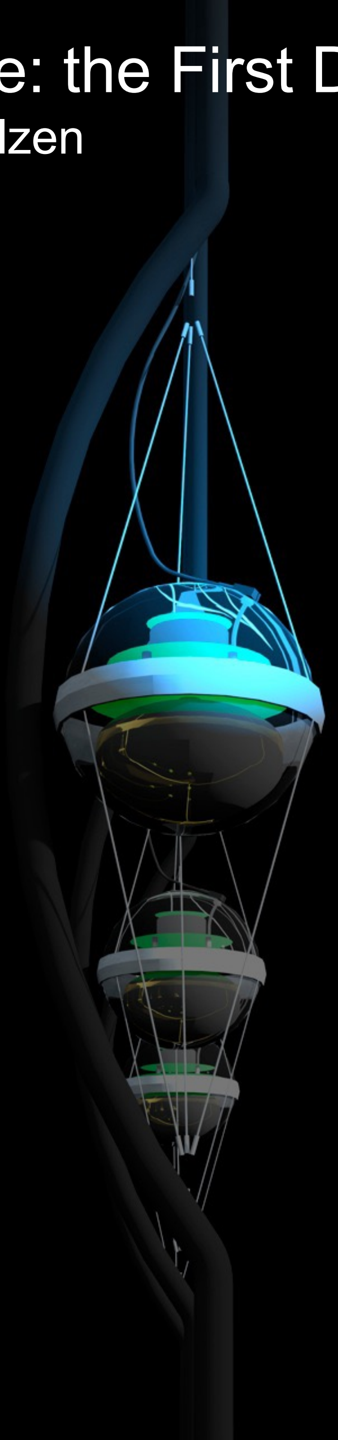
IceCube: the First Decade of Neutrino Astronomy

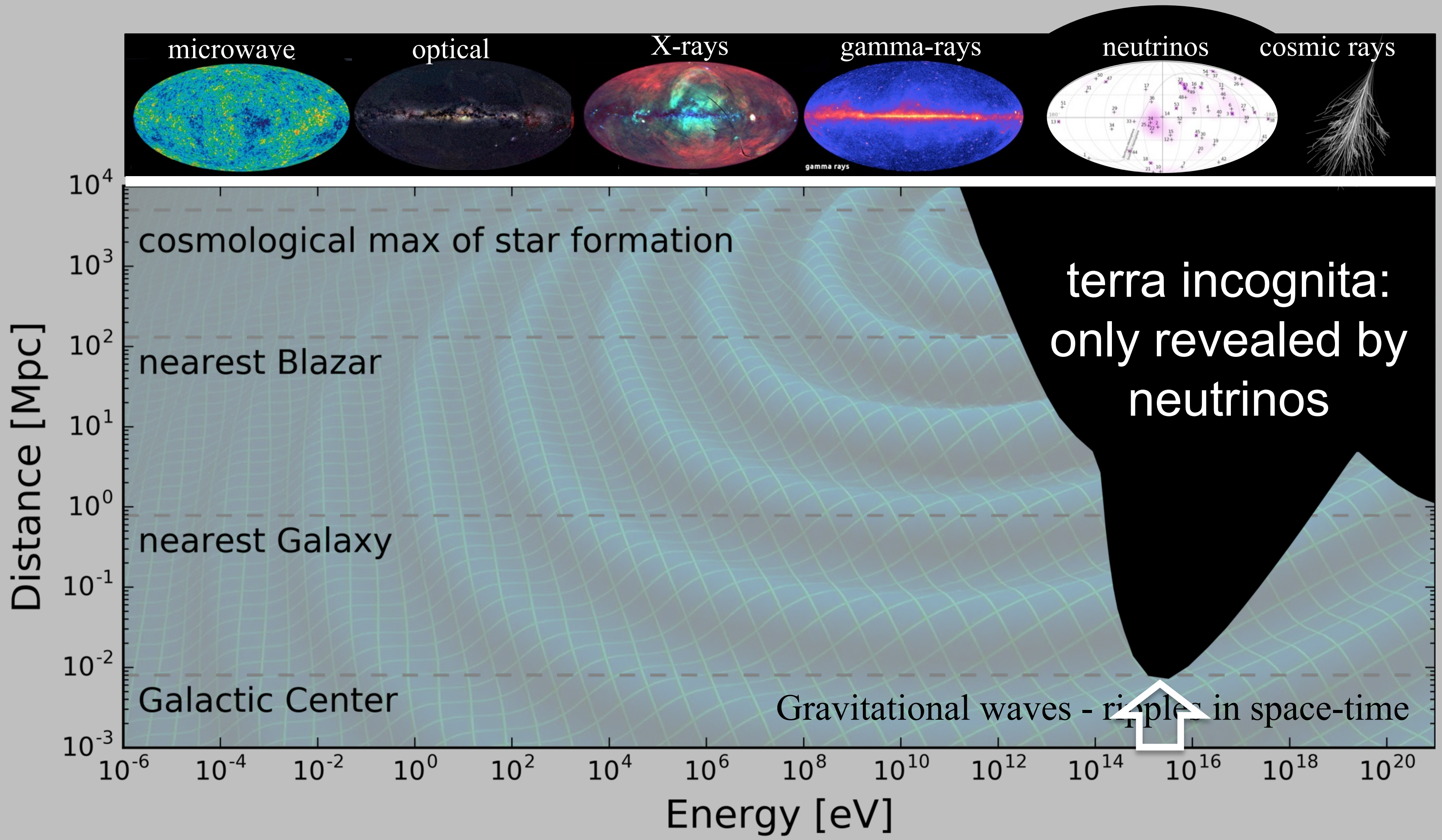
francis halzen



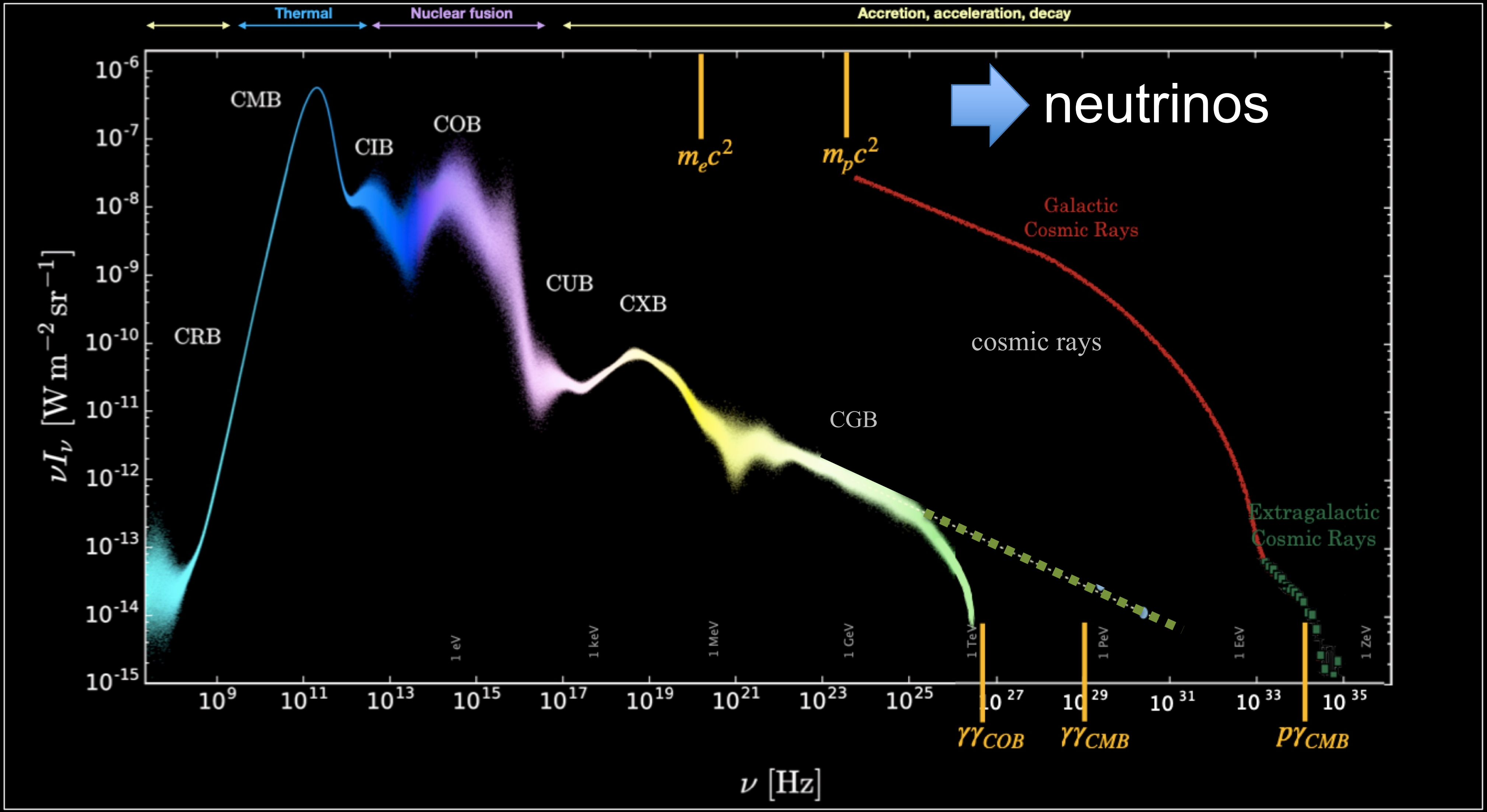
- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- and the answer is: supermassive black holes at the cores of active galaxies ?

IceCube.wisc.edu

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

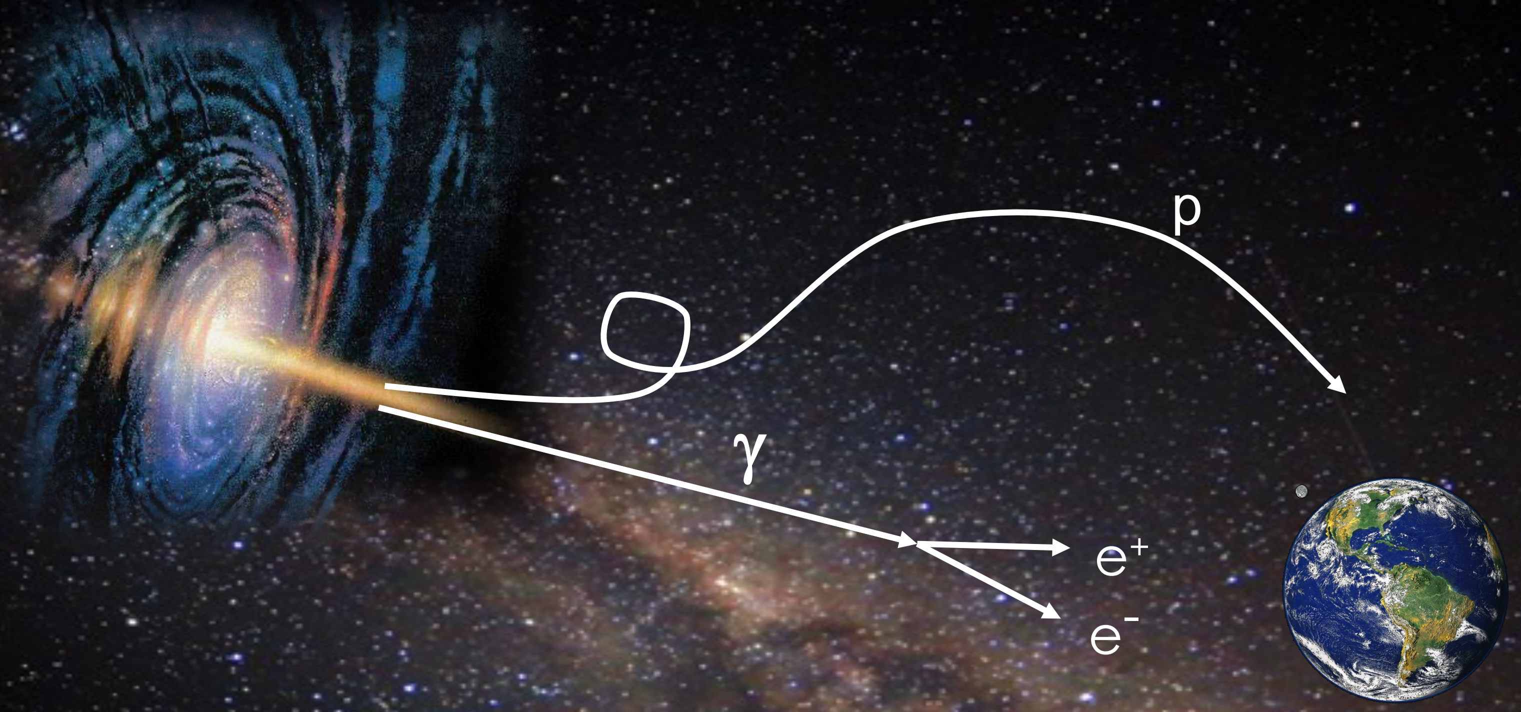


the Extreme Universe is opaque to gamma rays beyond our Galaxy photon energy in the Universe as a function of color



in the extreme universe neutrinos are unique astronomical messengers

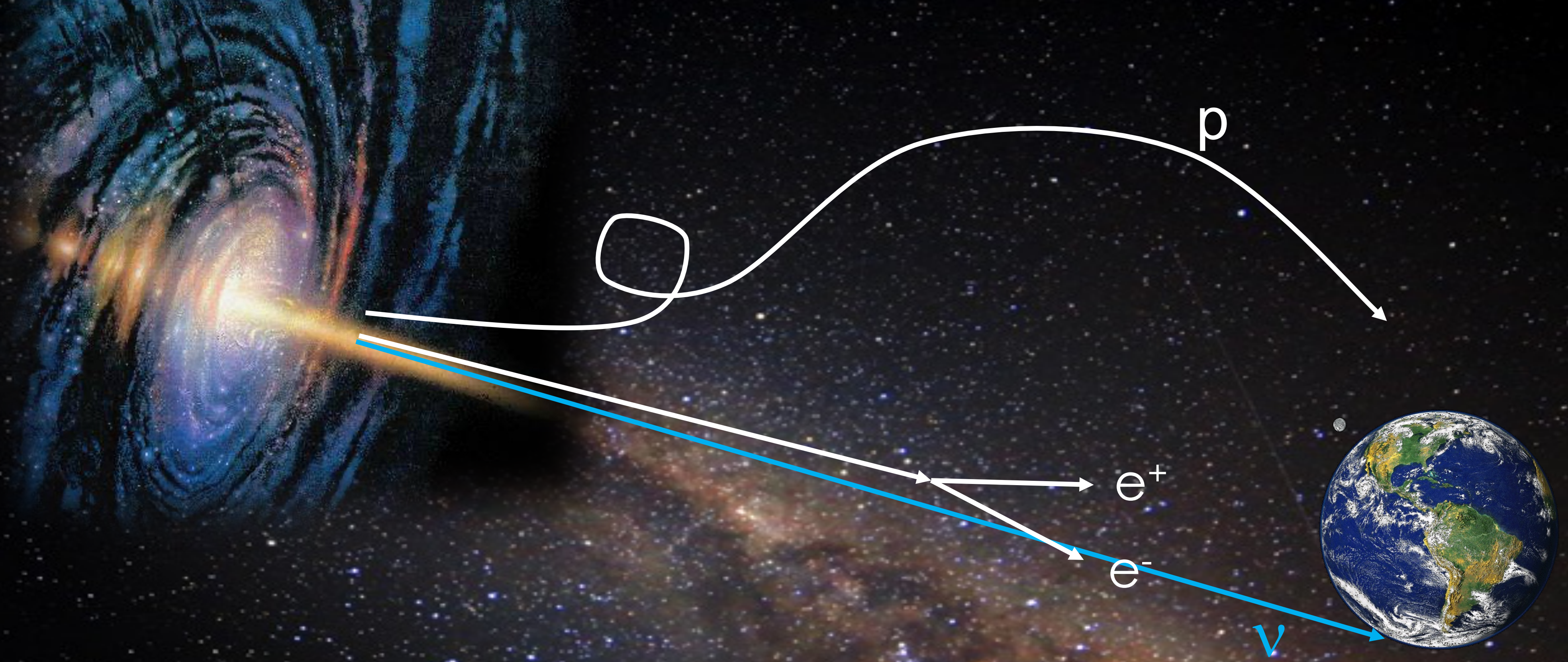
the opaque extreme Universe:



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

- > PeV photons interact with microwave photons (411/cm^3) before reaching our telescopes
- their energy appears reprocessed in GeV photons or beyond

neutrinos: perfect messengers

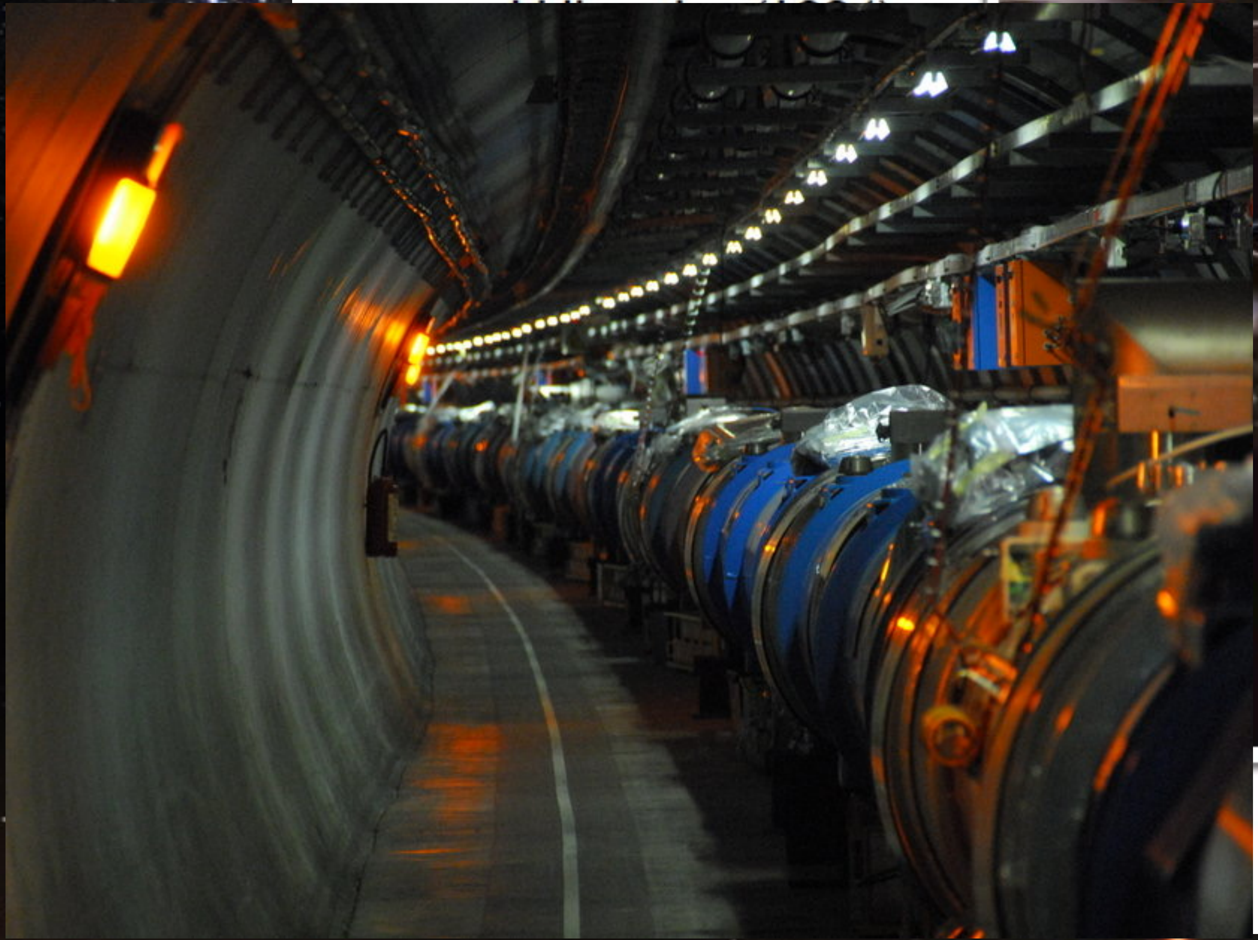


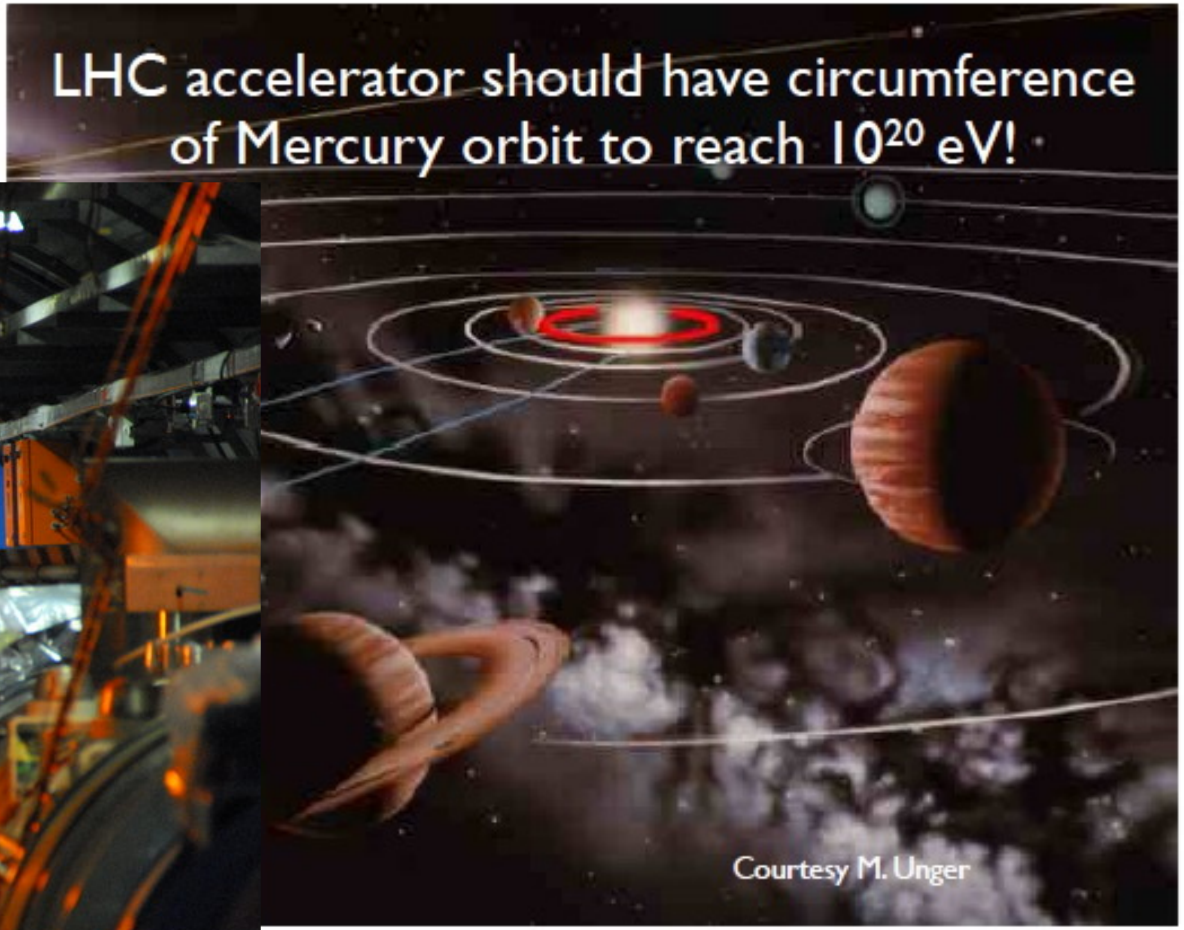
- electrically neutral
- massless (in this talk)
- like a photon but weakly interacting
- track cosmic ray sources

- … but difficult to detect

highest energy radiation from the Universe: not γ-rays !

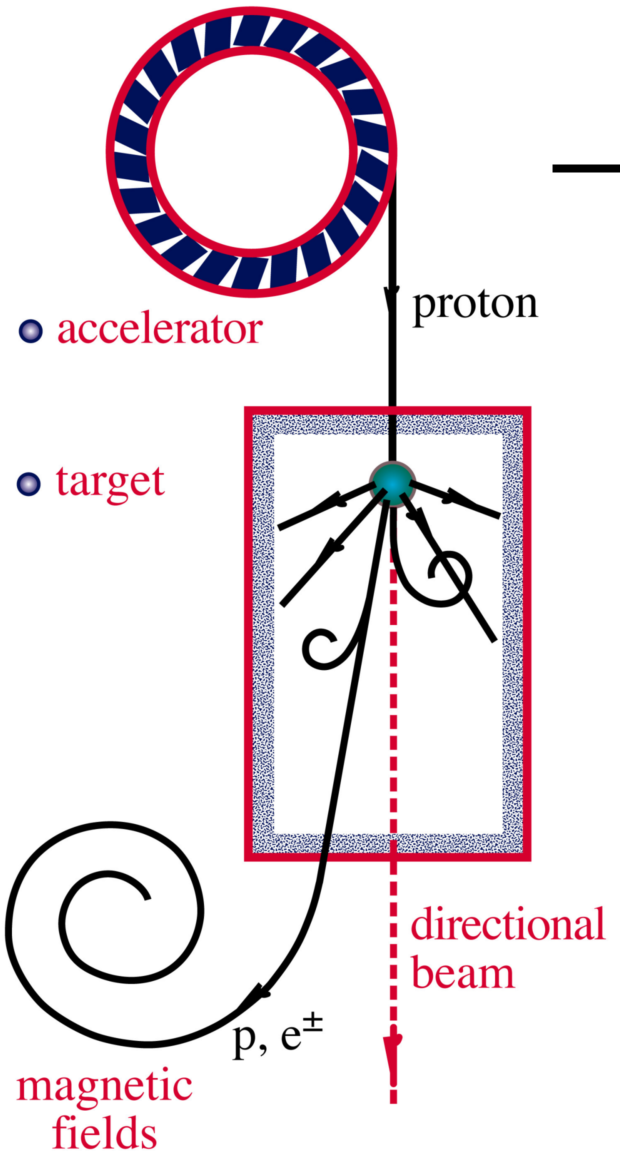
high energy
high luminosity





Fly’s Eye 1991
300,000,000 TeV

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

supermassive black hole

nearby radiation

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

~ cosmic ray + neutrino

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

~ cosmic ray + gamma

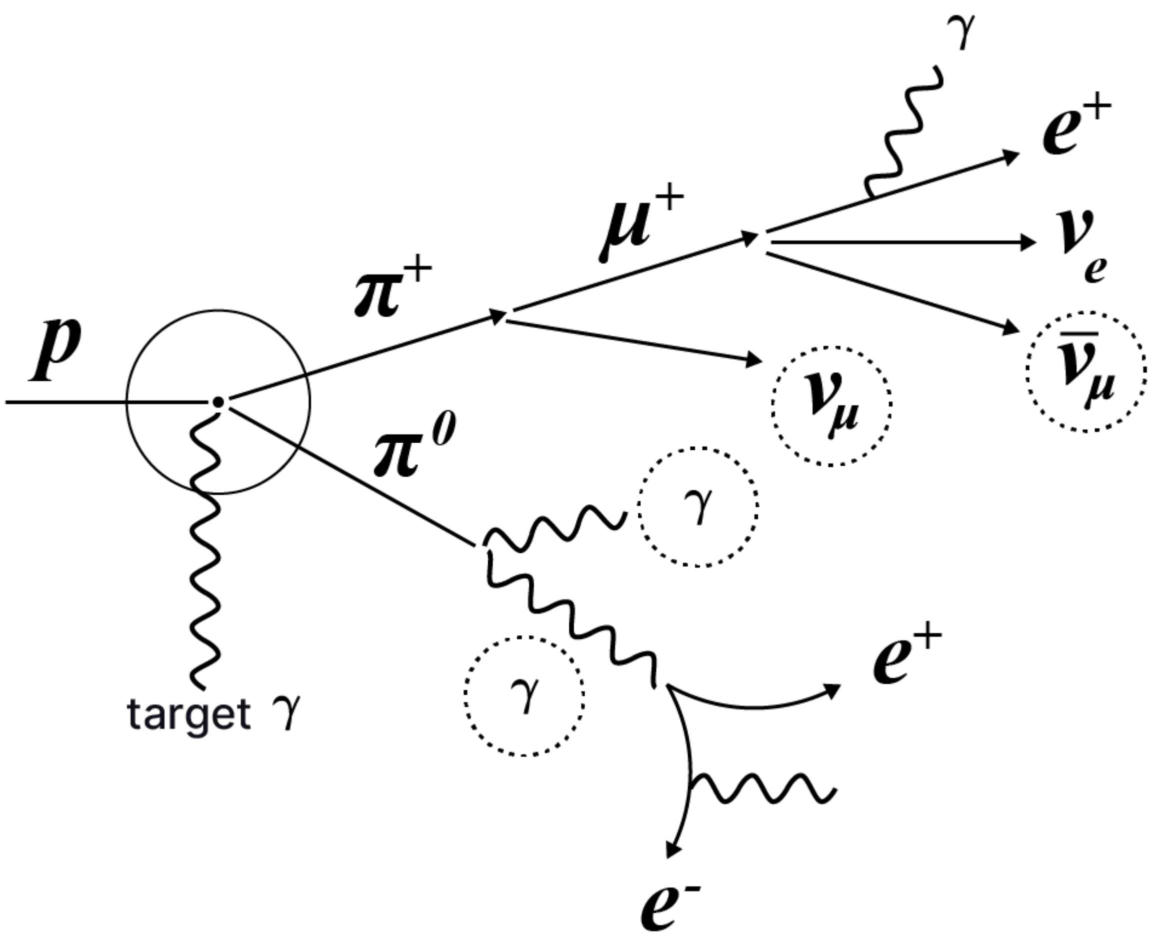
black hole accelerating protons submersed in radiation

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

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

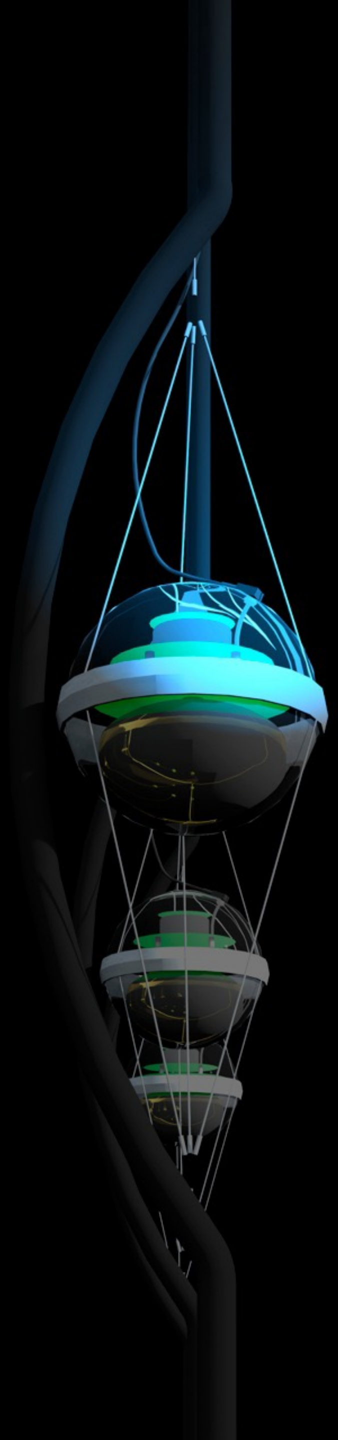
$$\pi^0 \rightarrow \gamma + \gamma$$

cosmic ray sources:
a gamma ray for
every neutrino



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

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



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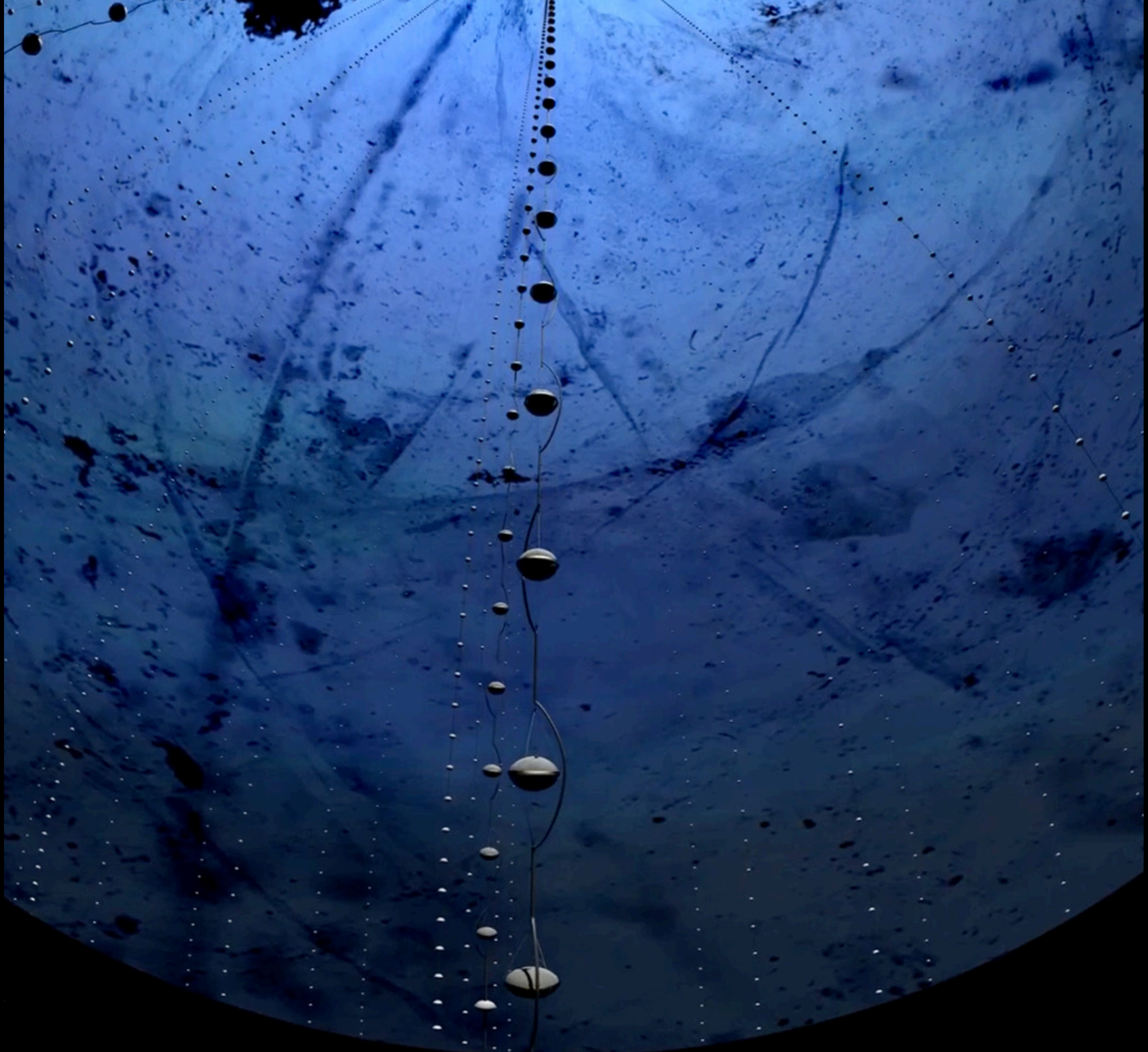
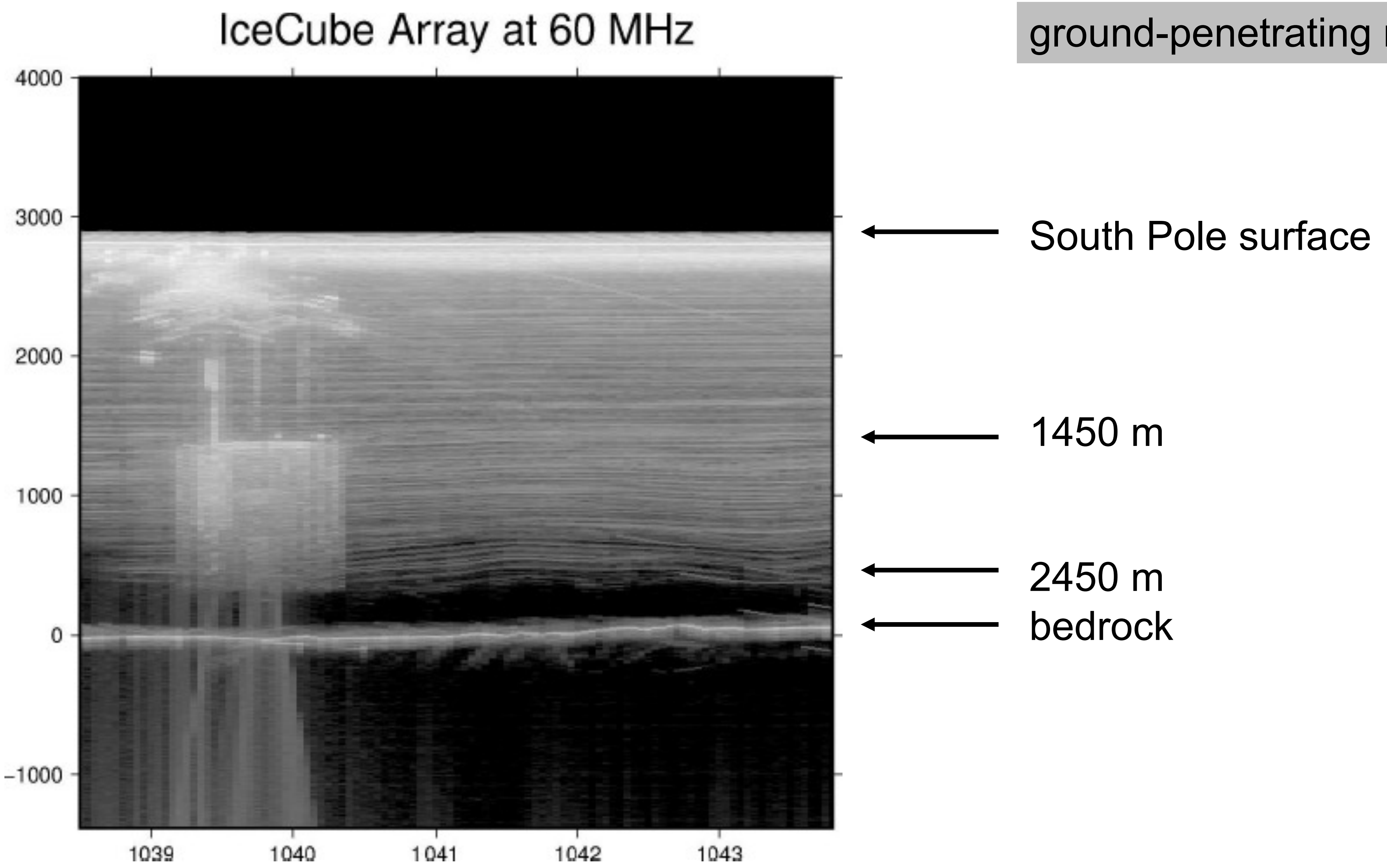
IceCube.wisc.edu

