# REVELING THE NEUTRINO SKY: A DECADE OF ICECUBE'S OBSERVATIONS


***S. Toscano*** *on behalf of the IceCube Collaboration*

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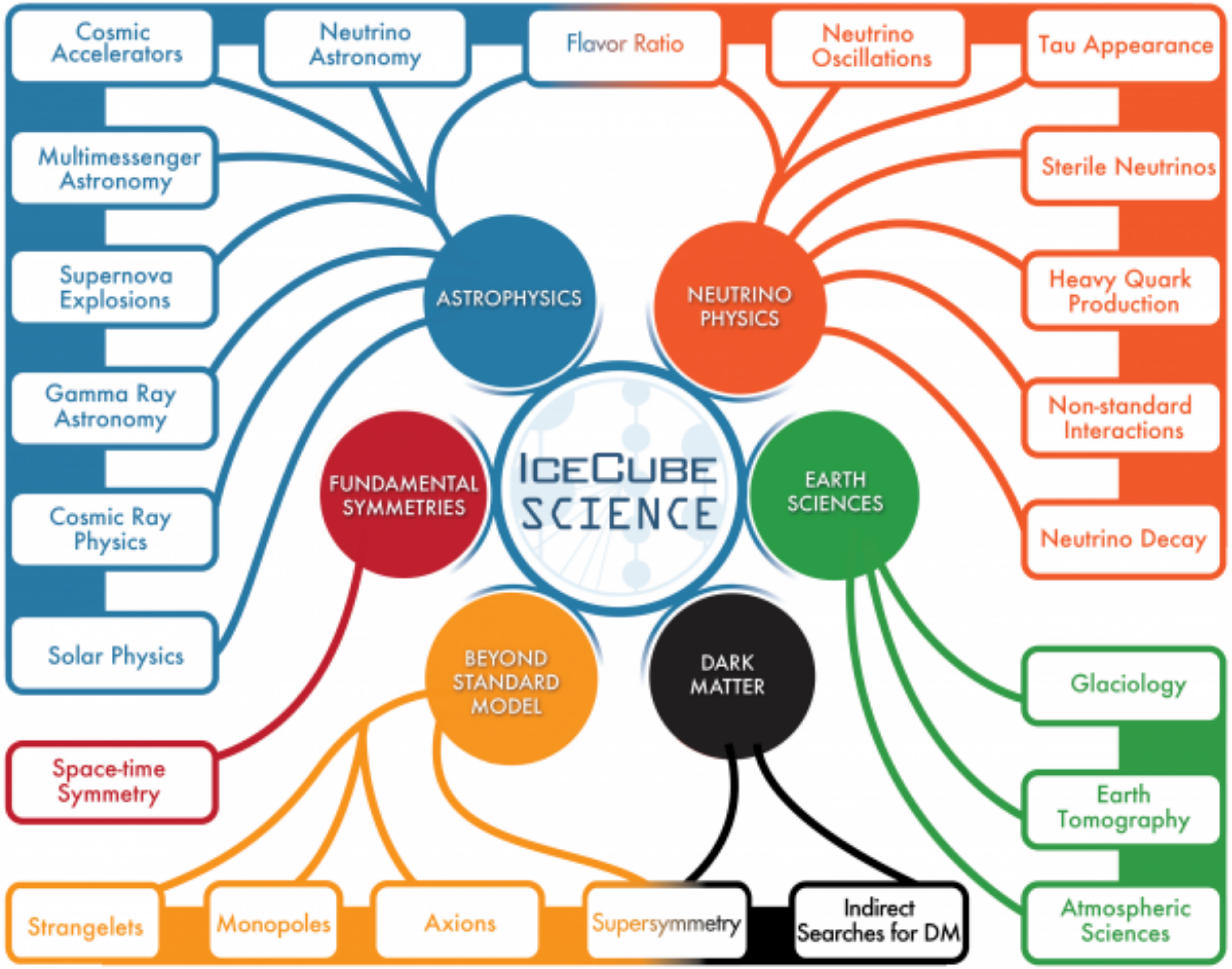
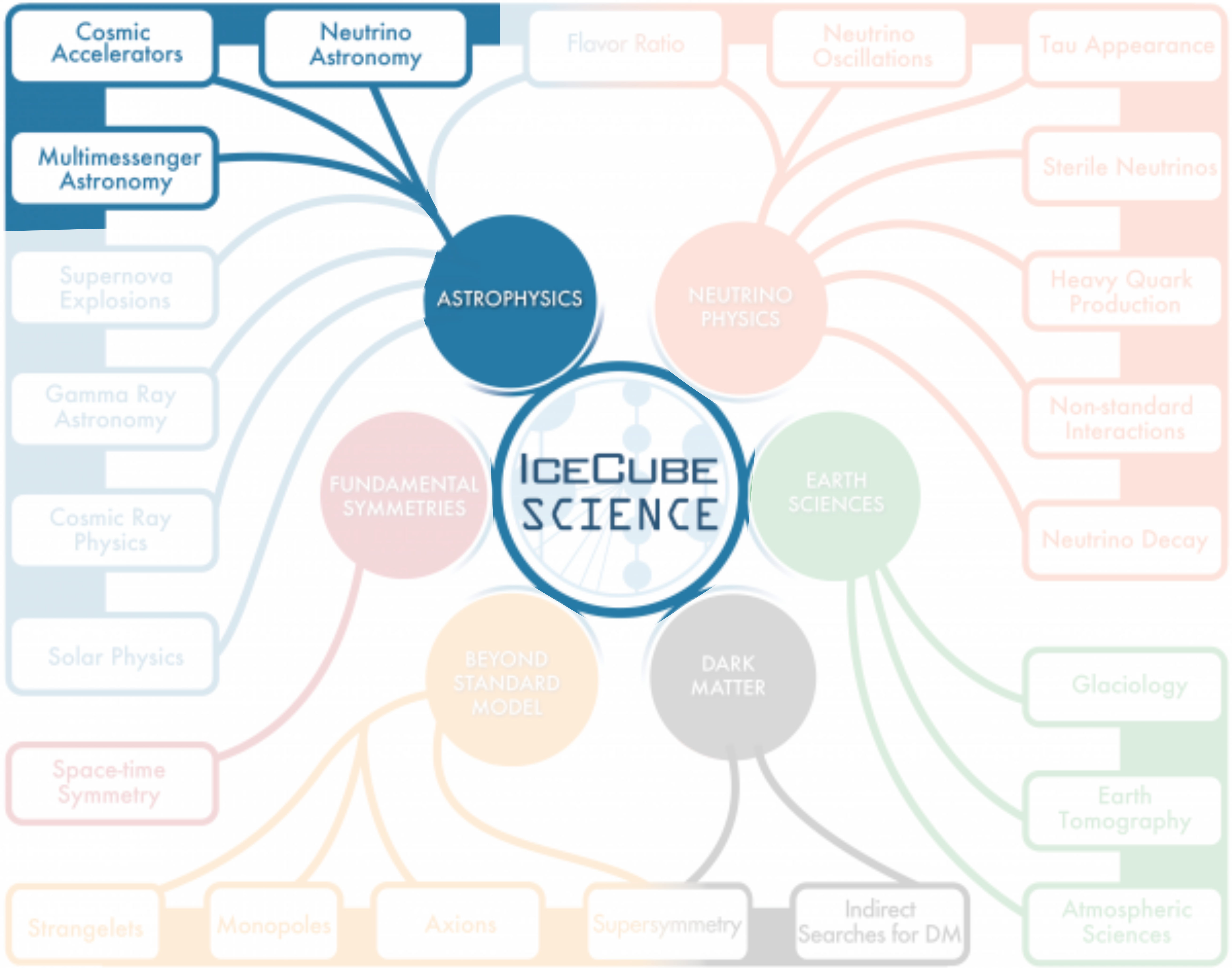
# Science program





# Science program

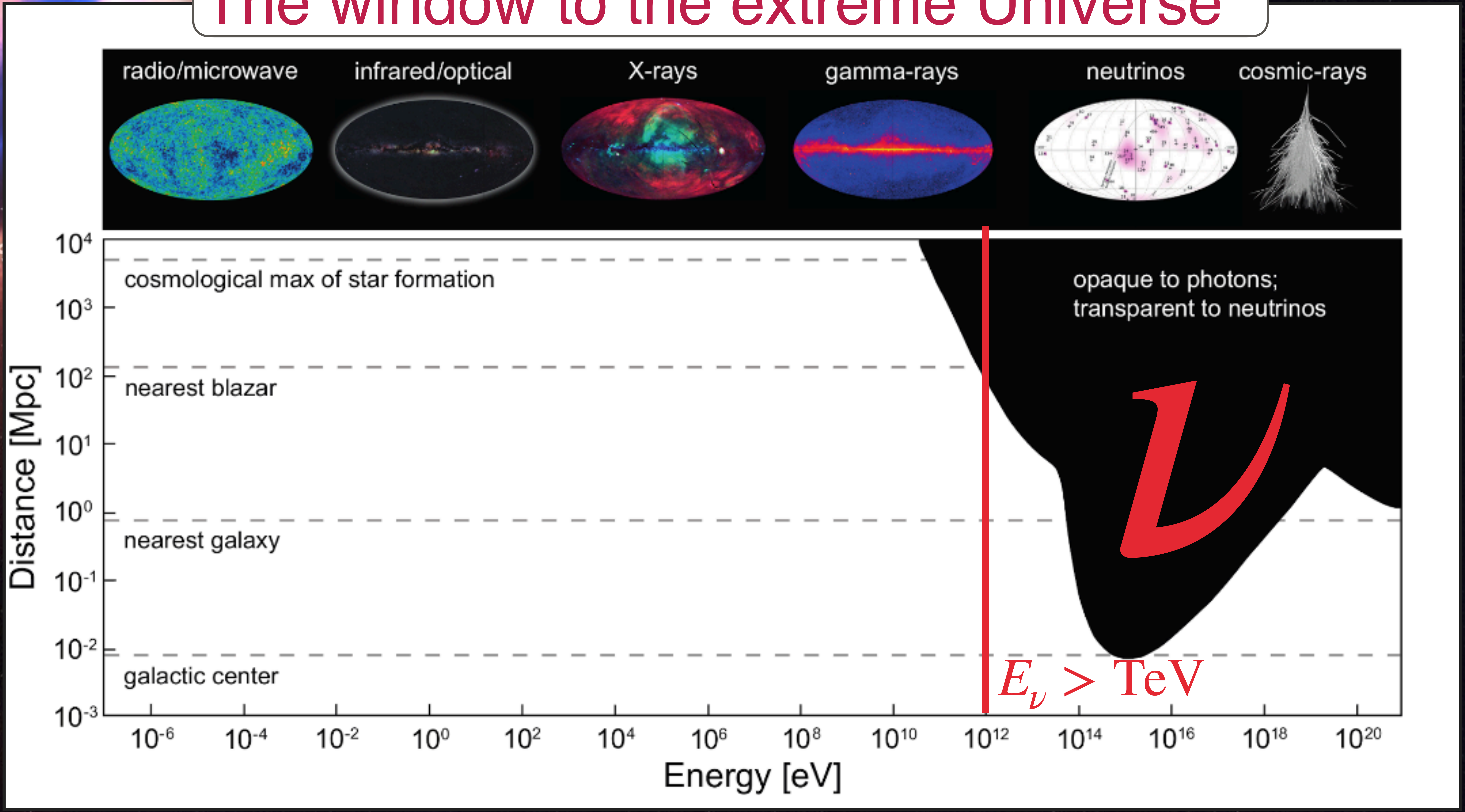


Multiwavelength Crab

# From multiwavelength to *multimessenger astronomy*

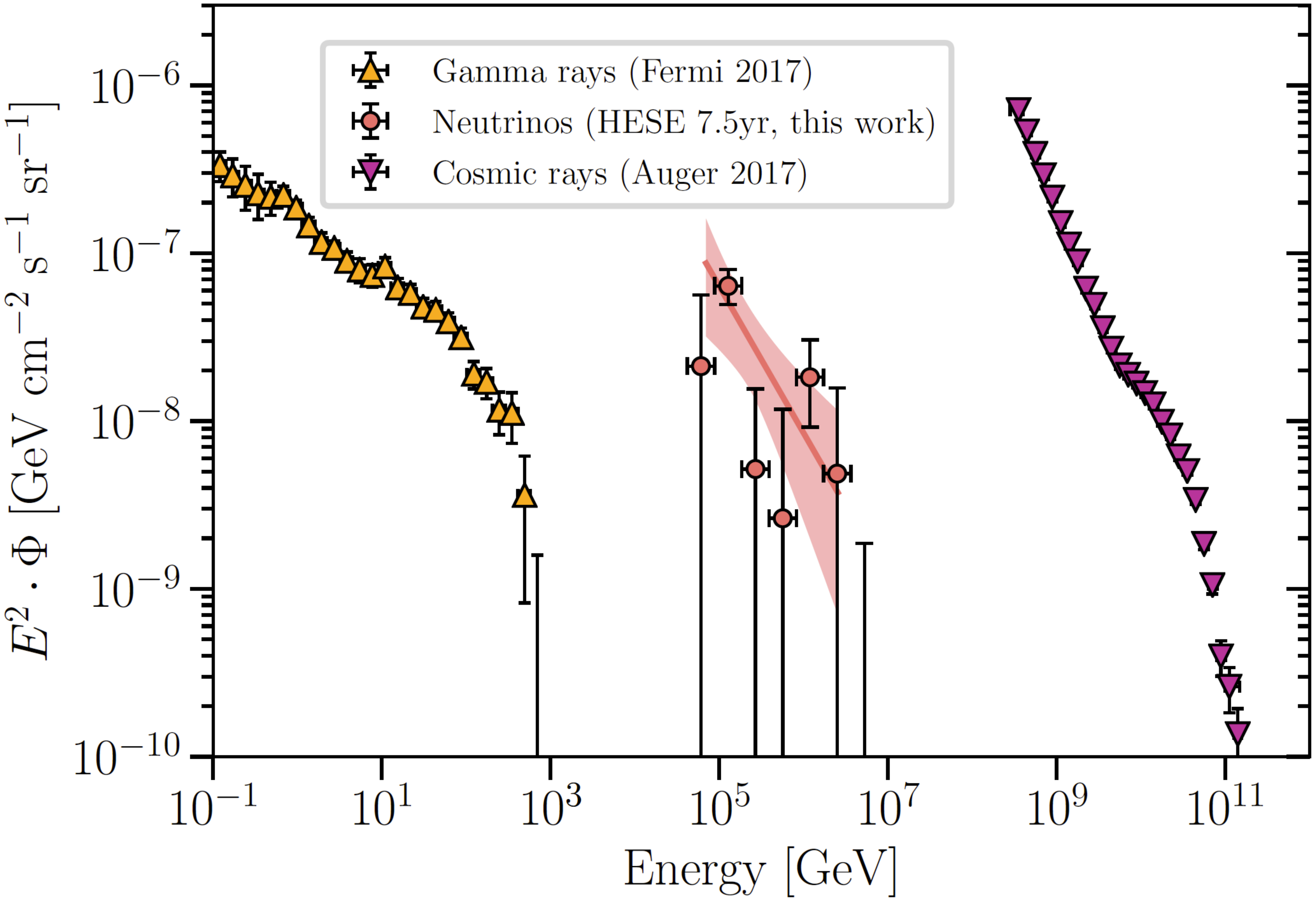
# From multiwavelength to ***multimessenger astronomy***

