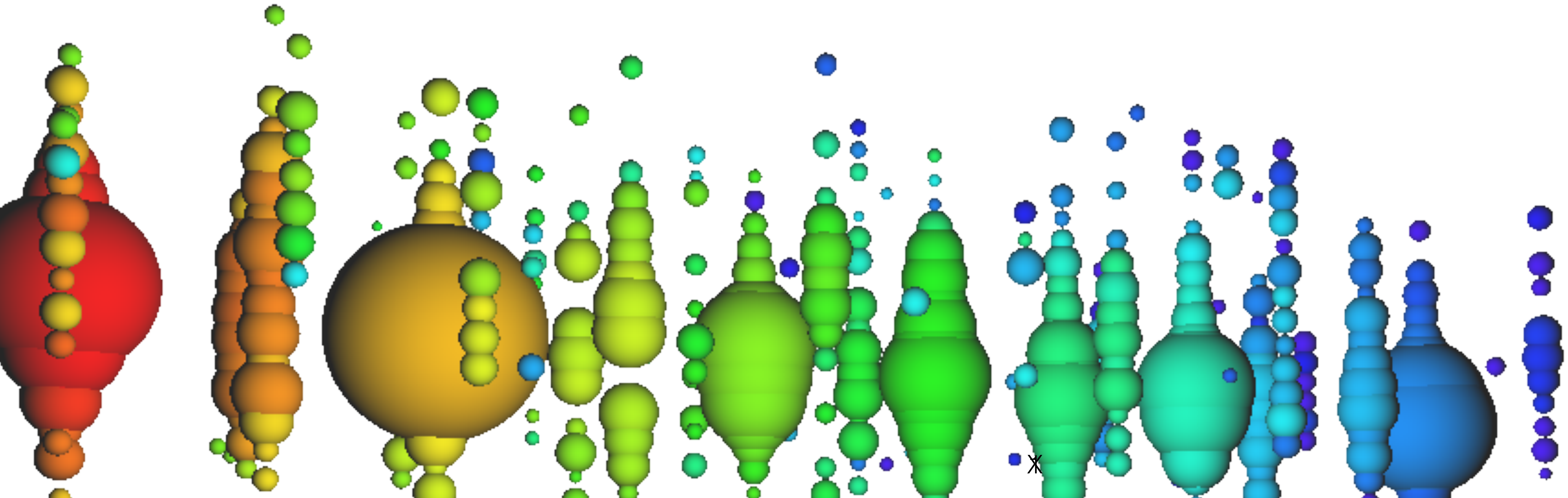
Neutrino Astrophysics

with IceCube

Anna Pollmann

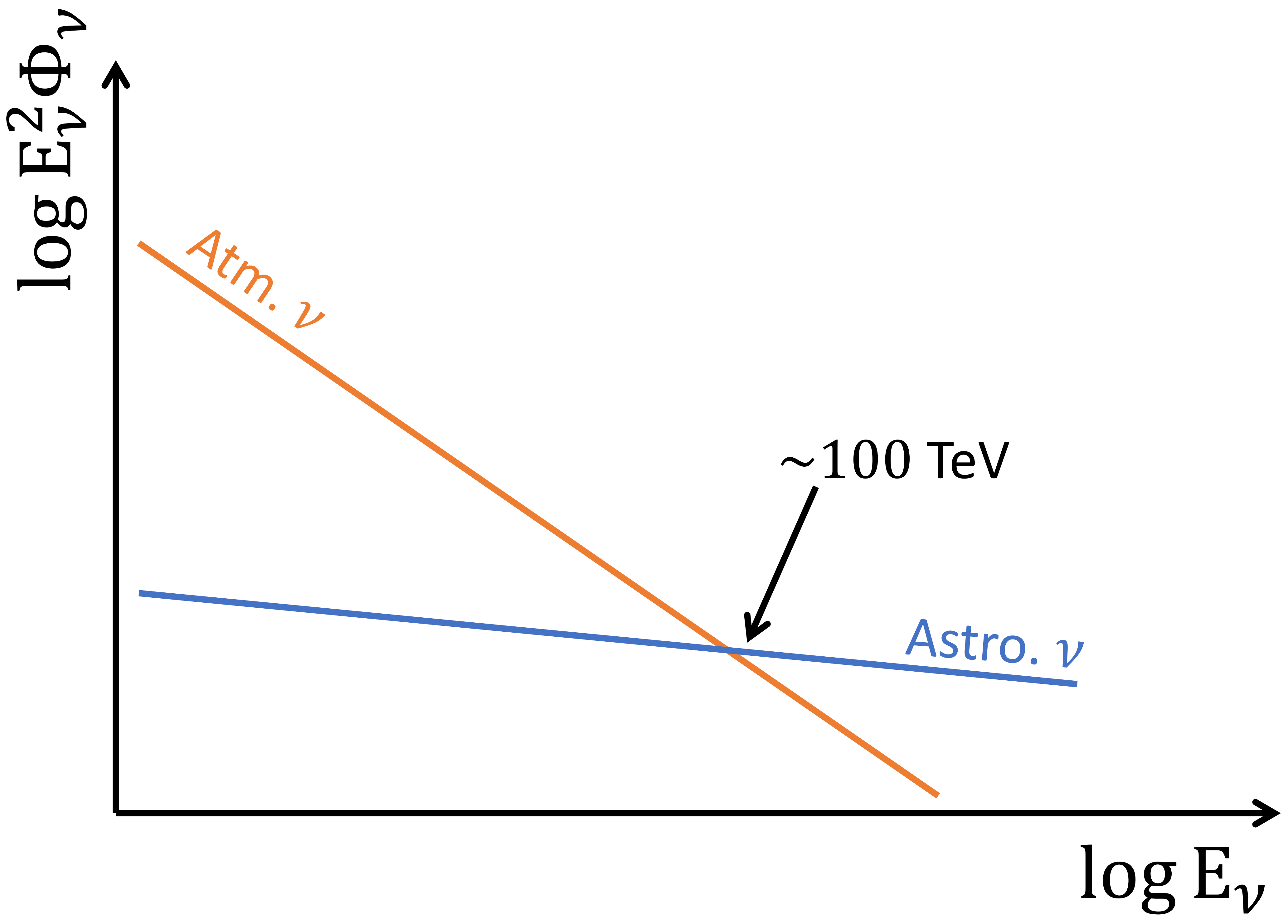


千葉大学
CHIBA UNIVERSITY

Using neutrinos for Astrophysics

Neutrinos
- point back to their source
- could unveil hidden phenomena

Neutrino flux at Earth

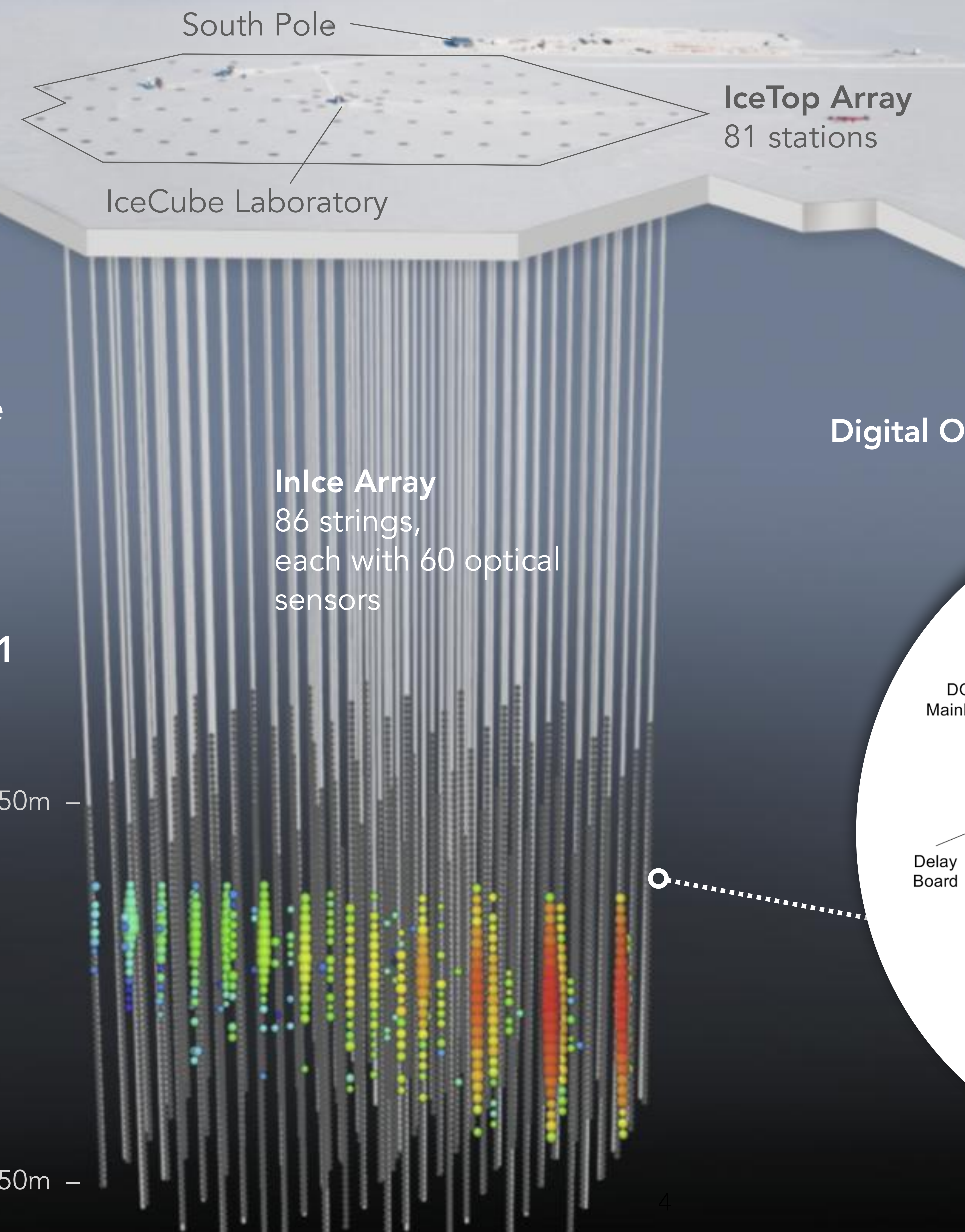


Power-law flux $\Phi_\nu = \Phi_0 E^{-\gamma}$

Flux falls off faster than cross section increases

→ Large statistics at lower energies

IceCube



Working principle

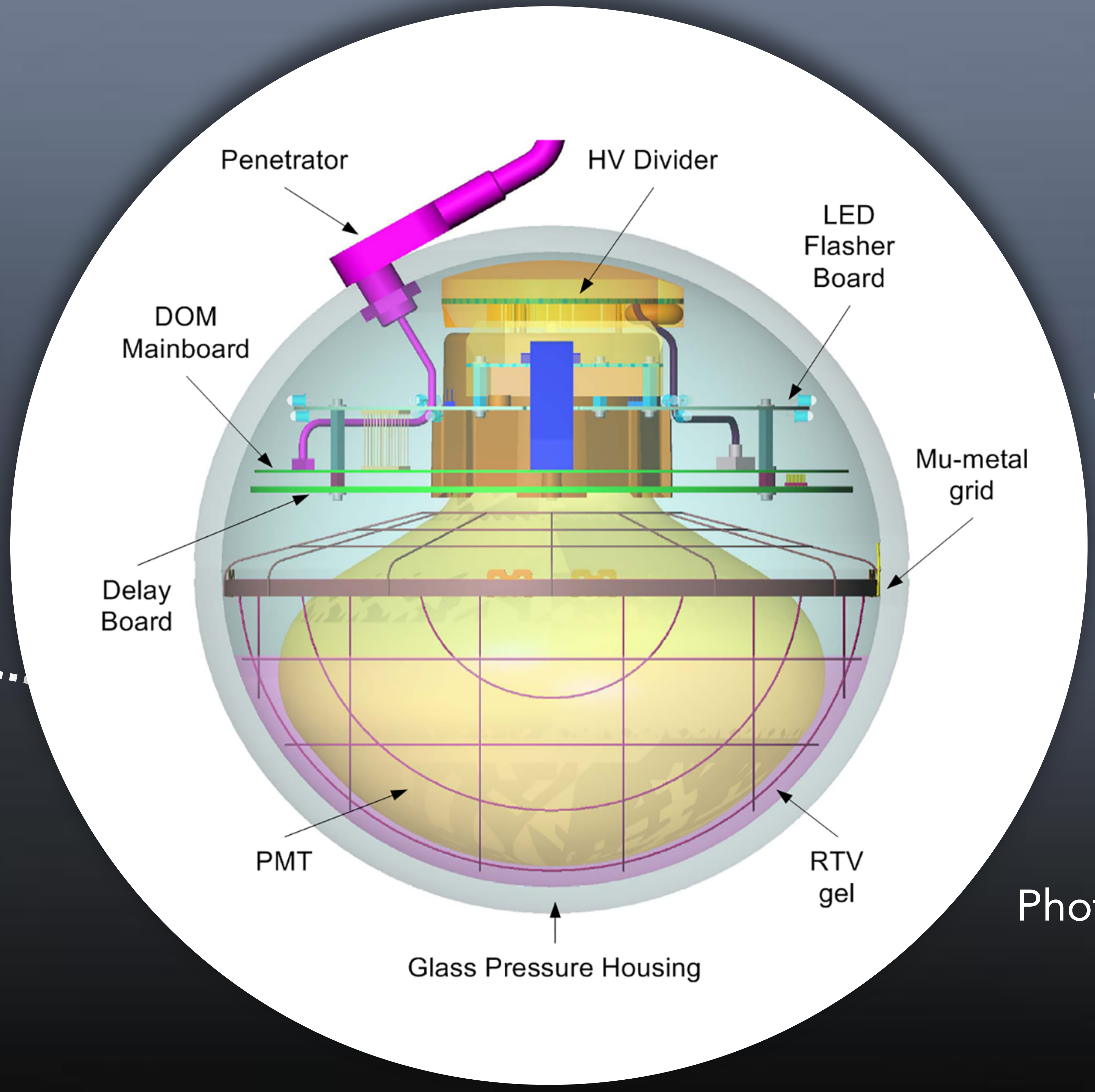
- Particles interact with the deep clear ice
- Emitted light is detected by sensors

Fully operational since 2011

Geometry

- volume 1 km^3
- vertical spacing 17 m
- horizontal spacing 125 m

Digital Optical Module (DOM)



Readout electronics

Photomultiplier

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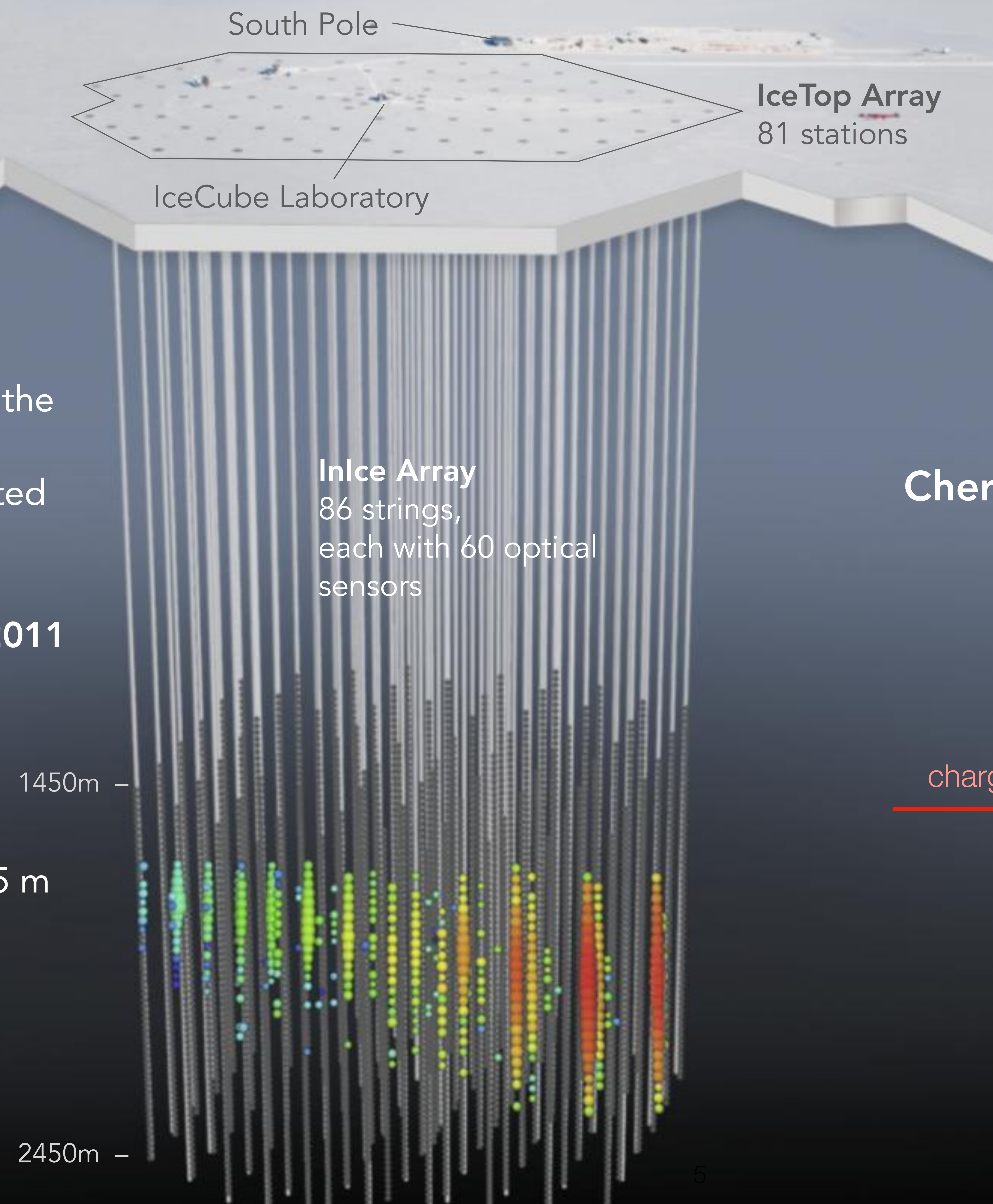
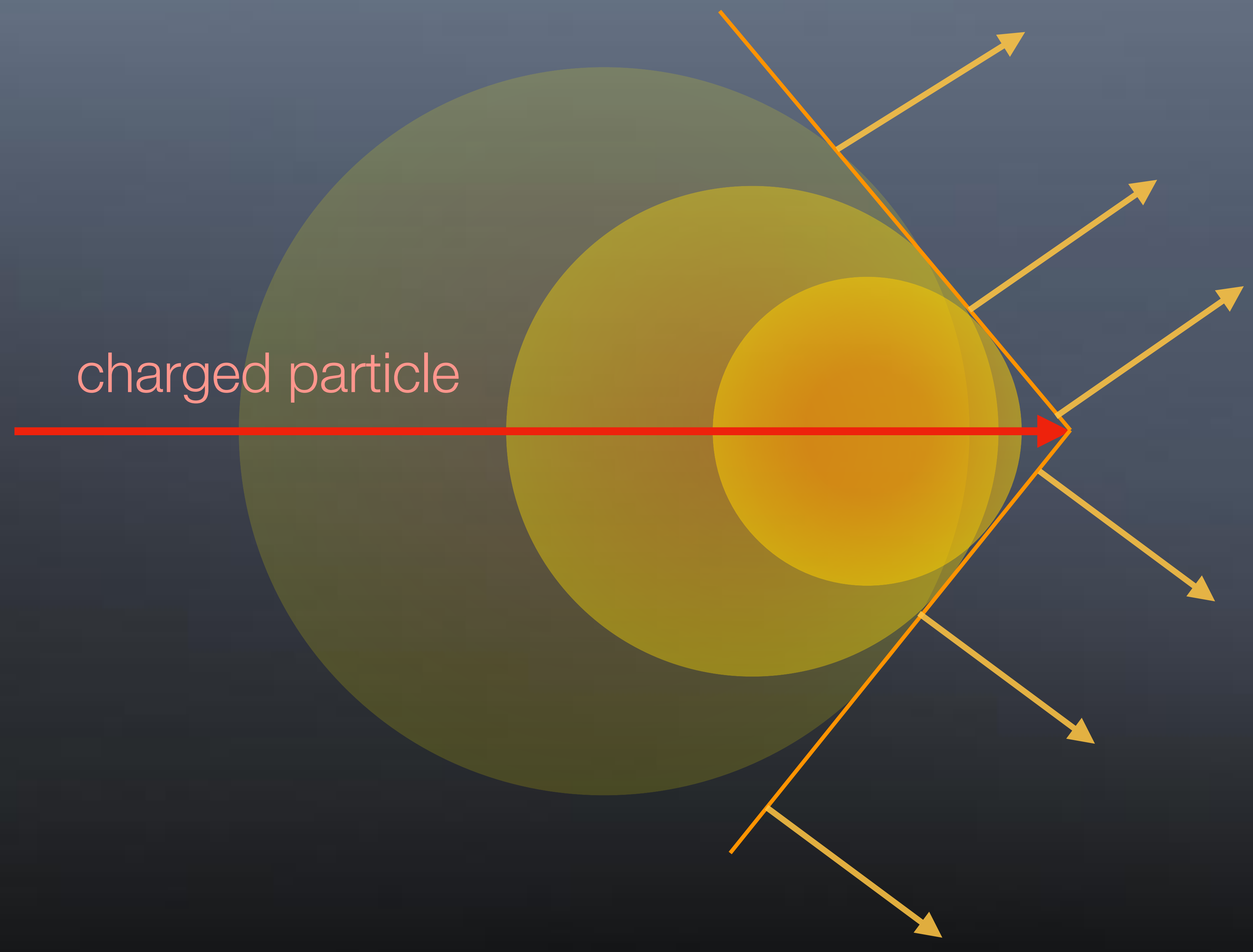


Cherenkov Light



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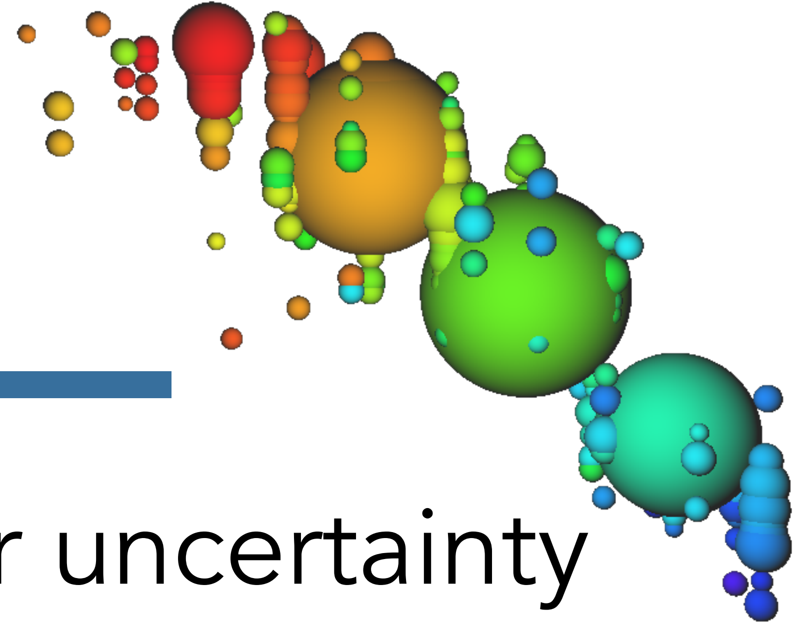
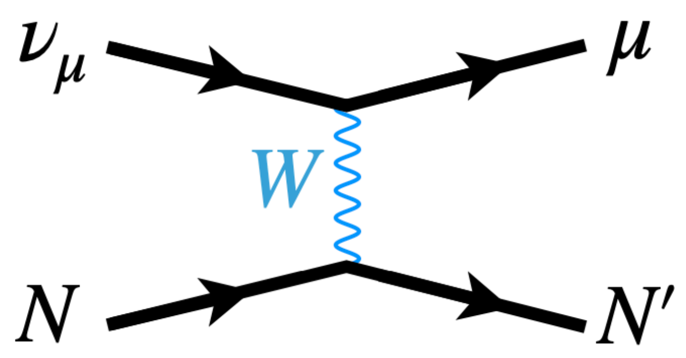
Neutrino signatures

