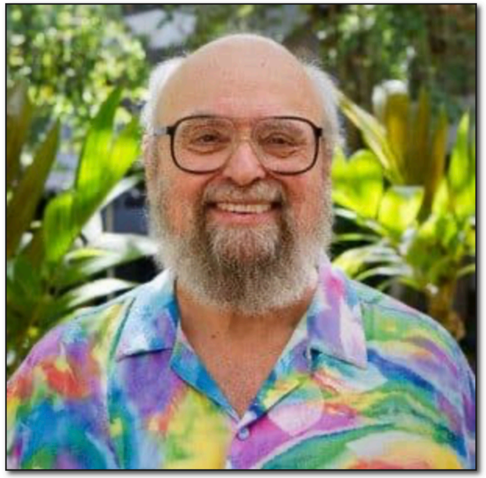
Workshop on Ghost Particle Hunting: Neutrino Physics and its Applications to World Peace

Francis Halzen



Research Interest:

Particle Astrophysics, particularly neutrinos astrophysics and related phenomenology, Variable Stars and SETI.

Specialty:

Neutrino Studies
Oscillations and Mass (SuperK, K2K, and KamLAND)
Neutrino Astronomy (ANITA)
Other Budding Endeavors

Career History:

- B.A Columbia, 1957 – 1961
- G.D. Astronomy Engineer, 1961 – 1962
- M.S. University of Pennsylvania, 1962 – 1963
- Boeing Engineer, 1963 – 1965
- Ph.D. U. Washing, 1965 – 1968
- Post Doc, Research Assistant, Professor, University of Wisconsin (1968 – 1976)
- Visiting Associate Professor (1976 – 1979)
- Professor, Department of Physics and Astronomy, University of Hawai'i at Mānoa (1980 – present)

Project involvement in:

SuperKamiokande – active collaborator taking shifts in Japan and working in several paper groups
KamLAND – Active collaborator, hosting collaboration meetings in Hawaii, and participating in paper groups.
Neutrino monitoring of reactors: pioneered long range reactor detection and monitoring studies on 2002, and began annual conference series AAP
Watchman – One of the founders, and still interested, but with withdrawal from Boulby and stalled attempt at a new detector in Fairport, negligible progress
DUNE – While JGL wrote (with three others) perhaps the first proposal for a giant liquid argon detector, LANNDD, and though a member of DUNE, he is not an active participant.
Small Neutrino and Neutron Detectors – Over the last several decades John has invented and developed various configurations of small neutrino detectors (the neutrino time cube) and directional neutron detectors (eg. the double scatter neutron camera).
Presently FROST – developing a small directional neutrino detector project (forest of scintillating tubes): Under initial feasibility testing in the lab.
HyperKamiokande – recent small NSF funding to participate, involvement developing, project under construction
Underwater Neutrino detectors – as leader of the DUMAND project to put a km^3 detector in the ocean near Hawaii, while pushing towards neutrino astronomy finally achieved by IceCube in 2022, John's initiatives pushed neutrino astronomy starting in the 1970's and continuing to this day. Involved with a revival of our old ideas for an underwater low energy neutrino detector Hanohano, with collaborators in Japan.
First proposed a detector to observe the neutrino mass hierarchy at a range of 55km, JUNO now being carried out in China. John not a member due to US-China politics.
Neutrinos are Smart: Given a series of colloquia on the topic of neutrinos being the only fundamental particles which retain the information of the birth time (and hence range). In fact monitoring of neutrinos from a point source (reactor) can yield distance, direction, power, and even fuel, all without external information (called NUDAR, like radar but no transmitter needed).
Gravitationally Symmetric Universe: Presently fascinated with the prospect that the universe may be half anti-gravitating antimatter, and only neutrinos can resolve the situation. Talks and paper forthcoming.

Evidence for oscillation of atmospheric neutrinos #1

Super-Kamiokande Collaboration • Y. Fukuda (Tokyo U., ICRR) et al. (Jul, 1998)

Published in: *Phys.Rev.Lett.* 81 (1998) 1562-1567 • e-Print: hep-ex/9807003 [hep-ex]

Indications of neutrino oscillation in a 250 km long baseline experiment #6

K2K Collaboration • M.H. Ahn et al. (Dec, 2002)

Published in: *Phys.Rev.Lett.* 90 (2003) 041801 • e-Print: hep-ex/0212007 [hep-ex]

First results from KamLAND: Evidence for reactor anti-neutrino disappearance #2

KamLAND Collaboration • K. Eguchi (Tohoku U.) et al. (Dec, 2002)

Published in: *Phys.Rev.Lett.* 90 (2003) 021802 • e-Print: hep-ex/0212021 [hep-ex]

Charged-particle multiplicities of proton proton interactions between 90 and 800 gev #2

Lawrence W. Jones (Michigan U.), A.E. Bussian (Michigan U.), G.D. Demeester (Michigan U.), B.W. Loo (Michigan U.), D.E. Lyon (Michigan U.) et al. (1970)

Cosmic ray muon integral intensity measurement under water #6

H.F. Davis (Oregon State U.), J.G. Learned (Washington U., Seattle) (1973)

Published in: *Phys.Rev.D* 8 (1973) 8-12

Measurement of atmospheric neutrino composition with IMB-3 #1

D. Casper, R. Becker-Szendy, C.B. Bratton, D.R. Cady, R. Claus et al. (Sep, 1990)

Published in: *Phys.Rev.Lett.* 66 (1991) 2561-2564

Acoustic Radiation by Charged Atomic Particles in Liquids: An Analysis

John G. Learned (UC, Irvine) (Aug, 1978)

Published in: *Phys.Rev.D* 19 (1979) 3293

Determination of neutrino mass hierarchy and theta(13) with a remote detector of reactor antineutrinos

John Learned (Hawaii U.), Stephen T. Dye (Hawaii U. and Hawaii Pacific U.), Sandip Pakvasa (Hawaii U.), Robert C. Svoboda

Phys.Rev.D 78 (2008) 071302 • e-Print: hep-ex/0612022 • DOI: 10.1103/PhysRevD.78.071302

Limits on Nonconservation of Baryon Number

J. Learned (UC, Irvine), F. Reines (UC, Irvine), A. Soni (UC, Irvine) (Jul, 1979)

Published in: *Phys.Rev.Lett.* 43 (1979) 907, *Phys.Rev.Lett.* 43 (1979) 1626 (erratum)

DUMAND: The Ocean as a Neutrino Detector

#1

H. Blood (Naval Ocean Sys. Ctr., San Diego), J. Learned (Wisconsin U., Madison), F. Reines (UC, Irvine), A. Roberts (Fermilab) (Jun, 1976)

Contribution to: International Neutrino Conference 1976, 688-702

Detecting tau-neutrino oscillations at PeV energies

#1

John G. Learned (Hawaii U.), Sandip Pakvasa (Hawaii U.) (Aug, 1994)

Published in: *Astropart.Phys.* 3 (1995) 267-274 • e-Print: hep-ph/9405296 [hep-ph], hep-ph/9408296

High-energy neutrino astrophysics

#2

J.G. Learned (Hawaii U.), K. Mannheim (Gottingen U.) (2000)

Published in: *Ann.Rev.Nucl.Part.Sci.* 50 (2000) 679-749

HIGH-ENERGY NEUTRINO DETECTION IN DEEP POLAR ICE

#63

Francis Halzen (Wisconsin U., Madison), John G. Learned (Hawaii U.) (Jun, 1988)

AI Overview

In 1978, physicist John Learned began his research on neutrinos from nuclear reactors, later leading to the DUMAND project and pushing for neutrino astronomy. He spearheaded initiatives in the 1970s that ultimately led to the realization of neutrino astronomy by IceCube in 2022.

Elaboration:

Early Work:

John Learned's work in the 1970s and 1978 specifically focused on studying neutrinos produced by nuclear reactors.

DUMAND Project:

Learned's research laid the groundwork for the DUMAND project, which aimed to build a large underwater neutrino detector near Hawaii.

Neutrino Astronomy:

His work pushed for the development of neutrino astronomy, which was eventually achieved by IceCube.

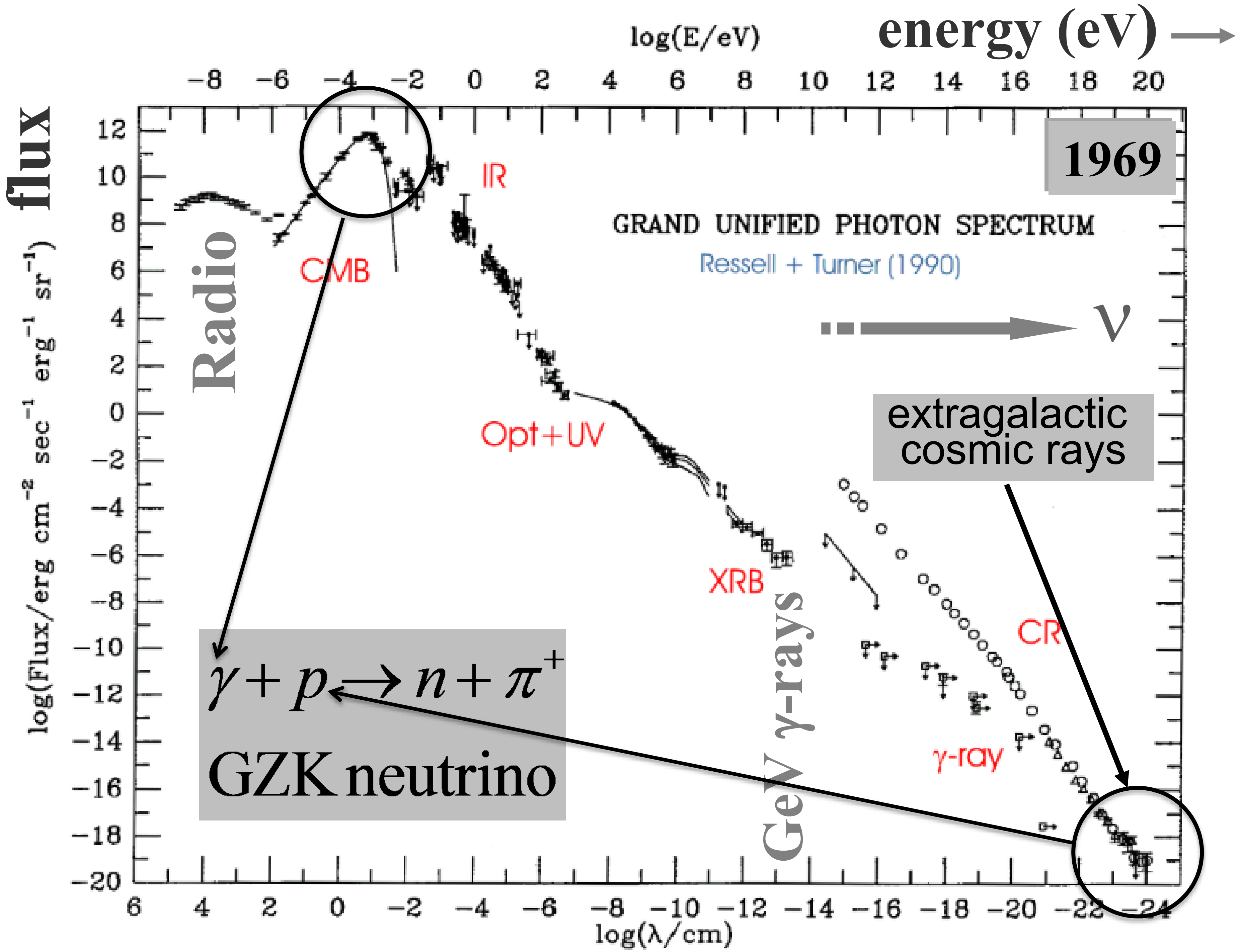
Other Research:

Learned's other research includes the idea of a low-energy neutrino detector, Hanohano, and a proposal for a detector to observe neutrino mass hierarchy, JUNO.

JUNO:

Learned's initial proposal for a detector to observe the neutrino mass hierarchy is now being carried out by JUNO in China, though Learned is not part of the project due to US-China politics.

the guaranteed neutrinos ☹



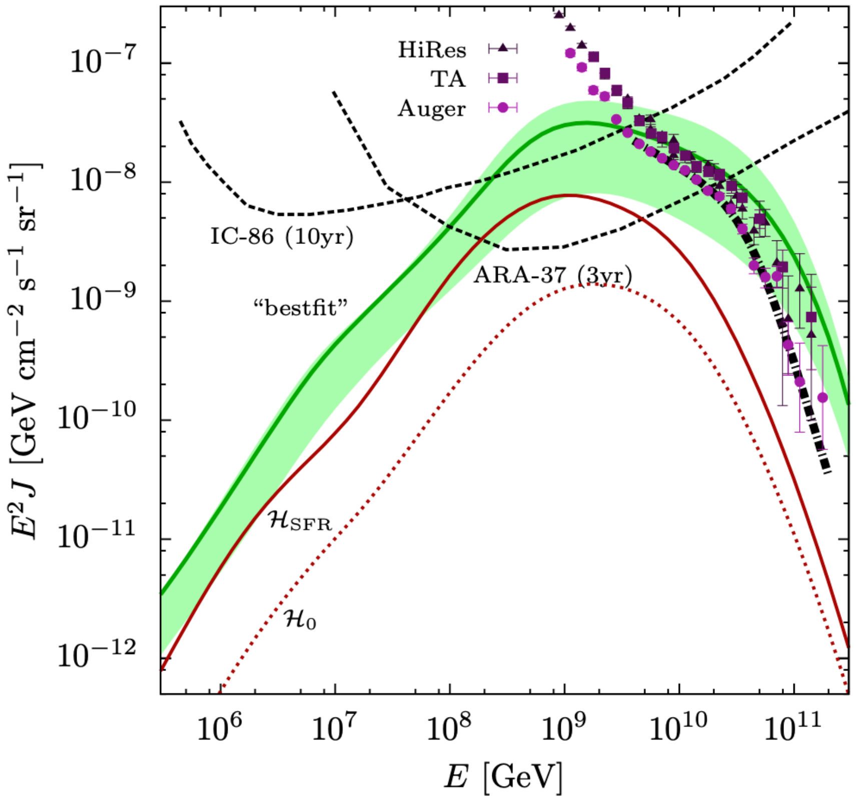
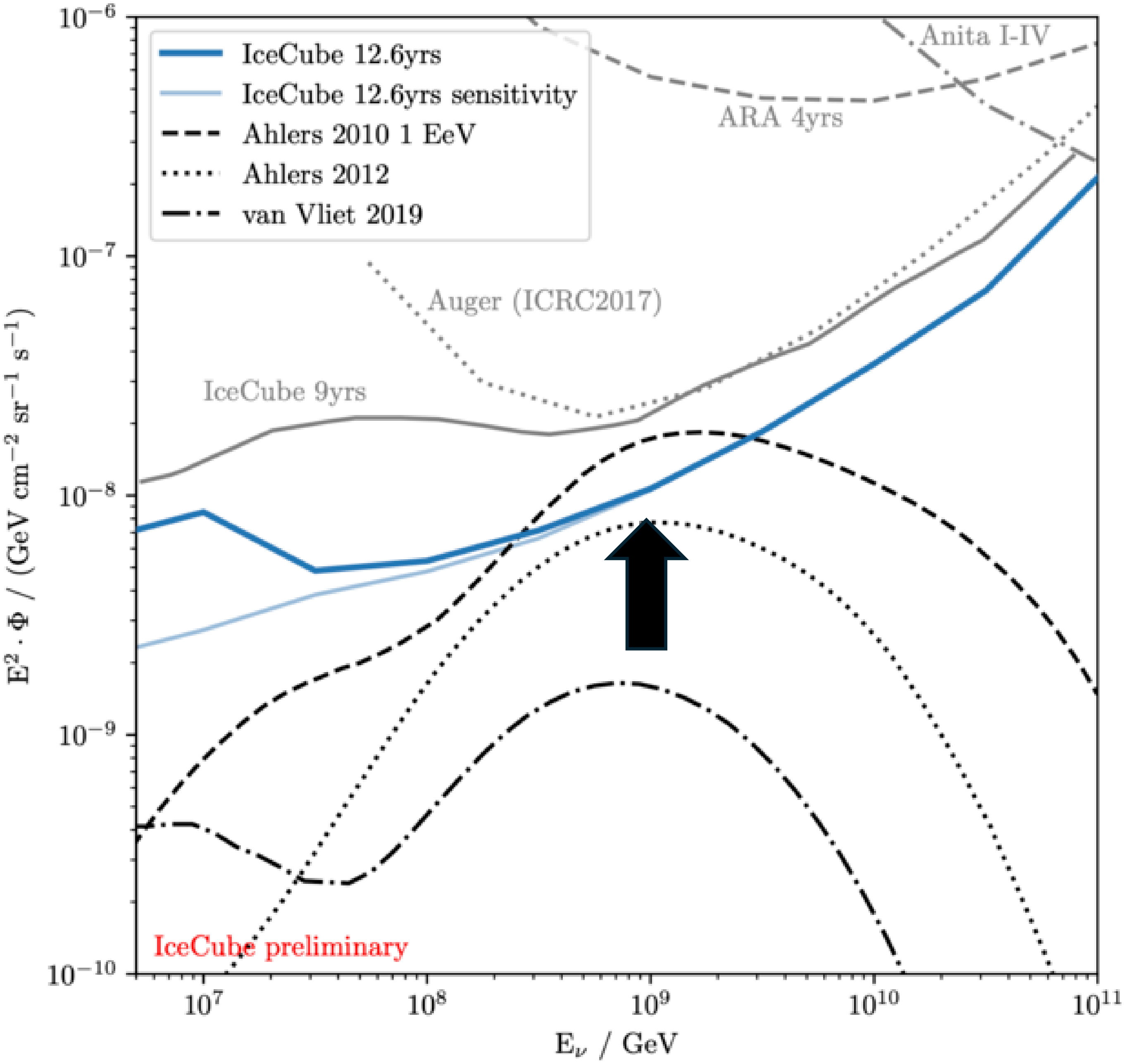
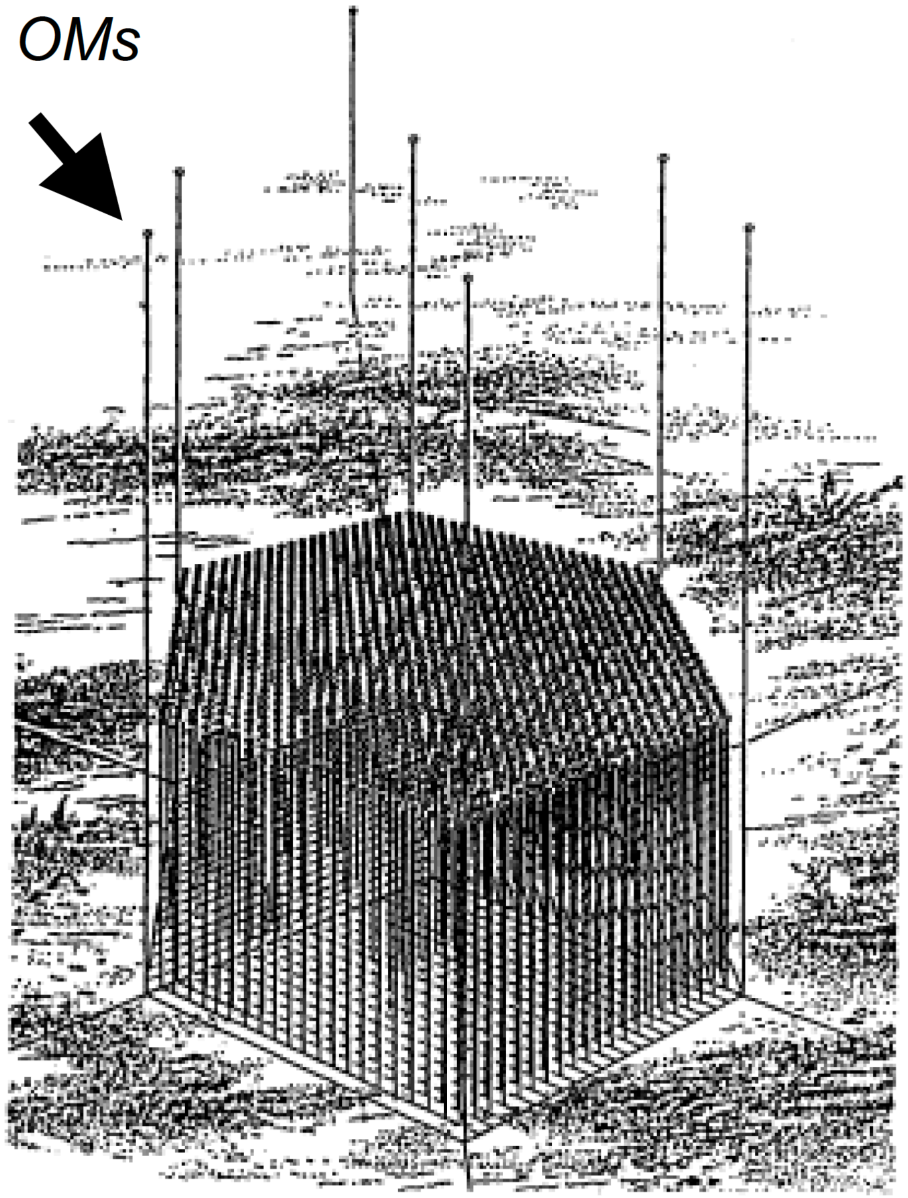


FIG. 1: Minimal flux of cosmogenic neutrinos assuming dominance of protons above 4 EeV. We show the results without source evolution (dotted) and assuming source evolution according to the star formation rate (solid). Also shown are the projected sensitivities of IceCube (10 years) and the ARA-37 (3 years) as dashed lines. The thick dashed-dotted line shows the approximation of the Auger spectrum above the ankle. For comparison, we also show the bestfit cosmogenic neutrino flux (green solid line) from Ref. [24] ($E_{\rm min} = 10^{18.5}$ eV) including the 99% C.L. (green shaded area) obtained by a fit to the HiRes spectrum.





