

The First Decade of High-Energy Neutrino Astronomy and Neutrino Physics

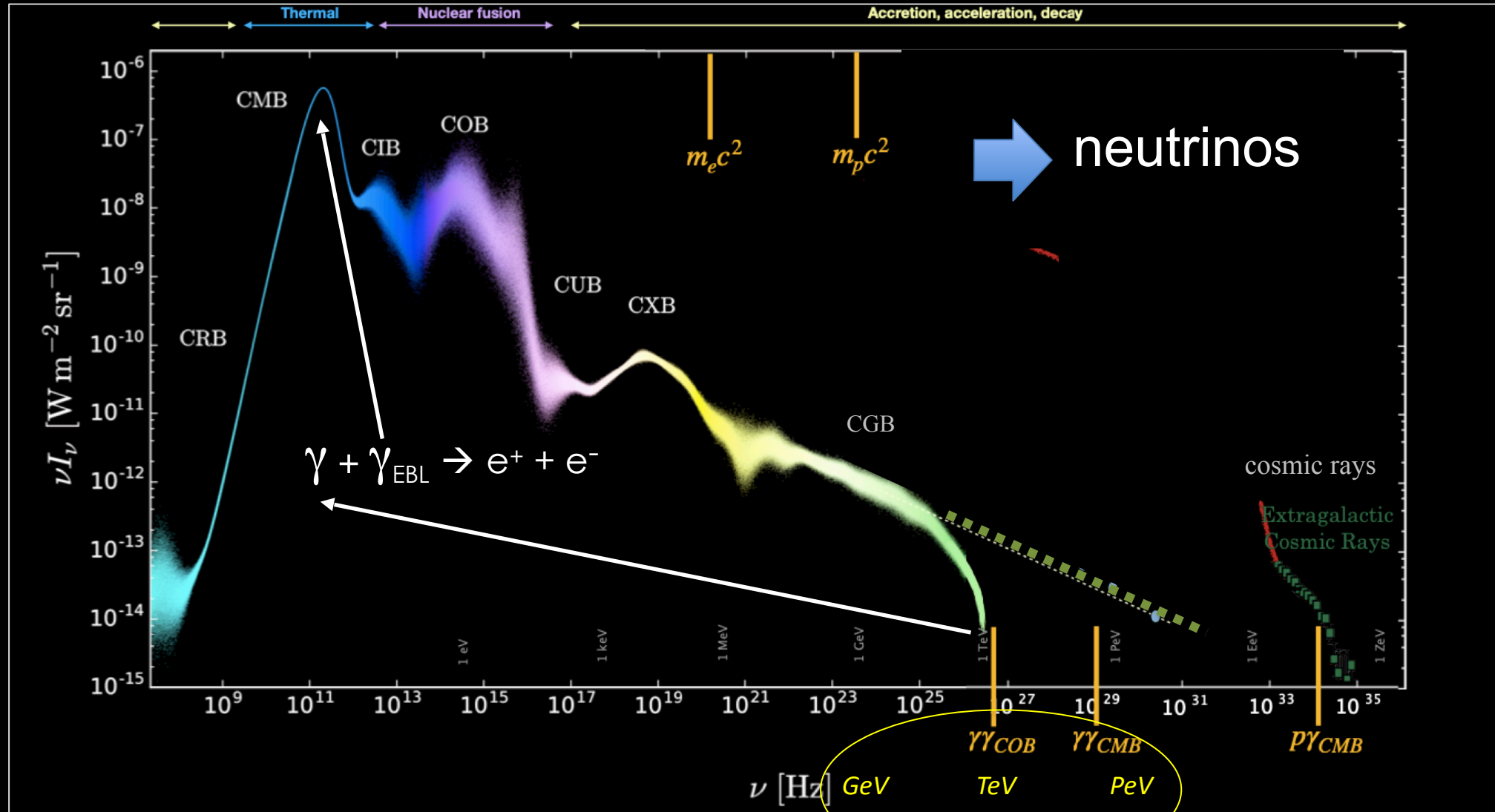


francis halzen

- High-Energy Neutrino Astronomy
- IceCube and the discovery of Cosmic Neutrinos: First Surprises
- The First Neutrino Sources: Supermassive Black Holes

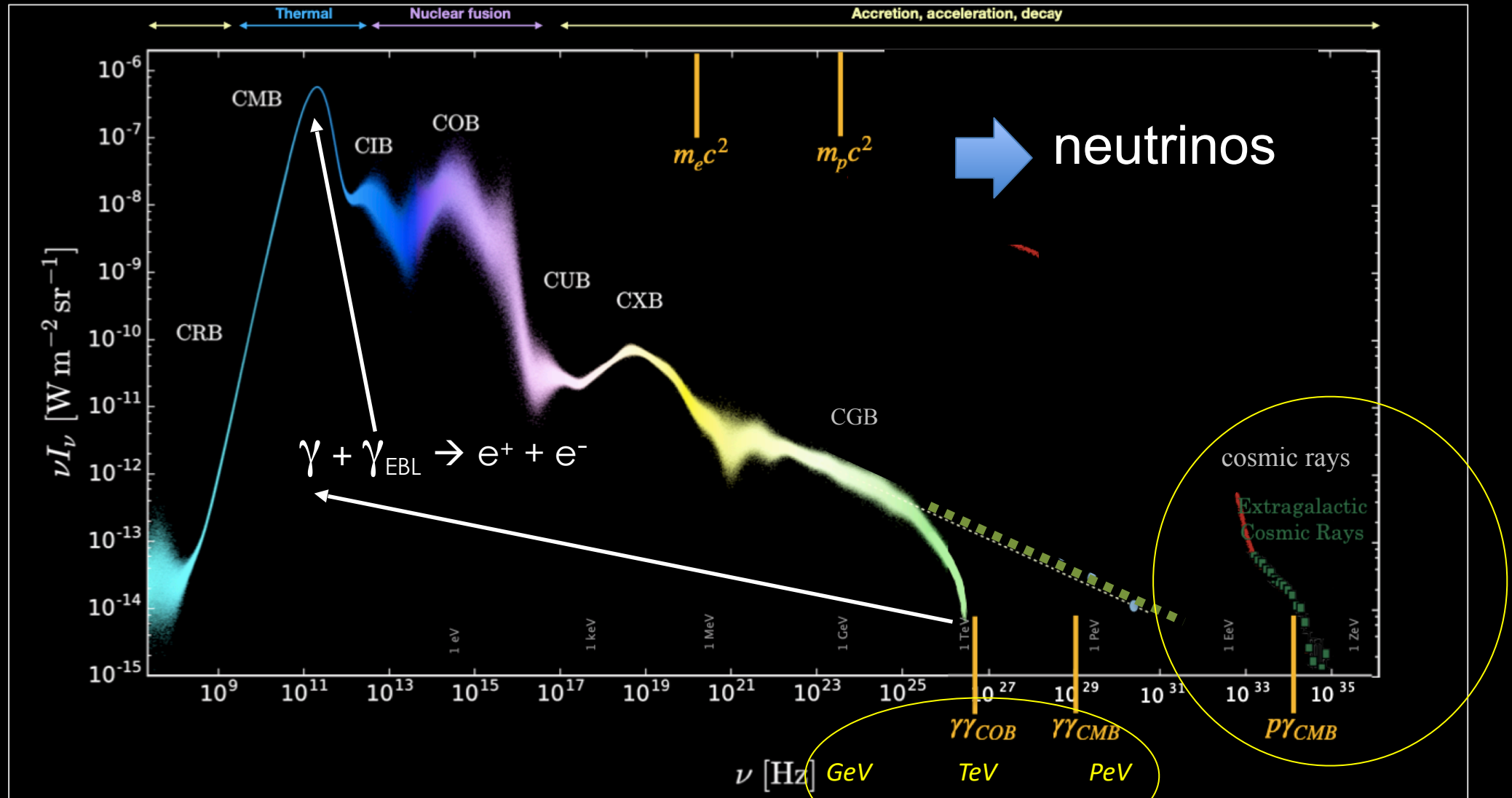
energy in photons in the Universe as a function of their frequency

$E^2 \frac{dN}{dE}$
vs
 E



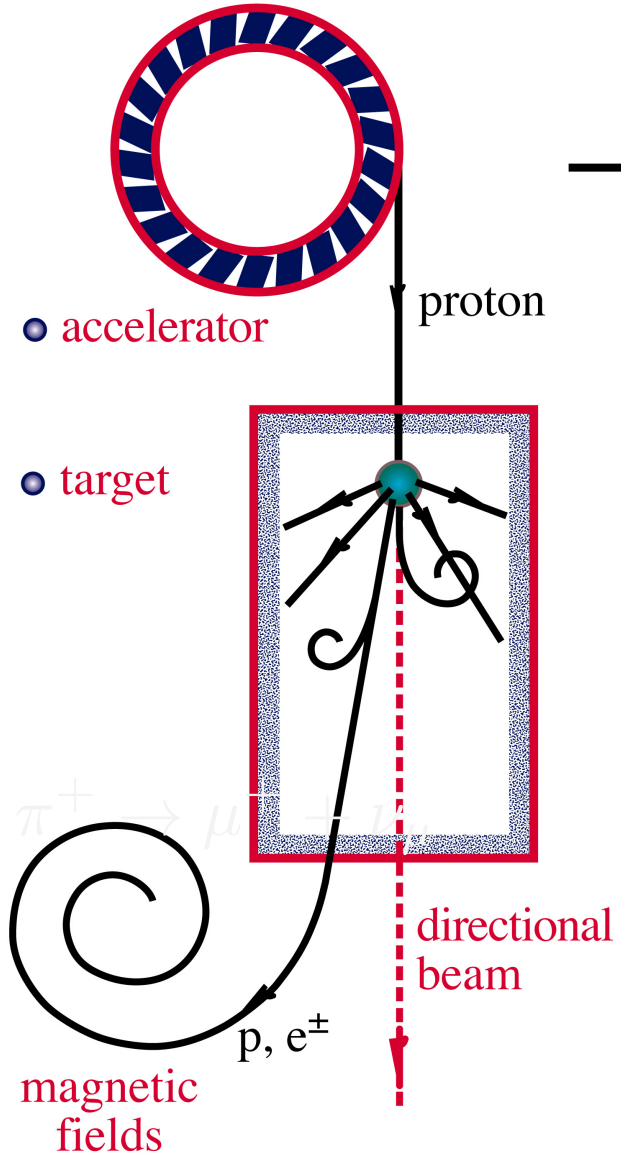
the Universe turns opaque to light at TeV energies: enter neutrinos

energy in photons in the Universe as a function of their frequency



the Universe turns opaque to light at TeV energies: enter neutrinos

ν and γ beams : heaven and earth



cosmic accelerators powered by gravity

**supermassive
black hole**

**nearby
radiation**

$$p + \gamma \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

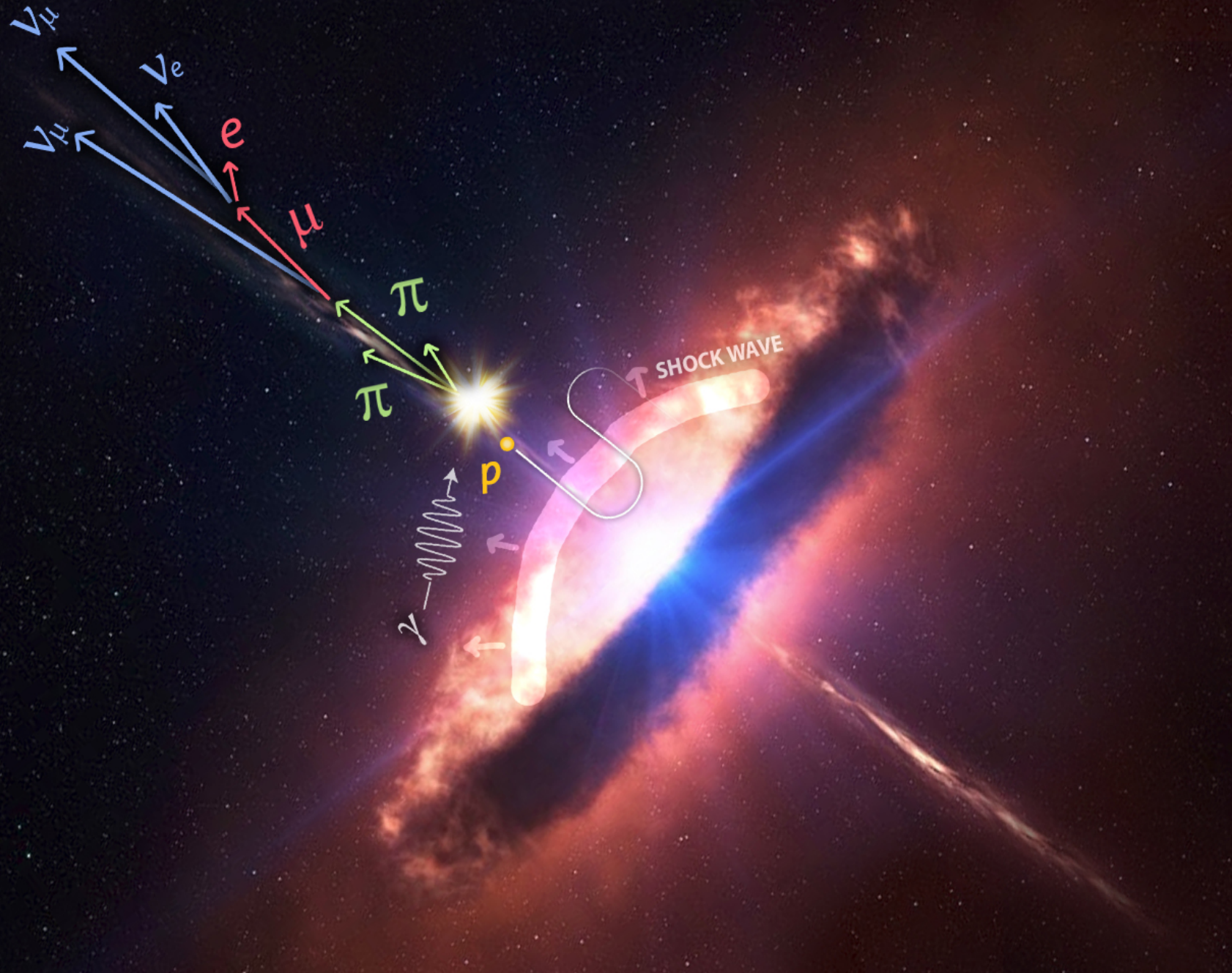
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\rightarrow p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

cosmic ray accelerators:

- protons accelerated near a black hole are submersed in a target of radiation and produce pions
- the gamma ray-neutrino interface: one photon for every neutrino
- neutrinos track cosmic ray (*proton*) accelerators making pions

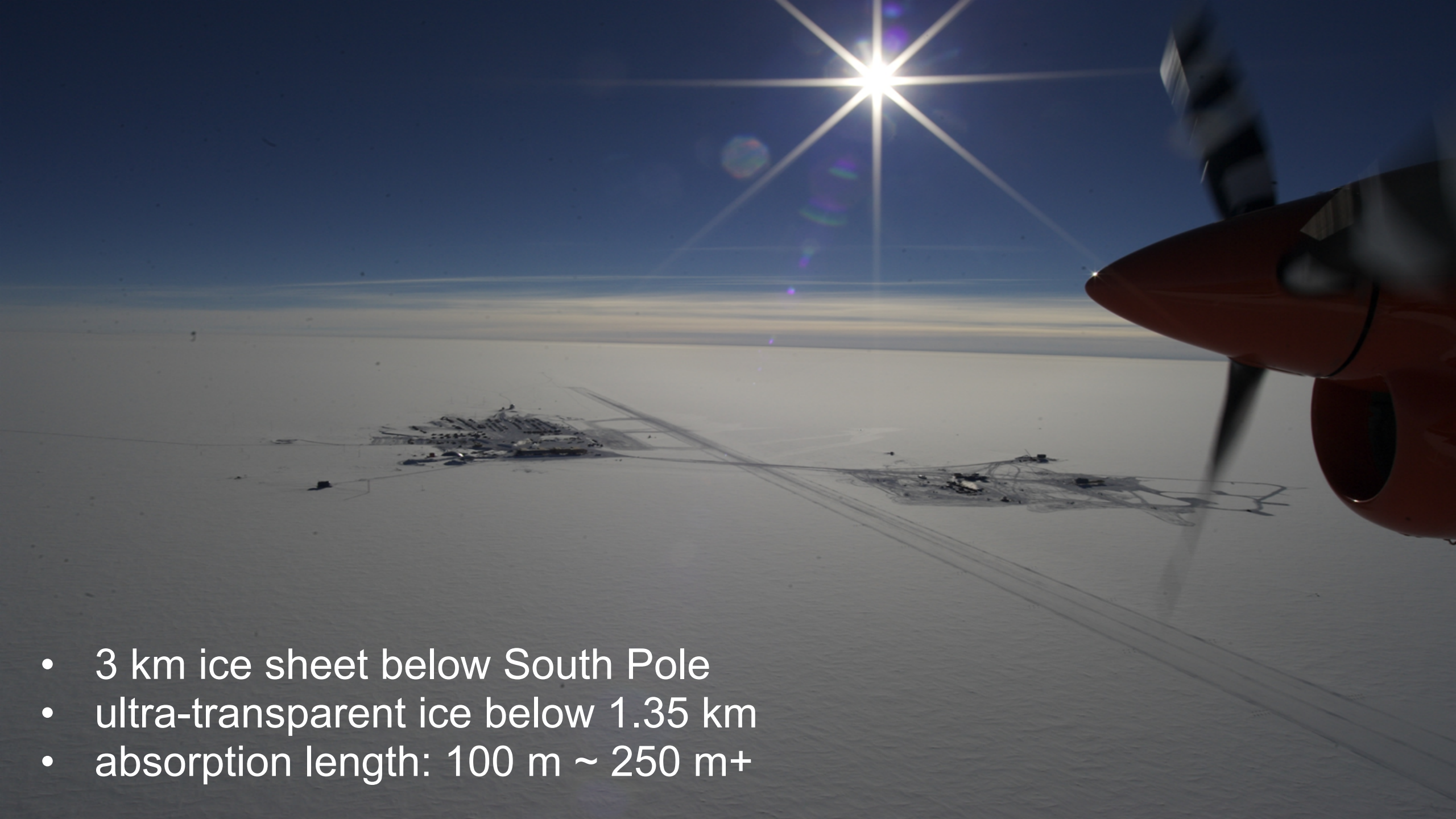


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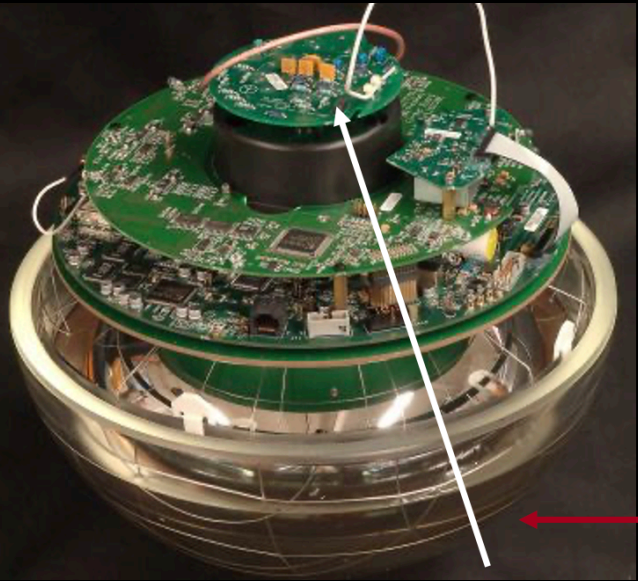
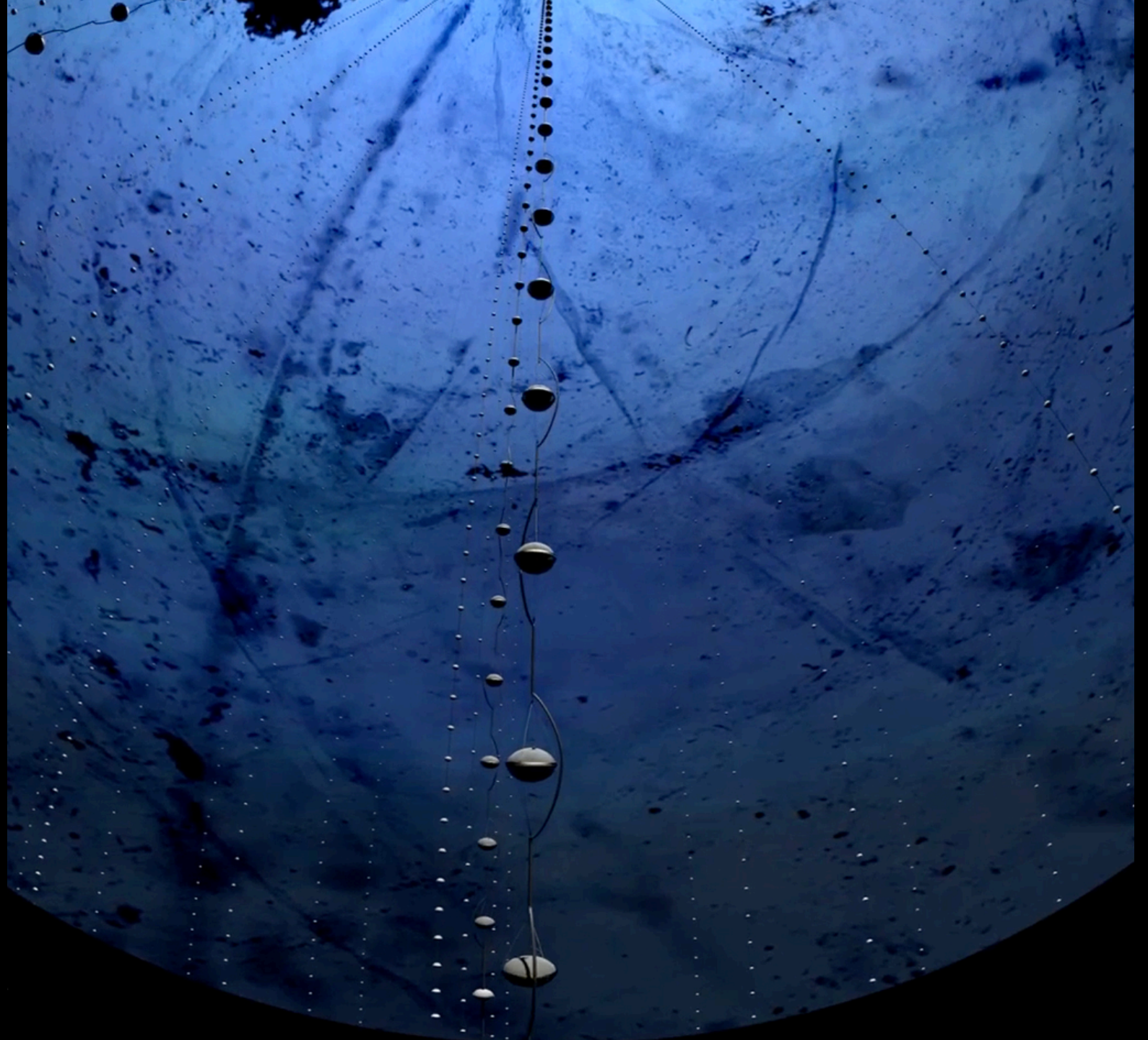
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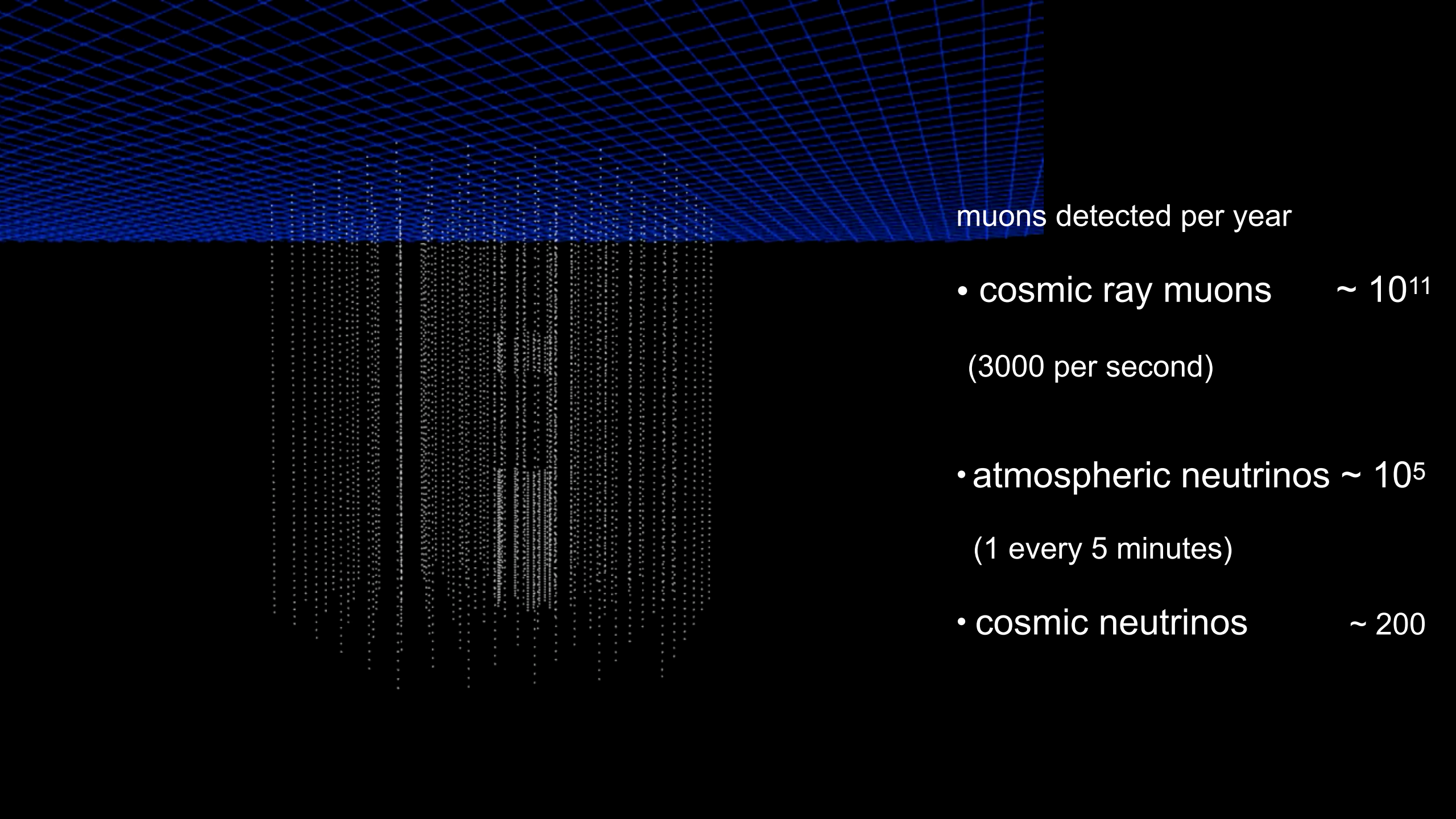
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- 3 km ice sheet below South Pole
- ultra-transparent ice below 1.35 km
- absorption length: 100 m ~ 250 m+

IceCube:
5160 10-inch photomultipliers,
60 per string on 86 strings,
instrument one km³ of
Antarctic ice between
1.4 and 2.4 km depth
as a Cherenkov detector

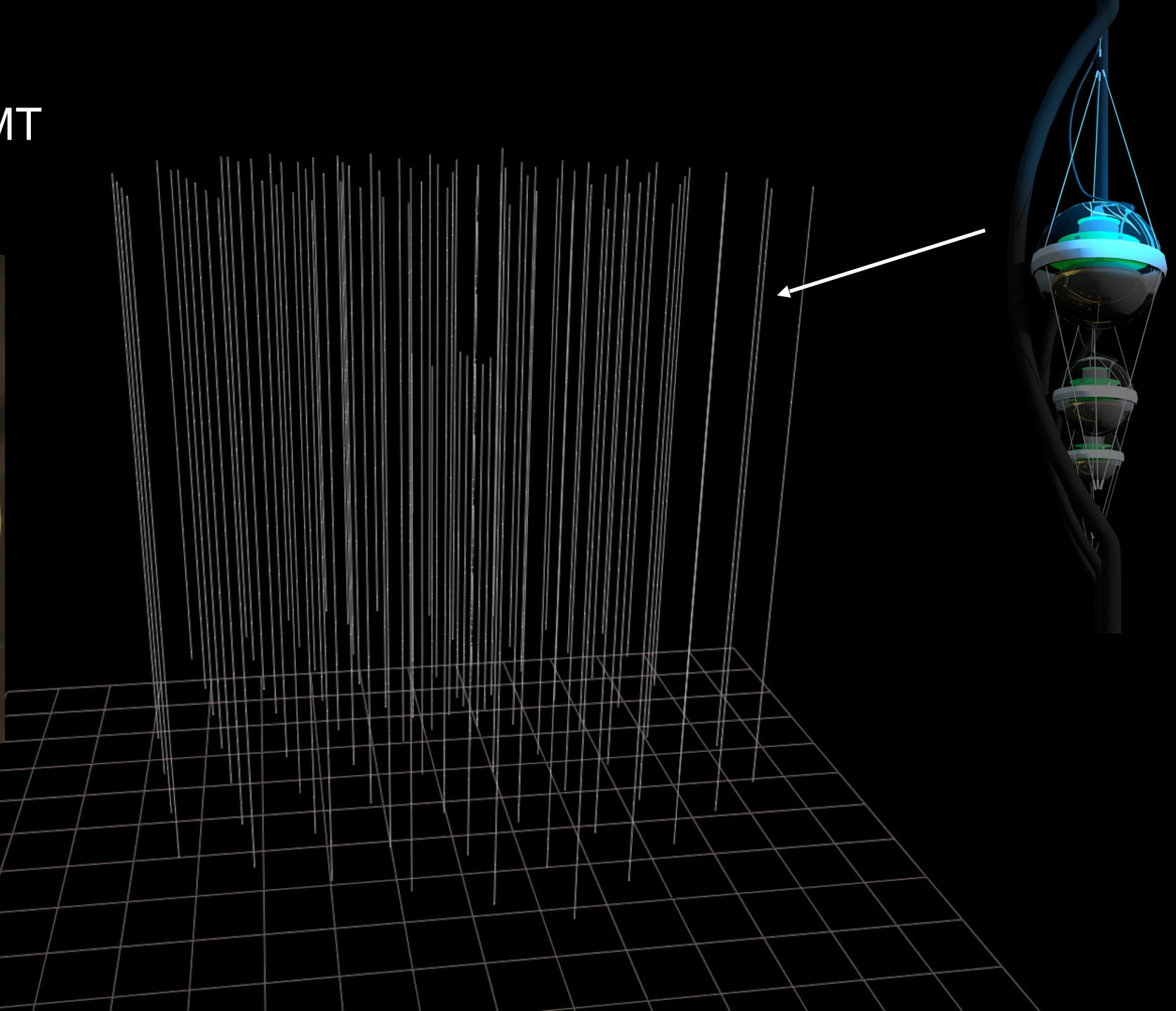
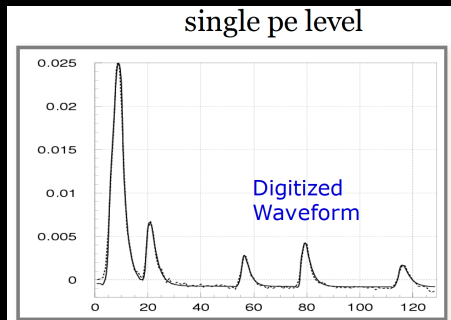




muons detected per year

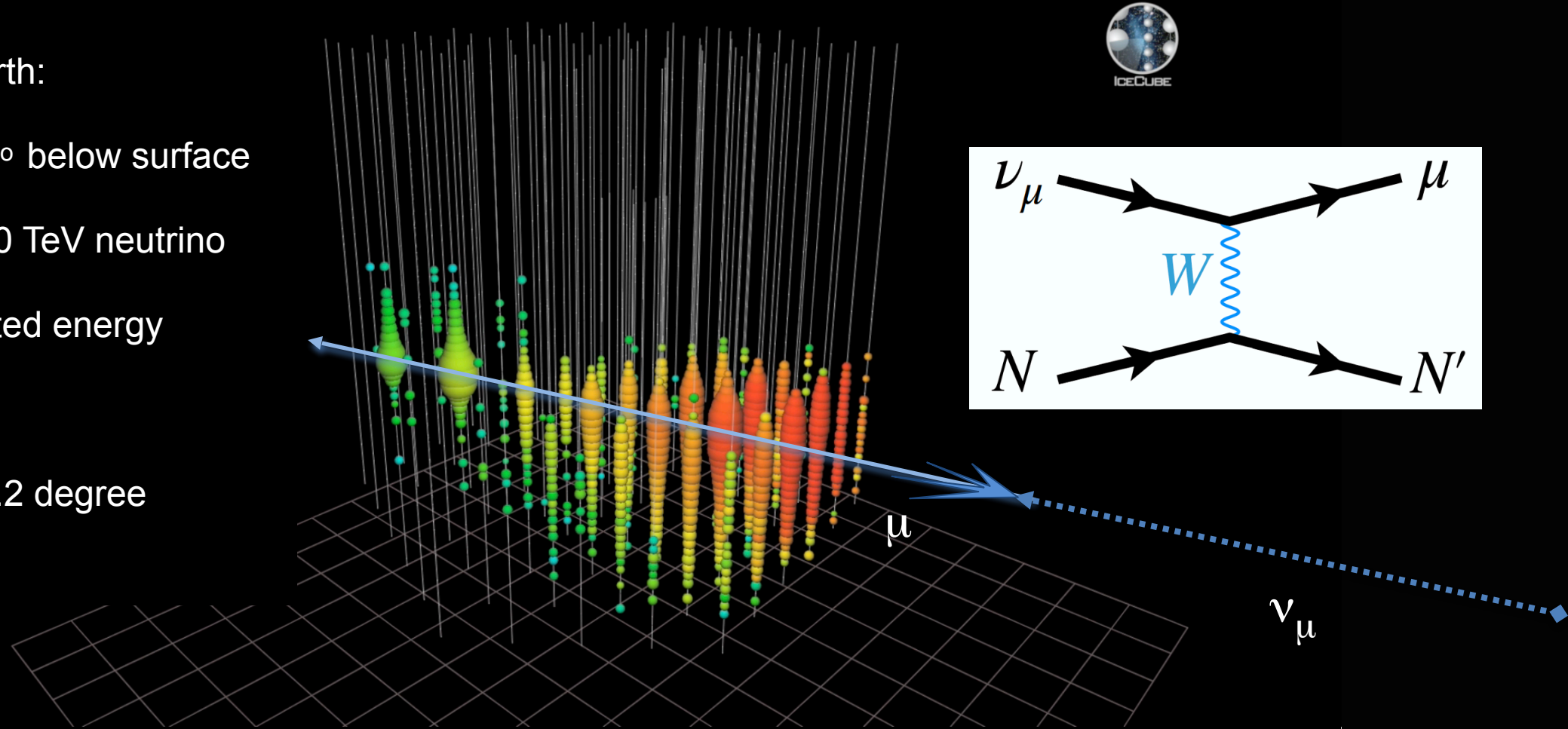
- cosmic ray muons $\sim 10^{11}$
(3000 per second)
- atmospheric neutrinos $\sim 10^5$
(1 every 5 minutes)
- cosmic neutrinos ~ 200

1 km³ of Antarctic ice
instrumented with 5160 PMT
(10inch) below 1450m



Look through the Earth:

- upgoing muon 11° below surface
- produced by 8,700 TeV neutrino
- 2,600 TeV deposited energy
- not atmospheric
- reconstructed < 0.2 degree
- astronomy

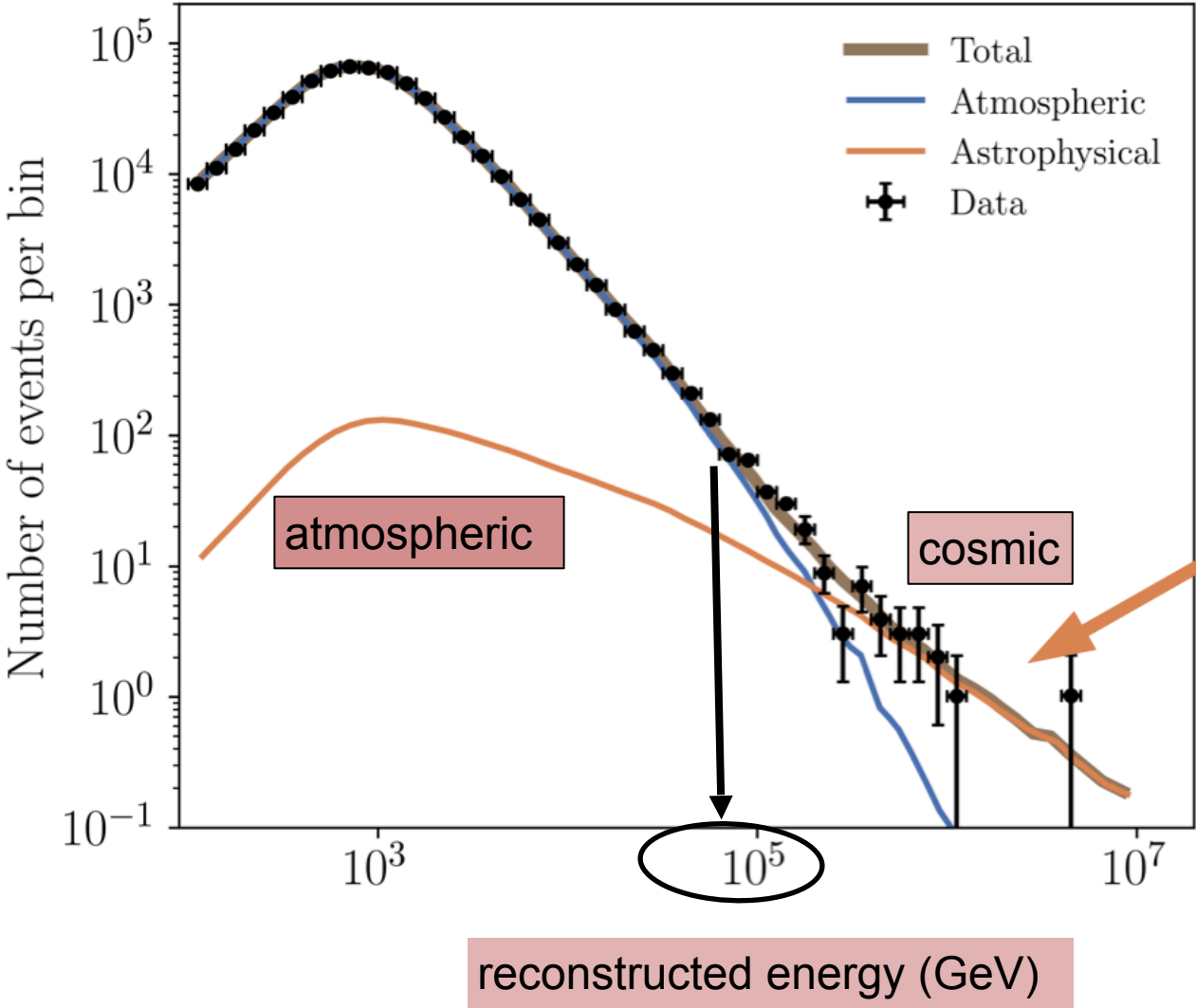
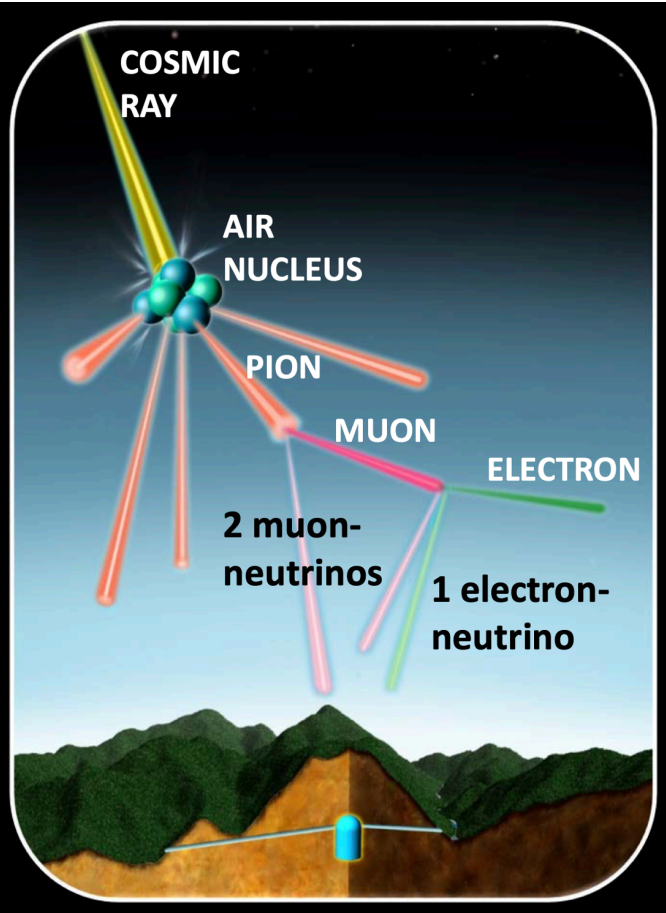


muon neutrino events
[filtered by the Earth]:
atmospheric vs cosmic

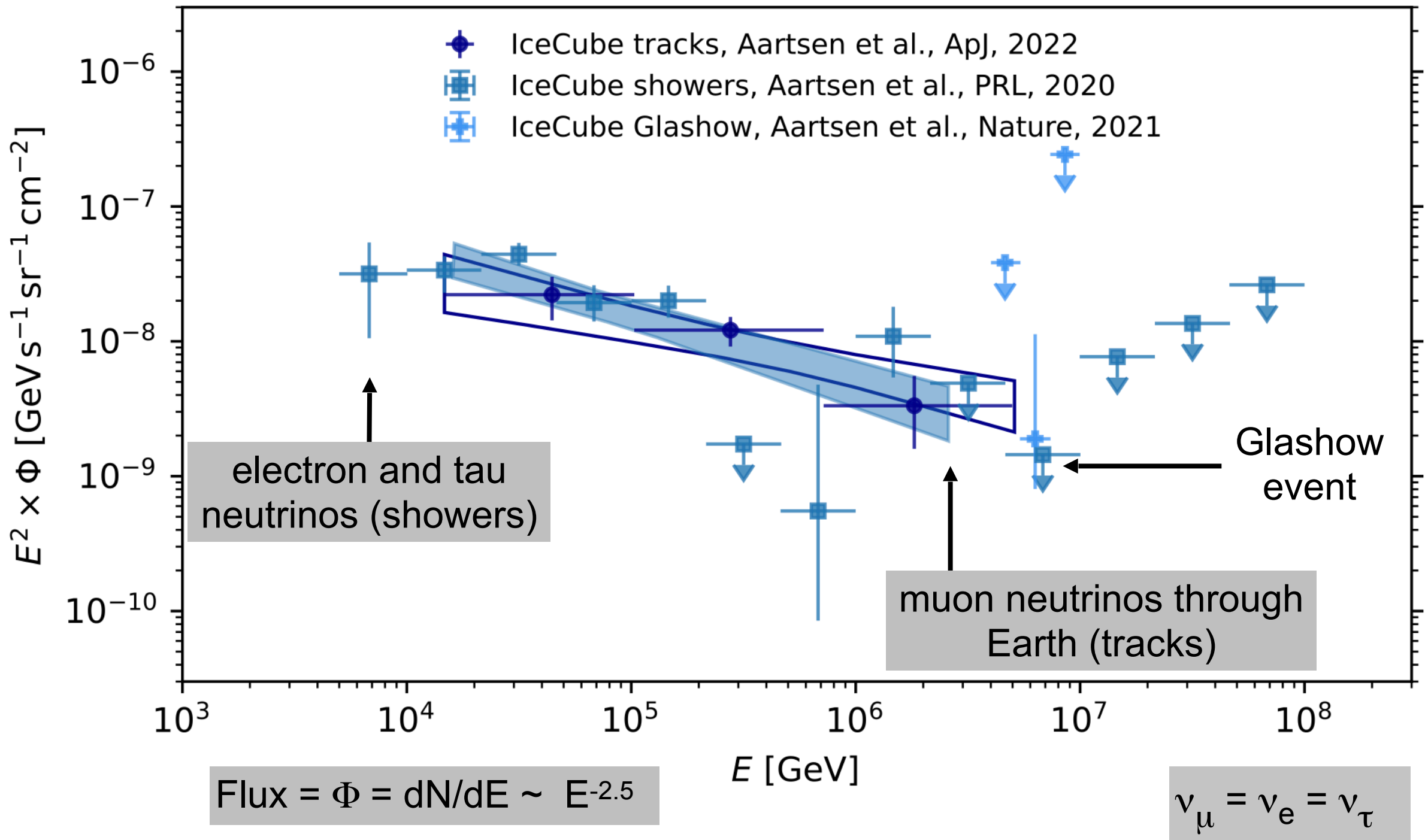
In 2013: Astrophysical diffuse neutrinos

