

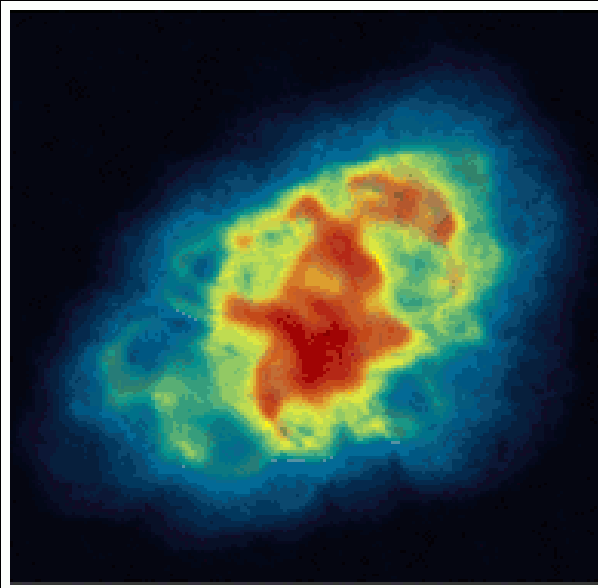
The First Decade of High-Energy Neutrino Astronomy and Neutrino Physics

francis halzen



- High-Energy Neutrino Astronomy
- IceCube and the discovery of Cosmic Neutrinos: First Surprises
- The First Cosmic Accelerators: Active Galaxies

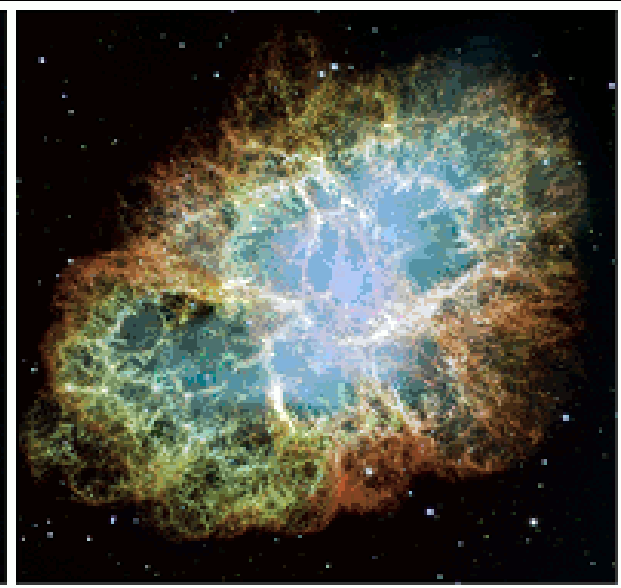
multiwavelengths
images of the
Crab supernova
remnant



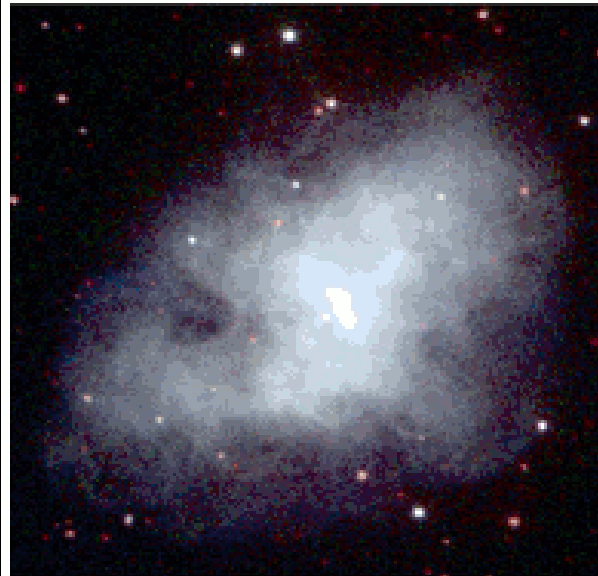
RADIO



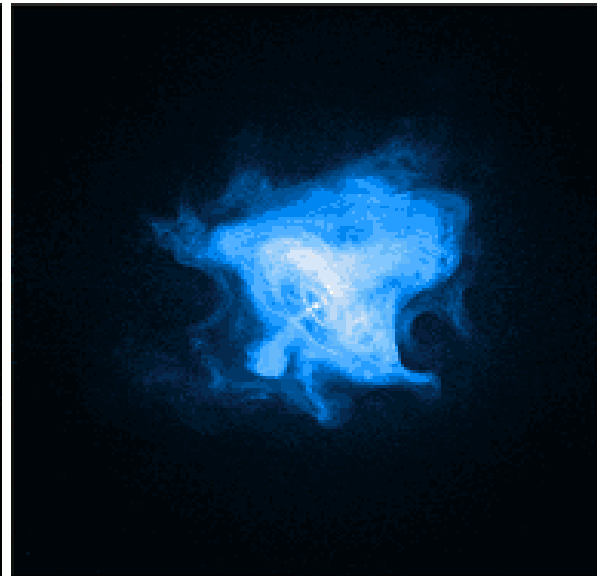
INFRARED



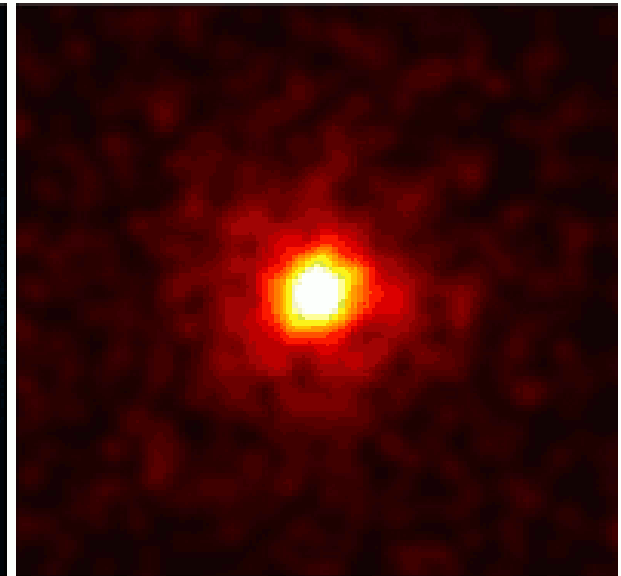
VISIBLE LIGHT



ULTRAVIOLET

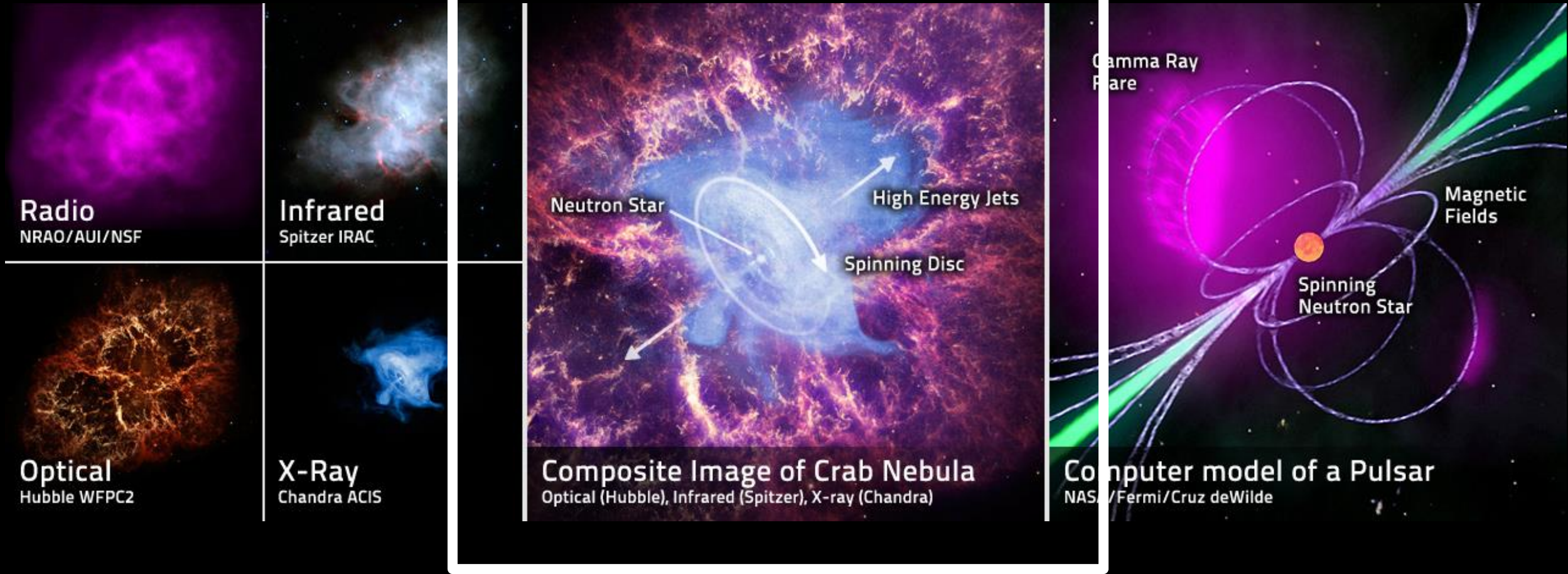


X-RAYS



GAMMA RAYS

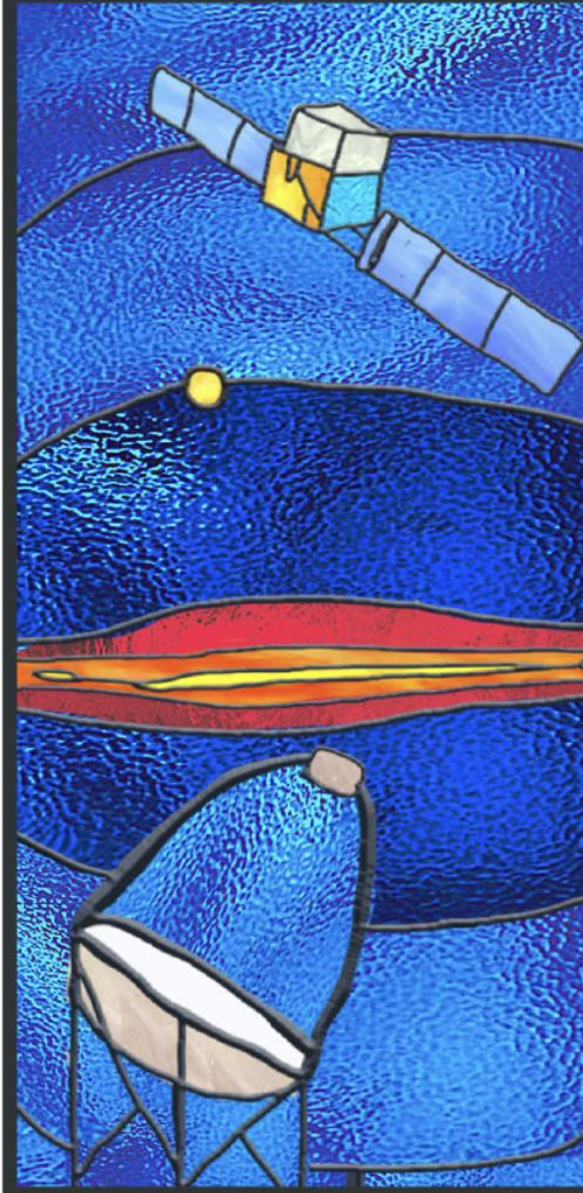
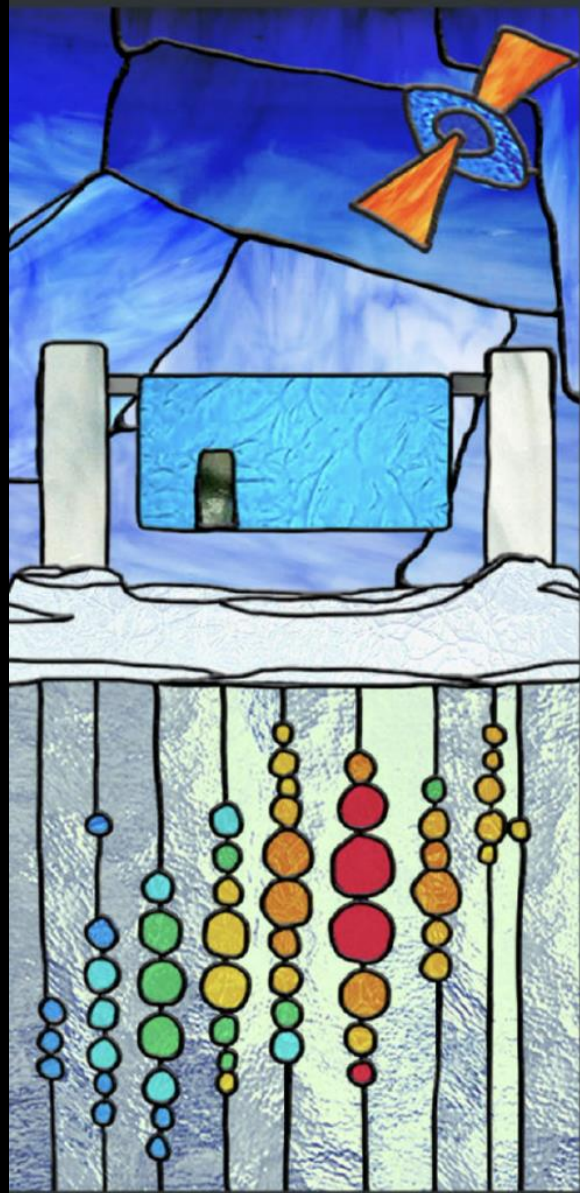
multiwavelength images of the Crab supernova remnant



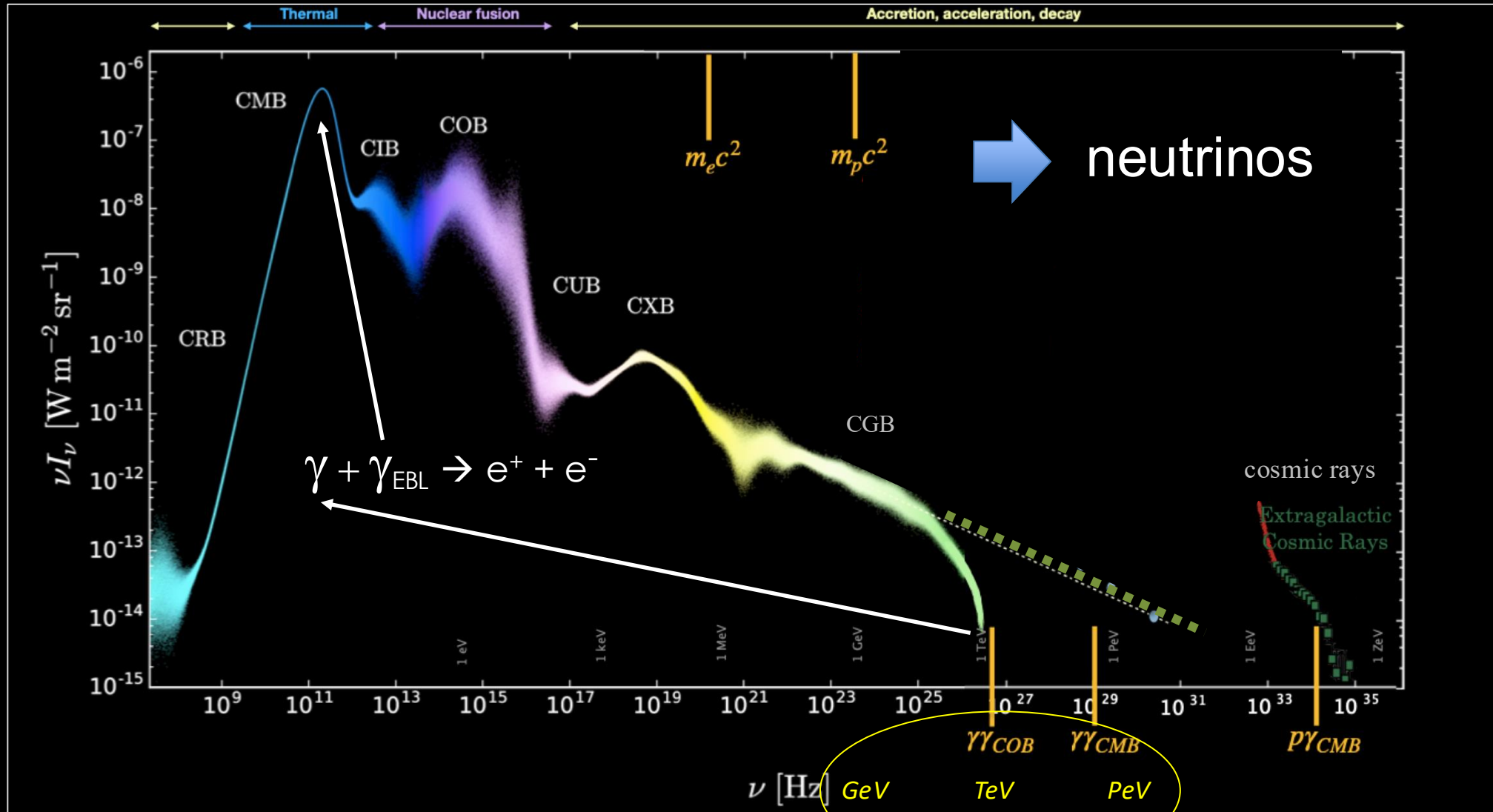
not a cosmic ray source: no neutrinos observed by IceCube (electron accelerator)

from
multiwavelength
to
multimessenger
astronomy:

towards longer
(gravity waves)
and shorter
(neutrinos)
wavelengths

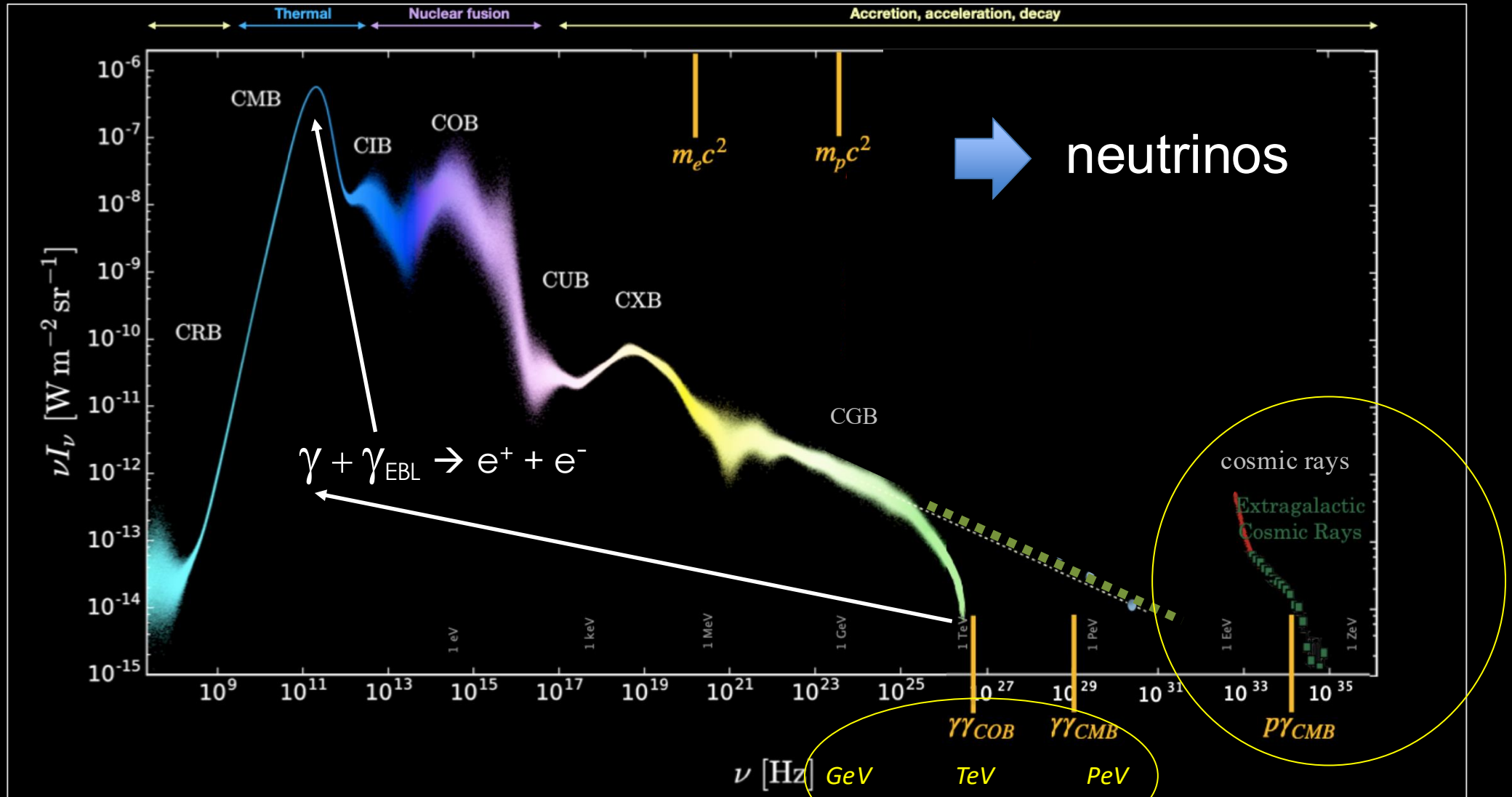


energy in photons in the Universe as a function of their frequency



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

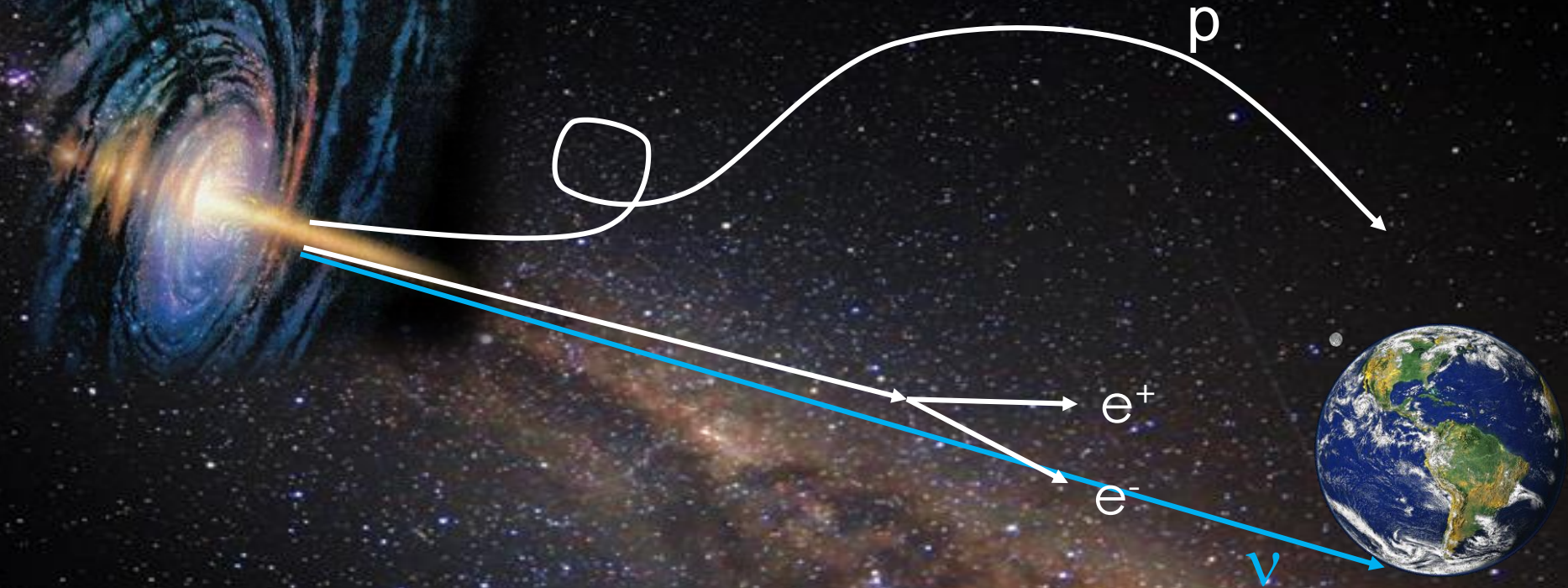
the opaque extreme Universe:



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

TeV~ PeV photons interact with extragalactic background light (CMB and higher energy background photons pervading the Universe) before reaching our telescopes

neutrinos as perfect messengers

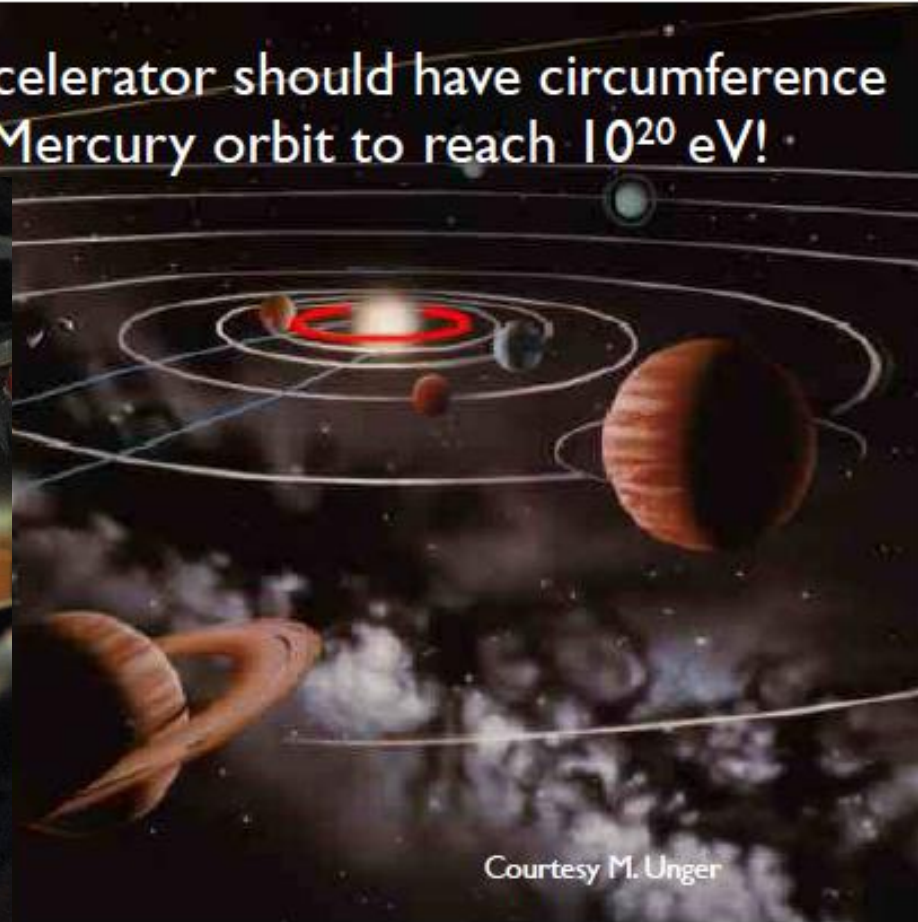
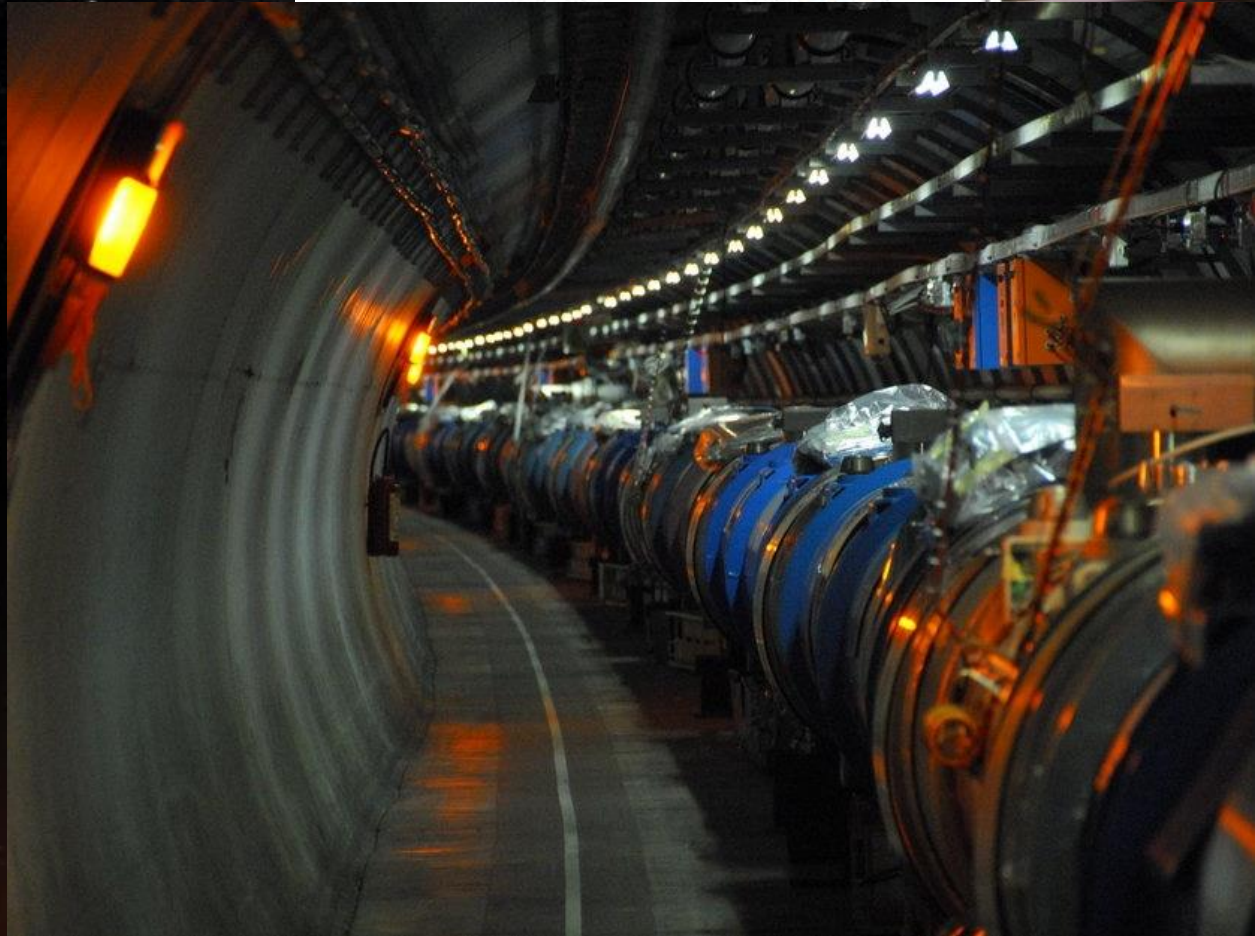


by Standard model particle physics neutrinos reach Earth from the edge of the Universe and from the beginning of time without absorption or deflection

where do cosmic rays come from
and how are they accelerated?

high energy and
high luminosity

LHC accelerator should have circumference
of Mercury orbit to reach 10^{20} eV!



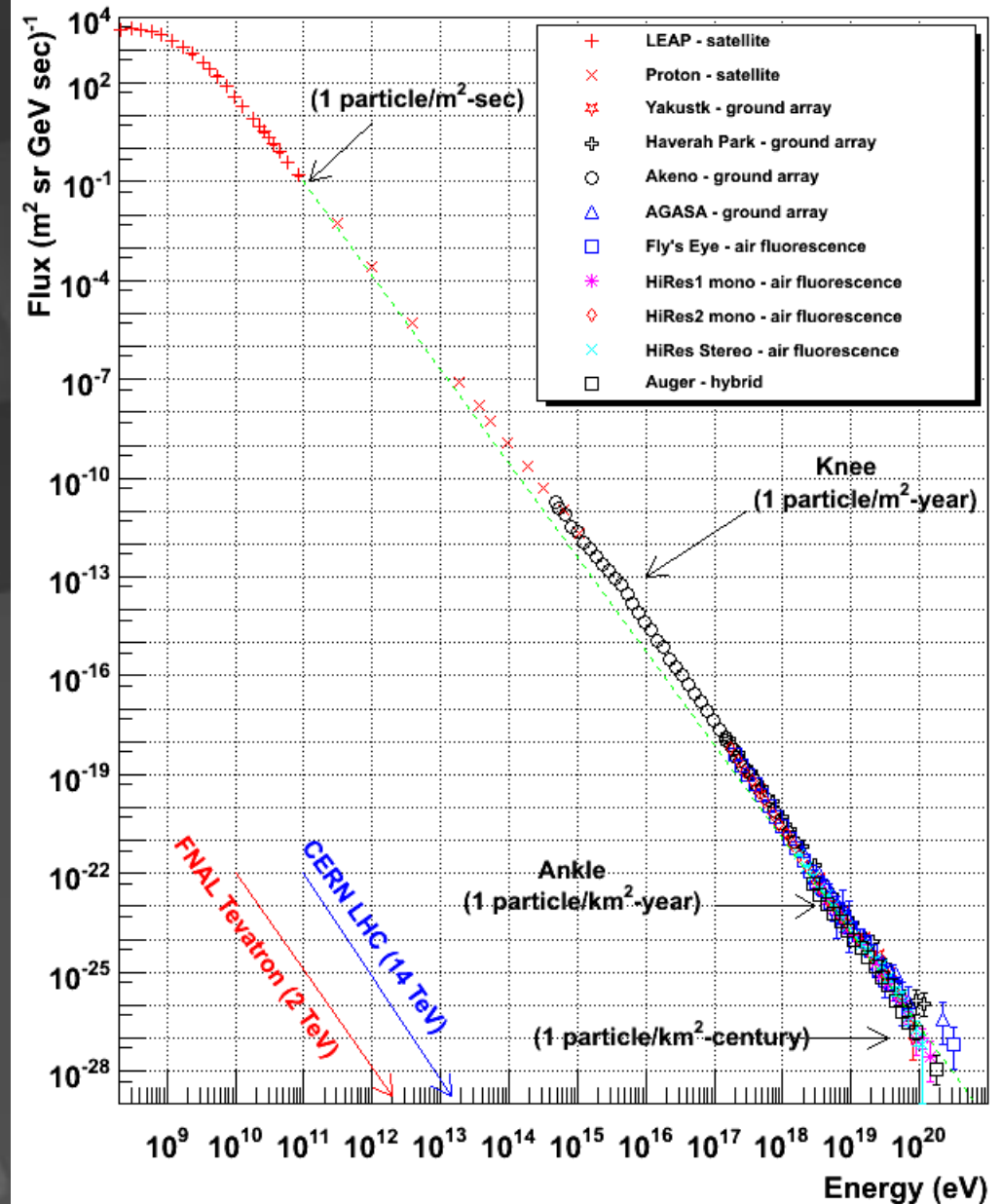
Fly's Eye 1991
300,000,000 TeV

cosmic ray challenge

both the energy of the particles and the total *luminosity* of the accelerators are large

gravitational energy from collapsing object is converted into particle acceleration?

Cosmic Ray Spectra of Various Experiments



theoretical ideas....

active galactic nuclei

gamma ray burst

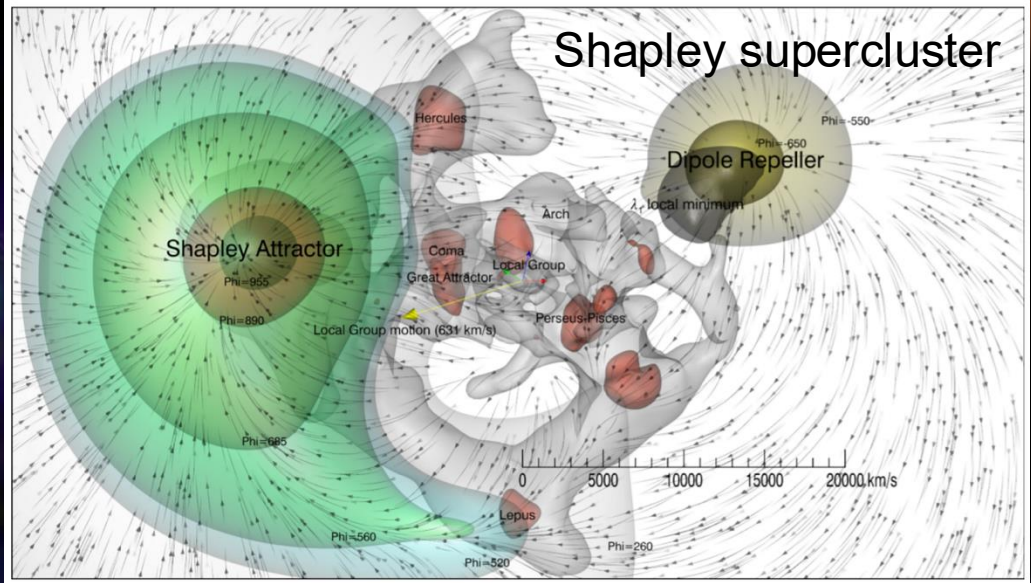
tidal disruption

cosmic strings

magnetars

starburst galaxies

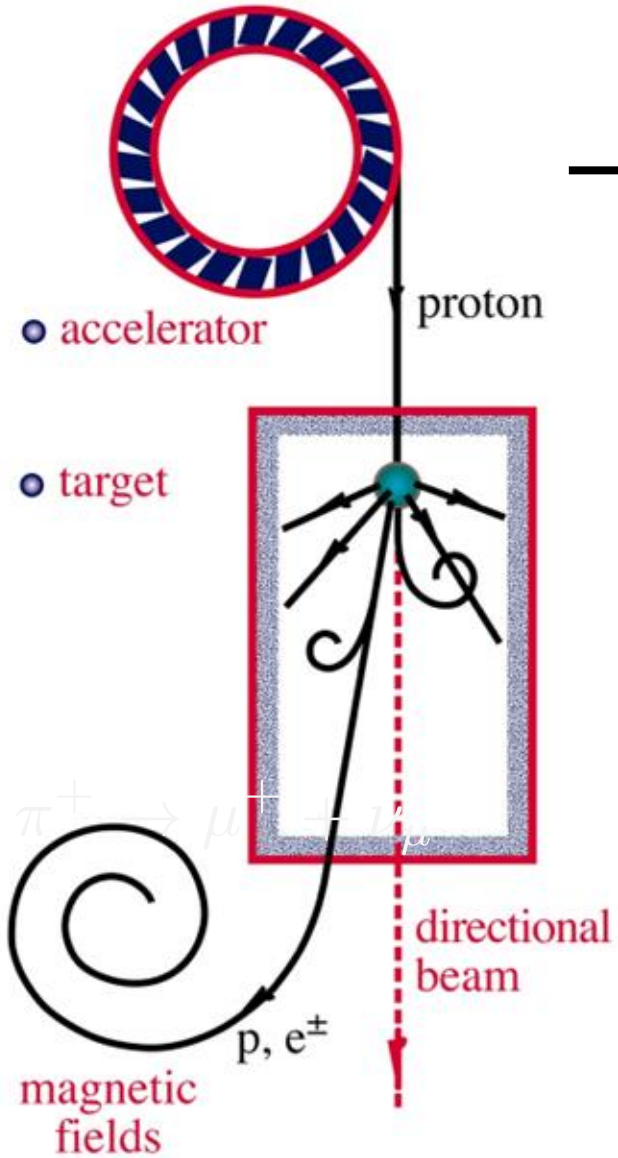
merging galaxies



Hess 1912: the sources of the cosmic rays?

ν and γ beams : heaven and earth

cosmic accelerators powered by gravity



**supermassive
black hole**

**nearby
radiation**

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

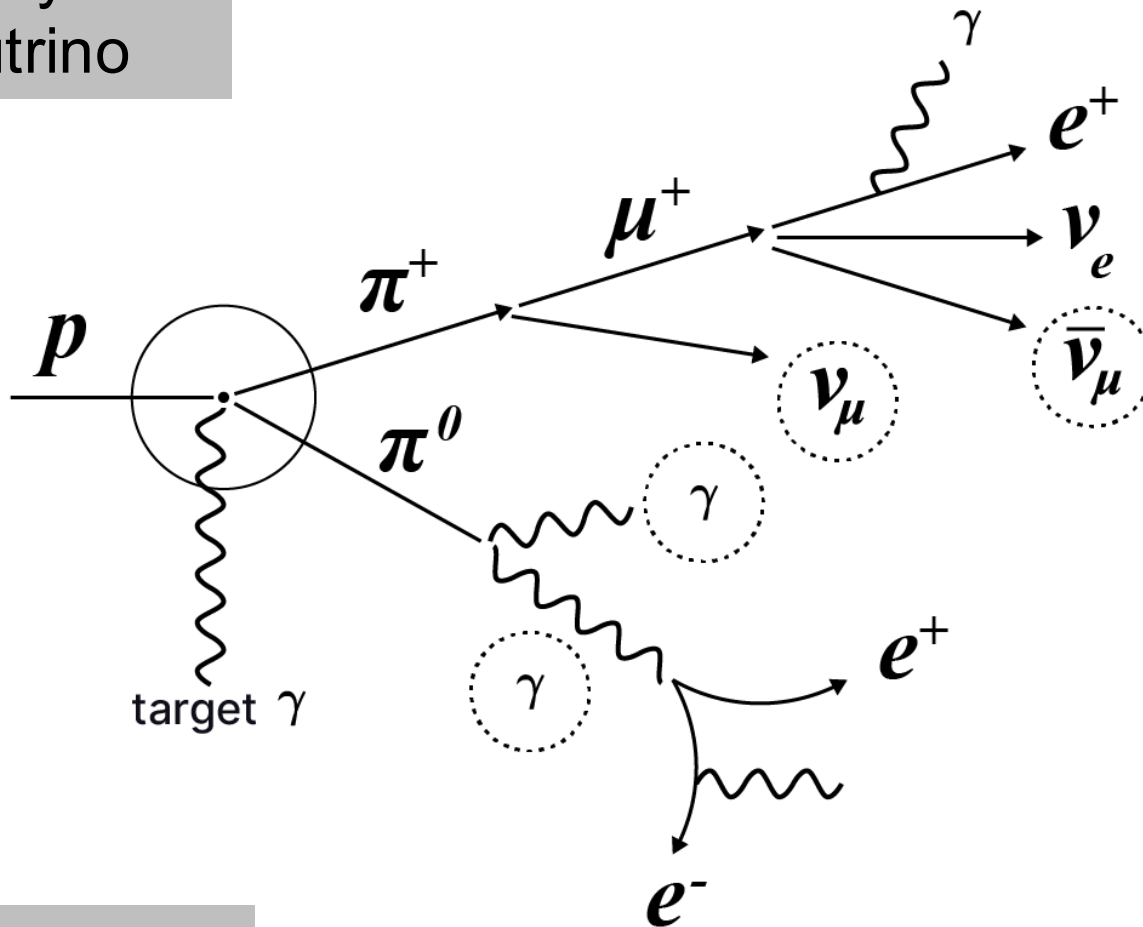
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

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

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

cosmic ray sources:
a gamma ray for
every neutrino



$$F_\nu(E_\nu) = F_\gamma(E_\gamma = 2E_\nu)$$

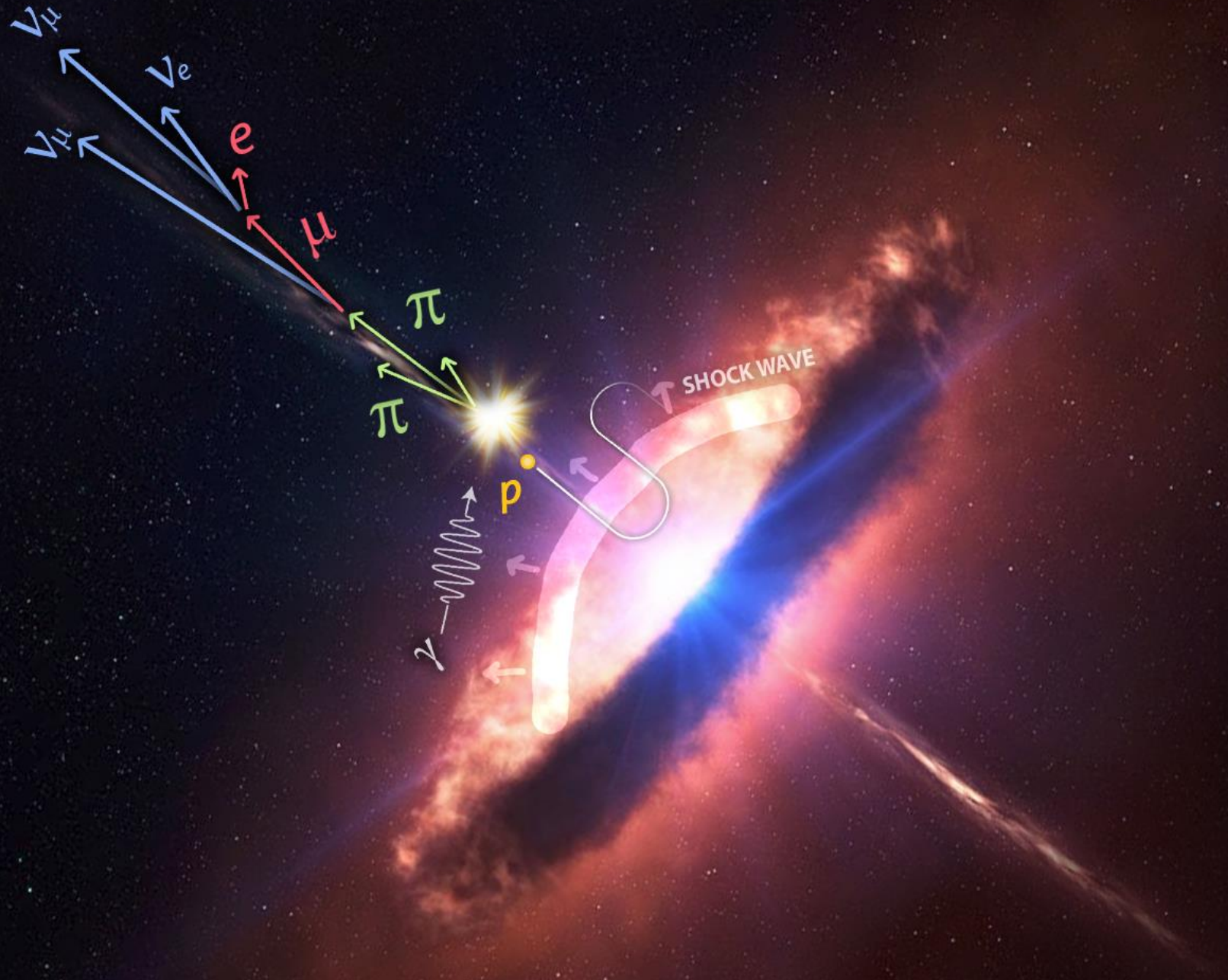
neutrino sources are
cosmic ray sources

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

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

cosmic accelerators:

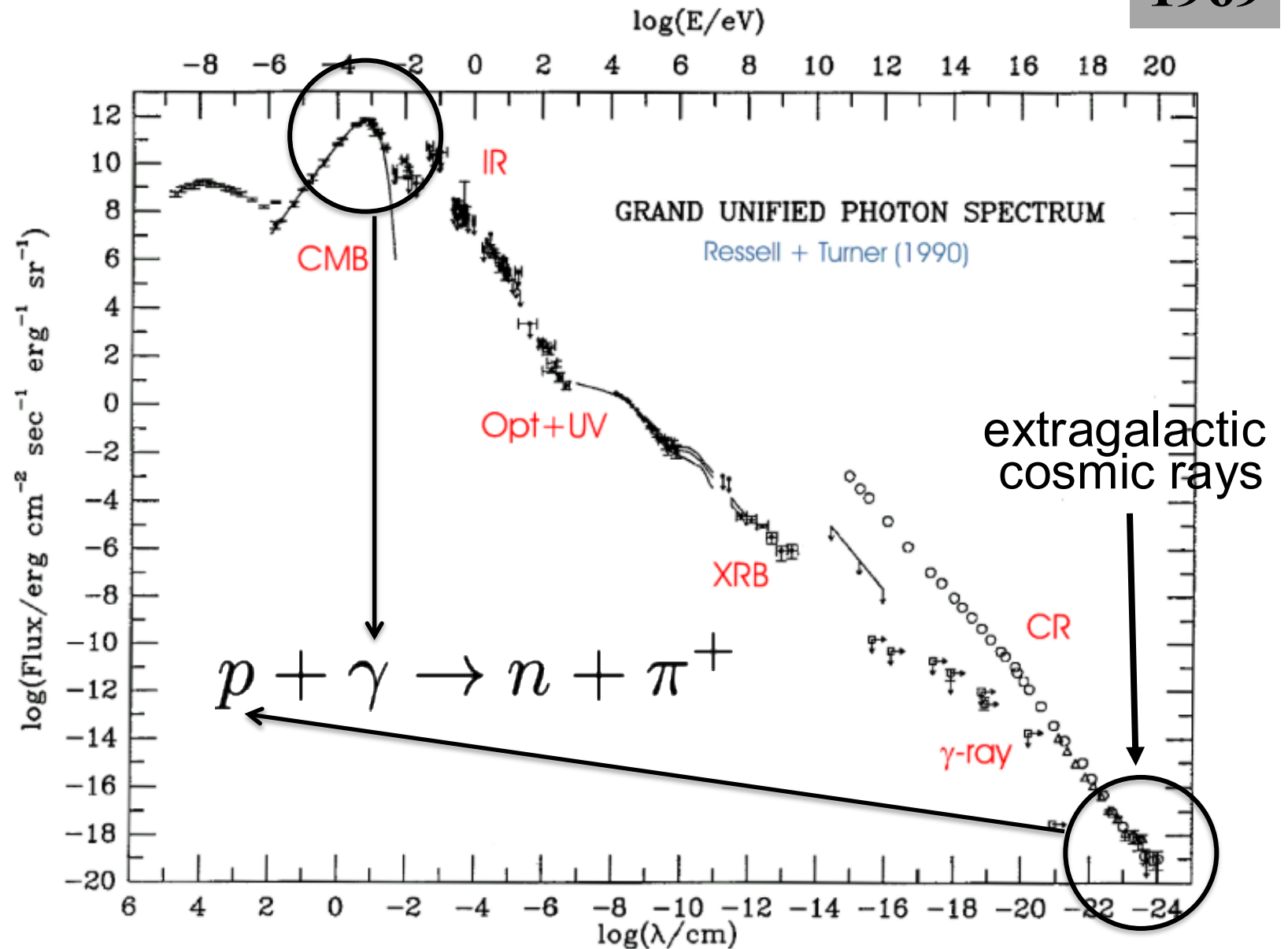
- protons accelerated near a black hole are submersed in a target of radiation and produce pions
- one photon for every neutrino
- neutrinos track cosmic ray (*proton*) accelerators making pions



flux

the “guaranteed neutrinos”

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



energy (eV)

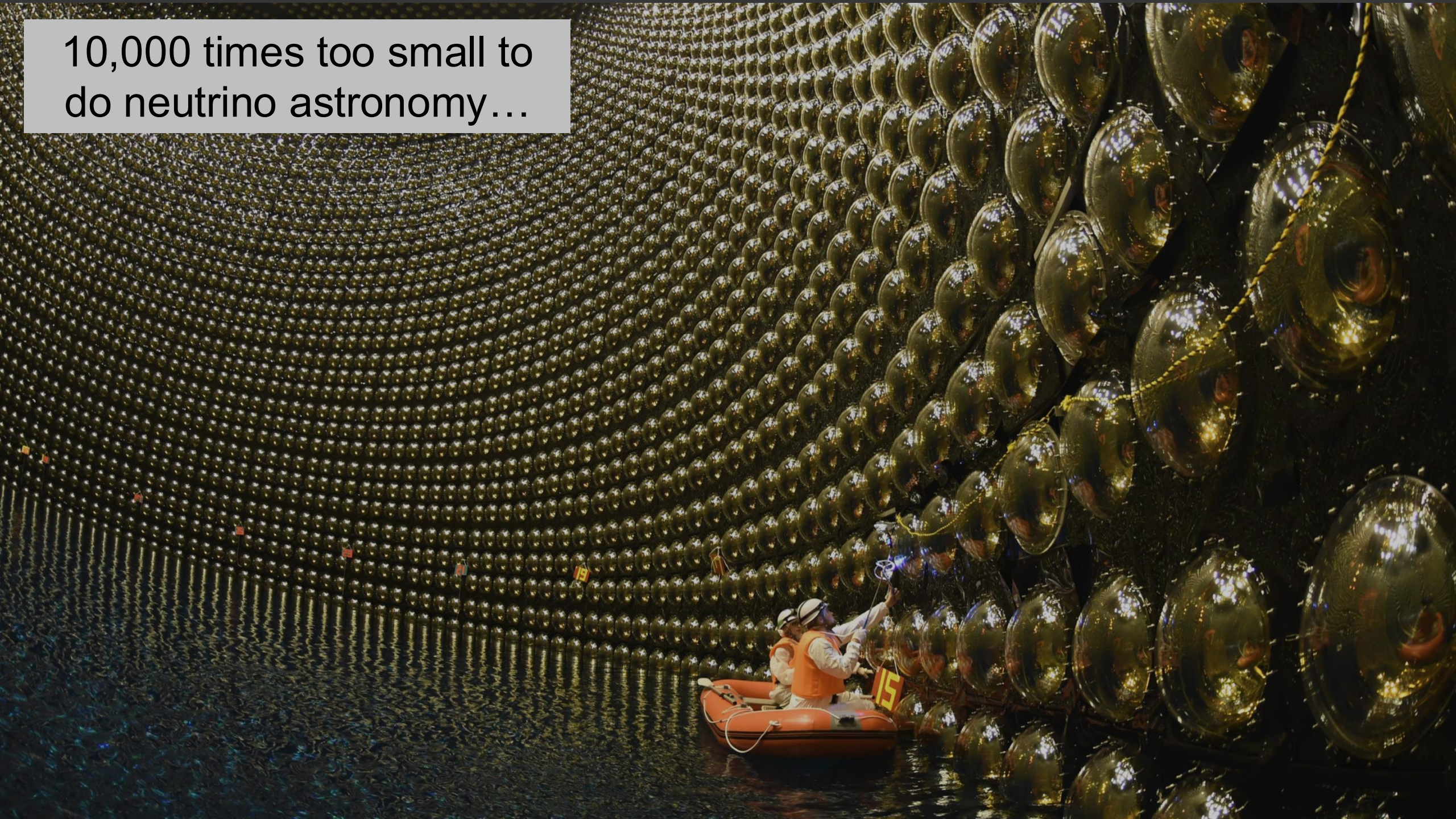
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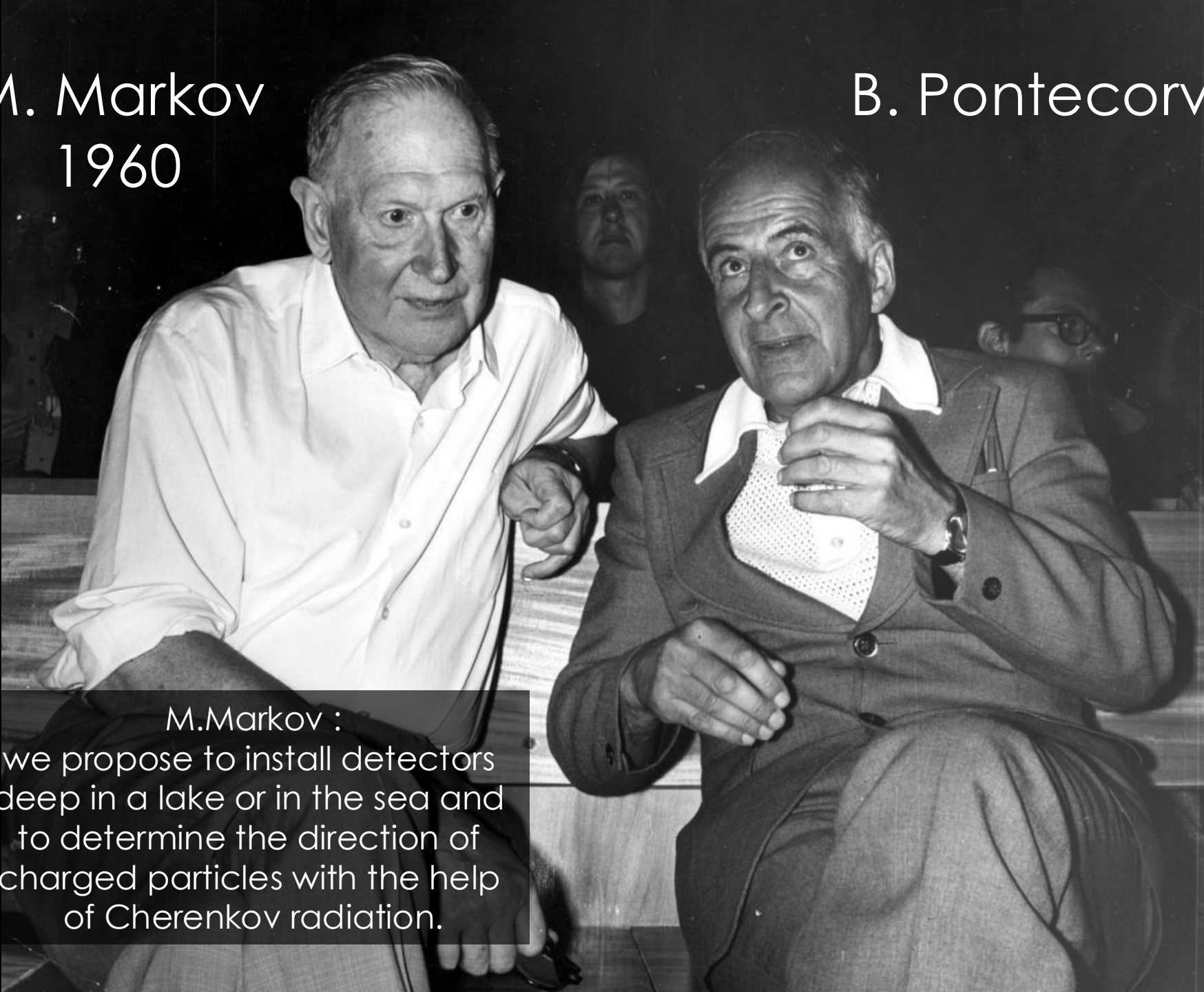
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10,000 times too small to
do neutrino astronomy...



