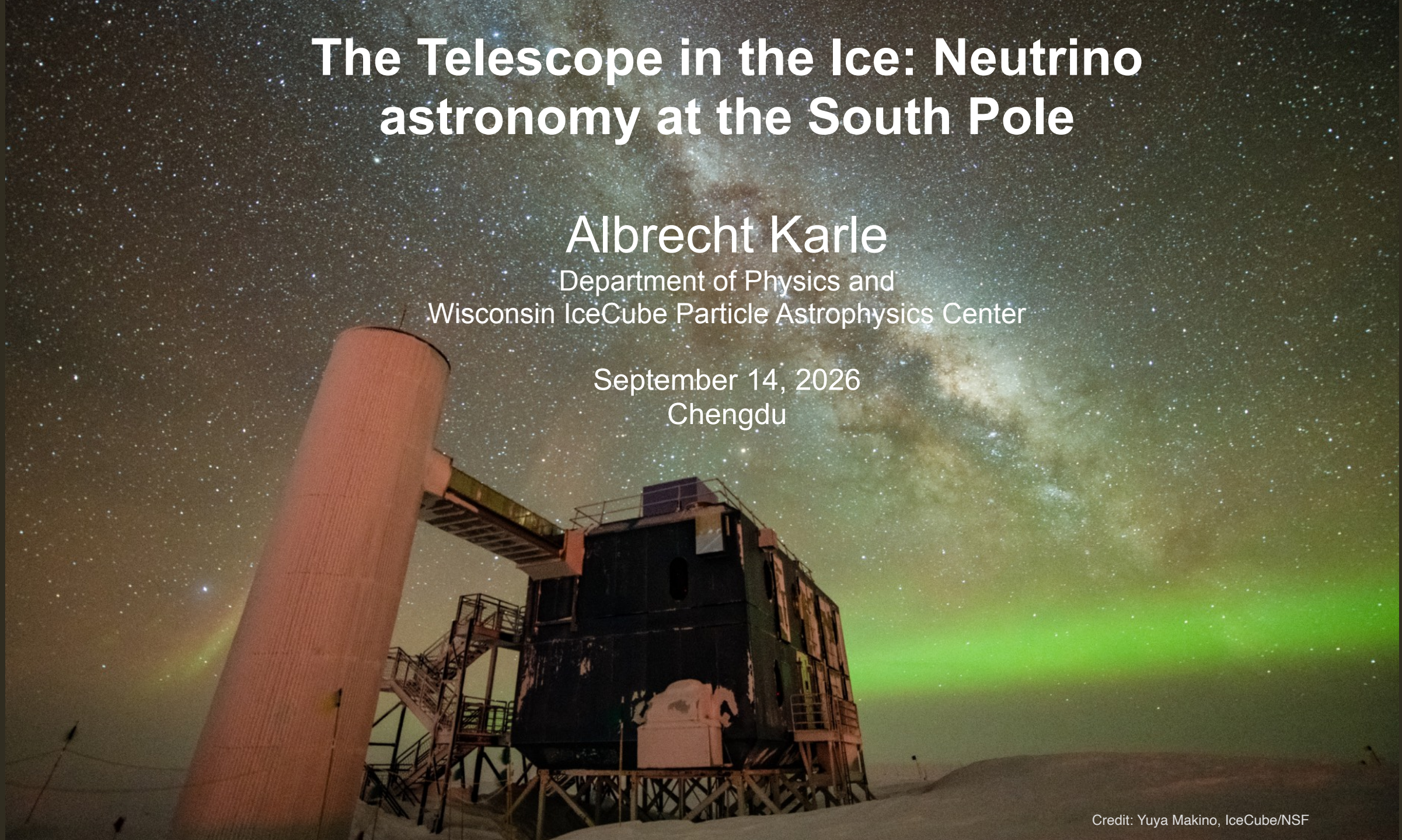
The Telescope in the Ice: Neutrino astronomy at the South Pole

Albrecht Karle
Department of Physics and
Wisconsin IceCube Particle Astrophysics Center

September 14, 2026
Chengdu



Credit: Yuya Makino, IceCube/NSF

Outline

- Introduction, neutrinos and cosmic rays
- Some History
- IceCube
  - Construction
  - The Detector and the Ice
  - Science results


At the geographic South Pole,
on top of 3 km of extremely transparent ice.

115 years ago

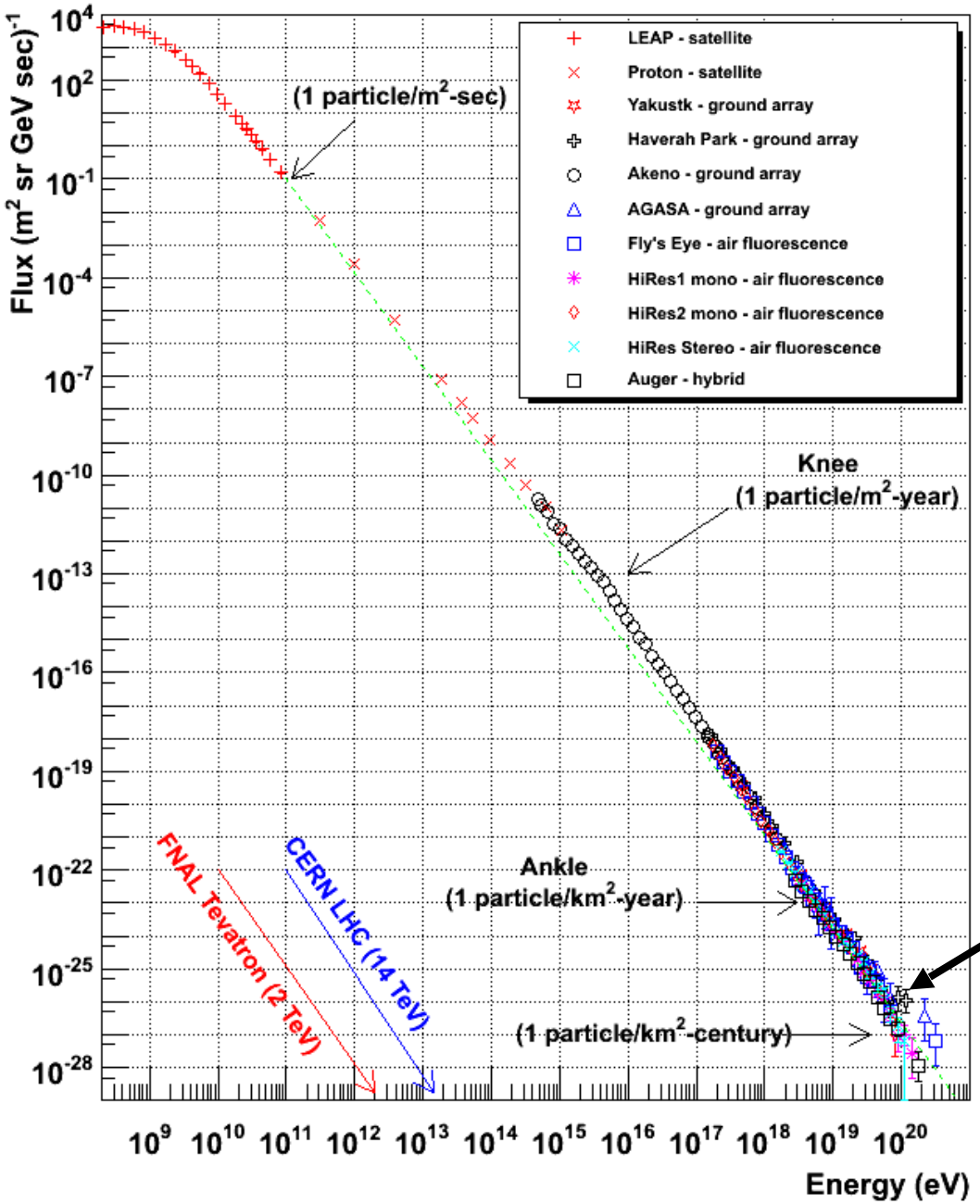
1911/1912:
Victor Hess discovers
Cosmic Rays



December 14, 1911:
Rould Amundson succeeds
to reach the South Pole



Cosmic Ray Spectra of Various Experiments



The origin of cosmic rays

- a century old problem

Can neutrinos help answer the question?

What are the accelerators?

What mechanism provides the power?

1956

Discovery of Neutrinos:
The neutrino was detected 26 years after Pauli's proposal, in 1956.

Reines and Cowan placed a detector of 1 m in size only 10 m near the core of a nuclear reactor.

Reines receives Nobel prize in 1995



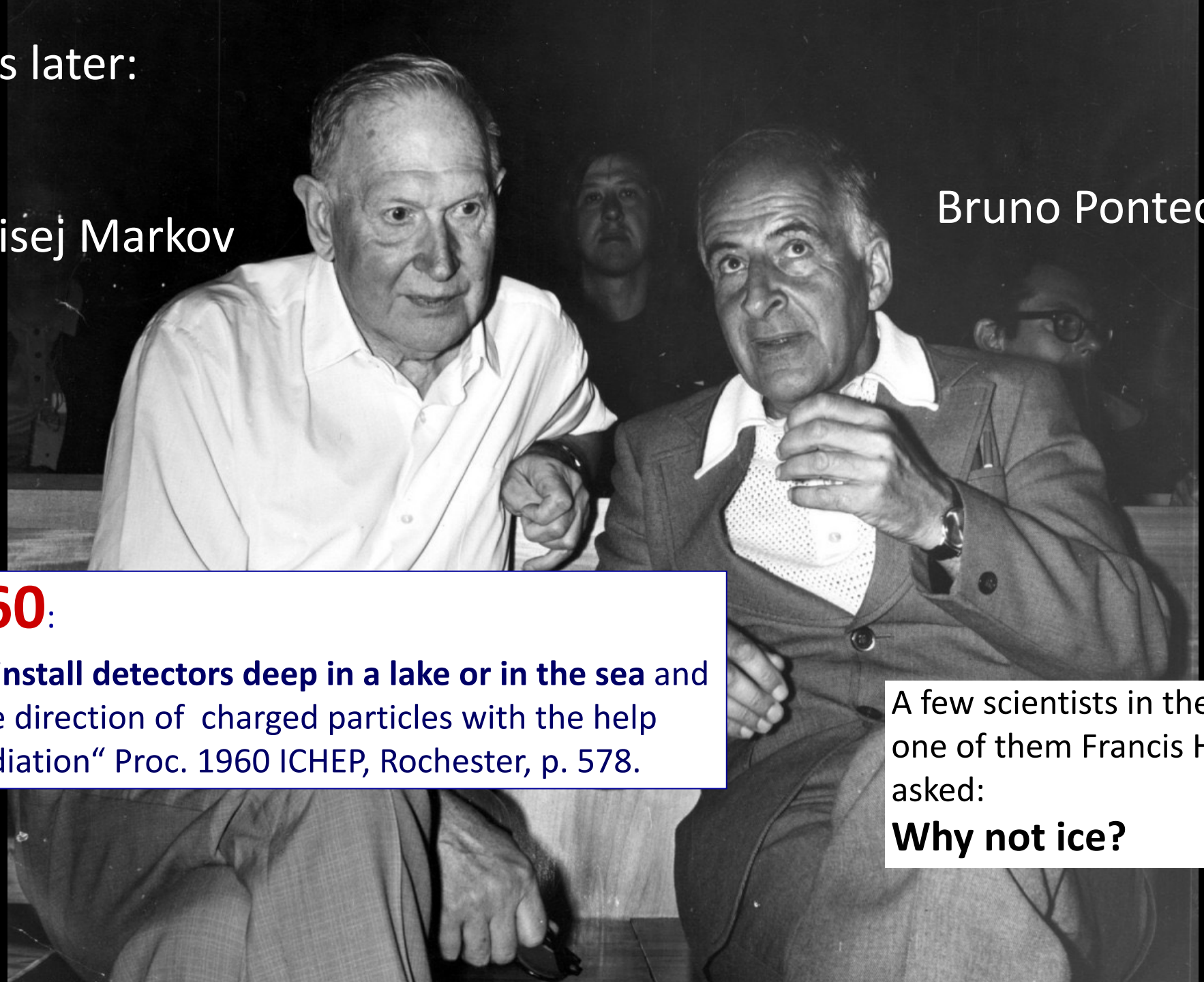




Only 4 years later:

Moisej Markov

Bruno Pontecorvo



M.Markov, **1960**:

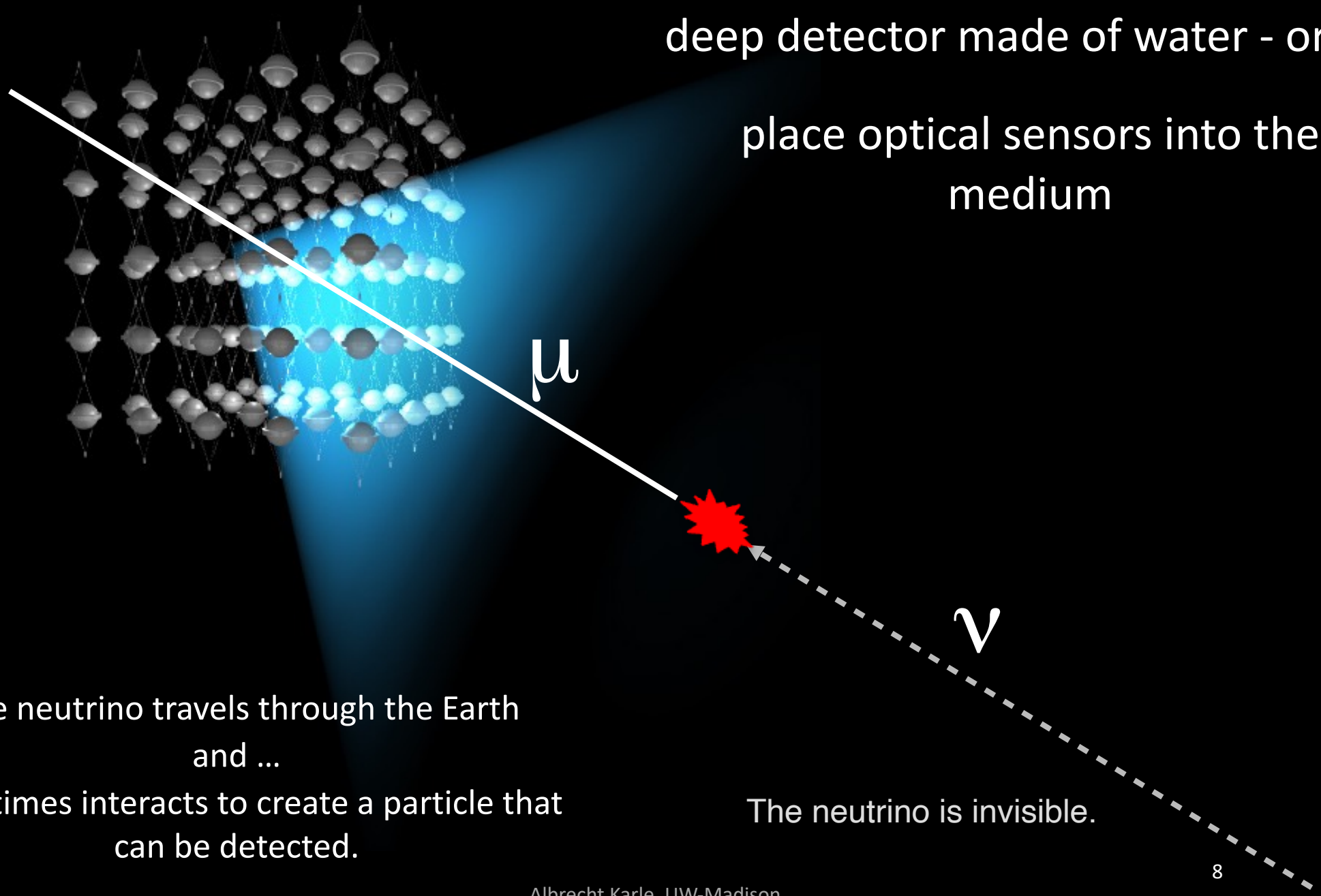
„We propose to **install detectors deep in a lake or in the sea** and to determine the direction of charged particles with the help of Cherenkov radiation“ Proc. 1960 ICHEP, Rochester, p. 578.

A few scientists in the late 80ies, one of them Francis Halzen, asked:

Why not ice?

deep detector made of water - or ice

place optical sensors into the medium



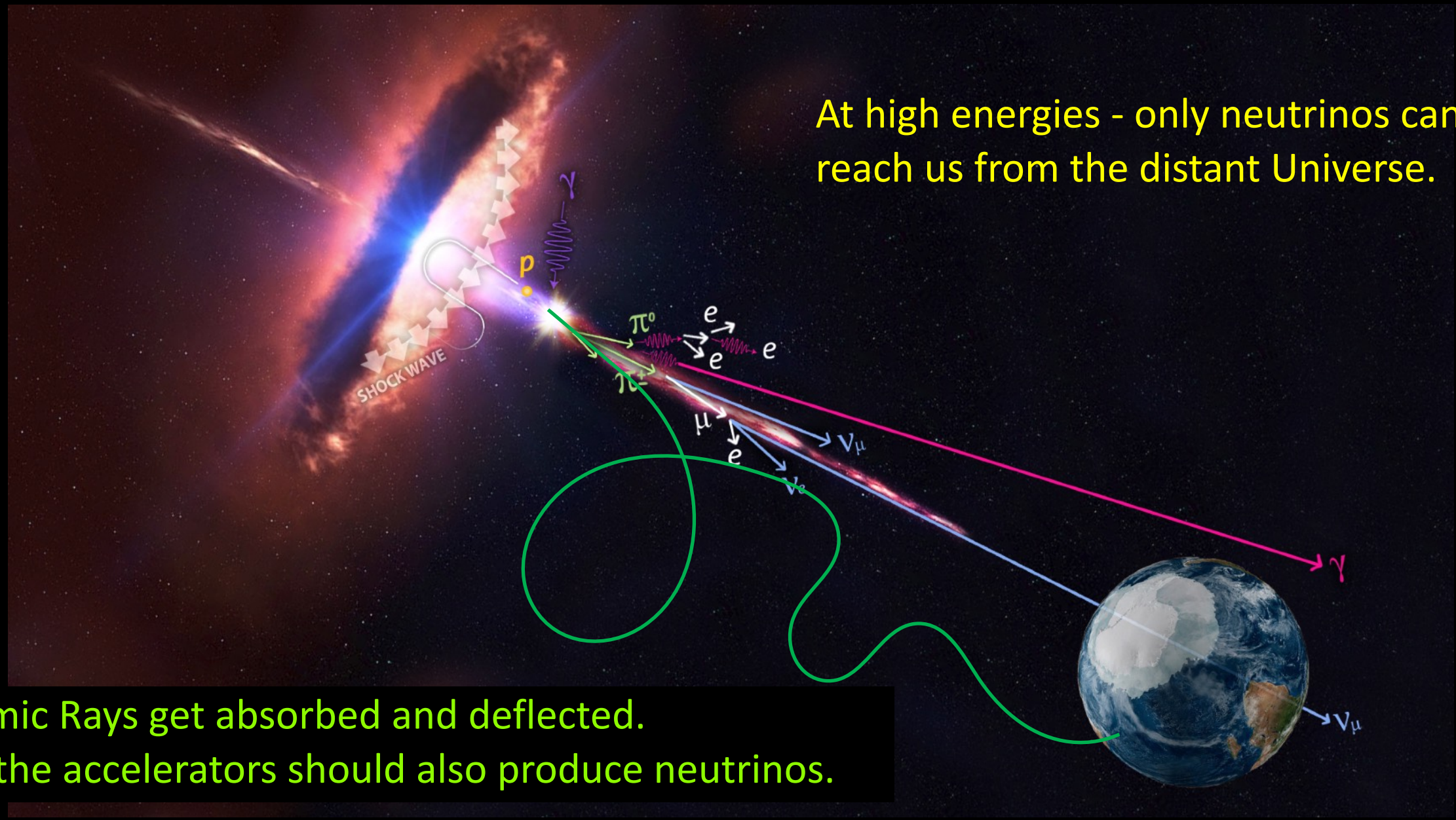
The neutrino travels through the Earth and …
sometimes interacts to create a particle that can be detected.

Neutrinos and Cosmic Rays at high energies

— Neutrino beams

Measure the origin of cosmic rays?

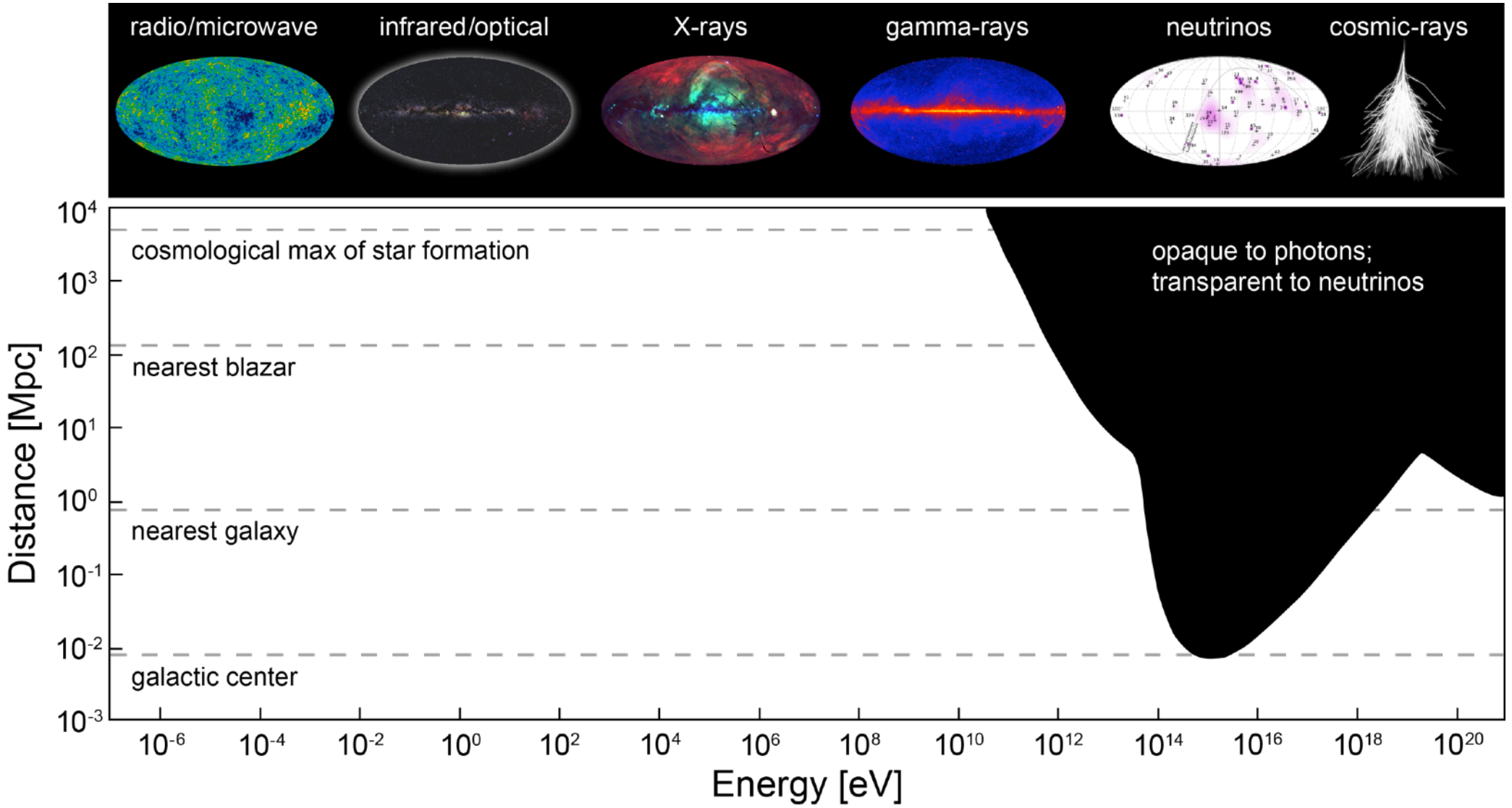
Problem: Cosmic rays don't point to their origin. —> Astronomy with Neutrinos!



Cosmic Rays get absorbed and deflected.

