H.E.S.S. real-time follow-up on high-energy neutrino alerts from IceCube

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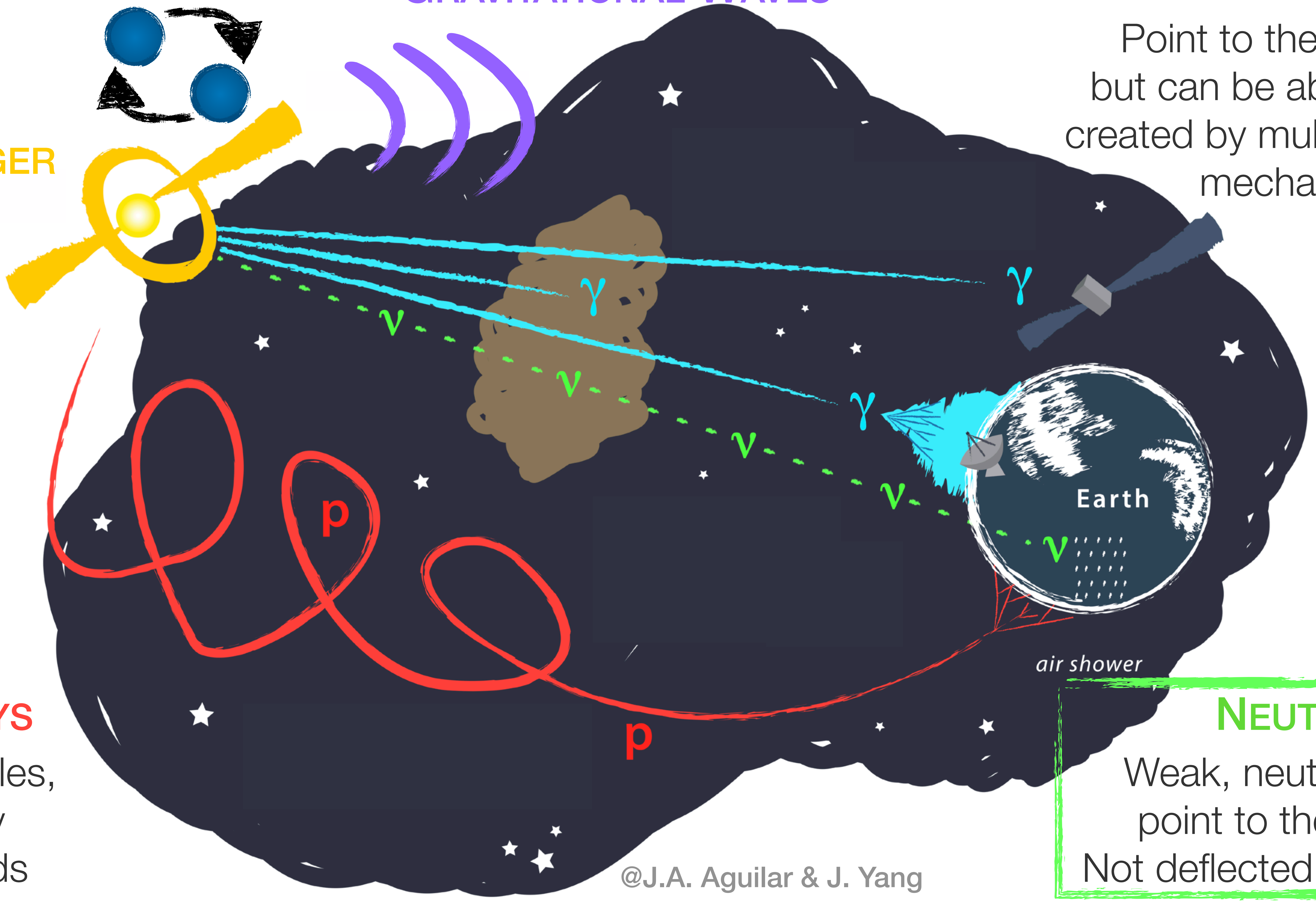
Multimessenger astronomy



Gamma Rays

Point to their sources, but can be absorbed and created by multiple emission mechanisms

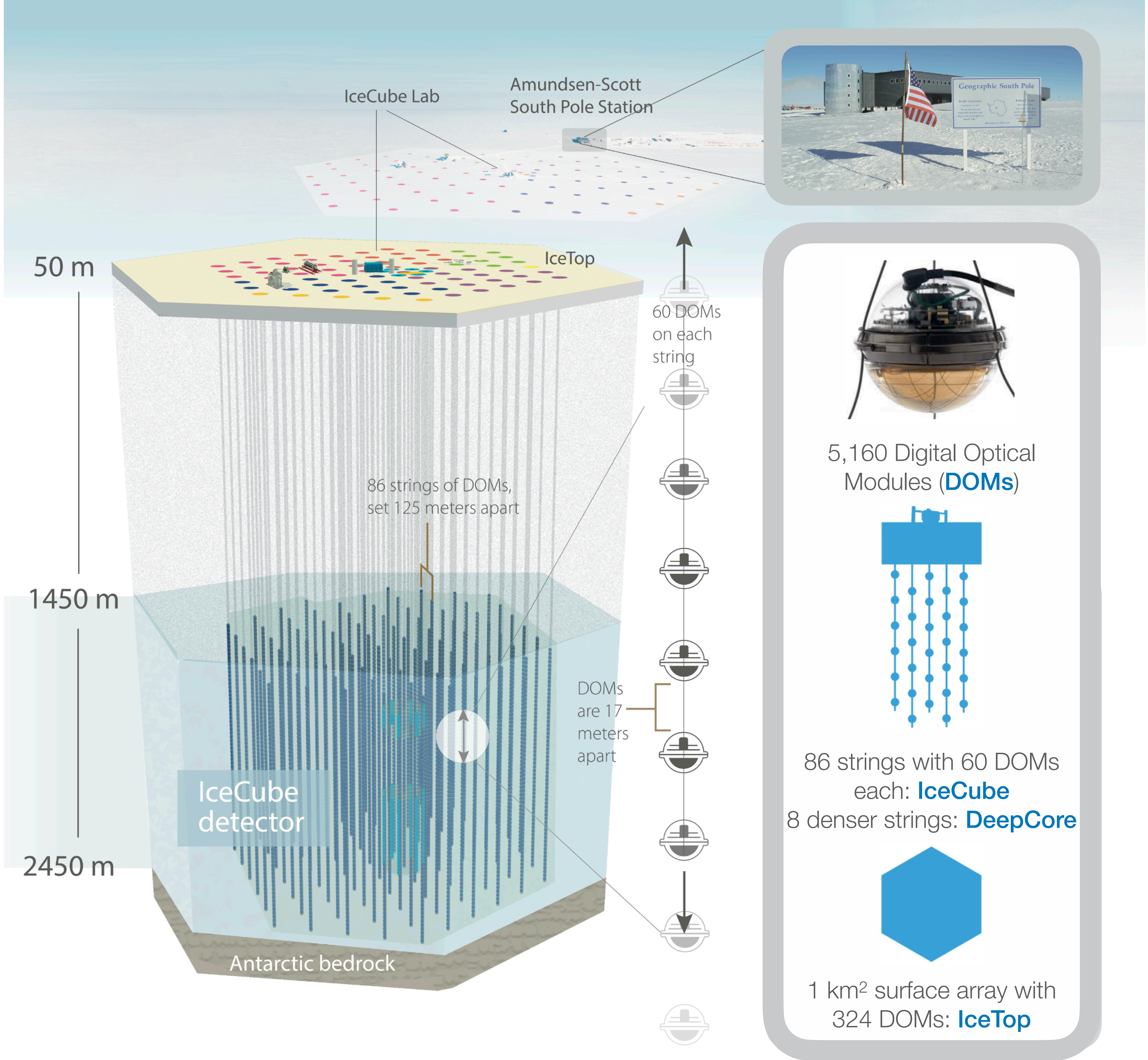
Cosmic Rays

Charged particles, deflected by magnetic fields

Neutrinos

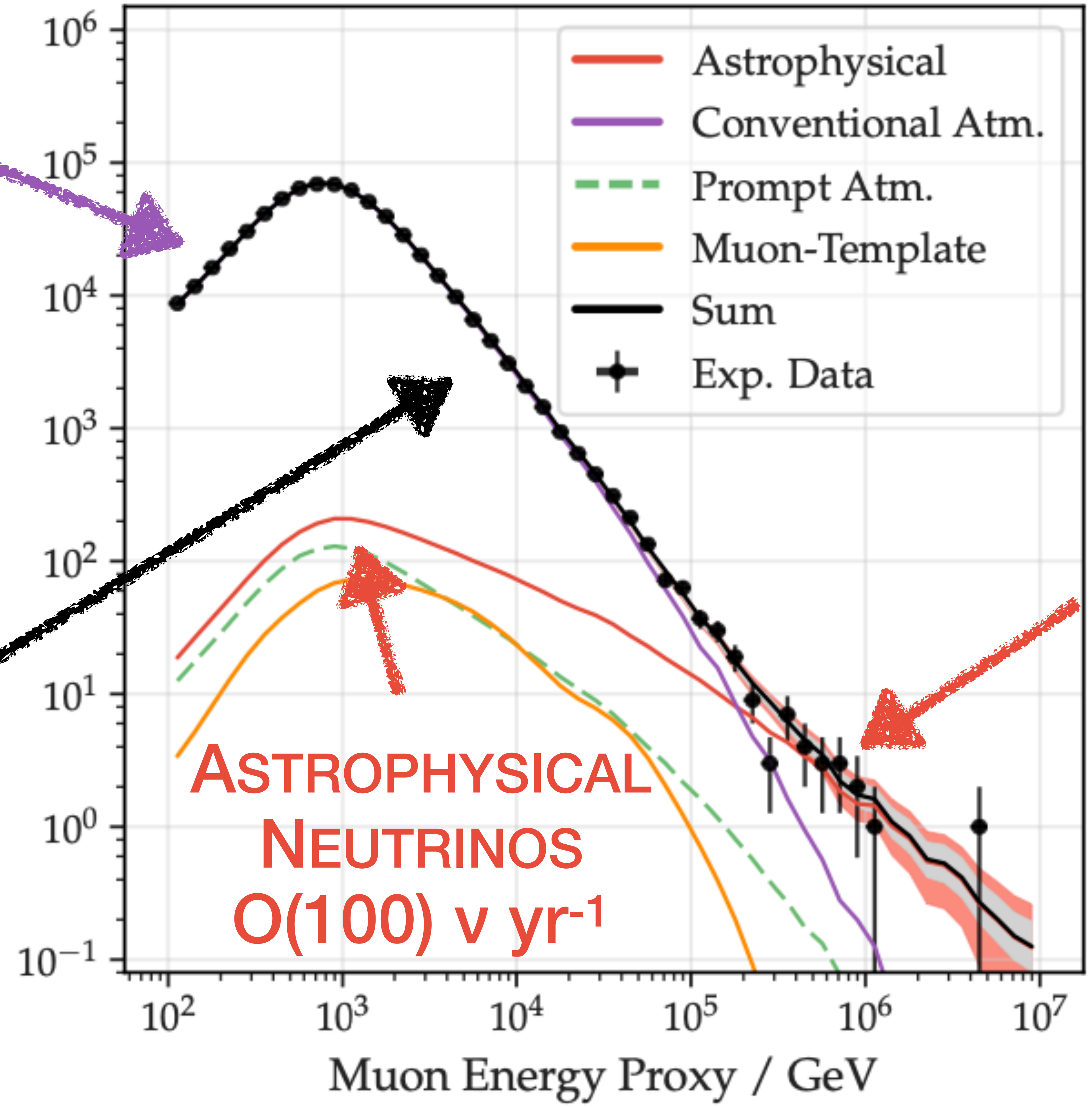
Weak, neutral particles, point to their sources, Not deflected, not absorbed

The IceCube Neutrino Observatory



How to search for neutrino sources?

ATMOSPHERIC BACKGROUND
O(10^5) ν yr^{-1}



Muon neutrino events using 9.5yr of IceCube data

ASTROPHYSICAL NEUTRINOS
O(10) ν yr^{-1}

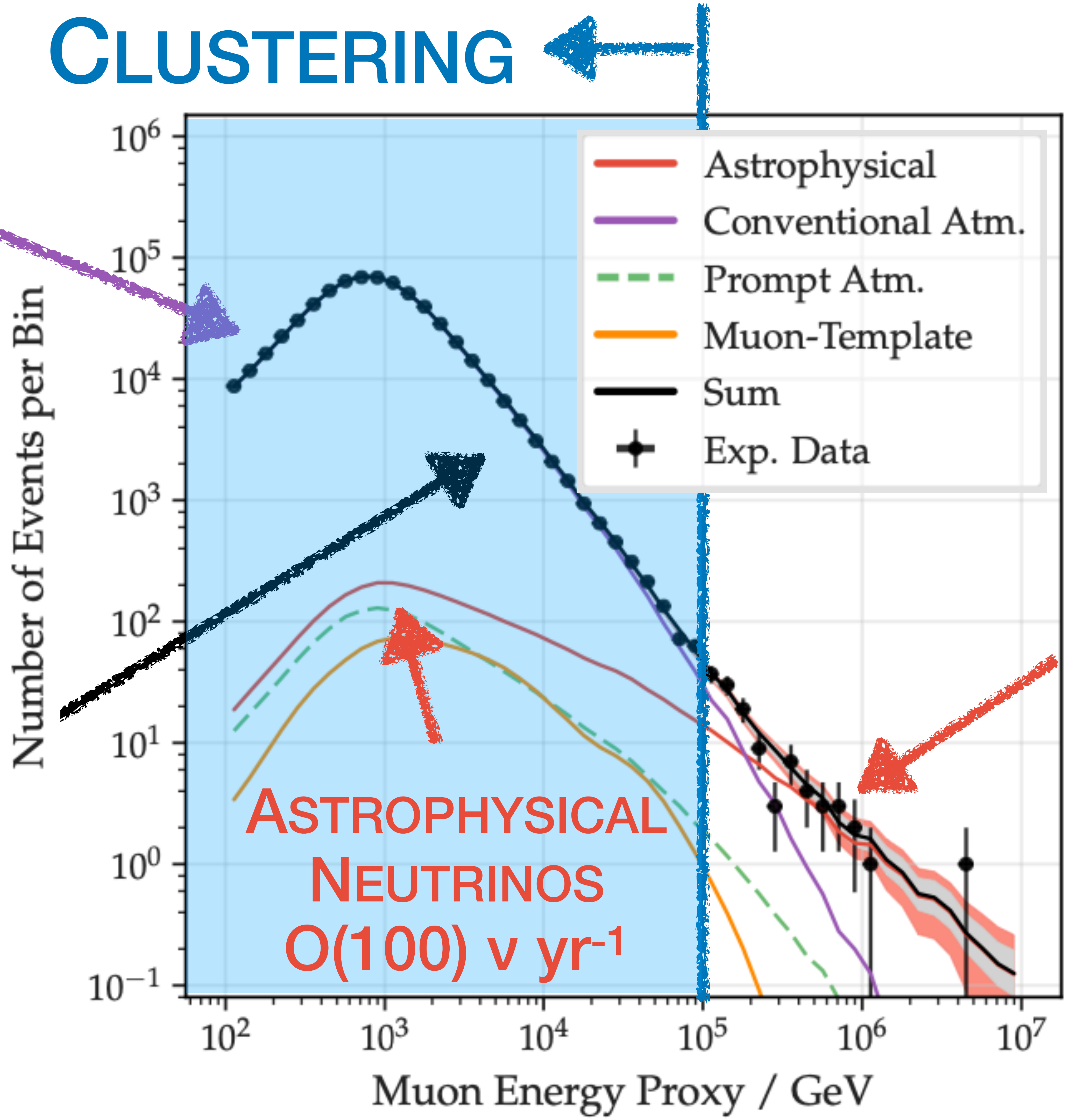
[Icecube 2022 *ApJ* **928** 50]

How to search for neutrino sources?

CLUSTERING

ATMOSPHERIC BACKGROUND
O(10^5) ν yr^{-1}

Muon neutrino events using 9.5yr of IceCube data



ASTROPHYSICAL NEUTRINOS
O(100) ν yr^{-1}

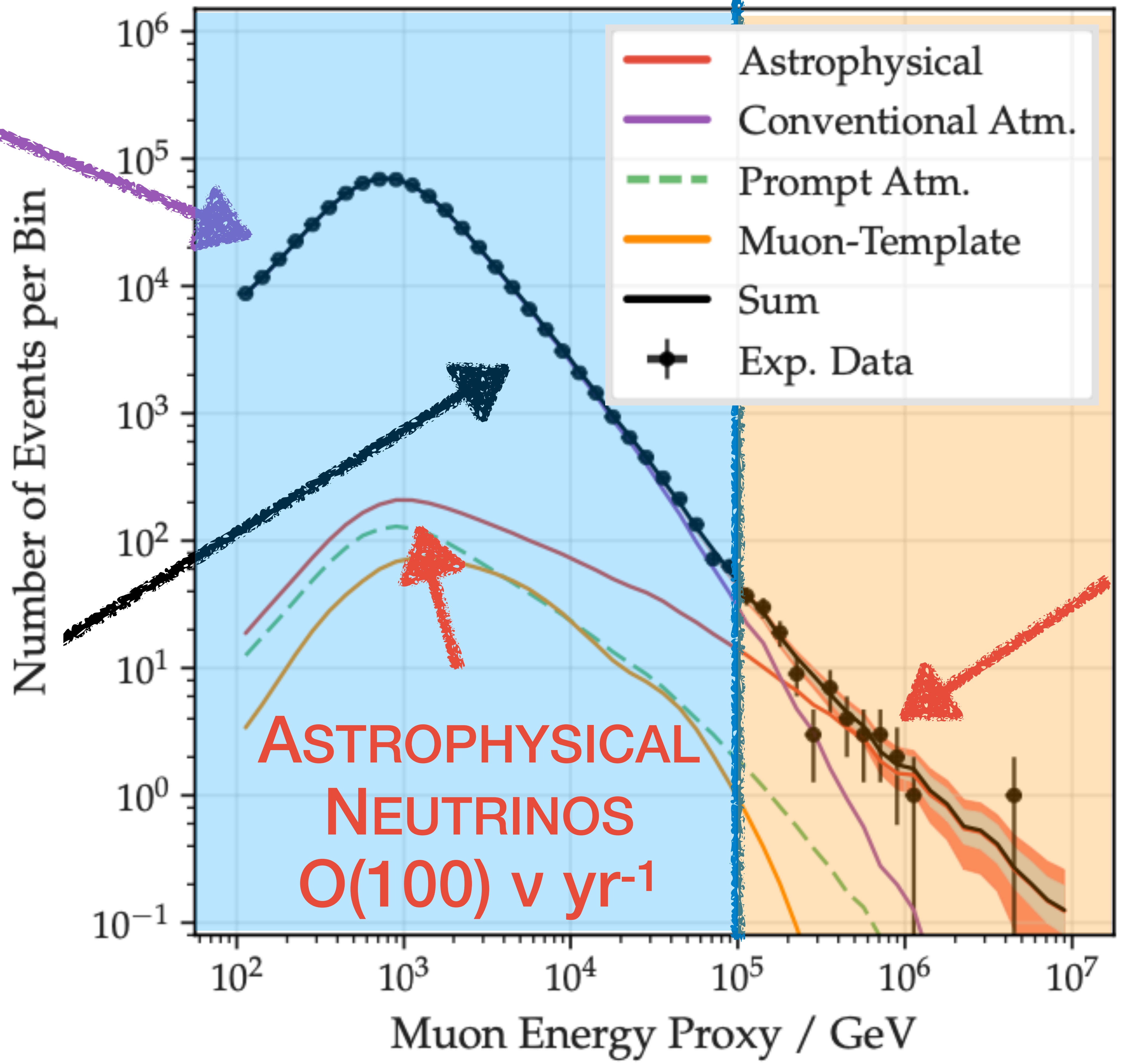
ASTROPHYSICAL NEUTRINOS
O(10) ν yr^{-1}

[Icecube 2022 *ApJ* **928** 50]

How to search for neutrino sources?