1973

first ideas on

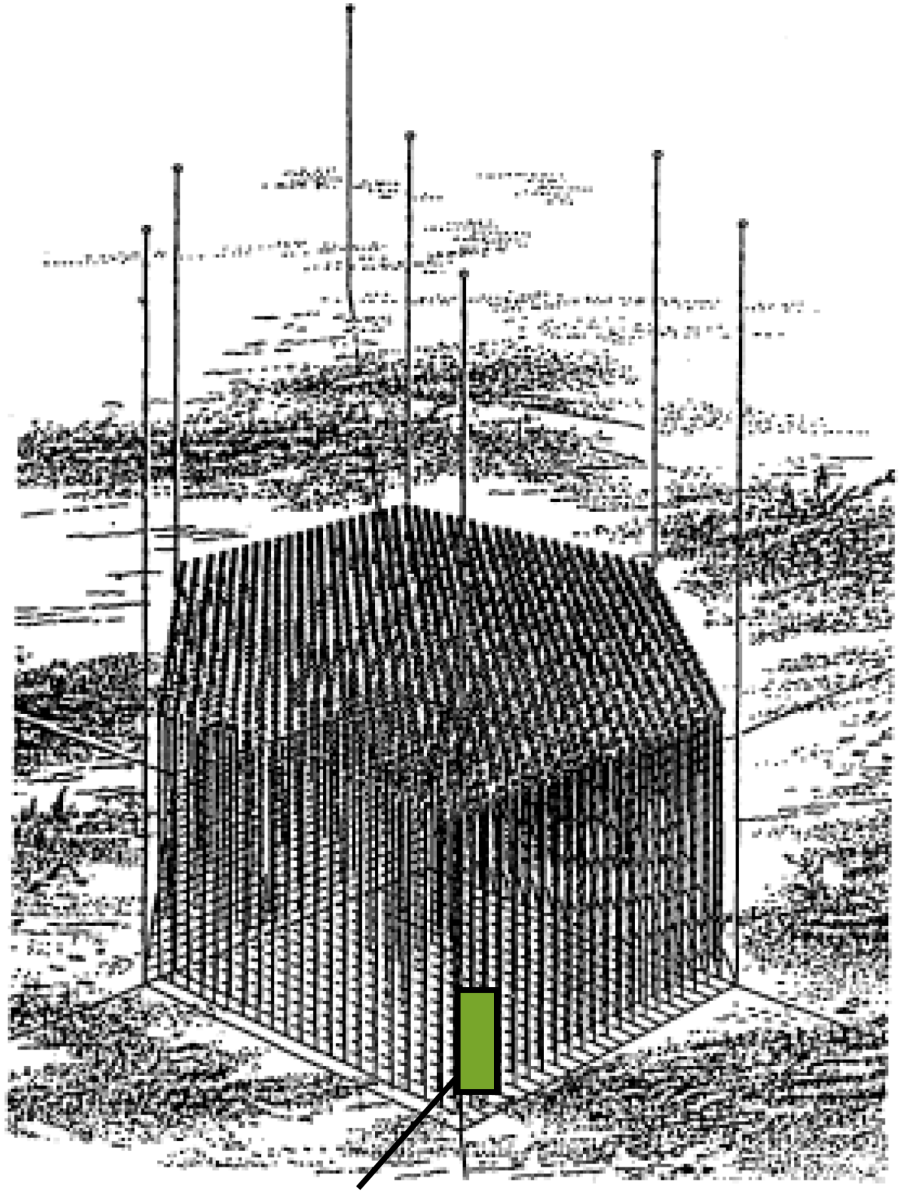
DUMAND

Hawaii

1993-1998
NT200
Lake Baikal

1995-2000
AMANDA
South Pole

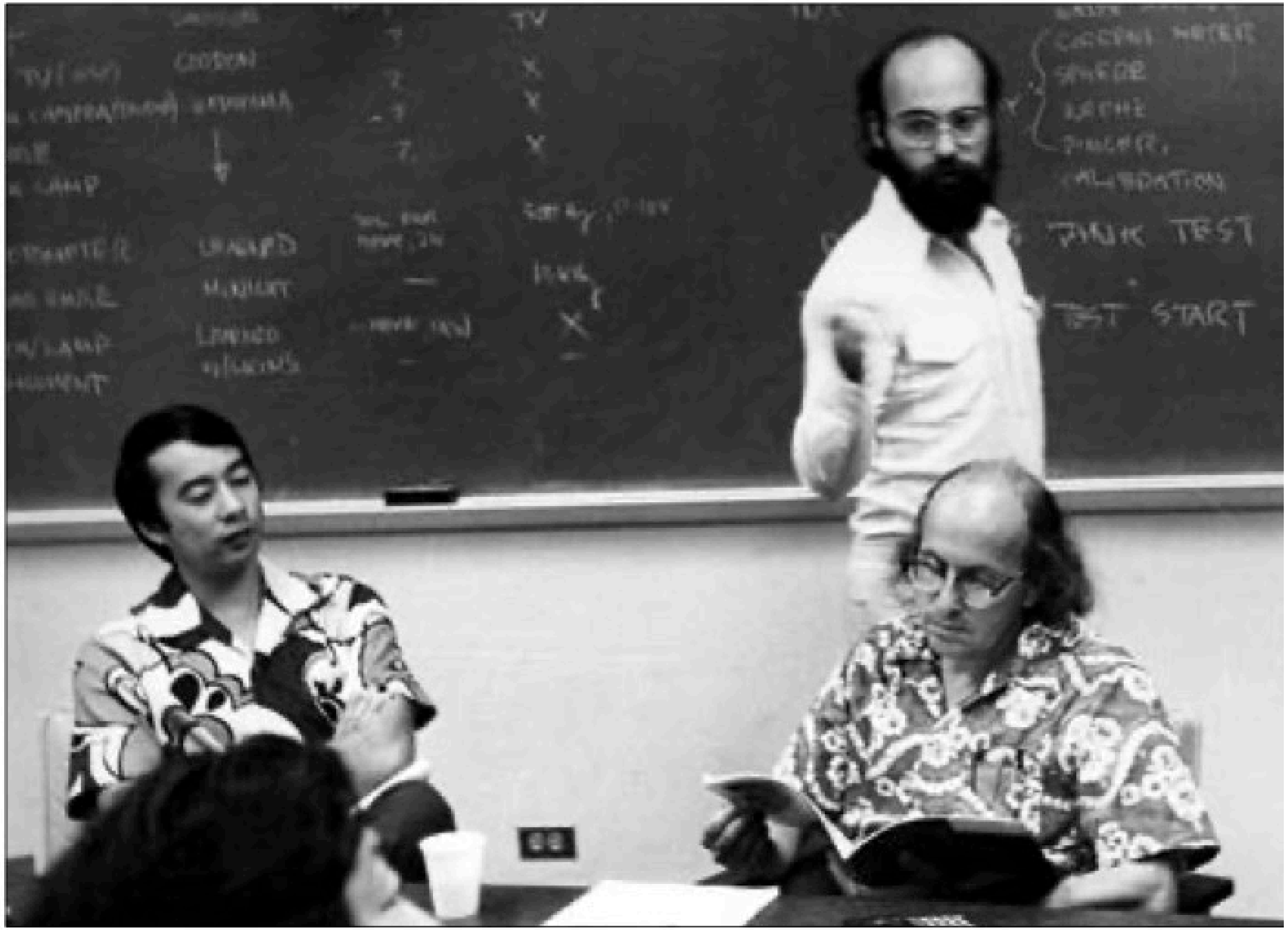
2002-2008
ANTARES
Mediterrannean



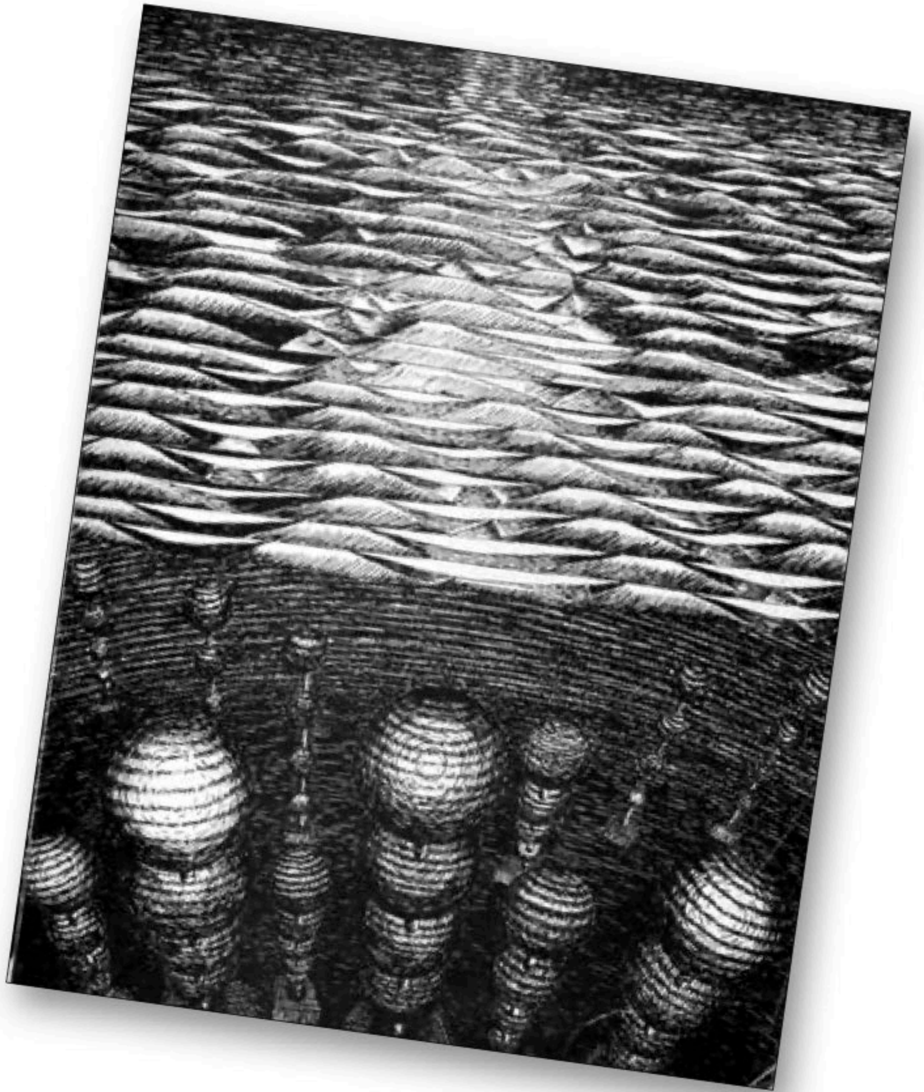
1988: reduced DUMAND design

DUMAND terminated 1996

Anatoly Pethruhkin



DUMAND'76 was of paramount importance for building personal bonds and stirring ideas. Here: John Learned at the blackboard, with Jed Hirota (left) and Dick Davisson.



Cover art from the DUMAND conference proceedings, showing the basic undersea neutrino-detection principle. (Image credit: Rene Donaldson, Fermilab.)

Anatoly Pethruhkin

Attendees of the 1976 workshop, showing Fred Reines (back, second from left) and one of the present authors, JL (back, third from left). Other attendees included theorist Venyamin Berezinski; cosmic-ray experts Alexander Chudakov, Boris Dolgoshein and Anatolij Petrukhin from Moscow; Saburo Miyake (founder of ICRR in Tokyo, later home of Kamiokande); and astronomer G A Tamman. US particle-physicists Ted Bowen, Sidney Bludman, David Cline, Marshall Crouch, Howard Davis, Richard Davisson, Vernon Jones, Peter Kotzer, Ken Lande, Karnig Mikaeilian, M Lynn Stevenson, Larry Sulak and Dave Yount were joined by astronomers and astrophysicists David Schramm, Ivan Linscott, Rein Silberberg and Craig Wheeler.

Dear Neutrino Colleagues:

It is with great sadness that I must communicate to you the demise of our beloved DUMAND project, at least as presently organized with DOE funding. Yesterday I received the long awaited SAGENAP Report from the 20 Feb 1996 DOE review of DUMAND and other projects. I have not had time to absorb the report yet, but I thought you ashould know the bad news before it percolates through the rumor mill. It is apparent to me that it was their intention to do this since 10/94, when the committee arrived in Hawaii with blood in their eyes, only to be won over by our week long presentations. What a pity they waited so long to take this decision.

I have taken much of the blame... "The fatal failure was laid [according to the DOE reviewers] on the project leadership, whose managerial skills and commitment [this really pisses me off... sure it was only 20 years] to the project were strongly deprecated. Many reviewers said the DUMAND 'Project Director' should have been a strong Engineer/Manager of the NASA project variety." They complained about our ineffective quality control and cost overruns.

On the positive side they said several nice things about our being pioneers, and such. And they say that "in general the reviewers expressed their belief that the problems of doing neutrino physics in the deep ocean are not insurmountable, and that the DUMAND concept can be made to work. In fact, the fundamental questions for operating such a device in the deep ocean, such as water purity, bioluminescence, etc., appear to be manageable." The report also supports a KM^3 instrument as a desirable goal. However, "although reviewers felt that completing the three string phase of DUMAND was desirable, especially to prepare for a much larger detector, no reviewer recommended going ahead with the proposed [DUMAND] work."

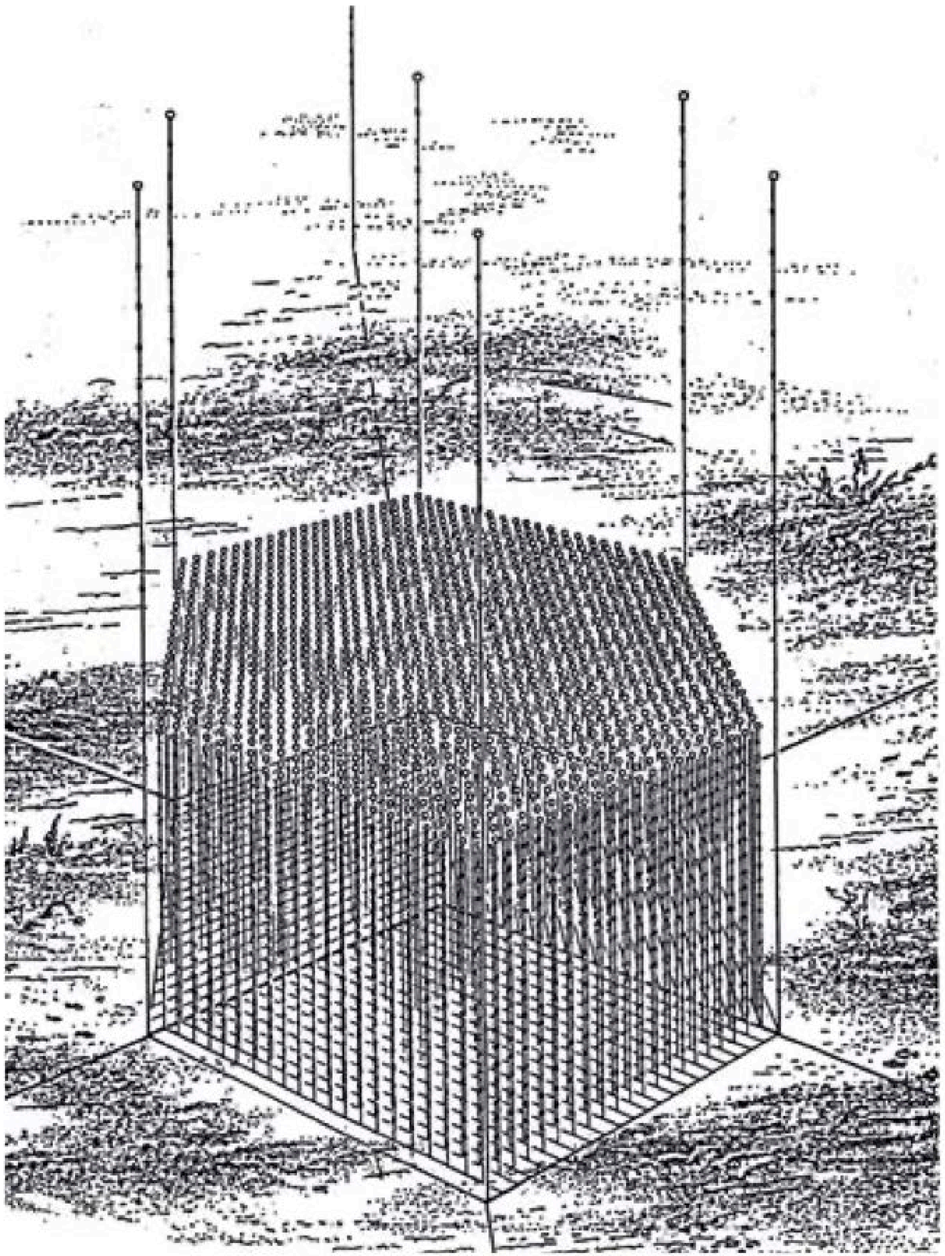
"DOE_HEP Recommendations:"

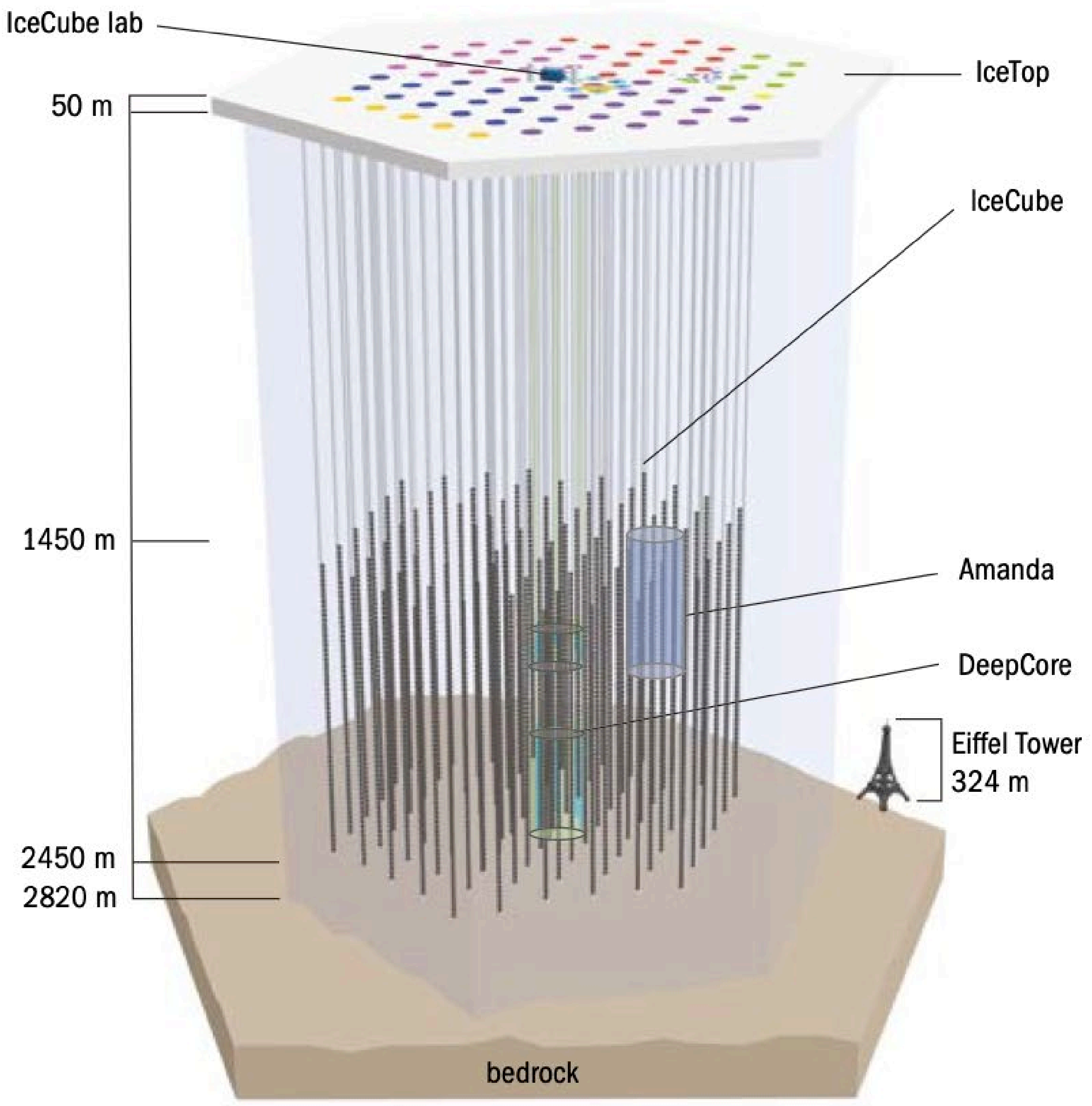
"Further support of the DUMAND Project is not recommended. At base, the reason is the track record of the collaboration in its work to date, and a judgement that the DUMAND team, including its leadership, lack the skills needed to carry out such a complex project in the unforgiving environment of the deep ocean. The project should be terminated, and is operations phased out in an orderly manner."

Thus we DUMANDers have reached the end of a long journey, or perhaps it is just a turning point in that journey. Now we must think about what to do next. We will surely ask for termination funds, as I believe we are committed to pull up the cable and JB. It is a great pity to be cut when we are so close. Certainly, given the damning review, we have no chance of funding from another source, at least without being able to demonstrate a greatly revised organization. We also must face the question of joining with another project. On the longer term we will almost surely join with the KM3 effort from LBL and JPL.

Perhaps in the Japanese tradition I should be taking up the sword of sacrifice, but my way is to fight back. Your thoughts are desired. I am sorry particularly for my colleagues and friends who have labored long over this dream. We shall not give up. Regards,

John





IceCube

The original DUMAND project (left), which was cancelled in 1995, and the present-day IceCube experiment located at the South Pole (right). Although there are no formal links between the two experiments, their configurations bear strong similarities.

search for the Glashow resonance with the Dumand test string

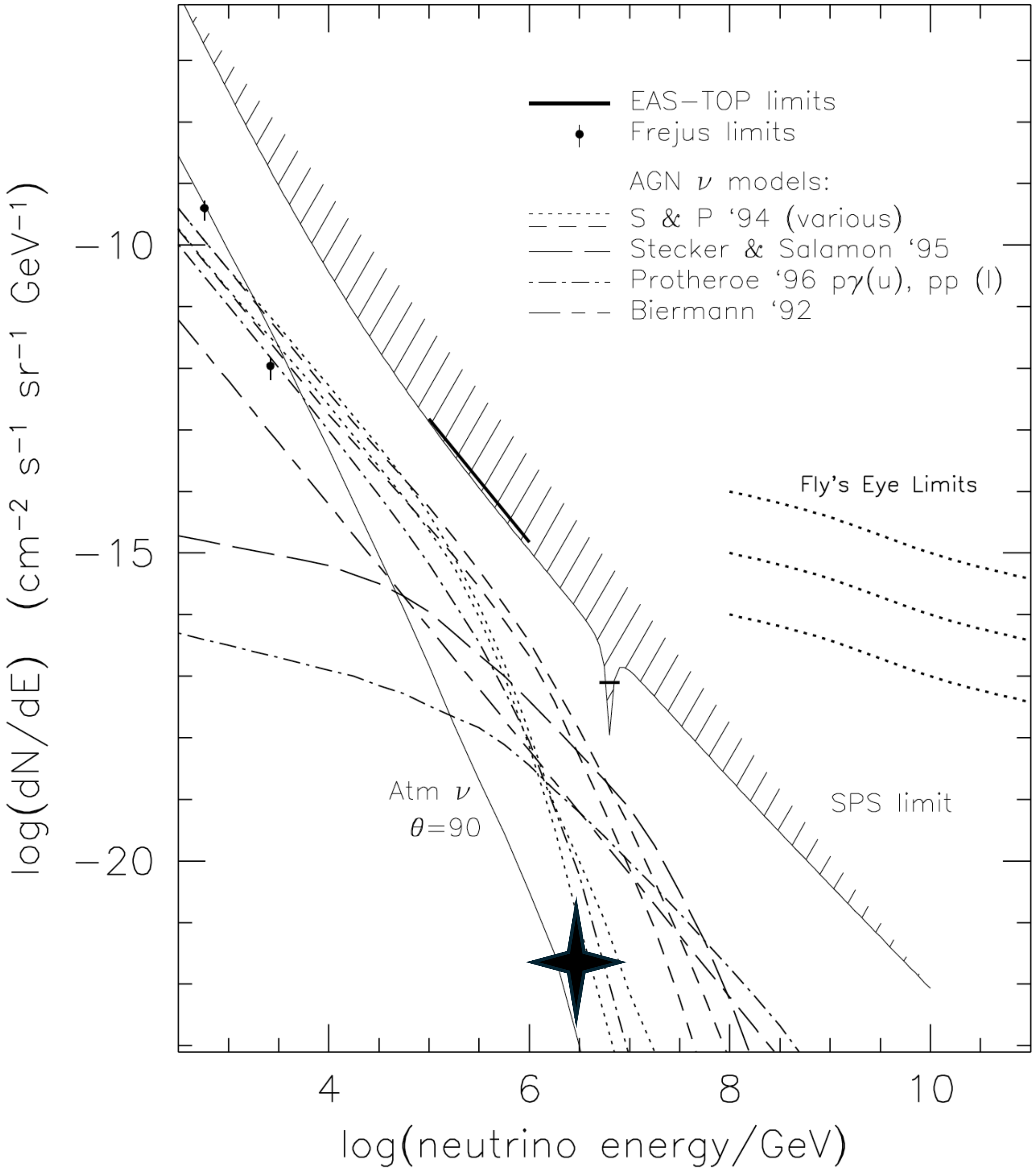
A SEARCH FOR VERY HIGH ENERGY NEUTRINOS FROM ACTIVE GALACTIC NUCLEI

J. W. Bolesta[1], H. Bradner[9], U. Camerini[12], J. Clem[7], S. T. Dye[8], J. George[11], P. W. Gorham[13], P. K. F. Grieder[6], J. Hauptman[5], T. Hayashino[3], M. Jaworski[12], T. Kitamura[4], S. Kondo[1], J. G. Learned[1], R. March[12], T. Matsumoto[3], S. Matsuno[1], K. Mauritz[5], P. Minkowski[6], T. Narita[12], D. J. O'Connor[1], Y. Ohashi[2], A. Okada[2], V. Peterson[1], V. J. Stenger[1], S. Uehara[4], M. Webster[10], R. J. Wilkes[11], K. K. Young[11], A. Yamaguchi[3]

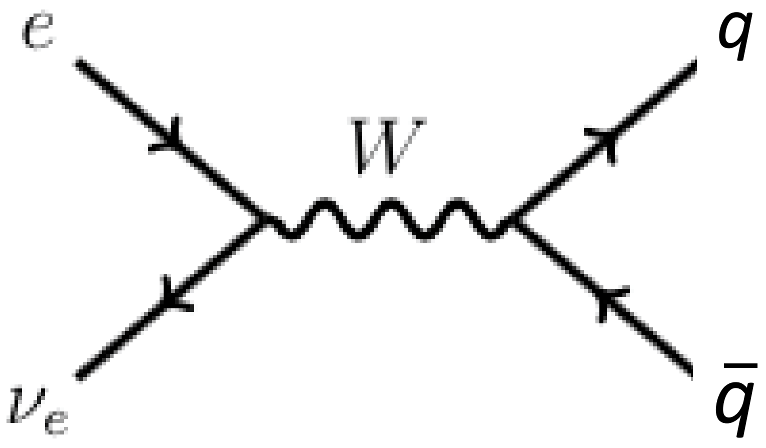
[1]*University of Hawaii, USA* [2]*Institute of Cosmic Ray Research, University of Tokyo, Japan* [3]*Tohoku University, Japan* [4]*KEK, Japan* [5]*Iowa State University, USA* [6]*University of Bern, Switzerland* [7]*Bartol Research Institute, USA* [8]*Hawaii Pacific University, USA* [9]*Scripps Institute of Oceanography, USA* [10]*Vanderbilt University* [11]*University of Washington, USA* [12]*University of Wisconsin, USA* [13]*NASA Jet Propulsion Laboratory, USA*

