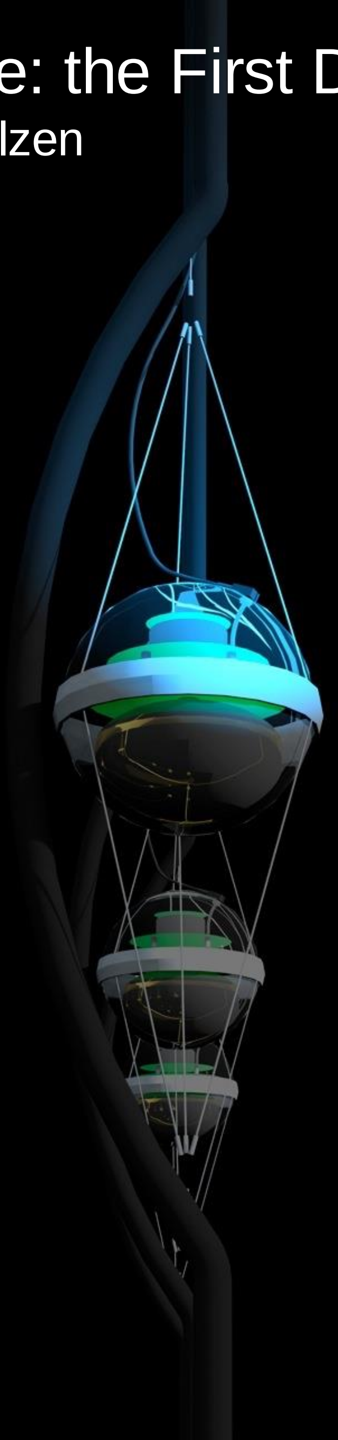
IceCube: the First Decade of Neutrino Astronomy

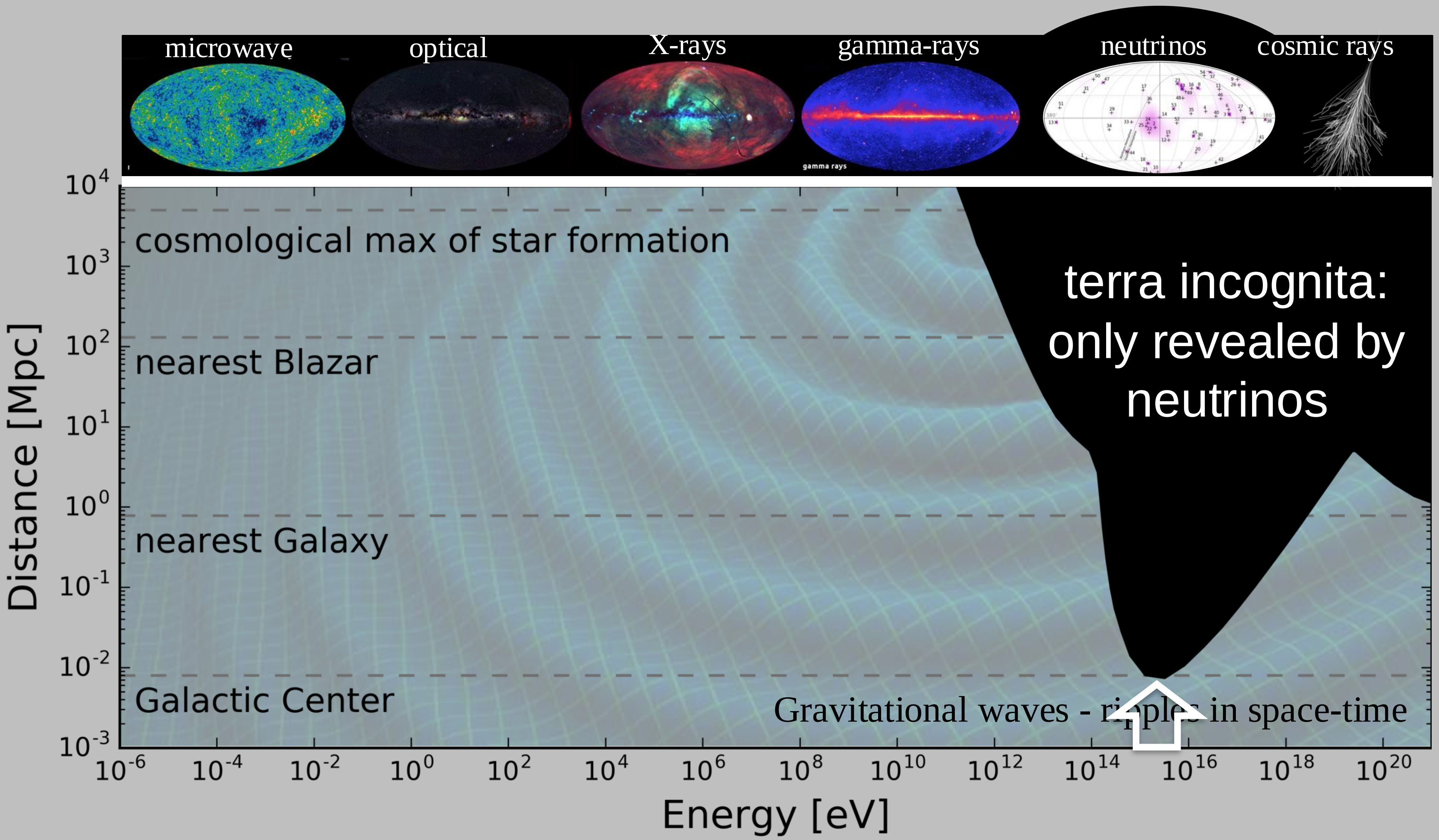
francis halzen



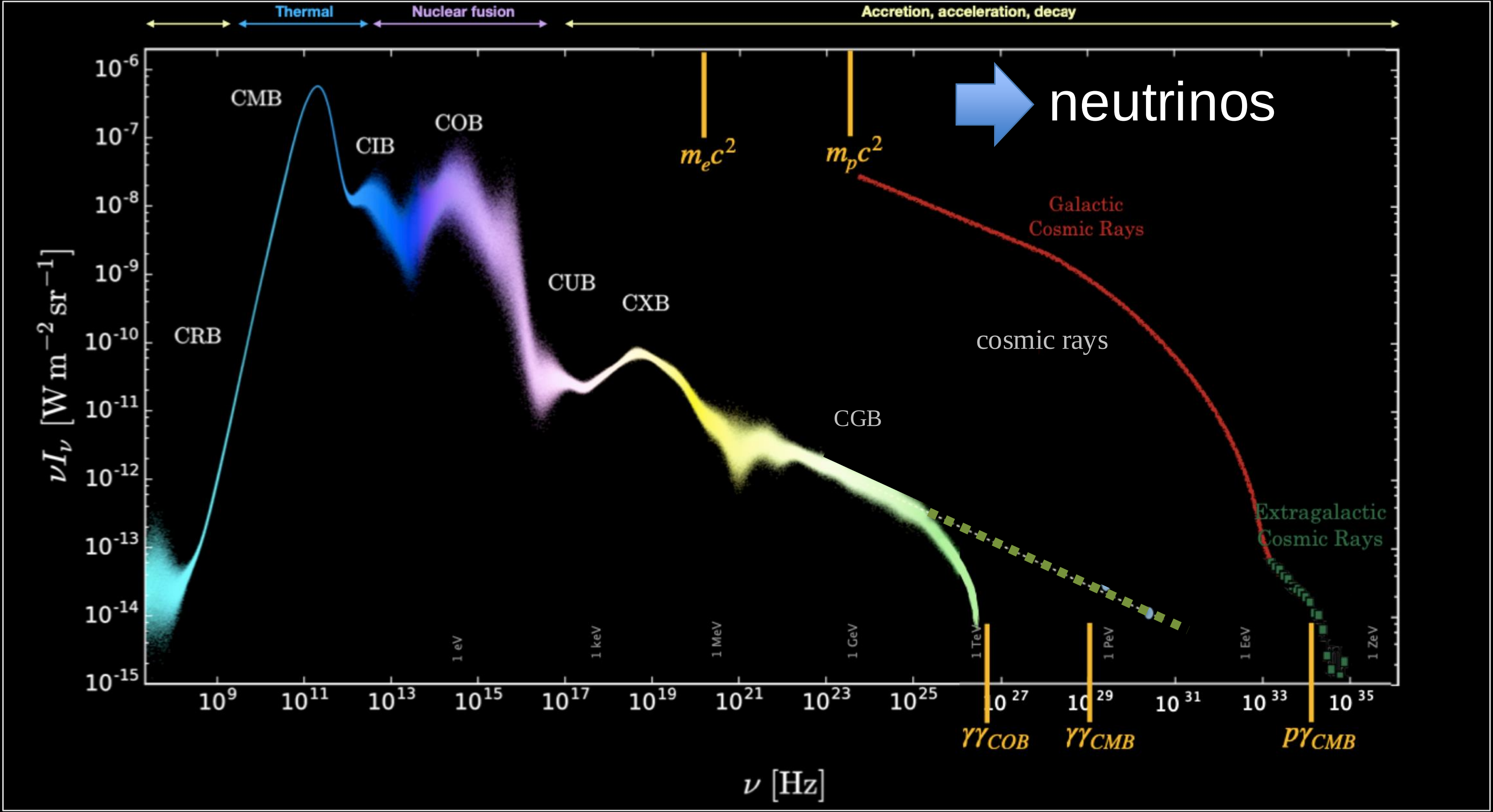
- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- and the answer is: supermassive black holes at the cores of active galaxies ?

IceCube.wisc.edu

highest energy “radiation” from the Universe: cosmic rays, mostly protons

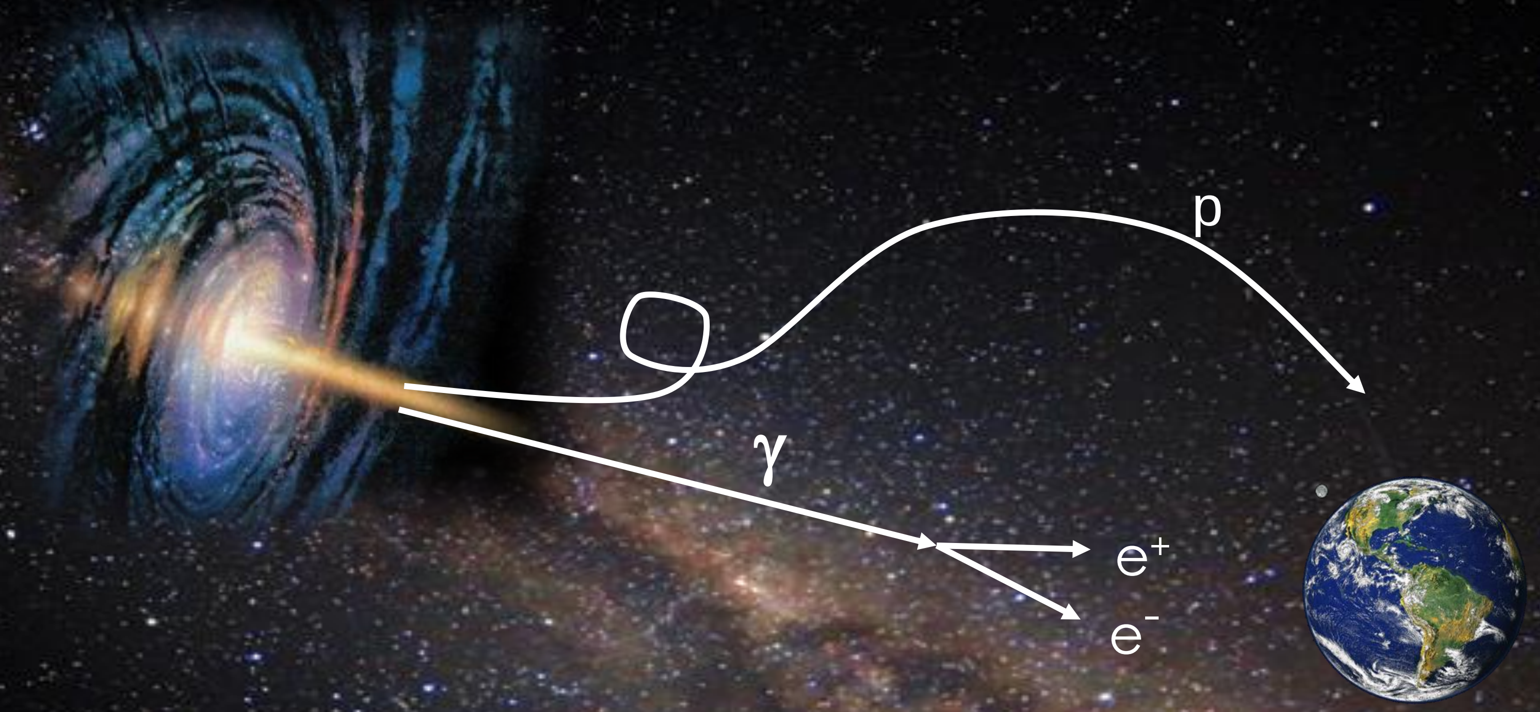


the Extreme Universe is opaque to gamma rays beyond our Galaxy photon energy in the Universe as a function of color



in the extreme universe neutrinos are unique astronomical messengers

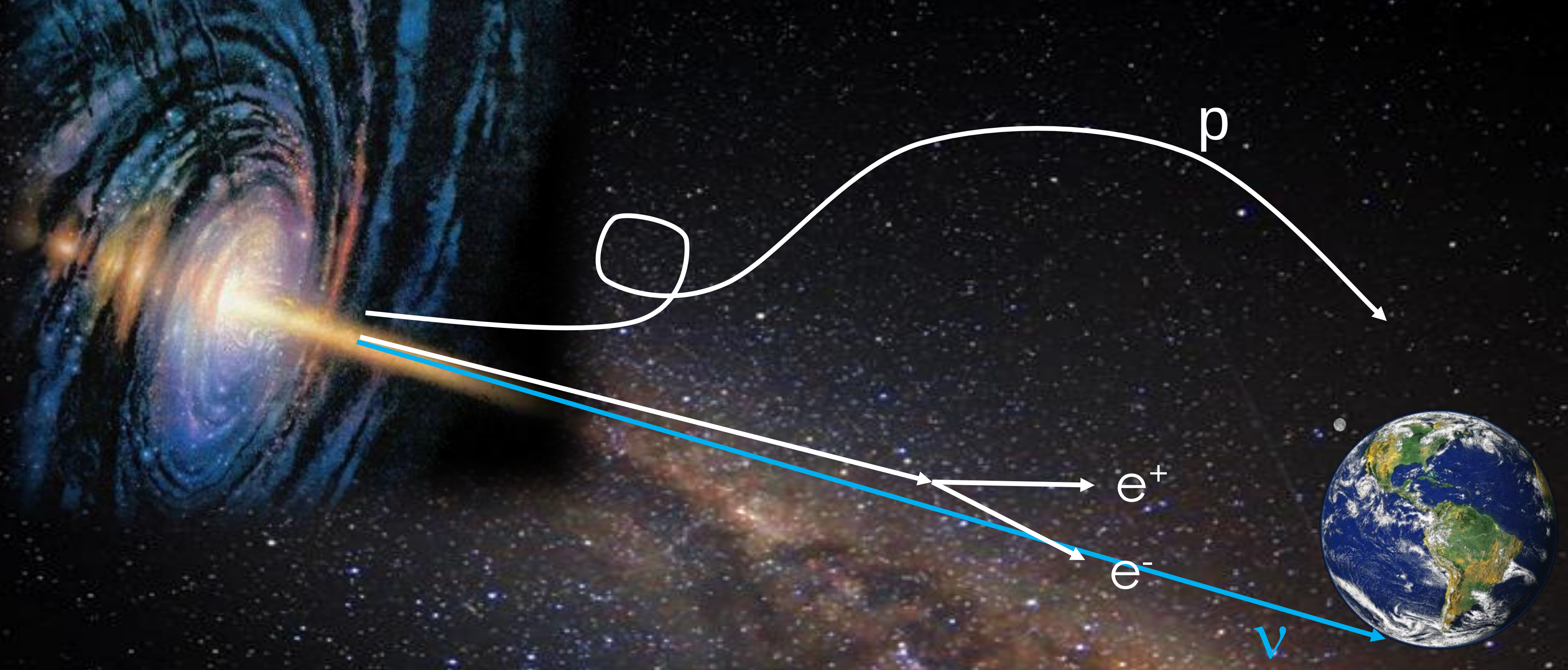
the opaque extreme Universe:



$$\gamma + \gamma_{EBL} \rightarrow e^{+} + e^{-}$$

- > PeV photons interact with extragalactic background light (CMB and higher energy photons) before reaching our telescopes
- their energy appears reprocessed in GeV photons, or beyond

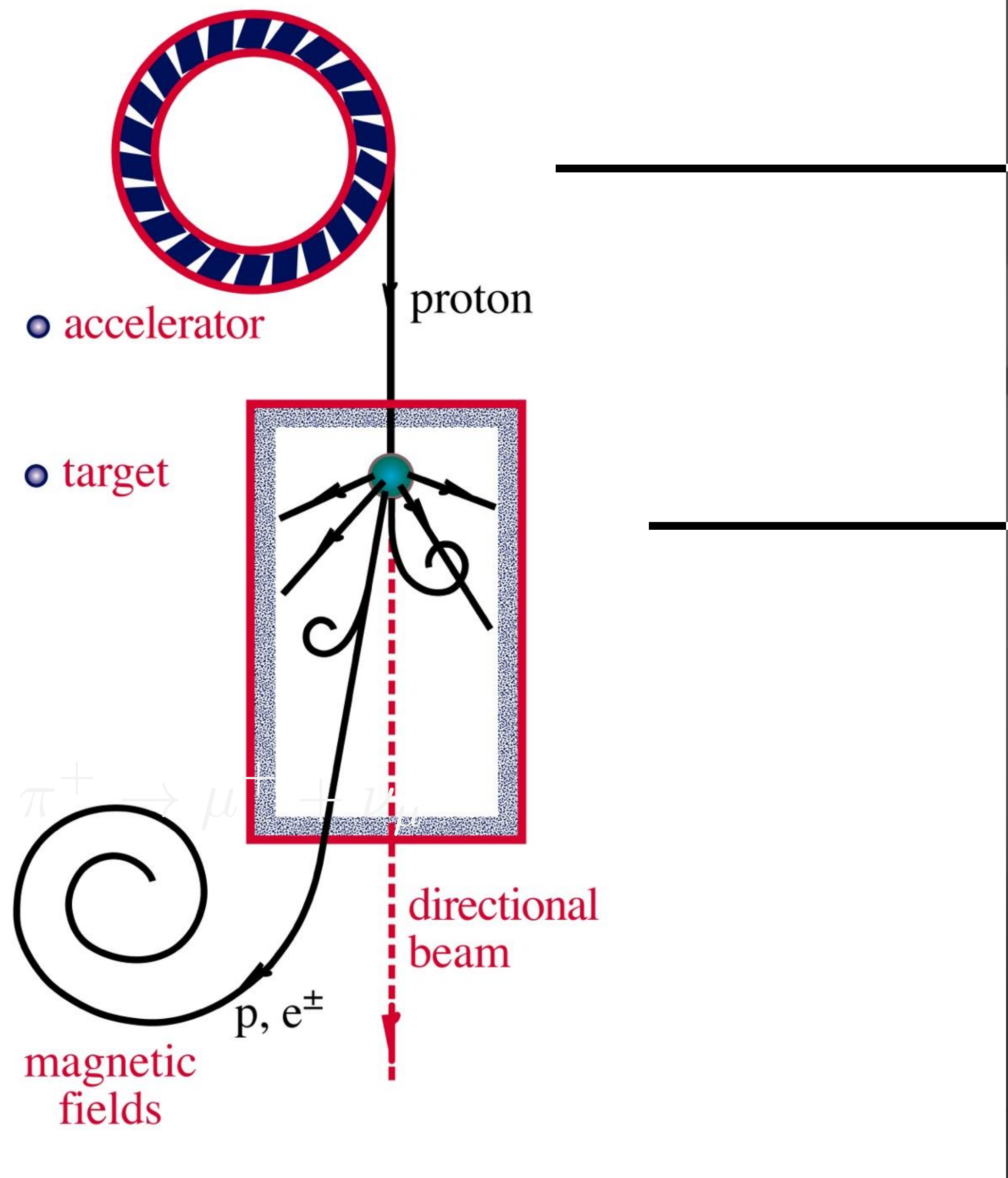
neutrinos: perfect messengers



- electrically neutral
- massless (in this talk)
- like a photon but weakly interacting
- track cosmic ray sources

- … but difficult to detect

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

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

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

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

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

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

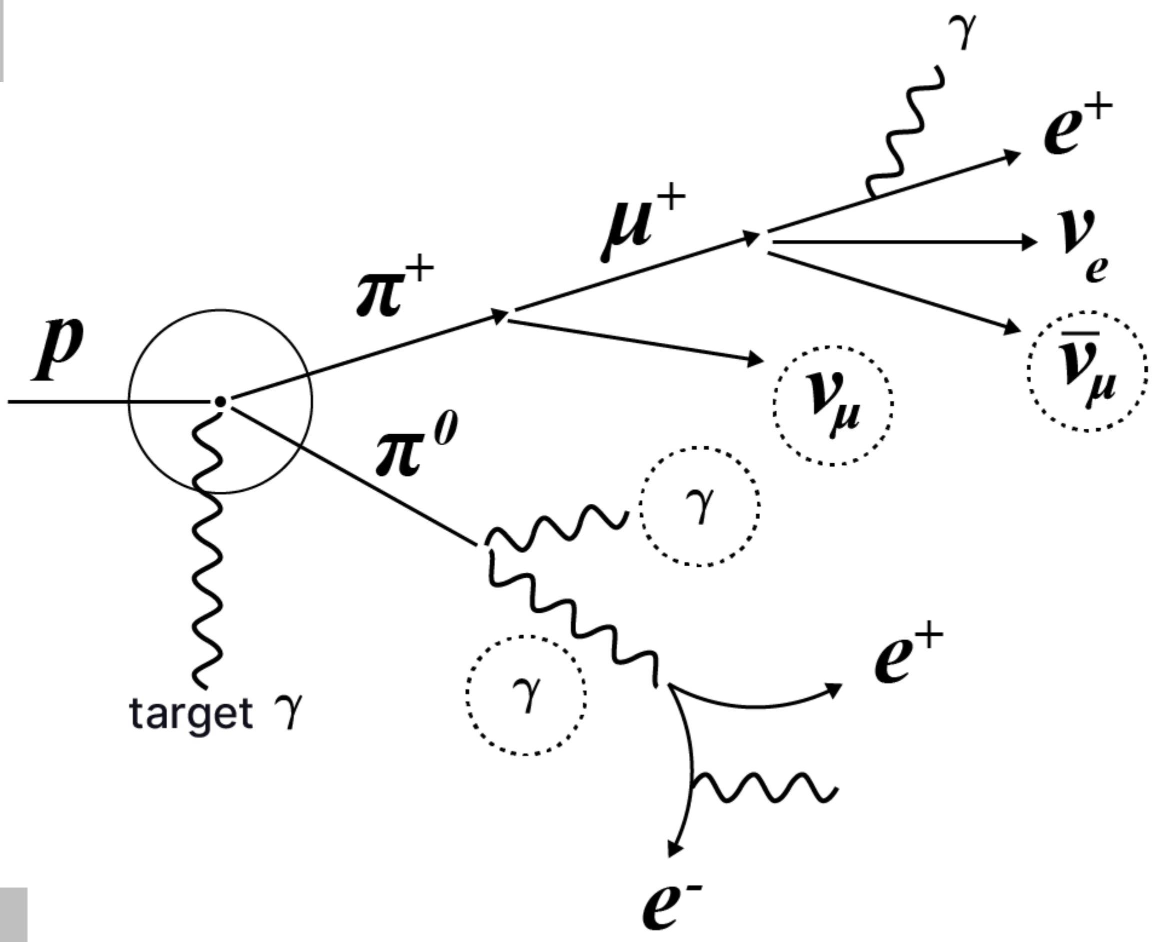
black hole accelerating protons submersed in a target of radiation produce pions

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

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

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

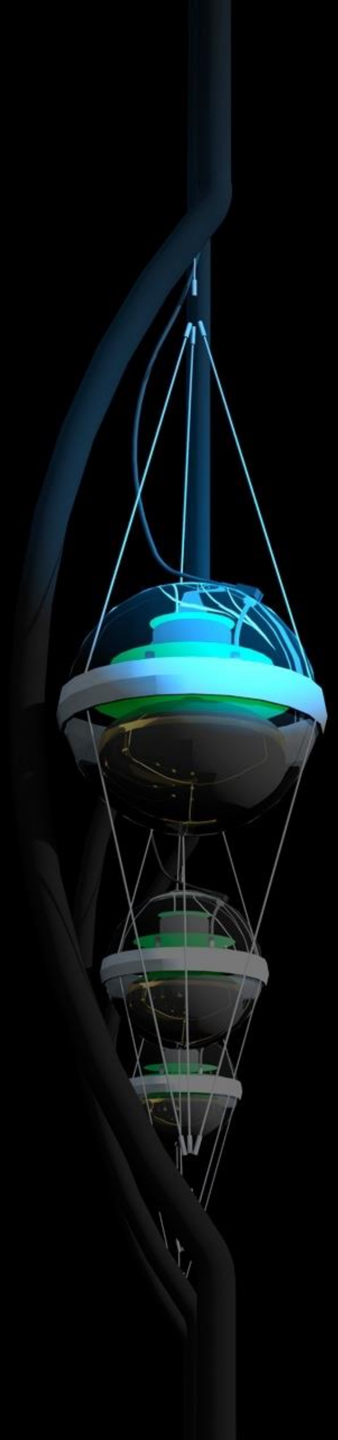
cosmic ray sources: a gamma ray for every neutrino



neutrino sources are cosmic ray sources

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

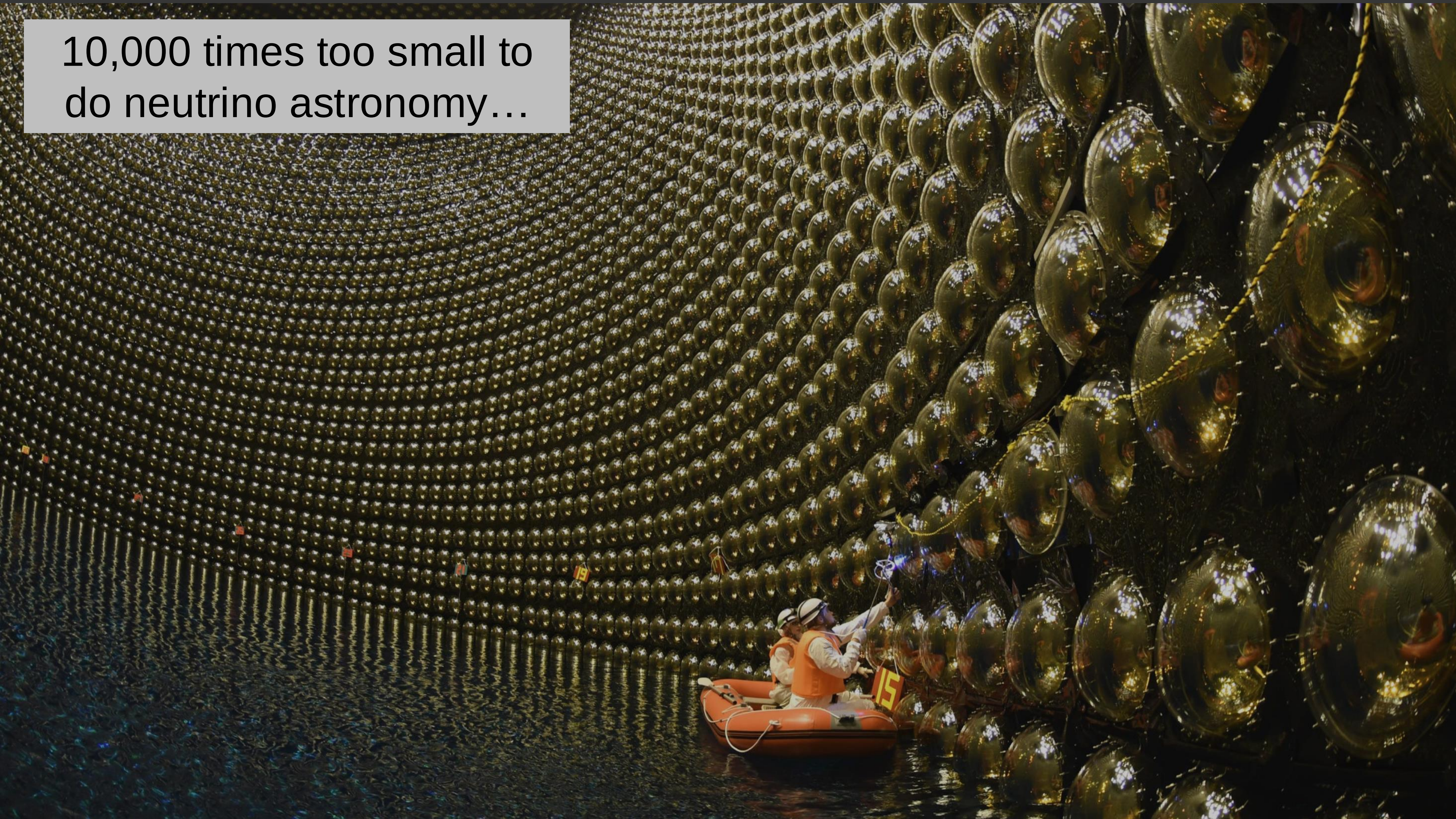
$$E_\gamma = 2\, E_\nu$$



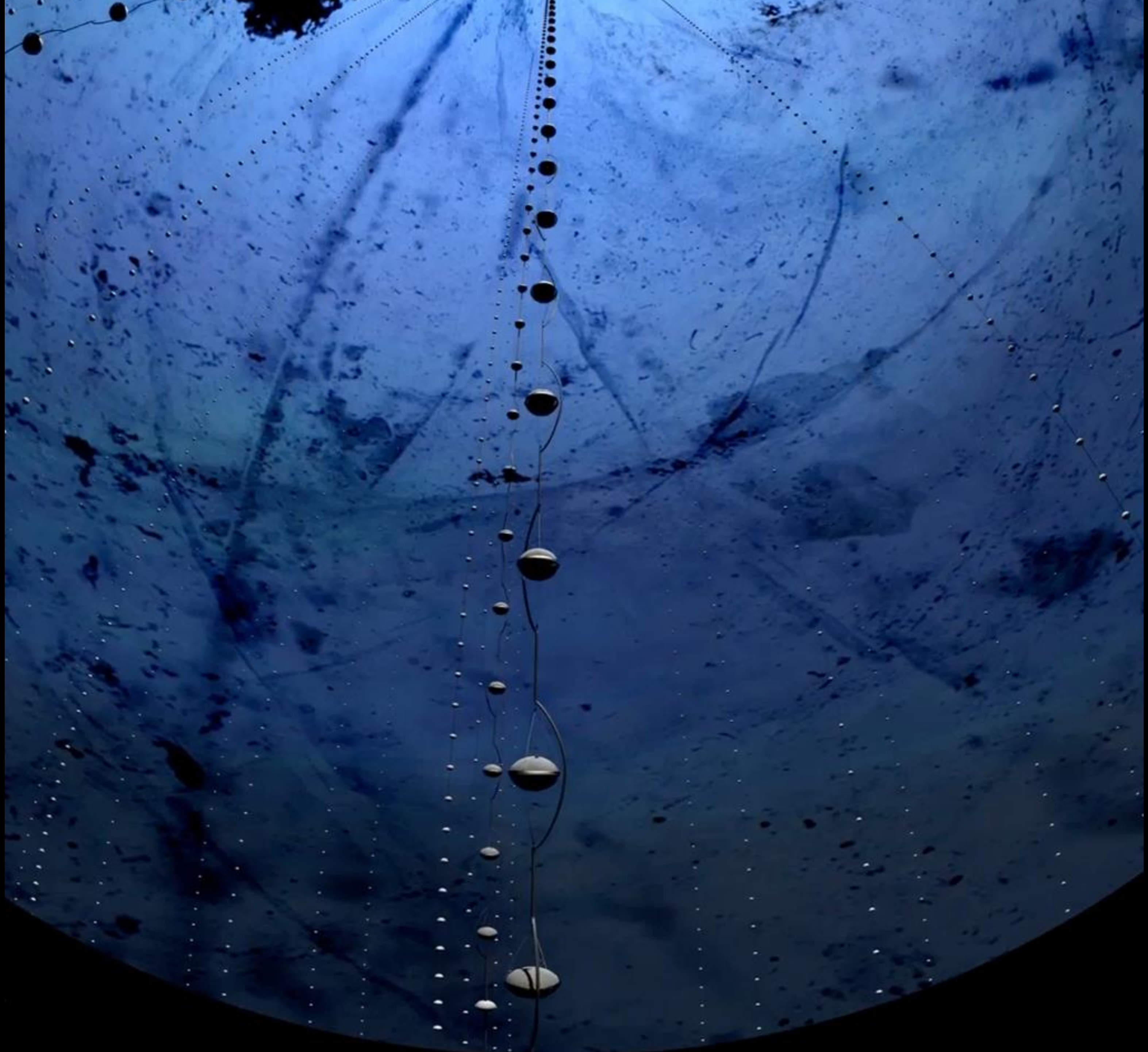
- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- and the answer is: supermassive black holes at the cores of active galaxies

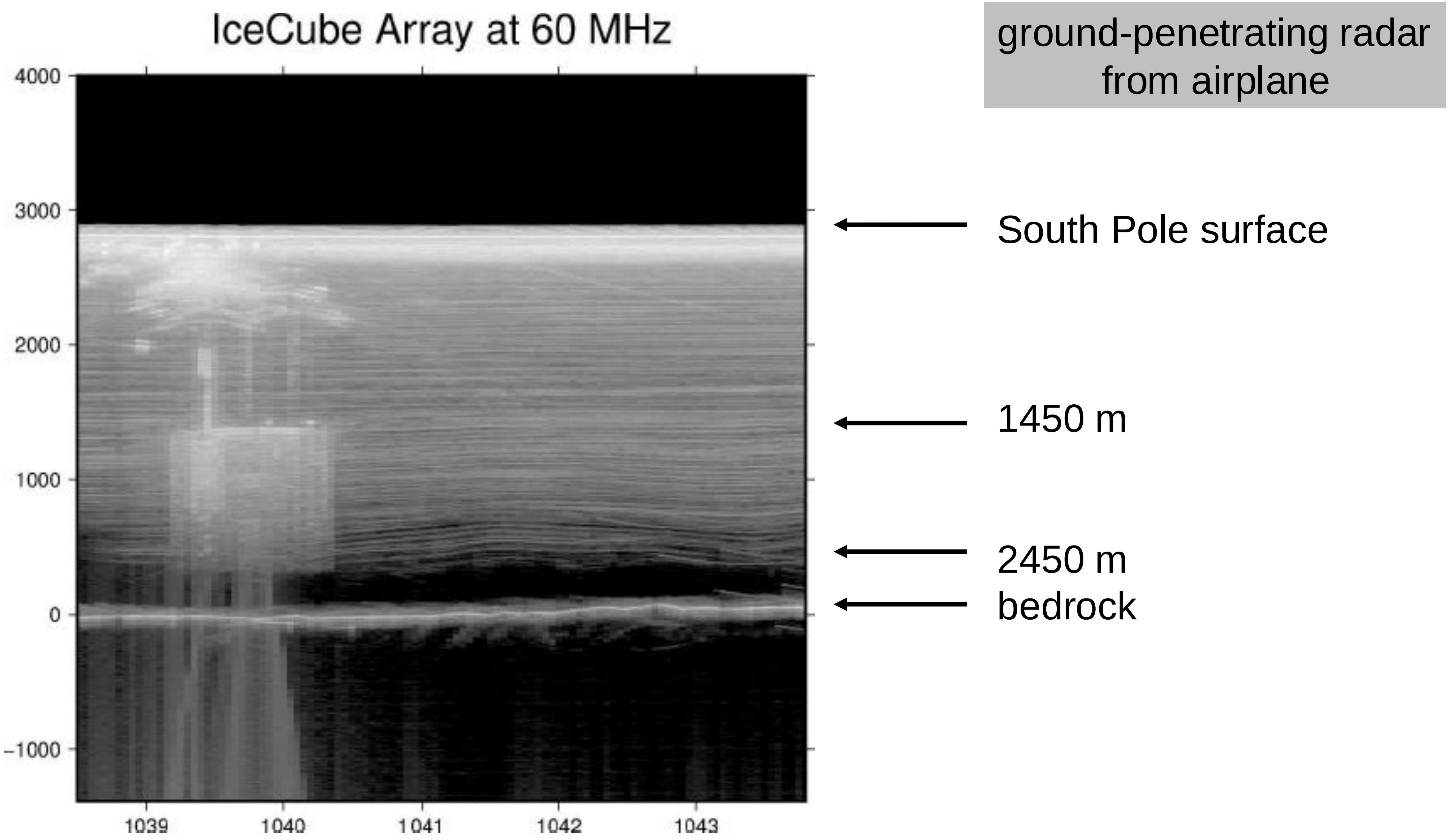
IceCube.wisc.edu

10,000 times too small to do neutrino astronomy…

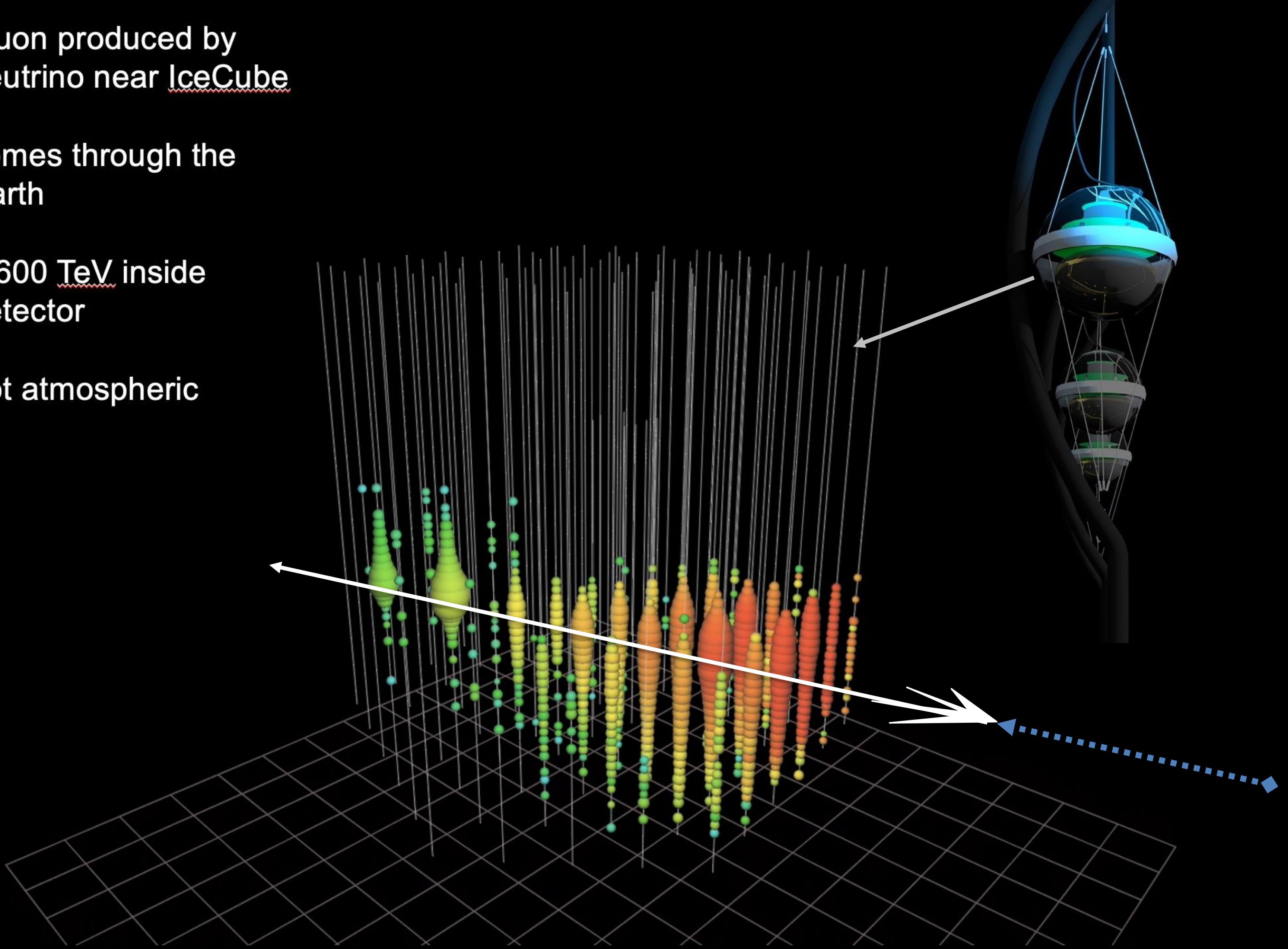


IceCube:
5160 photomultipliers
instrument one km^3 of
Antarctic ice between
1.4 and 2.4 km depth
as a Cherenkov detector