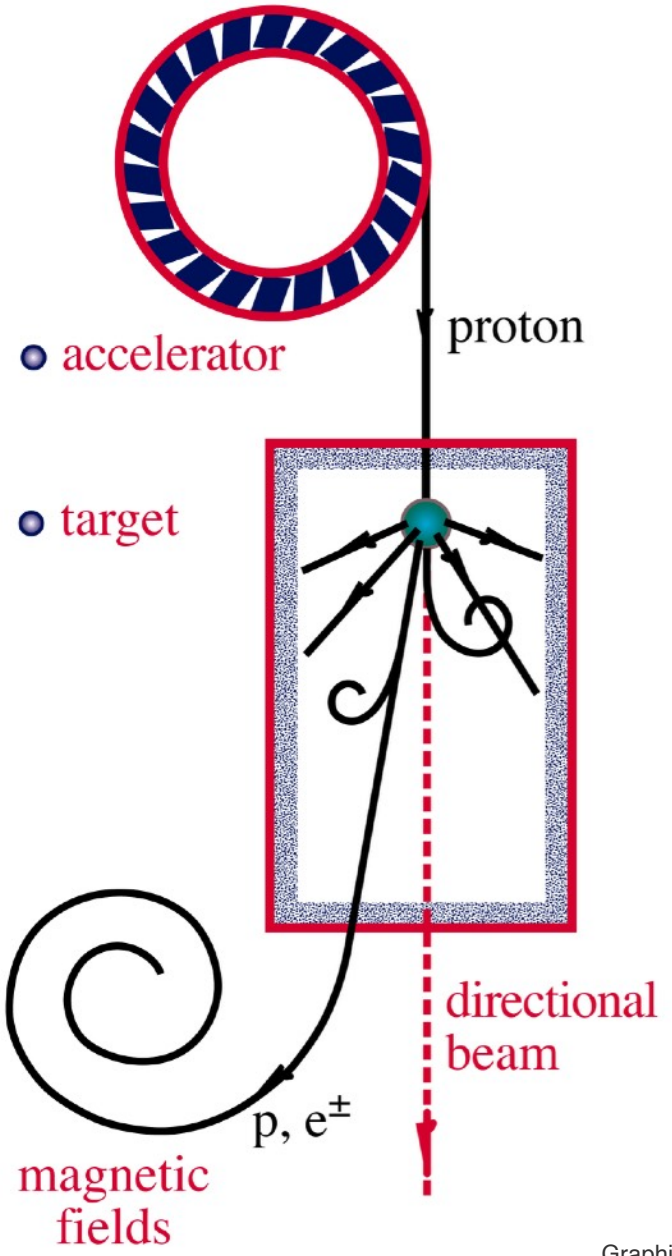
But the accelerators should also produce neutrinos.

Pushing the energy frontier in Astronomy with Neutrinos



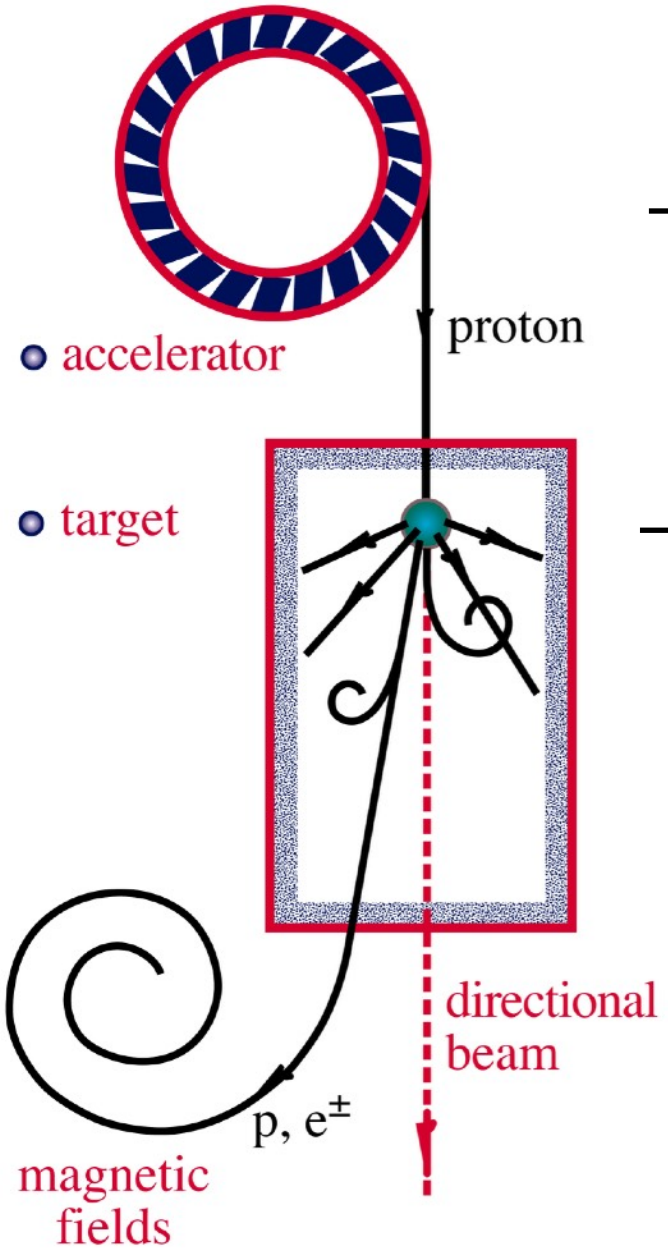
At high energies: The Universe is opaque to the EM spectrum - ***and sometimes also at lower energies***

Cosmic Particle Accelerator + Target: —> Neutrino Beam



Graphic: F. Halzen

Cosmic Particle Accelerator + Target: —> Neutrino Beam



Black Hole

Radiation and Dust

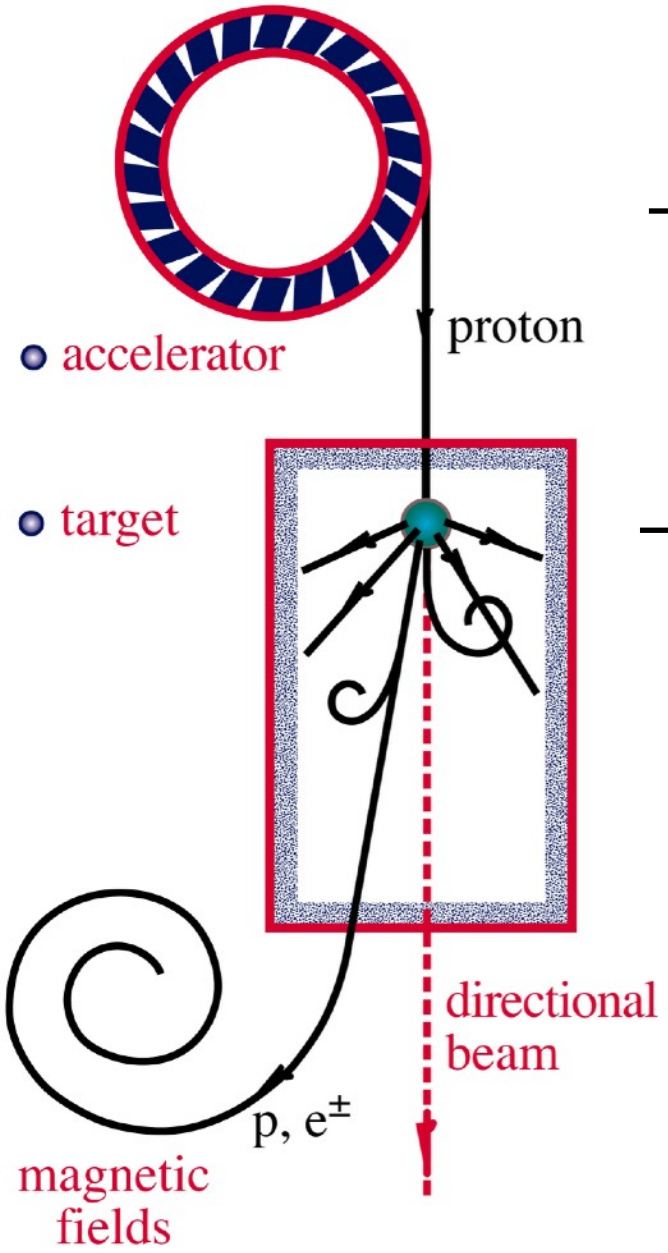
$$p + \gamma \rightarrow p + \pi^0$$

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

cosmic ray + gamma ray

Graphic: F. Halzen

Cosmic Particle Accelerator + Target: —> Neutrino Beam



Black Hole

Radiation and Dust

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

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

cosmic ray + gamma rays

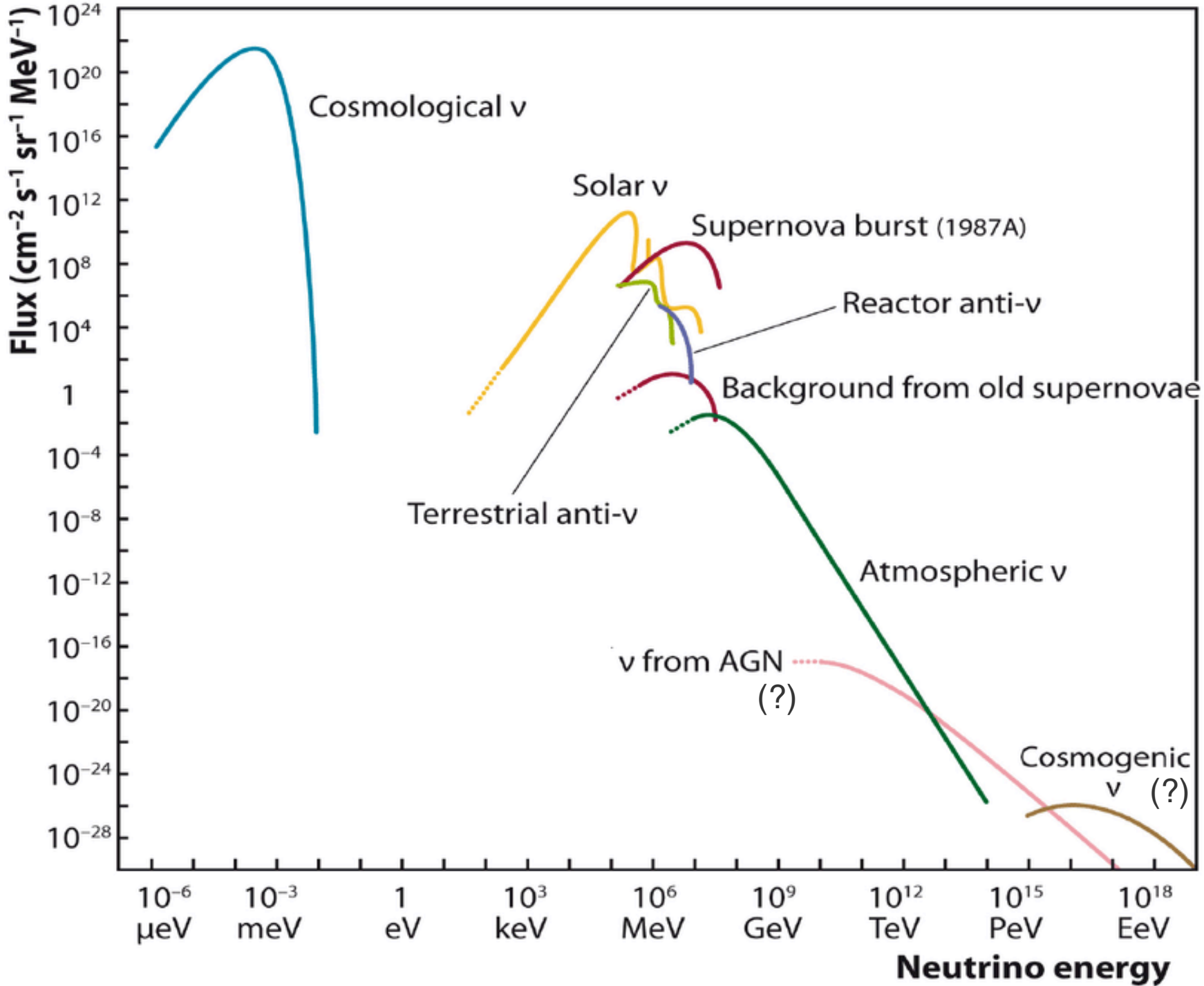
$$p + \gamma \rightarrow n + \pi^+$$

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

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

cosmic ray + neutrinos

Graphic: F. Halzen


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
(?)
Cosmogenic
ν (?)
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

Detecting Cosmic Neutrinos?

Event Rates are small.
Neutrinos are very penetrating,
- they don't want to interact.

It was clear already early on:

Need a very big detector!

—> a target of 1 billion tons or 1 km^3

Early efforts

- DUMAND, first experiments off Hawaii isald
- Baikal, —> Lake Baikal
- NESTOR —> first steps in the Mediterranean Sea
- AMANDA: —> South POle

The Early Days

From first tests in Greenland to
the Antarctic Muon and Neutrino Detector Array
(AMANDA), 1990 - 2005

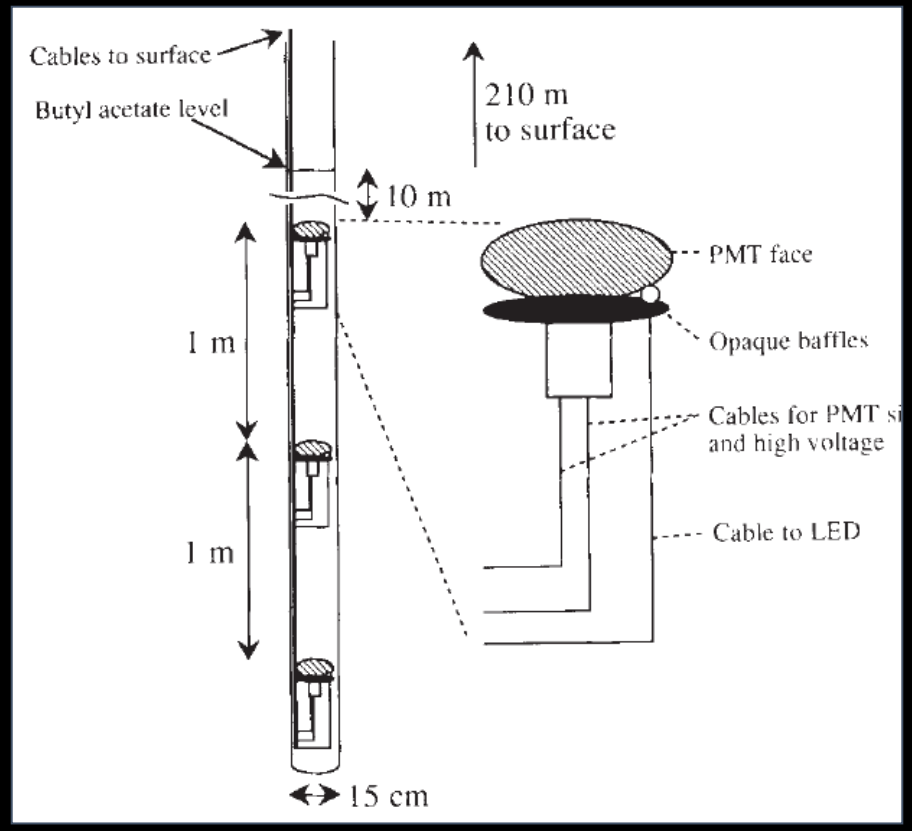


1990: Detection of cosmic ray muons using PMT in natural ice in Greenland.

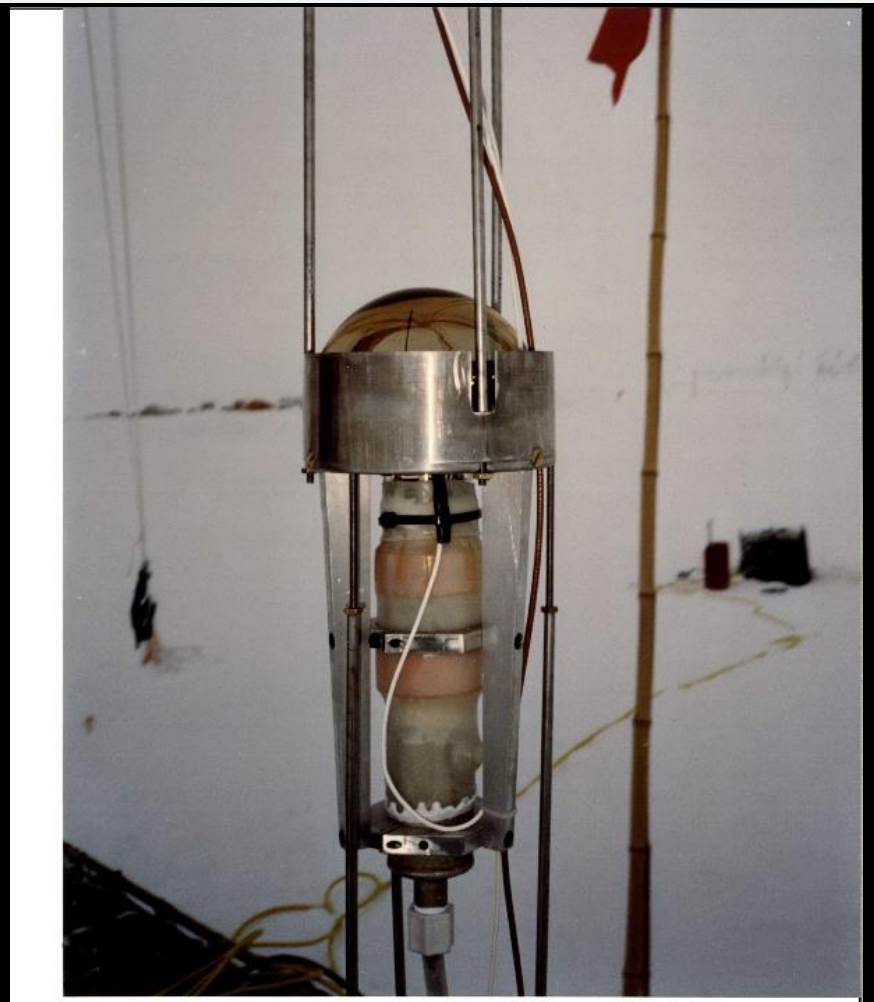
Nature 353, 331-333 (26 September 1991)

Observation of muons using the polar ice cap as a Cerenkov detector

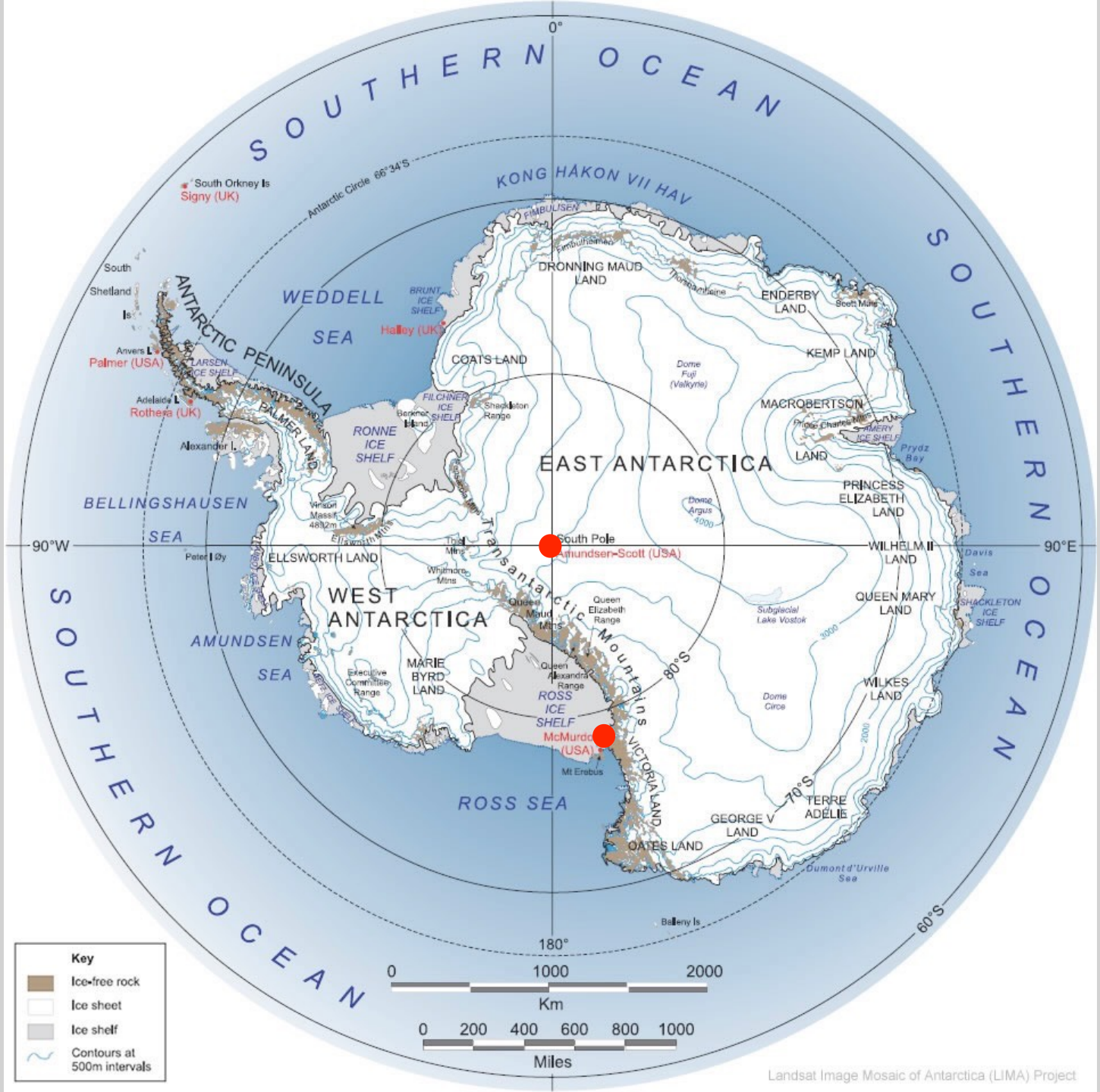
D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡



"Cerenkov radiation from muons was detected, and a comparison of count rate with the expected muon flux indicates that the ice is very transparent, with an absorption length greater than 18 m. **Our results suggest that a full-scale Antarctic ice detector is technically quite feasible.**"



Location: South Pole



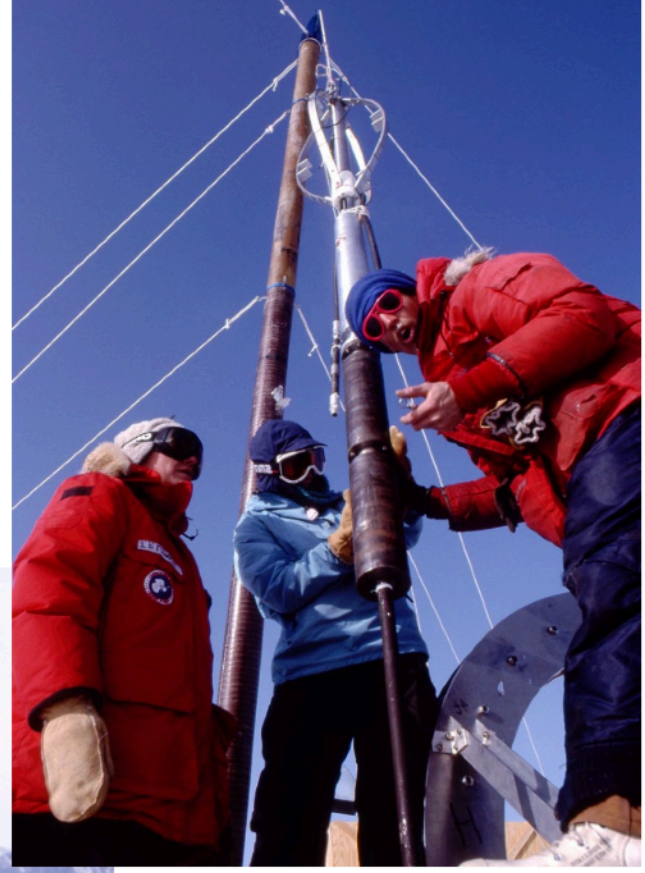
1991/92: First tests at the South Pole



- Small PMTs deployed
- First test of hot water drilling at South Pole

Heaters and pumps to melt the holes





1996/97: add 6 strings to complete AMANDA-B10



1996/97

The connector to the drilled shorted out in consecutive attempts due to water.
Rewiring the drill head to switch to low voltage saved the season.

