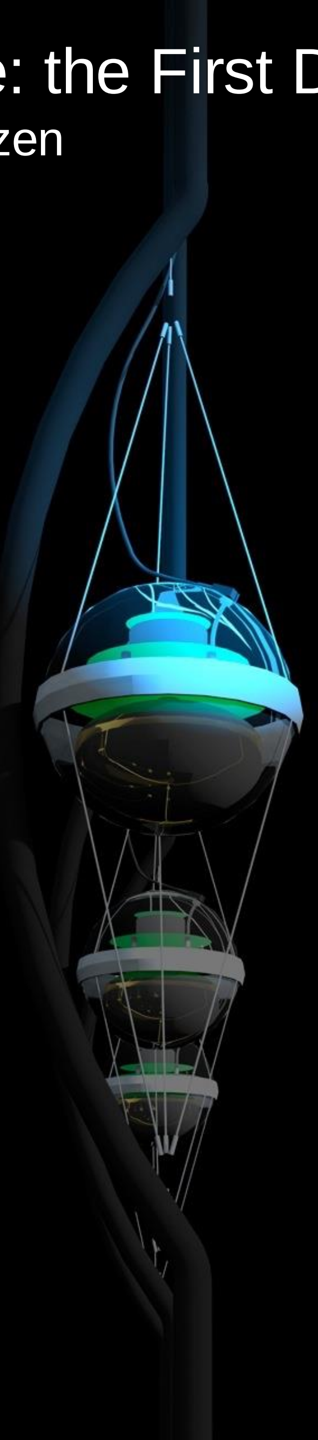
# IceCube: the First Decade of Neutrino Astronomy

francis halzen



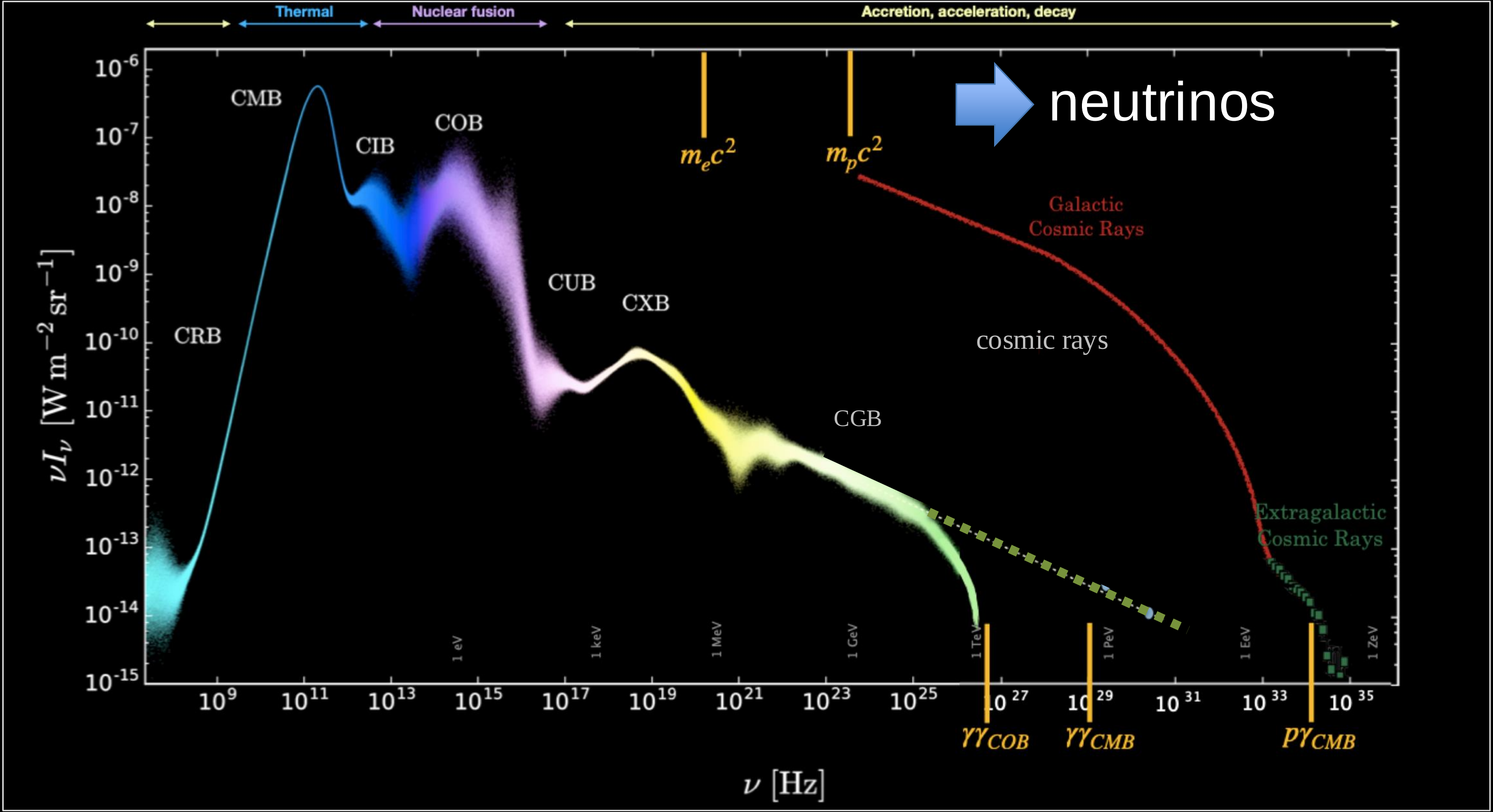
IceCube revealed:

- the large diffuse flux of $\pi^0$ gamma rays accompanying high energy neutrinos are not seen by Fermi: they appear at MeV energies, or below

- a Galactic neutrino flux that is an order of magnitude smaller than the flux in a typical galaxy contributing to the extragalactic diffuse flux: what is missing in our Galaxy?

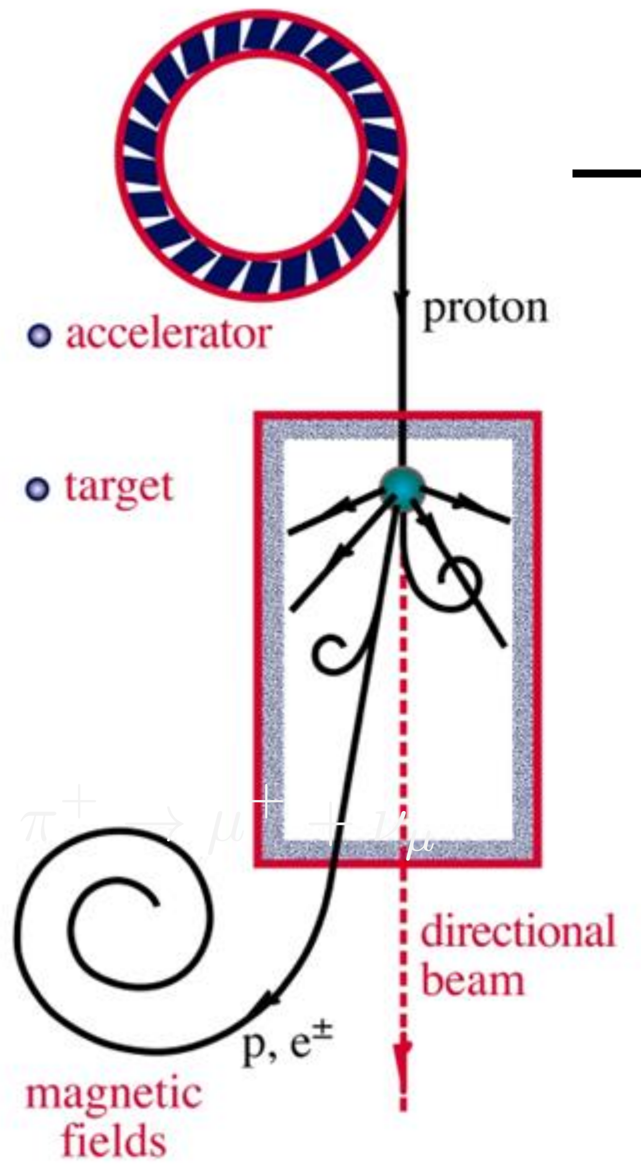
- first sources: neutrinos are produced in the dense cores of active galaxies

energy in the Universe as a function of the color of light




in the extreme universe neutrinos are unique astronomical messengers

# $\nu$ and $\gamma$ beams : heaven and earth




accelerator is powered by large gravitational energy

**supermassive black hole**

**nearby radiation**

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

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

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

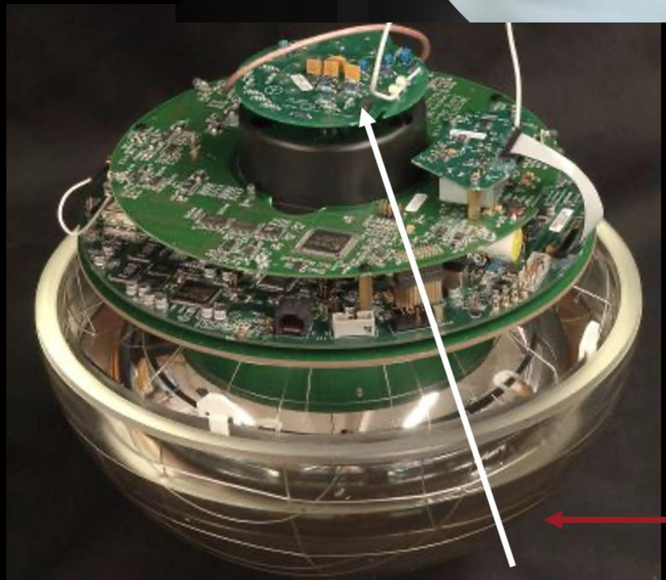
$$\rightarrow p + \pi^0$$

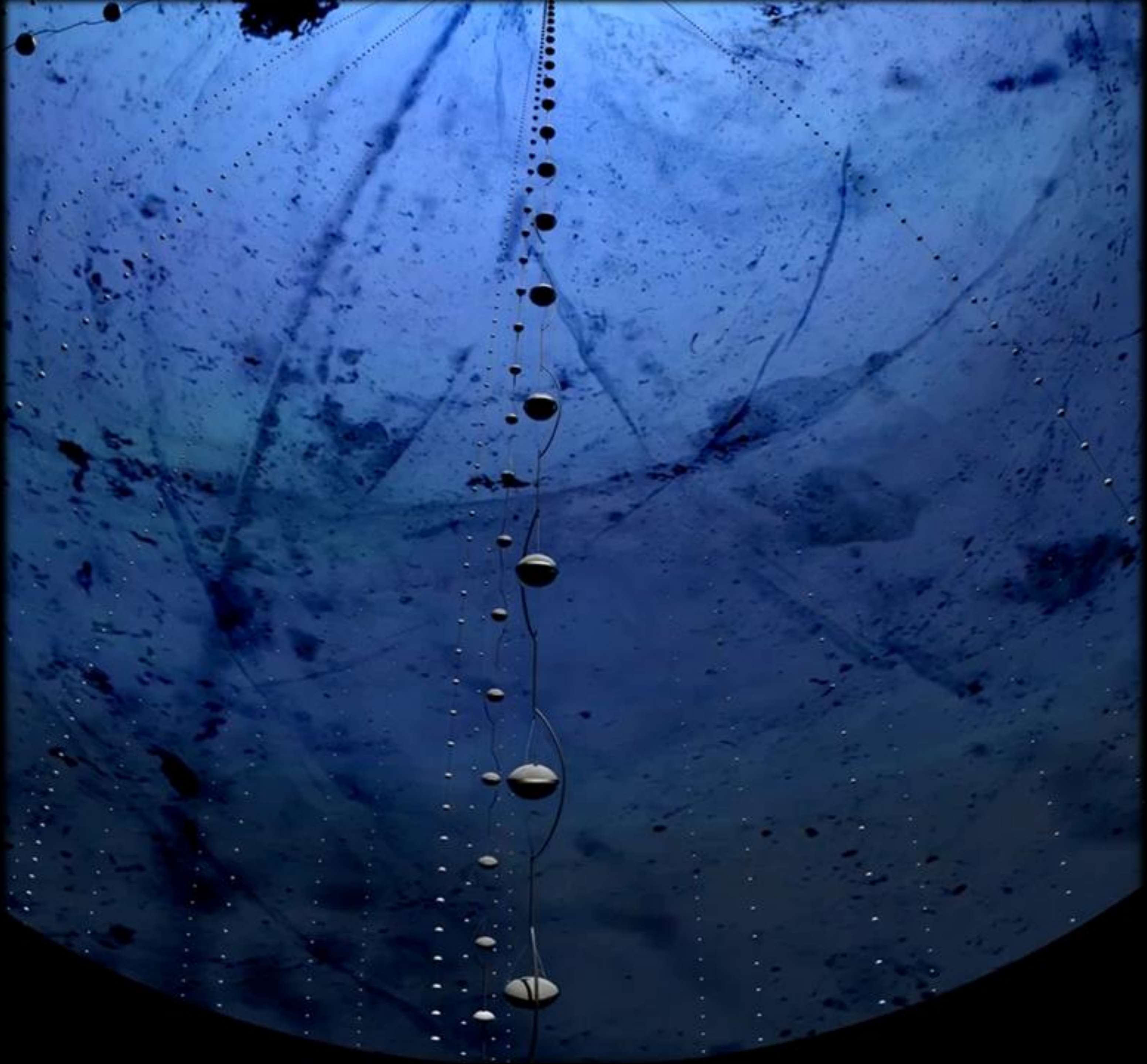
$$\pi^0 \rightarrow \gamma + \gamma$$

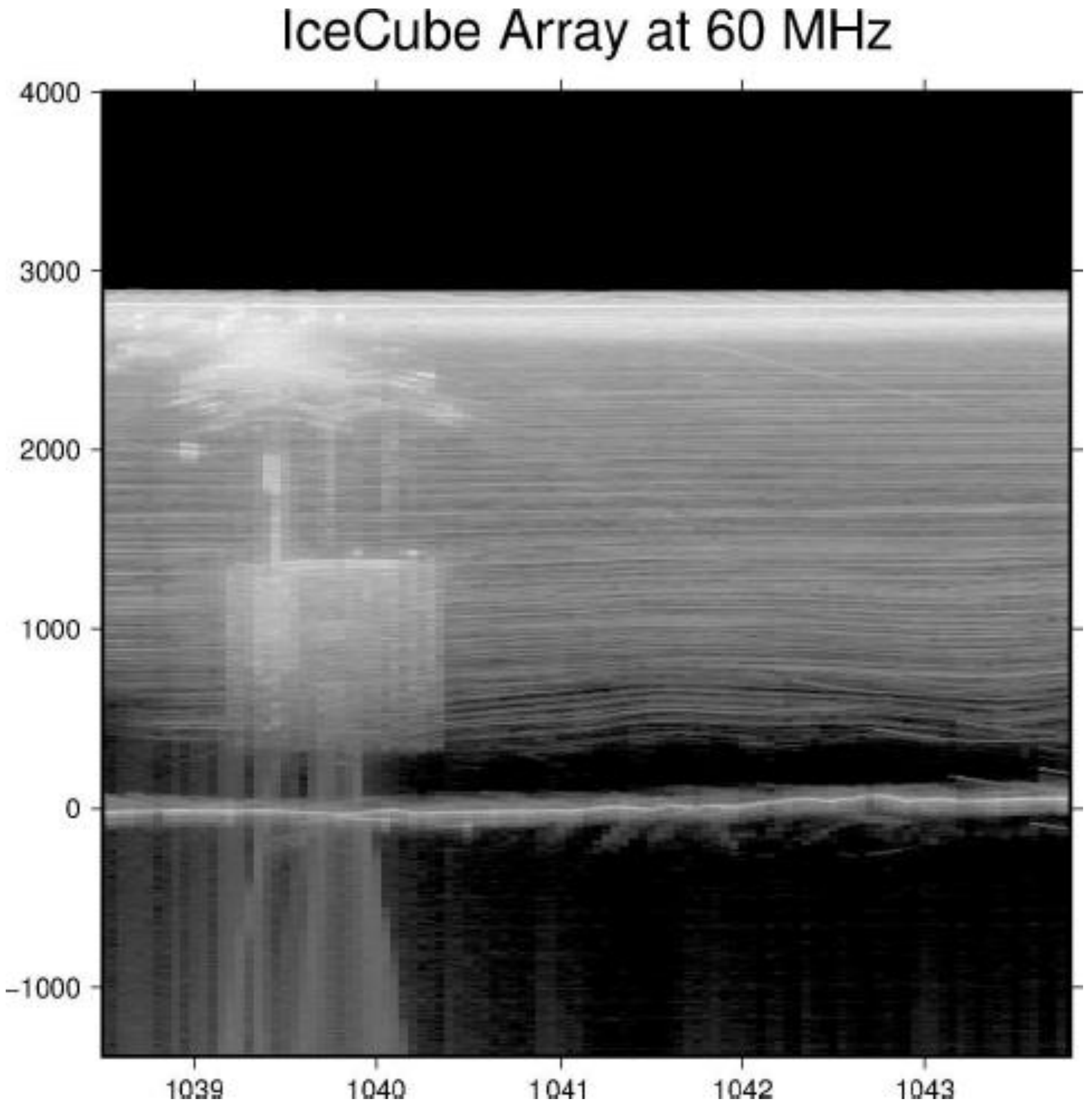
- ultra-transparent ice below 1.35 km
- absorption length: 100 ~ 250+ m

# IceCube:

5160 10-inch photomultipliers,
60 per string on 86 strings,
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

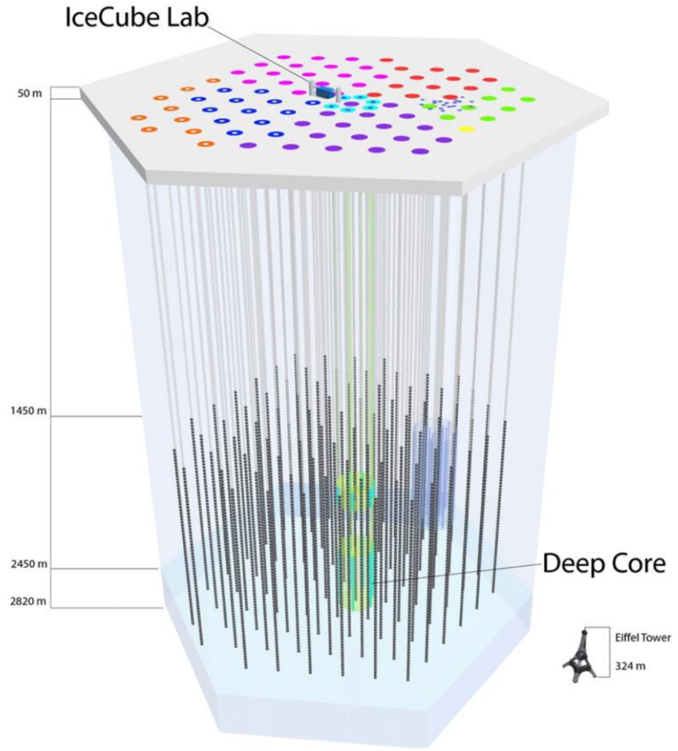
1450 m

2450 m

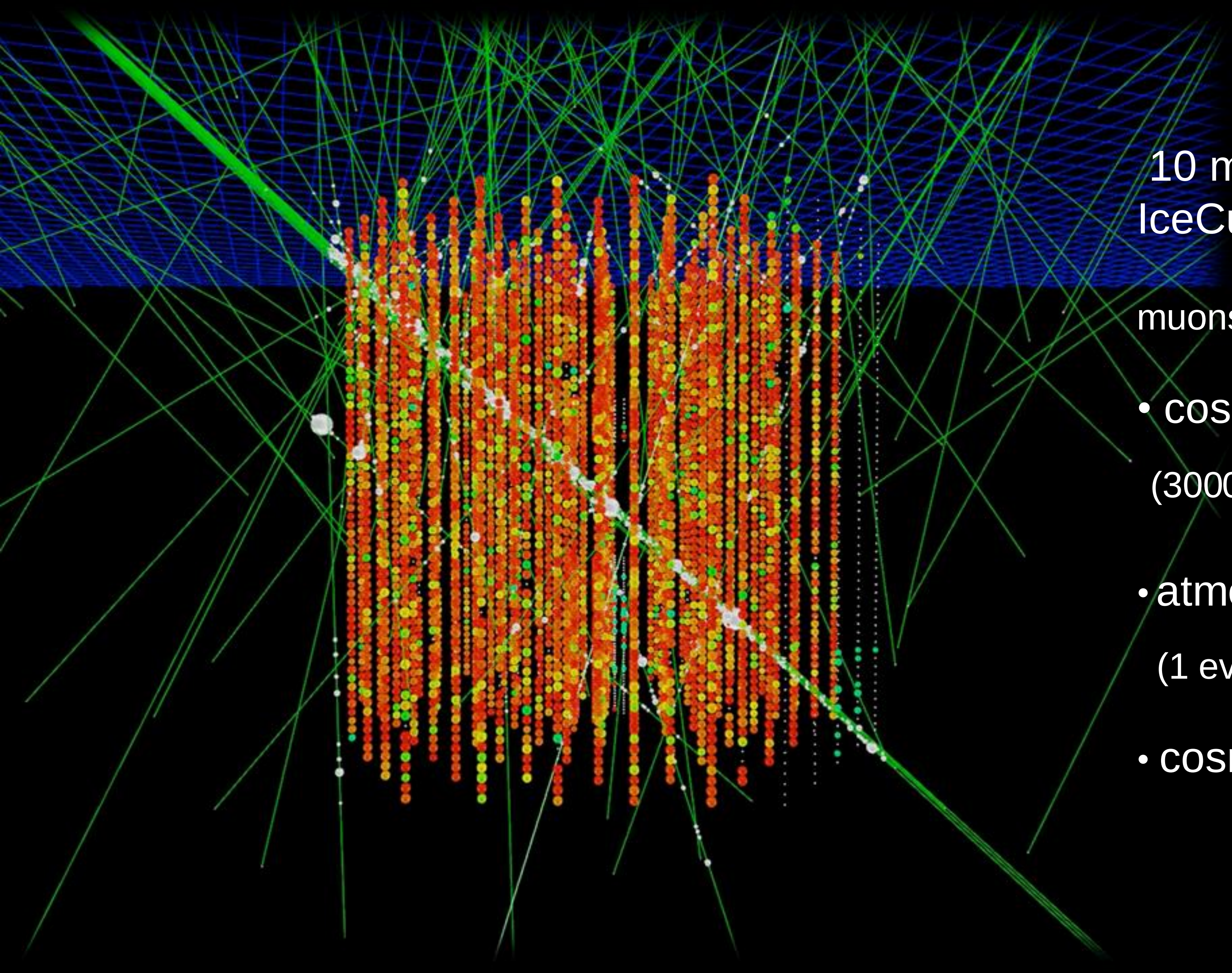
bedrock

# IceCube construction

(new upgrade 2025)




- 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



10 msec movie of IceCube taking data

muons detected per year

- cosmic ray muons ~ $10^{11}$

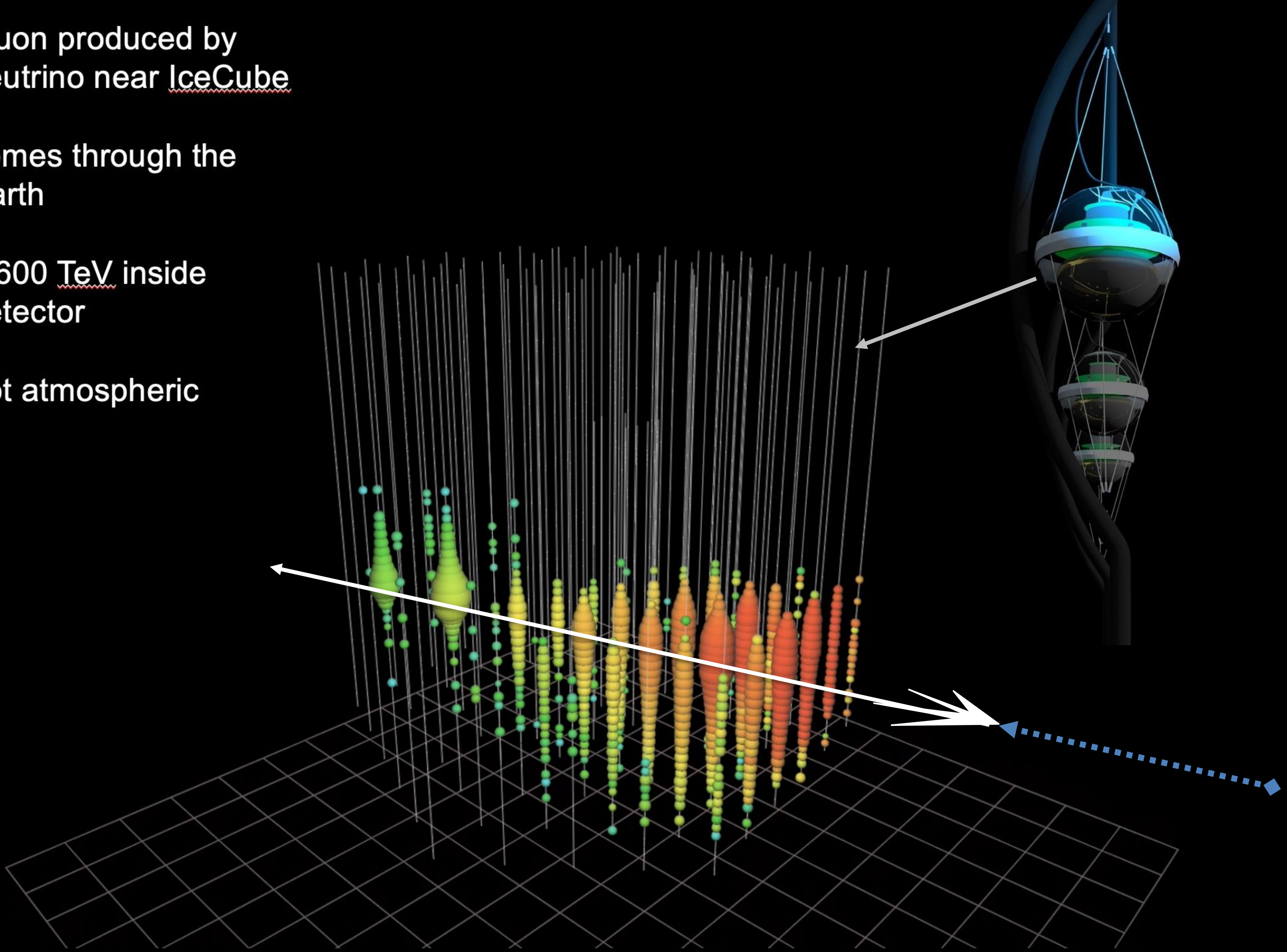
  (3000 per second)

- atmospheric neutrinos ~ $10^{5}$

  (1 every 5 minutes)

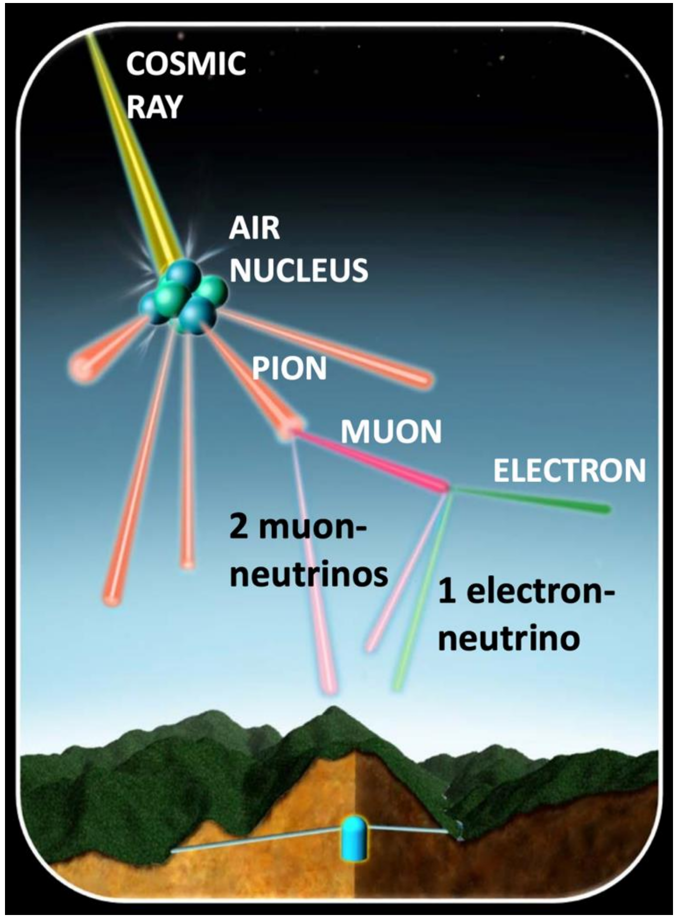
- cosmic neutrinos ~ 200

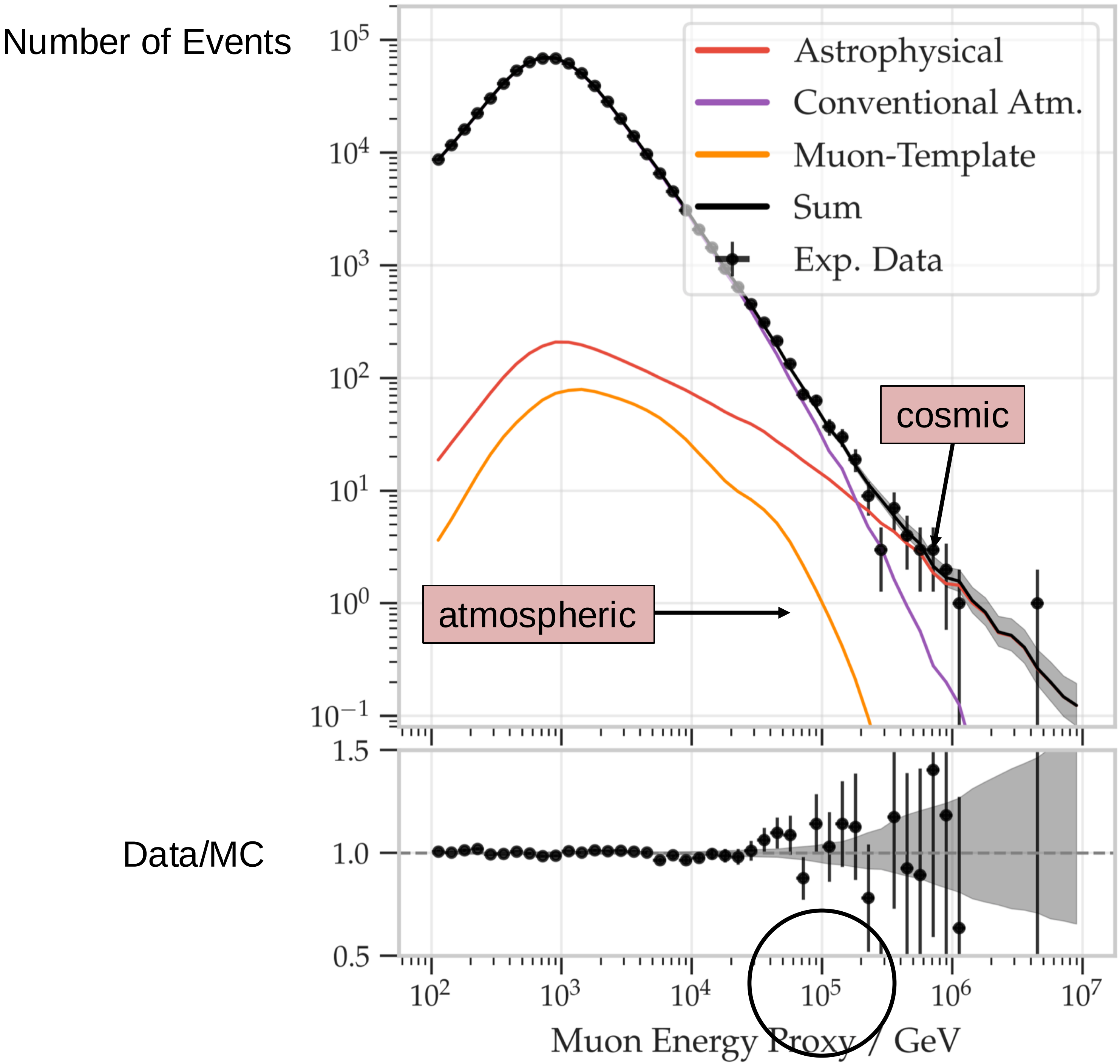
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric

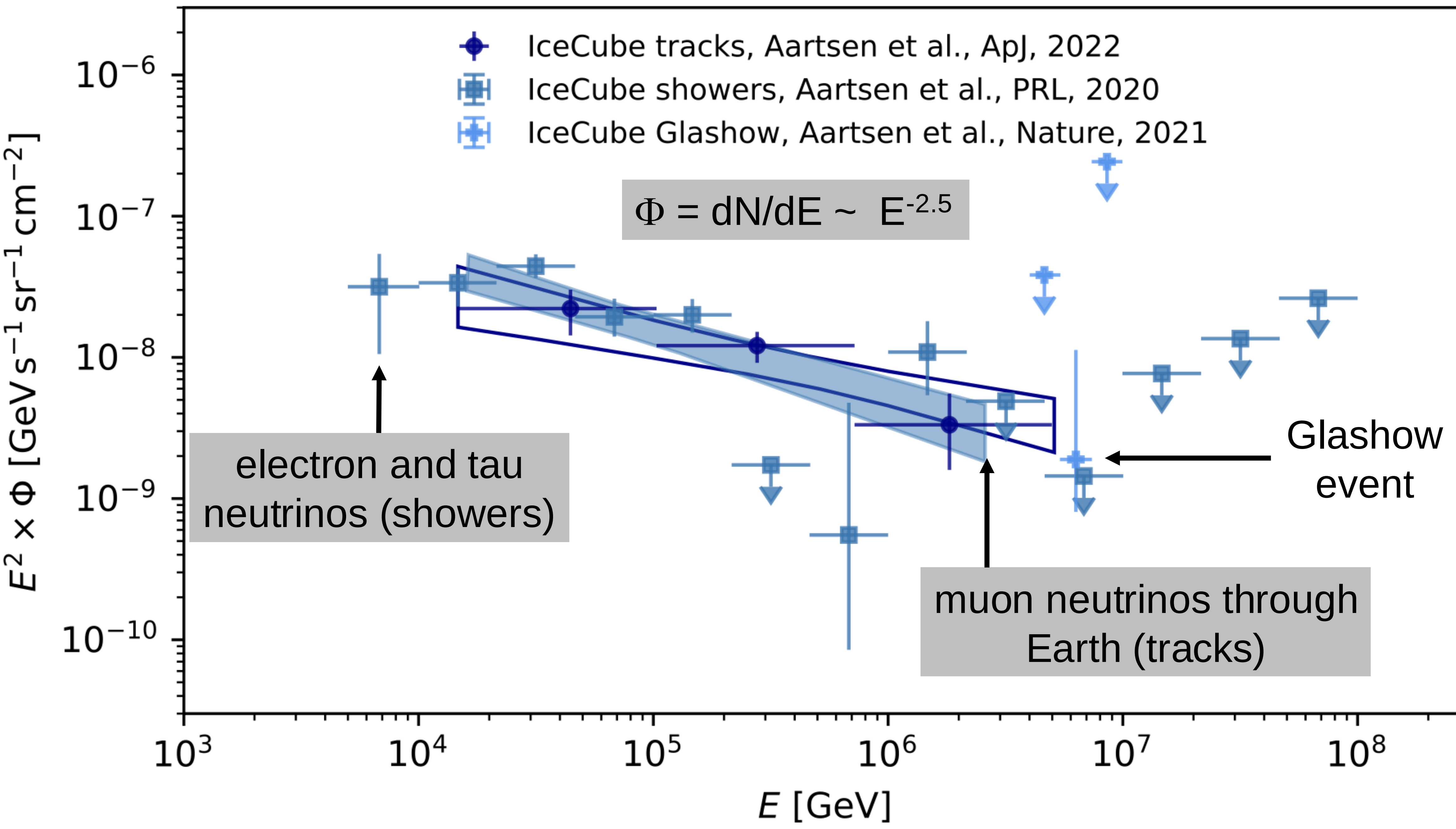


1 km$^3$ instrumented with 5160 PMT (10inch) below 1450m

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

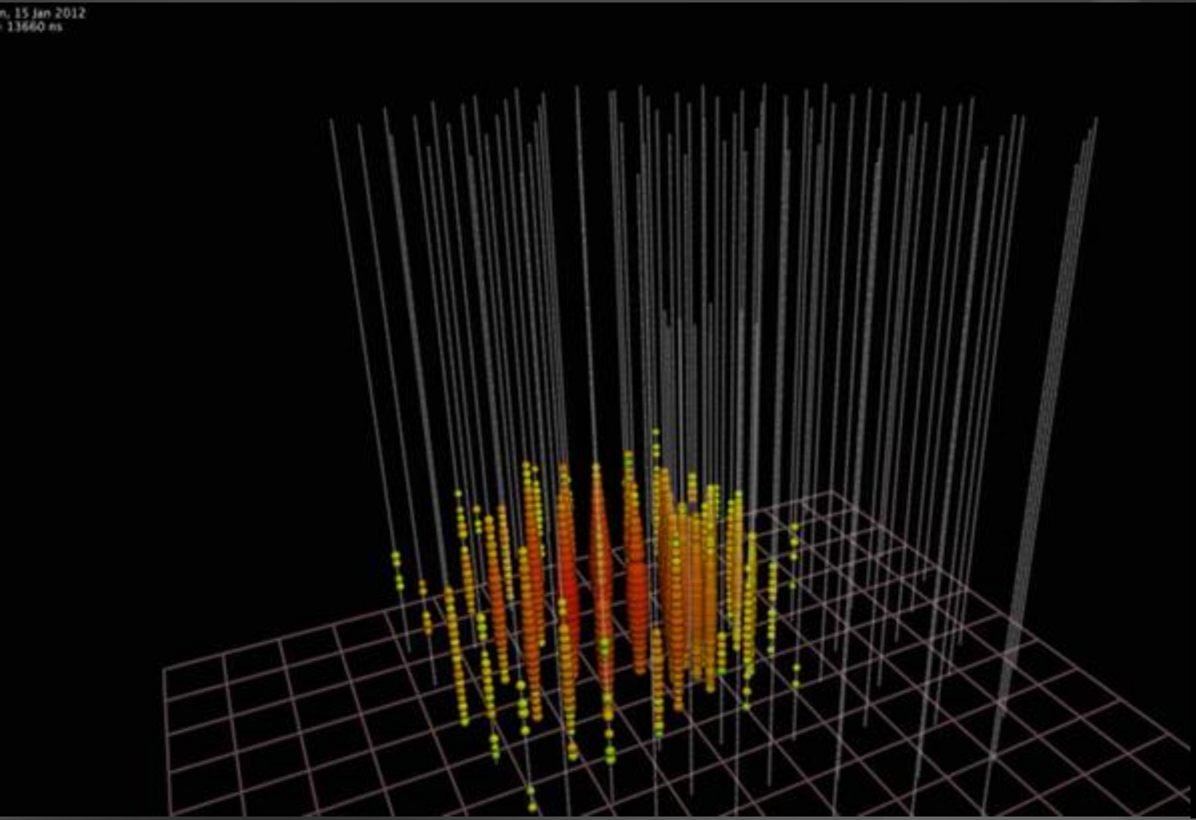




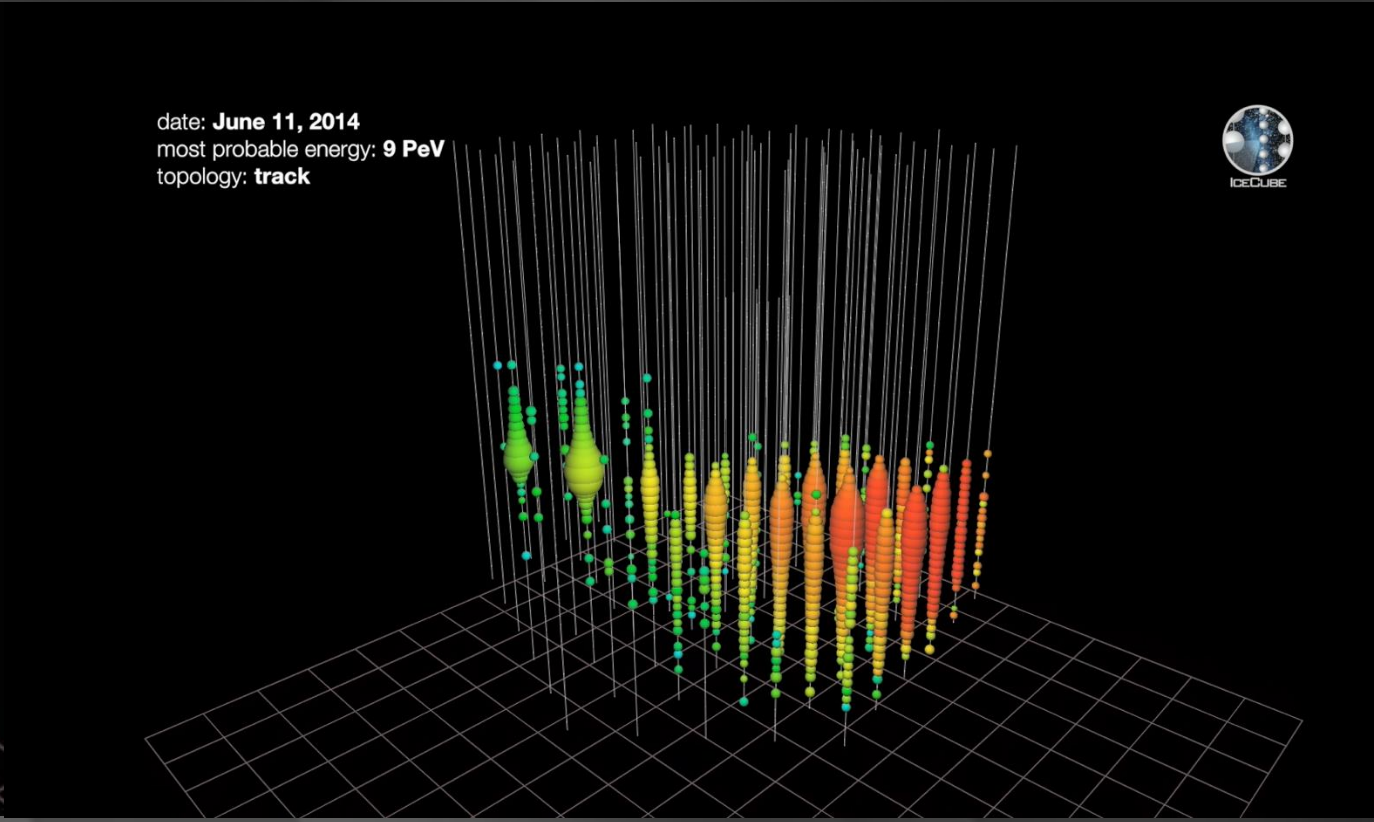
IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
$\Phi$ = dN/dE ~ $E^{-2.5}$
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
$E^2 \times \Phi$ [GeV s$^{-1}$ sr$^{-1}$ cm$^{-2}$]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

neutrinos interacting
inside the detector

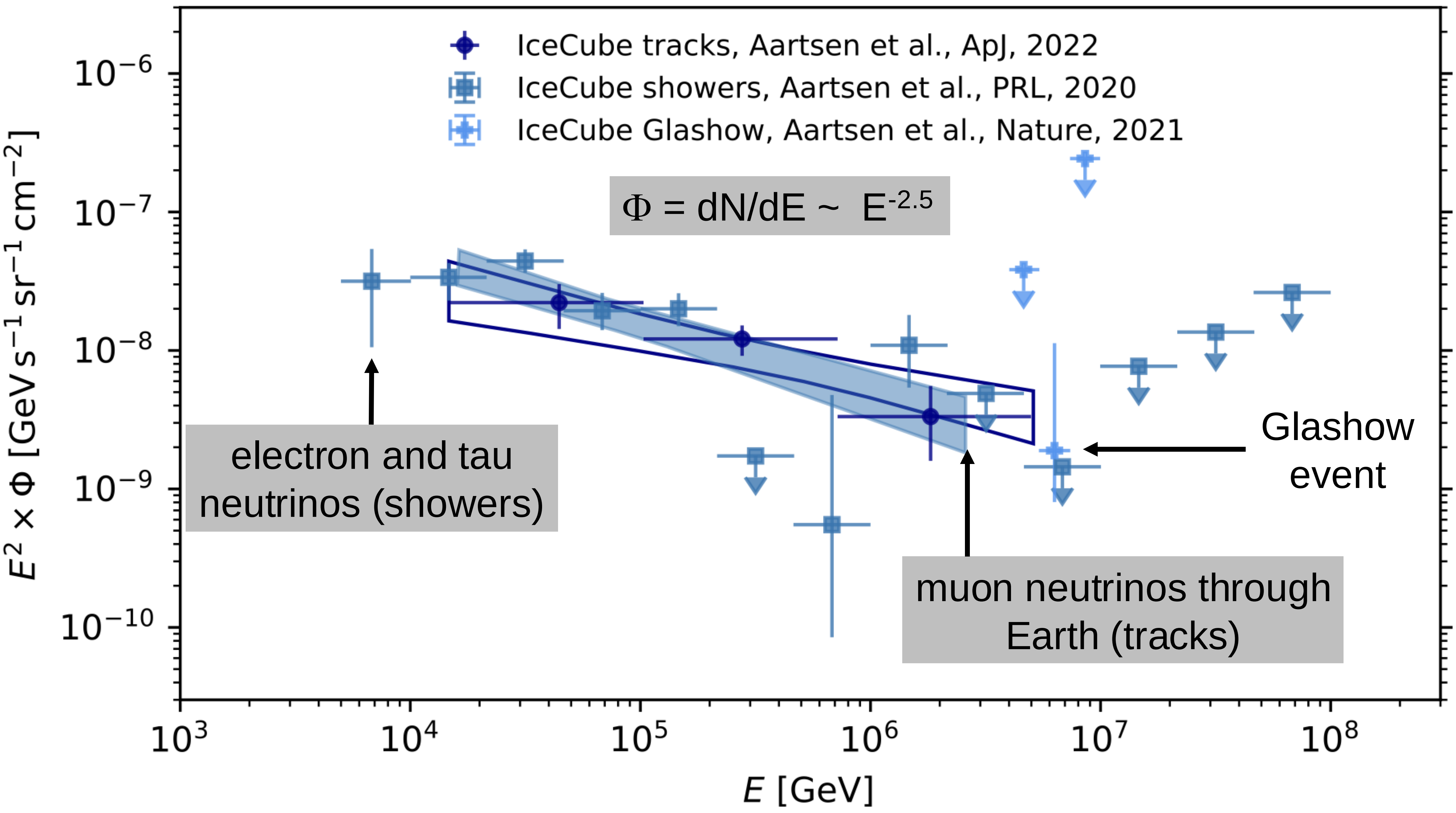


superior total energy
measurement
to 10%, all flavors, all sky

muon neutrinos
filtered by the Earth




superior angular resolution 0.3$^{o}$
including systematics



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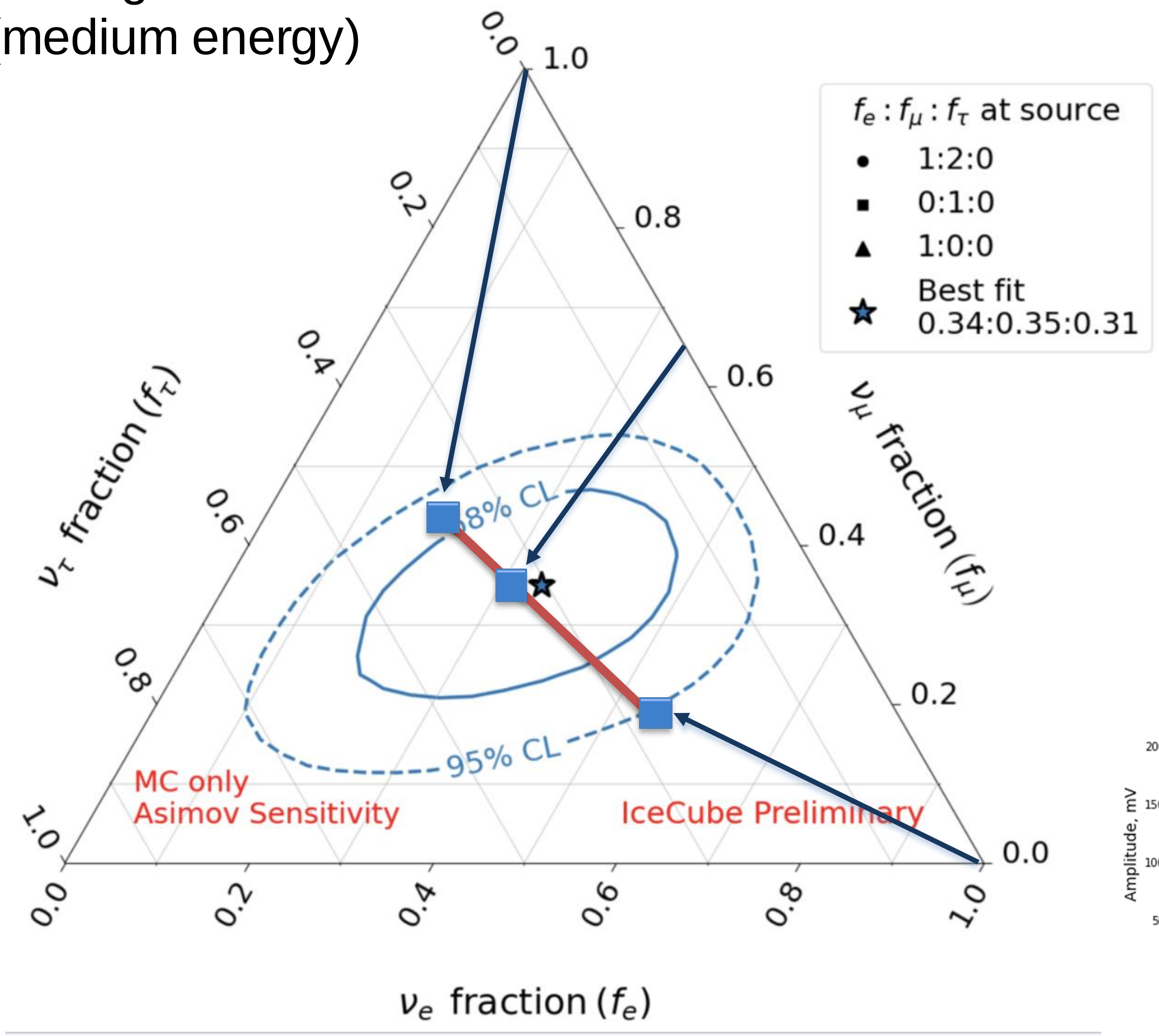
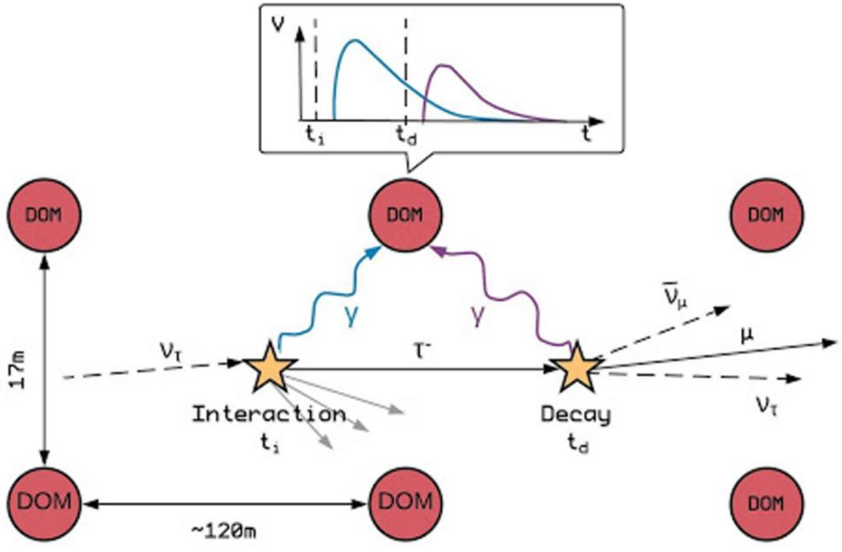
$10^7$
$10^8$

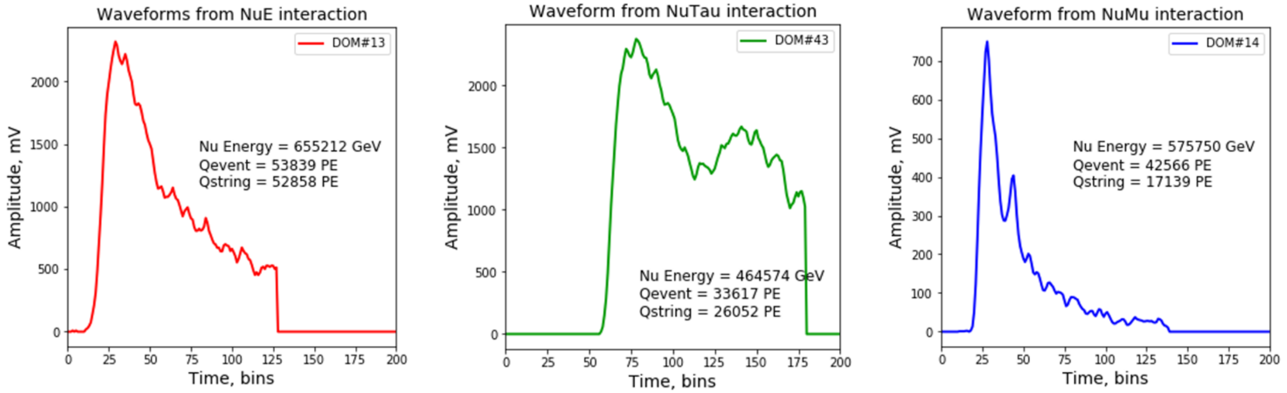
- oscillations of PeV neutrinos over cosmic distances to 1:1:1
- high energy (> PeV) nutau neutrinos are of cosmic origin

starting events
(medium energy)



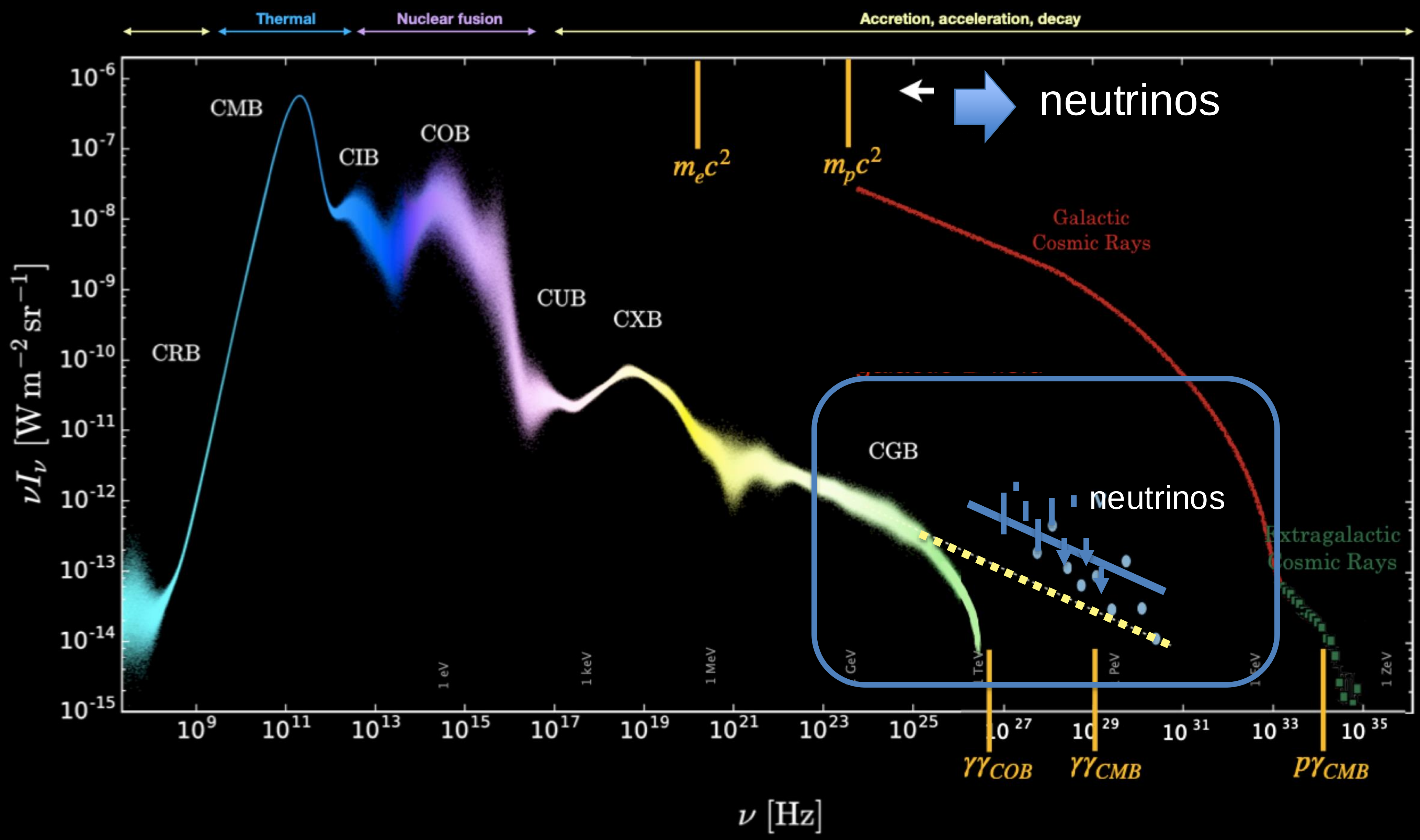

machine learning
PMT signals



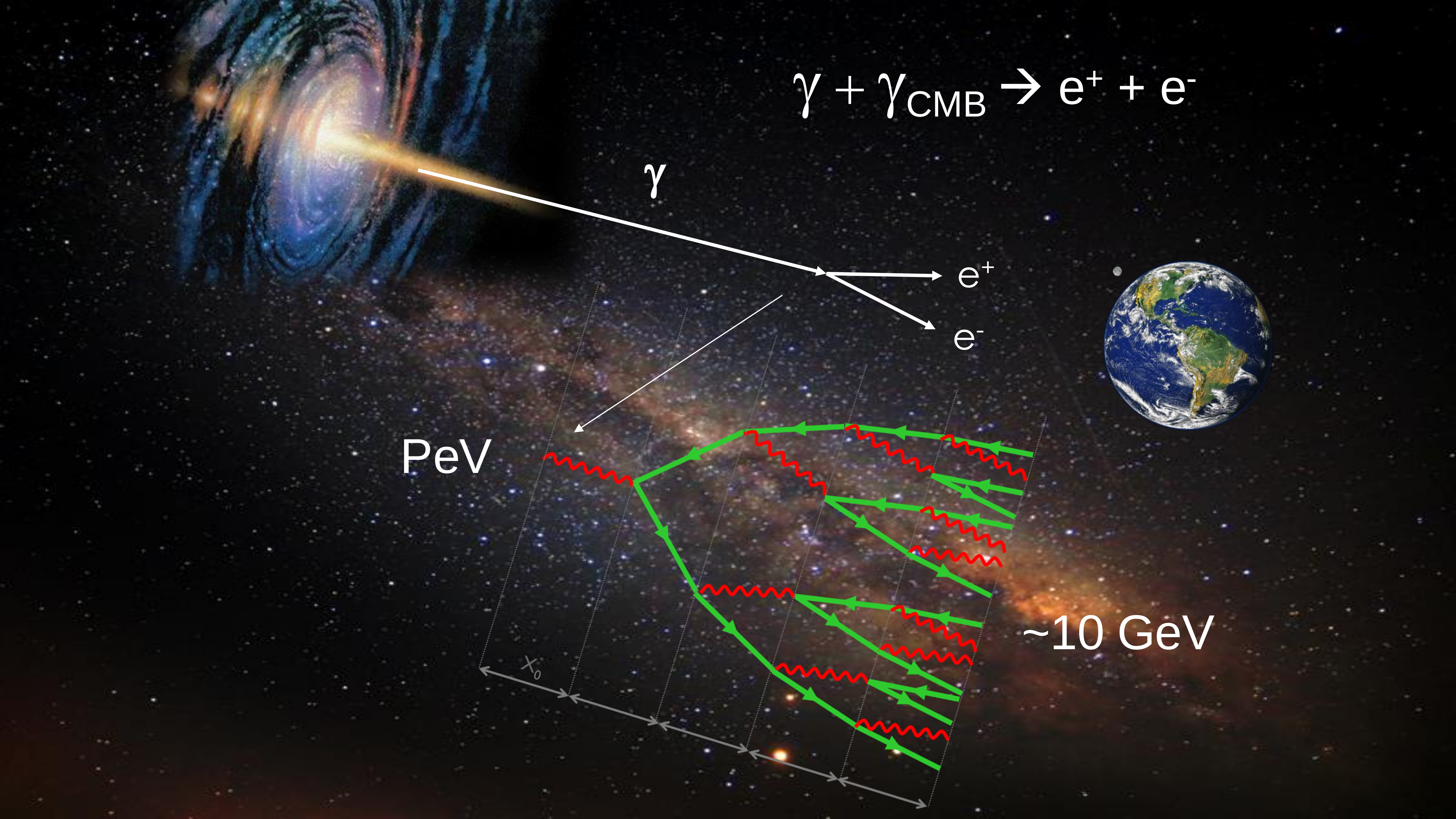
two surprises:

- cosmic neutrinos sources originate in a target from which gamma rays do not escape
- powerful accelerators produce neutrinos in other galaxies that do not exist in our own



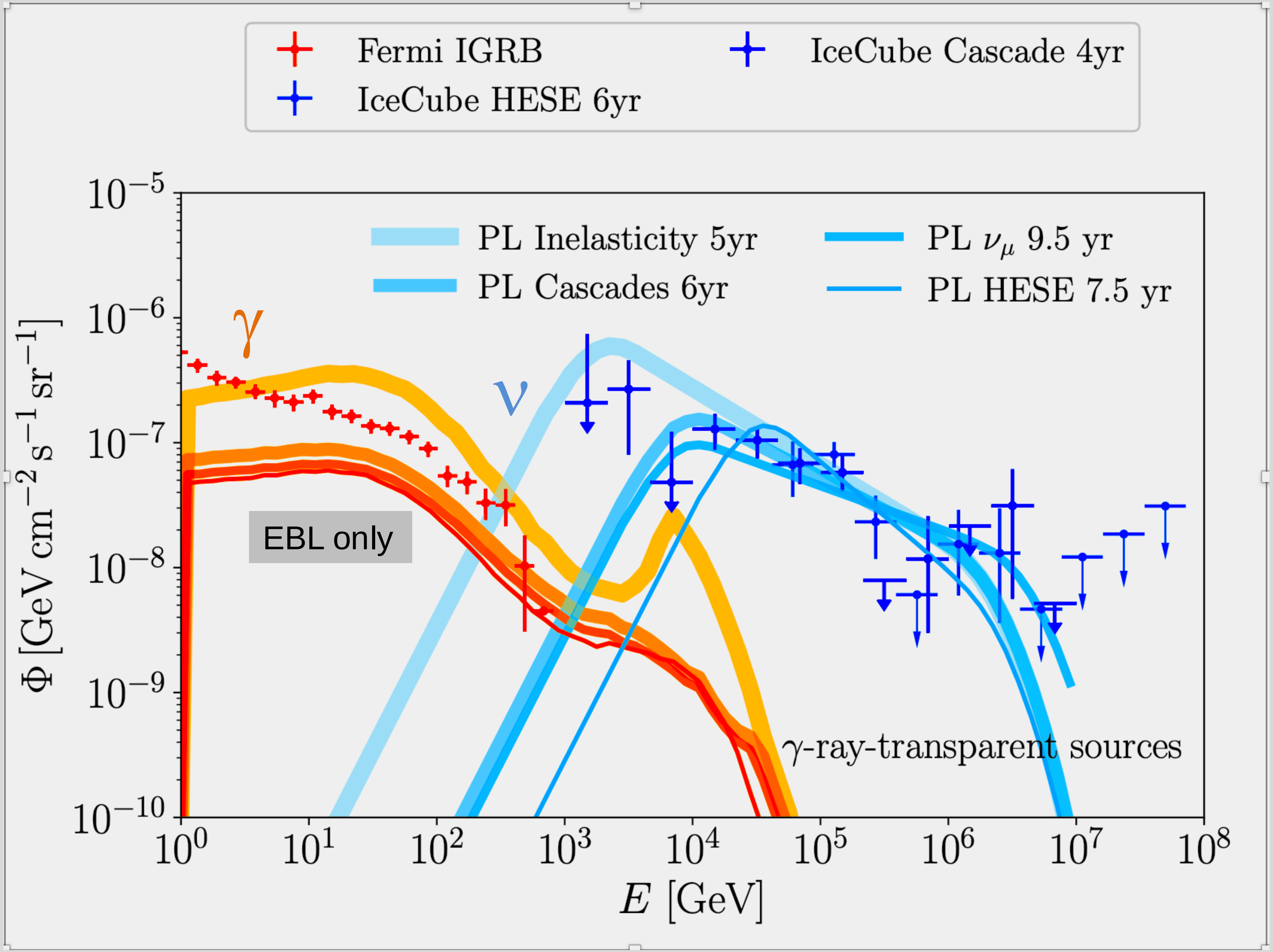

- Fermi does not detect the gamma rays of $\pi^0$ origin
- they lose energy in the dense target that produces the neutrinos

in the extreme universe the energy in neutrinos is larger than the energy in gamma rays observed by Fermi