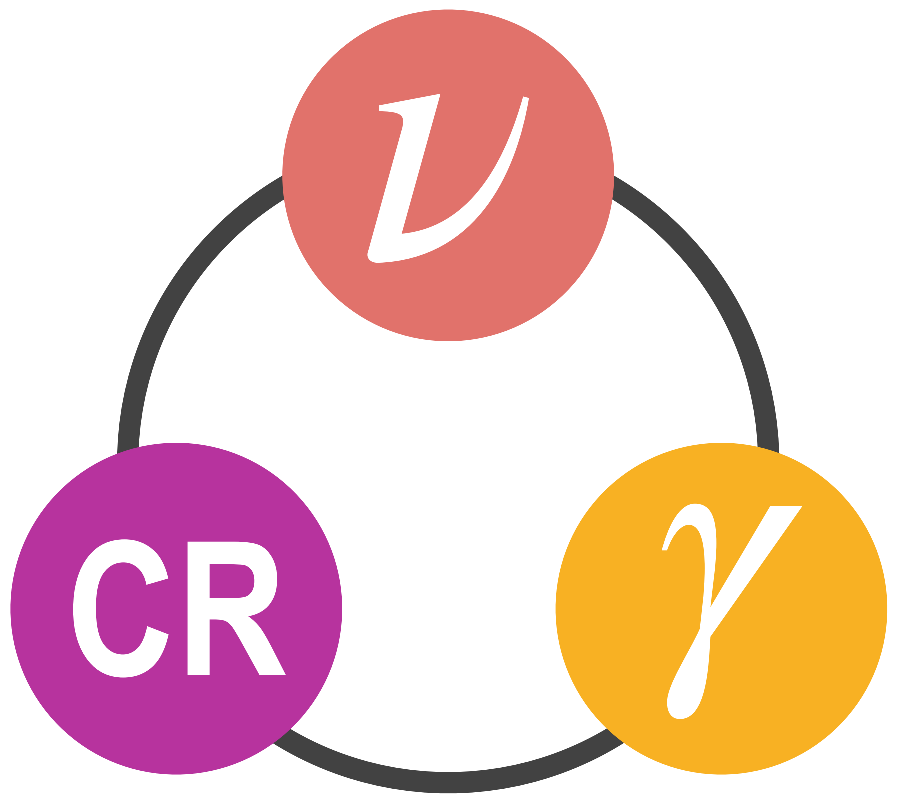
## The window to the extreme Universe



# Neutrino astronomy: The multi-messenger connection





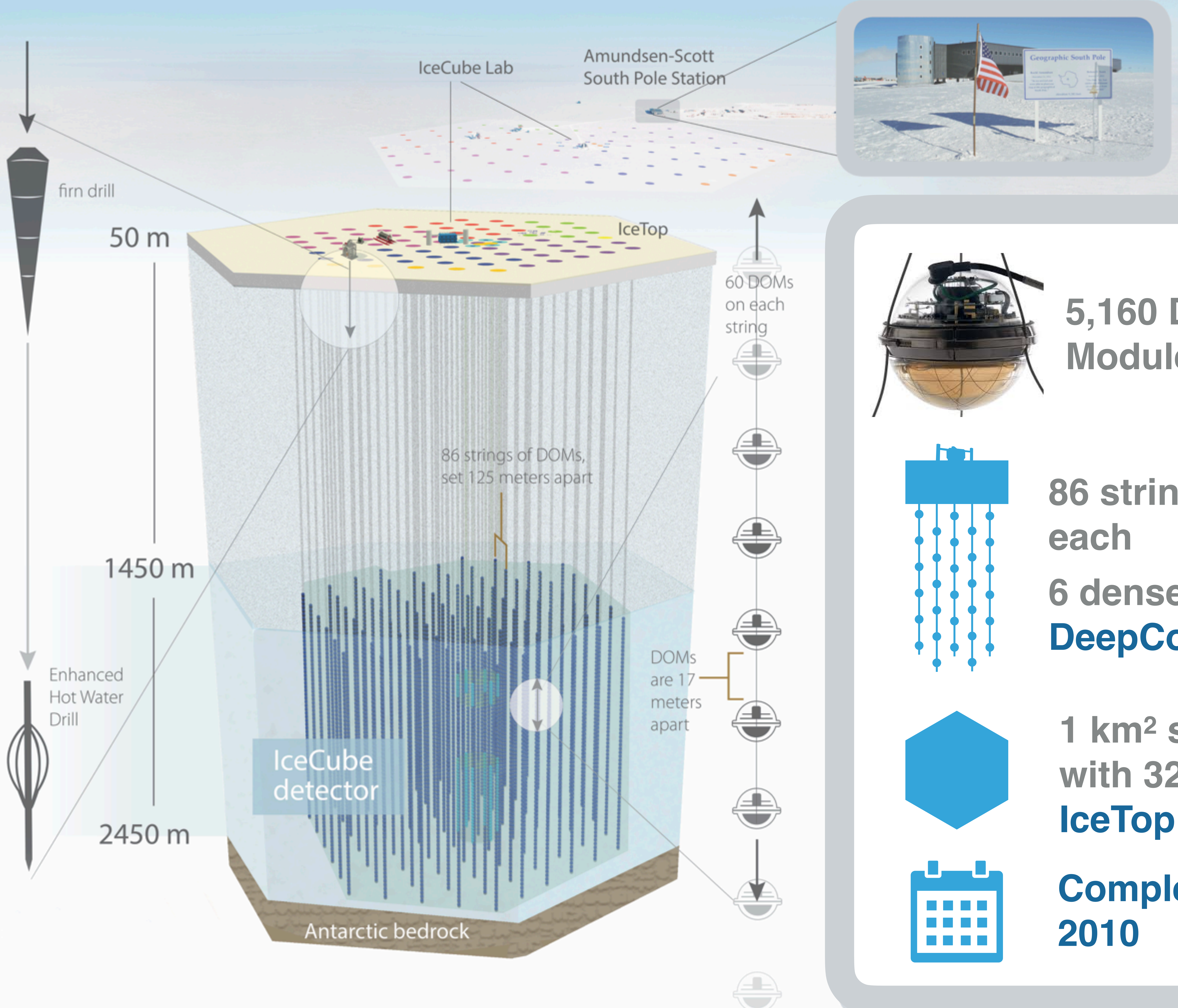

$$p + \gamma_{target} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, Br = 2/3 \\ n + \pi^+, Br = 1/3 \end{cases}$$

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \overline{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$


Admunsen-Scott South Pole Station
Geographic South Pole
IceCube outline
Skiway

# IceCube Neutrino Observatory




5,160 Digital Optical Modules (DOMs)

86 string with 60 DOMs each

6 denser strings called **DeepCore**

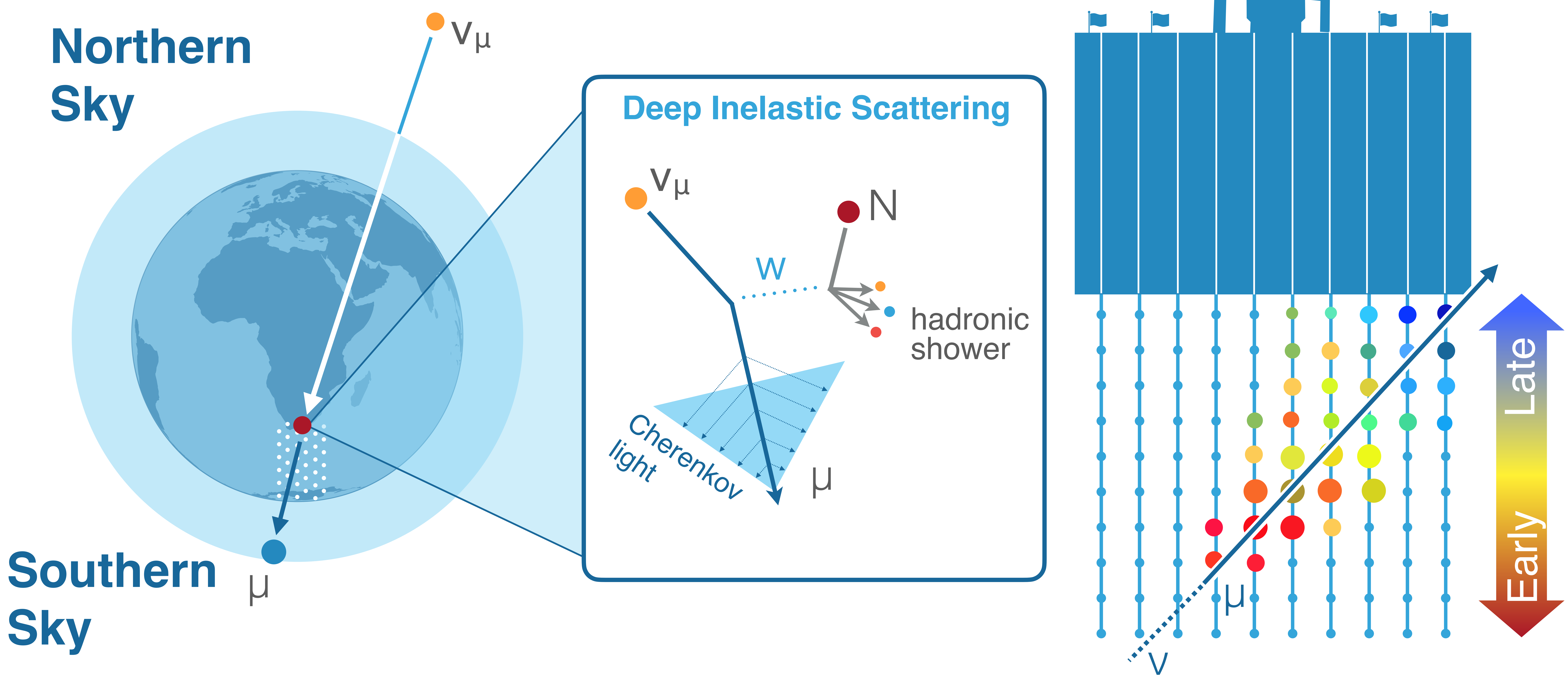
1 km² surface array with 324 DOMs: **IceTop**

**Completion in December 2010**

# Detection principle



Credit: J. A. Aguilar




IceCube detects Cherenkov radiation from secondary charged particles

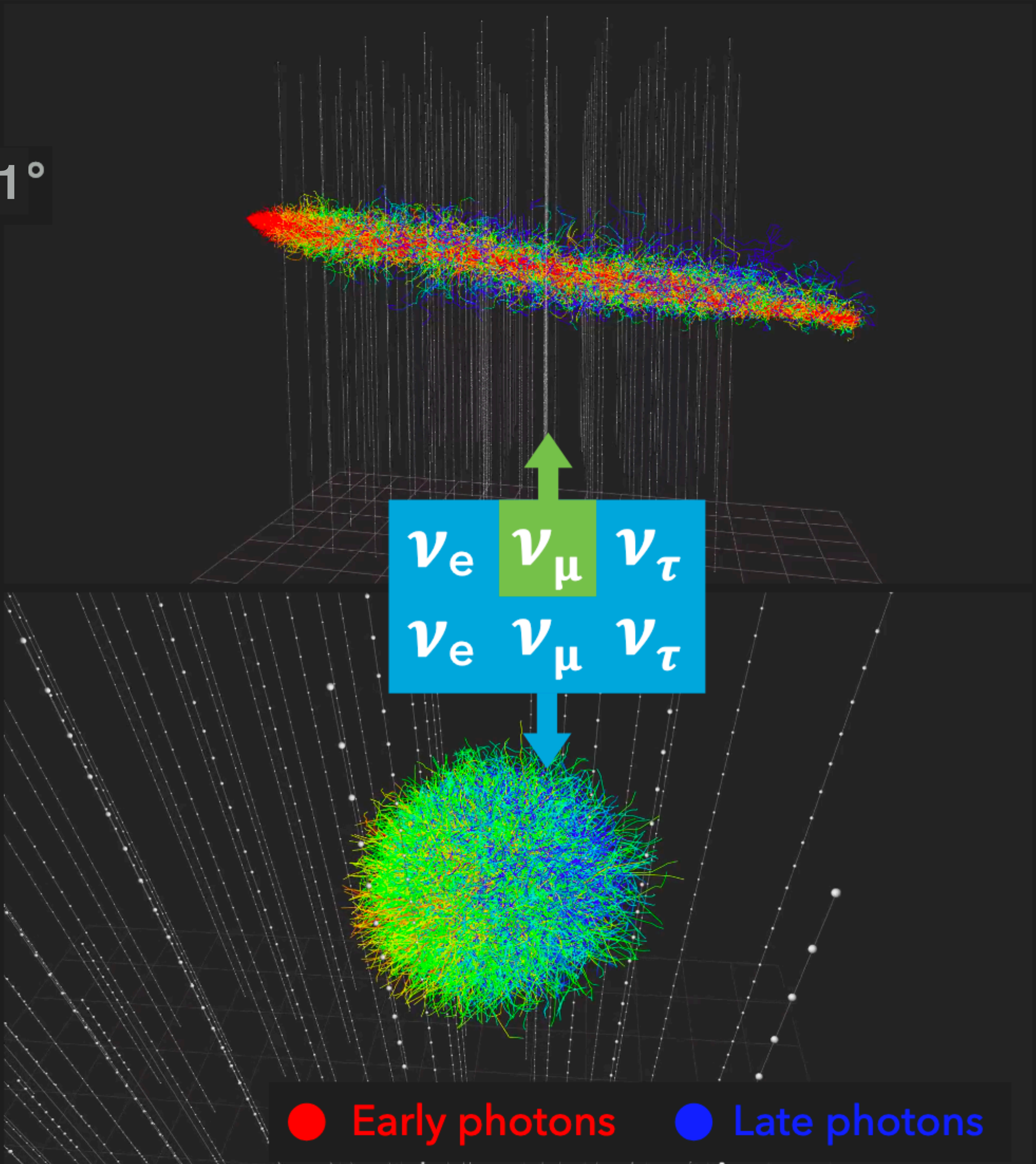
In-ice signatures

## Track topology

- Good angular resolution 0.1° - 1°
  → Neutrino Astronomy
- Vertex can be outside the detector → Increased effective volume

## Cascade topology

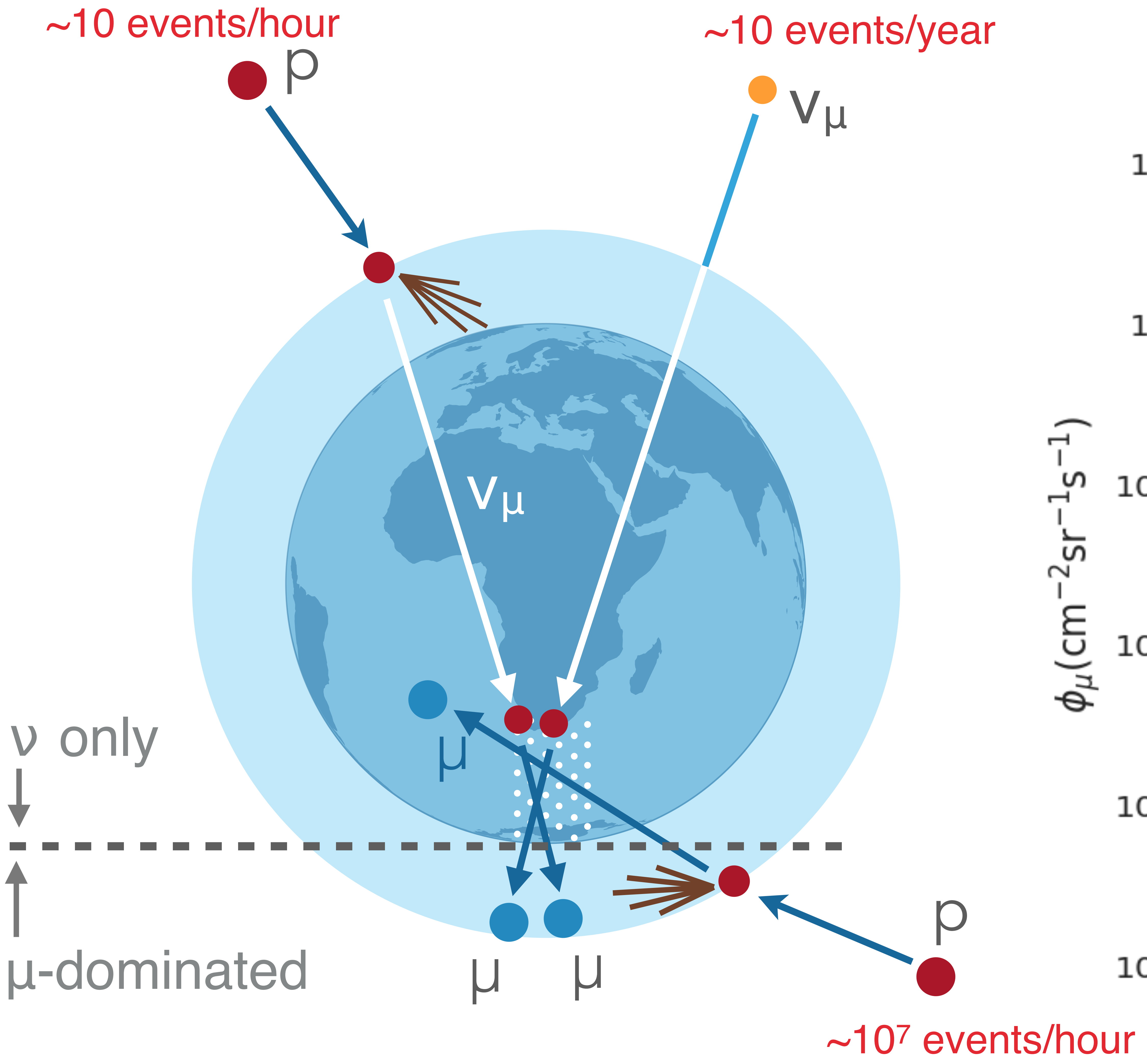
- All flavors
- Fully active calorimeter → Good energy resolution ±15% deposited energy
- Angular reconstruction possible → ~10° > 100 TeV