CLUSTERING ← → REALTIME + MWL FOLLOW-UP

ATMOSPHERIC BACKGROUND O(10^5) ν yr^{-1}



ASTROPHYSICAL NEUTRINOS O(10) ν yr^{-1}

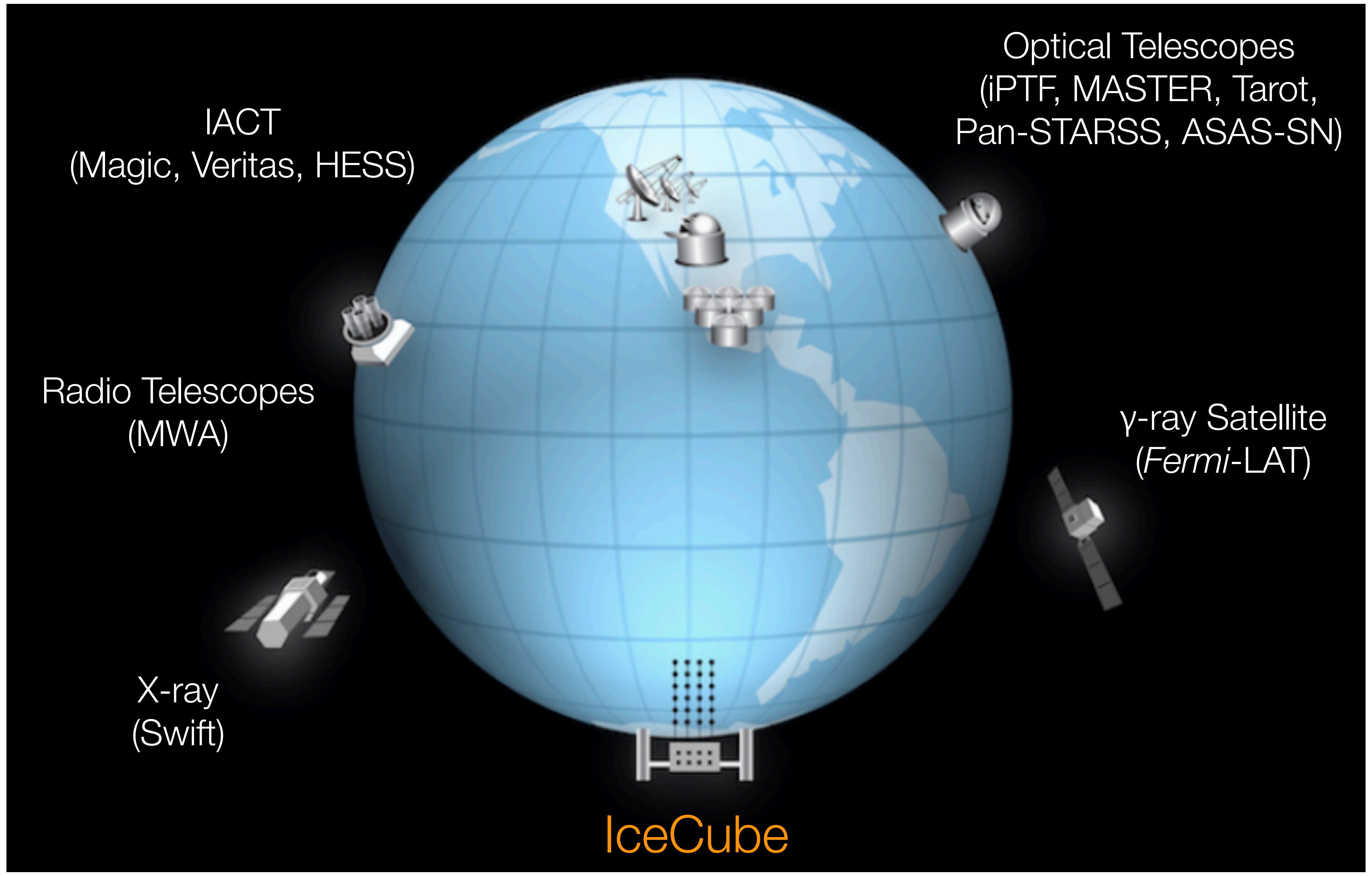
Muon neutrino events using 9.5yr of IceCube data

[Icecube 2022 *ApJ* **928** 50]

IceCube realtime alert system

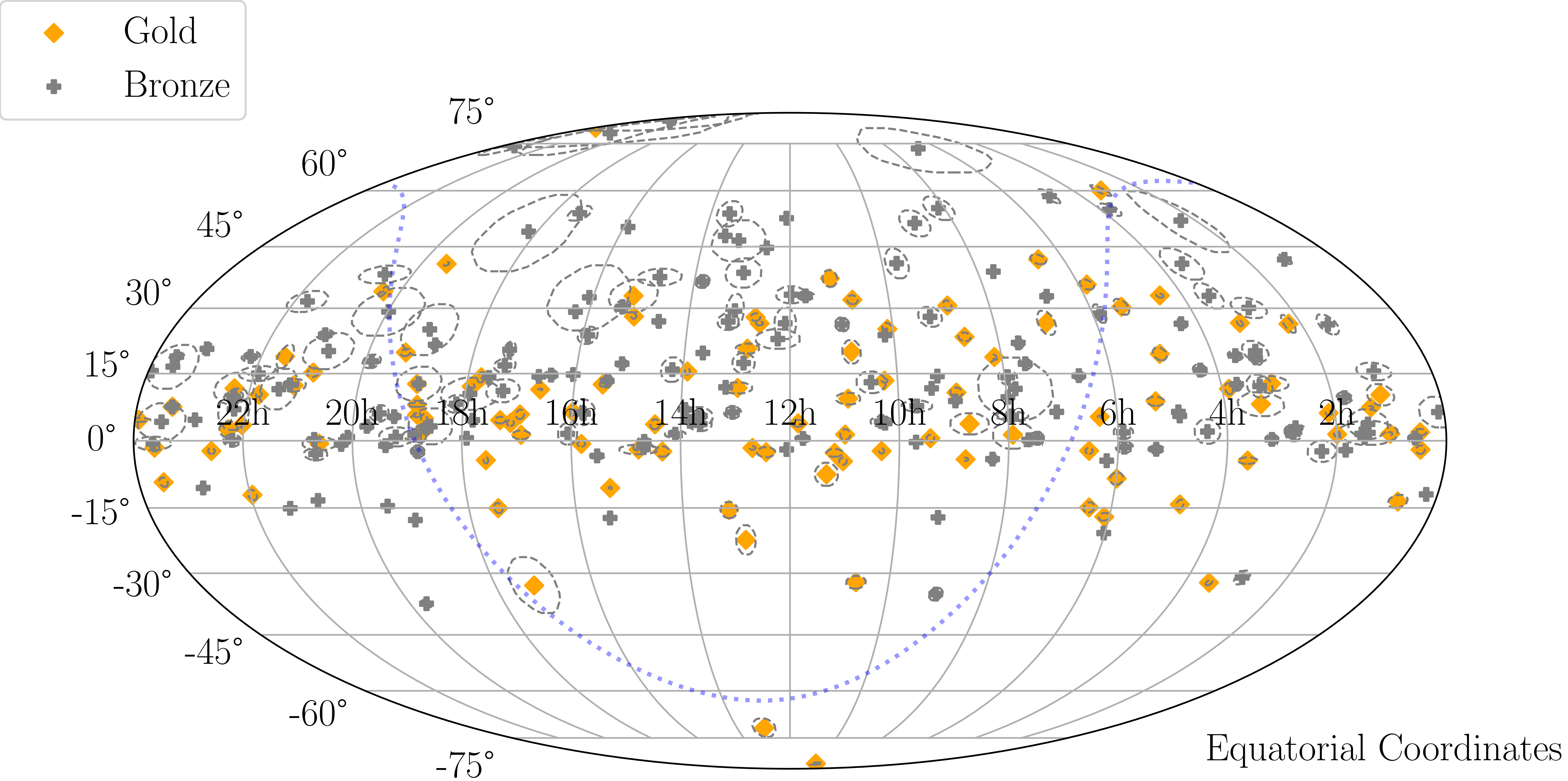
Follow-up of astrophysical neutrino events

- Single high-energy muon track events with high probability of being astrophysical ($E \gtrsim 100$ TeV)
- Since 2016, alerts are distributed through GCN network to ground and space-based observatories for rapid follow-ups
- Average alerts rate of ~2/month
- Median latency ~30 sec



Single neutrino public alert stream

Neutrino alerts with **50%** and **30%** probability of being astrophysical

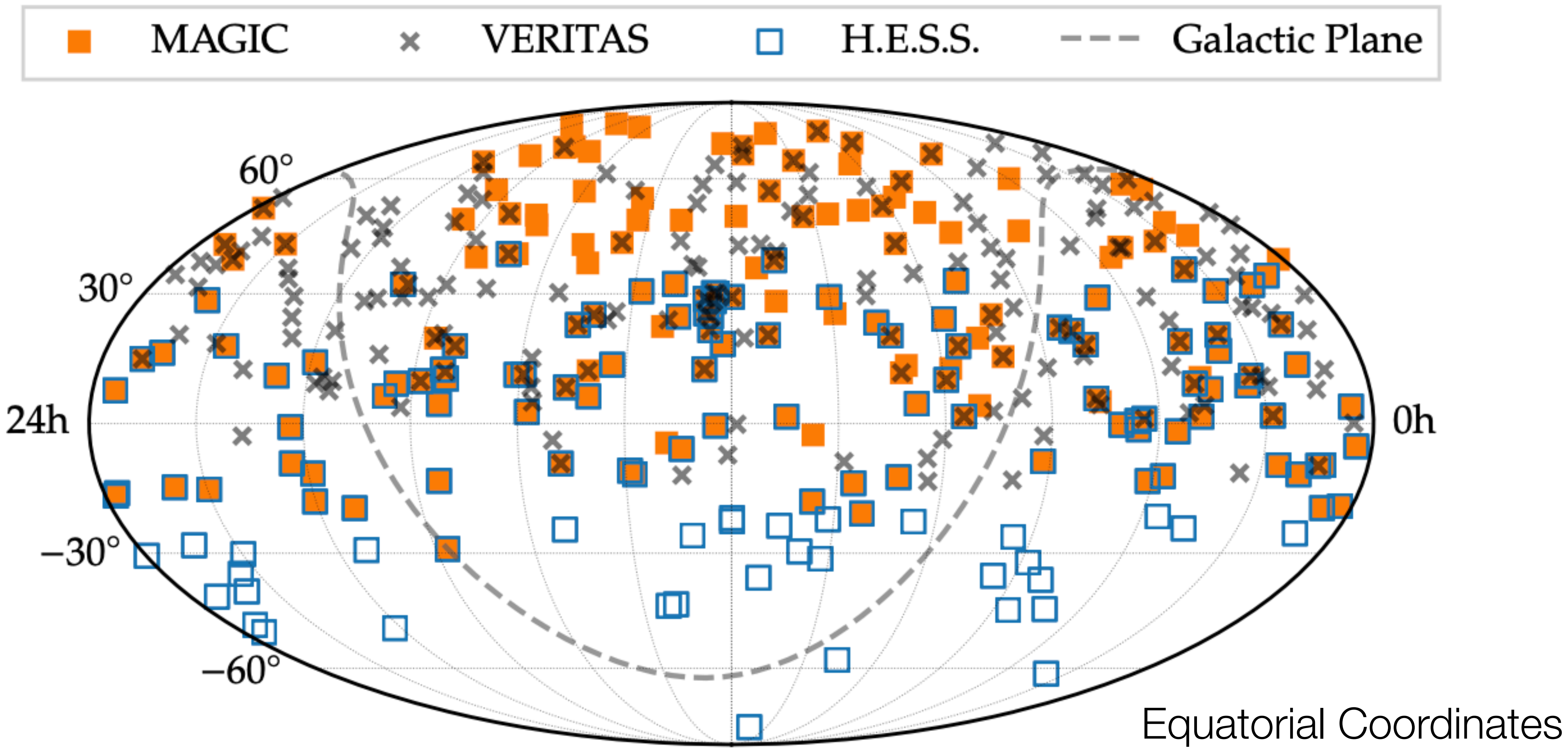


[IceCube 2023 arXiv:2304.01174]

Goal: find electromagnetic counterpart to the neutrino event

Gamma-ray **F**ollow-**U**p (GFU) private stream

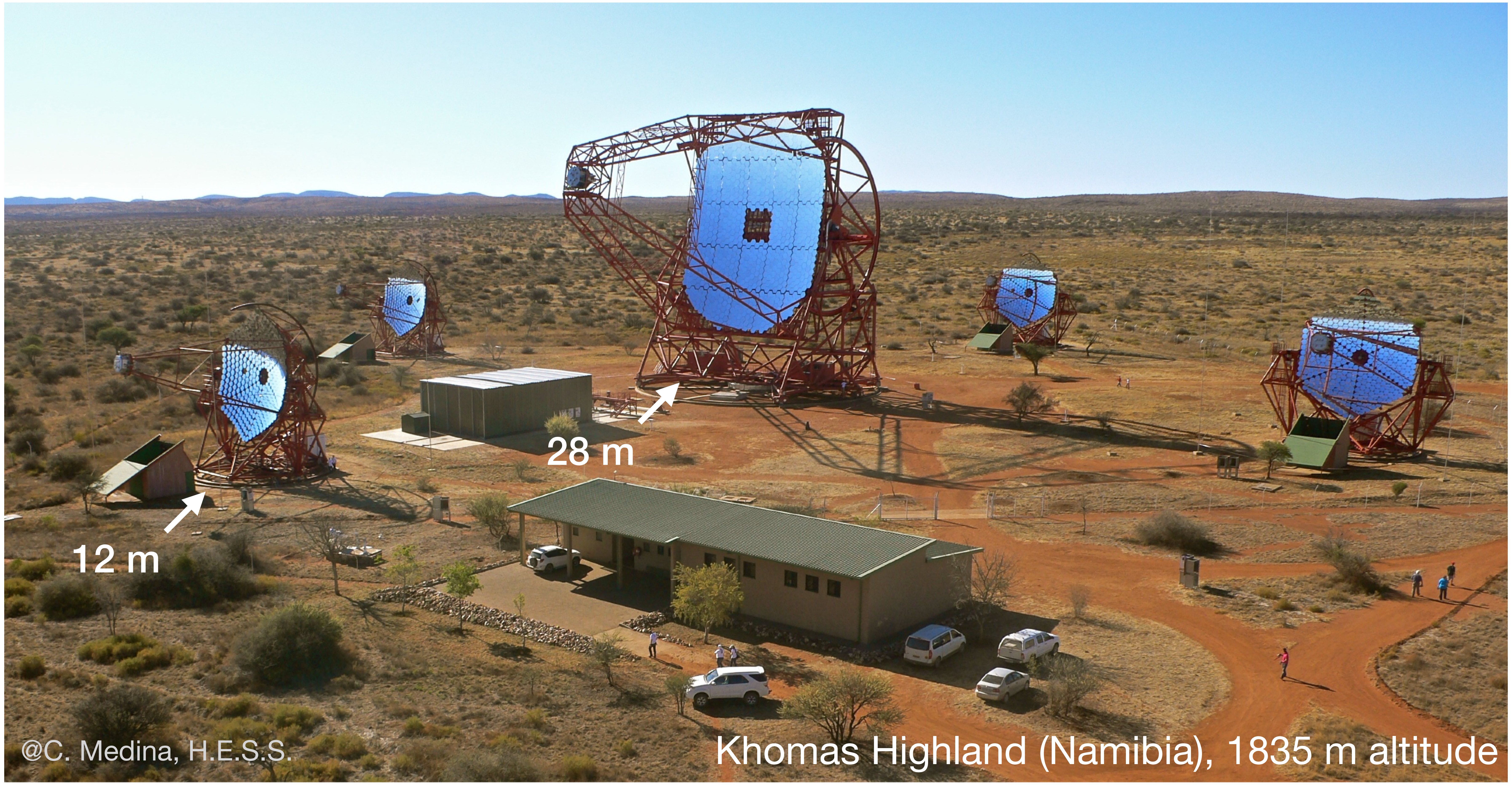
Neutrino multiplets (*flares*) from pre-defined source list:
339 sources from 3LAC/3FHL and TeVCAT



[T. Kintscher, PhD thesis, 2020, doi:10.18452/21948]

Goal: determine changes in the source state

H.E.S.S.