Lesson learned:
Working together is a powerful tool!



Rewiring drill power system with Swedish drill engineer Pontus.
In a Jamesway, about a week before Christmas 1996.

1999/2000:
AMANDA-II drill site



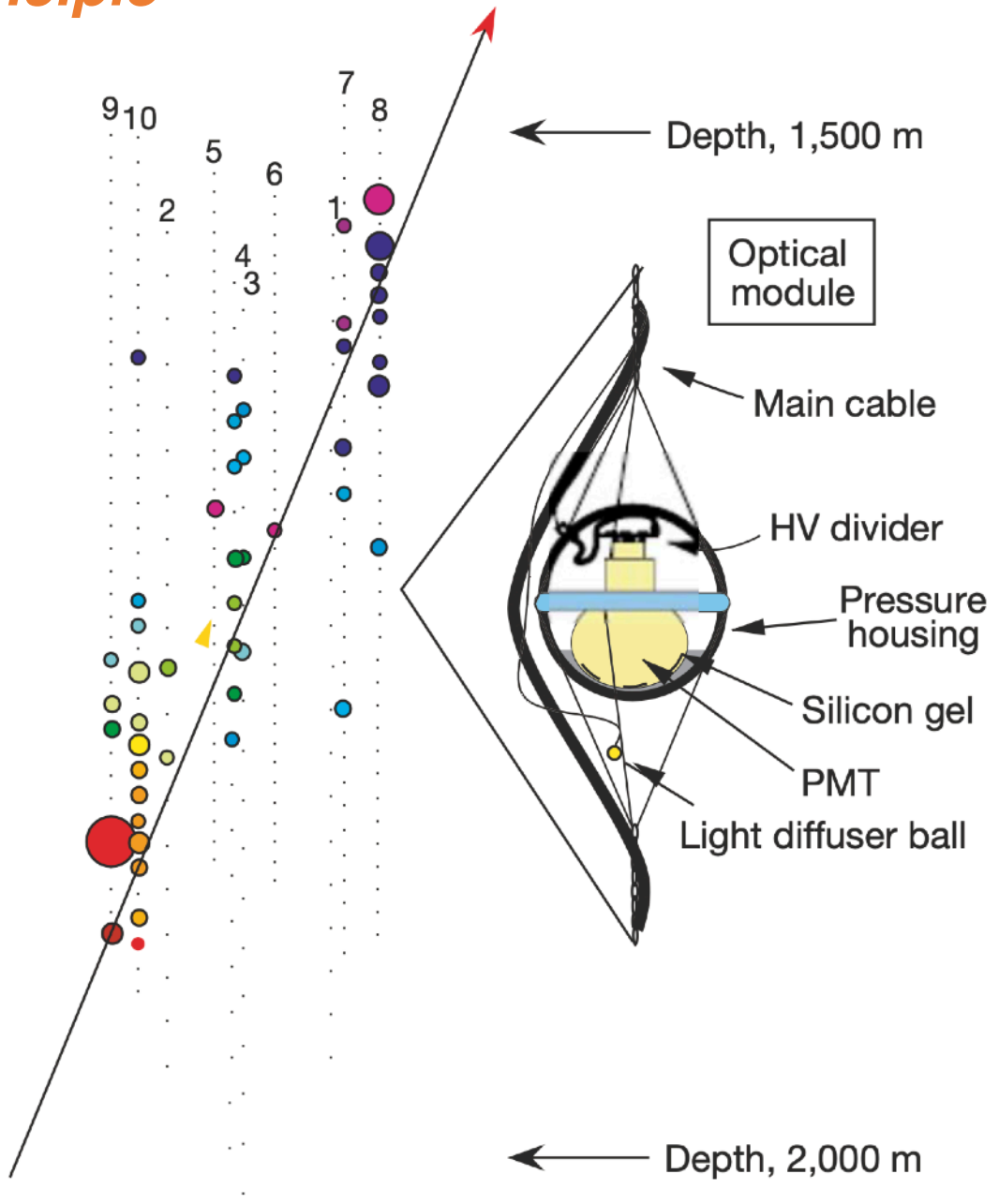
Proof of principle

Observation of high-energy neutrinos using Čerenkov detectors embedded deep in Antarctic ice

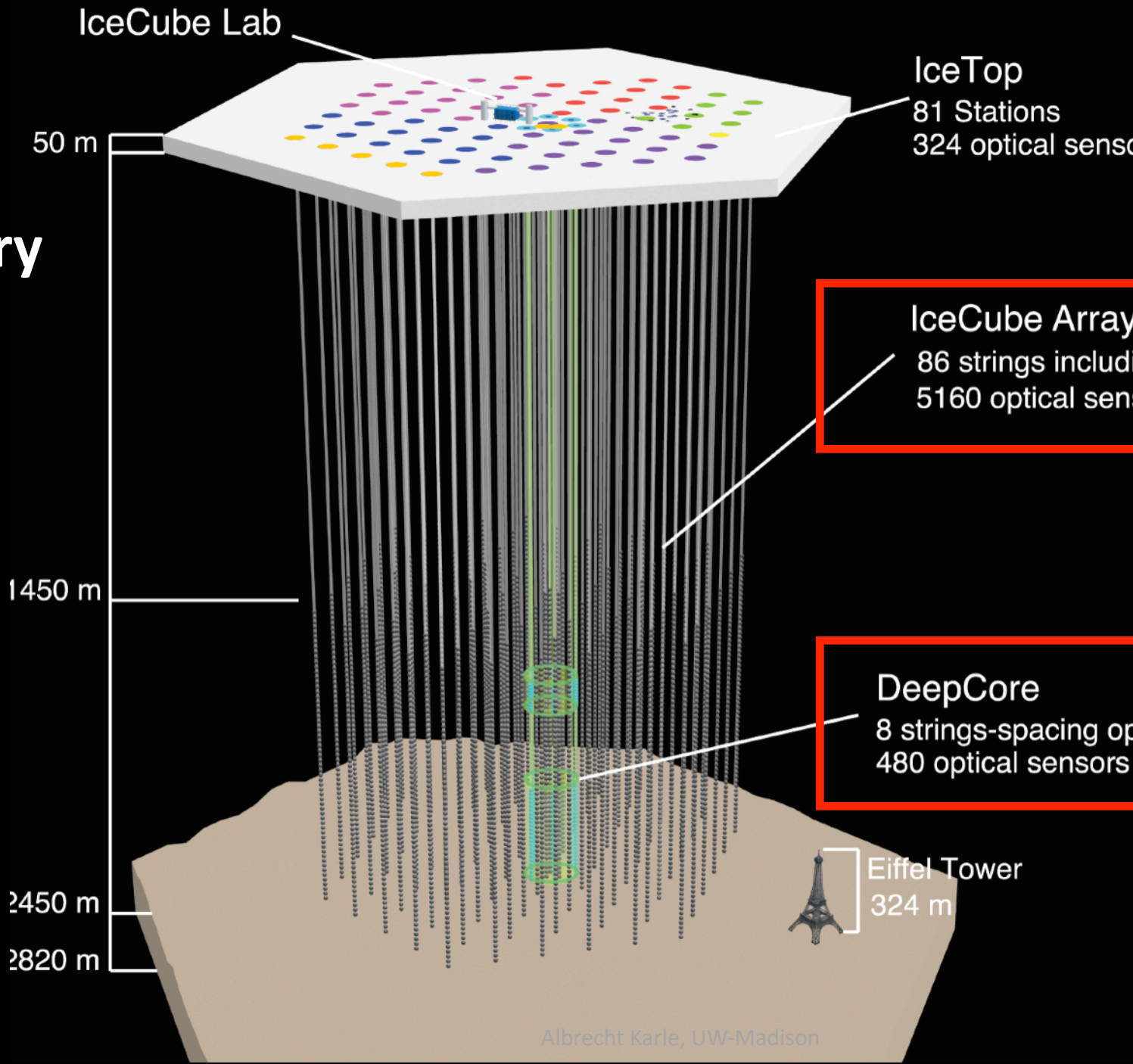
AMANDA-B10 detector

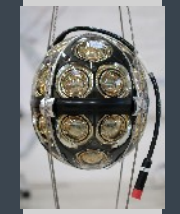
E. Andrés*, P. Askebjer†, X. Bai‡, G. Barouch*, S. W. Barwick§, R. C. Bay‖, K.-H. Becker¶, L. Bergström†, D. Bertrand#, D. Bierenbaum§, A. Biron☆, J. Booth§, O. Botner**, A. Bouchta☆, M. M. Boyce*, S. Carius††, A. Chen*, D. Chirkin‖¶, J. Conrad**, J. Cooley*, C. G. S. Costa#, D. F. Cowen‡‡, J. Dailing§, E. Dalberg†, T. DeYoung*, P. Desiati☆, J.-P. Dewulf#, P. Doksus*, J. Edsjö†, P. Ekström†, B. Erlandsson†, T. Feser§§, M. Gaug☆, A. Goldschmidt‖‖, A. Goobar†, L. Gray*, H. Haase☆, A. Hallgren**, F. Halzen*, K. Hanson‡‡, R. Hardtke*, Y. D. He‖, M. Hellwig§§, H. Heukenkamp☆, G. C. Hill*, P. O. Hulth†, S. Hundertmark§, J. Jacobsen‖‖, V. Kandhadai*, A. Karle*, J. Kim§, B. Koci*, L. Köpke§§, M. Kowalski☆, H. Leich☆, M. Leuthold☆, P. Lindahl††, I. Liubarsky*, P. Loaiza**, D. M. Lowder‖, J. Ludvig‖‖, J. Madsen*, P. Marciniewski**, H. S. Matis‖‖, A. Mihalyi‡‡, T. Mikolajski☆, T. C. Miller‡, Y. Minaeva†, P. Miočinović‖, P. C. Mock§, R. Morse*, T. Neunhöffer§§, F. M. Newcomer‡‡, P. Niessen☆, D. R. Nygren‖‖, H. Ögelman*, C. Pérez de los Heros**, R. Porrata§, P. B. Price‖, K. Rawlins*, C. Reed§, W. Rhode¶, A. Richards‖, S. Richter☆, J. Rodríguez Martino†, P. Romenesko*, D. Ross§, H. Rubinstein†, H.-G. Sander§§, T. Scheider§§, T. Schmidt☆, D. Schneider*, E. Schneider§, R. Schwarz*, A. Silvestri¶☆, M. Solarz‖, G. M. Spiczak‡, C. Spiering☆, N. Starinsky*, D. Steele*, P. Steffen☆, R. G. Stokstad‖‖, O. Streicher☆, Q. Sun†, I. Taboada‡‡, L. Thollander†, T. Thon☆, S. Tilav*, N. Usechak§, M. Vander Donckt#, C. Walck†, C. Weinheimer§§, C. H. Wiebusch☆, R. Wischnewski☆, H. Wissing☆, K. Woschnagg‖, W. Wu§, G. Yodh§ & S. Young§

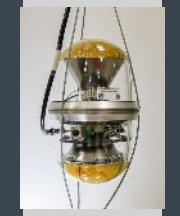
nature 2001

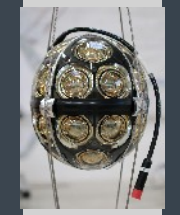


The **IceCube Neutrino Observatory**





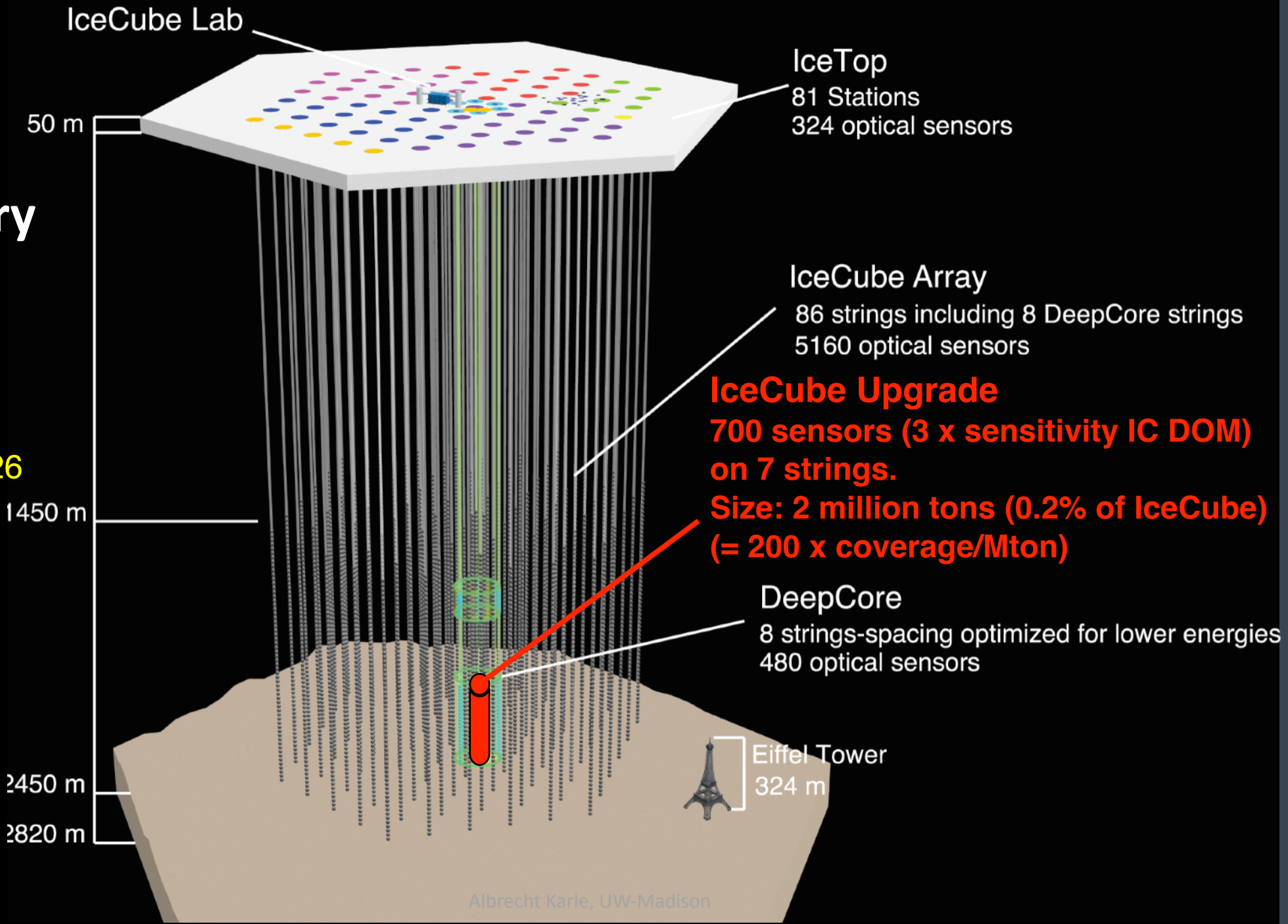


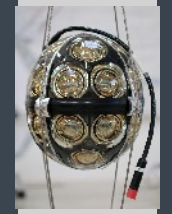


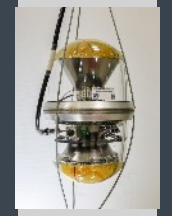


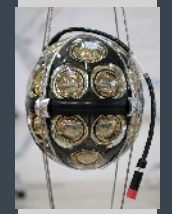
The IceCube Neutrino Observatory + IceCube Upgrade

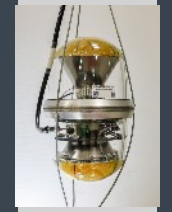
Deploy in 2025/26









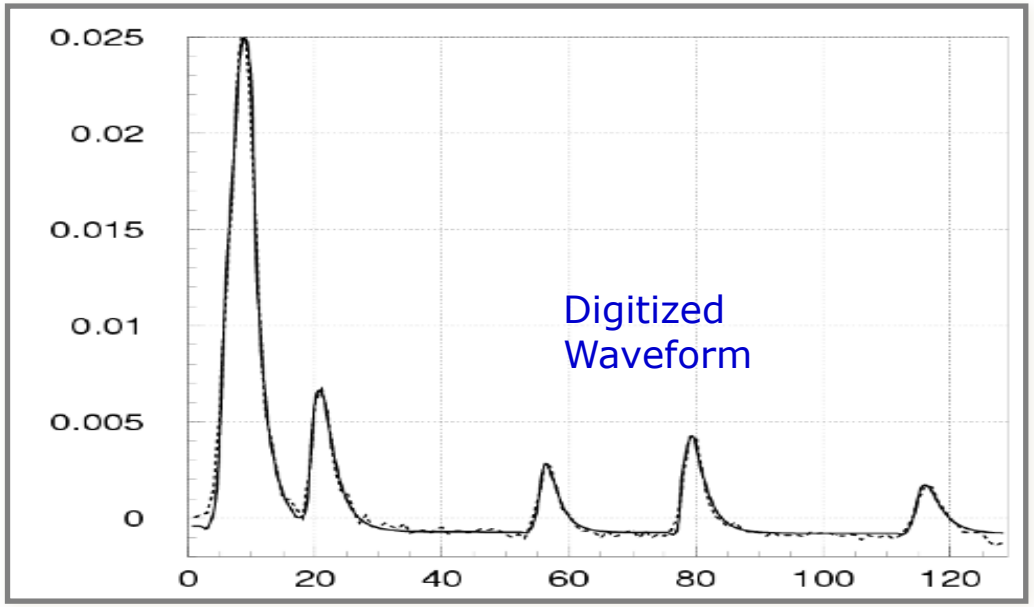


Digital Optical Module (DOM)

25 cm photomultiplier
Power: ~ 3.5W
fully digital,
noise rate < 500 photoelectrons/sec
calibration tools

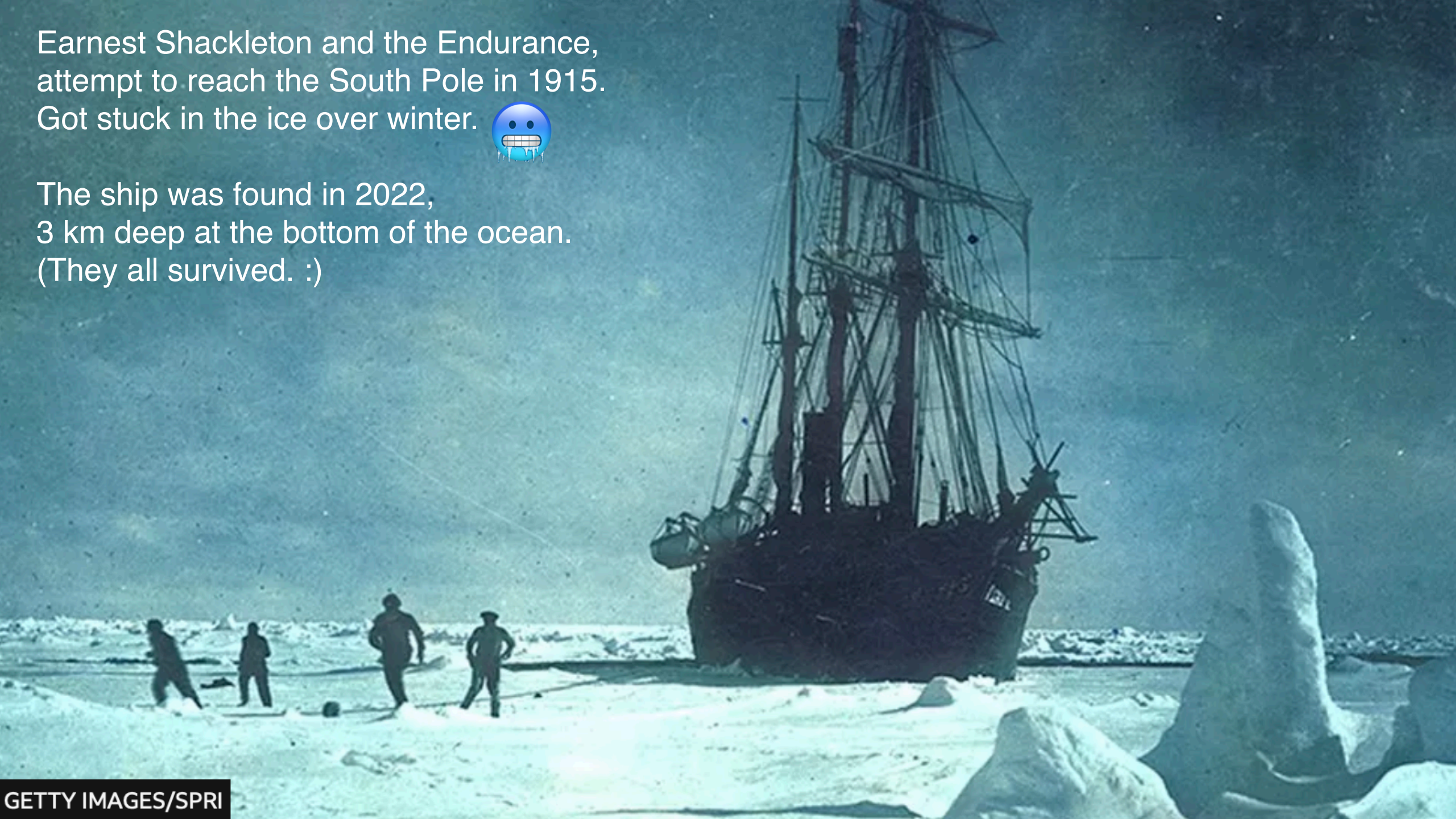






IceCube Construction (2004-2011)

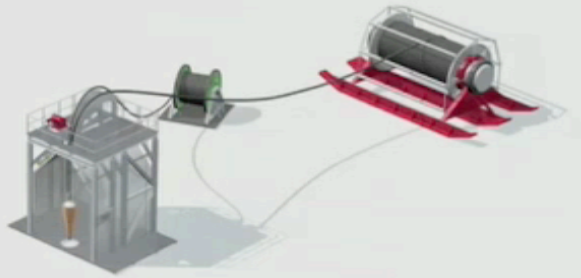
Construction start just 3 years after the first neutrino paper.