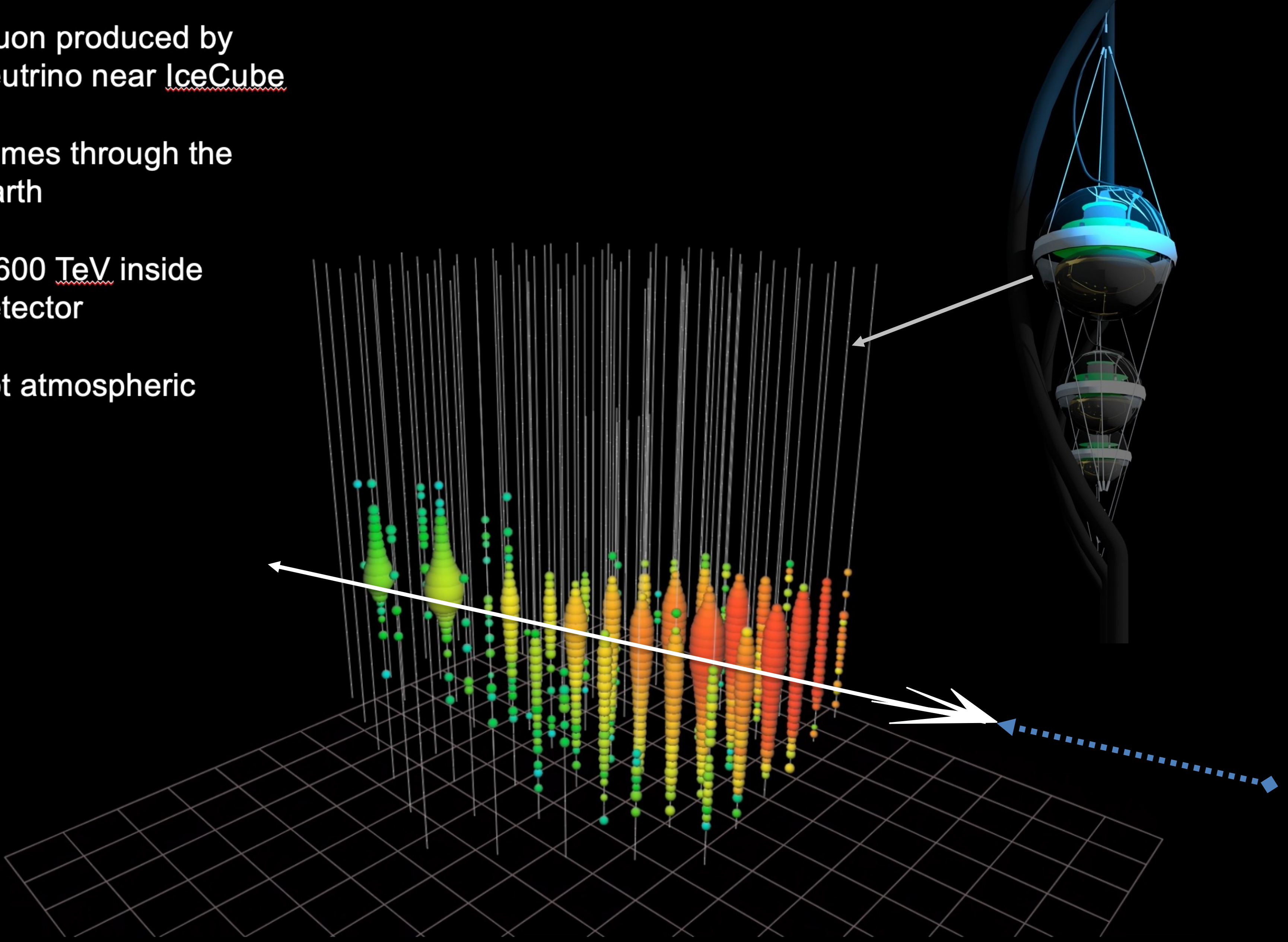
IceCube:
5160 photomultipliers instrument one km^3 of Antarctic ice between 1.4 and 2.4 km depth as a Cherenkov detector



ground-penetrating radar

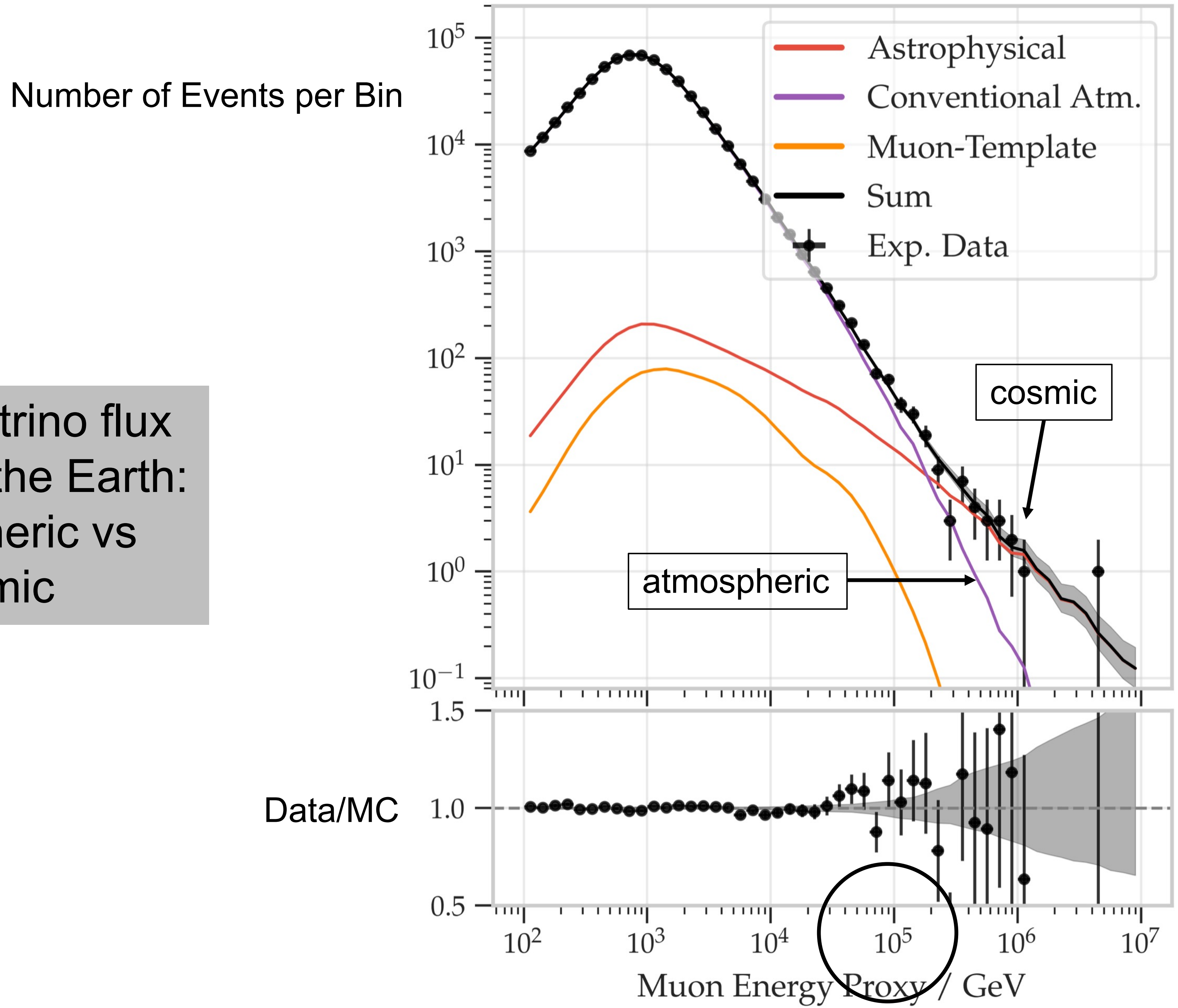


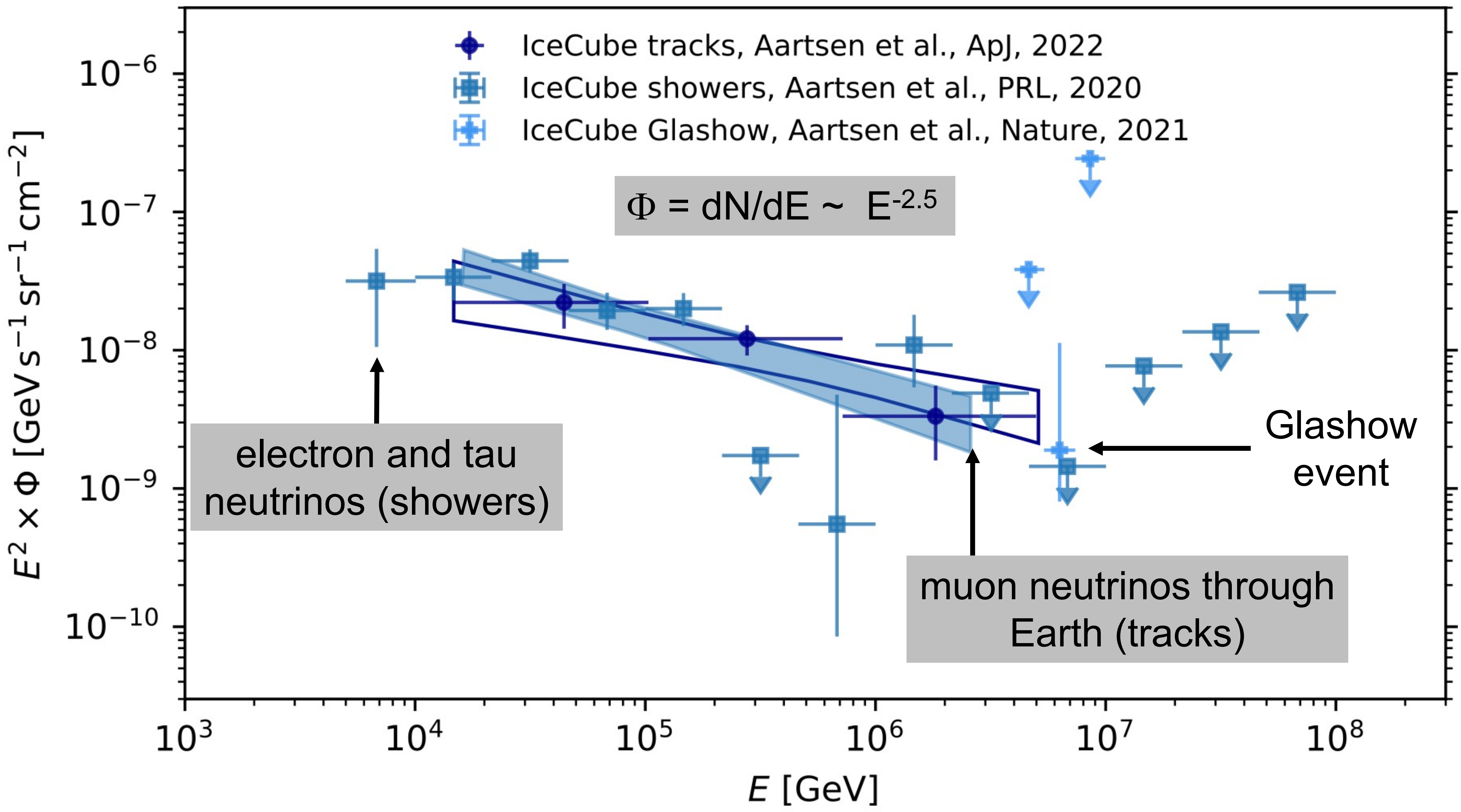
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric



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

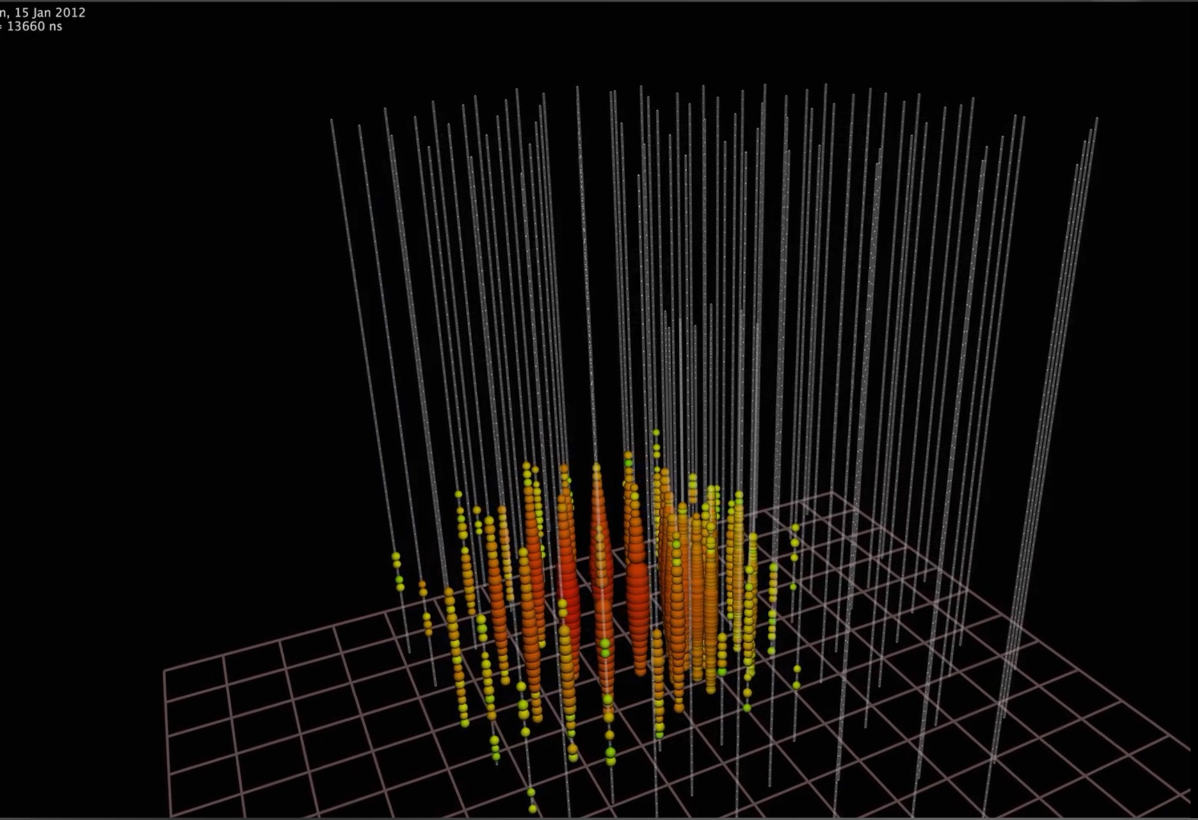
muon neutrino flux filtered by the Earth: atmospheric vs cosmic





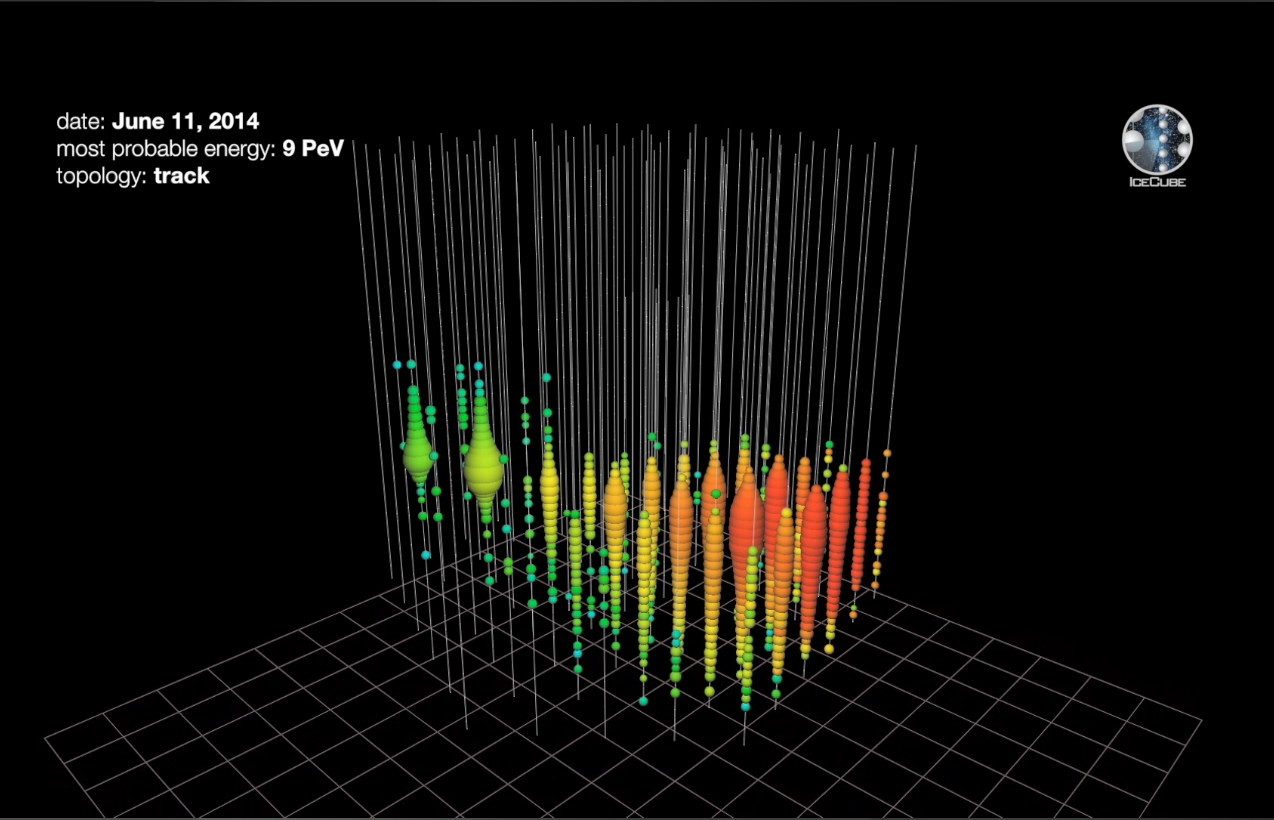
IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ E-2.5
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
E2 × Φ [GeV s−1 sr−1 cm−2]
E [GeV]

neutrinos interacting
inside the detector

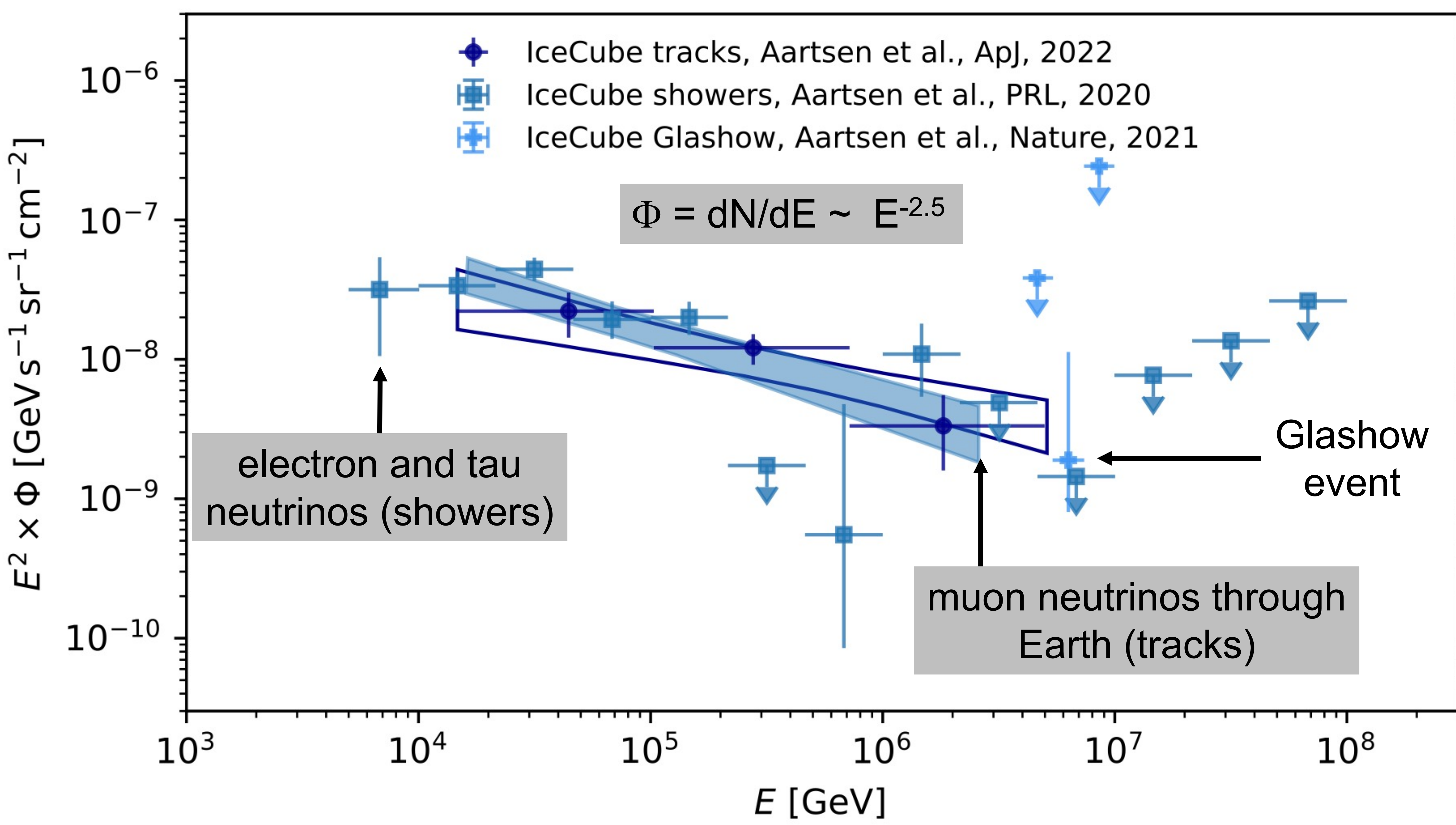


superior total energy
measurement
to 10%, all flavors, all sky

muon neutrinos
filtered by the Earth



superior angular resolution 0.3°
including systematics



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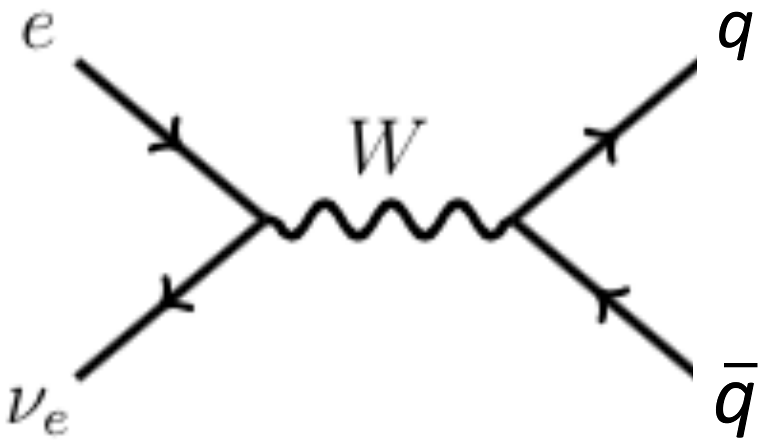
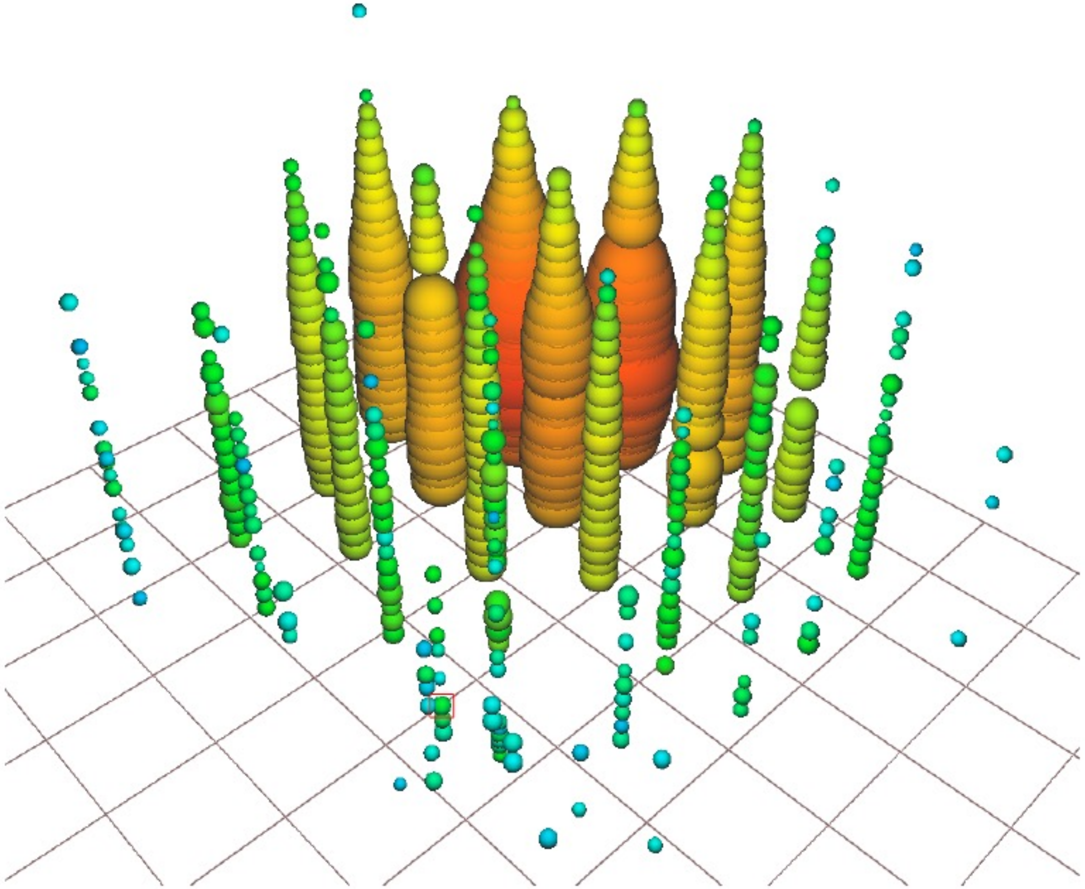
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ $E^{-2.5}$
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^3
10^4
10^5
10^6
10^7
10^8
E [GeV]

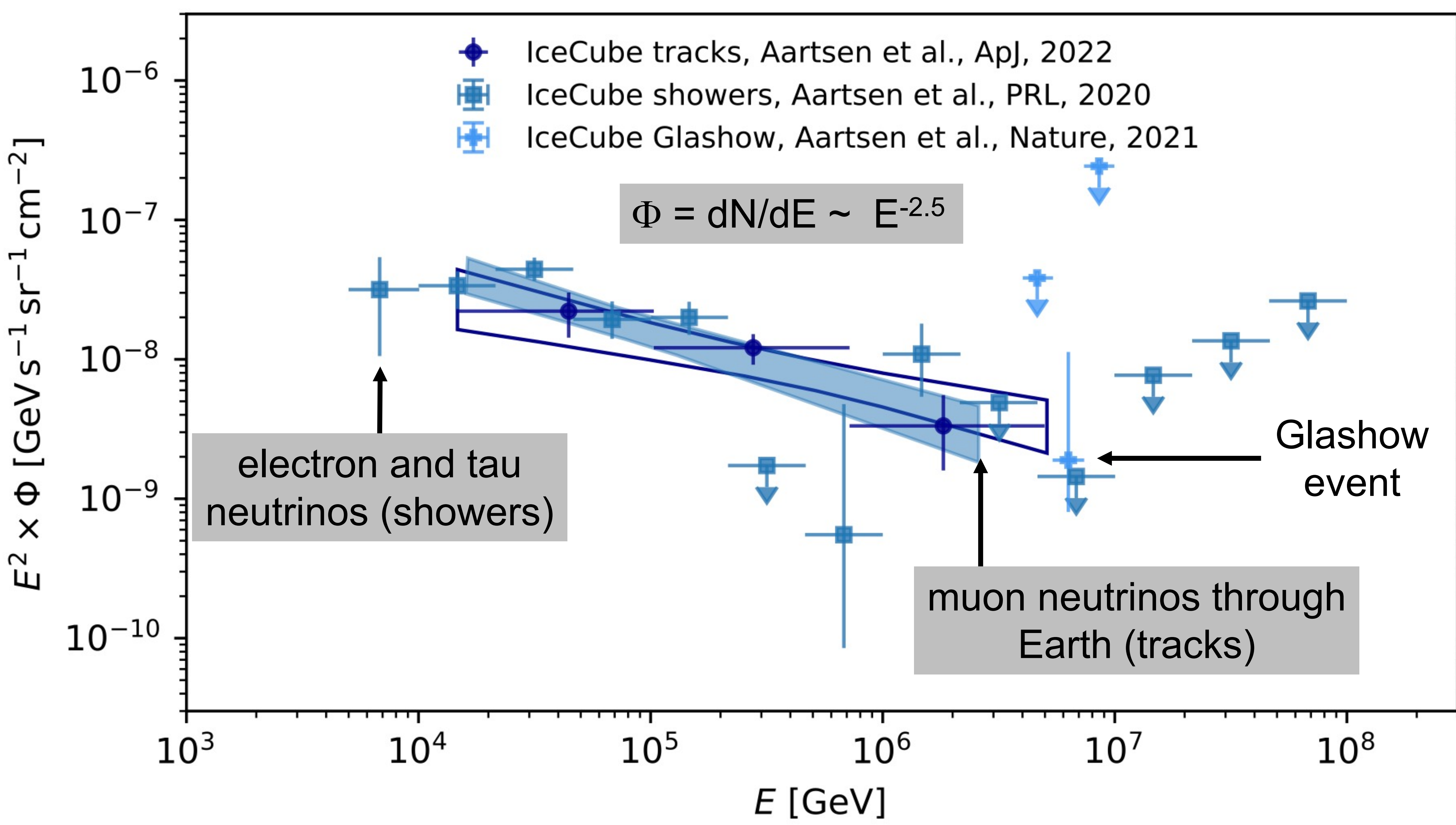
Glashow resonance event with energy 6.3 PeV