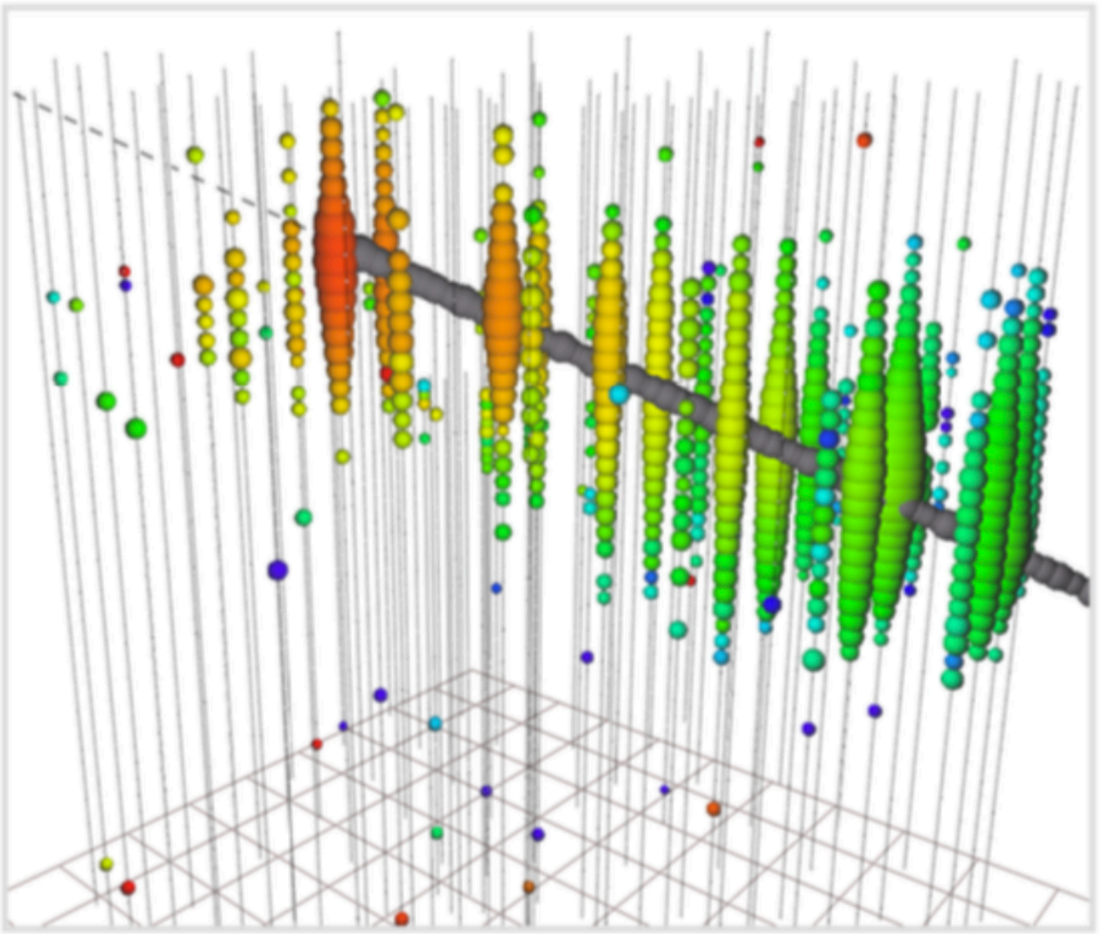


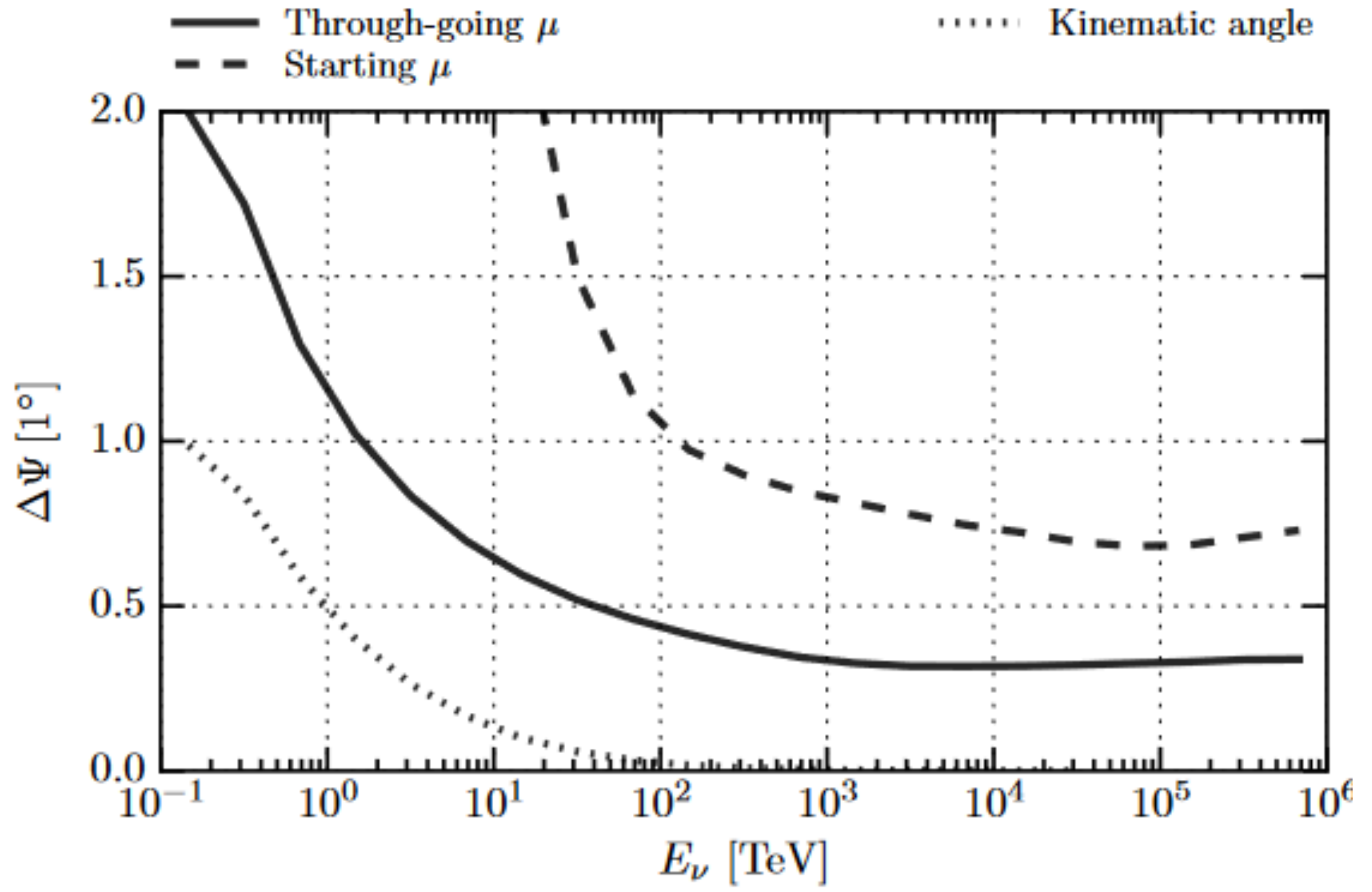
neutrino events are characterized by reconstructed quantities direction, energy, angular uncertainty

Track like topology

- good angular resolution 0.1° - 1°
- increased effective volume (vertex outside volume)
- challenging energy resolution

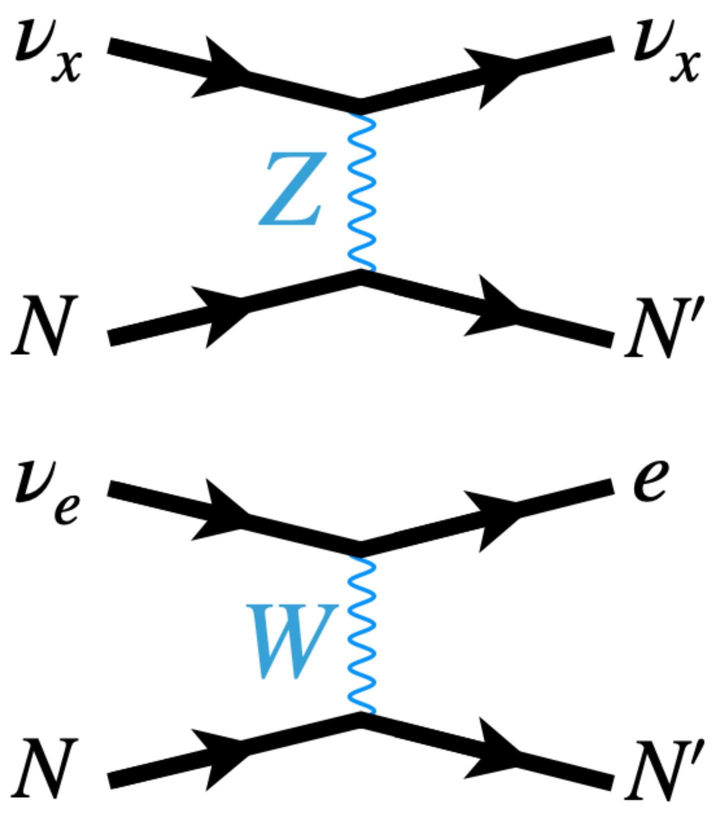


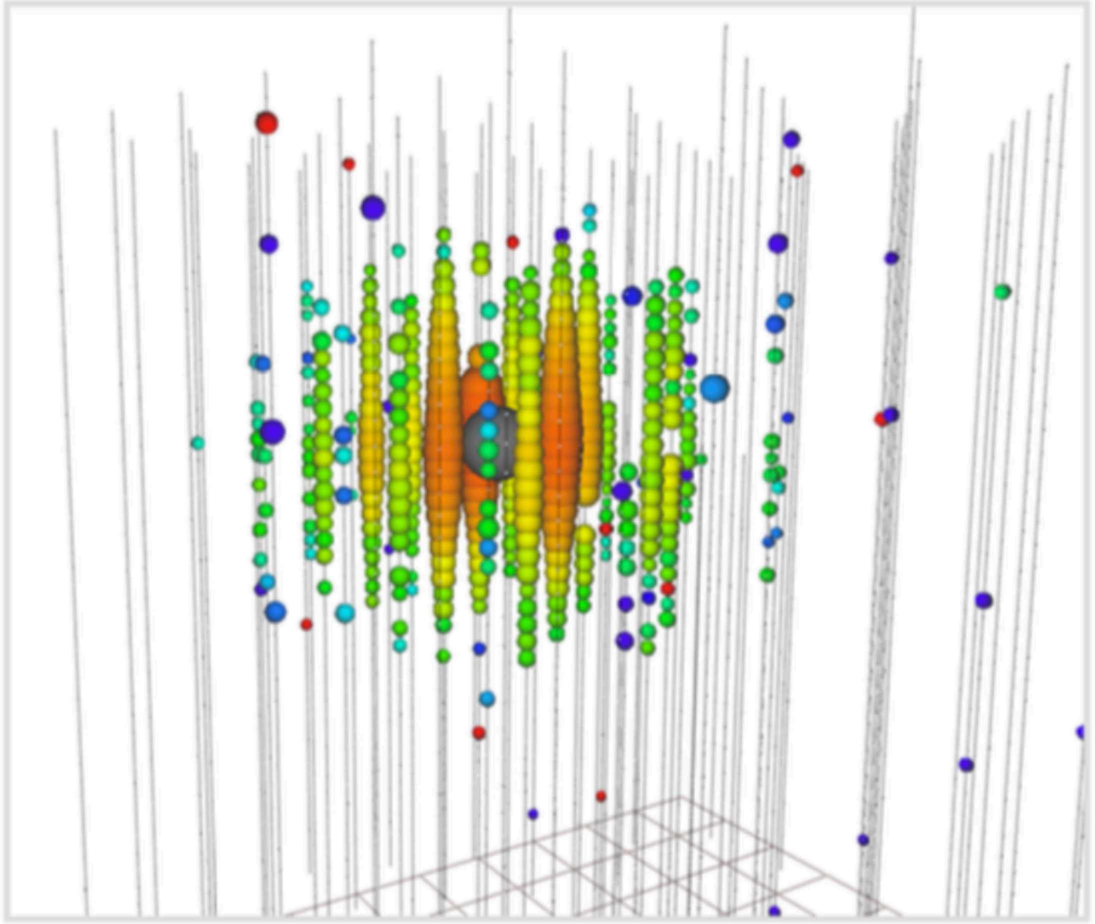


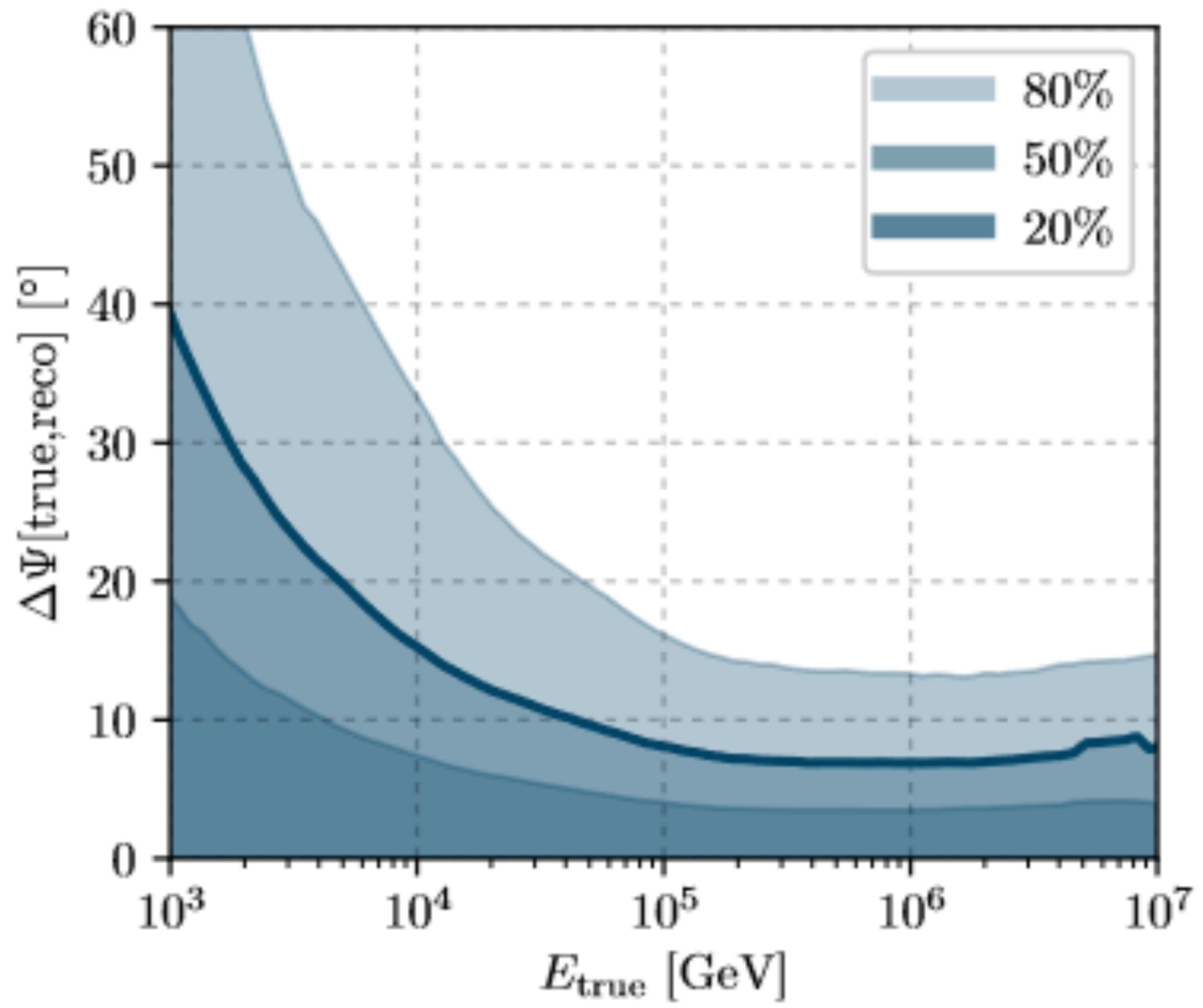


Cascade like topology

- all flavours
- calometric measurement of energy resolution ~15%
- angular resolution around 10° > 100 TeV







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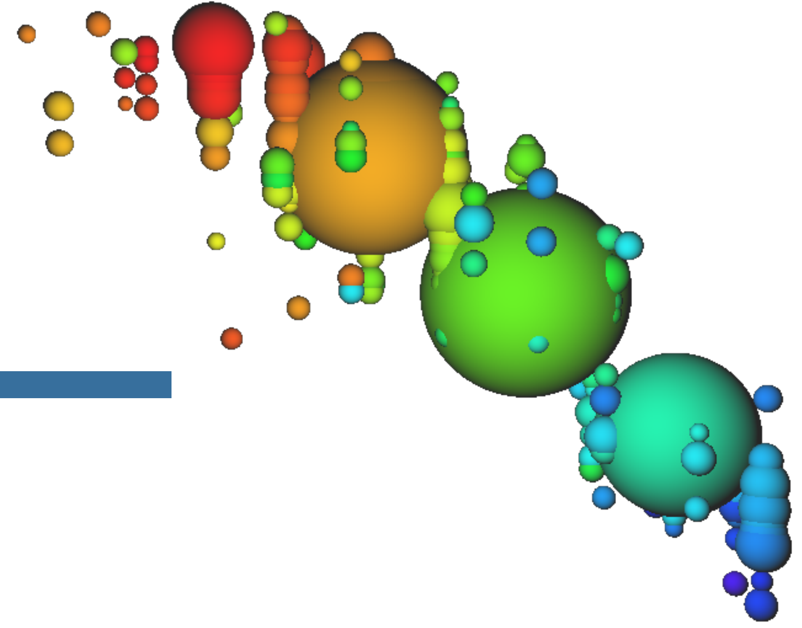
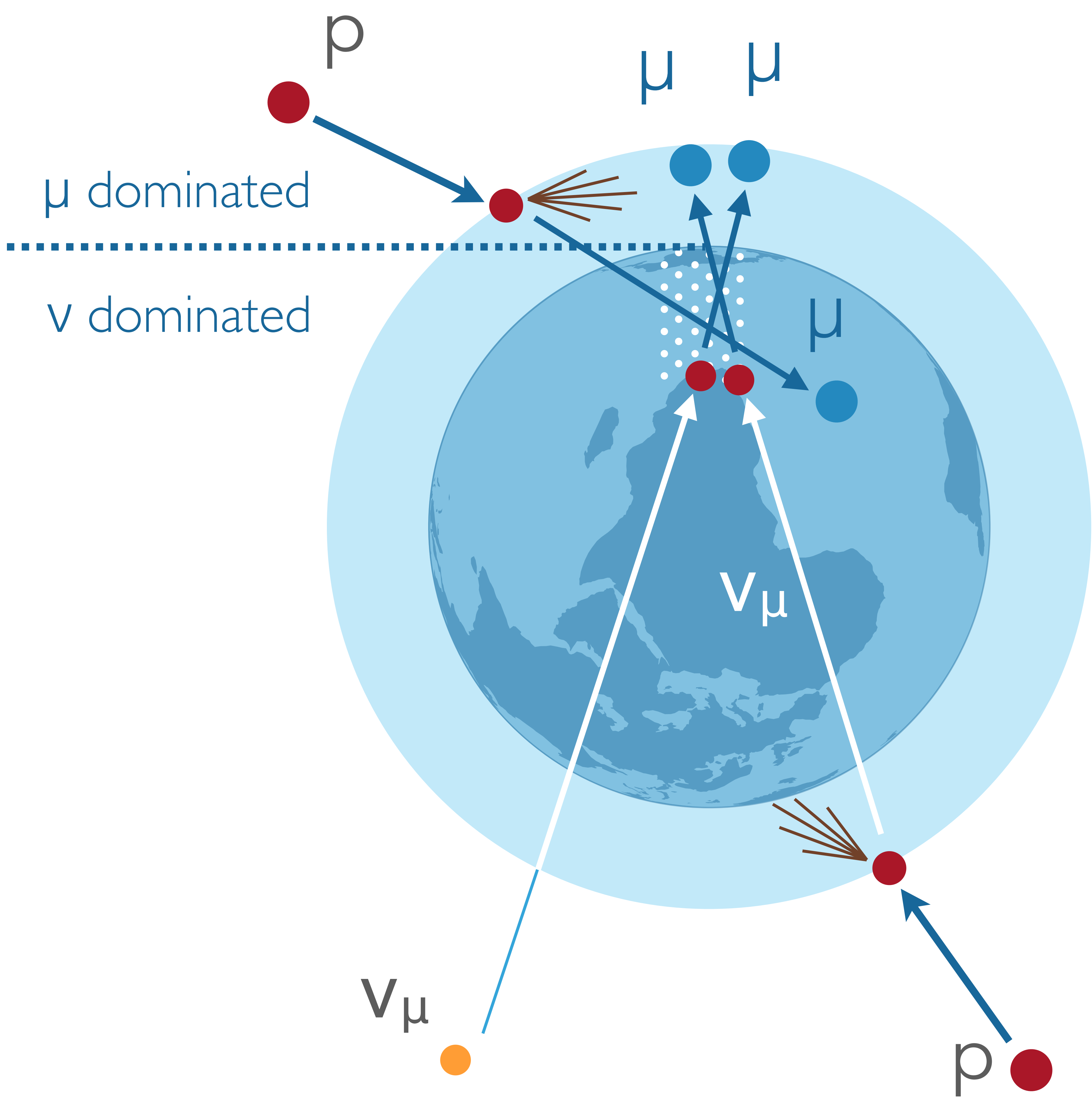
Rejecting background