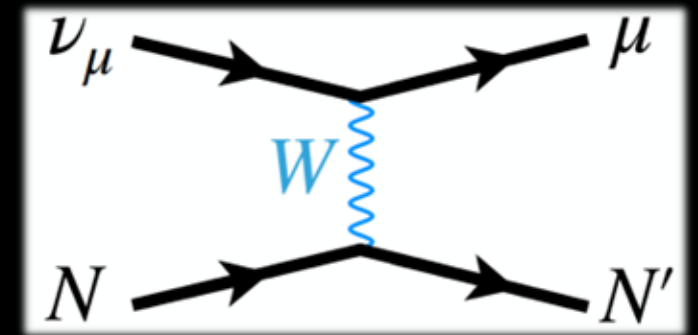
M. Markov
1960

B. Pontecorvo



M. Markov :
we propose to install detectors
deep in a lake or in the sea and
to determine the direction of
charged particles with the help
of Cherenkov radiation.

the invisible neutrino
turns into charged
particles that emit
light

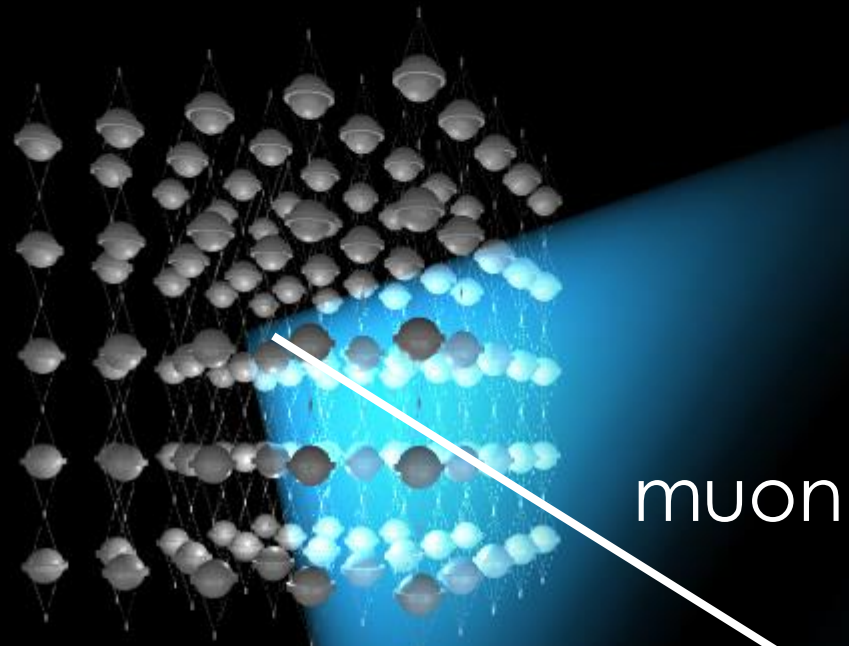


• lattice of photomultipliers

• muon

• nuclear interaction
with ice nucleus

• neutrino



- muon travels for kilometers through the water at the speed of light emitting blue light along its track

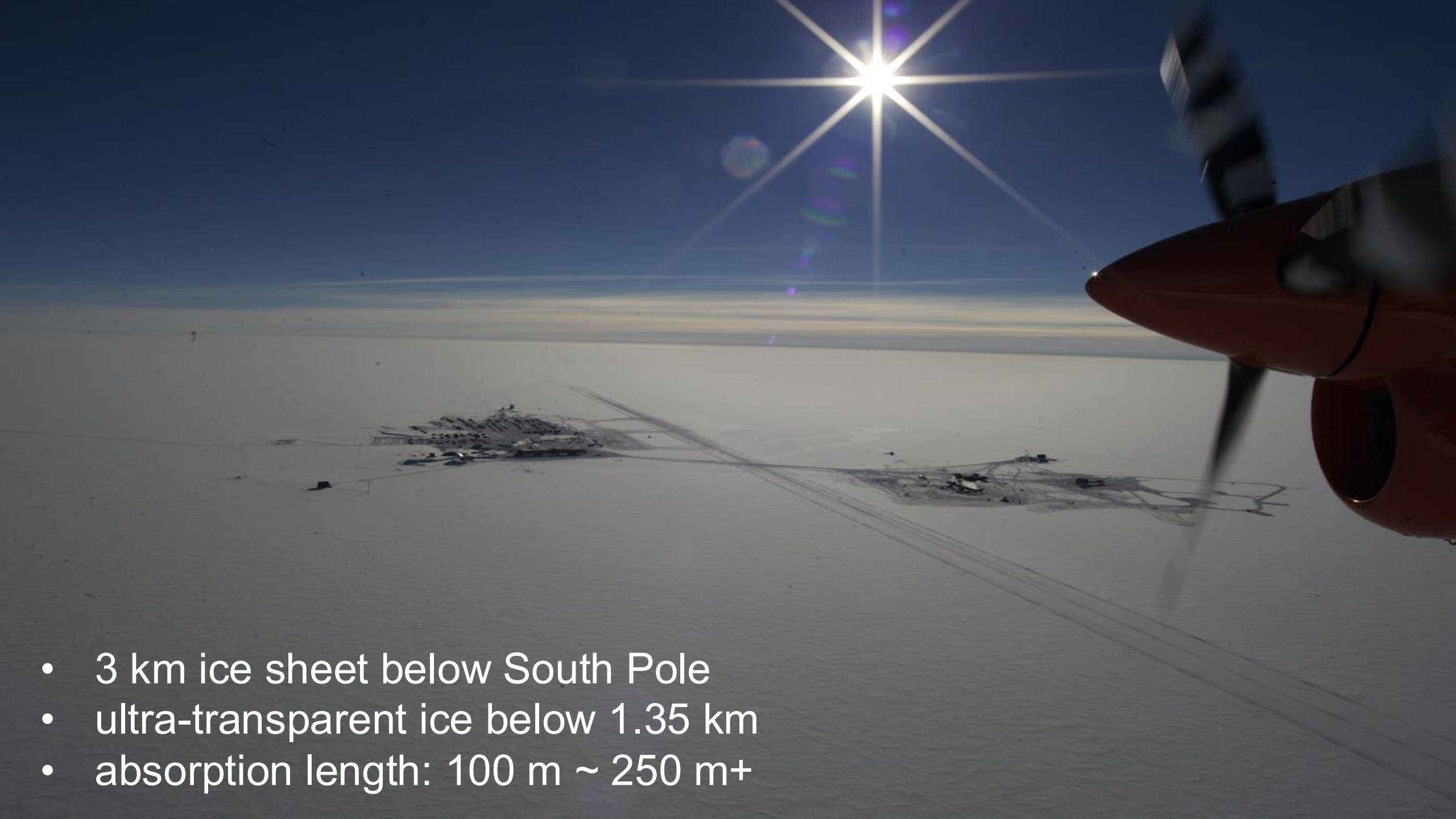


- speed of light in water is only three quarters of the speed of light $\rightarrow$ shockwave

muon-neutrino



“In summary, this is a detector that requires a number of happy accidents to make it feasible. But if these should come to pass, it may provide the least expensive route to a truly large neutrino telescope. Exploratory studies may begin at the South Pole Station within the next few years”
First Venice Meeting on Neutrino Telescopes (1988).



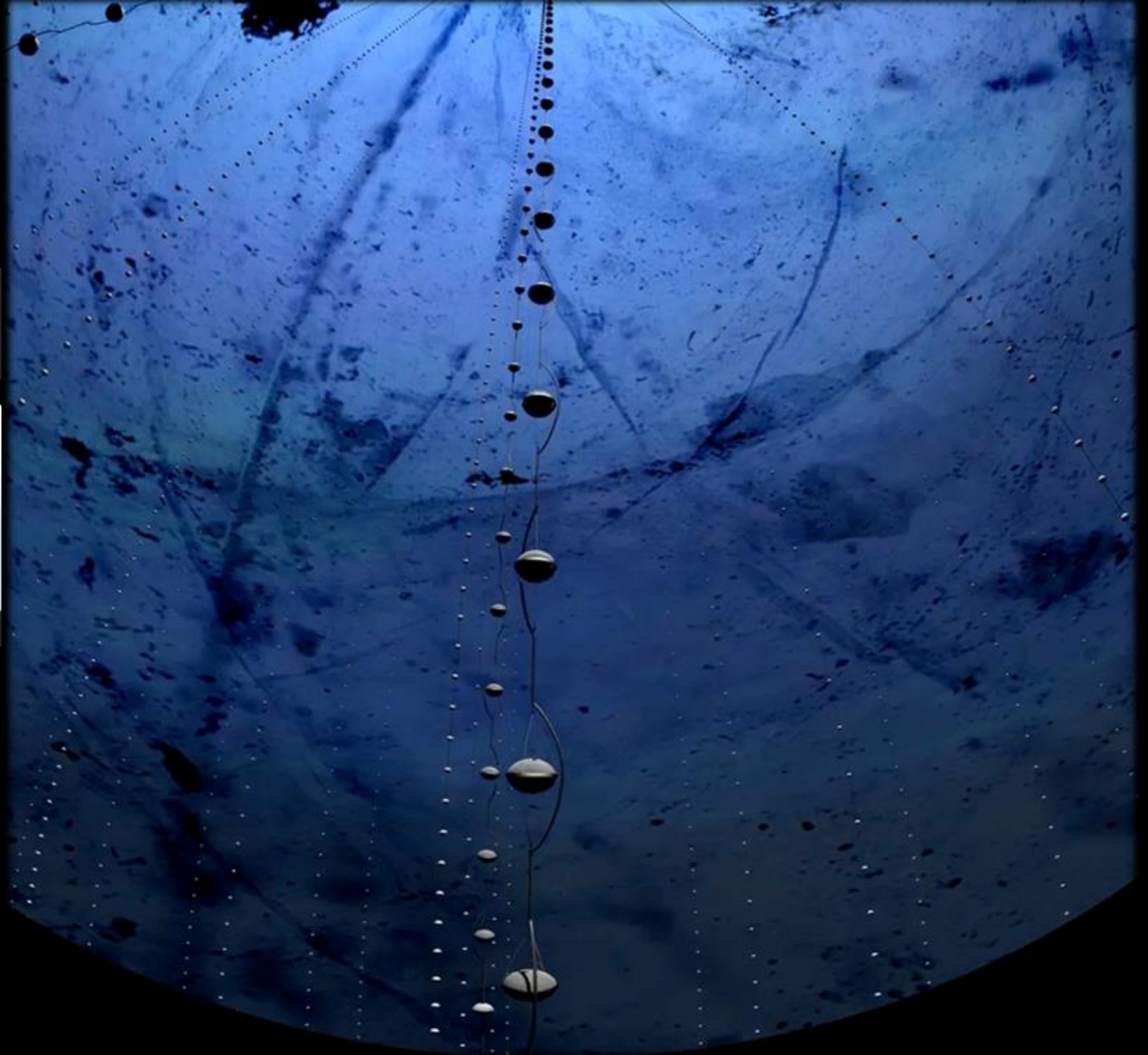
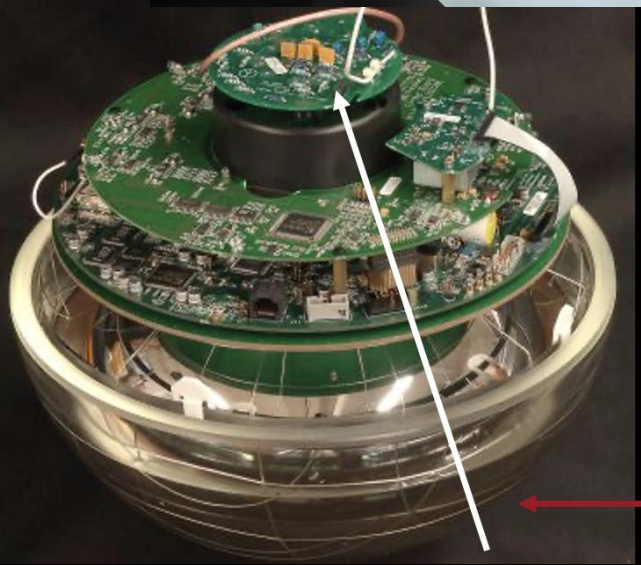
- 3 km ice sheet below South Pole
- ultra-transparent ice below 1.35 km
- absorption length: 100 m ~ 250 m+

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



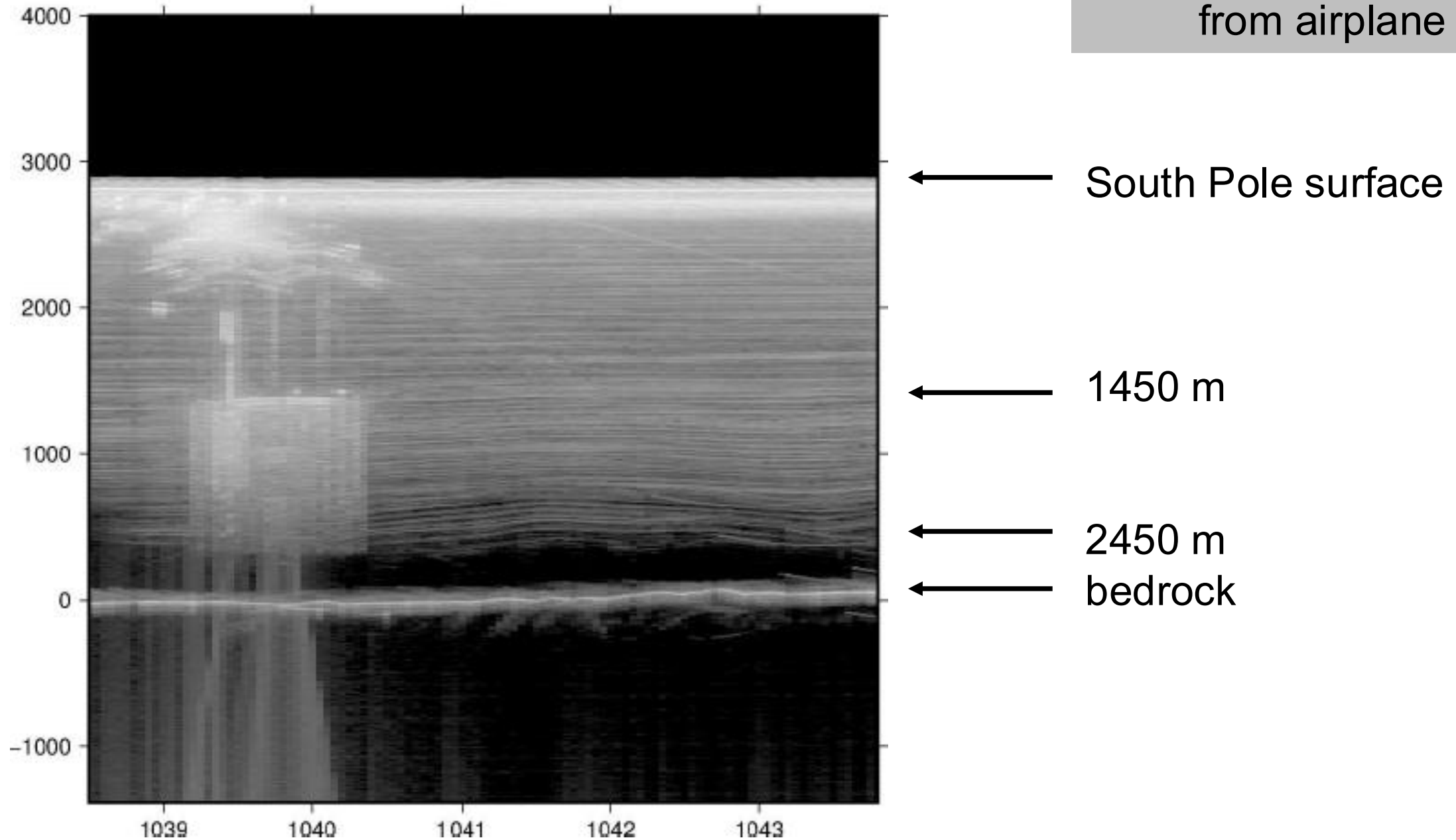
IceCube:

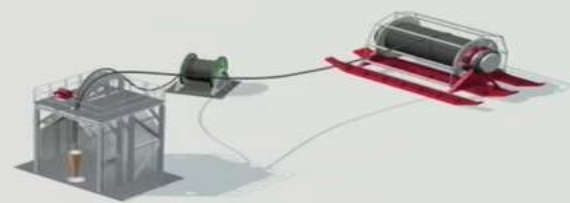
5160 10-inch photomultipliers,
60 per string on 86 strings,
instrument one km³ of
Antarctic ice between
1.4 and 2.4 km depth
as a Cherenkov detector



IceCube Array at 60 MHz

ground-penetrating radar
from airplane





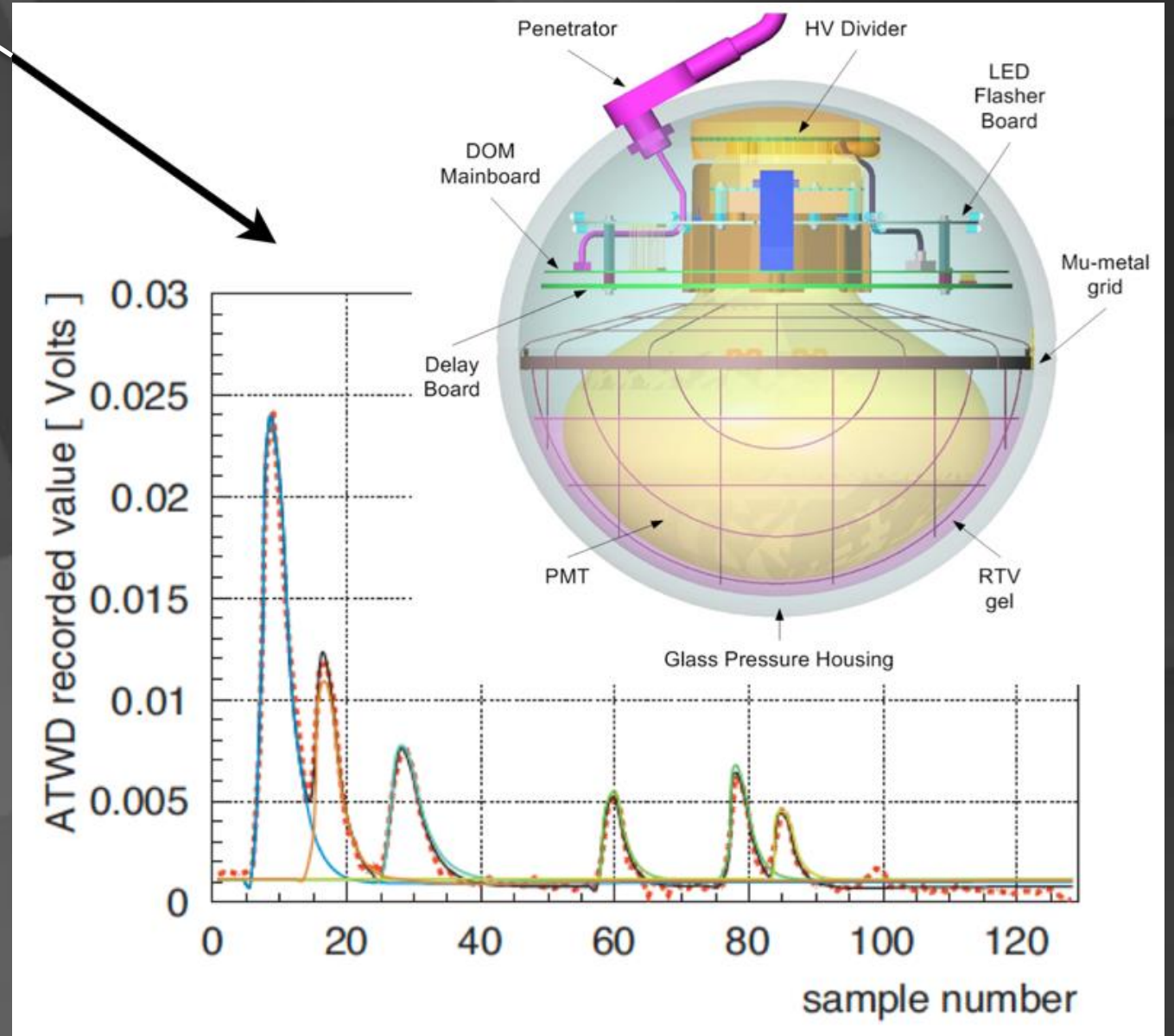
electrical cables supply the
voltage to the photomultipliers
and return their digitized signals
which are assembled into
neutrino events at the surface



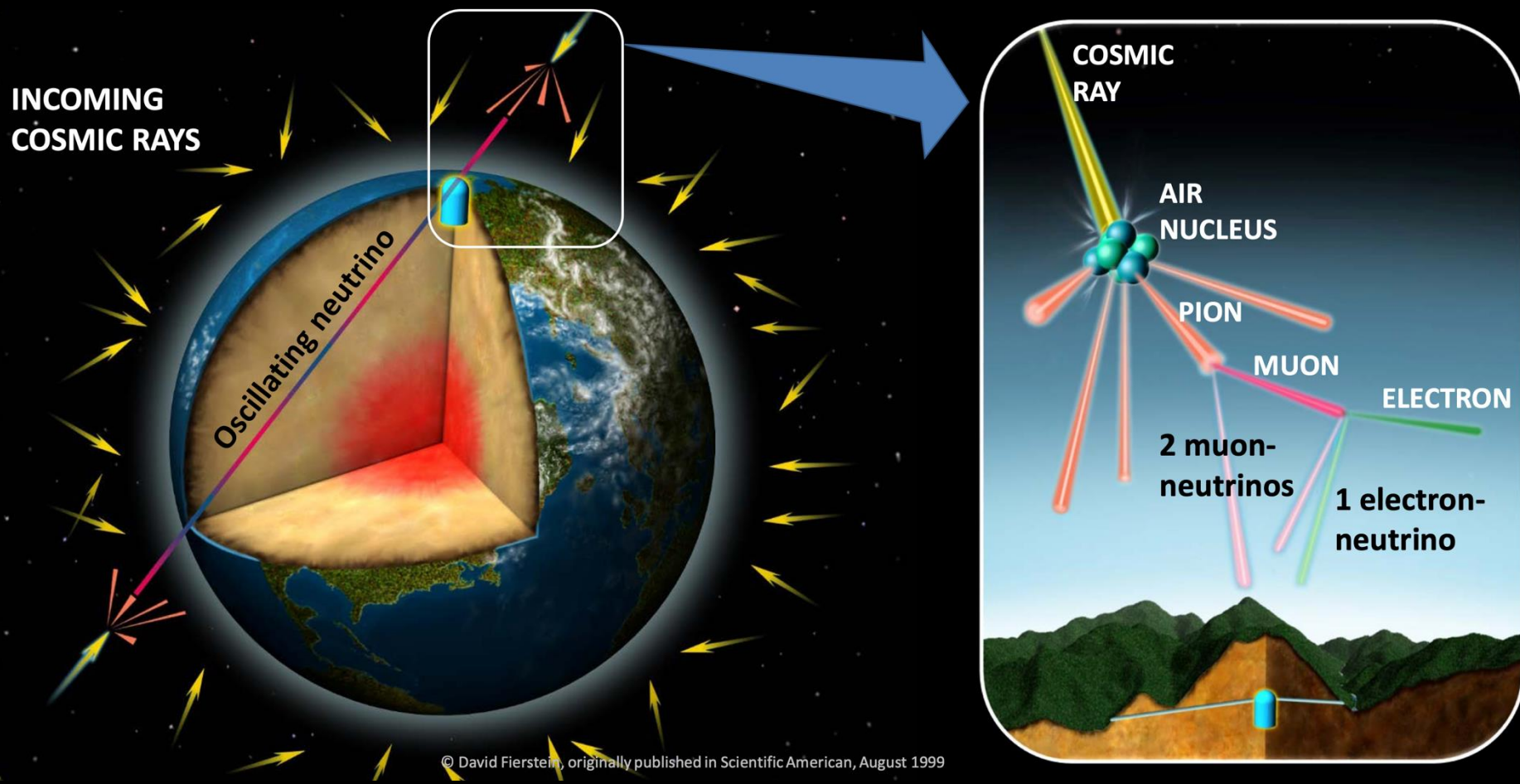


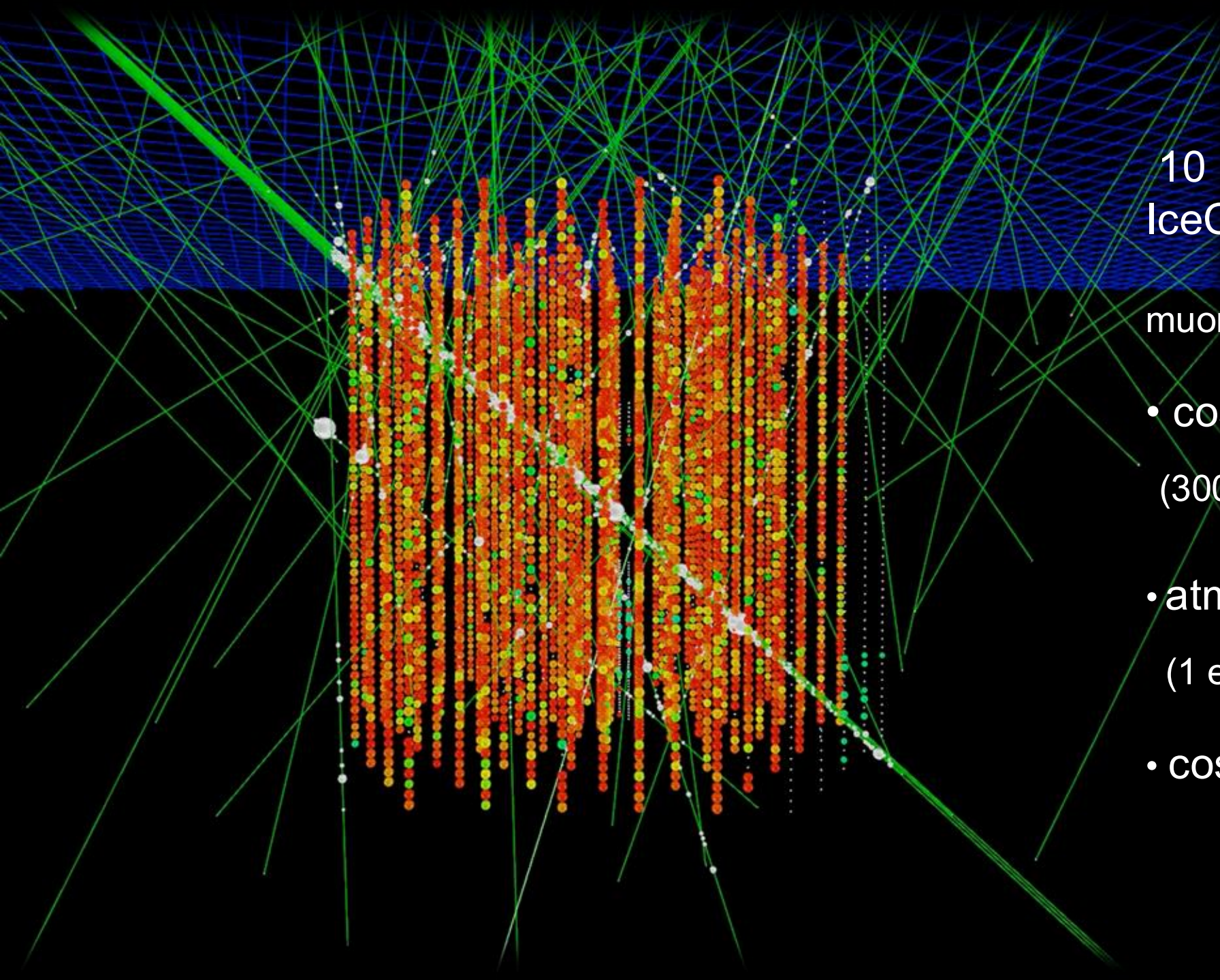
digitized light signals (waveforms)

- each Digital Optical Module independently collects light signals like this, digitizes them and
- time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them in events...



What does IceCube “see”?



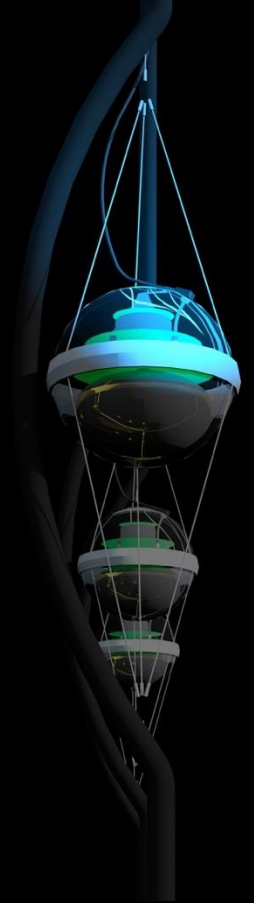
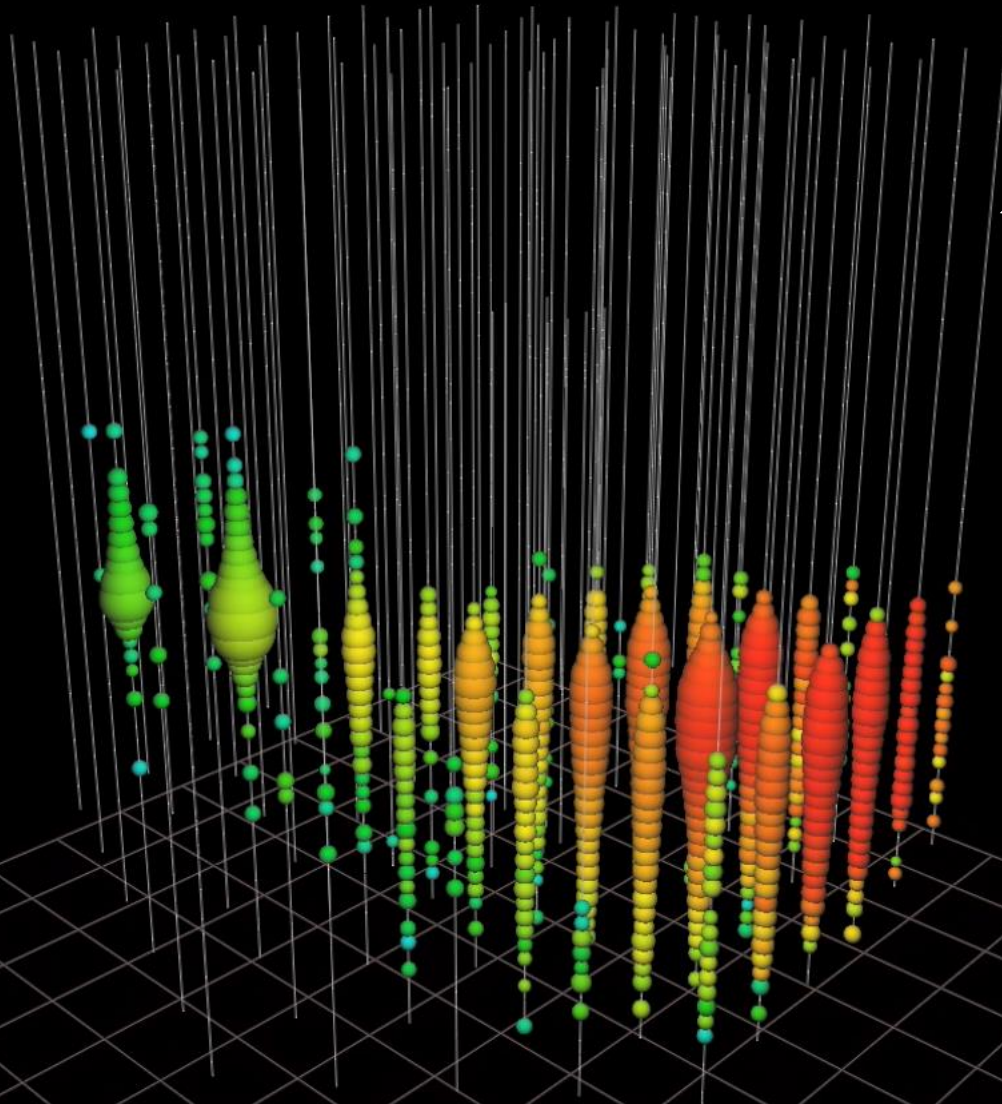
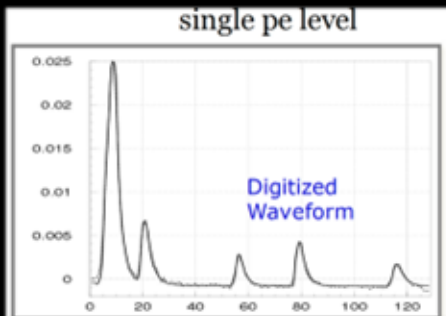


10 msec movie of
IceCube taking data

muons detected per year

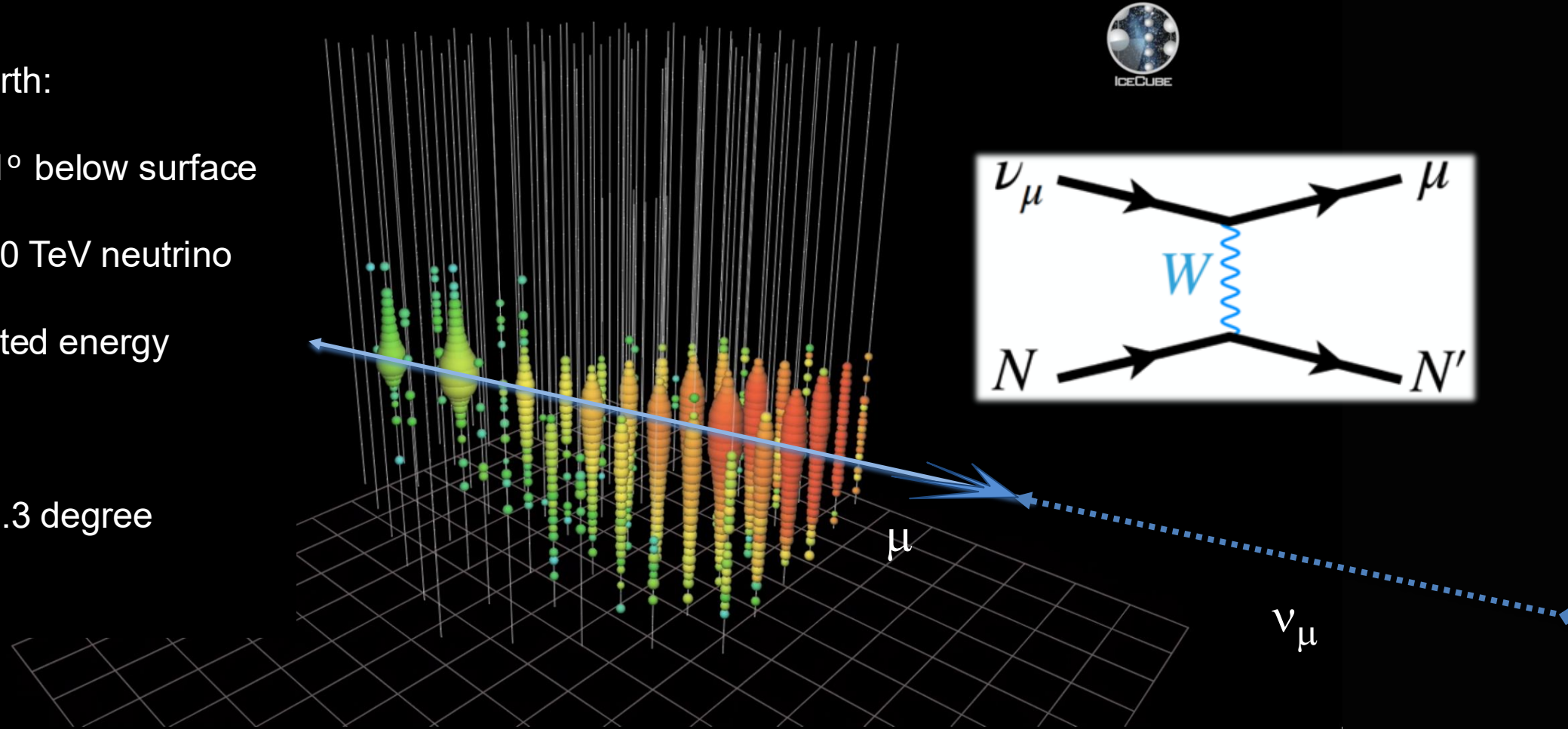
- cosmic ray muons $\sim 10^{11}$
(3000 per second)
- atmospheric neutrinos $\sim 10^5$
(1 every 5 minutes)
- cosmic neutrinos ~ 200

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

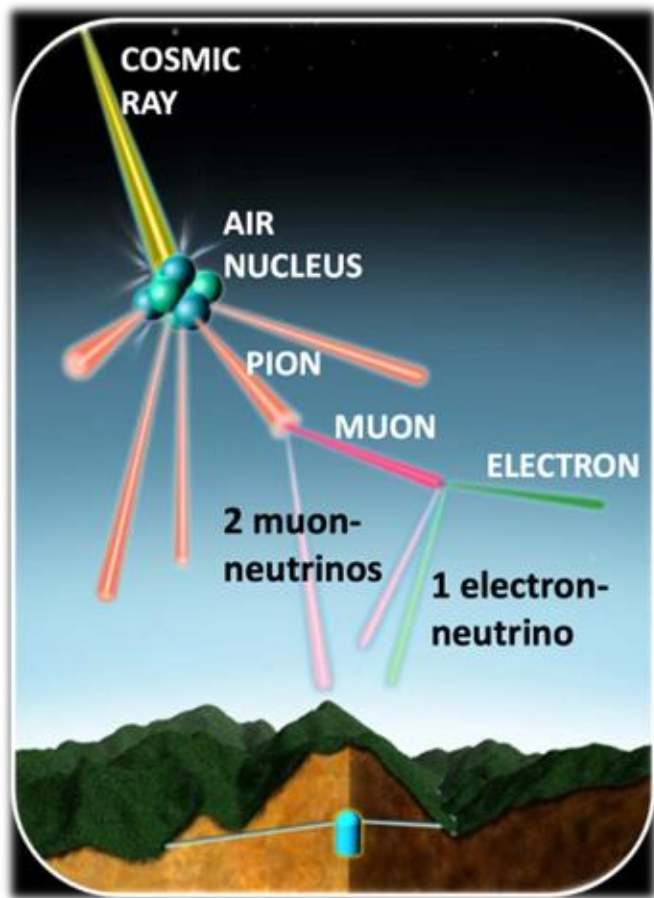


Look through the Earth:

- upgoing muon 11° below surface
- produced by 8,700 TeV neutrino
- 2,600 TeV deposited energy
- not atmospheric
- reconstructed < 0.3 degree
- astronomy



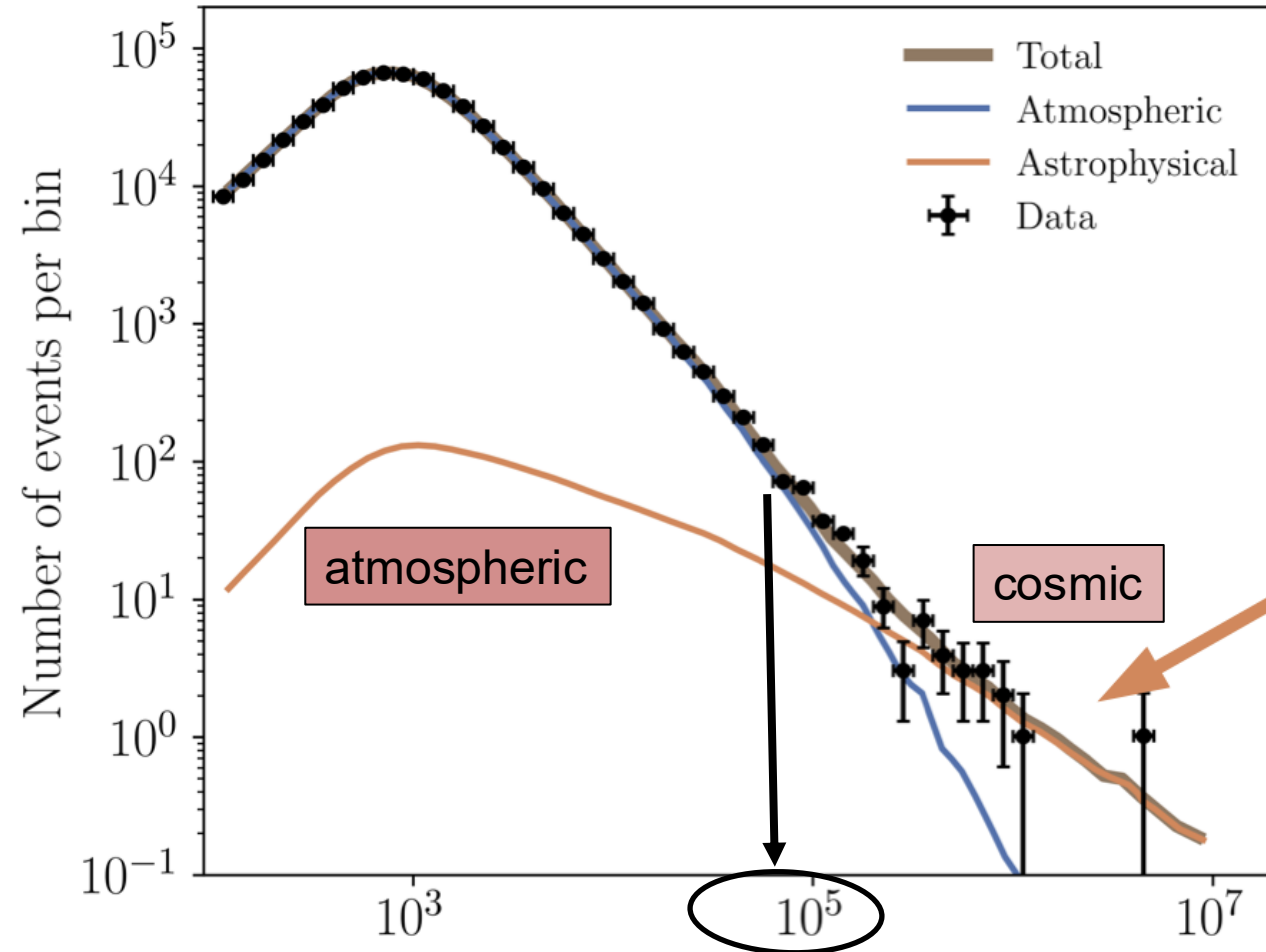
muon neutrino events
[filtered by the Earth]:
atmospheric vs
cosmic



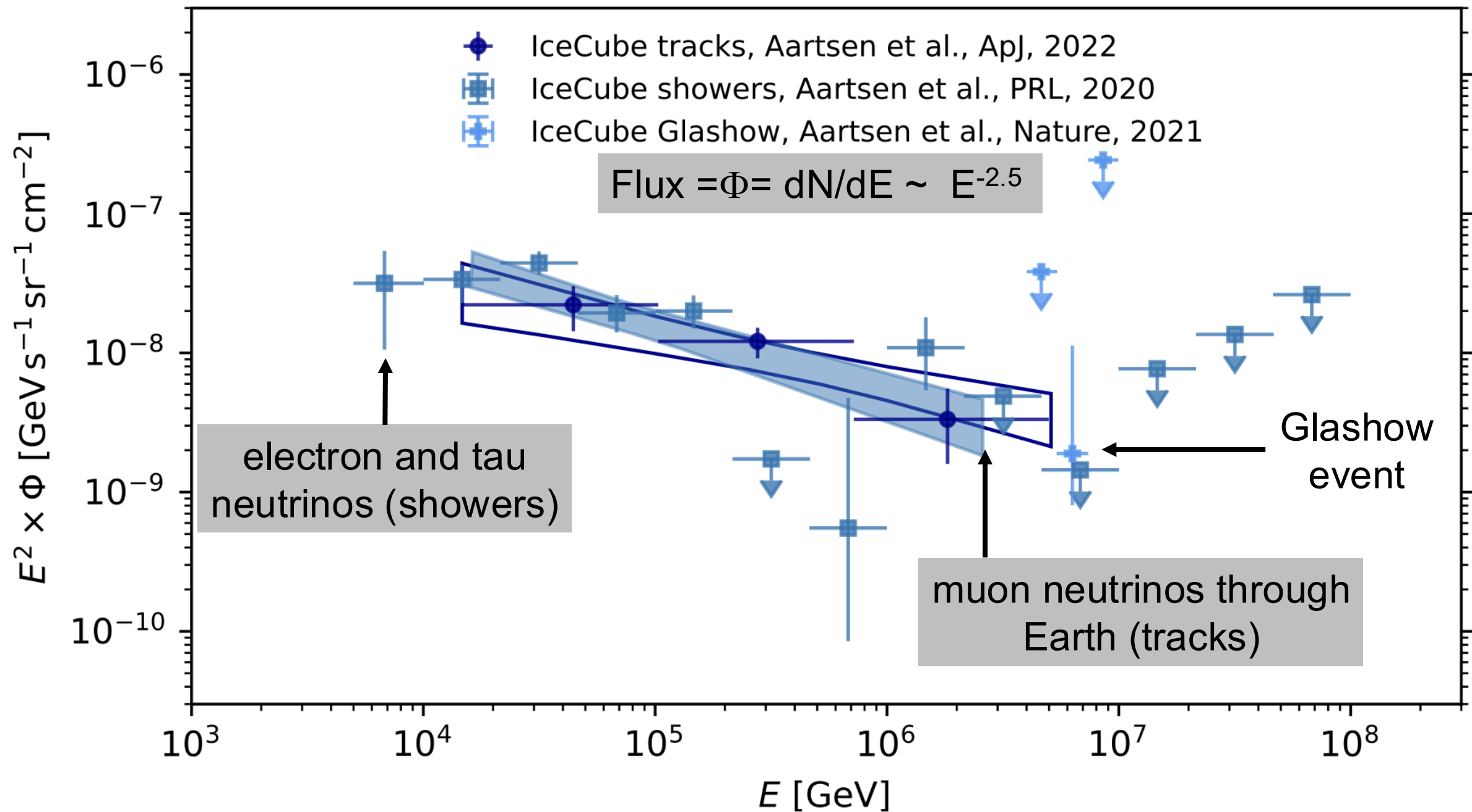
In 2013: Astrophysical diffuse neutrinos

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

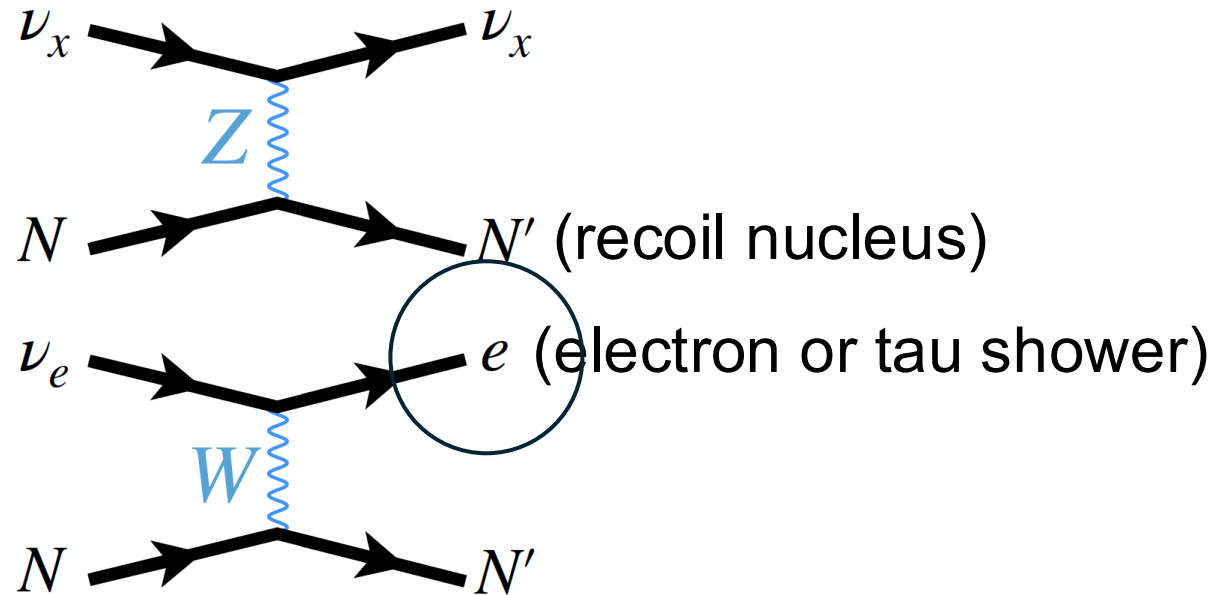
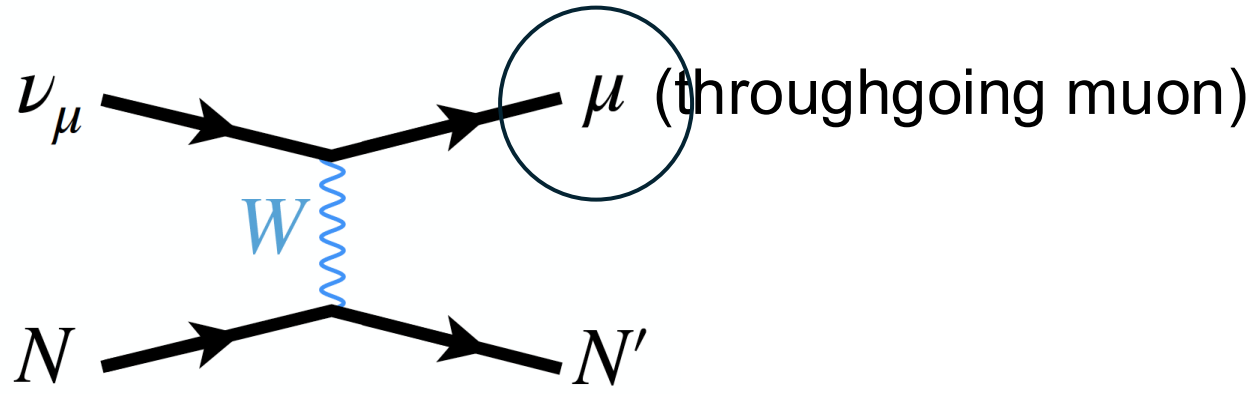
number of events



reconstructed energy (GeV)

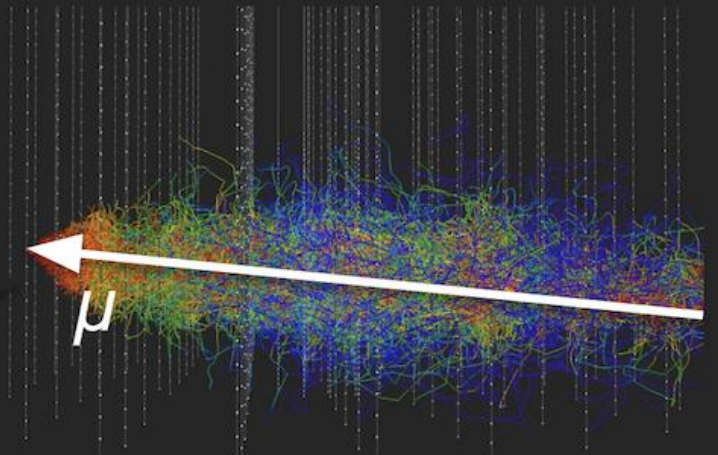


other neutrino flavors

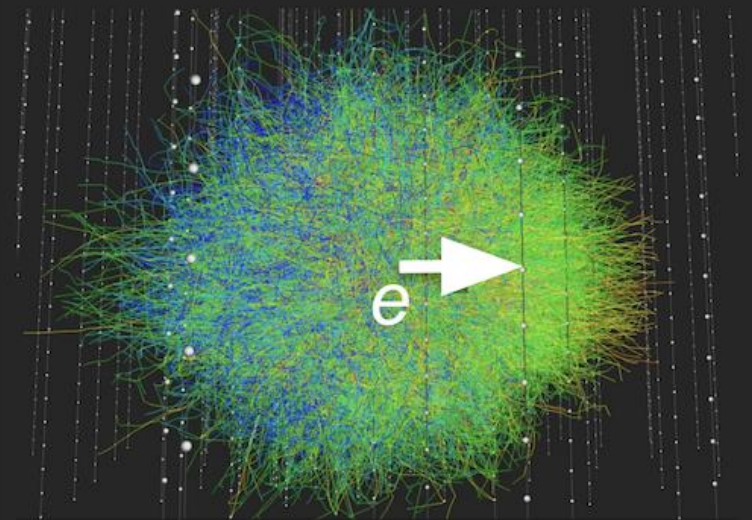


Deep inelastic scattering of Neutrinos

□ Cherenkov light

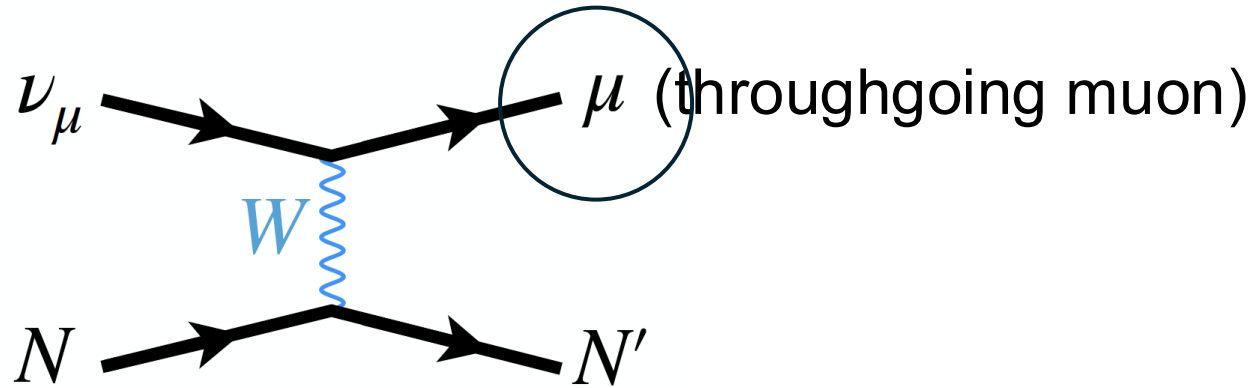


muon-induced tracks

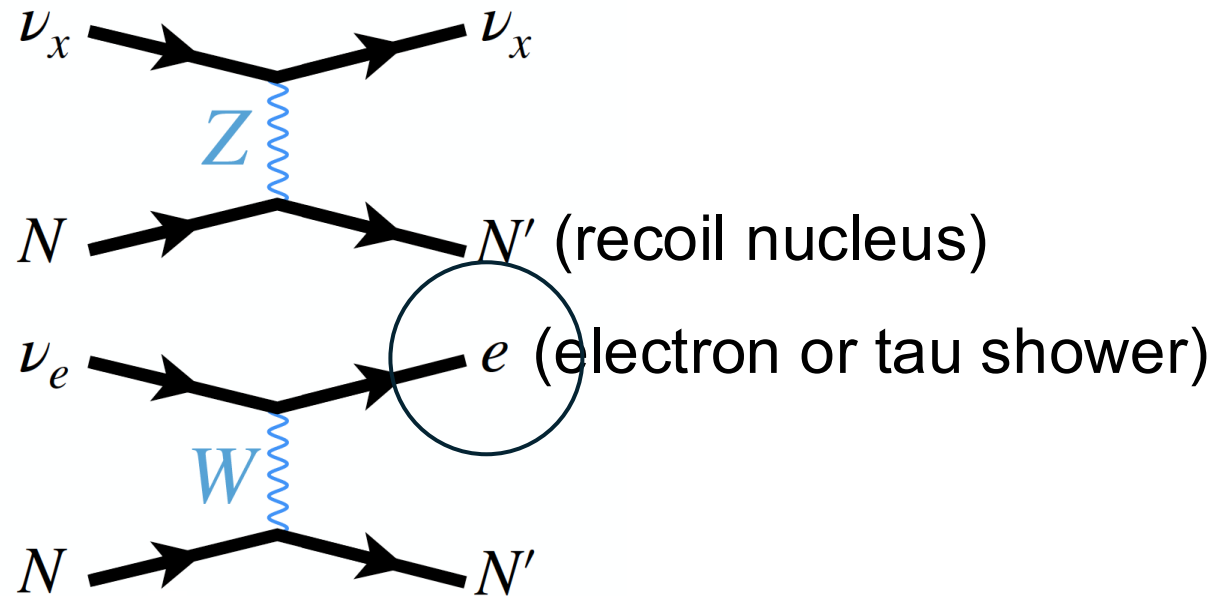
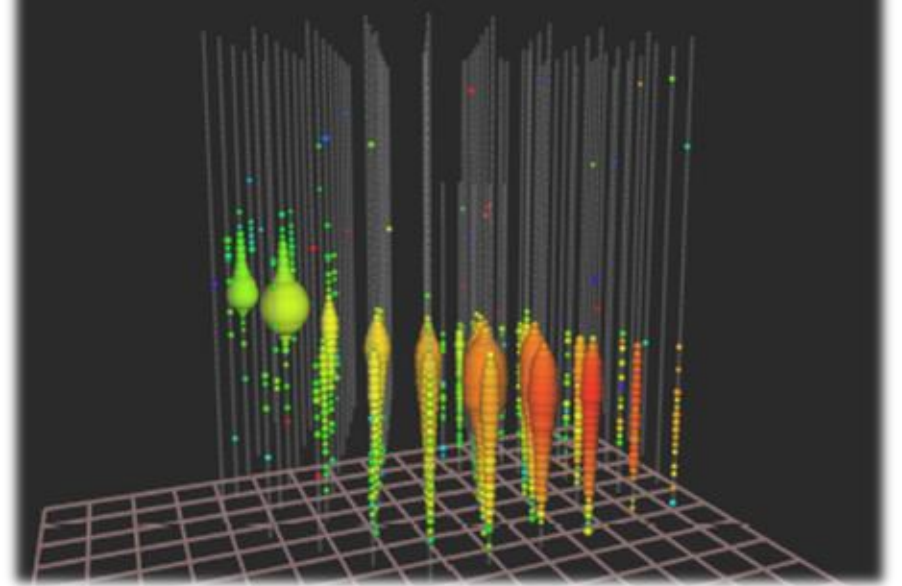


cascades (no muon)

