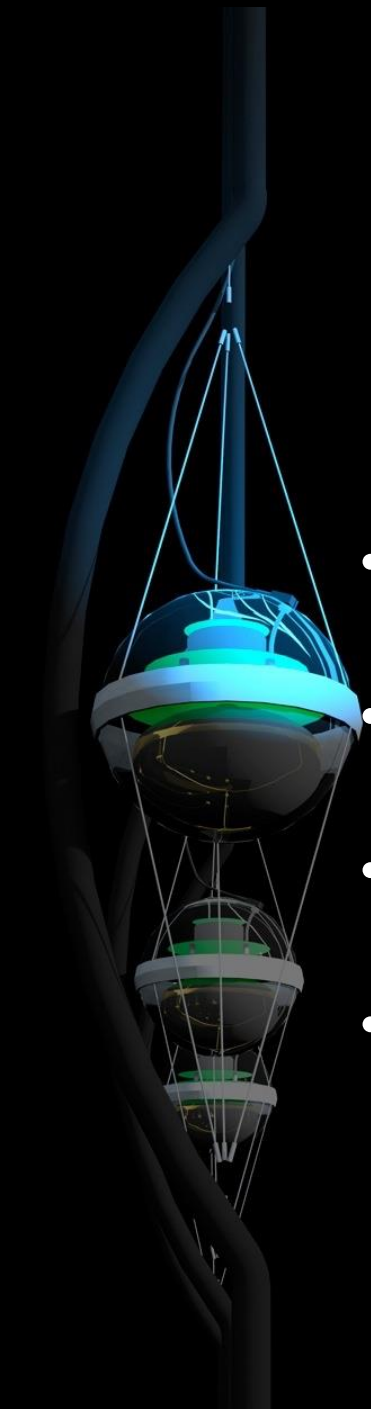
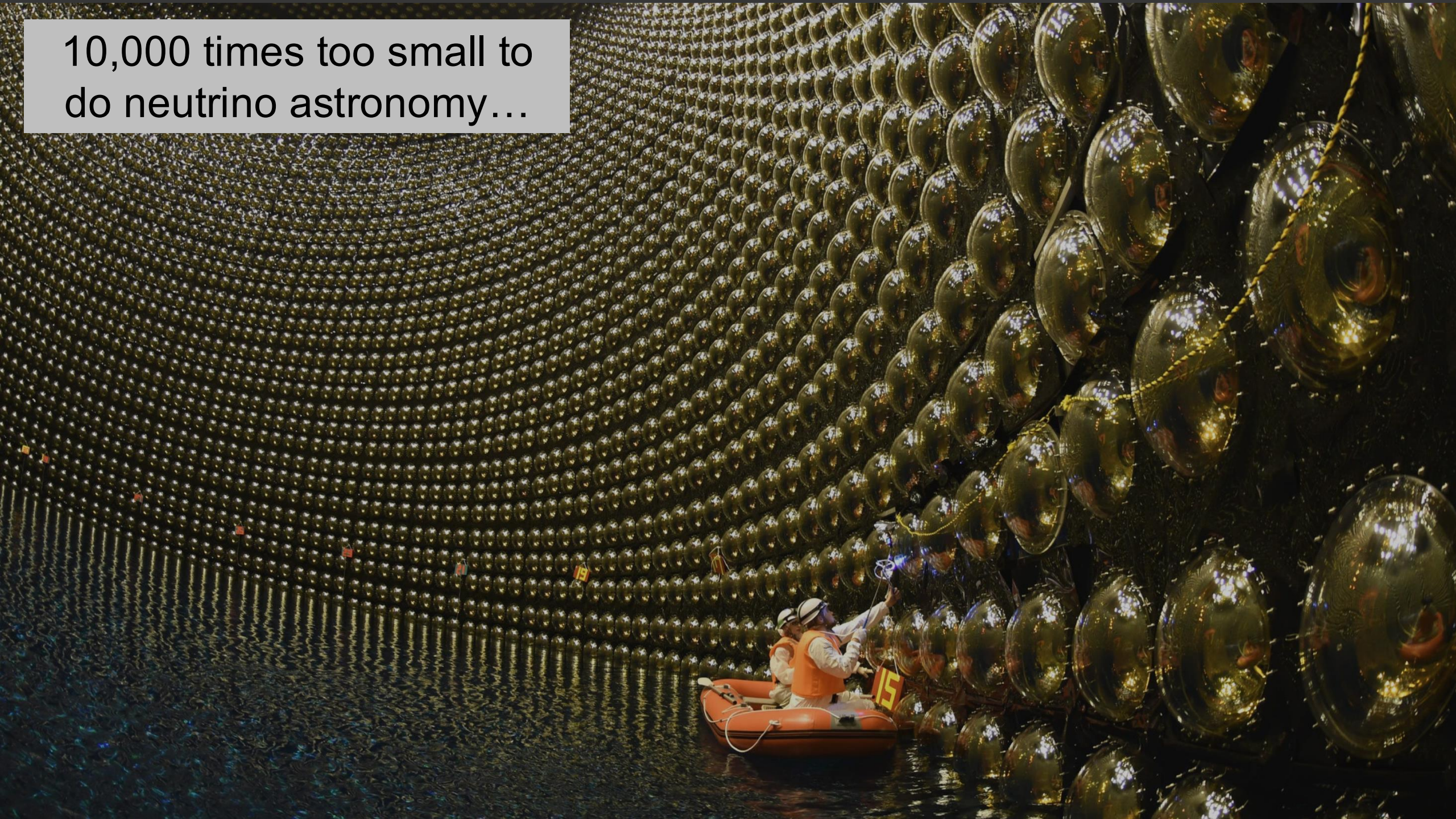
The First Decade of High-Energy Neutrino Astronomy and Neutrino Physics

francis halzen

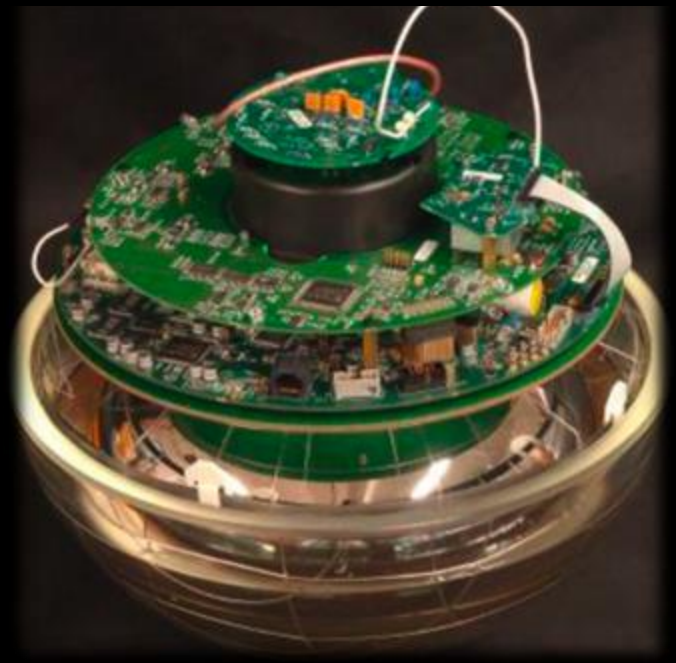


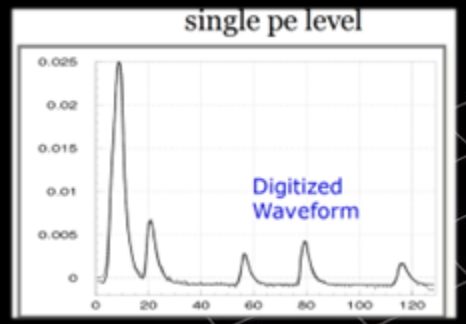
- from discovery to astronomy: there is a lot happening
- the high-energy neutrino sky and the discovery of the first neutrino sources
- KM3NeT: a 220 PeV neutrino!
- neutrino physics at PeV energy

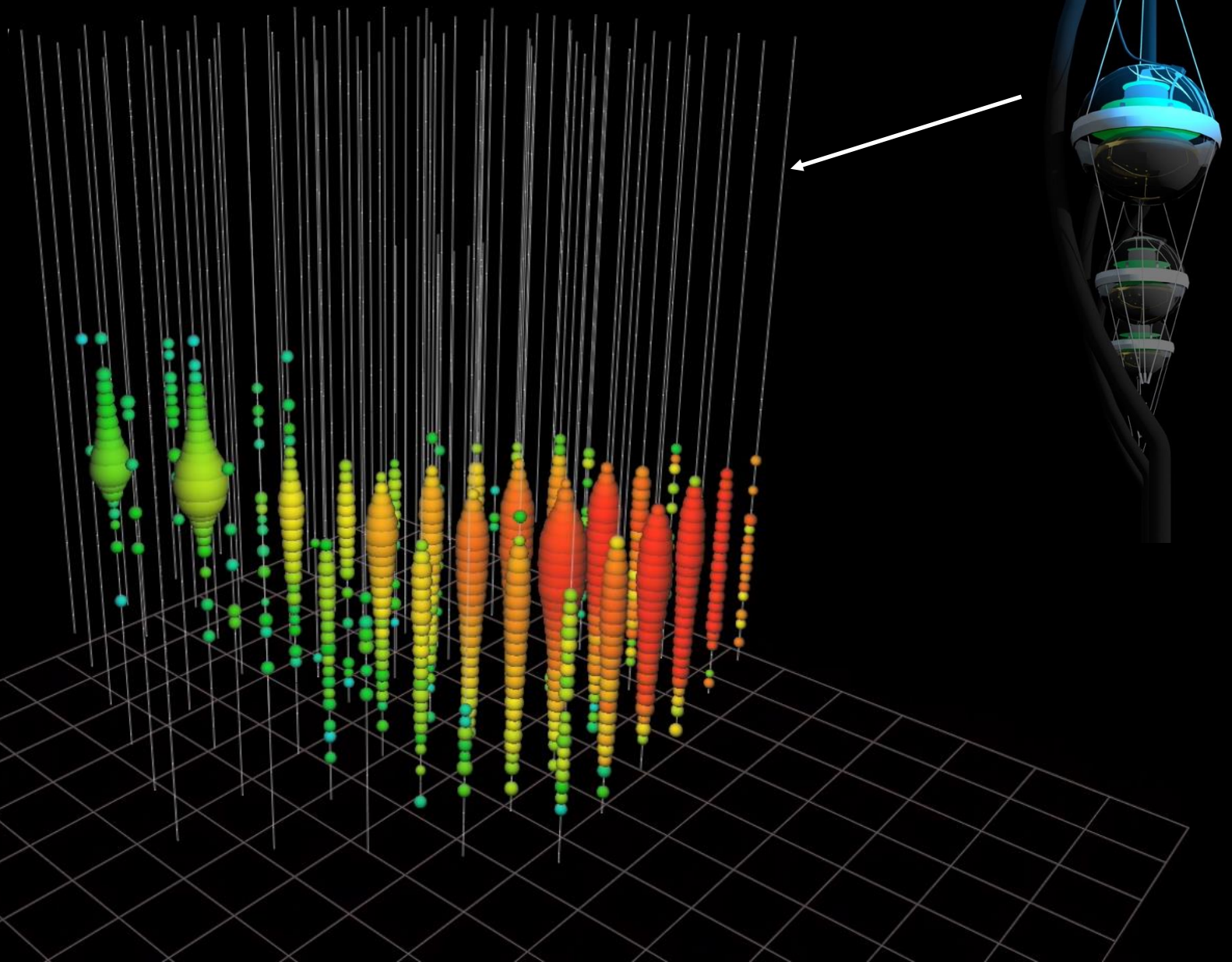
IceCube.wisc.edu


10,000 times too small to
do neutrino astronomy…

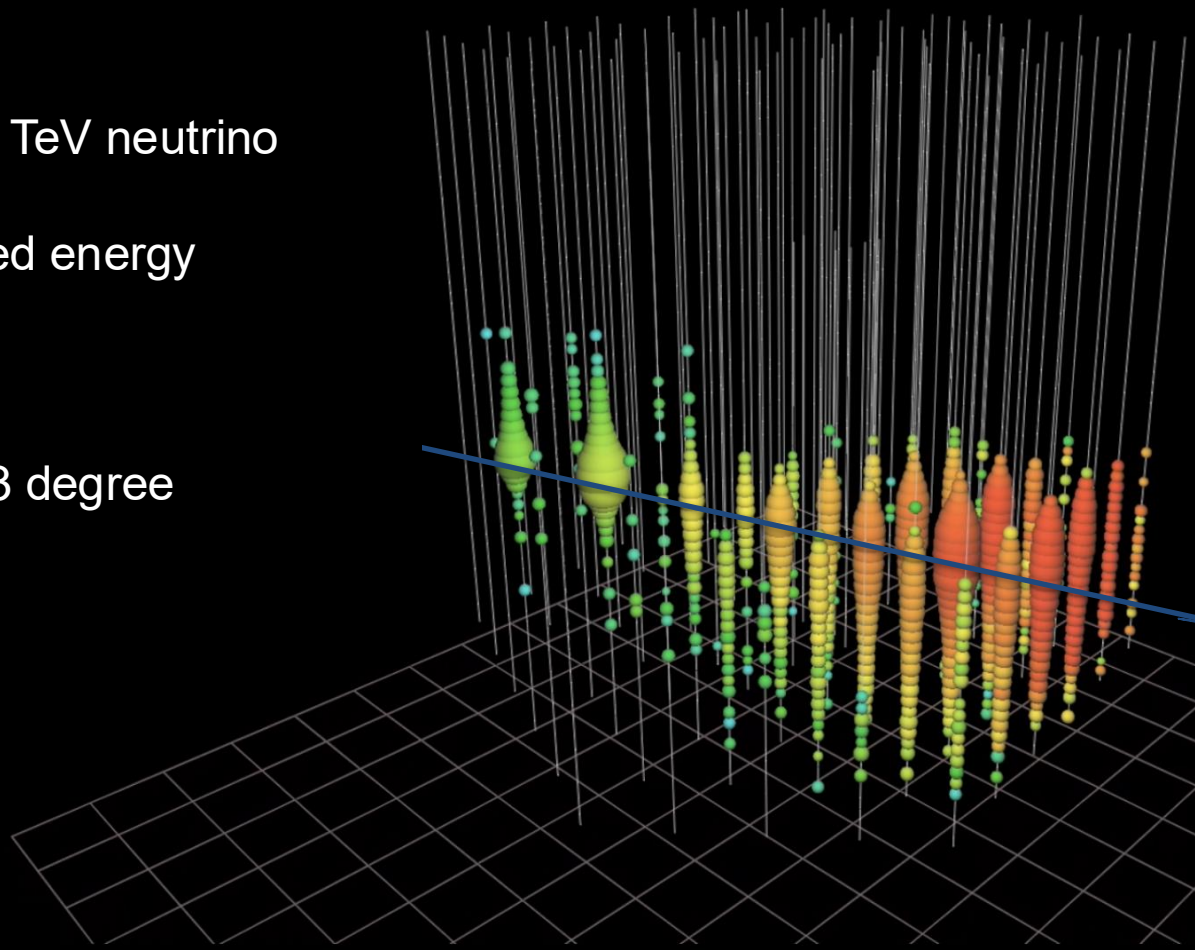
1 km^3 of Antarctic ice instrumented with 5160 PMT (10inch) below 1450m

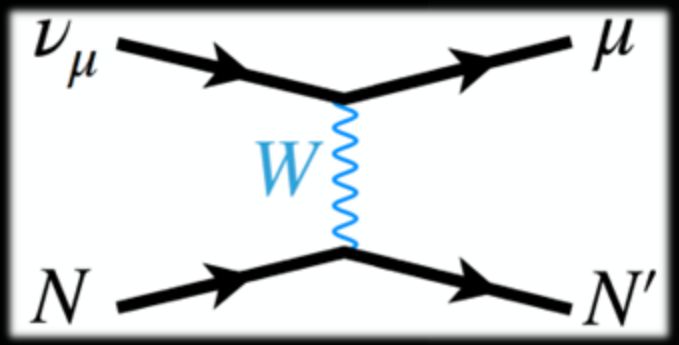




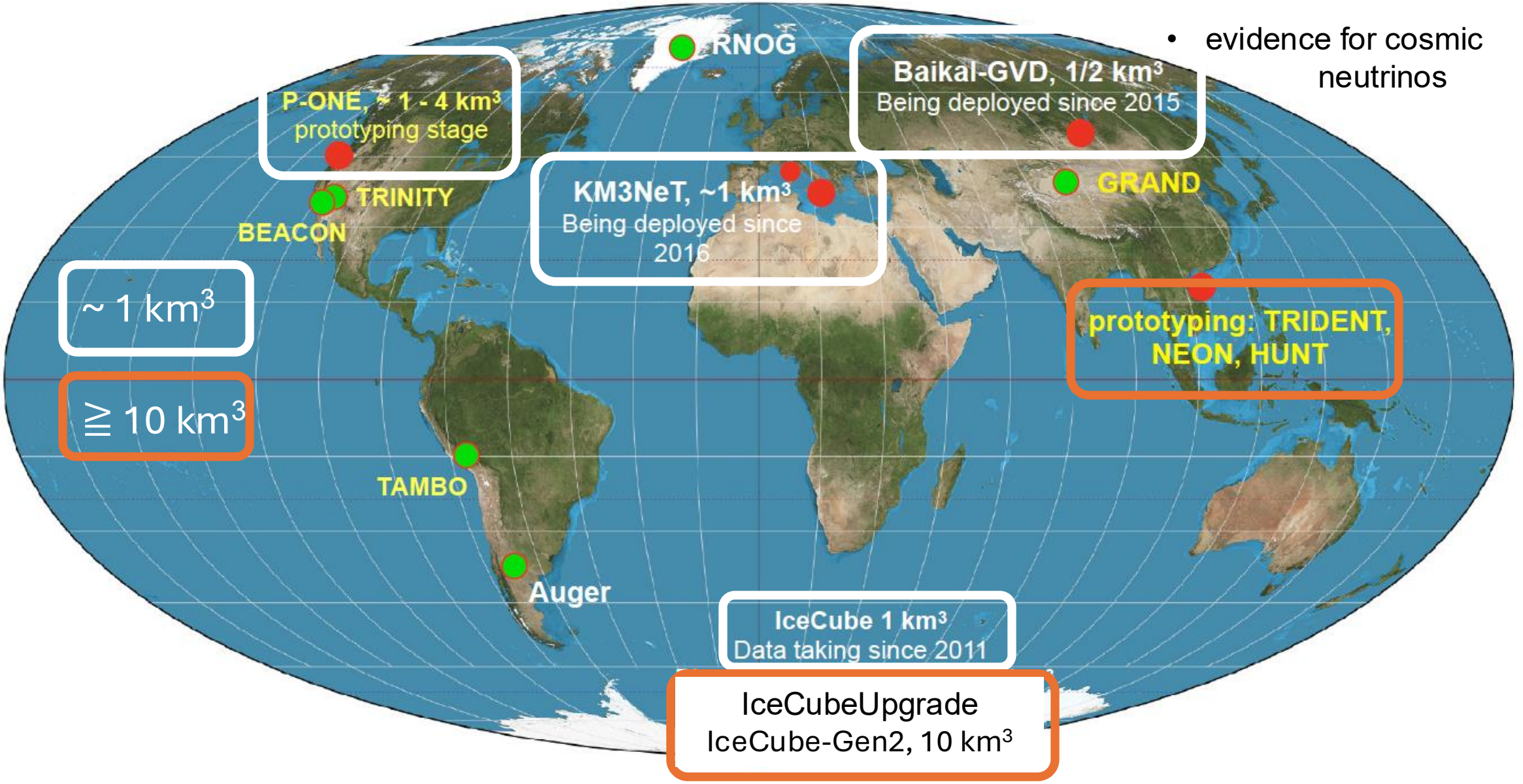


- upgoing muon
- produced by 8,700 TeV neutrino
- 2,600 TeV deposited energy
- not atmospheric
- reconstructed < 0.3 degree
- astronomy





- from discovery to astronomy and neutrino physics: rapid progress !

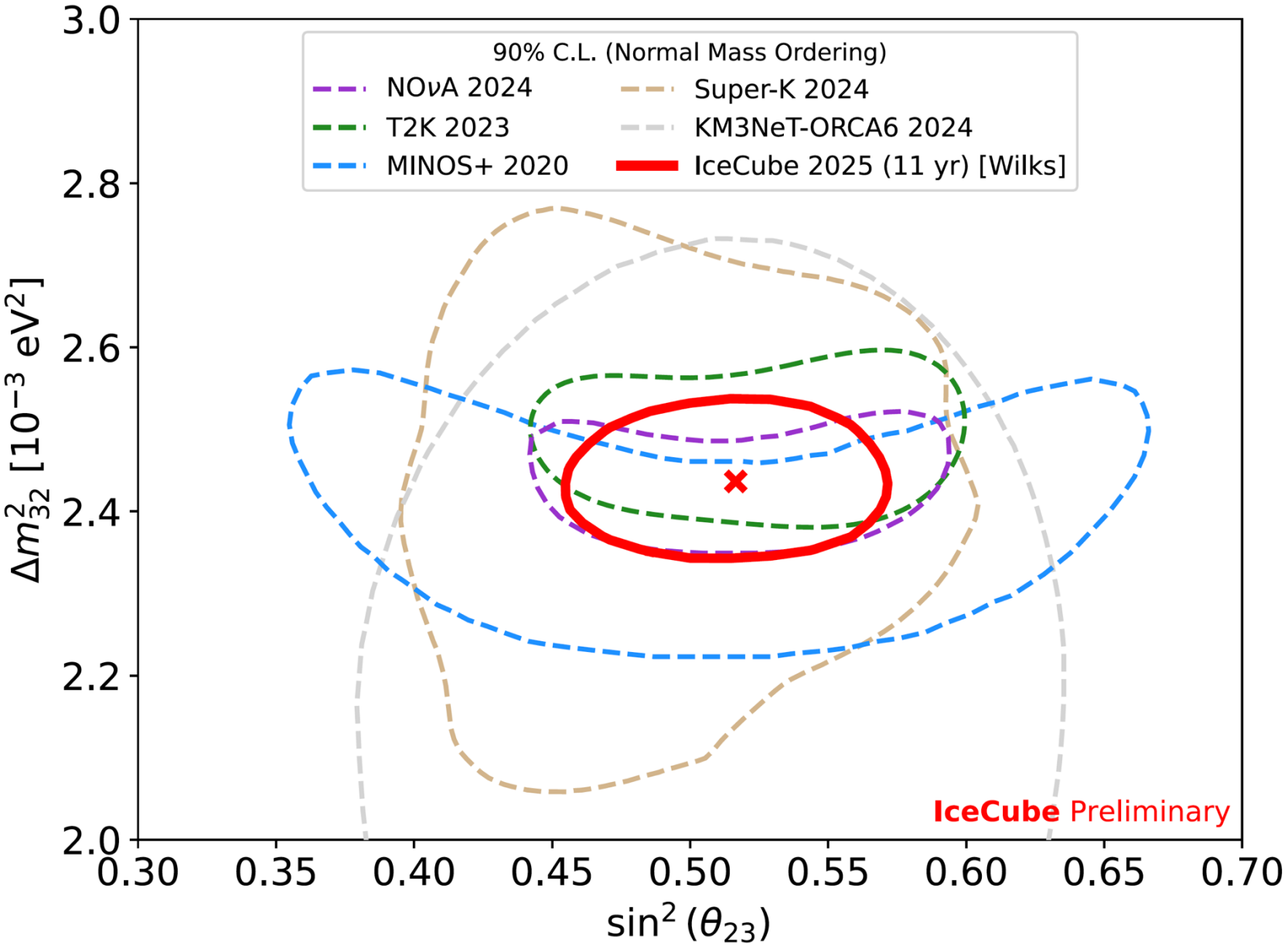


- evidence for cosmic neutrinos

- megaton GeV detectors: IceCube Upgrade, ORCA, HUNT

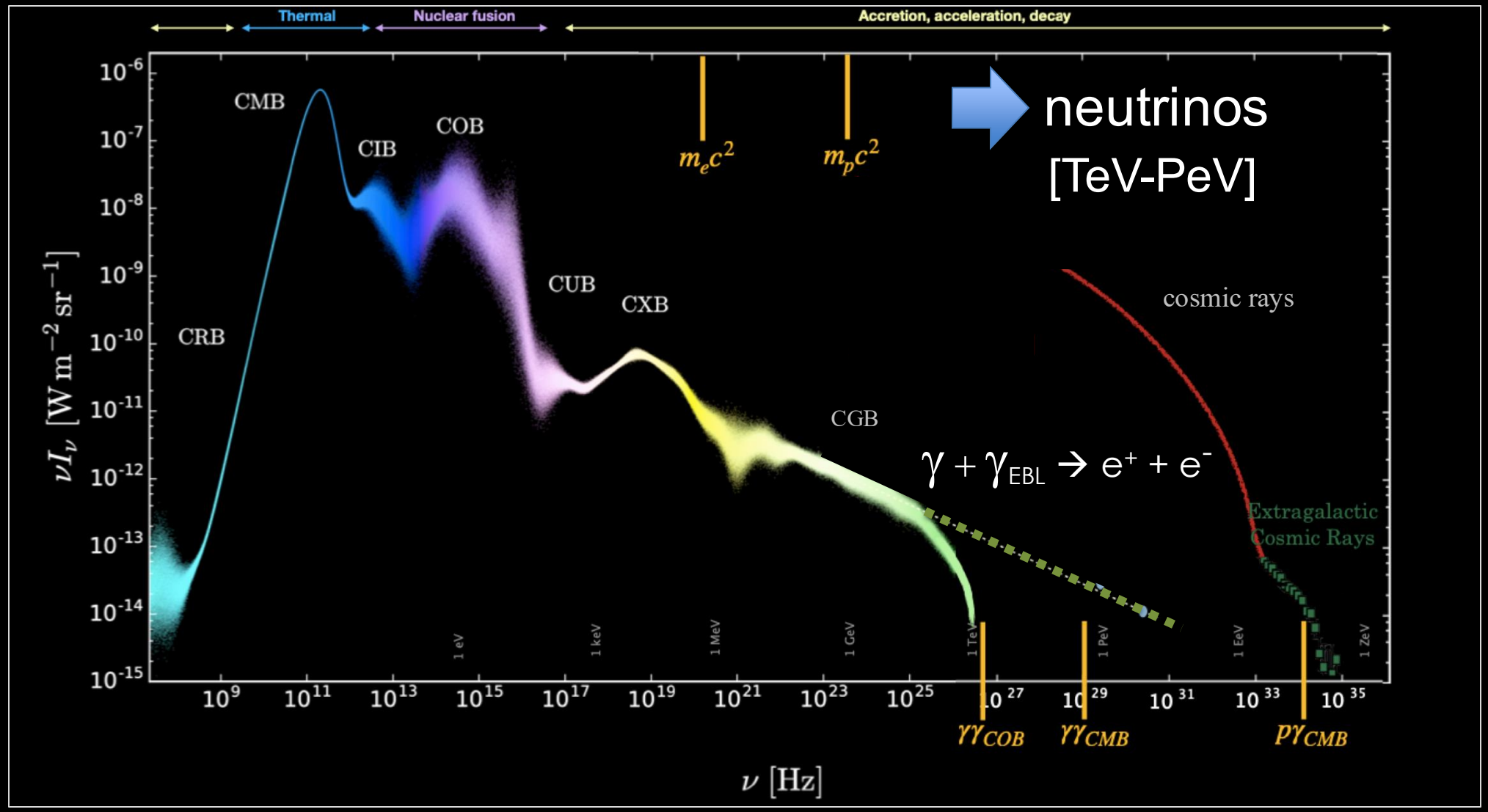
- EeV detectors

- KM3NeT ORCA
- IceCube Upgrade (December 2025)
- interesting complimentarities with JUNO



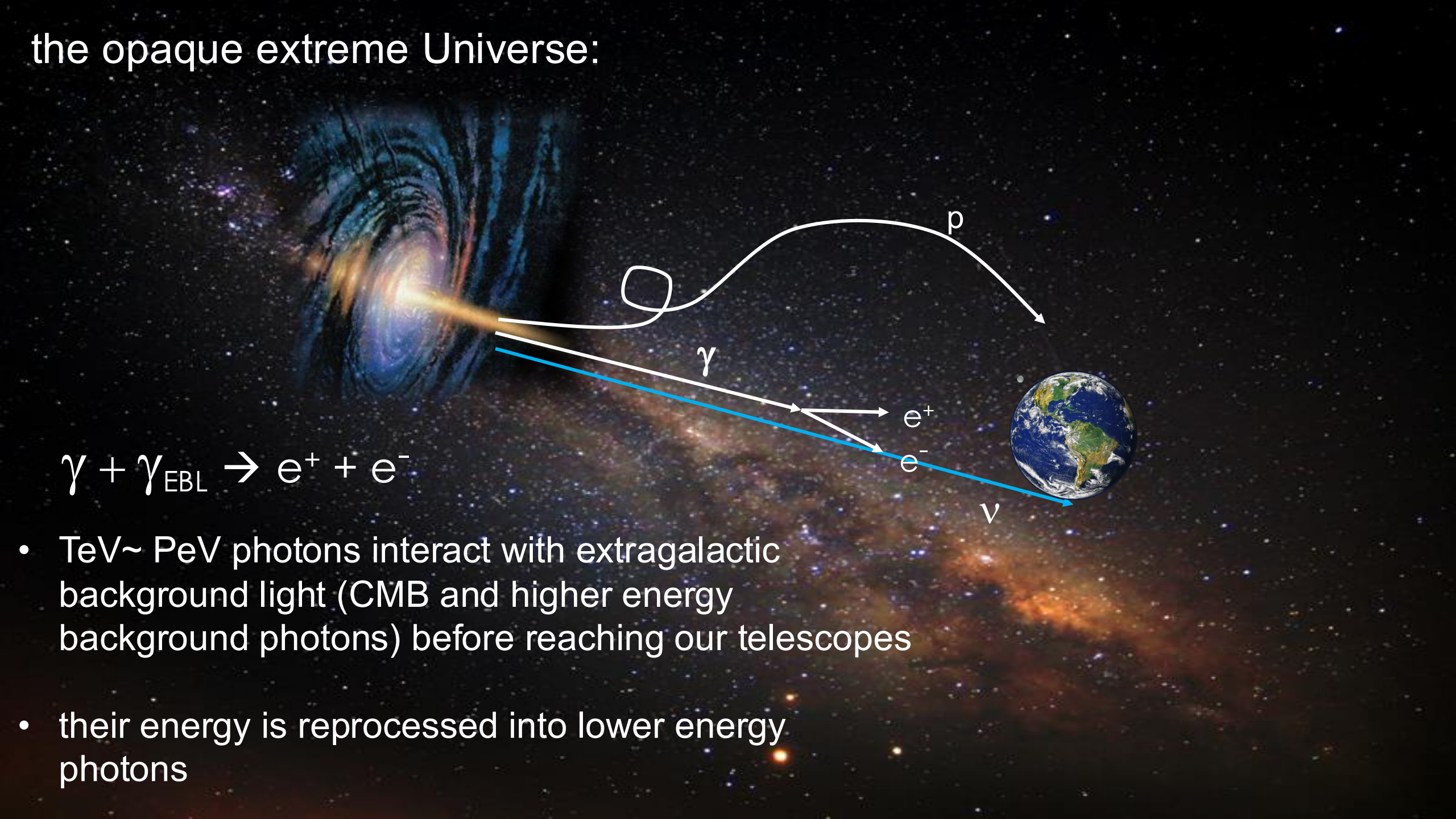
NUFACT 2025

energy in photons in the Universe as a function of their frequency



in the extreme energy universe neutrinos are unique astronomical messengers

the opaque extreme Universe:



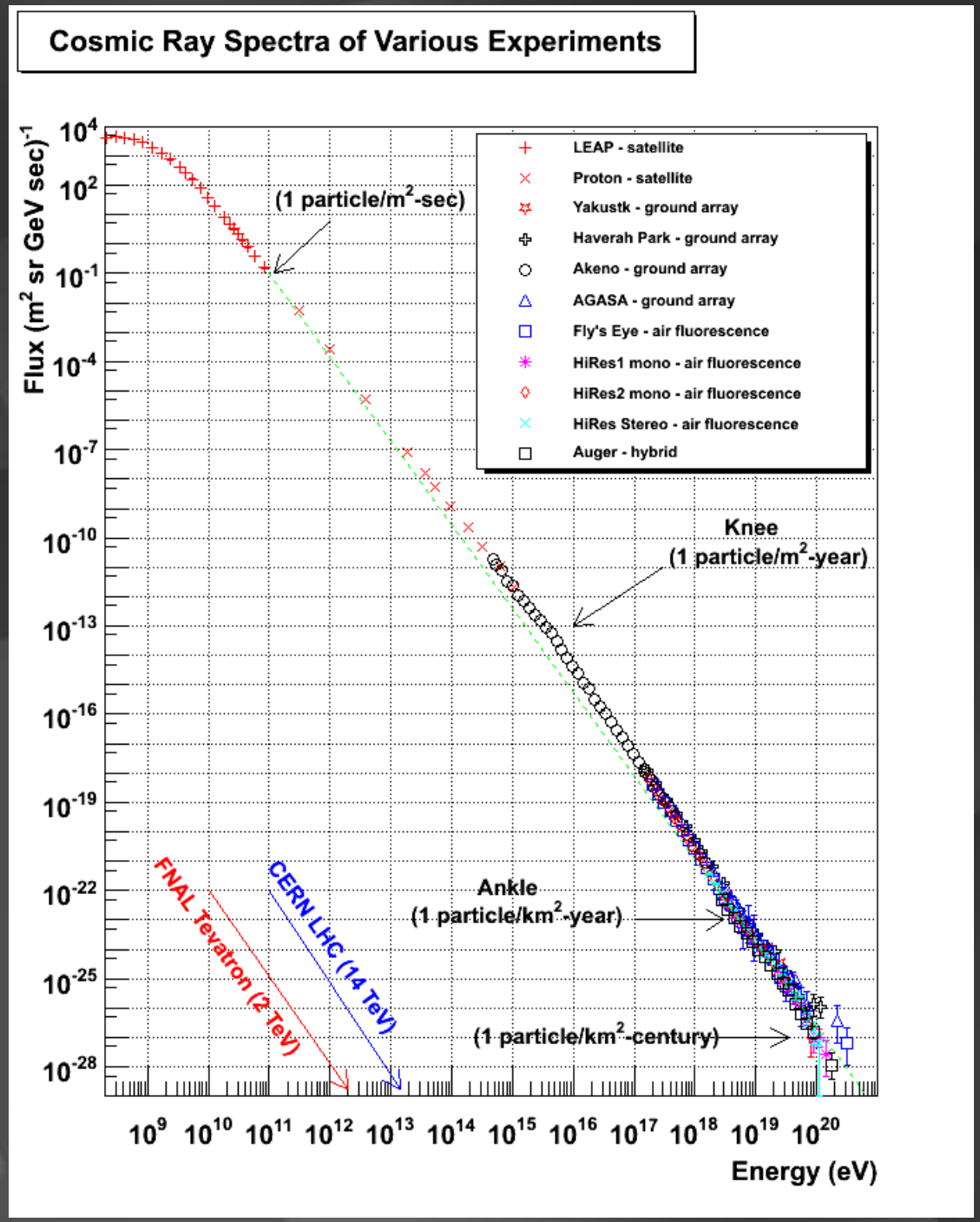
$\gamma + \gamma_{EBL} \rightarrow e^+ + e^-$

- TeV~ PeV photons interact with extragalactic background light (CMB and higher energy background photons) before reaching our telescopes
- their energy is reprocessed into lower energy photons

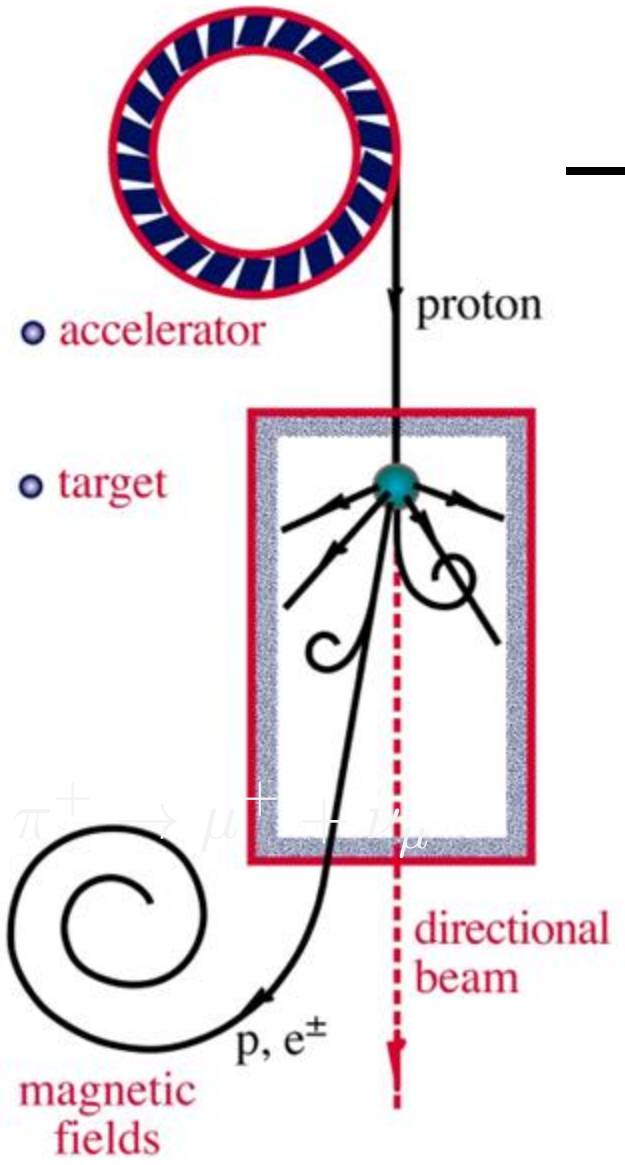
cosmic ray challenge

both the energy of the particles and the total *luminosity* of the accelerators are large

gravitational energy from collapsing object is converted into particle acceleration?