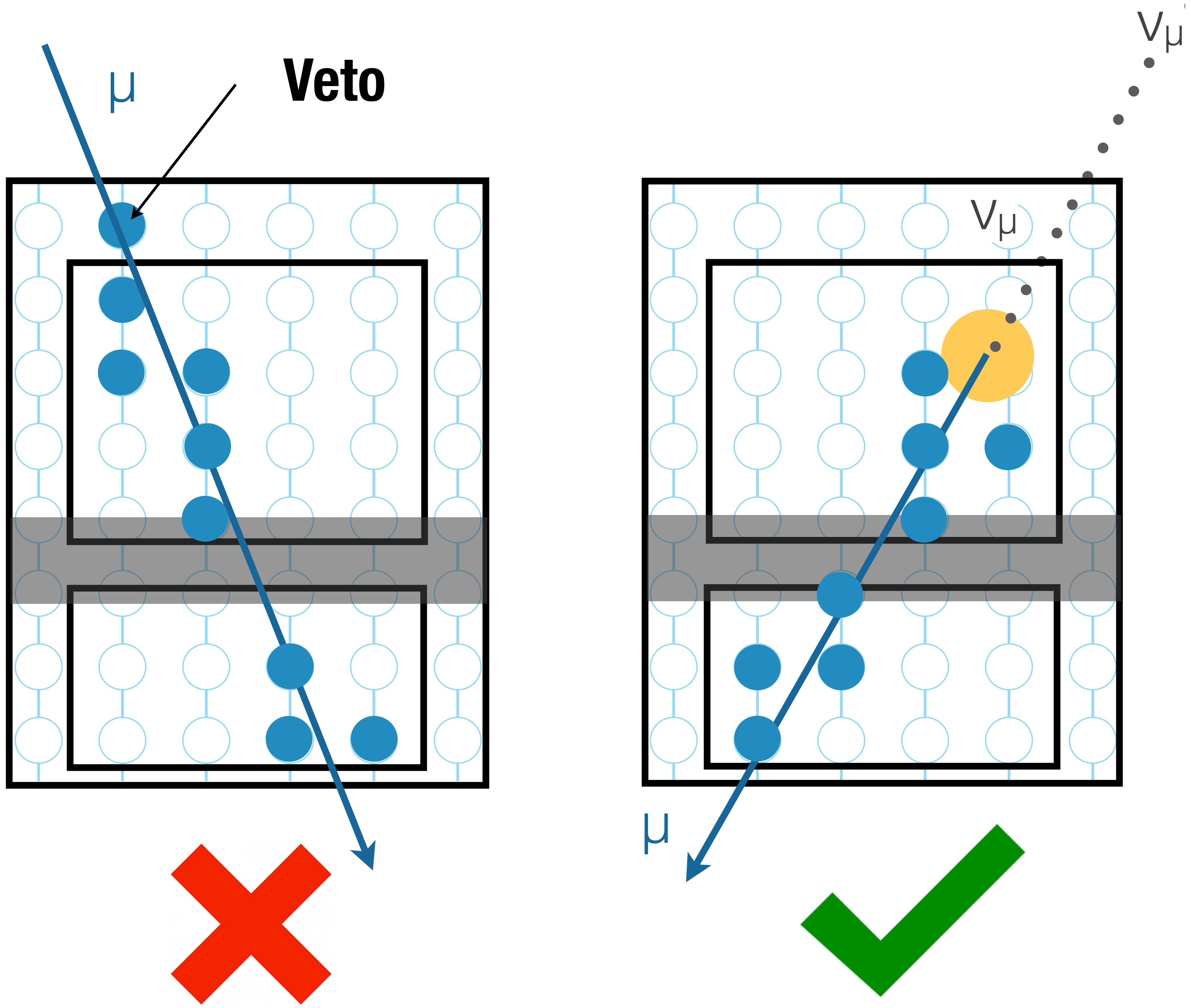
Shielding:

- record through-going μ-neutrinos
- use earth to filter atmospheric μ



Veto:

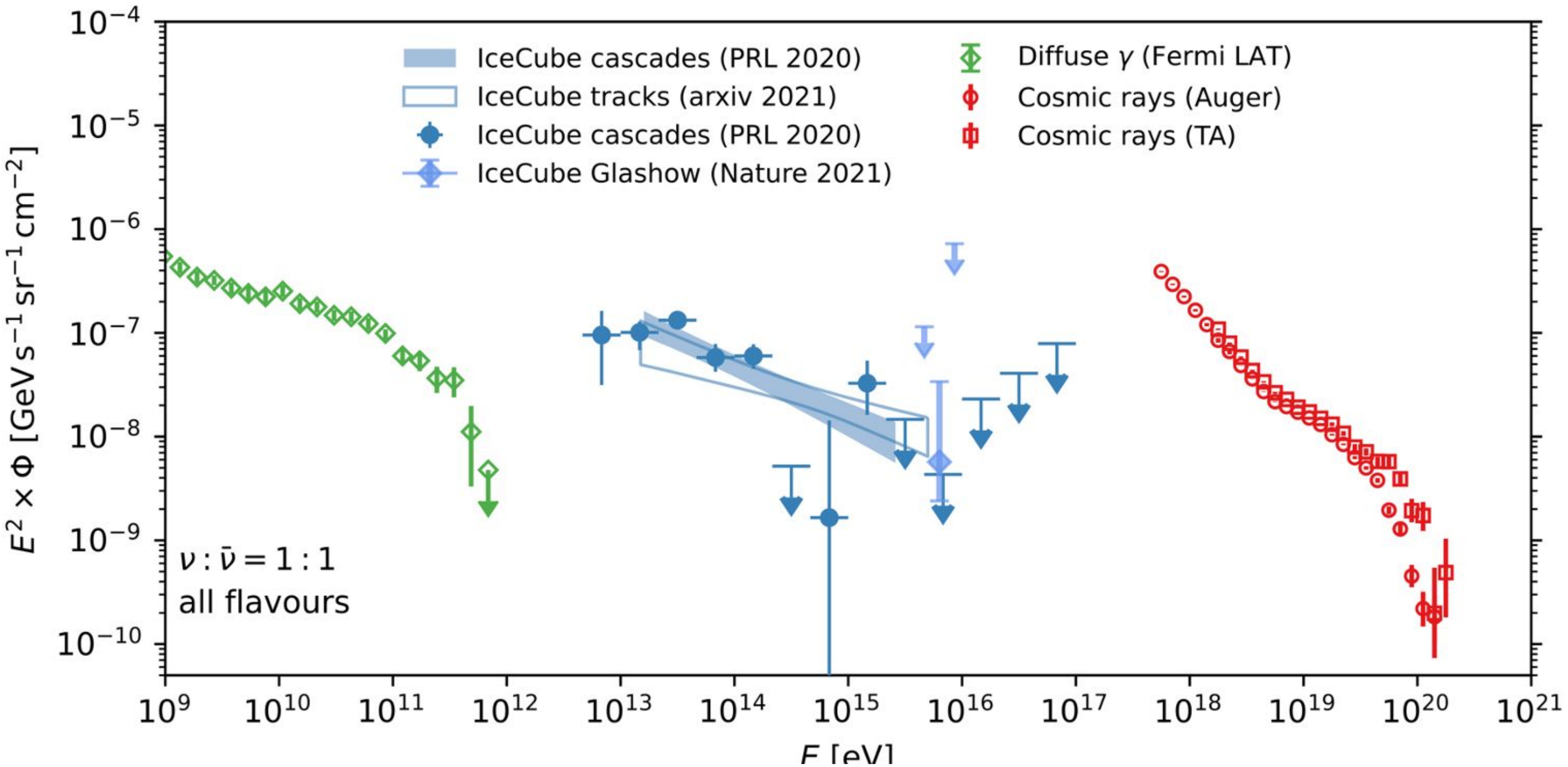
- outer layer as veto volume
- select starting events



Juan A. Aguilar

Astrophysical neutrinos

The universe glows brightly in Neutrinos
Energie density of γ and ν matches over many orders of magnitudes

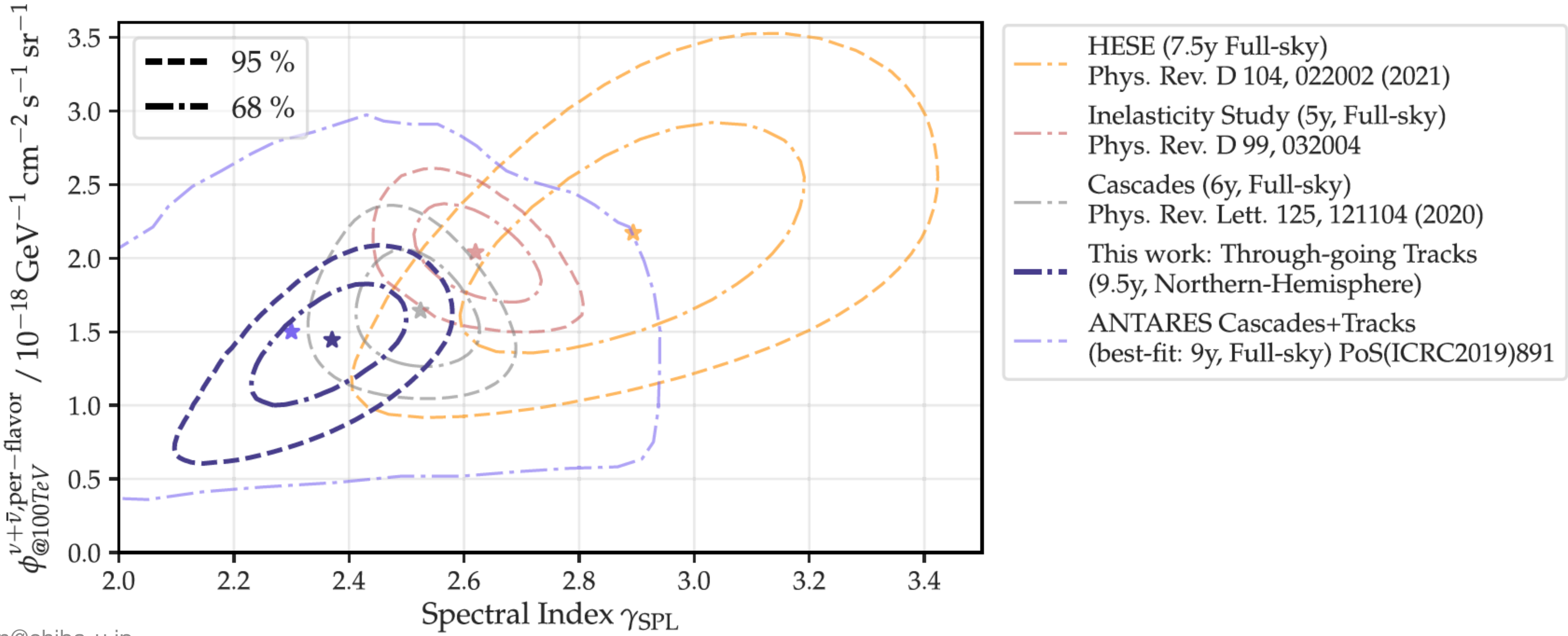


Neutrino presence hints to hadronic processes

$$\begin{matrix} p+p \\ p+\gamma \end{matrix} \rightarrow X + \pi \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\ n \rightarrow p + e^- + \bar{\nu}_e \end{cases}$$

Flavour of neutrinos at Earth

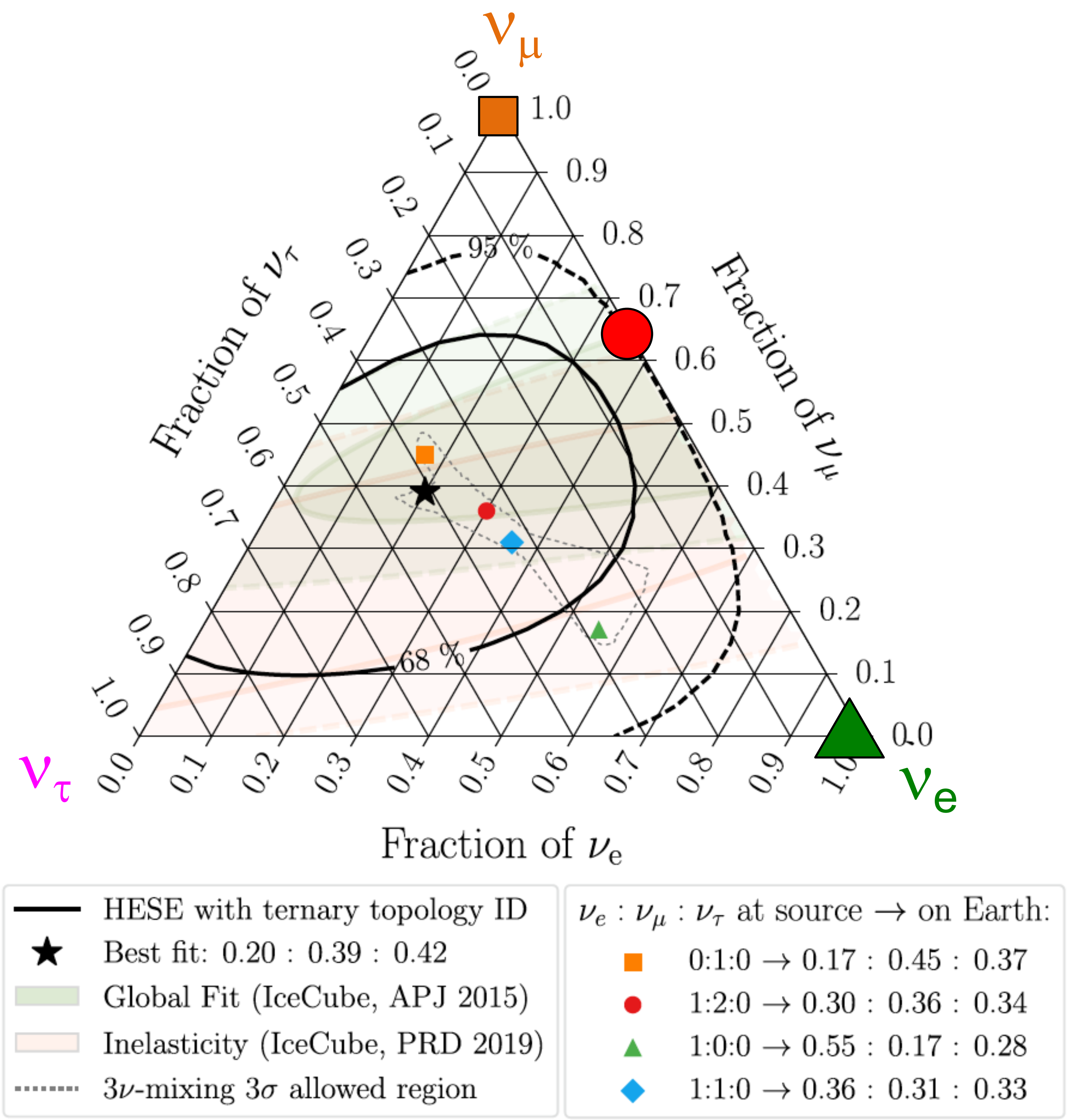
- between different analyses: tension in spectral index
- caveat: tracks vs cascades & Northern vs Southern sky



Flavour of neutrinos at Earth

- neutrinos with 60 TeV - 2 PeV
- ν_τ hard to identify

Production model: $\nu_e : \nu_\mu : \nu_t \sim 1 : 2 : 0$
After mixing: $\nu_e : \nu_\mu : \nu_t \sim 1 : 1 : 1$



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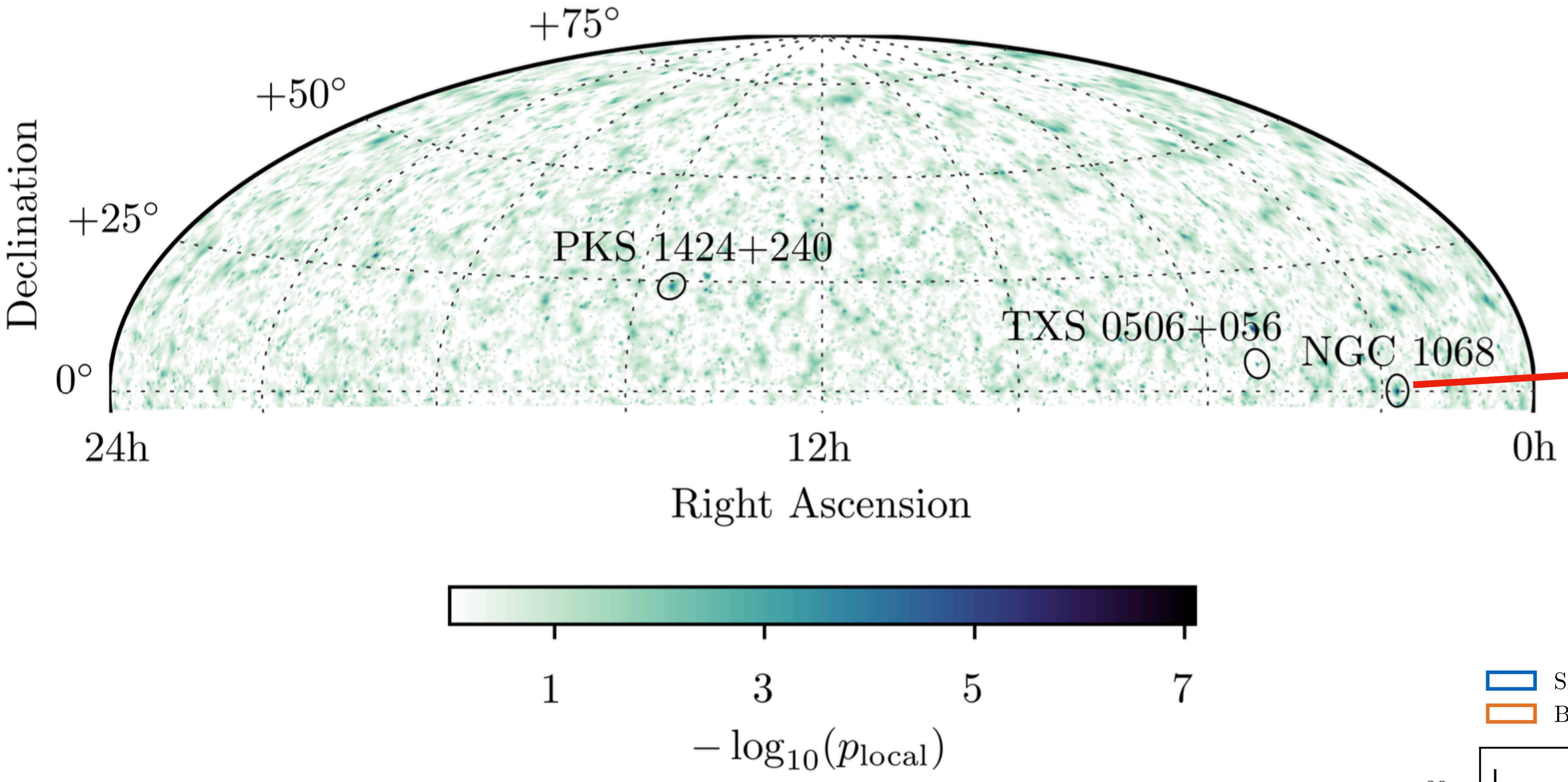
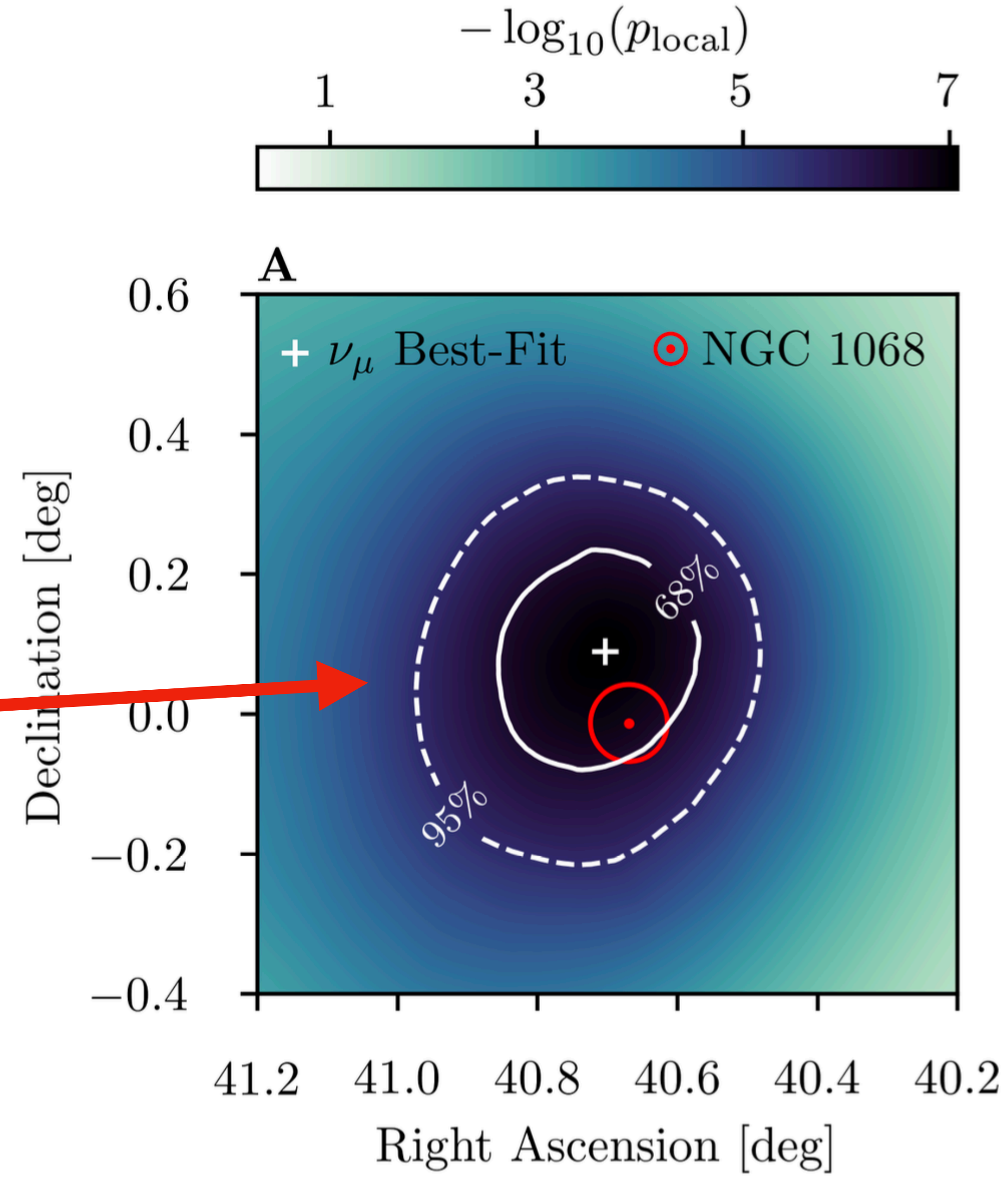
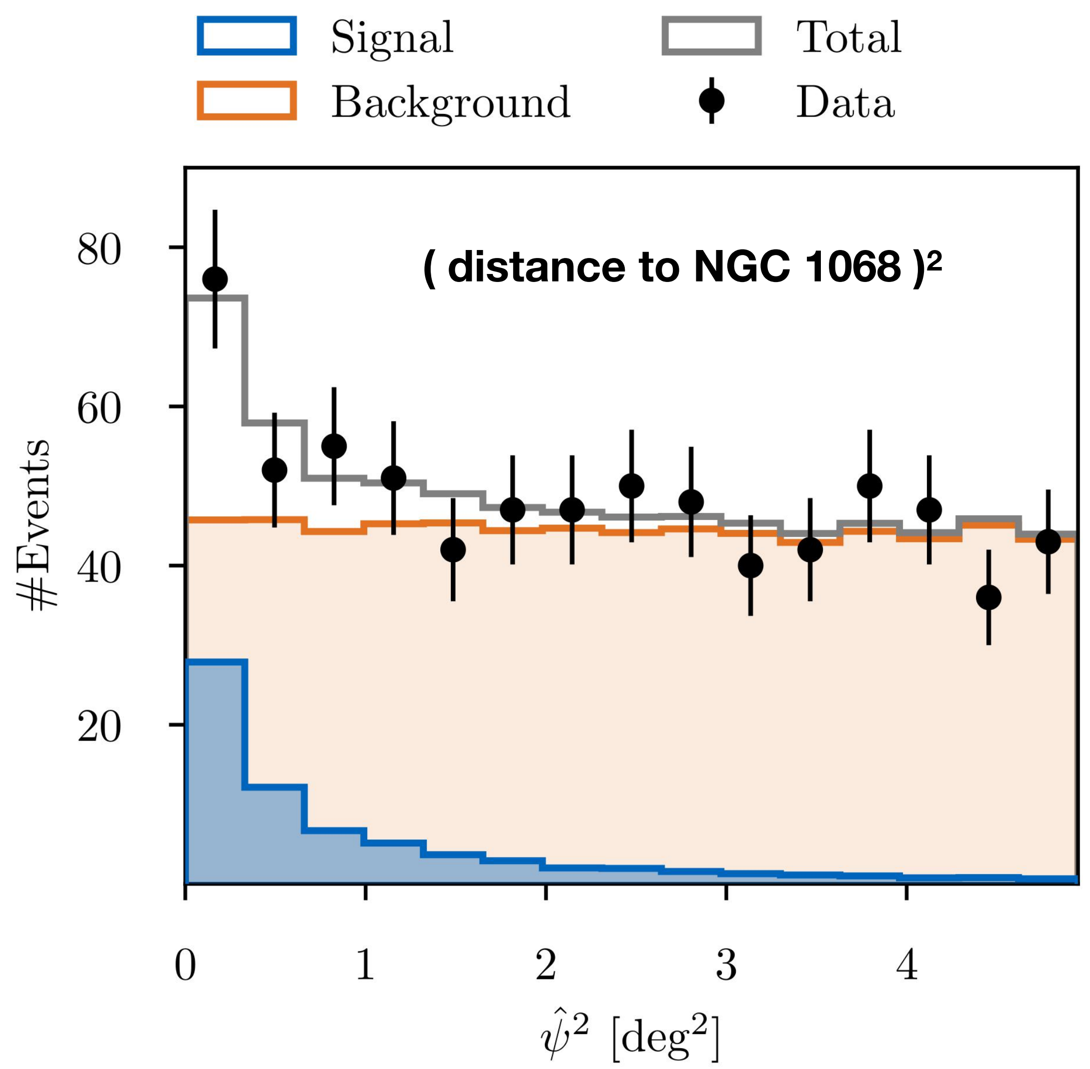
Neutrino emission from NGC1068