Array of 5 Imaging Atmospheric Cherenkov Telescopes
to detect VHE gamma rays from ~30 GeV to 100 TeV

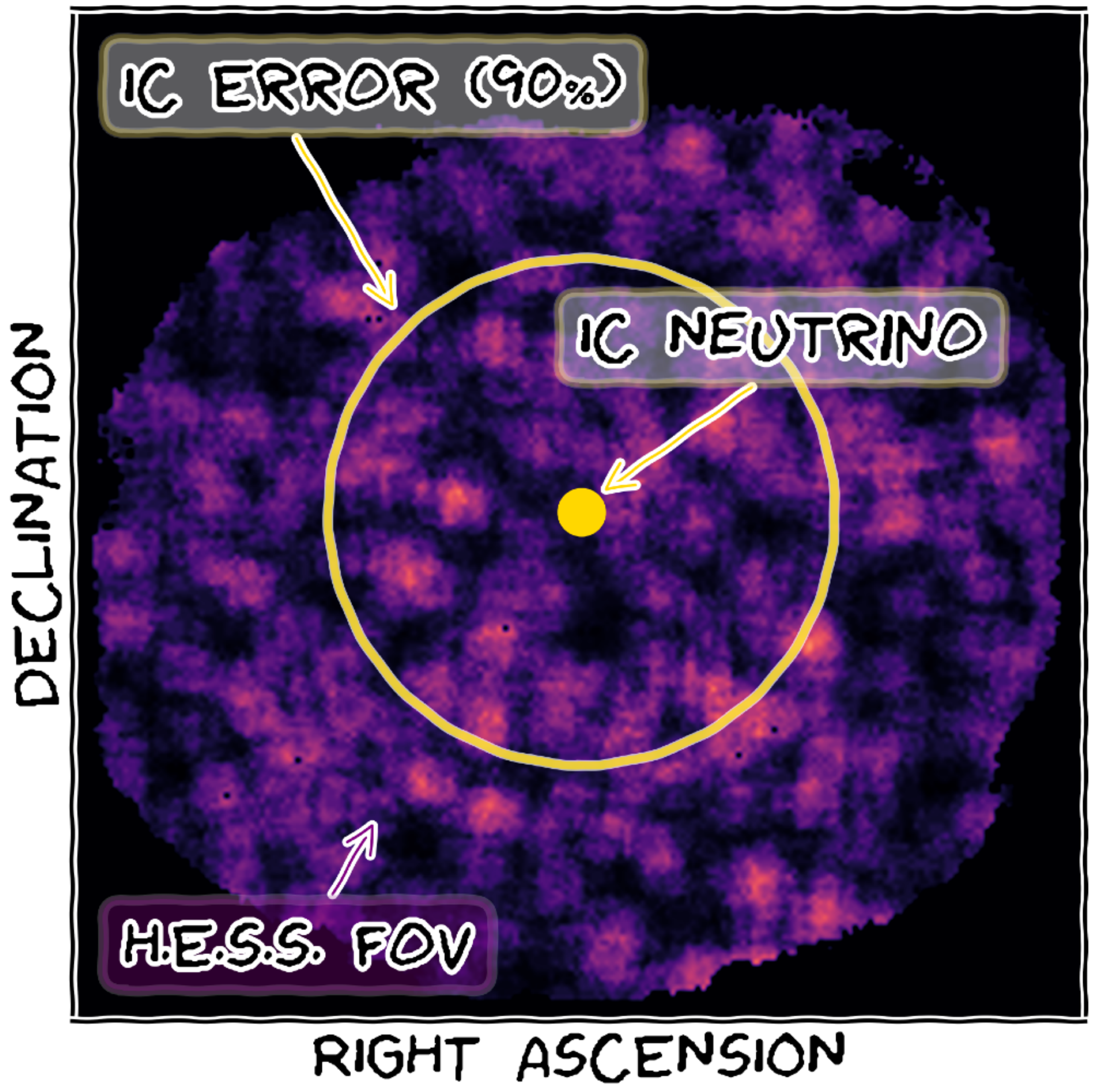
H.E.S.S. **T**arget **o**f **O**pportunity (ToO) program

Fully automatised neutrino ToO alert system since 2012

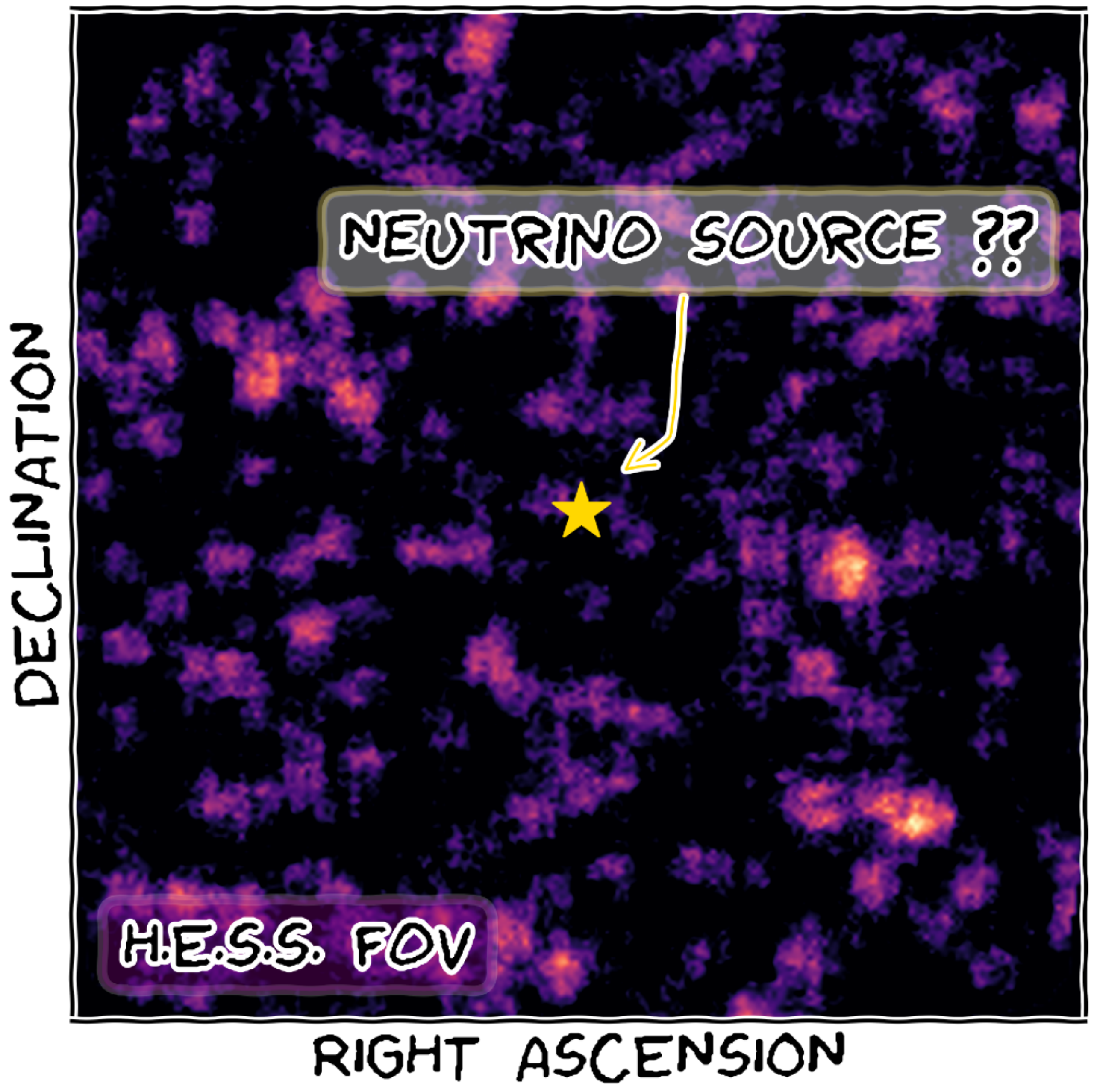
- ~20 hours/year of deep observations of few (~5/yr) candidates
    - Extension of observations for potential signal or interesting MWL info
- Rapid response time
    - Automatic re-pointing for immediate observations of $P_{astro} > 50\%$ events if conditions permit (e.g., dark night, favorable weather)
    - Observations typically occur within a few days if immediate conditions are not met
- MWL observations with ATOM, *Swift*-UVOT and *Swift*-XRT

H.E.S.S. **T**arget **o**f **O**pportunity (ToO) program

Pointing strategy: All IC error region often covered thanks to large FoV



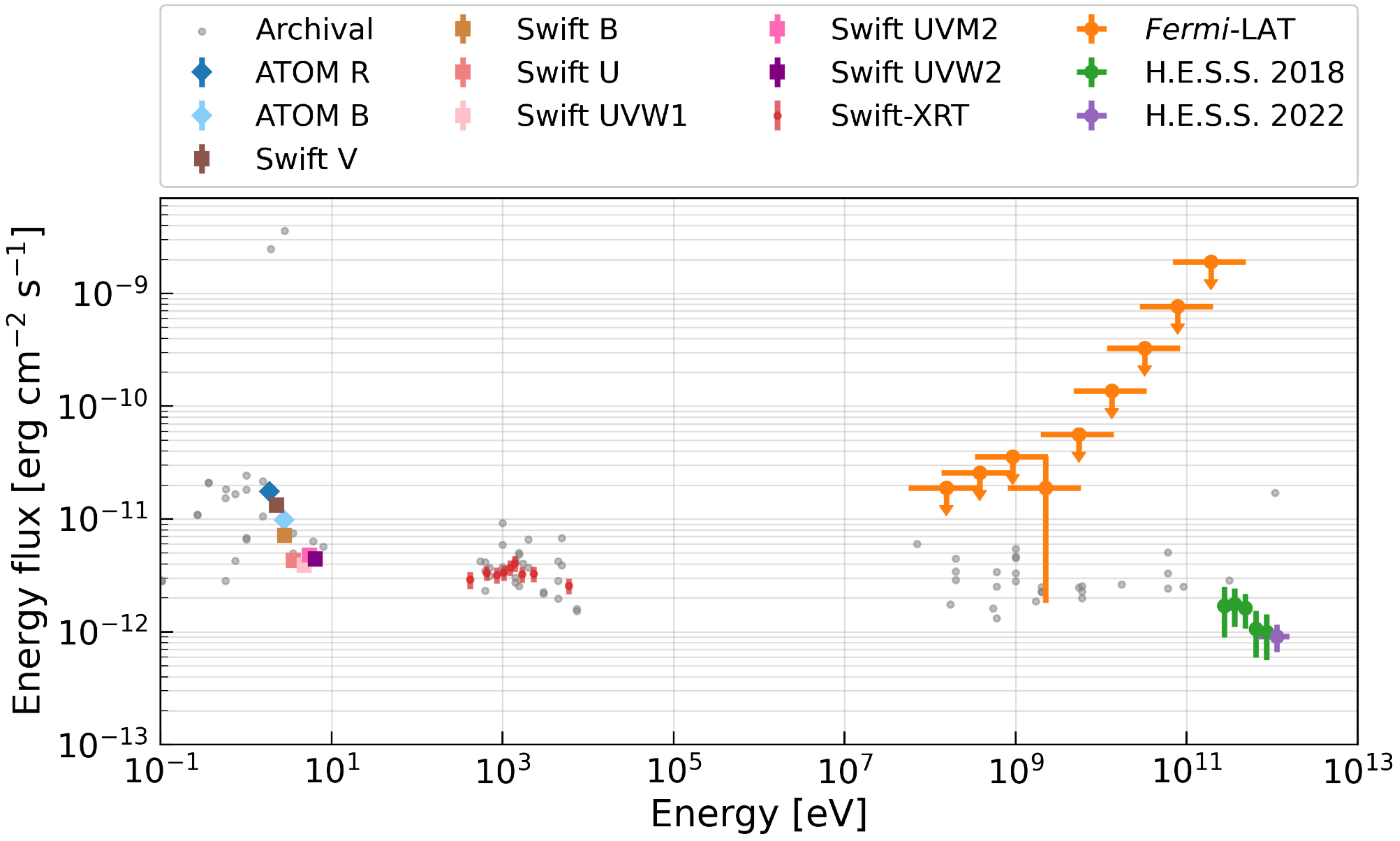
Searches over entire **R**egion **o**f **I**nterest
(neutrino error) without prior source candidates



Searches focused on source(s)
if candidates (e.g. GFU alerts)

GFU PKS 0625-35

Flare of 3 neutrinos with E_{max} = 302 TeV for 3 days (3.56σ pre-trial)

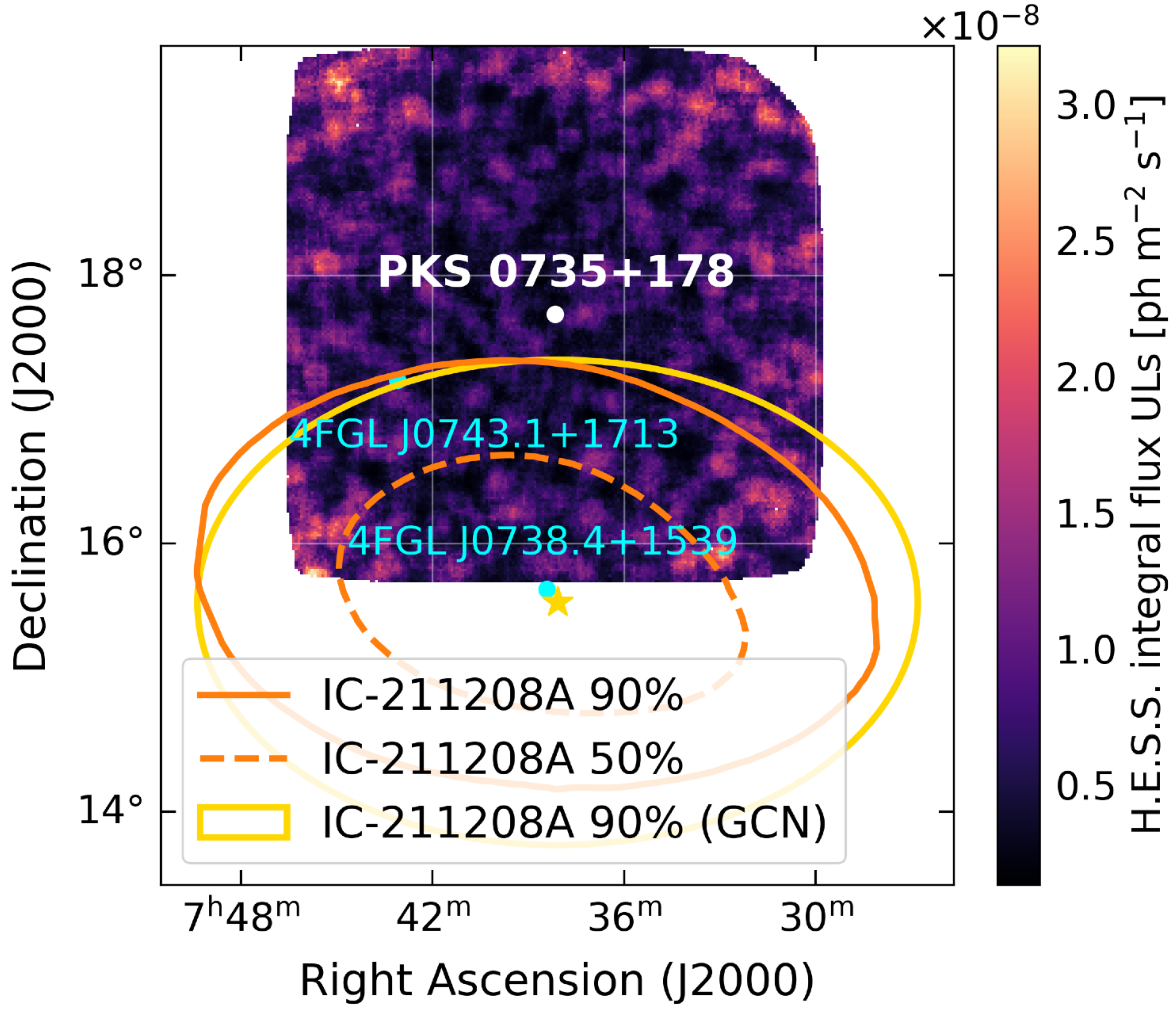


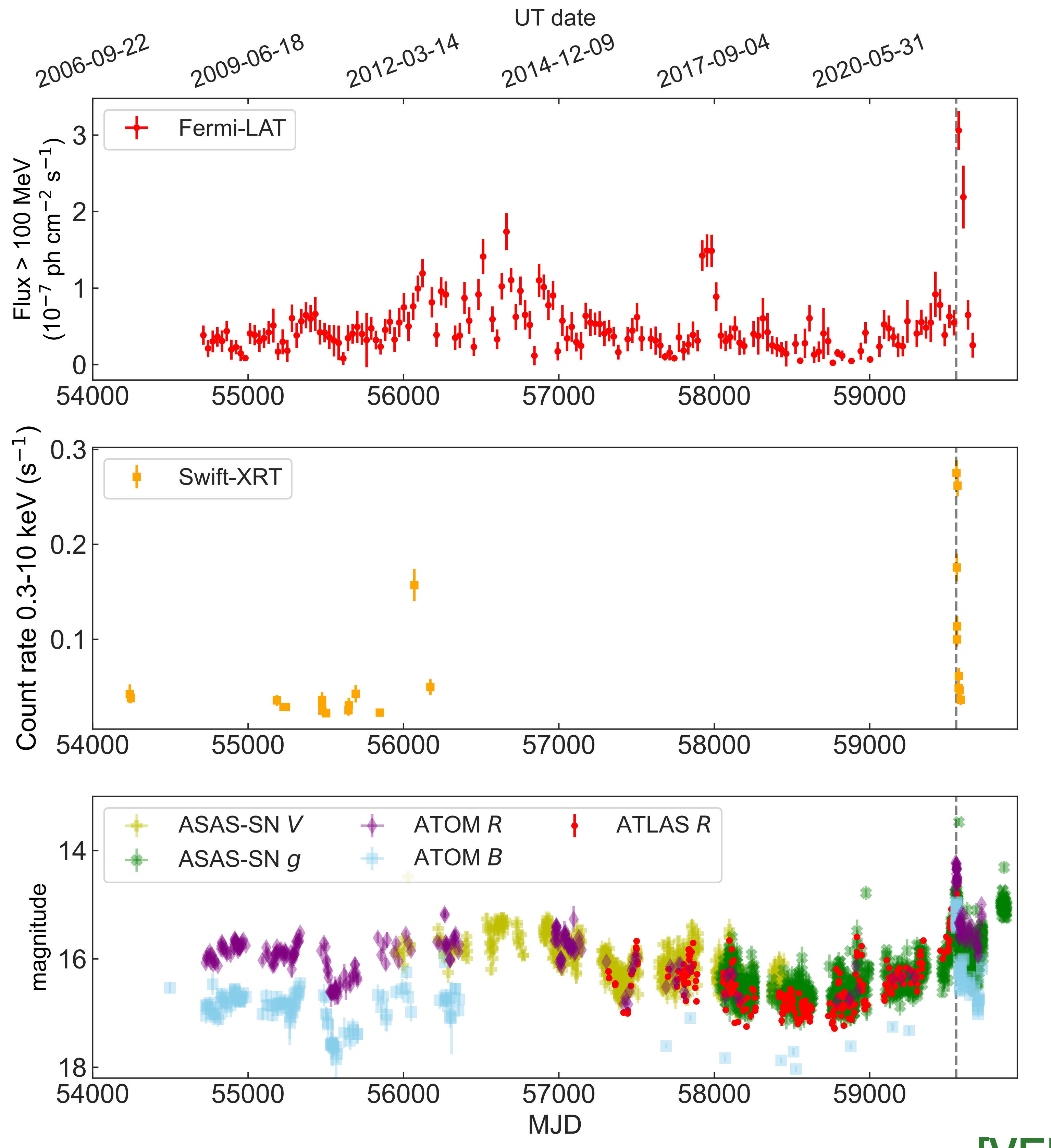
H.E.S.S. re-observed the source for ~3h ⇒ detection at **3.5 σ** in [0.35,100] TeV