Data from arXiv:1908.09551 [astro-ph.HE]

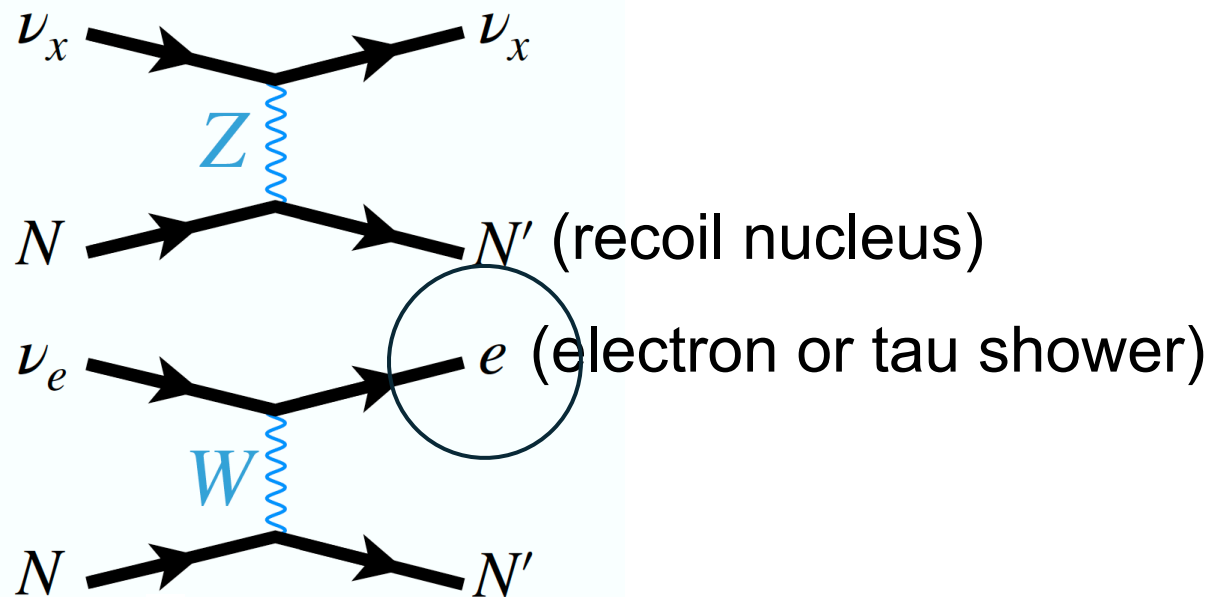
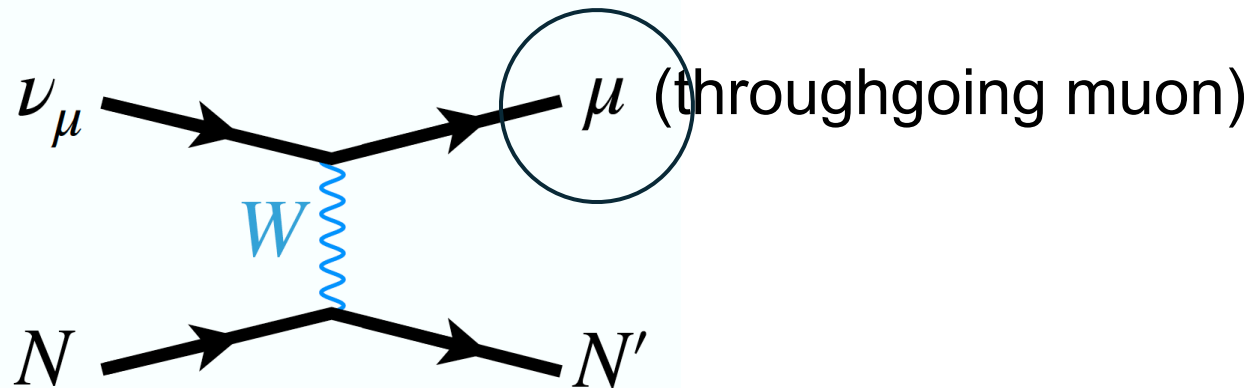
number of events



More
abundant
at higher
energies

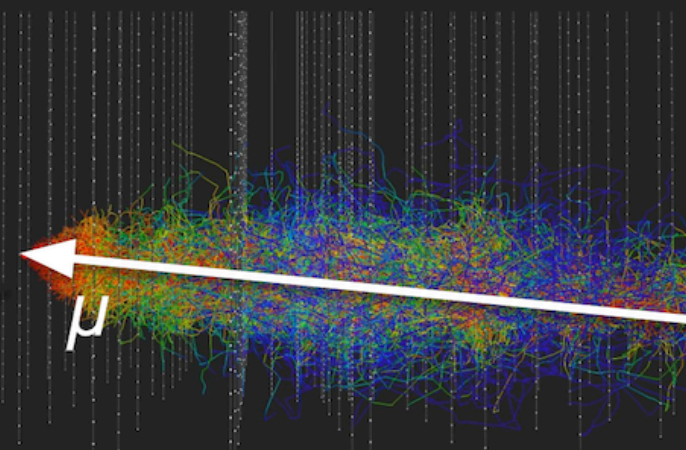


other neutrino flavors

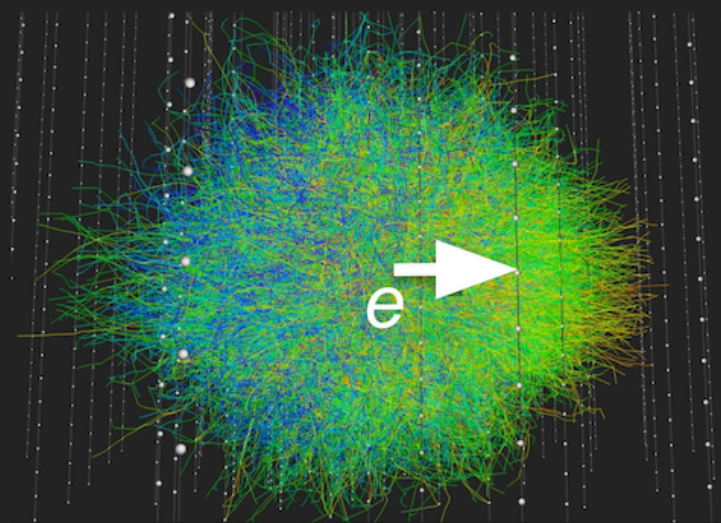


Deep inelastic scattering of Neutrinos

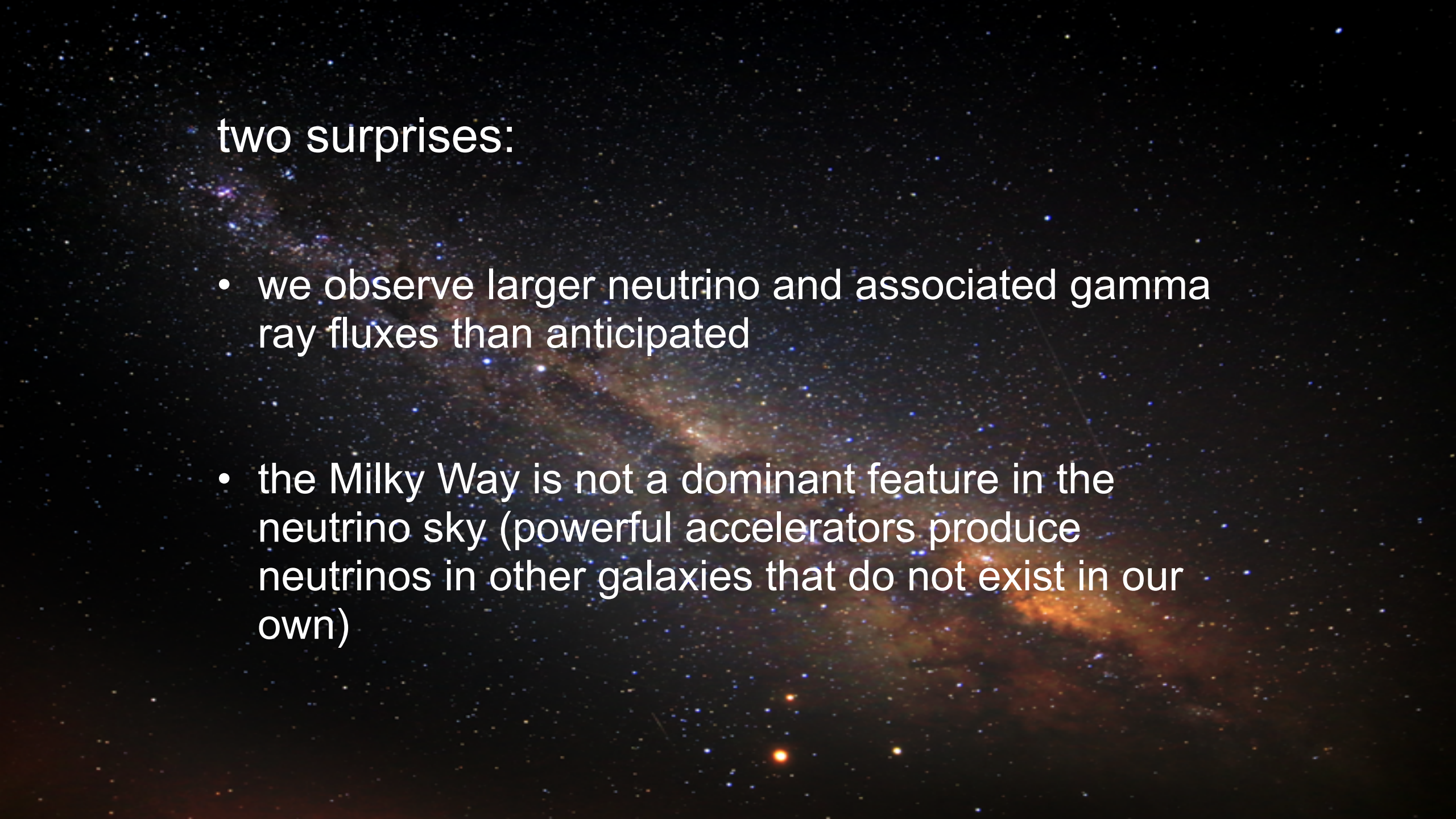
□ Cherenkov light



muon-induced tracks



cascades (no muon)

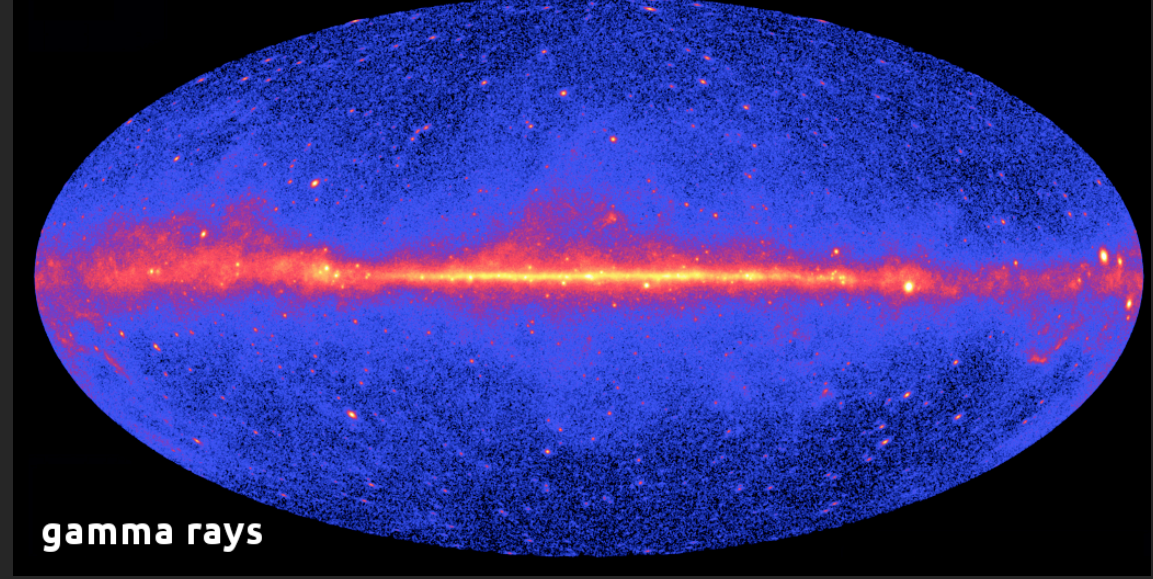


two surprises:

- we observe larger neutrino and associated gamma ray fluxes than anticipated
- the Milky Way is not a dominant feature in the neutrino sky (powerful accelerators produce neutrinos in other galaxies that do not exist in our own)



visible

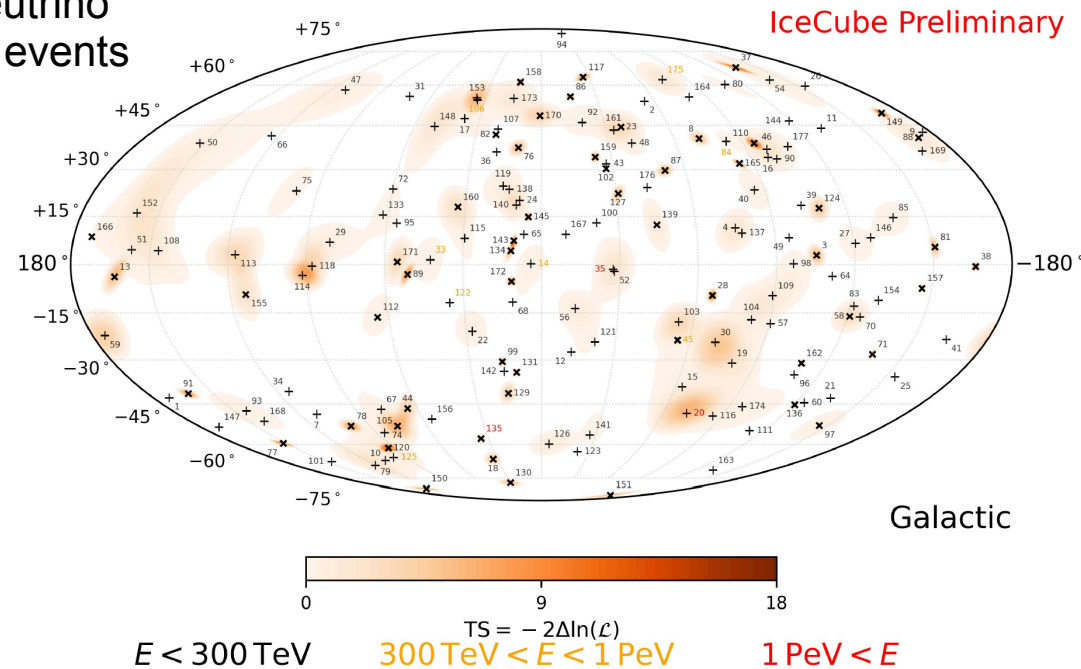


gamma rays

where is the neutrino Galactic plane?

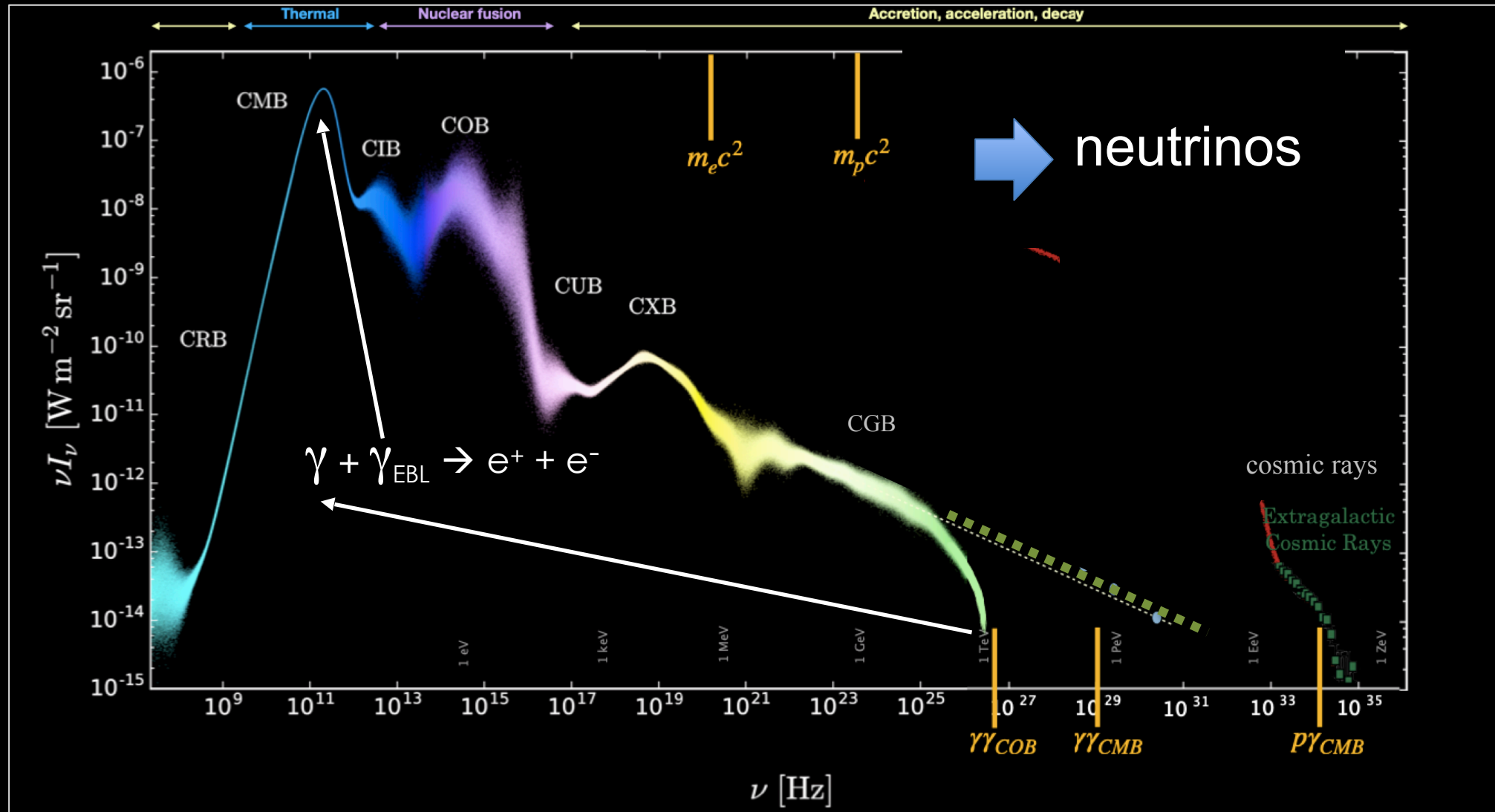
by geometry the flux from your own Galaxy should dominate the diffuse flux from all other galaxies combined!

166 neutrino starting events



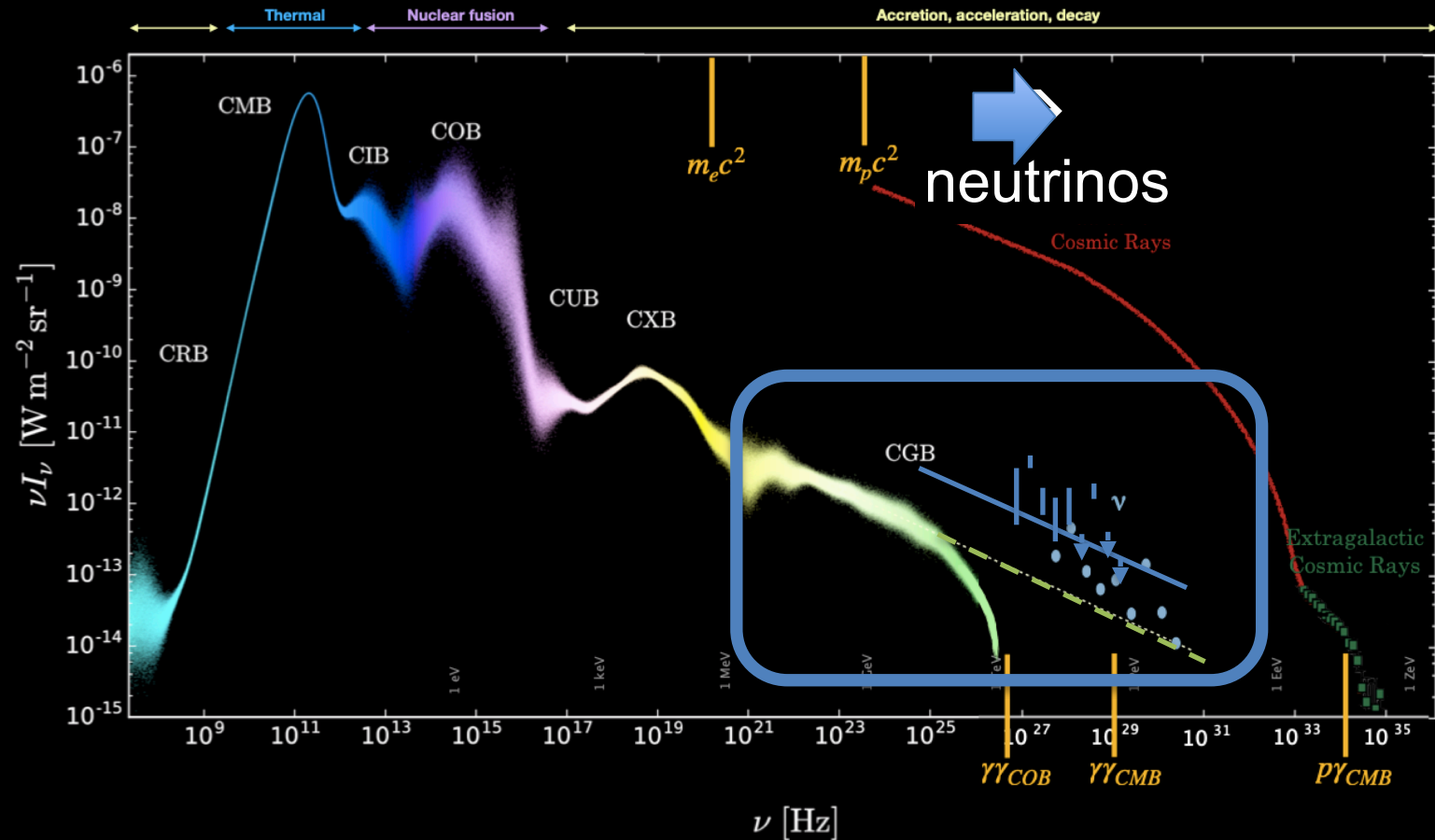
there are sources of neutrinos in other galaxies that do not exist in our own

energy in photons in the Universe as a function of their frequency



the Universe turns opaque to light at TeV energies: enter neutrinos

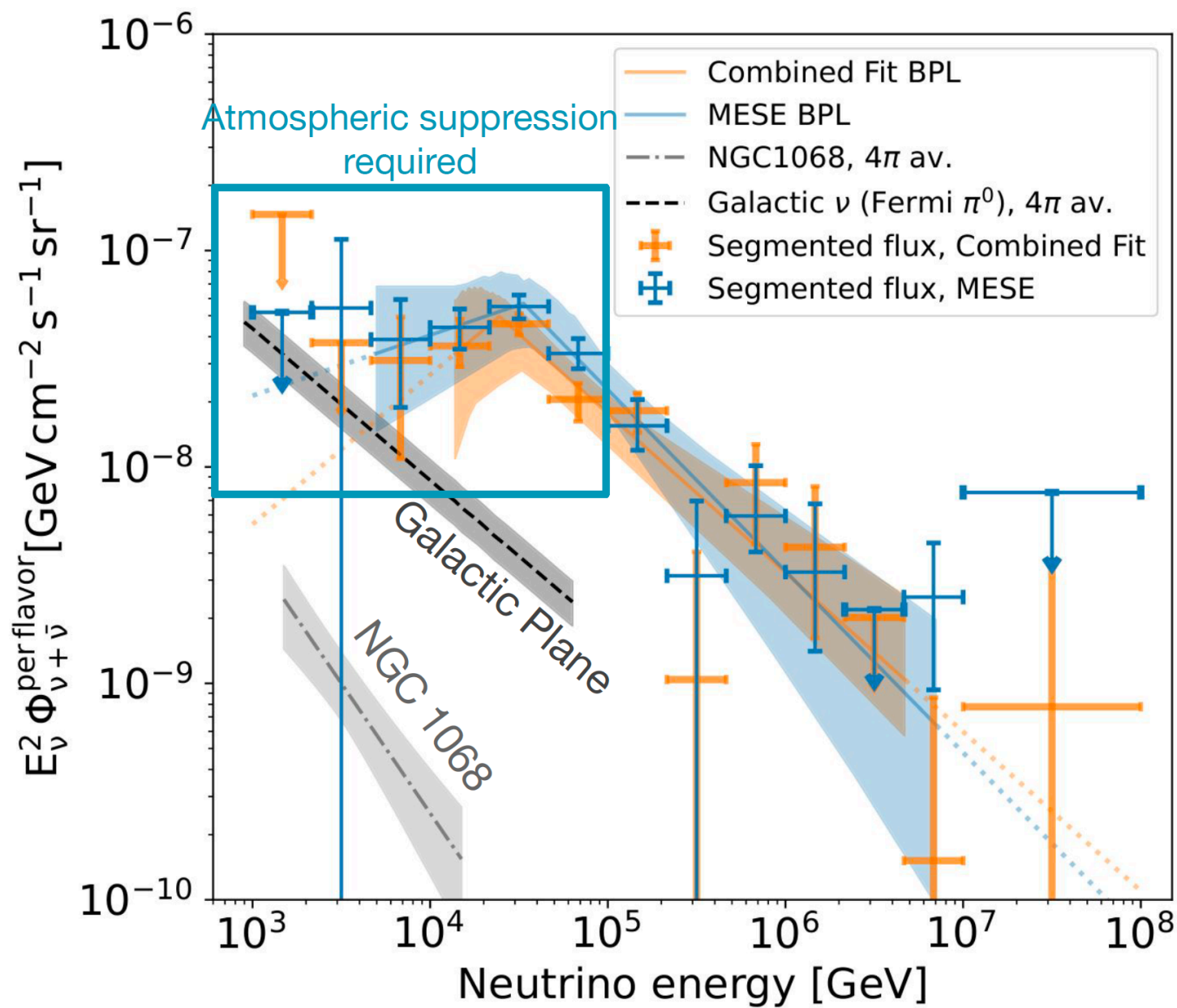
Fermi and IceCube do not observe the same gamma ray sources



Fermi NASA gamma-ray satellite

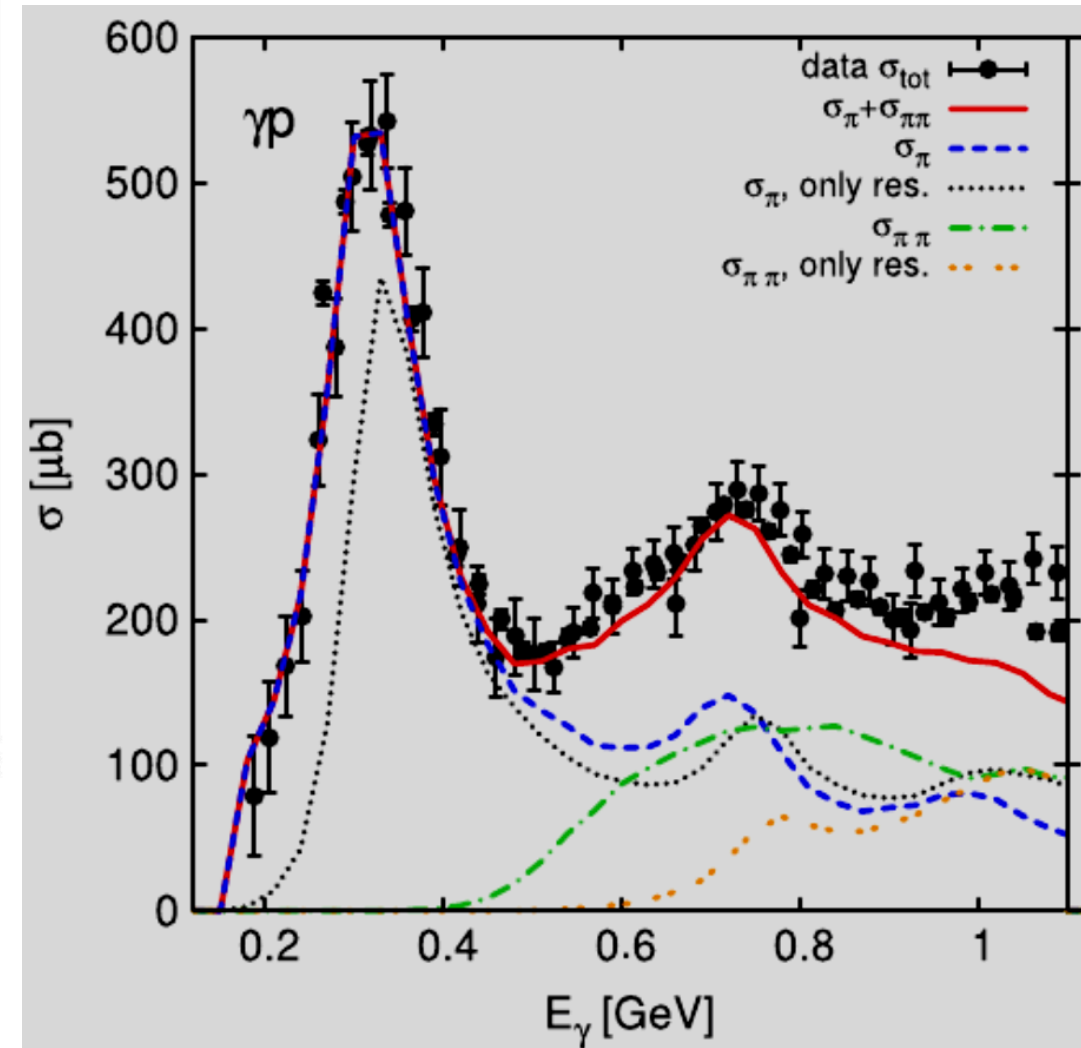


in the extreme universe the energy in neutrinos (and π^0 gamma rays) is larger than the (cascaded) energy in TeV gamma rays observed by Fermi

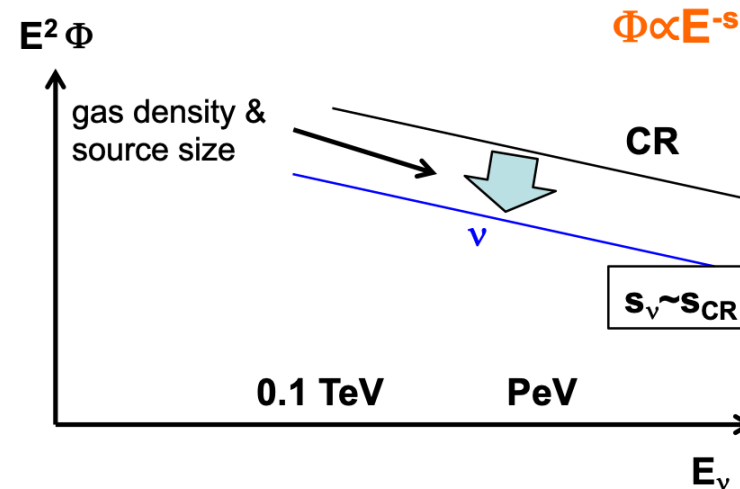
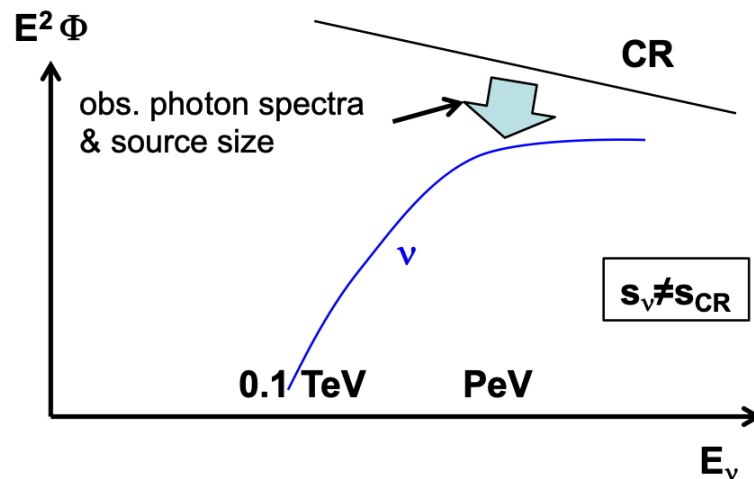
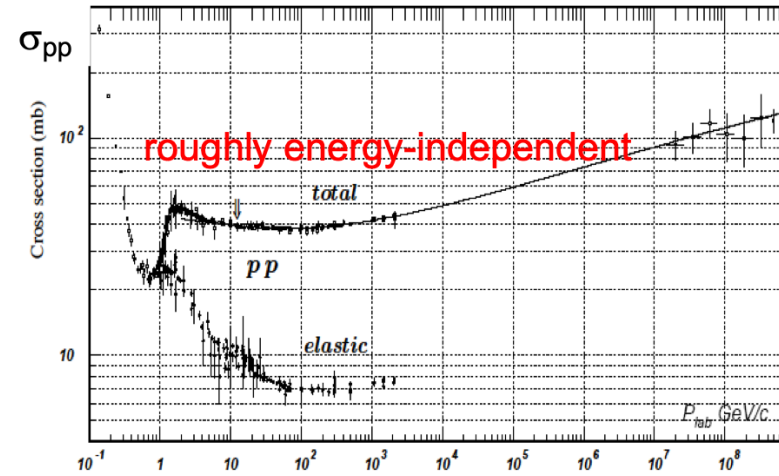
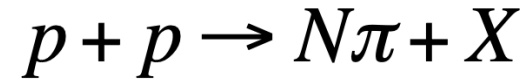
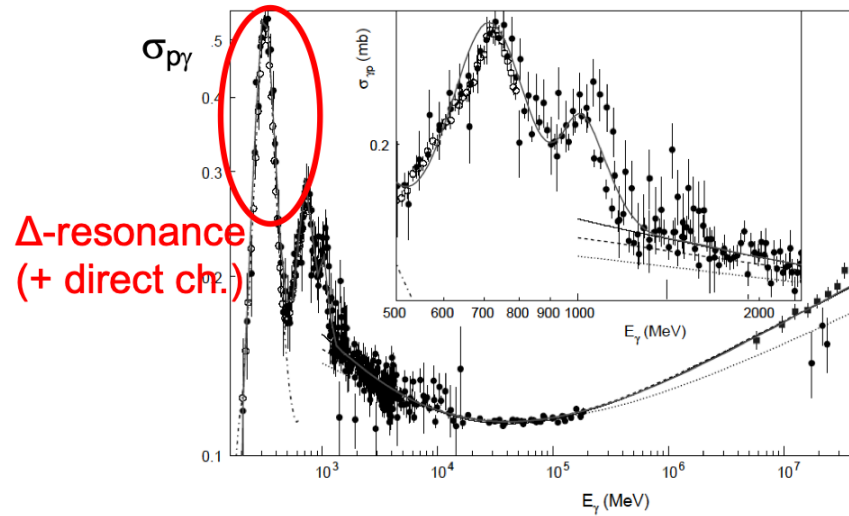
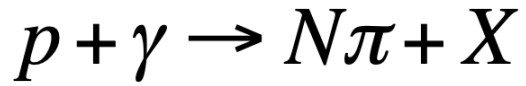