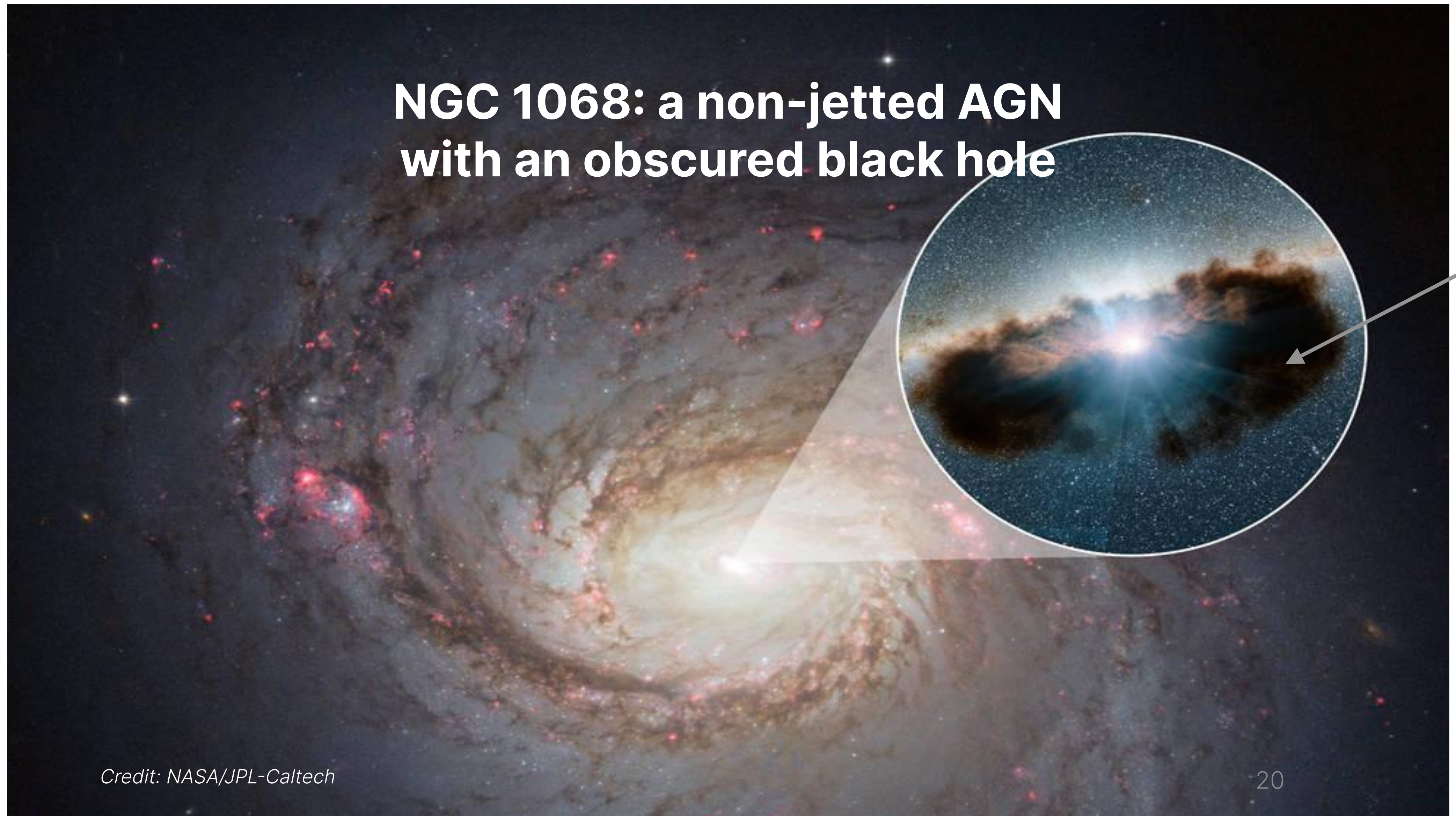




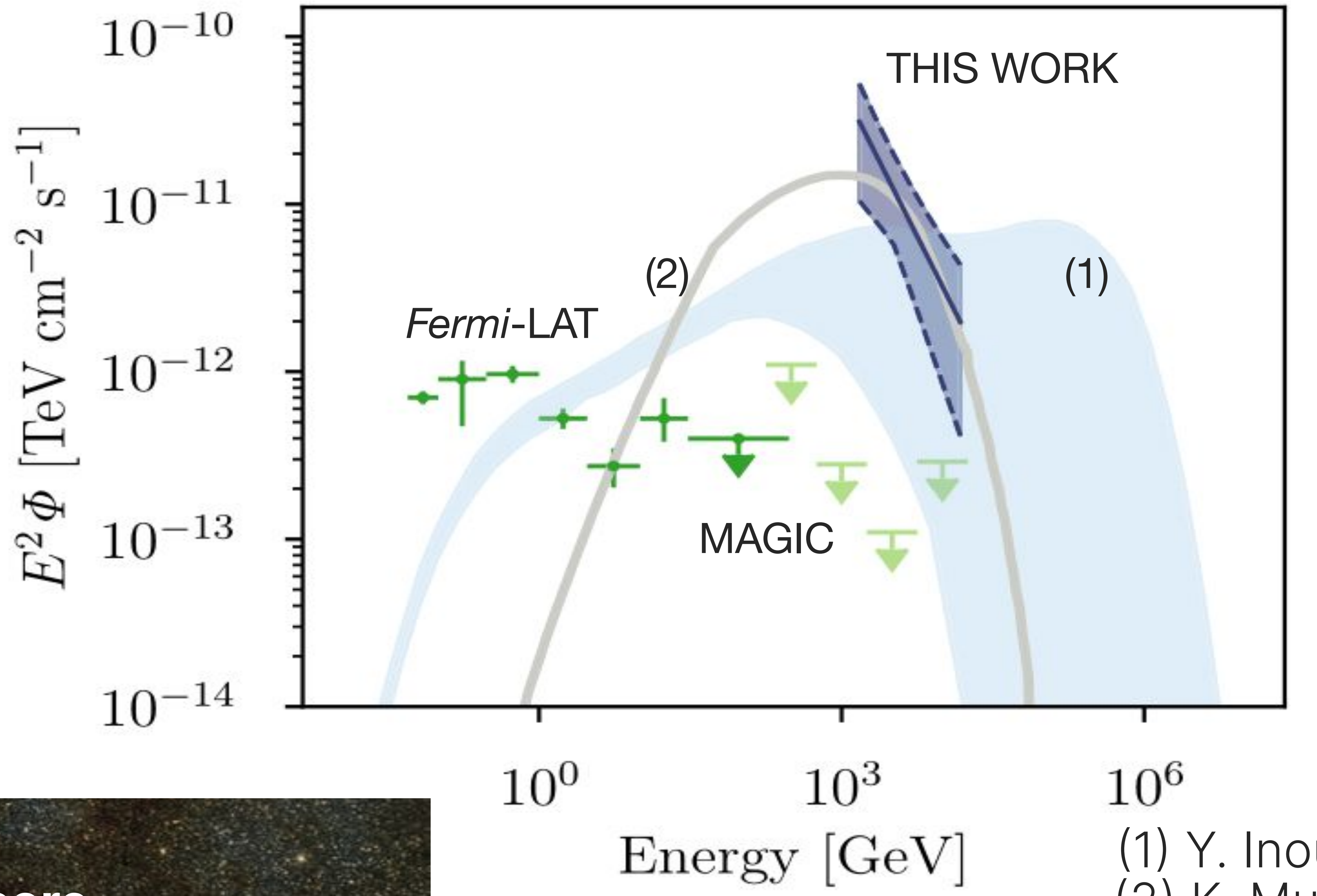


- search for "hot-spots" in IceCube ν_μ map $\Phi_{\nu_\mu+\bar{\nu}_\mu}(E_\nu) = \Phi_0 \cdot (E_\nu/E_0)^{-\gamma}$
- identified spot with excess of ~79 ν and mean spectral index of 3.2
- distribution matches model prediction
- coincidence with NGC1068
- global significance 4.2 σ

NGC1068: an obscured accelerator



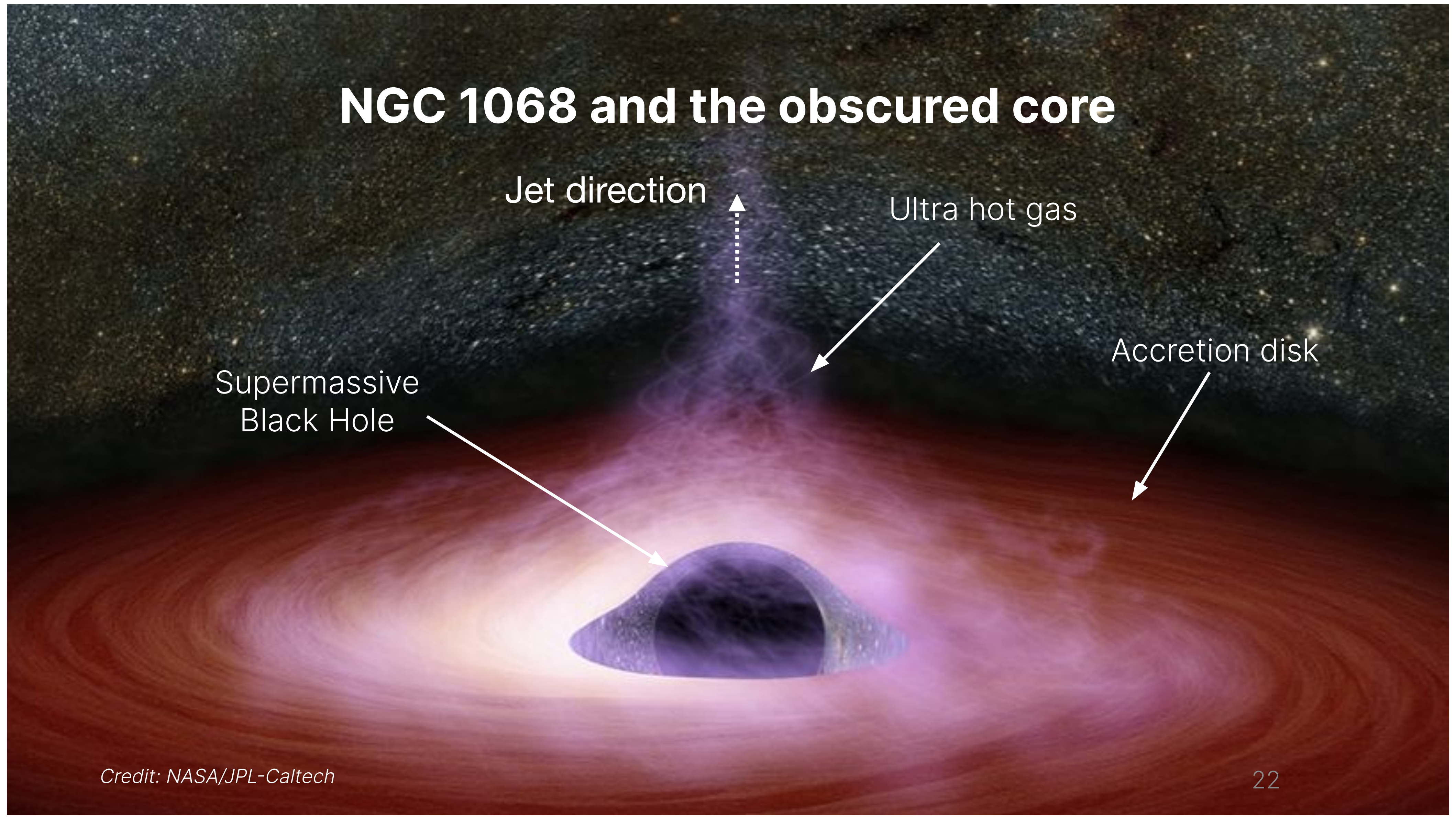
Dusty Torus



observables of AGN depend on viewing angle

Seyfert II galaxies: edge-on i.e. through dusty torus

Blazar: in / close to jet direction



Models:
Inoue et al, ApJL 891 (2020) 33
Murase et al, PRL 125 (2020) 011101

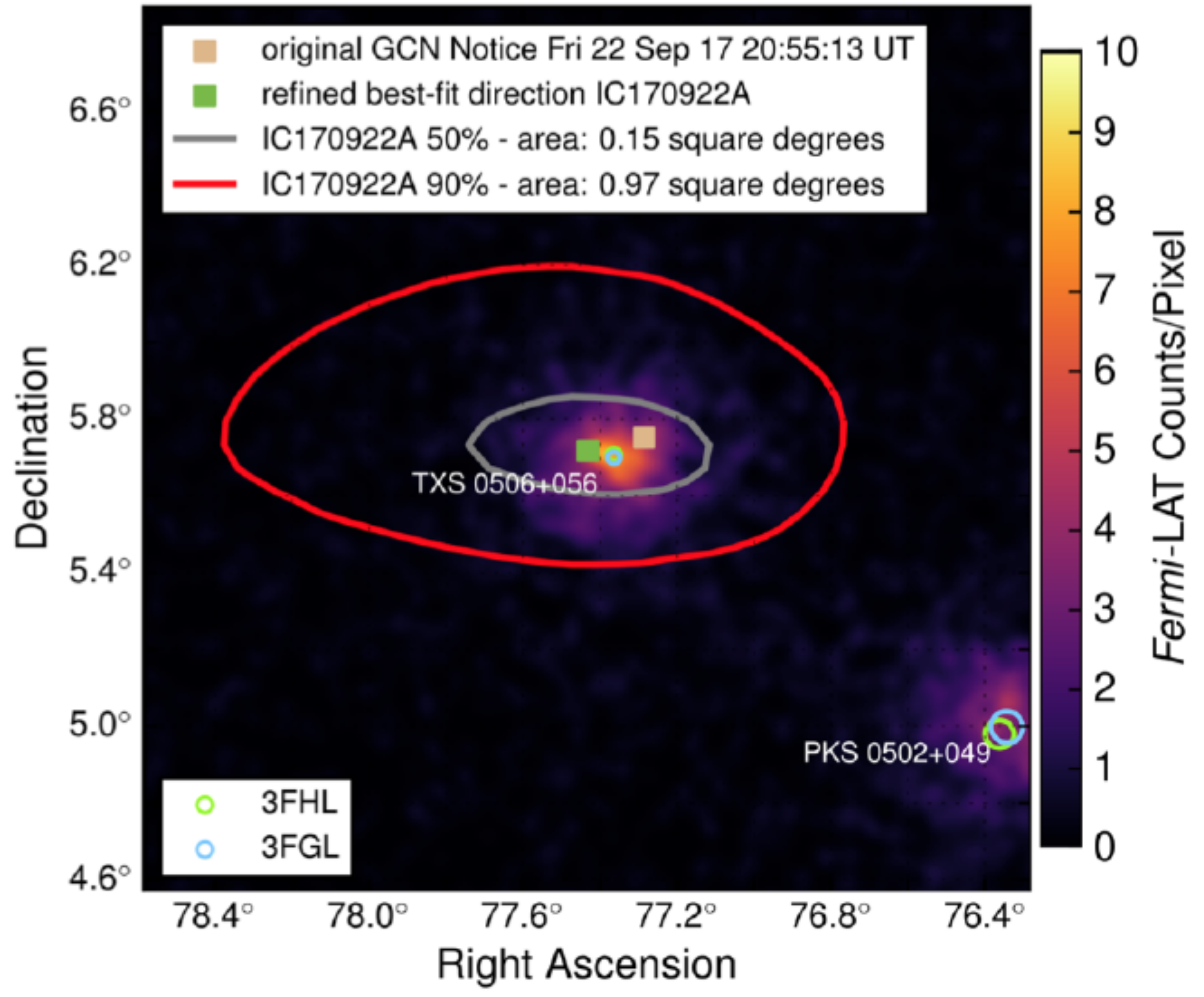
Neutrino real-time alert system - first astrophysical ν source

Singlet ν:

- since 2016, re-designed 2019
- gold events: 10/y, signalness > 50%
- silver events: 20/y, signalness > 30%
- latency: 2 min to *GCN notices*

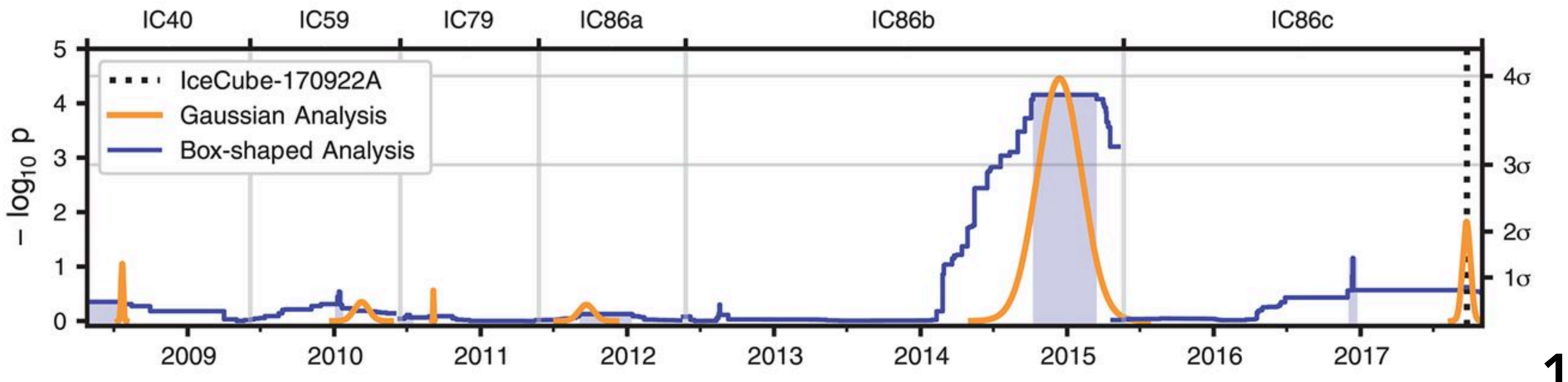
IceCube-170922A (in GCN Circ. 21916)

- counterpart in X-rays and optics: TXS 0506+056
- blazar with typical accretion disk and dusty torus
- flaring state at time of neutrino emission
- additional neutrino flare (3.5 σ) found in archival data w/o γ-counterpart

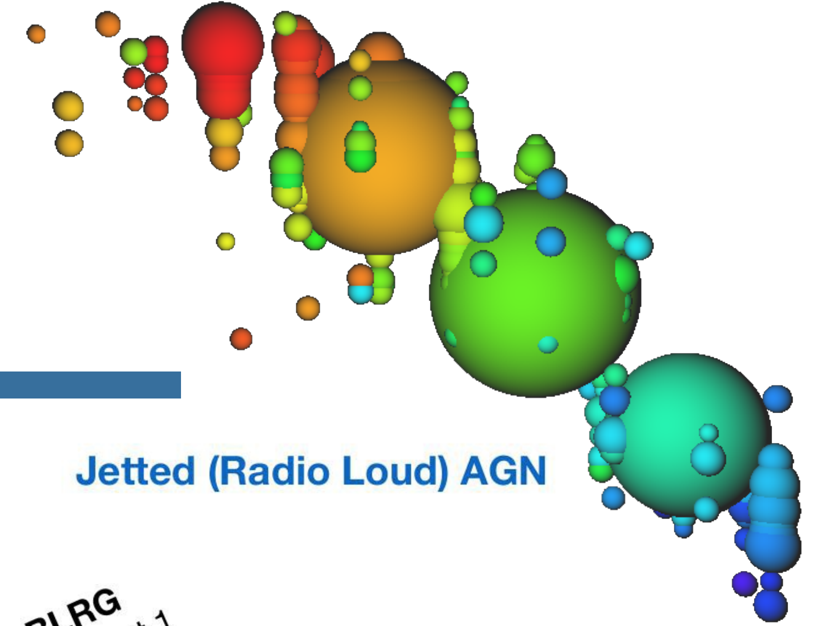


Current status

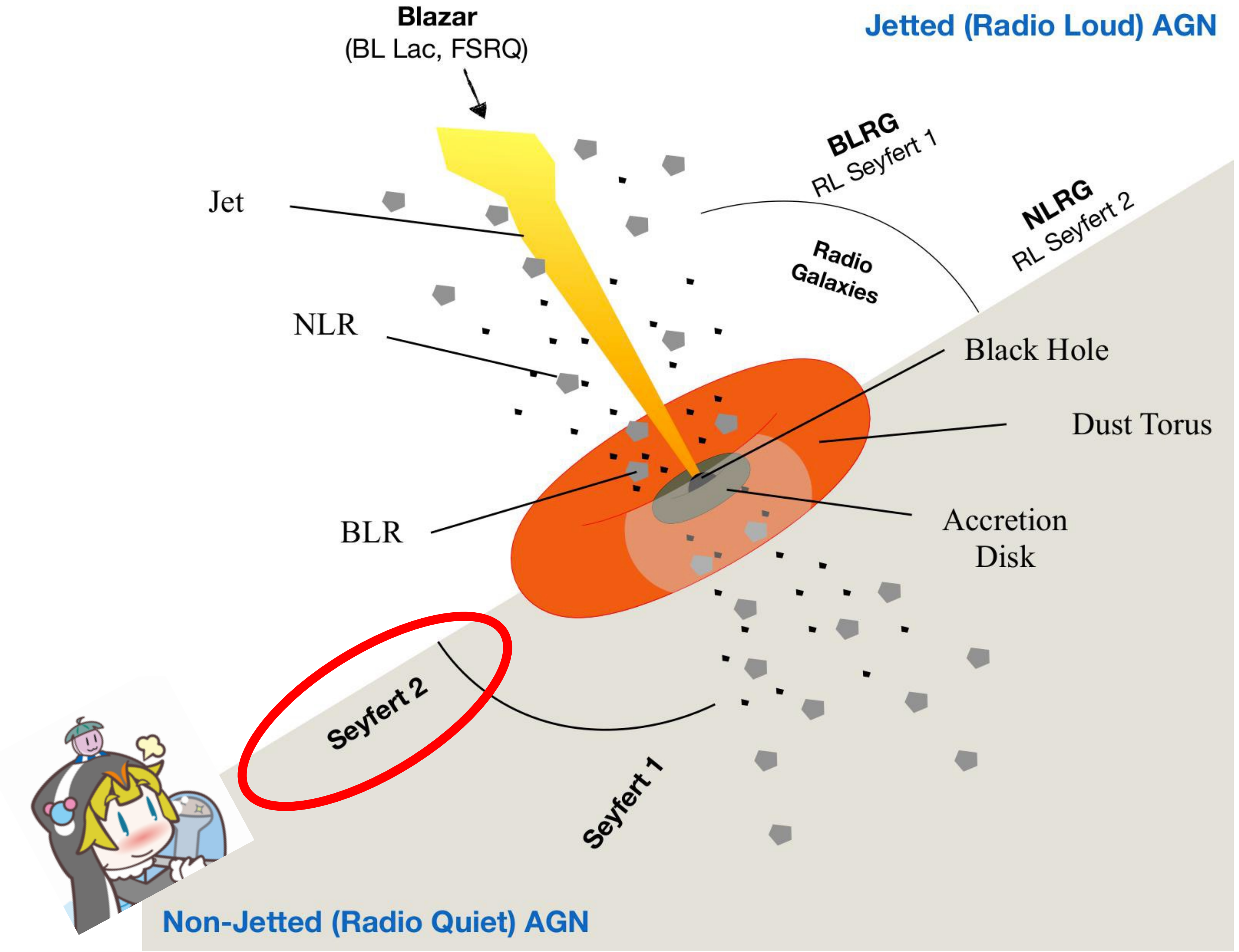
- 58 analyses performed 2016 – 2020, more stud since
- typical latency is a few days.