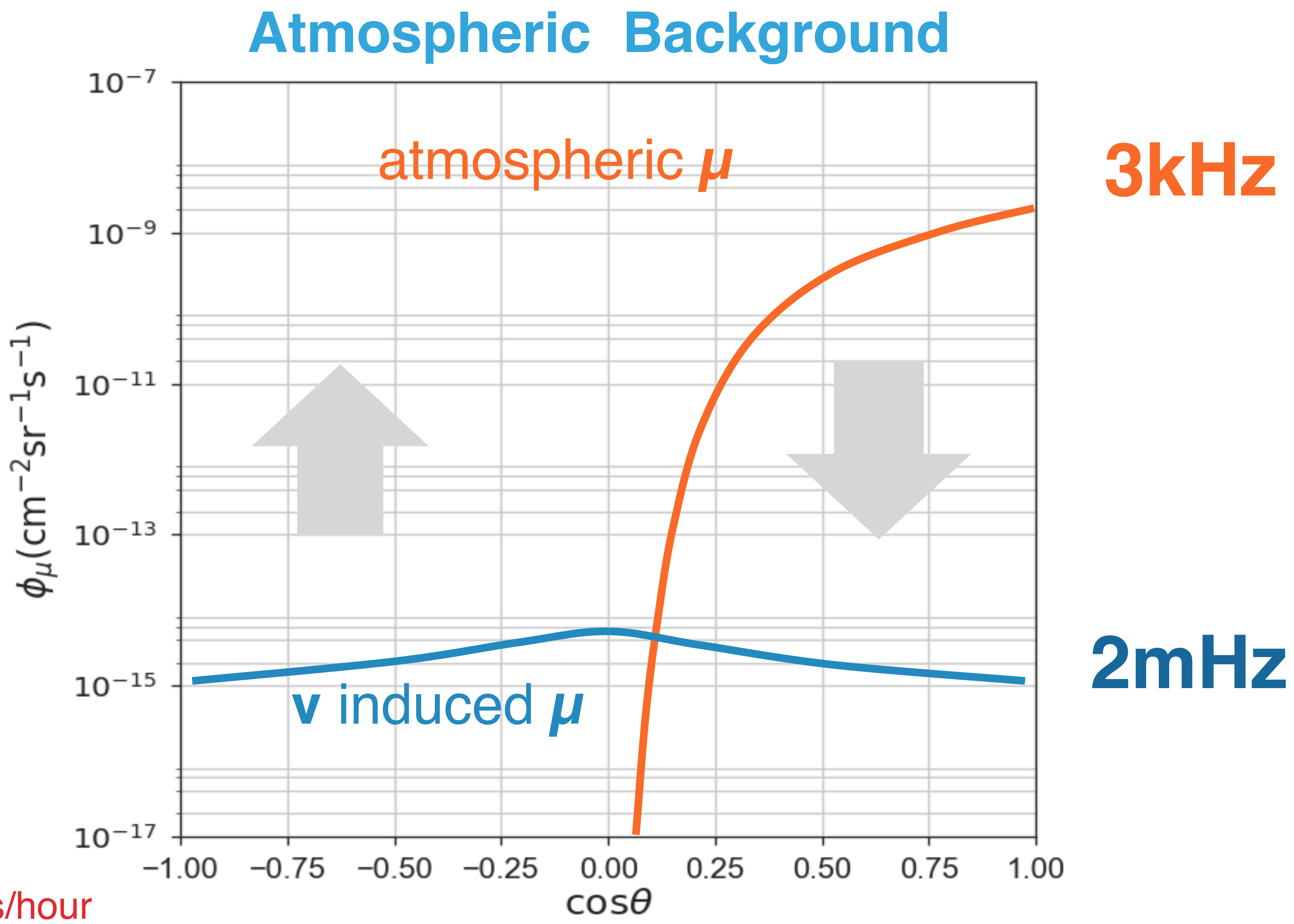


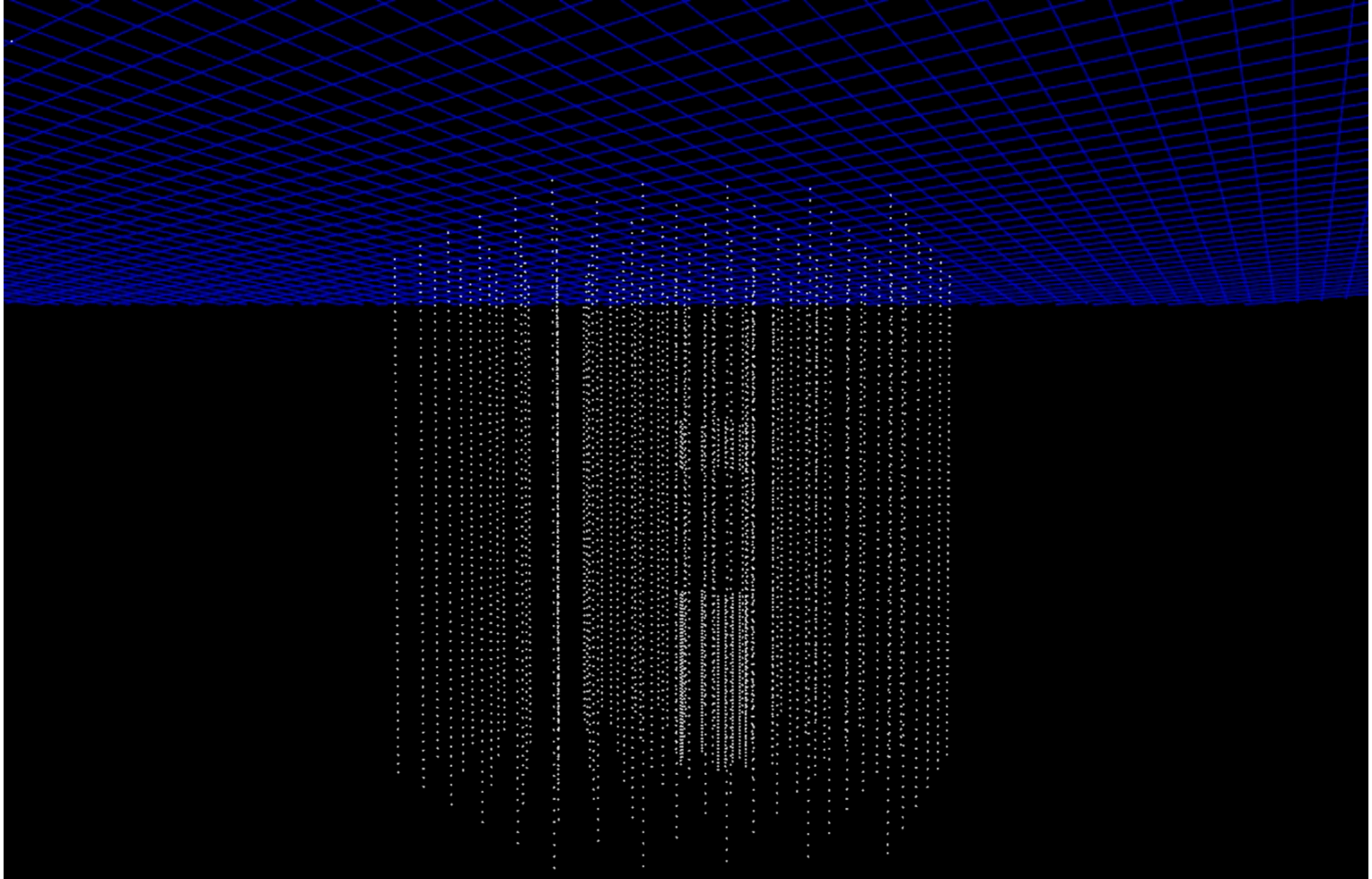
# The atmospheric background



Credit: J. A. Aguilar

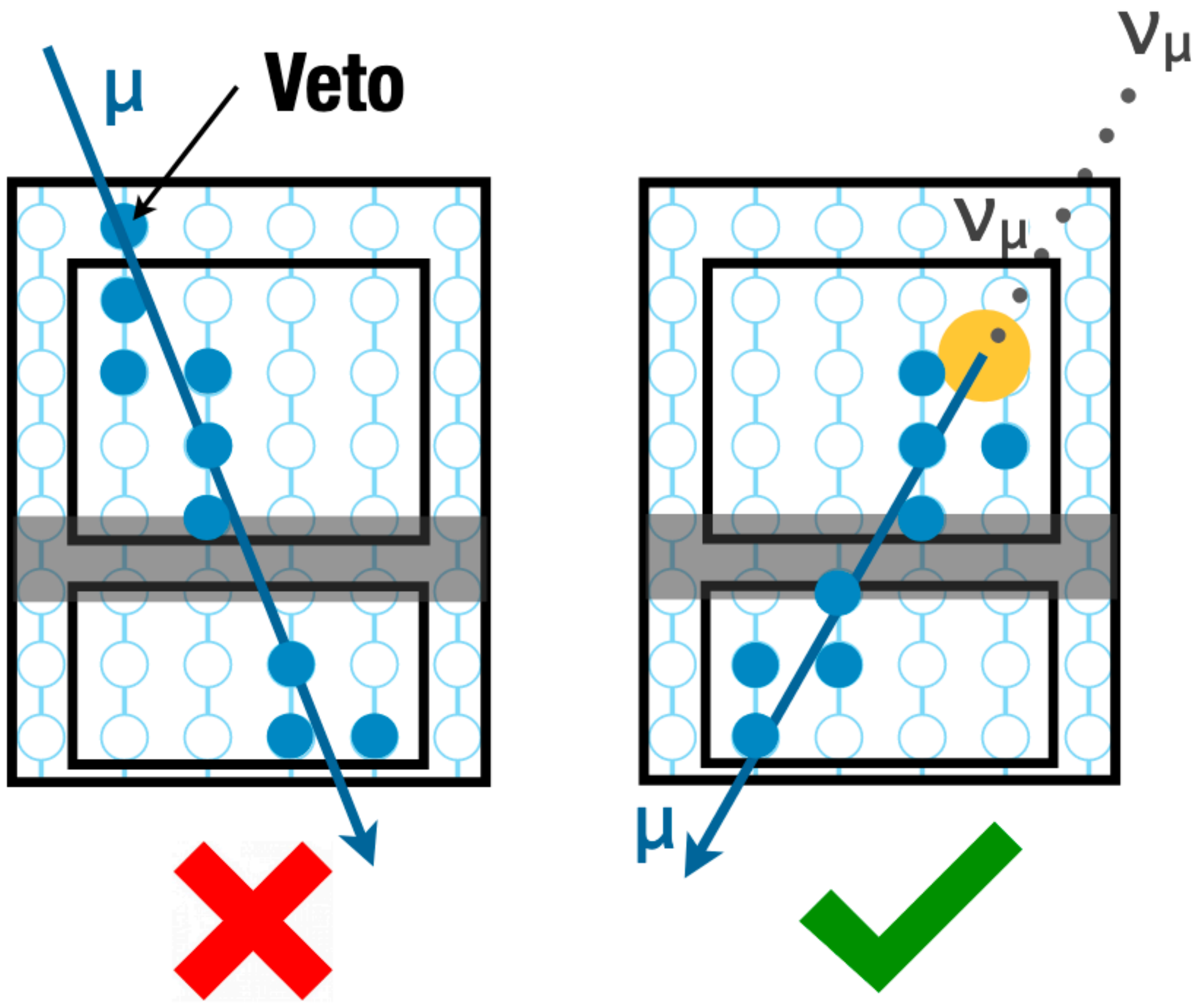




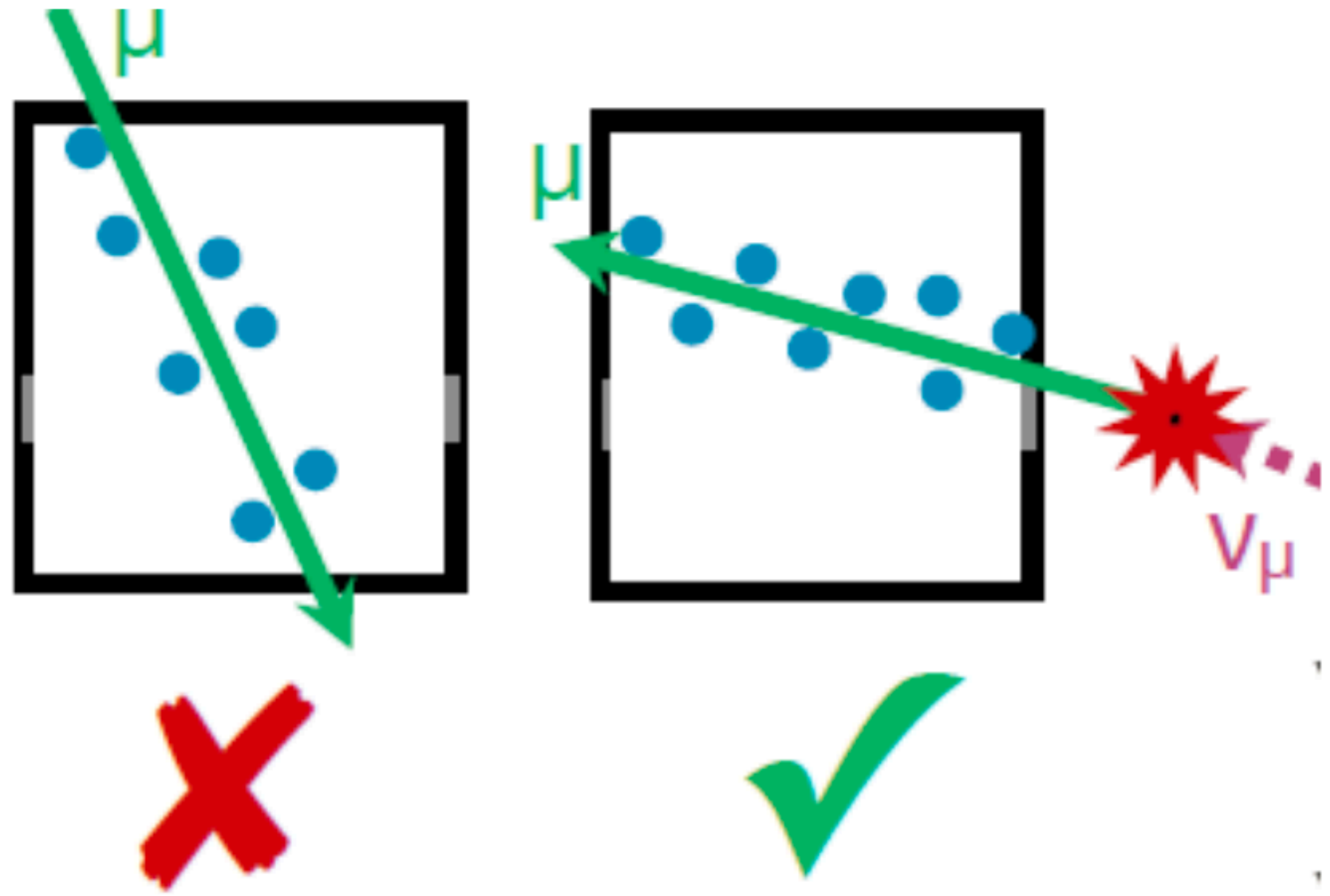
You just saw 10 msec of IceCube data!

## High Energy Starting Events (HESE)



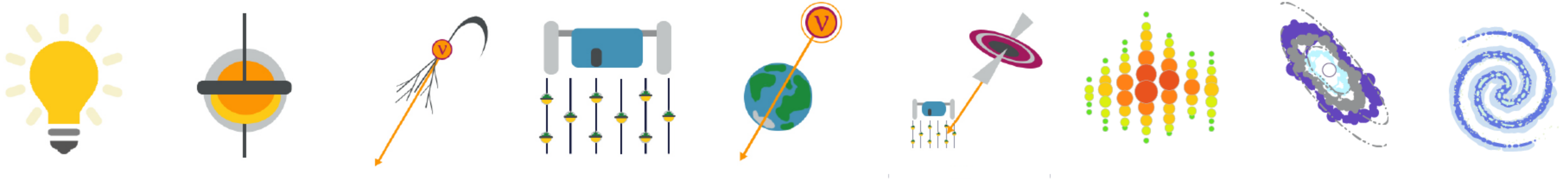

Hybrid (tracks and cascades) - $4\pi$

## Up-going through-going muons travelled through the Earth




Diffuse-$\nu_\mu$ sample (Northern Sky)

# A History of Neutrino Astronomy in Antarctica




**1988** — Telescope in the Ice Envisioned

**2000** — AMANDA Completed

**2001** — Atmospheric Neutrinos Detected

**2011** — IceCube Completed

**2013** — Astrophysical Neutrinos Discovered

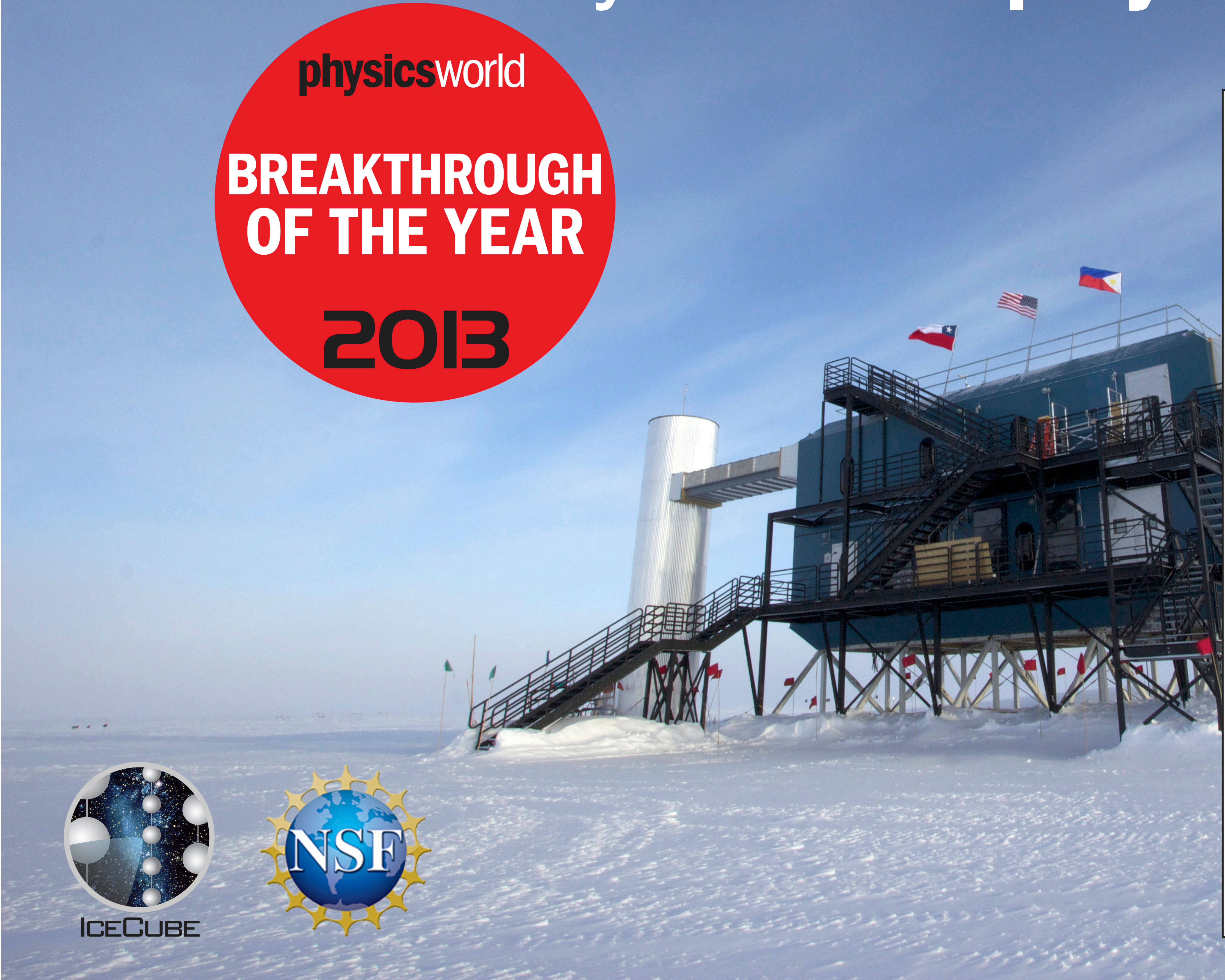
**2018** — First Source TXS 0506+056 Identified