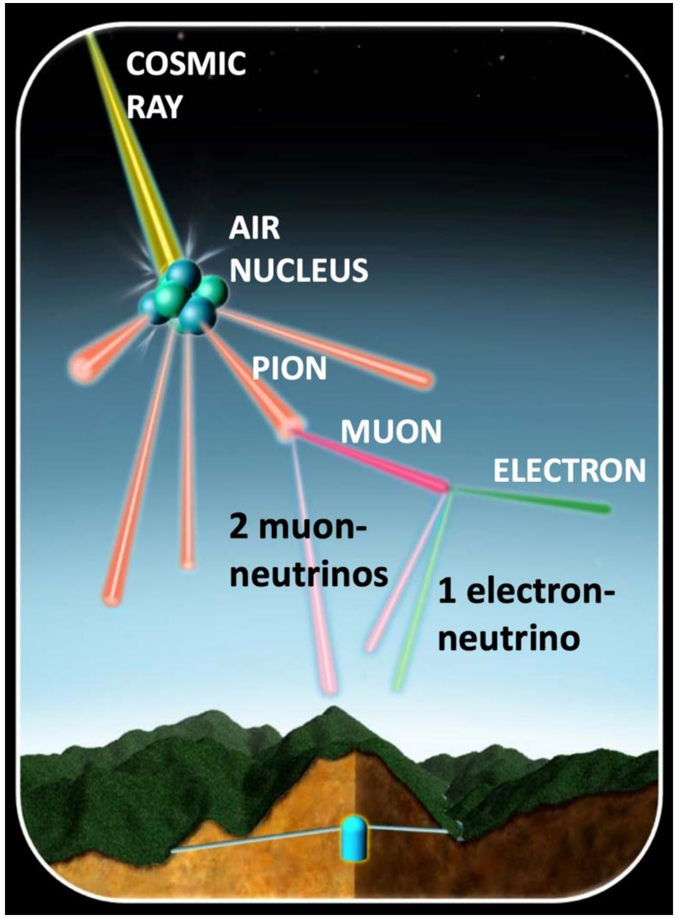

IceCube Array at 60 MHz
4000
3000
2000
1000
0
−1000
1039
1040
1041
1042
1043
ground-penetrating radar from airplane
South Pole surface
1450 m
2450 m
bedrock

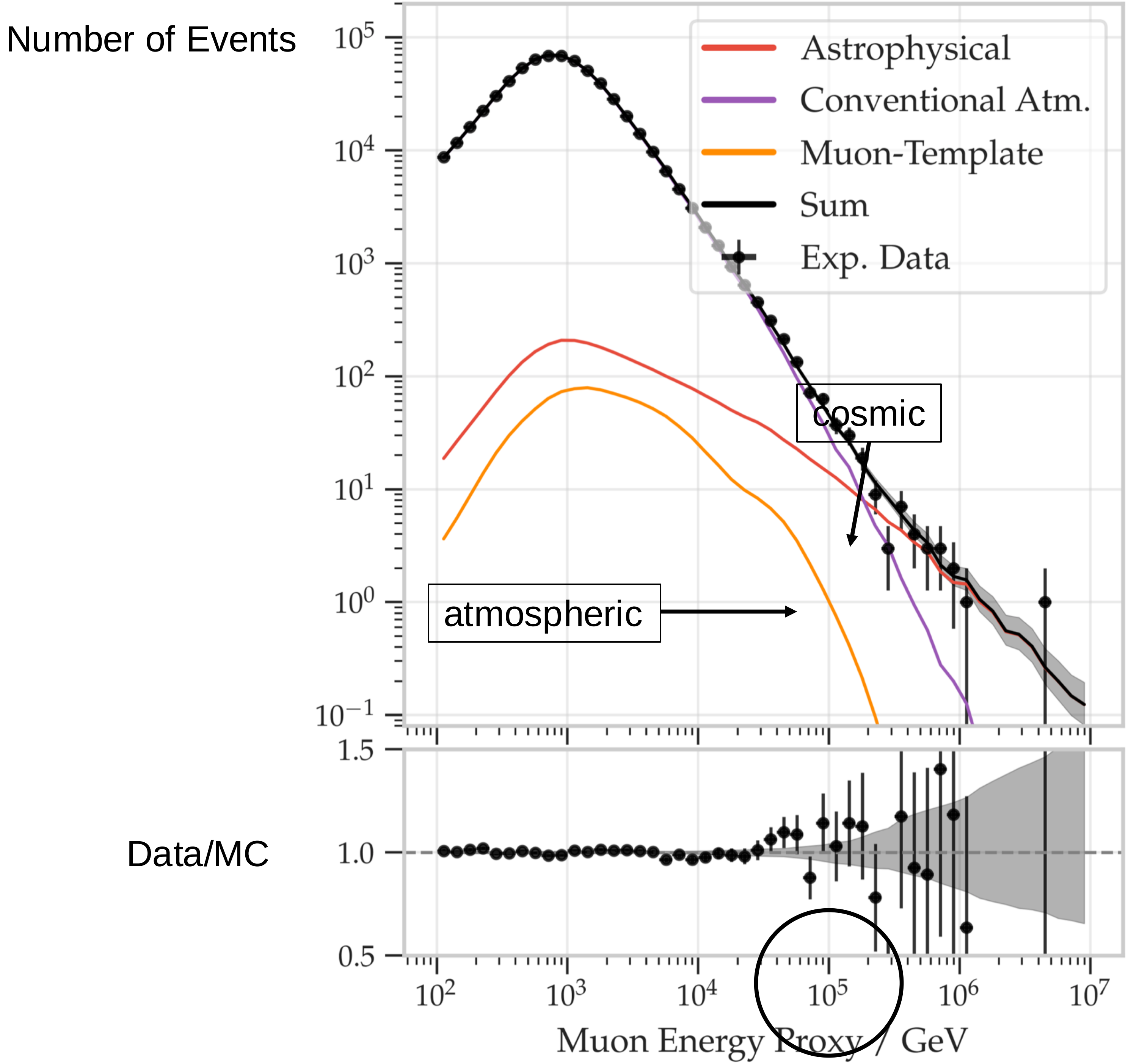
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric

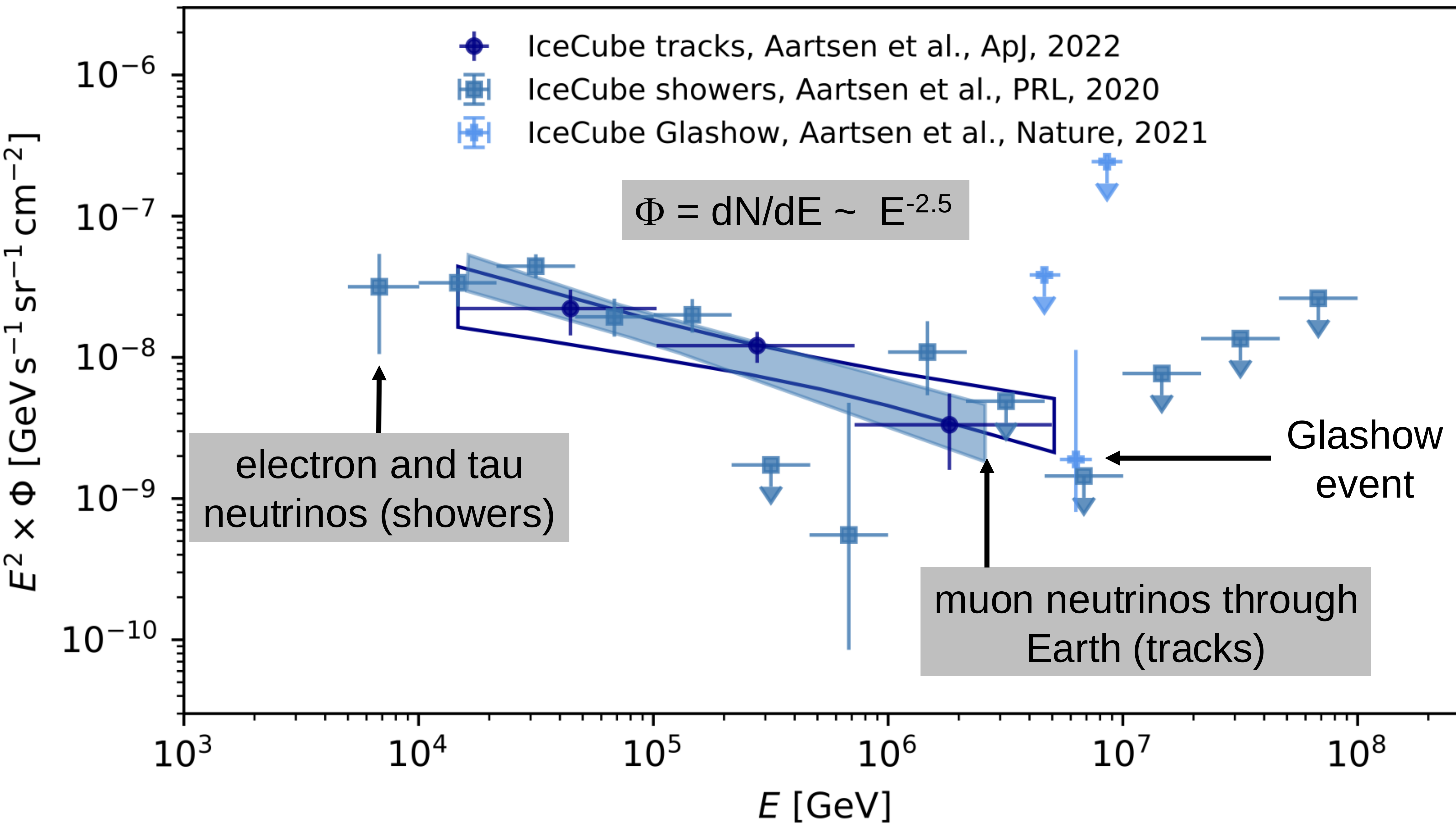


1 km^3 instrumented with 5160 PMT (10inch) below 1450m

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

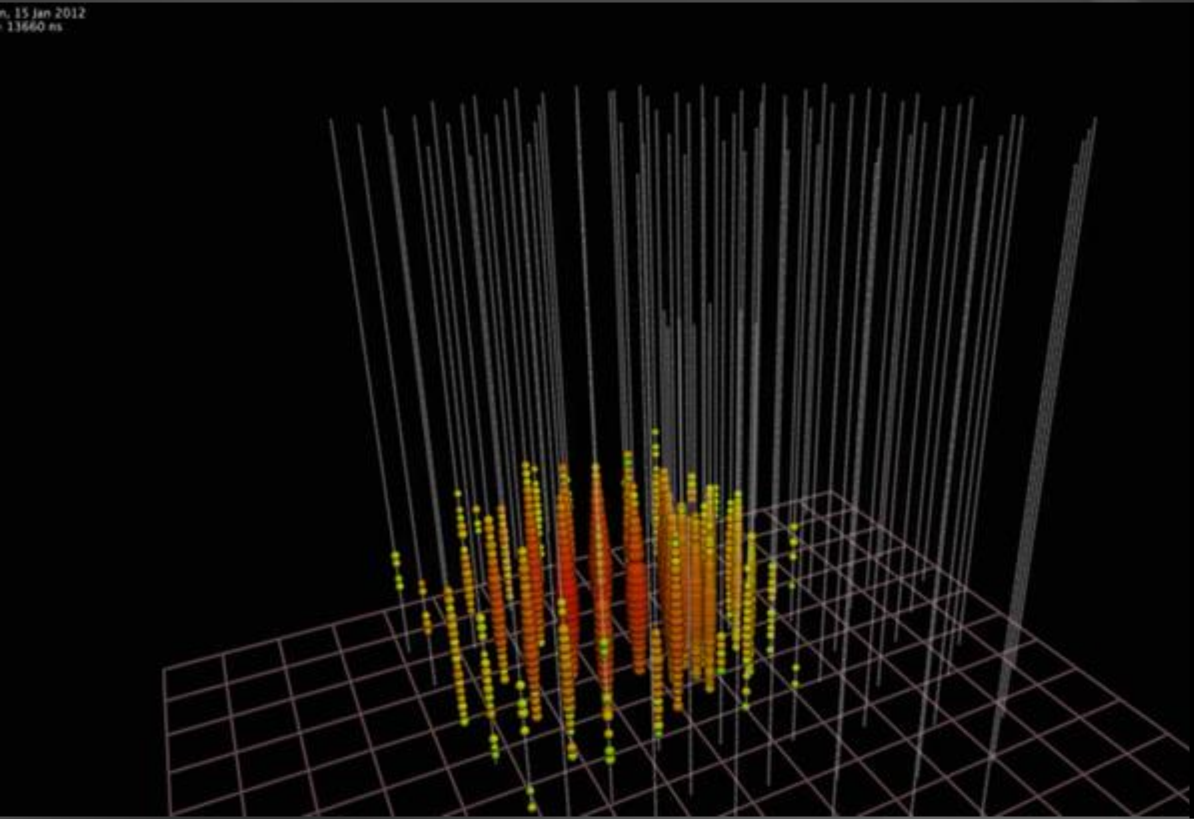


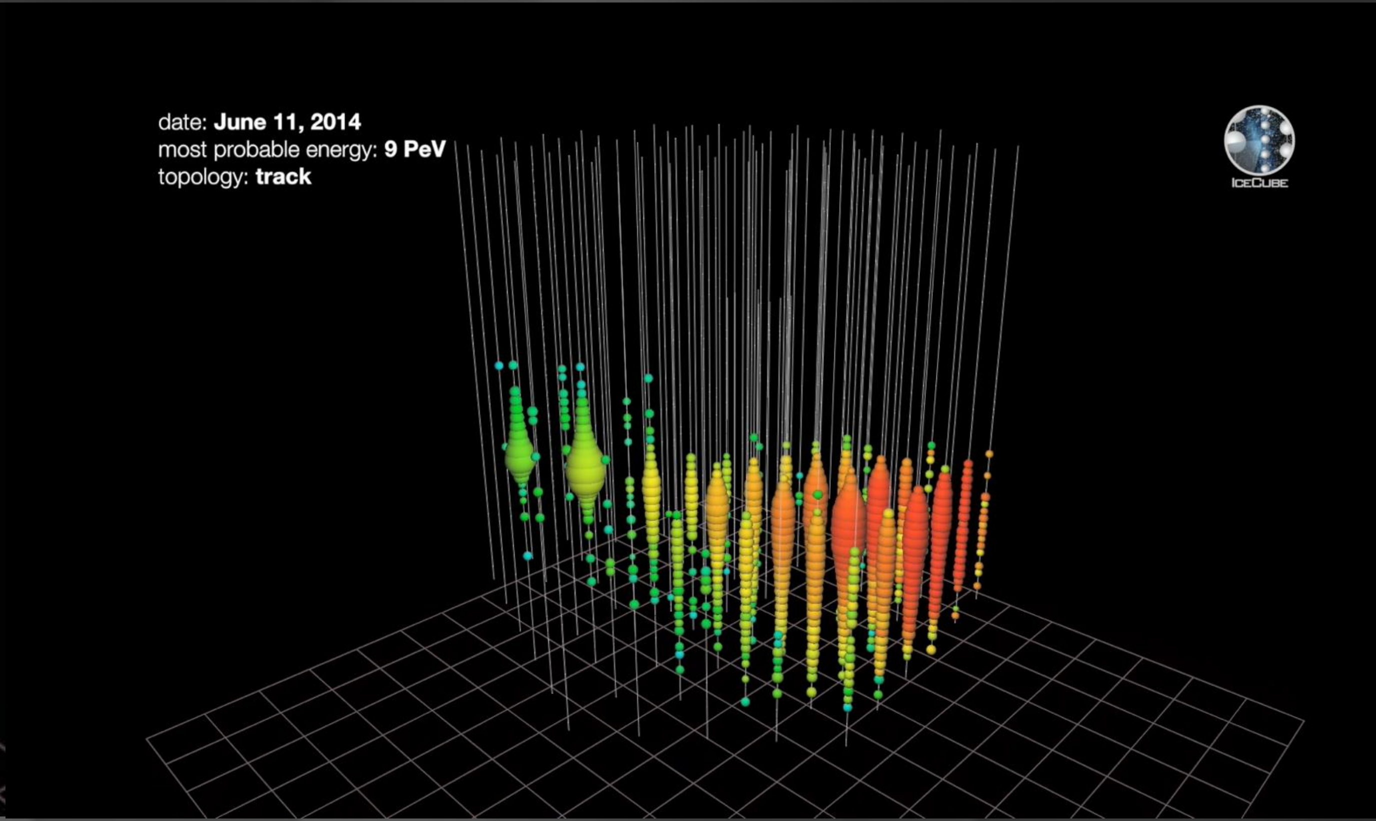



IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ E^-2.5
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
E^2 × Φ [GeV s^−1 sr^−1 cm^−2]
E [GeV]
10^−6
10^−7
10^−8
10^−9
10^−10
10^3
10^4
10^5
10^6
10^7
10^8

neutrinos interacting
inside the detector

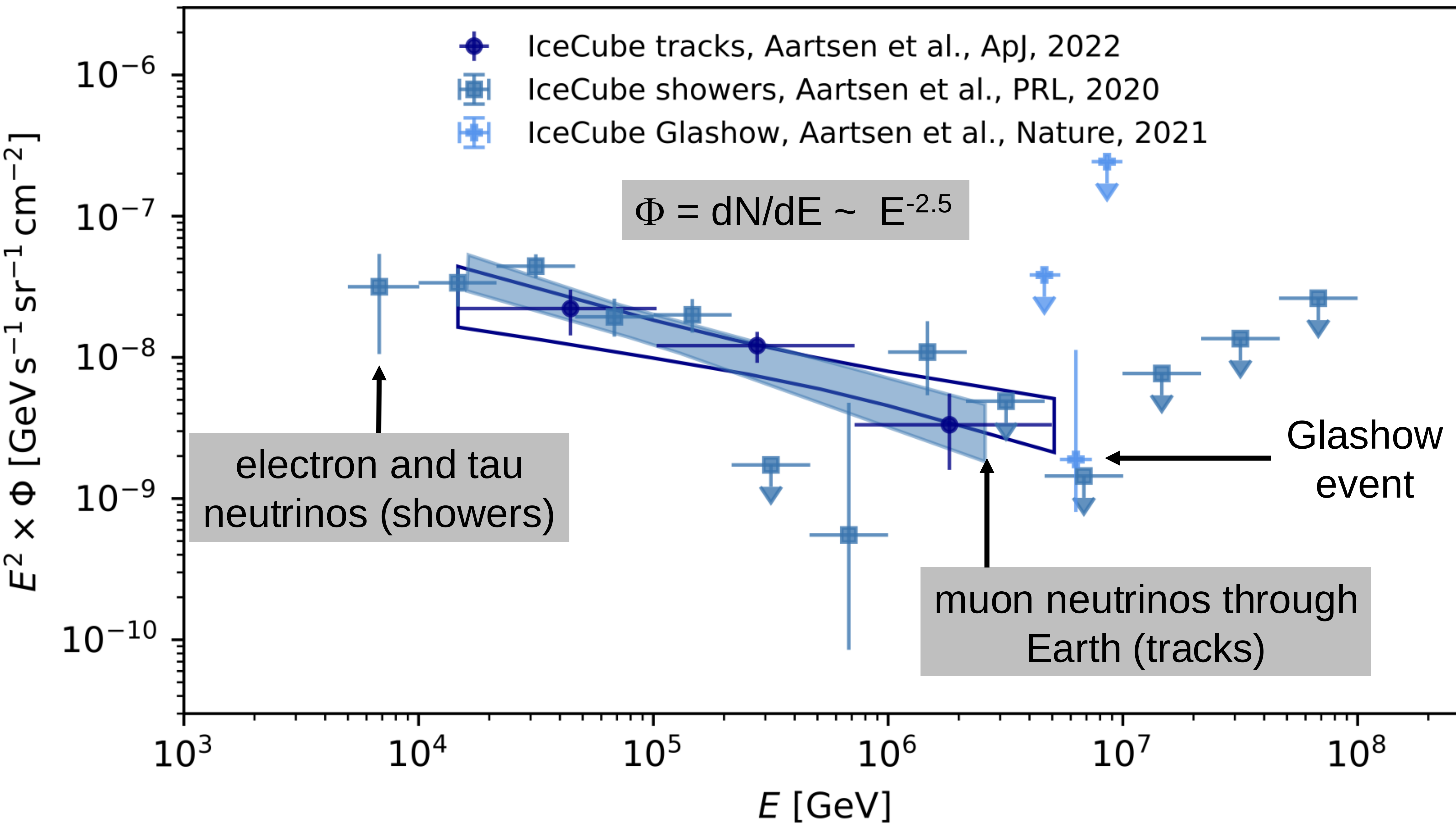
muon neutrinos
filtered by the Earth



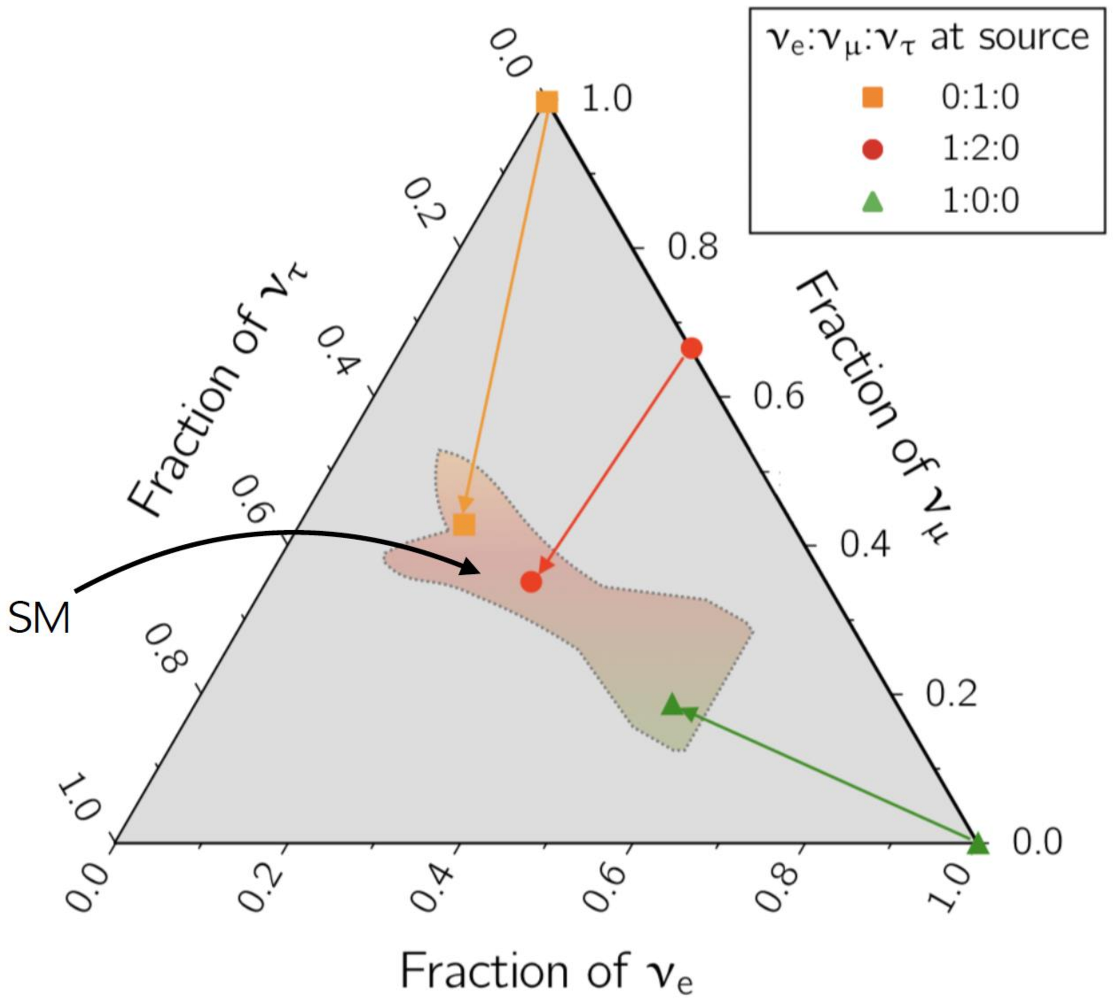


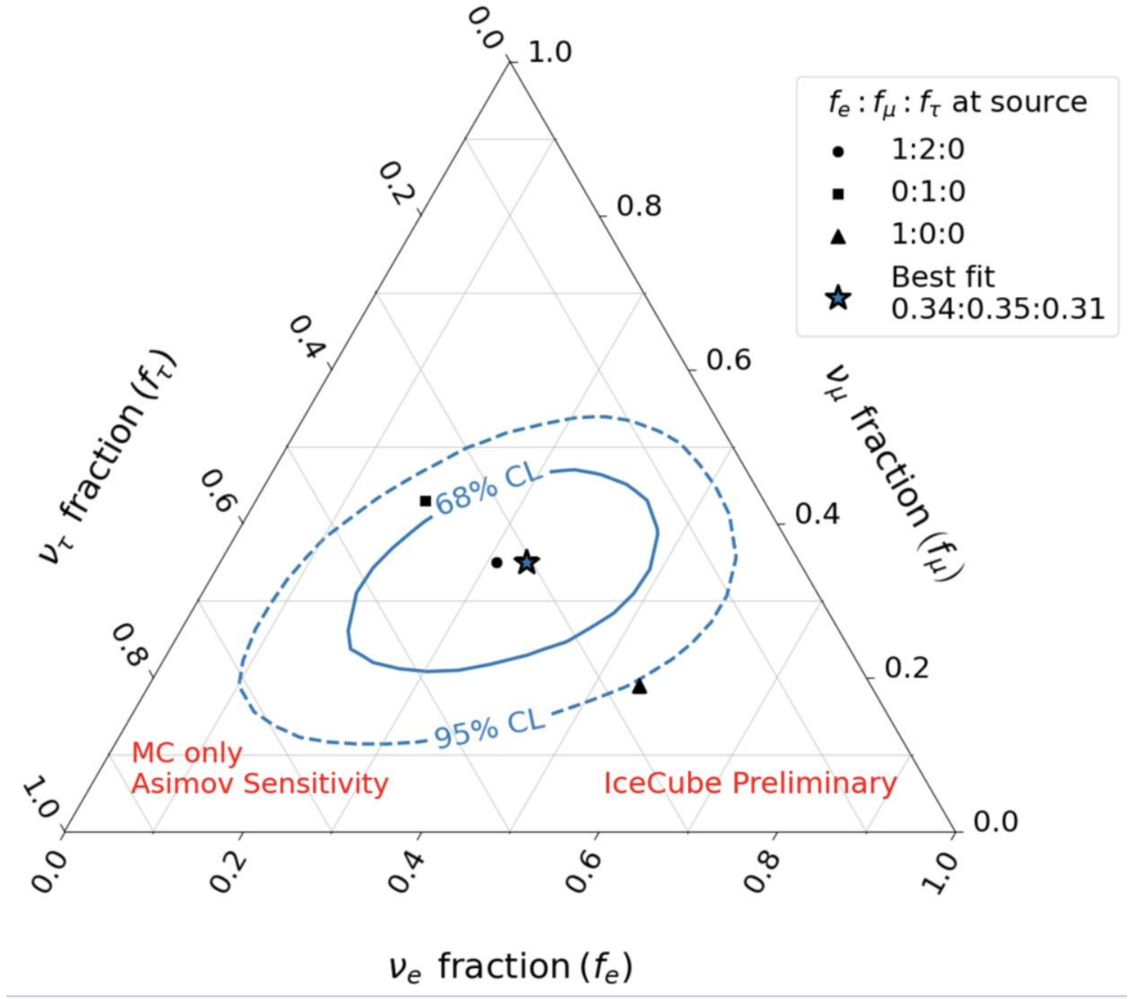
superior total energy
measurement
to 10%, all flavors, all sky

superior angular resolution 0.3^{o}
including systematics

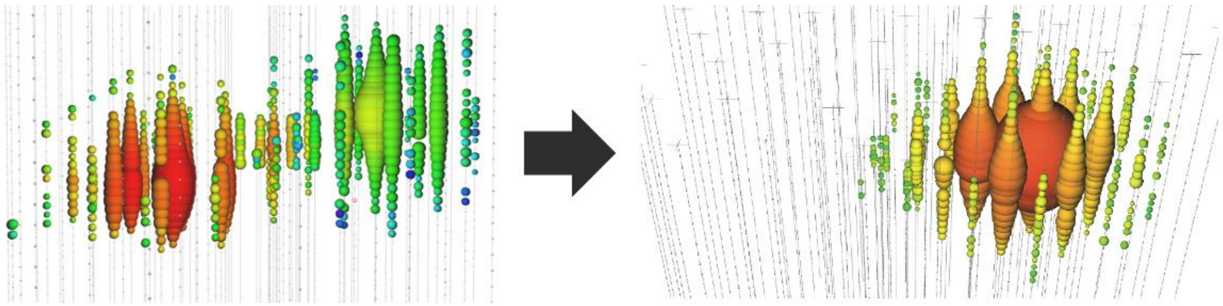

IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ E^-2.5
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^3
10^4
10^5
10^6
10^7
10^8

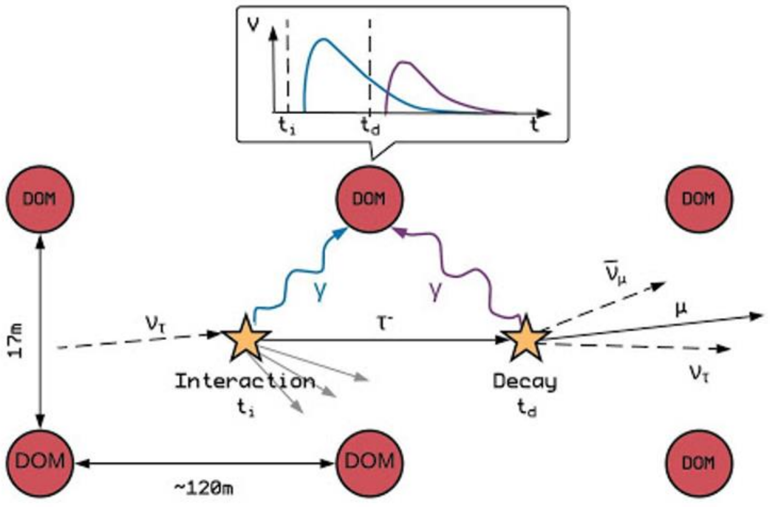
- oscillations of PeV neutrinos over cosmic distances to 1:1:1
- high energy (> teV) nutaus neutrino is of cosmic origin



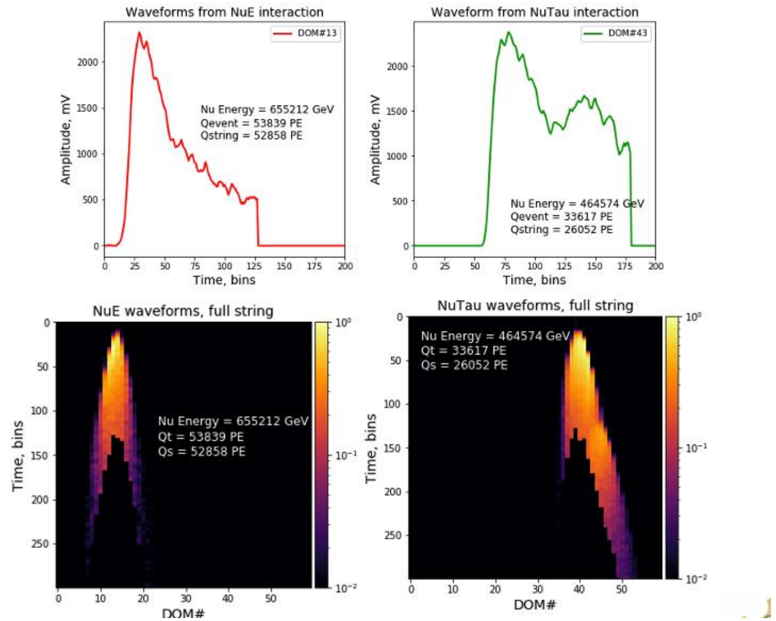


Astrophysical Tau Neutrino Search

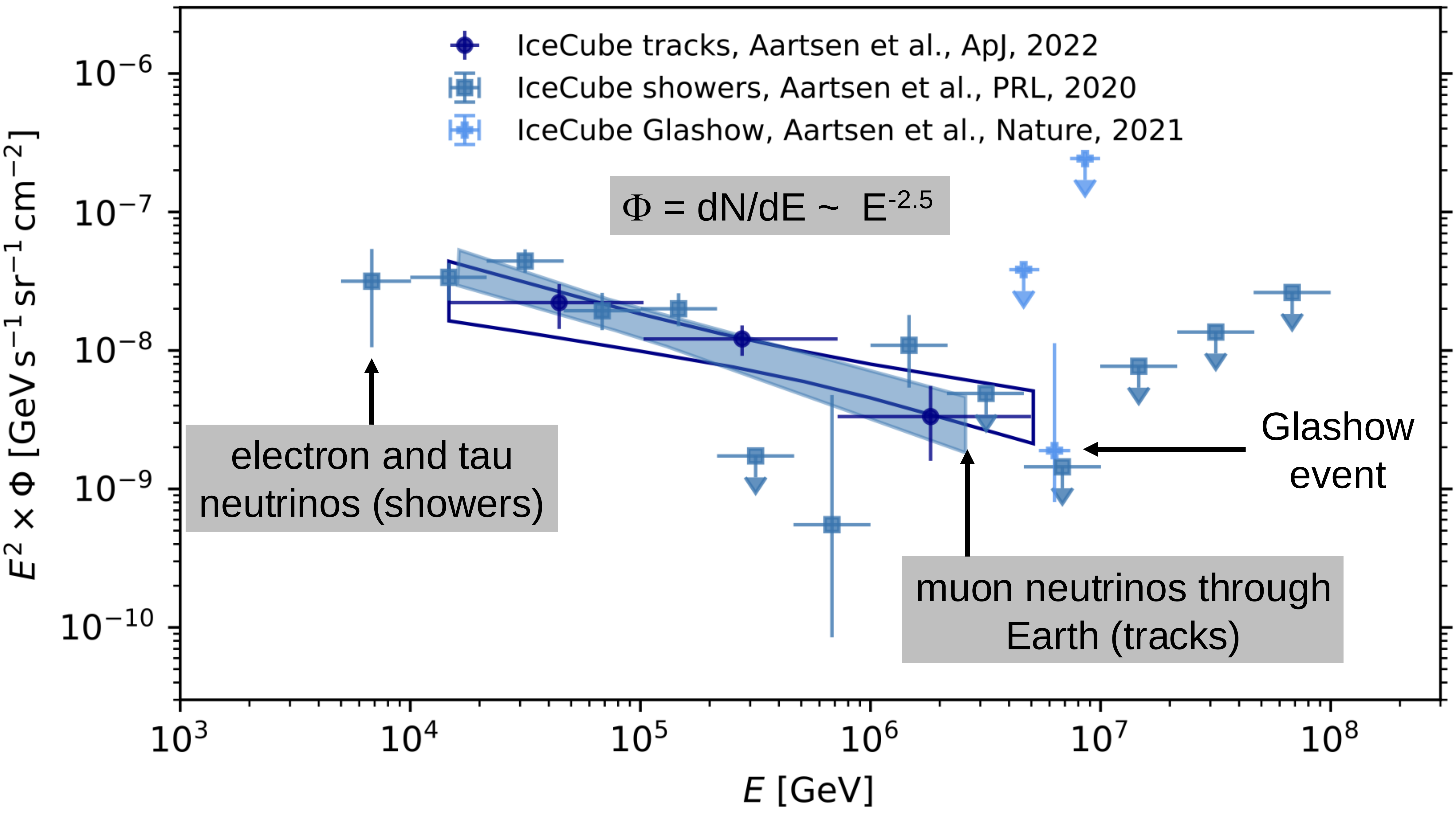




- TeV – O(1) PeV Tau neutrinos look like Electron neutrinos due to sparse instrumentation
- Differentiation by shape of waveform in a given module, i.e. two waveforms in the same module offset by a certain quantity
- Create an image (2D histogram) of the of the charge distribution in time along a string
- CNN used to find the subtle difference in waveform shapes

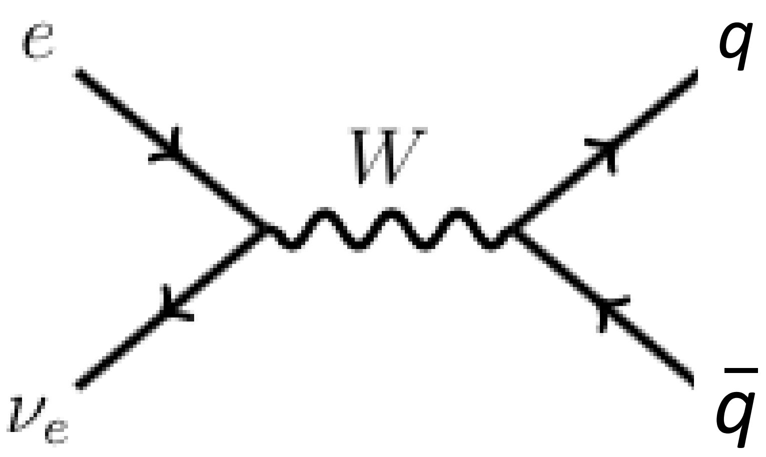


→ Standard Model: 8 expected on a background of 1 and 7 found for a flavor ratio 1:1:1