Implications of first neutrino sources

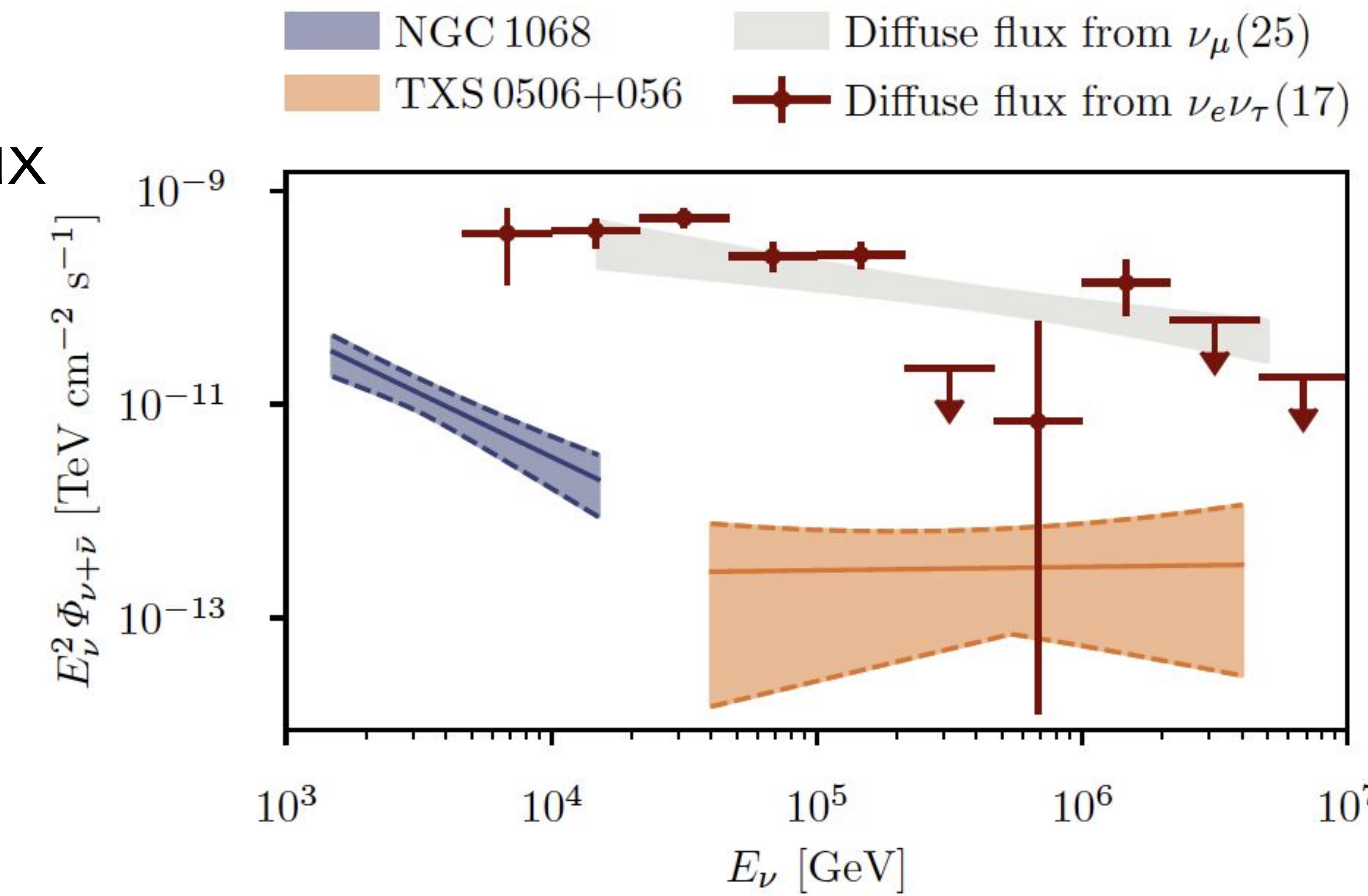


- NGC1068 and TXS0506-056 are different source classes
  - **TXS:**
    - blazar, > 1Gpc
    - leptonic processes can explain all optical signals (synchroton self-Compton scattering)
  - **NGC:**
    - radio galaxy, nearby AGN (14.4 Mpc)
    - opaque to high energy γ-rays



- Active Galactic Nuclei may contribute significantly to extragalactic neutrino flux

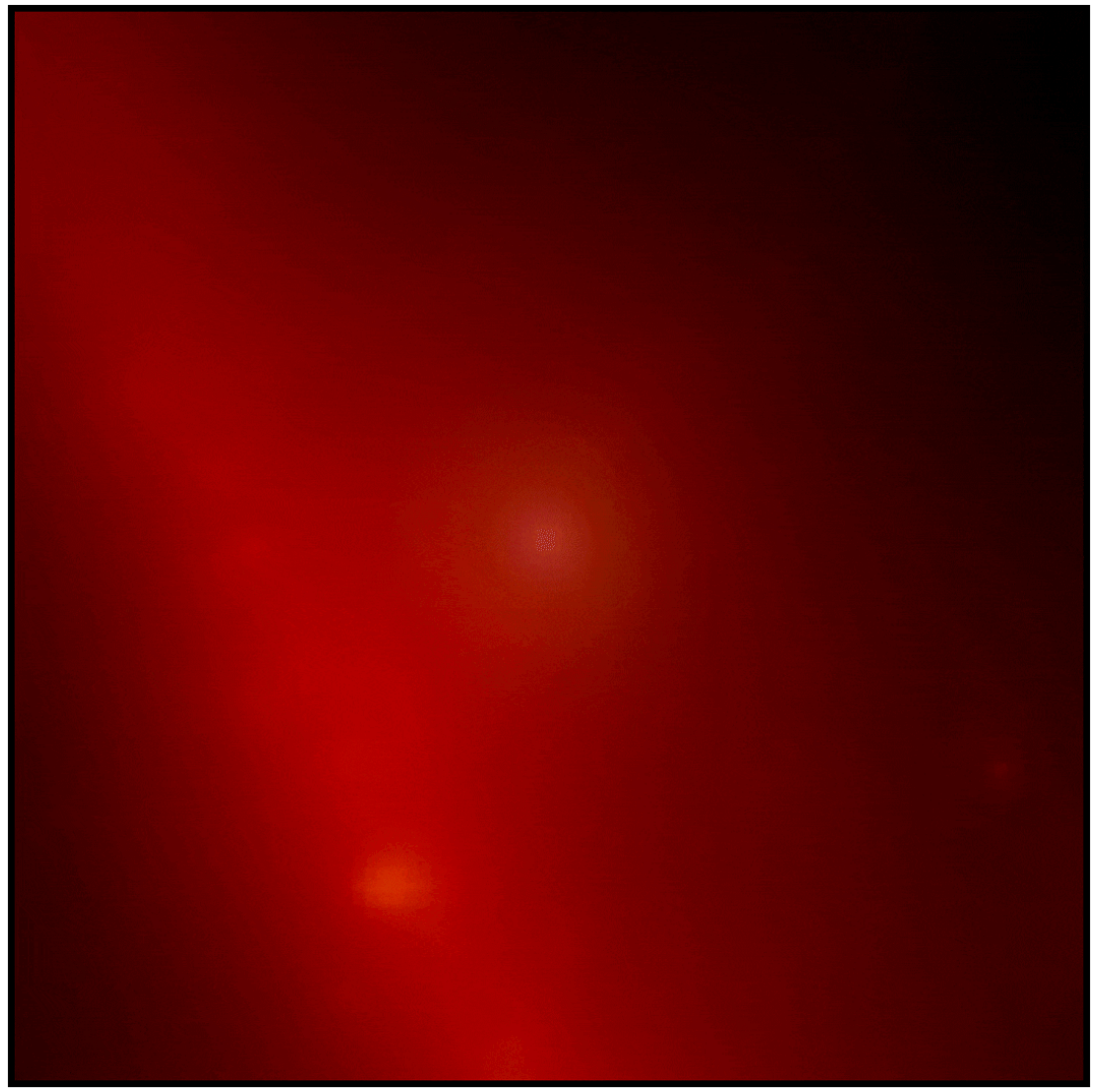
- NGC energy smaller 6 spectral index softer than diffuse ν: there might be more accessible high-energy astrophysical neutrino sources



GRB 221009A

- brightest GRB of all time, $z = 0.151$
- highest energy photon (LHAASO) at around 18 TeV / first above 10 TeV (Huang et al. GCN 32677)
- ~325 sec, i.e. long-duration GRB, likely triggered by core collapse of a super-massive star
- Fast Response Analysis by IceCube: no neutrino emission found in -1 day to +2 days (Thwaites et al. GCN Circular 32665)

- 4 further studies
  - covering different energy ranges from MeV to PeV
  - 300 sec to 14 days
  - giving constraints on some acceleration models (Murase et al. 2022, Liu et al. 2022, Rudolph et al. 2022)



10-hour time lapse – Fermi LAT

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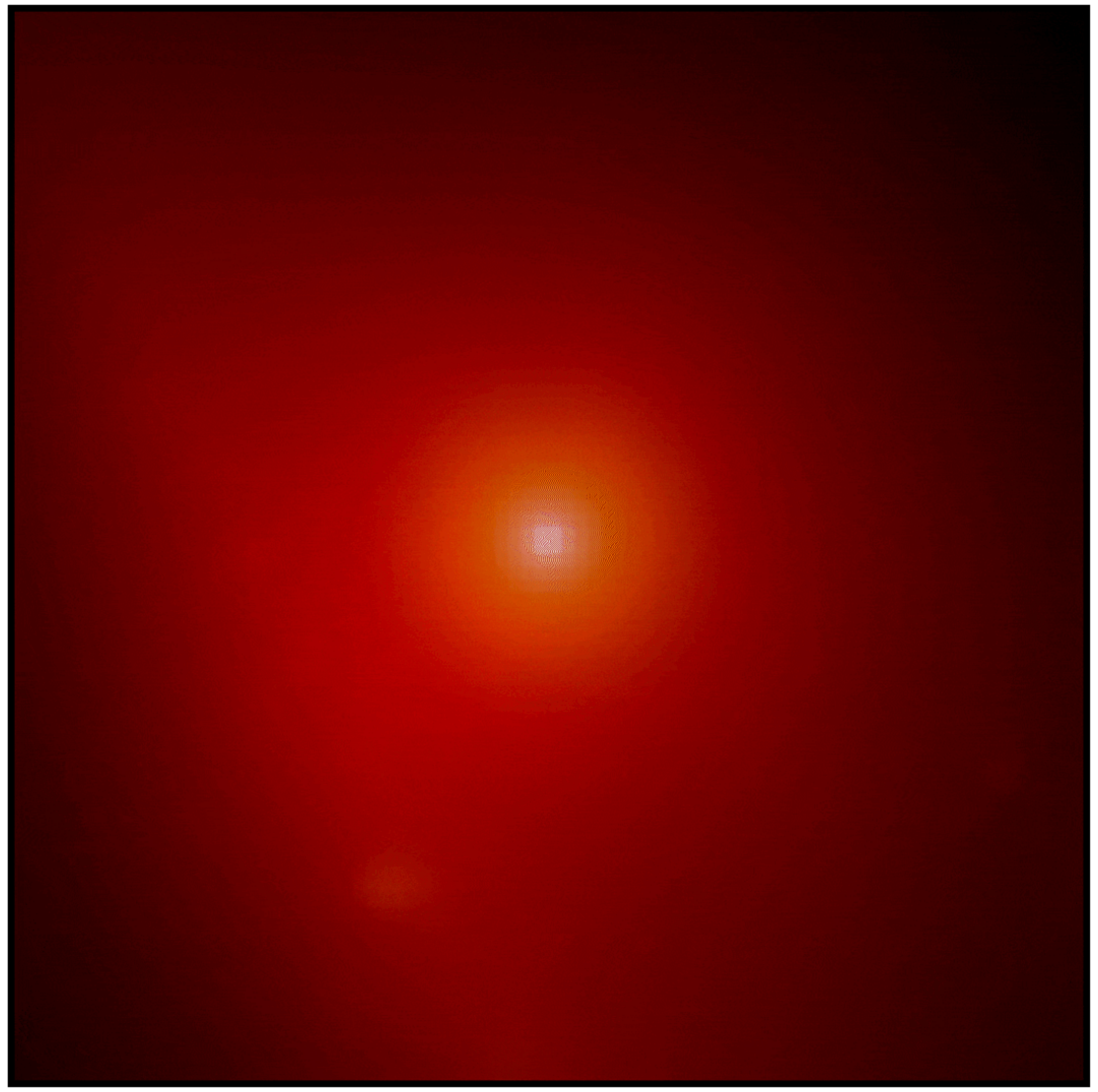

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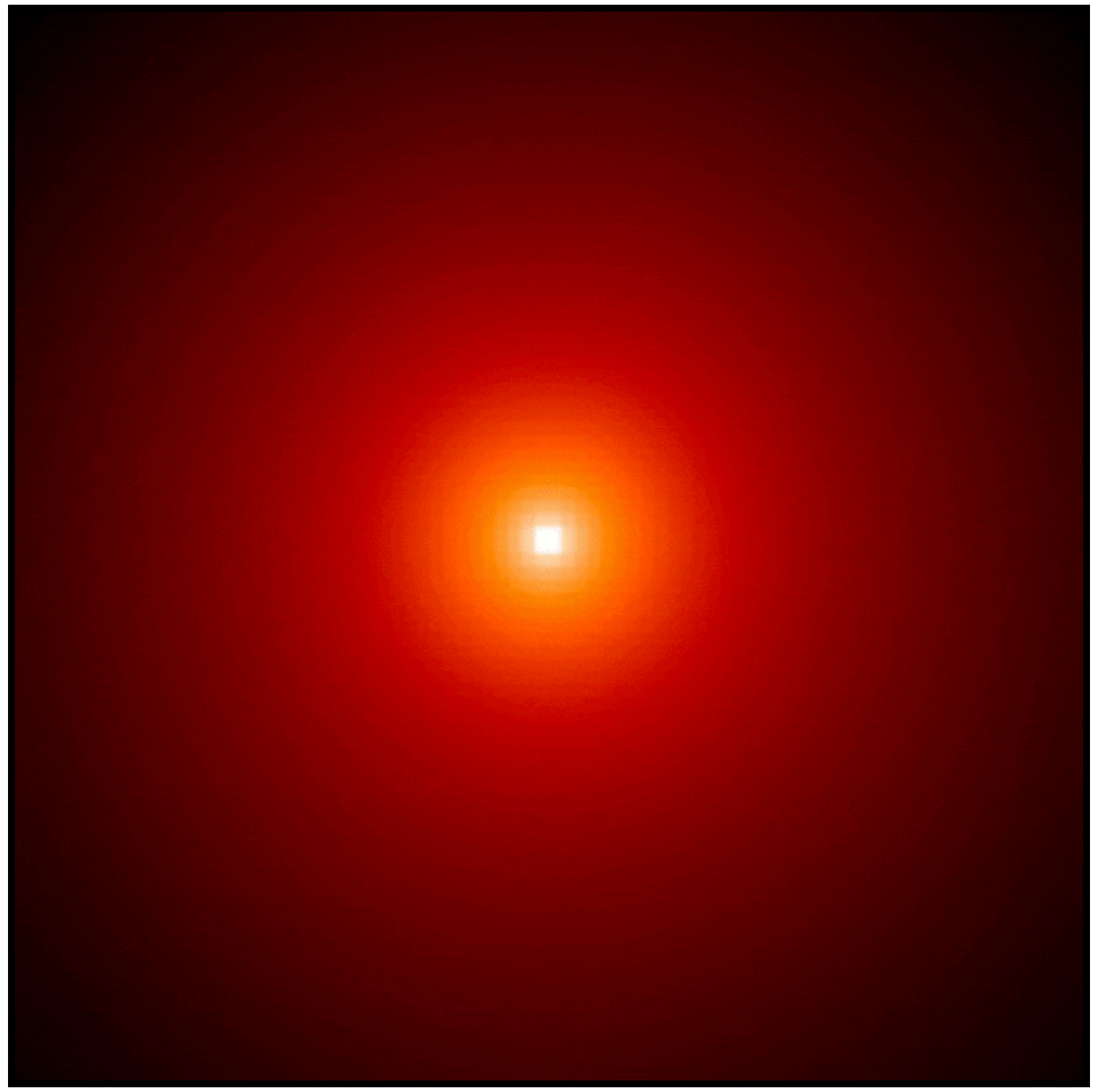

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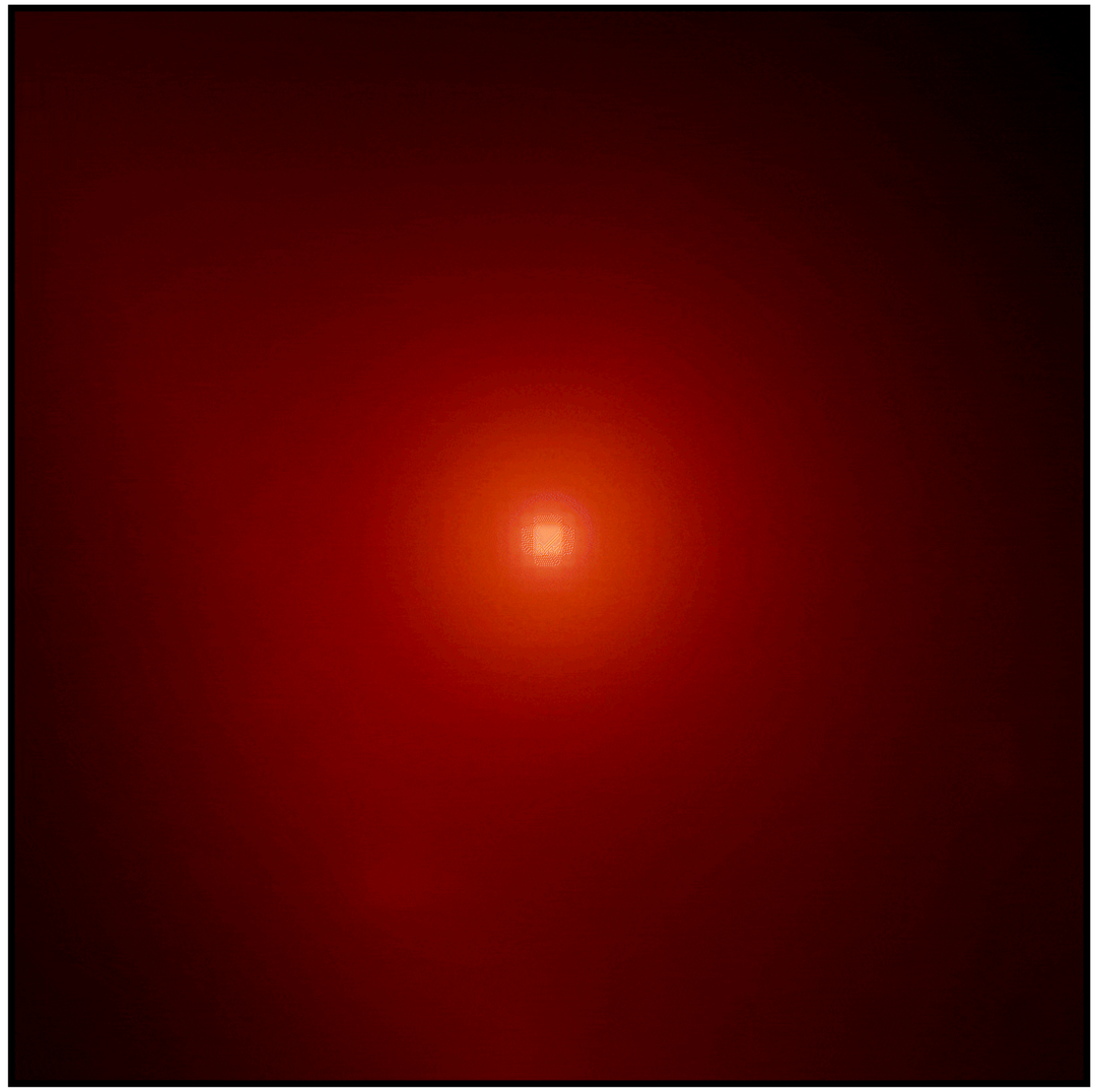