IceCube:

log (dN/dE) =1.24 10^{-22} $cm^{-2}s^{-1}sr^{-1}GeV^{-1}$

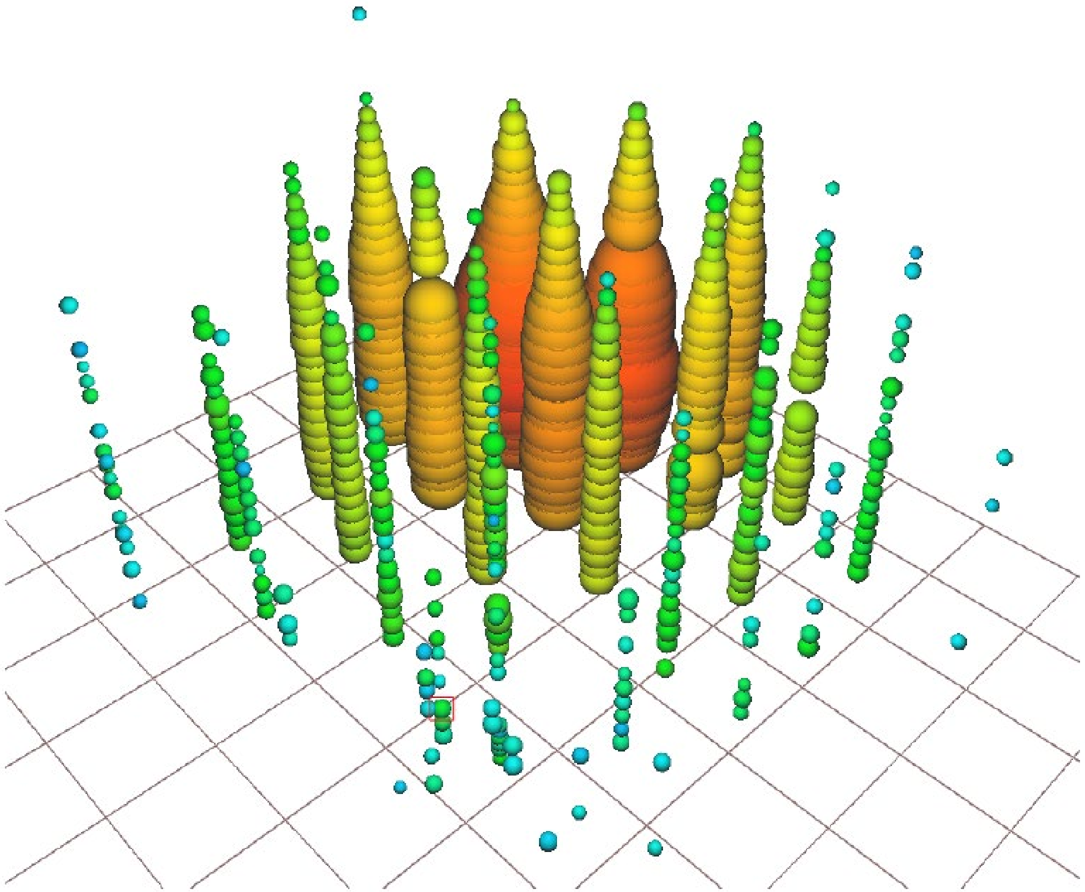


Glashow resonance event with energy 6.3 PeV

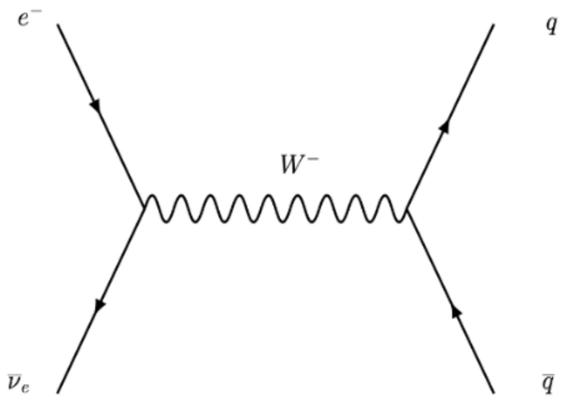


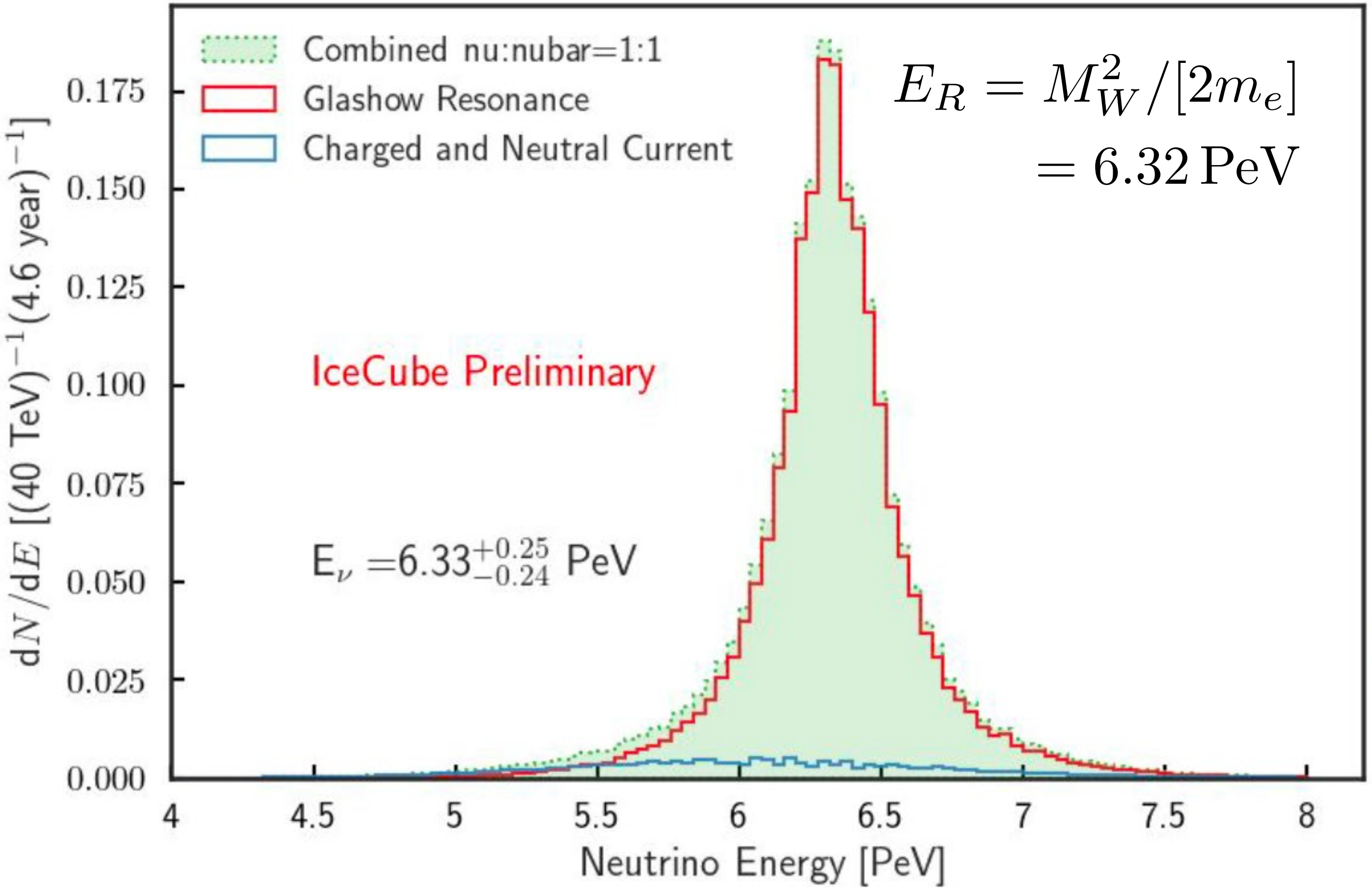
resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

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



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

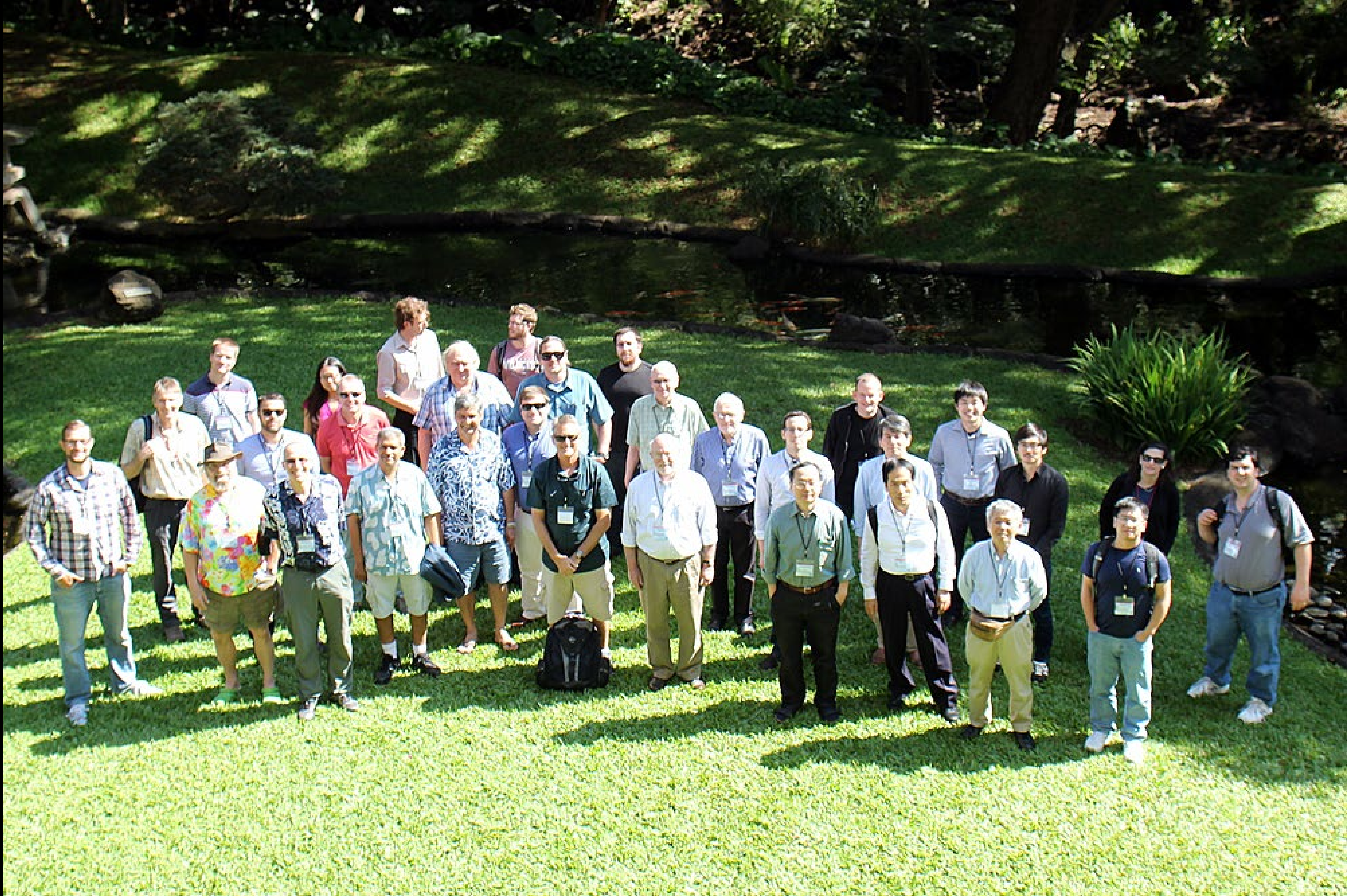




JPL 1994

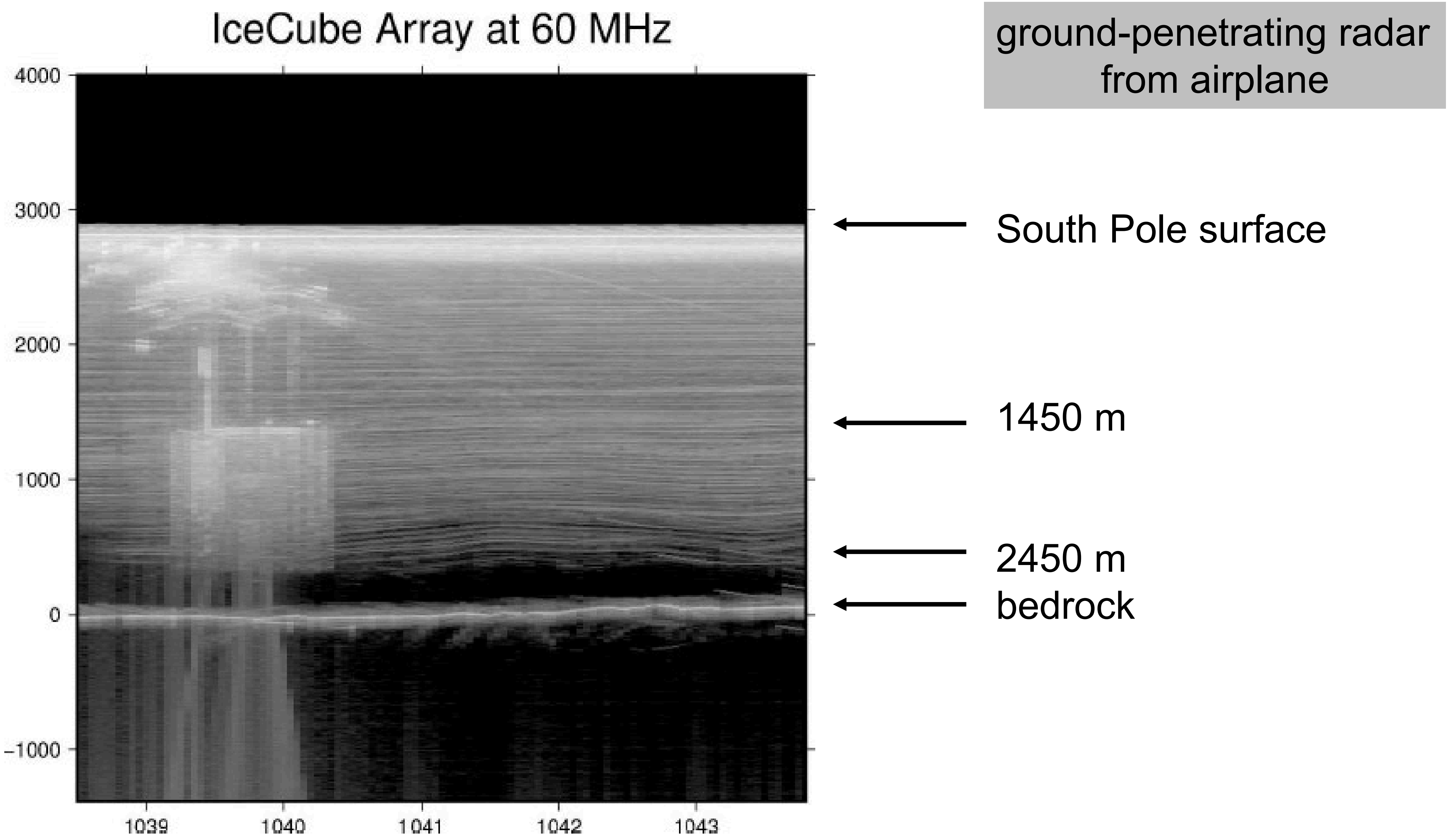
UH 1980

UH 2016

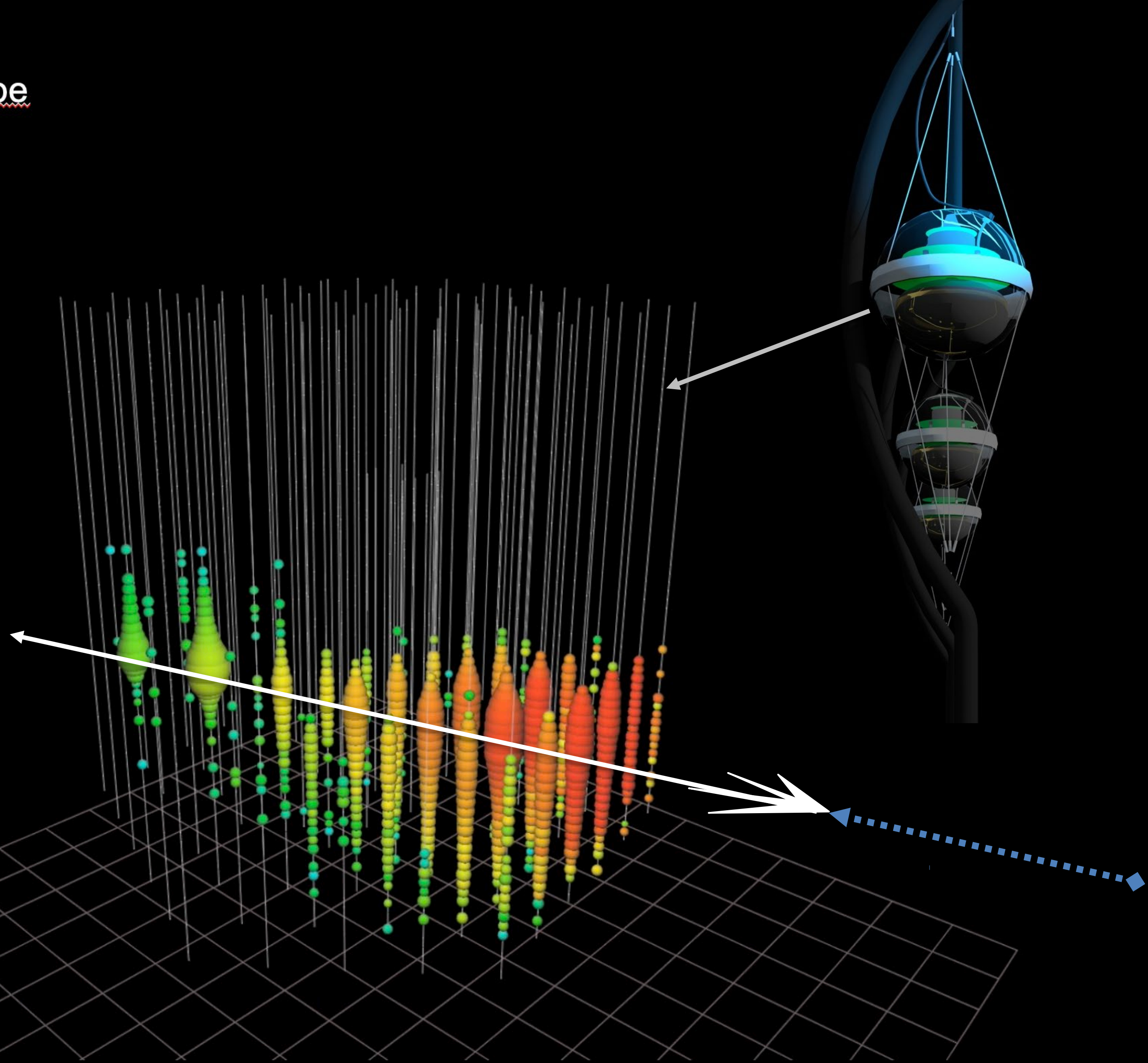


standing on the shoulders of giants

1987: DUMAND test string


IceCube Array at 60 MHz
4000
3000
2000
1000
0
−1000
1039
1040
1041
1042
1043
ground-penetrating radar from airplane
South Pole surface
1450 m
2450 m
bedrock