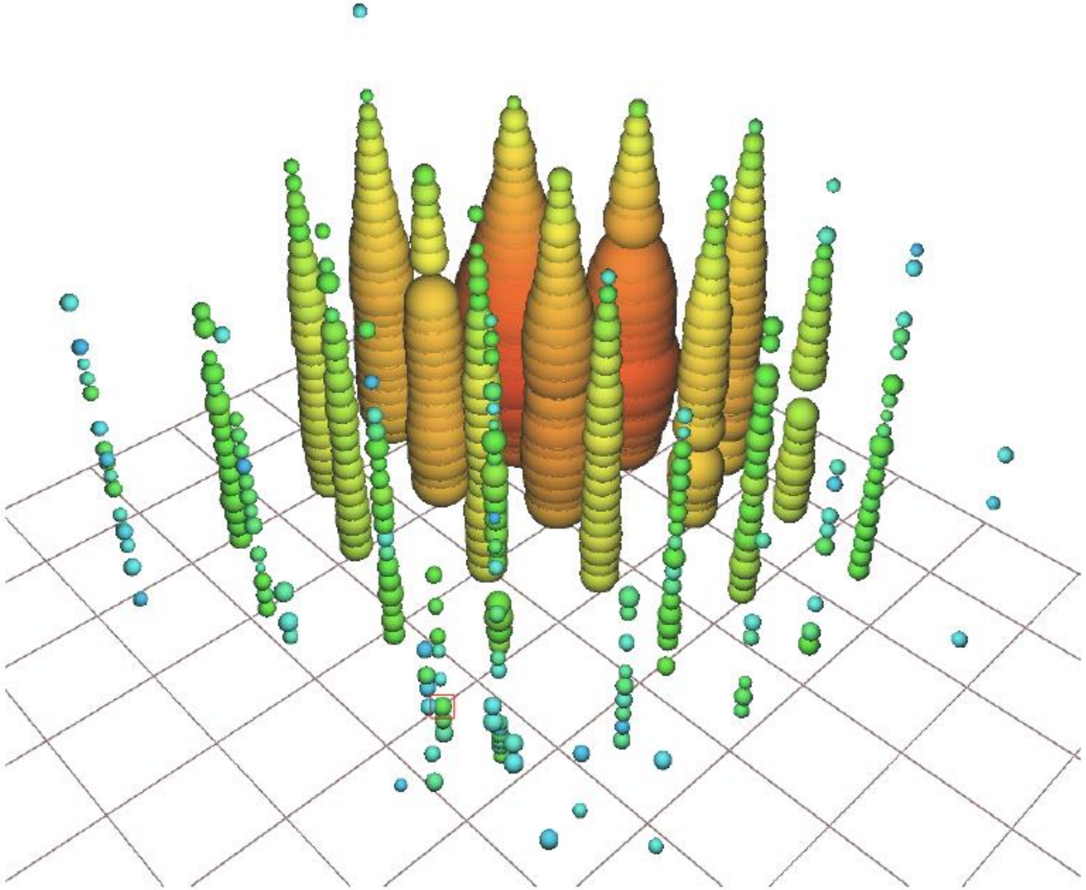
IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ $E^{-2.5}$
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^3
10^4
10^5
10^6
10^7
10^8
E [GeV]

Glashow resonance event with energy 6.3 PeV

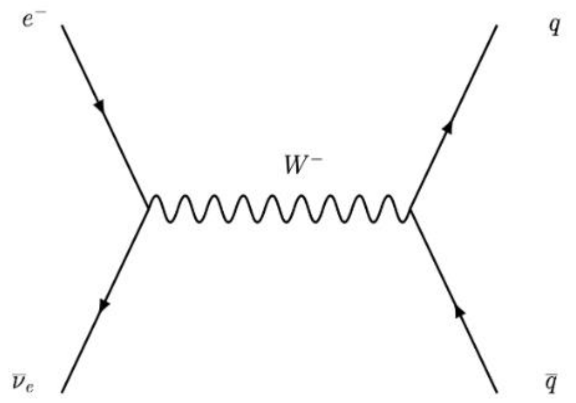


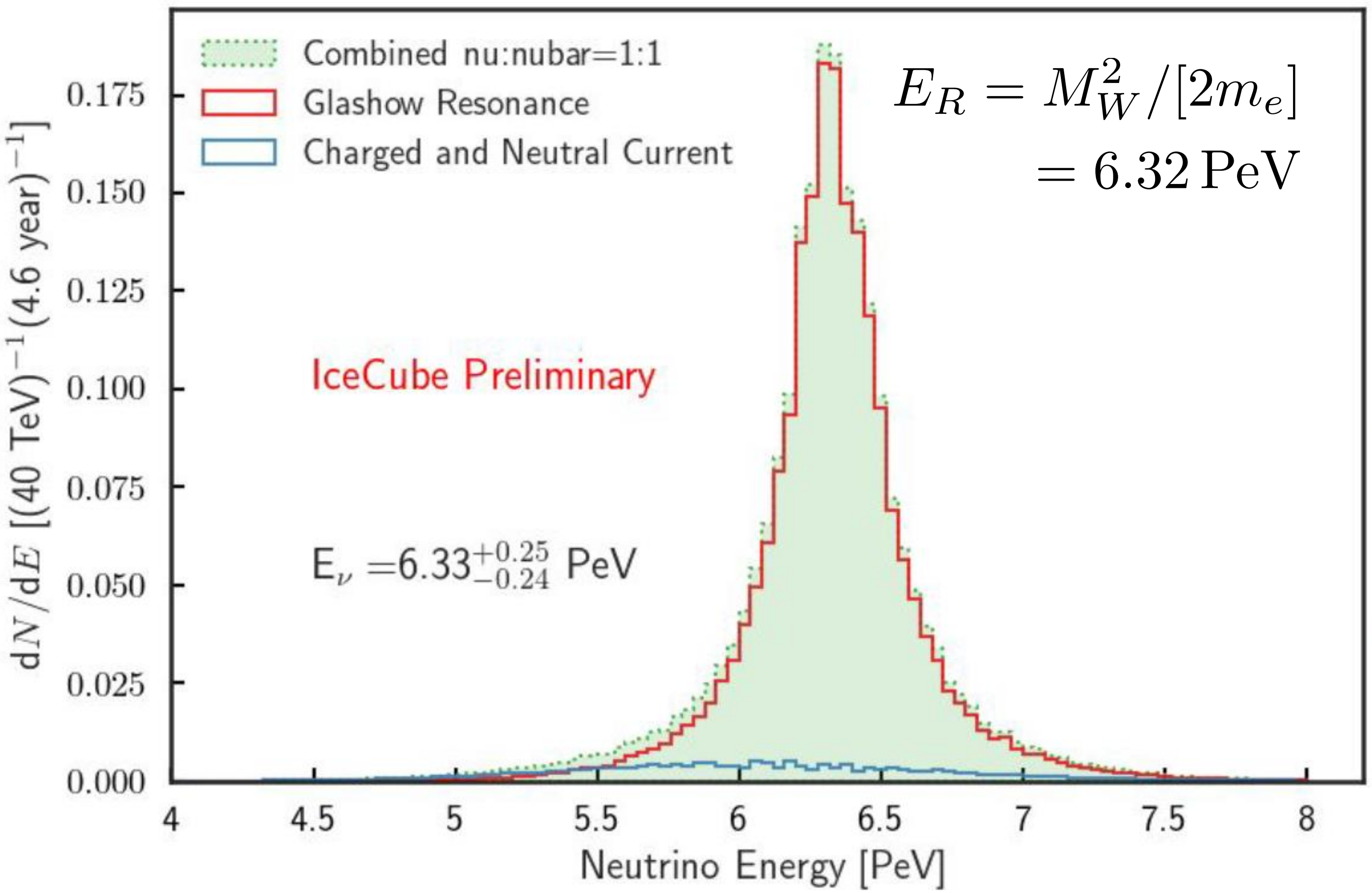
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

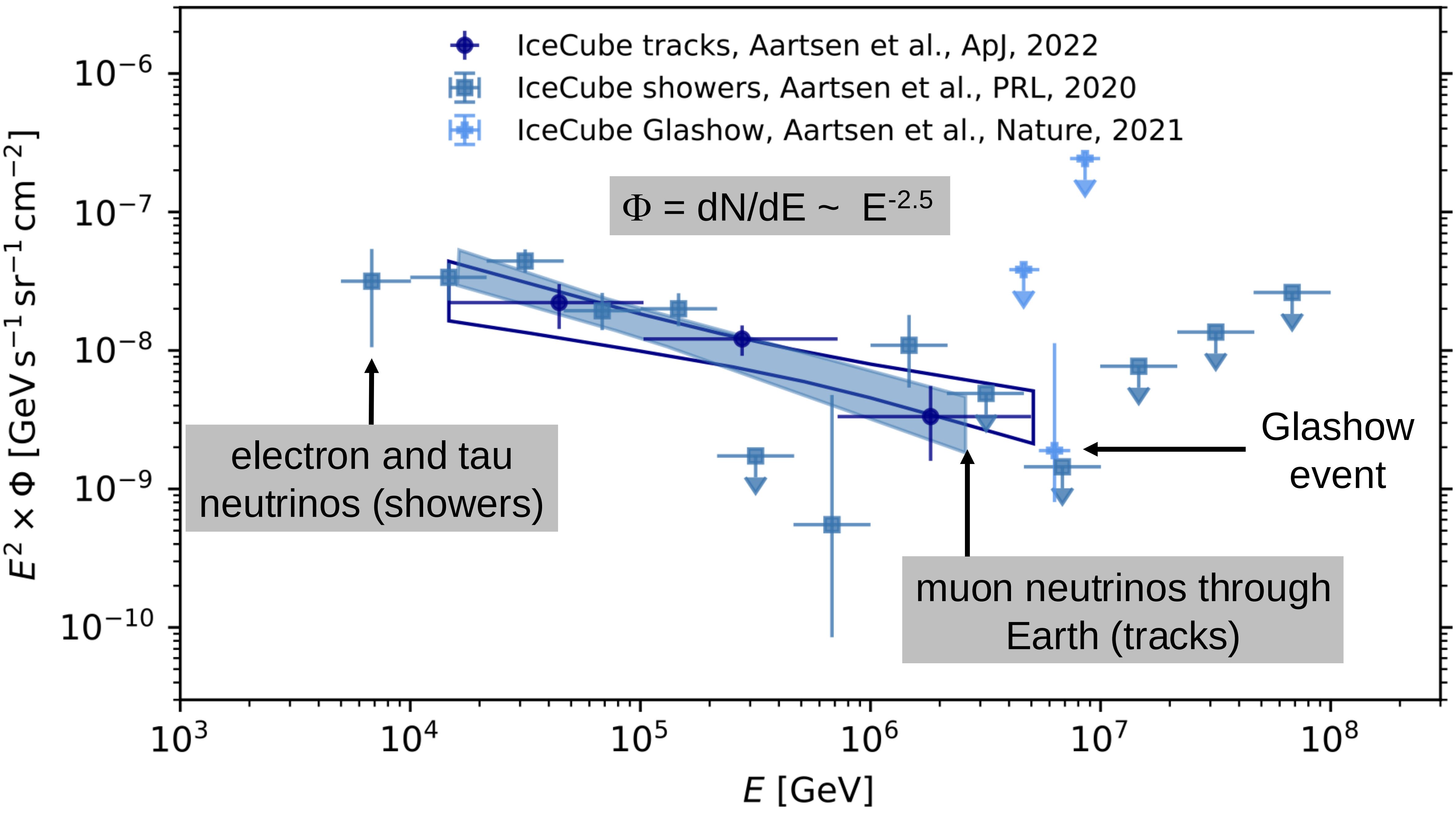
$$E_R = M_W^2/[2m_e] = 6.32\,\mathrm{PeV}$$



- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino
- SM cross section known → measure flux

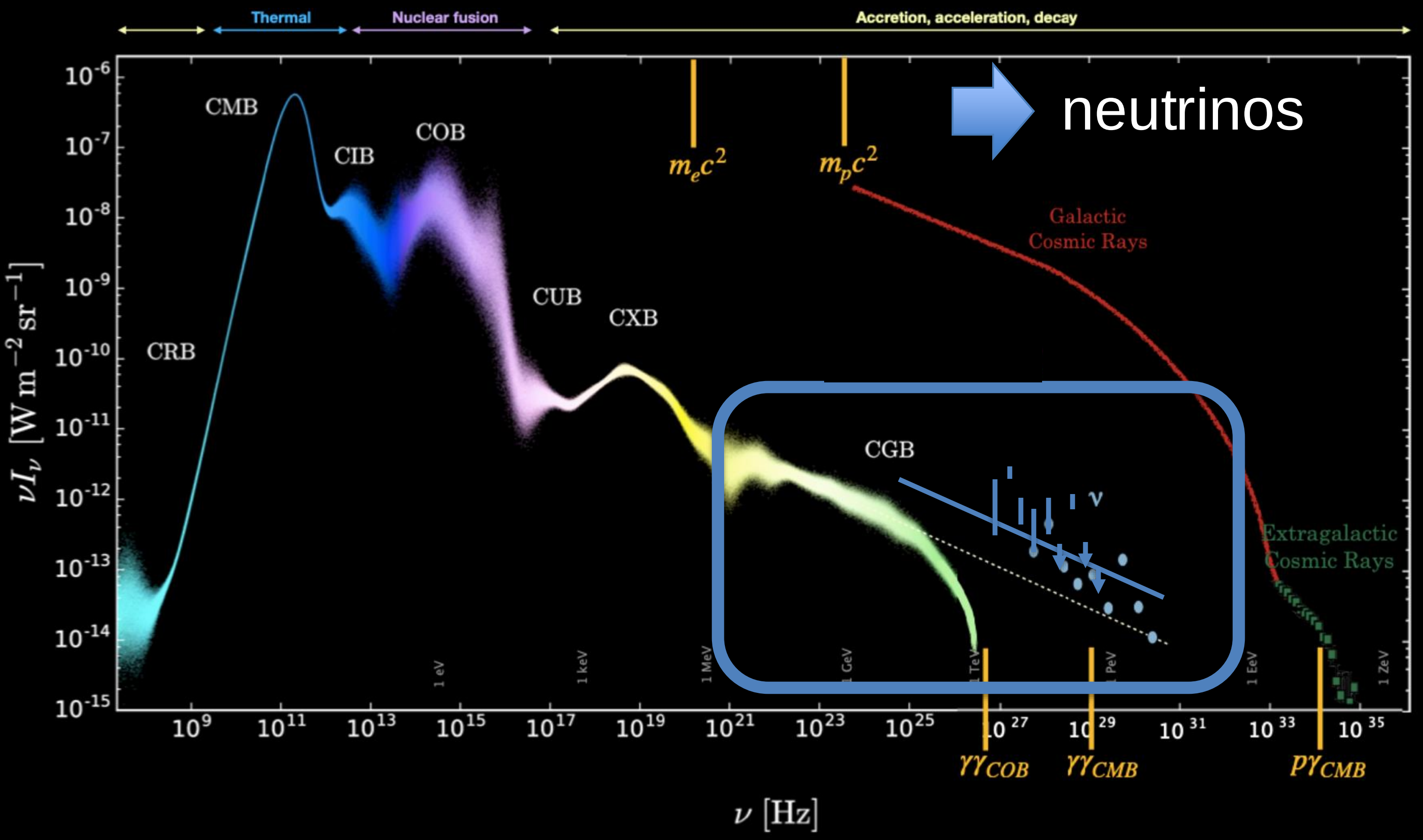




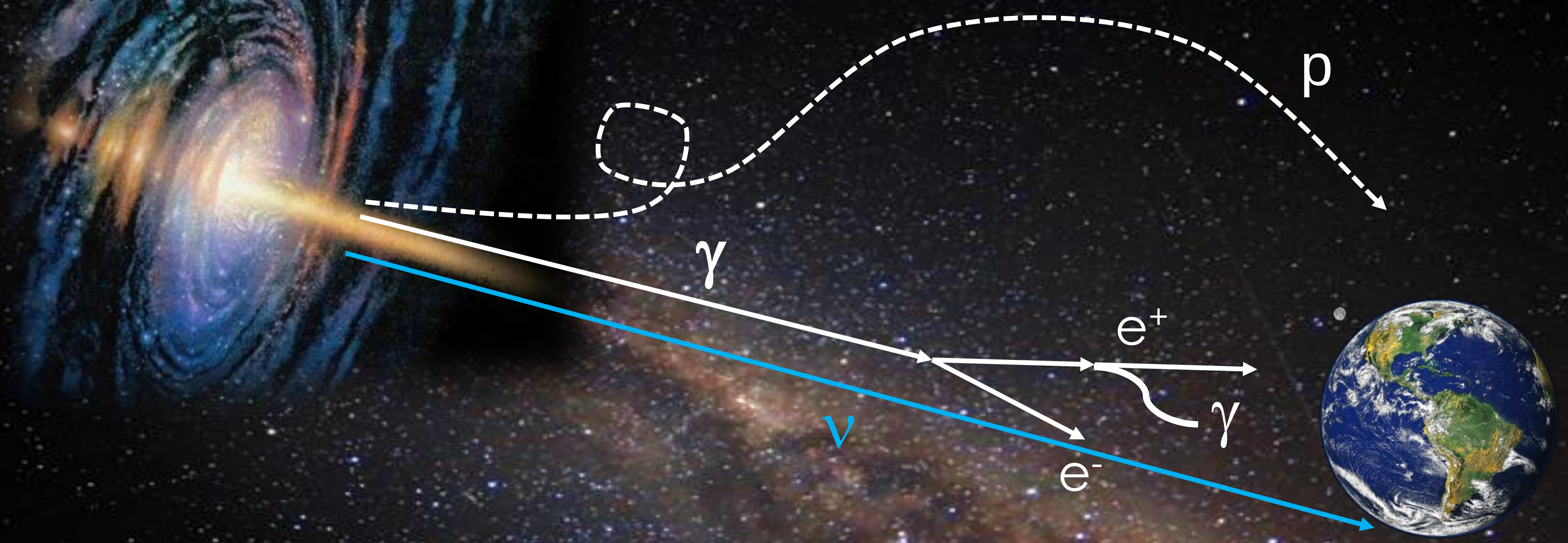


IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ E^-2.5
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
E² × Φ [GeV s⁻¹ sr⁻¹ cm⁻²]
E [GeV]

in the extreme universe the energy in neutrinos is larger than the energy in gamma rays observed at GeV energies

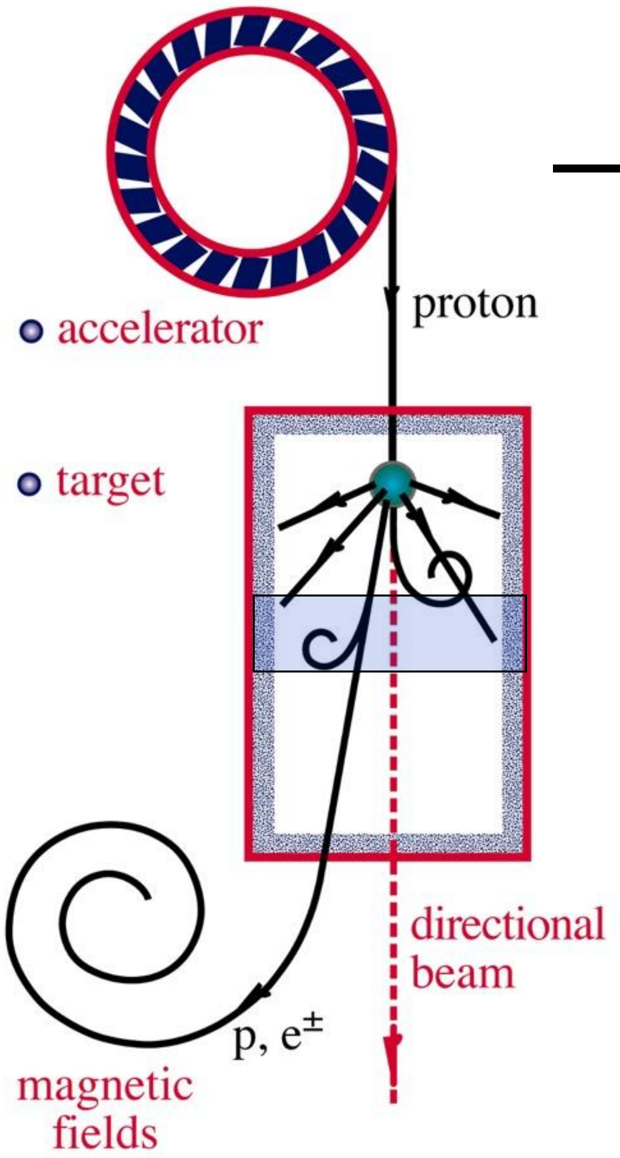


energy in neutrinos (and accompanying gamma rays) dominates?



- gamma rays from π^0 accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth
- they appear at MeV energies, or below [2205.03740 ph.HE]

ν and γ beams : heaven and earth



where are the gamma rays from π^0 ?

supermassive black hole

nearby radiation

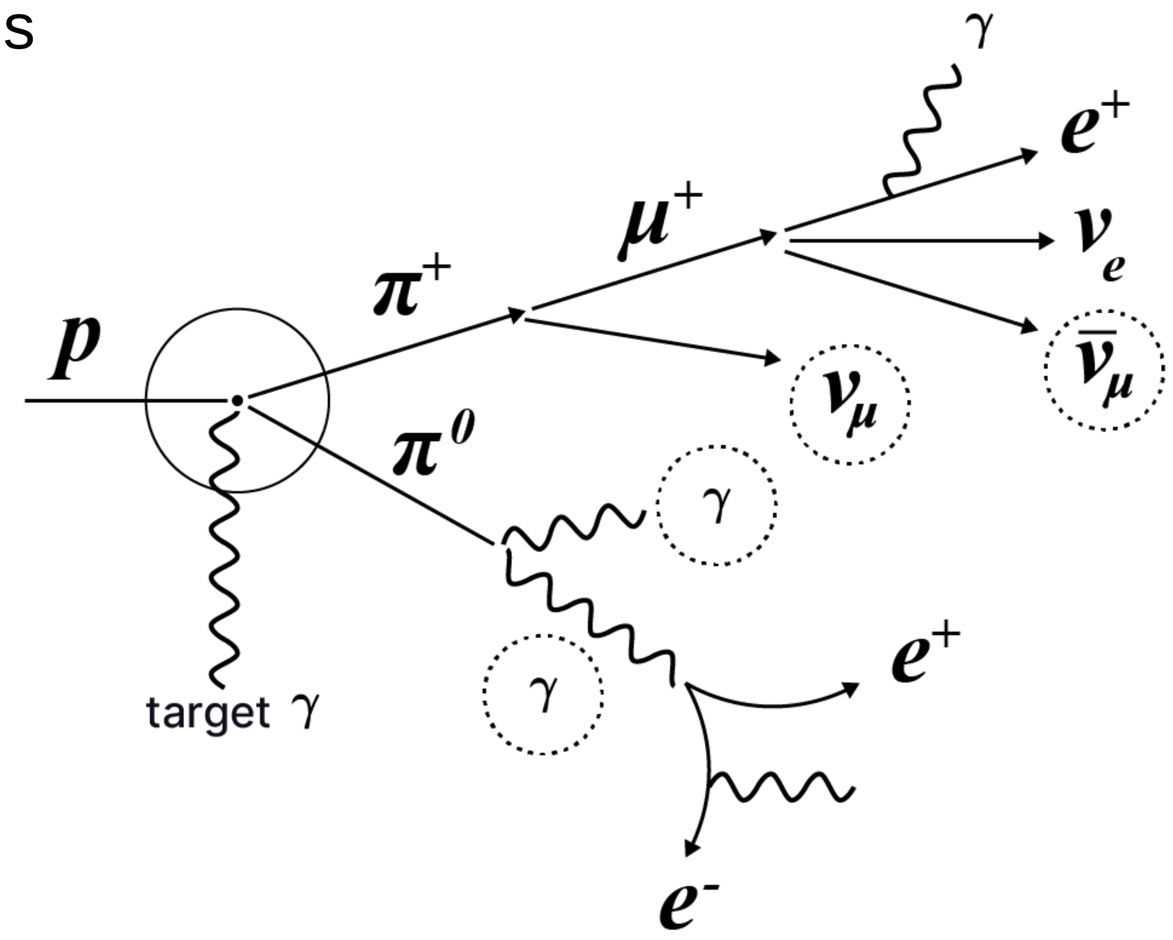
$$p + \gamma \rightarrow n + \pi^+$$

~ cosmic ray + neutrino

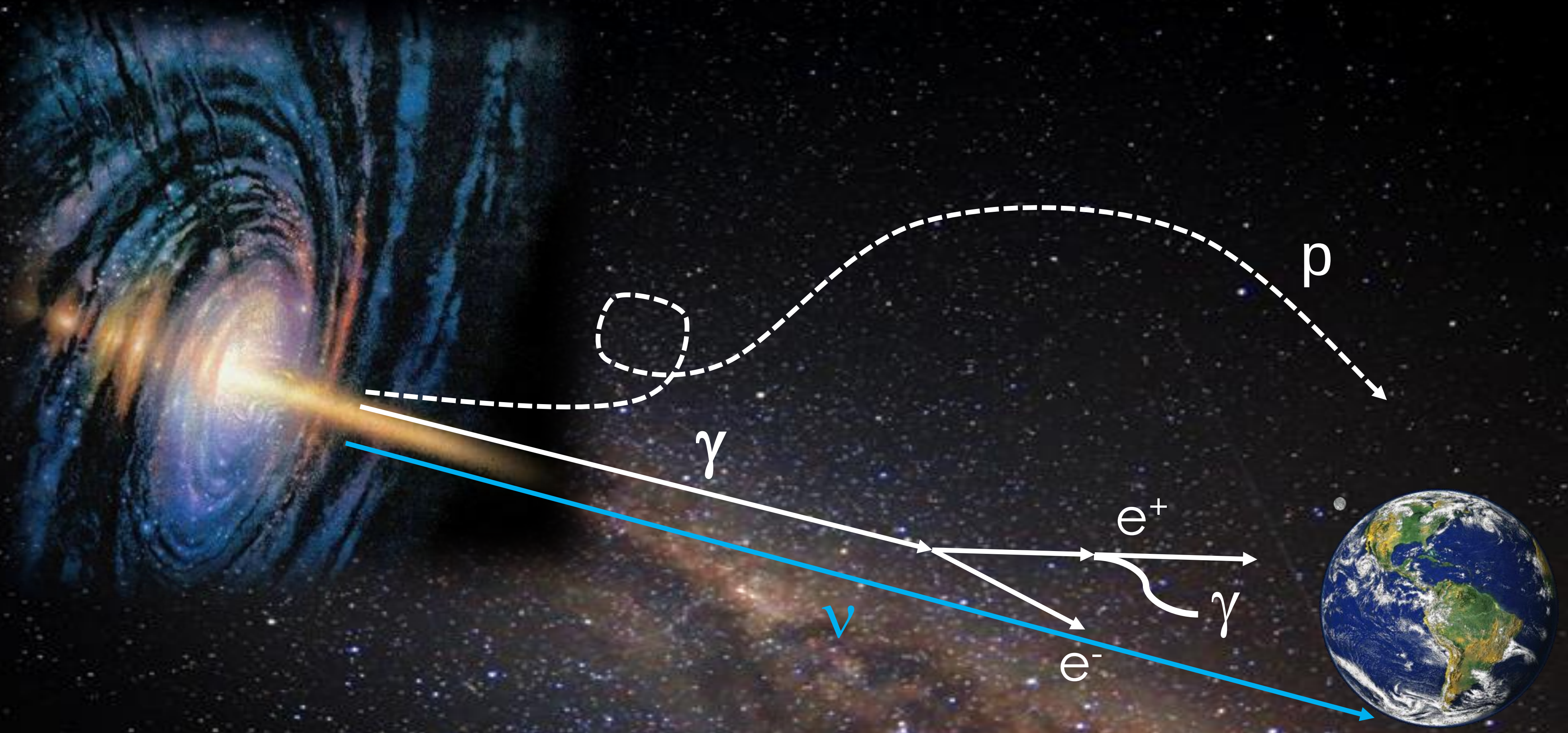
$$\rightarrow p + \pi^0$$

~ cosmic ray + gamma

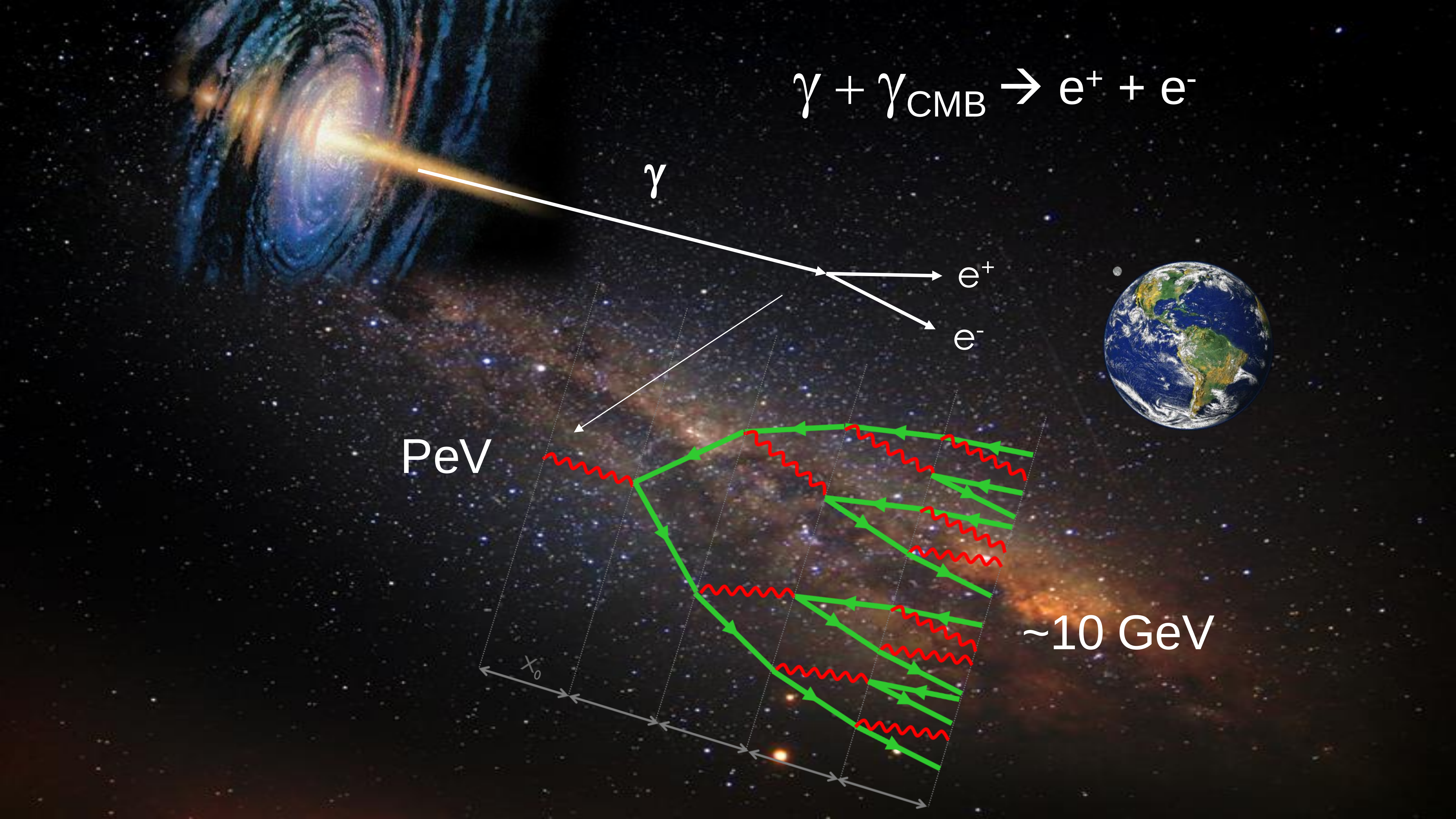
cosmic ray sources



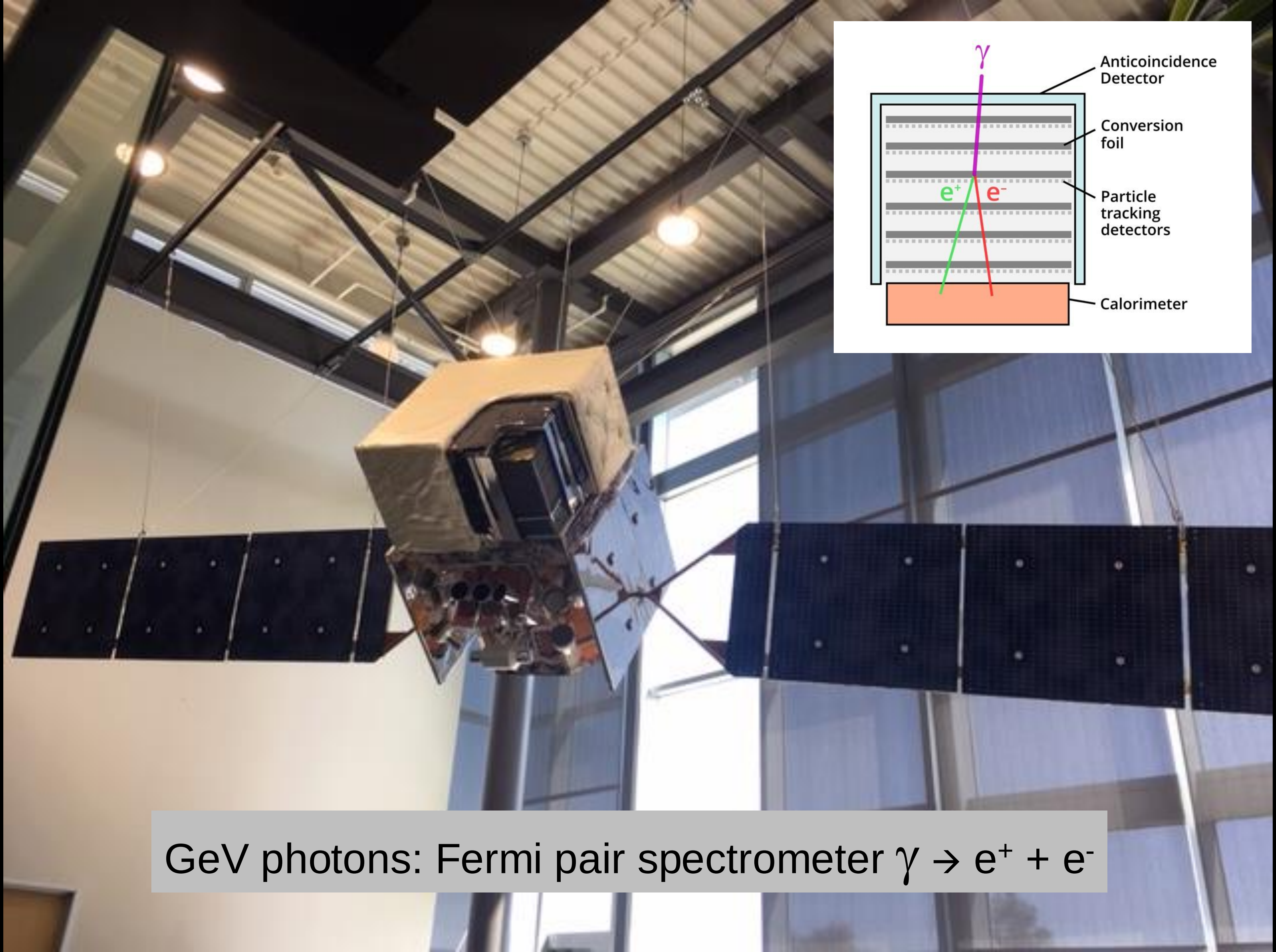
$$\gamma \simeq \nu_\mu + \bar{\nu}_\mu$$



gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

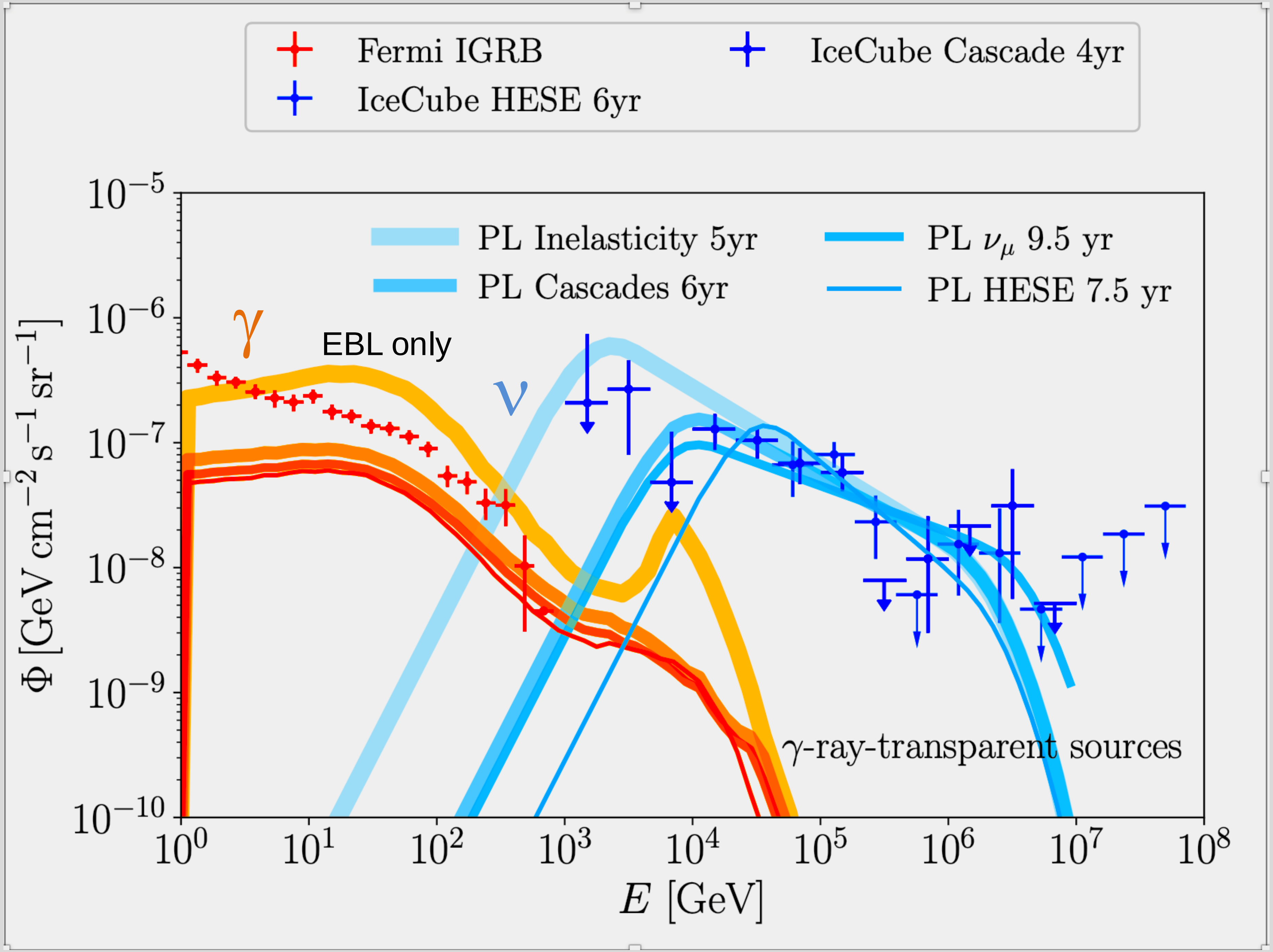


$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
~10 GeV
X_0



GeV photons: Fermi pair spectrometer $\gamma \rightarrow e^+ + e^-$

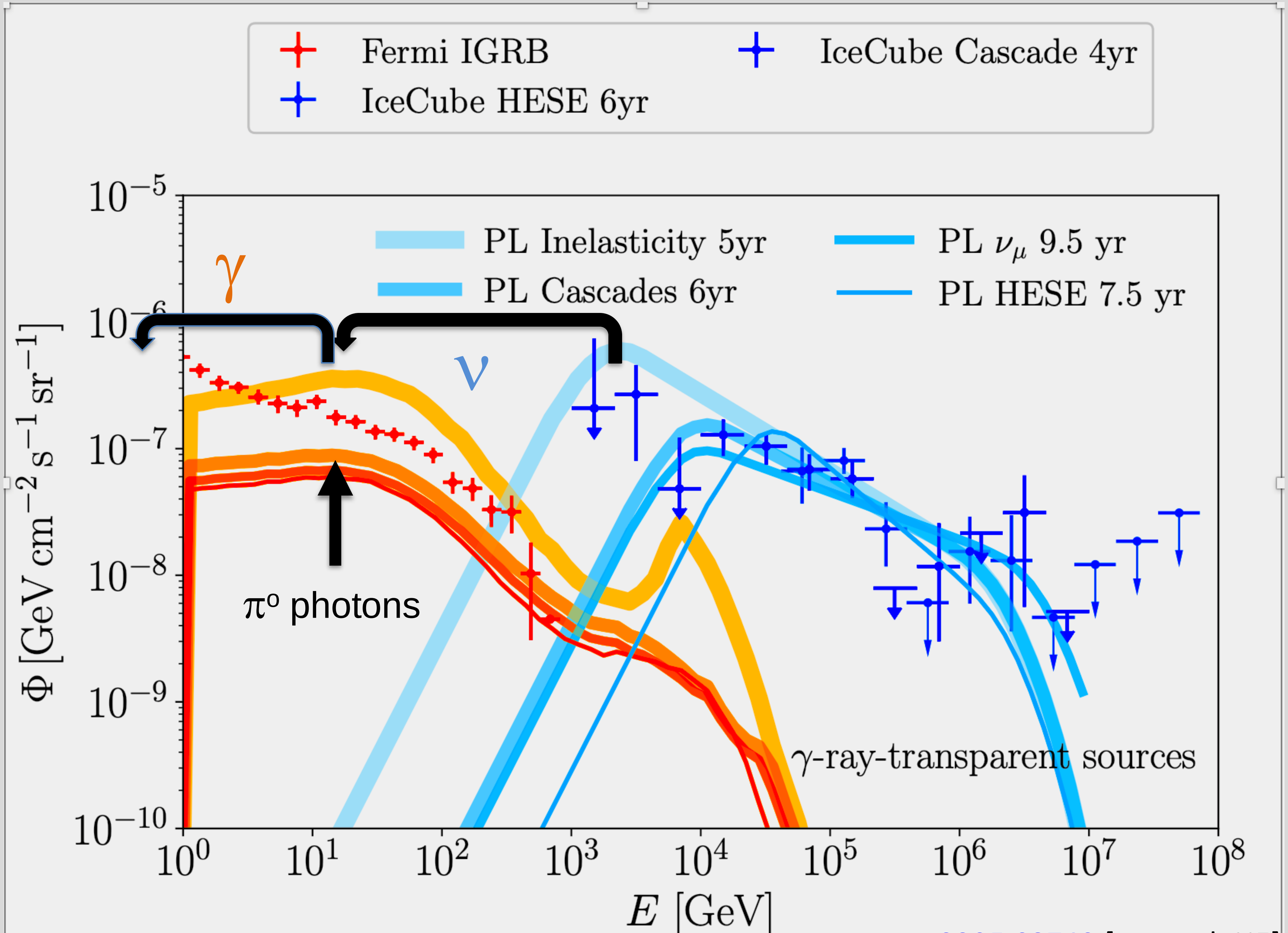
gamma rays from neutral pions must lose energy in the sources if not, they would dominate the Fermi IGRB



the neutrino sources are likely opaque to gamma rays

or

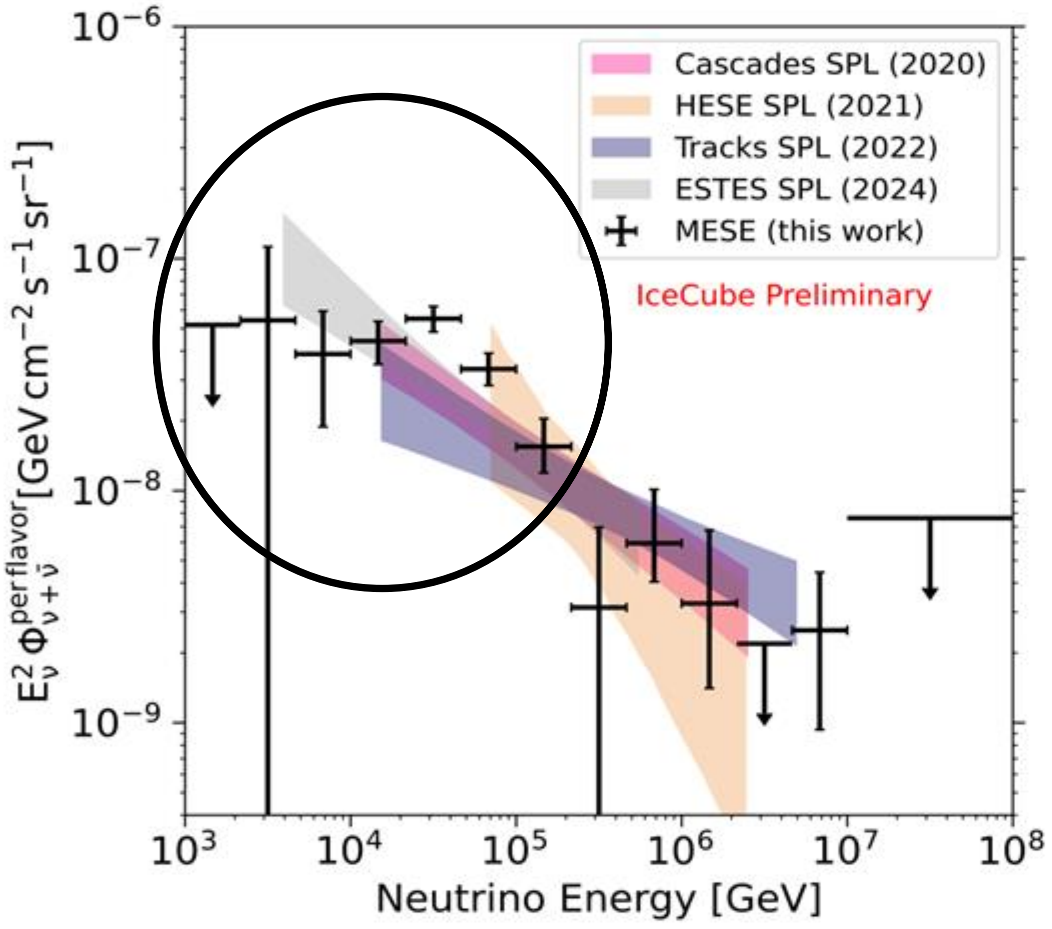
pionic gamma rays accompanying neutrinos appear at MeV energies or below

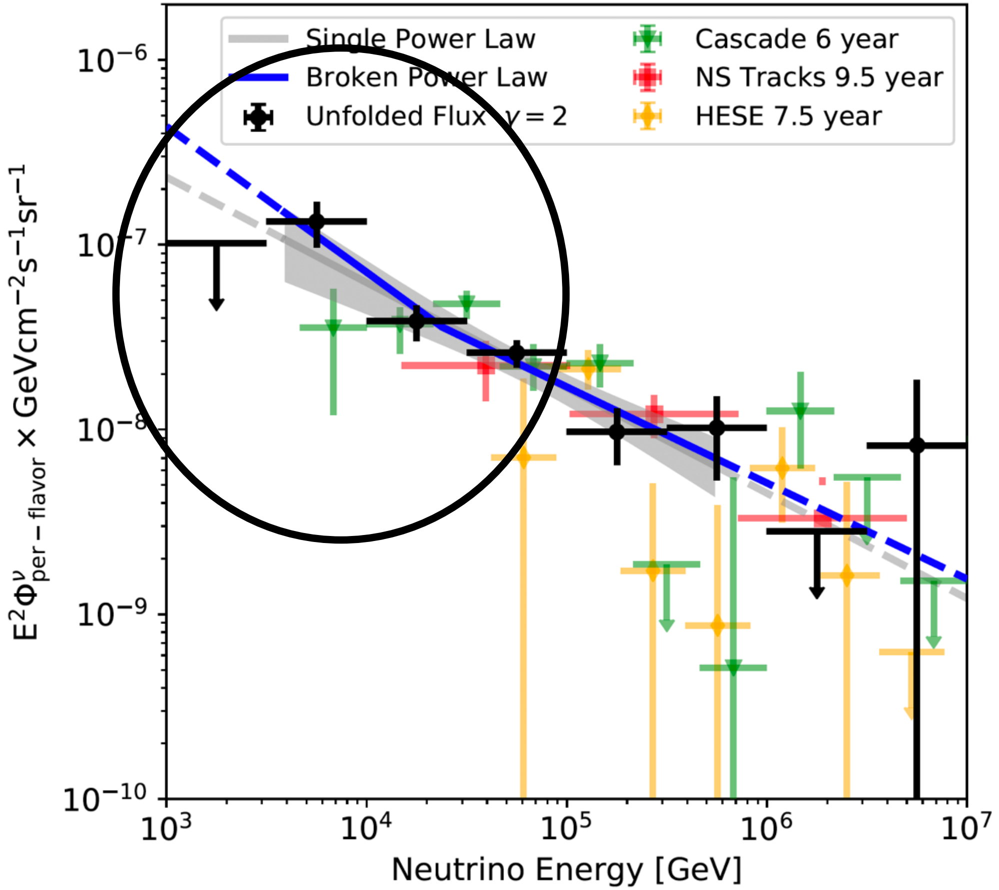


2205.03740 [astro-ph.HE]

energy in neutrinos in the Universe determined by the turnover at low energies:

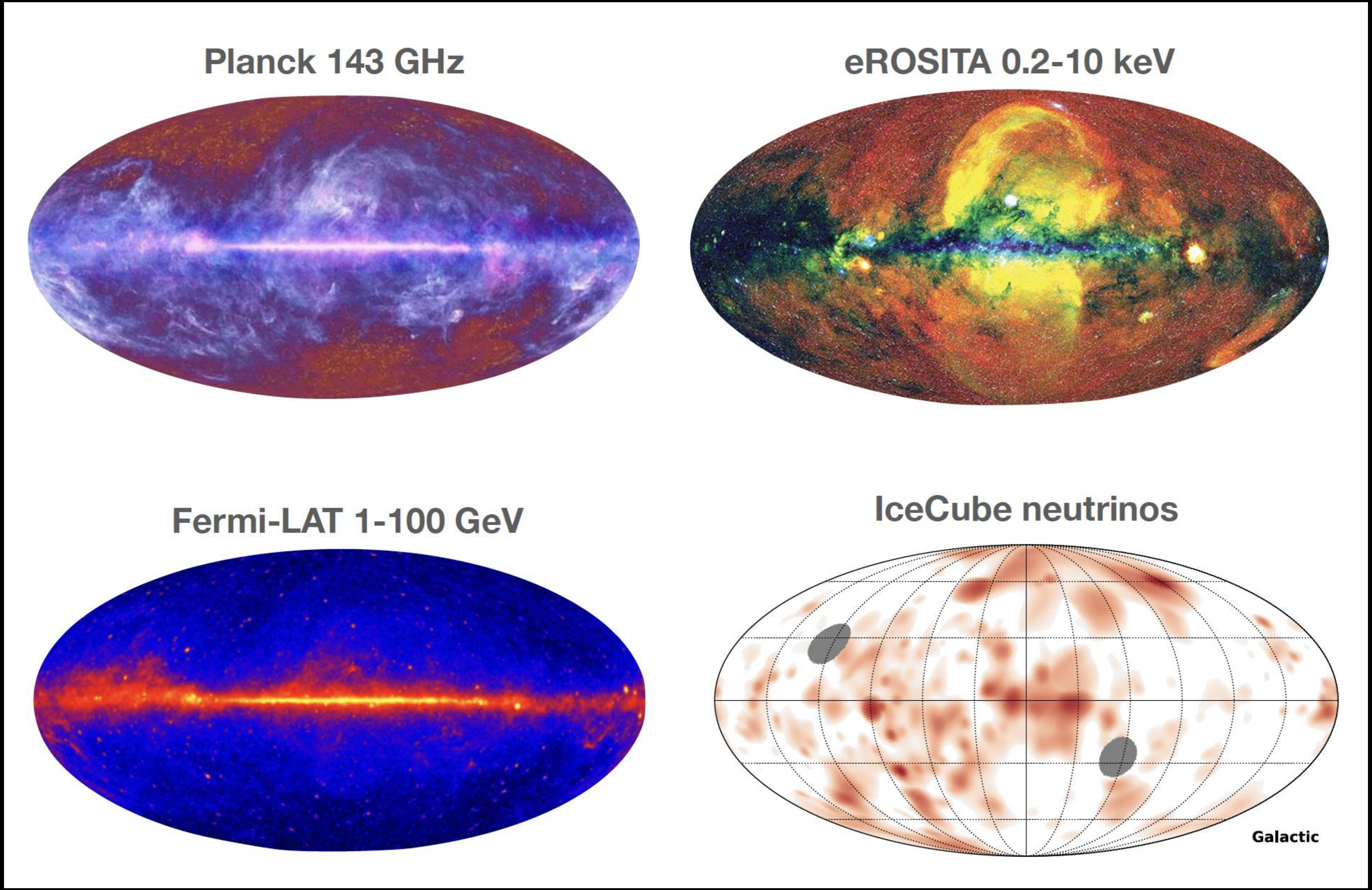
starting event and starting track analyses track analyses

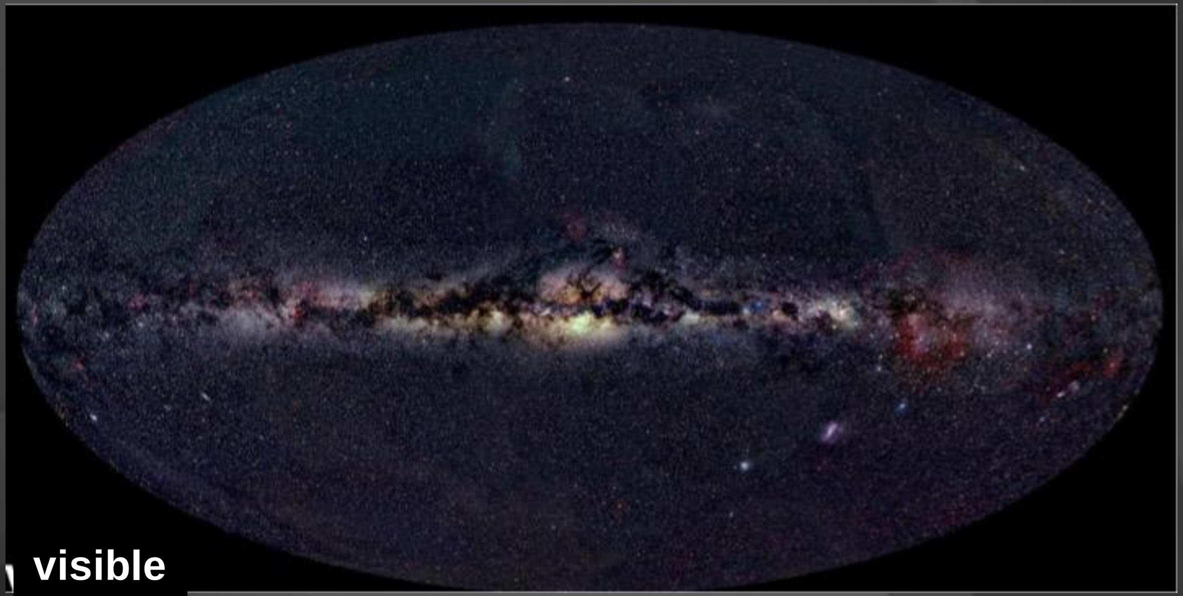


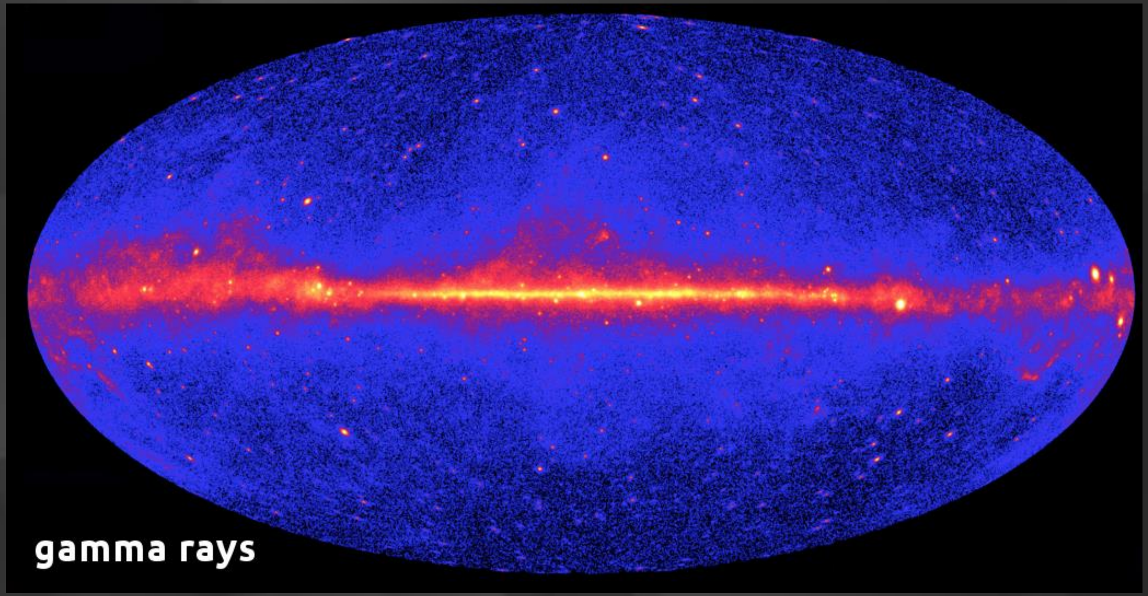


where is the neutrino Galactic plane?

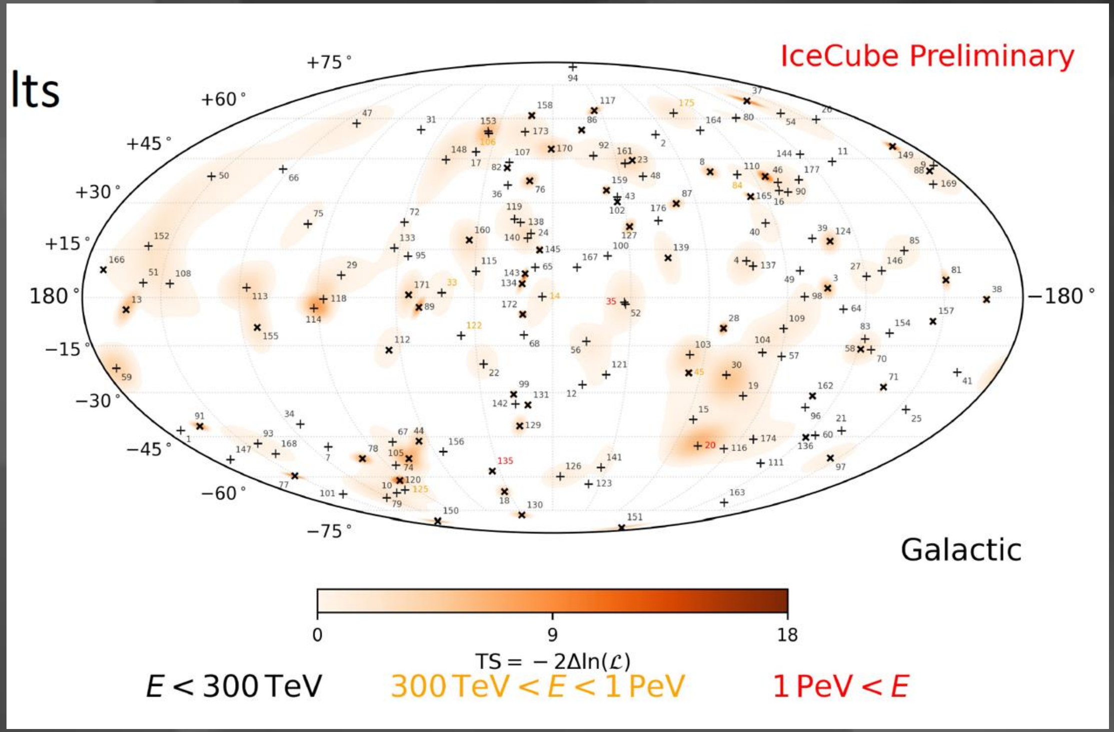
by geometry the flux from your own Galaxy should dominate the diffuse flux from all other galaxies combined!







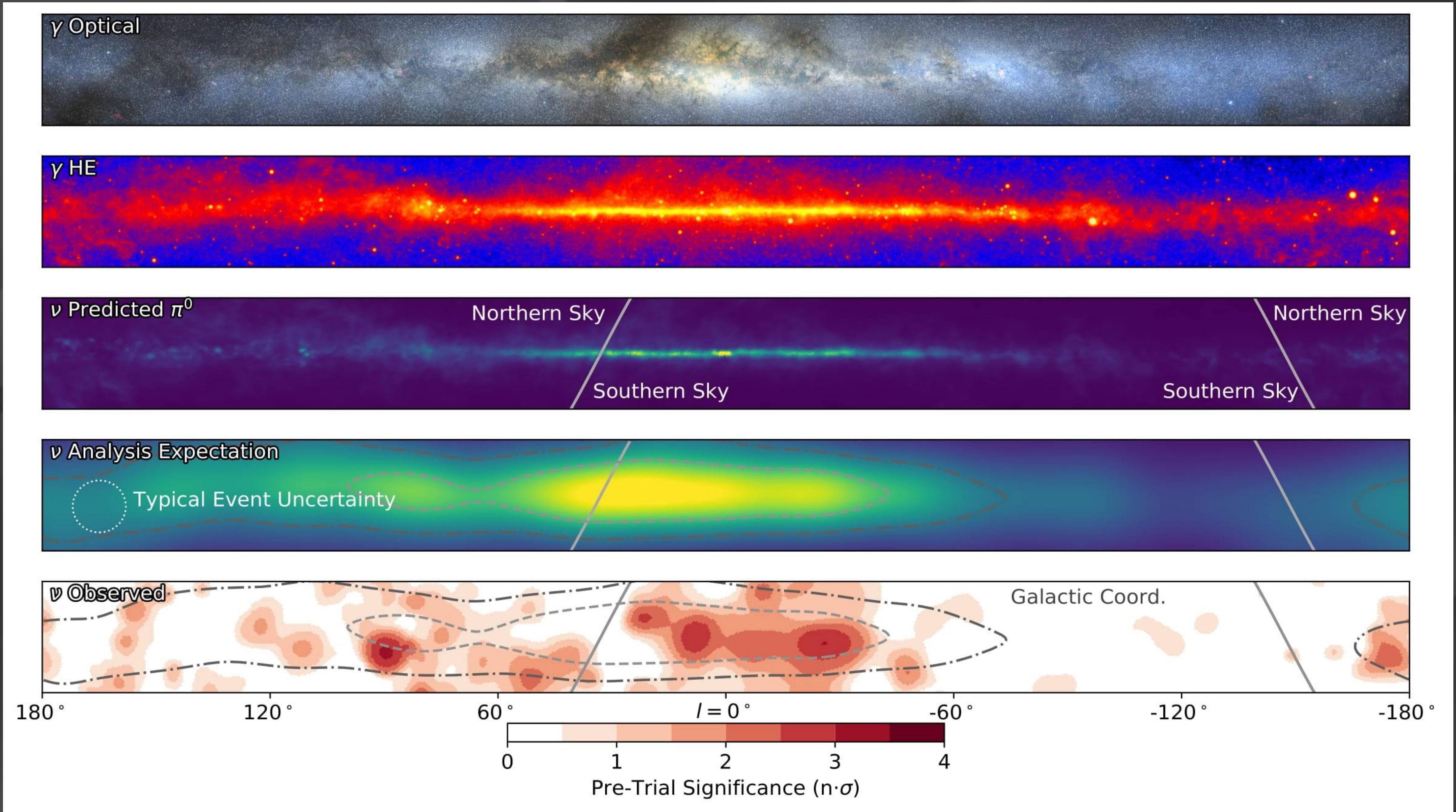
166 neutrino starting events



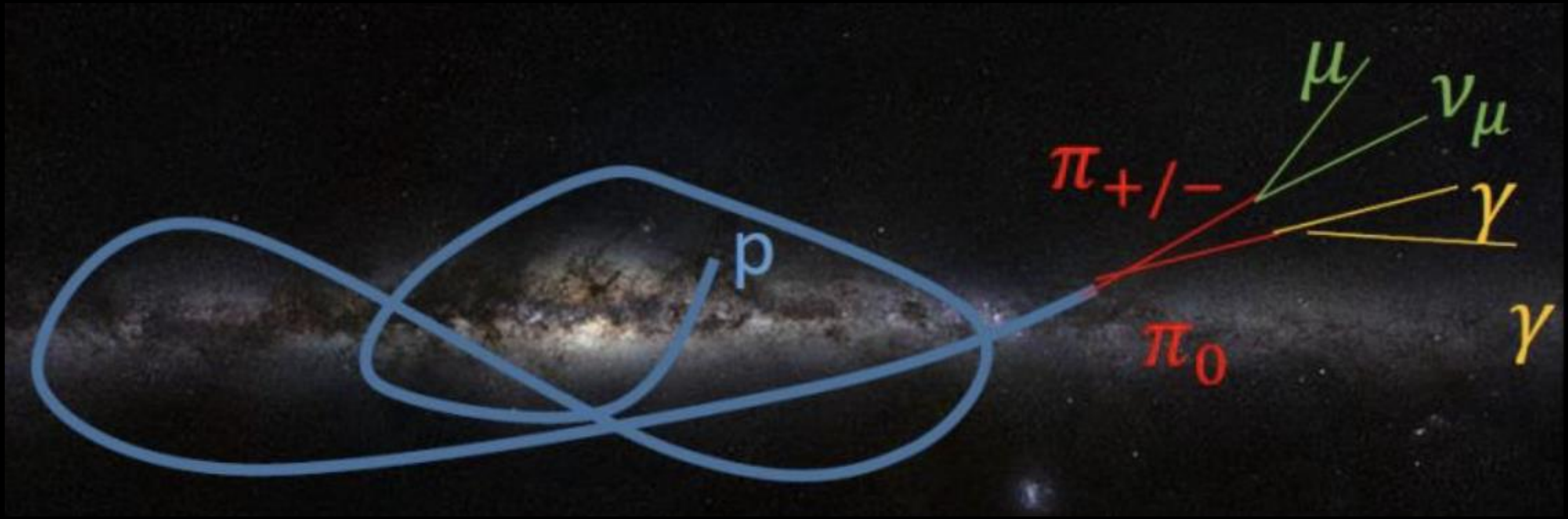
where is the neutrino Galactic plane?

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

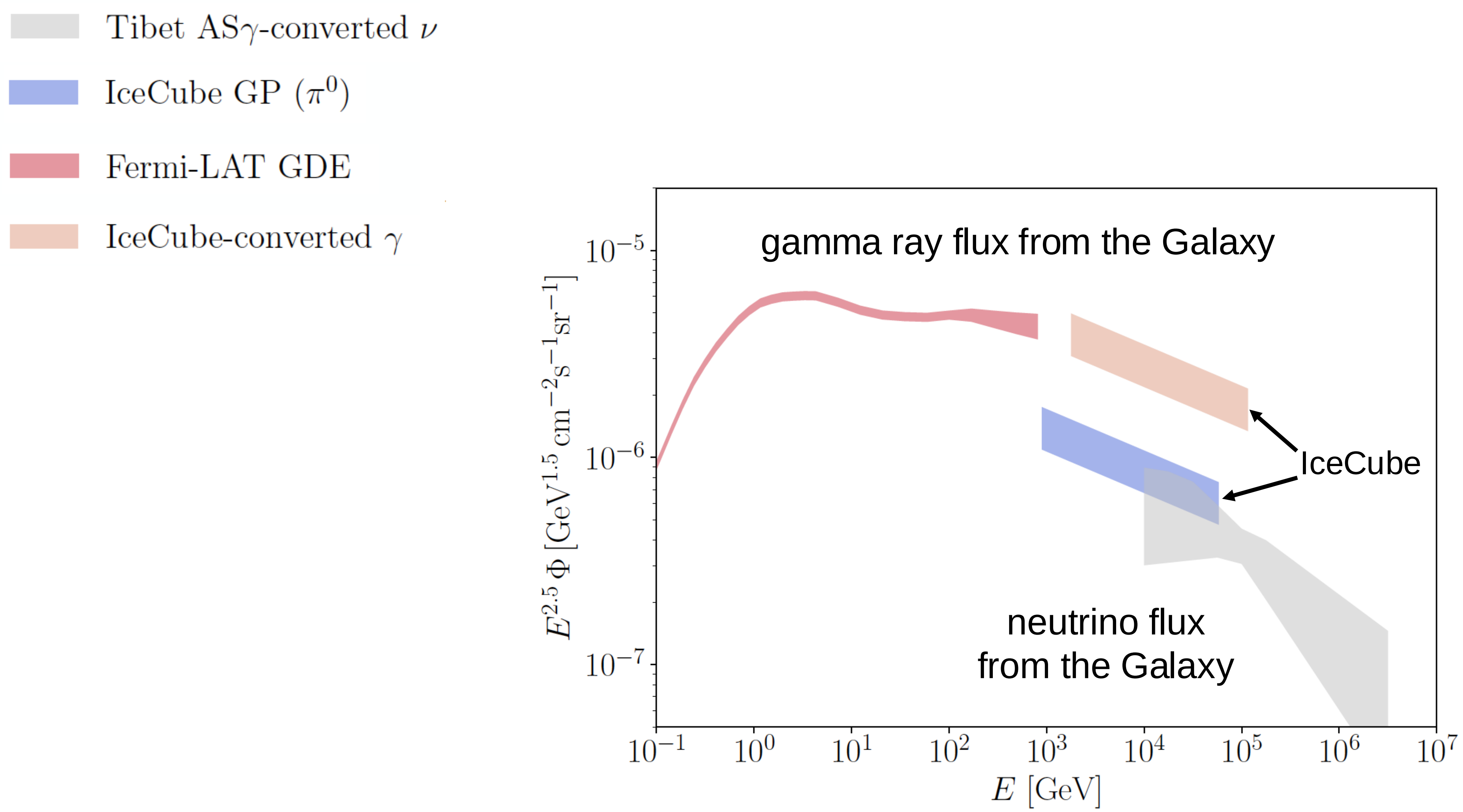

maximum likelihood:
point source template
→
Fermi GeVGalactic plane
data as template
→
match with a P-value
of 4.2 σ



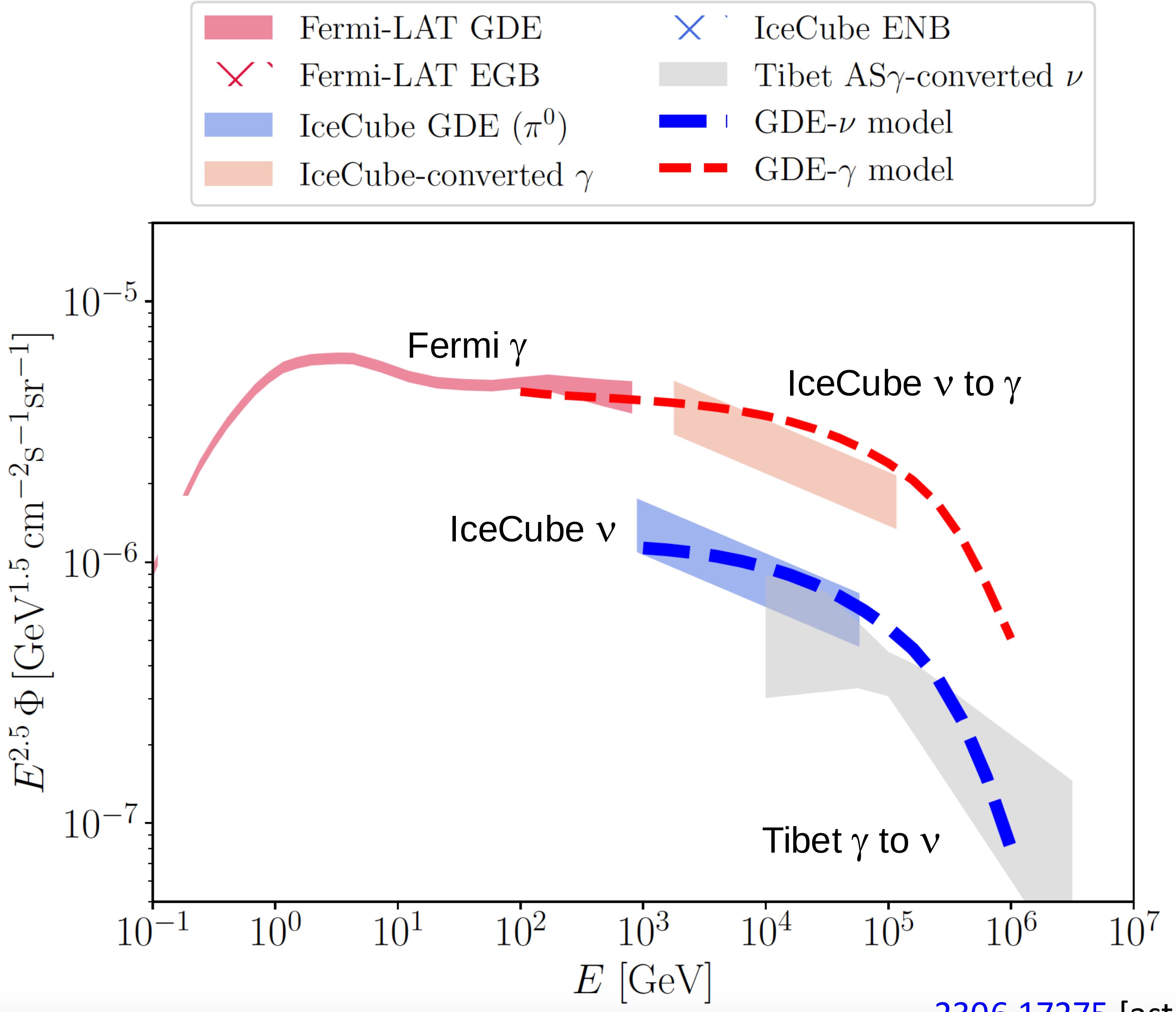
Fermi (GeV gamma rays) and IceCube (TeV neutrinos) see the same Galactic plane



neutrinos produced in Galactic cosmic rays
interactions with interstellar medium

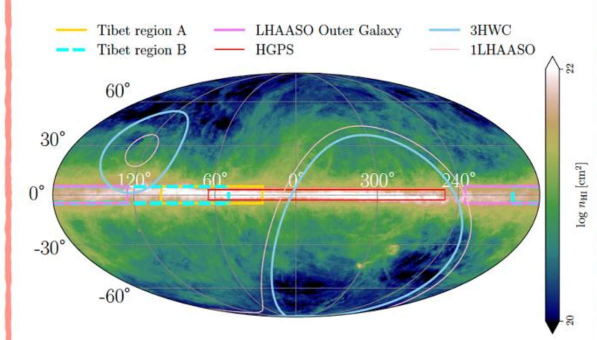


Tibet ASγ-converted ν
IceCube GP (π⁰)
Fermi-LAT GDE
IceCube-converted γ
gamma ray flux from the Galaxy
IceCube
neutrino flux
from the Galaxy
$E^{2.5}\,\Phi$ [GeV$^{1.5}$ cm^{-2}s^{-1}sr^{-1}]
10^{-5}
10^{-6}
10^{-7}
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
E [GeV]



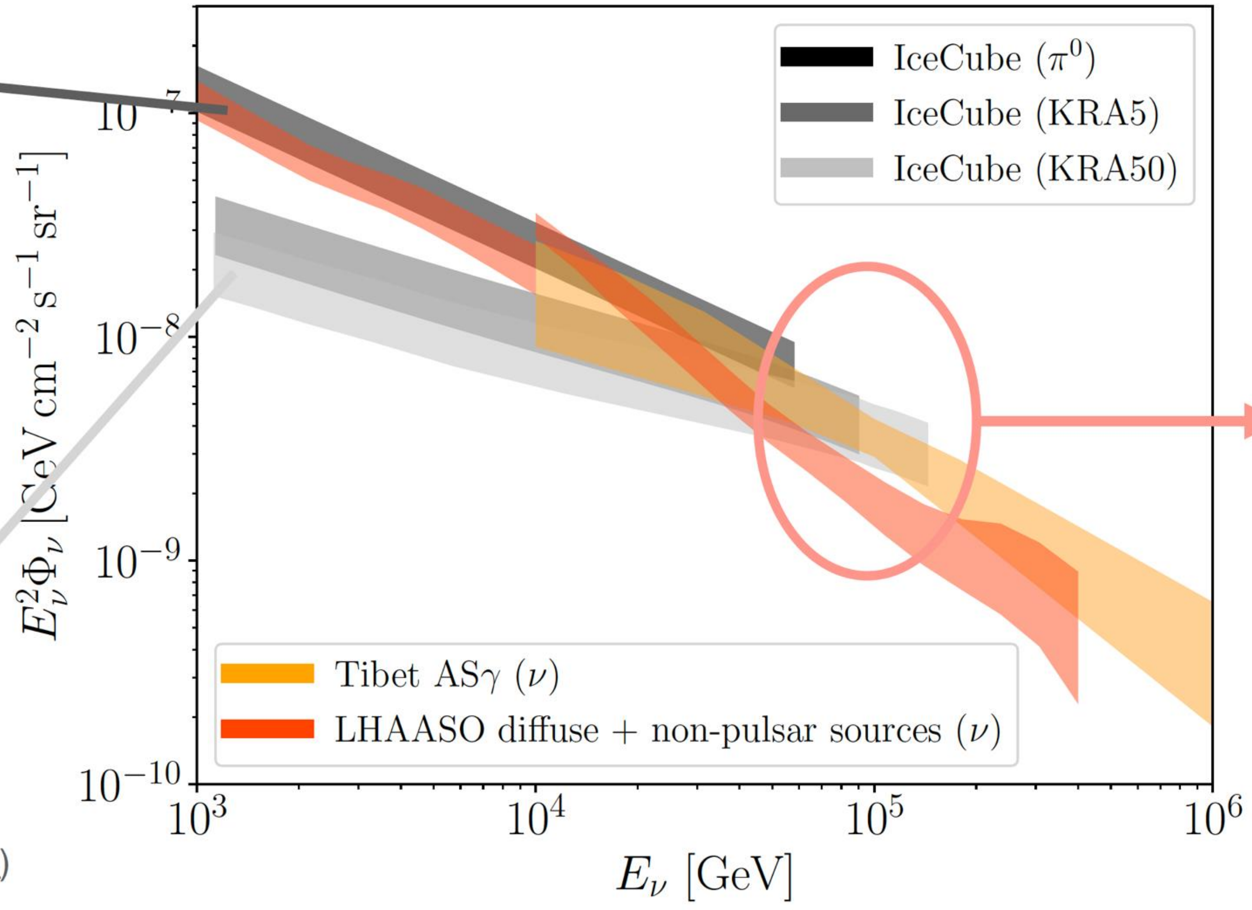
2306.17275 [astro-ph.HE]