No significant change in the non-thermal emission of the source during the ToO

IC-211208A

Bronze neutrino event detected on Dec 8, 2021 with P_{astro} = 50.2%



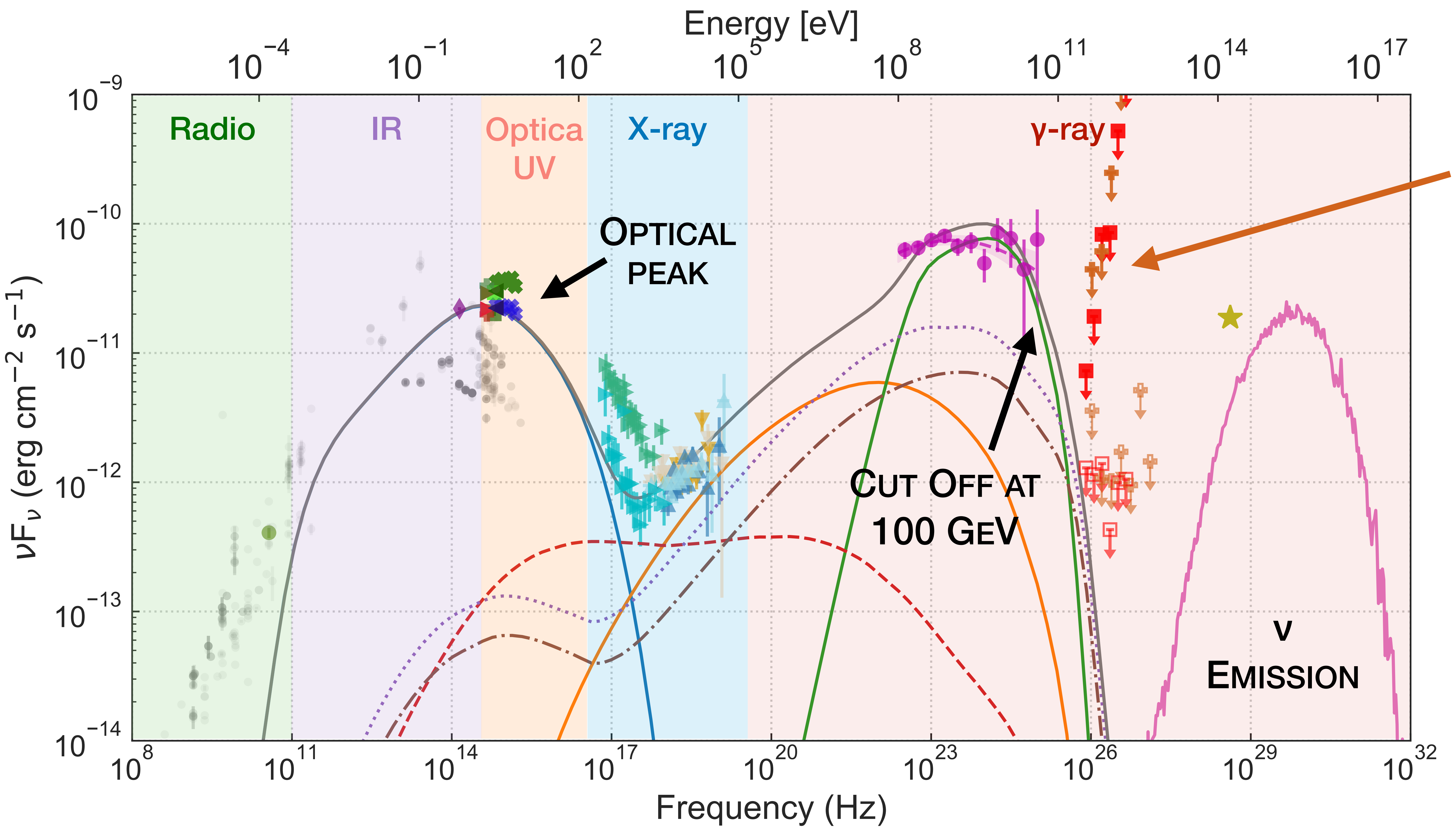


Blazar PKS0735+178 in flaring state in radio, X-ray, optical and γ-ray at ~2.0° from ν best-fit position

[VERITAS, H.E.S.S. & K.Mori, ApJ 954 70, 2023]

IC-211208A

H.E.S.S. observations for ~16h (3.8h of data) from Dec 8 to Dec 15



H.E.S.S. ULS
(EBL CORRECTED)

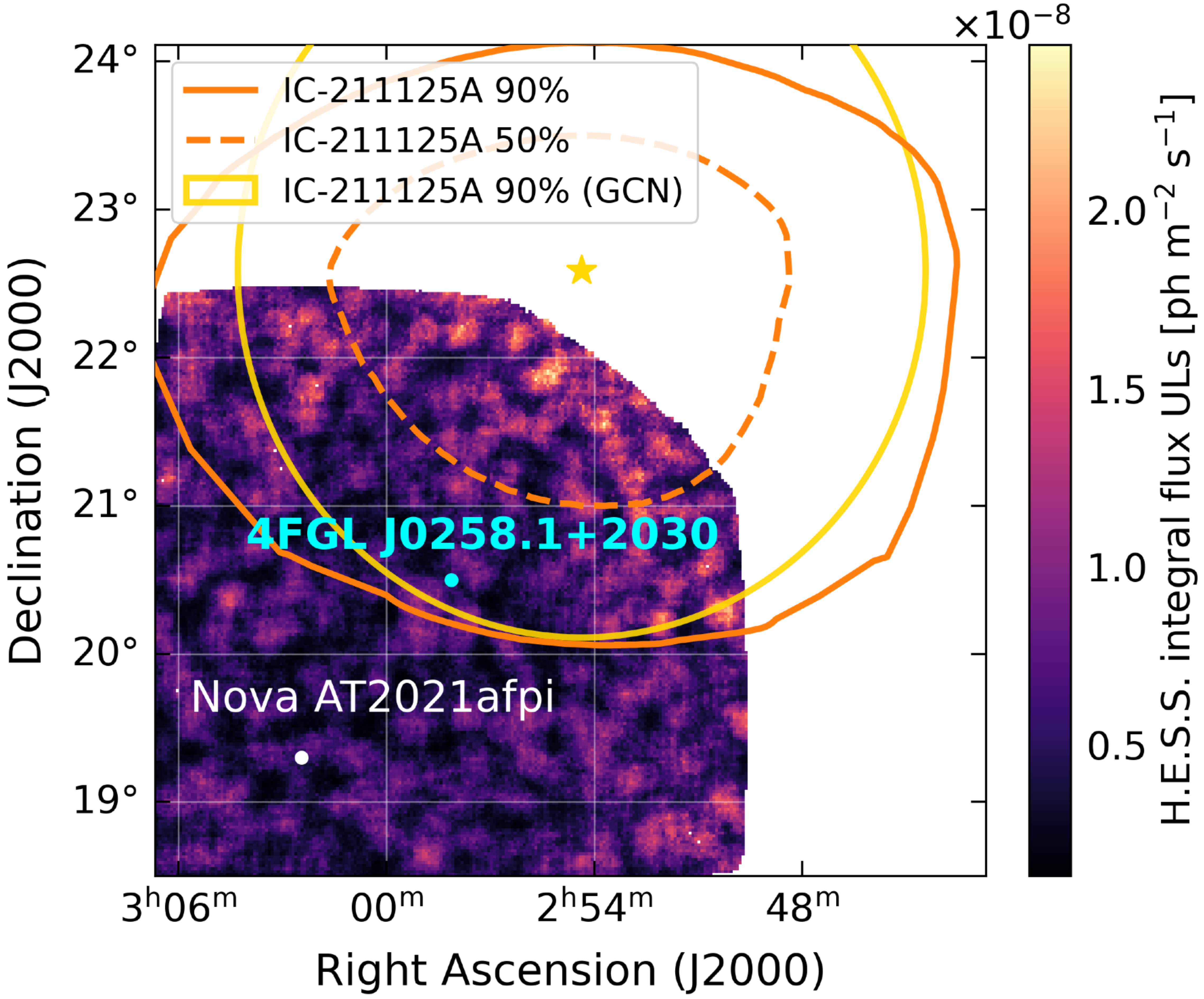
[VERITAS, H.E.S.S. & K.Mori, ApJ 954 70, 2023]

Lepto-hadronic model with BLR photon field marginally consistent with ν event

IC-211125A

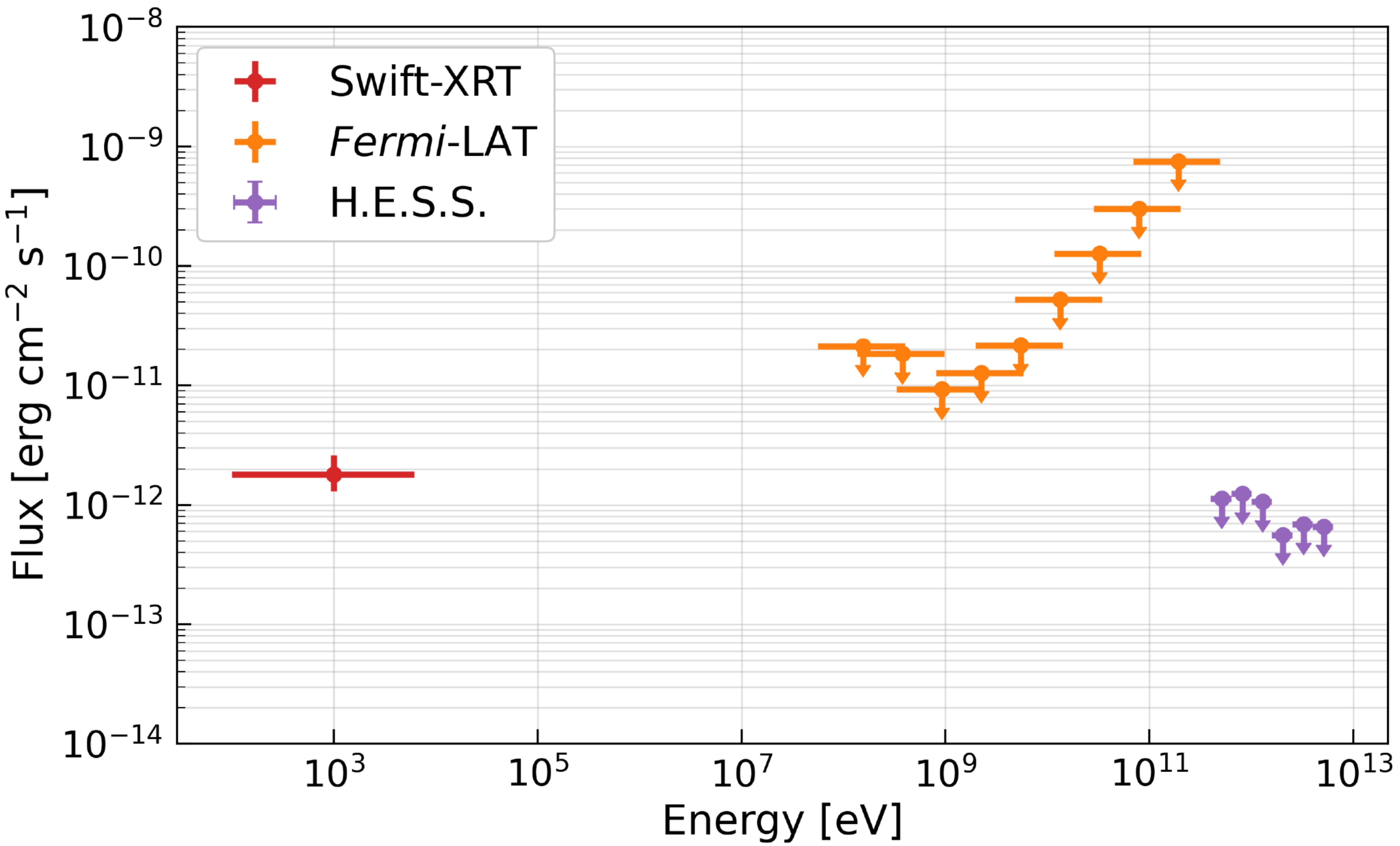
Bronze neutrino event detected on Nov 25, 2021 with P_{astro} = 39%

- Potentially associated to 2 sources:
  - Nova AT2021afpi detected by MASTER
  - AGN *Fermi*-LAT 4FGL J0258.1+2030
- H.E.S.S. observations between both sources for 4 nights
- Total of ~5 hours data
- No significant excess in the FoV on both sources



IC-211125A

Contemporaneous MWL observations on 4FGL J0258.1+2030



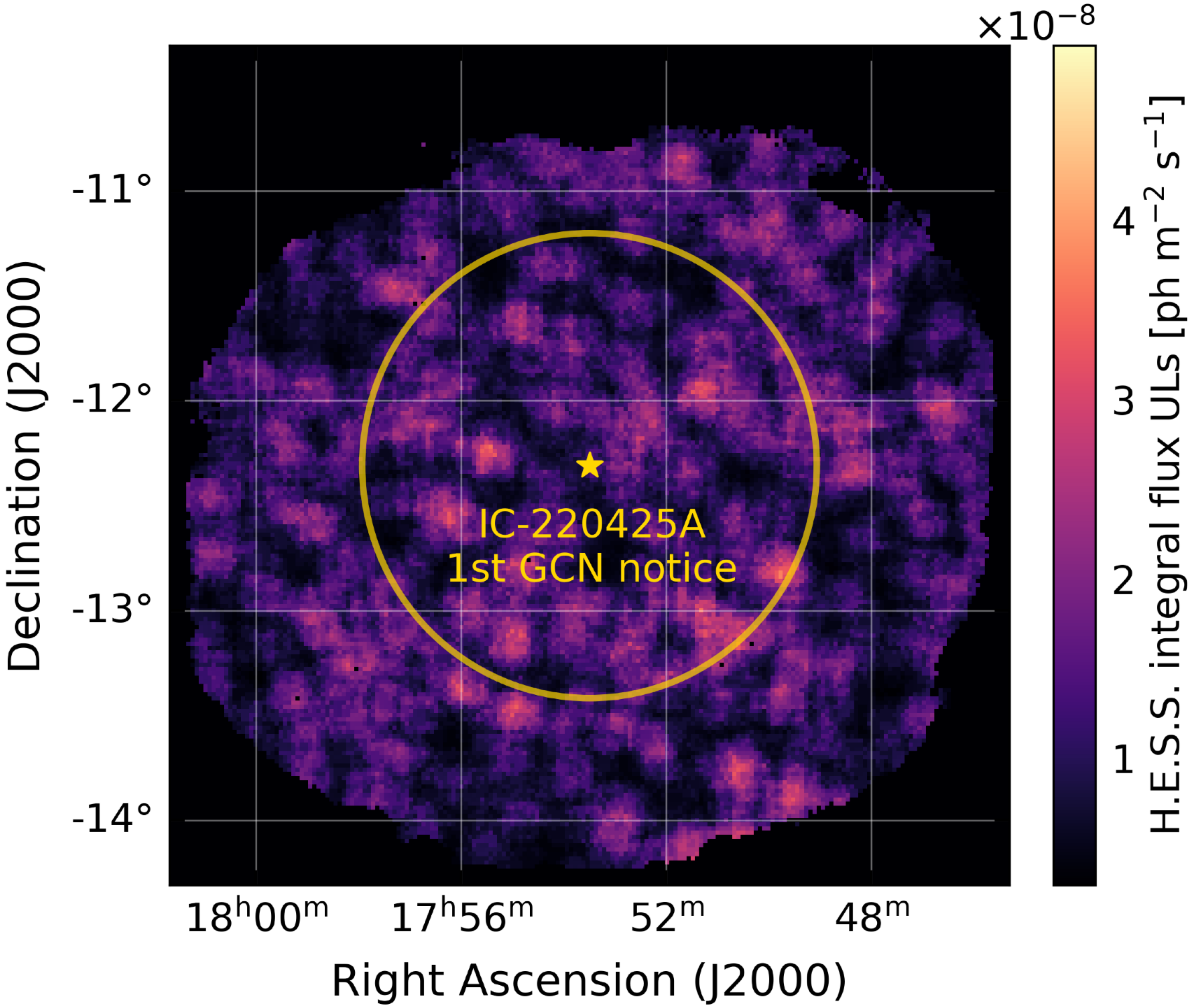
Source detected only in X-ray, ULs in γ-ray (95% C.L. assuming E^{-2} spectrum)