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



- muon produced by neutrino near IceCube

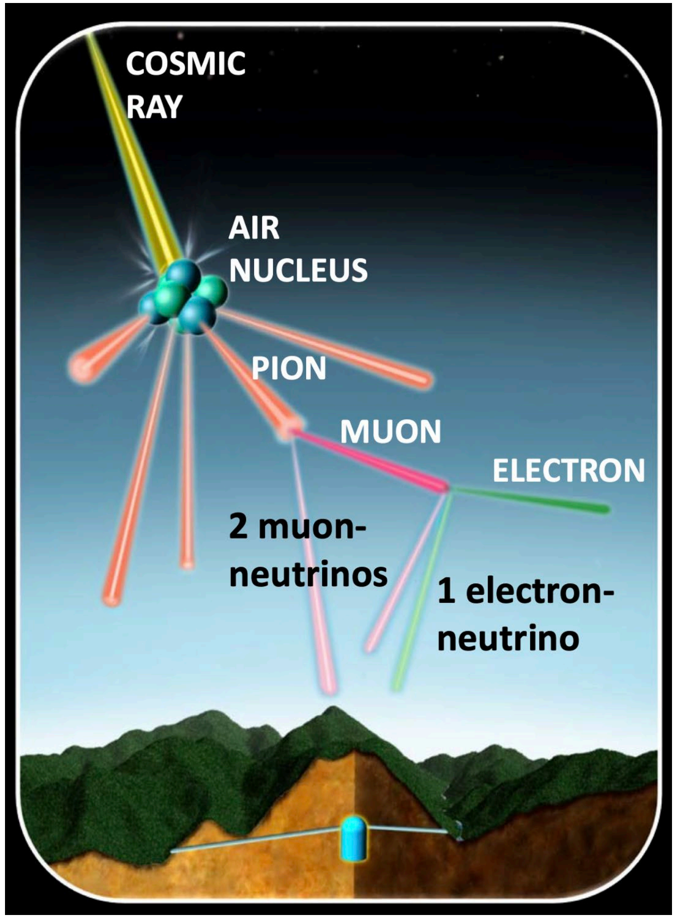
- comes thro

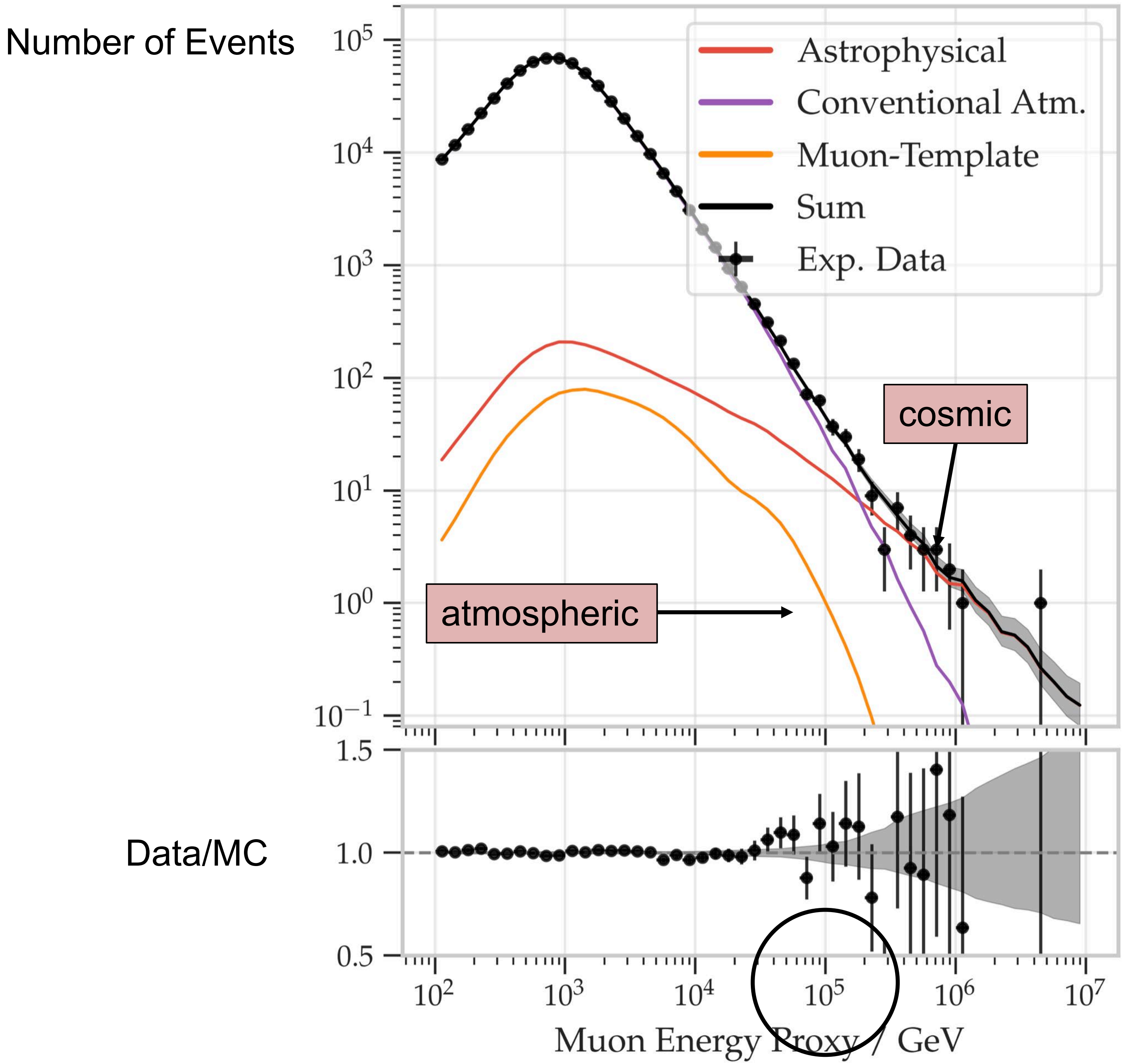
- 2,600 TeV

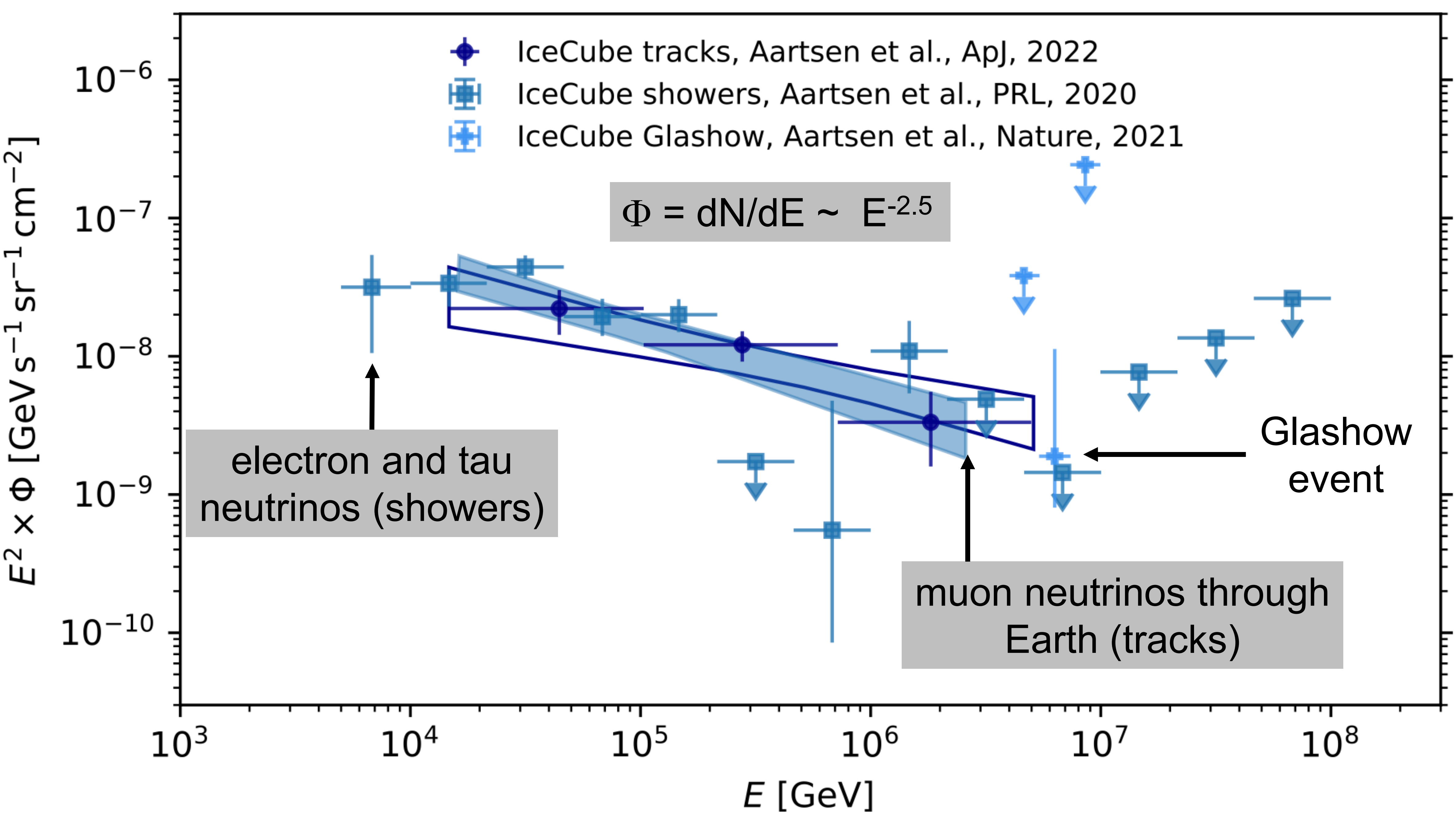
- not atmosp

- angular res
  0.3º → ast

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







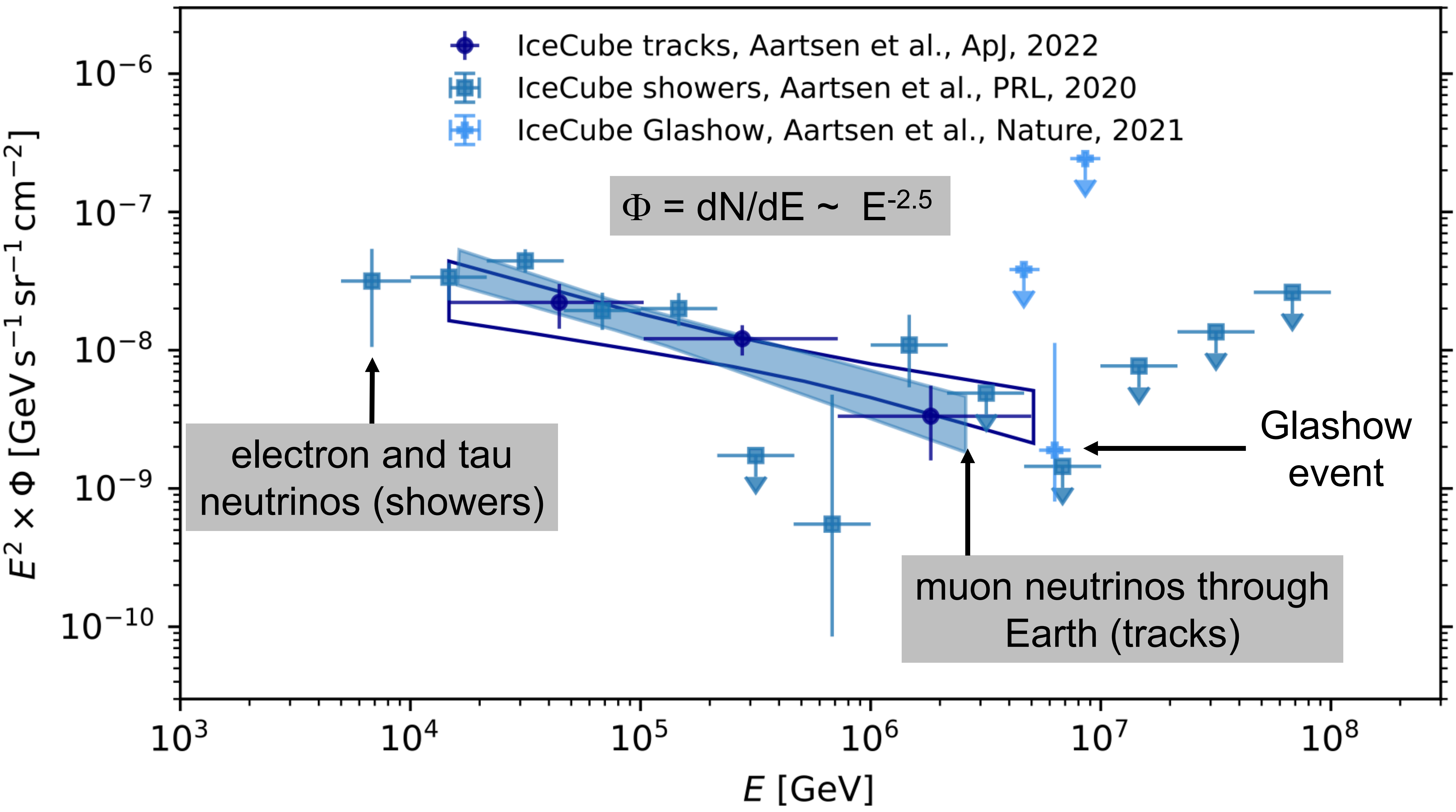
IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ E^-2.5
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
E^2 × Φ [GeV s^-1 sr^-1 cm^-2]
10^-6
10^-7
10^-8
10^-9
10^-10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

neutrinos interacting inside the detector

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

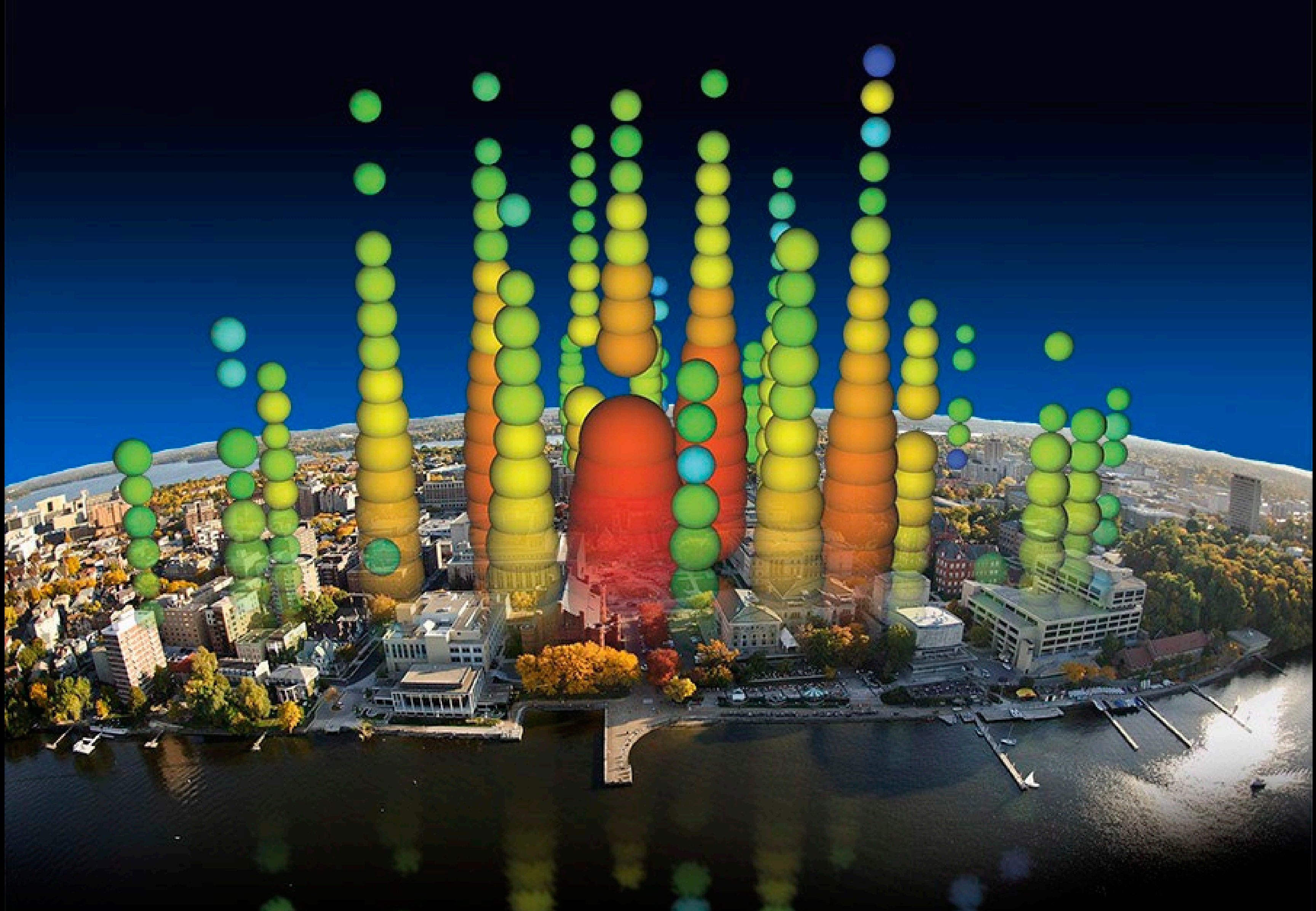
muon neutrinos filtered by the Earth

superior angular resolution 0.3°
including systematics



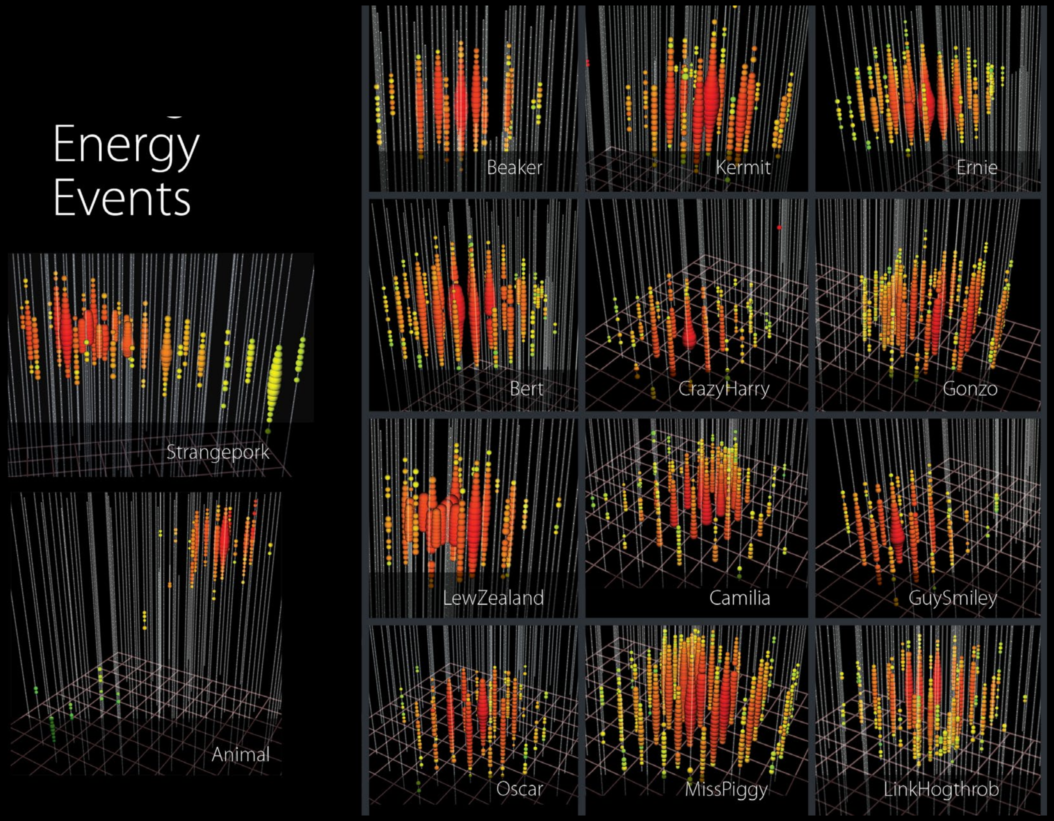
IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ $E^{-2.5}$
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [GeV]
10^{-6}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

Bert and Ernie

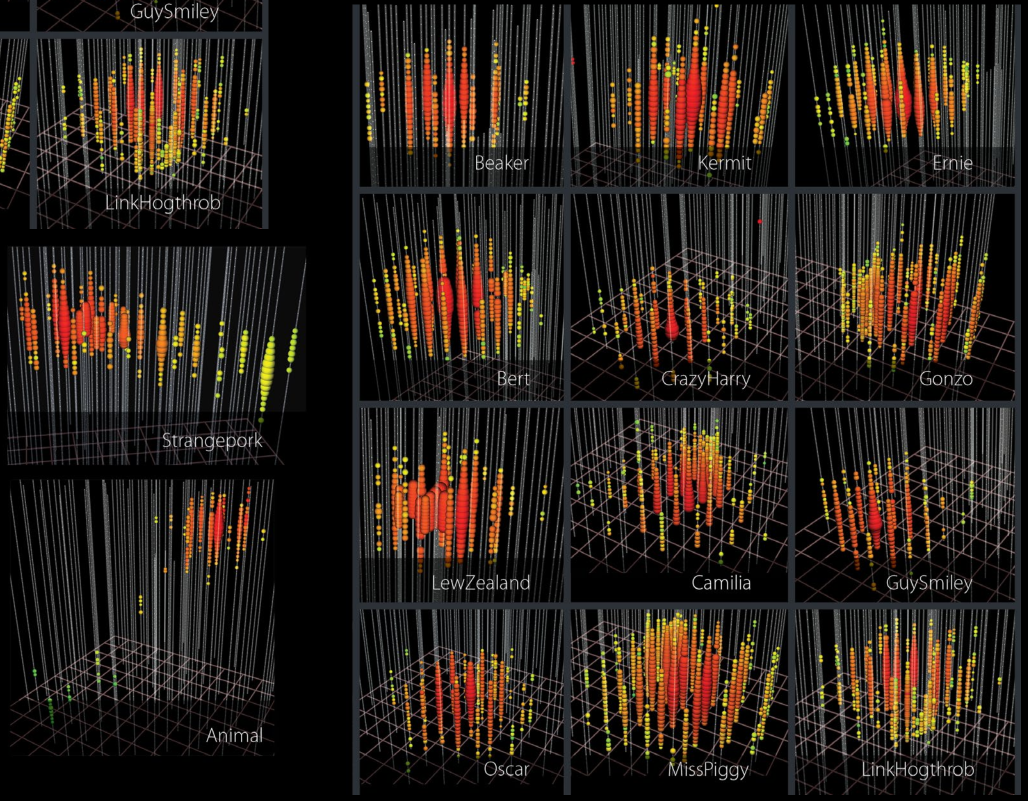


Cherenkov radiation from PeV electron (tau) shower
> 300 sensors > 100,000 pe reconstructed to 2 nsec

Energy
Events

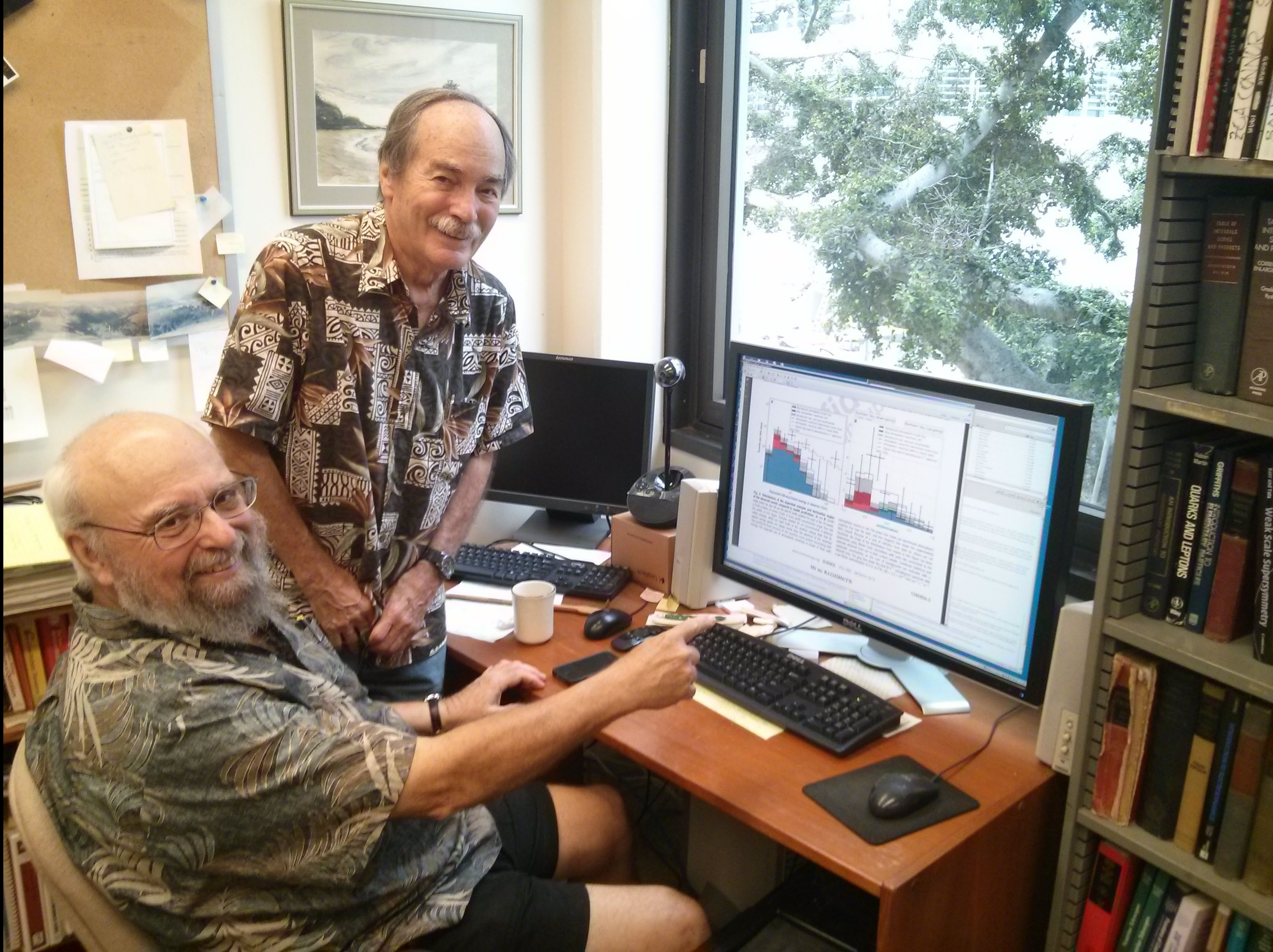


systematic search for
contained events



26 more events found
in first two years of data

UH 2013

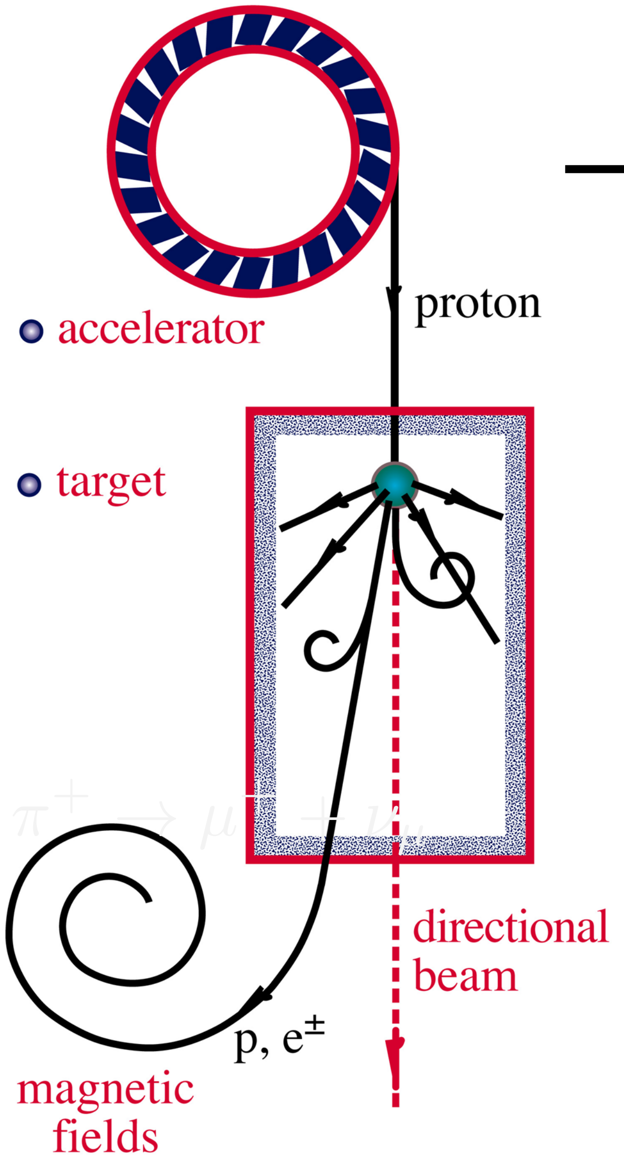


two surprises:

- cosmic neutrinos sources originate in a target from which gamma rays do not escape

- powerful accelerators produce neutrinos in other galaxies that do not exist in our own

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

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

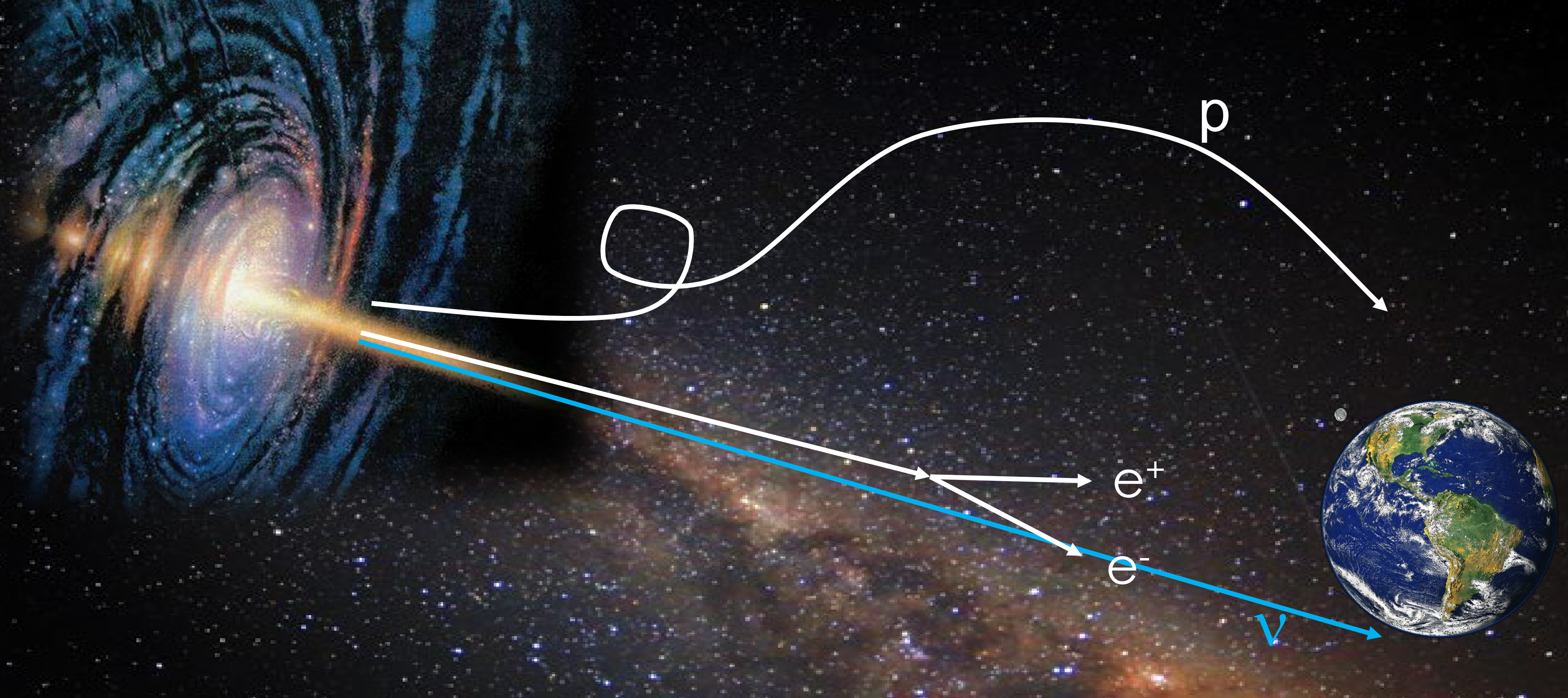
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