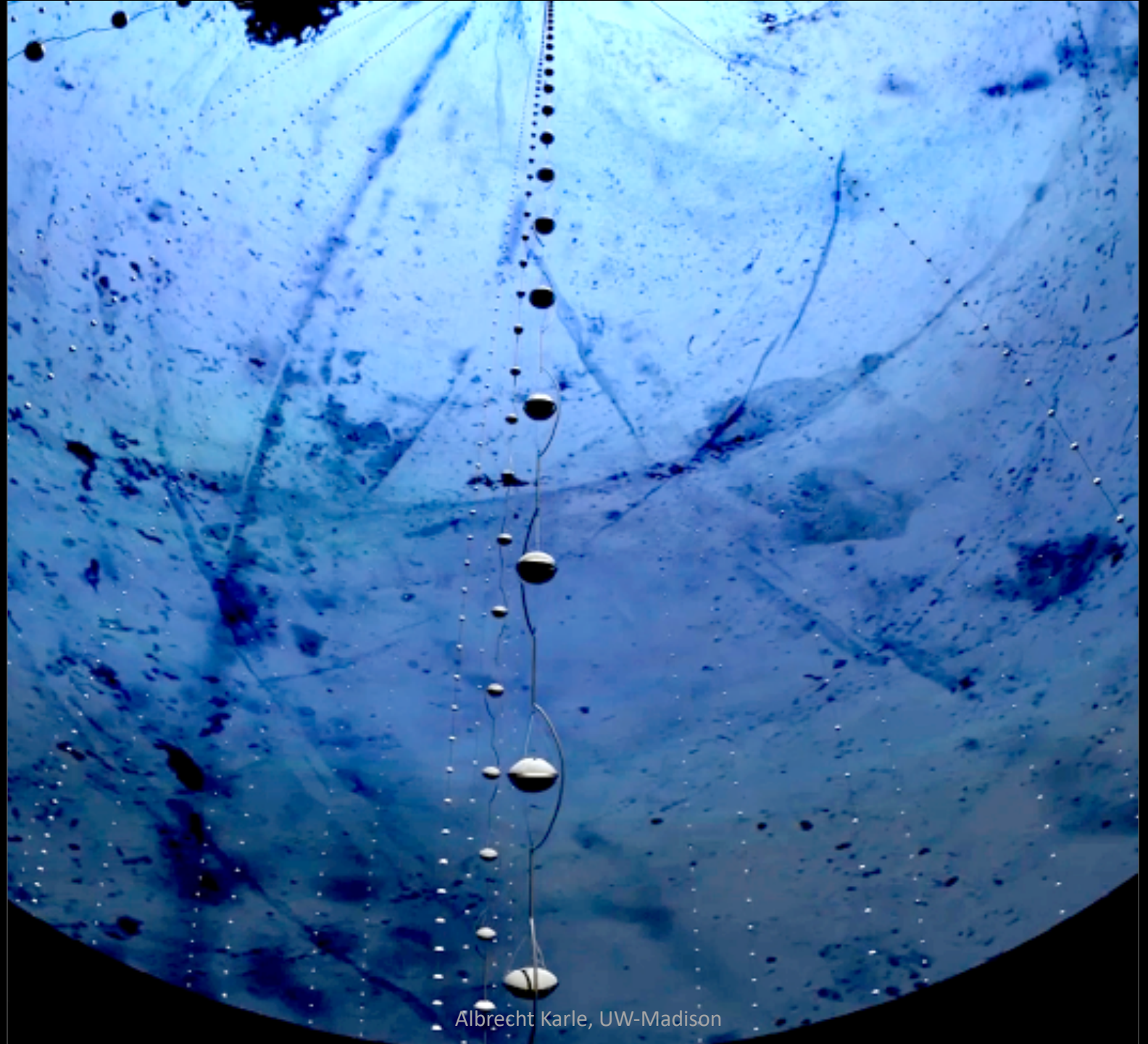

Earnest Shackleton and the Endurance,
attempt to reach the South Pole in 1915.
Got stuck in the ice over winter.
The ship was found in 2022,
3 km deep at the bottom of the ocean.
(They all survived. :)
GETTY IMAGES/SPRI


Fortunately we
don’t need to
travel by ship,
today!


Auckland
Christchurch
McMurdo Station
© 2007 Europa Technologies
Image © 2007 NASA
Image © 2007 TerraMetrics
©2006
Goog






Albrecht Karle, UW-Madison

Construction



South Pole 10m Telescope



MAPO



IceCube Laboratory (ICL)

TOS - Drilling site (79 & 80 in 10/11)



IceCube Enhanced Hot Water Drill (EHWD)



Photo: Ben Tibbets ~2009

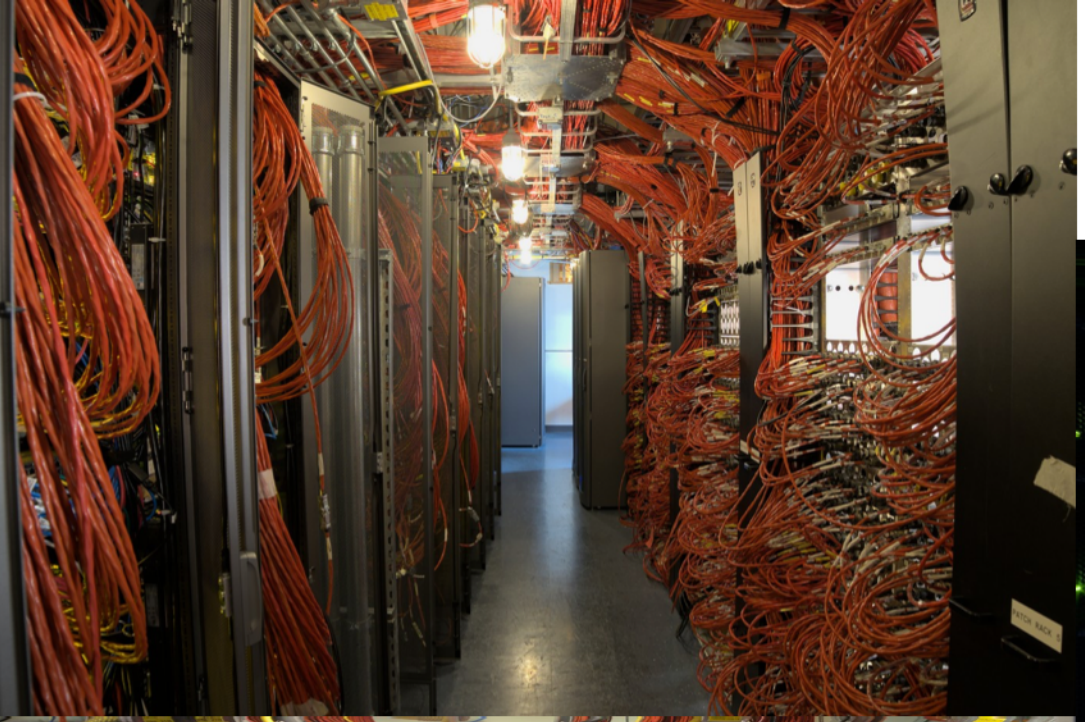
IceCube Laboratory

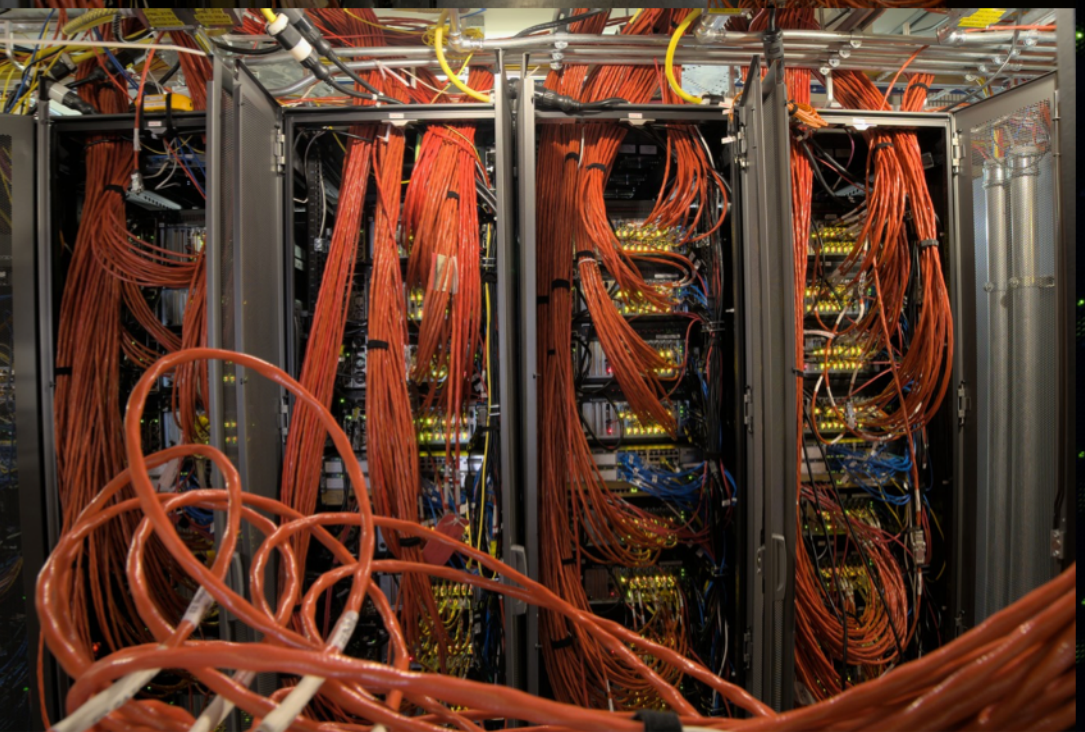


~60 kW power to electronics
90 GB/day over satellite
2 winterovers
summer population (around 5-7 pop Dec - Jan)

ICL server room

(IceCube Lab)







- ~200 machines
- Power the sensors and receive the data
- Send 10% of the 1TB/day of produced data via satellite
- Alert other experiments in case of interesting event detection (high energy, supernova)

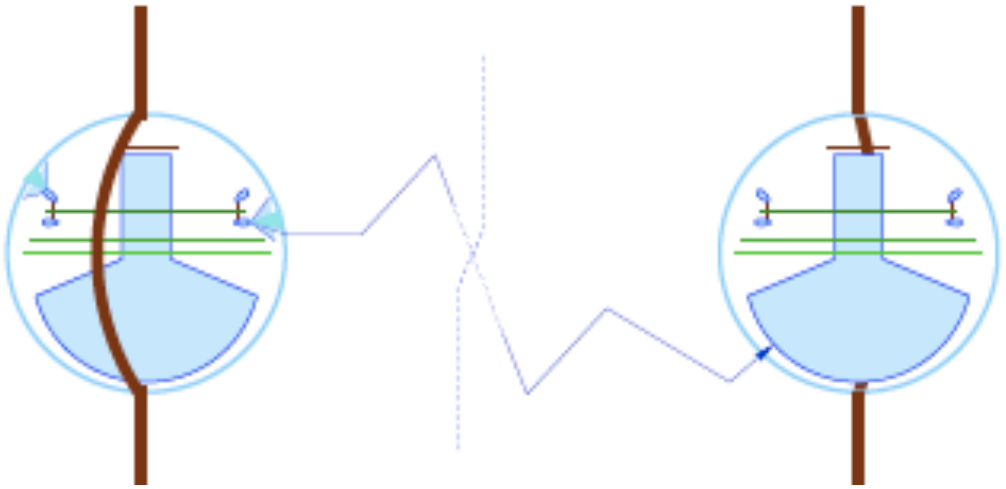
From Detector,

to Data,

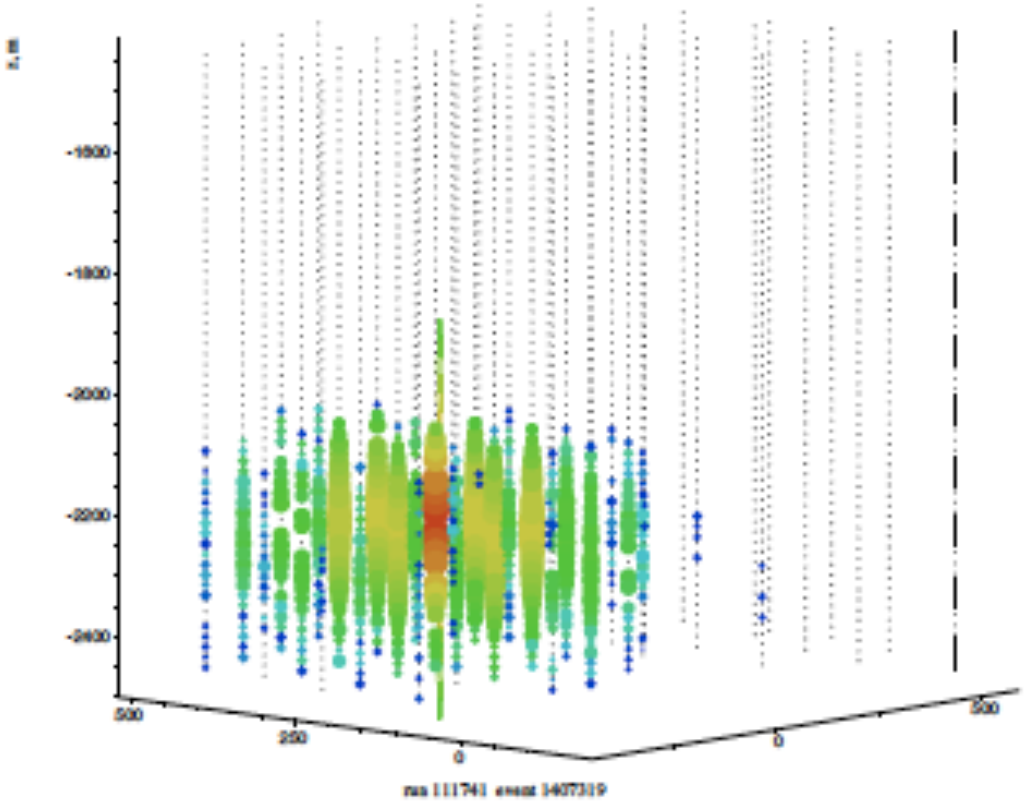
to Science …


Albrecht Karle, UW-Madison

Flasher events used for calibration of the ice.



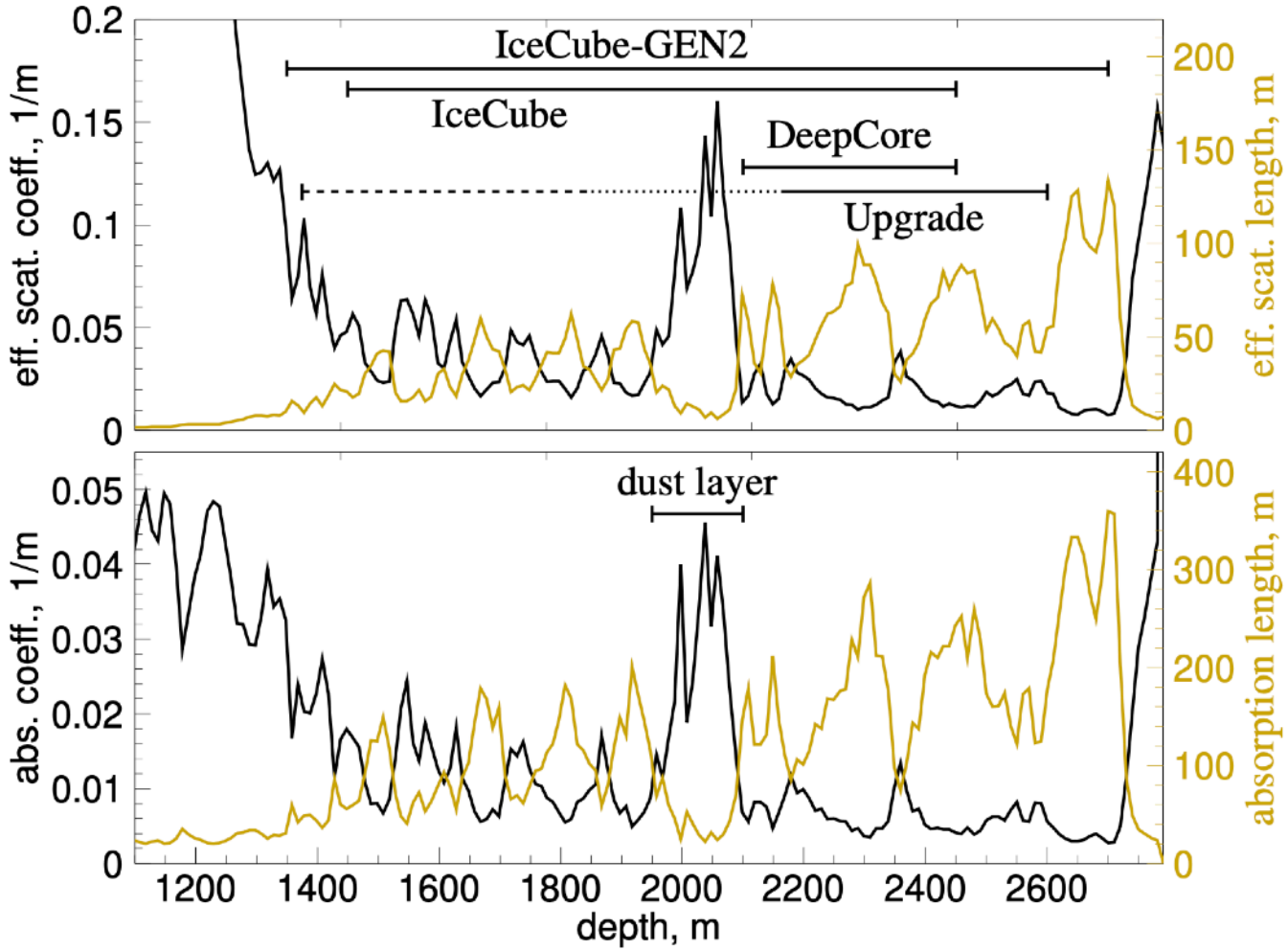
All sensors are equipped
with a set of 12 LED flashers.
A 30 ns pulse of 10 billion photons (400nm) is visible to a distance of 600m.



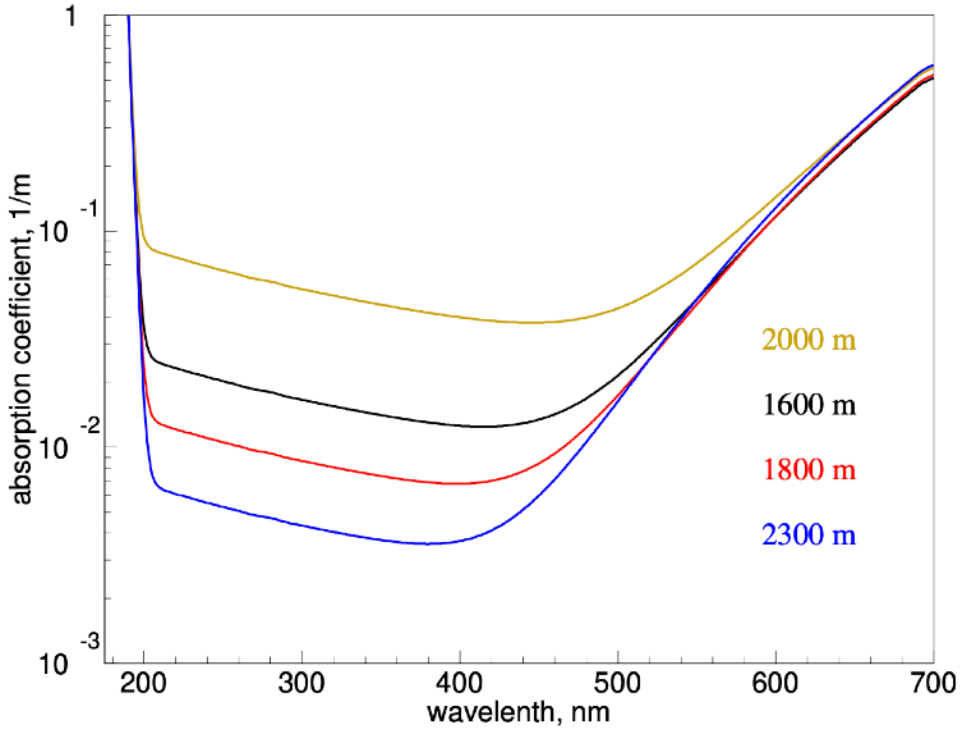
These measurements are used
to calibrate the detector
- timing
- geometry
- optical properties of the ice

Optical Properties of the South Pole Ice

Scattering coefficient vs depth



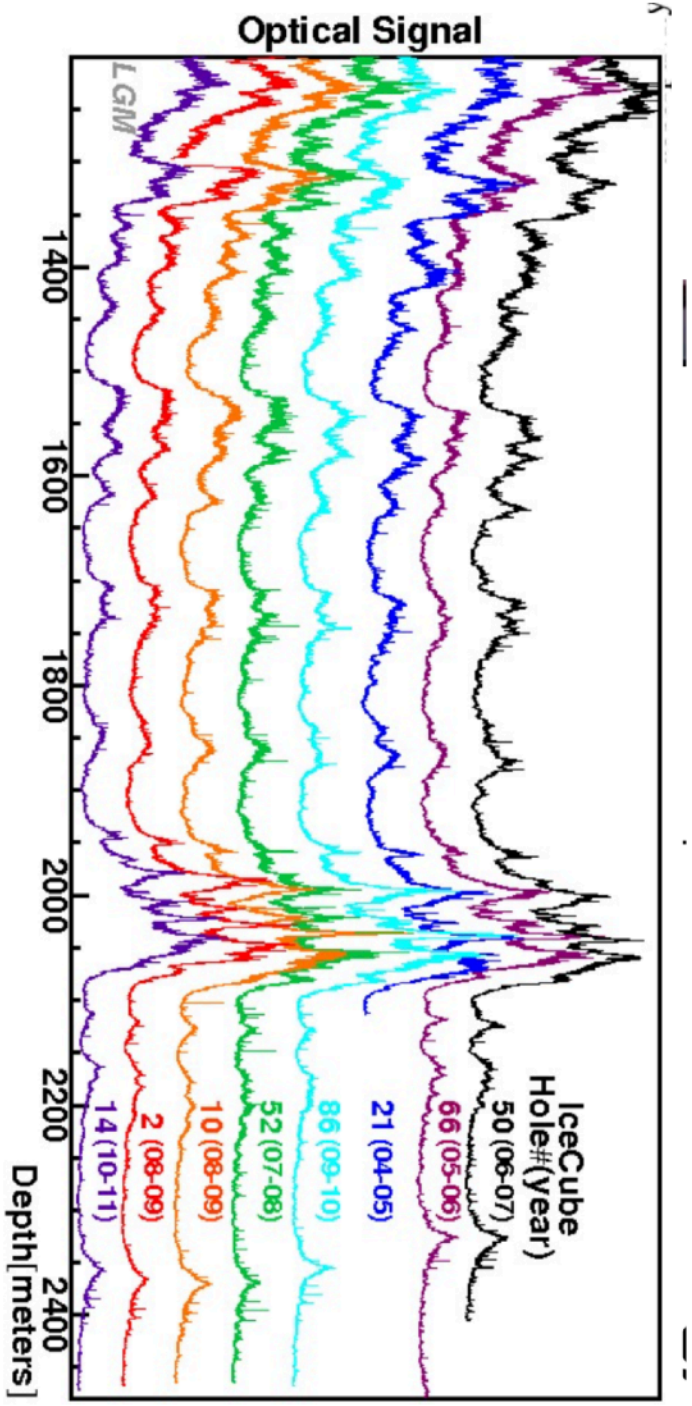
Absorption coefficient vs wavelength



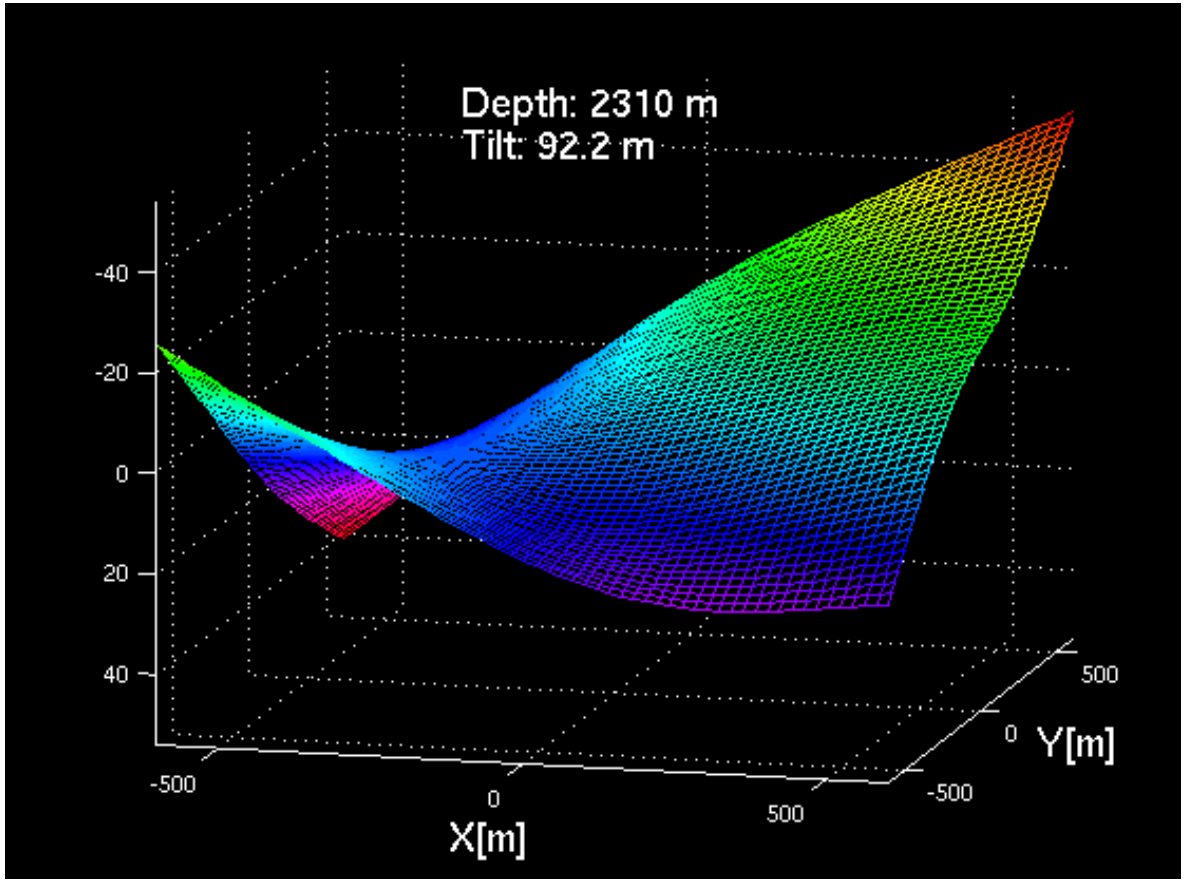
200 nm 700 nm

Ice transparent to UV light

Depth dependence of optical properties
Structure is a reflection of 200k years of climate history