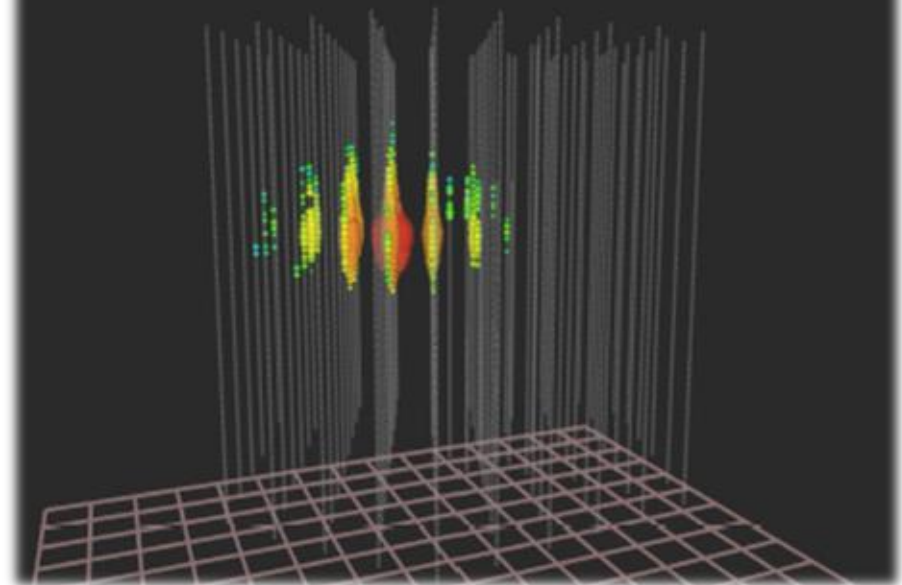
other neutrino flavors



8.7 PeV muon neutrino

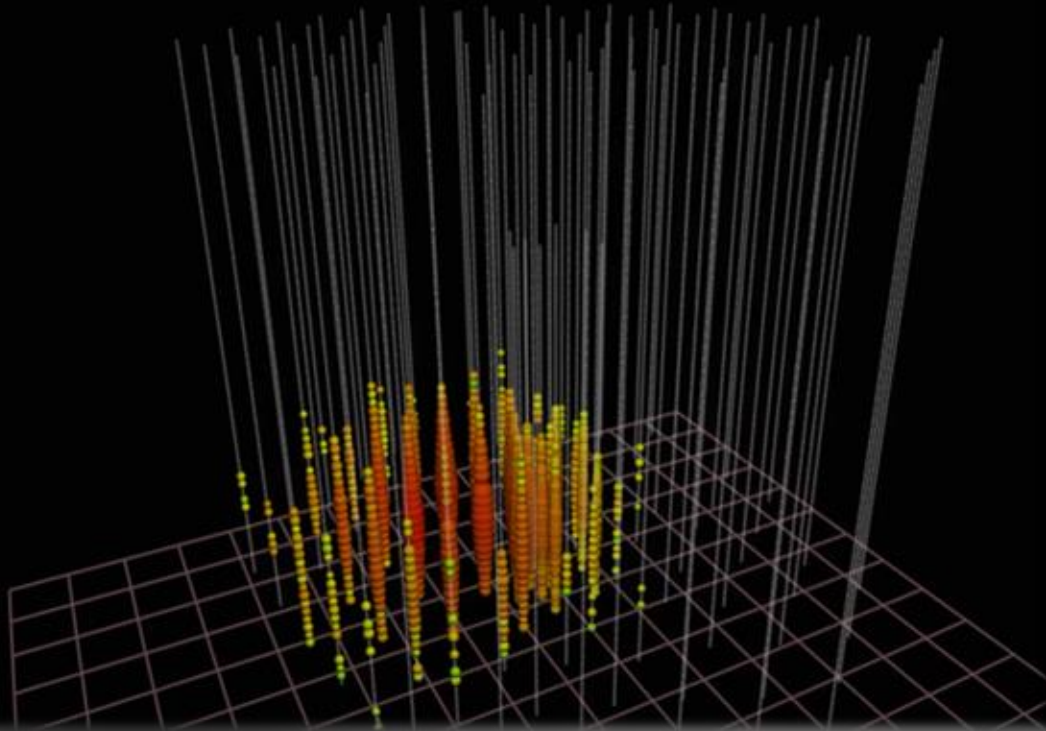


PeV electron neutrino

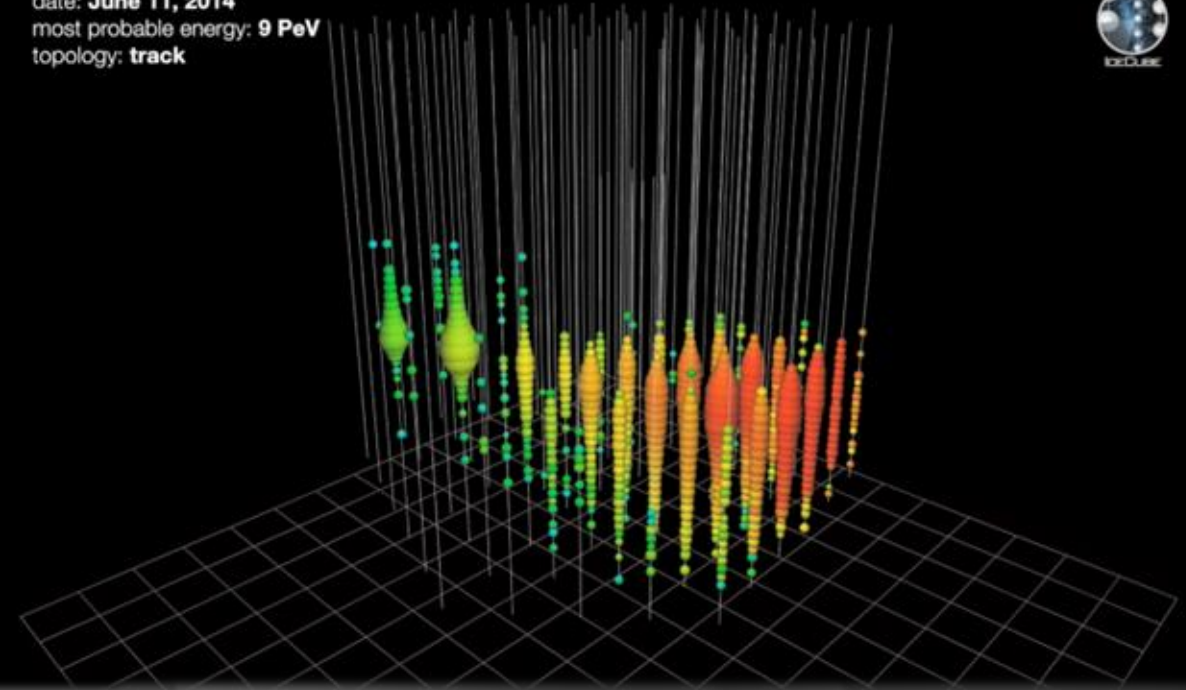


neutrinos interacting
inside the detector

muon neutrinos
filtered by the Earth



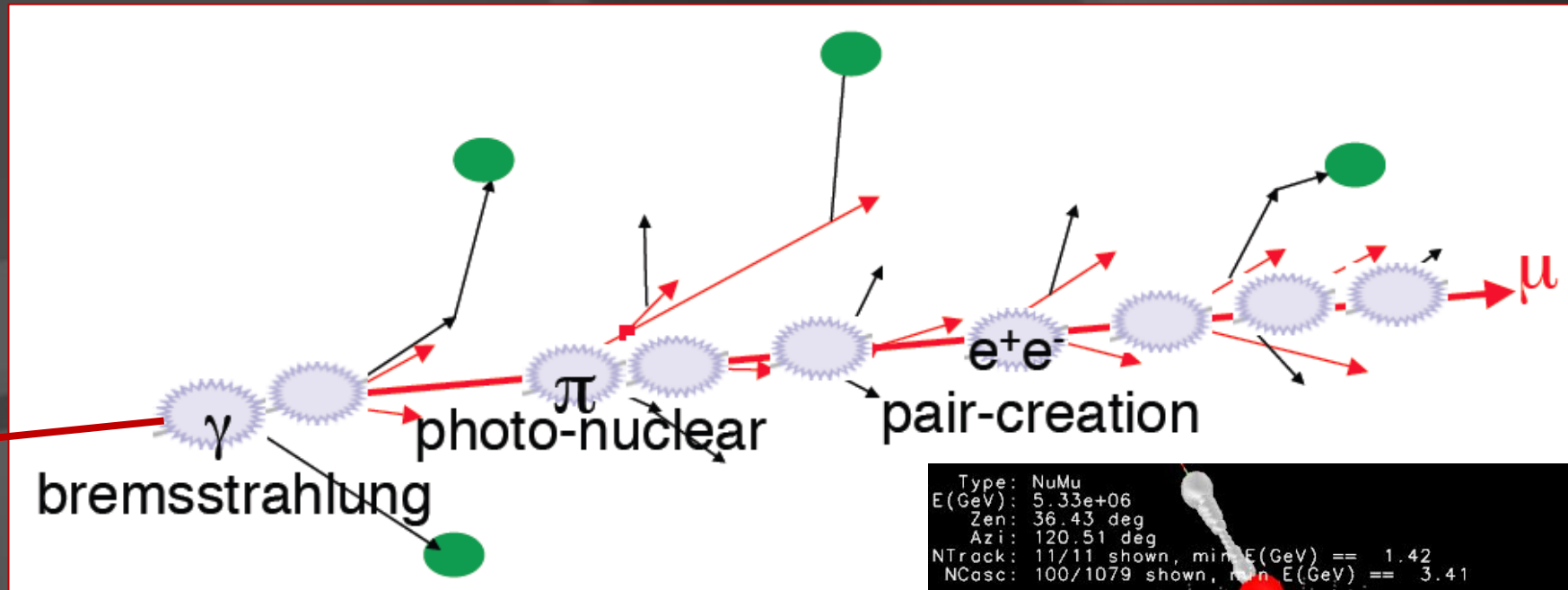
date: June 11, 2014
most probable energy: 9 PeV
topology: track



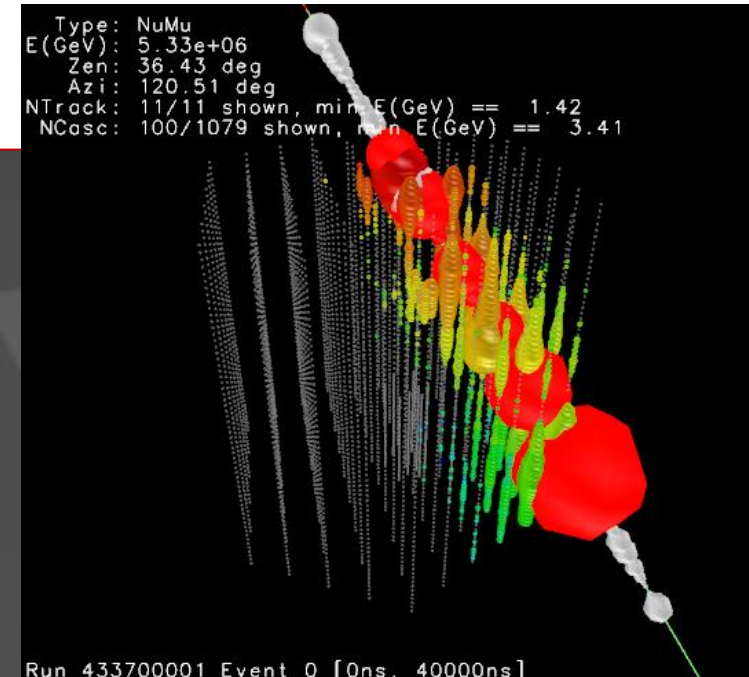
superior total energy
measurement
to 10%, all flavors, all sky

superior angular resolution $< 0.3^\circ$
including systematics

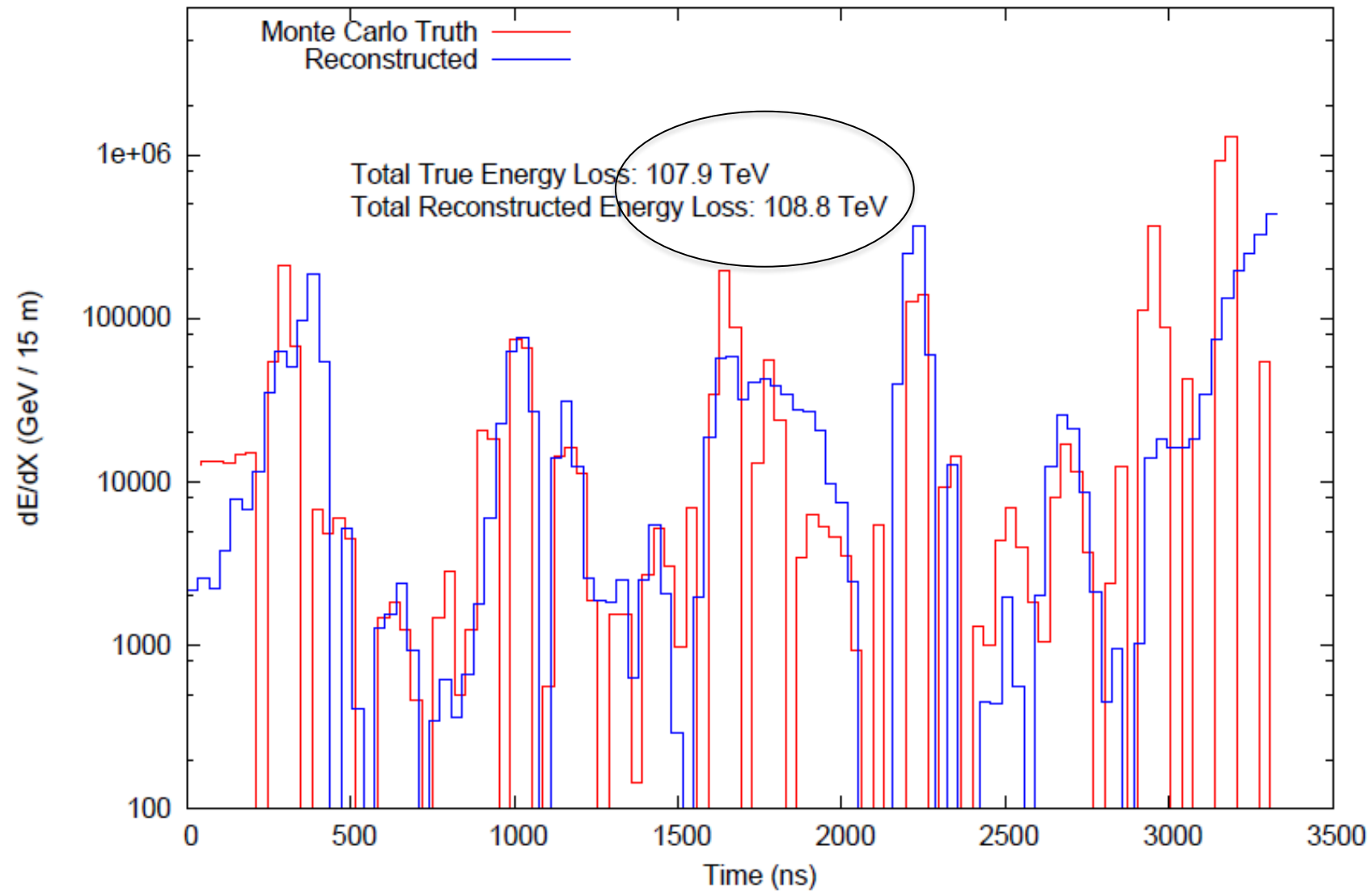
energy measurement of muon tracks



convert the amount of Cherenkov light emitted and its stochasticity to a measurement of the energy muon track

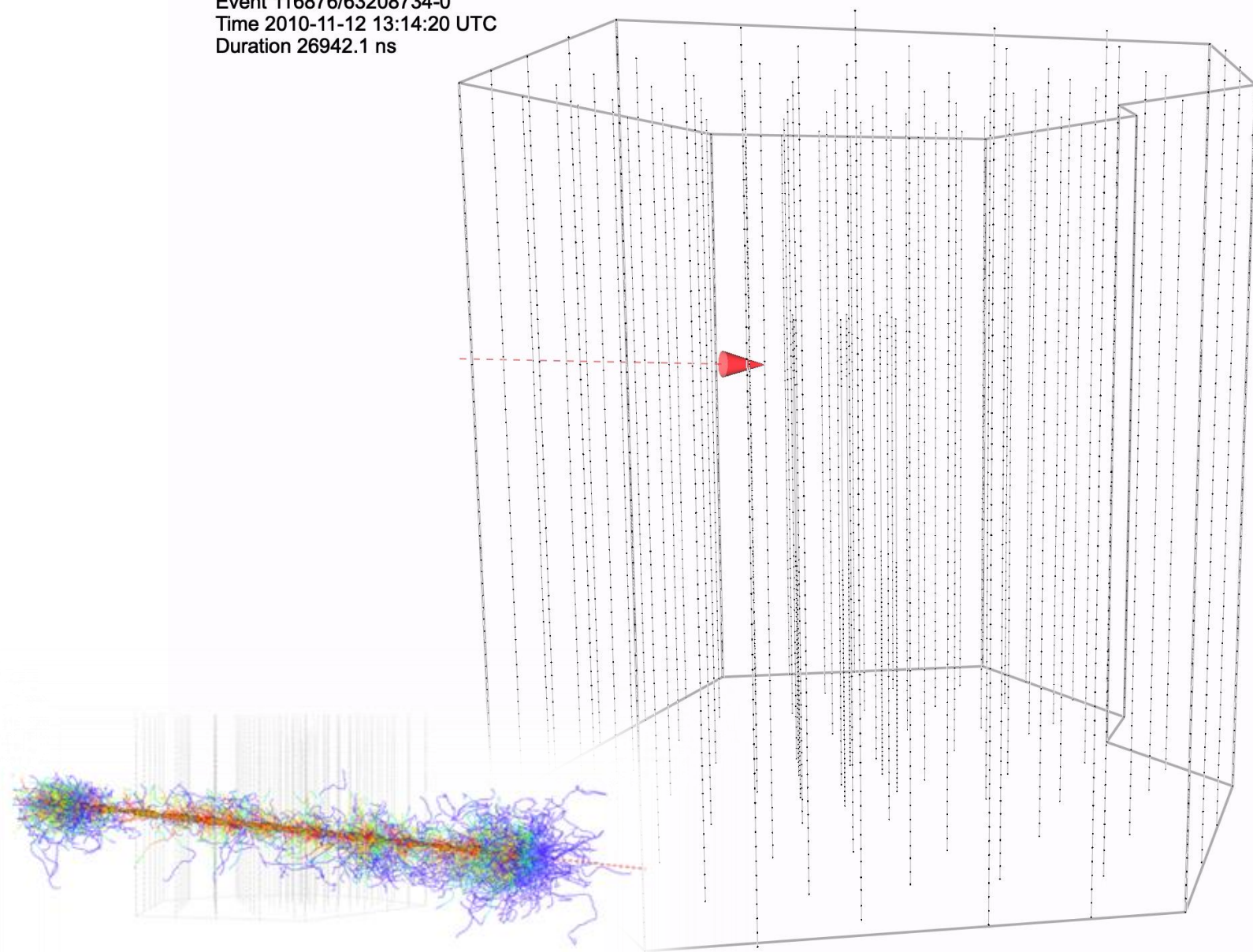


Differential Energy Reconstruction of 5 PeV Muon in IC-86

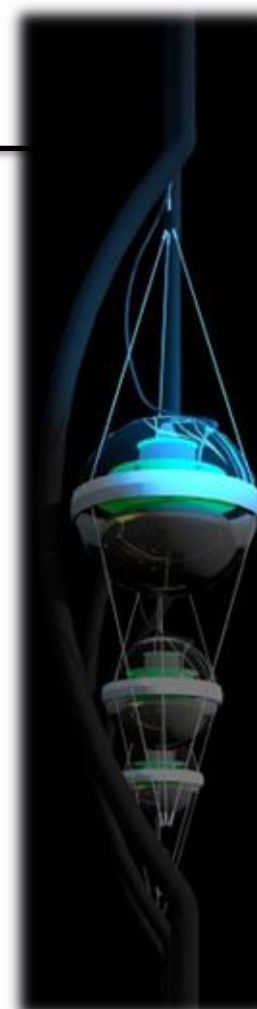


← 1.1 km →
improving energy and angular resolution

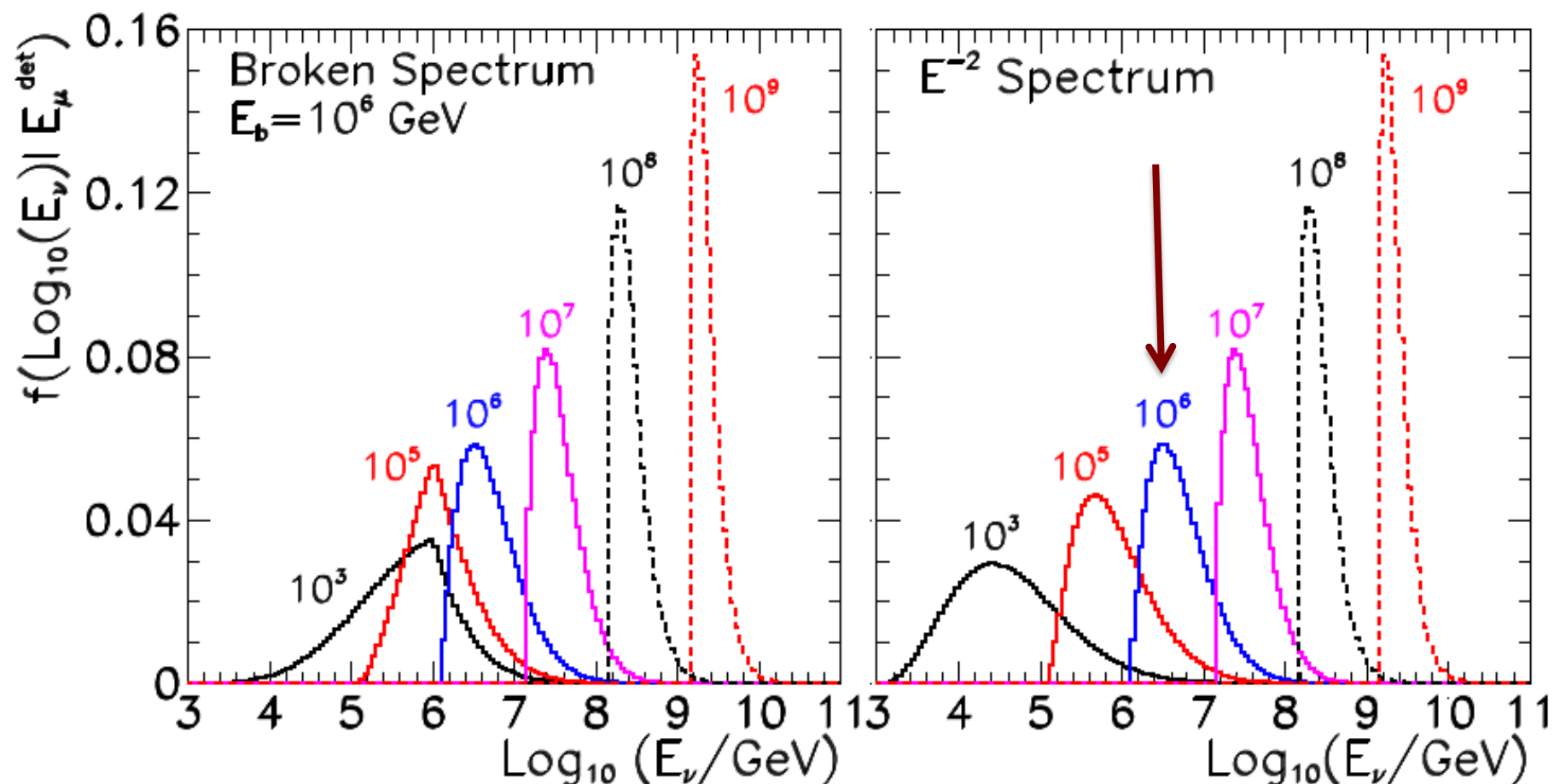
Event 116876/63208734-0
Time 2010-11-12 13:14:20 UTC
Duration 26942.1 ns



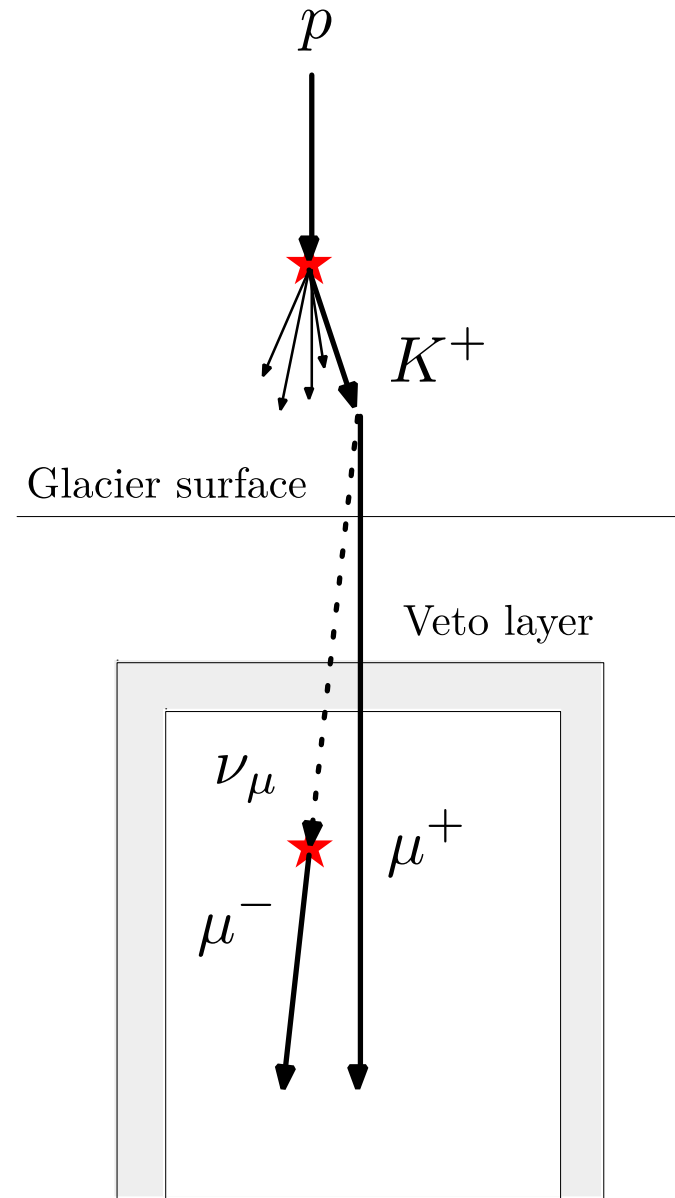
strings of
optical
sensors



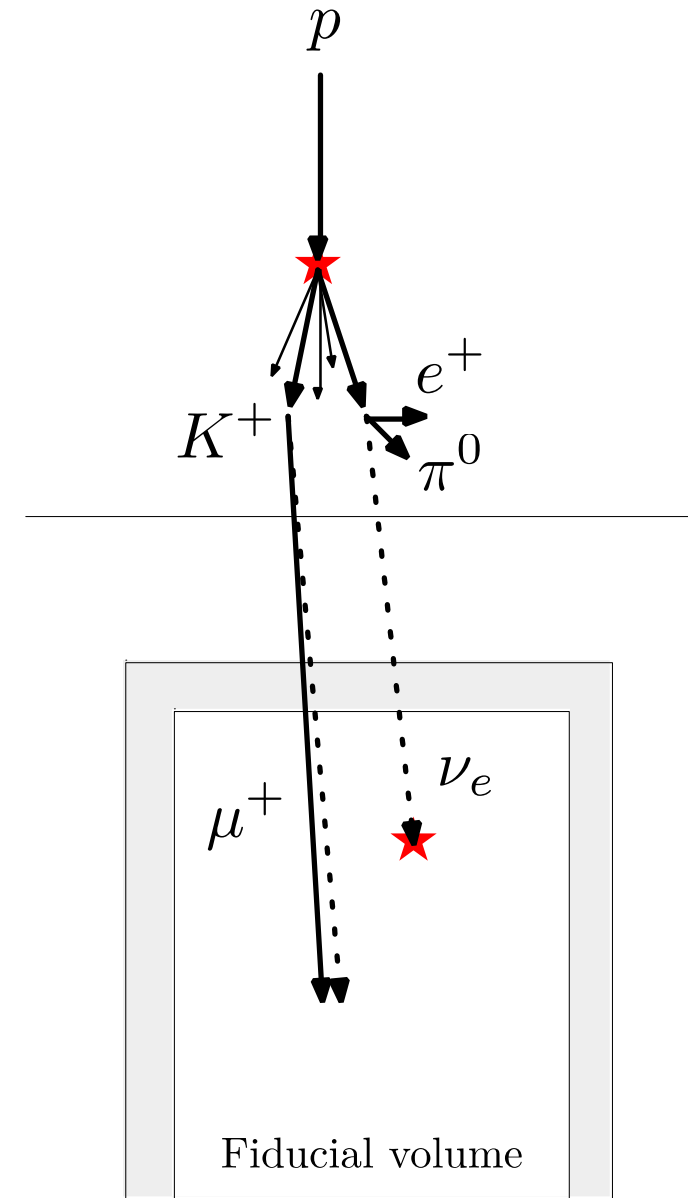
distribution of the parent neutrino energy able to yield the energy deposited by the secondary muon inside IceCube



no accompanying
muon(s) when
the neutrino is
produced at
cosmic distances



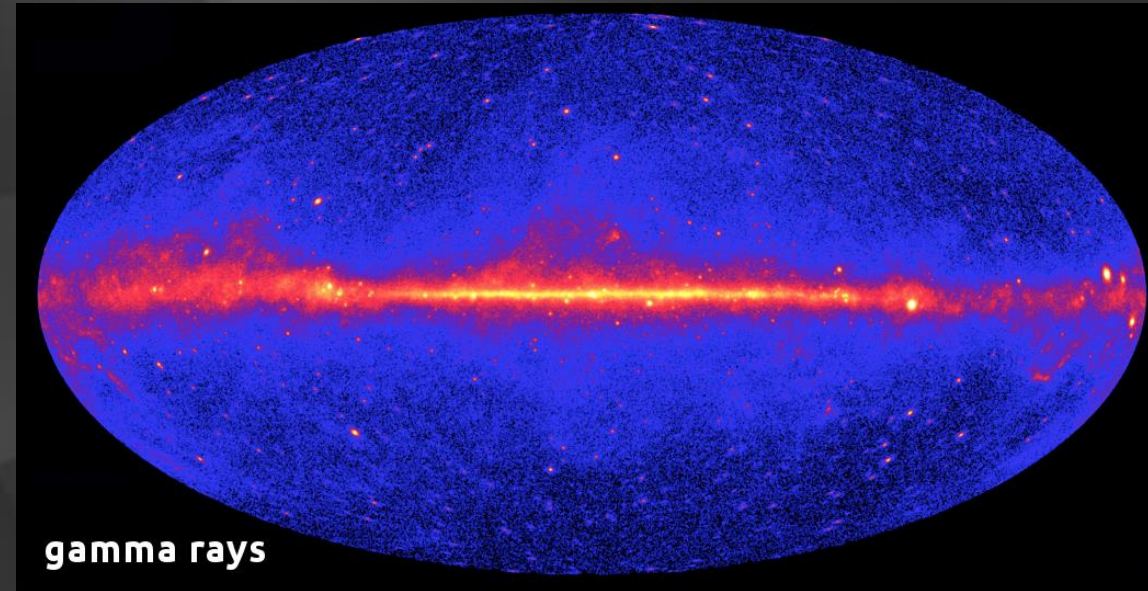
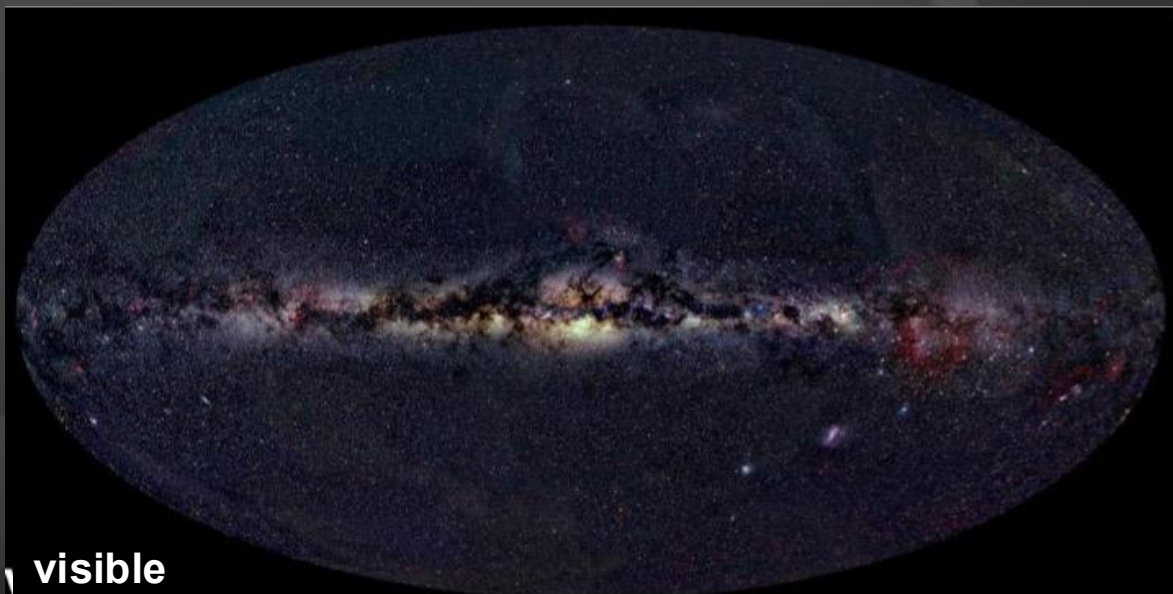
Veto by correlated muon



Veto by uncorrelated muon

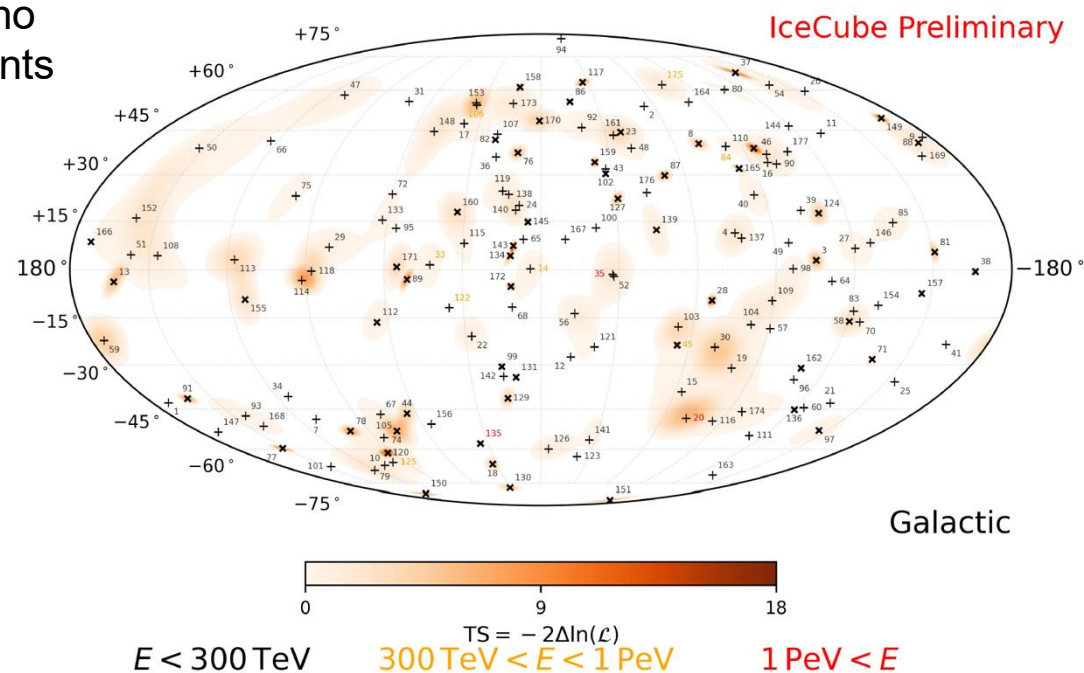
two surprises:

- 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)



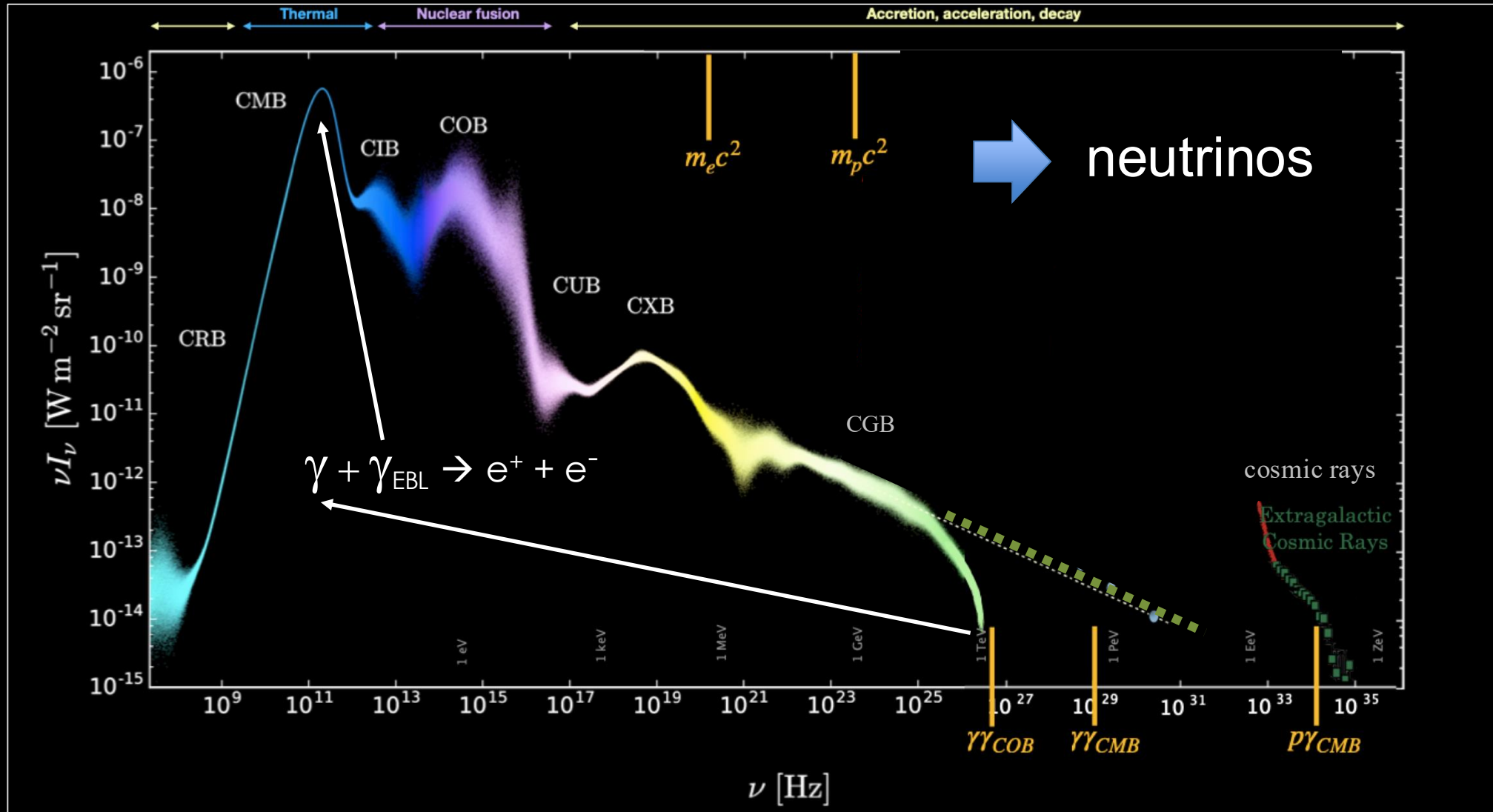
166 neutrino
starting events

where is the
neutrino Galactic
plane?



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

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



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

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

γ

e^+

e^-

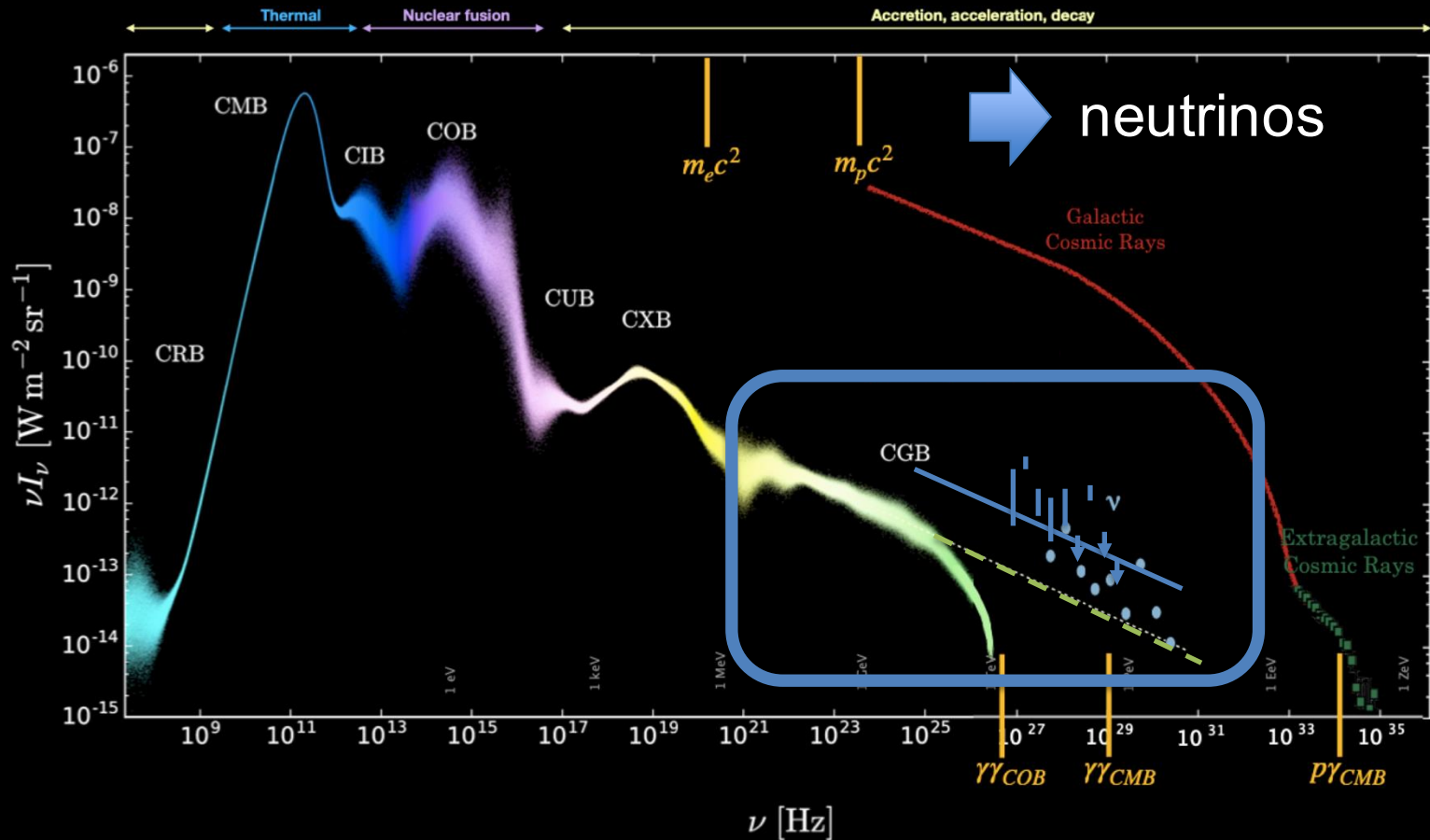
PeV

$\sim 10 \text{ GeV}$

x_0



Fermi and IceCube do not observe the same gamma ray sources



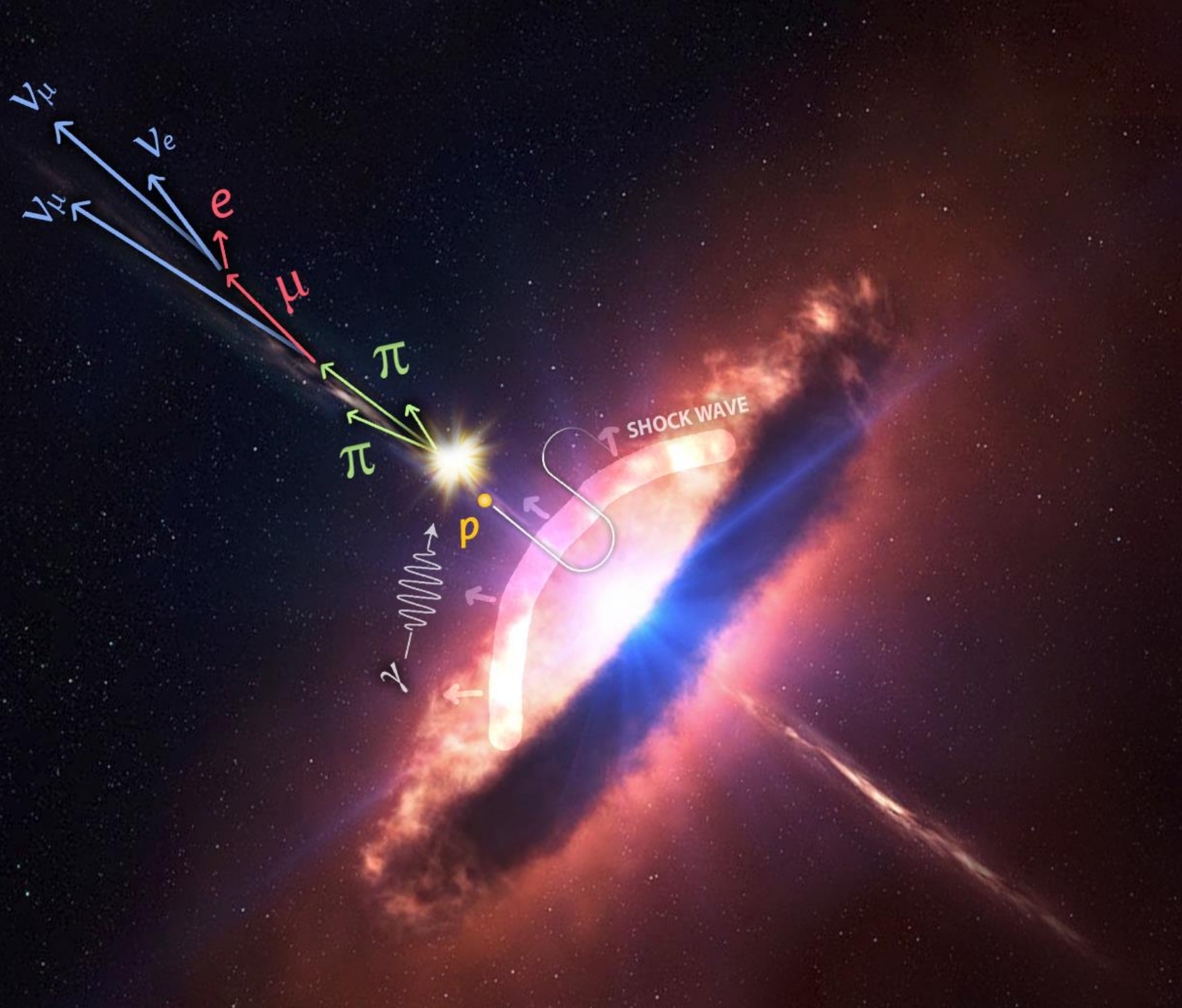
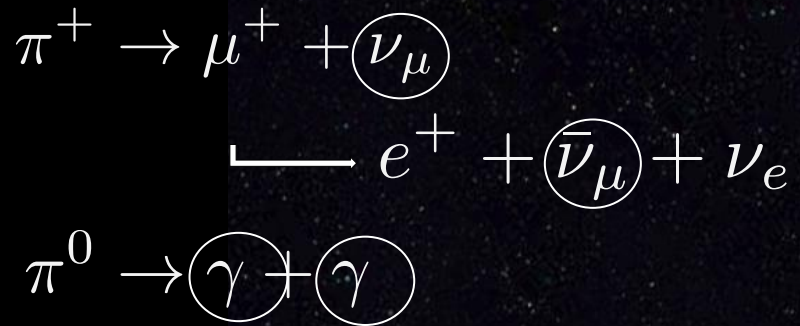
Fermi NASA gamma-ray satellite



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

the neutrinos escape
from the target,

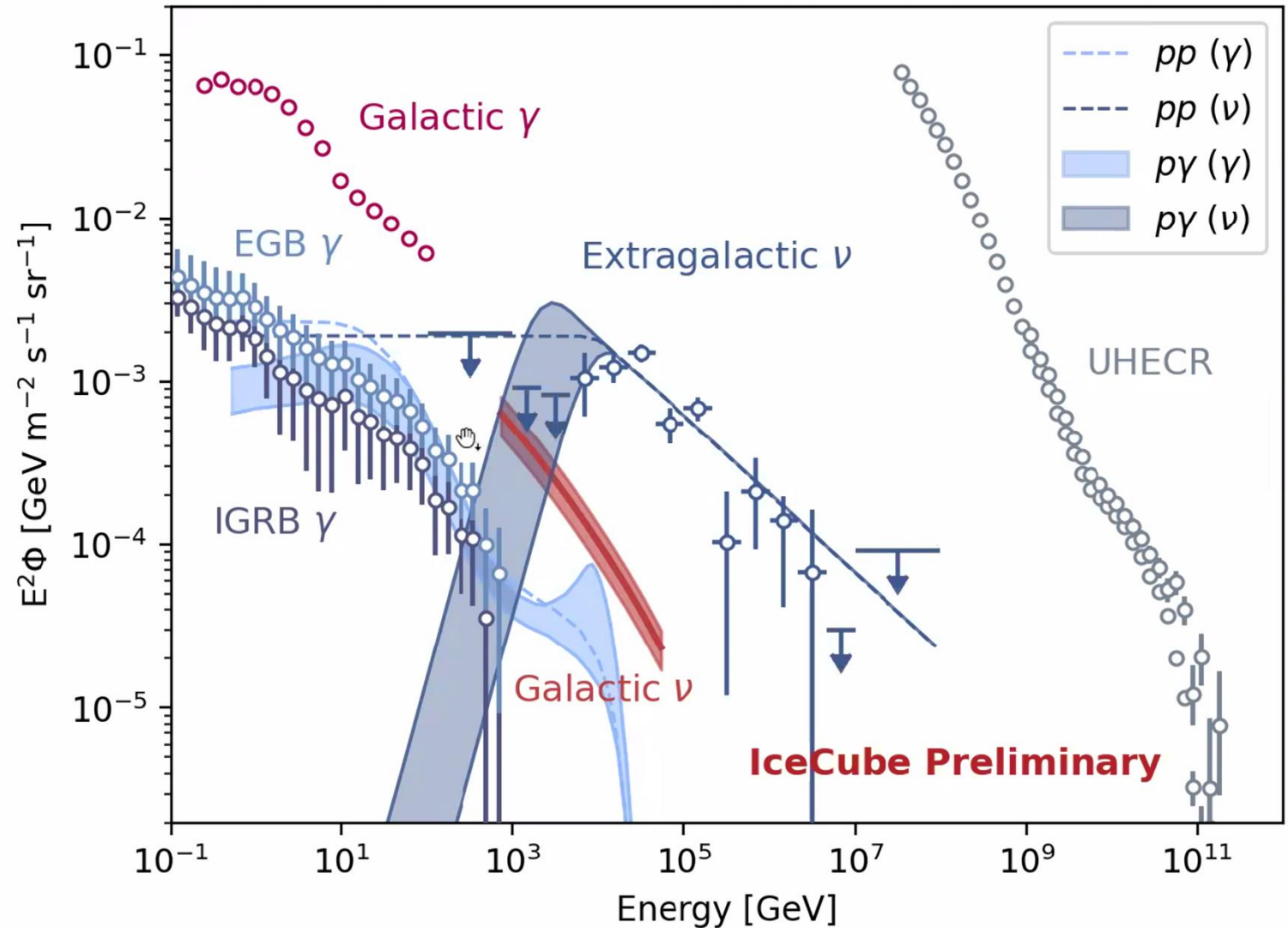
gamma rays lose energy
in the source
to appear below Fermi's
detection threshold



- concentrate on the $p\gamma$ colored bands

neutrinos from γ obscured sources

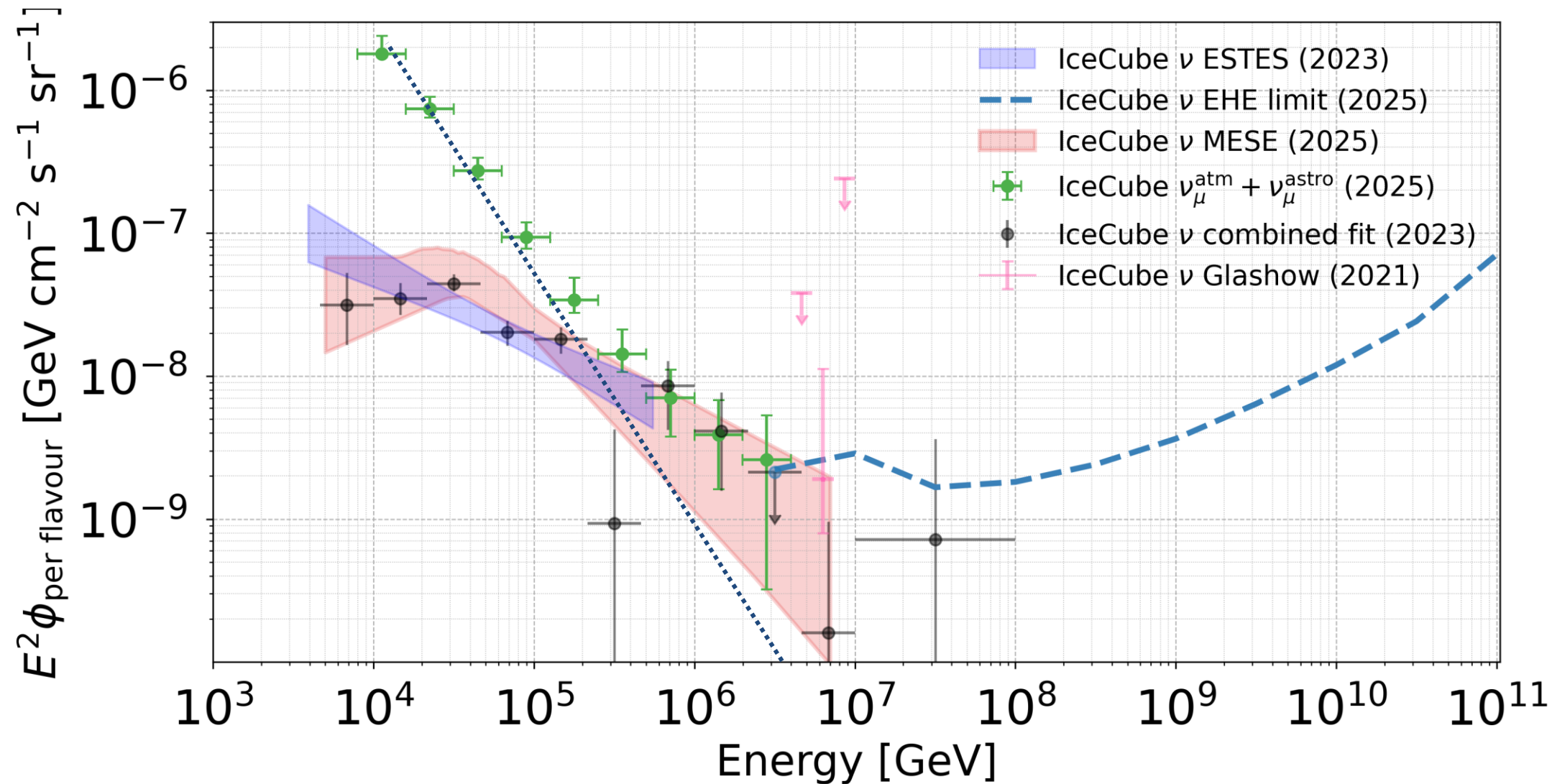
- γ from π^0 saturate extragalactic gamma ray flux
- but this flux comes from blazars which are not observed in neutrinos!
- Fermi does not see the γ from π^0 which lose energy in the target producing the neutrinos
- appear at MeV or below



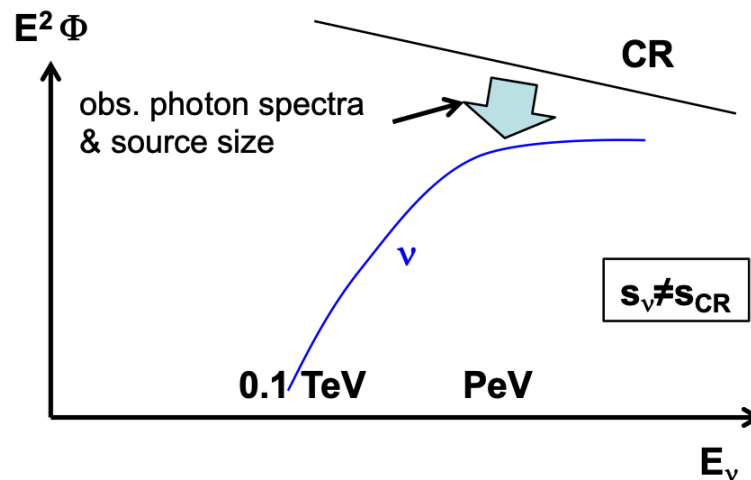
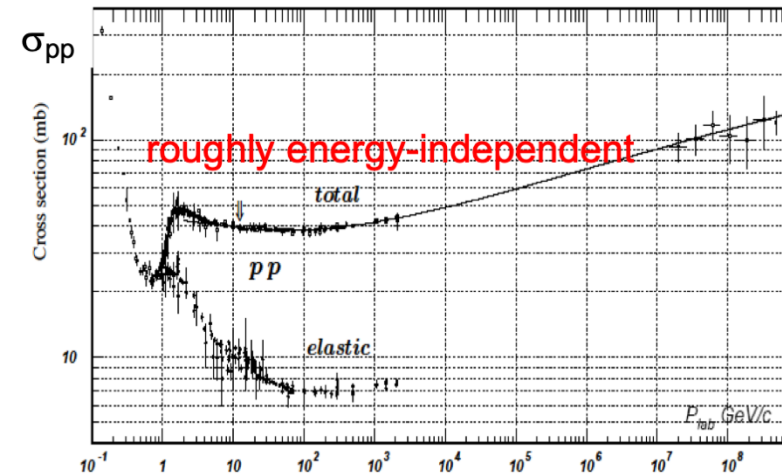
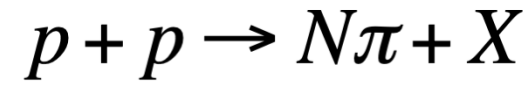
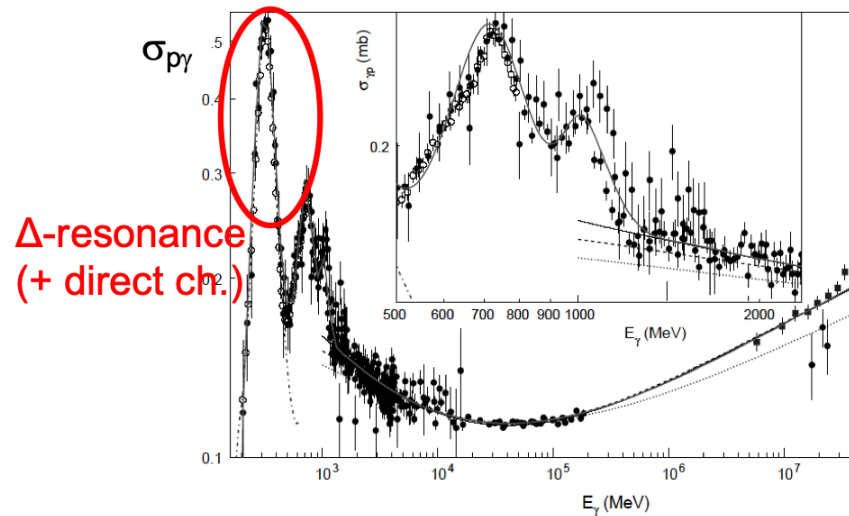
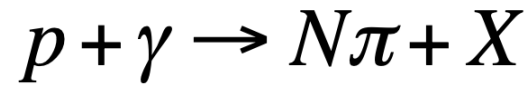
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- we observe larger neutrino and associated gamma ray fluxes than anticipated
- the Milky Way is not a dominant feature in the neutrino sky (powerful accelerators produce neutrinos in other galaxies that do not exist in our own)