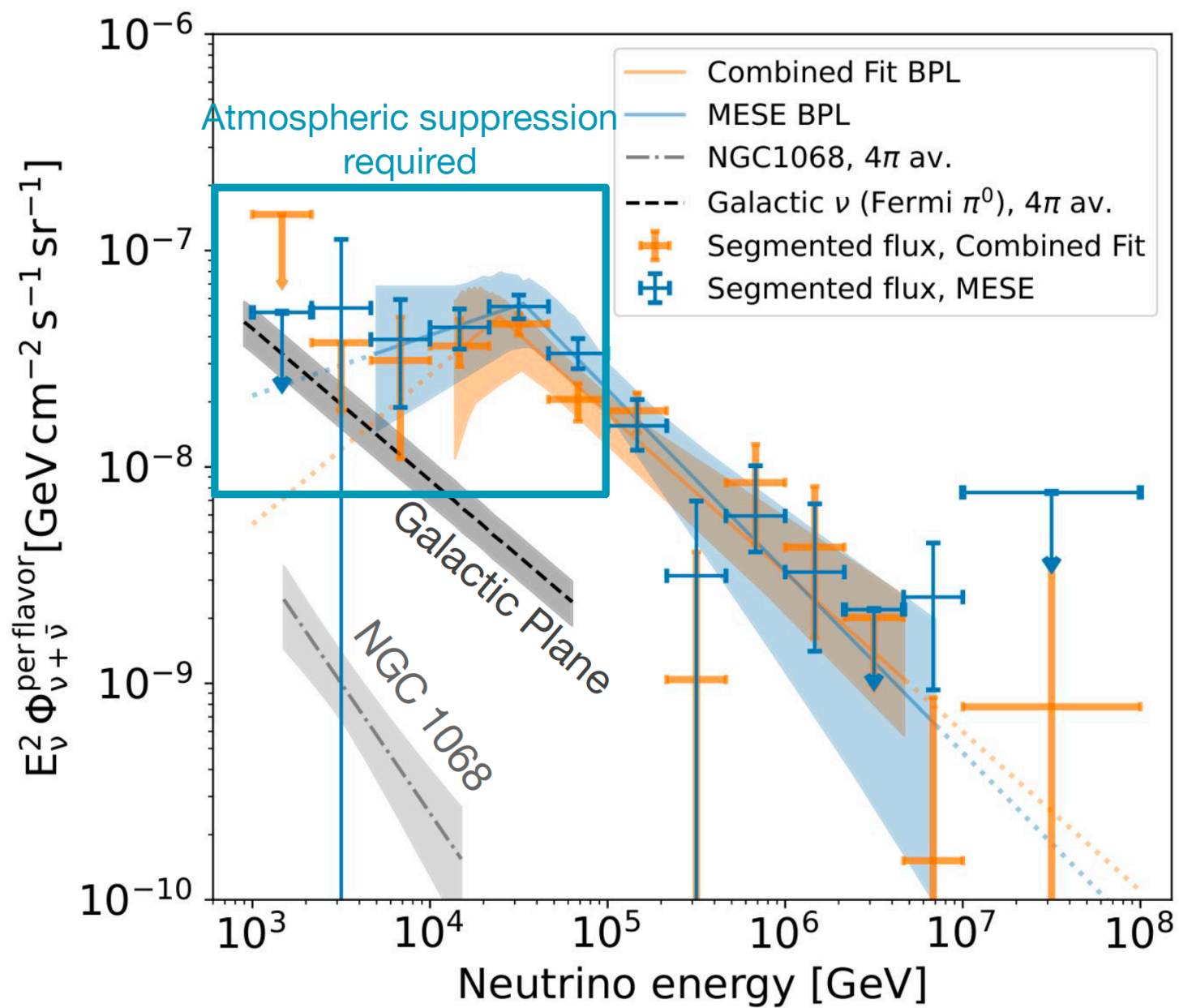
the delta resonance in the neutrino sky

gamma ray target
consistent with first sources observed



neutrino spectrum: p-gamma versus pp interactions





gamma target: 1~10 KeV X-rays



30 TeV

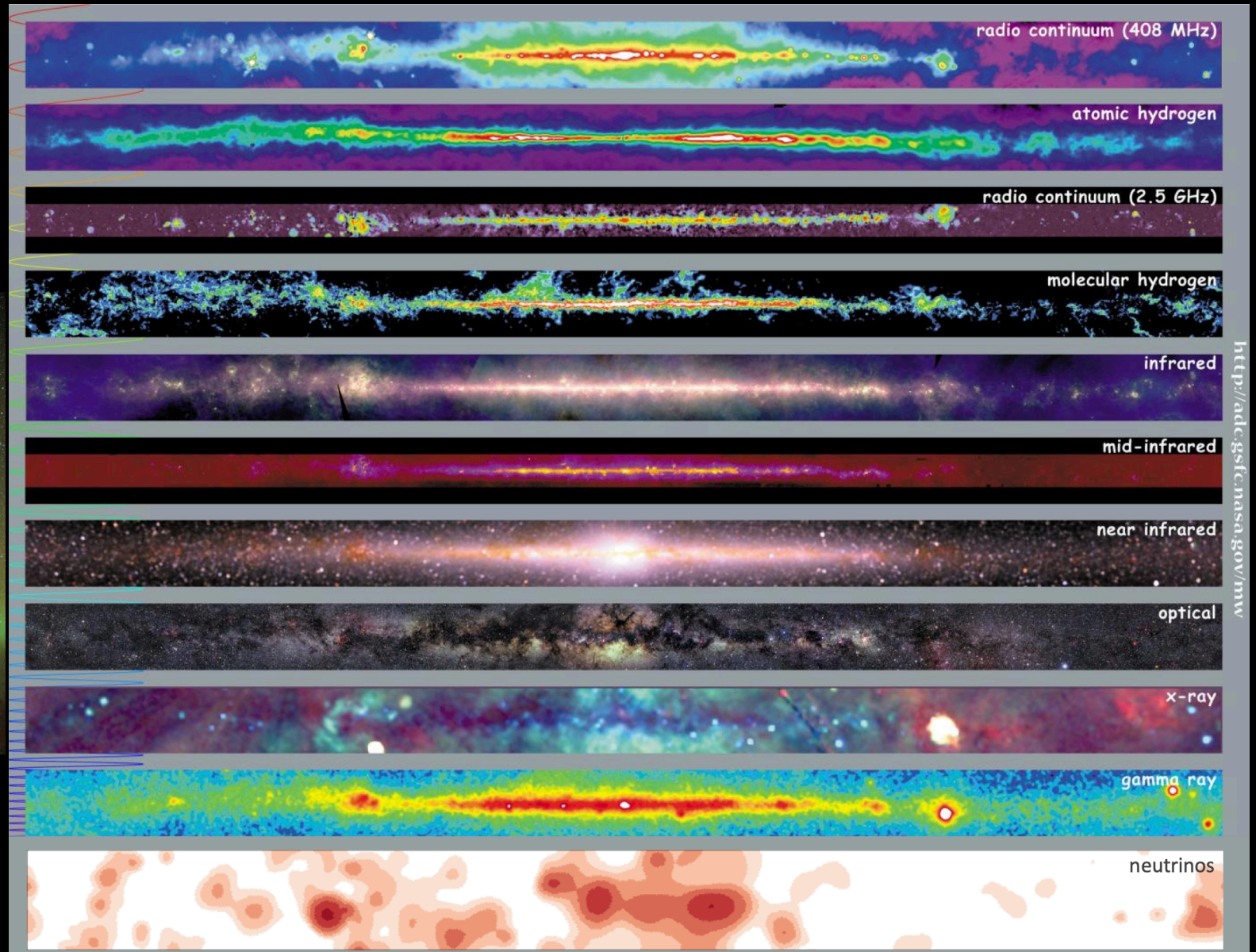
the delta resonance in the neutrino sky

NEW

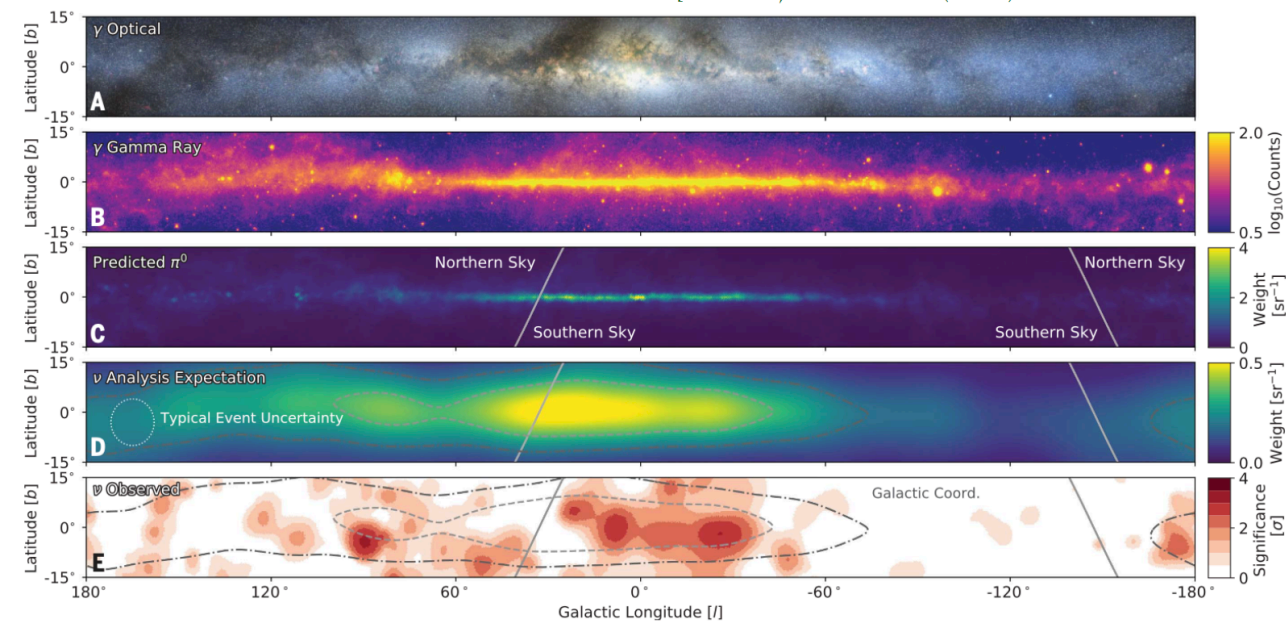
with the help of machine learning we did find the Galactic plane at a flux level of 10% of the astrophysical flux at 30 TeV



Milky Way
viewed in
neutrinos

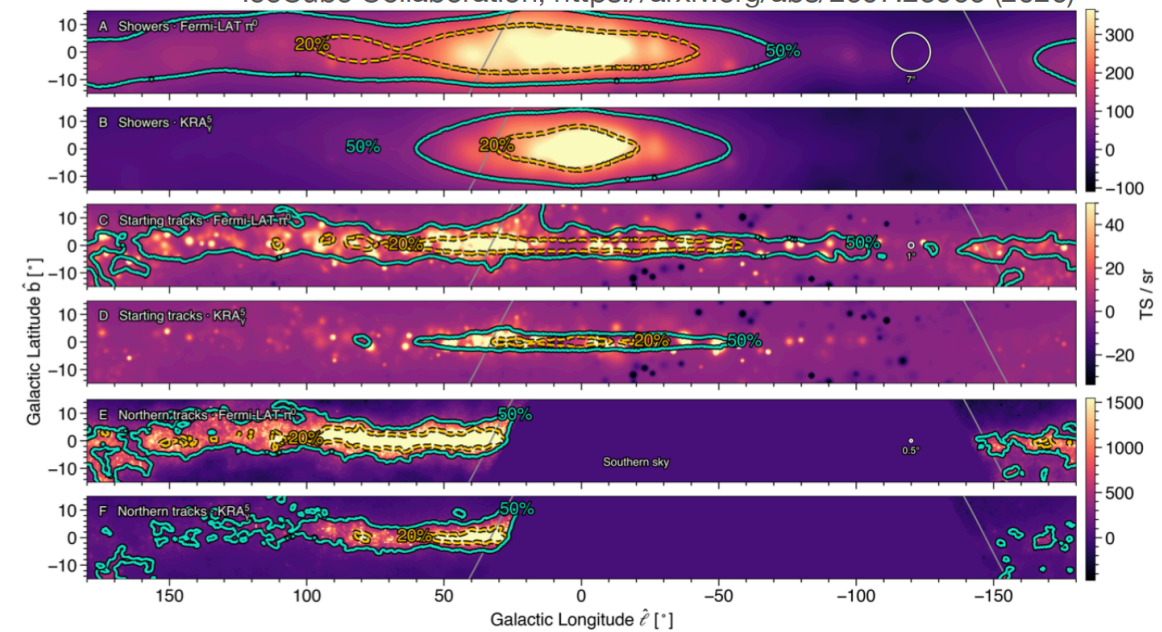


<http://adc.gsfc.nasa.gov/mw>



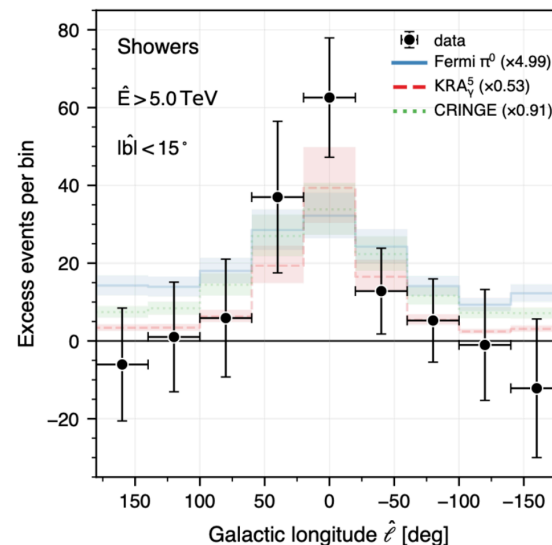
The Galactic Plane: 10 years of cascade data identified neutrino emission from the Milky Way at 4.5σ

2023



The Galactic Plane: diffuse emission from the Milky Way now (12 years) measured at 5.7σ using cascade events

2026



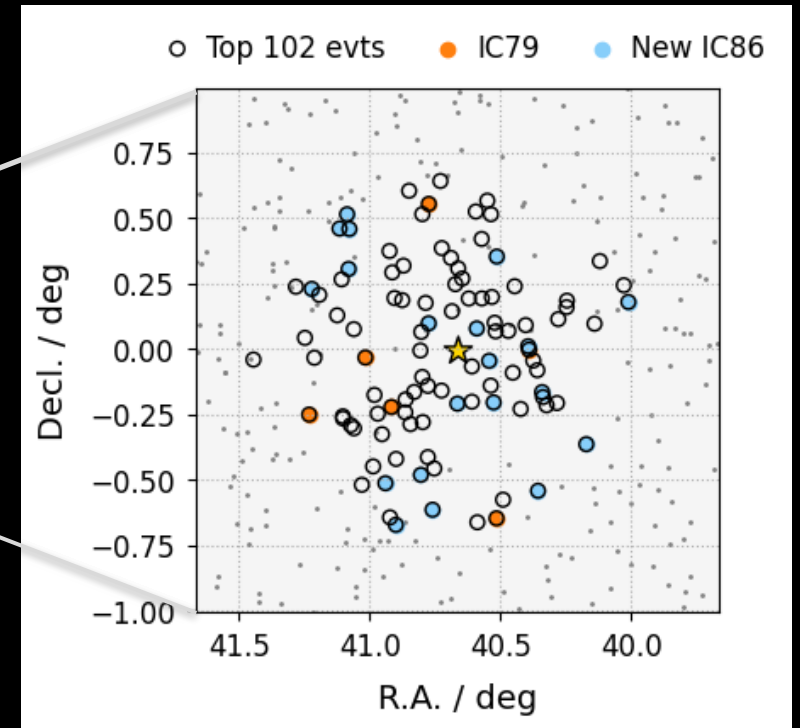
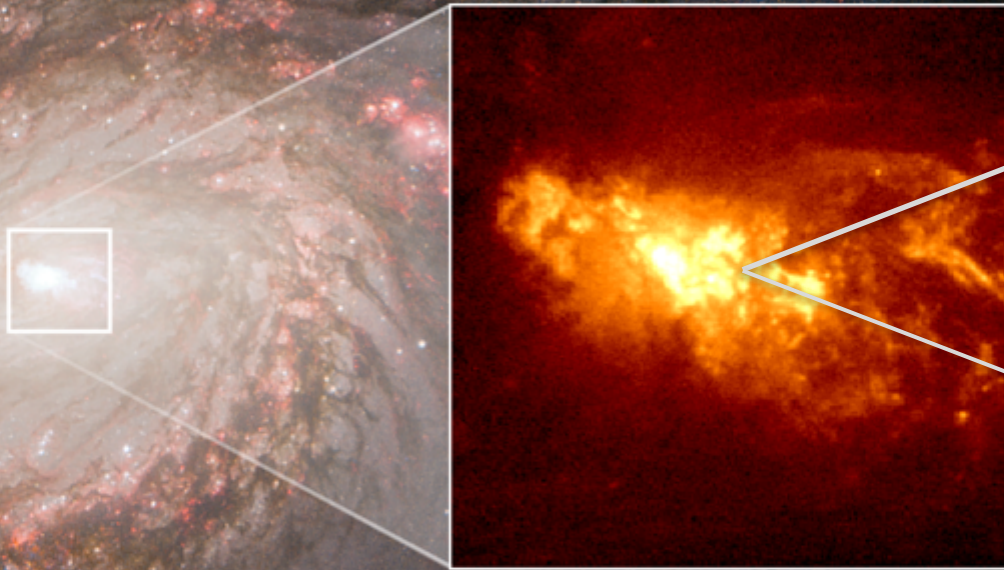
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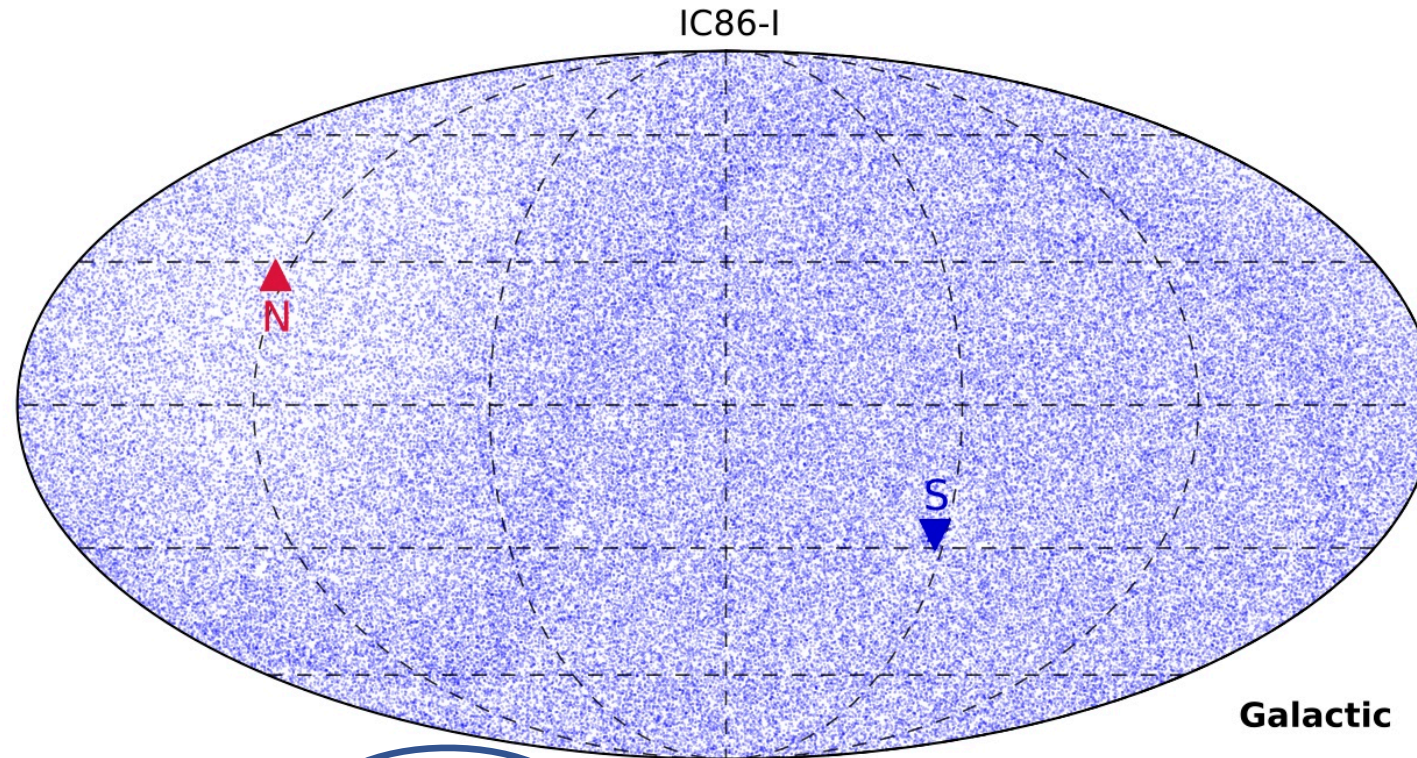
the first cosmic accelerator
in the IceCube neutrino skymap:
the *active galaxy* NGC 1068



neutrinos originate in the dense core within ~ 10 Schwarzschild radii of the
supermassive black hole--- *the source is opaque to gamma rays*

one year of IceCube neutrinos >100 GeV

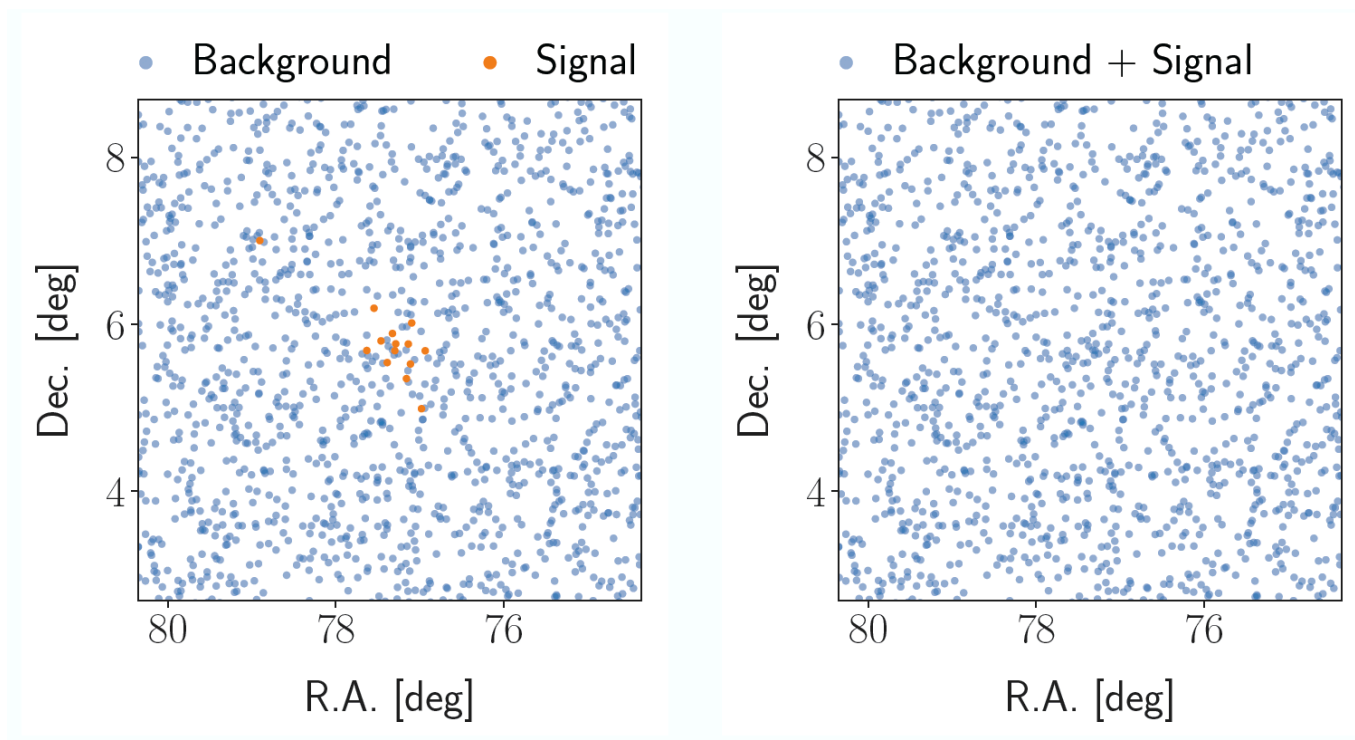
(reaches neutrino purity of 97% but overwhelmingly atmospheric)



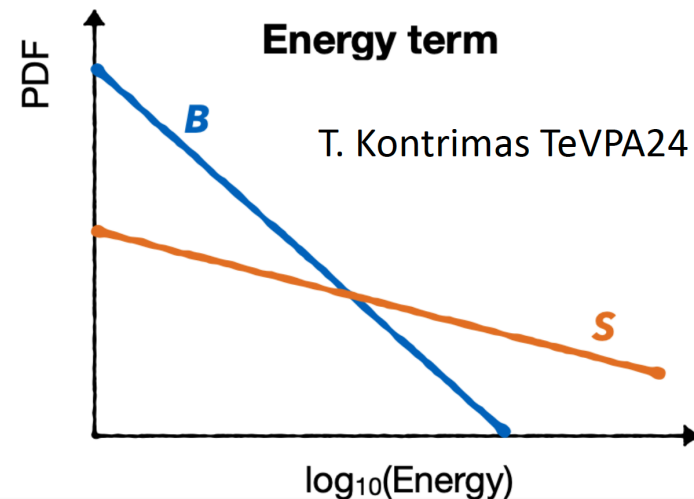
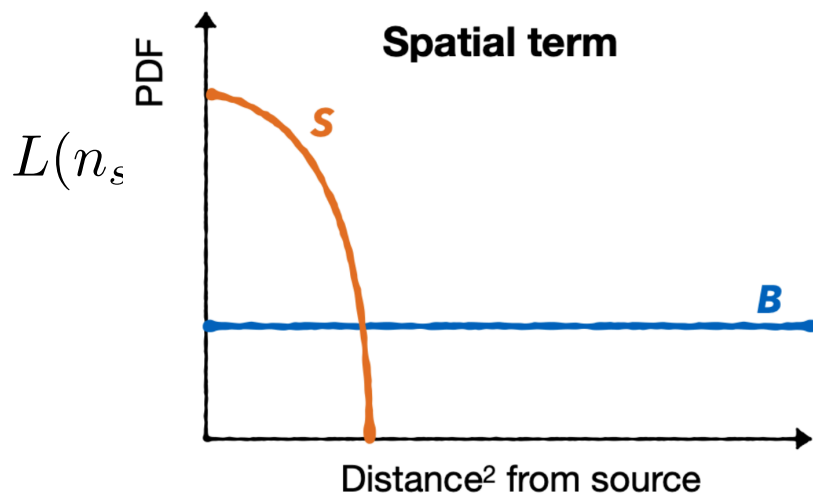
138322 neutrino candidates in one year

~200 cosmic neutrinos

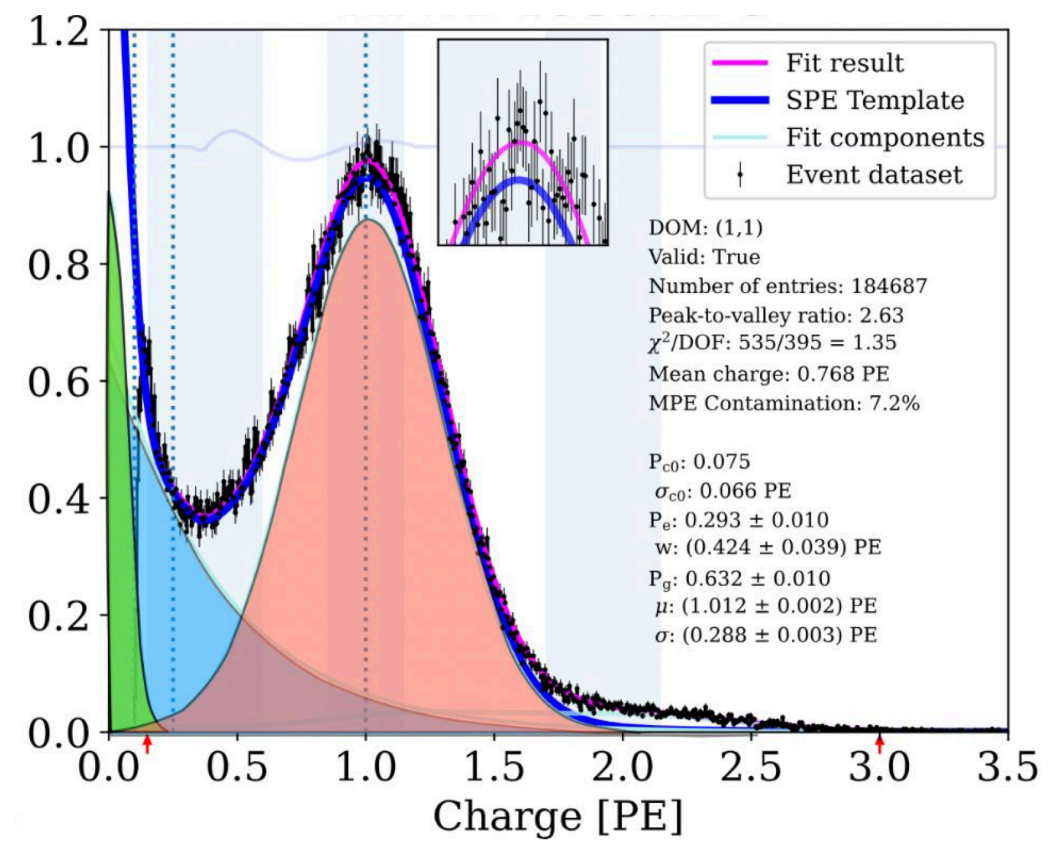
search for clusters of neutrino events with on average higher energy



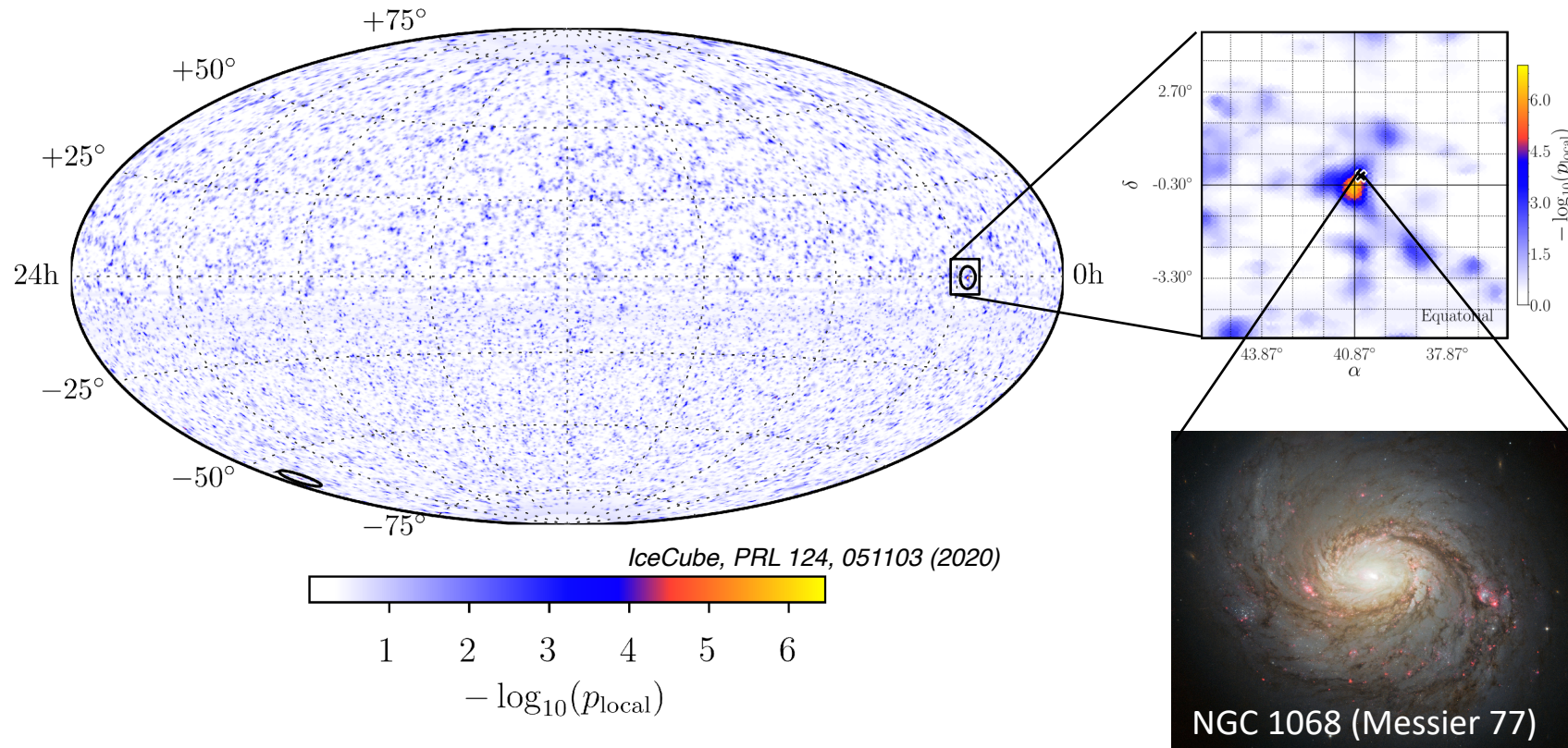
- maximize the (model agnostic) likelihood L at each point in the sky



Source List Results																	
Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(P_{local})$	$\phi_{90\%}$		PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4	
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3		Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3	
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1		4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4	
PKS 2214-06	FSRQ	341.00	10.44	3.1	3.8	0.42	4.6		1H 0123+018	BLL	153.77	40.43	0.0	2.6	0.28	4.5	
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1		4C +07.07	FSRQ	119.12	55.63	11.0	2.3	0.27	10.6	
CTA 102	FSRQ	338.15	11.73	5.5	2.7	0.30	2.8		M 82	SBG	148.95	69.67	0.0	2.6	0.36	8.8	
BL Lac	BLL	330.69	42.28	0.0	2.7	0.40	4.0		PMN 0058+092	AGN	147.24	0.37	9.3	4.0	0.76	3.9	
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1		3C 287	BLL	133.71	20.12	0.0	2.6	0.32	3.5	
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9		PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.28	2.1	
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2		S4 0814+42	BLL	124.56	42.38	0.0	2.3	0.30	4.9	
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2		OJ 014	BLL	122.87	1.78	16.1	4.0	0.99	4.4	
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9		1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.31	4.7	
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0		PKS 0736+01	FSRQ	114.82	1.62	0.0	2.8	0.26	2.4	
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6		PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.30	3.5	
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8		4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.60	4.8	
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3		S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.38	7.4	
1RXS J194246.3+1	BLL	295.70	10.56	0.0	2.7	0.33	2.6		PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.51	4.4	
RX J1931.1+0937	BLL	292.78	9.63	0.0	2.9	0.29	2.8		1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.27	3.0	
NVSS J190836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3		B3 0609+413	BLL	93.22	41.37	1.8	1.7	0.42	5.3	
MGRO J1908+06	GAL	287.17	6.18	4.2	2.0	1.42	5.7		Crab nebula	GAL	83.63	22.01	1.1	2.2	0.31	3.7	
TXS 1902+556	BLL	285.80	55.68	11.7	4.0	0.85	9.9		OG +050	FSRQ	83.18	7.55	0.0	3.2	0.28	2.9	
HESS J1857+026	GAL	284.30	2.67	7.4	3.1	0.53	3.5		TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.92	6.6	
GRS 1285.0	UNIDB	283.15	0.69	1.7	3.8	0.27	2.3		TXS 0506+056	BLL	77.35	5.70	12.3	2.1	3.72	10.1	
HESS J1852-000	GAL	283.00	0.00	3.3	3.7	0.38	2.6		PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.66	4.1	
HESS J1849-000	GAL	282.26	-0.02	0.0	3.0	0.28	2.2		S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.33	2.7	
HESS J1843-033	GAL	280.75	-3.30	0.0	2.8	0.31	2.5		PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.46	3.1	
OT 081	BLL	267.87	9.65	12.2	3.2	0.73	4.8		MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.28	4.5	
S4 1749+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0		PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.27	2.3	
1H 1720+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2		PKS 0420-01	FSRQ	65.83	-1.33	9.3	4.0	0.52	3.4	
PKS 1717+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3		PKS 0336-01	FSRQ	54.88	-1.77	15.5	4.0	0.99	4.4	
Mkn 501	BLL	253.47	39.76	10.3	4.0	0.61	7.3		NGC 1275	AGN	49.96	41.51	3.6	3.1	0.41	5.5	
4C +38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0		NGC 1068	SBG	40.67	-0.01	50.4	3.2	4.74	10.5	
PG 1553+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2		PKS 0235+164	BLL	39.67	16.62	0.0	3.0	0.28	3.1	
GB6 J1542+6129	BLL	235.75	61.50	29.7	3.0	2.74	22.0		4C +28.07	FSRQ	39.48	28.80	0.0	2.8	0.30	3.6	
B2 1520+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3		3C 66A	BLL	35.67	43.04	0.0	2.8	0.30	3.9	
PKS 1502+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9		B2 0218+357	FSRQ	35.28	35.94	0.0	3.1	0.33	4.3	
PKS 1502+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6		PKS 0215+015	FSRQ	34.46	1.74	0.0	3.2	0.27	2.3	
PKS 1441+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3		MG1 J021114+1051	BLL	32.81	10.86	1.6	1.7	0.43	3.5	
PKS 1424+240	BLL	216.76	23.80	41.5	3.9	2.80	12.3		TXS 0141+268	BLL	26.15	27.09	0.0	2.5	0.31	3.5	
NVSS J141826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0		B3 0133+388	BLL	24.14	39.10	0.0	2.6	0.28	4.1	
B3 1343+451	FSRQ	206.40	44.88	0.0	2.8	0.32	5.0		NGC 598	SBG	23.52	30.62	11.4	4.0	0.63	6.3	
S4 1250+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9		S2 0109+22	BLL	18.03	22.75	2.0	3.1	0.30	3.7	
PG 1246+586	BLL	192.08	58.34	0.0	2.8	0.35	6.4		4C +01.02	FSRQ	17.16	1.59	0.0	3.0	0.26	2.4	
MG1 J123931+0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4		M 31	SBG	10.82	41.24	11.0	4.0	1.09	9.6	
M 87	AGN	187.71	12.39	0.0	2.8	0.29	3.1		PKS 0019+058	BLL	5.64	6.14	0.0	2.9	0.29	2.4	
ON 246	BLL	187.56	25.30	0.9	1.7	0.37	4.2		PKS 2233-148	BLL	339.14	-14.56	5.3	2.8	1.26	21.4	
3C 273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9		HESS J1841-055	GAL	280.23	-5.55	3.6	4.0	0.55	4.8	
4C +21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5		HESS J1837-069	GAL	279.43	-6.93	0.0	2.8	0.30	4.0	
W Comae	BLL	185.38	28.24	0.0	3.0	0.32	3.7		PKS 1510-089	FSRQ	228.21	-9.10	0.1	1.7	0.41	7.1	
PG 1218+304	BLL	185.34	30.17	11.1	3.9	0.70	6.7		PKS 1329-049	FSRQ	203.02	-5.16	6.1	2.7	0.77	5.1	
PKS 1216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1		NGC 4945	SBG	196.36	-49.47	0.3	2.6	0.31	50.2	
B2 1215+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5		3C 279	FSRQ	194.04	-5.79	0.3	2.4	0.20	2.7	
Ton 599	FSRQ	179.88	29.24	0.0	2.2	0.29	4.5		PKS 0805-07	FSRQ	122.07	-7.86	0.0	2.7	0.31	4.7	
									PKS 0727-11	FSRQ	112.58	-11.69	1.9	3.5	0.59	11.4	
									LMC	SBG	80.00	-68.75	0.0	3.1	0.36	41.1	
									SMC	SBG	14.50	-72.75	0.0	2.4	0.37	44.1	
									PKS 0048-09	BLL	12.68	-9.49	3.9	3.3	0.87	10.0	
									NGC 253	SBG	11.90	-25.29	3.0	4.0	0.75	37.7	

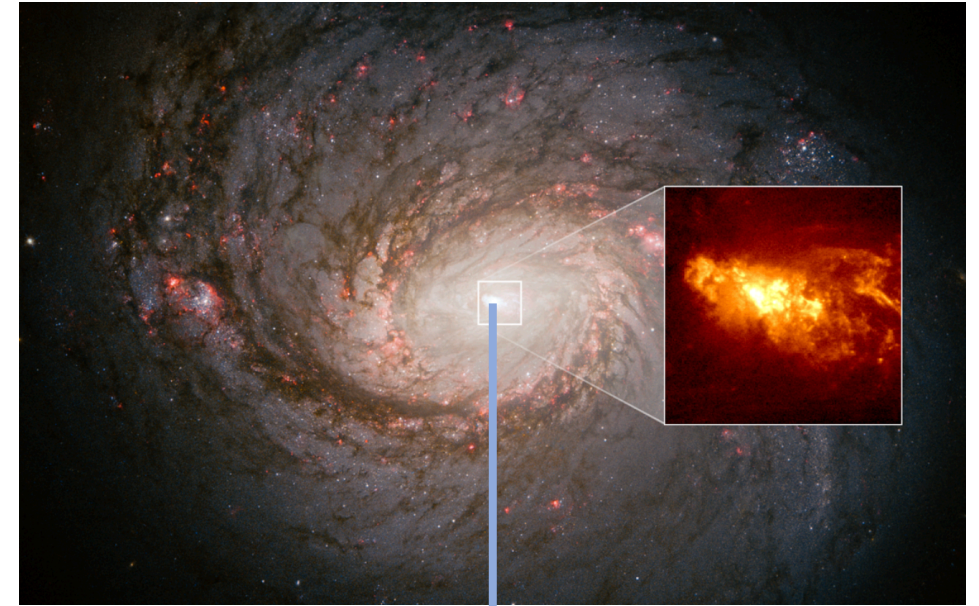
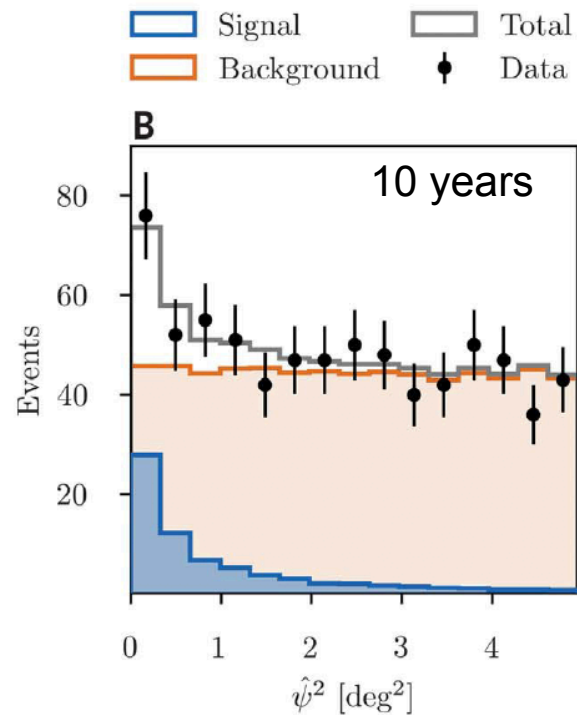
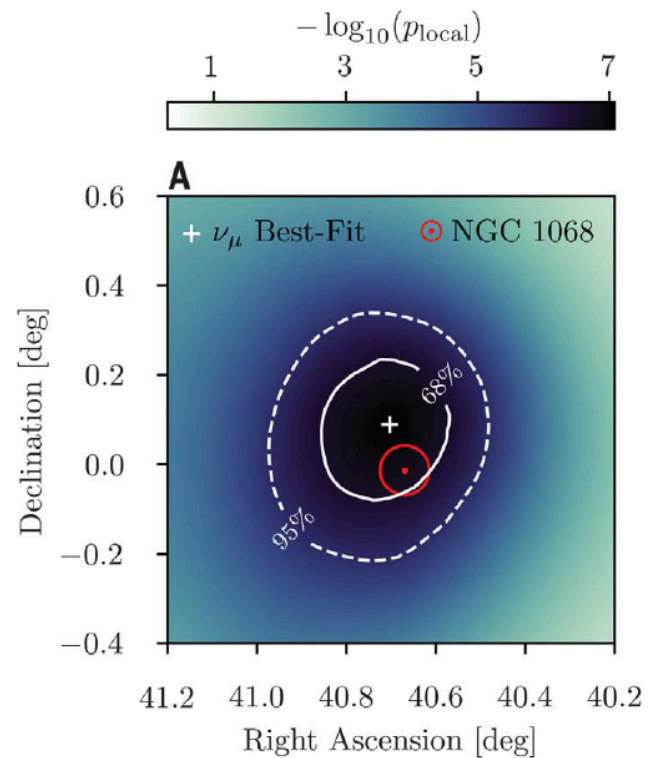