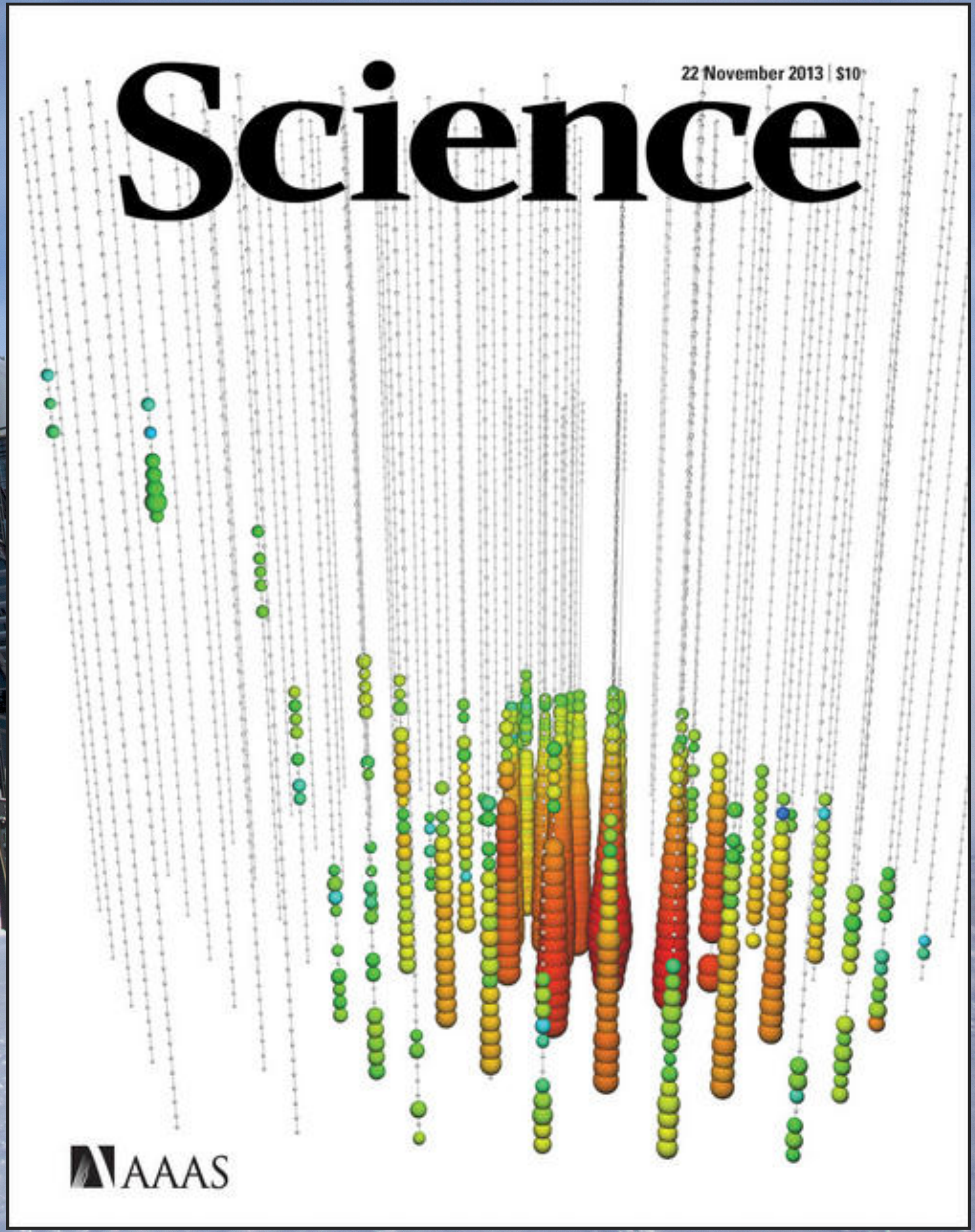
**2021** — Glashow Resonance Neutrino Identified

**2022** — Second Source NGC 1068 Identified

**2023** — Third Source Milky Way Identified

# The discovery of **astrophysical neutrinos**



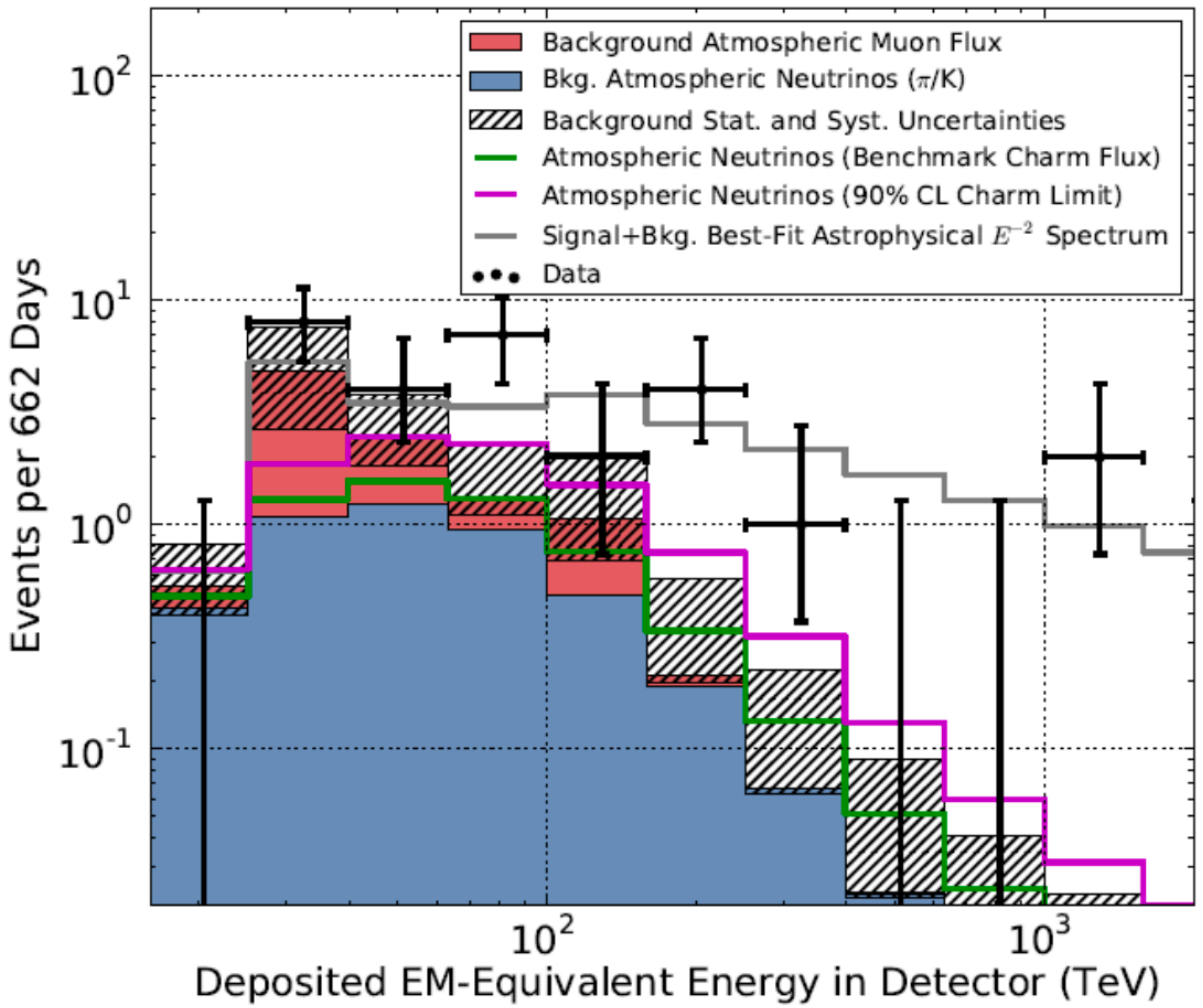



# Astrophysical neutrinos: diffuse flux

Only 2 years of data to find evidence of astrophysical neutrinos!

- $E^2\,\Phi$: ~1.2 x $10^{-8}$ $E^{-2}$ [GeV/cm²/s/sr]
- Best fit spectral index: -2.2
- 28 events (expected ~ 10 background events)
- Significance ~ 4σ

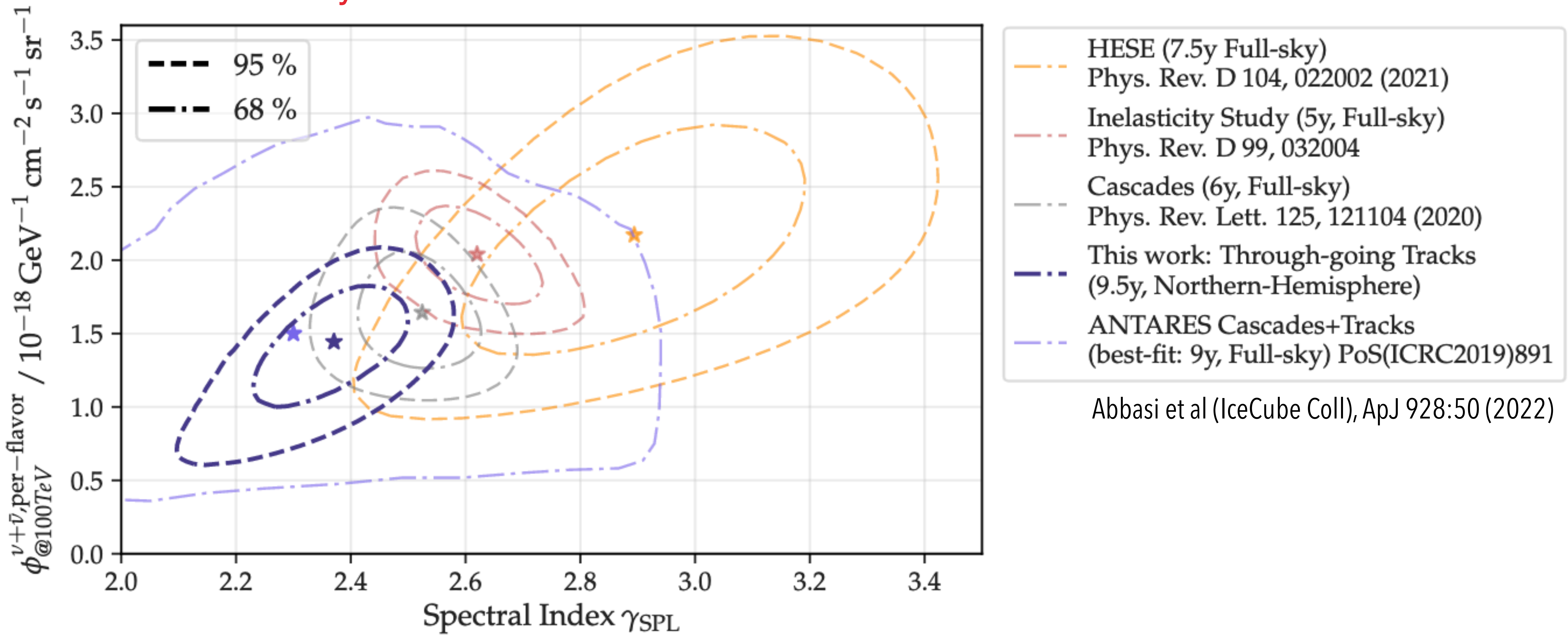
Aartsen et al (IceCube Coll.) Science 342, 1242856 (2013)



# Astrophysical neutrinos: power law



Several analysis confirm the detection at > 5σ

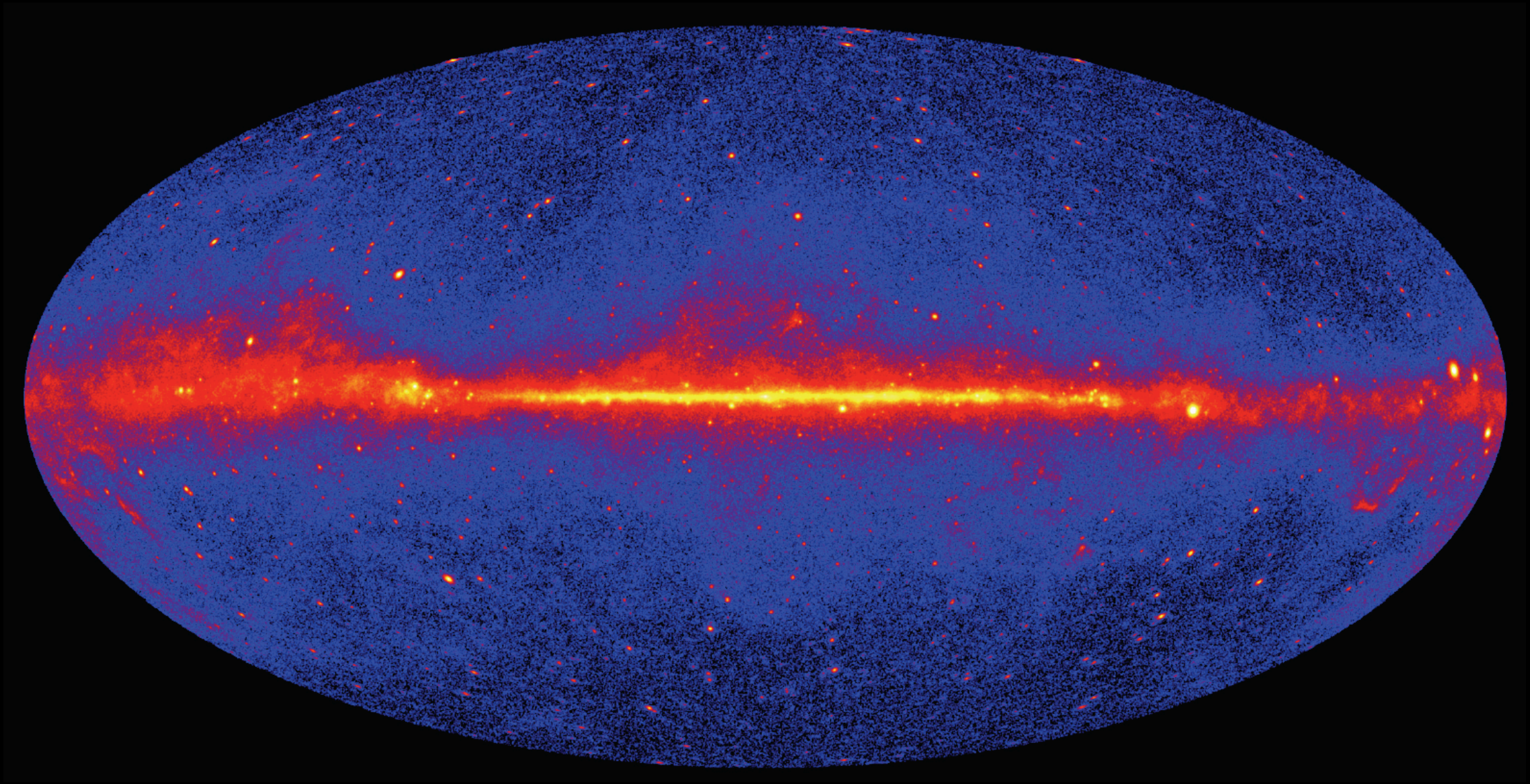



Abbasi et al (IceCube Coll), ApJ 928:50 (2022)

Comparison difficult since datasets have different energy cuts and select different morphologies (hemispheres)