ν and γ beams : heaven and earth



cosmic accelerators powered by gravity

supermassive black hole

nearby radiation

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

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

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

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

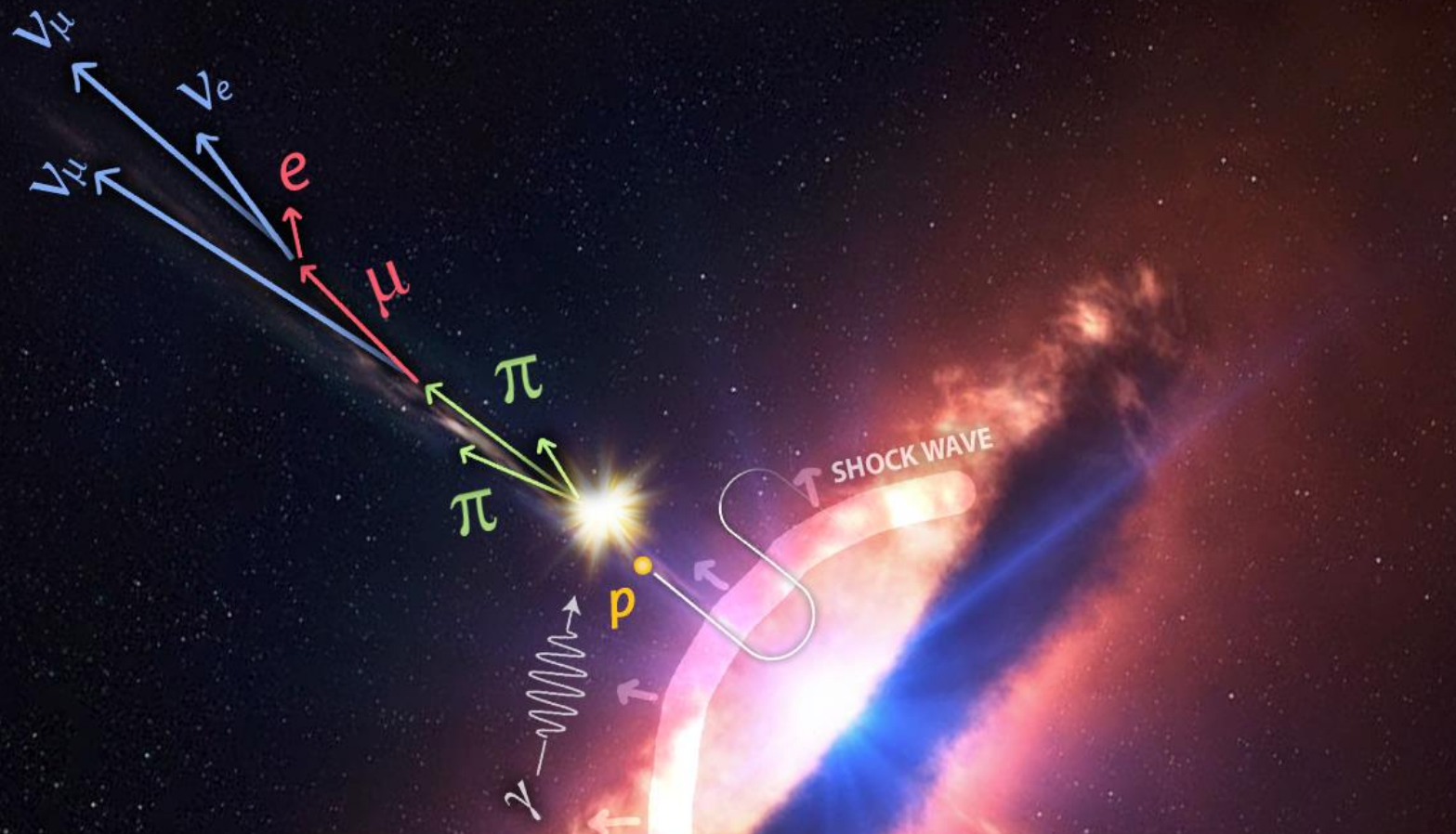
$$\pi^0 \rightarrow \gamma + \gamma$$

cosmic accelerators:

protons accelerated near a black hole are submersed in a target of radiation and produce pions

neutrino sources track cosmic ray accelerators

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



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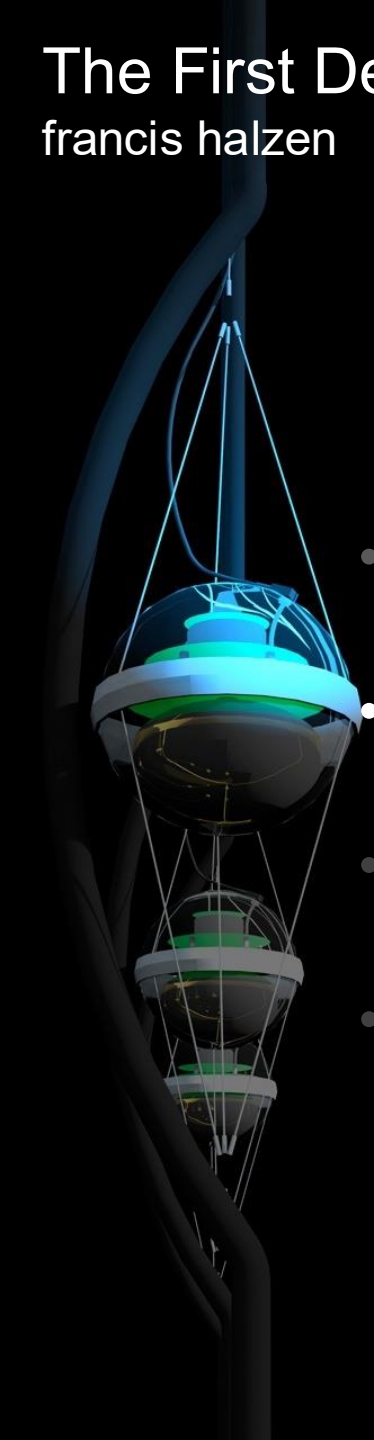

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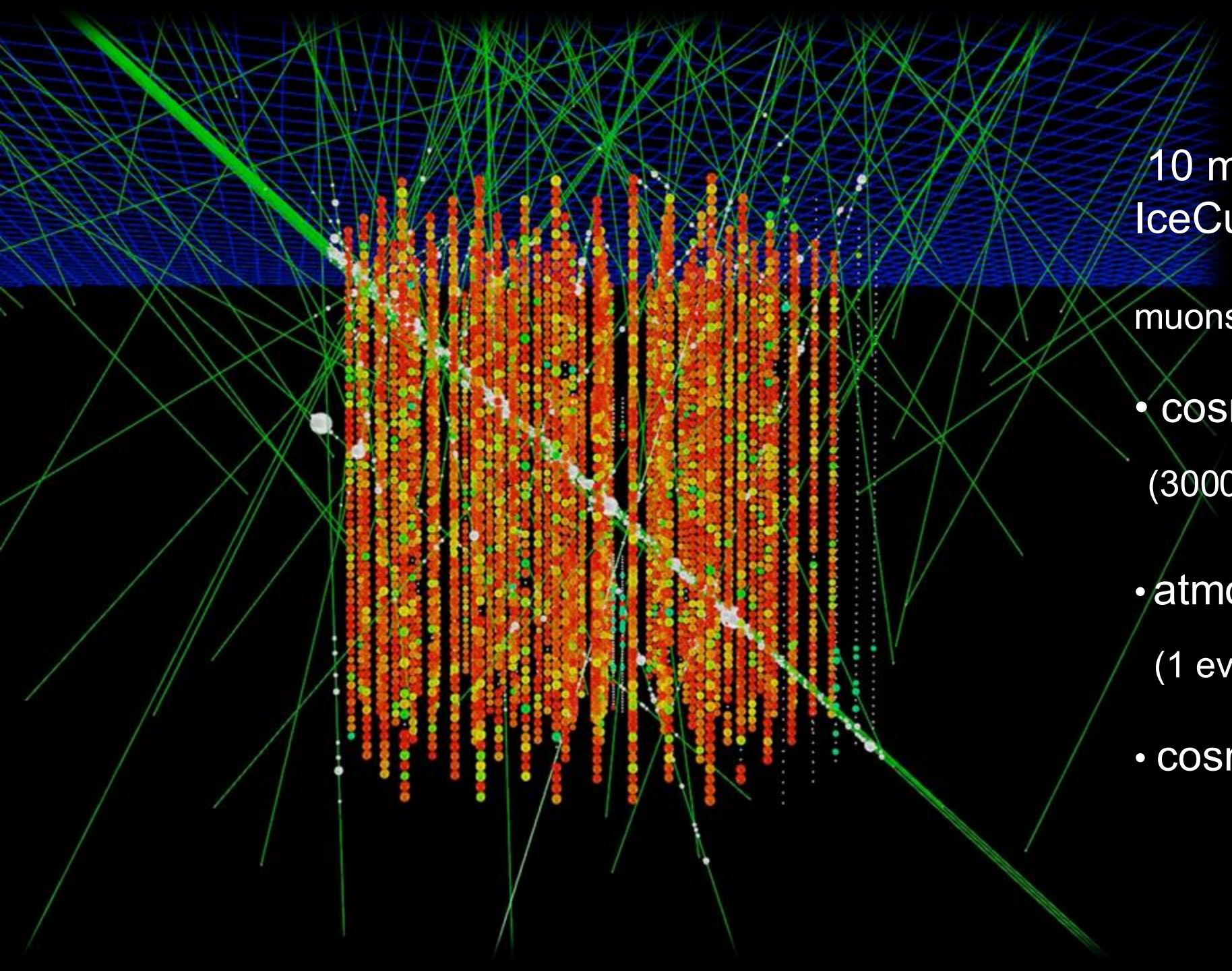


10 msec movie of IceCube taking data

muons detected per year

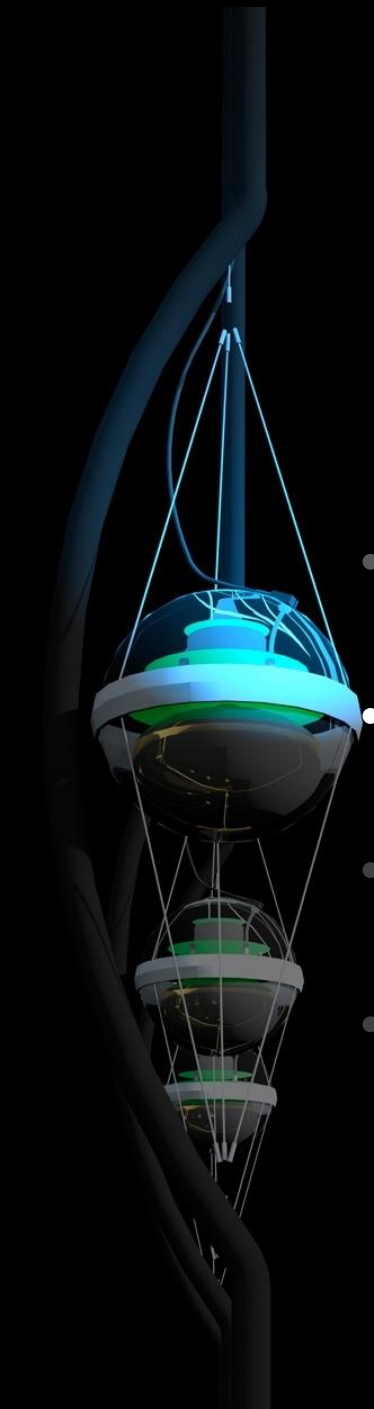
- cosmic ray muons ~ 10^{11}

  (3000 per second)

- atmospheric neutrinos ~ 10^{5}

  (1 every 5 minutes)

- cosmic neutrinos ~ 200



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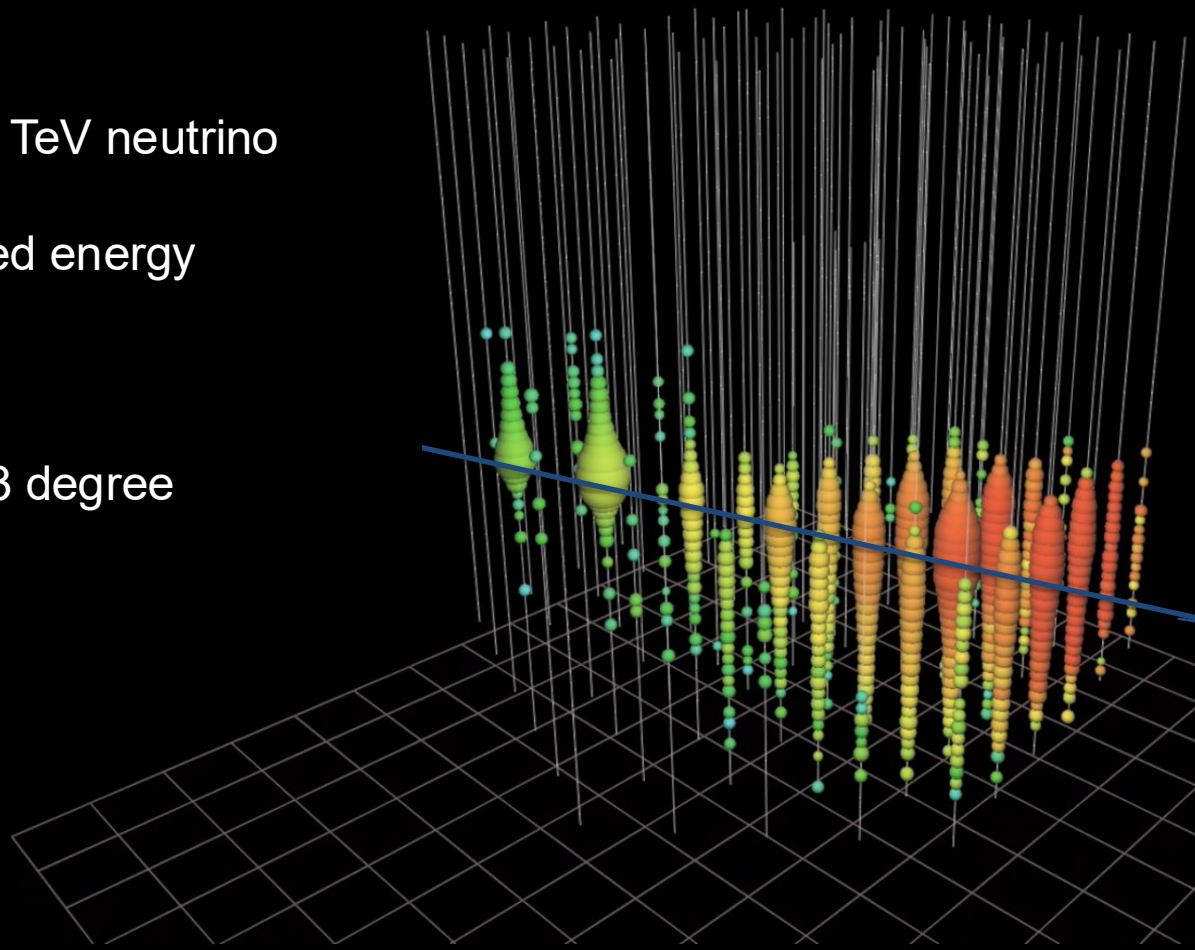
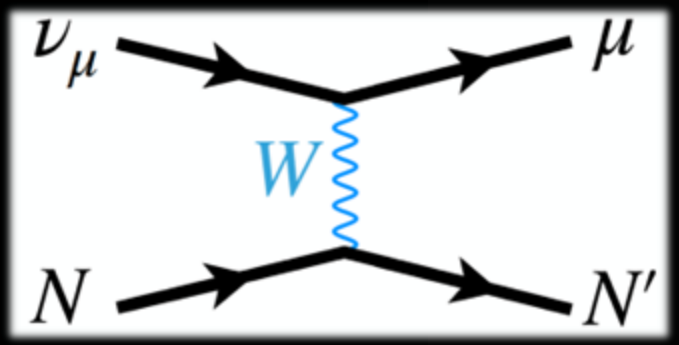
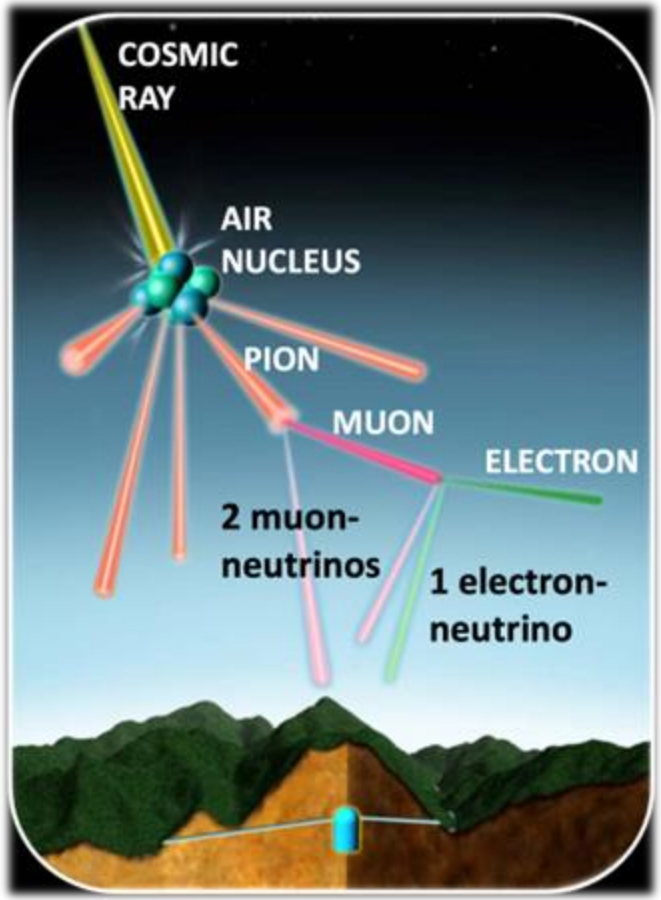


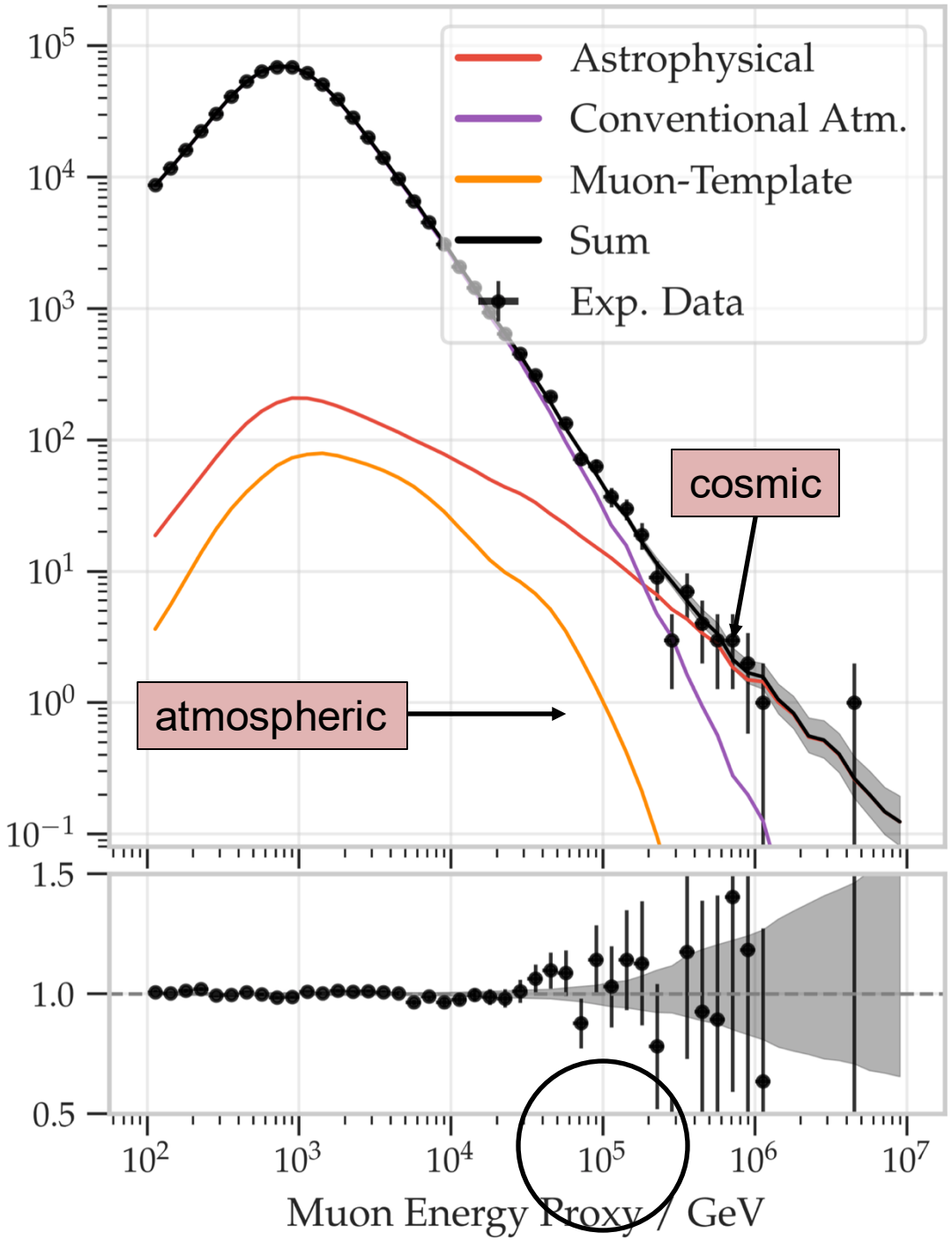


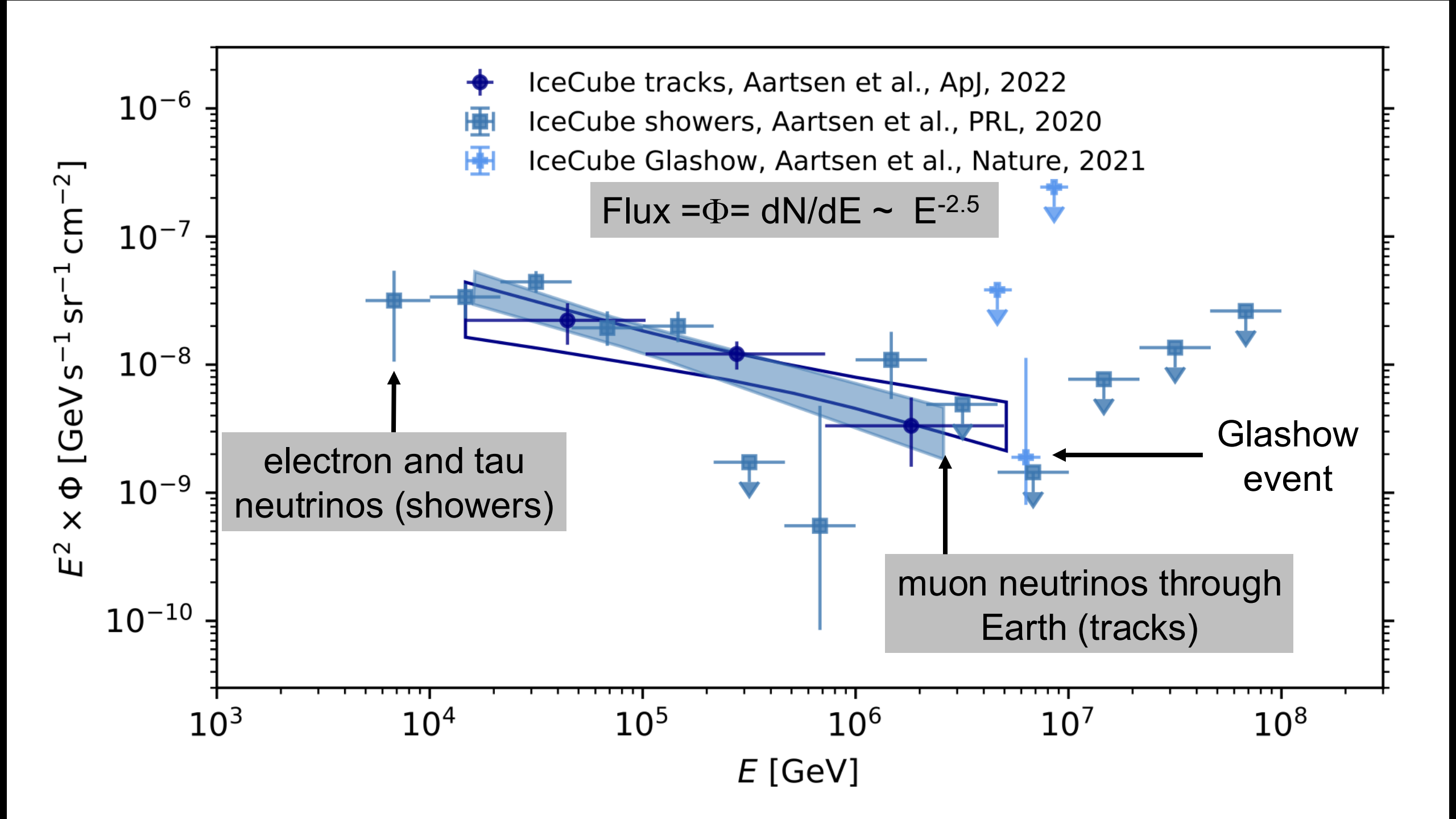
muon neutrino events [filtered by the Earth]: atmospheric vs cosmic



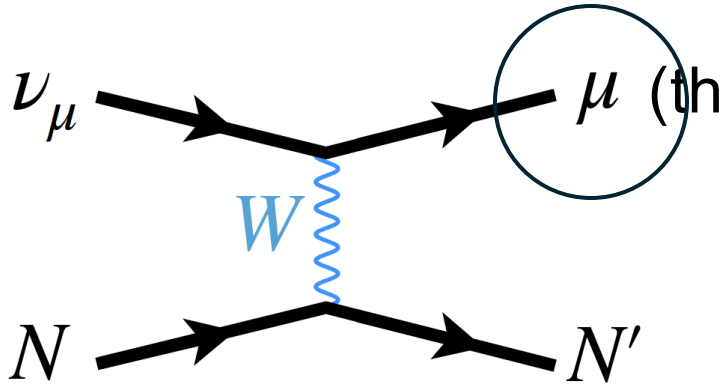
Number of Events

Data/MC

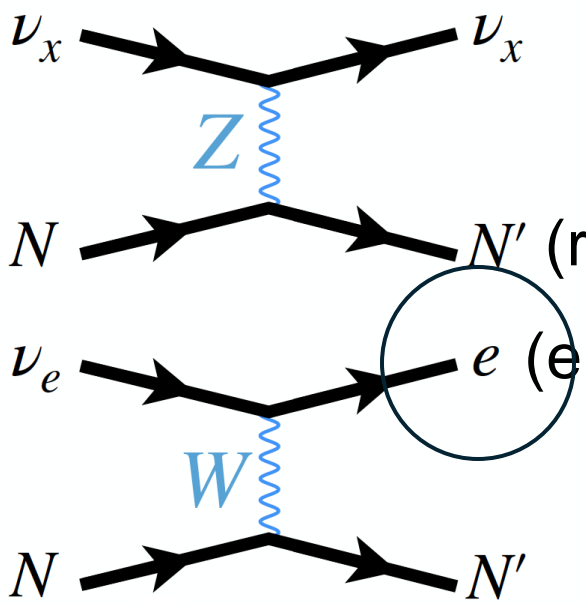



IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Flux =Φ= dN/dE ~ E^-2.5
electron and tau neutrinos (showers)
Glashow event
muon neutrinos through Earth (tracks)
E² x Φ [GeV s⁻¹ sr⁻¹ cm⁻²]
E [GeV]
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10³
10⁴
10⁵
10⁶
10⁷
10⁸

other neutrino flavors

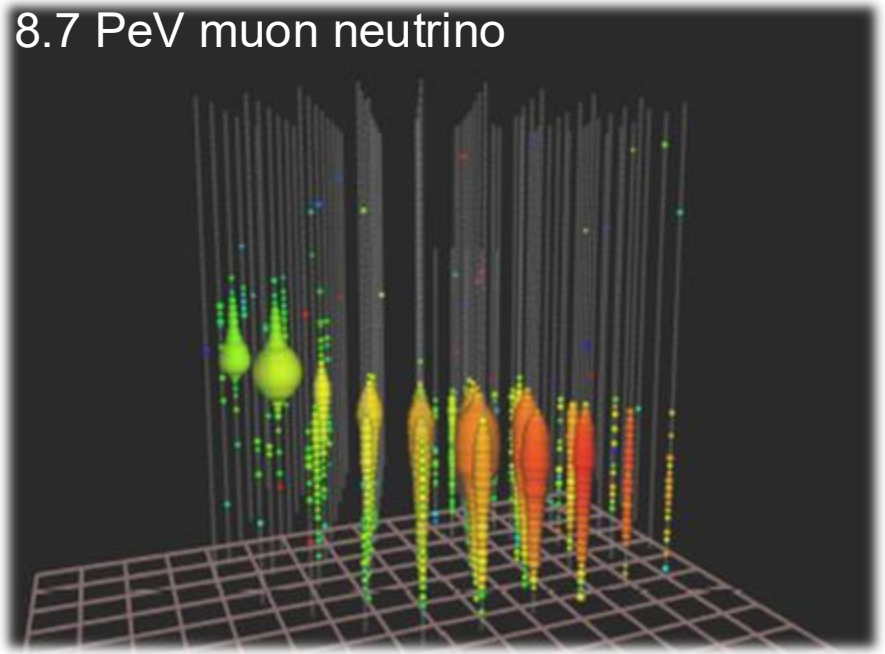


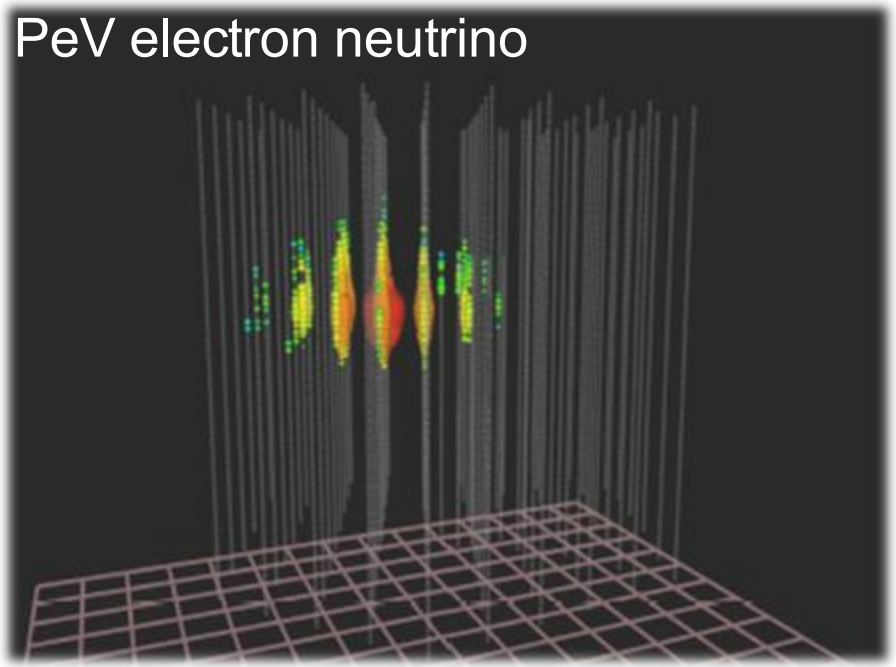
(throughgoing muon)



(recoil nucleus)

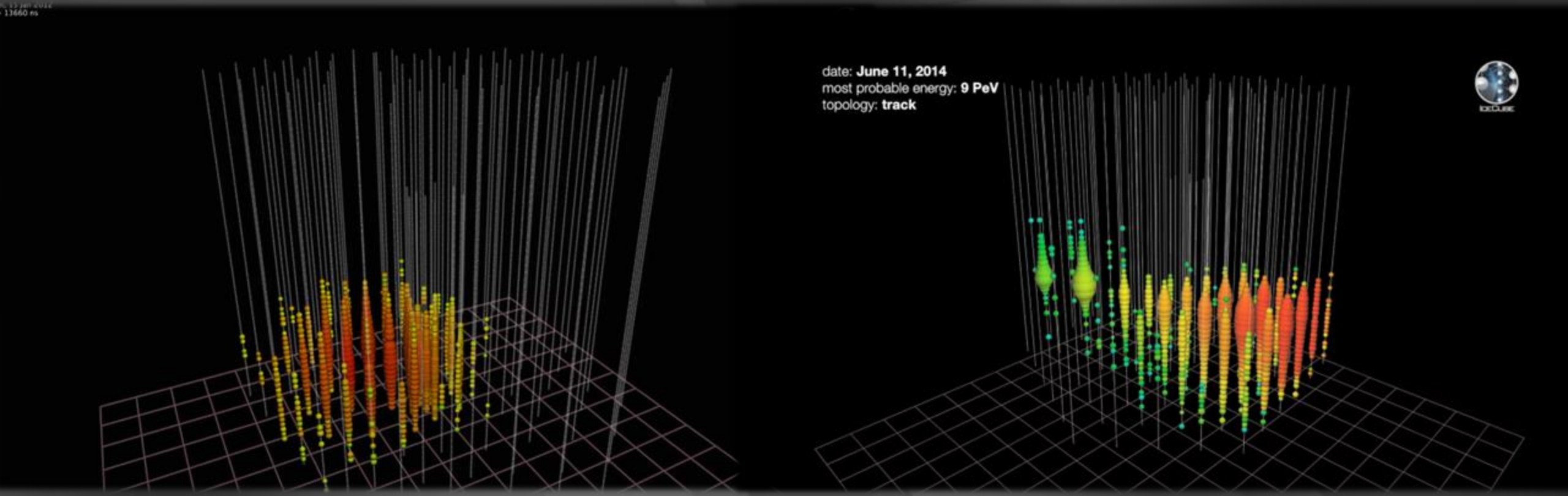
(electron or tau shower)





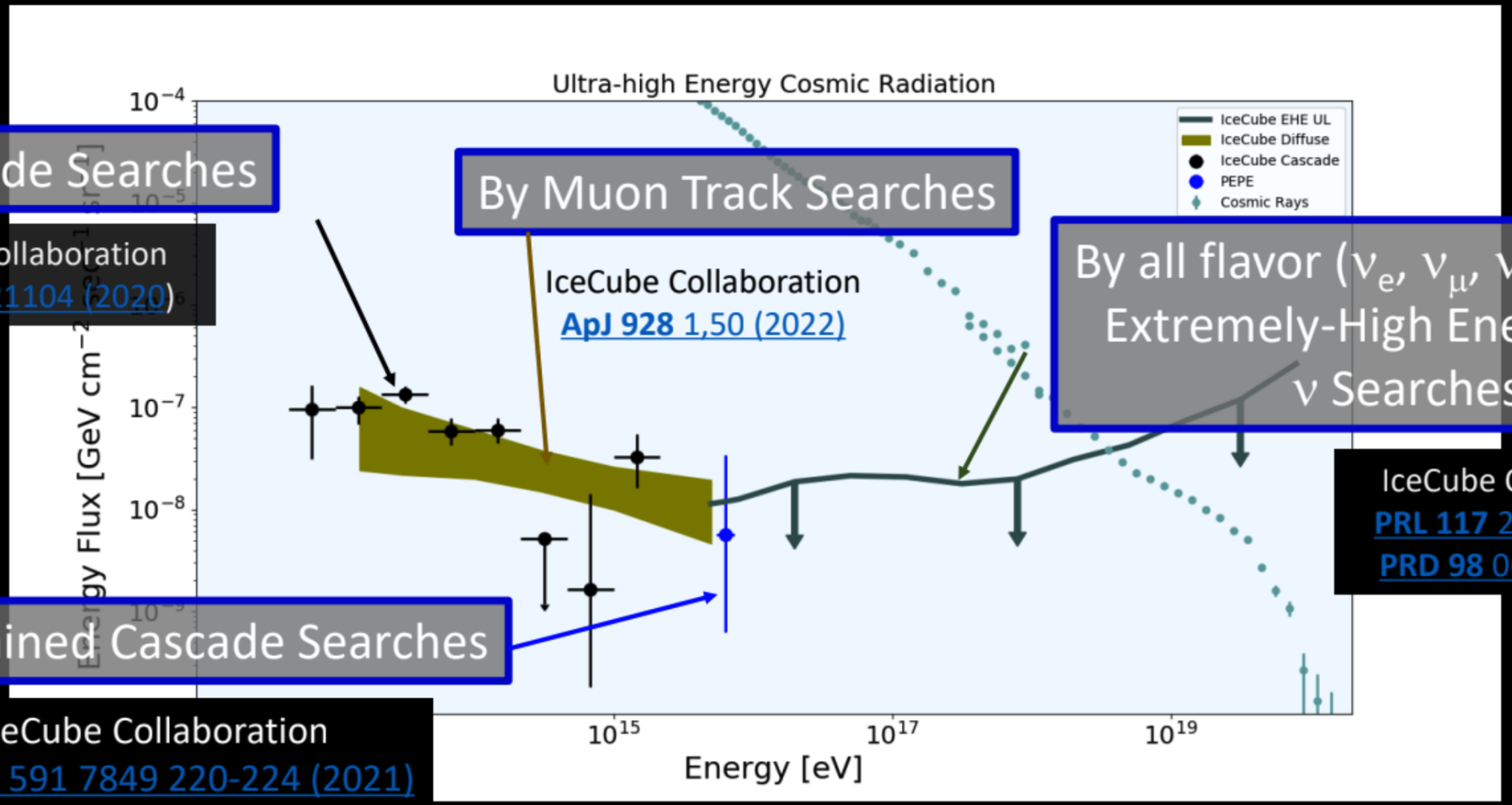
neutrinos interacting
inside the detector

muon neutrinos
filtered by the Earth



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

superior angular resolution < 0.3^{o}
including systematics



By Cascade Searches

IceCube Collaboration
PRL 125 121104 (2020)

By Muon Track Searches

IceCube Collaboration
ApJ 928 1,50 (2022)

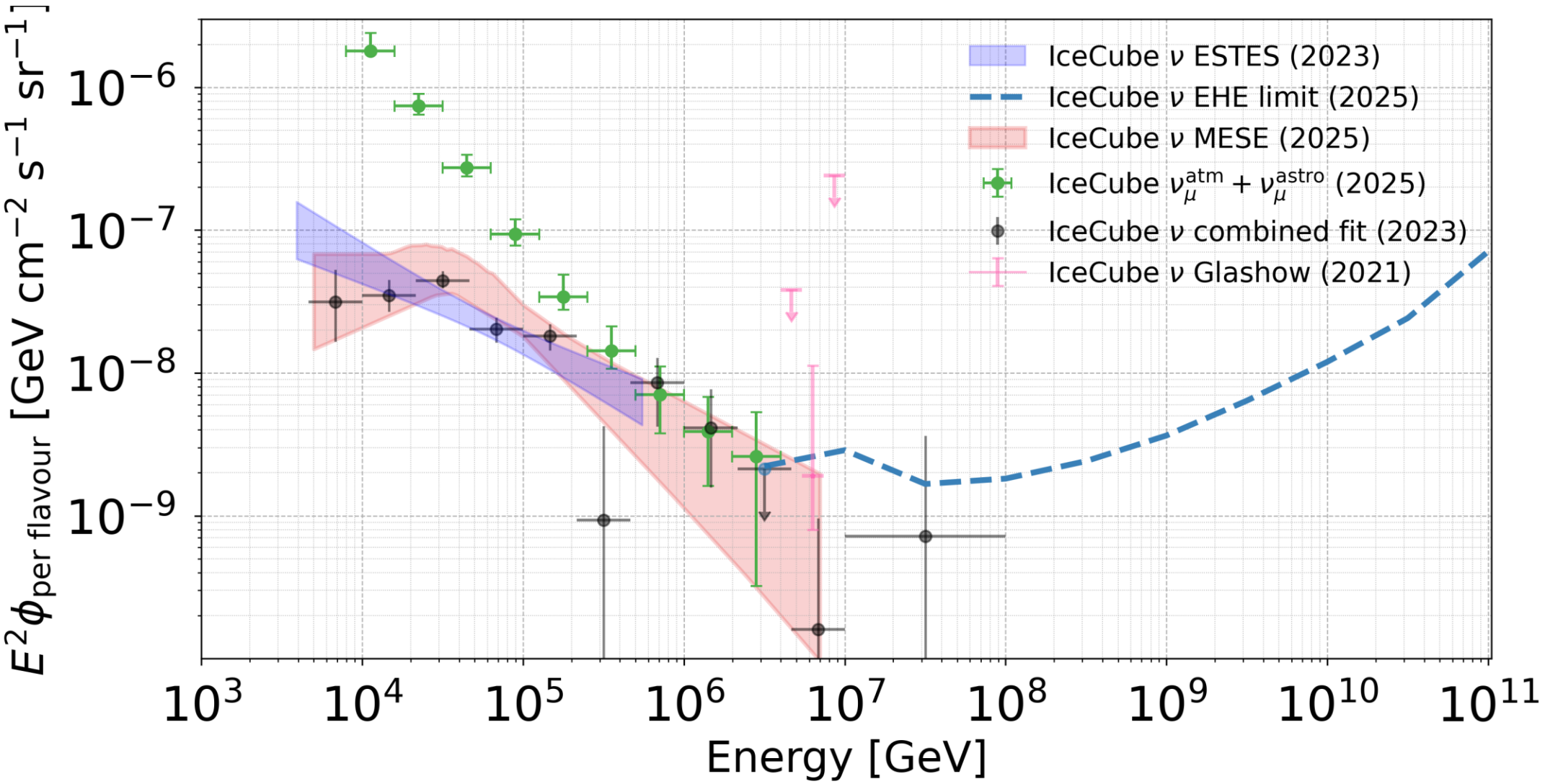
By all flavor (ν_e, ν_μ, ν_τ) sensitive Extremely-High Energy (EHE) ν Searches

IceCube Collaboration
PRL 117 241101 (2016)
PRD 98 062003 (2018)

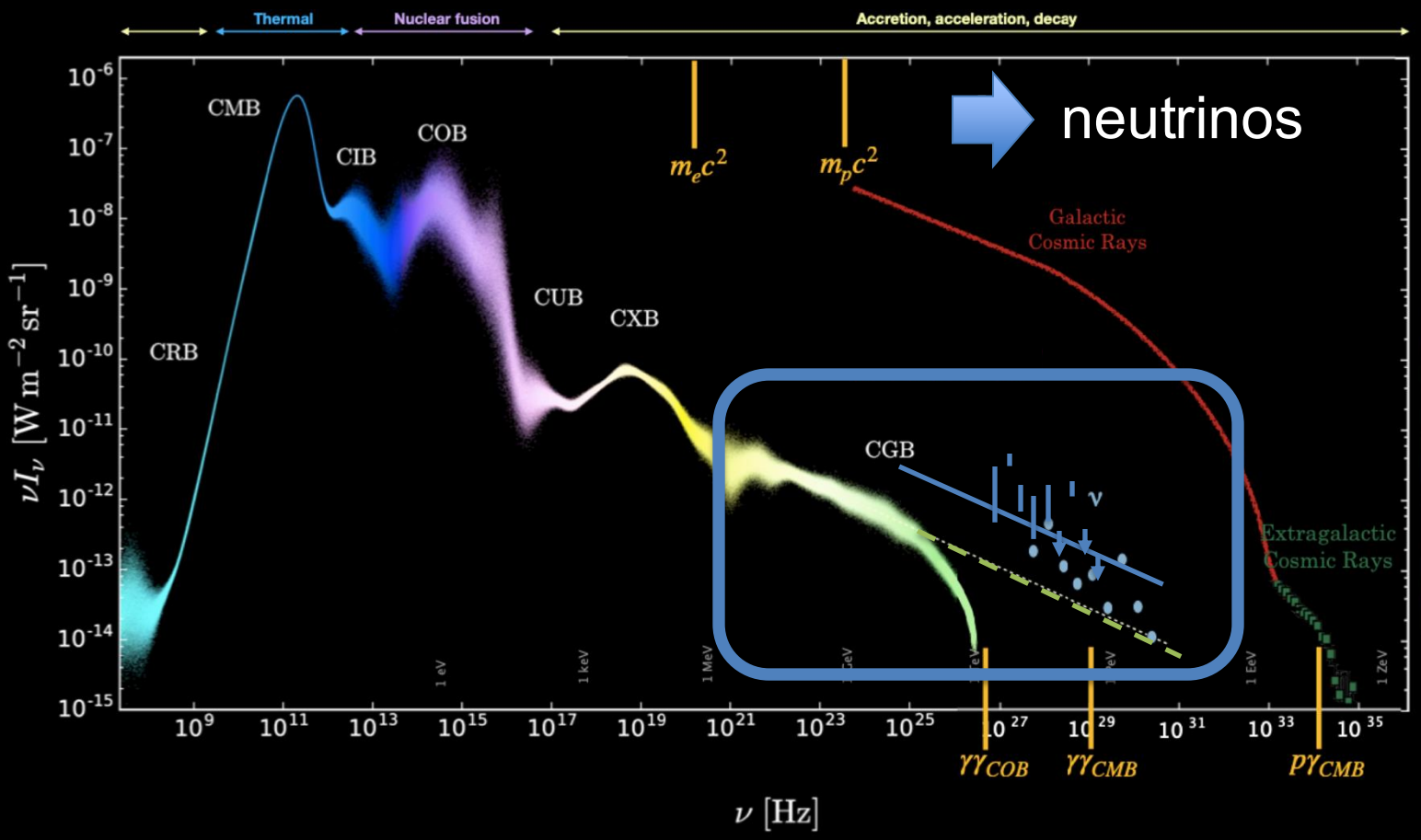
By Uncontained Cascade Searches

IceCube Collaboration
Nature 591 7849 220-224 (2021)

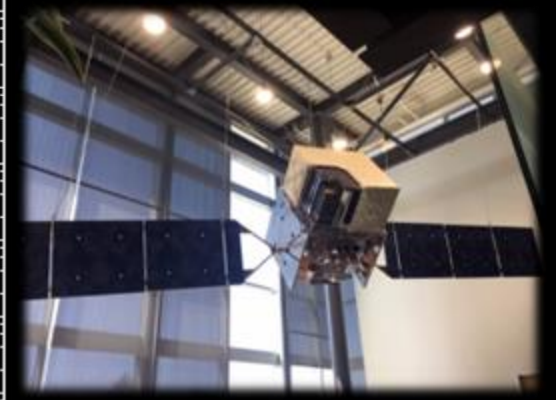
structure emerging in the neutrino spectrum?



