.5 σ)	5.0
KS 1717+177	BLL	259.81	17.75	34	4.3	1.0 (1.2 σ)	5.1
H 1720+117	BLL	261.27	11.87	0	4.3	0.0 (0.0 σ)	2.7
4 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

Binomial test: statistical tests that looks at the distribution of p-values and compares them to a uniform p-value distribution

Chance of getting
3 or more objects at $\geq 3.5\ \sigma = 3.7\ \sigma$

Evidence for neutrino emission from NGC 1068





Catalog search (110 objects)

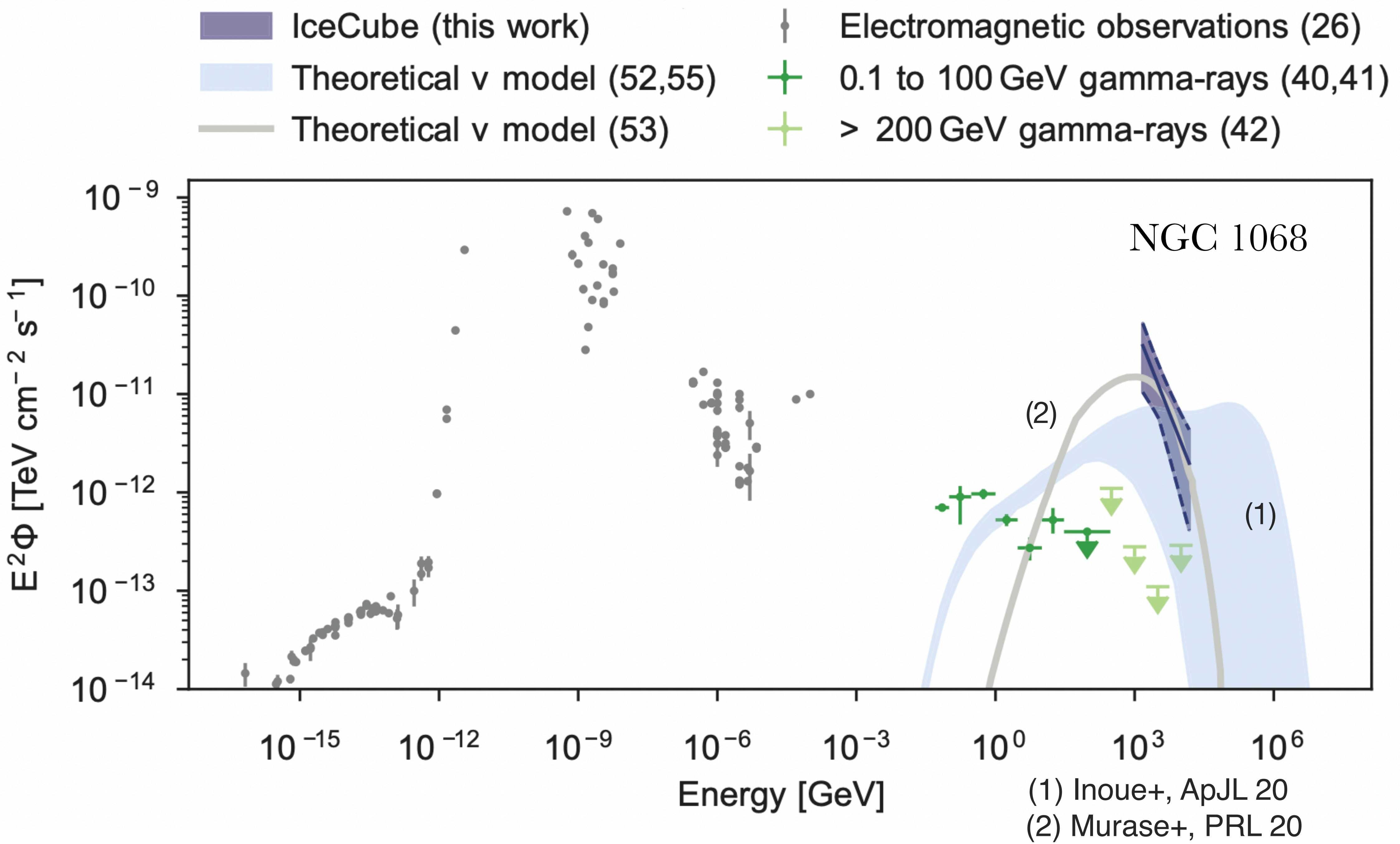
Most significant object: NGC 1068

Astrophysical neutrino events = 79^{+22}_{-20}