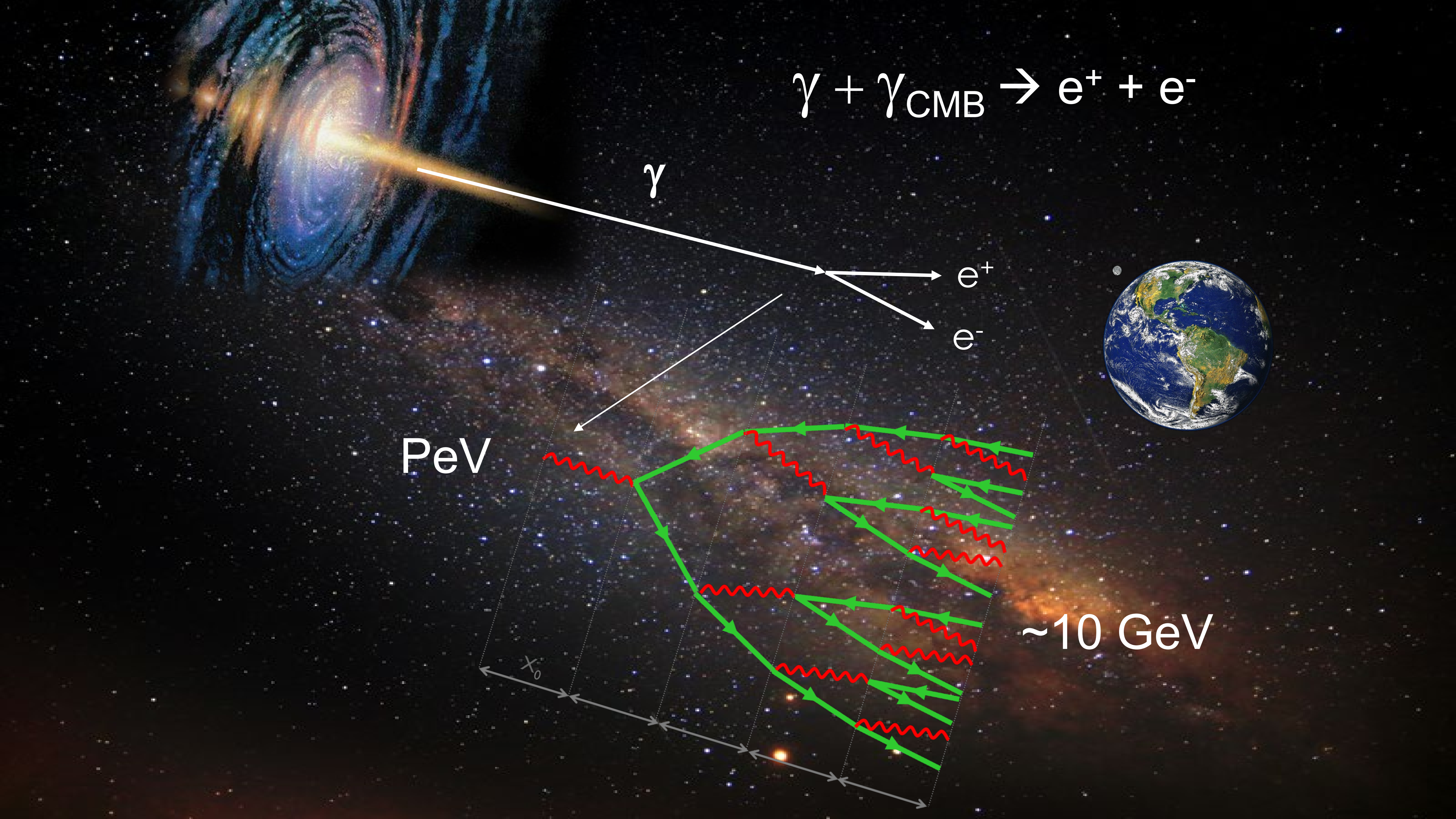
$$\rightarrow p + \pi^0$$

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

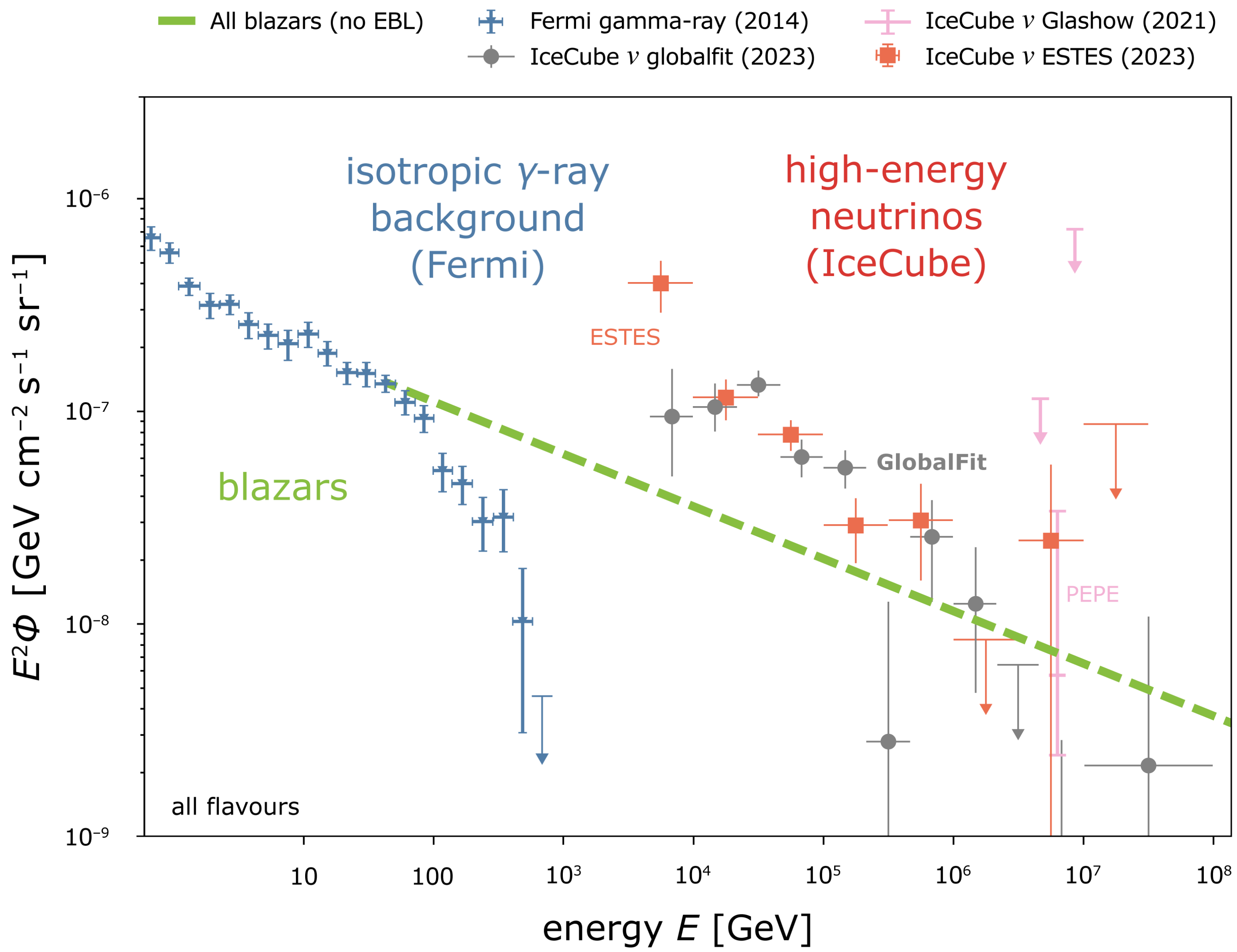
neutrinos: perfect messengers



gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

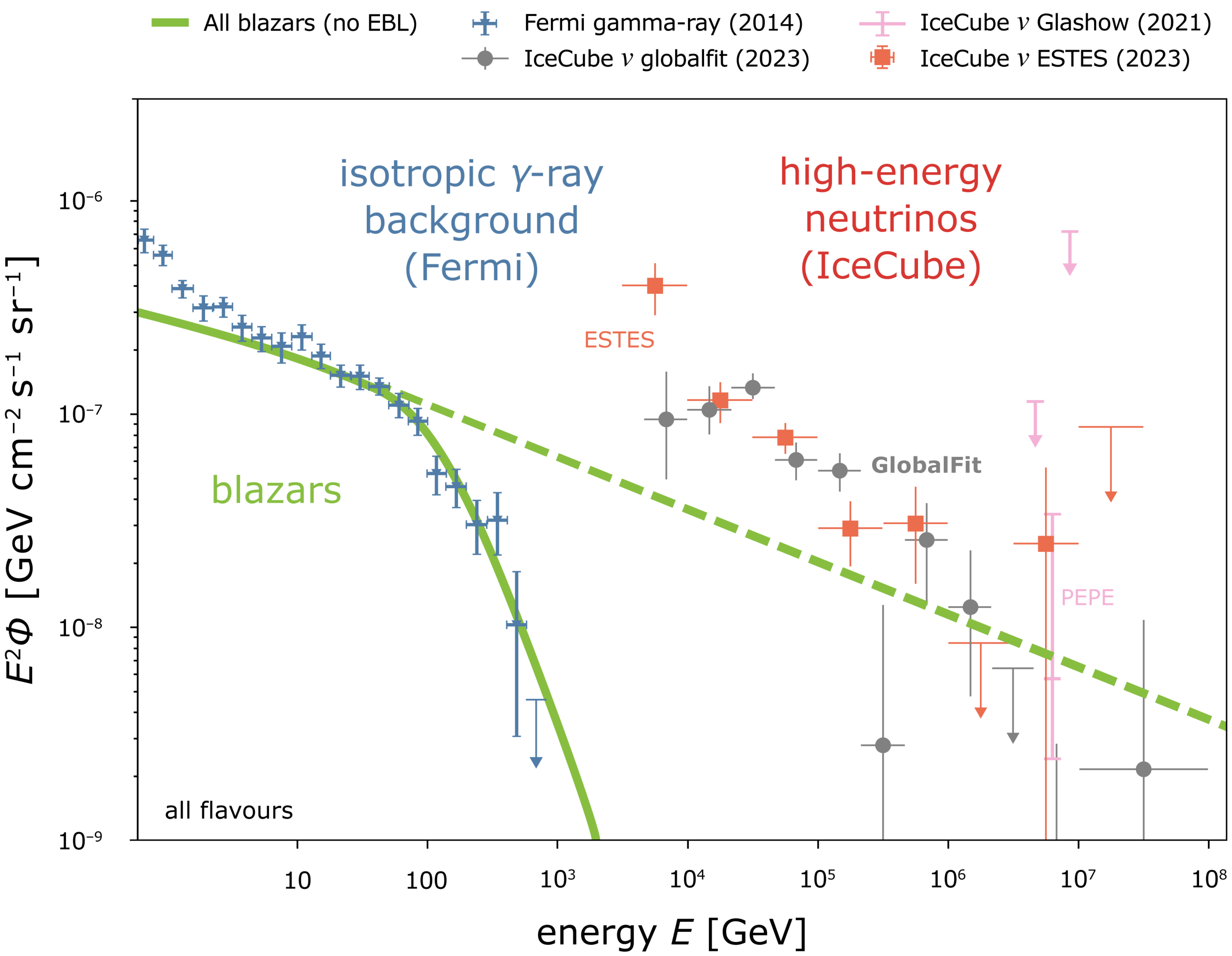


$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
~10 GeV
X_0


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
blazars
PEPE
all flavours
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
10^3
10^4
10^5
10^6
10^7
10^8
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
energy E [GeV]

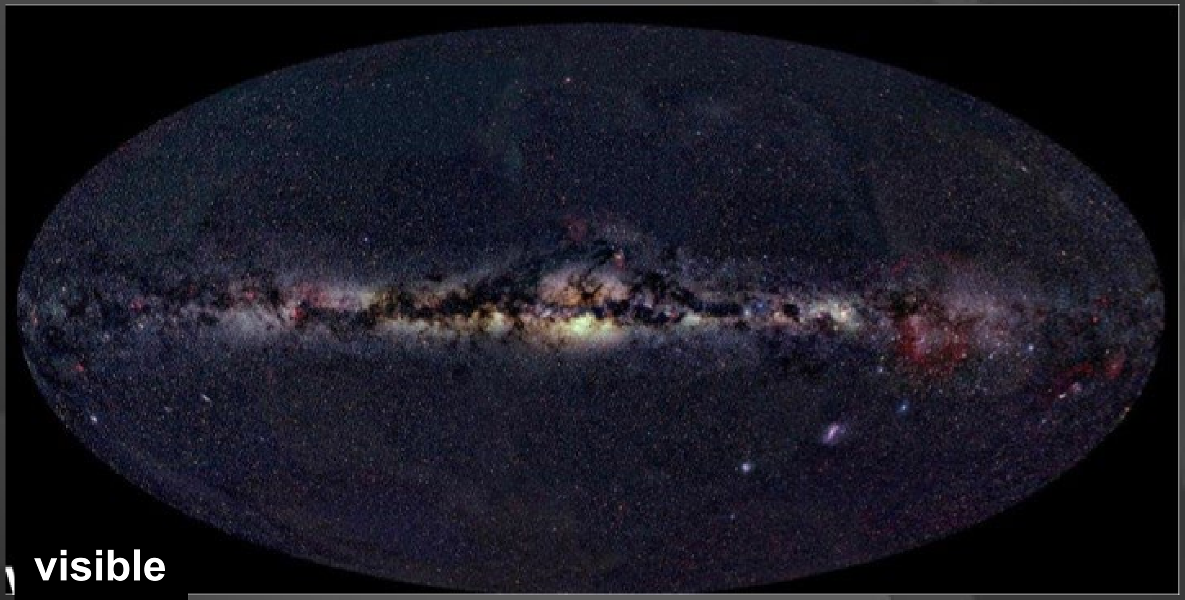
NASA Fermi satellite does not observe the gamma rays that accompany IceCube neutrinos

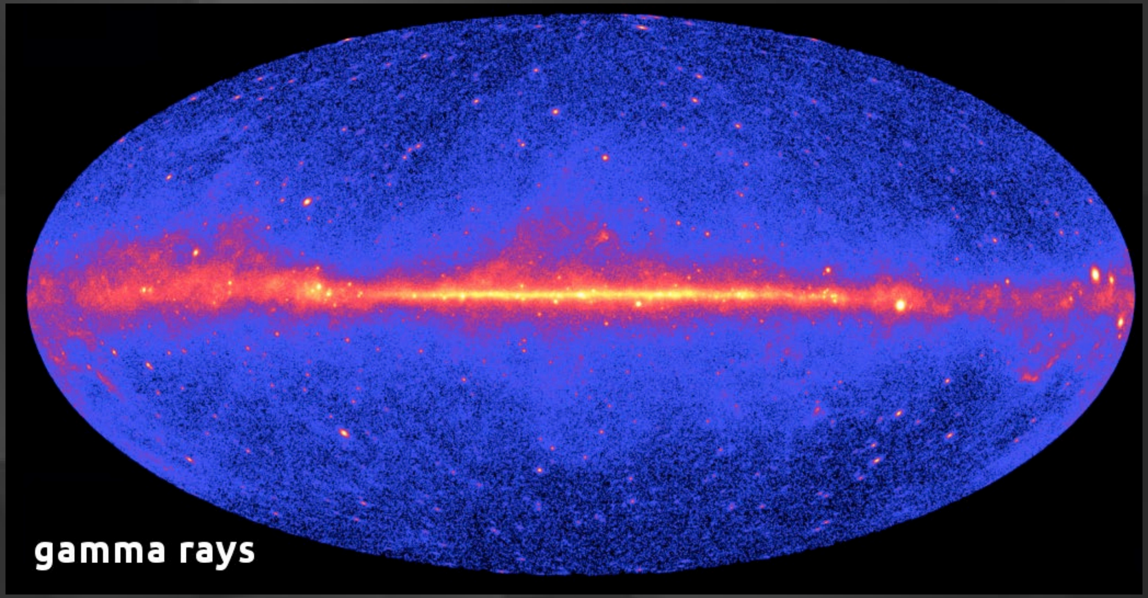
they appear at MeV energies or below



two surprises:

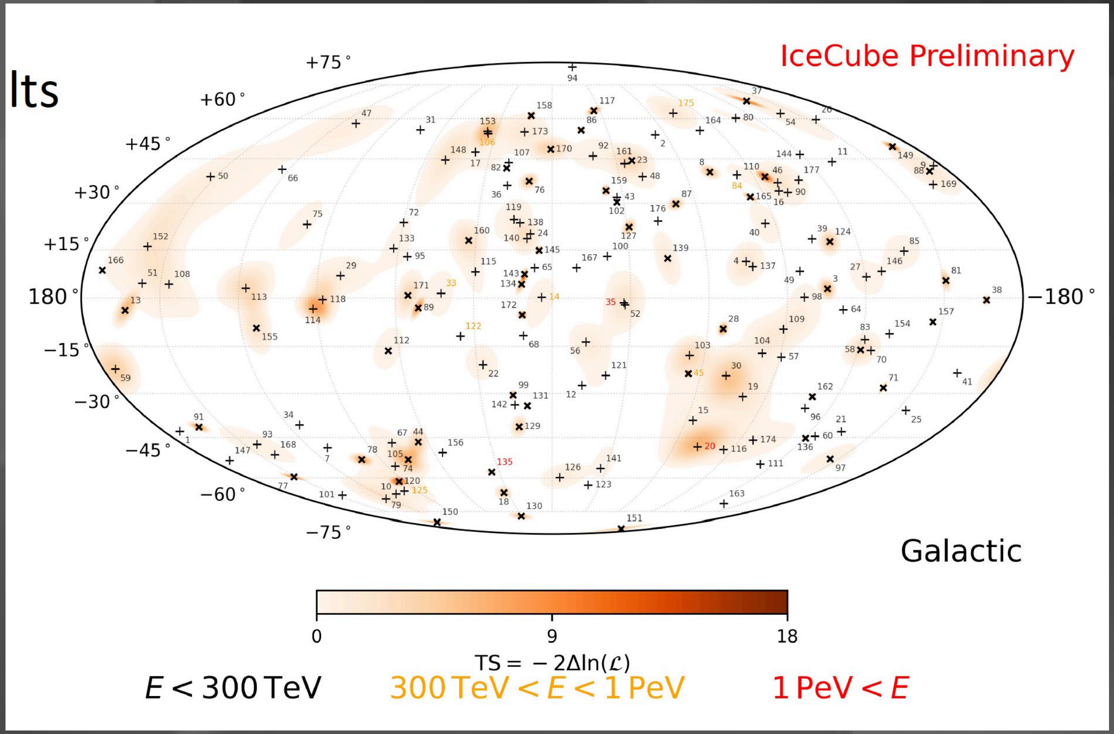
- cosmic neutrinos sources originate in a target from which gamma rays do not escape
- powerful accelerators produce neutrinos in other galaxies that do not exist in our own





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!

- populate all galaxies in the Universe with neutrino sources

- seen from Earth you should see the sources in your own galaxy first; this is geometry

- the Milky Way should dominate the sky, as is the case for all wavelengths of light

→ powerful accelerators operate in other galaxies that do not exist in our own

→ our supermassive black hole has not been active for a few million years?

Lessons from the diffuse cosmic neutrino flux:

- neutrino sources originate in a target from which gamma rays do not escape

- powerful accelerators operate produce neutrinos in other galaxies that do not exist in our own

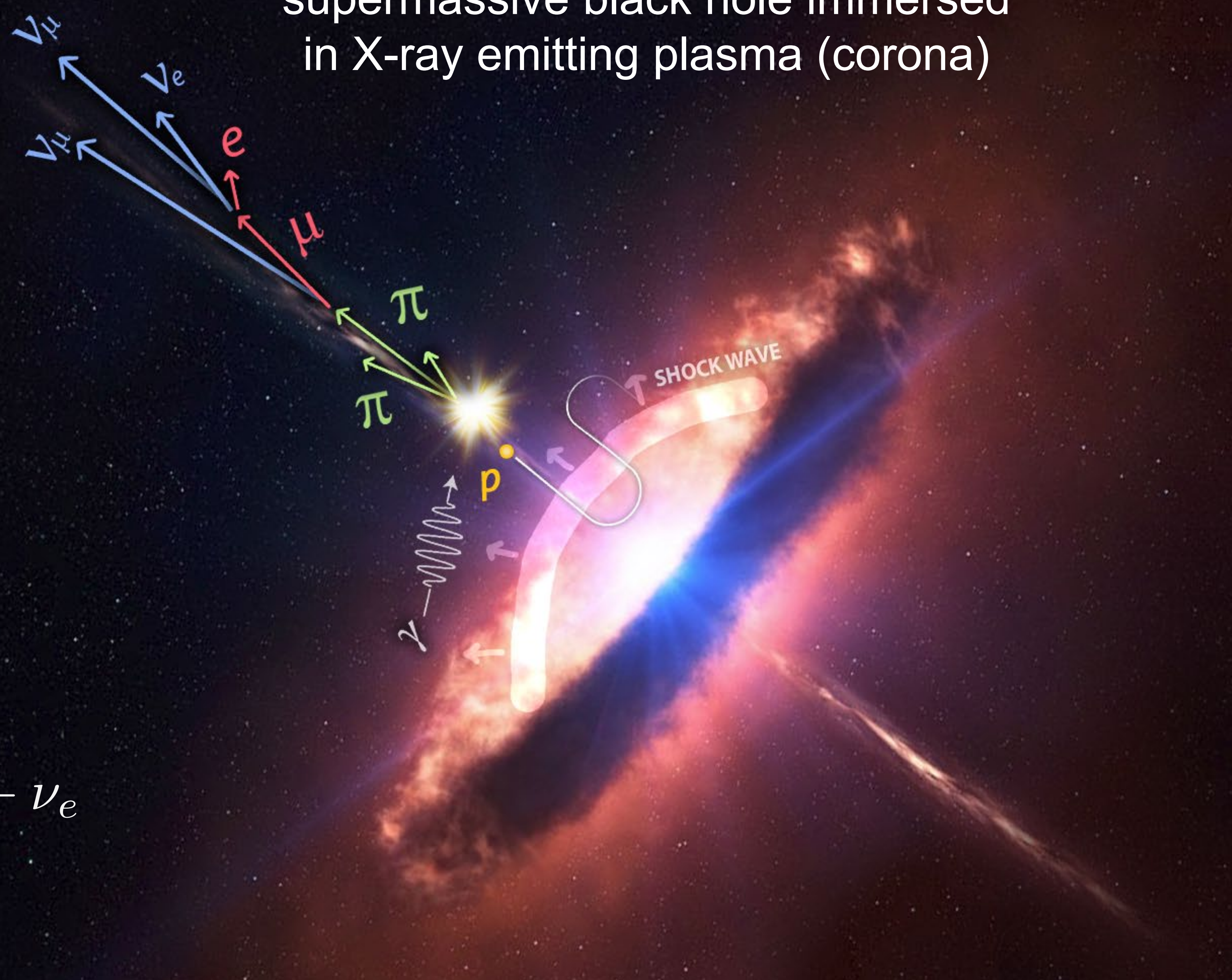
→ dense cores of active galaxies with the central supermassive black hole cannibalizing its own galaxy

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

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



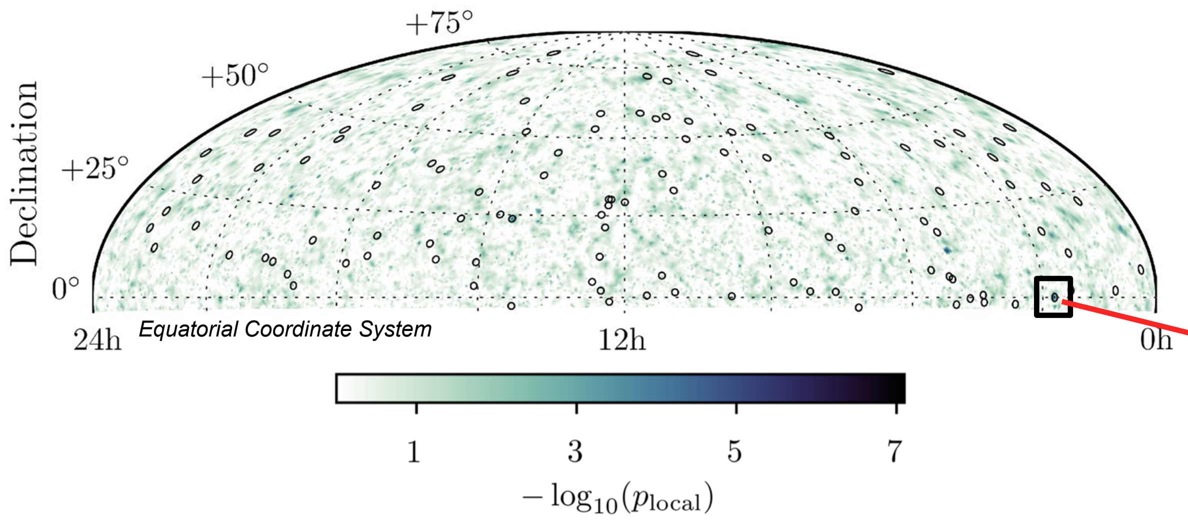
$$\pi^+ \to \mu^+ + \nu_\mu$$

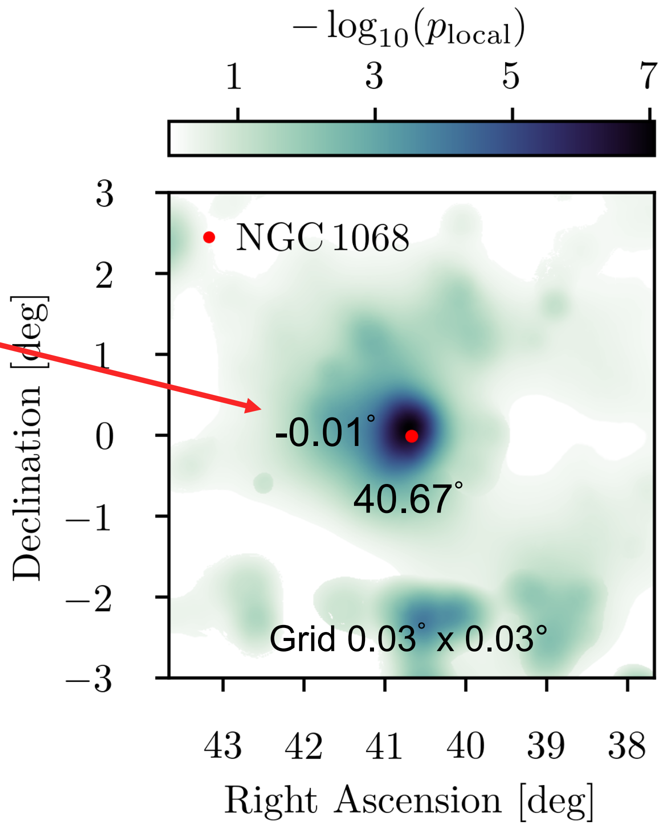
$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\pi^0 \to \gamma + \gamma$$