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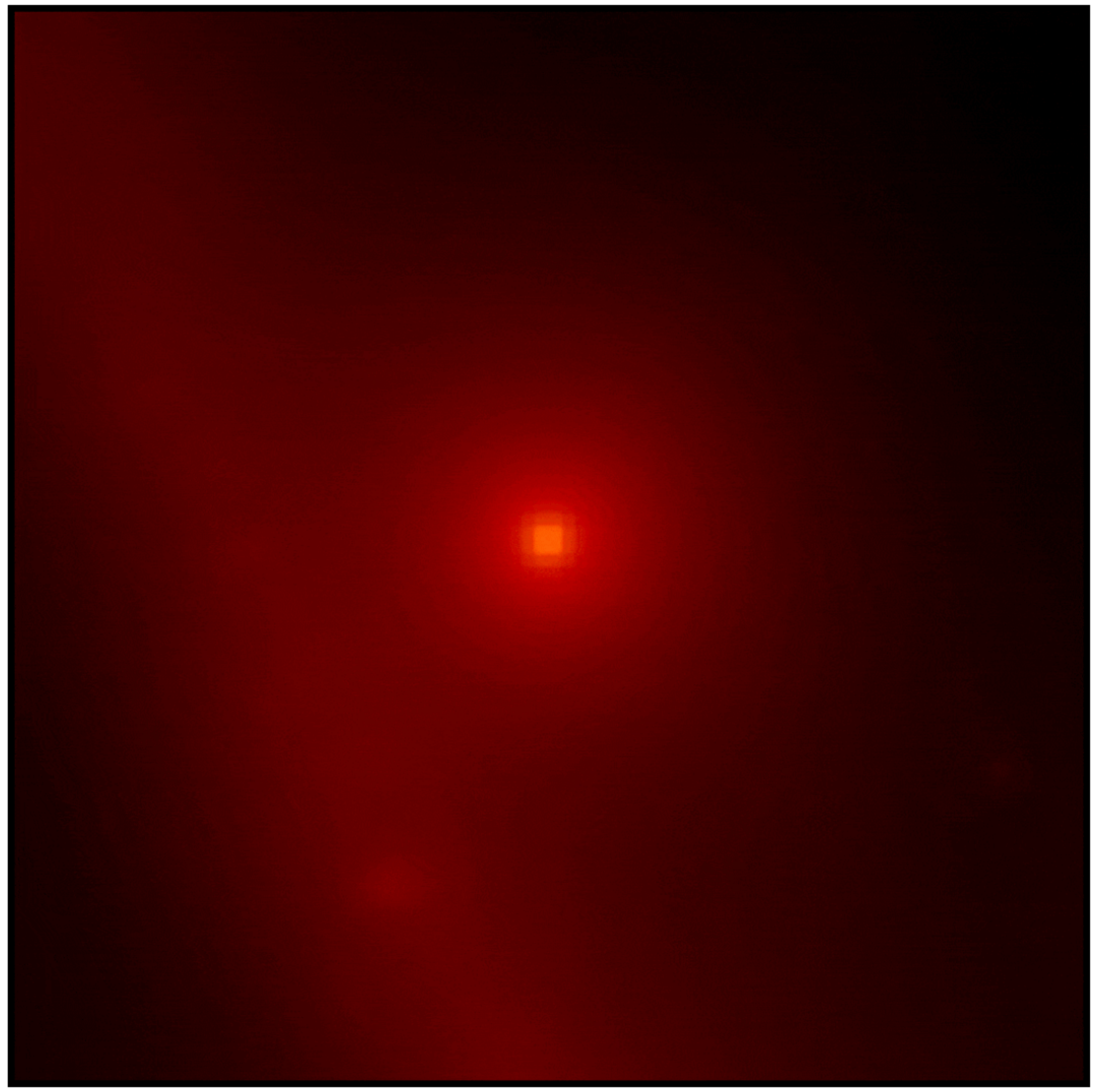

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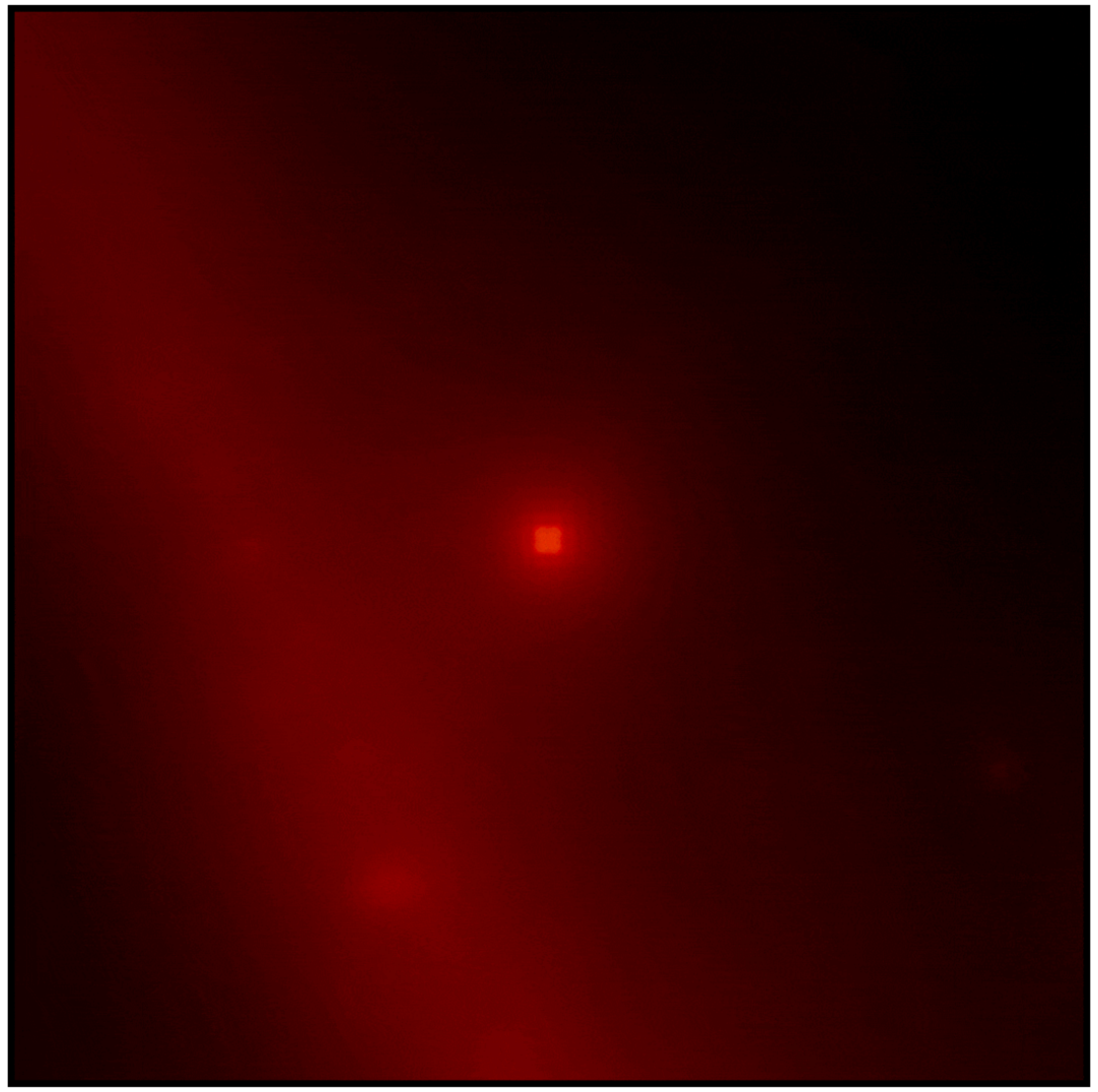

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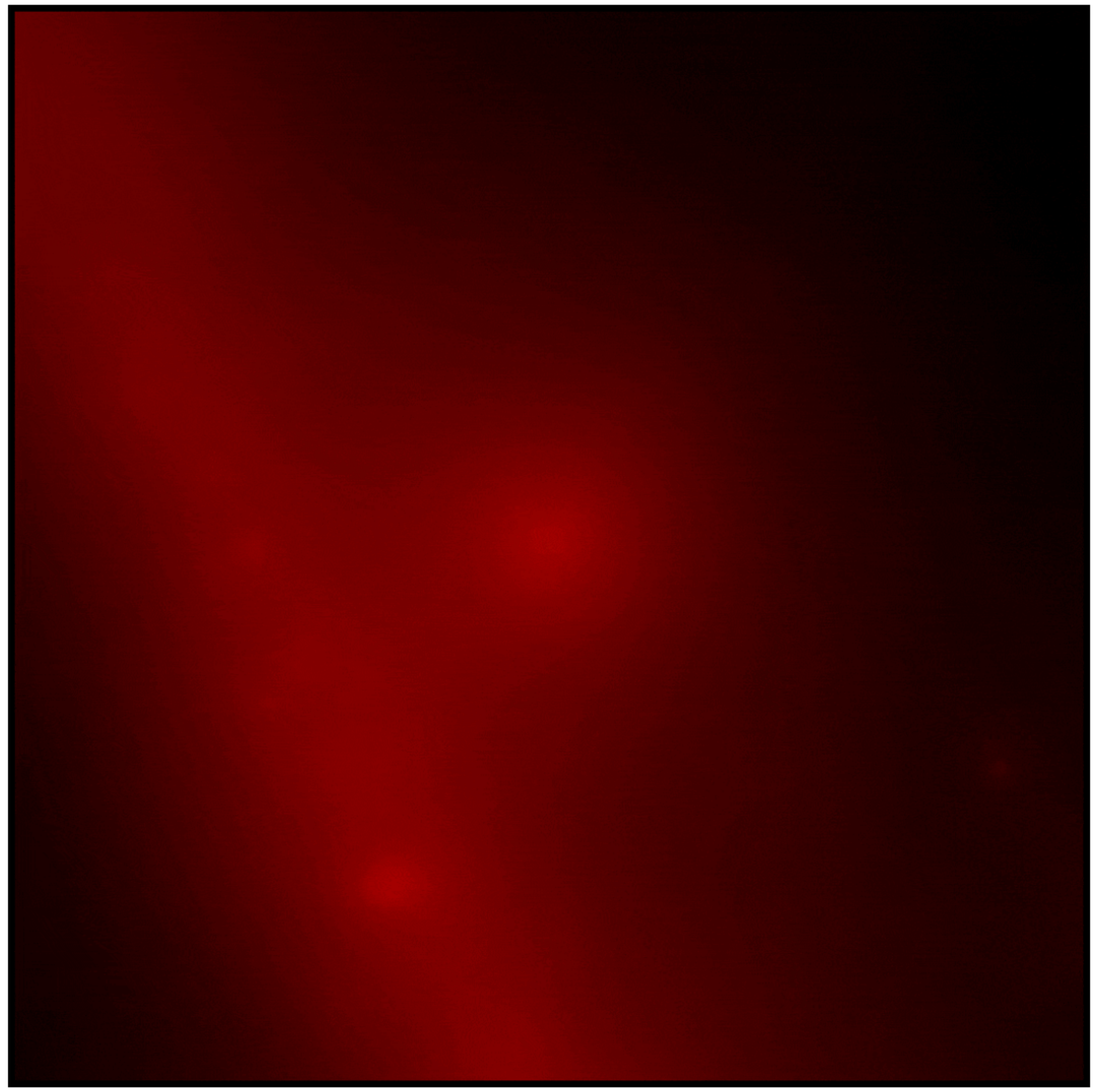

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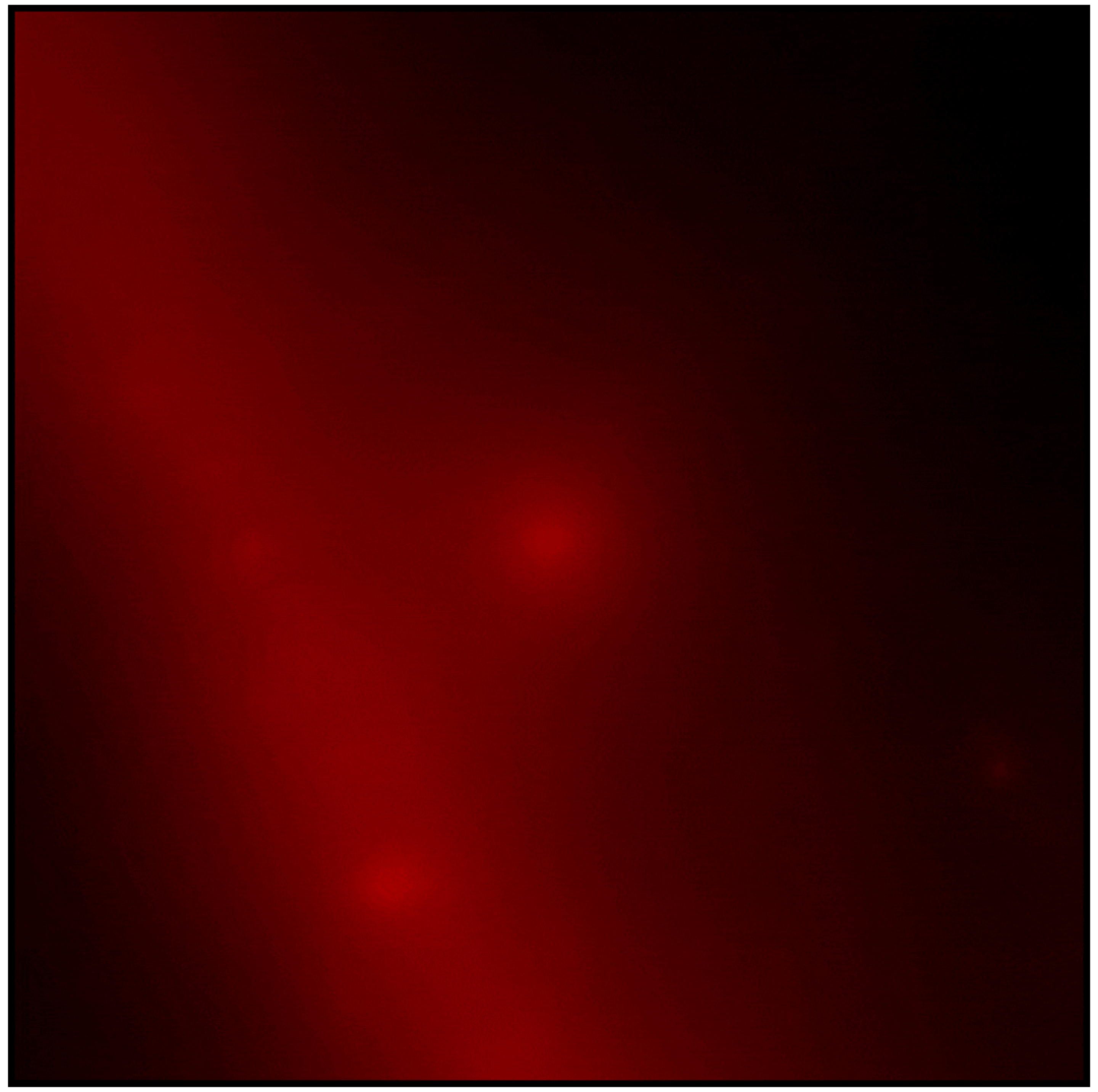

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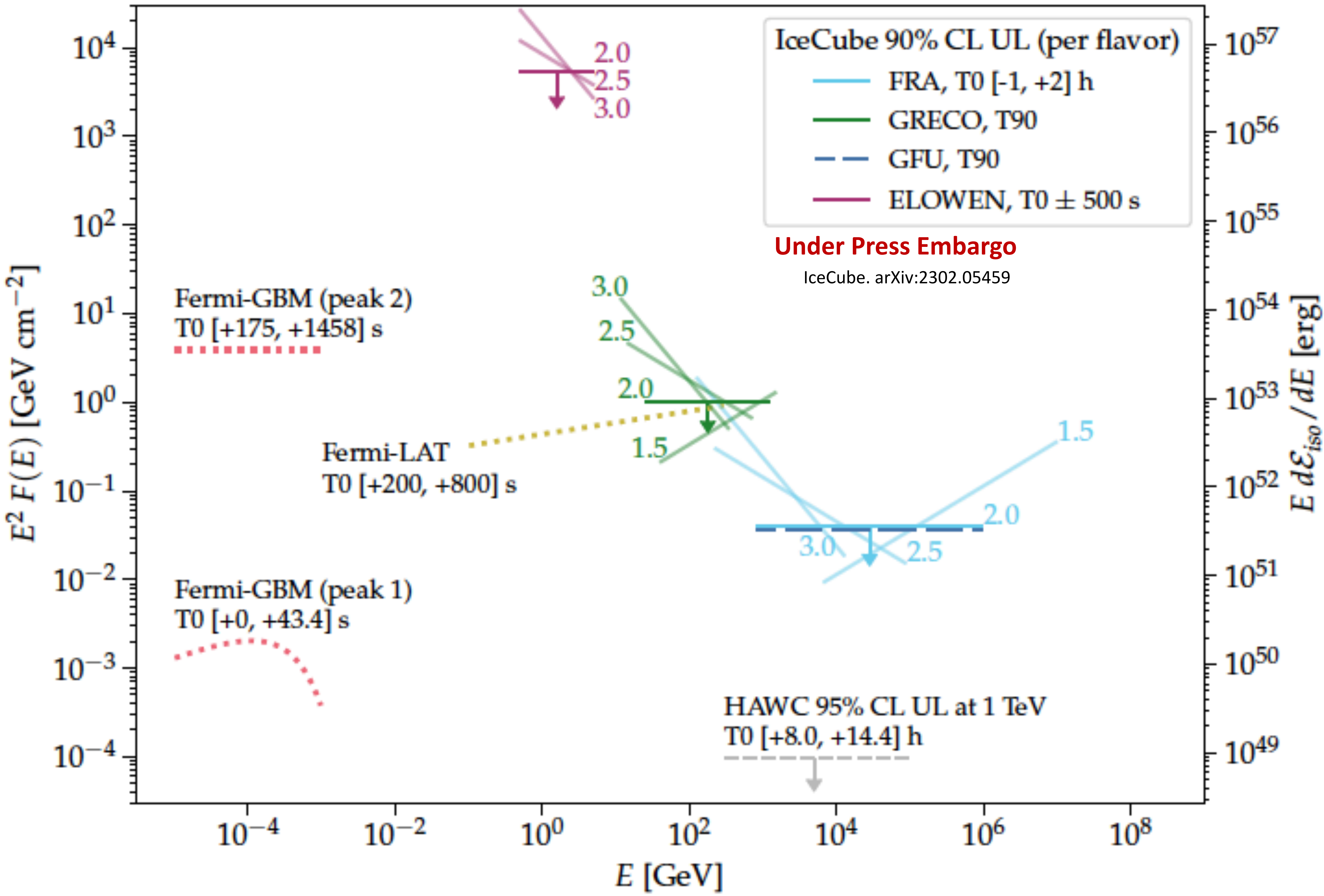

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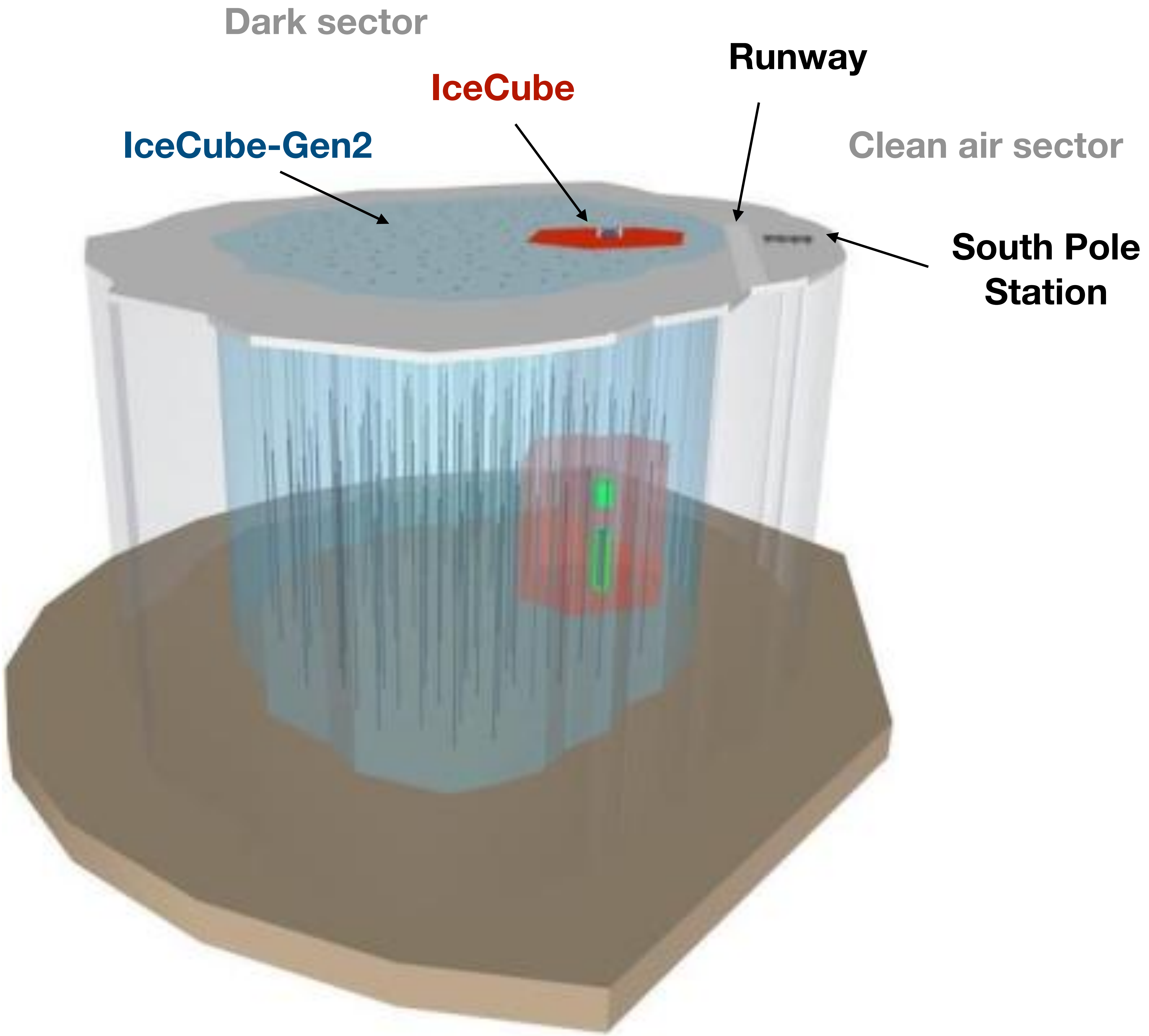
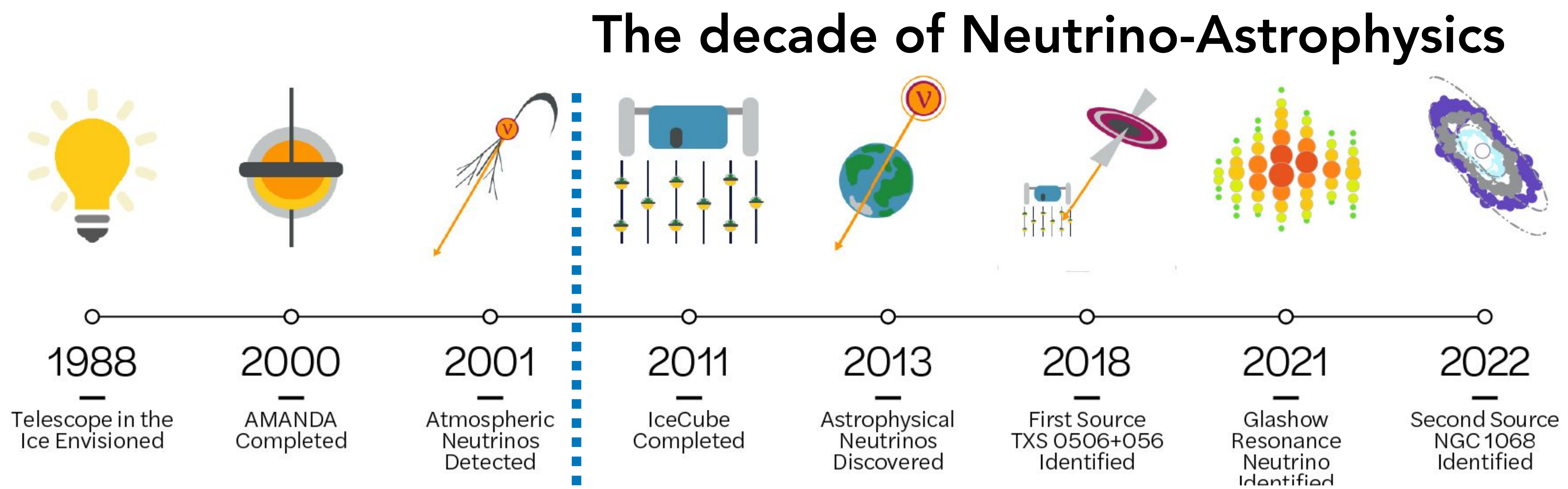
IceCube Gen-2