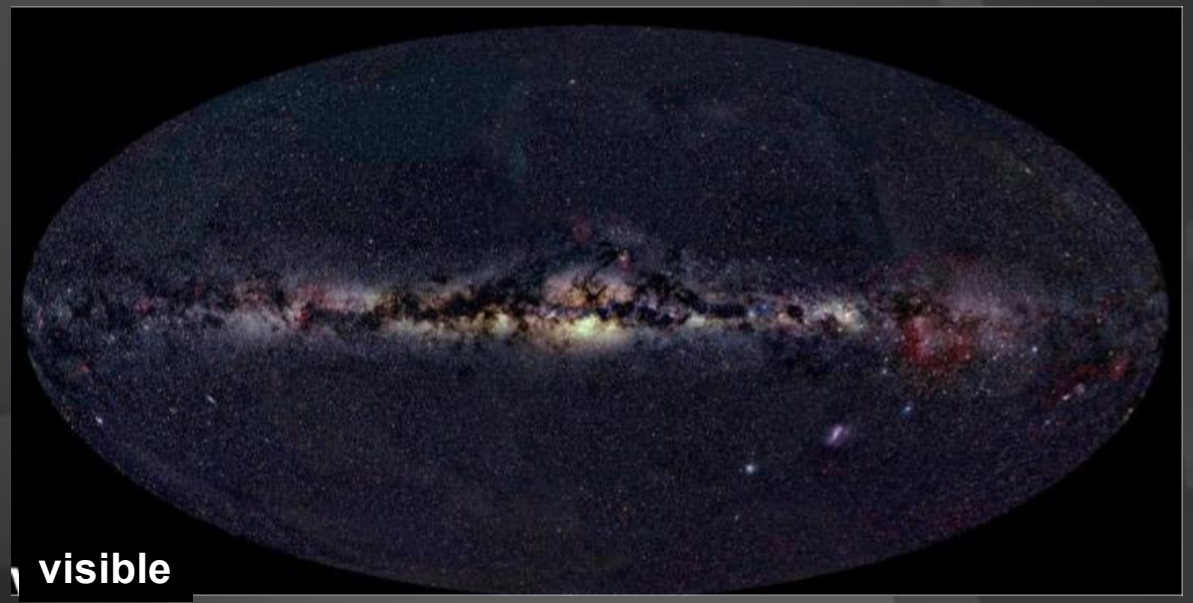
energy density in the Universe as a function of frequency

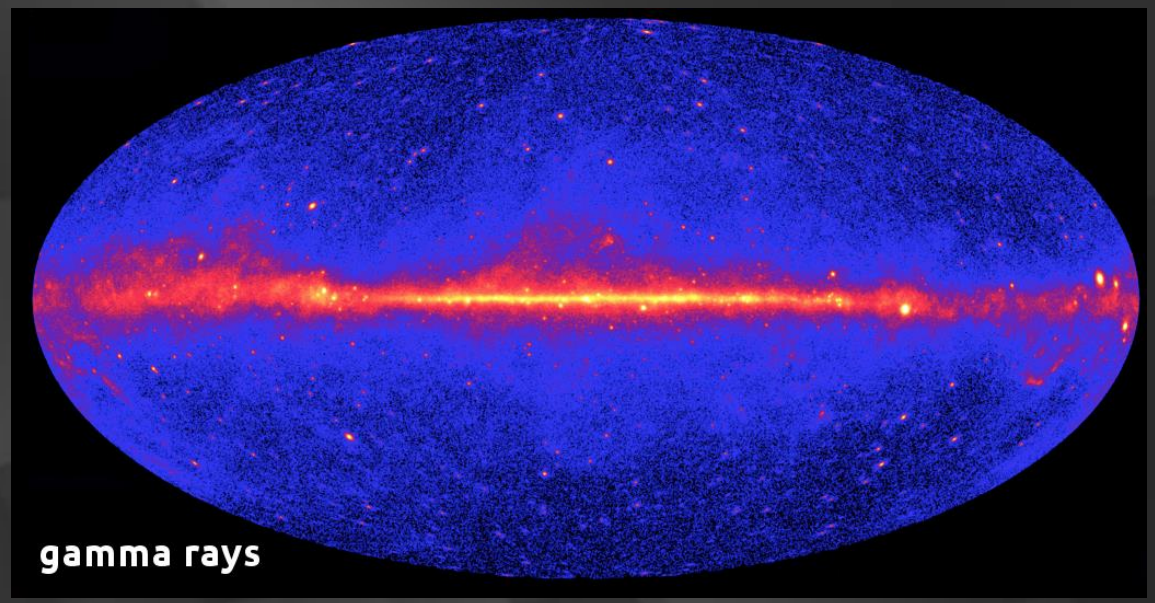


Fermi NASA gamma-ray satellite



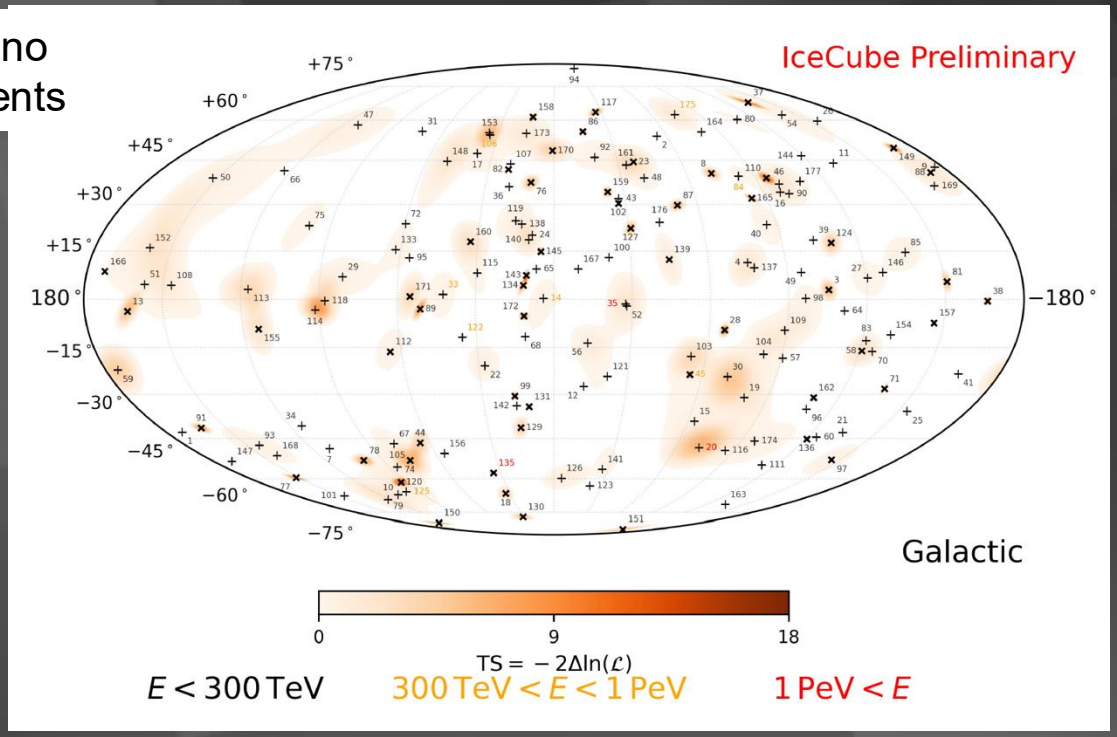
in the extreme universe the energy in neutrinos (and π^0 gamma rays) is larger than the energy in GeV gamma rays observed by Fermi





where is the neutrino Galactic plane?

166 neutrino starting events



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

two surprises:

- the large neutrino and associated gamma ray flux
- the Milky Way is not a dominant feature in the neutrino sky (powerful accelerators produce neutrinos in other galaxies that do not exist in our own)

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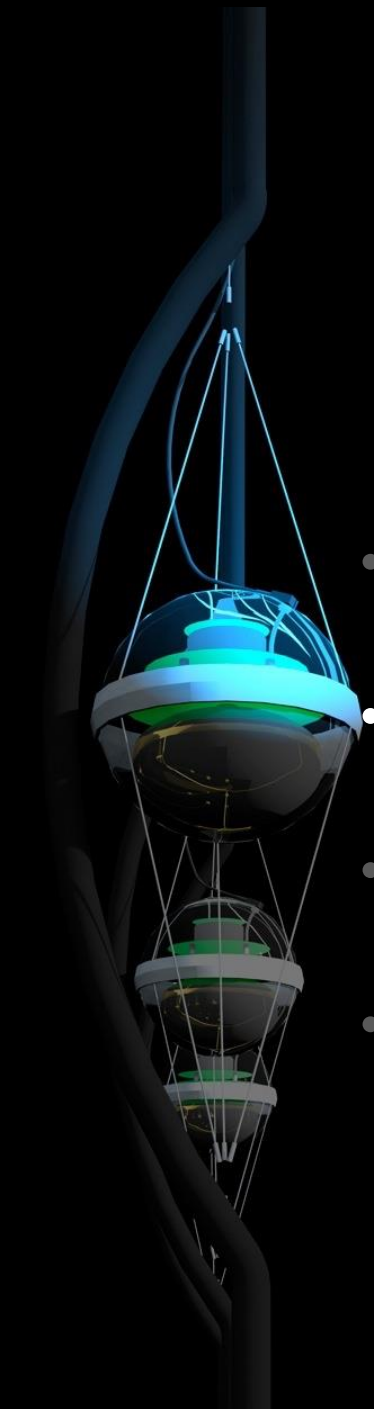

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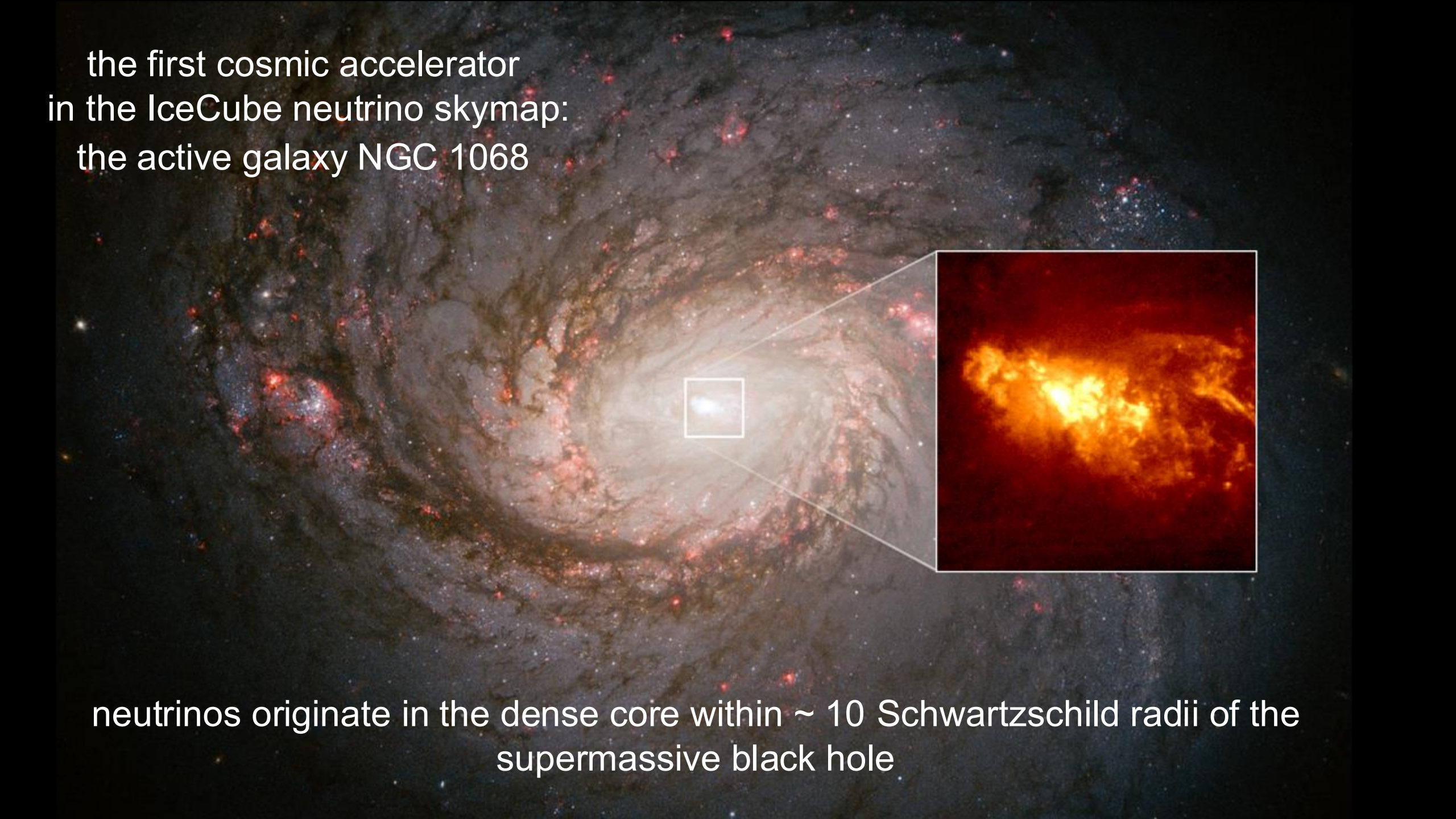
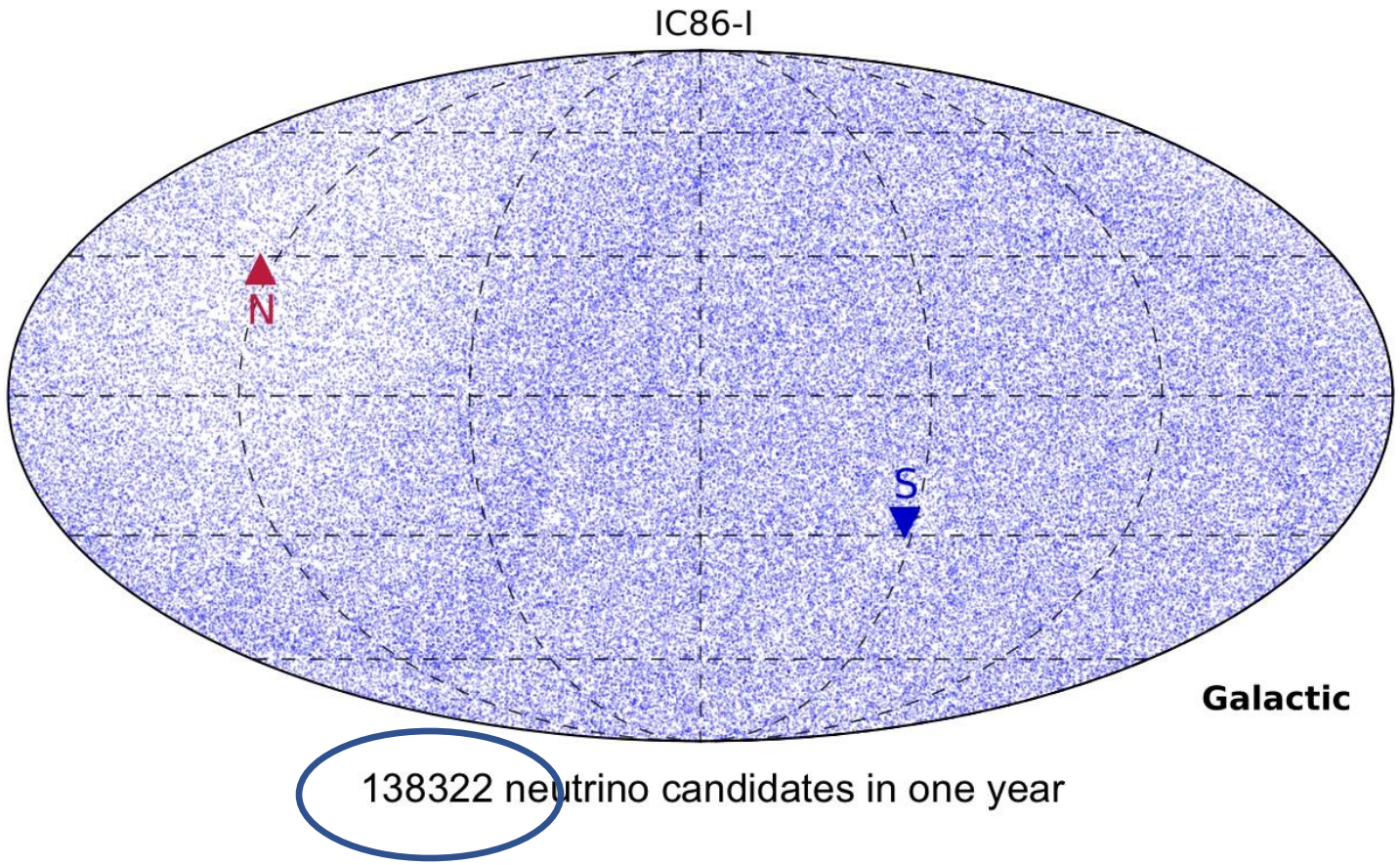
the first cosmic accelerator
in the IceCube neutrino skymap:
the active galaxy NGC 1068



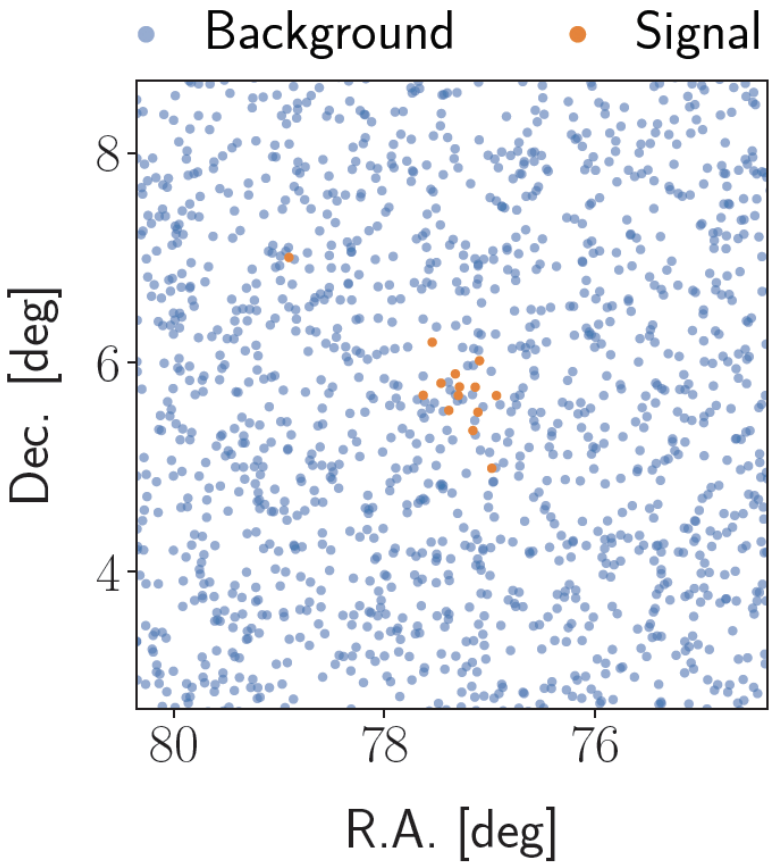
neutrinos originate in the dense core within ~ 10 Schwartzschild radii of the supermassive black hole

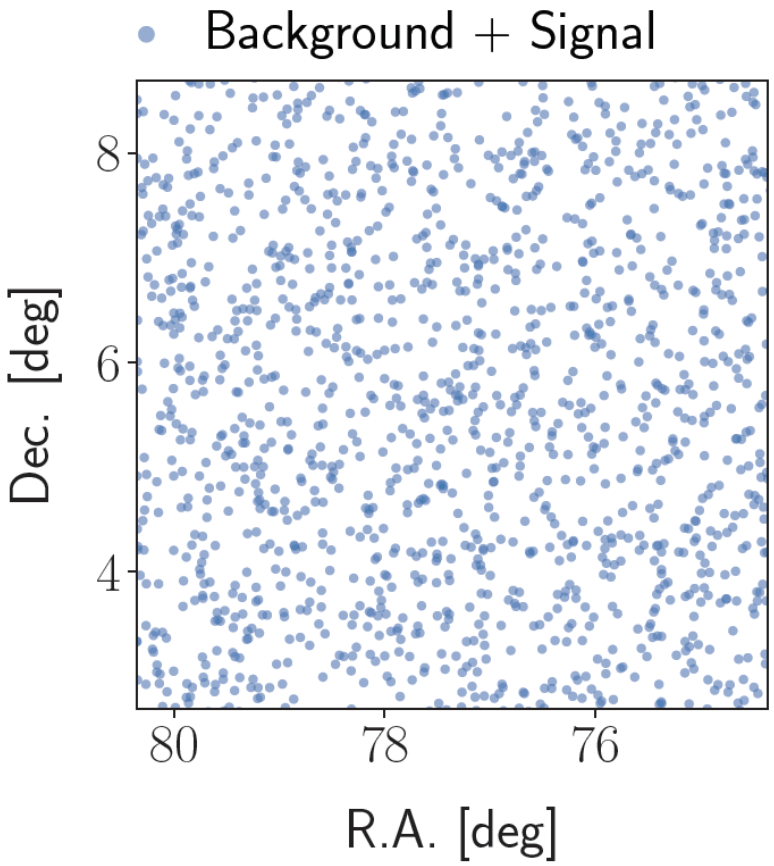
one year of IceCube neutrinos >100 GeV

(reaches neutrino purity of 97% but overwhelmingly atmospheric)

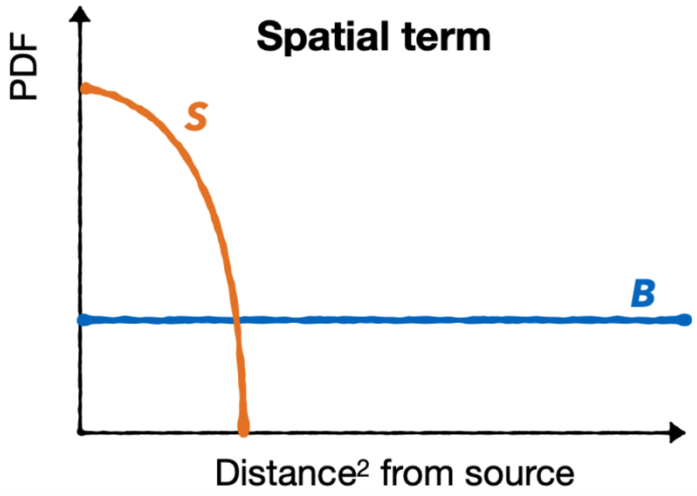


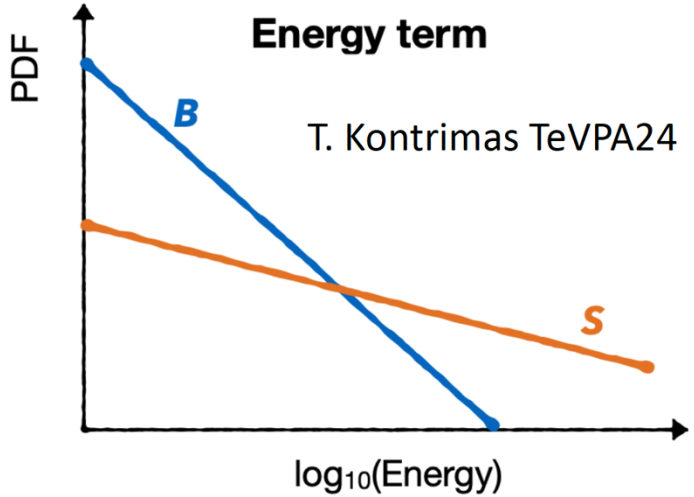
~200 cosmic neutrinos





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

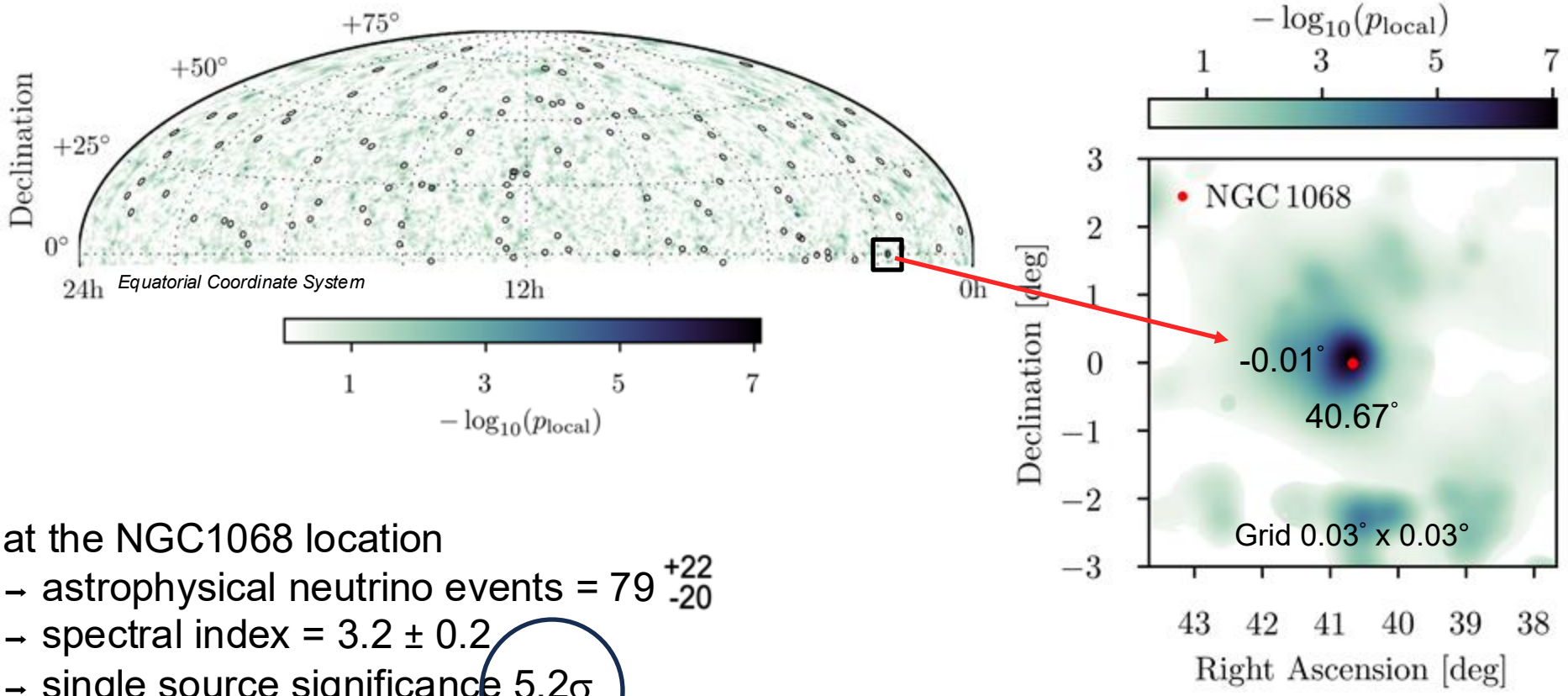




T. Kontrimas TeVPA24

NGC 1068

- most significant of 110 preselected sources
- leading hotspot in the neutrino sky



at the NGC1068 location

→ astrophysical neutrino events = 79 $^{+22}_{-20}$

→ spectral index = 3.2 ± 0.2

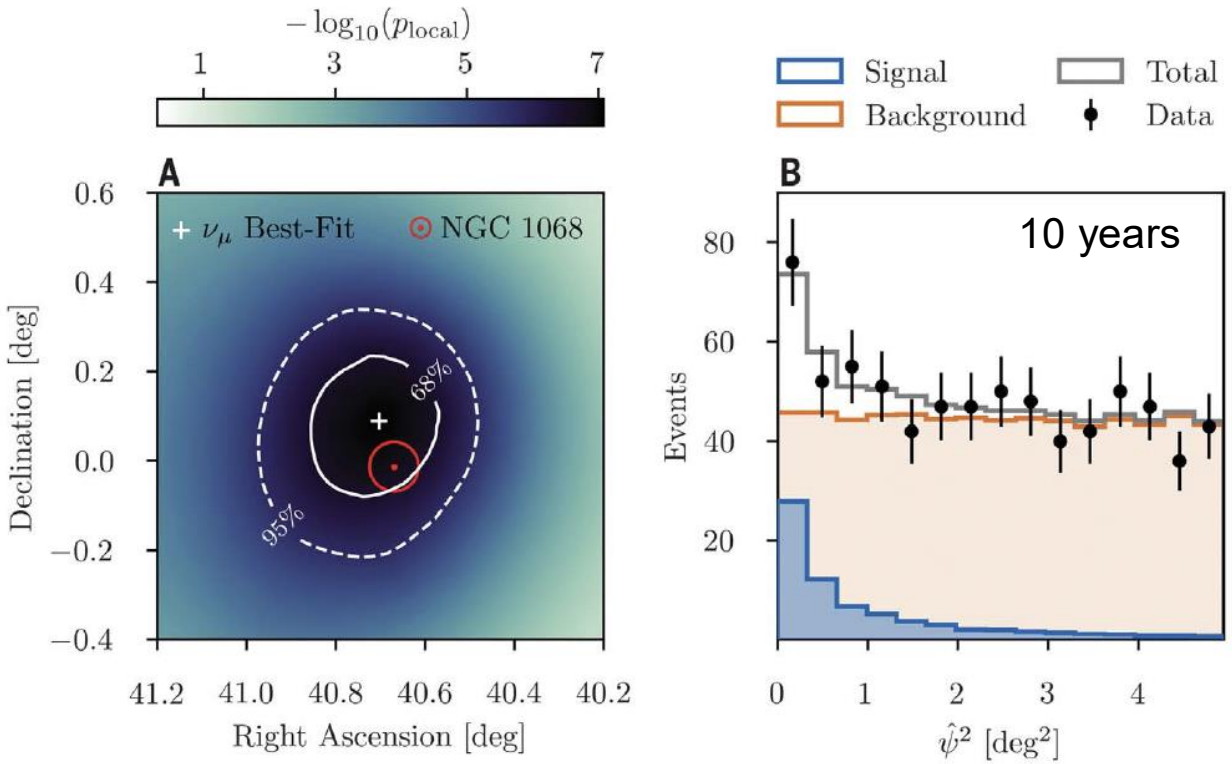
→ single source significance 5.2σ

→ (offset 0.11^0)

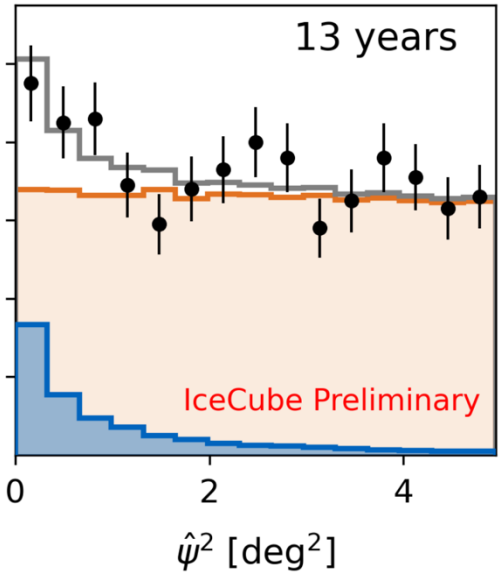
→ 1 in 100,000 scrambled data sets have object ≥ 5.2**σ** = 4.2**σ**

→ p-value $<10^{-5}$ including all trials

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

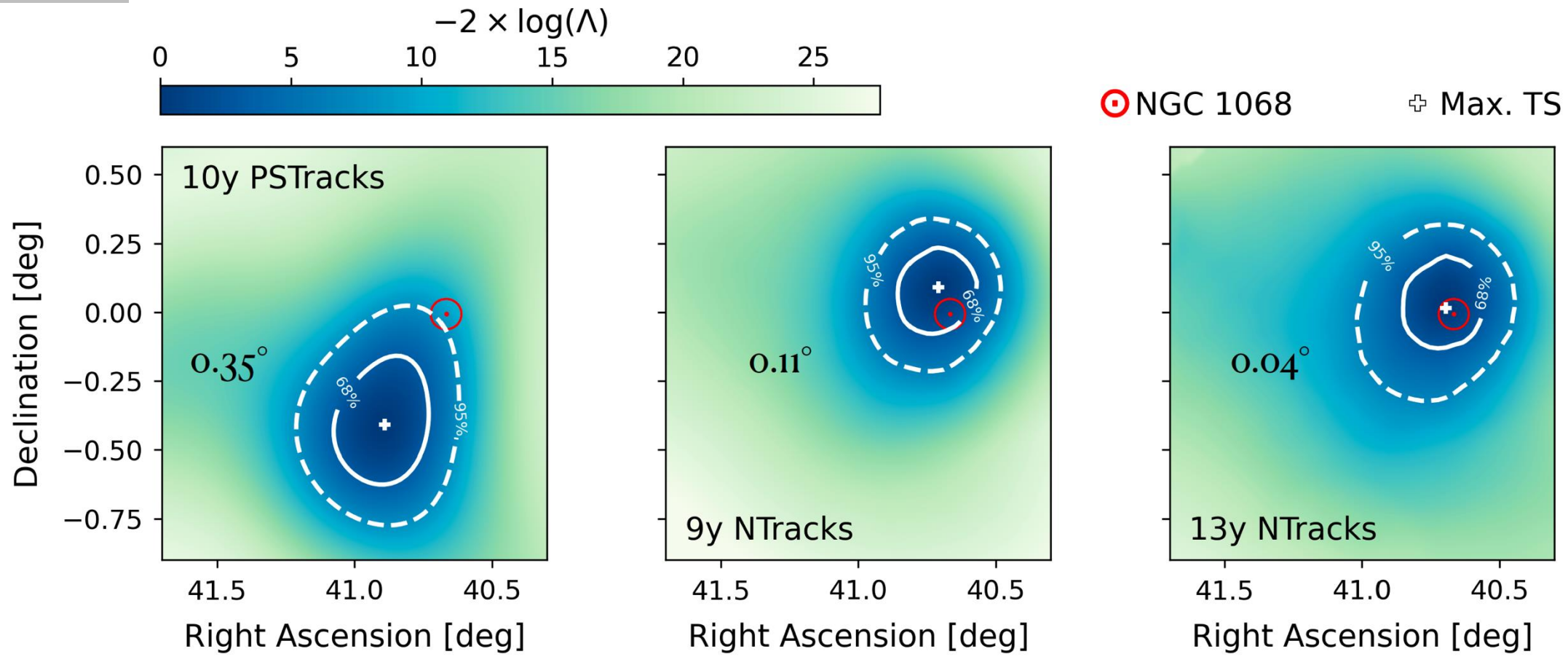


update: 80→100 neutrinos 10→13 years

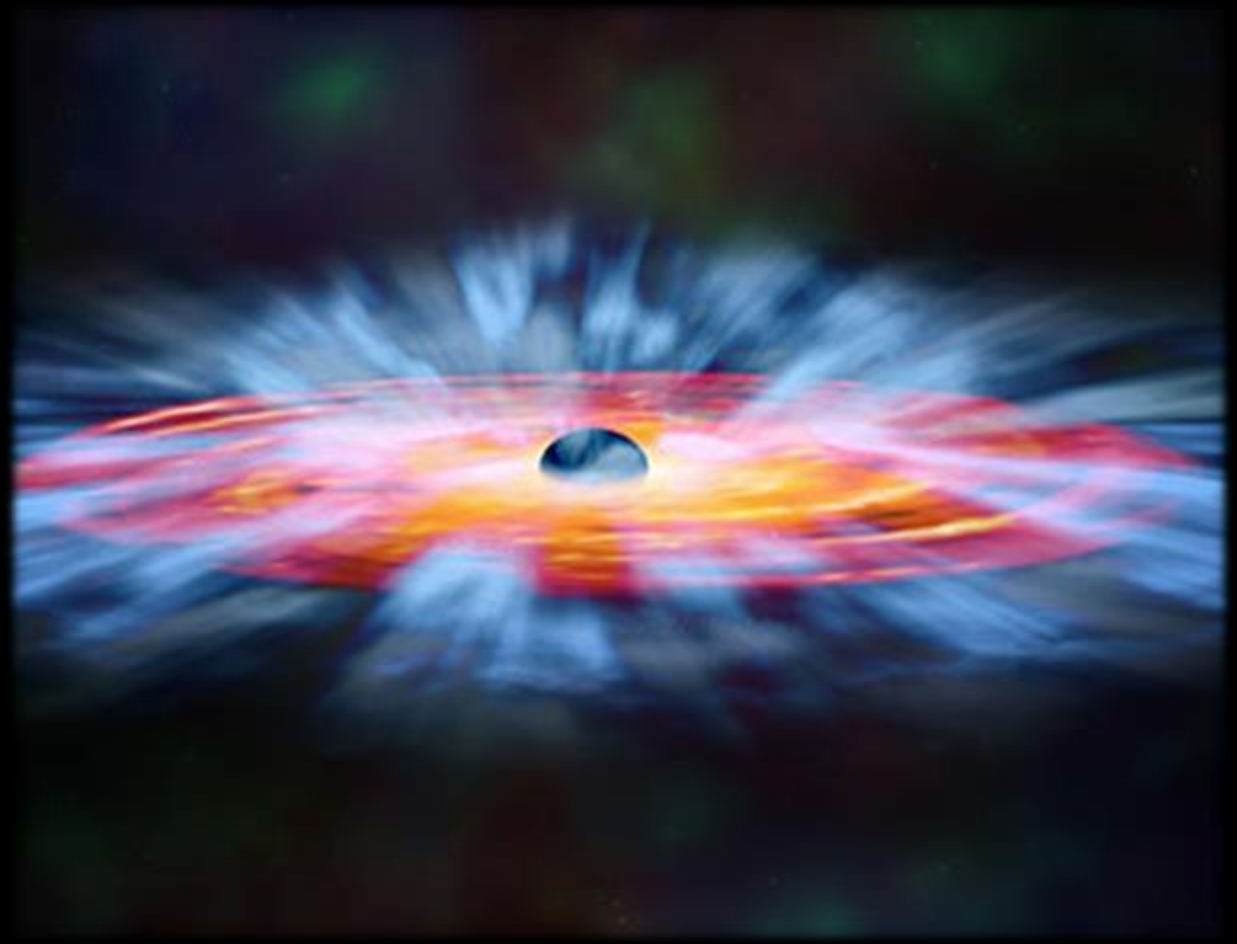


NGC 1068 comes into focus

0.35 deg → 0.1 deg → 0.04 deg



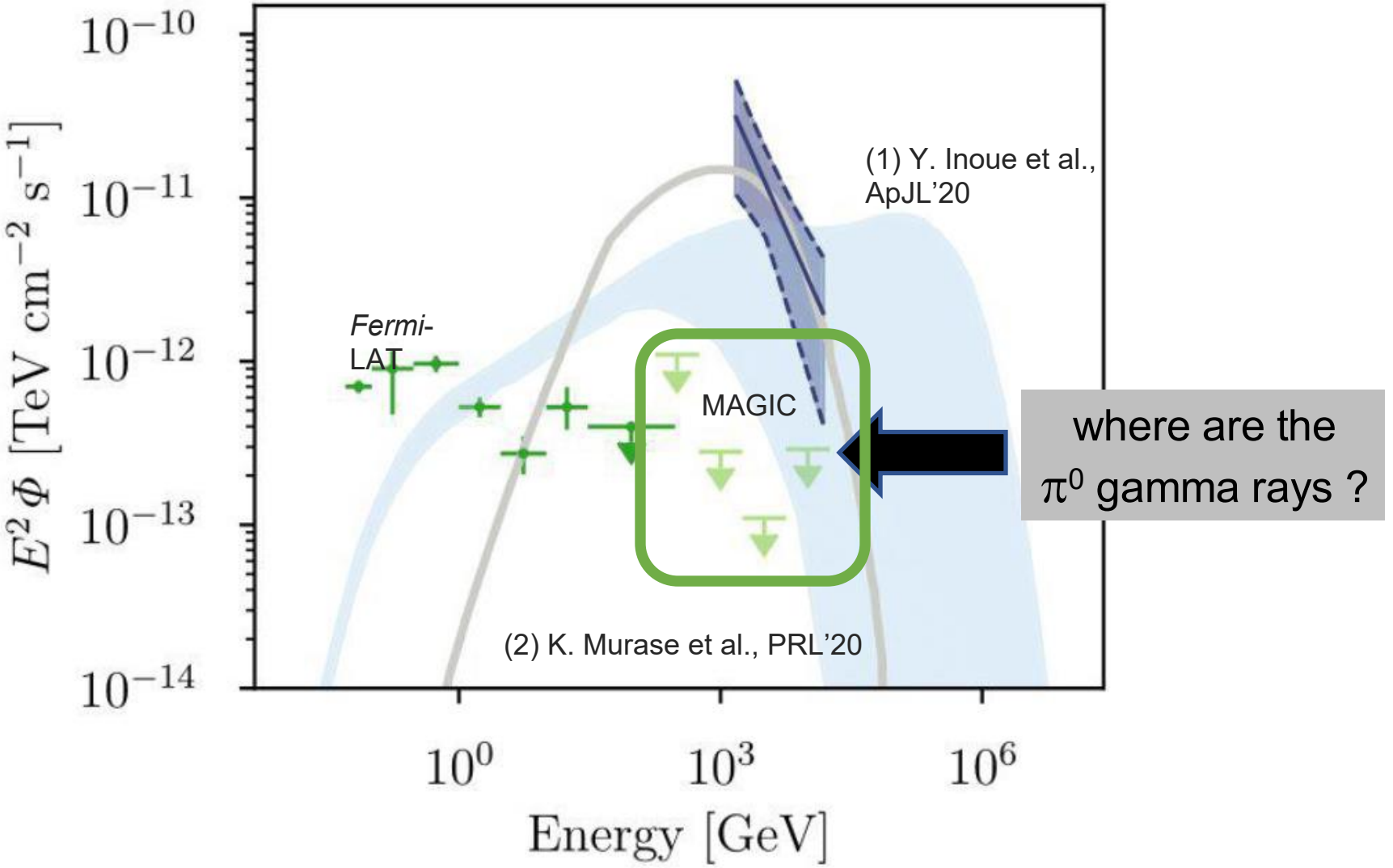
- accelerator(s): electrons and protons are accelerated in the turbulent magnetic fields associated with the accretion disk, in the infall onto the black hole,…



- target: the neutrinos are produced in the optically thick core of plasma emitting X-rays (corona) and dense clouds of hydrogen (protons)

a gamma ray for every neutrino?

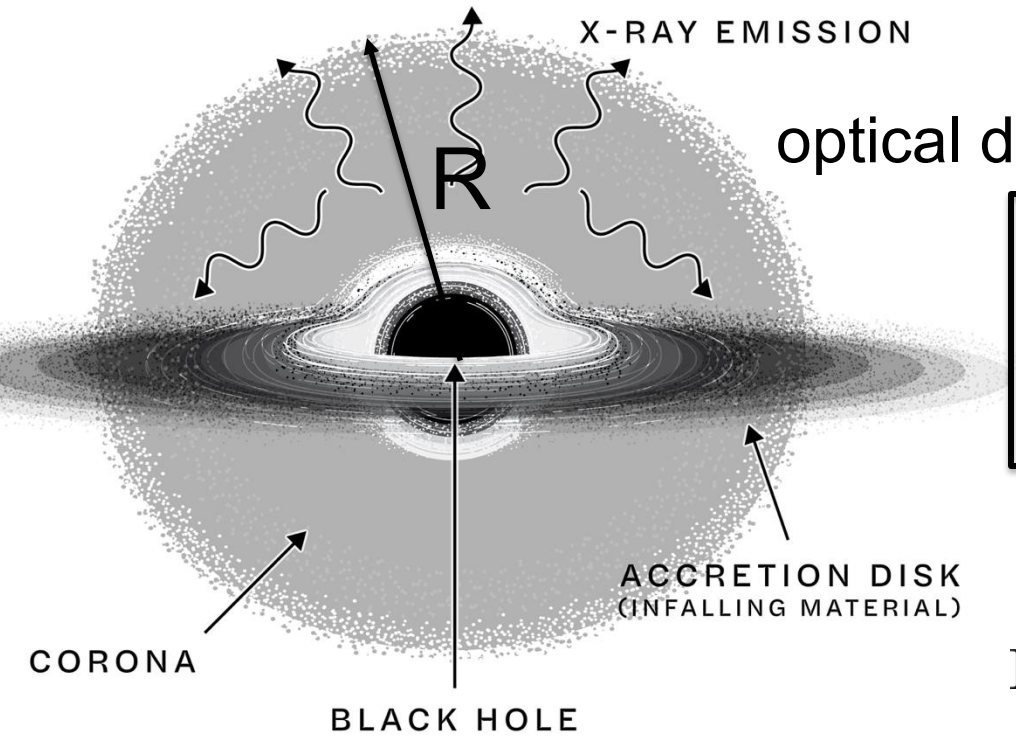
NGC 1068: an obscured cosmic accelerator



where are the π^0 gamma rays ?