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



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



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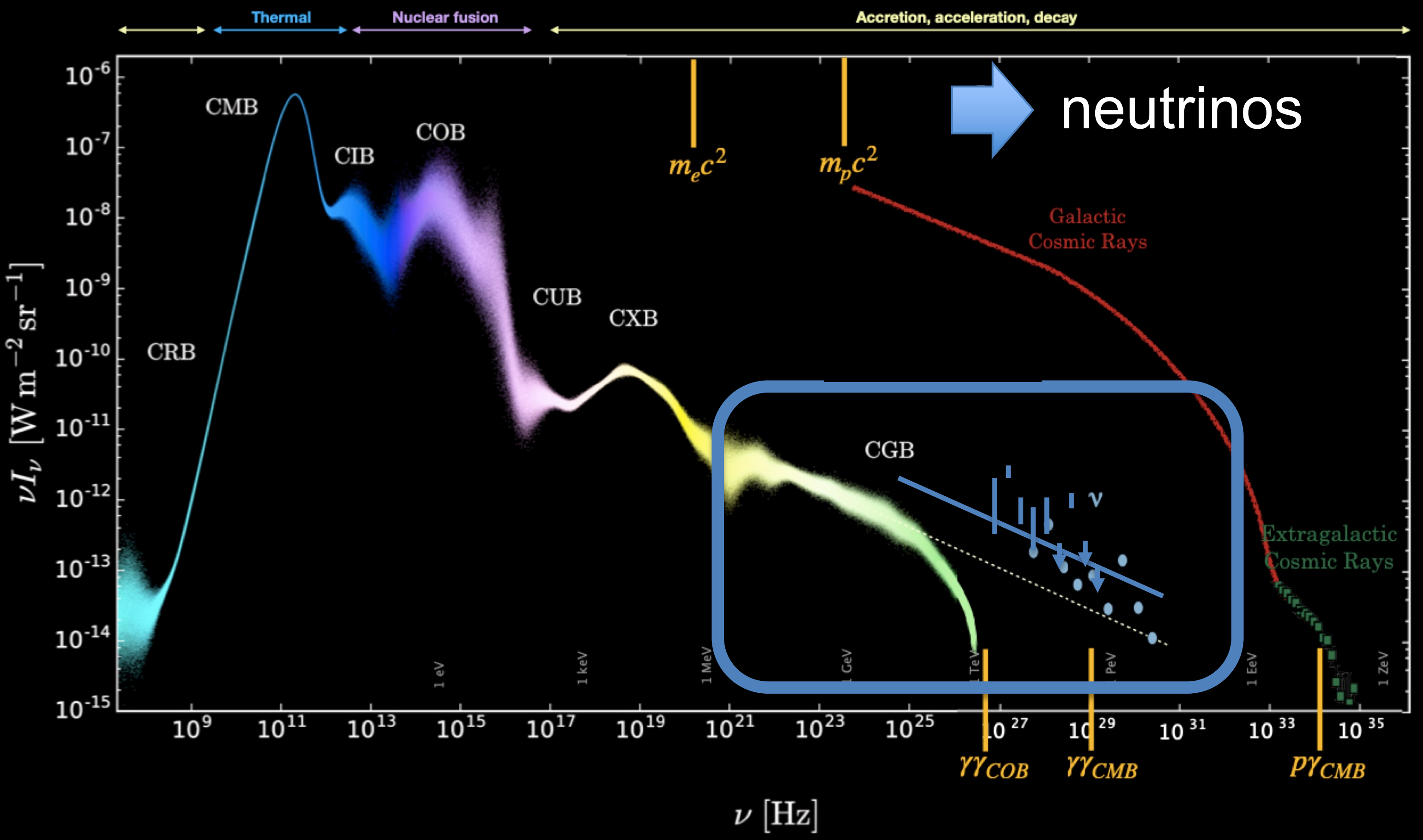
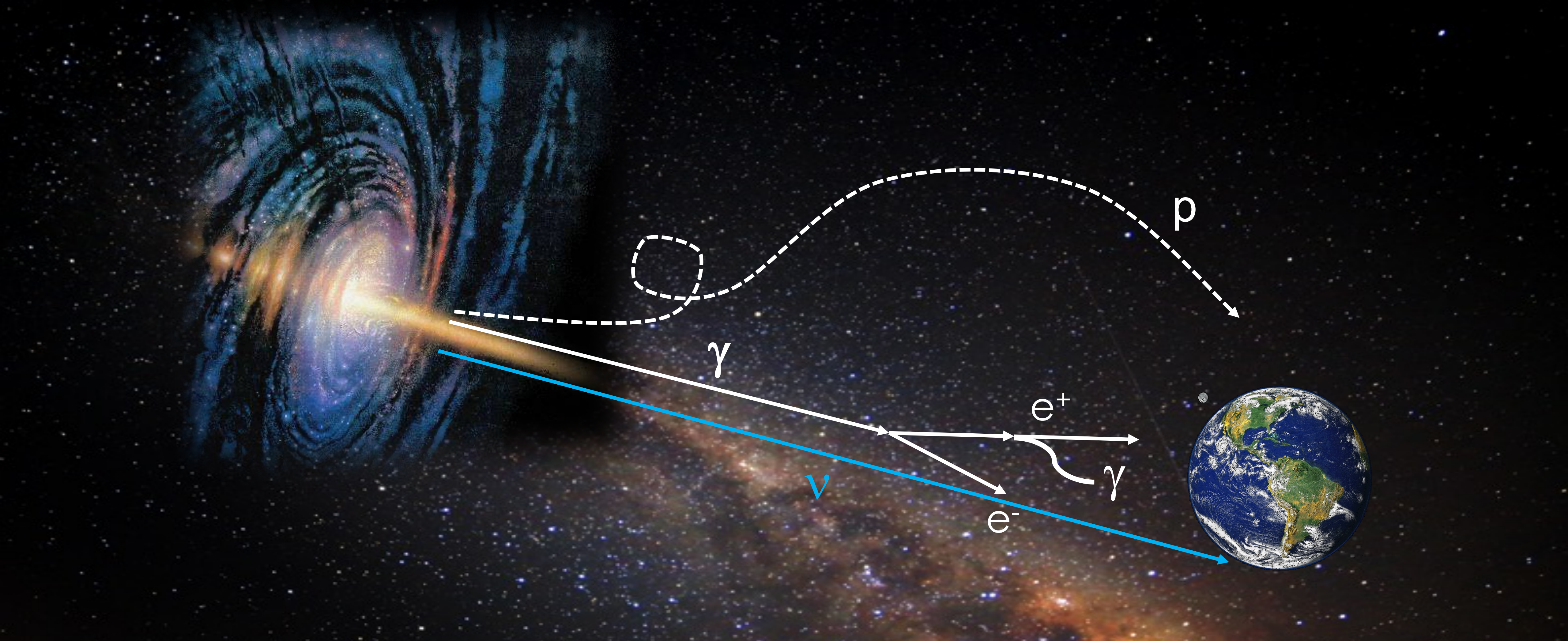
Glashow event
E^2 × Φ [GeV s^-1 sr^-1 cm^-2]
E [GeV]
10^-6
10^-7
10^-8
10^-9
10^-10
10^3
10^4
10^5
10^6
10^7
10^8

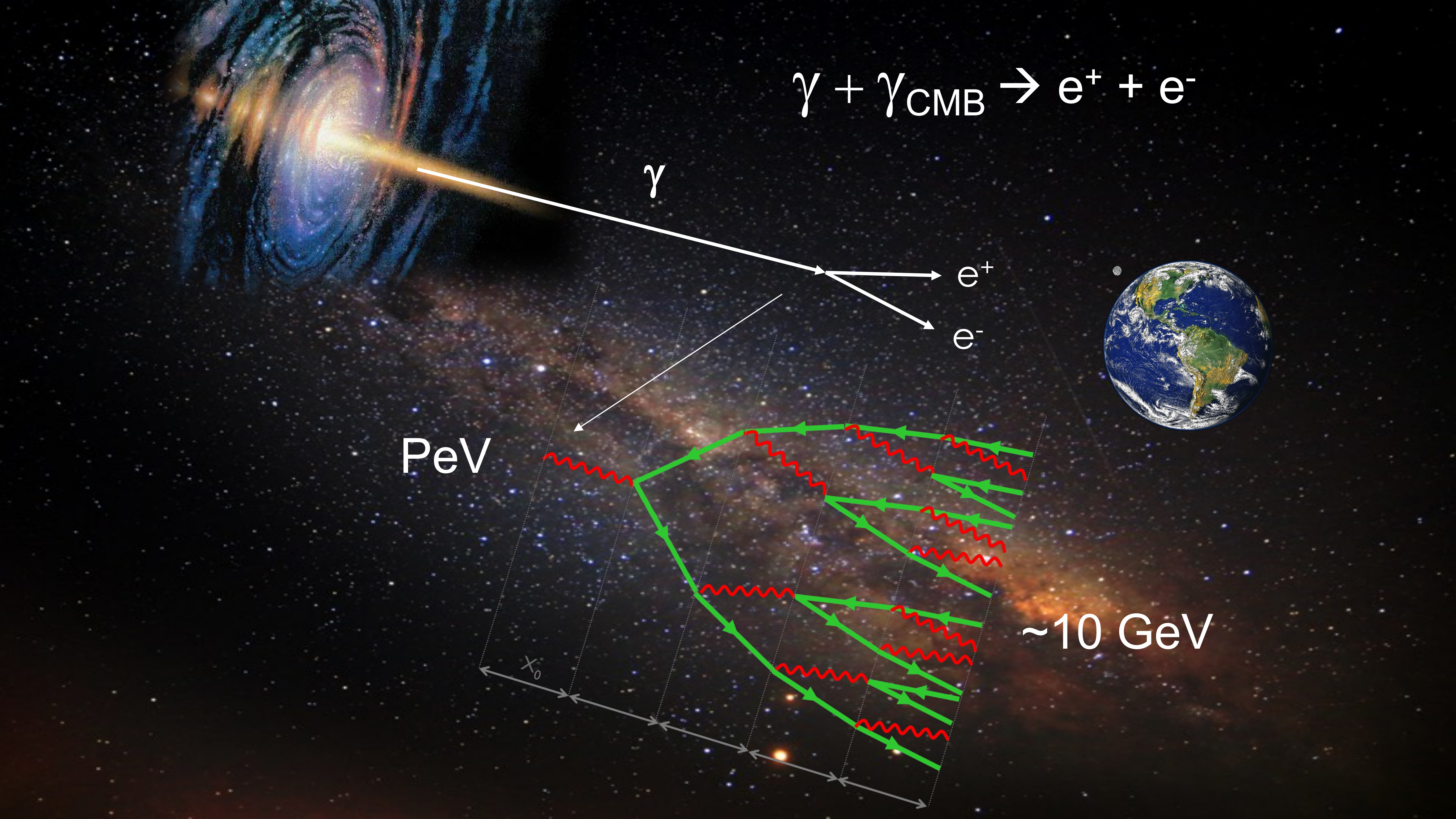
in the extreme universe the energy in neutrinos is larger than the energy in gamma rays



one gamma ray for every neutrino?

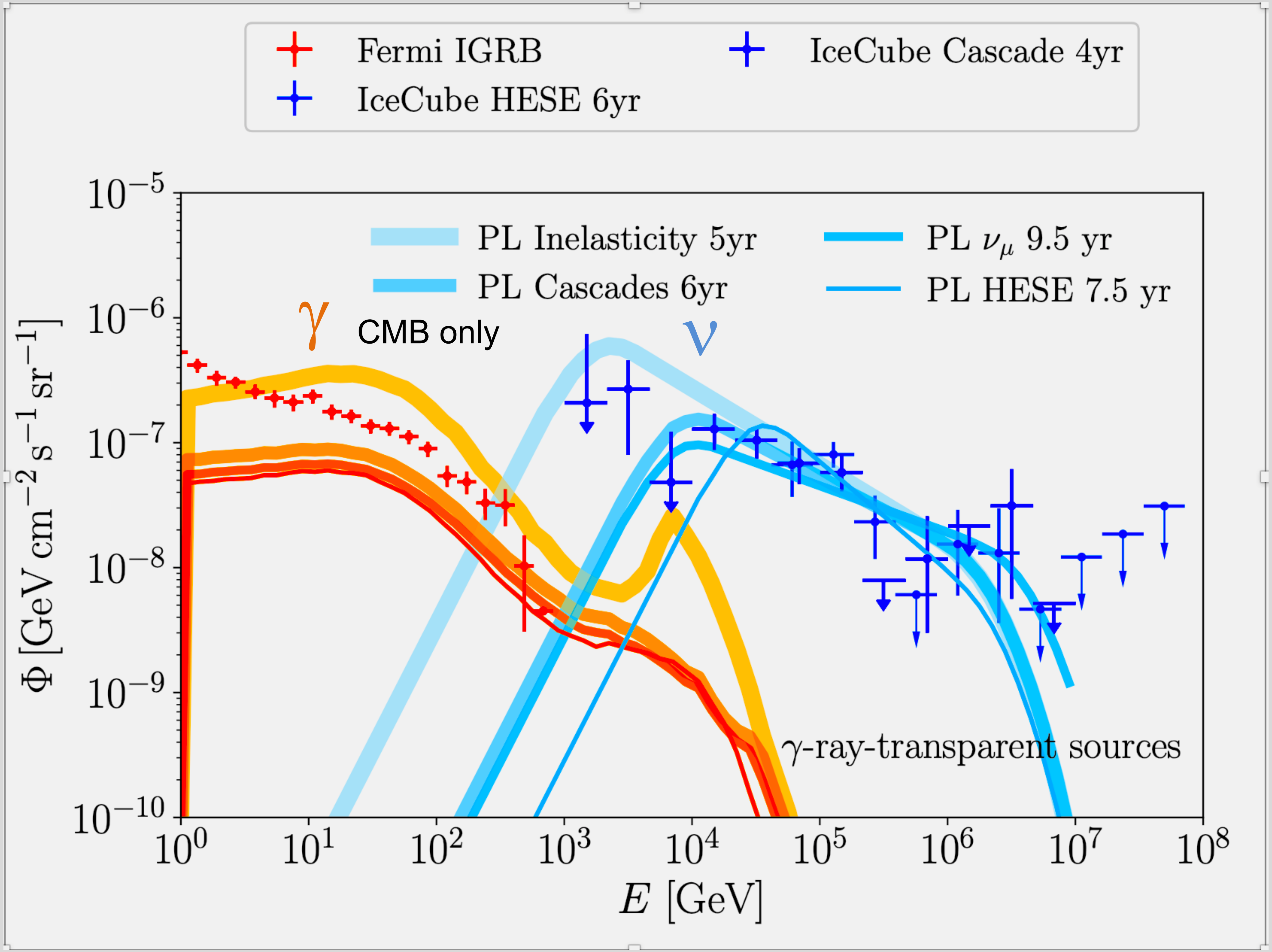


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth



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

gamma rays from neutral pions must lose energy in the sources

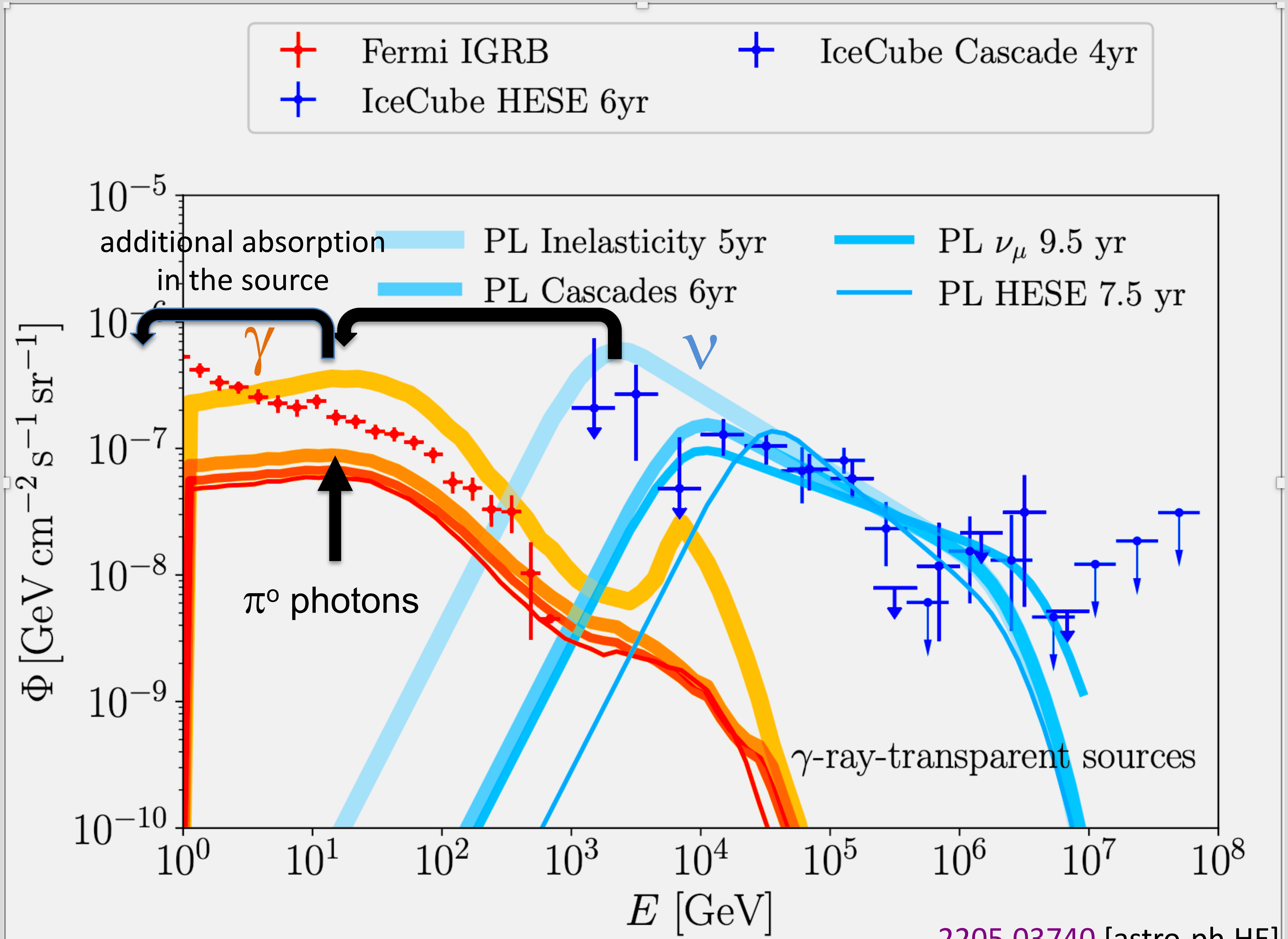


- the gamma ray flux from neutral pions exceeds the total flux observed at GeV energies by Fermi showing additional energy loss in source

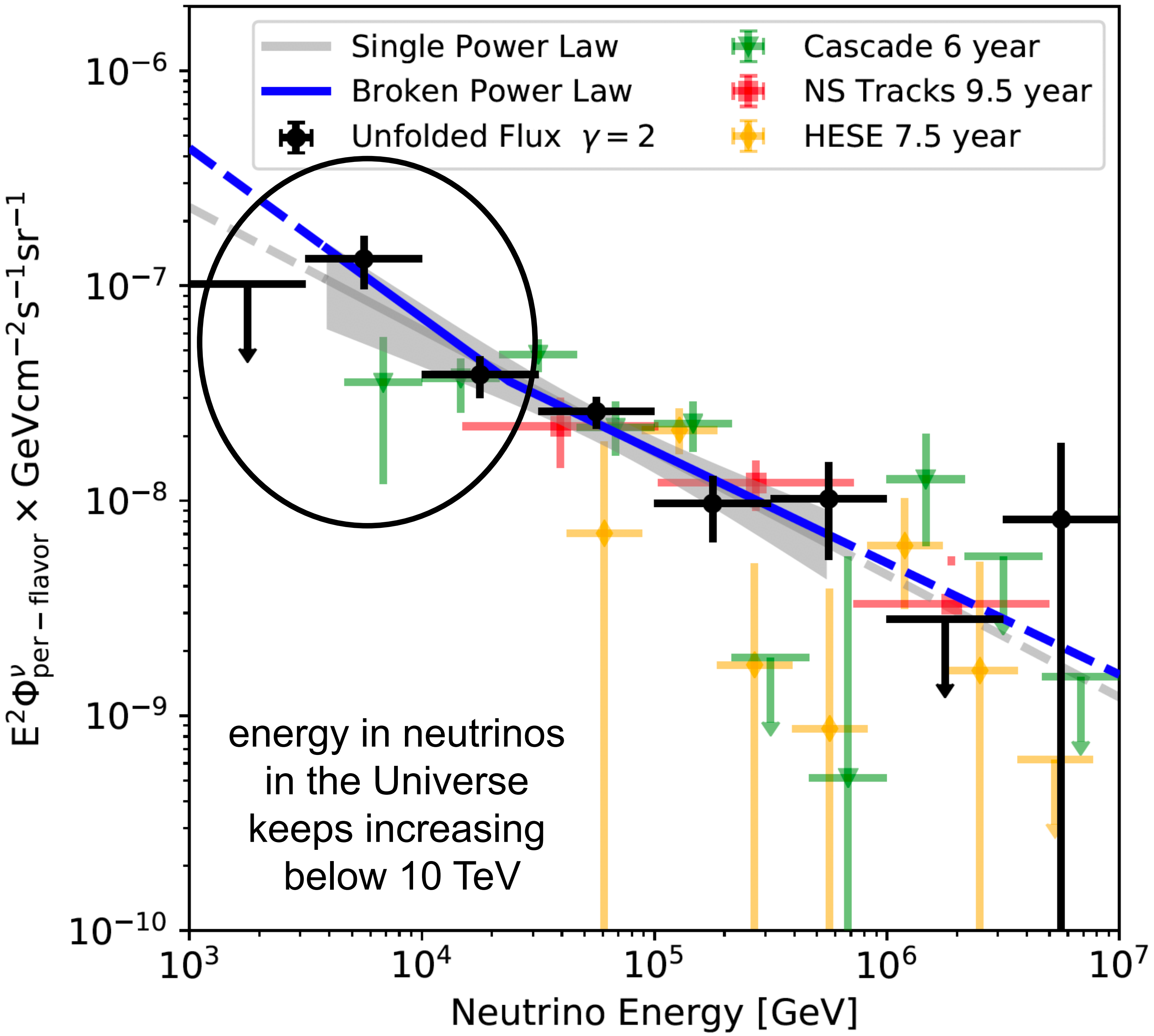
- neutrino sources do not emit gamma rays

- the flux from neutral pions accompanying neutrinos appears at MeV energy, or below

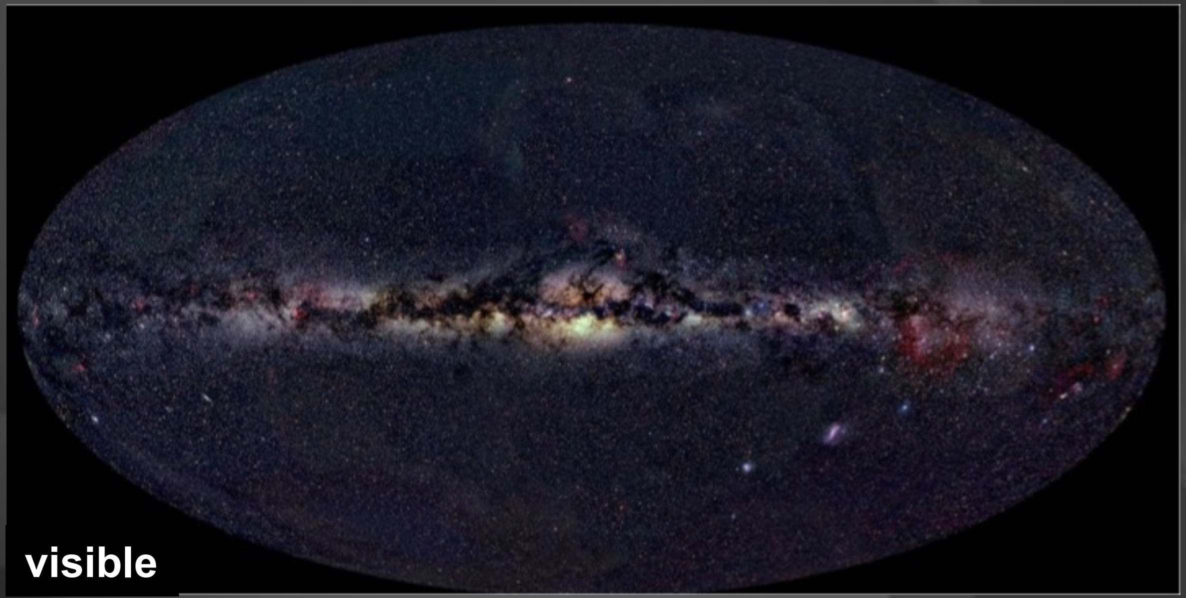
- the neutrino sources are opaque to gamma rays

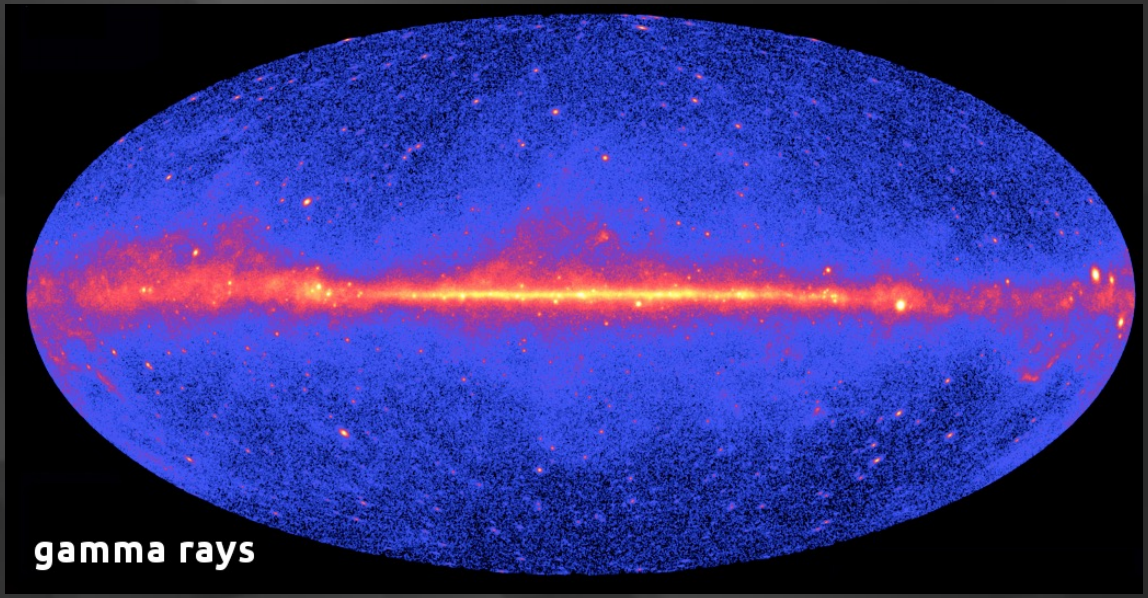


2205.03740 [astro-ph.HE]

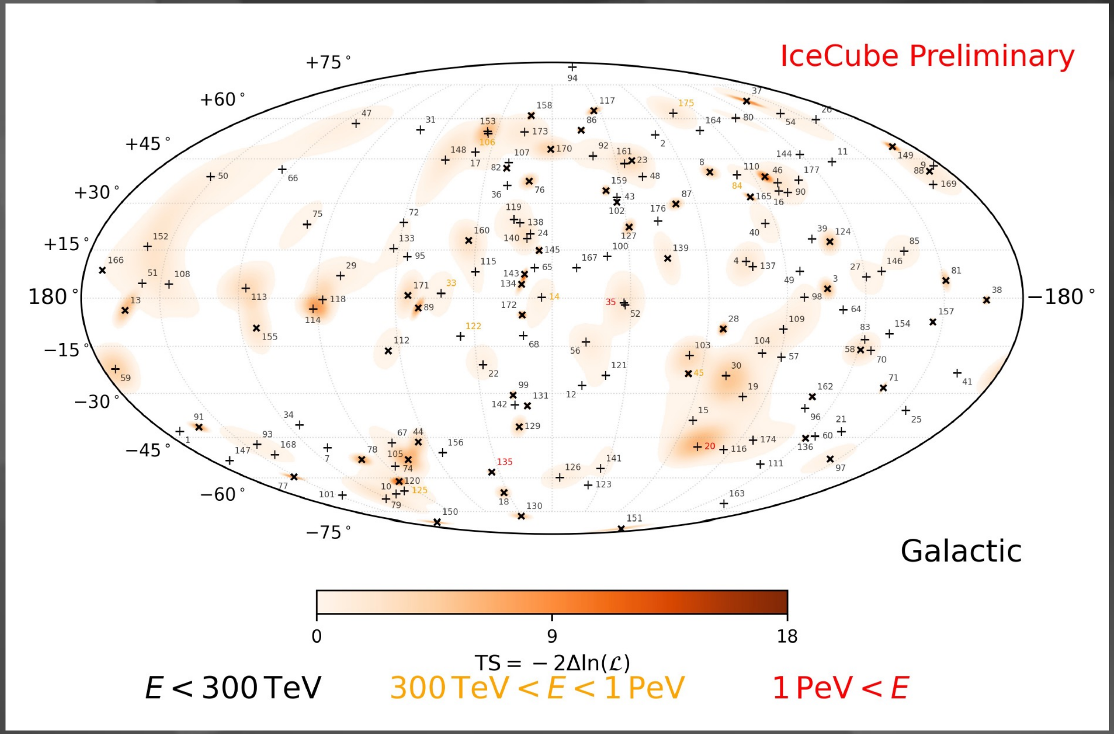


Single Power Law
Broken Power Law
Unfolded Flux $\gamma = 2$
Cascade 6 year
NS Tracks 9.5 year
HESE 7.5 year
$E^2\Phi^{\nu}_{per-flavor} \times \mathrm{GeVcm^{-2}s^{-1}sr^{-1}}$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Neutrino Energy [GeV]
energy in neutrinos
in the Universe
keeps increasing
below 10 TeV





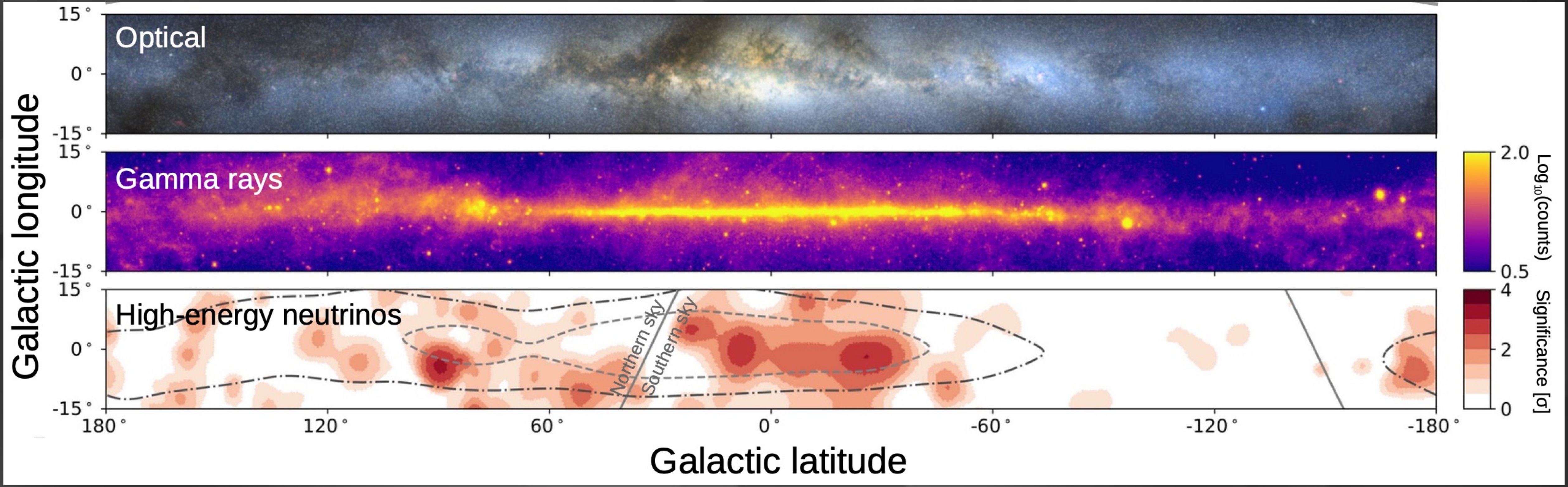
166 neutrino starting events



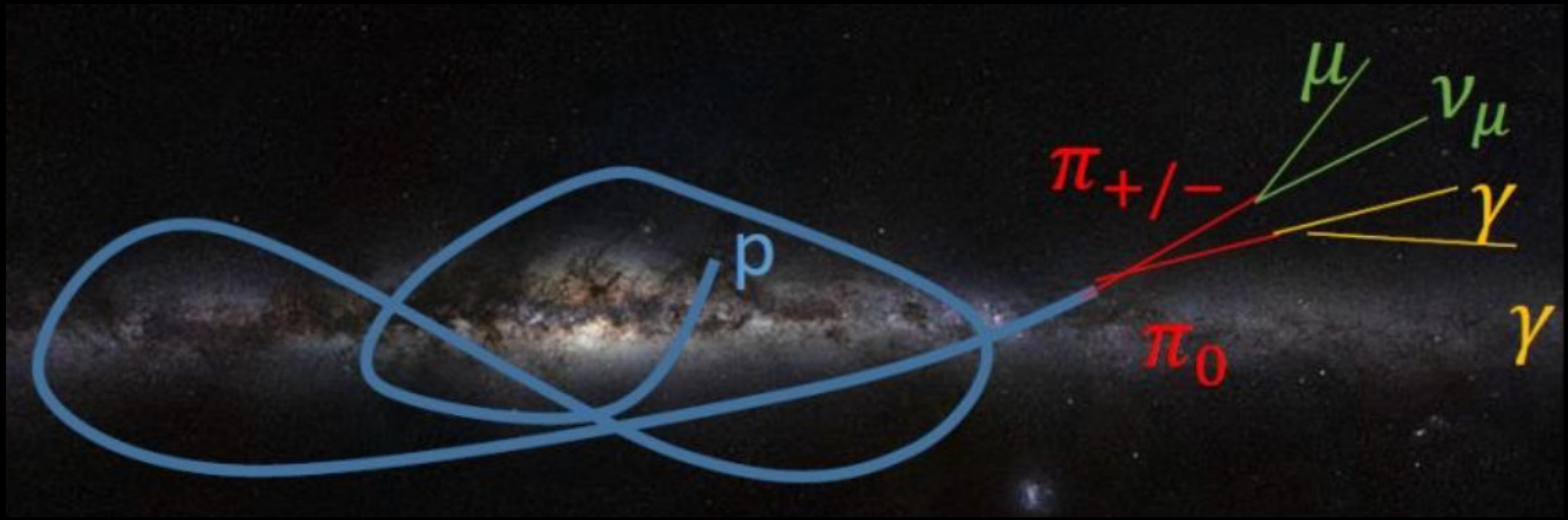
where is the neutrino Galactic plane?