Galactic Diffuse Emission: Source Contribution



Partial contribution by unresolved hadronic sources such as star-formation regions and molecular clouds

(Neronov+2023, Abhijit+2024)



Hadronic diffuse emission or/and a population of **γ-ray opaque neutrino emitters**

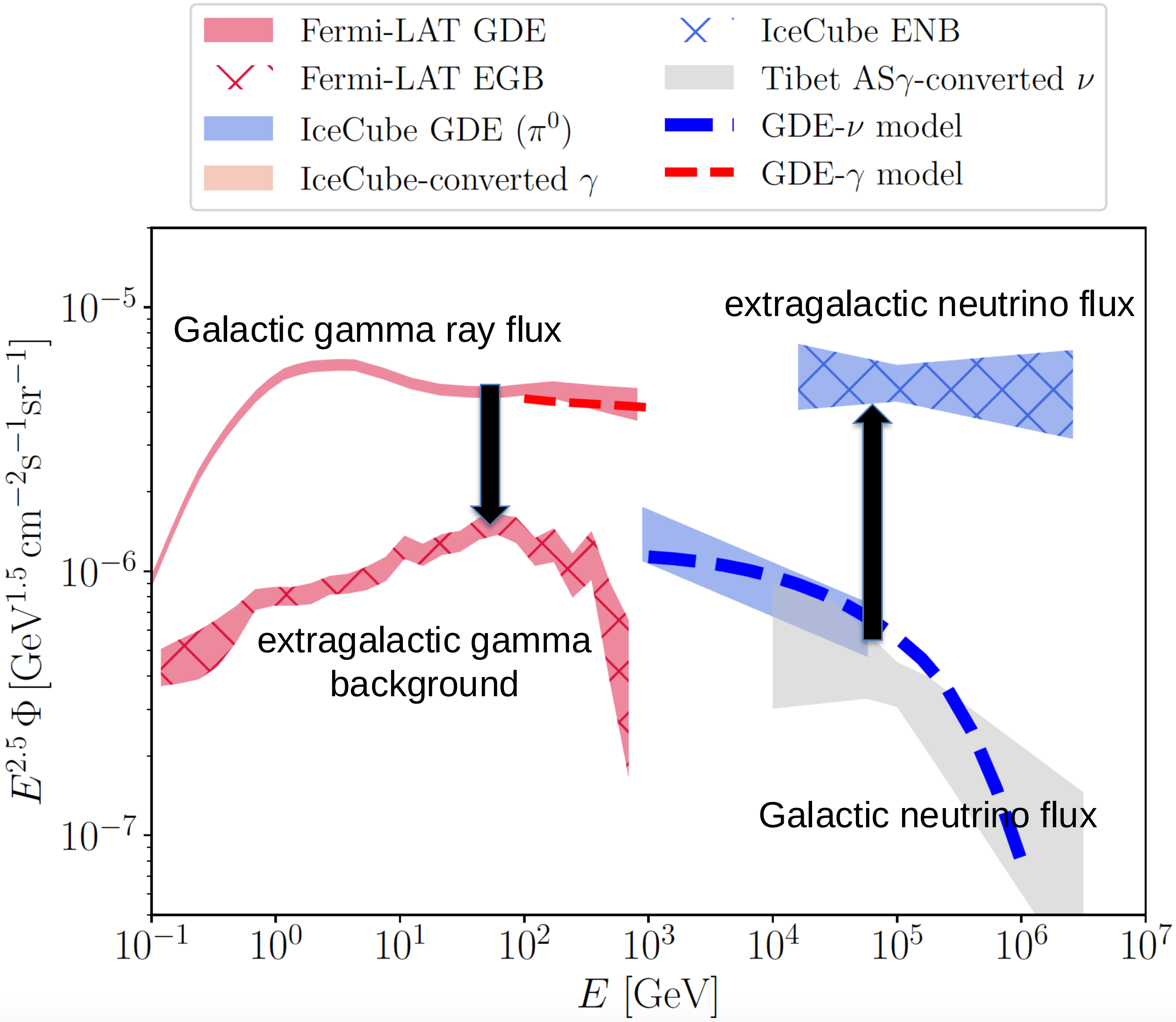
Room left for **leptonic emitters** such as TeV halos

(Dekker+2024, Kai+2024, Kaci+2024)

KF & Murase ApJL (2023)

See also analysis of Vecchiotti+2023, Silvia+2024

- we do not have the sensitivity to see LHAASO sources
- rule out that the Crab is a hadronic source



Fermi-LAT GDE
Fermi-LAT EGB
IceCube GDE (π^0)
IceCube-converted γ
IceCube ENB
Tibet ASγ-converted ν
GDE-ν model
GDE-γ model
Galactic gamma ray flux
extragalactic neutrino flux
extragalactic gamma background
Galactic neutrino flux
$E^{2.5}\,\Phi$ [GeV$^{1.5}$ cm^{-2}s^{-1}sr^{-1}]
10^{-5}
10^{-6}
10^{-7}
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
E [GeV]

- populate all galaxies in the Universe with neutrino sources
- seen from Earth you should see the sources in your own galaxy first; this is geometry
- the Milky Way should dominate the sky, as is the case for all wavelengths of light

→ powerful accelerators operate in other galaxies that do not exist in our own

→ our supermassive black hole has not been active for a few million years?

$$\frac{L_\nu^{EG}}{L_\nu^{MW}} \sim 120\,[\frac{\Phi_\nu^{EG}/\Phi_\nu^{MW}}{5}][\frac{n_0}{0.01\,\mathrm{Mpc}^{-3}}]^{-1}[\frac{\xi}{3}]^{-1}[\frac{F_\epsilon}{1}]$$

measured IceCube fluxes

factors of order unity

neutrino flux in active galaxies from diffuse flux observed

$$\Phi_\nu = n_0 c t_H\, L_\nu^{EG} \quad \xi \quad \text{(cosmology)}$$

neutrino flux in Milky Way from flux at Earth

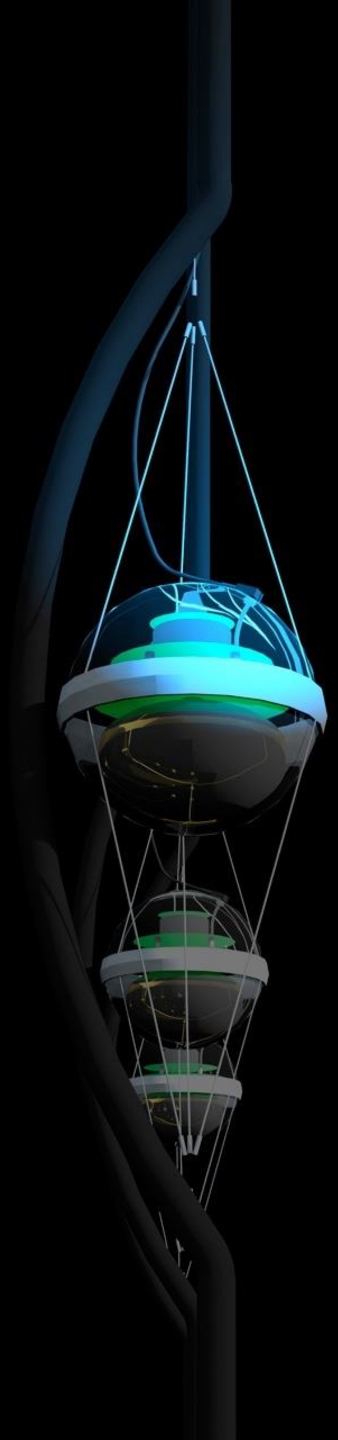
$$\Phi_{MW} = \frac{3}{4\pi r_0^2}\; L_\nu^{MW} \quad F_\epsilon \quad \text{(geometry)}$$

- in the extreme universe more energy is emitted in neutrinos than in gamma rays

- the π^0 photons accompanying cosmic rays appear at MeV energy, or below

- powerful accelerators operate in other galaxies that do not exist in our own

- [our supermassive black hole has not been active for a few million years?]

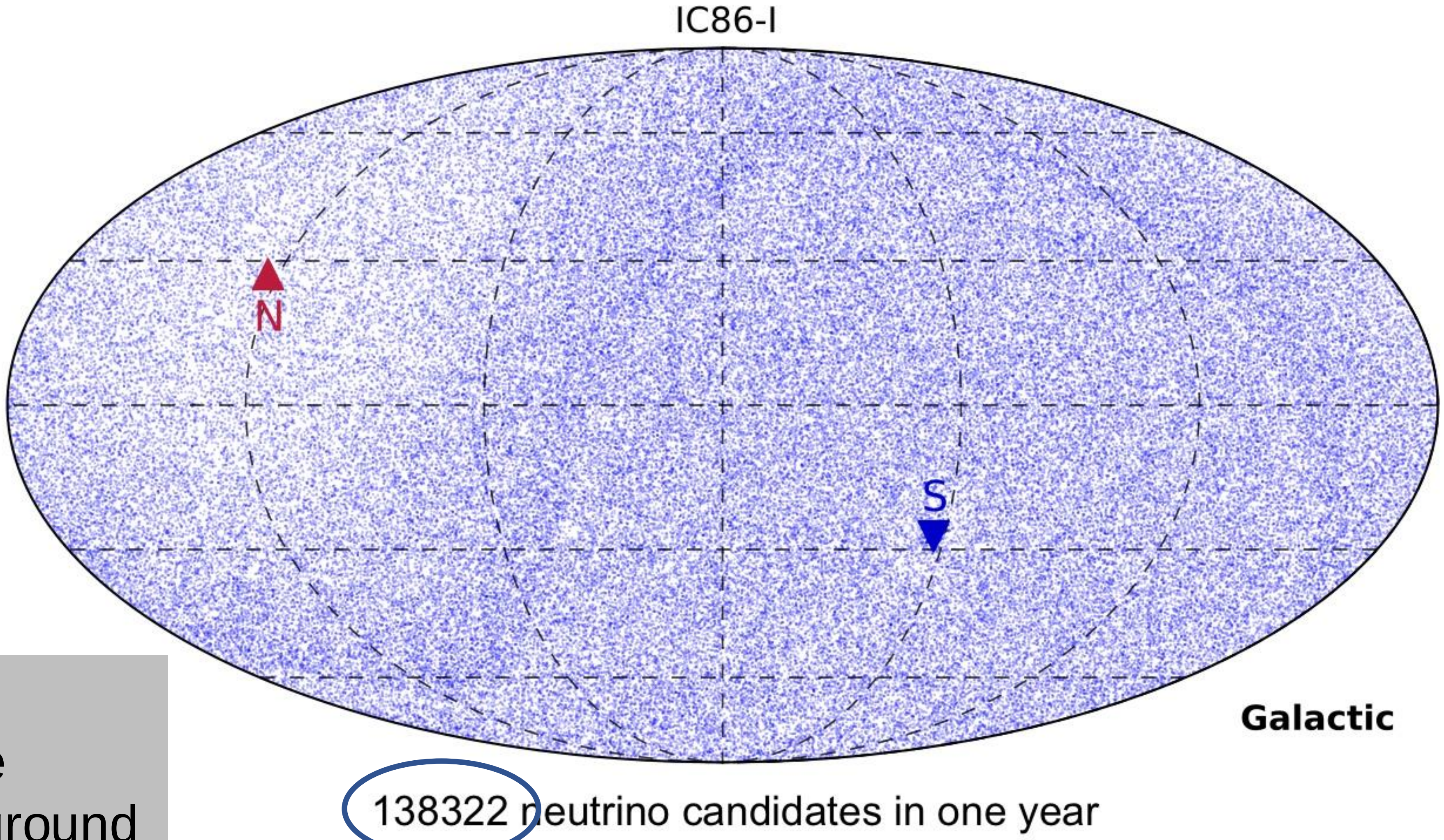


- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- and the answer is: supermassive black holes at the cores of active galaxies

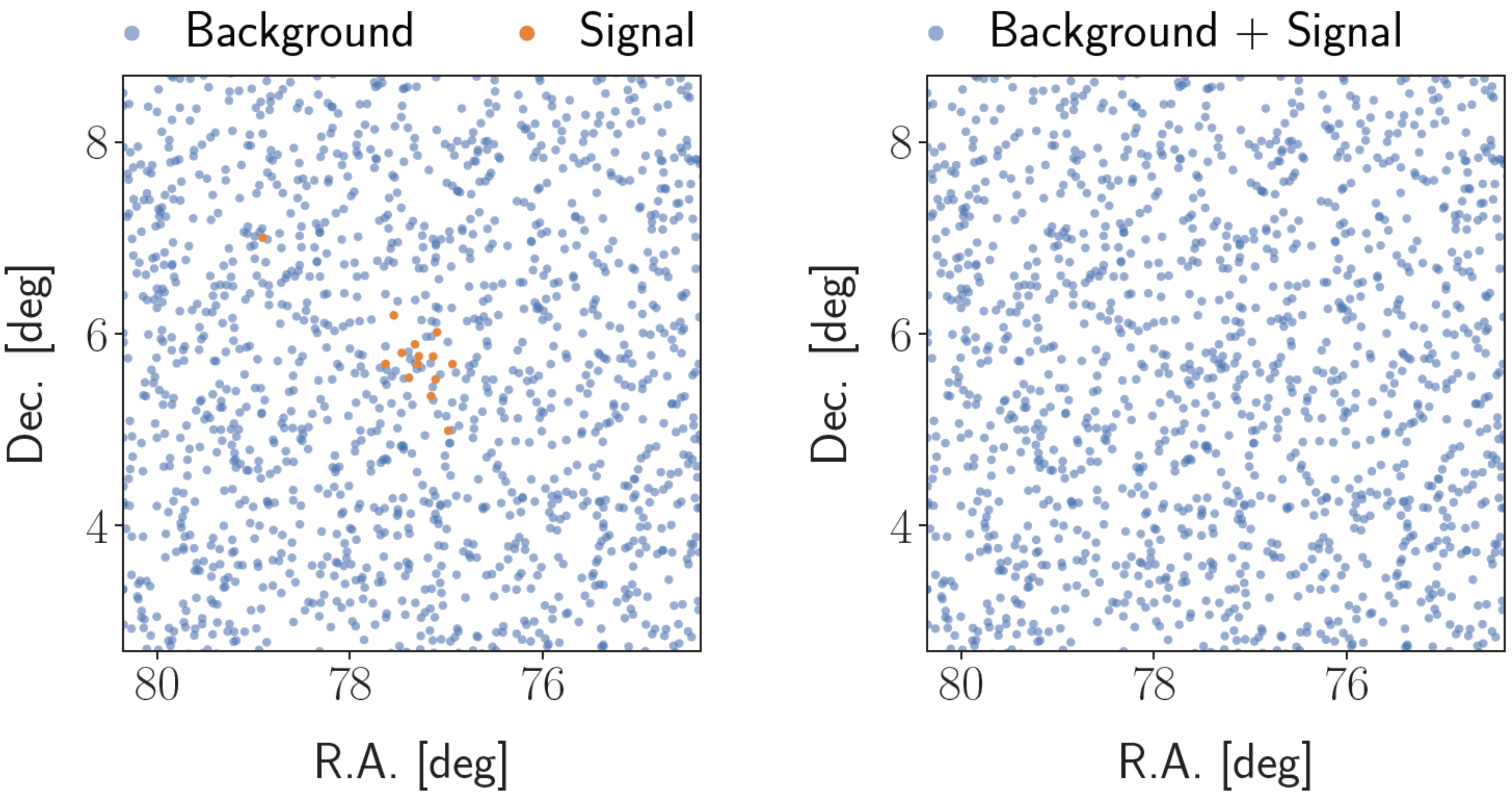
IceCube.wisc.edu

IceCube neutrinos >100 GeV (one year shown)

(reaches neutrino purity of > 97% but overwhelmingly atmospheric)



~ 200 cosmic neutrinos
~12 separated from the atmospheric background with E>60 TeV



- maximize the (model agnostic) likelihood L at each point in the sky
- usually, add energy term to the signal likelihood S

$$L(n_s, x_s, \gamma) = \prod_i^{events} \left(\frac{n_s}{N} S_i(|x_i - x_s|\sigma_i, E_i, \gamma) + \frac{N - n_s}{N} B_i(\delta_i, E_i)\right)$$

$$S_i(|\vec{x}_i - \vec{x}_s|, \sigma_i) = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}\right)$$

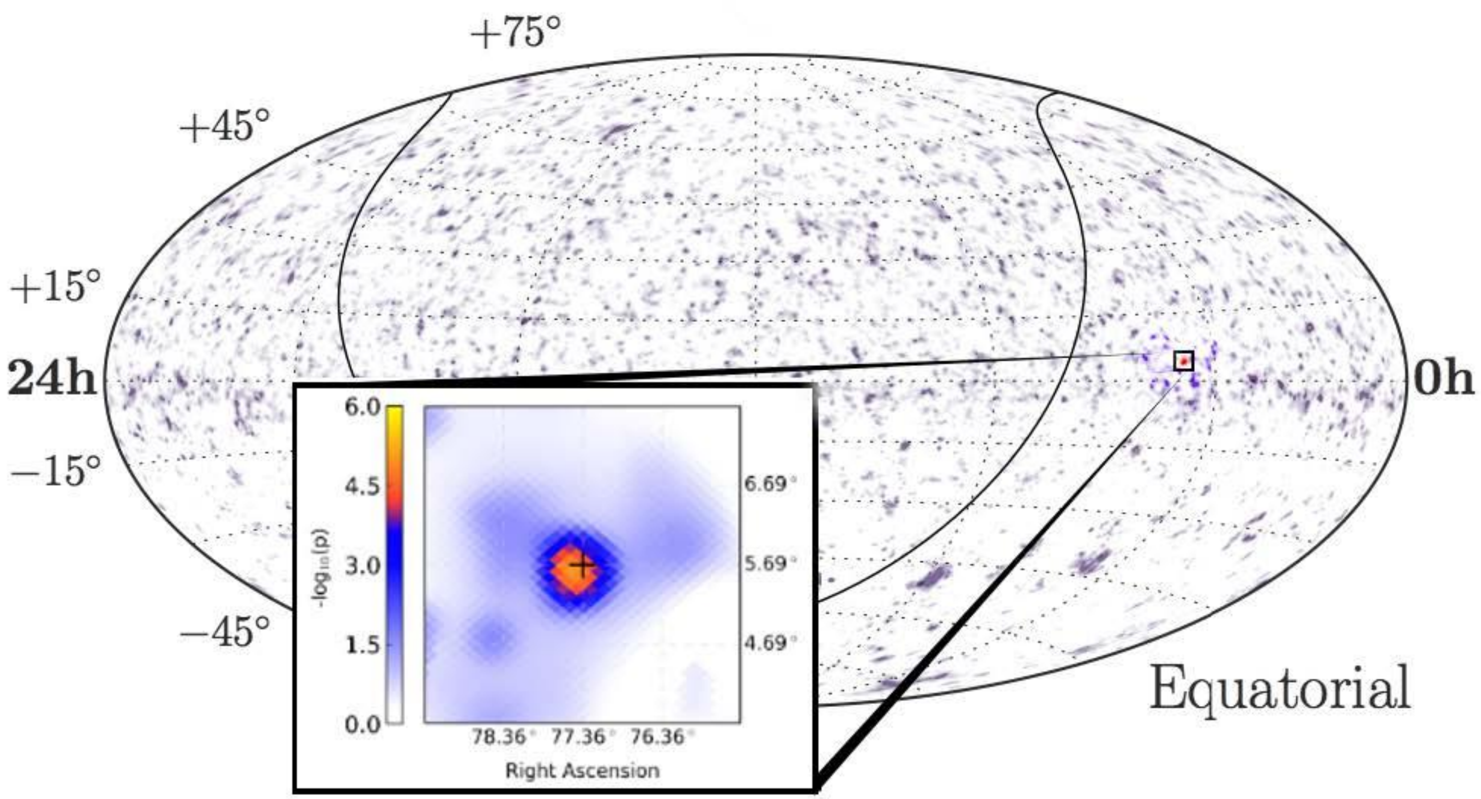
search in the directions of 110 preselected source candidates: hints of sources!

Phys.Rev.Lett. 124 (2020)

Source List Results

Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	-$\log_{10}(p_{local})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8
BL Lac	BLL	330.69	42.28	0.0	2.7	0.31	4.9
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3
1RXS J194246.3+1	BLL	295.70	10.56	0.0	2.7	0.33	2.6
RX J1931.1+0937	BLL	292.78	9.63	0.0	2.9	0.29	2.8
NVSS J190836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3
MGRO J1908+06	GAL	287.17	6.18	4.2	2.0	1.42	5.7
TXS 1902+556	BLL	285.80	55.68	11.7	4.0	0.85	9.9
HESS J1857+026	GAL	284.30	2.67	7.4	3.1	0.53	3.5
GRS 1285.0	UNIDB	283.15	0.69	1.7	3.8	0.27	2.3
HESS J1852-000	GAL	283.00	0.00	3.3	3.7	0.38	2.6
HESS J1849-000	GAL	282.26	-0.02	0.0	3.0	0.28	2.2
HESS J1843-033	GAL	280.75	-3.30	0.0	2.8	0.31	2.5
OT 081	BLL	267.87	9.65	12.2	3.2	0.73	4.8
S4 1749+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0
1H 1720+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2
PKS 1717+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3
Mkn 501	BLL	253.47	39.76	10.3	4.0	0.61	7.3
4C +38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0
PG 1553+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2
GB6 J1542+6129	**BLL**	**235.75**	**61.50**	**29.7**	**3.0**	**2.74**	**22.0**
B2 1520+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3
PKS 1502+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9
PKS 1502+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6
PKS 1441+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3
PKS 1424+240	**BLL**	**216.76**	**23.80**	**41.5**	**3.9**	**2.80**	**12.3**
NVSS J141826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0
B3 1343+451	FSRQ	206.40	44.88	0.0	2.8	0.32	5.0
S4 1250+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9
PG 1246+586	BLL	192.08	58.34	0.0	2.8	0.35	6.4
MG1 J123931+0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4
M 87	AGN	187.71	12.39	0.0	2.8	0.29	3.1
ON 246	BLL	187.56	25.30	0.9	1.7	0.37	4.2
3C 273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9
4C +21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5
W Comae	BLL	185.38	28.24	0.0	3.0	0.32	3.7
PG 1218+304	BLL	185.34	30.17	11.1	3.9	0.70	6.7
PKS 1216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1
B2 1215+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5
Ton 599	FSRQ	179.88	29.24	0.0	2.2	0.29	4.5
PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4
Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3
4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4
1H 1013+498	BLL	153.77	49.43	0.0	2.6	0.29	4.5
4C +55.17	FSRQ	149.42	55.38	11.9	3.3	1.02	10.6
M 82	SBG	148.95	69.67	0.0	2.6	0.36	8.8
PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	0.76	3.9
OJ 287	BLL	133.71	20.12	0.0	2.6	0.32	3.5
PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.28	2.1
S4 0814+42	BLL	124.56	42.38	0.0	2.3	0.30	4.9
OJ 014	BLL	122.87	1.78	16.1	4.0	0.99	4.4
1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.31	4.7
PKS 0736+01	FSRQ	114.82	1.62	0.0	2.8	0.26	2.4
PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.30	3.5
4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.60	4.8
S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.38	7.4
PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.51	4.4
1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.27	3.0
B3 0609+413	BLL	93.22	41.37	1.8	1.7	0.42	5.3
Crab nebula	GAL	83.63	22.01	1.1	2.2	0.31	3.7
OG +050	FSRQ	83.18	7.55	0.0	3.2	0.28	2.9
TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.92	6.6
TXS 0506+056	**BLL**	**77.35**	**5.70**	**12.3**	**2.1**	**3.72**	**10.1**
PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.66	4.1
S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.33	2.7
PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.46	3.1
MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.28	4.5
PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.27	2.3
PKS 0420-01	FSRQ	65.83	-1.33	9.3	4.0	0.52	3.4
PKS 0336-01	FSRQ	54.88	-1.77	15.5	4.0	0.99	4.4
NGC 1275	AGN	49.96	41.51	3.6	3.1	0.41	5.5
NGC 1068	**SBG**	**40.67**	**-0.01**	**50.4**	**3.2**	**4.74**	**10.5**
PKS 0235+164	BLL	39.67	16.62	0.0	3.0	0.28	3.1
4C +28.07	FSRQ	39.48	28.80	0.0	2.8	0.30	3.6
3C 66A	BLL	35.67	43.04	0.0	2.8	0.30	3.9
B2 0218+357	FSRQ	35.28	35.94	0.0	3.1	0.33	4.3
PKS 0215+015	FSRQ	34.46	1.74	0.0	3.2	0.27	2.3
MG1 J021114+1051	BLL	32.81	10.86	1.6	1.7	0.43	3.5
TXS 0141+268	BLL	26.15	27.09	0.0	2.5	0.31	3.5
B3 0133+388	BLL	24.14	39.10	0.0	2.6	0.28	4.1
NGC 598	SBG	23.52	30.62	11.4	4.0	0.63	6.3
S2 0109+22	BLL	18.03	22.75	2.0	3.1	0.30	3.7
4C +01.02	FSRQ	17.16	1.59	0.0	3.0	0.26	2.4
M 31	SBG	10.82	41.24	11.0	4.0	1.09	9.6
PKS 0019+058	BLL	5.64	6.14	0.0	2.9	0.29	2.4
PKS 2233-148	BLL	339.14	-14.56	5.3	2.8	1.26	21.4
HESS J1841-055	GAL	280.23	-5.55	3.6	4.0	0.55	4.8
HESS J1837-069	GAL	279.43	-6.93	0.0	2.8	0.30	4.0
PKS 1510-089	FSRQ	228.21	-9.10	0.1	1.7	0.41	7.1
PKS 1329-049	FSRQ	203.02	-5.16	6.1	2.7	0.77	5.1
NGC 4945	SBG	196.36	-49.47	0.3	2.6	0.31	50.2
3C 279	FSRQ	194.04	-5.79	0.3	2.4	0.20	2.7
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

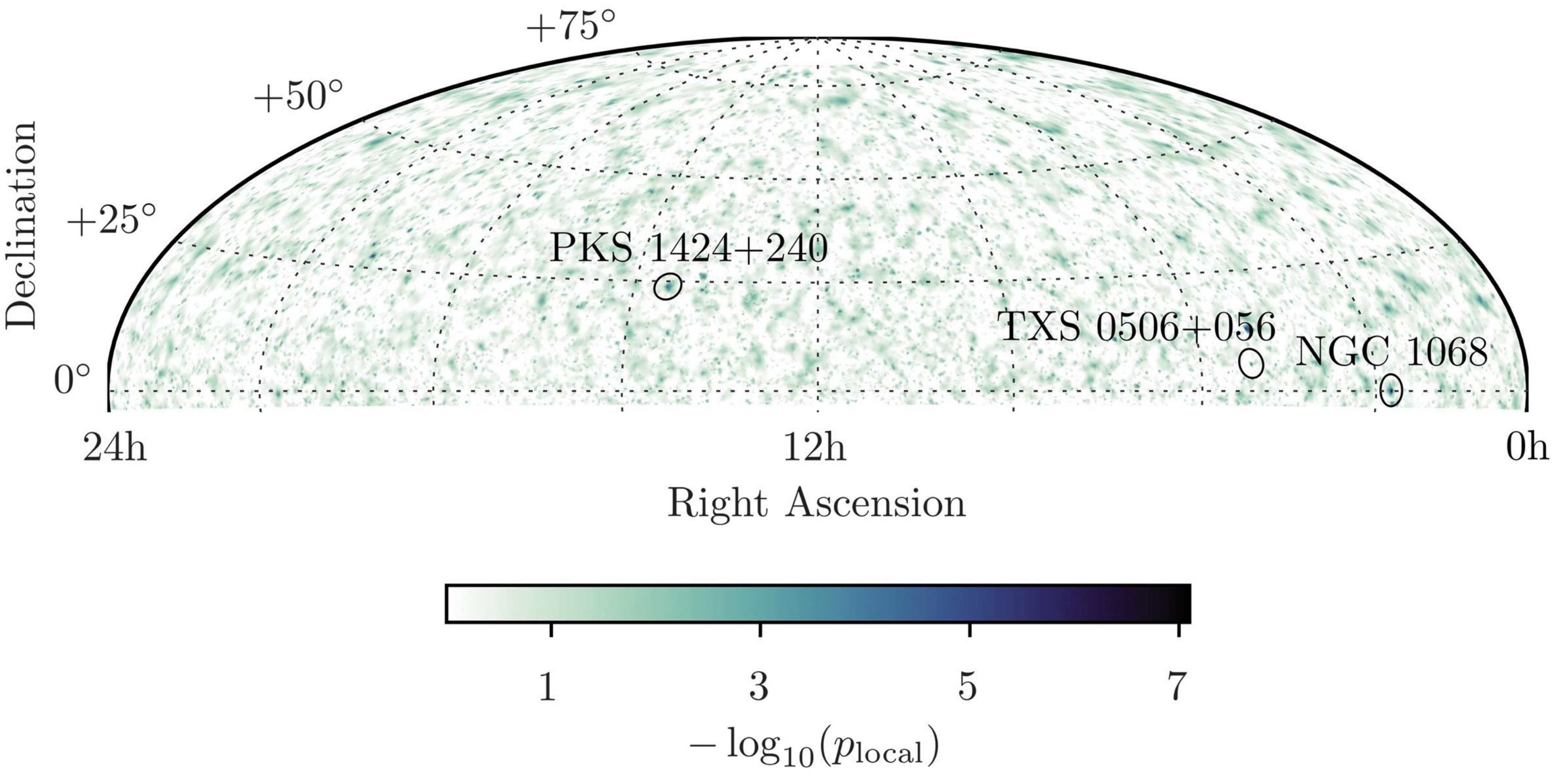
pre-trial p-value for clustering of high energy neutrinos



- hottest spot coincident with NGC 1068
- also hottest spot in the sources list (2.9σ)

statistical fluctuations or neutrino sources?

sub-leading sources: binomial analysis

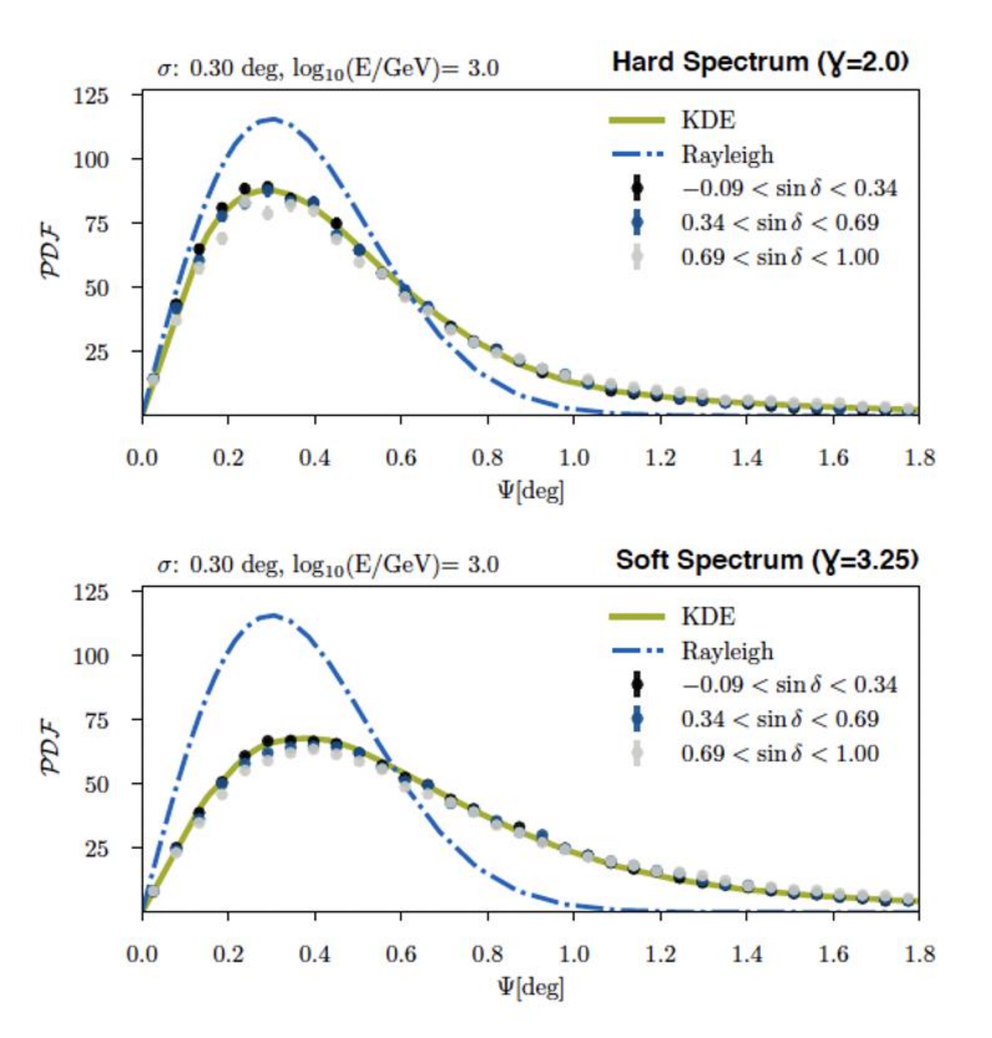


interesting fluctuations or neutrino sources?