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

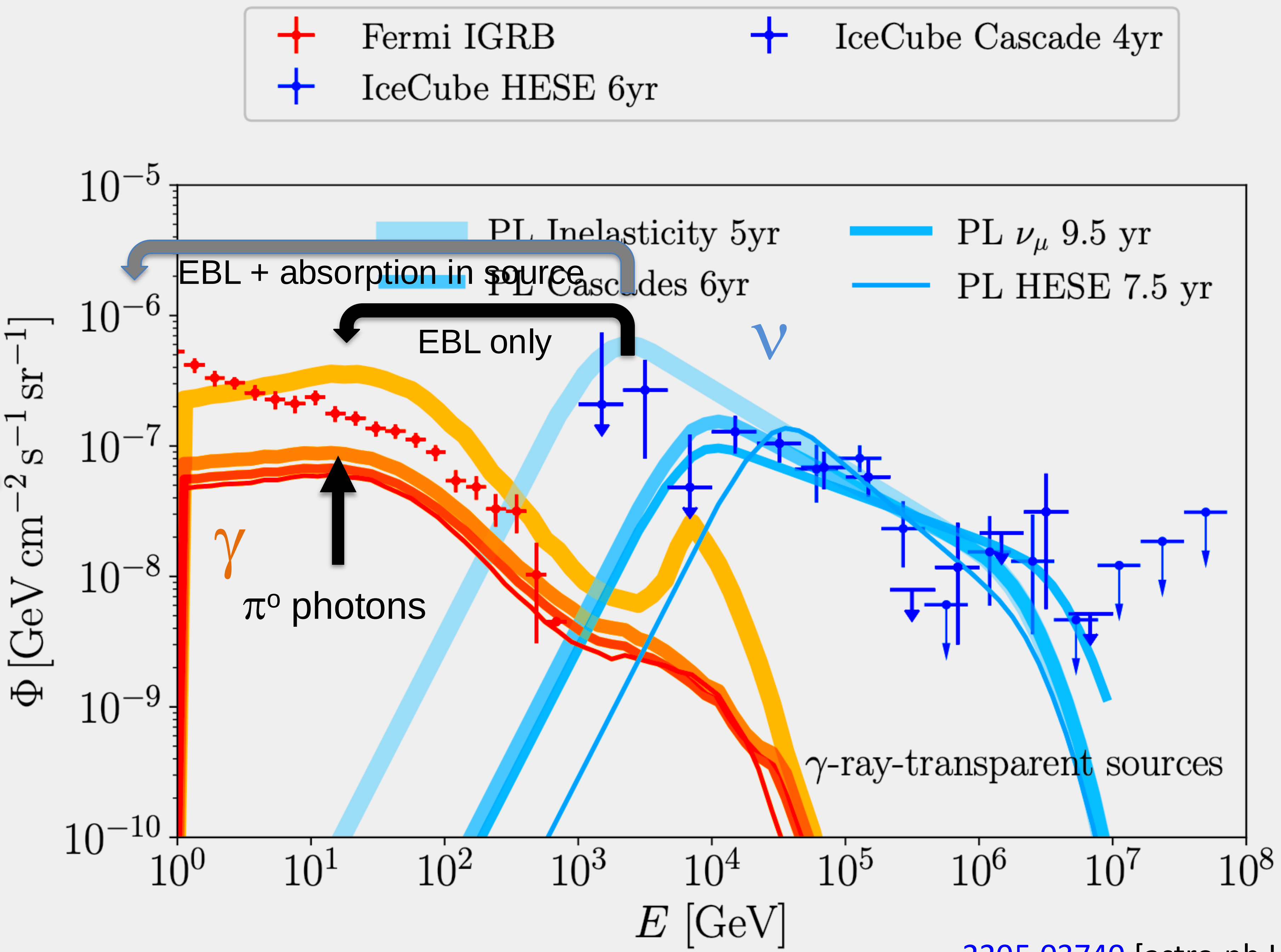
gamma rays from neutral pions are not seen by Fermi: they lose energy in the sources (not just in the EBL)



typical neutrino sources contributing to the diffuse flux are opaque to gamma rays

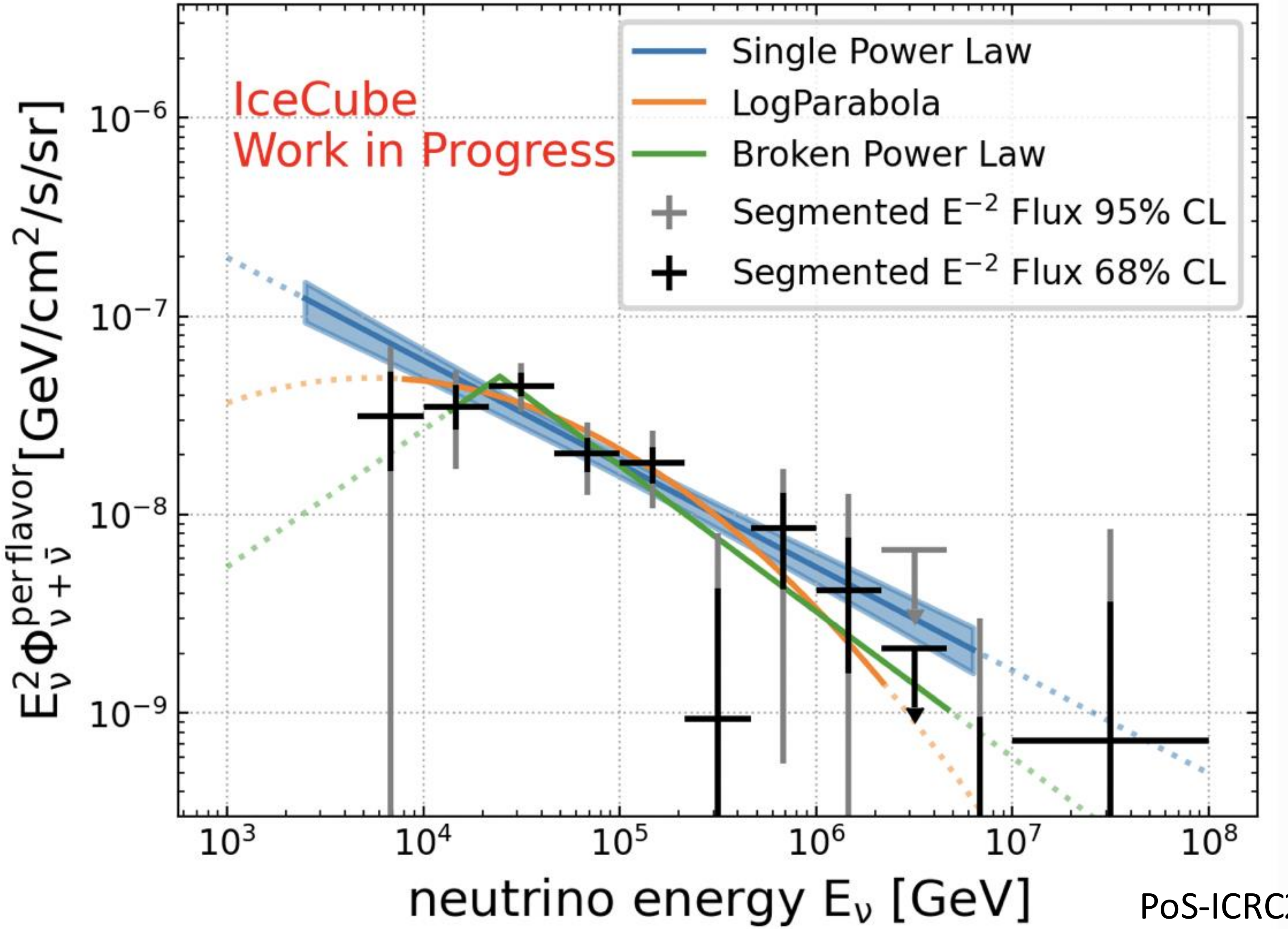
or

pionic gamma rays accompanying neutrinos appear at MeV energies or below



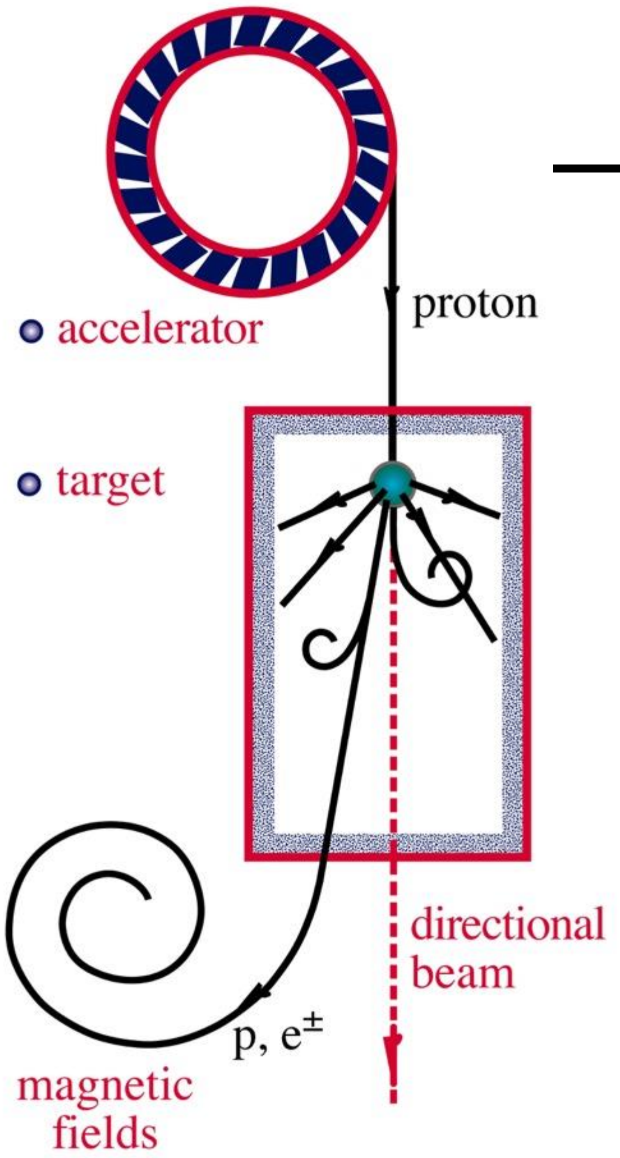

2205.03740 [astro-ph.HE]

# global analysis of the spectral shape of astrophysical neutrinos (more than a million neutrinos)




PoS-ICRC2023-1064, 2308.00191

# $\nu$ and $\gamma$ beams : heaven and earth




where are the gamma rays from $\pi^0$ ?

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

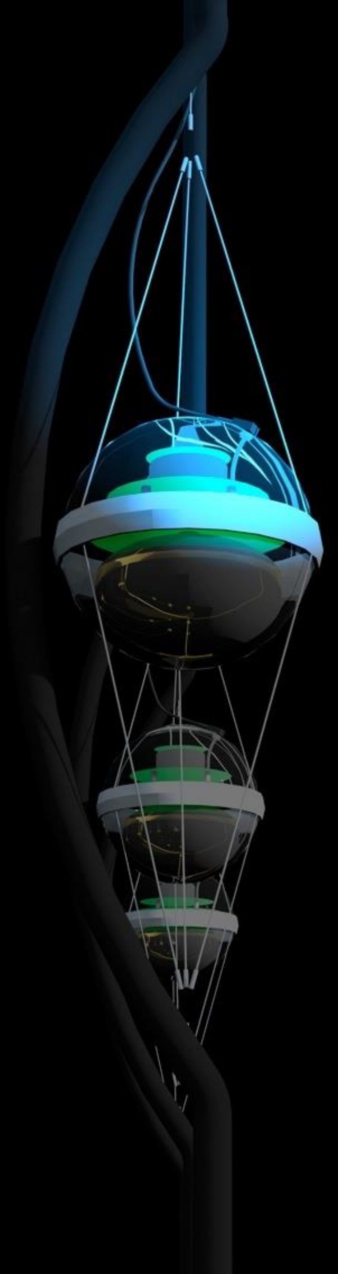
$$\tau_{\gamma\gamma} \simeq 10^3 \, \tau_{p\gamma}$$

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

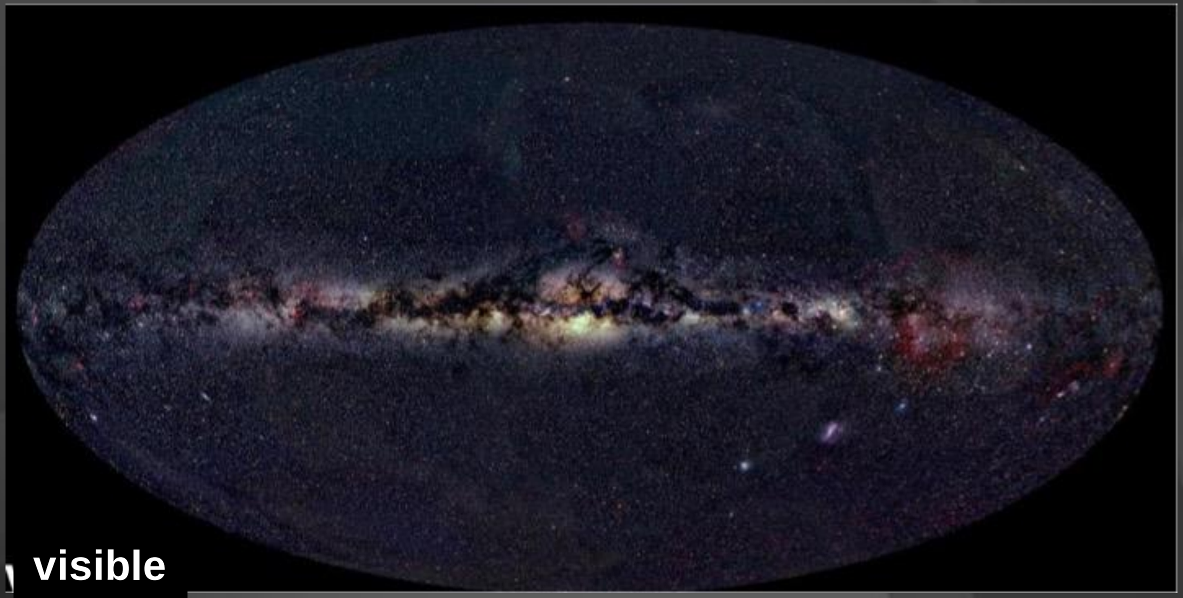


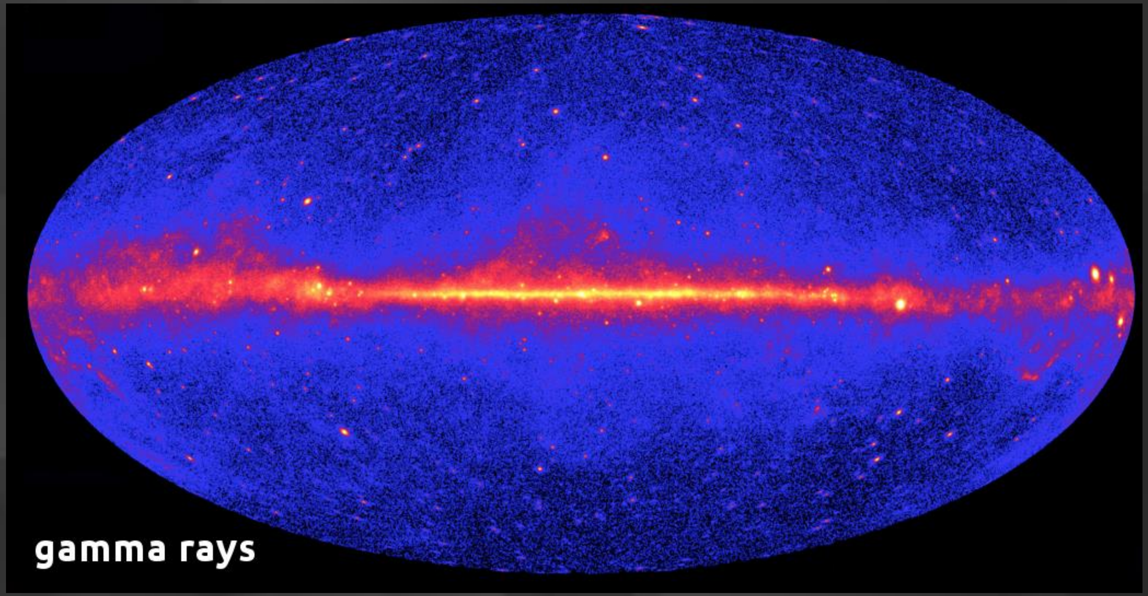
## IceCube revealed:

- a diffuse extragalactic neutrino flux from gamma-ray obscured sources: gamma rays accompanying high energy neutrinos appear at MeV energies, or below

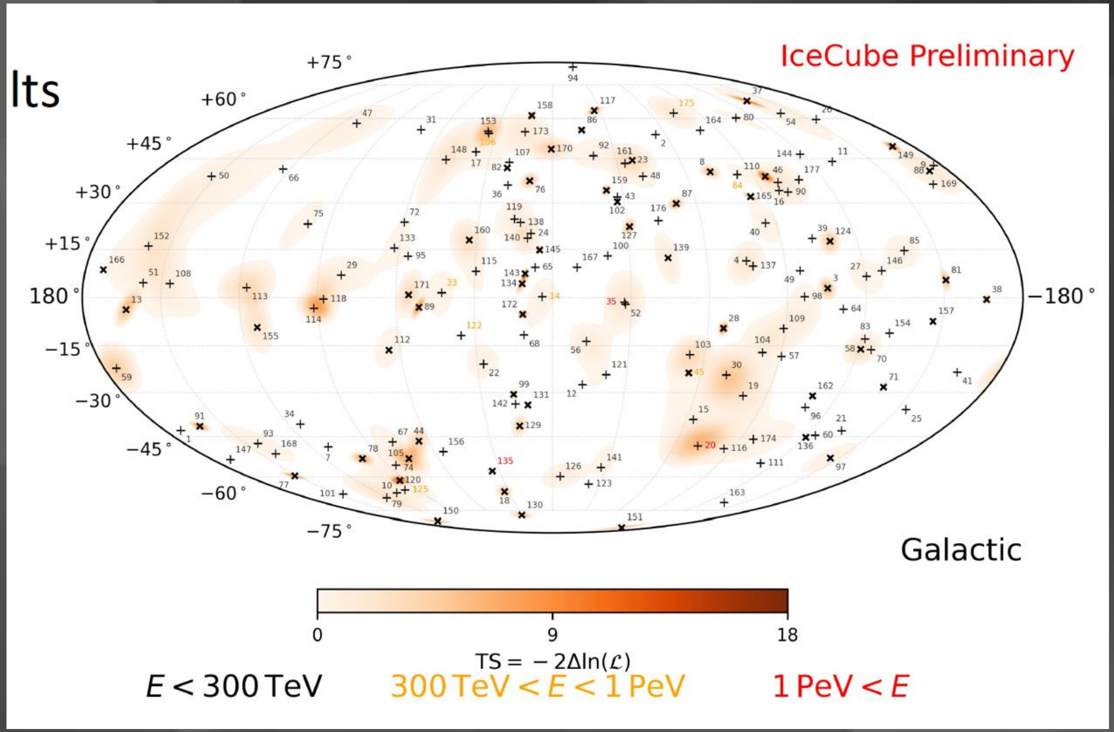
- a Galactic neutrino flux that is an order of magnitude smaller than the flux in a typical galaxy contributing to the extragalactic diffuse flux: what is missing?

- first sources: neutrinos are produced in the dense cores of active galaxies




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!

- 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

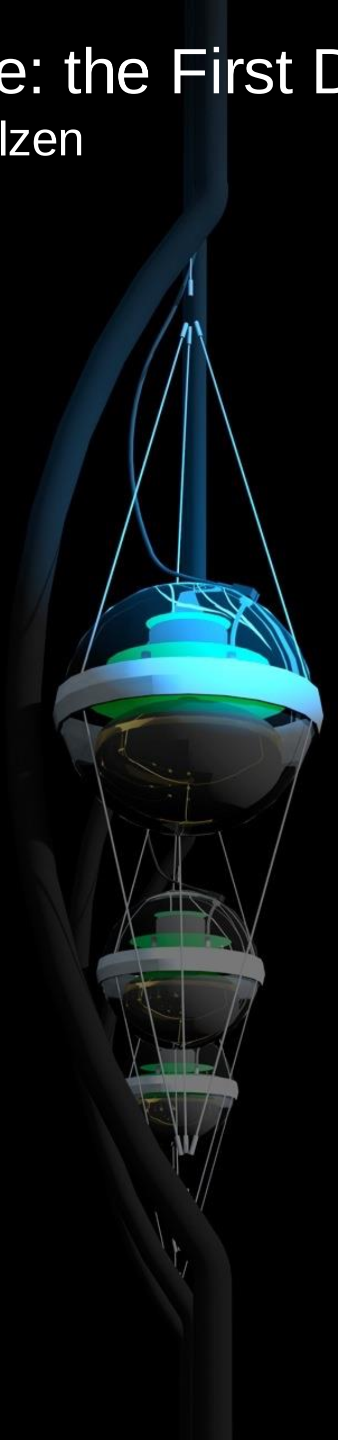
neutrino flux in active galaxies from diffuse flux observed

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

neutrino flux in Milky Way from flux at Earth

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

e-Print: 2306.17275 [astro-ph.HE]



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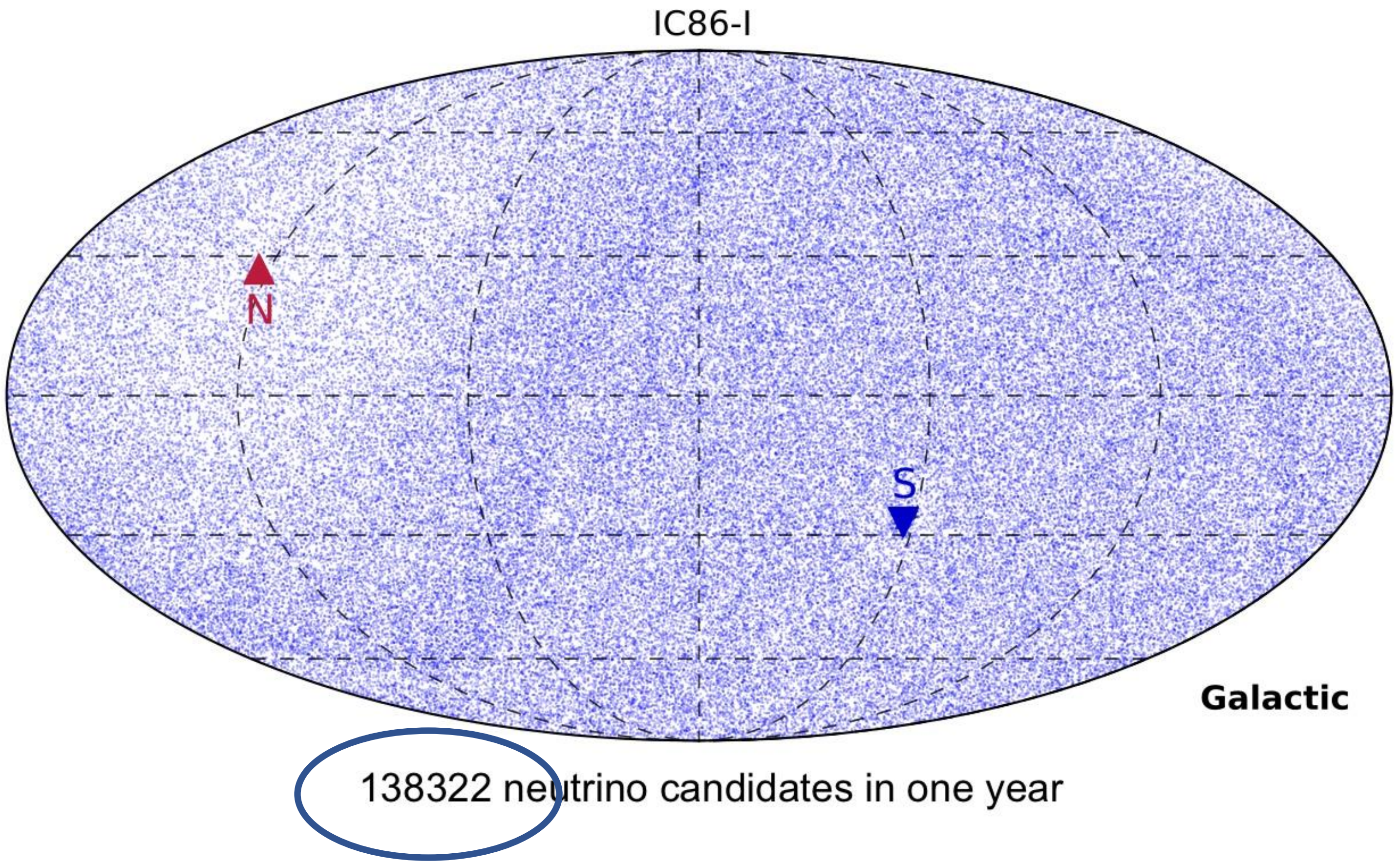
# Lessons from the diffuse cosmic neutrino flux:

- neutrino sources originate in a target from which gamma rays do not escape
- powerful accelerators operate produce neutrinos in other galaxies that do not exist in our own

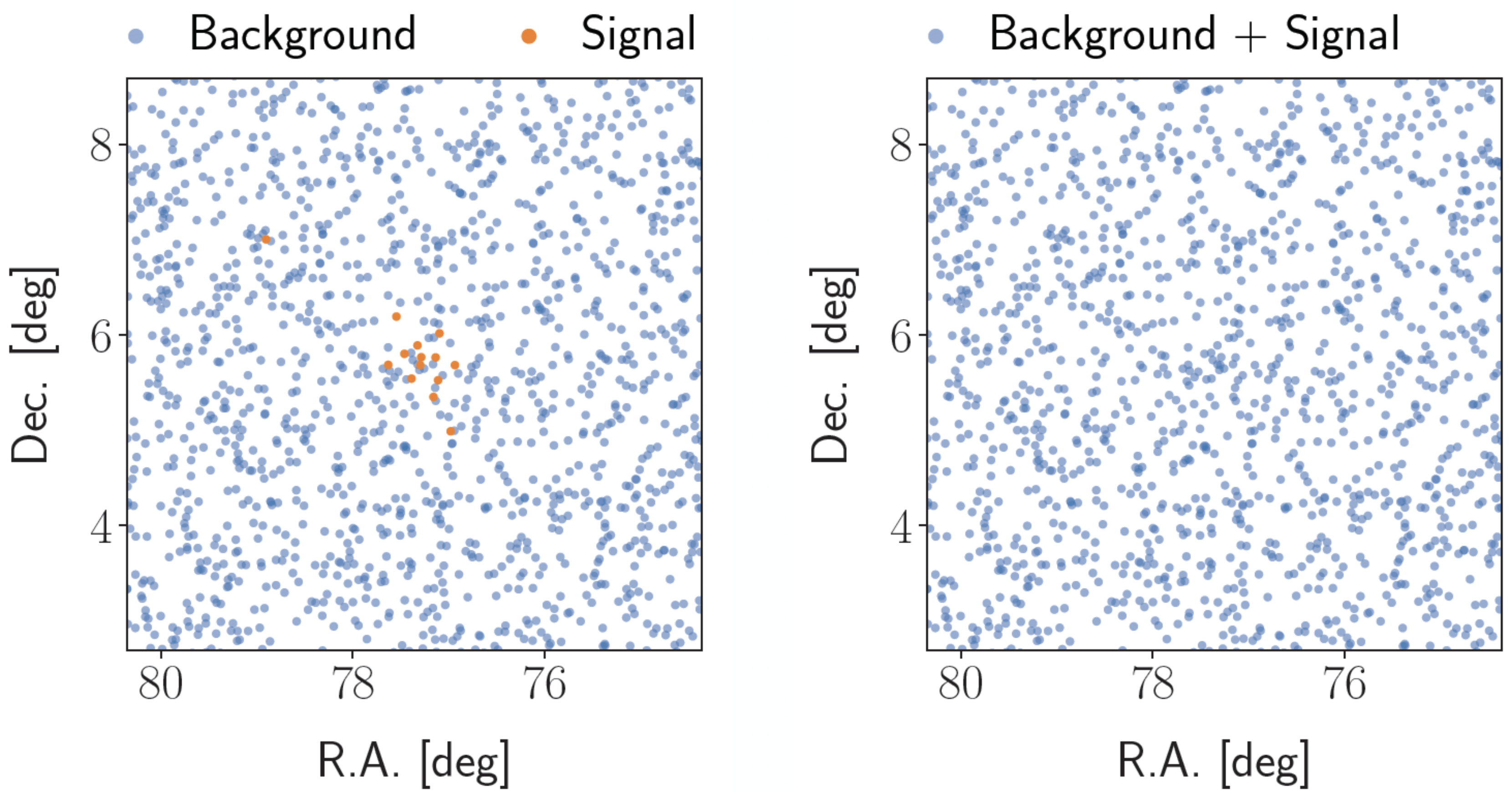
→ dense cores of active galaxies with the central supermassive black hole cannibalizing its own galaxy

# one year of IceCube neutrinos >100 GeV

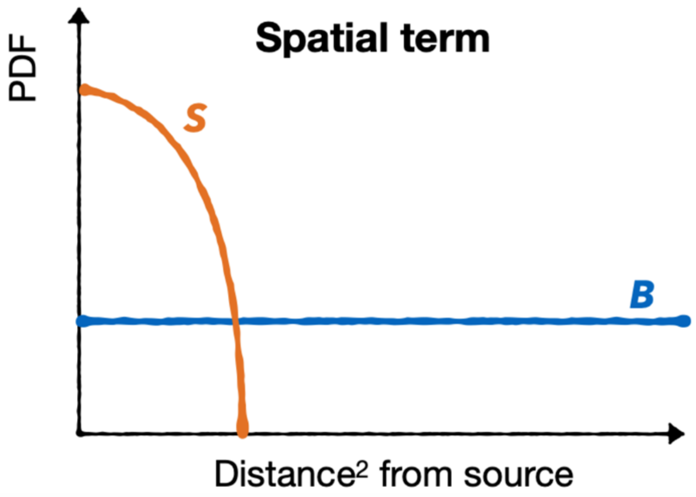
(reaches neutrino purity of 97% but overwhelmingly atmospheric)