NGC 1068

- hotspot in the neutrino sky
- most signifiant of 110 preselected sources

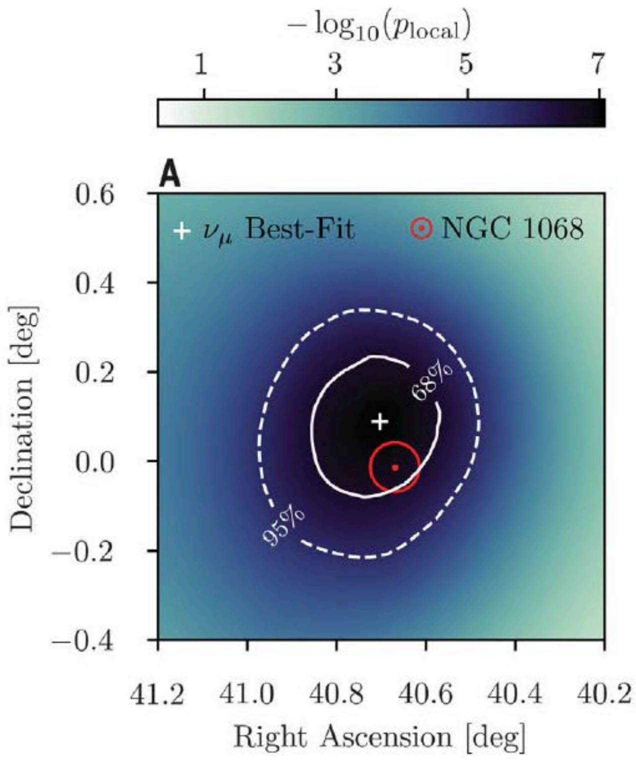


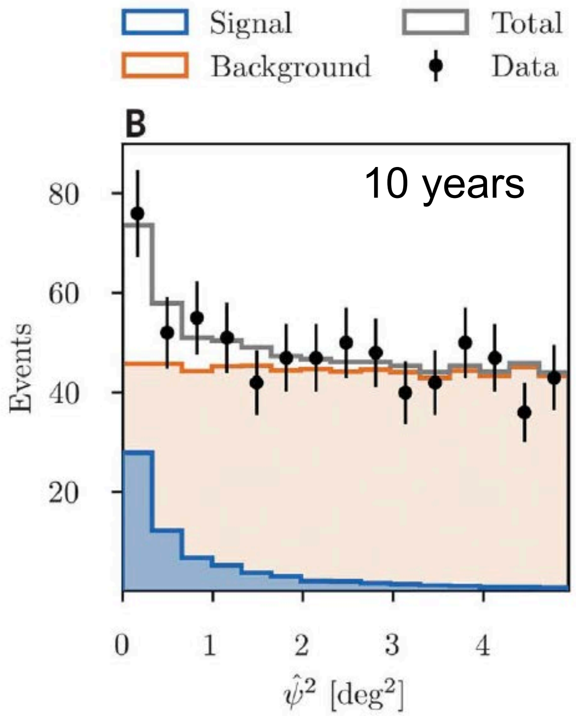


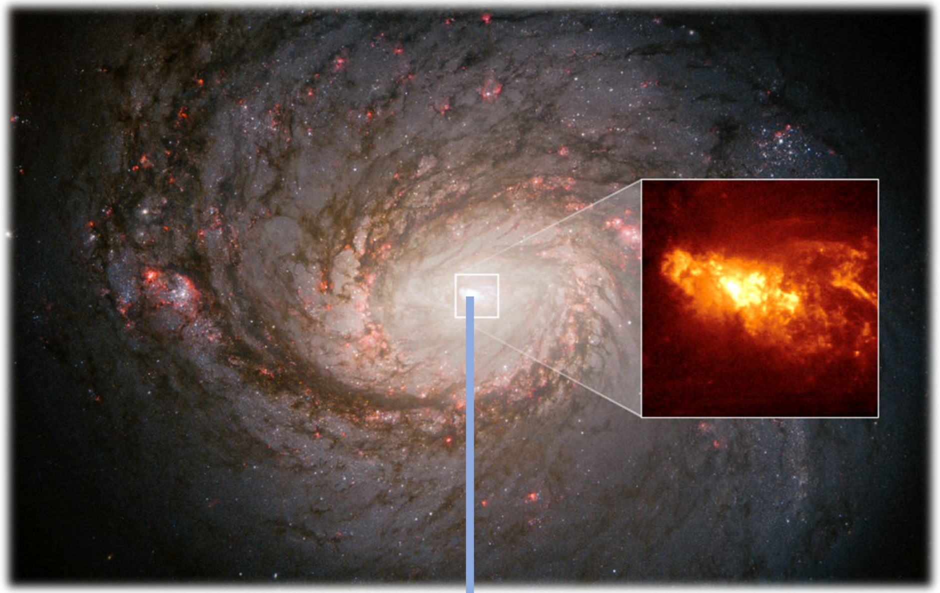
at the NGC1068 location

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

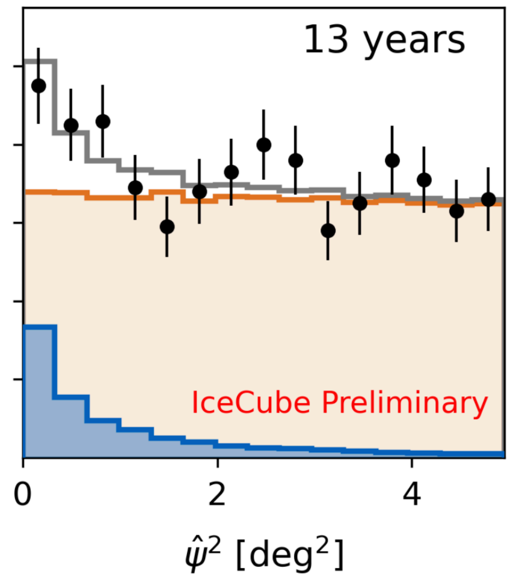
80 high-energy neutrinos from the direction of the active galaxy NGC 1068





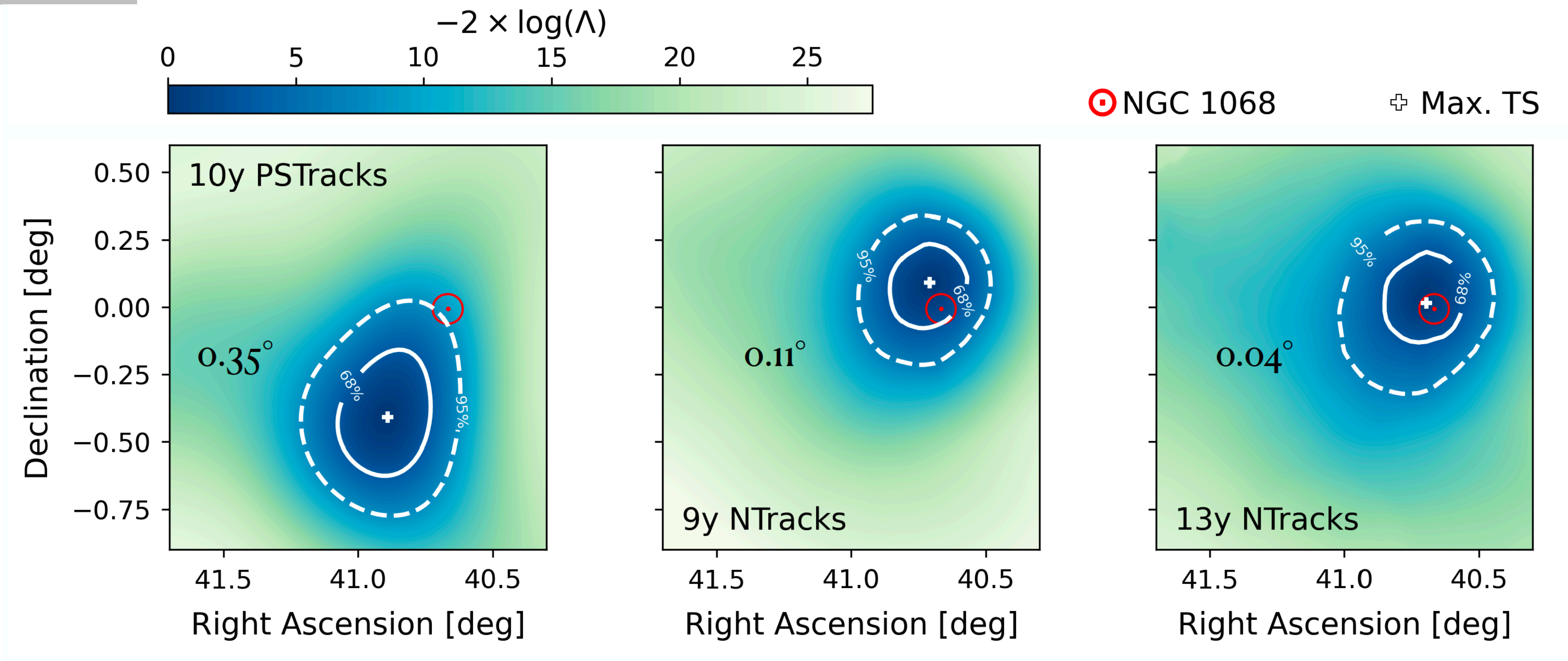


update:
80→100 neutrinos
10→13 years

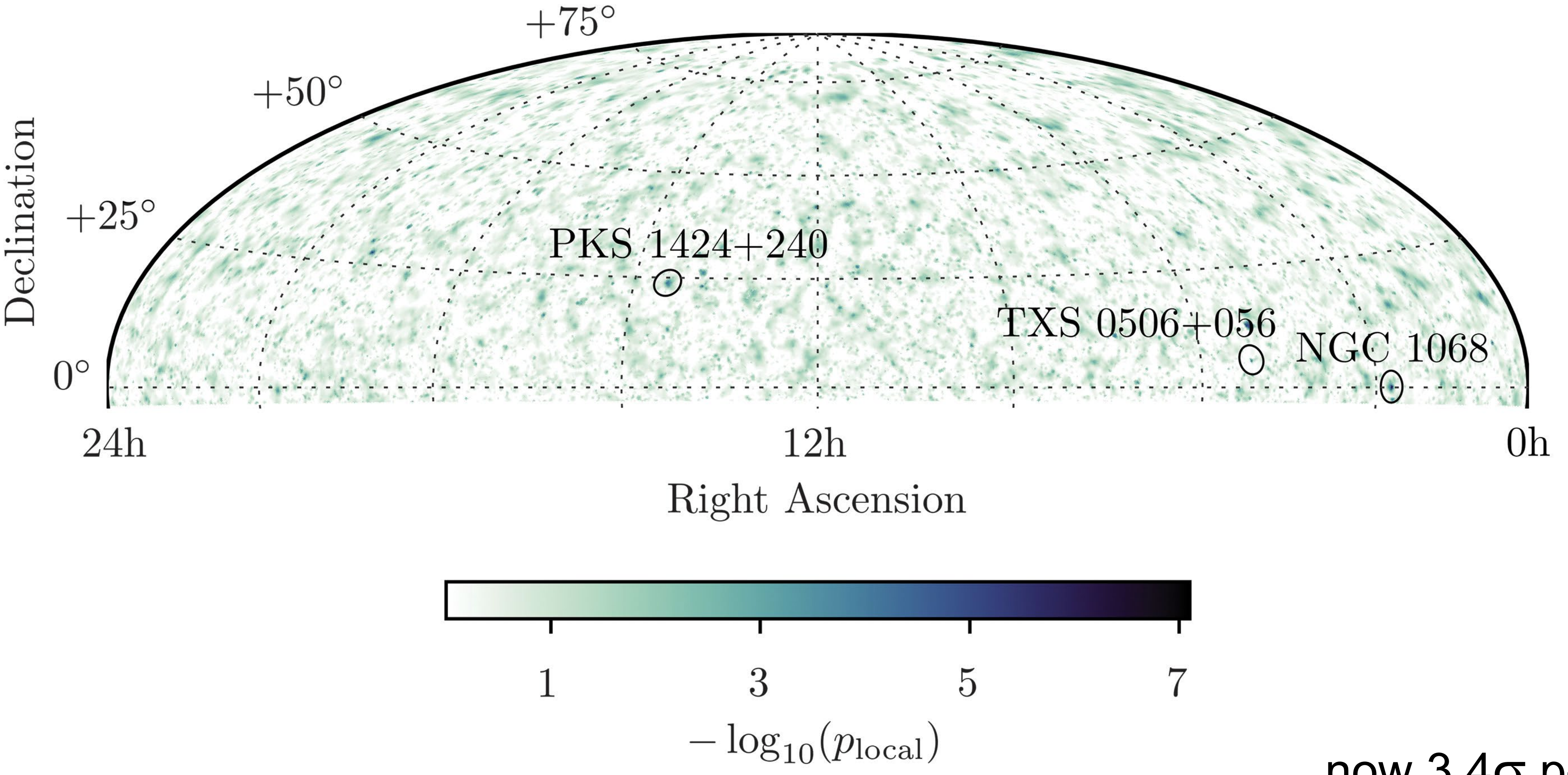


NGC 1068 comes into focus

0.35 deg → 0.1 deg → 0.04 deg



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

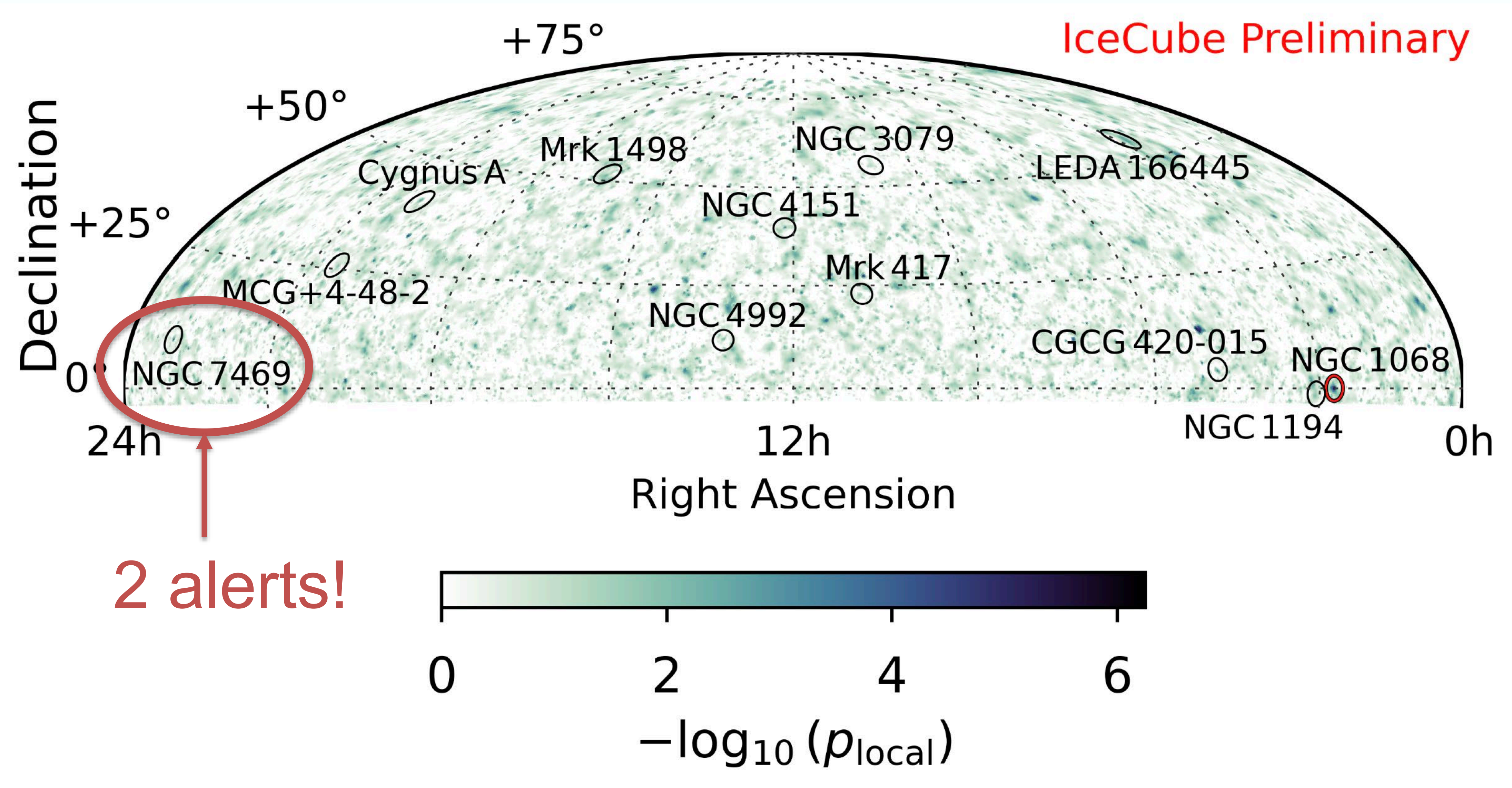
NEUTRINO ASTROPHYSICS

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

TXS 0506+056 detections

- multimessenger
- IceCube archival data
- observation optical flash



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

non-jetted X-ray sources

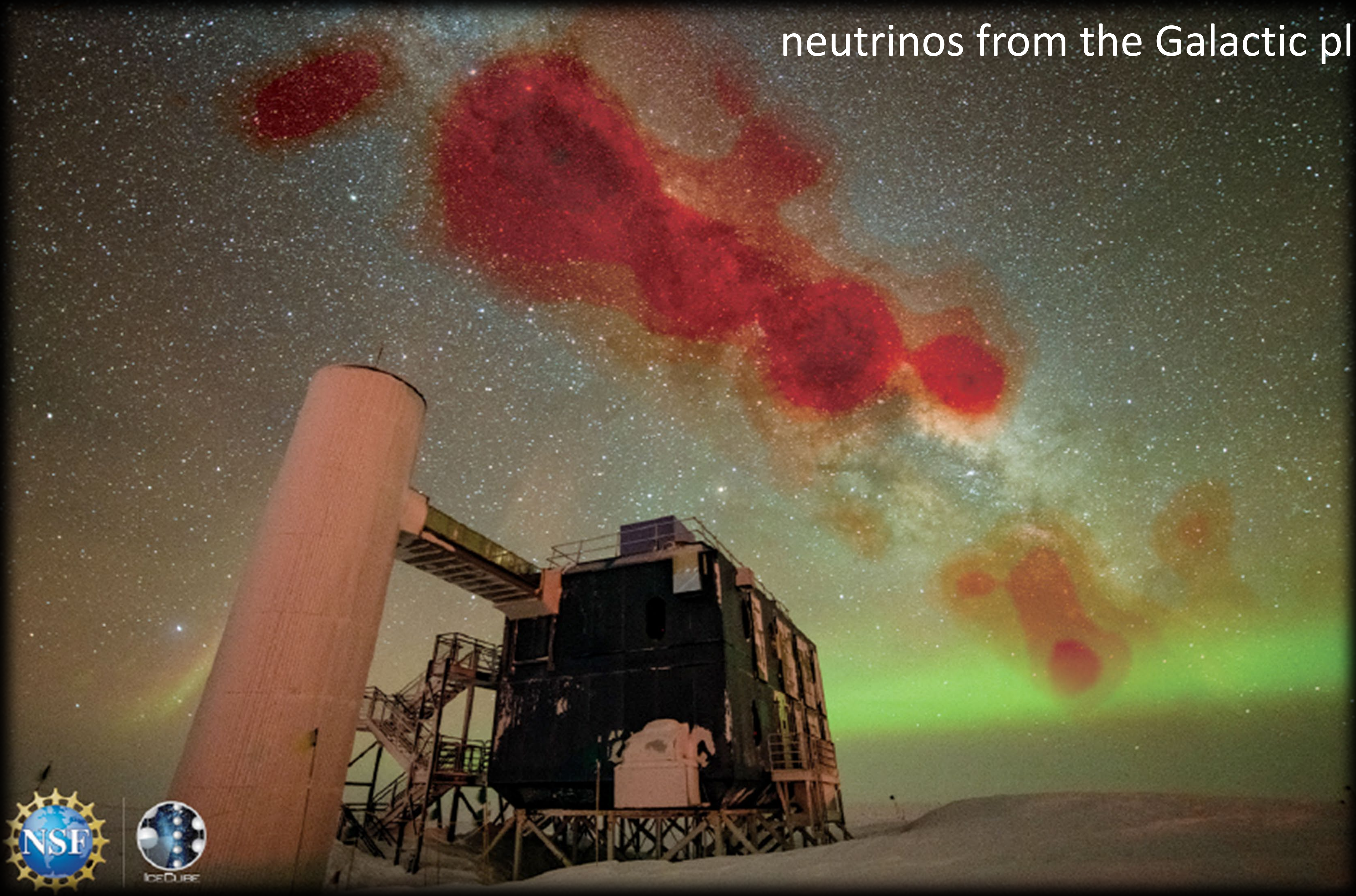
Table 1. Summary of the most significant sources from IceCube searches and the stacking result using the disc-corona model (Kheirandish et al. 2021). The table lists the best-fit number of signals ($\hat{n}_s$), spectral index ($\hat{\gamma}$), pre-trial p-value ($p$local), best-fit flux ($\phi^{1\mathrm{TeV}}_{\nu_\mu+\bar{\nu}_\mu}$), and the 90% confidence level upper limit for all analysis results. Upper limits per flavor are estimated at a normalization energy of 1 TeV with a flux spectral index of E^{-3}, in units of $\times 10^{-13}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for the power-law analysis. For model-based analyses, the expected number of signal events (n_{exp}) is listed.

	$\hat{n}_s$	$\hat{\gamma}$	p_{local}	$\phi^{1TeV}_{\nu_\mu+\bar{\nu}_\mu}$	90% U.L.
NGC 1068[1]	81.7	3.1	1.27×10^{-6} ($4.7\,\sigma$)	4.02×10^{-11}	–
NGC 4151[1]	49.8	2.83	3.99×10^{-5} ($3.9\,\sigma$)	1.51×10^{-11}	–
NGC 3079[1]	29.53	4.0	0.003 ($2.7\,\sigma$)	–	203.50
CGCG 420-015[2]	35	2.8	0.003 ($2.7\,\sigma$)	–	25.9
Circinus Galaxy[3]	3.1	2.5	0.001 ($3.1\,\sigma$)	–	63.80
Stacked sources				n_{exp}	n_{event}
13 sources (Southern sky)[3]	6.7	–	0.0013 ($3.0\,\sigma$)	4.7	14.3

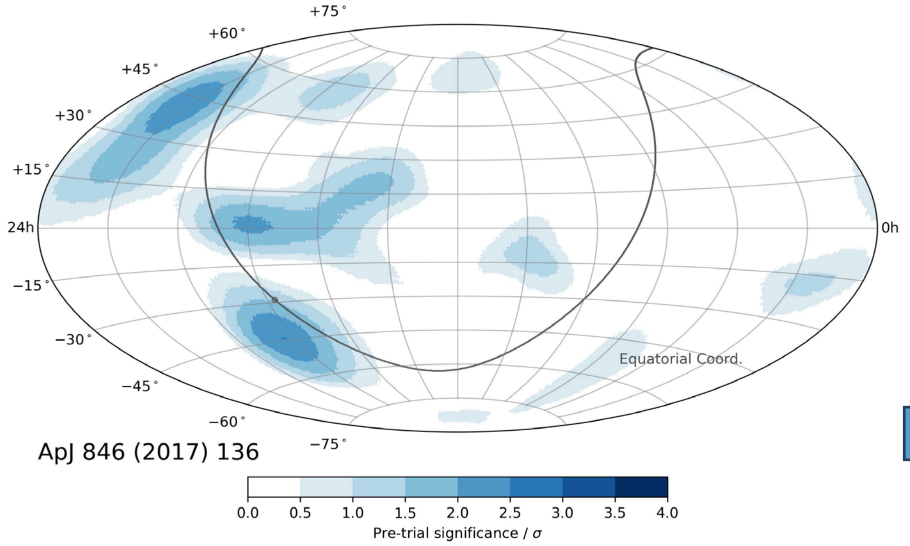
[1] R.A. et al. (2024), [2] Abbasi et al. (2024c), [3] Yu et al. (2024)

but also TXS 0506+056

neutrinos from the Galactic plane !