Global fit to unify all detection channels and test tensions between results

# Where are the source of neutrinos?

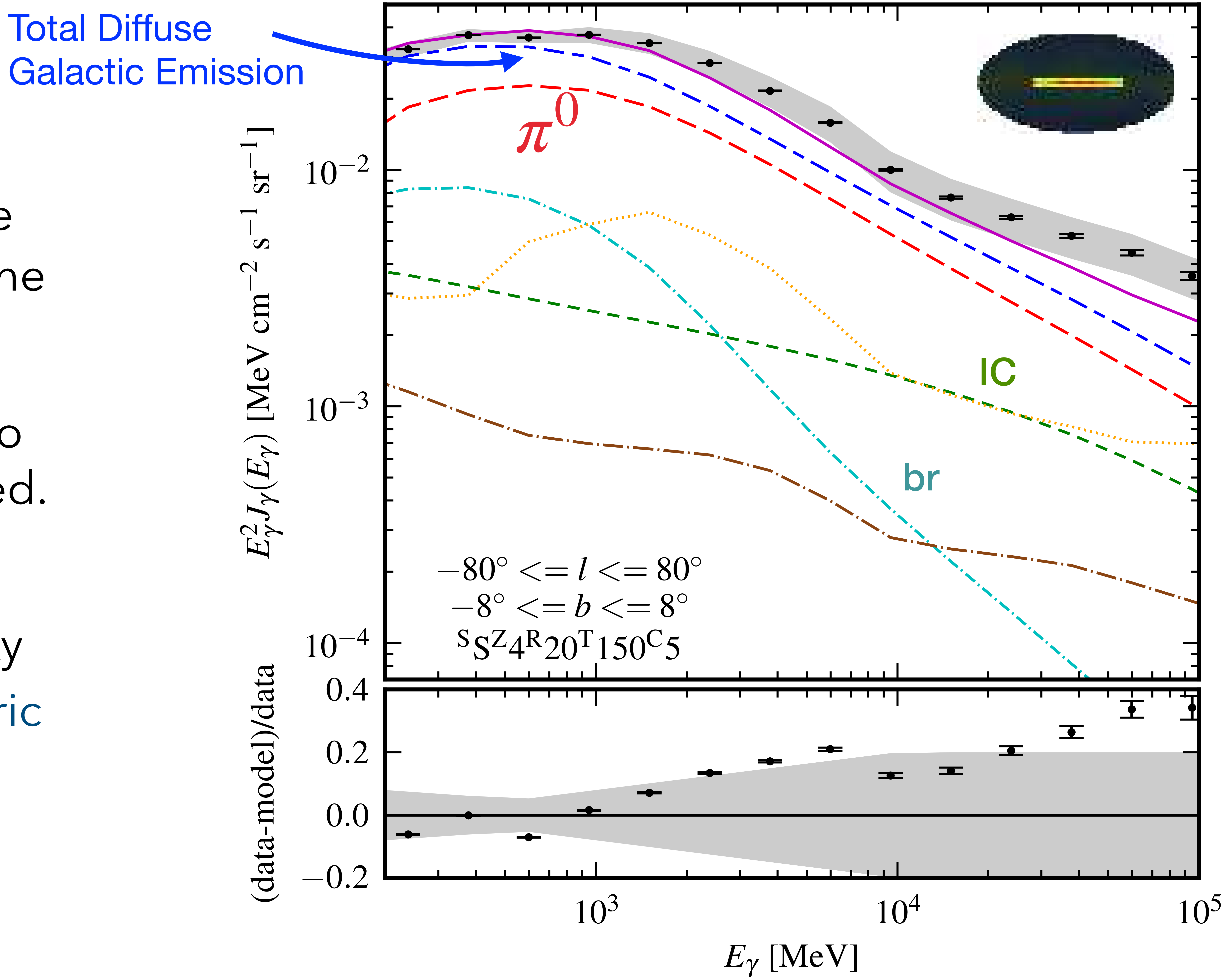


# The galaxy in gamma-rays



- Cosmic-ray interactions with the ISM dominate the diffuse $\gamma$-ray emission of the Galaxy!
- If pions are produced, also neutrinos should produced.
- Much of the Galactic Center in the Southern Sky
  - Large muon atmospheric background

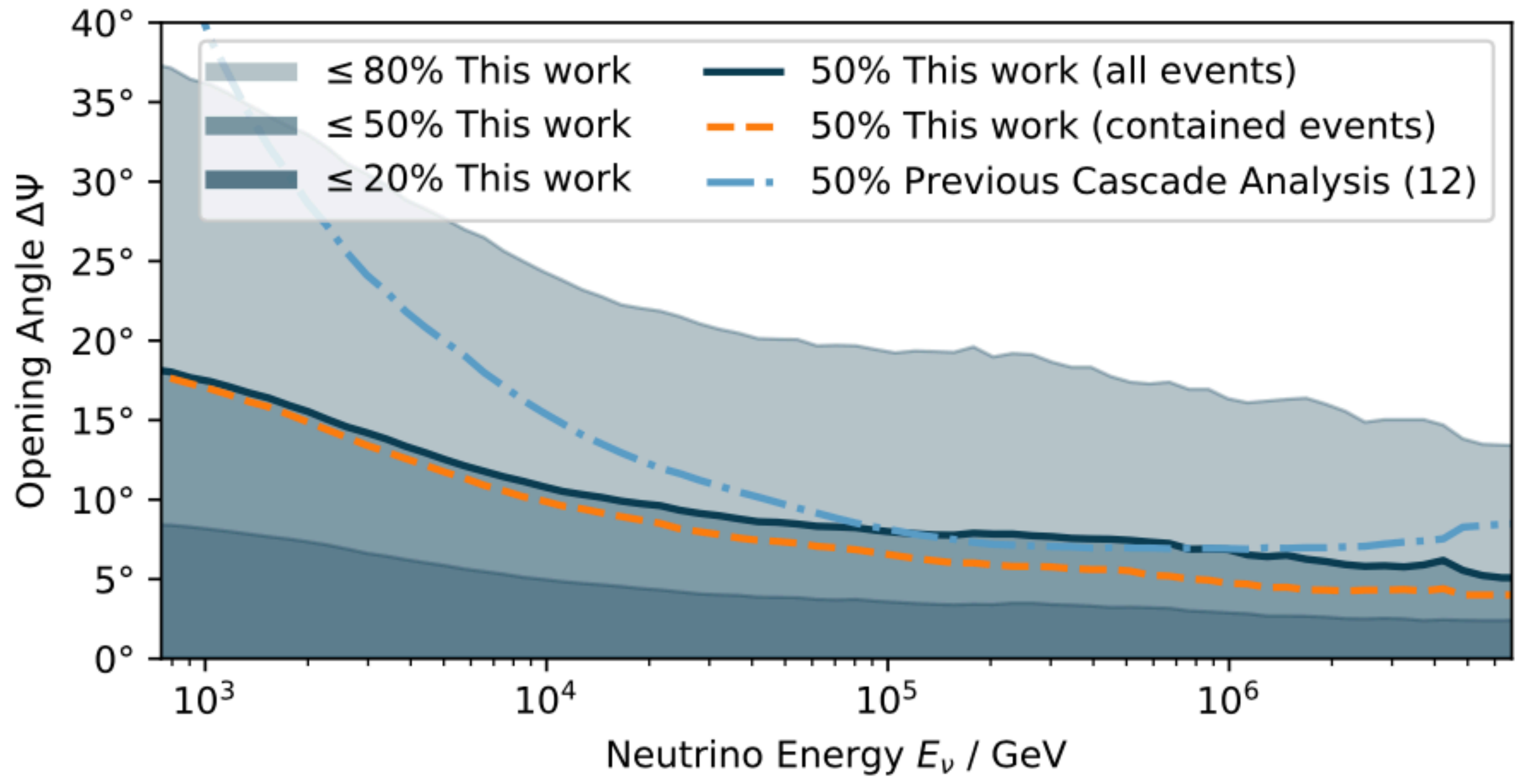
M. Ackermann *et al* 2012 *ApJ* **750** 3

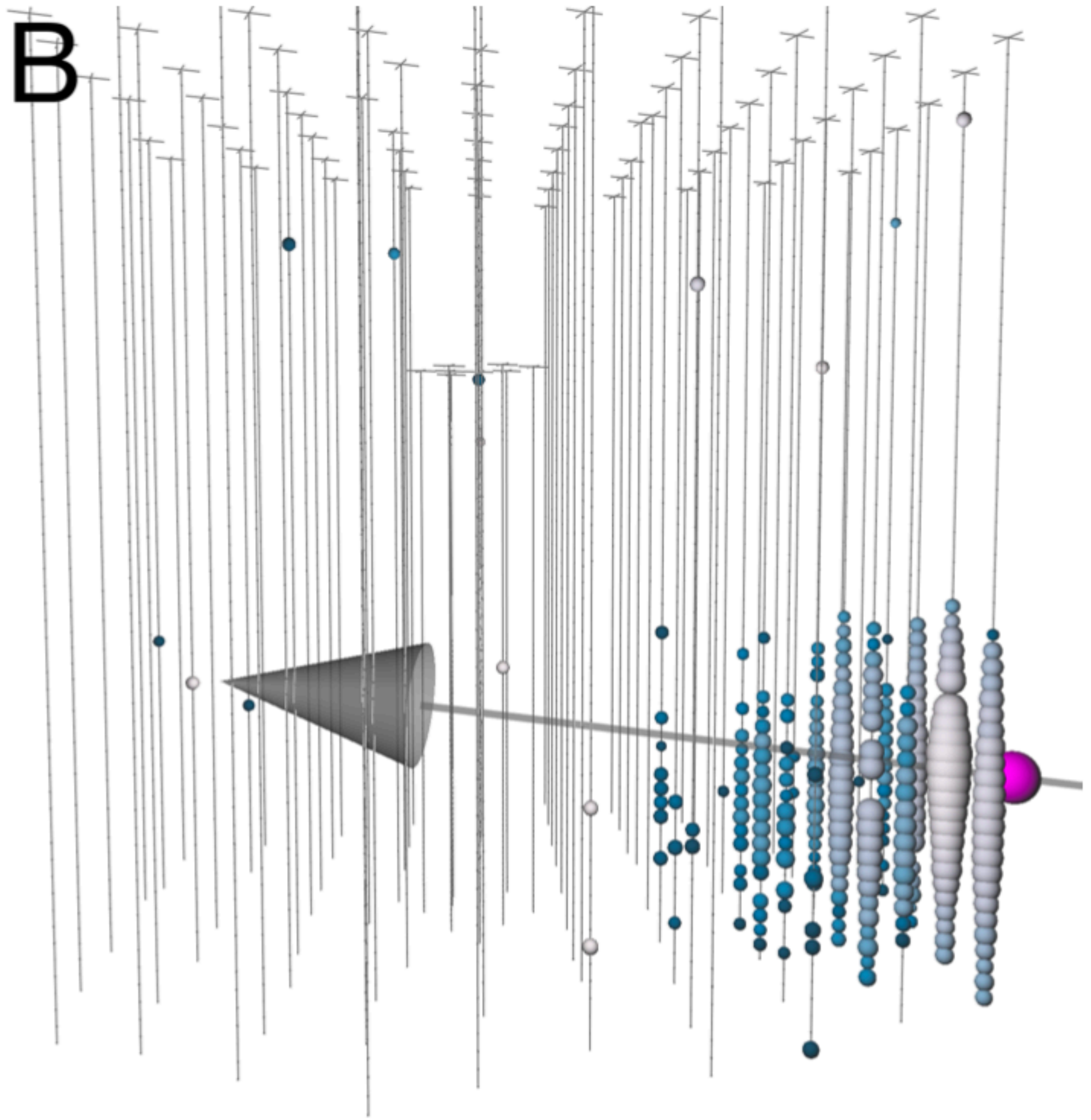


# Improved cascade reconstruction



- Deep Neural Networks improves angular resolutions for cascade **a factor 2 at TeV**.
- **Order of magnitude** increases in acceptance in Southern Sky by reconstructing even partially contained events.

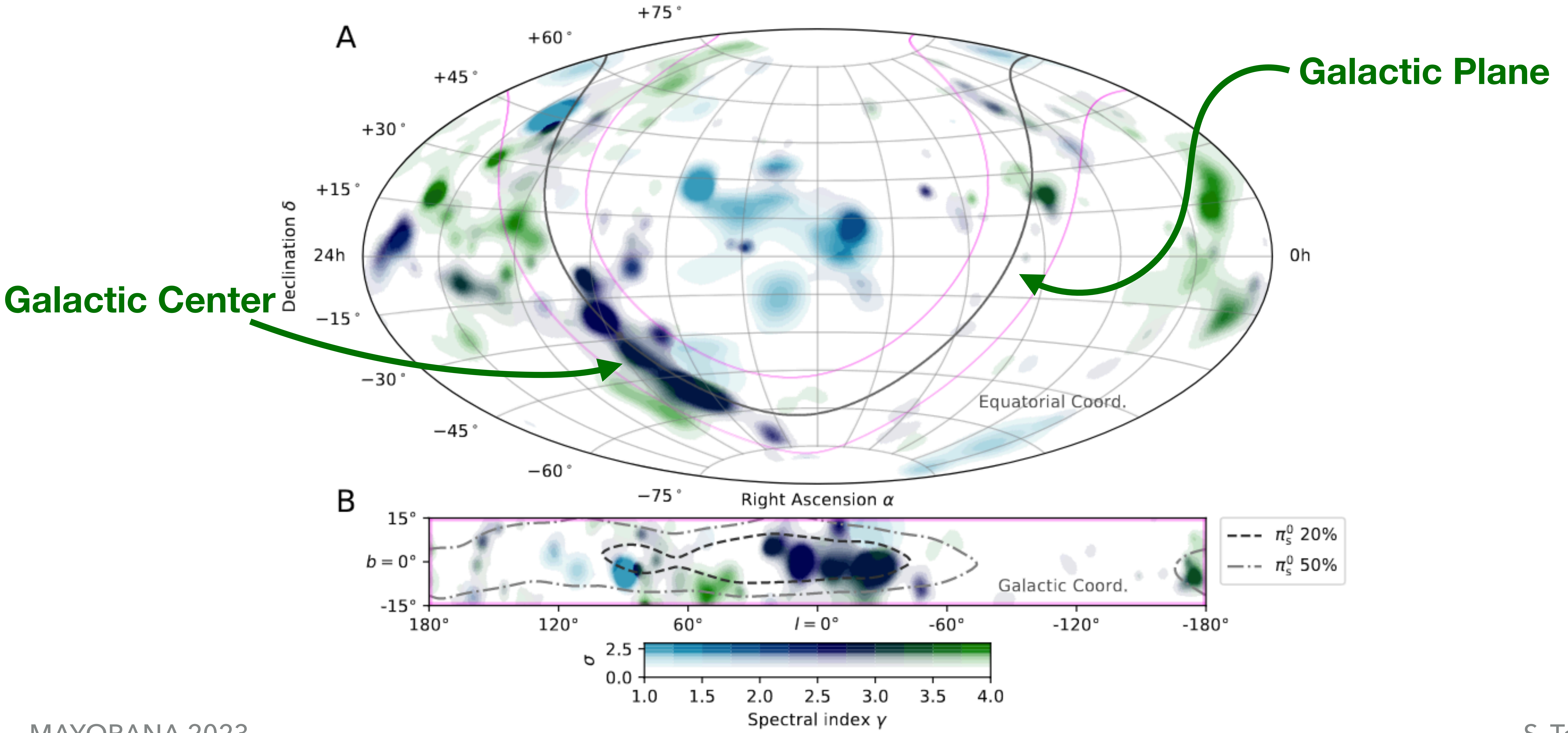


# Our galaxy in neutrinos



Science 380(6652):1338-1343

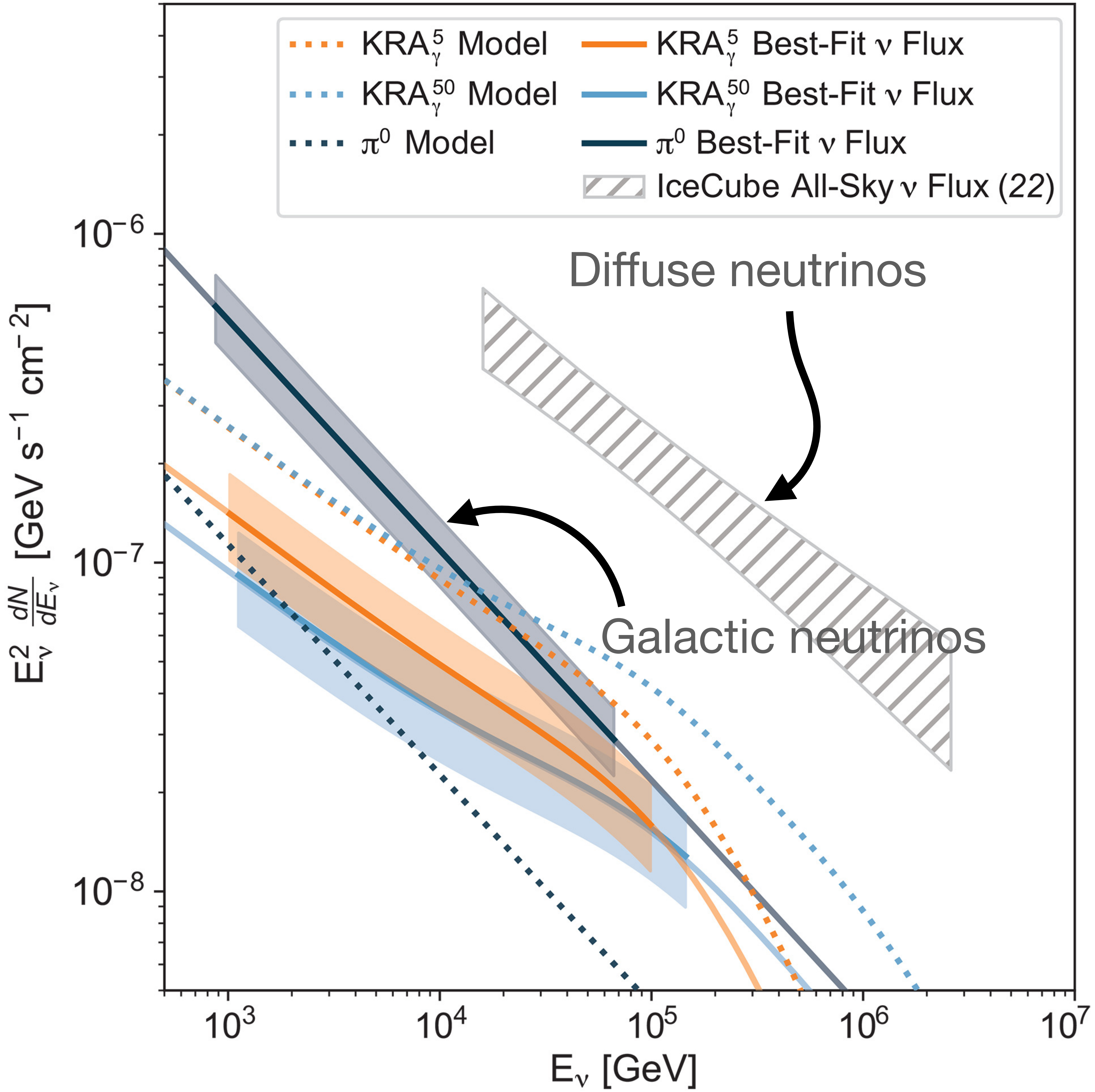


# Galactic neutrinos



**We observe the Galactic plane in >TeV neutrinos:** $4.5\sigma$

- Only 6–13% of the total cosmic neutrino flux reaches us from our own Galaxy (30 TeV)
- The nearby sources from our own Galaxy do not outshine the neutrino flux from the Universe
  - Powerful accelerators operate in galaxies other than our own