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

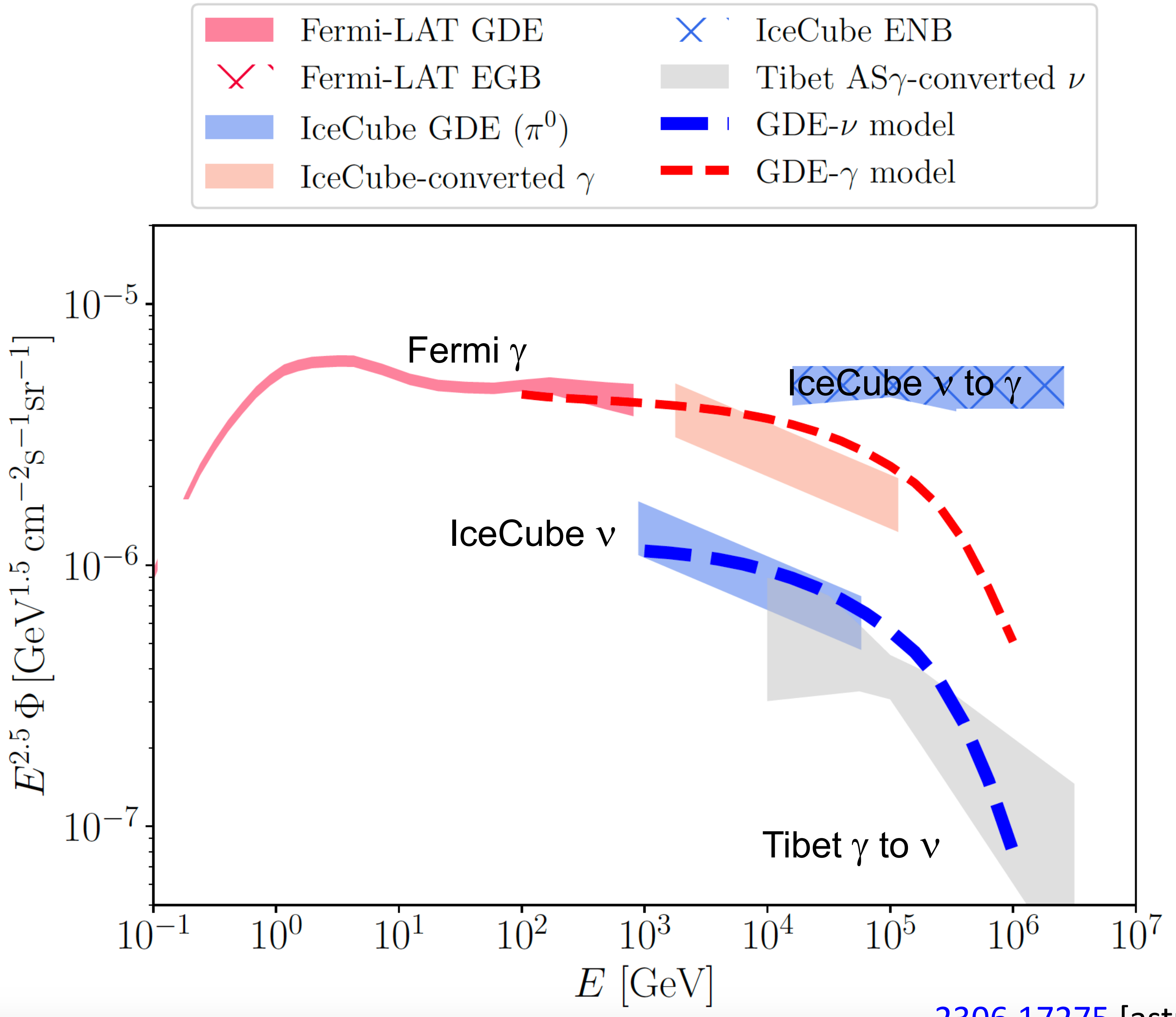

NSF
IceCube



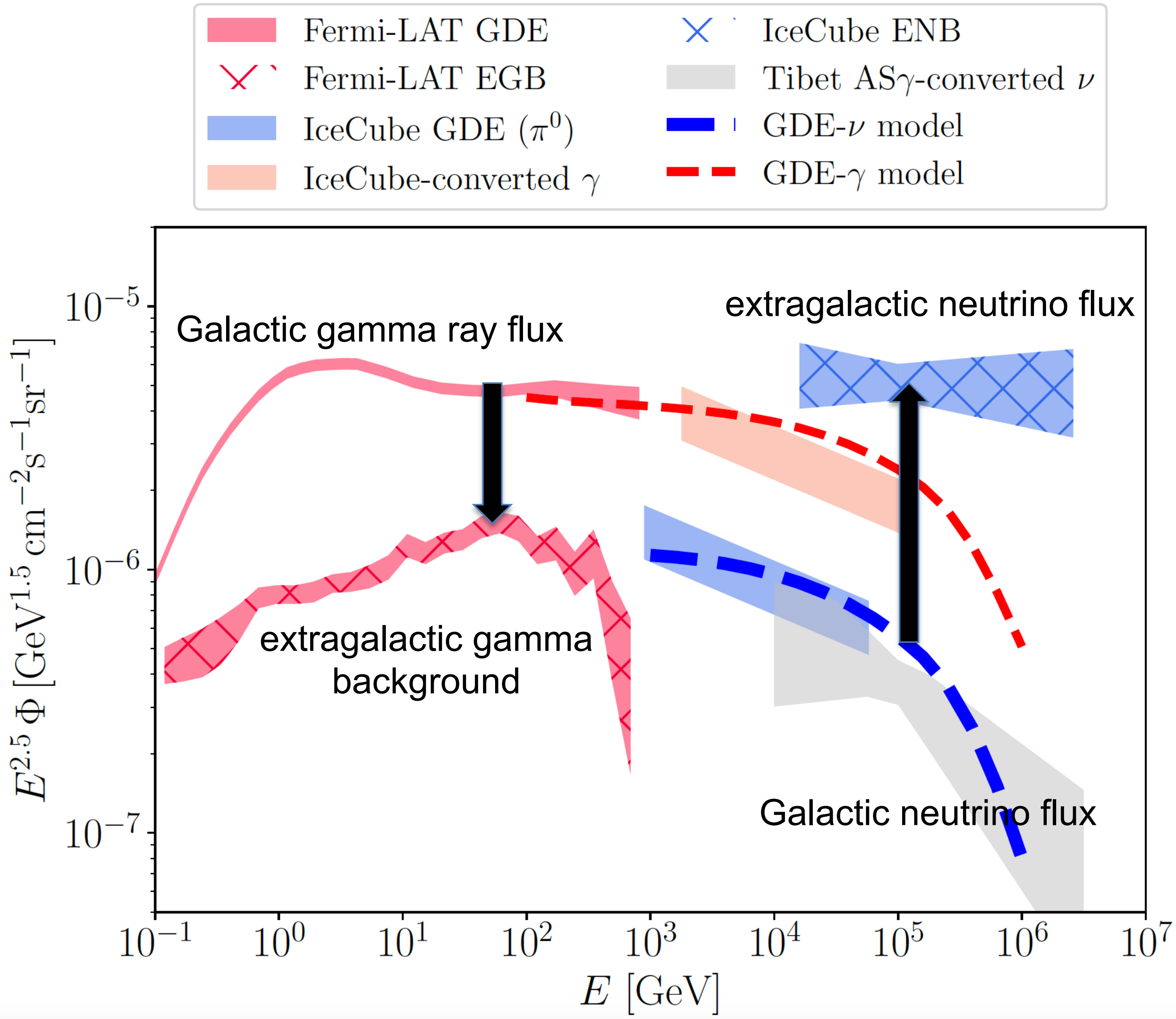
Fermi (GeV gamma rays) and IceCube (TeV neutrinos)
see the same Galactic plane



neutrinos produced in Galactic cosmic rays
interactions with interstellar medium



2306.17275 [astro-ph.HE]



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}]
E [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

- 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?

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

measured IceCube fluxes

factors of order unity

neutrino flux in active galaxies from diffuse flux observed

$$\Phi_\nu = n_0 c t_H\, L_\nu^{EG}$$

ξ (cosmology)

neutrino flux in Milky Way from flux at Earth

$$\Phi_{MW} = \frac{3}{4\pi r_0^2}\; L_\nu^{MW}$$

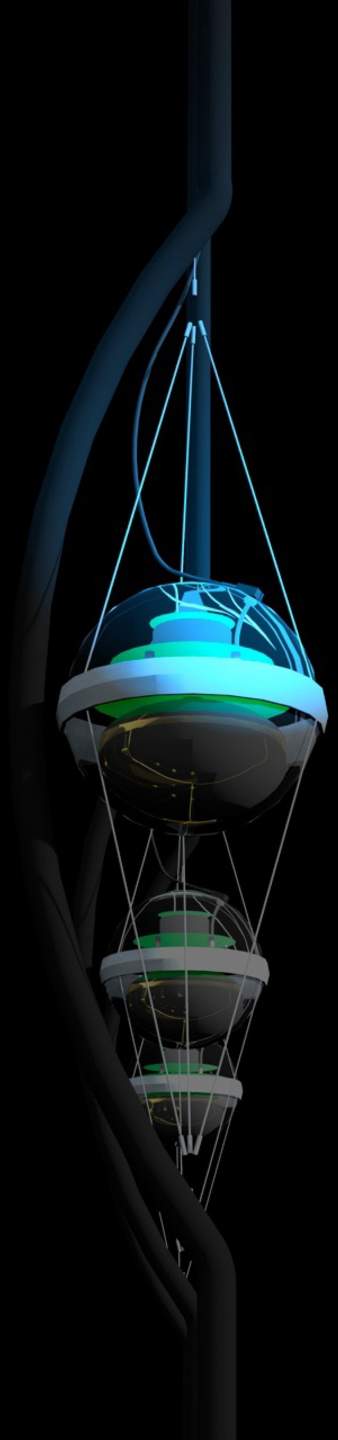
F_ϵ (geometry)

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

- neutrino sources are gamma-ray obscured

- 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?



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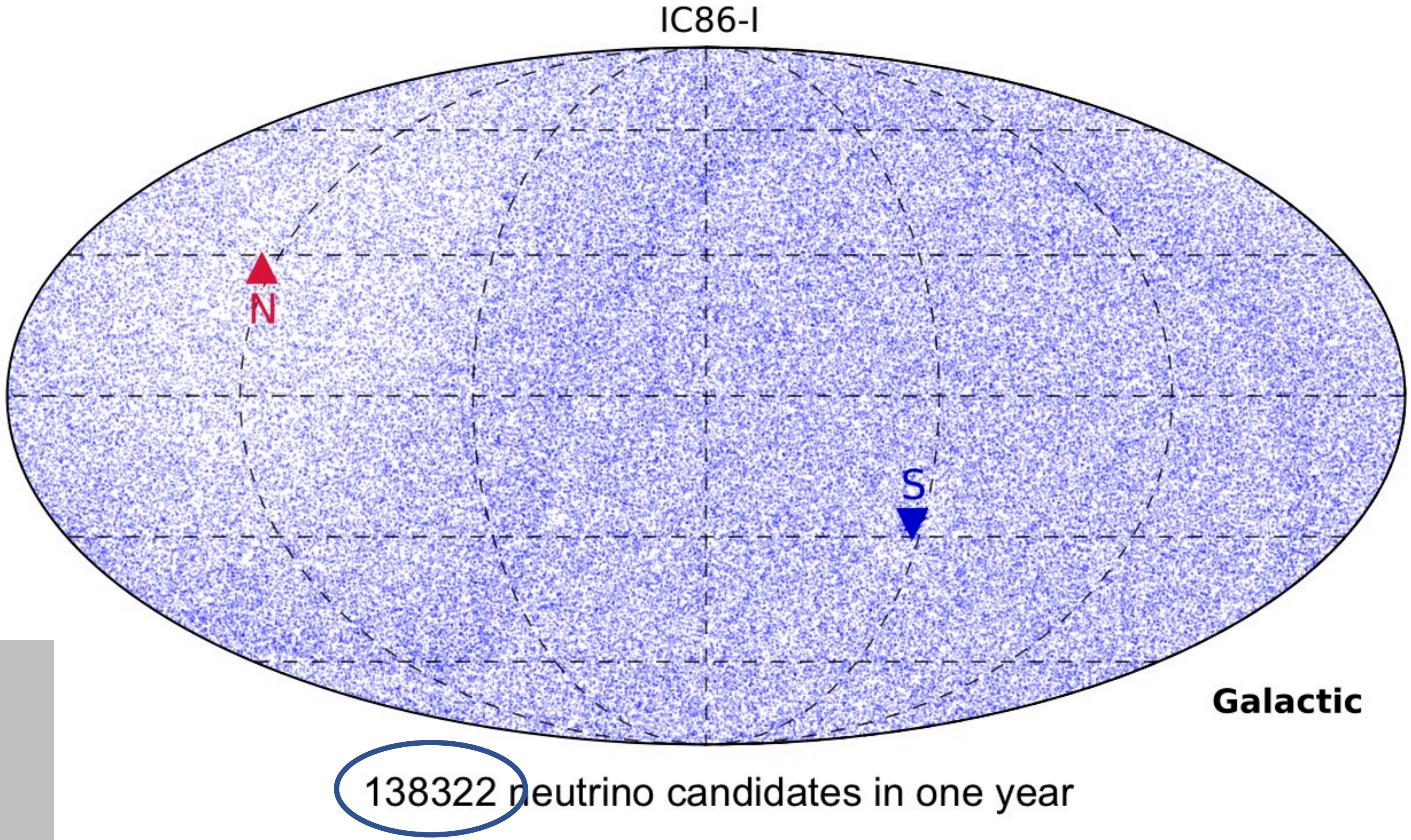
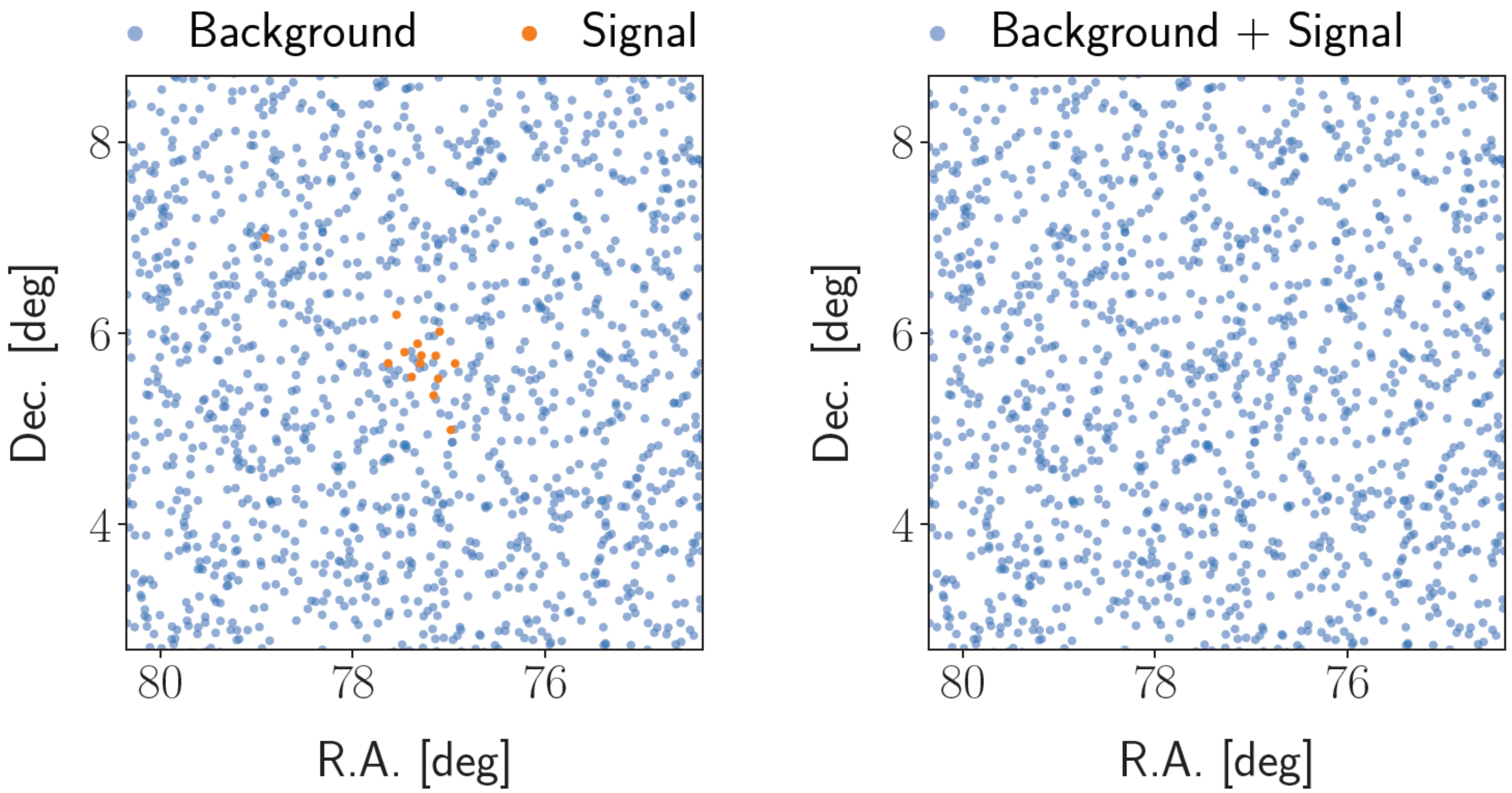
IceCube neutrinos >100 GeV (one year shown)

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



~ 200 cosmic neutrinos
~12 separated from 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*

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

$$\downarrow$$

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

search in the directions of 110 preselected source candidates:

hints of sources!

Phys.Rev.Lett. 124 (2020)

Source List Results

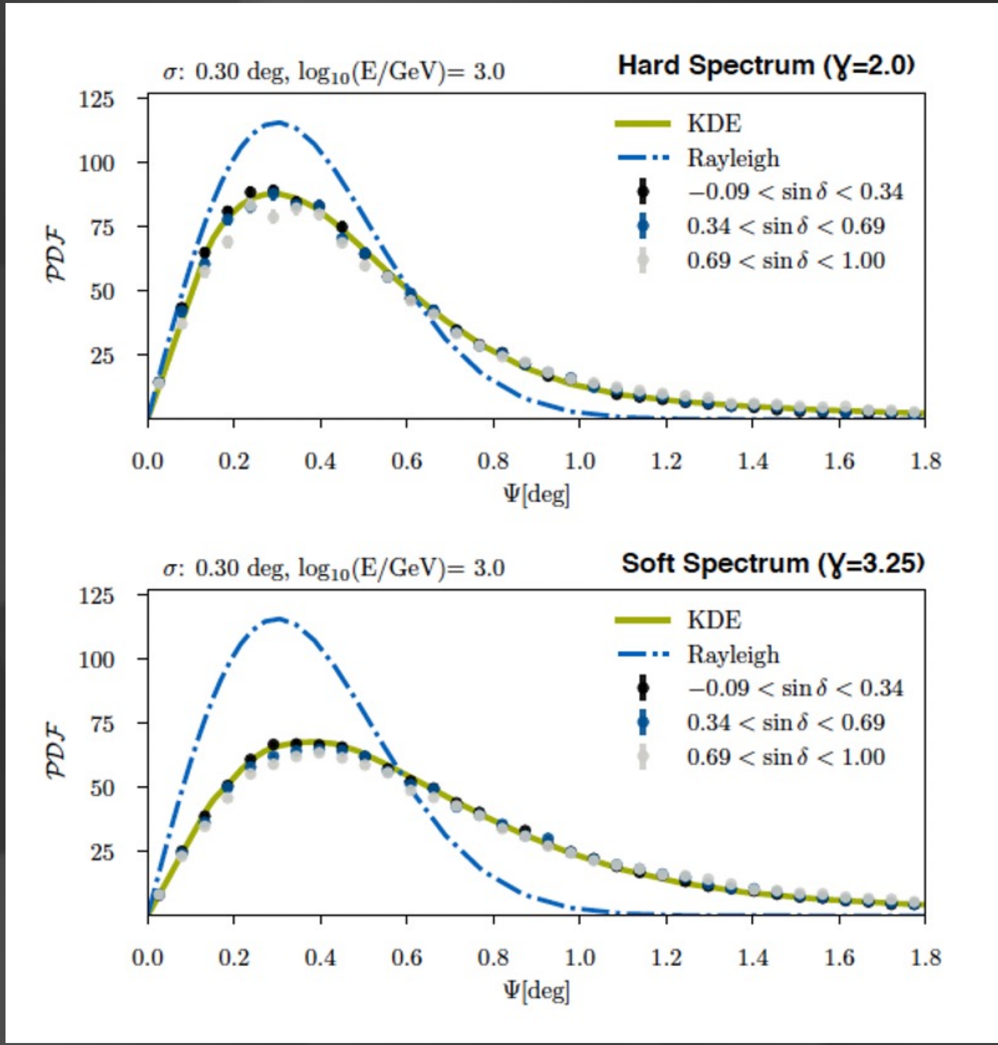
Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	-$\log_{10}(p_{local})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	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	2.0	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	3.8	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

interesting fluctuations or neutrino sources?

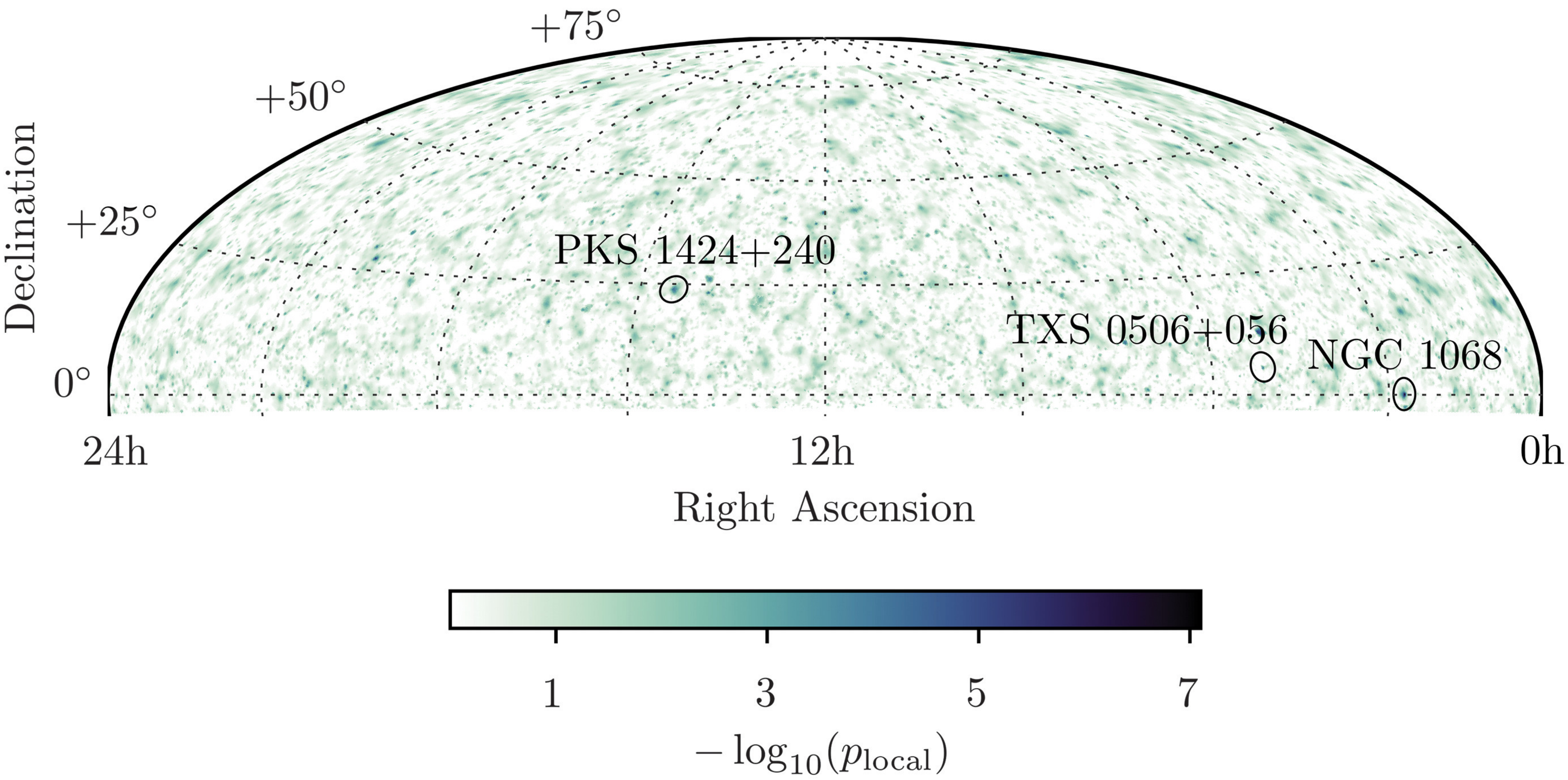
→ crash program to upgrade the performance of IceCube

- 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*
- *…*

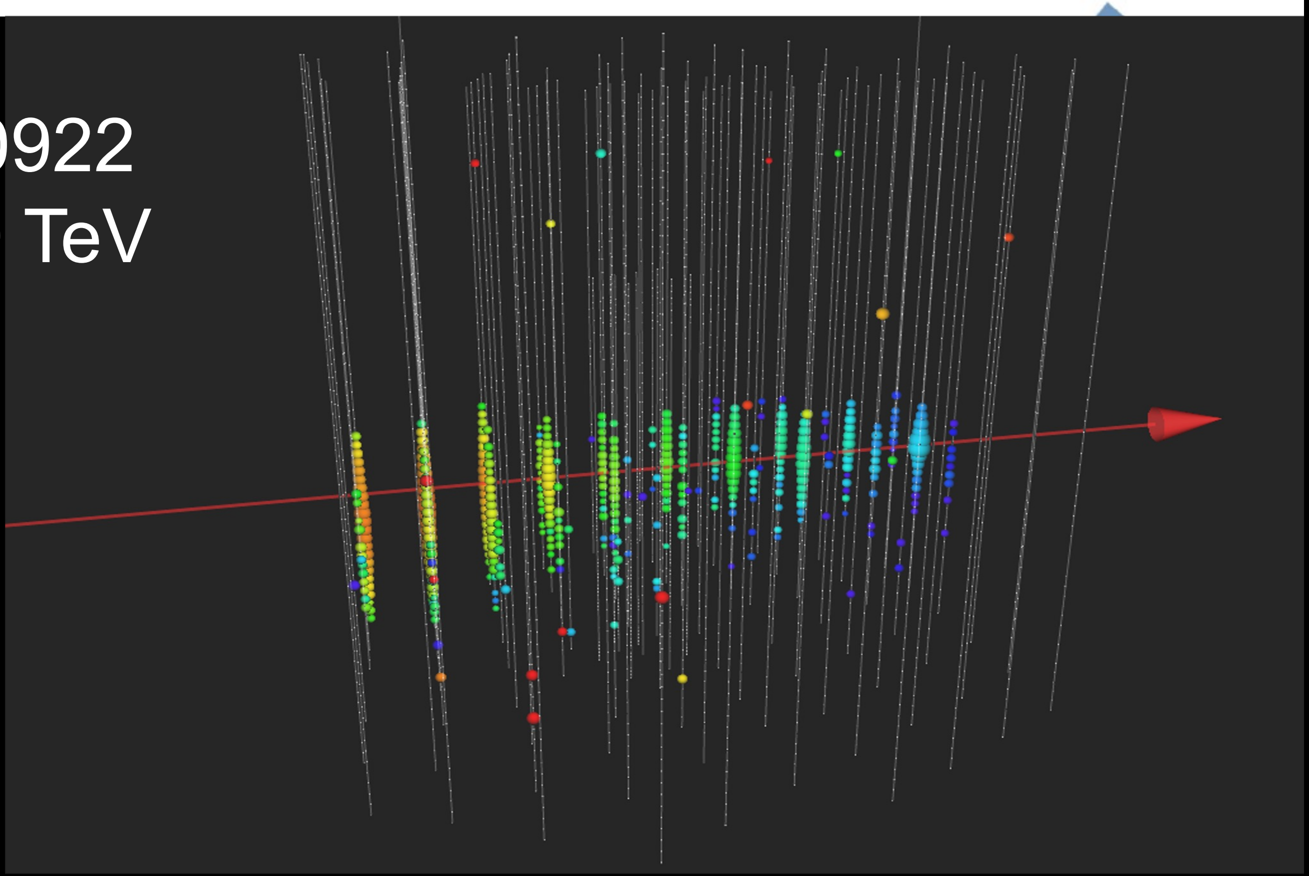
applied to 10 years of archival data (pass 2), data unblinded, result …



binomial analysis: 3 active galaxies

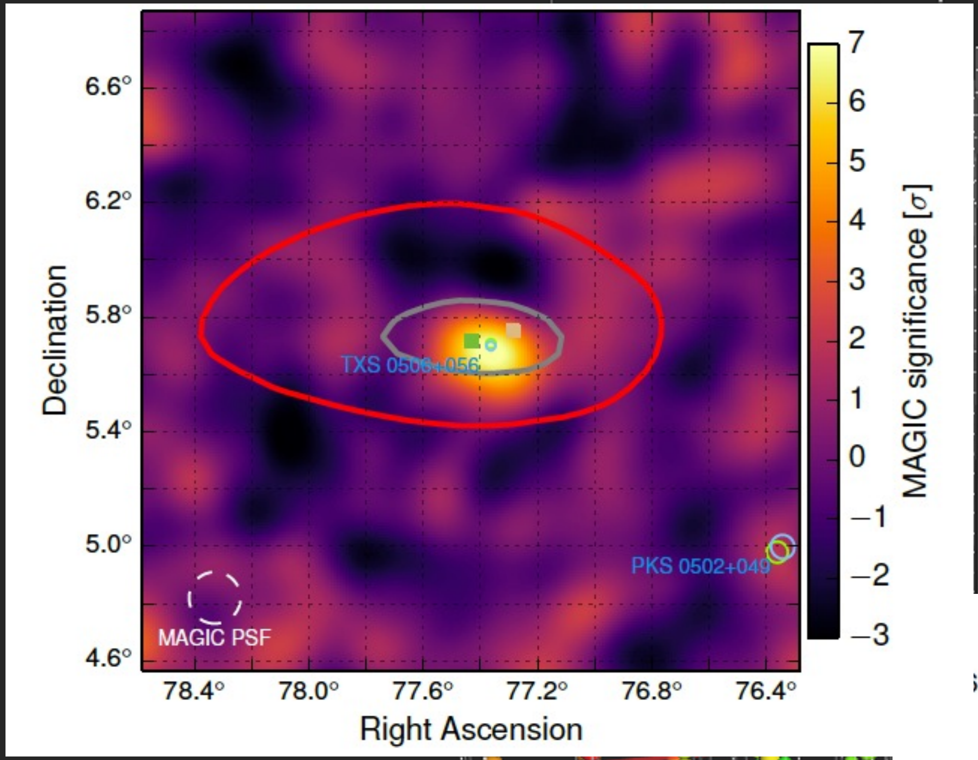


IceCube 170922
290 TeV



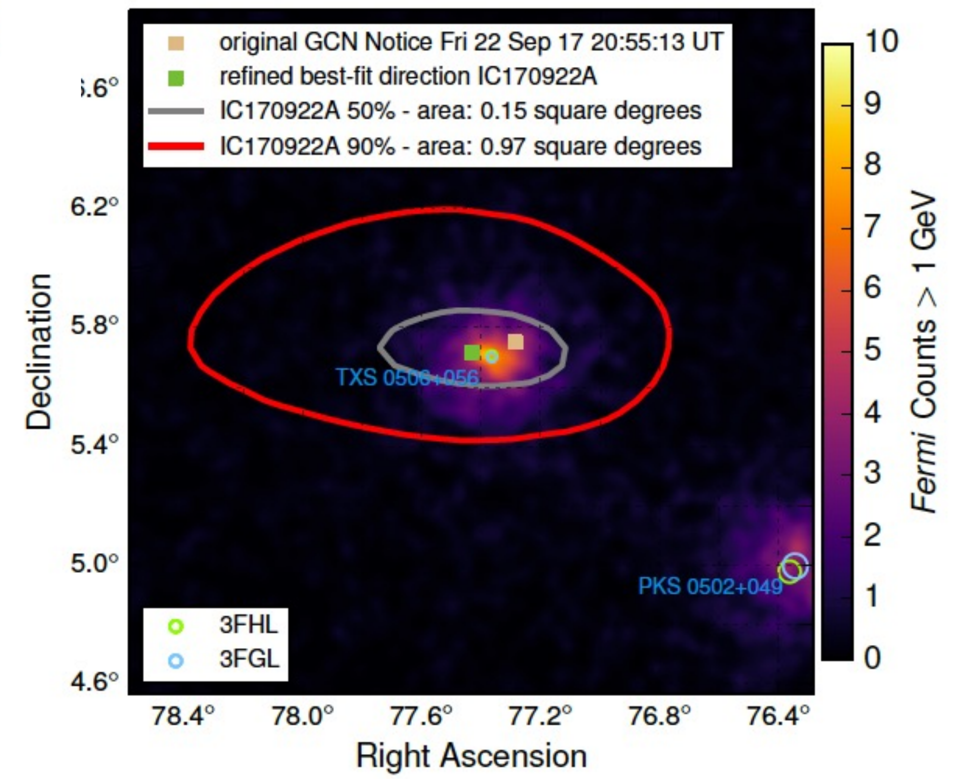
from light in the ice to astronomer in less than one minute