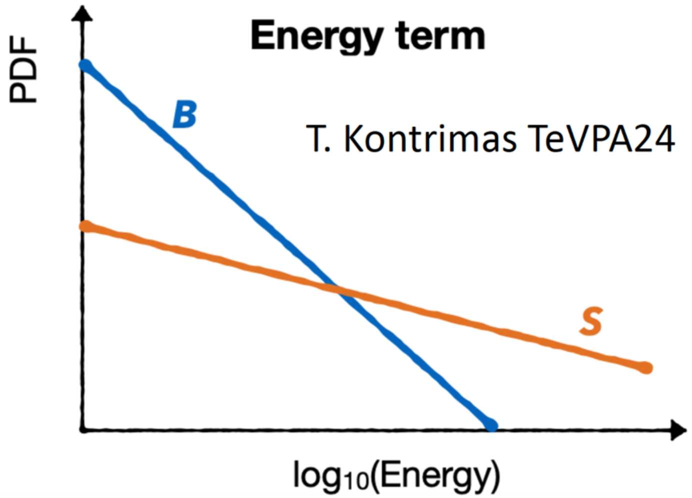


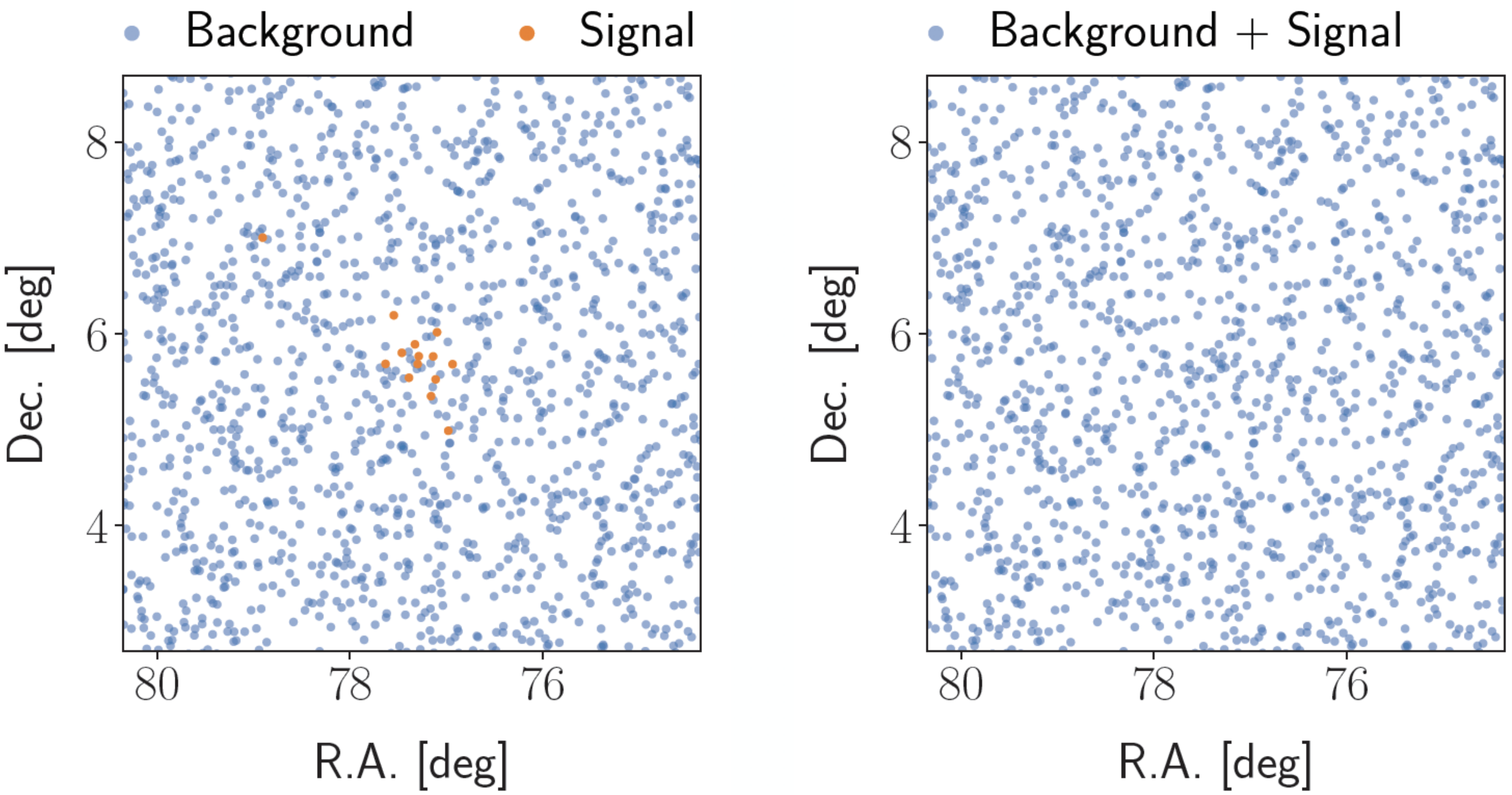

~200 cosmic neutrinos




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



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

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

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

*Phys.Rev.Lett.* 124 (2020)

Source List Results

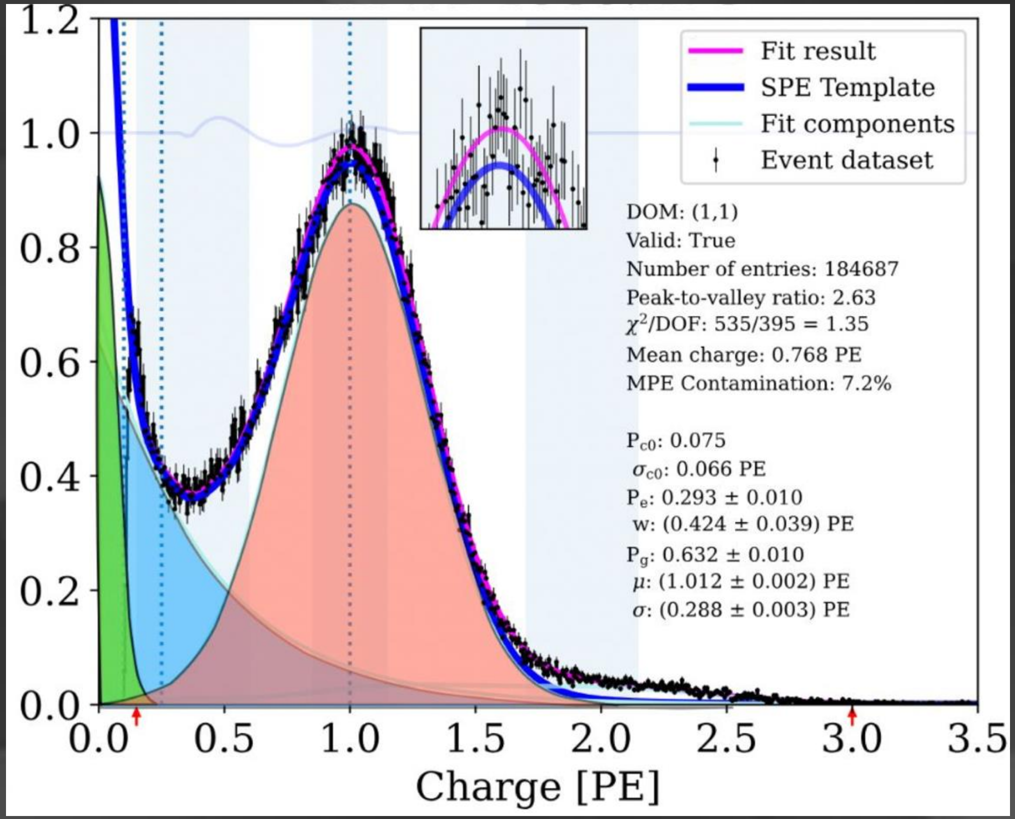
| Name | Class | $\alpha$ [deg] | $\delta$ [deg] | $\hat{n}_s$ | $\hat{\gamma}$ | $-\log_{10}(p_{local})$ | $\phi_{90\%}$ |
|---|---|---|---|---|---|---|---|
| PKS 2320-035 | FSRQ | 350.88 | -3.29 | 4.8 | 3.6 | 0.45 | 3.3 |
| 3C 454.3 | FSRQ | 343.50 | 16.15 | 5.4 | 2.2 | 0.62 | 5.1 |
| TXS 2241+406 | FSRQ | 341.06 | 40.96 | [illegible] | [illegible] | [illegible] | [illegible] |
| 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 | [illegible] | [illegible] |
| OX 169 | FSRQ | 325.89 | 17.73 | 2.0 | 1.7 | 0.69 | 3.1 |
| 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 | [illegible] | [illegible] | [illegible] |
| 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] | 1.02 | 10.6 |
| M 82 | SBG | 148.95 | 69.67 | 0.0 | 2.6 | 0.36 | 8.8 |
| PMN J0948+0022 | AGN | 147.24 | 0.37 | 9.3 | 4.0 | 0.76 | 3.9 |
| OJ 287 | BLL | 133.71 | 20.12 | 0.0 | 2.6 | 0.32 | 3.5 |
| PKS 0829+046 | BLL | 127.97 | 4.49 | 0.0 | 2.9 | 0.28 | 2.1 |
| S4 0814+42 | BLL | 124.56 | 42.38 | 0.0 | 2.3 | 0.30 | 4.9 |
| OJ 014 | BLL | 122.87 | 1.78 | 16.1 | 4.0 | 0.99 | 4.4 |
| 1ES 0806+524 | BLL | 122.46 | 52.31 | 0.0 | 2.8 | 0.31 | 4.7 |
| PKS 0736+01 | FSRQ | 114.82 | 1.62 | 0.0 | 2.8 | 0.26 | 2.4 |
| PKS 0735+17 | BLL | 114.54 | 17.71 | 0.0 | 2.8 | 0.30 | 3.5 |
| 4C +14.23 | FSRQ | 111.33 | 14.42 | 8.5 | 2.9 | 0.60 | 4.8 |
| S5 0716+71 | BLL | 110.49 | 71.34 | 0.0 | 2.5 | 0.38 | 7.4 |
| PSR B0656+14 | GAL | 104.95 | 14.24 | 8.4 | 4.0 | 0.51 | 4.4 |
| 1ES 0647+250 | BLL | 102.70 | 25.06 | 0.0 | 2.9 | 0.27 | 3.0 |
| B3 0609+413 | BLL | 93.22 | 41.37 | 1.8 | 1.7 | 0.42 | 5.3 |
| Crab nebula | GAL | 83.63 | 22.01 | 1.1 | 2.2 | 0.31 | 3.7 |
| OG +050 | FSRQ | 83.18 | 7.55 | 0.0 | 3.2 | 0.28 | 2.9 |
| TXS 0518+211 | BLL | 80.44 | 21.21 | 15.7 | 3.8 | 0.92 | 6.6 |
| **TXS 0506+056** | **BLL** | **77.35** | **5.70** | **12.3** | **2.1** | **3.72** | **10.1** |
| PKS 0502+049 | FSRQ | 76.34 | 5.00 | 11.2 | 3.0 | 0.66 | 4.1 |
| S3 0458-02 | FSRQ | 75.30 | -1.97 | 5.5 | 4.0 | 0.33 | 2.7 |
| PKS 0440-00 | FSRQ | 70.66 | -0.29 | 7.6 | 3.9 | 0.46 | 3.1 |
| MG2 J043337+2905 | BLL | 68.41 | 29.10 | 0.0 | 2.7 | 0.28 | 4.5 |
| PKS 0422+00 | BLL | 66.19 | 0.60 | 0.0 | 2.9 | 0.27 | 2.3 |
| PKS 0420-01 | FSRQ | 65.83 | -1.33 | 9.3 | 4.0 | 0.52 | 3.4 |
| PKS 0336-01 | FSRQ | 54.88 | -1.77 | 15.5 | 4.0 | 0.99 | 4.4 |
| NGC 1275 | AGN | 49.96 | 41.51 | 3.6 | 3.1 | 0.41 | 5.5 |
| **NGC 1068** | **SBG** | **40.67** | **-0.01** | **50.4** | **3.2** | **4.74** | **10.5** |
| PKS 0235+164 | BLL | 39.67 | 16.62 | 0.0 | 3.0 | 0.28 | 3.1 |
| 4C +28.07 | FSRQ | 39.48 | 28.80 | 0.0 | 2.8 | 0.30 | 3.6 |
| 3C 66A | BLL | 35.67 | 43.04 | 0.0 | 2.8 | 0.30 | 3.9 |
| B2 0218+357 | FSRQ | 35.28 | 35.94 | 0.0 | 3.1 | 0.33 | 4.3 |
| PKS 0215+015 | FSRQ | 34.46 | 1.74 | 0.0 | 3.2 | 0.27 | 2.3 |
| MG1 J021114+1051 | BLL | 32.81 | 10.86 | 1.6 | 1.7 | 0.43 | 3.5 |
| TXS 0141+268 | BLL | 26.15 | 27.09 | 0.0 | 2.5 | 0.31 | 3.5 |
| B3 0133+388 | BLL | 24.14 | 39.10 | 0.0 | 2.6 | 0.28 | 4.1 |
| NGC 598 | SBG | 23.52 | 30.62 | 11.4 | 4.0 | 0.63 | 6.3 |
| S2 0109+22 | BLL | 18.03 | 22.75 | 2.0 | 3.1 | 0.30 | 3.7 |
| 4C +01.02 | FSRQ | 17.16 | 1.59 | 0.0 | 3.0 | 0.26 | 2.4 |
| M 31 | SBG | 10.82 | 41.24 | 11.0 | 4.0 | 1.09 | 9.6 |
| PKS 0019+058 | BLL | 5.64 | 6.14 | 0.0 | 2.9 | 0.29 | 2.4 |
| PKS 2233-148 | BLL | 339.14 | -14.56 | 5.3 | 2.8 | 1.26 | 21.4 |
| HESS J1841-055 | GAL | 280.23 | -5.55 | 3.6 | 4.0 | 0.55 | 4.8 |
| HESS J1837-069 | GAL | 279.43 | -6.93 | 0.0 | 2.8 | 0.30 | 4.0 |
| PKS 1510-089 | FSRQ | 228.21 | -9.10 | 0.1 | 1.7 | 0.41 | 7.1 |
| PKS 1329-049 | FSRQ | 203.02 | -5.16 | 6.1 | 2.7 | 0.77 | 5.1 |
| NGC 4945 | SBG | 196.36 | -49.47 | 0.3 | 2.6 | 0.31 | 50.2 |
| 3C 279 | FSRQ | 194.04 | -5.79 | 0.3 | 2.4 | 0.20 | 2.7 |
| PKS 0805-07 | FSRQ | 122.07 | -7.86 | 0.0 | 2.7 | 0.31 | 4.7 |
| PKS 0727-11 | FSRQ | 112.58 | -11.69 | 1.9 | 3.5 | 0.59 | 11.4 |
| LMC | SBG | 80.00 | -68.75 | 0.0 | 3.1 | 0.36 | 41.1 |
| SMC | SBG | 14.50 | -72.75 | 0.0 | 2.4 | 0.37 | 44.1 |
| PKS 0048-09 | BLL | 12.68 | -9.49 | 3.9 | 3.3 | 0.87 | 10.0 |
| NGC 253 | SBG | 11.90 | -25.29 | 3.0 | 4.0 | 0.75 | 37.7 |

interesting fluctuations or neutrino sources?

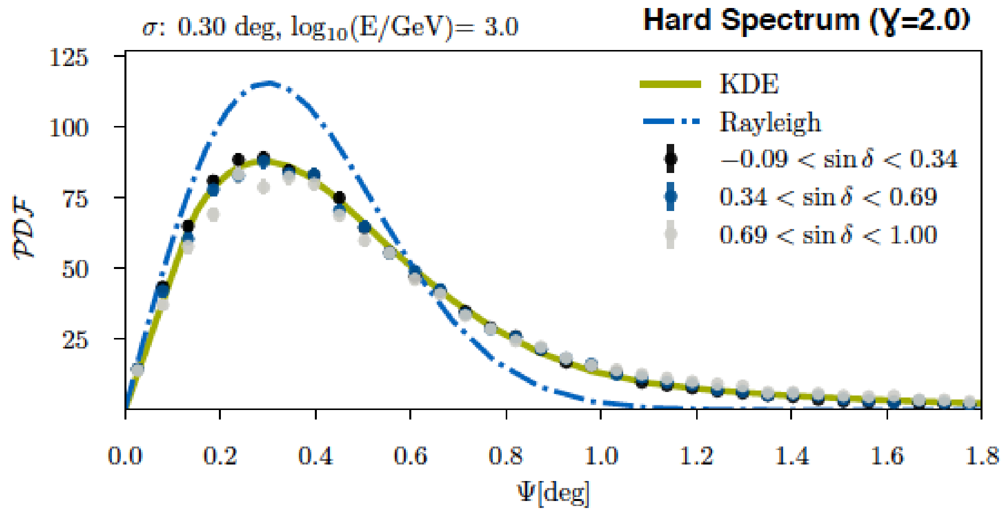
→ crash program to upgrade the performance of IceCube

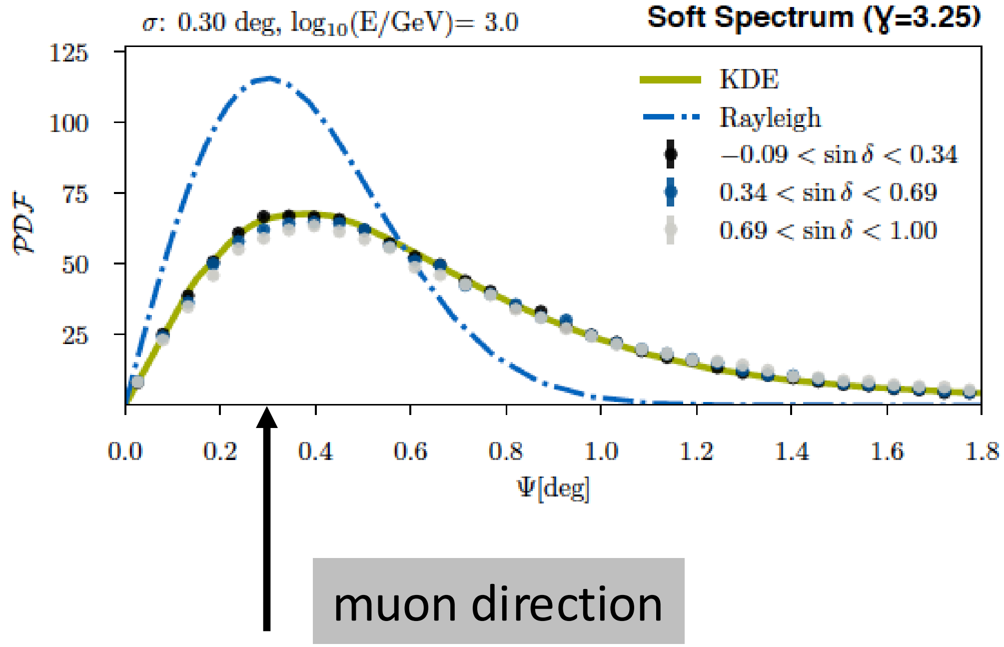
- improved detector geometry
- each photomultiplier calibrated individually
- improved characterization of the optics of the ice
- improved muon angular resolution and energy reconstruction using machine learning
- *point spread function consistent with simulation or, we were partially blind*
- *…*

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



- point spread function consistent with simulation
- insensitive to systematics

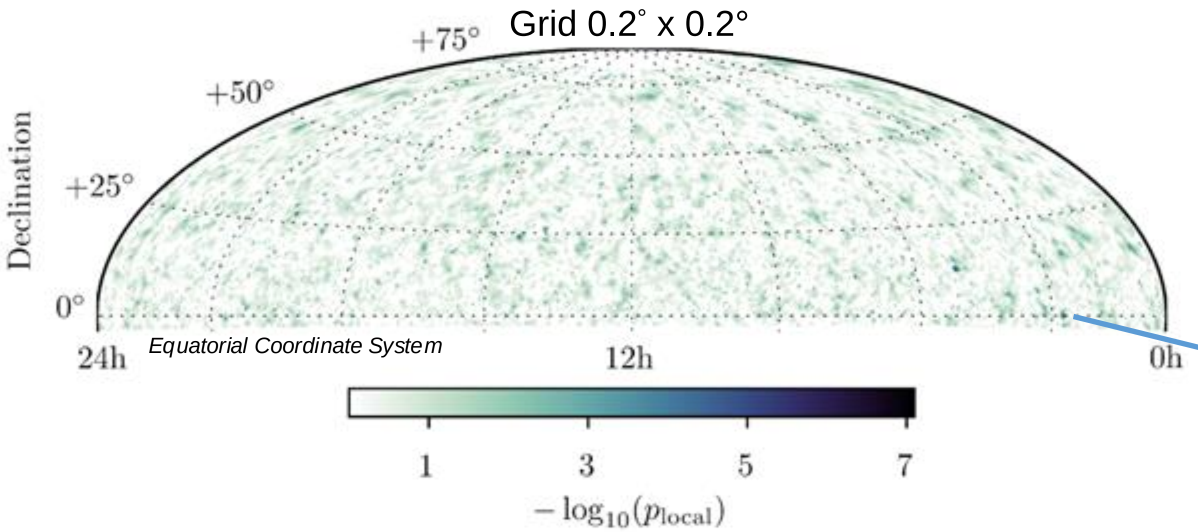


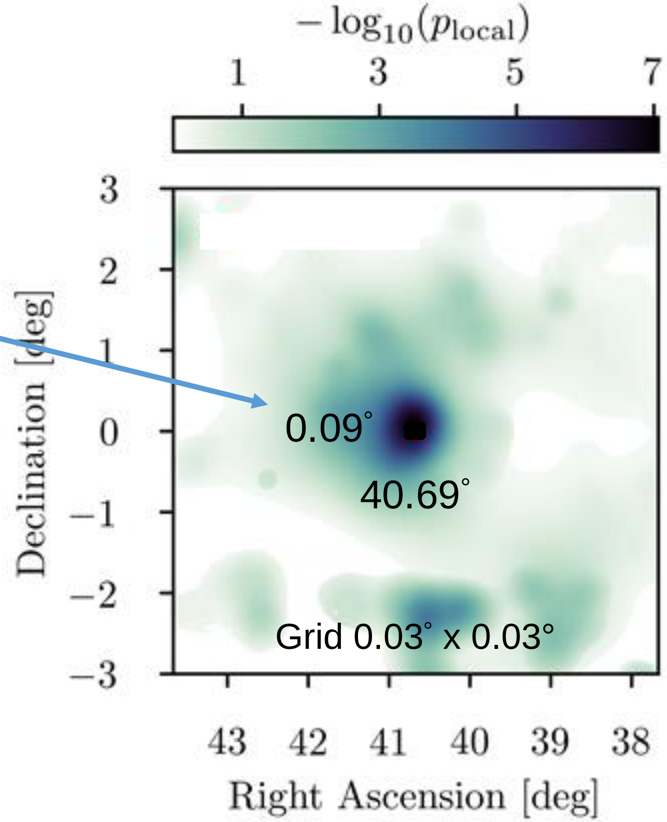




- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at < 10 TeV energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation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

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

# NGC 1068 is also the hottest spot in the new IceCube neutrino map



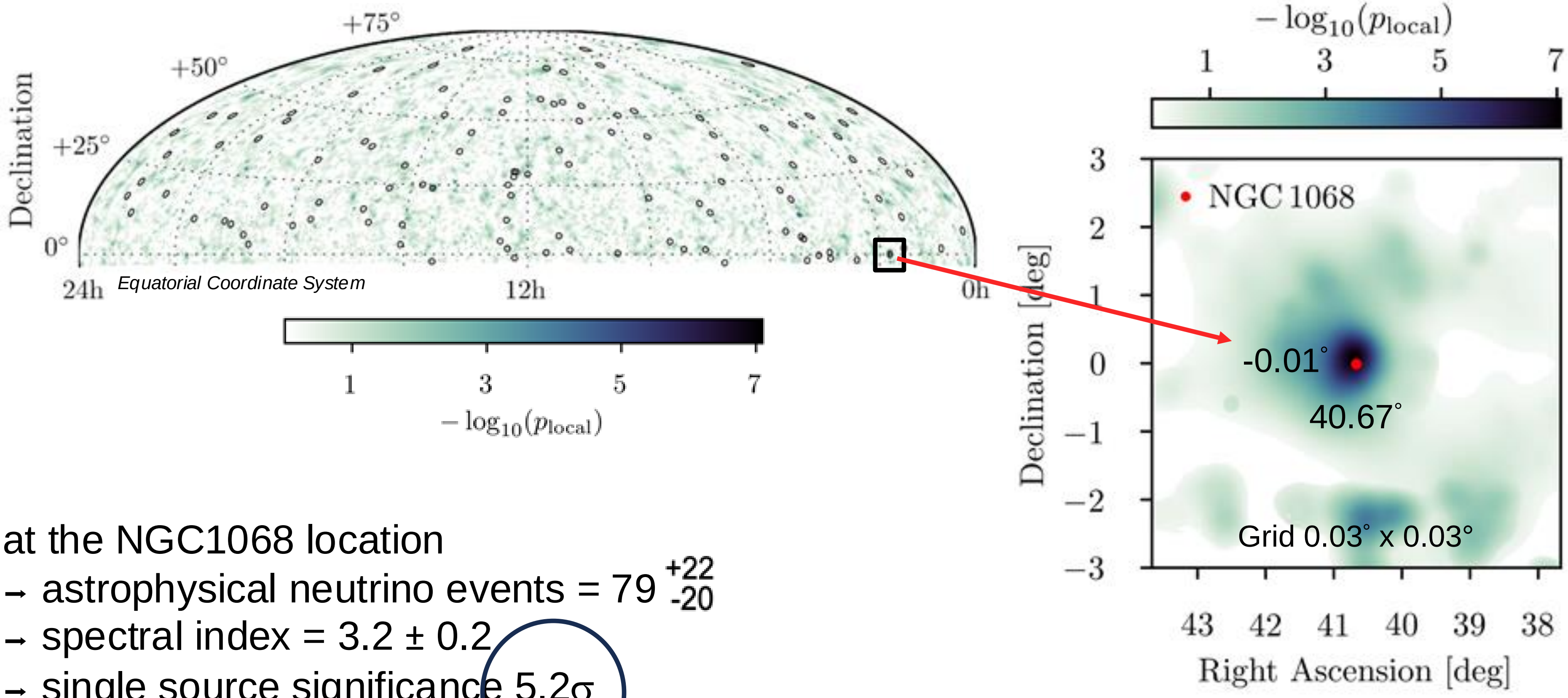

the brightest location in full sky scan:

→ astrophysical neutrino events = 81

→ spectral index = 3.2

local significance 5.3 σ

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

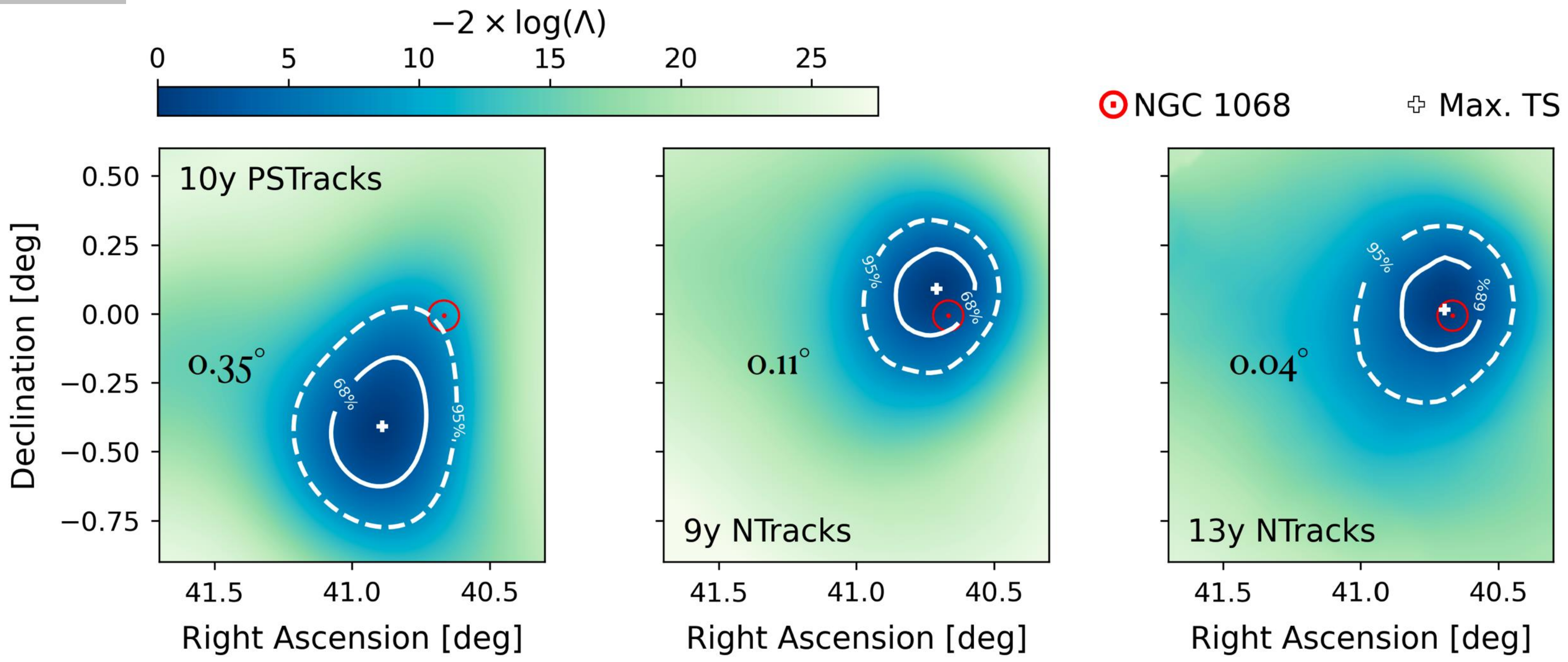


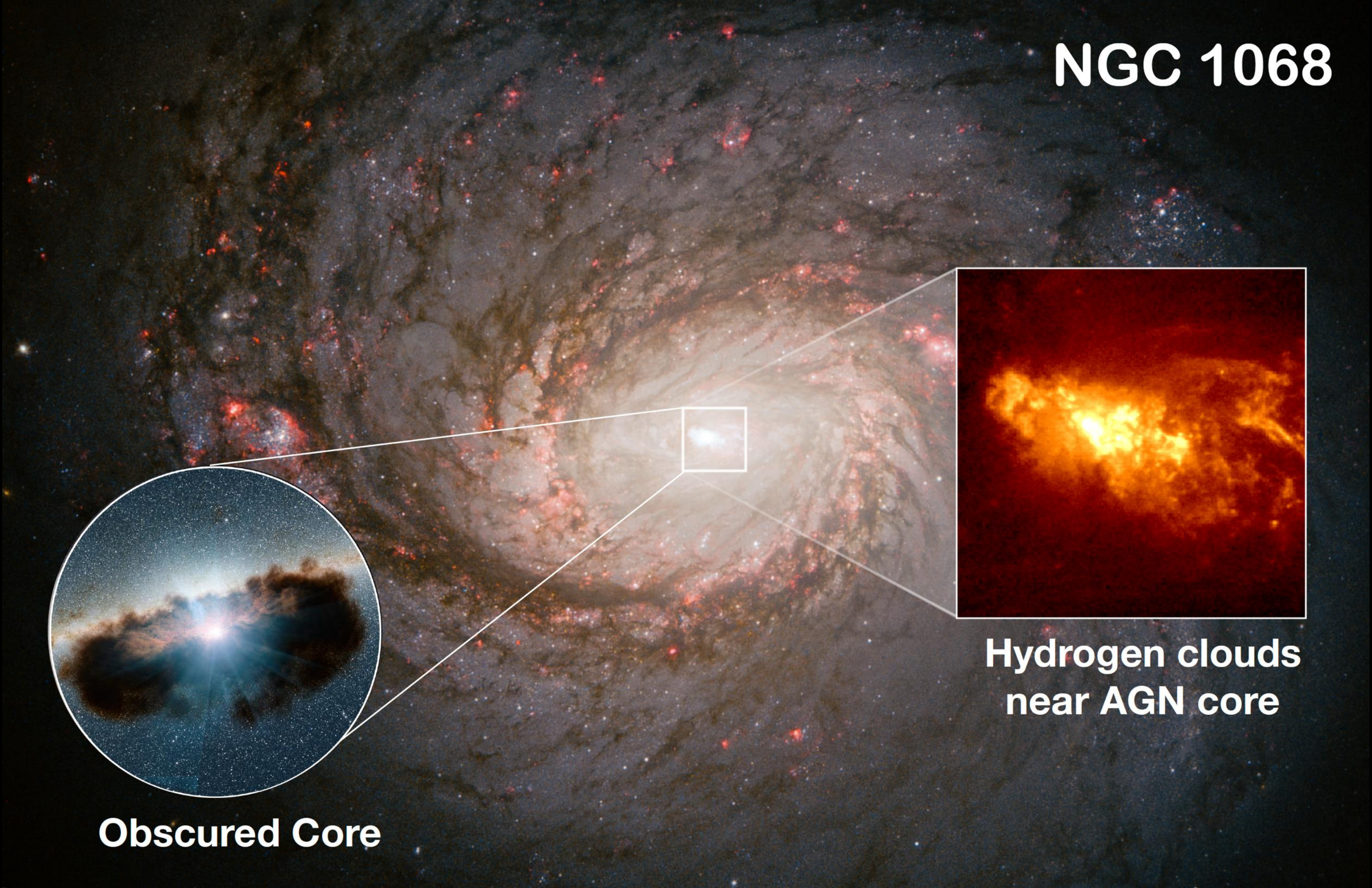

at the NGC1068 location

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

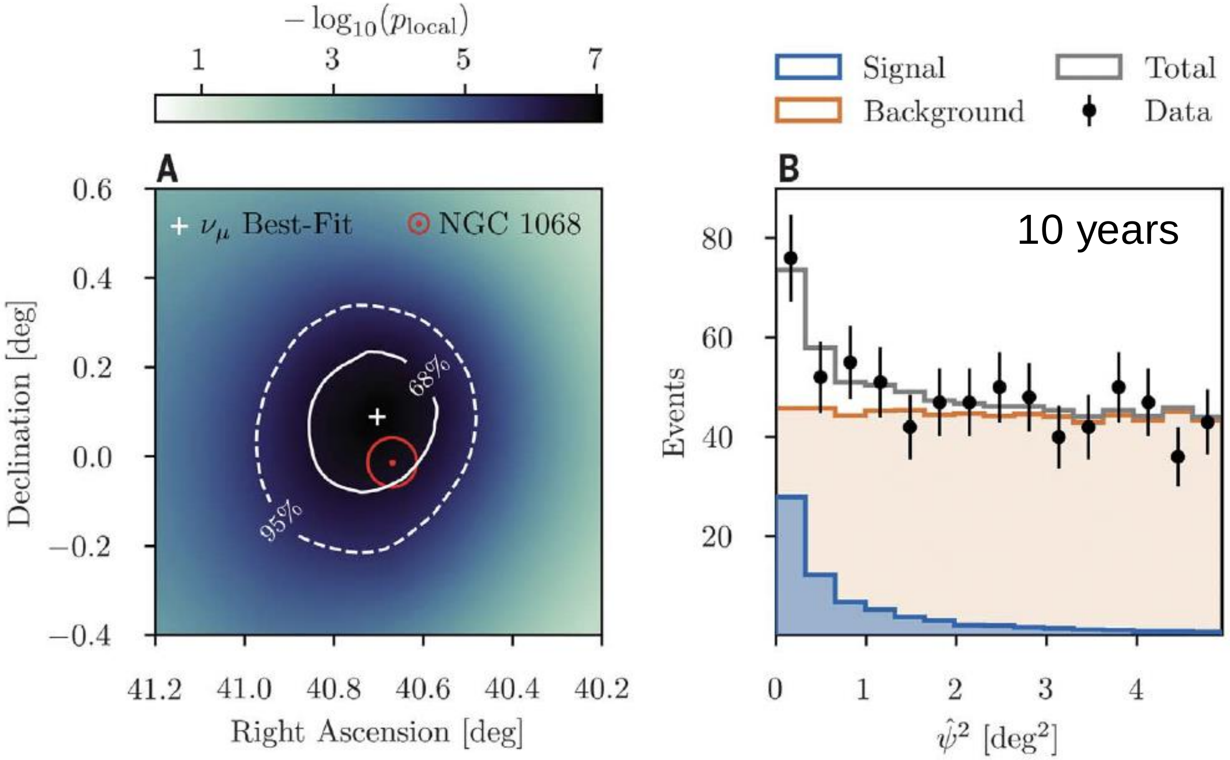
NGC 1068 comes into focus

0.35 deg → 0.1 deg → 0.04 deg

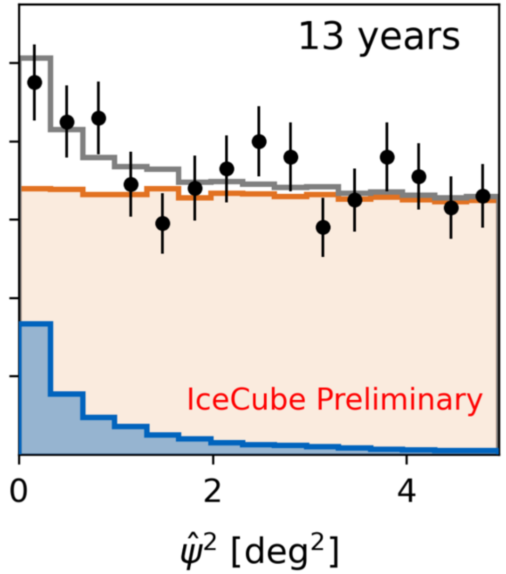



NGC 1068
Hydrogen clouds
near AGN core
Obscured Core

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

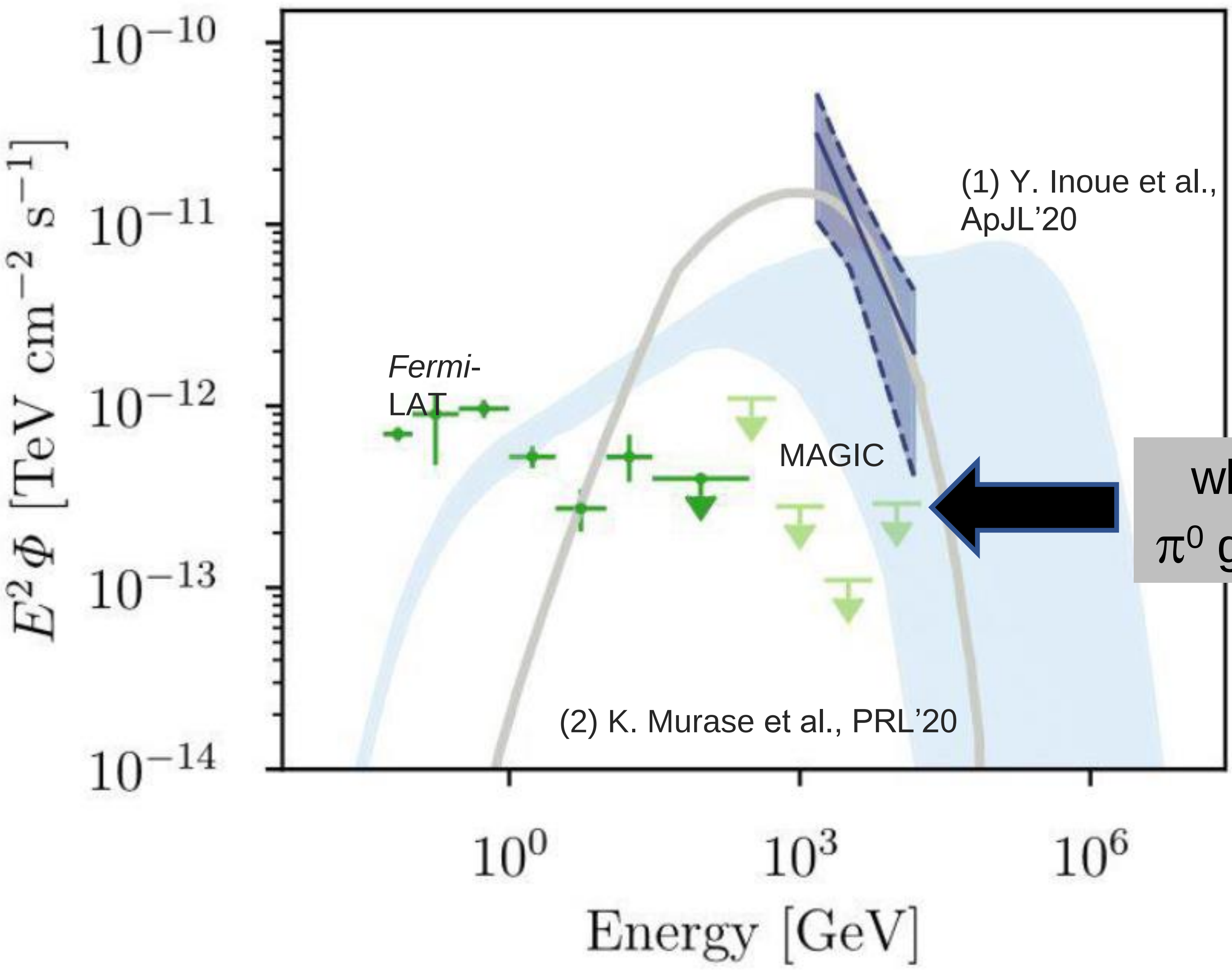



update:
80→100 neutrinos
10→13 years



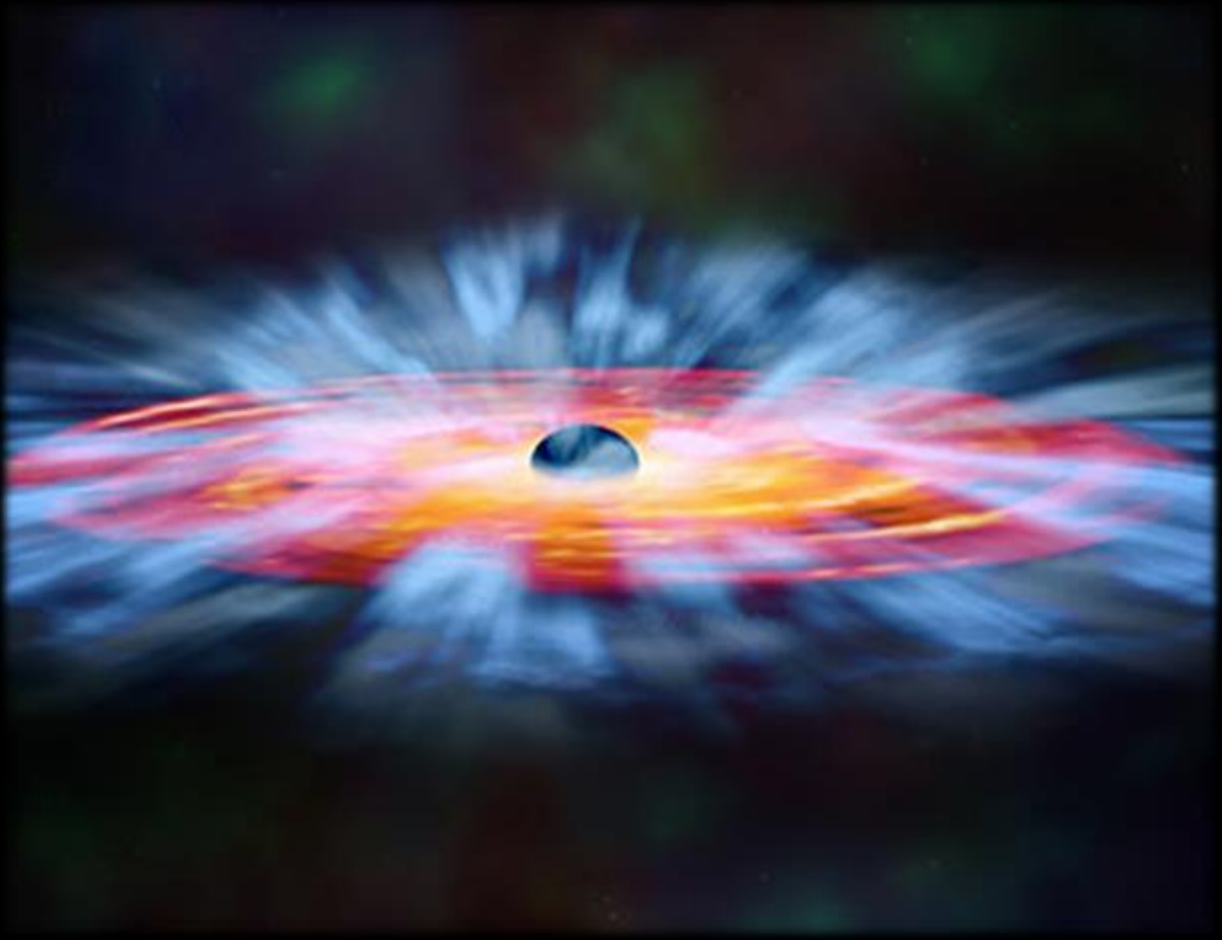
# a gamma ray for every neutrino?

## NGC 1068: an obscured cosmic accelerator

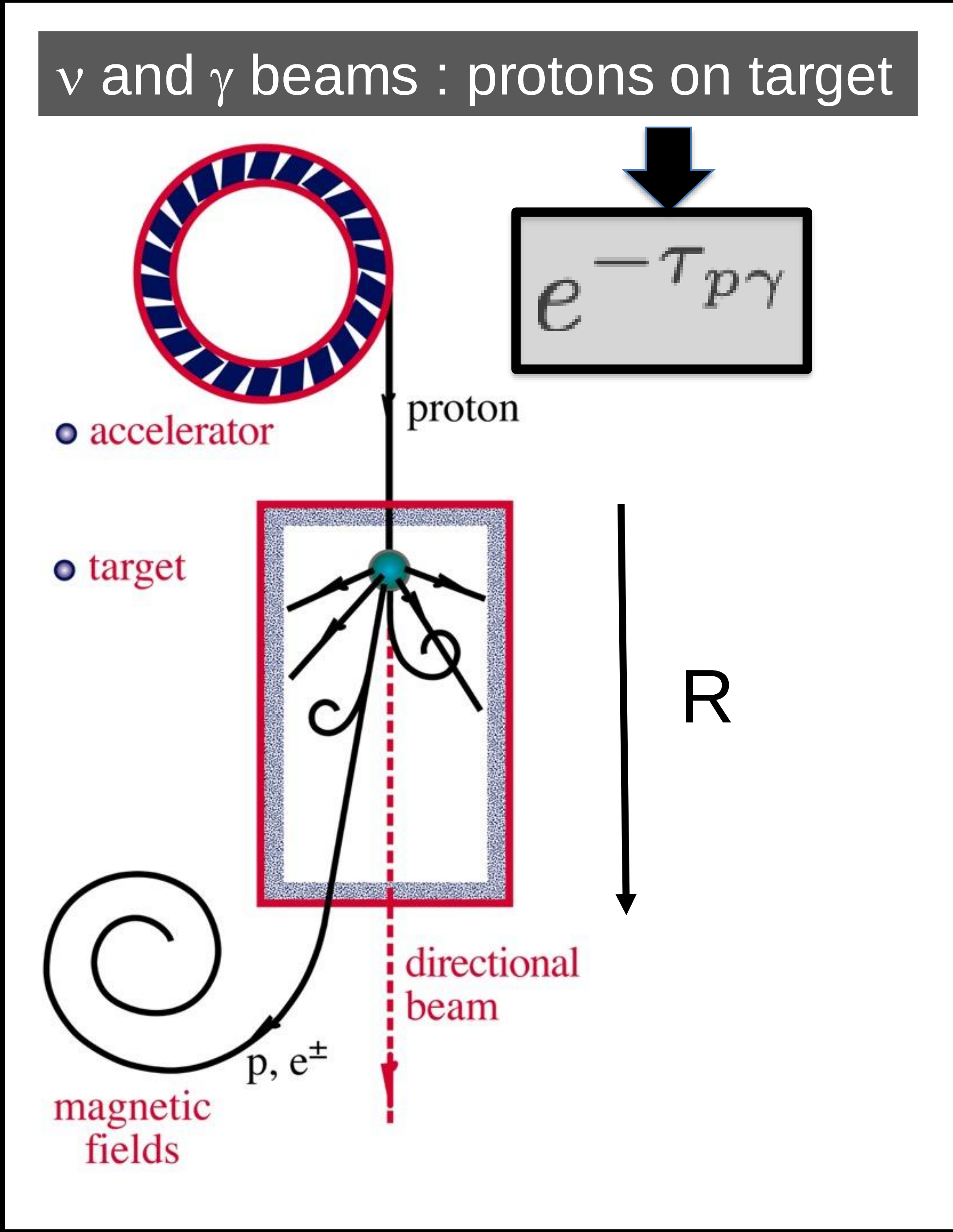



where are the $\pi^0$ gamma rays ?

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



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




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

~ cosmic ray + neutrino

- optical depth τ = cross section x target density

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

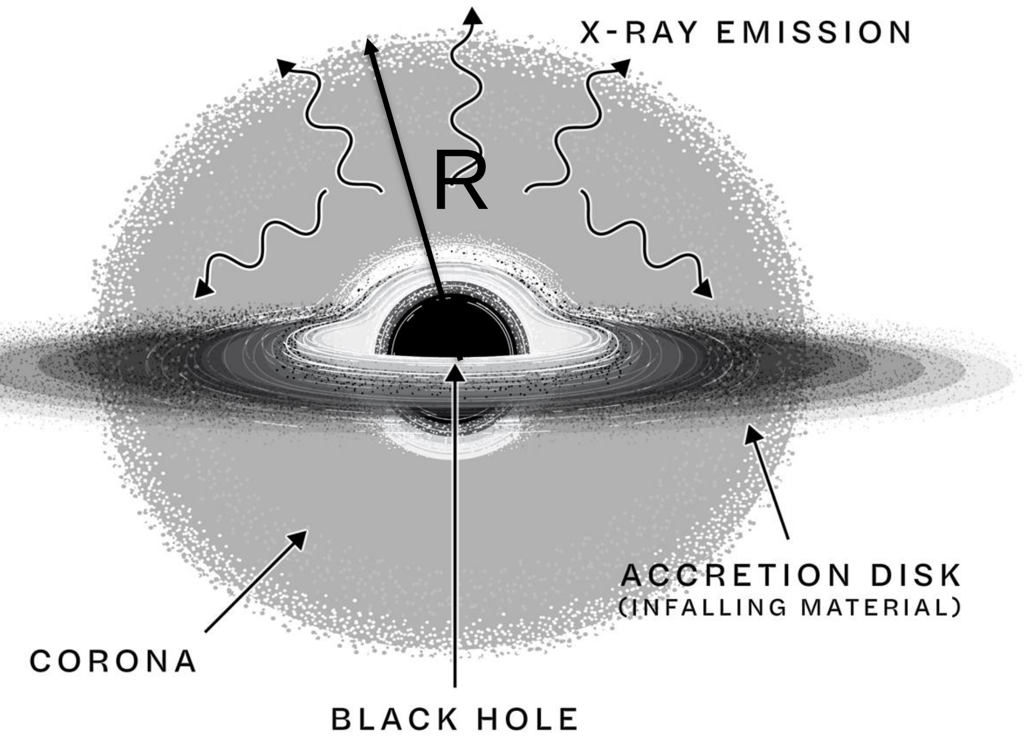
- pionic gamma rays are absorbed in the target that produces the neutrinos

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

~ cosmic ray + gamma

$$\tau_{\gamma\gamma} \simeq 10^3\, \tau_{p\gamma}$$

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




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

$$\mathrm{E_X} = 1\,\mathrm{keV}$$

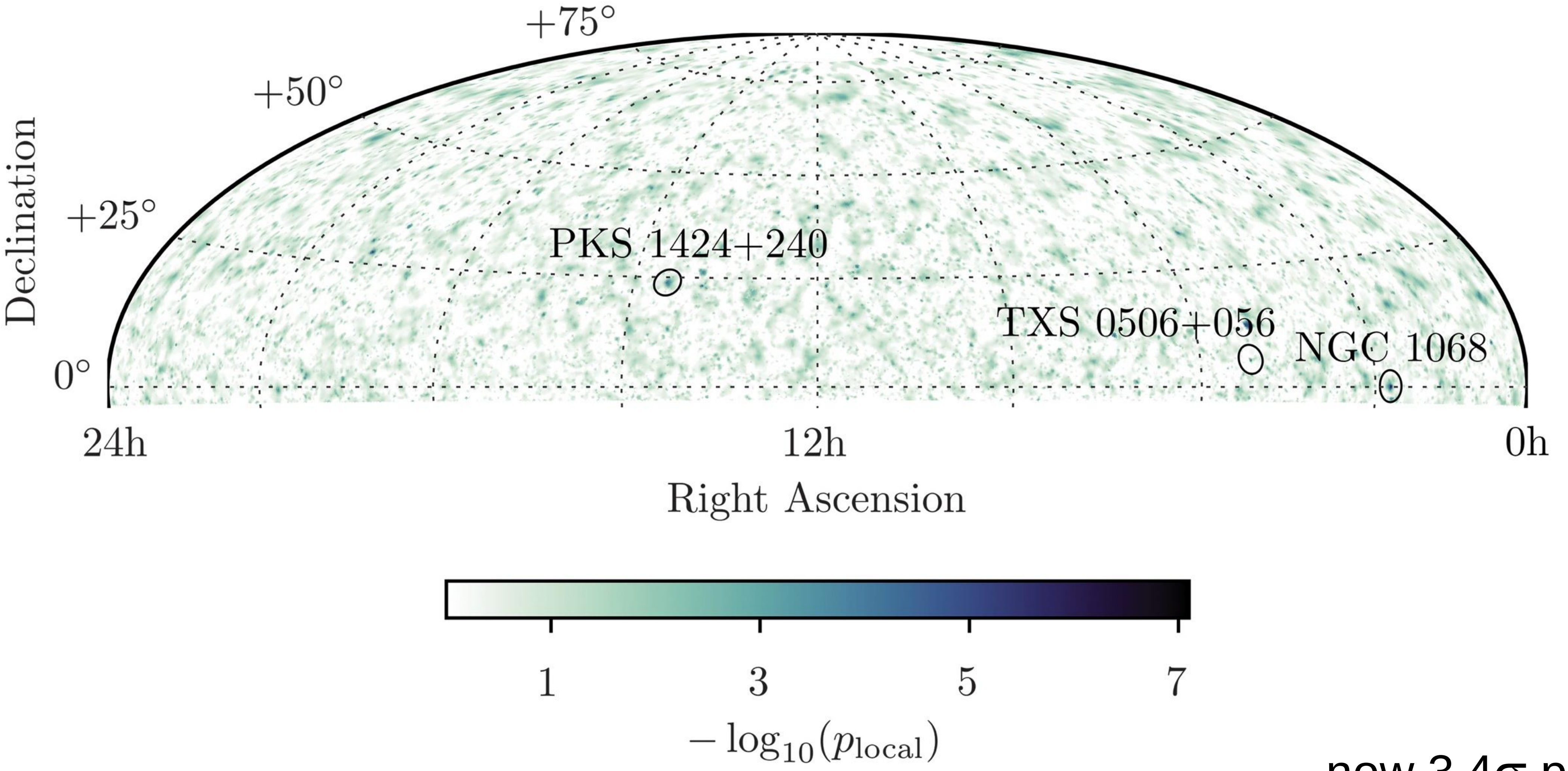
$$L_X \sim 10^{43}\,\mathrm{ergs}^{-1}$$

$$\mathrm{corona:}\ \ \tau_{\mathrm{p}\gamma} \sim 0.1 \ \rightarrow\ \tau_{\gamma\gamma} \sim 10^2 \rightarrow \mathrm{obscured}$$

$$\mathrm{large\ N_H:}\ \tau_{\mathrm{pp}} \sim 1 \ \rightarrow\ 1 \sim 100\,\mathrm{TeV\ neutrinos}$$

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

sub-leading sources: binomial analysis
also the 3 top sources




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.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]

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

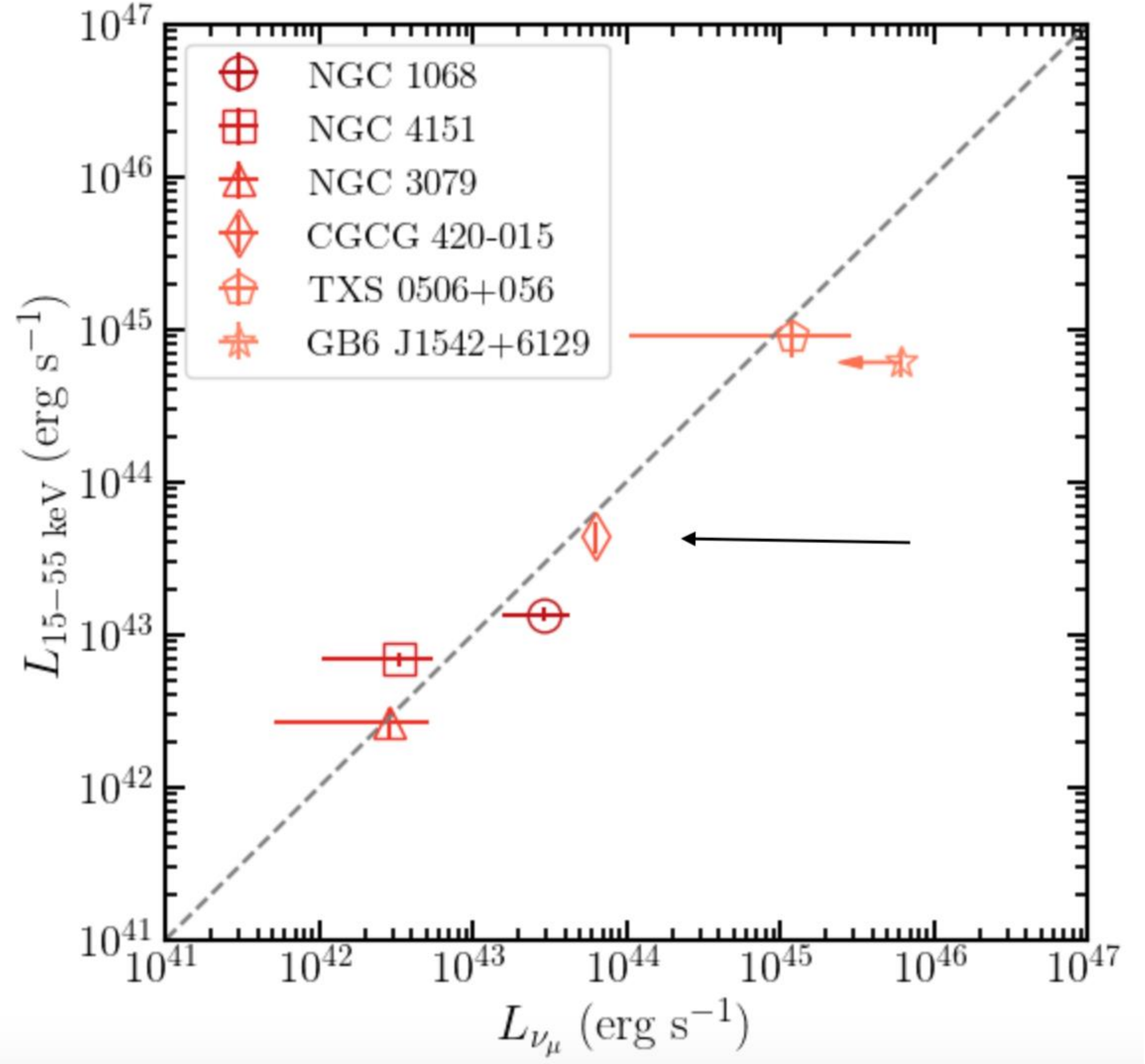
IceCube Collaboration*†

TXS 0506+056 detections

- multimessenger
- IceCube archival data
- observation optical flash

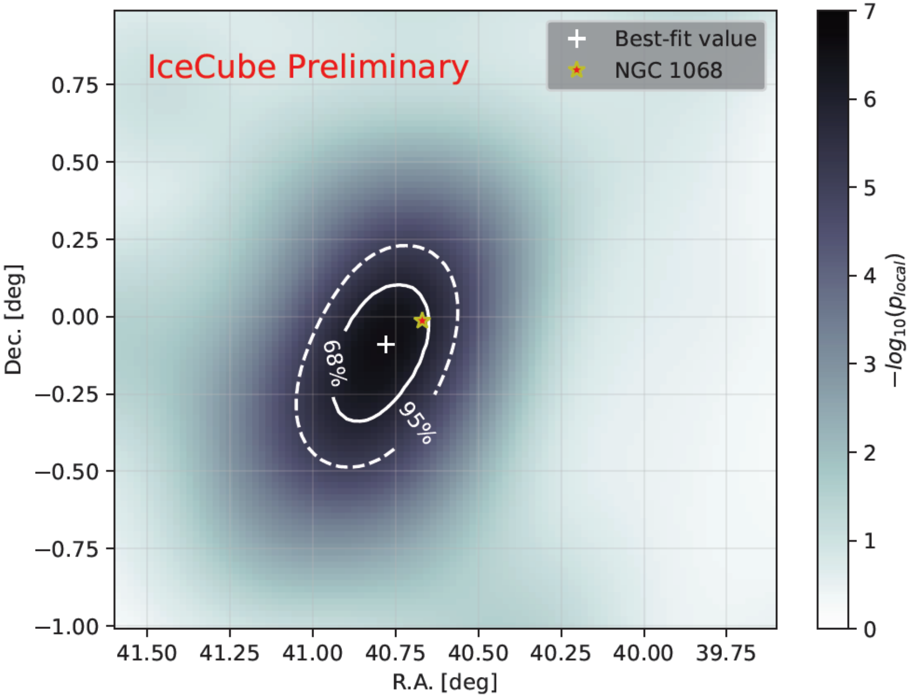
# X-ray vs neutrino flux

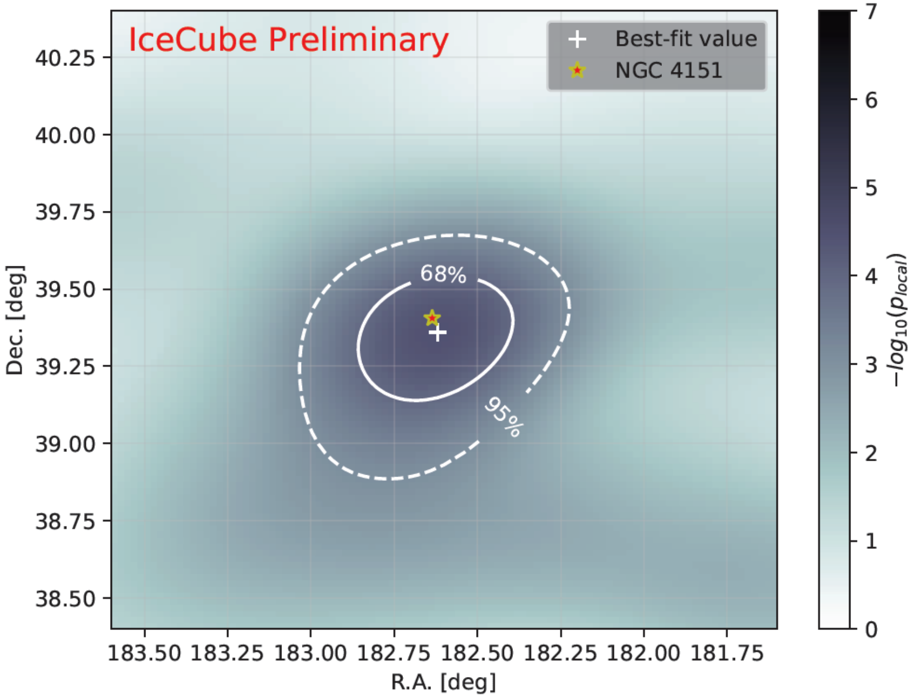
- hint from NGC 1068
- a correlation between the X-ray and neutrino flux of active galaxies producing neutrinos?
- X-ray flux of TXS 0506+056 is consistent with this pattern: neutrinos are produced in the core, not the jet ?



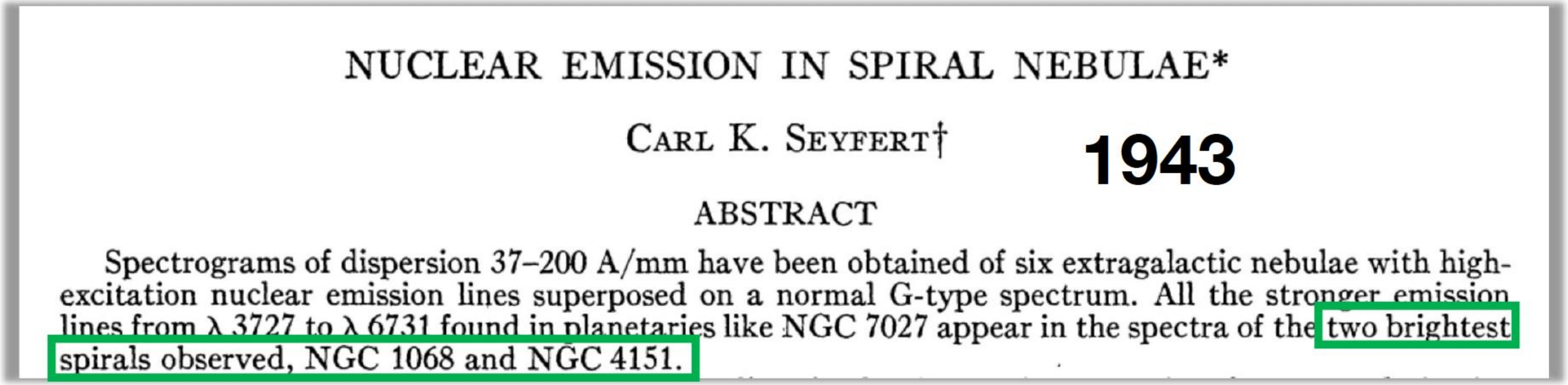

(Emma Kun et al., Neronov et al.)