- search in a preselected list of 110 gamma-ray sources [5.3(4.2) σ pre(post) trial]
- also the hottest spot in the skymap

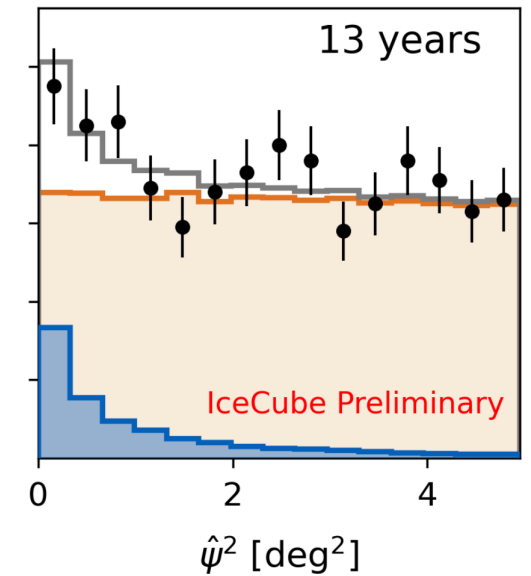


pre-trial p-value for clustering of high energy neutrinos

80 high-energy neutrinos
from the direction of the
active galaxy NGC 1068



update:
80 → 100
neutrinos
10 → 13
years

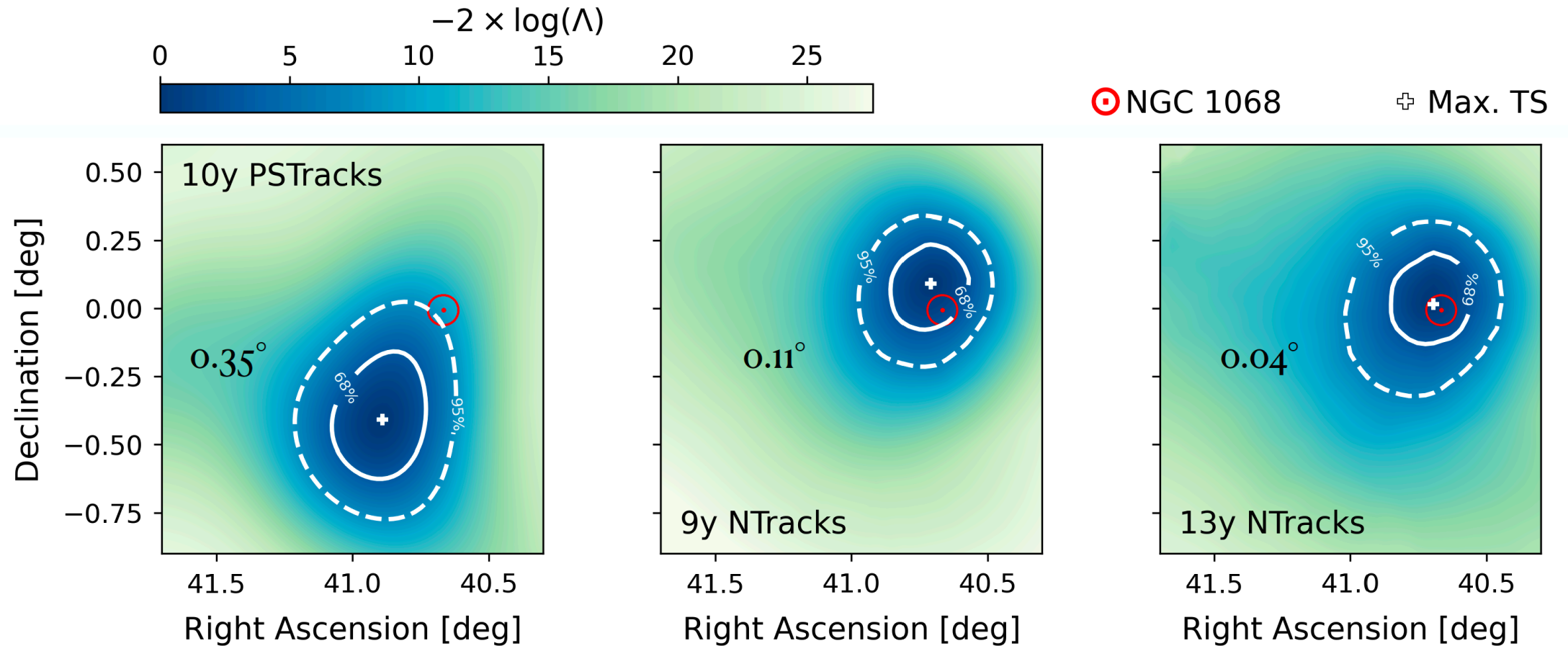


NGC 1068
comes
into focus

0.35 deg
0.04 deg

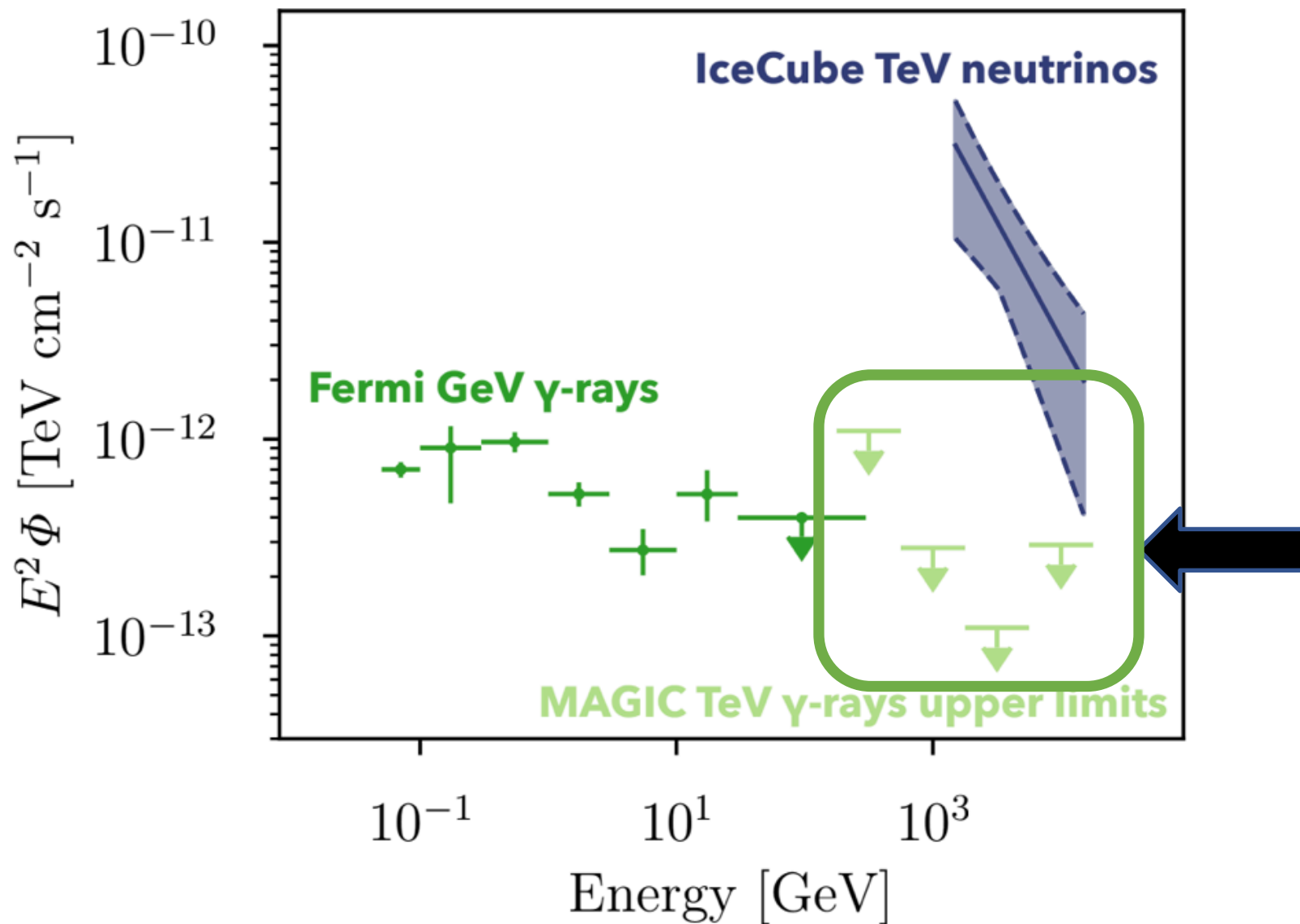


0.1 deg



a gamma ray for every neutrino?

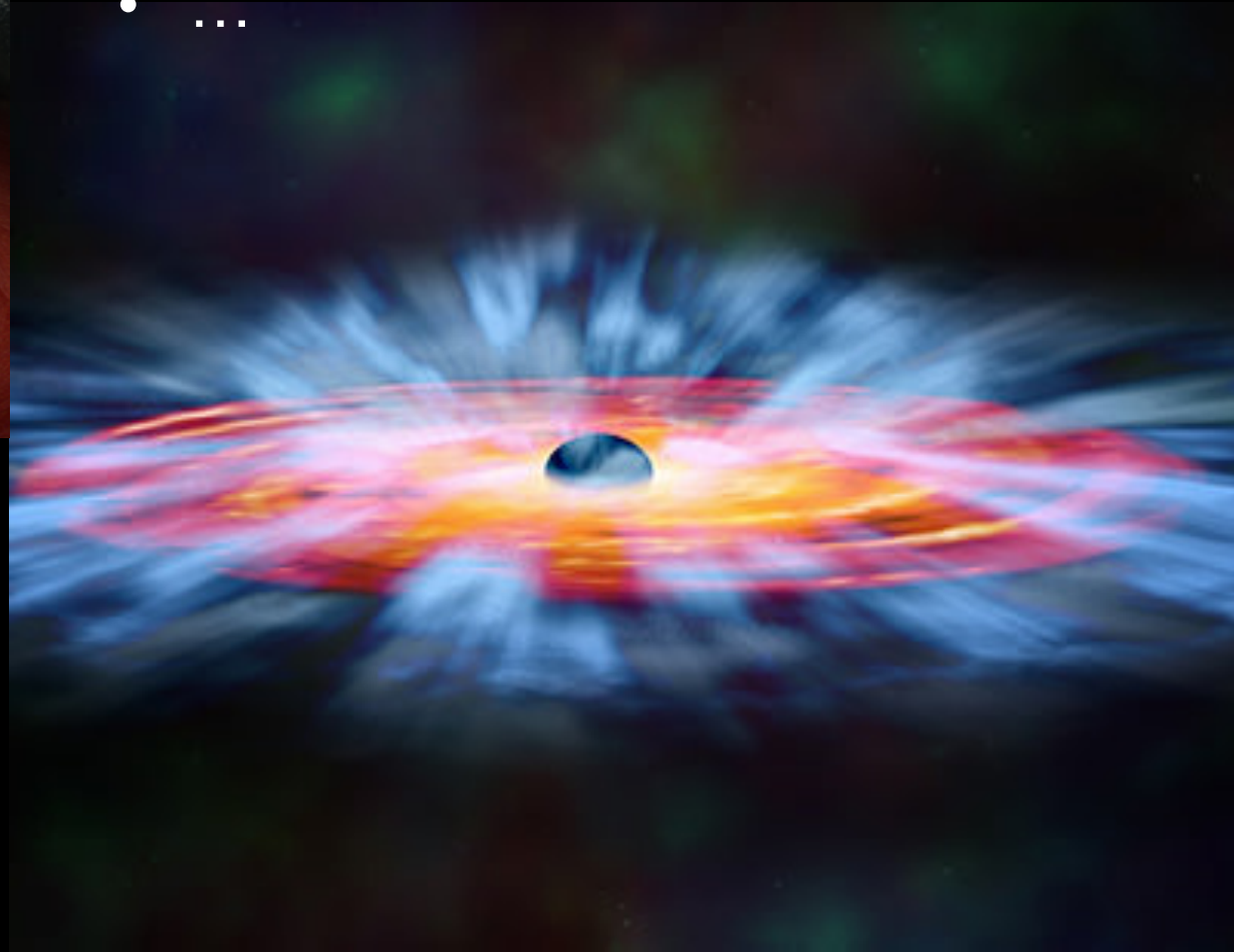
NGC 1068: an obscured cosmic accelerator



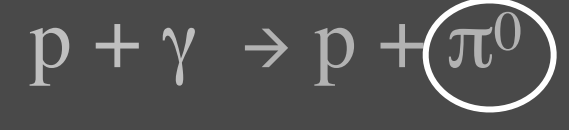
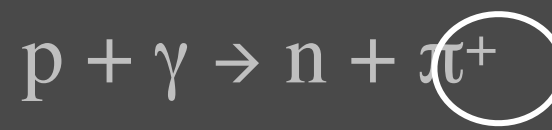
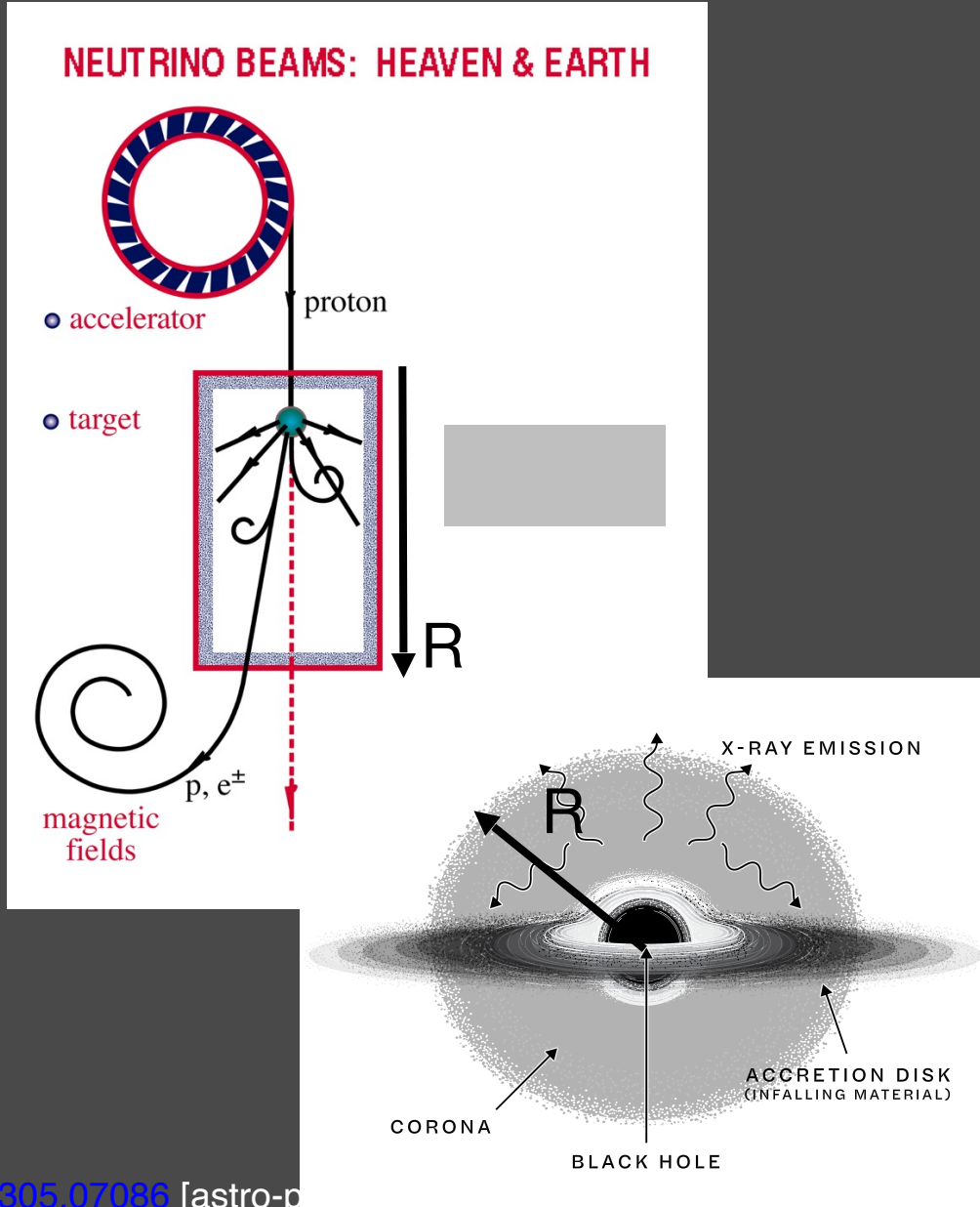
where are the π^0 gamma rays ?

- accelerator(s)*: electrons and protons are accelerated
- in the turbulent magnetic fields associated with the accretion disk
 - in the infall onto the black hole
 - ...

- target*: the neutrinos are produced in
- the corona of X-rays (UV photons upscattered by electrons)
 - dense clouds of hydrogen
 - ...



ν and γ beams : protons on target



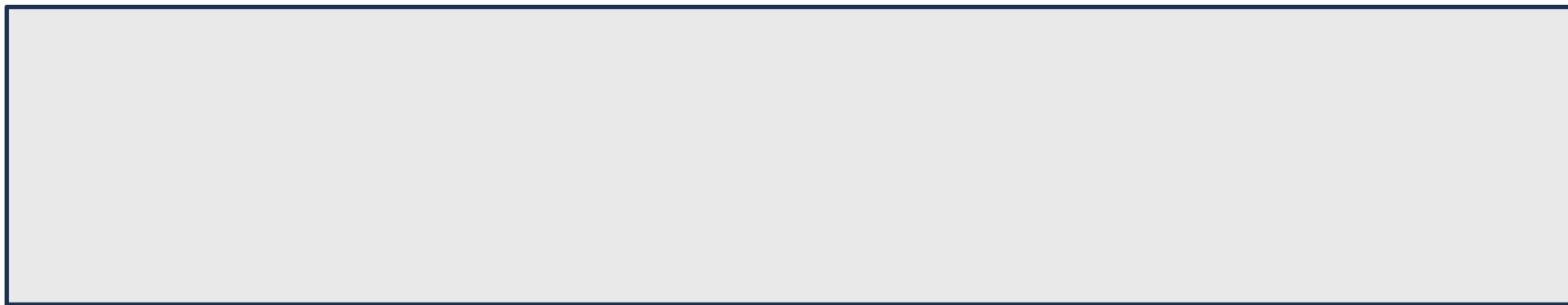
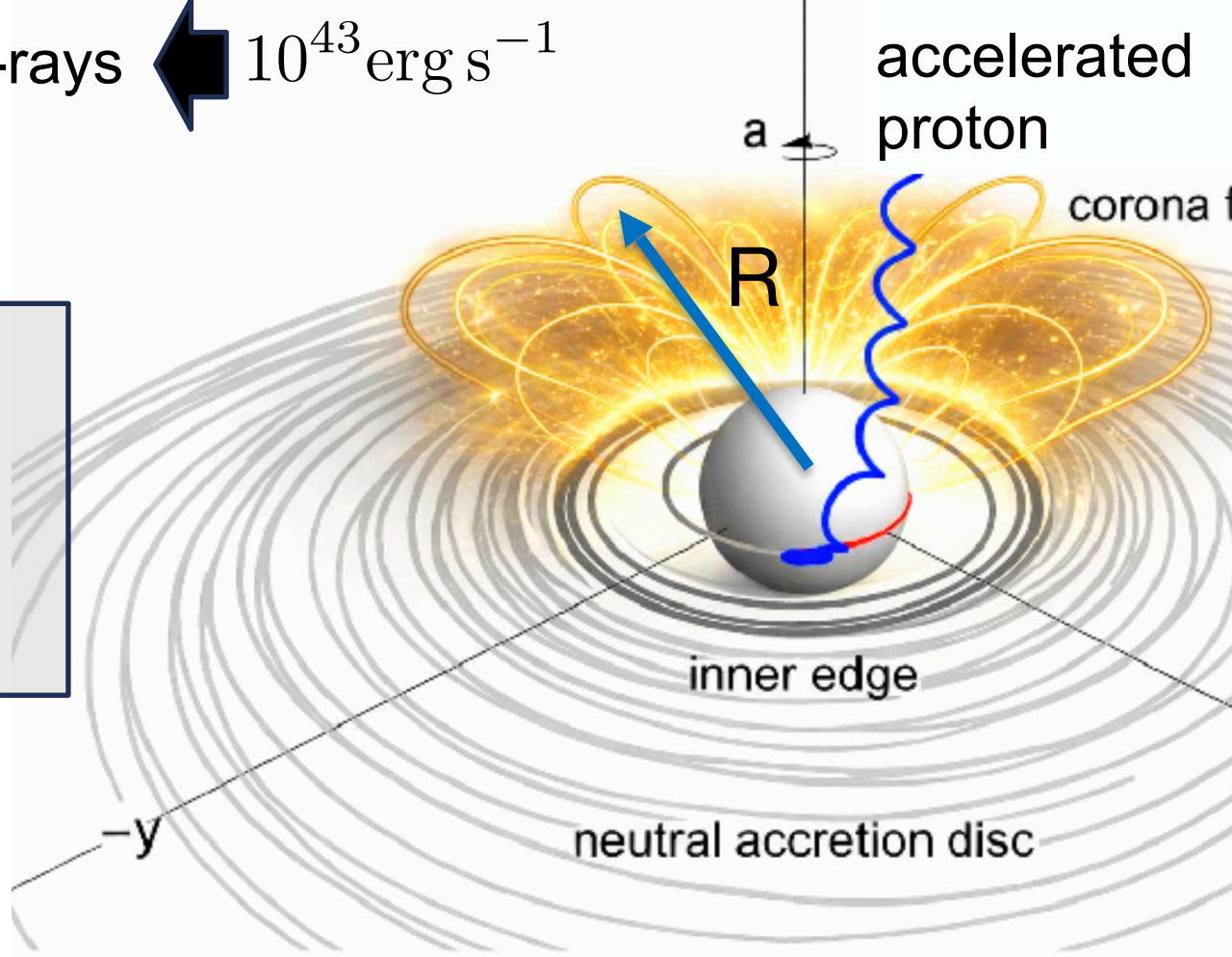
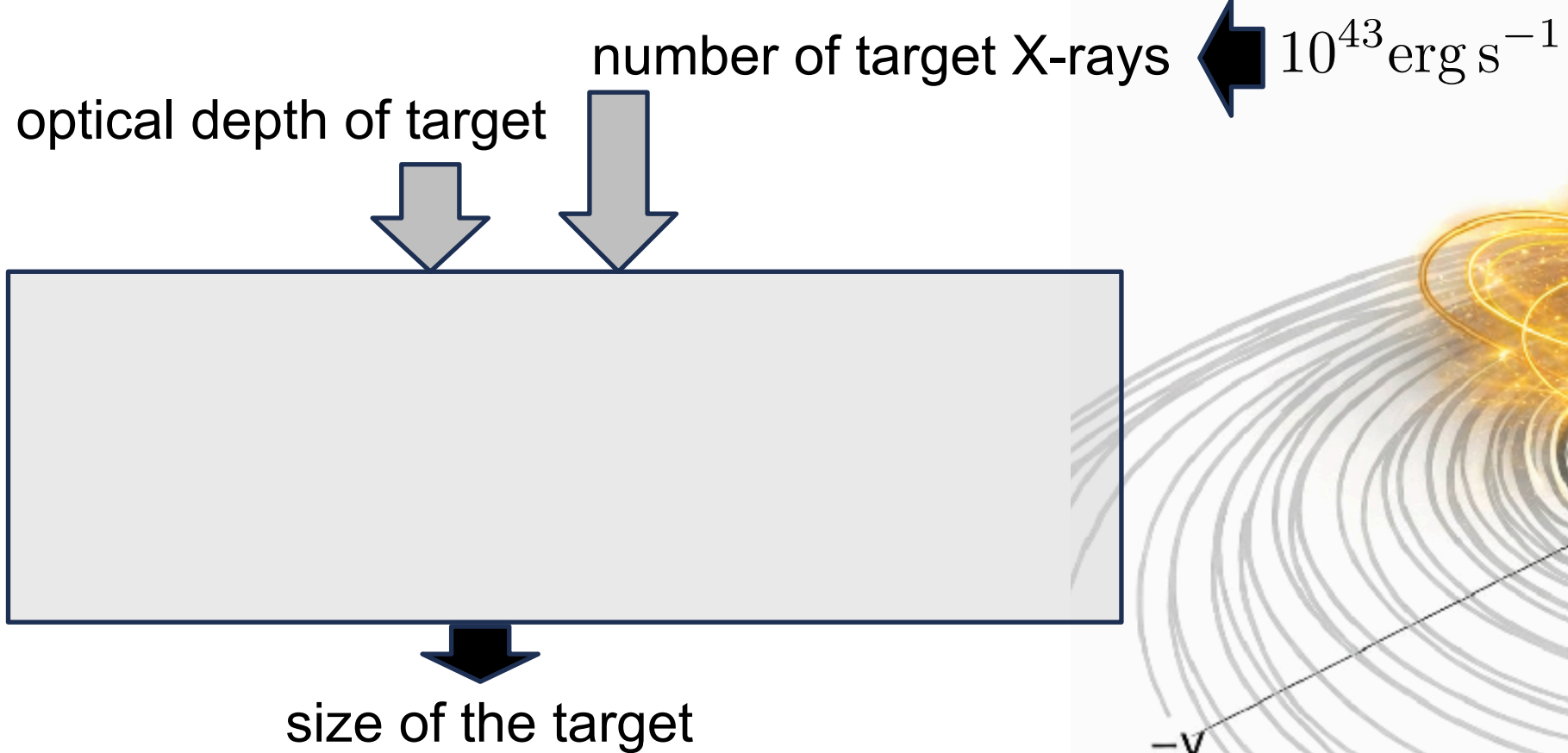
cosmic ray + neutrino

cosmic ray + gamma

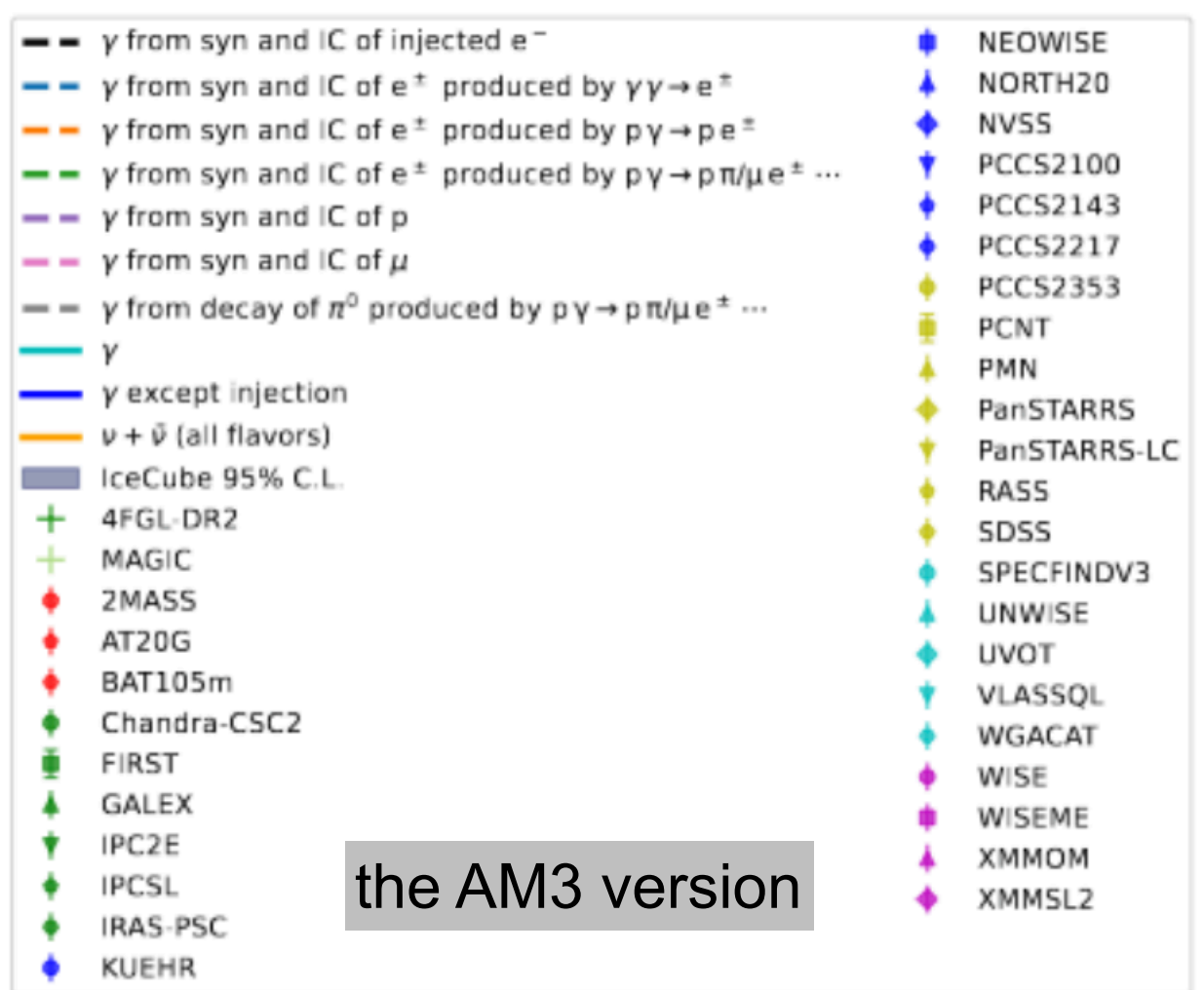
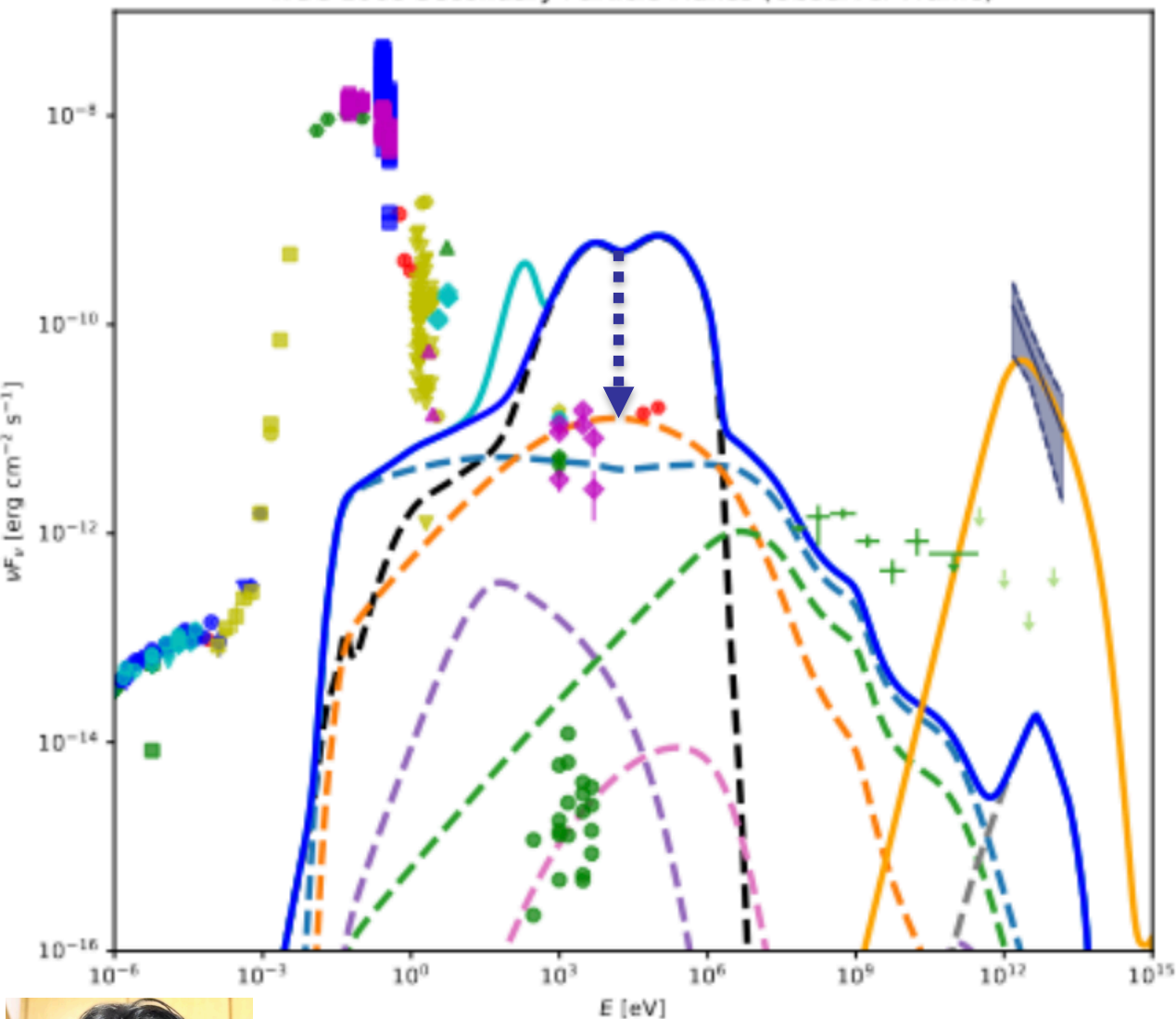
- optical depth τ of protons in target

in terms of X-ray luminosity measured at Earth

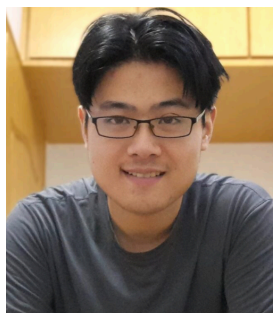
pionic gamma rays are absorbed in the target that produces the neutrinos with



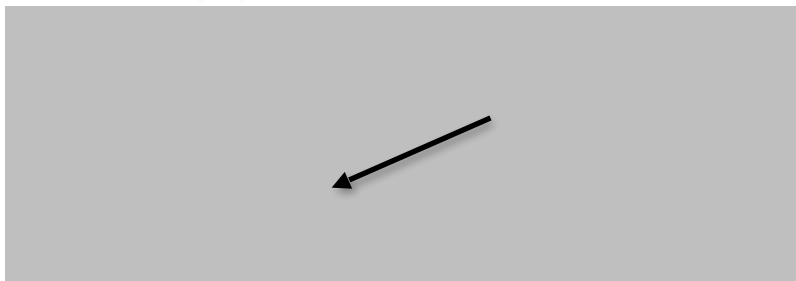
NGC 1068 Secondary Particle Fluxes (Observer Frame)



the AM3 version



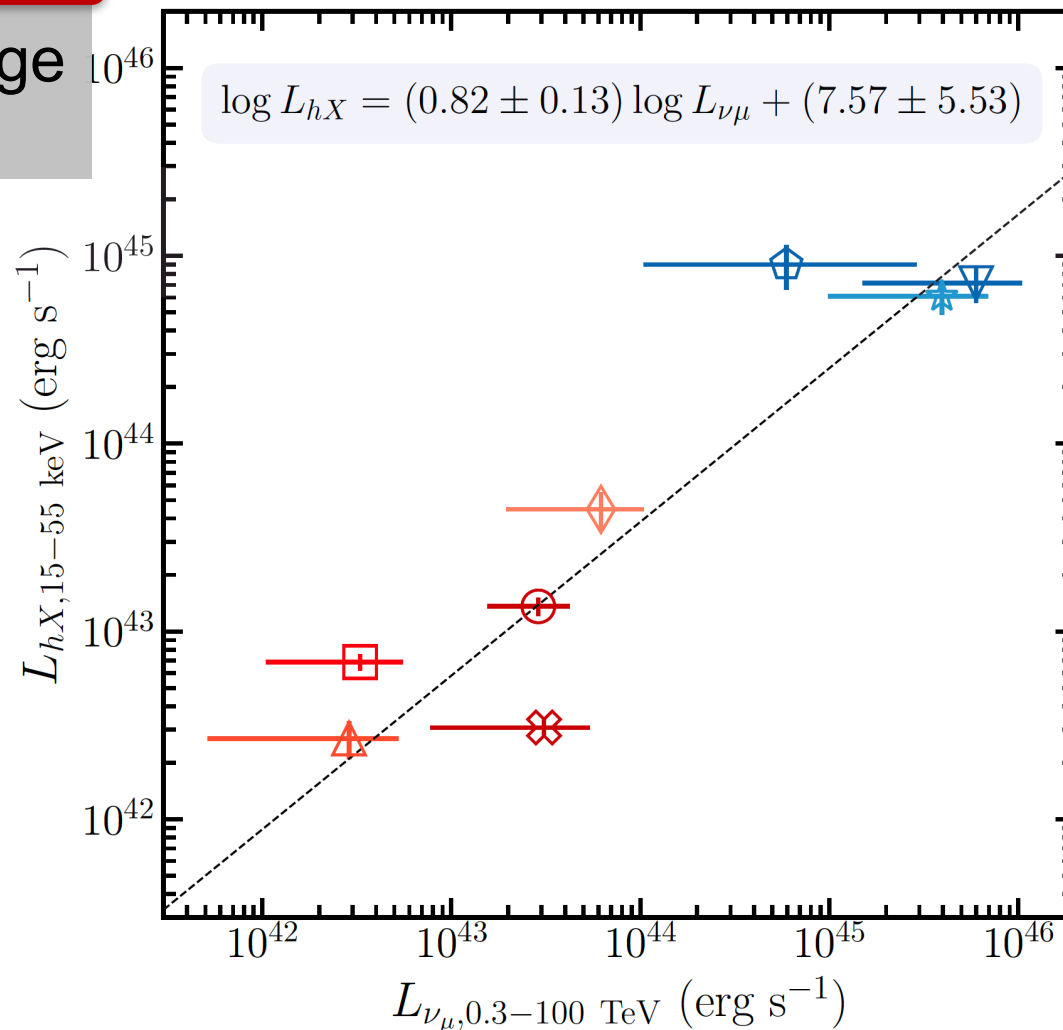
Chen Li



NuSTAR catches the unveiling nucleus of NGC 1068

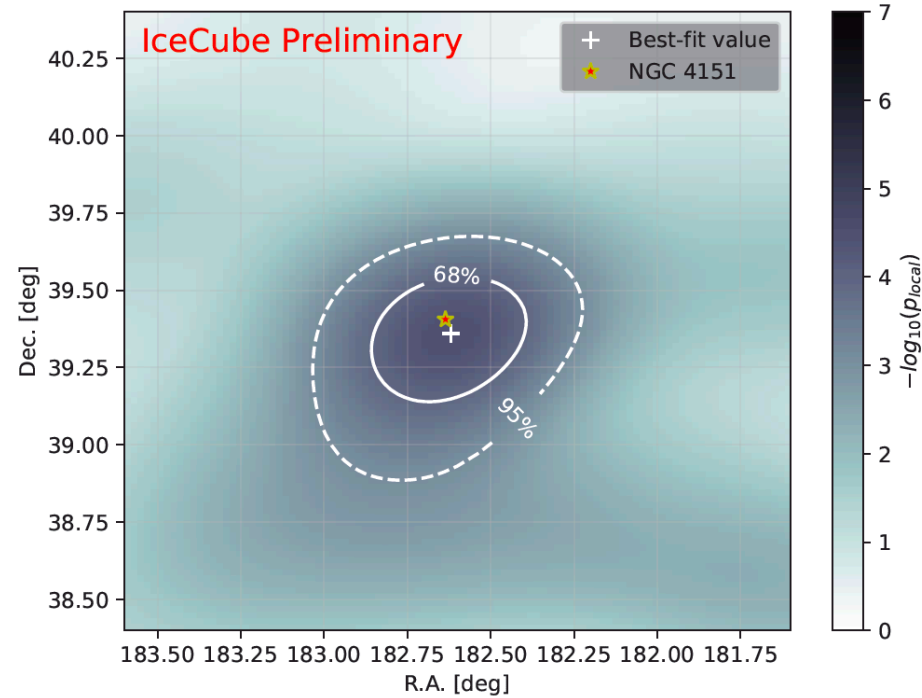
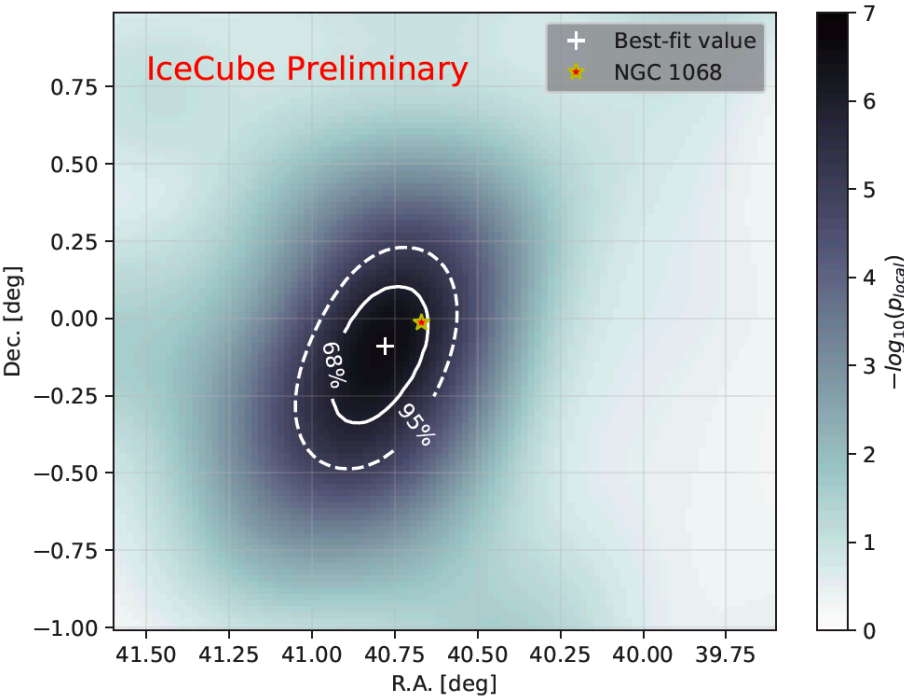
A. Marinucci^{1*}, S. Bianchi¹, G. Matt¹, D. M. Alexander², M. Baloković³,
F. E. Bauer^{4,5,6}, W. N. Brandt^{7,8,9}, P. Gandhi², M. Guainazzi¹⁰, F. A. Harrison³,
K. Iwasawa¹¹, M. Koss¹², K. K. Madsen³, F. Nicastro^{13,14,15}, S. Puccetti^{13,16},
C. Ricci⁴, D. Stern¹⁷, D. J. Walton^{17,3}