IceCube 170922
290 TeV

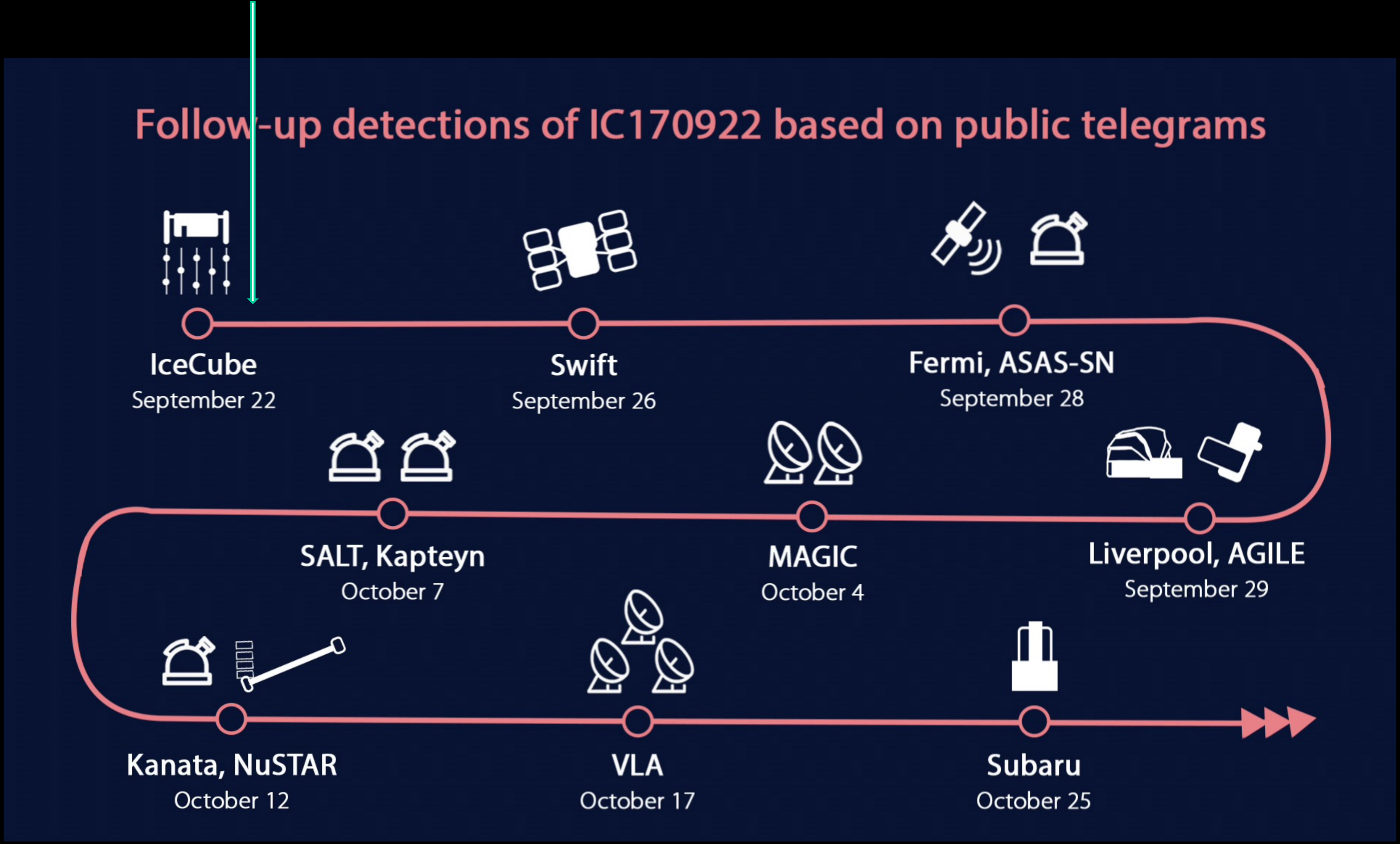


Fermi
detects a flaring
blazar within 0.06°

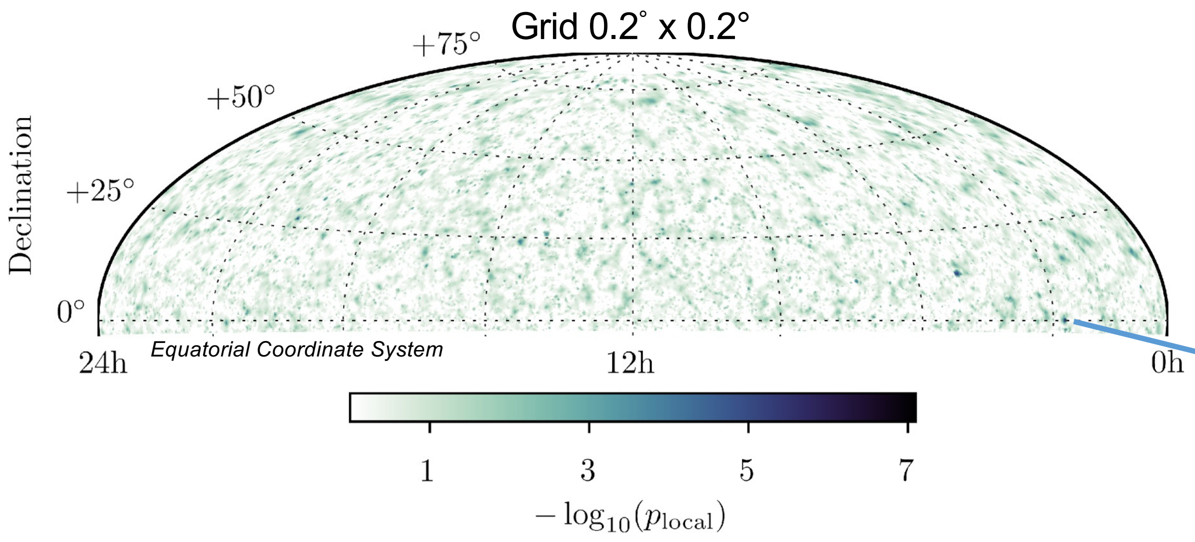
MAGIC
detects emission of
> 100 GeV gammas

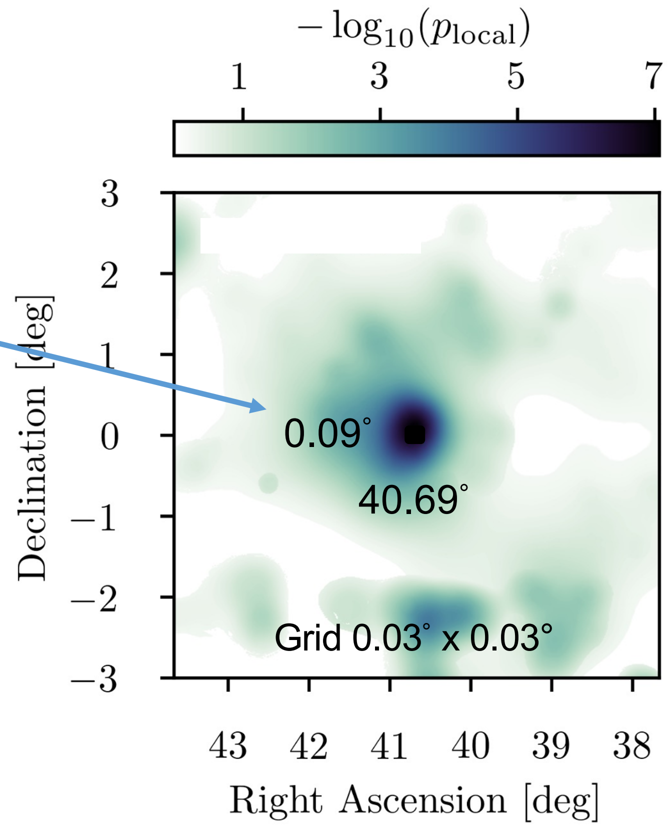


MASTER robotic optical telescope network: observing within 73 seconds
optical flash after 2 hours: highest statistical association of TXS 0506 with IC170922



the new IceCube neutrino map: hottest spot





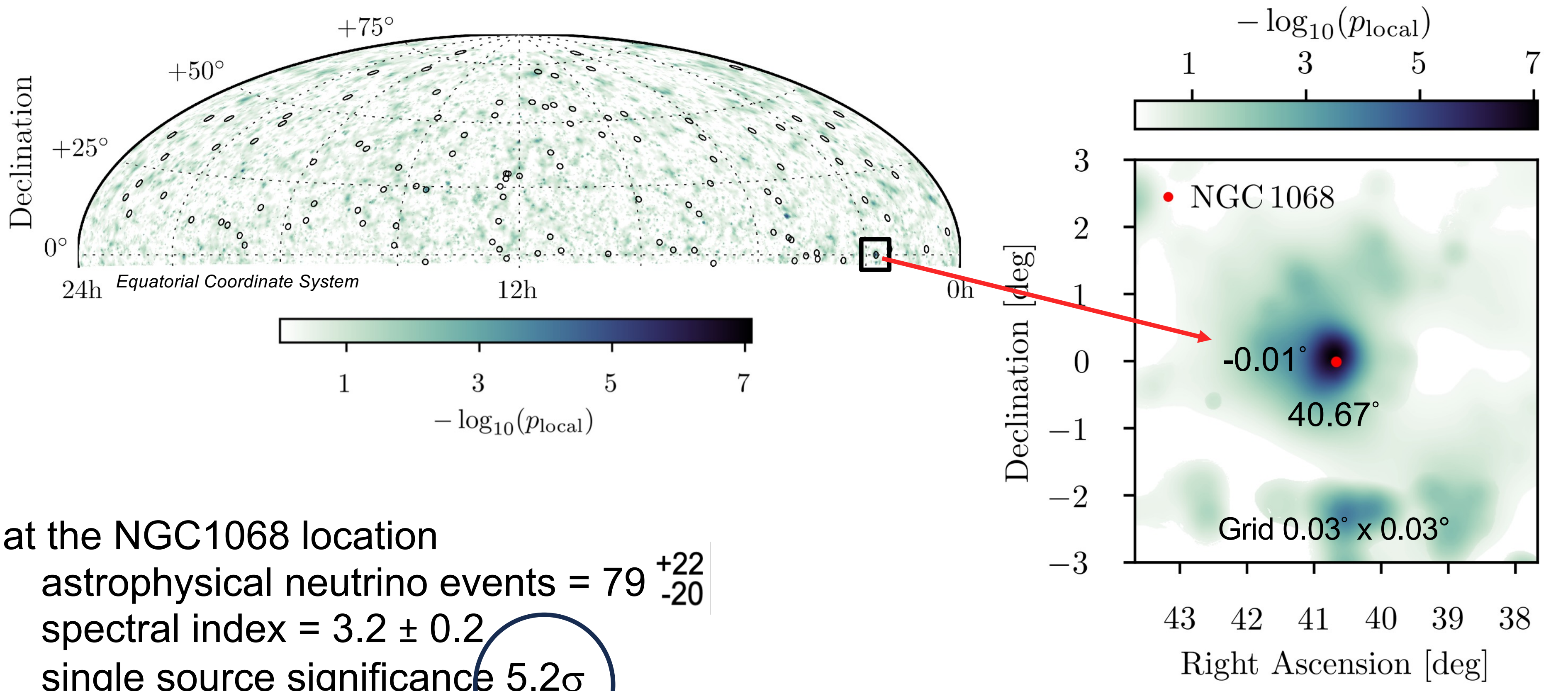
the brightest location in full sky scan:

- 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}

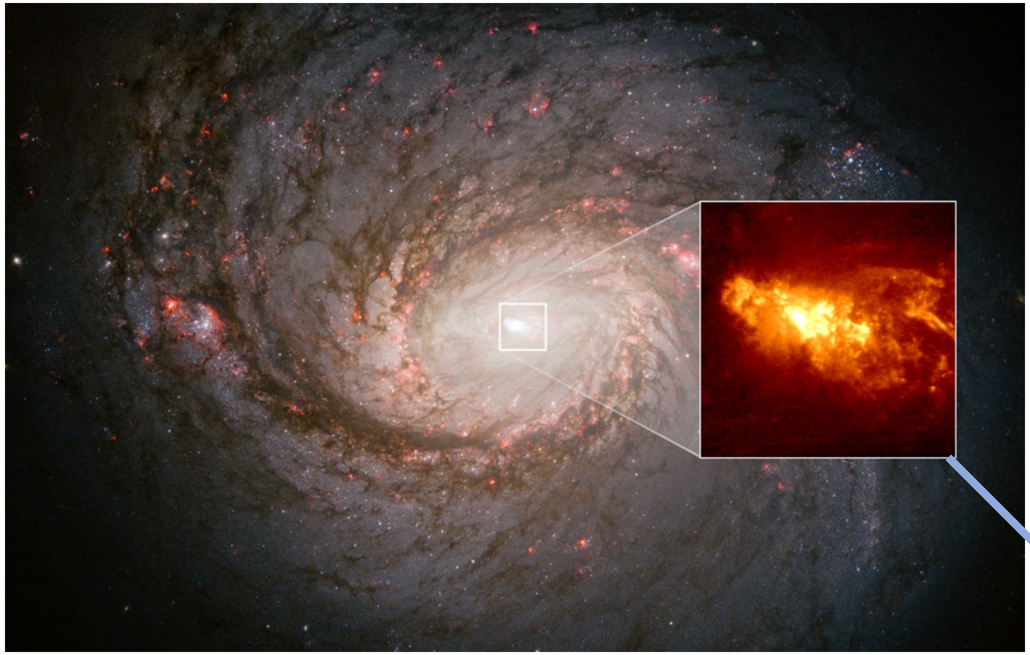
spectral index = 3.2 ± 0.2

single source significance 5.2σ

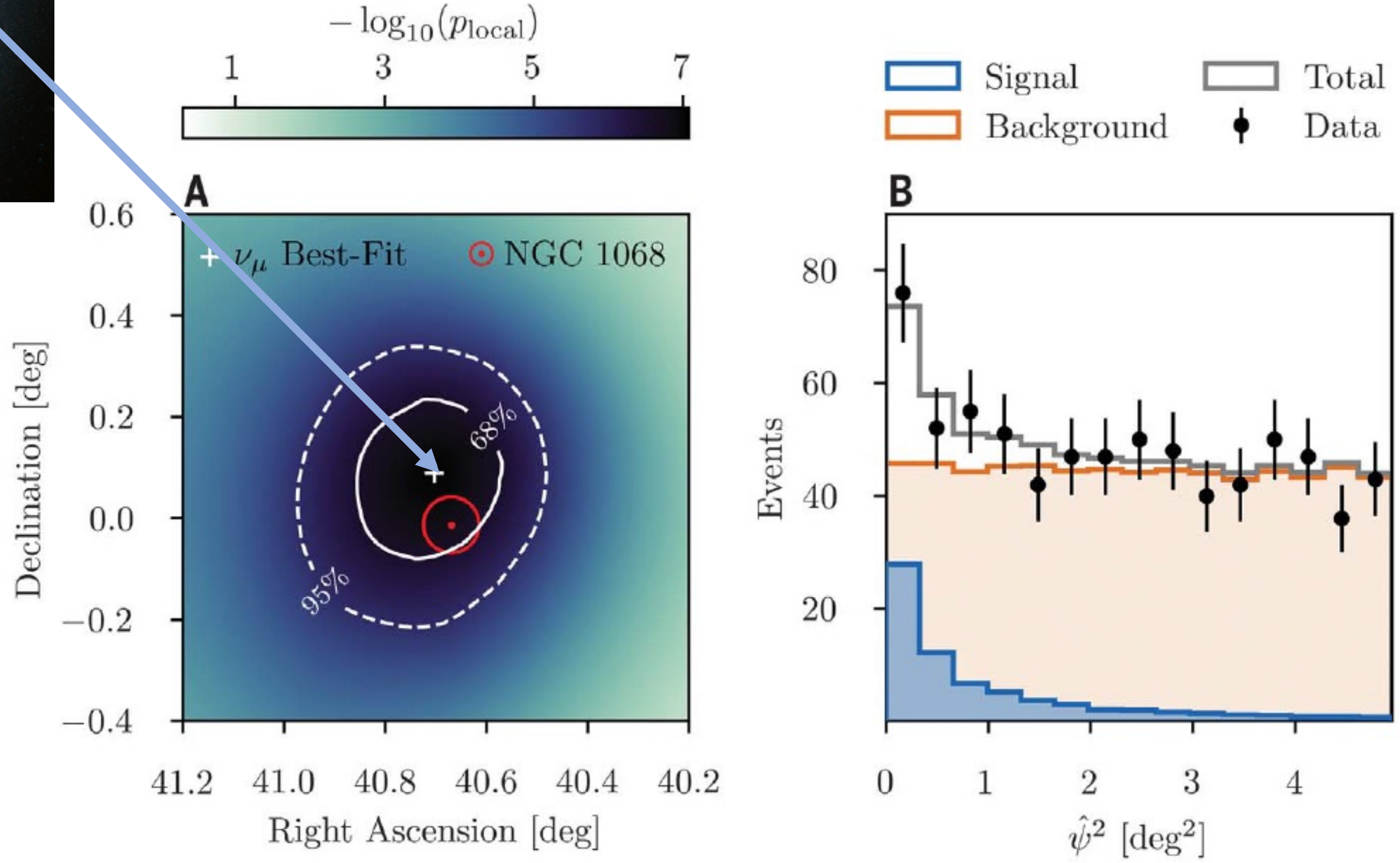
(offset 0.11^0)

1 in 100,000 scrambled data sets have object ≥ 5.2 **σ** = 4.2 **σ**

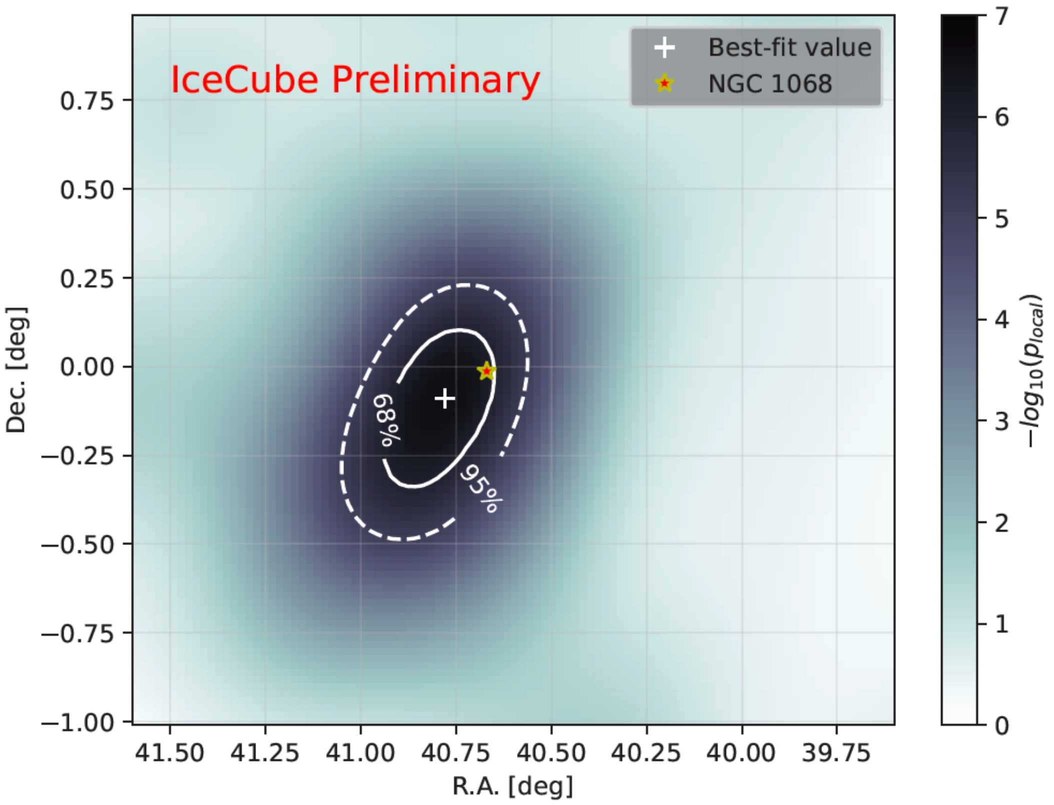
p-value $<10^{-5}$ including all trials

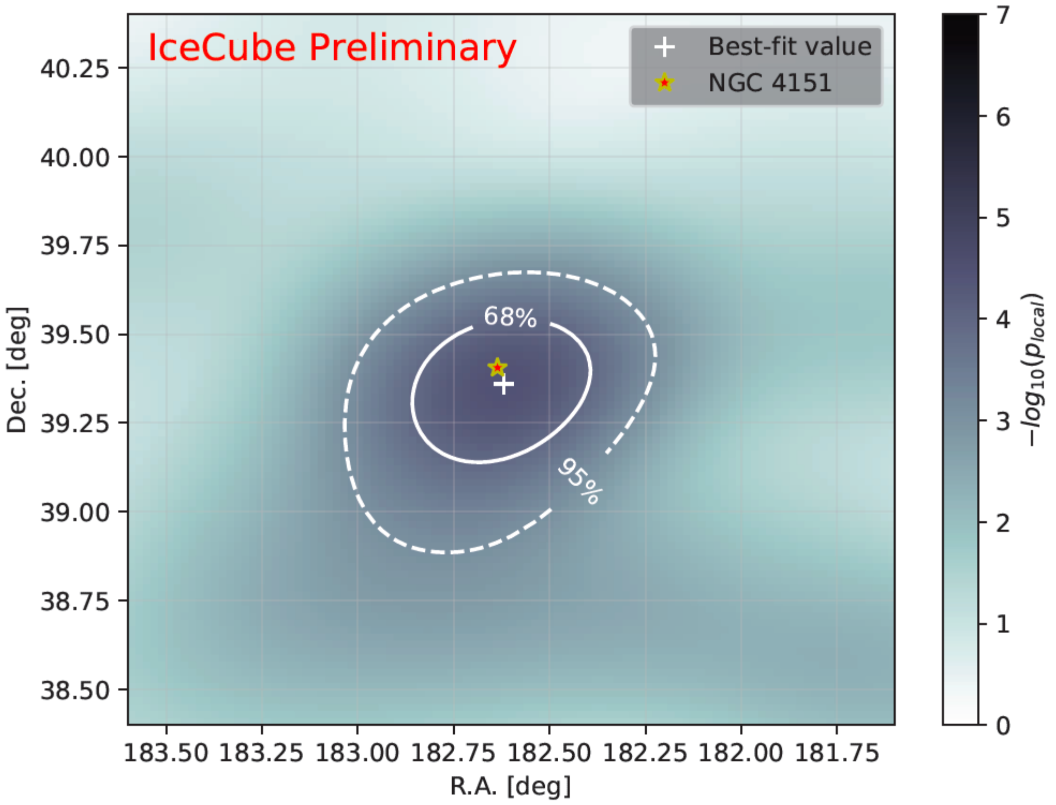


80 high-energy neutrinos from the direction of the active galaxy NGC 1068



multimessenger astronomy with X-ray sources





two brightest active galaxies discovered by Seyfert in 1943

NUCLEAR EMISSION IN SPIRAL NEBULAE*

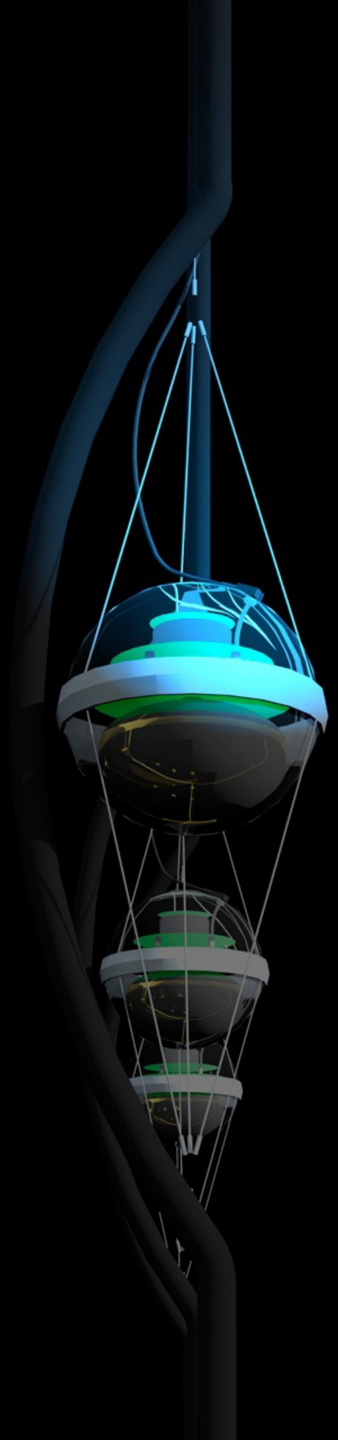
CARL K. SEYFERT†

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.

southern hemisphere soon

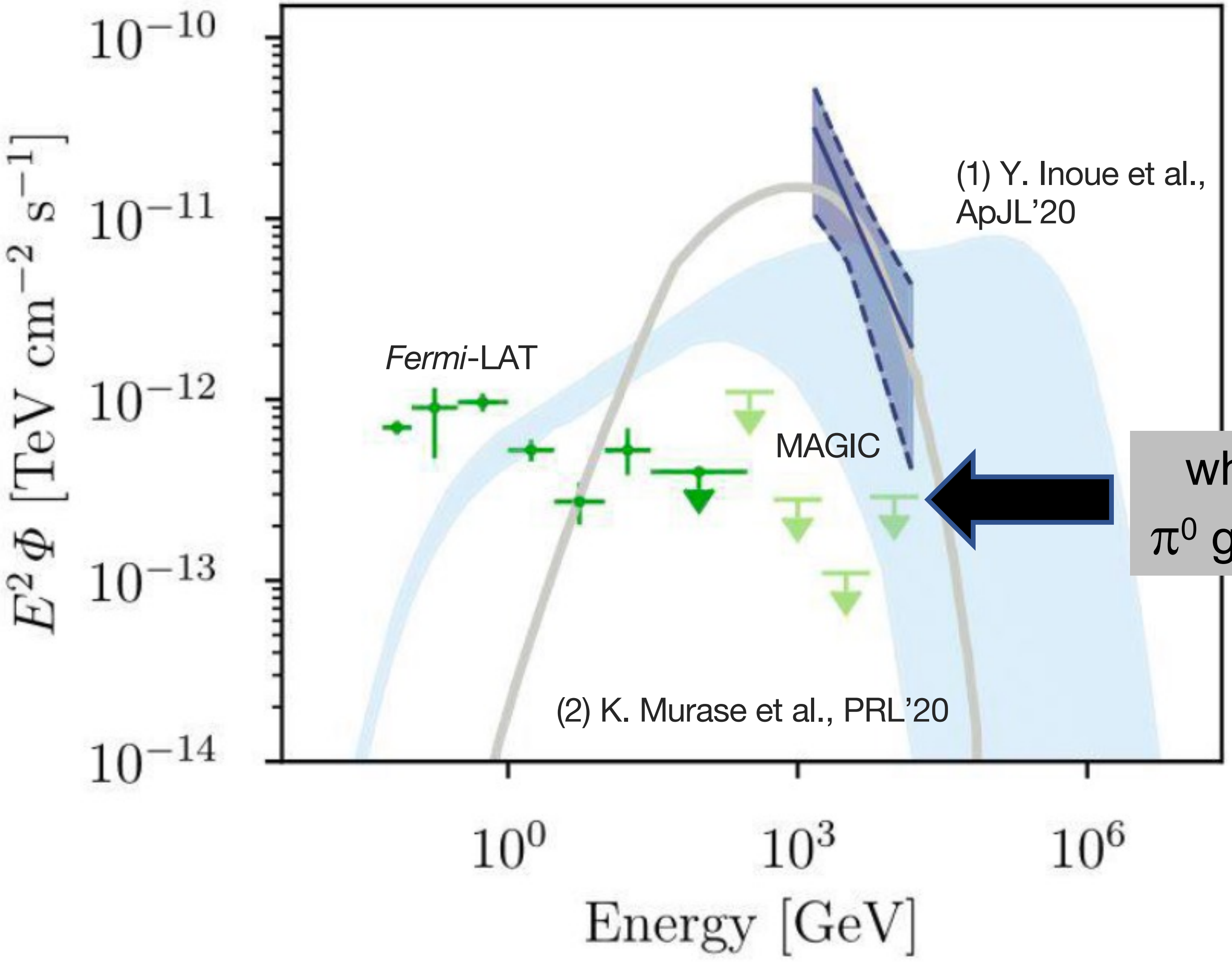


- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- and the answer is: supermassive black holes at the cores of active galaxies?

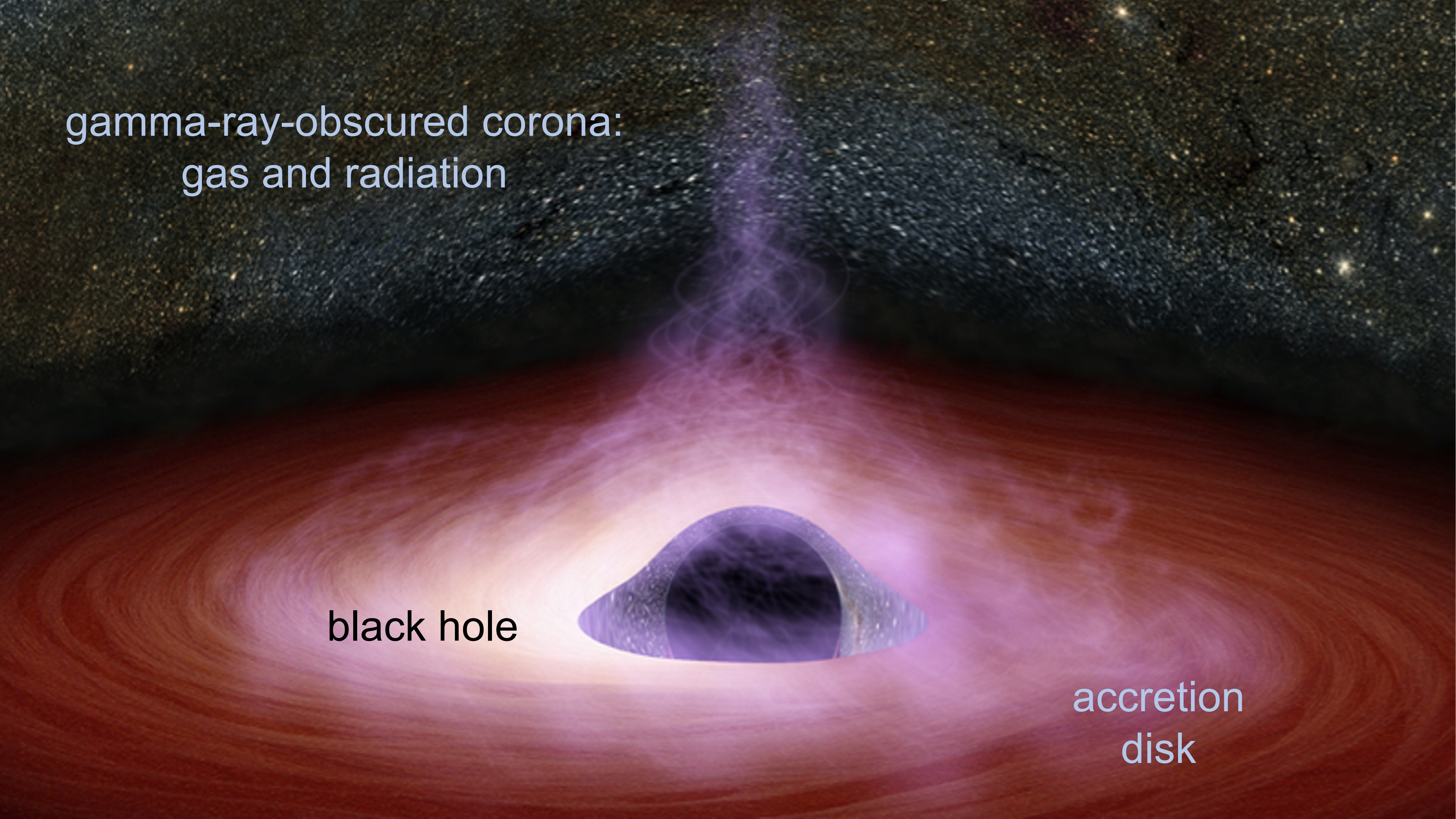
IceCube.wisc.edu

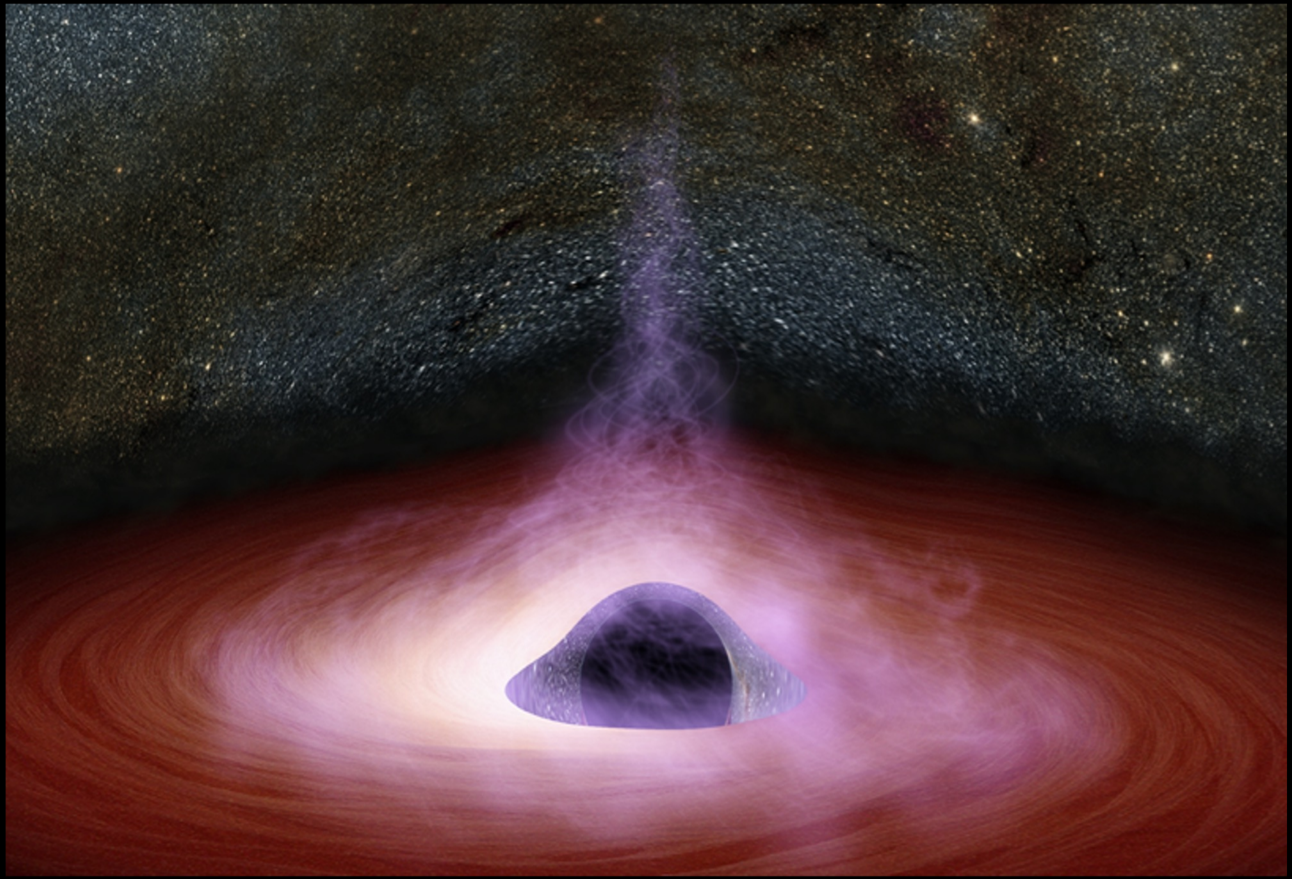
a gamma ray for every neutrino?