# more sources …




- two brightest active galaxies discovered by Seyfert in 1943



NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

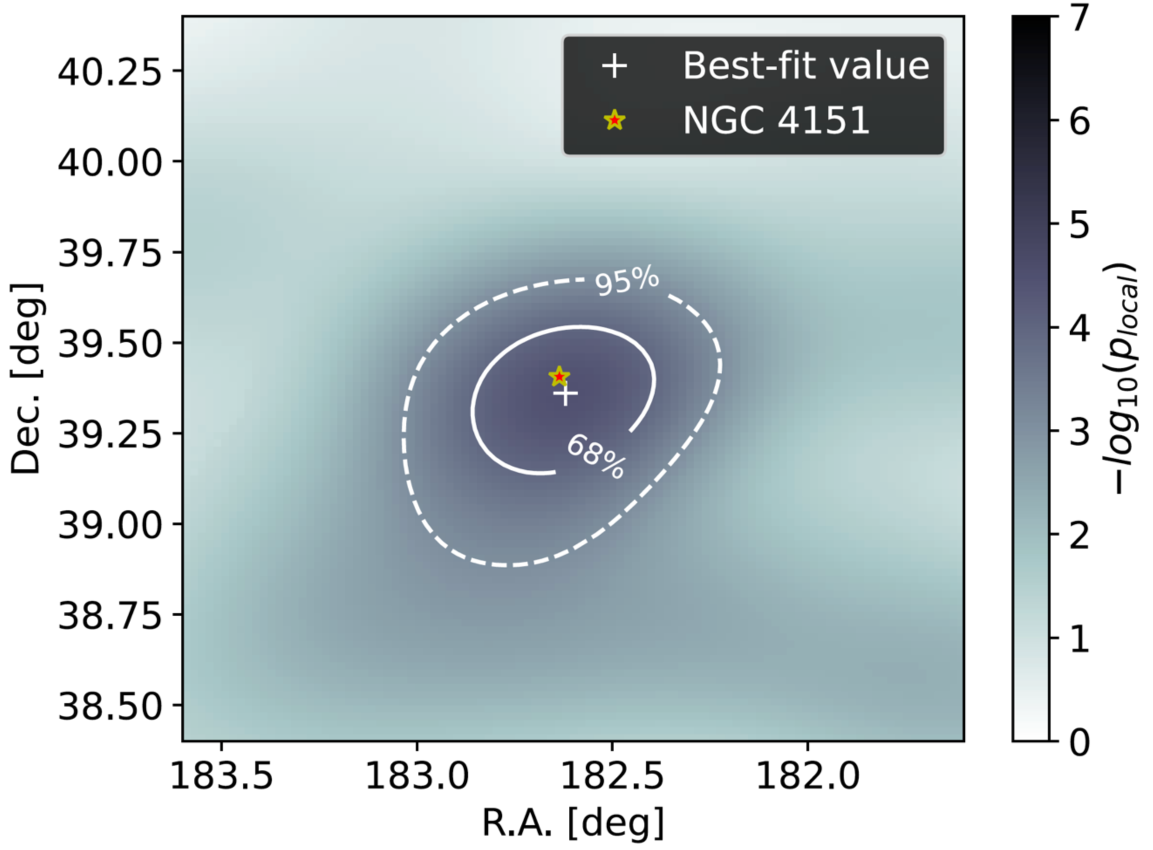
1943

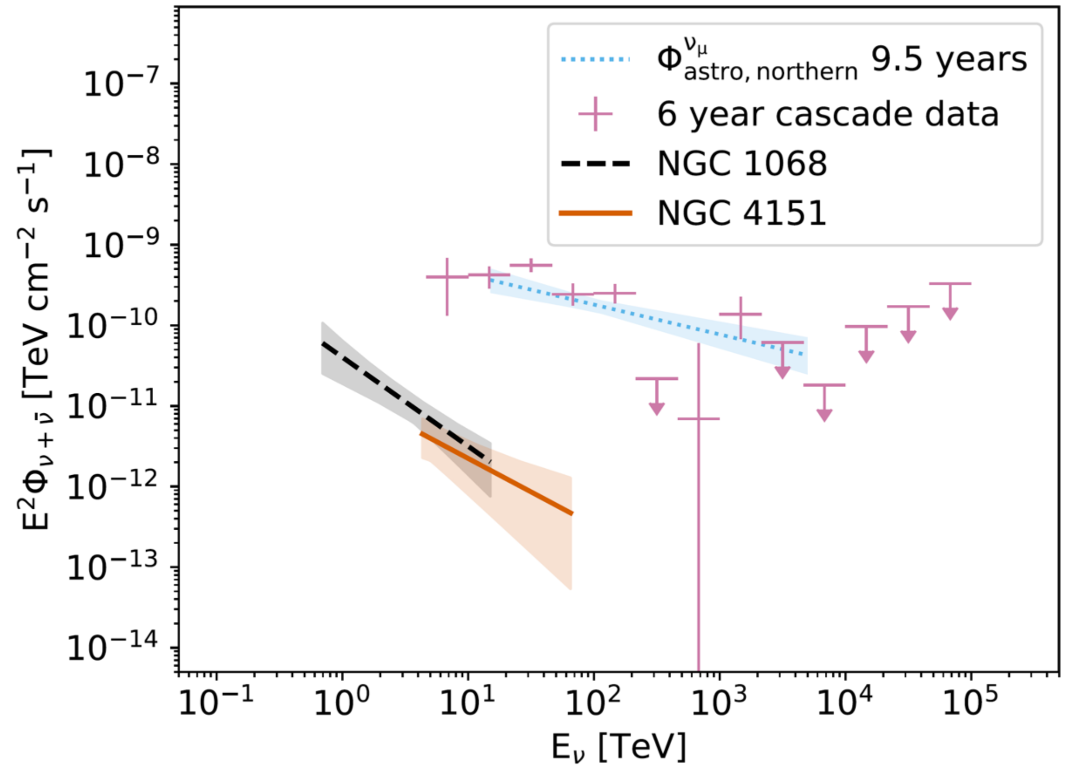
ABSTRACT

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

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

# multimessenger astronomy with X-ray sources



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

## The emergence of a new class of sources: high X-ray active galaxies

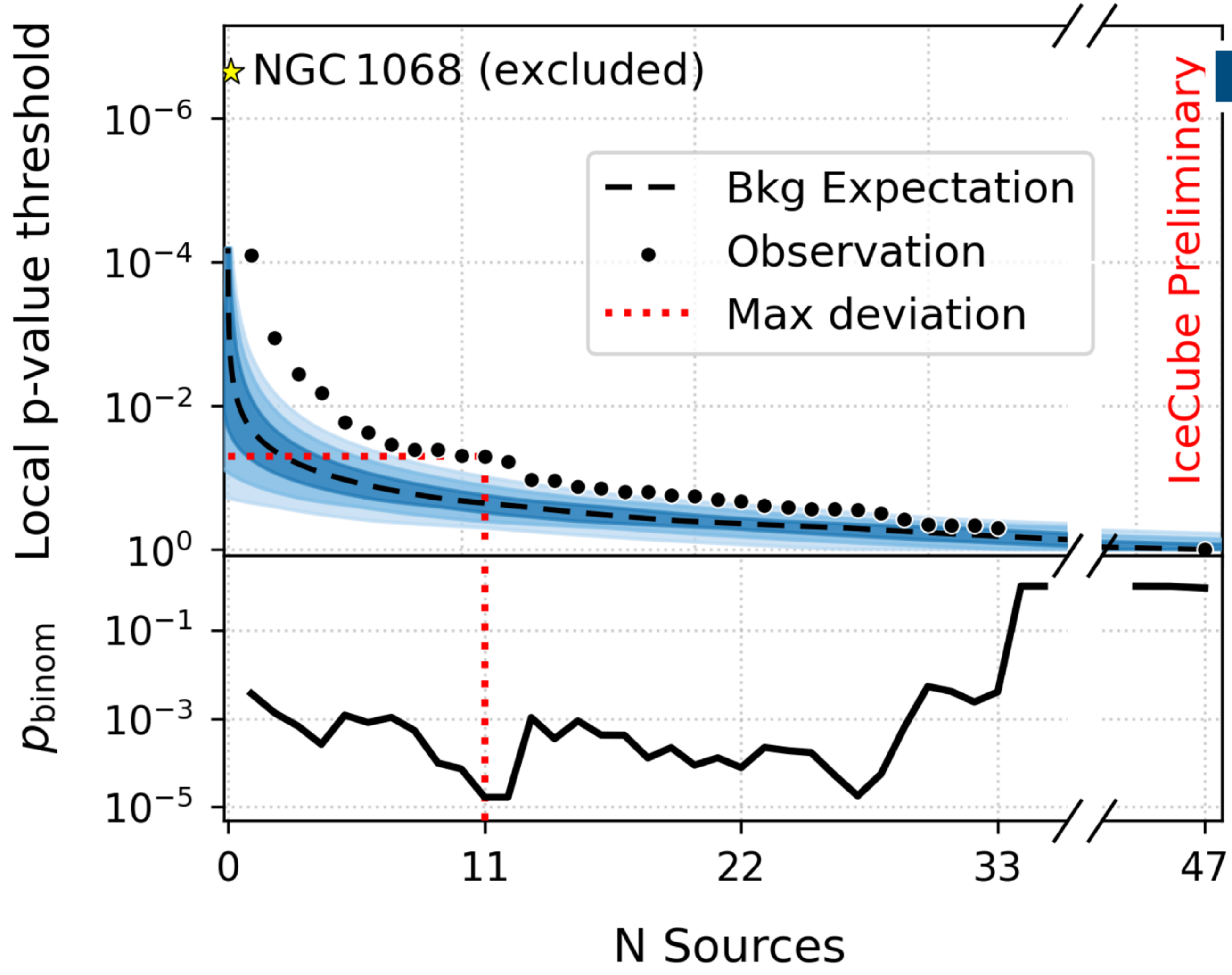
→ 2024: IceCube Search for Neutrino Emission from X-ray Bright Seyfert Galaxies
Northern sky NGC 4151 and CGCG 420-015
arXiv:2406.07601

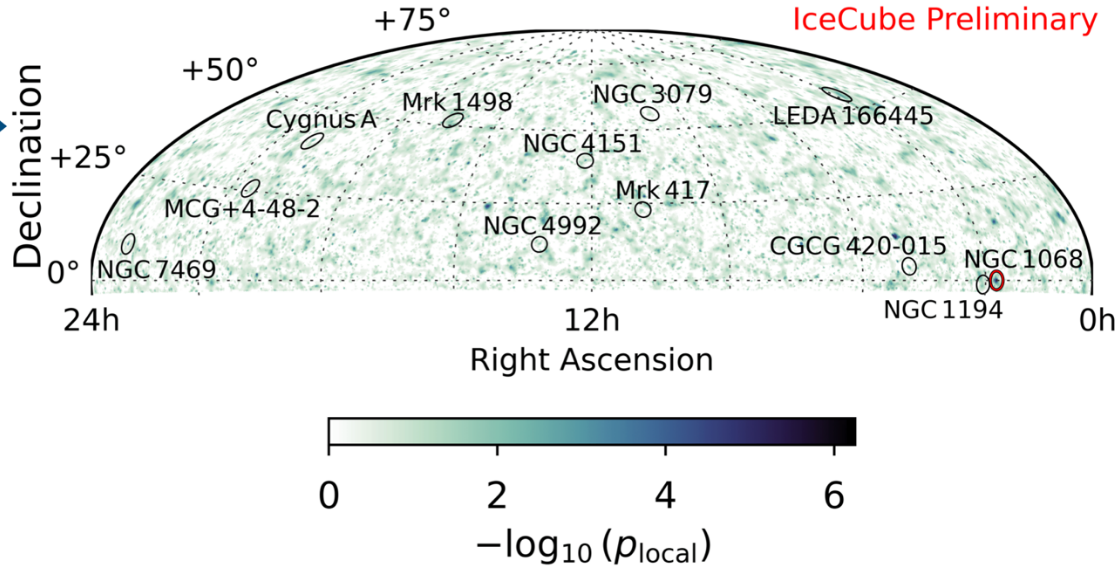
→ 2024 Search for neutrino emission from hard X-ray AGN with IceCube
NGC 4151
arXiv:2406.06684

→ 2024 Starting event search for Seyfert galaxies
TeVPA 2024
Circinus (not cenA)

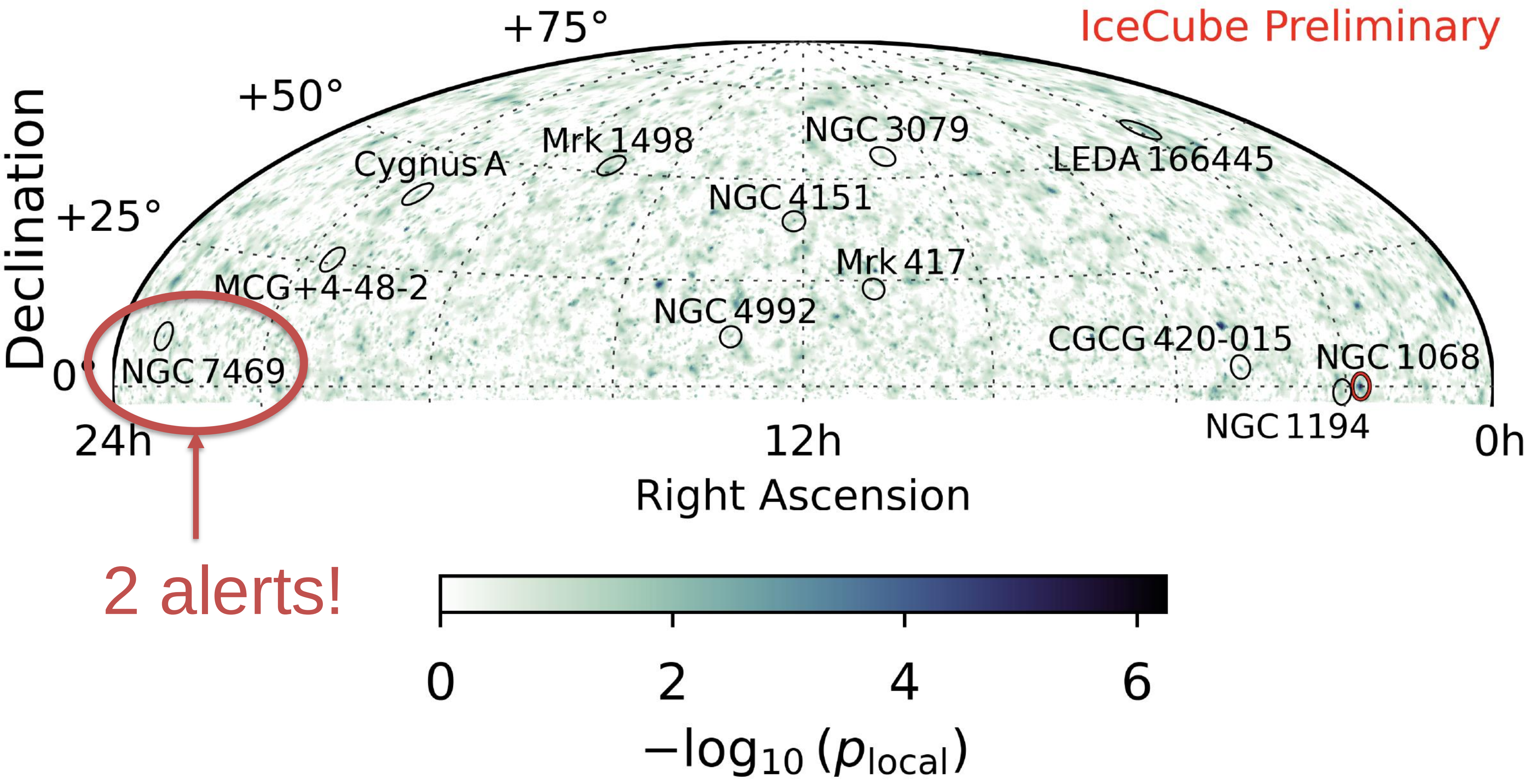
→ 2024 Binomial excess from 12 X-ray bright non-jetted AGN (update)
TeVPA 2024

# Binomial Test




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




binomial test of X-ray bright (non-jetted) active galaxies

maximum likelihood:

point source template

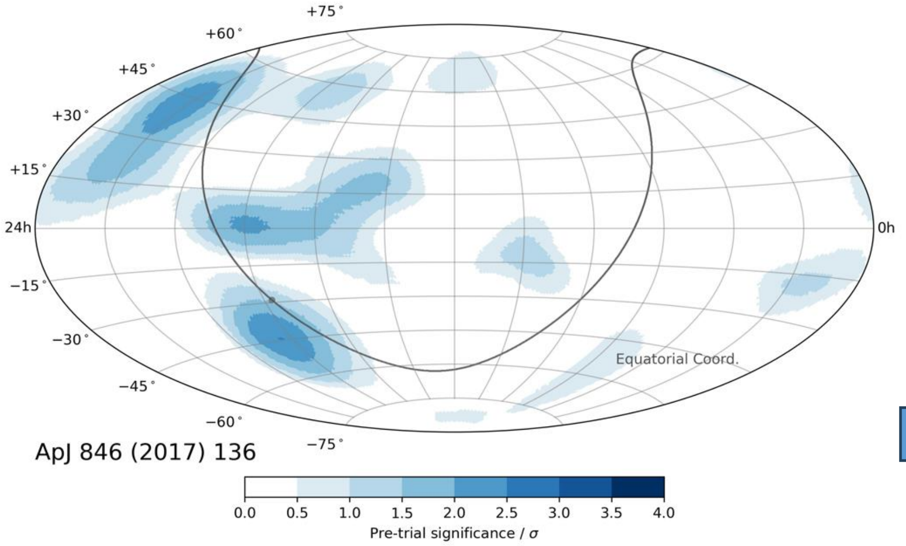
→

Fermi GeV Galactic plane data as template

→

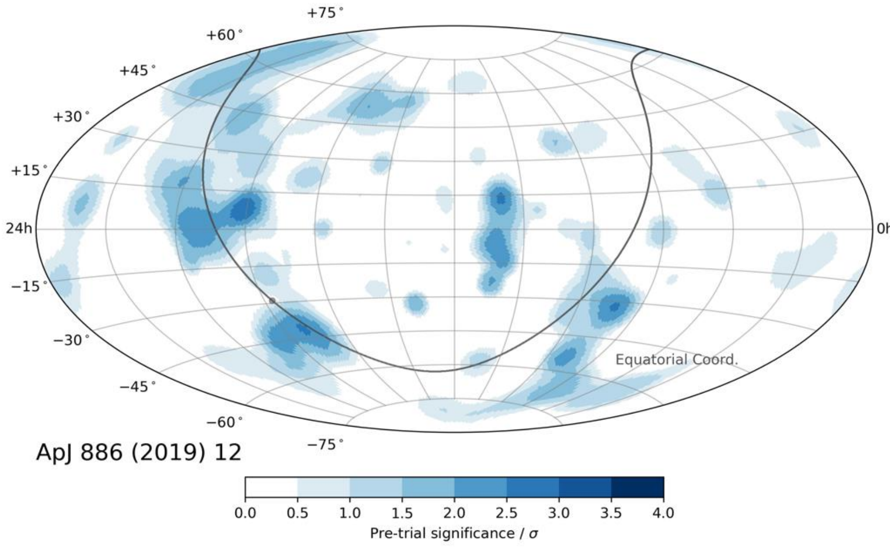
match with a P-value of 4.2 $\sigma$

**2017 paper**




ApJ 846 (2017) 136

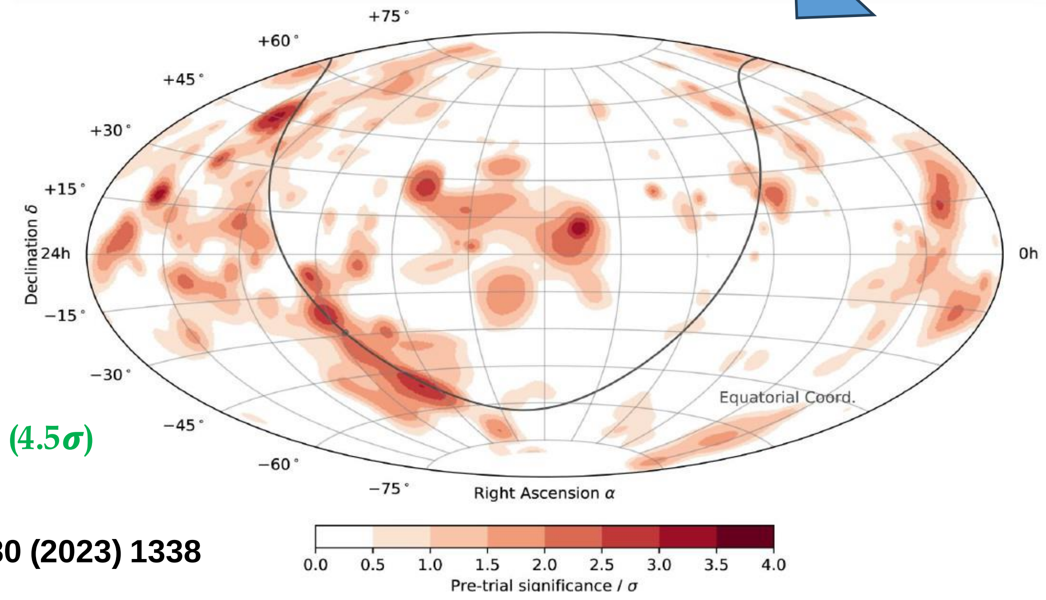
**2019 paper**




ApJ 886 (2019) 12

2 years of data
Galactic Plane p-value: 65%

7 years of data
Galactic Plane p-value: 2.1% ($2\sigma$)

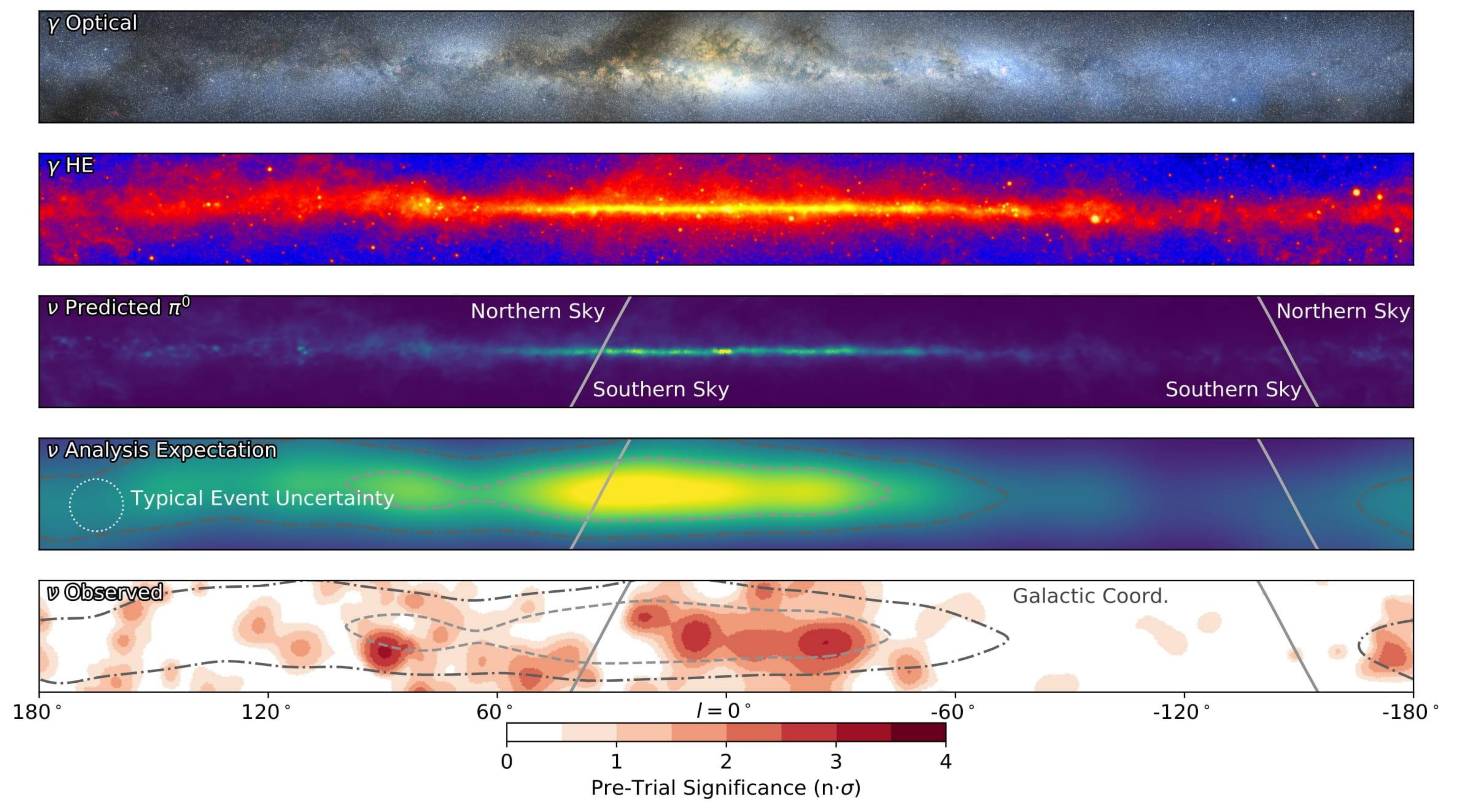



Deep learning improved resolution by ~2, sensitivity ~3

10 years of data
Galactic Plane p-value: 0.0004% ($4.5\sigma$)

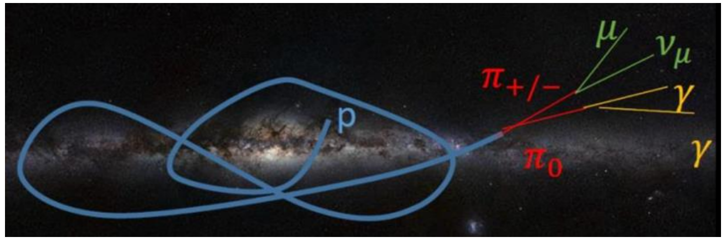
**Science 380 (2023) 1338**

Courtesy Naoko Kurahashi Neilson (ICRC 2023)

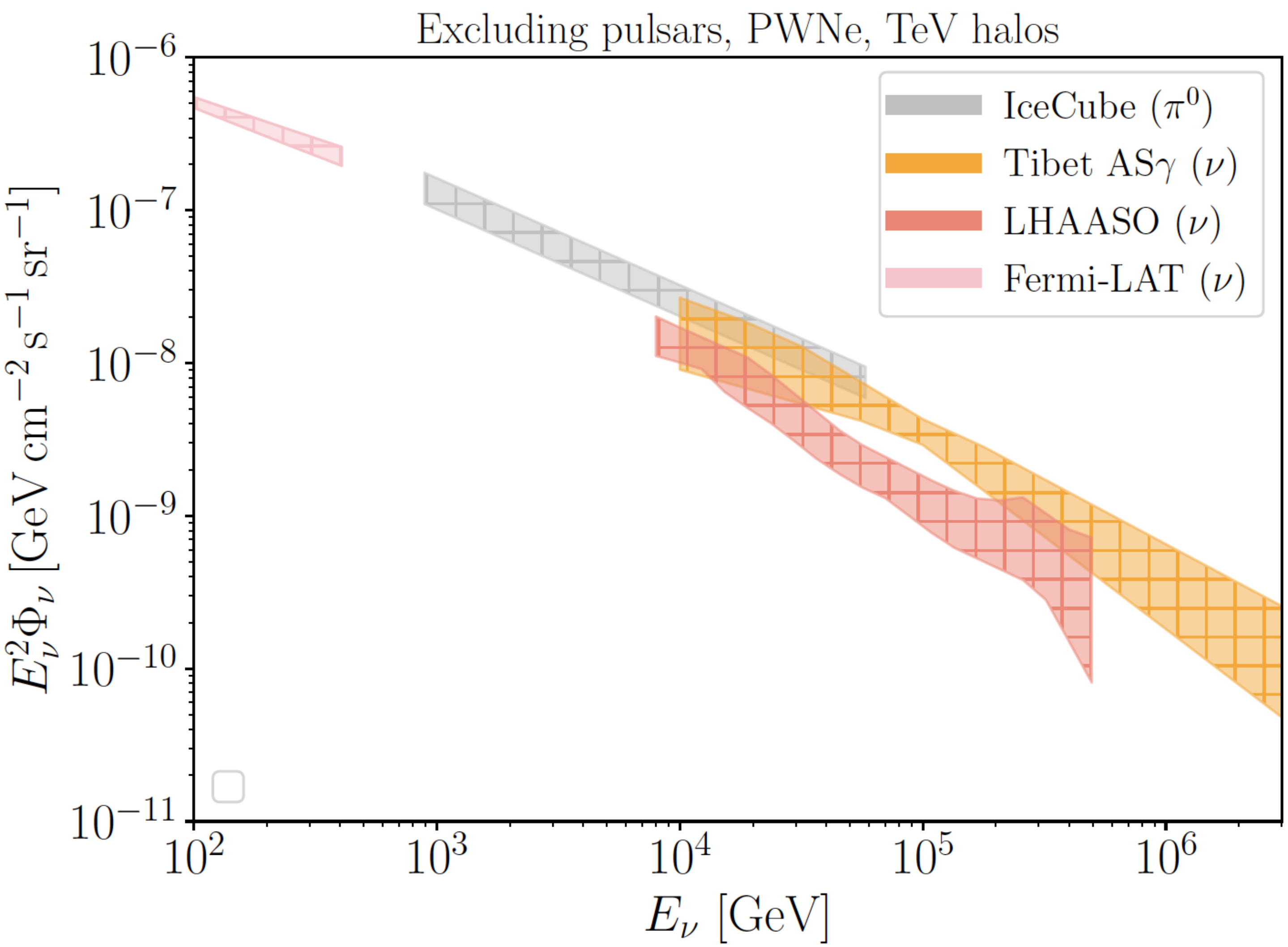



the Galactic flux is only at the 10% level of the total flux at 30 TeV !