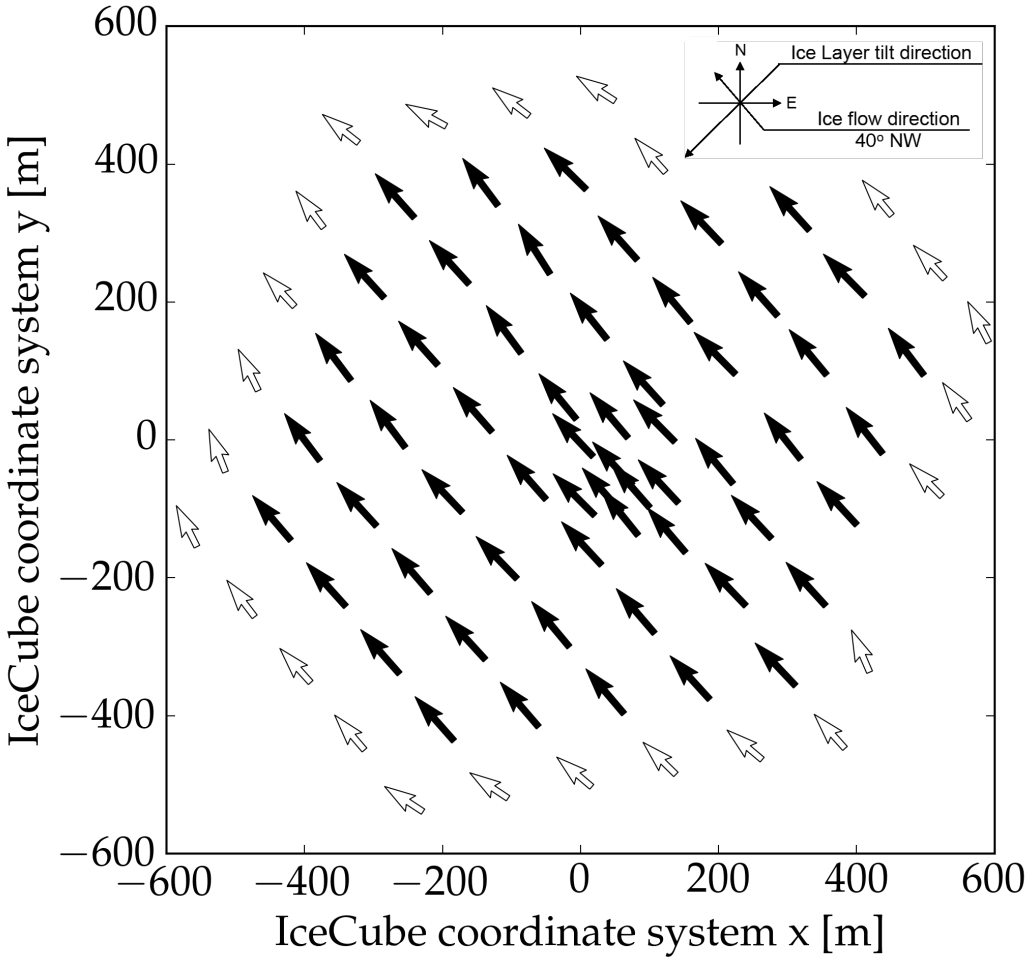
Dust layers are tilted as a result of ice flow,
a 3 dimensional structure

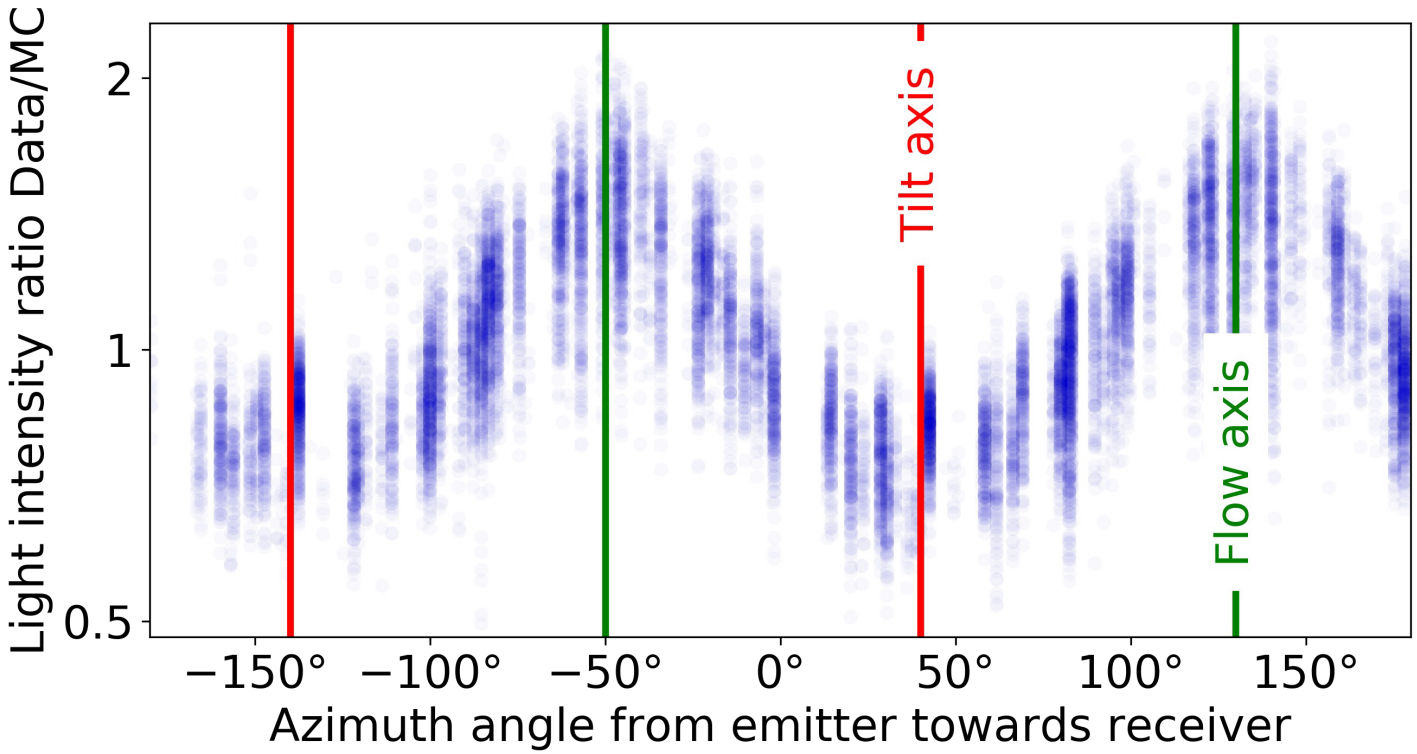


Anisotropy of light propagation

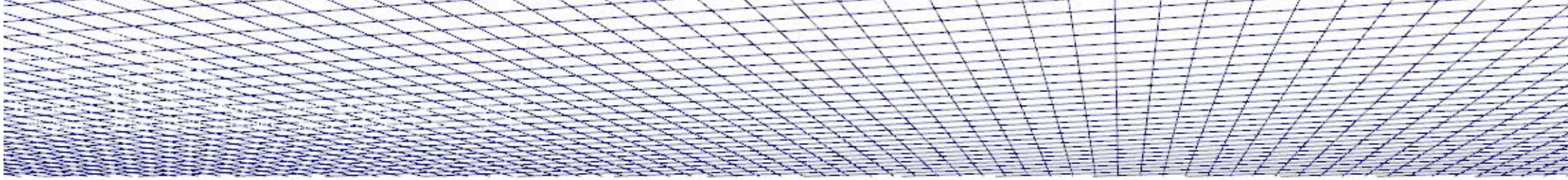
Comparison of flasher data to simulation indicated an azimuthally dependent light-intensity profile

Cause: ***Microstructure of ice crystal alignment causes birefringence***

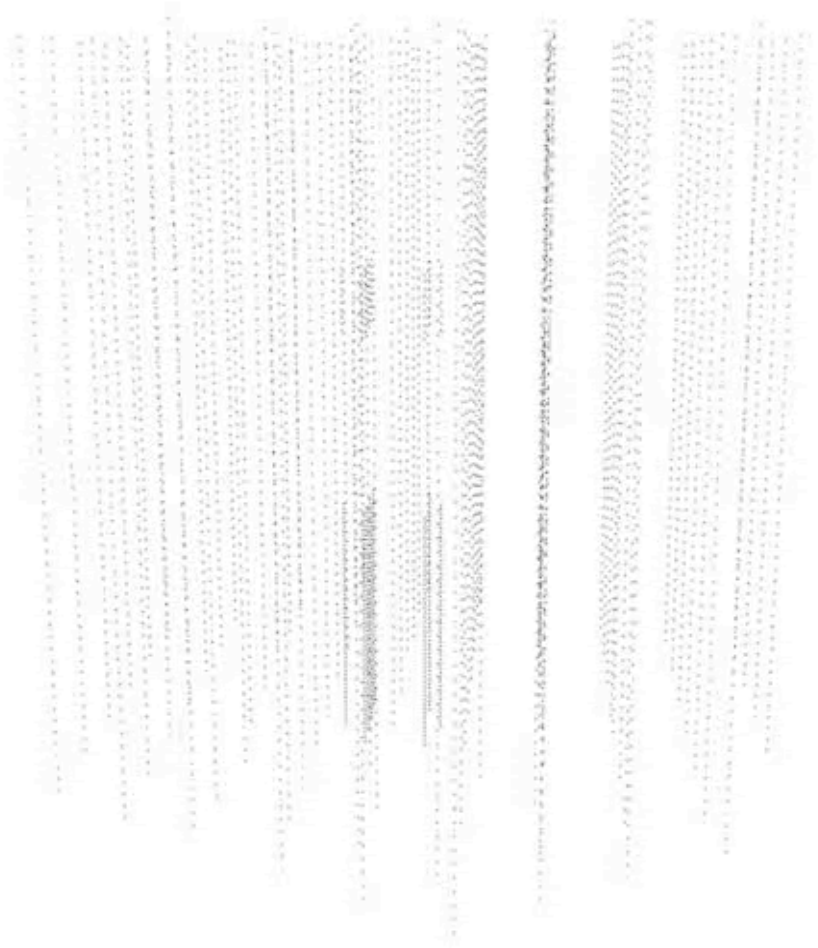




doi.org/10.5194/tc-2022-174



Backgrounds: Simulation: 1 ms of μ's and noise



Trigger rate: 3000 events/sec (muons)
Shown are also muons that will not form a trigger
noise rate: only 300 photoelectrons/s (at -30°C)

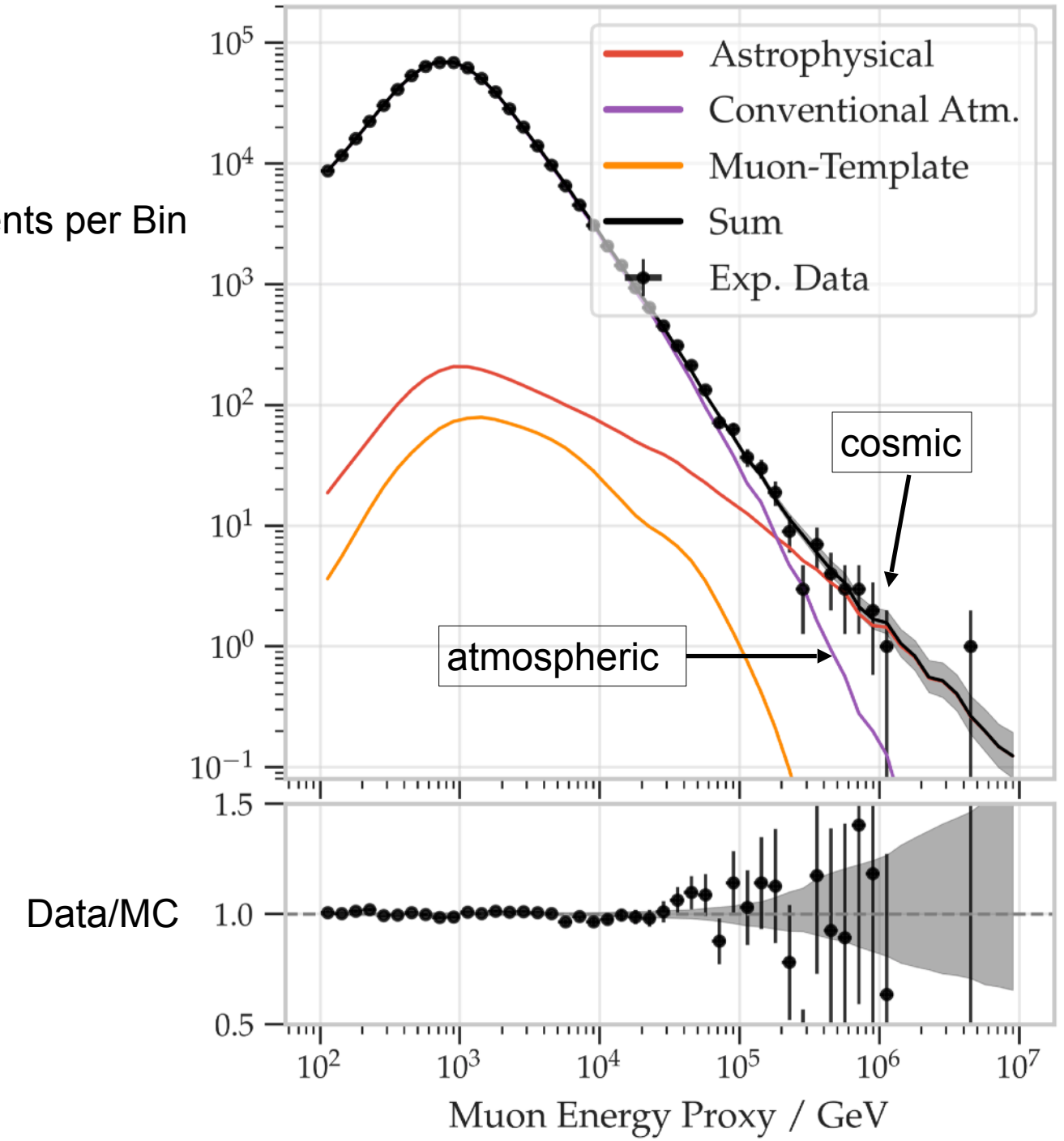
“Dr. Strangepork”

Deposited energy: 71 TeV
= 7.1 x 10^13 eV

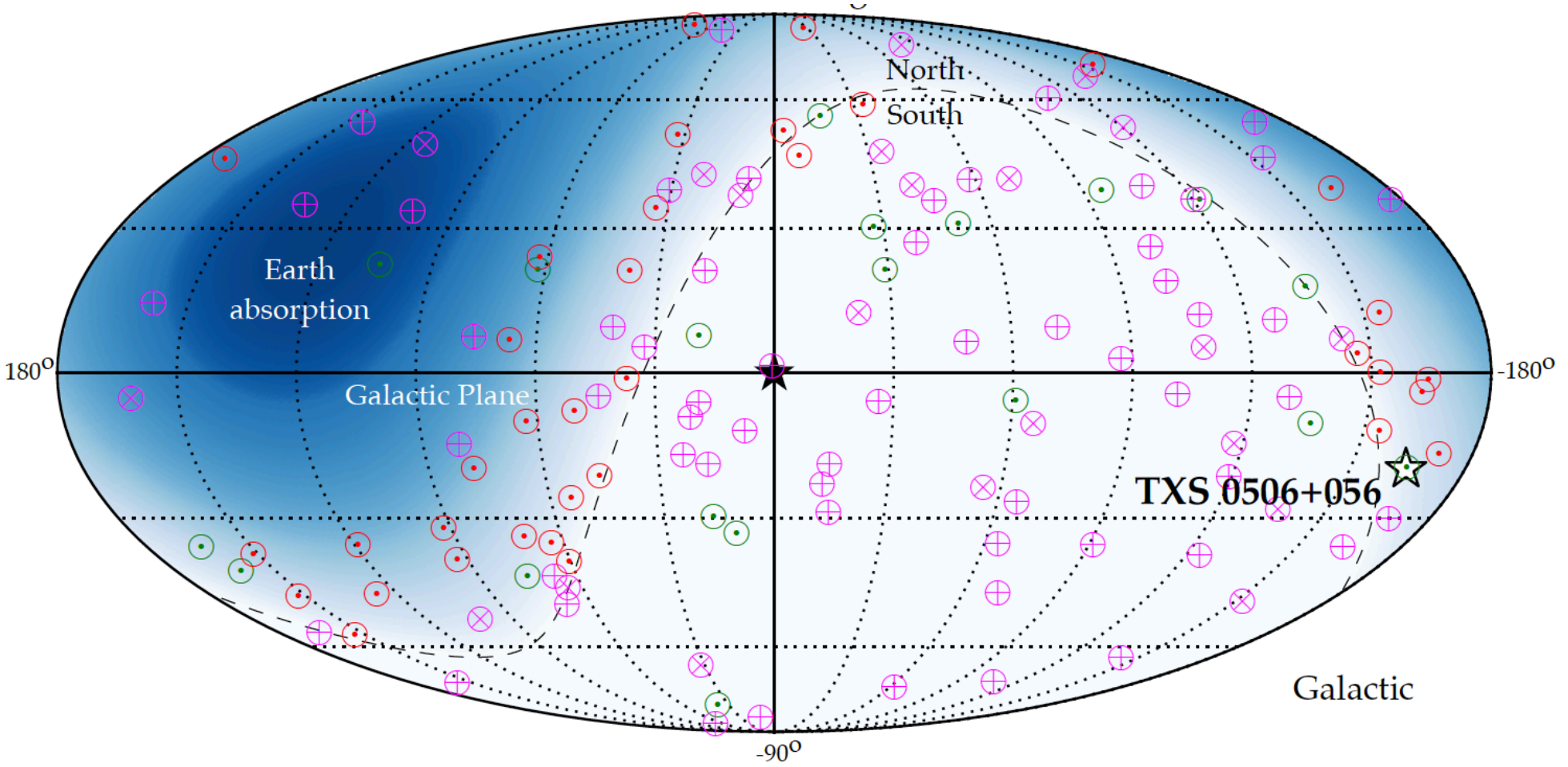
Neutrino interaction inside the detector.



muon neutrino flux filtered by the Earth: atmospheric vs cosmic

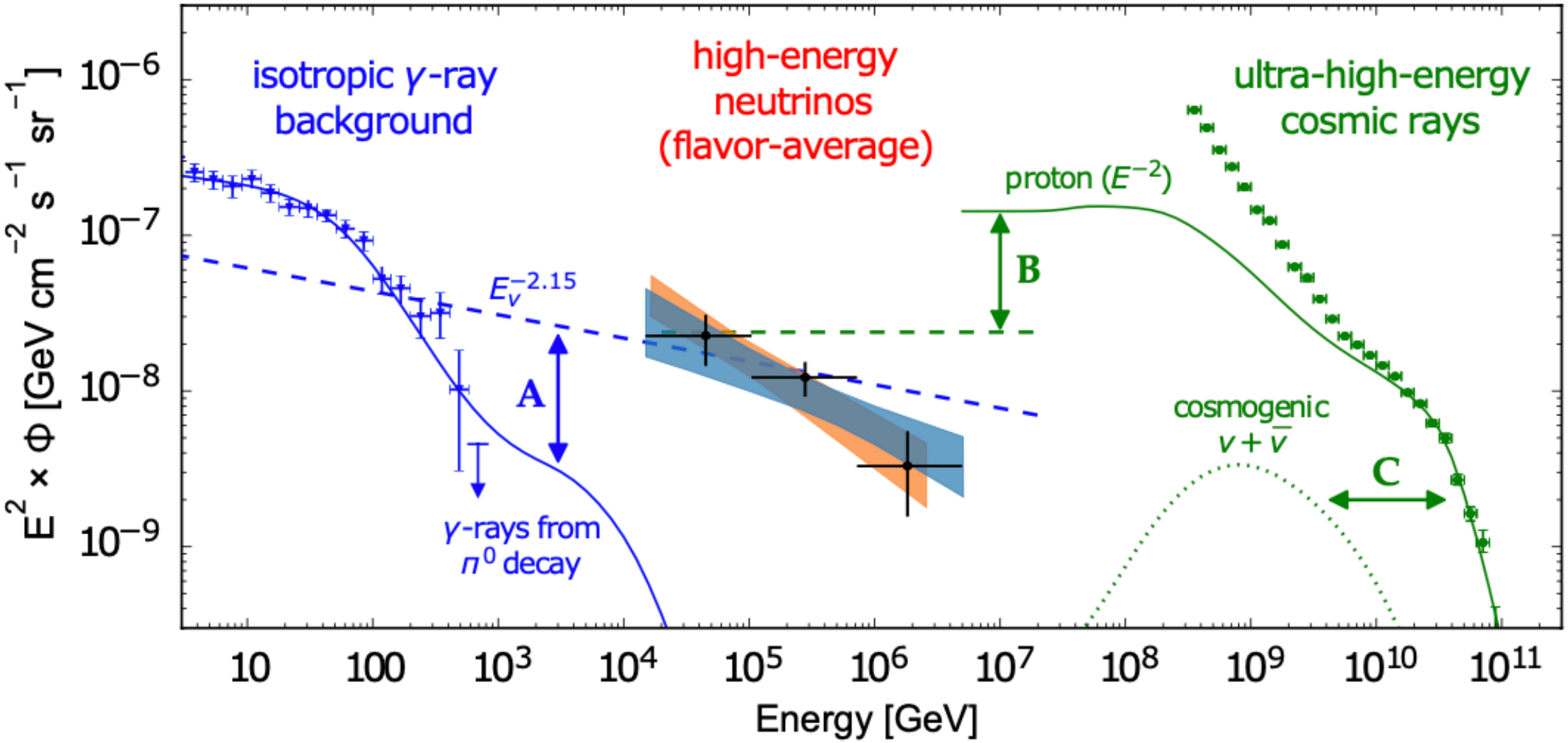


10 years of IceCube: The high energy neutrino sky

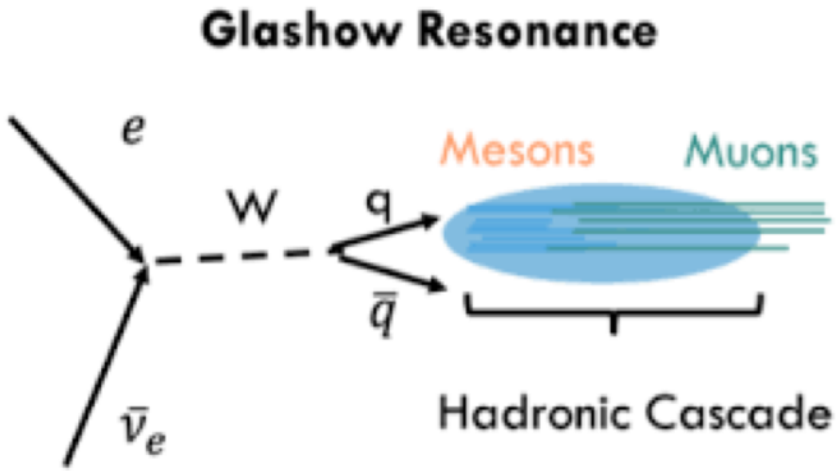


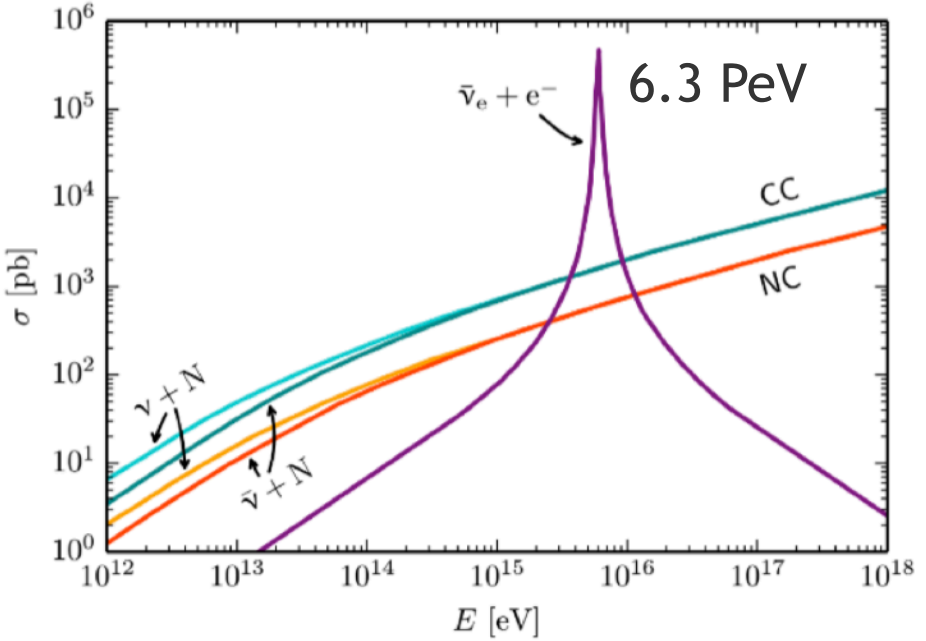
High energy events only (> 100 TeV)