NGC 1068: an obscured cosmic accelerator



where are the π^0 gamma rays ?


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



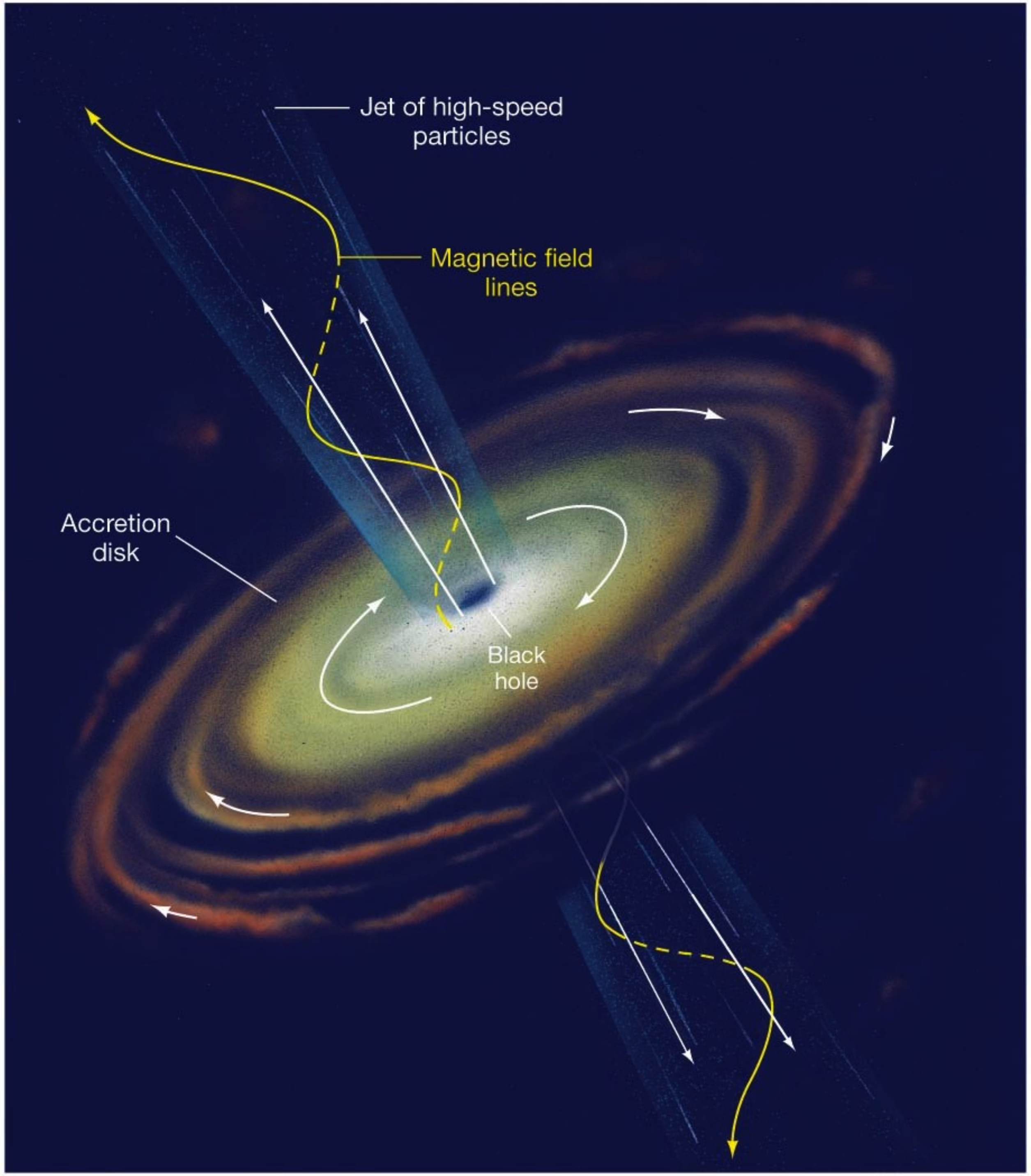
- accelerator(s): electrons and protons are accelerated in the turbulent magnetic fields associated with the accretion disk, in the infall onto the black hole,…

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

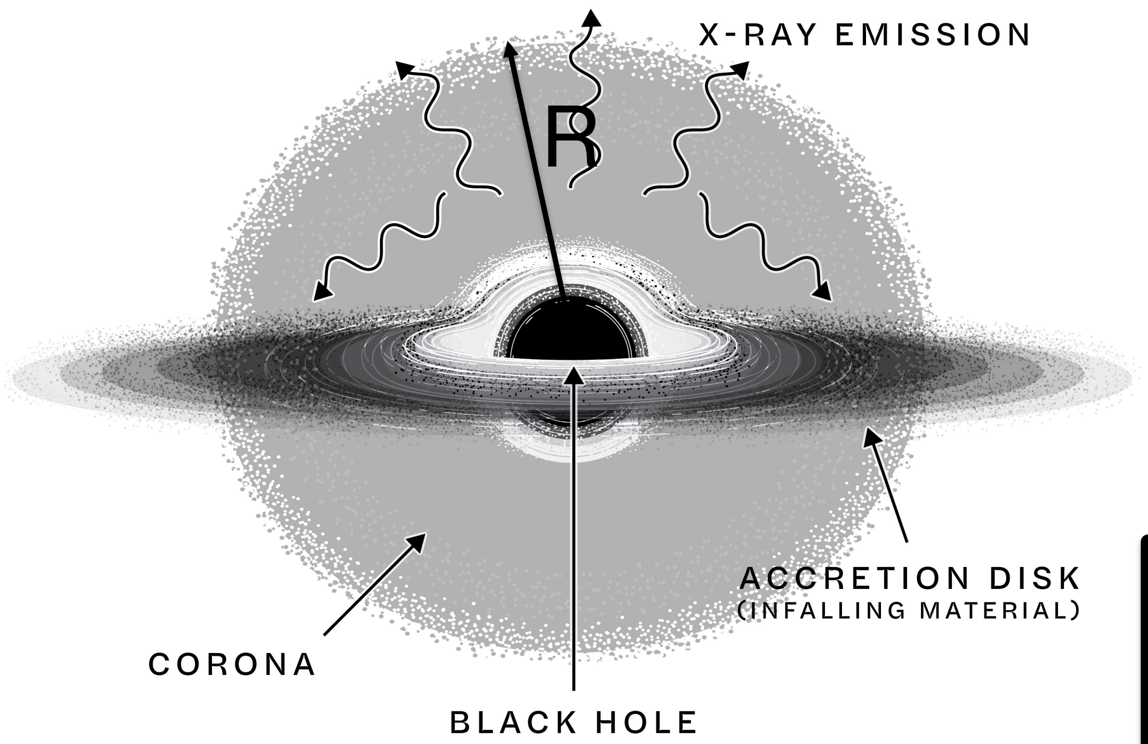
target densities required

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

requires a production within < 100 Schwarzschild radii of 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

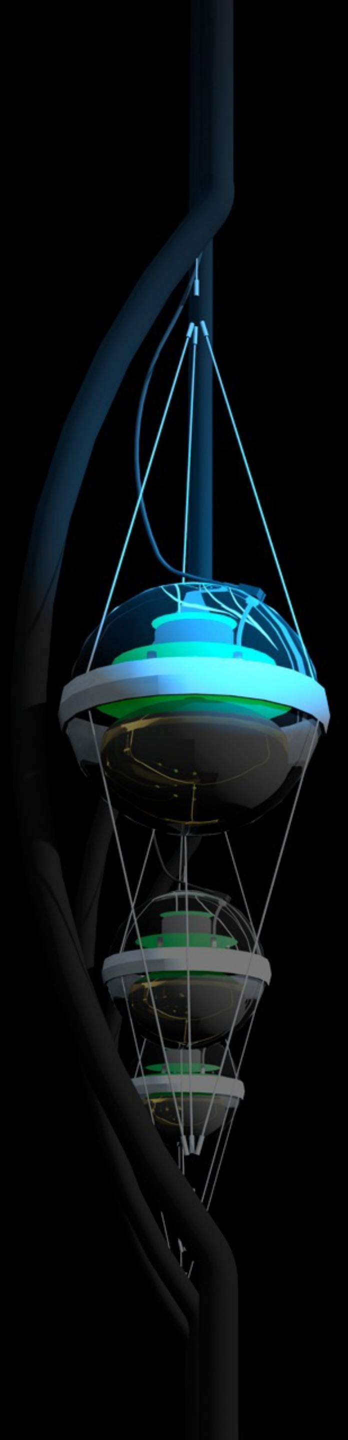
$$\tau_{p\gamma} \sim 0.1 \;\rightarrow\; \mathrm{PeV\,neutrinos}$$

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

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

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

M 87



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

THE ICECUBE COLLABORATION

RALIA 1

1

TED KINGDOM 1

UNITED STATES 25

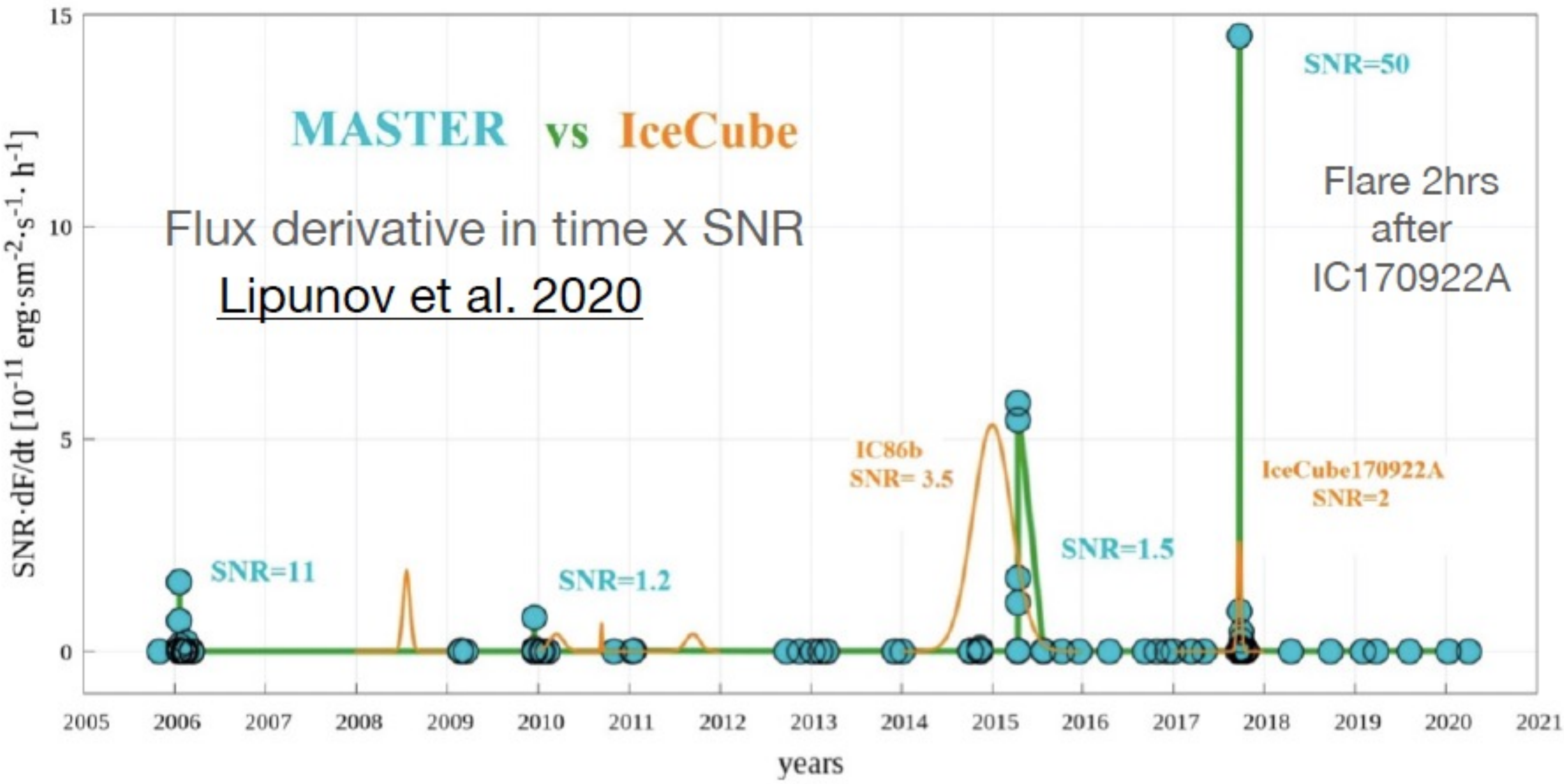
ICECUBE
South Pole Neutrino Observatory

global robotic network of optical telescopes connects TXS 0506+056 to IC170922A in the time domain

"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 Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

V.M. Lipunov[1,2], V.G. Kornilov [1,2], K.Zhirkov[1], E. Gorbovskoy[2], N.M. Budnev[4], D.A.H.Buckley[3], R. Rebolo[5], M. Serra-Ricart[5], R. Podesta[9,10], N .Tyurina [2], O. Gress[4,2], Yu.Sergienko[8], V. Yurkov[8], A. Gabovich[8] , P.Balanutsa[2], I.Gorbunov[2], D.Vlasenko[1,2], F.Balakin[1,2], V.Topolev[1], A.Pozdnyakov[1], A.Kuznetsov[2], V.Vladimirov[2], A. Chasovnikov[1], D. Kuvshinov[1,2], V.Grinshpun[1,2], E.Minkina [1,2], V.B.Petkov [7], S.I.Svertilov[2,6] , C. Lopez[9], F. Podesta[9], H.Levato[10], A. Tlatov[11] B. Van Soelen[12], S. Razzaque[13], M. Böttcher[14]

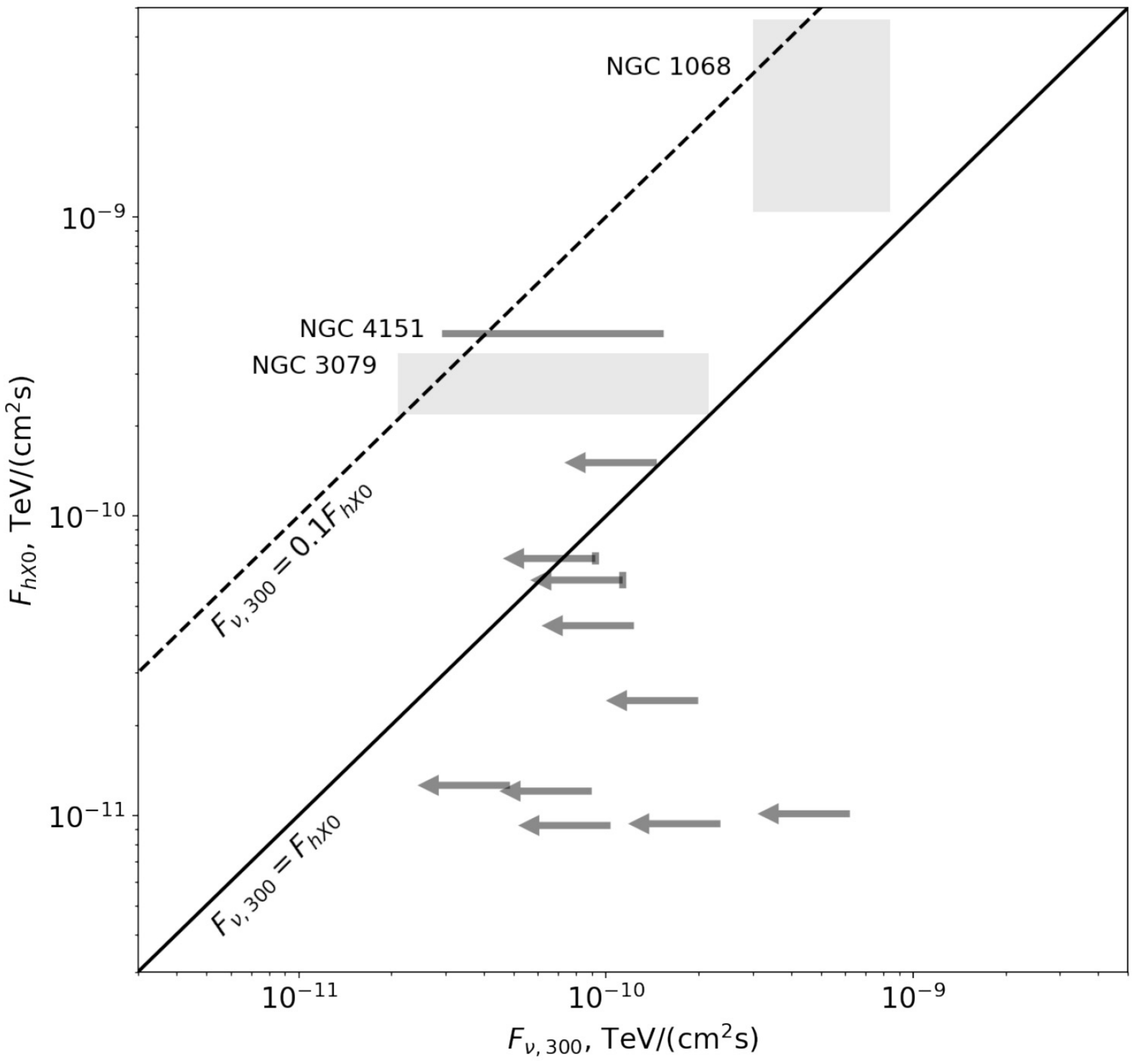


- optical flare of IC170922, 2 hours *after* the neutrino
- often originate from magnetohydrodynamical instabilities triggered by processes modulated by the magnetic field of the accretion disk

- X-ray vs neutrino flux

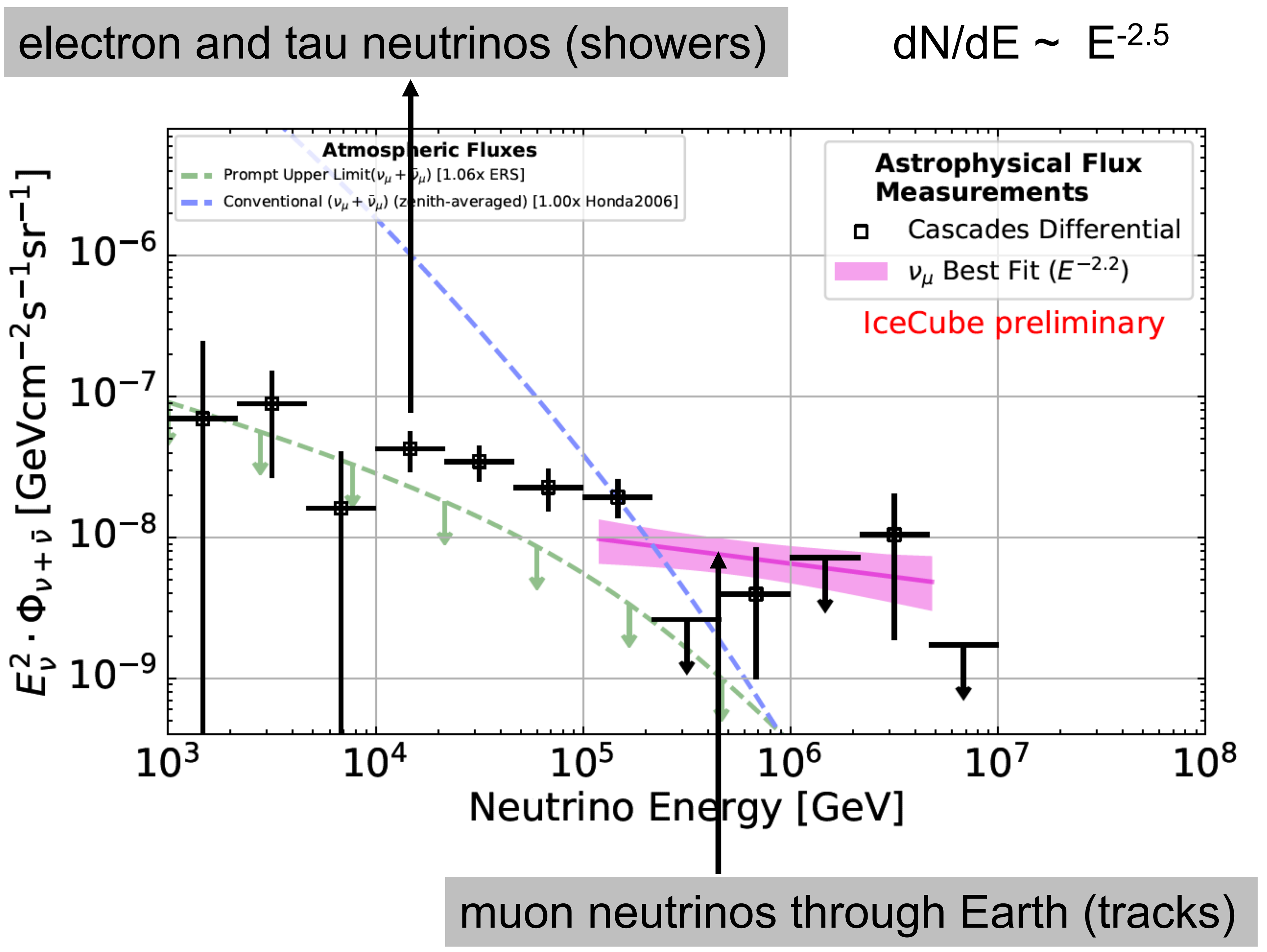
- a correlation between the X-ray and neutrino flux of active galaxies producing neutrinos?

- X-ray flux of TXS 0506+056 is consistent with this pattern

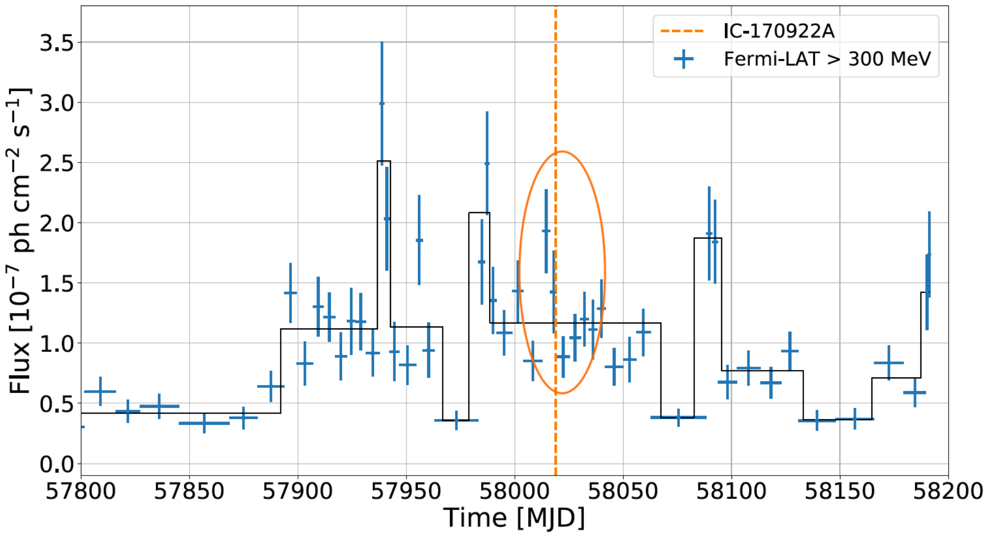


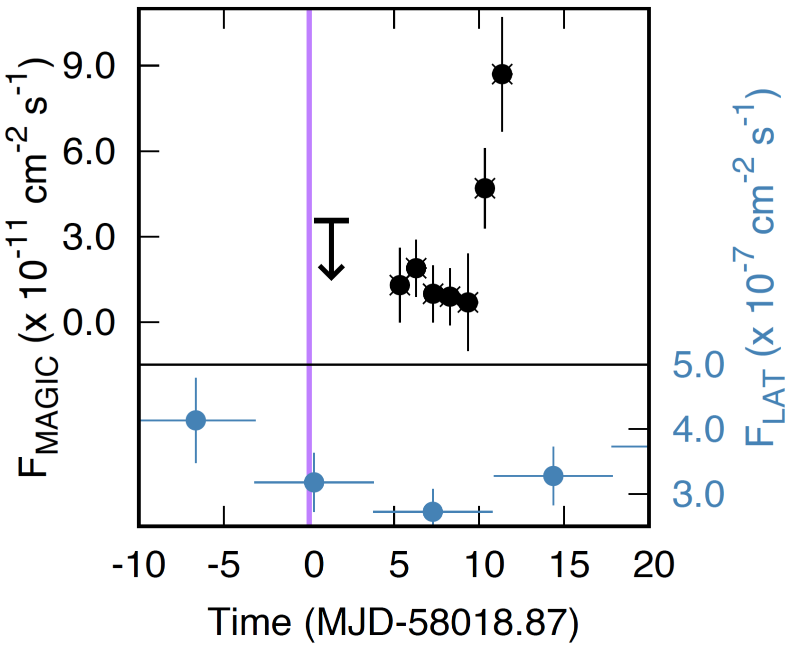
Neronov et al.

overflow sides


electron and tau neutrinos (showers)
dN/dE ~ E-2.5
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]
muon neutrinos through Earth (tracks)

gamma rays in 2017 at the time the neutrino is produced ?
a few ~10 GeV photons and not much else, consistent with an obscured source, not a blazar





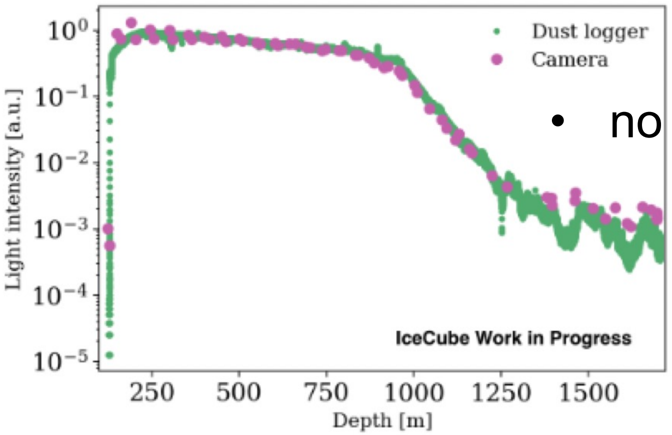
- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced

- MAGIC: onset of the TeV flux 5 days after IC170922

- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

ice: step by step

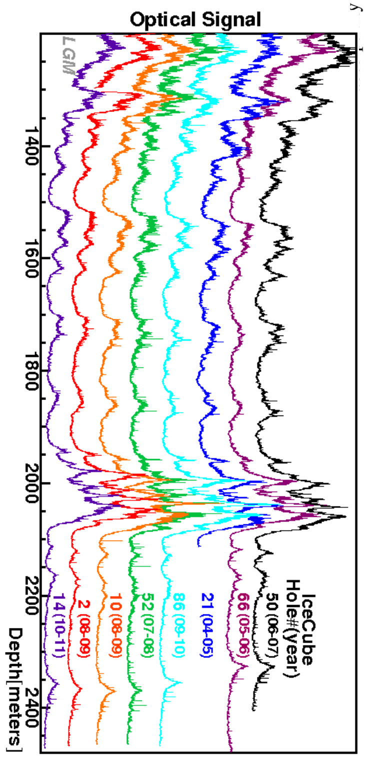
- hole ice ?

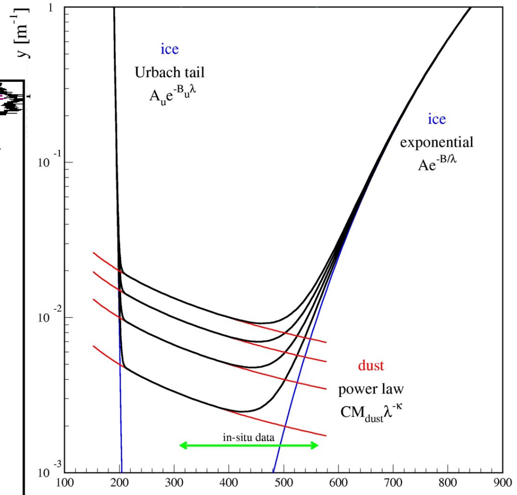


- no air bubbles/hydrates below 1350 m

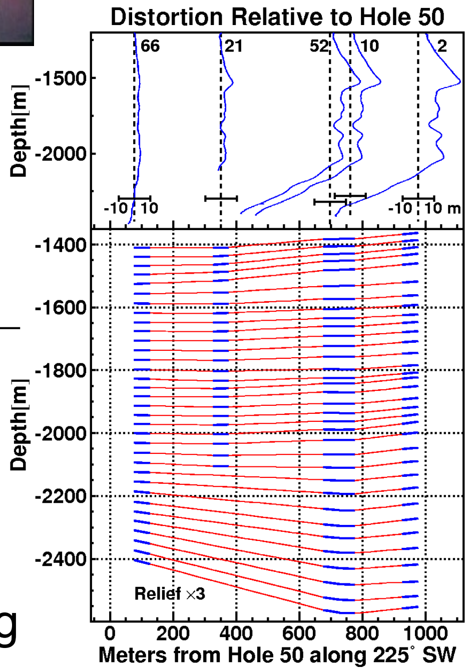
- > 100 m absorption length limited by dust

- ice layers

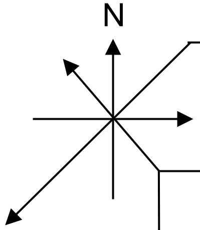




- tilted ice layers



- birefringence of the crystal boundaries ?