NGC 1068 core: large optical depth of protons (and π^0 gamma rays) in X-ray corona

2411.14598 [astro-ph.HE]



optical depth τ = cross section x target density

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

number of target X-rays

size of the target

$E_X = 1\,\mathrm{keV} \quad L_X \sim 10^{43}\,\mathrm{ergs}^{-1} \quad M_{BH} \sim 10^7 \mathrm{solar\ masses}$

$$\tau_{p\gamma} = 0.1 \sim 1 \rightarrow \text{neutrinos produced for } R \sim 10\,R_S$$

$$\tau_{\gamma\gamma} \sim [\sigma_{\gamma\gamma}/\sigma_{p\gamma}]\,\tau_{p\gamma} \sim 10^2 \rightarrow \pi^0 \text{ gamma rays absorbed}$$

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

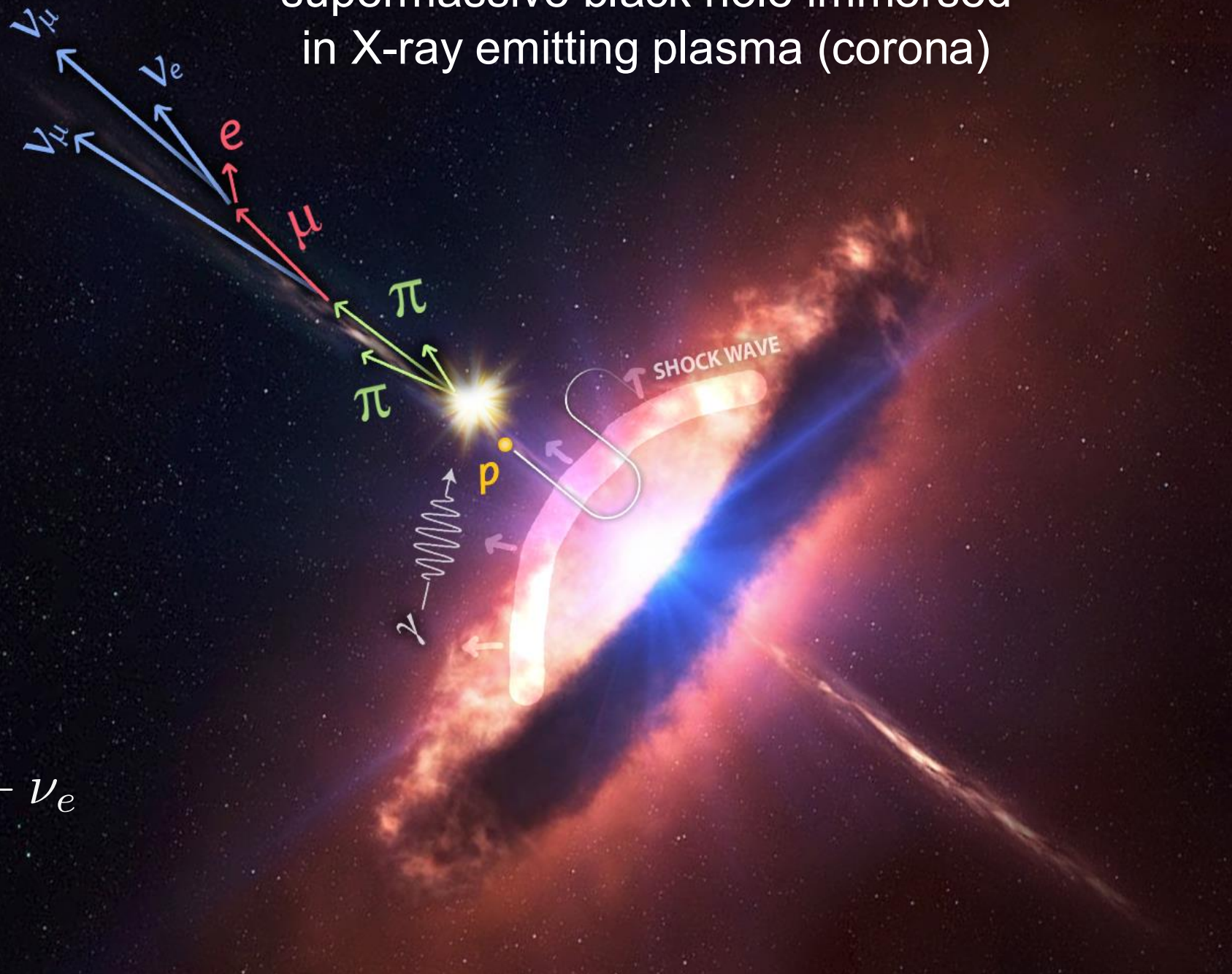
the neutrinos escape
the gamma rays do not
… like at Fermilab

gamma rays lose energy
to appear below Fermi's
threshold

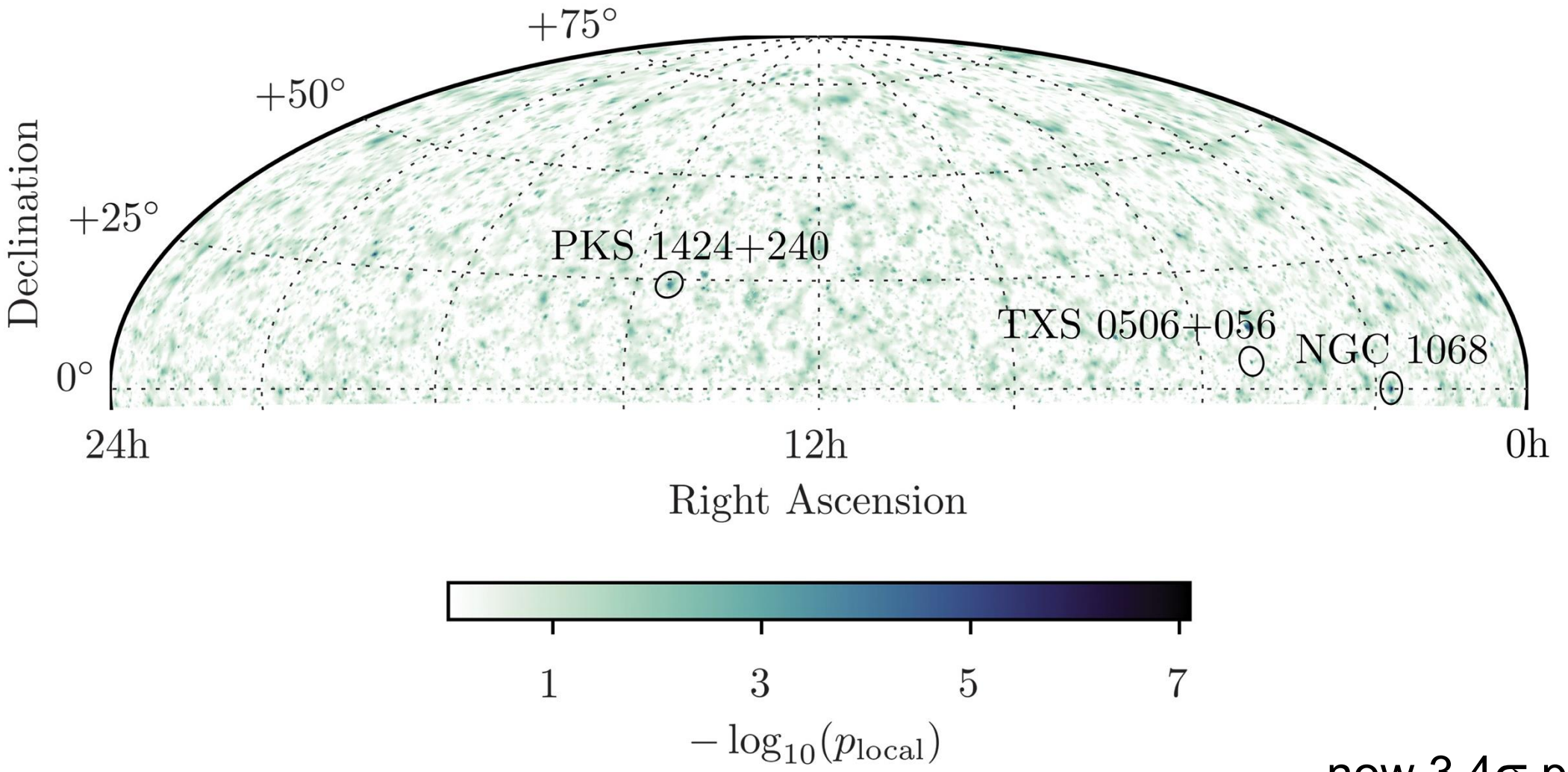
neutrinos produced at
10 Schwartzschild radii
from the black hole

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

supermassive black hole immersed
in X-ray emitting plasma (corona)



sub-leading sources from 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 detected in 2017

- multimessenger
- IceCube archival data
- observation of optical flash 2hours after IC170922
- associates the neutrino with the source at the 50σ level

→ 2022 Evidence for Neutrino Emission from NGC 1068
Binomial analysis TXS 0506 and PKS 1420

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

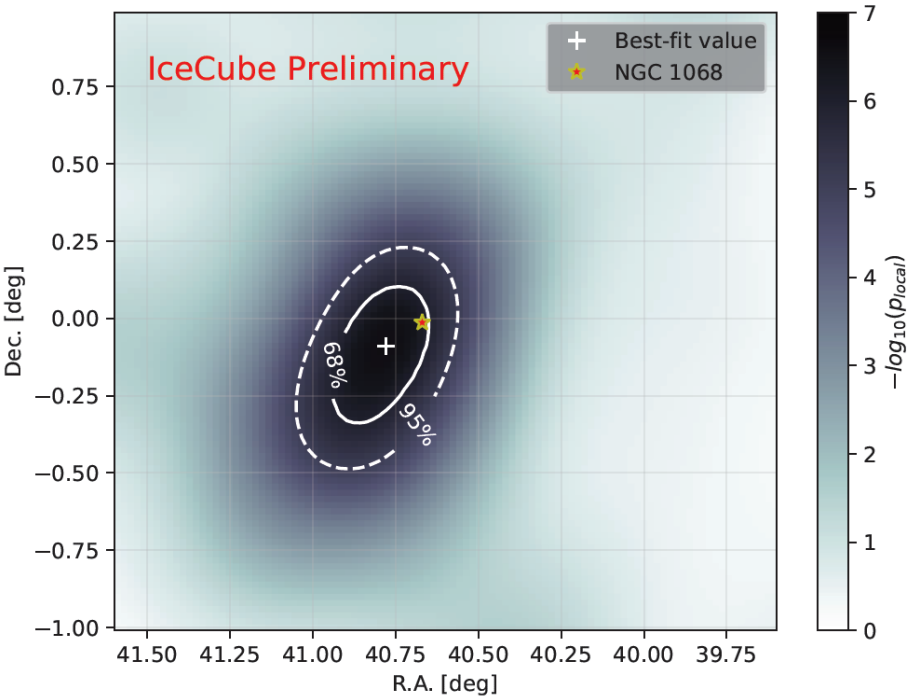
→ 2024: IceCube Search for Neutrino Emission from X-ray Bright Seyfert Galaxies
Northern sky NGC 4151 and CGCG 420-015
arXiv:2406.07601

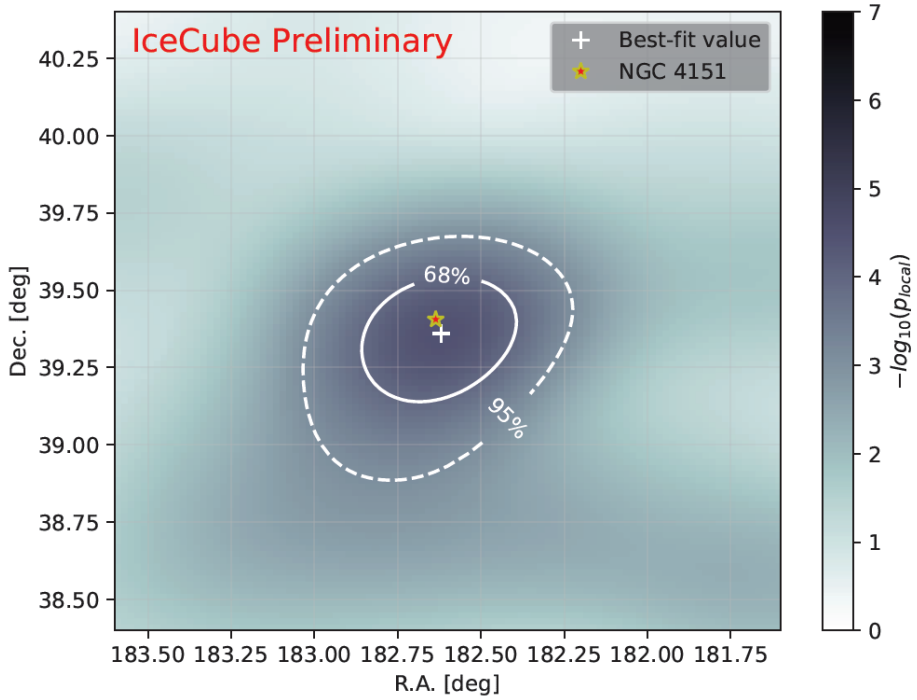
→ 2024 Search for neutrino emission from hard X-ray AGN with IceCube
NGC 4151
arXiv:2406.06684

→ 2024 Starting event search for Seyfert galaxies
TeVPA 2024
Circinus

→ 2024 Binomial excess from 12 X-ray bright Seyferts (update) TeVPA 2024

more sources …





- two brightest active galaxies discovered by Seyfert in 1943

NUCLEAR EMISSION IN SPIRAL NEBULAE*

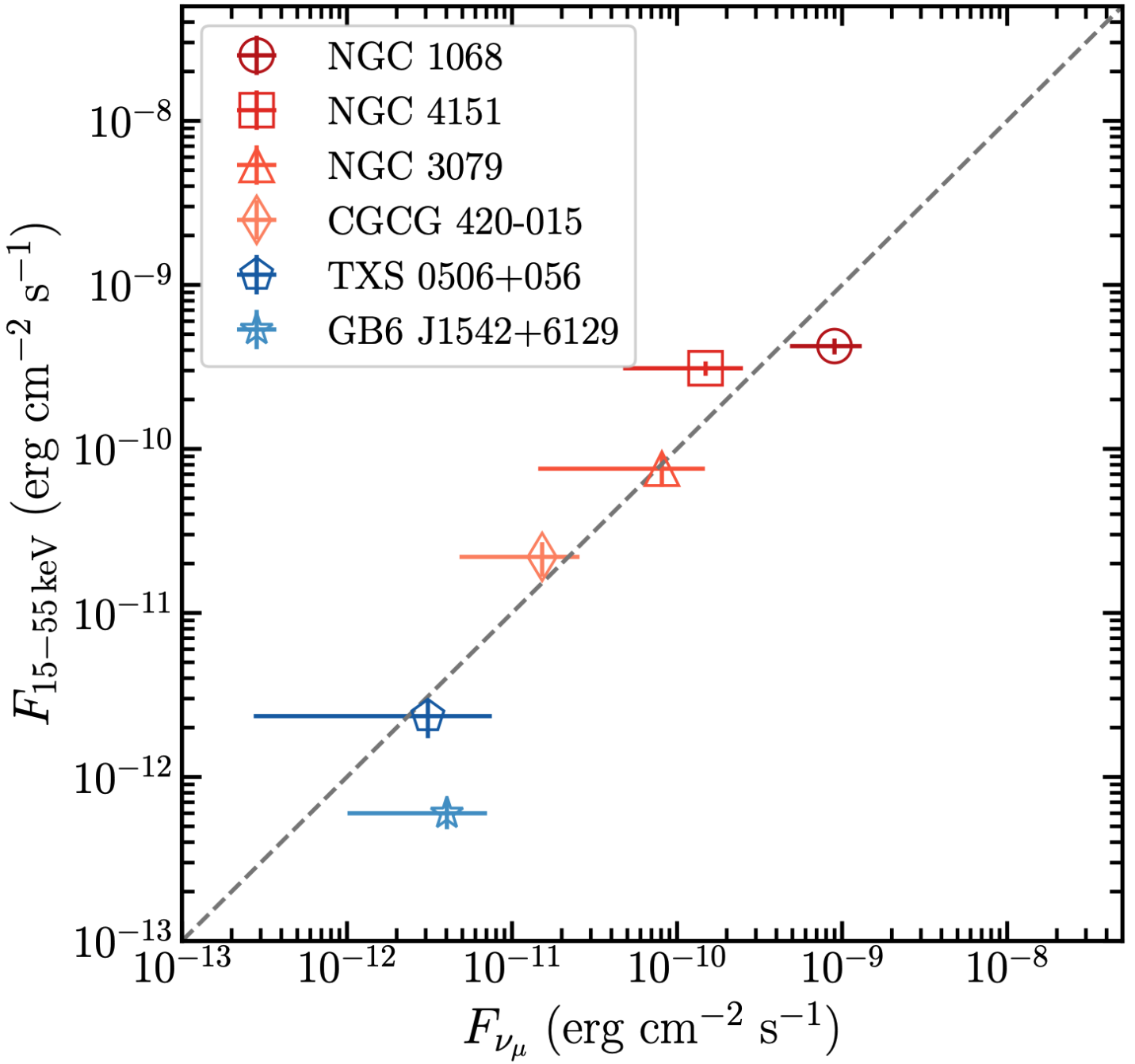
CARL K. SEYFERT† **1943**

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)

- hint from NGC 1068
- is there a correlation between the X-ray and neutrino flux ?



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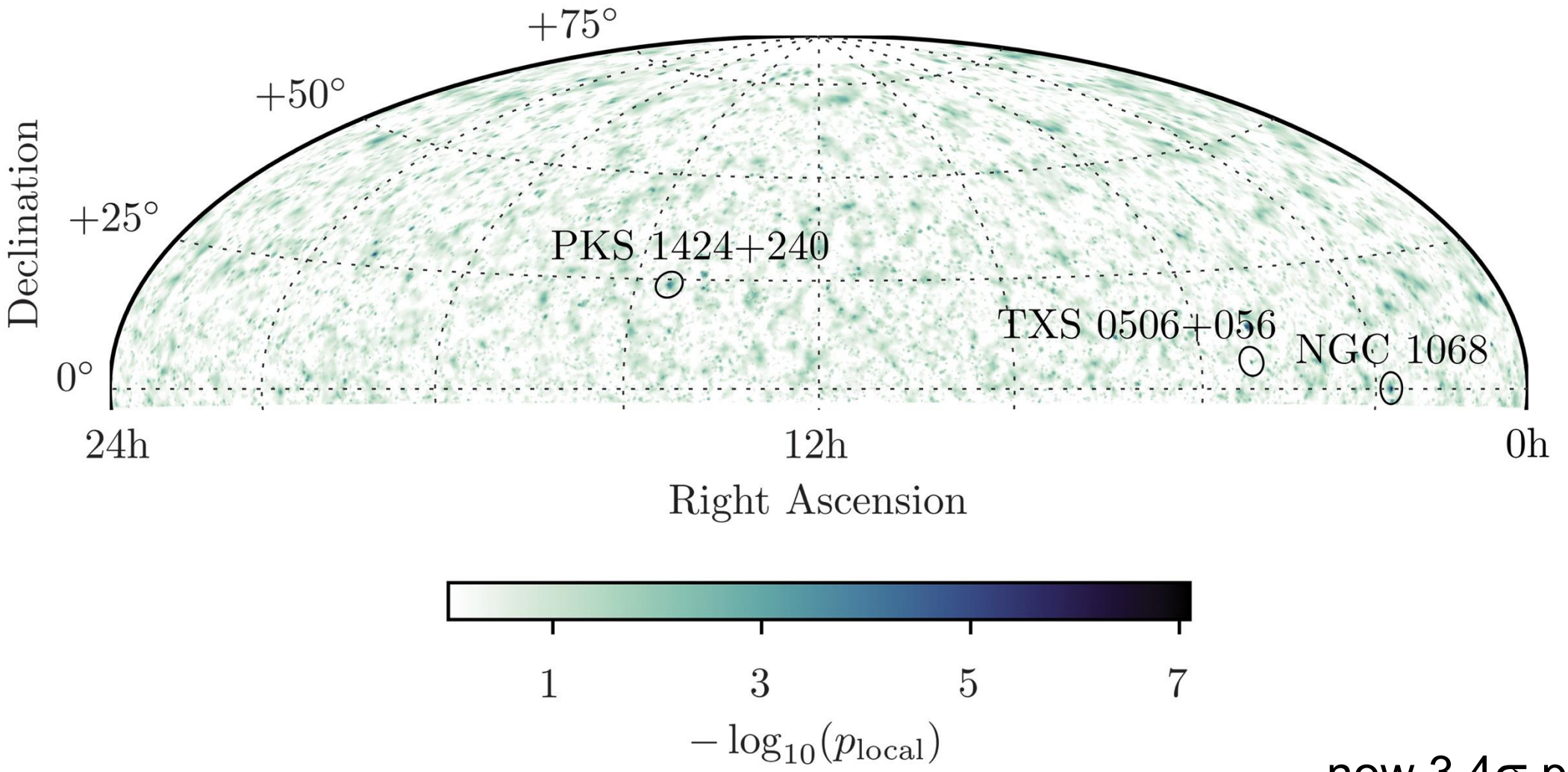
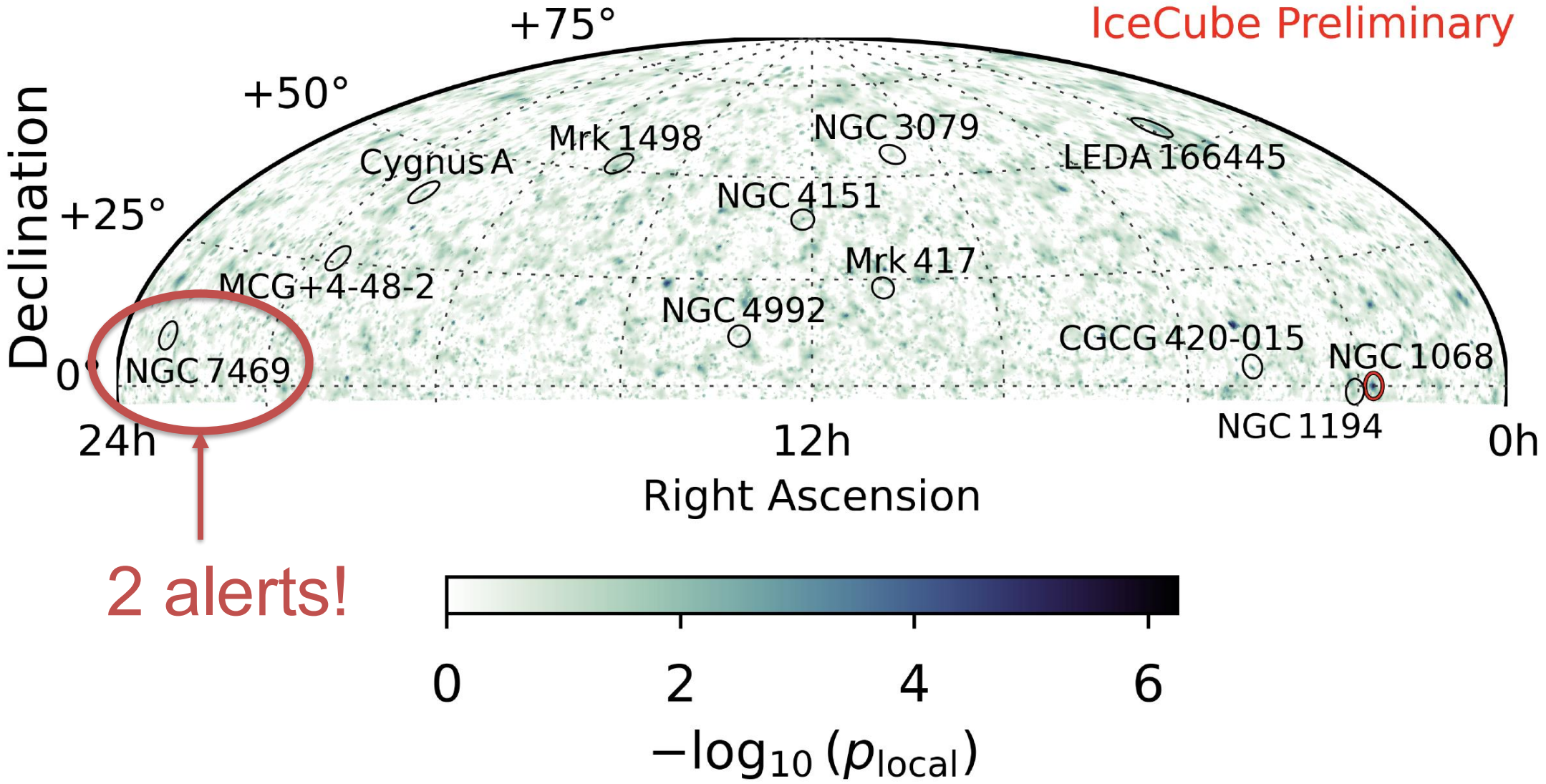
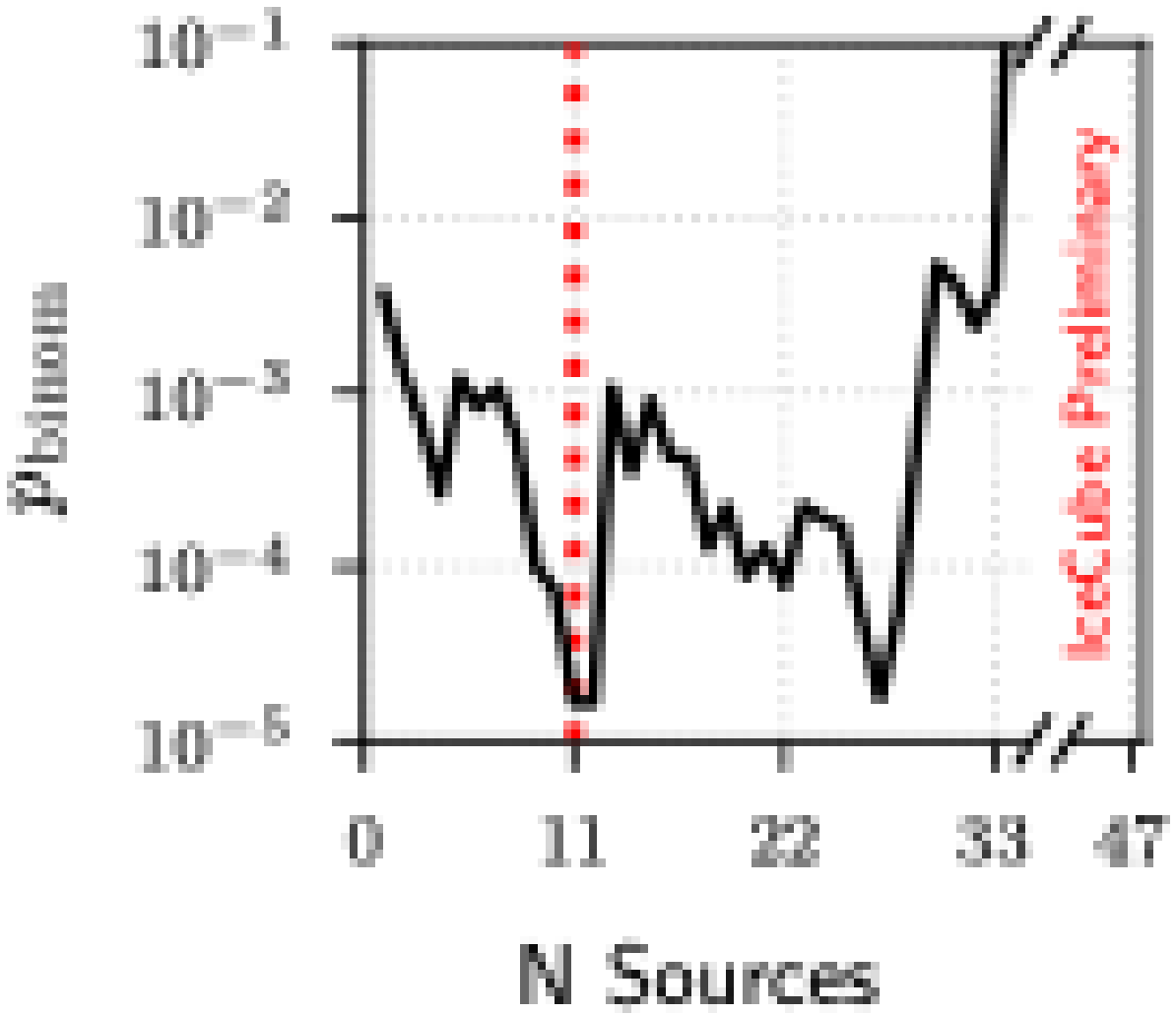


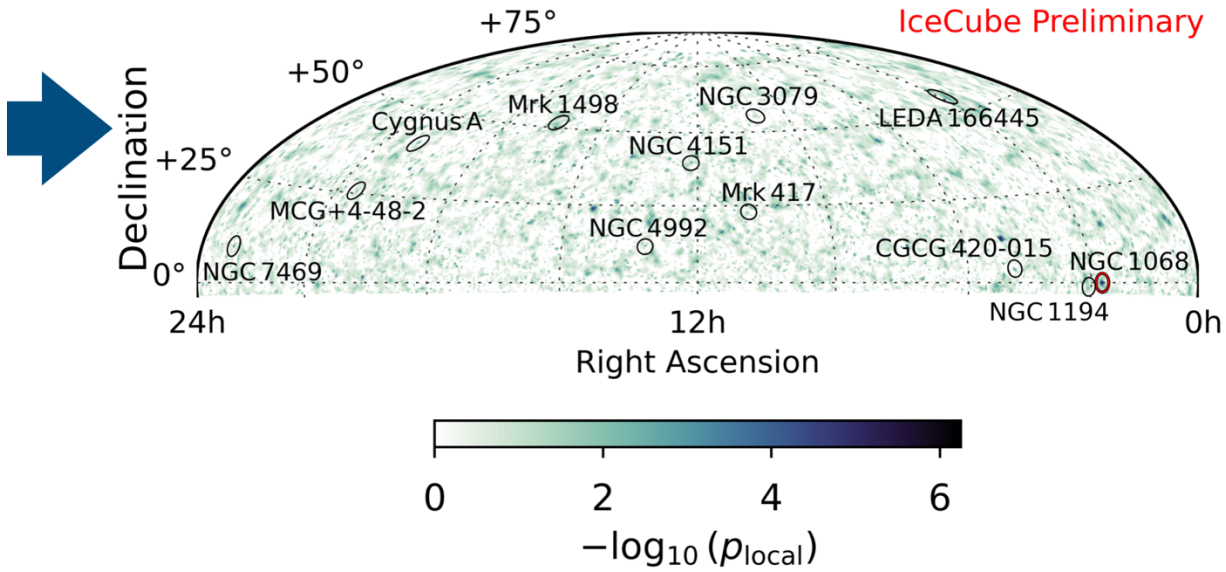
now 3.4σ p-value



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

Binomial test of non-jetted sources





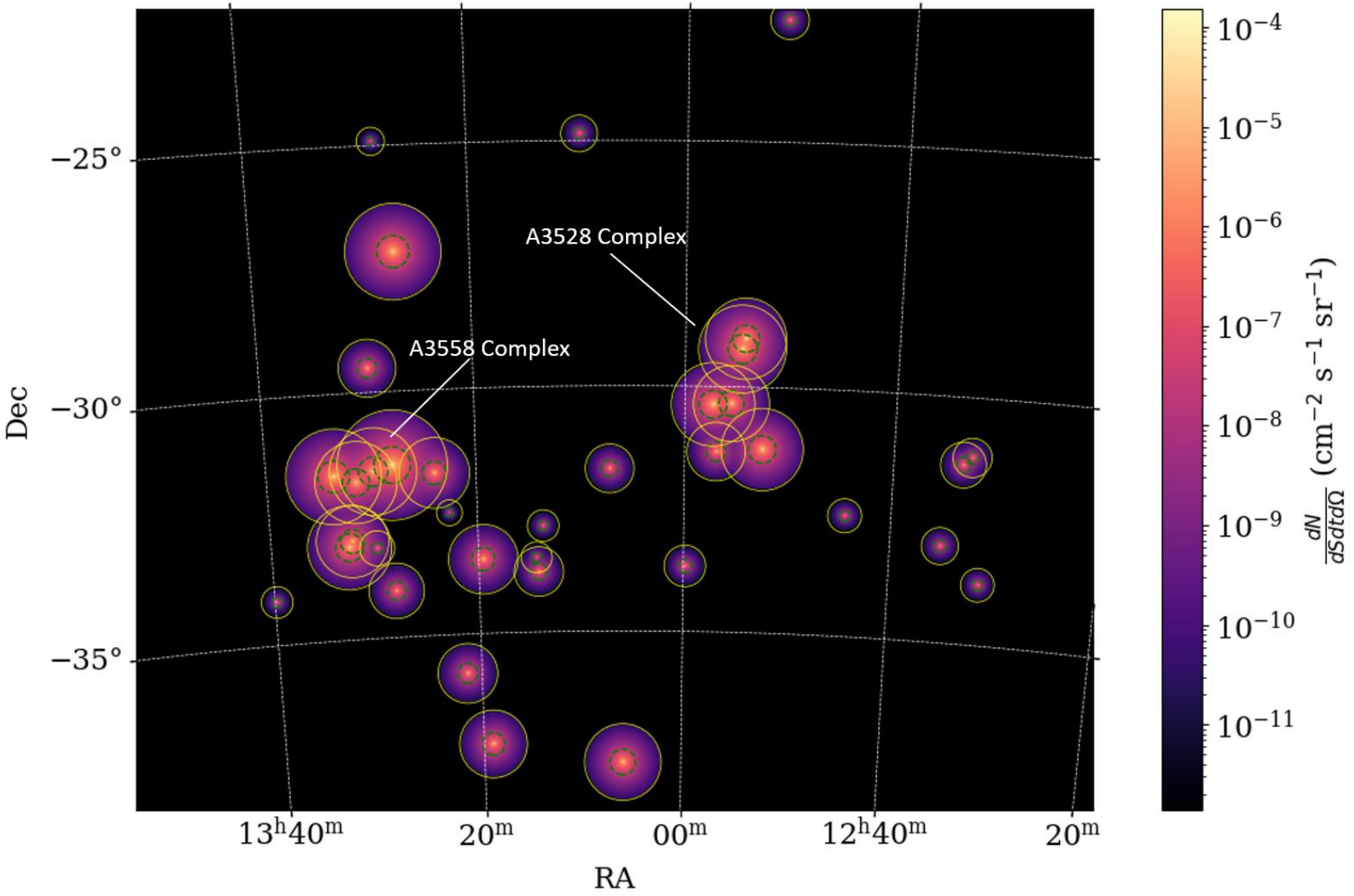
- Binomial Test: Probability of finding a signal from 47 AGNs too weak to be identified individually
- Result: 3.3σ excess for 11 sources (excluding NGC1068)

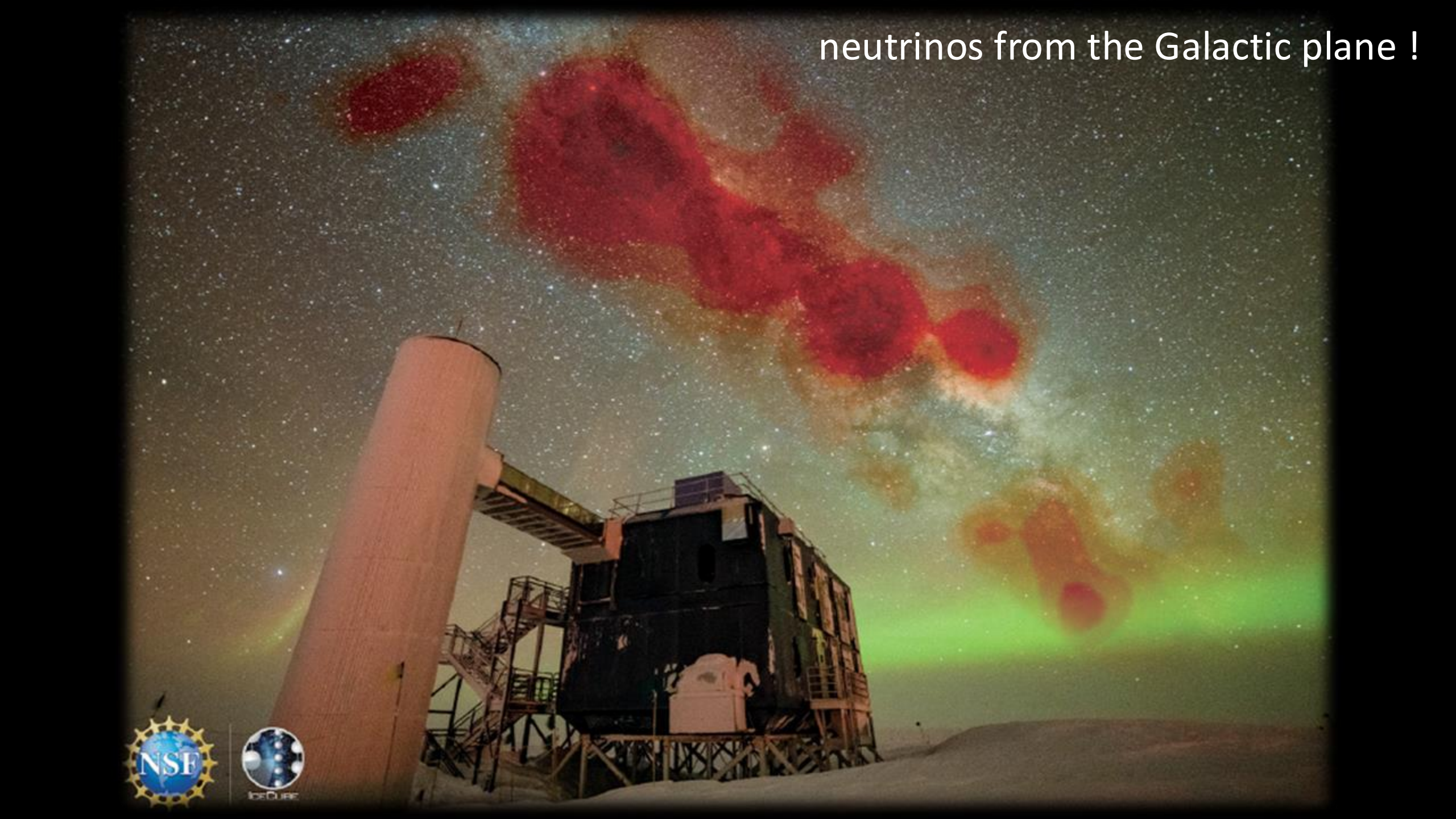
solution to the extragalactic cosmic ray problem?