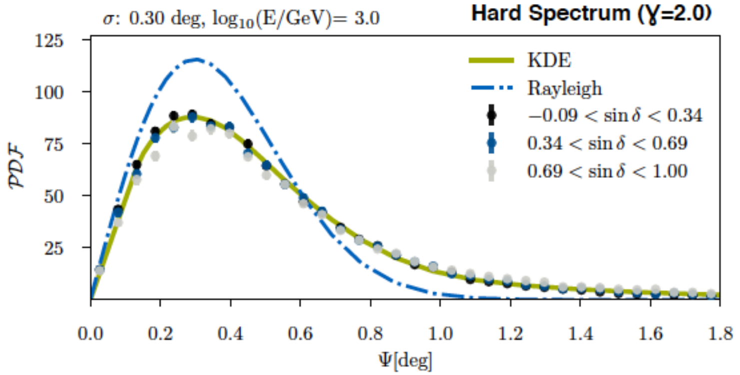
→ crash program to upgrade the performance of IceCube

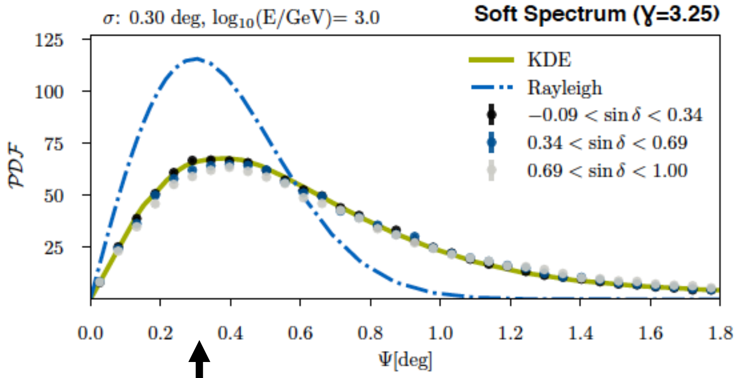
- improved detector geometry
- each photomultiplier calibrated individually
- improved characterization of the optics of the ice
- improved muon angular resolution and energy reconstruction using machine learning
- *point spread function consistent with simulation or, we were partially blind*
- …

applied to 10 years of archival data (pass 2), data unblinded, result …



- point spread function consistent with simulation
- insensitive to systematics



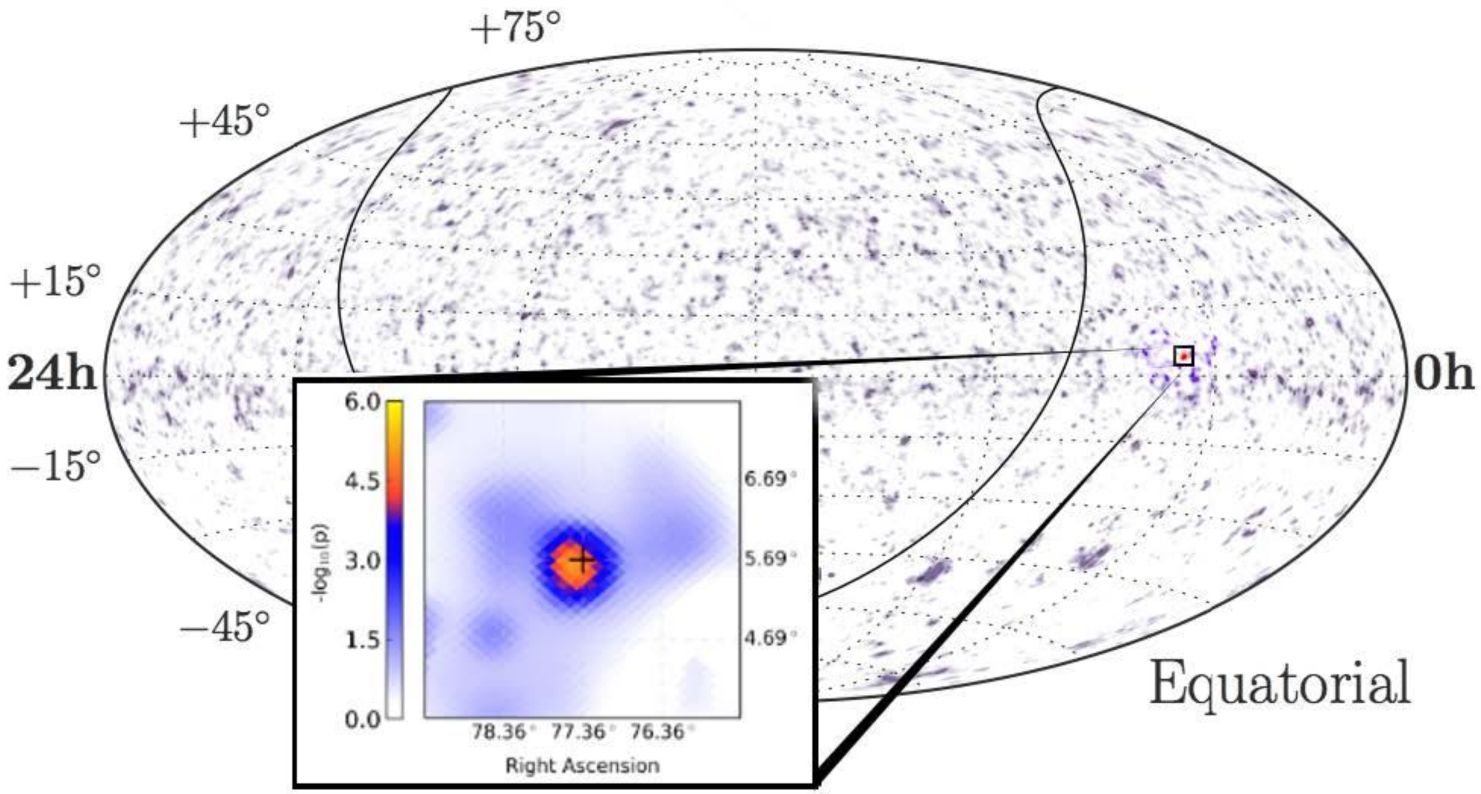


muon direction

- 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 TeV energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation of the ɣ-dependent spatial term from MC simulation (for example using KDEs)

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

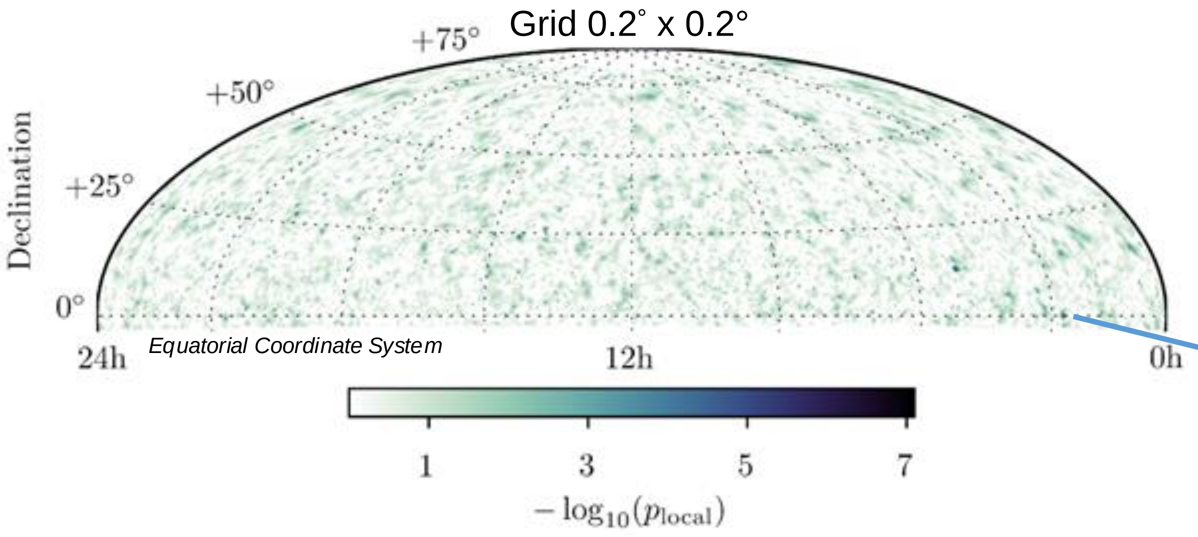
pre-trial p-value for clustering of high energy neutrinos

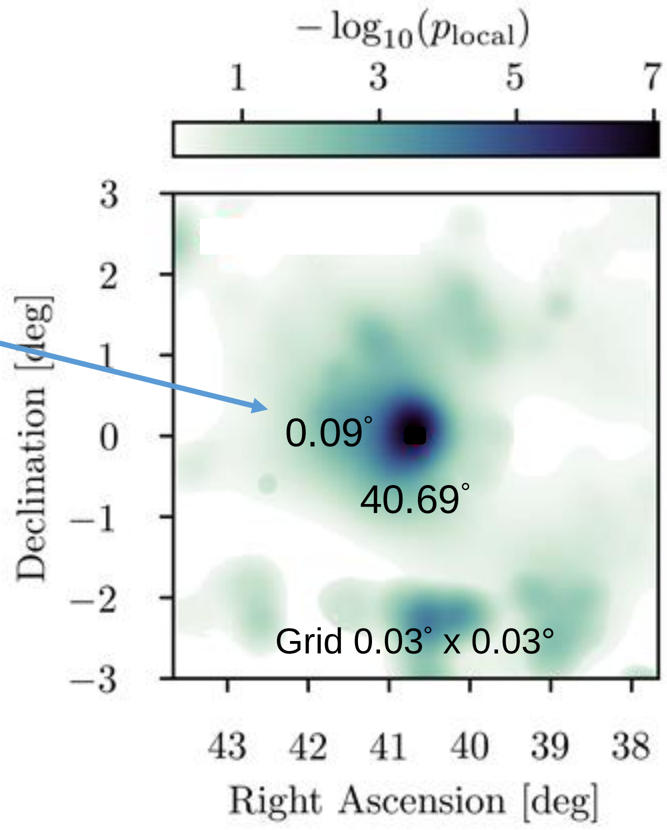


- hottest spot coincident with NGC 1068
- also hottest spot in the sources list (2.9σ)

statistical fluctuations or neutrino sources?

the new IceCube neutrino map: hottest spot





the brightest location in full sky scan:

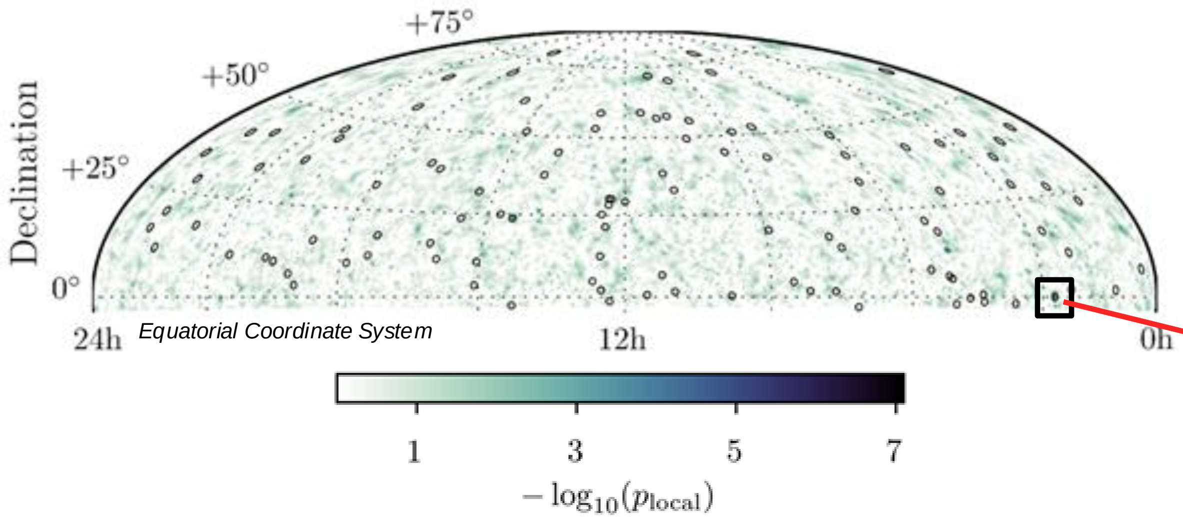
→ astrophysical neutrino events = 81

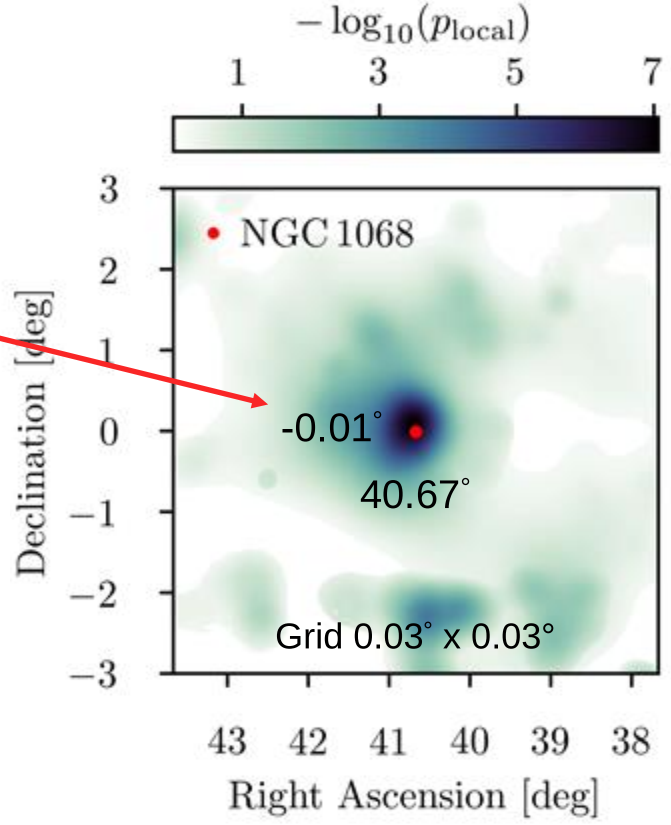
→ spectral index = 3.2

local significance 5.3σ

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

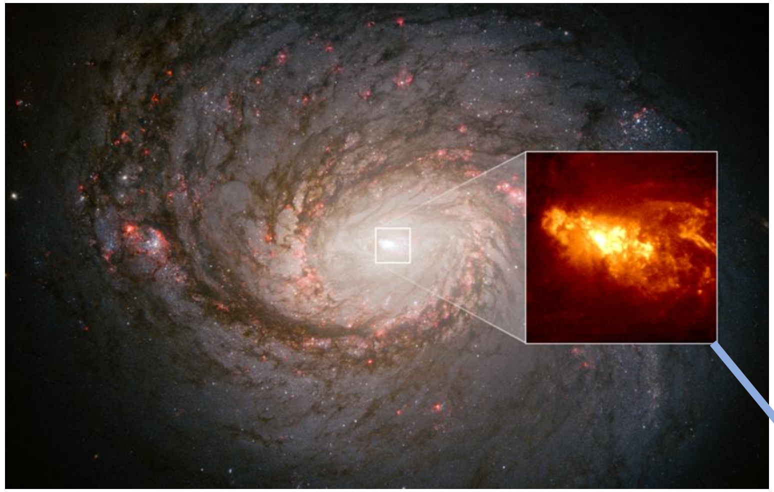
is the hot spot coincident with one of the 110 preselected sources?





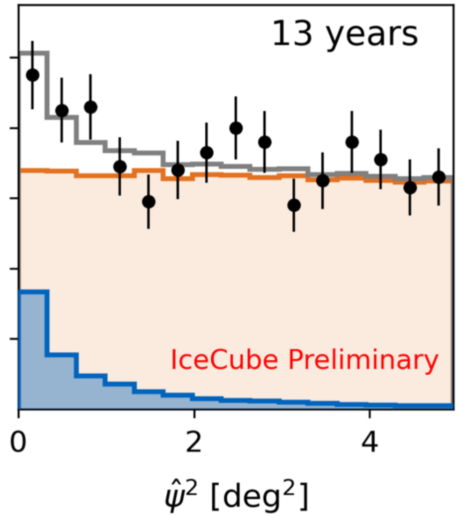
at the NGC1068 location

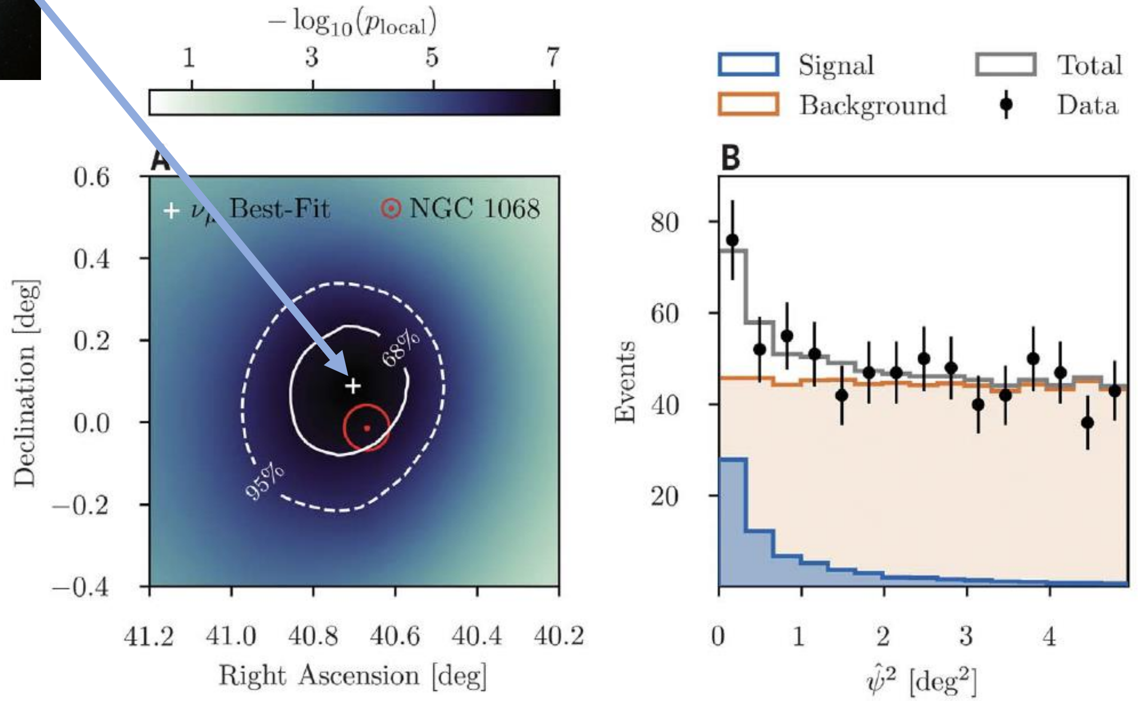
- astrophysical neutrino events = 79 $^{+22}_{-20}$
- spectral index = 3.2 ± 0.2
- single source significance 5.2σ
- (offset 0.11^0)
- 1 in 100,000 scrambled data sets have object ≥ 5.2 **σ** = 4.2 **σ**
- p-value $<10^{-5}$ including all trials

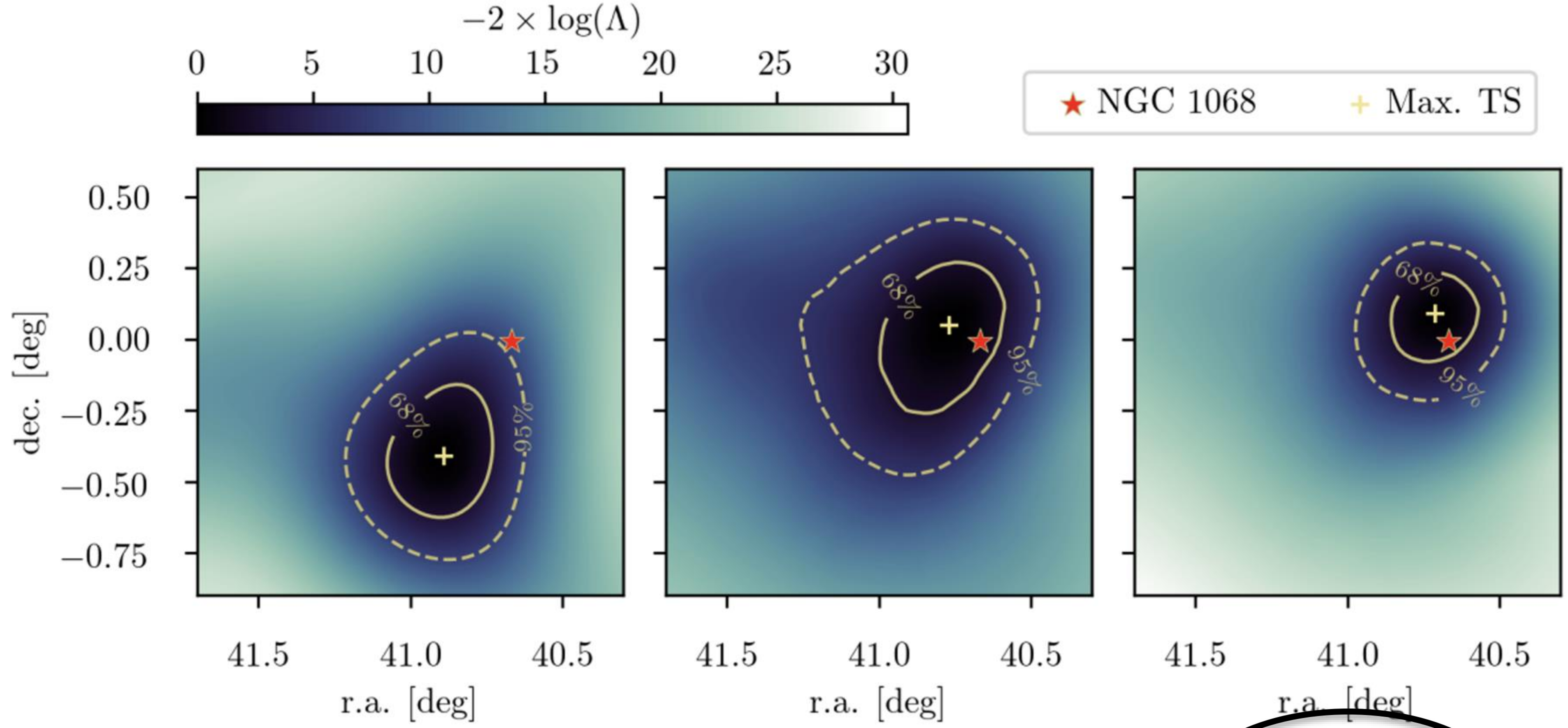


80 high-energy neutrinos from the direction of the active galaxy NGC 1068

update: 100 events







NGC 1068 comes into focus

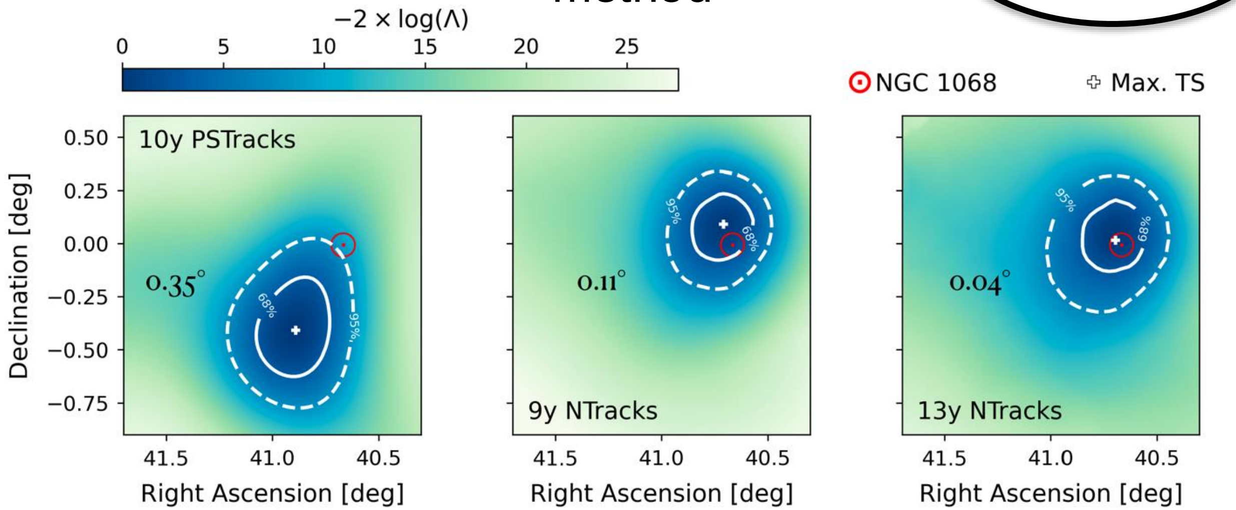
2.9σ
- 10-year analysis

3.3σ
- new likelihood method

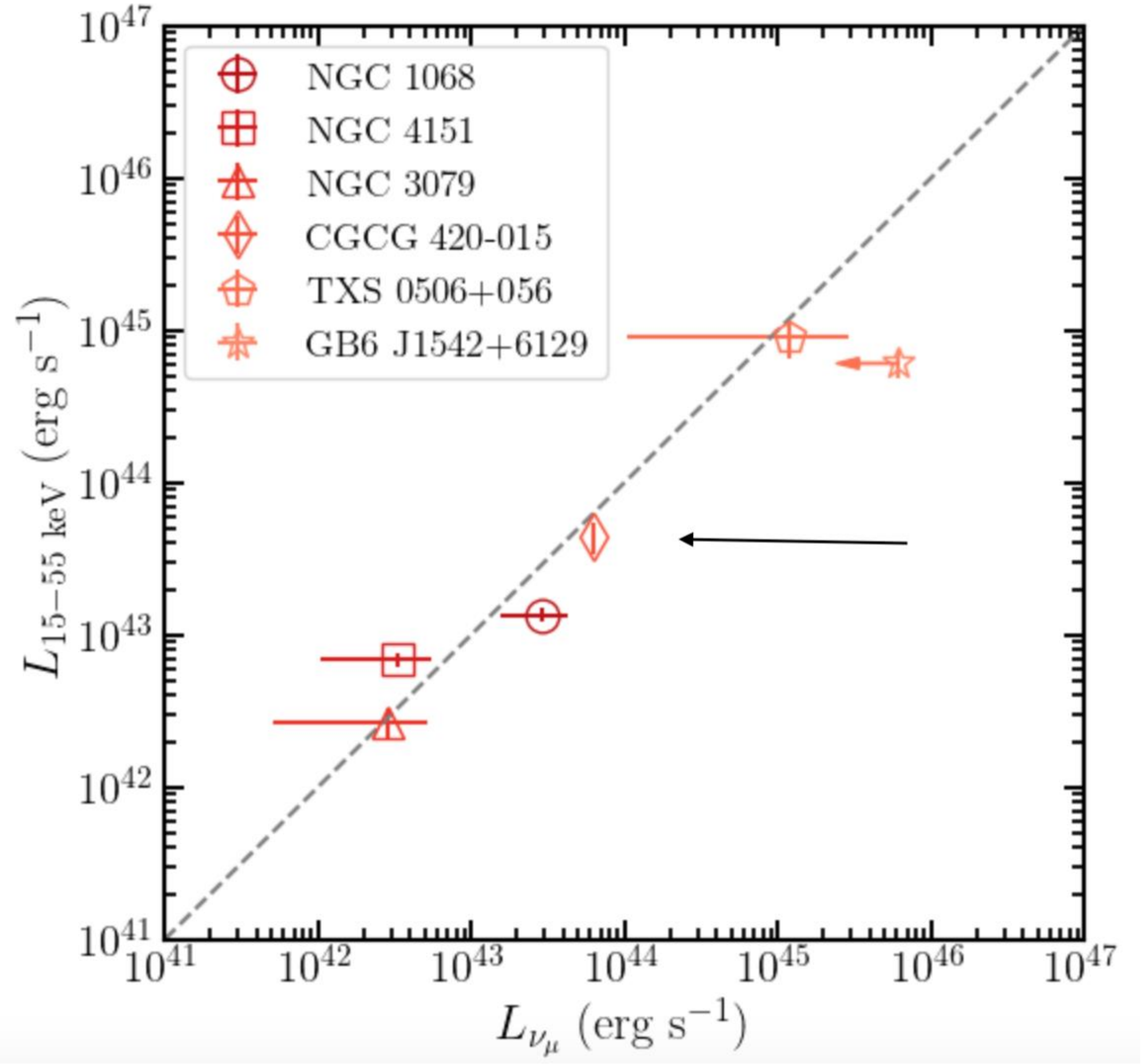
4.2σ
- pass 2

5.2σ local significance

update



- X-ray vs neutrino flux
- a correlation between the X-ray and neutrino flux of active galaxies producing neutrinos?
- X-ray flux of TXS 0506+056 is consistent with this pattern: neutrinos are produced in the core, not the jet



(Emma Kun et al., Neronov et al.)

The Emergence of a new class of sources?

→ 2022 Evidence for Neutrino Emission from NGC 1068 (Science)
Binomial analysis TXS 05060 and PKS 1420

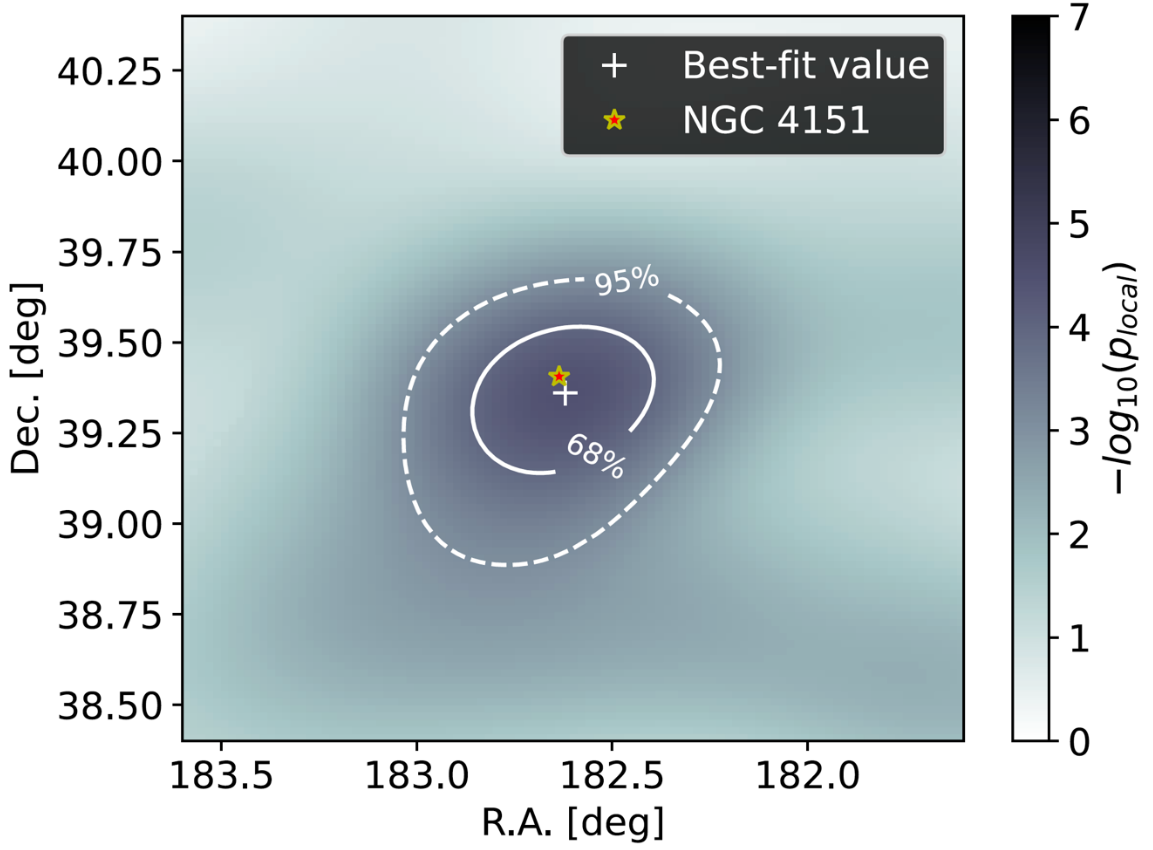
→ 2024: IceCube Search for Neutrino Emission from X-ray Bright Seyfert Galaxies
Northern sky NGC 4151 and CGCG 420-015
arXiv:2406.07601

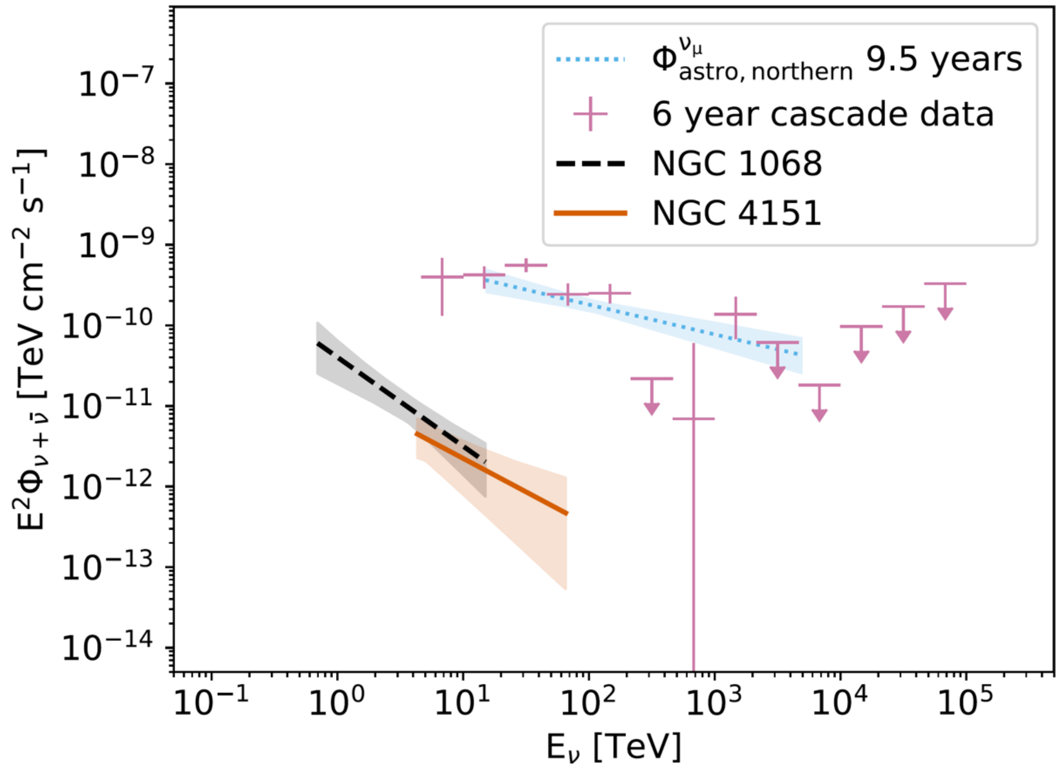
→ 2024 Starting event search for Seyfert galaxies
TeVPA 2024
Circinus

→ 2024 Search for neutrino emission from hard X-ray AGN with IceCube
NGC 4151
arXiv:2406.06684

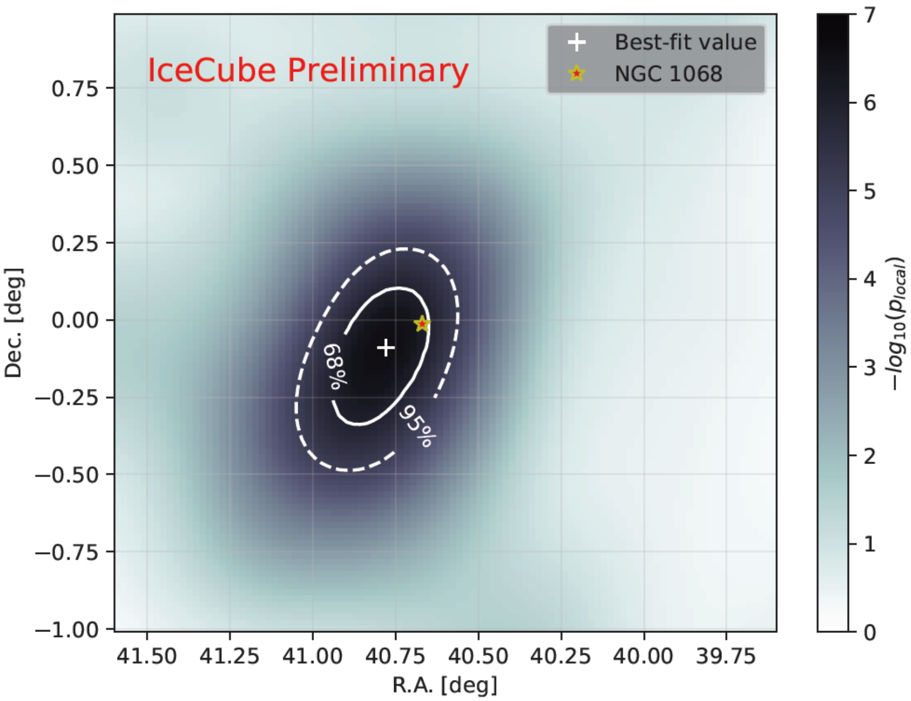
→ 2024 Binomial excess from 12 X-ray bright Seyferts (update)

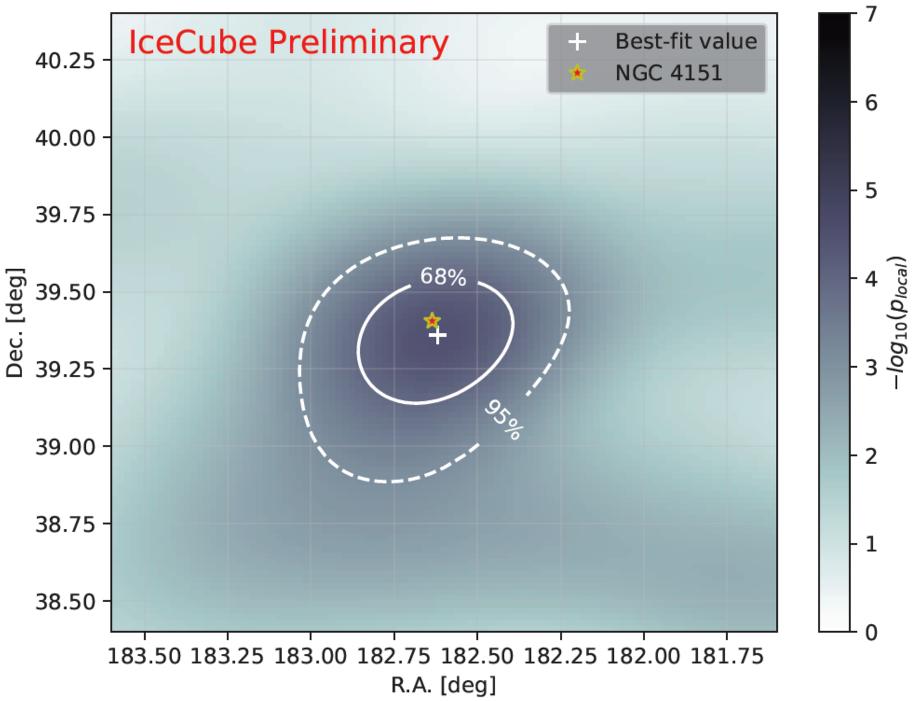
multimessenger astronomy with X-ray sources