Ice Layer tilt direction
225° SW

Ice flow direction
41° NW

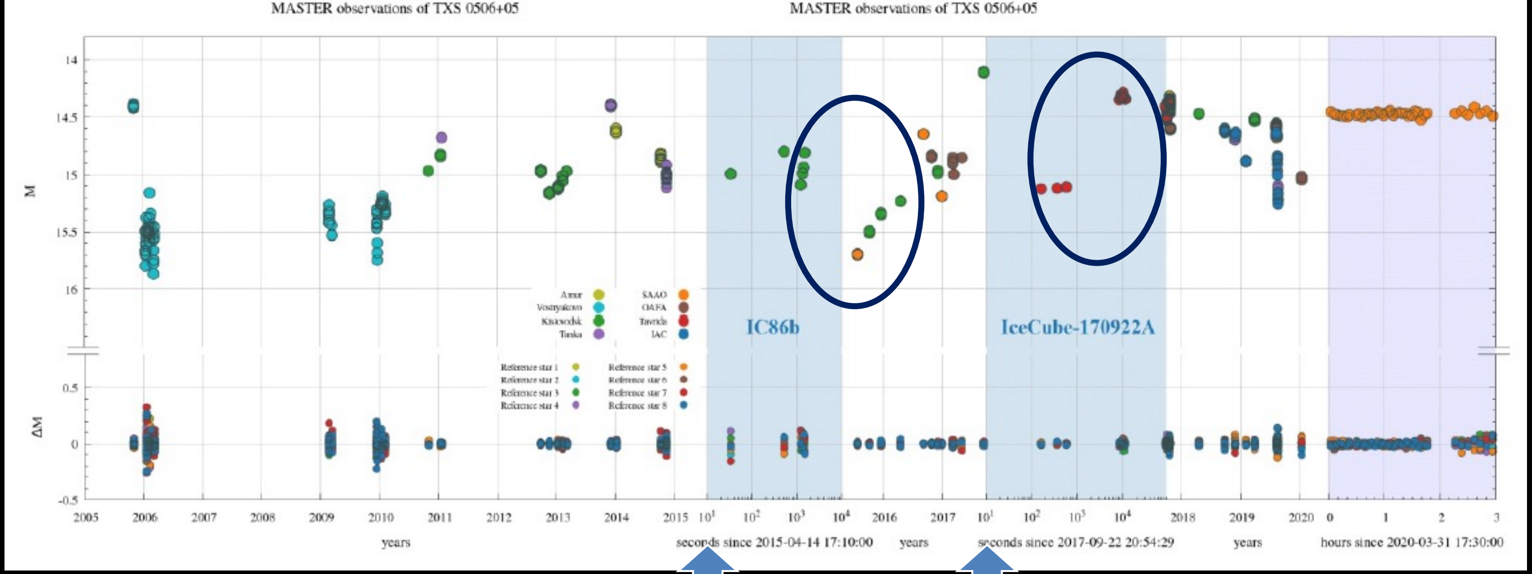
- anisotropy
~8% less scattering
41° NW

MASTER

robotic network

optical observations
TXS 0506+056
since 2005

blue panels:
expanded time axis
years → seconds

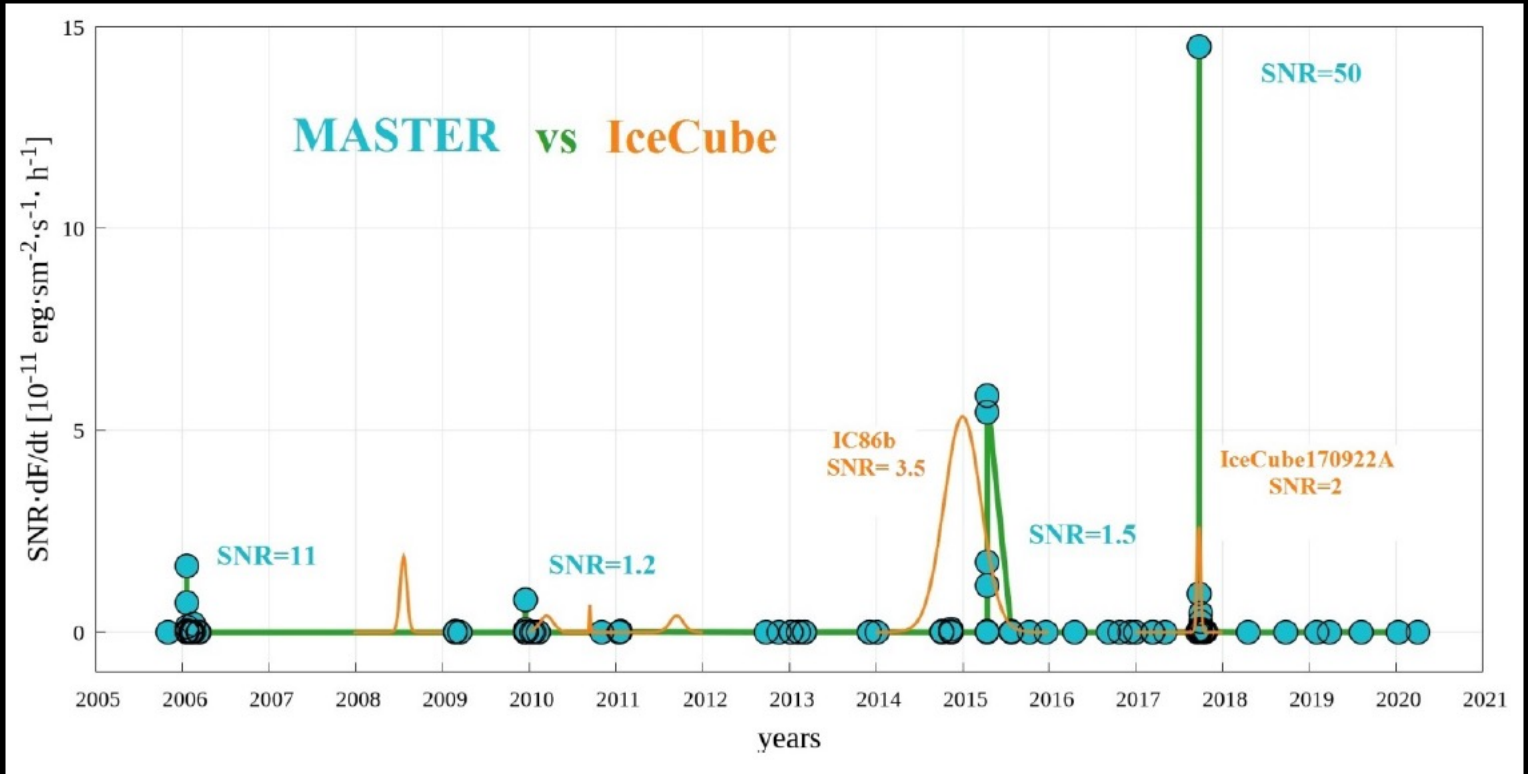


seconds after
2014-15 burst

seconds after
IC170922

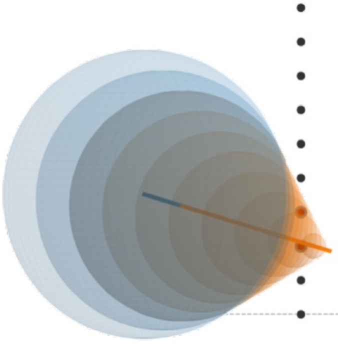
time variation of flux
times
signal-to-noise

hour-scale
variability of the
source after
neutrino emission

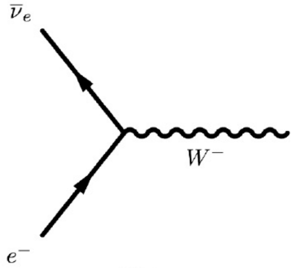


First hint of W boson resonance in data (Glashow resonance)

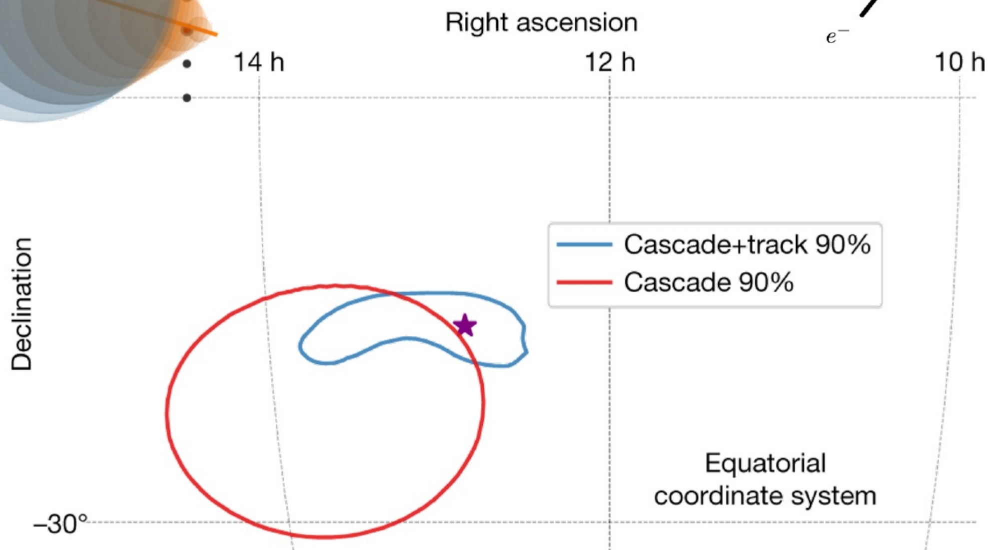
Nature **591,** 220–224 (2021)

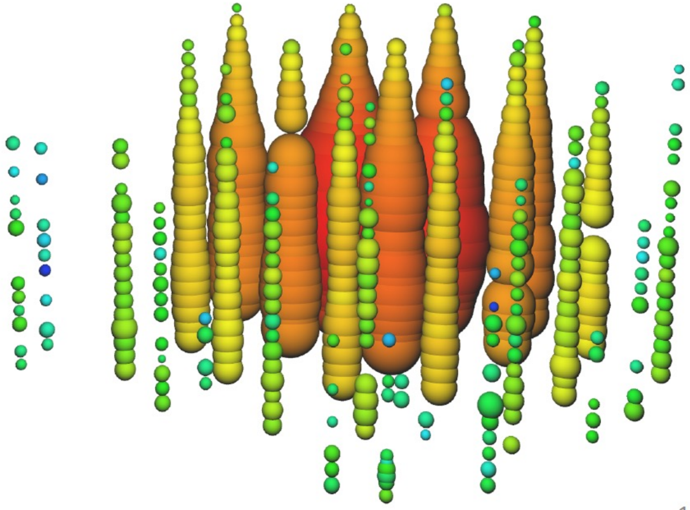


$$E_R = M_W^2/(2m_e) = 6.32\text{PeV}$$



By measuring nu/nubar -> probe source environment directly (magnetic field, pp/pgamma)

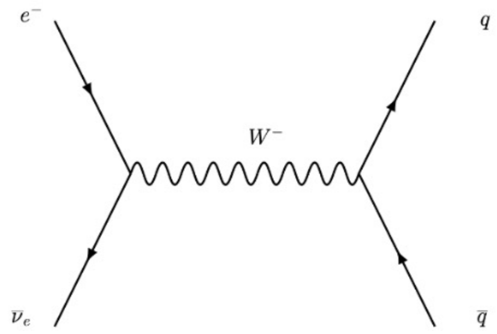


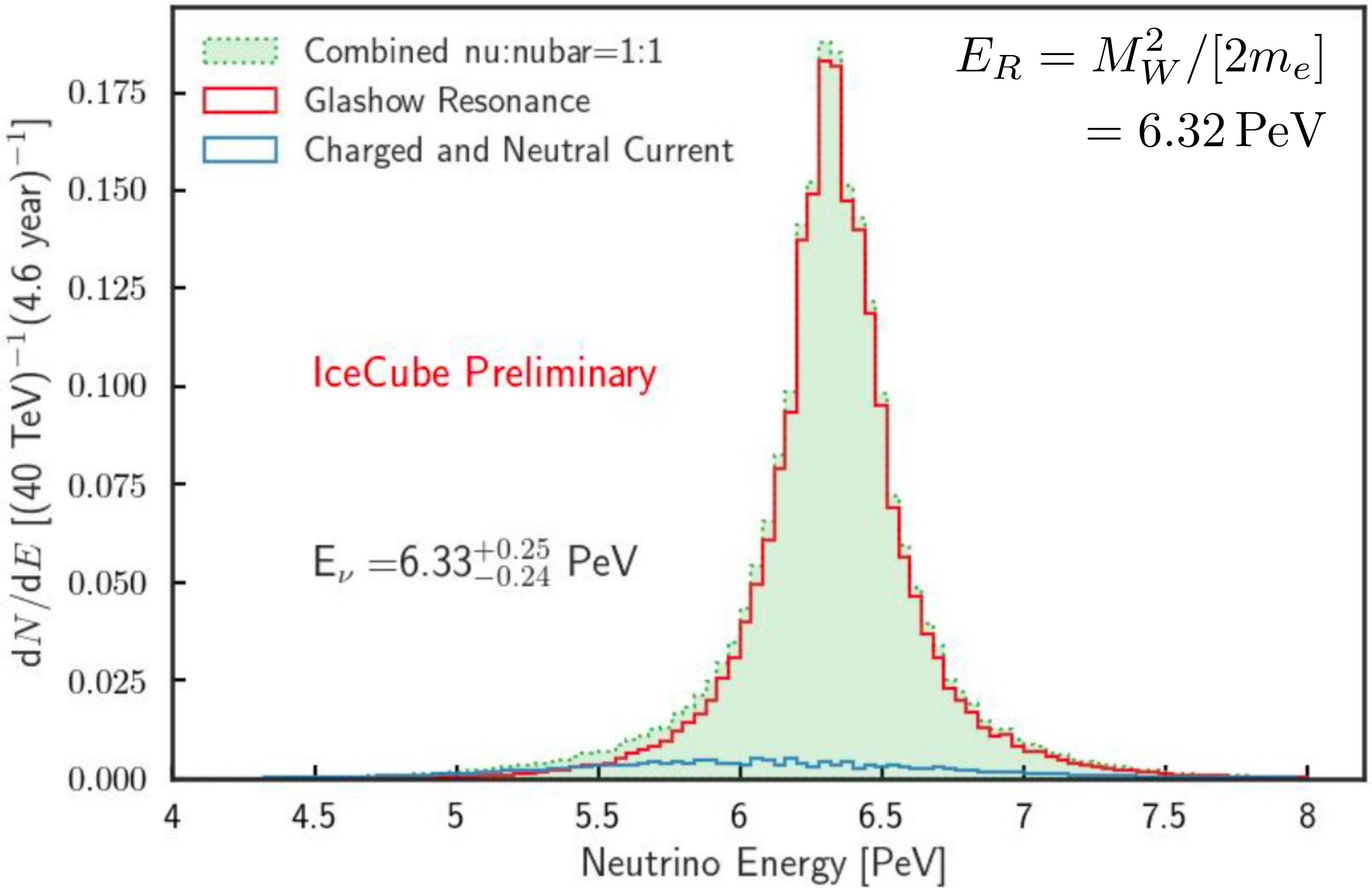


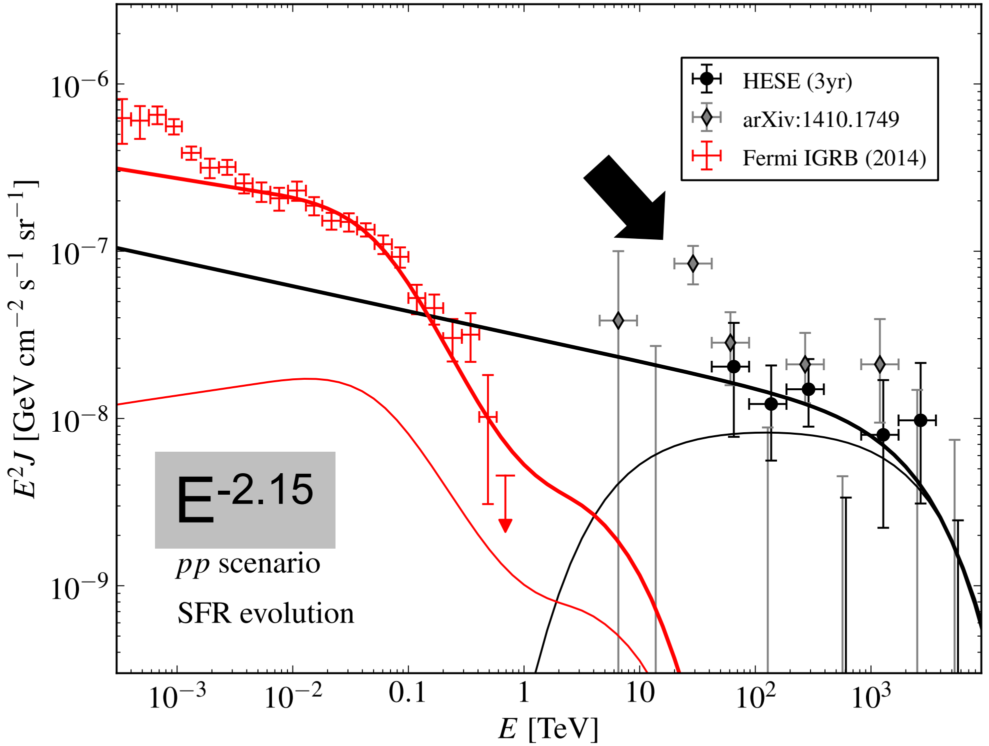
Identified muonic component from the hadronic shower

angular uncertainty contour shrinks by a factor of 5 with hybrid reco

- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino

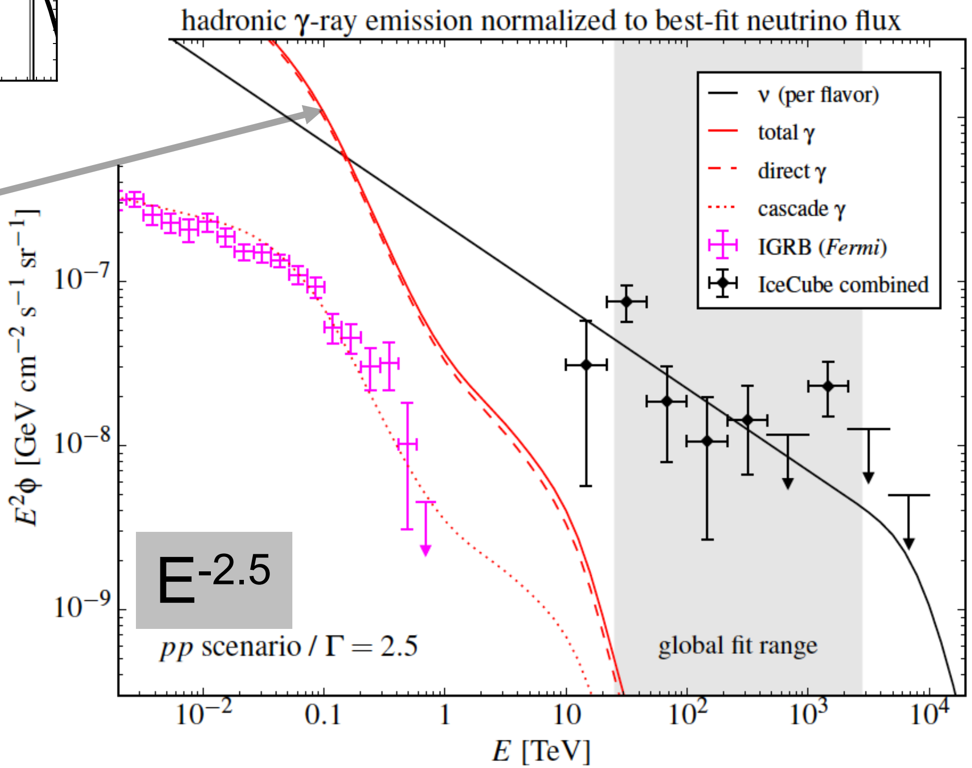


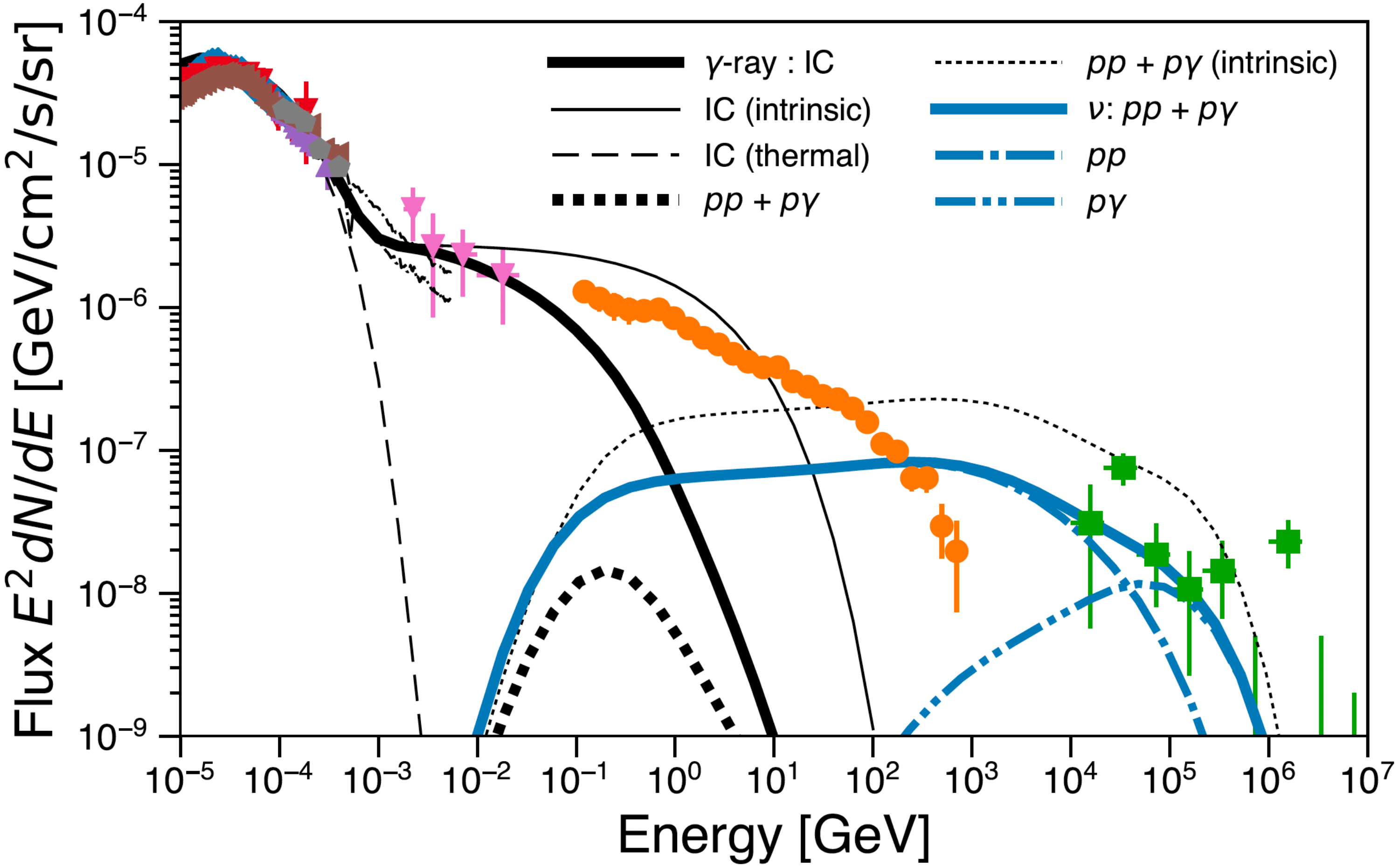




a source opaque to protons that efficiently produces neutrinos is opaque to gamma rays

- the pionic photons accompanying the neutrinos lose energy in the source even before reaching the extragalactic background.
- as a result, the photons emerge below Fermi threshold, at MeV energies and below, in X-rays, … radio.

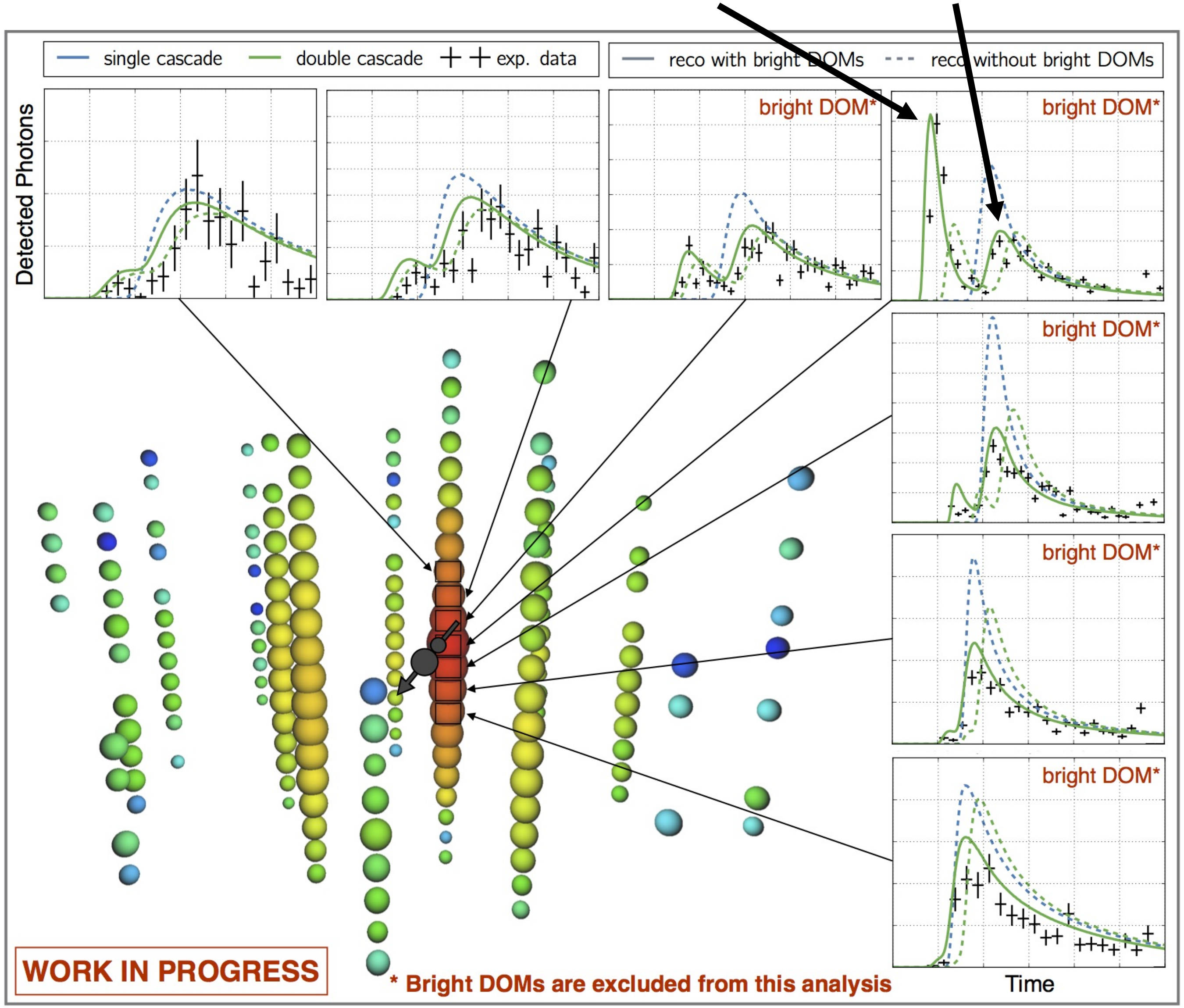




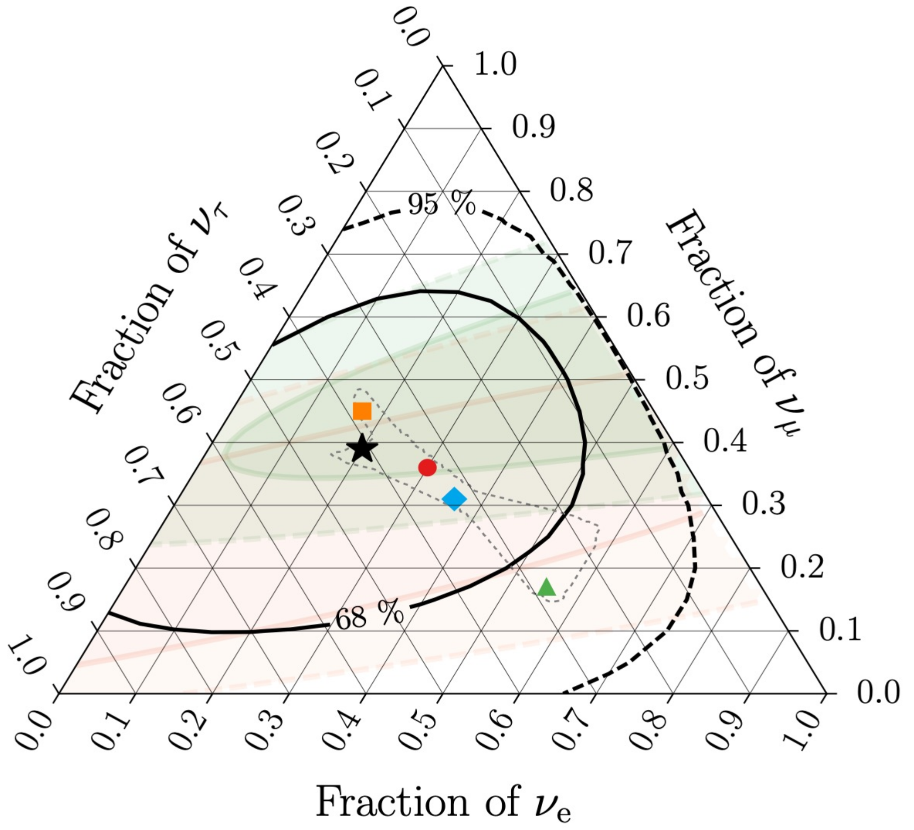
Flux E^2dN/dE [GeV/cm^2/s/sr]
Energy [GeV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
γ-ray : IC
IC (intrinsic)
IC (thermal)
$pp + p\gamma$
$pp + p\gamma$ (intrinsic)
ν: $pp + p\gamma$
pp
$p\gamma$

a cosmic tau neutrino with 17m lifetime

light from nutau interaction and tau decay

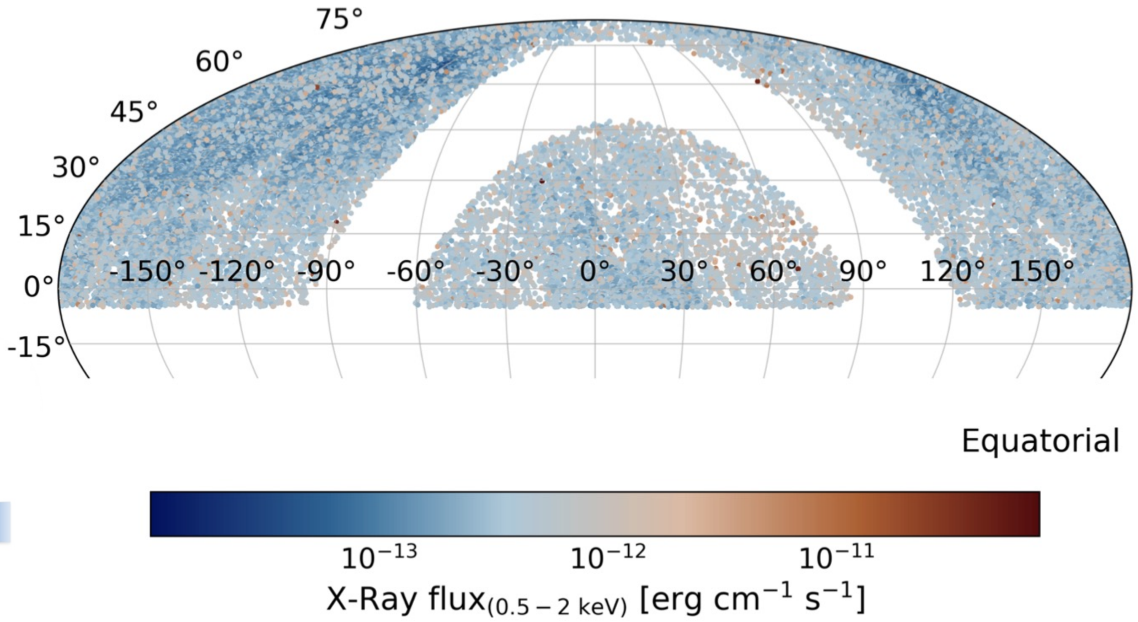


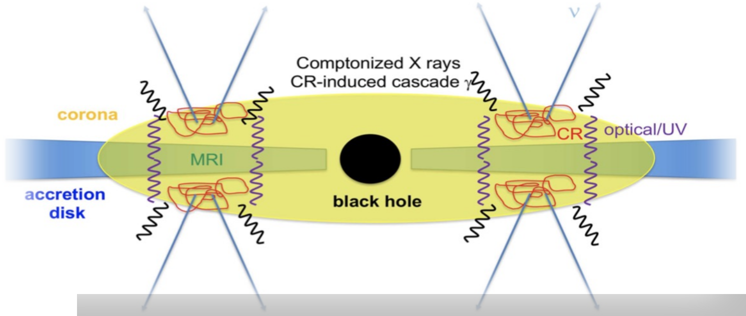
oscillations of PeV neutrinos over cosmic distances to 1:1:1



oscillating PeV neutrinos (7.5 years starting events) correlation between cores of active galaxies and cosmic neutrinos

(γ = -2.03; 2.6σ post trial)



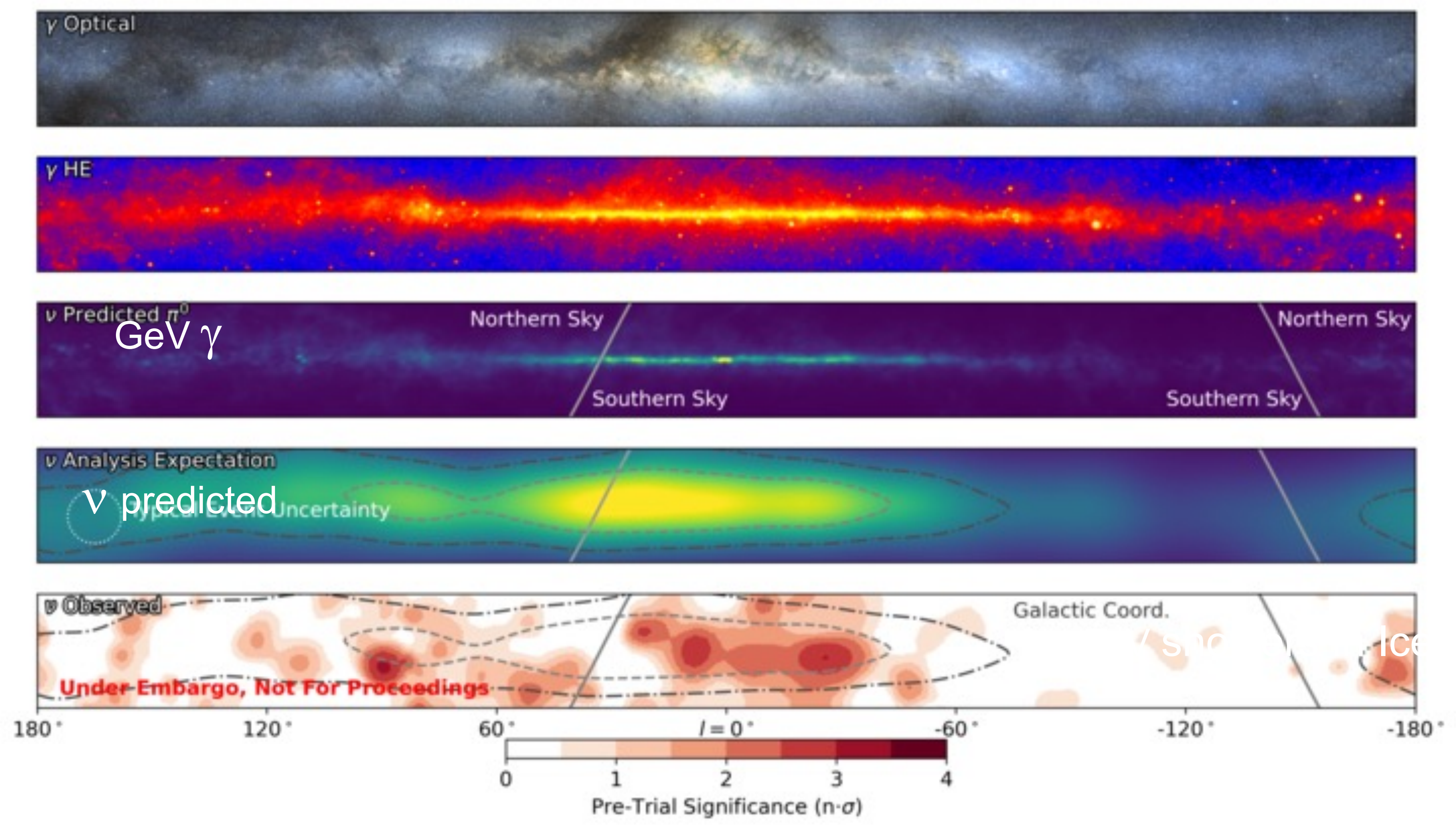


selection:

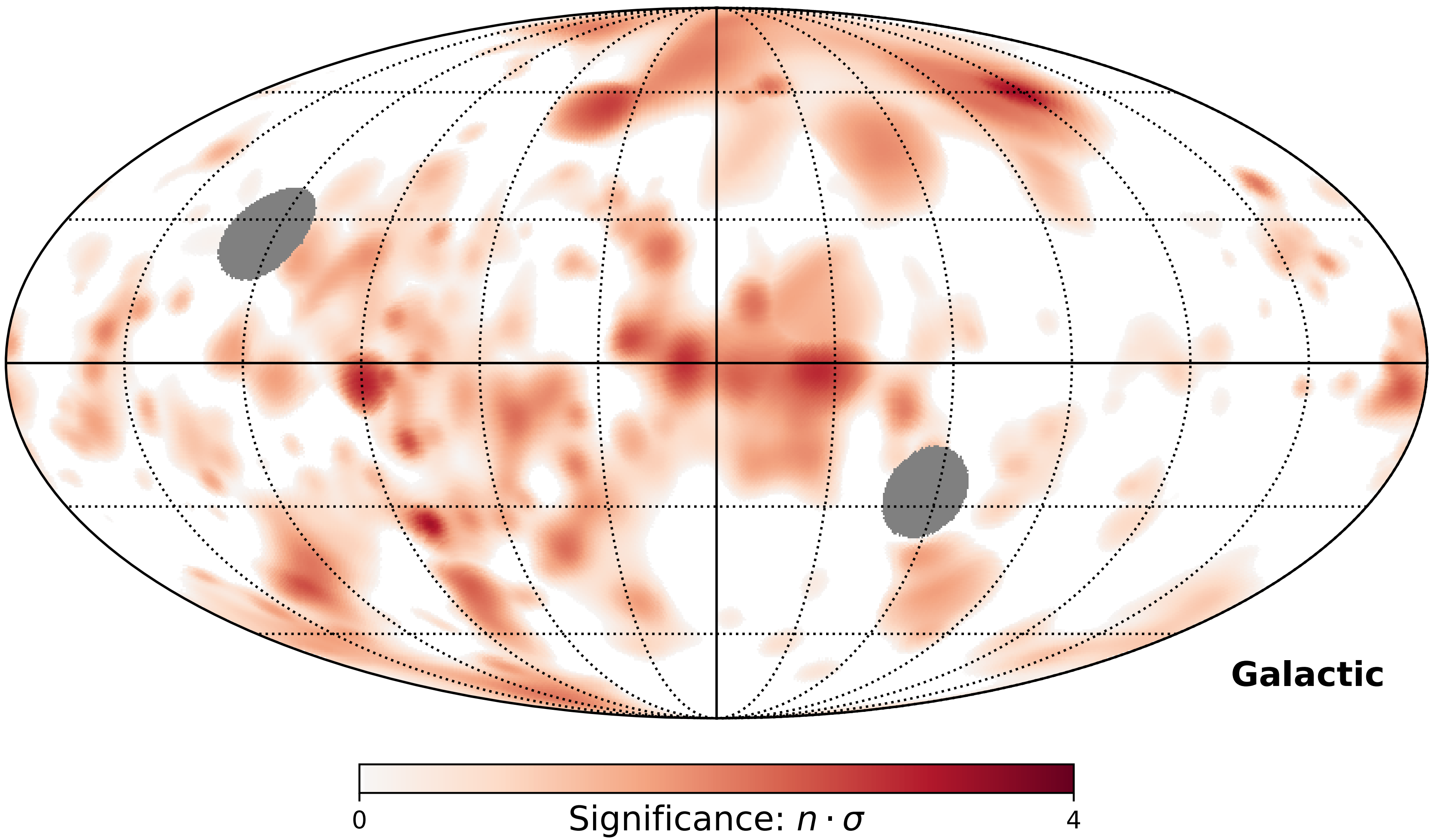
- X-ray catalogues 2RXS + XMMSL2
- IR WISE catalogue: X-rays associated with the core produce infrared light on dust at the center of the galaxy

TABLE I. Properties of the AGN samples created for the analysis. The surveys used for the cross-match to derive each sample, the final number of selected sources, cumulative X-ray flux in the 0.5-2 keV energy range from the selected sources and the completeness (fraction of total X-ray flux from all AGN in the universe contained in the sample) are listed.