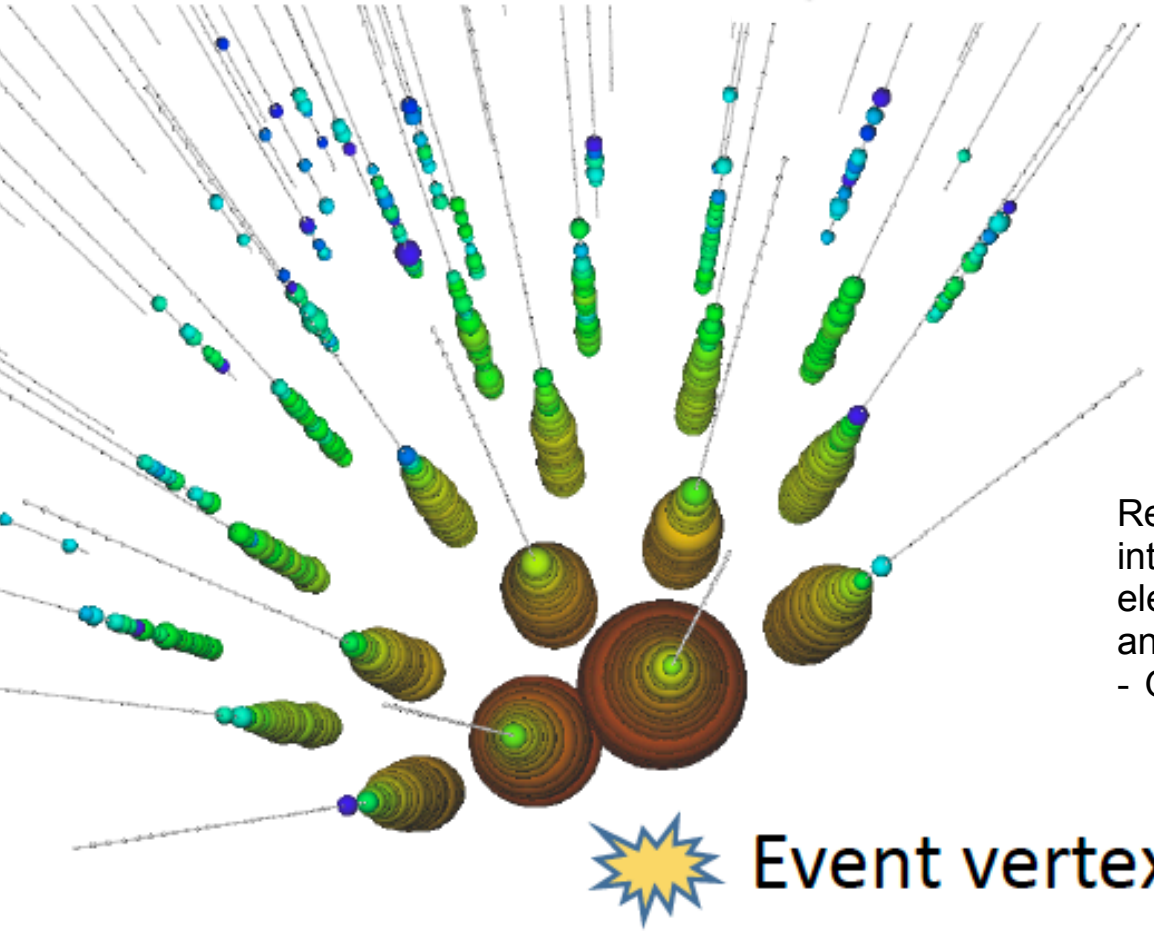
Multi-messenger Astrophysics
Non-thermal radiation: Gamma rays - Neutrinos - Cosmic Rays



Observation of a 6 PeV neutrino: “Glashow Resonance”

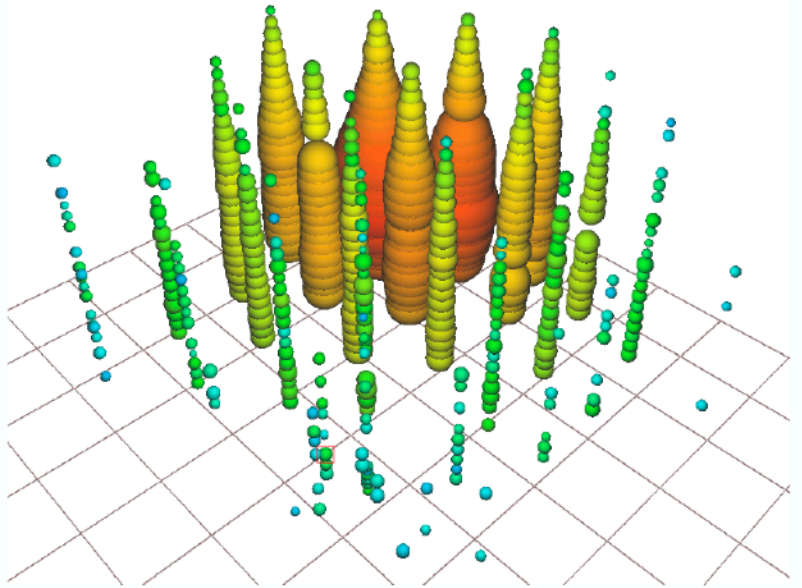




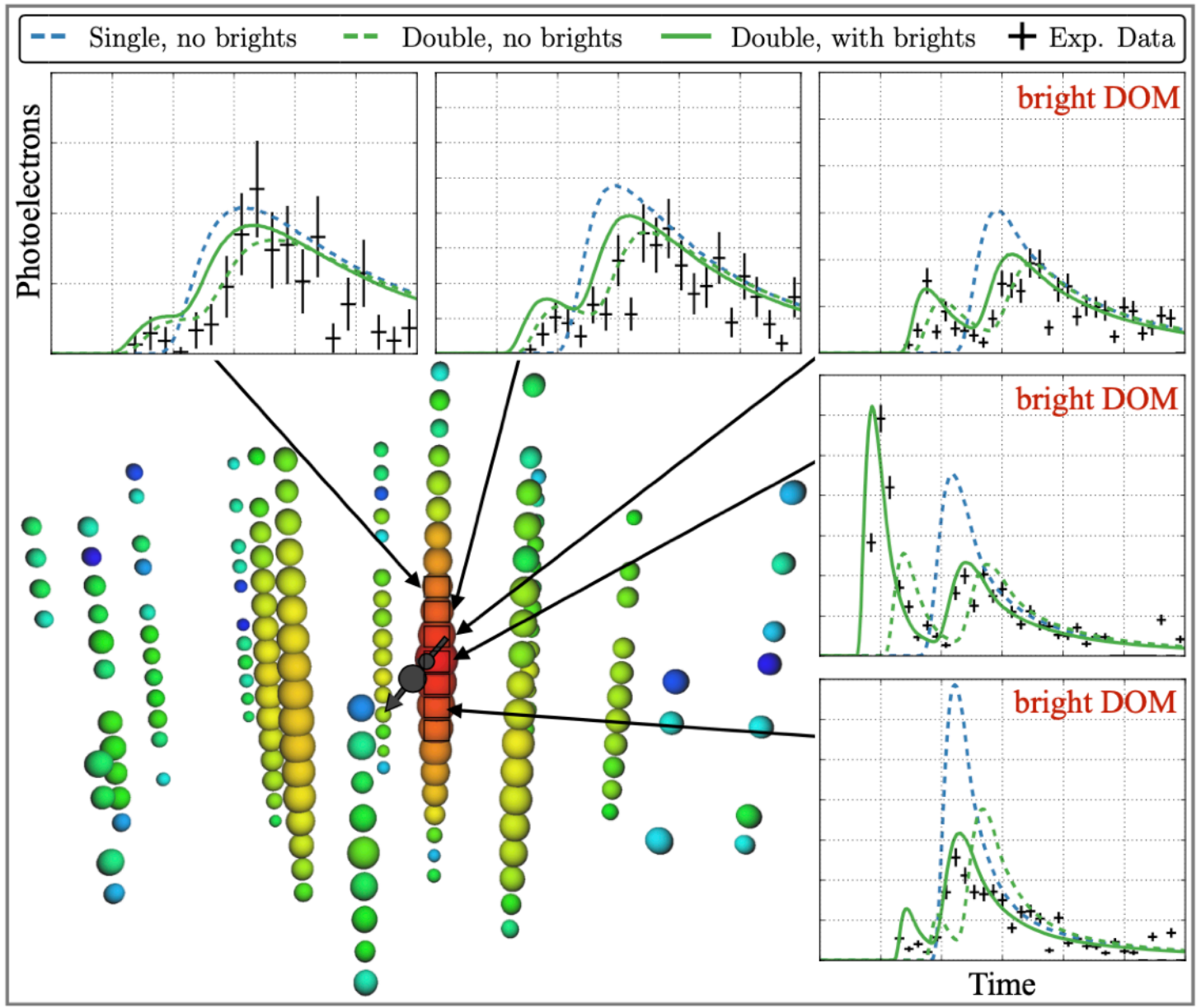


Nature **591,** 220–224 (2021)

Resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron
- Glashow resonance.



A **tau neutrino** candidate with characteristic double pulse signature



Tau signature:
"double Bang" event
1st cascade: Initial neutrino CC
2nd cascade: tau decay

Decay length: ~50m/PeV

	Event #1	Event #2
Year	2012	2014
Energy of 1st cascade	1.2 PeV	9 TeV
Energy of 2nd cascade	0.6 PeV	80 TeV
Energy Asymmetry	0.29	-0.80
Length	16 m	17 m

2013: Discovered the diffuse cosmic neutrino flux.

Next step: Search for point sources of cosmic neutrinos

Science Magazine — Nov. 4, 2022

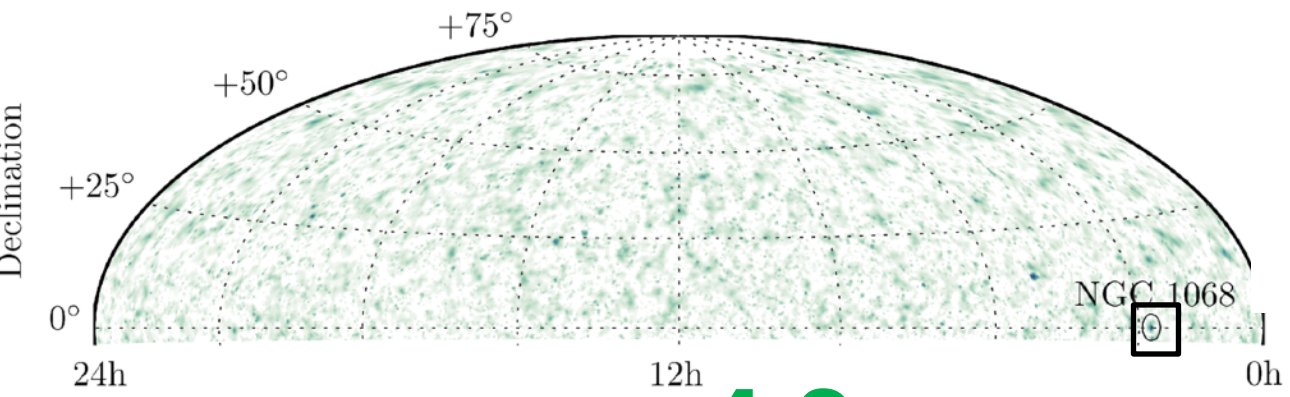
RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†



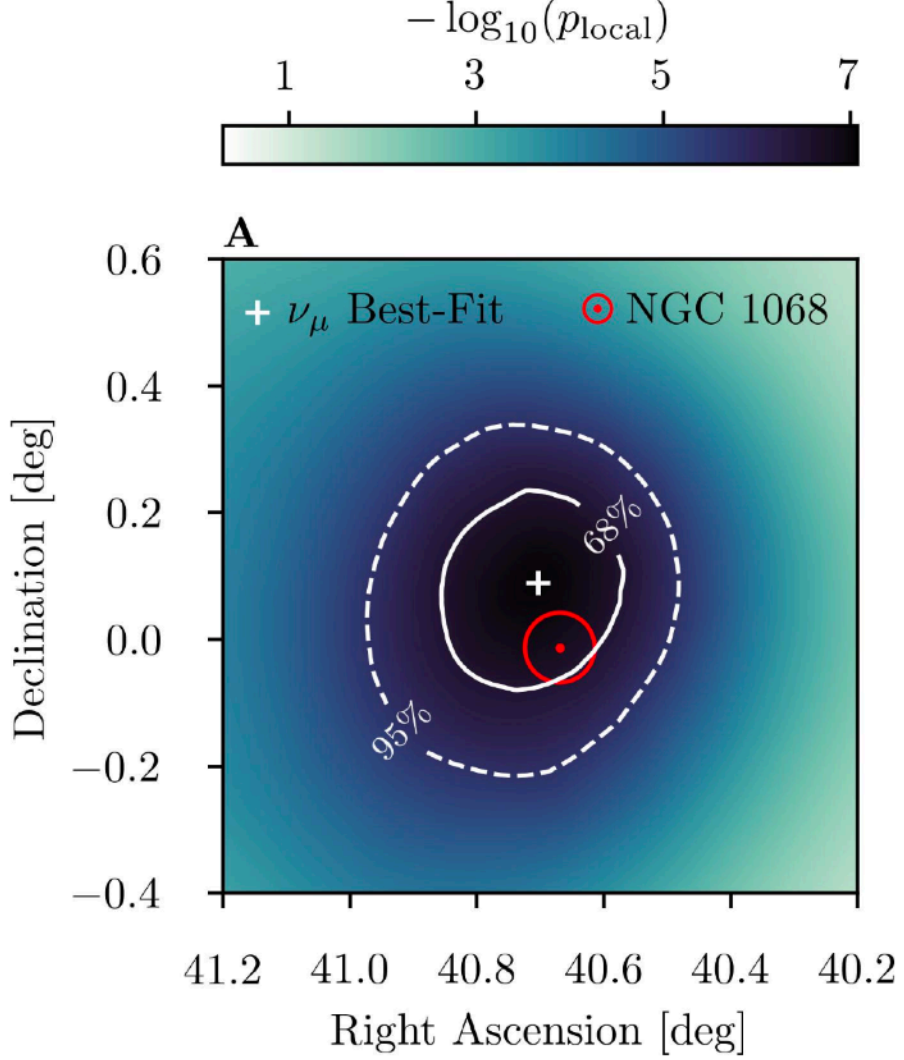
... significance **4.2σ**

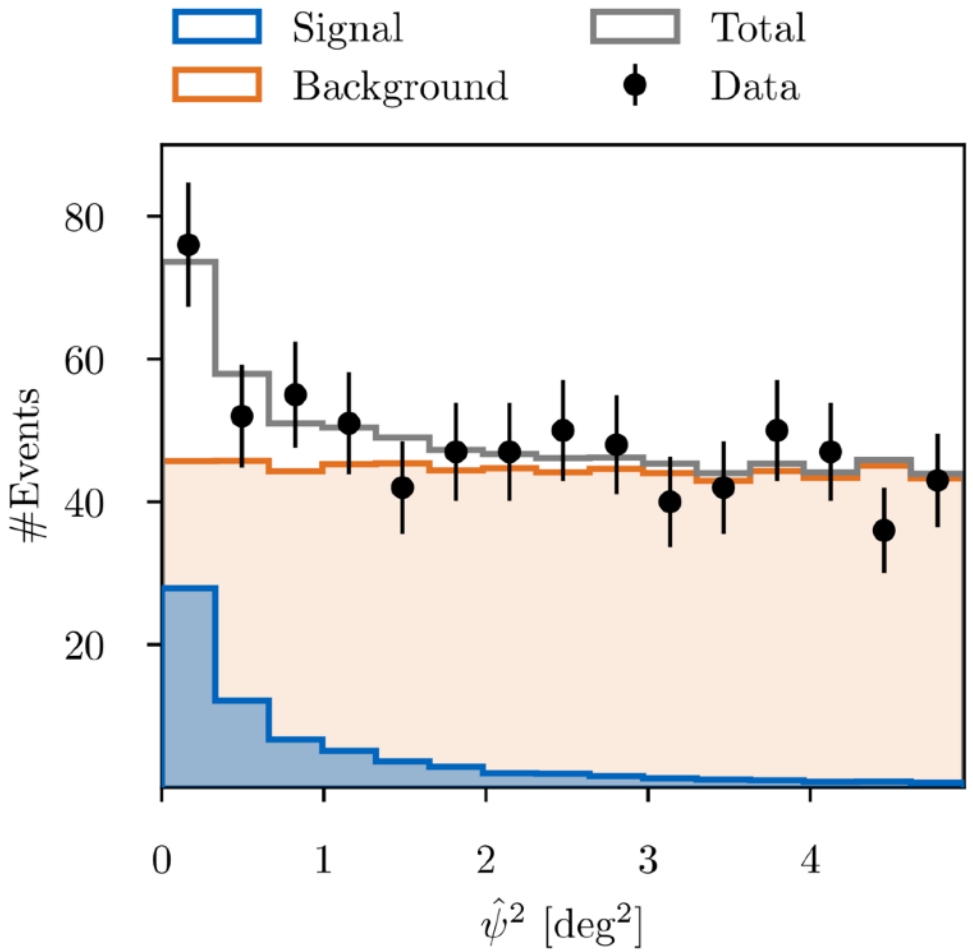
analyzed 110 gamma-ray sources (from 4FGL-DR2)

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\text{local}}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5
PKS 0019+058	BLL	5.64	6.13	1	2.4	0.4 (0.2 σ)	2.6
1ES 0033+595 (*)	BLL	8.98	59.83	0	4.3	0.0 (0.0 σ)	5.0
M 31	GAL	10.82	41.24	13	3.3	0.8 (1.0 σ)	6.2
4C +01.02	FSRQ	17.17	1.58	0	4.3	0.0 (0.0 σ)	2.1
S2 0109+22	BLL	18.03	22.75	10	2.8	0.7 (0.8 σ)	4.8
B3 0133+388	BLL	24.14	39.10	0	4.3	0.0 (0.0 σ)	3.8
TXS 0141+268	BLL	26.15	27.09	0	4.3	0.0 (0.0 σ)	3.2
MITG J021114+1051	BLL	32.81	10.86	0	4.3	0.0 (0.0 σ)	2.6
PKS 0215+015	FSRQ	34.46	1.73	2	3.9	0.2 (0.0 σ)	1.9
B2 0218+357	FSRQ	35.28	35.94	8	4.3	0.4 (0.2 σ)	4.1
3C 66A	BLL	35.67	43.04	0	4.3	0.0 (0.0 σ)	3.9
4C +28.07	FSRQ	39.47	28.80	3	2.9	0.3 (0.0 σ)	3.4
PKS 0235+164	BLL	39.67	16.62	5	3.9	0.3 (0.0 σ)	2.8
NGC 1275	RDG	49.96	41.51	8	3.0	0.5 (0.5 σ)	5.1
PKS 0336-01	FSRQ	54.88	-1.78	4	4.3	0.3 (0.1 σ)	2.1
PKS 0420-01	FSRQ	65.83	-1.33	0	4.3	0.0 (0.0 σ)	2.0
4C +41.11 (*)	BLL	65.98	41.83	0	4.3	0.0 (0.0 σ)	3.9
PKS 0422+00	BLL	66.19	0.60	0	4.3	0.0 (0.0 σ)	2.1
MG2 J043337+2905	BLL	68.41	29.10	0	4.3	0.0 (0.0 σ)	3.4
PKS 0440-00	FSRQ	70.66	-0.30	1	2.7	0.3 (0.0 σ)	2.0
S3 0458-02	FSRQ	75.30	-1.97	9	4.3	0.5 (0.4 σ)	2.4
PKS 0502+049	FSRQ	76.34	5.00	0	4.3	0.0 (0.0 σ)	2.3

Right Ascension

Albrecht Karle, UW-Madison





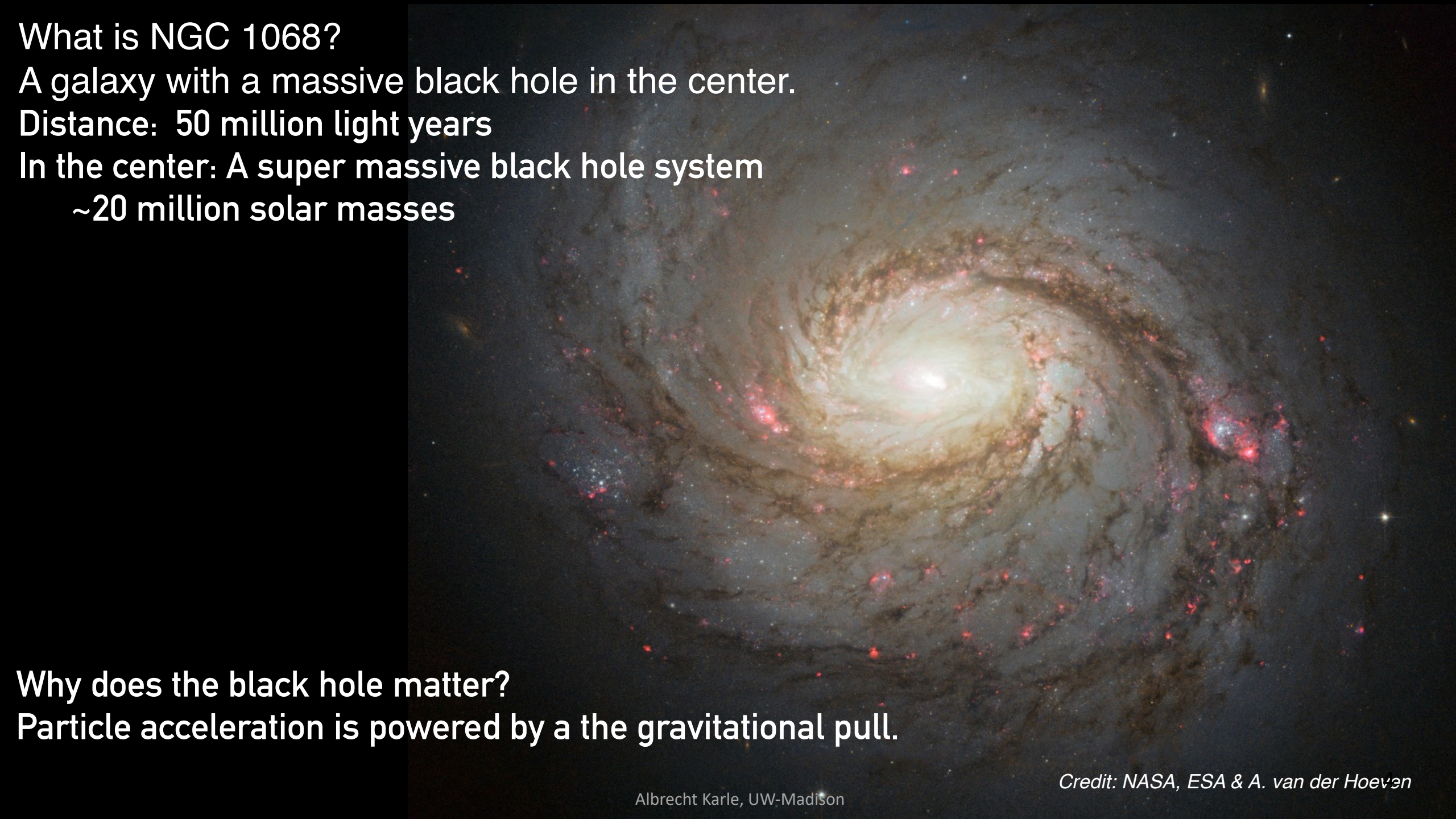
At the NGC 1068 location:

Astrophysical neutrino events = $79\ ^{+22}_{-20}$

Spectral index = 3.2 ± 0.2

NGC 1068 is consistent with location of strongest clustering of neutrinos in the sky distribution of neutrino events matches our model predictions

What is NGC 1068?
A galaxy with a massive black hole in the center.
Distance: 50 million light years
In the center: A super massive black hole system
~20 million solar masses



Why does the black hole matter?
Particle acceleration is powered by a the gravitational pull.