IC-220425A

143

Gold neutrino event detected on Apr 25, 2022 with P_{astro} = 17%

- H.E.S.S. observations triggered automatically in less than 70 seconds



IC-220425A

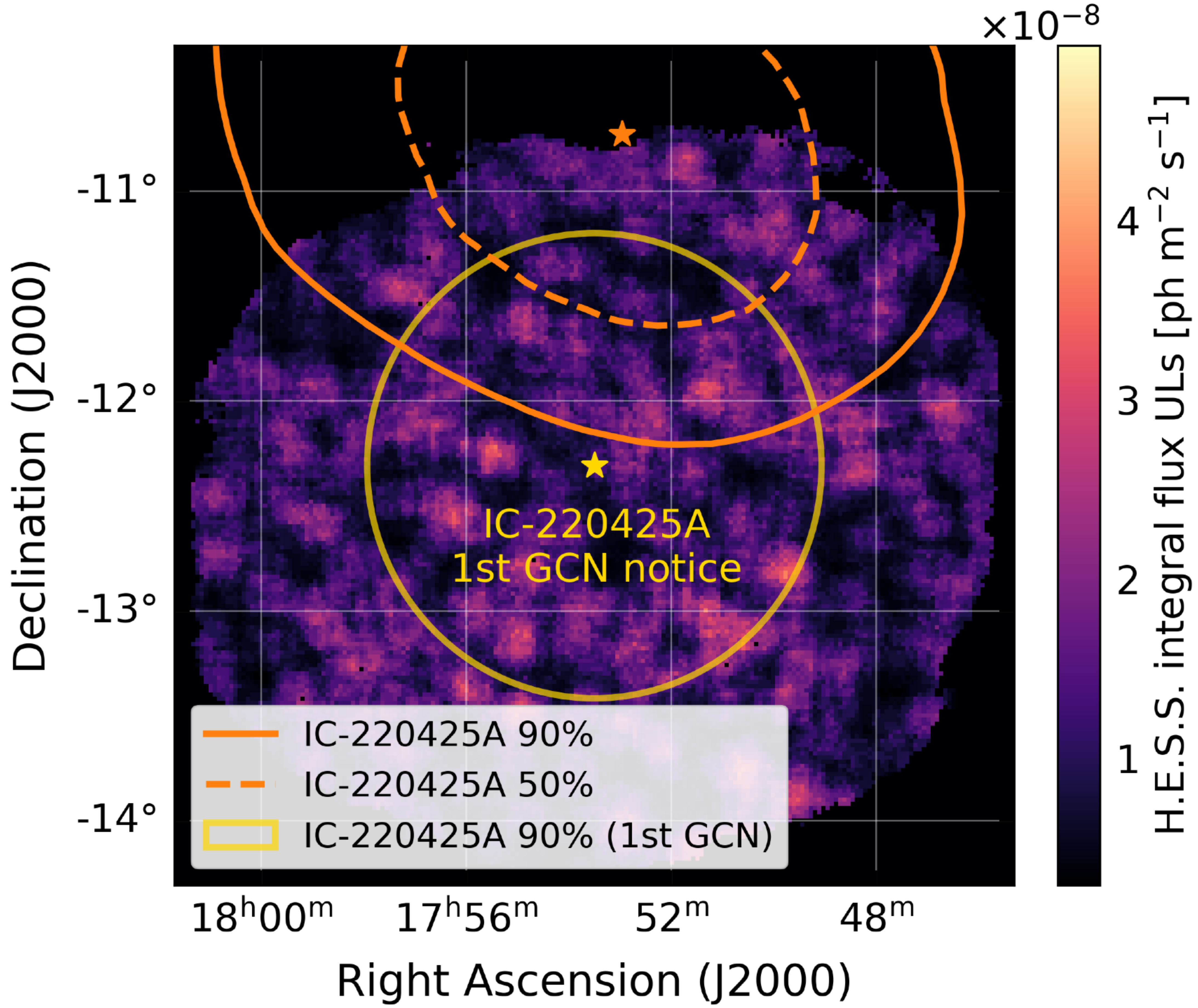
143

Gold neutrino event detected on Apr 25, 2022 with P_{astro} = 17%

- H.E.S.S. observations triggered automatically in less than 70 seconds

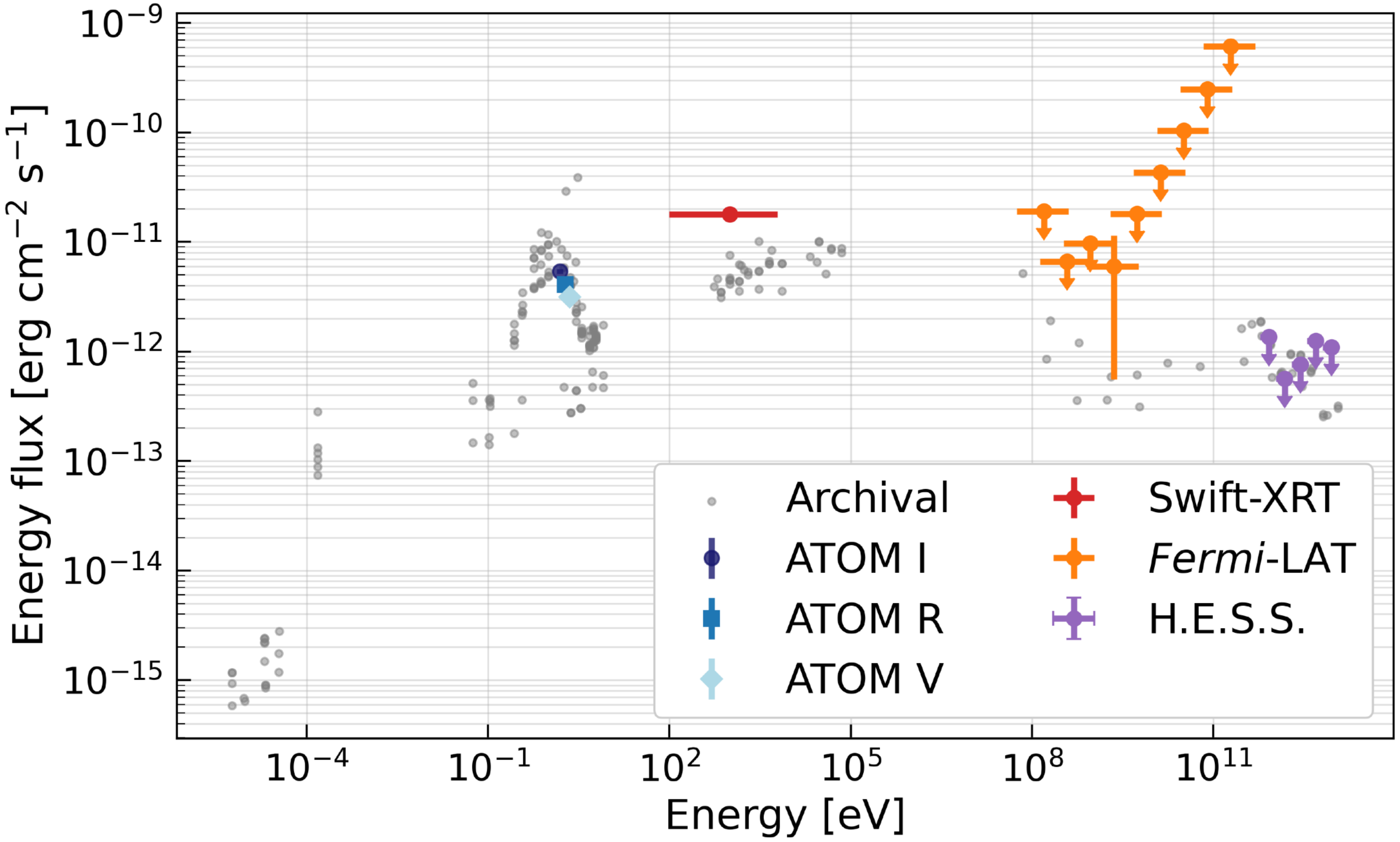
  ➡ Updated neutrino position outside FOV

- ~75 minutes moonlight observations
- No detection, ULs between 0.37 and 100 TeV



GFU 1ES0229+200

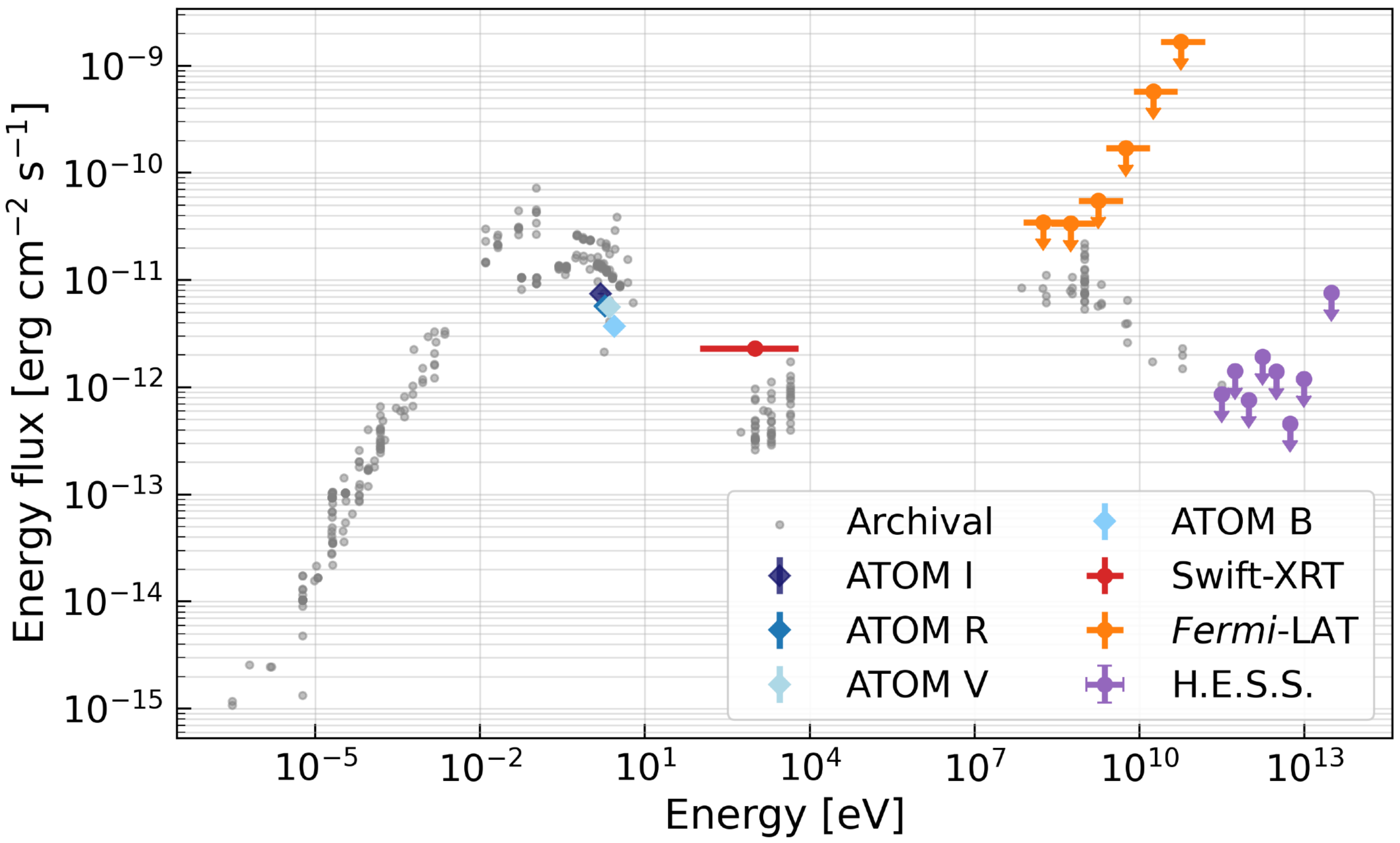
Flare of 4 neutrinos with E_{max} = 1.3 TeV for ~1.2 days (3.09σ pre-trial)



H.E.S.S. observed on Aug 27th, 2022 for 5 nights (~8h) ⇒ no variation in MWL SED

GFU PKS 0829+046

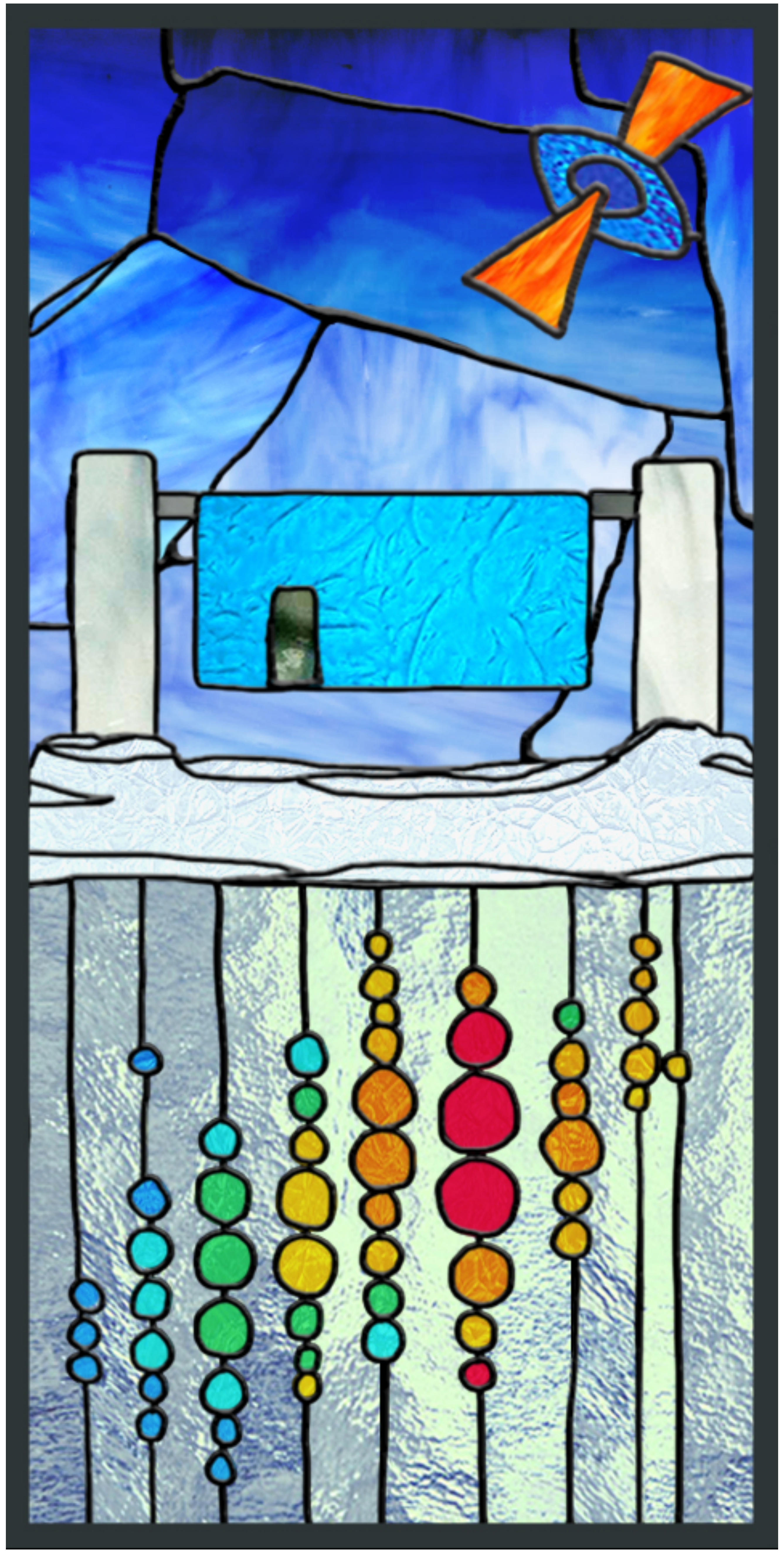
Flare of 8 neutrinos with E_{max} = 2 TeV for ~8 days (3.03σ pre-trial)



H.E.S.S. observed on Dec 30th, 2021 for 2 nights (~4.7h) ⇒ ULs in [0.22, 100] TeV

Summary

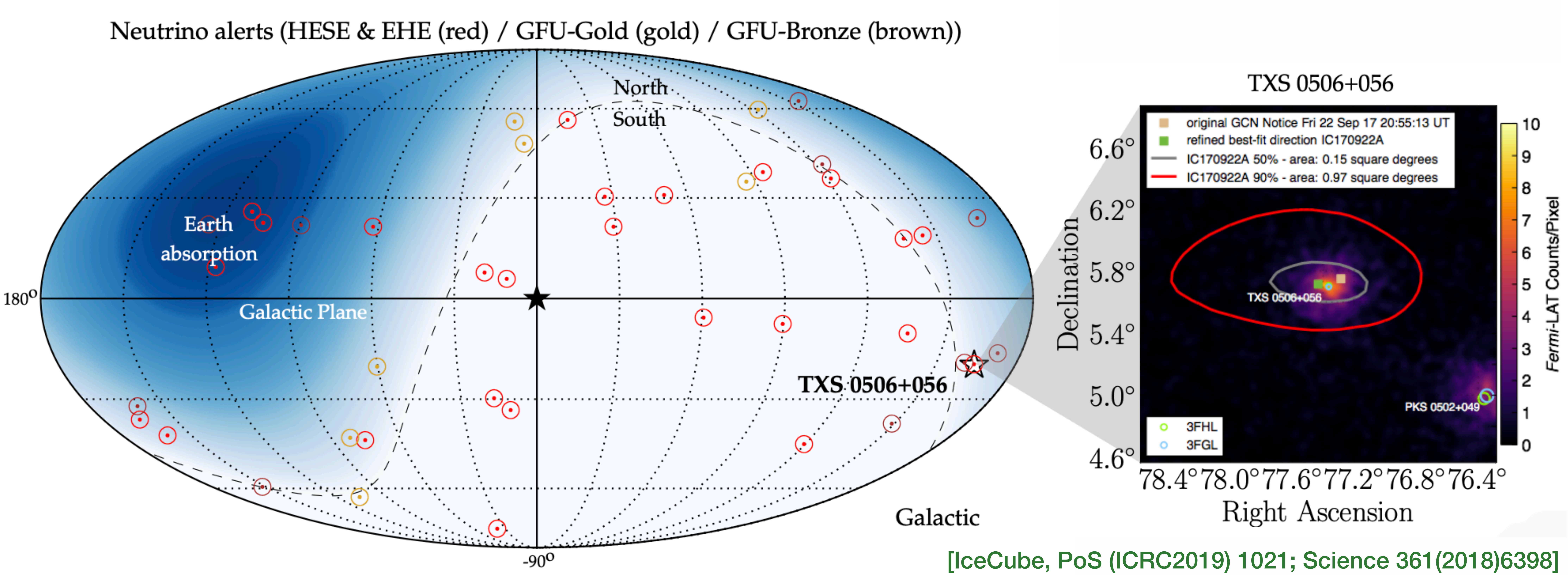
- **IceCube**'s decade-long investigation of a diffuse flux of astrophysical neutrinos > TeV
  - Evidence for neutrinos from flaring blazar TXS 0506+056 (3σ) and nearby Seyfert galaxy NGC 1068 (4.3σ)
  - Realtime searches complementary to clustering methods
- **H.E.S.S.** actively involved in IC neutrino follow-up programs since 2016
  - Detection of blazar PKS 0625-35, but flux at previously observed levels
  - Observations of flaring blazar PKS 0735+178 in spatial and temporal coincidence with IC-211208A



Backup

Neutrino emission from the direction of TXS 0506+056

IC-170922A (290 TeV) observed in coincidence with flaring **gamma-ray blazar**

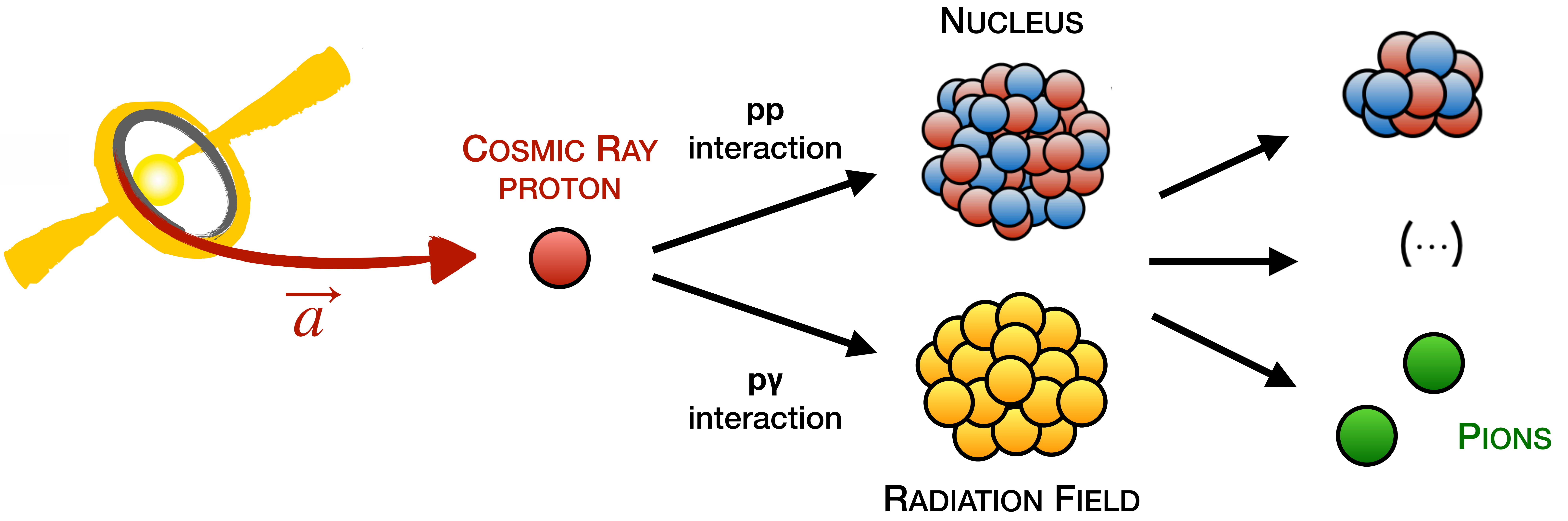


[IceCube, PoS (ICRC2019) 1021; Science 361(2018)6398]

Chance correlation can be rejected at the 3σ-level

Why astronomy with neutrinos?