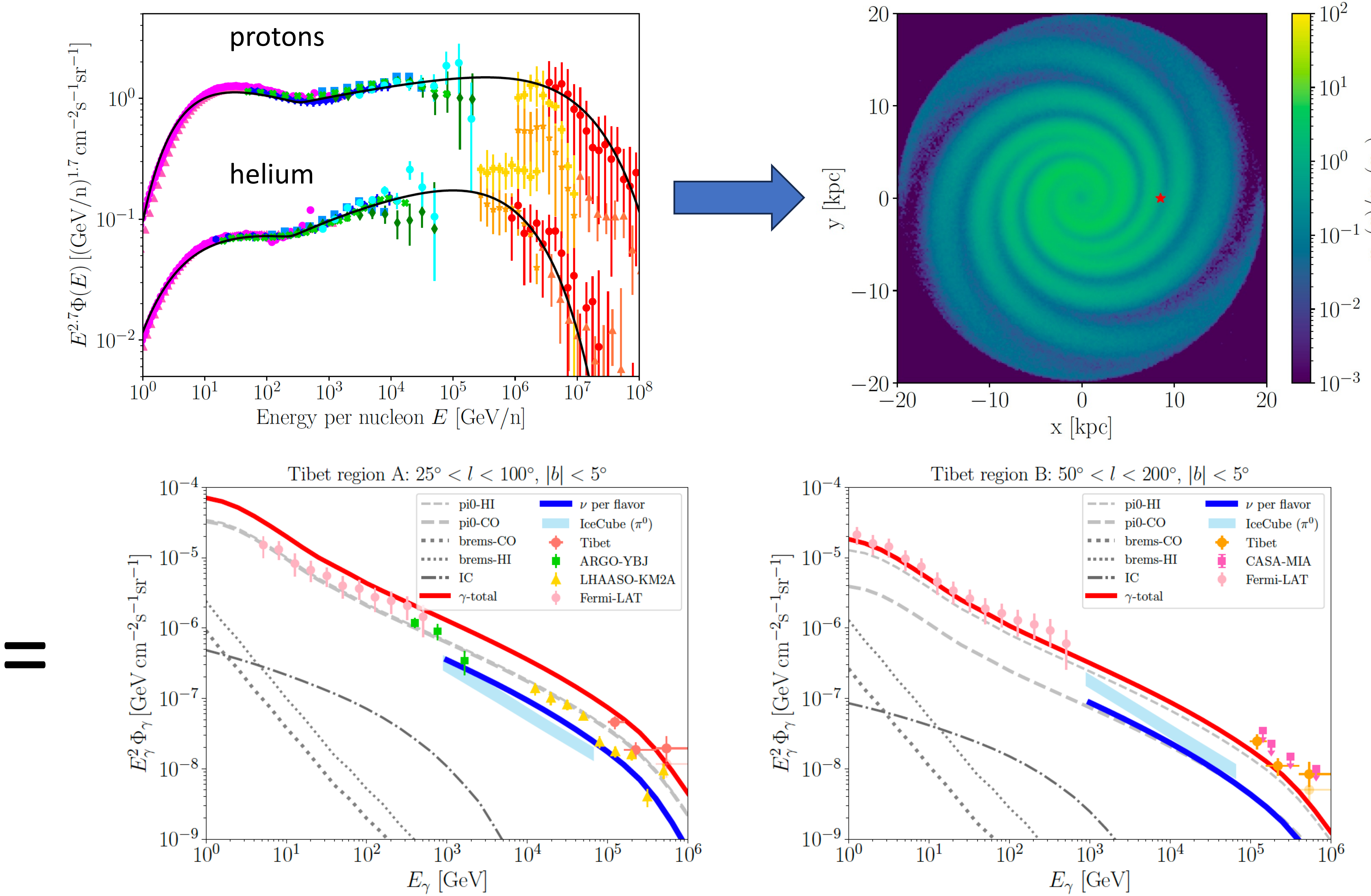
	Radio–selected AGN	IR–selected AGN	LLAGN
Matched catalogues	NVSS + 2RXS + XMMSL2	ALLWISE + 2RXS + XMMSL2	ALLWISE + 2RXS
Nr. of sources	9749	32249	15887
Cumulative X-ray flux [erg cm^{-2} s^{-1}]	7.71×10^{-9}	1.43×10^{-8}	7.26×10^{-9}
Completeness	$5^{+5}_{-3}\%$	$11^{+12}_{-7}\%$	$6^{+7}_{-4}\%$



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

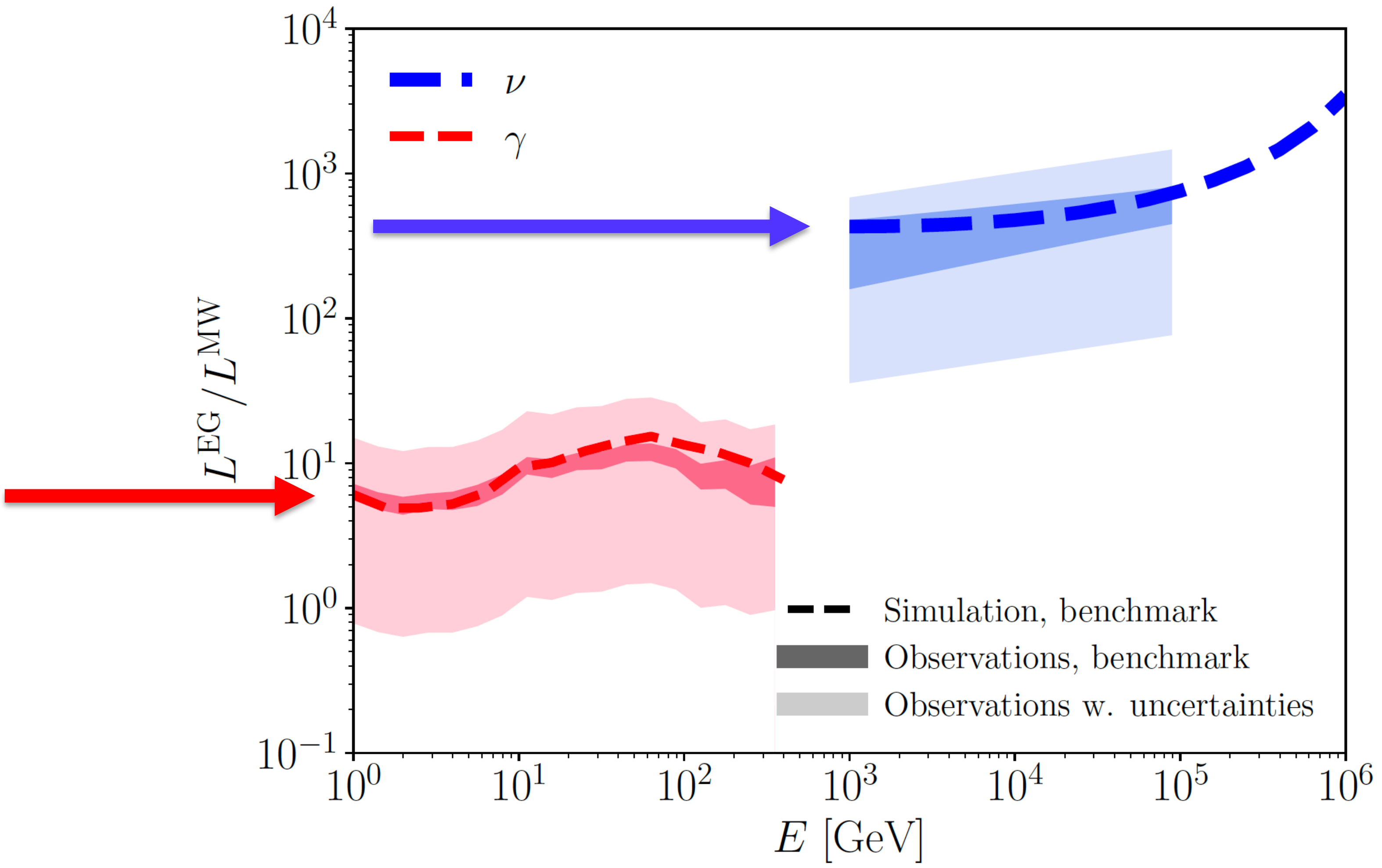


the flux is ~ 10% of the extragalactic flux at 30 TeV

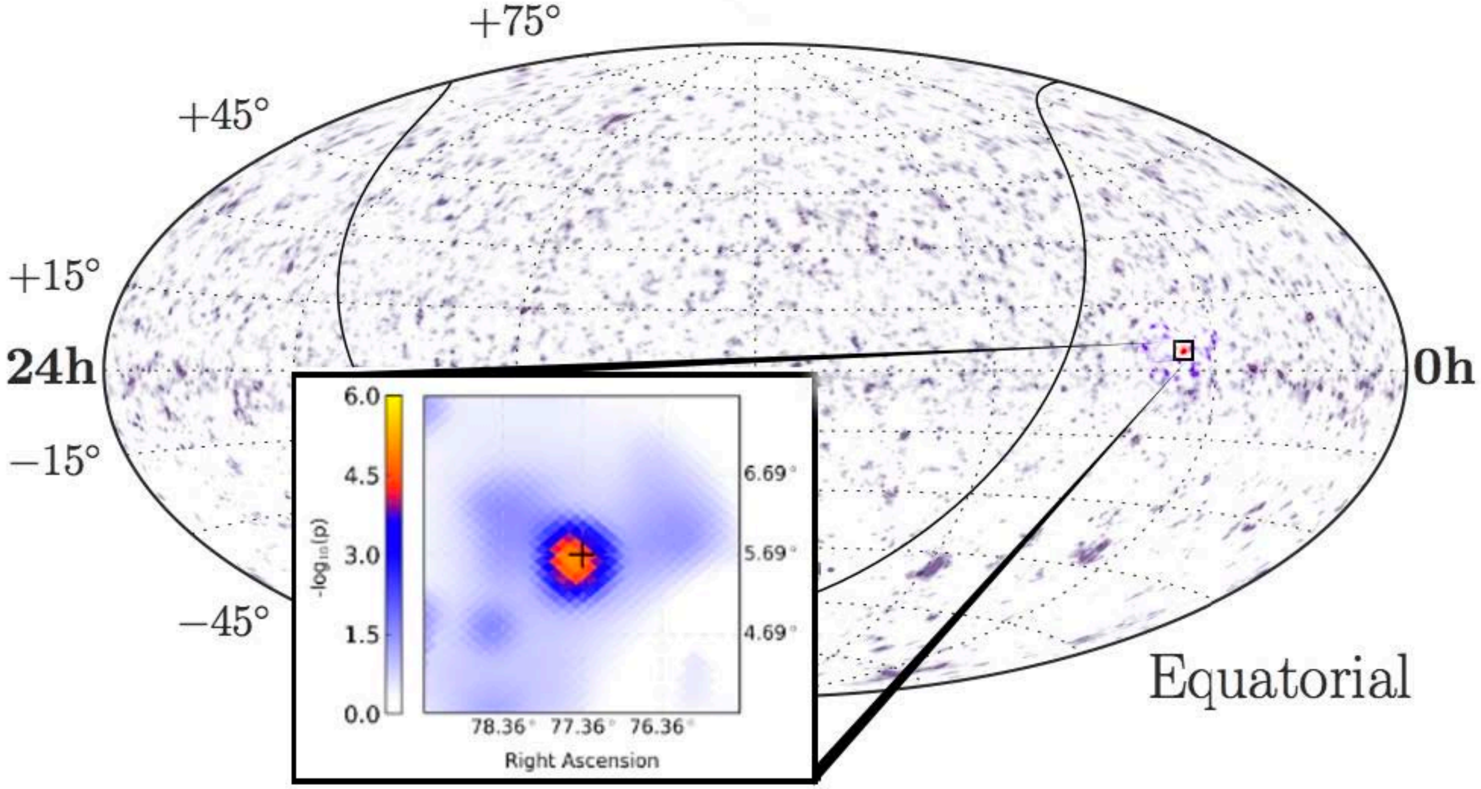


protons
helium
$E^{2.7}\Phi(E)$ [(GeV/n)$^{1.7}$ cm^{-2}s^{-1}sr^{-1}]
Energy per nucleon E [GeV/n]
y [kpc]
x [kpc]
$n_{\rm cr}(x)/n_{\rm cr}(x_\odot)$
=
Tibet region A: $25° < l < 100°$, $|b| < 5°$
Tibet region B: $50° < l < 200°$, $|b| < 5°$
pi0-HI
pi0-CO
brems-CO
brems-HI
IC
γ-total
ν per flavor
IceCube (π^0)
Tibet
ARGO-YBJ
LHAASO-KM2A
Fermi-LAT
CASA-MIA
$E_\gamma^2\,\Phi_\gamma$ [GeV cm^{-2}s^{-1}sr^{-1}]
E_γ [GeV]

flux in other galaxies relative to our own:
neutrinos (blue) and gamma rays (red)

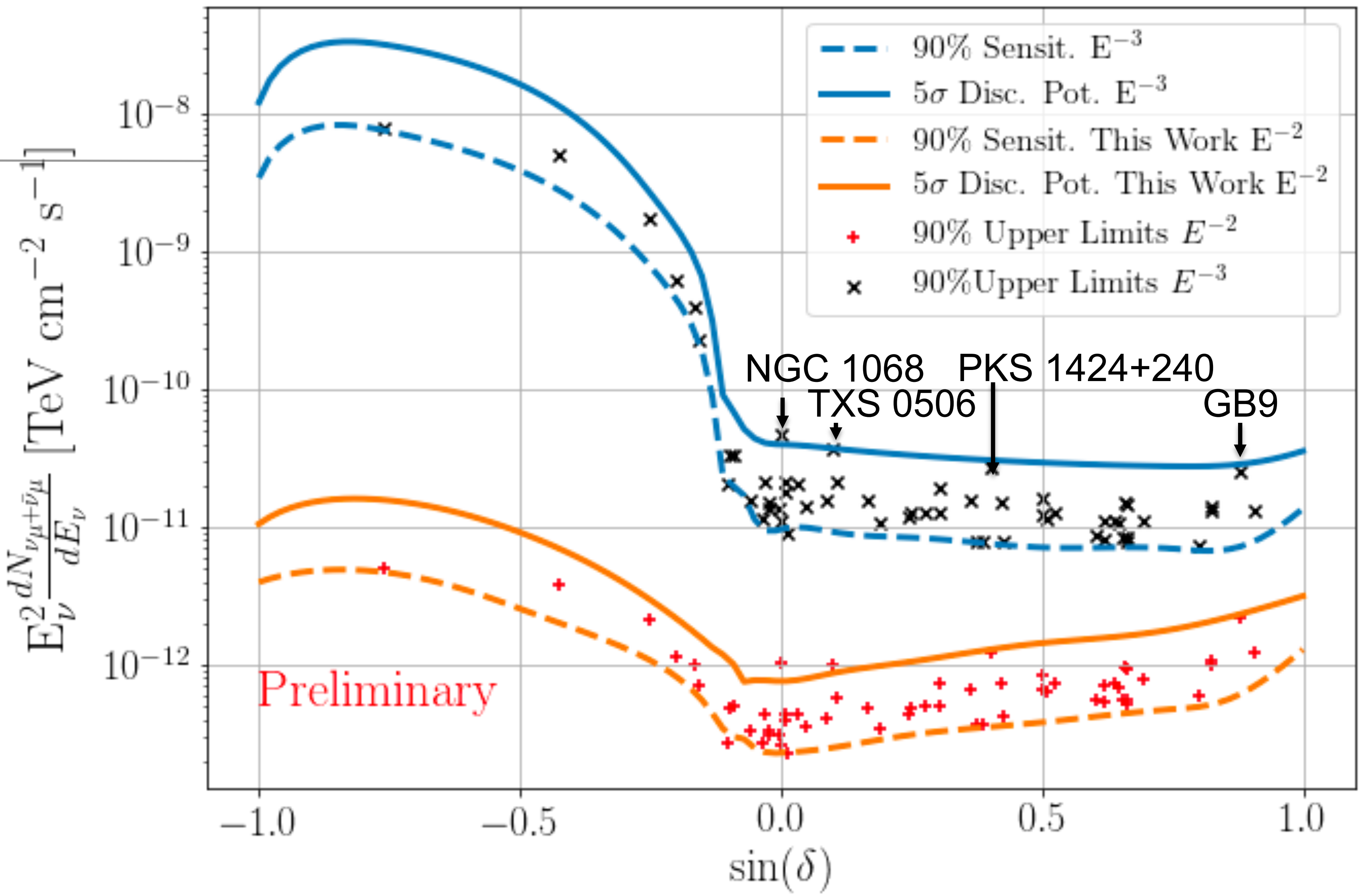


Fang, Gallagher, Halzen (Nature Astronomy) pre-trial p-value for clustering of high energy neutrinos



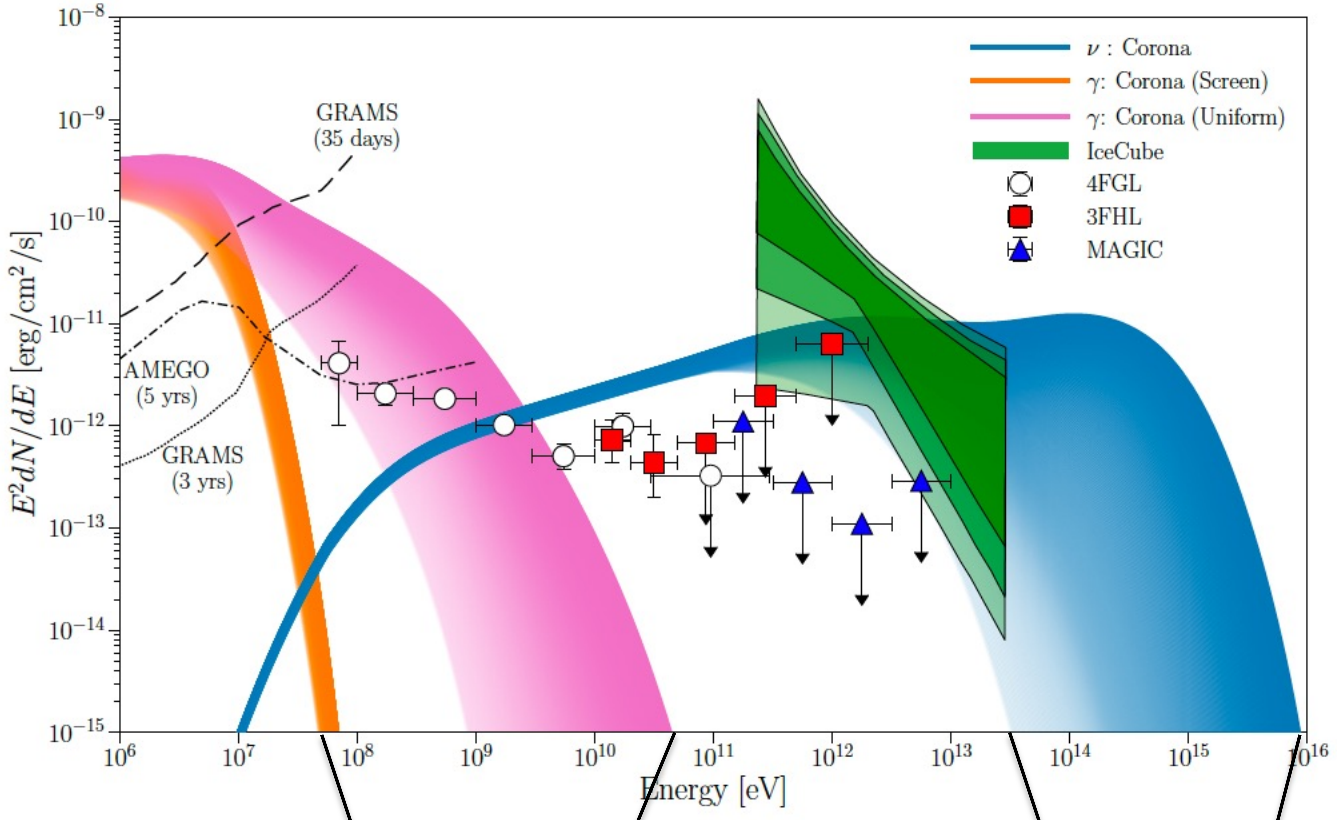
hottest spot coincident with
NGC 1068 (M77) (2.9σ)

evidence for non-uniform sky map in 10 years of IceCube data :
mostly resulting from 4 extragalactic source candidates



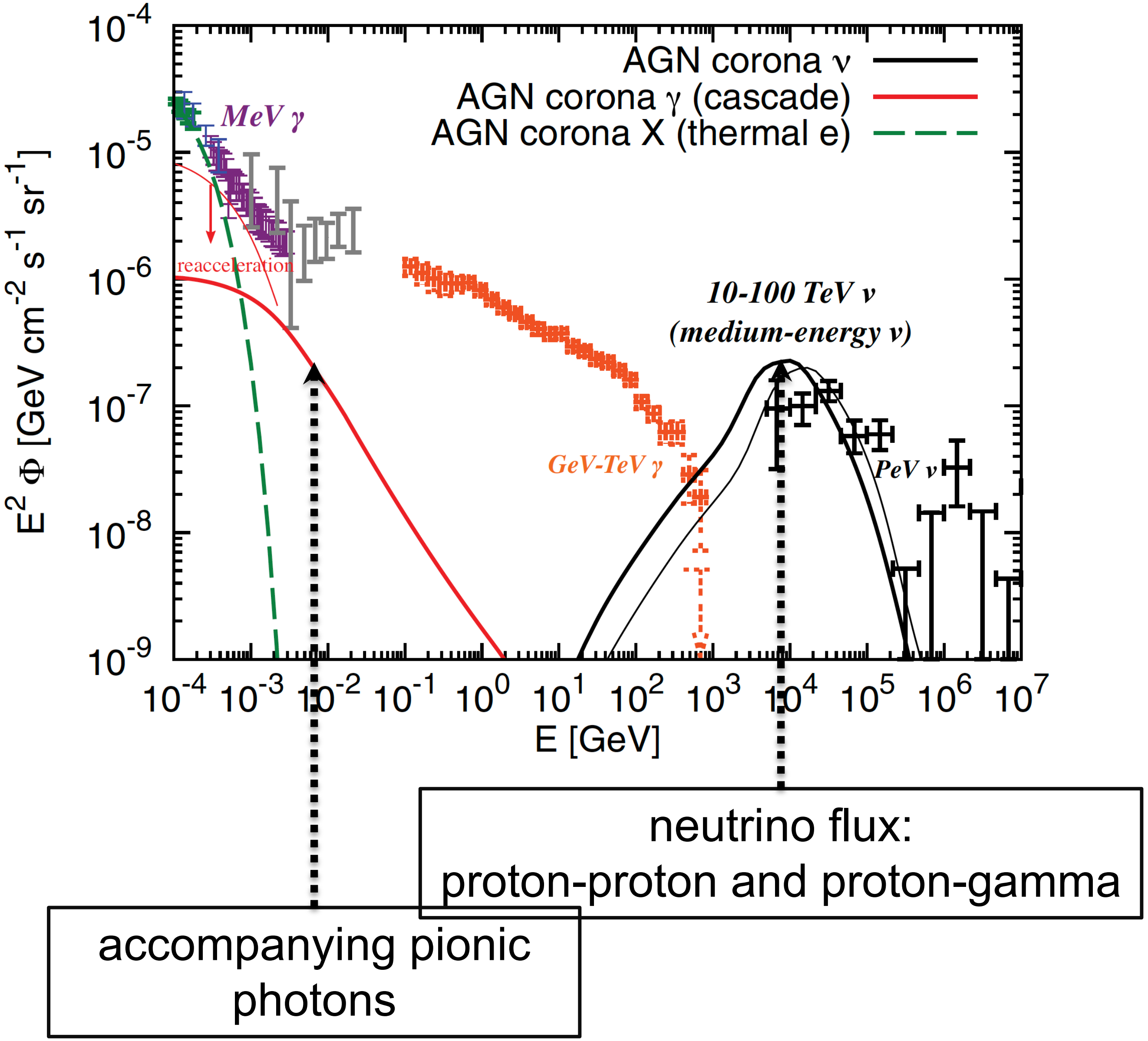
limits and interesting fluctuations (?)

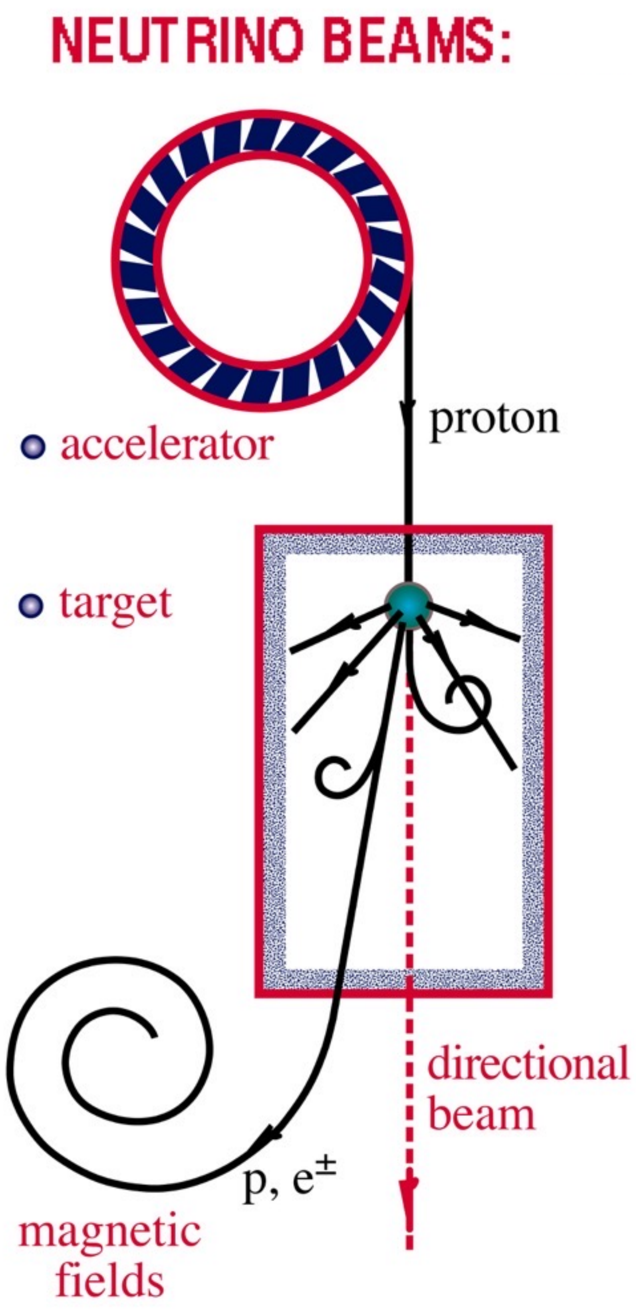
neutrinos produced in the gamma-ray obscured core of NGC 1068



accompanying pionic photons

range of neutrino flux: protons versus electrons neutrinos produced in the gamma-ray obscured core of NGC 1068





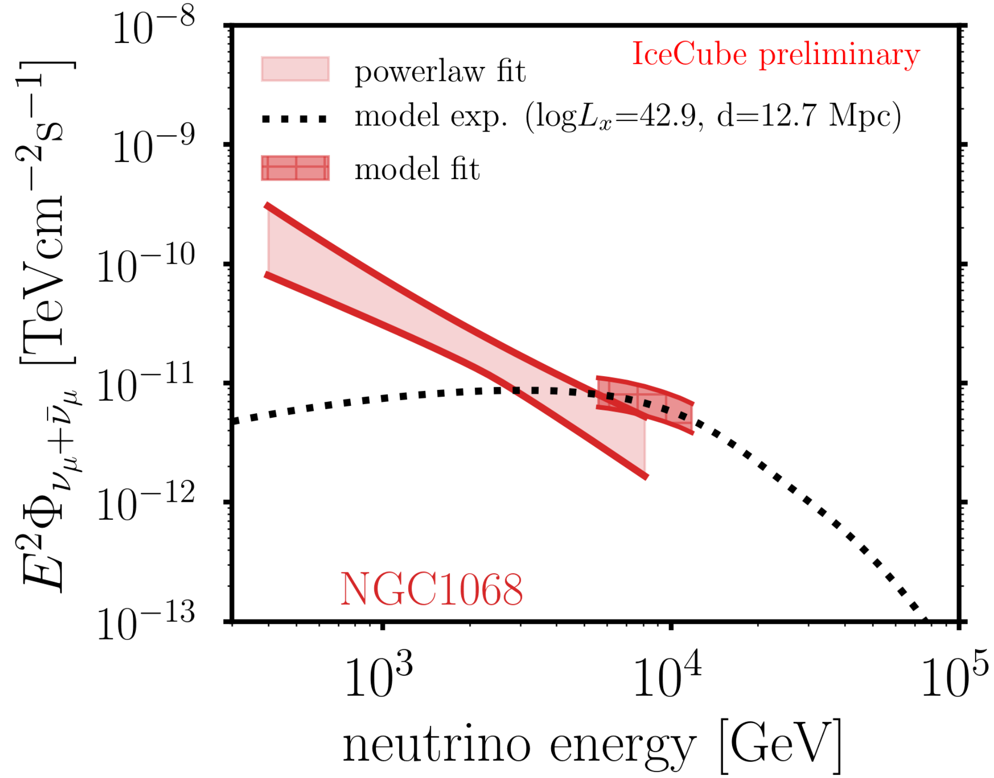
- efficient neutrino production sites are likely to be optically thick to gamma rays
- expect no correlation between gamma-ray and neutrino activity

→ a target efficient at converting protons into neutrinos is unlikely to be transparent to high energy photons.

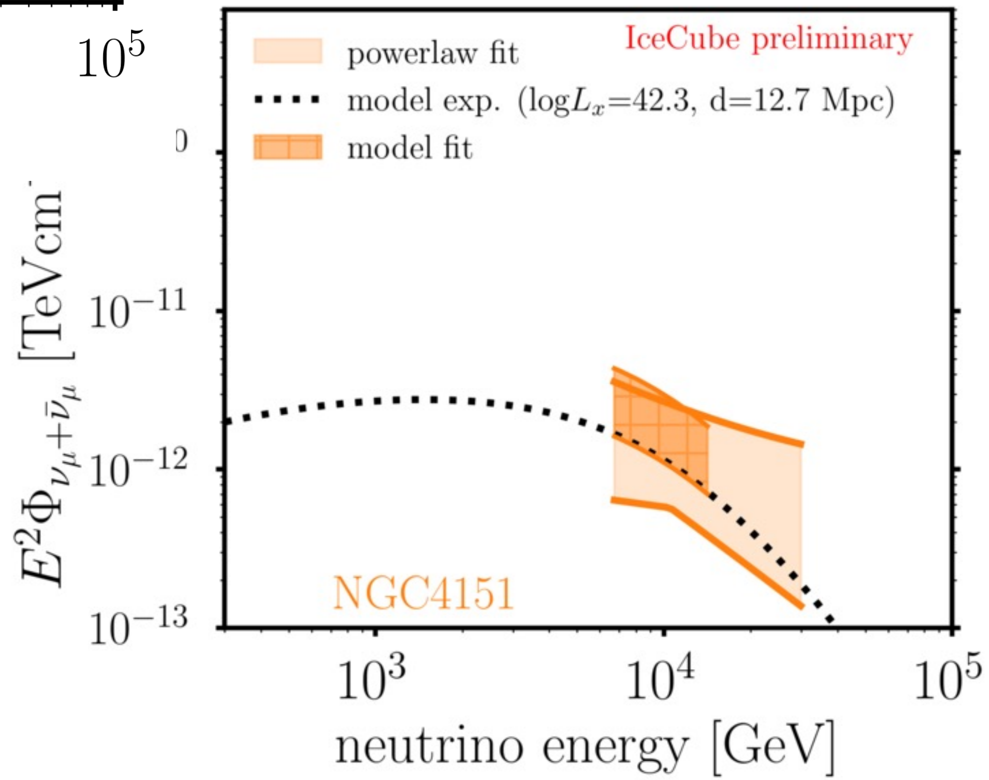
→ examples: diffuse flux below 100 TeV, TXS 2014-15 burst, NGC 1068.

→ the energy in pionic photons is already absorbed in the target and likely to appear at MeV energies or below.

→ IC170922? The source is not a blazar when the neutrino is emitted.



IceCube preliminary
powerlaw fit
model exp. (logL_x=42.9, d=12.7 Mpc)
model fit
NGC1068
$E^2\Phi_{\nu_\mu+\bar{\nu}_\mu}$ [TeVcm^{-2}s^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^3
10^4
10^5
neutrino energy [GeV]



IceCube preliminary
powerlaw fit
model exp. (logL_x=42.3, d=12.7 Mpc)
model fit
NGC4151
$E^2\Phi_{\nu_\mu+\bar{\nu}_\mu}$ [TeVcm
10^{-11}
10^{-12}
10^{-13}
10^3
10^4
10^5
neutrino energy [GeV]