Credit: NASA, ESA & A. van der Hoeven

NGC 1068



(insert: artist conception)

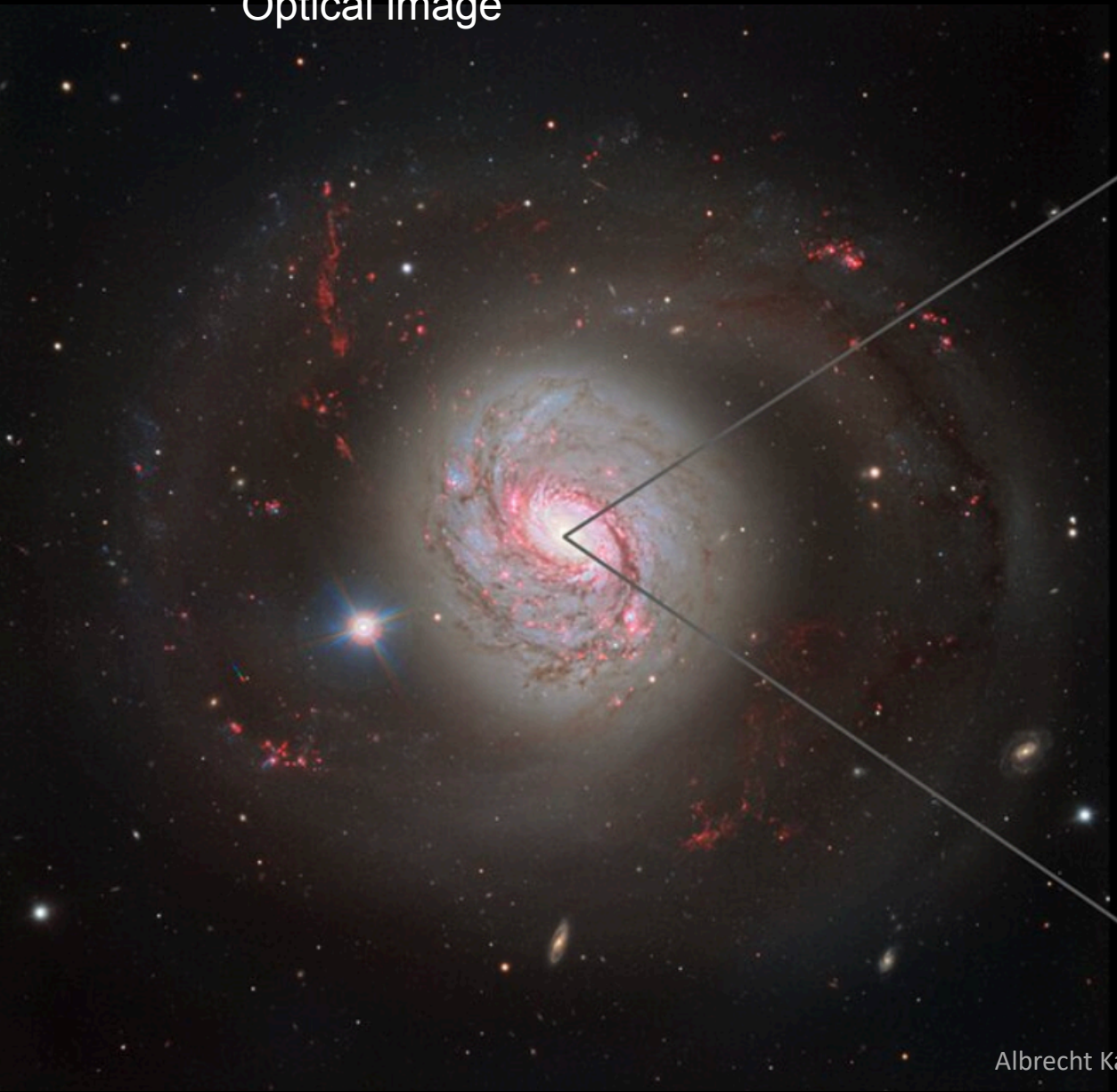
Credit: NASA/JPL-Caltech

NGC 1068: The black hole region is obscured by dust.

Optical image

Infrared image confirms dust cloud surrounding black hole

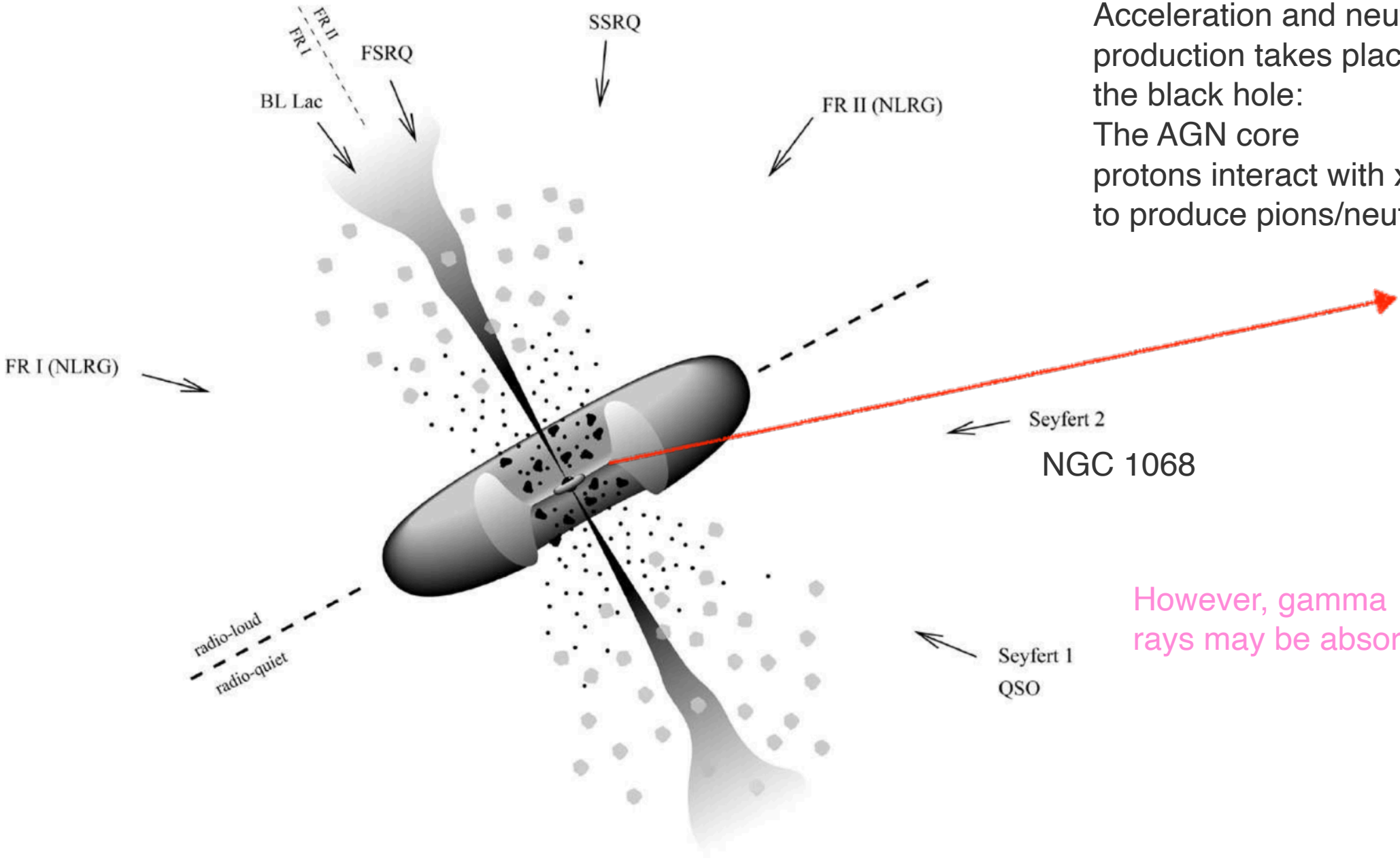
(Neutrinos don't care about dust.)





Rosas et al., Nature, volume 602, pages, 403–407 (2022)

Models:
Acceleration and neutrino production takes place close to the black hole:
The AGN core
protons interact with x-ray photons to produce pions/neutrinos



However, gamma rays may be absorbed.

How are neutrinos produced in non-jetted AGNs?

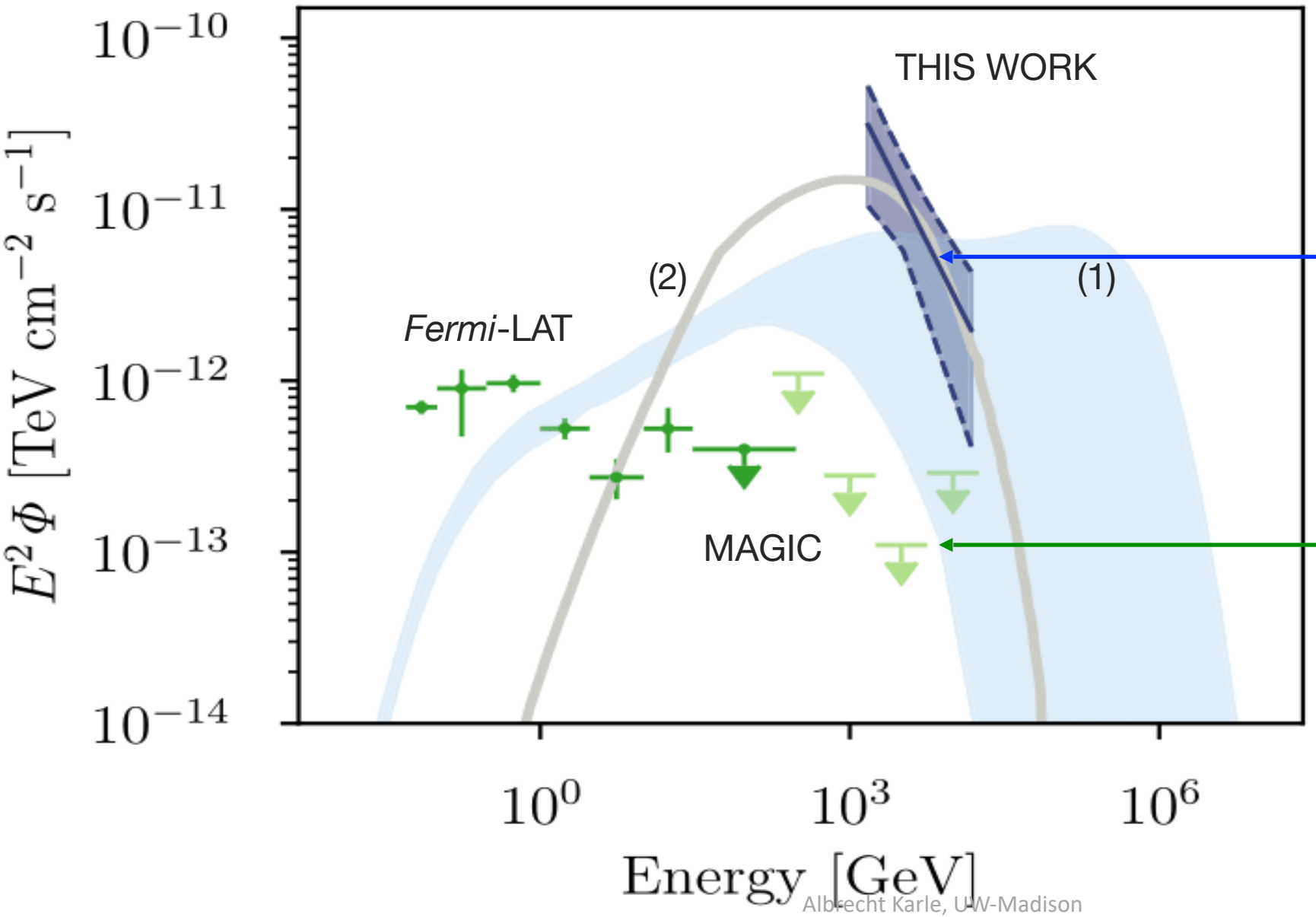
We conclude that active galactic nuclei are powerful sources for accelerating particles to cosmic ray energies. The bulk of meta-galactic cosmic rays is likely to ori
particular, in the Virgo supercluster
NGC 4151 and NGC 1068 are likely to b
"local" metagalactic cosmic rays, inc
the ultra-high energy ($E \geq 10^{19}$ eV) a
density of photons in the immediate v
be too high (Blumenthal, 1970) to permit the acceleration of protons beyond $\sim 10^{14}$ eV, (except by beaming processes). The highest energy protons hence are accelerated somewhat farther out, or else by beaming (Lovelace, 1976). Gamma rays from the ergosphere of a black hole are degraded at energies above $\sim$ 1 MeV, and from a spinar, above $\sim$ 1 GeV. Neutrinos are not thus affected and would provide information on very high energy particles in active galactic nuclei.

R. Silberberg and M. M. Shapiro

Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D.C. 20375

1982

Gamma Rays (photons) and Neutrinos



We know that neutrinos and gamma rays are produced together

Neutrinos flux observed

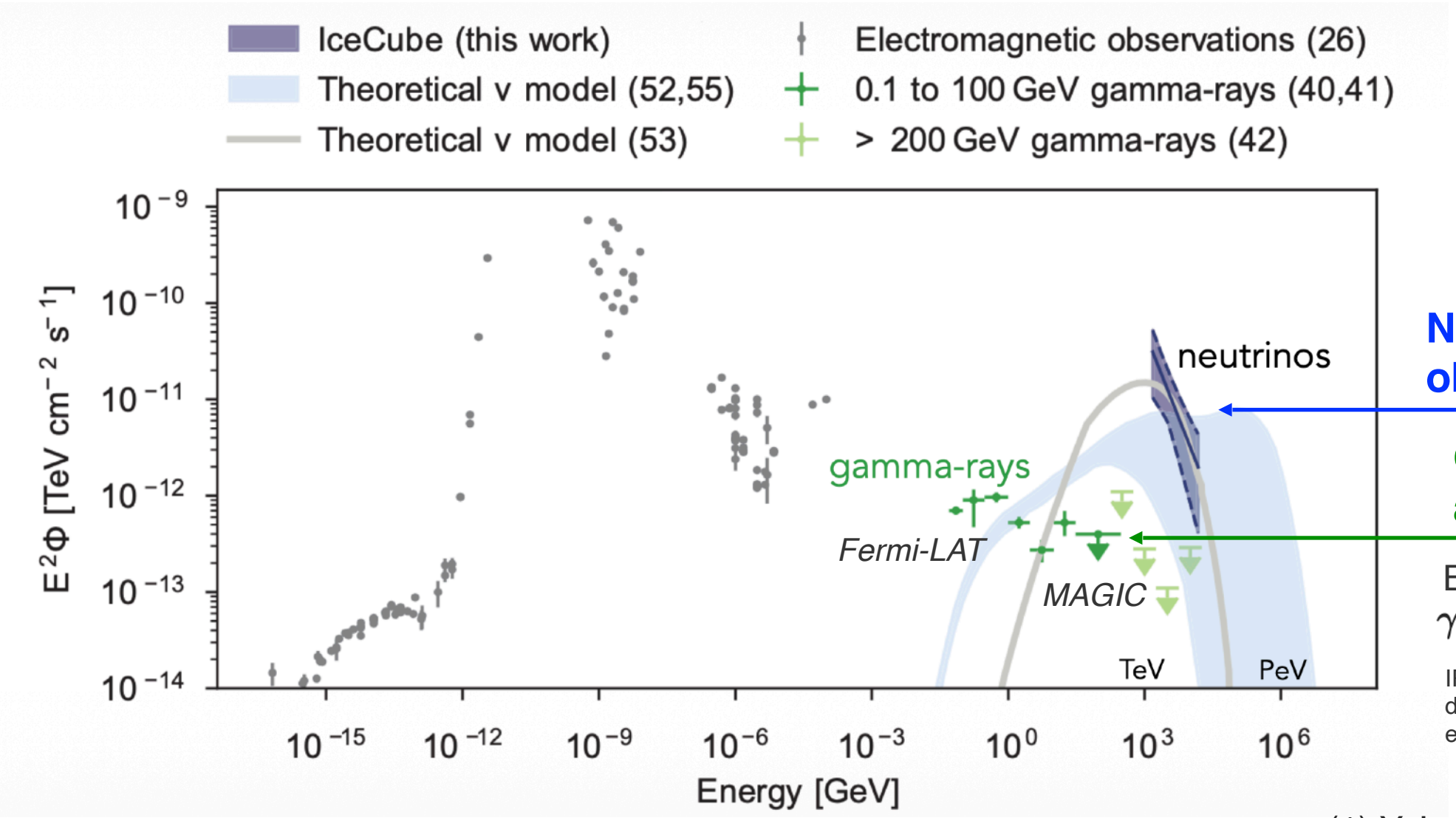
Gamma rays are missing

-

(1) Y. Inoue et al., ApJL'20

(2) K. Murase et al., PRL'20

NGC 1068: Energy spectrum



Neutrinos flux observed

Gamma rays are missing!

Basic picture:

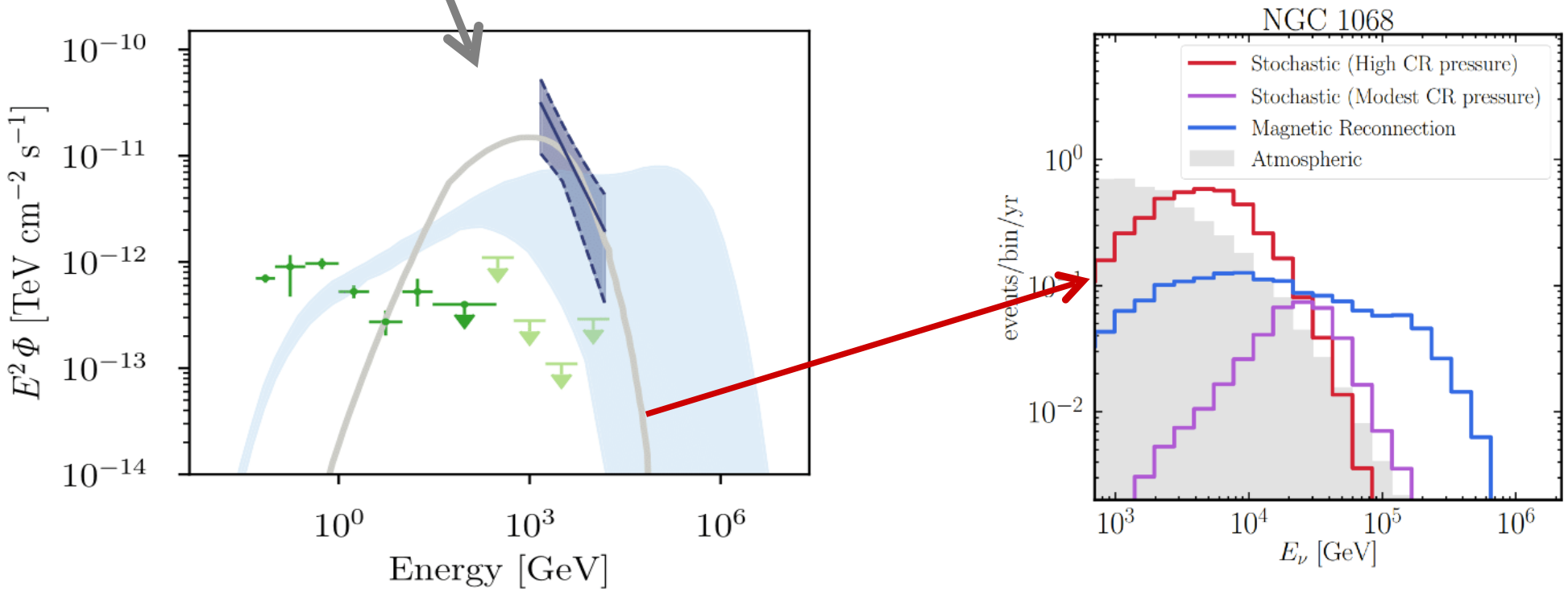
$$\gamma_{\rm TeV} + \gamma_{\rm IR} \rightarrow e^+e^-$$

IR field associated dust torus (heats up, absorbs and re-emits in IR)

(1) Y. Inoue et al., ApJL'20

(2) K. Murase et al., PRL'20

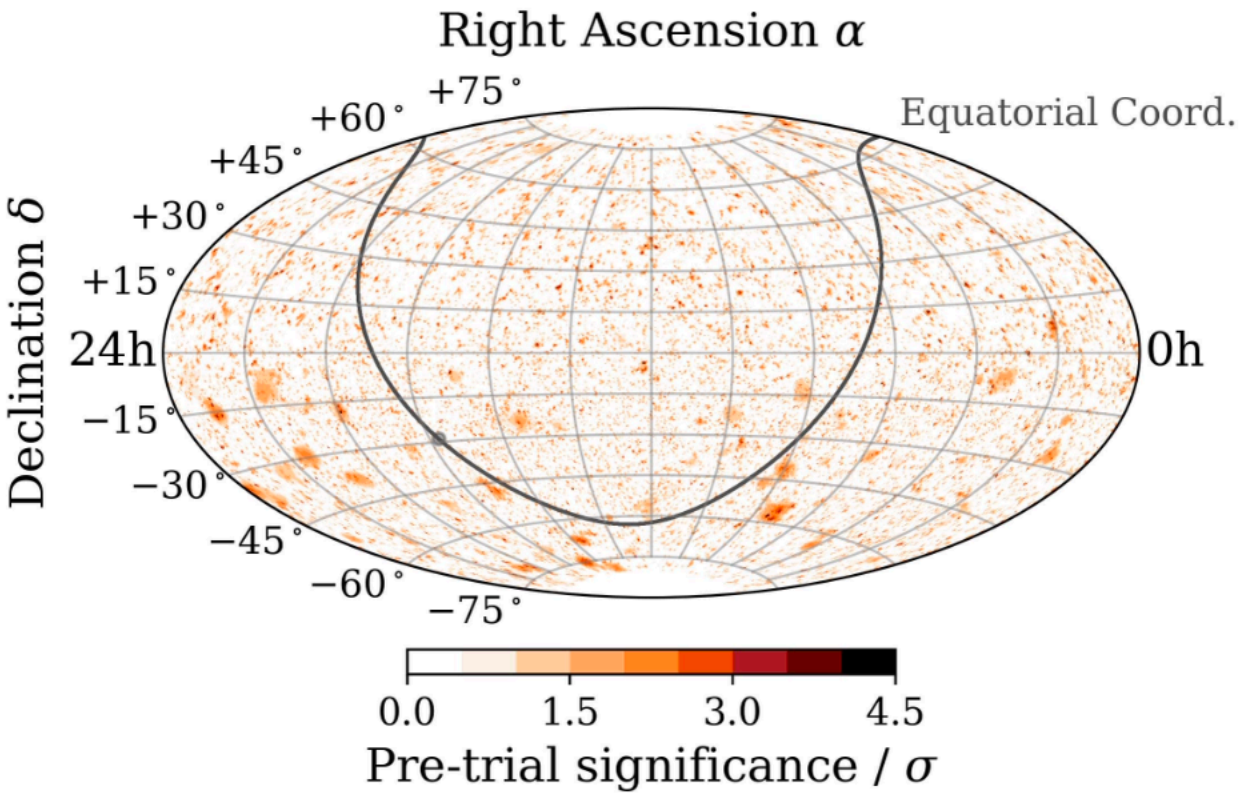
optimistic disc-corona scenario (Kheirandish et al., 2021) can match measured flux