- analyses of astrophysical neutrinos heavily limited by statistics
- aim to increase effective area by factor of ~10
  - by larger volume
  - more effective veto strategies
  - better sensors
- targeting 2030



Summary and outlook

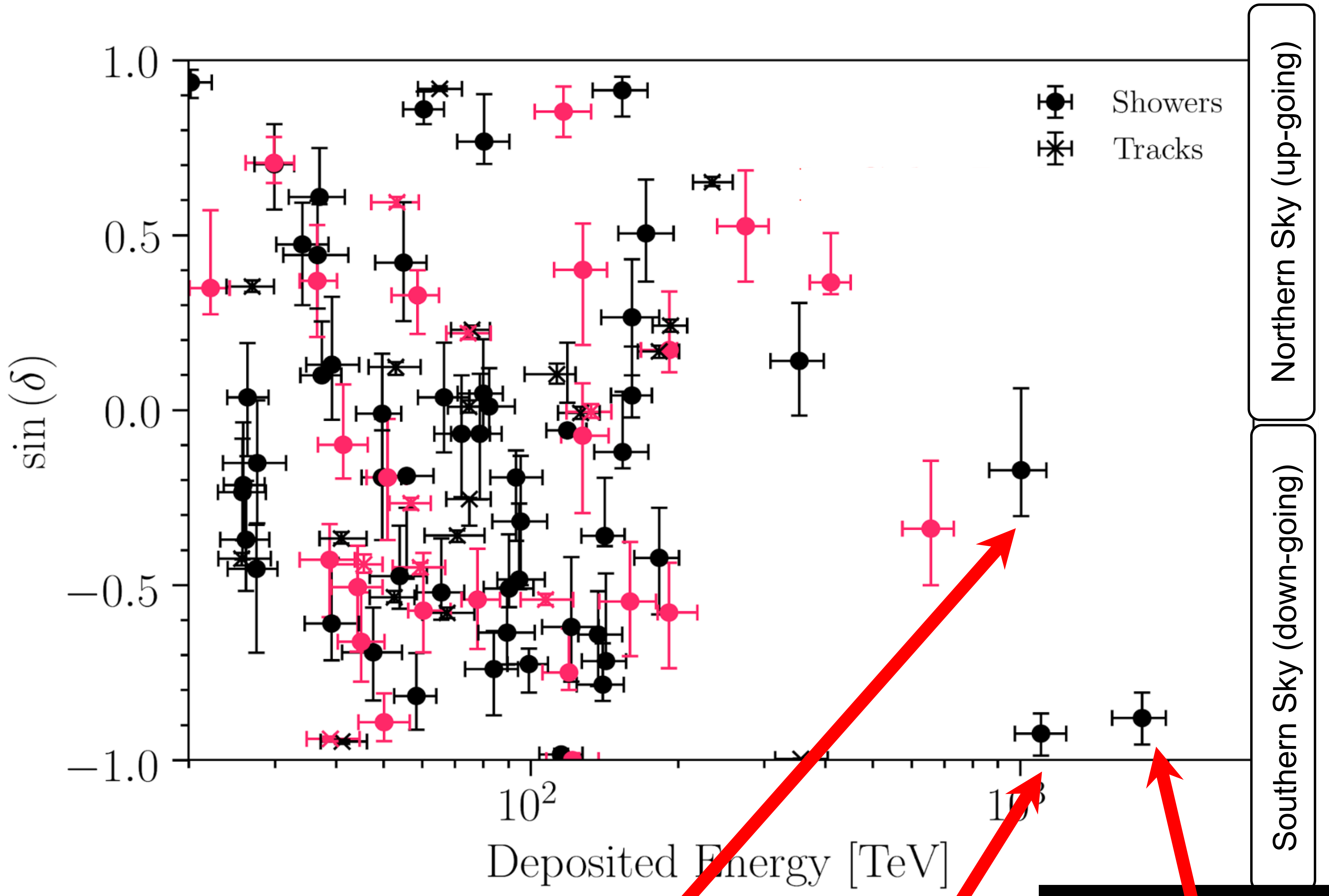


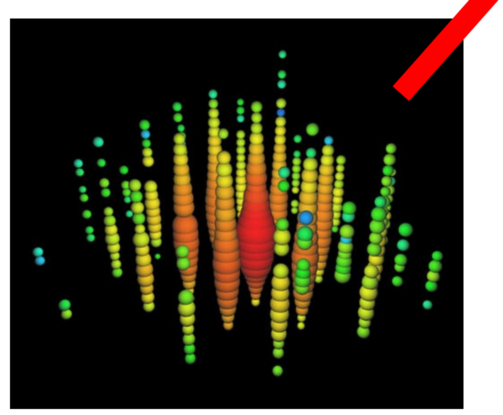
- 1 decade of astrophysical diffuse neutrino flux
  slowly narrowing the flux properties
- first evidences for sources → starting to derive source properties
  - blazar TXS 0506+056 (during & without flare)
  - nearby Seyfert galaxy NGC1068
- multi-messenger astronomy: real-time alarms, follow-ups and fast response analyses established (GW not covered today)

Backup

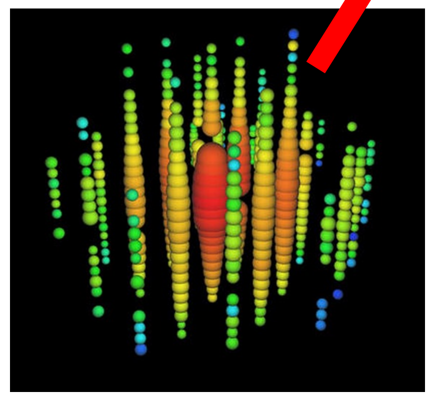
First astrophysical neutrinos

First observation (2013)
- 60-2000 TeV neutrinos

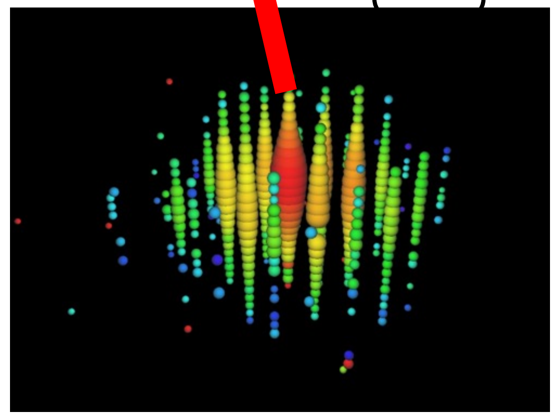




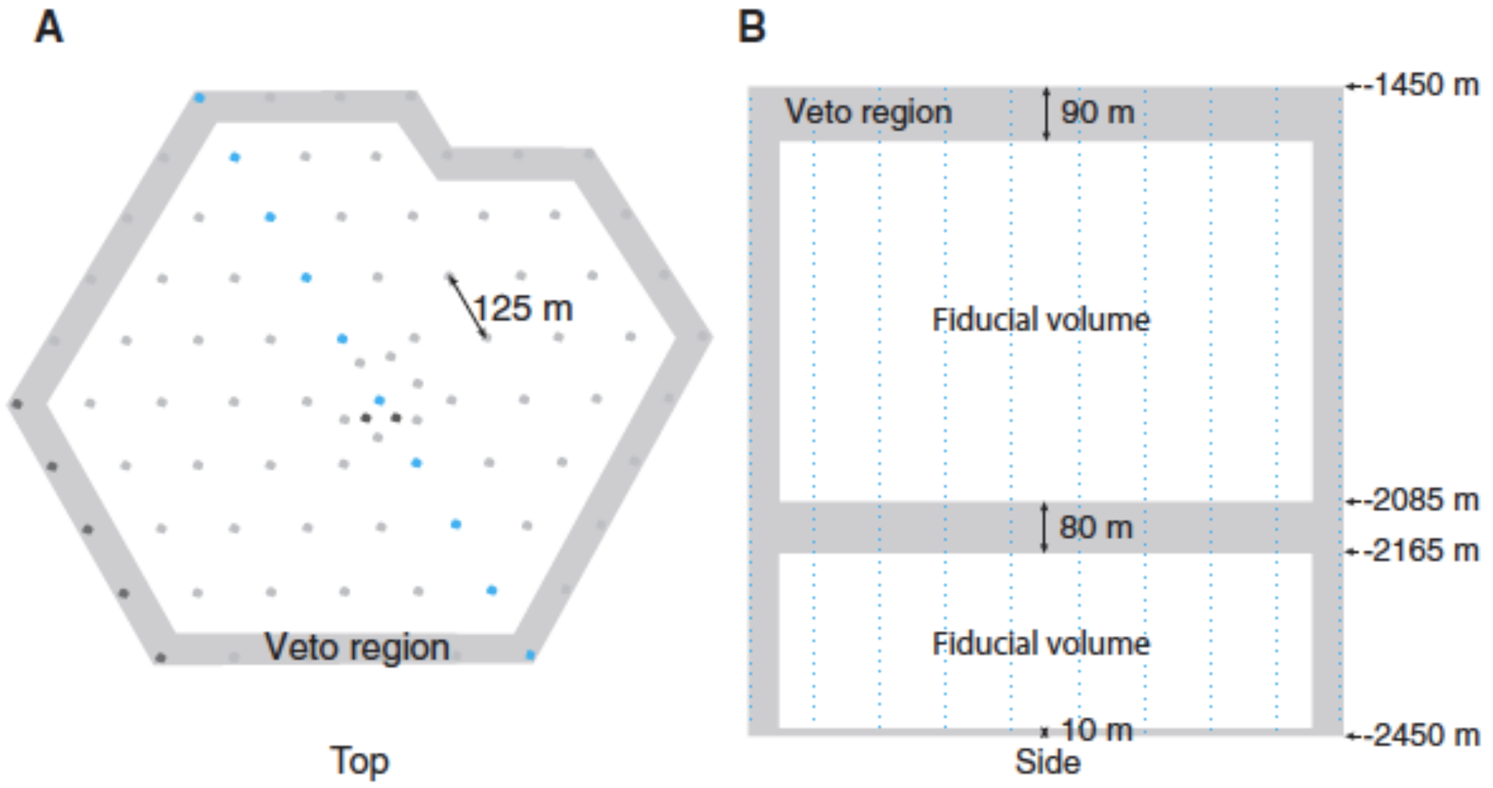
"Bert"
1.1 PeV

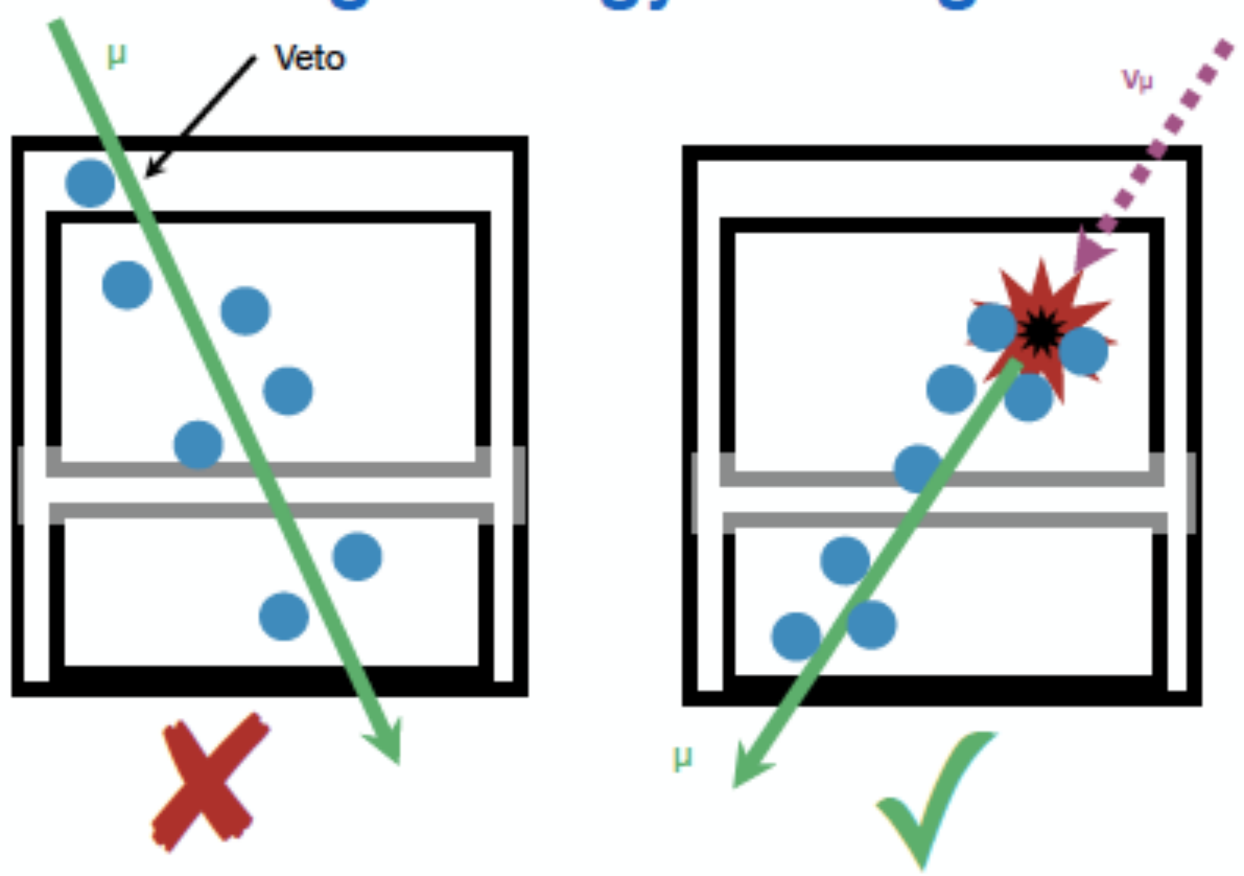


"Ernie"
1.0 PeV



"Big Bird"
2.0 PeV





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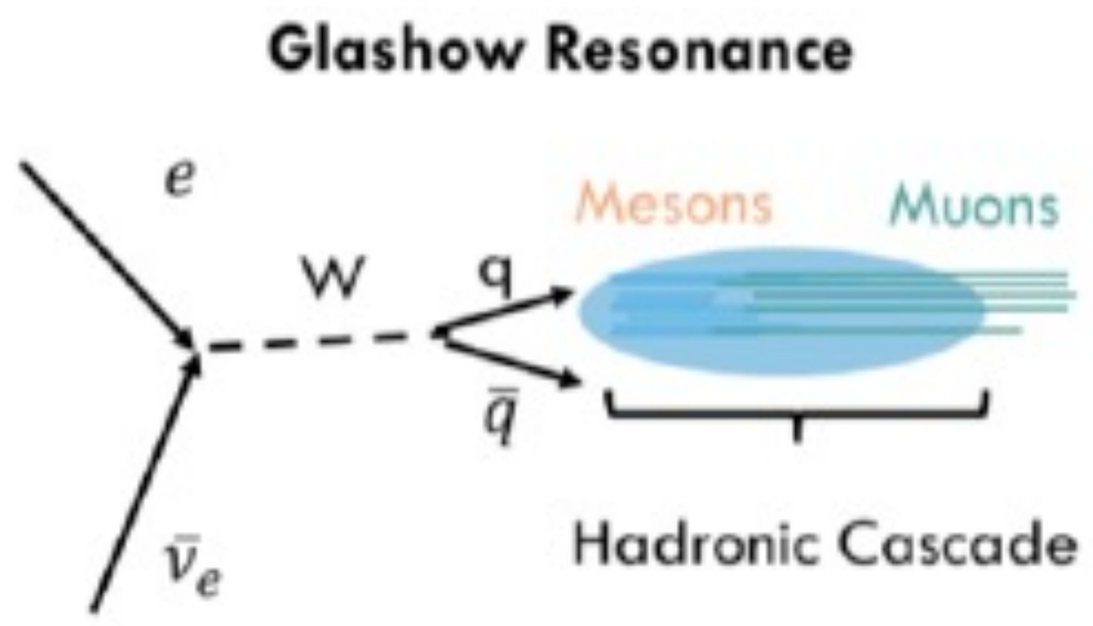
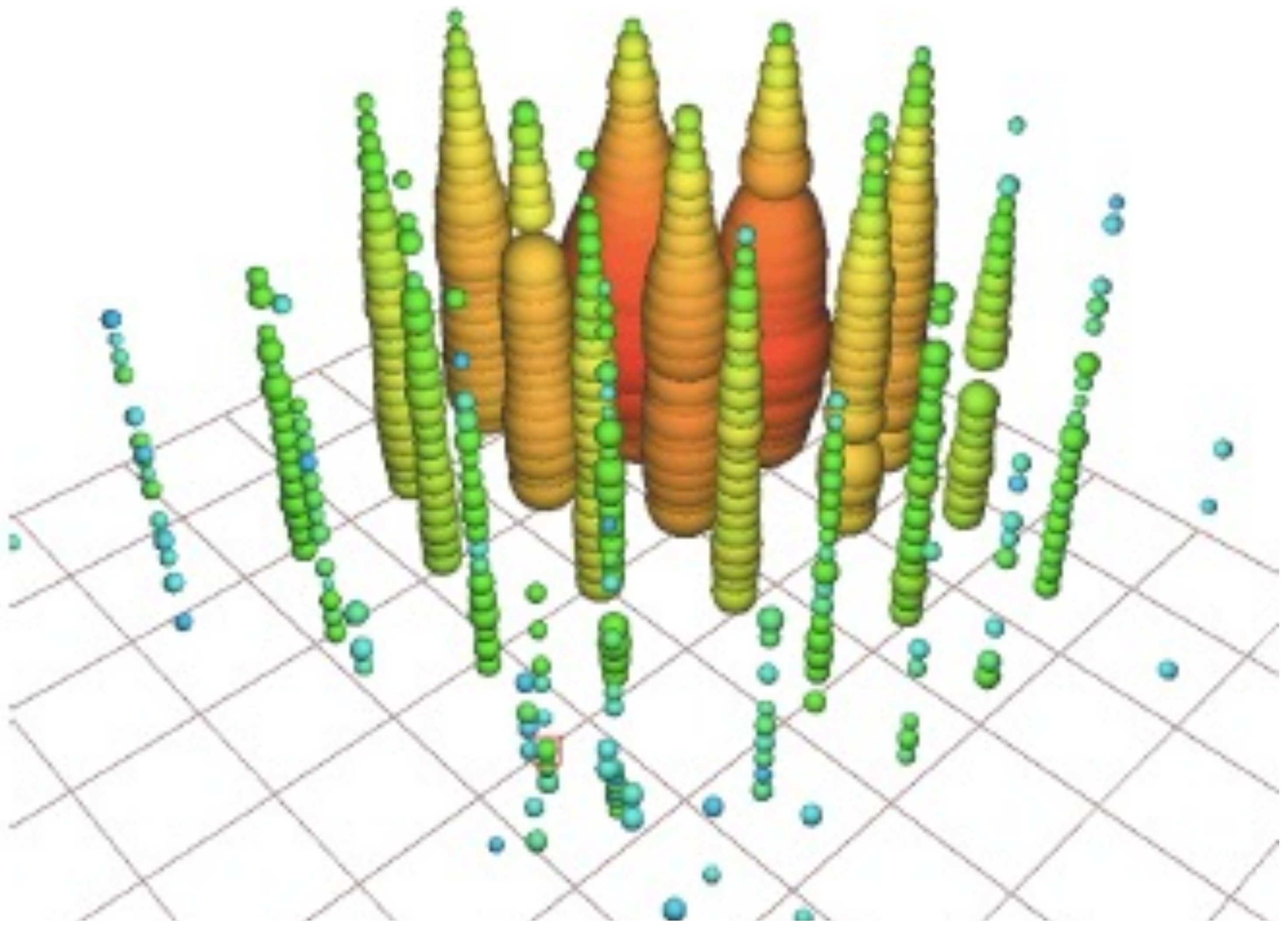
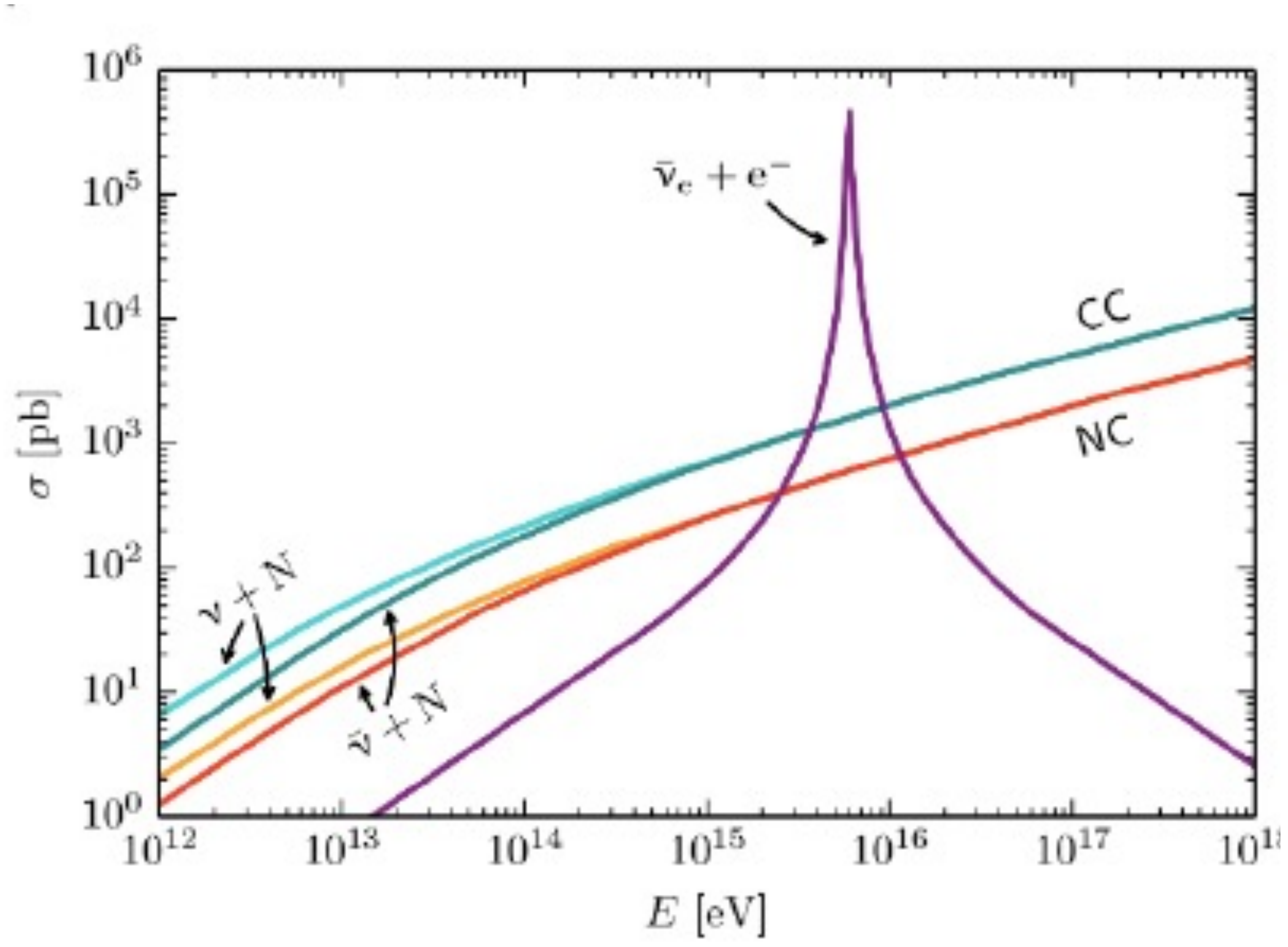
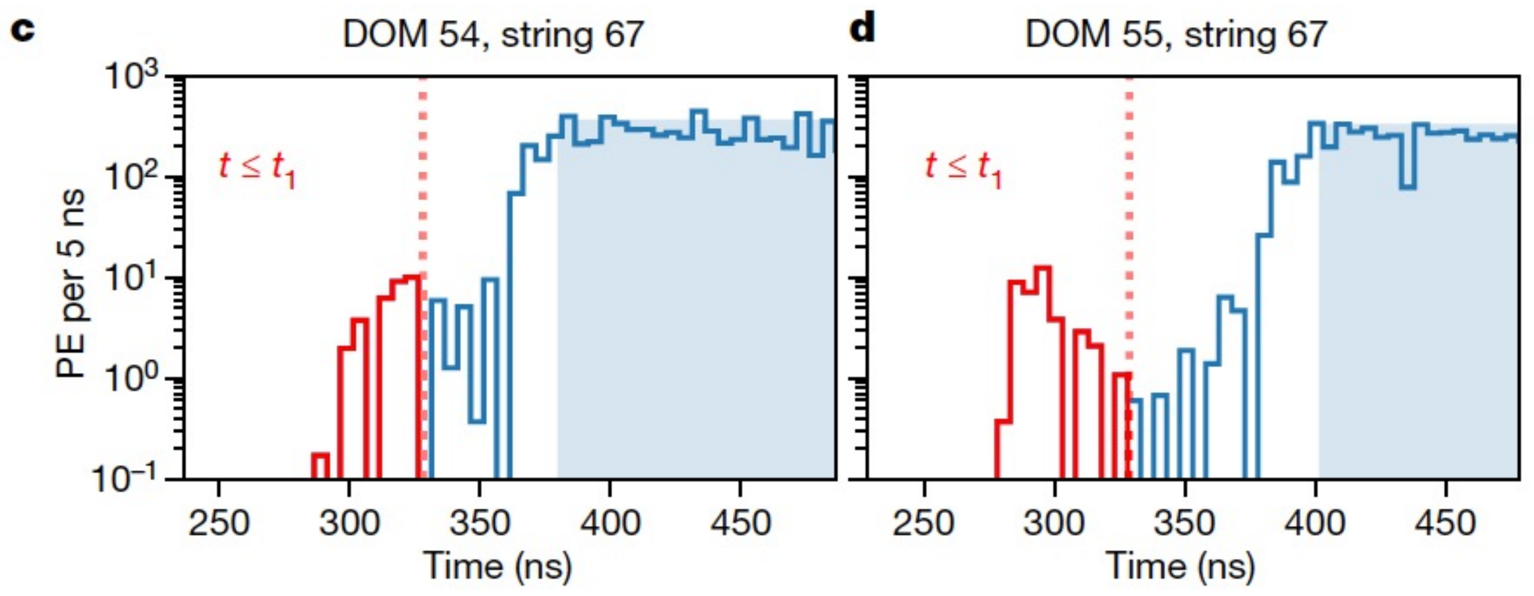
Glashow resonance