Neutrinos are smocking gun signature of hadronic processes



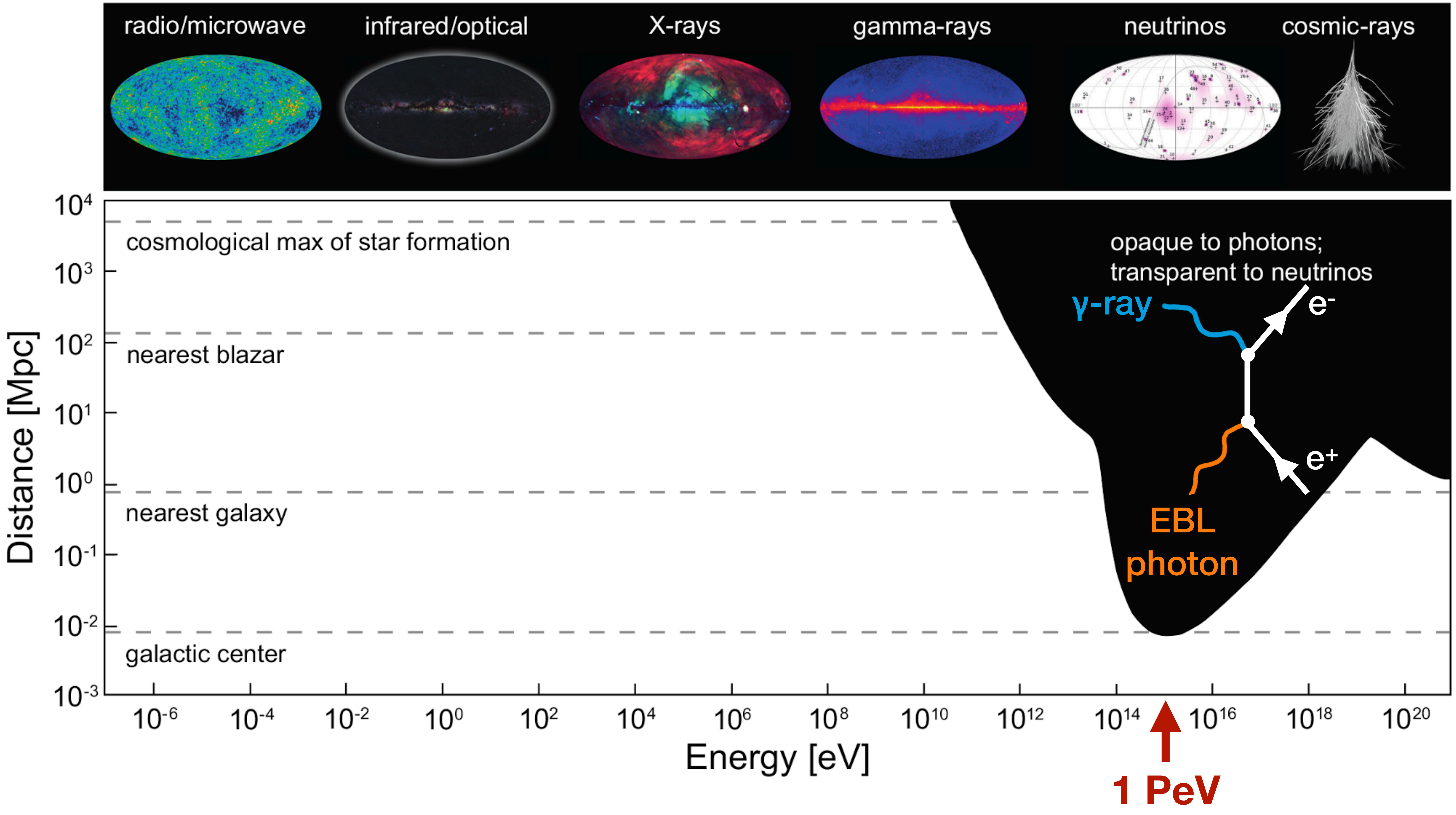
Secondary **neutrinos** and **γ-rays** from pion decays:

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

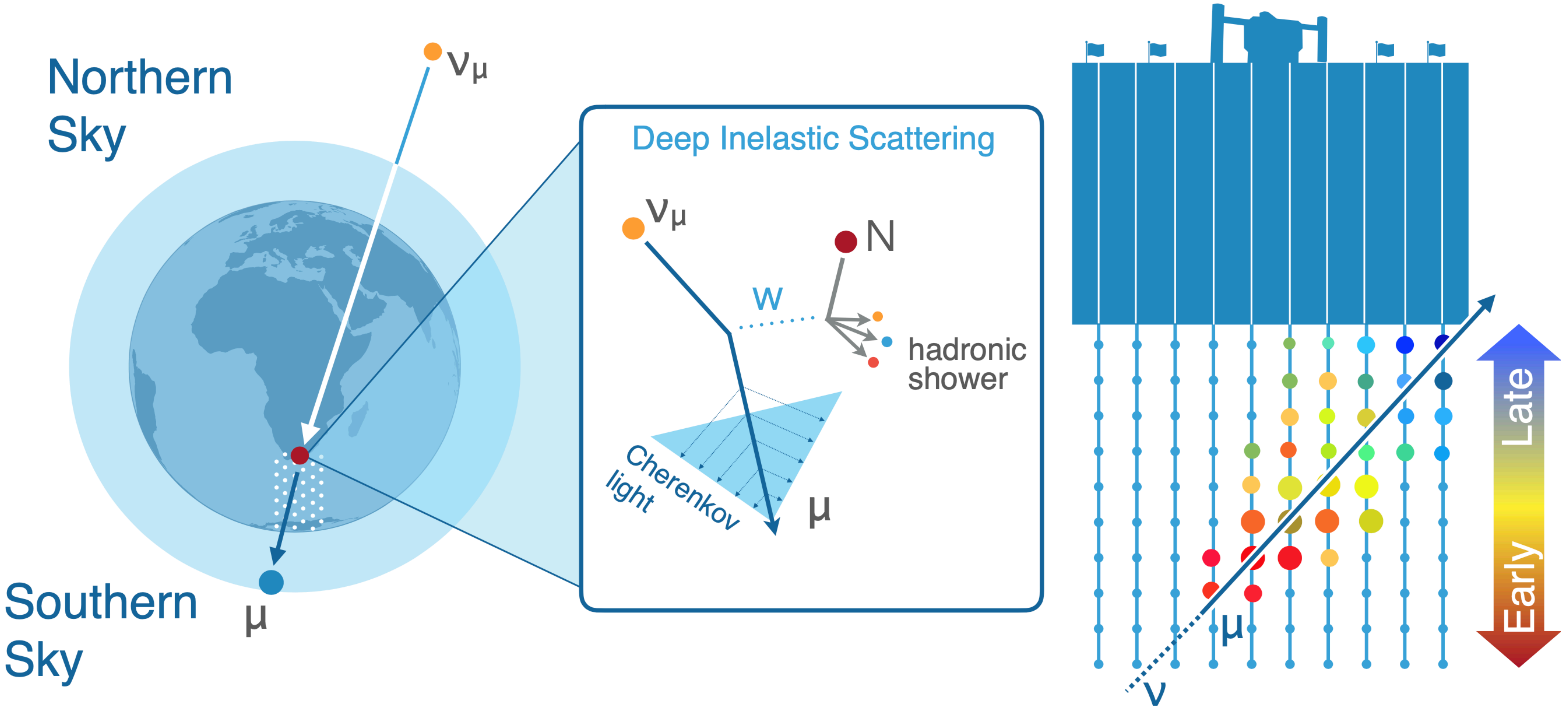
$$\Phi_{\gamma\text{-ray}} \approx \frac{1}{3}\Phi_\nu$$

Why astronomy with neutrinos?

To observe the extragalactic universe beyond PeV energies

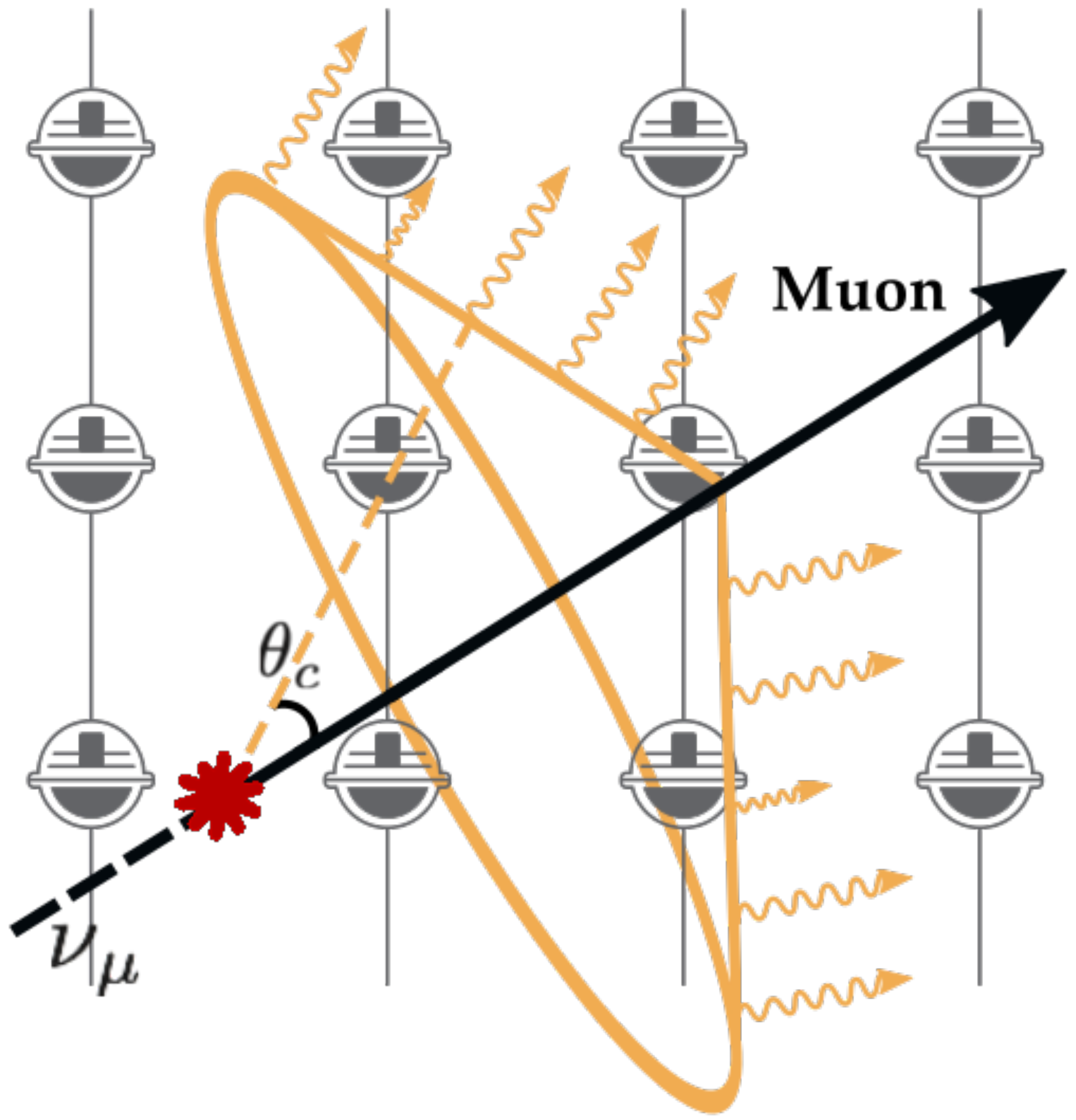


Neutrino detection principle



Neutrino event signature

Tracks

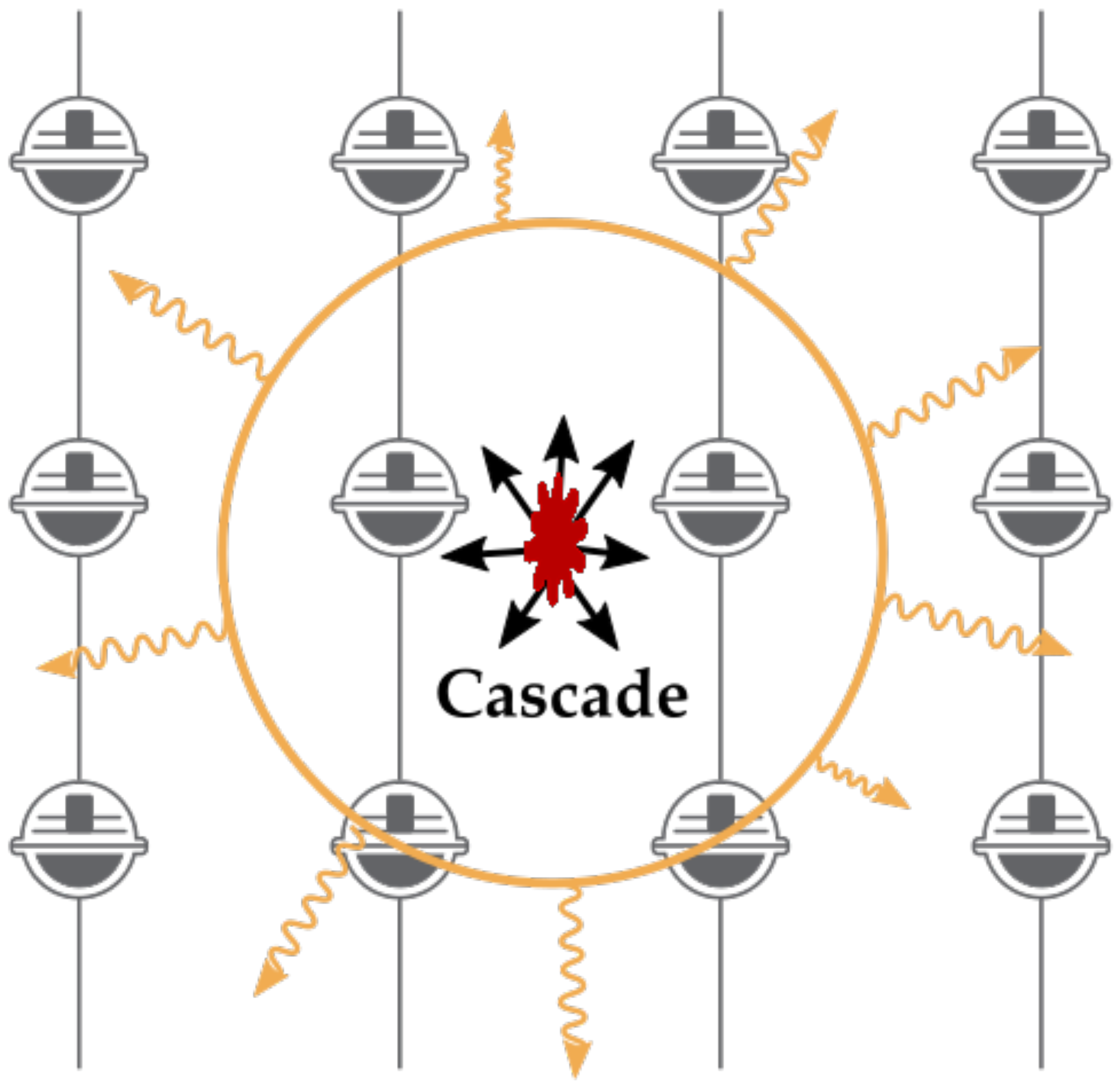


$$\nu_\mu + N \rightarrow \mu + X$$

Good angular resolution 0.1-1 deg

Neutrino astronomy

Cascades



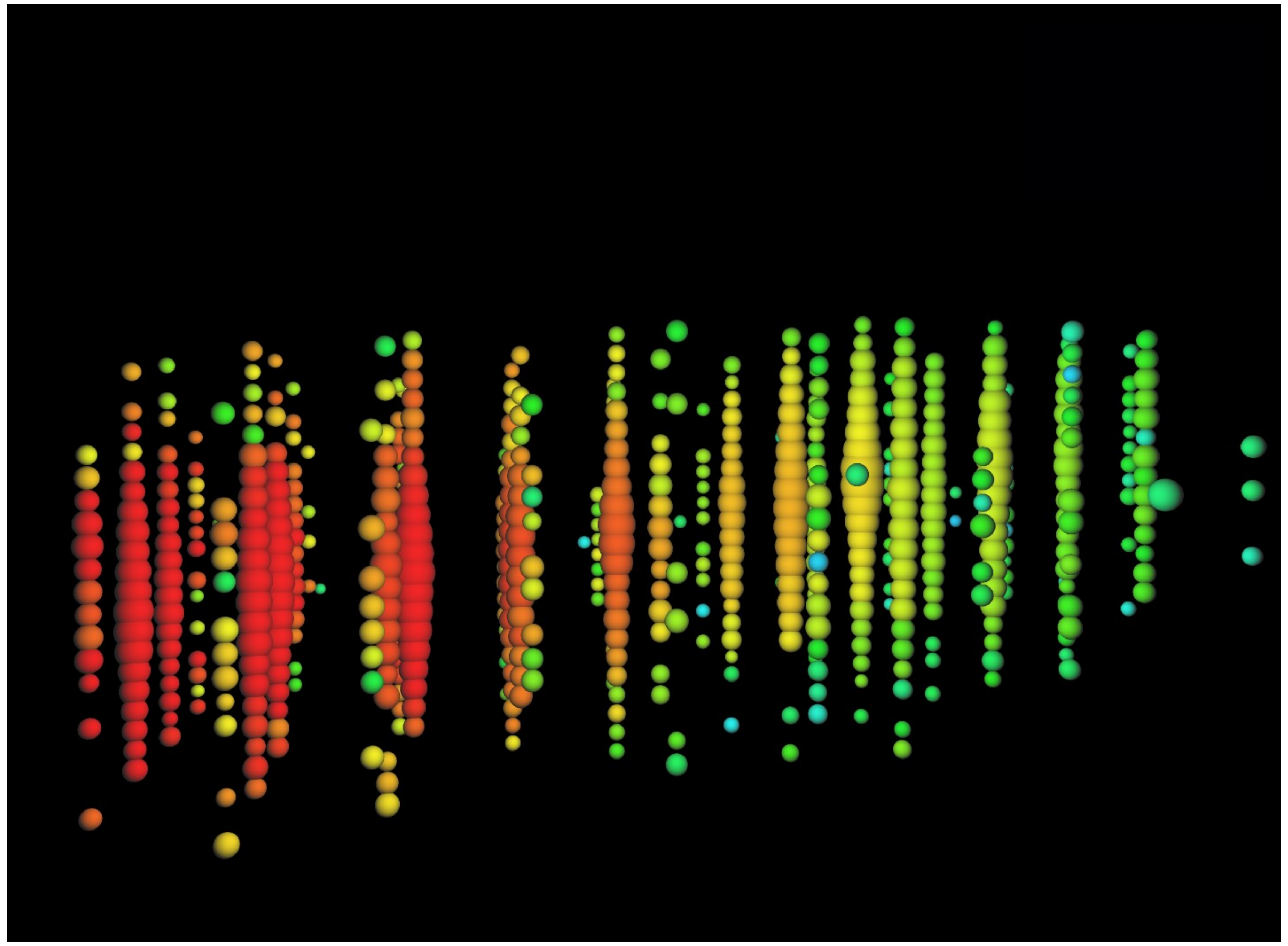
$$\nu_X + N \rightarrow \nu_X + X, \quad \nu_e + N \rightarrow e + X$$