clusters of superclusters

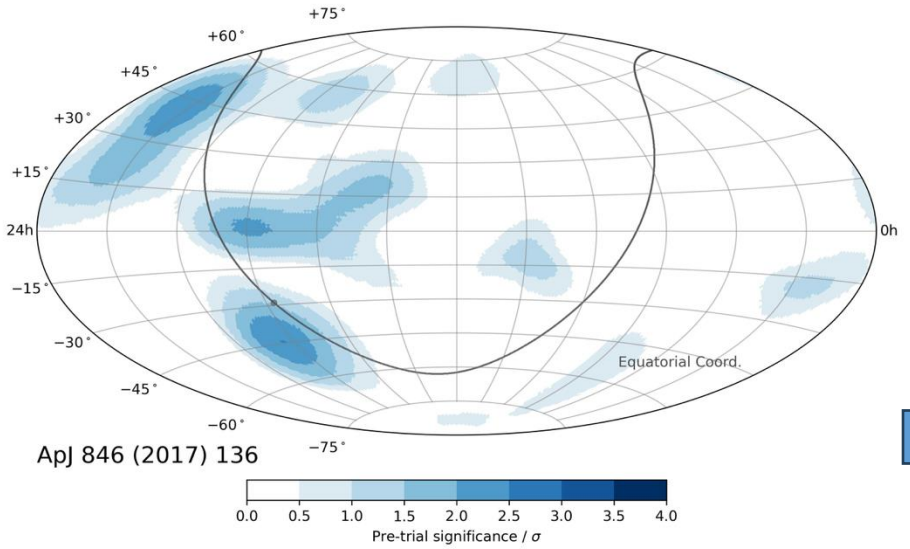
- neutrinos produced in individual active galaxies
- higher energy cosmic rays produced over the larger complex à la Hillas
- neutrino fluxes lower because of low target densities of larger scales
- need the next-generation detectors

the Shapley cluster of superclusters



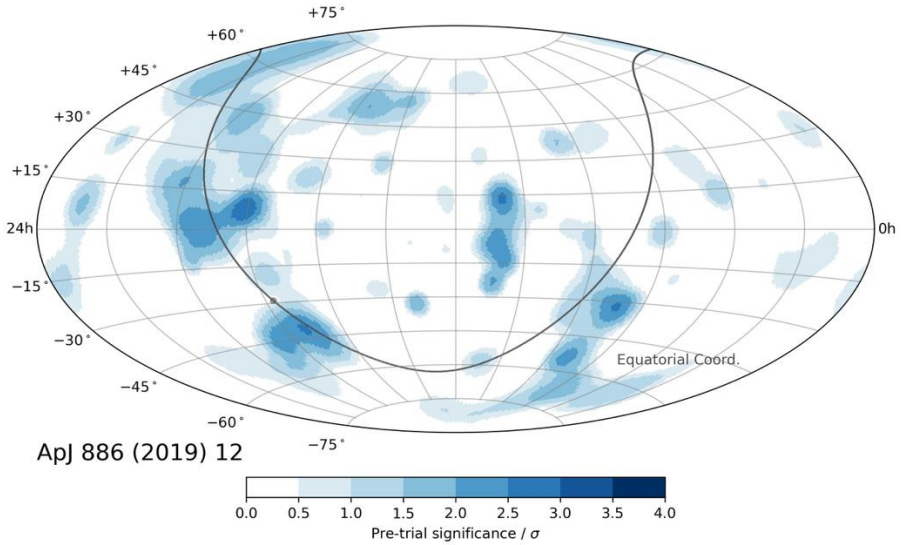

neutrinos from the Galactic plane !
NSF
IceCube

2017 paper



ApJ 846 (2017) 136

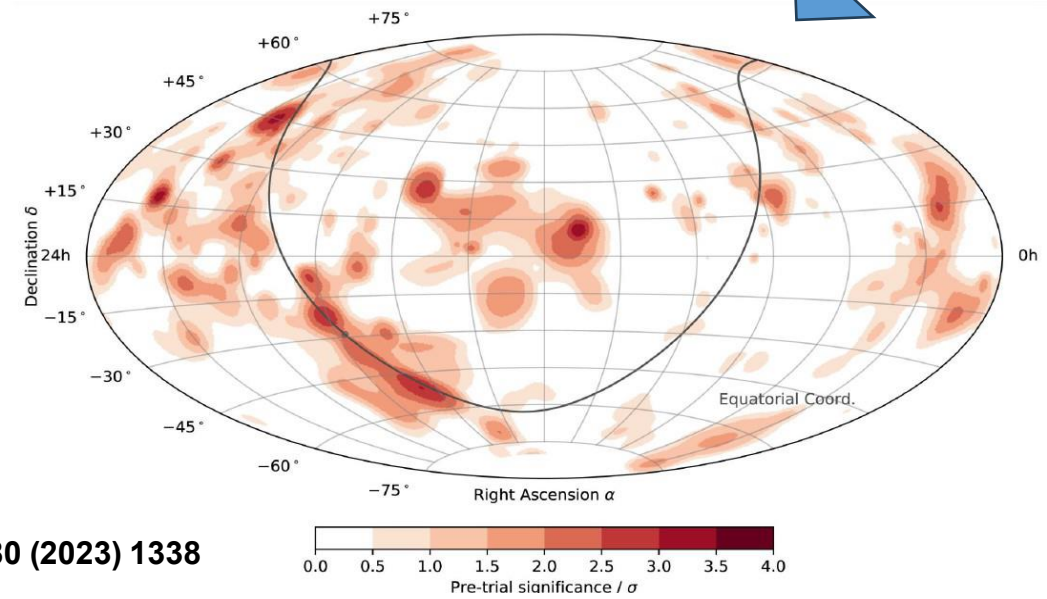
2019 paper



ApJ 886 (2019) 12

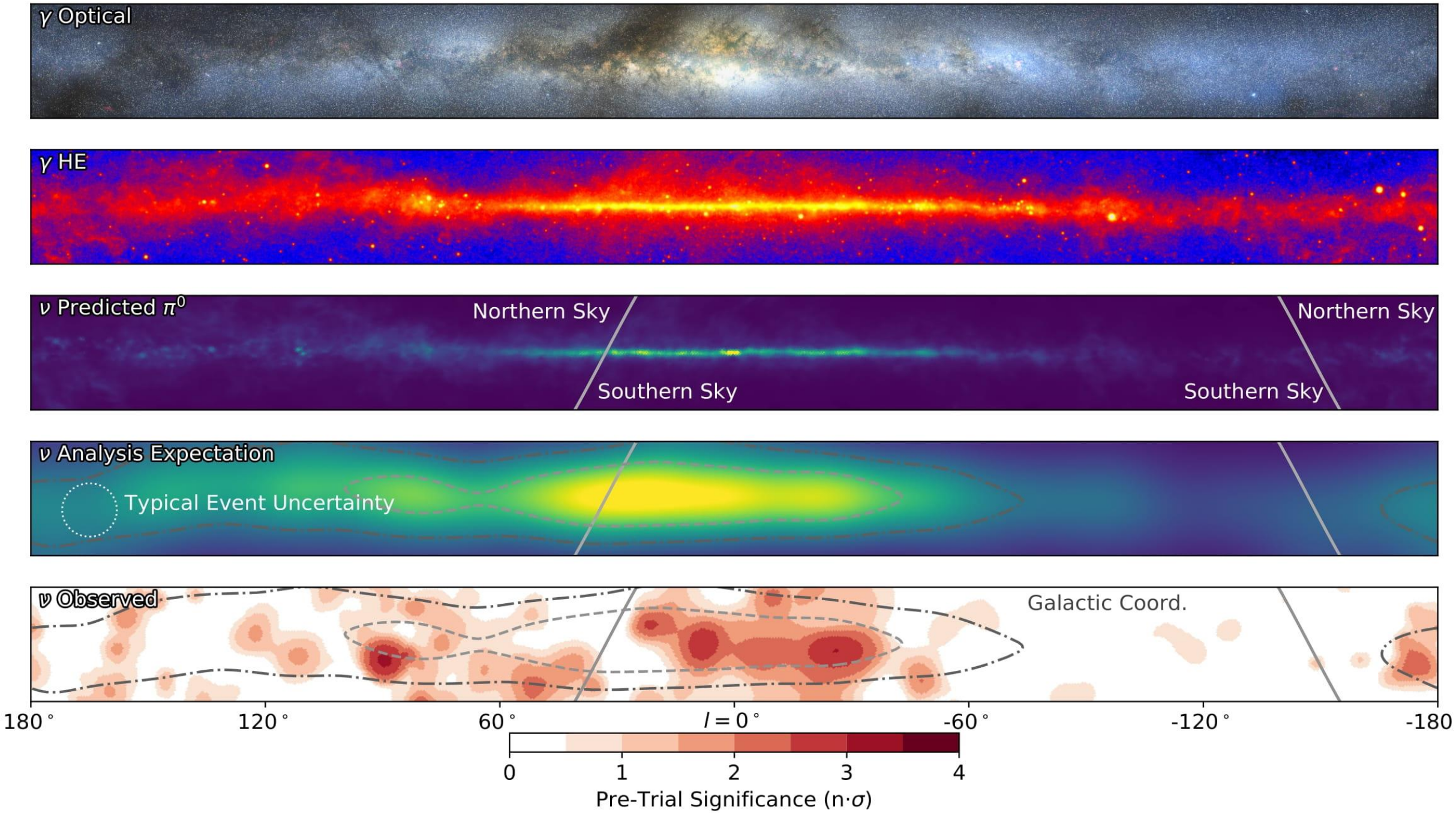
2 years of data
Galactic Plane p-value: 65%

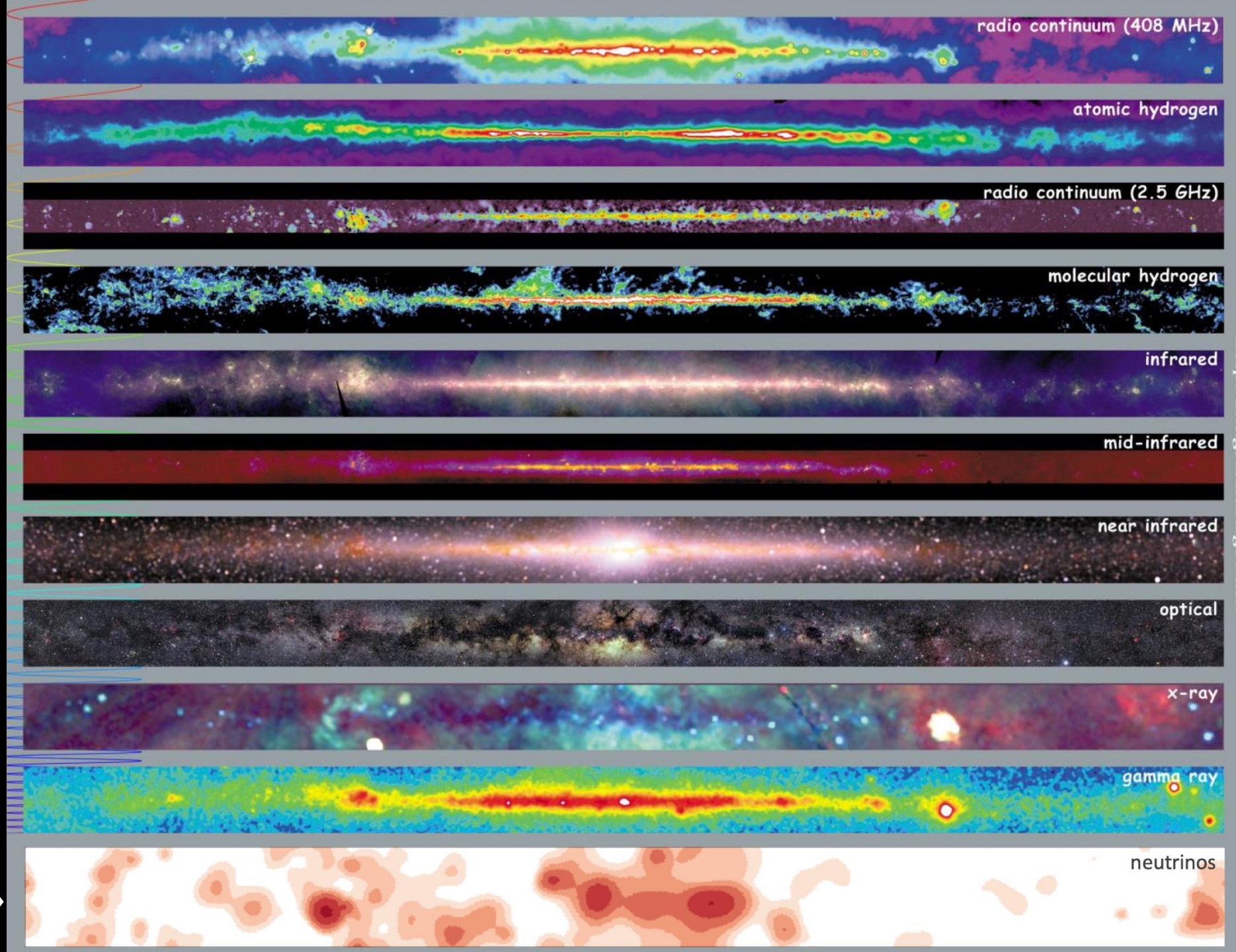
7 years of data
Galactic Plane p-value: 2.1% (2σ)



Science 380 (2023) 1338

- Deep learning improved resolution by 2, sensitivity by 3
- **13 years of data Galactic Plane: 5.7σ post trial (Lepton-Photon 2025, Madison)**

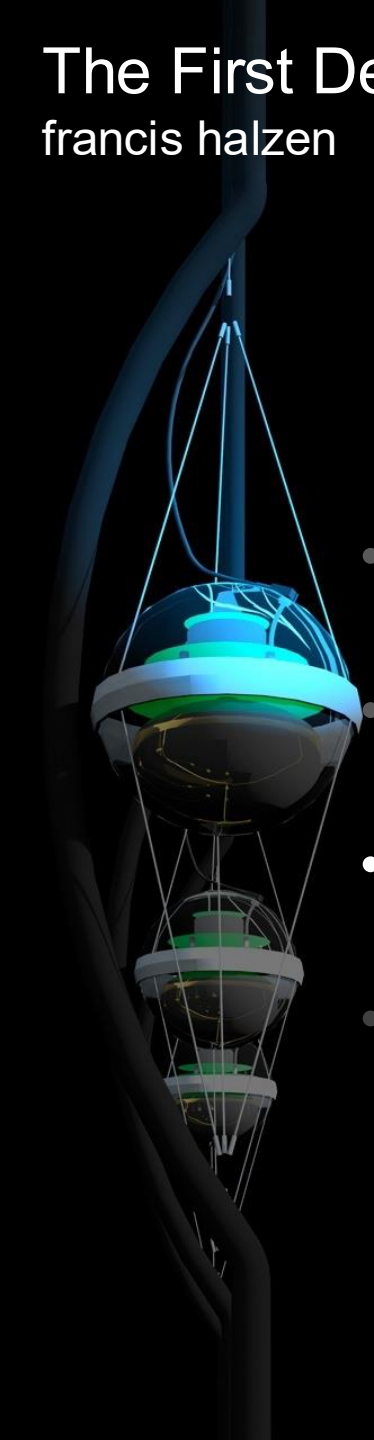

γ Optical
γ HE
ν Predicted π0
Northern Sky
Southern Sky
Northern Sky
Southern Sky
ν Analysis Expectation
Typical Event Uncertainty
ν Observed
Galactic Coord.
180°
120°
60°
l = 0°
-60°
-120°
-180°
0
1
2
3
4
Pre-Trial Significance (n·σ)



Milky Way viewed in neutrinos

The First Decade of Neutrino Astronomy and Neutrino Physics

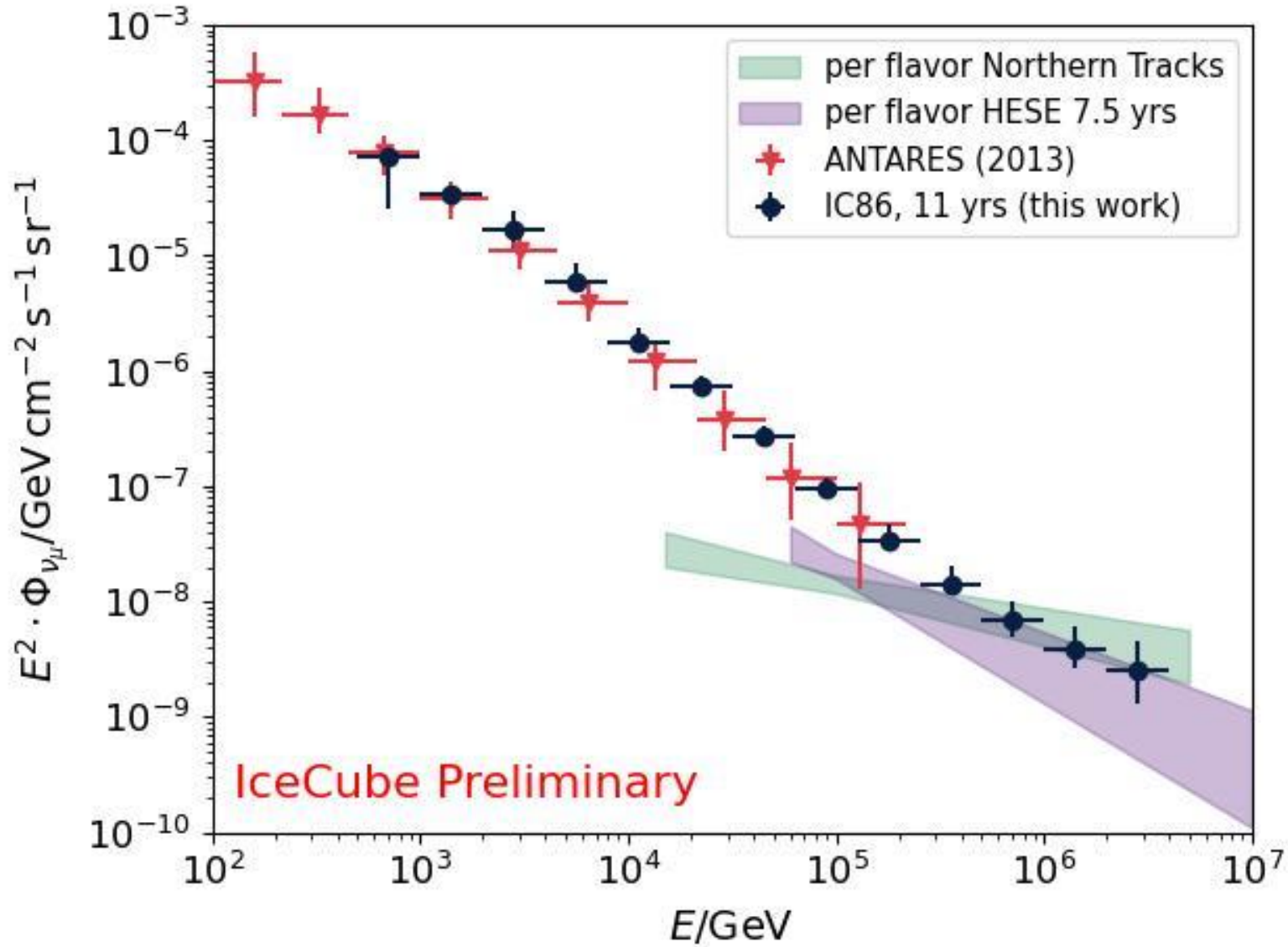
francis halzen



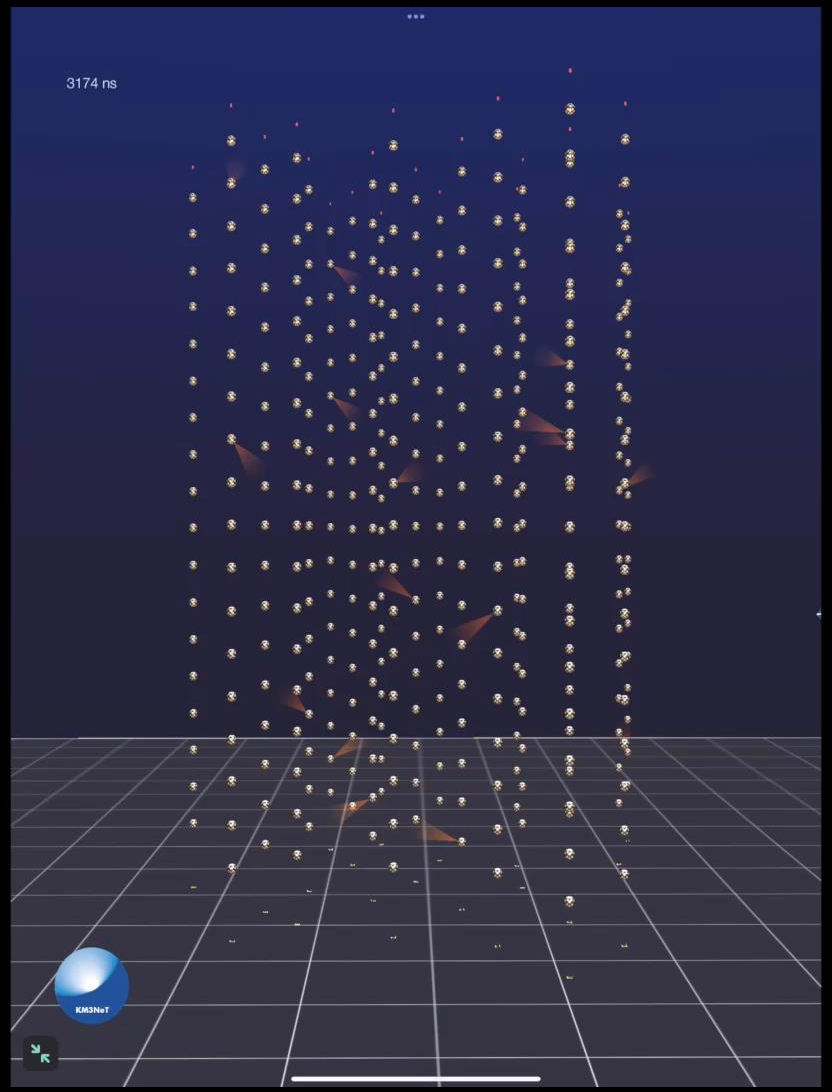
- from discovery to astronomy: there is a lot happening
- the high-energy neutrino sky and the discovery of the first neutrino sources
- KM3NeT: a 220 PeV neutrino!
- neutrino physics at PeV energy

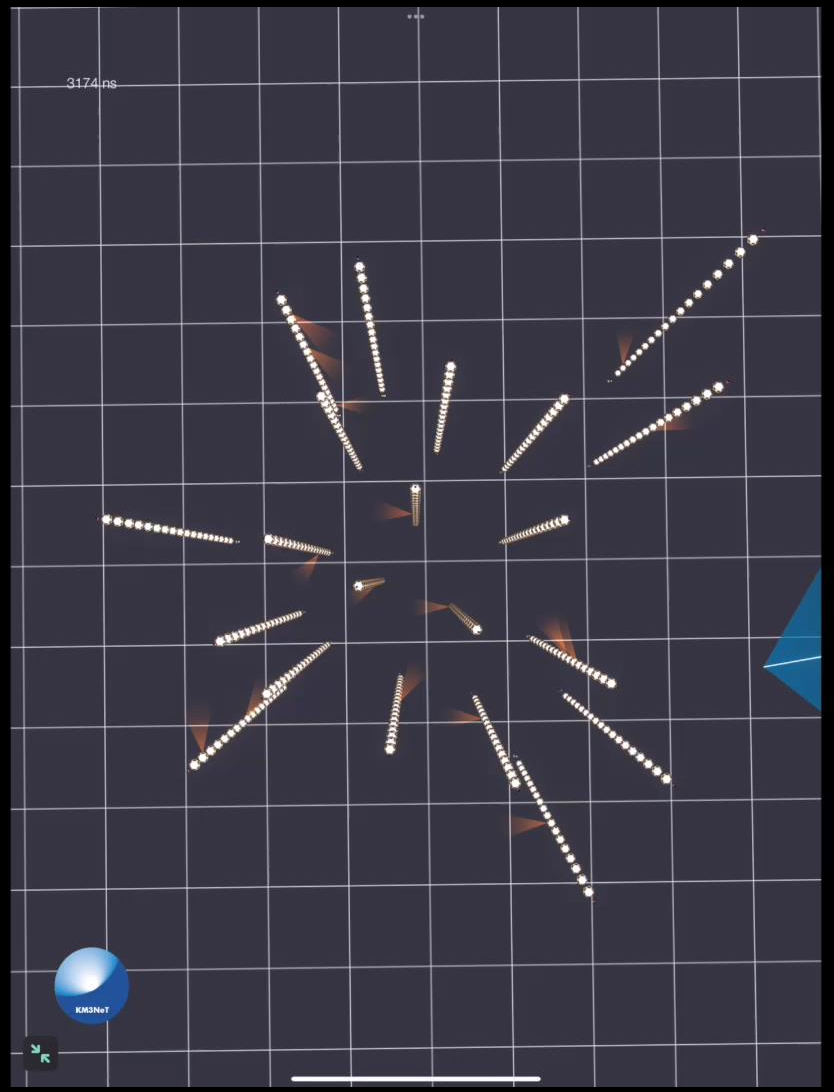
IceCube.wisc.edu

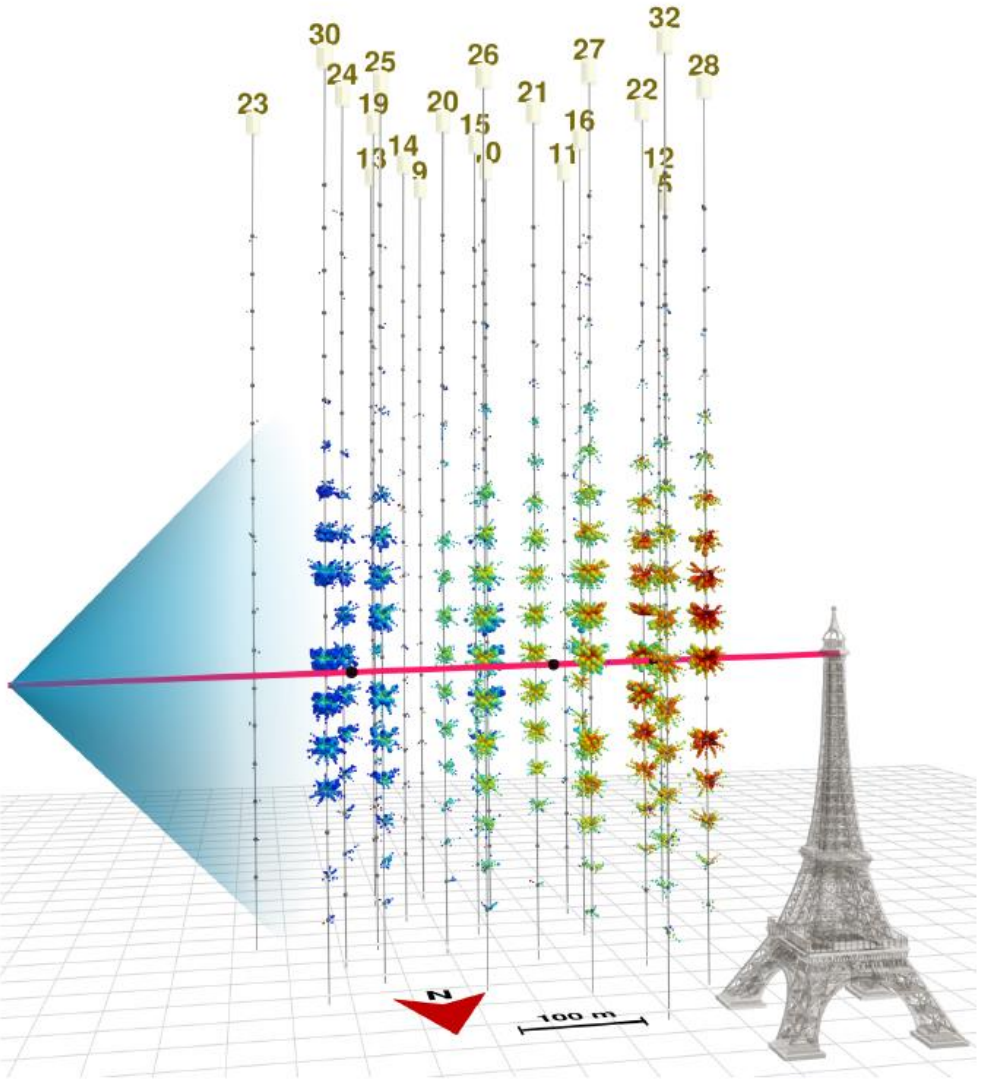
techniques mature (and improving) and agree on the muon neutrino spectrum

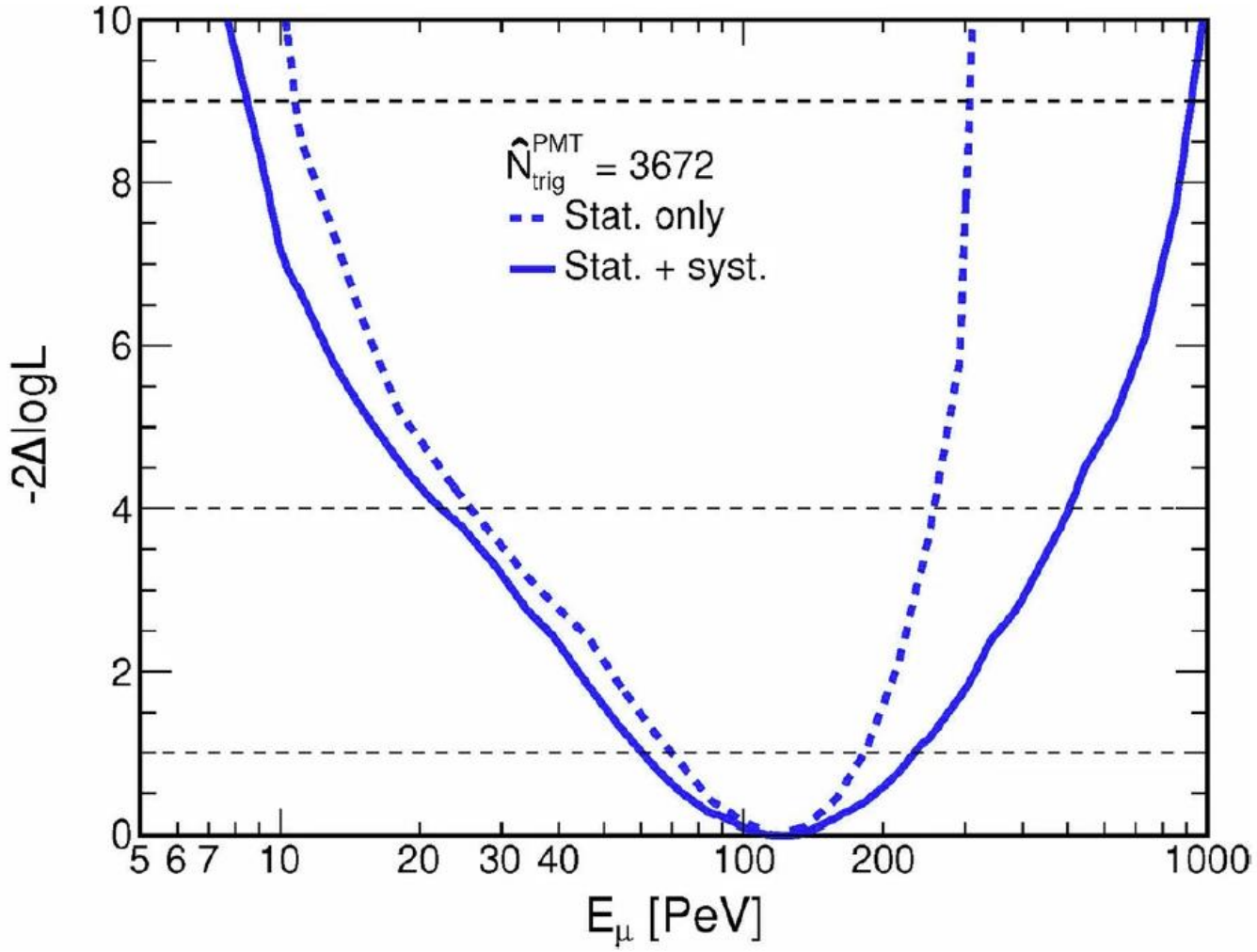


Uncharted Territory: E_ν = 220 PeV







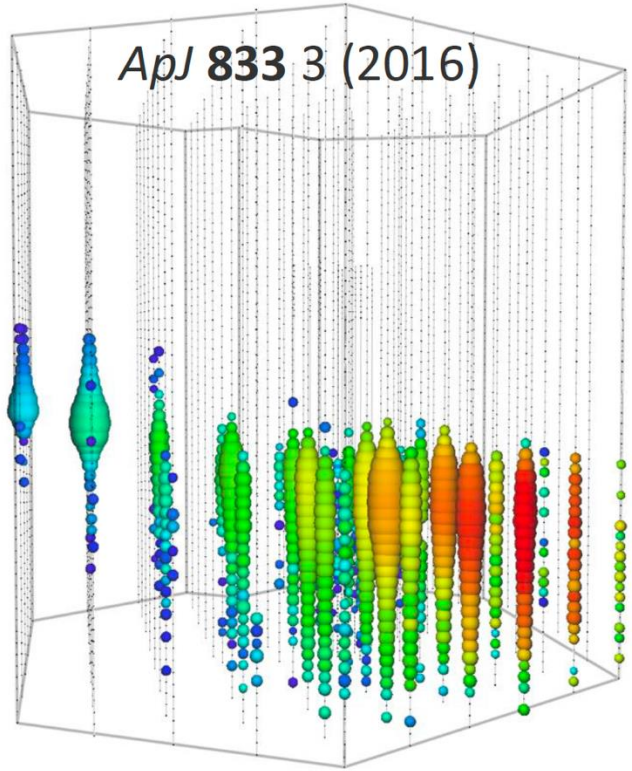


- Expected atmospheric muon contamination @ 100 PeV: << 10^{-10} event/year within 2σ reconstructed direction
- Expected rate of atmospheric neutrinos >100 PeV: << (1-5) x 10^{-5} event/year

The highest energy neutrinos

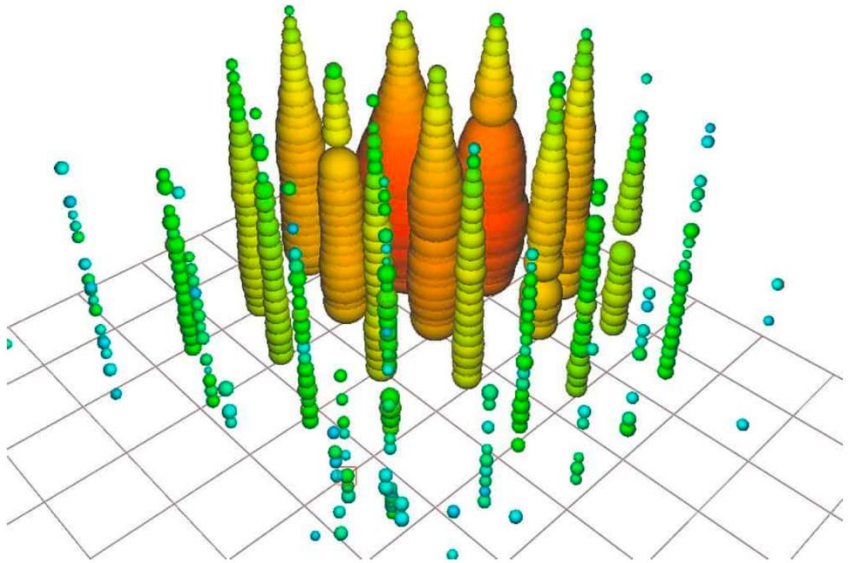
- 3 events with neutrino energy > 5 PeV over a decade of data taking

ApJ **833** 3 (2016)



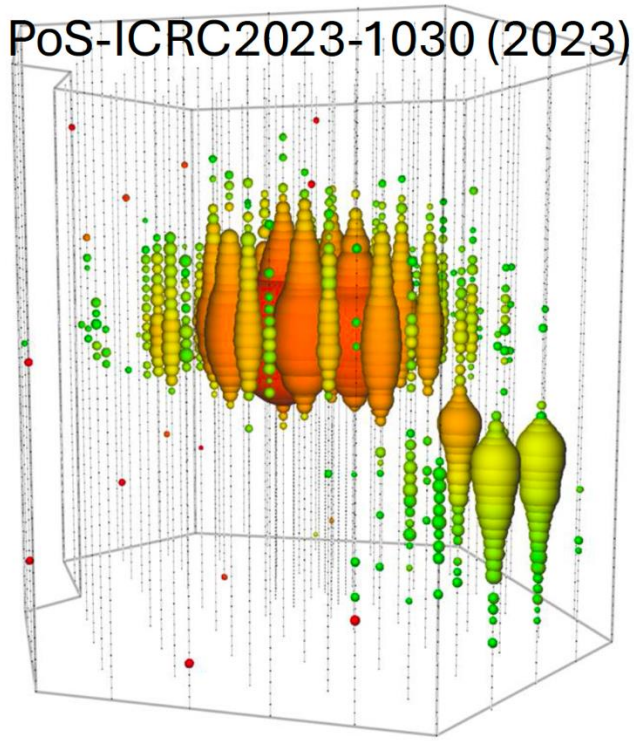
Muon energy: 4.5±1.2 PeV
Nu energy ~ 9 PeV

Nature **591**, 220–224 (2021)



Deposited energy: 6.05 ±0.72 PeV
Nu energy ~6.3 PeV

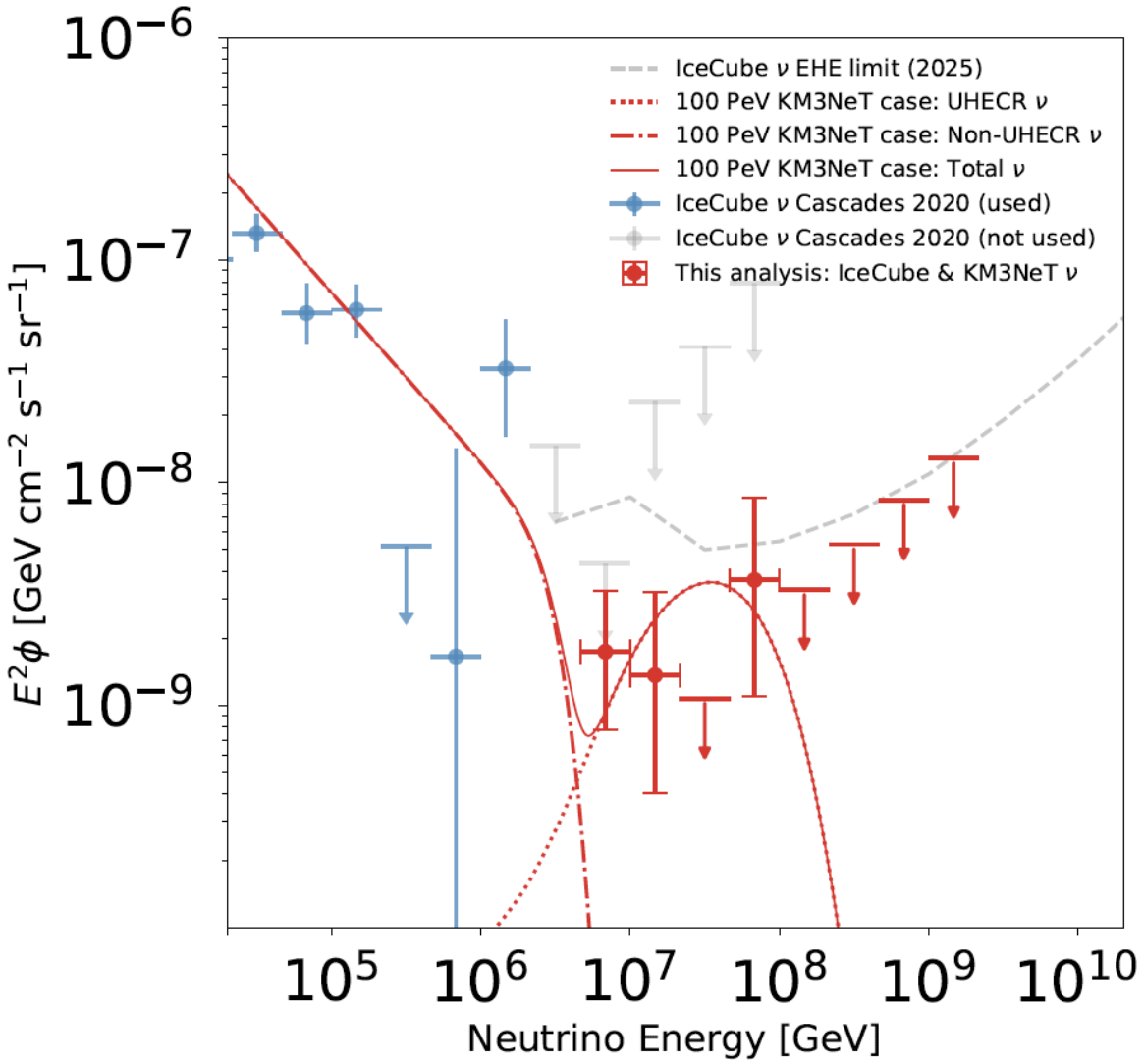
PoS-ICRC2023-1030 (2023)