Spectral index = 3.2 ± 0.2

For 100,000 scrambled data sets have a spot ≤ 5.2 σ → 4.2 σ

Local significance of 5.2 σ

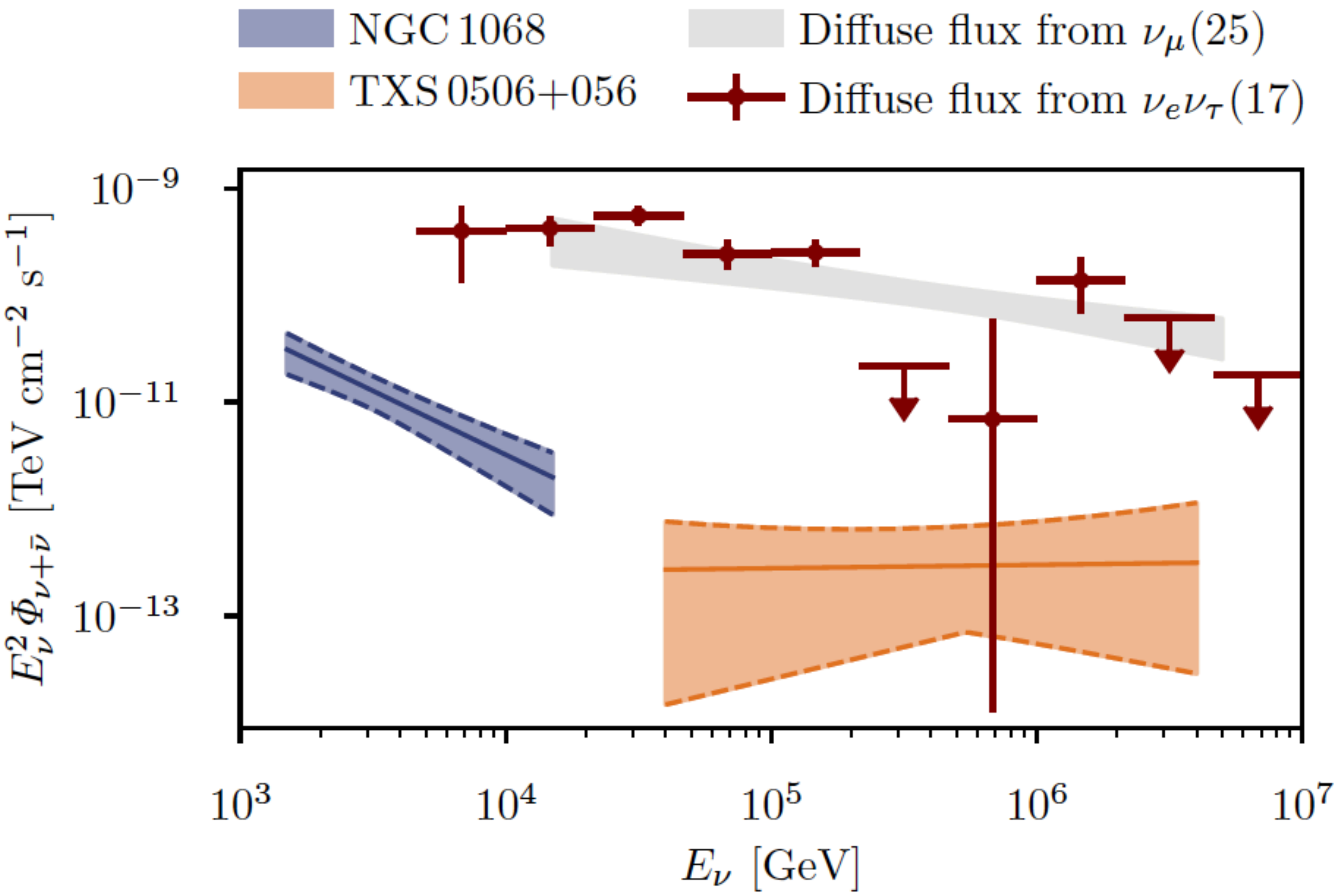

IceCube (this work)
Theoretical ν model (52,55)
Theoretical ν model (53)
Electromagnetic observations (26)
0.1 to 100 GeV gamma-rays (40,41)
> 200 GeV gamma-rays (42)
NGC 1068
(1)
(2)
$E^2\Phi$ [TeV cm^{-2} s^{-1}]
Energy [GeV]
(1) Inoue+, ApJL 20
(2) Murase+, PRL 20

Implications of the two observed sources of HE neutrinos

Active galaxies may contribute to significant fraction of extragalactic neutrino flux.