- hint from NGC 1068
- there is a correlation between the X-ray and neutrino flux
- select active galaxies with large X-ray fluxes



	NGC 1068
	NGC 4151
	NGC 3079
	CGCG 420-015
	TXS 0506+056
	GB6 J1542+6129*
	NGC 5610*
	PKS 1424+240*

search for X-ray bright sources



- two brightest active galaxies discovered by Seyfert in 1943

NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

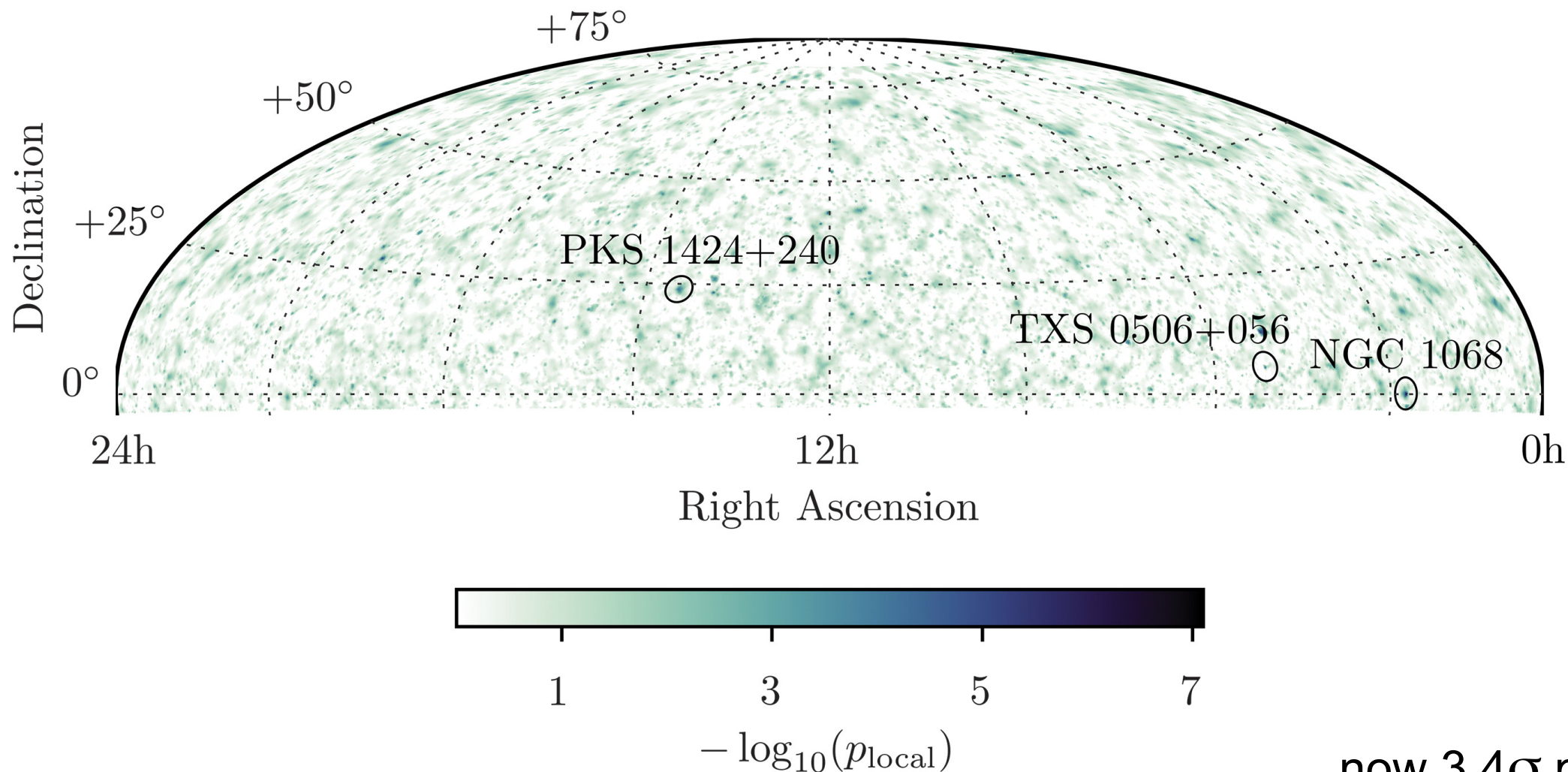
1943

ABSTRACT

Spectrograms of dispersion 37–200 Å/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.



we observe an excess from an ensemble of 3 (*gamma ray*) sources



now 3.4σ p-value

Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

RESEARCH ARTICLE SUMMARY

V.M. Lipunov^{1,2}, V.G. Kornilov^{1,2}, K.Zhirkov¹, E. Gorbovskoy², N.M. Budnev⁴, D.A.H.Buckley³, R. Rebolo⁵, M. Serra-Ricart⁵, R. Podesta^{9,10}, N.Tyurina², O. Gress^{4,2}, Yu.Sergienko⁸, V. Yurkov⁸, A. Gabovich⁸, P.Balanutsa², I.Gorbunov², D.Vlasenko^{1,2}, F.Balakin^{1,2}, V.Topolev¹, A.Pozdnyakov¹, A.Kuznetsov², V.Vladimirov², A. Chasovnikov¹, D. Kuvshinov^{1,2}, V.Grinshpun^{1,2}, E.Minkina^{1,2}, V.B.Petkov⁷, S.I.Svertilov^{2,6}, C. Lopez⁹, F. Podesta⁹, H.Levato¹⁰, A. Tlatov¹¹, B. Van Soelen¹², S. Razzaque¹³, M. Böttcher¹⁴

NEUTRINO ASTROPHYSICS

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*†

RESEARCH ARTICLE

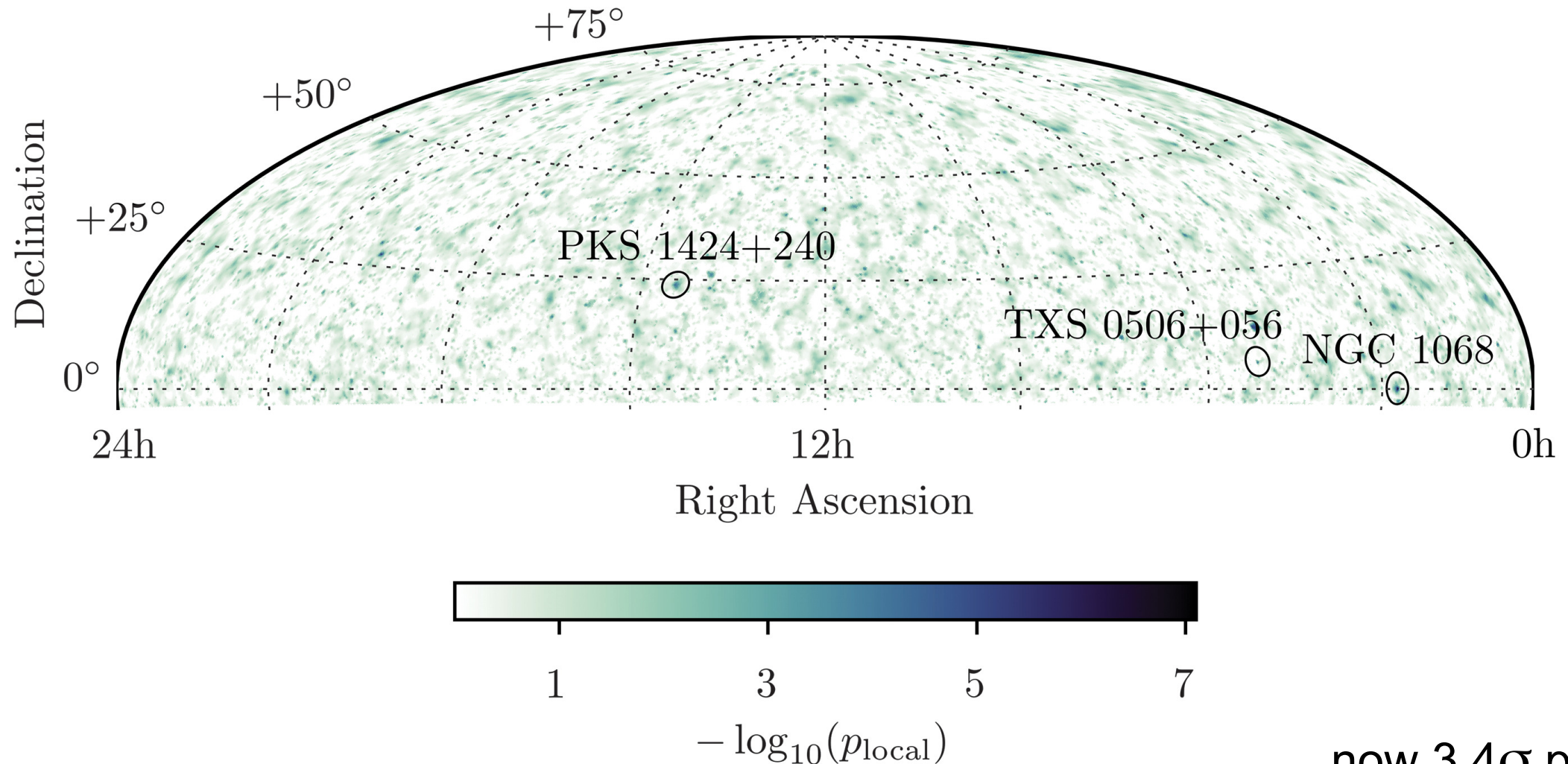
NEUTRINO ASTROPHYSICS

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

TXS 0506+056 detected in 2017

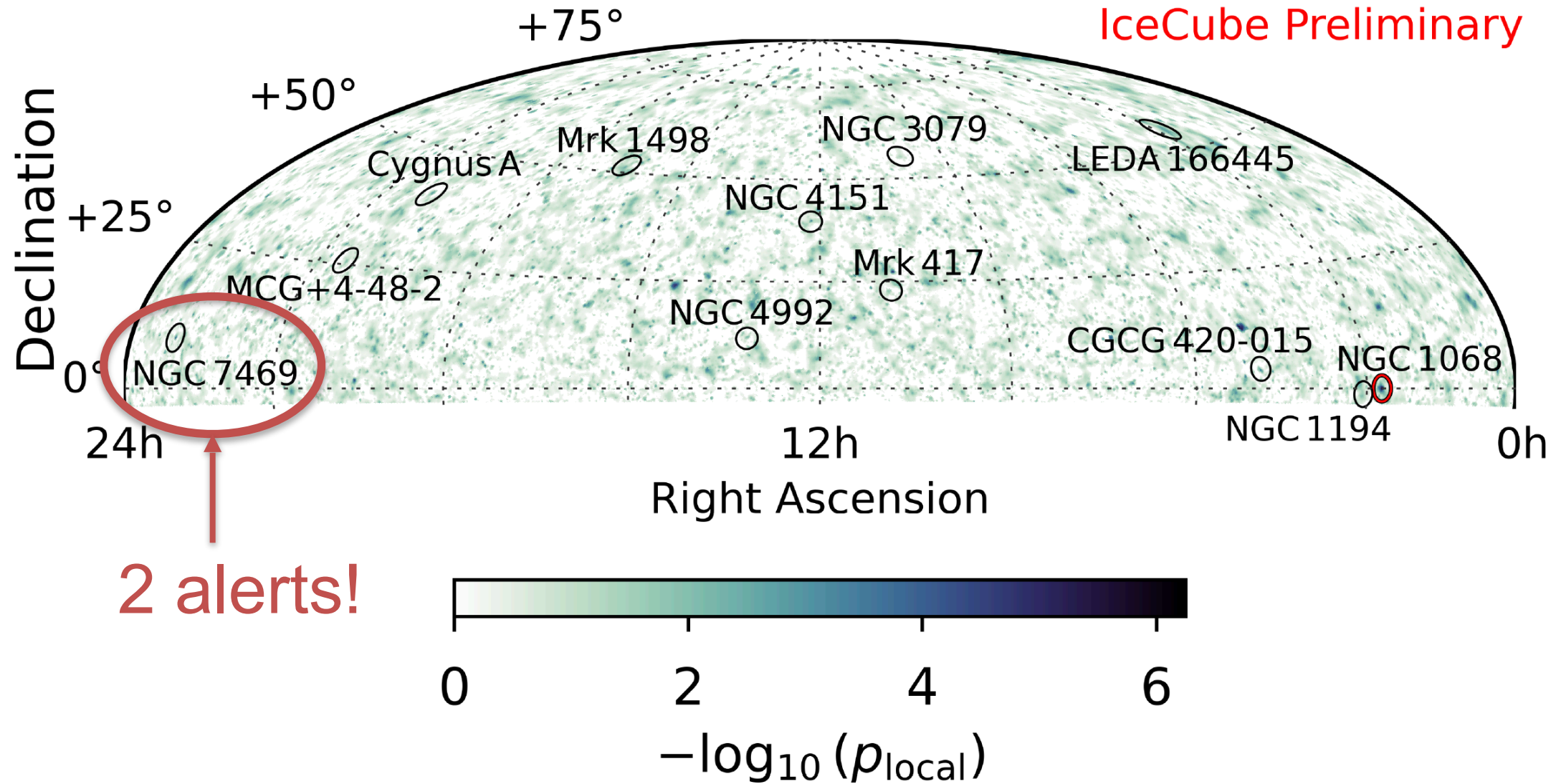
- multimessenger
 - IceCube archival data
 - observation of optical flash 2hours after IC170922
- associates the neutrino with the source at the 50σ level

- we observed an excess from an ensemble of 3 sources
- after selecting bright X-ray instead of γ -ray sources $\rightarrow$



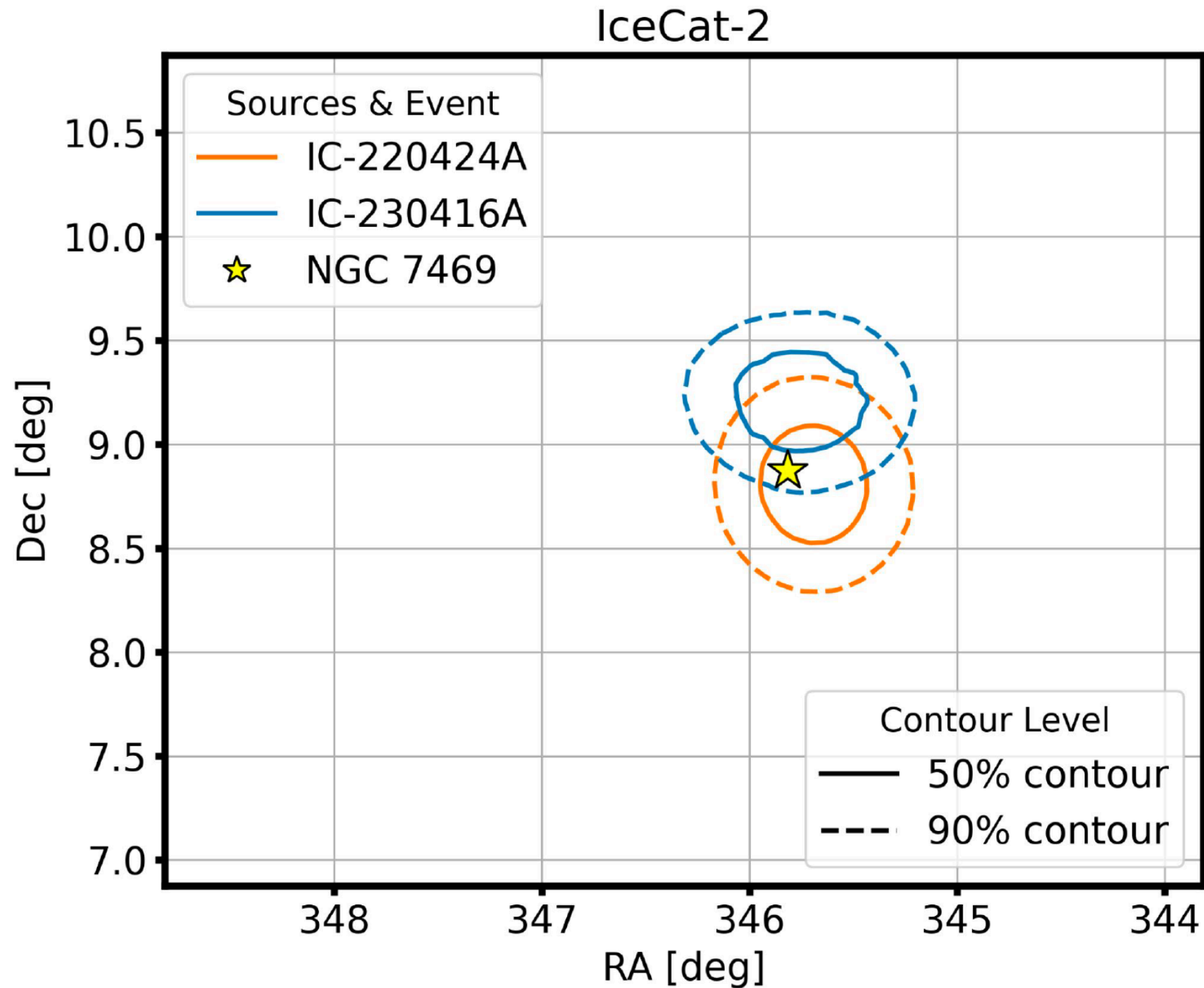
now 3.4σ p-value

IceCube Preliminary



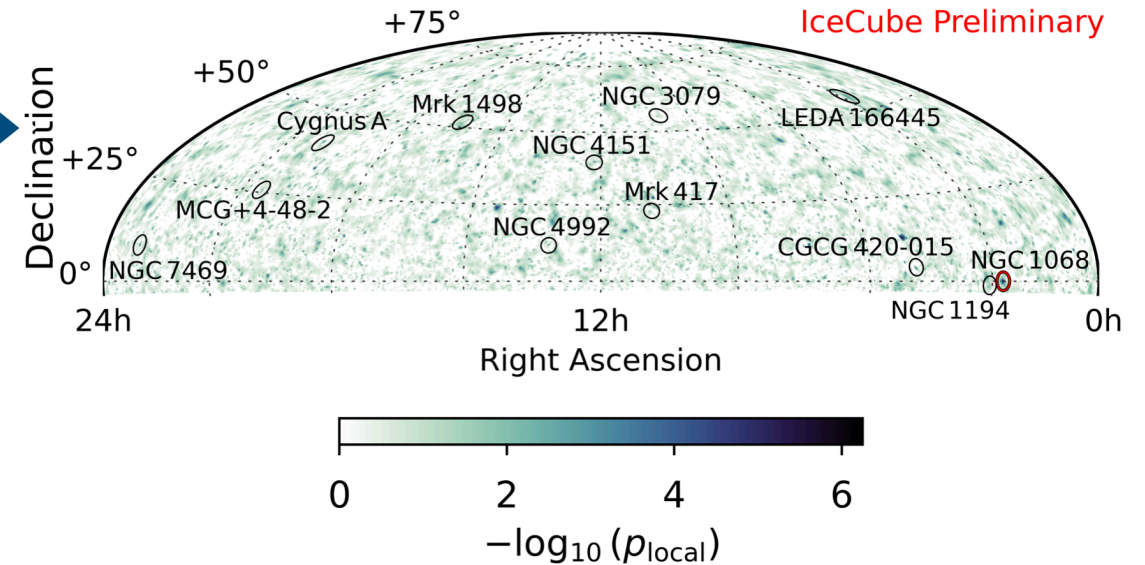
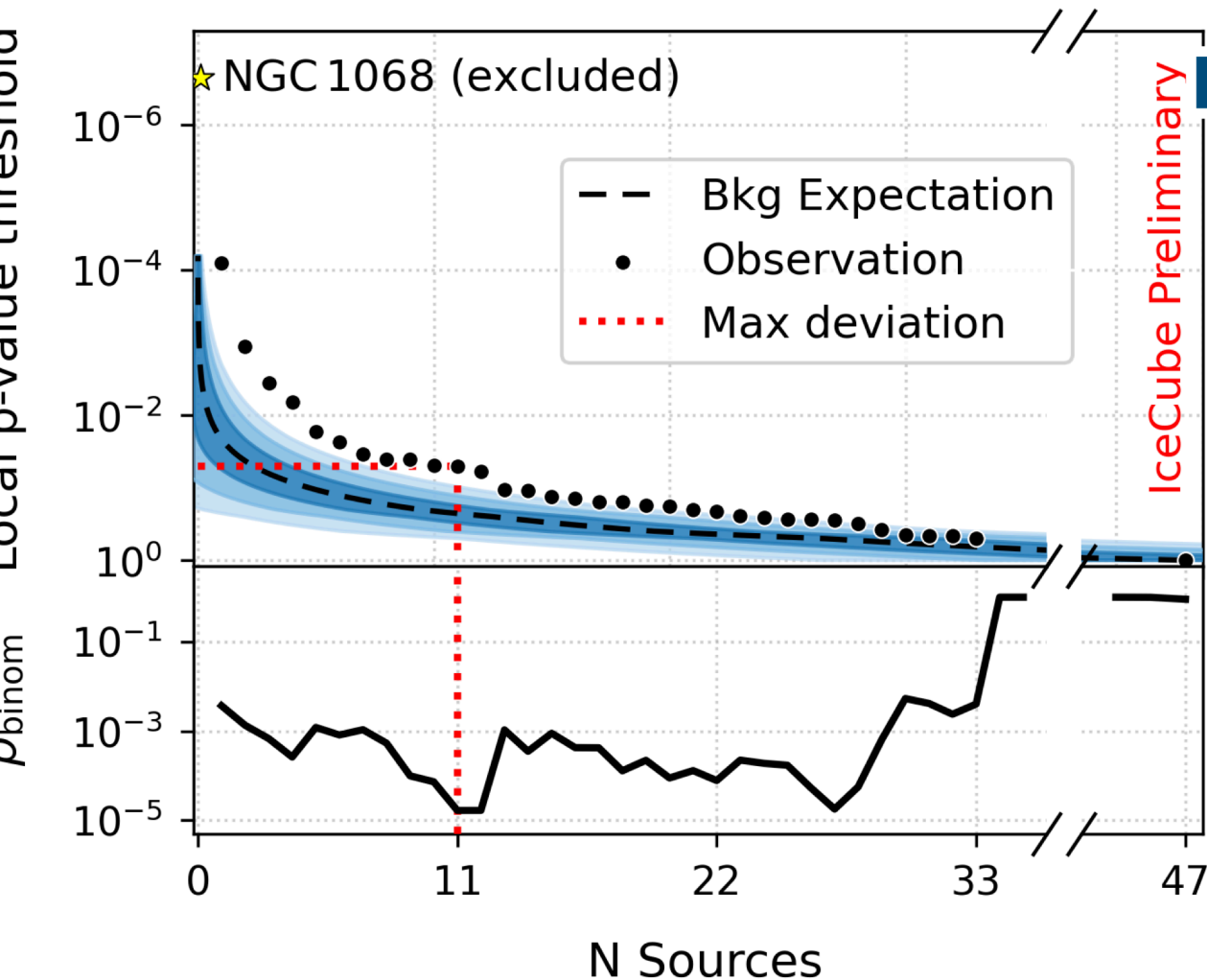
excess from an ensemble of *X-ray bright (non-jetted)* active galaxies

- directions of cosmic neutrinos are shared with other telescopes in less than one minute
- one alert repeated since 2016 (from the direction of NGC 7469)



Binomial test of X-ray-bright source list

Binomial Test



- Binomial Test: Probability of finding a signal from 47 AGNs too weak to be identified individually
- Result: 3.3σ excess for 11 sources (excluding NGC1068)

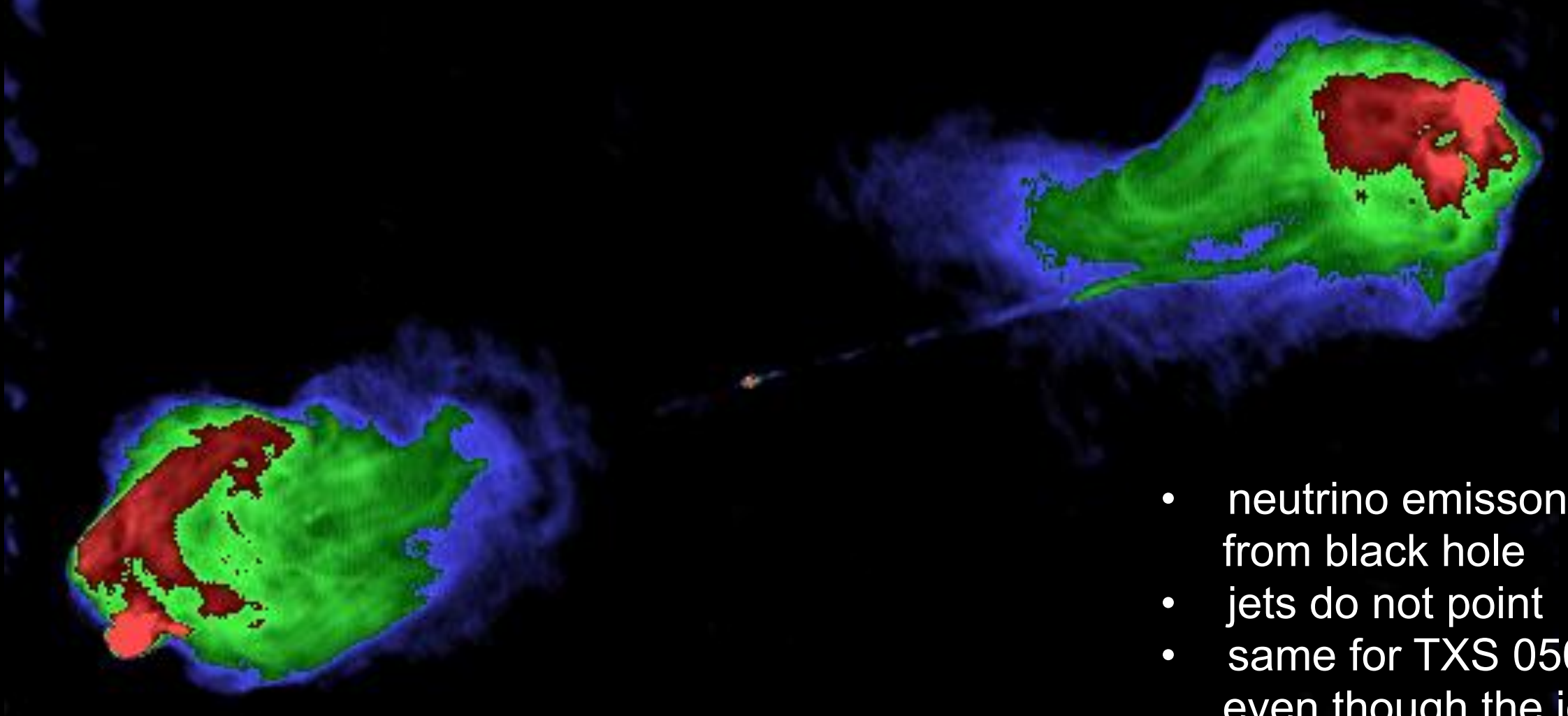
Source Name	R.A. (deg)	Dec. (deg)	z	$\log N_{\mathrm{H}}$	$F_{20-50\text{ keV}}^{\mathrm{intr}}$ ($\times 10^{-11} \text{ erg}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$)	$\hat{n}_{\mathrm{s}}$	$\hat{\gamma}$	TS	p_{local}
NGC 1068	40.67	-0.01	0.003	25.00	7.72	102.2	3.4	27.1	2.2×10^{-7} (5.0 σ)
NGC 7469	345.82	8.87	0.016	20.53	2.69	5.5	1.9	15.5	9.8×10^{-5} (3.7 σ)
NGC 4151	182.64	39.41	0.003	22.71	18.09	27.6	2.7	10.8	1.1×10^{-3} (3.1 σ)
CGCG 420-015	73.36	4.06	0.029	24.08	1.77	35.3	2.7	8.4	3.6×10^{-3} (2.7 σ)
Cygnus A	299.87	40.73	0.056	23.38	4.93	3.4	1.6	7.4	6.5×10^{-3} (2.5 σ)
LEDA 166445	42.68	54.70	0.015	24.01	1.61	57.1	4.4	5.2	0.02 (2.1 σ)
NGC 4992	197.27	11.63	0.025	23.69	2.34	27.3	2.9	5.0	0.02 (2.0 σ)
NGC 1194	45.95	-1.10	0.014	24.18	3.87	43.2	4.4	4.1	0.03 (1.8 σ)
Mrk 1498	247.02	51.78	0.055	23.23	1.86	39.9	3.6	3.7	0.04 (1.7 σ)
MCG+4-48-2	307.15	25.73	0.014	23.86	4.32	36.7	3.2	4.1	0.04 (1.7 σ)
NGC 3079	150.49	55.68	0.004	24.56	3.33	33.8	3.6	3.3	0.05 (1.7 σ)
Mrk 417	162.38	22.96	0.033	23.90	1.73	4.4	1.9	3.5	0.05 (1.6 σ)

IceCube 13 yrs source list: 48
[2602.10208](#) [astro-ph.HE]

Public data 14 yrs source list: 735
[2602.02390](#) [astro-ph.HE]

Source Name	TS	$\hat{n}_s$	p_{local}		TS
NGC 1068	27.1	102.2	2.2×10^{-7} (5.0σ)	NGC 1068	31.00
NGC 7469	15.5	5.5	9.8×10^{-5} (3.7σ)	NGC 4151	12.53
NGC 4151	10.8	27.6	1.1×10^{-3} (3.1σ)	CGCG 420-015	11.63
CGCG 420-015	8.4	35.3	3.6×10^{-3} (2.7σ)	MCG +10-17-061	10.25
Cygnus A	7.4	3.4	6.5×10^{-3} (2.5σ)	NGC 3079	9.67
LEDA 166445	5.2	57.1	0.02 (2.1σ)	IC 0751	9.19
NGC 4992	5.0	27.3	0.02 (2.0σ)	NGC 4945	8.76
NGC 1194	4.1	43.2	0.03 (1.8σ)	ZMASX J08551746-2854218	8.72
Mrk 1498	3.7	39.9	0.04 (1.7σ)	PKS 2349-01	8.44
MCG+4-48-2	4.1	36.7	0.04 (1.7σ)	NGC 1194	8.24
NGC 3079	3.3	33.8	0.05 (1.7σ)	UGC 03995A	7.27
Mrk 417	3.5	4.4	0.05 (1.6σ)	RX J0718.0+4405	6.68

Cygnus A at 5 GHz



- neutrino emission from black hole
- jets do not point
- same for TXS 0506 even though the jets point at us

more X-ray bright and
gamma ray-obscured
sources:

NGC 1068

TXS 0506+056

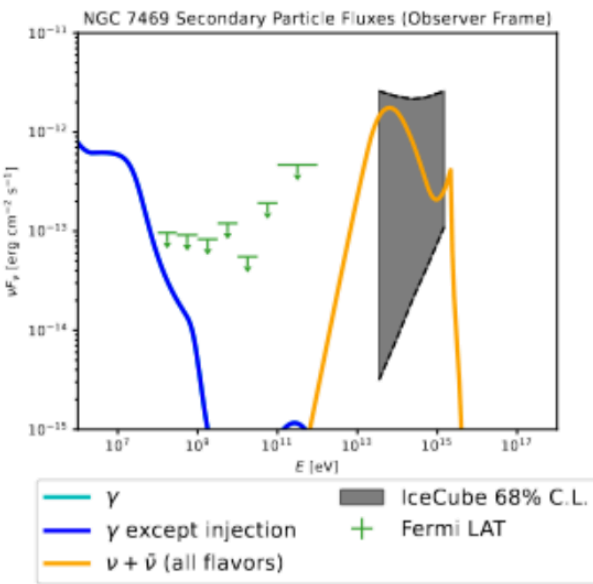
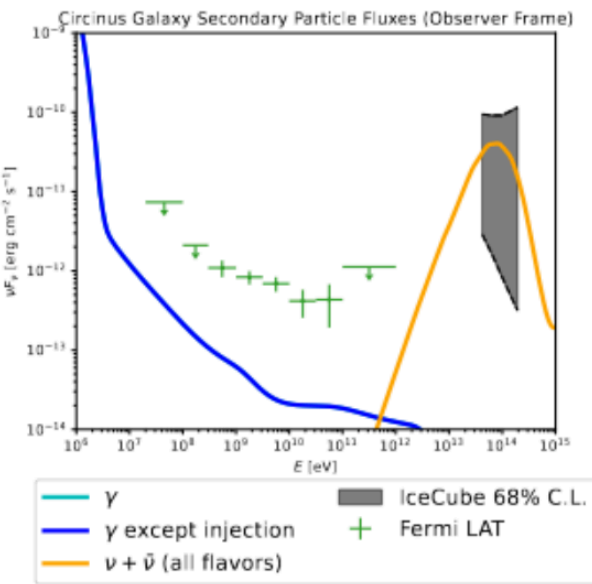
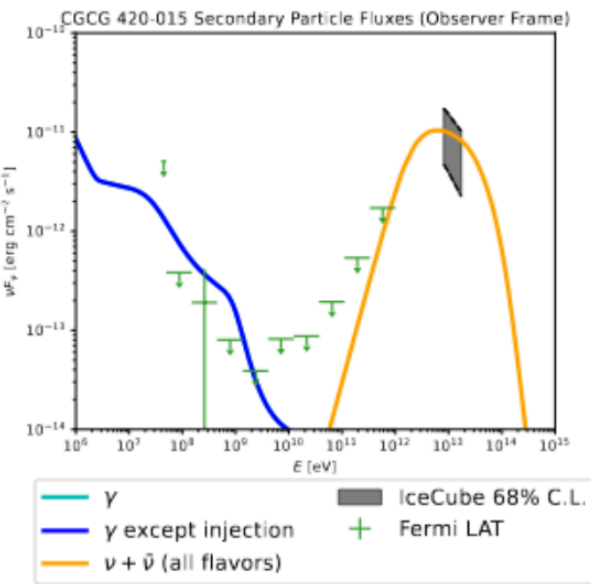
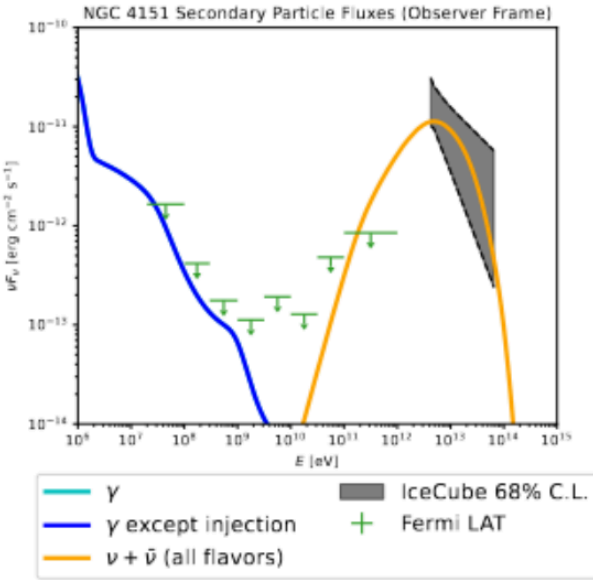
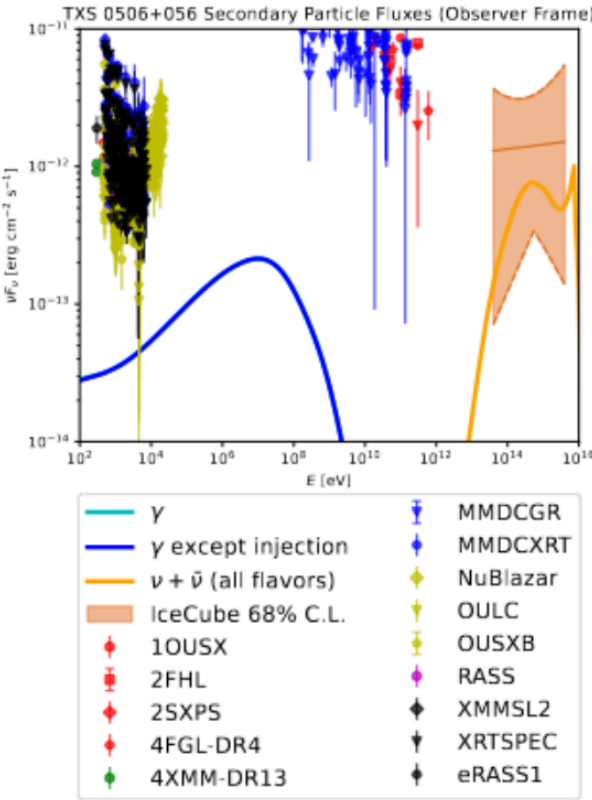
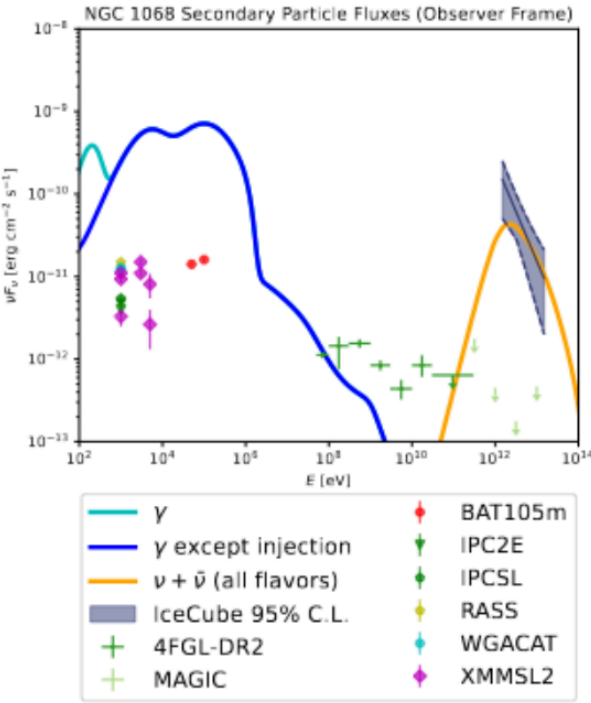
NGC 4151