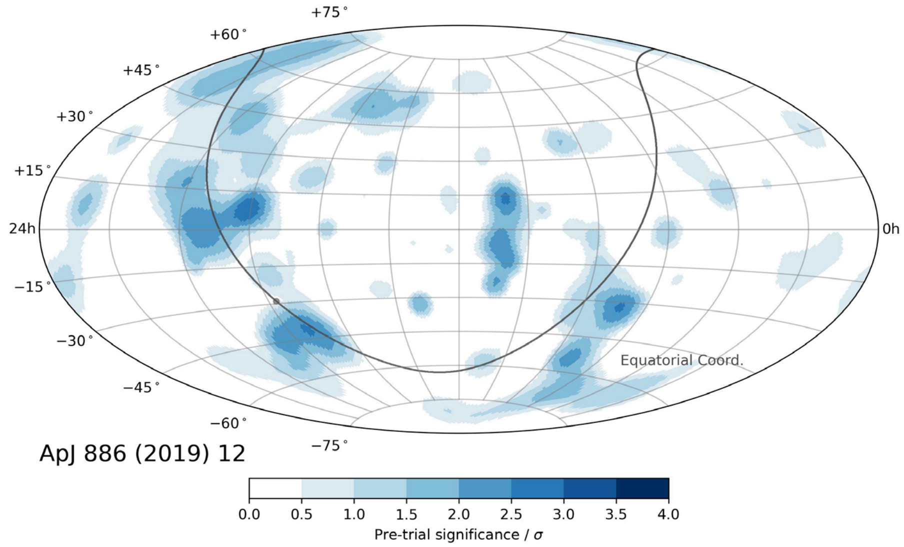


2017 paper



ApJ 846 (2017) 136

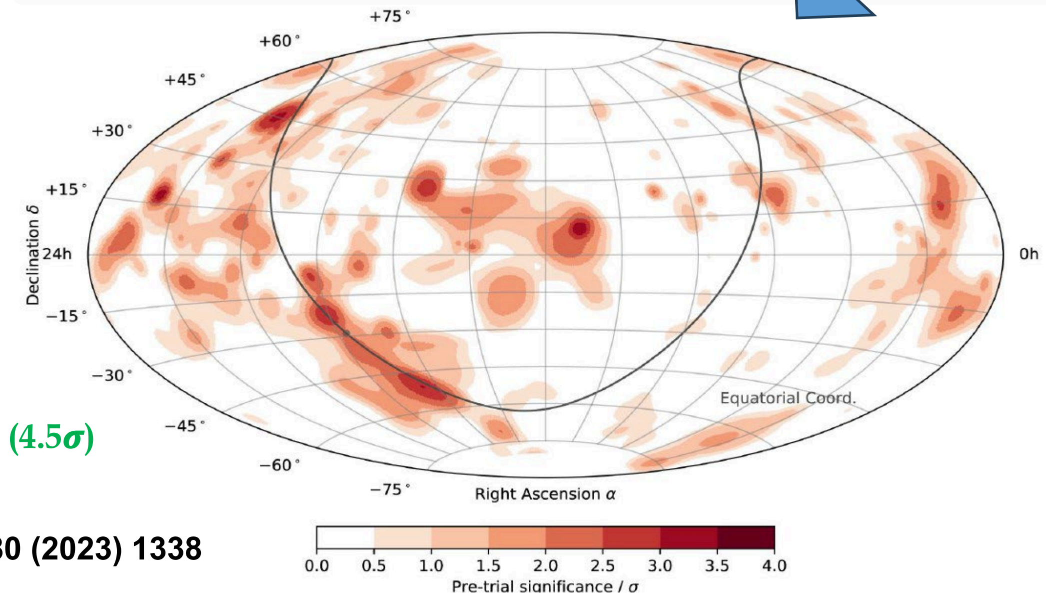
2019 paper



ApJ 886 (2019) 12

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

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



Deep learning improved resolution by ~2, sensitivity ~3

10 years of data
Galactic Plane p-value: 0.0004% (4.5σ)

Science 380 (2023) 1338

In astrophysics and astronomy, ANNs have also become a standard data analysis tool. A recent example is an ANN-driven analysis of data from the IceCube neutrino detector at the South Pole, which resulted in a neutrino image of the Milky Way [47]. Exoplanet transits have been identified by the Kepler Mission using ANNs [48]. The Event Horizon Telescope image of the black hole at the centre of the Milky Way used ANNs for data processing [49].

Scientific Background to the Nobel Prize in Physics 2024

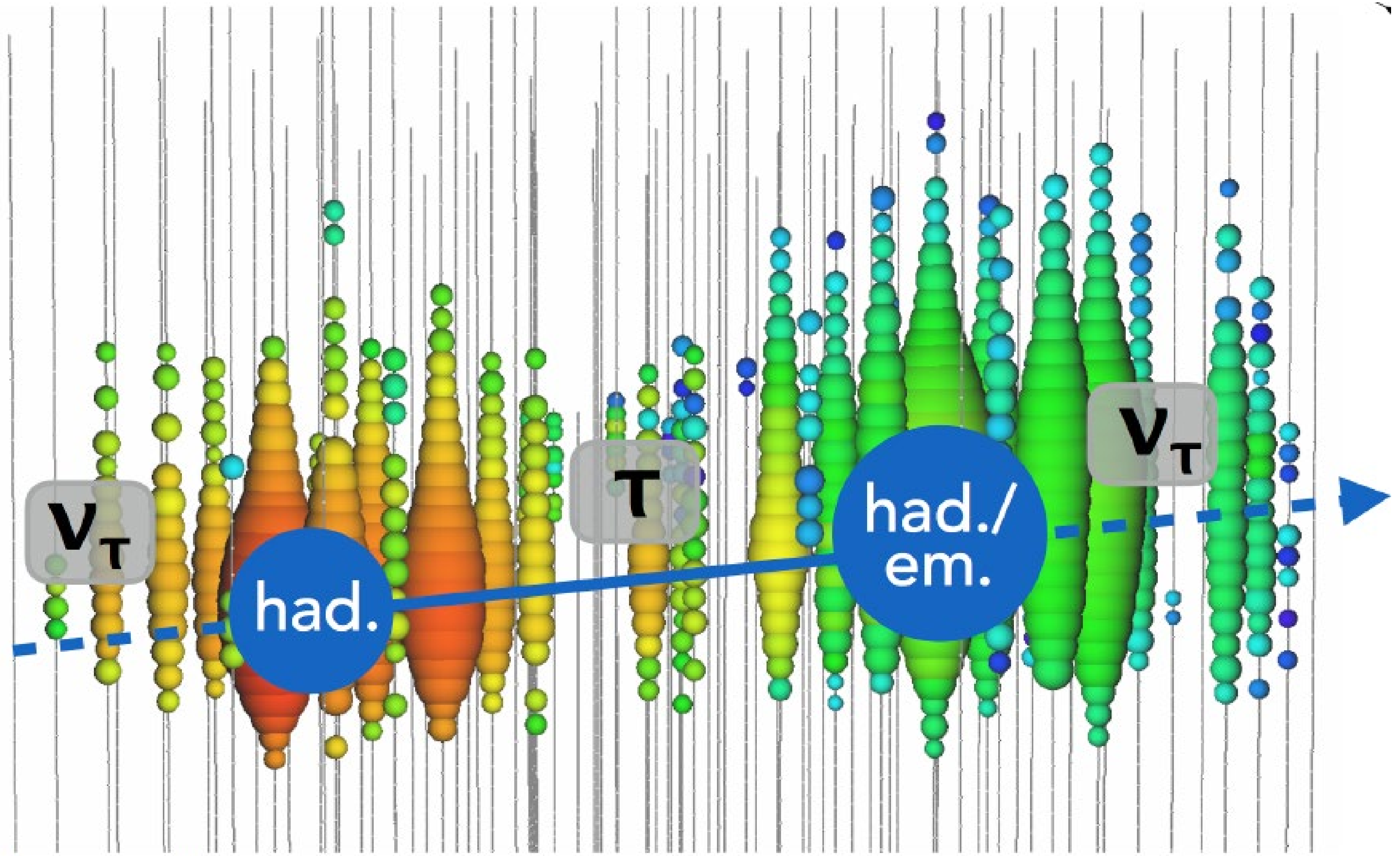
“FOR FOUNDATIONAL DISCOVERIES AND INVENTIONS THAT ENABLE MACHINE LEARNING WITH ARTIFICIAL NEURAL NETWORKS”

Detecting tau-neutrino oscillations at PeV energies #1

John G. Learned (Hawaii U.), Sandip Pakvasa (Hawaii U.) (Aug, 1994)

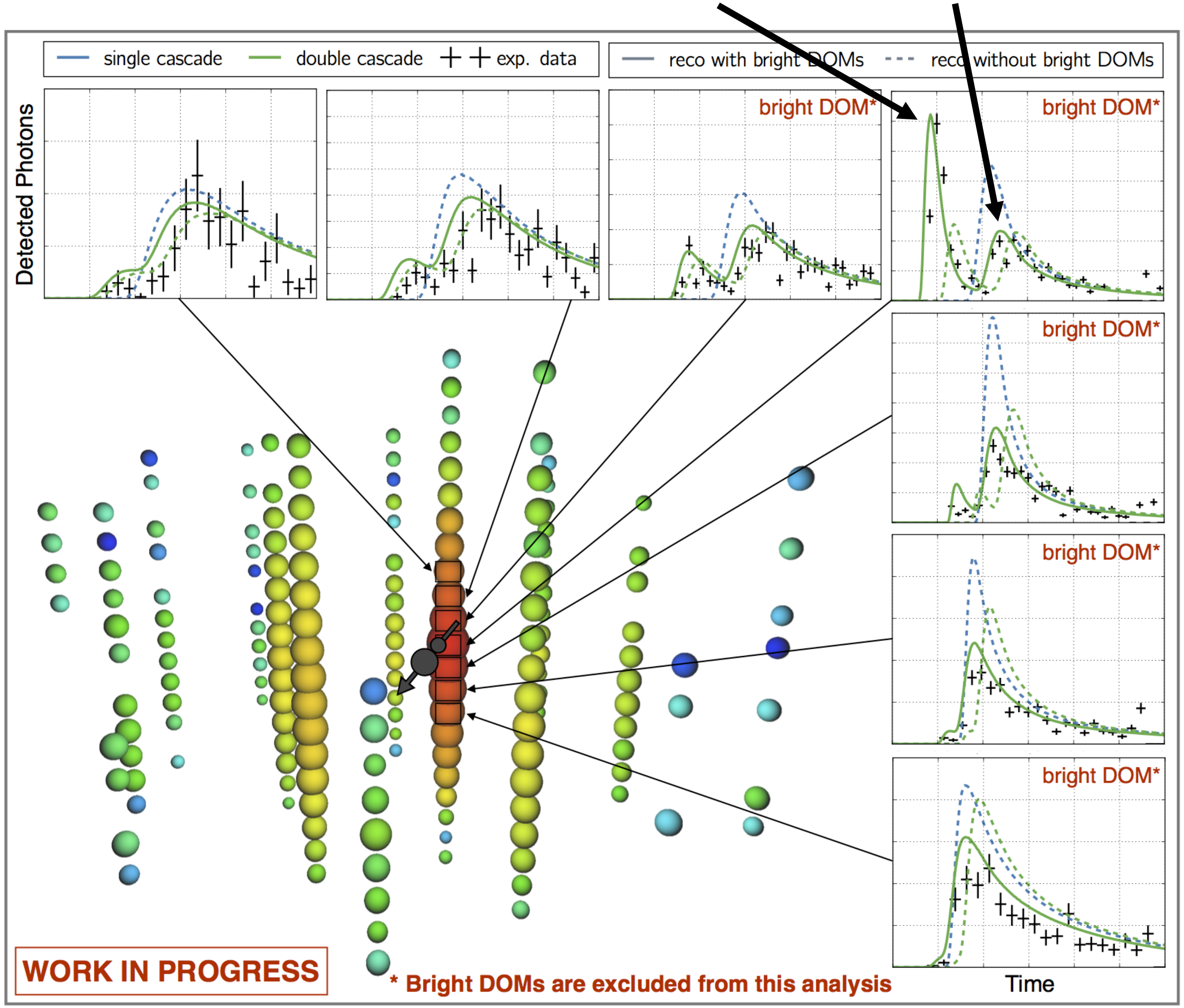
Published in: *Astropart.Phys.* 3 (1995) 267-274 • e-Print: hep-ph/9405296 [hep-ph], hep-ph/9408296

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

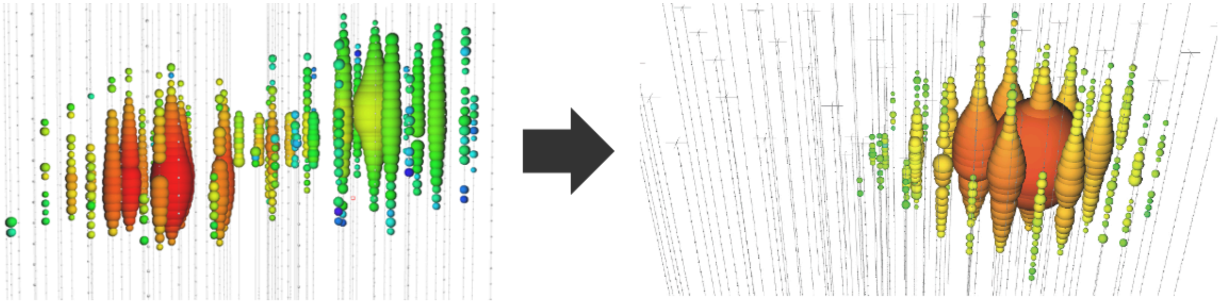


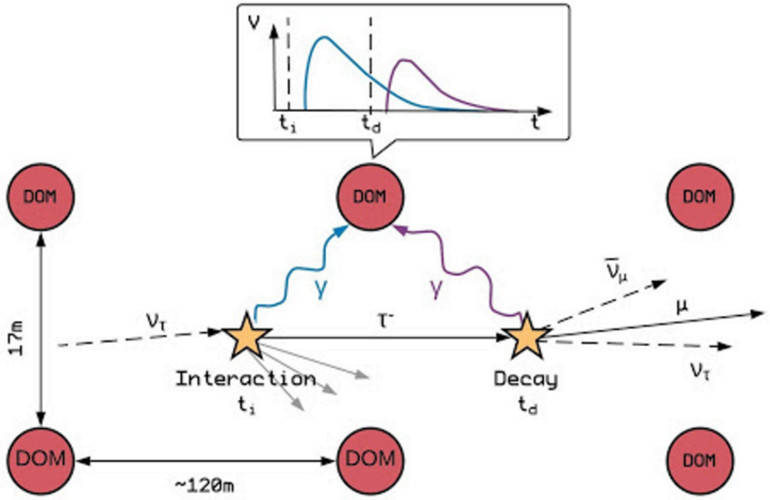
a cosmic tau neutrino with 17m lifetime

light from nutau interaction and tau decay

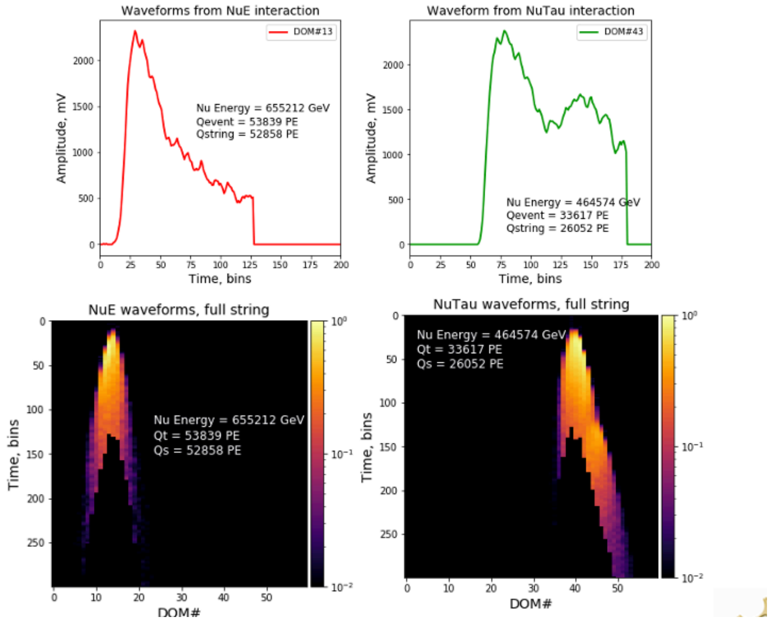


Astrophysical Tau Neutrino Search





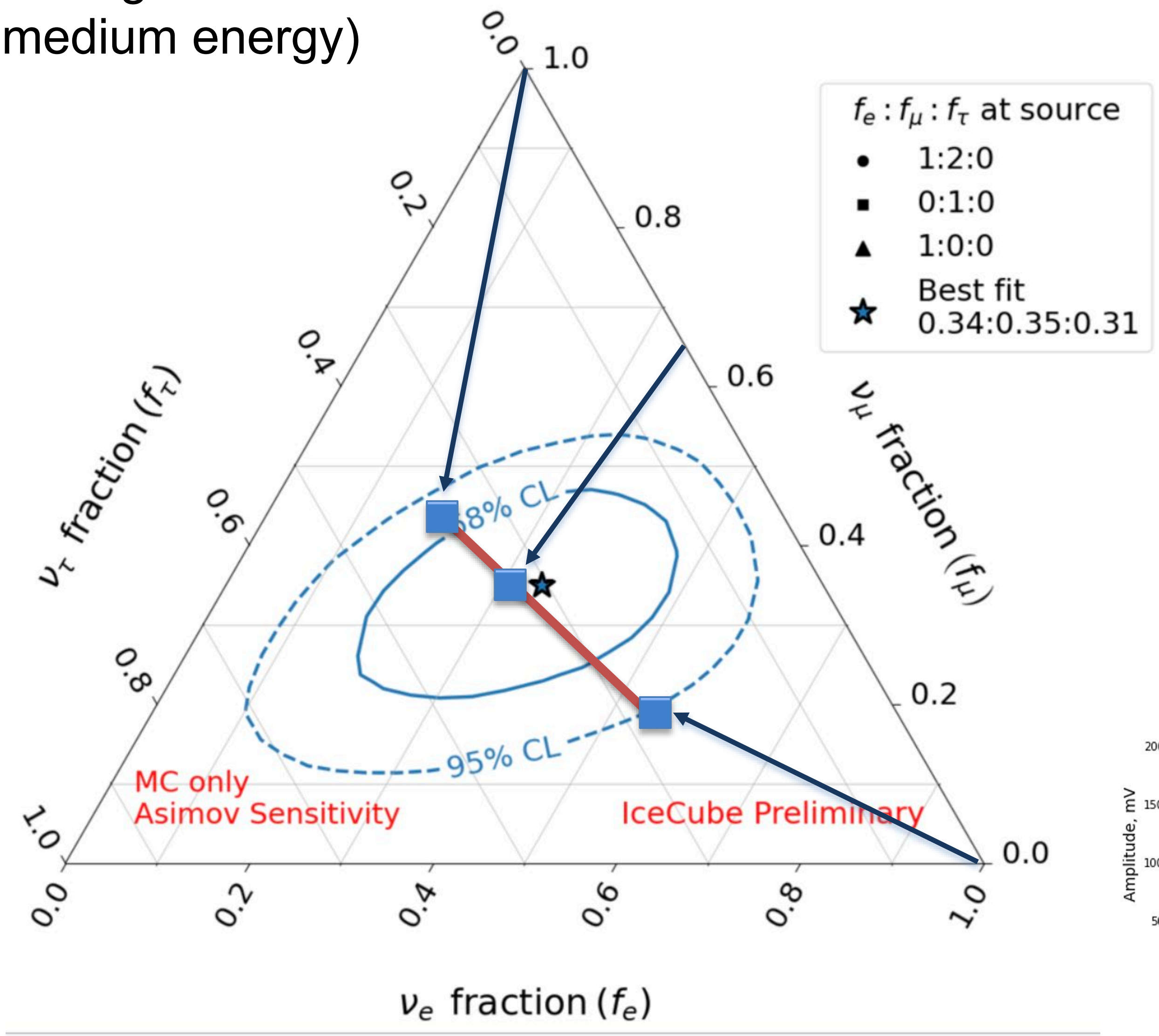
- TeV – O(1) PeV Tau neutrinos look like Electron neutrinos due to sparse instrumentation
- Differentiation by shape of waveform in a given module, i.e. two waveforms in the same module offset by a certain quantity
- Create an image (2D histogram) of the charge distribution in time along a string
- CNN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



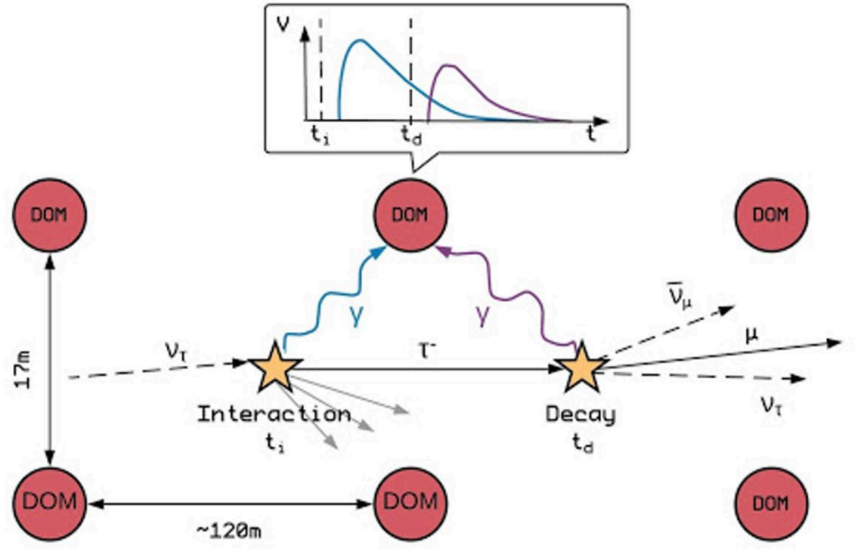
→ Standard Model: 8 expected on a background of 1 and 7 found for a flavor ratio 1:1:1

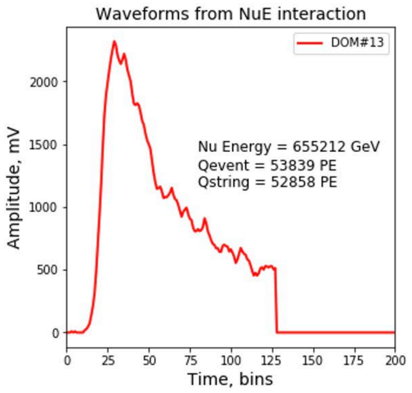
- oscillations of PeV neutrinos over cosmic distances to 1:1:1
- high energy (> PeV) nutau neutrinos are of cosmic origin

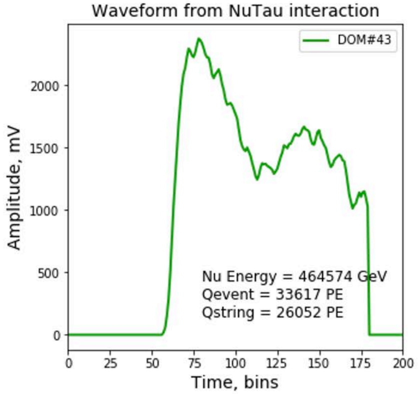
starting events
(medium energy)