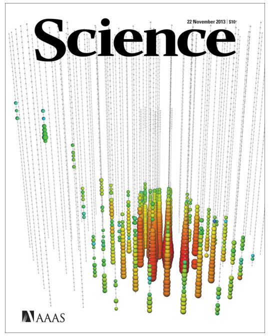
NGC 1068 and the 2014/15 TXS flare are opaque to high-energy gamma-rays

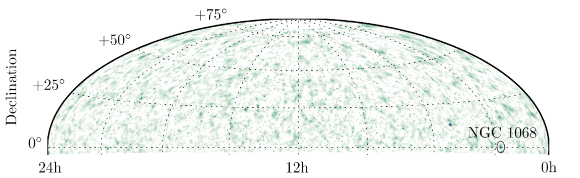
The properties of neutrino emission from NGC 1068 and TXS 0506+056 are different.



[25] IceCube. ApJ 928, 50 (2020)

[17] IceCube. PRL. 125, 121104 (2020)




RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

?

2013
Discovery of the high energy astrophysical neutrino flux

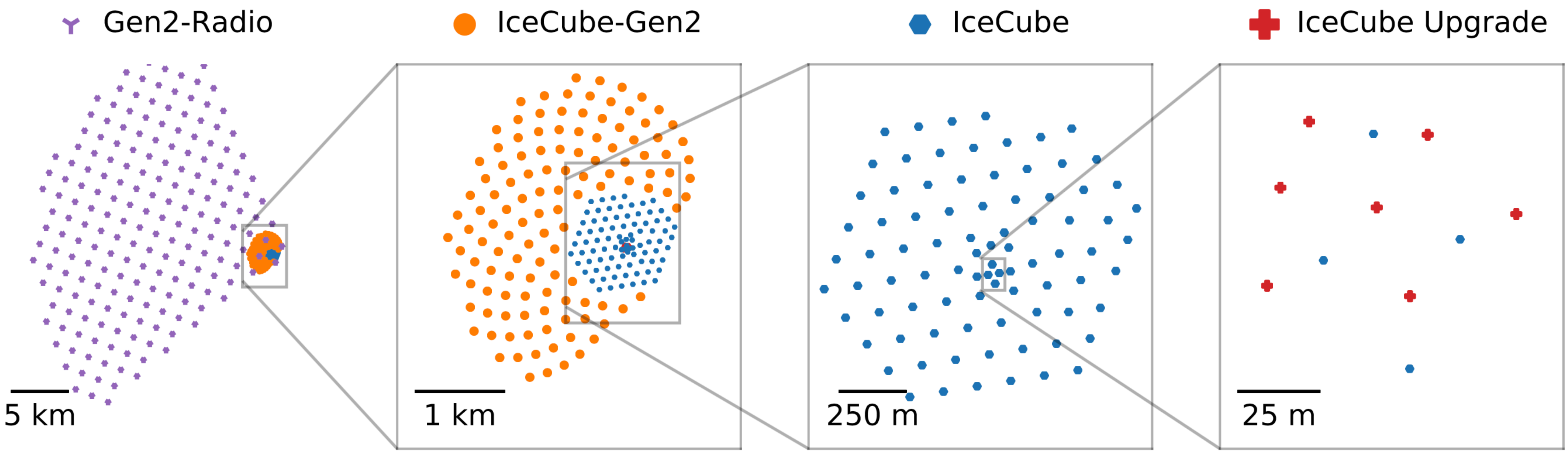
2018
Observation of the first source of high energy neutrinos