- Galactic flux dominated by hadronic sources




- (unresolved) sources



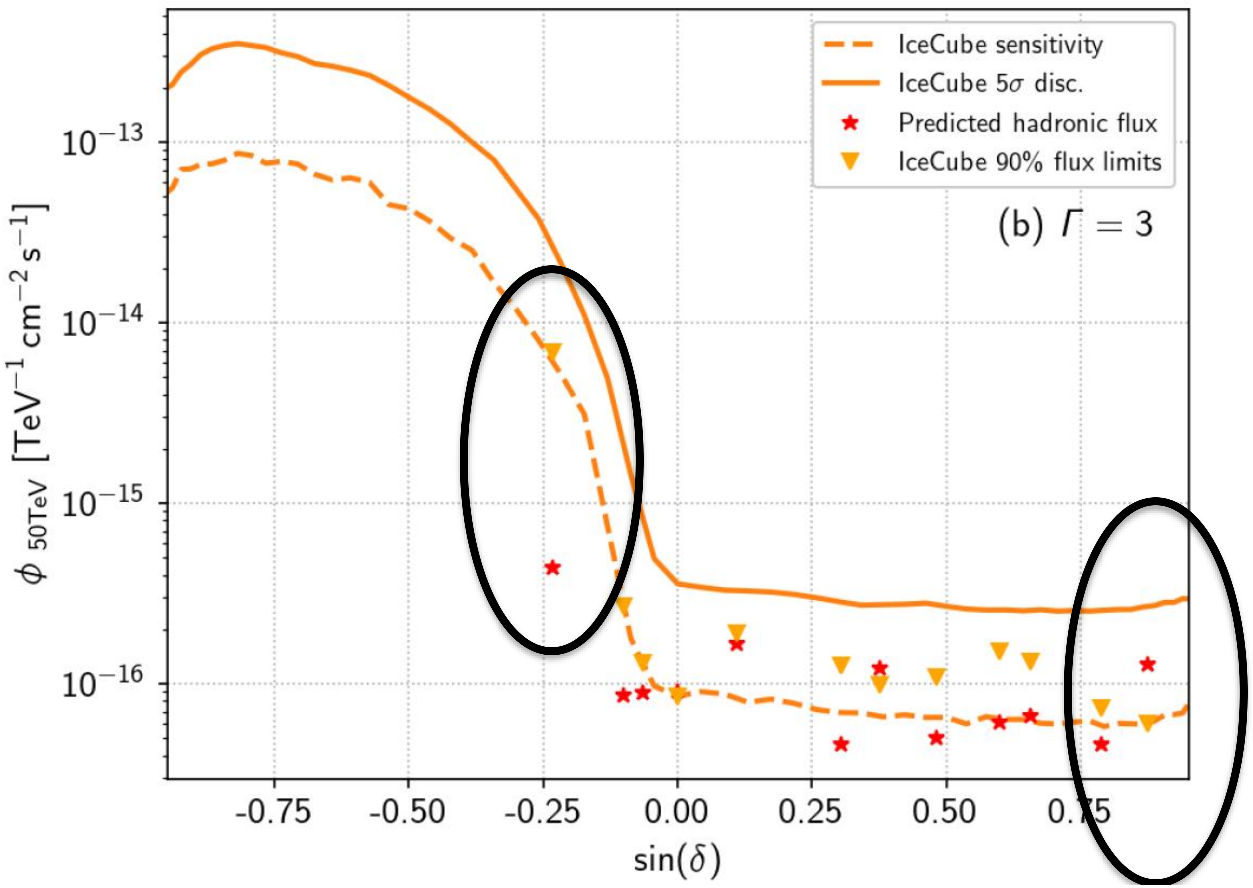
# Galactic sources?

neutrino flux(red) calculated from HAWC and LHAASO data is compared to the IceCube upper limit(orange)

→ no observation

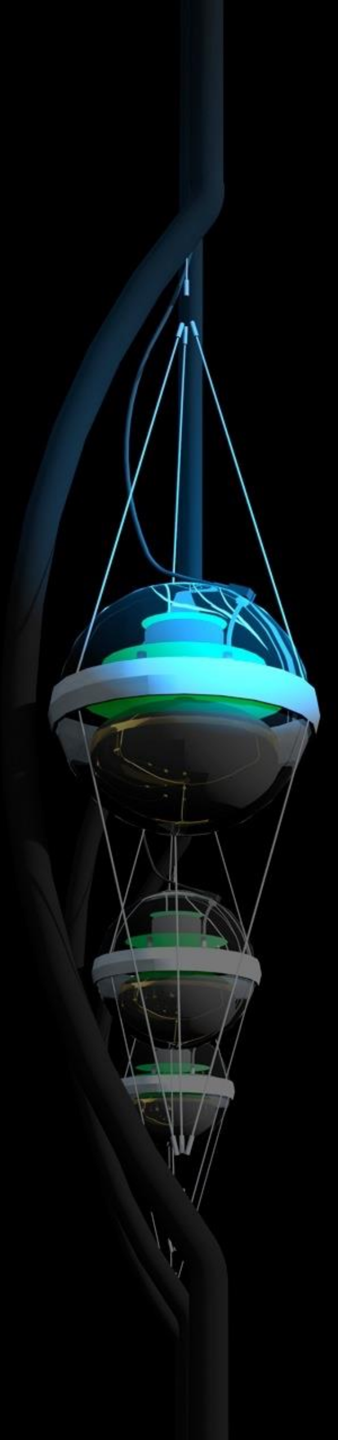
→ a few sources constained →

we need better neutrino sensitivity




| LHAASO name | TeV counterpart | Index / $\alpha$ | $\beta$ | Energy range [TeV] | Extension [deg.] | $\phi_{90\%}$ | $\phi_{\rm Predicted}$ | Constraints | Refs |
|---|---|---|---|---|---|---|---|---|---|
| J1849−0003 | HESSJ1849−000 | 1.99 | — | 0.4 – 100 | 0.09 | 0.85 | 0.90 | <94% | [a] |
| J0534+2202 | Crab Nebula. | 3.12 | — | 10 – 1600 | 0.00 | 0.70 | 1.2 | <59% | [b] |
| | | 2.79 | 0.1 | 1 – 177 | 0.00 | 1.0 | 1.2 | <84% | [c] |
| J2226+6057 | SNR G106.3+02.7 | 3.01 | — | 20 – 500 | 0.36 | 0.60 | 1.3 | <47% | [d] |
| | | 1.56 | 0.88 | 20 – 500 | 0.36 | 2.1 | 1.3 | — | [d] |

**Table 3.** Table of TeV spectral parameters and the corresponding hadronic constraints, neutrino upper limits, and expected neutrino fluxes at 50 TeV. The parameter $\phi_{90\%}$ represents the neutrino 90% C.I. flux limits parameterized as : $\frac{dN_{\nu_\mu+\nu_{\bar{\mu}}}}{dE_\nu} = \phi_{90\%}\cdot(\frac{E_\nu}{50\mathrm{TeV}})^{-\alpha-\beta\cdot\log\frac{E_\nu}{50\mathrm{TeV}}}\times10^{-16}\ \mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}}$. The parameter $\phi_{\rm Predicted}$ is the predicted neutrino flux with the assumption of $\gamma$-ray s are entirely hadronic. Hadronic constraints correspond to the ratio $\phi_{90\%}/\phi_{\rm Predicted}$ at 50 TeV calculated with fixed spectral parameters. The TeV spectral and morphology information (columns 3 – 6) is taken from [a] Huang & Li (2021), [b] Cao et al. (2021b), [c] Abeysekara et al. (2019b), and [d] Cao et al. (2021a).



neutrino astronomy 2025

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

icecube.wisc.edu

Arctic Ocean
Baikal-GVD
( Lake Baikal )
KM3NeT
( Mediterranean )
P-One
( East Pacific )
Atlantic
Ocean
Pacific
Ocean
TRIDENT
(South China Sea) + NEON + HUNT
Indian
Ocean
Pacific
Ocean
Southern Ocean
IceCube-Gen2
( South Pole )

# THE ICECUBE COLLABORATION

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Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

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Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
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RWTH Aachen University
Technische Universität Dortmund
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Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
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German Research Foundation (DFG)
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# THE ICECUBE COLLABORATION

ALIA 1

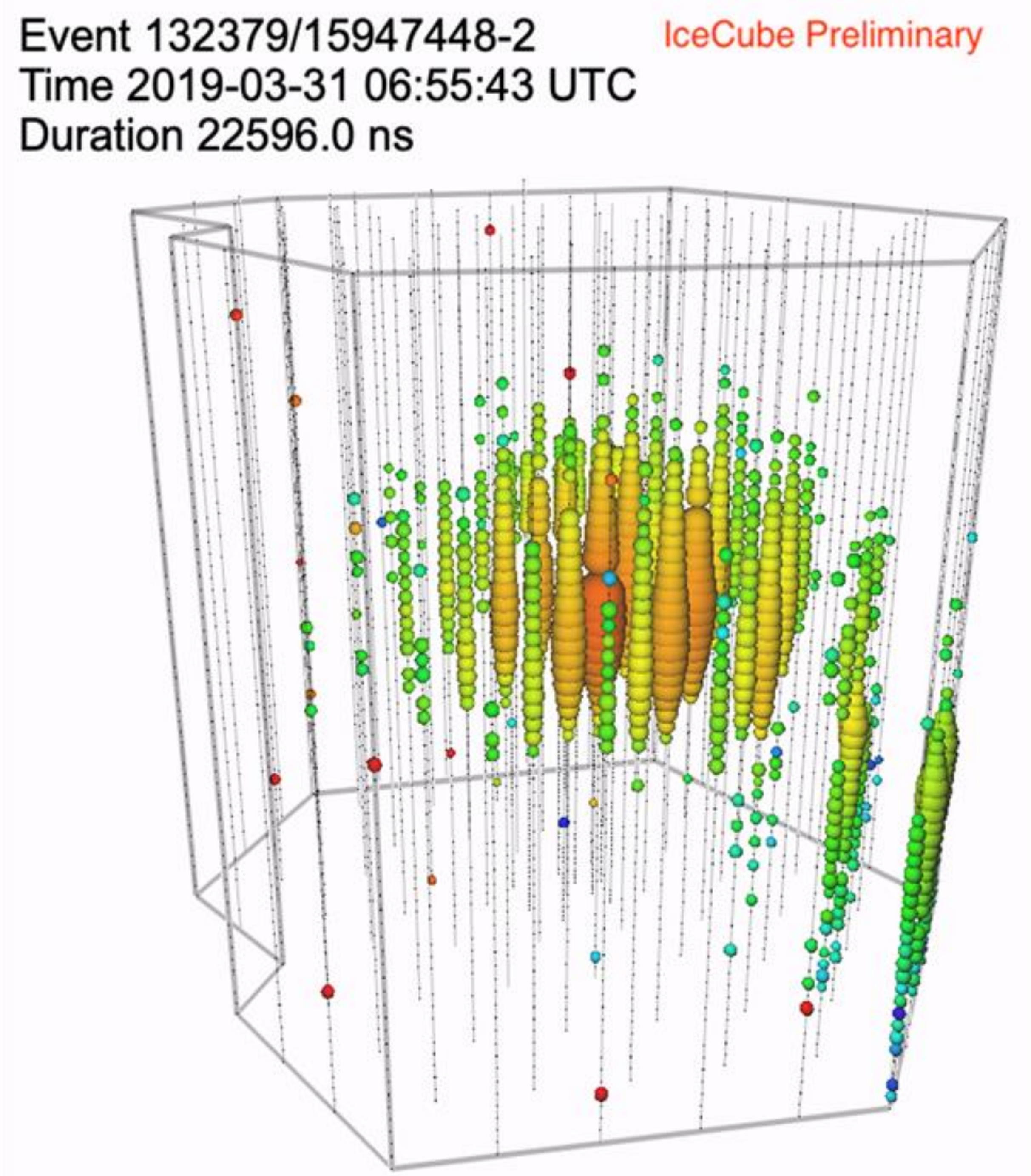
1

TED KINGDOM 1

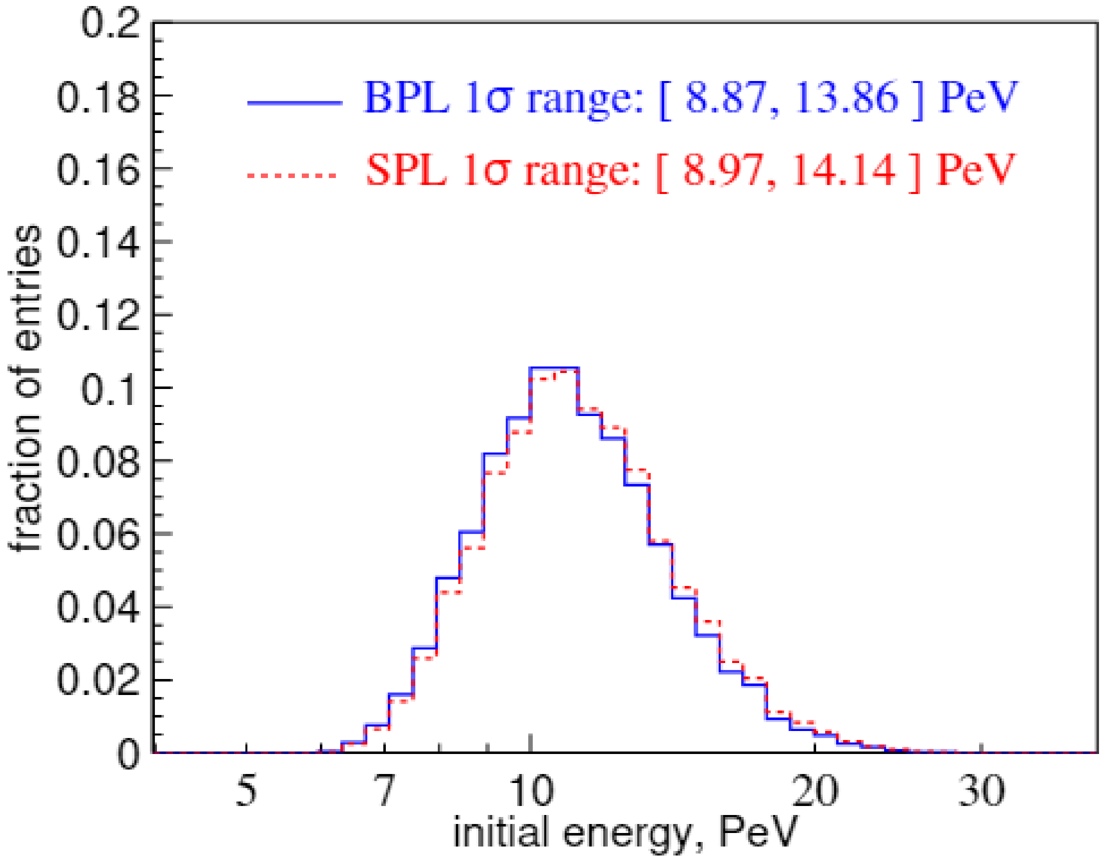
UNITED STATES 25

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

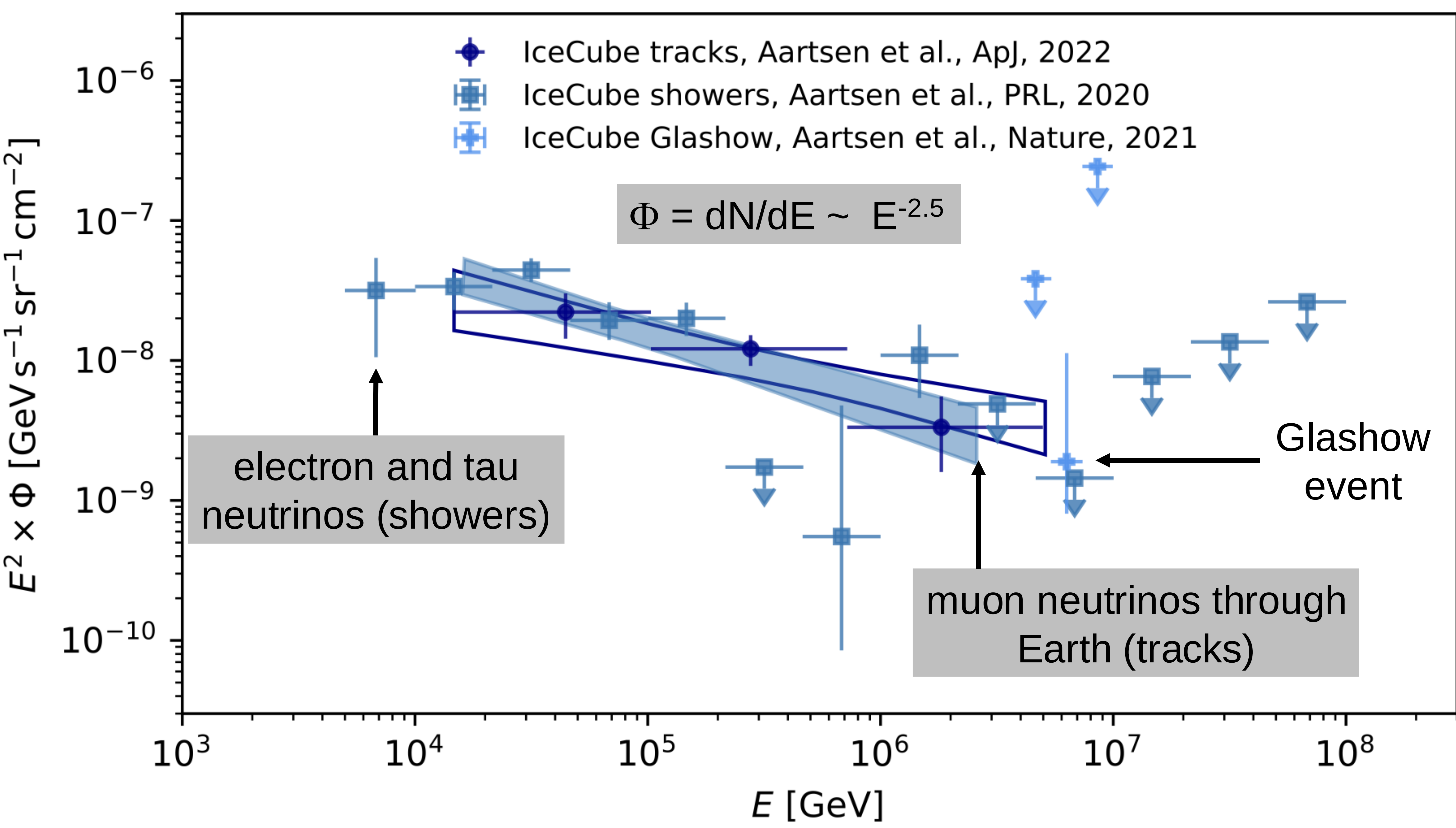
# IceCube's Highest Energy Event:




## 11.4 PeV (3 with $E_\nu$ >10 PeV)

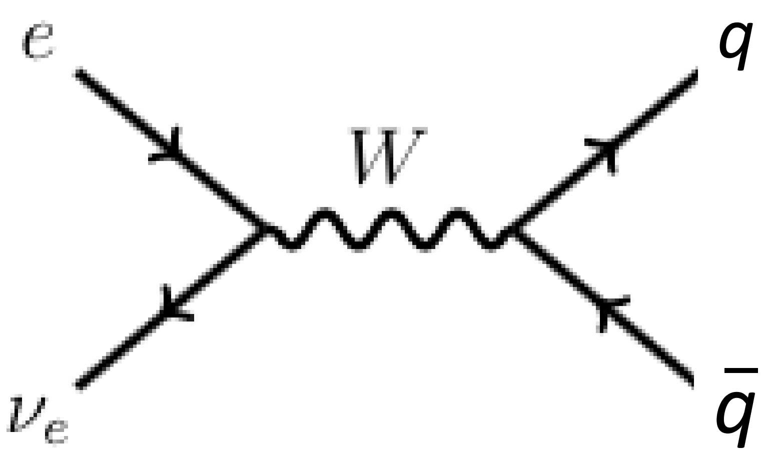



*Most probable neutrino energy when assuming a BPL spectrum ($\gamma_1$ ,$\gamma_2$)=(1.72,2.84) [Data Release]



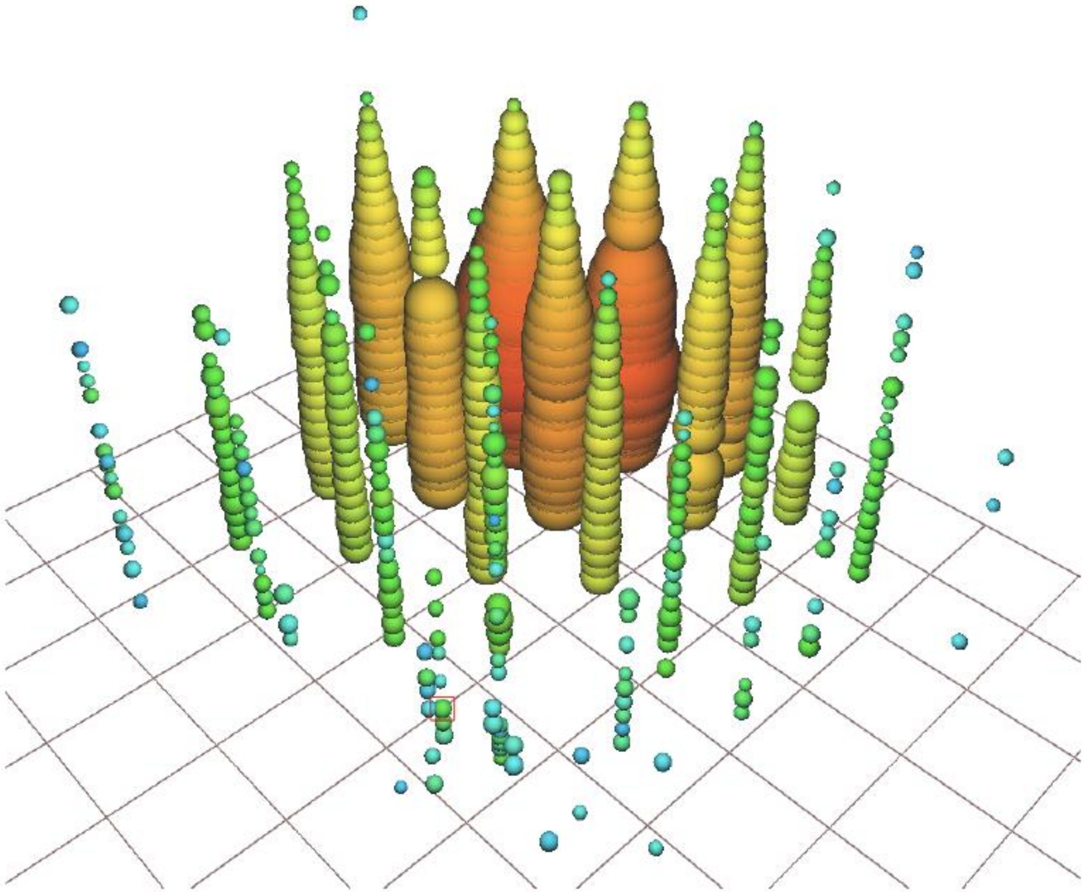
IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ E-2.5
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
$E^2 \times \Phi$ [GeV s$^{-1}$ sr$^{-1}$ cm$^{-2}$]
$E$ [GeV]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

# Glashow resonance event with energy 6.3 PeV

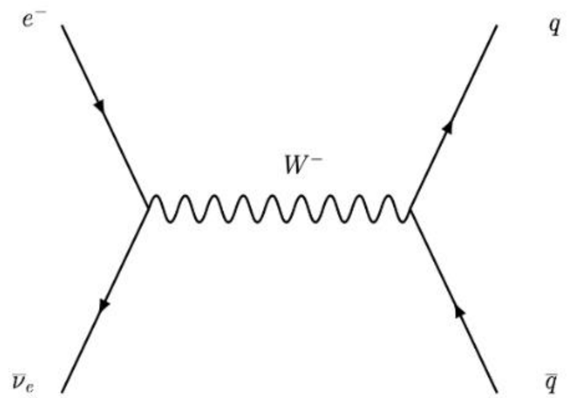


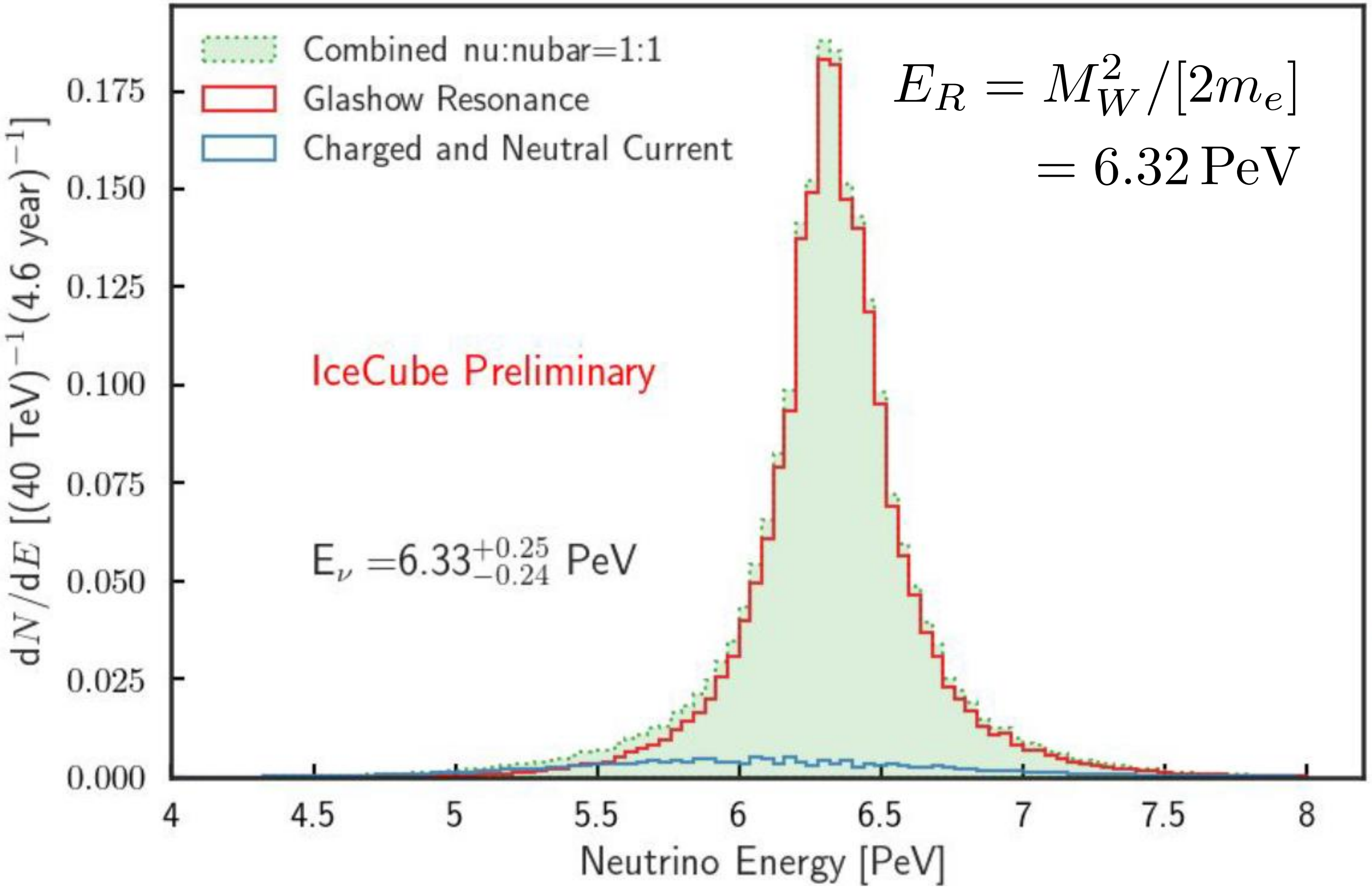

resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

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



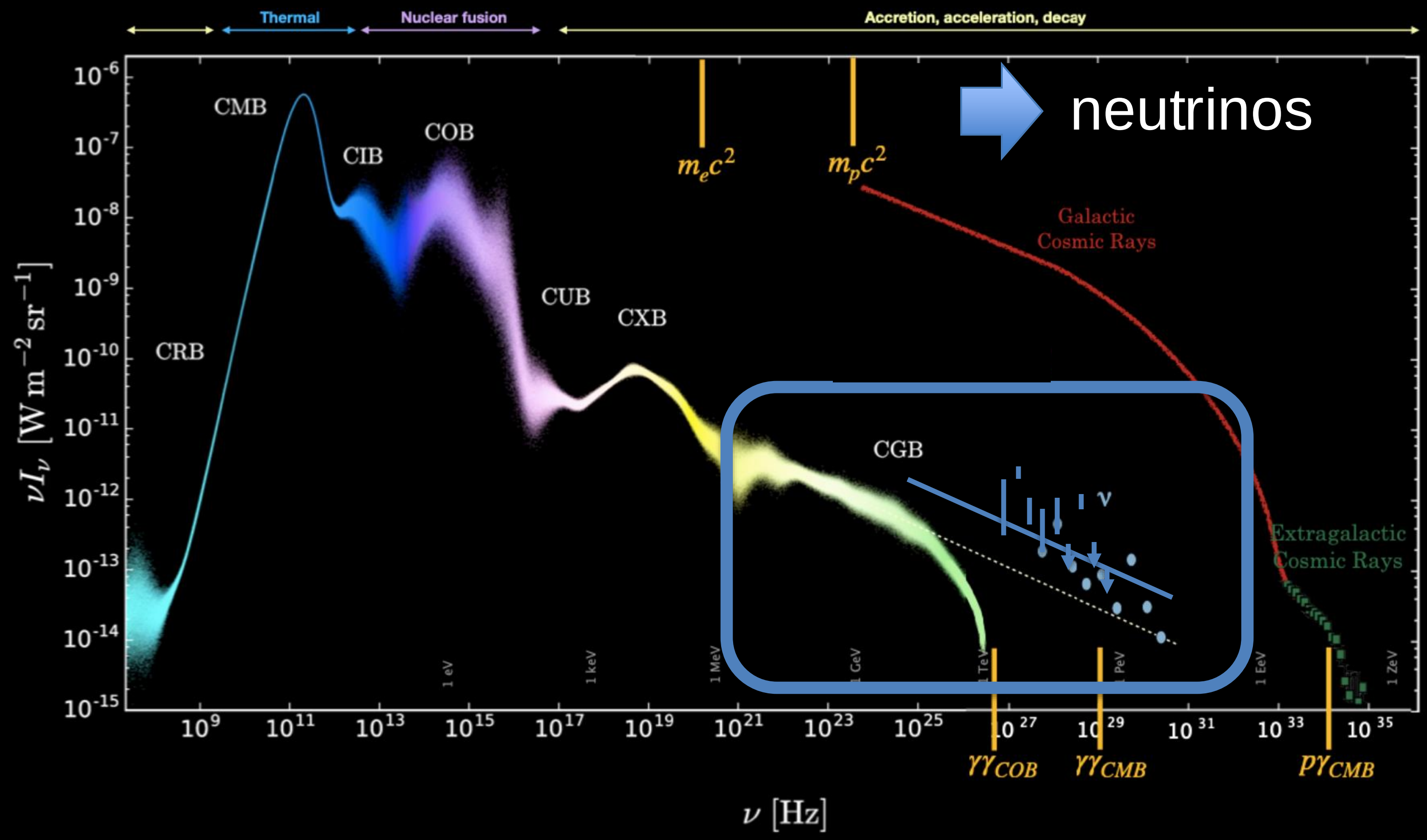
- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino
- SM cross section known → measure flux




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

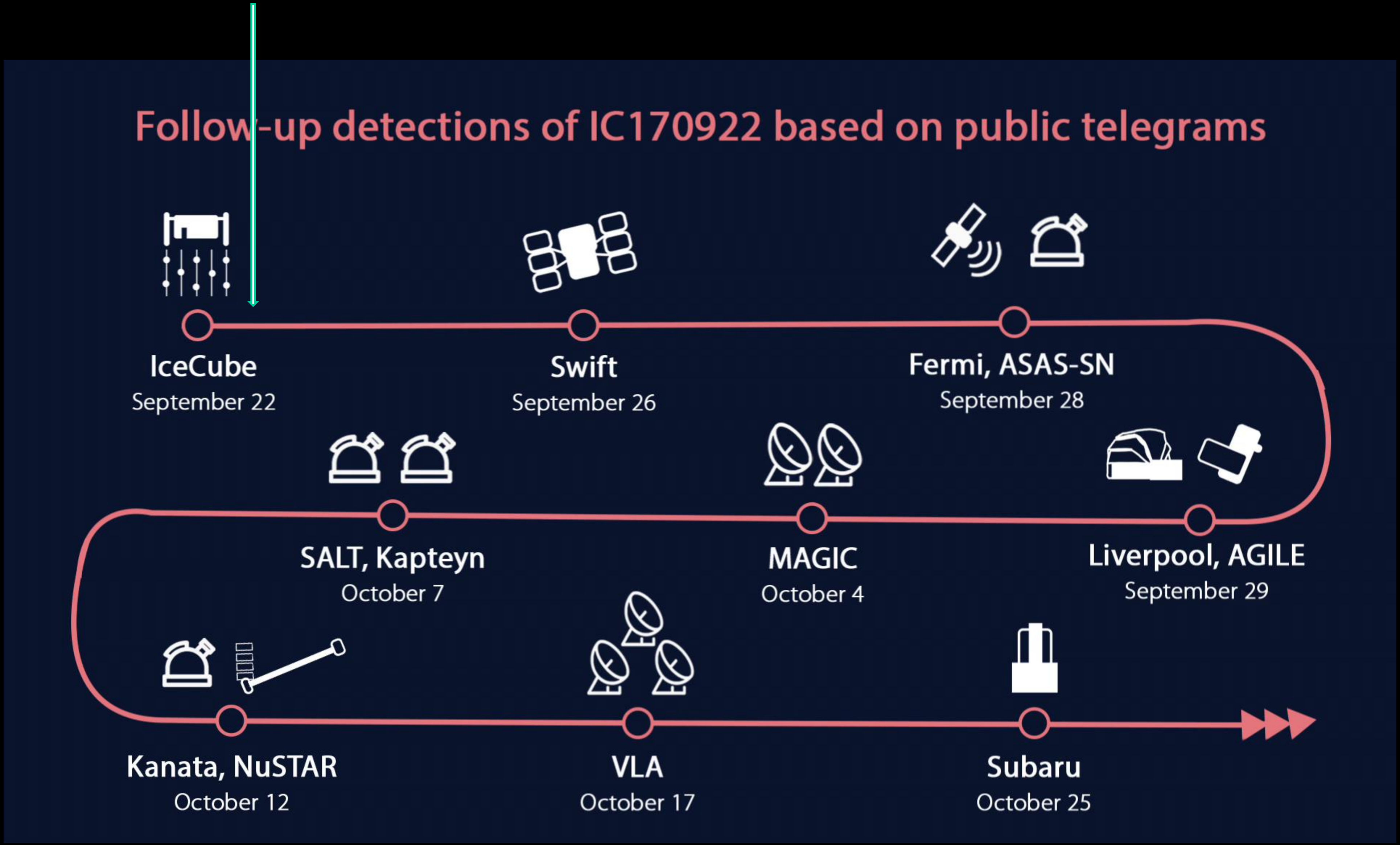
# energy density in the Universe as a function of frequency