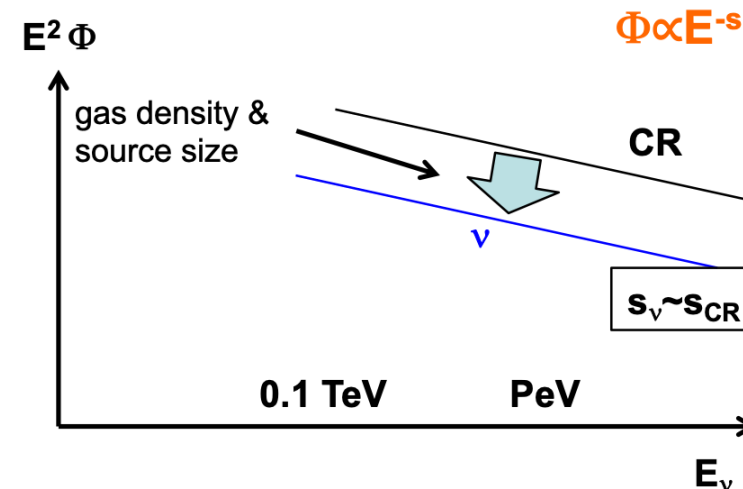
NEW! energy spectrum of cosmic neutrinos: a break at 30 TeV

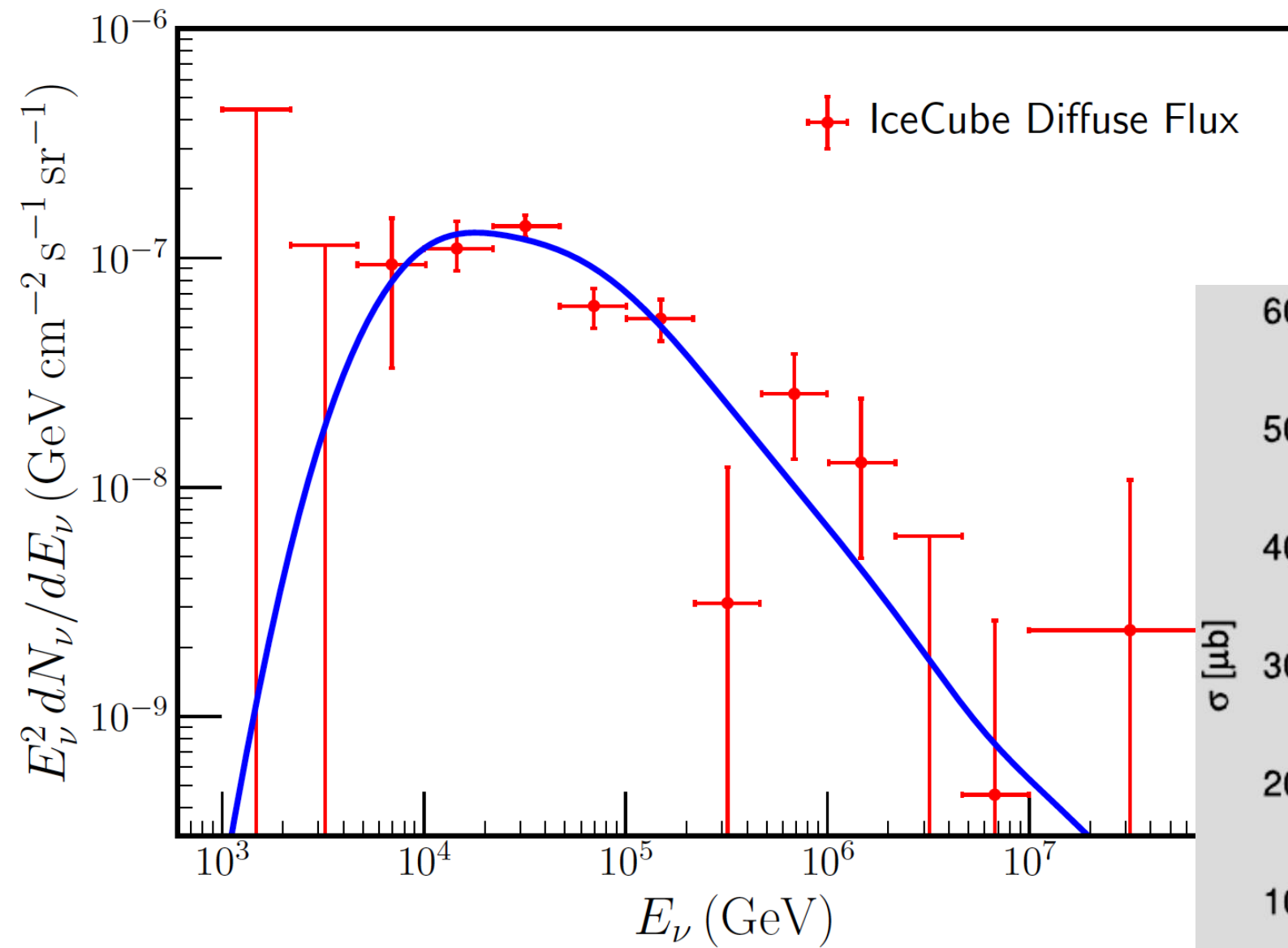


neutrino spectrum: p-gamma versus pp interactions



Credit: K. Murase

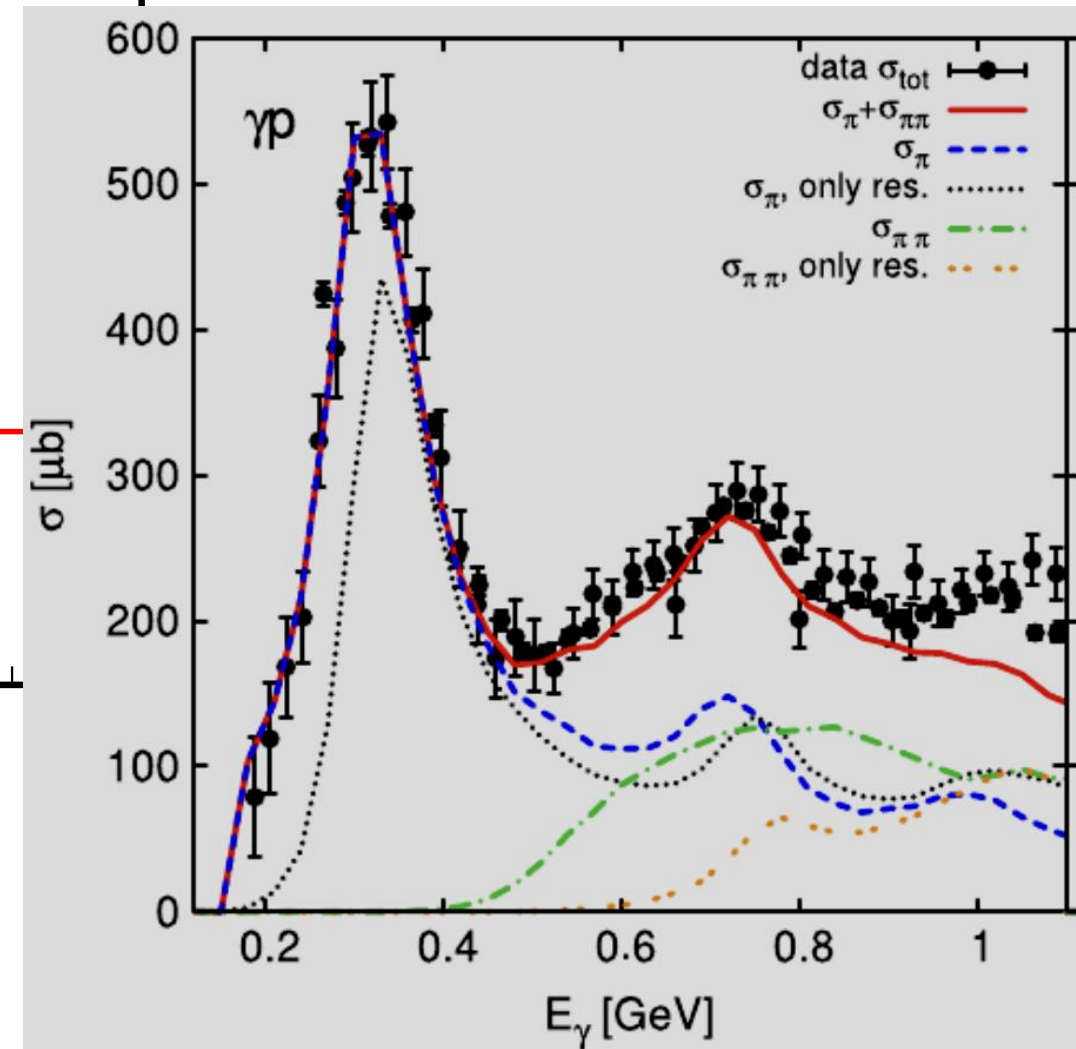




the delta resonance in the neutrino sky

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

gamma target $\sim$ X-rays

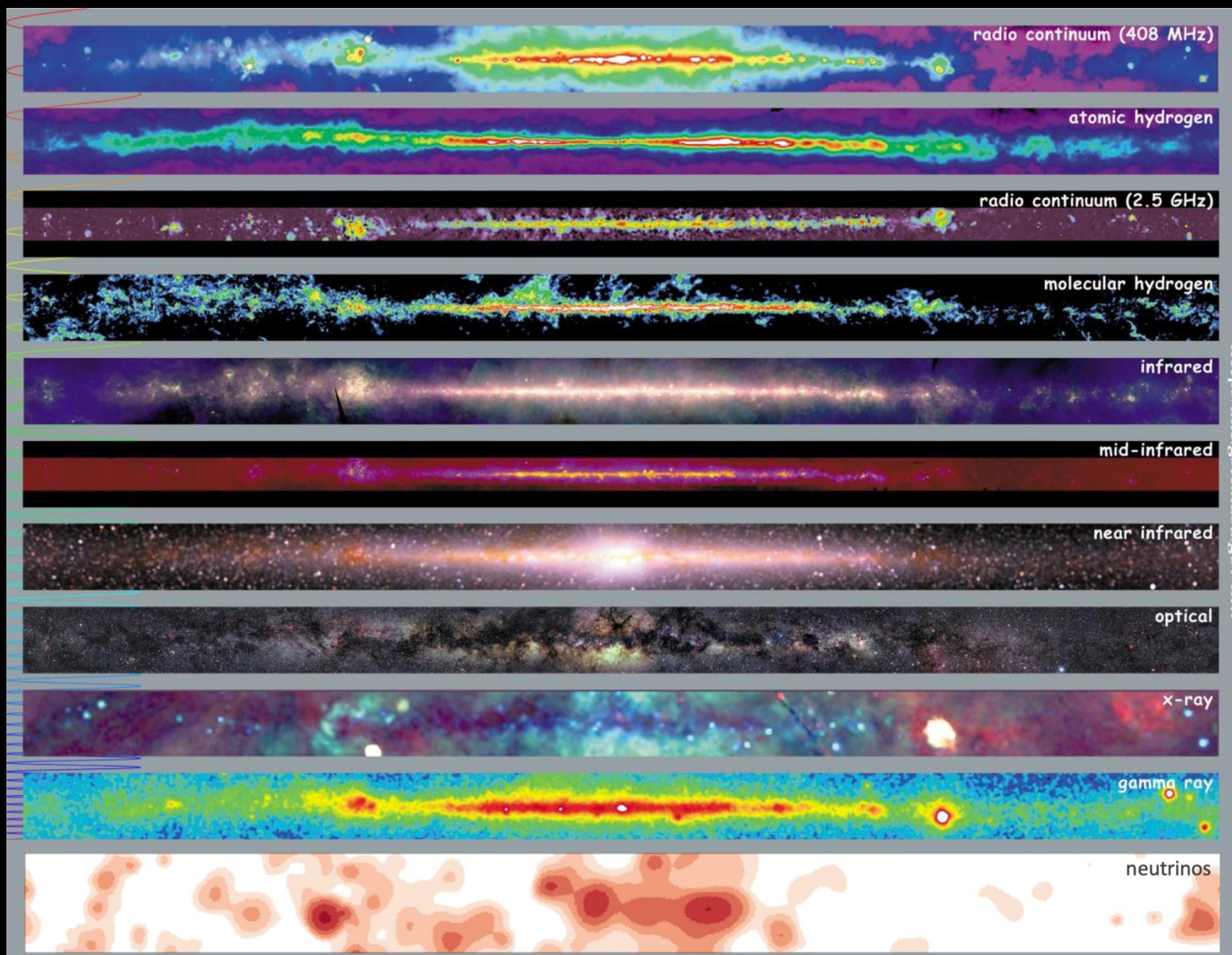


NEW

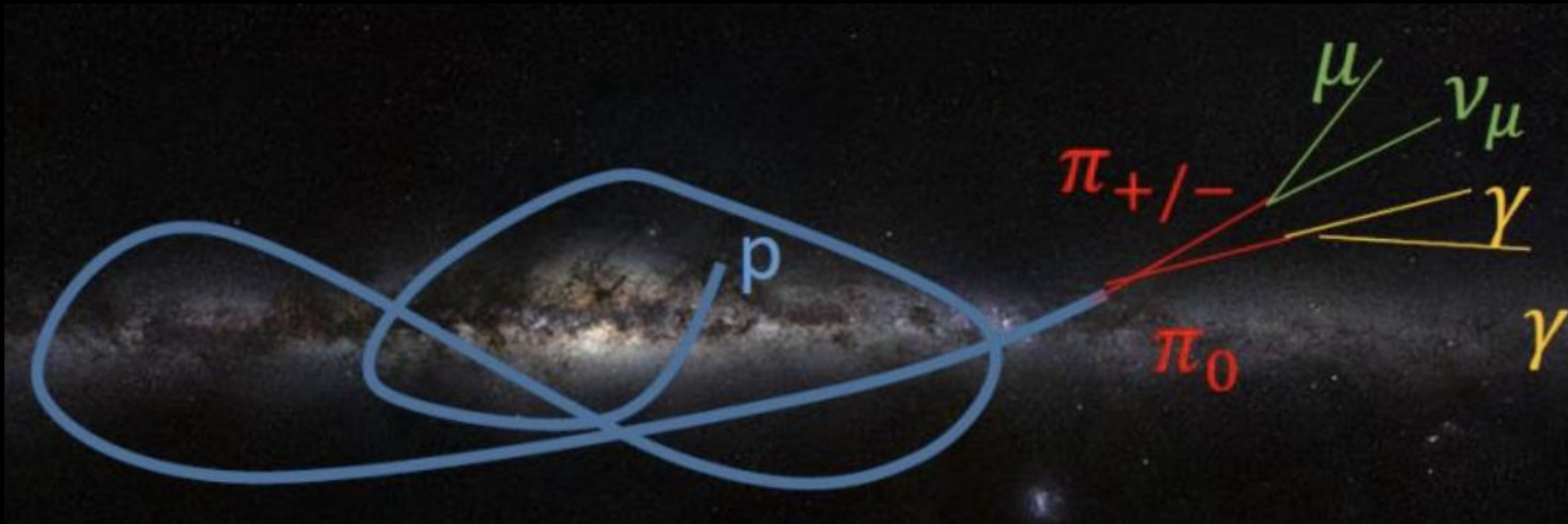
with the help of machine learning we did find the Galactic plane at a flux level of 10% of the astrophysical flux at 30 TeV



Milky Way
viewed in
neutrinos



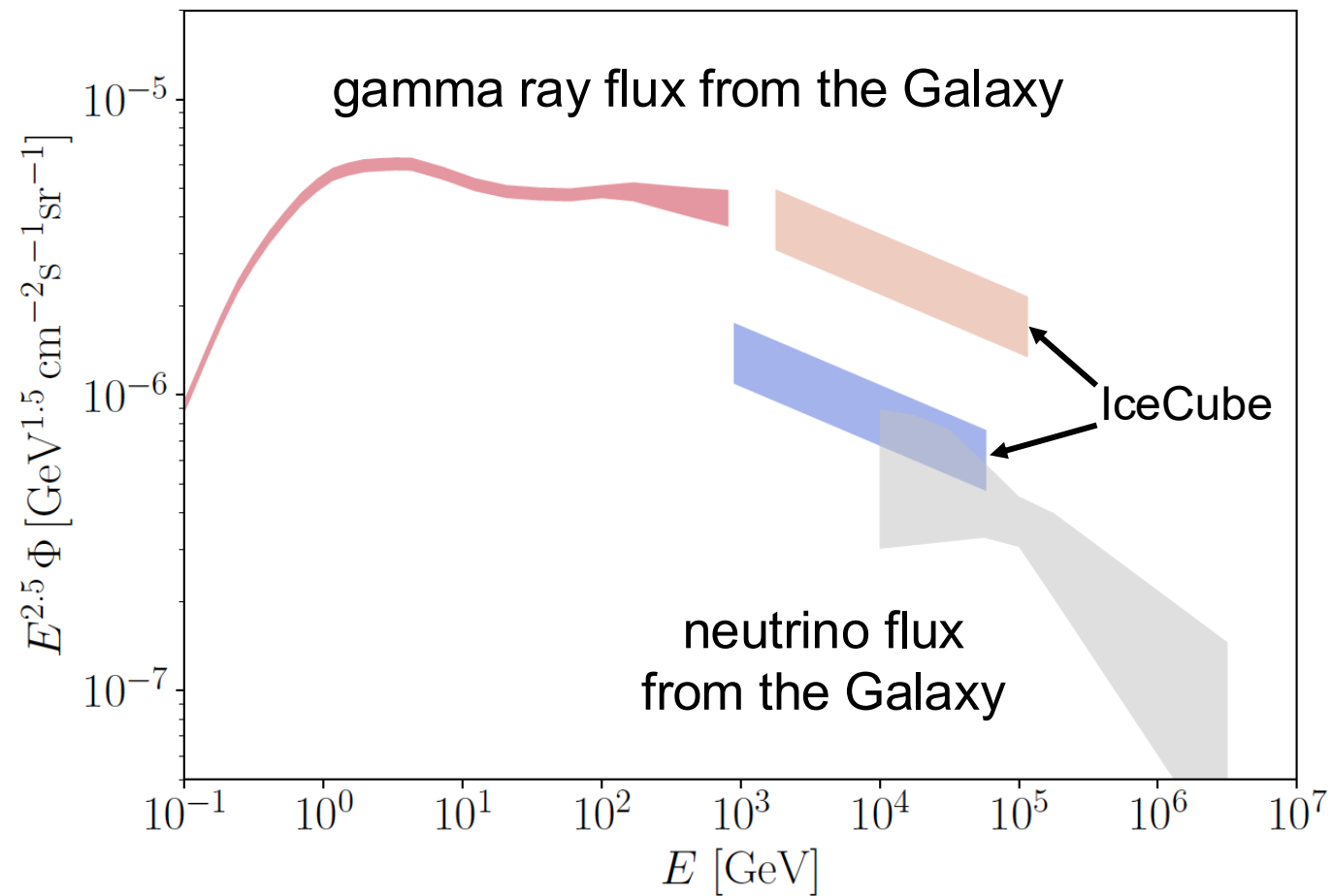
<http://adc.gsfc.nasa.gov/mw>

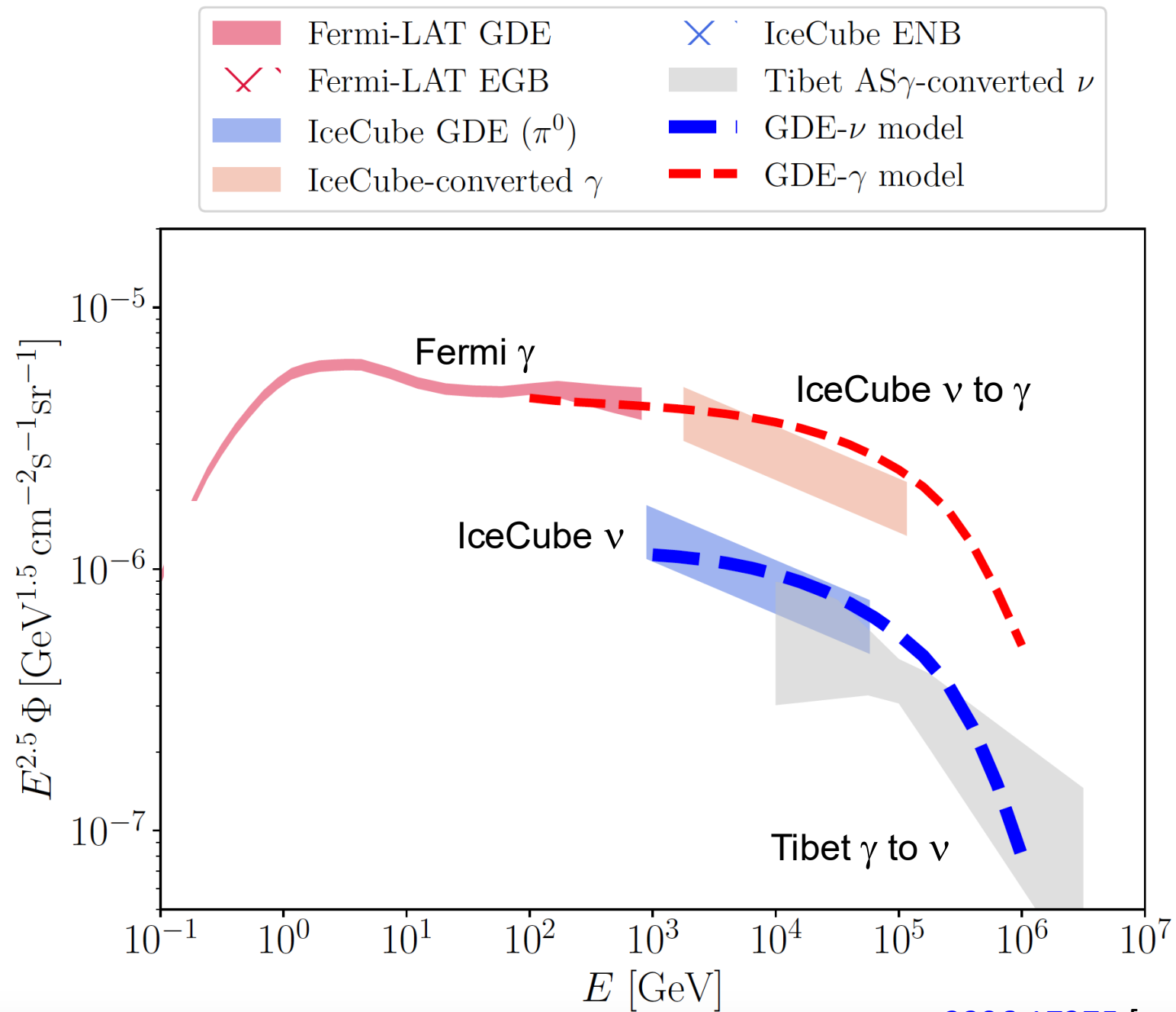


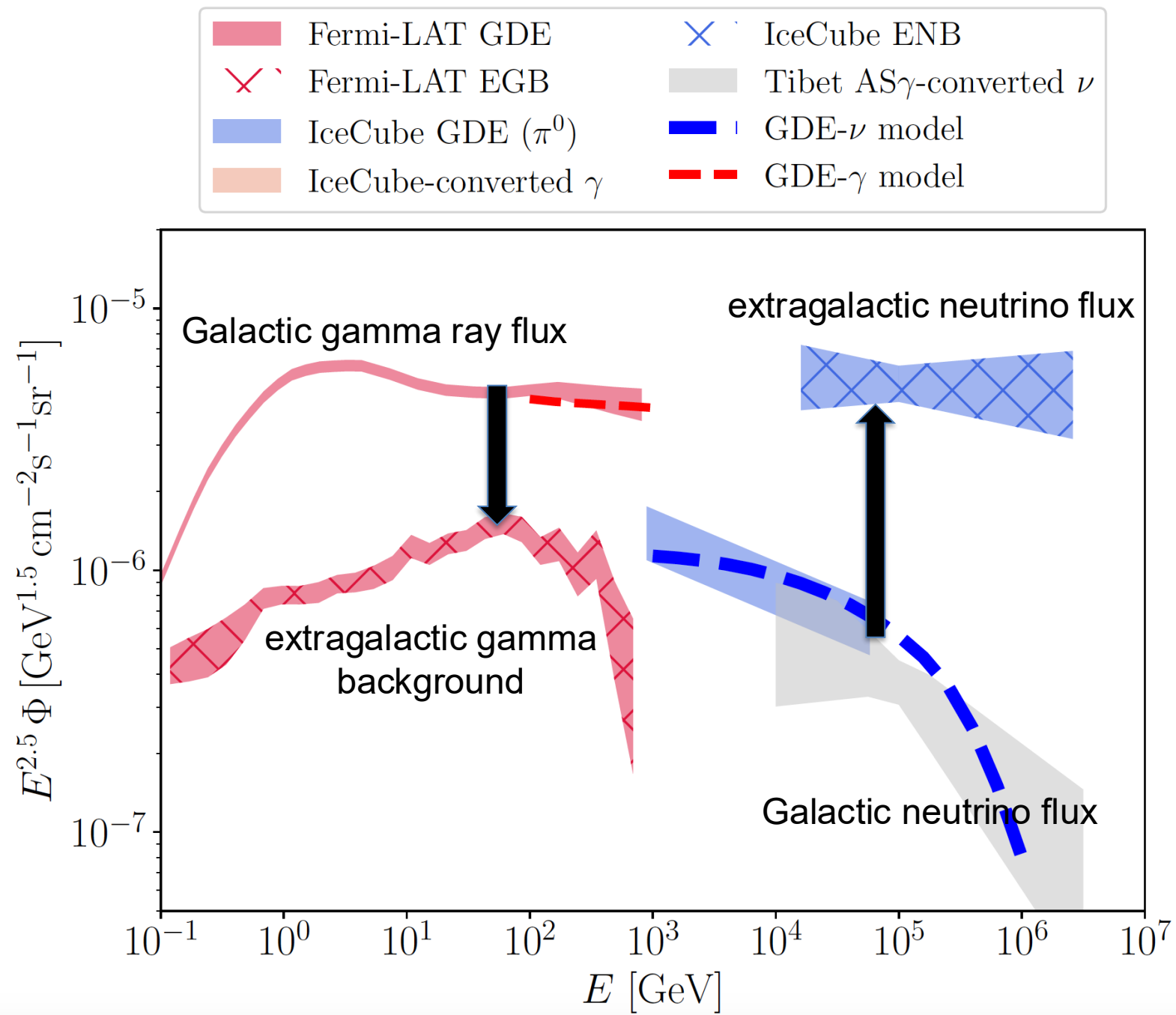
neutrinos produced in Galactic cosmic rays
interactions with interstellar medium

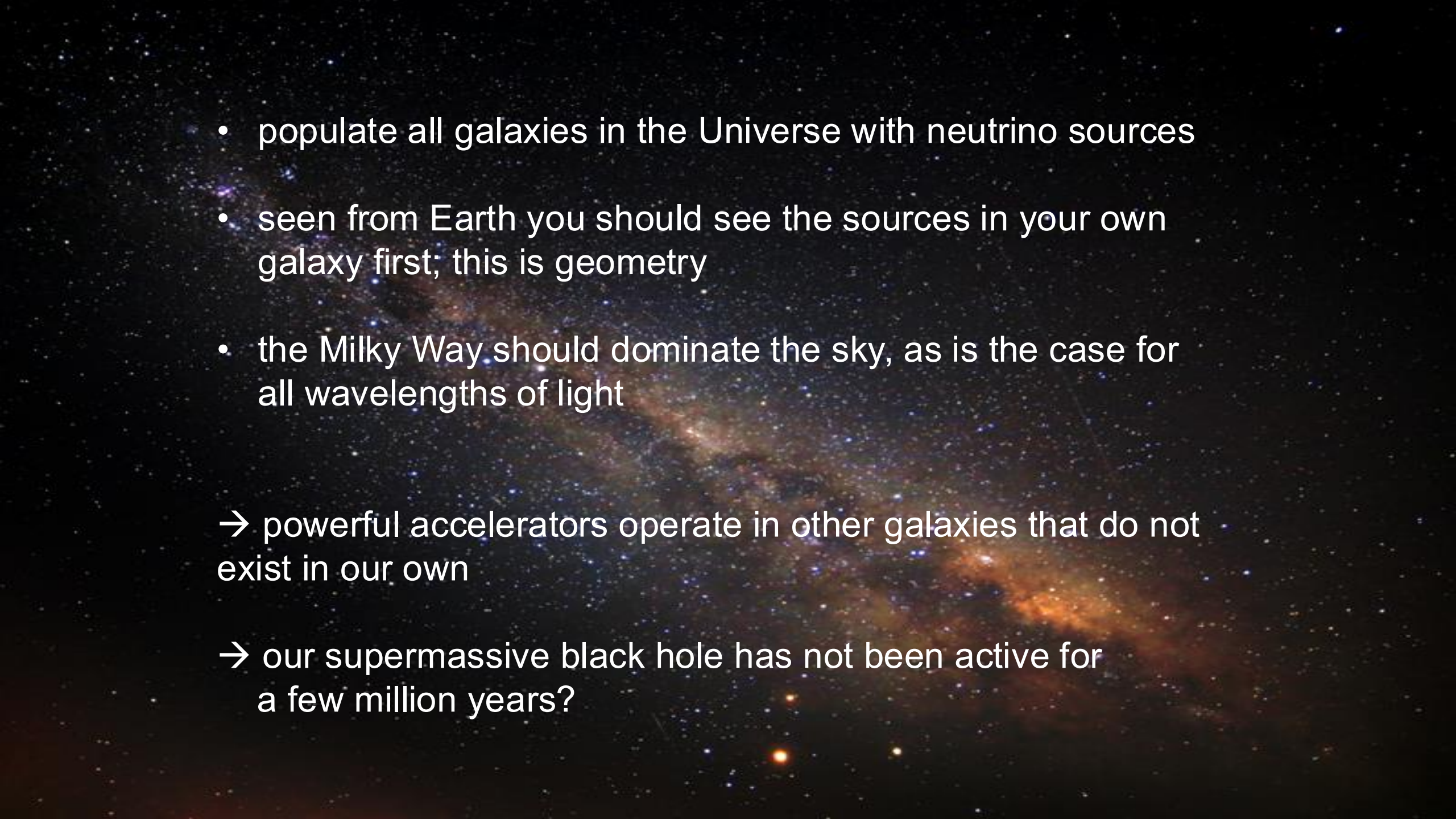
unresolved sources?

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







- 
- 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?

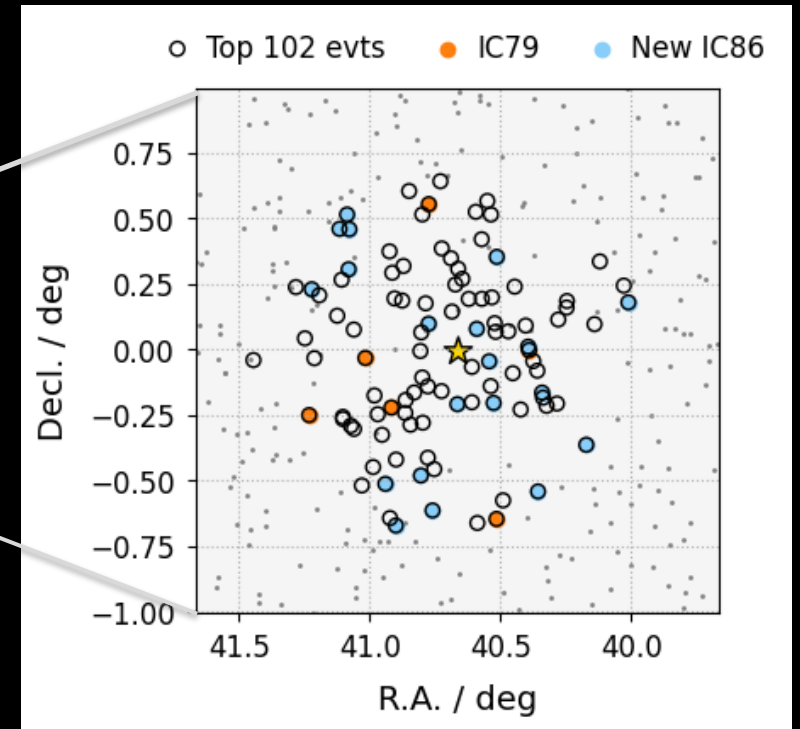
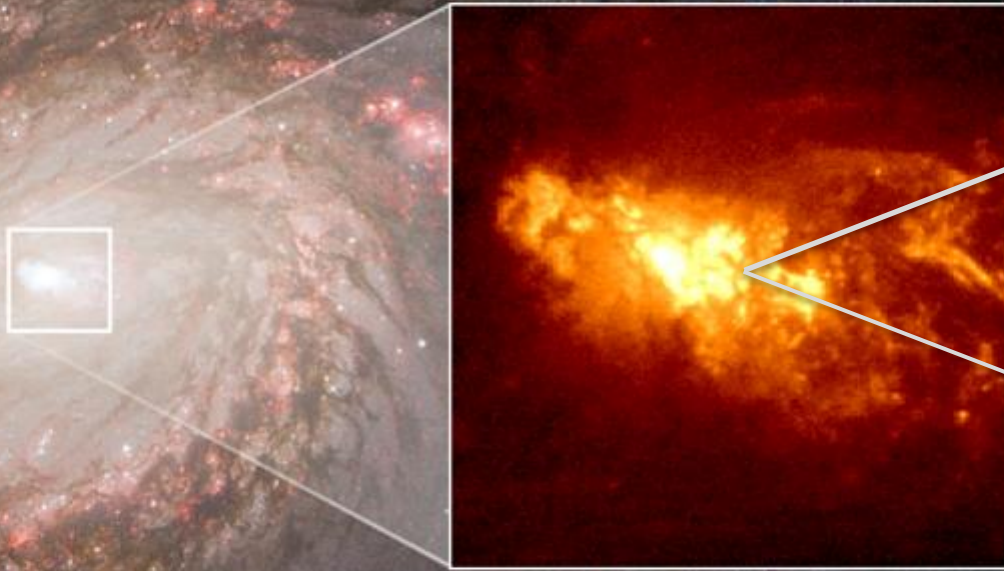
The First Decade of High-Energy Neutrino Astronomy and Neutrino Physics

francis halzen



- High-Energy Neutrino Astronomy
 - IceCube and the discovery of Cosmic Neutrinos: First Surprises
 - The First Cosmic Accelerators: Active Galaxies
- resolves the puzzles associated with the diffuse flux

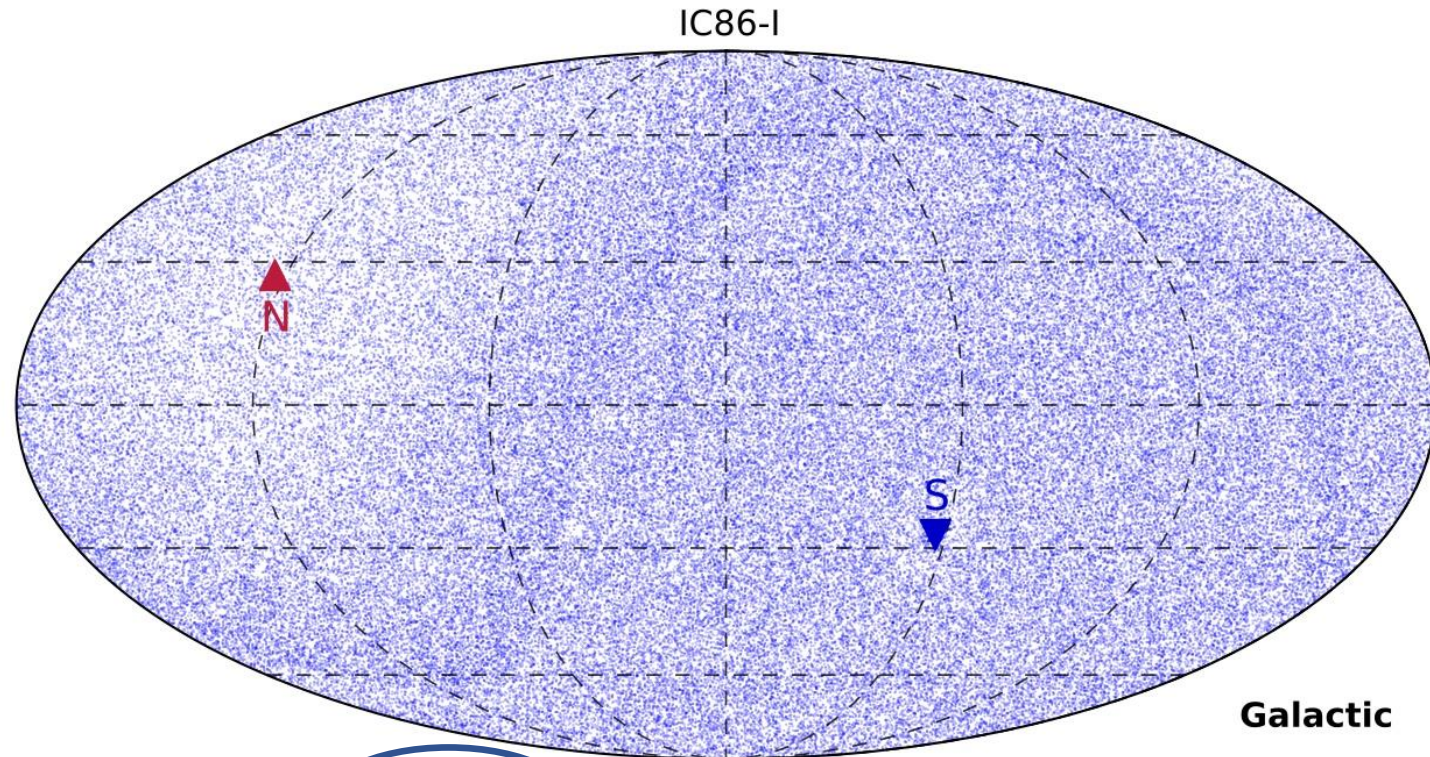
the first cosmic accelerator
in the IceCube neutrino skymap:
the *active galaxy* NGC 1068



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

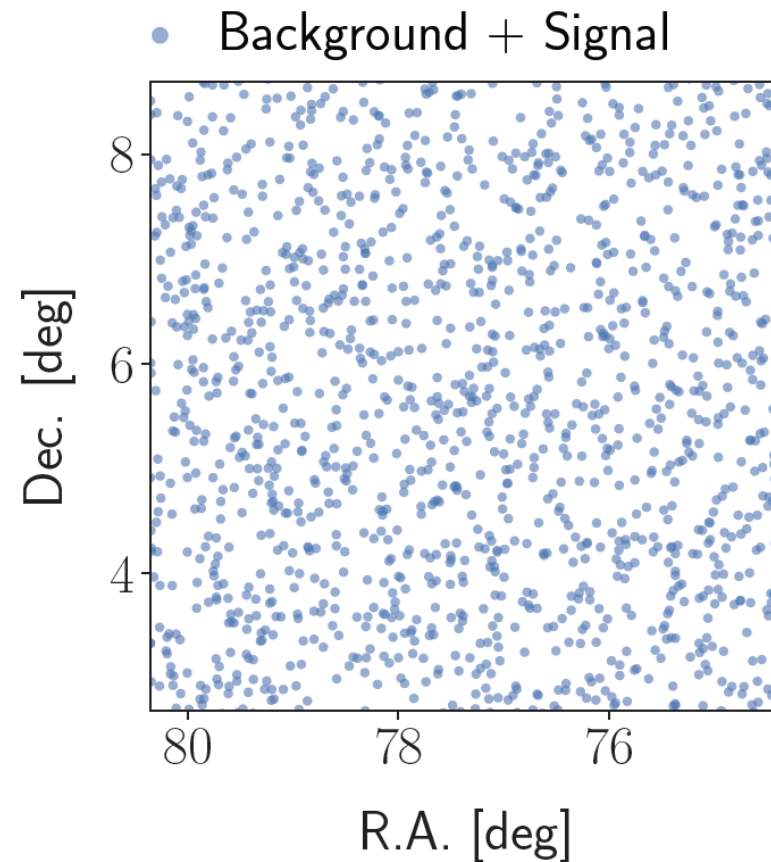
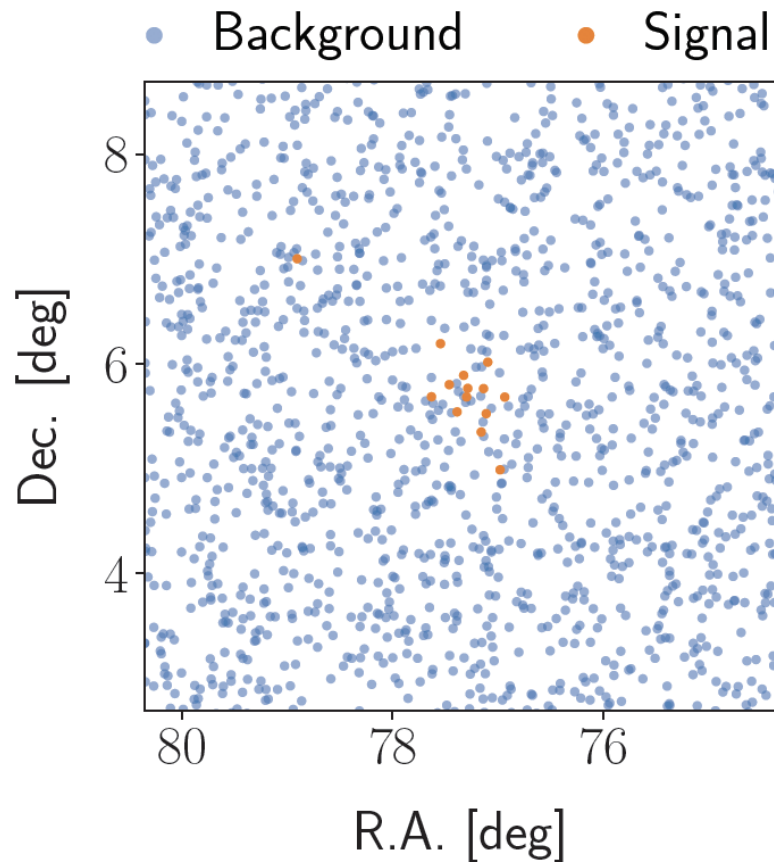
one year of IceCube neutrinos >100 GeV

(reaches neutrino purity of 97% but overwhelmingly atmospheric)

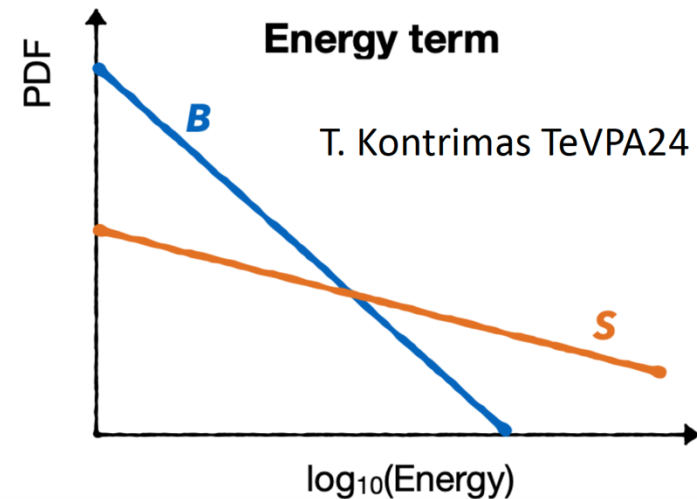
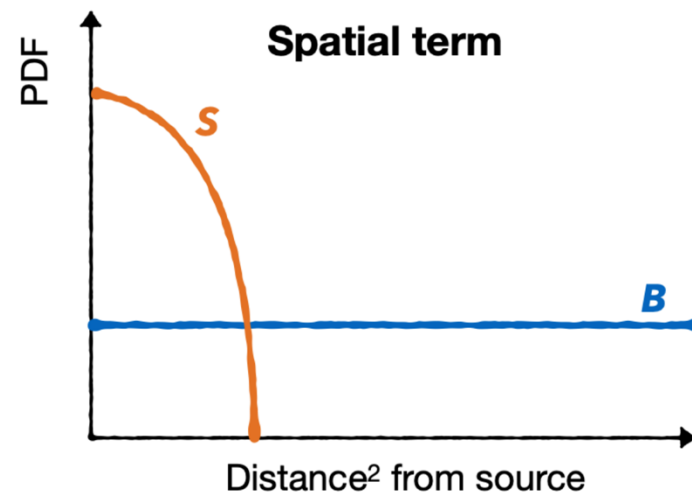


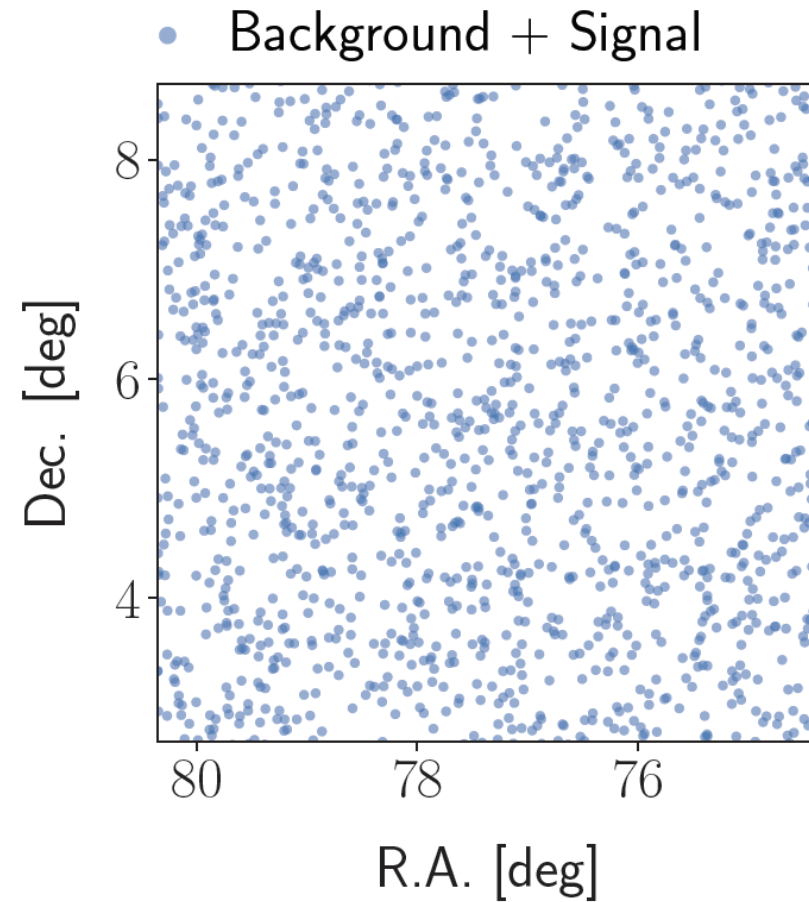
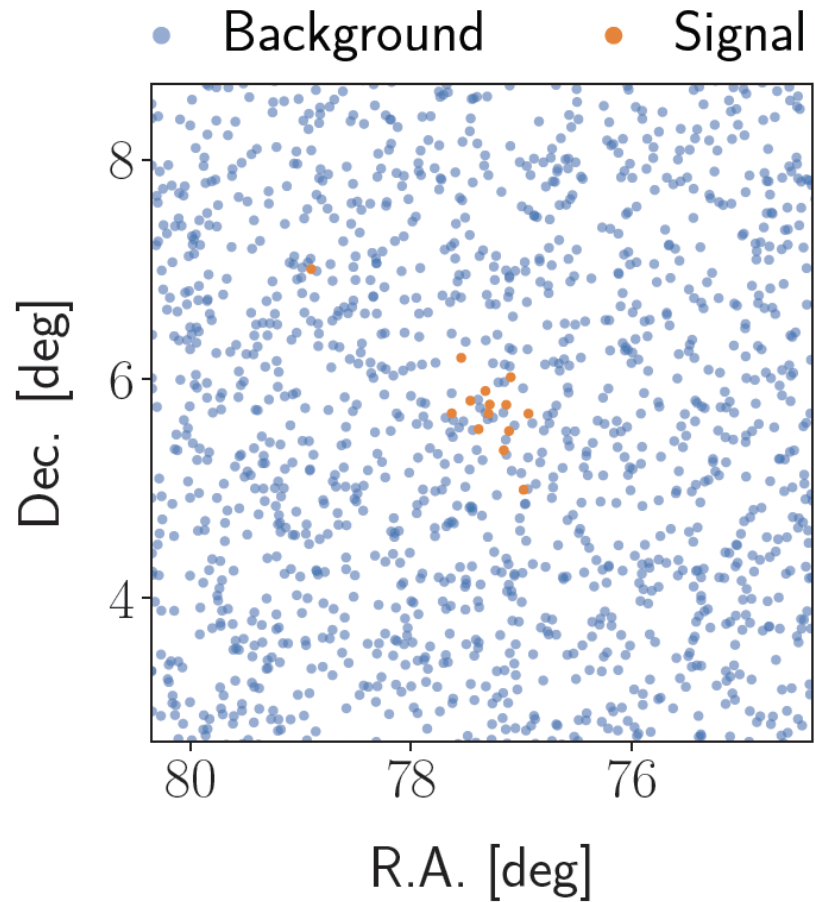
138322 neutrino candidates in one year

~200 cosmic neutrinos



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





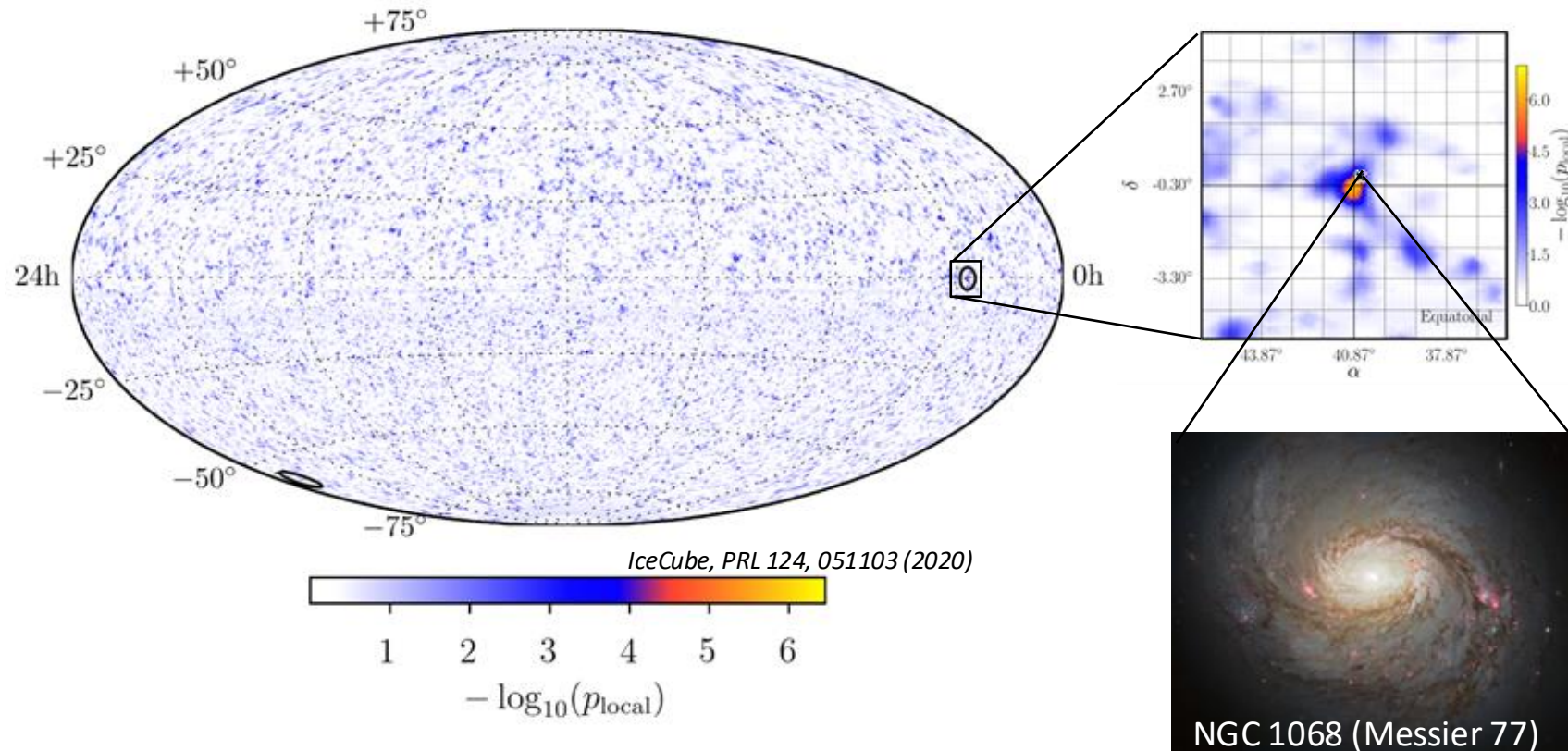
- maximize the (model agnostic) likelihood L at each point in the sky
- usually, add energy term to the signal likelihood S

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

↓

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

- search for clusters of neutrino events with on average higher energy
- search in a preselected list of 110 gamma-ray sources [5.3(4.2) σ pre(post) trial]

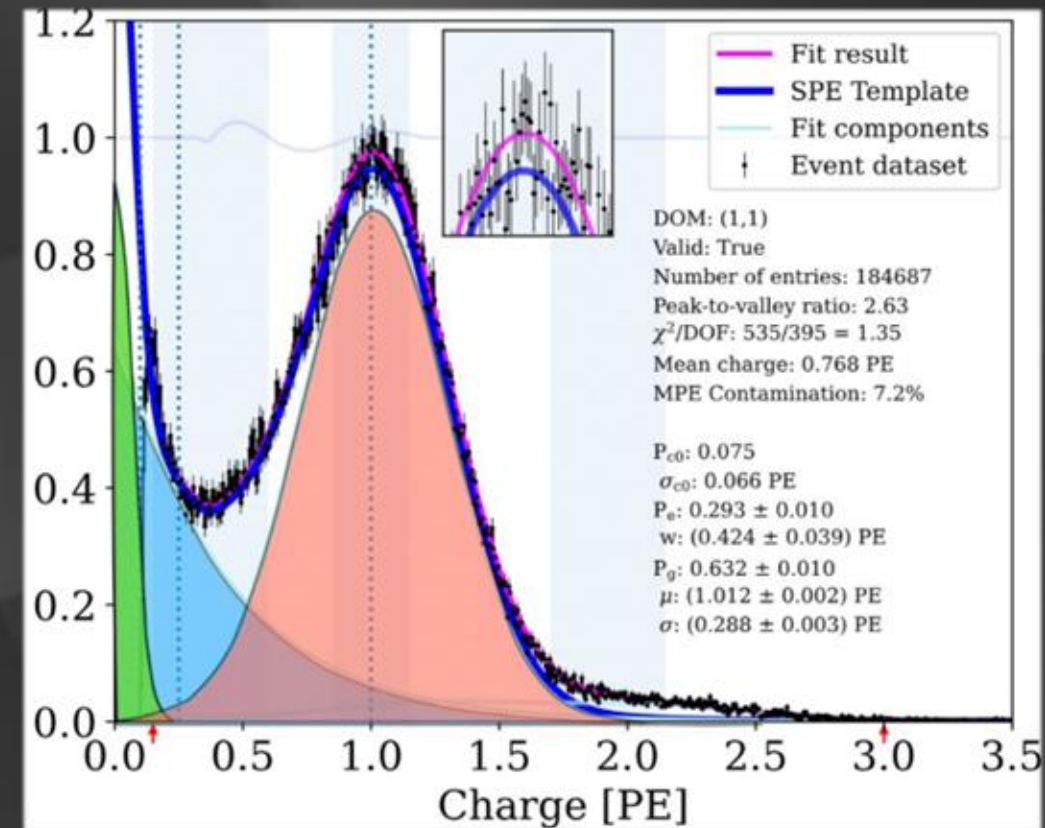


pre-trial p-value for clustering of high energy neutrinos

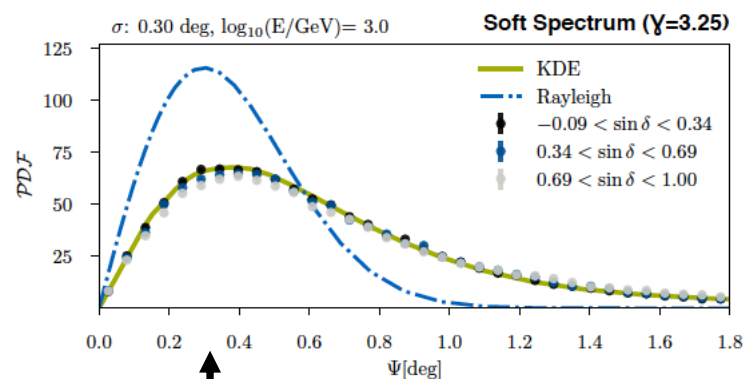
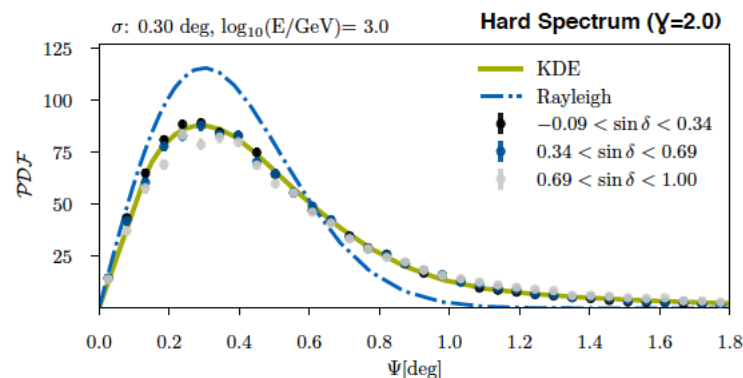
Source List Results									Phys.Rev.Lett. 124 (2020)								
Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$		PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4	
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3		Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3	
3C 454.3	FSRQ	243.50	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	
TXS 0106	FSRQ	244.46	6.5	3.1	0.3	0.56	5.6		1H 1014+498	BLL	153.77	49.43	0.0	1.6	0.29	4.5	
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1		4C +24.46	FSRQ	144.46	55.36	1.1	1.1	0.7	10.6	
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.29	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	2.4	0.3	4.4		PKS 10918+0991	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 48	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	0.22	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	

after 10 years: 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



- point spread function consistent with simulation
- insensitive to systematics

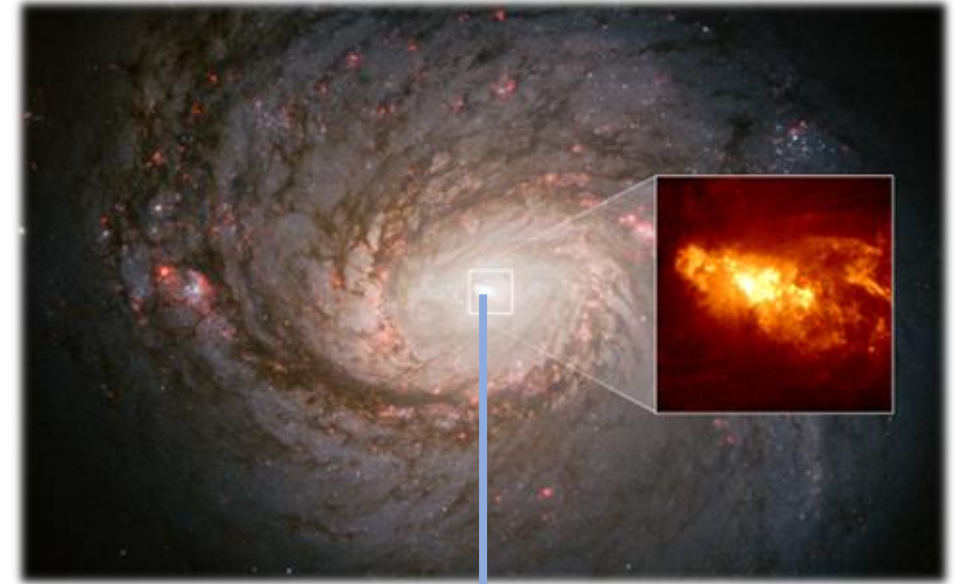
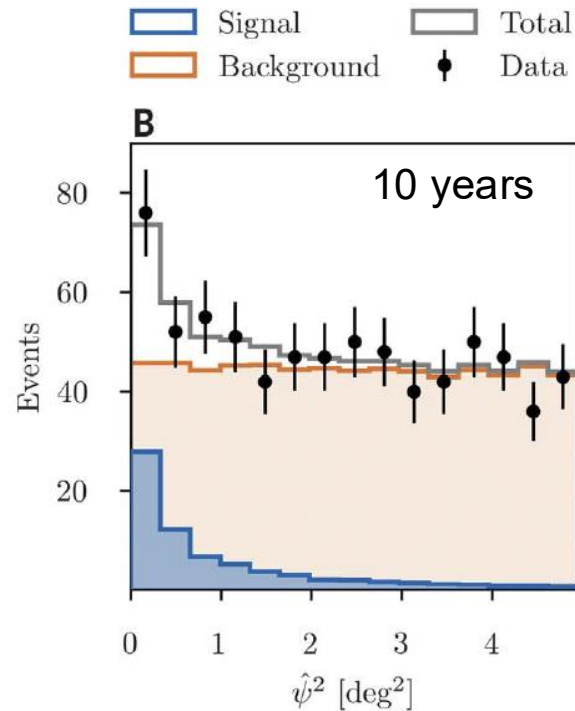
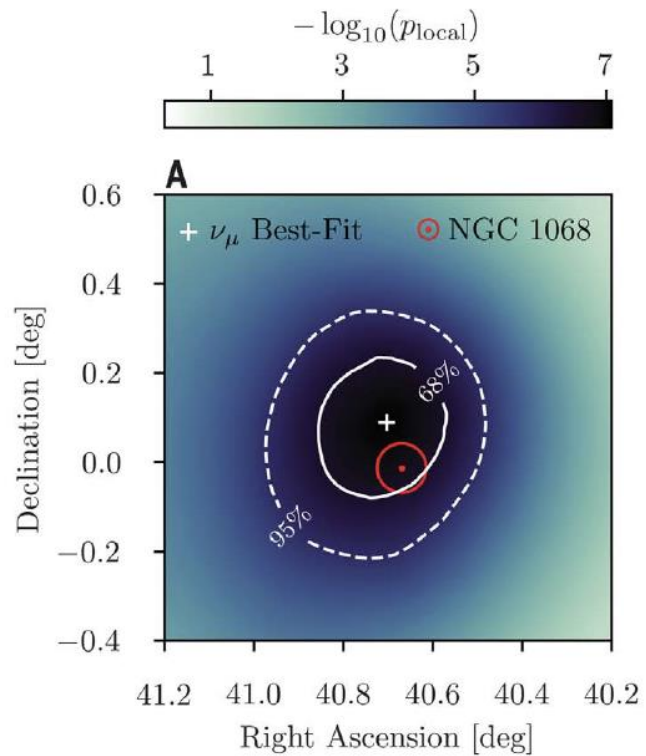


muon direction

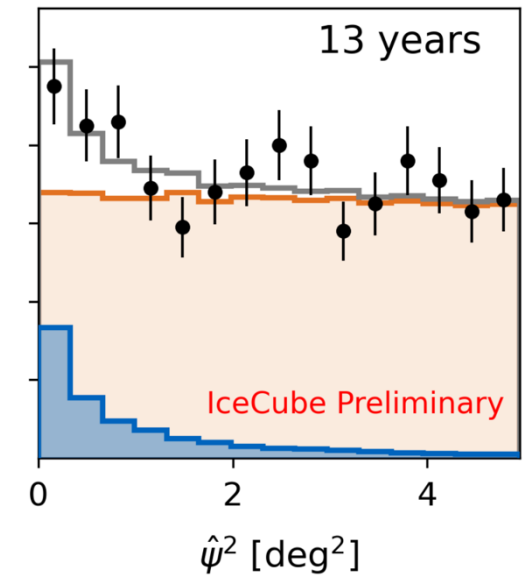
- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at $< 10 \text{ TeV}$ energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical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