2022
Observation of the second source of high energy neutrinos

2023

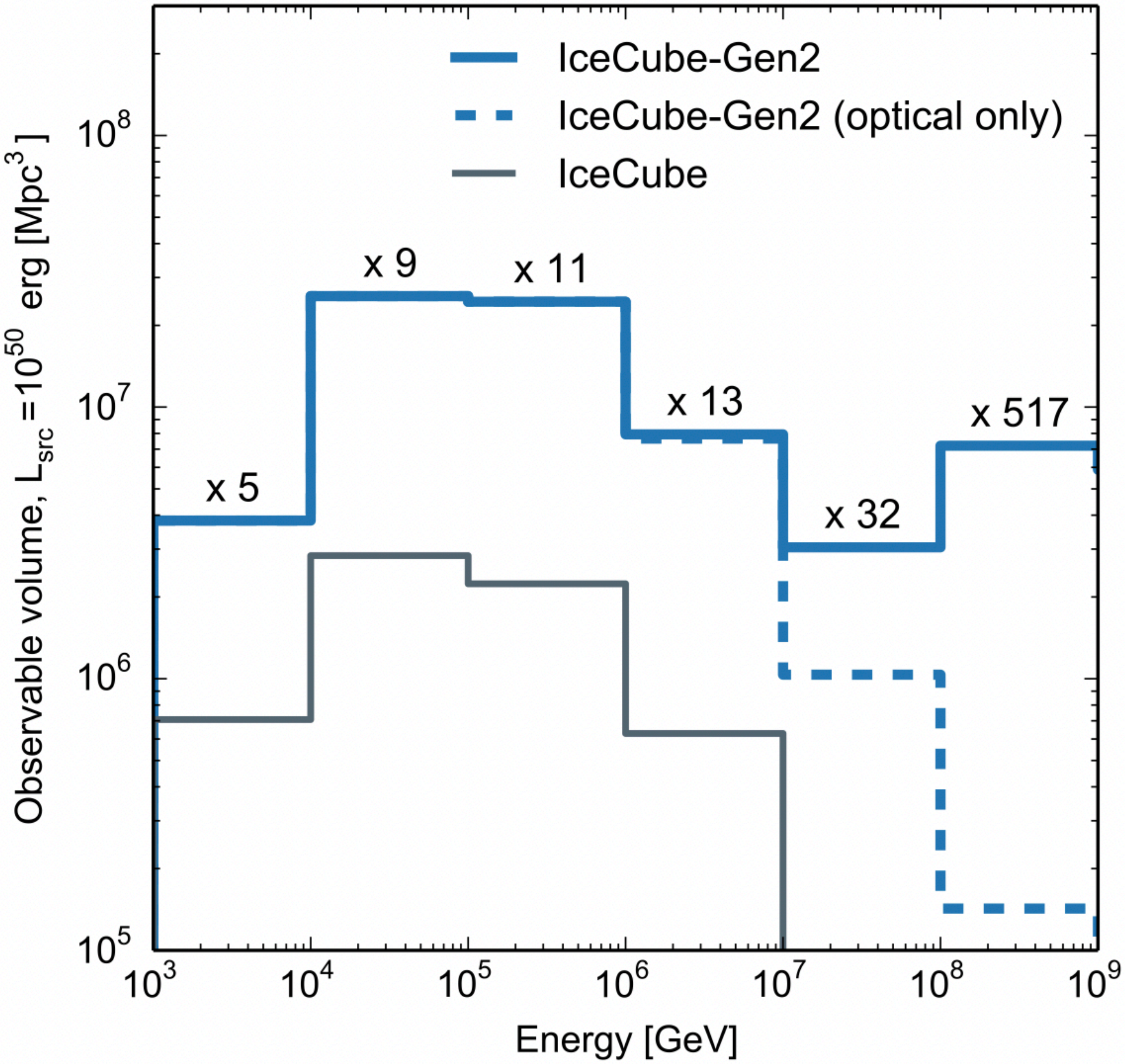
Exploring the extreme sky in IceCube-Gen2

8 x more volume



Existing detector

2025/26


IceCube-Gen2
IceCube-Gen2 (optical only)
IceCube
x 5
x 9
x 11
x 13
x 32
x 517
Observable volume, $L_{src}=10^{50}$ erg [Mpc^3]
Energy [GeV]
10^5
10^6
10^7
10^8
10^3
10^4
10^5
10^6
10^7
10^8
10^9

We have observed the first sources of neutrinos: blazar TXS 0505+056, AGN NGC1068

- Already can see that neutrinos play a unique role in obsured sources and in characterizing source behaviour

Open questions:

- More than one source population contributing to the diffuse flux?
- Connection to electromagnetic radiation?