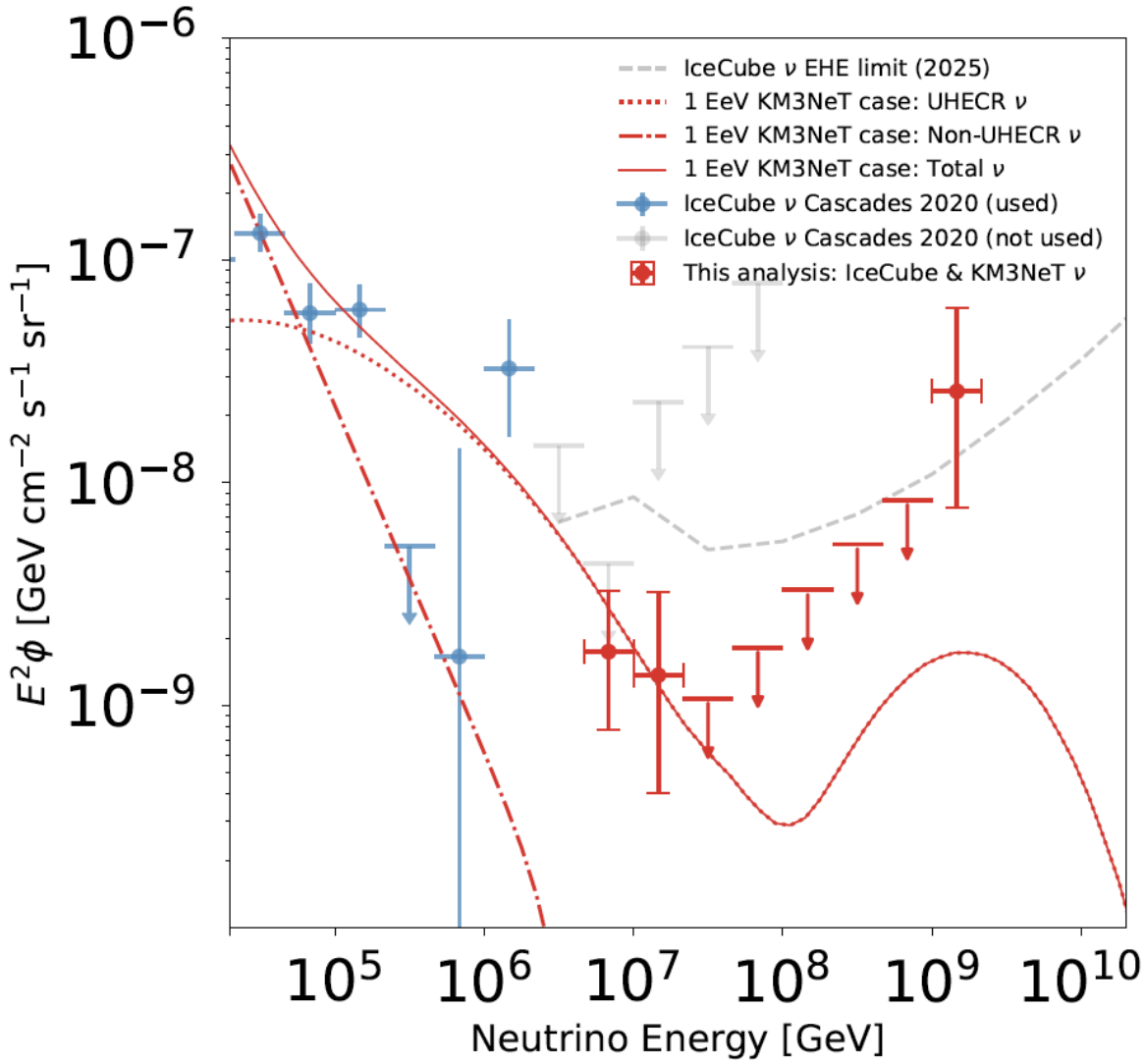


Nu energy ~11.4±2.5 PeV

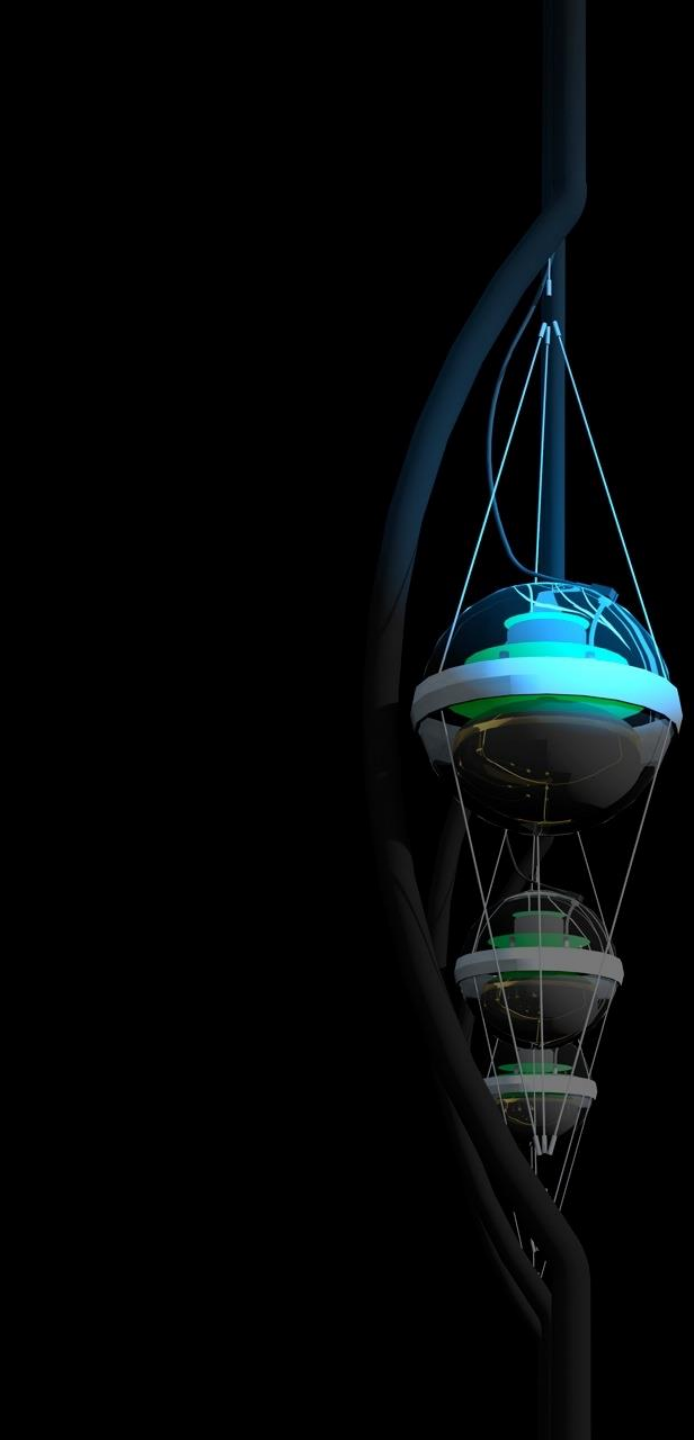
* Also new search using IceTop as veto: 2025 PRD 112, 012022

common fit of KM3NeT event and IceCube events





(Lu Lu, Lepton-Photon 2025, Madison)



neutrino astronomy 2025

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

icecube.wisc.edu

THE ICECUBE COLLABORATION

ALIA 1

1

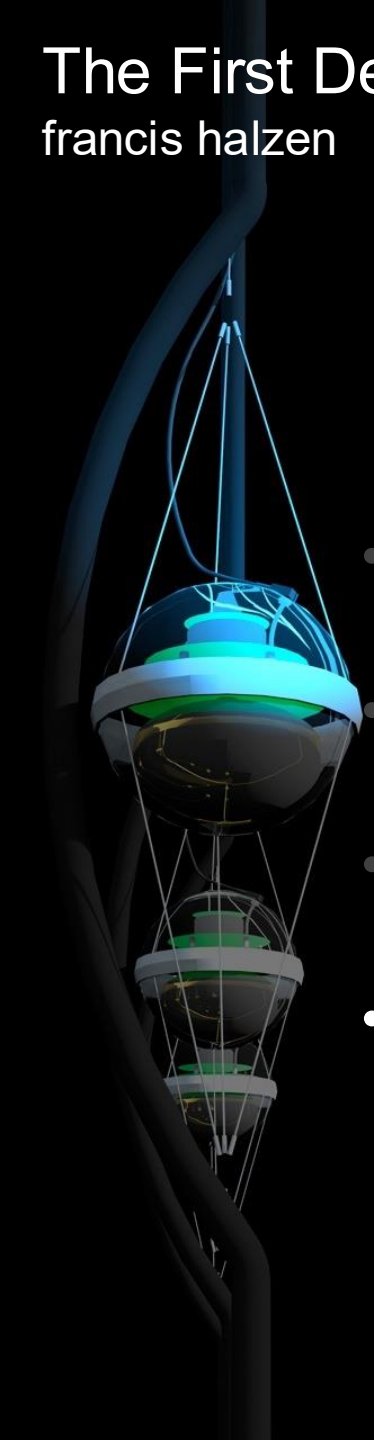
ED KINGDOM 1

UNITED STATES 25

IceCube
South Pole Neutrino Observatory

The First Decade of Neutrino Astronomy and Neutrino Physics

francis halzen



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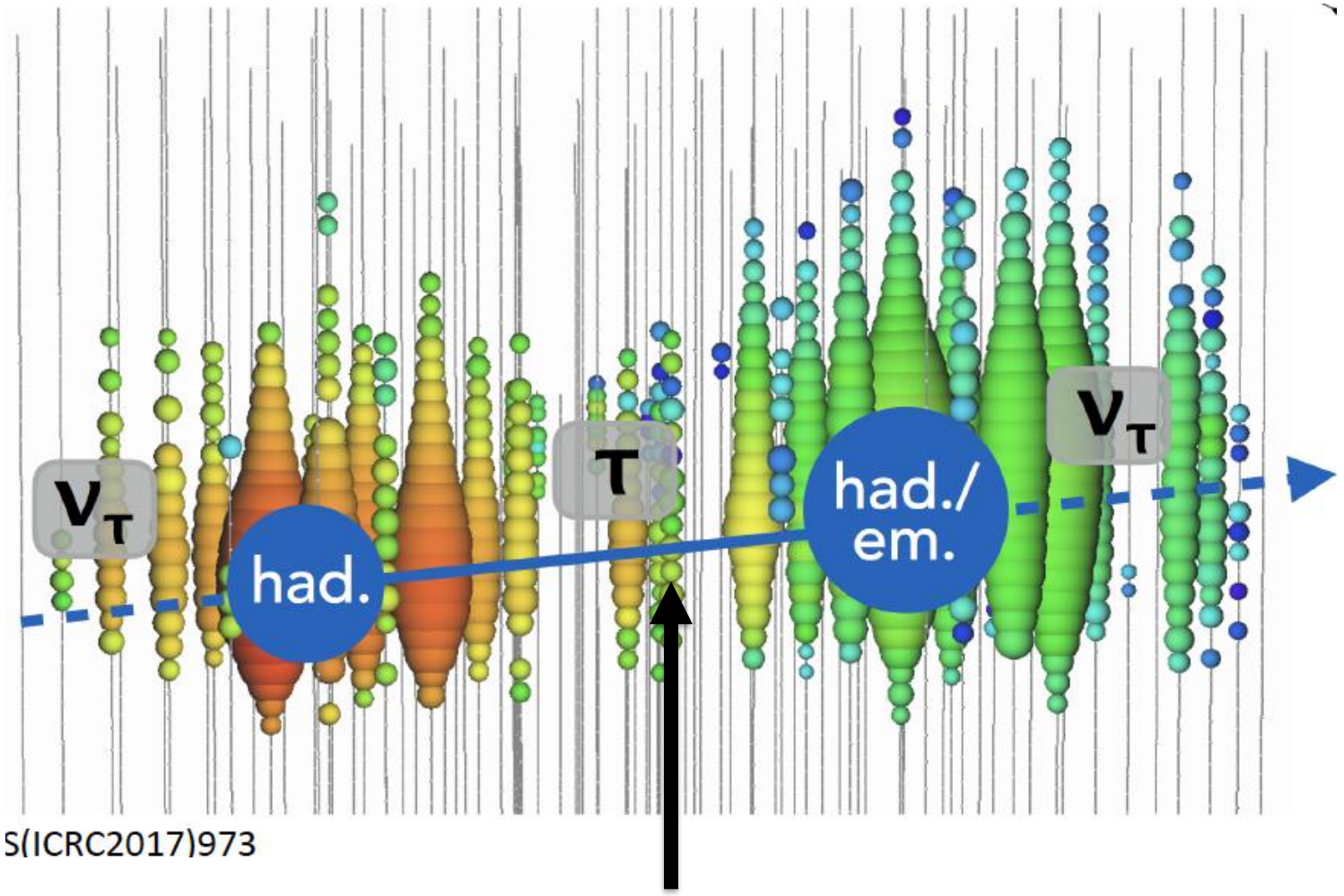
IceCube.wisc.edu

tau neutrino production and decay

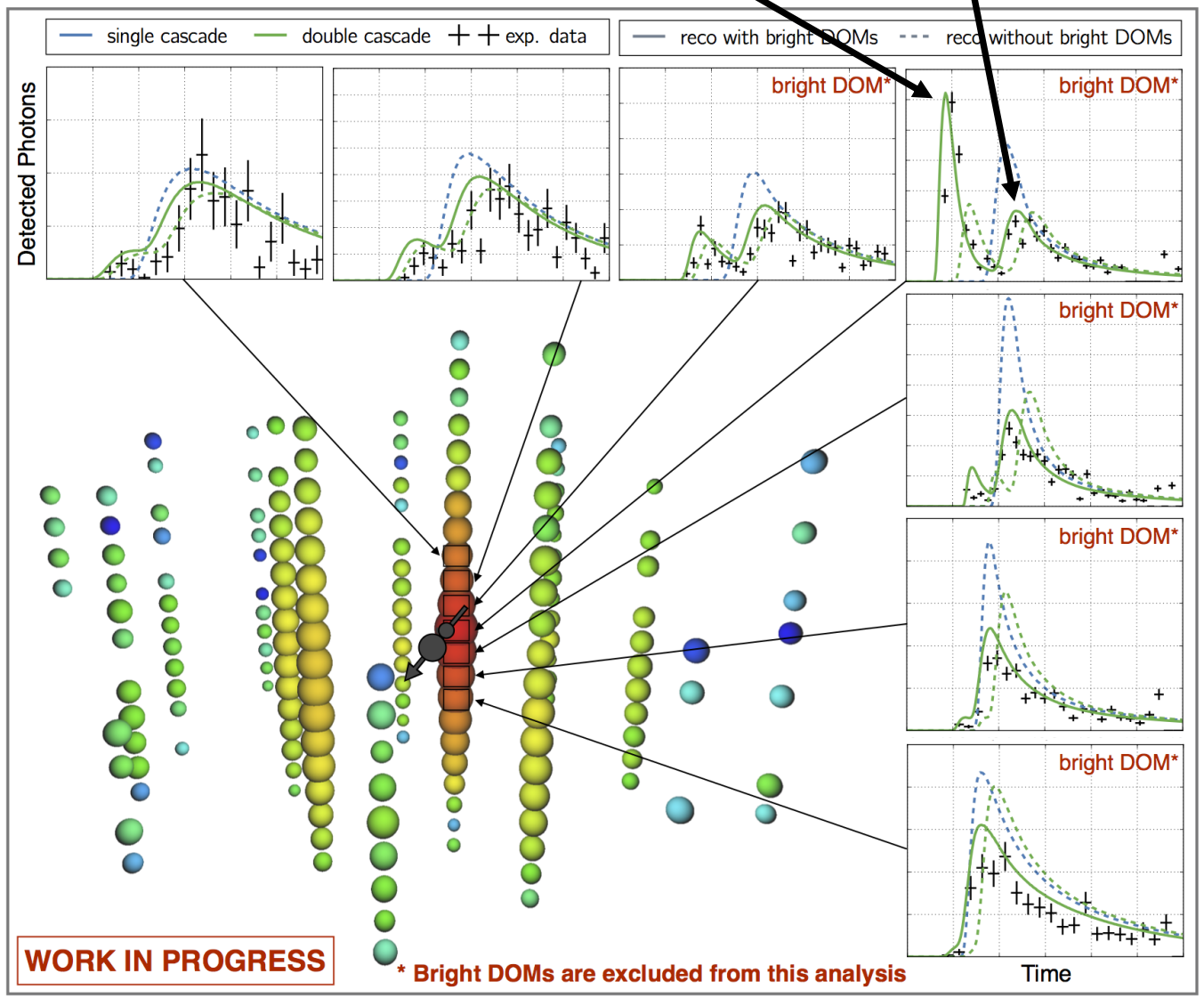


S(ICRC2017)973

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

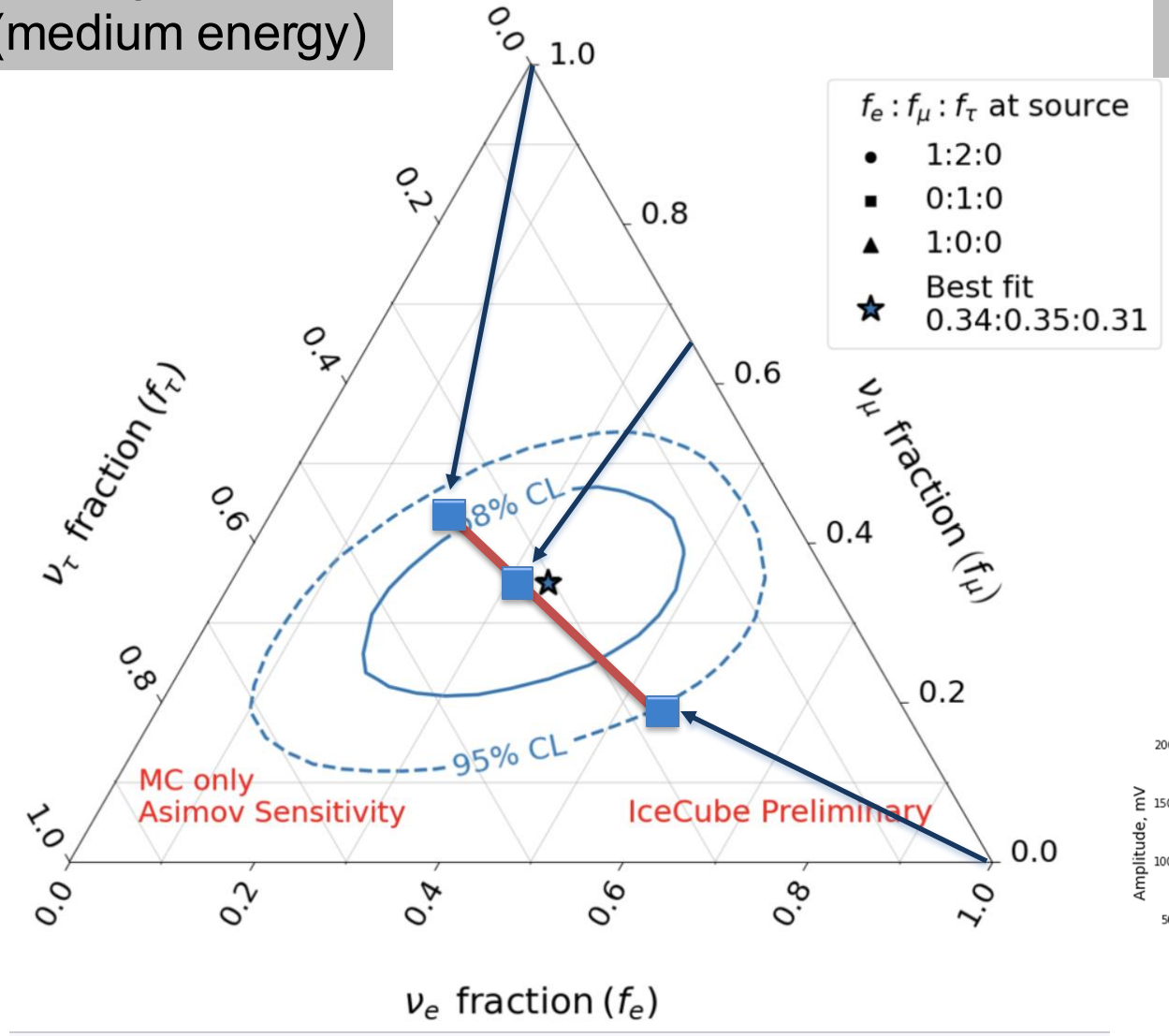
a cosmic tau neutrino with 17m lifetime

light from nutau interaction and tau decay

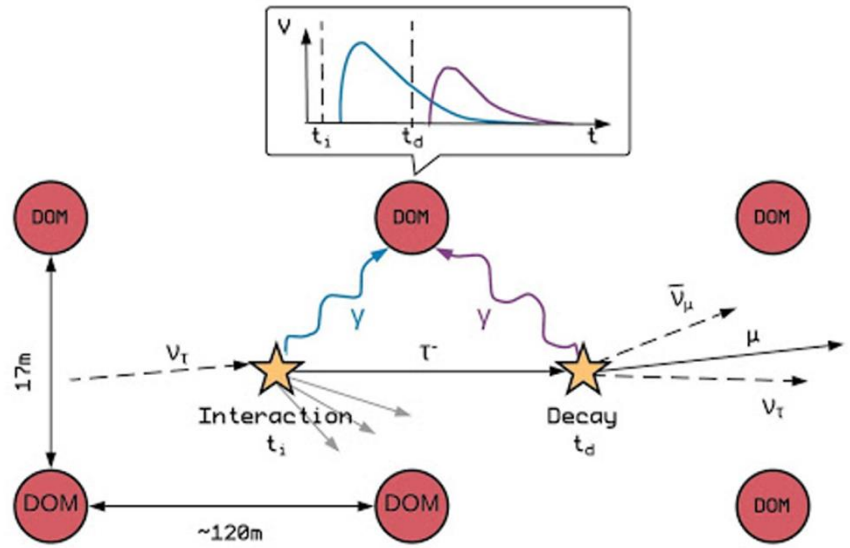


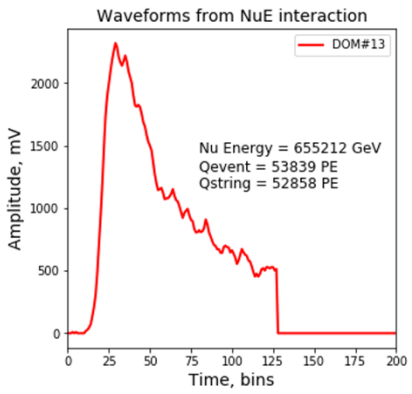
- $(\nu_e:\nu_\mu:\nu_\tau) = (1:2:0)$ at the source oscillates to $(\nu_e:\nu_\mu:\nu_\tau) = (1:1:1)$ at Earth
- high energy (~ PeV) nutau neutrinos are of cosmic origin: 7 events consistent with 1:1:1

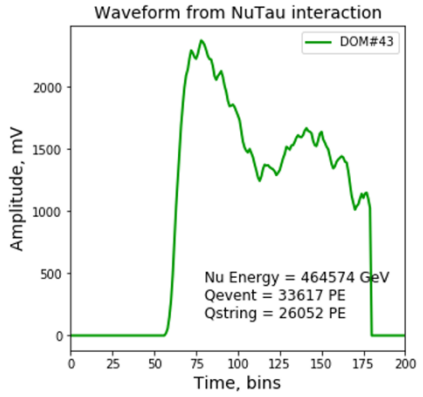
starting events (medium energy)

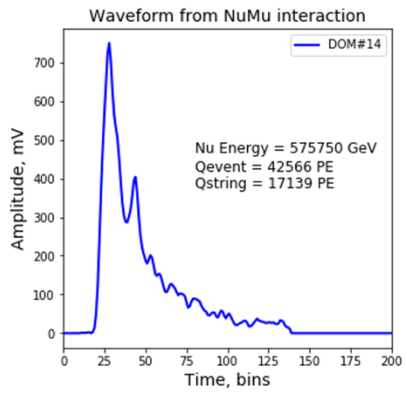


machine learning PMT signals



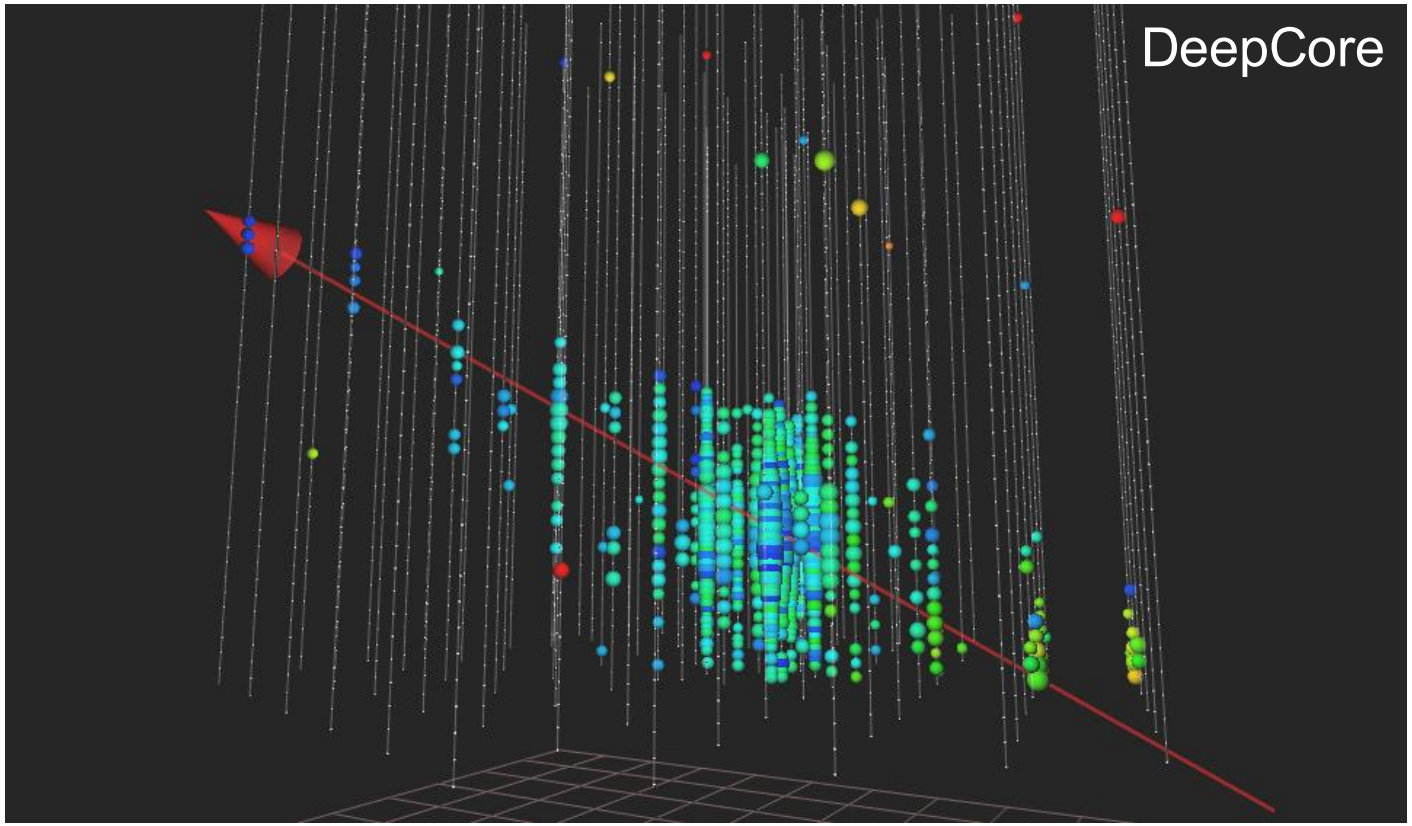




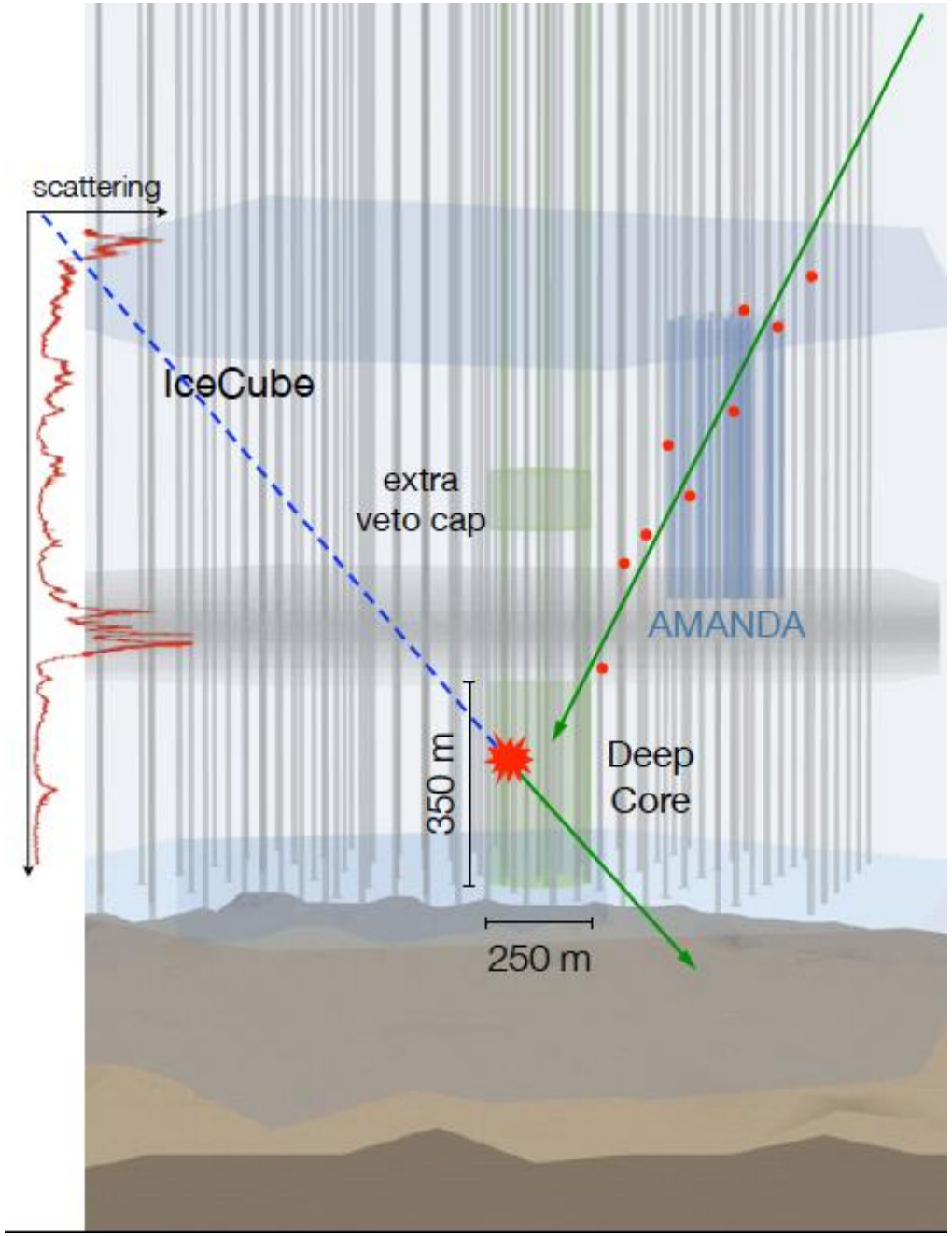


one million atmospheric neutrinos:

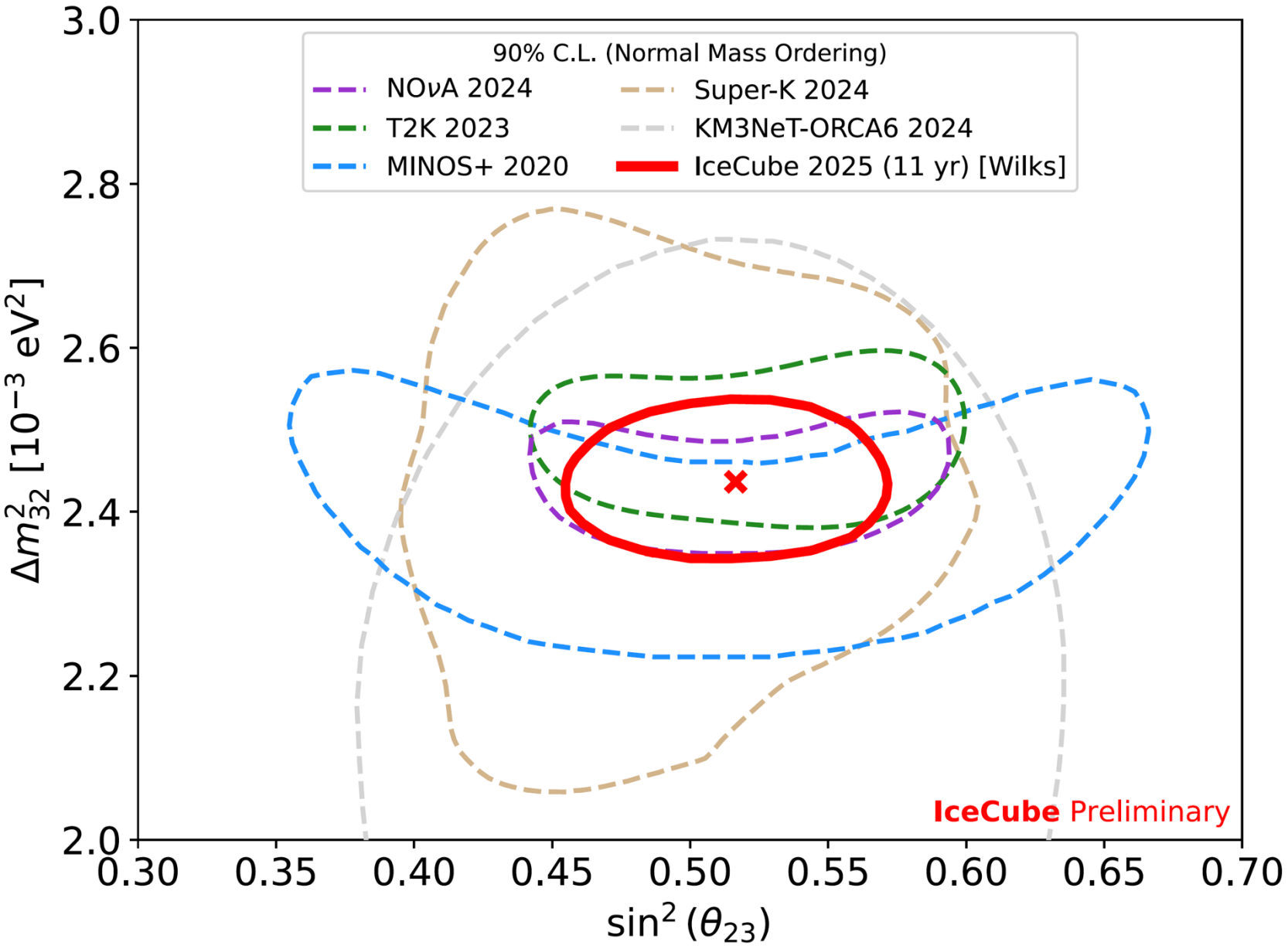
- threshold 100 TeV → 5 GeV
- > 2 megaton detector
- near 25 GeV energy nearly all muon neutrinos reappear as tau neutrinos. We measure both!



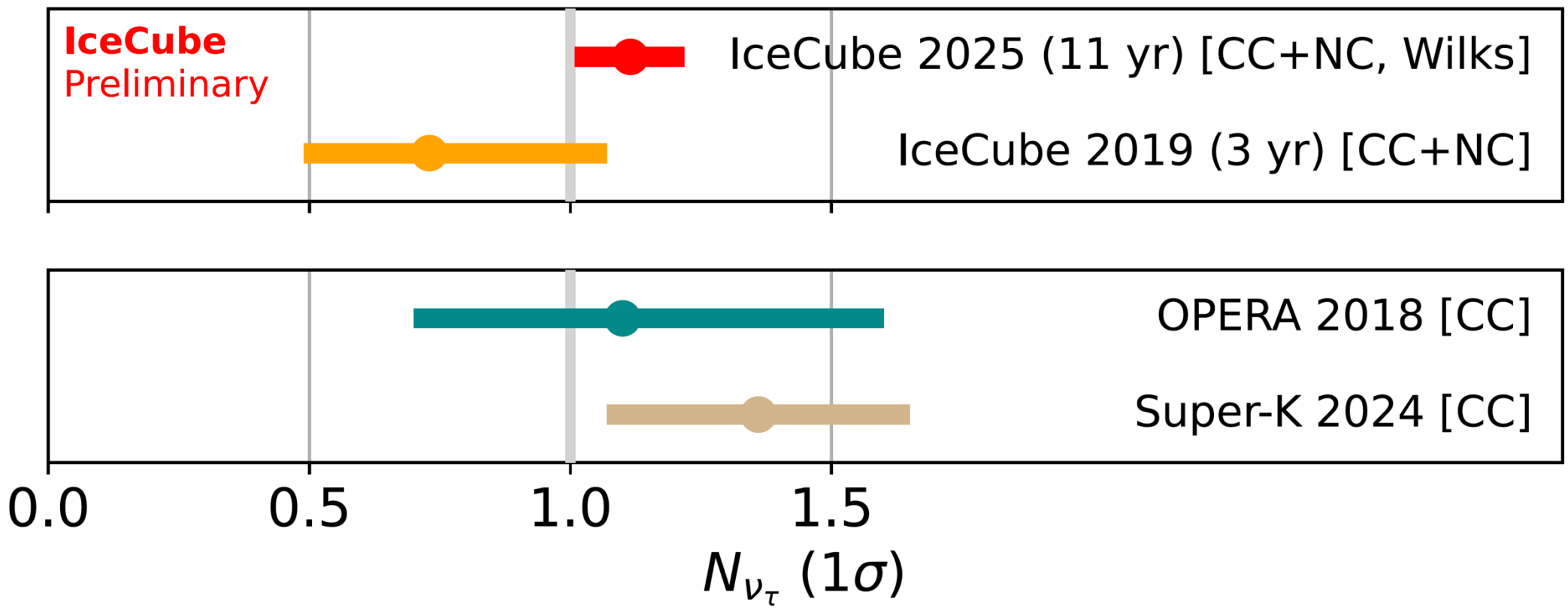
IceCube veto: less background than SNOLAB



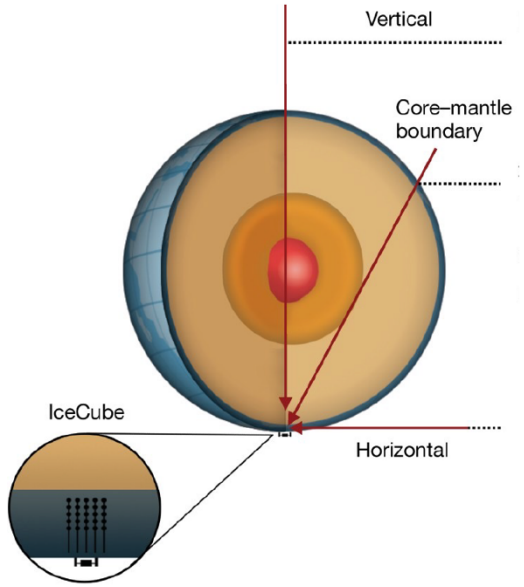
KM3NeT ORCA
and
IceCubeUpgrade
soon



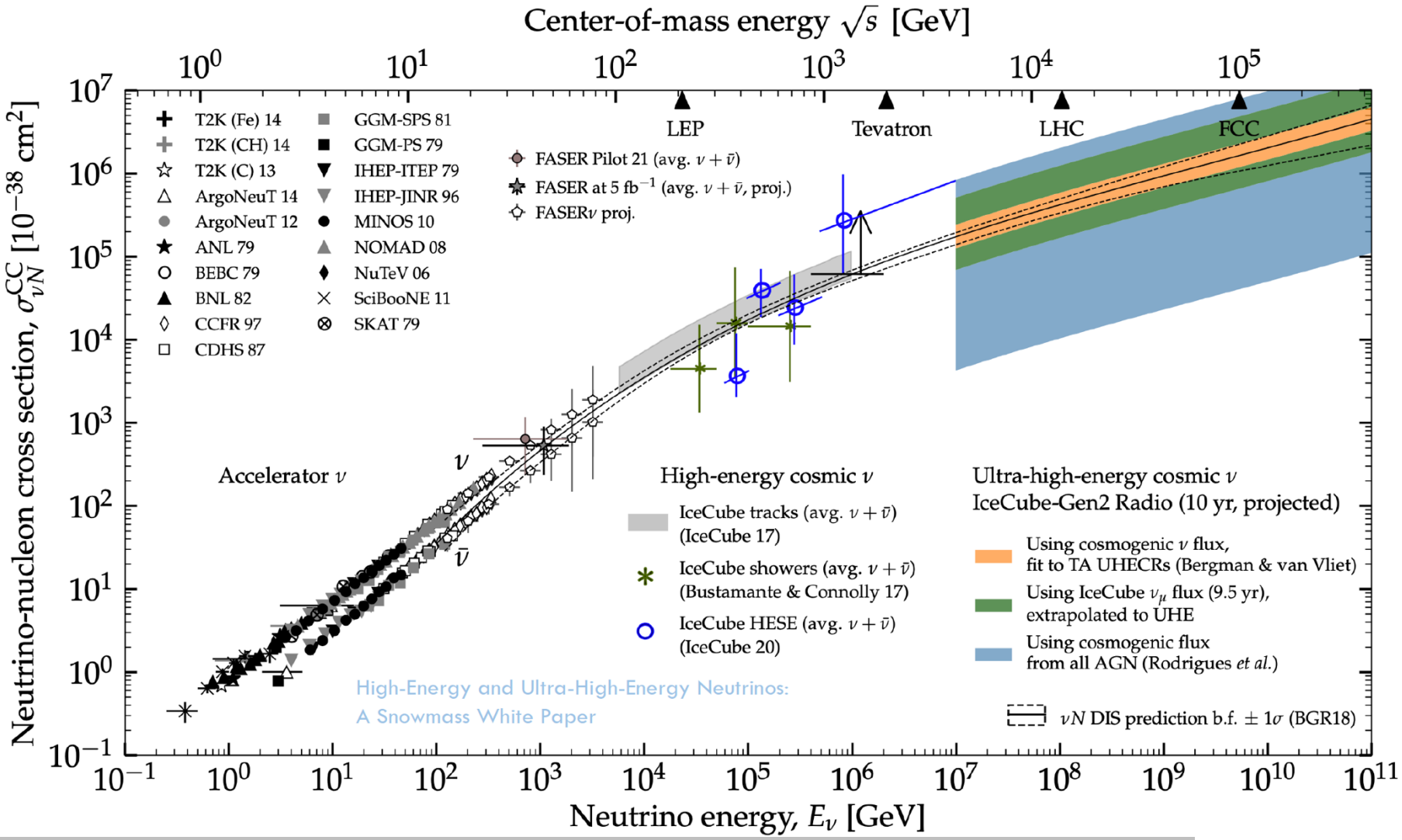
NUFACT 2025


IceCube
Preliminary
IceCube 2025 (11 yr) [CC+NC, Wilks]
IceCube 2019 (3 yr) [CC+NC]
OPERA 2018 [CC]
Super-K 2024 [CC]
0.0
0.5
1.0
1.5
N_{ν_τ} (1σ)

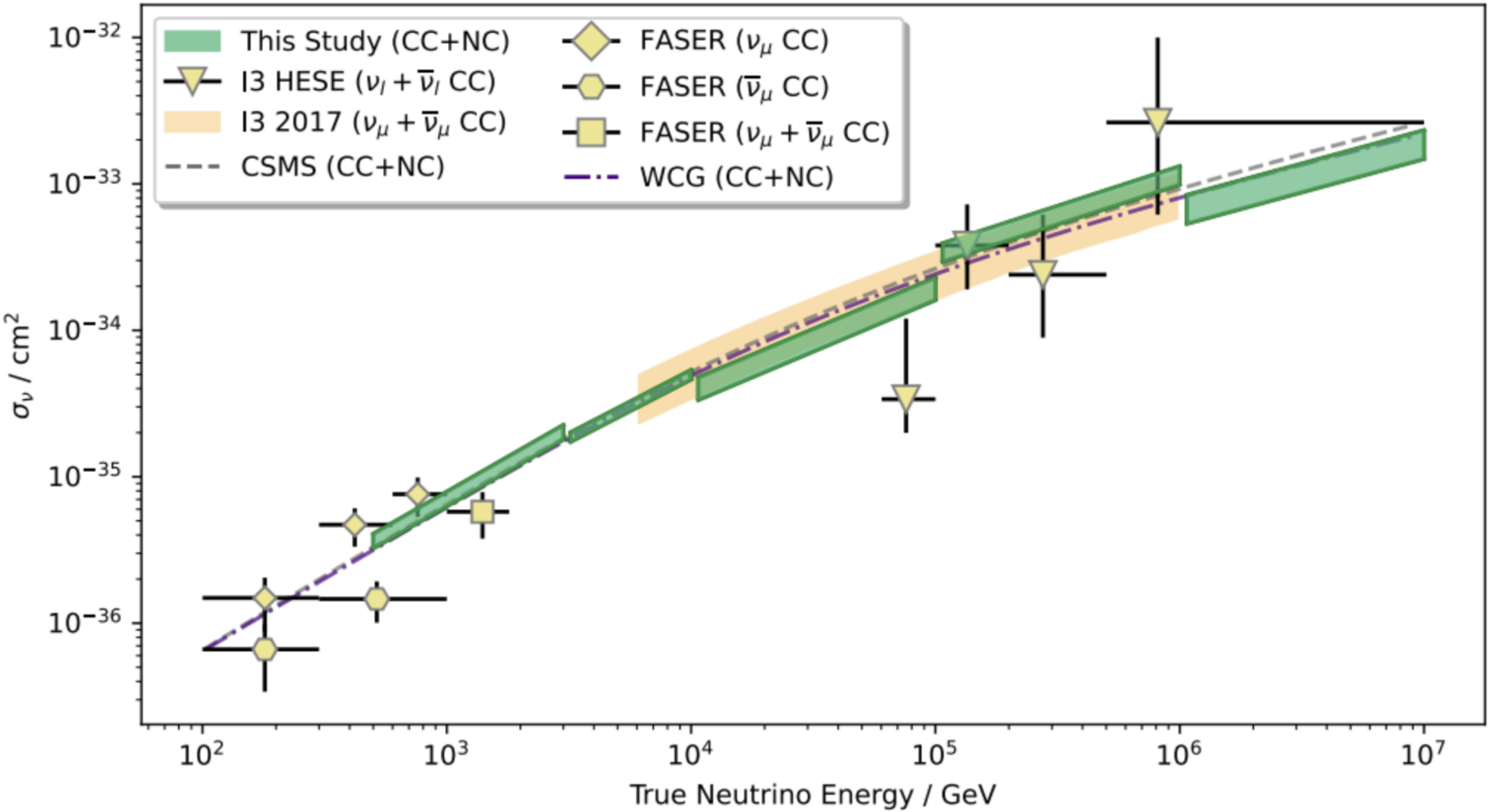
CROSS SECTION WITH EARTH AS THE TARGET

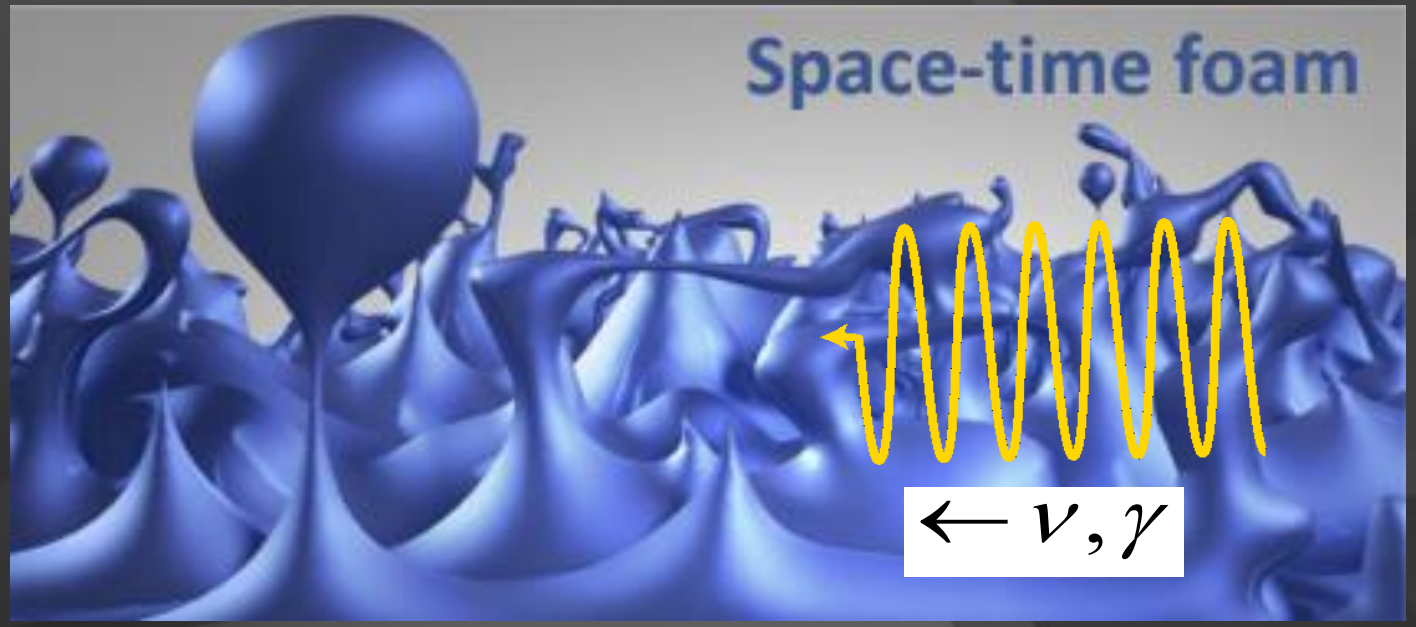


Extending x-section measurements to energies beyond Earth-based accelerators



also dark matter, BSM physics, supernova watch,…glaciology


This Study (CC+NC)
I3 HESE ($\nu_l + \overline{\nu}_l$ CC)
I3 2017 ($\nu_\mu + \overline{\nu}_\mu$ CC)
CSMS (CC+NC)
FASER (ν_μ CC)
FASER ($\overline{\nu}_\mu$ CC)
FASER ($\nu_\mu + \overline{\nu}_\mu$ CC)
WCG (CC+NC)
σ_ν / cm^2
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^2
10^3
10^4
10^5
10^6
10^7
True Neutrino Energy / GeV