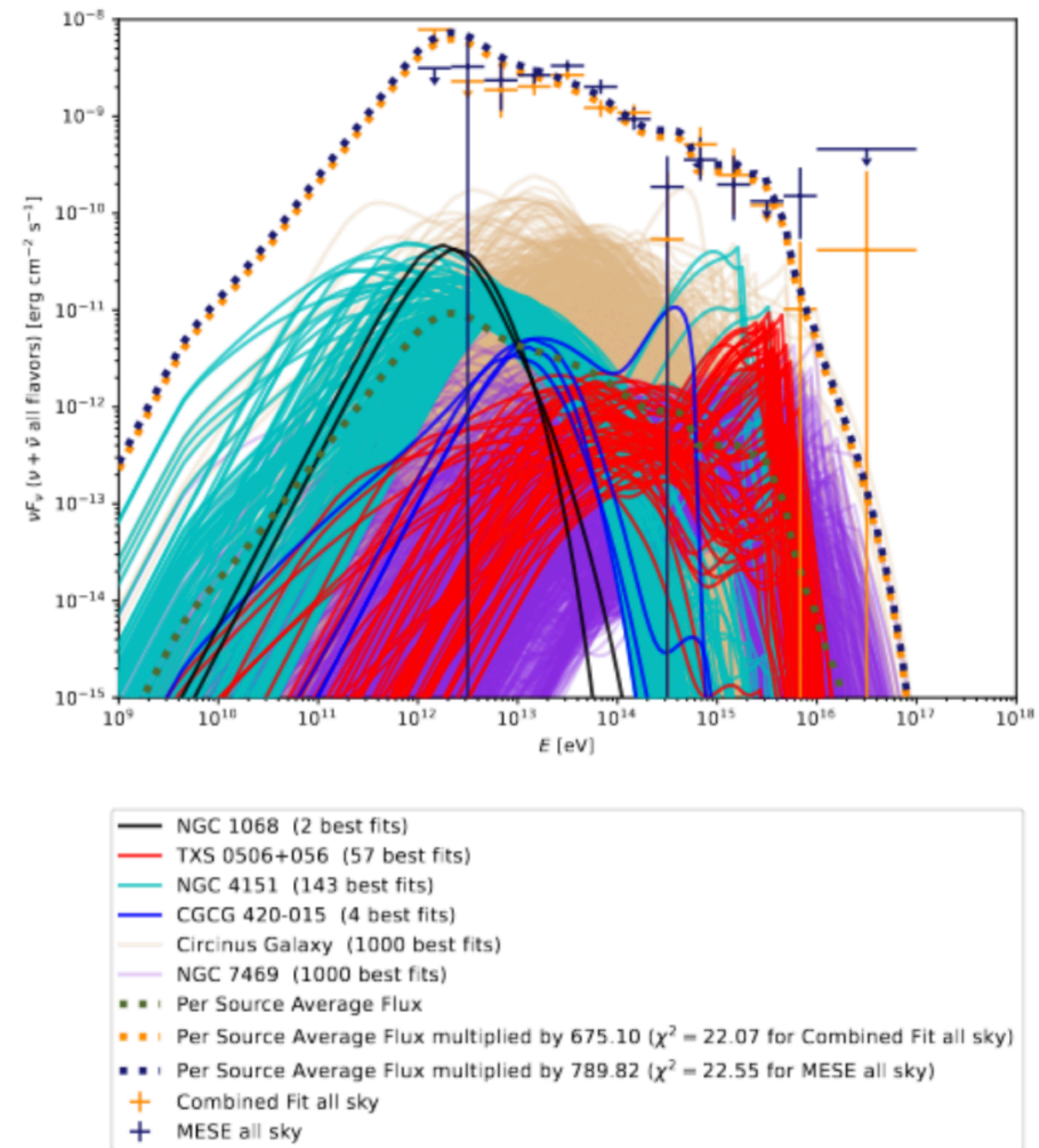
CGCG 420-015

Circinus

NGC 7469

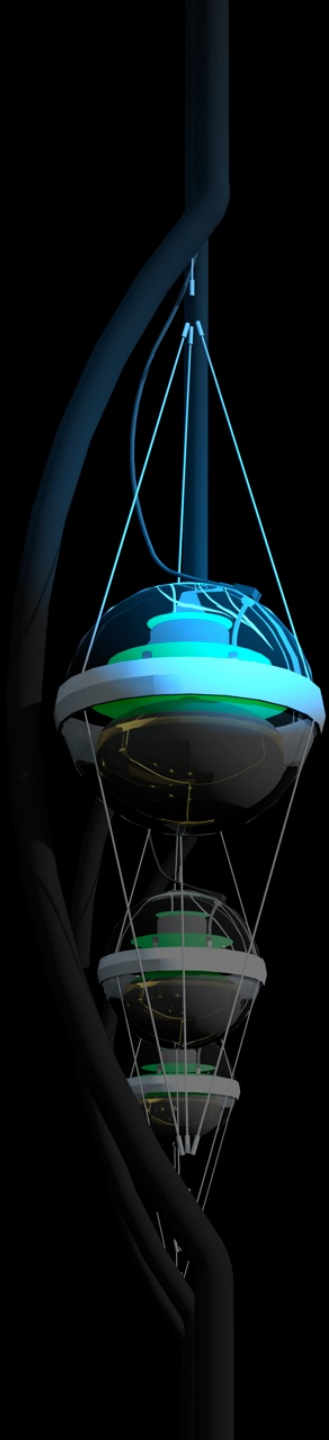
[PKS 1425+240
NGC 5610]





fitting the diffuse neutrino flux requires
a number of ~ 800 active galaxies like
the 6 sources fitted

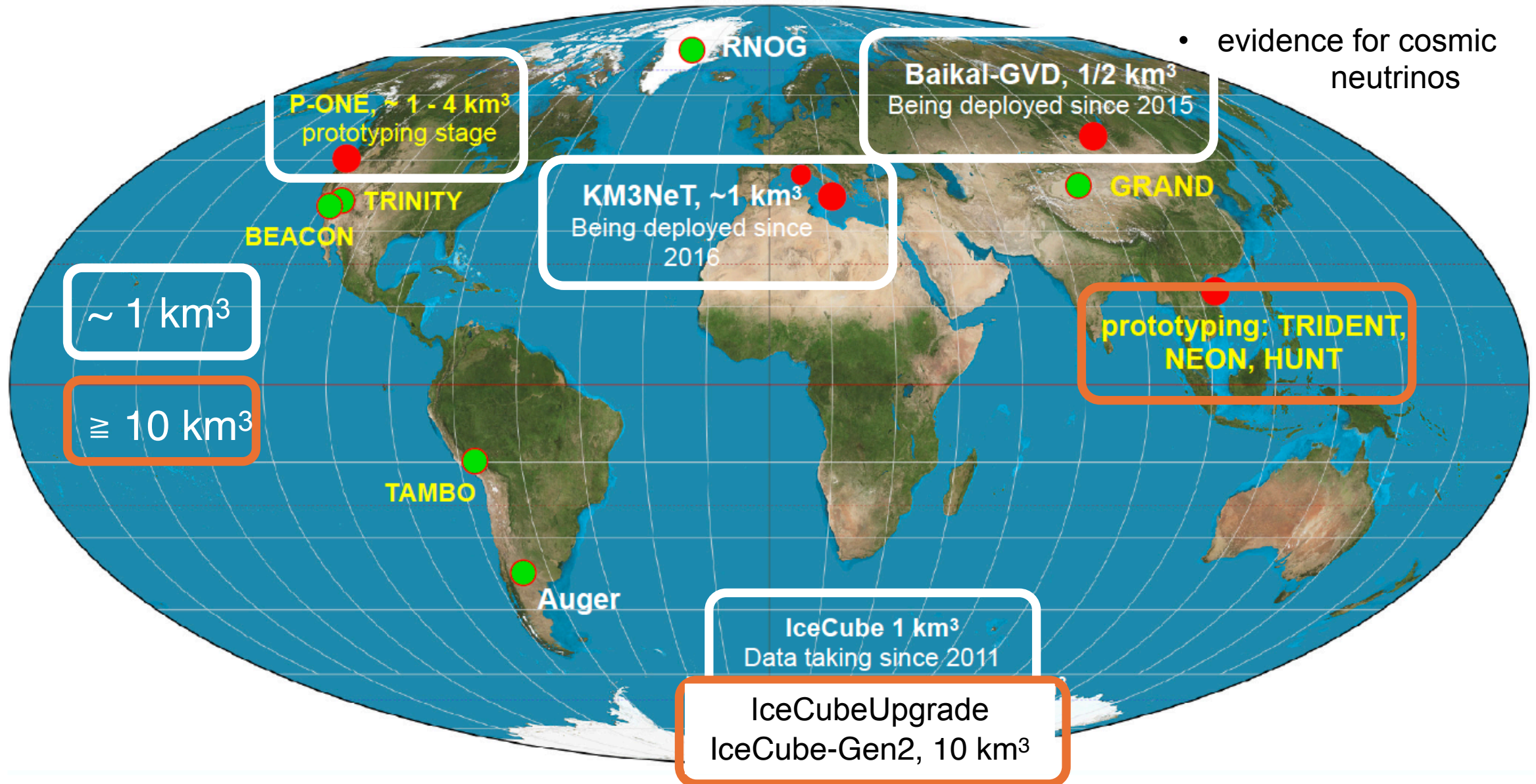
consistent with the number of agn
with
[NGC 1068]



neutrino astronomy 2025

- it exists
- more neutrinos, better neutrinos, more telescopes
- closing in on cosmic ray sources a century after their discovery
- Galactic PeVatrons?

- from discovery to astronomy and neutrino physics: rapid progress!



- megaton GeV detectors: IceCube Upgrade, ORCA, HUNT

- EeV detectors

THE ICECUBE COLLABORATION



ITALIA 1

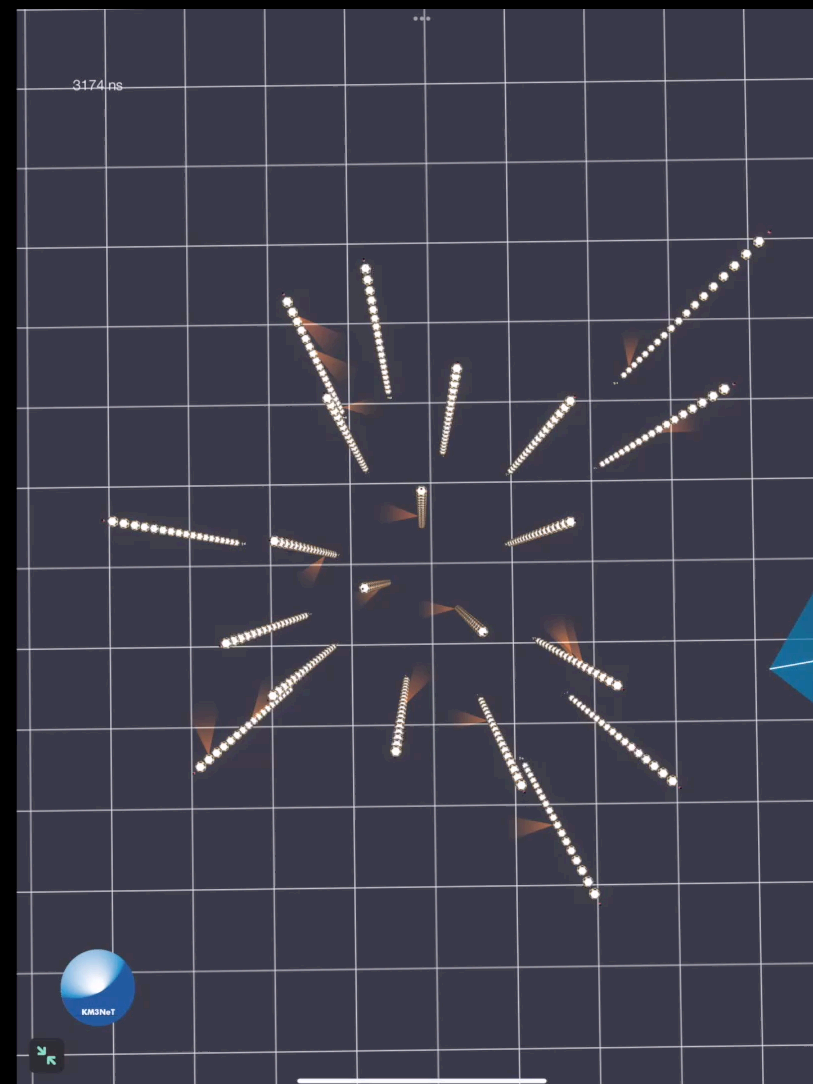
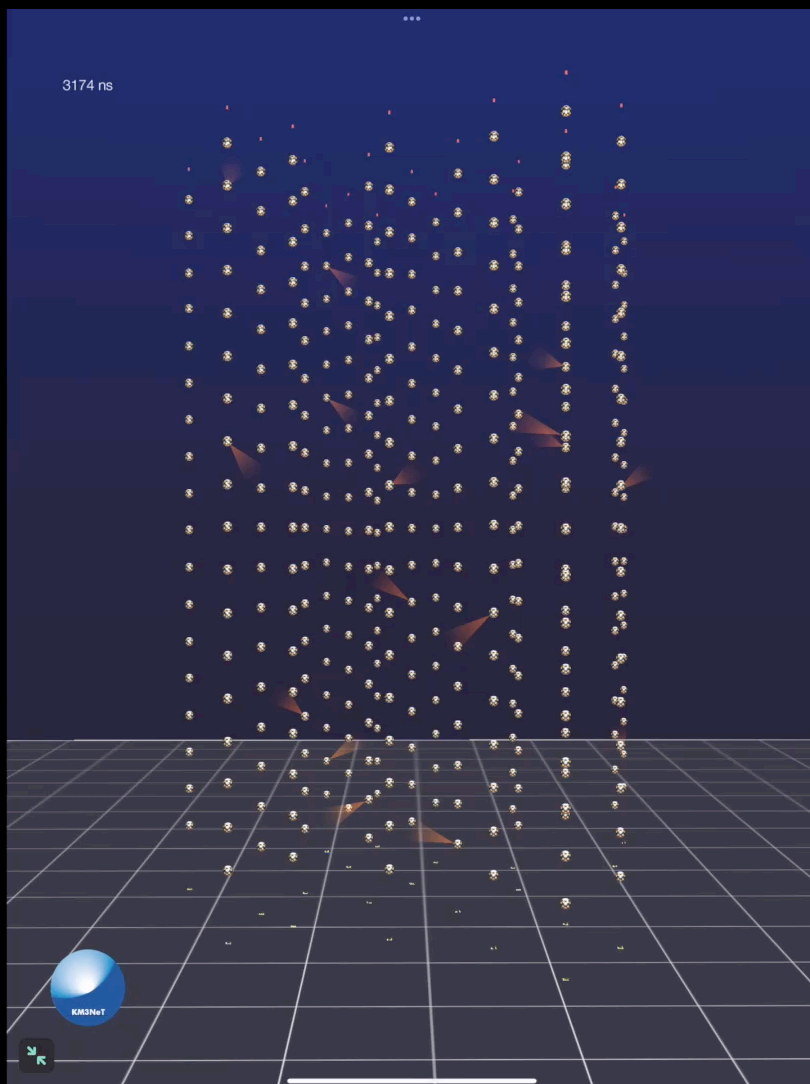
1

UNITED KINGDOM 1

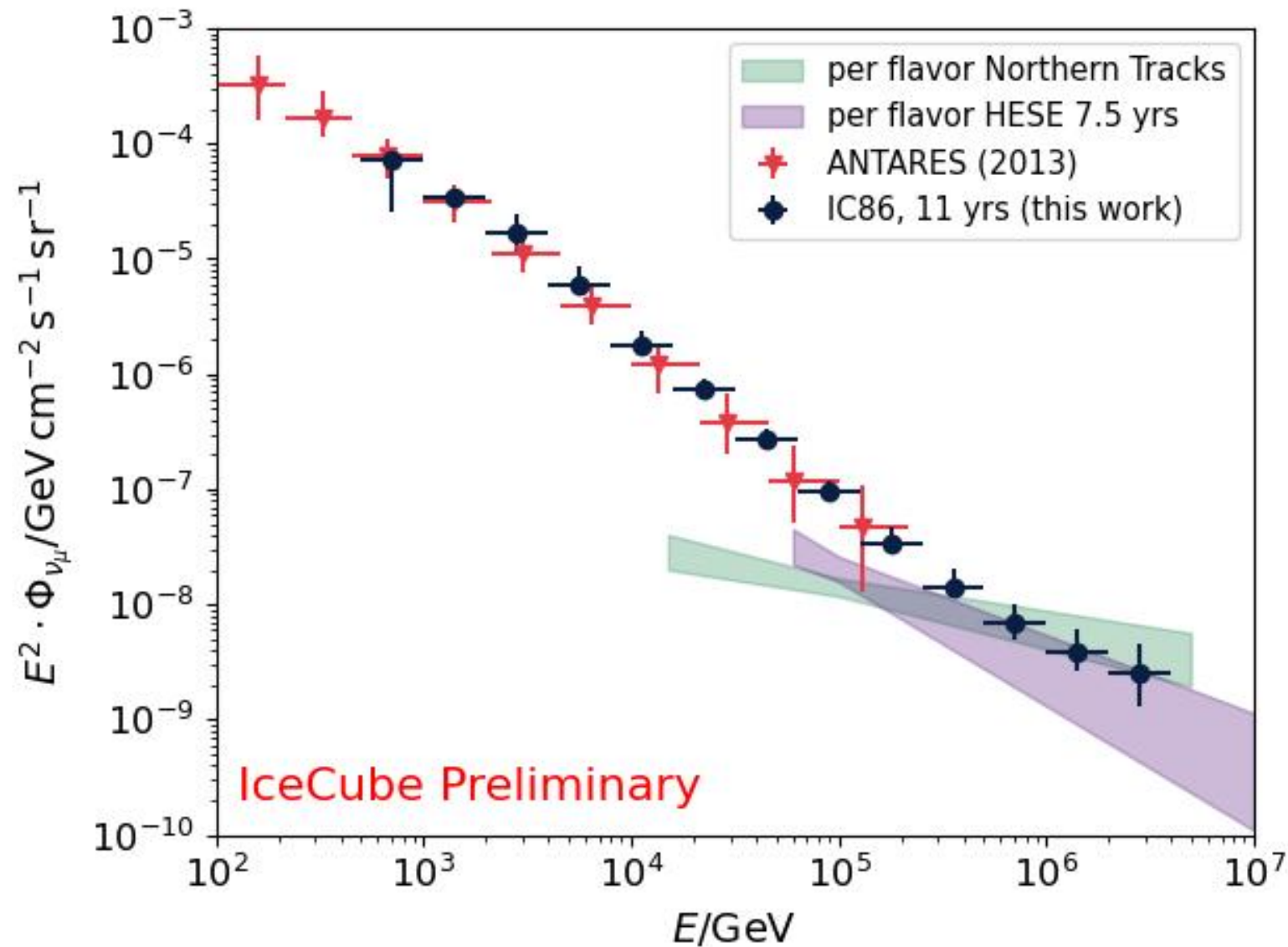
UNITED STATES 25



Uncharted Territory: $E_\nu = 220$ PeV



techniques mature (and improving): detectors agree on the muon neutrino spectrum



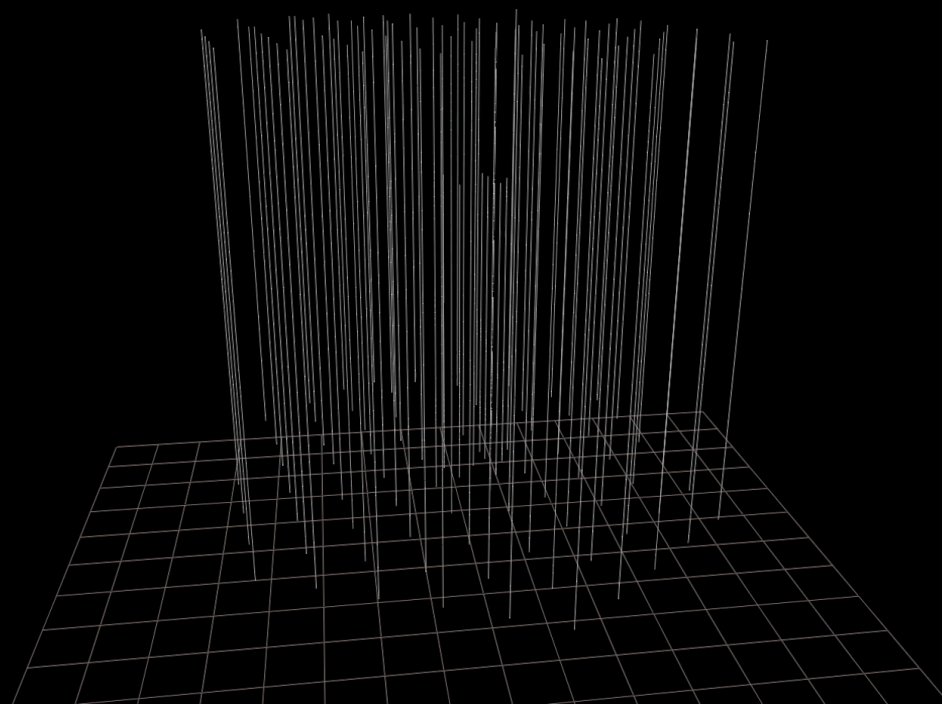
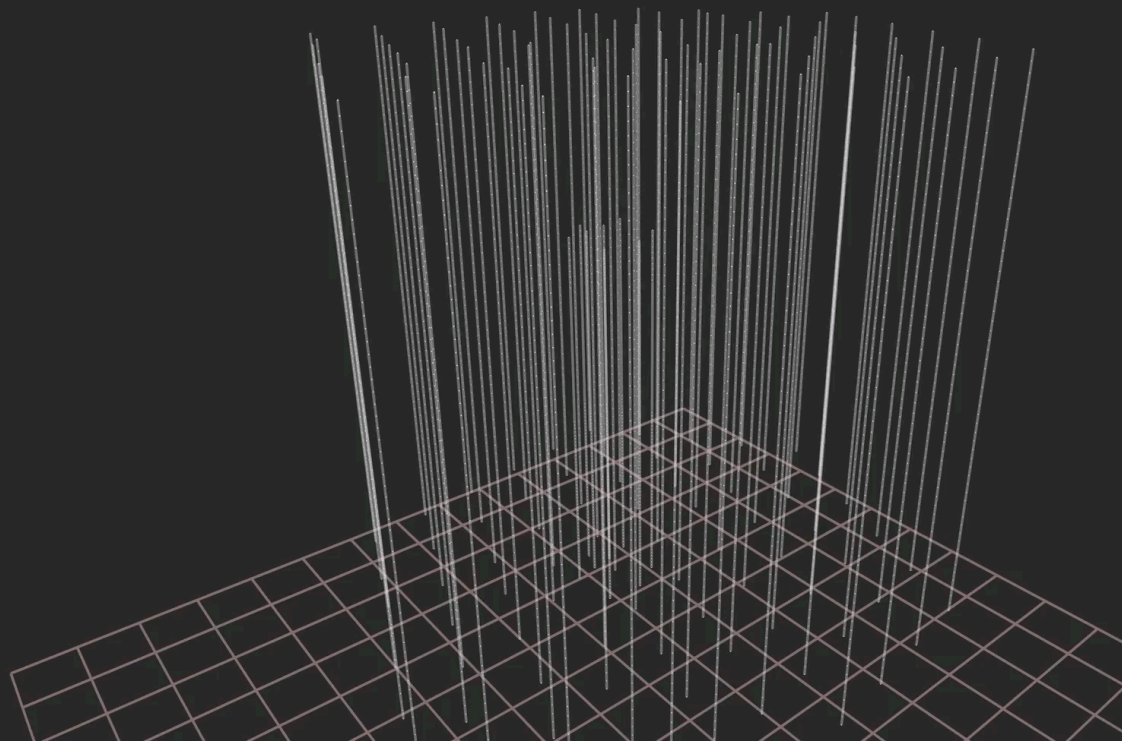
and there is more...

electrical cables supply the
voltage to the photomultipliers
and return their digitized signals
which are assembled into
neutrino events at the surface



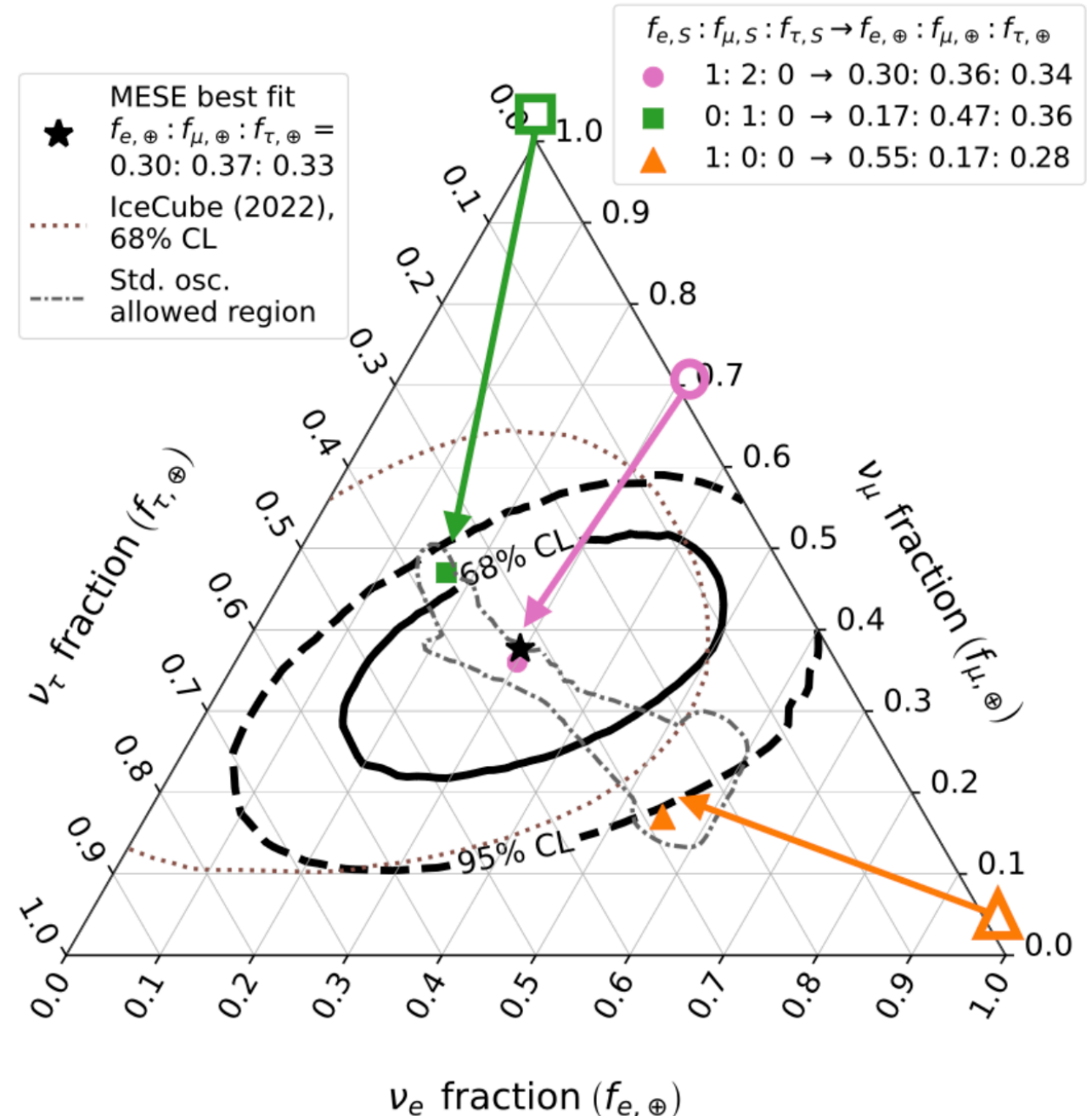


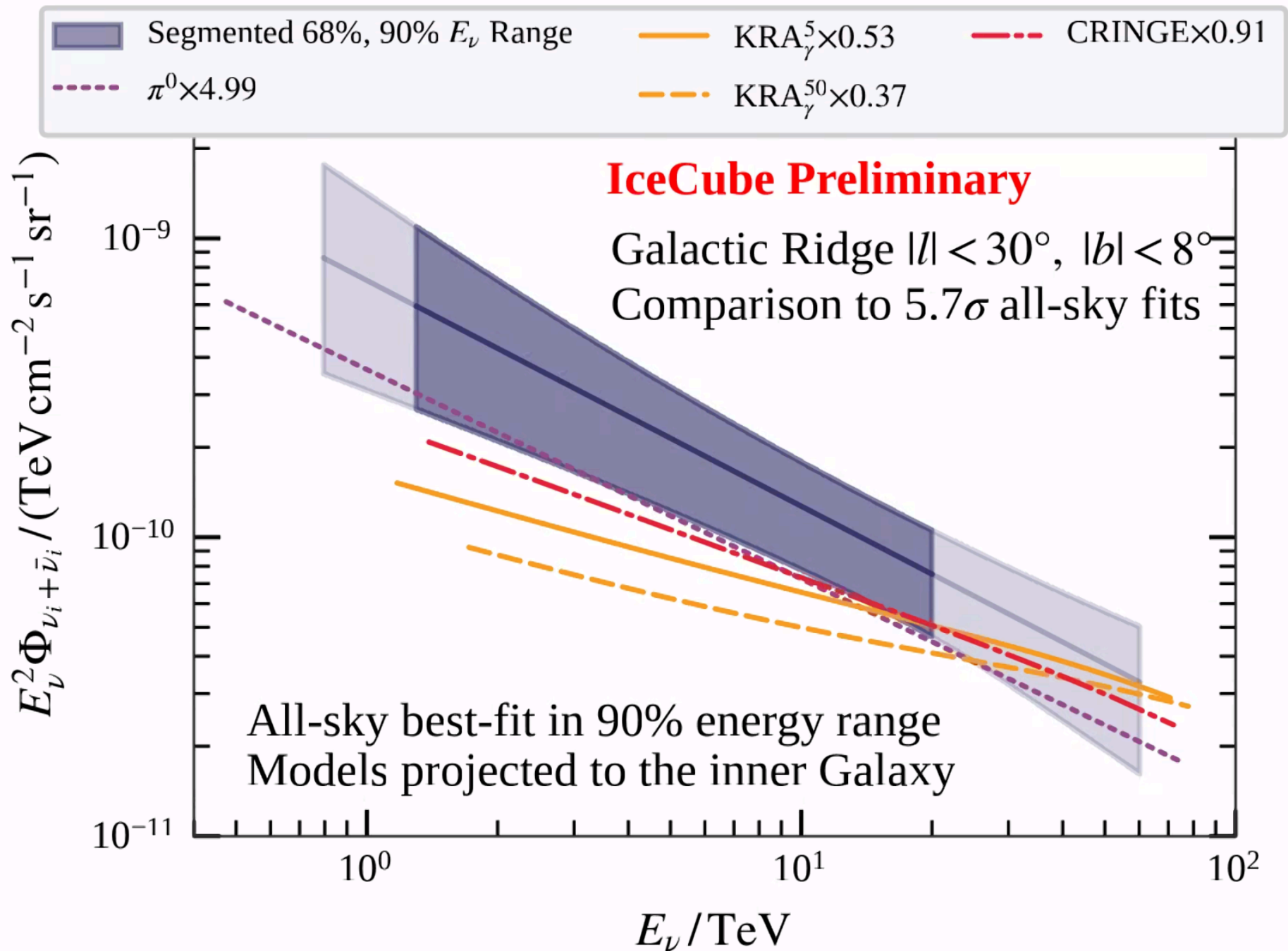
n, 15 Jan 2012
9735 ns

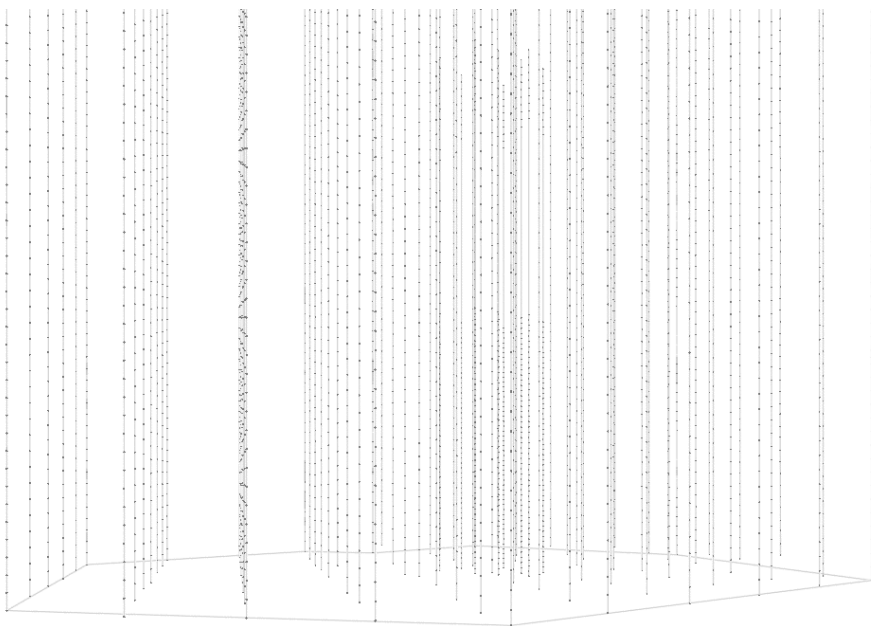


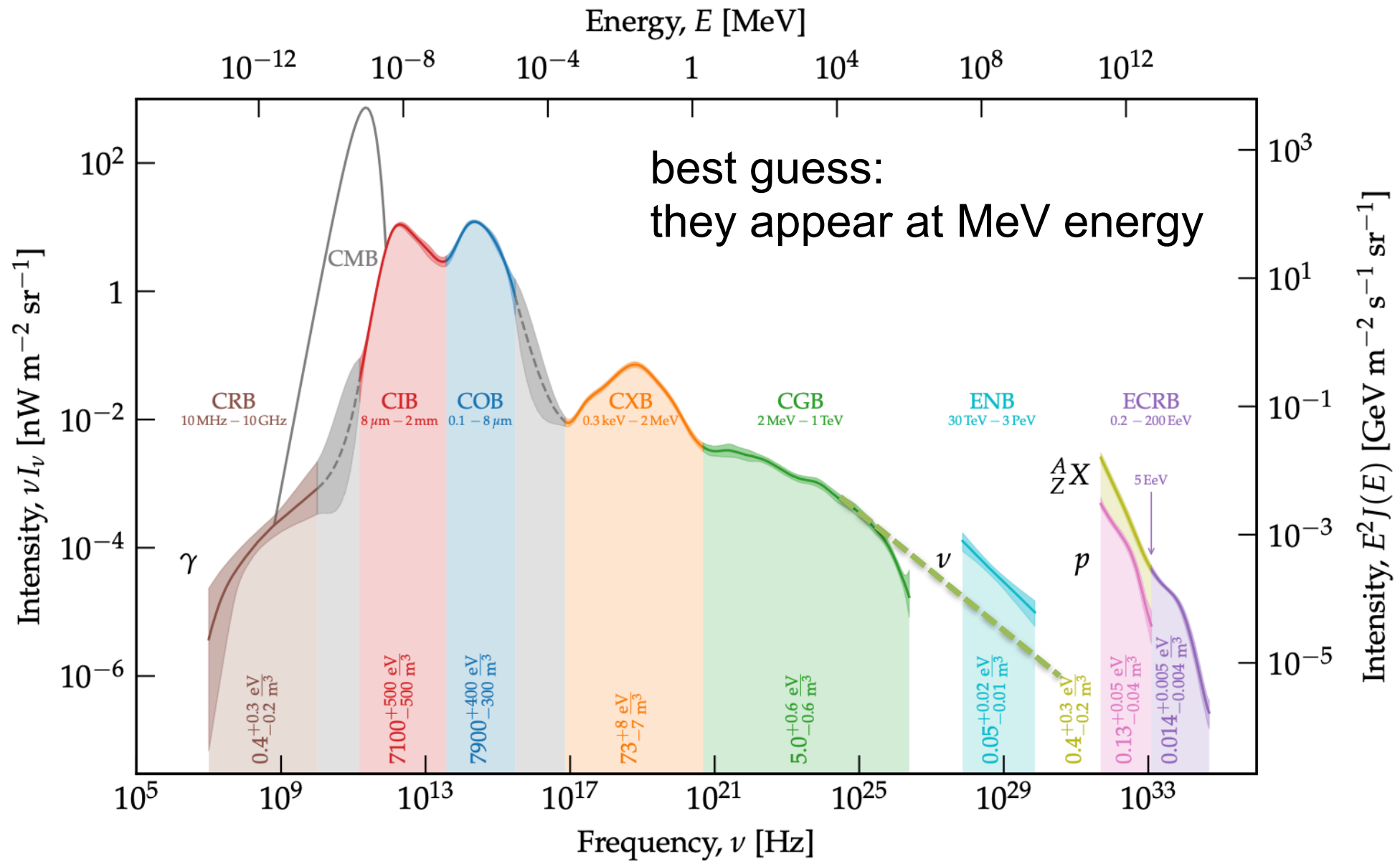
particle physics:

- neutrino oscillations over cosmic baselines: $\nu_\mu = \nu_e = \nu_\tau$
- dark matter
- next Galactic supernova
- quantum decoherence of very high energy neutrinos traveling over cosmic distances
- ...