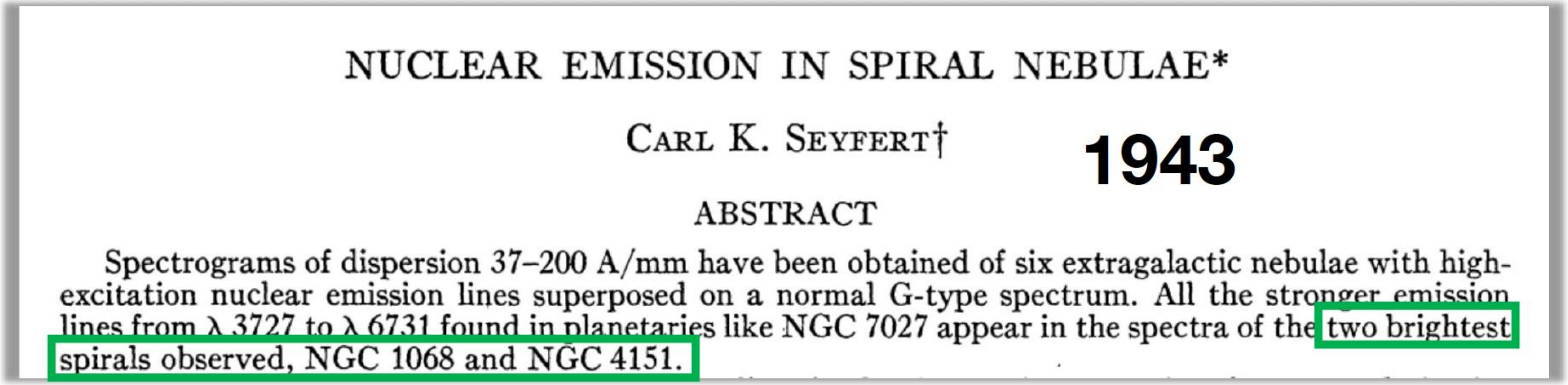


more sources …





- two brightest active galaxies discovered by Seyfert in 1943



NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

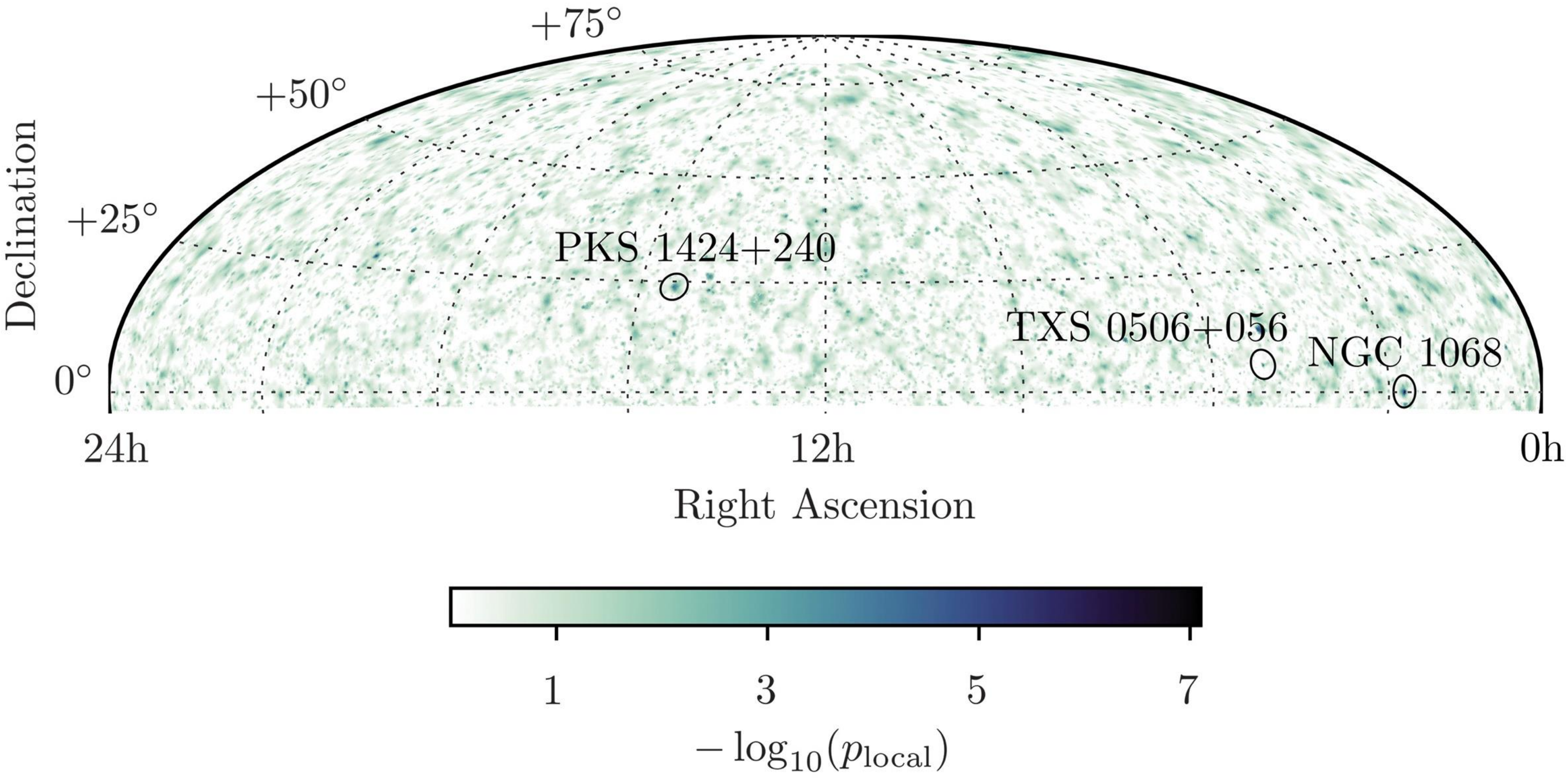
1943

ABSTRACT

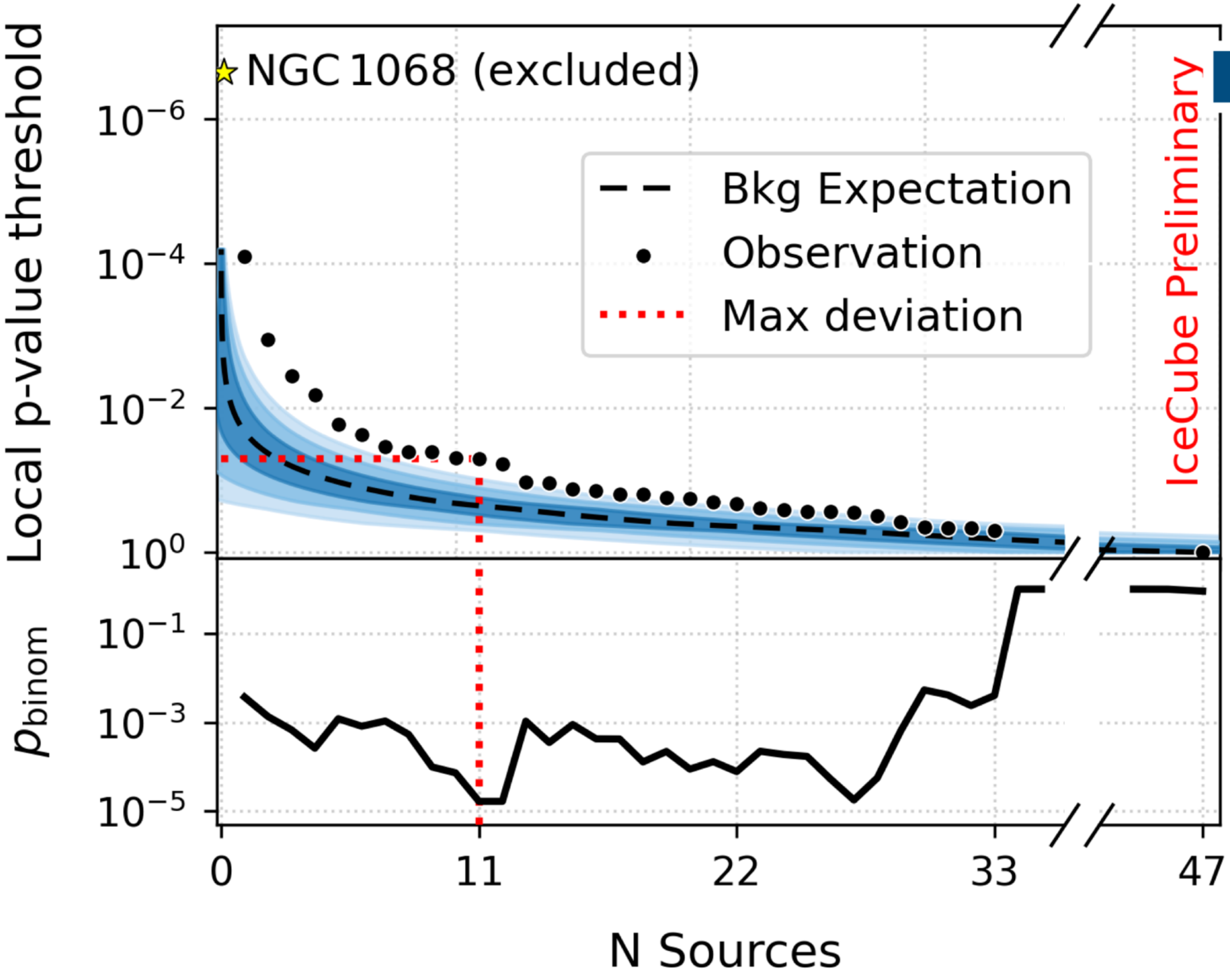
Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest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

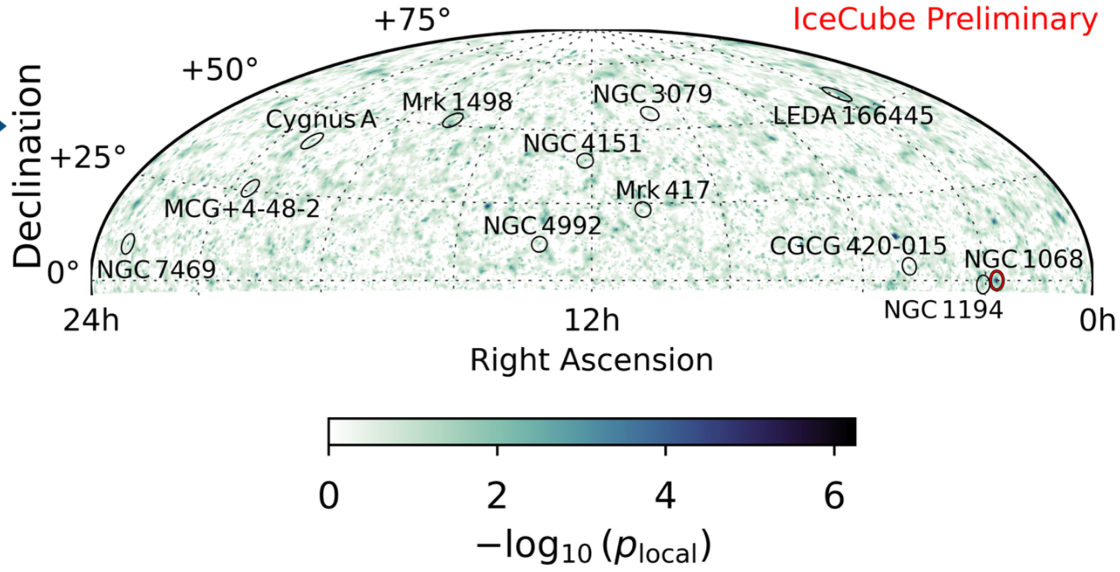
Carl K. Seyfert (VANDERBILT SPECIAL COLLECTIONS AND UNIVERSITY ARCHIVES)

binomial analysis: 3 active galaxies



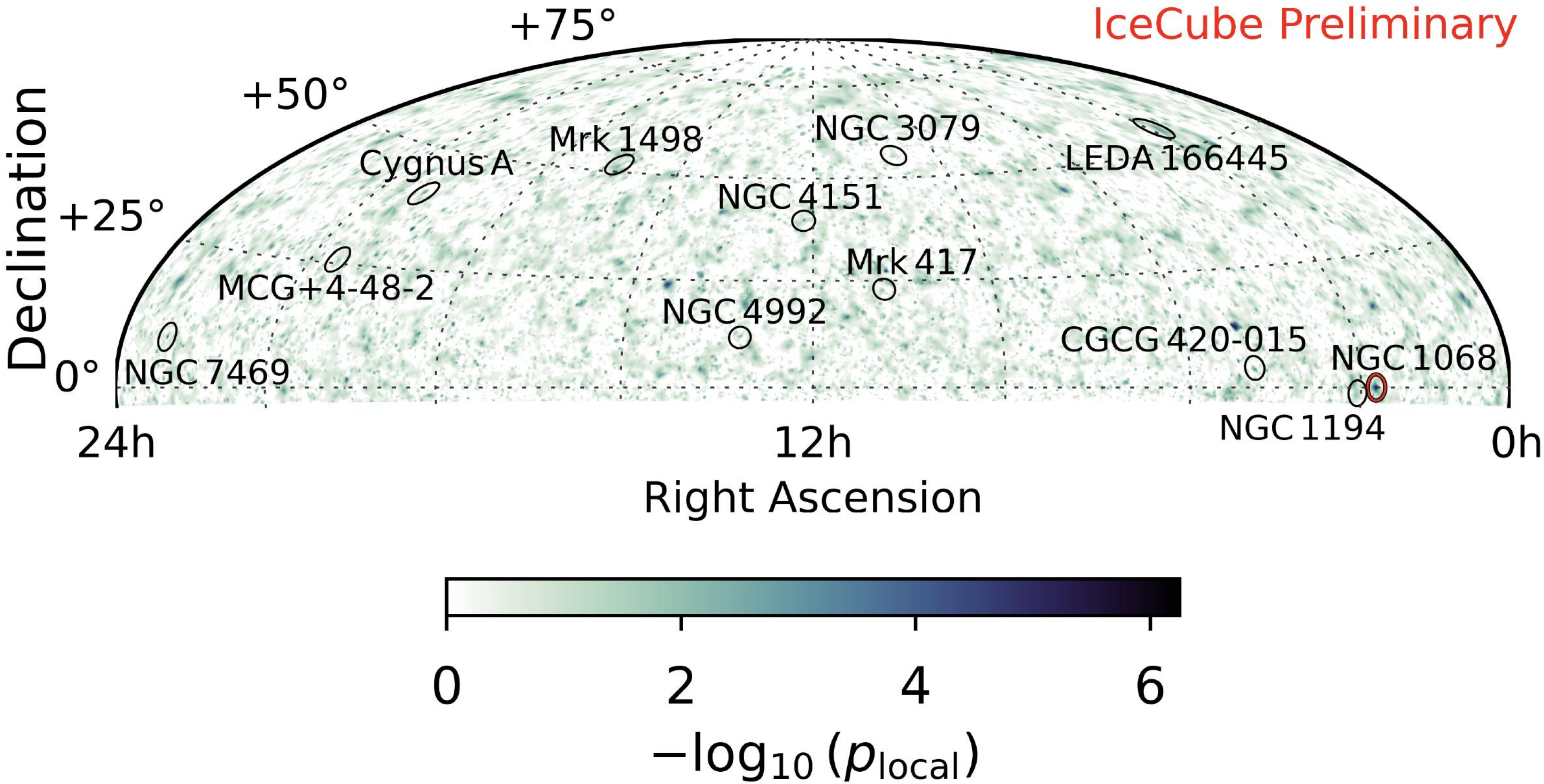
Binomial Test



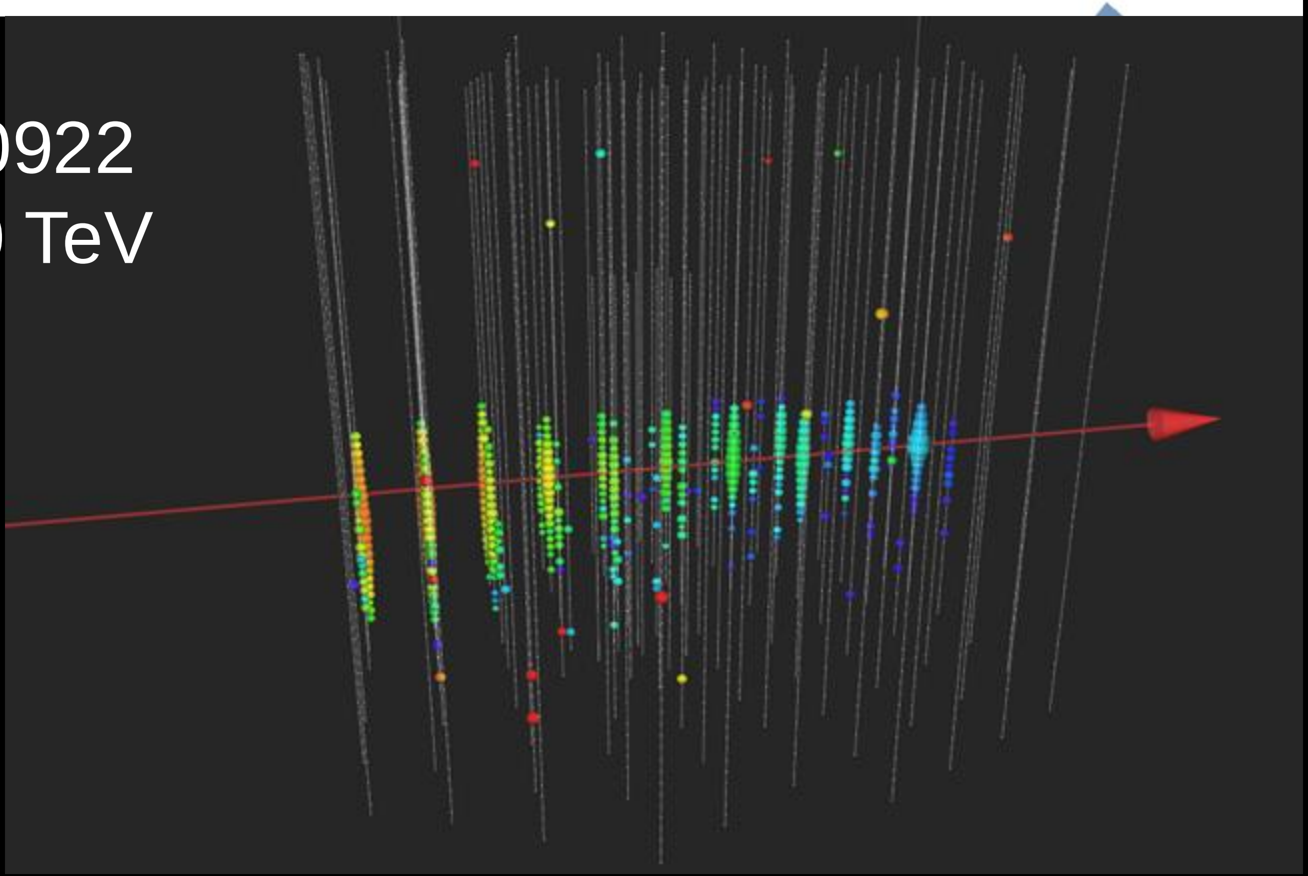


- Binomial Test: Probability of finding a signal from 47 AGNs too weak to be identified individually
- Result: 3.3σ excess for 11 sources (excluding NGC1068)

binomial test of X-ray bright Seyfert galaxies



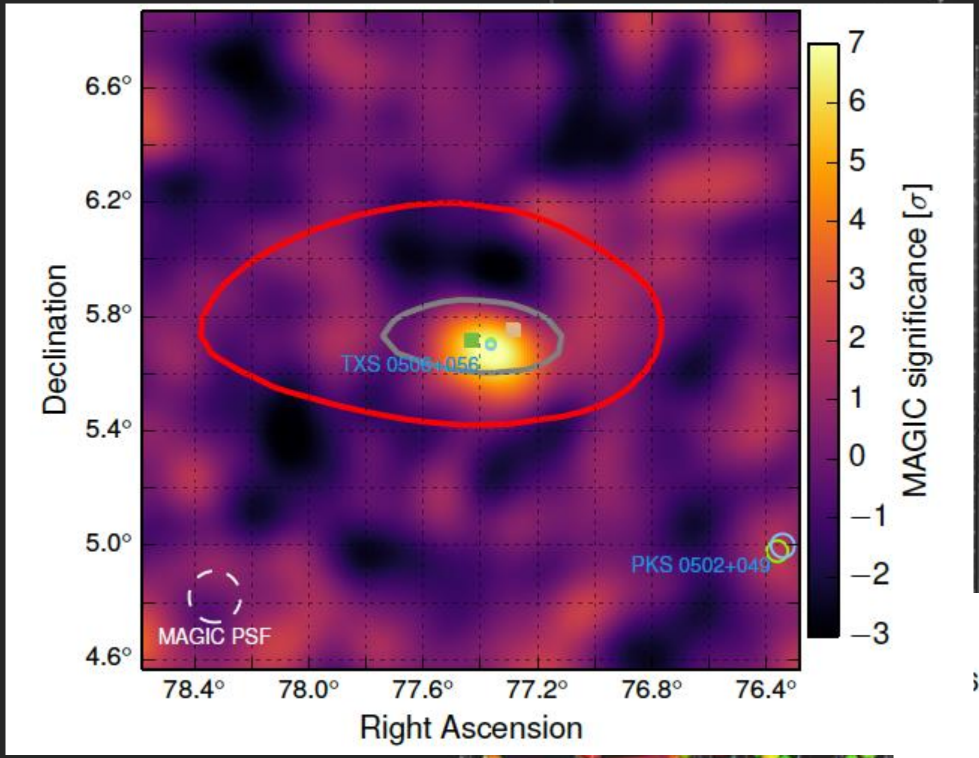
IceCube 170922
290 TeV

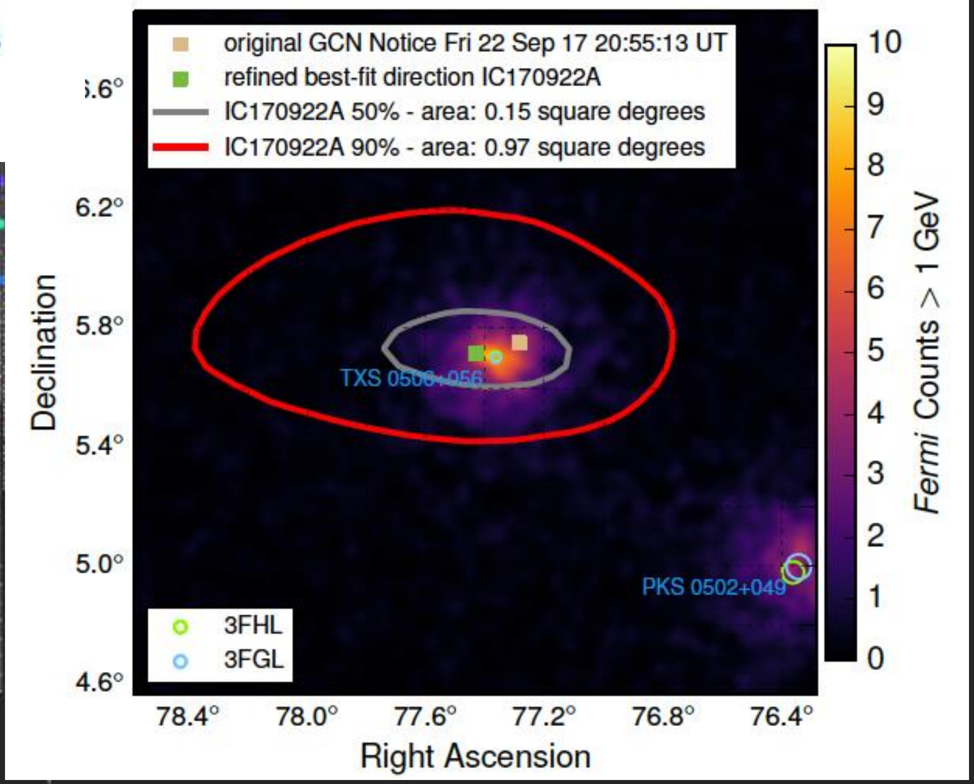


from light in the ice to astronomer in less than one minute

IceCube 170922
290 TeV

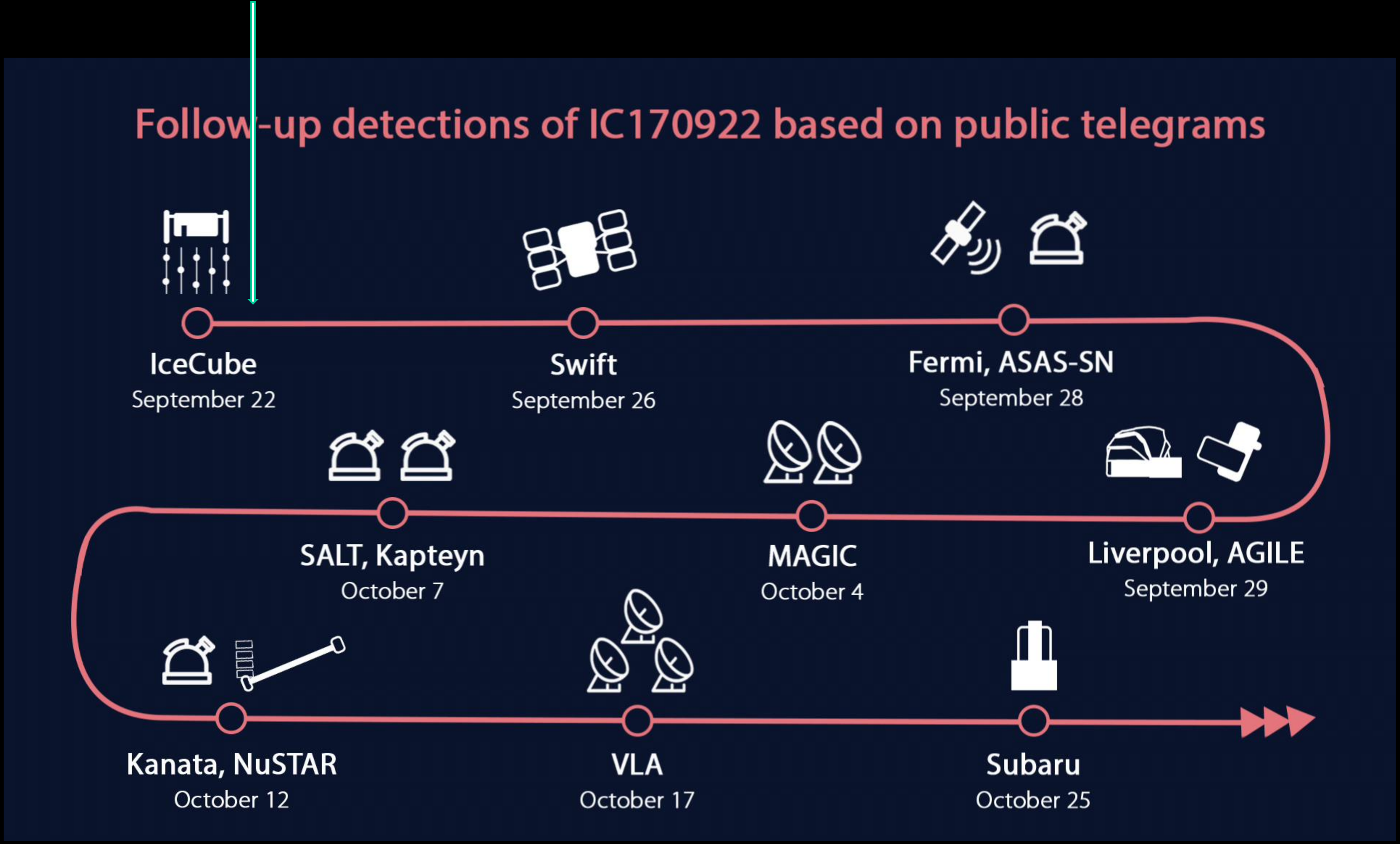
Fermi
detects a flaring blazar within 0.06°





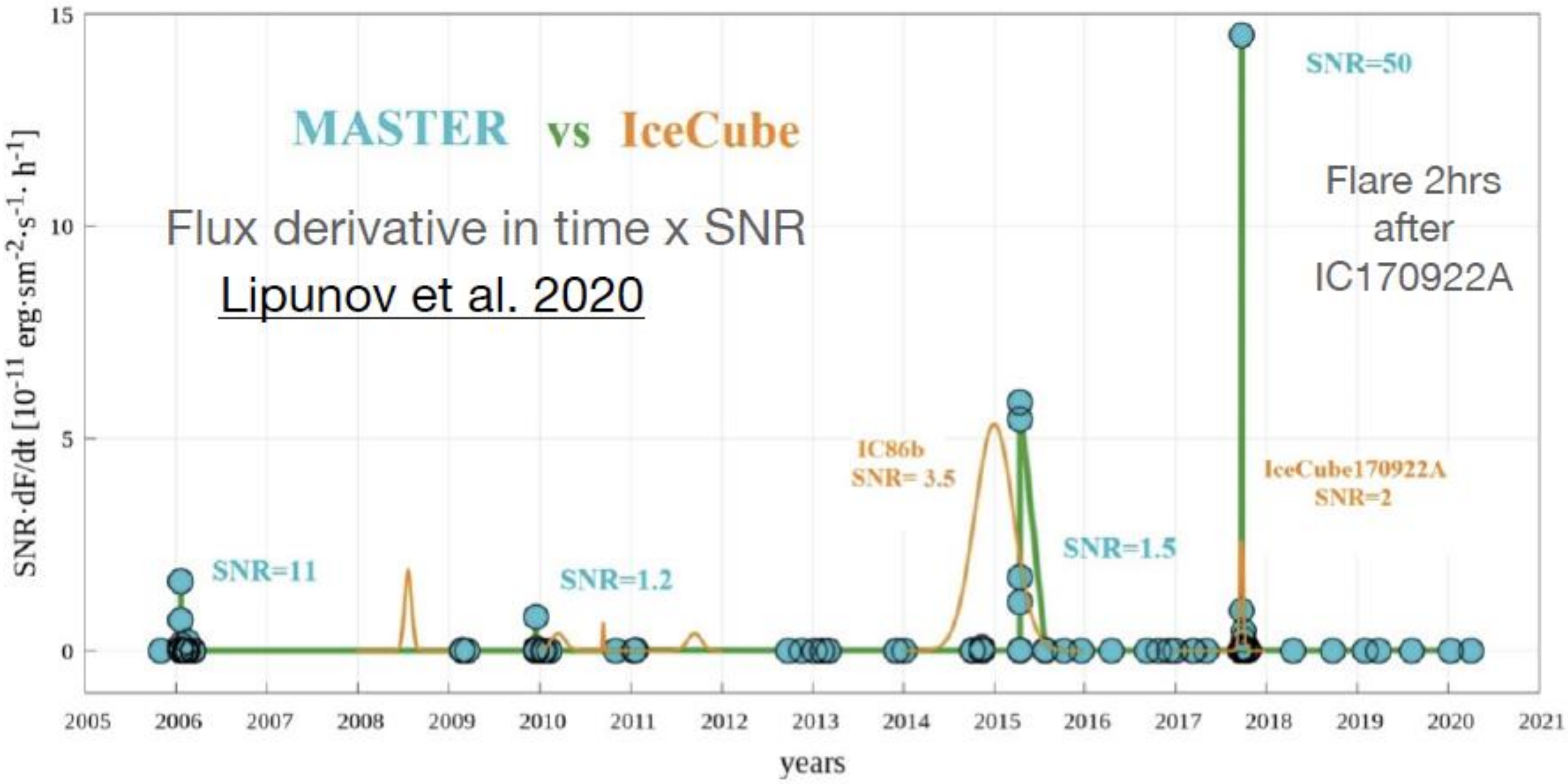
MAGIC
detects emission of
> 100 GeV gammas

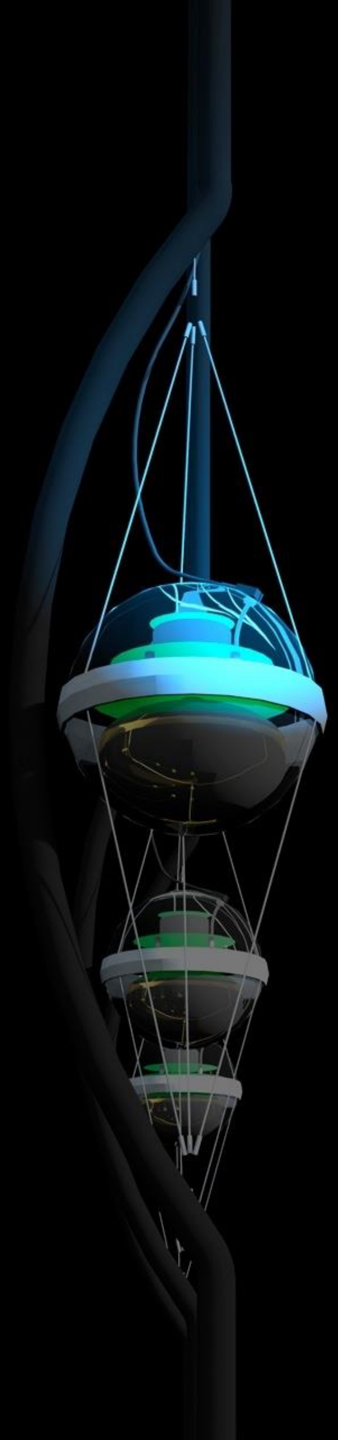
MASTER robotic optical telescope network: observing within 73 seconds
optical flash after 2 hours: highest statistical association of TXS 0506 with IC170922



“MASTER found the blazar in the off-state *after one minute* and then switched to on-state two hours after the event. The effect is observed at a 50-sigma significance level”

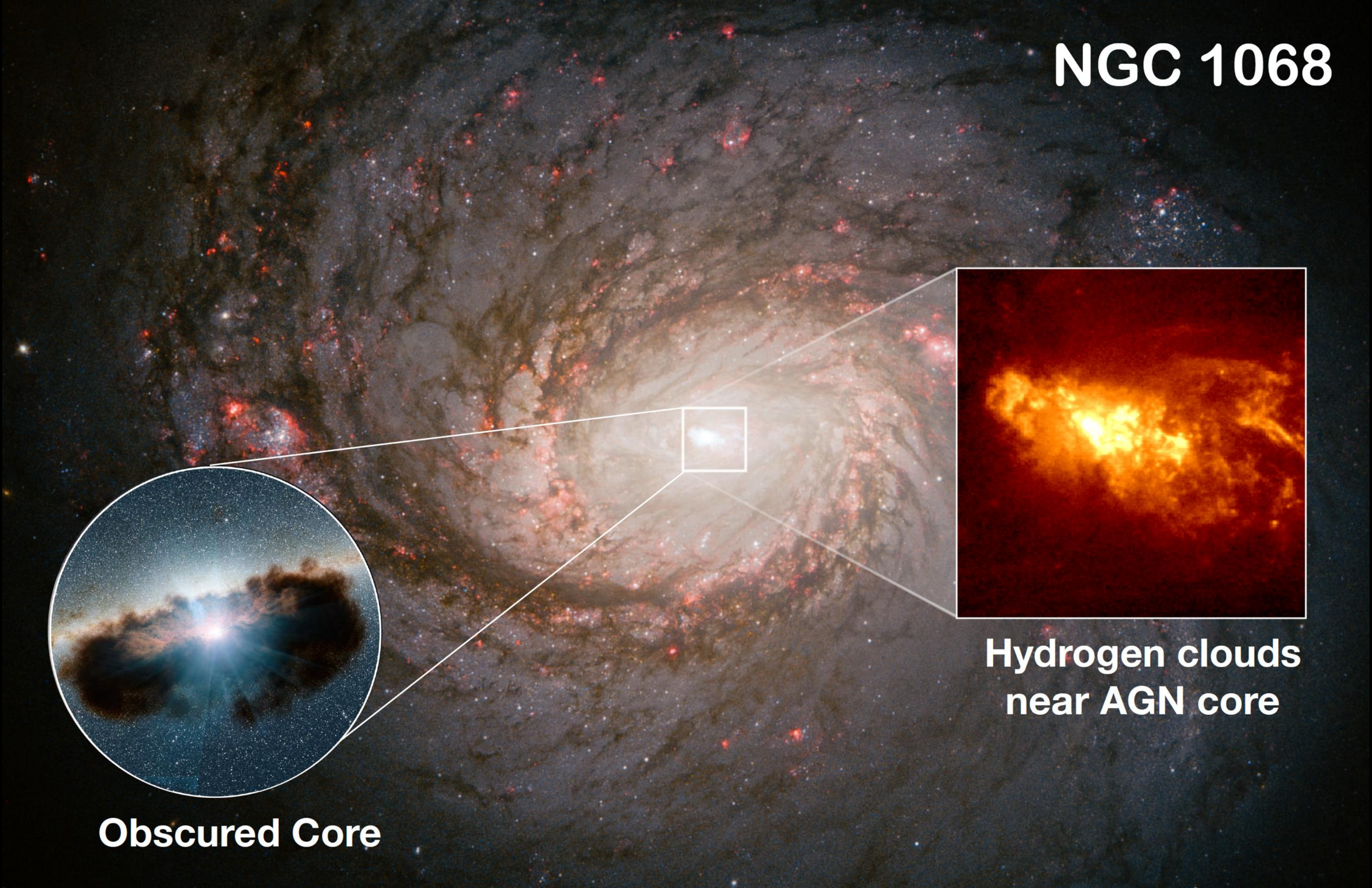
optical flashes may originate from magnetohydrodynamical instabilities triggered by processes modulated by the magnetic field of the accretion disk

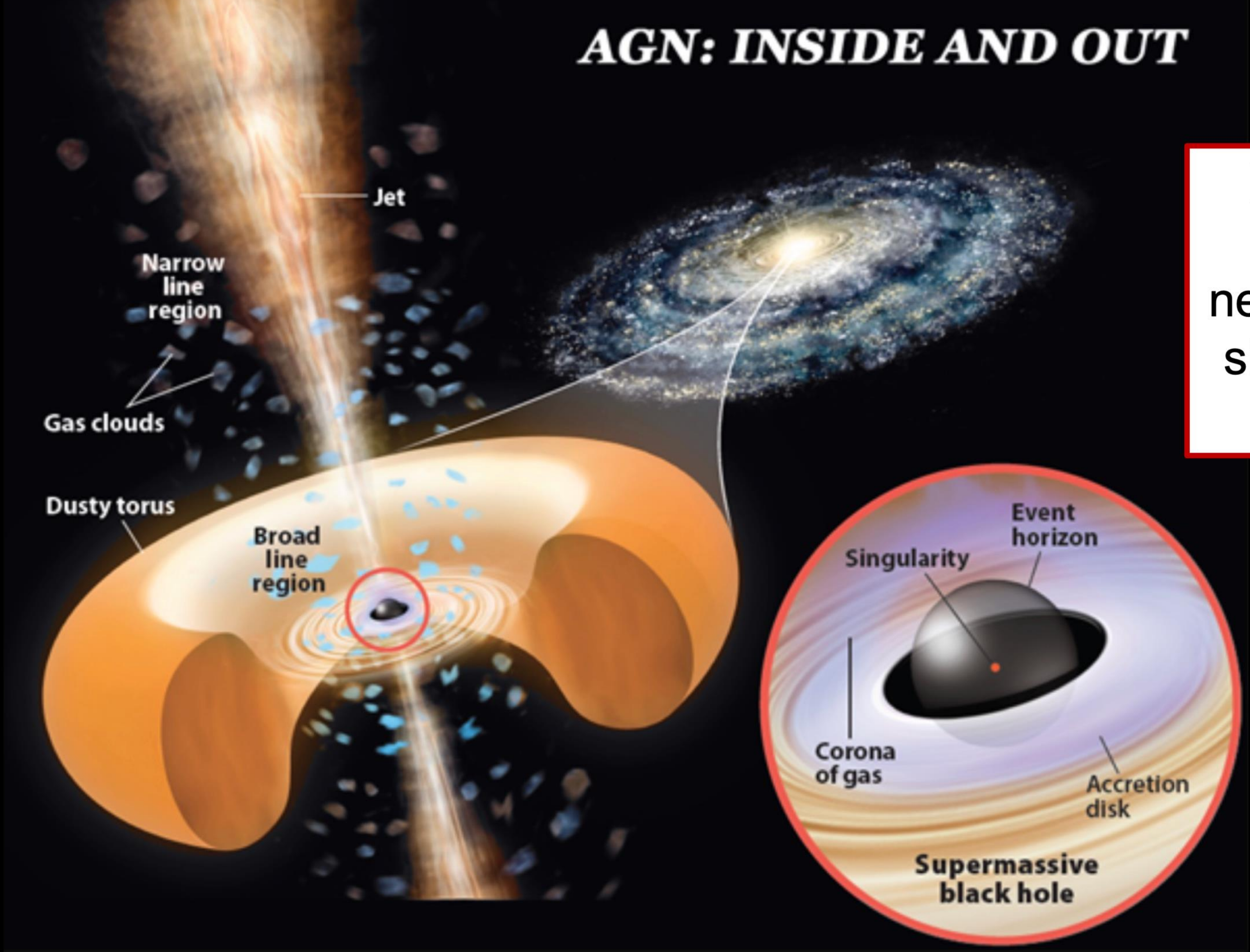




- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- and the answer is: supermassive black holes at the cores of active galaxies?