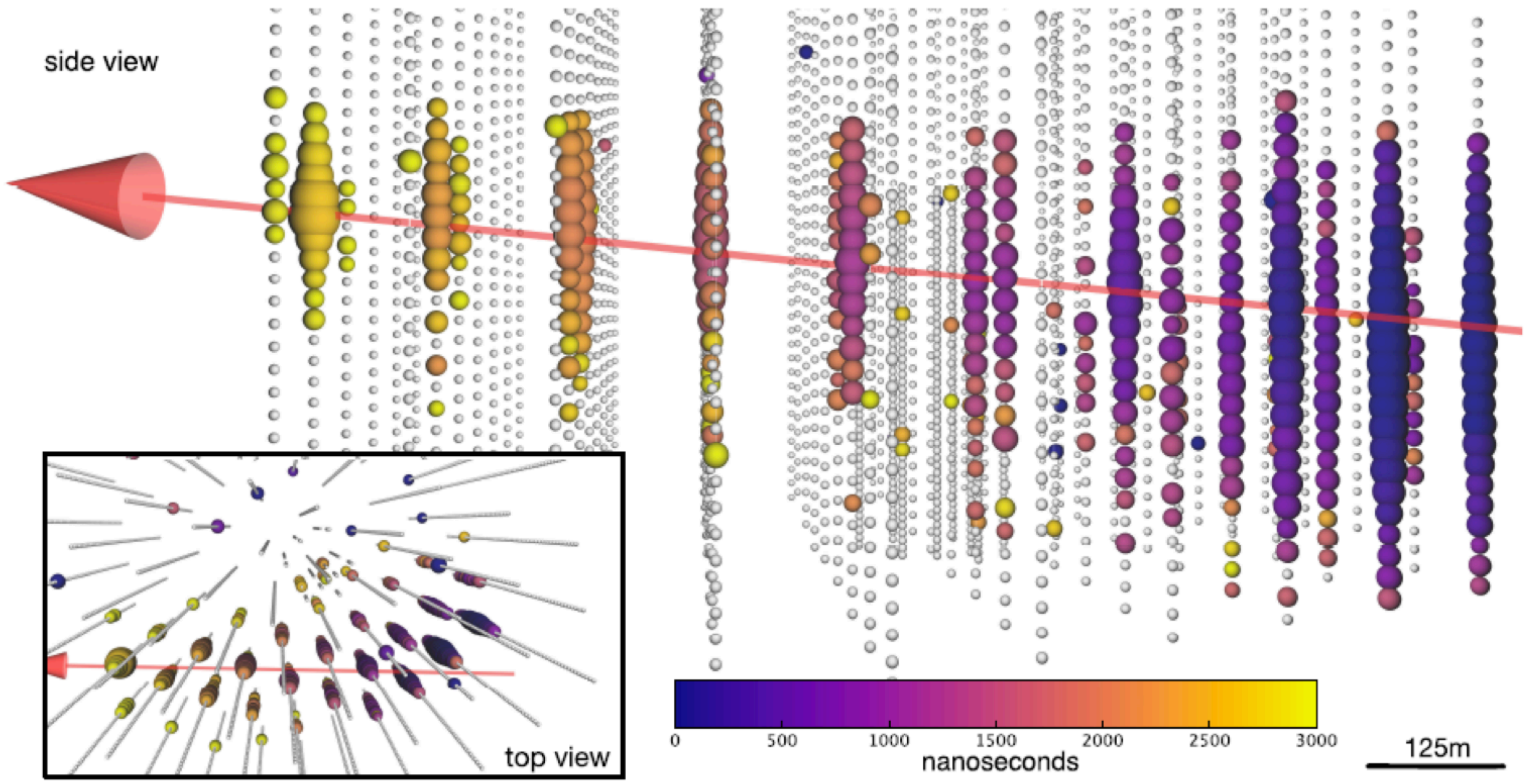


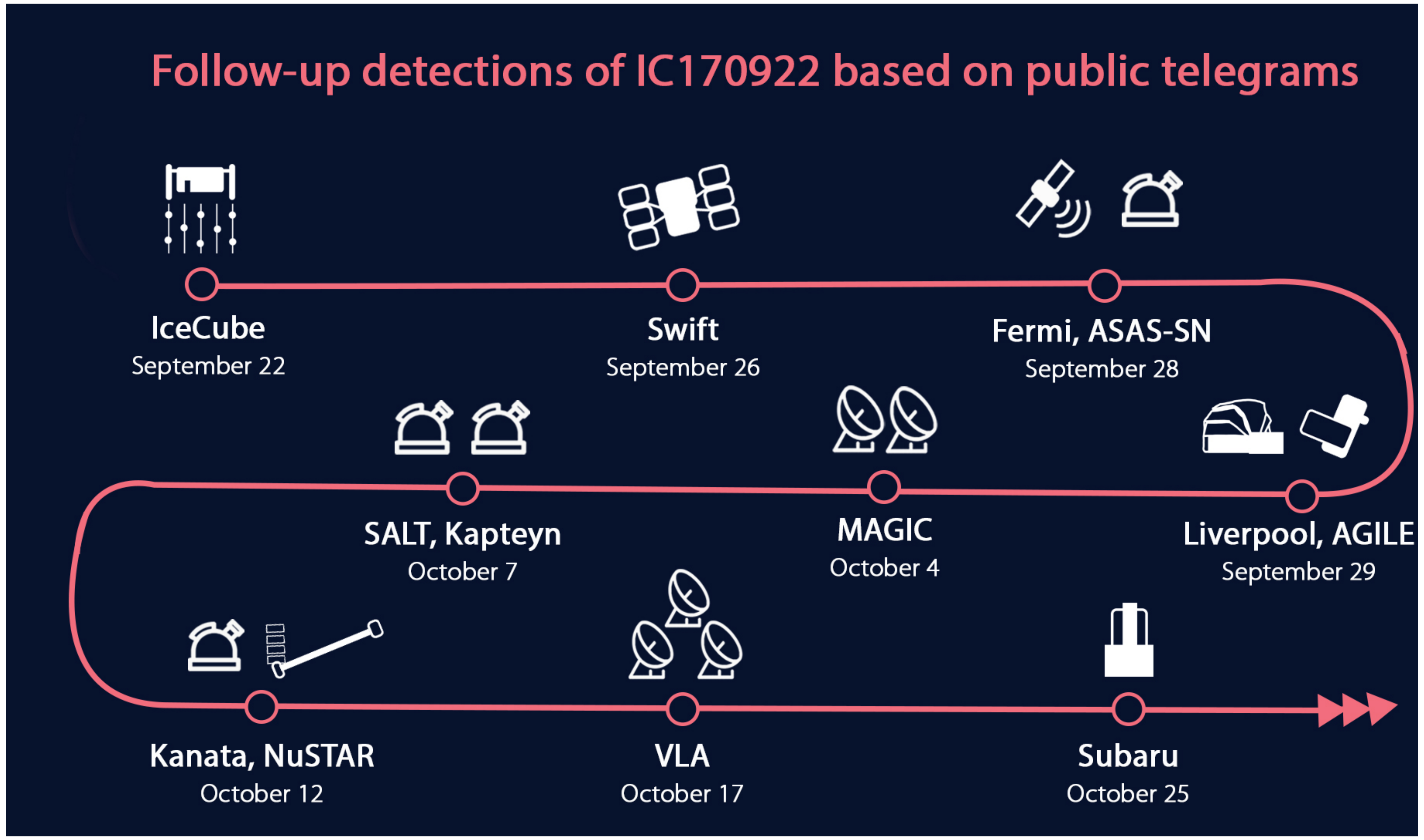
# Cosmic sources

# Multimessenger astronomy



**IceCube-170922A** E = 290 TeV



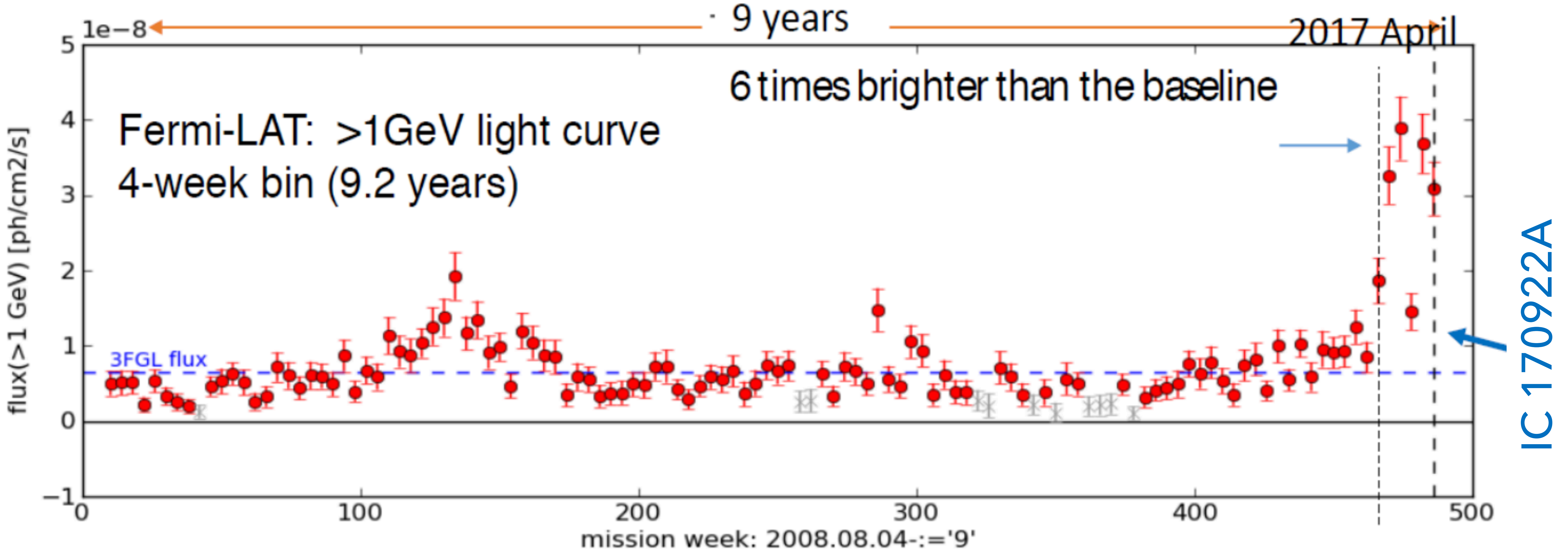

*Science* 13 Jul 2018: Vol. 361, Issue 6398

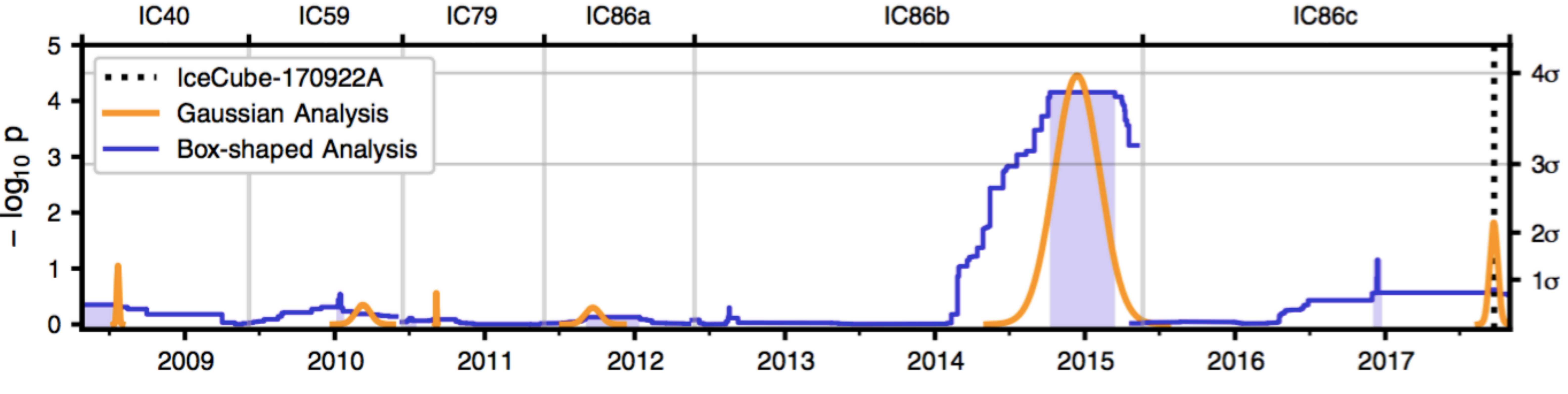
- An alert system based on HESE track-like events and Extreme High Energy events. Operating since April 2016
- Sep 22 2017: An alert on was sent corresponding to a high energy event 300 TeV

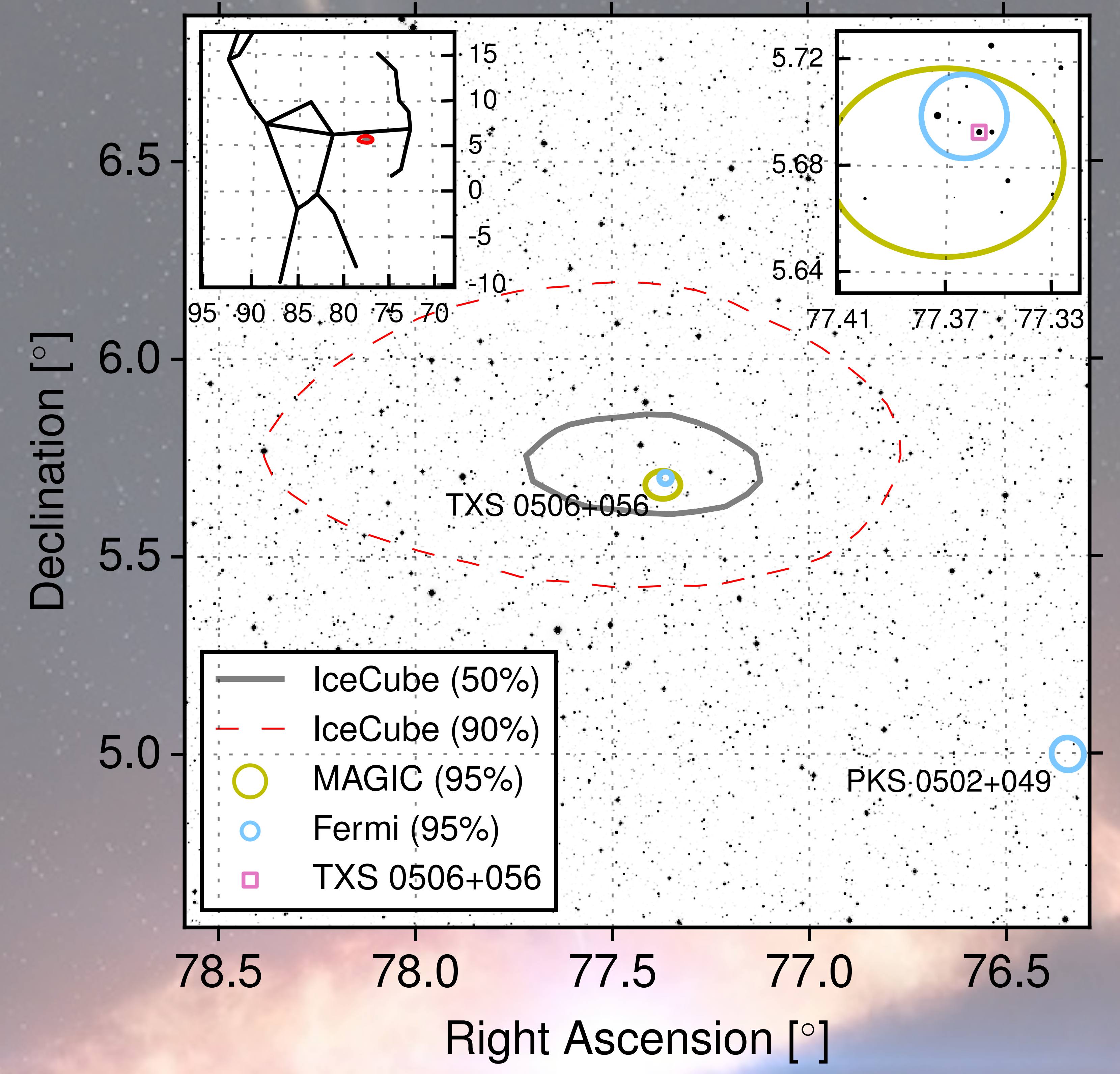
# Neutrino emission from TXS 0506+056



Multimessenger coincidence: p-value = **3σ**. [Science 361 (2018) eaat1378]