- Fermi does not observe the gamma rays of $\pi^0$ origin
- the sources are $\gamma$-ray obscured

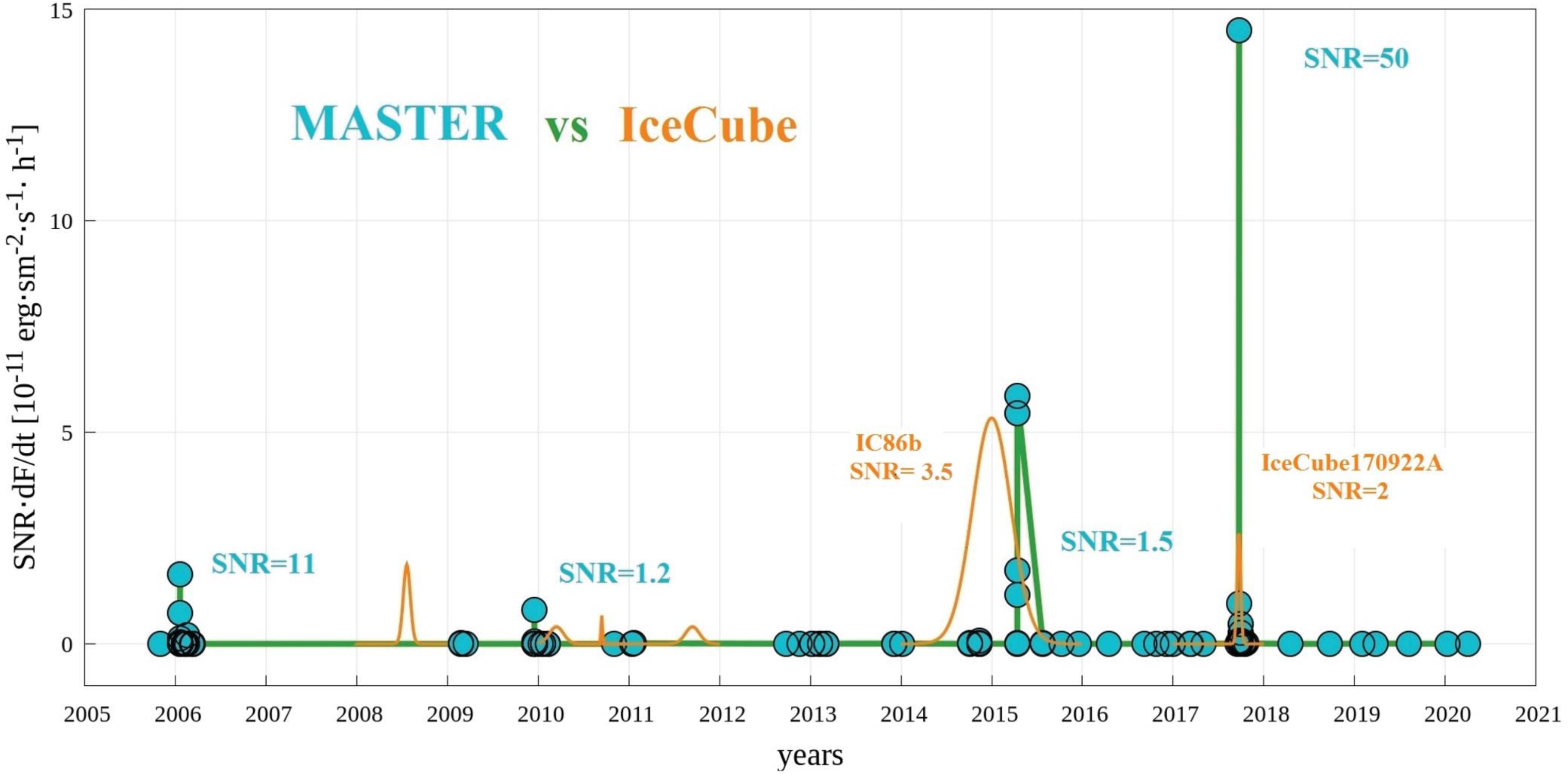
in the extreme universe the energy in neutrinos is larger than the energy in gamma rays observed by Fermi

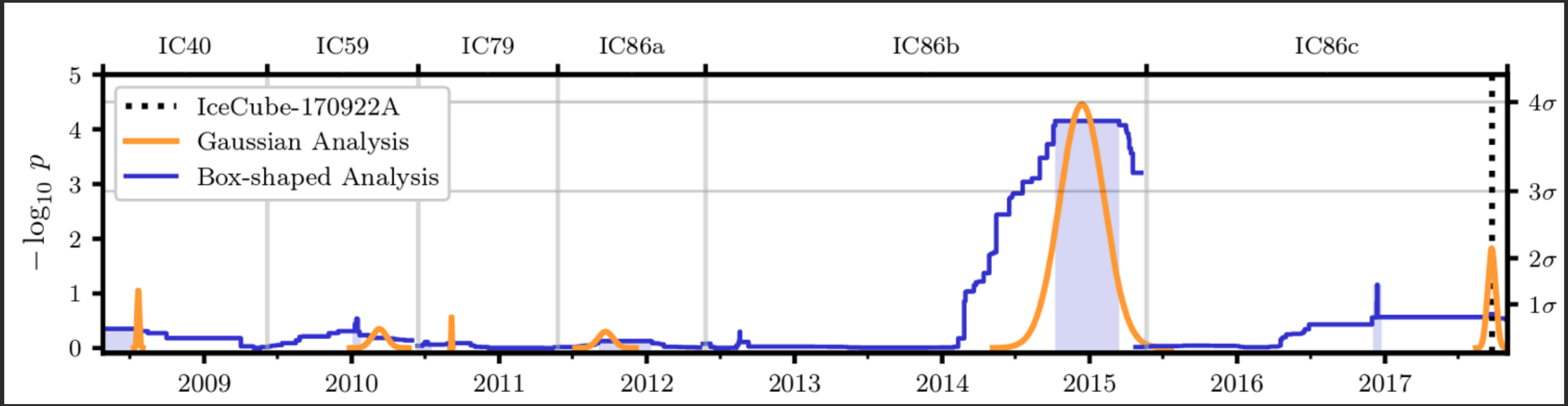
MASTER robotic optical telescope network: observing within 73 seconds
optical flash after 2 hours: highest statistical association of TXS 0506 with IC170922

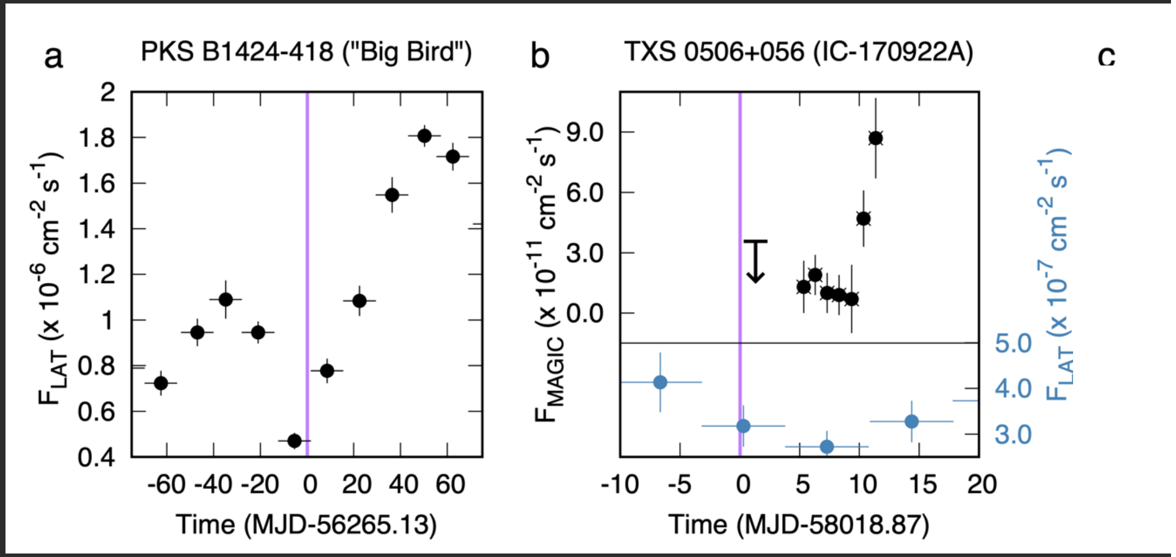


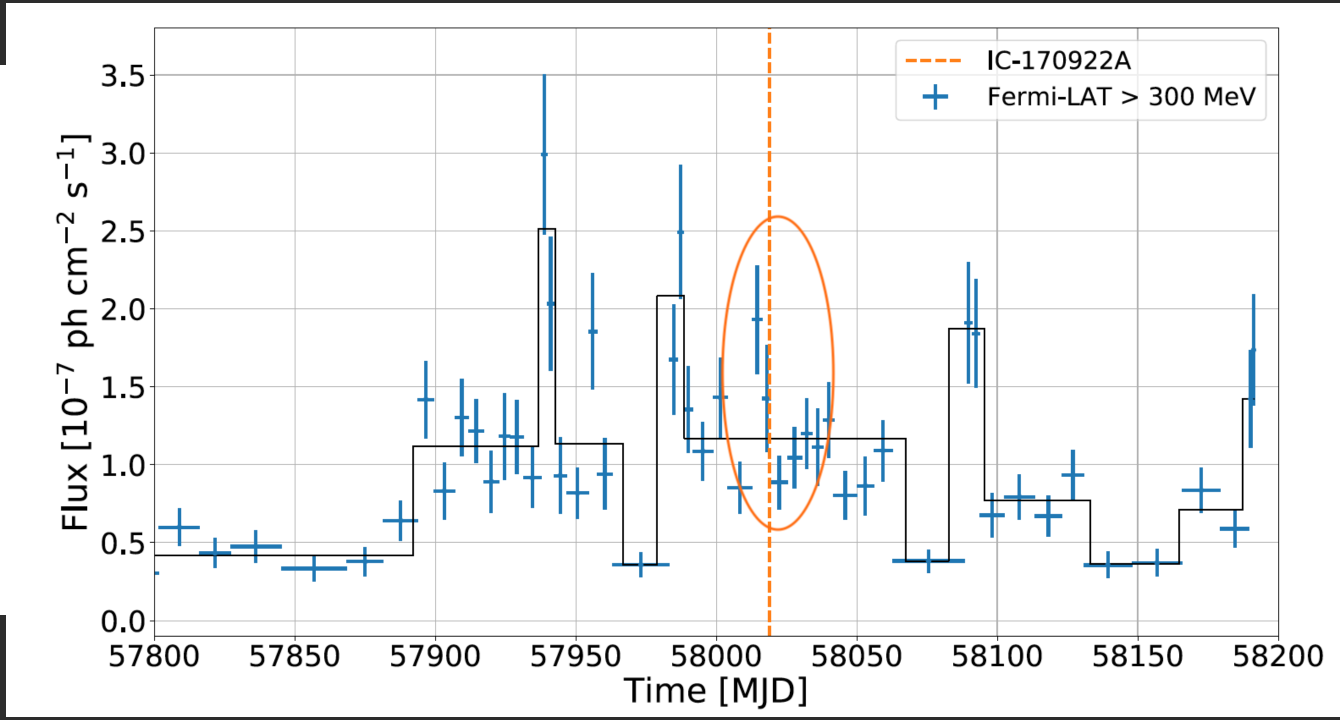
“MASTER found the blazar in the off-state *after one minute* and then switched to on-state two hours after the event. The effect is observed at a “50-sigma significance level”

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






TXS is an obscured source in 2014 and, possibly, also in 2017

2411.14598 [astro-ph.HE]
2411.17632 [astro-ph.HE]

# MASTER
robotic network

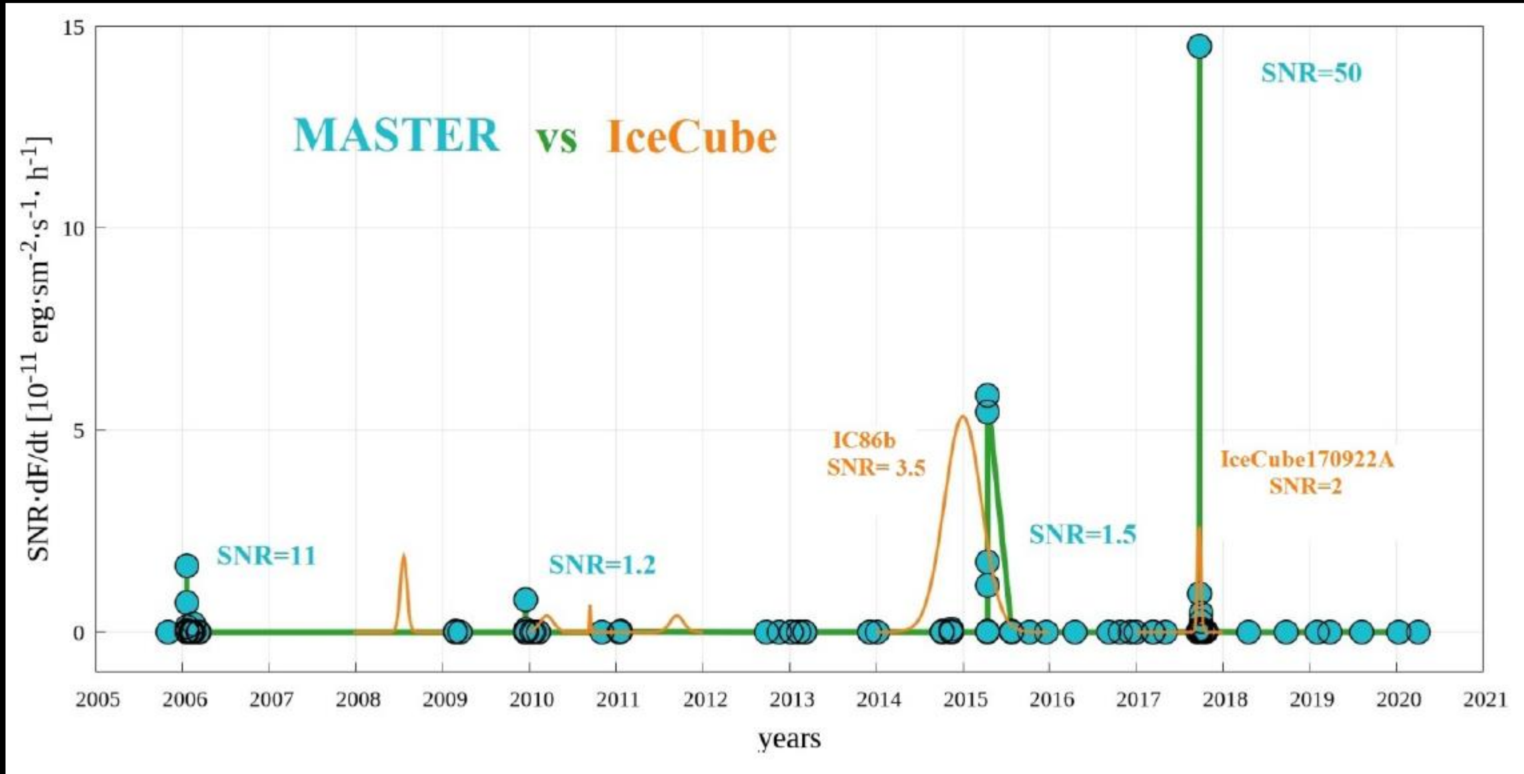
optical observations
TXS 0506+056
since 2005

blue panels:
expanded time axis
years → seconds


seconds after
2014-15 burst

seconds after
IC170922

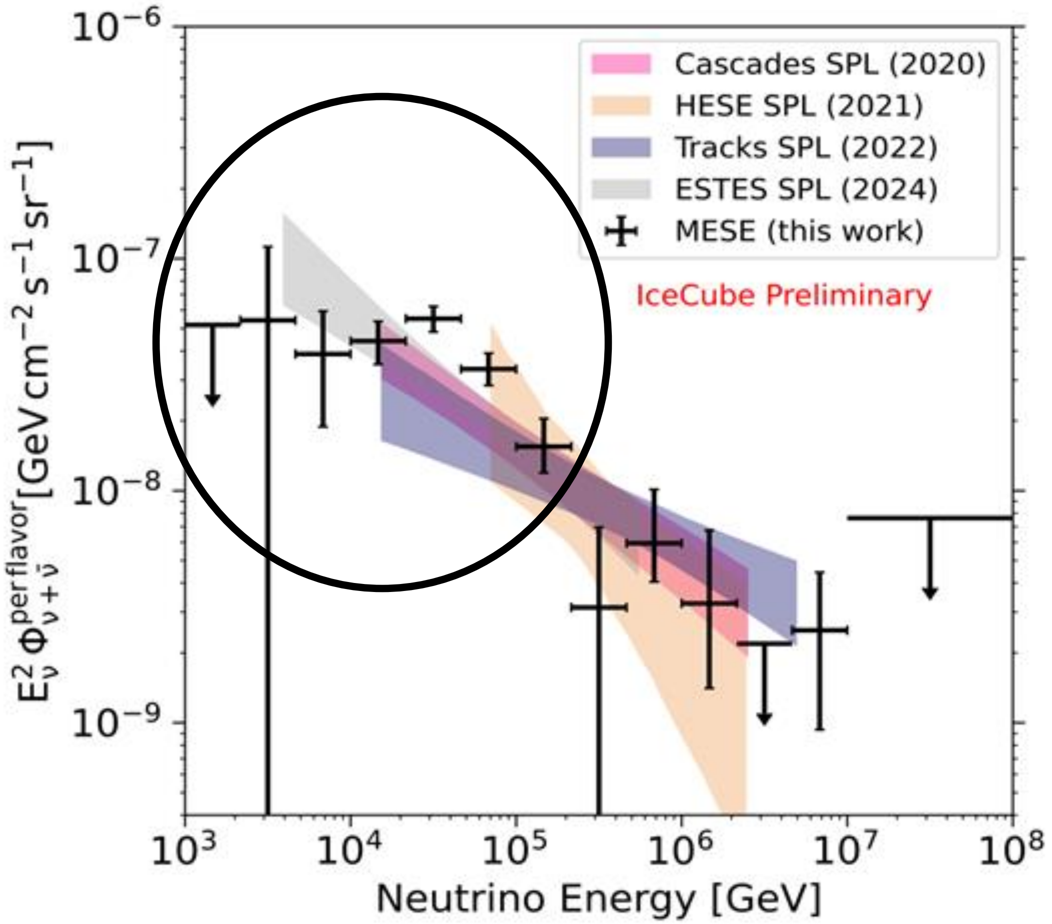
time variation of flux
times
signal-to-noise

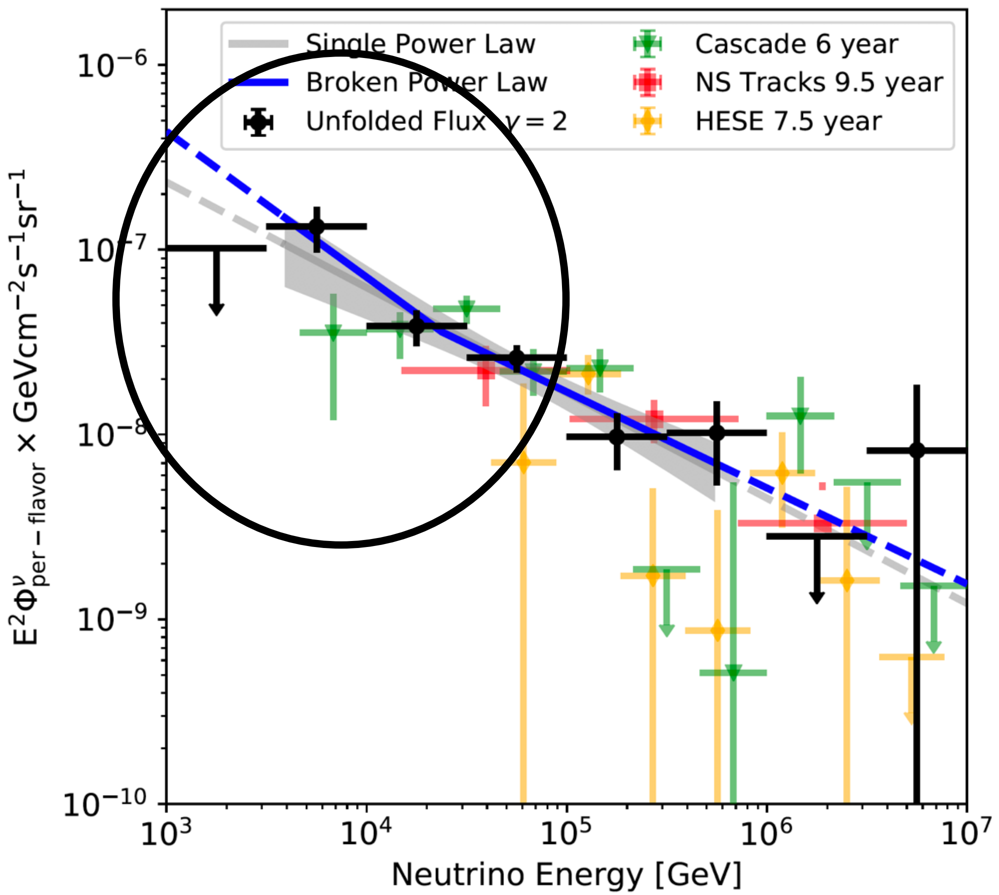



hour-scale
variability of the
source after
neutrino emission

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

starting event and starting track analyses track analyses

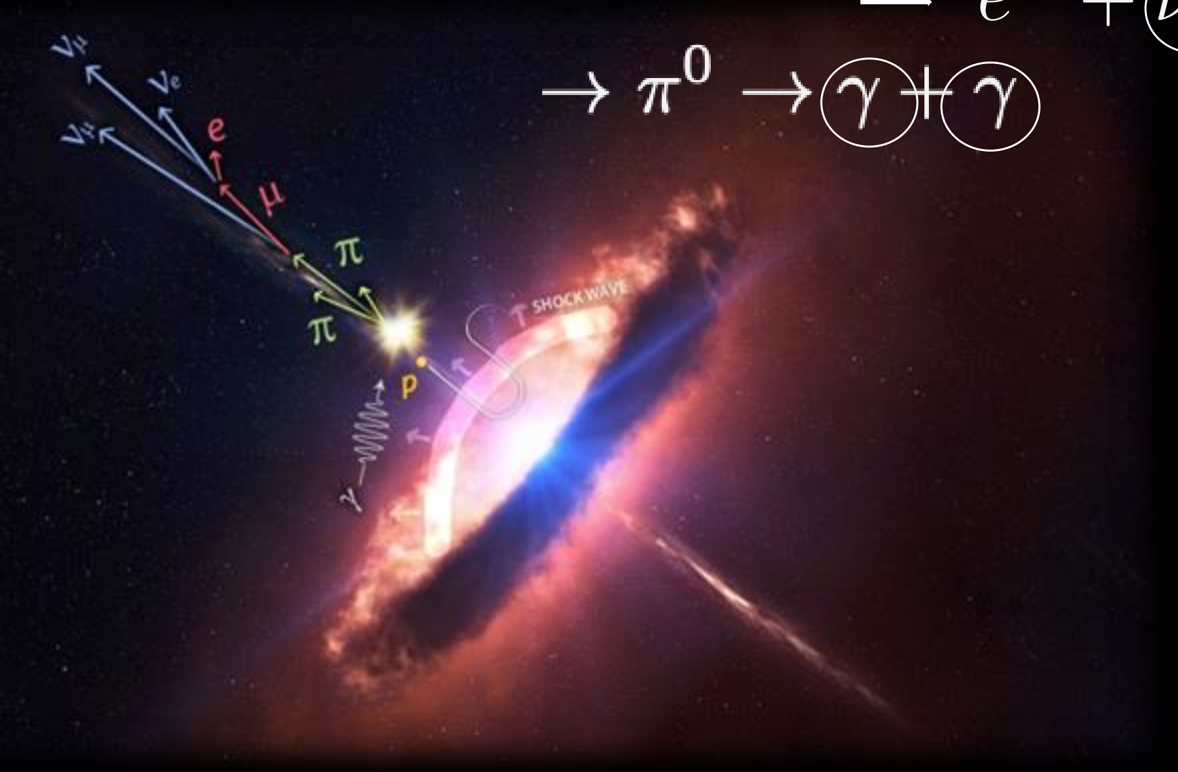


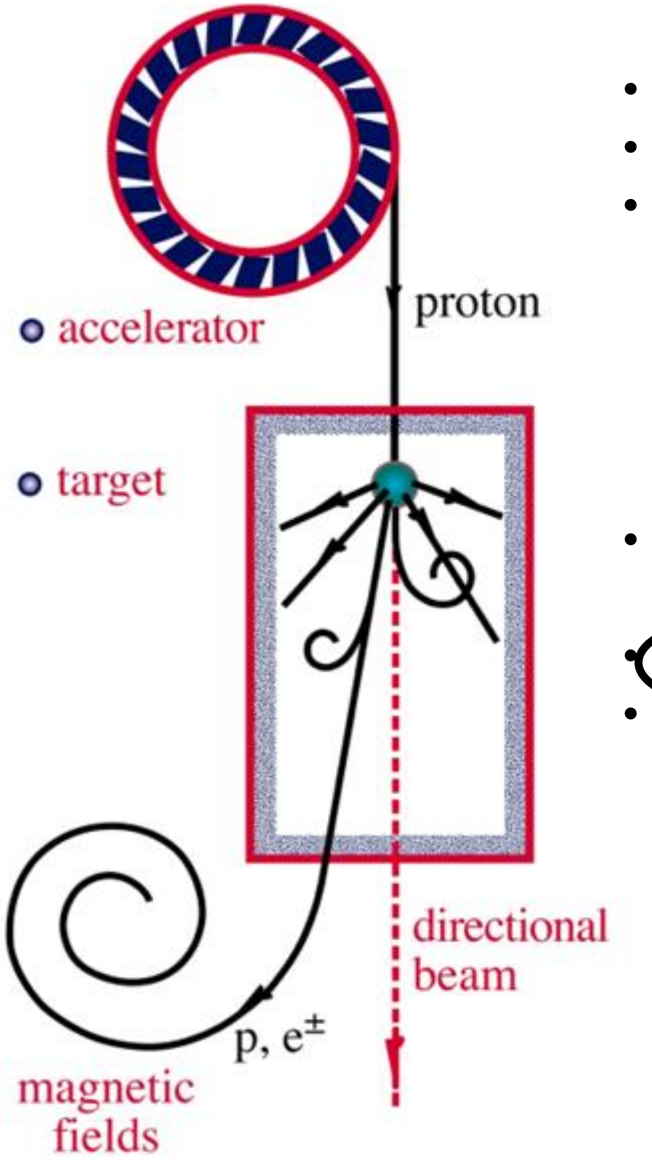
density of target to produce neutrinos
and absorb gamma rays from neutral pions?

at 10 Schwarzschild radii from the black hole

$$p + \gamma \to \pi^+ \to \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$
$$\to \pi^0 \to \gamma + \gamma$$

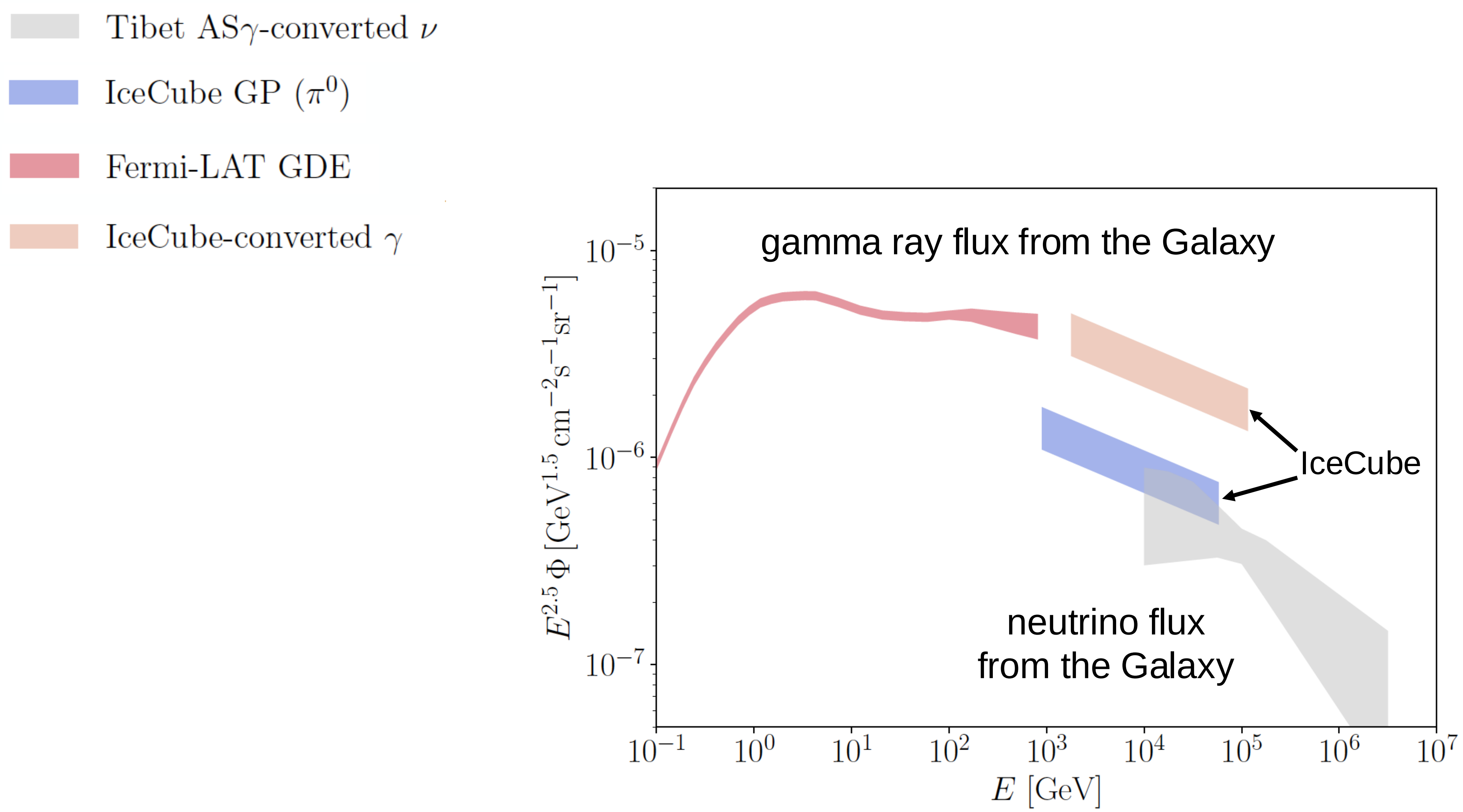



## Neutrino Beams: Heaven and Earth




- black hole
- accretion disk
- …

- hydrogen clouds
- X-rays
- …



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