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

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

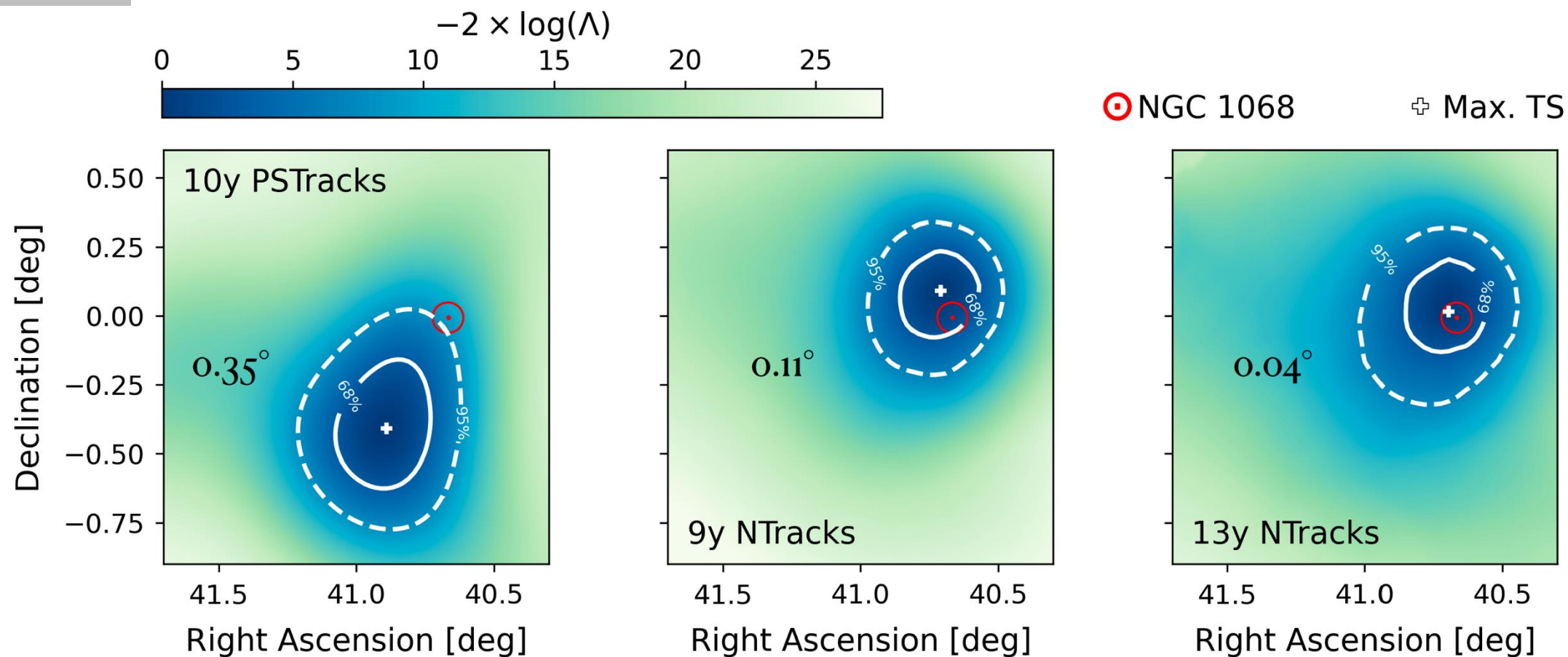
0.35 deg



0.1 deg

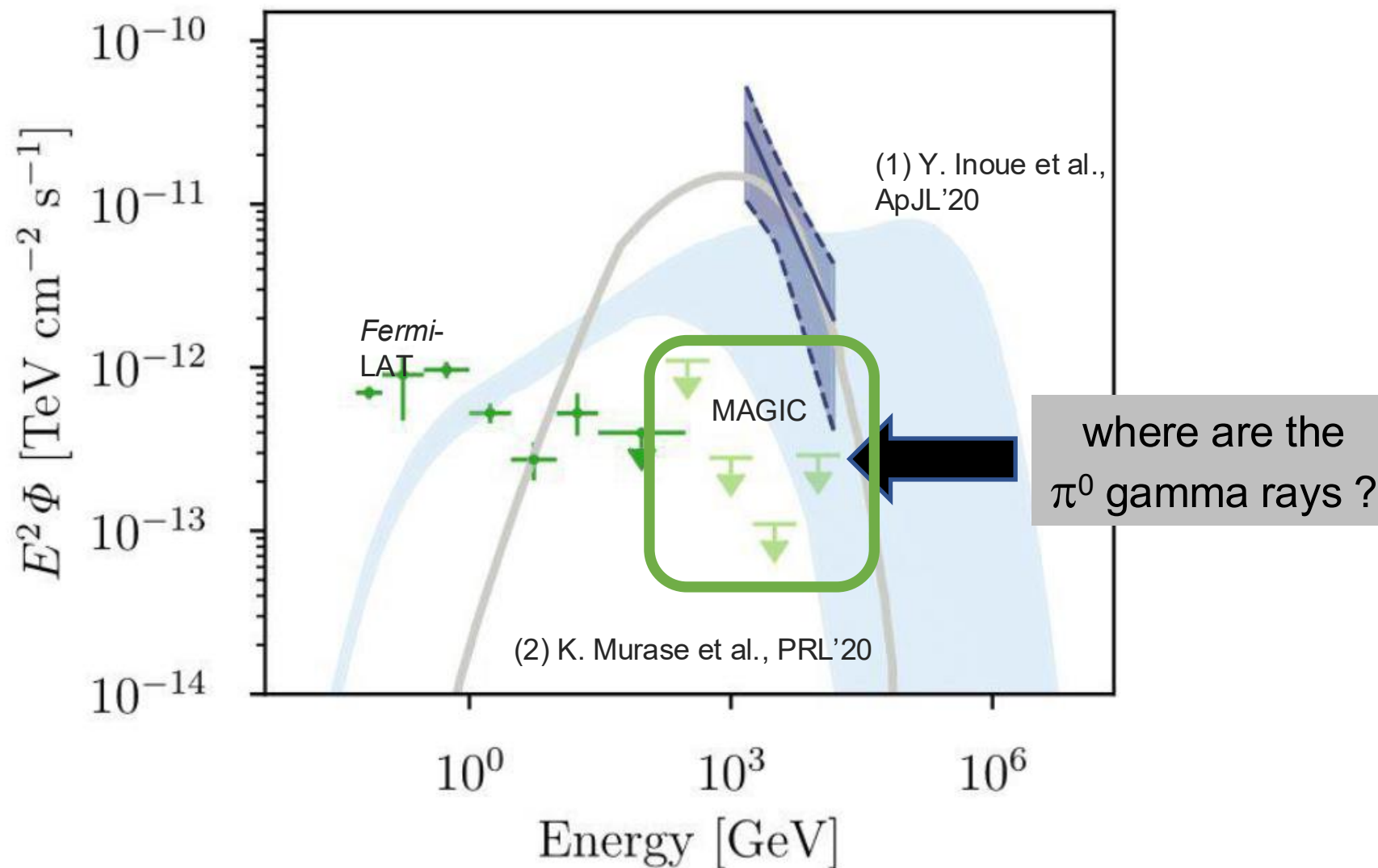


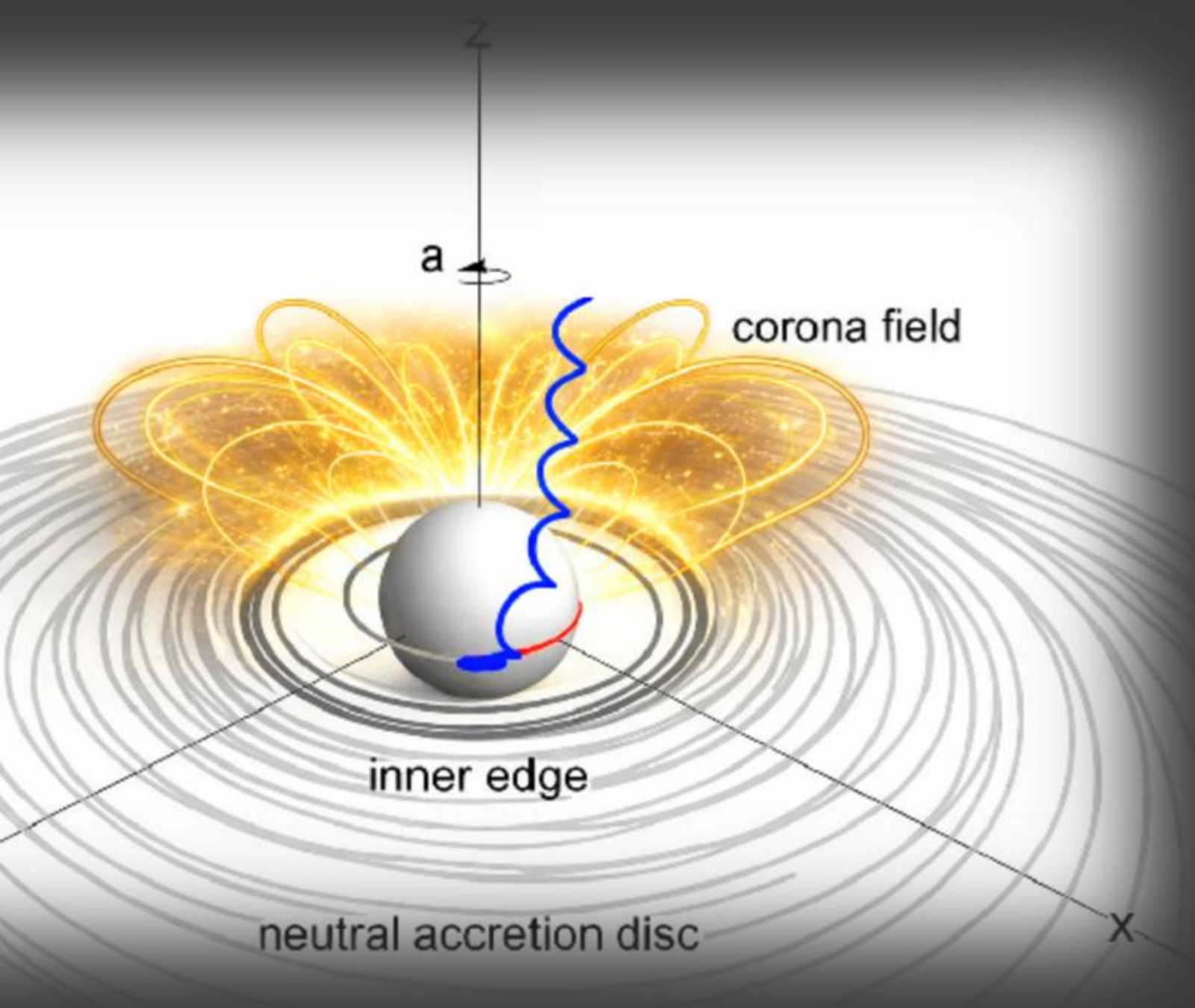
0.04 deg



a gamma ray for every neutrino?

NGC 1068: an obscured cosmic accelerator





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

$$\dot{M}c^2 \sim 0.5 M_{\text{sun}}/\text{yr} \sim 0.5 M_{\text{edd}}$$

- velocity of particle falling into a black hole

$$v = \sqrt{\frac{2GM}{r}}$$

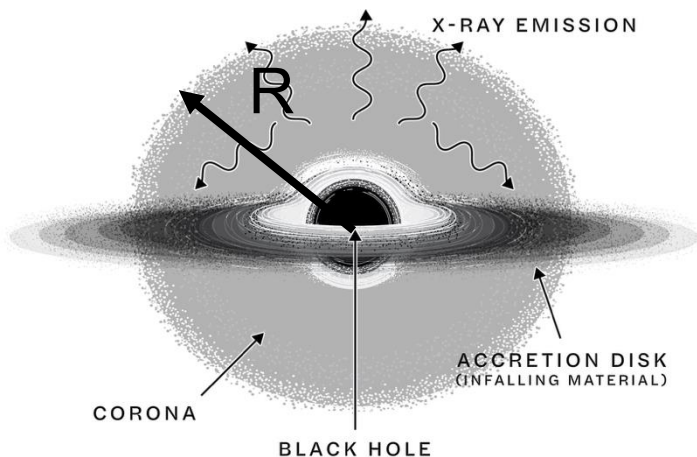
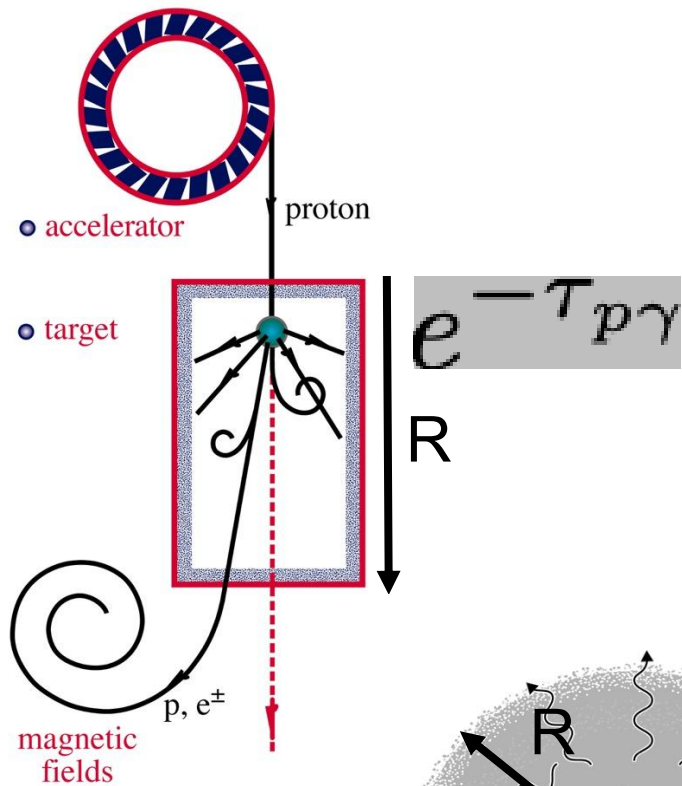
$$v = c\sqrt{\frac{R_g}{r}}$$

- magnetic reconnection

ν and γ beams : protons on target



NEUTRINO BEAMS: HEAVEN & EARTH



- optical depth τ and interaction length $\lambda_{p\gamma}$

$$\tau_{p\gamma} \sim \frac{R}{\lambda_{p\gamma}} \sim \sigma_{p\gamma} n_\gamma R \sim \sigma_{p\gamma} \frac{1}{R} \frac{L_\gamma}{E_\gamma}$$

- in terms of X-ray luminosity measured at Earth

$$n_\gamma \sim \frac{1}{c} \frac{1}{E_\gamma} \left[\frac{1}{4\pi R^2} L_\gamma \right]$$

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

$$\tau_{\gamma\gamma} \sim [\sigma_{\gamma\gamma}/\sigma_{p\gamma}] \tau_{p\gamma} \sim 10^3$$

optical depth of target

number of target X-rays

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

accelerated
proton

$$L_\nu \sim L_p \tau_{pX}$$

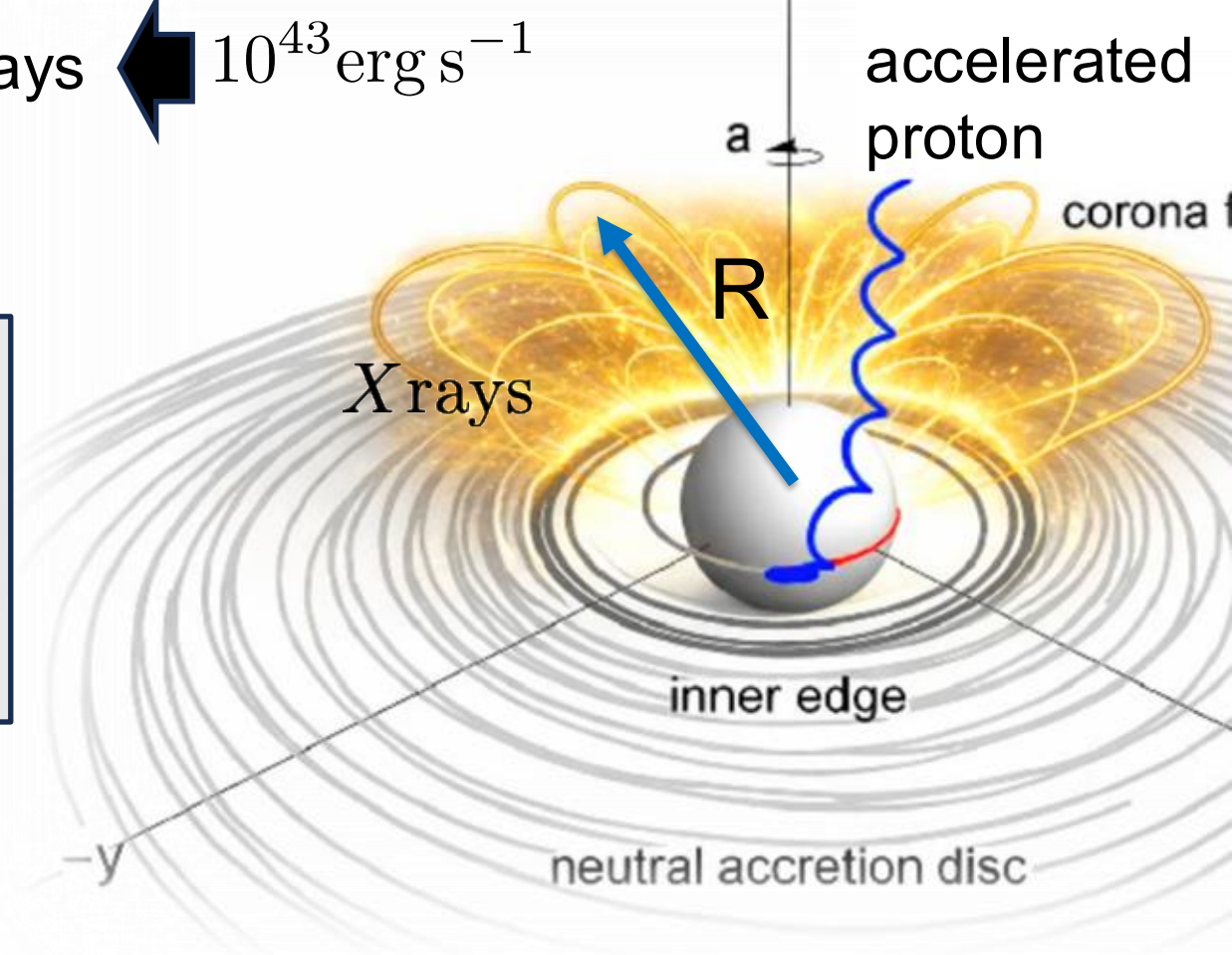
$$\tau_{pX} \sim \sigma_{pX} \frac{1}{R} \frac{L_X}{E_X} \simeq 10^{-3} \tau_{\gamma\gamma}$$

size of the target

$$R \simeq 10 R_g$$

$\tau_{p\gamma} \gtrsim 0.1 \rightarrow$ neutrinos produced for $R \sim 10 R_S$

$\tau_{\gamma\gamma} \sim [\sigma_{\gamma\gamma}/\sigma_{p\gamma}] \tau_{p\gamma} \sim 10^2 \rightarrow \pi^0$ gamma rays absorbed



M 87





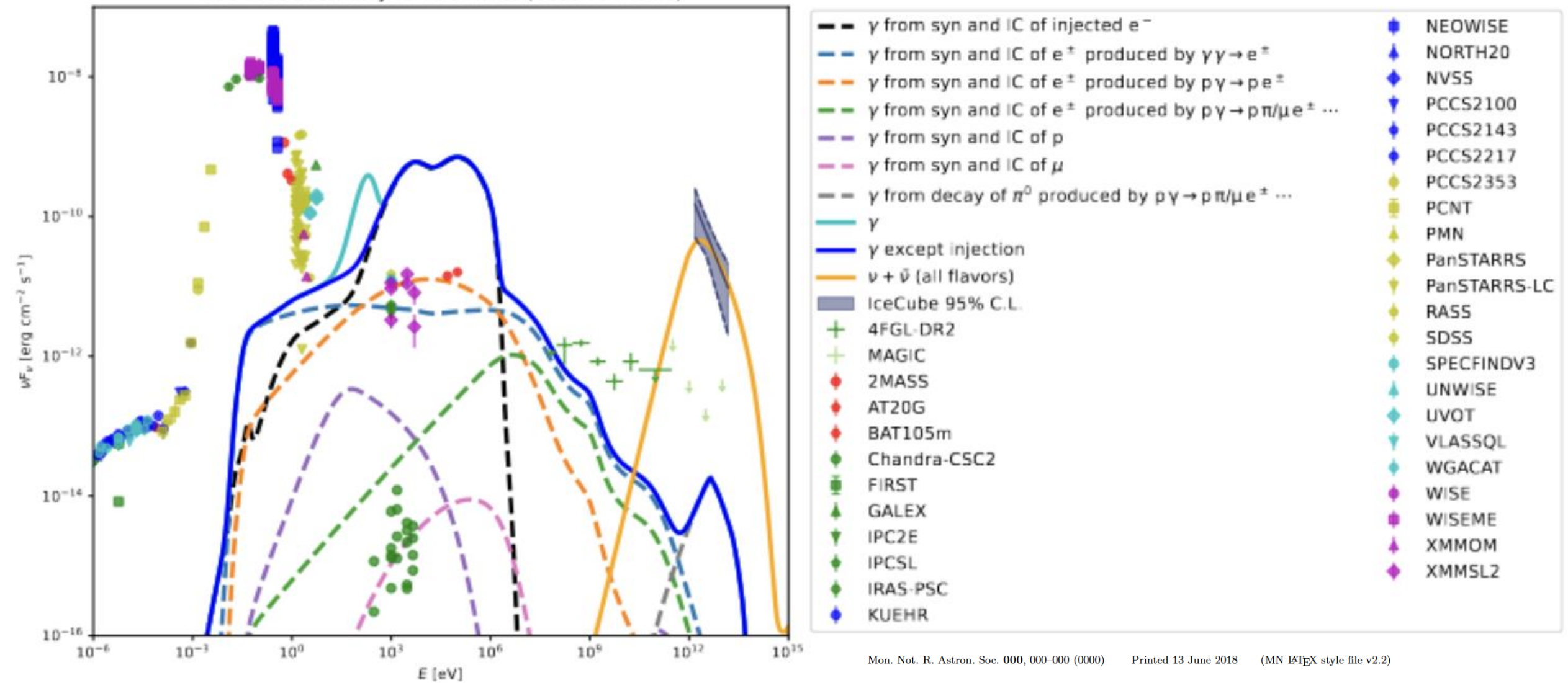
- accelerator(s)*: electrons and protons are accelerated
- in the turbulent magnetic fields associated with the accretion disk
 - in the infall onto the black hole
 - ...

target: the neutrinos are produced in

- optically thick core of plasma emitting X-rays (corona)
- dense clouds of hydrogen
- ...



NGC 1068 Secondary Particle Fluxes (Observer Frame)



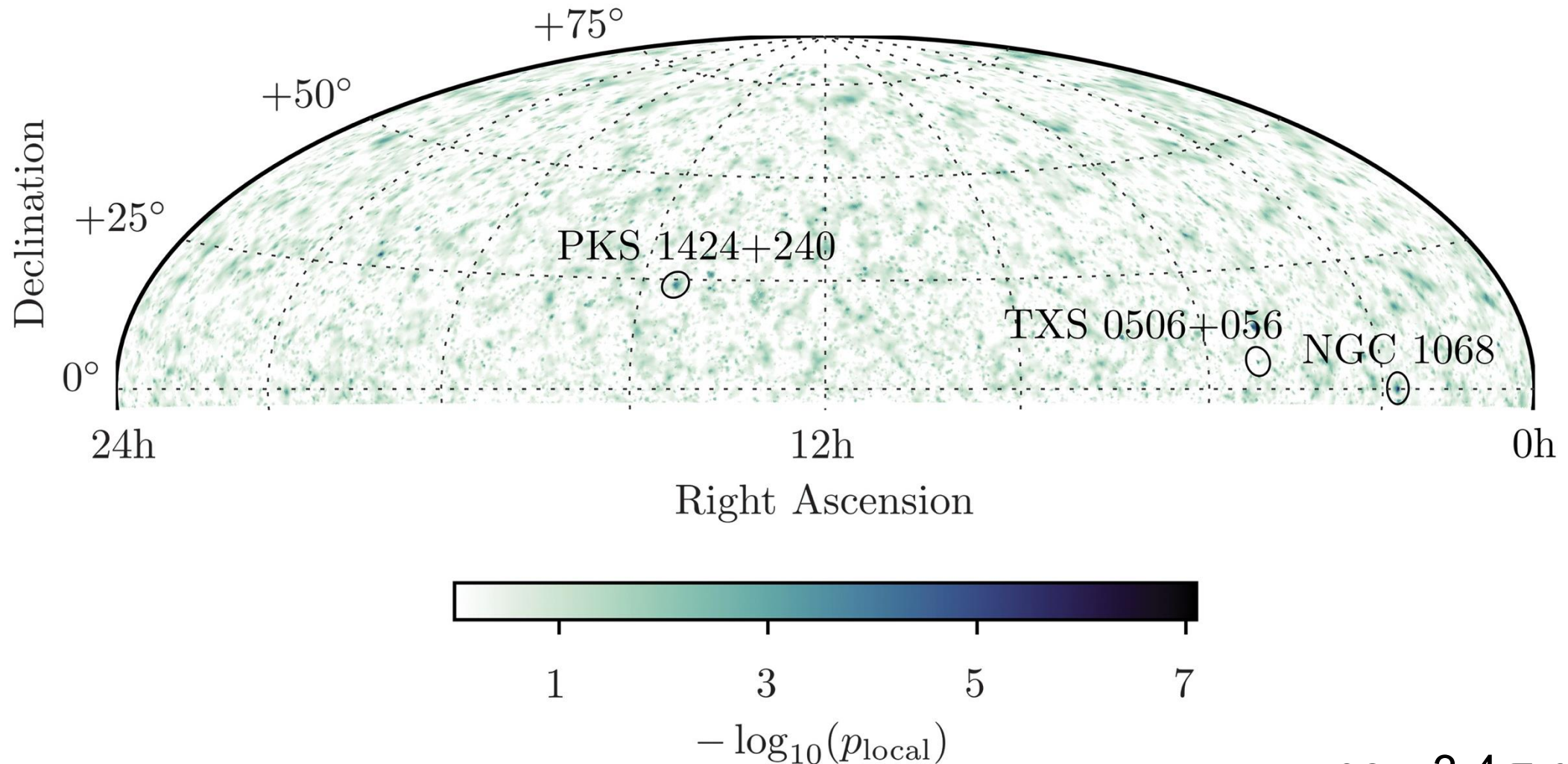
Mon. Not. R. Astron. Soc. 000, 000–000 (0000) Printed 13 June 2018 (MN $\LaTeX$ style file v2.2)

NuSTAR catches the unveiling nucleus of NGC 1068

the AM3 version

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}

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



now 3.4σ p-value

Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

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

RESEARCH ARTICLE SUMMARY

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*†

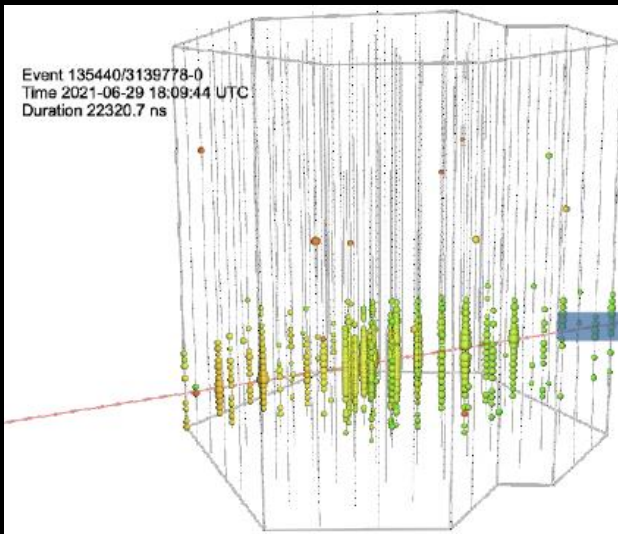
RESEARCH ARTICLE

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



HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!

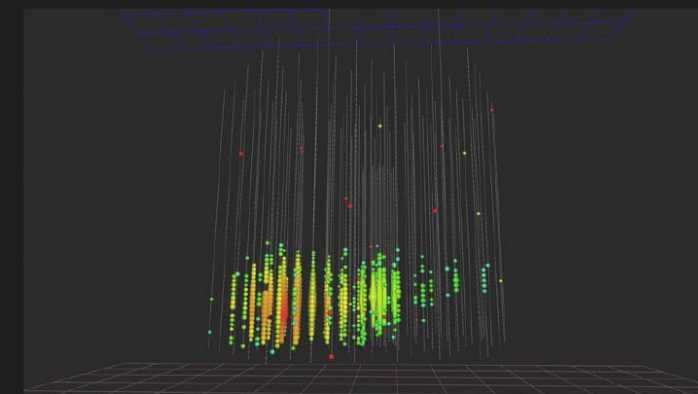
47

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

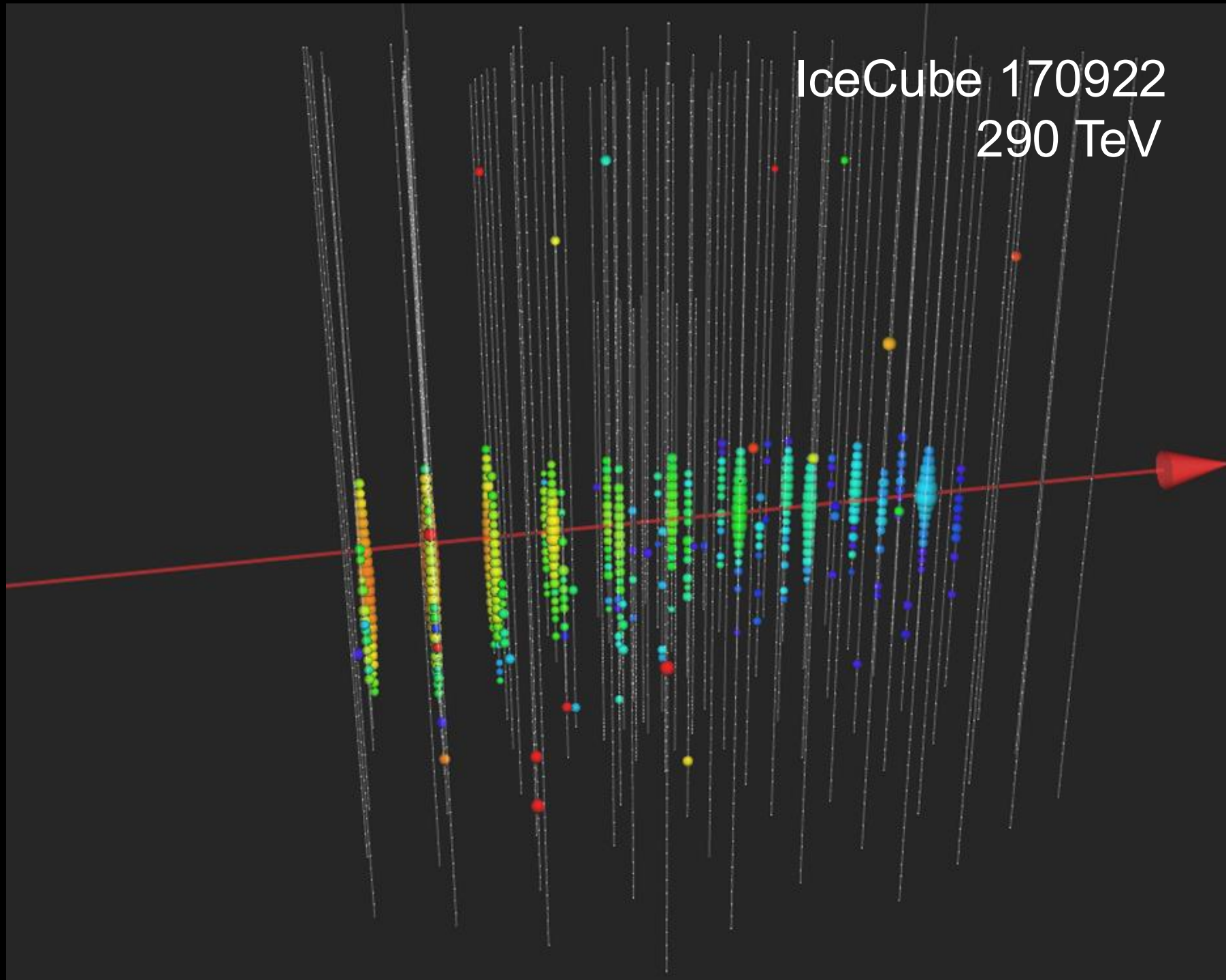
TITLE:	GCN/AMON NOTICE
NOTICE_DATE:	Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:	AMON ICECUBE HESE
RUN_NUM:	127853
EVENT_NUM:	67093193
SRC_RA:	240.5683d {+16h 02m 16s} (J2000), 240.7644d {+16h 03m 03s} (current), 239.9678d {+15h 59m 52s} (1950)
SRC_DEC:	+9.3417d {+09d 20' 30"} (J2000), +9.2972d {+09d 17' 50"} (current), +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:	35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:	0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:	17505 TJD; 118 DOY; 16/04/27 (yy/mm/dd)
DISCOVERY_TIME:	21152 SOD {05:52:32.00} UT
REVISION:	2
N_EVENTS:	1 [number of neutrinos]
STREAM:	1
DELTA_T:	0.0000 [sec]
SIGMA_T:	0.0000 [sec]
FALSE_POS:	0.0000e+00 [s ⁻¹ sr ⁻¹]
PVALUE:	0.0000e+00 [dn]
CHARGE:	18883.62 [pe]
SIGNAL_TRACKNESS:	0.92 [dn]
SUN_POSTN:	35.75d {+02h 23m 00s} +14.21d {+14d 12' 45"}]

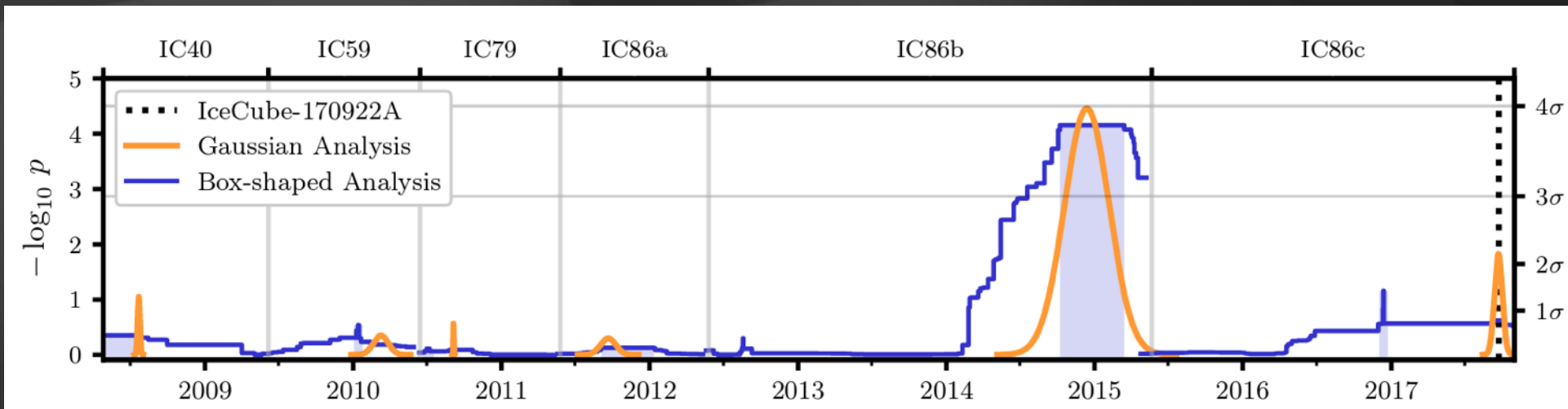
GCN notice for starting track sent Apr 27

We send **rough reconstructions**
first and then **update them**.



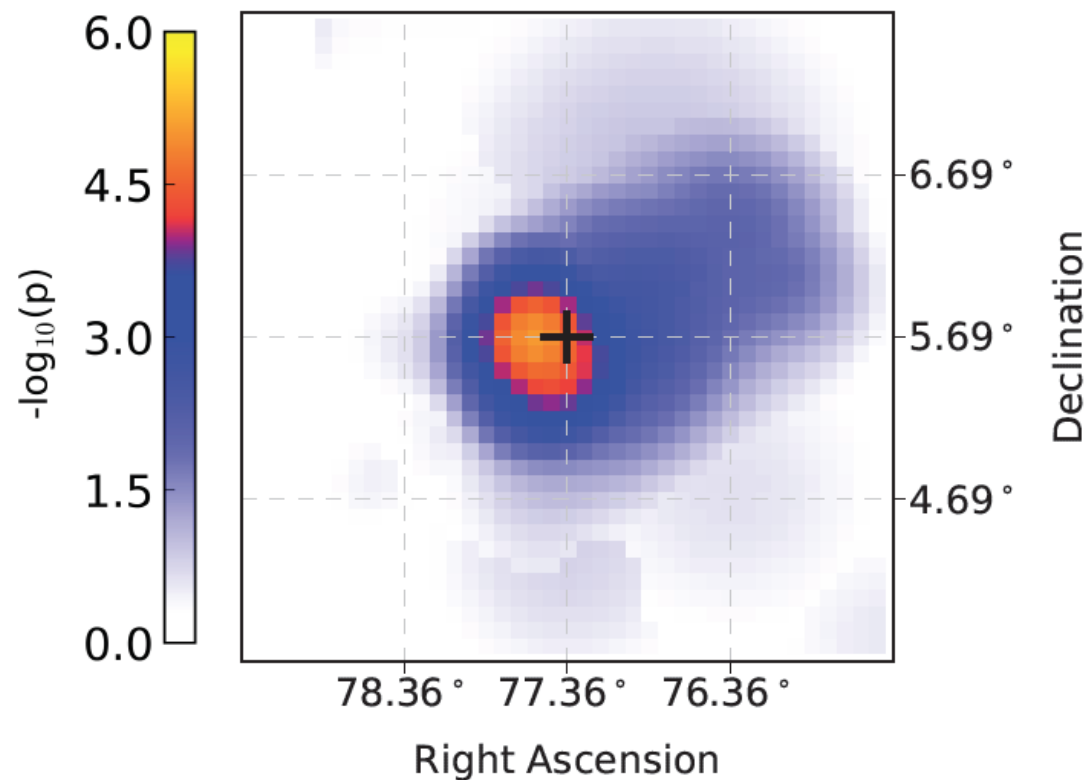
IceCube 170922
290 TeV

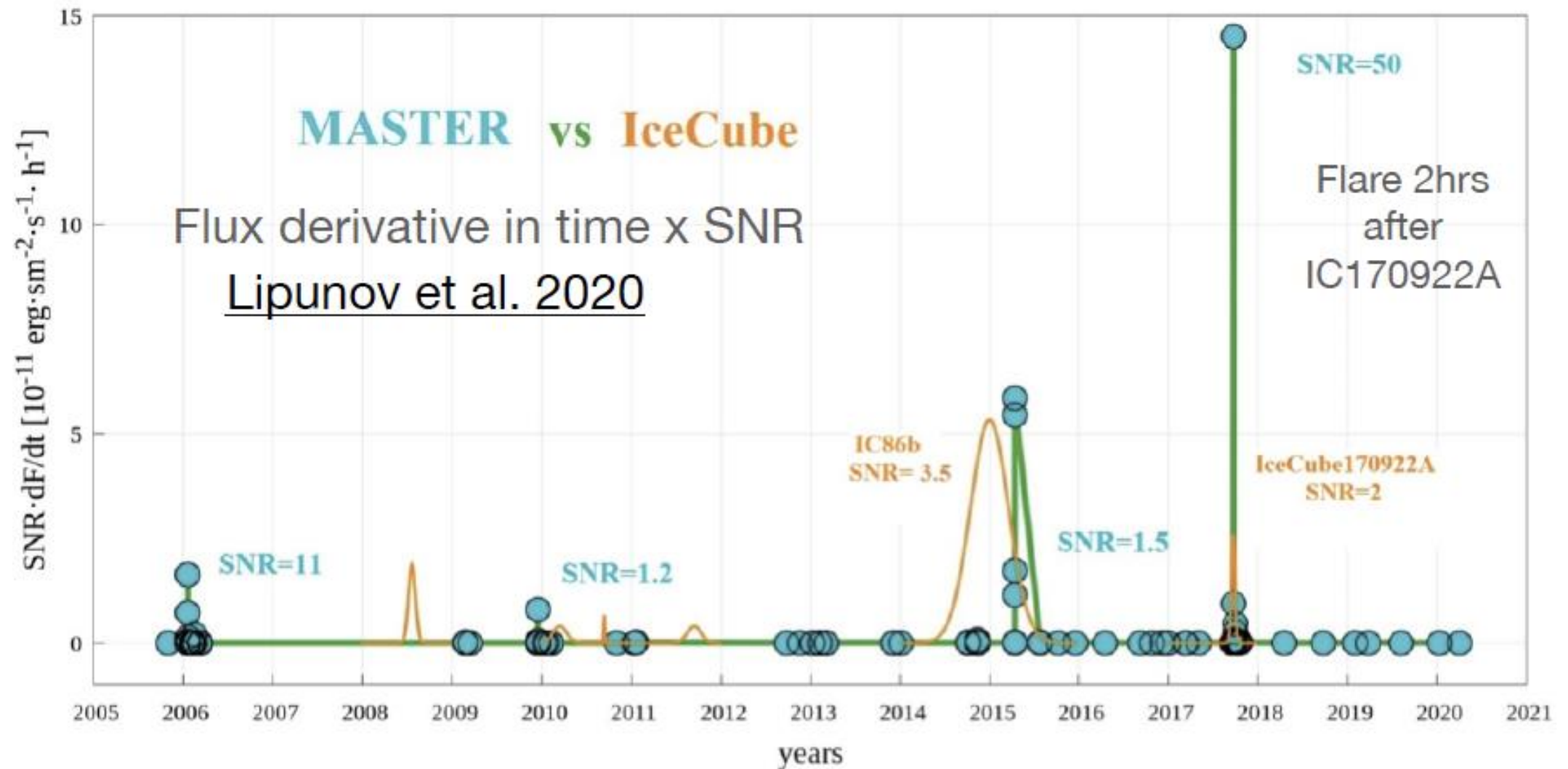




search in archival
IceCube data:

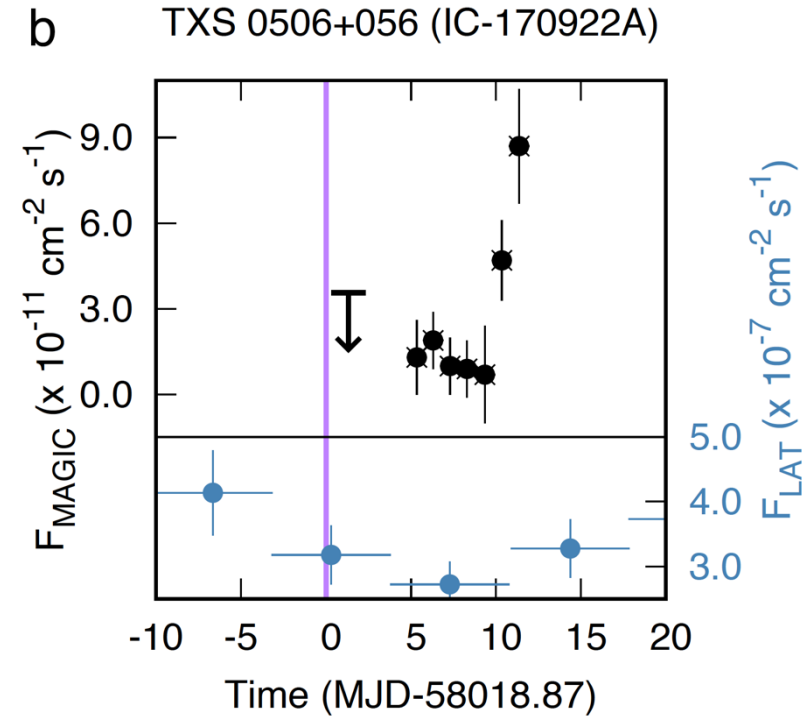
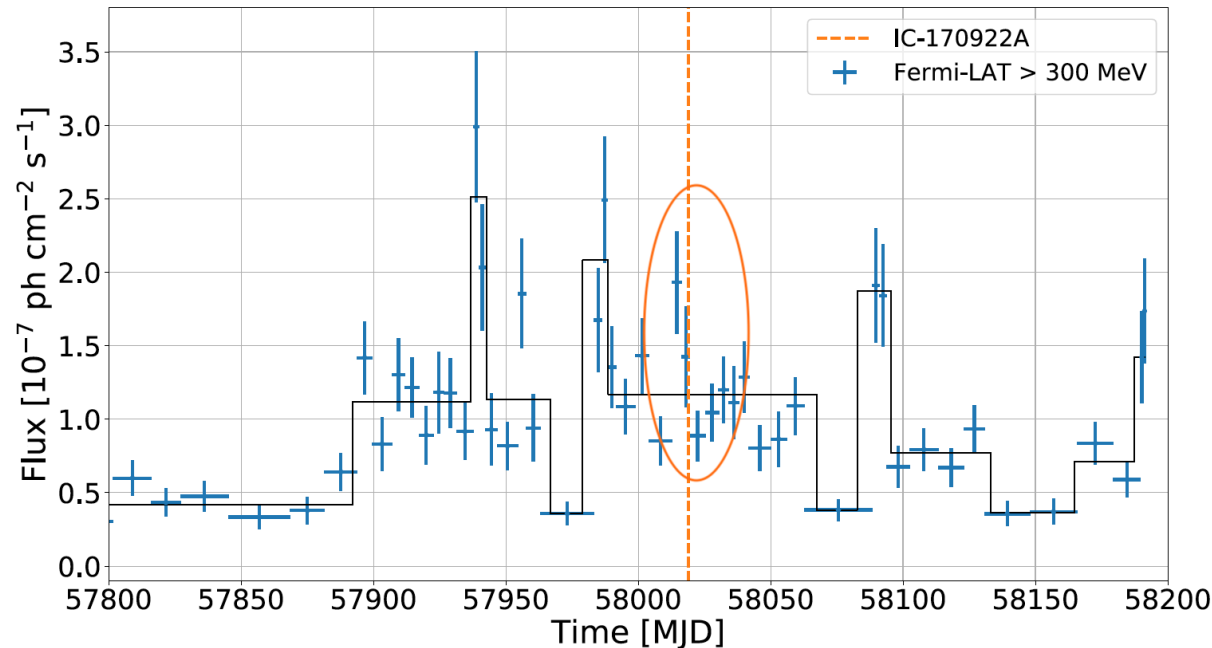
- 100-day flare in 2014
- spectrum $E^{-2.2}$
- $L_v \sim L_{\text{Eddington}}$
- no gamma ray flare!





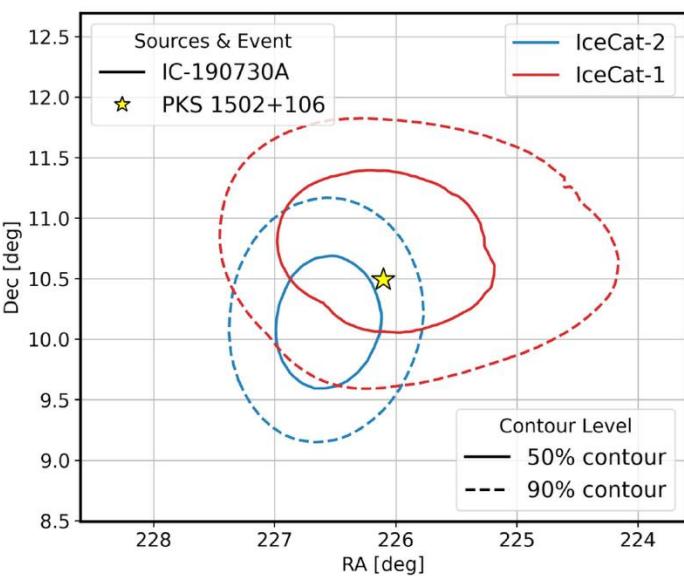
- optical flare of IC170922, 2 hours *after* the neutrino
- often originate from magnetohydrodynamical instabilities triggered by processes modulated by the magnetic field of the accretion disk

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



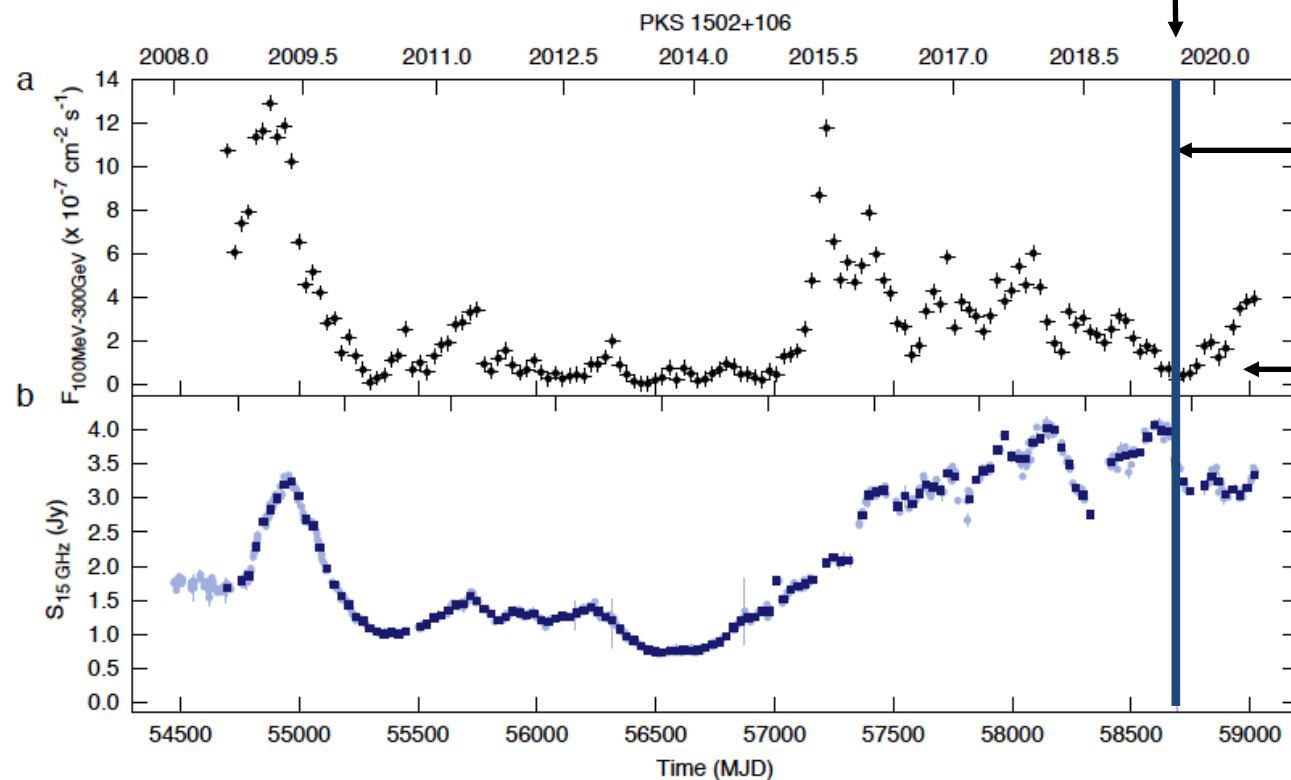
- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

PKS 1502+106



γ -ray

radio

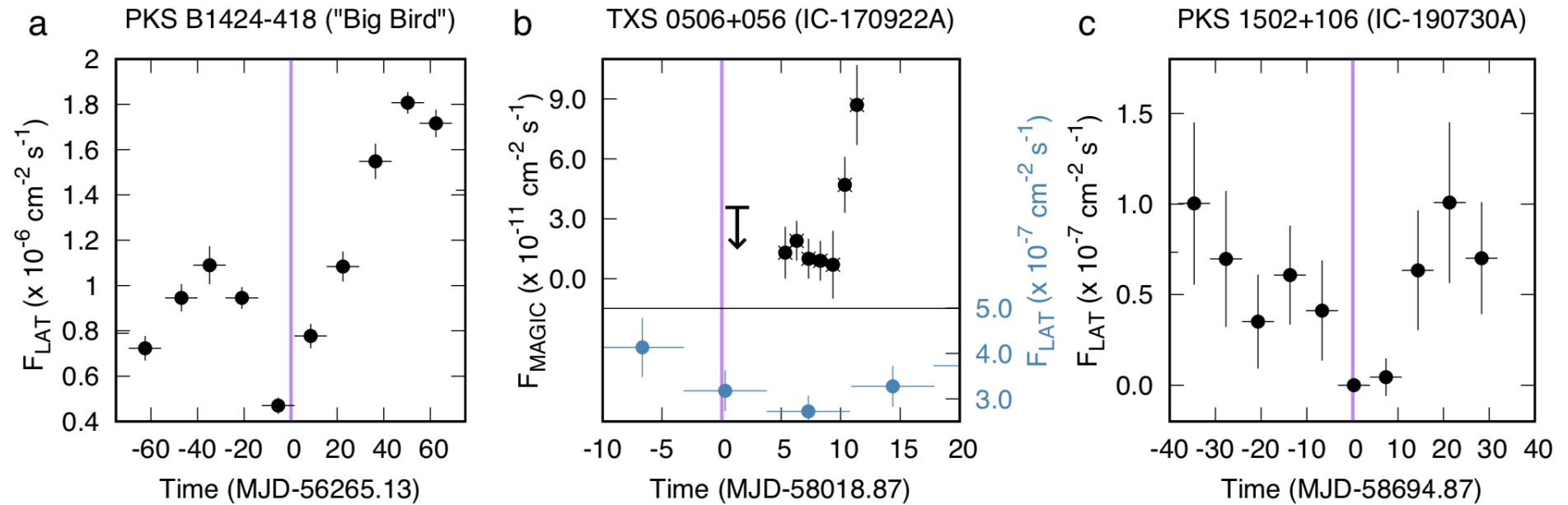


neutrino

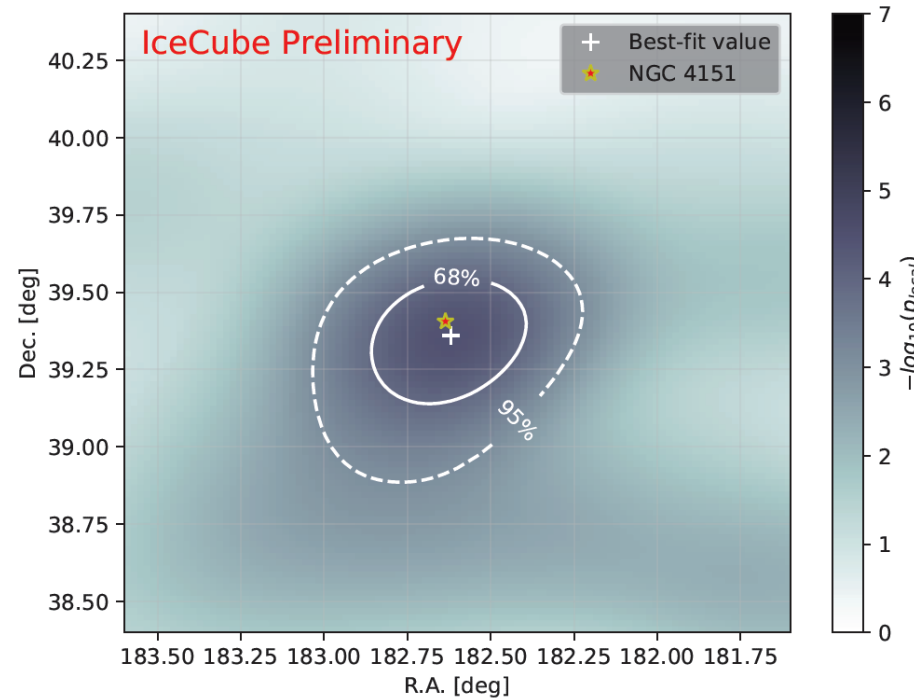
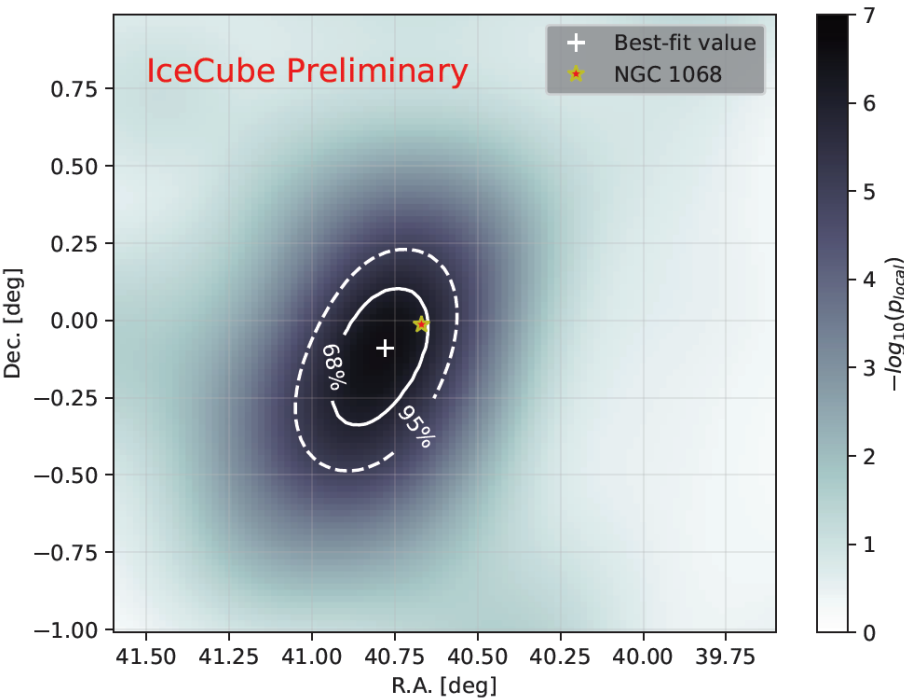
300 TeV
neutrino
produced

thick target
formed and
neutrinos
produced:
photons
absorbed

emerging feature: γ -ray suppression at the time of neutrino emission



search for X-ray bright sources



- two brightest active galaxies discovered by Seyfert in 1943

NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

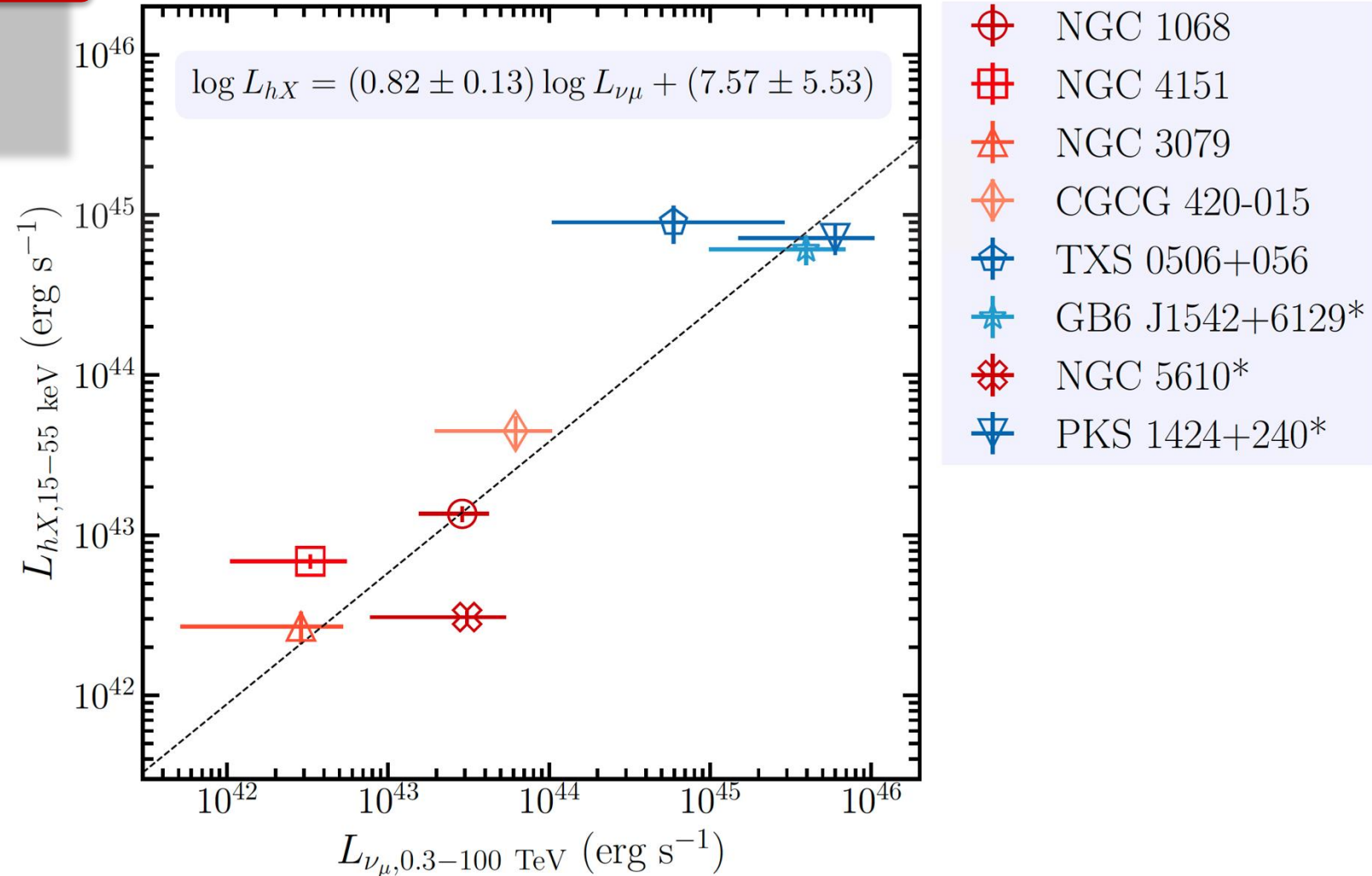
1943

ABSTRACT

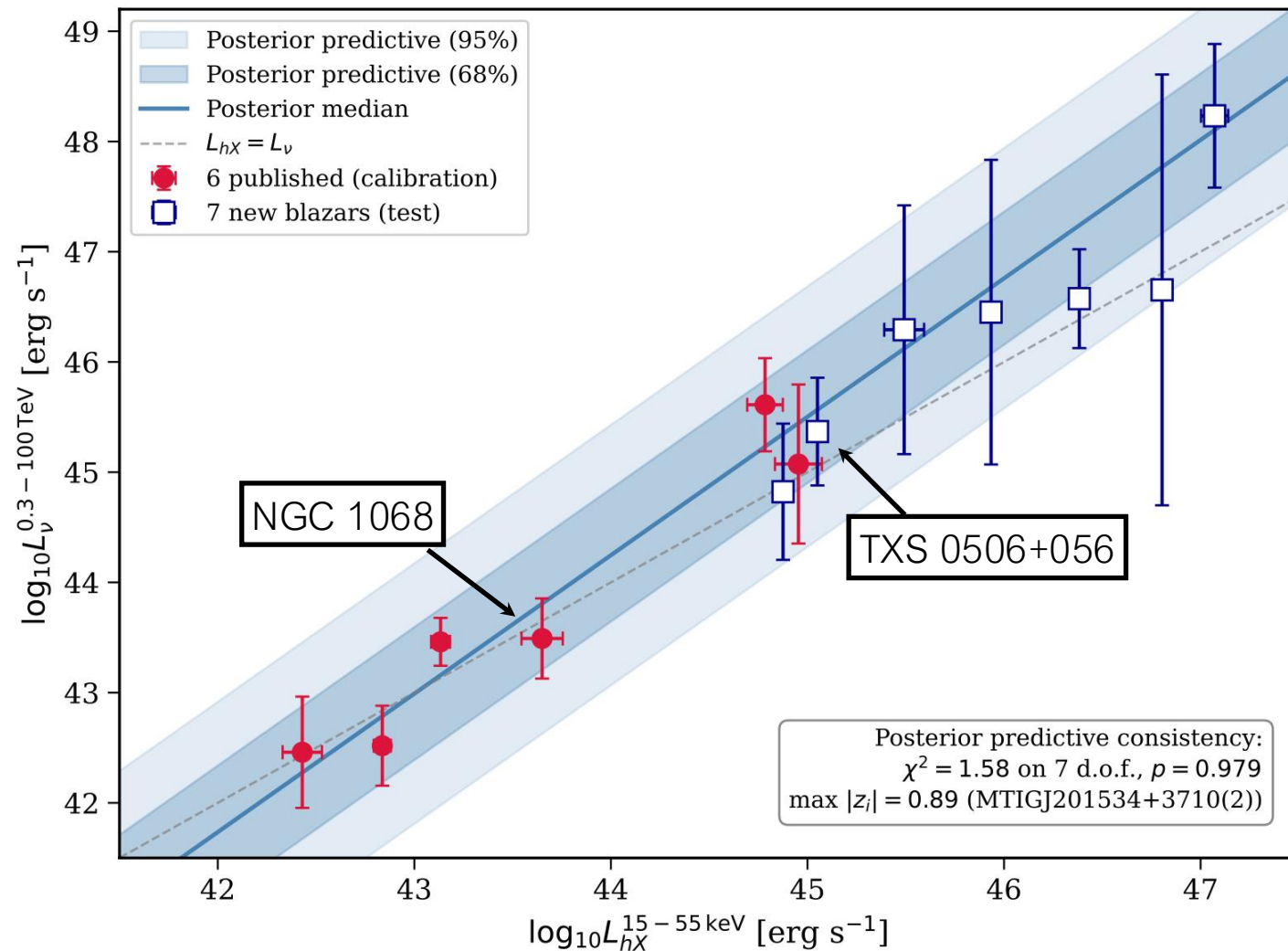
Spectrograms of dispersion 37–200 Å/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest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



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



neutrino-X-ray correlation ?



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

NGC 1068

TXS 0506+056

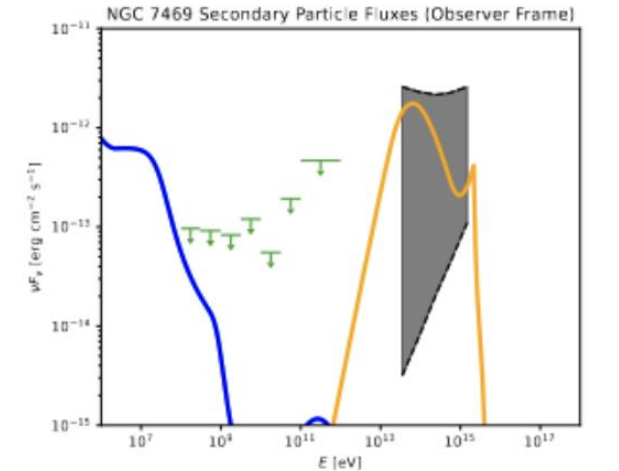
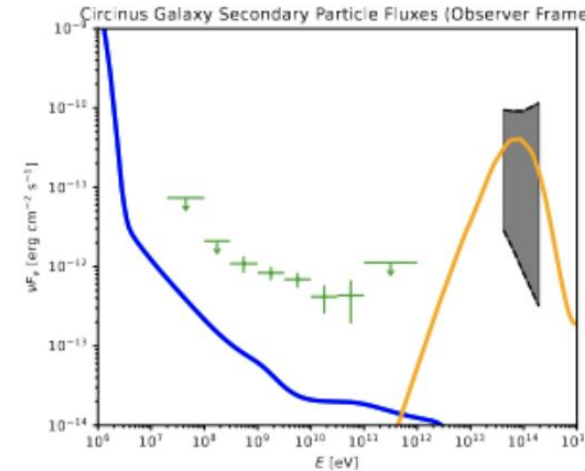
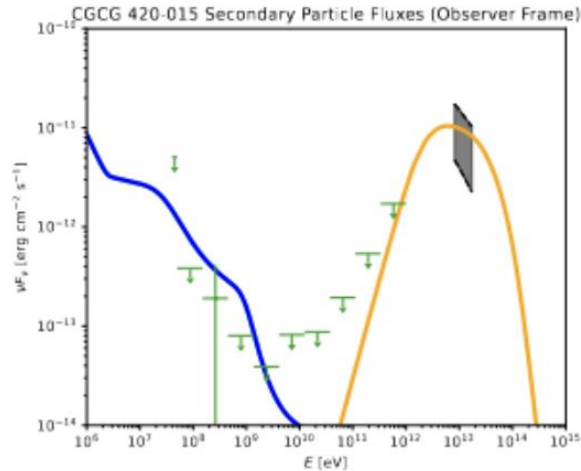
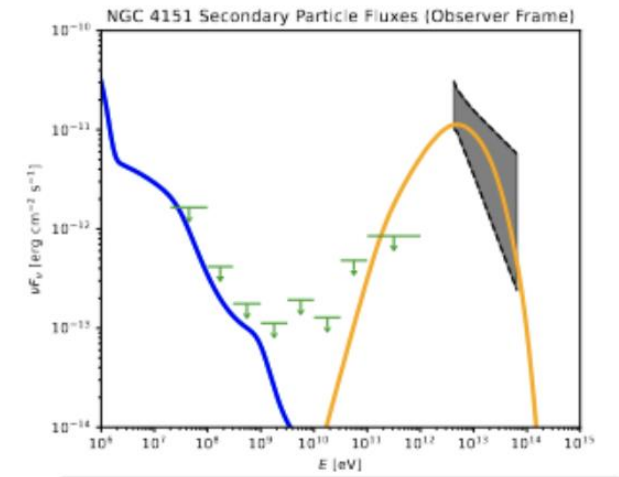
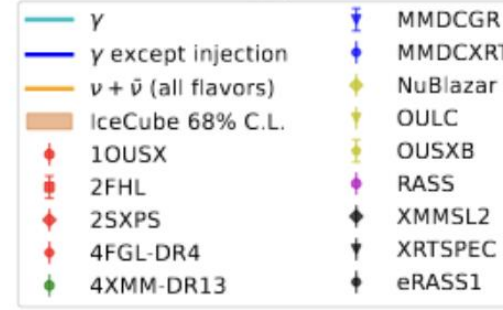
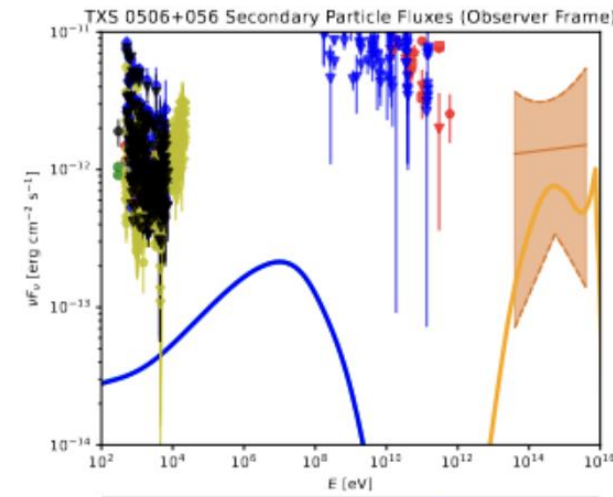
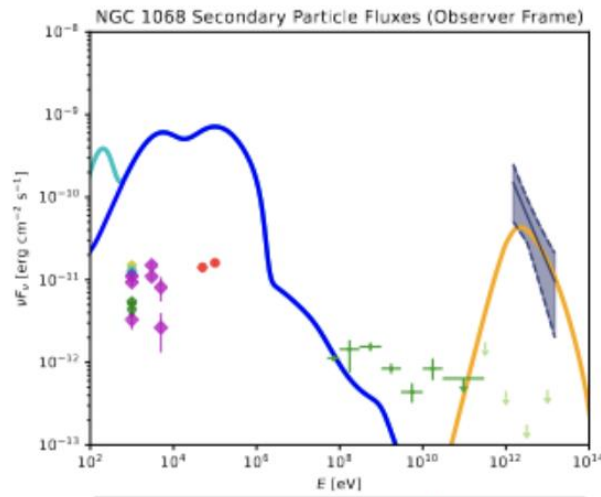
NGC 4151

CGCG 420-015

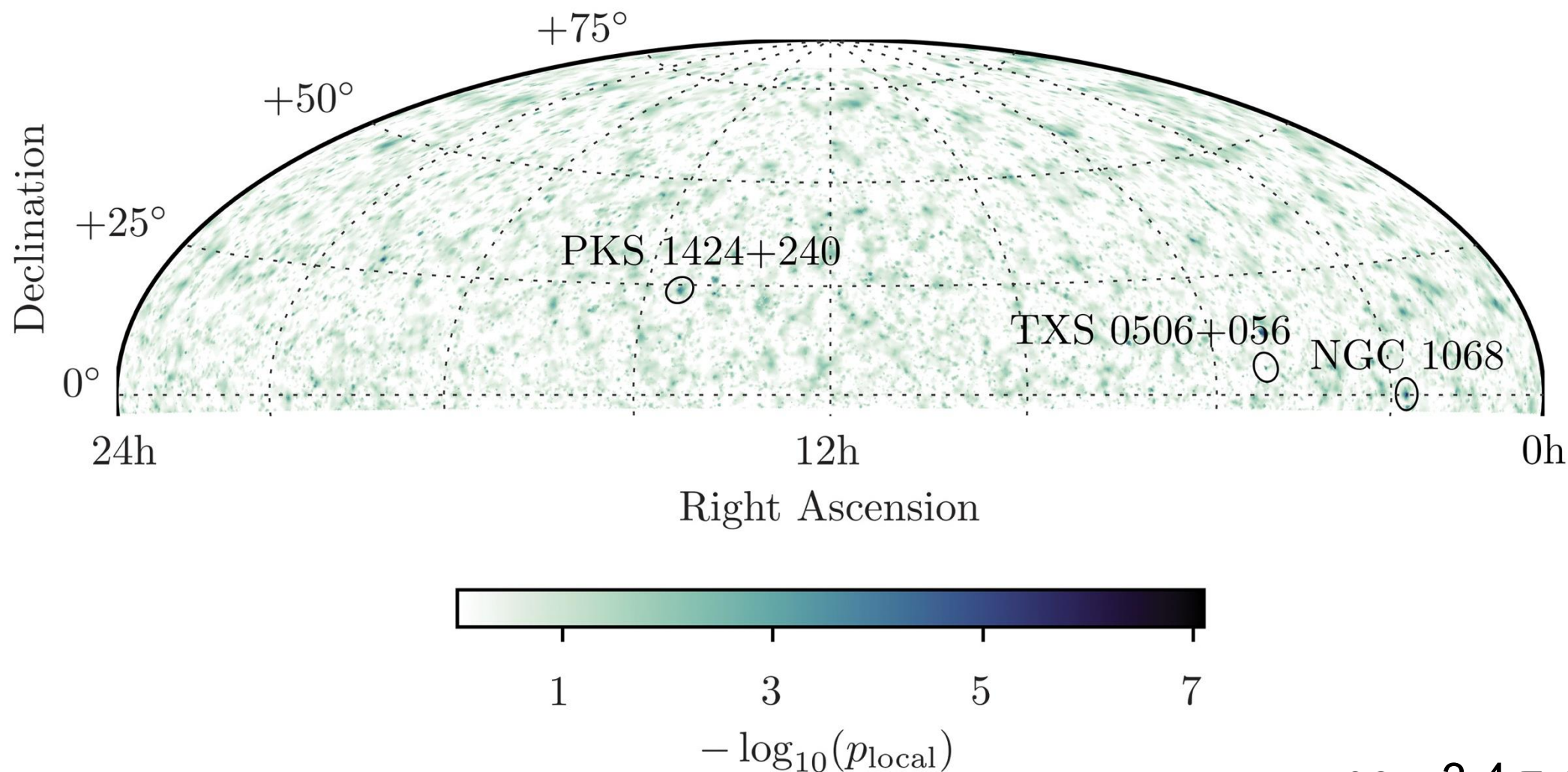
Circinus

NGC 7469

[PKS 1425+240
NGC 5610]

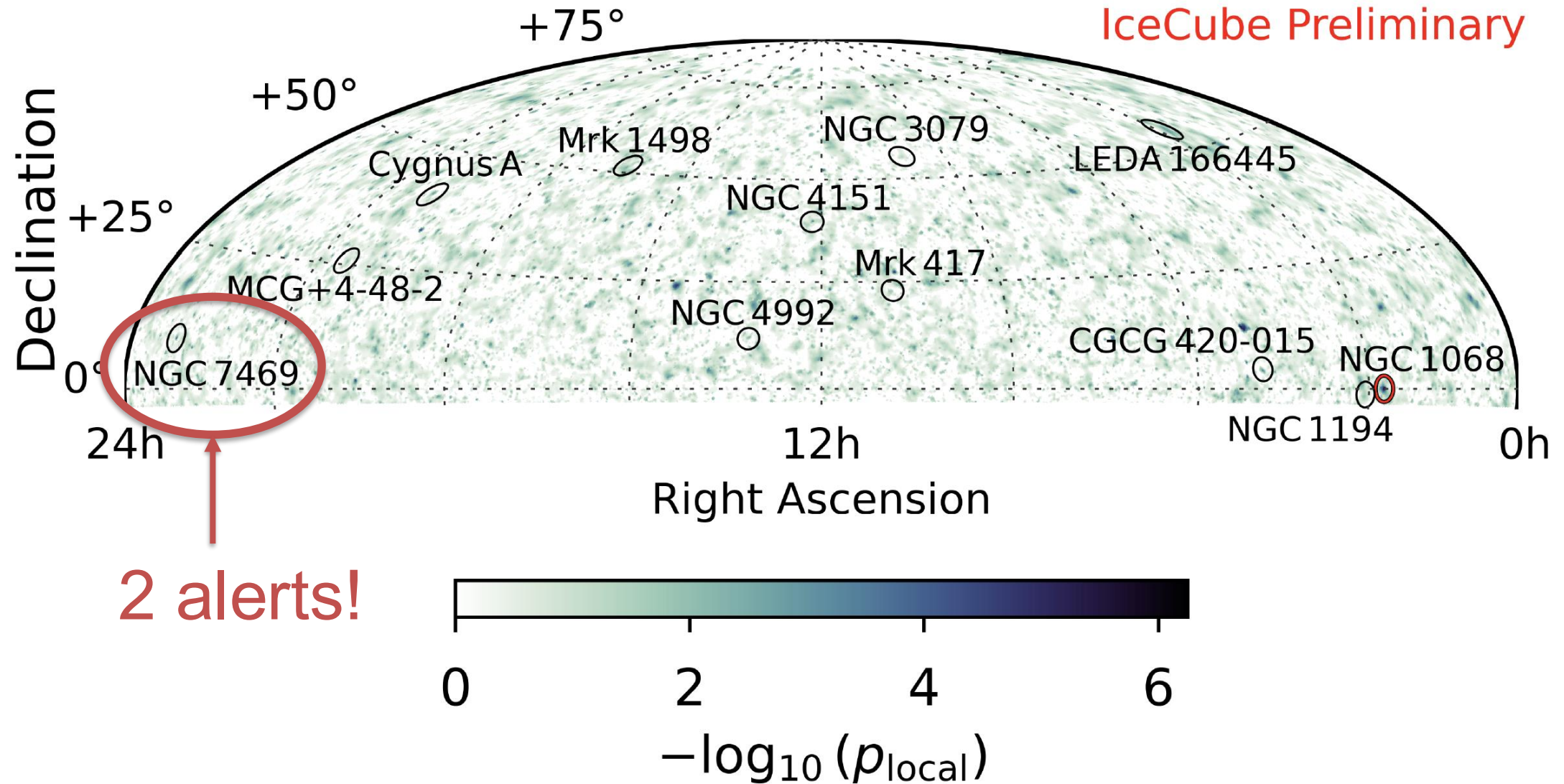


we observe an excess from an ensemble of 3 (*gamma ray*) sources



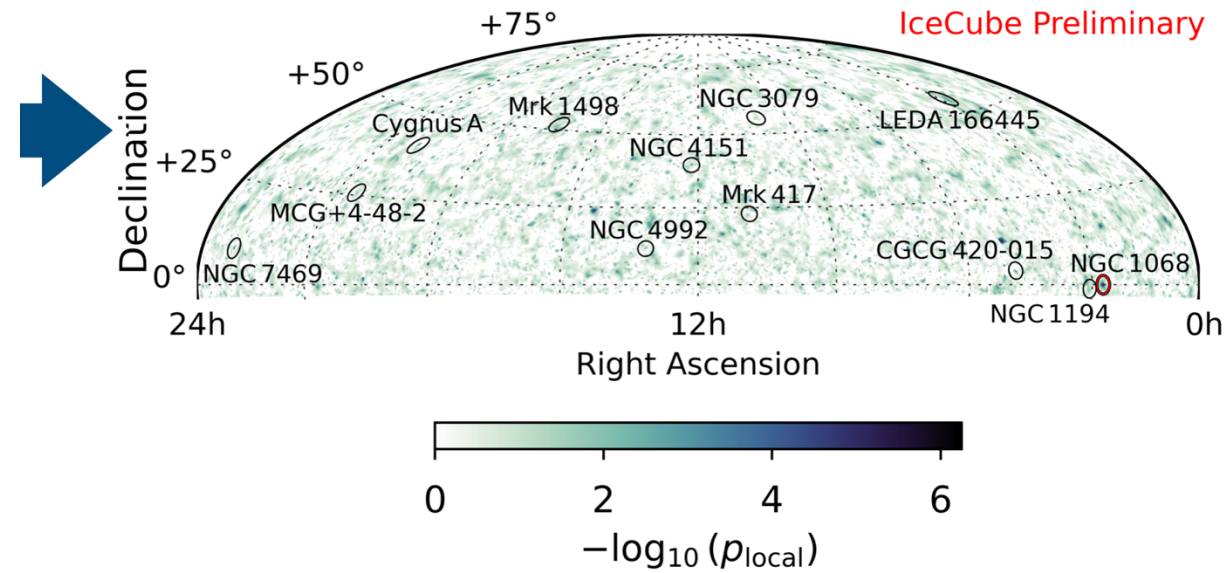
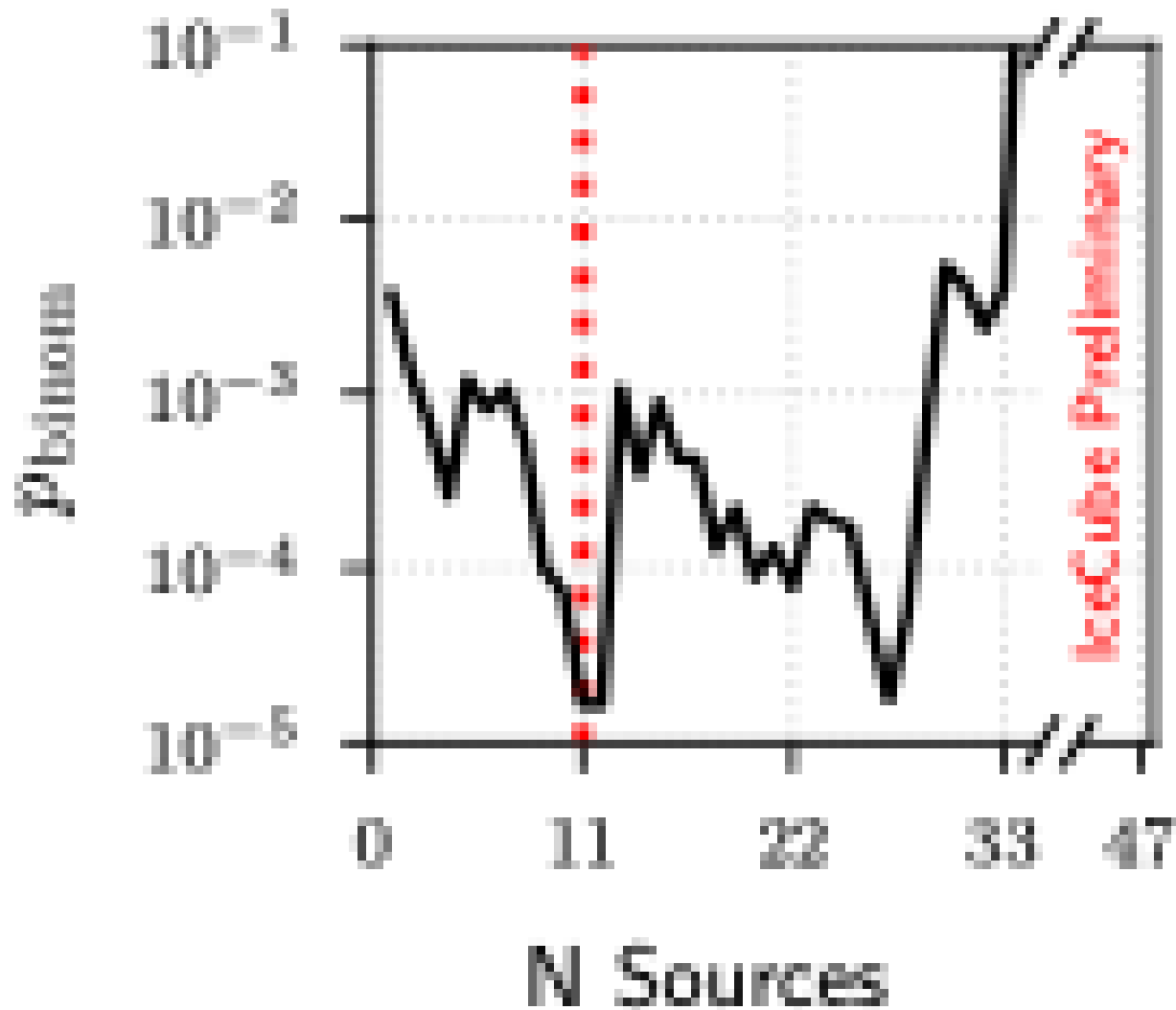
now 3.4σ p-value

IceCube Preliminary



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

Binomial test of non-jetted sources



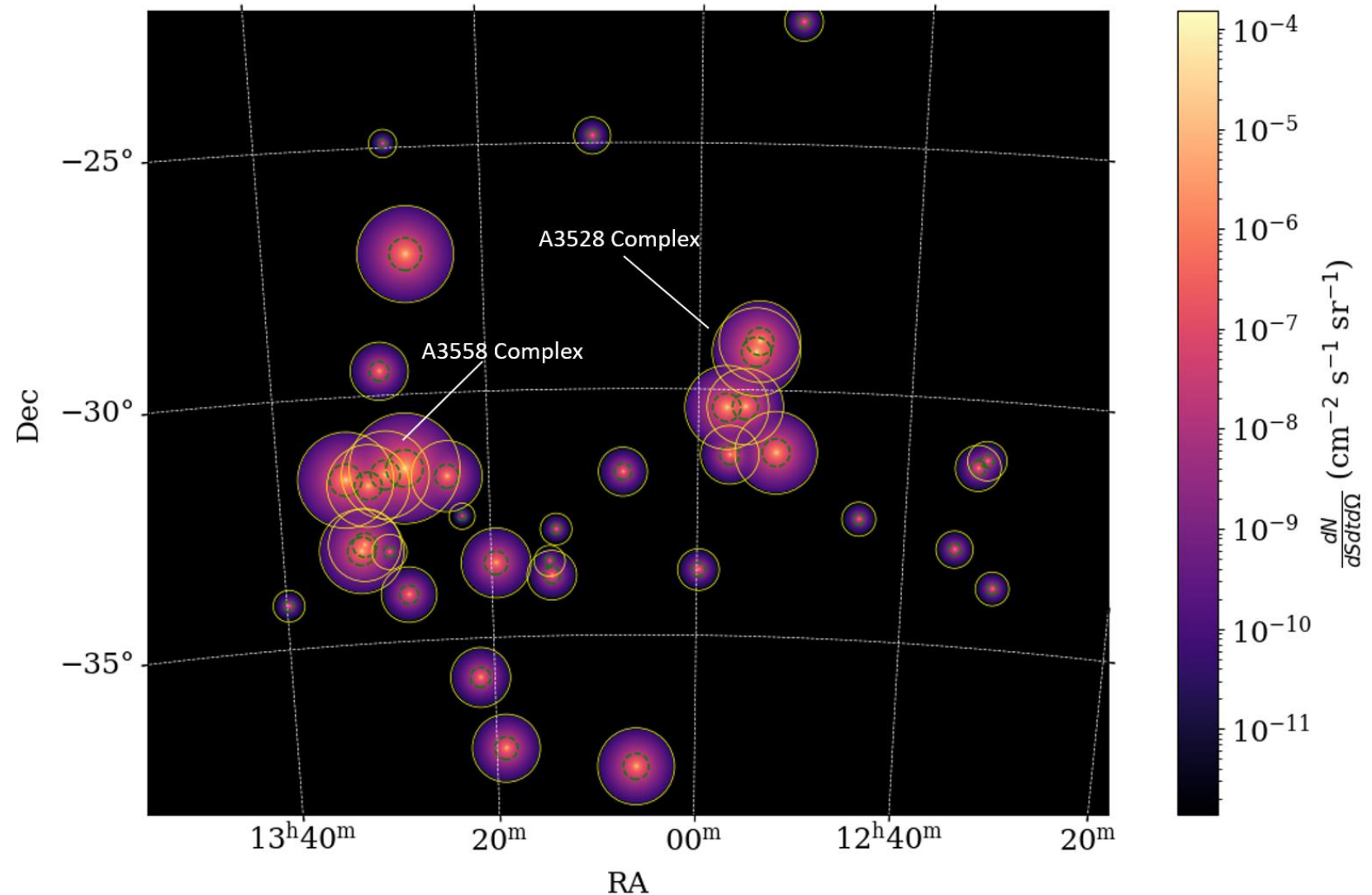
- Binomial Test: Probability of finding a signal from 47 AGNs too weak to be identified individually
- Result: 3.3σ excess for 11 sources (excluding NGC1068)

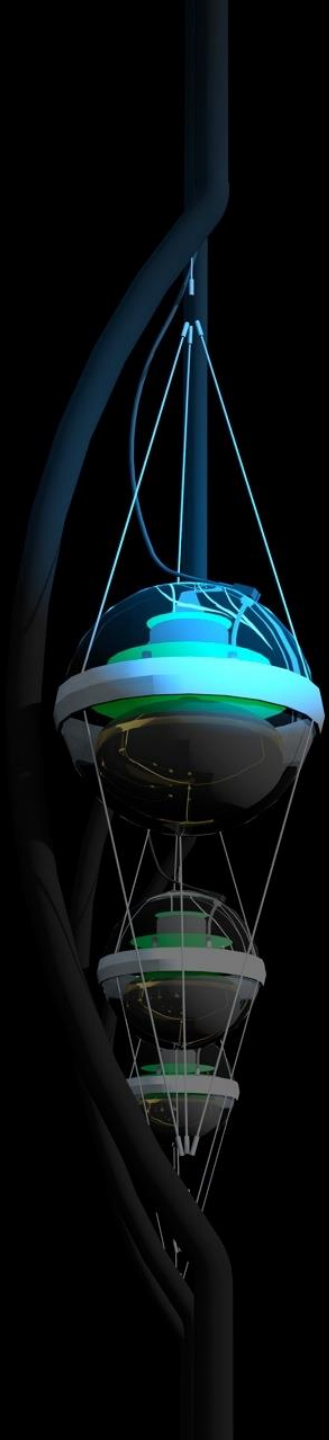
solution to the extragalactic cosmic ray problem?

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

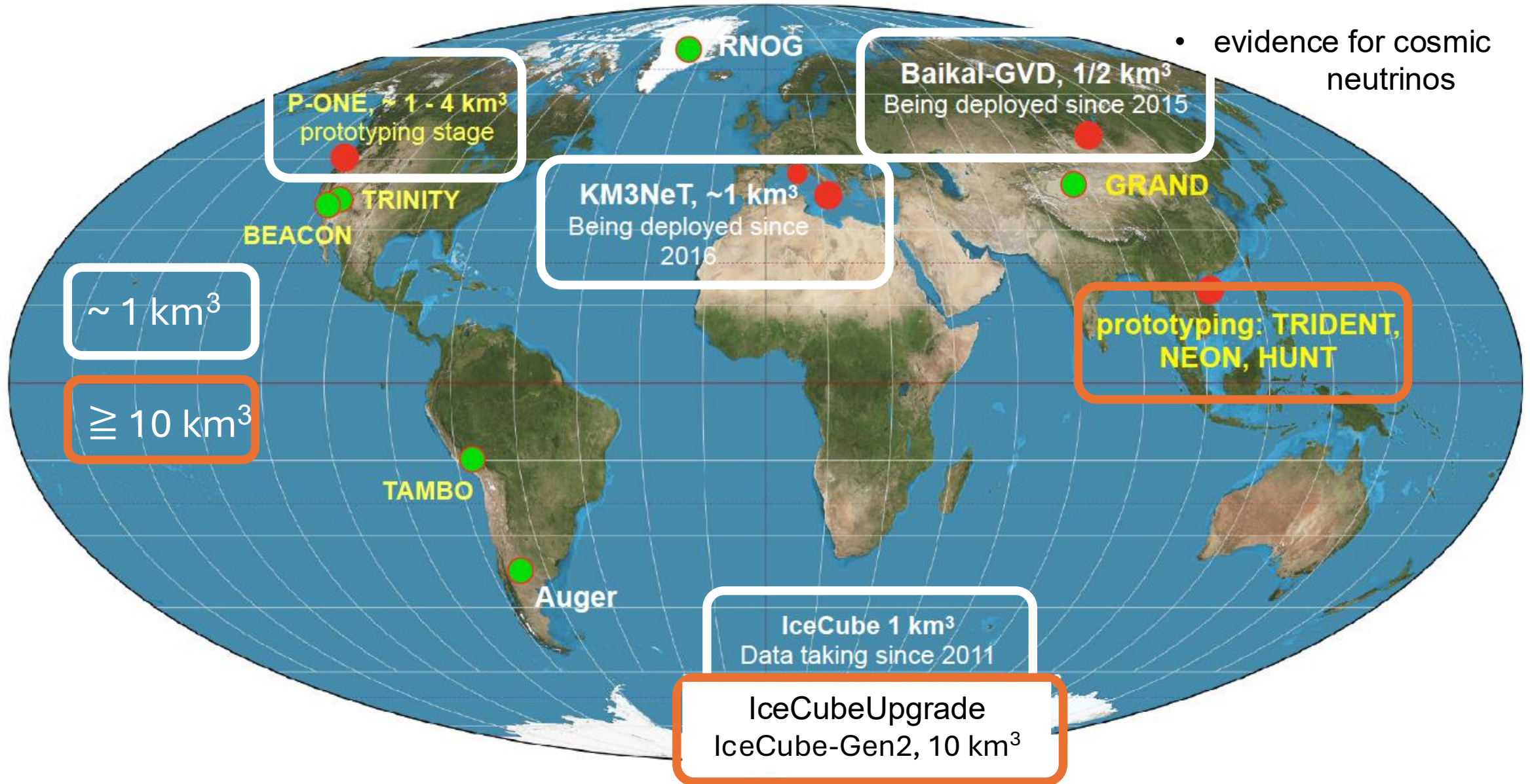




neutrino astronomy 2025

- 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!



- evidence for cosmic neutrinos

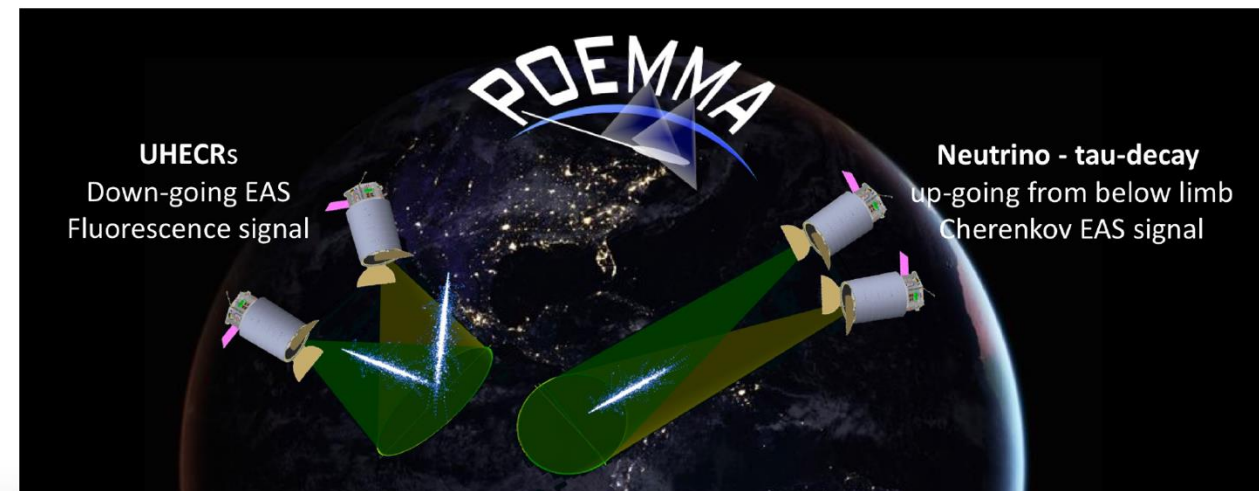
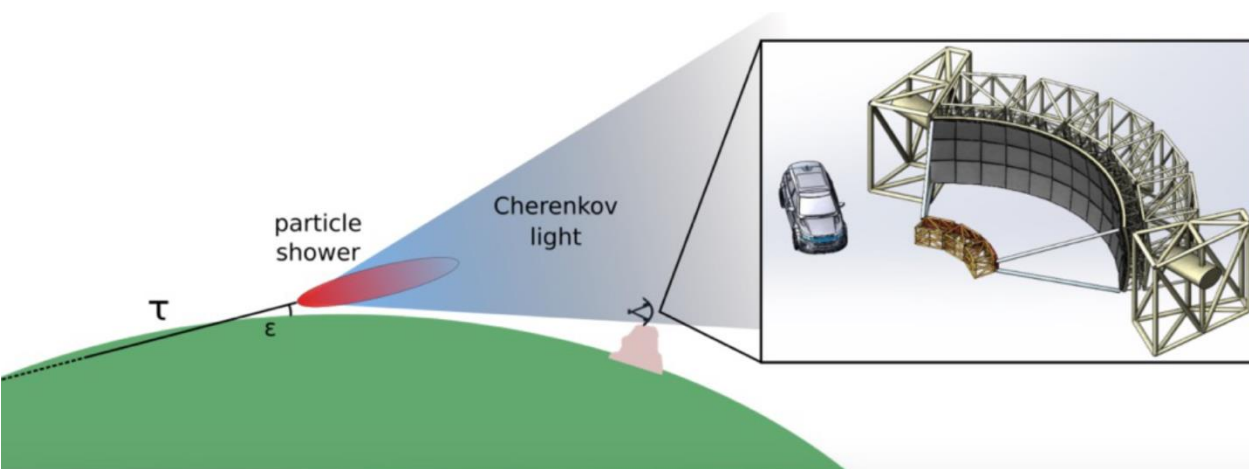
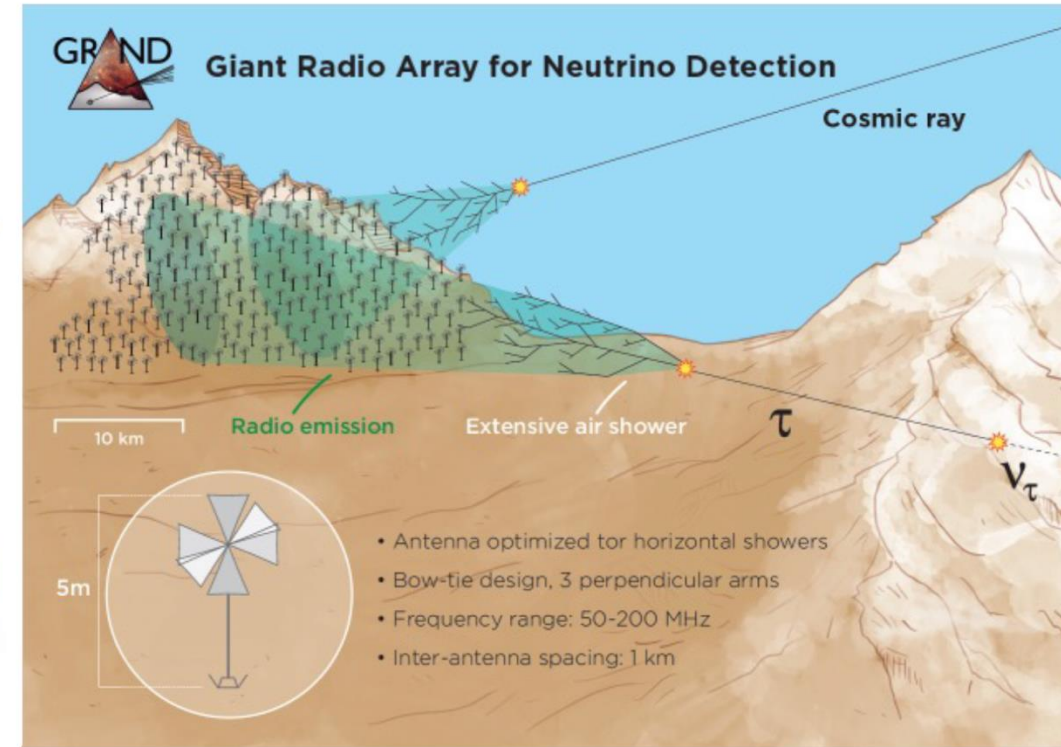
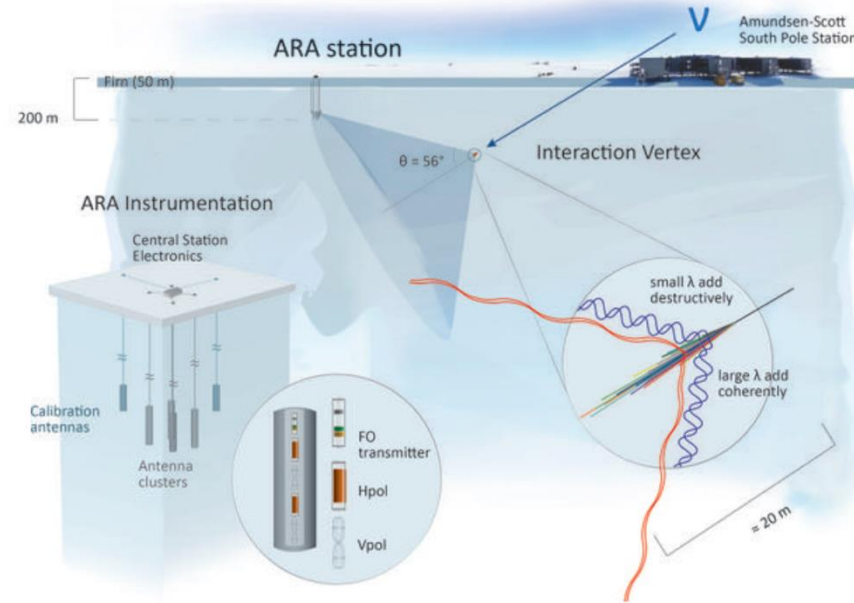
- megaton GeV detectors: IceCube Upgrade, ORCA, HUNT

- EeV detectors

Ultra-high energy neutrinos

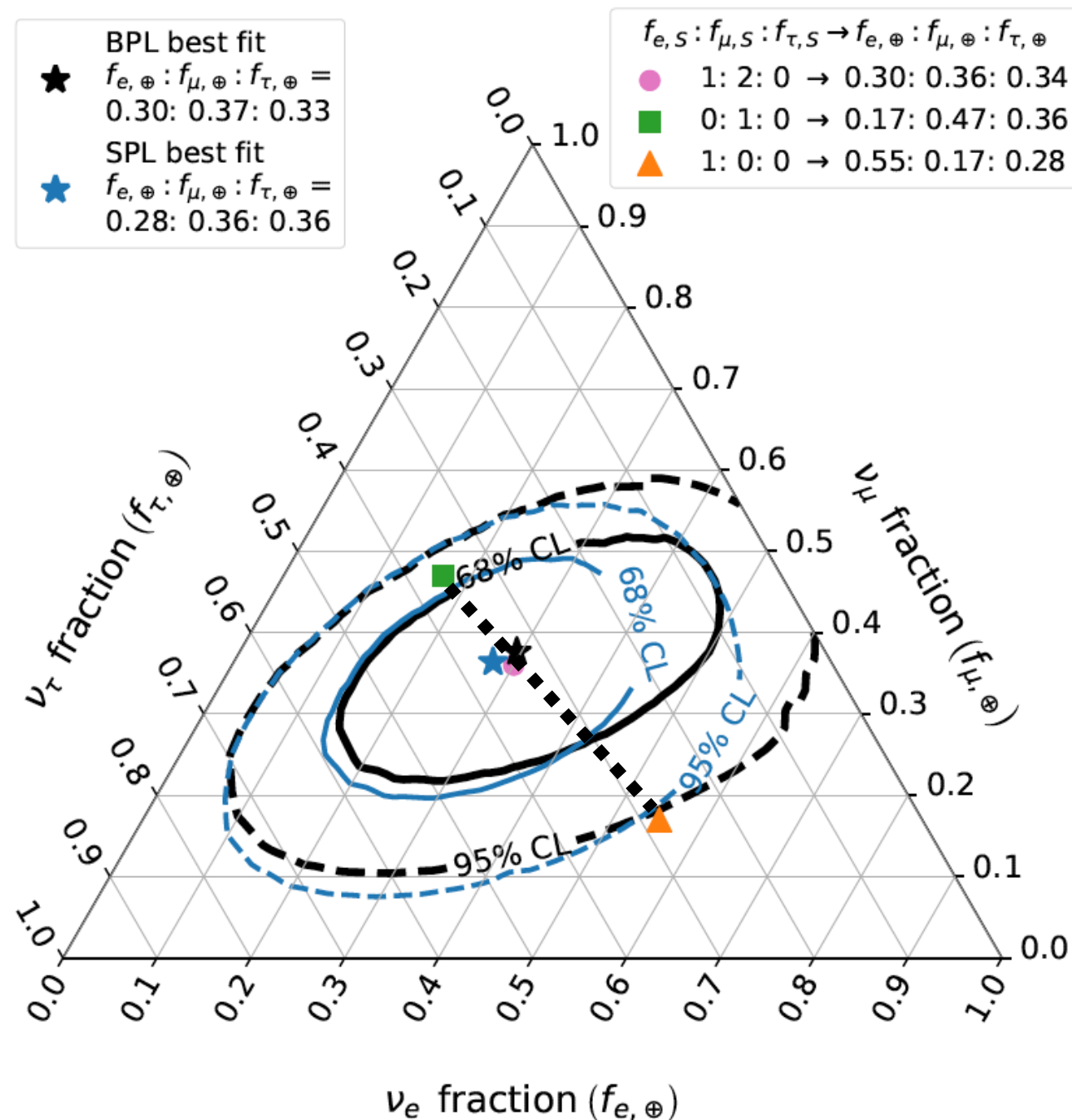


Detection of ultrahigh-energy neutrinos in ARA

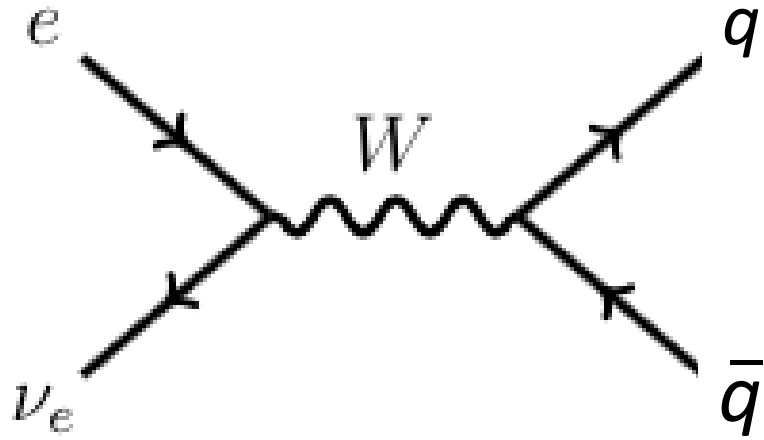


particle physics:

- 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
- ...

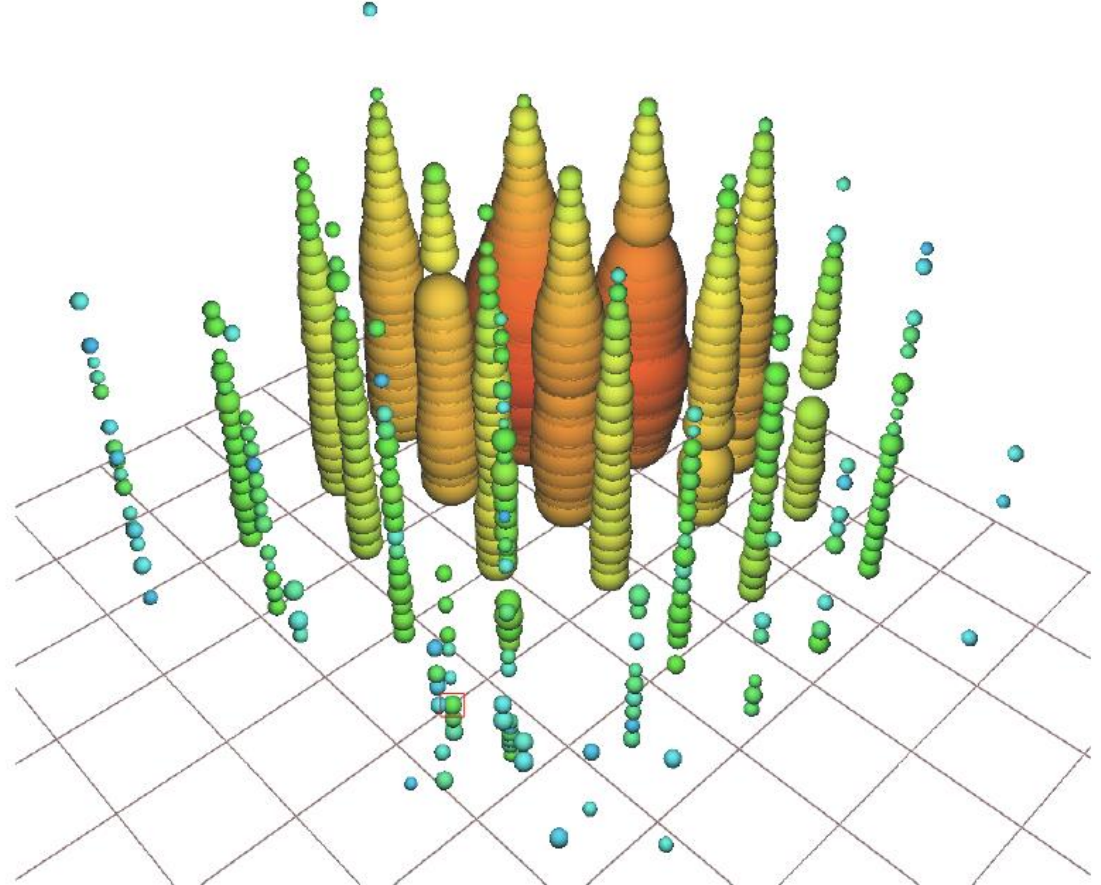


Glashow resonance event with energy 6.3 PeV

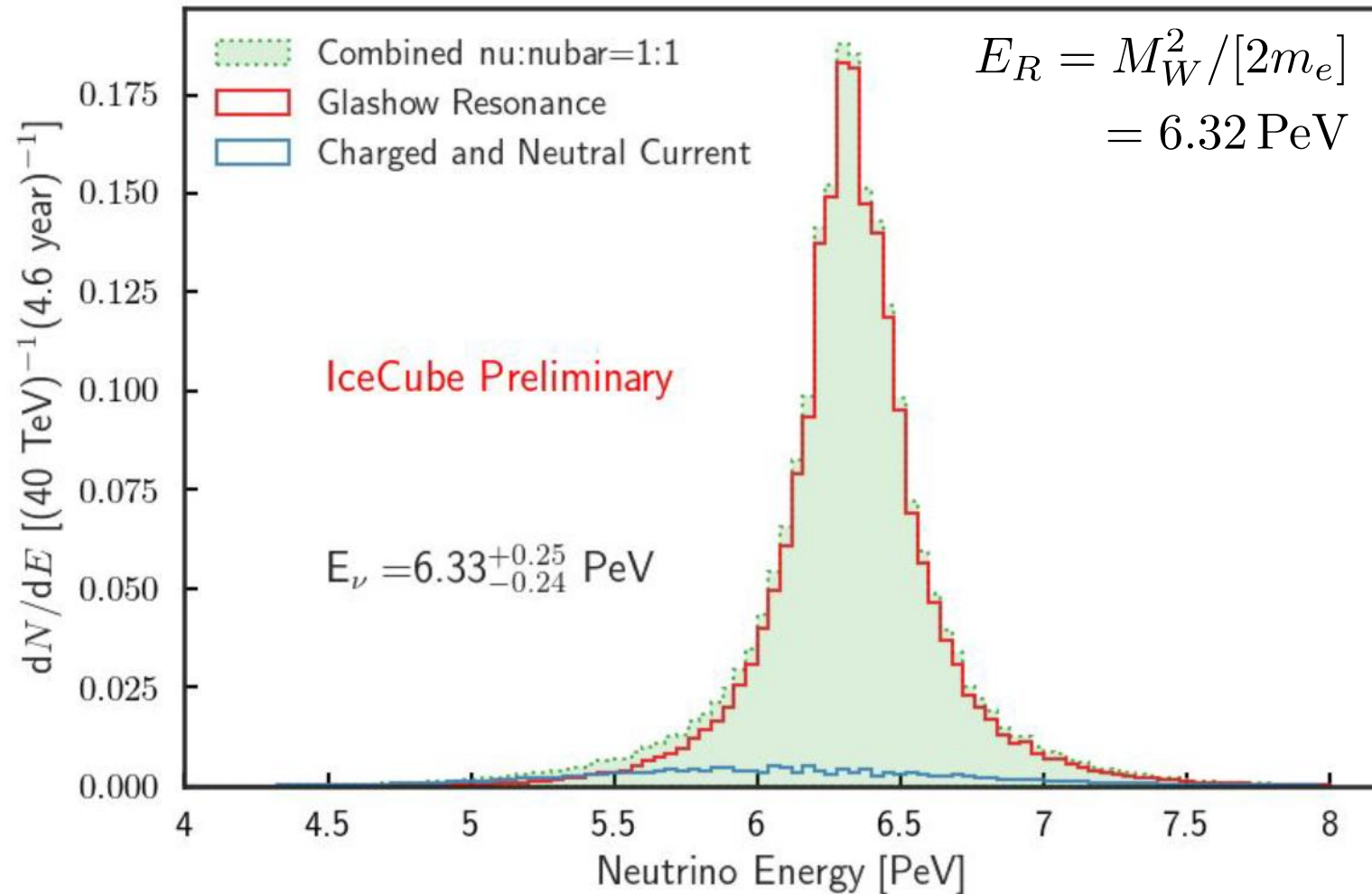
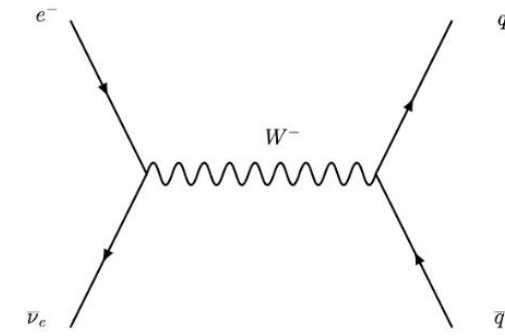


$$E_R = M_W^2 / [2m_e] \\ = 6.32 \text{ PeV}$$

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

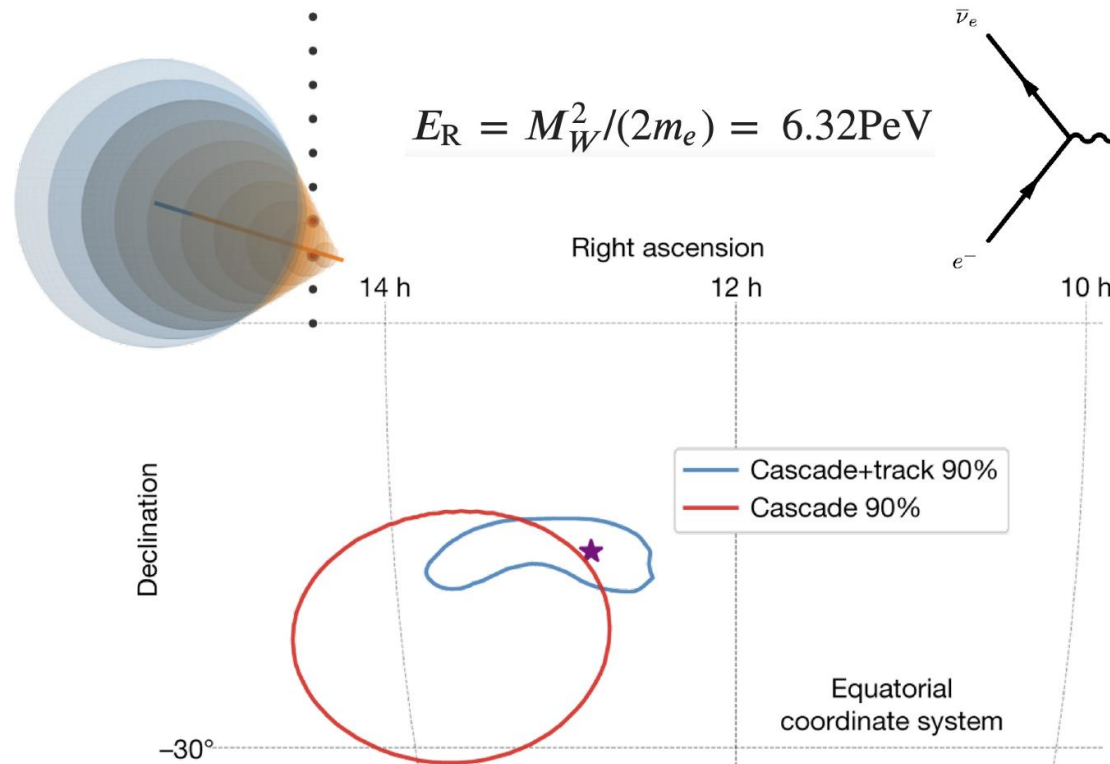


- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino

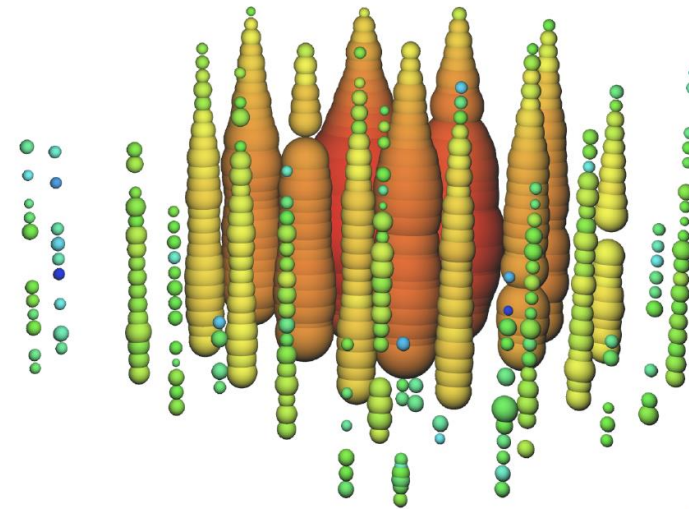


First hint of W boson resonance in data (Glashow resonance)

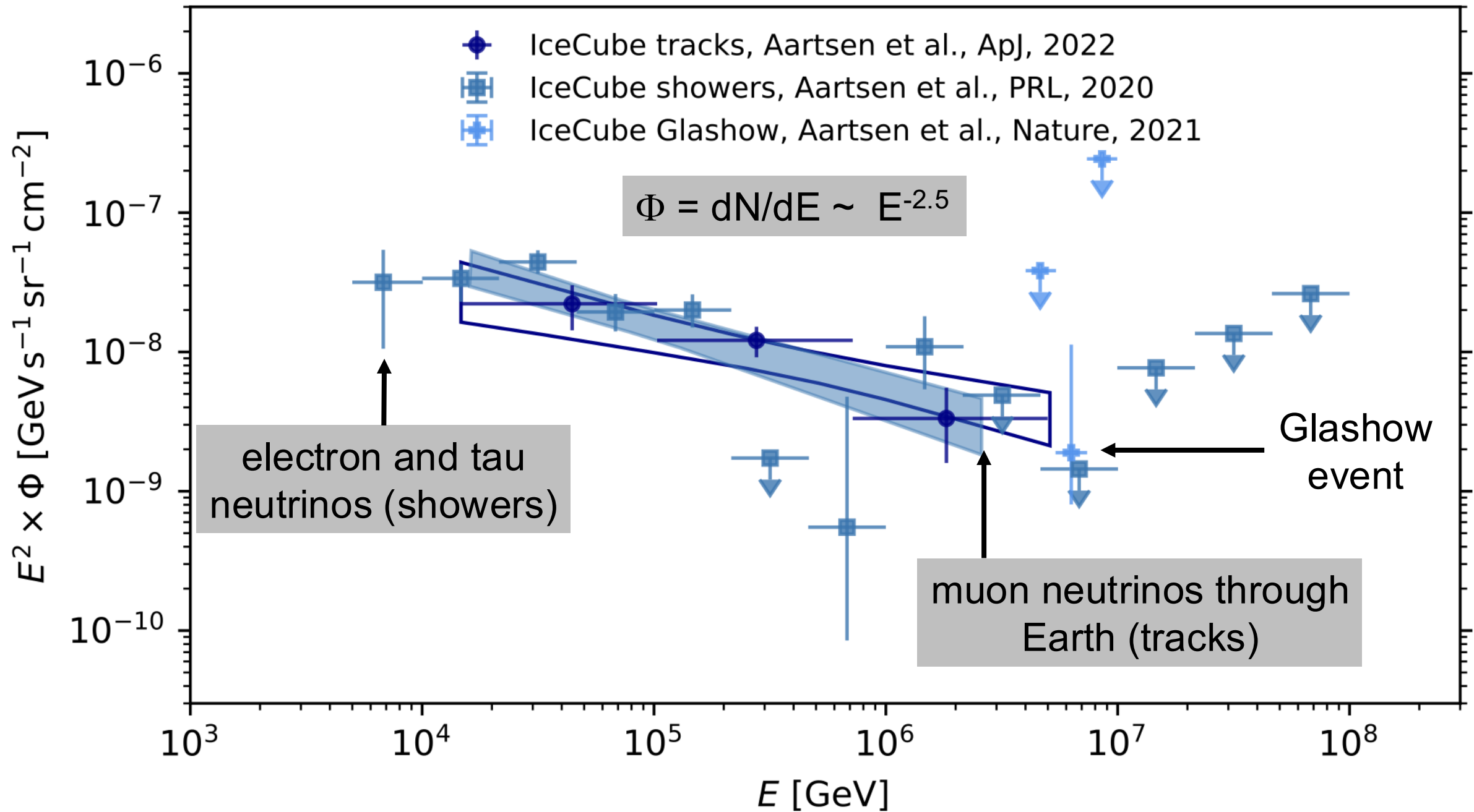
Nature **591**, 220–224 (2021)



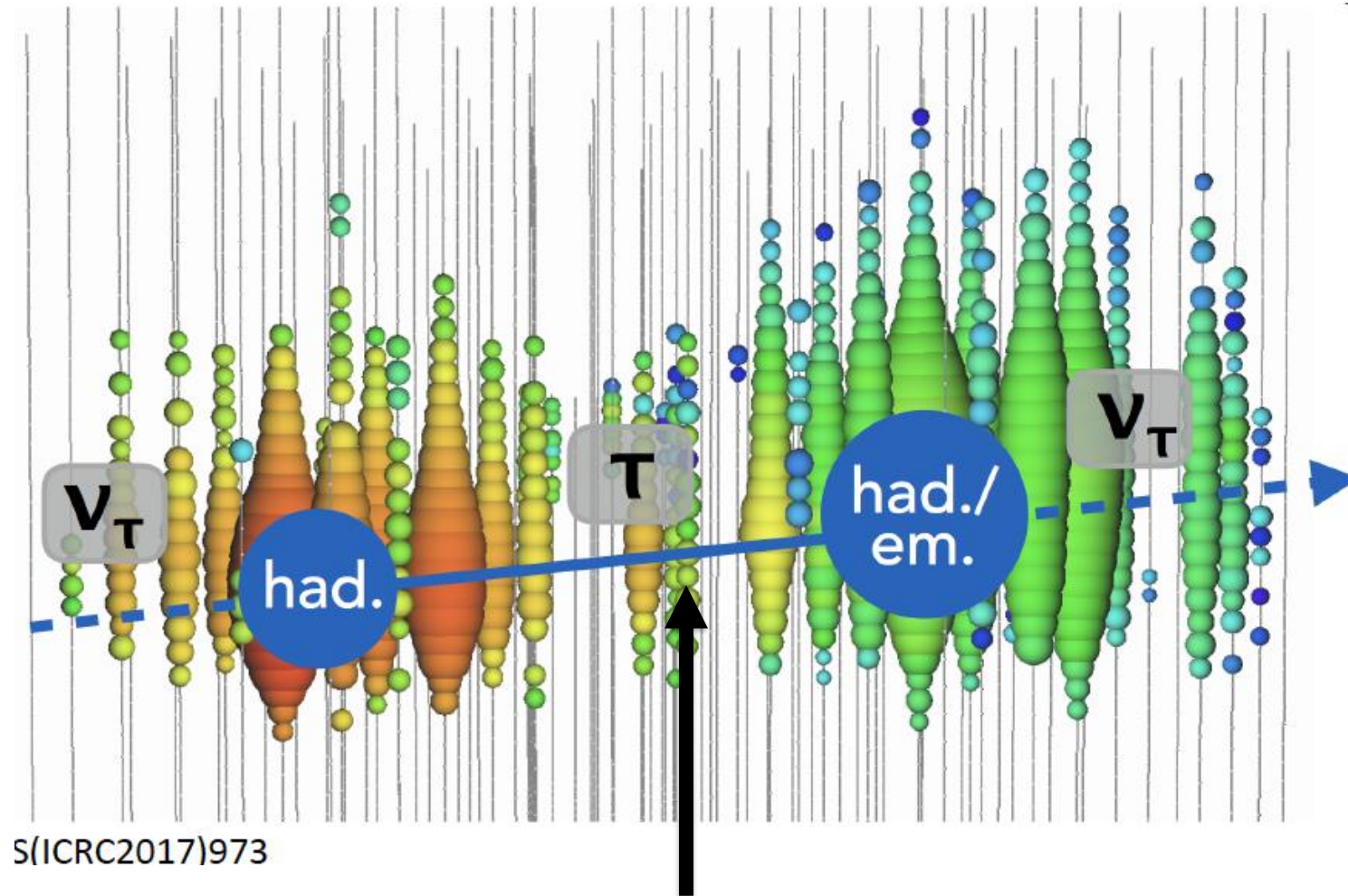
By measuring $\nu/\bar{\nu}$ -> probe source environment directly (magnetic field, pp/pgamma)



Identified muonic component from the hadronic shower
angular uncertainty contour shrinks by a factor of 5 with hybrid reco



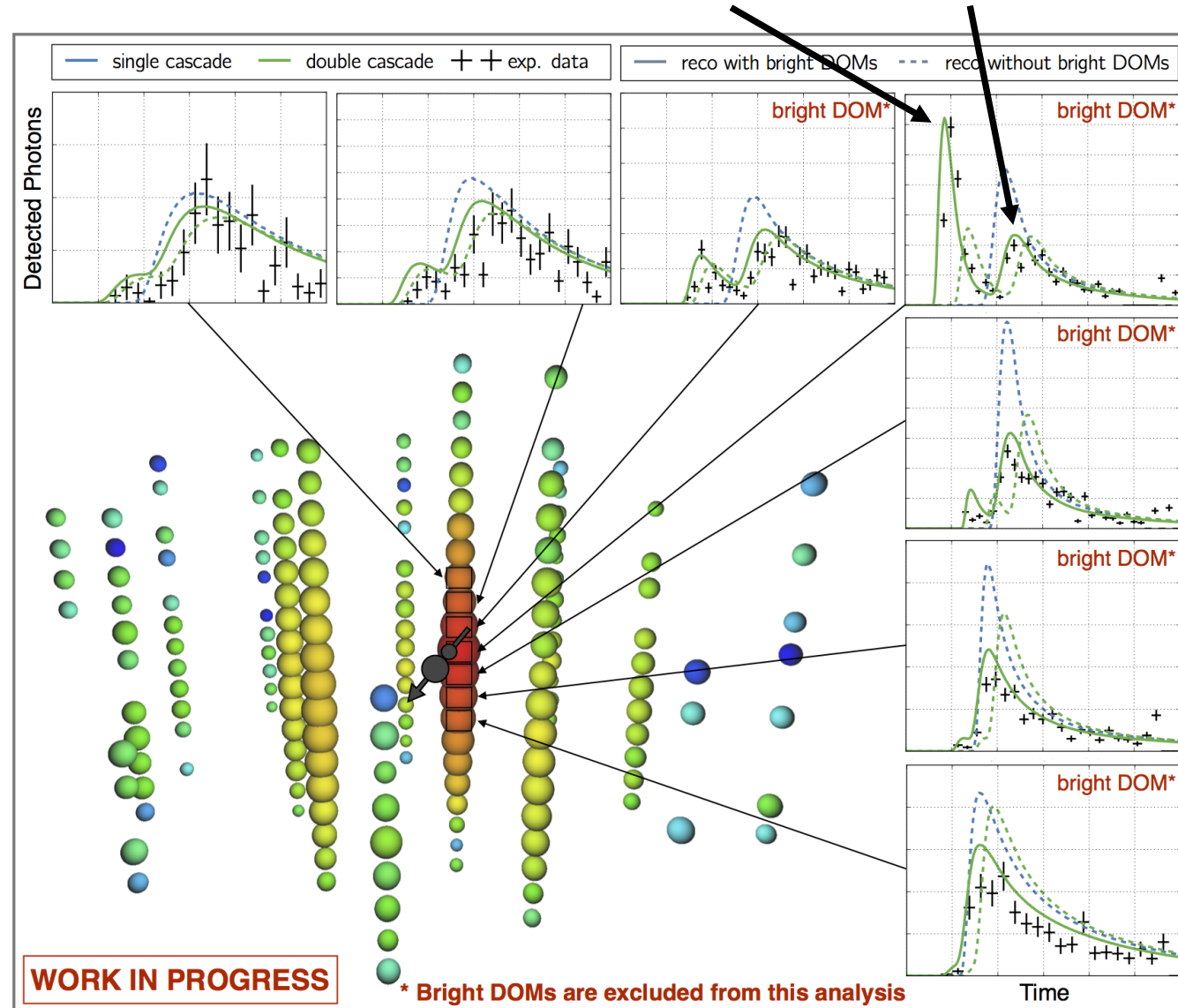
tau neutrino production and decay



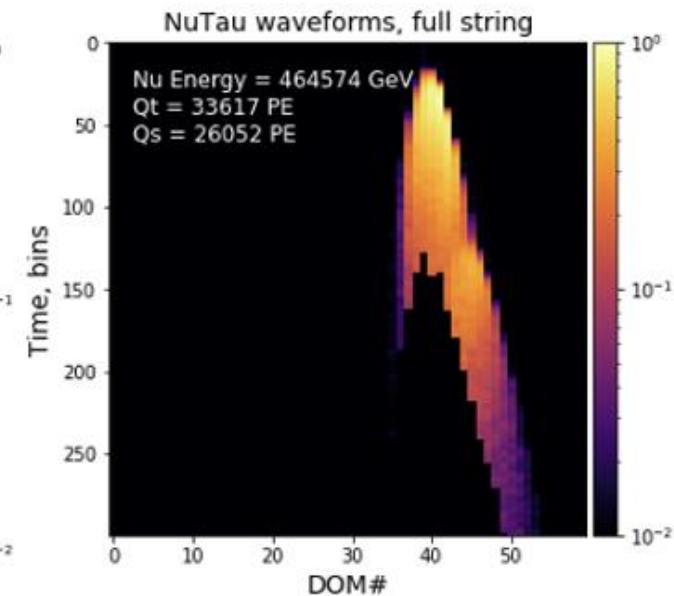
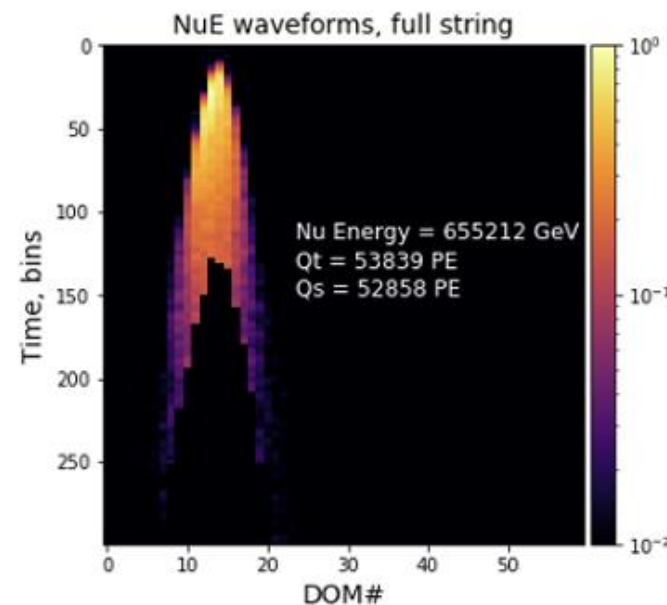
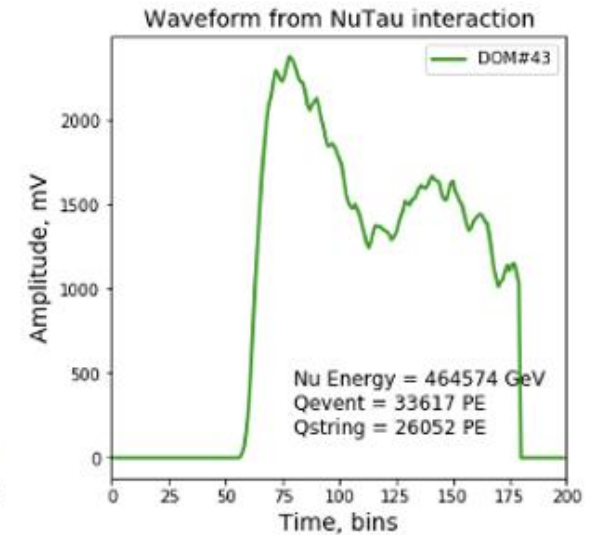
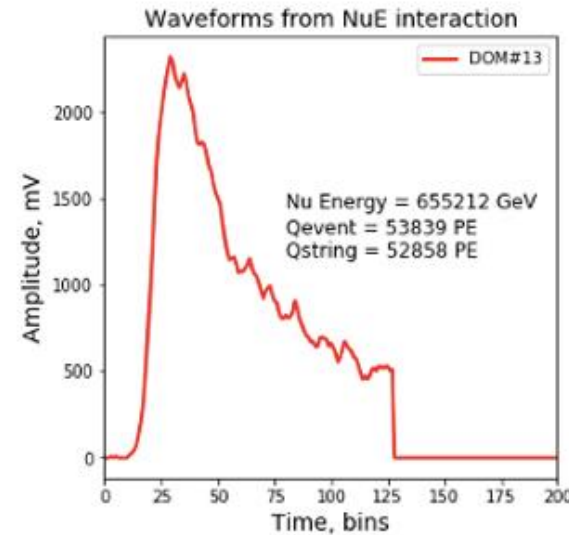
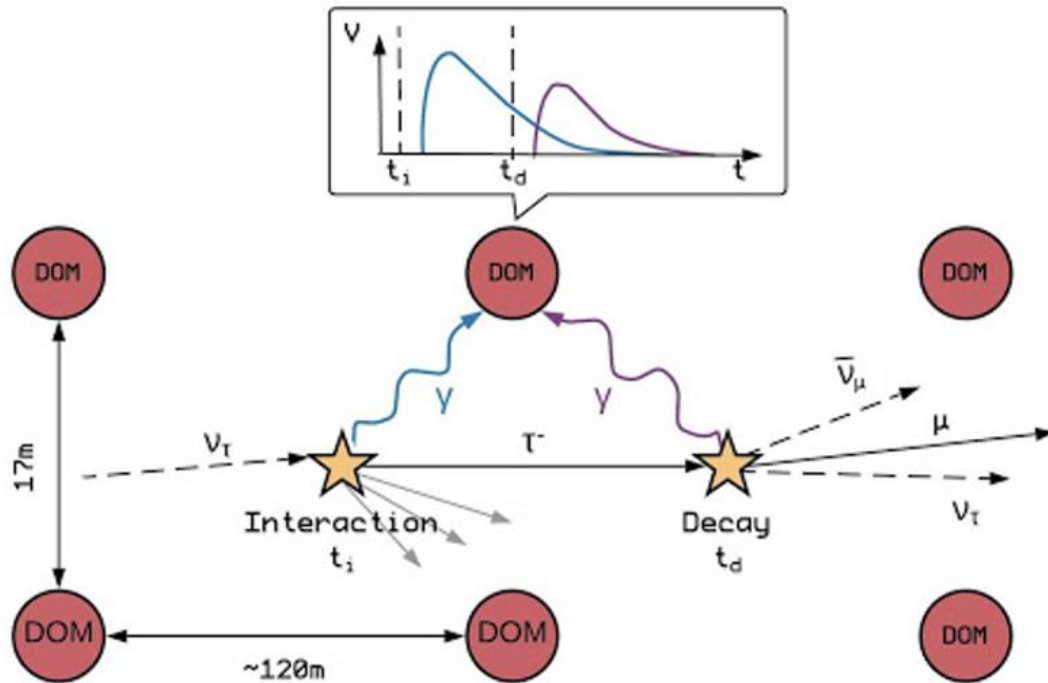
tau decay length:
 $\gamma c \tau = 50\text{m per PeV}$

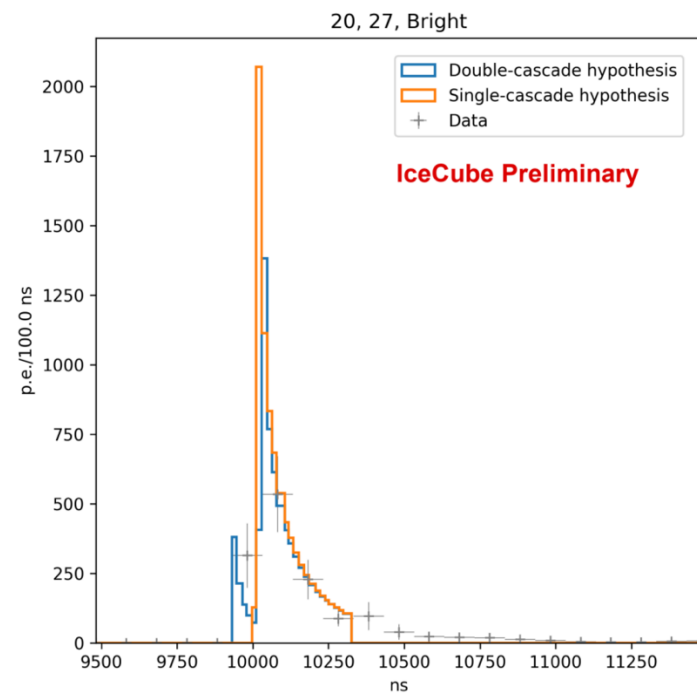
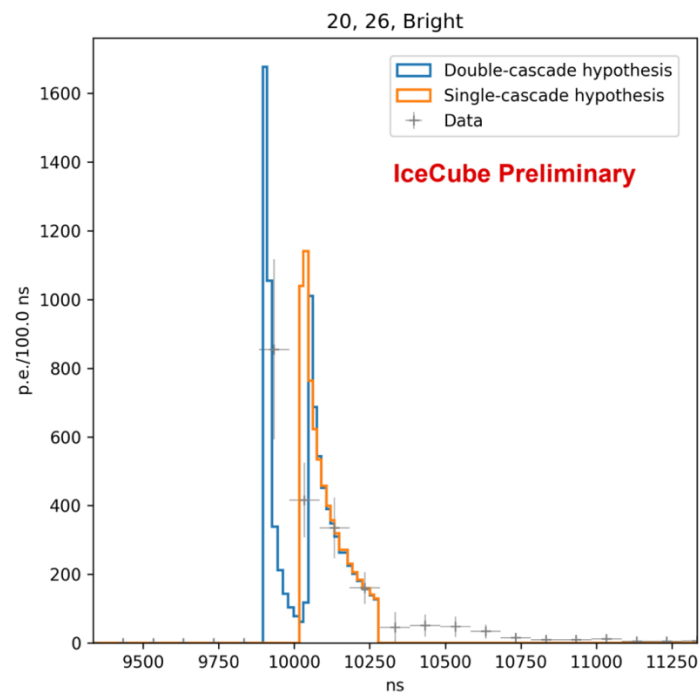
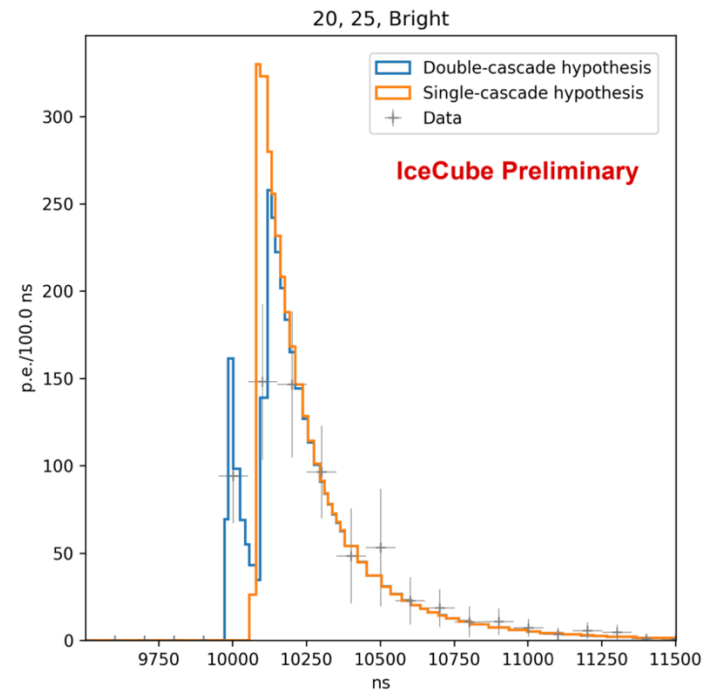
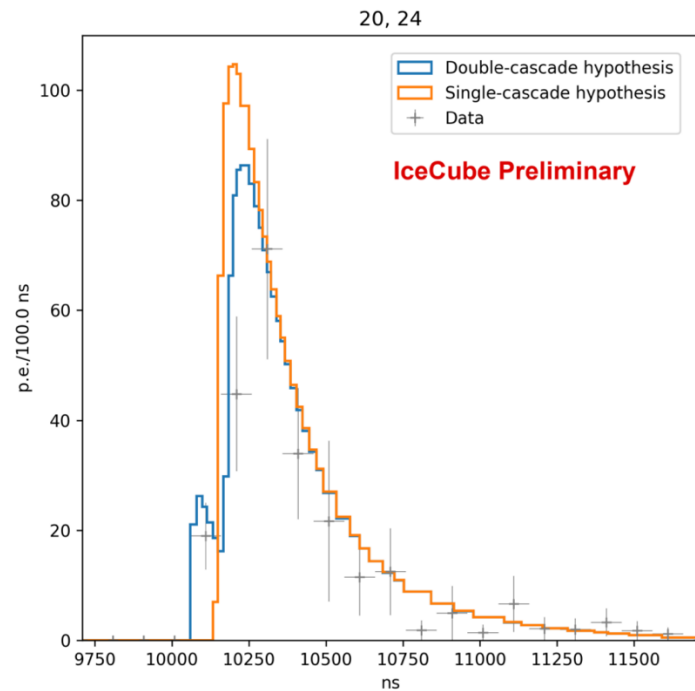
a cosmic tau neutrino with 17m lifetime

light from nutau interaction and tau decay

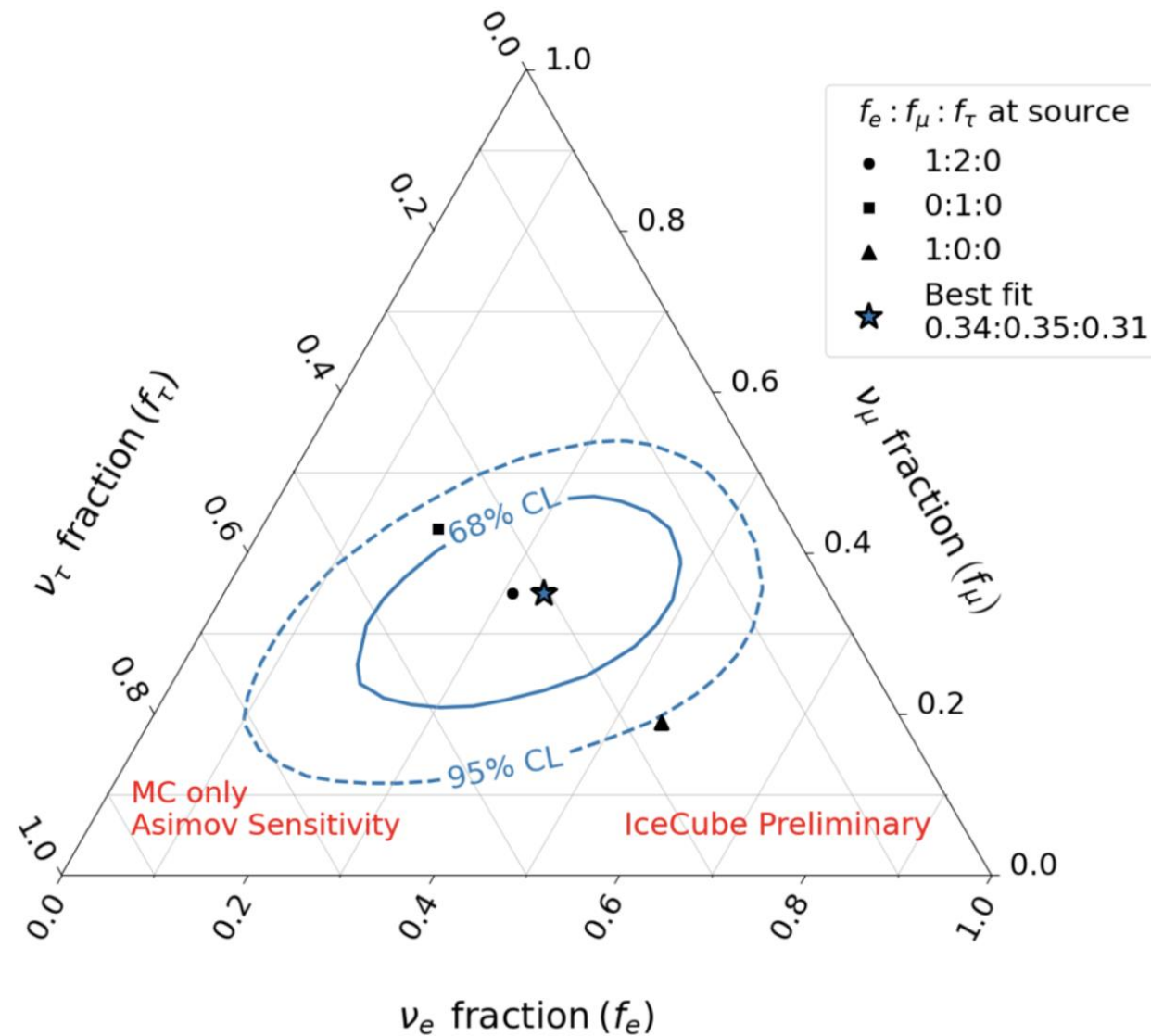
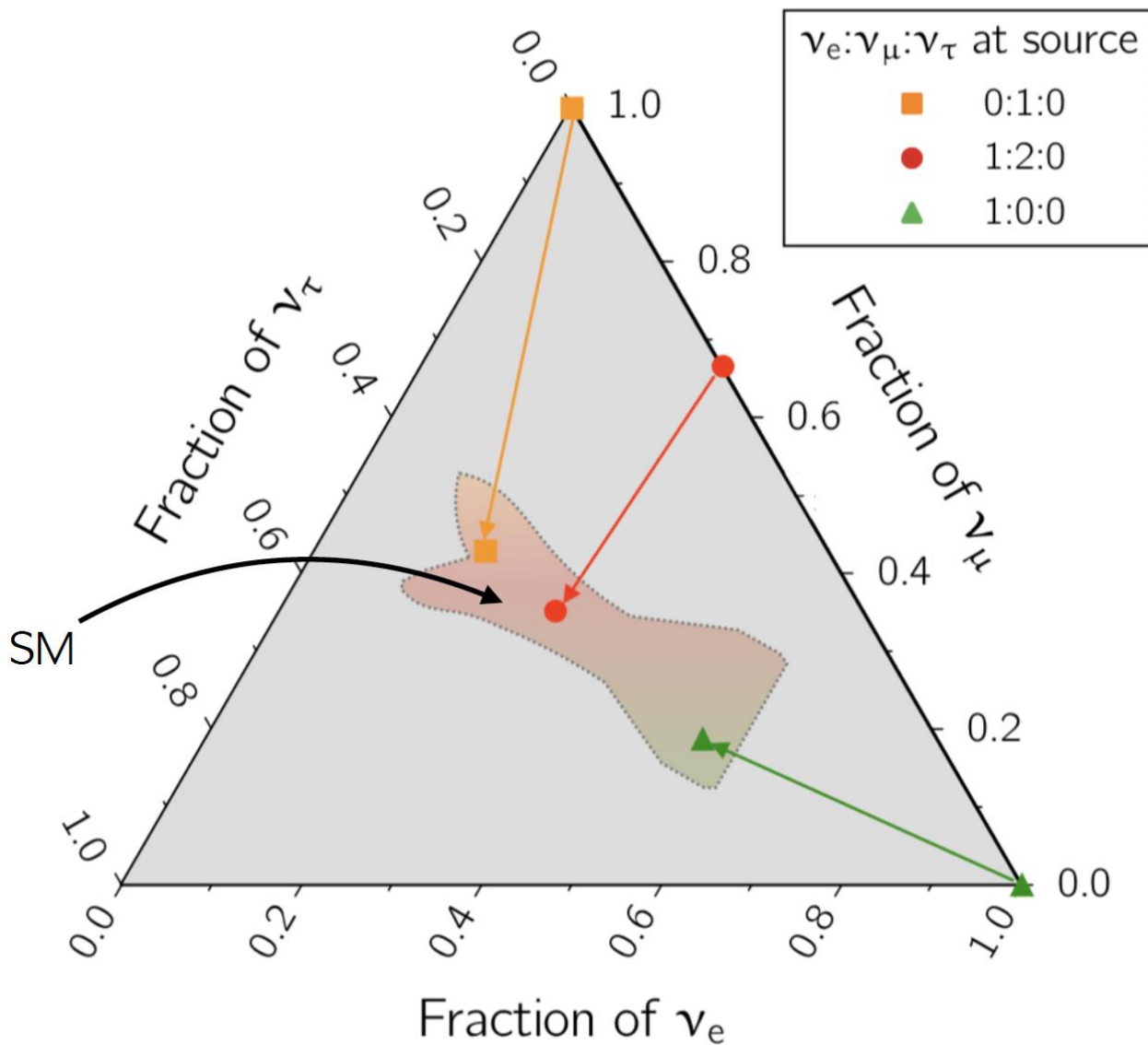


- double bang events: 8 predicted on a background of 1 and 7 observed
 - each nutau event is an extragalactic neutrinos search

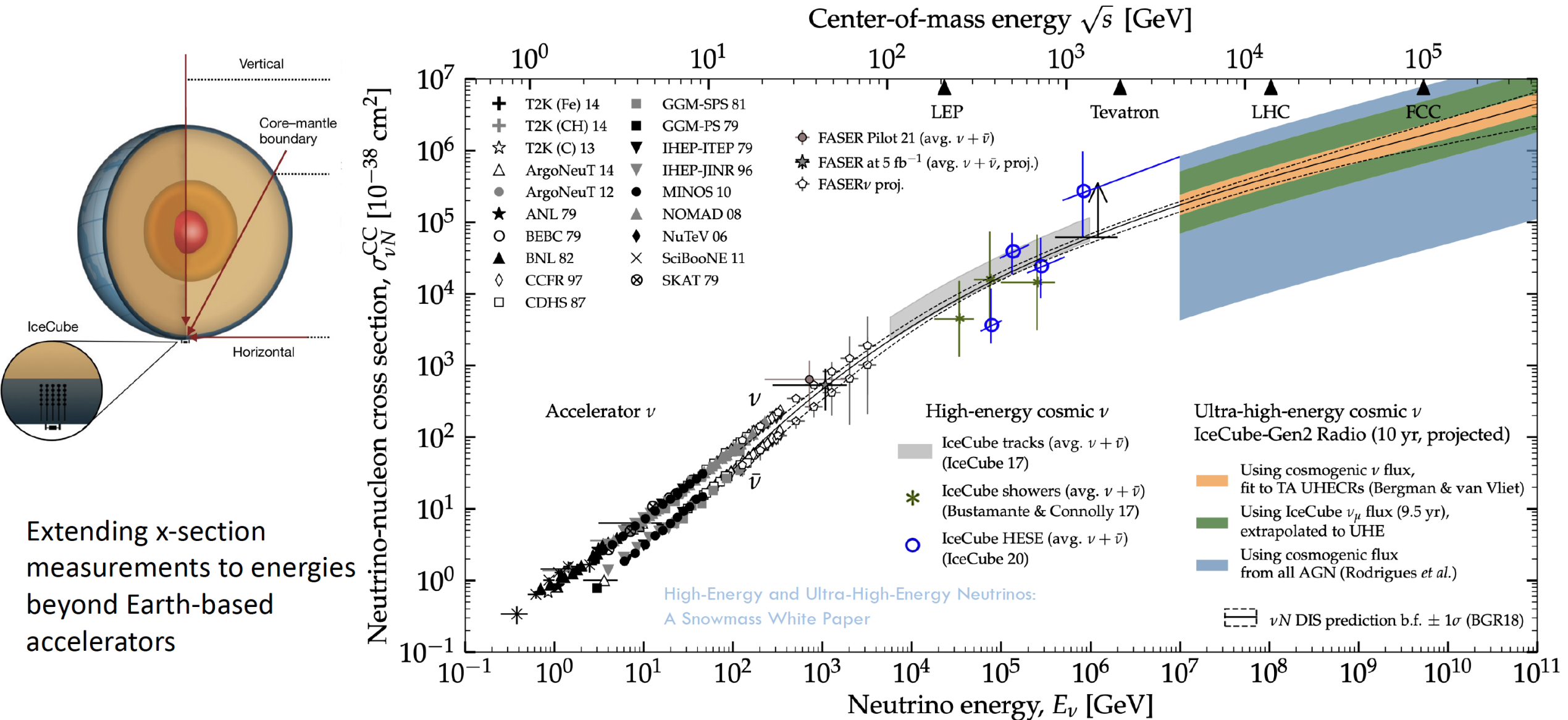




oscillations of PeV neutrinos over cosmic distances to 1:1:1

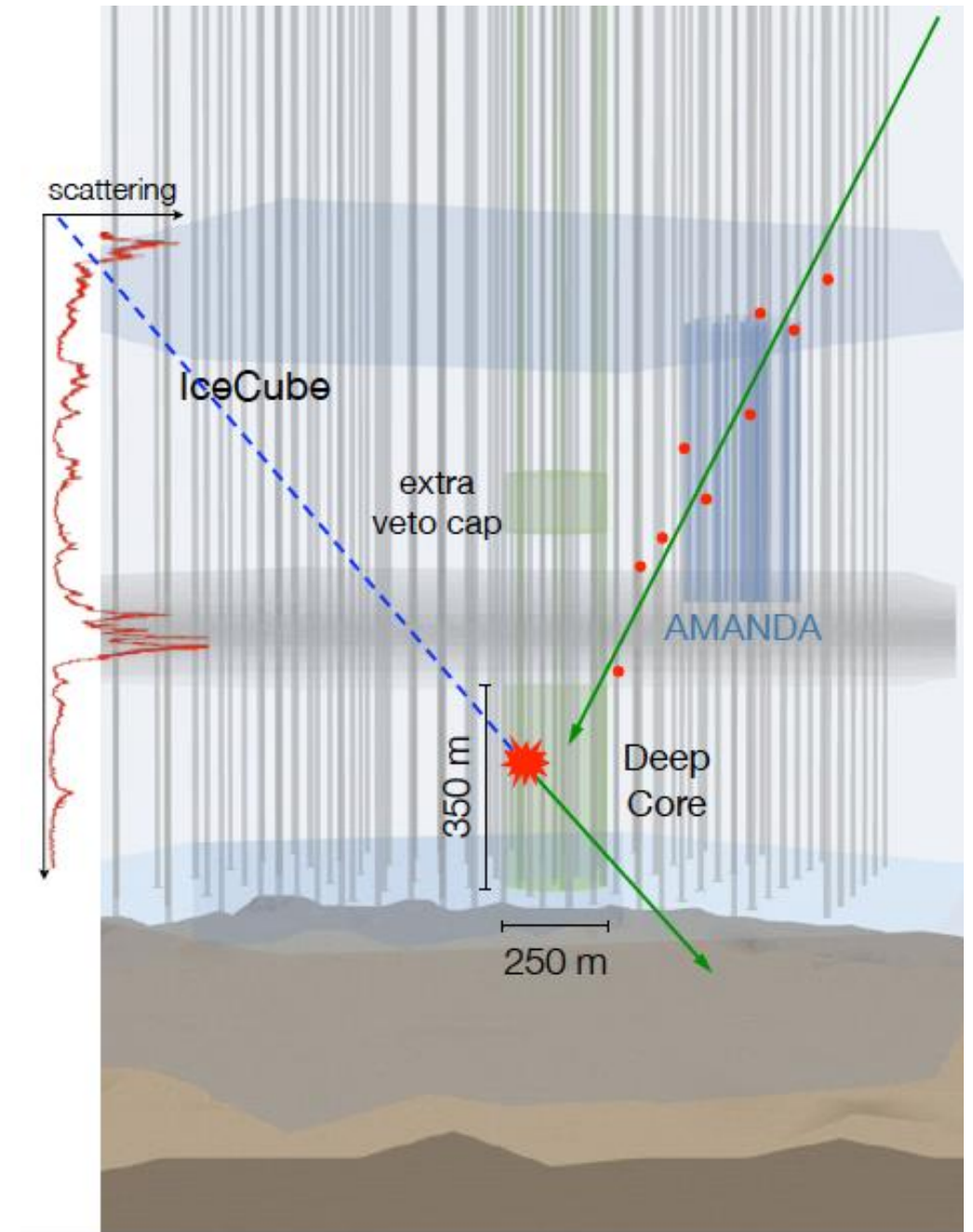
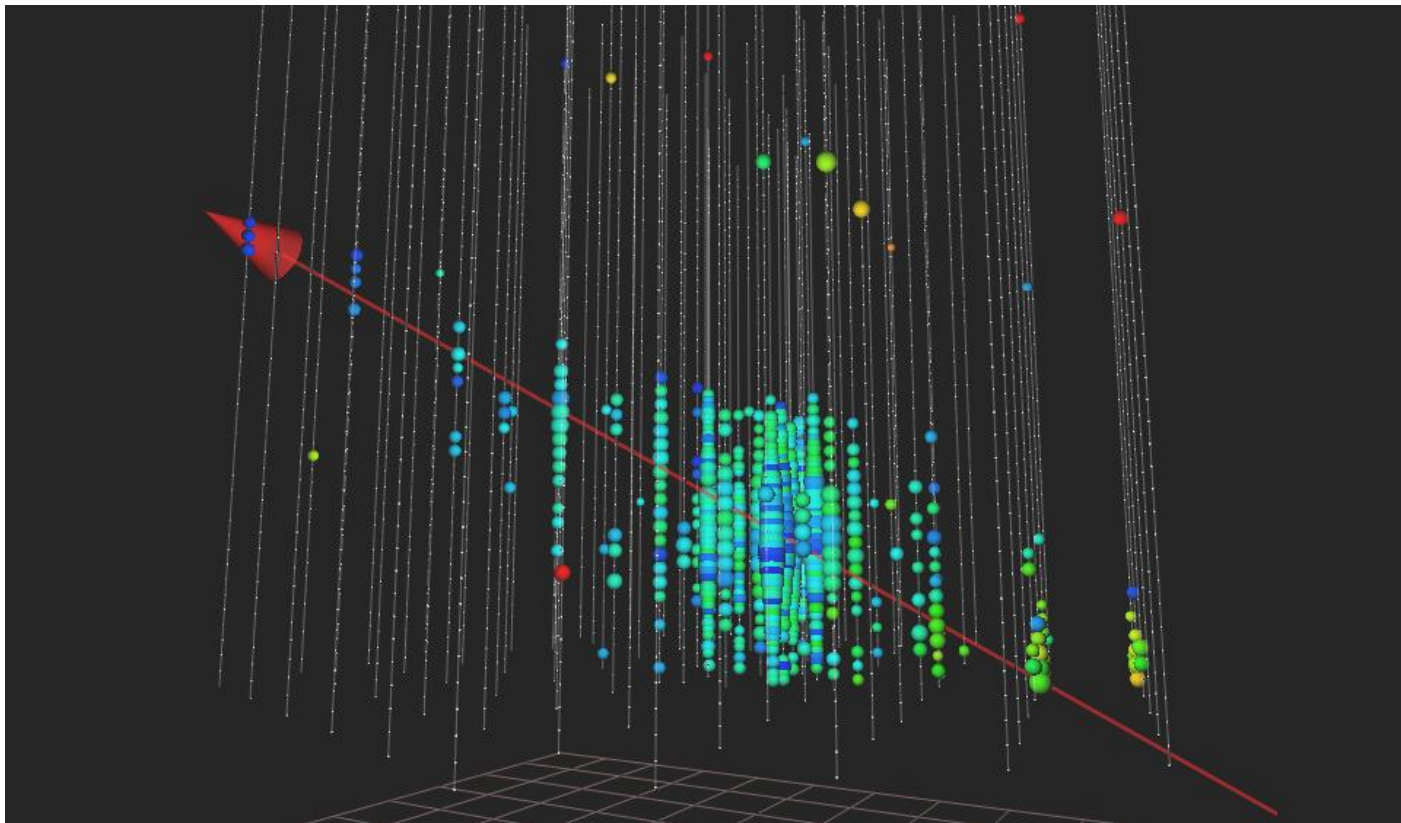


CROSS SECTION WITH EARTH AS THE TARGET



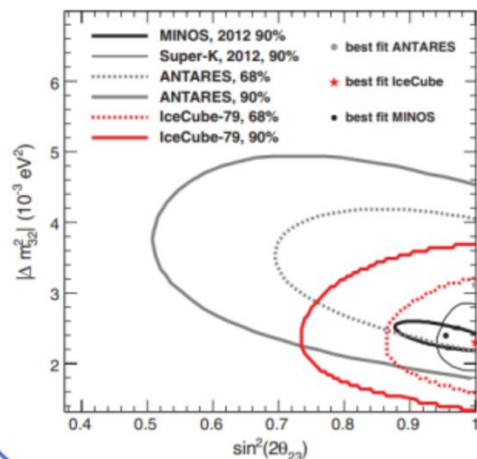
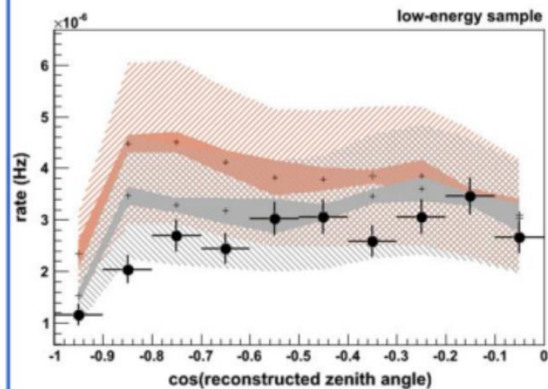
one million atmospheric
neutrinos

- 5 GeV threshold
- one event every 15 min
at analysis level
- 2 megaton detector

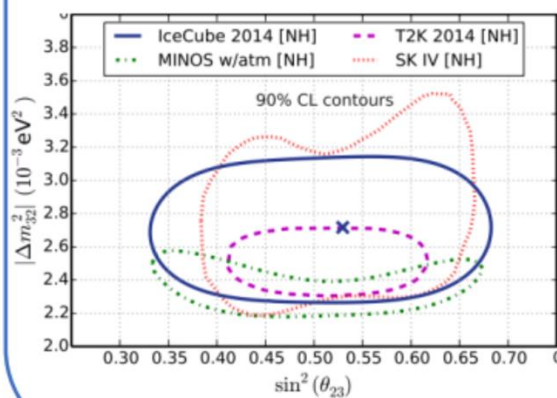
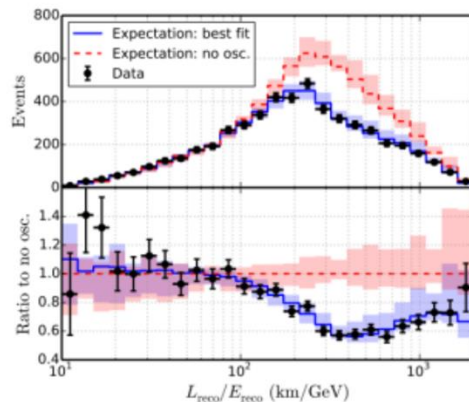


Atmospheric oscillations progression

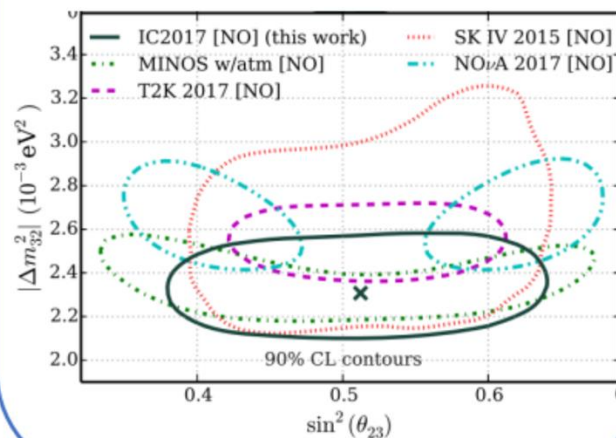
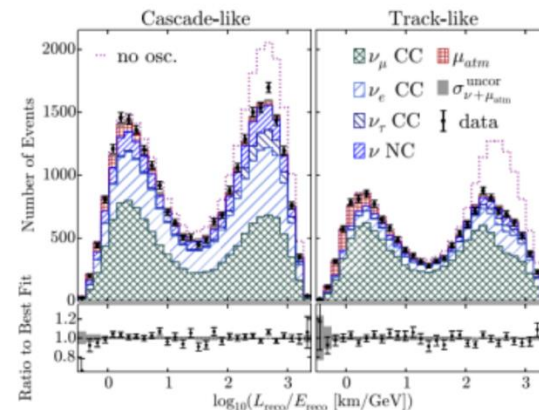
IceCube, PRL 111, 081801 (2013)
700 events



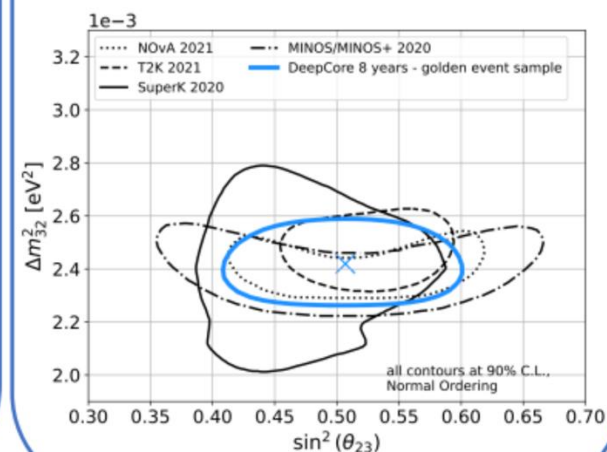
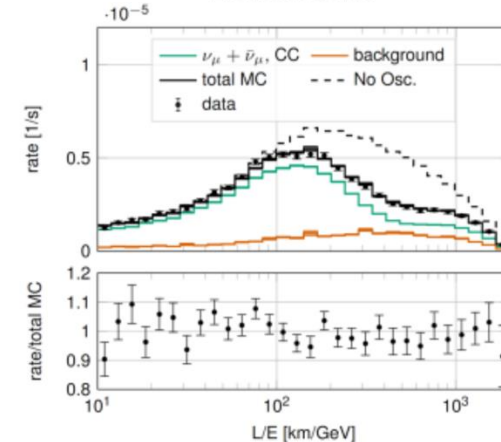
IceCube, PRD 91, 072004 (2015)
~5k events



IceCube, PRL 120, 071801 (2018)
~35k events



IceCube, PRD 108, 012014 (2023)
~22k events

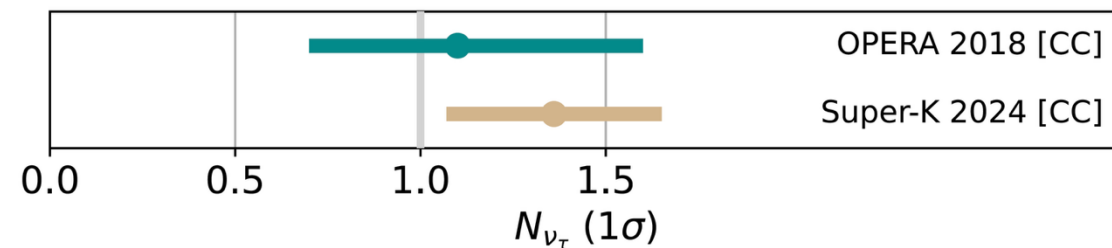
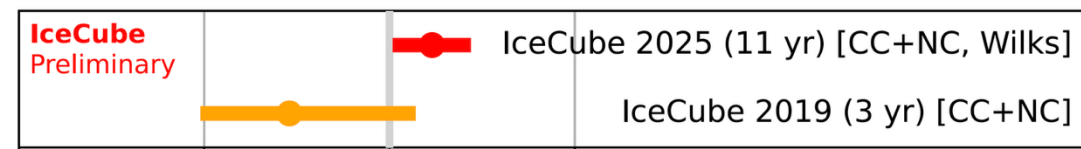
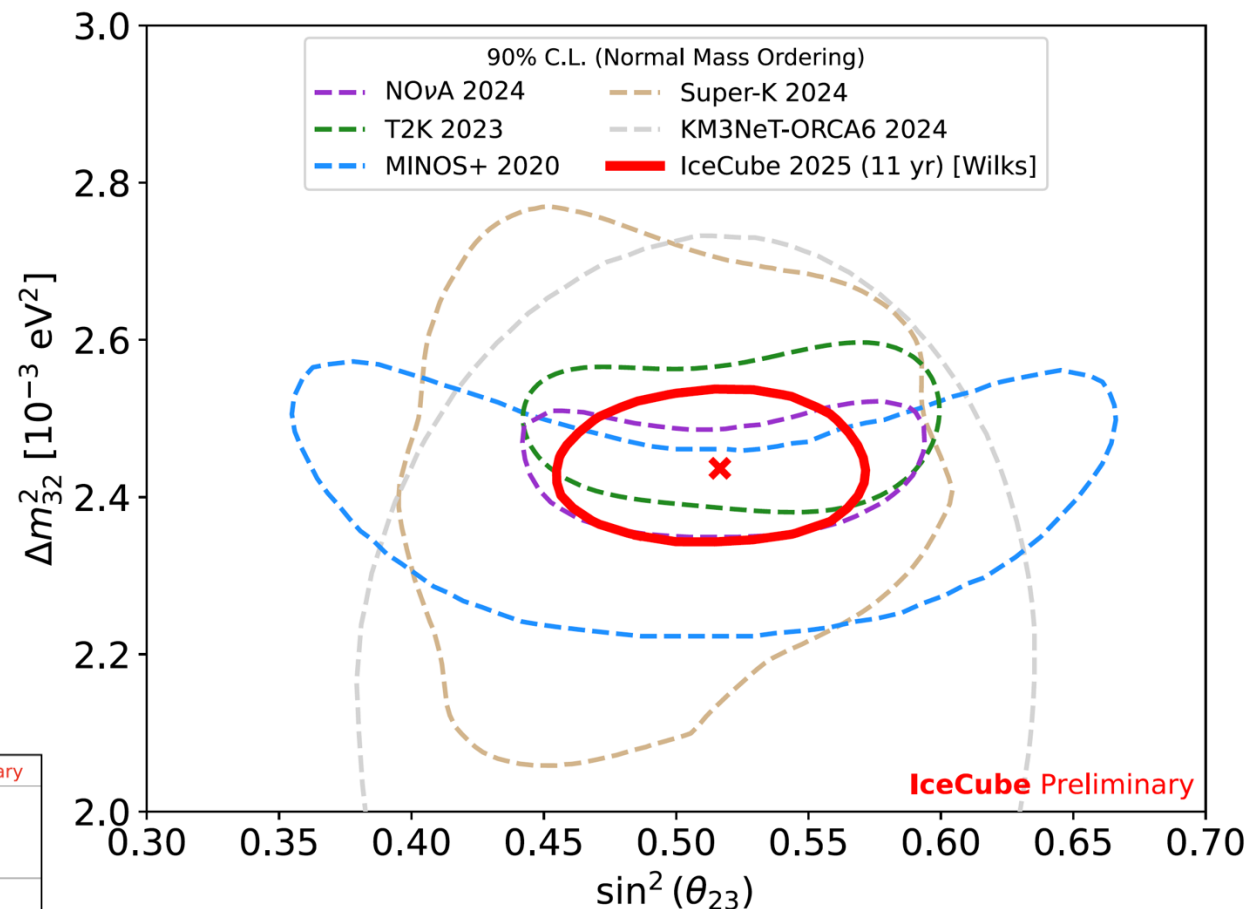
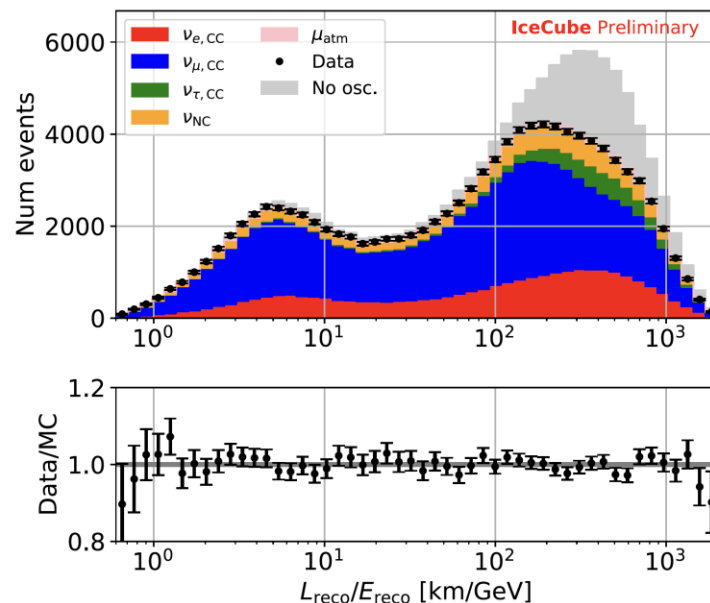


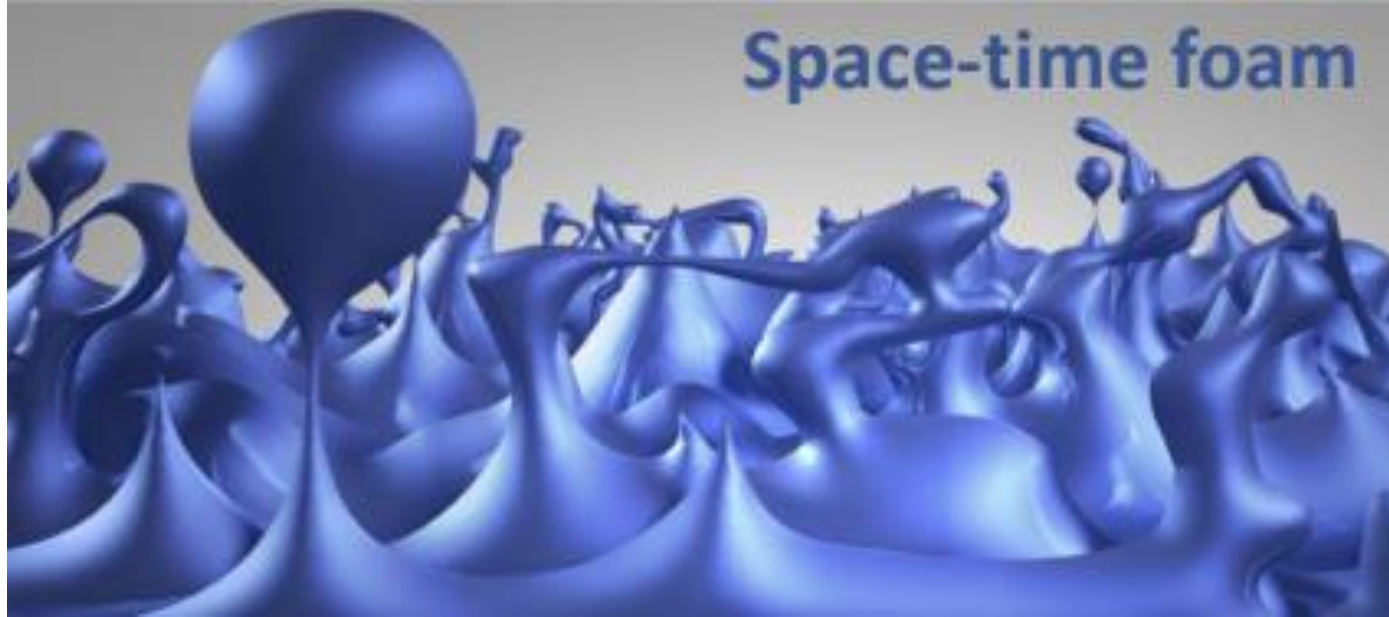
Upgrade next

- large statistics
- low background (IceCube veto)
- fit both the atmospheric flux and the oscillation parameters
- blind analysis

- Broad coverage of L/E phase-space

- Baselines ranging from ~200km to ~12700km
- Reconstructed energies from 5 GeV - 100 GeV





- neutrino decoherence from quantum gravitational space-time fluctuations
- modifies the neutrino dispersion relation over long baselines
- IceCube reaches record sensitivities at the Planck scale even using atmospheric neutrinos
- signature: Lorentz violation

THE ICECUBE COLLABORATION



THE ICECUBE COLLABORATION



ITALIA 1

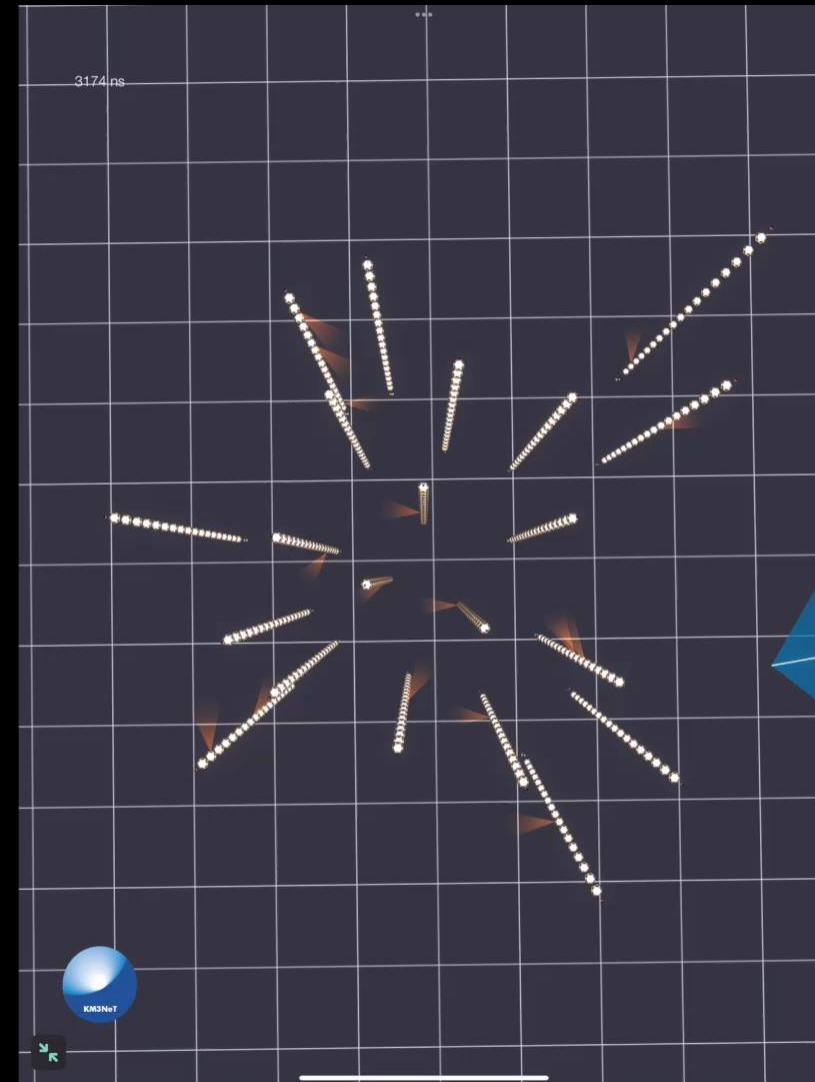
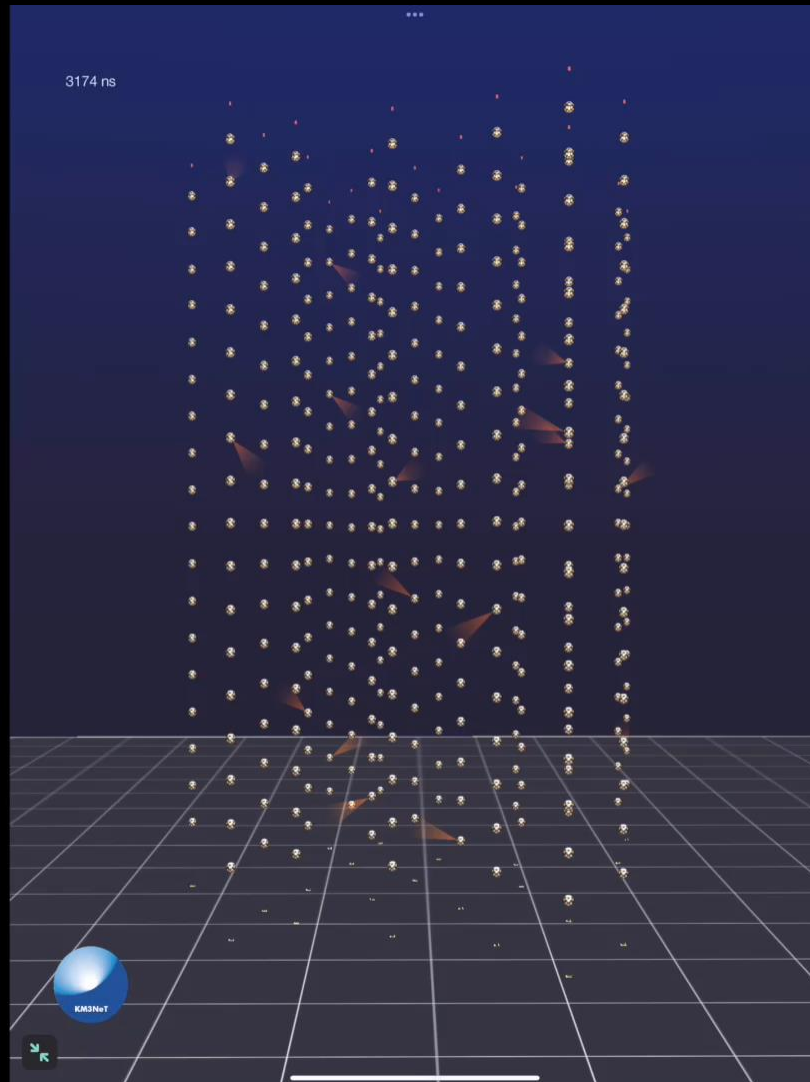
1

UNITED KINGDOM 1

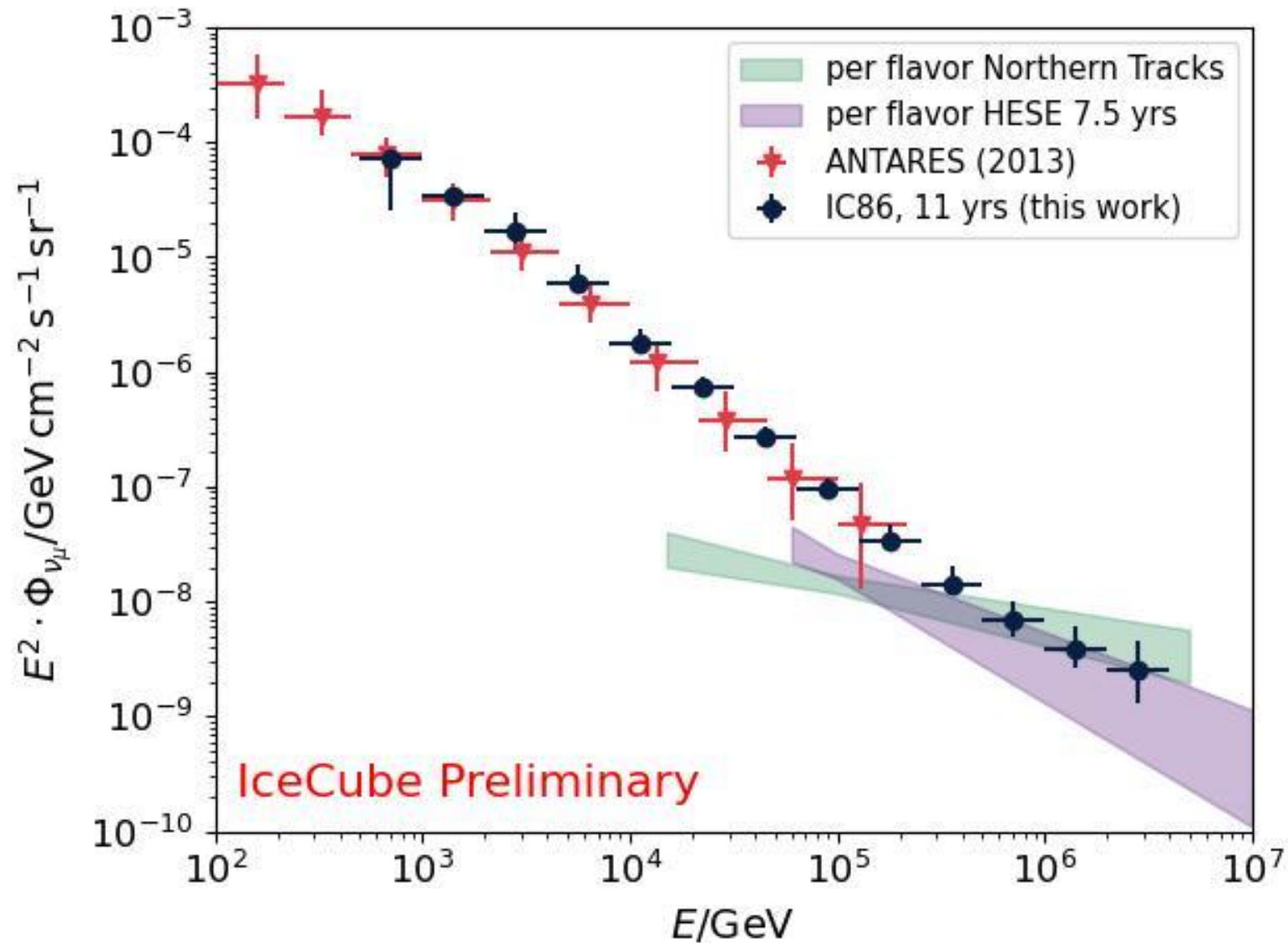
UNITED STATES 25



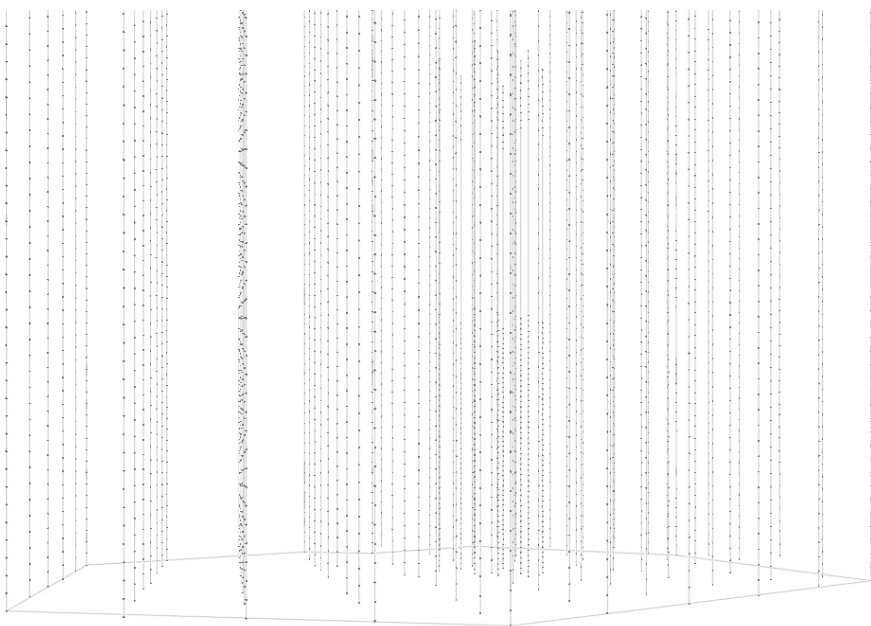
Uncharted Territory: $E_\nu = 220$ PeV

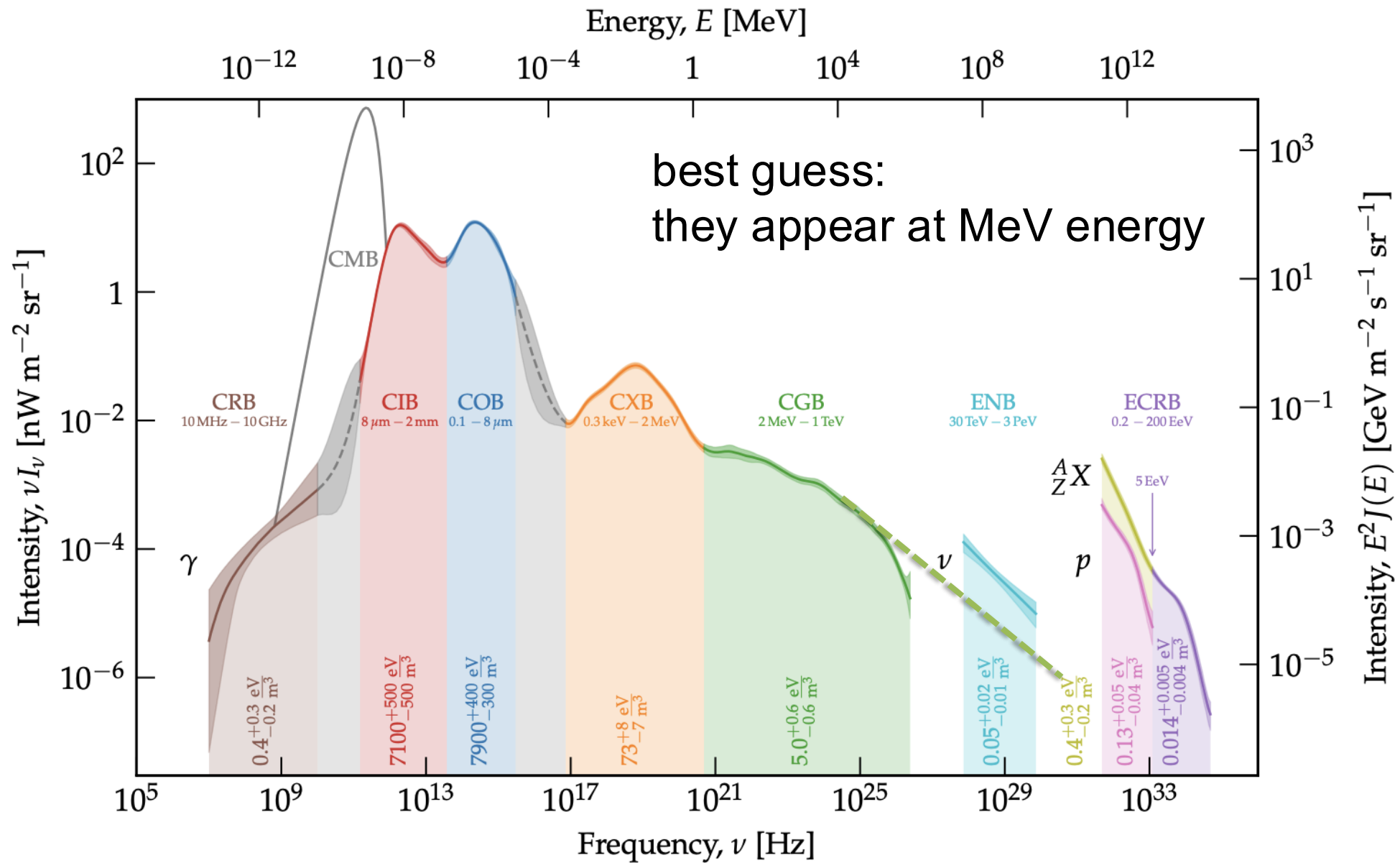


techniques mature (and improving): detectors agree on the muon neutrino spectrum

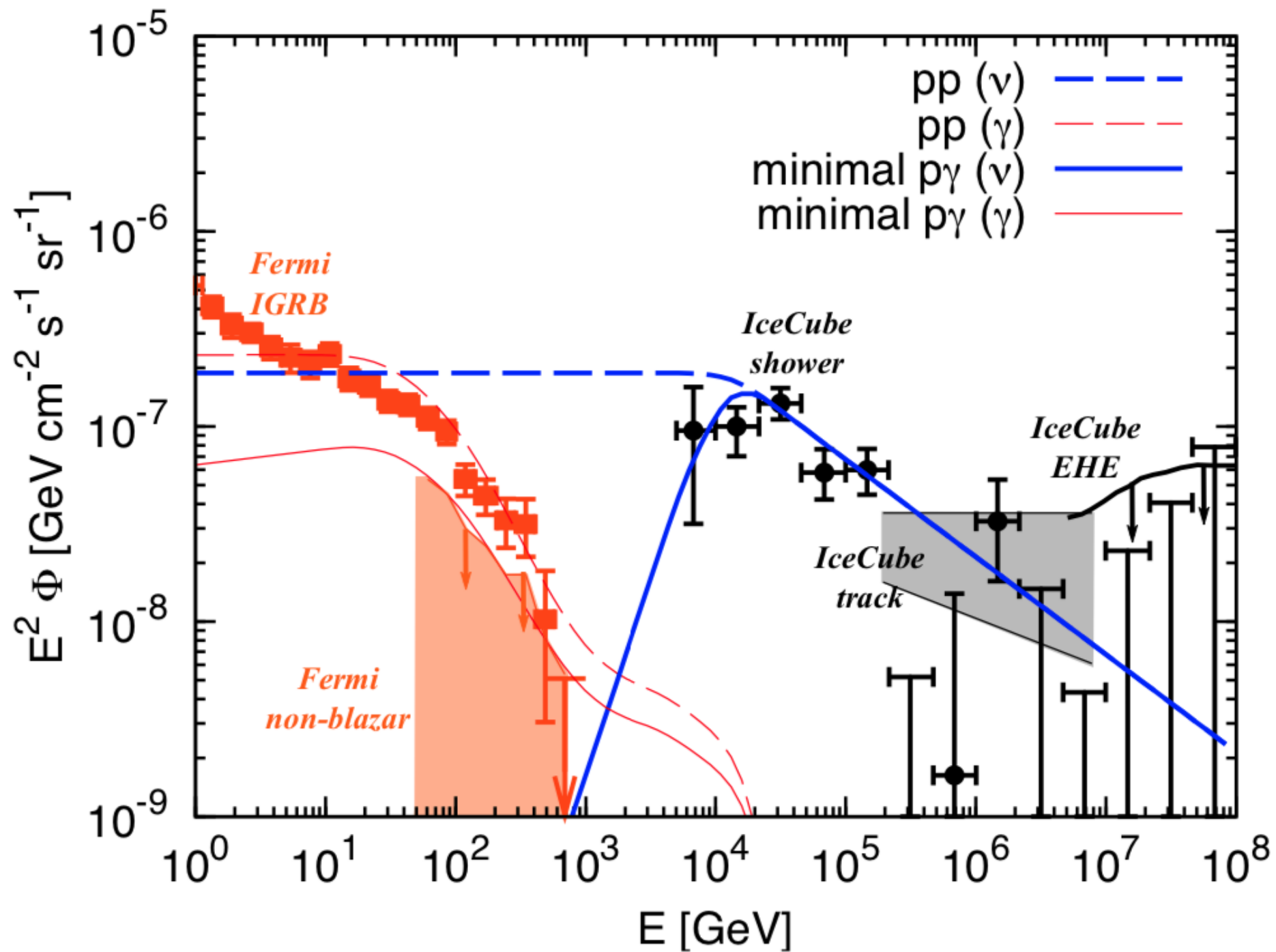


and there is more...

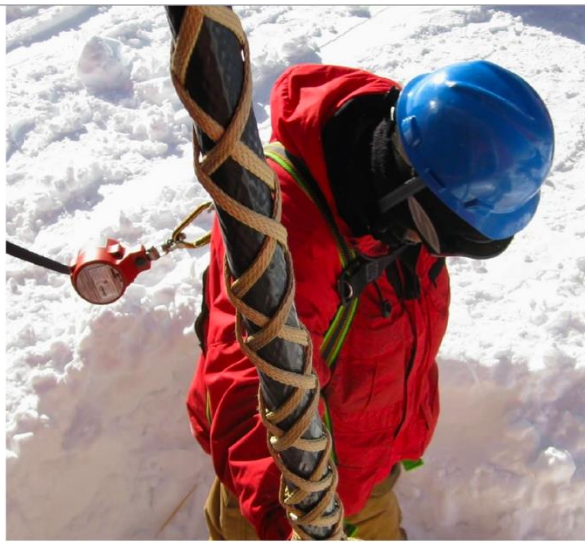
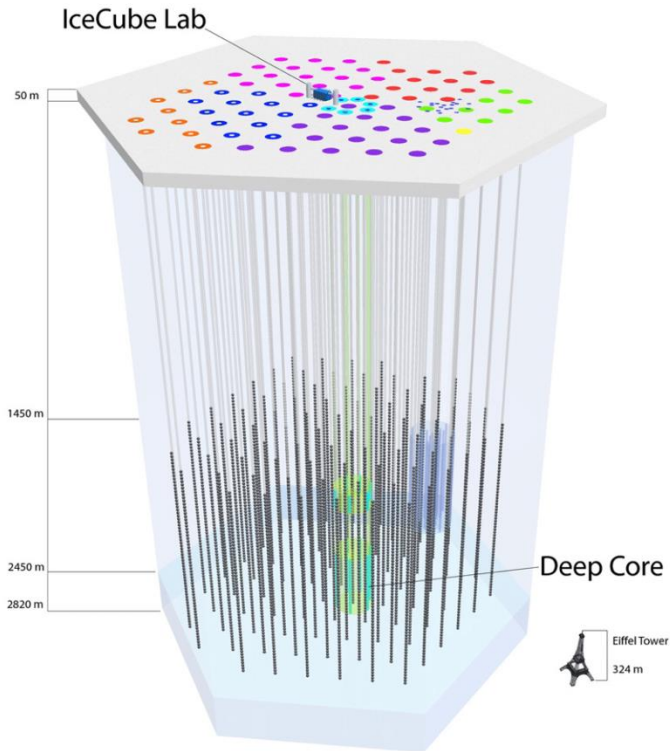




the π^0 gamma rays lose energy in the target and escape Fermi detection



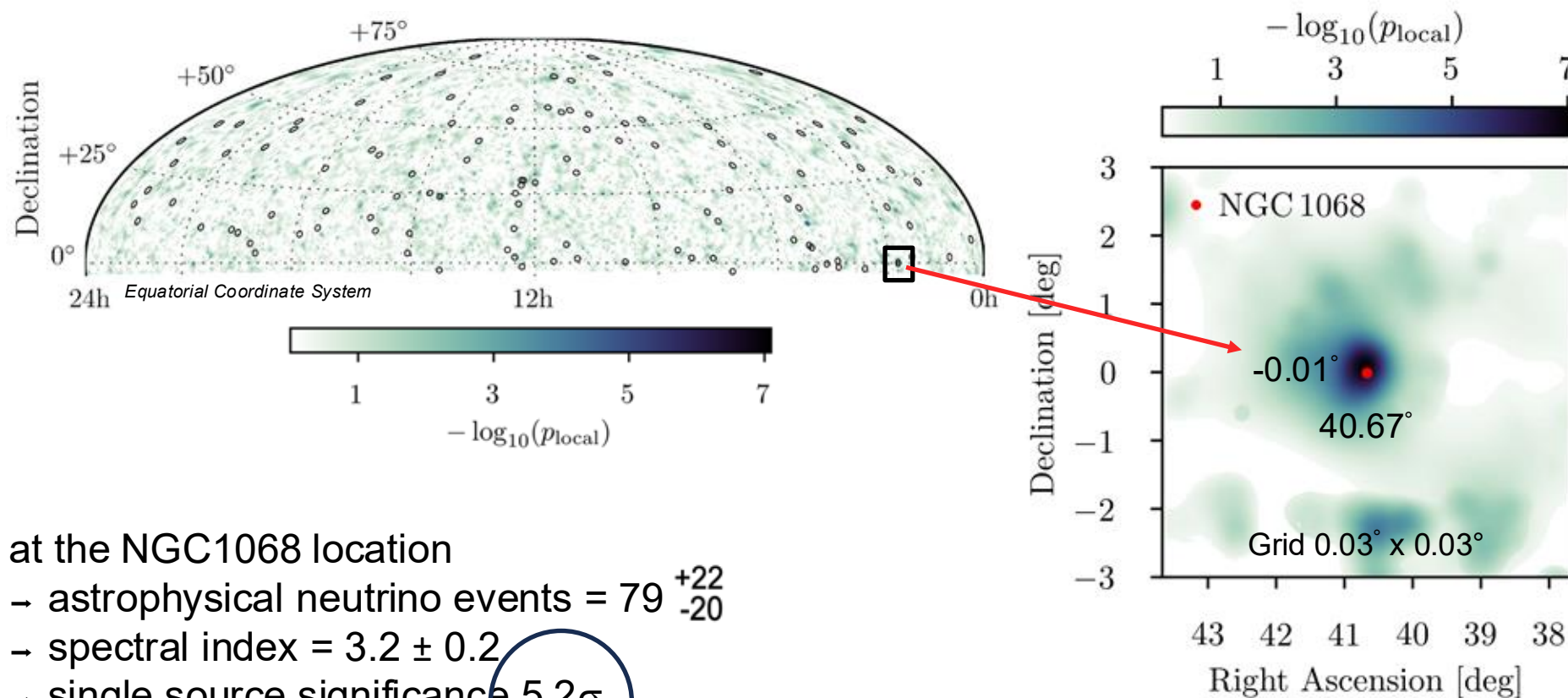
IceCube construction (Upgrade 2026)



- 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



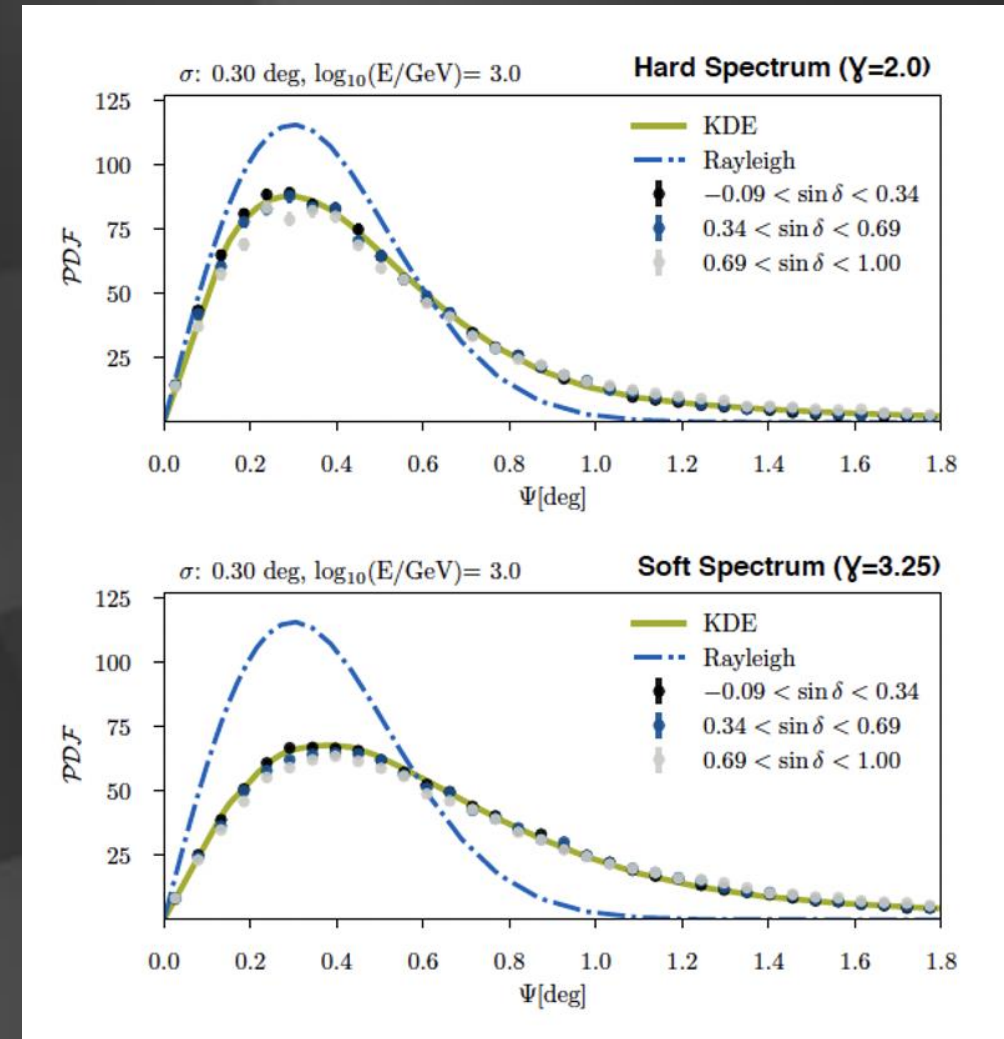
at the NGC1068 location

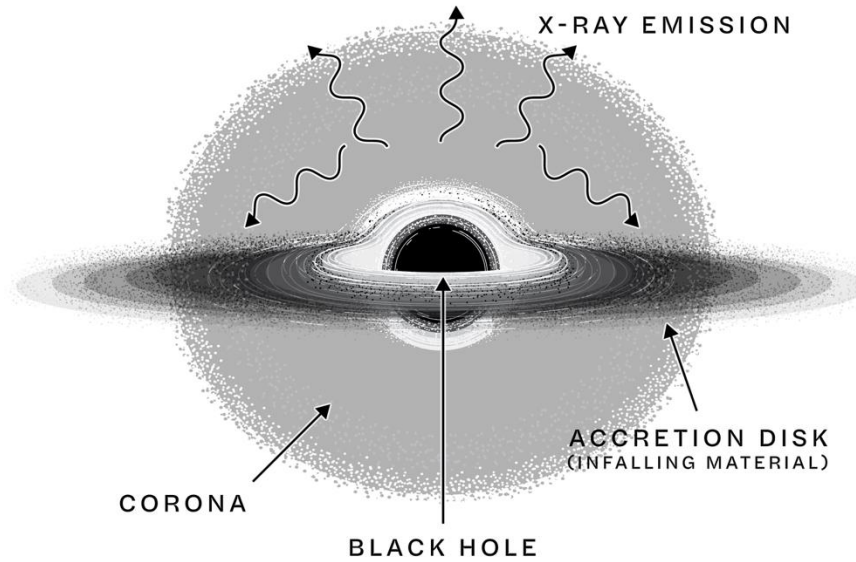
- astrophysical neutrino events = 79^{+22}_{-20}
- spectral index = 3.2 ± 0.2
- single source significance 5.2σ
- (offset 0.11°)
- 1 in 100,000 scrambled data sets have object $\geq 5.2\sigma = 4.2\sigma$
- p-value $< 10^{-5}$ including all trials

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 ...





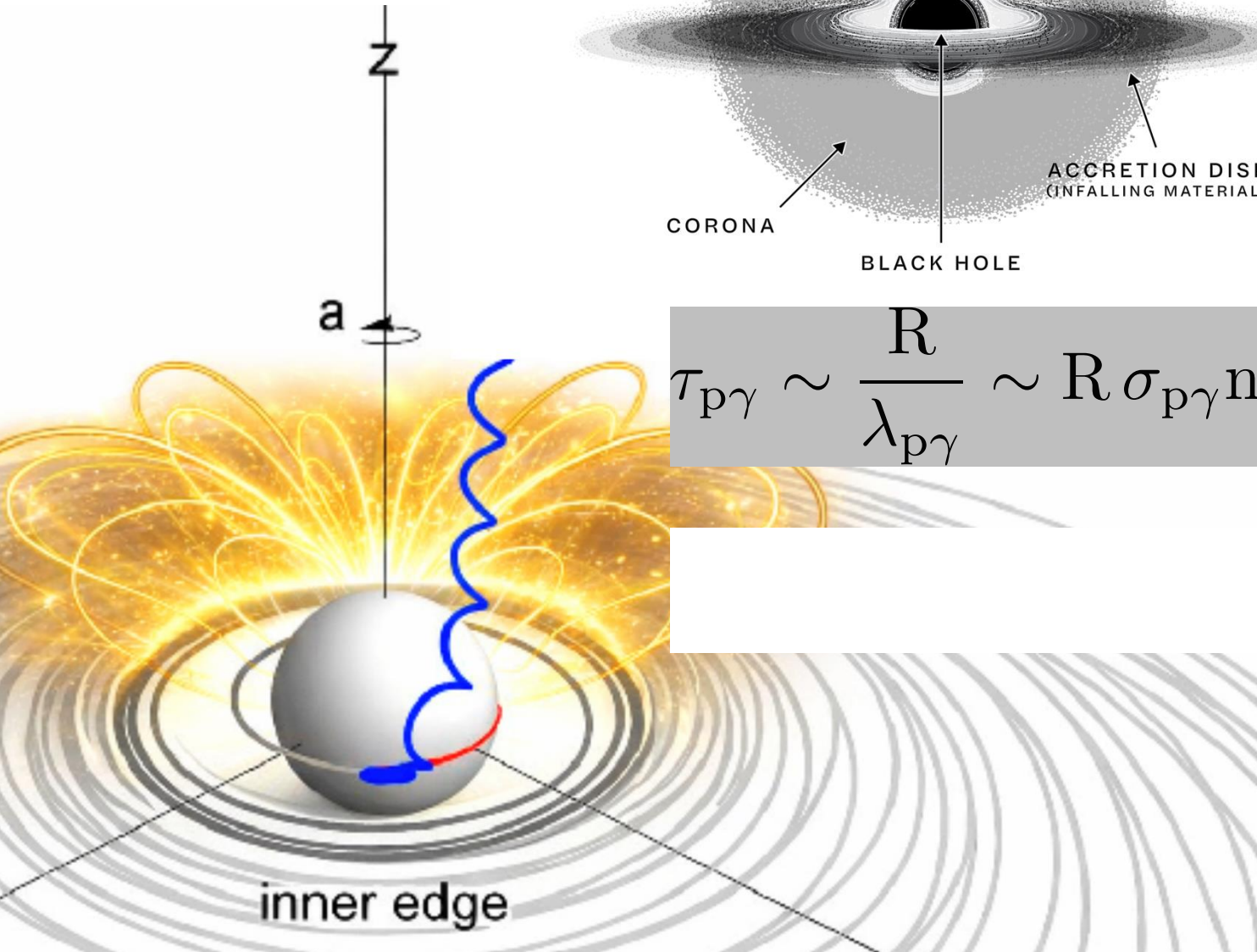
in order to produce neutrinos

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

therefore

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

→ gamma-obscured source

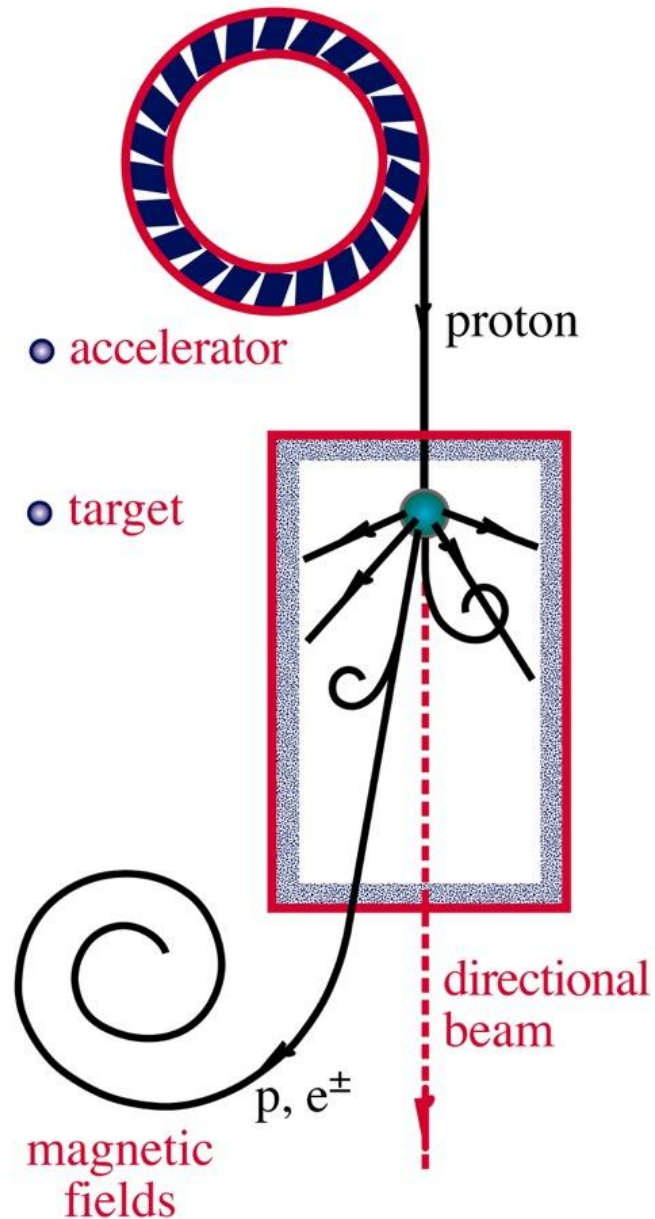


$$\tau_{p\gamma} \sim \frac{R}{\lambda_{p\gamma}} \sim R \sigma_{p\gamma} n_{\gamma} \sim \frac{\sigma_{p\gamma}}{c} \left[\frac{1}{R} \frac{L_X}{E_X} \right] \sim 10^{-3} \tau_{\gamma\gamma}$$

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

$$R \sim 10 R_s$$

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

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

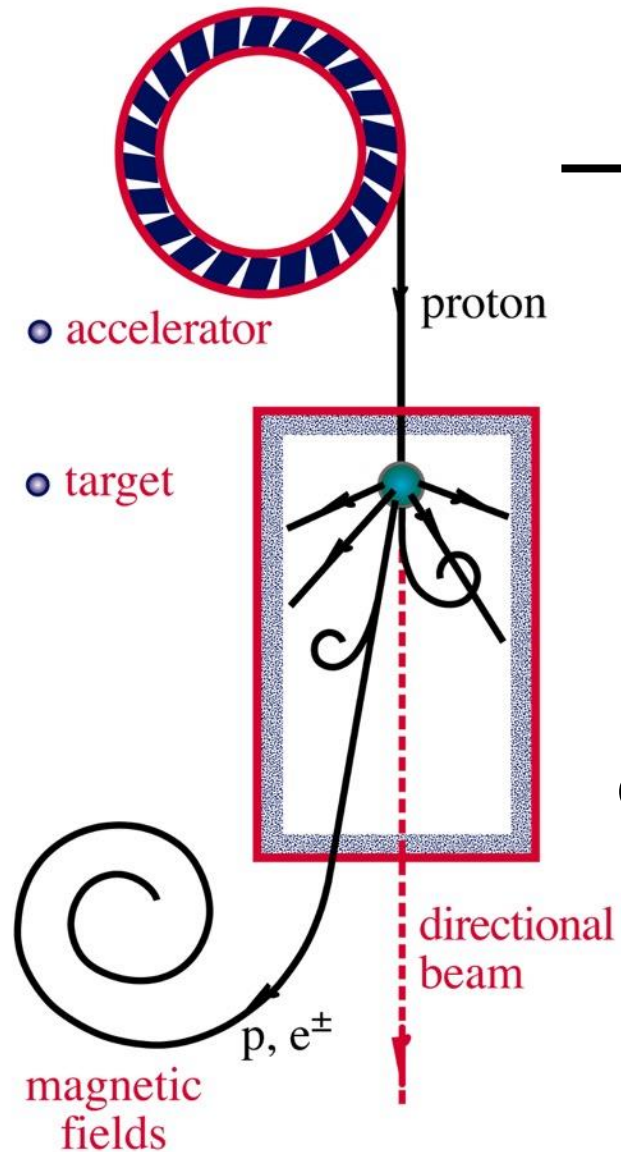
→ therefore, with $R_{\text{escape}} \sim R_{\text{target}}$

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

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

→ blazar jets are out

ν and γ beams : heaven and earth

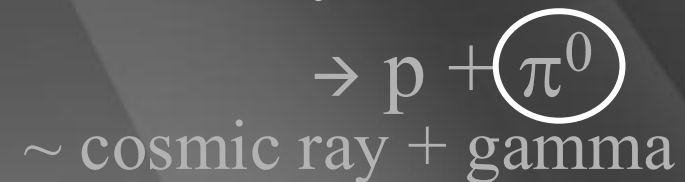
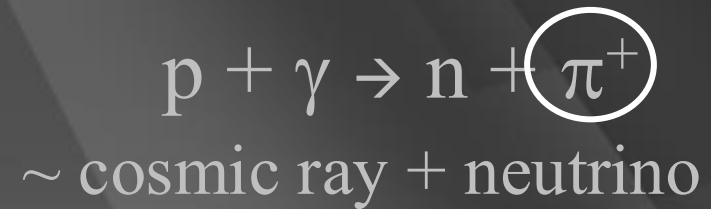


ratio of
optical depths

where are the gamma
rays from π^0 ?

pionic gamma rays
lose energy in a
target that produces
neutrinos

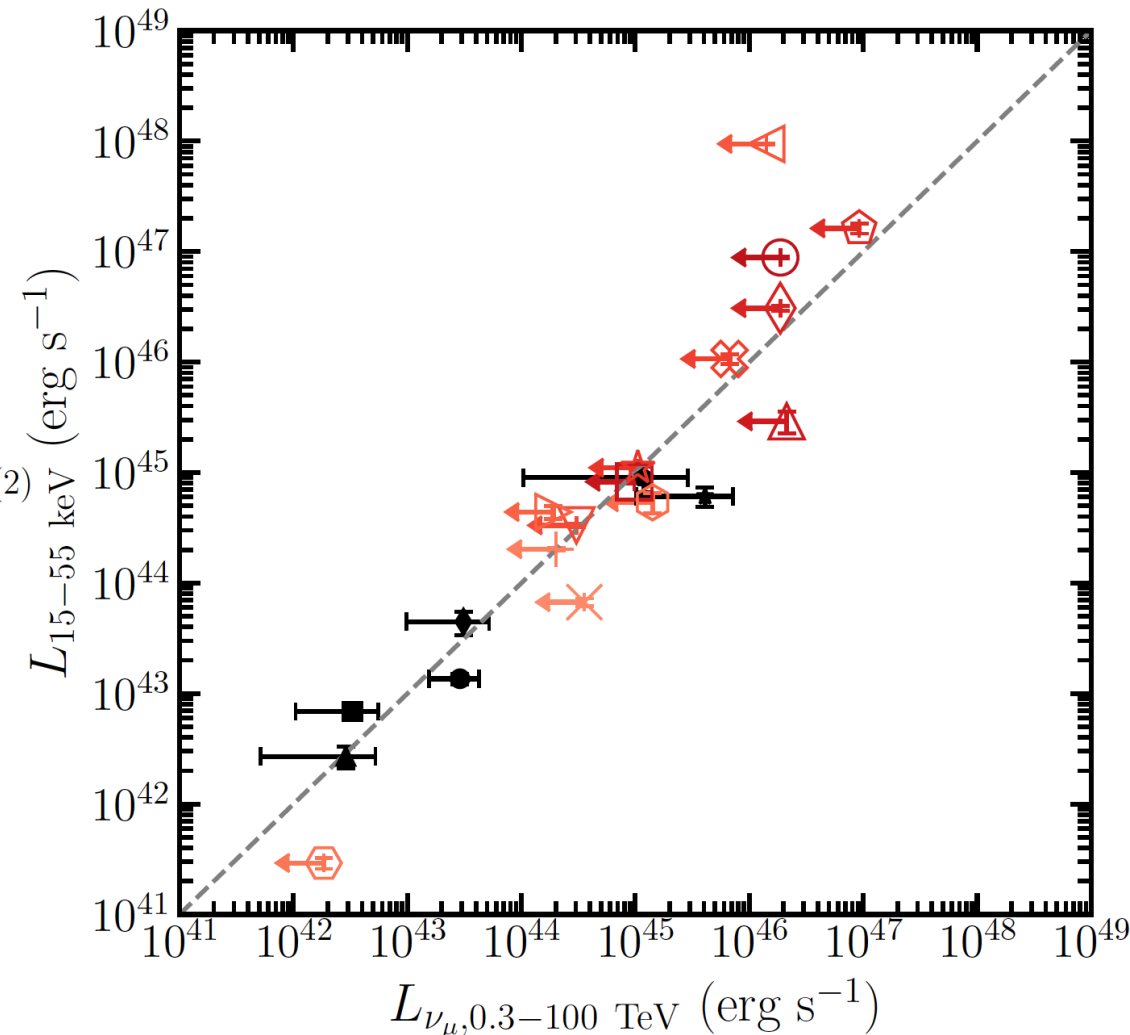
$$\frac{\tau_{\gamma\gamma}}{\tau_{p\gamma}} \sim \frac{\sigma_{\gamma\gamma}}{\sigma_{p\gamma}} \sim 10^3$$

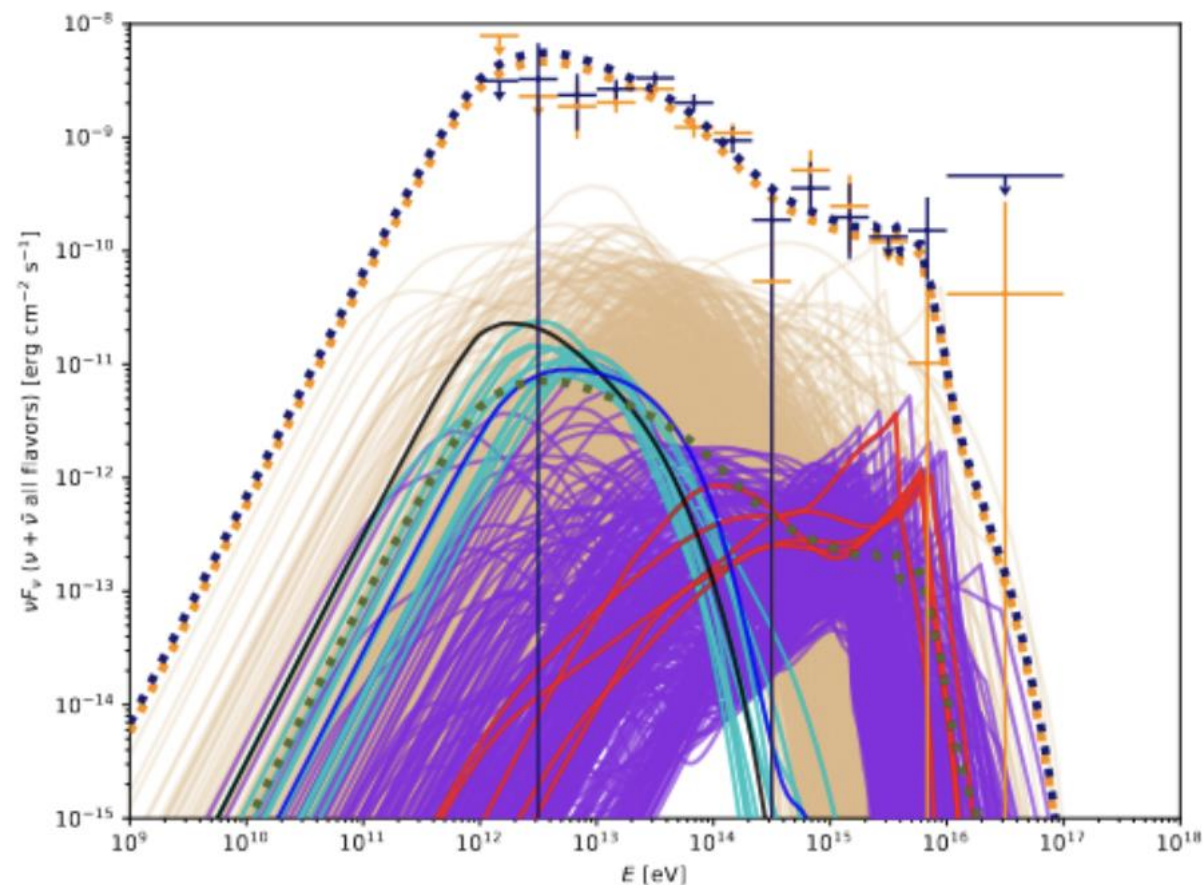


- hint from NGC 1068
- there is a correlation between the X-ray and neutrino flux
- select active galaxies with large X-ray fluxes

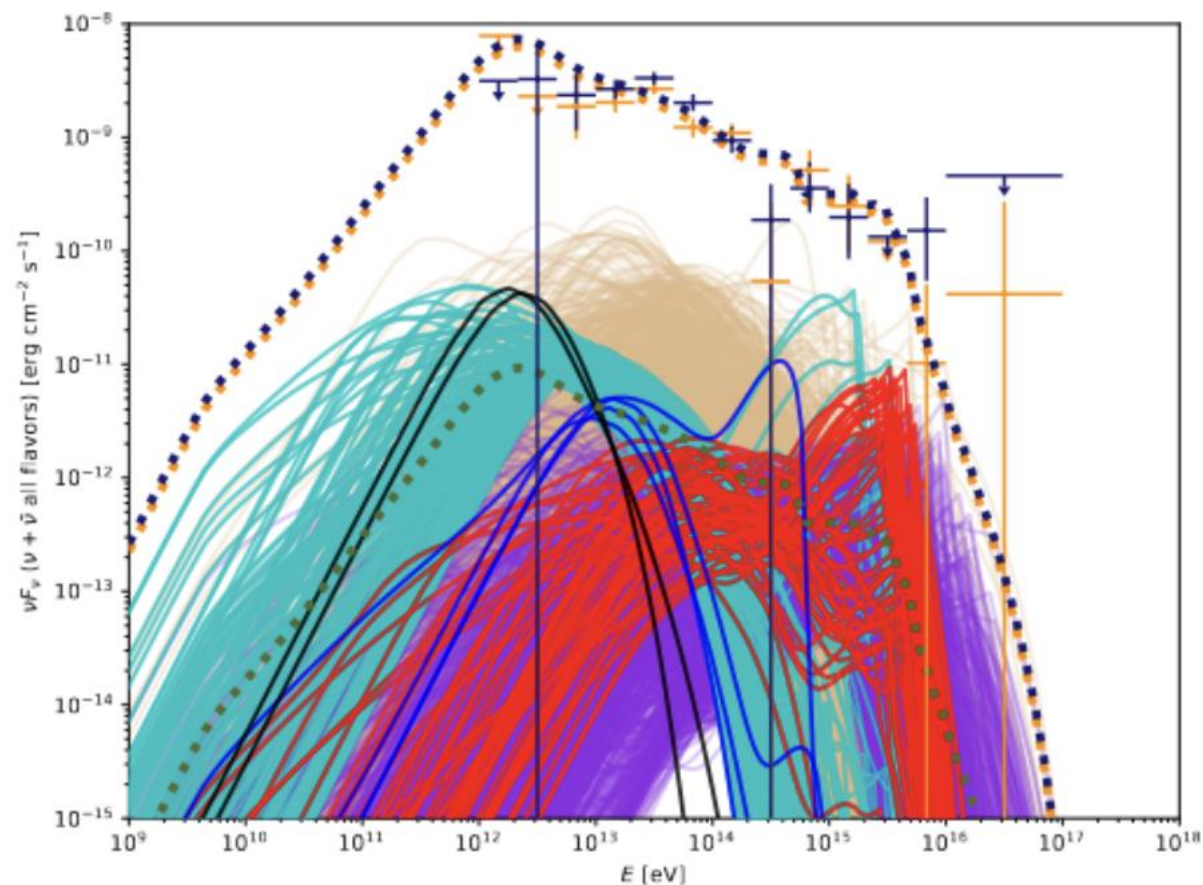
	NGC1068
	NGC4151
	NGC3079
	CGCG420-015
	TXS0506+056
	GB6J1542+6129
	3C454.3(5)
	S20109+22(2)
	PKS1441+25
	MG2J201534+3710(2)
	S30458-02
	OJ287(5)
	Ton599(2)
	PG1218+304
	CTA102
	4C+01.28
	3C66A
	1H1720+117
	1ES0806+524
	1ES0647+250

Emma Kun





- NGC 1068 (1 best fits)
- TXS 0506+056 (5 best fits)
- NGC 4151 (11 best fits)
- CGCG 420-015 (1 best fits)
- Circinus Galaxy (1000 best fits)
- NGC 7469 (296 best fits)
- Per Source Average Flux
- Per Source Average Flux multiplied by 646.18 ($\chi^2 = 20.57$ for Combined Fit all sky)
- Per Source Average Flux multiplied by 775.39 ($\chi^2 = 18.16$ for MESE all sky)
- + Combined Fit all sky
- + MESE all sky



- NGC 1068 (2 best fits)
- TXS 0506+056 (57 best fits)
- NGC 4151 (143 best fits)
- CGCG 420-015 (4 best fits)
- Circinus Galaxy (1000 best fits)
- NGC 7469 (1000 best fits)
- Per Source Average Flux
- Per Source Average Flux multiplied by 675.10 ($\chi^2 = 22.07$ for Combined Fit all sky)
- Per Source Average Flux multiplied by 789.82 ($\chi^2 = 22.55$ for MESE all sky)
- + Combined Fit all sky
- + MESE all sky