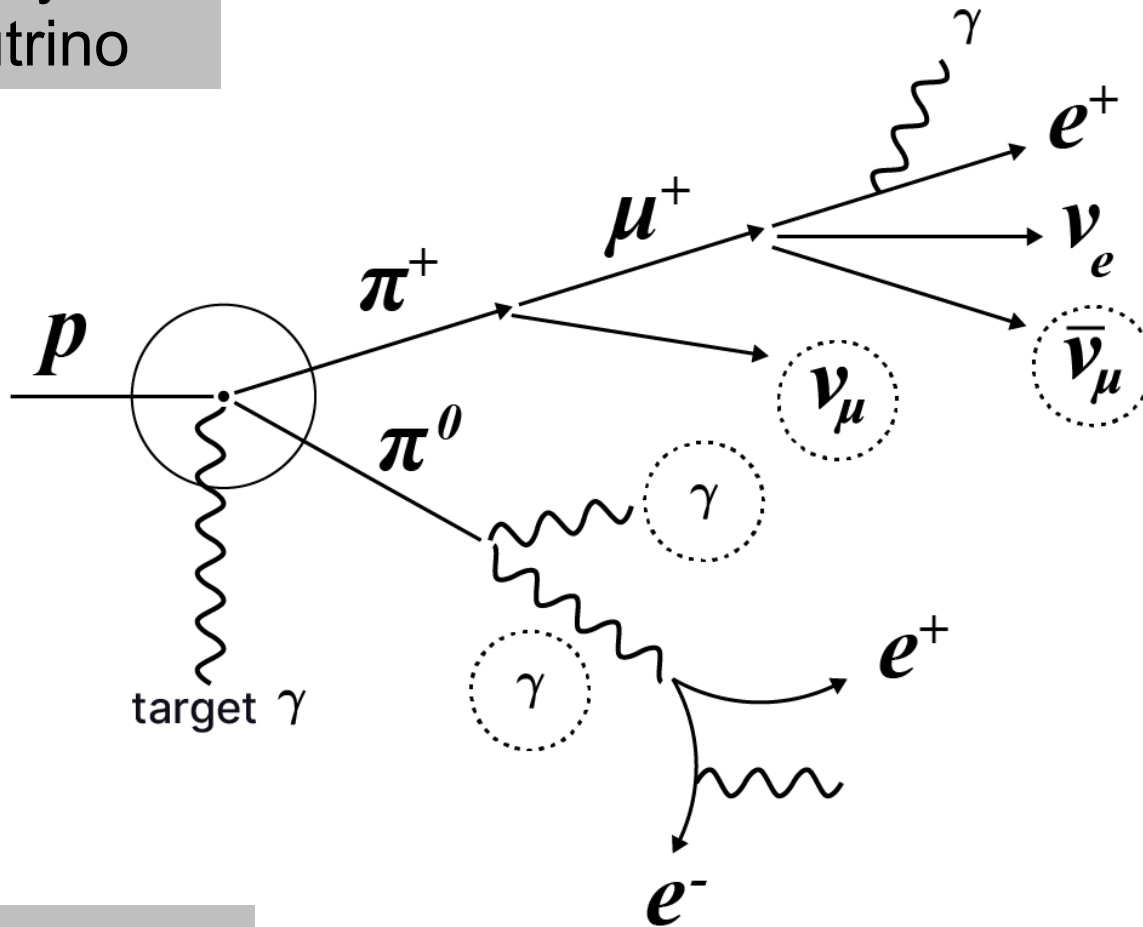






the π^0 gamma rays lose energy in the target and escape Fermi detection

cosmic ray sources:
a gamma ray for
every neutrino

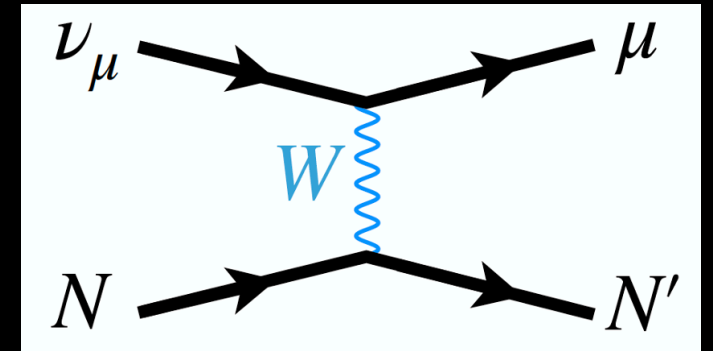


neutrino sources are
cosmic ray sources

$$\gamma + \gamma \simeq \nu_\mu + \bar{\nu}_\mu$$

$$E_\gamma = 2 E_\nu$$

the invisible neutrino
turns into charged
particles that emit
light



• lattice of photomultipliers

• muon

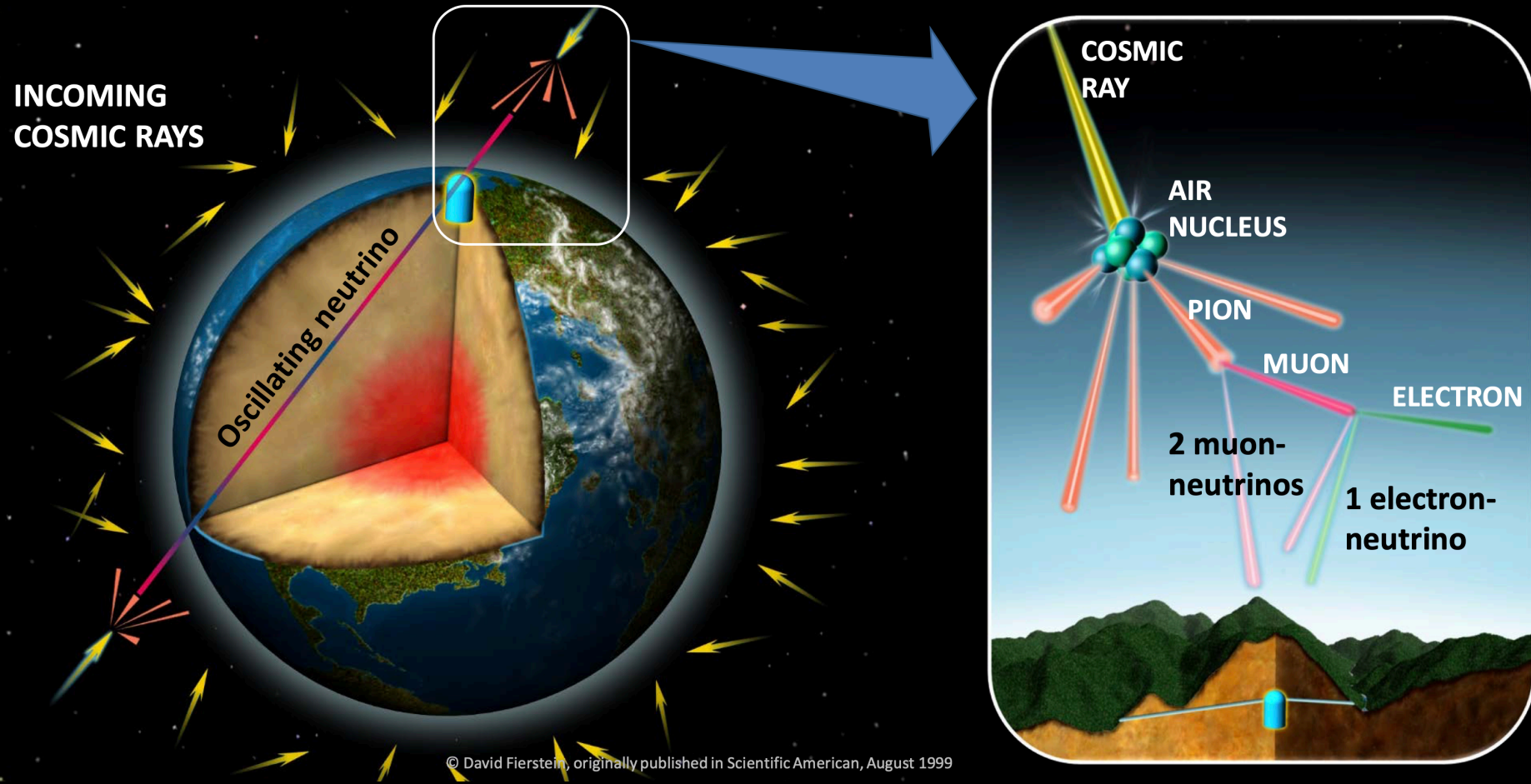
• nuclear interaction
with ice nucleus

• neutrino



light signals from 10 inch photomultiplier
embedded in the deep ice are
digitized and sent to computers at surface

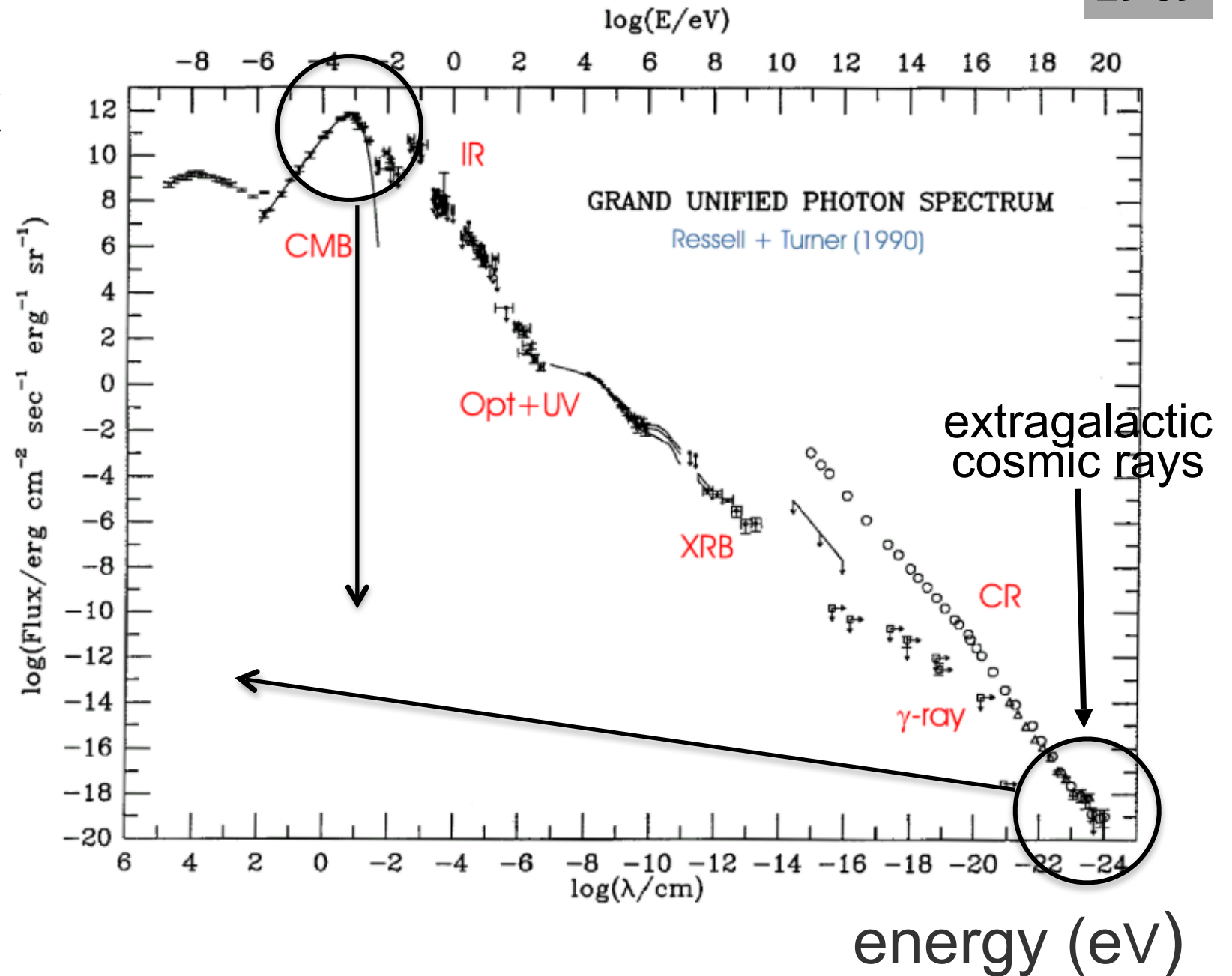
What does IceCube “see”?

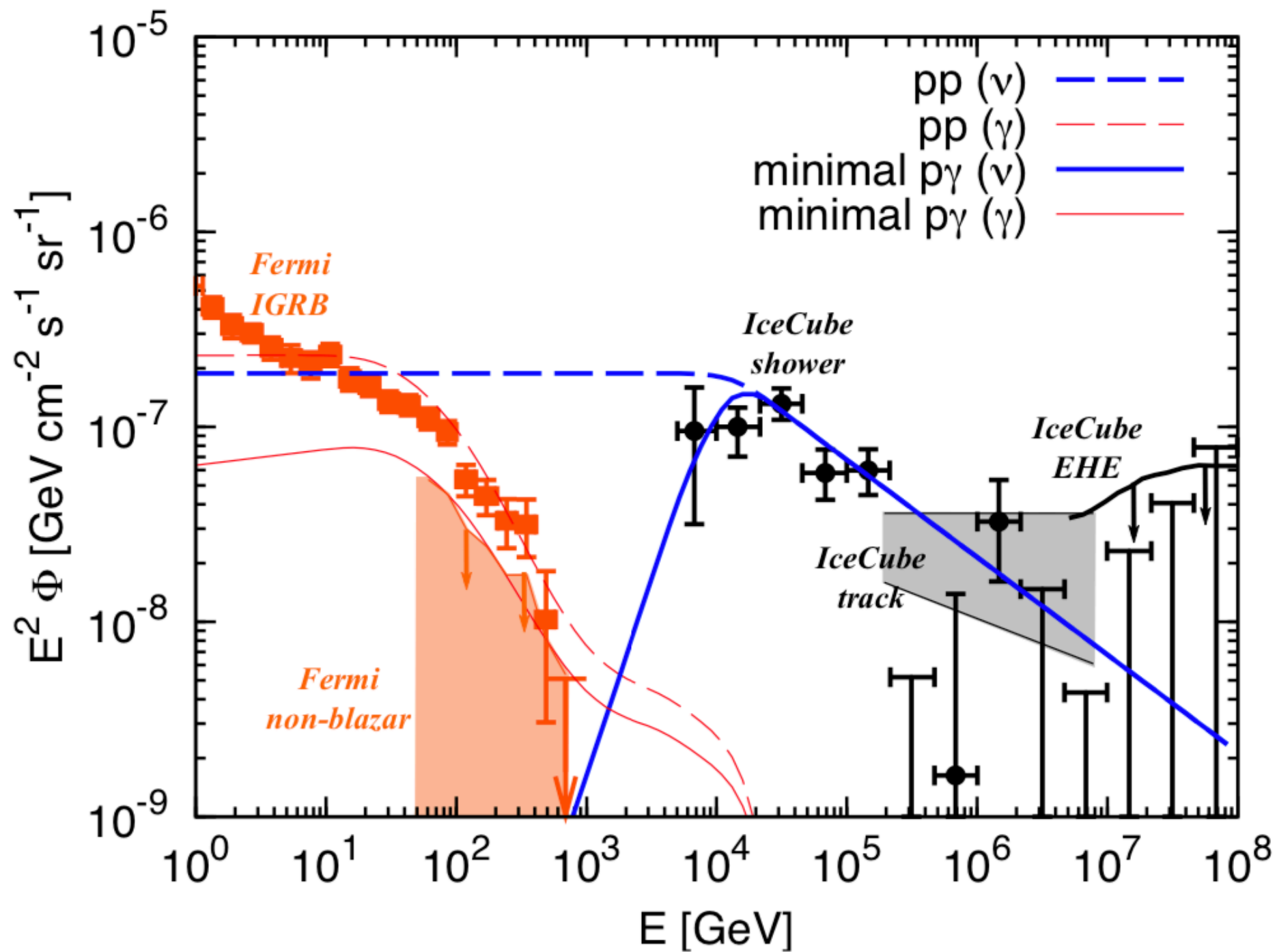


flux

the “guaranteed neutrinos”

- the pions decay into “GZK” neutrinos
- observation requires cubic kilometer detector

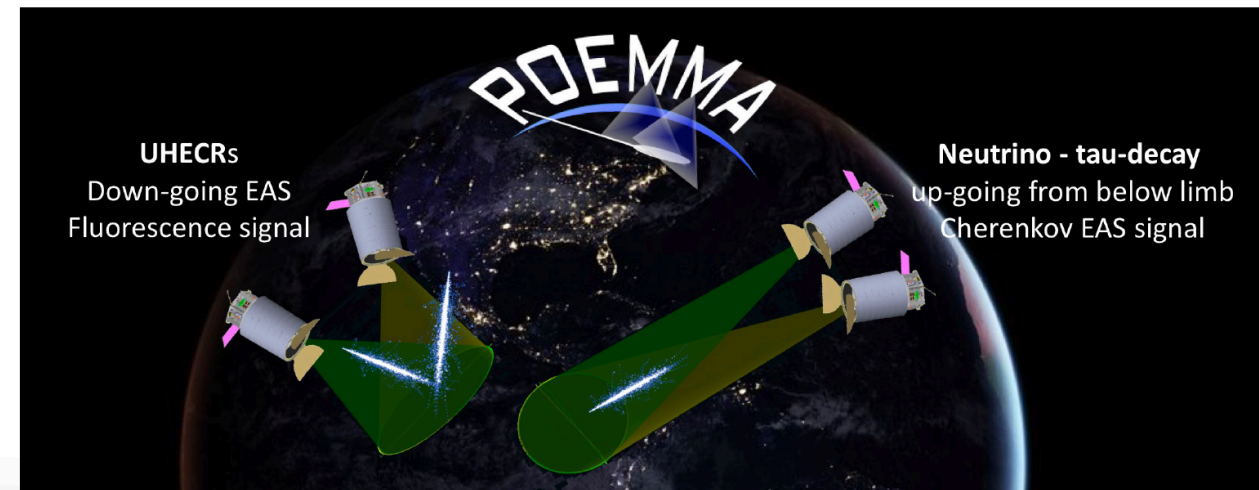
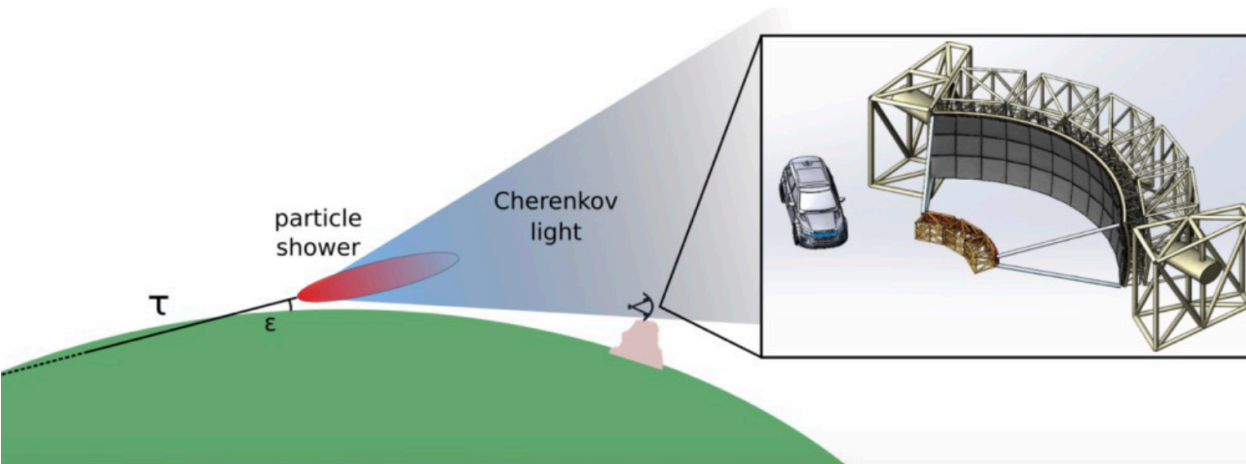
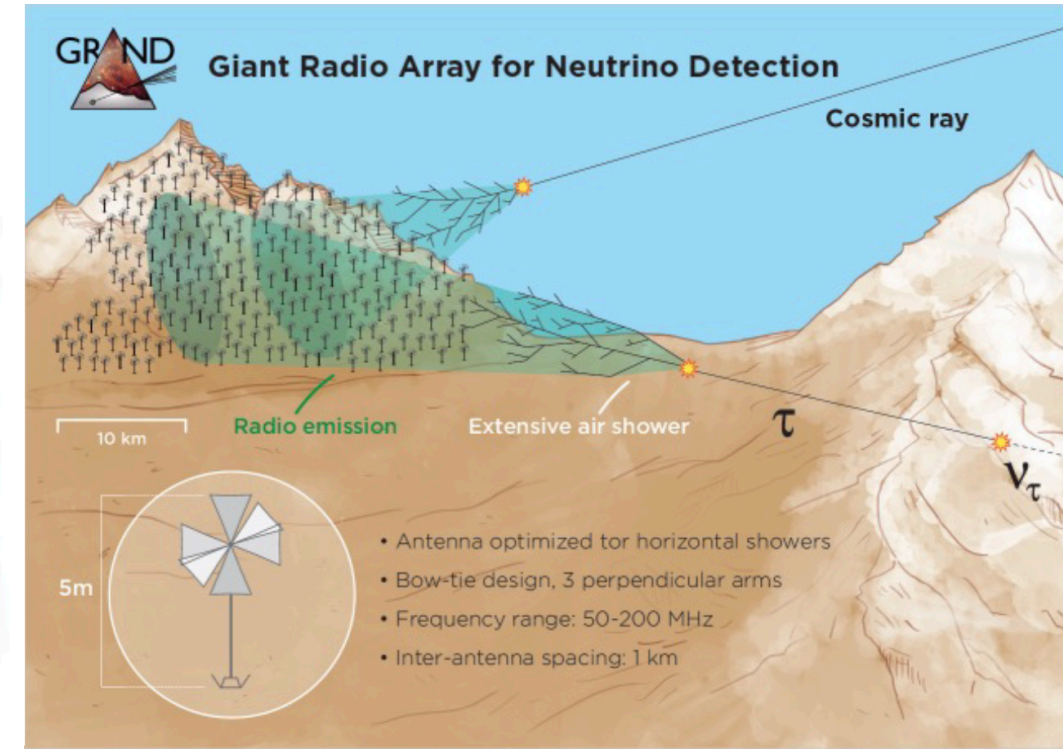
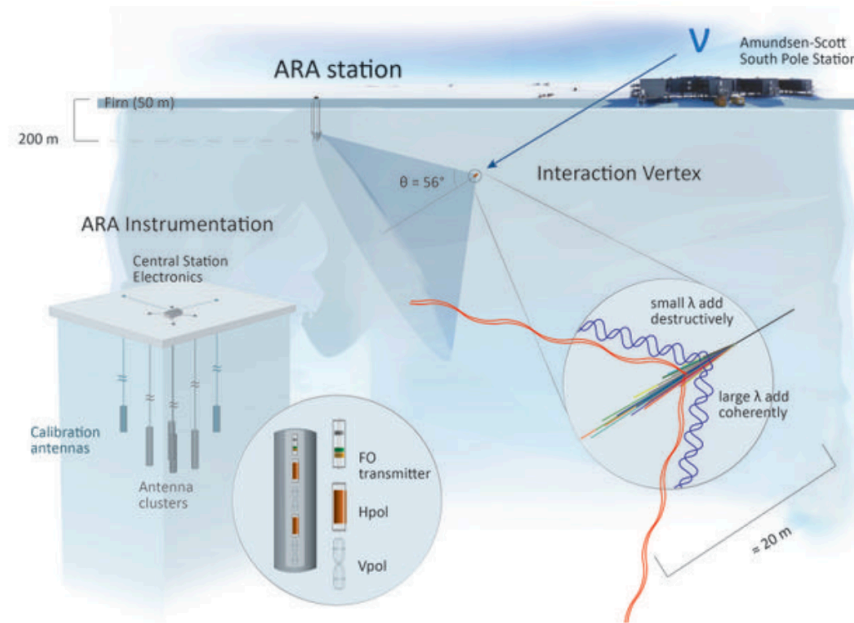




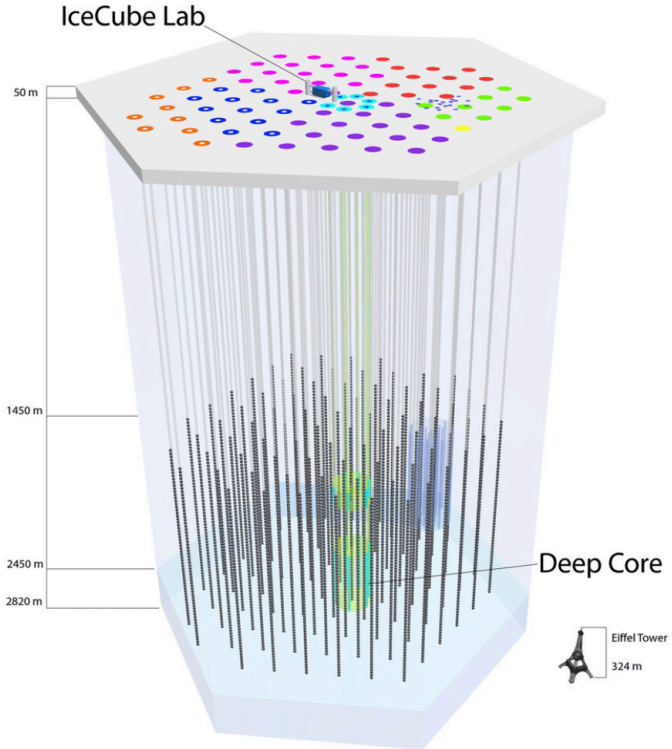
Ultra-high energy neutrinos



Detection of ultrahigh-energy neutrinos in ARA



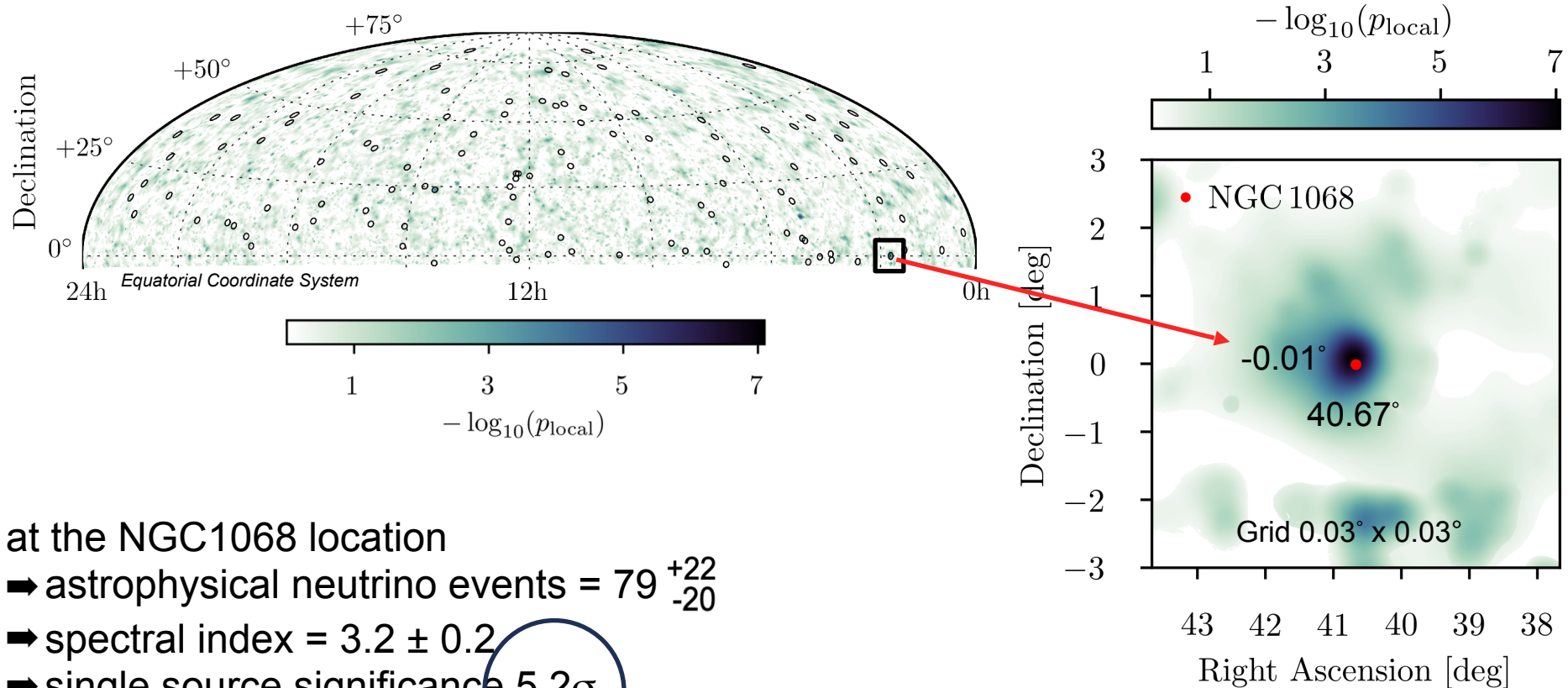
IceCube construction (Upgrade 2026)



- instrument 1 cubic kilometer of natural ice below 1.45 km with 5160 10-inch photomultiplier tubes
- totally stable detector after deployment: 1 failure every 2 years

NGC 1068

- most significant of 110 preselected sources
- leading hotspot in the neutrino sky



at the NGC1068 location

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

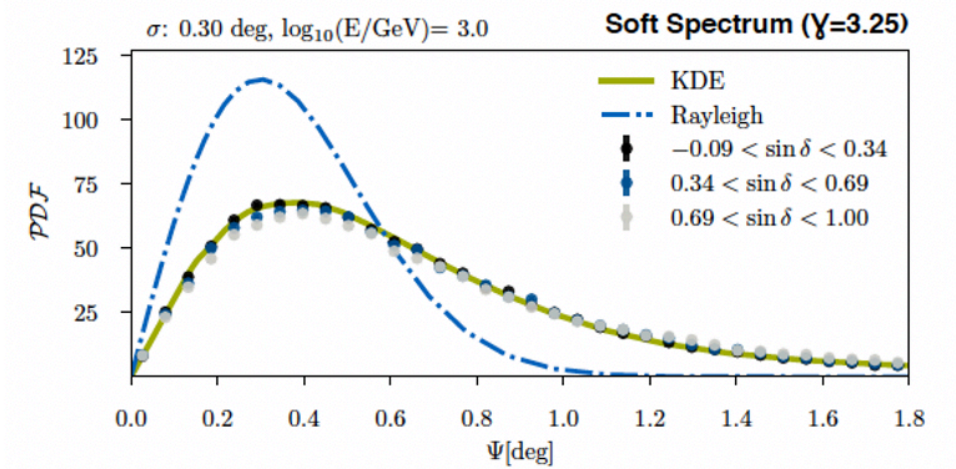
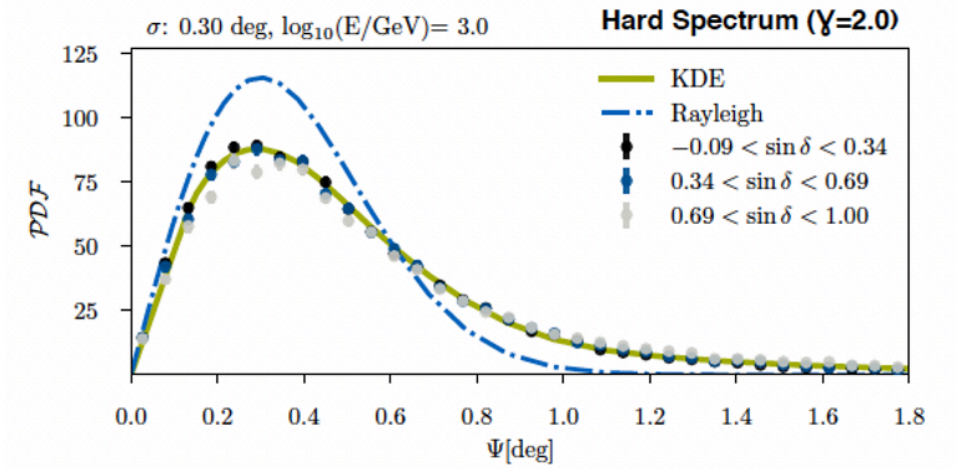
➔ spectral index = 3.2 ± 0.2

➔ single source significance 5.2σ

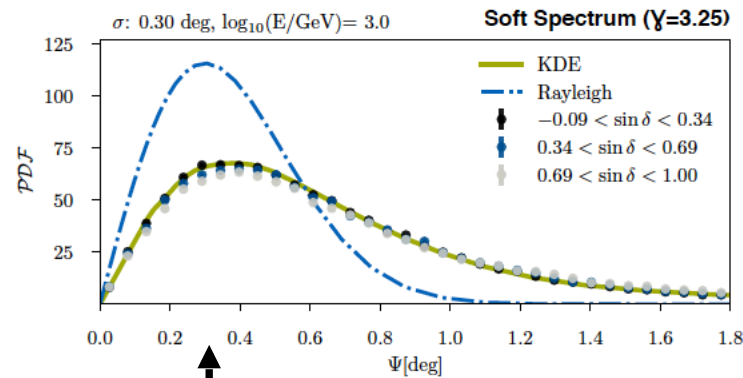
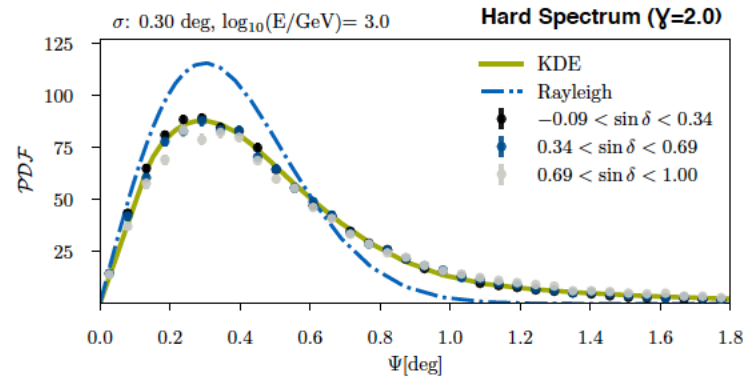
➔ (offset 0.11°)

➔ 1 in 100,000 scrambled data sets have object $\geq 5.2\sigma = 4.2\sigma$

➔ p-value $< 10^{-5}$ including all trials



- point spread function consistent with simulation
- insensitive to systematics

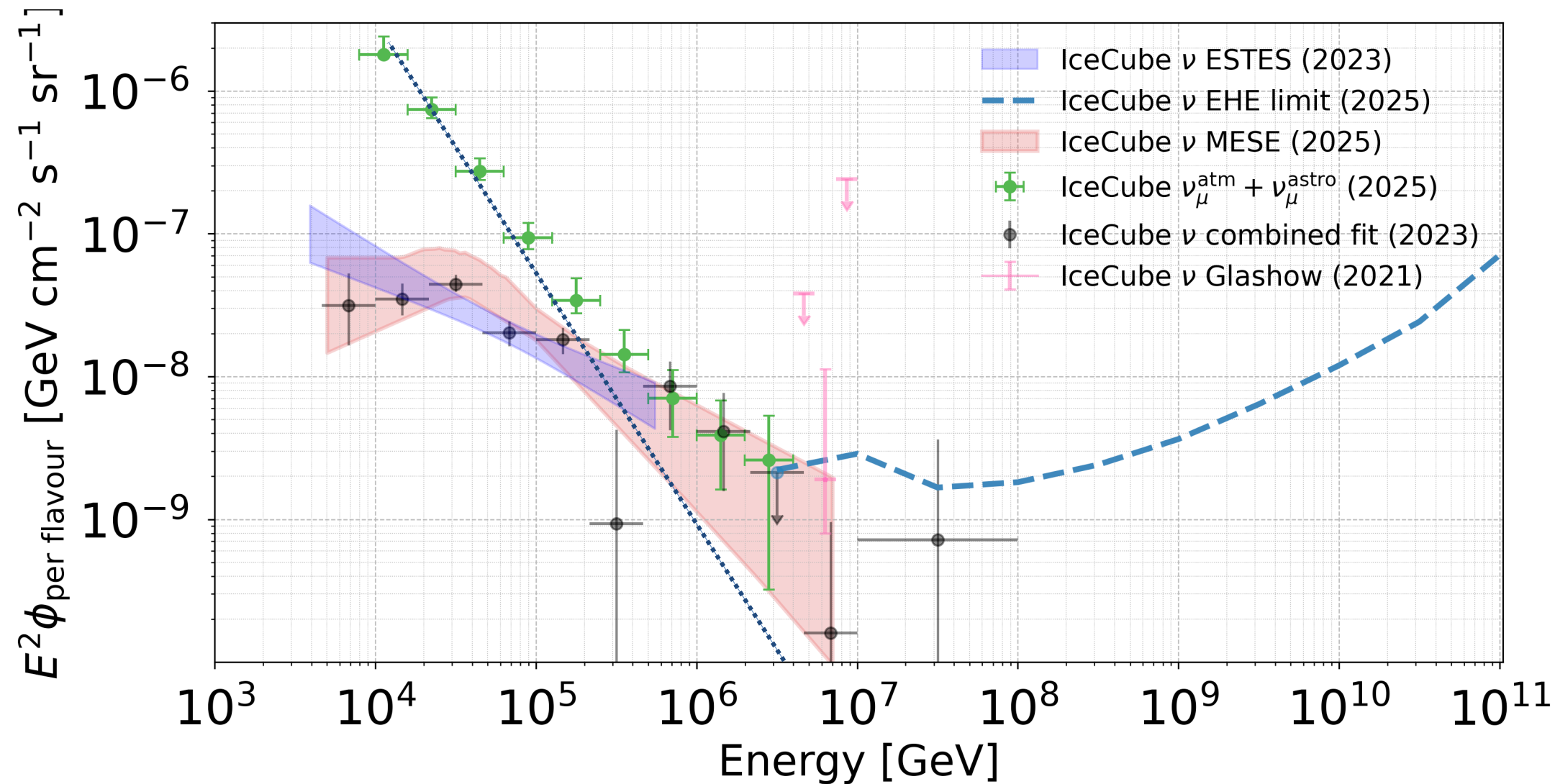


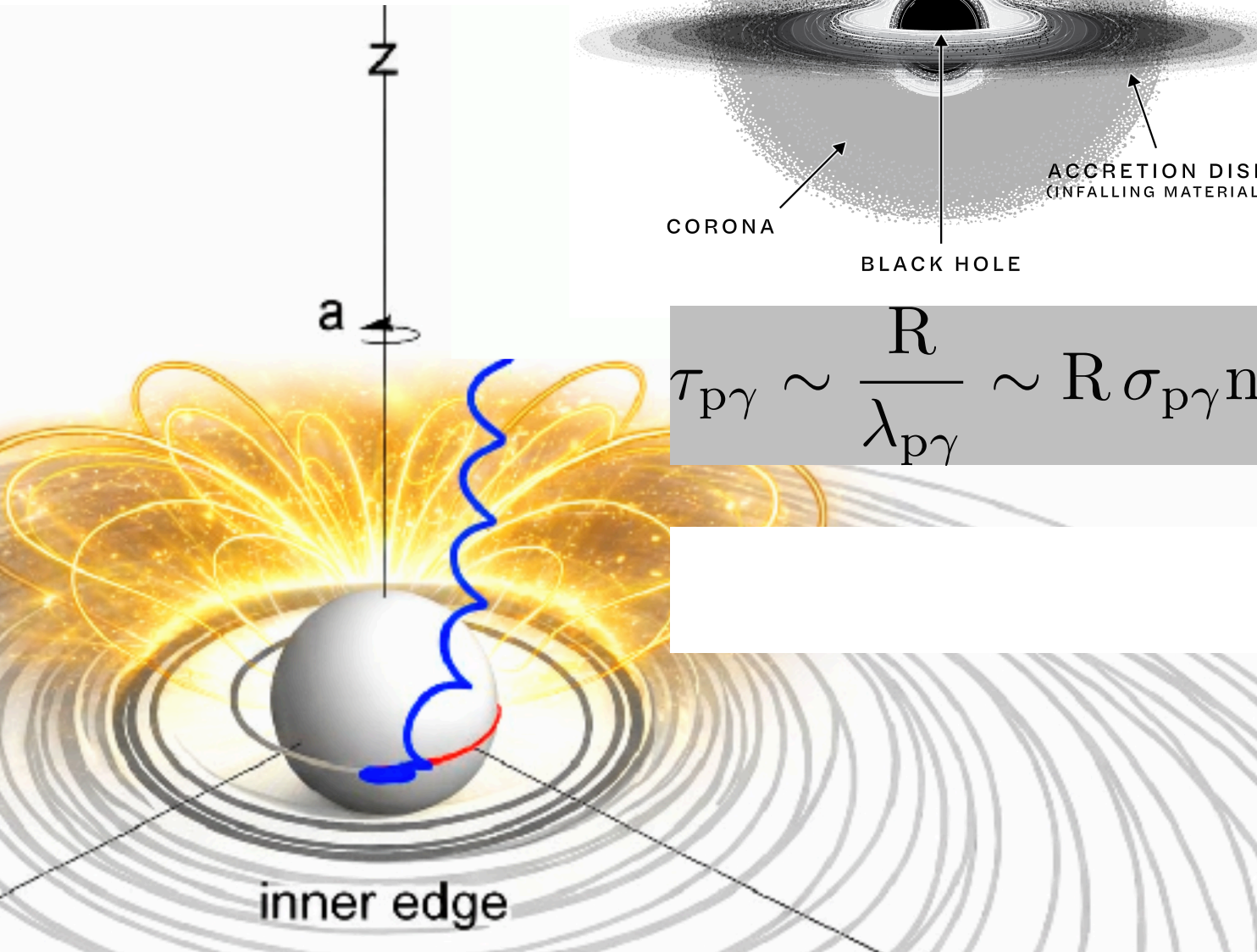
muon direction

- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at $< 10 \text{ TeV}$ energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation of the γ -dependent spatial term from MC simulation (for example using KDEs)

$$\frac{1}{2\pi\sigma^2} e^{-\frac{\psi^2}{2\sigma^2}} \rightarrow \mathcal{S}(\psi | \sigma, E_\mu, \gamma)$$

NEW! energy spectrum of cosmic neutrinos: a break at 30 TeV





in order to produce neutrinos

$$\tau_{p\gamma} \geq 0.1$$

therefore

$$\tau_{\gamma\gamma} \simeq 10^3 \tau_{p\gamma} \geq 10^2$$

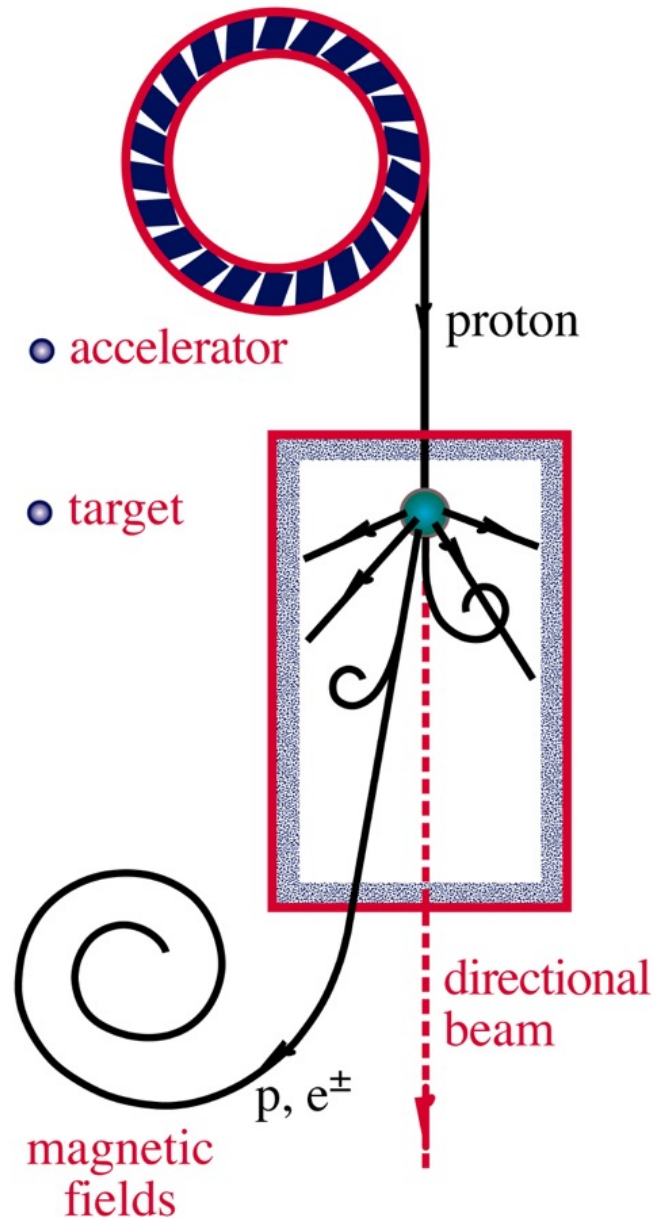
→ gamma-obscured source

$$\tau_{p\gamma} \sim \frac{R}{\lambda_{p\gamma}} \sim R \sigma_{p\gamma} n_{\gamma} \sim \frac{\sigma_{p\gamma}}{c} \left[\frac{1}{R} \frac{L_X}{E_X} \right] \sim 10^{-3} \tau_{\gamma\gamma}$$

$$10^{43} \text{ erg s}^{-1}$$

$$R \sim 10 R_s$$

NEUTRINO BEAMS



the $p\gamma$ efficiency dilemma

- efficiency for producing the neutrinos in the photon target:

$$\tau_{p\gamma} = R_{\text{escape}} \eta_{p\gamma} \sigma_{p\gamma} n_{\text{photons}}$$

- likelihood of the multimessenger photons to be absorbed in target

$$\tau_{\gamma\gamma} = R_{\text{target}} \eta_{\gamma\gamma} \sigma_{\gamma\gamma} n_{\text{photons}}$$

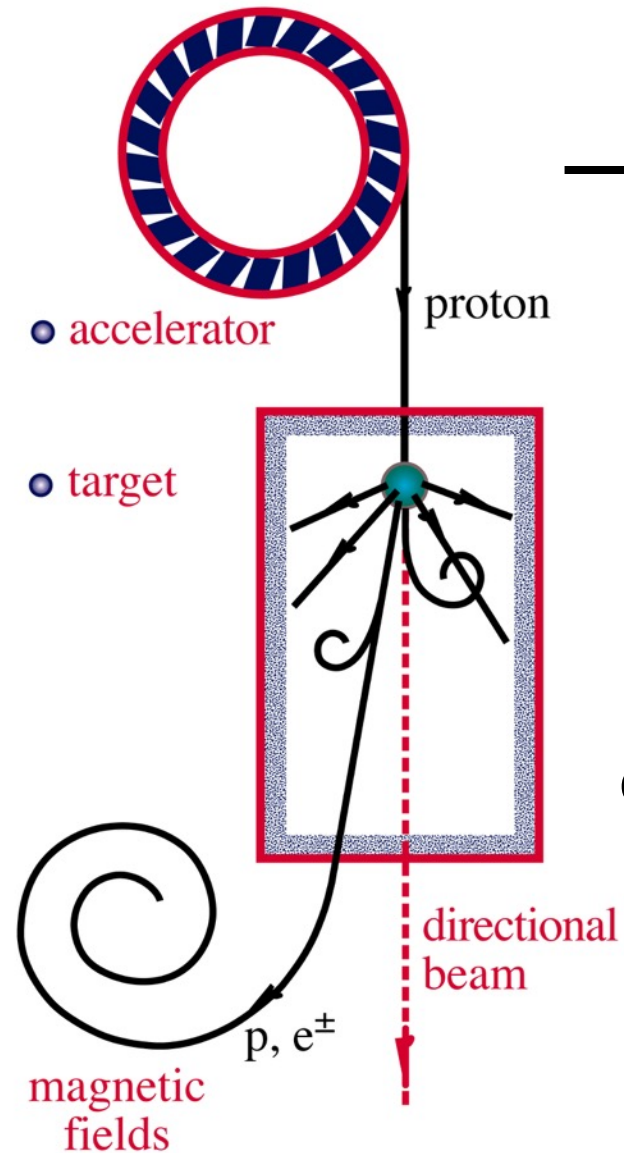
→ therefore, with $R_{\text{escape}} \sim R_{\text{target}}$

$$\tau_{\gamma\gamma} = \frac{\eta_{\gamma\gamma} \sigma_{\gamma\gamma}}{\eta_{p\gamma} \sigma_{p\gamma}} \frac{R_{\text{target}}}{R_{\text{escape}}} \tau_{p\gamma} \simeq 10^{-3} \tau_{p\gamma}$$

→ do not expect high energy gamma rays to accompany cosmic neutrinos

→ blazar jets are out

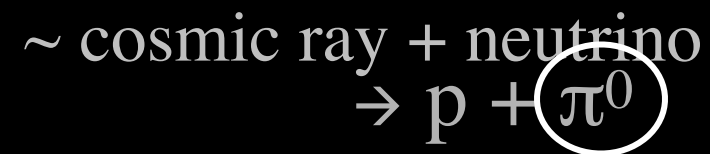
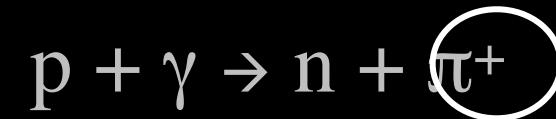
ν and γ beams : heaven and earth



ratio of
optical depths

where are the gamma
rays from π^0 ?