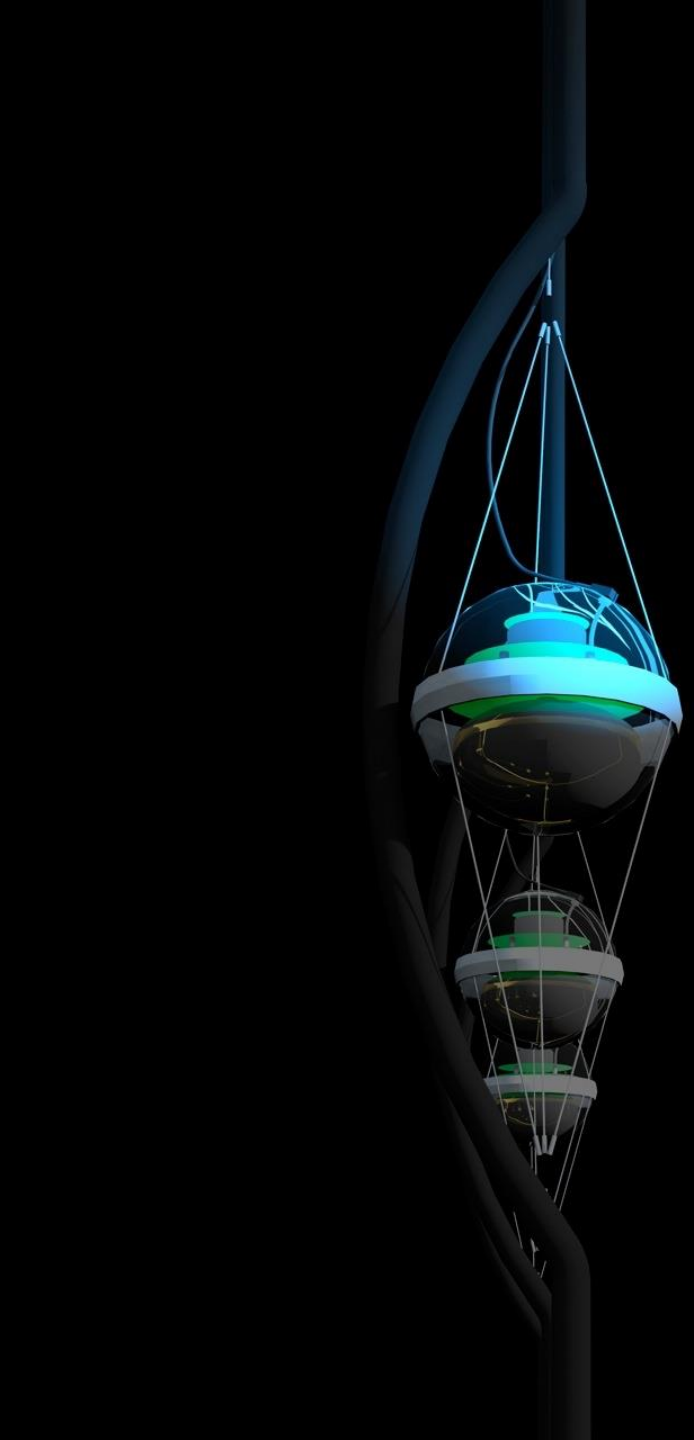


- quantized space: quantum fluctuations of space-time when geometry is activated
- oscillations as interferometer sensin quantum fluctuations
- the effects are small but become observable for high energies and lo distances

$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{M_{QG}}\right)^n \pm \ldots$$

so far standard oscillations prevail with no evidence for decoherence even after probing $M_{QG} > M_{Planck}$

[2308.00105 [hep-ex]]



neutrino astronomy 2025

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

icecube.wisc.edu

THE ICECUBE COLLABORATION

ALIA 1

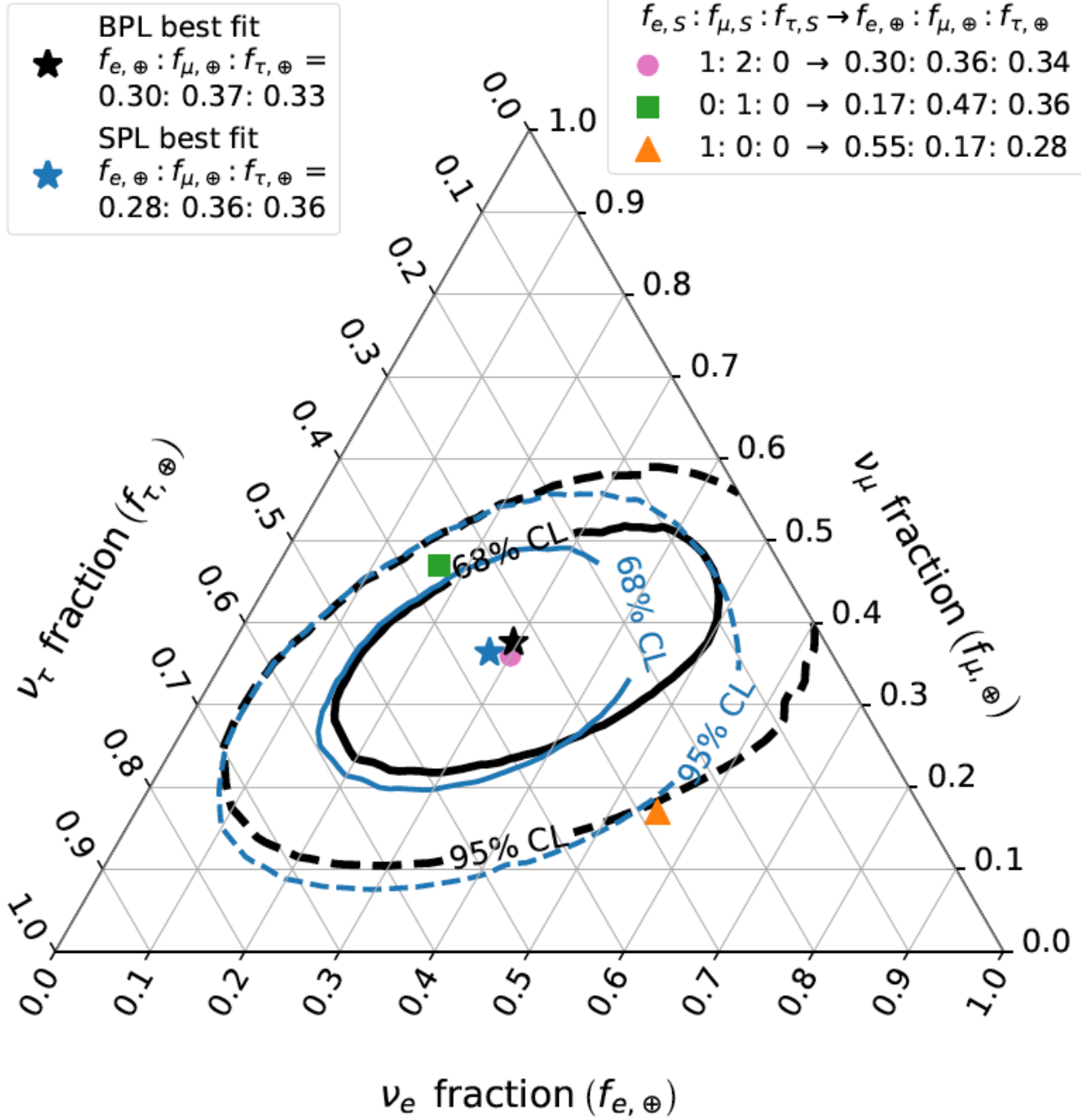
1

ED KINGDOM 1

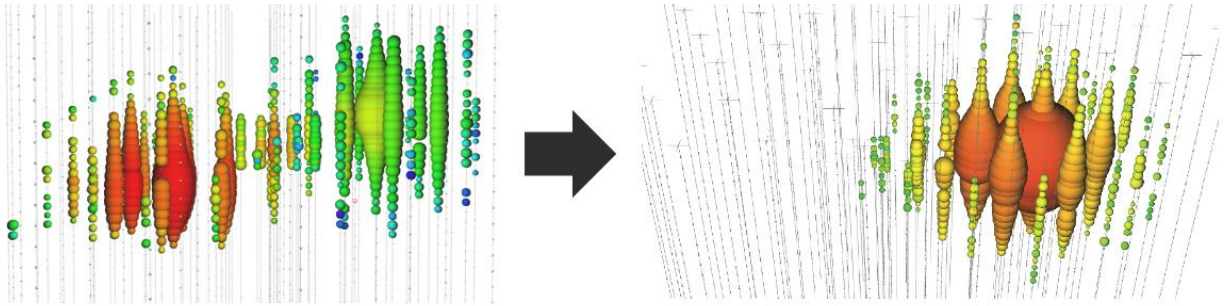
UNITED STATES 25

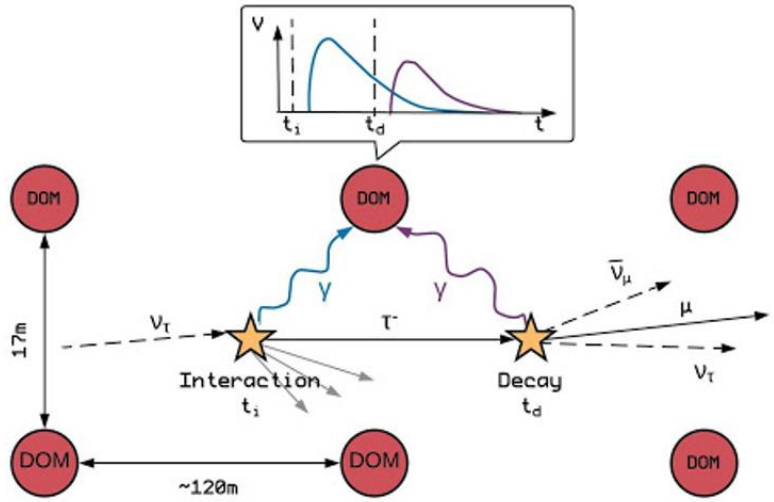
IceCube
South Pole Neutrino Observatory

overflow sides

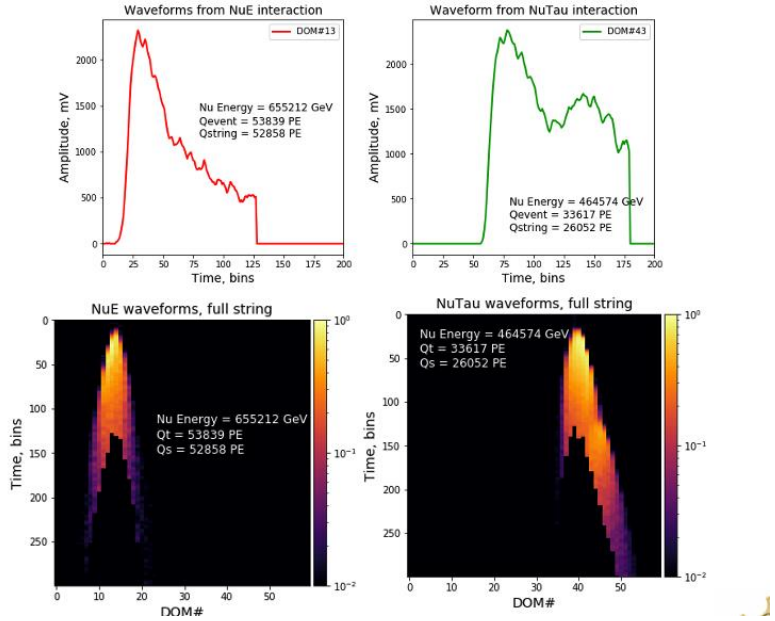

BPL best fit
$f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus}$ =
0.30: 0.37: 0.33
SPL best fit
$f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus}$ =
0.28: 0.36: 0.36
$f_{e,S} : f_{\mu,S} : f_{\tau,S} \rightarrow f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus}$
1: 2: 0 → 0.30: 0.36: 0.34
0: 1: 0 → 0.17: 0.47: 0.36
1: 0: 0 → 0.55: 0.17: 0.28
68% CL
68% CL
95% CL
95% CL
ν_τ fraction ($f_{\tau,\oplus}$)
ν_μ fraction ($f_{\mu,\oplus}$)
ν_e fraction ($f_{e,\oplus}$)

Astrophysical Tau Neutrino Search





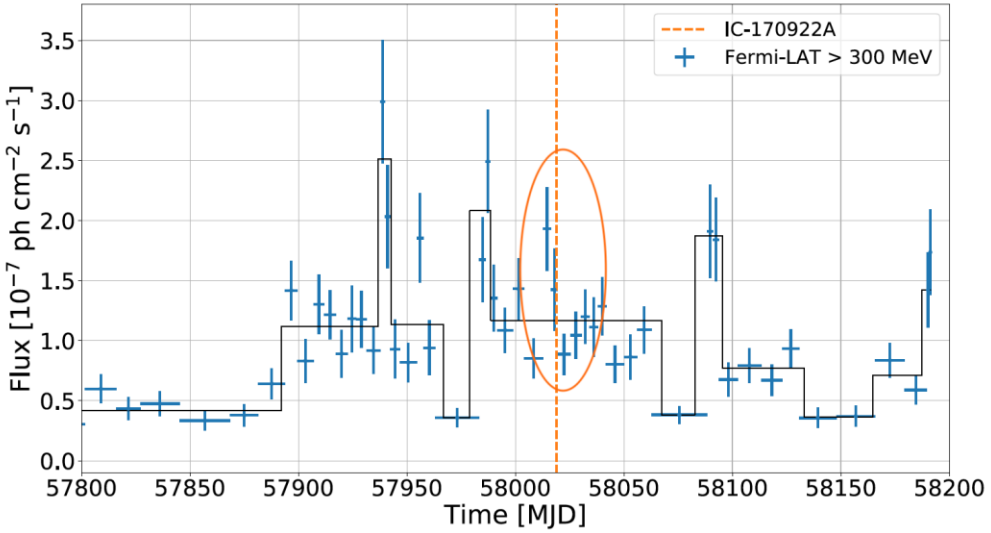
- TeV – O(1) PeV Tau neutrinos look like Electron neutrinos due to sparse instrumentation
- Differentiation by shape of waveform in a given module, i.e. two waveforms in the same module offset by a certain quantity
- Create an image (2D histogram) of the charge distribution in time along a string
- CNN used to find the subtle difference in waveform shapes

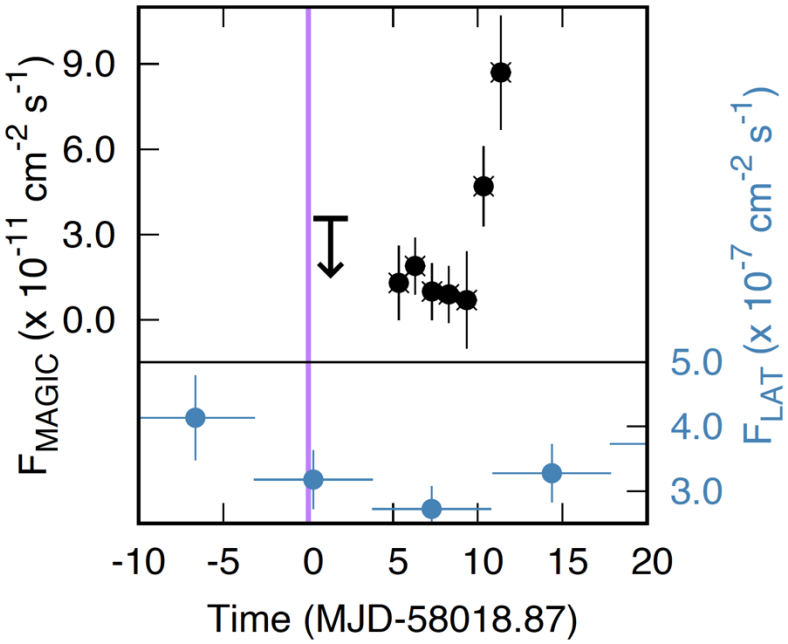


→ Standard Model: 8 expected on a background of 1 and 7 found for a flavor ratio 1:1:1

gamma rays in 2017 at the time the neutrino is produced ?

a few ~10 GeV photons and not much else, consistent with an obscured source, not a blazar





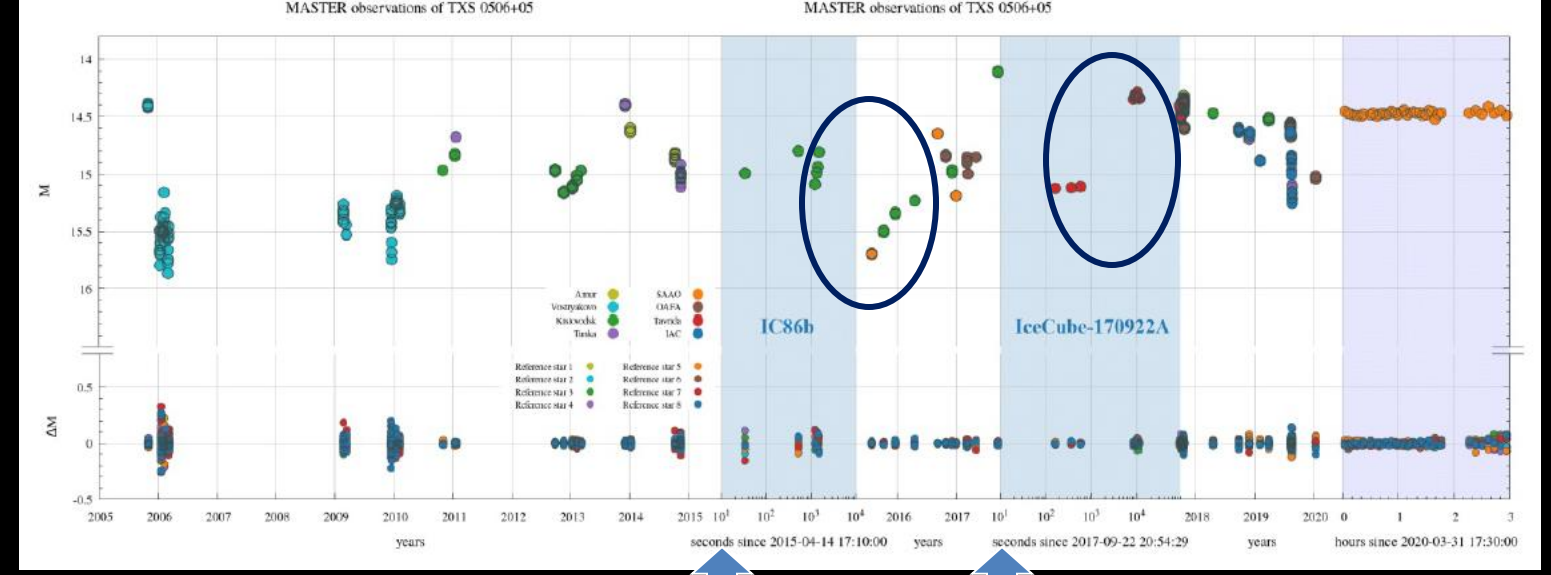
- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

MASTER

robotic network

optical observations
TXS 0506+056
since 2005

blue panels:
expanded time axis
years → seconds

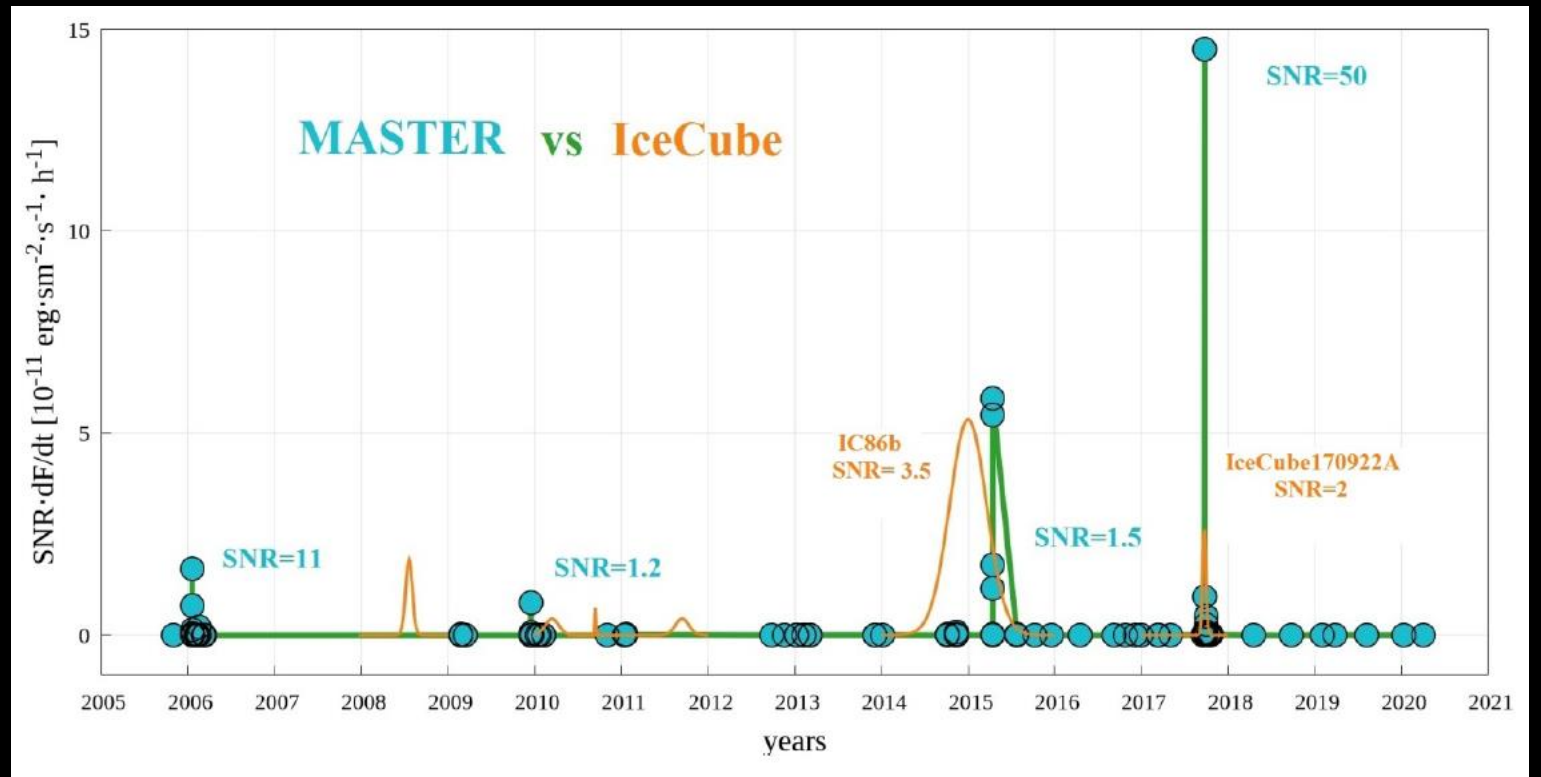


seconds after 2014-15 burst

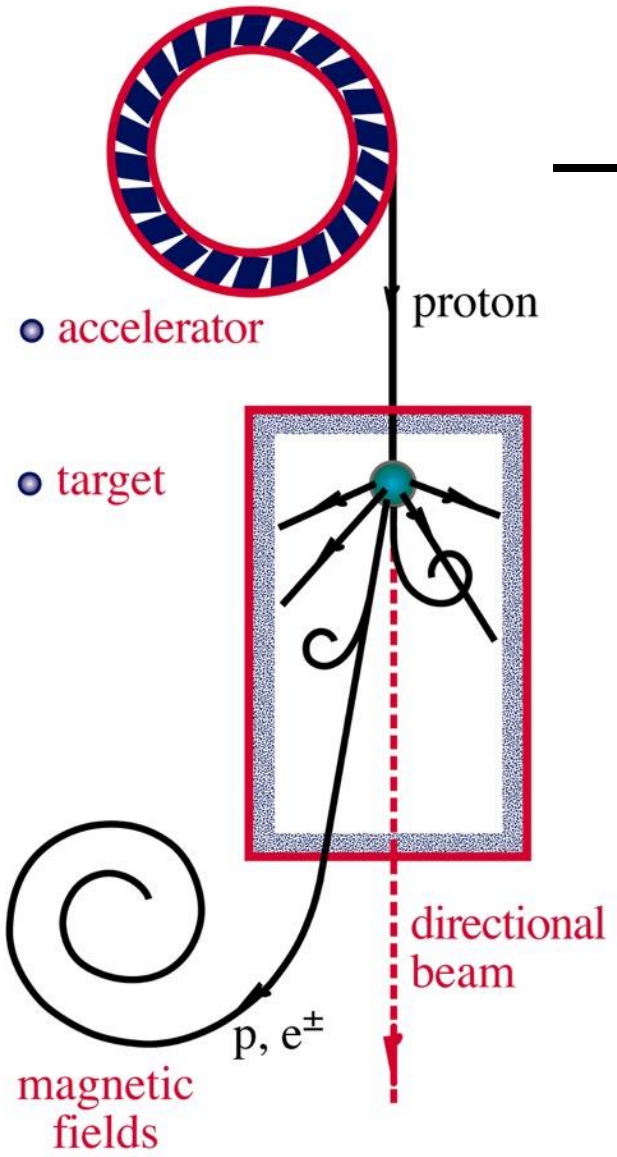
seconds after IC170922

time variation of flux
times
signal-to-noise

hour-scale variability of the source after neutrino emission



ν and γ beams : heaven and earth



where are the gamma rays from π^0 ?

pionic gamma rays lose energy in the target that produces the neutrinos

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

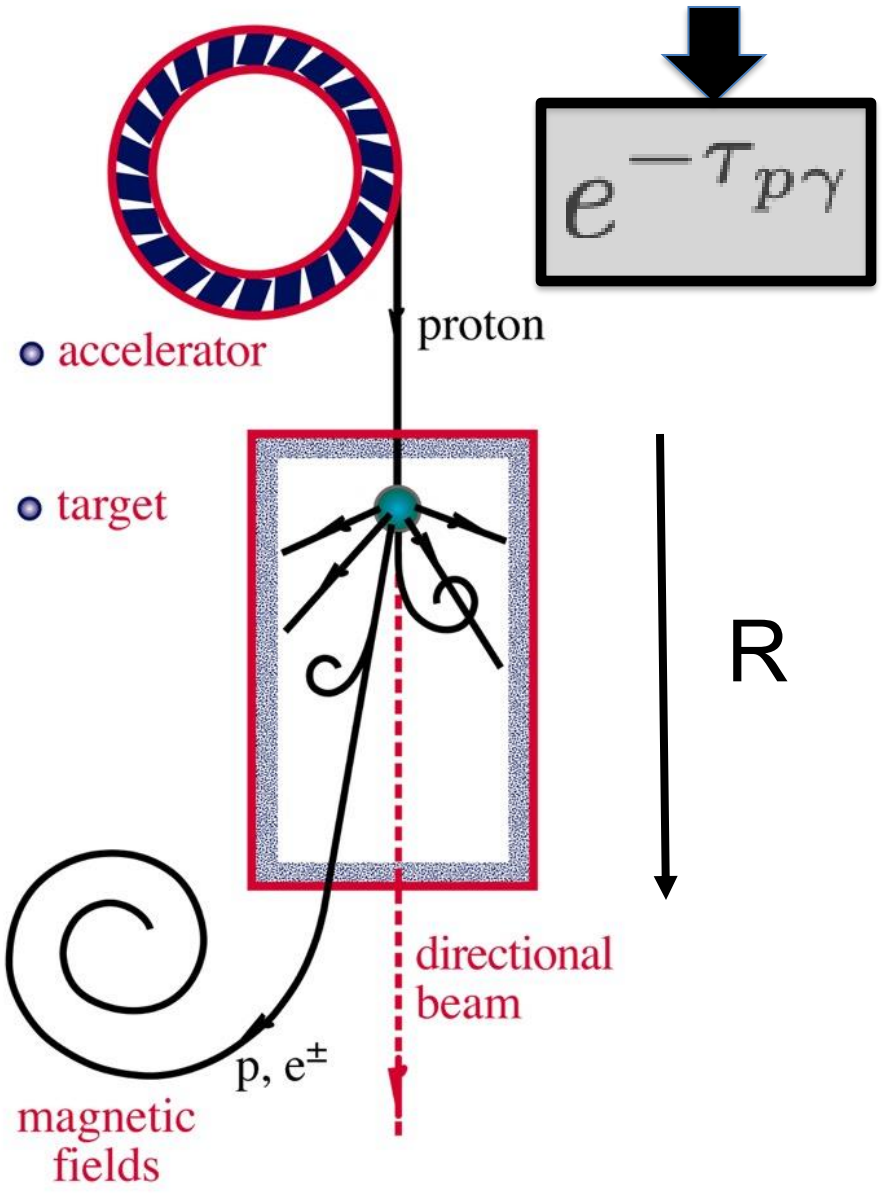
$$p + \gamma \rightarrow n + \pi^+$$

~ cosmic ray + neutrino

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

~ cosmic ray + gamma

ν and γ beams : protons on target



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

~ cosmic ray + neutrino

- optical depth τ = cross section x target density

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

$$e^{-\tau_{p\gamma}} \quad \tau_{p\gamma} \sim \sigma_{p\gamma}\, \frac{L_x}{R}\, \frac{L_\gamma}{E_x}$$

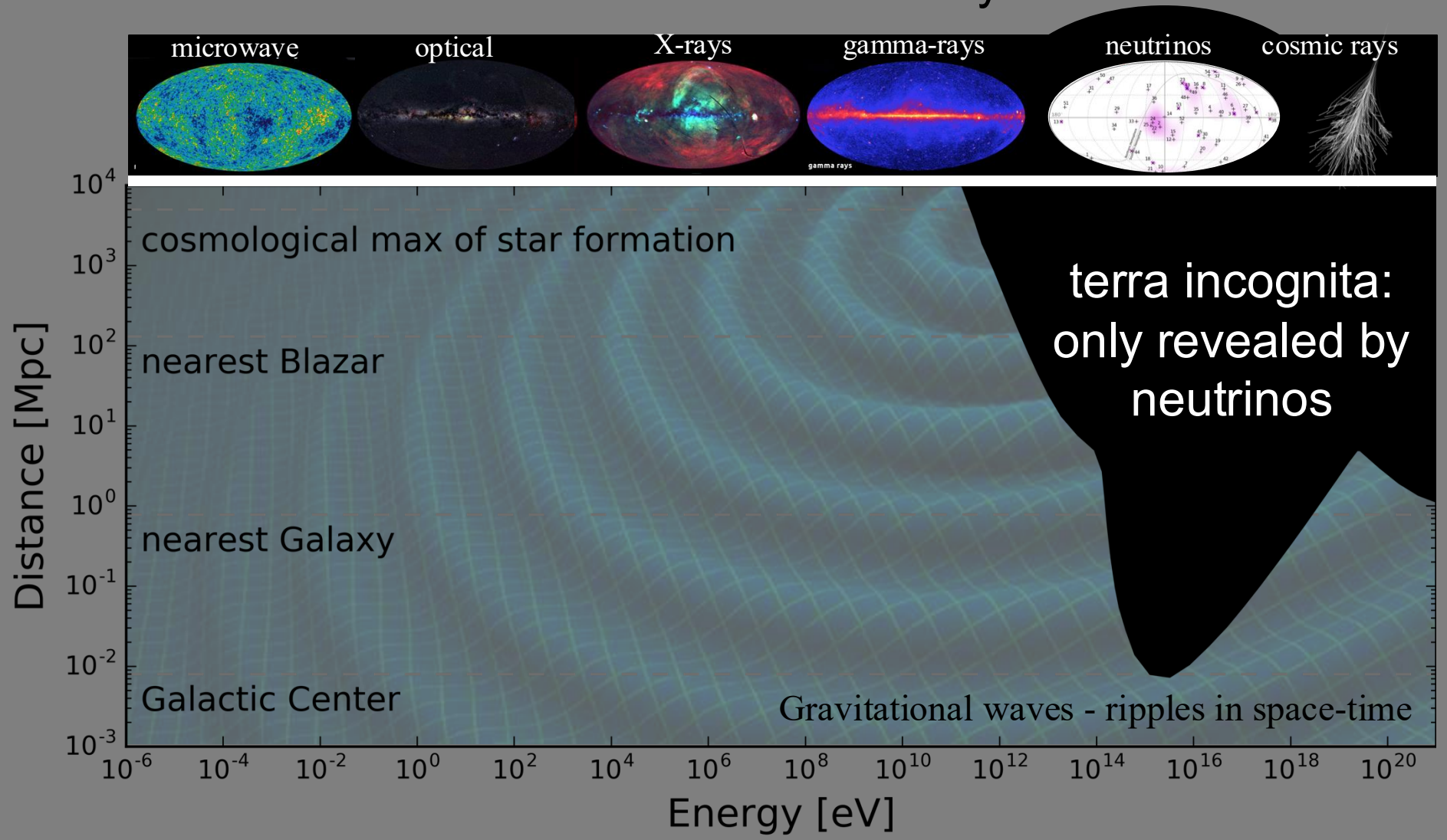
- pionic gamma rays are absorbed in the target that produces the neutrinos

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

~ cosmic ray + gamma

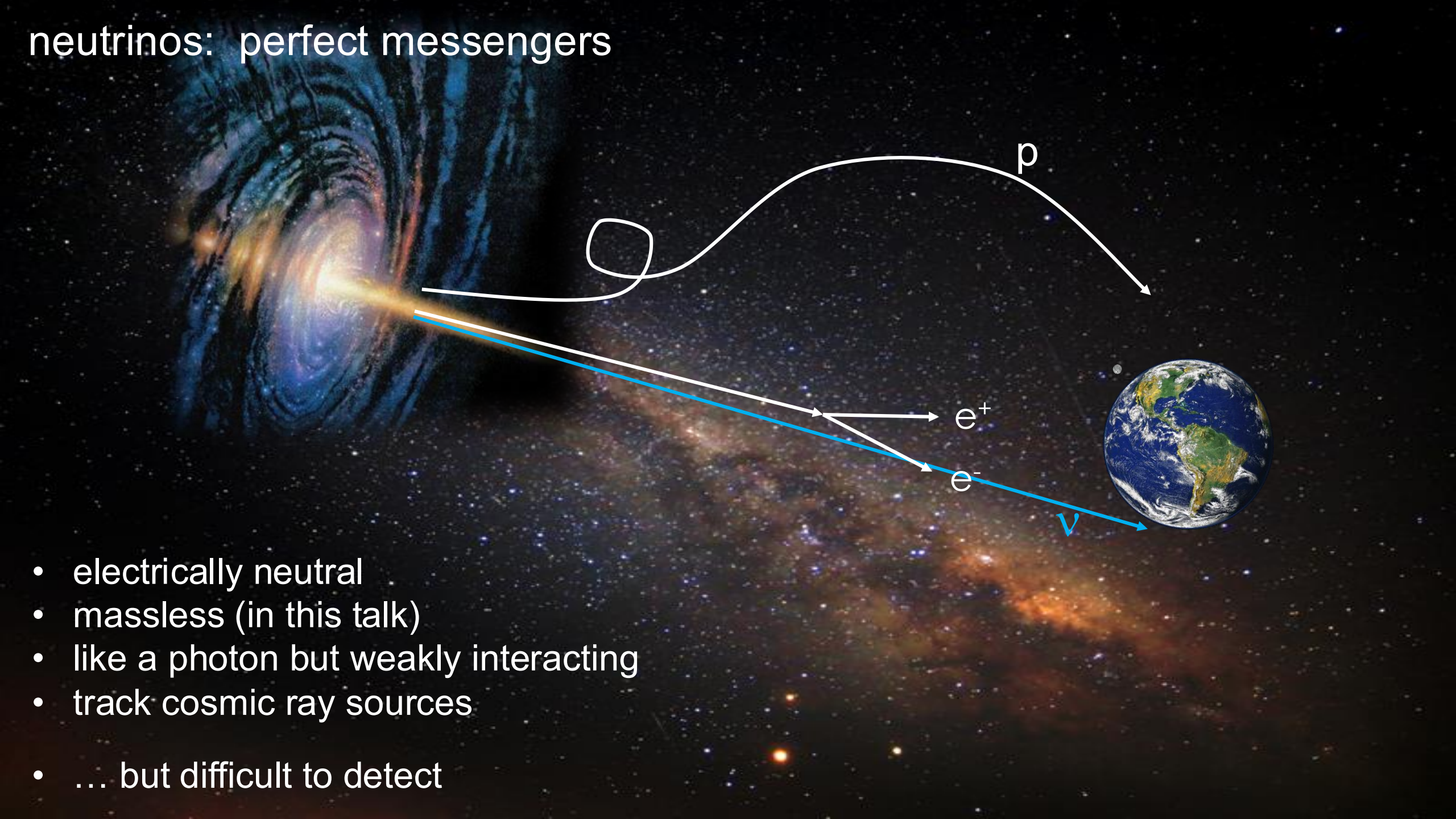
$$\tau_{\gamma\gamma} \simeq 10^3\, \tau_{p\gamma}$$

highest energy “radiation” from the Universe: neutrinos and cosmic rays



Universe beyond our Galaxy is opaque to gamma rays

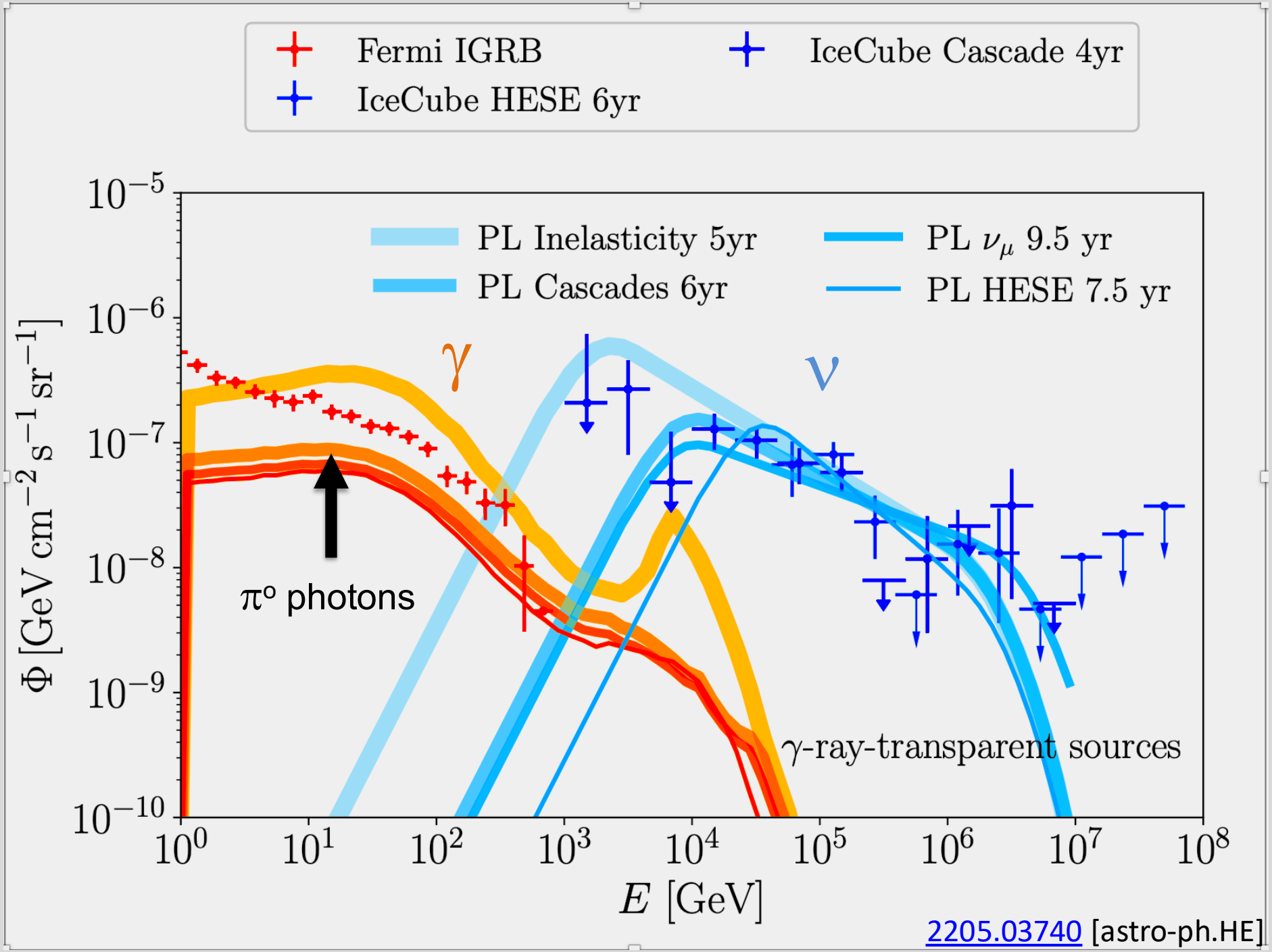
neutrinos: perfect messengers



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

- … but difficult to detect

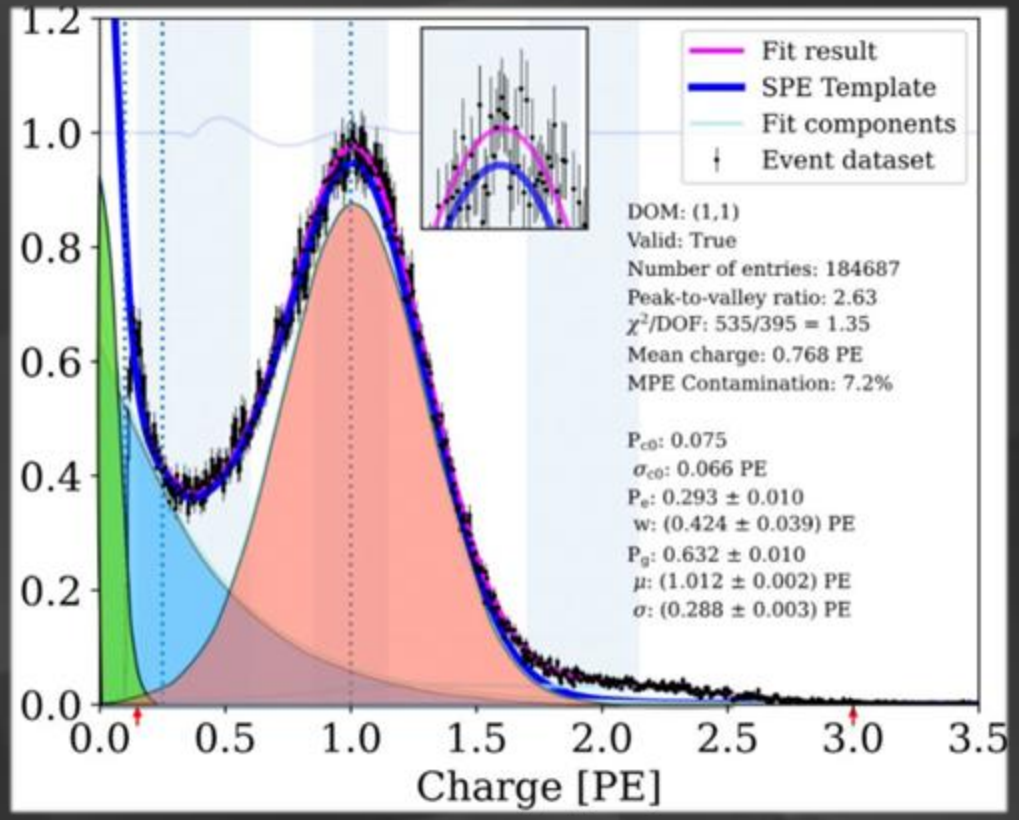
- gamma rays from neutral pions lose energy in the sources
- they emerge below Fermi threshold