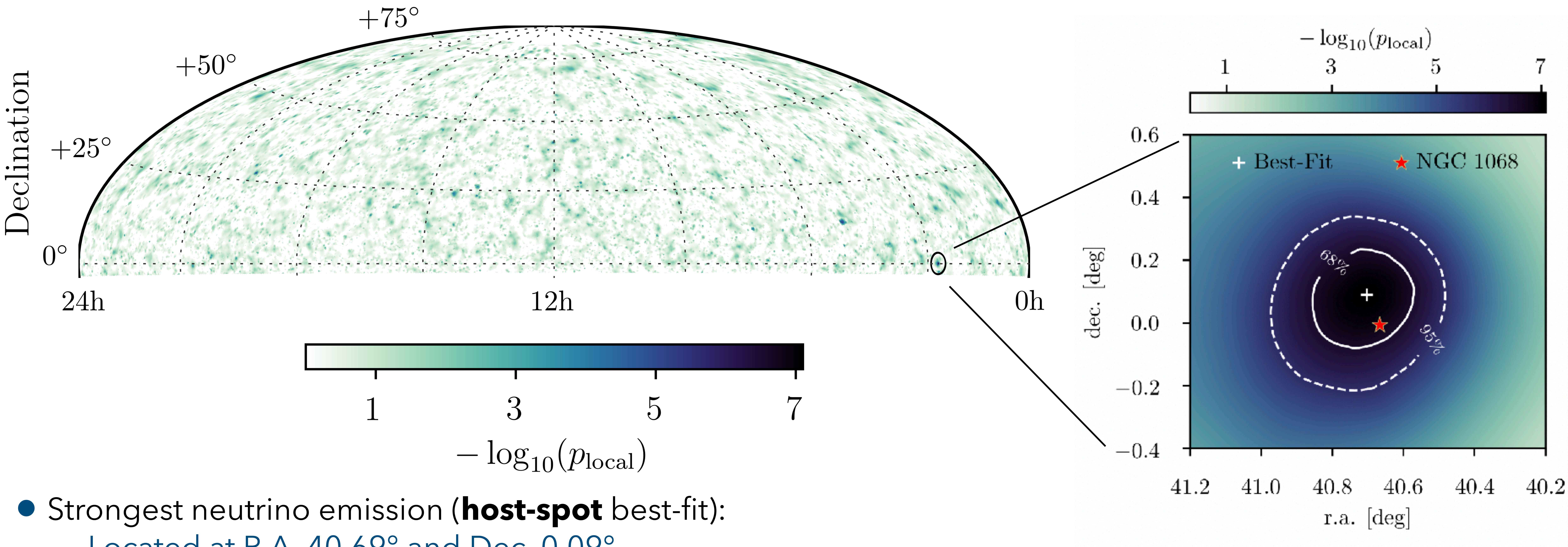

Archival neutrino search find an excess between September 2014 and March 2015: background only hypothesis rejected at **3.5σ** [Science 361 (2018) 147-151].

S. Toscano

# All Sky Search



Science 378 (2022) 538-543

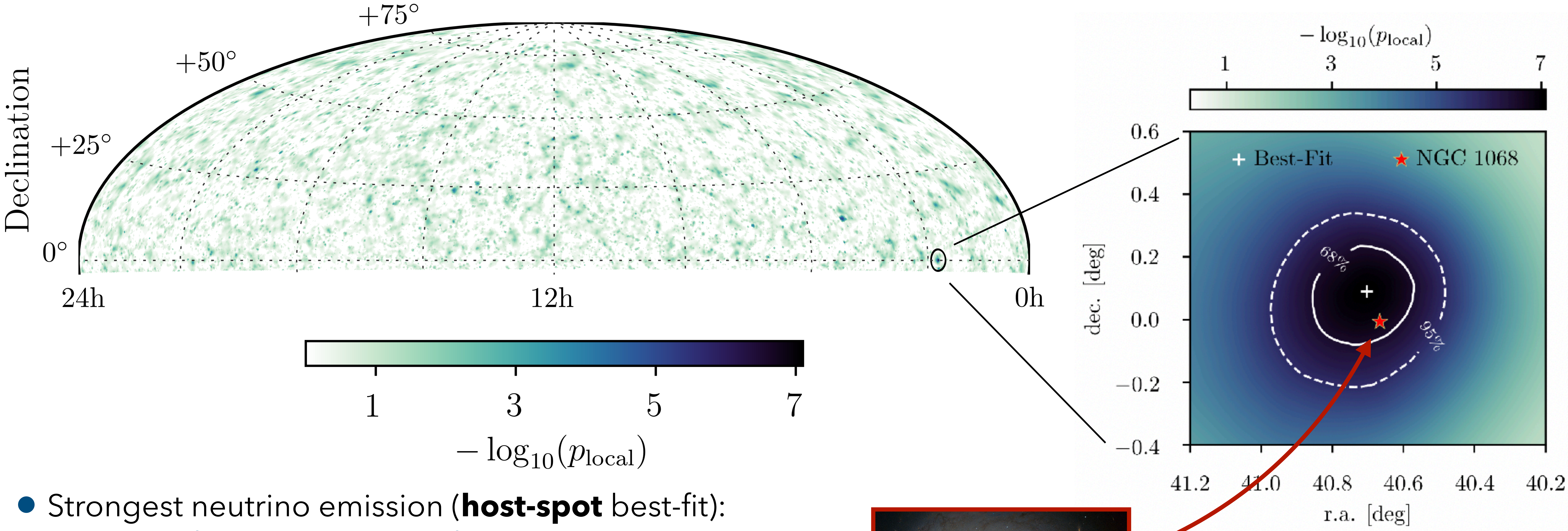



- Strongest neutrino emission (**host-spot** best-fit):
  - Located at R.A. 40.69° and Dec. 0.09°.
  - $\hat{n} = 81$
  - $\hat{\gamma} = 3.2$
  - Local significance **5.3** $\sigma$
- 1% of scrambled data sets have a spot ≥ 5.3 $\sigma$

# All Sky Search



Science 378 (2022) 538-543

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Hottest spot is 0.11° away from center of NGC 1068

S. Toscano

ICECUBE
NEUTRINO OBSERVATORY

# Catalog Search

- A priori catalog of 110 pre-selected candidates.
- Based on 4th Fermi catalog of gamma-ray sources: 4FGL-2DR
- Selected a priori based on gamma-ray brightness and IceCube sensitivity at object's declination
- NGC1068 Best Fit Source
  - $\hat{n} = 79$
  - $\hat{\gamma} = 3.2$
  - Local significance **5.2** $\sigma$
- 1 in 100,000 scrambled data sets have object ≥ 5.2 σ

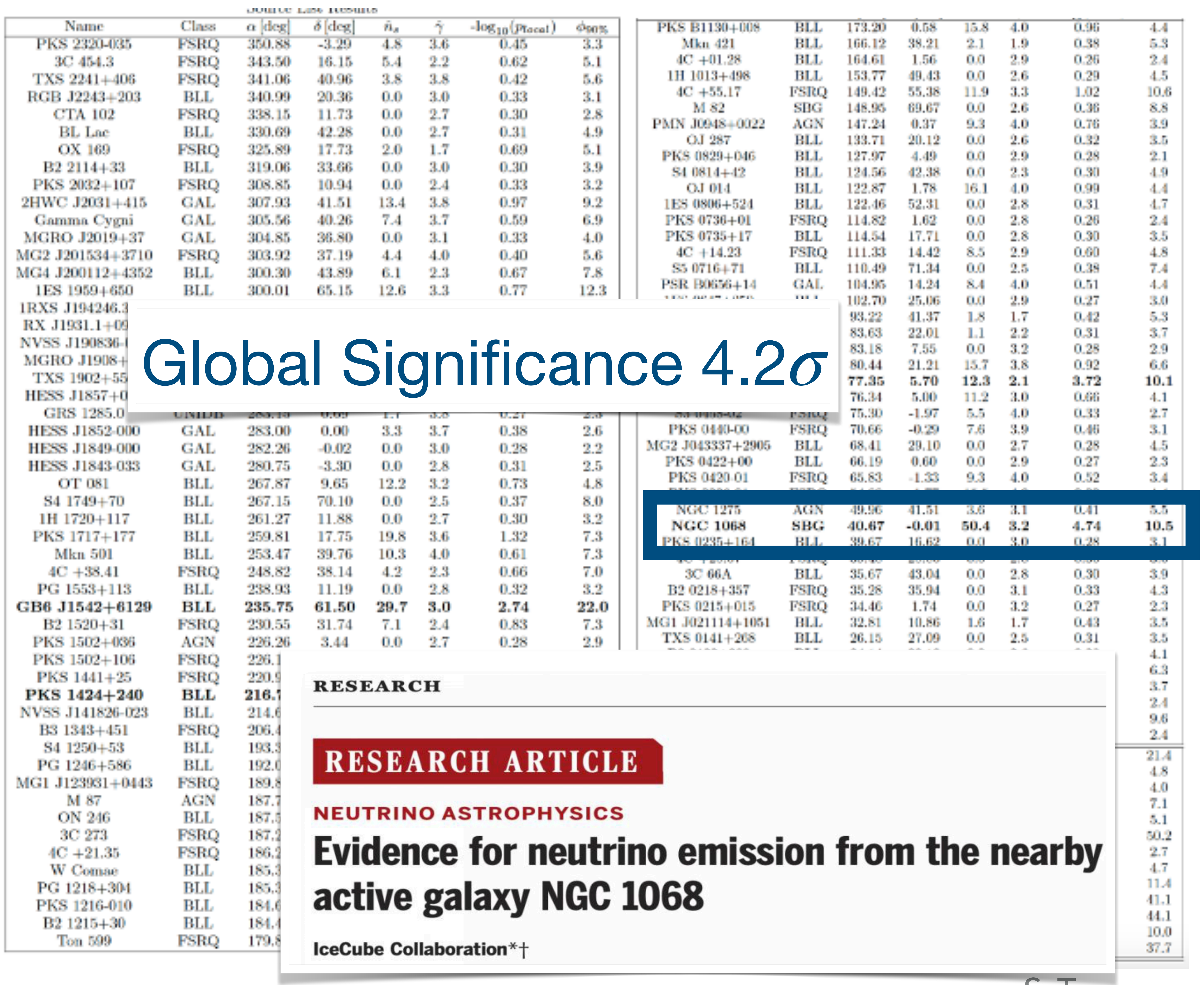
Source List Results

| 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 | 3.8 | 3.8 | 0.42 | 5.6 |
| RGB J2243+203 | BLL | 340.99 | 20.36 | 0.0 | 3.0 | 0.33 | 3.1 |
| CTA 102 | FSRQ | 338.15 | 11.73 | 0.0 | 2.7 | 0.30 | 2.8 |
| BL Lac | BLL | 330.69 | 42.28 | 0.0 | 2.7 | 0.31 | 4.9 |
| OX 169 | FSRQ | 325.89 | 17.73 | 2.0 | 1.7 | 0.69 | 5.1 |
| B2 2114+33 | BLL | 319.06 | 33.66 | 0.0 | 3.0 | 0.30 | 3.9 |
| PKS 2032+107 | FSRQ | 308.85 | 10.94 | 0.0 | 2.4 | 0.33 | 3.2 |
| 2HWC J2031+415 | GAL | 307.93 | 41.51 | 13.4 | 3.8 | 0.97 | 9.2 |
| Gamma Cygni | GAL | 305.56 | 40.26 | 7.4 | 3.7 | 0.59 | 6.9 |
| MGRO J2019+37 | GAL | 304.85 | 36.80 | 0.0 | 3.1 | 0.33 | 4.0 |
| MG2 J201534+3710 | FSRQ | 303.92 | 37.19 | 4.4 | 4.0 | 0.40 | 5.6 |
| MG4 J200112+4352 | BLL | 300.30 | 43.89 | 6.1 | 2.3 | 0.67 | 7.8 |
| 1ES 1959+650 | BLL | 300.01 | 65.15 | 12.6 | 3.3 | 0.77 | 12.3 |
| 1RXS J194246.3+1 | BLL | 295.70 | 10.56 | 0.0 | 2.7 | 0.33 | 2.6 |
| RX J1931.1+0937 | BLL | 292.78 | 9.63 | 0.0 | 2.9 | 0.29 | 2.8 |
| NVSS J190836-012 | UNIDB | 287.20 | -1.53 | 0.0 | 2.9 | 0.22 | 2.3 |
| MGRO J1908+06 | GAL | 287.17 | 6.18 | 4.2 | 2.0 | 1.42 | 5.7 |
| TXS 1902+556 | BLL | 285.80 | 55.68 | 11.7 | 4.0 | 0.85 | 9.9 |
| HESS J1857+026 | GAL | 284.30 | 2.67 | 7.4 | 3.1 | 0.53 | 3.5 |
| GRS 1285.0 | UNIDB | 283.15 | 0.69 | 1.7 | 3.8 | 0.27 | 2.3 |
| HESS J1852-000 | GAL | 283.00 | 0.00 | 3.3 | 3.7 | 0.38 | 2.6 |
| HESS J1849-000 | GAL | 282.26 | -0.02 | 0.0 | 3.0 | 0.28 | 2.2 |
| HESS J1843-033 | GAL | 280.75 | -3.30 | 0.0 | 2.8 | 0.31 | 2.5 |
| OT 081 | BLL | 267.87 | 9.65 | 12.2 | 3.2 | 0.73 | 4.8 |
| S4 1749+70 | BLL | 267.15 | 70.10 | 0.0 | 2.5 | 0.37 | 8.0 |
| 1H 1720+117 | BLL | 261.27 | 11.88 | 0.0 | 2.7 | 0.30 | 3.2 |
| PKS 1717+177 | BLL | 259.81 | 17.75 | 19.8 | 3.6 | 1.32 | 7.3 |
| Mkn 501 | BLL | 253.47 | 39.76 | 10.3 | 4.0 | 0.61 | 7.3 |
| 4C +38.41 | FSRQ | 248.82 | 38.14 | 4.2 | 2.3 | 0.66 | 7.0 |
| PG 1553+113 | BLL | 238.93 | 11.19 | 0.0 | 2.8 | 0.32 | 3.2 |
| **GB6 J1542+6129** | **BLL** | **235.75** | **61.50** | **29.7** | **3.0** | **2.74** | **22.0** |
| B2 1520+31 | FSRQ | 230.55 | 31.74 | 7.1 | 2.4 | 0.83 | 7.3 |
| PKS 1502+036 | AGN | 226.26 | 3.44 | 0.0 | 2.7 | 0.28 | 2.9 |
| PKS 1502+106 | FSRQ | 226.10 | 10.50 | 0.0 | 3.0 | 0.33 | 2.6 |
| PKS 1441+25 | FSRQ | 220.99 | 25.03 | 7.5 | 2.4 | 0.94 | 7.3 |
| **PKS 1424+240** | **BLL** | **216.76** | **23.80** | **41.5** | **3.9** | **2.80** | **12.3** |
| NVSS J141826-023 | BLL | 214.61 | -2.56 | 0.0 | 3.0 | 0.25 | 2.0 |
| B3 1343+451 | FSRQ | 206.40 | 44.88 | 0.0 | 2.8 | 0.32 | 5.0 |
| S4 1250+53 | BLL | 193.31 | 53.02 | 2.2 | 2.5 | 0.39 | 5.9 |
| PG 1246+586 | BLL | 192.08 | 58.34 | 0.0 | 2.8 | 0.35 | 6.4 |
| MG1 J123931+0443 | FSRQ | 189.89 | 4.73 | 0.0 | 2.6 | 0.28 | 2.4 |
| M 87 | AGN | 187.71 | 12.39 | 0.0 | 2.8 | 0.29 | 3.1 |
| ON 246 | BLL | 187.56 | 25.30 | 0.9 | 1.7 | 0.37 | 4.2 |
| 3C 273 | FSRQ | 187.27 | 2.04 | 0.0 | 3.0 | 0.28 | 1.9 |
| 4C +21.35 | FSRQ | 186.23 | 21.38 | 0.0 | 2.6 | 0.32 | 3.5 |
| W Comae | BLL | 185.38 | 28.24 | 0.0 | 3.0 | 0.32 | 3.7 |
| PG 1218+304 | BLL | 185.34 | 30.17 | 11.1 | 3.9 | 0.70 | 6.7 |
| PKS 1216-010 | BLL | 184.64 | -1.33 | 6.9 | 4.0 | 0.45 | 3.1 |
| B2 1215+30 | BLL | 184.48 | 30.12 | 18.6 | 3.4 | 1.09 | 8.5 |
| Ton 599 | FSRQ | 179.88 | 29.24 | 0.0 | 2.2 | 0.29 | 4.5 |
| PKS B1130+008 | BLL | 173.20 | 0.58 | 15.8 | 4.0 | 0.96 | 4.4 |
| Mkn 421 | BLL | 166.12 | 38.21 | 2.1 | 1.9 | 0.38 | 5.3 |
| 4C +01.28 | BLL | 164.61 | 1.56 | 0.0 | 2.9 | 0.26 | 2.4 |
| 1H 1013+498 | BLL | 153.77 | 49.43 | 0.0 | 2.6 | 0.29 | 4.5 |
| 4C +55.17 | FSRQ | 149.42 | 55.38 | 11.9 | 3.3 | 1.02 | 10.6 |
| M 82 | SBG | 148.95 | 69.67 | 0.0 | 2.6 | 0.36 | 8.8 |
| PMN J0948+0022 | AGN | 147.24 | 0.37 | 9.3 | 4.0 | 0.76 | 3.9 |
| OJ 287 | BLL | 133.71 | 20.12 | 0.0 | 2.6 | 0.32 | 3.5 |
| PKS 0829+046 | BLL | 127.97 | 4.49 | 0.0 | 2.9 | 0.28 | 2.1 |
| S4 0814+42 | BLL | 124.56 | 42.38 | 0.0 | 2.3 | 0.30 | 4.9 |
| OJ 014 | BLL | 122.87 | 1.78 | 16.1 | 4.0 | 0.99 | 4.4 |
| 1ES 0806+524 | BLL | 122.46 | 52.31 | 0.0 | 2.8 | 0.31 | 4.7 |
| PKS 0736+01 | FSRQ | 114.82 | 1.62 | 0.0 | 2.8 | 0.26 | 2.4 |
| PKS 0735+17 | BLL | 114.54 | 17.71 | 0.0 | 2.8 | 0.30 | 3.5 |
| 4C +14.23 | FSRQ | 111.33 | 14.42 | 8.5 | 2.9 | 0.60 | 4.8 |
| S5 0716+71 | BLL | 110.49 | 71.34 | 0.0 | 2.5 | 0.38 | 7.4 |
| PSR B0656+14 | GAL | 104.95 | 14.24 | 8.4 | 4.0 | 0.51 | 4.4 |
| 1ES 0647+250 | BLL | 102.70 | 25.06 | 0.0 | 2.9 | 0.27 | 3.0 |
| B3 0609+413 | BLL | 93.22 | 41.37 | 1.8 | 1.7 | 0.42 | 5.3 |
| Crab nebula | GAL | 83.63 | 22.01 | 1.1 | 2.2 | 0.31 | 3.7 |
| OG +050 | FSRQ | 83.18 | 7.55 | 0.0 | 3.2 | 0.28 | 2.9 |
| TXS 0518+211 | BLL | 80.44 | 21.21 | 15.7 | 3.8 | 0.92 | 6.6 |
| **TXS 0506+056** | **BLL** | **77.35** | **5.70** | **12.3** | **2.1** | **3.72** | **10.1** |
| PKS 0502+049 | FSRQ | 76.34 | 5.00 | 11.2 | 3.0 | 0.66 | 4.1 |
| S3 0458-02 | FSRQ | 75.30 | -1.97 | 5.5 | 4.0 | 0.33 | 2.7 |
| PKS 0440-00 | FSRQ | 70.66 | -0.29 | 7.6 | 3.9 | 0.46 | 3.1 |
| MG2 J043337+2905 | BLL | 68.41 | 29.10 | 0.0 | 2.7 | 0.28 | 4.5 |
| PKS 0422+00 | BLL | 66.19 | 0.60 | 0.0 | 2.9 | 0.27 | 2.3 |
| PKS 0420-01 | FSRQ | 65.83 | -1.33 | 9.3 | 4.0 | 0.52 | 3.4 |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 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 |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 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 |