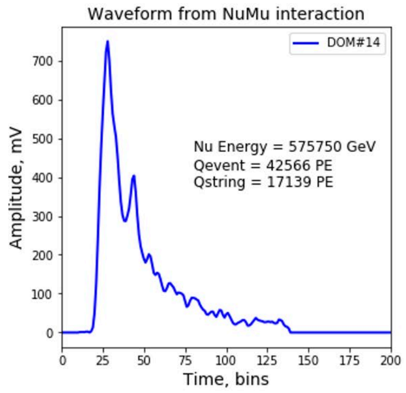


machine learning
PMT signals

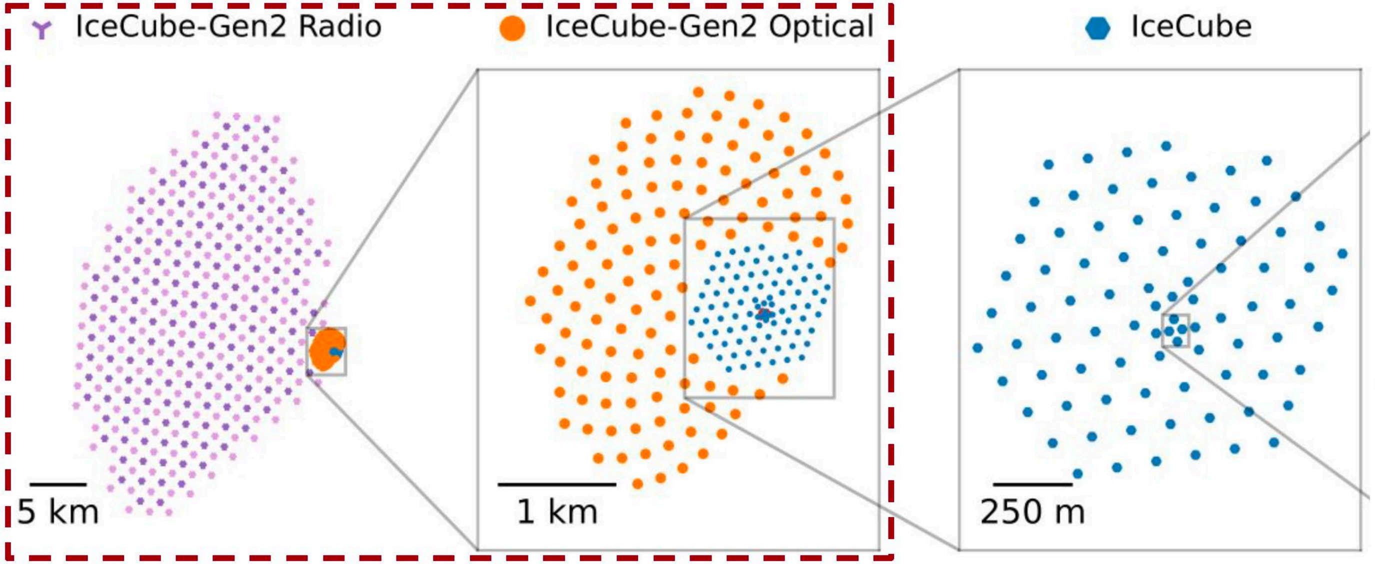


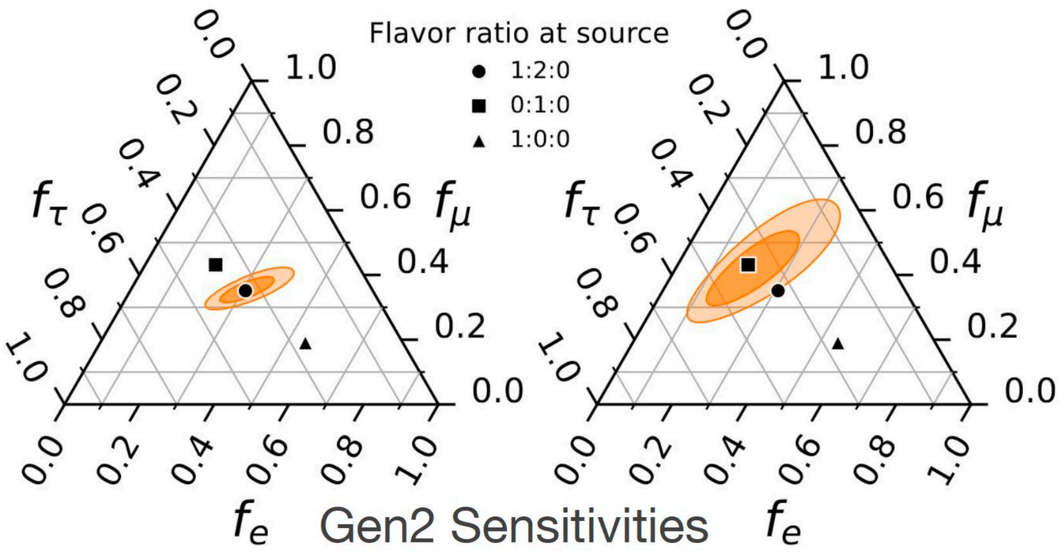






The next generation of IceCube: IceCube-Gen2



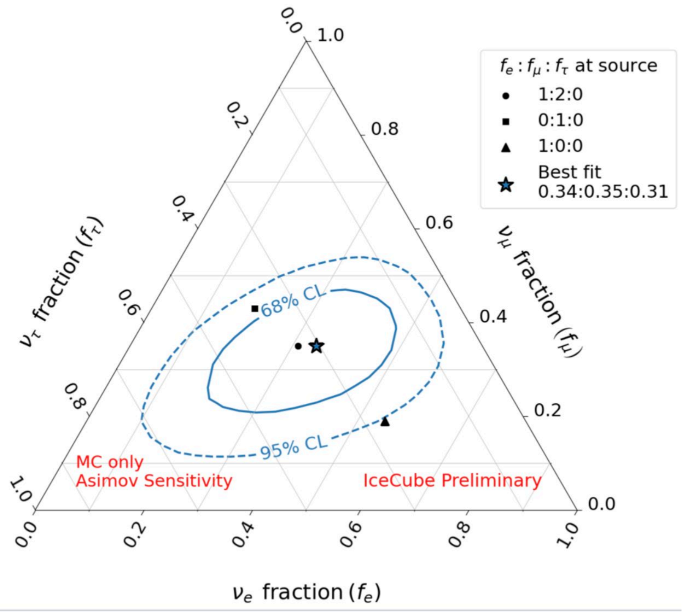


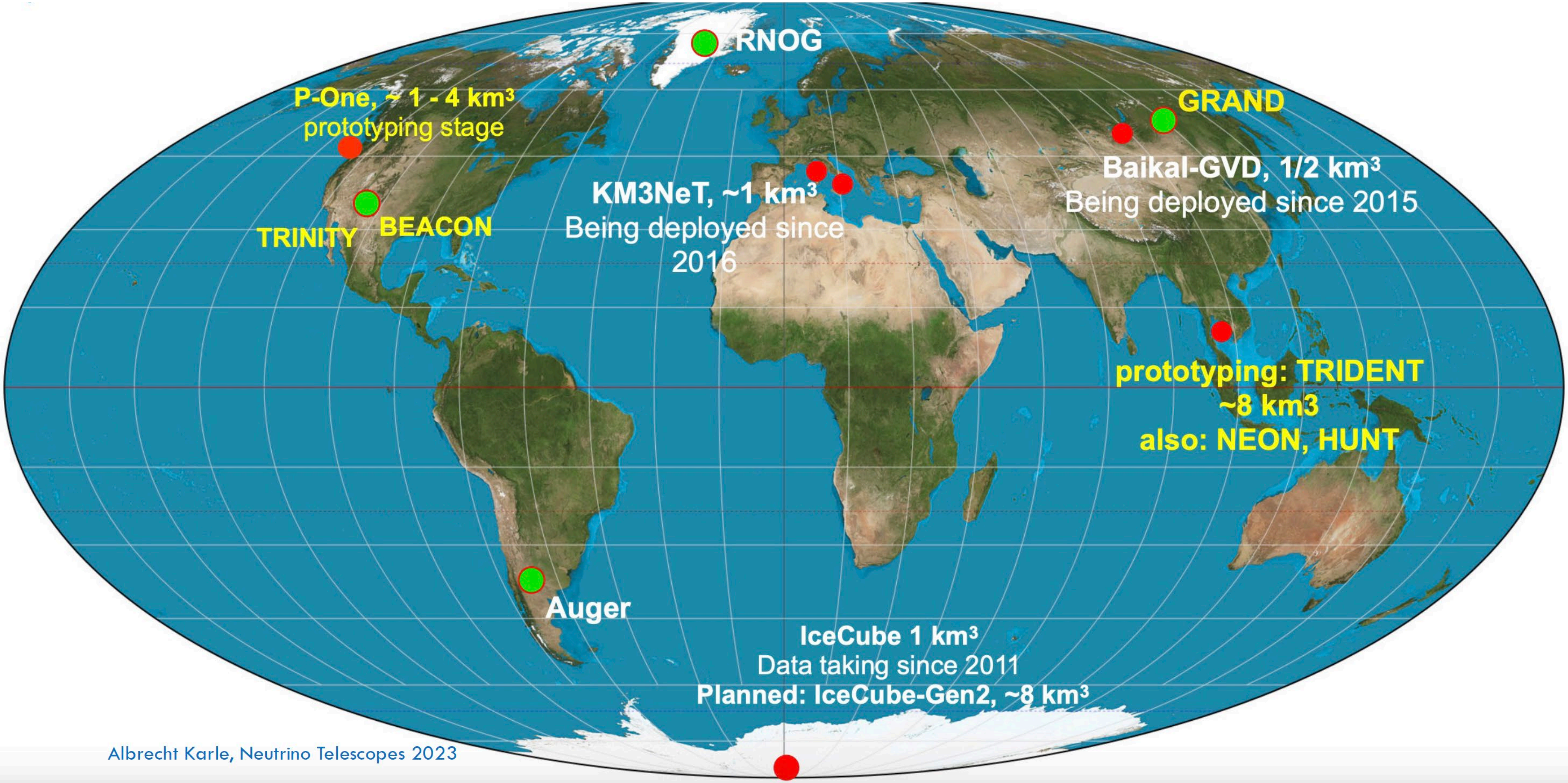
IceCube-Gen2

- Increase effective volume
- Increase upper energy threshold

Goals:

- Measure neutrino flux at extreme energies (PeV+)
- Improve sensitivity to astrophysical neutrino sources by factor of ~5

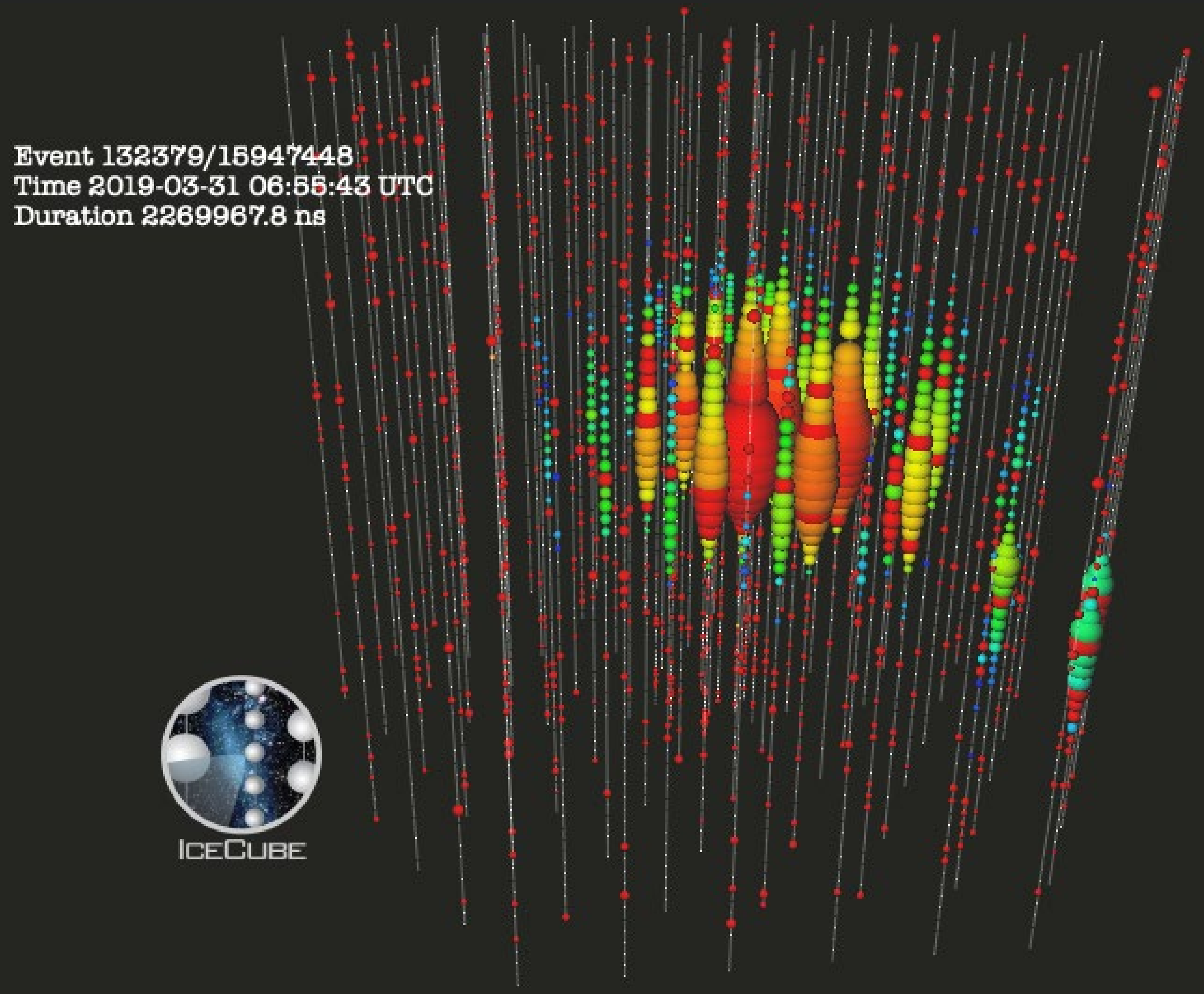



RNOG
P-One, ~ 1 - 4 km³
prototyping stage
GRAND
Baikal-GVD, 1/2 km³
Being deployed since 2015
KM3NeT, ~1 km³
Being deployed since 2016
TRINITY
BEACON
prototyping: TRIDENT
~8 km3
also: NEON, HUNT
Auger
IceCube 1 km³
Data taking since 2011
Planned: IceCube-Gen2, ~8 km³

Uncharted Territory

$E_{\nu} = 220$ PeV

IC190331: 5300 TeV deposited inside the detector

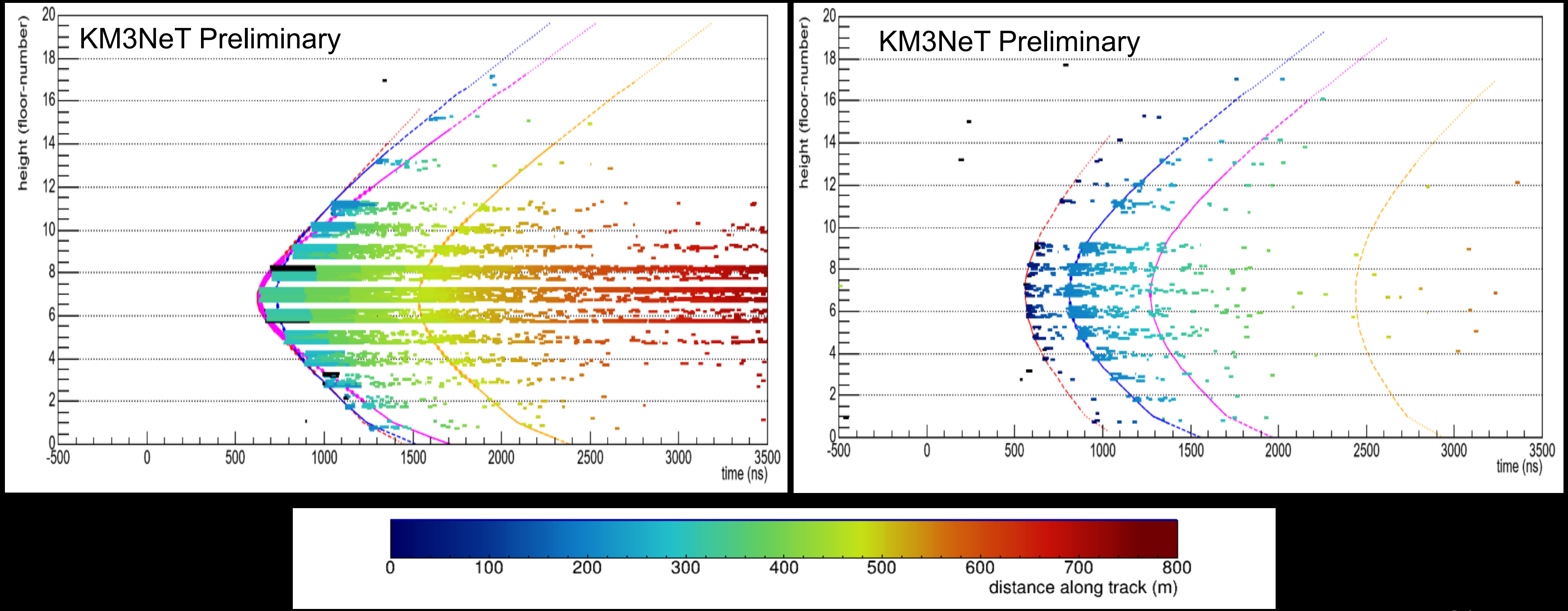


initial neutrino energy 11.4 pm 2.5 PeV

overflow slides

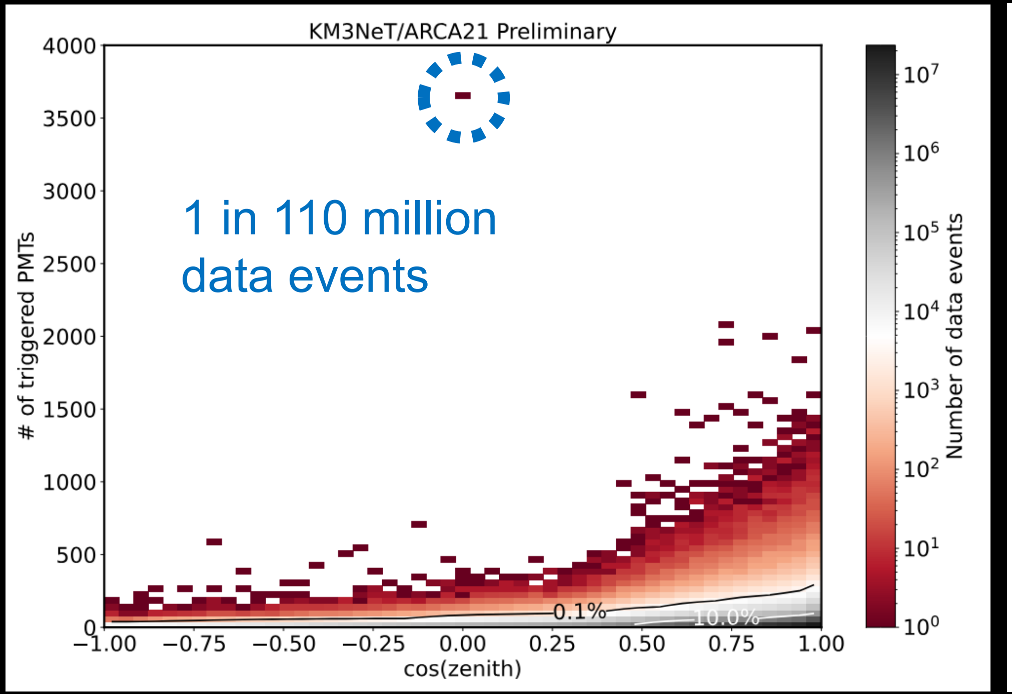
Uncharted Territory

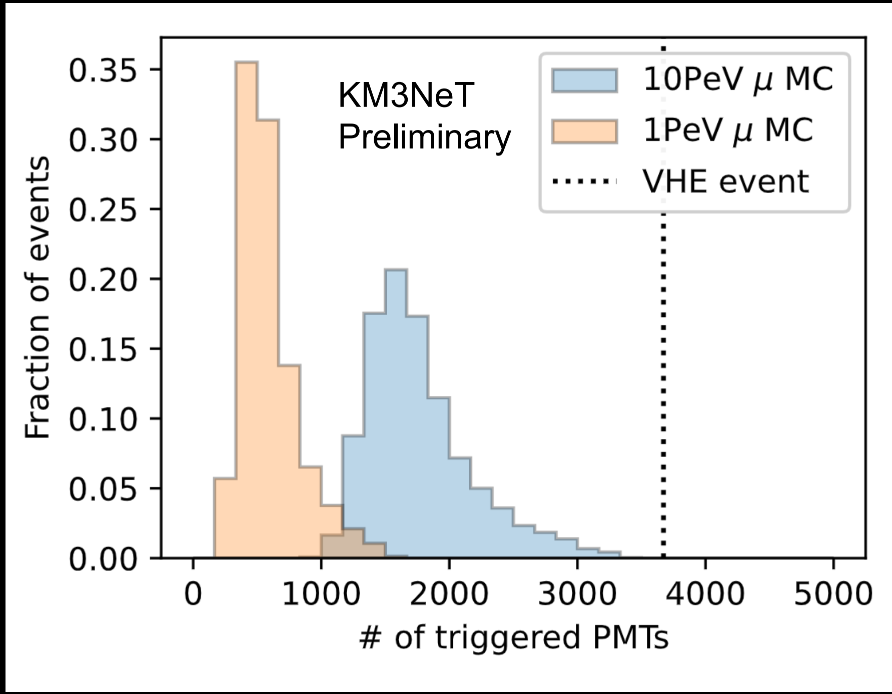
- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons
- Space-time distribution of light consistent with shower hypothesis associated with these energy depositions
- Low scattering is key to observing this richness of detail



Uncharted Territory

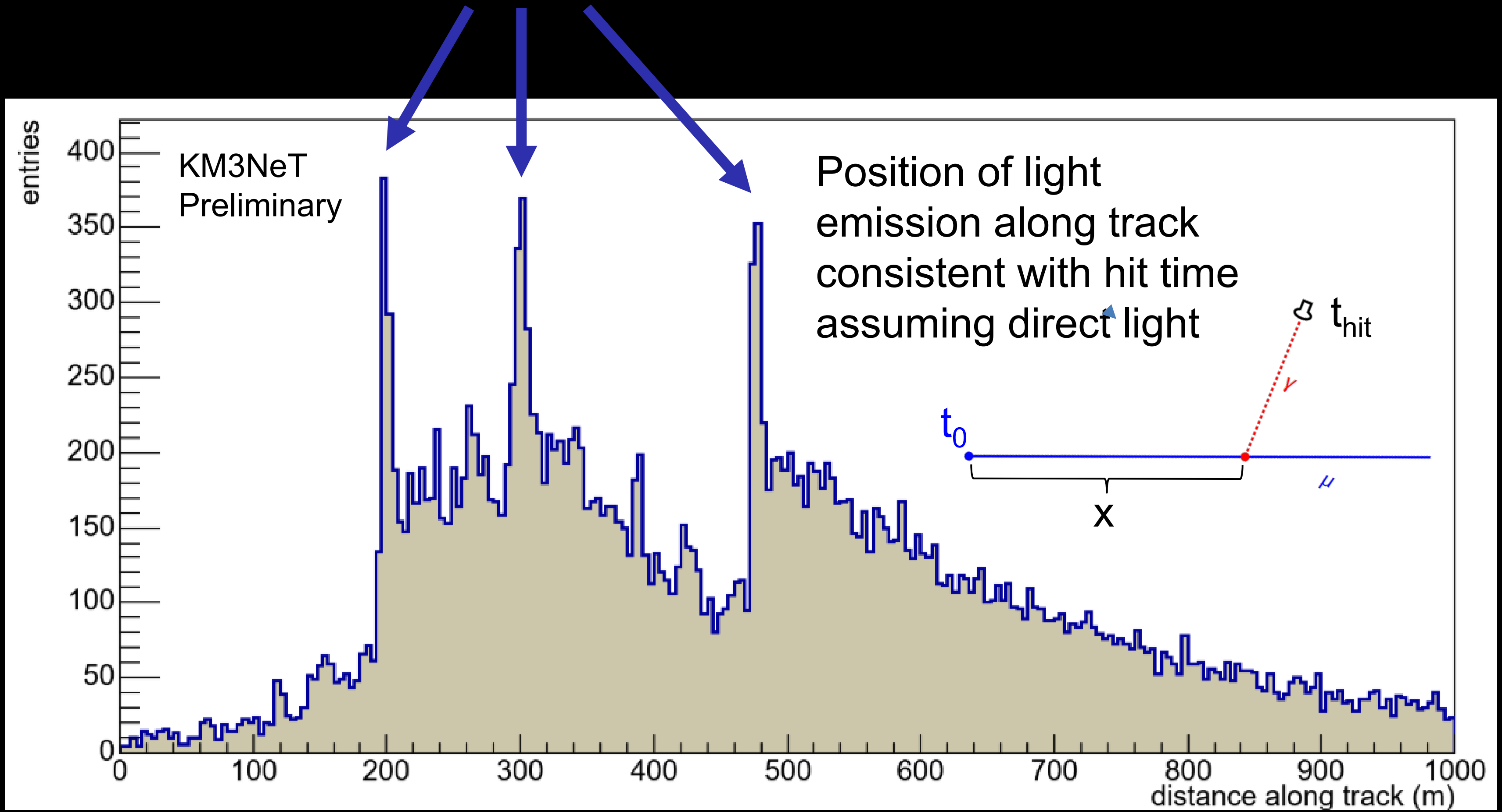
- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV



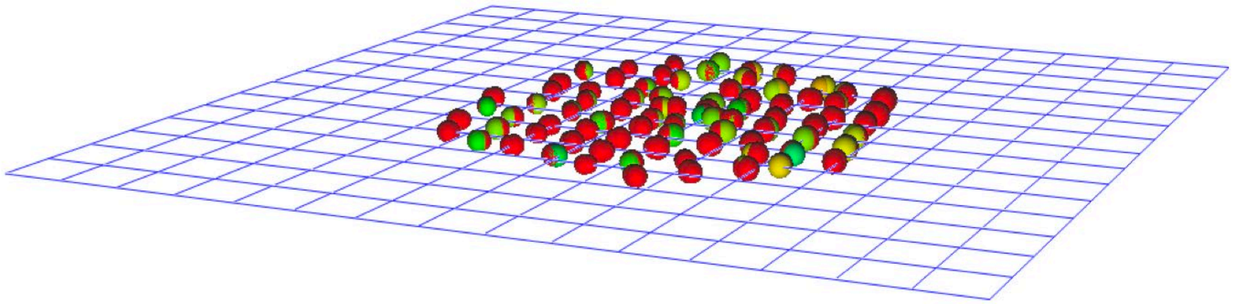


Uncharted Territory

- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons



horizontal event
~1 EeV
IceCube



with an angular resolution of 1.2 degrees the KM3NeT event is seperated by ~ 3 sigma from the downgoing muon background