Fully active calorimeter

Good energy resolution ~15%

Neutrino event signature

Tracks



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Neutrino astronomy

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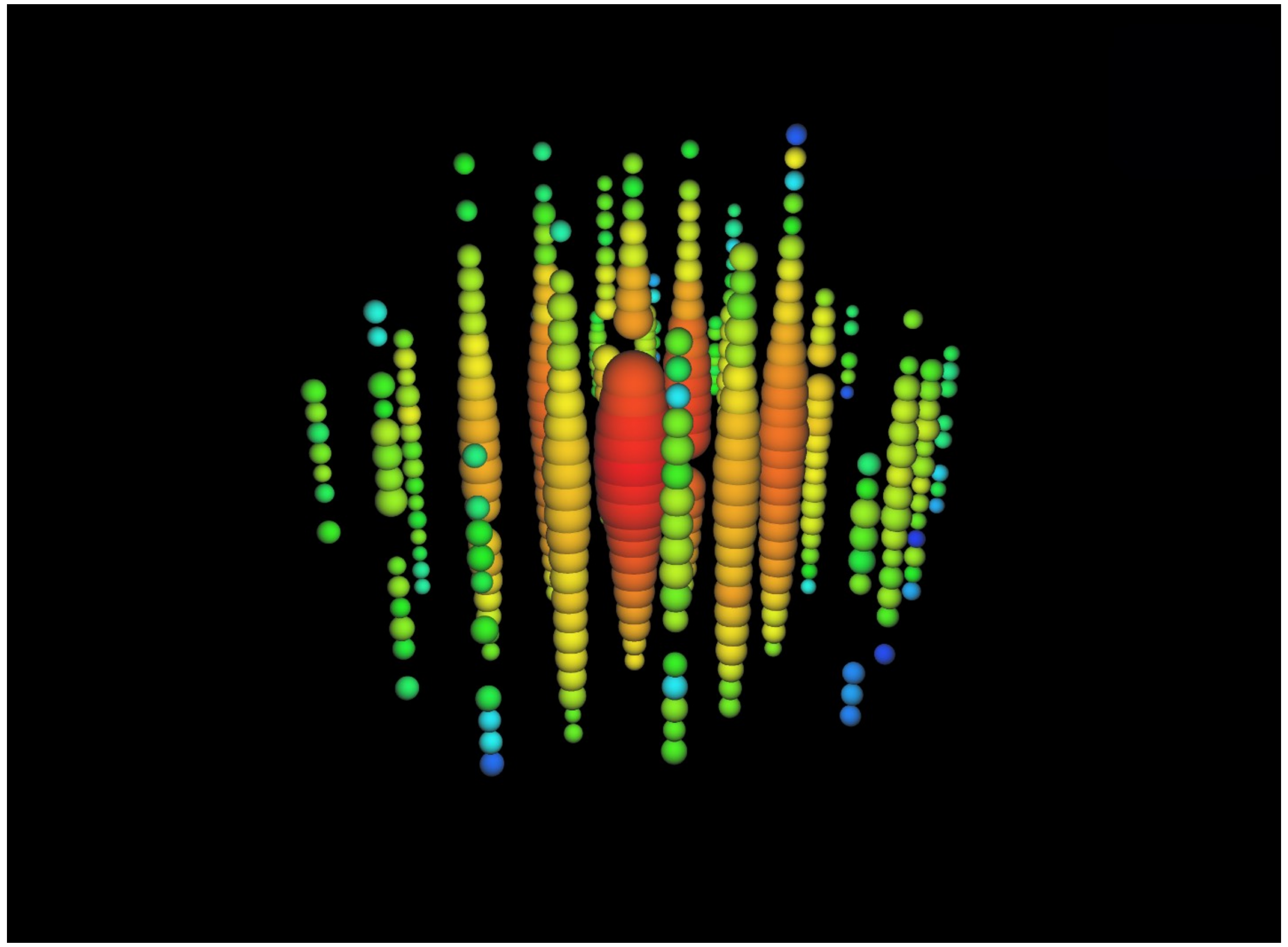

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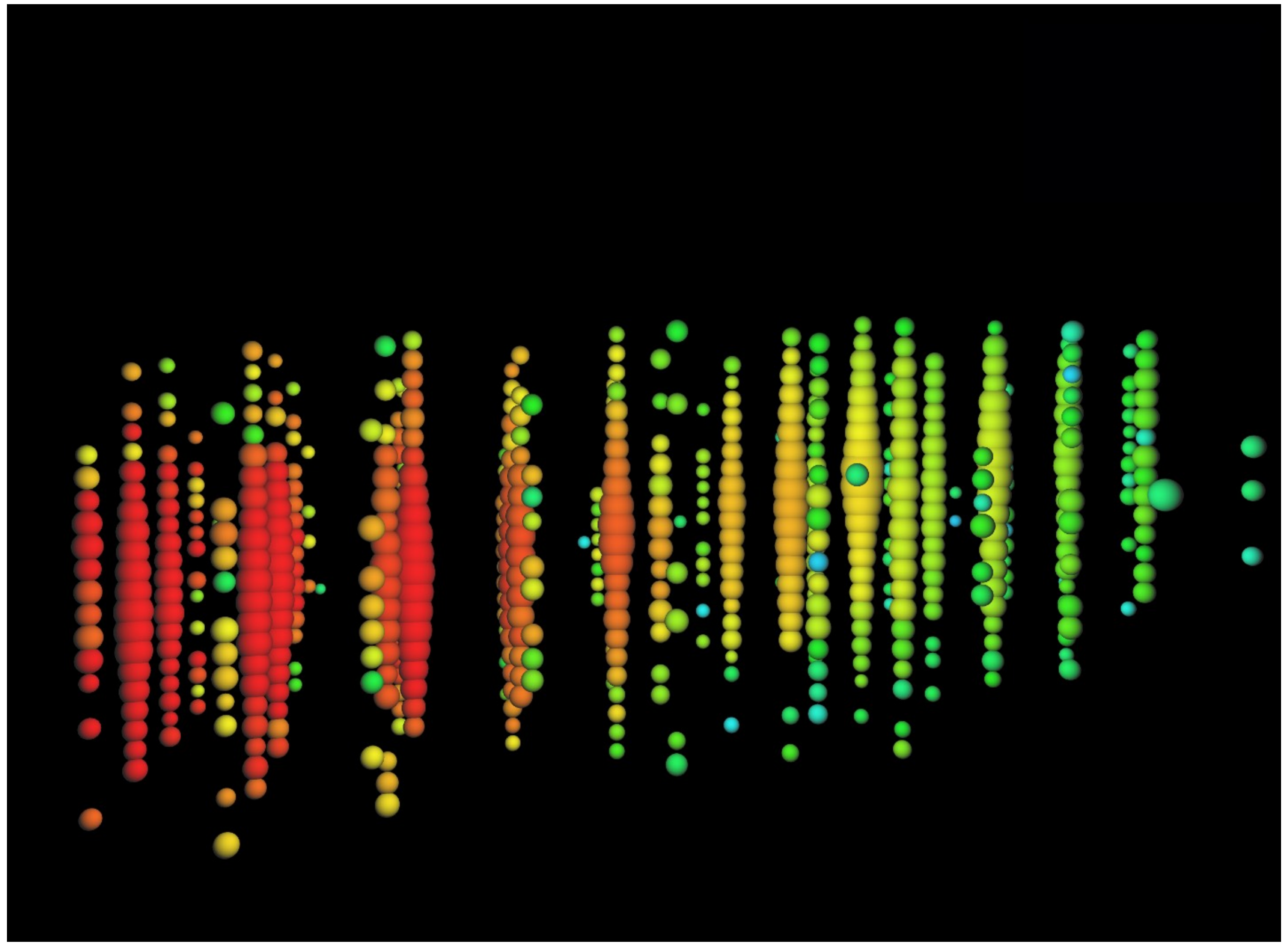

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Neutrino astronomy

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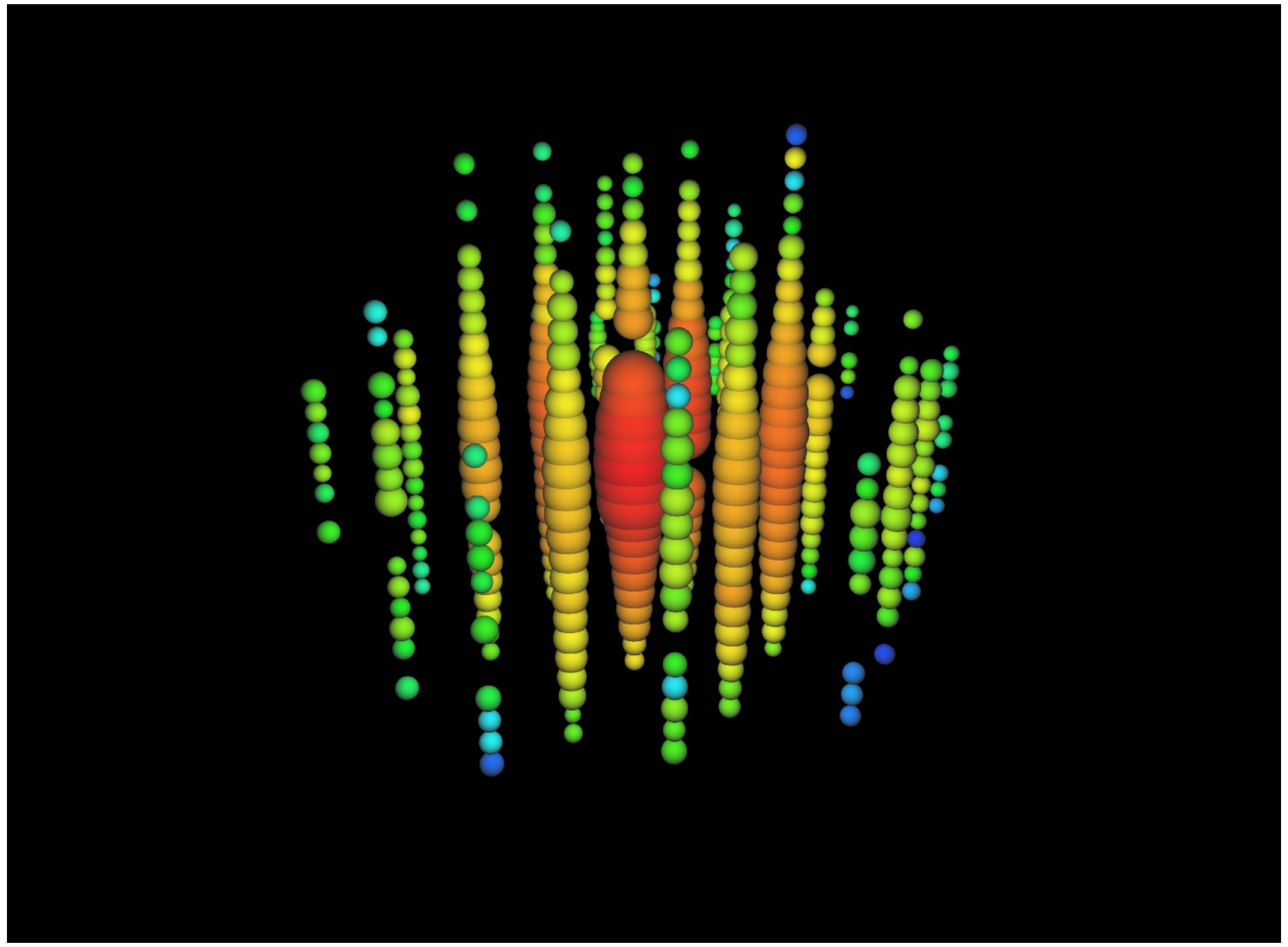
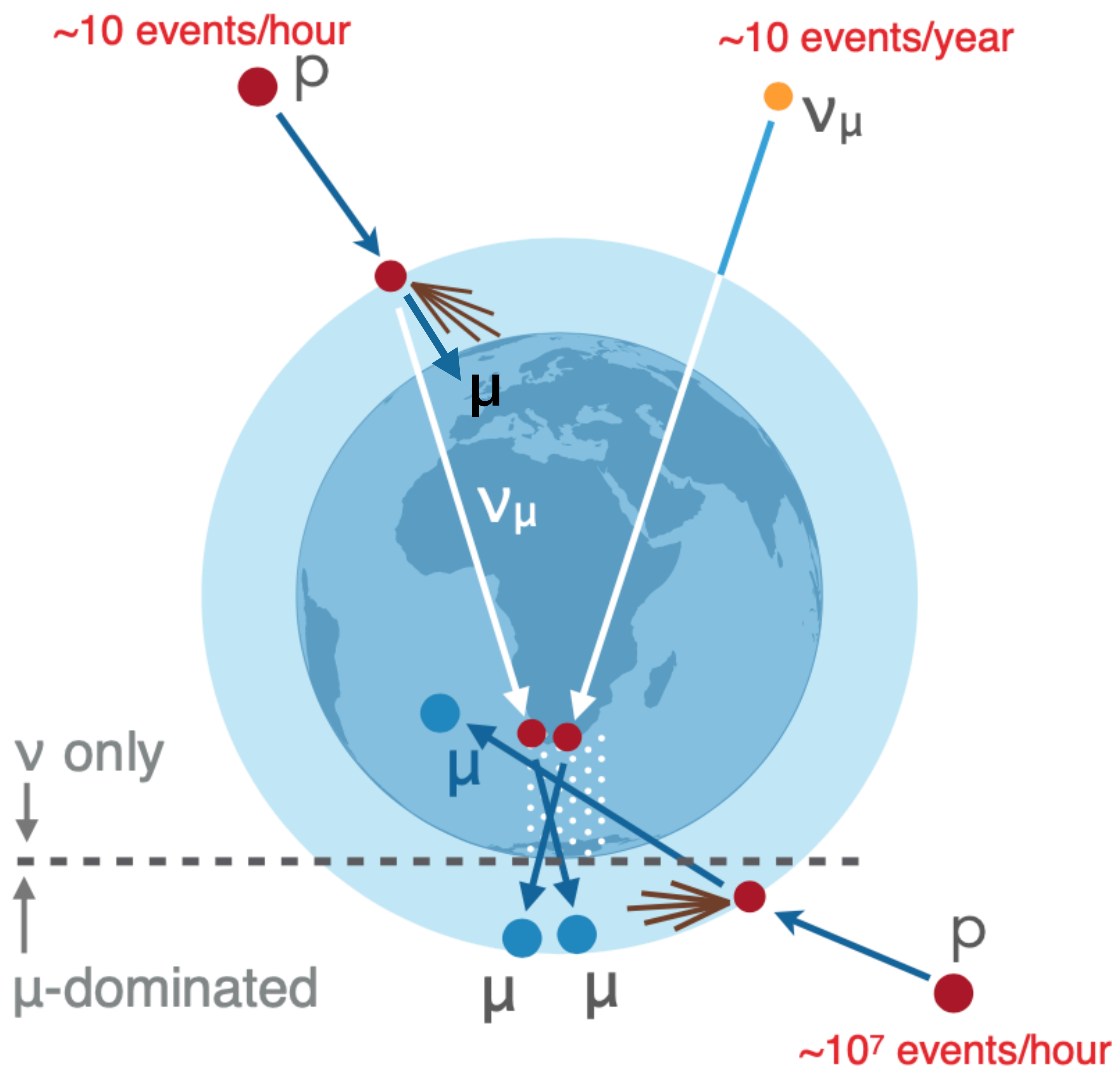


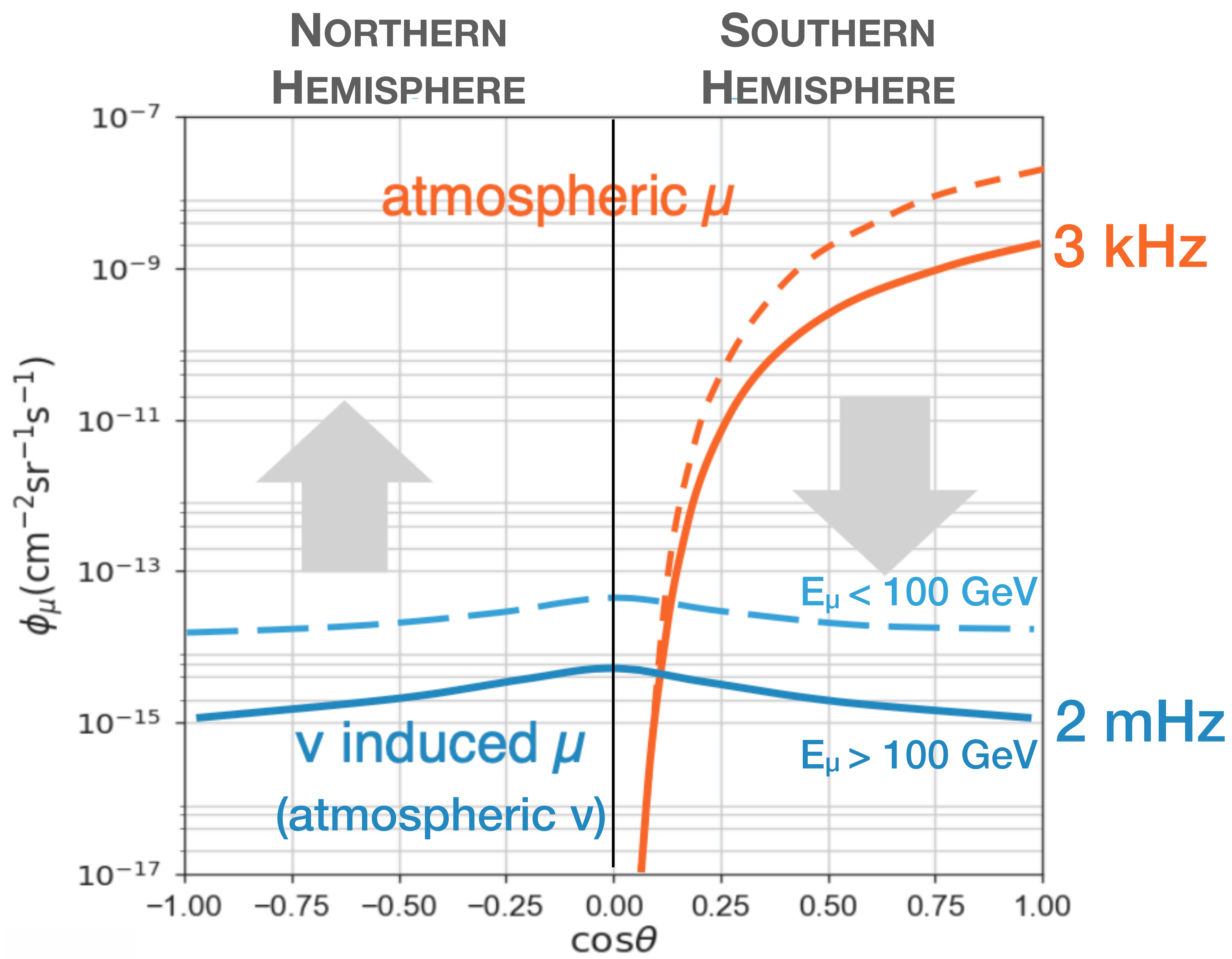
$$\nu_X + N \rightarrow \nu_X + X, \quad \nu_e + N \rightarrow e + X$$