# Catalog Search



- A priori catalog of 110 pre-selected candidates.
- Based on 4th Fermi catalog of gamma-ray sources: 4FGL-2DR
- Selected a priori based on gamma-ray brightness and IceCube sensitivity at object's declination
- NGC1068 Best Fit Source
  - $\hat{n} = 79$
  - $\hat{\gamma} = 3.2$
  - Local significance **5.2** $\sigma$
- 1 in 100,000 scrambled data sets have object ≥ 5.2 σ



# NGC 1068



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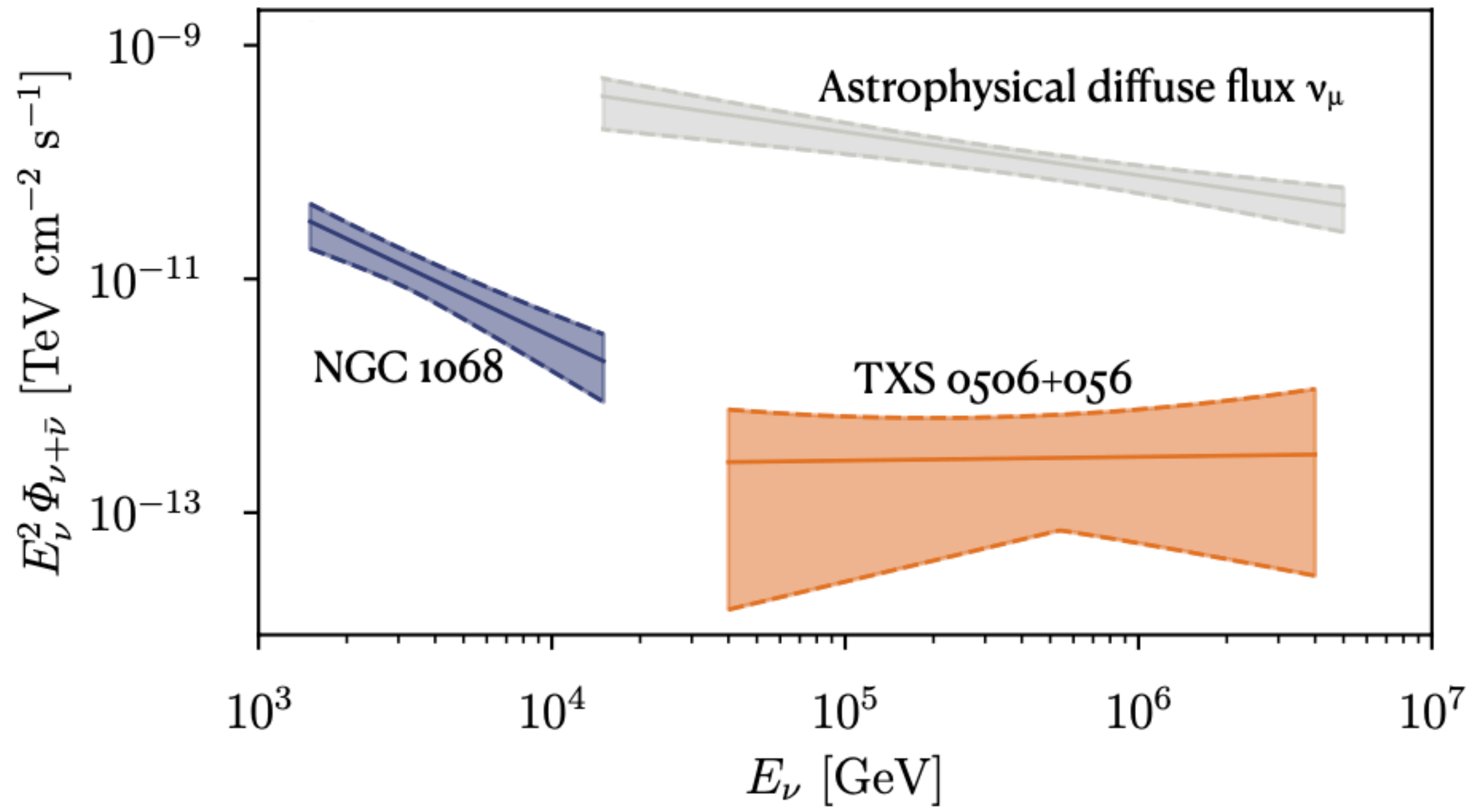


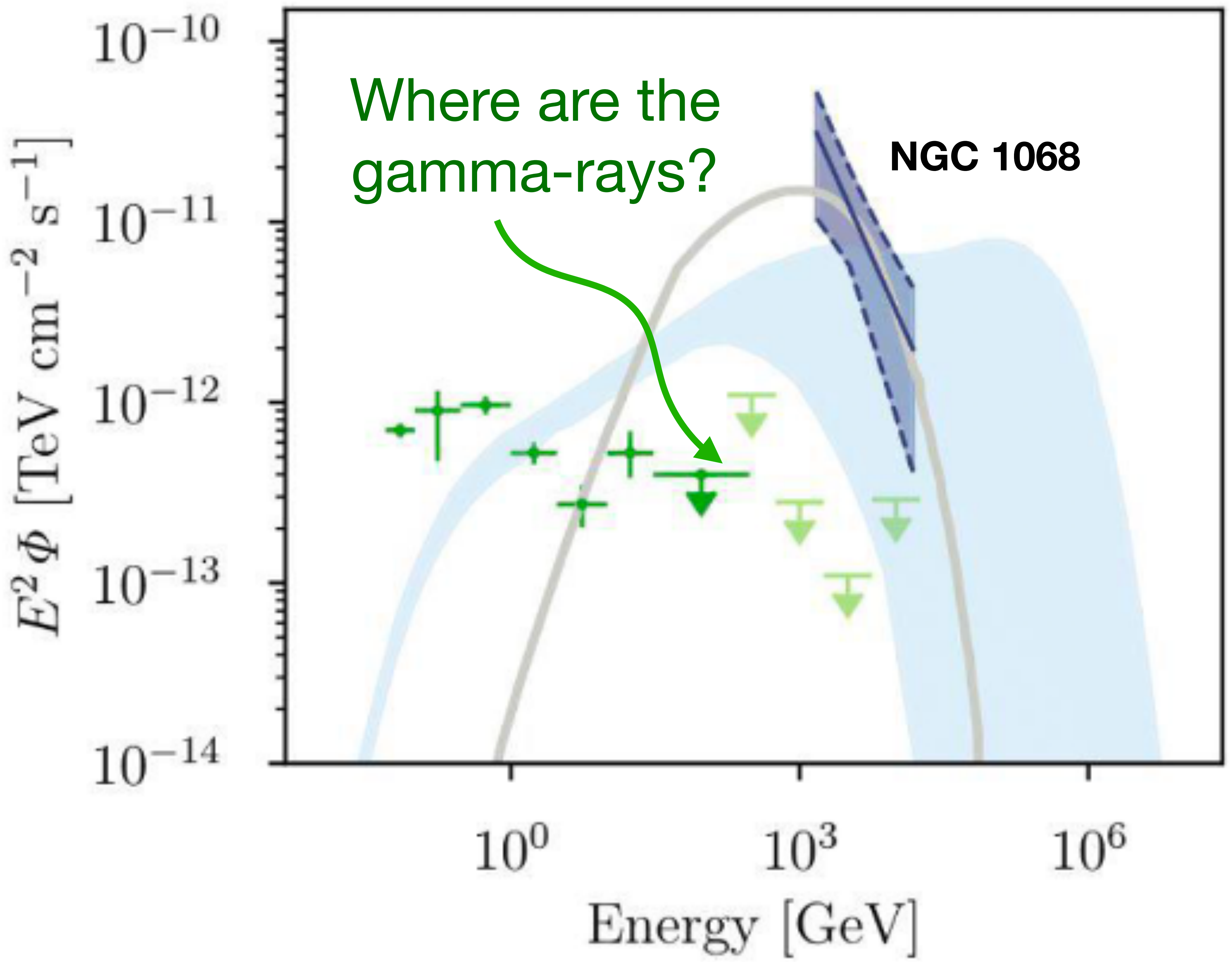


- TXS 0506+056 and NGC 1068 contribute each ~1% of the total astrophysical diffuse neutrino
- Measured neutrino flux exceeds TeV gamma-ray upper limits

# NGC 1068

## Seyfert Galaxy with an obscured black hole

- Very active starburst spiral galaxy.
- It is close! (~14.4 Mpc)
- It hosts a Compton-thick AGN
- AGN powered by a SMBH with mass ~$10^7$ - $10^8$ $M_\odot$
- Intrinsically the brightest Seyfert in the X-ray band

# The Disk-Corona Model

- Electron and protons are accelerated in the high field regions associated with the black hole and the accretion disk
- They produce neutrinos in the optical thick corona
  - **Gamma-rays are absorbed**

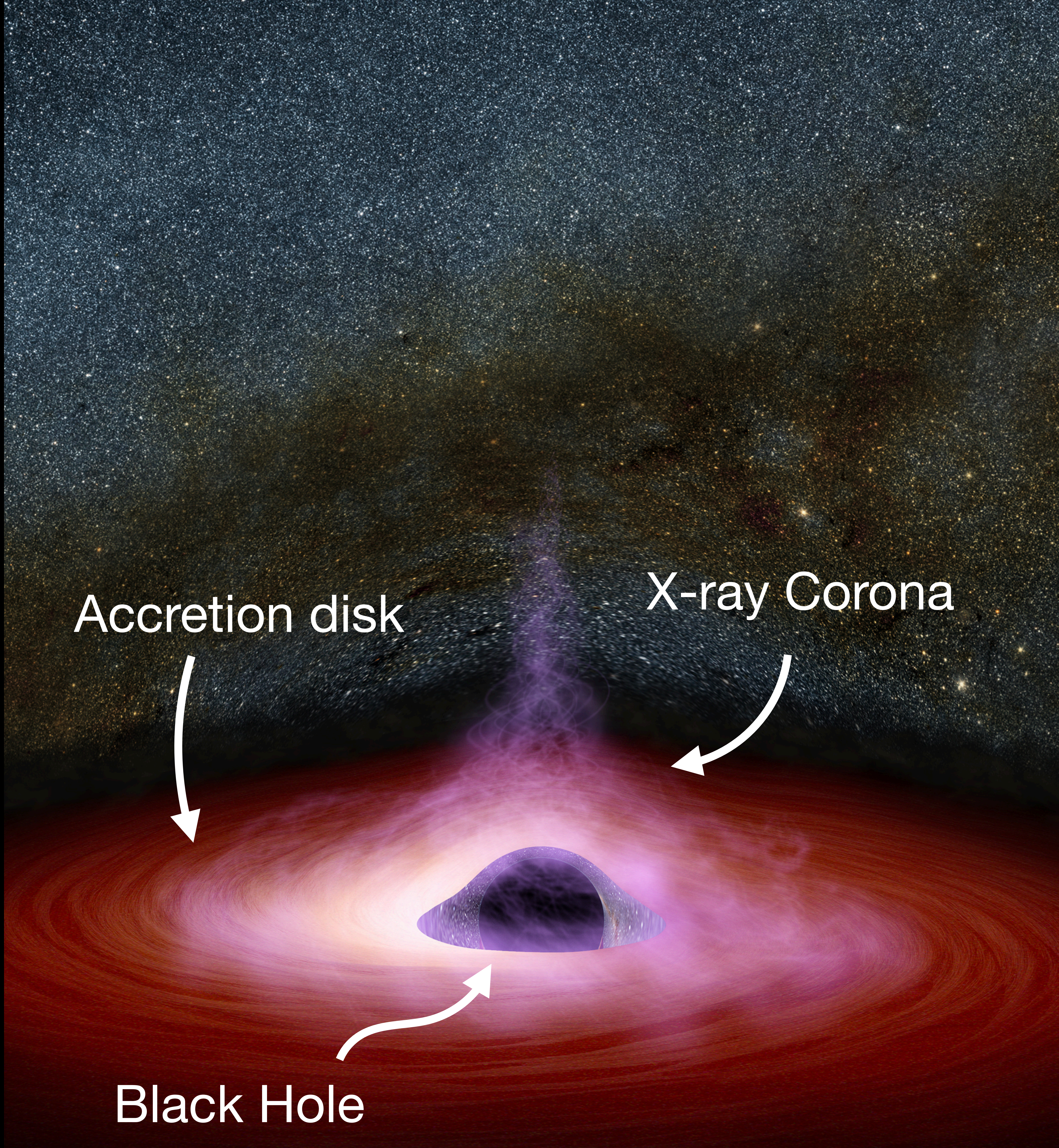


Image credit: NASA/JPL-Caltech

# SUMMARY

- IceCube has been investigating a diffuse flux of astrophysical >TeV neutrinos for almost a decade providing the **first neutrino view of the Universe**

- First sources of neutrinos are being unveiled and we start having a blueprint of the solution of the cosmic-ray problem…

- … however cosmic rays physics is never that simple and we can expect more surprises.

- IceCube-Gen2 on its way (within next decade)

Future is bright in neutrino!