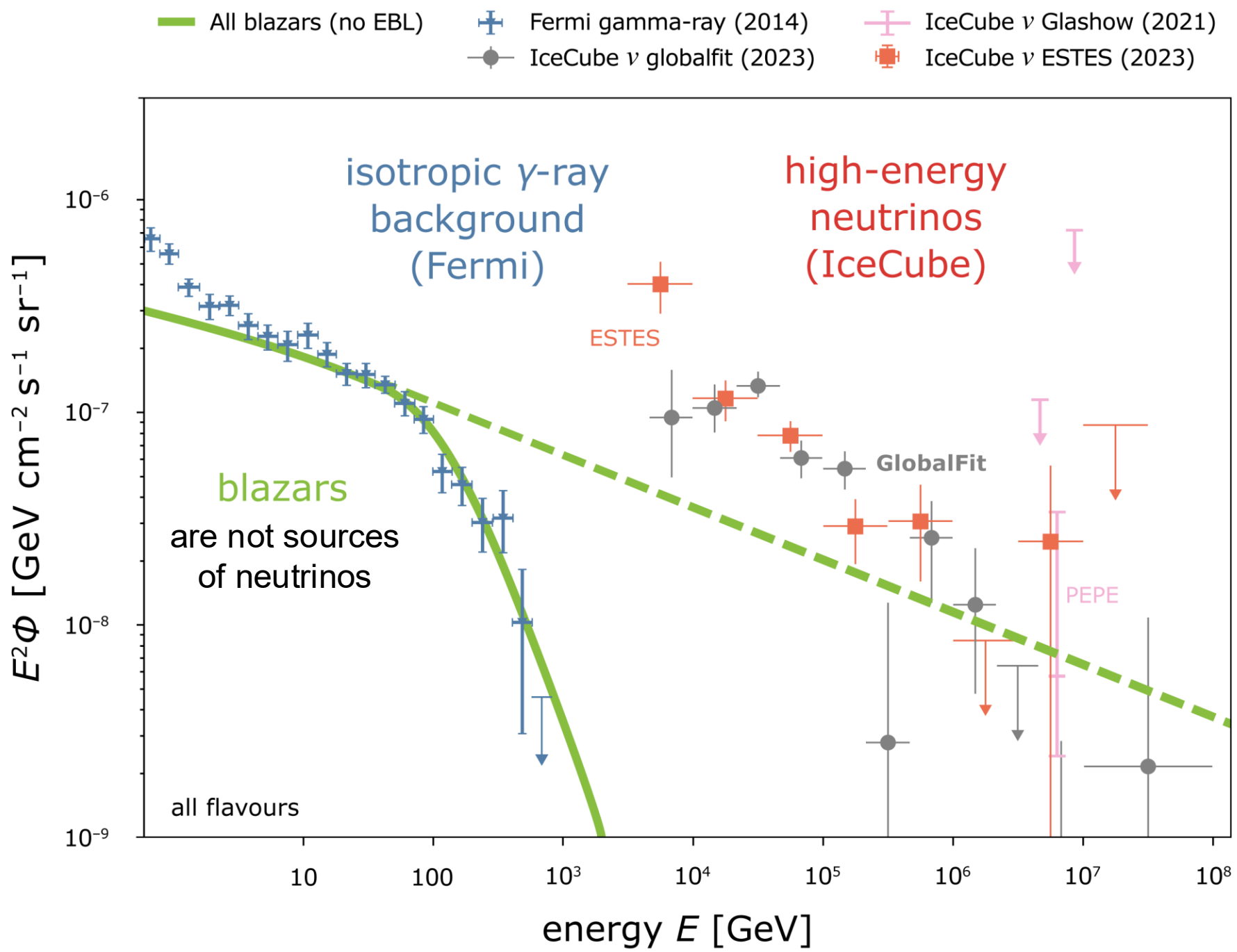
2205.03740 [astro-ph.HE]

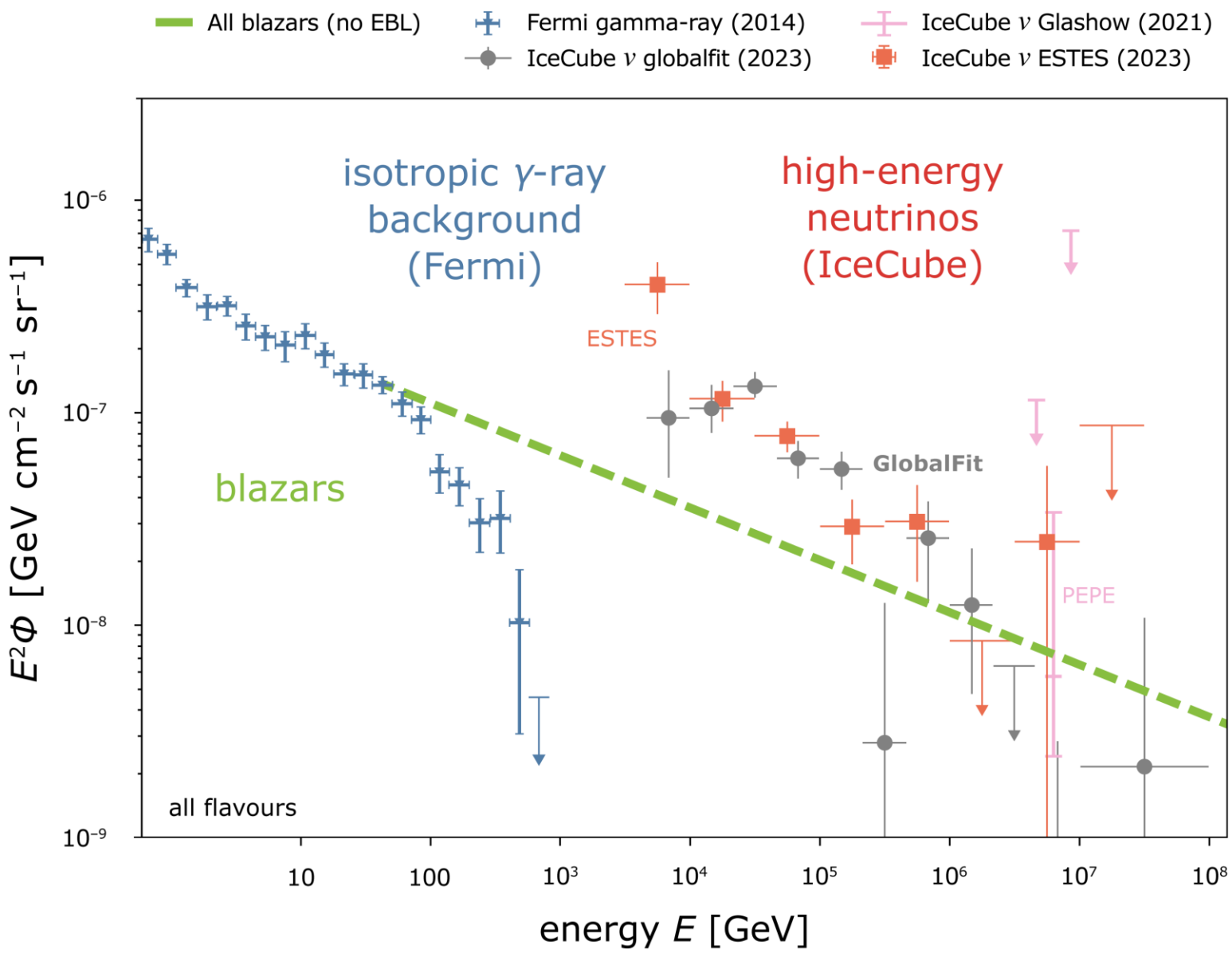
→ crash program to upgrade the performance of IceCube

- 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 …


All blazars (no EBL)
Fermi gamma-ray (2014)
IceCube ν Glashow (2021)
IceCube ν globalfit (2023)
IceCube ν ESTES (2023)
isotropic γ-ray background (Fermi)
high-energy neutrinos (IceCube)
ESTES
GlobalFit
PEPE
blazars
are not sources of neutrinos
all flavours
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
10^3
10^4
10^5
10^6
10^7
10^8
energy E [GeV]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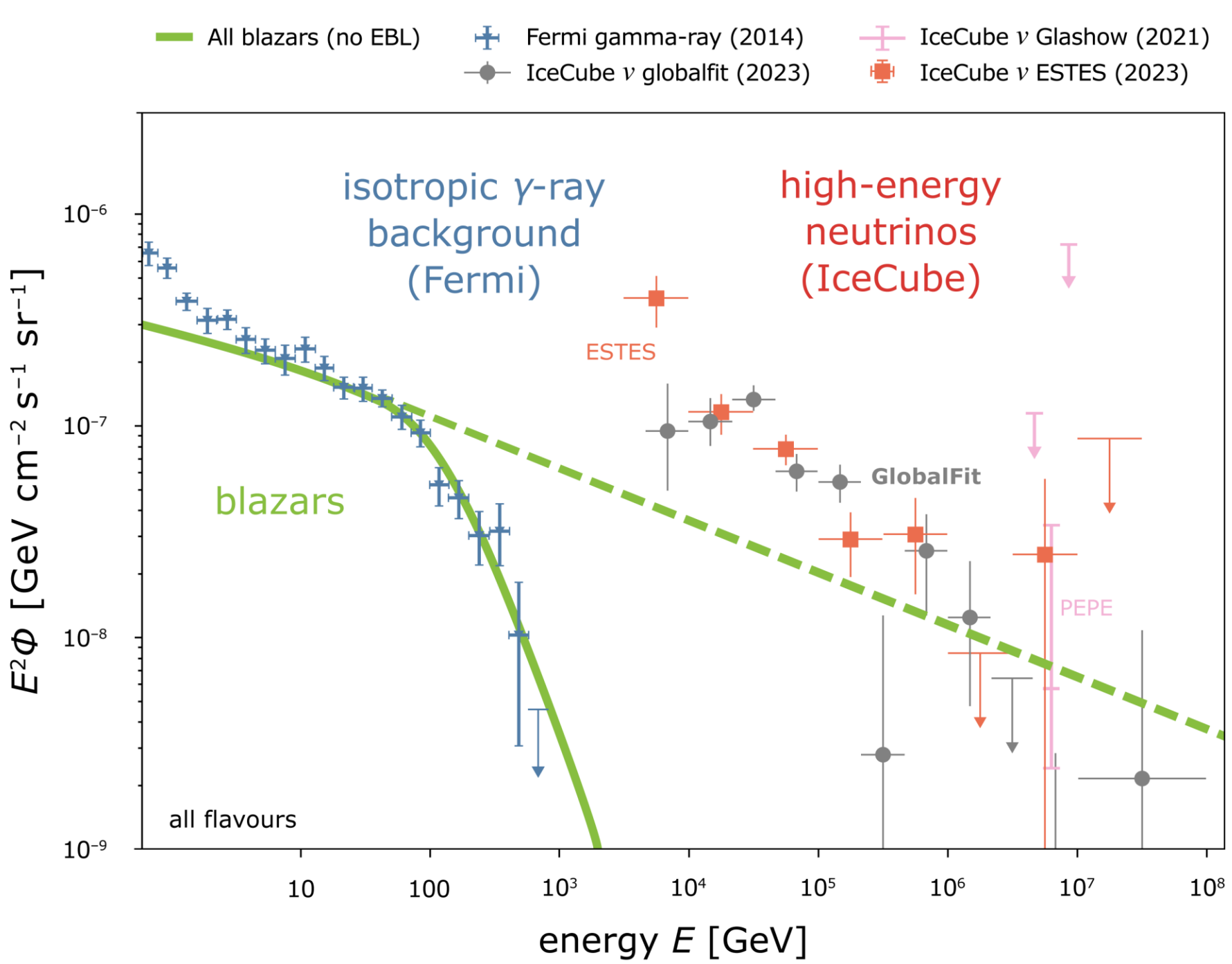
energy E [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
10^3
10^4
10^5
10^6
10^7
10^8

NASA Fermi satellite does not observe the gamma rays that accompany IceCube neutrinos

they appear at MeV energies or below



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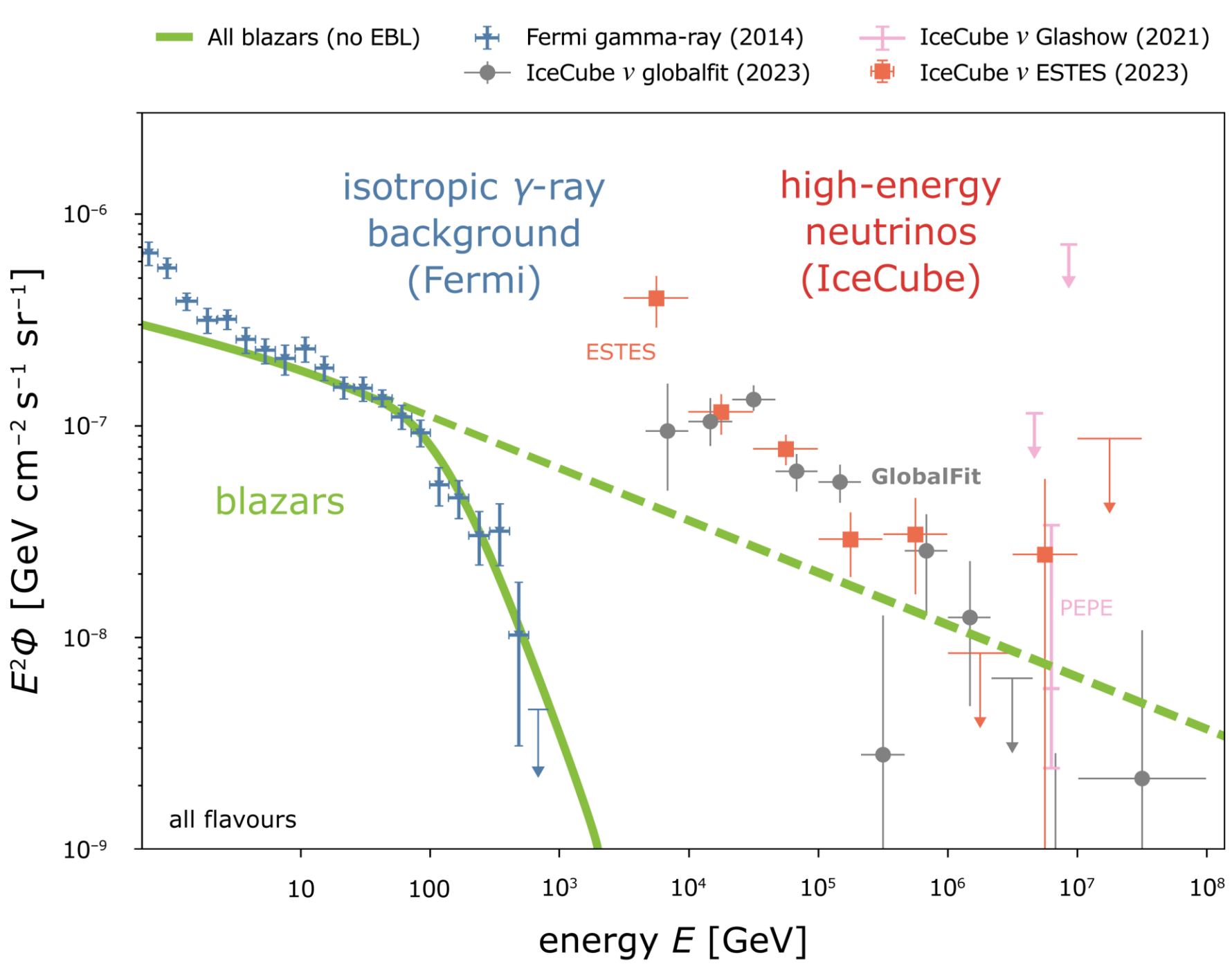
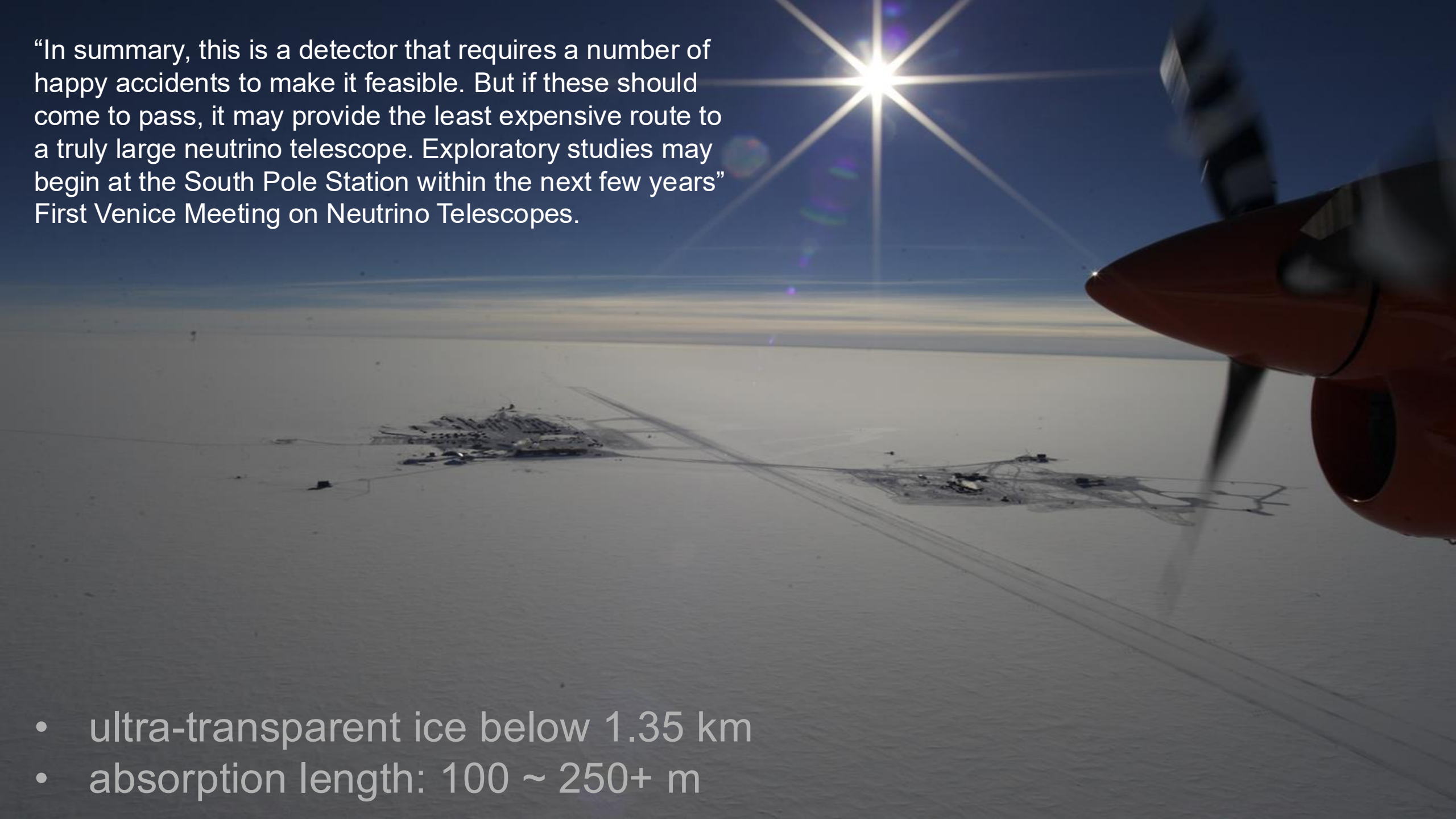
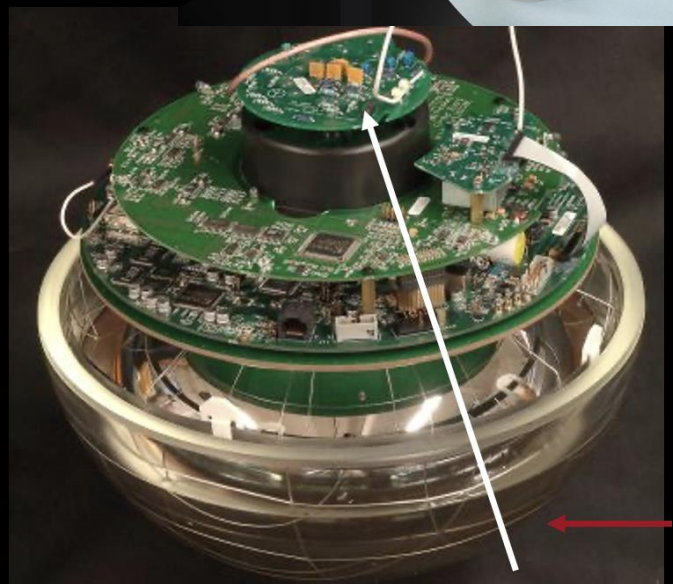


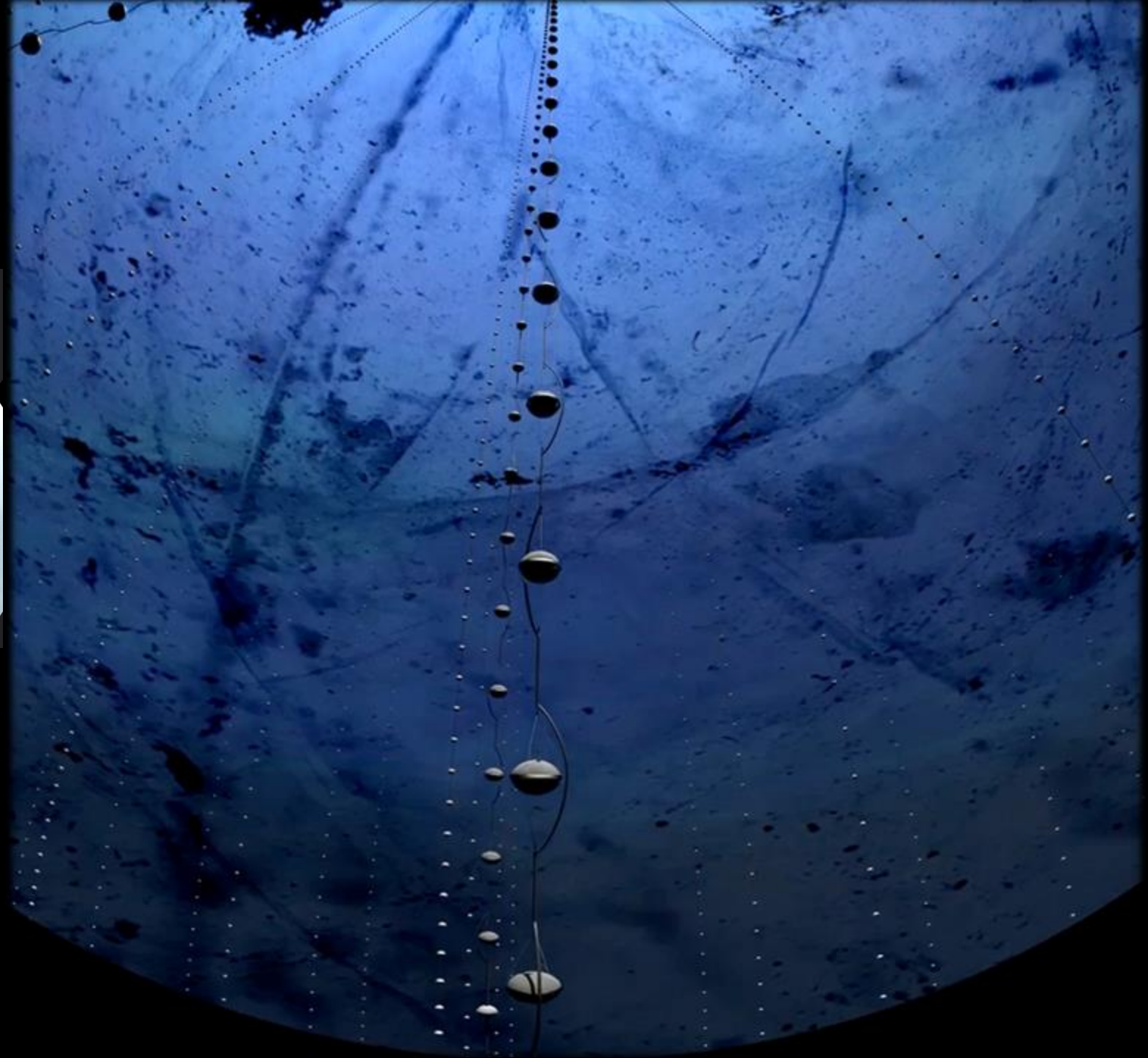


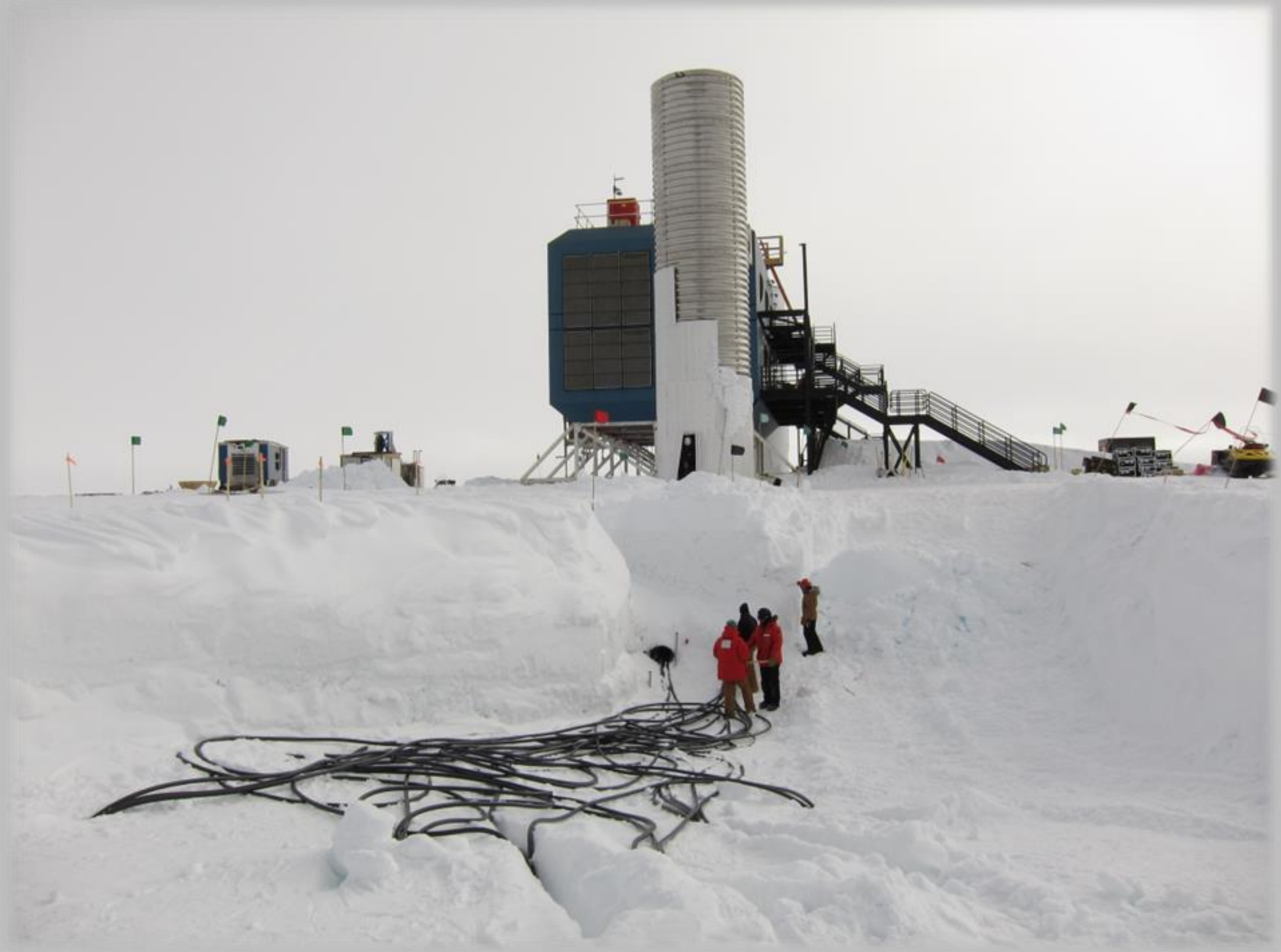
“In summary, this is a detector that requires a number of happy accidents to make it feasible. But if these should come to pass, it may provide the least expensive route to a truly large neutrino telescope. Exploratory studies may begin at the South Pole Station within the next few years”
First Venice Meeting on Neutrino Telescopes.

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

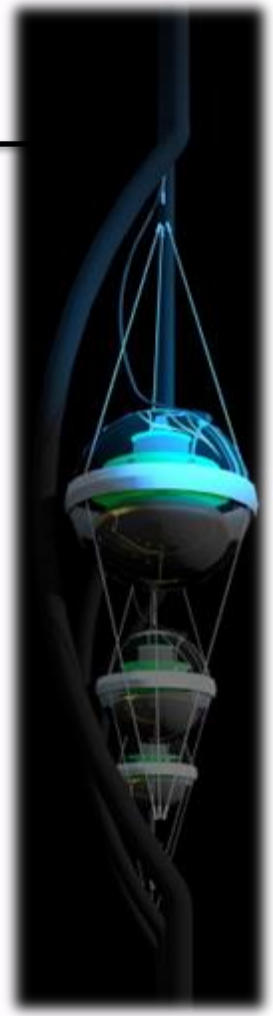
IceCube:
5160 10-inch photomultipliers,
60 per string on 86 strings,
instrument one km^3 of
Antarctic ice between
1.4 and 2.4 km depth
as a Cherenkov detector

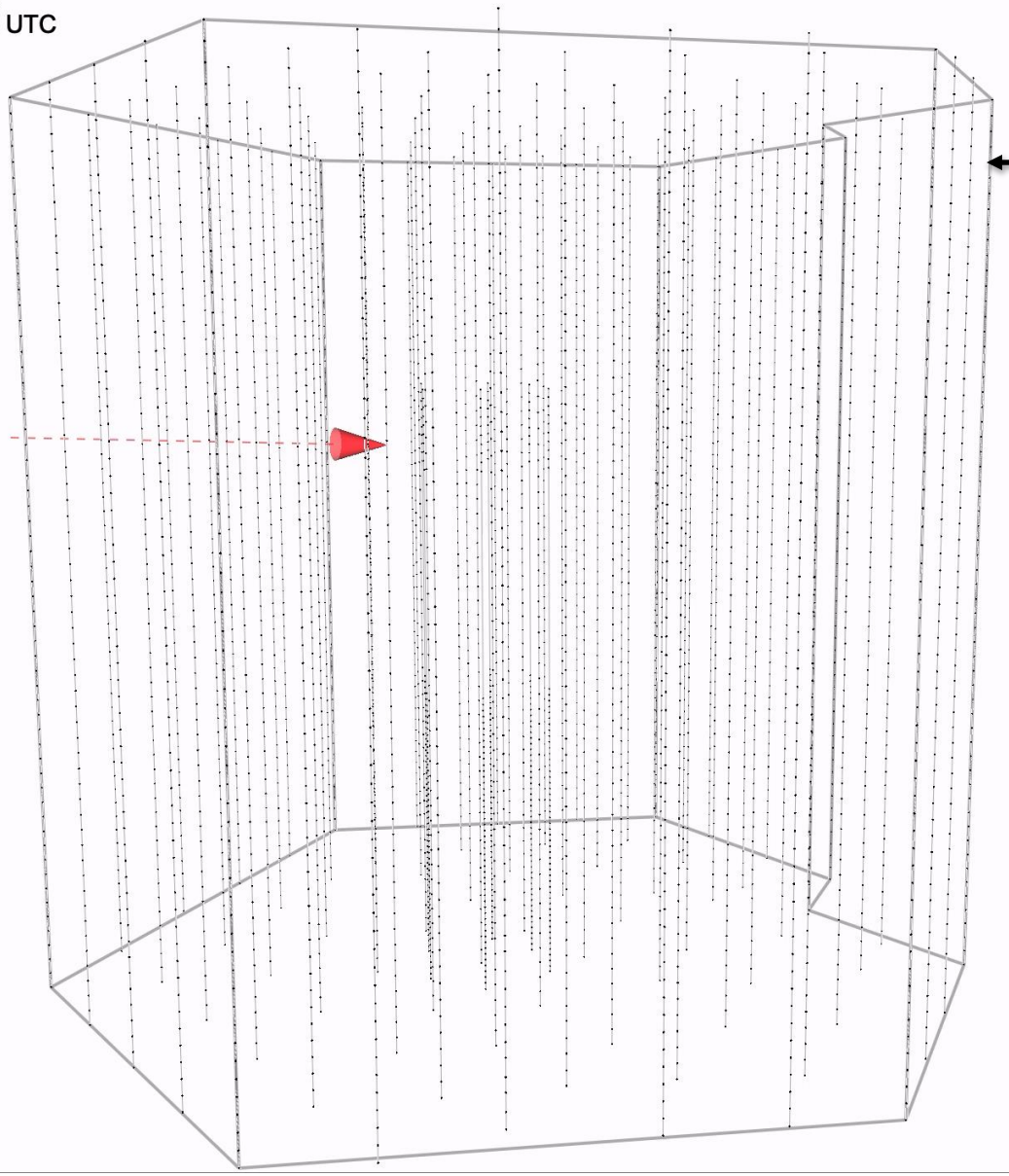




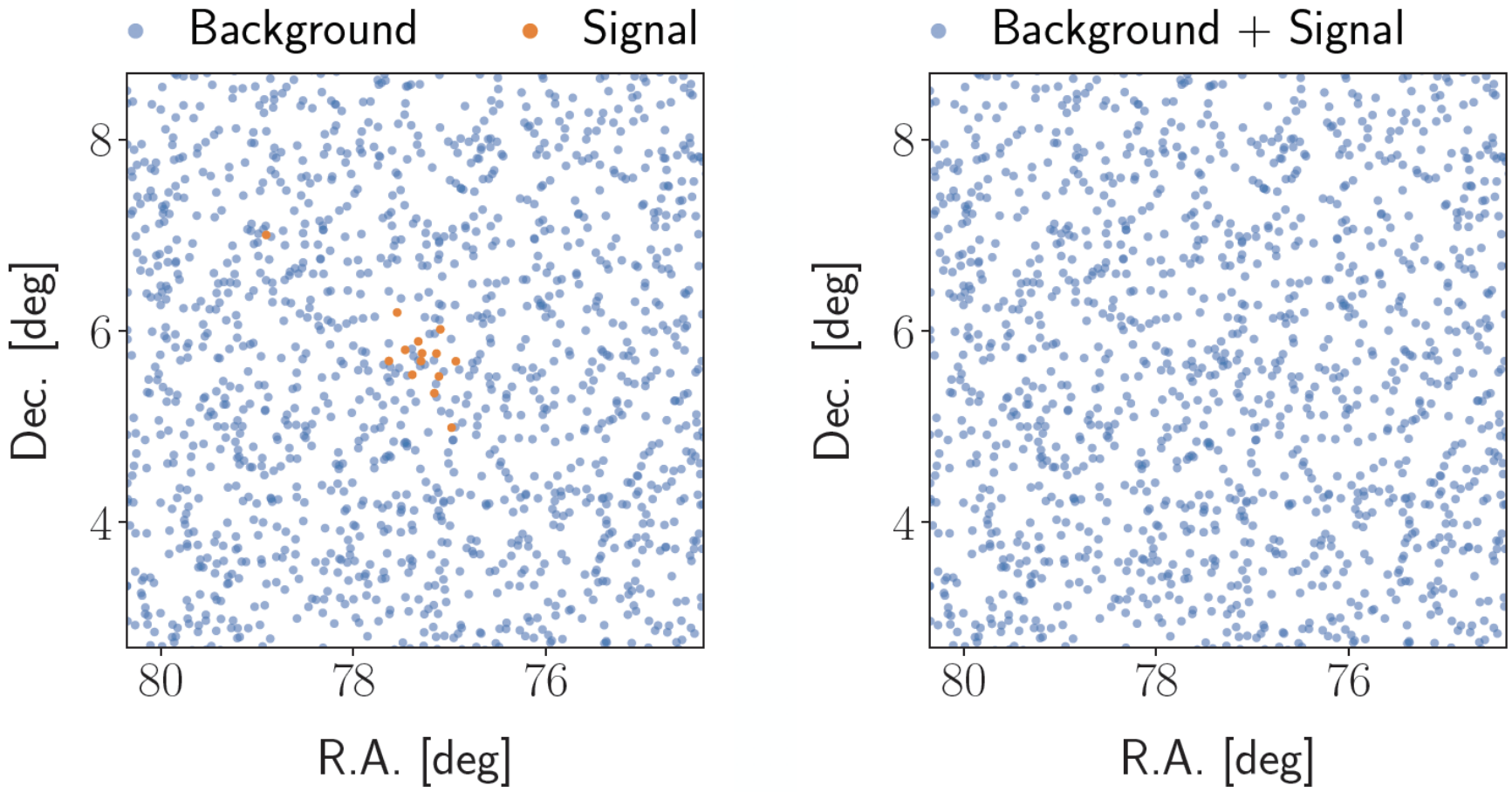


strings of optical sensors





a muon speeds through the ice leaving a trail of blue light which reveals its direction and the direction of the neutrino

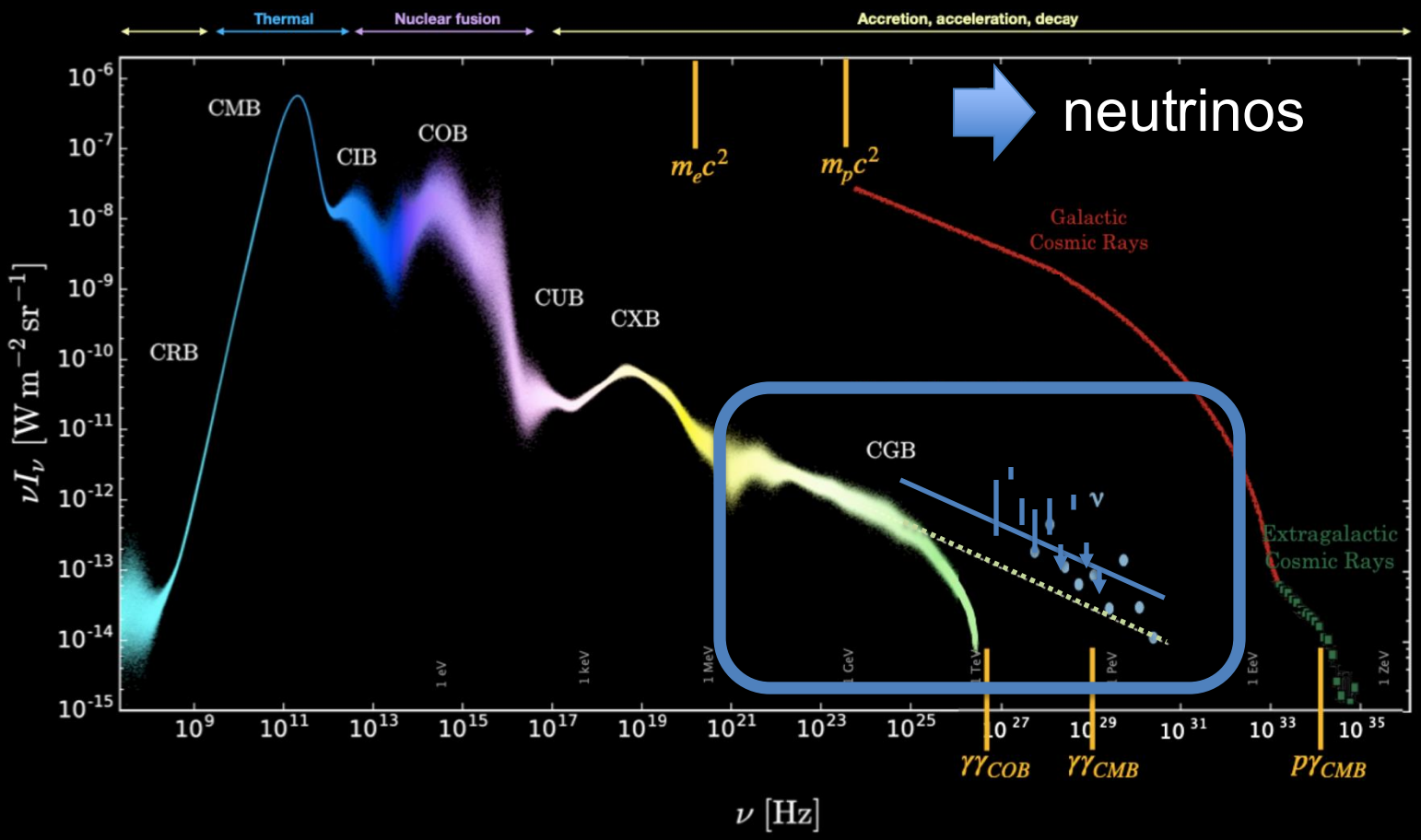


- maximize the (model agnostic) likelihood *L* at each point in the sky
- usually, add energy term to the signal likelihood *S*

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

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

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



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