Fully active calorimeter

Good energy resolution ~15%

The atmospheric background

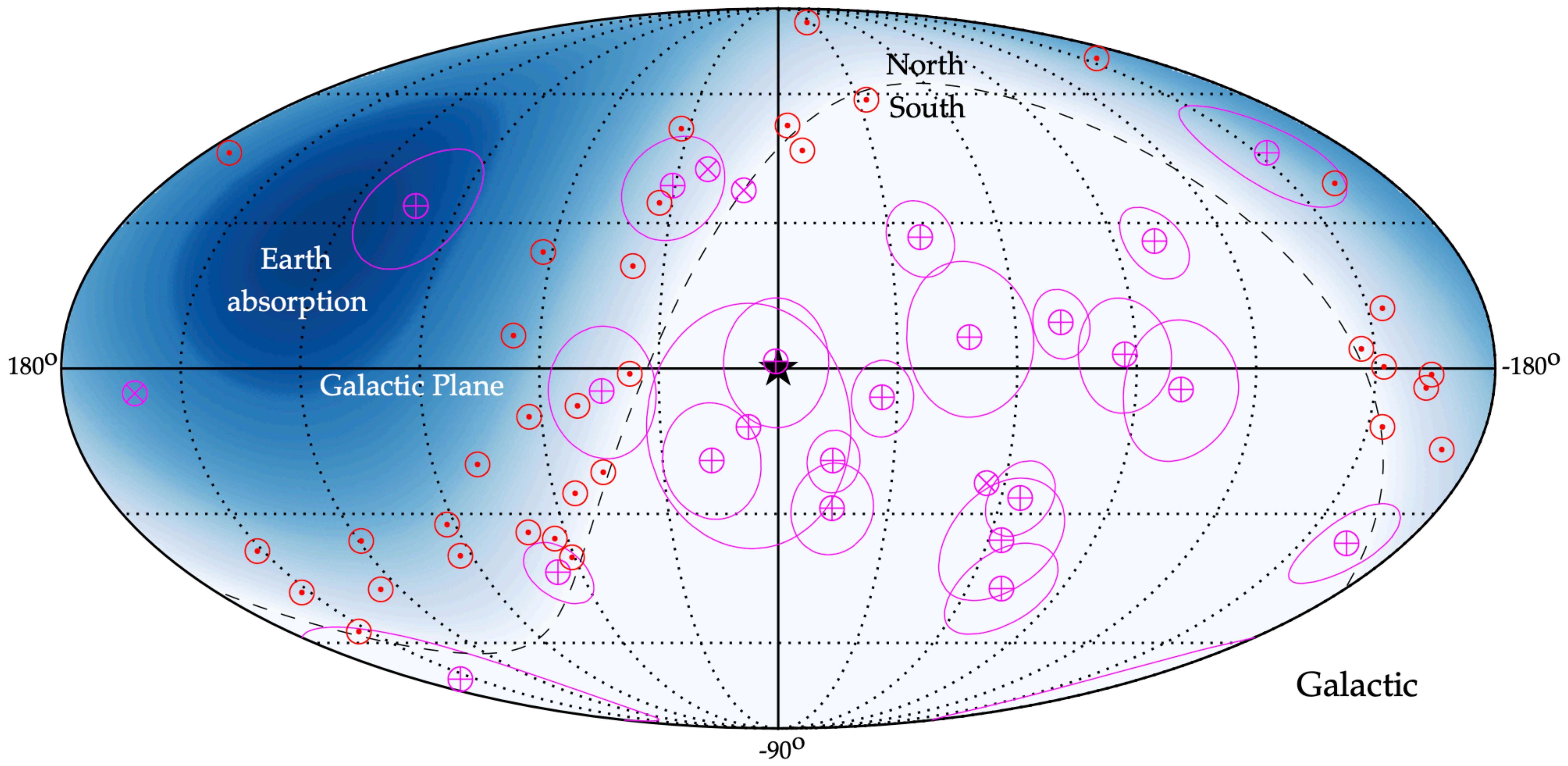




Status of neutrino astronomy

Extragalactic origin favoured by quasi-isotropic distribution

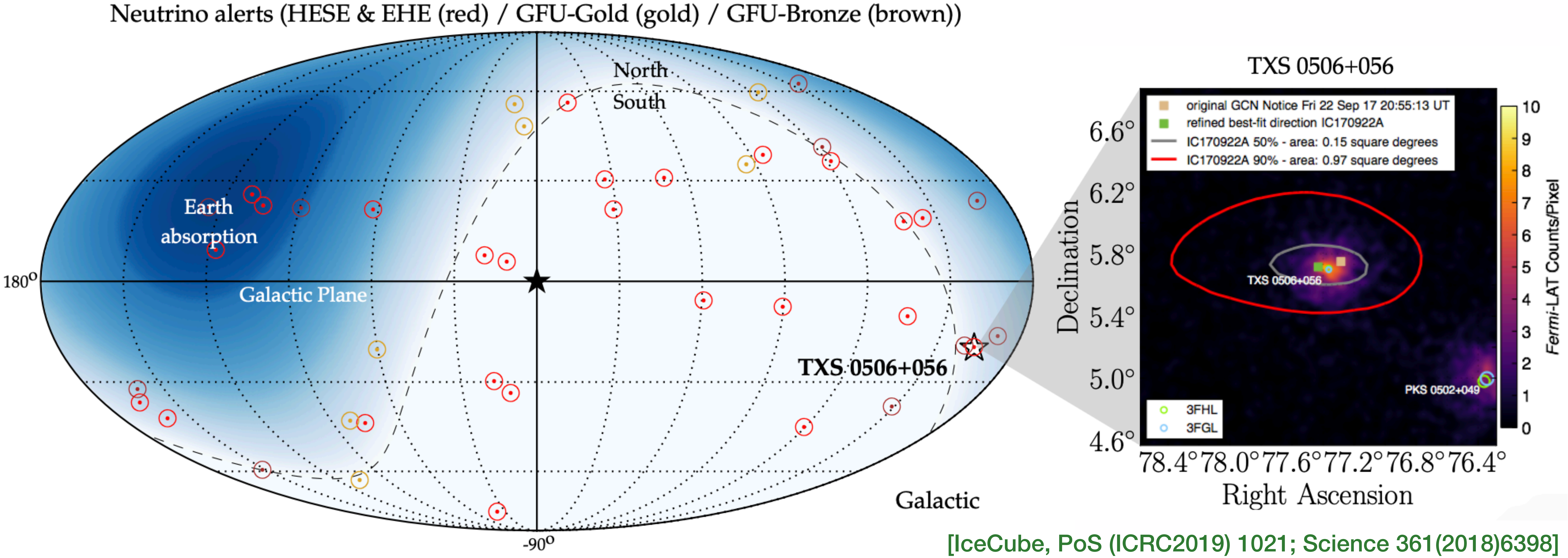
Most energetic neutrino events HESE 6yr (magenta) & $\nu_\mu + \bar{\nu}_\mu$ 8yr (red)



No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates (e.g. AGN)**

Neutrino emission from the direction of TXS 0506+056

IC-170922A (290 TeV) observed in coincidence with flaring **gamma-ray blazar**

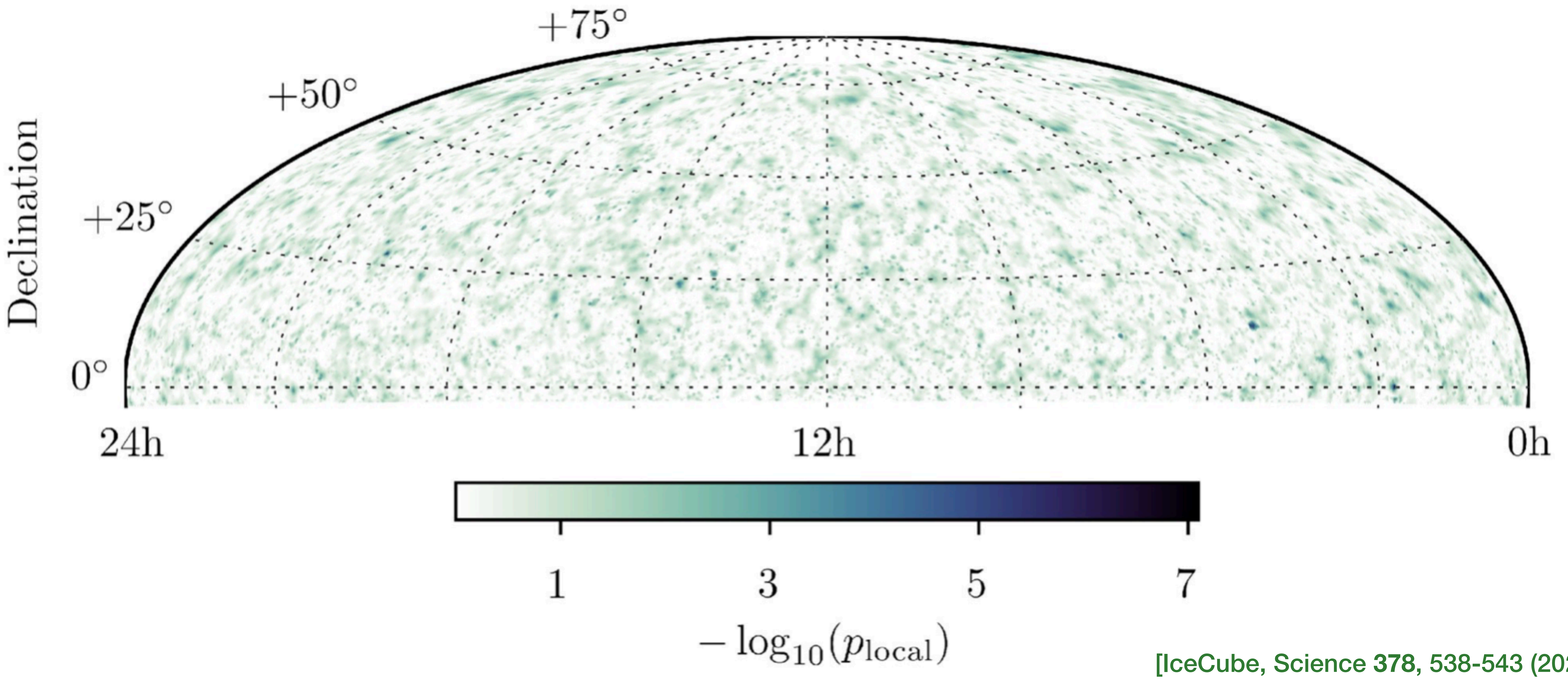


[IceCube, PoS (ICRC2019) 1021; Science 361(2018)6398]

Chance correlation can be rejected at the 3σ-level

IceCube 10 years (2011-2020) neutrino map

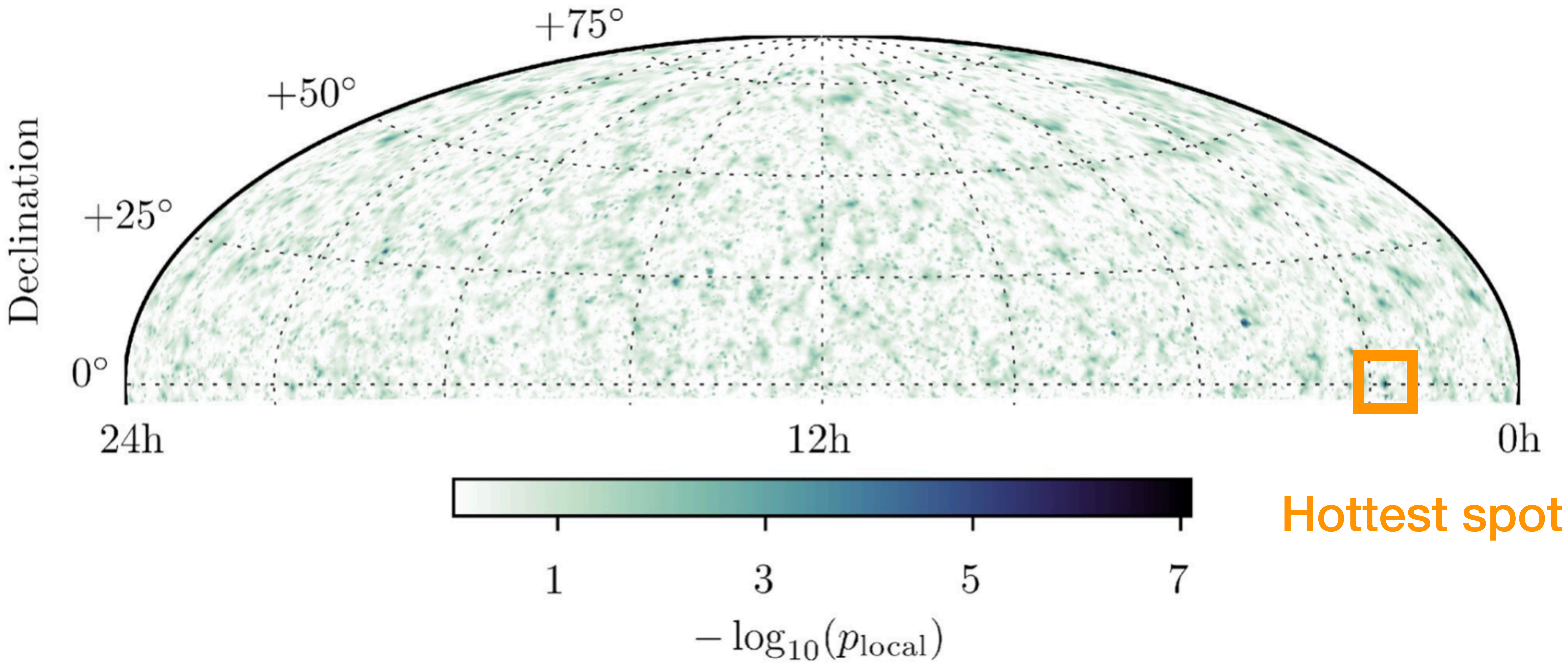
Northern-sky point source cluster search (6.7 x 10^5 events)



[IceCube, Science **378**, 538-543 (2022)]

Hottest spot in the Northern-sky

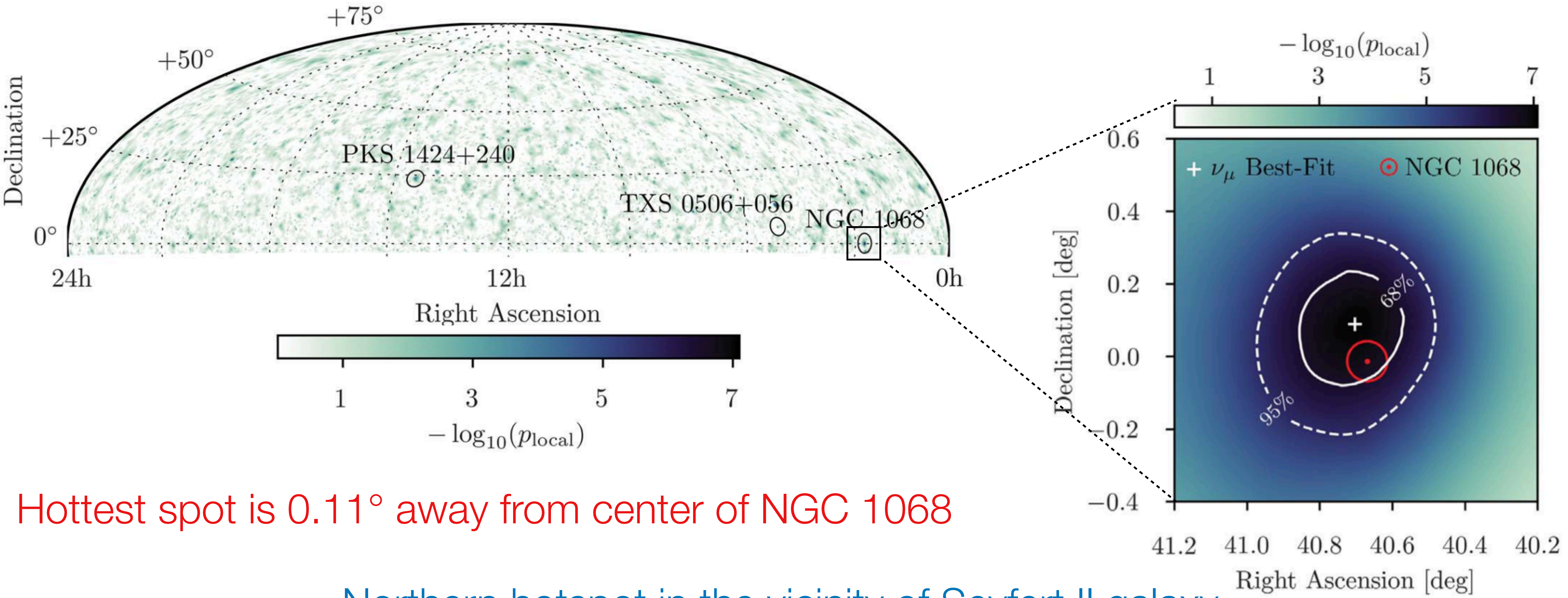
Pre-trial p-value of 5×10^{-8} (5.3σ), post-trial significance of 2σ



"Look elsewhere" effect: have our results arisen by chance?

Excess from NGC 1068 (M77)

By looking only at 110 selected sources



Hottest spot is 0.11° away from center of NGC 1068

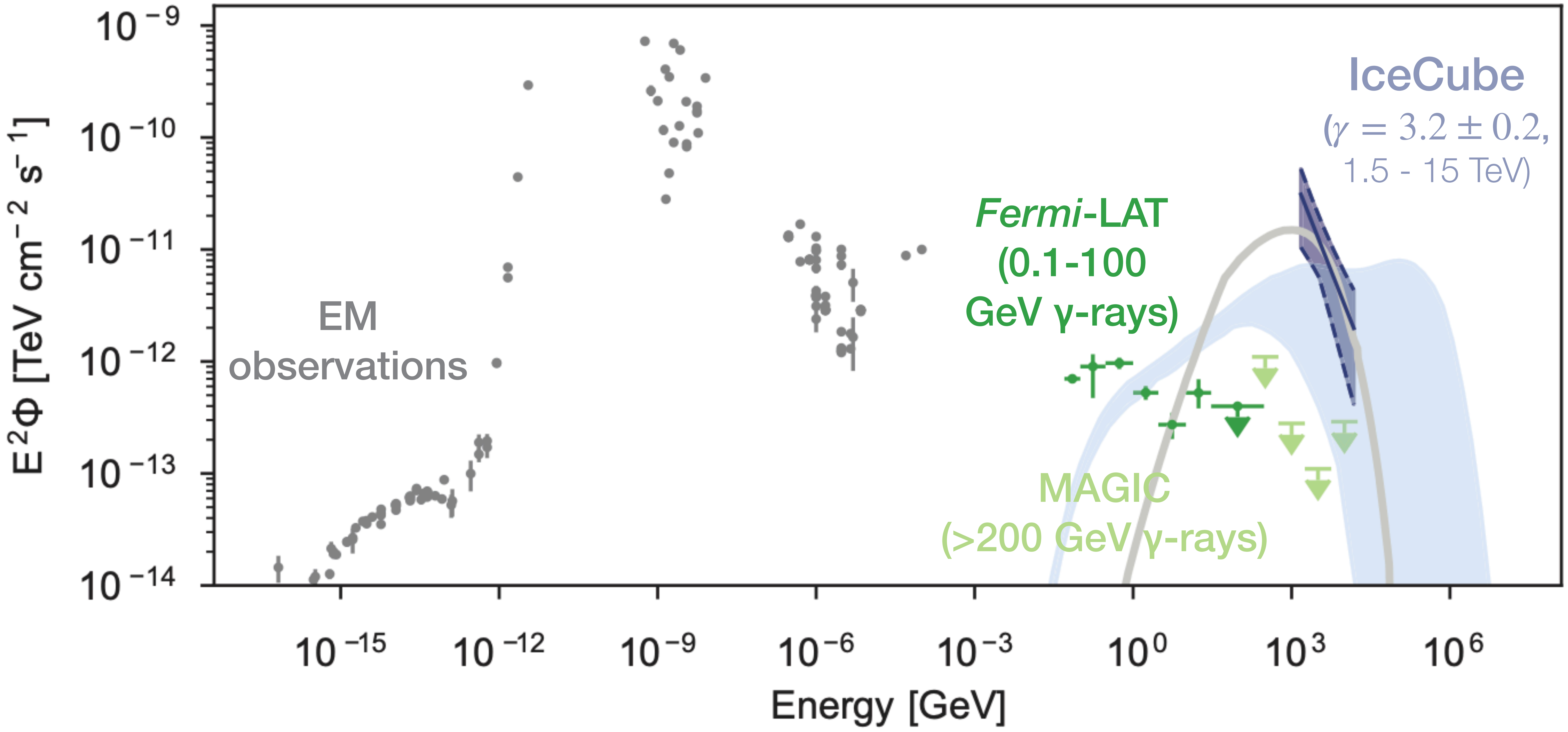
Northern hotspot in the vicinity of Seyfert II galaxy

NGC 1068 with significance of **4.2σ** (trial-corrected for 110 sources)

AGN corona model

Measured neutrino flux exceeds TeV gamma-ray upper limits

[IceCube, Science **378**, 538-543 (2022)]



Neutrinos produced in gamma-ray obscured environment