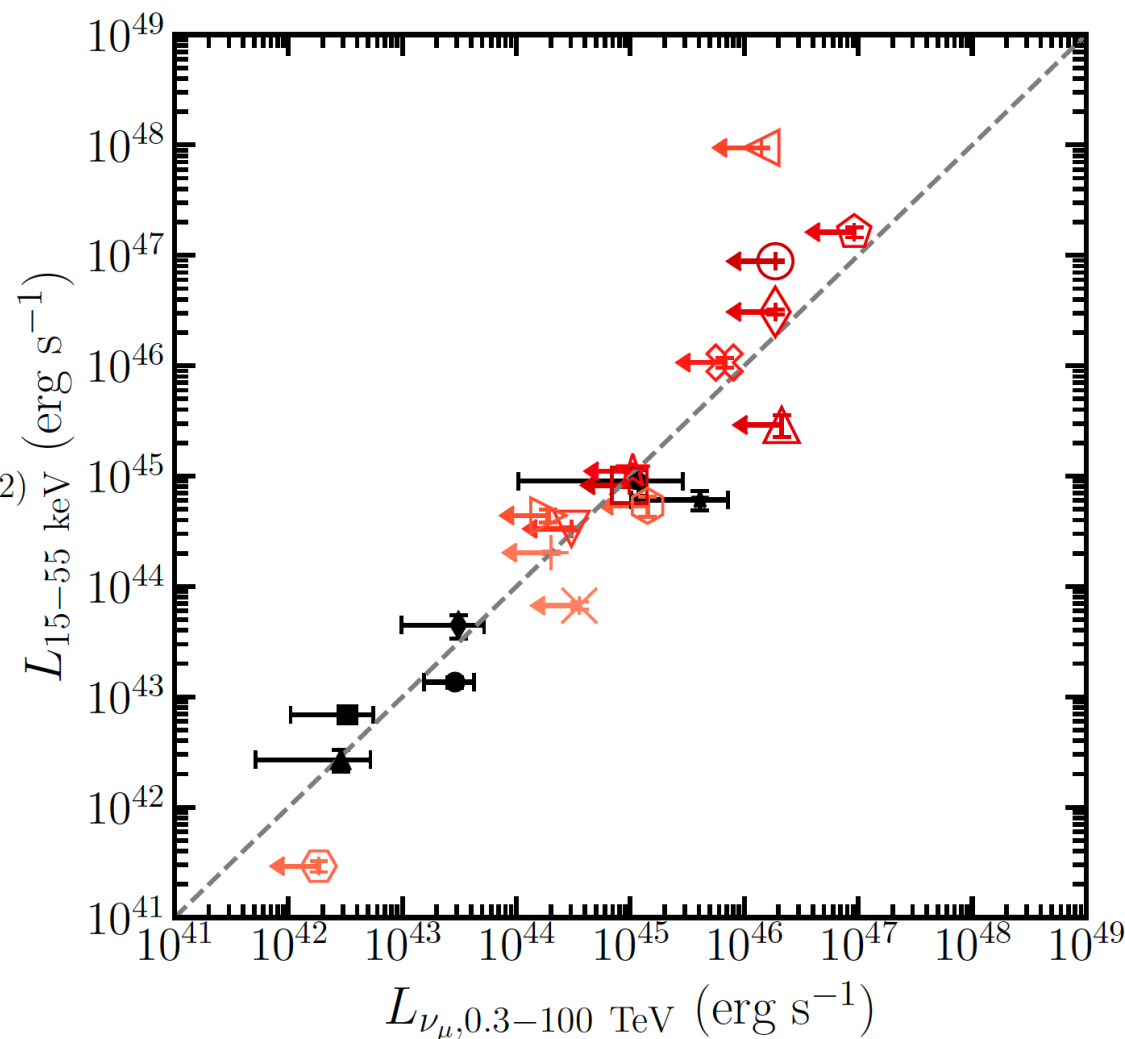
pionic gamma rays
lose energy in a
target that produces
neutrinos

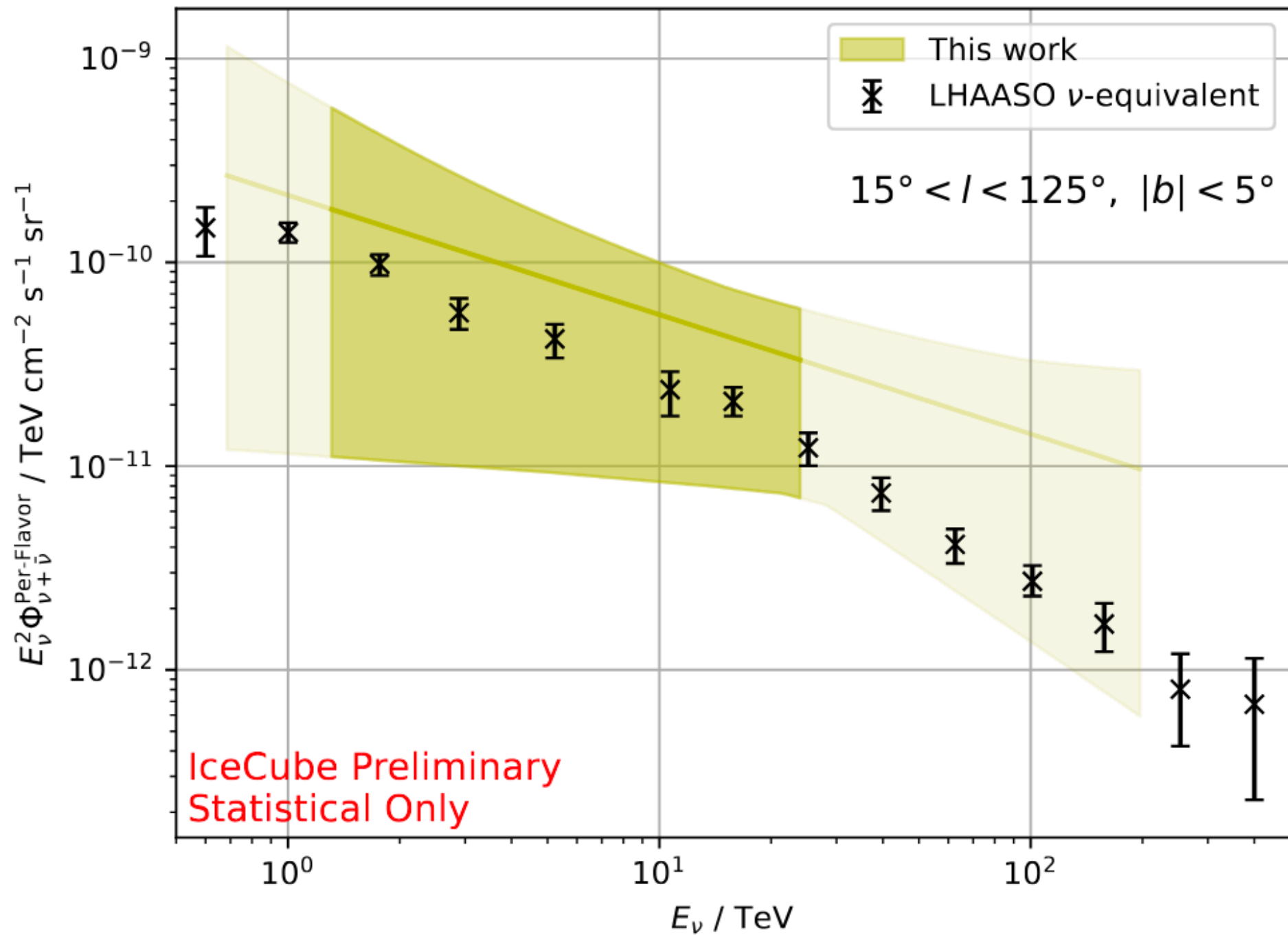


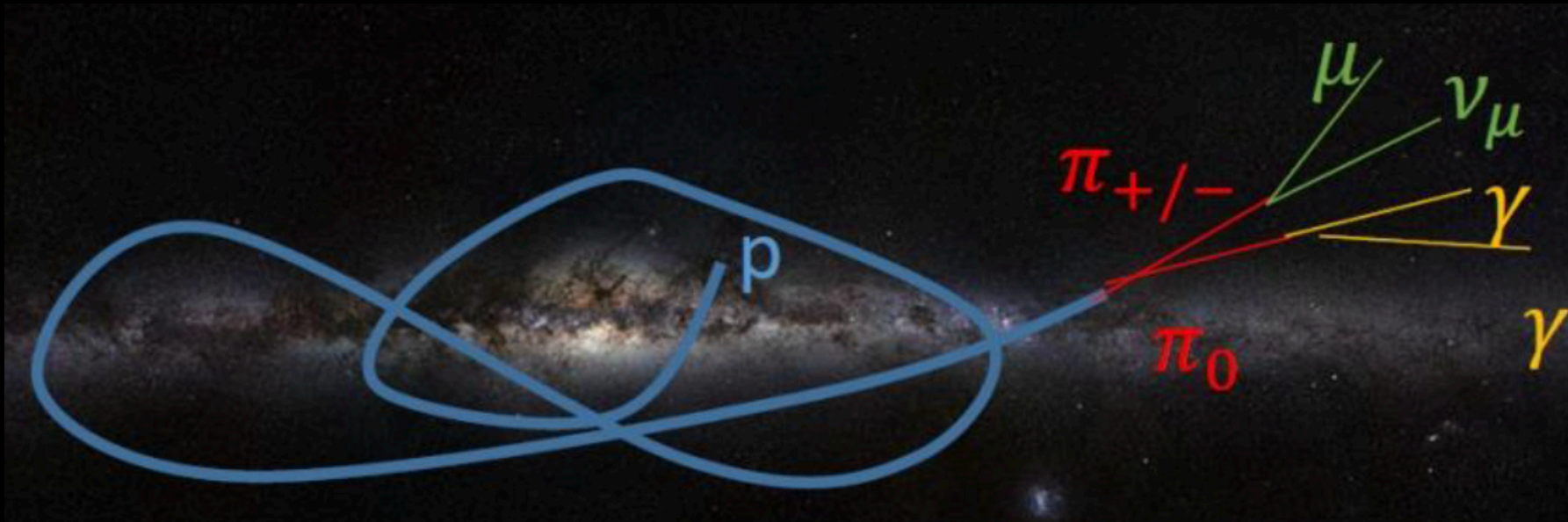
- hint from NGC 1068
- there is a correlation between the X-ray and neutrino flux
- select active galaxies with large X-ray fluxes

⬛	NGC1068
⬛	NGC4151
⬛	NGC3079
⬛	CGCG420-015
⬛	TXS0506+056
⬛	GB6J1542+6129
⬛	3C454.3(5)
⬛	S20109+22(2)
⬛	PKS1441+25
⬛	MG2J201534+3710(2)
⬛	S30458-02
⬛	OJ287(5)
⬛	Ton599(2)
⬛	PG1218+304
⬛	CTA102
⬛	4C+01.28
⬛	3C66A
⬛	1H1720+117
⬛	1ES0806+524
⬛	1ES0647+250

Emma Kun



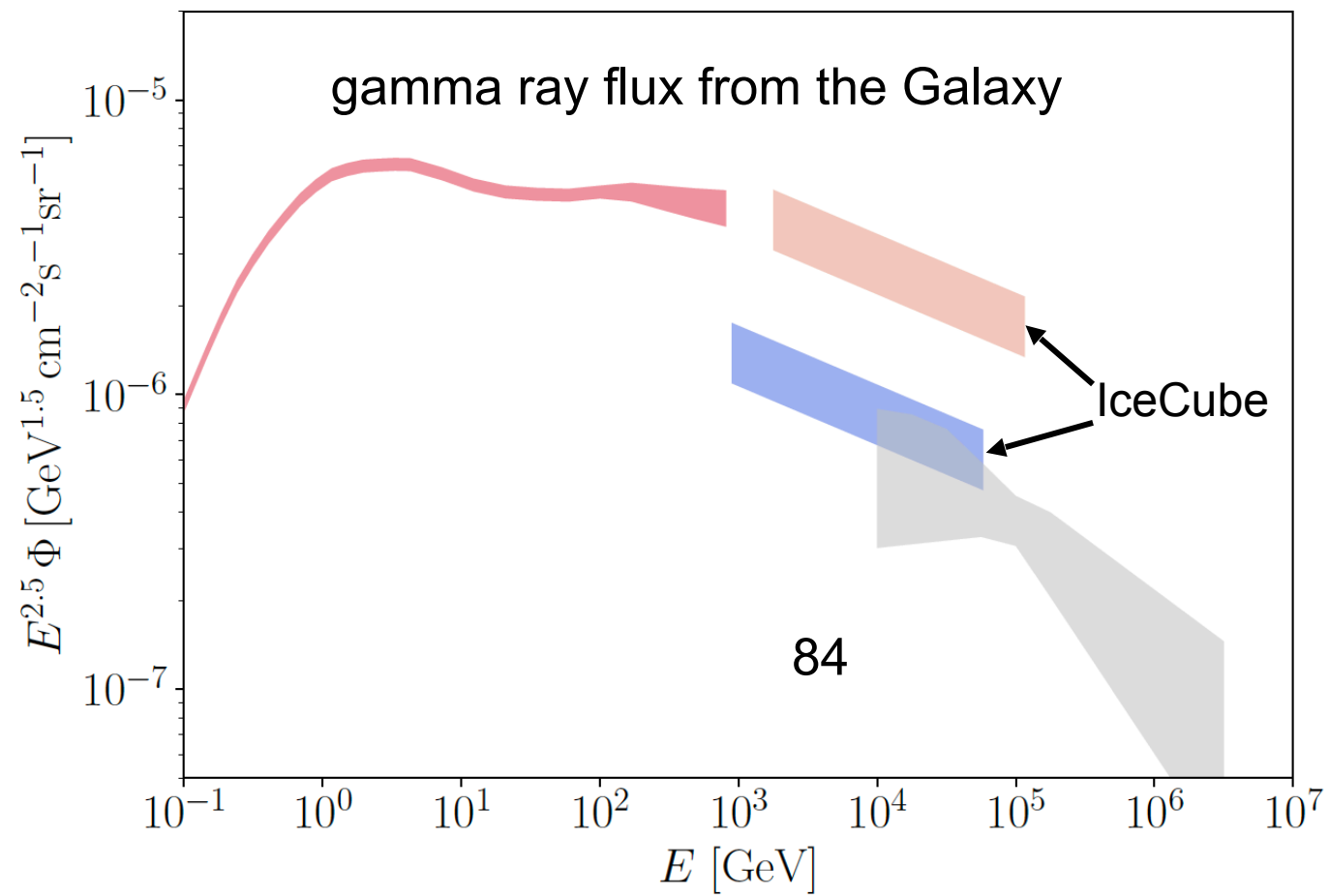


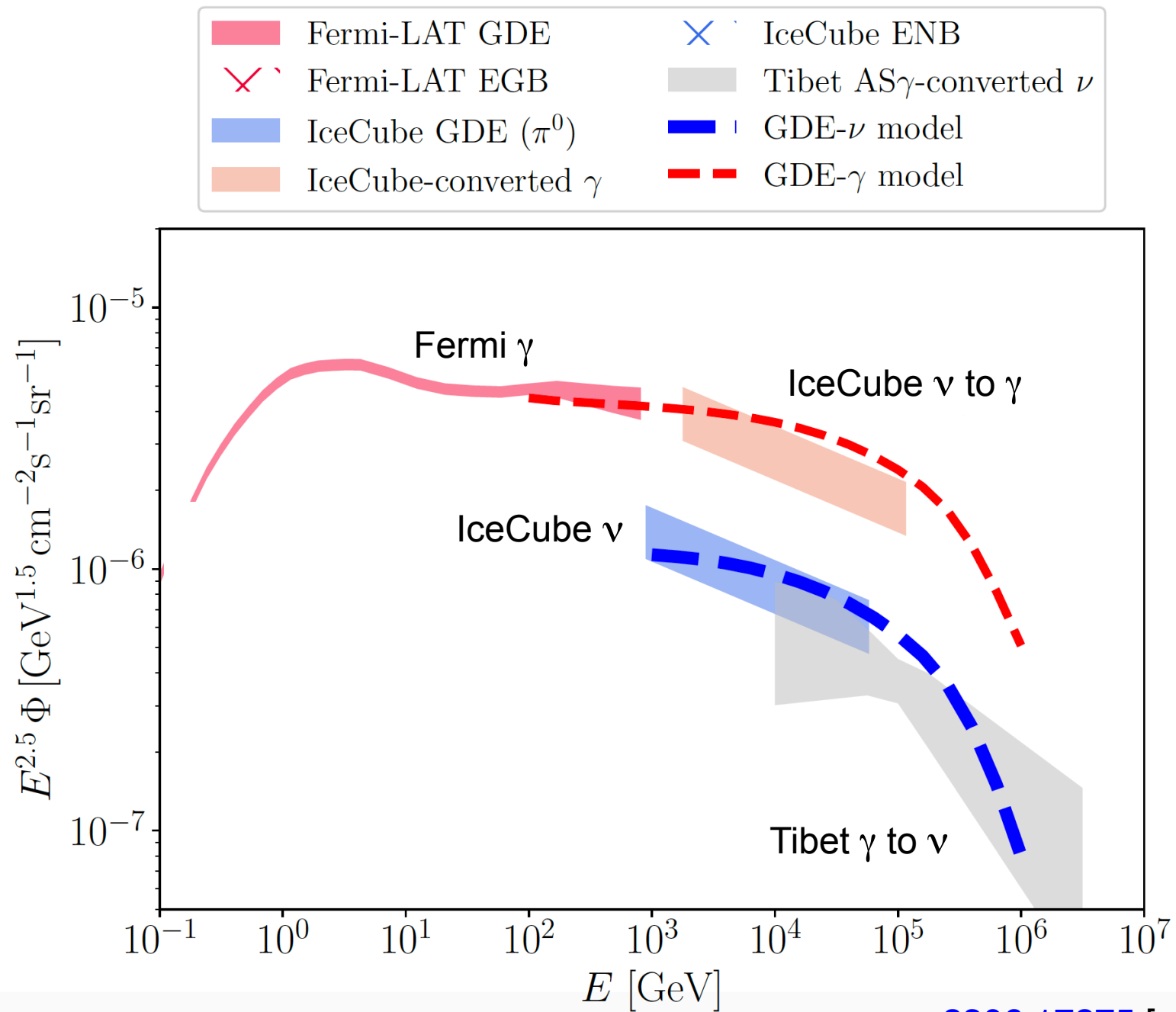


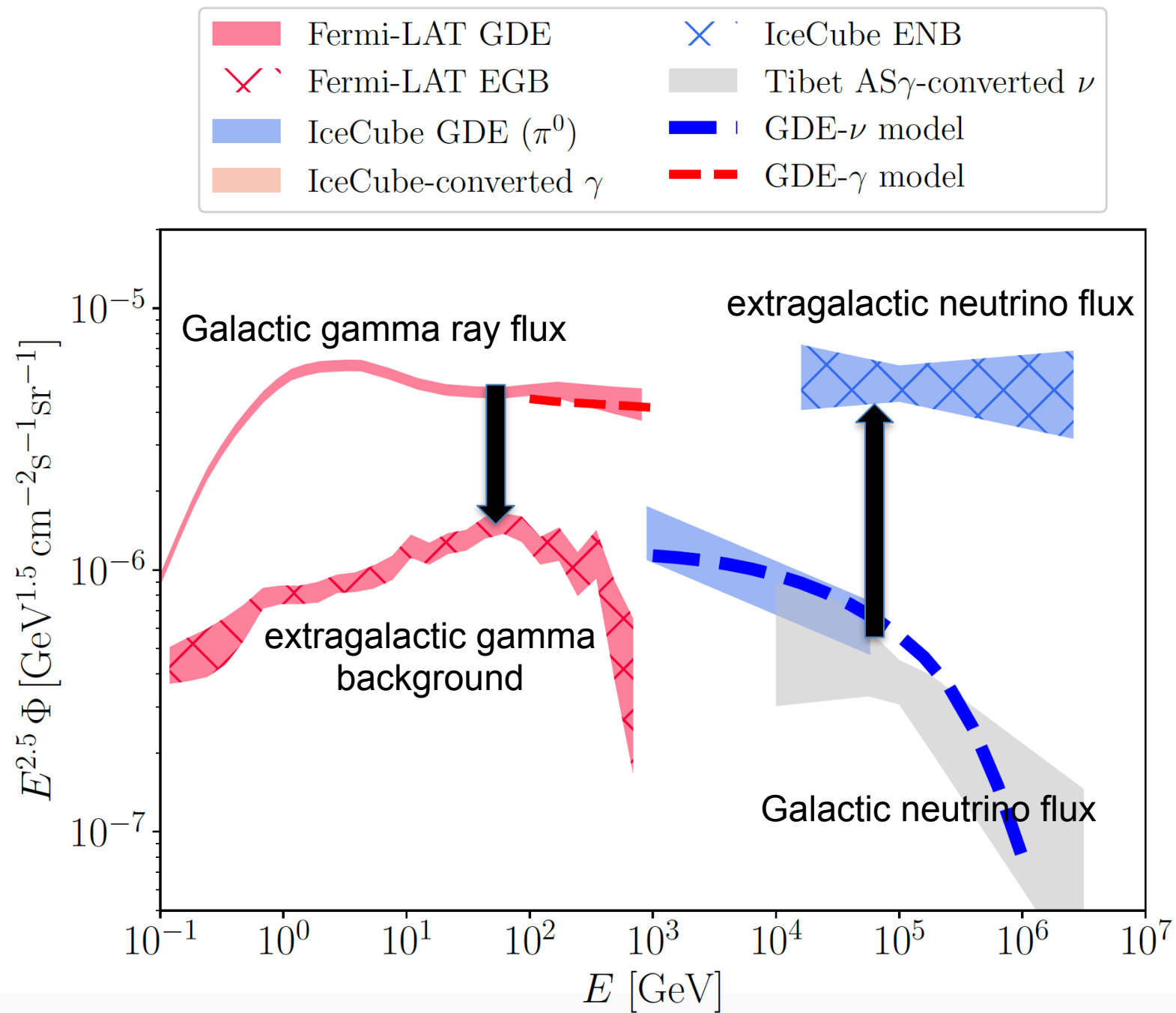
neutrinos produced in Galactic cosmic rays
interactions with interstellar medium

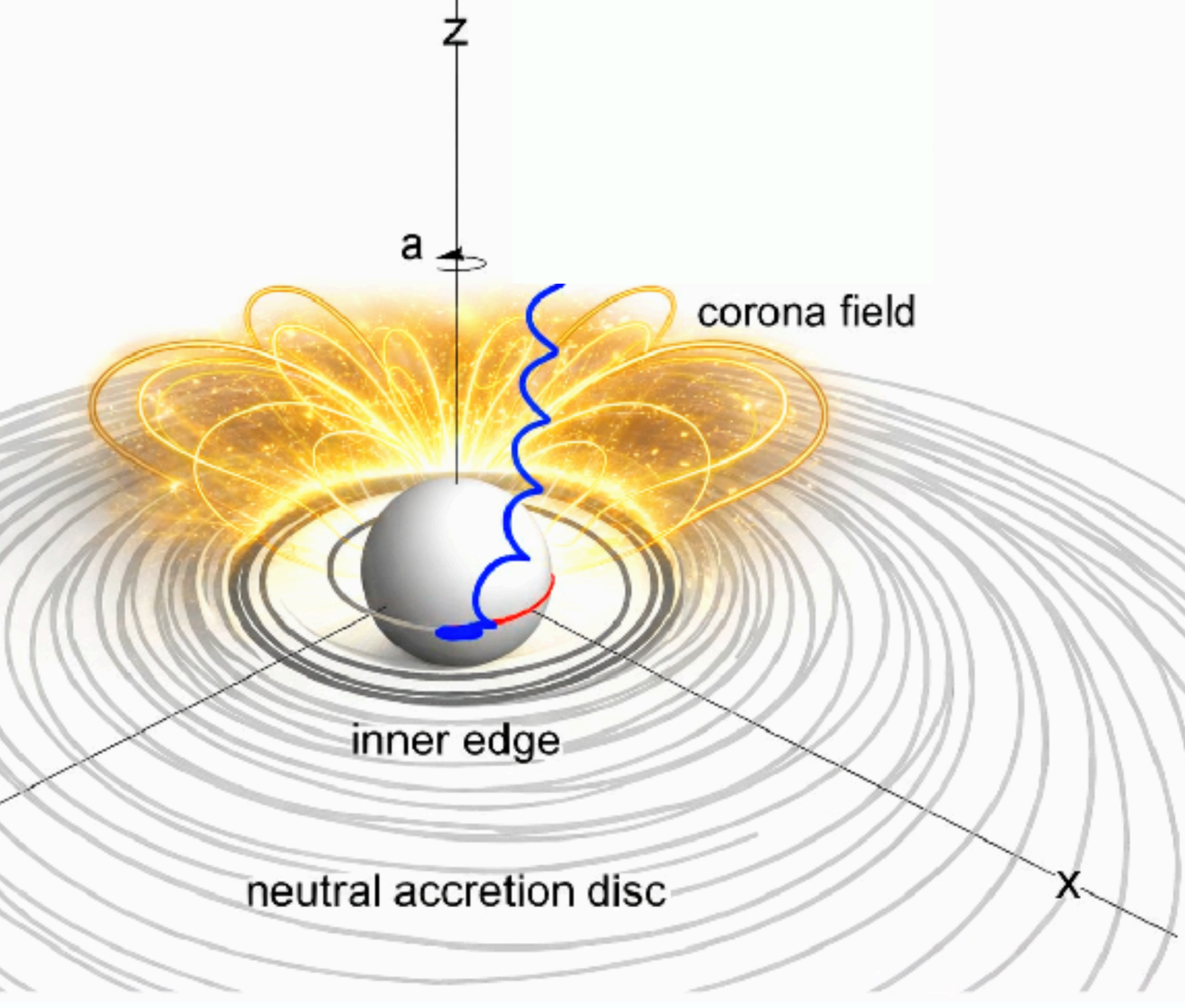
unresolved sources?

- Tibet AS γ -converted ν
- IceCube GP (π^0)
- Fermi-LAT GDE
- IceCube-converted γ









the accretion disk taps the gravitational energy of the black hole very efficiently producing radiation with accretion rate

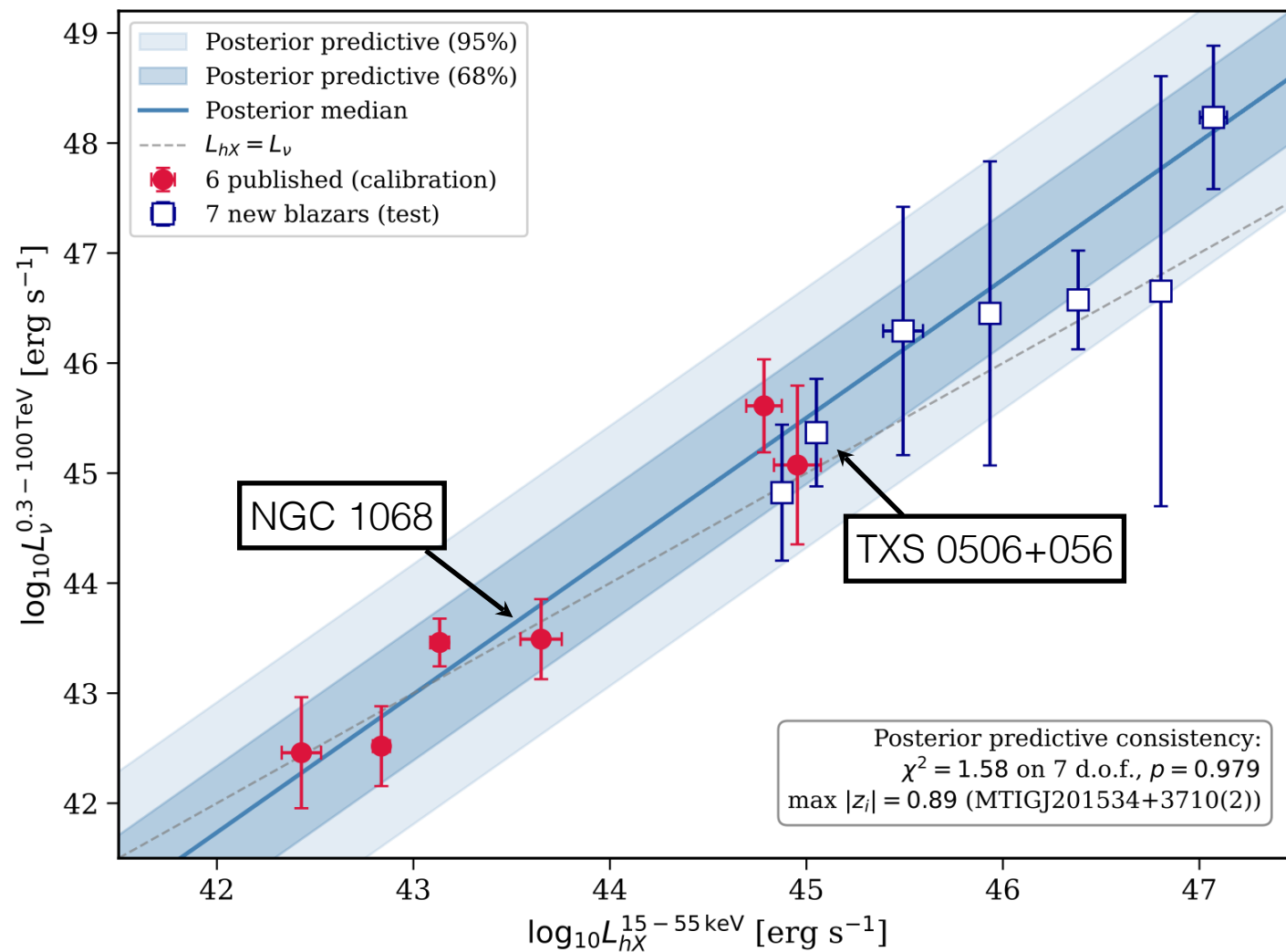
velocity of particle falling into a black hole

magnetic reconnection

M 87



neutrino-X-ray correlation ?

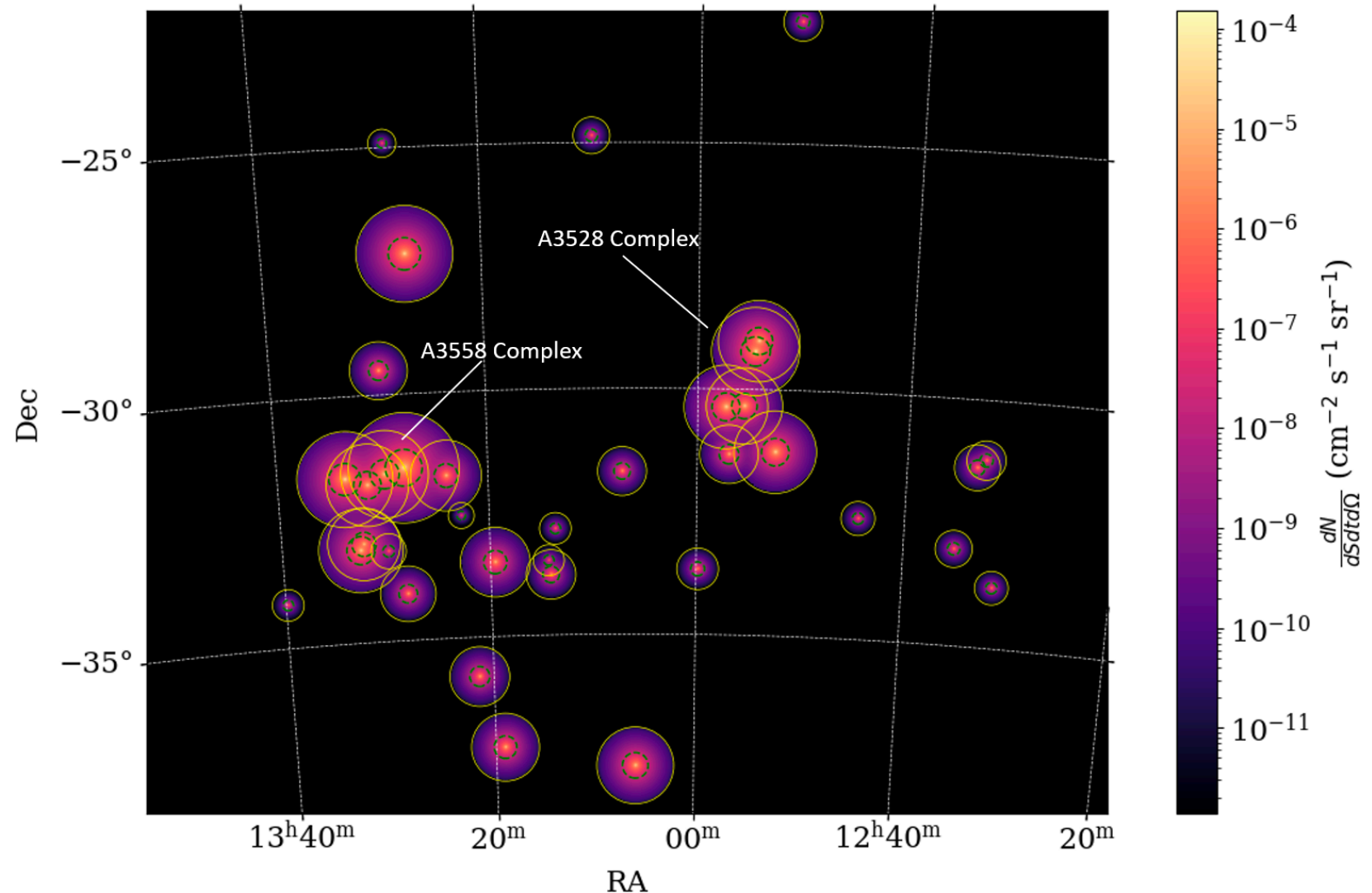


solution to the extragalactic cosmic ray problem?

clusters of superclusters

- neutrinos produced in individual active galaxies
- higher energy cosmic rays produced over the larger complex à la Hillas
- neutrino fluxes lower because of low target densities of larger scales
- need the next-generation detectors

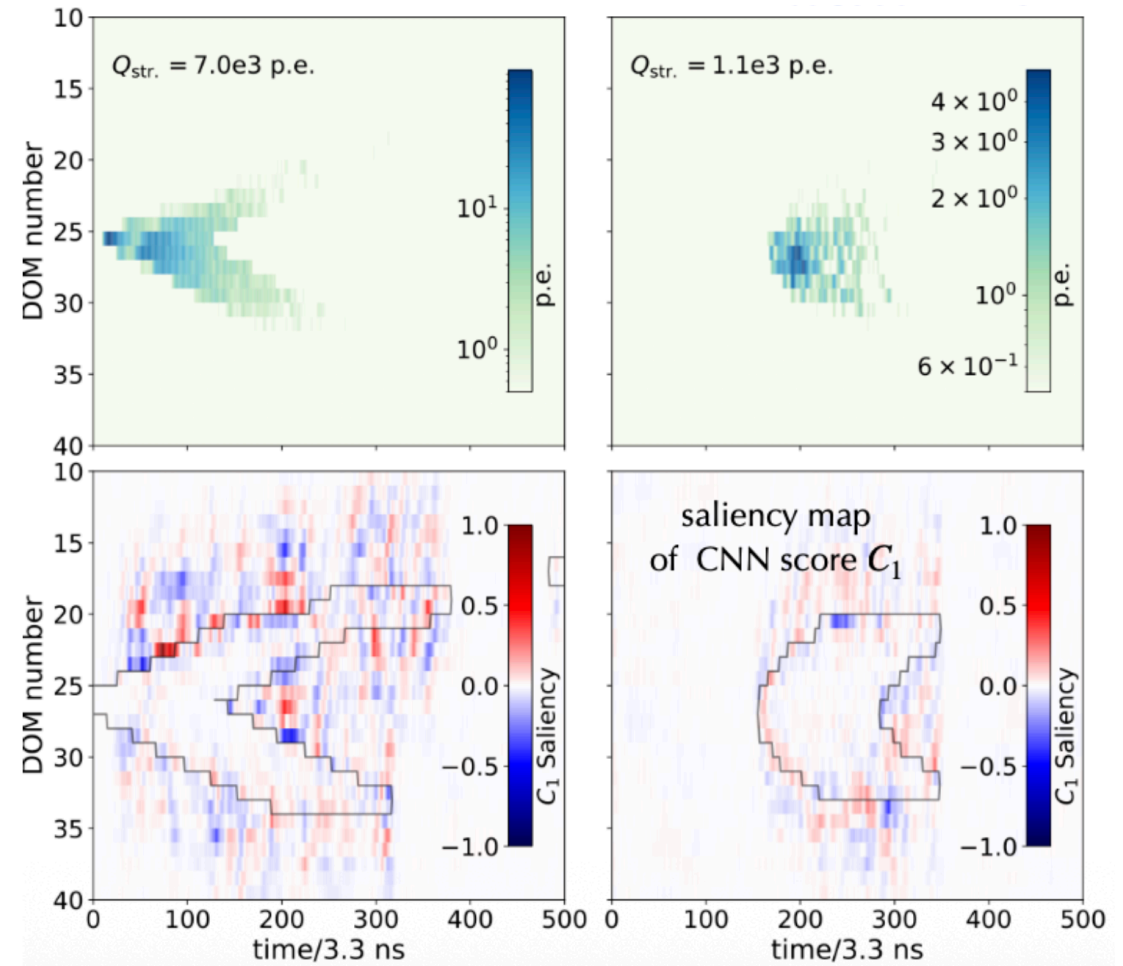
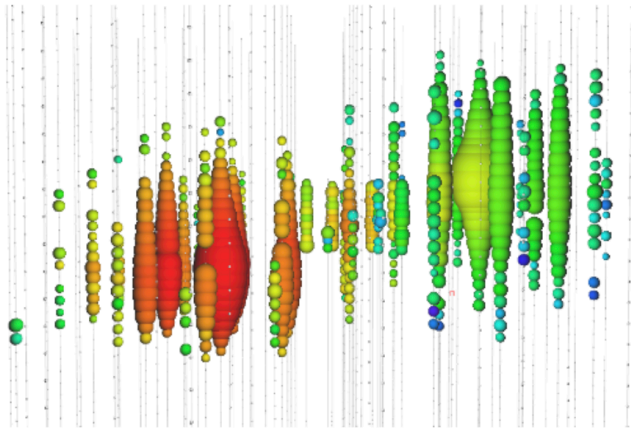
the Shapley cluster of superclusters



Identified through double cascade signature

- **2 candidates in 7.5 years** of High Energy Starting Events (HESE) $\rightarrow 2.8\sigma$
- 7 candidates in 10 years of data selected for high-Q strings via machine learning $\rightarrow 5\sigma$
- 9 candidates in 11.4 years of MESE (70% purity)

Charged-current ν_τ



Best fit model: Broken Power Law, followed by SPL+ Bump and then LogParabola.
 We reject SPL with respect to BPL with 4.7σ with MESE, with a spectral break at ~ 30 TeV.

IceCube Collaboration, Phys. Rev. Lett. 136 (2026) 121002