IceCube.wisc.edu

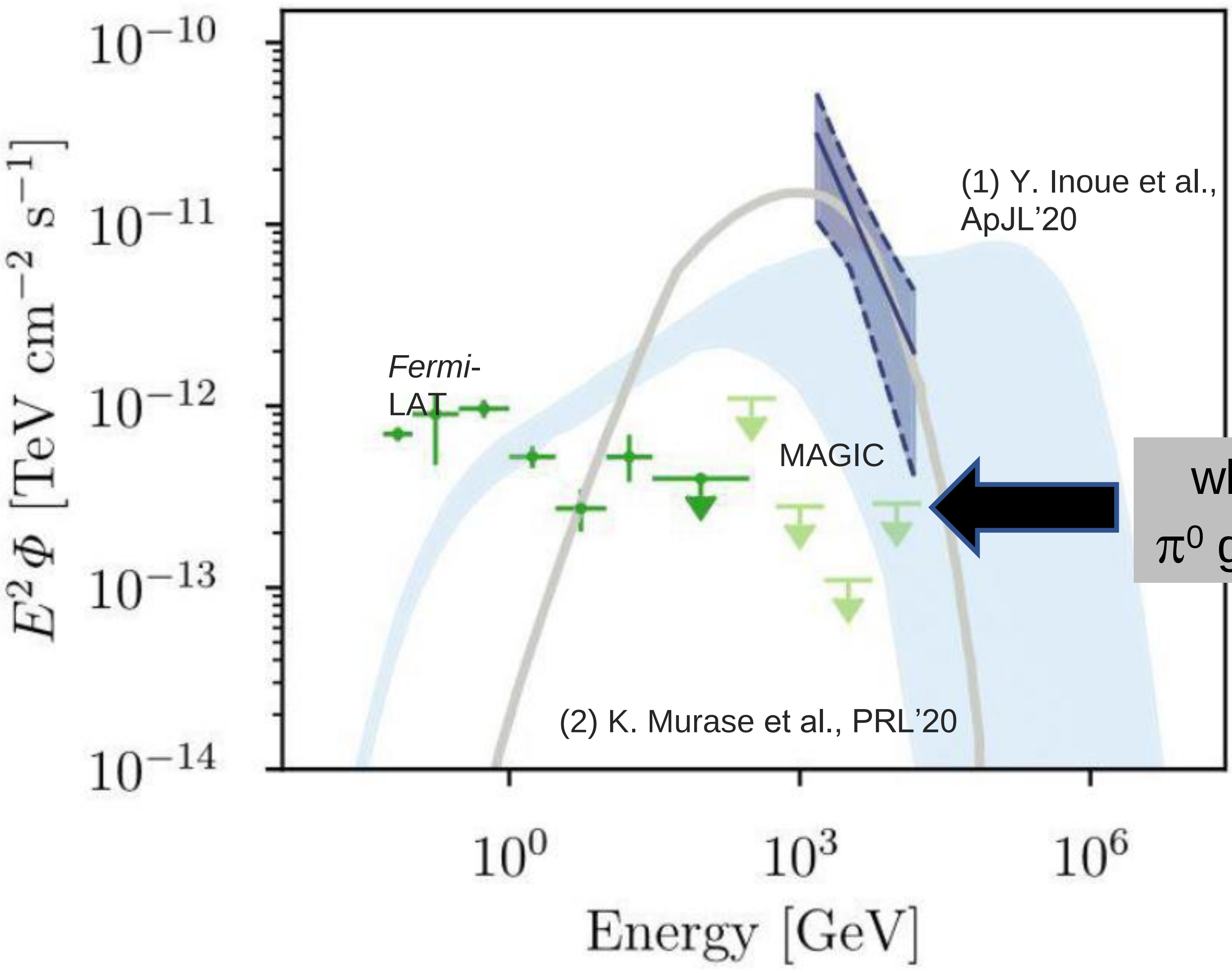

NGC 1068
Hydrogen clouds
near AGN core
Obscured Core



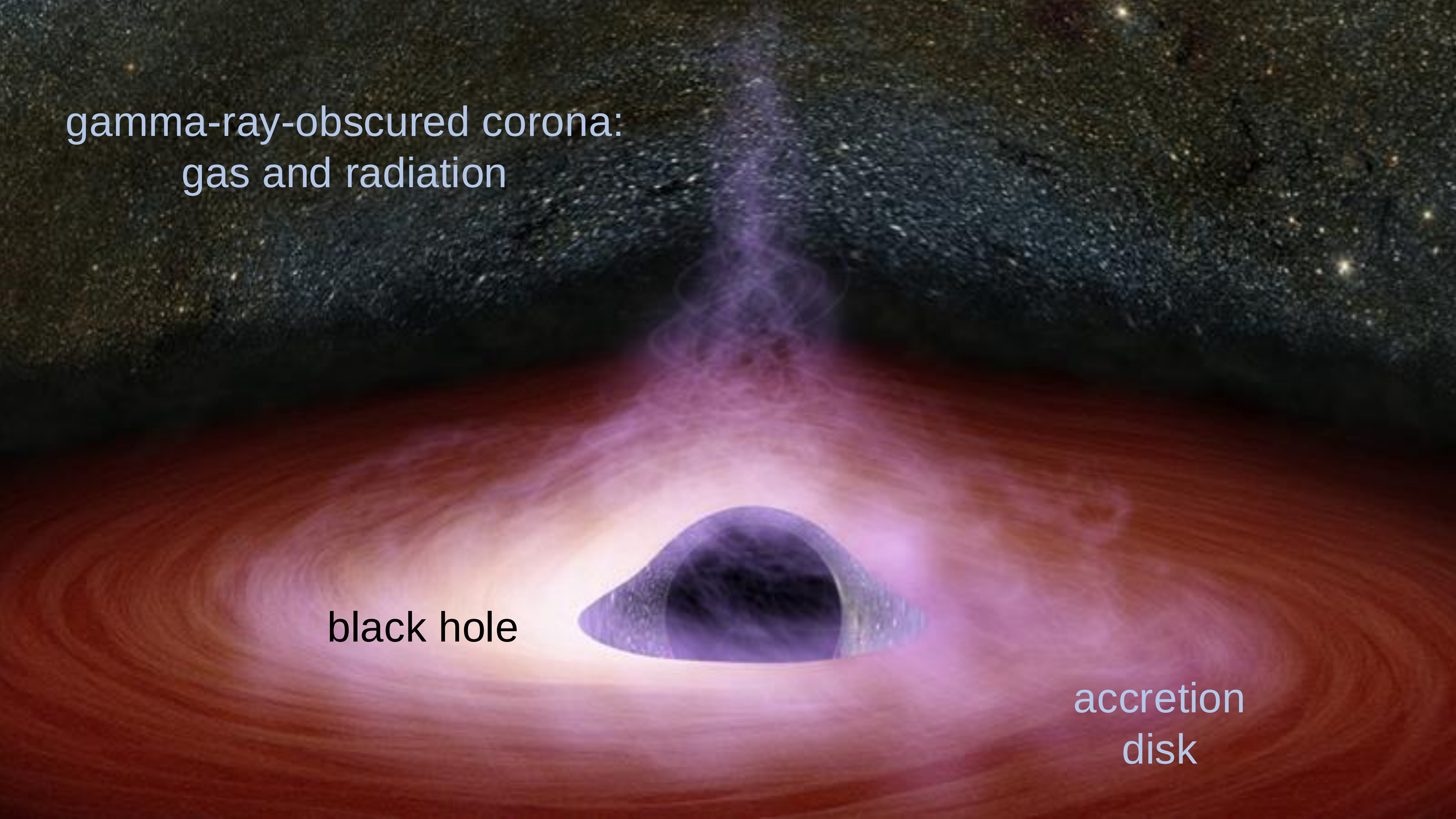
Lack of gamma rays places neutrino production site in the heart of the galaxy

a gamma ray for every neutrino?

NGC 1068: an obscured cosmic accelerator



where are the π^0 gamma rays ?


gamma-ray-obscured corona:
gas and radiation
black hole
accretion
disk

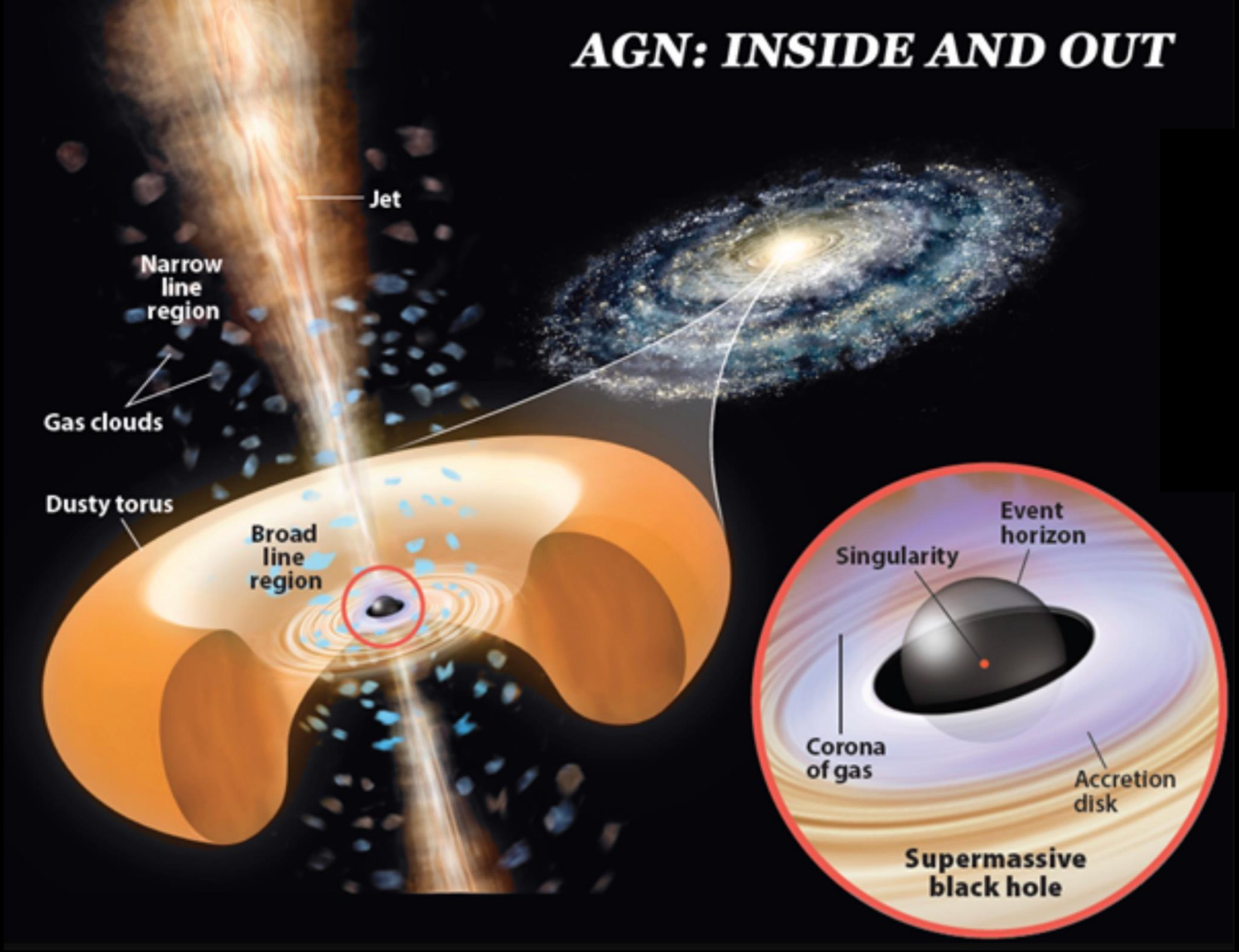
- accelerator(s): electrons and protons are accelerated in the turbulent magnetic fields associated with the accretion disk, in the infall onto the black hole,…

- target: the neutrinos are produced in the optically thick core with a high density of gammas (corona X-rays) and dense clouds of hydrogen (protons) cores of active galaxies

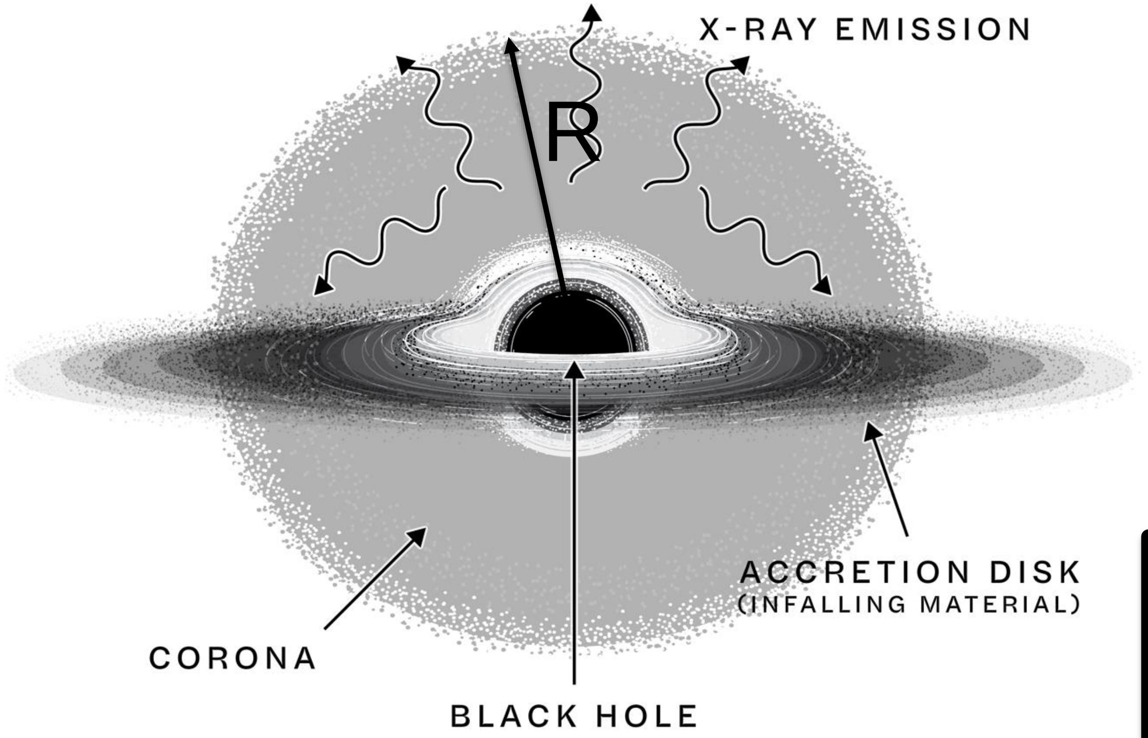
target densities required

- to produce the neutrino flux
- to suppress the flux of the accompanying gamma ray from π^0s

requires a target density only found within < 100 Schwarzschild radii of the black hole



NGC 1068 core: large optical depth in photons (X-ray) and matter



$$\tau_{p\gamma} \sim \sigma_{p\gamma}\,[\frac{1}{\mathrm{R}}\,\frac{L_X}{E_X}]$$

cross section x target density

= optical depth τ

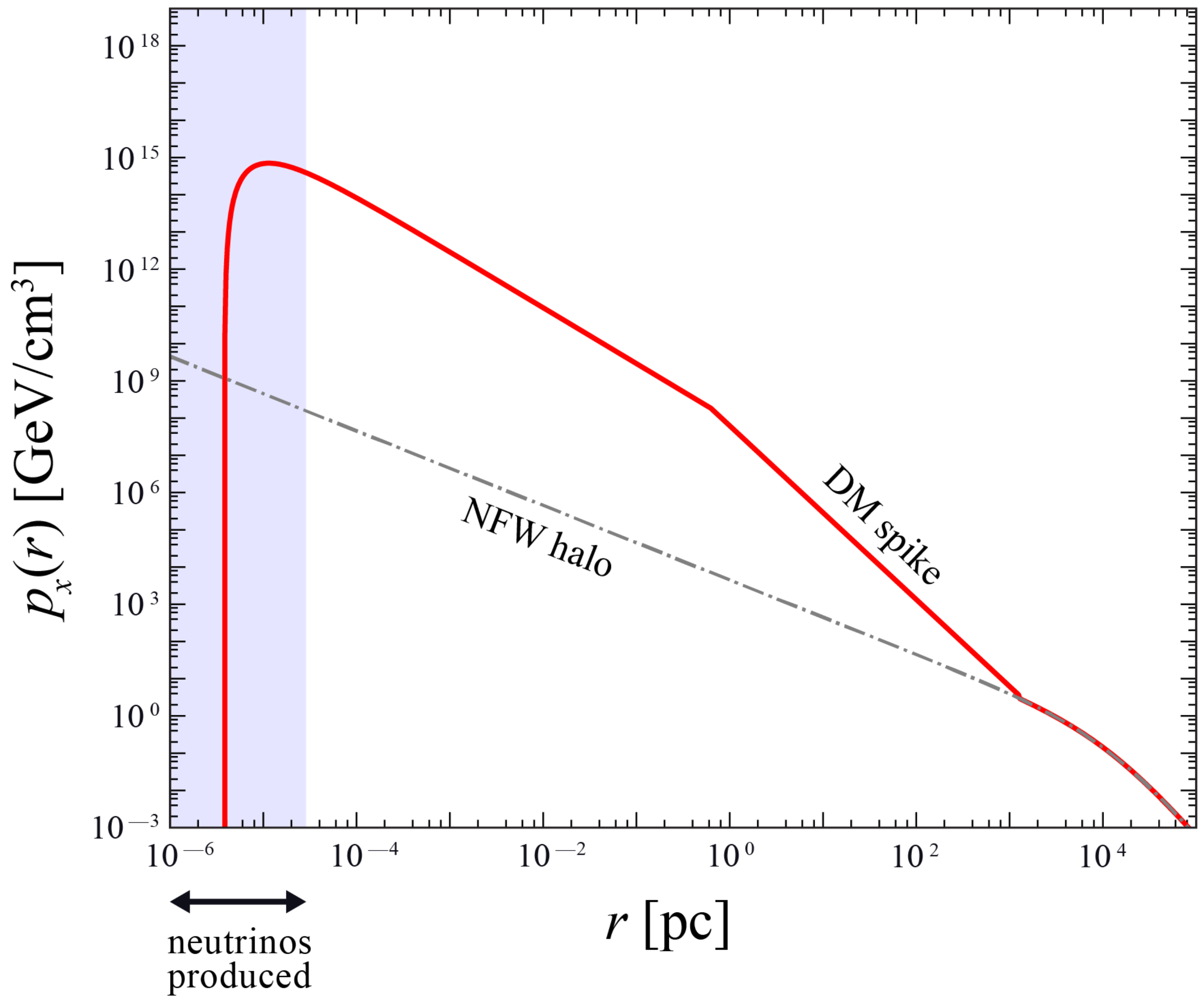
$$\tau_{p\gamma} \sim 0.1 \;\rightarrow\; \mathrm{PeV\,neutrinos}$$

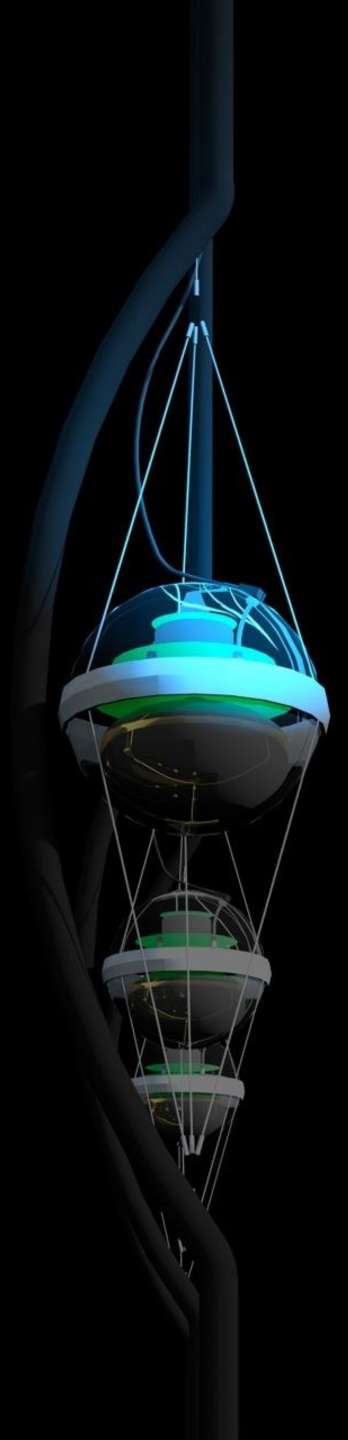
$$\tau_{pp} \sim 1 \;\rightarrow\; 1 \sim 100\,\mathrm{TeV\,neutrinos}$$

$$E_X = 1\,\mathrm{keV}\,;\;\; \mathrm{L_X} \sim 10^{43}\,\mathrm{ergs}^{-1}$$

neutrinos originate within $10 \sim 10^2$ Schwarzschild radii from the BH

neutrinos are produced inside the dark matter spike at the center of the Galaxy



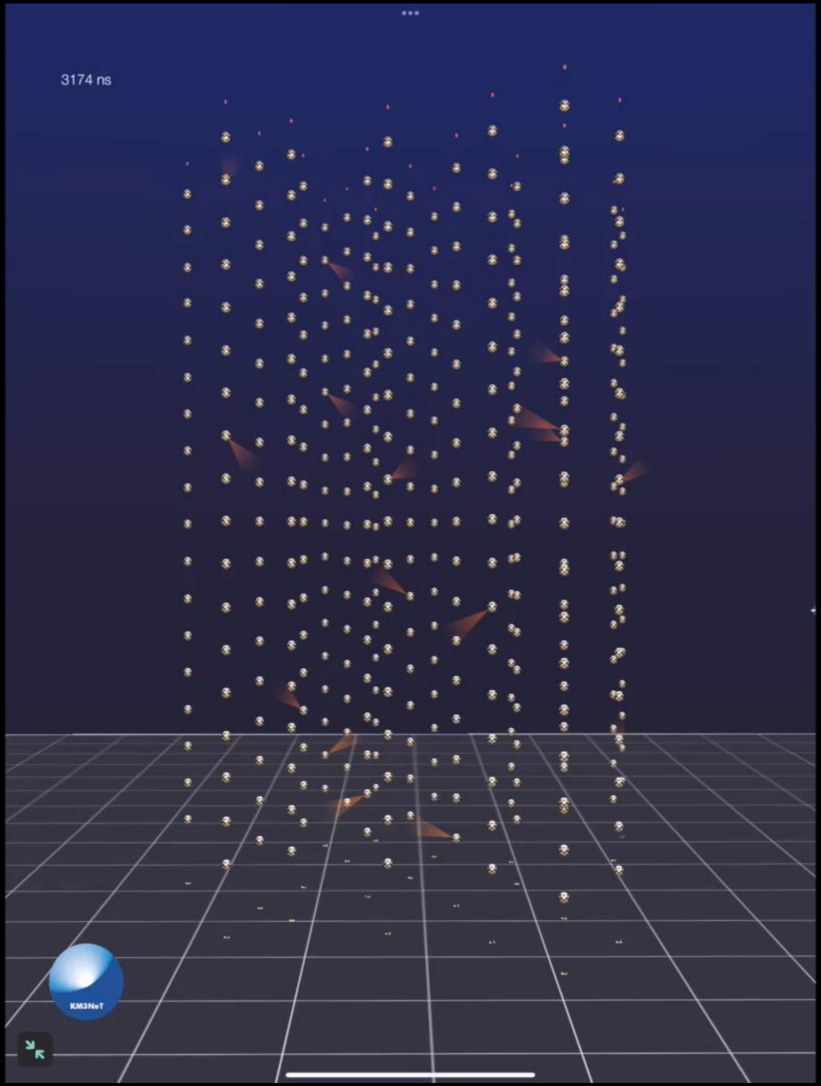


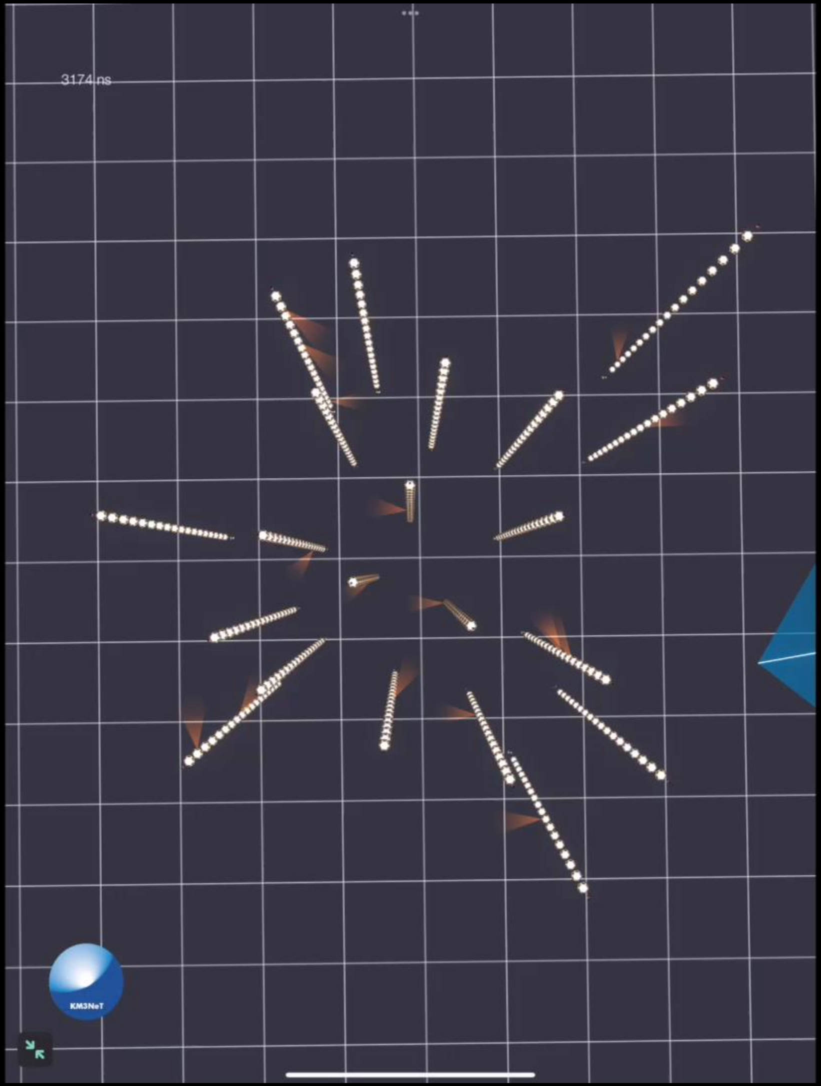
neutrino astronomy 2024

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

icecube.wisc.edu

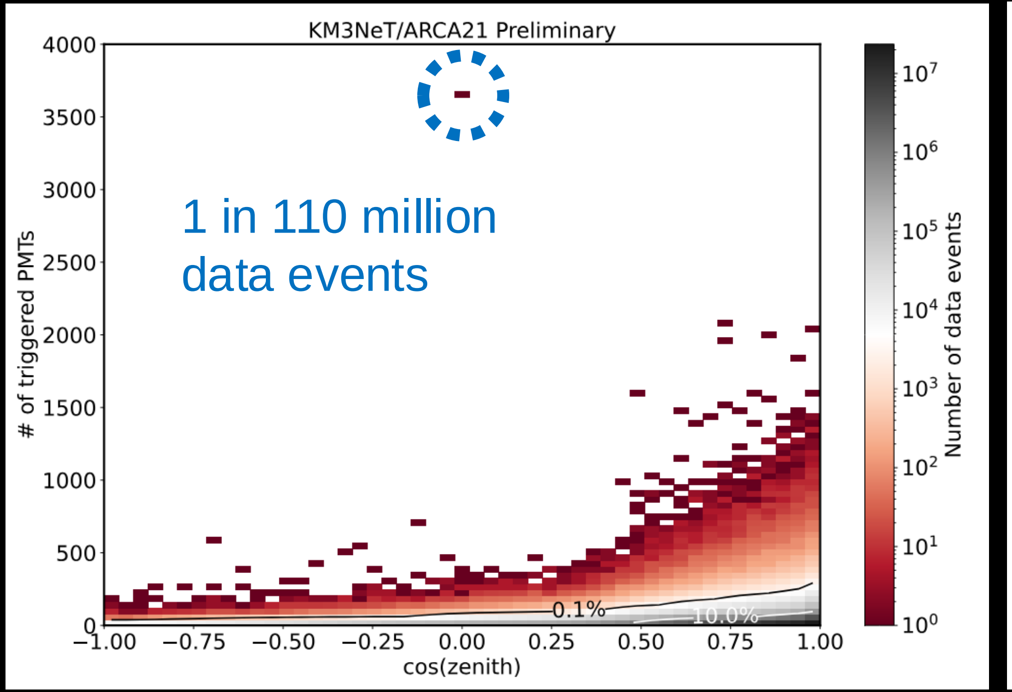
Uncharted Territory

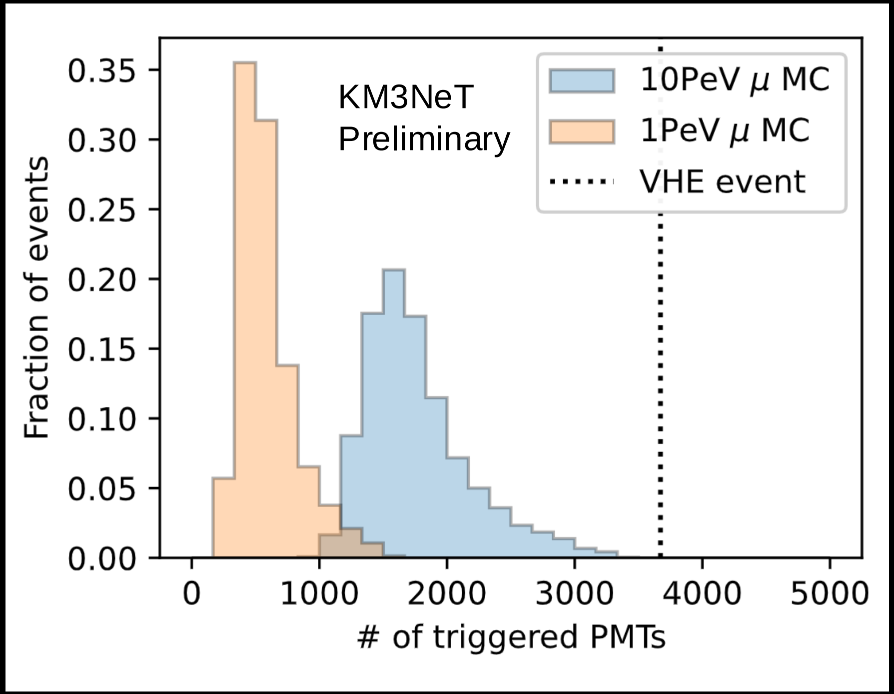




Uncharted Territory

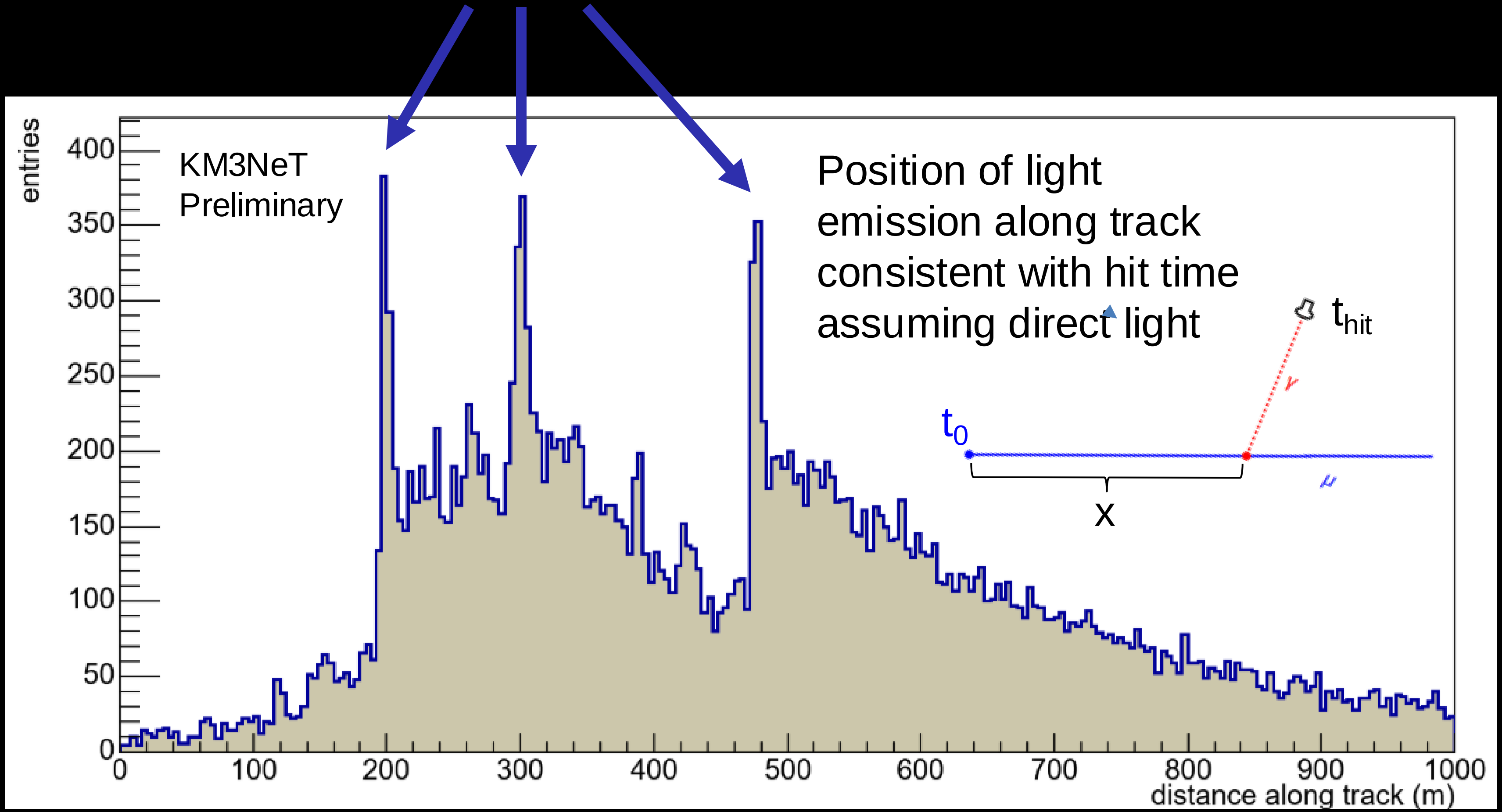
- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV

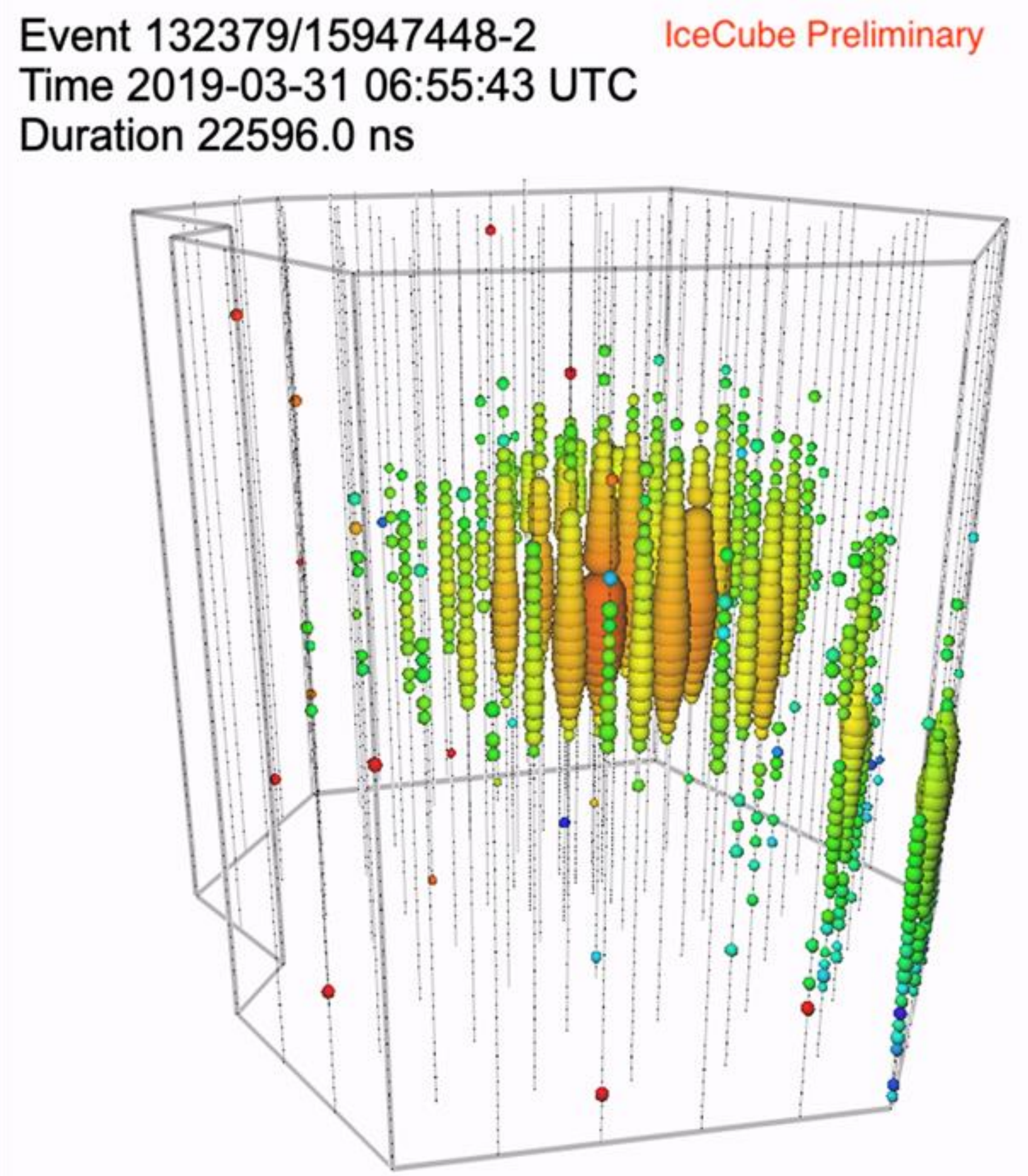




Uncharted Territory

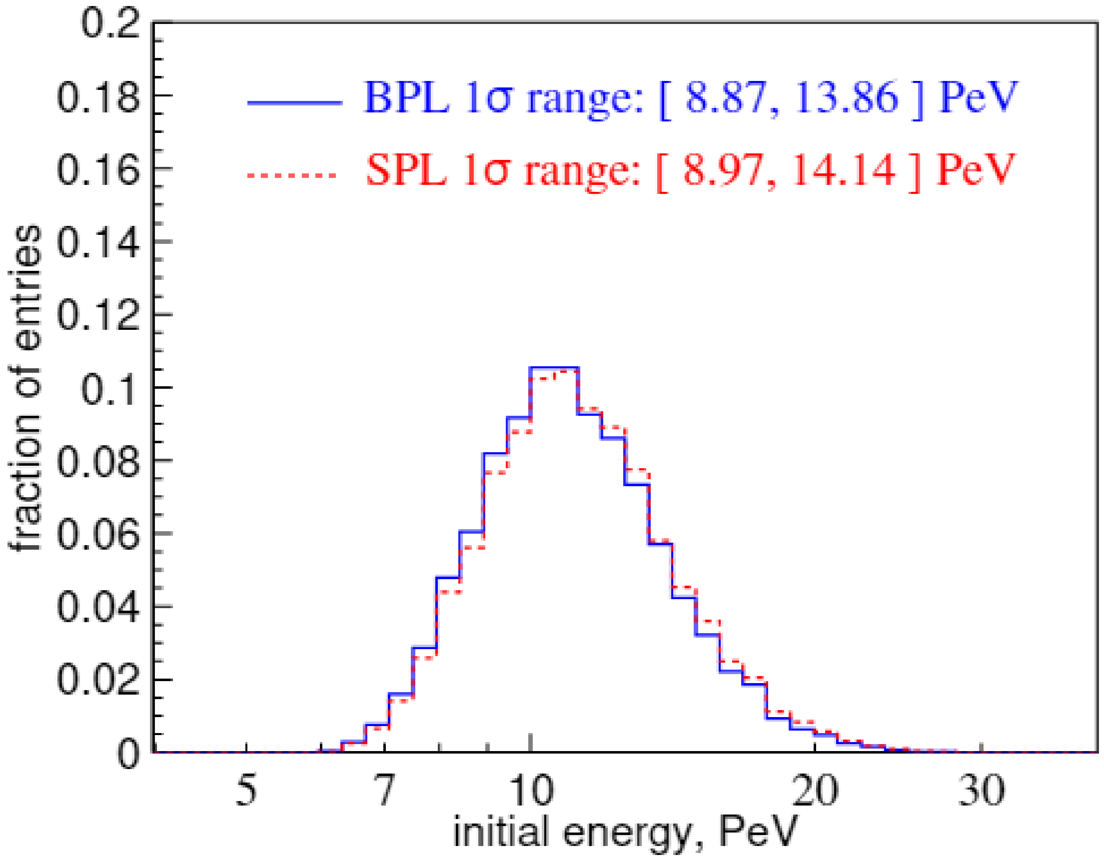
- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons





IceCube's Highest Energy Event:

11.4 PeV (3 with E_ν >10 PeV)



*Most probable neutrino energy when assuming a BPL spectrum (γ_1 ,γ_2)=(1.72,2.84) [Data Release]

THE ICECUBE COLLABORATION

ALIA 1

1

ED KINGDOM 1

UNITED STATES 25

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY