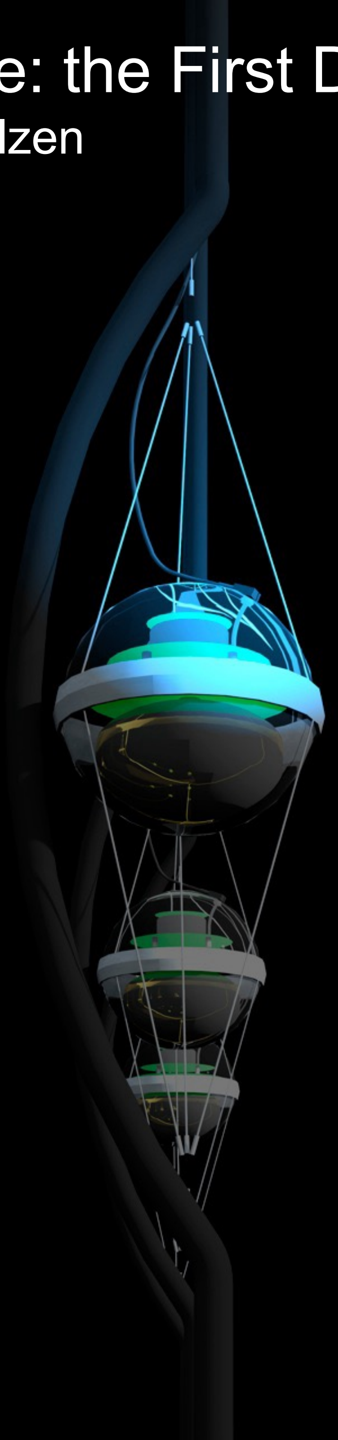
IceCube: the First Decade of Neutrino Astronomy

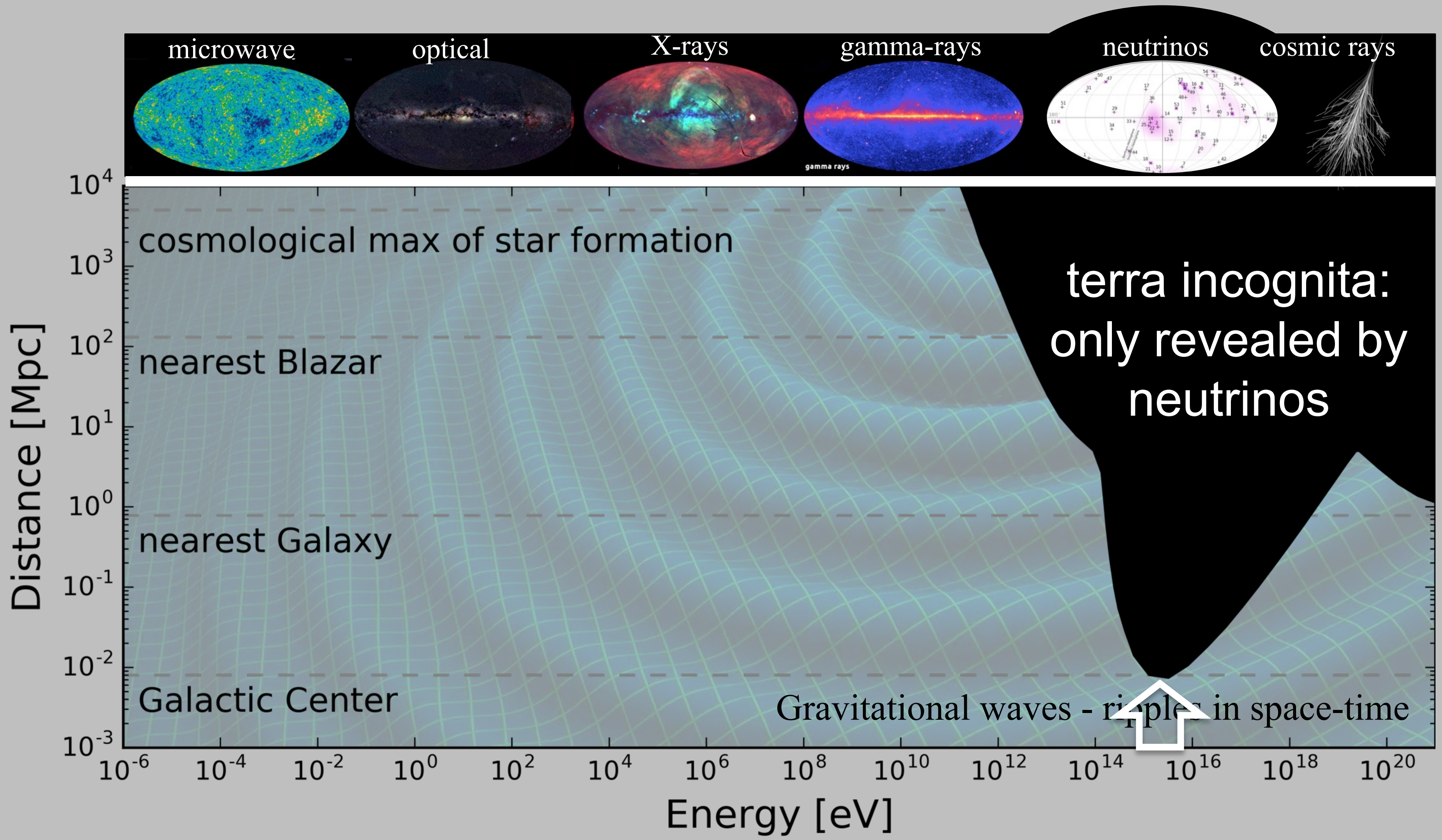
francis halzen



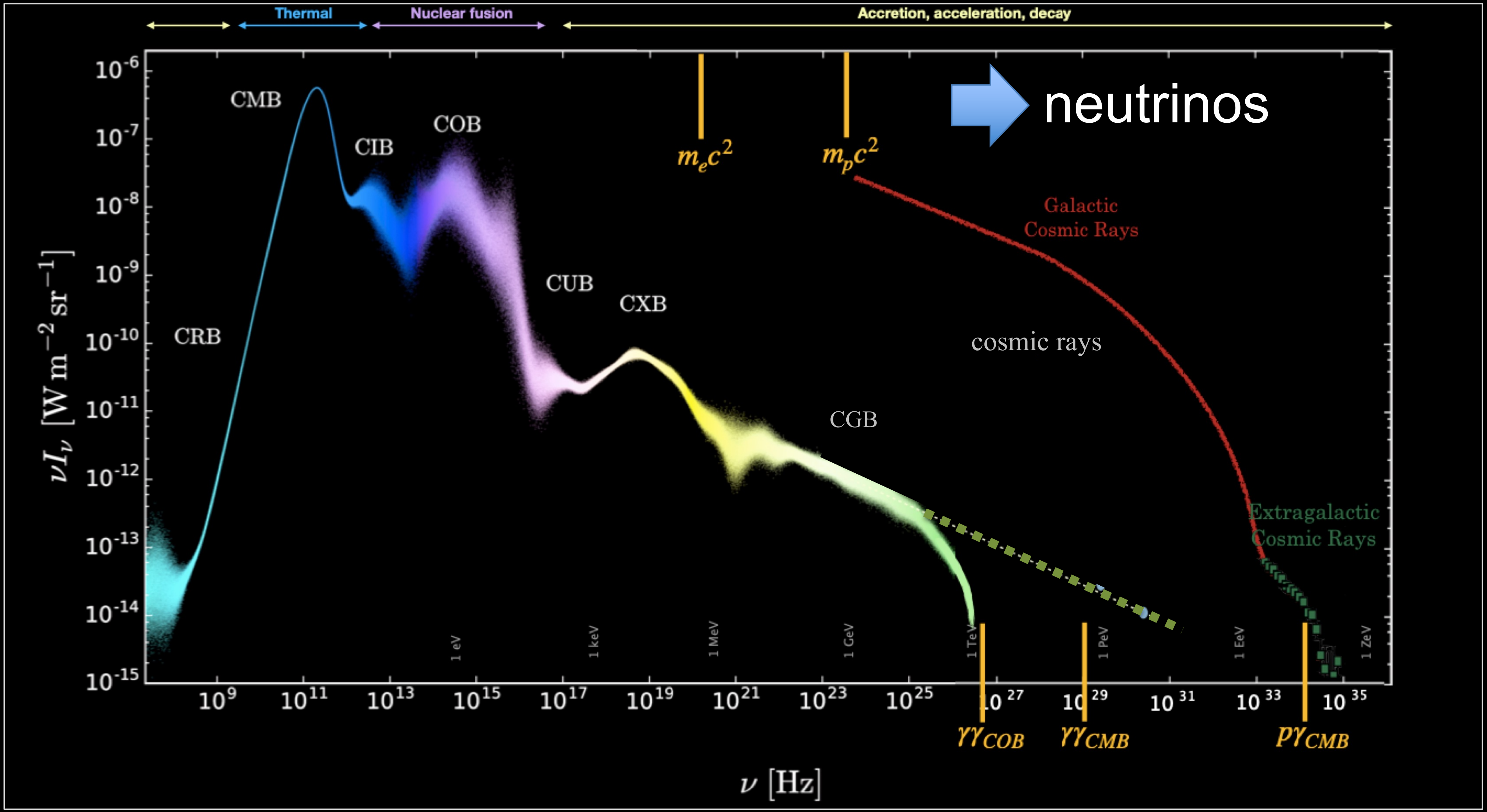
- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- and the answer is: supermassive black holes at the cores of active galaxies?

IceCube.wisc.edu

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

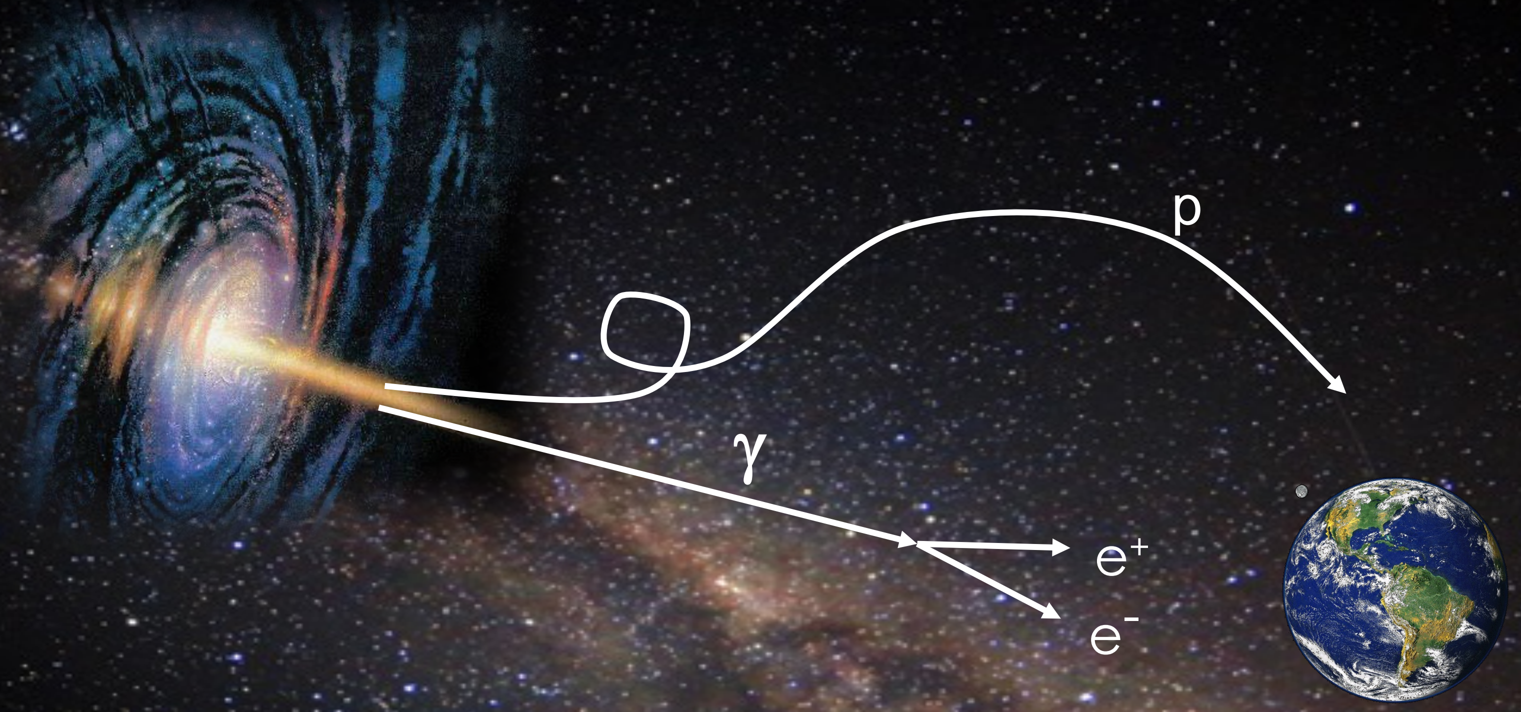


the Extreme Universe is opaque to gamma rays beyond our Galaxy energy in the Universe as a function of the color of light



in the extreme universe neutrinos are unique astronomical messengers

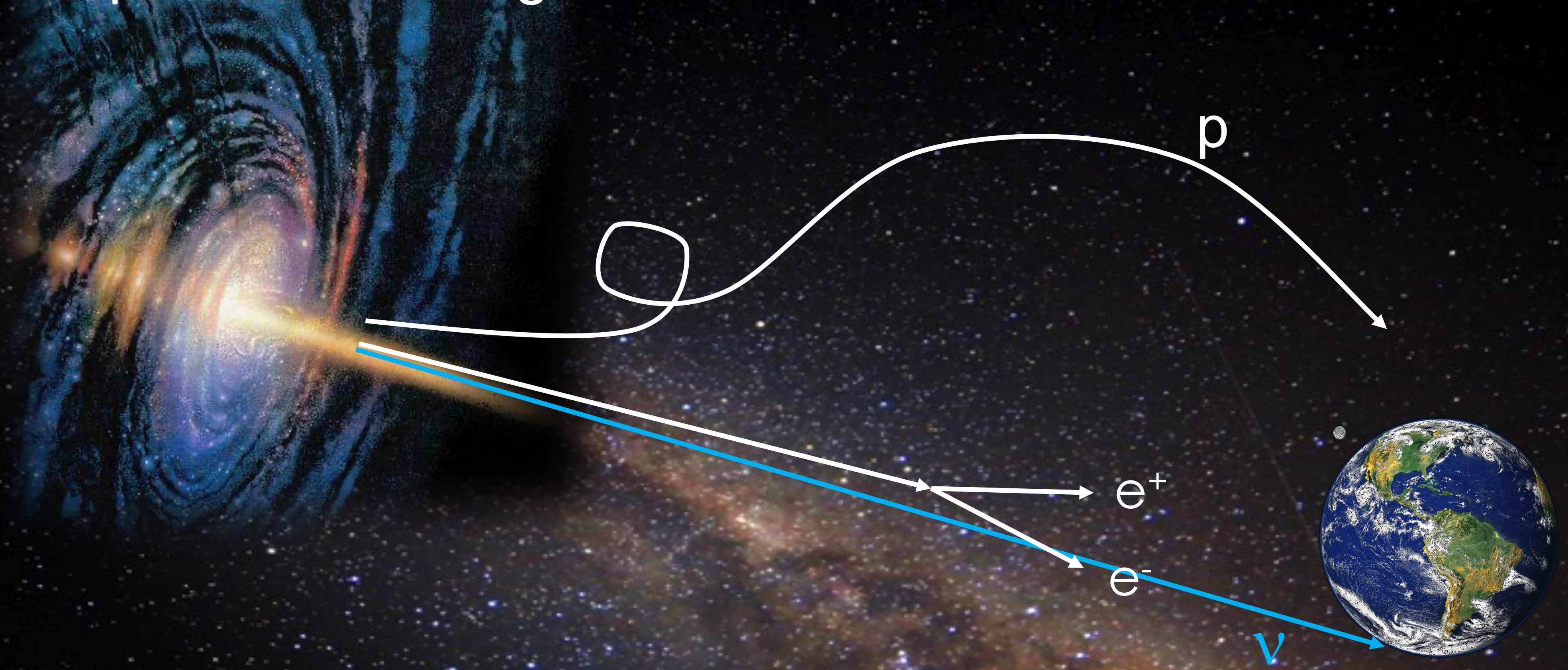
the opaque extreme Universe:



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

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

neutrinos: perfect messengers

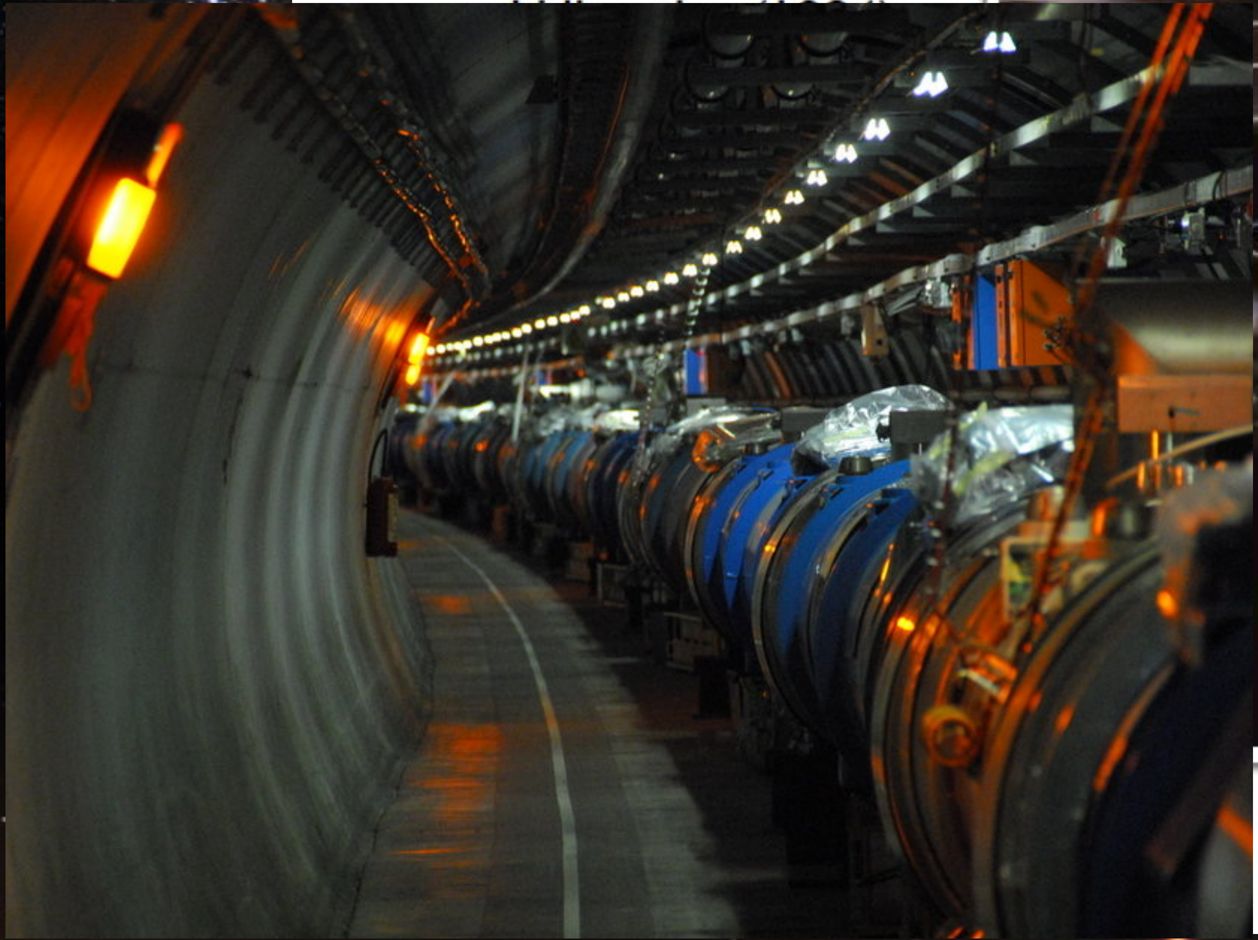


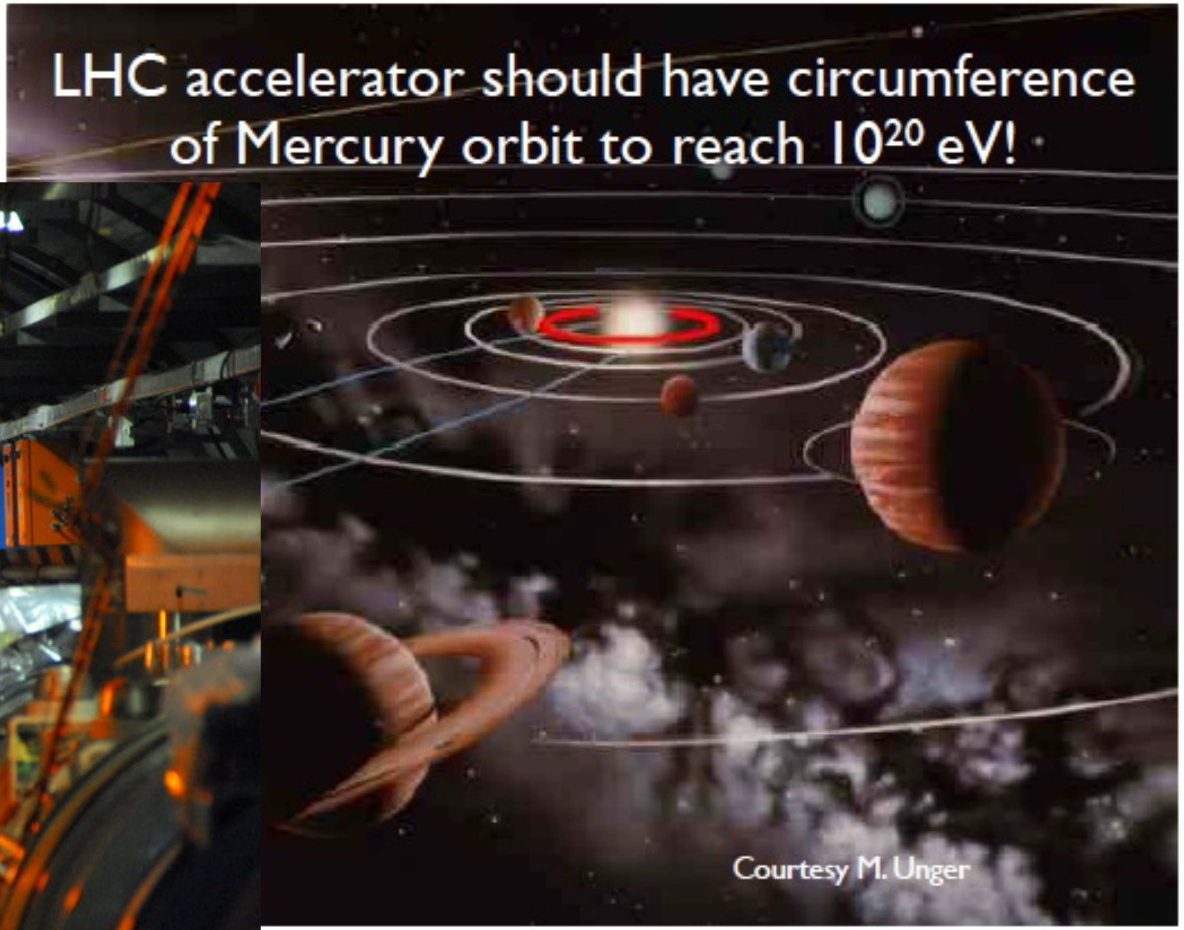
- electrically neutral
- massless (in this talk)
- like a photon but weakly interacting
- track cosmic ray sources

- … but difficult to detect

highest energy “radiation” from the Universe: mostly protons !

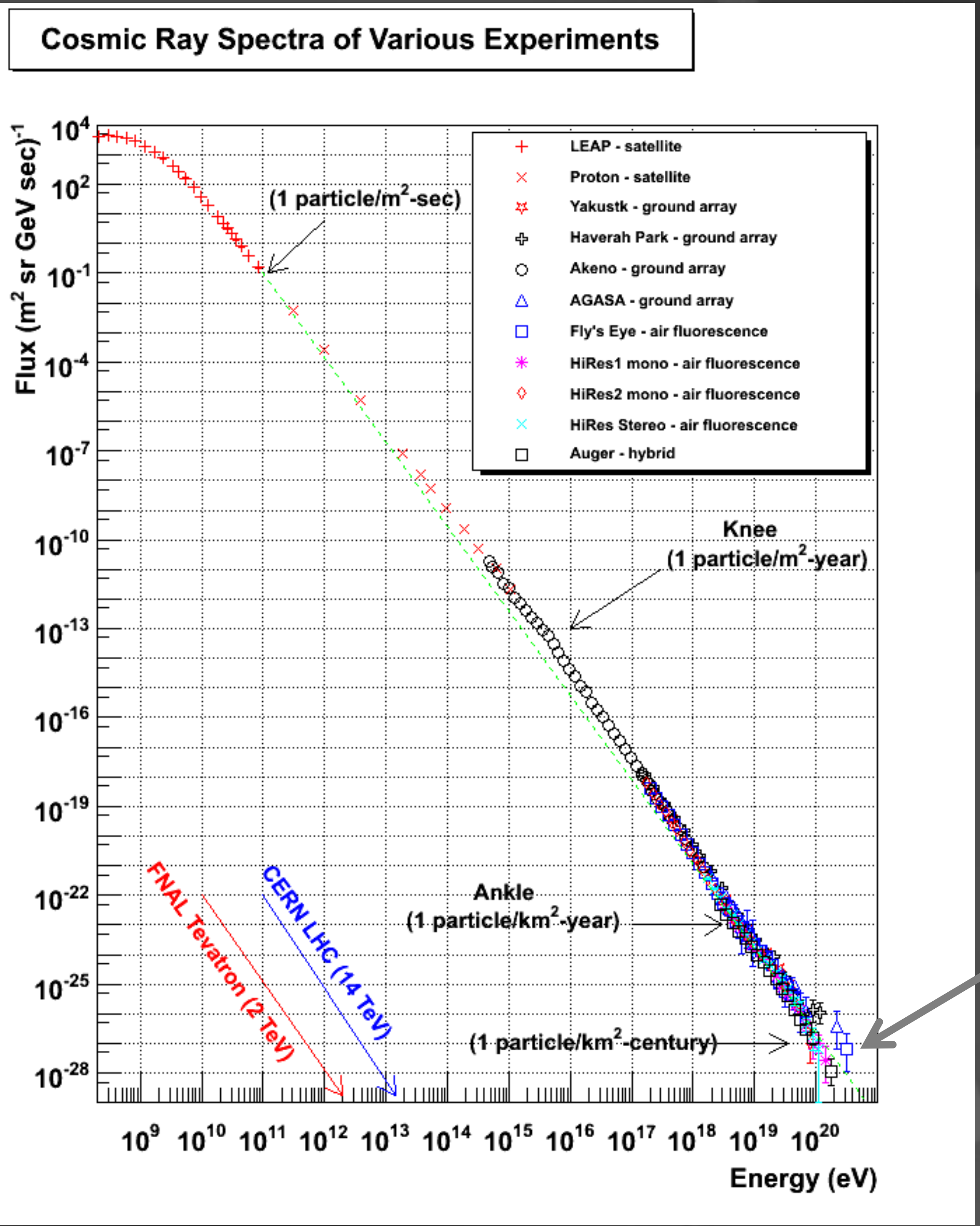
high energy
high luminosity





Fly’s Eye 1991
300,000,000 TeV

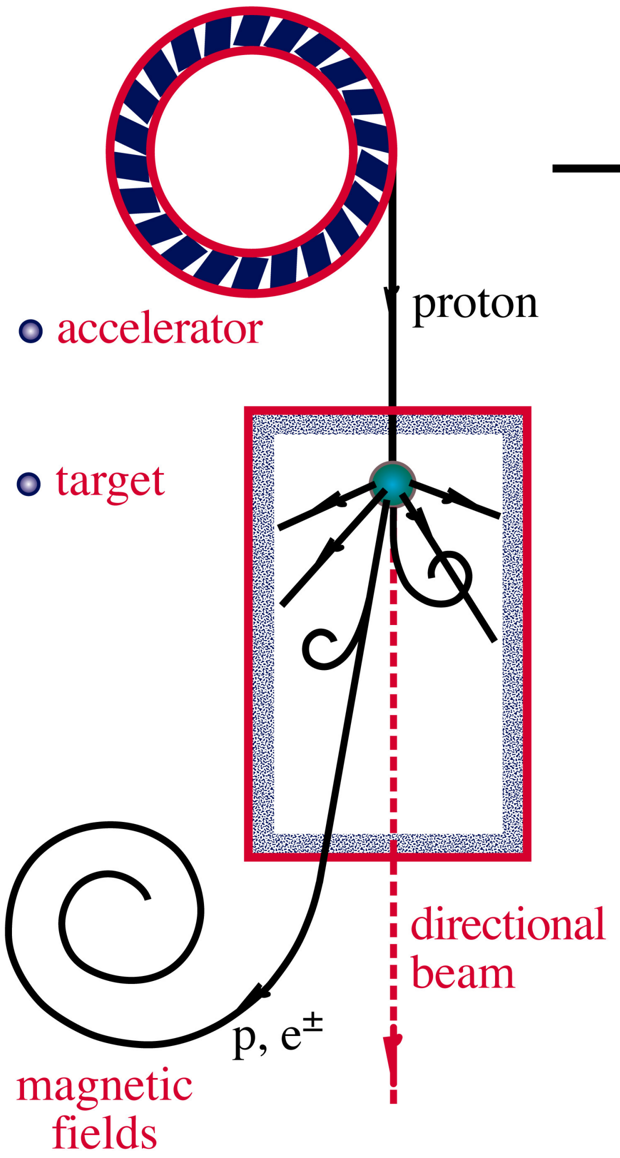
origin of cosmic rays: oldest problem in astronomy



cosmic ray challenge

- both the energy of the particles and the total *luminosity* of the accelerators are large
- gravitational energy from matter accreting on black holes is converted into particle acceleration?
- gamma ray bursts, active galaxies, galaxy clusters, or…?

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

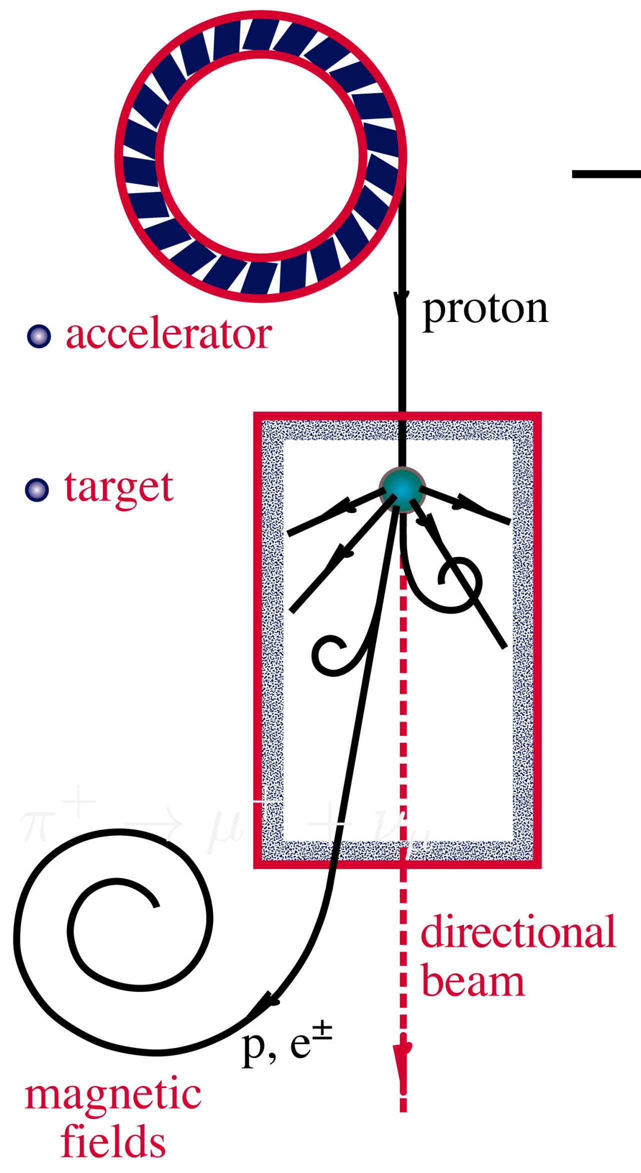
$$p + \gamma \rightarrow n + \pi^{+}$$

~ cosmic ray + neutrino

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

~ cosmic ray + gamma

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

supermassive black hole

nearby radiation

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

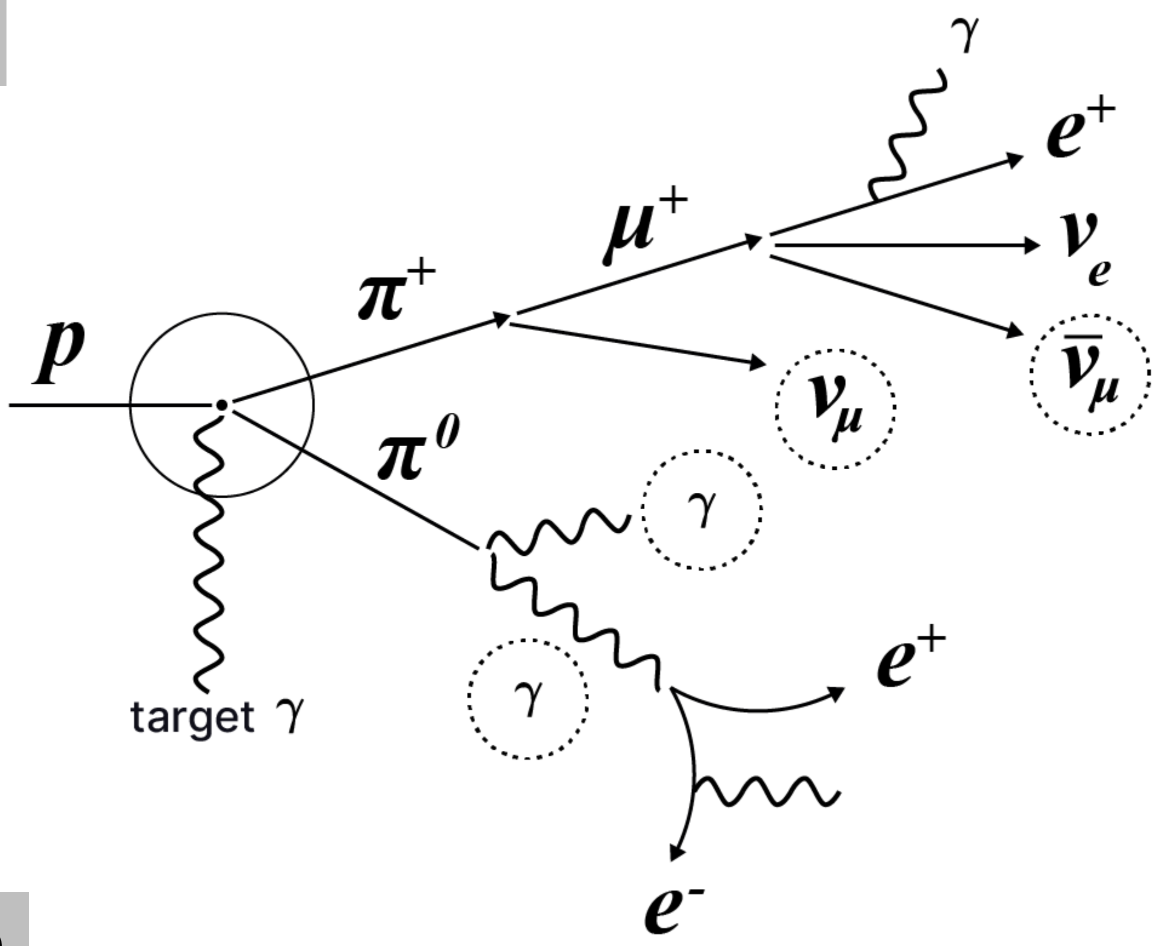
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

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

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

cosmic ray sources: a gamma ray for every neutrino

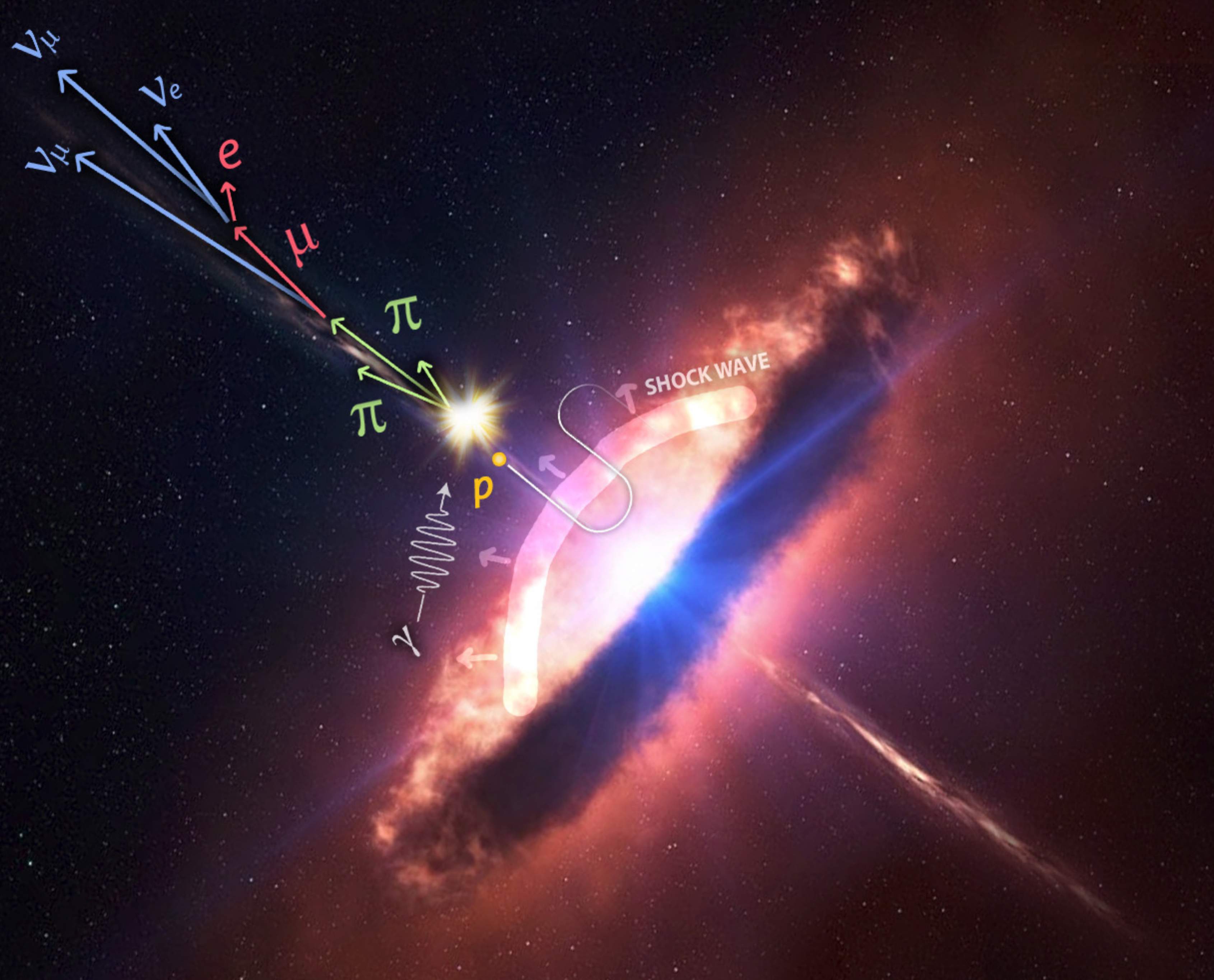


neutrino sources are cosmic ray sources

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

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

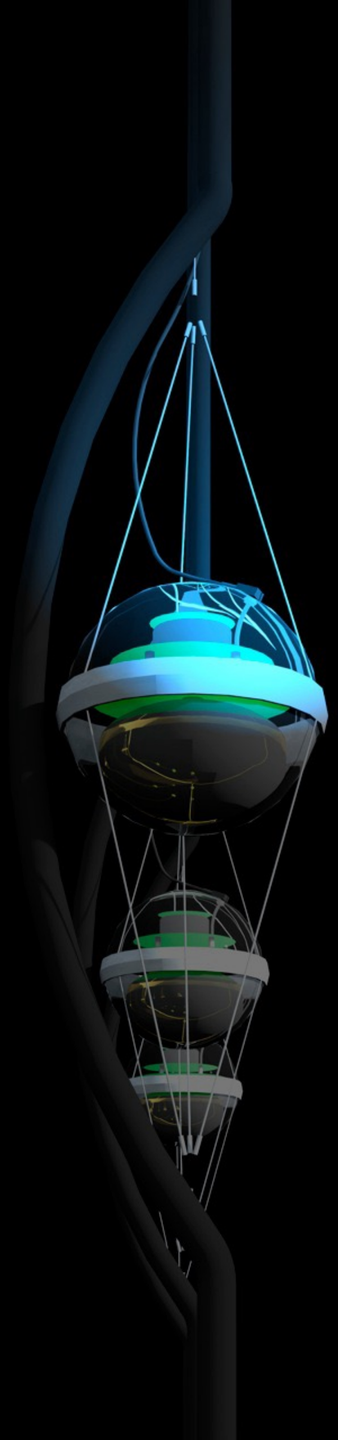
[redacted]hole accelerating
[redacted]ns submersed in
[redacted]get of radiation
[redacted]roduce pions



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

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

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



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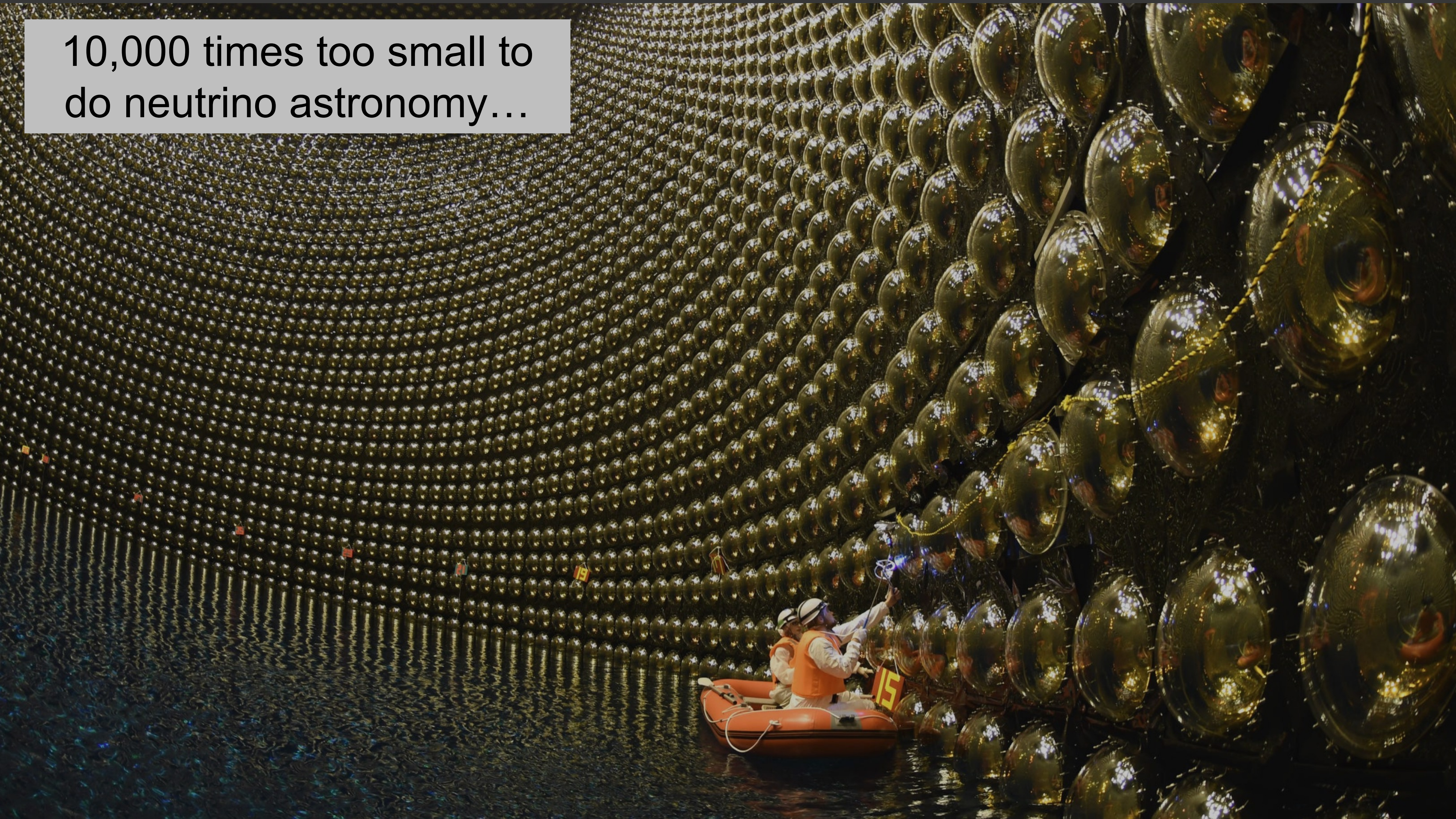
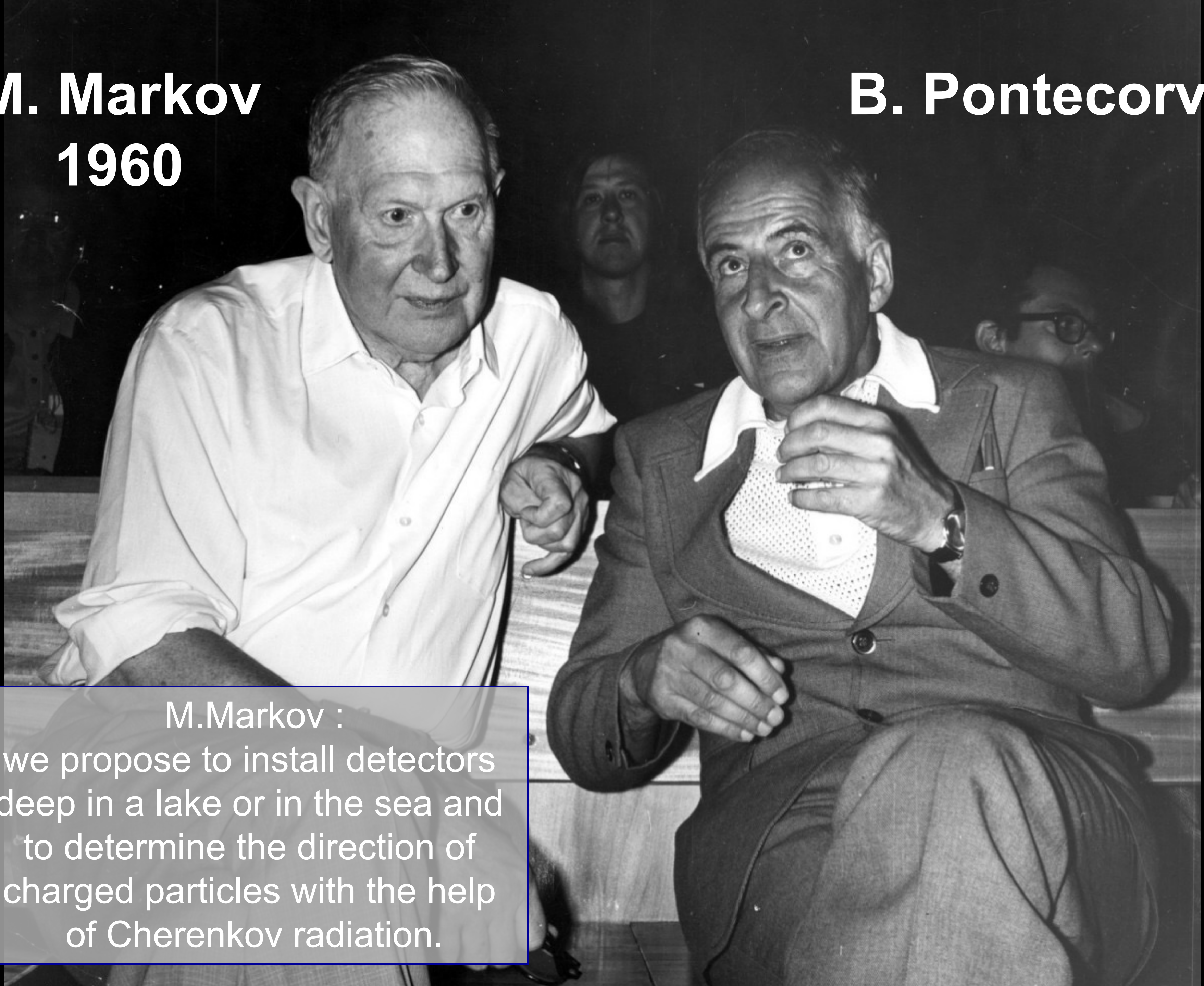
10,000 times too small to do neutrino astronomy…

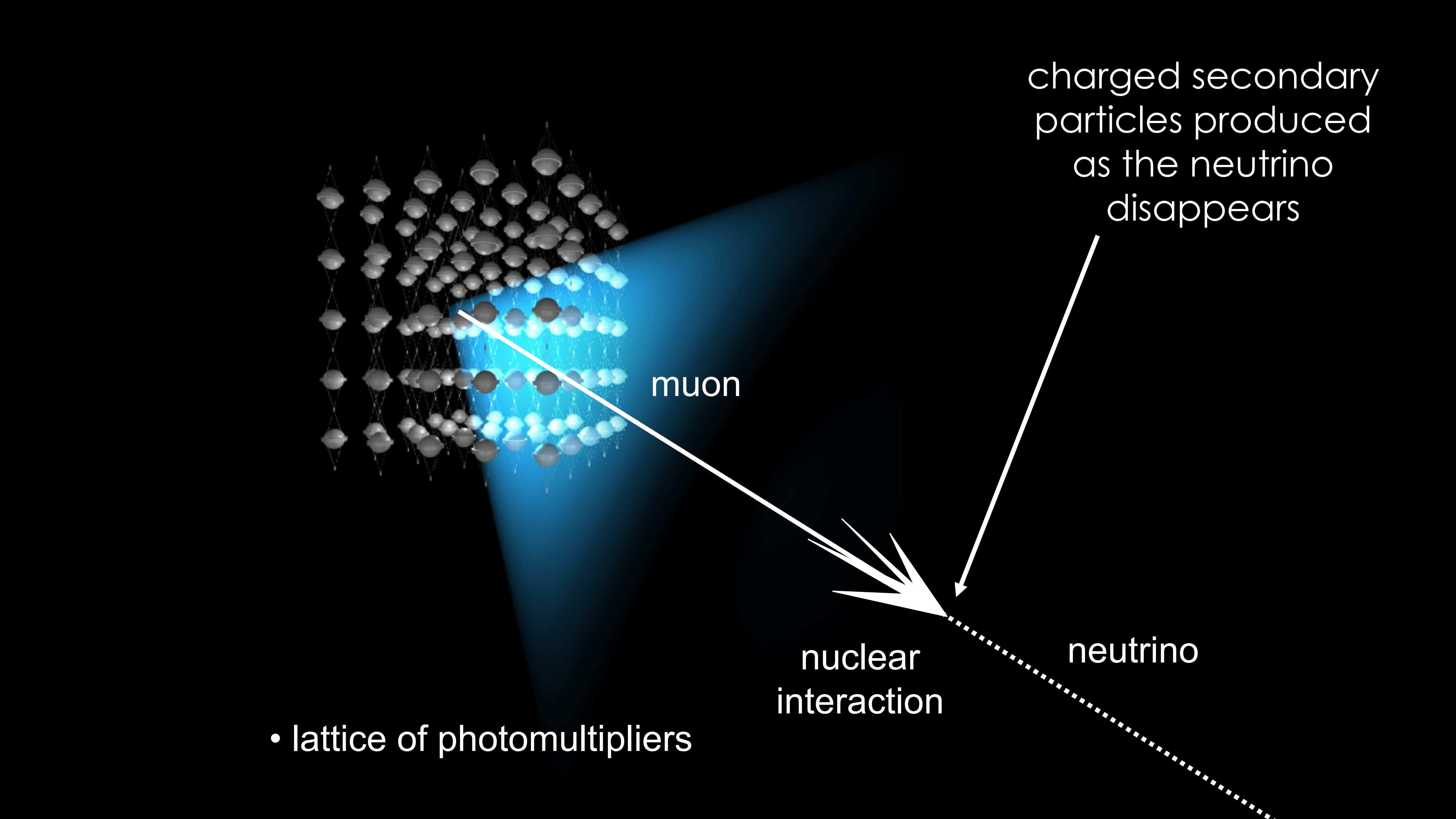


M. Markov
1960

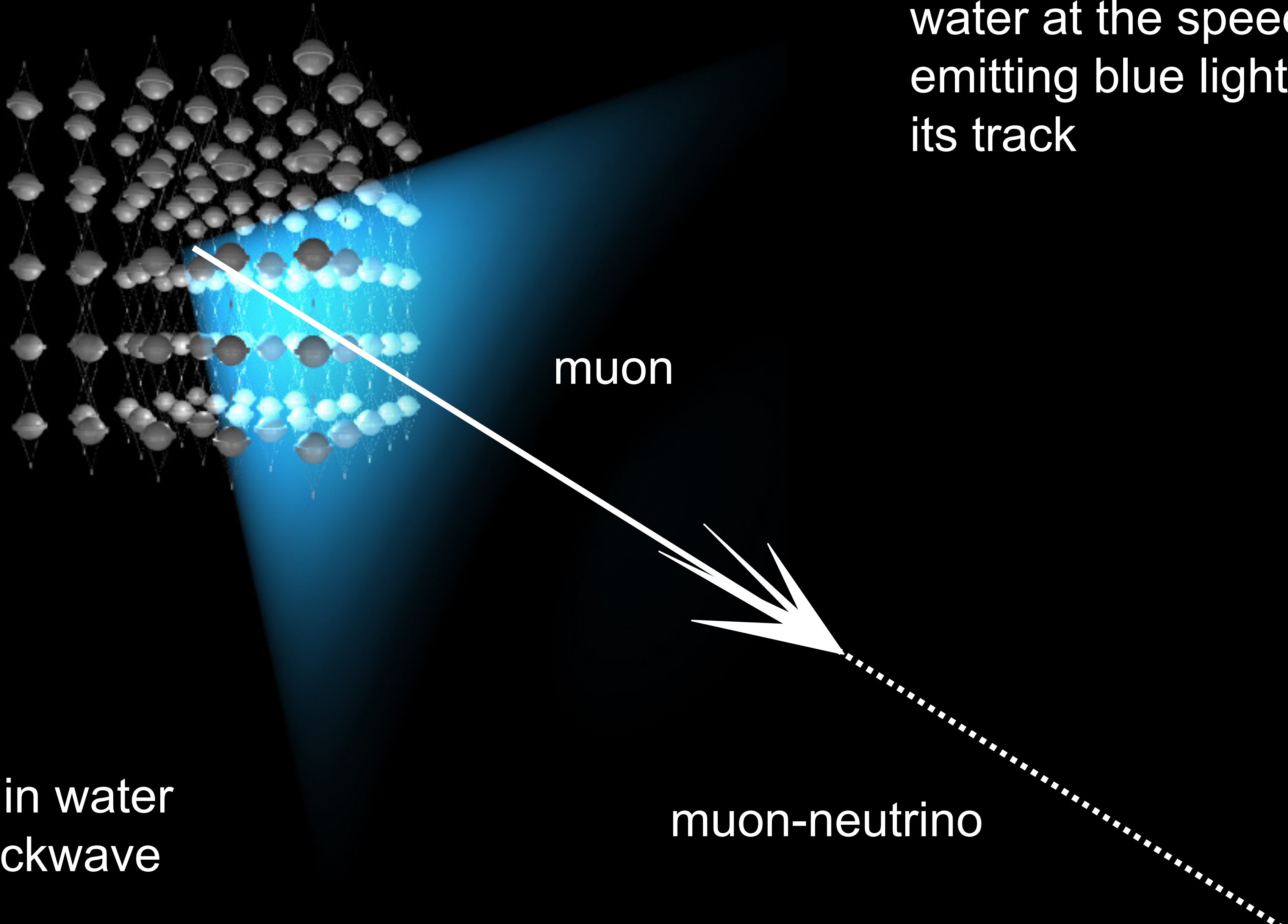
B. Pontecorvo



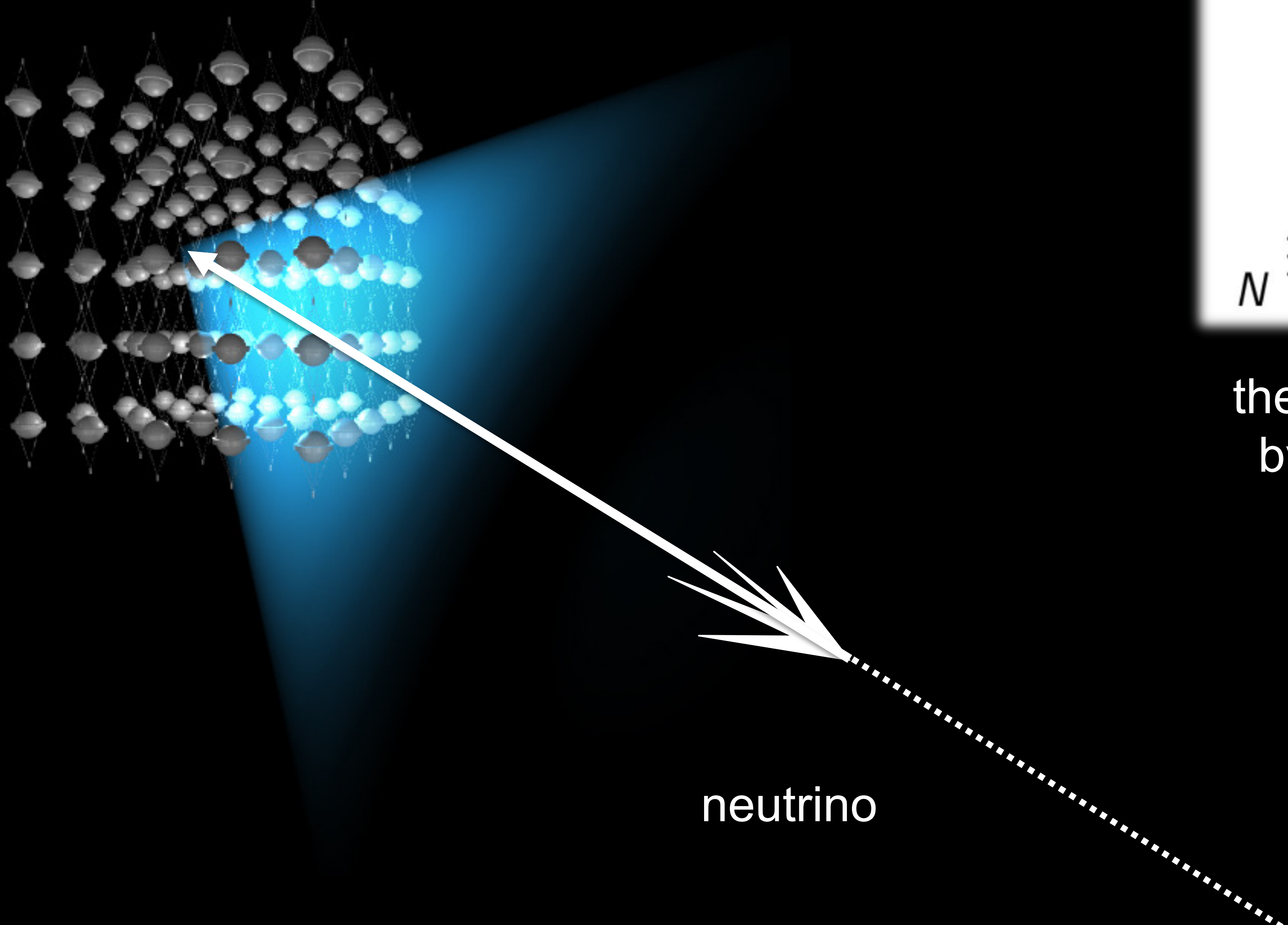
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

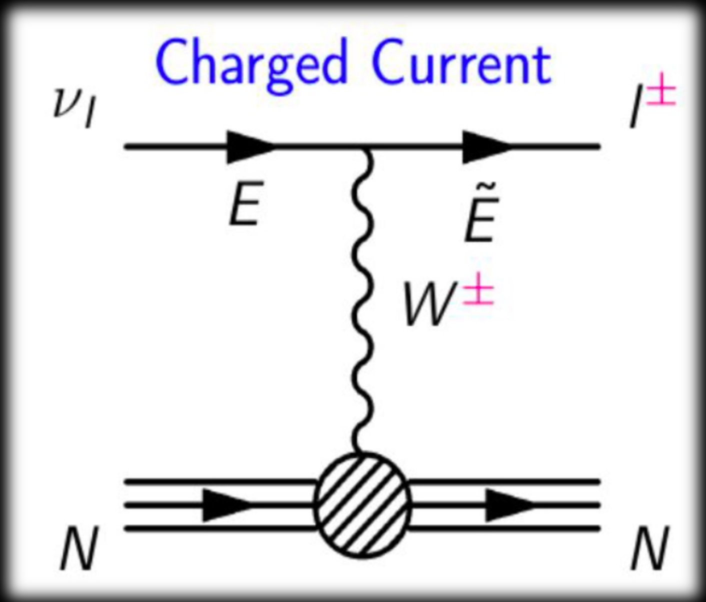

charged secondary particles produced as the neutrino disappears
muon
nuclear interaction
neutrino
• lattice of photomultipliers

- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



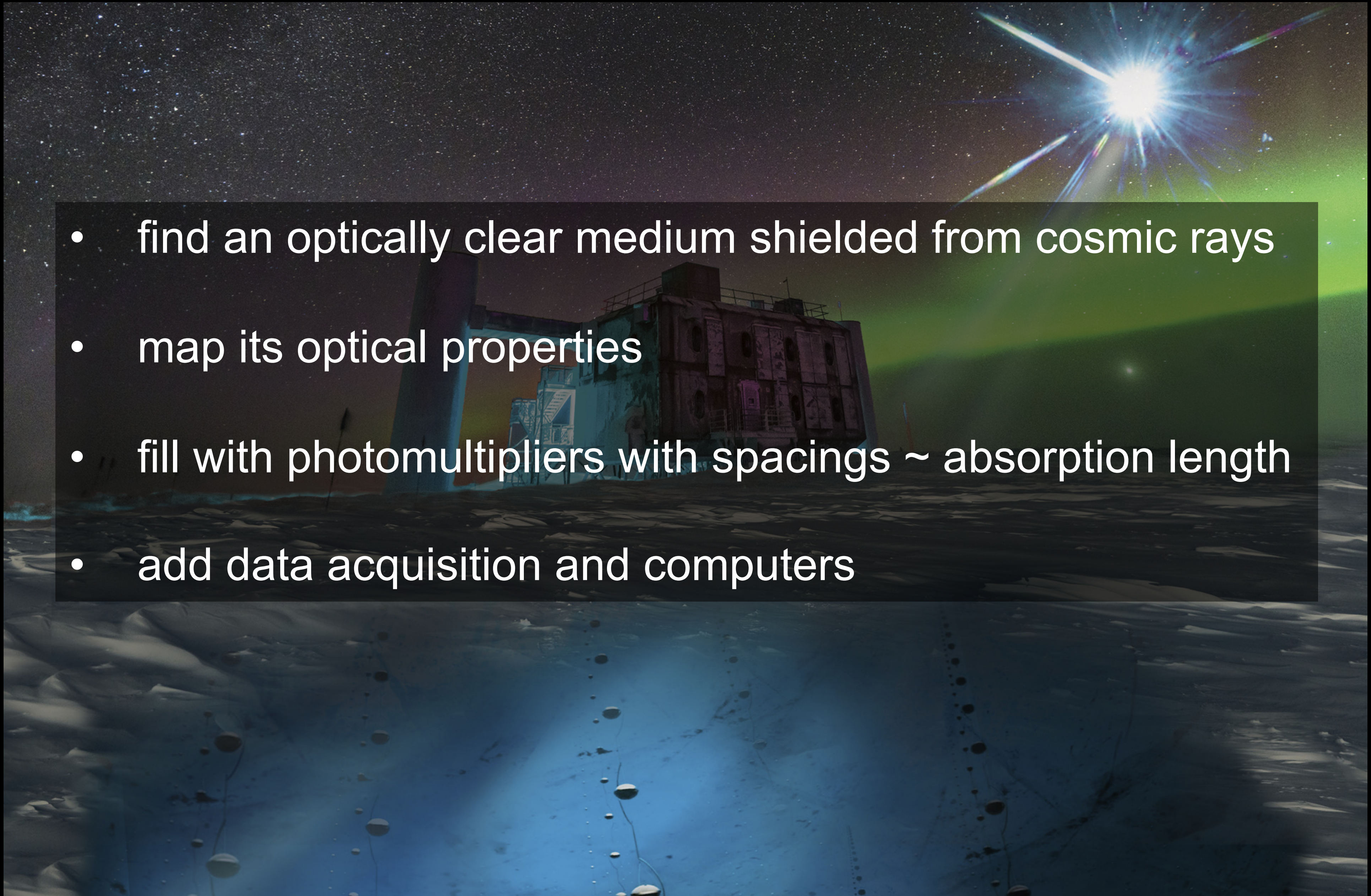
- speed of light in water ~ 3/4 c → shockwave



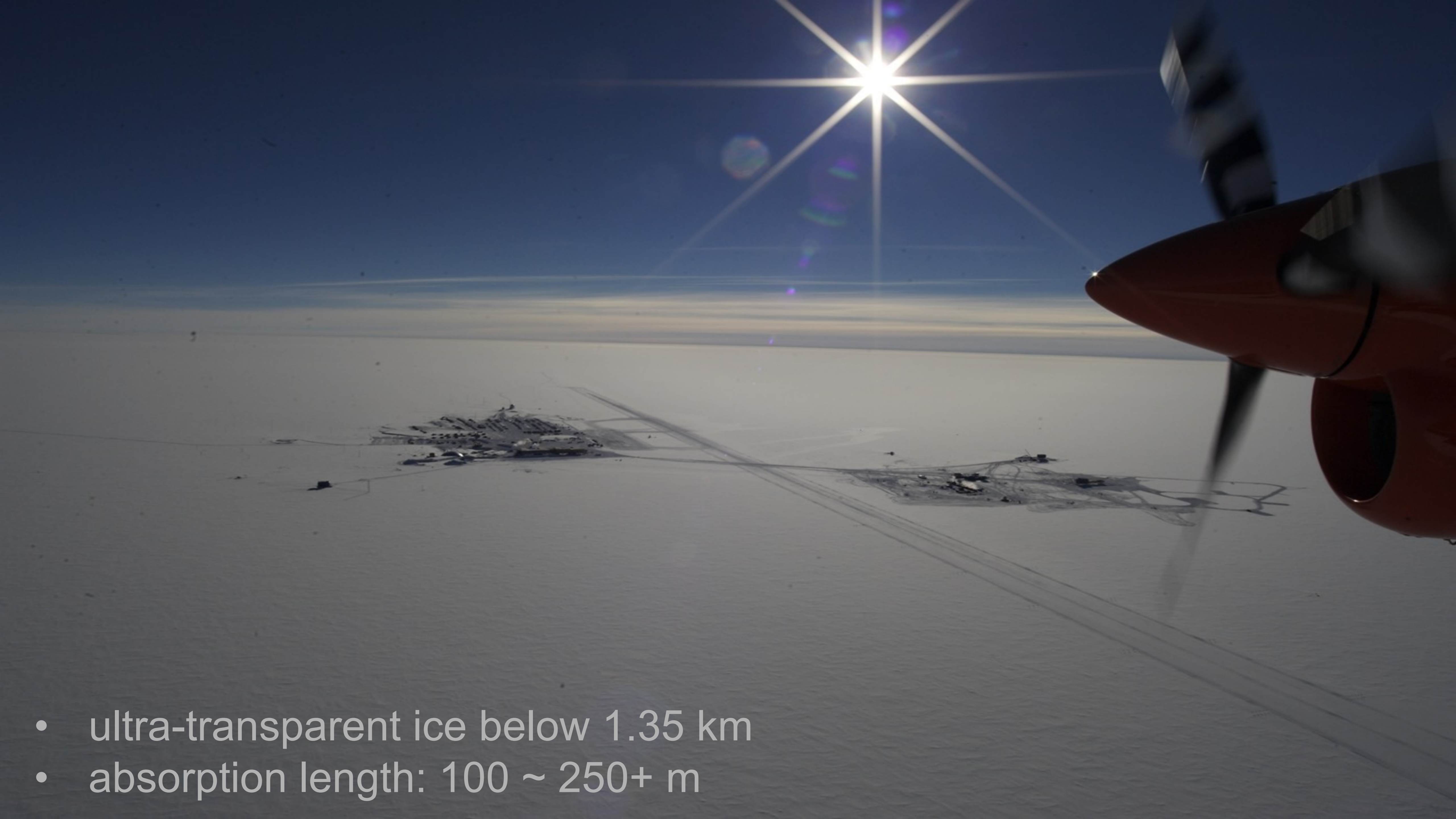


the detector operates by Standard Model physics

ice 1.4 kilometers below geographic South Pole

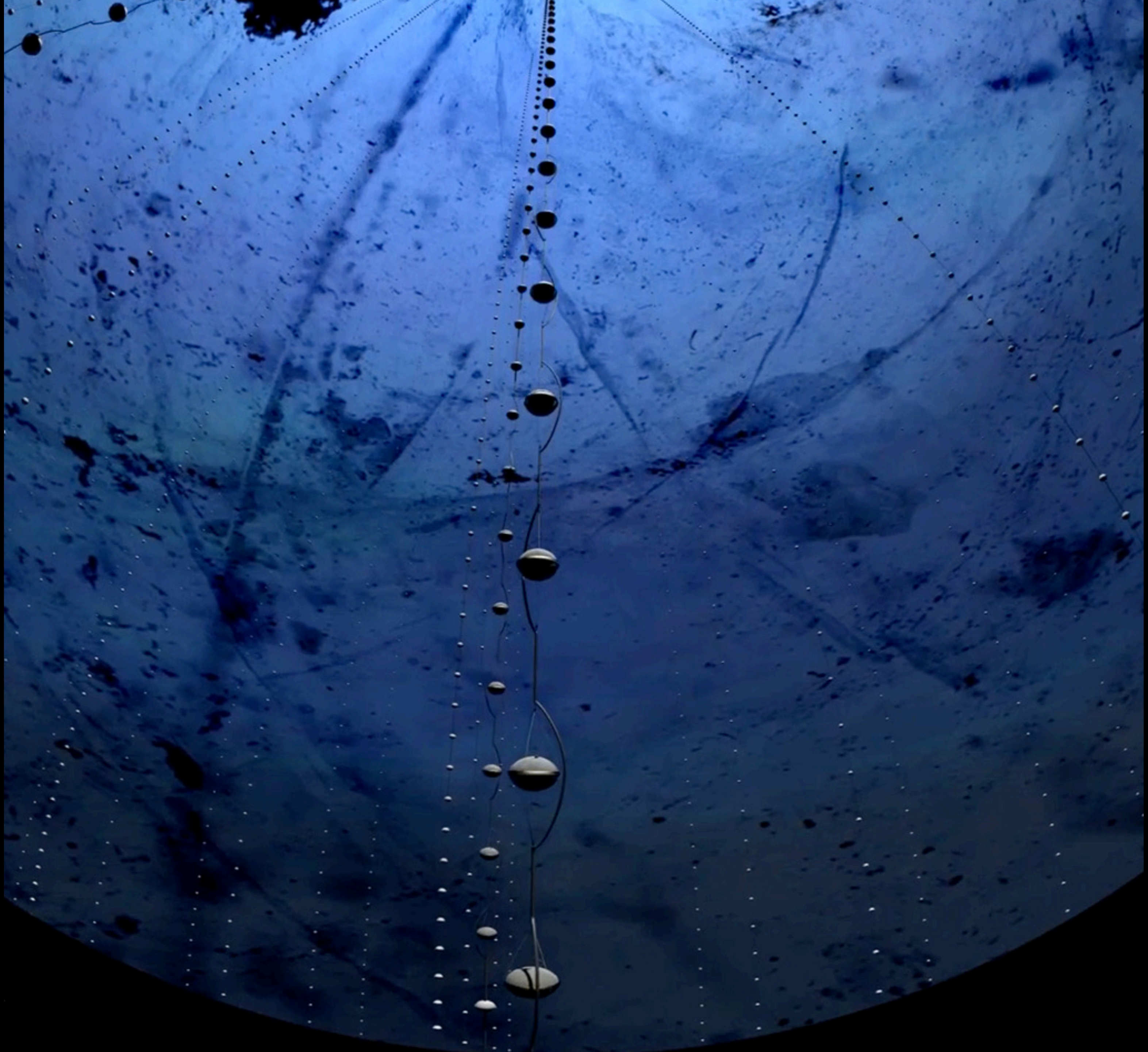


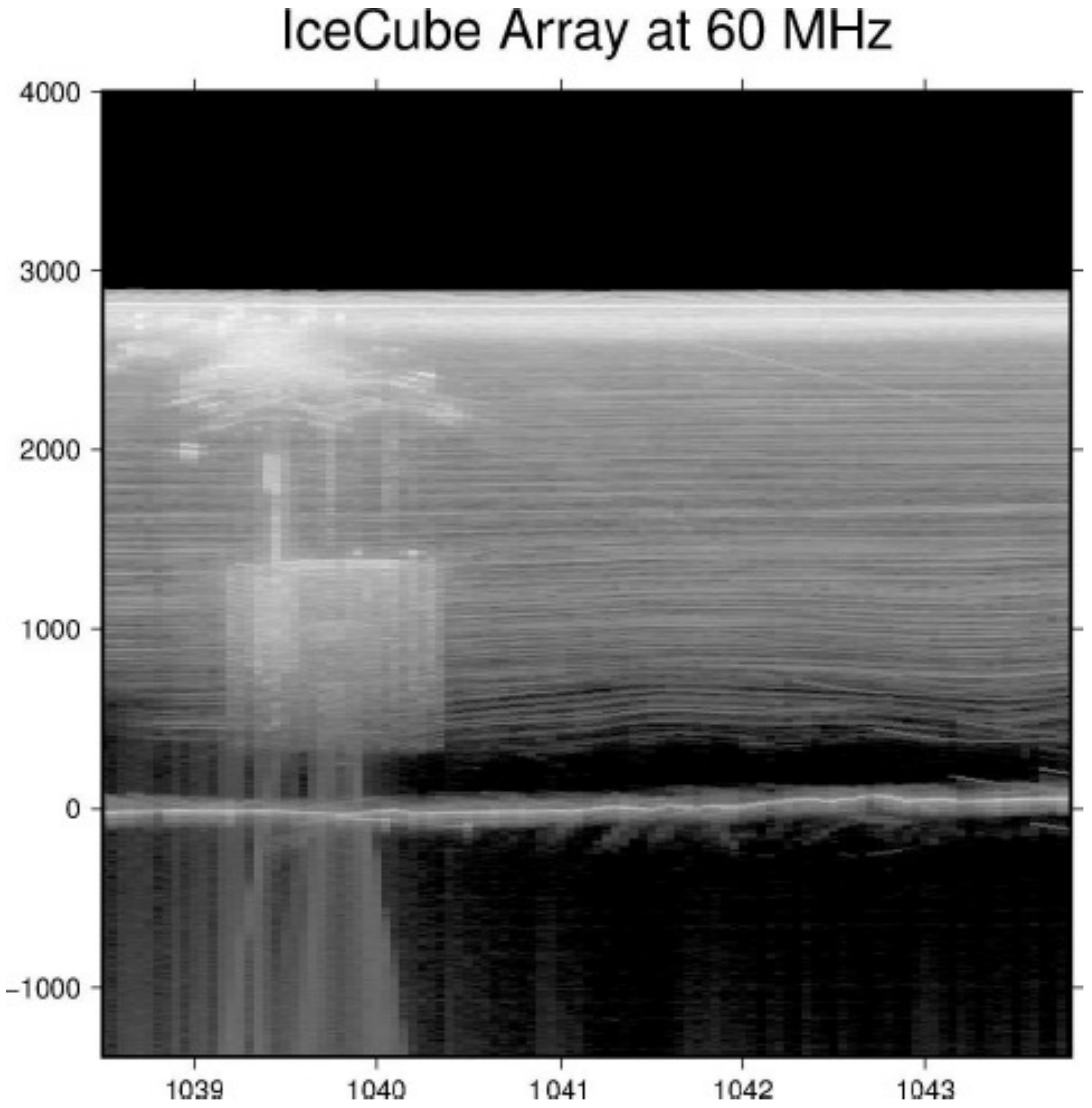
- find an optically clear medium shielded from cosmic rays
- map its optical properties
- fill with photomultipliers with spacings ~ absorption length
- add data acquisition and computers



- ultra-transparent ice below 1.35 km
- absorption length: 100 ~ 250+ m

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 from airplane

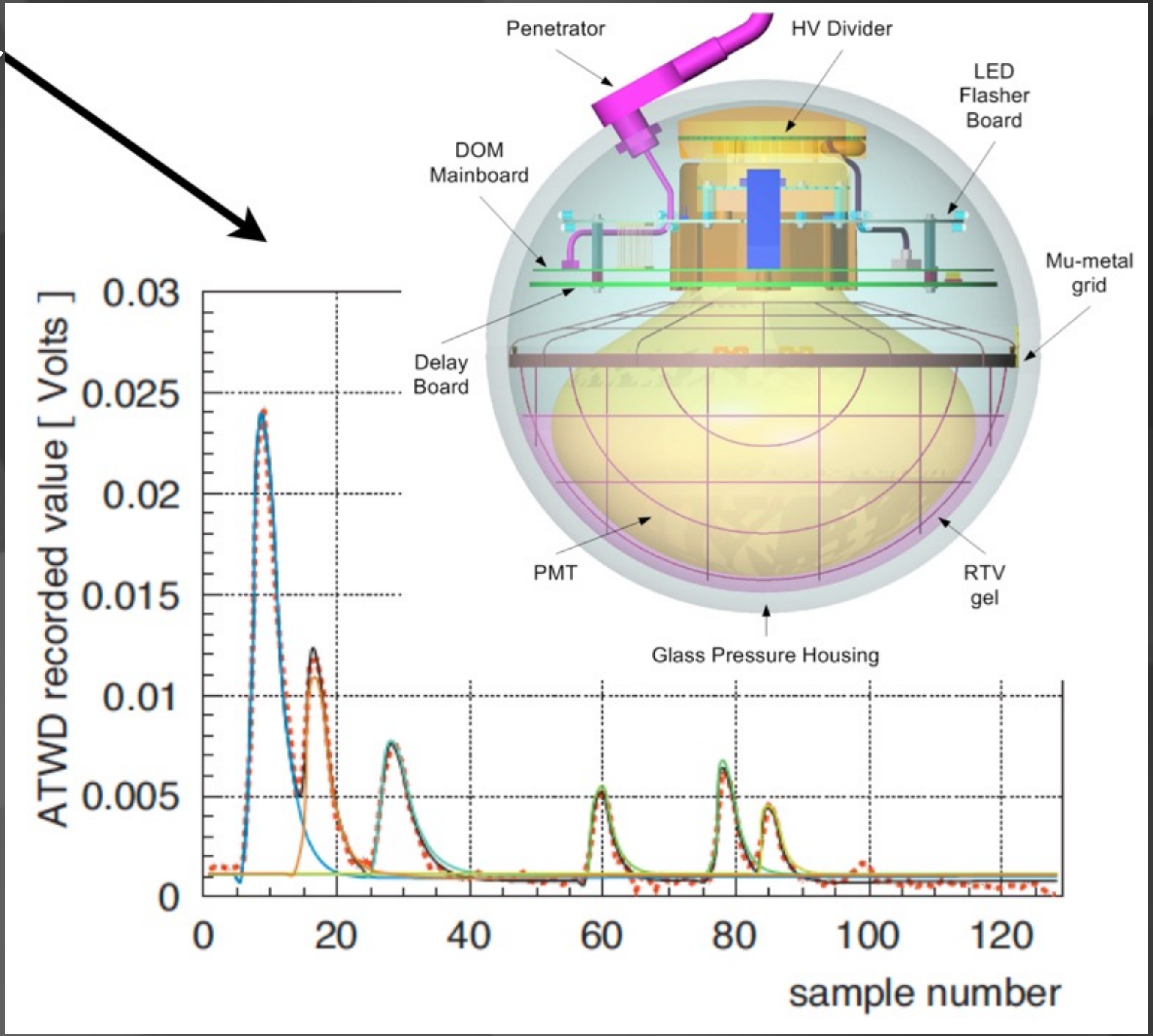
South Pole surface

1450 m

2450 m

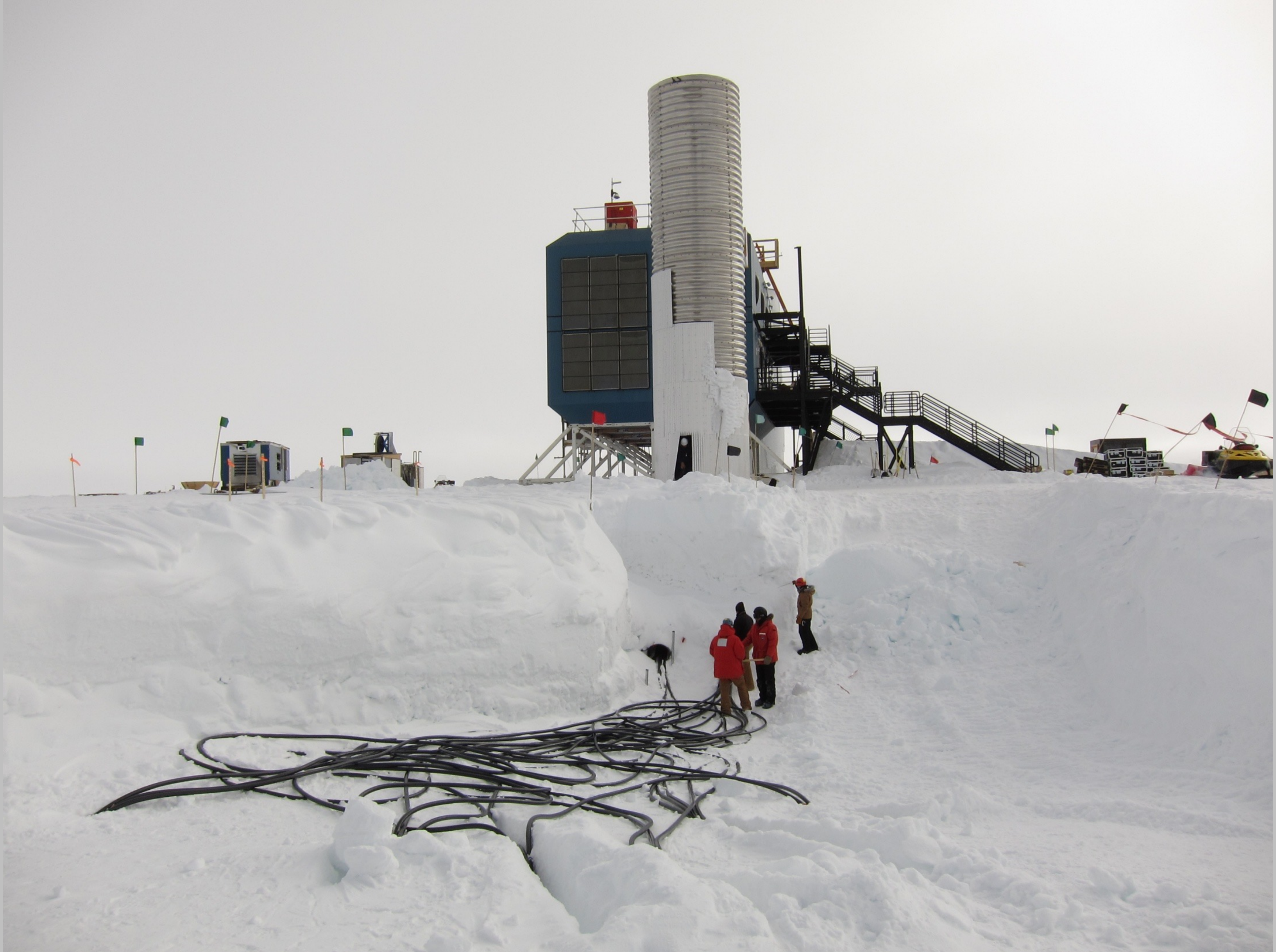
bedrock

digitized light signals
(waveforms)

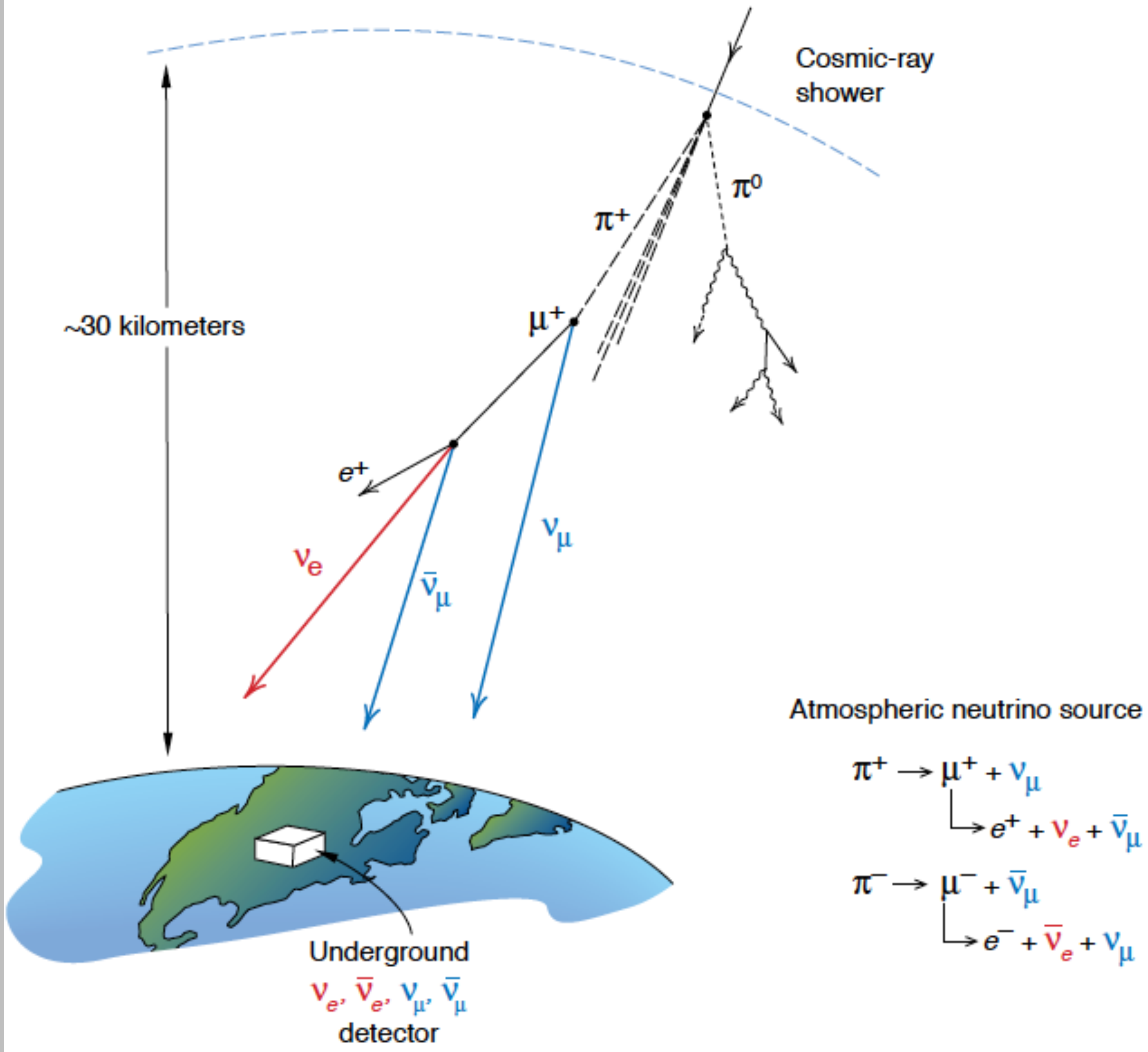


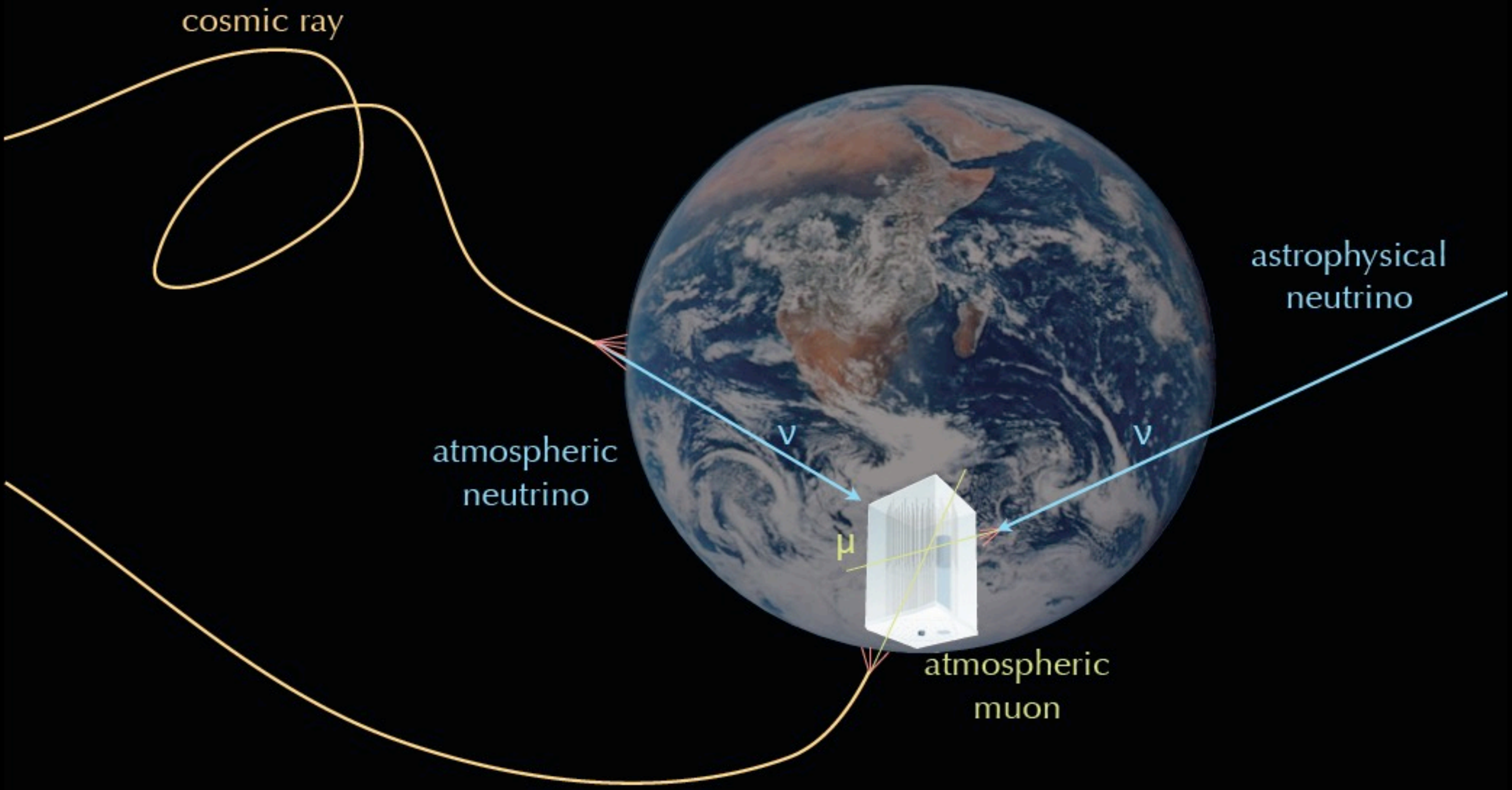
- each Digital Optical Module independently collects light signals like this, digitizes them and

- time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them in events…

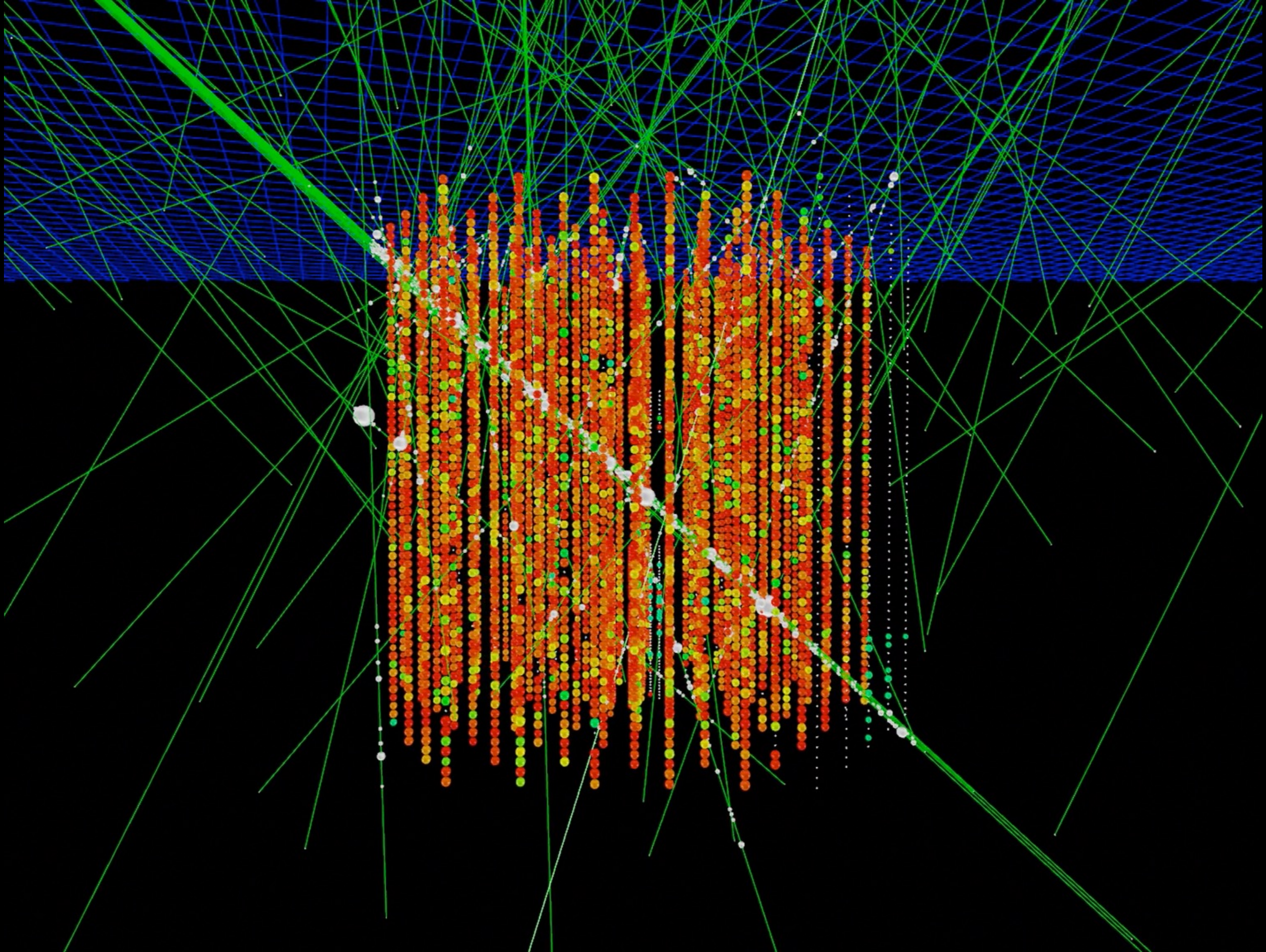


what does IceCube reveal ?
atmospheric muons and atmospheric neutrinos





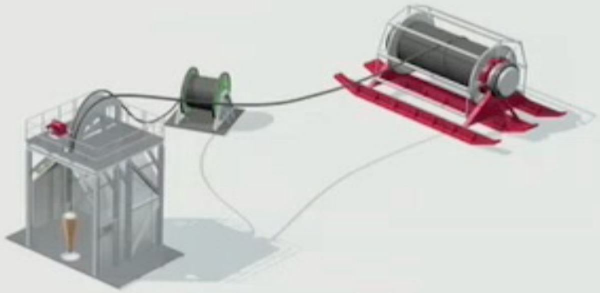
cosmic ray
astrophysical neutrino
ν
ν
atmospheric neutrino
μ
atmospheric muon

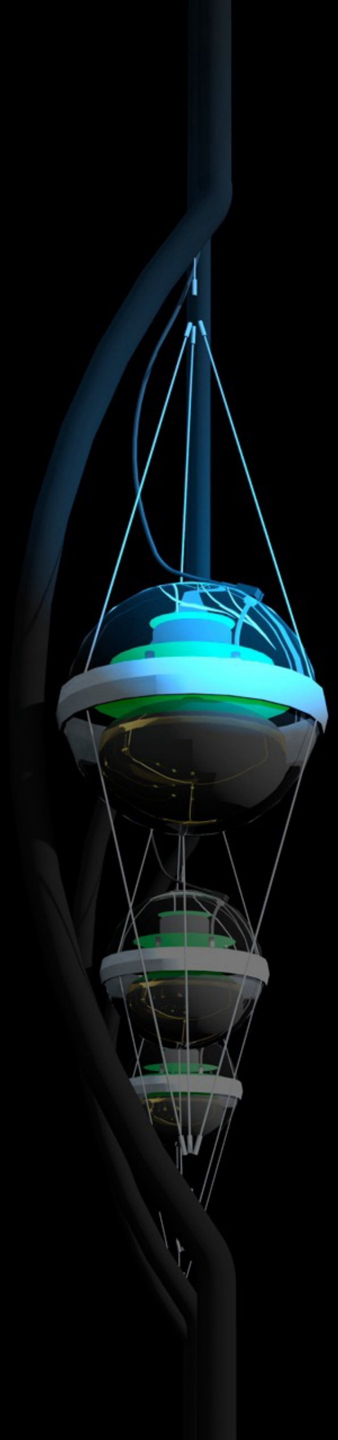


you just saw a 10 msec movie

muons detected per year:

• atmospheric	μ	$\sim 10^{11}$	→	3000 per second
• atmospheric	$\nu \rightarrow \mu$	$\sim 10^{5}$	→	1 every 5 minutes
• cosmic	$\nu \rightarrow \mu$	> 200	→	depends on the precise spectrum





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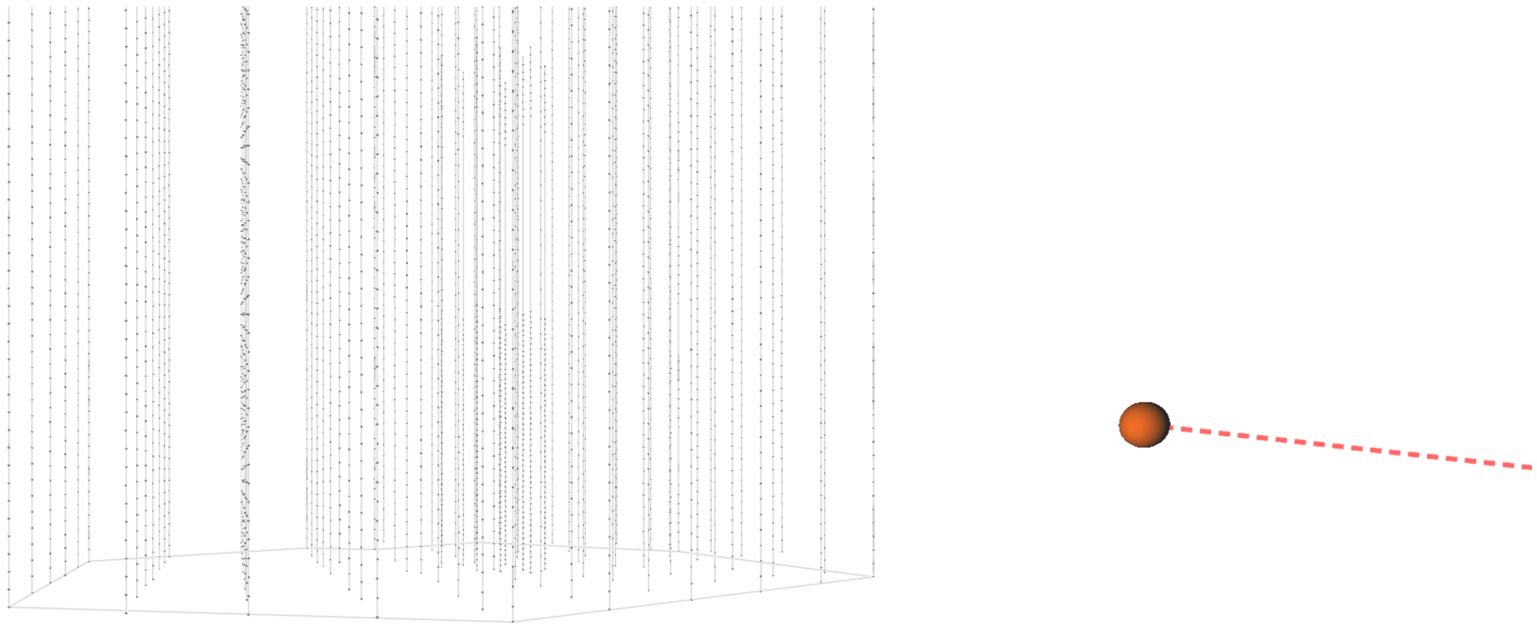
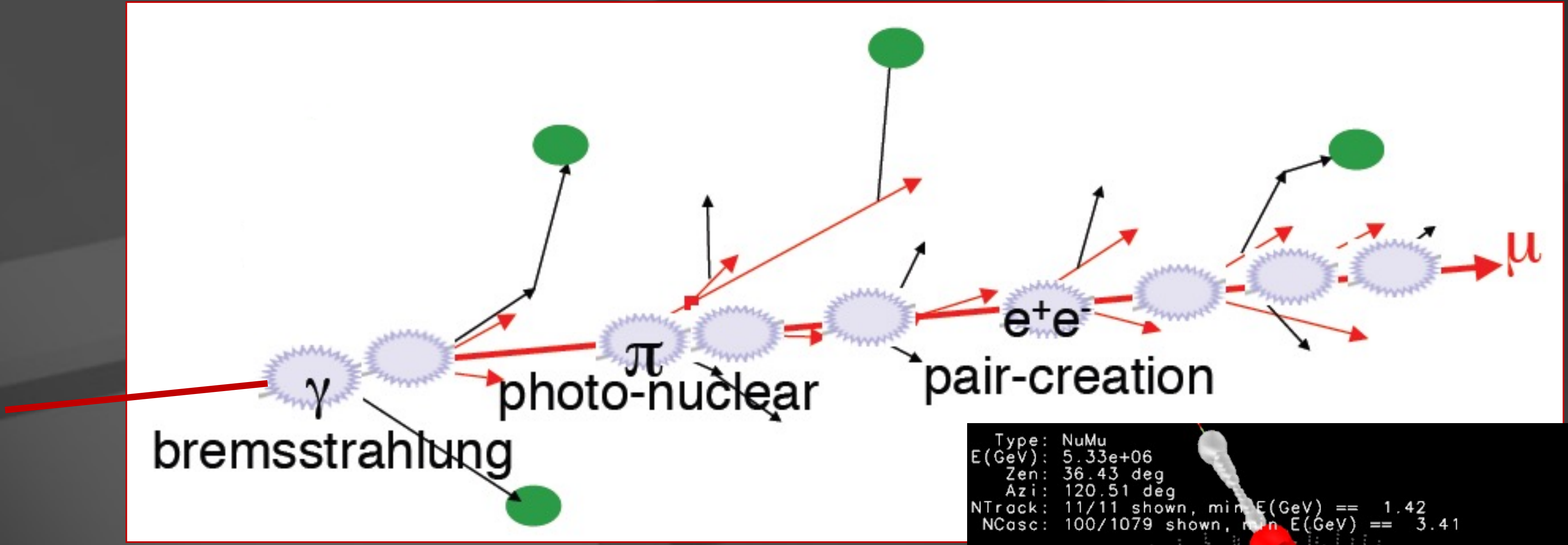
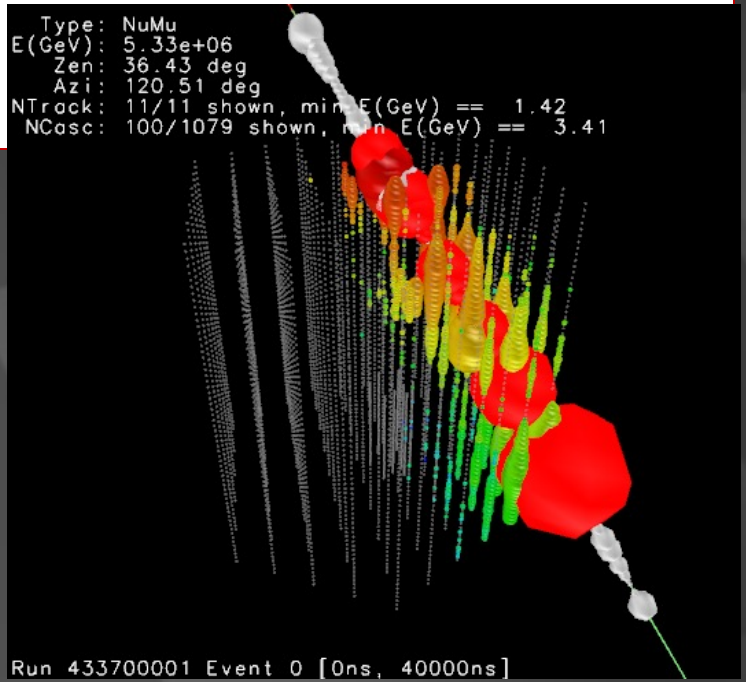
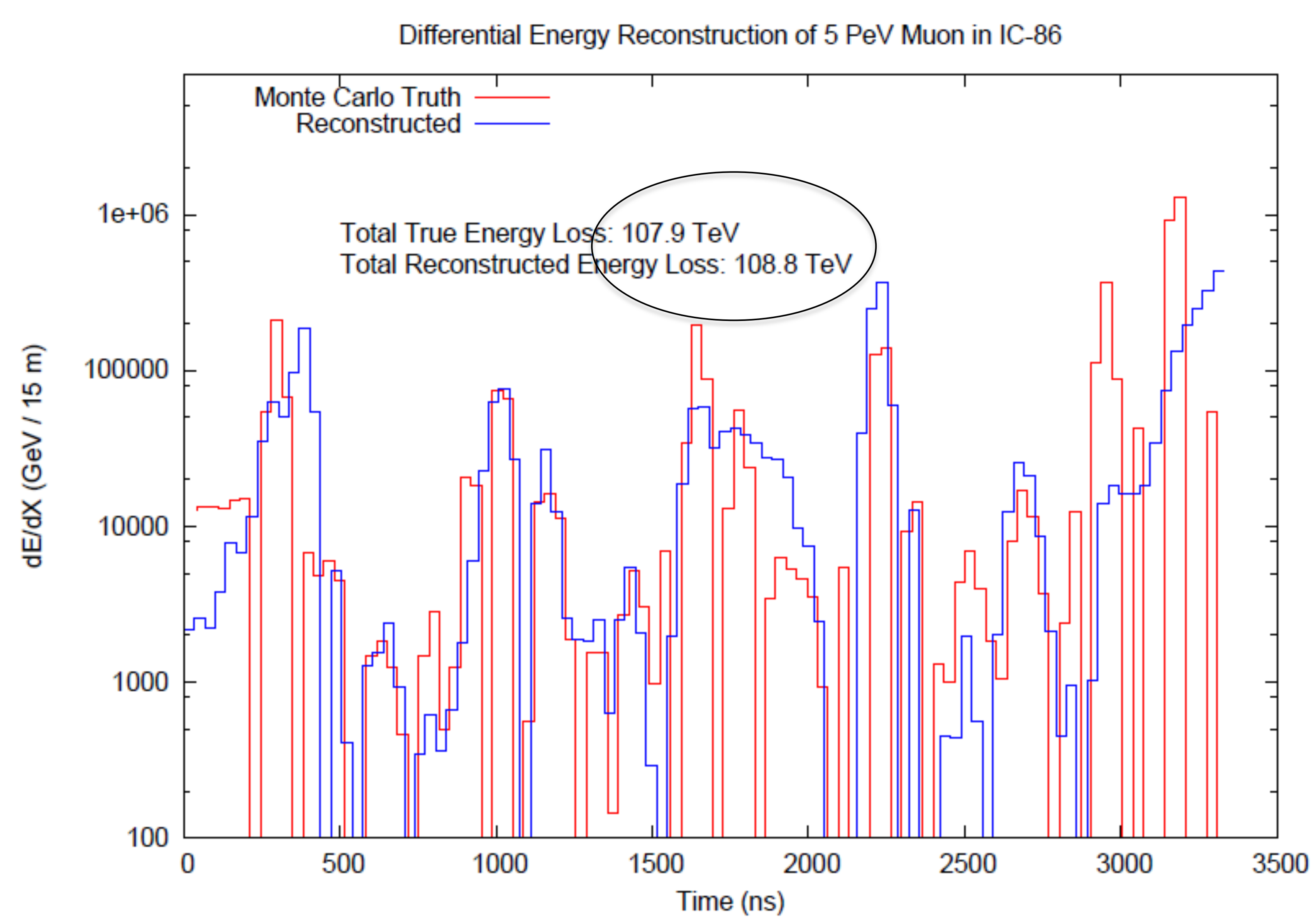


energy measurement





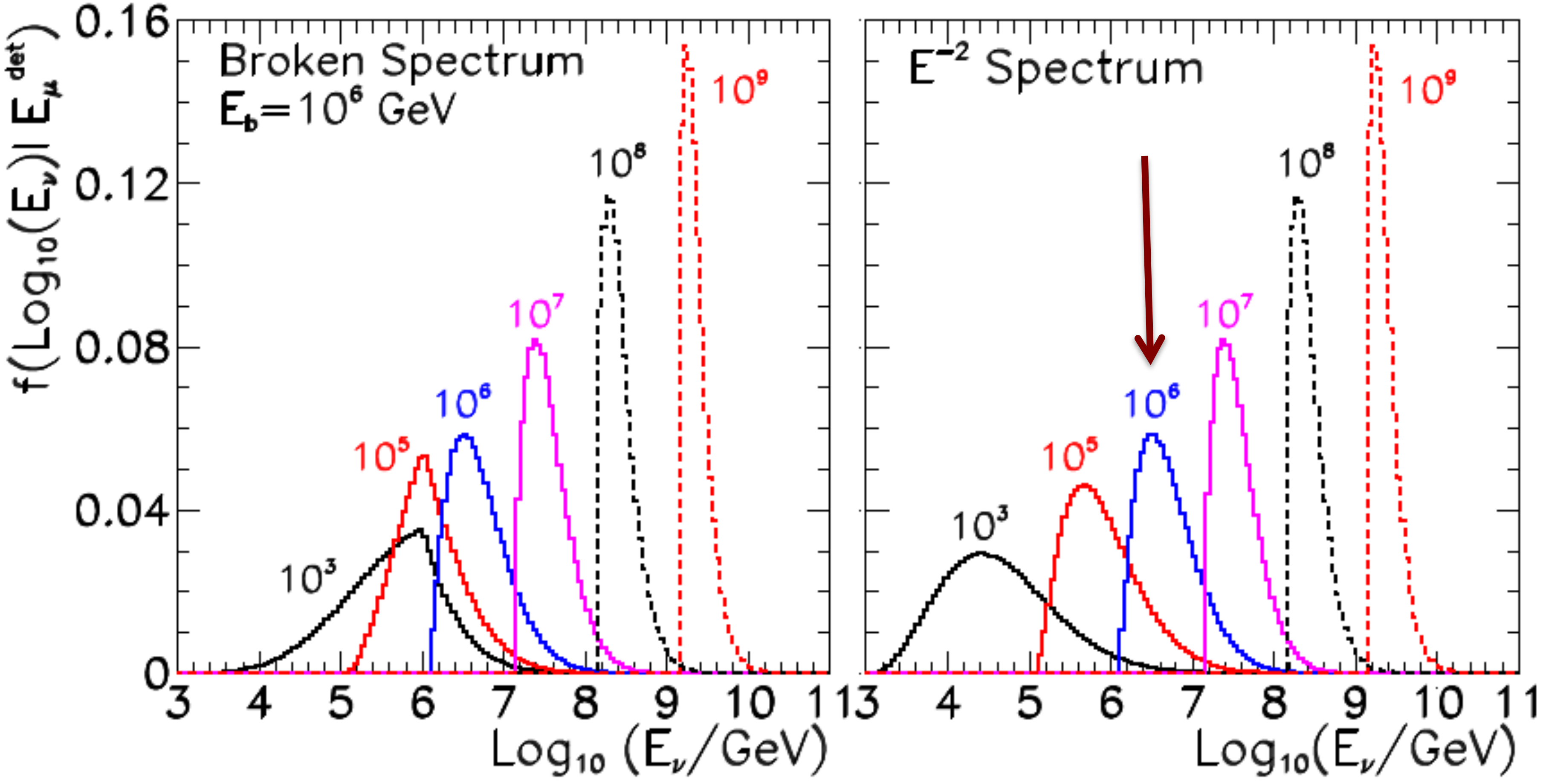
convert the amount of Cherenkov light emitted and its stochasticity to a measurement of the energy muon track

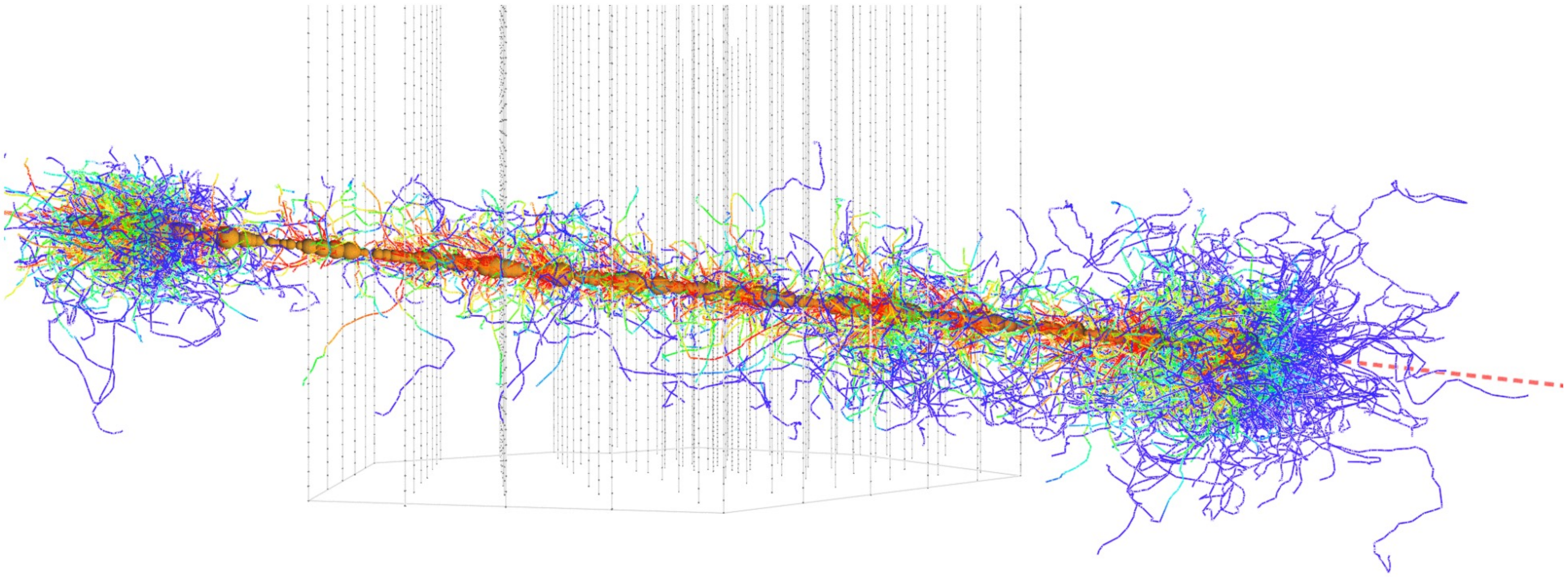


1.1 km

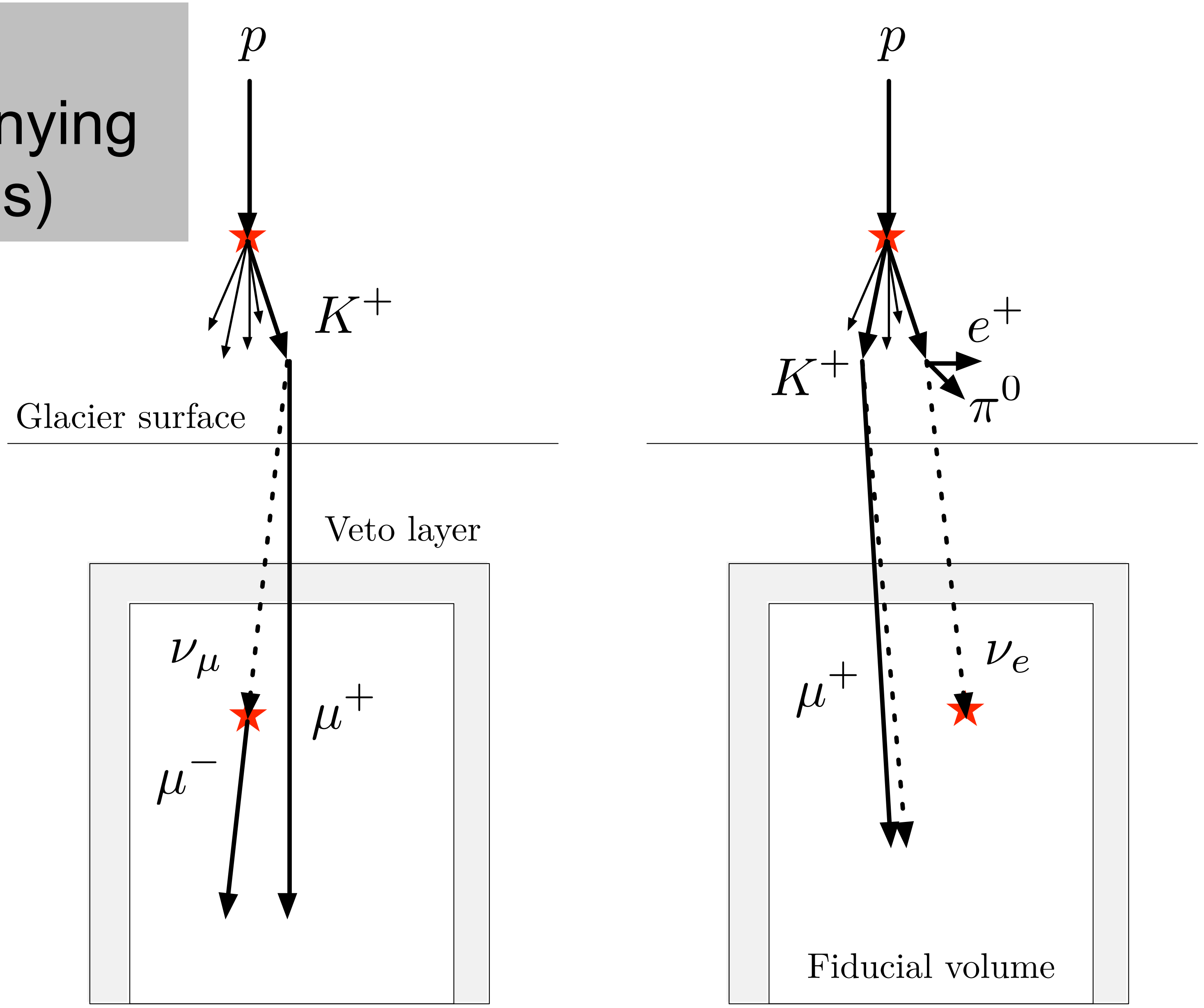
improving energy and angular resolution

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





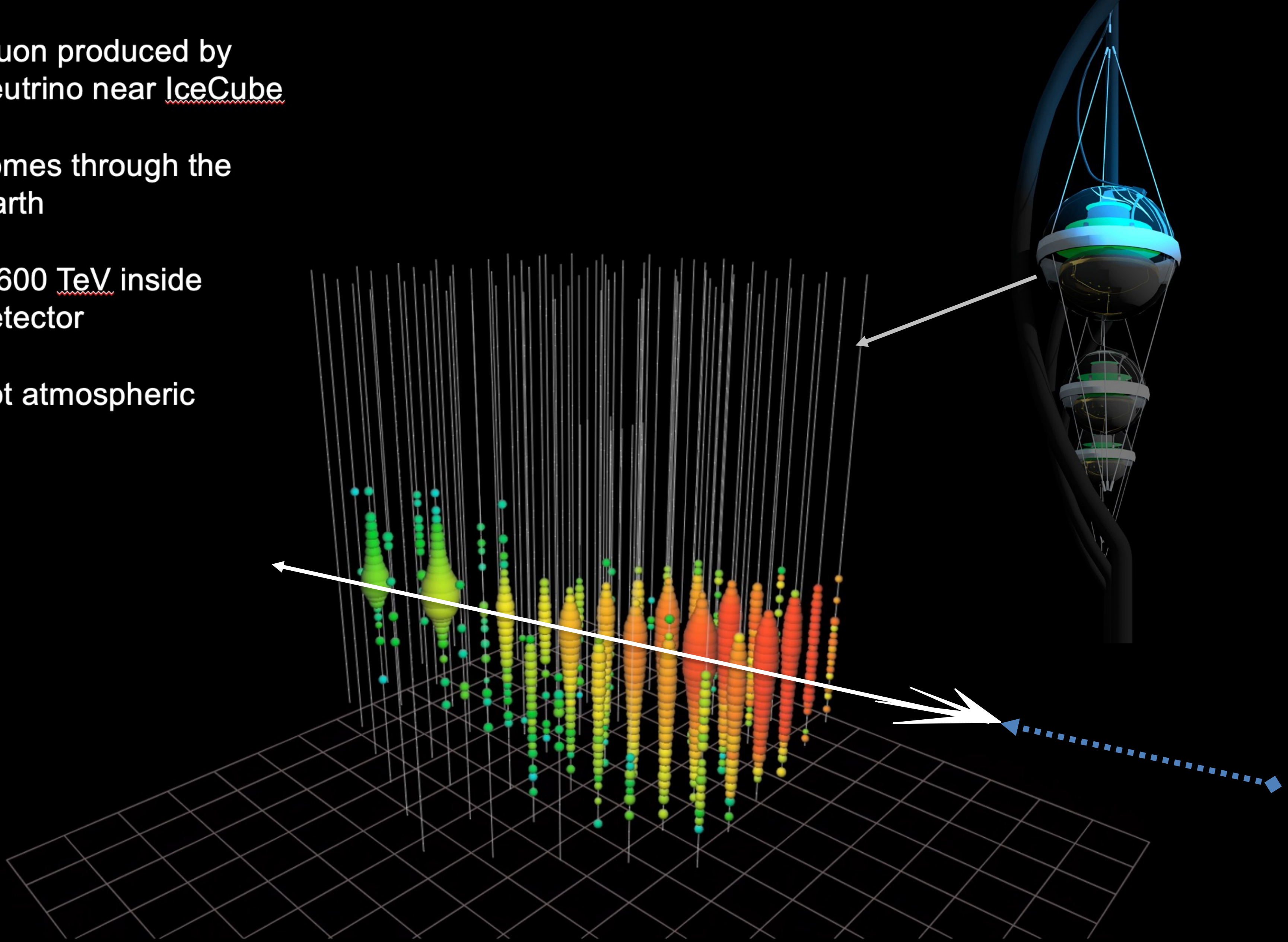
no accompanying muon(s)



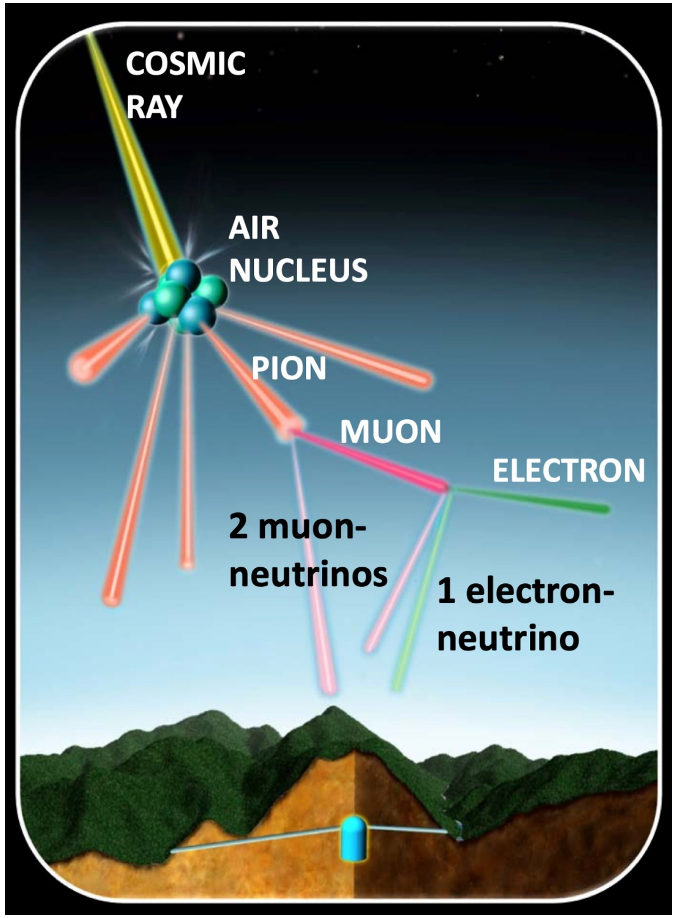
Veto by correlated muon

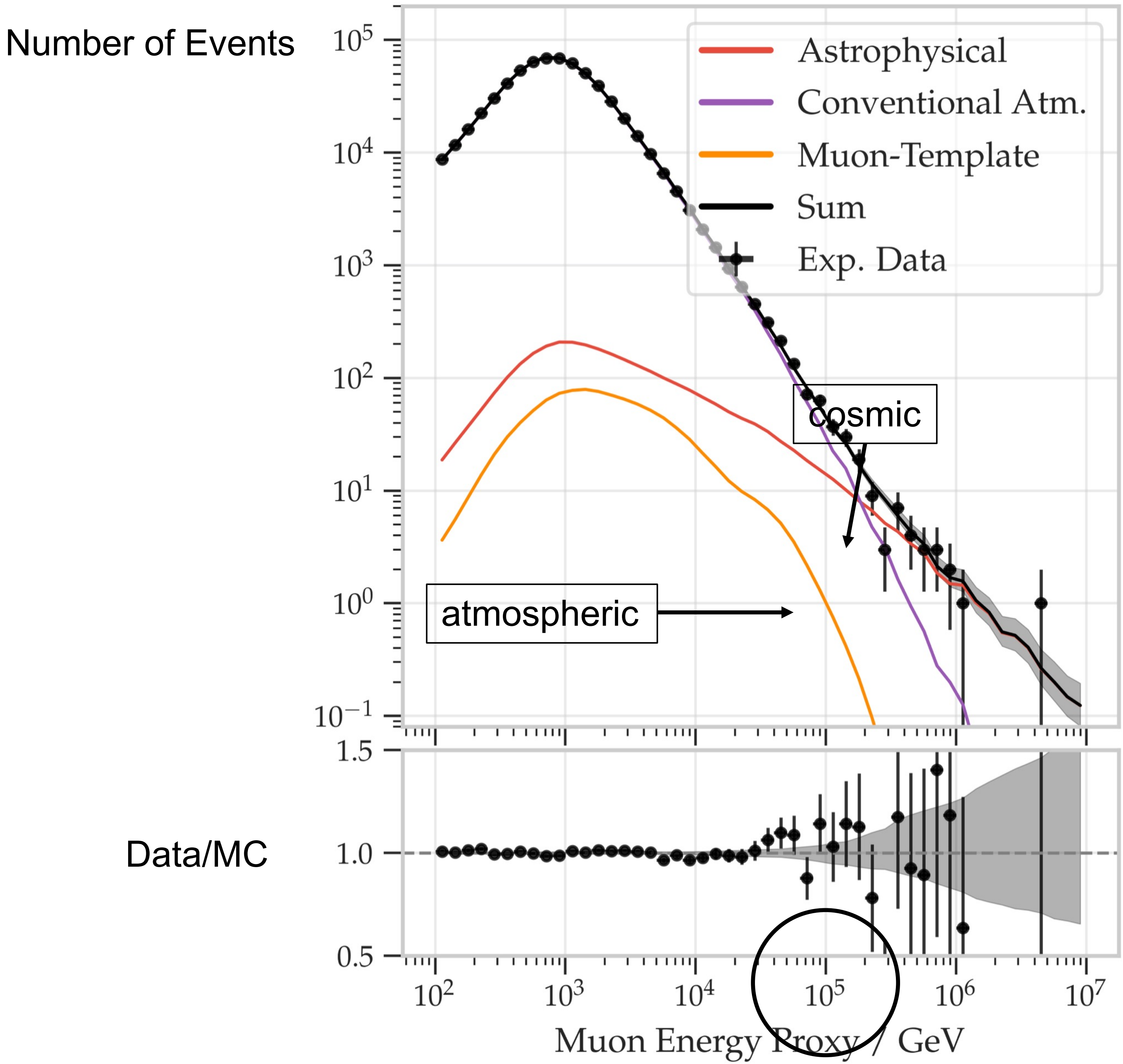
Veto by uncorrelated muon

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

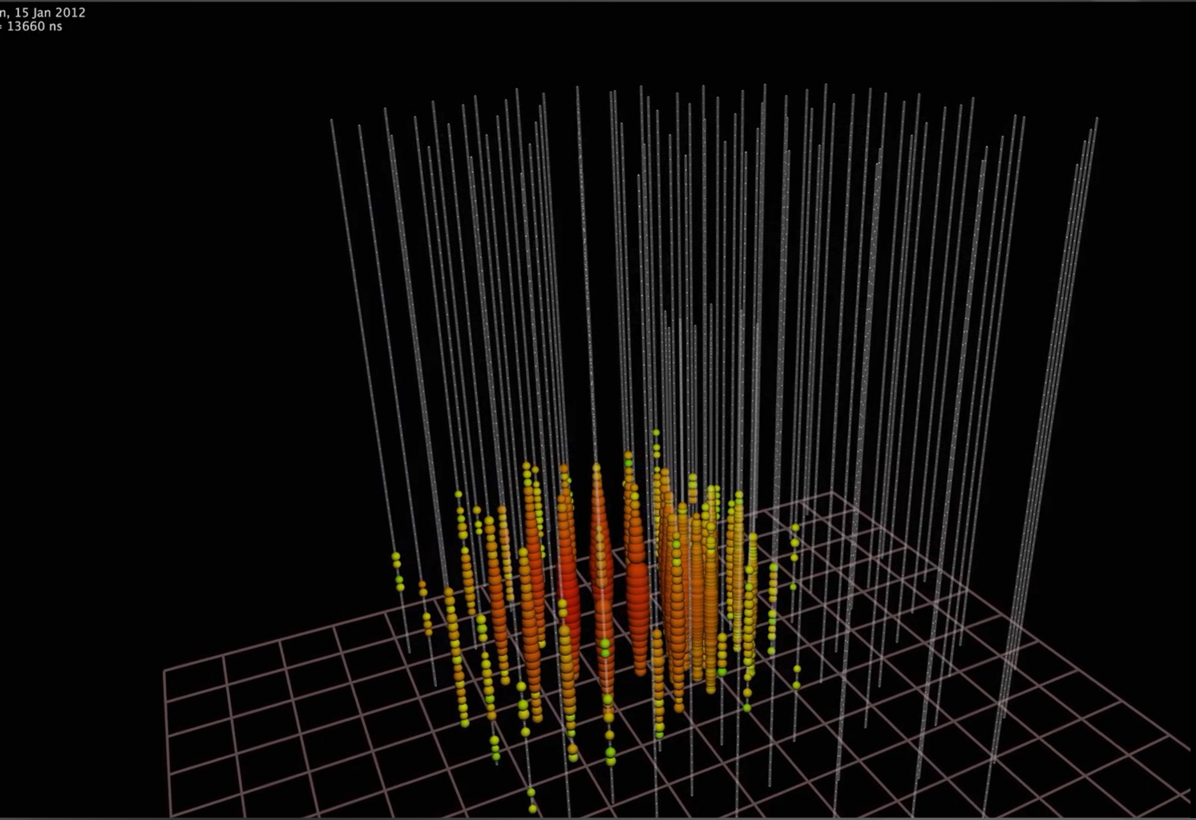


muon neutrino events [filtered by the Earth]: atmospheric vs cosmic



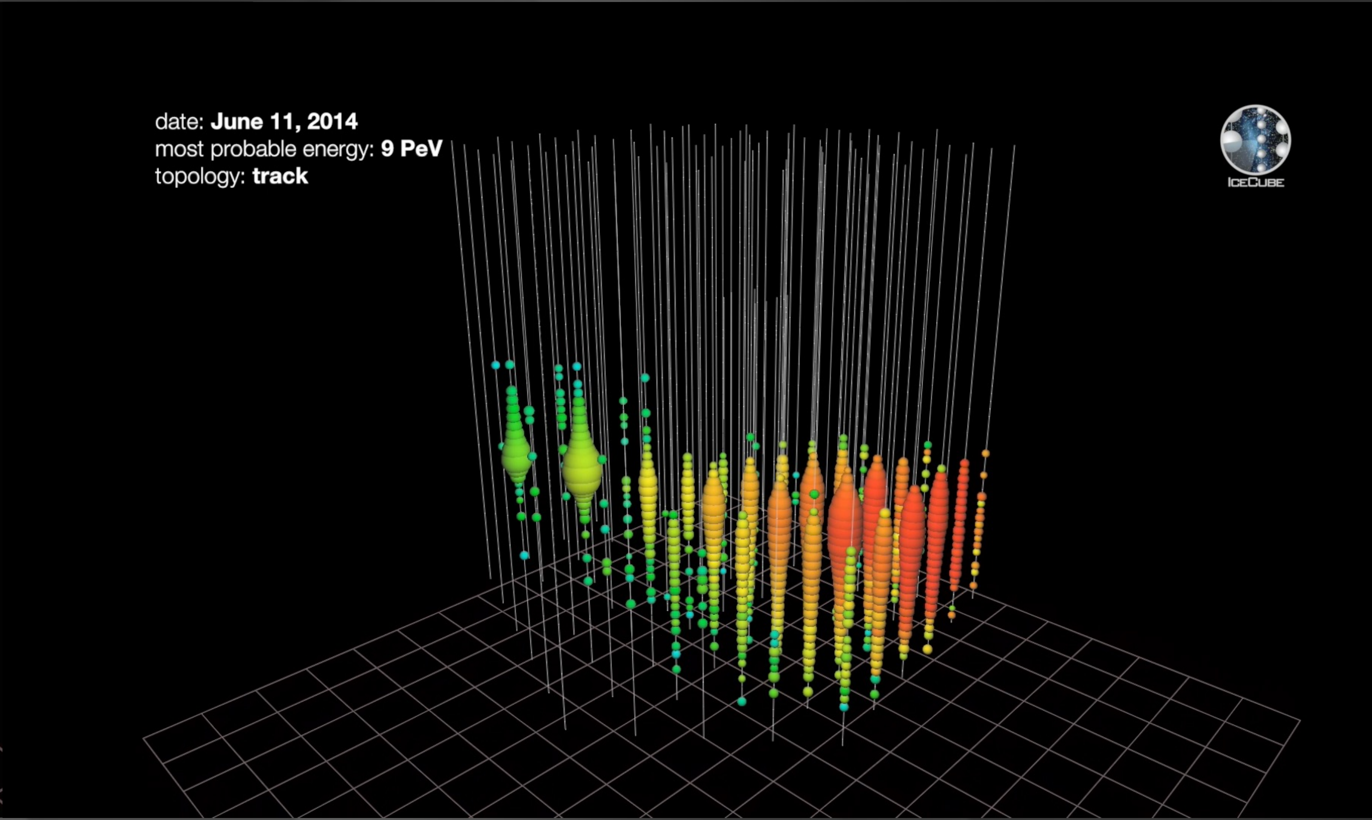


neutrinos interacting
inside the detector



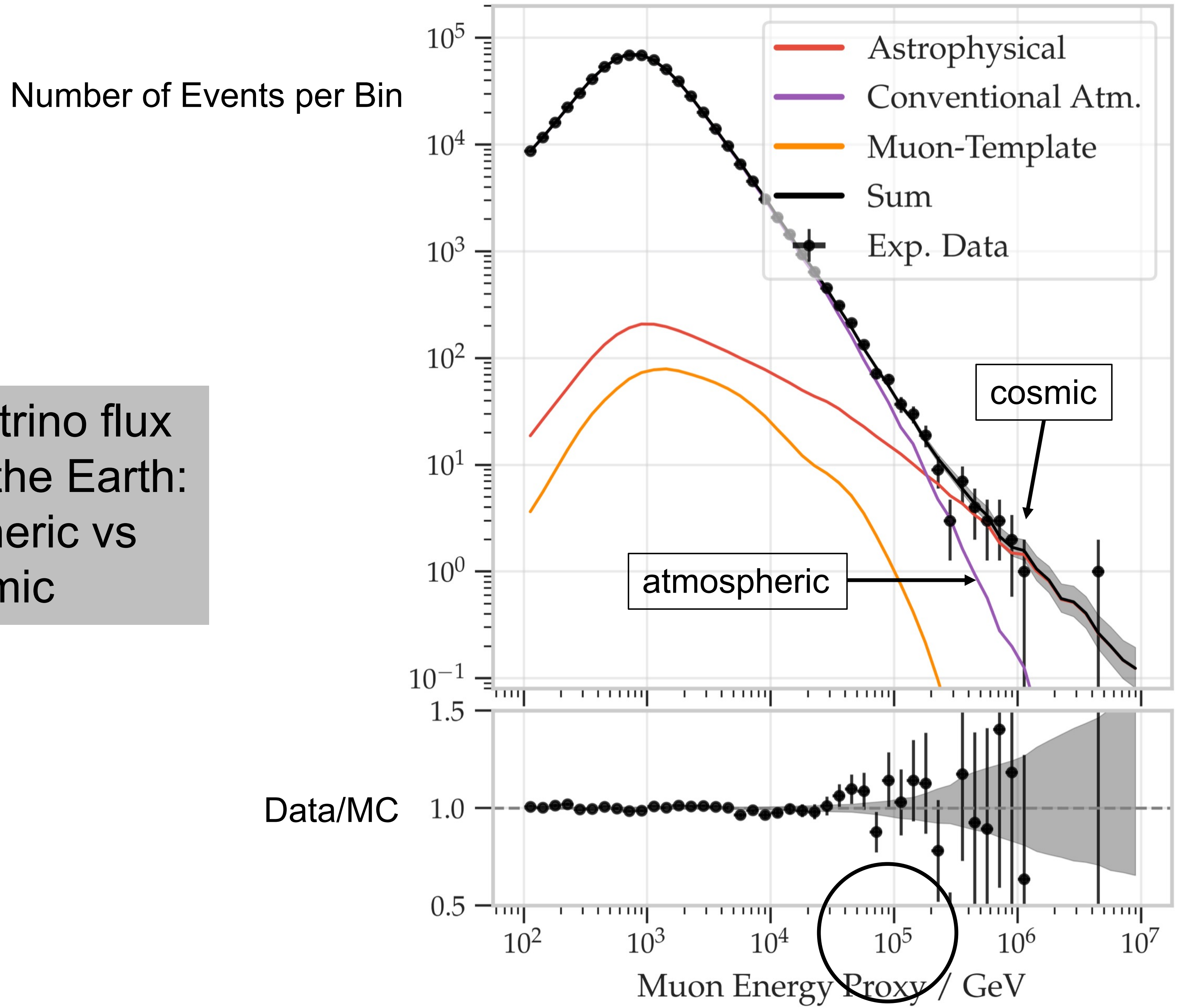
superior total energy
measurement
to 10%, all flavors, all sky

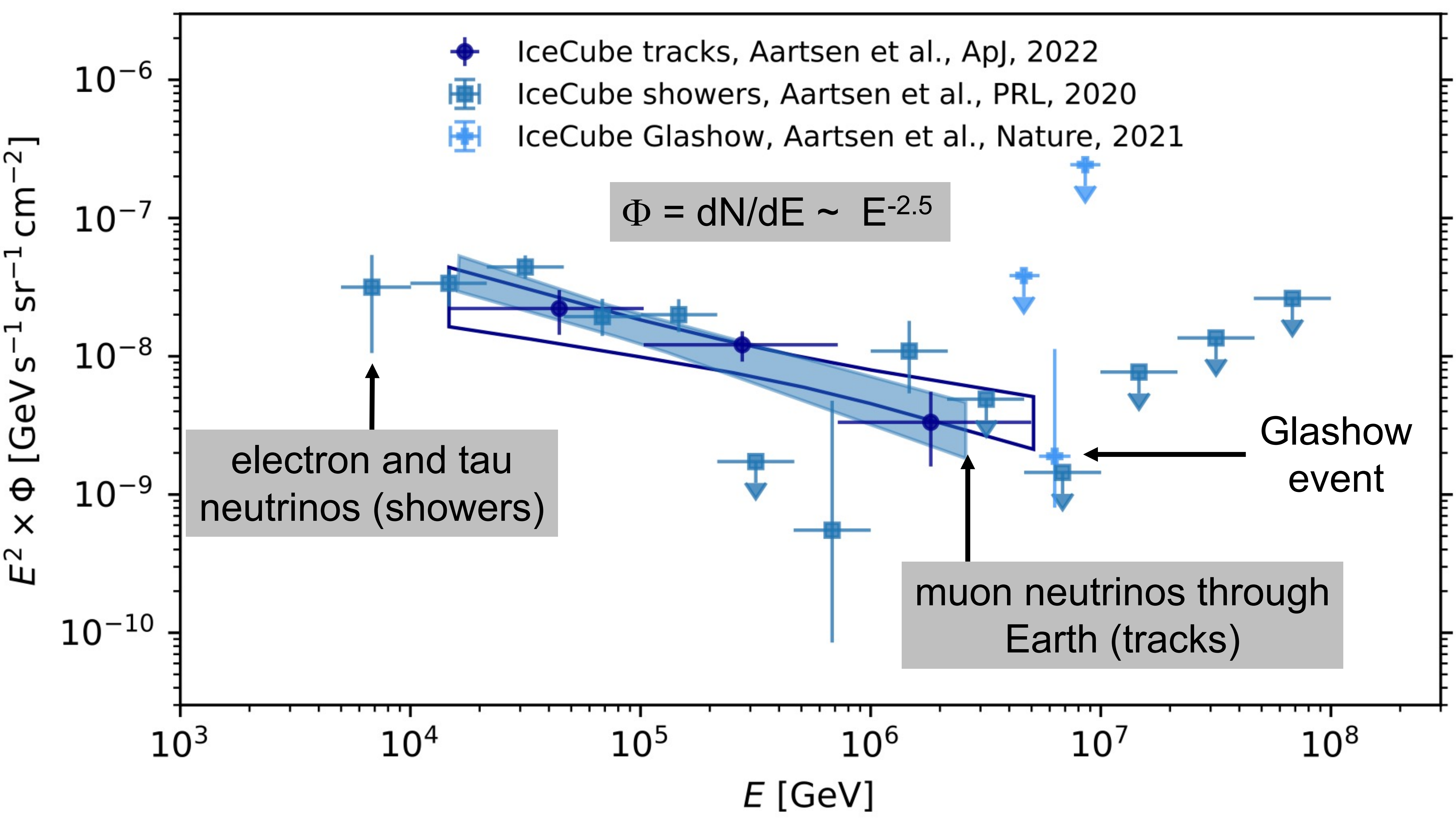
muon neutrinos
filtered by the Earth



superior angular resolution 0.3^o
including systematics

muon neutrino flux filtered by the Earth: atmospheric vs cosmic



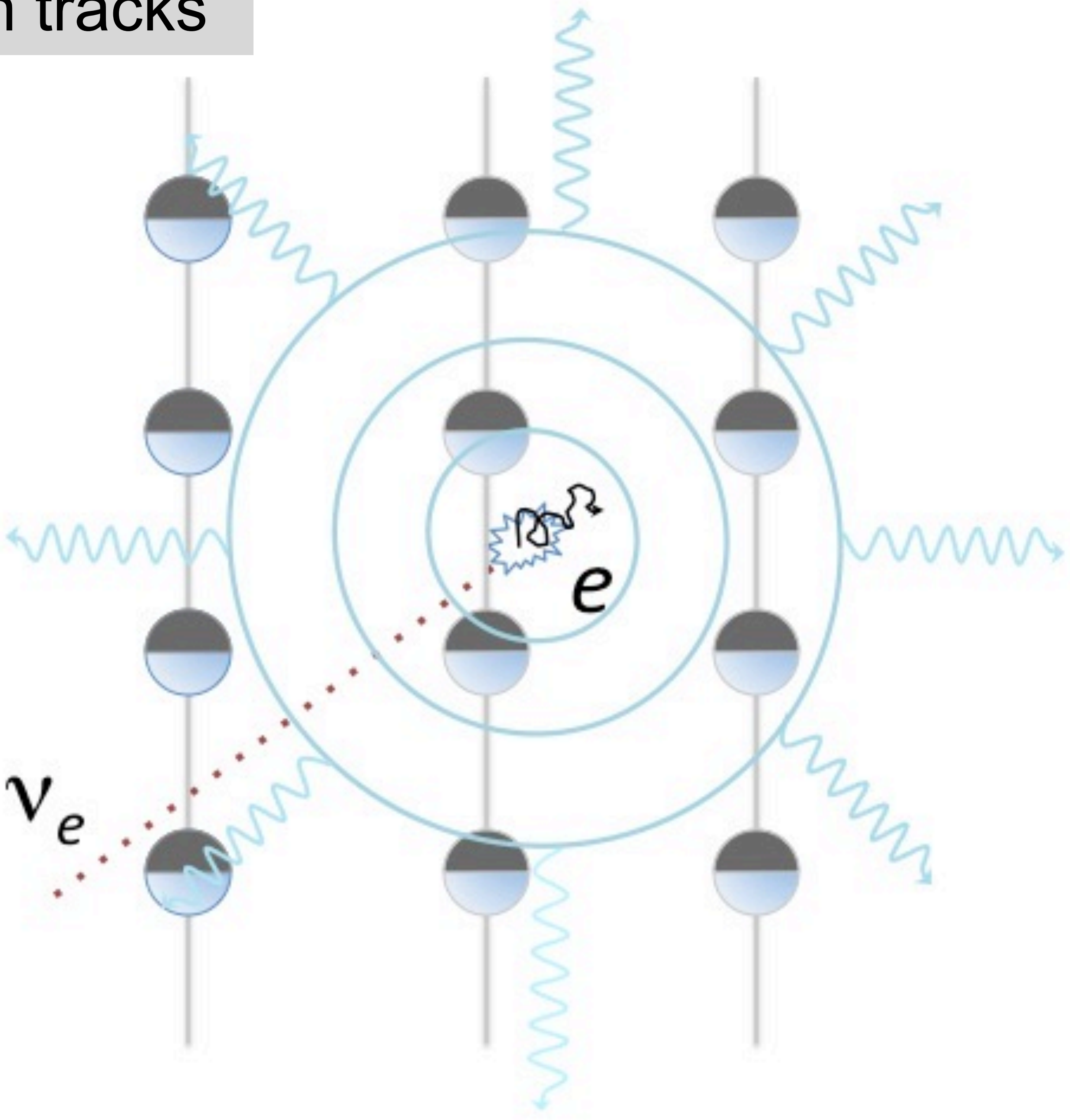


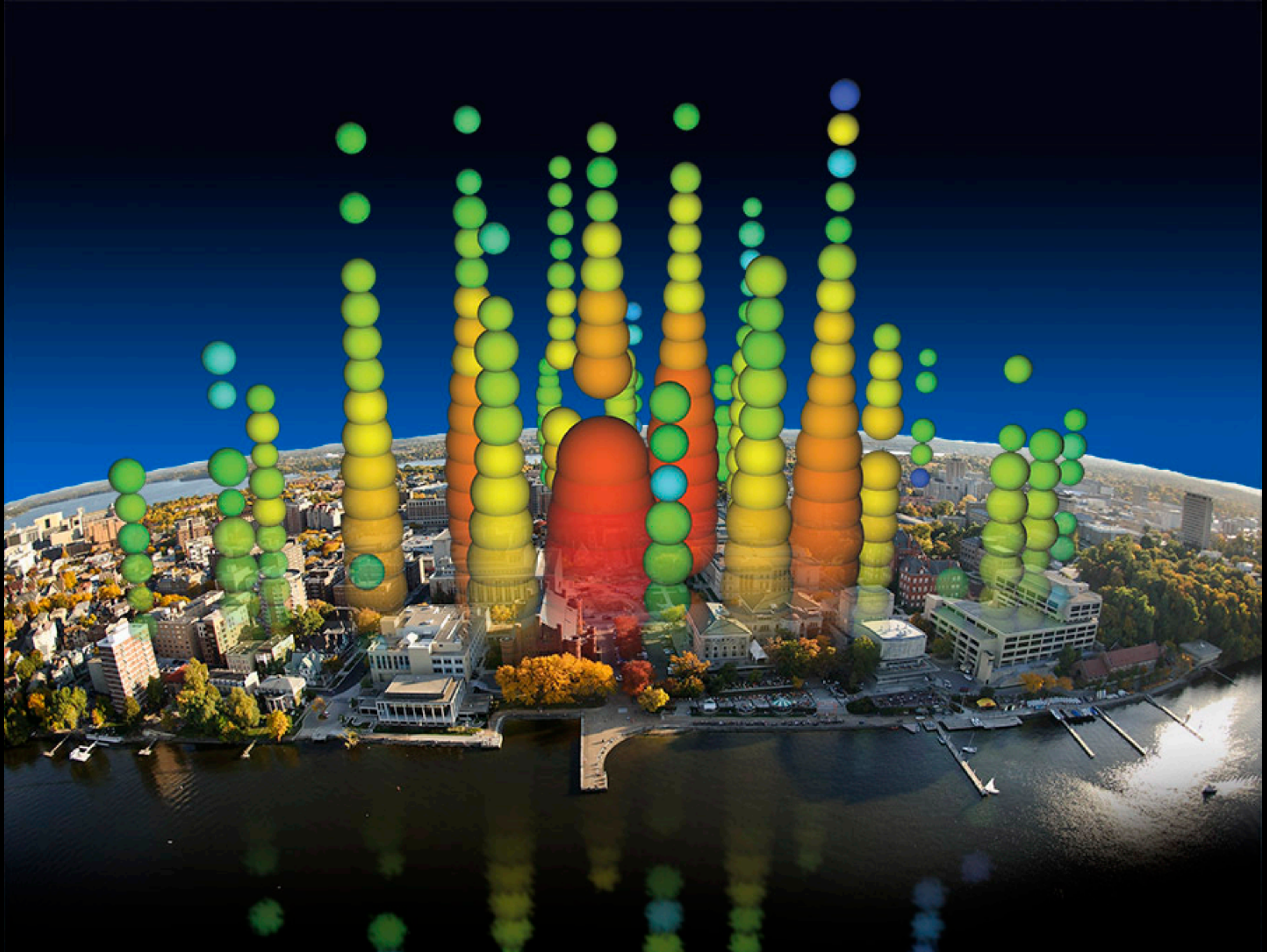
IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ E^-2.5
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
E^2 × Φ [GeV s^-1 sr^-1 cm^-2]
E [GeV]
10^-6
10^-7
10^-8
10^-9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

electron showers versus muon tracks

PeV ν_e and ν_τ showers:

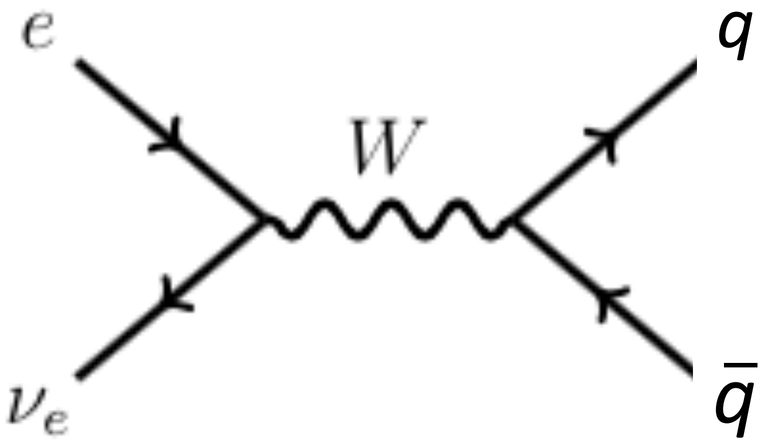
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~50 m





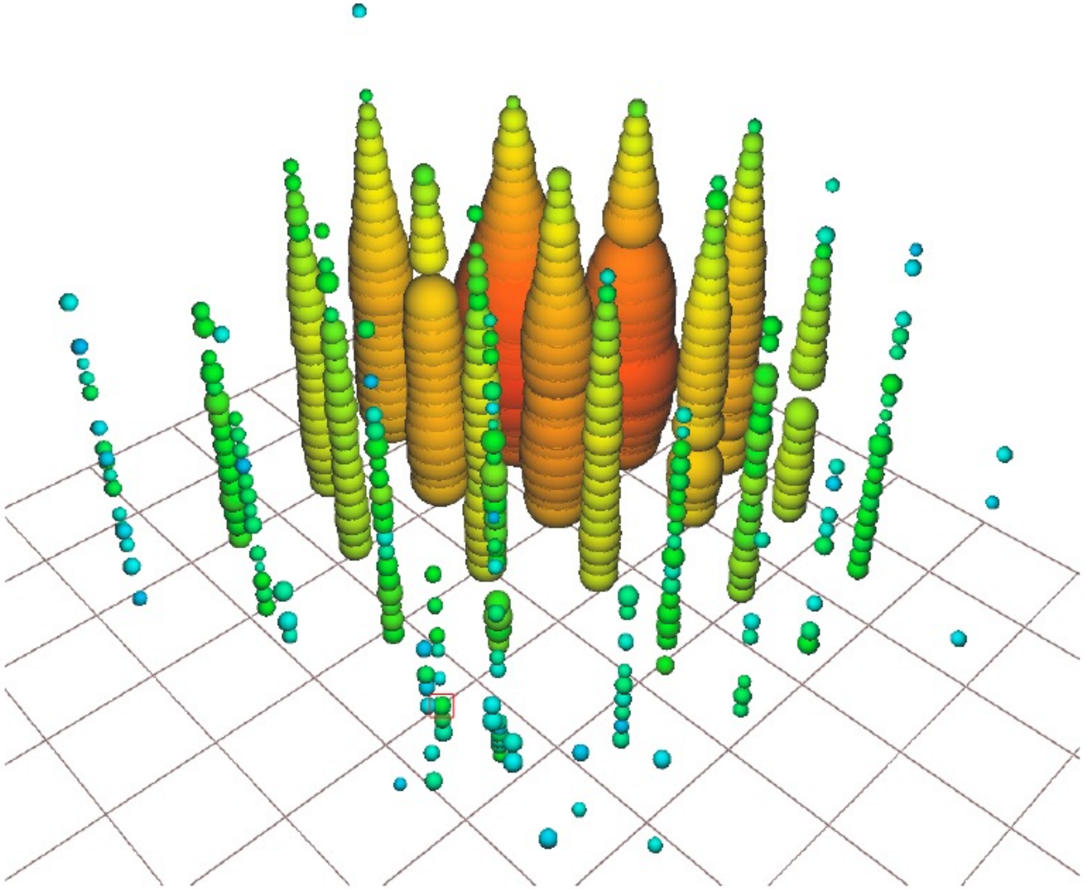
Cherenkov radiation from PeV electron (tau) shower
> 300 sensors > 100,000 pe reconstructed to 2 nsec

Glashow resonance event with energy 6.3 PeV

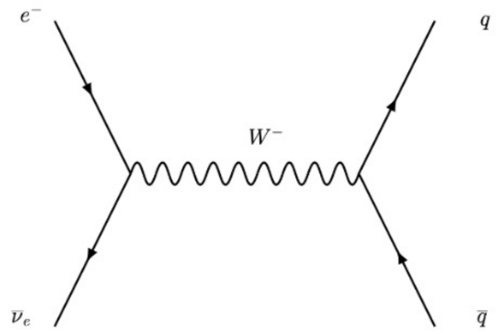


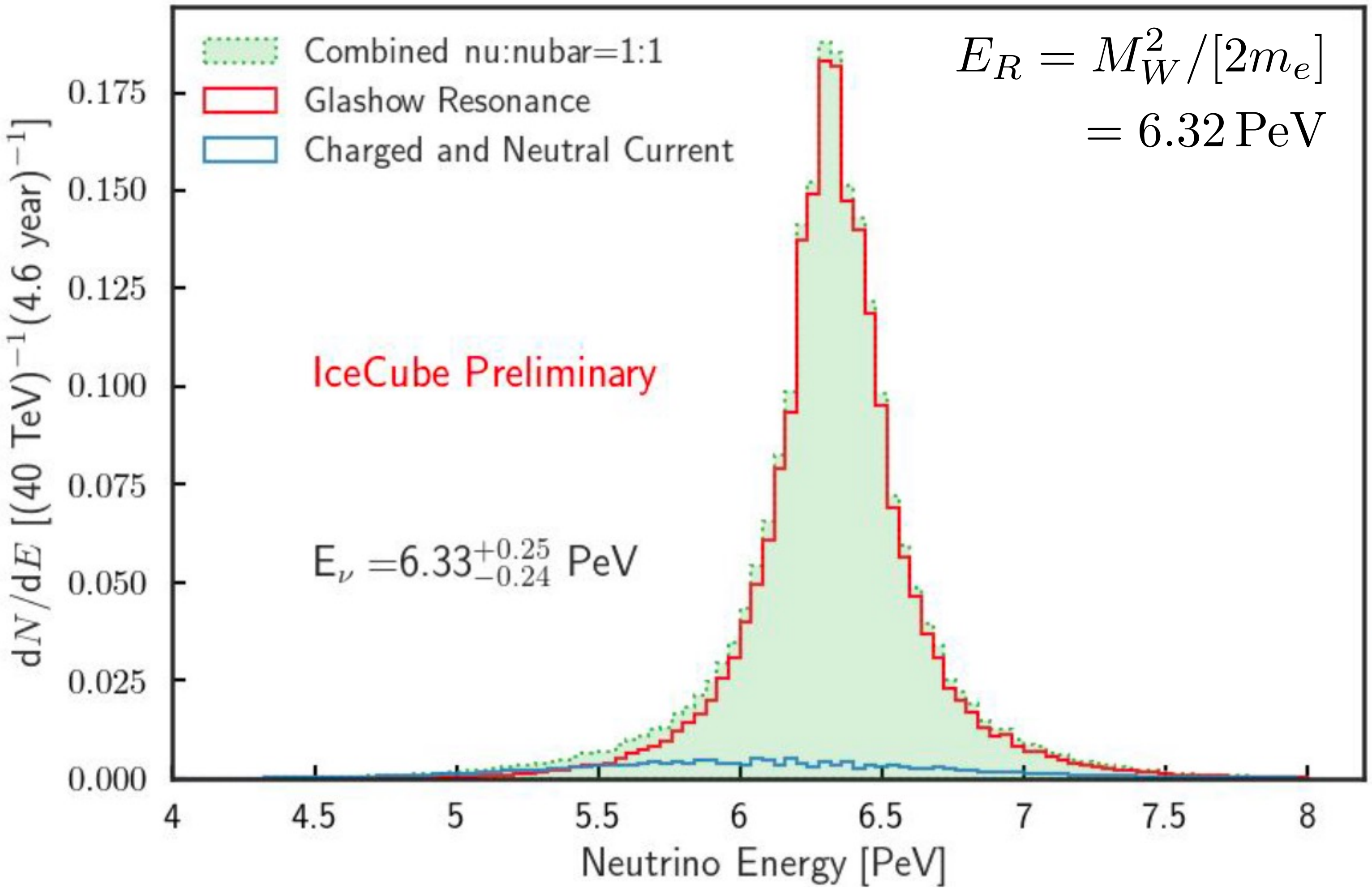
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

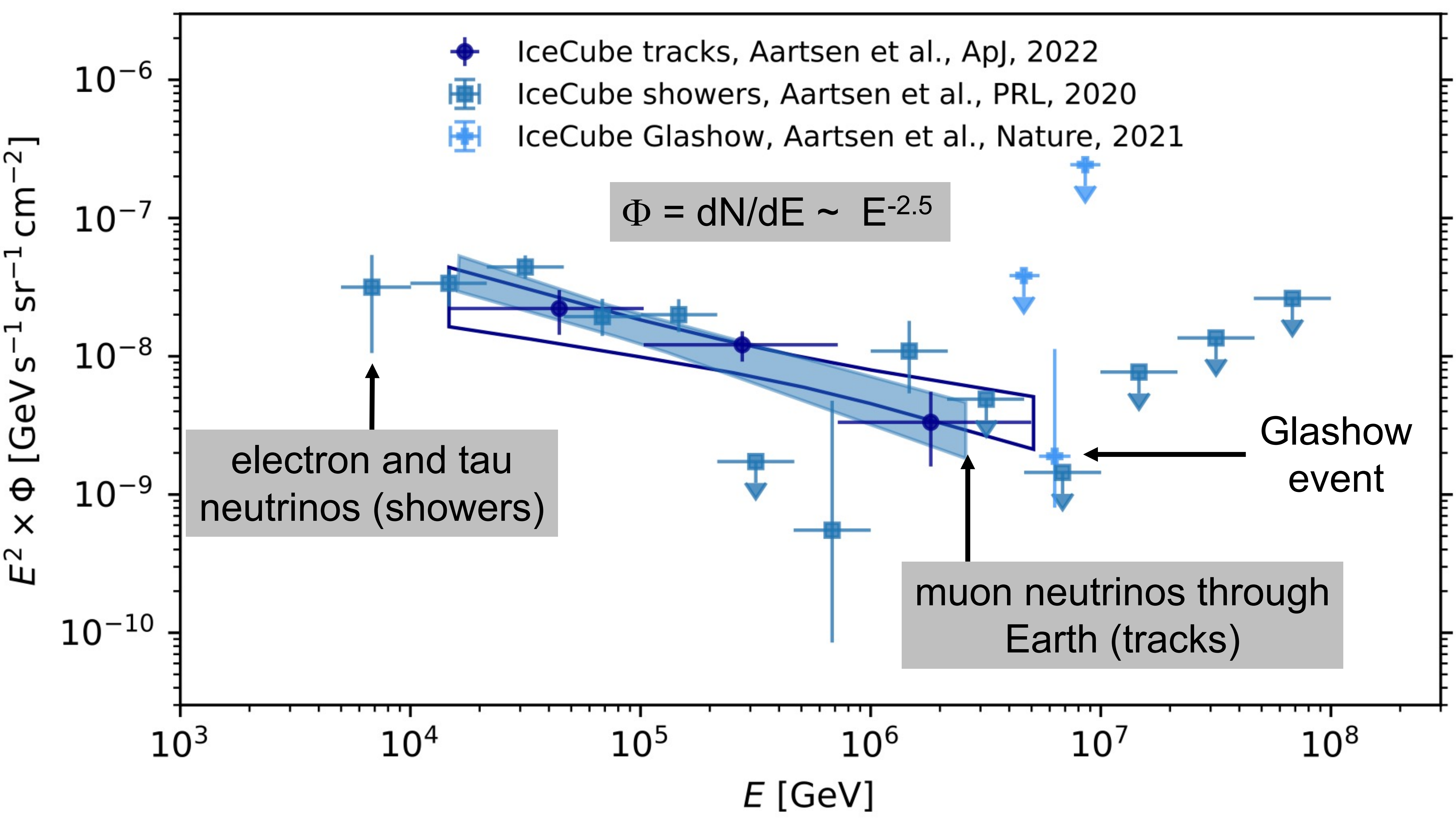
$$E_R = M_W^2/[2m_e] = 6.32\,\mathrm{PeV}$$



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







IceCube tracks, Aartsen et al., ApJ, 2022
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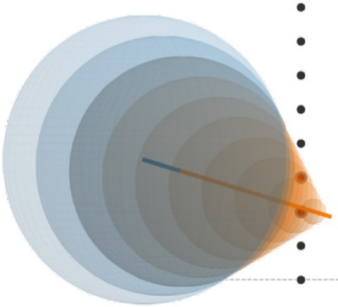
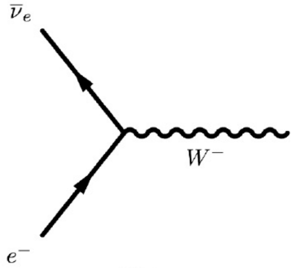
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
E2 × Φ [GeV s−1 sr−1 cm−2]
E [GeV]
10−6
10−7
10−8
10−9
10−10
103
104
105
106
107
108

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

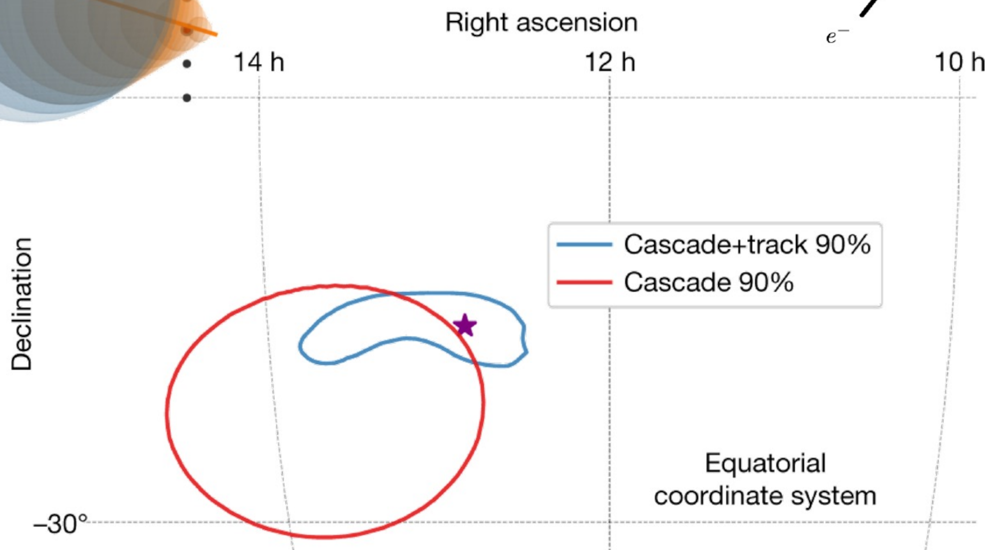
Nature **591,** 220–224 (2021)

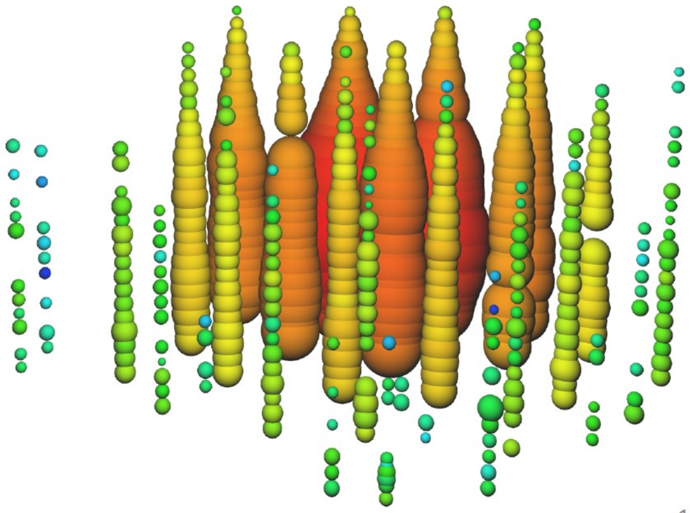


$$E_R = M_W^2/(2m_e) = 6.32\text{PeV}$$



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

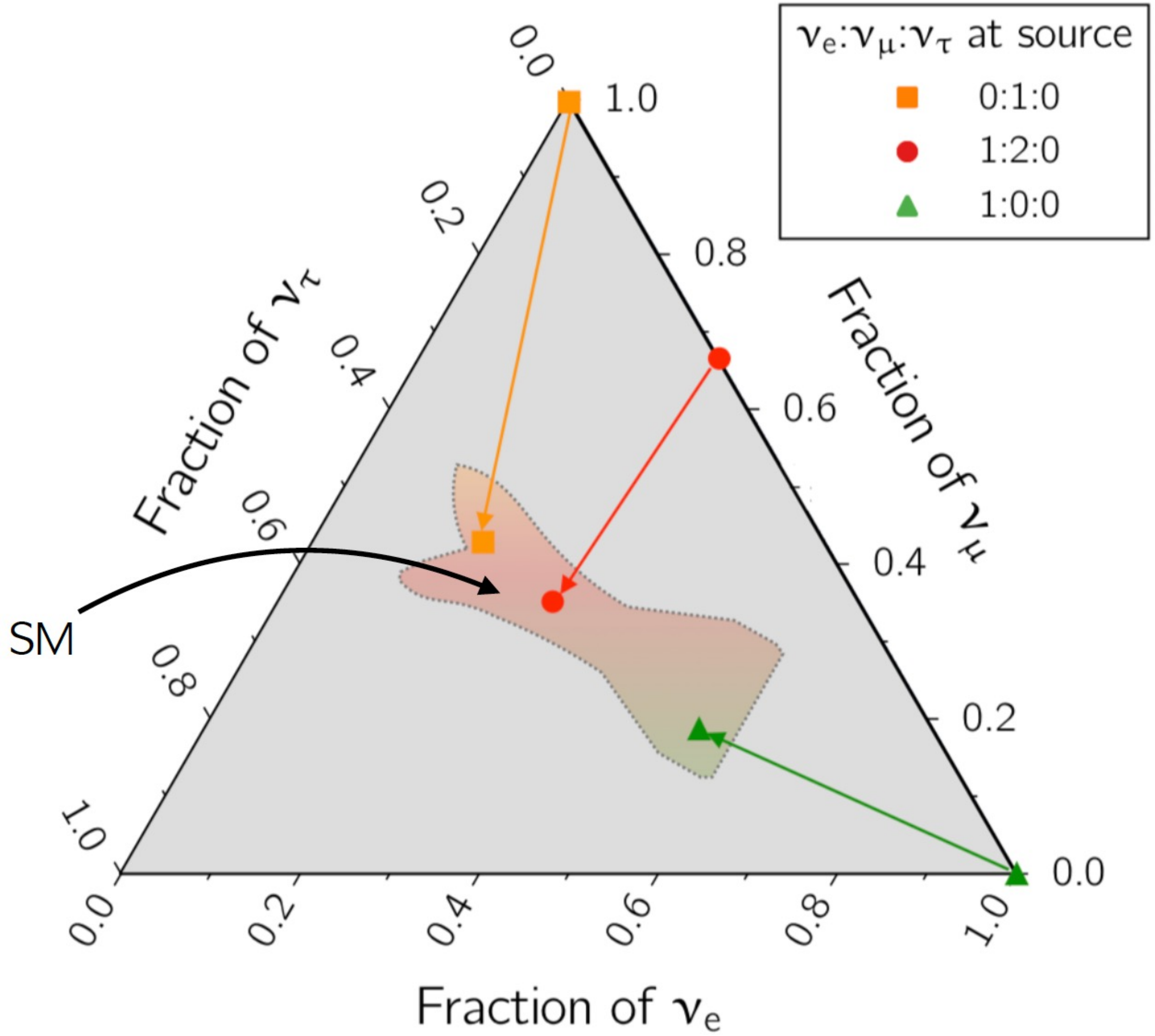


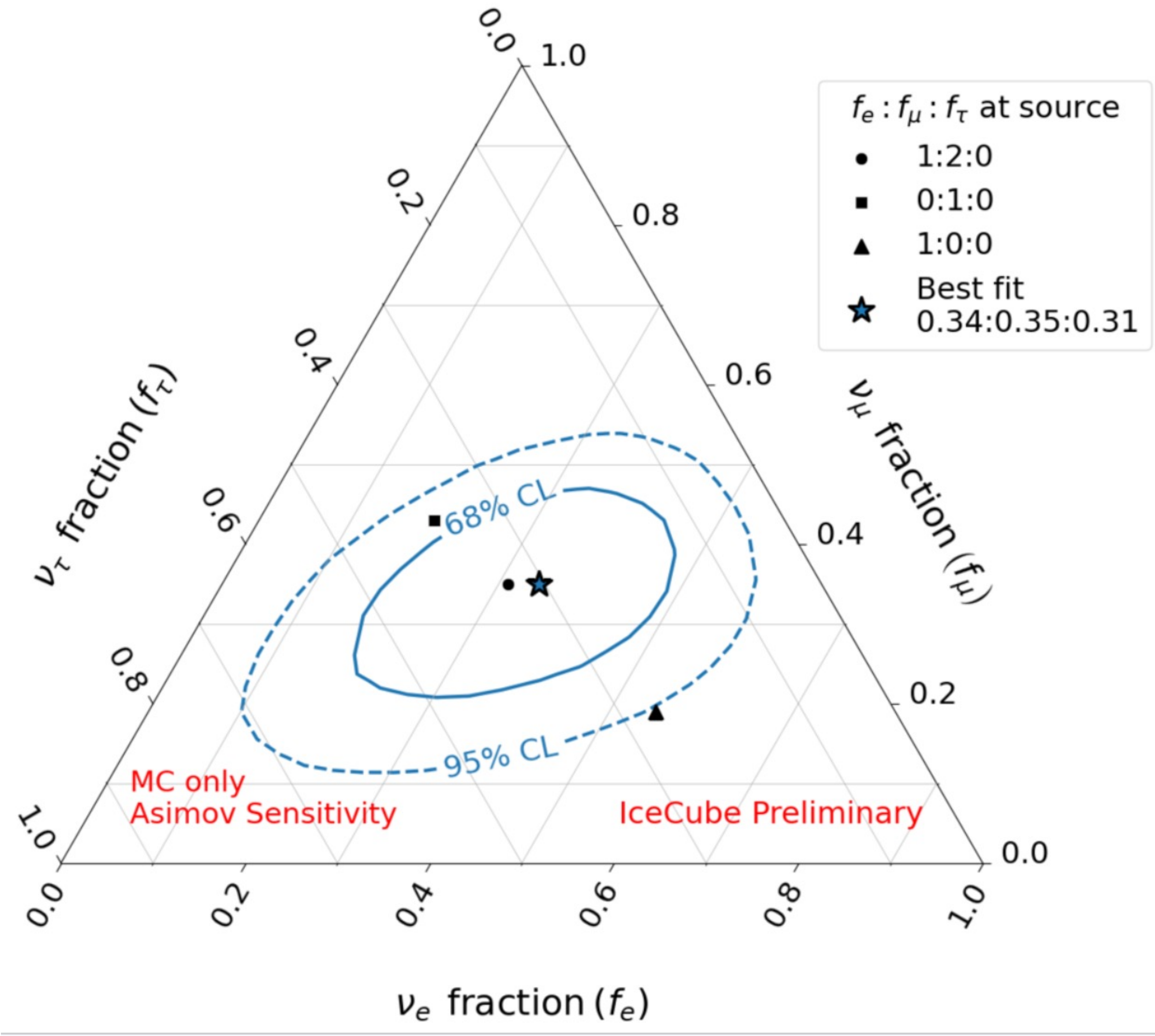


Identified muonic component from the hadronic shower

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

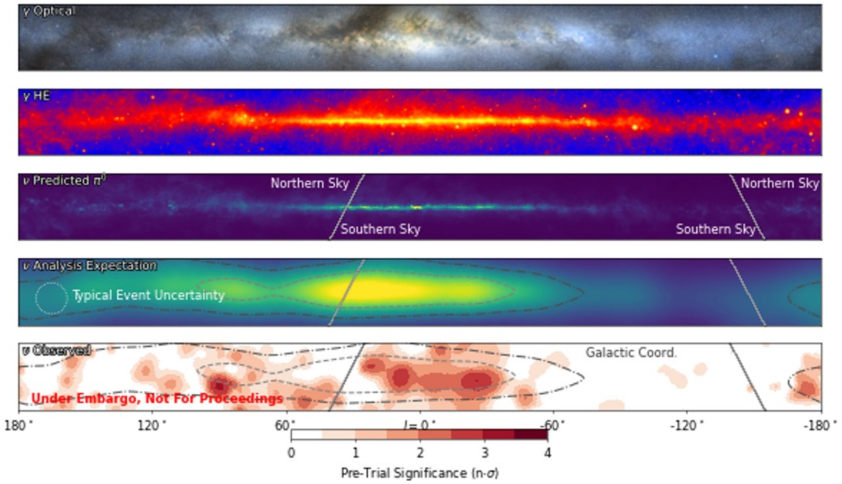
oscillations of PeV neutrinos over cosmic distances to 1:1:1



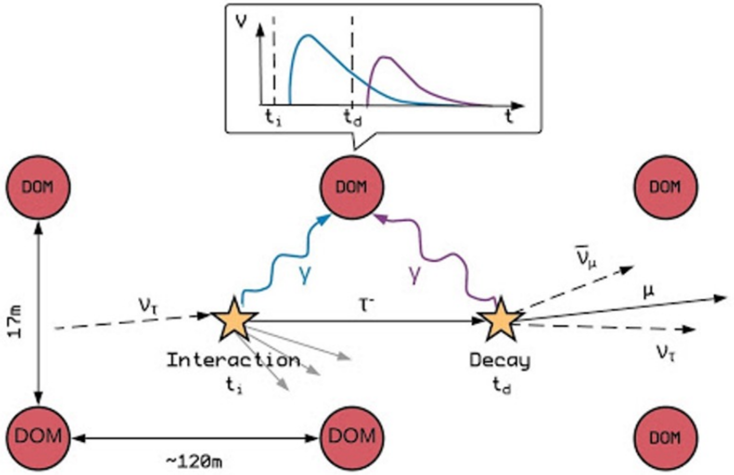


ML Driven Science Results

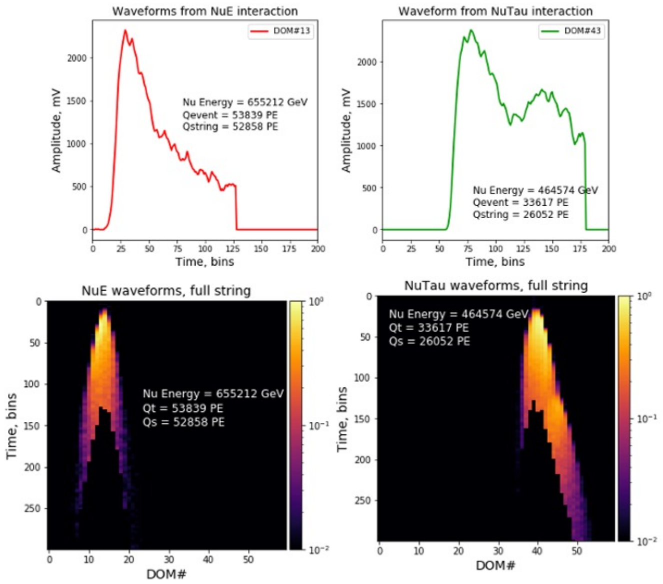
Galactic plane search



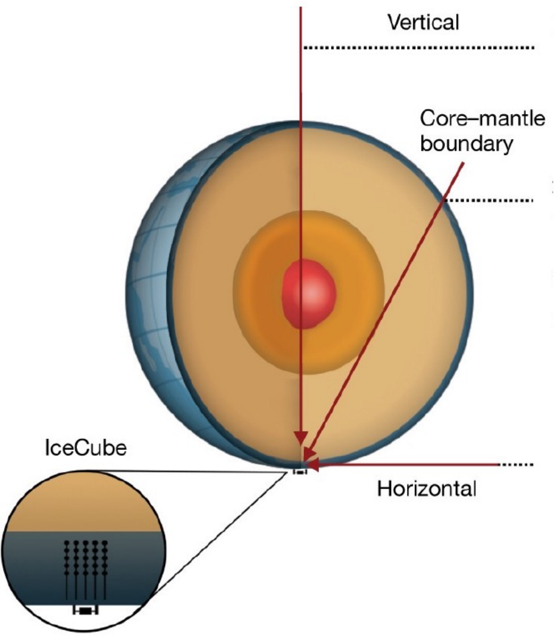
- Using Cascade events for "large" (e.g. Milky Way) or isolated sources a good option for Southern Sky point source search – Clear differentiation from background
- Maximum-Likelihood method for cascade pointing insufficient to find a source – Using BDT and CNN to find and reconstruct cascade events



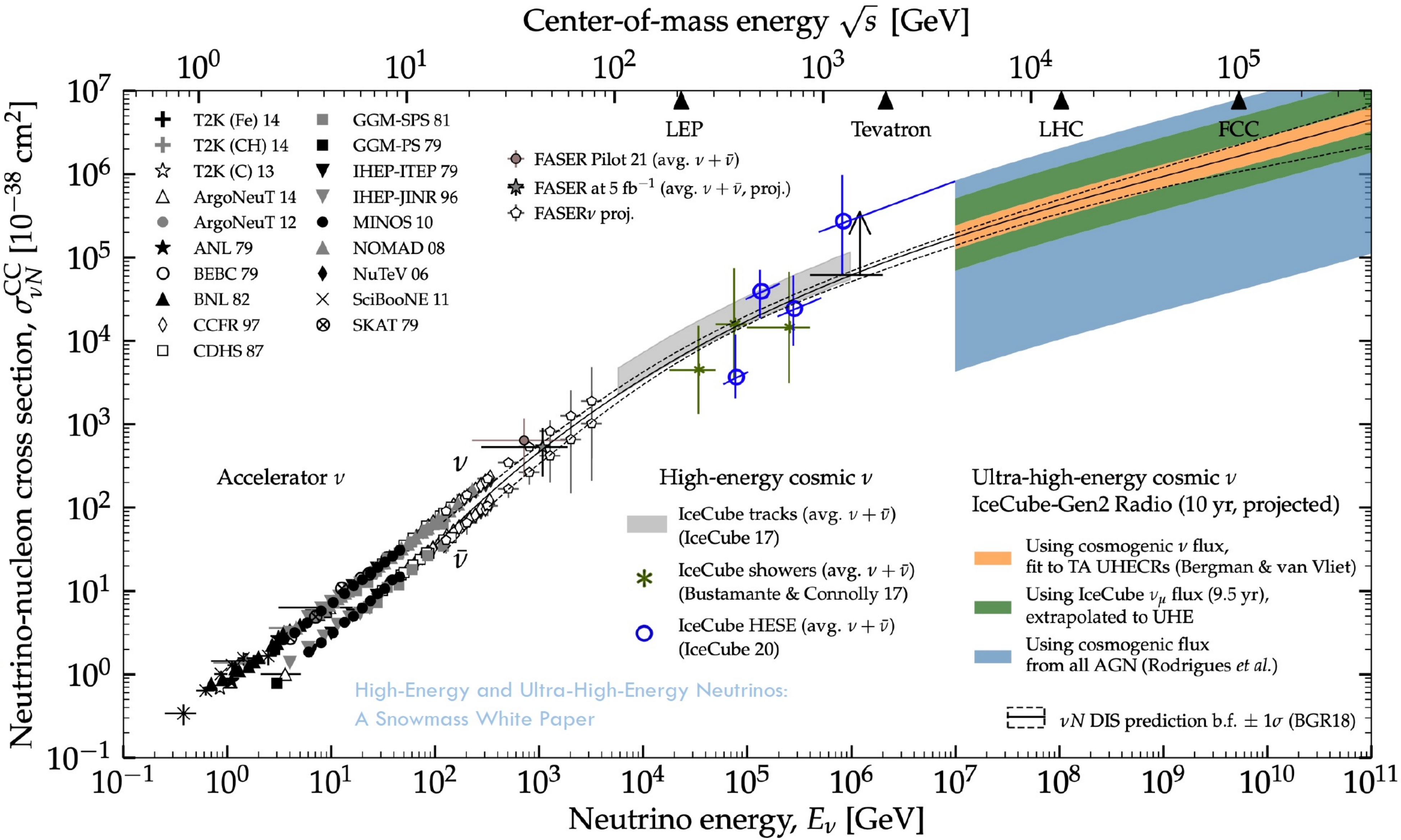
nutau search

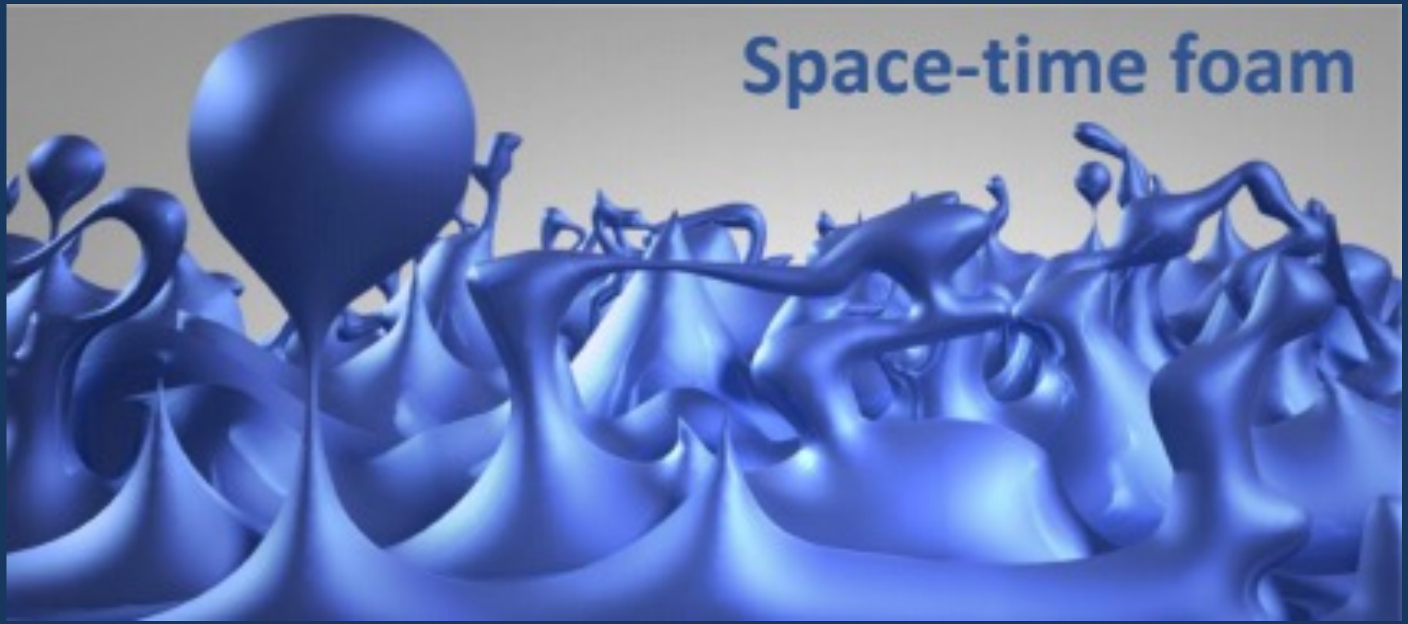


CROSS SECTION WITH EARTH AS THE TARGET



Extending x-section measurements to energies beyond Earth-based accelerators

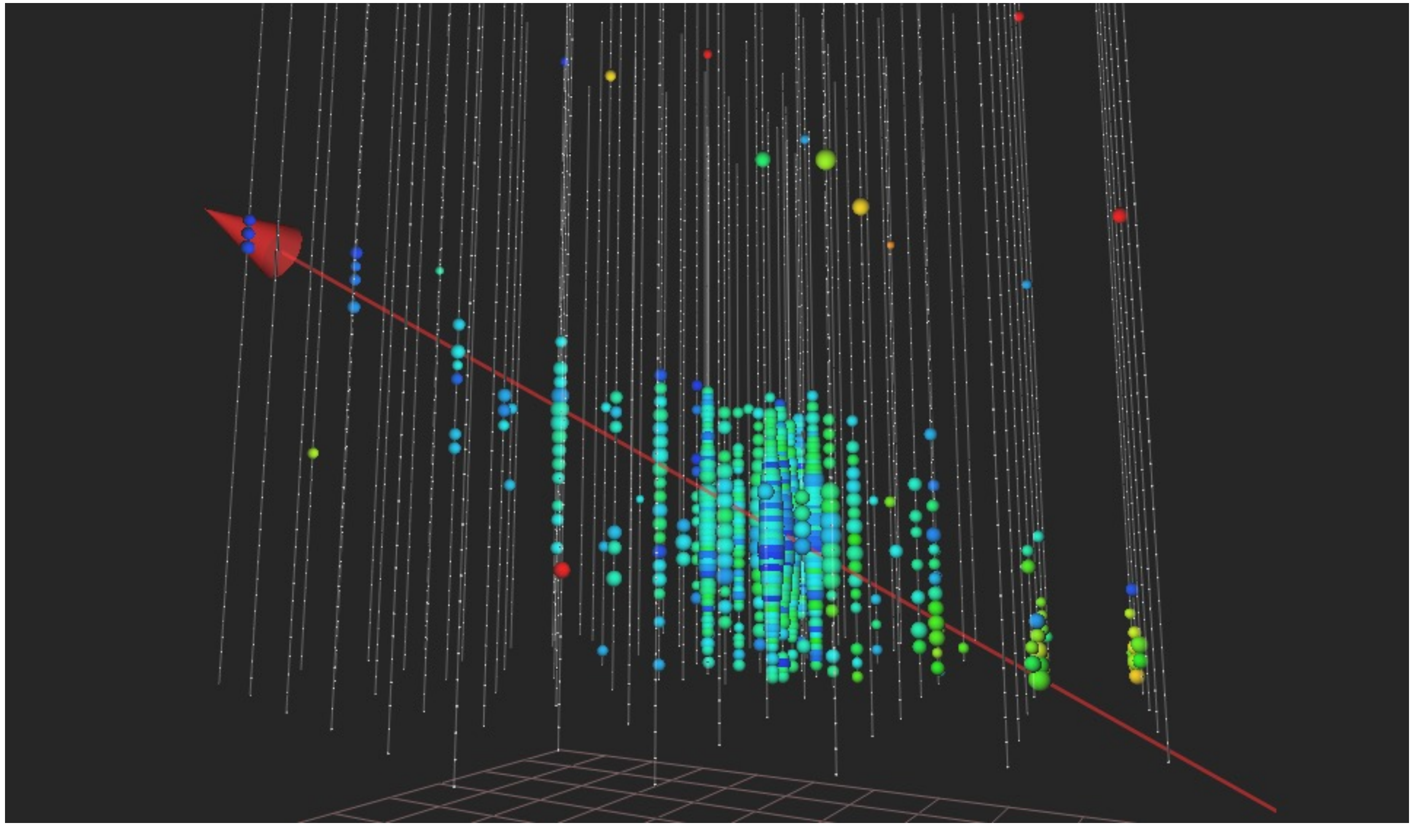


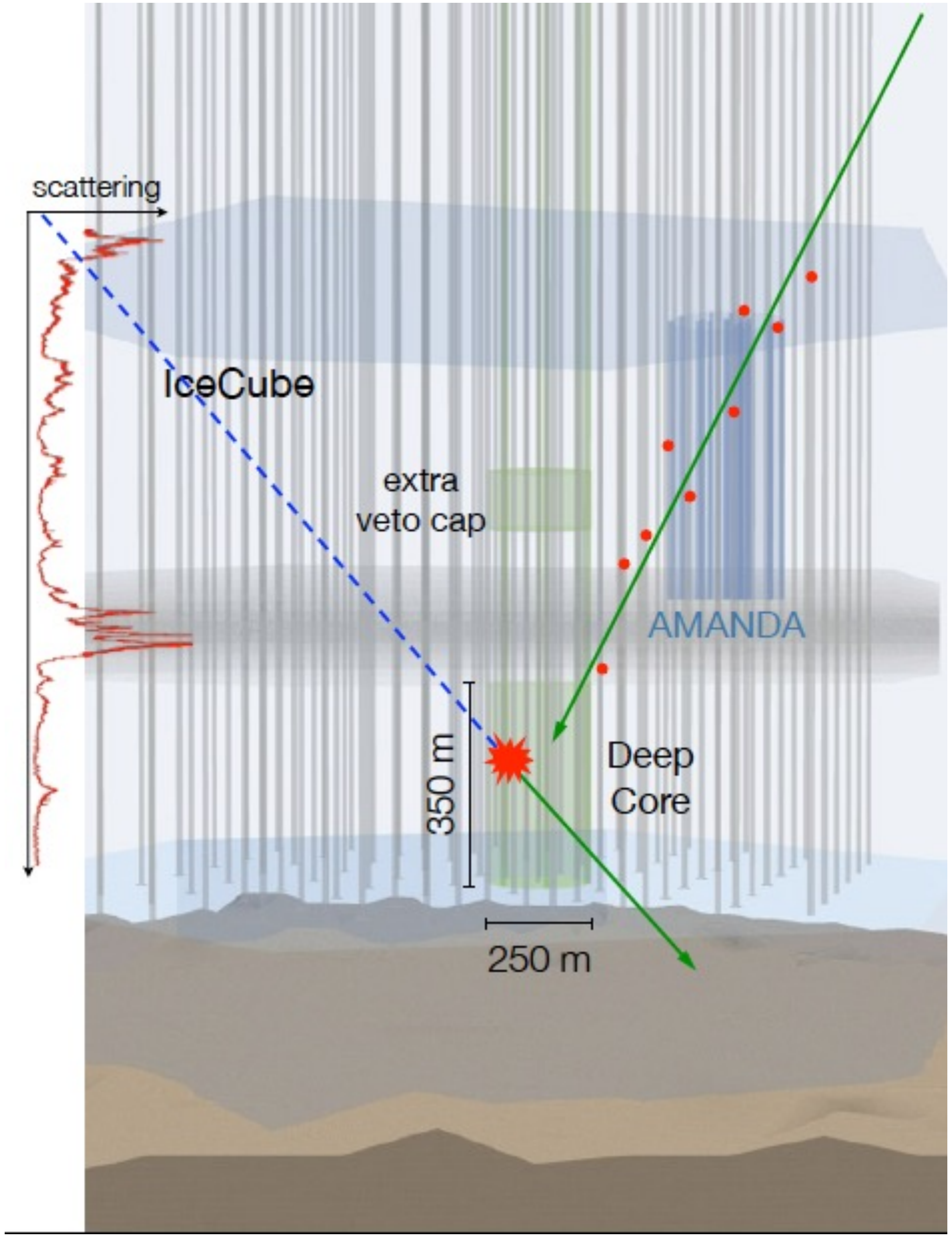


- neutrino decoherence from quantum gravitational space-time fluctuations
- modifies the neutrino dispersion relation over long baselines
- IceCube reaches record sensitivities at the Planck scale even using atmospheric neutrinos

one million atmospheric neutrinos

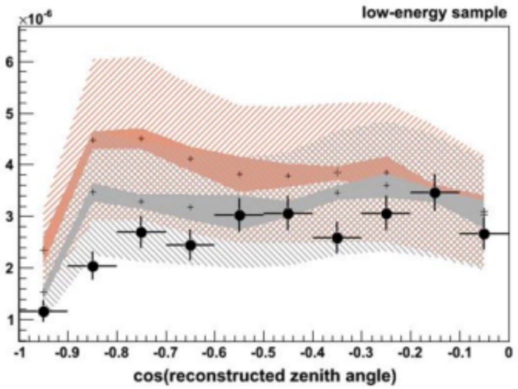
- 5 GeV threshold
- one event every 15 min at analysis level
- 2 megaton detector

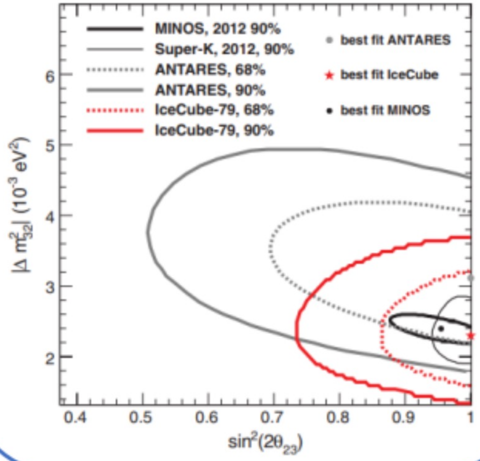




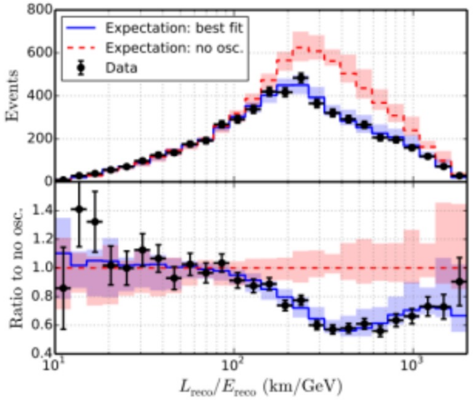
Atmospheric oscillations progression

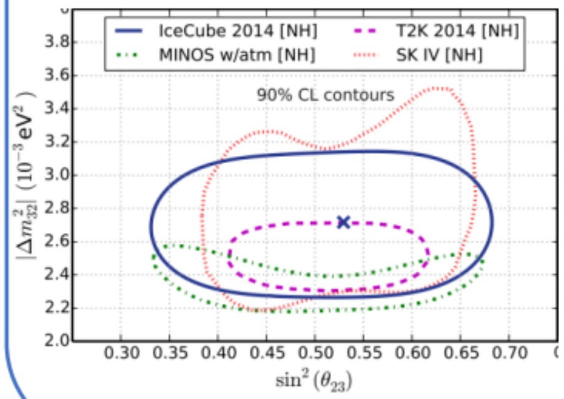
IceCube, PRL 111, 081801 (2013)
700 events



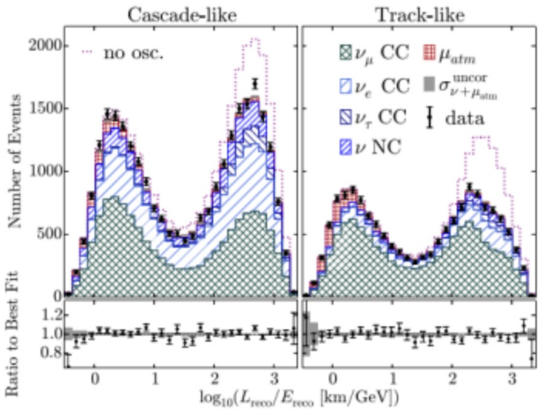


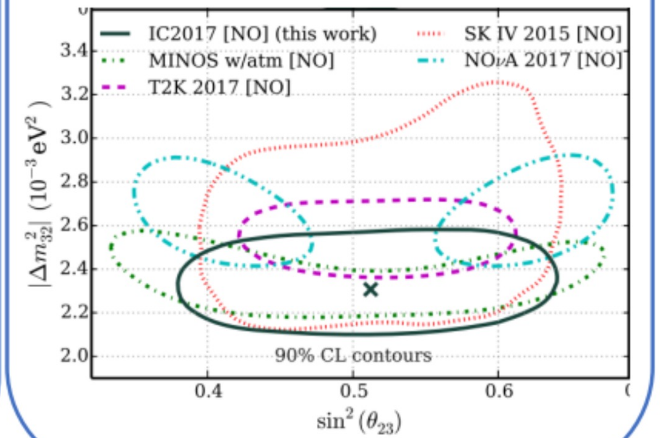
IceCube, PRD 91, 072004 (2015)
~5k events



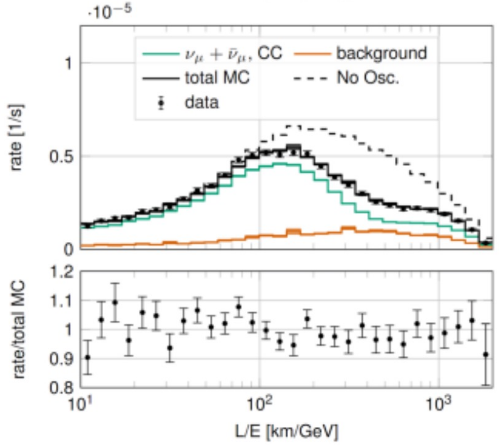


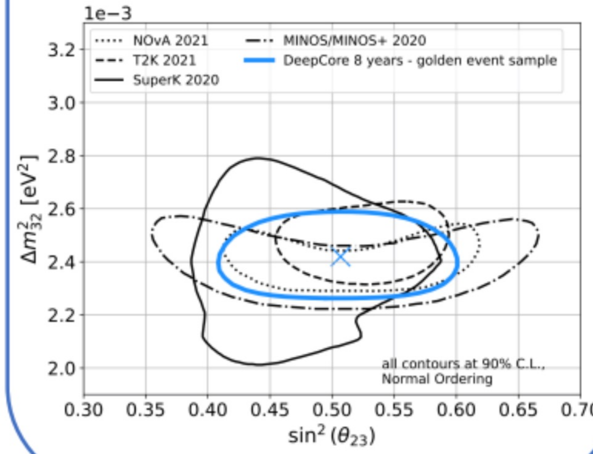
IceCube, PRL 120, 071801 (2018)
~35k events





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





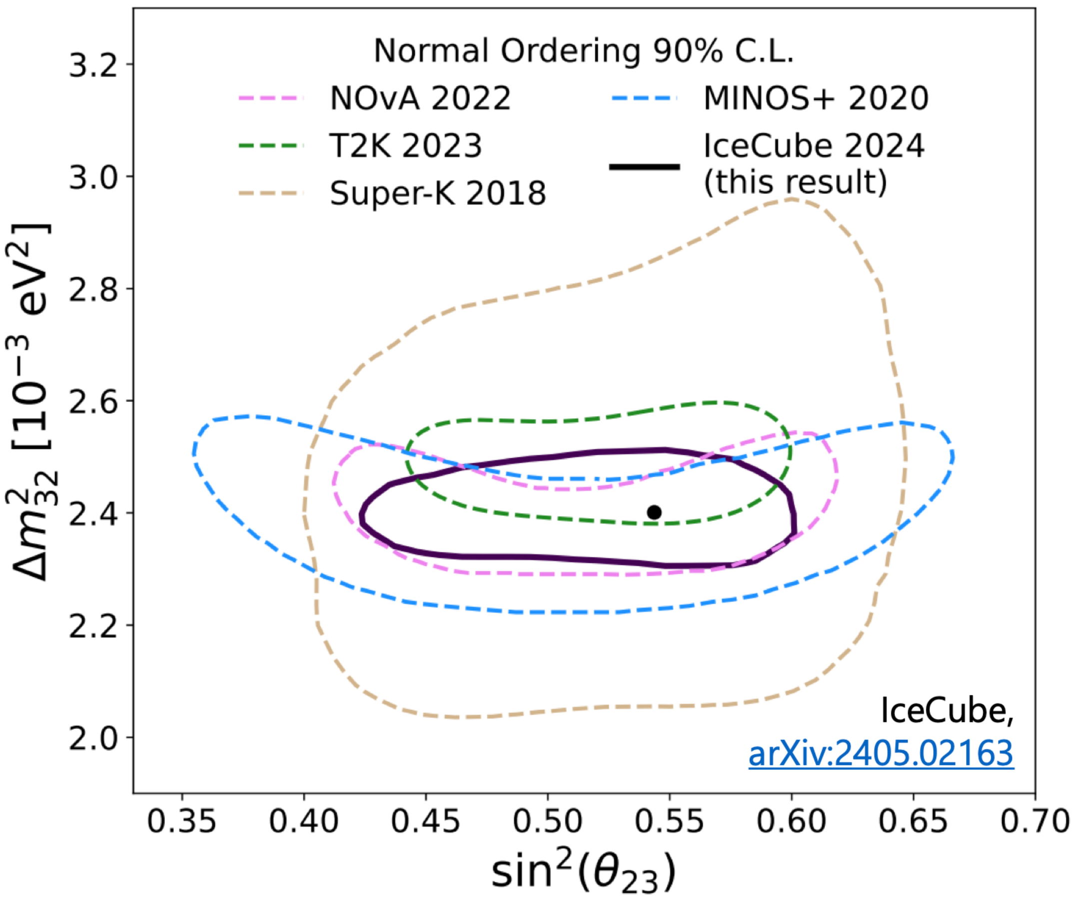
Atm. Osc. - **Newest result**

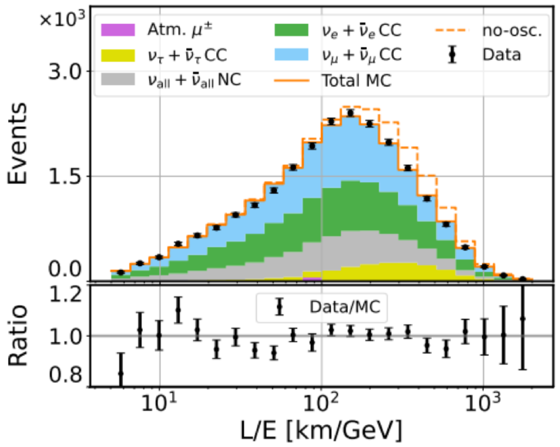
- CNN-based classification and reco
  - Uses inputs that our MC describes well
  - Recovers events that are hard to handle
  - 150,000 ν candidates in 9 years of data
- Best fit

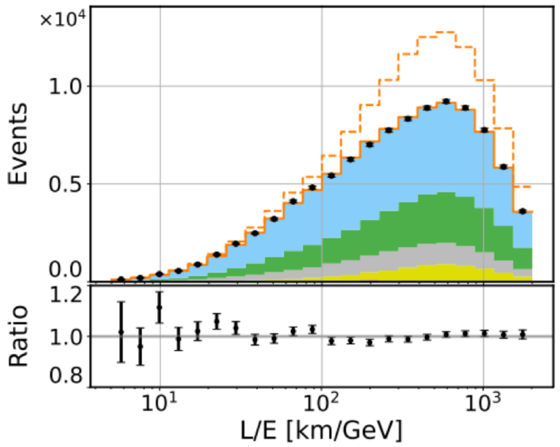
  $\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$

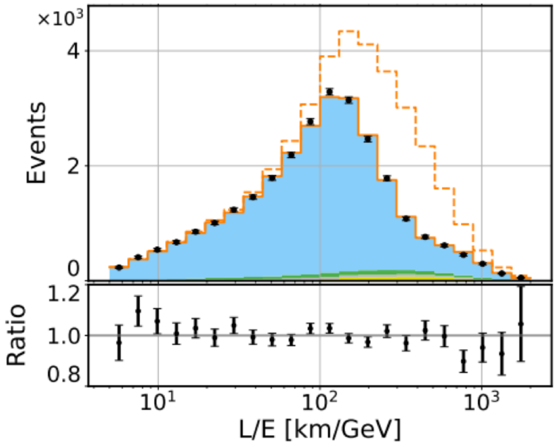
  $\Delta m^2_{32} = 2.40^{+0.05}_{-0.04} \times 10^{-3}$ eV²

  GoF *p*-value: 19%

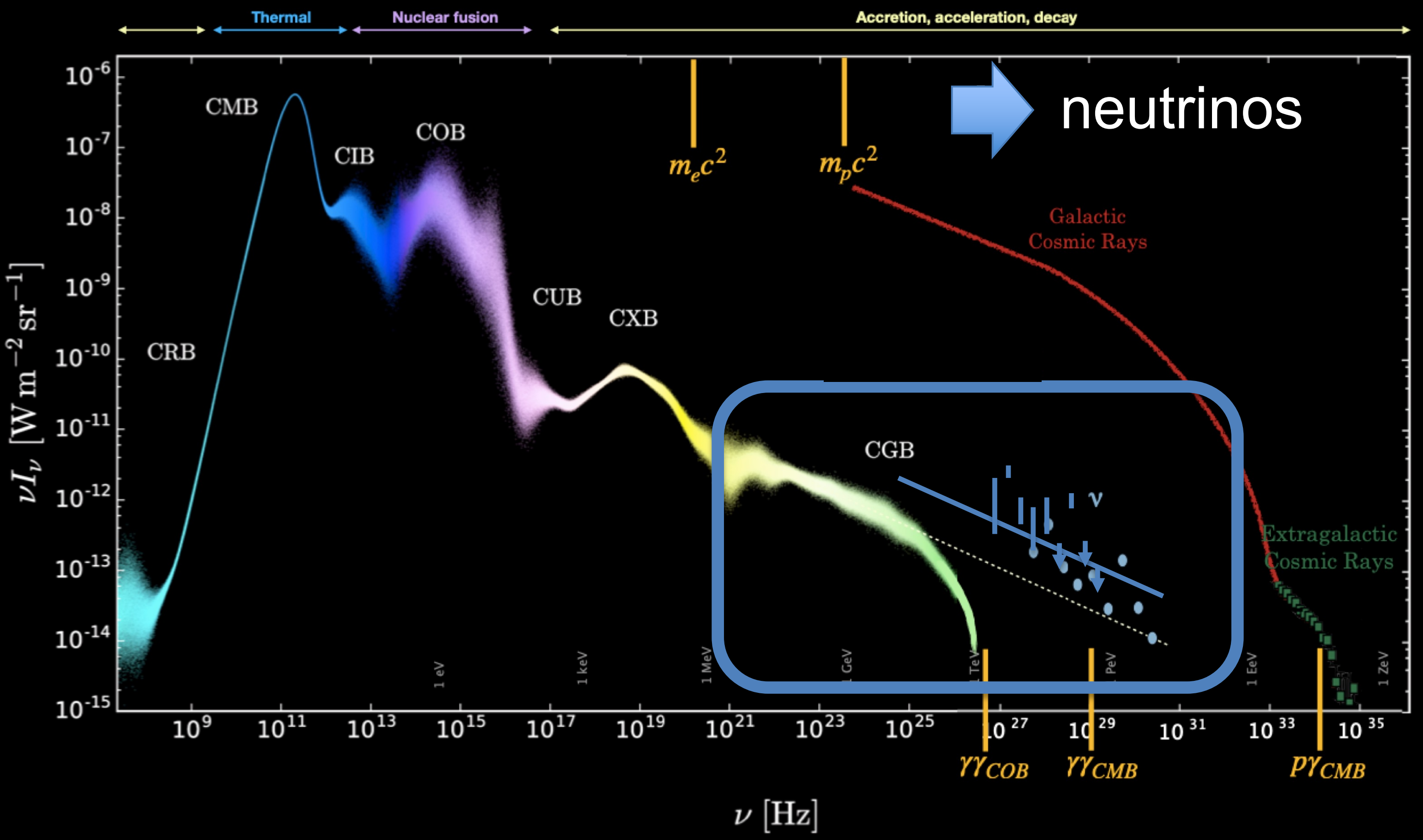






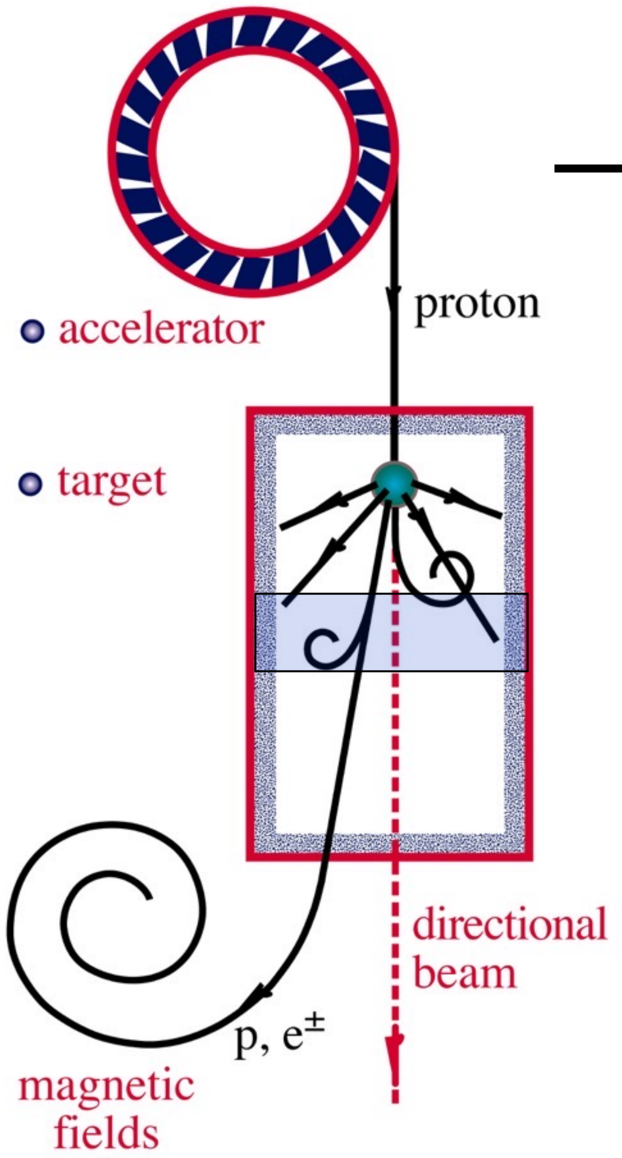


in the extreme universe the energy in neutrinos is larger than the energy in gamma rays observed at GeV energies



one gamma ray for every neutrino?

ν and γ beams : heaven and earth



where are the gamma rays from π^0 ?

supermassive black hole

nearby radiation

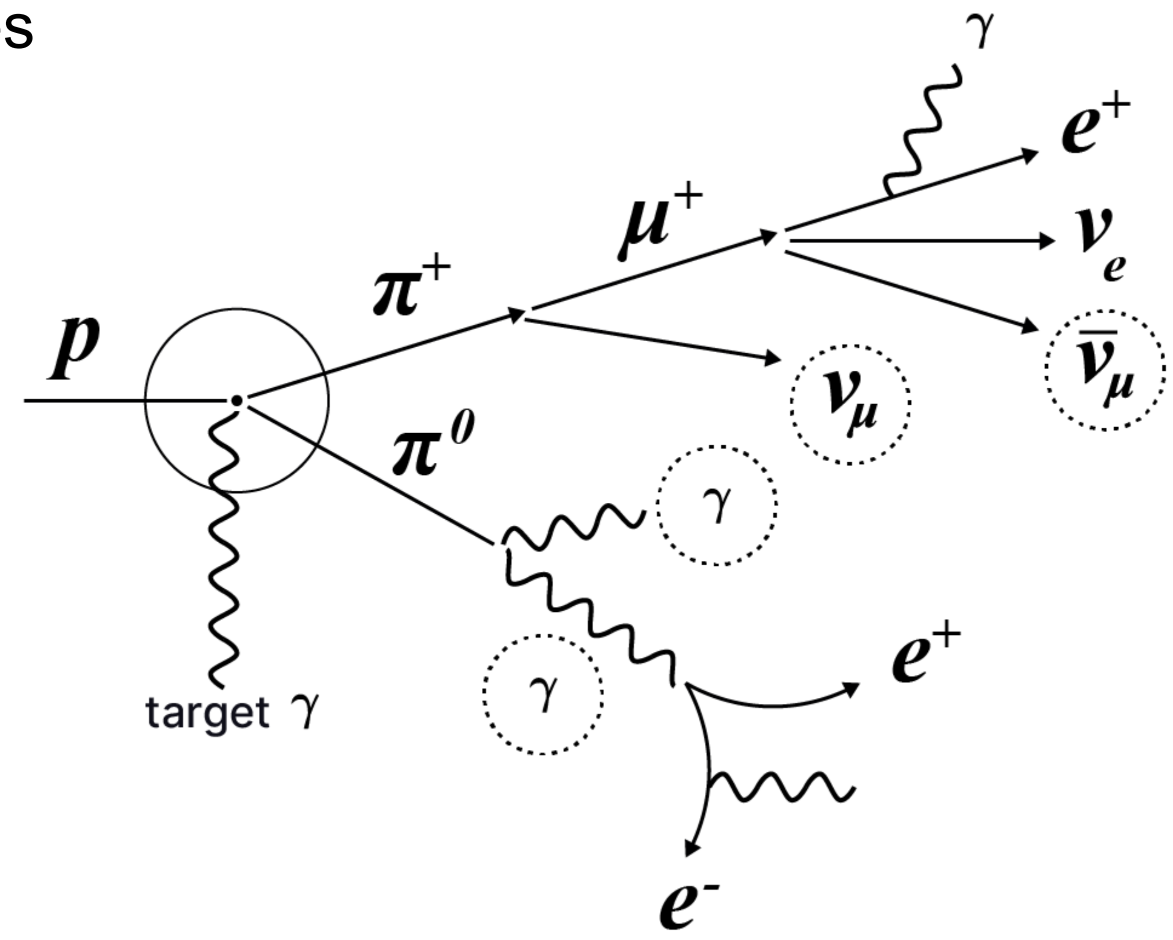
$$p + \gamma \rightarrow n + \pi^+$$

~ cosmic ray + neutrino

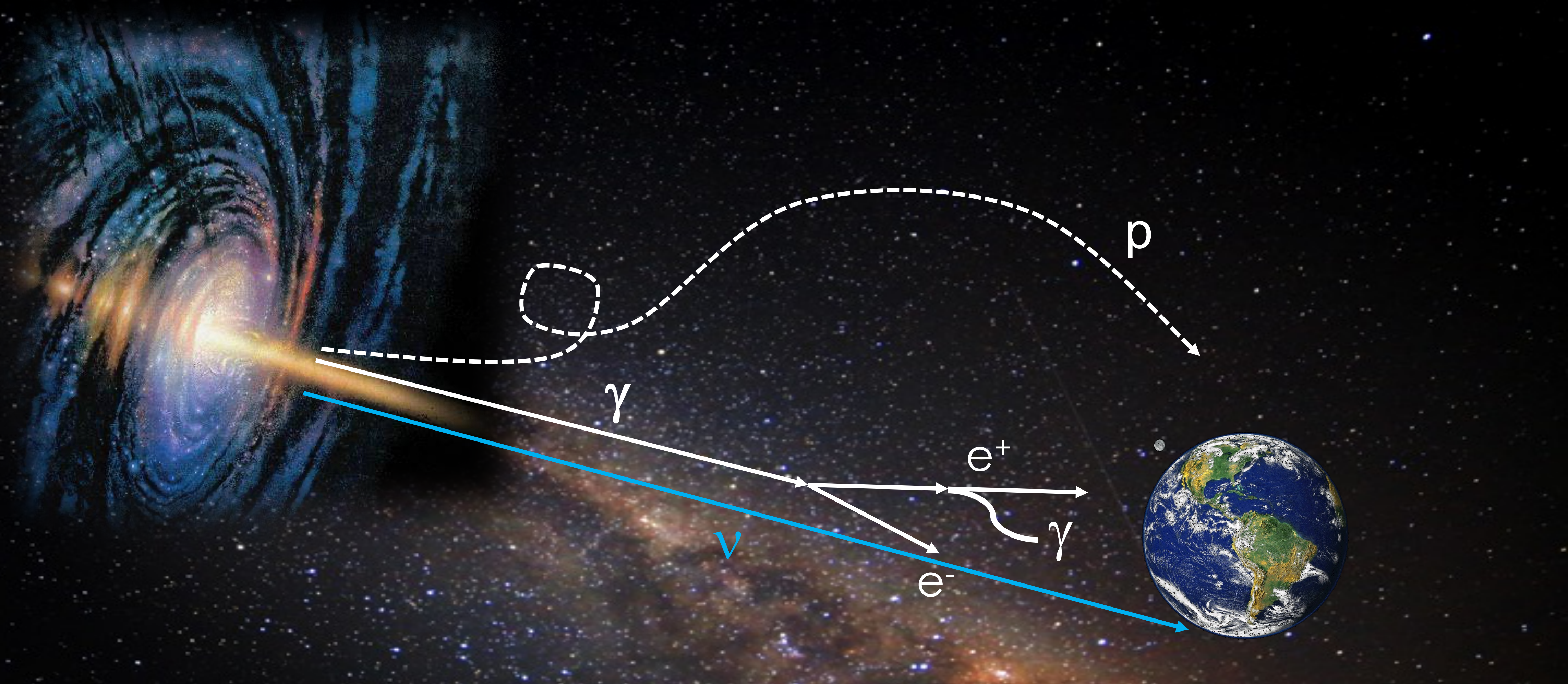
$$\rightarrow p + \pi^0$$

~ cosmic ray + gamma

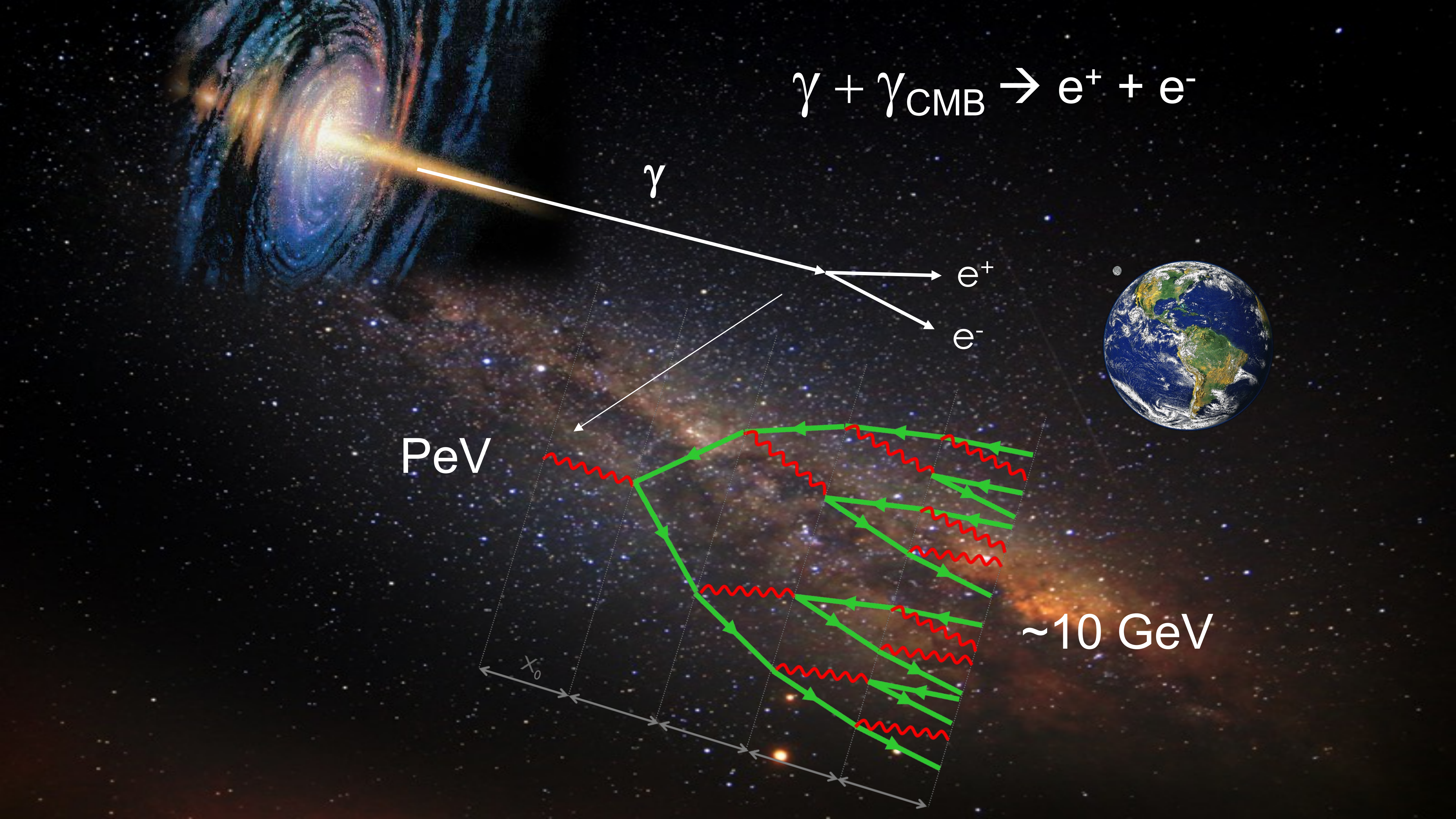
cosmic ray sources

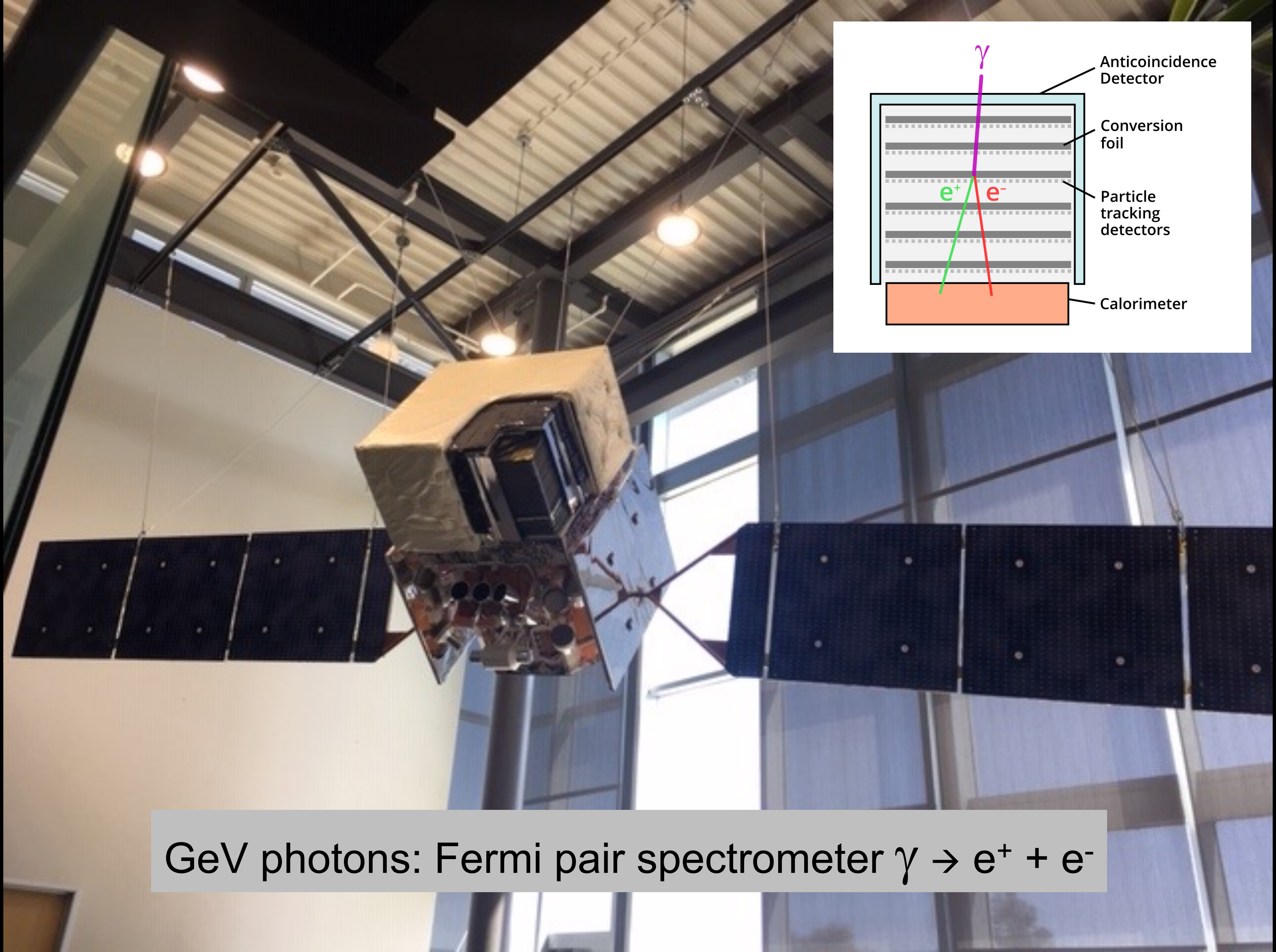


$$\gamma \simeq \nu_\mu + \bar{\nu}_\mu$$



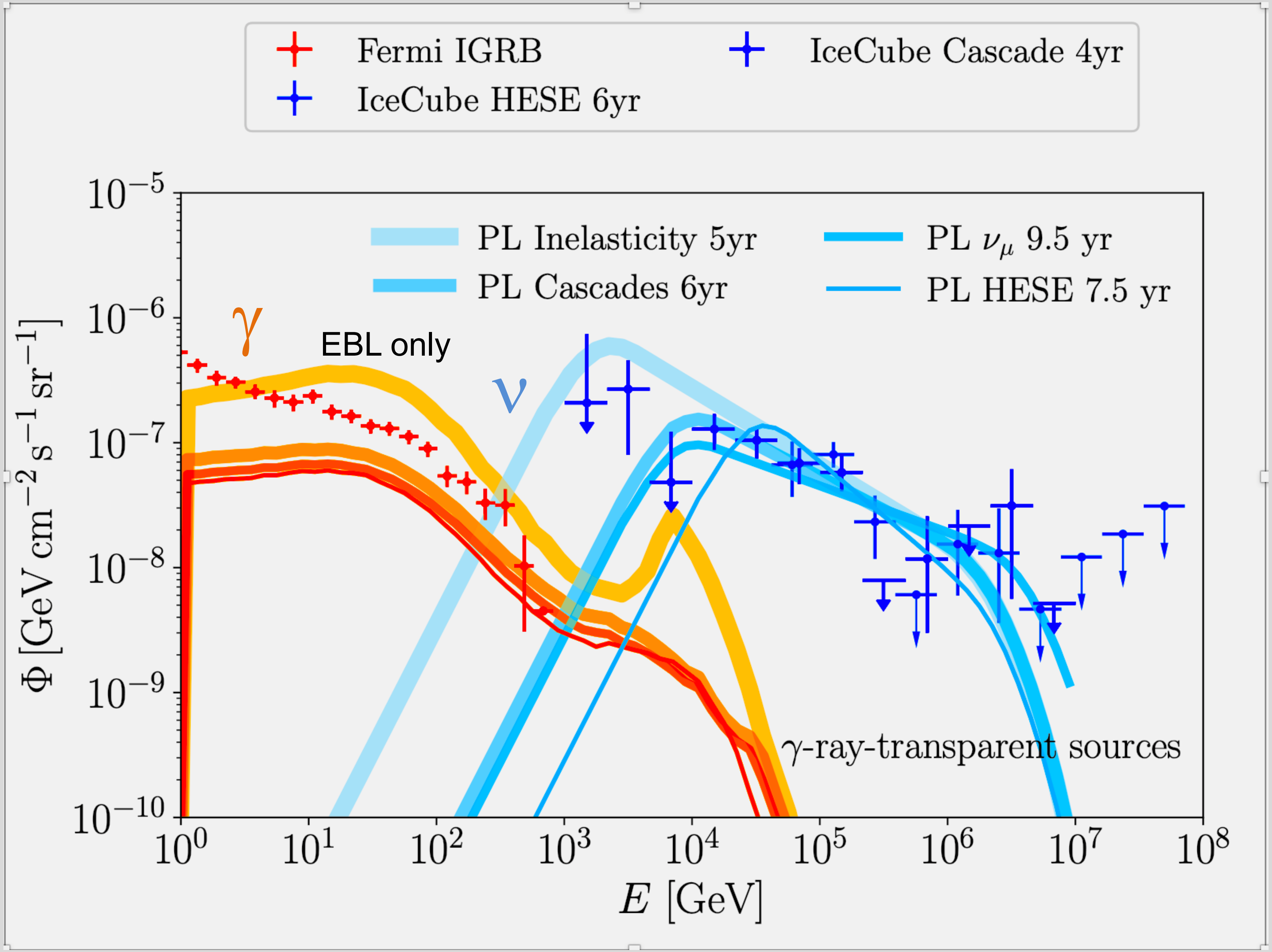
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth


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



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

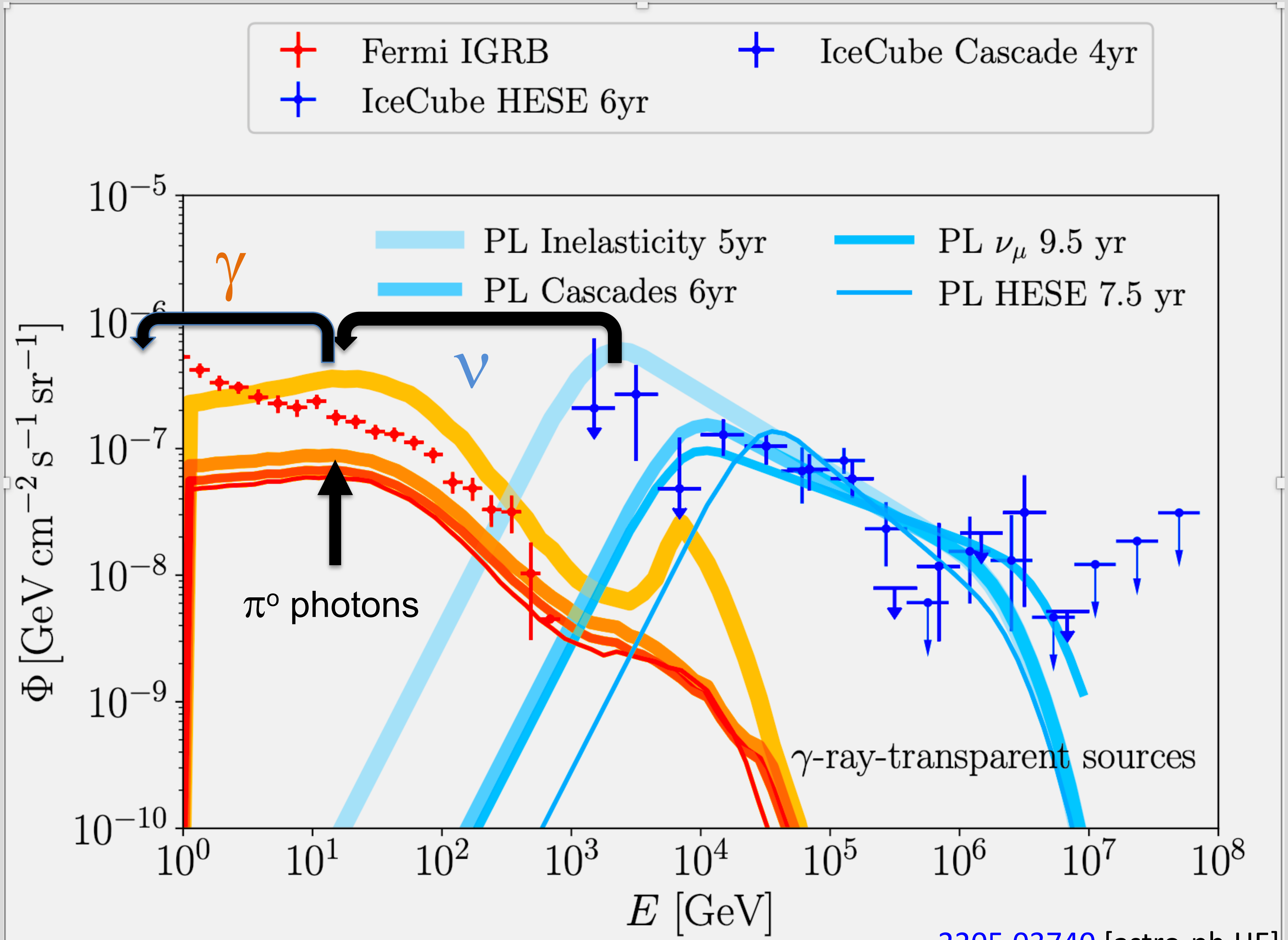
gamma rays from neutral pions must lose energy in the sources



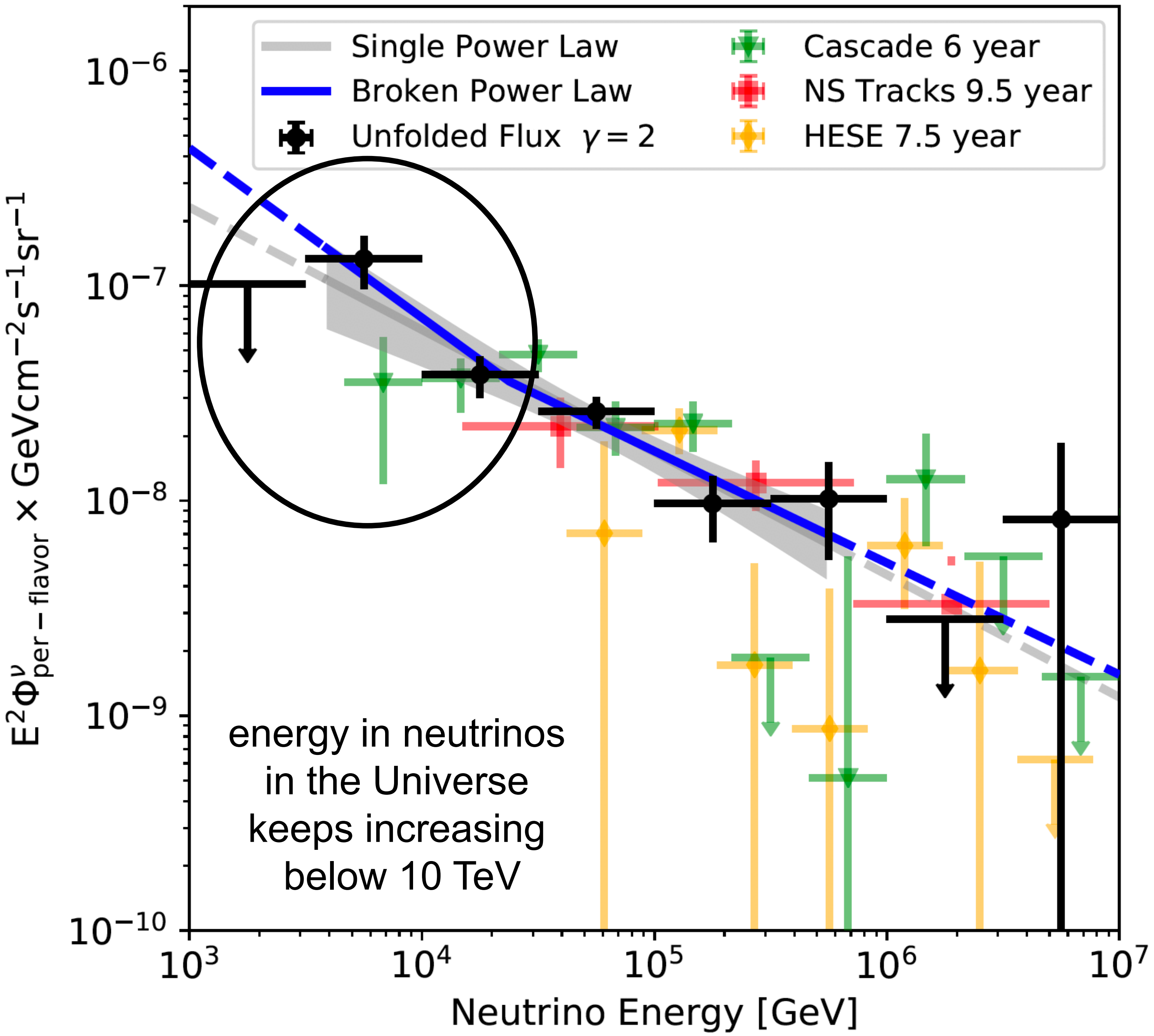
the neutrino sources are likely opaque to gamma rays

or

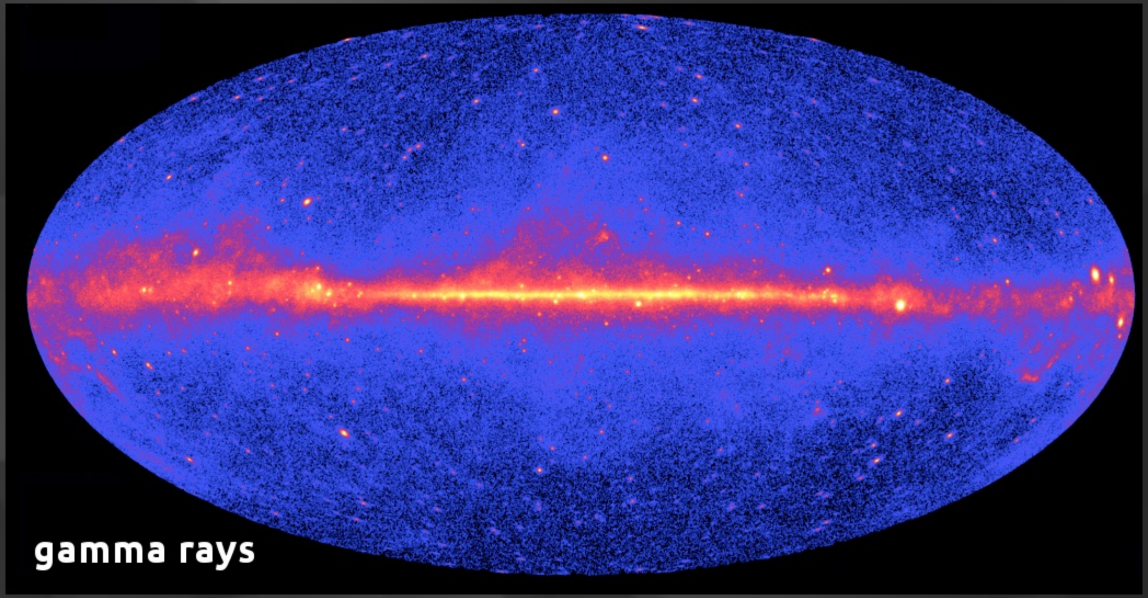
pionic gamma rays accompanying neutrinos appear at MeV energies or below



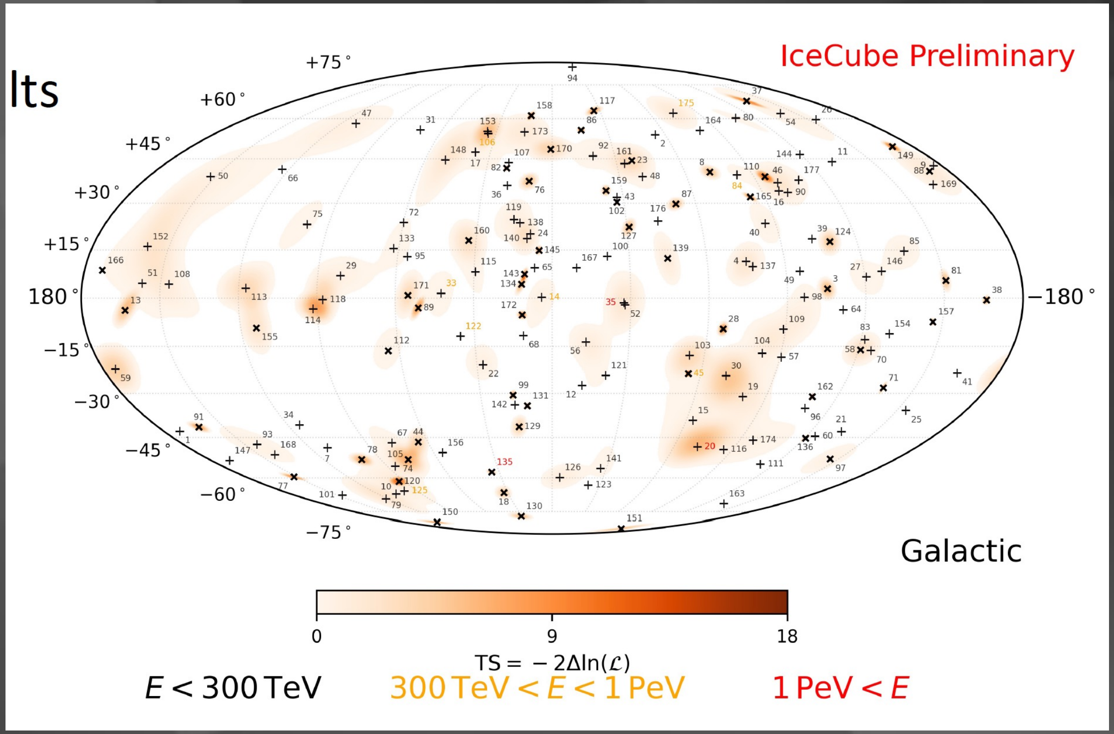
2205.03740 [astro-ph.HE]



Single Power Law
Broken Power Law
Unfolded Flux $\gamma = 2$
Cascade 6 year
NS Tracks 9.5 year
HESE 7.5 year
$E^2\Phi^{\nu}_{per-flavor} \times$ 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

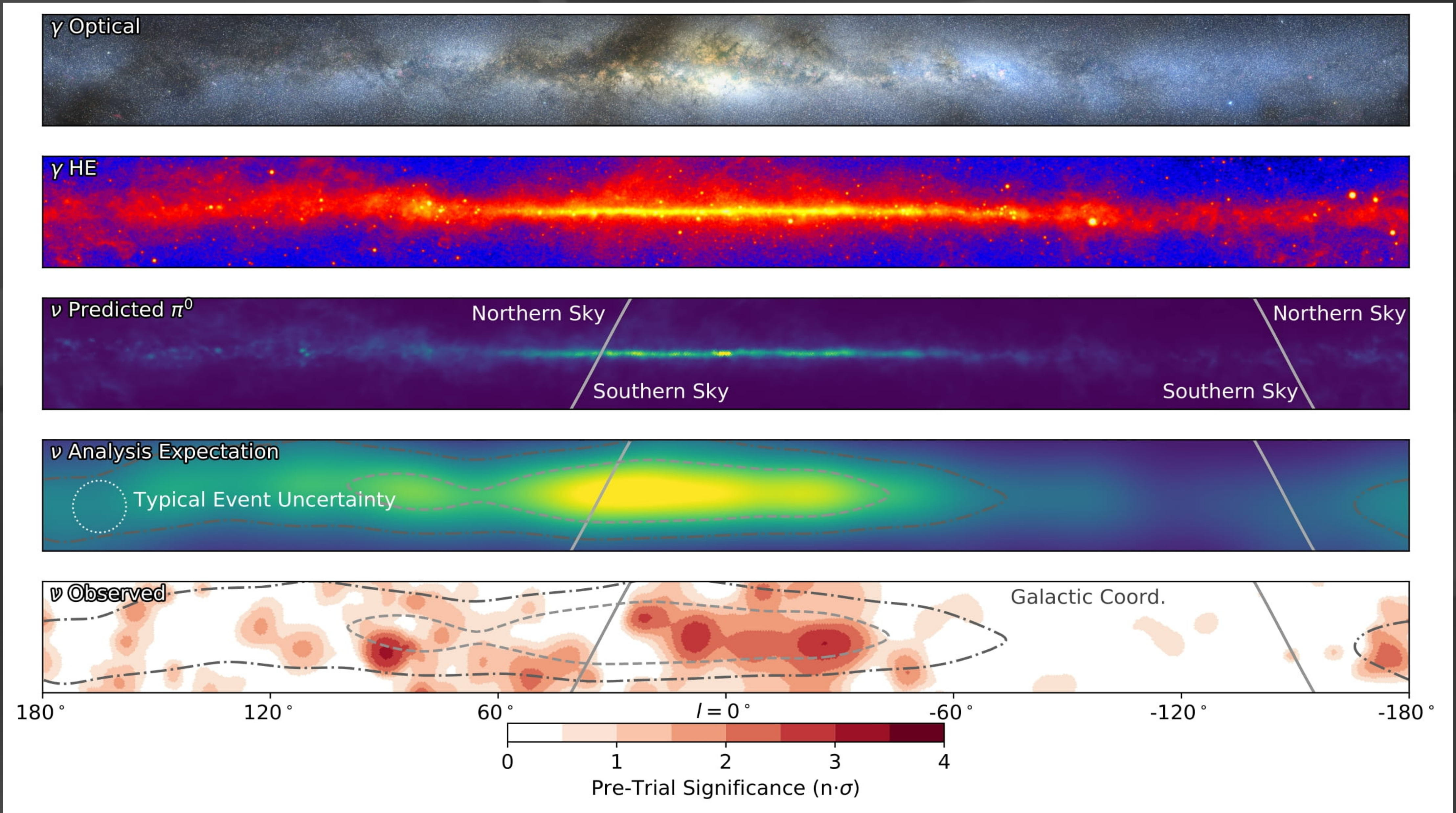


166 neutrino starting events

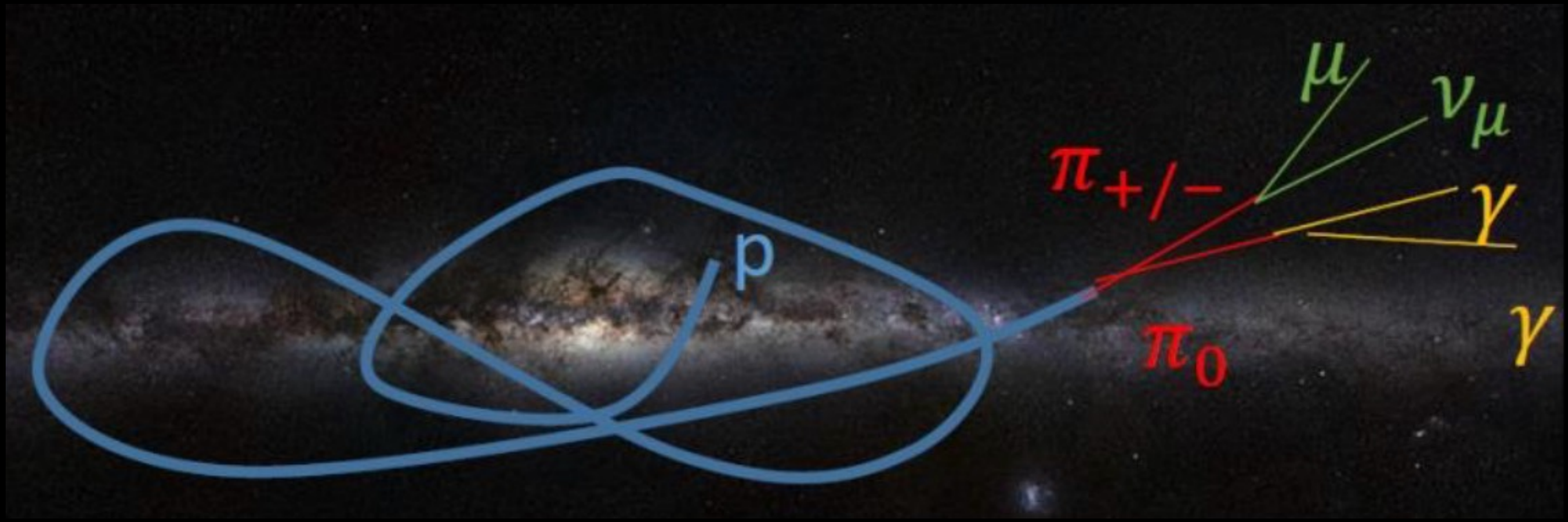


where is the neutrino Galactic plane?

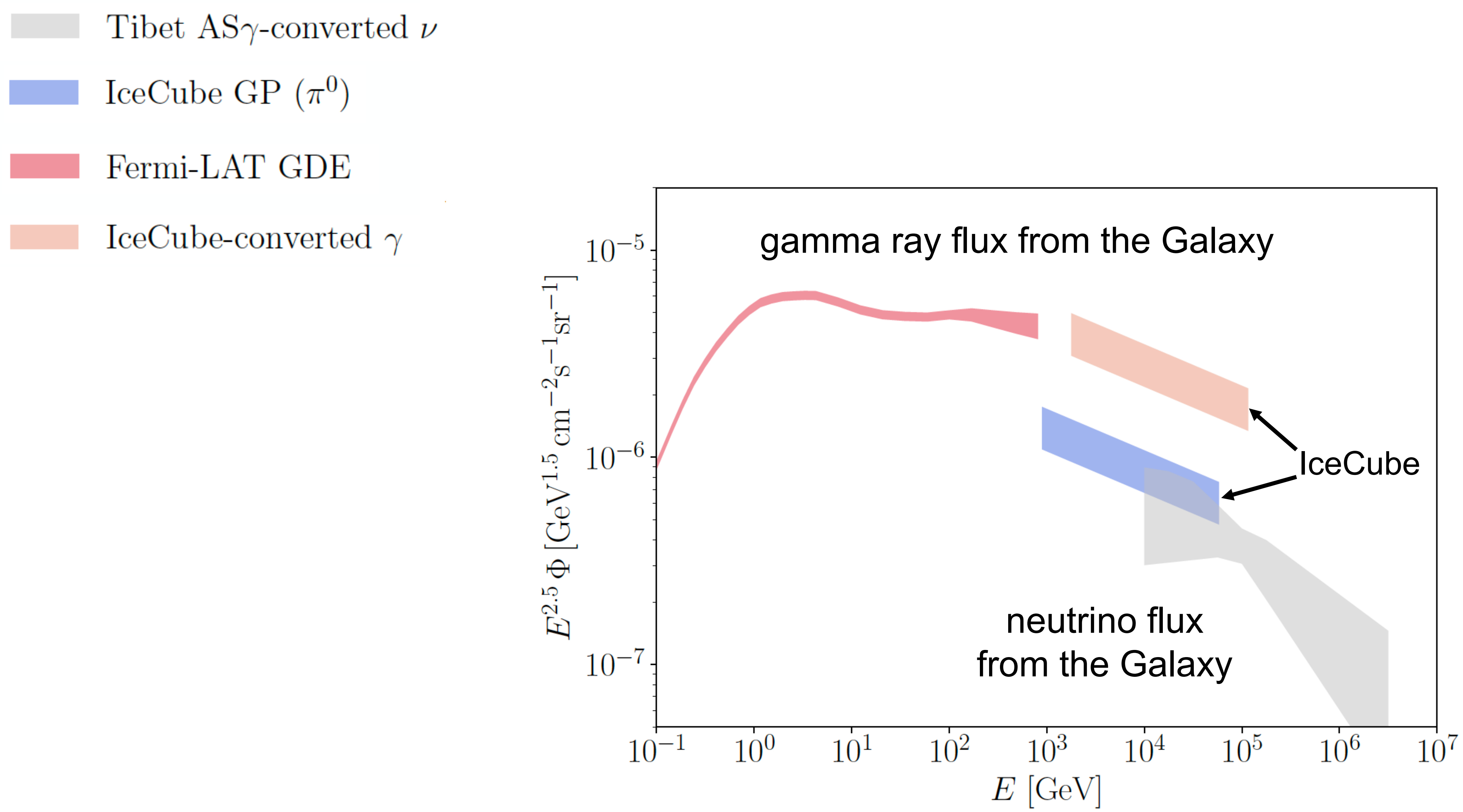
by geometry the flux from your own Galaxy should dominate the diffuse flux from all other galaxies combined!



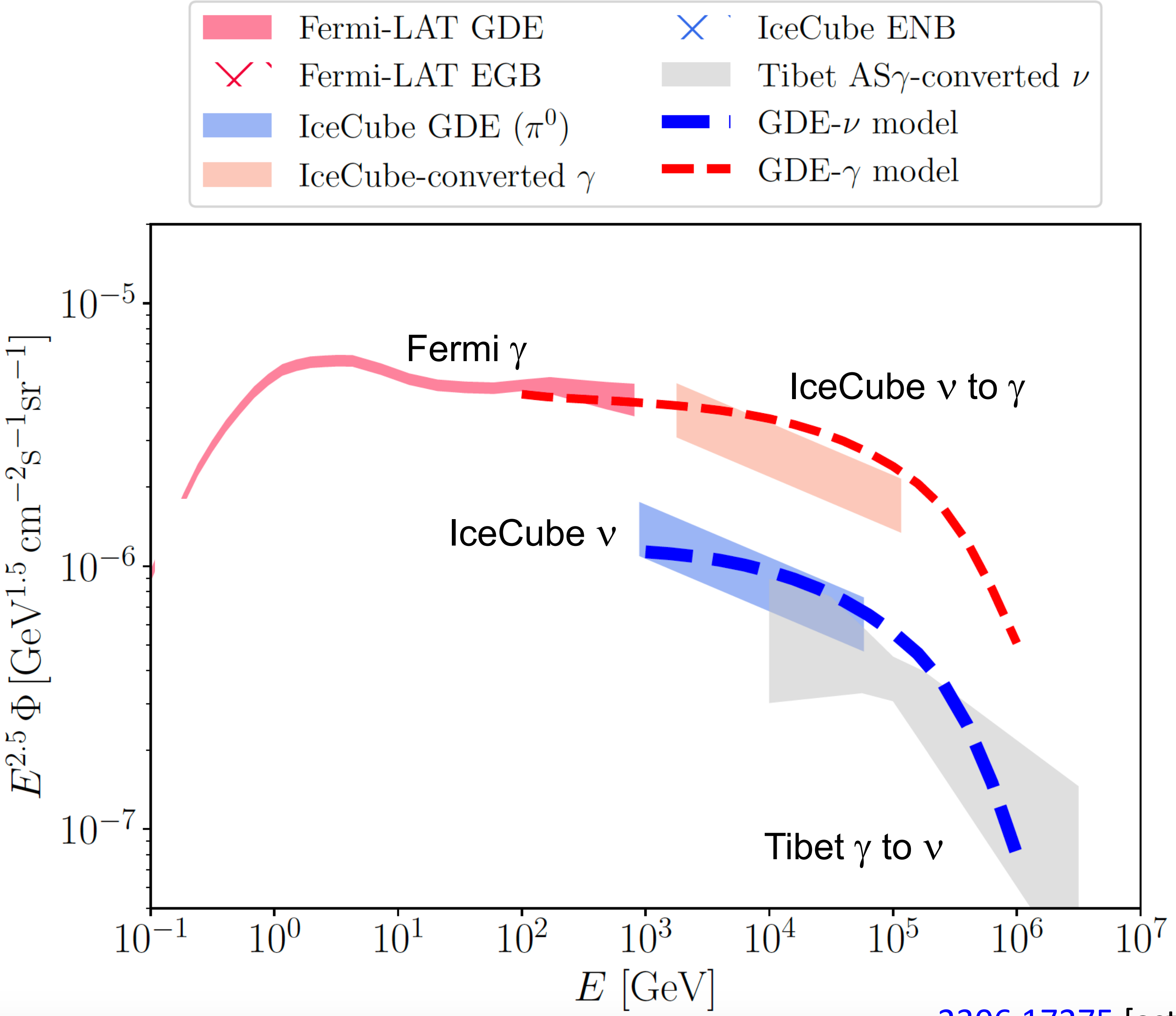
Fermi (GeV gamma rays) and IceCube (TeV neutrinos) see the same Galactic plane



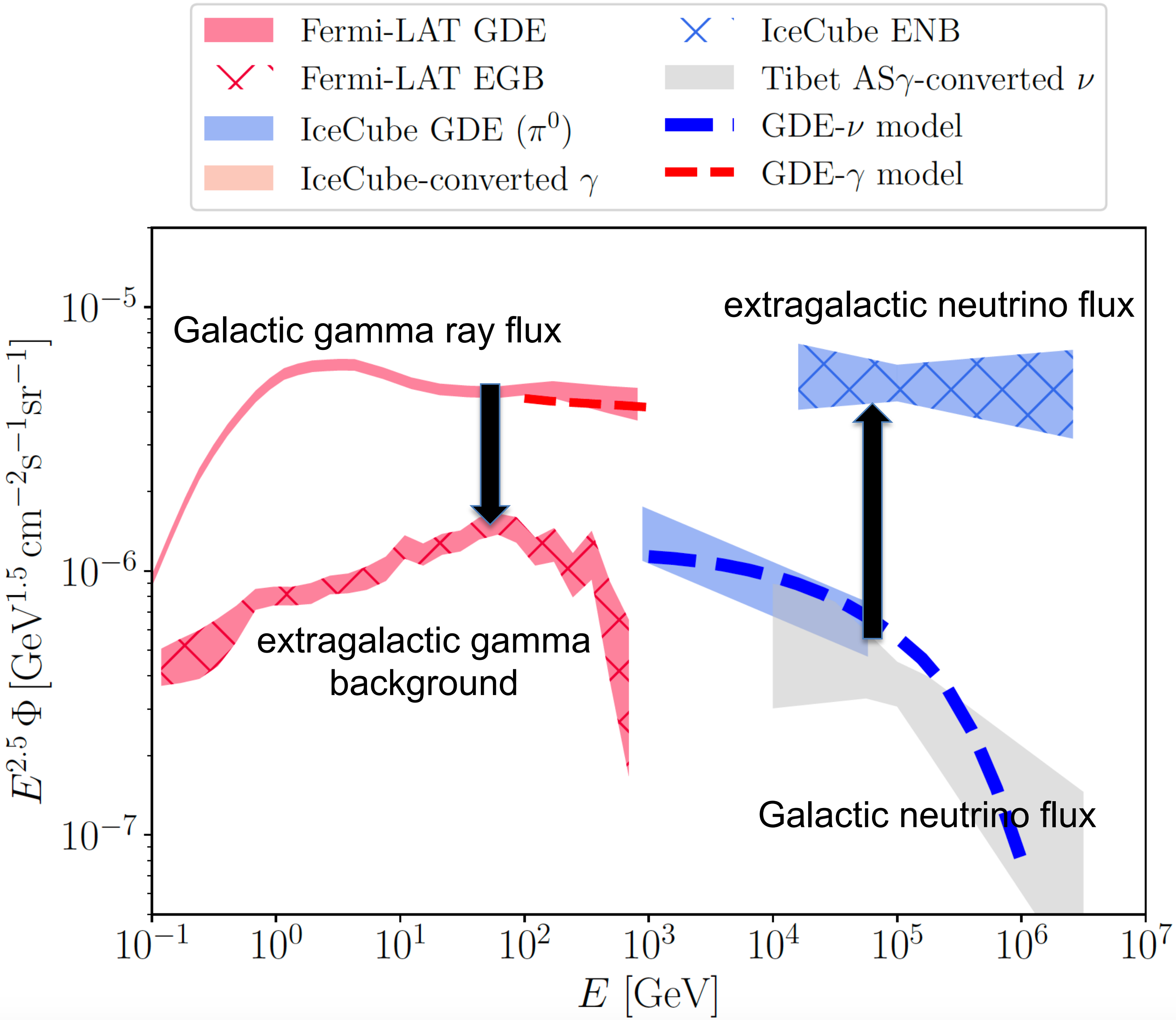
neutrinos produced in Galactic cosmic rays
interactions with interstellar medium



Tibet ASγ-converted ν
IceCube GP (π0)
Fermi-LAT GDE
IceCube-converted γ
gamma ray flux from the Galaxy
IceCube
neutrino flux
from the Galaxy
E2.5 Φ [GeV1.5 cm−2s−1sr−1]
10−5
10−6
10−7
10−1
100
101
102
103
104
105
106
107
E [GeV]



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

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

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

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

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

measured IceCube fluxes

factors of order unity

neutrino flux in active galaxies from diffuse flux observed

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

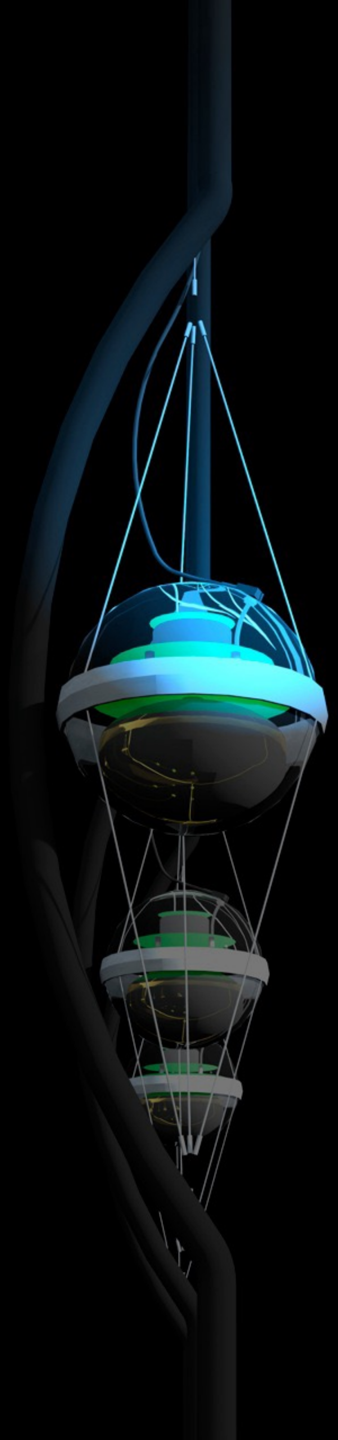
ξ (cosmology)

neutrino flux in Milky Way from flux at Earth

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

F_ϵ (geometry)

- in the extreme universe more energy is emitted in neutrinos than in gamma rays
- the π^0 photons accompanying cosmic rays appear at MeV energy, or below
- powerful accelerators operate in other galaxies that do not exist in our own
- [our supermassive black hole has not been active for a few million years?]

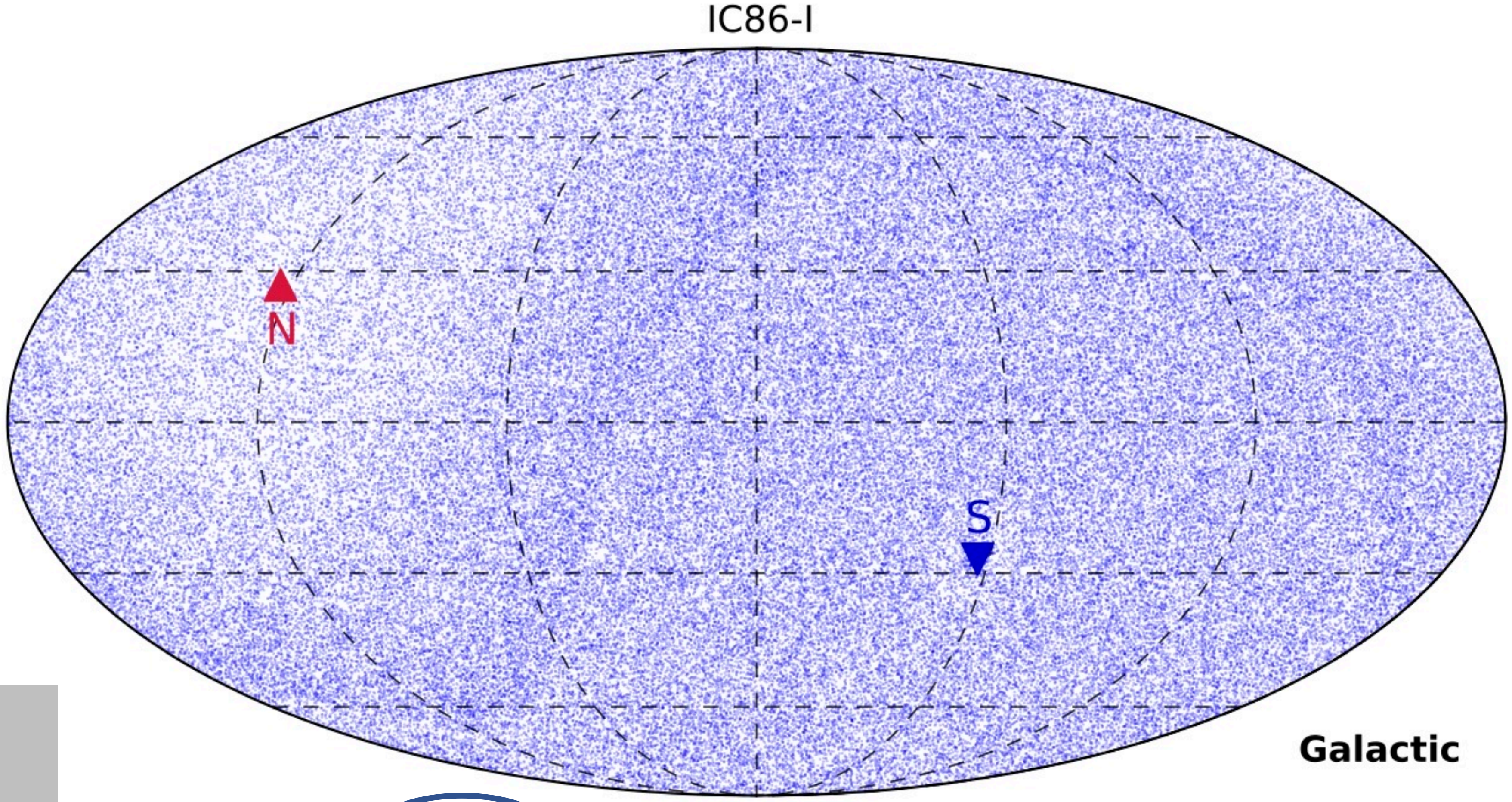


- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- and the answer is: supermassive black holes at the cores of active galaxies

IceCube.wisc.edu

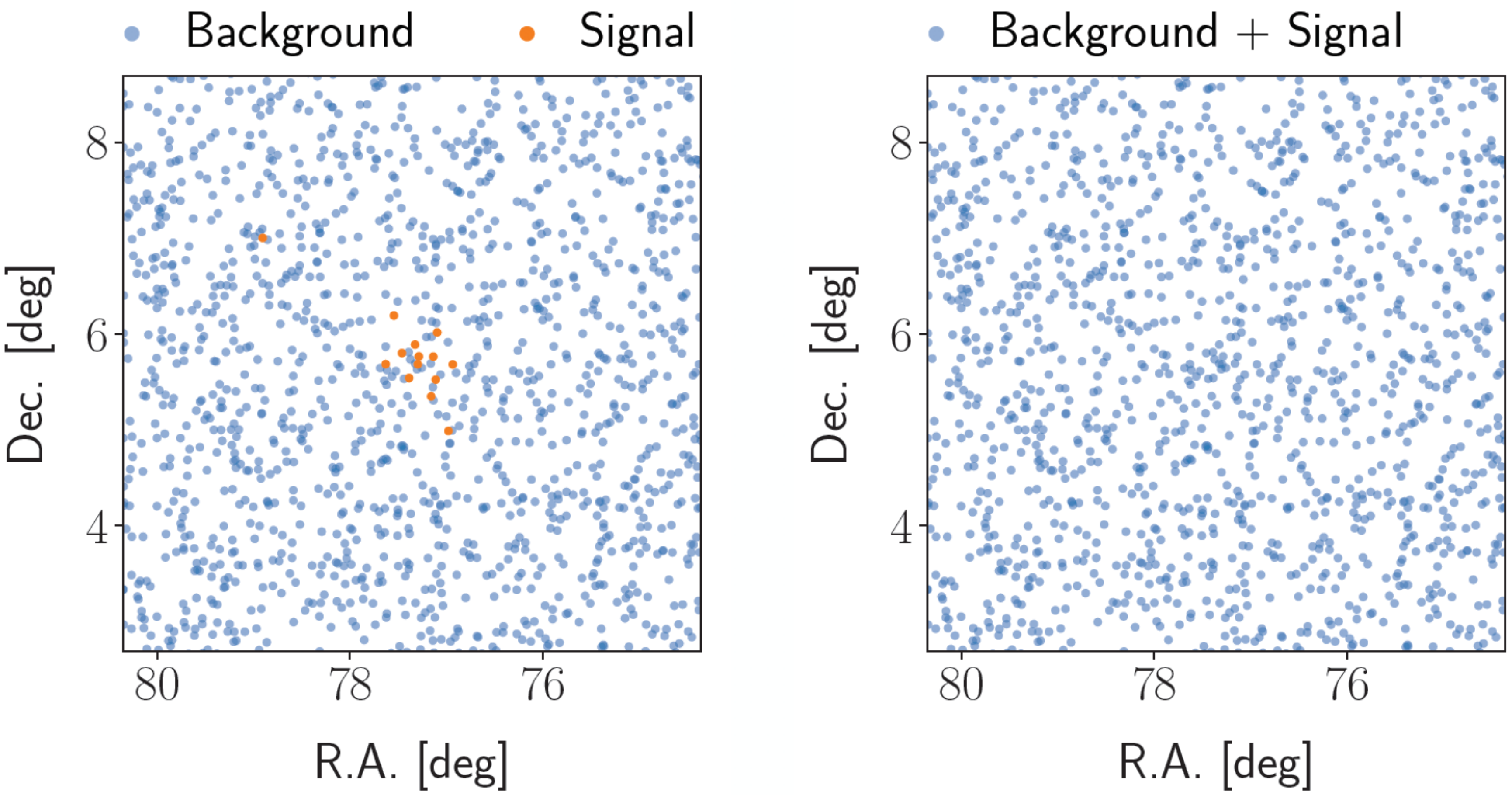
one year of IceCube neutrinos >100 GeV

(reaches neutrino purity of 97% but overwhelmingly atmospheric)



138322 neutrino candidates in one year

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

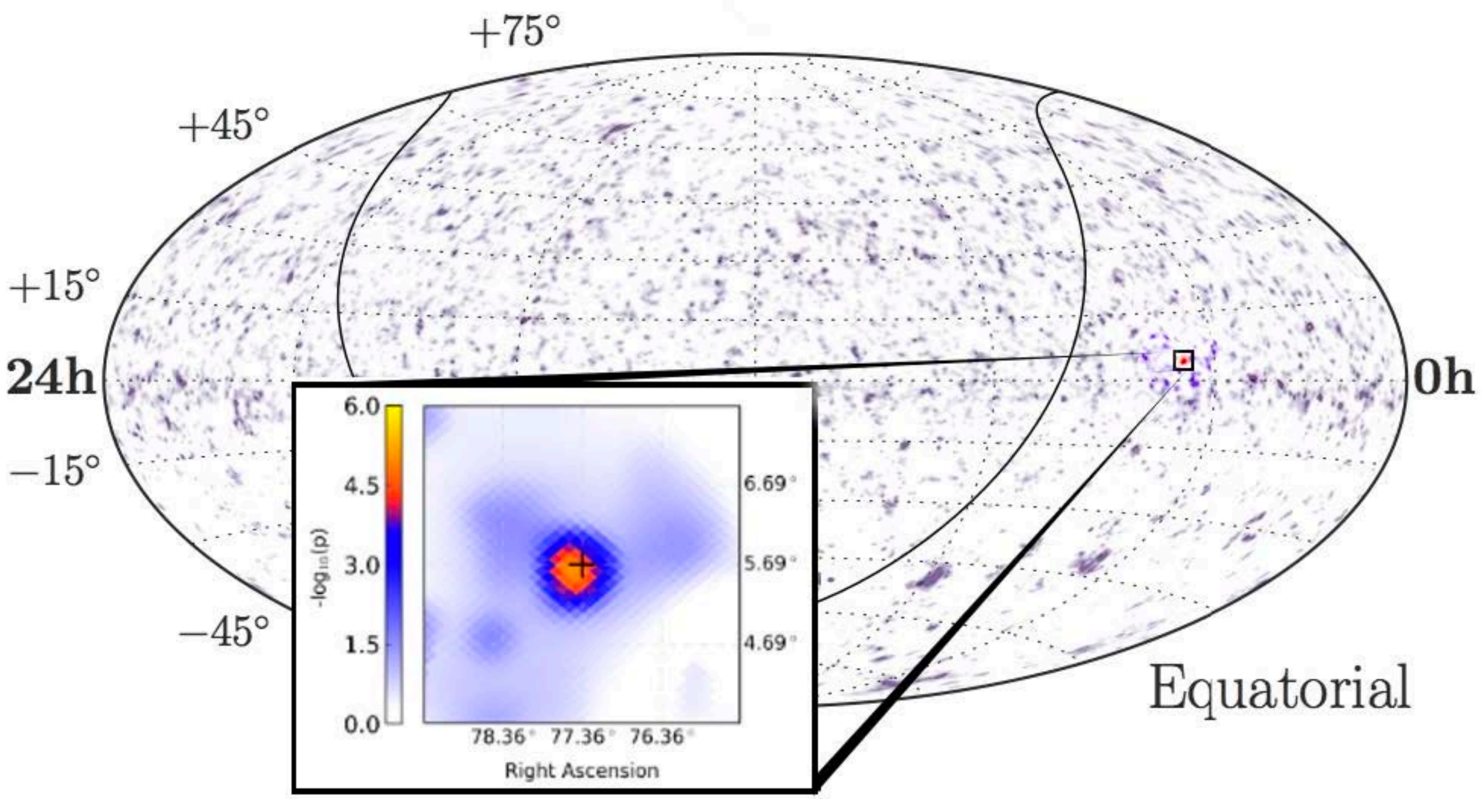


- maximize the likelihood *L* at each point in the sky
- usually, add energy term to the signal likelihood *S*

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

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

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



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

statistical fluctuations or neutrino sources?

search in the directions of 110 preselected source candidates

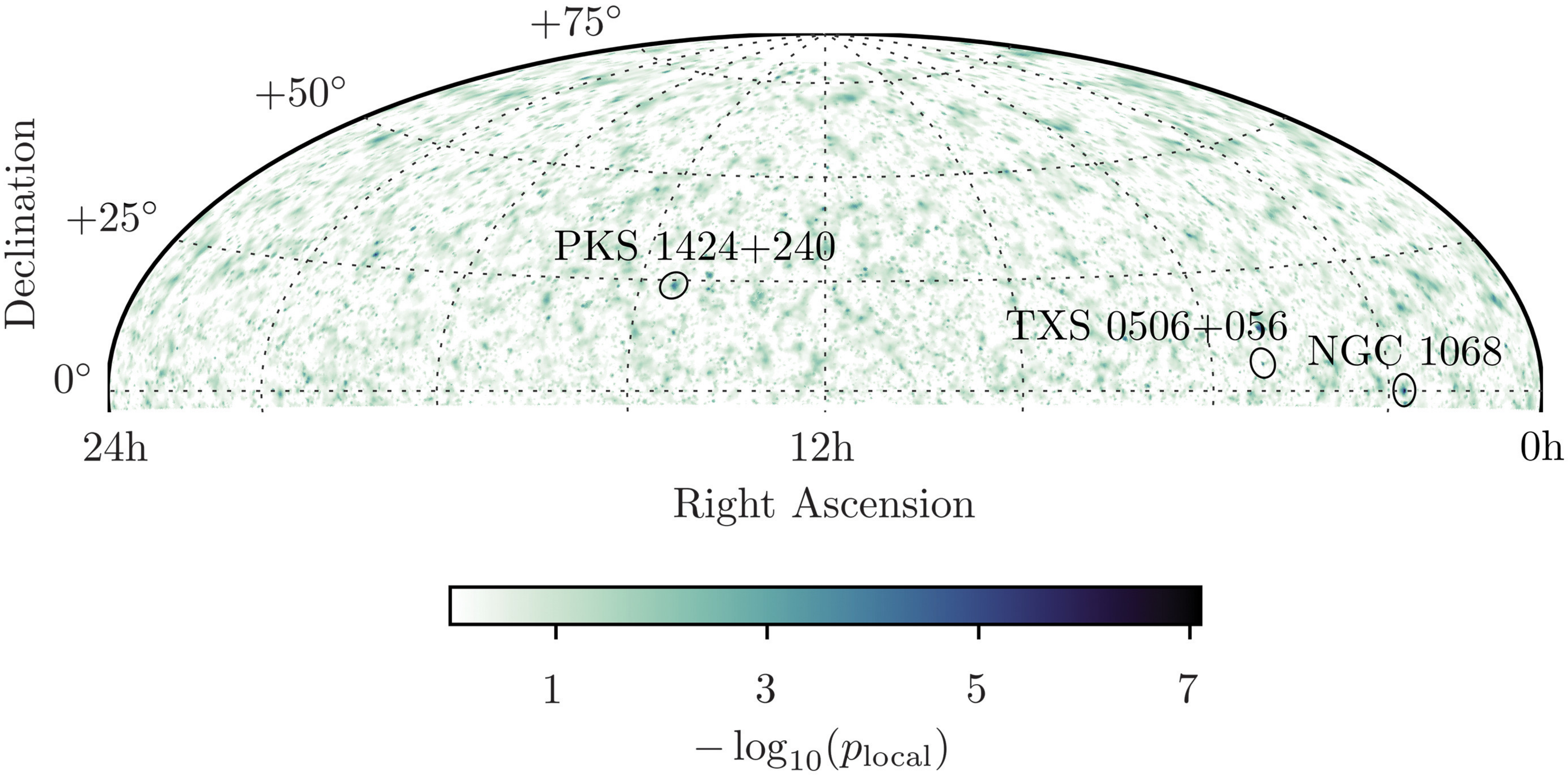
Phys.Rev.Lett. 124 (2020)

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	[illegible]	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	4.0
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3
1RXS J194246.3+1	BLL	295.70	10.56	0.0	2.7	0.33	2.6
RX J1931.1+0937	BLL	292.78	9.63	0.0	2.9	0.29	2.8
NVSS J190836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3
MGRO J1908+06	GAL	287.17	6.18	4.2	2.0	1.42	5.7
TXS 1902+556	BLL	285.80	55.68	11.7	4.0	0.85	9.9
HESS J1857+026	GAL	284.30	2.67	7.4	3.1	0.53	3.5
GRS 1285.0	UNIDB	283.15	0.69	1.7	3.8	0.27	2.3
HESS J1852-000	GAL	283.00	0.00	3.3	3.7	0.38	2.6
HESS J1849-000	GAL	282.26	-0.02	0.0	3.0	0.28	2.2
HESS J1843-033	GAL	280.75	-3.30	0.0	2.8	0.31	2.5
OT 081	BLL	267.87	9.65	12.2	3.2	0.73	4.8
S4 1749+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0
1H 1720+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2
PKS 1717+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3
Mkn 501	BLL	253.47	39.76	10.3	4.0	0.61	7.3
4C +38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0
PG 1553+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2
GB6 J1542+6129	**BLL**	**235.75**	**61.50**	**29.7**	**3.0**	**2.74**	**22.0**
B2 1520+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3
PKS 1502+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9
PKS 1502+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6
PKS 1441+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3
PKS 1424+240	**BLL**	**216.76**	**23.80**	**41.5**	**3.9**	**2.80**	**12.3**
NVSS J141826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0
B3 1343+451	FSRQ	206.40	44.88	0.0	2.8	0.32	5.0
S4 1250+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9
PG 1246+586	BLL	192.08	58.34	0.0	2.8	0.35	6.4
MG1 J123931+0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4
M 87	AGN	187.71	12.39	0.0	2.8	0.29	3.1
ON 246	BLL	187.56	25.30	0.9	1.7	0.37	4.2
3C 273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9
4C +21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5
W Comae	BLL	185.38	28.24	0.0	3.0	0.32	3.7
PG 1218+304	BLL	185.34	30.17	11.1	3.9	0.70	6.7
PKS 1216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1
B2 1215+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5
Ton 599	FSRQ	179.88	29.24	0.0	2.2	0.29	4.5
PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4
Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3
4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4
1H 1013+498	BLL	153.77	49.43	0.0	2.6	0.29	4.5
4C +55.17	FSRQ	149.42	55.38	11.9	[illegible]	[illegible]	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

sub-leading sources: binomial analysis

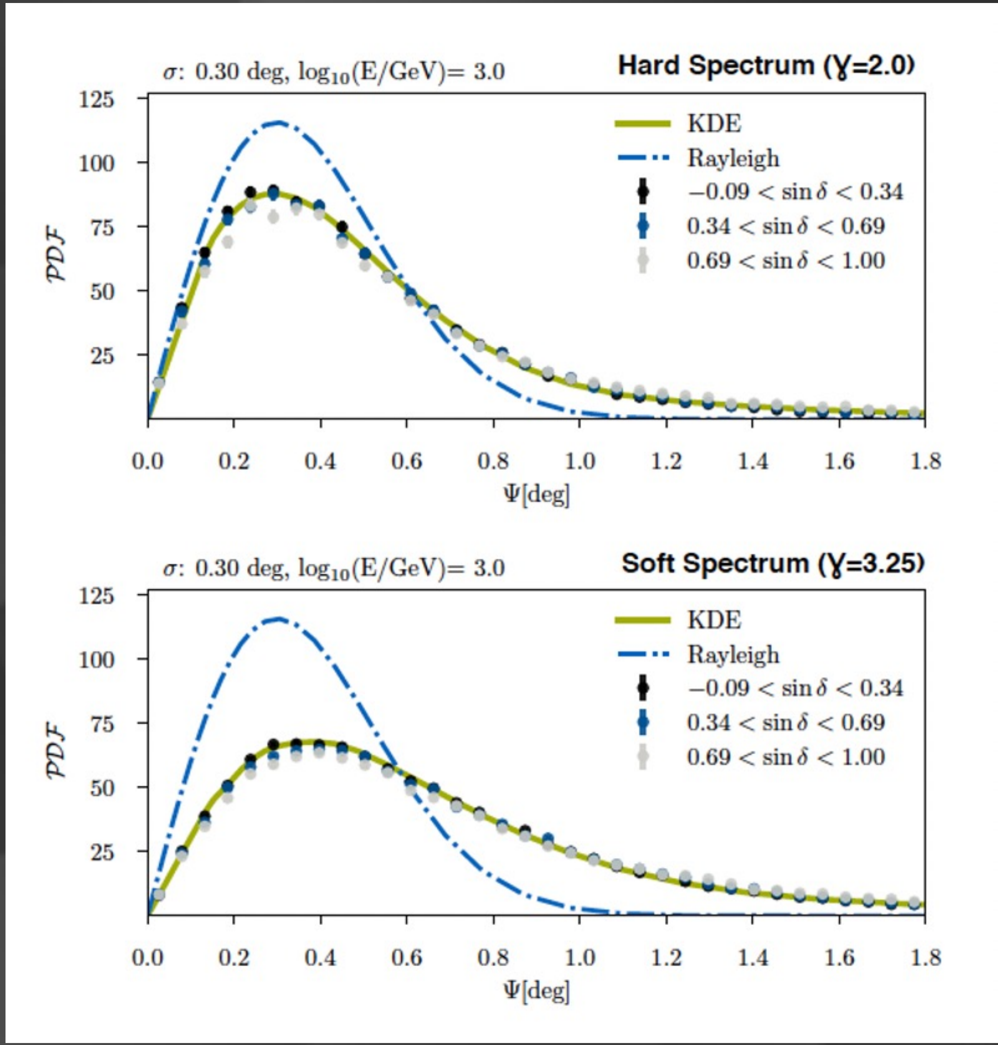


interesting fluctuations or neutrino sources?

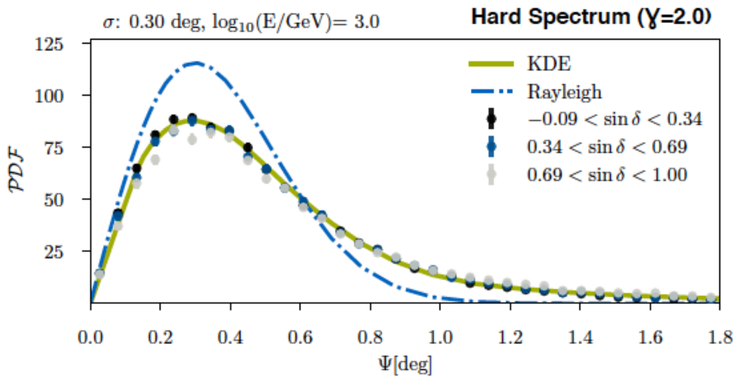
→ crash program to upgrade the performance of IceCube

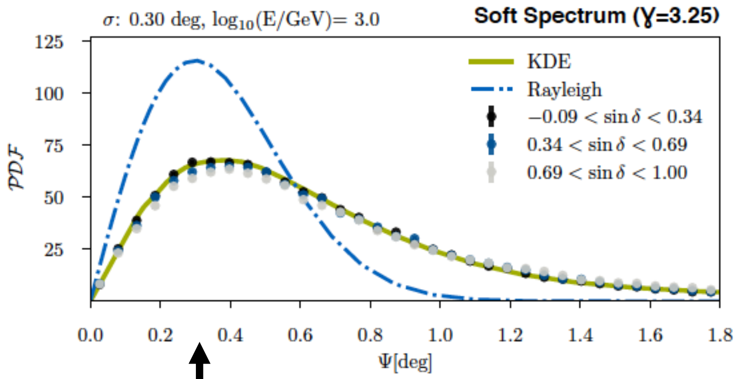
- improved detector geometry
- each photomultiplier calibrated individually
- improved characterization of the optics of the ice
- improved muon angular resolution and energy reconstruction using **machine learning**
- *point spread function consistent with simulation or, we were partially blind*
- *…*

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



- point spread function consistent with simulation
- insensitive to systematics



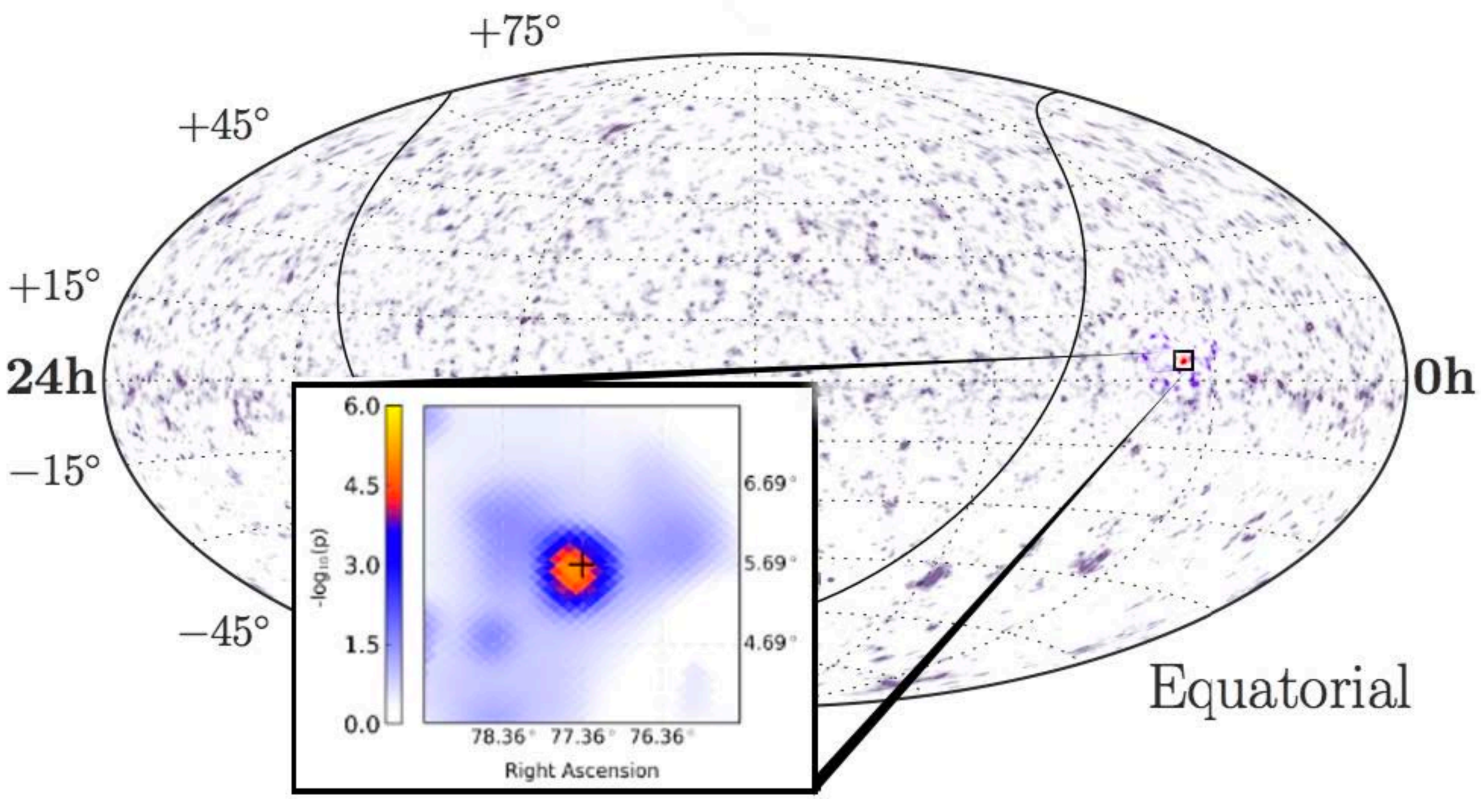


muon direction

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

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

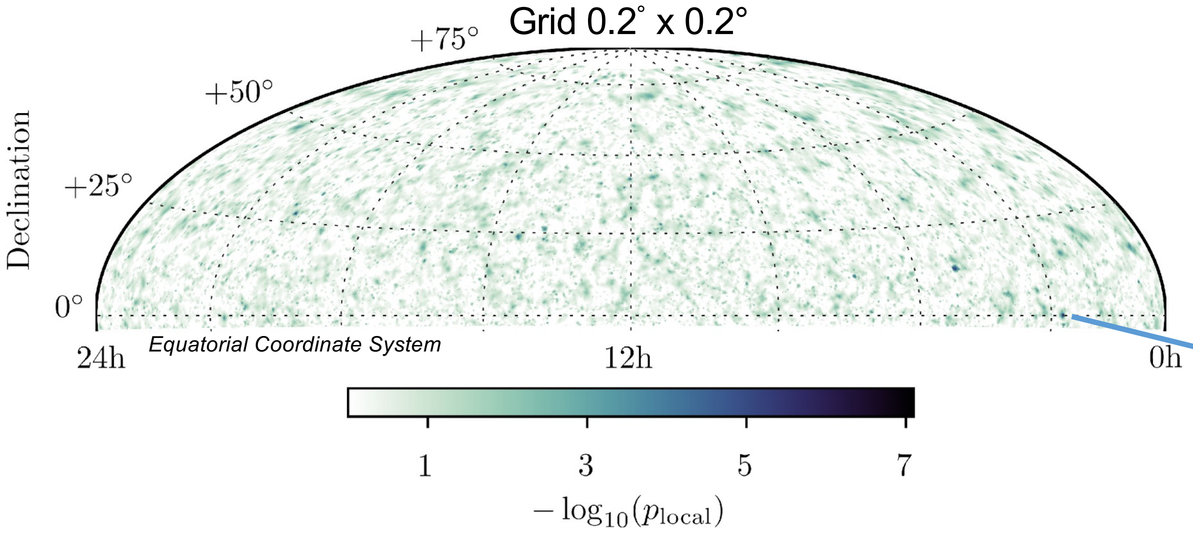
pre-trial p-value for clustering of high energy neutrinos

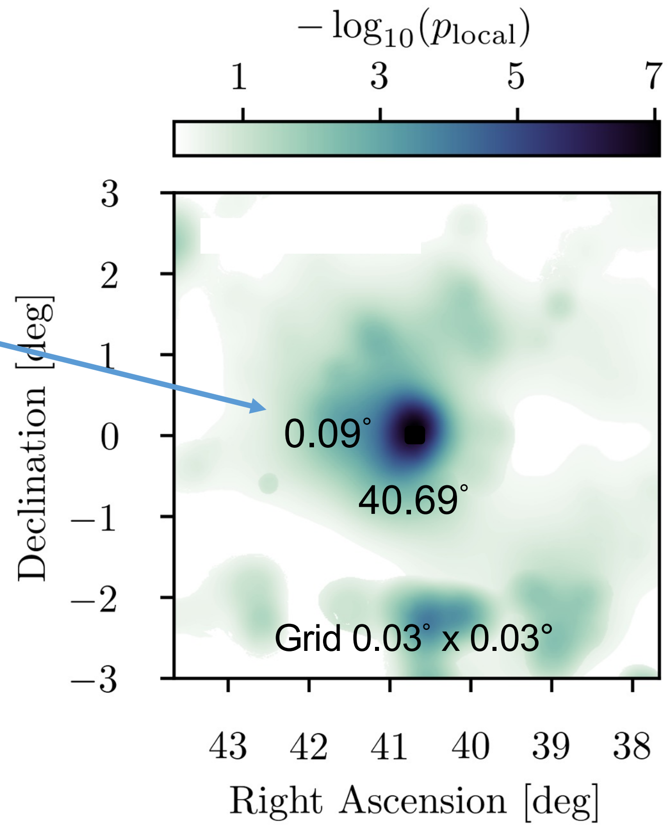


- hottest spot coincident with NGC 1068
- also hottest spot in the sources list (2.9σ)

statistical fluctuations or neutrino sources?

the new IceCube neutrino map: hottest spot





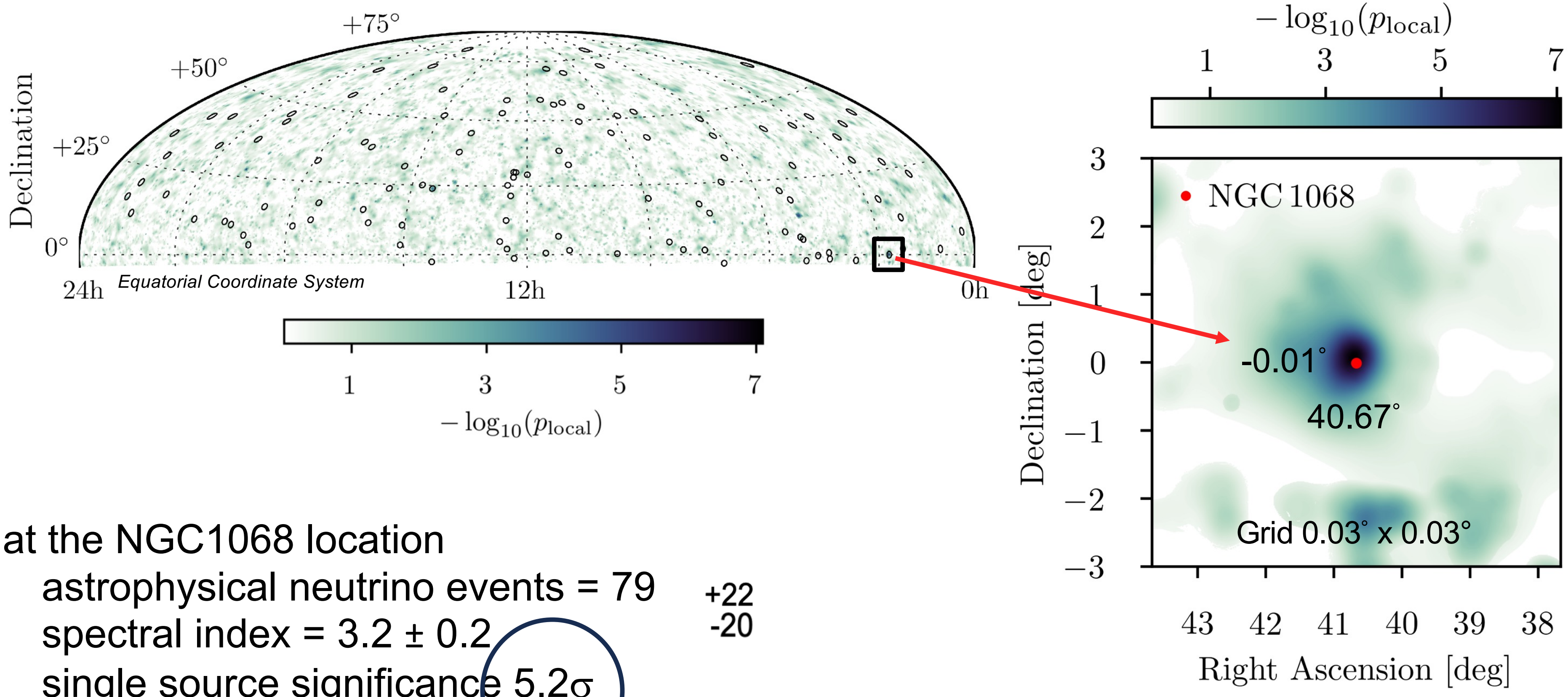
the brightest location in full sky scan:

- astrophysical neutrino events = 81
- spectral index = 3.2

local significance 5.3σ

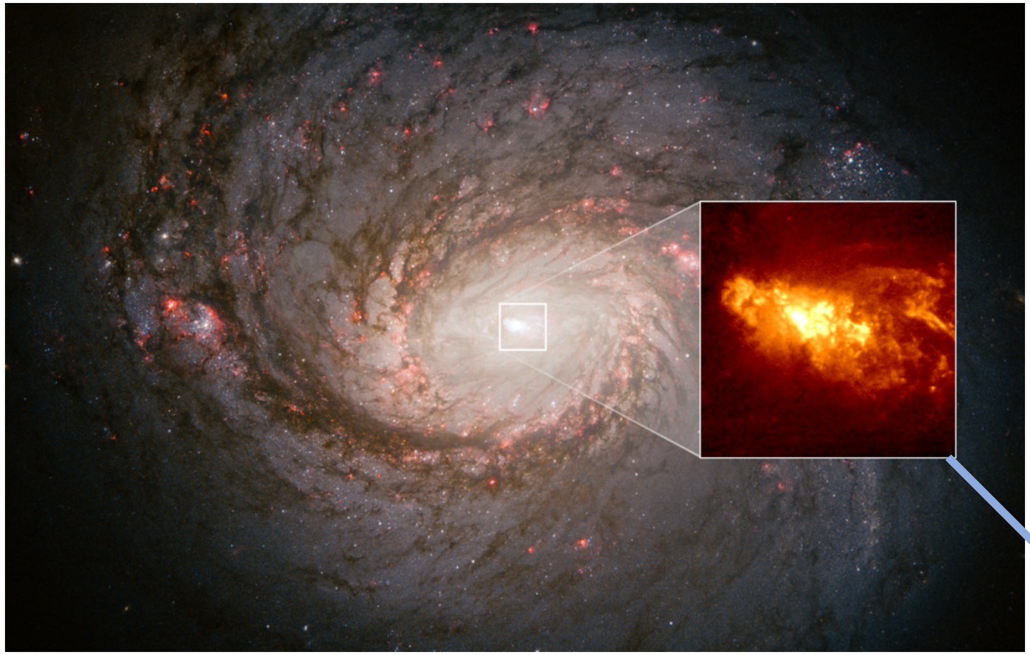
1% of scrambled data sets have a spot ≥ 5.3**σ**

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

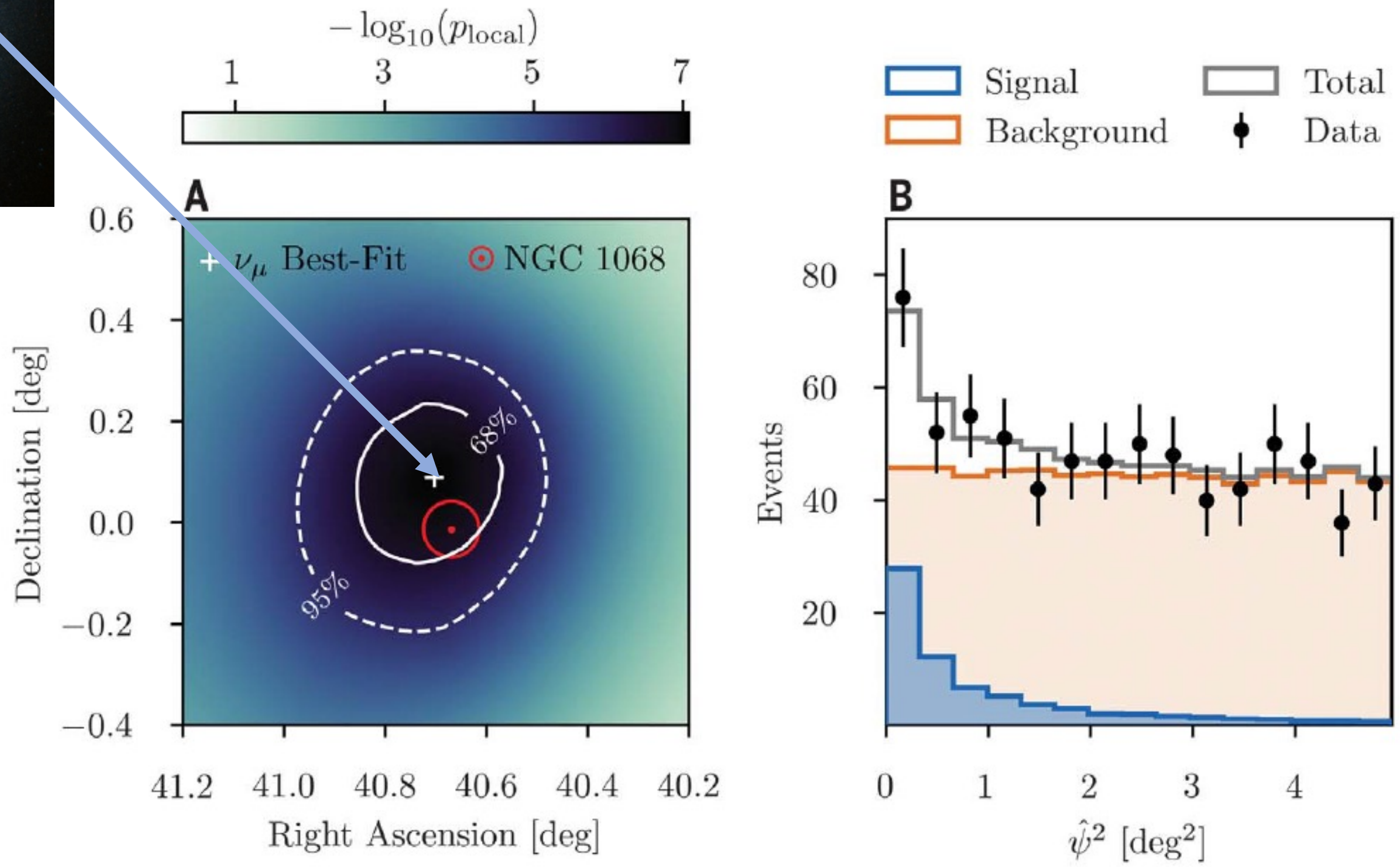


at the NGC1068 location

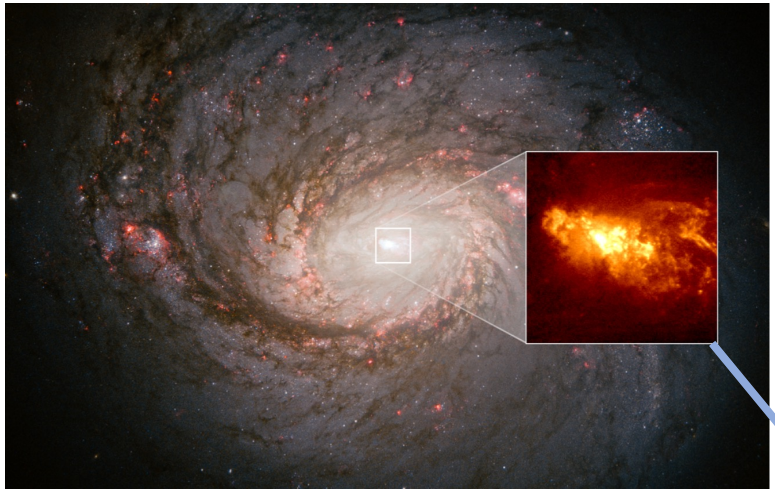
- astrophysical neutrino events = 79^{+22}_{-20}
- spectral index = 3.2 ± 0.2
- single source significance 5.2σ
- (offset 0.11^{0})
- 1 in 100,000 scrambled data sets have object ≥ 5.2 **σ** = 4.2 **σ** evidence



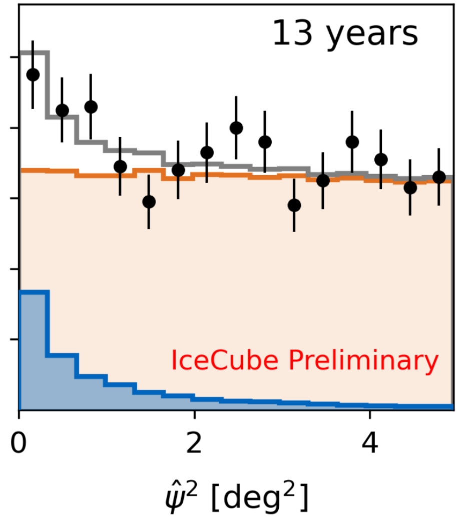
80 high-energy neutrinos from the direction of the active galaxy NGC 1068

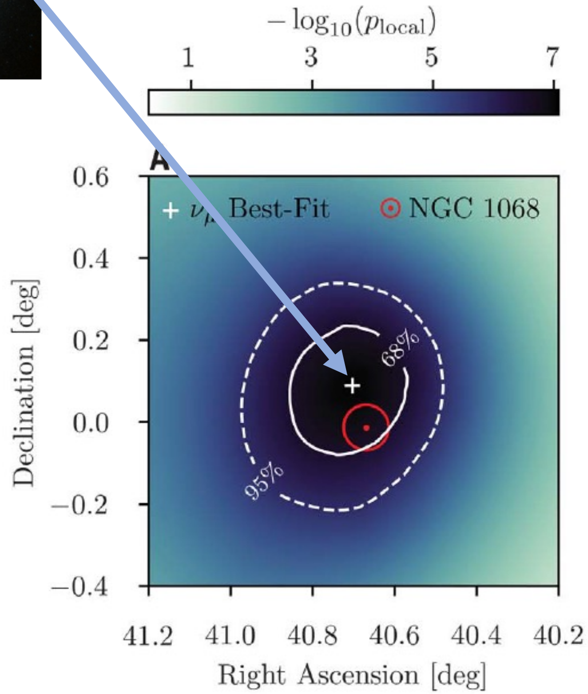


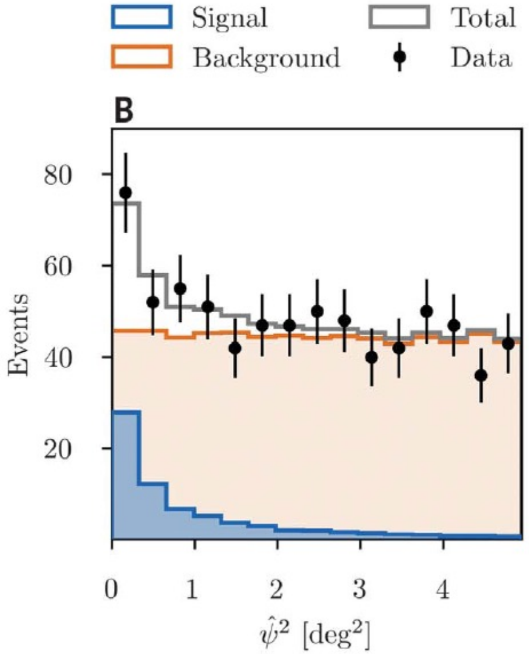
80 high-energy neutrinos from the direction of the active galaxy NGC 1068



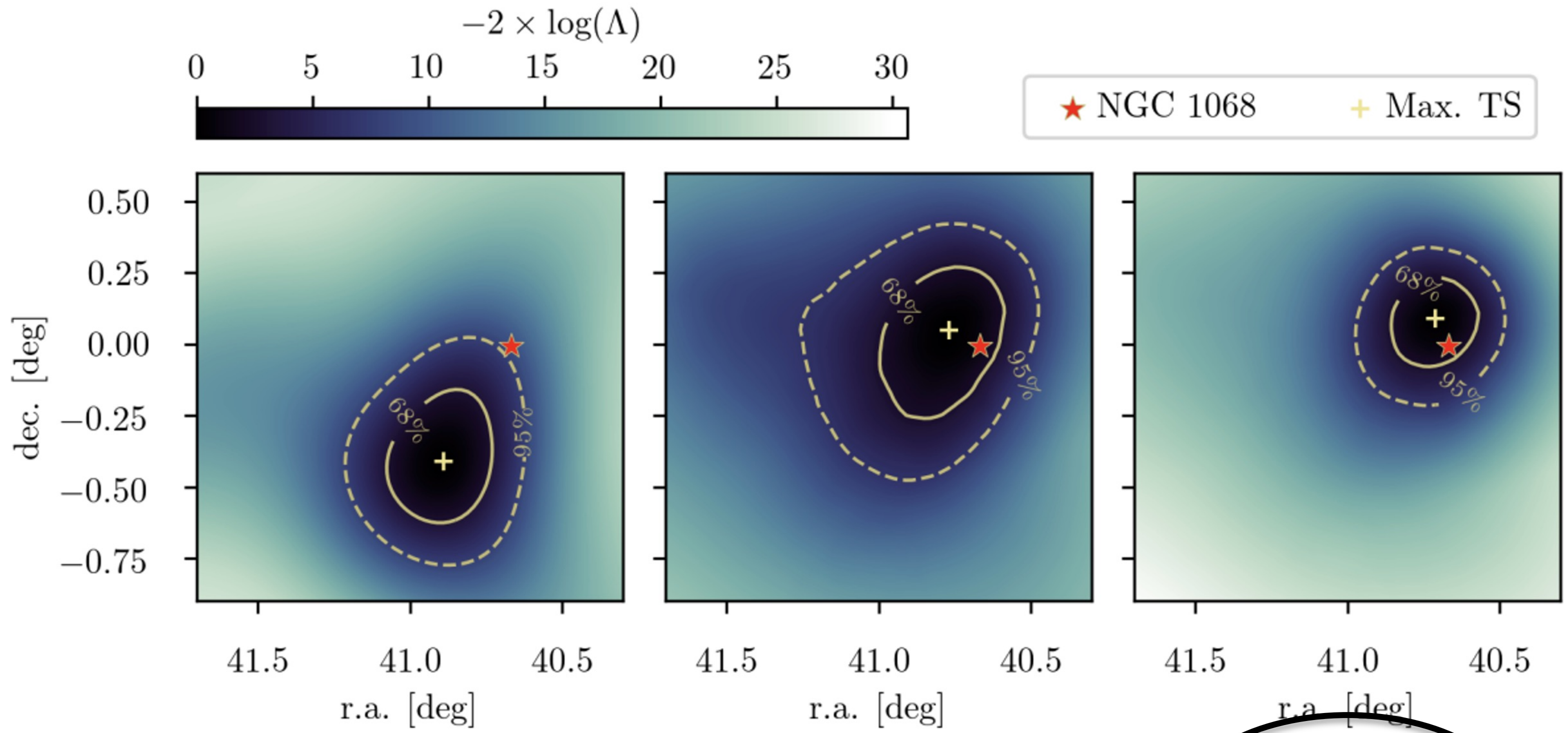
update







NGC 1068 comes into focus



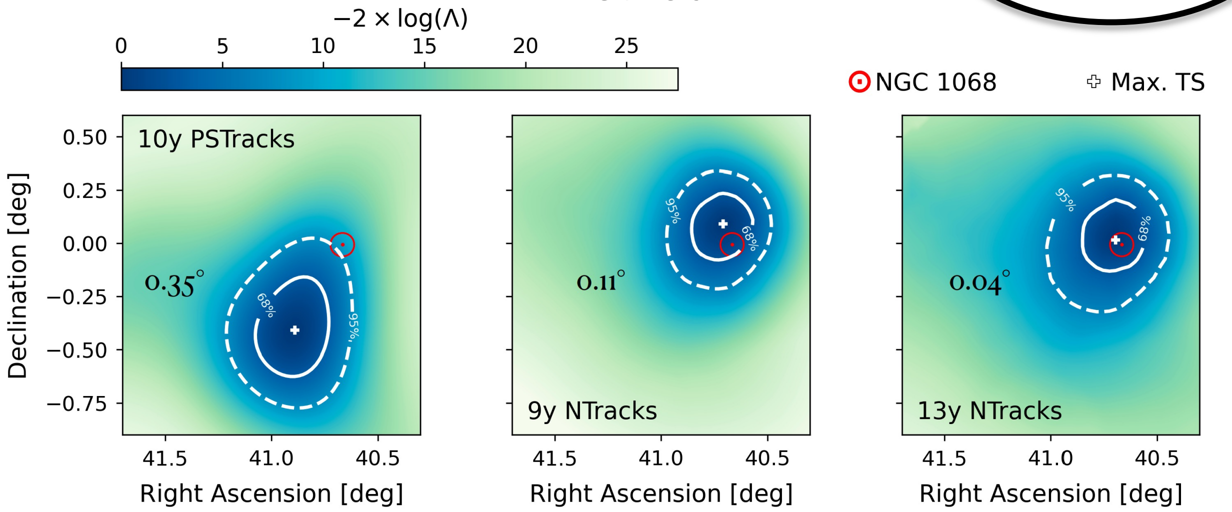
5.2σ local significance

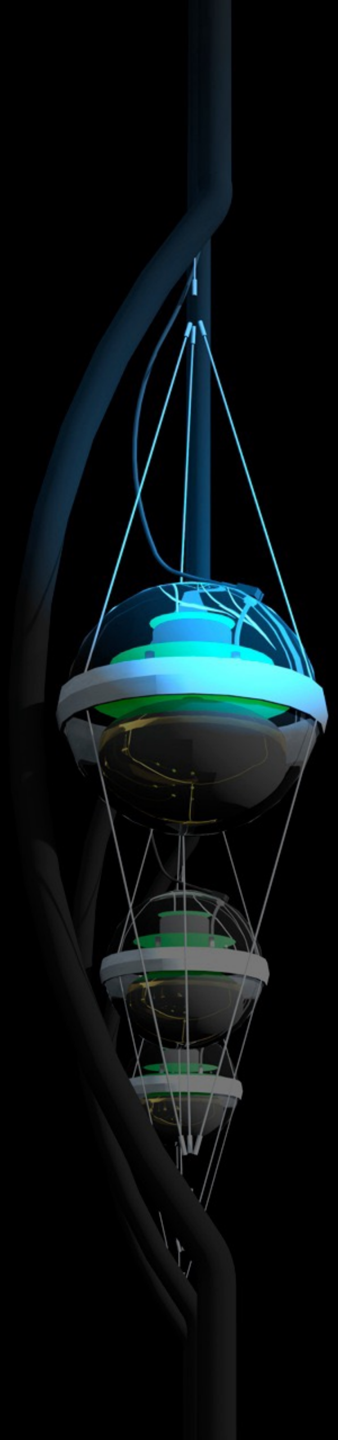
2.9σ
- 10-year analysis

3.3σ
- new likelihood method

4.2σ
- pass 2

update



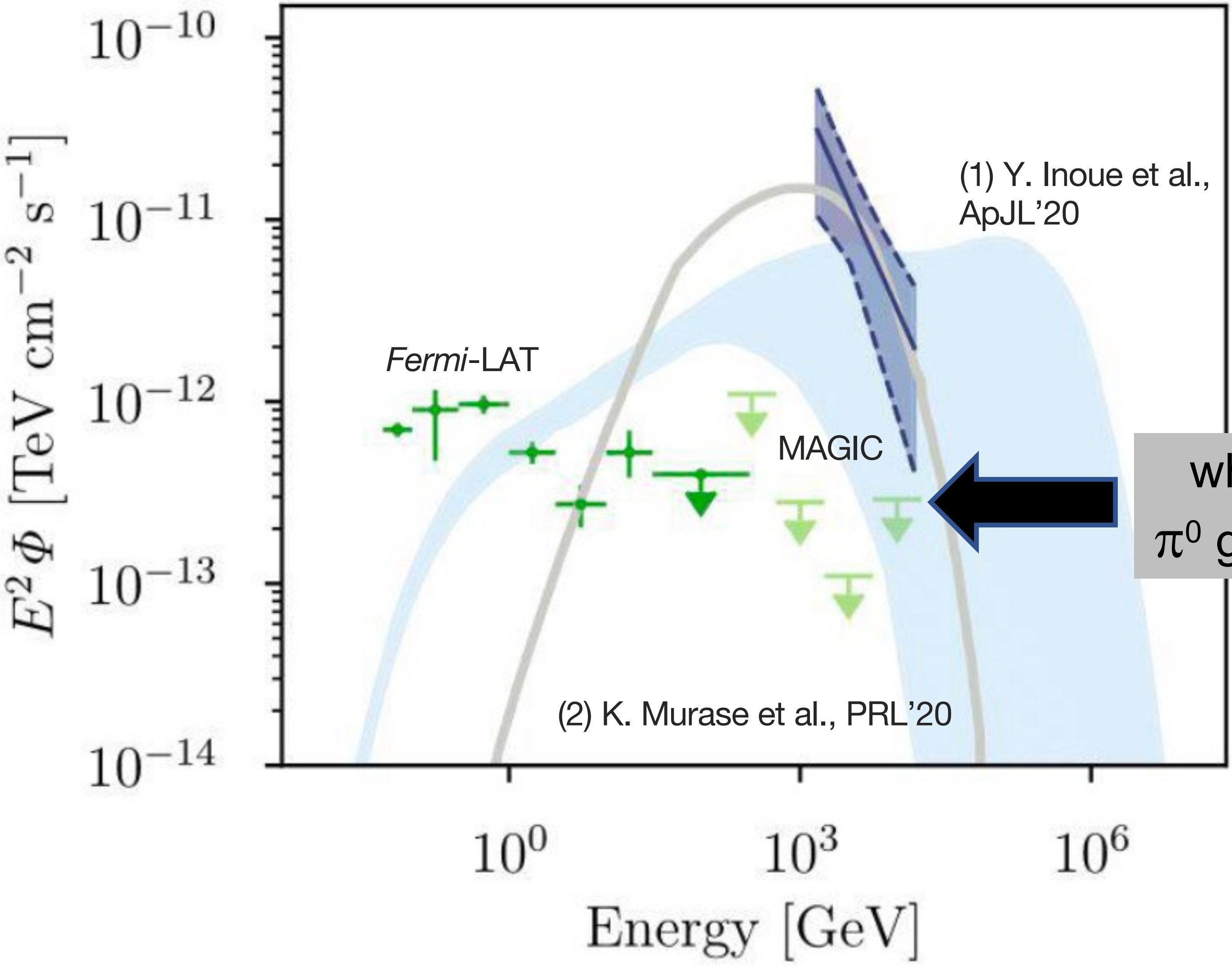


- neutrino astronomy and the origin of cosmic rays
- IceCube
- the cosmic neutrino energy spectrum
- first sources of neutrinos
- and the answer is: supermassive black holes at the cores of active galaxies

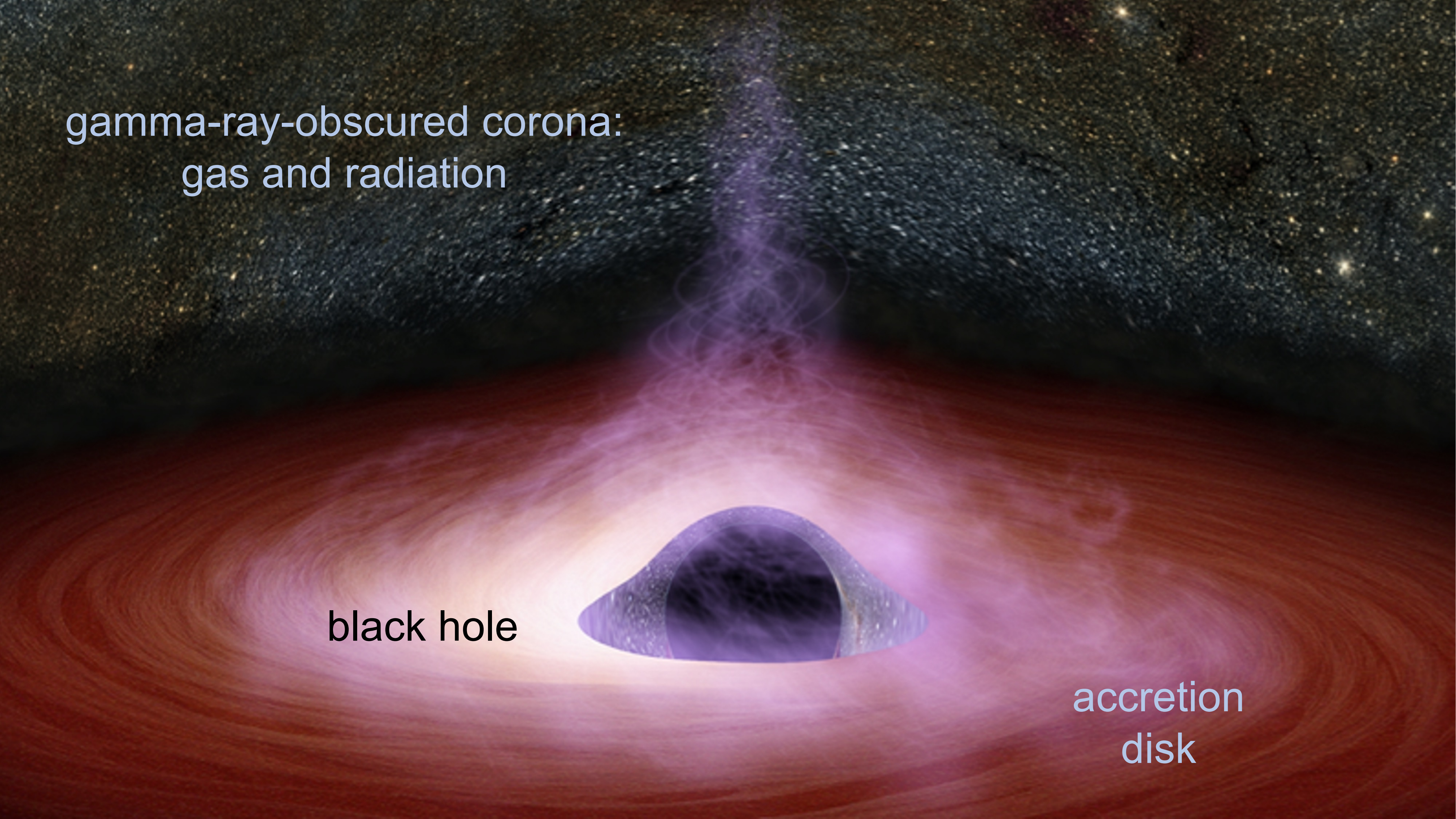
IceCube.wisc.edu

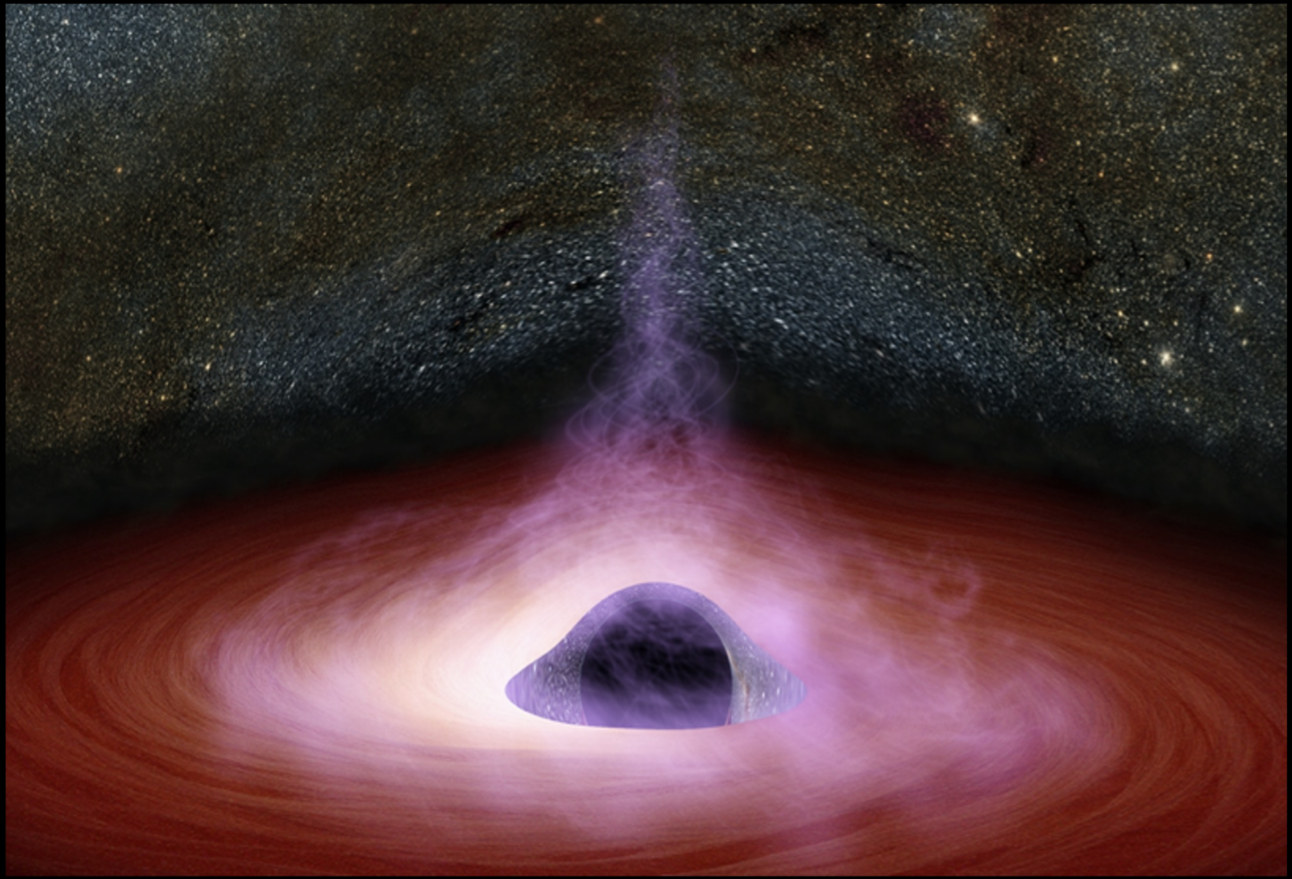
a gamma ray for every neutrino?

NGC 1068: an obscured cosmic accelerator



where are the π^0 gamma rays ?

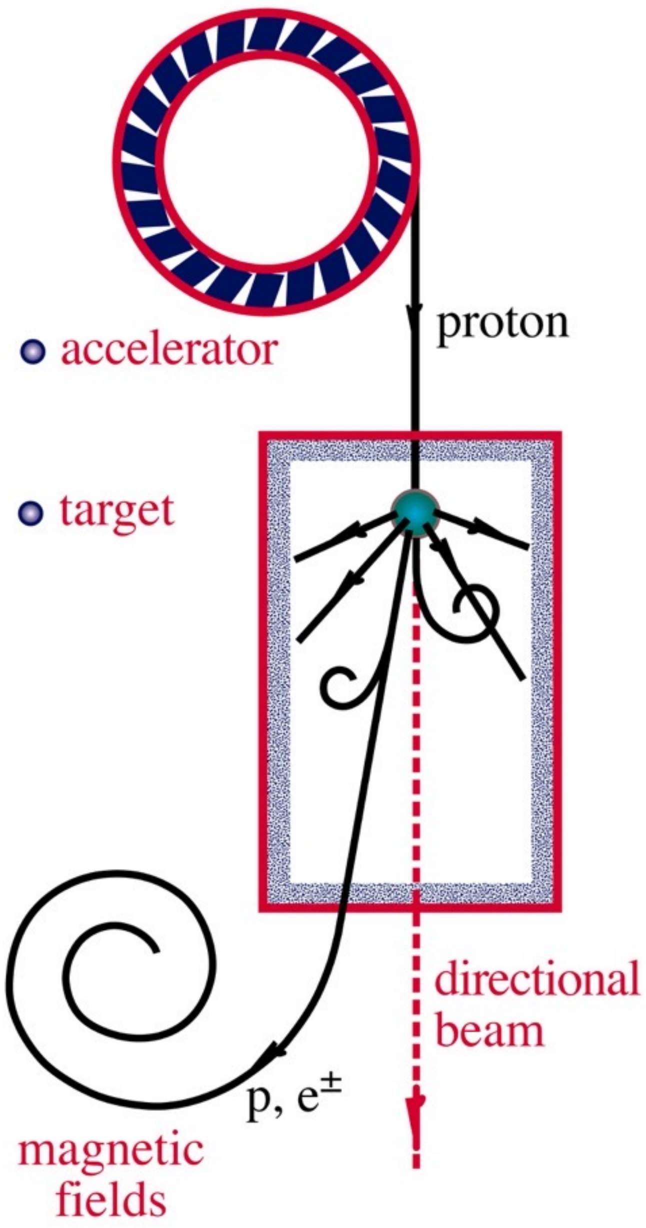

gamma-ray-obscured corona:
gas and radiation
black hole
accretion
disk



- 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)

NEUTRINO BEAMS



the pγ efficiency dilemma

- efficiency for producing the neutrinos in the photon target:

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

- likelihood of the multimessenger photons to be absorbed in target

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

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

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

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

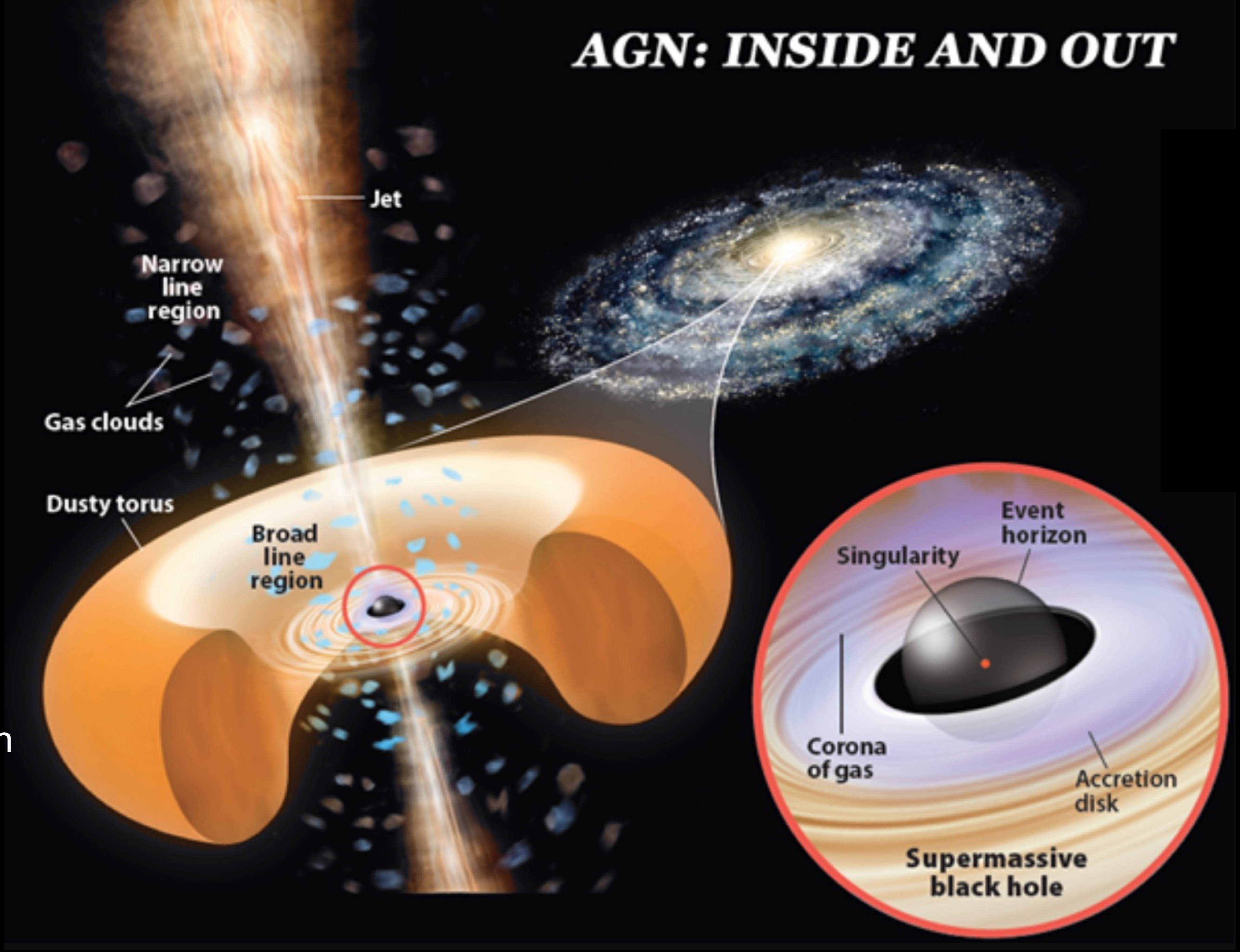
→ blazar jets are out

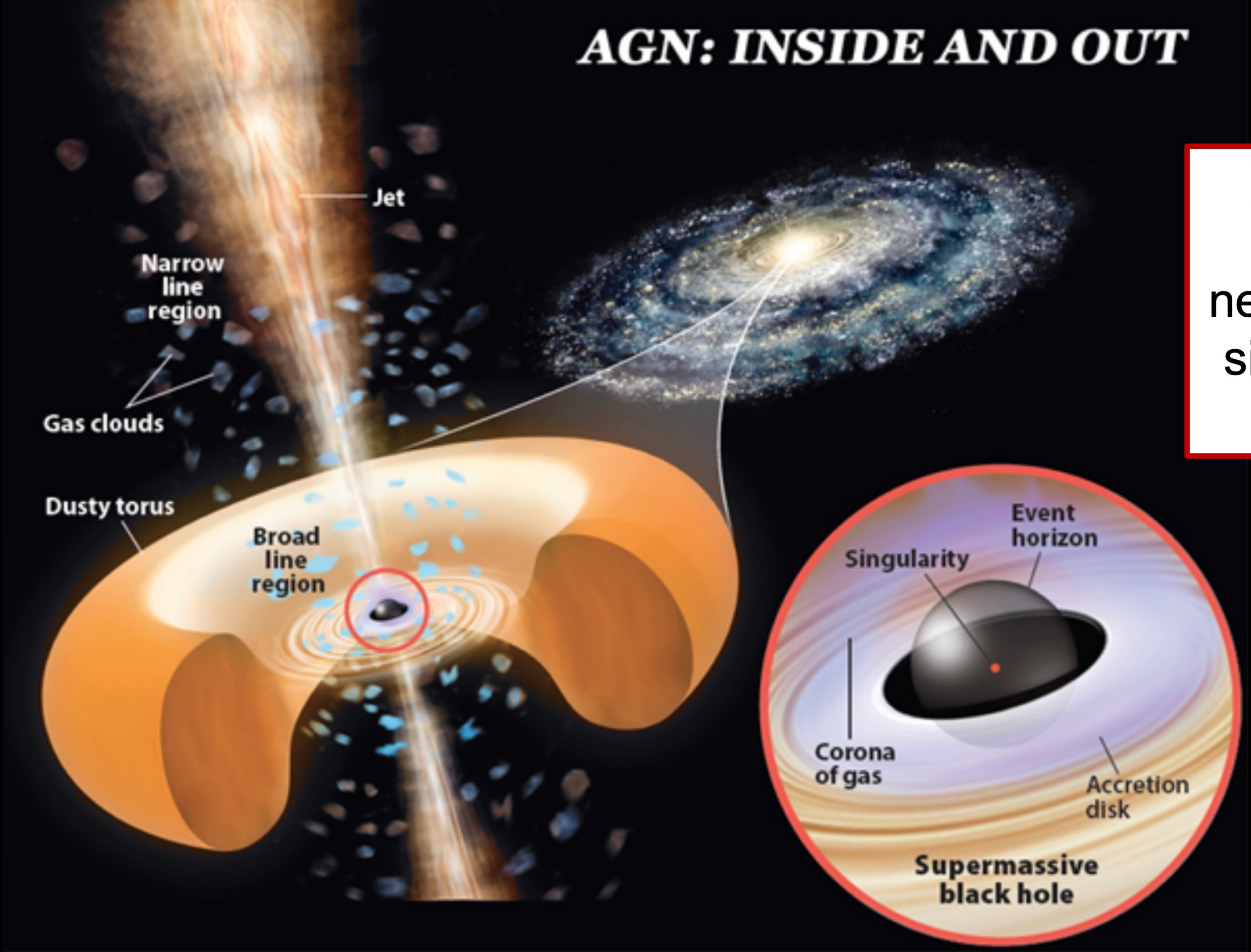
cores of active galaxies

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



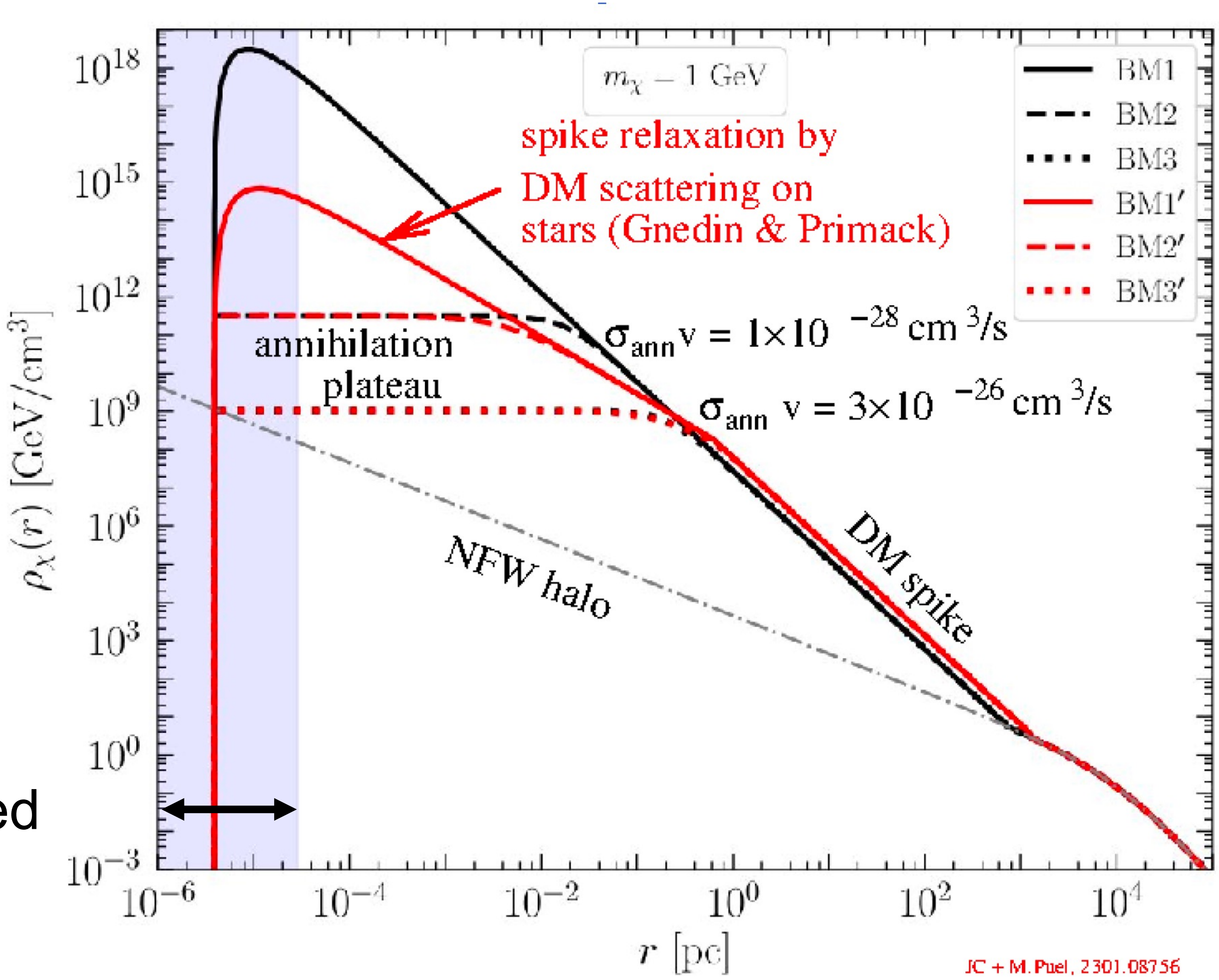


Lack of gamma rays places neutrino production site in the heart of the galaxy

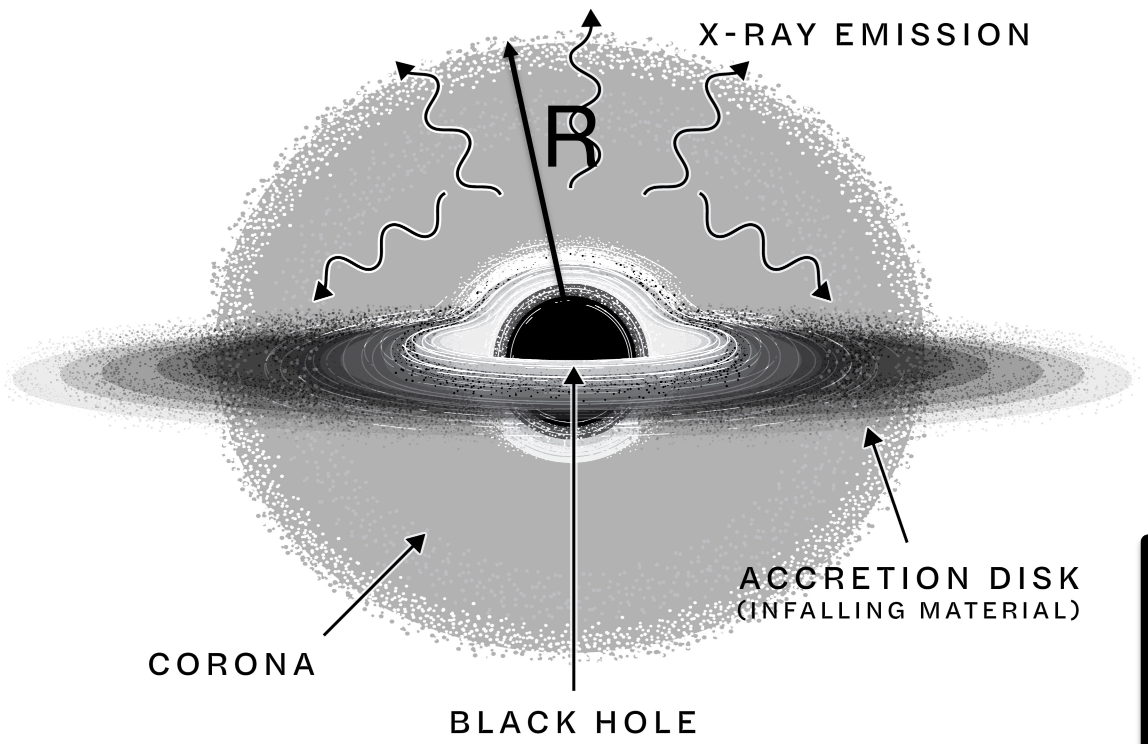
M 87

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

neutrinos produced



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



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

cross section x target density = optical depth τ

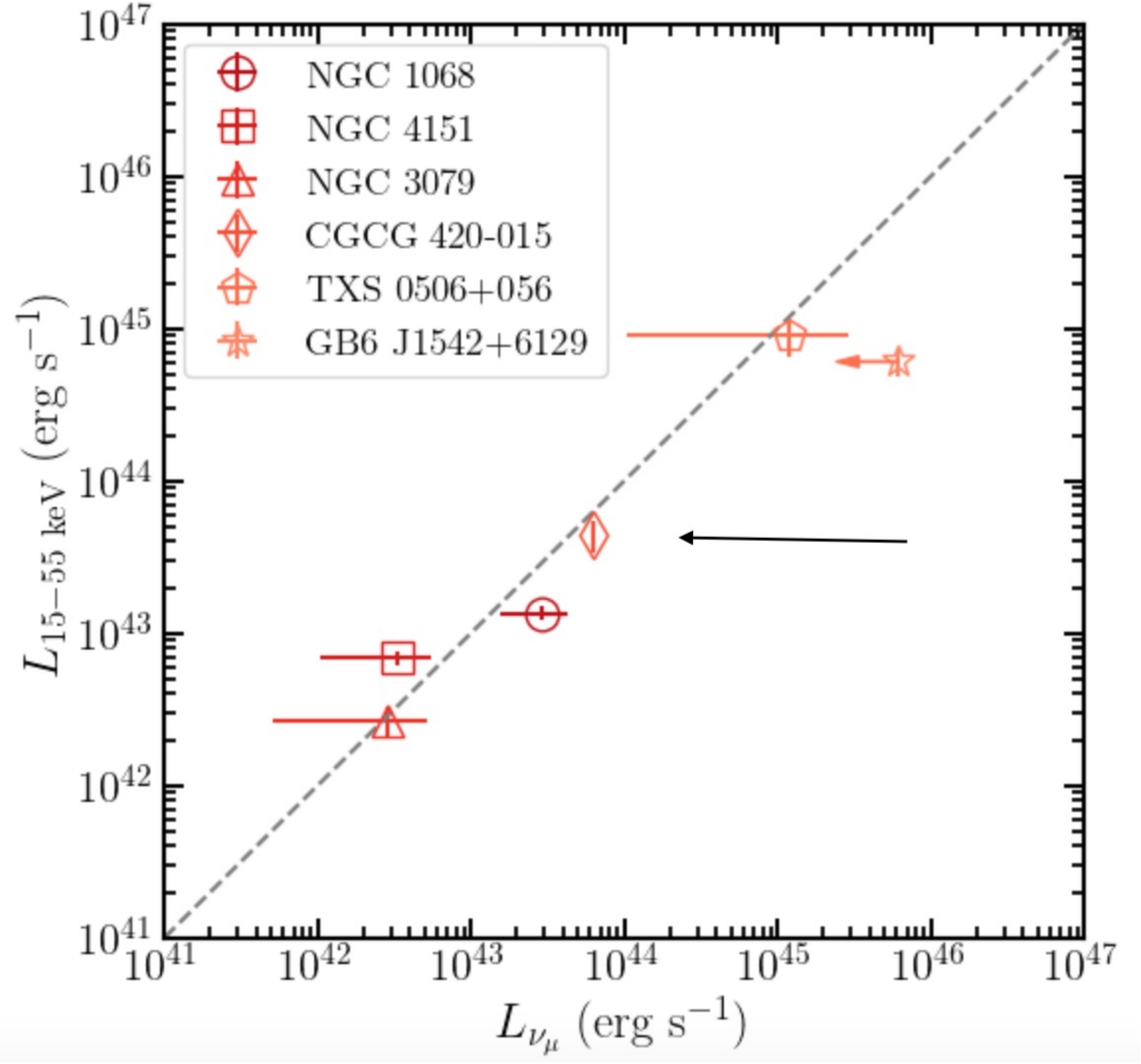
$$\tau_{p\gamma} \sim 0.1 \rightarrow \text{TeV neutrinos}$$

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

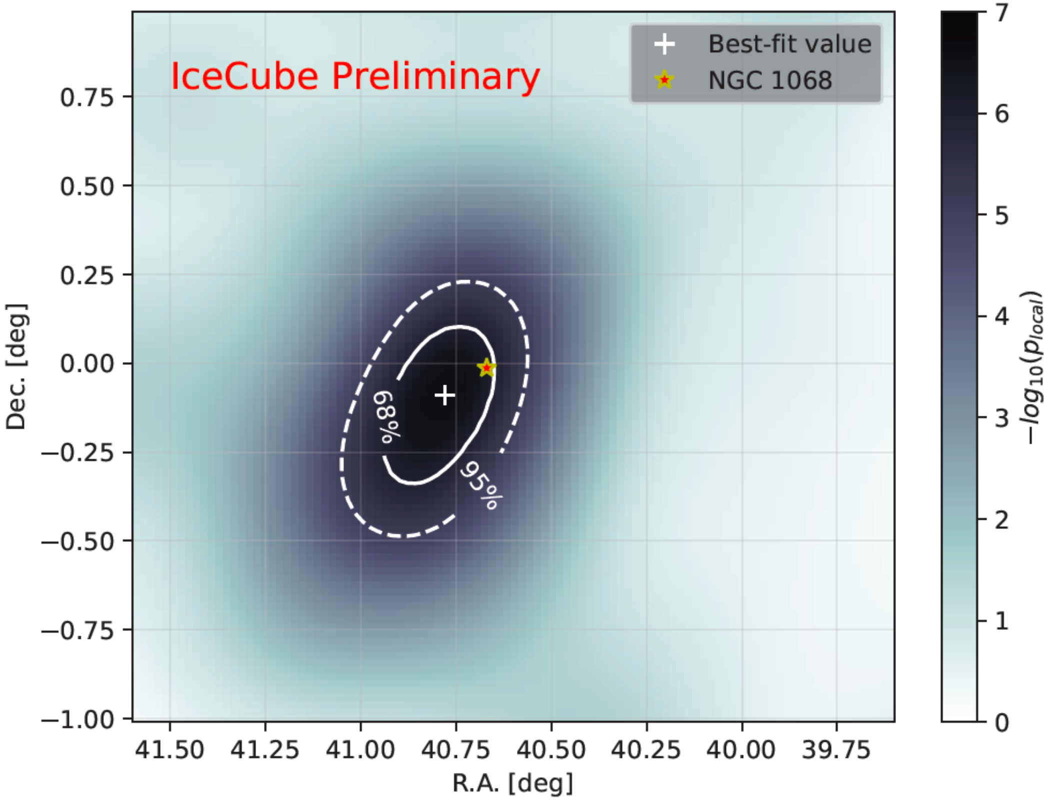
$$E_X = 1\,\text{keV}\,;\ \mathrm{L_X} \sim 10^{43}\,\text{ergs}^{-1}$$

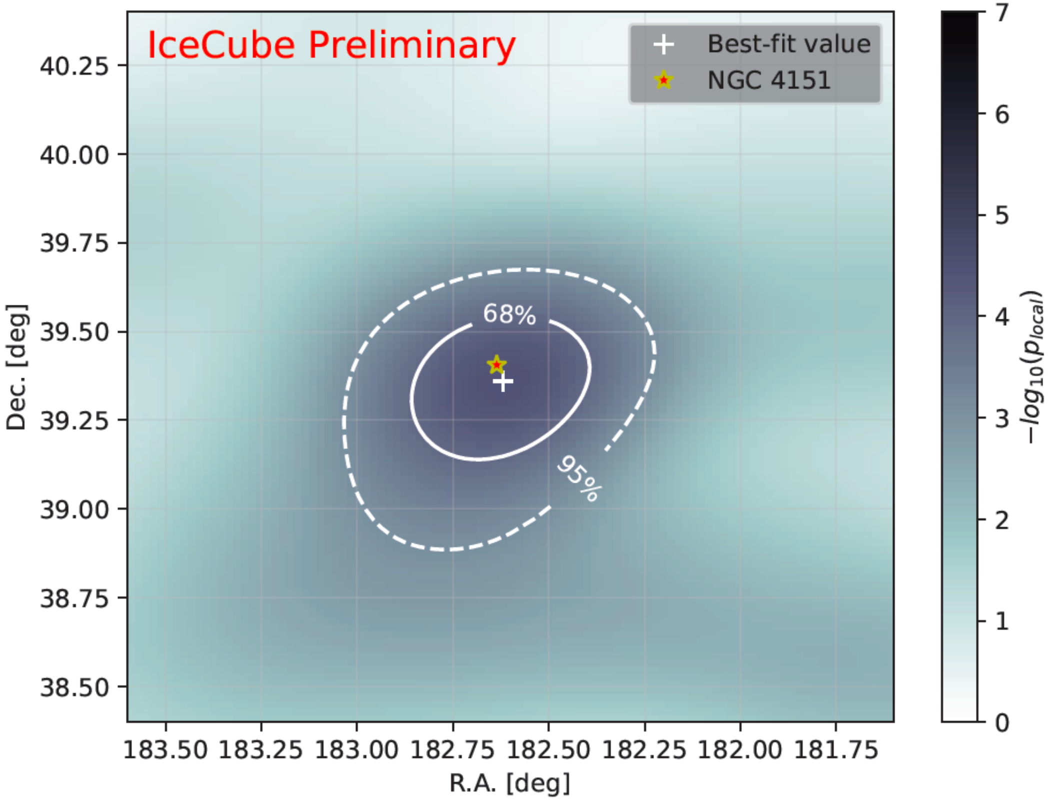
neutrinos originate within $10 \sim 10^2$ Schwarzschild radii from the BH

cosmic neutrino sources
tracking their X-ray flux ?



multimessenger astronomy with X-ray sources





two brightest active galaxies discovered by Seyfert in 1943

NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

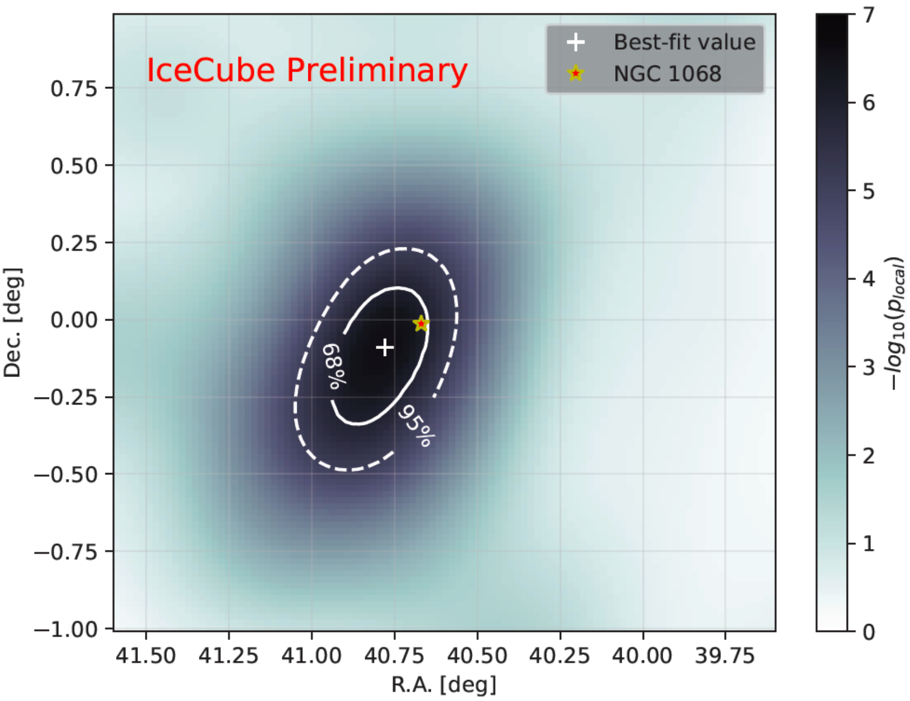
1943

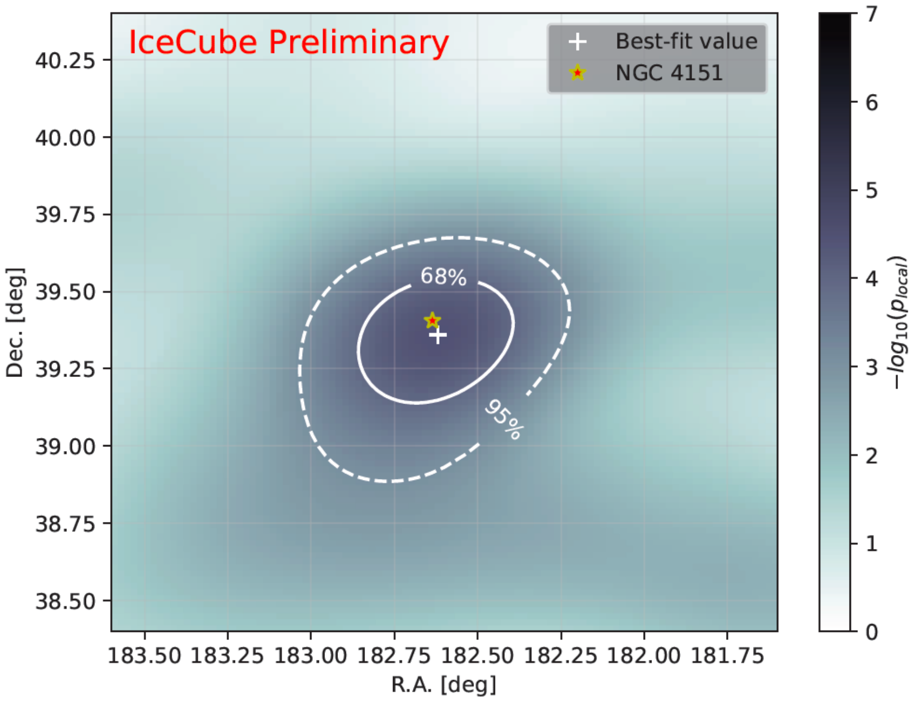
ABSTRACT

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.

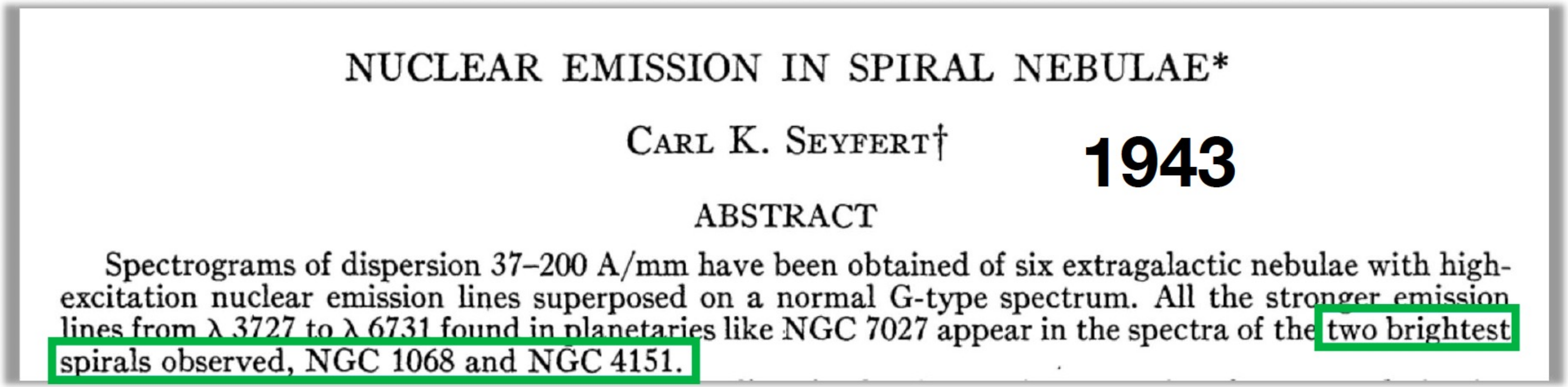
southern hemisphere soon

more sources …





- two brightest active galaxies discovered by Seyfert in 1943



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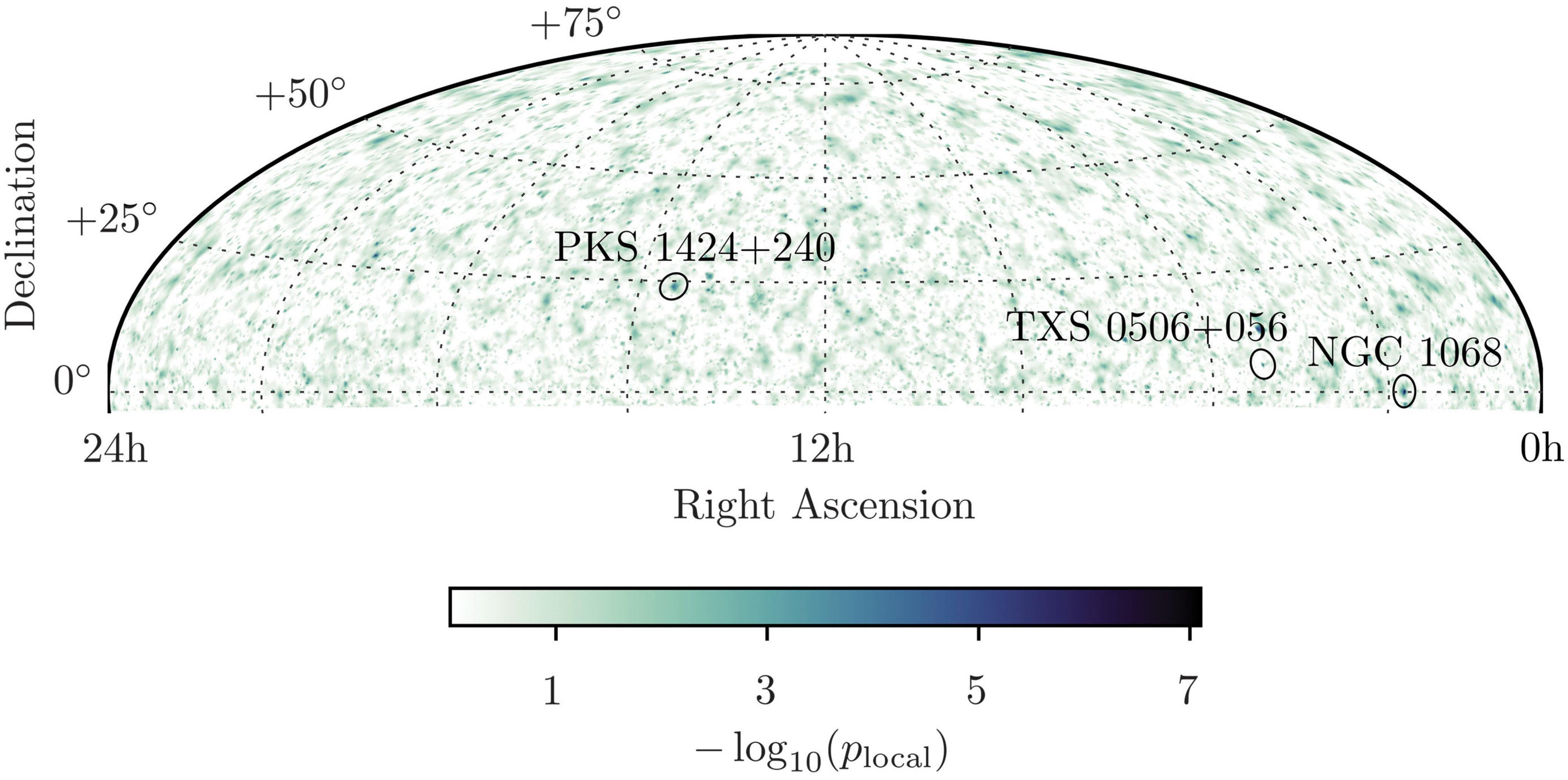
Carl K. Seyfert (VANDERBILT SPECIAL COLLECTIONS AND UNIVERSITY ARCHIVES)

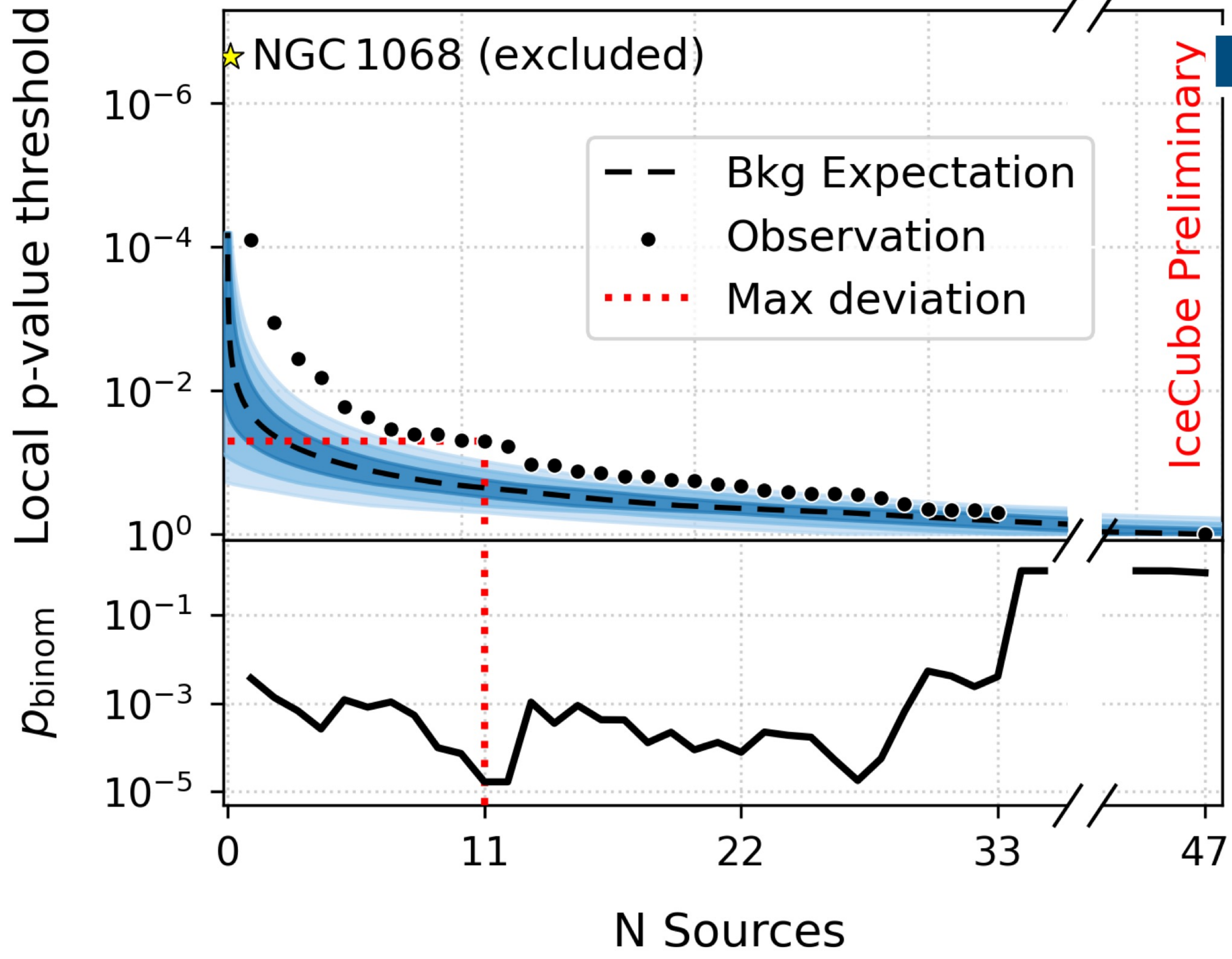
accumulating evidence for X-ray bright active galaxies as neutrino sources

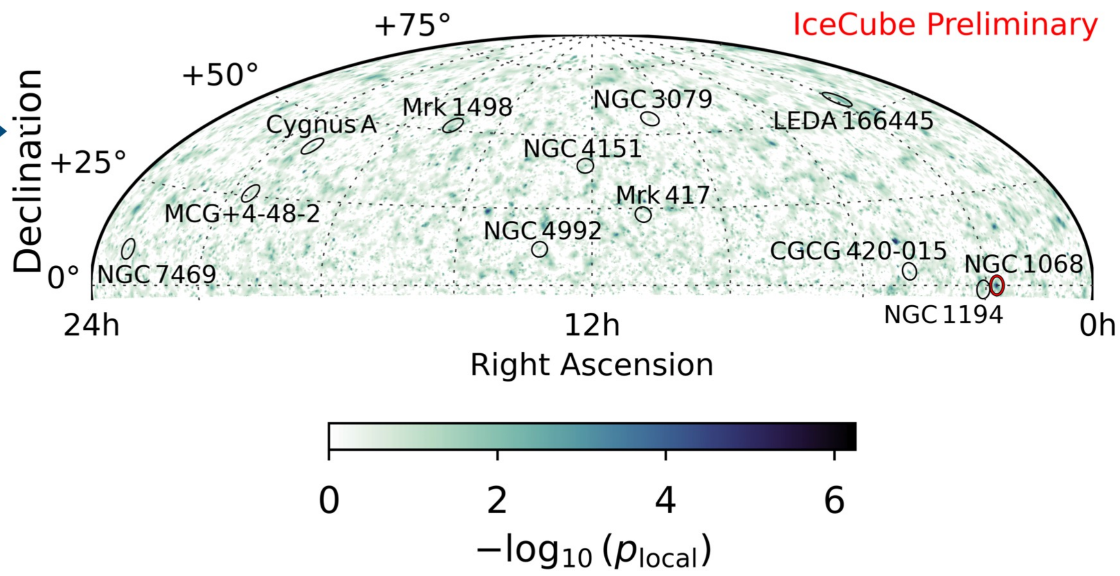
- multimessenger (2017) and IceCube source (2014)
  TXS 0506
- IceCube source
  NGC 1068
- binomial analysis all sky
- NGC 1068+TXS 0506+PKS 1424
  NGC 1068+NGC 4151 + NGC 7469 + CGCG 420 (?) +….
- active galacties with high X-ray flux (Seyferts or not)
  NGC 4151
  CGCG 420 (?)
  NGC 1068+NGC 4151+NGC 3079   IceCube public data (Neronov et al.)
- Galaxy
- Circinus

binomial analysis: 3 active galaxies



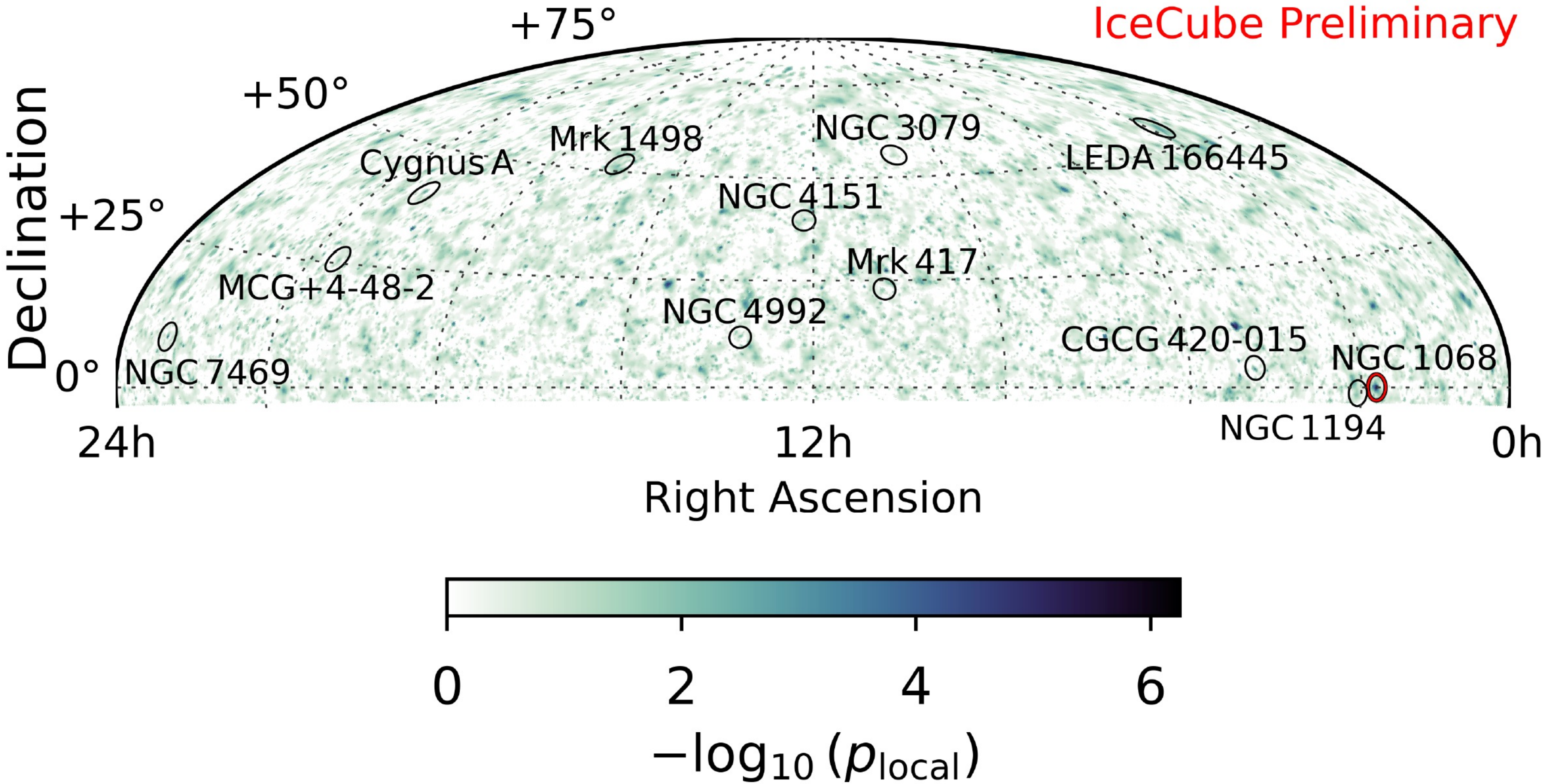
Binomial Test





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

binomial test of X-ray bright Seyfert galaxies



HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

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"}
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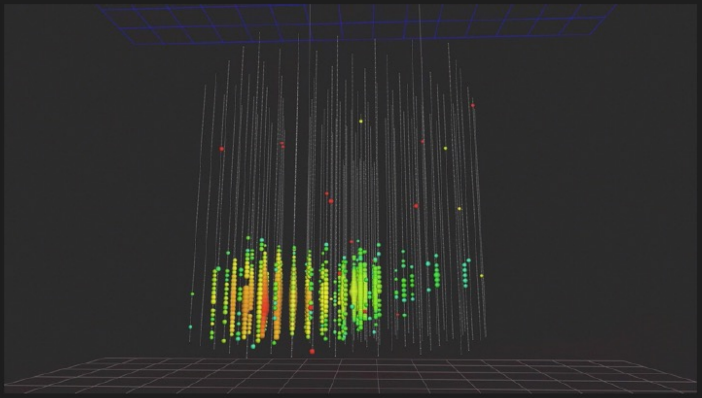
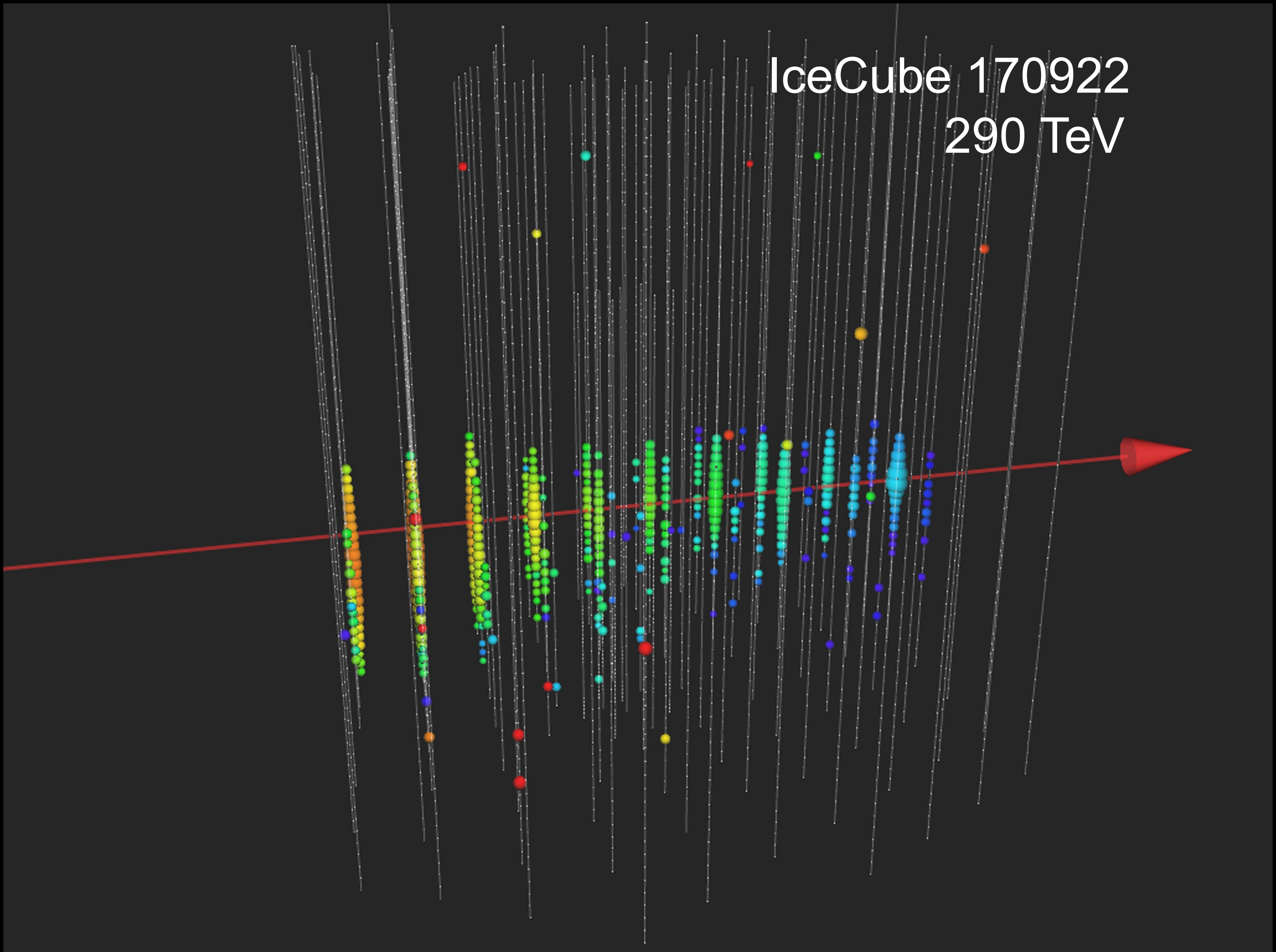
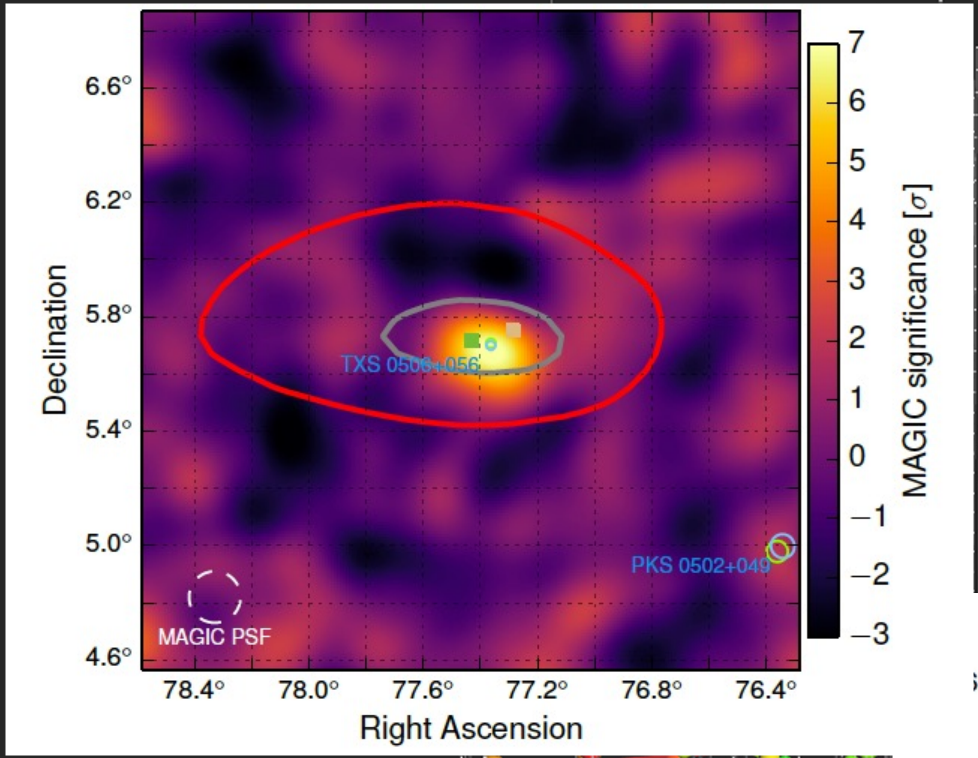
GCN notice for starting track sent Apr 27

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



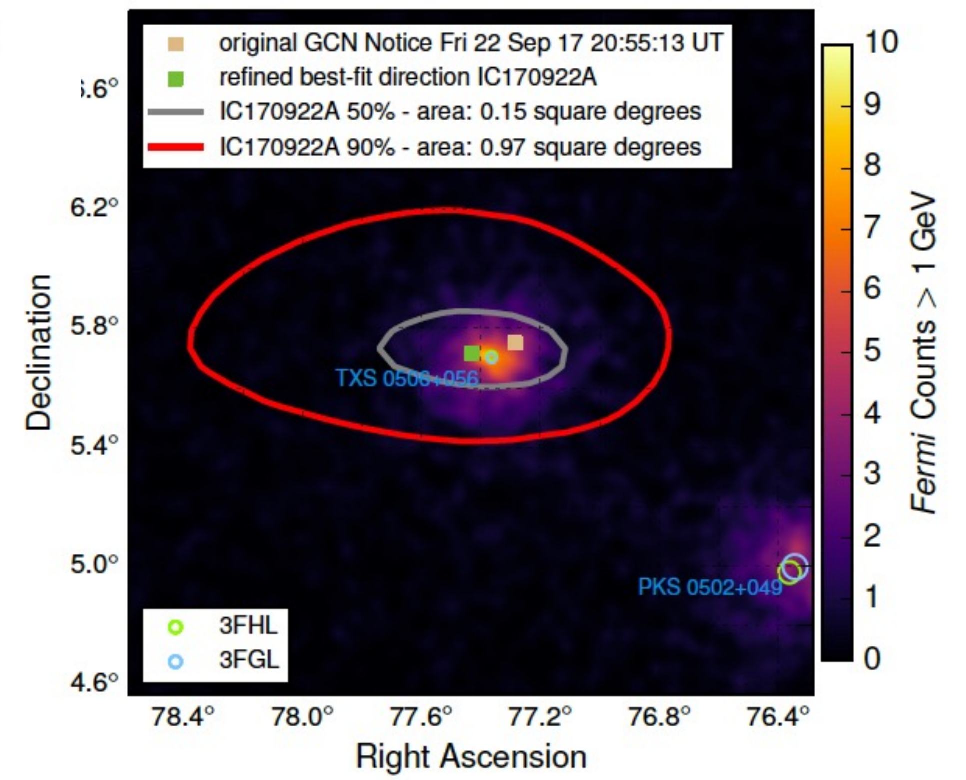

IceCube 170922
290 TeV

IceCube 170922
290 TeV

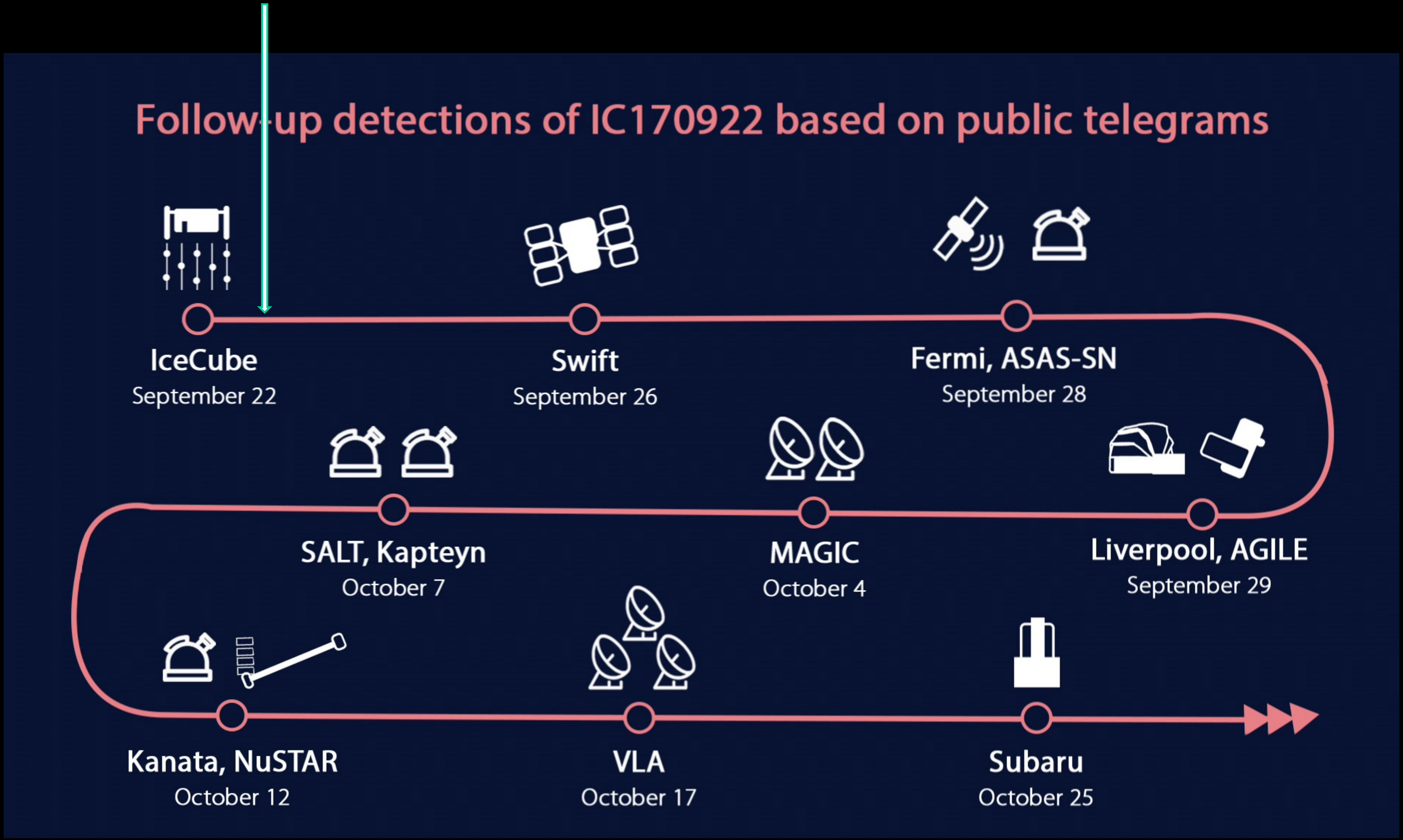


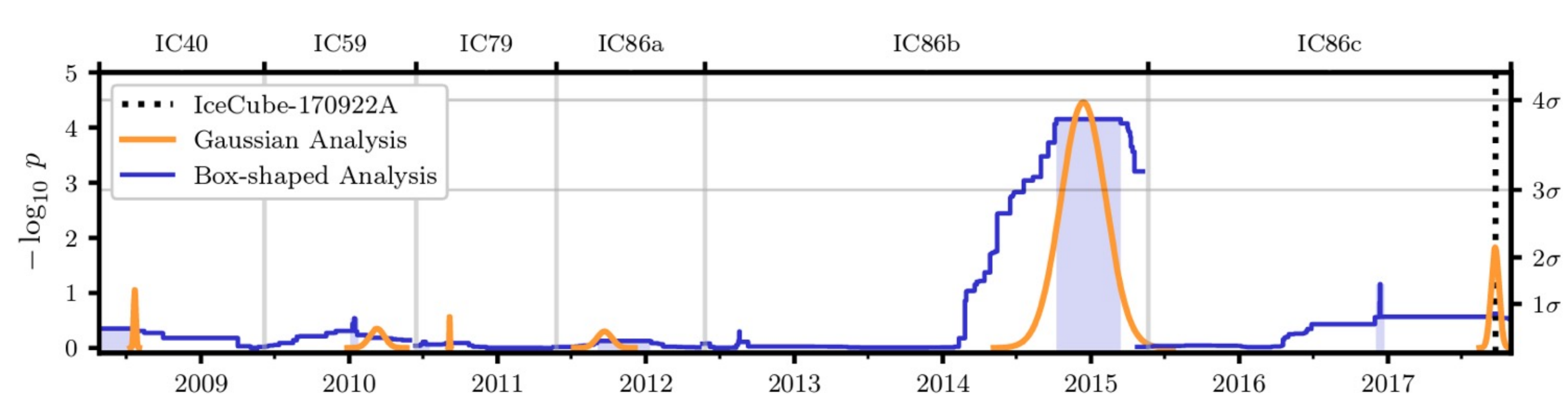
Fermi detects a flaring blazar within 0.06°

MAGIC detects emission of > 100 GeV gammas



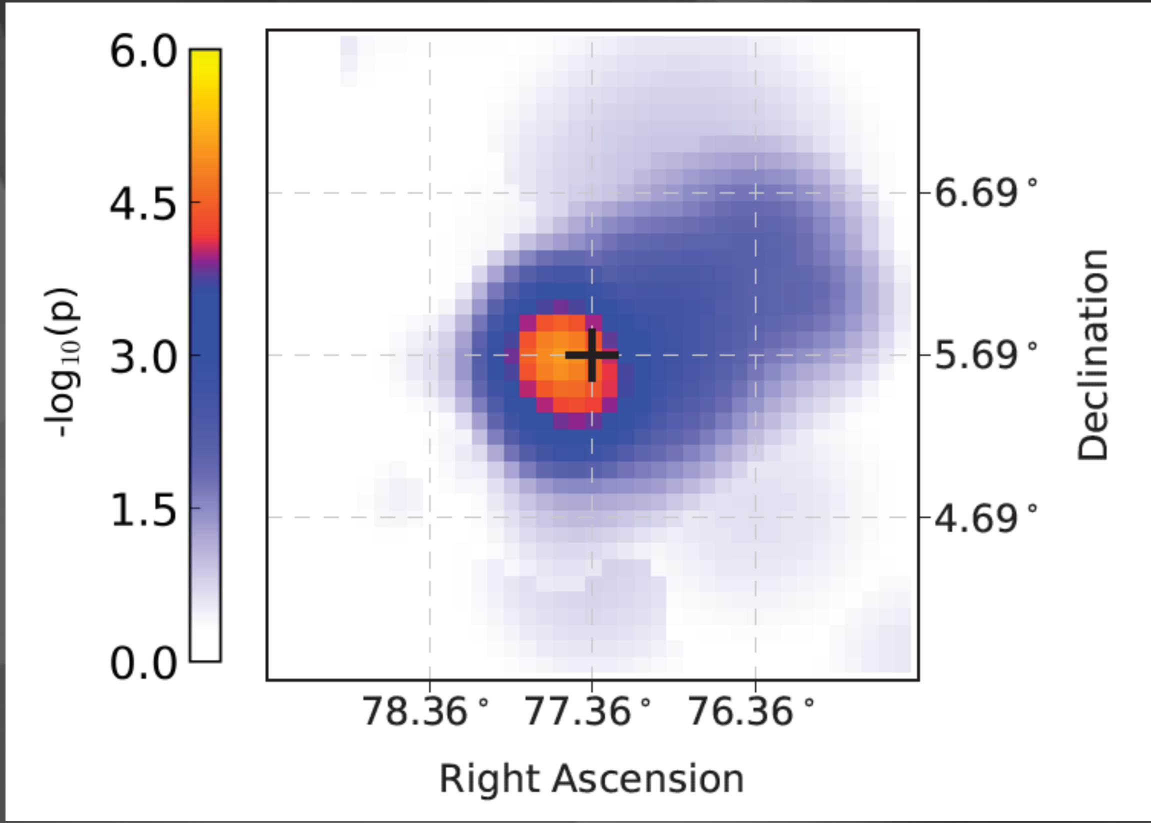
MASTER robotic optical telescope network: after 73 seconds





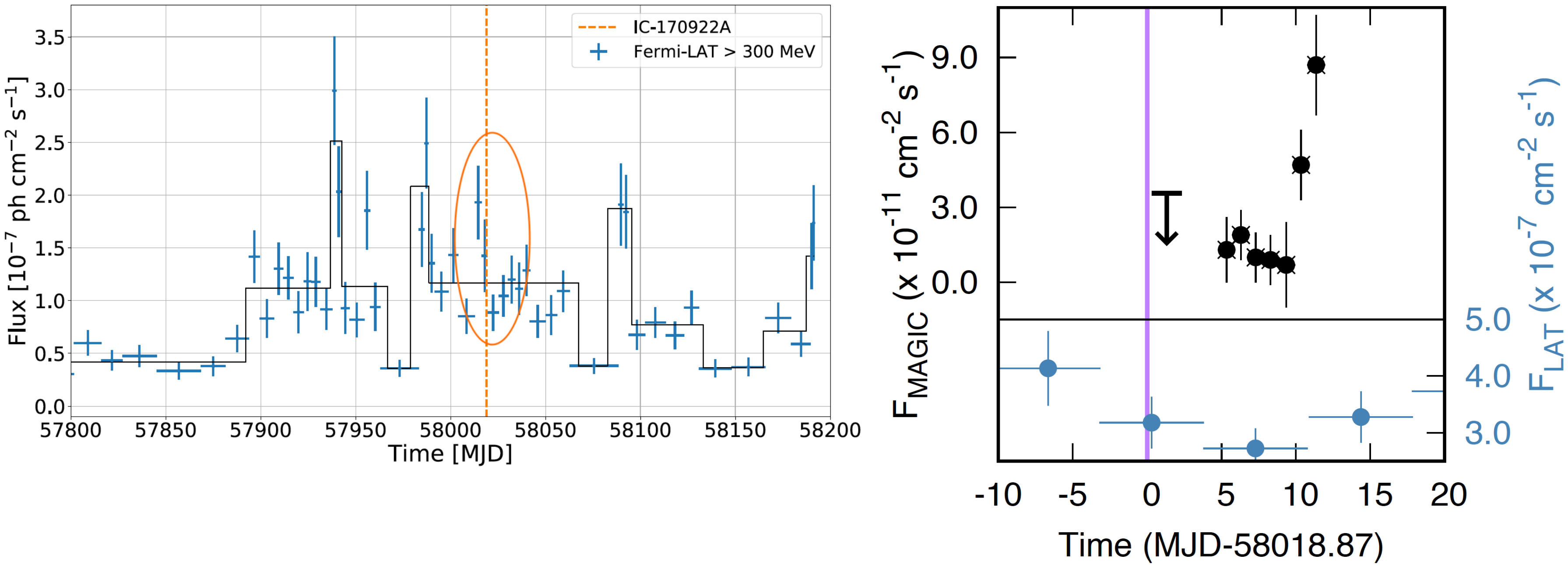
search in archival IceCube data:

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



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

Science
2017

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

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

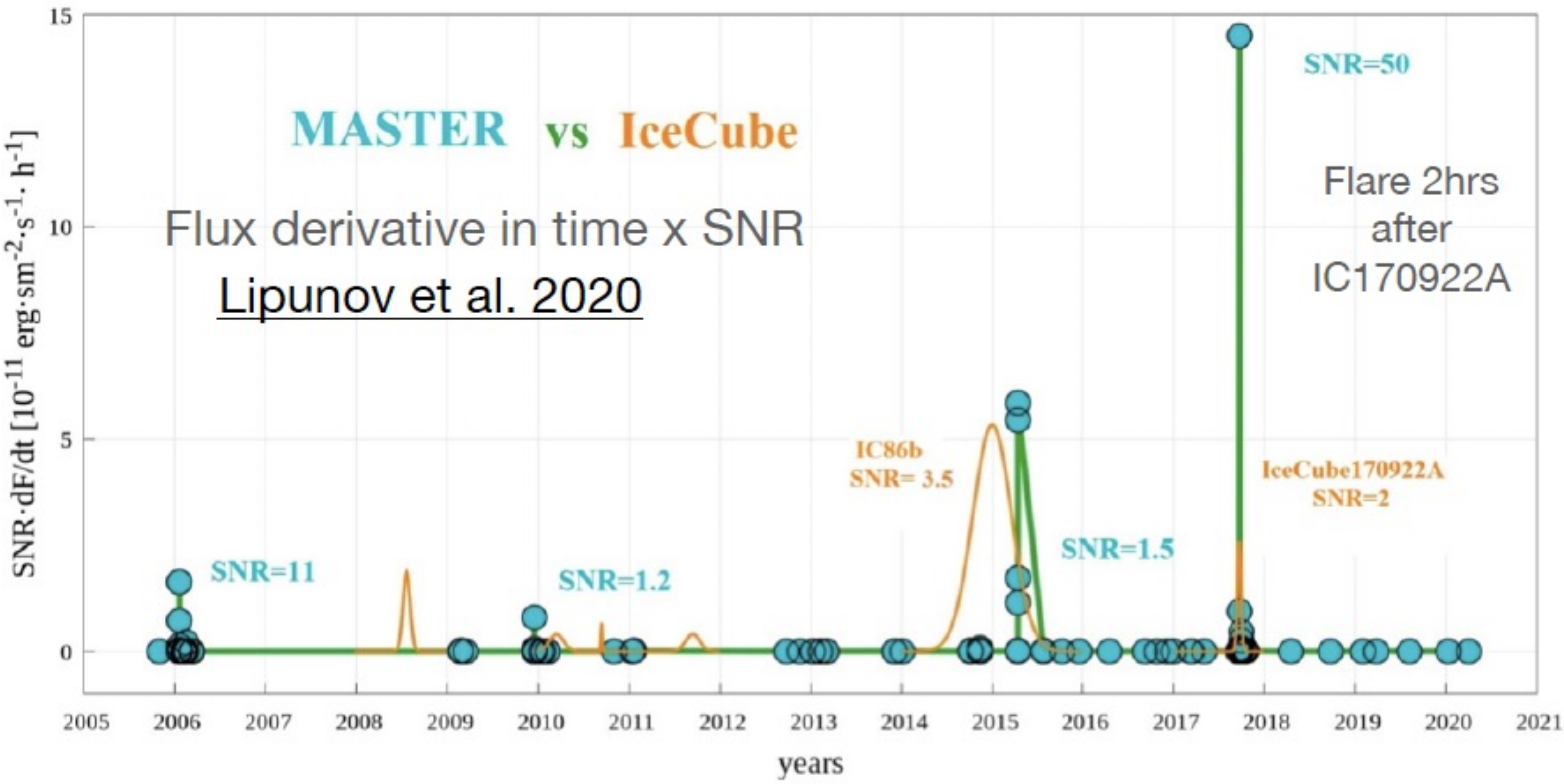
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

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

IceCube Collaboration*†



- 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

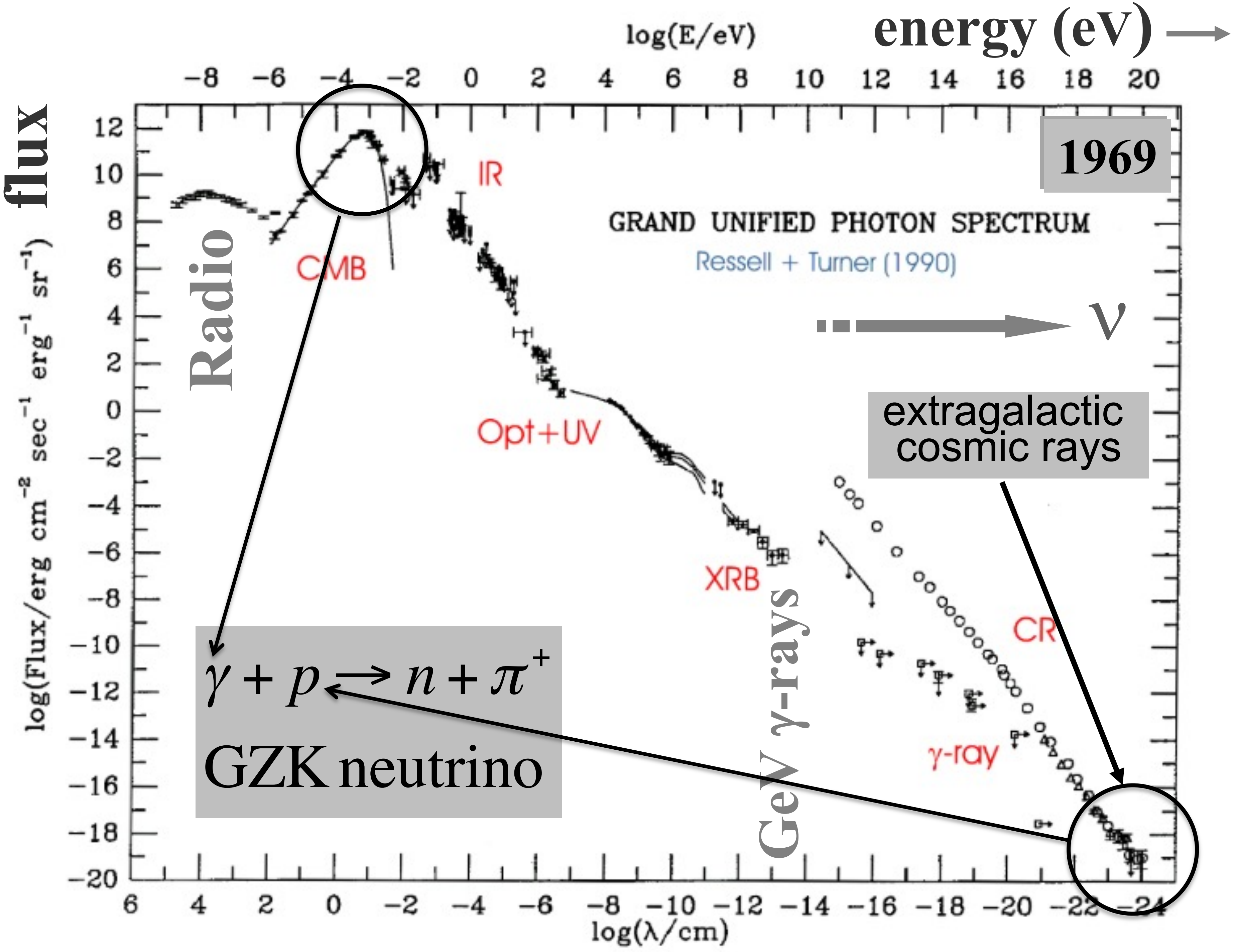
global robotic network of optical telescopes connects TXS 0506+056 to IC170922A in the time domain

"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]

the guaranteed neutrinos ☹



cosmic rays interact with the microwave background

$$p+\gamma \rightarrow n+\pi^{+} \ and \ p+\pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

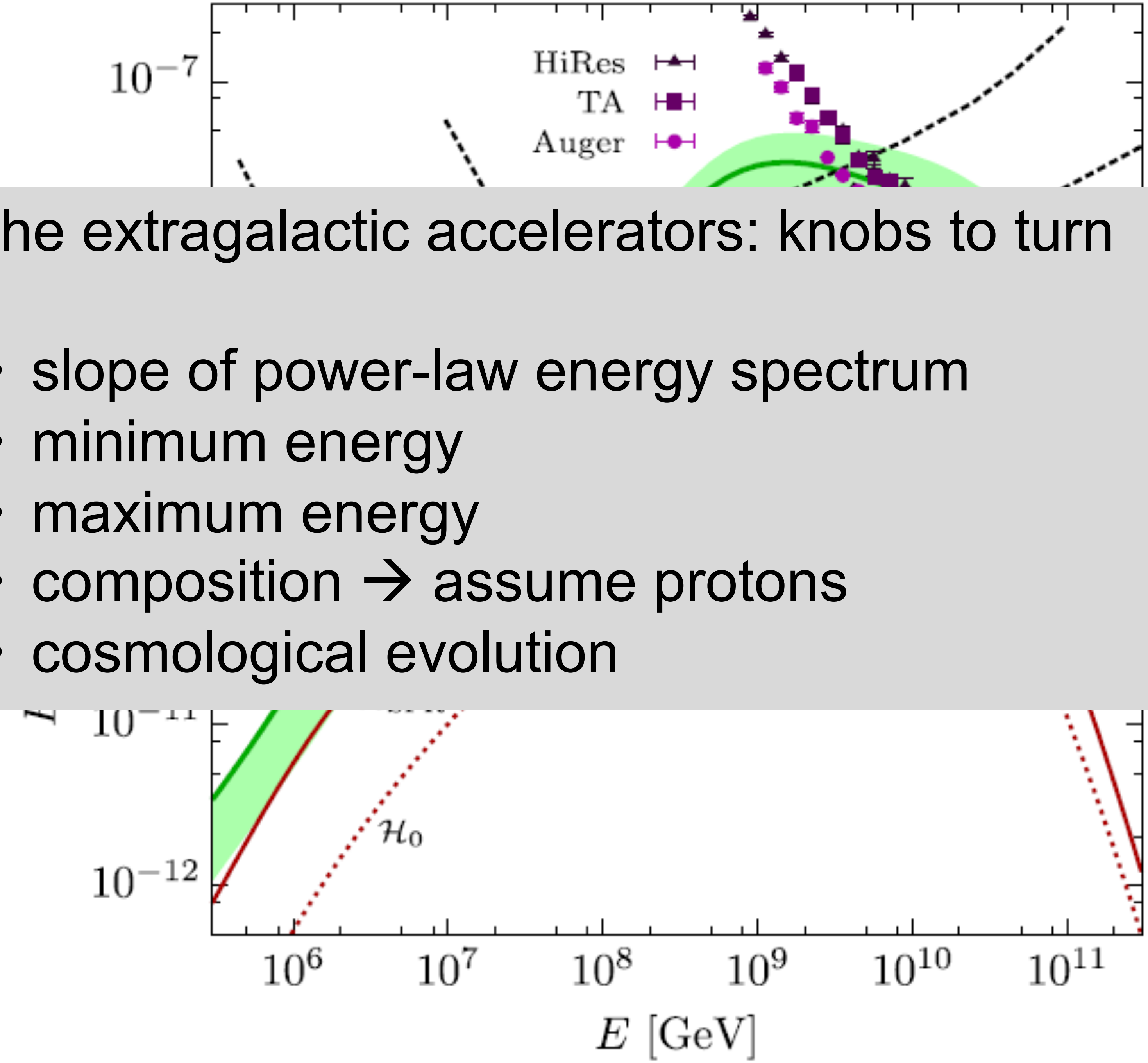
$$\pi \rightarrow \mu+\upsilon_{\mu} \rightarrow \{e+\overline{\upsilon_{\mu}}+\upsilon_{e}\}+\upsilon_{\mu}$$

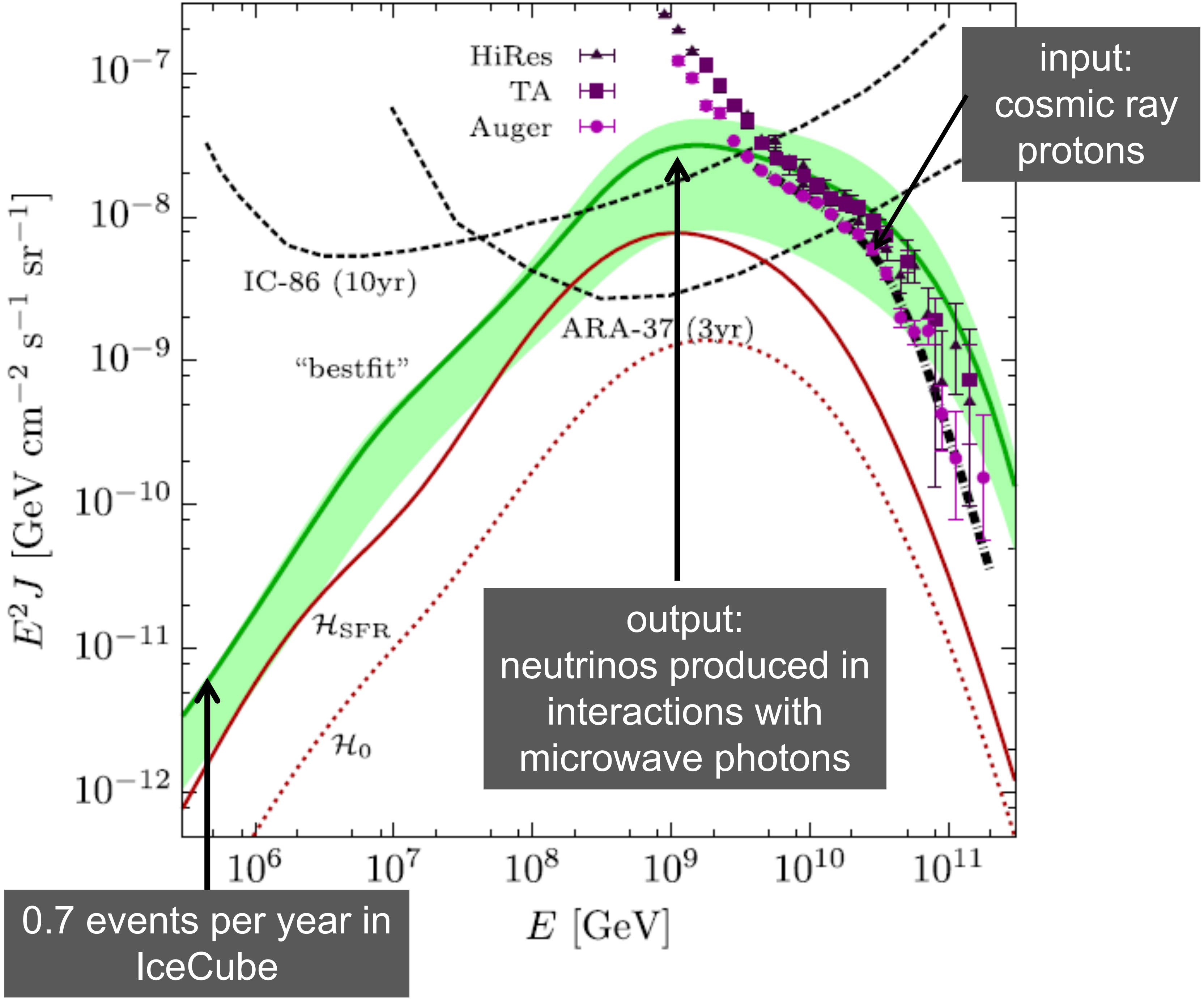
1 event per cubic kilometer per year

...but it points at its source!

the extragalactic accelerators: knobs to turn

- slope of power-law energy spectrum
- minimum energy
- maximum energy
- composition → assume protons
- cosmological evolution





HiRes
TA
Auger
input: cosmic ray protons
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{\rm SFR}$
$\mathcal{H}_0$
output: neutrinos produced in interactions with microwave photons
0.7 events per year in IceCube
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]

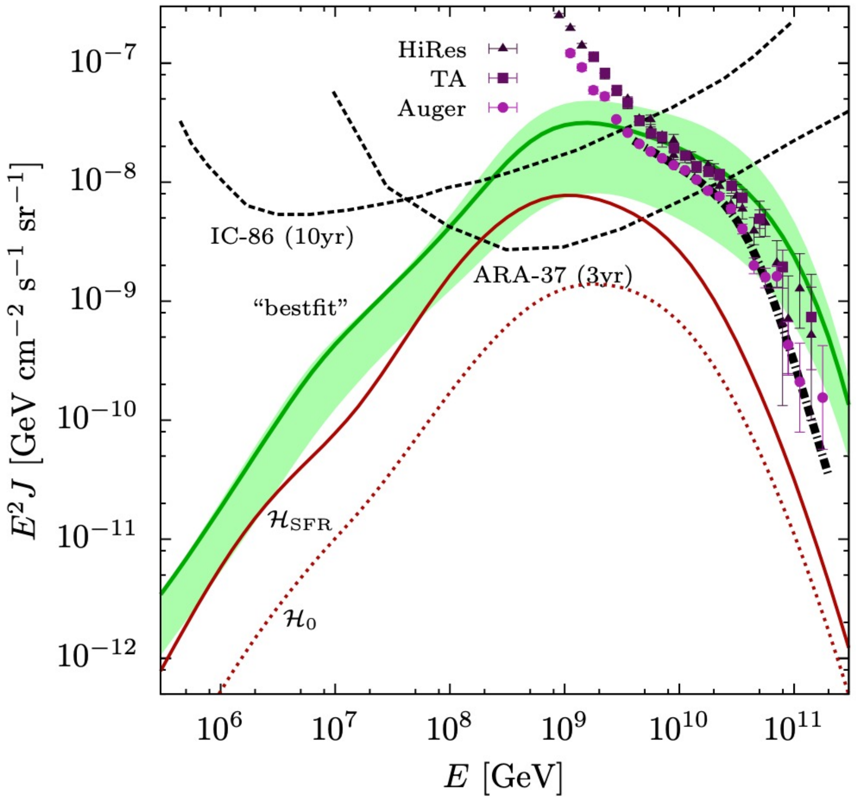
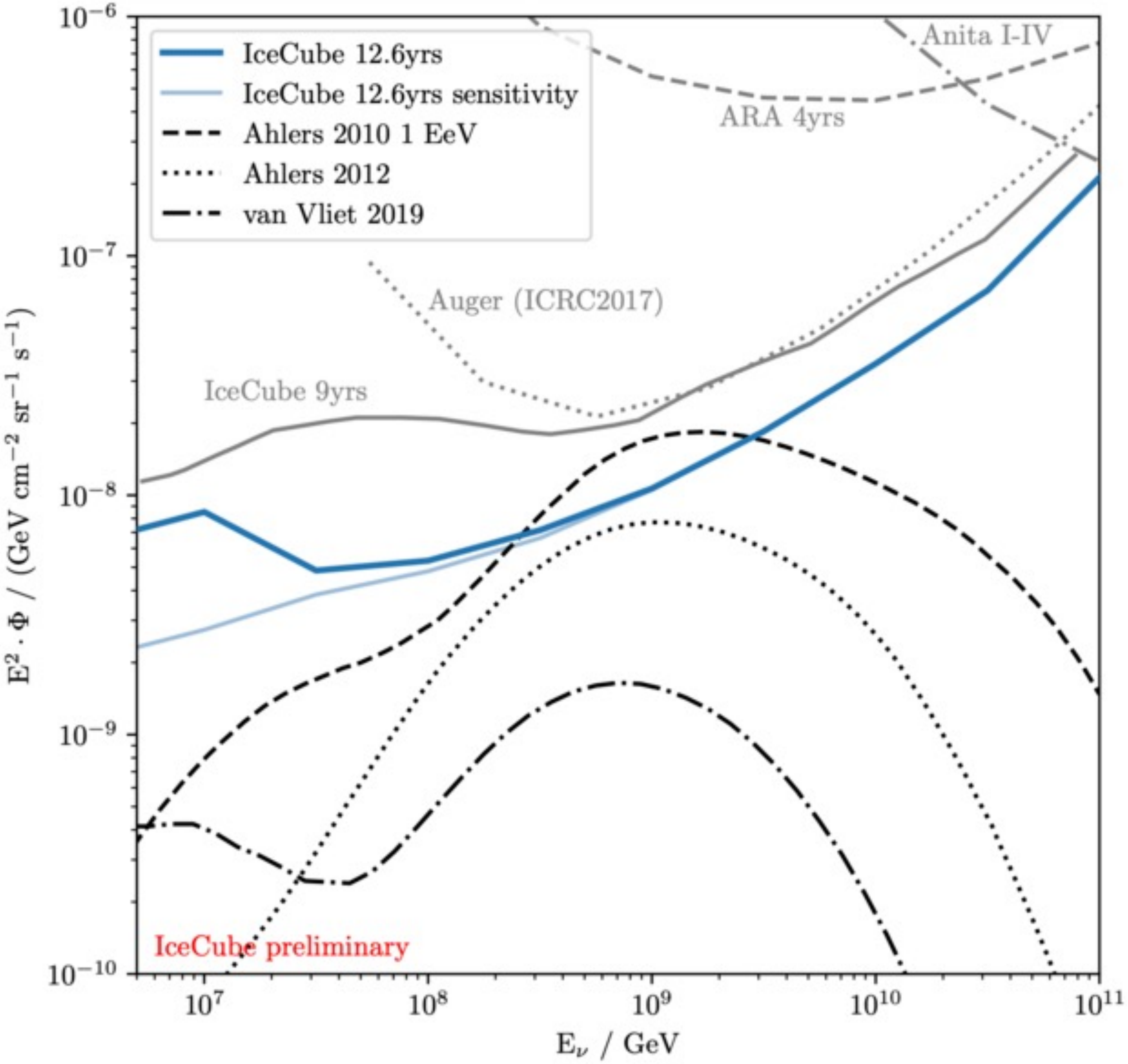
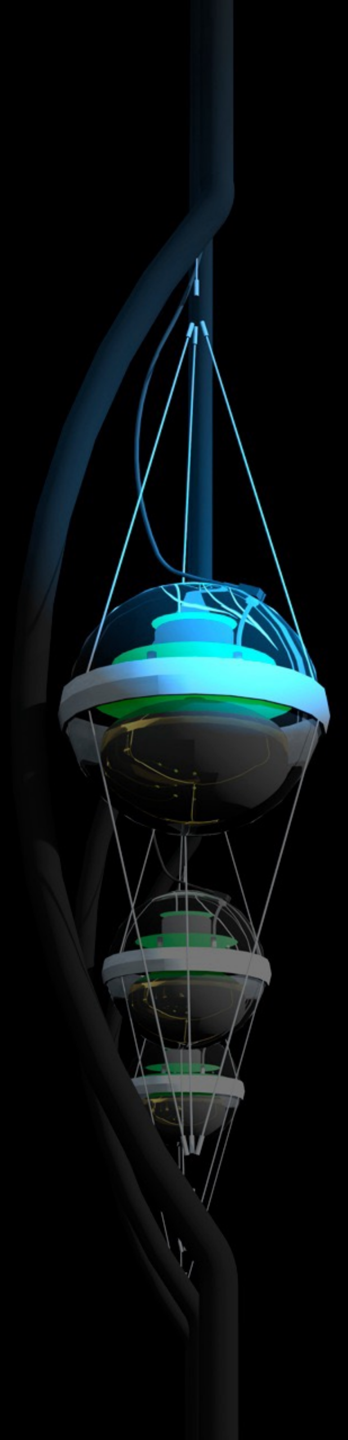


FIG. 1: Minimal flux of cosmogenic neutrinos assuming dominance of protons above 4 EeV. We show the results without source evolution (dotted) and assuming source evolution according to the star formation rate (solid). Also shown are the projected sensitivities of IceCube (10 years) and the ARA-37 (3 years) as dashed lines. The thick dashed-dotted line shows the approximation of the Auger spectrum above the ankle. For comparison, we also show the bestfit cosmogenic neutrino flux (green solid line) from Ref. [24] ($E_{\min} = 10^{18.5}$ eV) including the 99% C.L. (green shaded area) obtained by a fit to the HiRes spectrum.





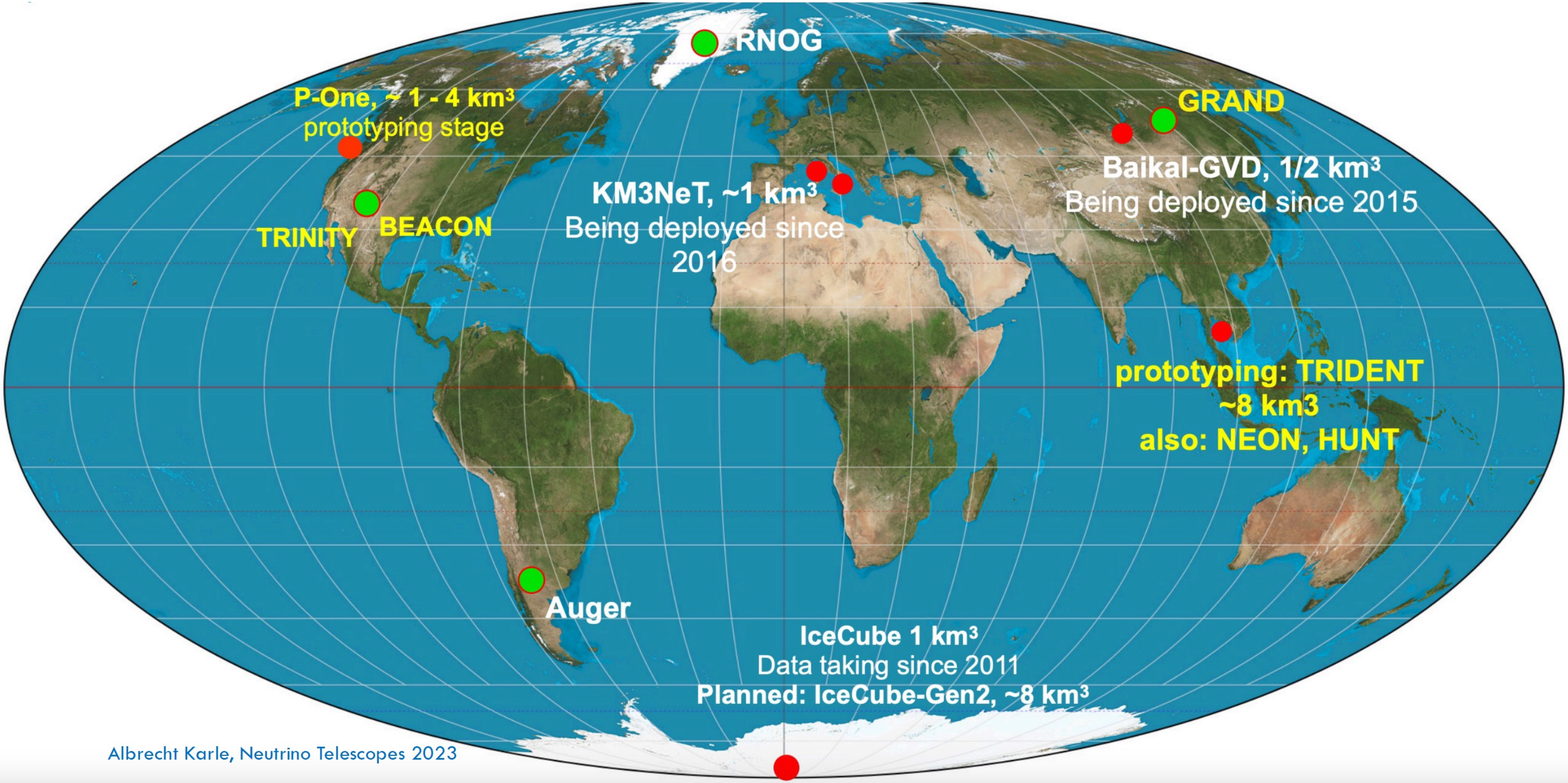
neutrino astronomy 2024

- it exists

- more neutrinos, better neutrinos, more telescopes

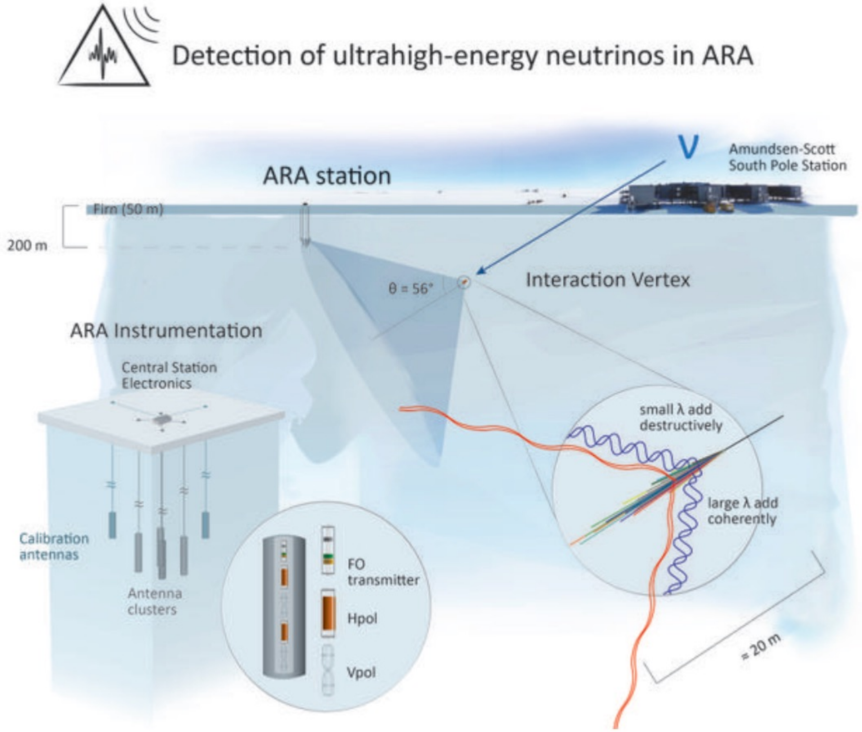
- closing in on cosmic ray sources a century after their discovery

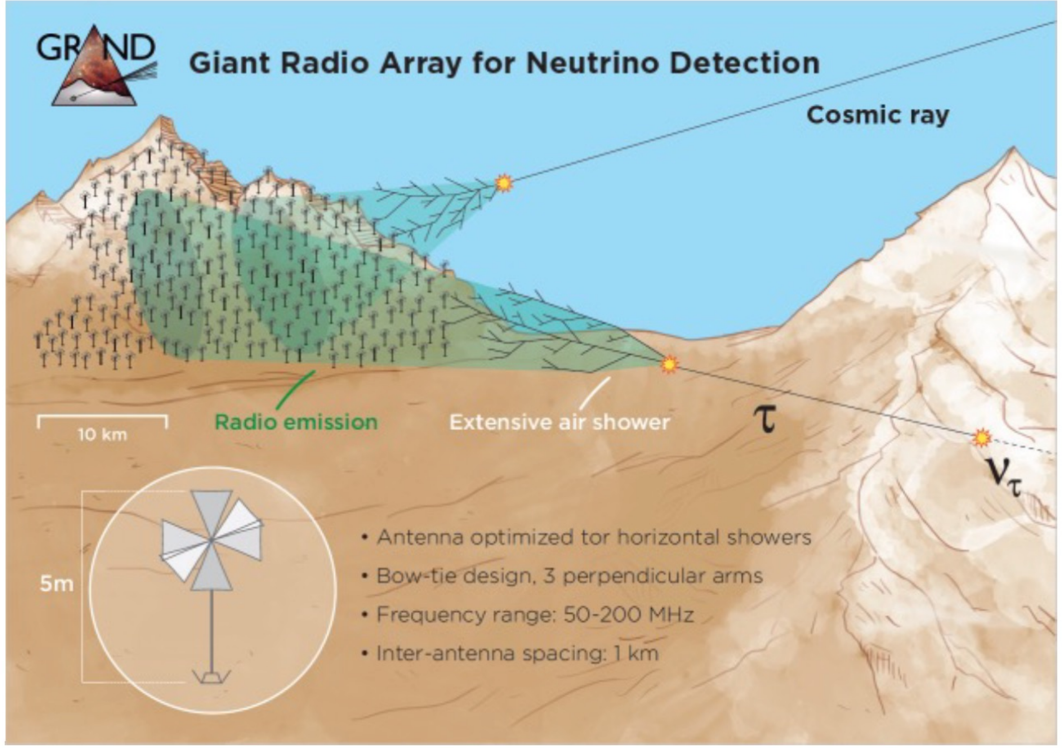
icecube.wisc.edu

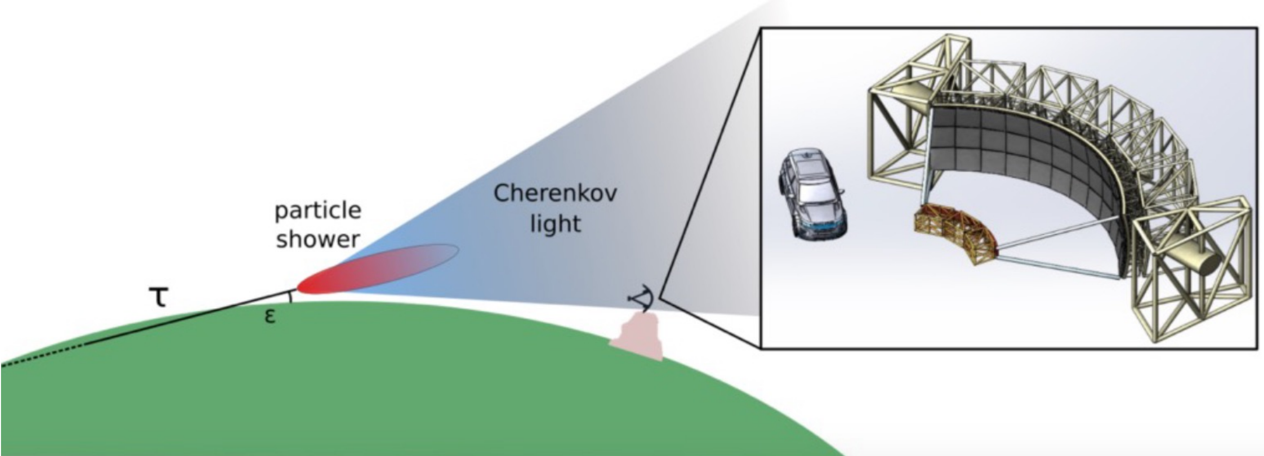


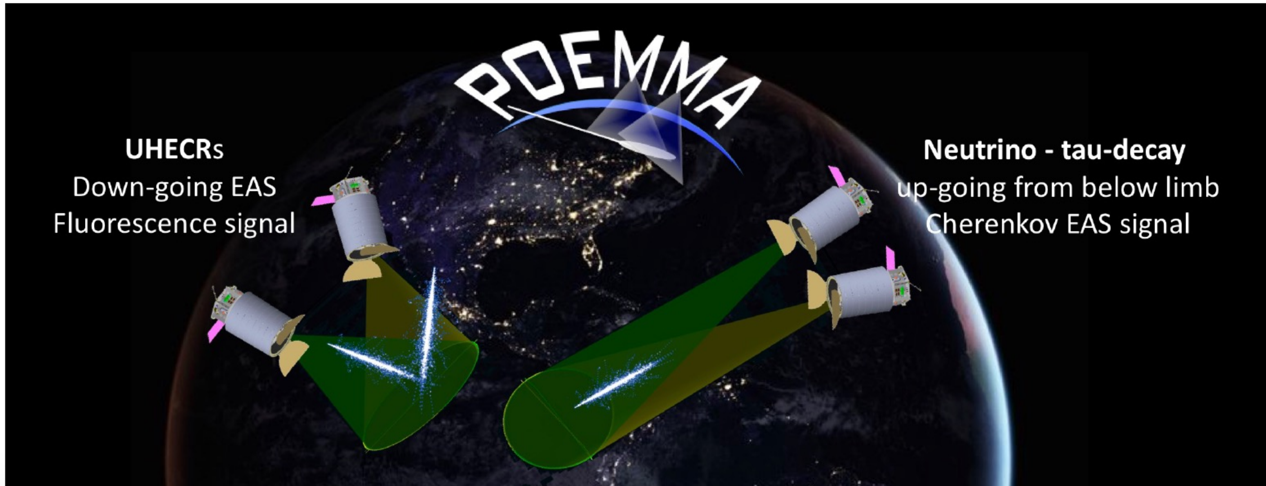
Albrecht Karle, Neutrino Telescopes 2023

Ultra-high energy neutrinos

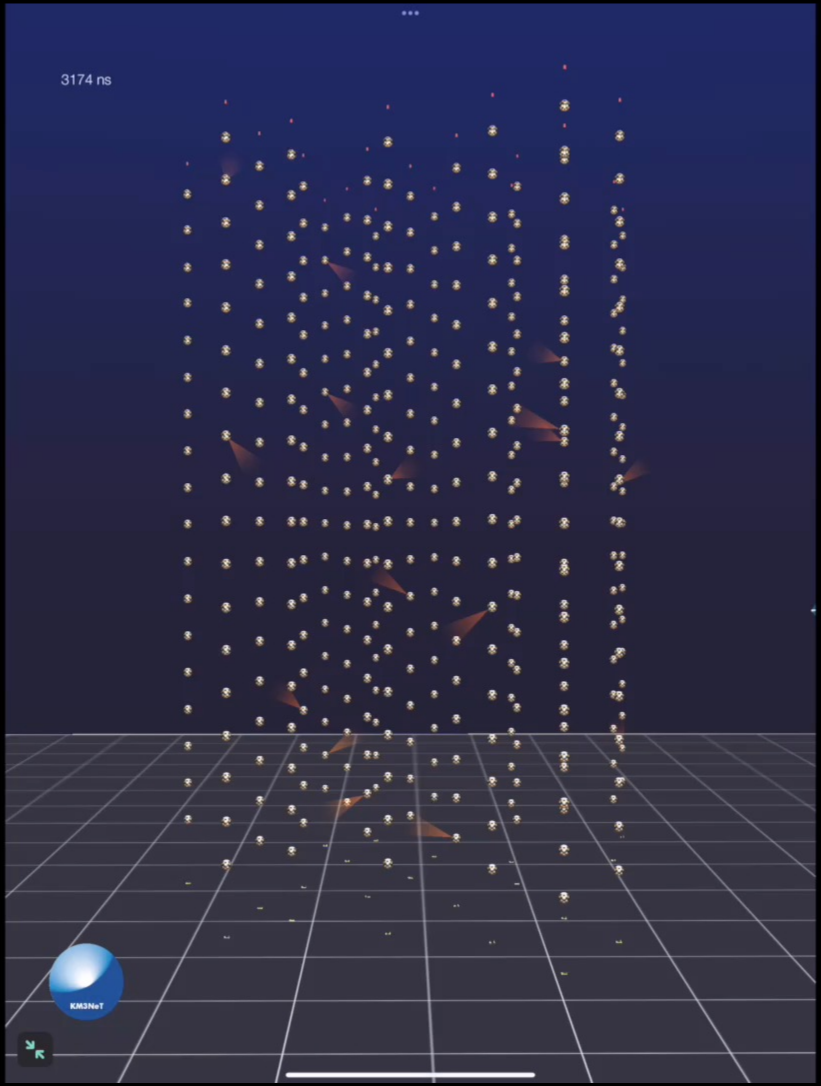


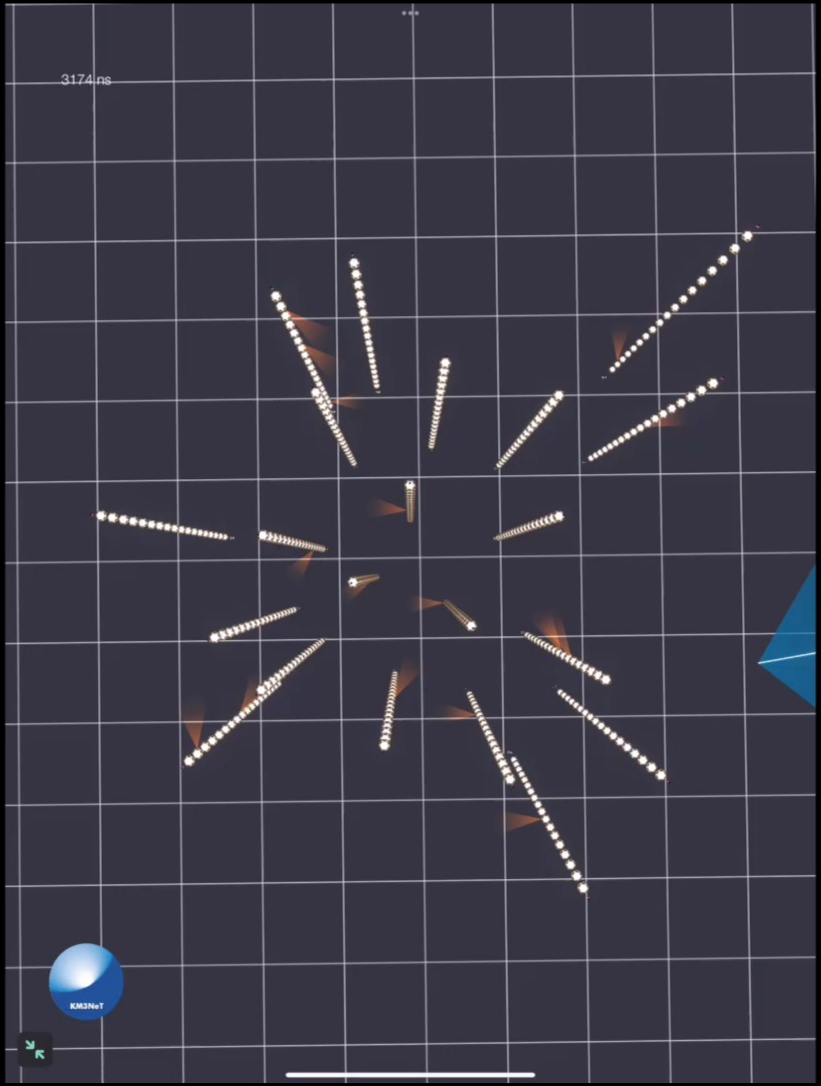






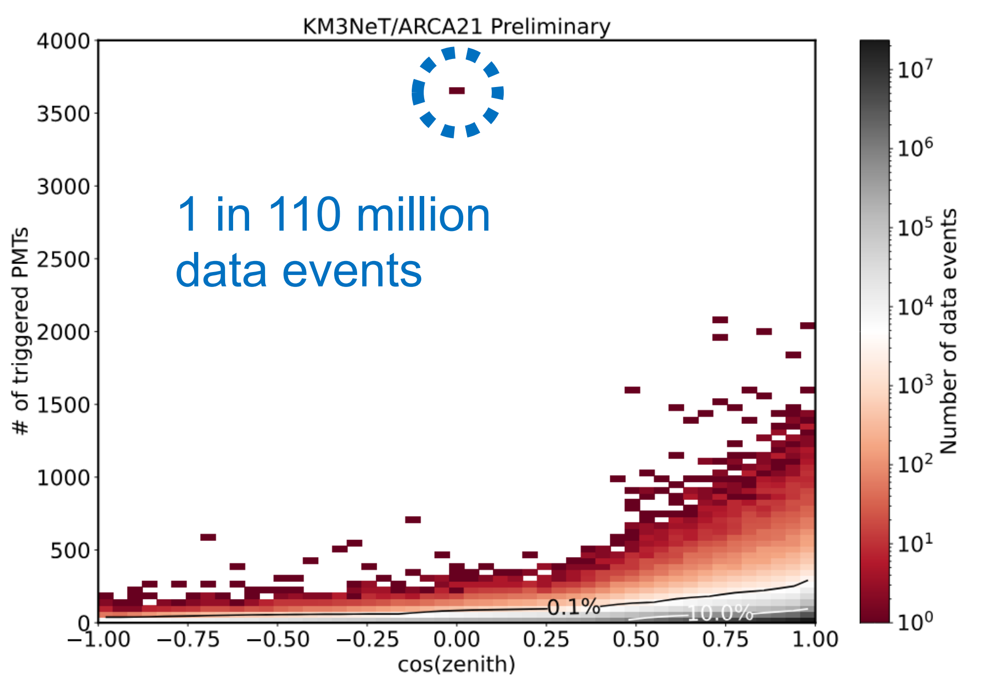
Uncharted Territory

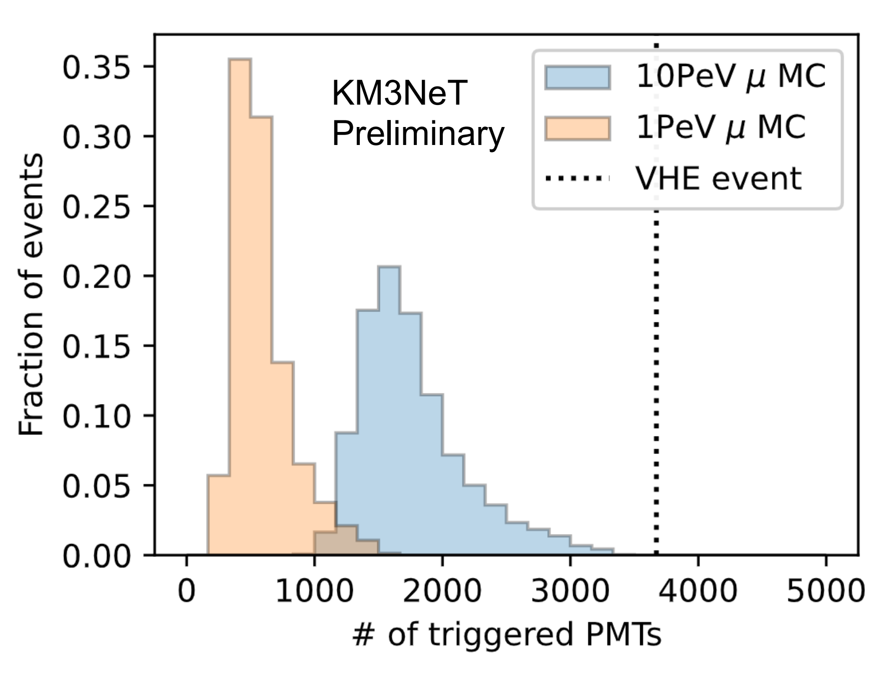




Uncharted Territory

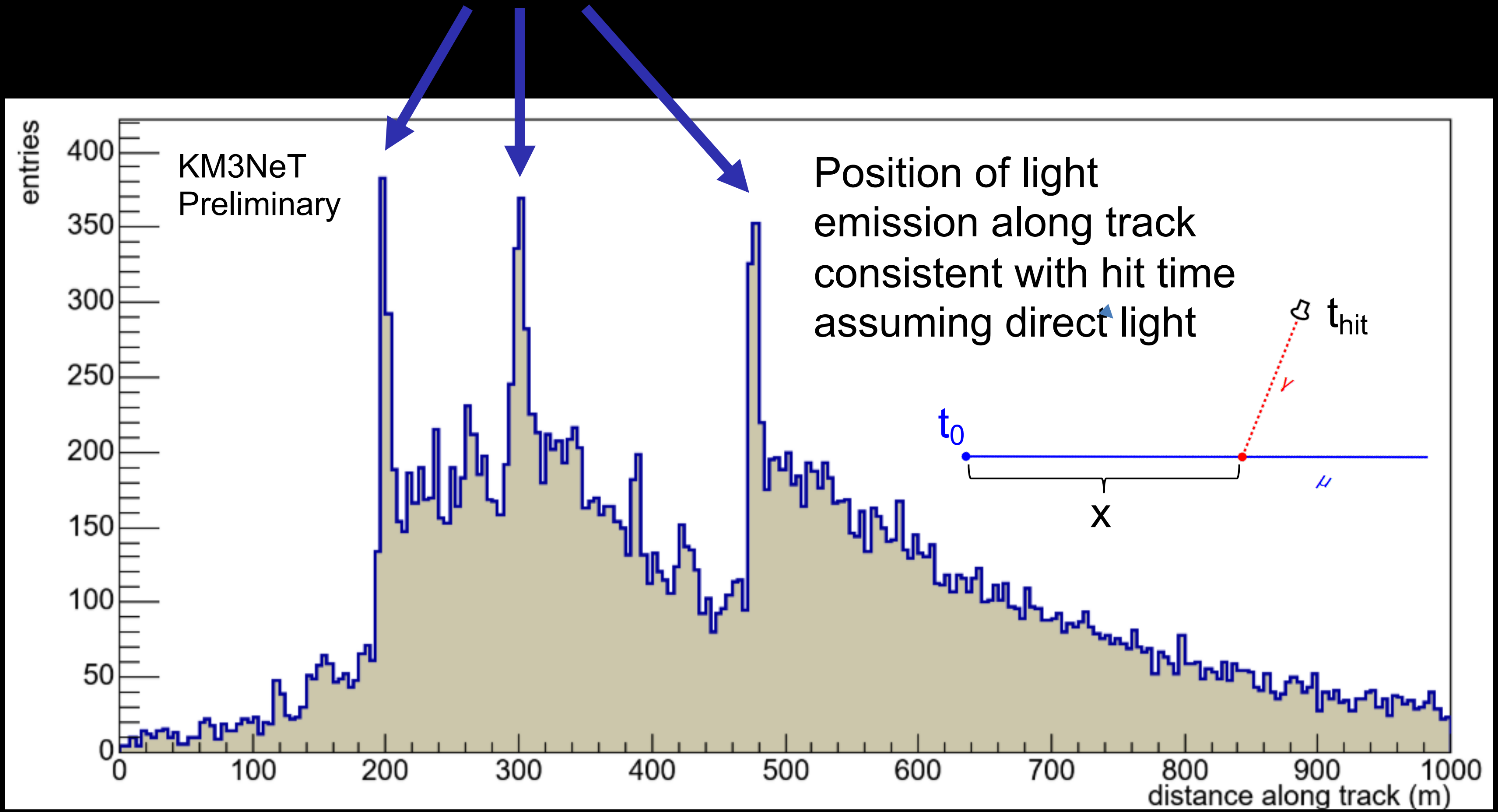
- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV





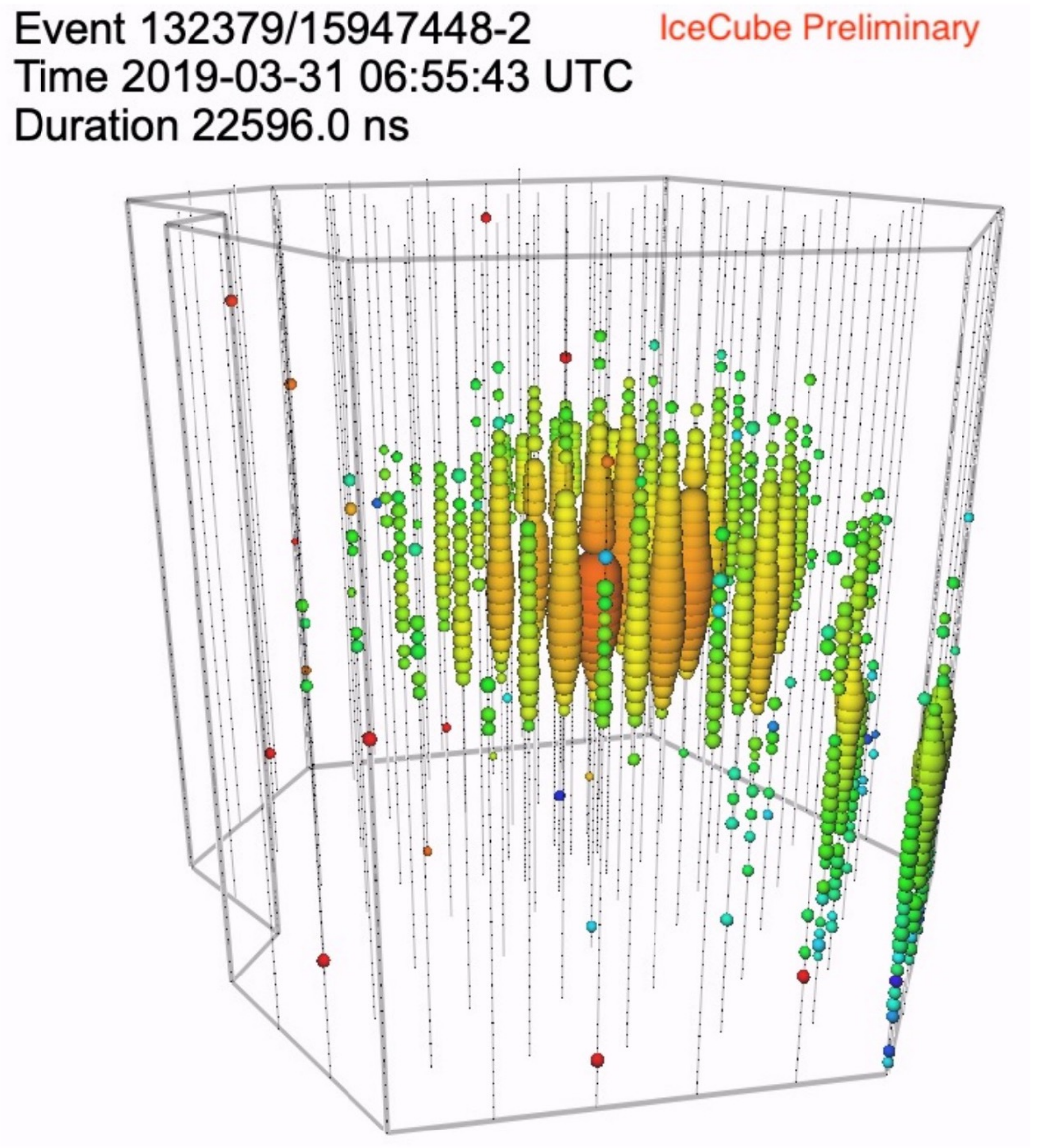
Uncharted Territory

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



THE HIGHEST ENERGY NEUTRINO

- Muon neutrino with contained vertex position
- Deposited energy 4.8 PeV
- dE/dx ~ 1.125 TeV/m over last 400m
- Resimulation: **neutrino energy 11.4 +-2.5 PeV**



THE ICECUBE COLLABORATION

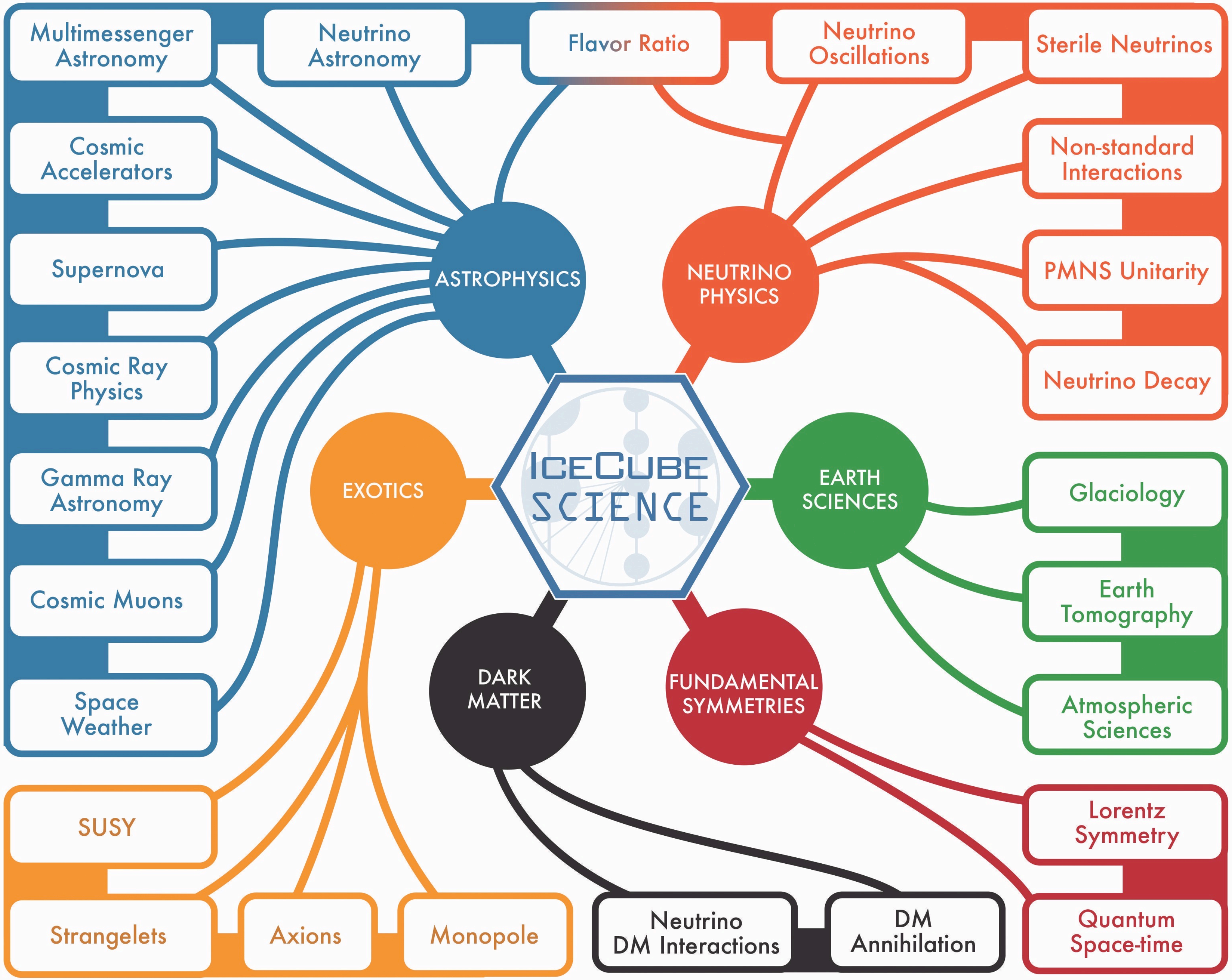
RALIA 1

1

TED KINGDOM 1

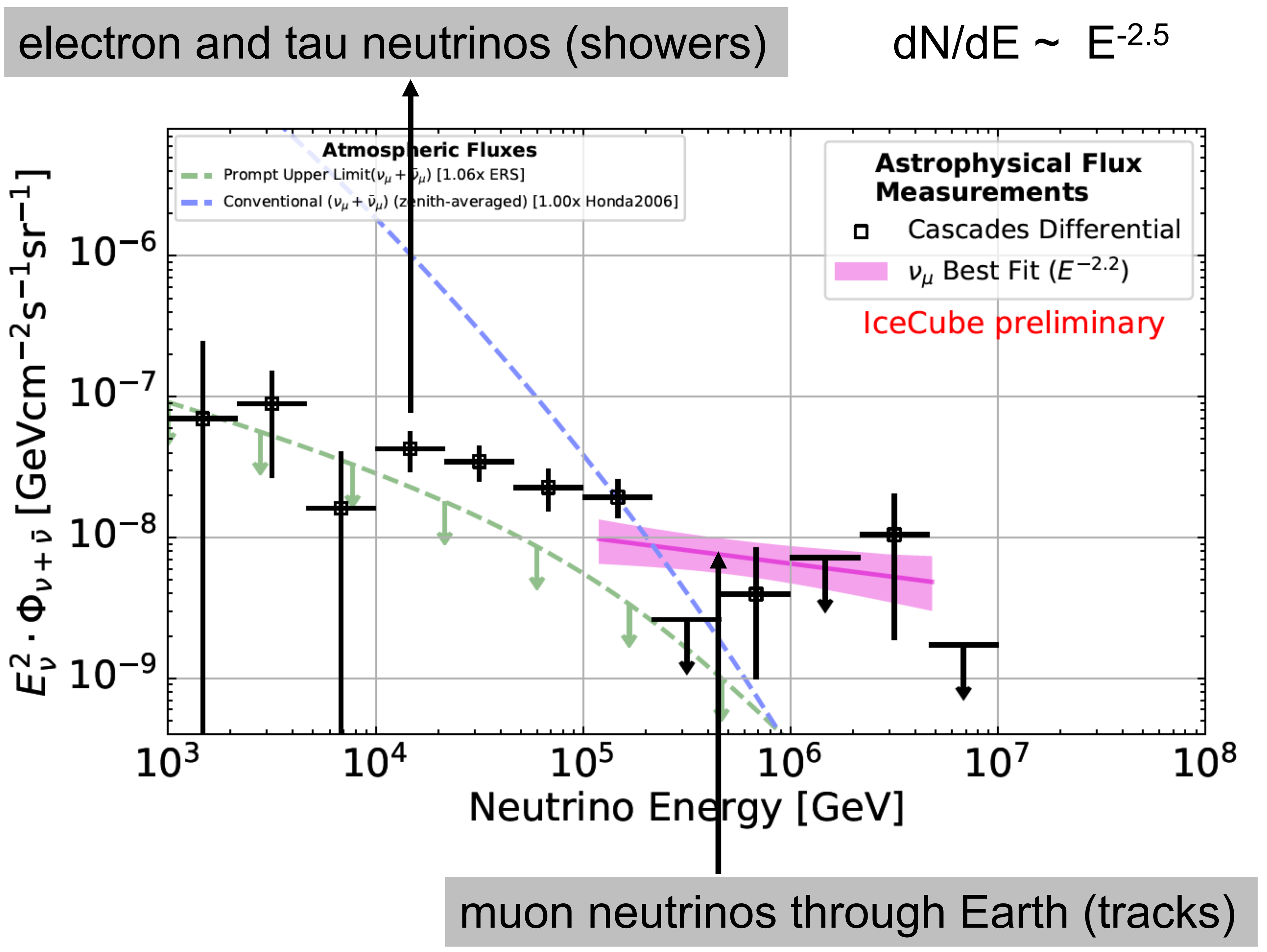
UNITED STATES 25

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



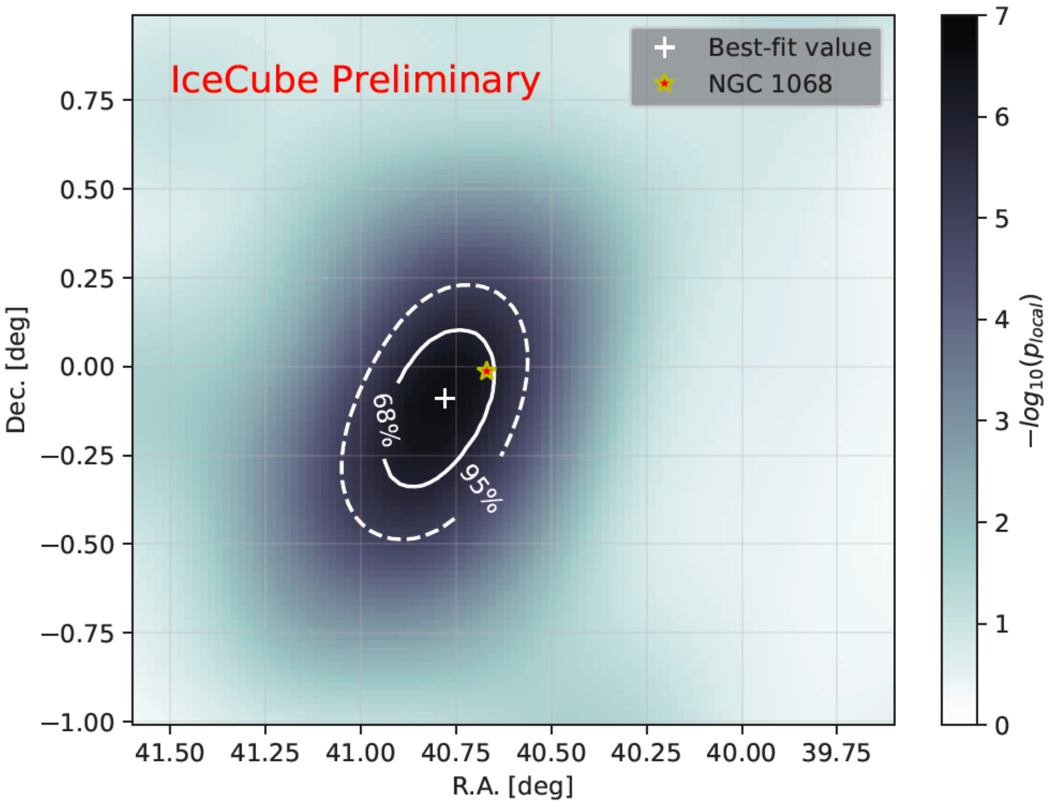
ICECUBE SCIENCE
ASTROPHYSICS
Multimessenger Astronomy
Neutrino Astronomy
Flavor Ratio
Cosmic Accelerators
Supernova
Cosmic Ray Physics
Gamma Ray Astronomy
Cosmic Muons
Space Weather
NEUTRINO PHYSICS
Neutrino Oscillations
Sterile Neutrinos
Non-standard Interactions
PMNS Unitarity
Neutrino Decay
EARTH SCIENCES
Glaciology
Earth Tomography
Atmospheric Sciences
FUNDAMENTAL SYMMETRIES
Lorentz Symmetry
Quantum Space-time
DARK MATTER
Neutrino DM Interactions
DM Annihilation
EXOTICS
SUSY
Strangelets
Axions
Monopole

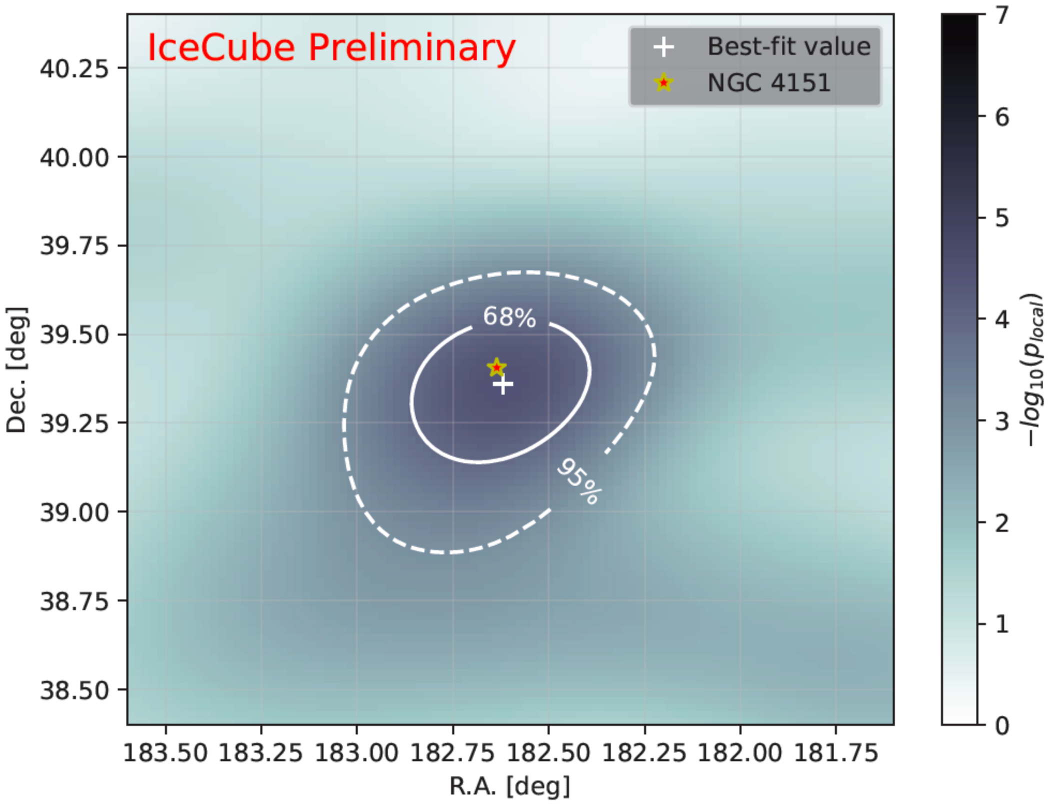
overflow sides



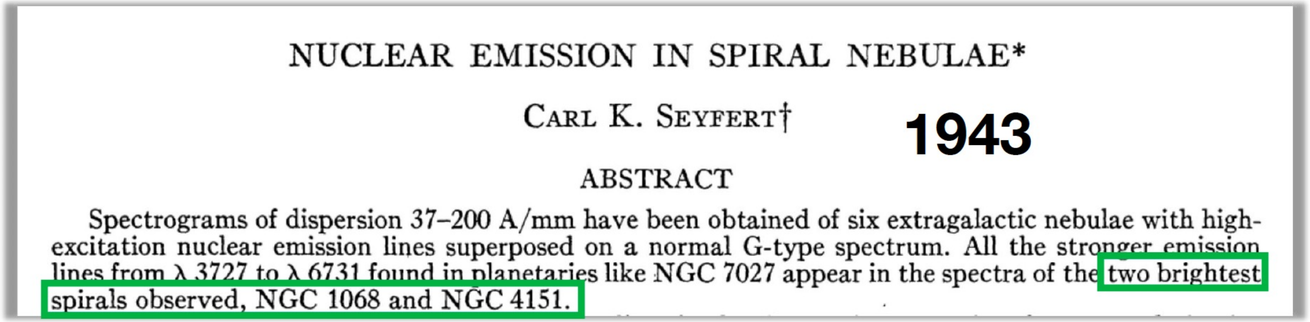
electron and tau neutrinos (showers)
dN/dE ~ E-2.5
Atmospheric Fluxes
Prompt Upper Limit(νμ + ν̄μ) [1.06x ERS]
Conventional (νμ + ν̄μ) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
νμ Best Fit (E−2.2)
IceCube preliminary
10−6
10−7
10−8
10−9
103
104
105
106
107
108
Neutrino Energy [GeV]
muon neutrinos through Earth (tracks)

multimessenger astronomy with X-ray sources





two brightest active galaxies discovered by Seyfert in 1943



NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

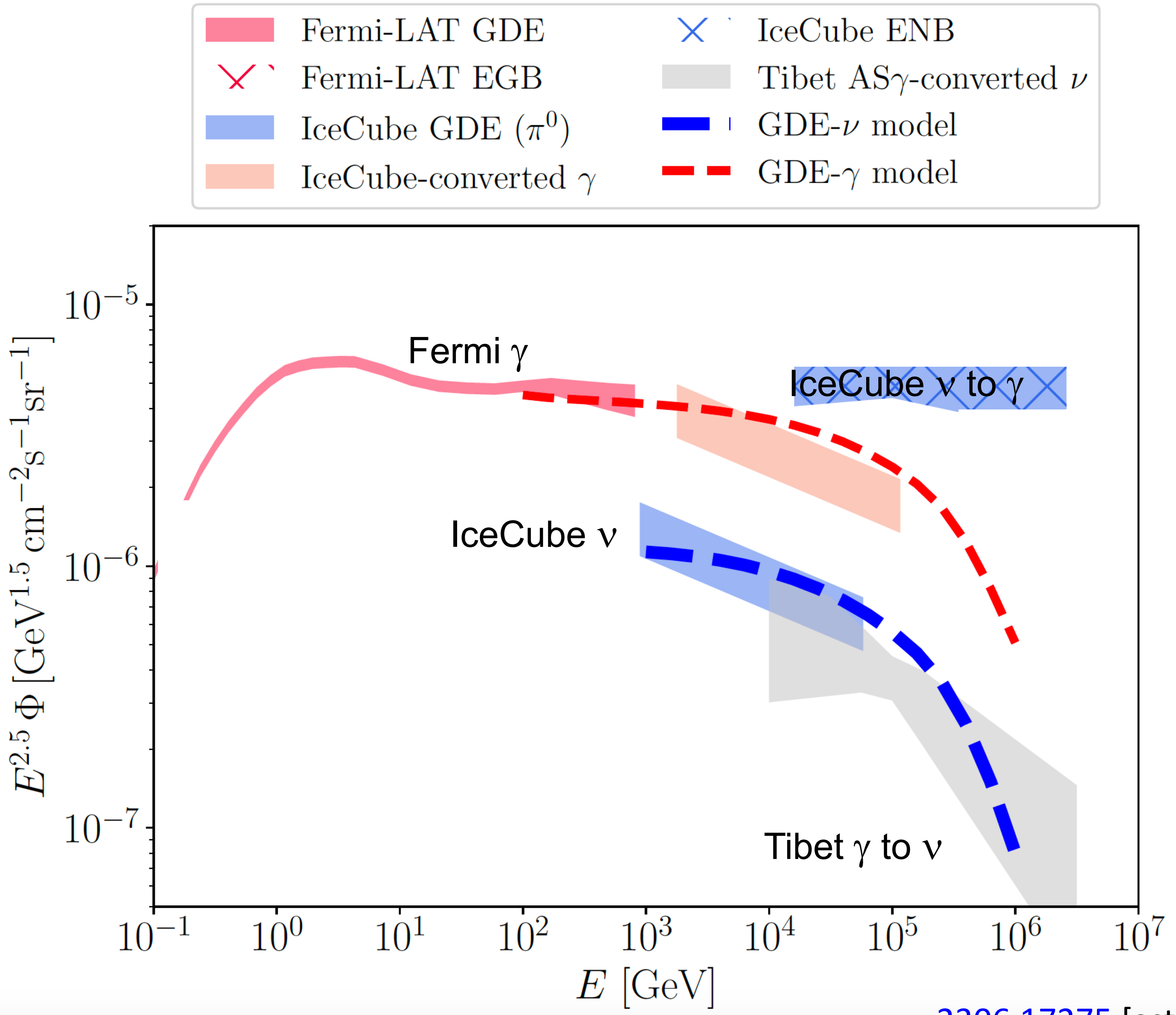
1943

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.

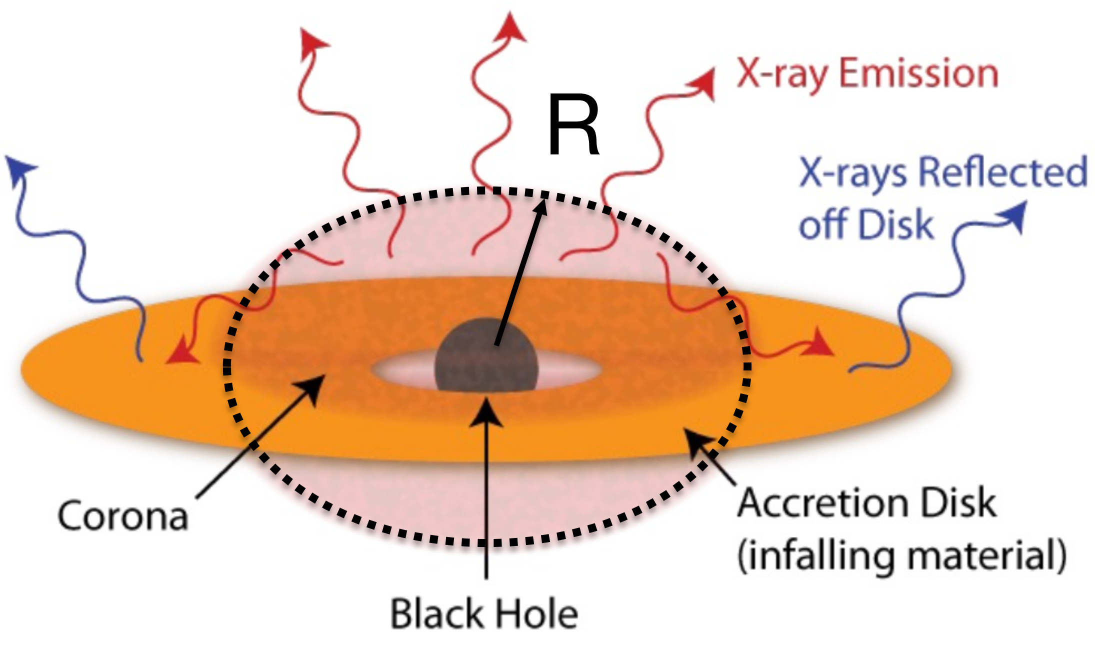
southern hemisphere soon


NSF
IceCube



2306.17275 [astro-ph.HE]

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

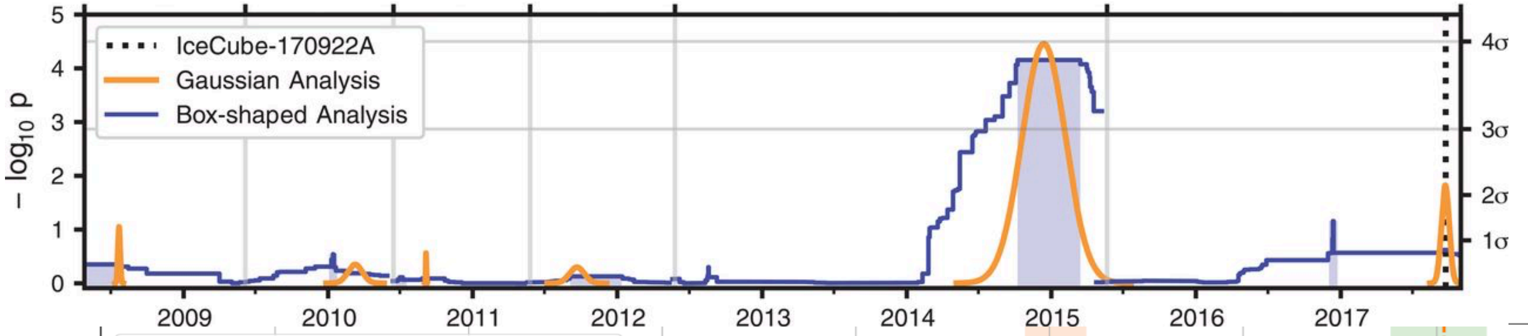


$$\tau_{p\gamma} \geqslant 1 \text{ and}$$
$$\tau_{pp} \geqslant 1$$

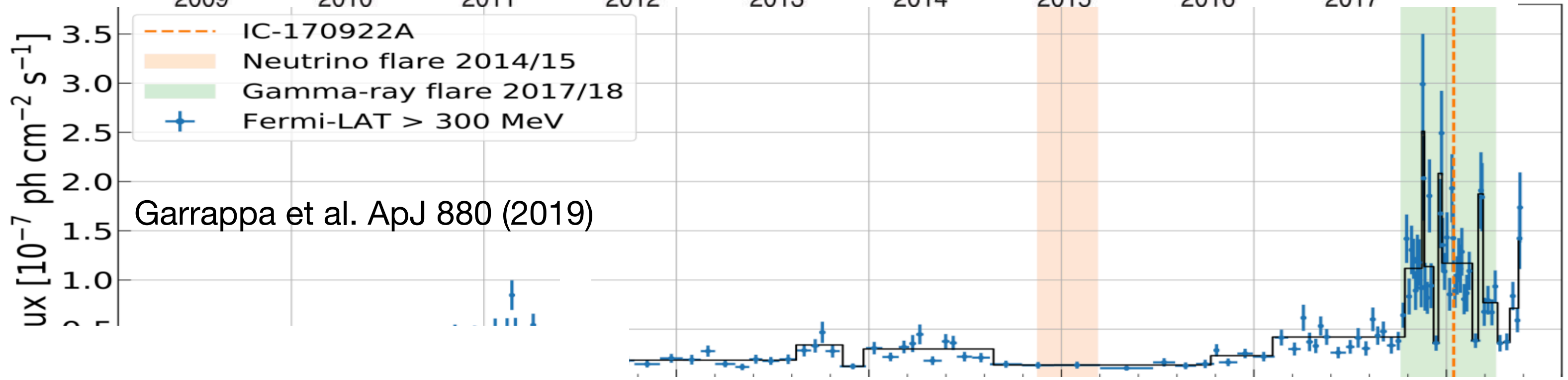
$$\tau_{p\gamma} \sim \sigma_{p\gamma} \left[\frac{1}{\mathrm{R}} \frac{L_X}{E_X}\right]$$

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

neutrinos originate within 10~10^2 Schwarzschild radii from the BH neutrino

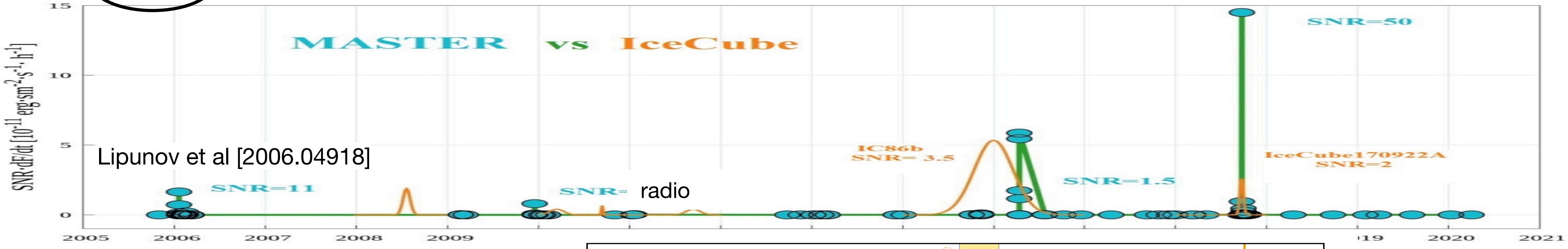


gamma ray



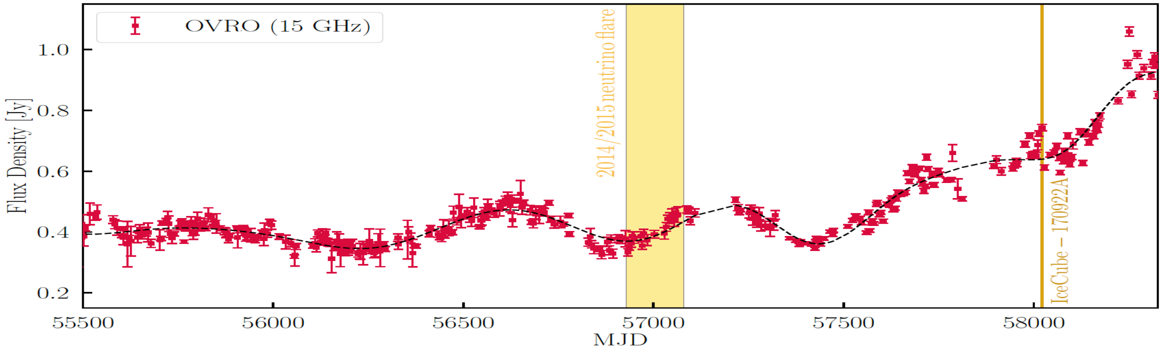
Garrappa et al. ApJ 880 (2019)

optical



Lipunov et al [2006.04918]

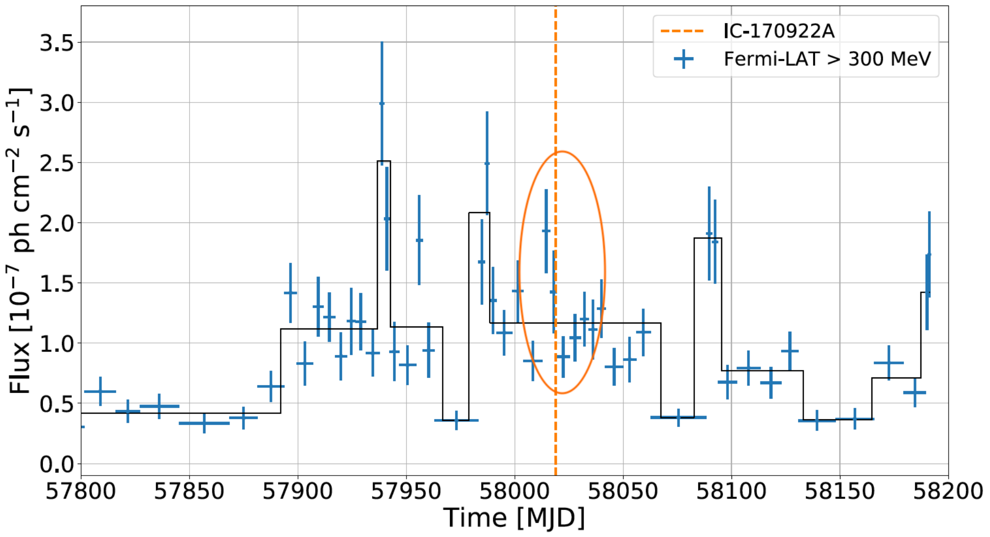
radio

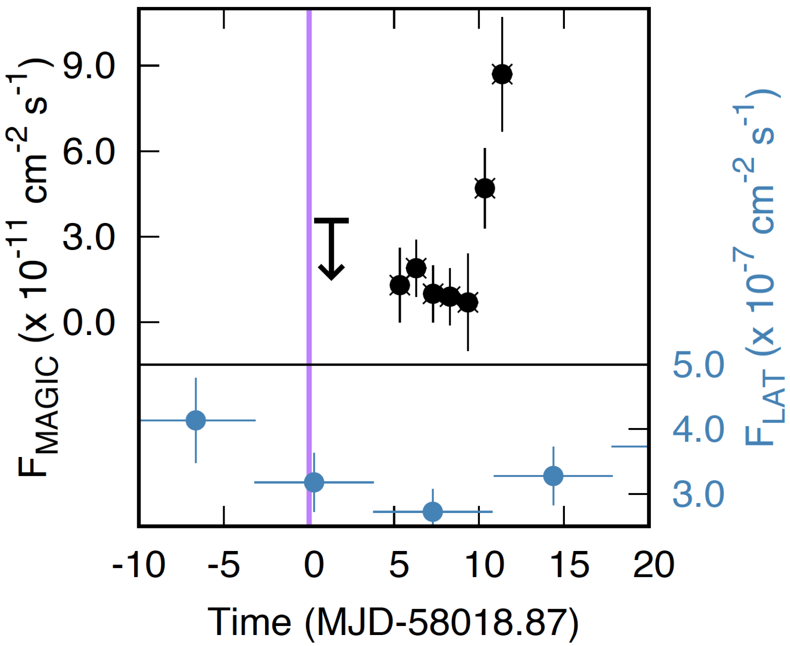


TXS 0506+056

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

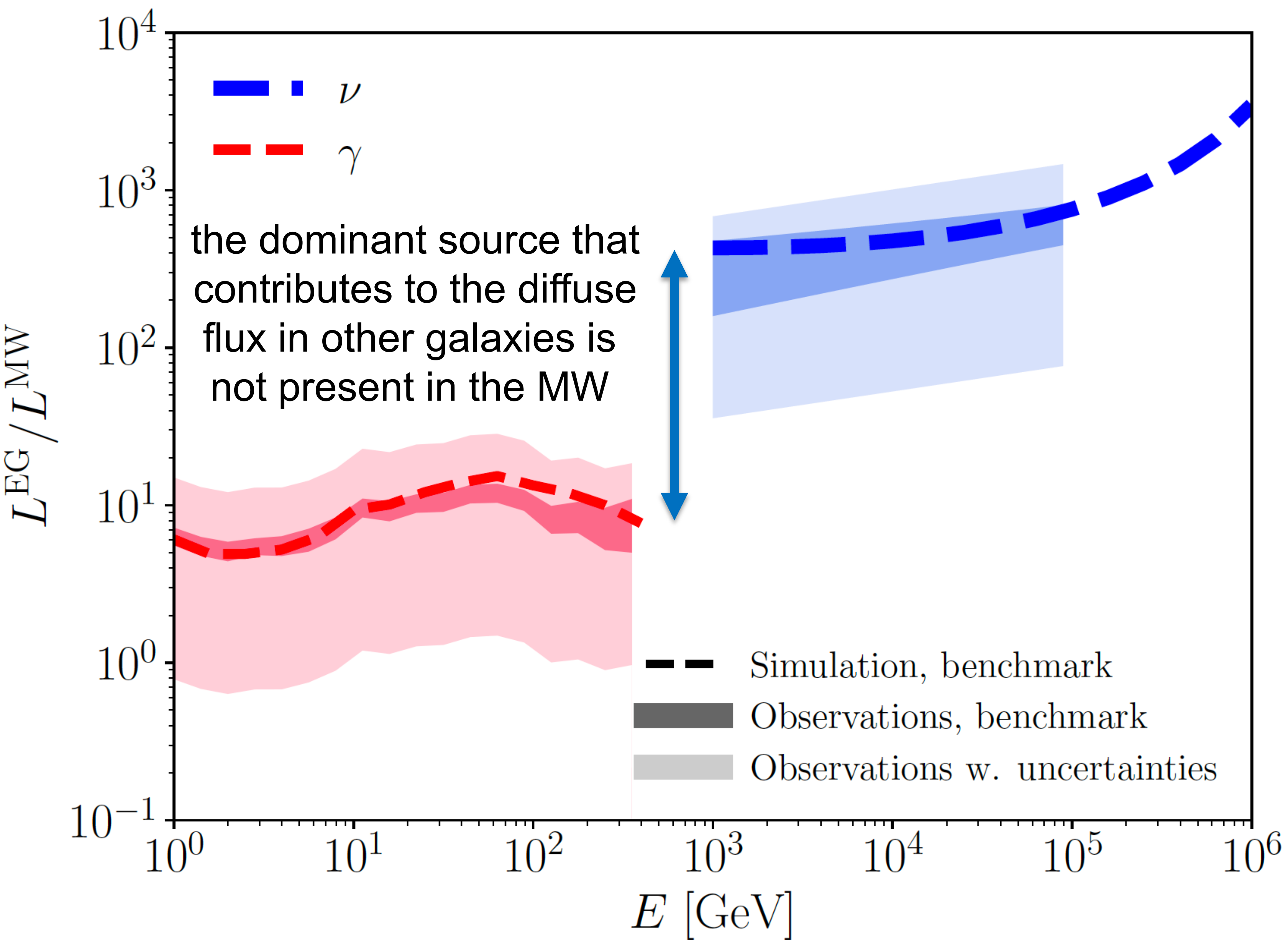




- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced

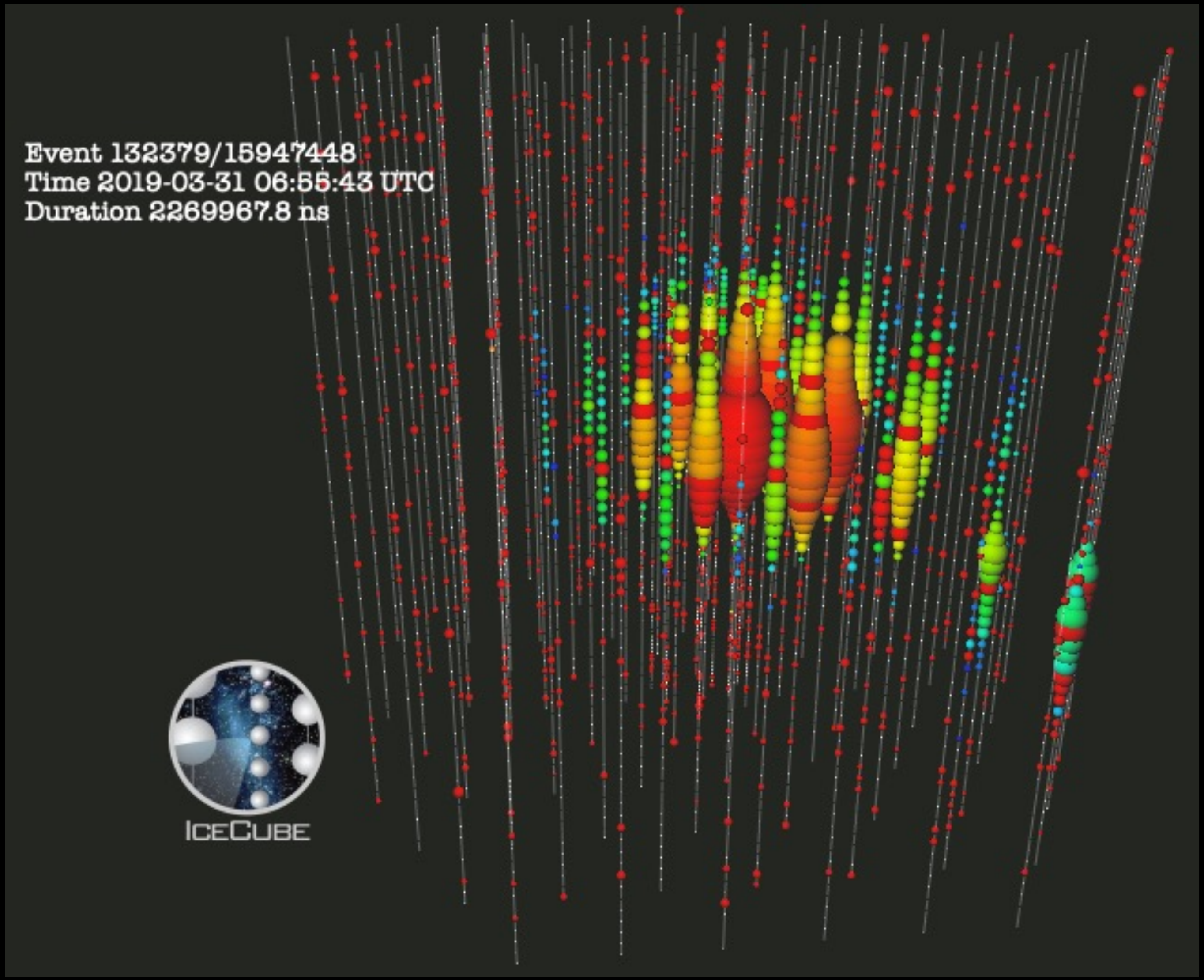
- MAGIC: onset of the TeV flux 5 days after IC170922

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



ν
γ
the dominant source that contributes to the diffuse flux in other galaxies is not present in the MW
Simulation, benchmark
Observations, benchmark
Observations w. uncertainties
$L^{\mathrm{EG}}/L^{\mathrm{MW}}$
E [GeV]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}

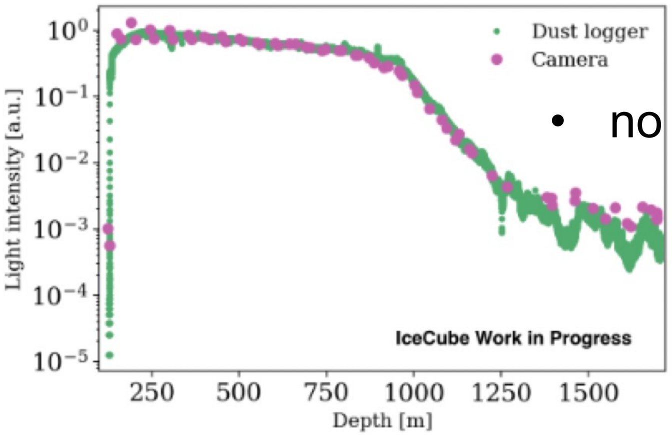
IC190331: 5300 TeV deposited inside the detector



initial neutrino energy > 10 PeV

ice: step by step

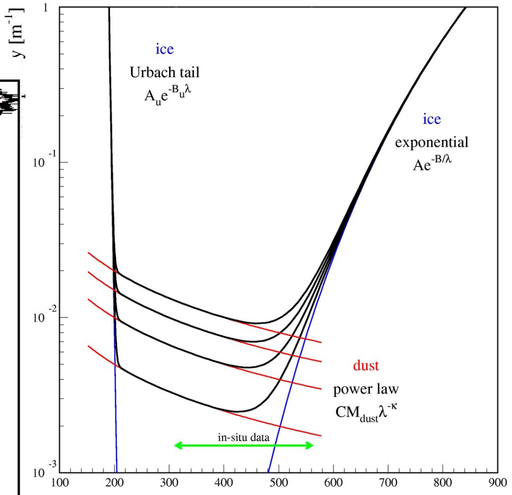
- hole ice ?



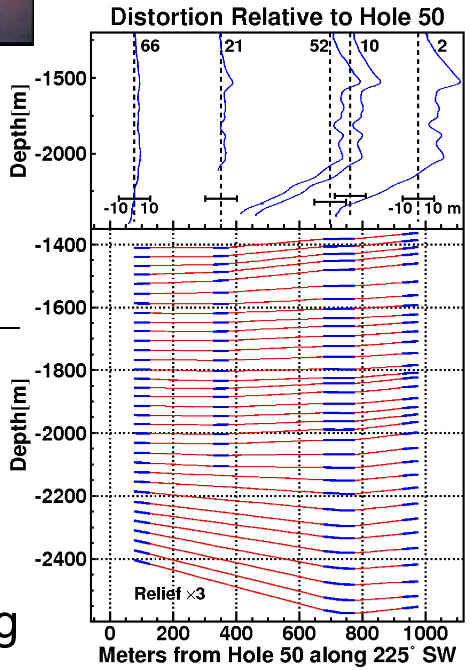
- no air bubbles/hydrates below 1350 m

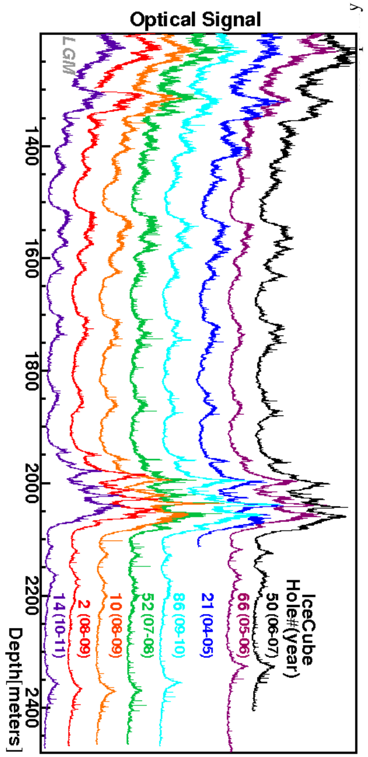
- > 100 m absorption length limited by dust

- ice layers

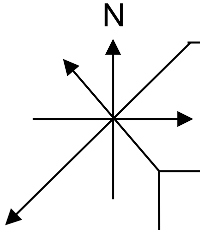


- tilted ice layers





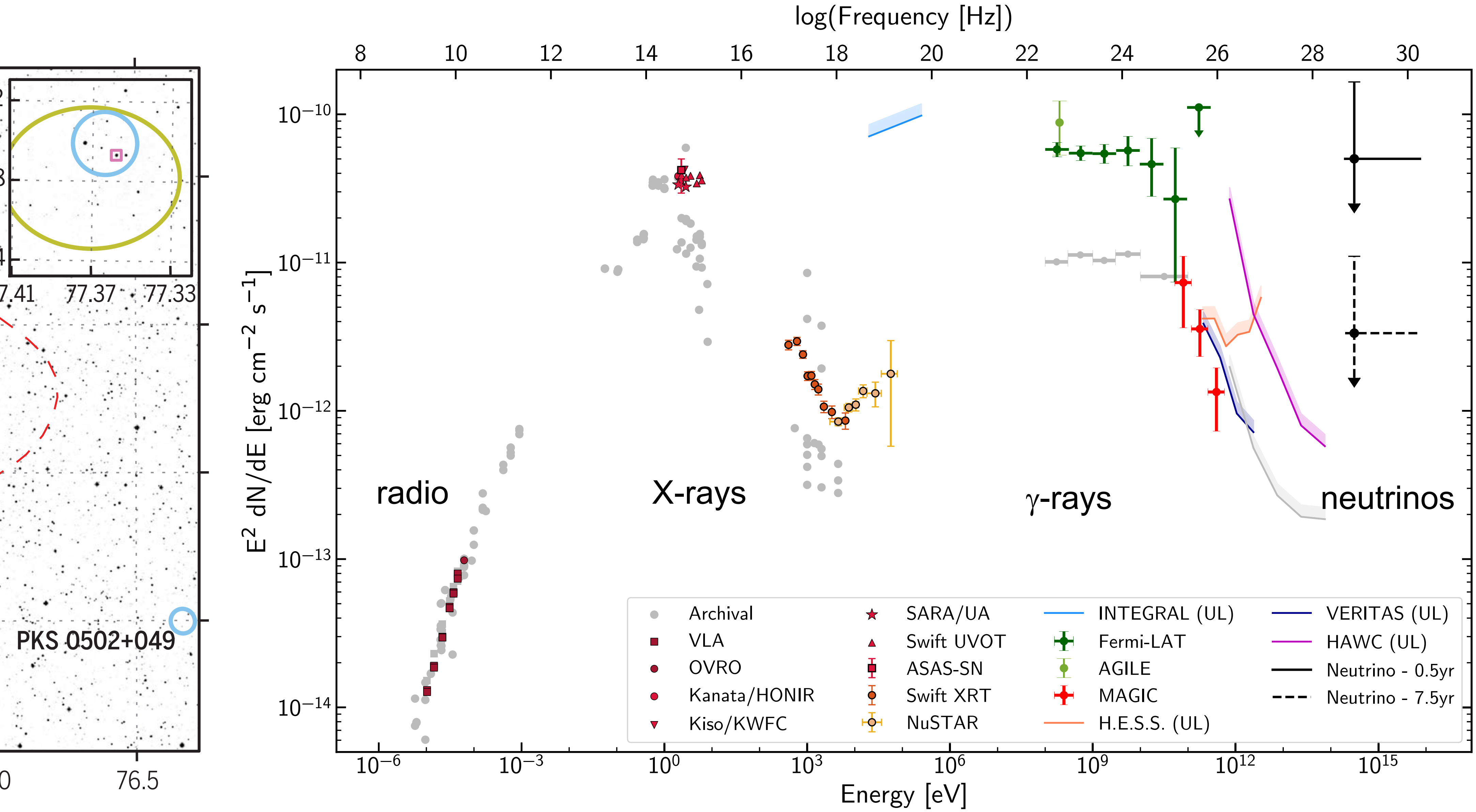
- birefringence of the crystal boundaries ?



Ice Layer tilt direction
225° SW

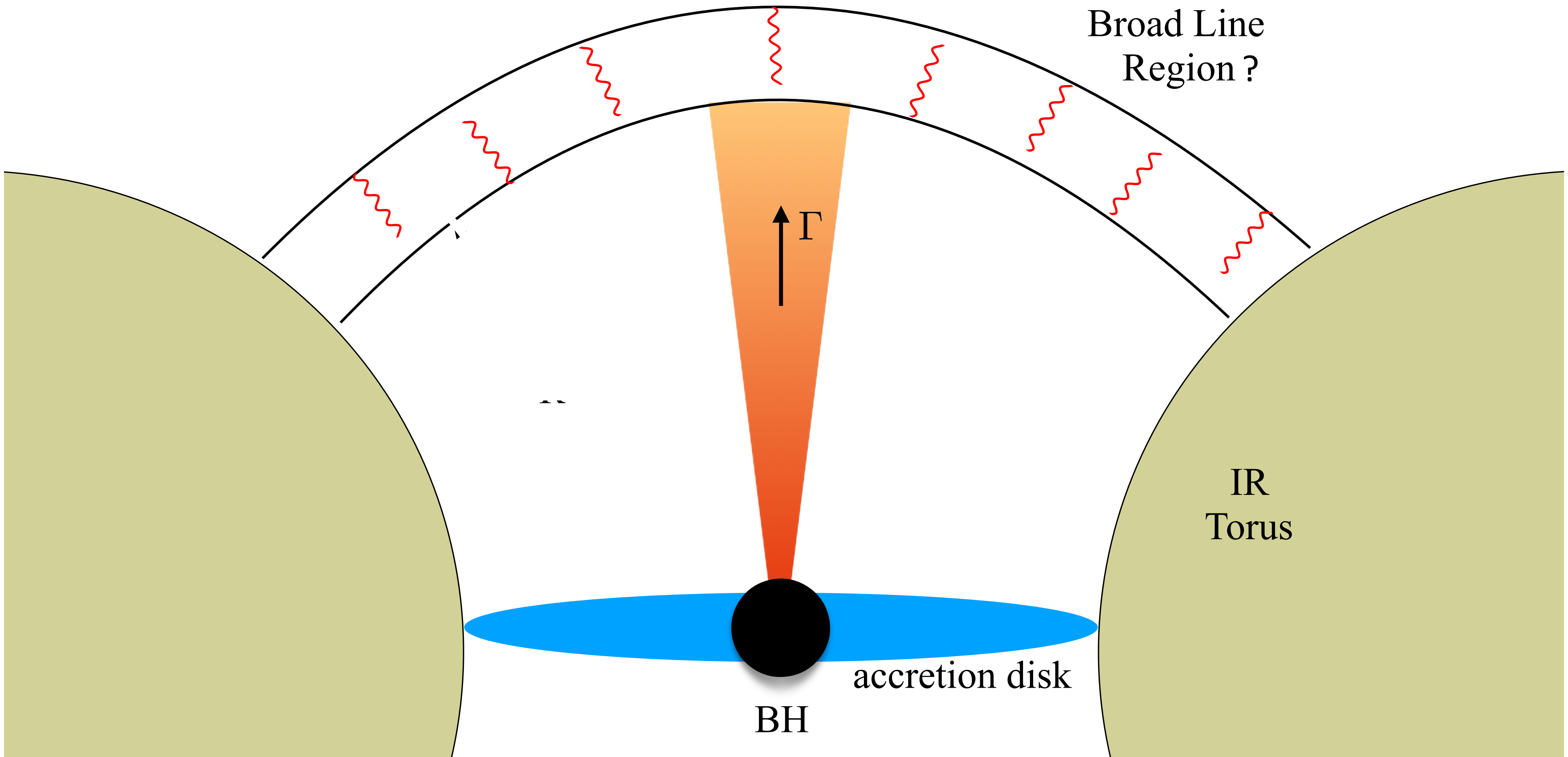
Ice flow direction
41° NW

- anisotropy
~8% less scattering
41° NW

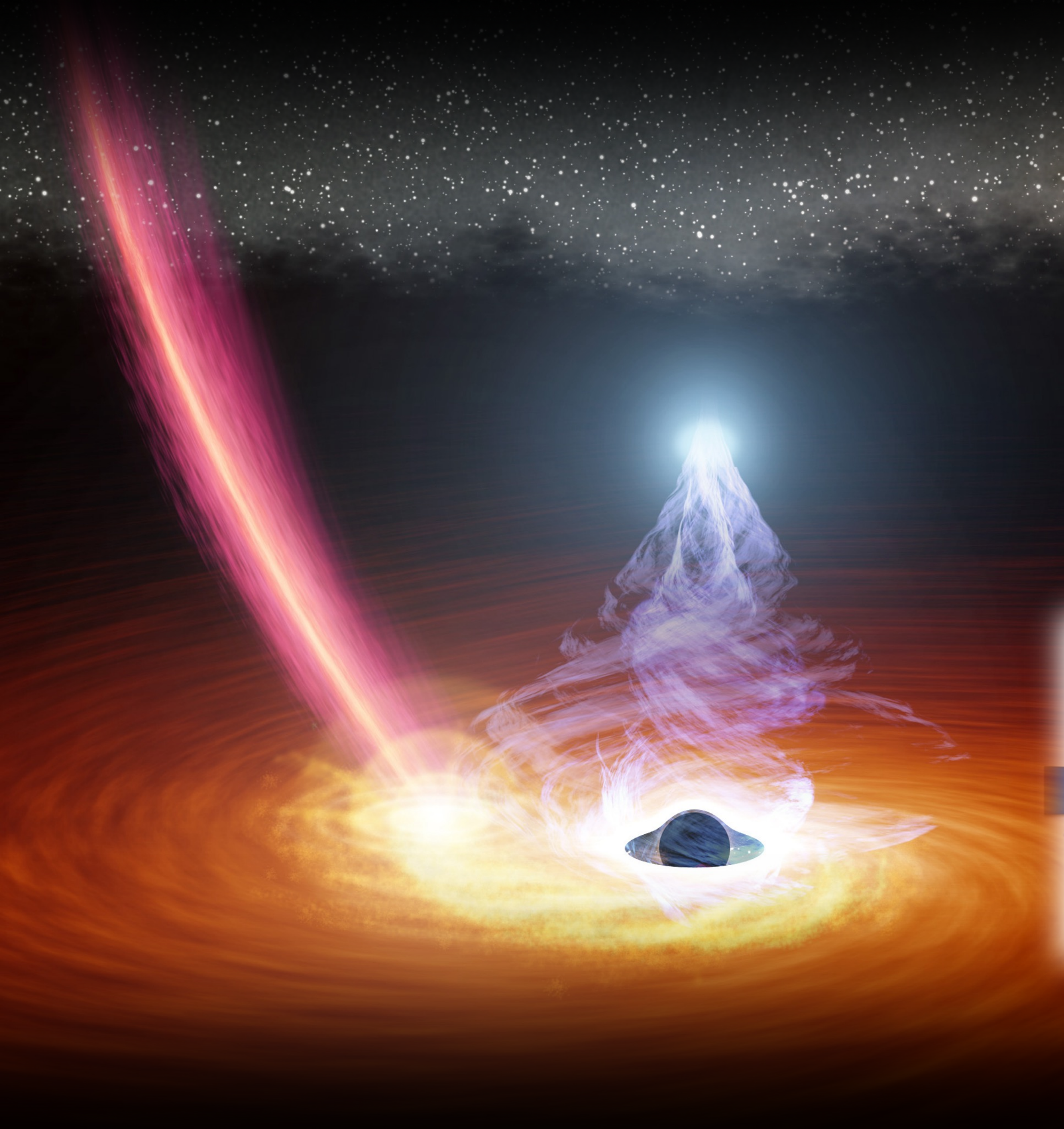


blazar models cannot produce a single neutrino at this level blazar modeling was spectacularly unsuccessful and should be:

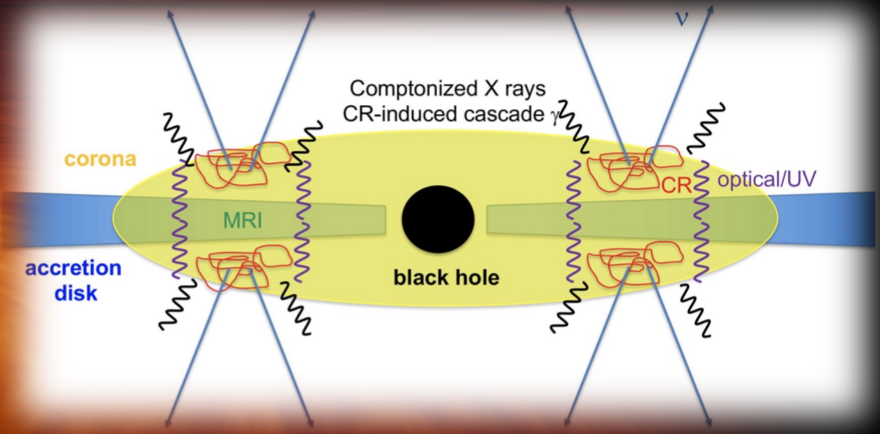
- no target to produce neutrinos because the jet is transparent to photons
- neutrinos are produced in bursts



cores of active galaxies as cosmic accelerators



acceleration of electrons and protons
in the high field regions associated
with the accretion disk and the optically
thick corona of X-rays

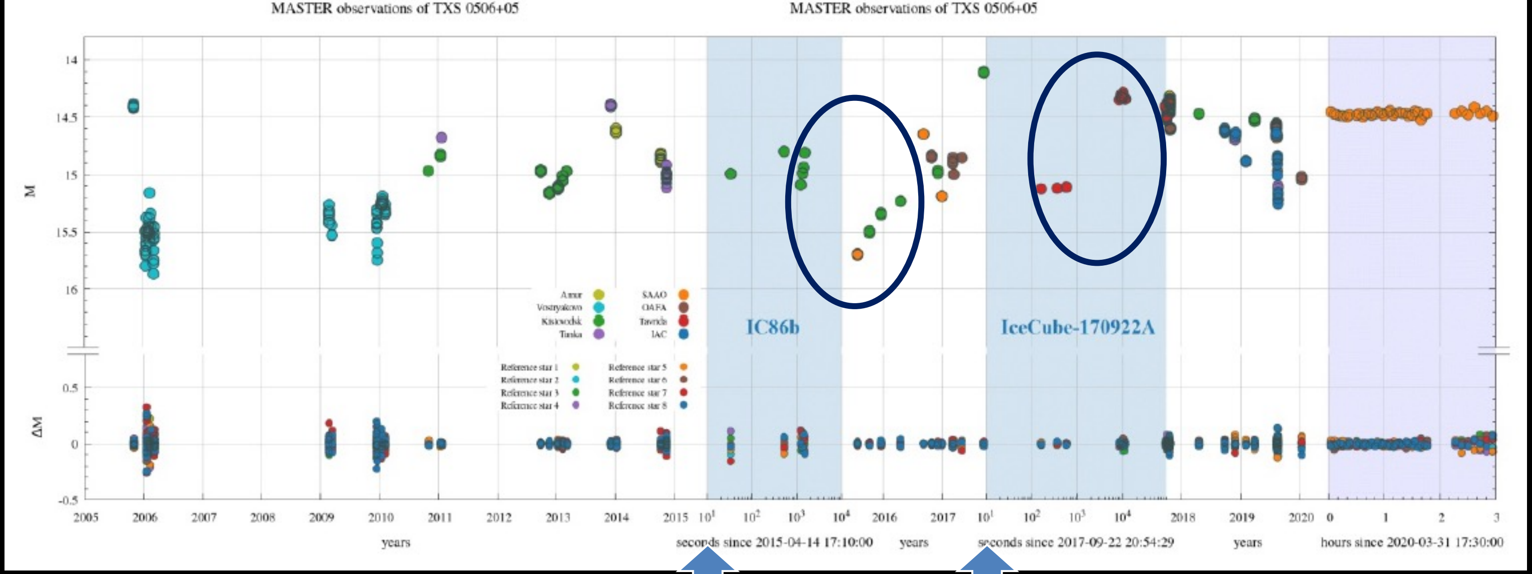


MASTER

robotic network

optical observations
TXS 0506+056
since 2005

blue panels:
expanded time axis
years → seconds

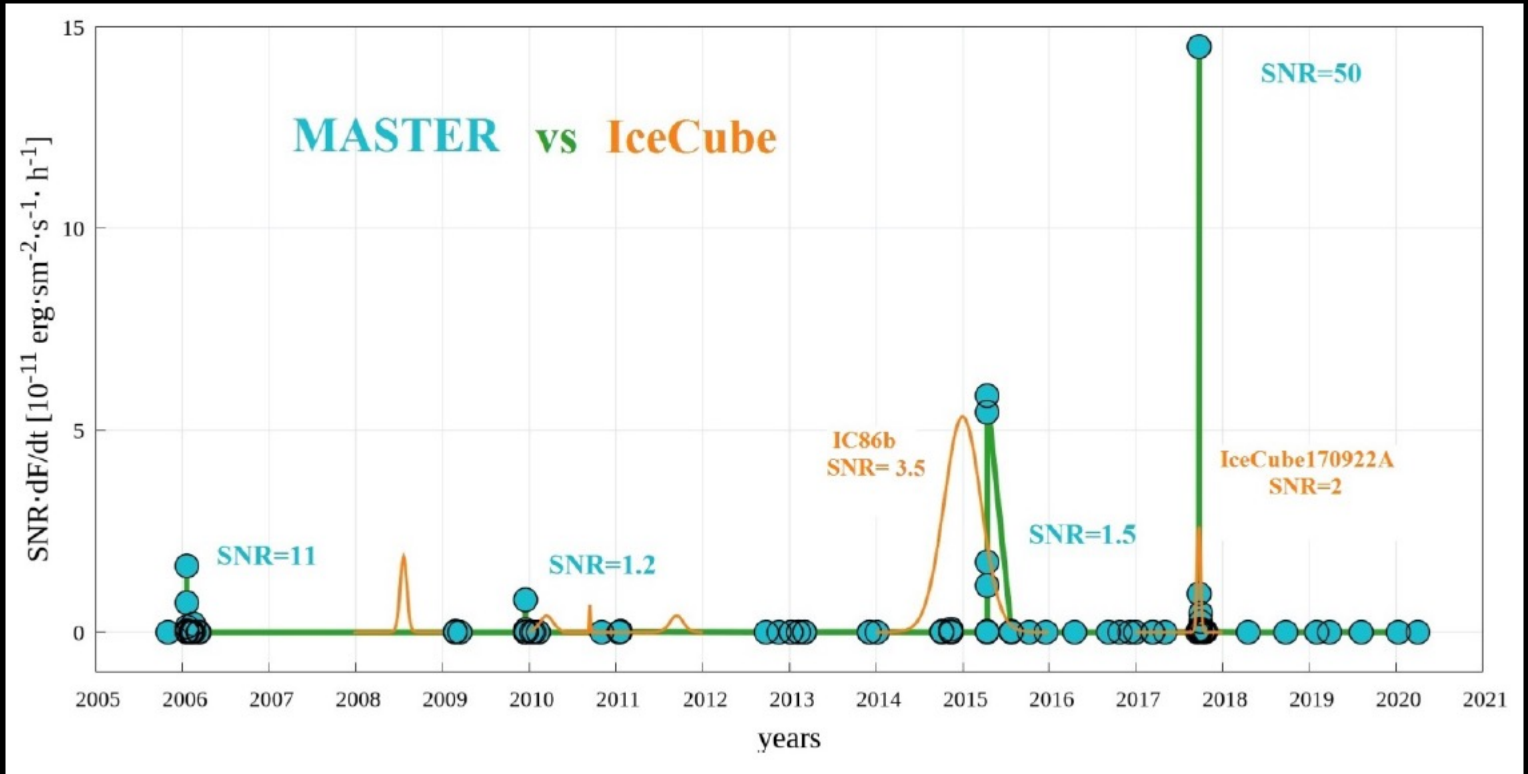


seconds after
2014-15 burst

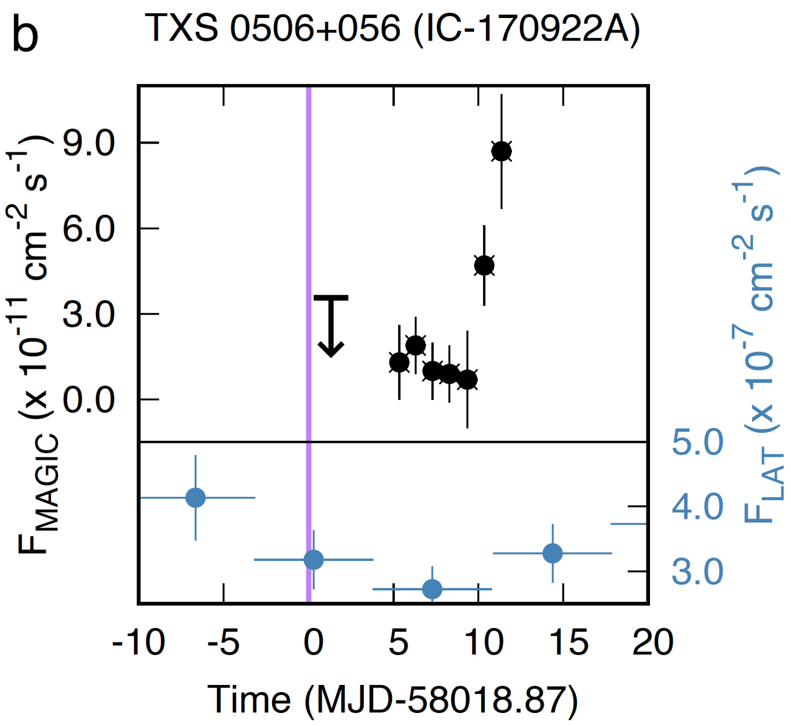
seconds after
IC170922

time variation of flux
times
signal-to-noise

hour-scale
variability of the
source after
neutrino emission

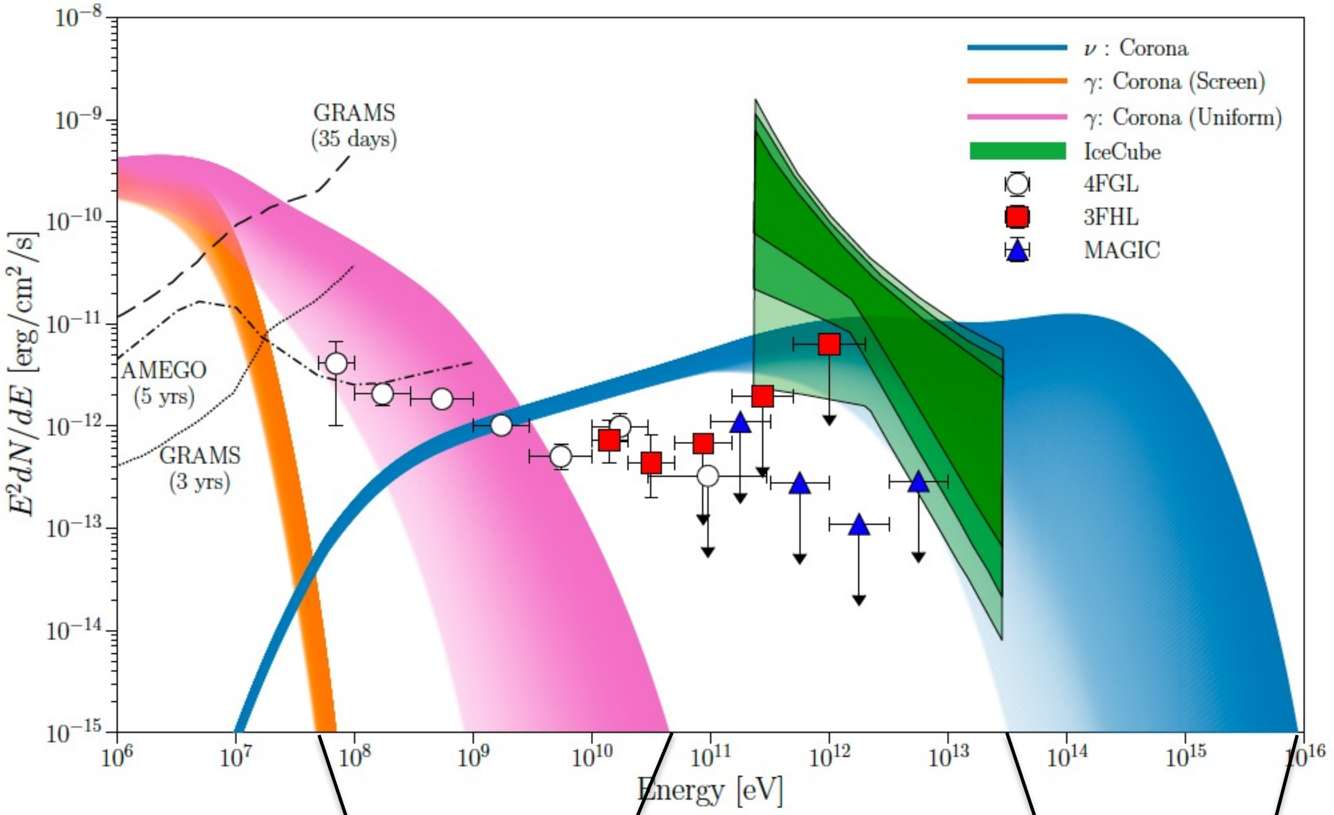


no gamma rays in 2017 at the time the neutrino is produced ?



- MAGIC, HESS and VERITAS: source exhibited daily variations with no TeV gamma rays observed 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

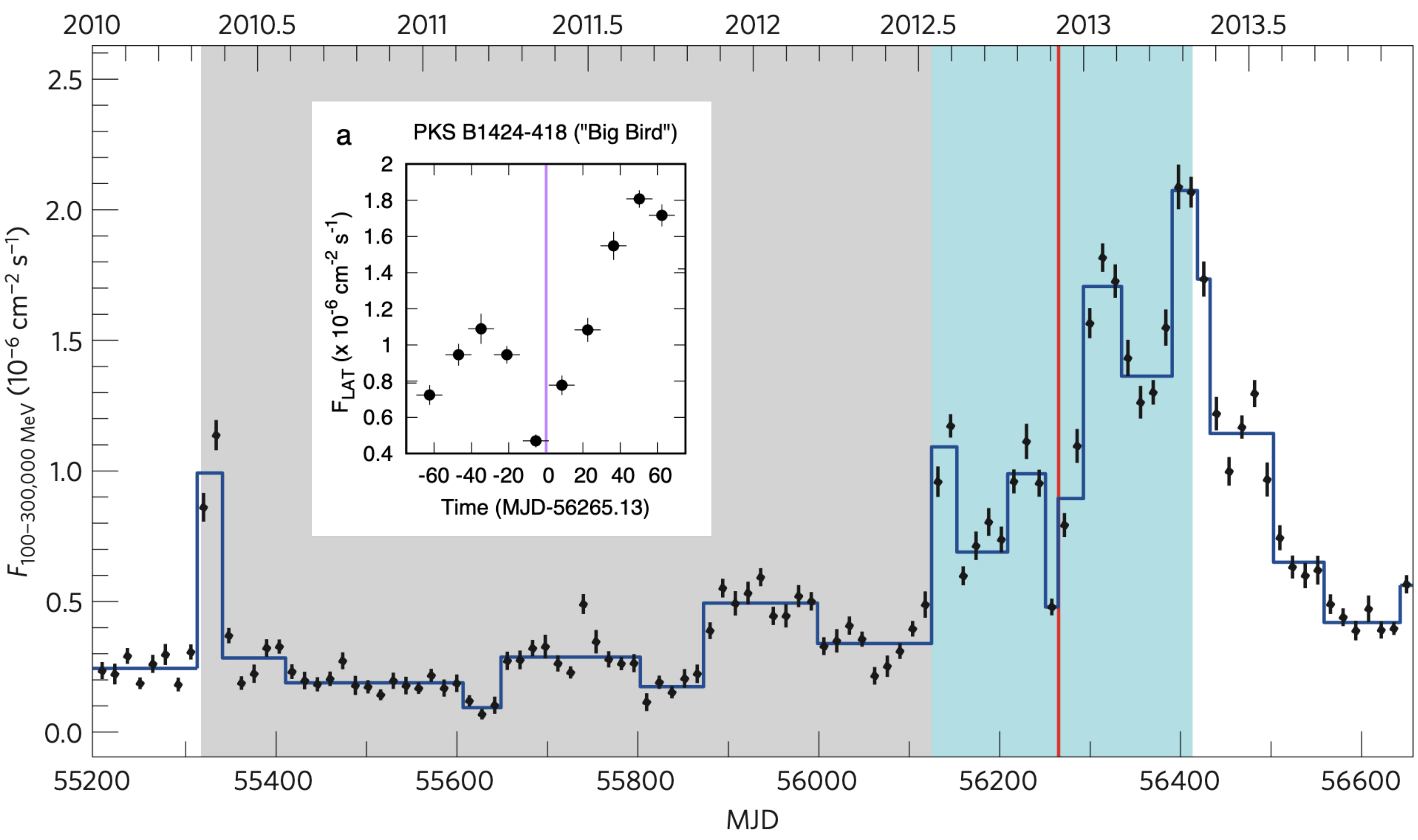
neutrinos produced in the gamma-ray obscured core of NGC 1068



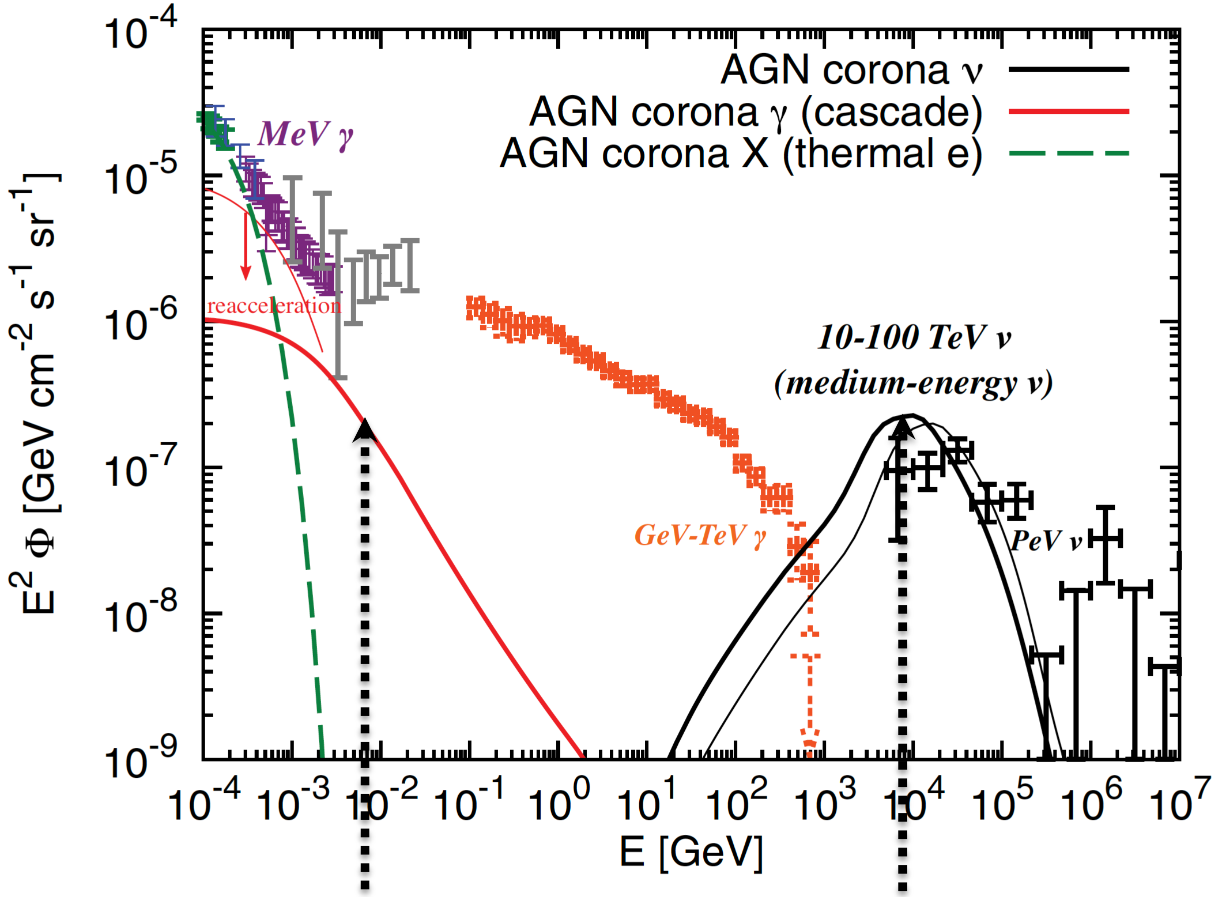
accompanying pionic photons

range of neutrino flux: protons versus electrons

big bird (~ 2 PeV) and PKS 1424-418

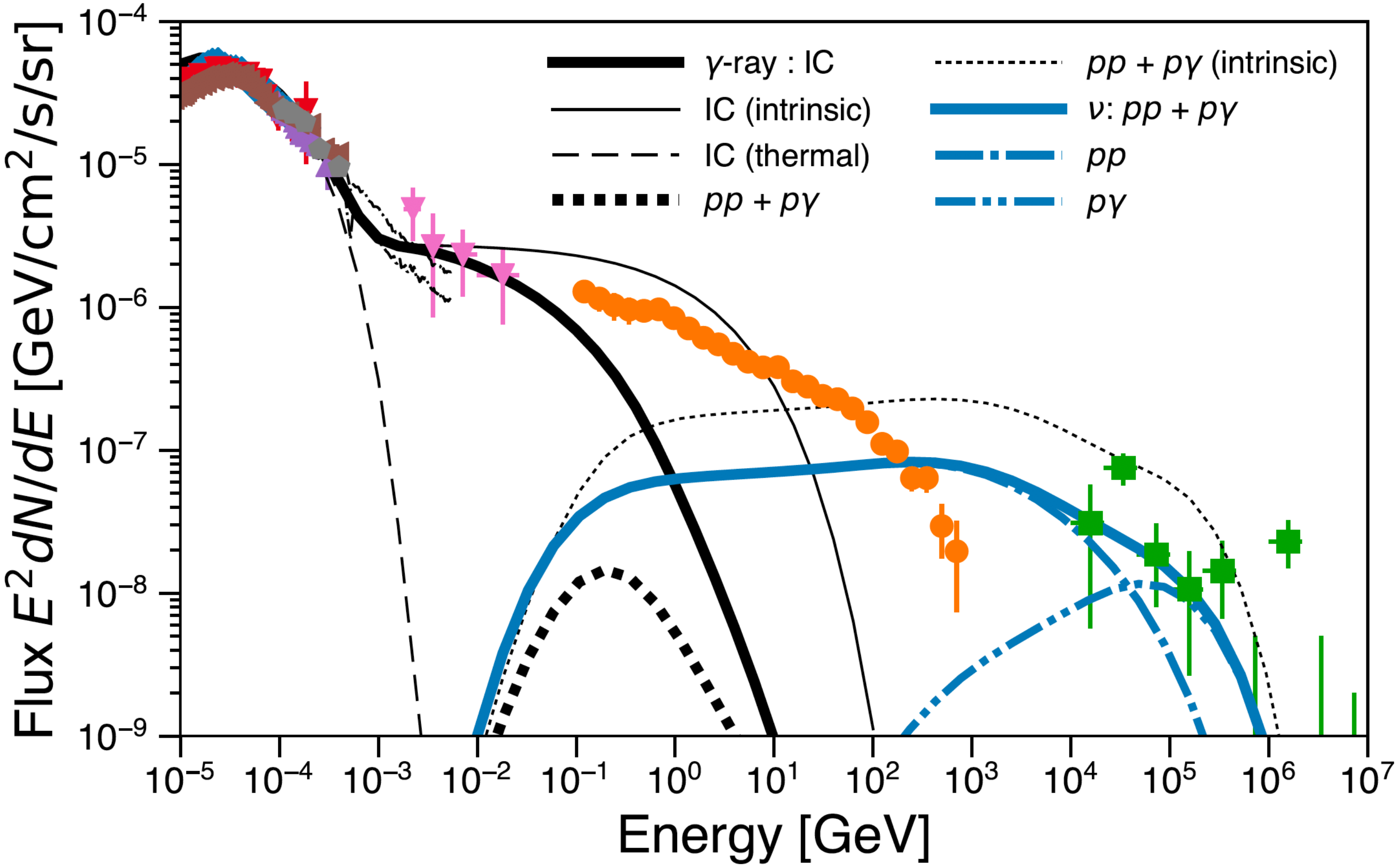


neutrinos produced in the gamma-ray obscured core of NGC 1068

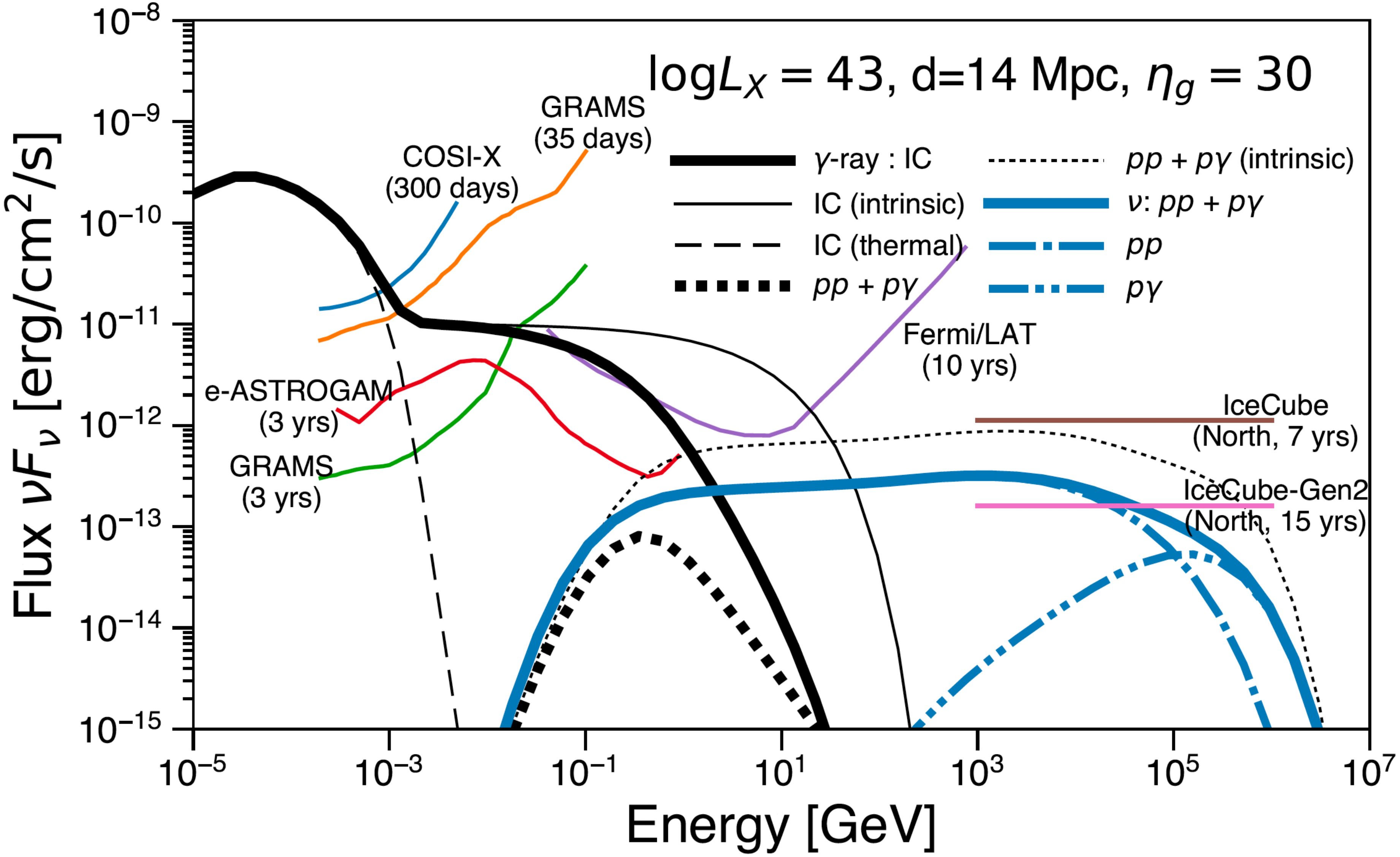


neutrino flux:
proton-proton and proton-gamma

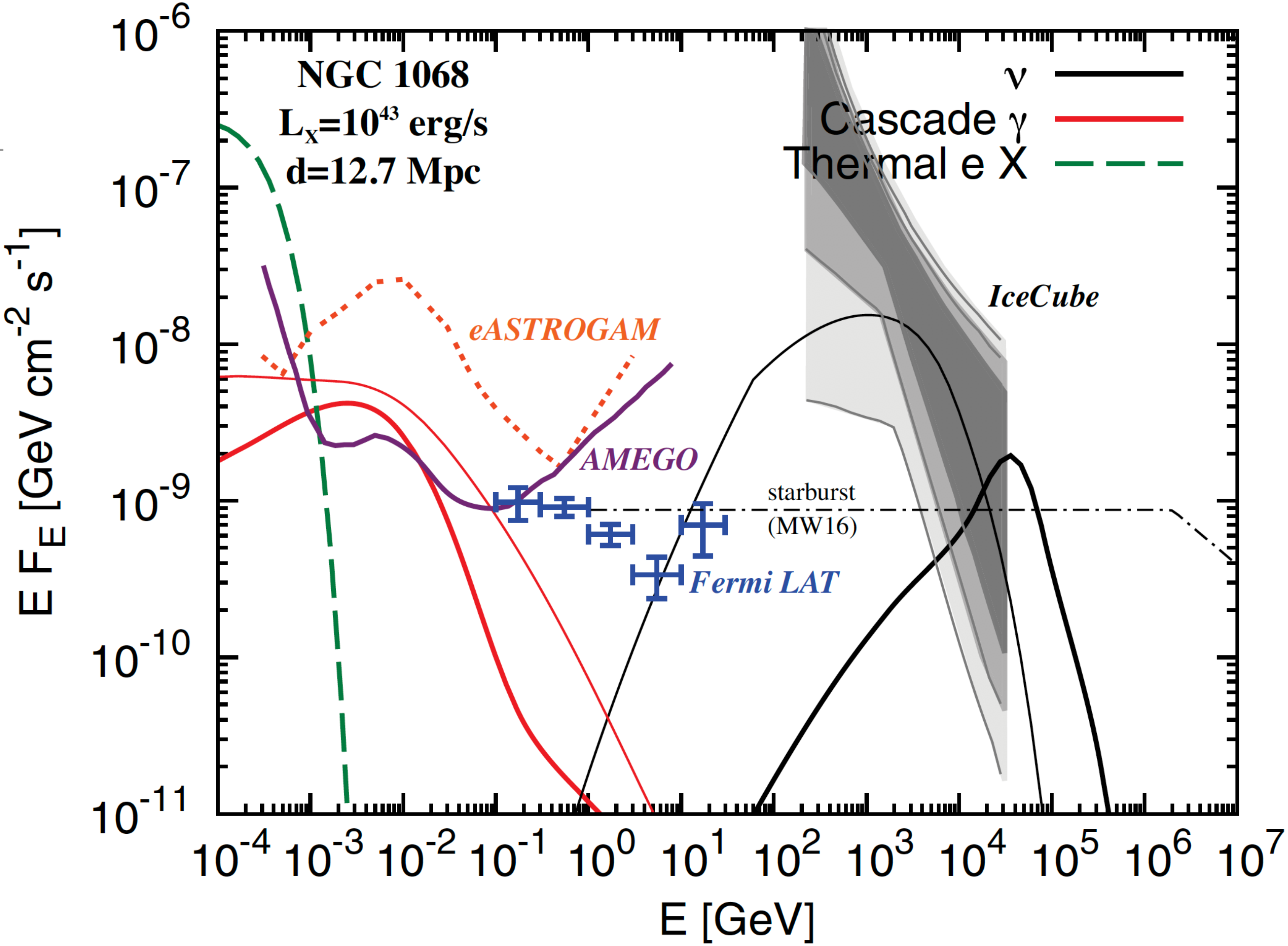
accompanying pionic photons



Flux $E^2 dN/dE$ [GeV/cm^2/s/sr]
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}
Energy [GeV]
γ-ray : IC
IC (intrinsic)
IC (thermal)
$pp + p\gamma$
$pp + p\gamma$ (intrinsic)
ν: $pp + p\gamma$
pp
$p\gamma$



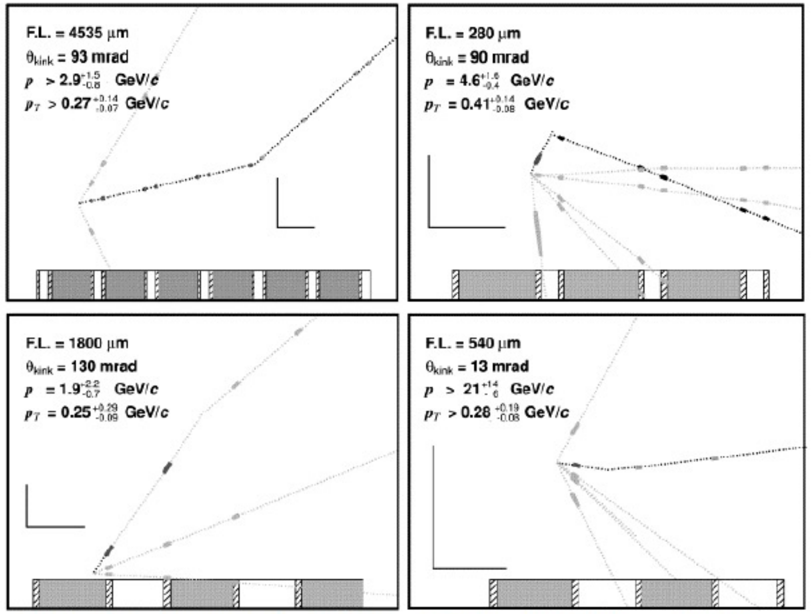
$\log L_X = 43$, d=14 Mpc, $\eta_g = 30$
γ-ray : IC
IC (intrinsic)
IC (thermal)
$pp + p\gamma$
$pp + p\gamma$ (intrinsic)
ν: $pp + p\gamma$
pp
$p\gamma$
GRAMS (35 days)
COSI-X (300 days)
e-ASTROGAM (3 yrs)
GRAMS (3 yrs)
Fermi/LAT (10 yrs)
IceCube (North, 7 yrs)
IceCube-Gen2 (North, 15 yrs)
Flux νF_ν [erg/cm^2/s]
Energy [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}



NGC 1068
Lx=10^43 erg/s
d=12.7 Mpc
ν
Cascade γ
Thermal e X
IceCube
eASTROGAM
AMEGO
starburst
(MW16)
Fermi LAT
E F_E [GeV cm^-2 s^-1]
E [GeV]
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-4 10^-3 10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7

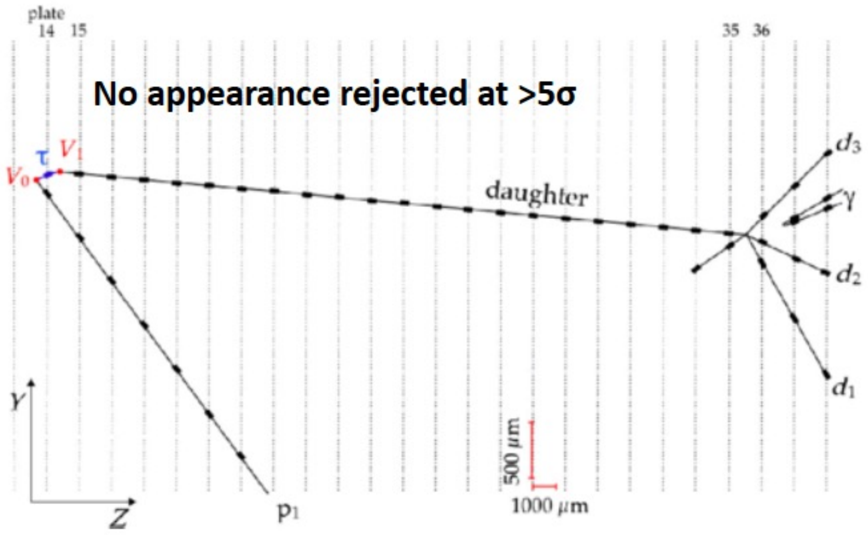
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



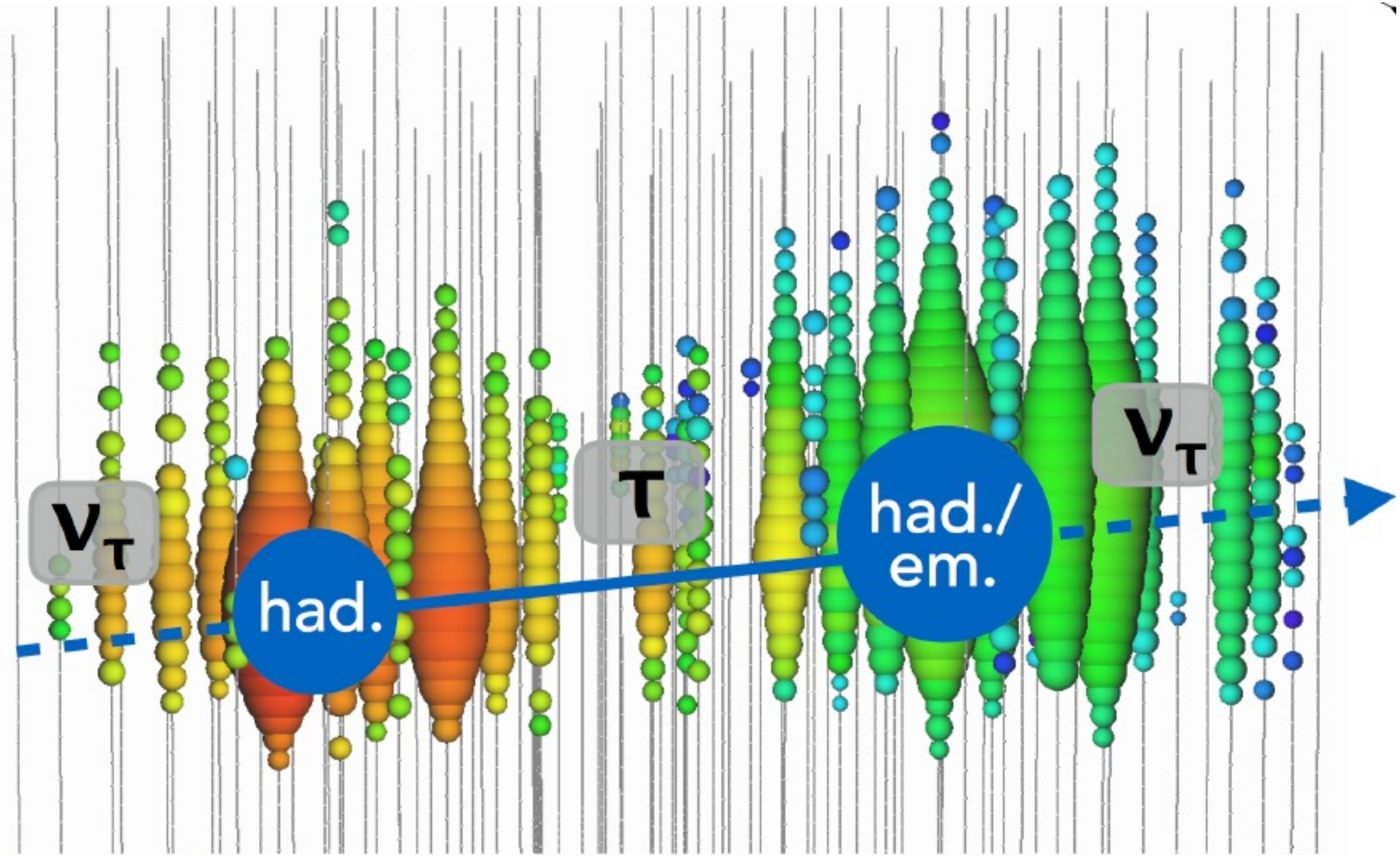
DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



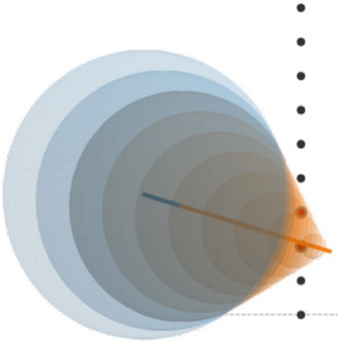
OPERA Phys. Rev. Lett. 115, 121802 (2015) tau neutrino production and decay

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

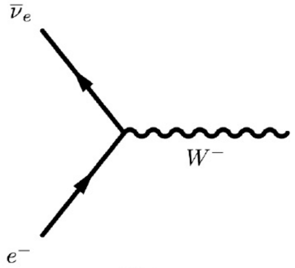


First hint of W boson resonance in data (Glashow resonance)

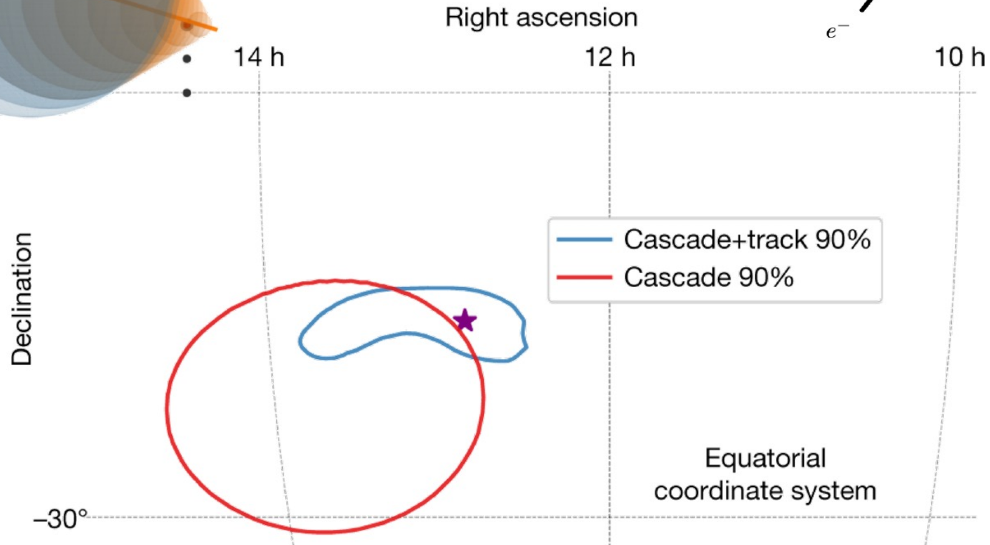
Nature **591,** 220–224 (2021)

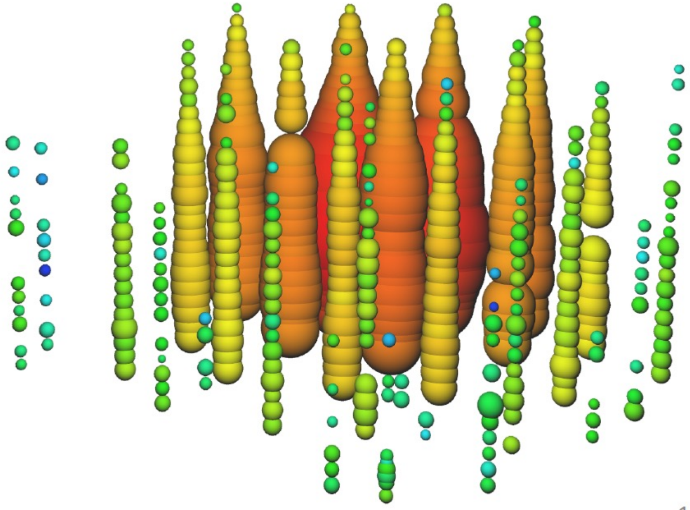


$$E_R = M_W^2/(2m_e) = 6.32\text{PeV}$$

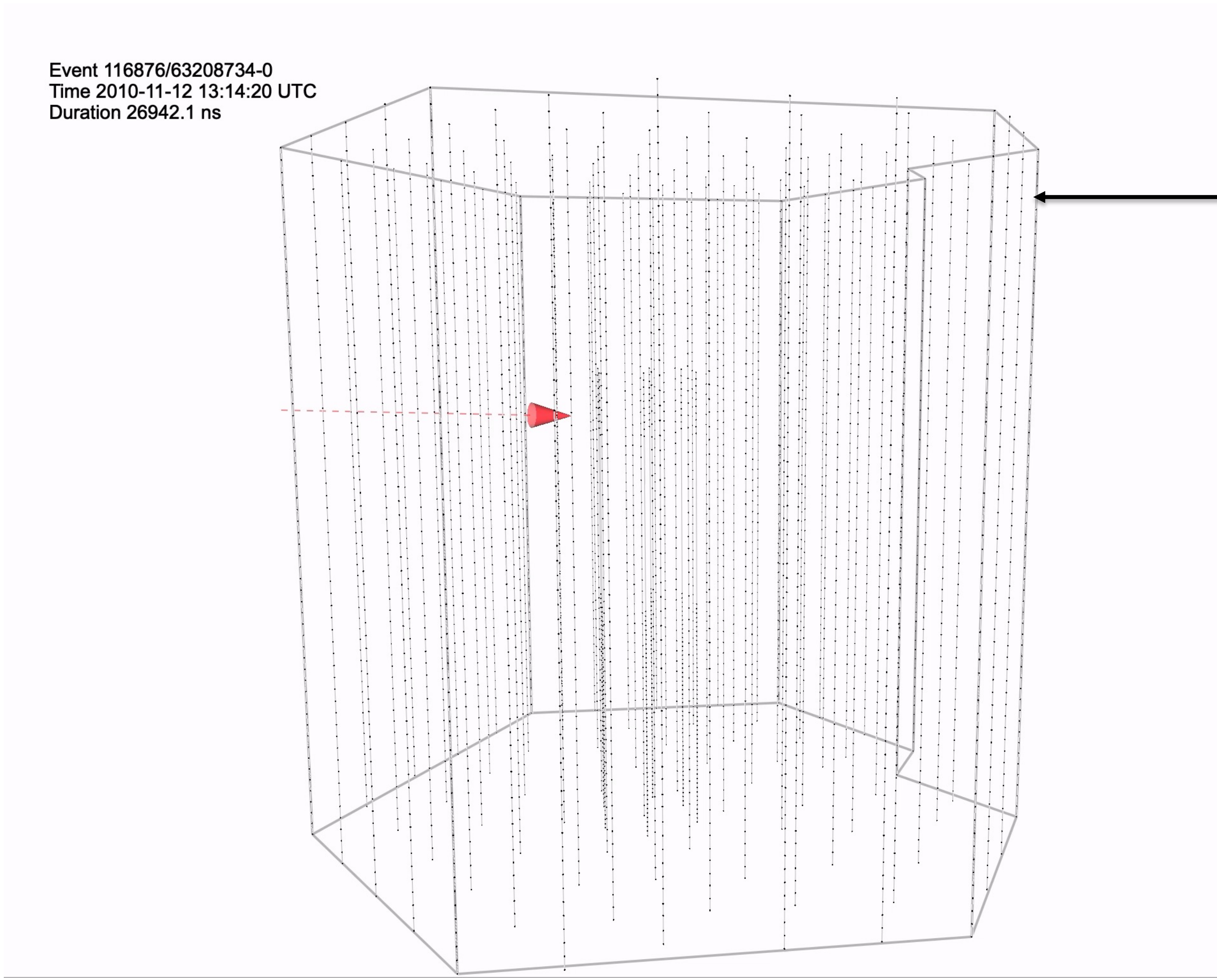


By measuring nu/nubar -> probe source environment directly (magnetic field, pp/pgamma)

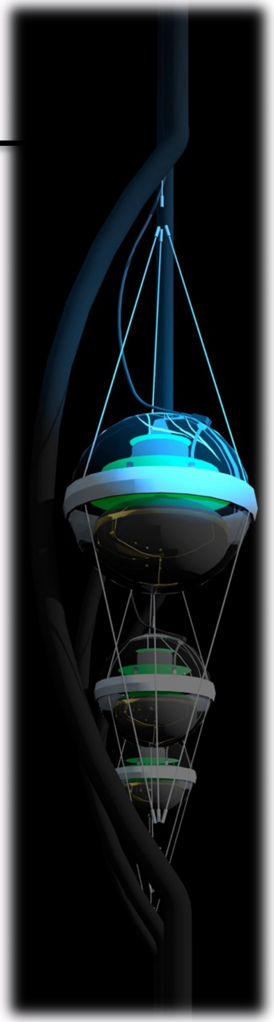




Identified muonic component from the hadronic shower angular uncertainty contour shrinks by a factor of 5 with hybrid reco

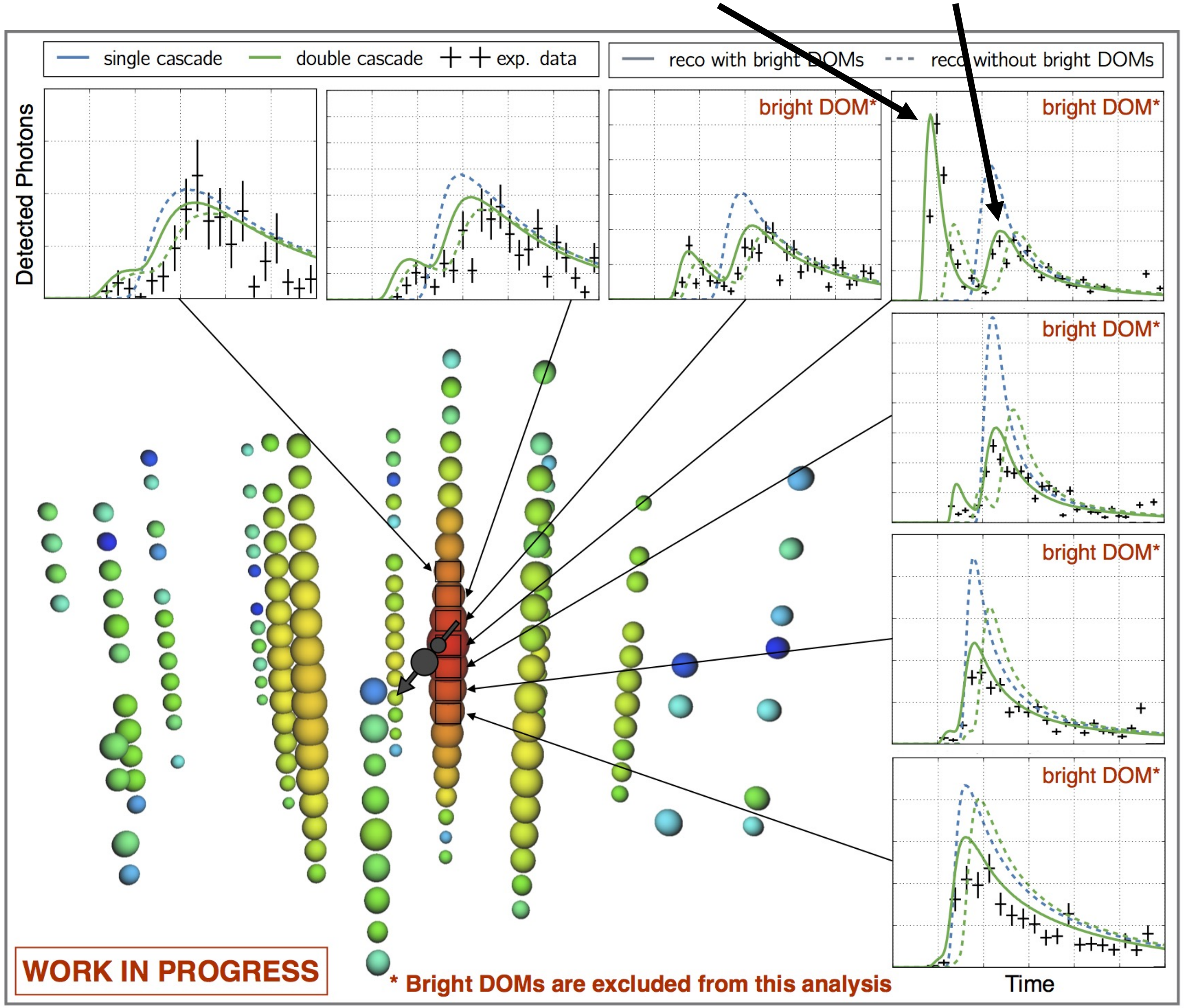


strings of optical sensors

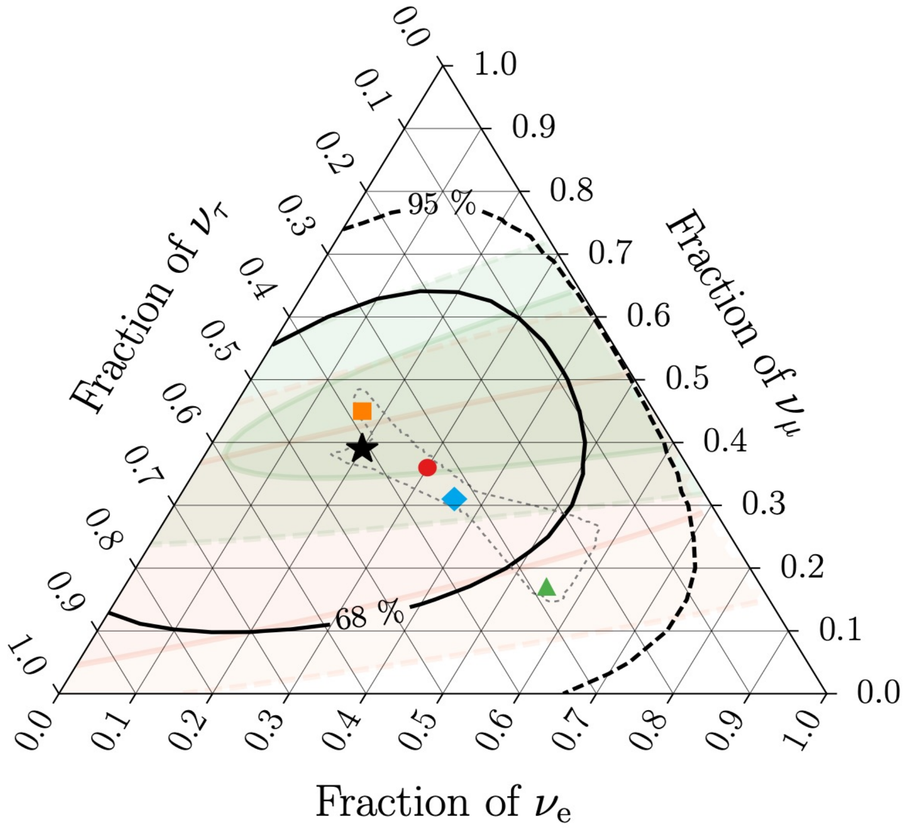


a cosmic tau neutrino with 17m lifetime

light from nutau interaction and tau decay



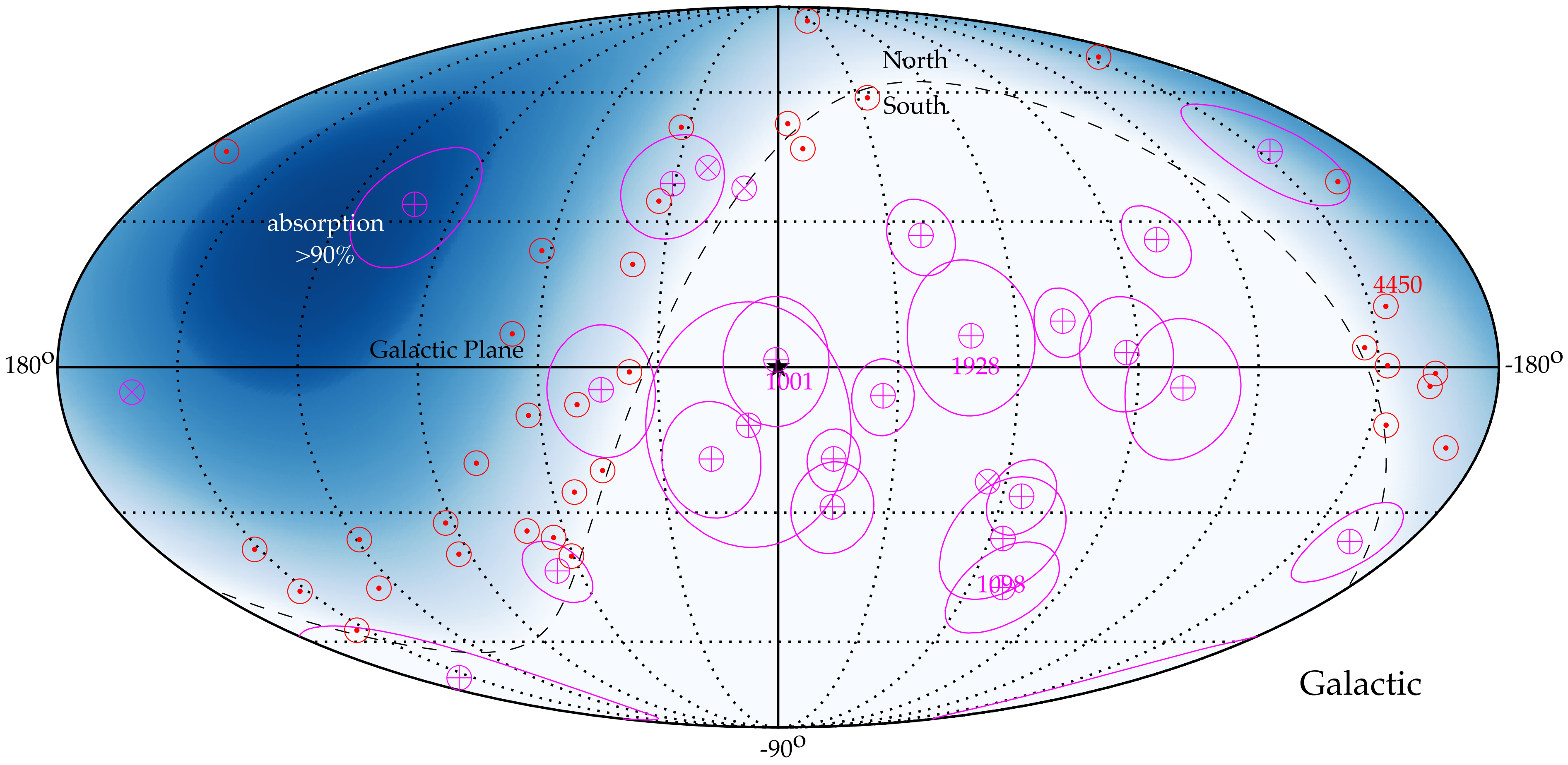
oscillations of PeV neutrinos over cosmic distances to 1:1:1



oscillating PeV neutrinos (7.5 years starting events)

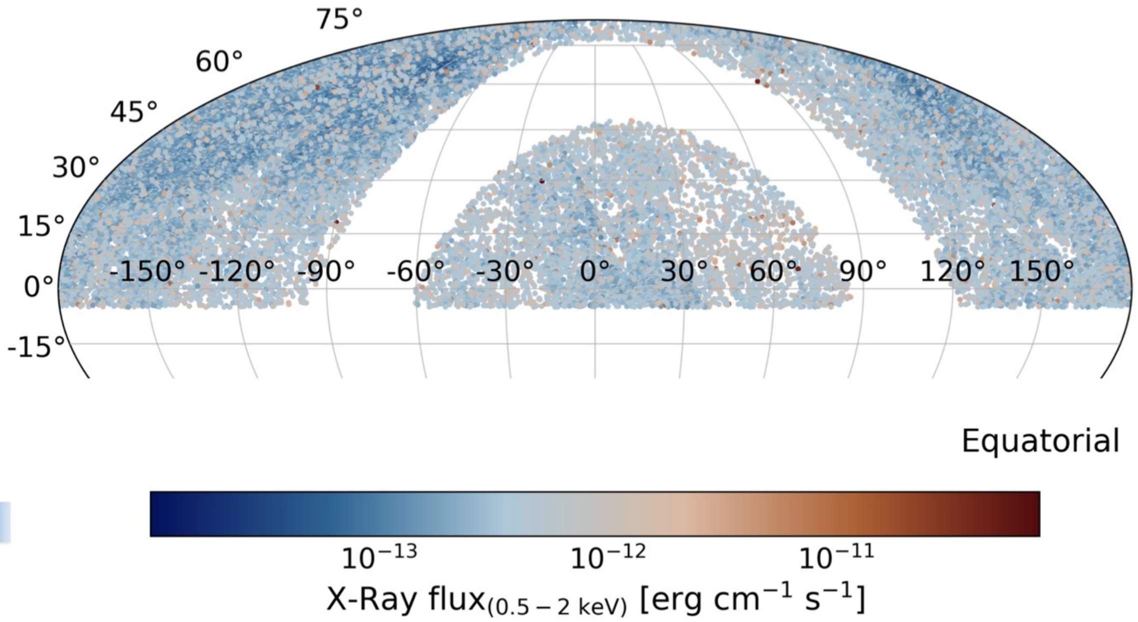
neutrinos with probable cosmic origin:
are they correlated to astronomical sources?

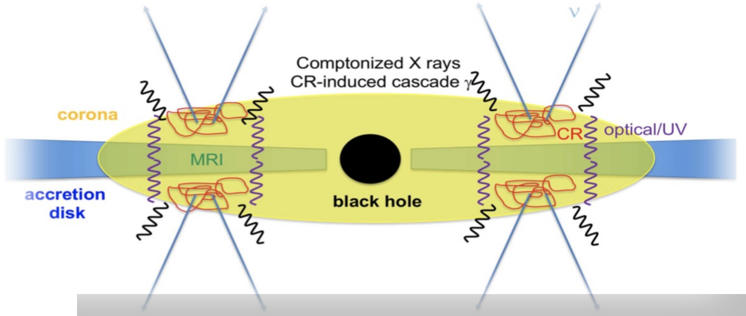
Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \bar{\nu}_\mu$ 8yr (red))



correlation between cores of active galaxies and cosmic neutrinos

(γ = -2.03; 2.6σ post trial)



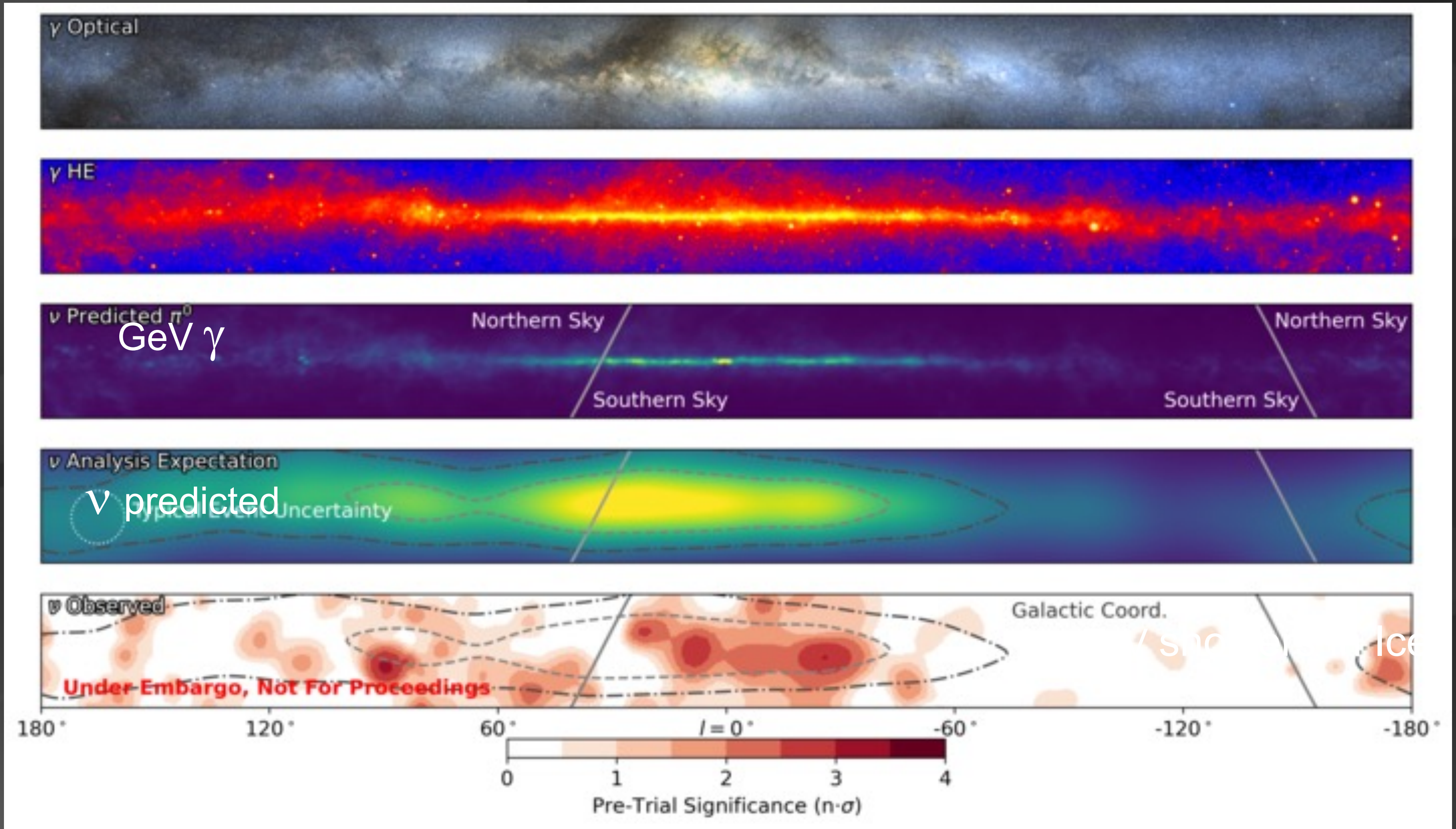


selection:

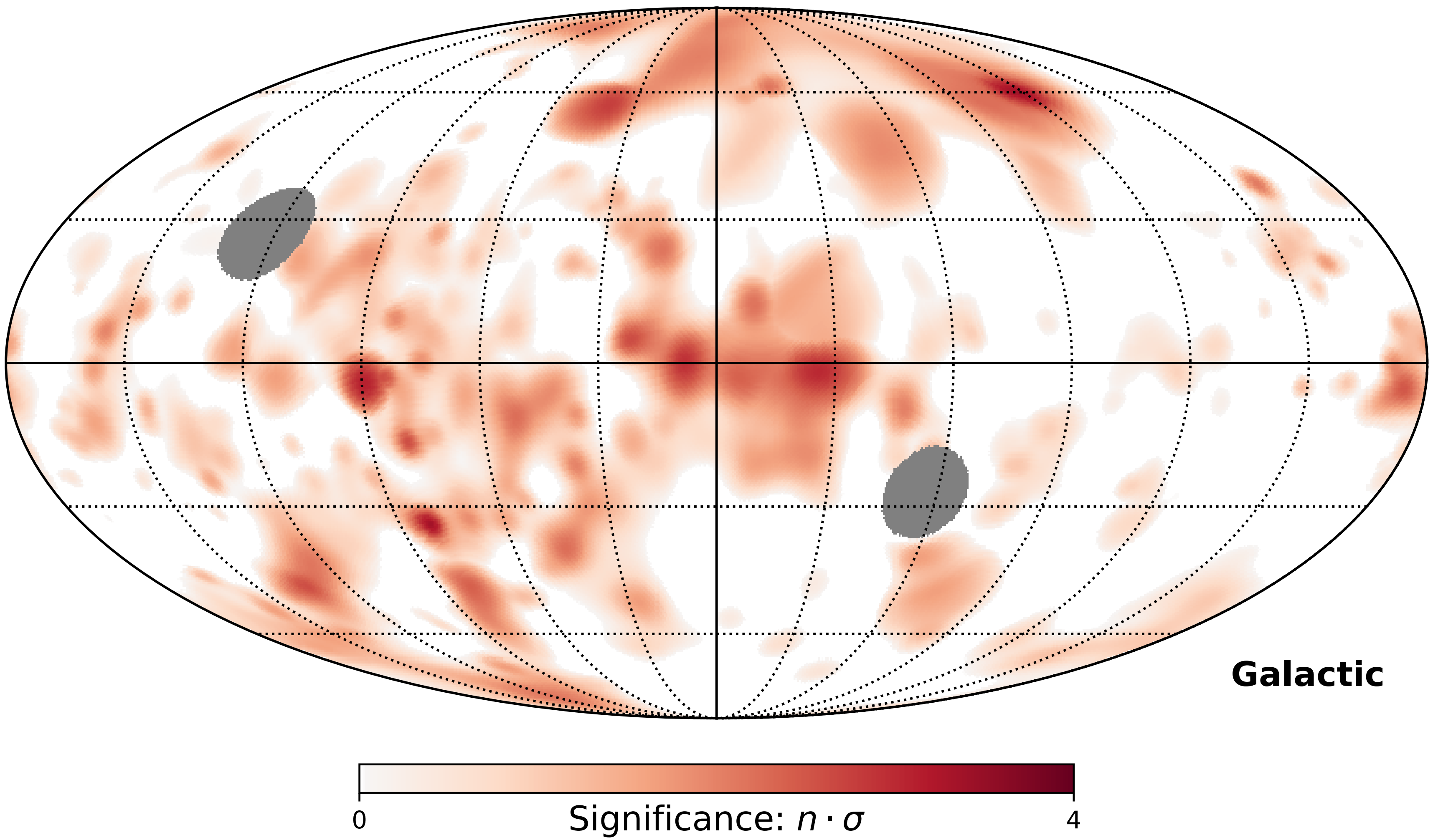
- X-ray catalogues 2RXS + XMMSL2
- IR WISE catalogue: X-rays associated with the core produce infrared light on dust at the center of the galaxy

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	$5^{+5}_{-3}\%$	$11^{+12}_{-7}\%$	$6^{+7}_{-4}\%$

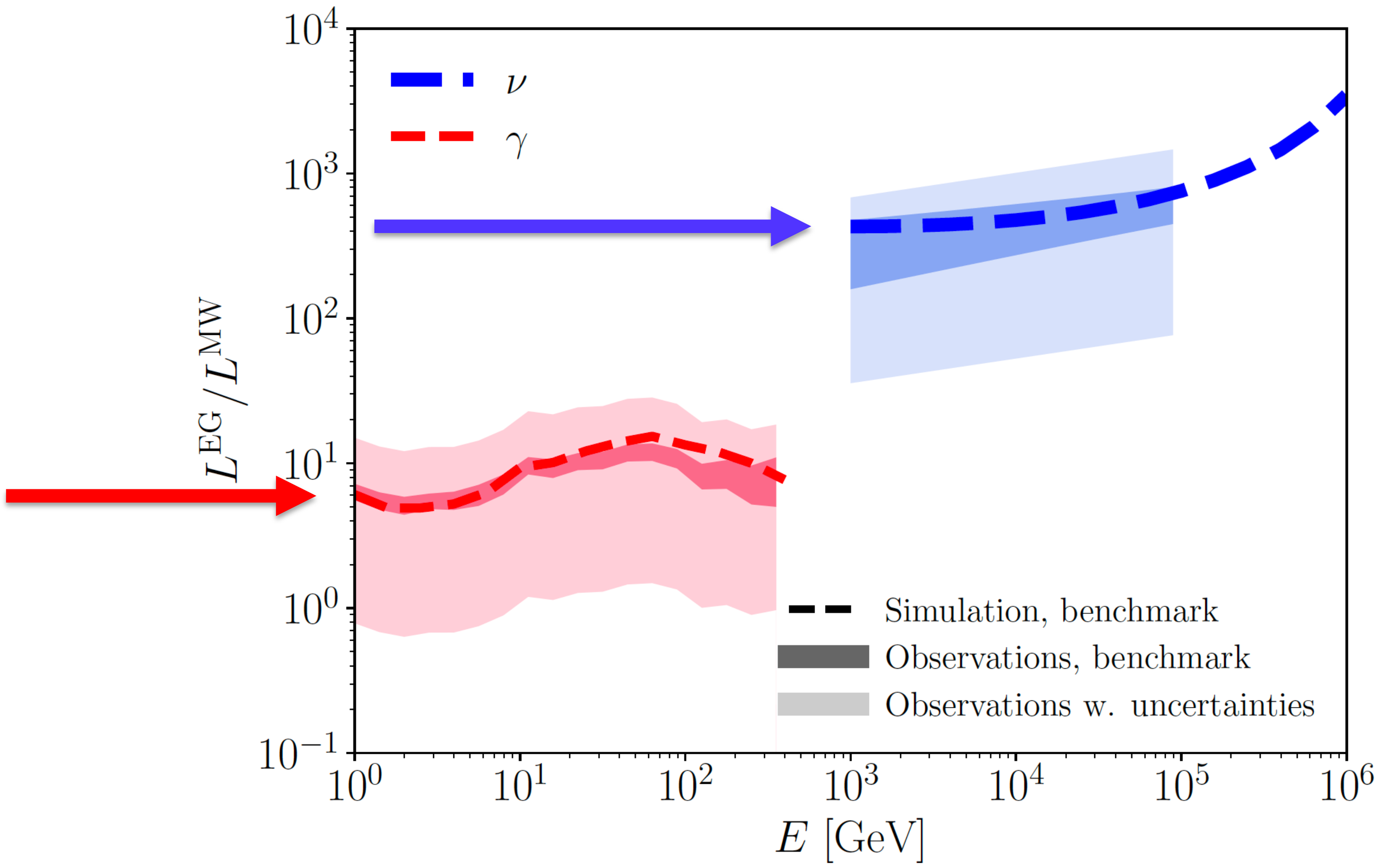


Fermi (GeV gamma rays) and IceCube (TeV neutrinos) see the same Galactic plane

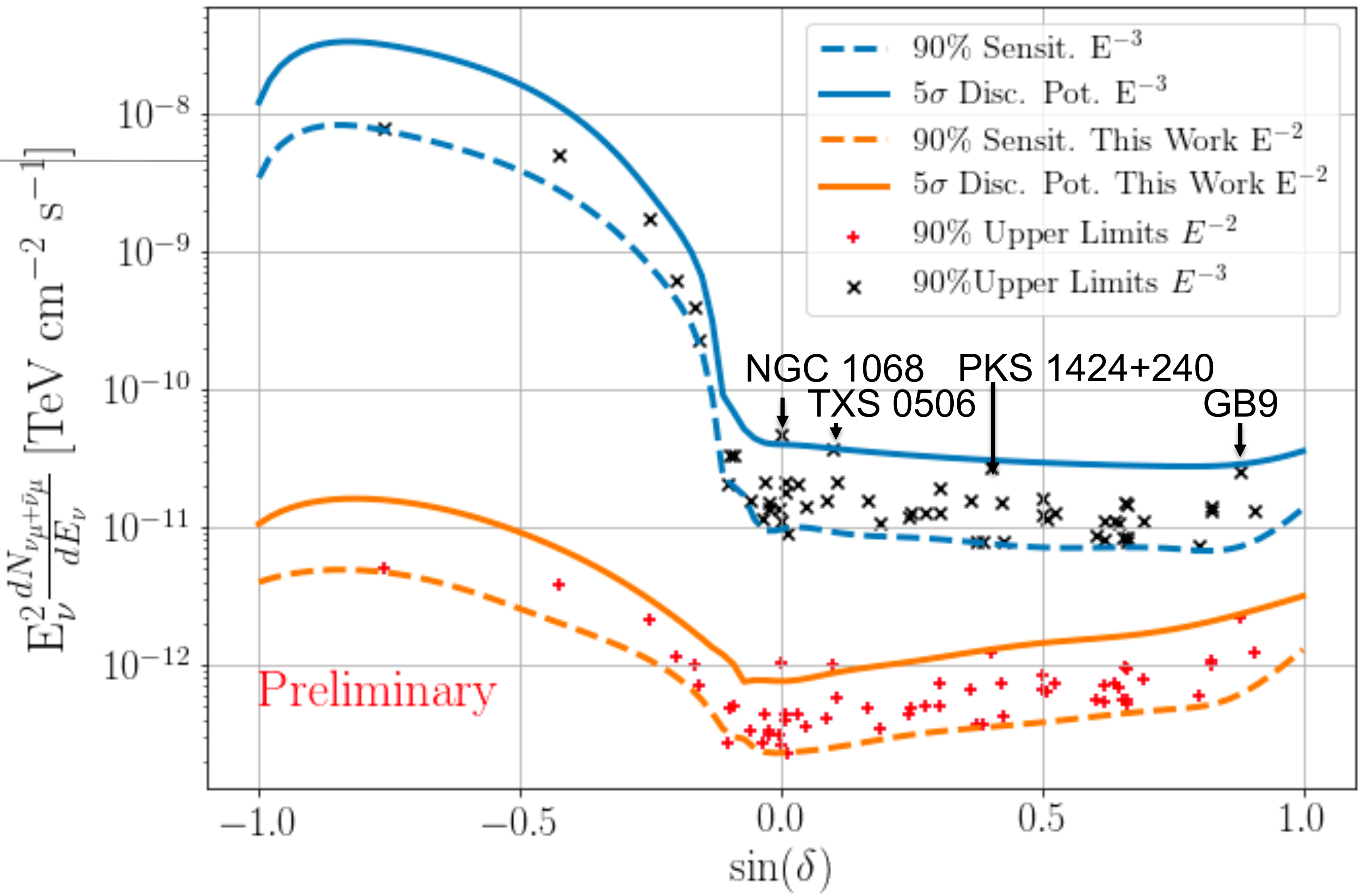


the flux is ~ 10% of the extragalactic flux at 30 TeV

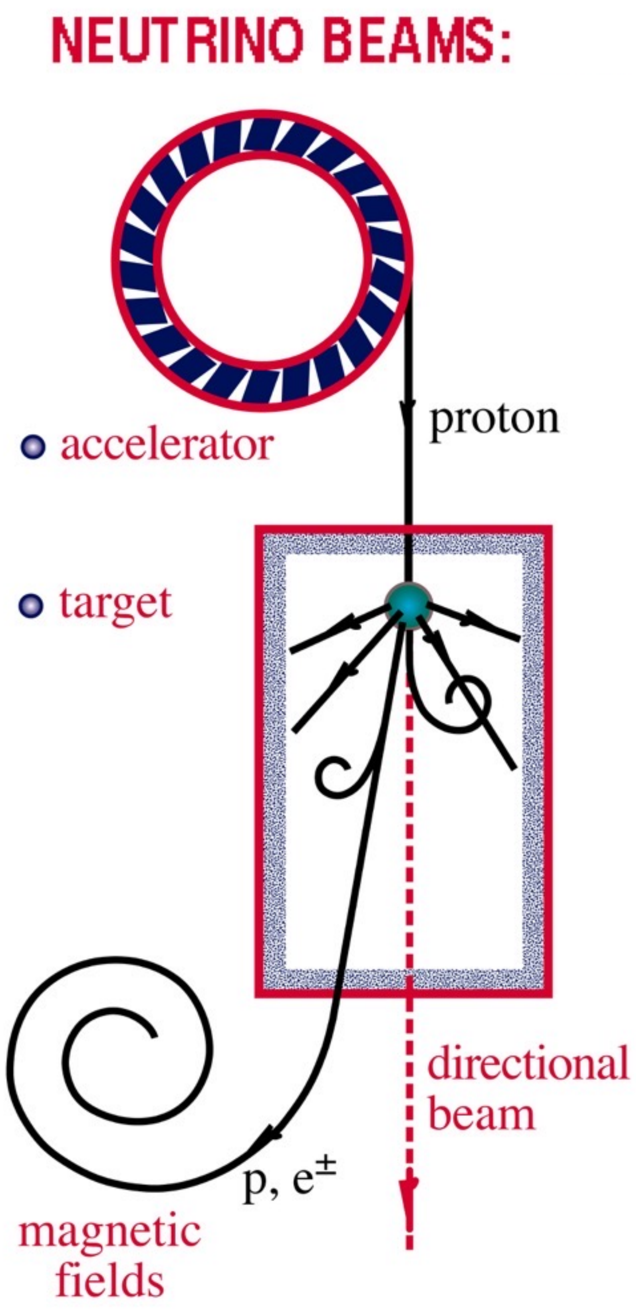
flux in other galaxies relative to our own: neutrinos (blue) and gamma rays (red)



Fang, Gallagher, Halzen (Nature Astronomy)



limits and interesting fluctuations (?)



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

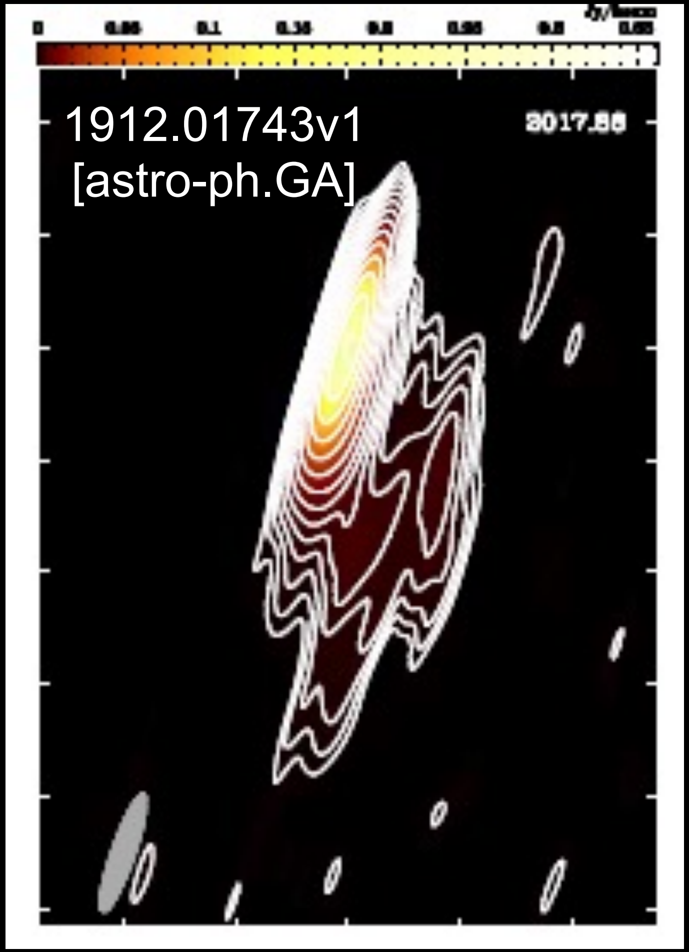
→ a target efficient at converting protons into neutrinos is unlikely to be transparent to high energy photons.

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

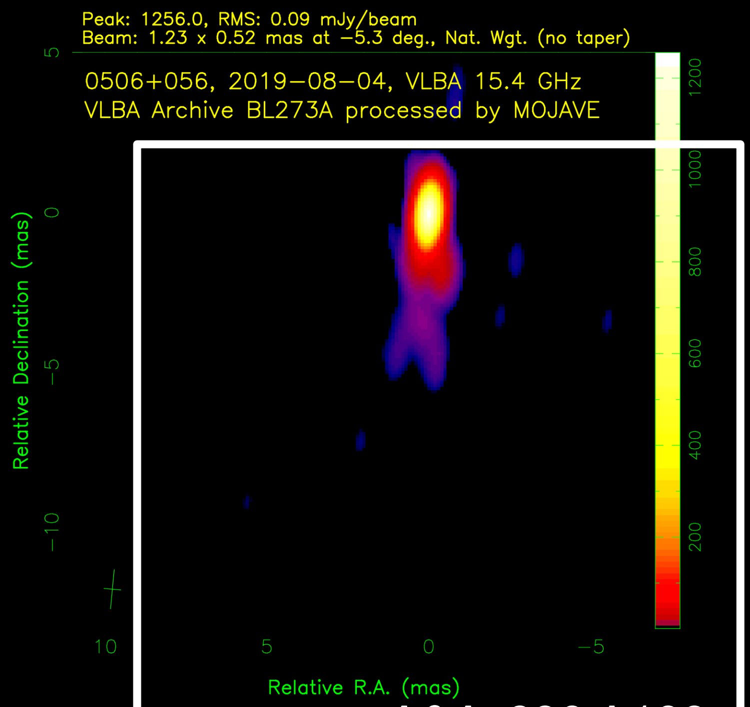
→ the energy in pionic photons is already absorbed in the target and likely to appear at MeV energies or below.

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

RADIO INTERFEROMETRY



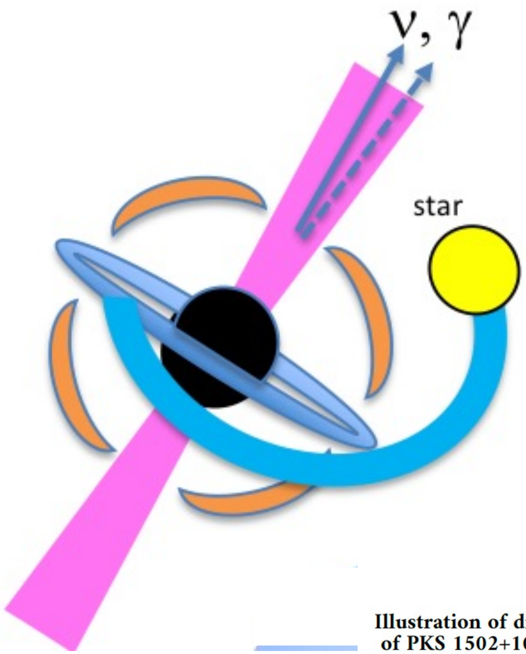
- core brightening observed in a radio burst that started 5 years ago
- beyond 5 milliarcseconds the jet loses its tight collimation



A&A. 630 A103
A&A. 632 C3

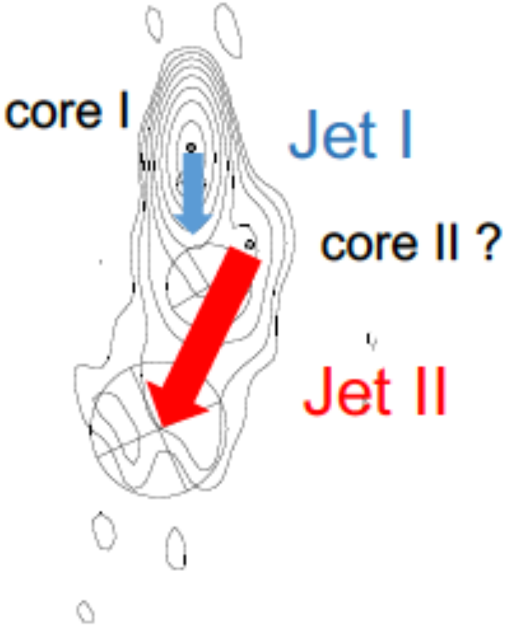
- PARSEC-SCALE JET STRUCTURE

- jet found a target after tens of pc to produce neutrinos
- obscures the gamma rays

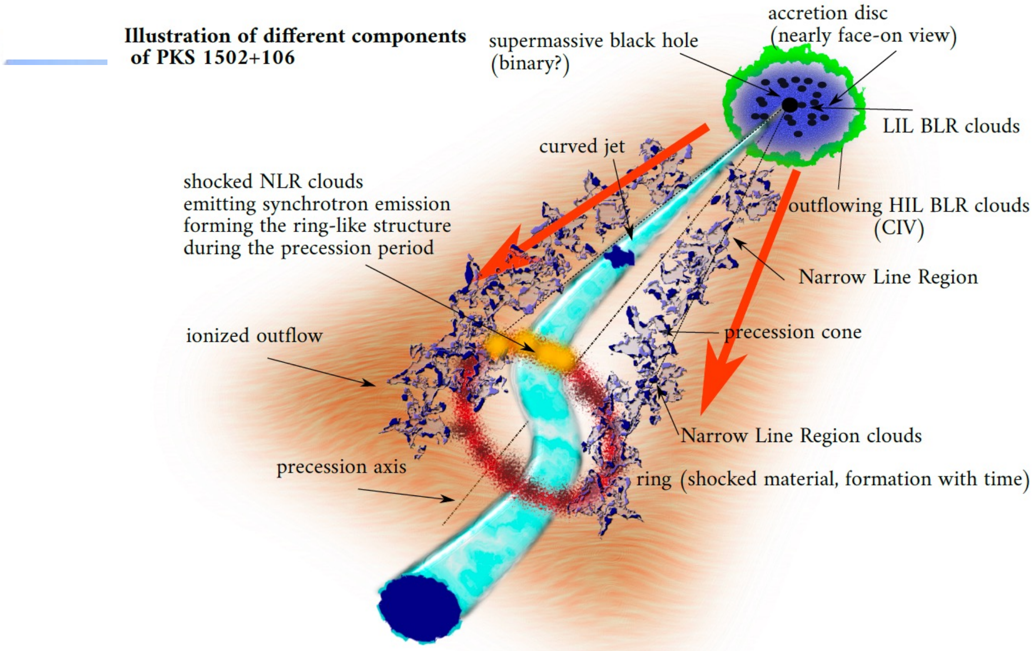


super
massive
star?

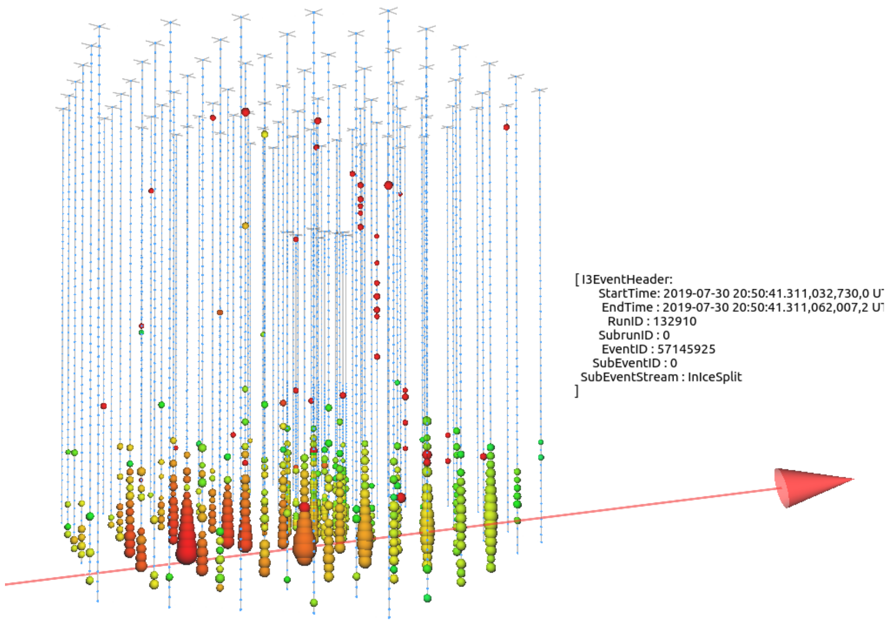
merging
galaxy?

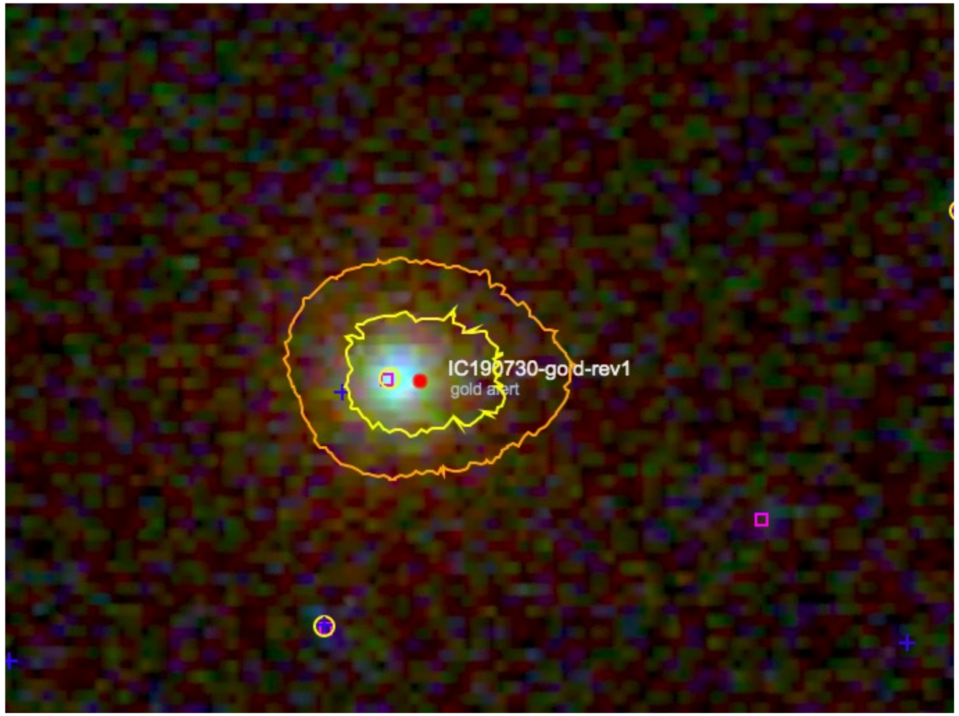


warped jet?



a second cosmic ray source ?





IC 190730: 300 TeV

- coincident with PKS 1502+106
- radio burst

[Previous | Next]

Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)*
on 7 Aug 2019; 12:31 UT
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

Tweet

On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.

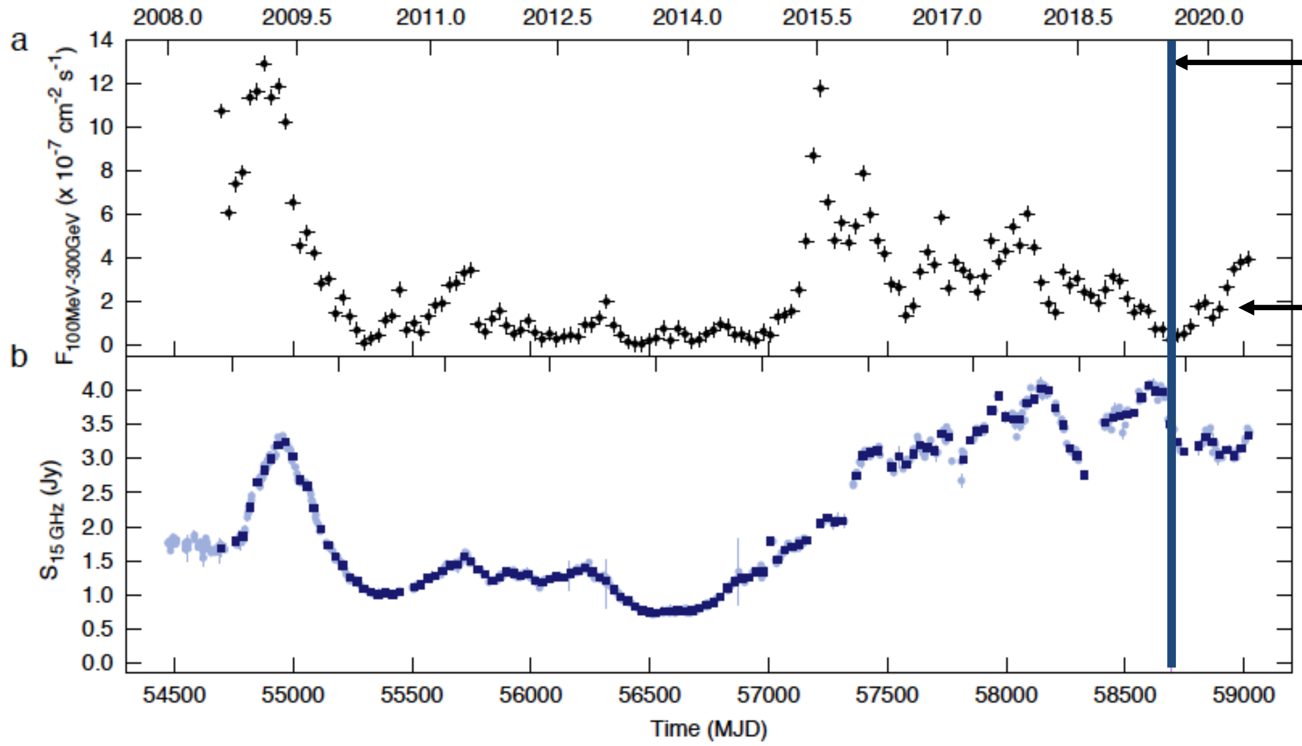
Related

12996	Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
12985	IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
12983	Optical fluxes of candidate neutrino blazar PKS 1502+106
12981	ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A
12974	Optical follow-up of IceCube-190730A with ZTF
12971	IceCube-190730A: MASTER alert observations and analysis
12967	IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106
12926	VLA observations reveal increasing brightness of 1WHSP J104516.2+275133, a potential source of IC190704A

PKS 1502+106

γ-ray

radio



300 TeV neutrino produced

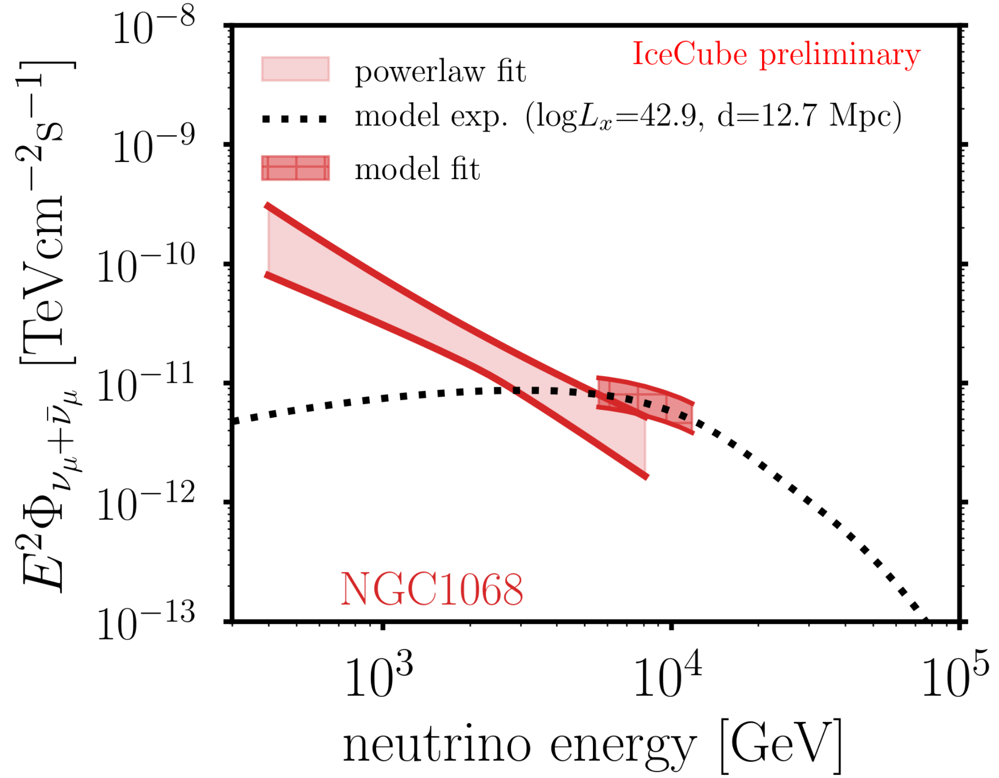
target moves through the jet: blocks photons

2009.09792 [astro-ph.HE]

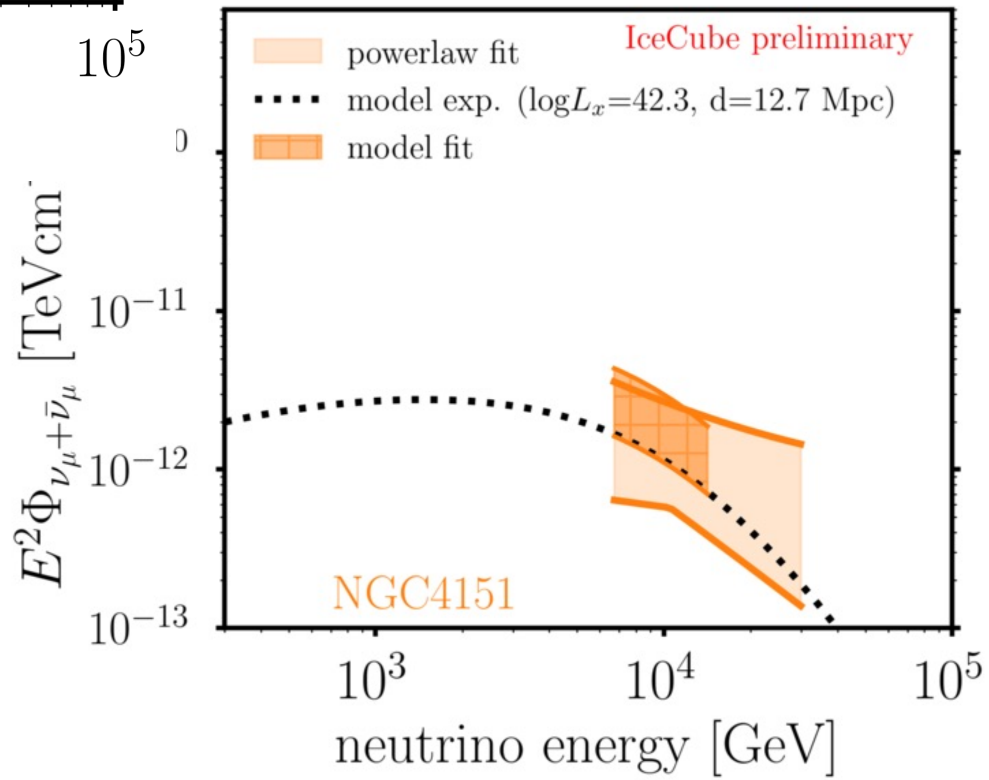
IceCube Trigger

43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```



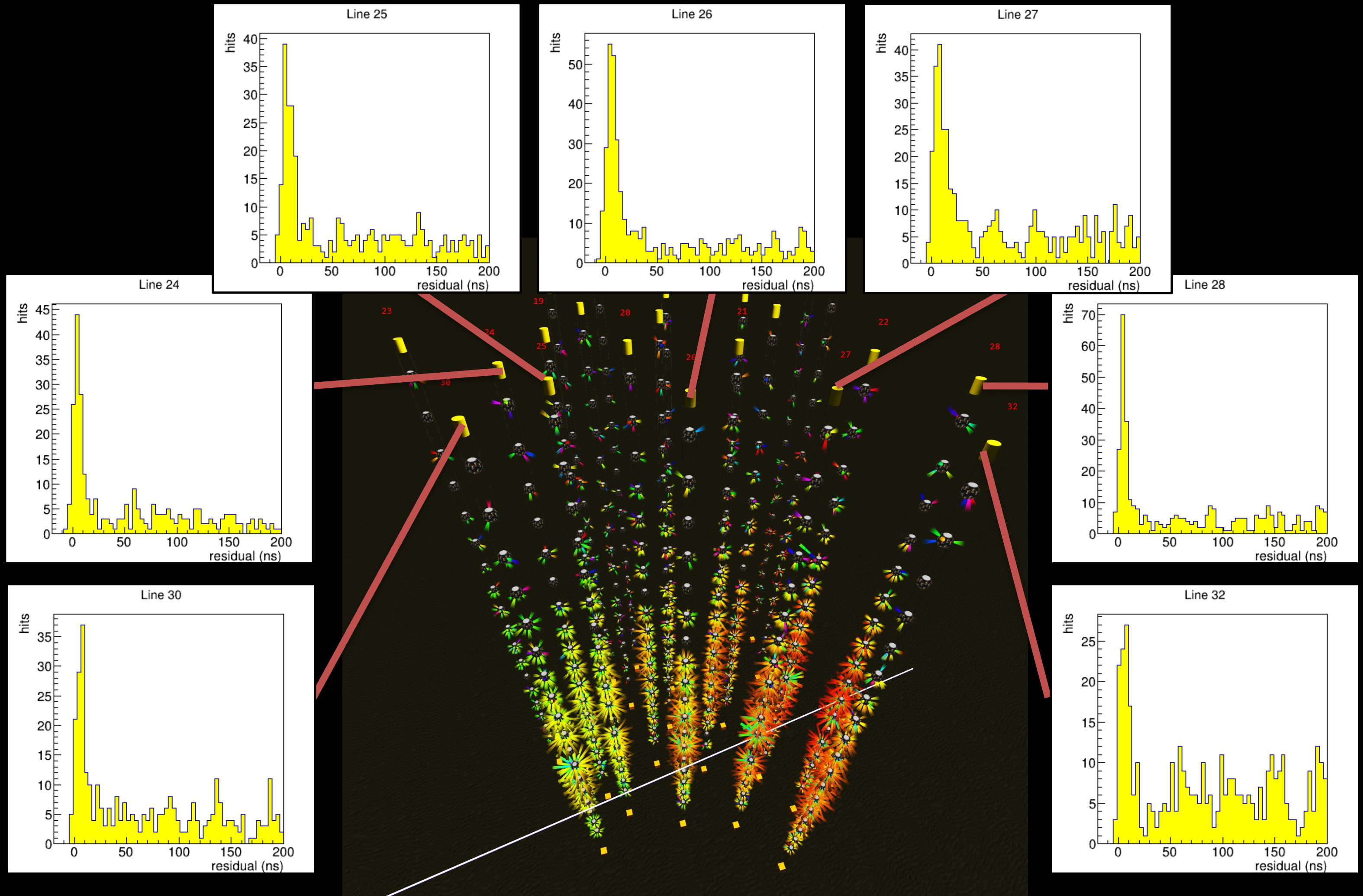
IceCube preliminary
powerlaw fit
model exp. (logL_x=42.9, d=12.7 Mpc)
model fit
NGC1068
$E^2\Phi_{\nu_\mu+\bar{\nu}_\mu}$ [TeVcm^{-2}s^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^3
10^4
10^5
neutrino energy [GeV]



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]

Uncharted Territory

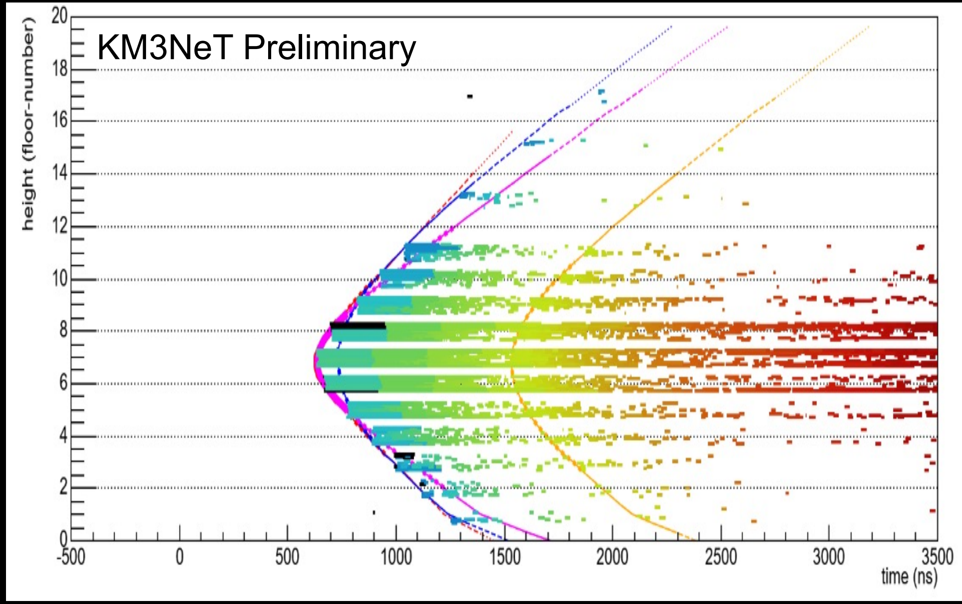
- Event is well reconstructed as a high energy muon crossing entire ARCA21 detector

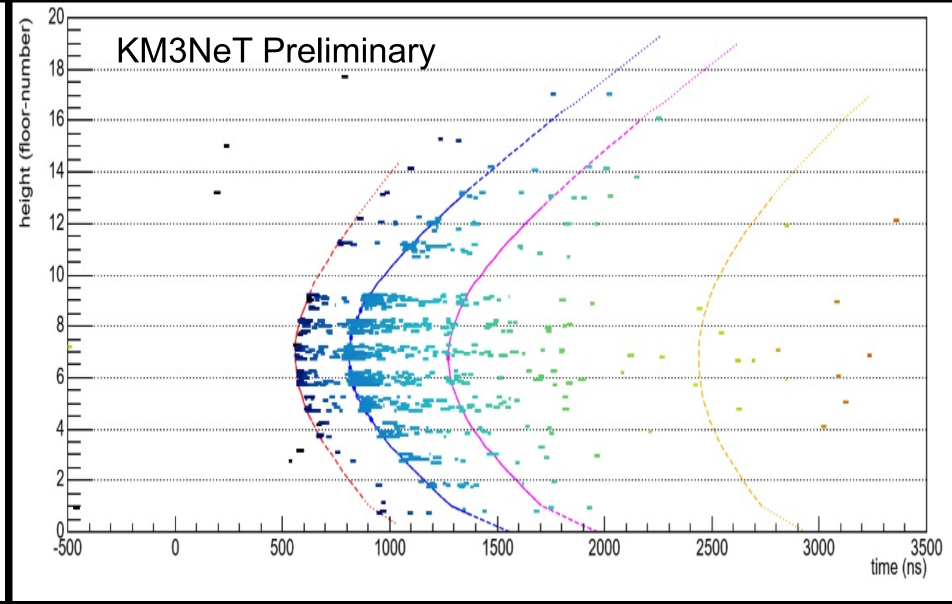


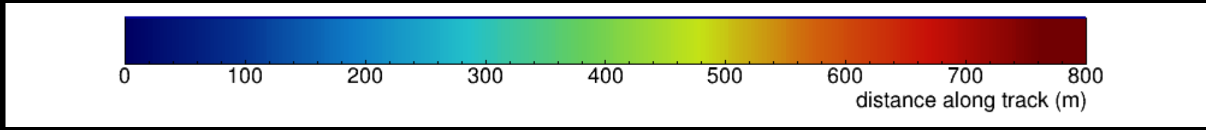
Obs: Lines numbered based on seabed layout

Uncharted Territory

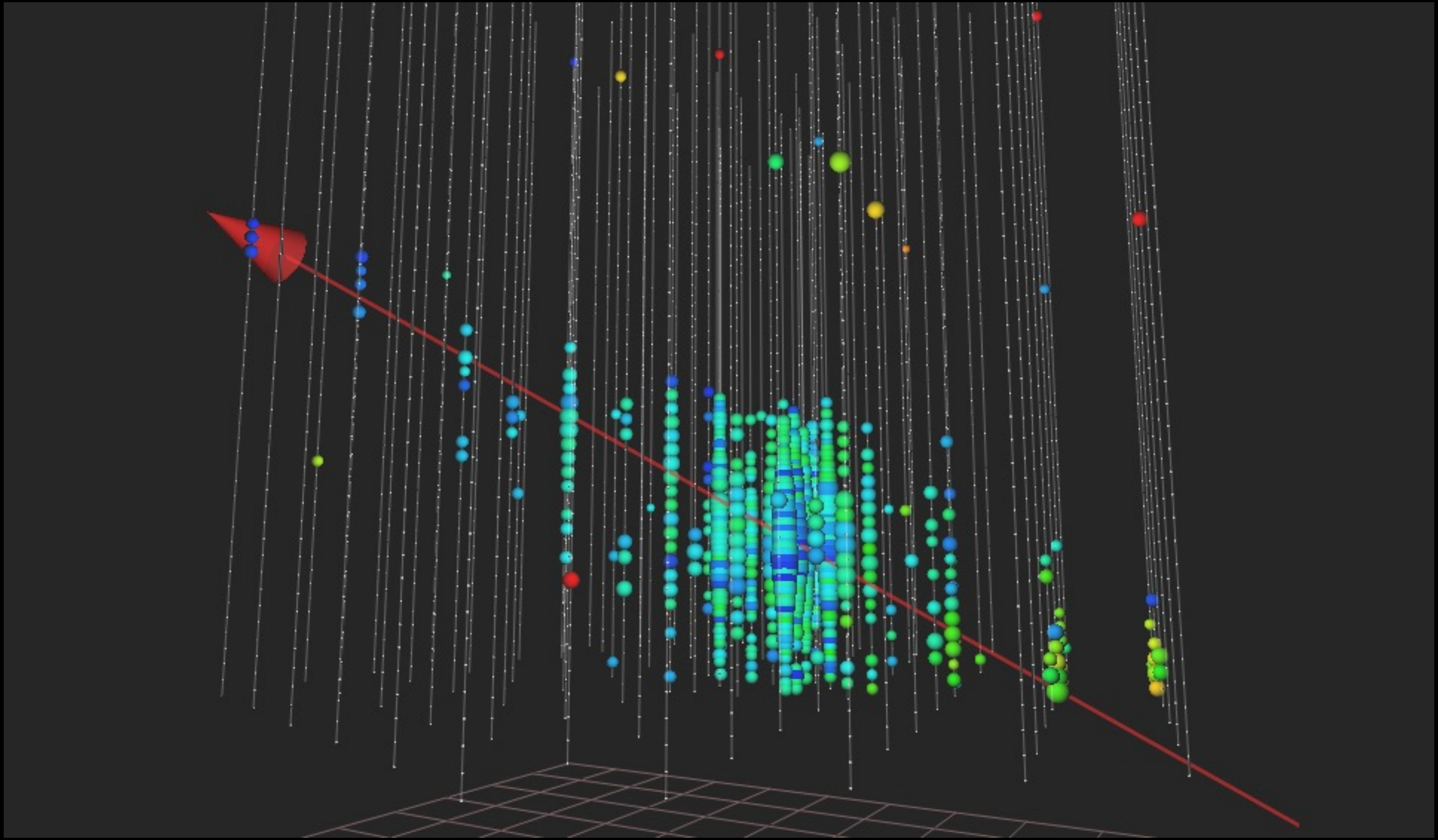
- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons
- Space-time distribution of light consistent with shower hypothesis associated with these energy depositions
- Low scattering is key to observing this richness of detail







IceCube and DeepCore

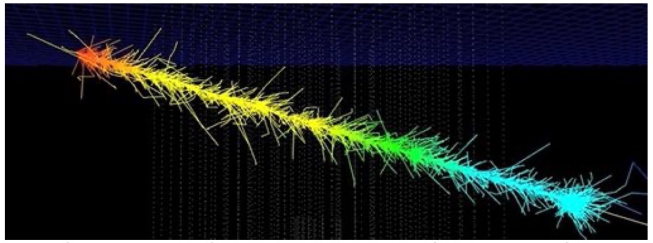


Galactic
- good pointing (energy not as helpful)
- Northern hemisphere
- smaller okay

Extragalactic
- good pointing
- large detector

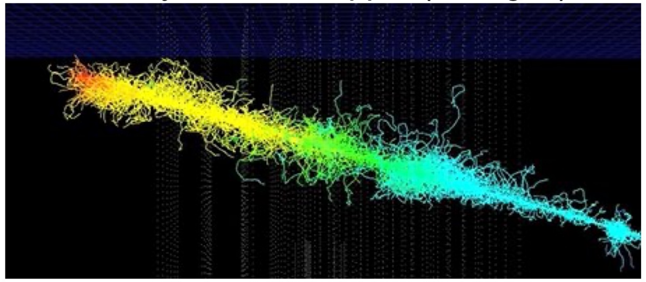
EHE/GZK
- large detector
- signal that travels
- sparse okay

Water Cherenkov
- Scattering ✓ → Good Pointing
- Absorption ✗ → Harder to make large detector

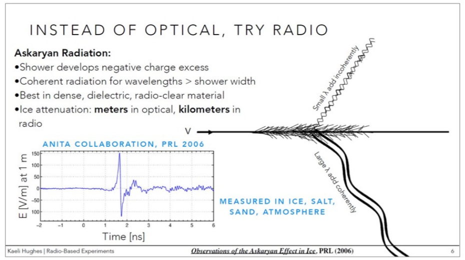


Courtesy: Claudio Kopper (Erlangen)

Ice Cherekov
- Scattering ✗ → Harder to point
- Absorption ✓ → Easier to make large detector

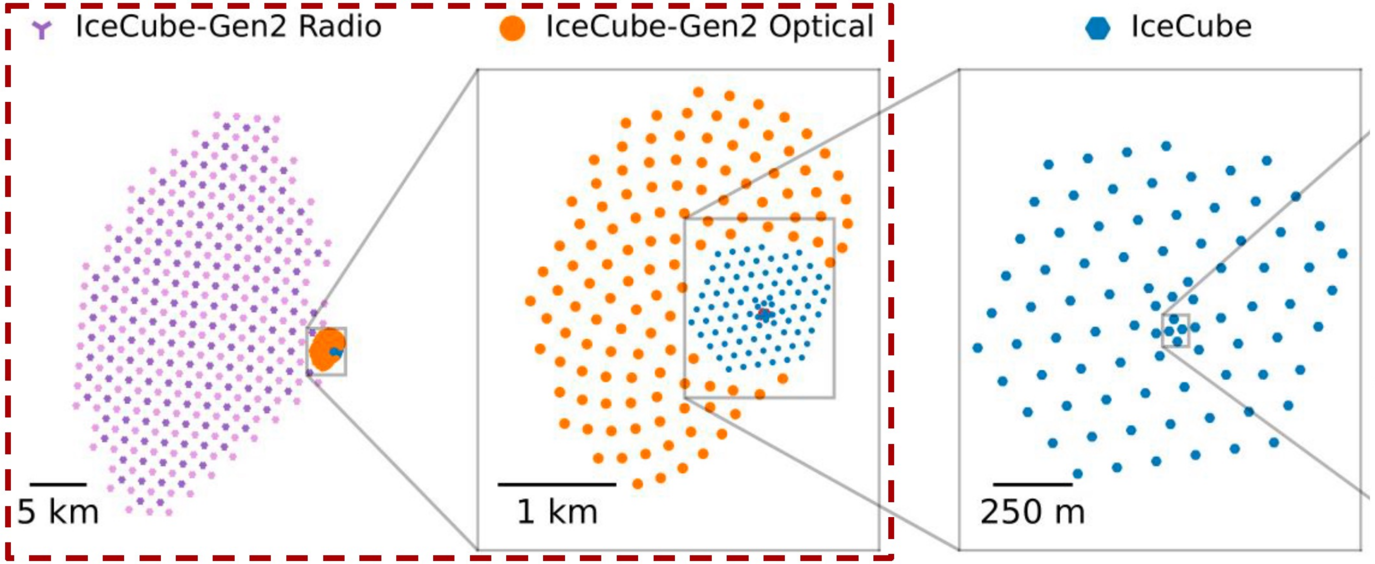


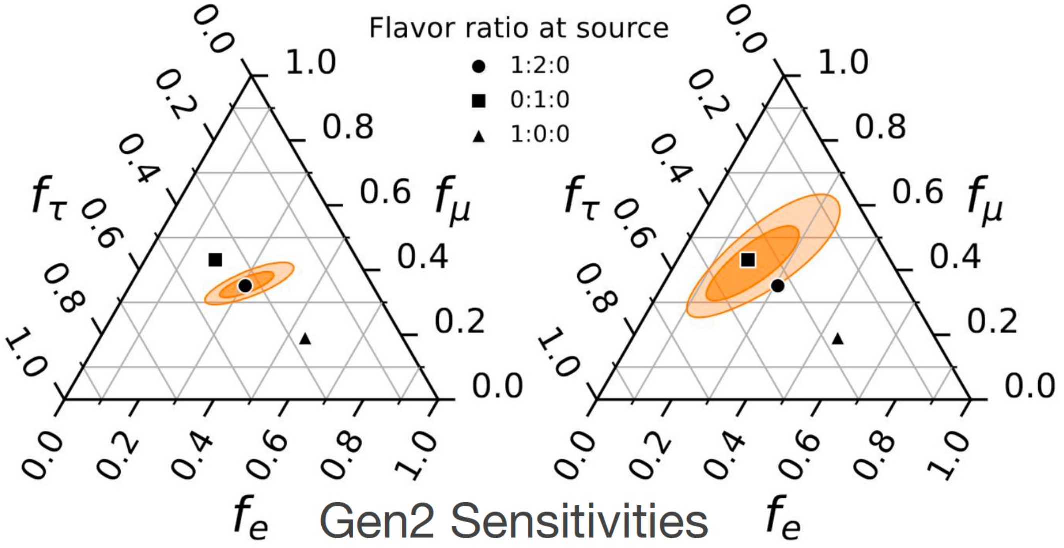
Radio
- Absorption ✓✓ → Can make detector very large
- Energy threshold very high



See talk by K. Hughes

The next generation of IceCube: IceCube-Gen2





IceCube-Gen2

- Increase effective volume
- Increase upper energy threshold

Goals:

- Measure neutrino flux at extreme energies (PeV+)
- Improve sensitivity to astrophysical neutrino sources by factor of ~5