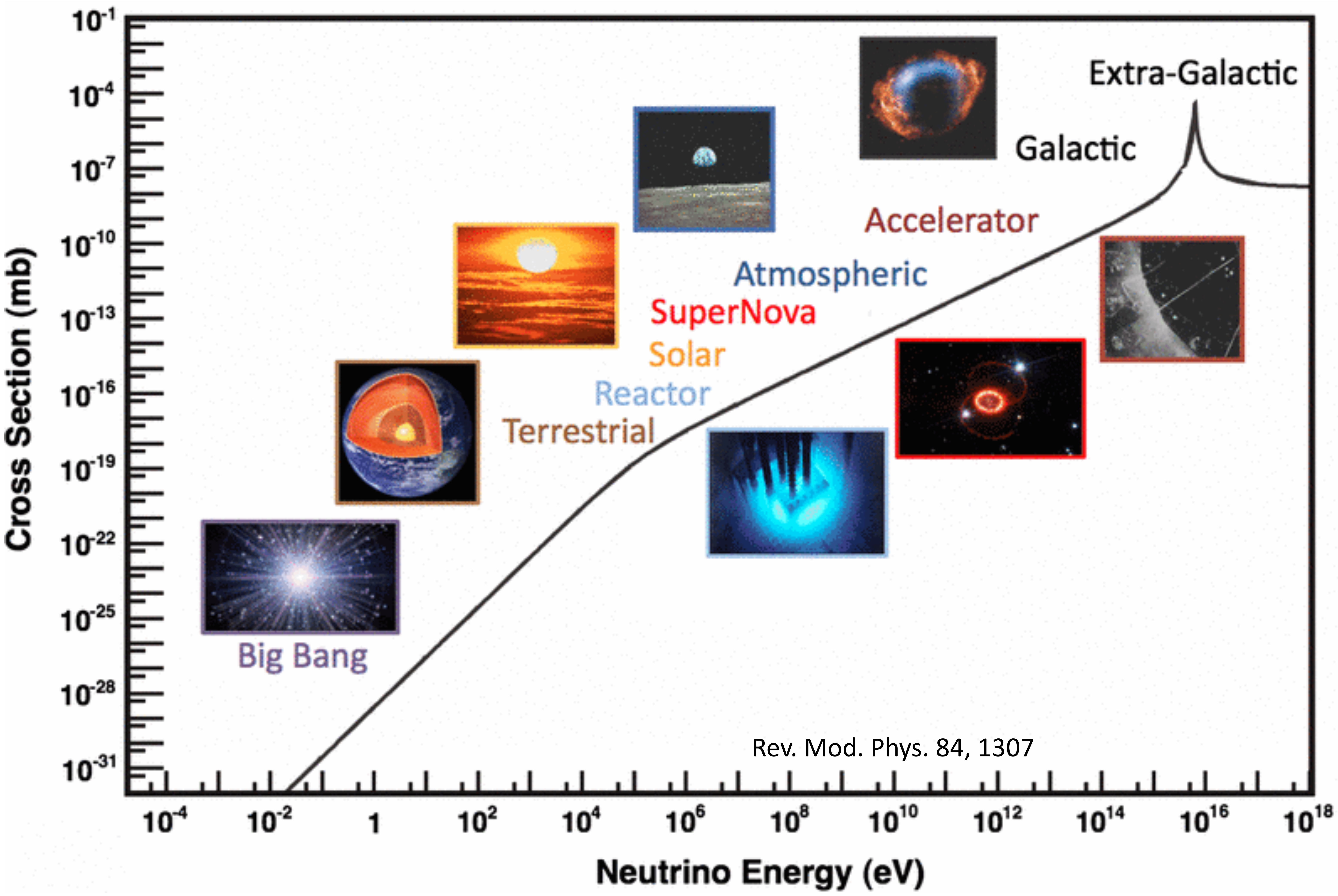
Hydrangea
- Partially contained
- Detected muon from faster than Cherenkov cone
- 5.9±0.2 PeV







Neutrino production

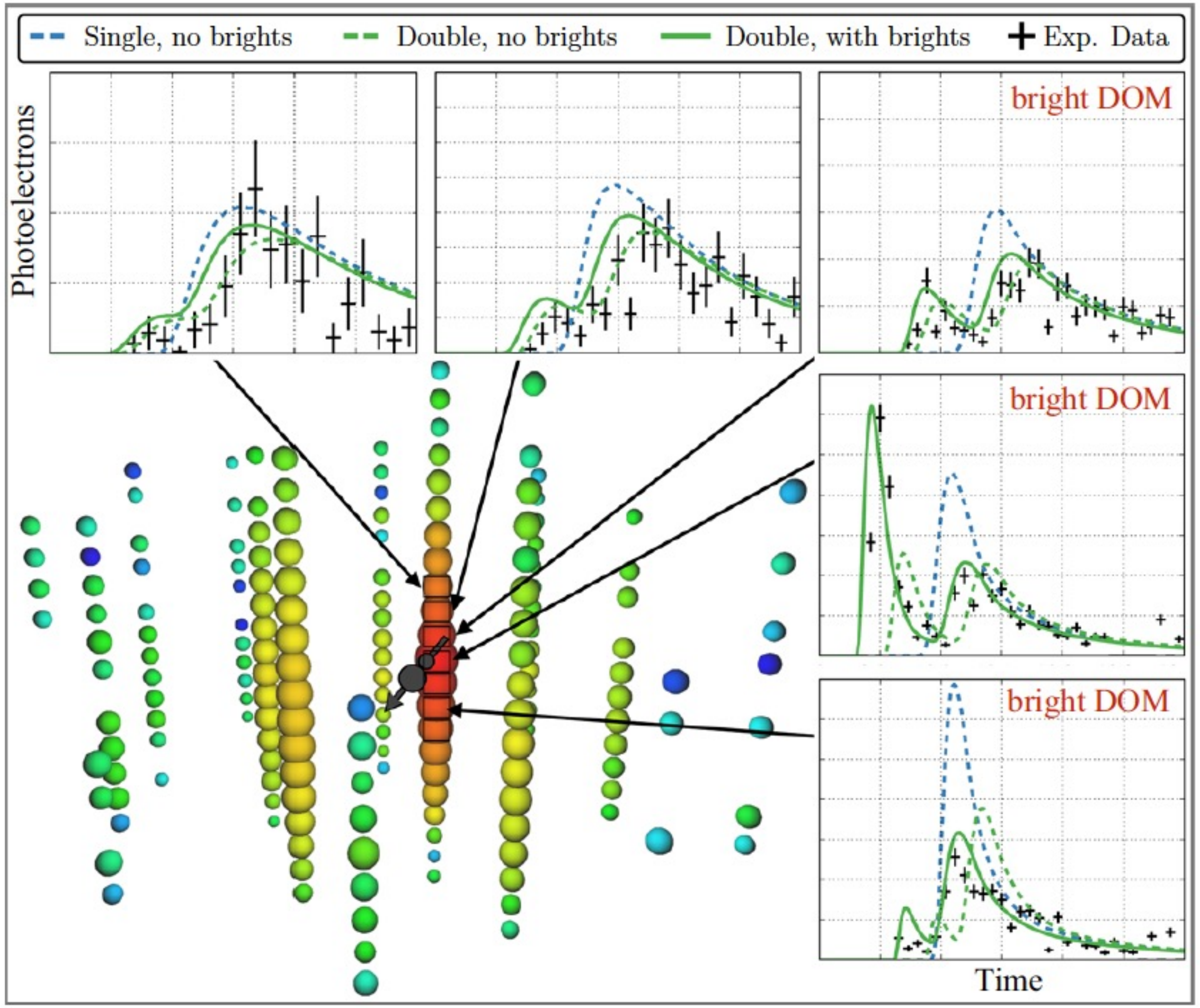


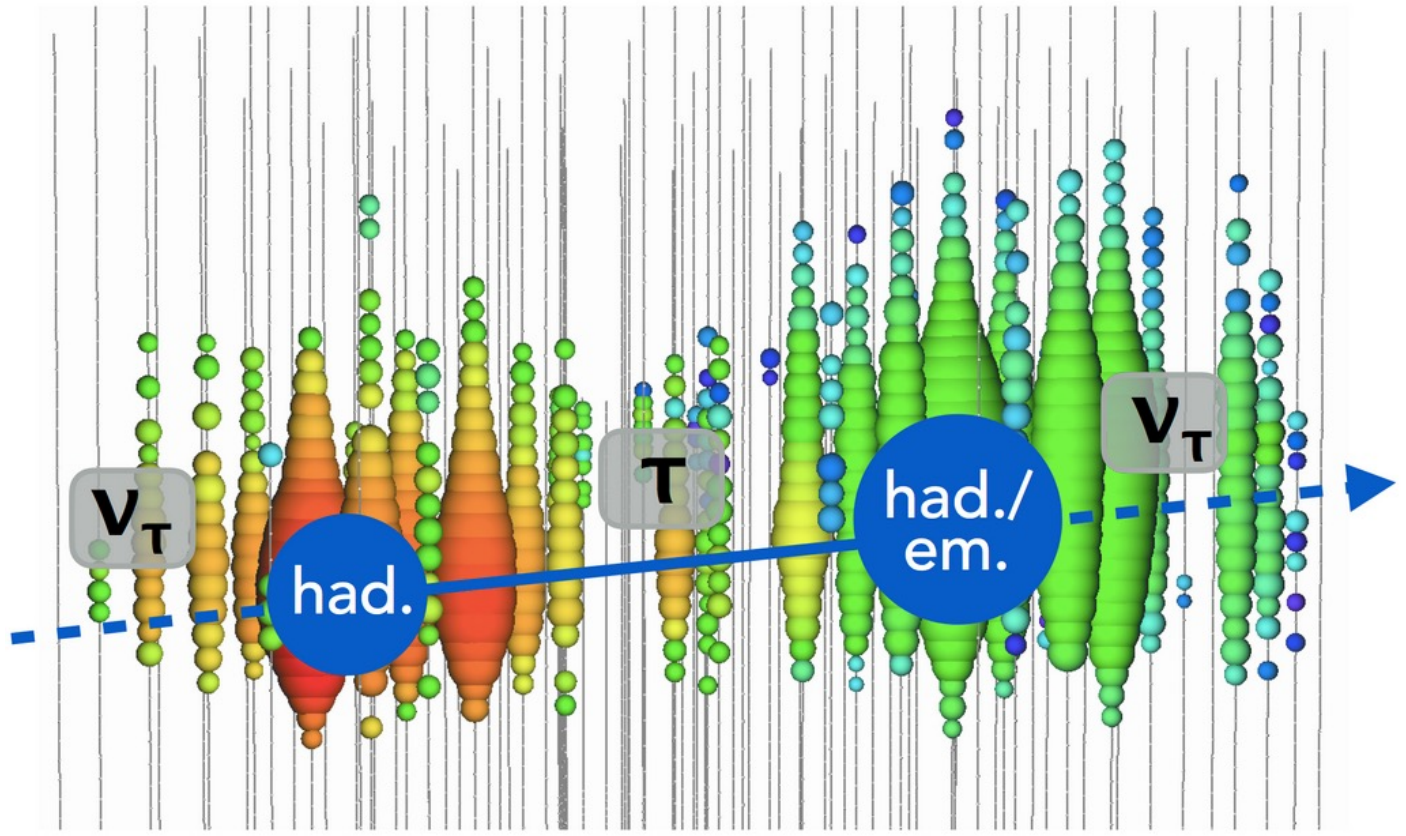
Tau neutrino identification

Double Double

- newly discovered tau neutrino candidate

“Double bang” is rare (~50m xE/1PeV)



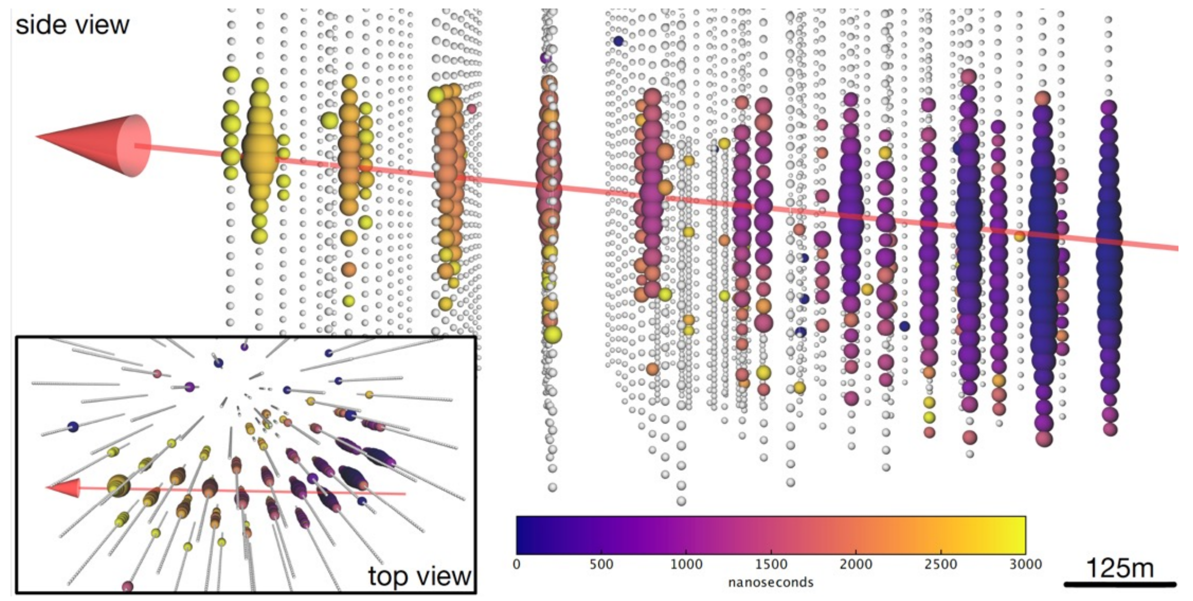


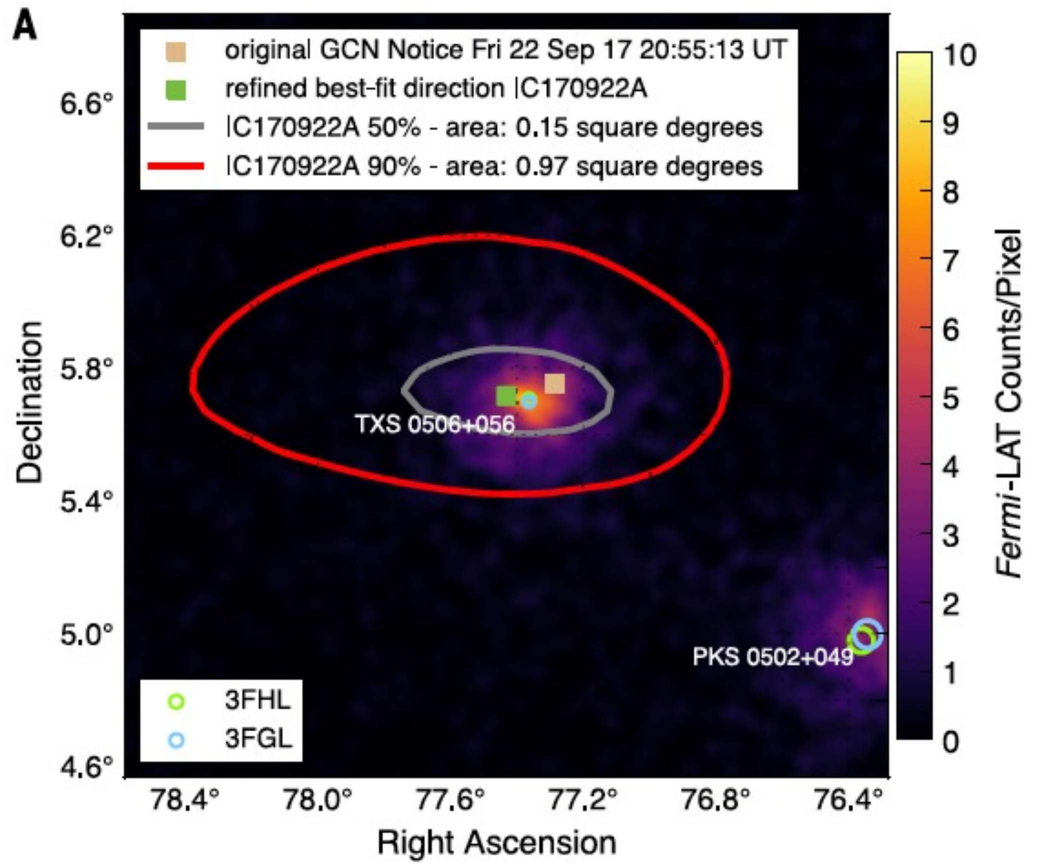
Double pulse can be found using timing information.

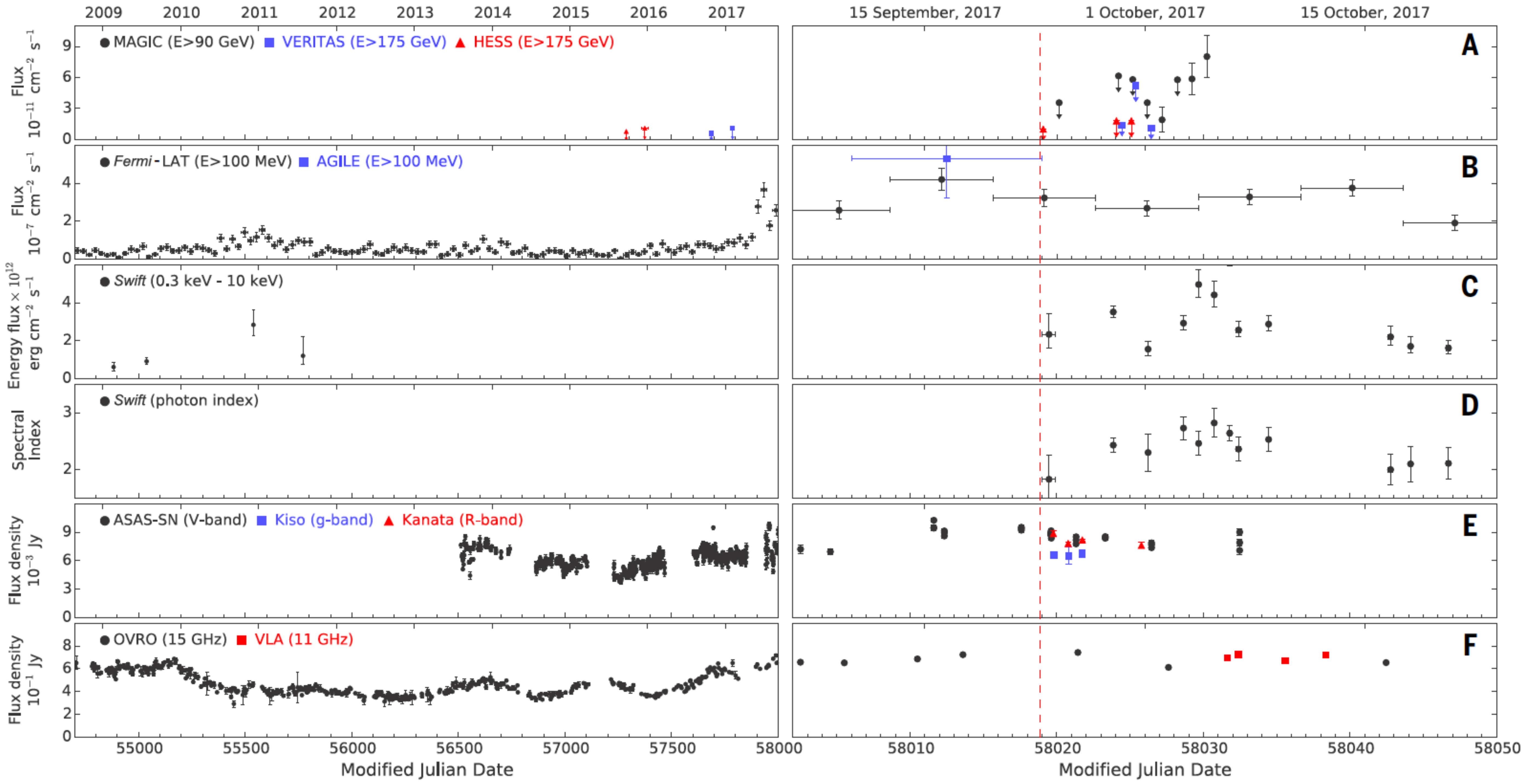
Improved tau PID algorithm is used for the flavour ratio

Alert follow up for TXS

290 TeV







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