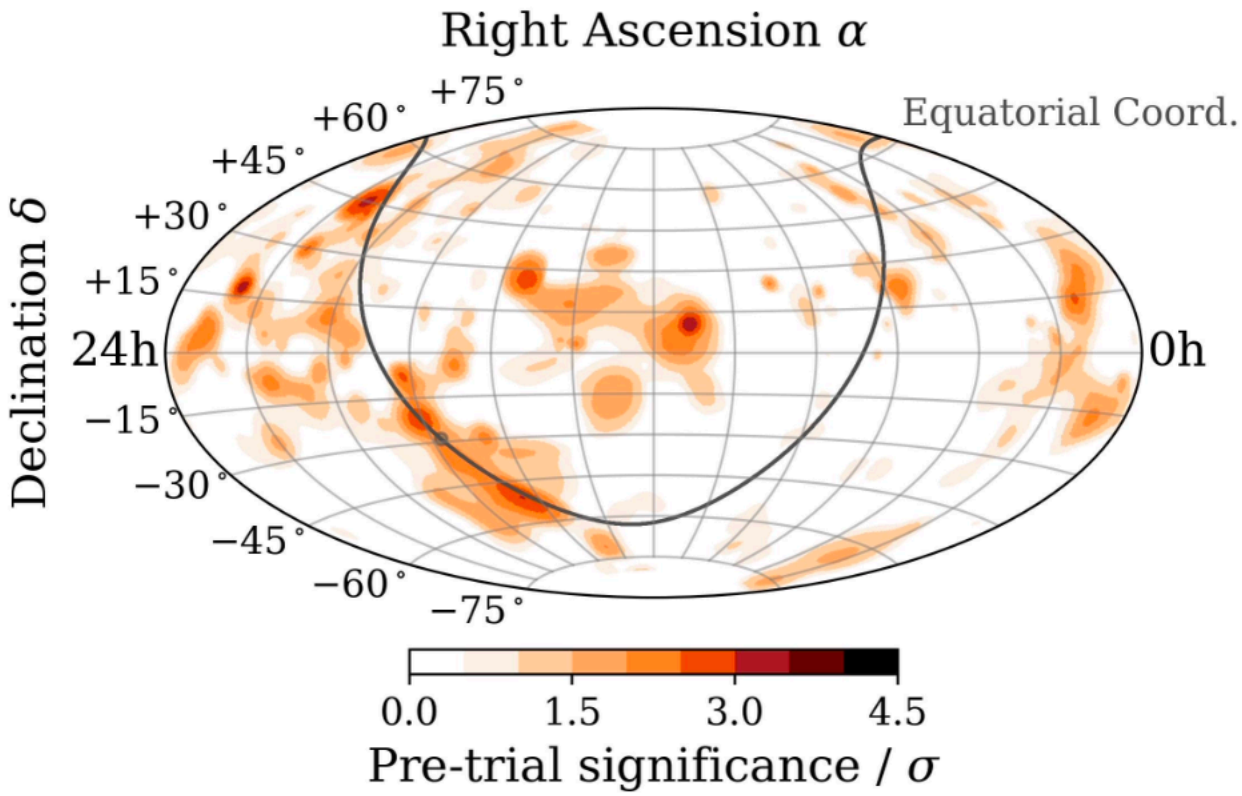
The Neutrino Sky as Seen by IceCube

All-sky neutrino point-source search with IceCube combined track and cascade data

Data: 14 years
1.64 x 10^6 track events



59.6 x 10^3 cascade events

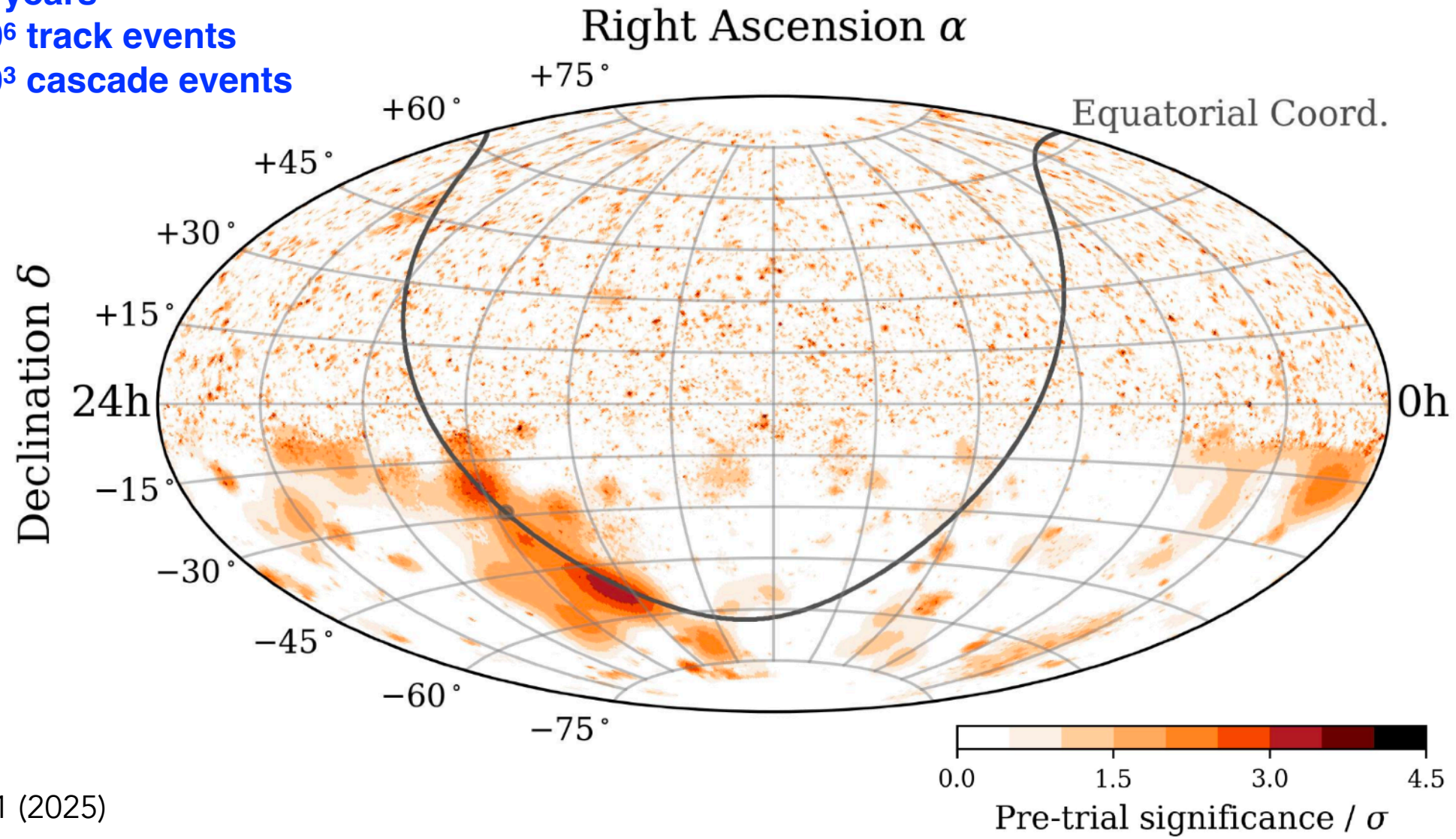


ApJ 995,11 (2025)

The Neutrino Sky as Seen by IceCube

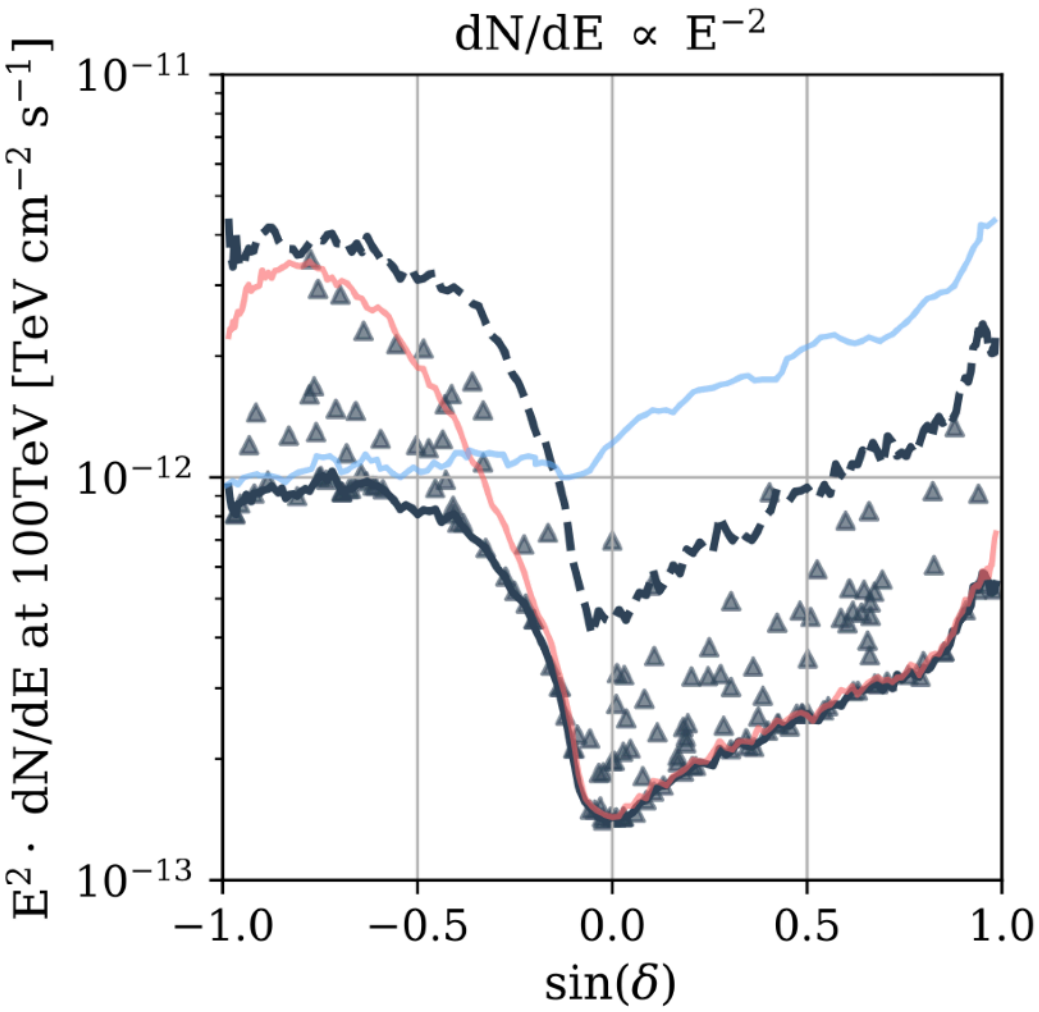
All-sky neutrino point-source search with IceCube combined track and cascade data

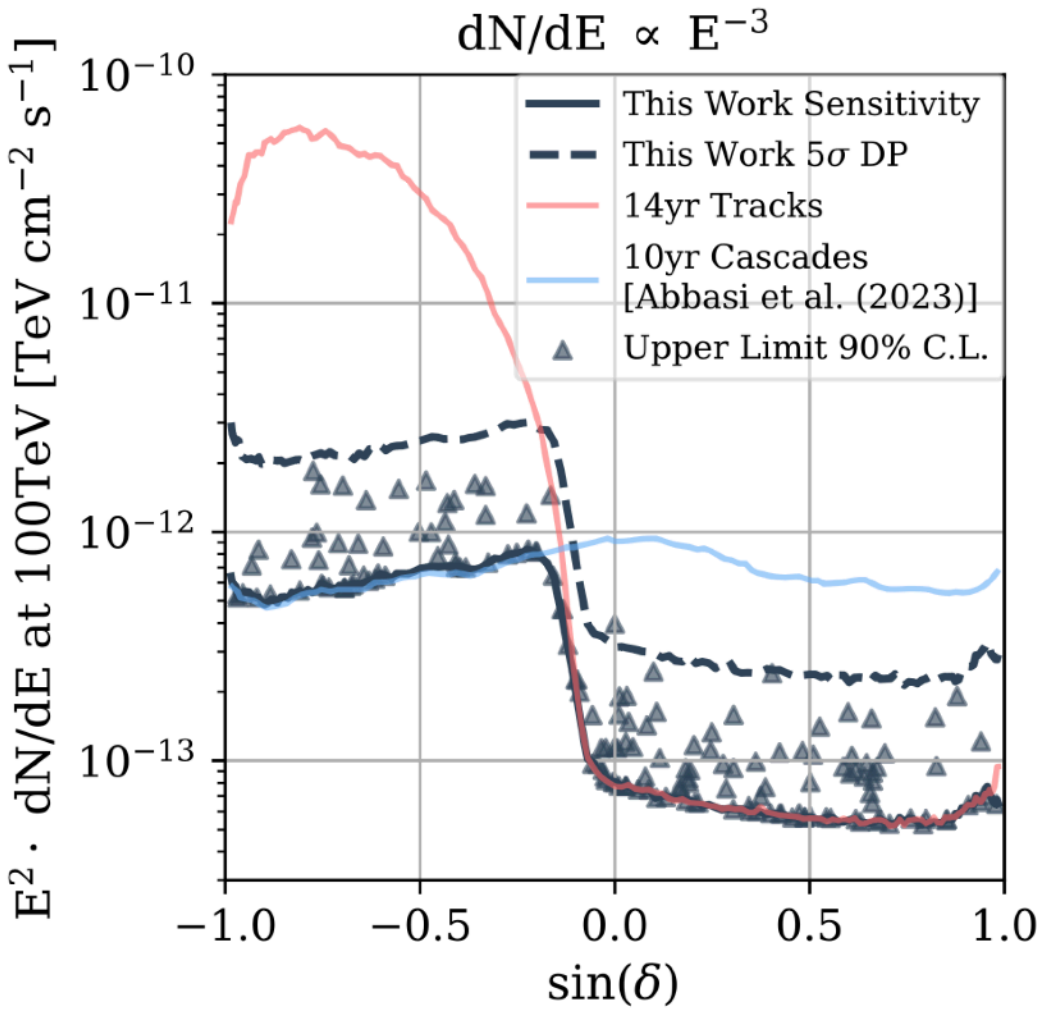
Data: 14 years
1.64 x 10^6 track events
59.6 x 10^3 cascade events



ApJ 995,11 (2025)

Source list: sensitivity, discovery potential and upper limits

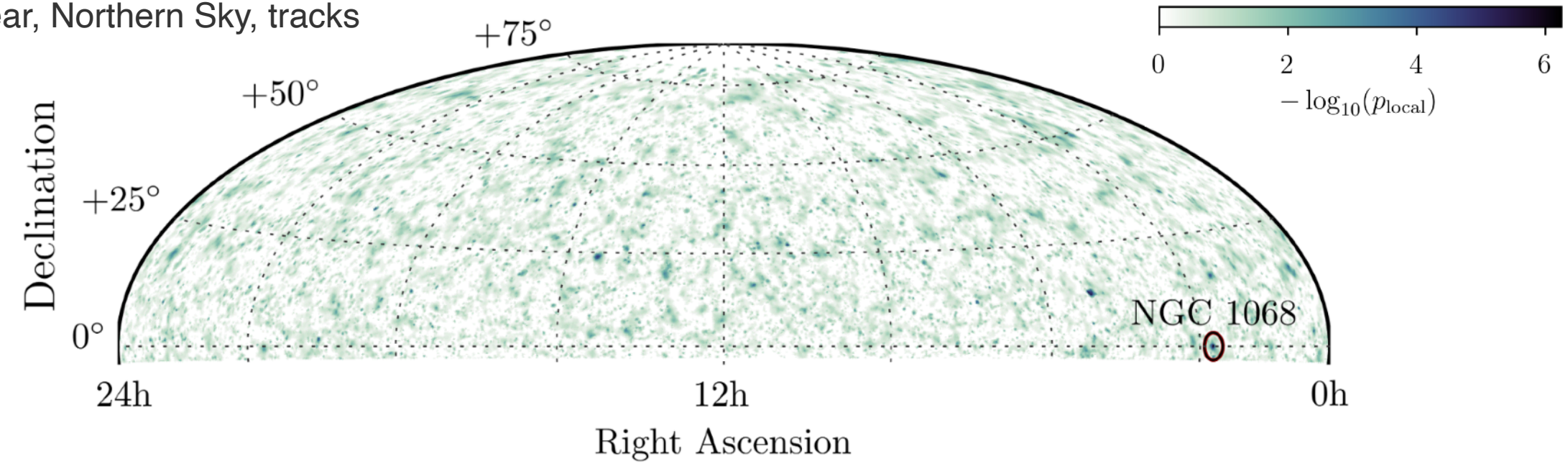




Evidence for Neutrino Emission from X-ray Bright Active Galactic Nuclei

ApJL 1000,26 (2026)

Data: 13 year, Northern Sky, tracks

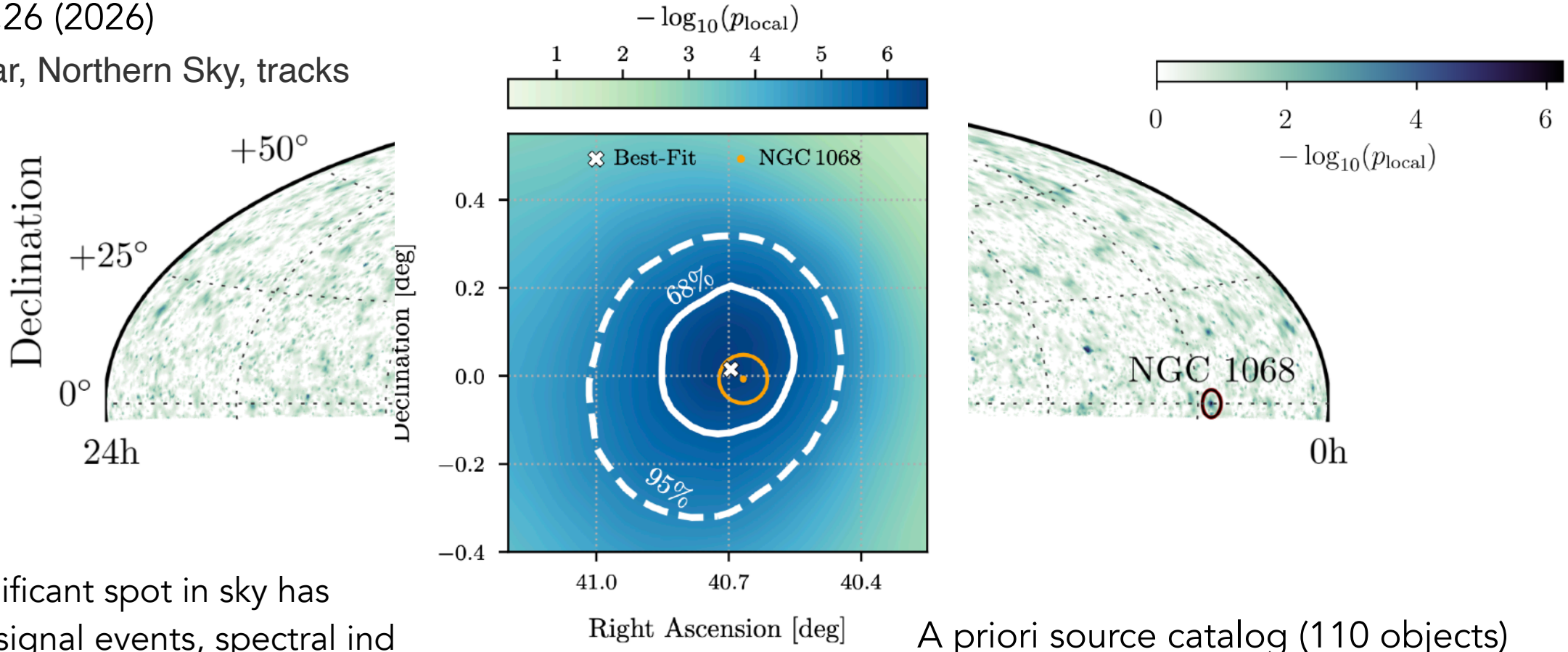


Most significant spot in sky has
ns = 102 signal events, spectral index = 3.4
Local significance: 5.0 **σ**
8% of scrambled data sets have a 5 **σ**
hotspot somewhere
Not significant in context of entire skymap.

Evidence for Neutrino Emission from X-ray Bright Active Galactic Nuclei

ApJL 1000,26 (2026)

Data: 13 year, Northern Sky, tracks



Most significant spot in sky has
ns = 102 signal events, spectral ind
Local significance: 5.0 **σ**
8% of scrambled data sets have a 5 **σ** hotspot somewhere
Not significant in context of entire skymap.

A priori source catalog (110 objects)
Most significant object: NGC 1068
Having a 5 **σ** source in catalog is rare
➔ 4.0 **σ** significance

Evidence for Neutrino Emission from X-ray Bright Active Galactic Nuclei

		R.A.	Dec.	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\text{local}}$	$-\log_{10} p_{\text{global}}$
Northern Sky Survey	Hottest Spot	40.69	0.02	102.6	3.4	6.6 (5.0σ)	1.1 (1.4σ)
110 gamma-ray sources							
Most significant source	NGC 1068	40.67	−0.01	102.2	3.4	6.6 (5.0σ)	4.5 (4.0σ)
Binomial test	3 Sources					4.8 (4.2σ)	2.9 (3.0σ)
Other sources in binomial excess	PKS 1424+240	216.76	23.80	96.3	3.6	4.1 (3.8σ)	–
	TXS 0506+056	77.36	5.69	4.9	1.9	3.4 (3.3σ)	–
47 X-ray bright AGN							
Most significant source	NGC 7469	345.82	8.87	5.5	1.9	4.1 (3.8σ)	2.1 (2.4σ)
Binomial test	11 Sources					4.8 (4.2σ)	3.3 (3.3σ)
Other sources in binomial excess	NGC 4151*	182.64	39.41	27.6	2.7	2.9 (3.1σ)	–
	CGCG 420-015*	73.36	4.06	35.3	2.7	2.4 (2.7σ)	–
	Cygnus A*	299.87	40.73	3.4	1.6	2.2 (2.5σ)	–
	LEDA 166445	42.68	54.70	57.1	4.4	1.8 (2.1σ)	–
	NGC 4992	197.27	11.63	27.3	2.9	1.6 (2.0σ)	–
	NGC 1194*	45.95	−1.10	43.2	4.4	1.5 (1.8σ)	–
	Mrk 1498	247.02	51.78	39.9	3.6	1.4 (1.7σ)	–
	MCG +4-48-2*	307.15	25.73	36.7	3.2	1.4 (1.7σ)	–
	NGC 3079	150.49	55.68	33.8	3.6	1.3 (1.7σ)	–
	Mrk 417	162.38	22.96	4.4	2.0	1.3 (1.6σ)	–

There is a cosmic neutrino flux at high energies.

Active Galactic Nuclei, specifically Seyfert type galxies, are leading candidates to be neutrino sources at TeV energies.

- evidence for neutrinos from nearby Seyfert galaxy NGC 1068 (4 sigma level)
- follow-up study of X-ray bright AGN, inspired by this observation and theroretical work suggests that these sources form a population of neutrino sources (3.3 sigma)

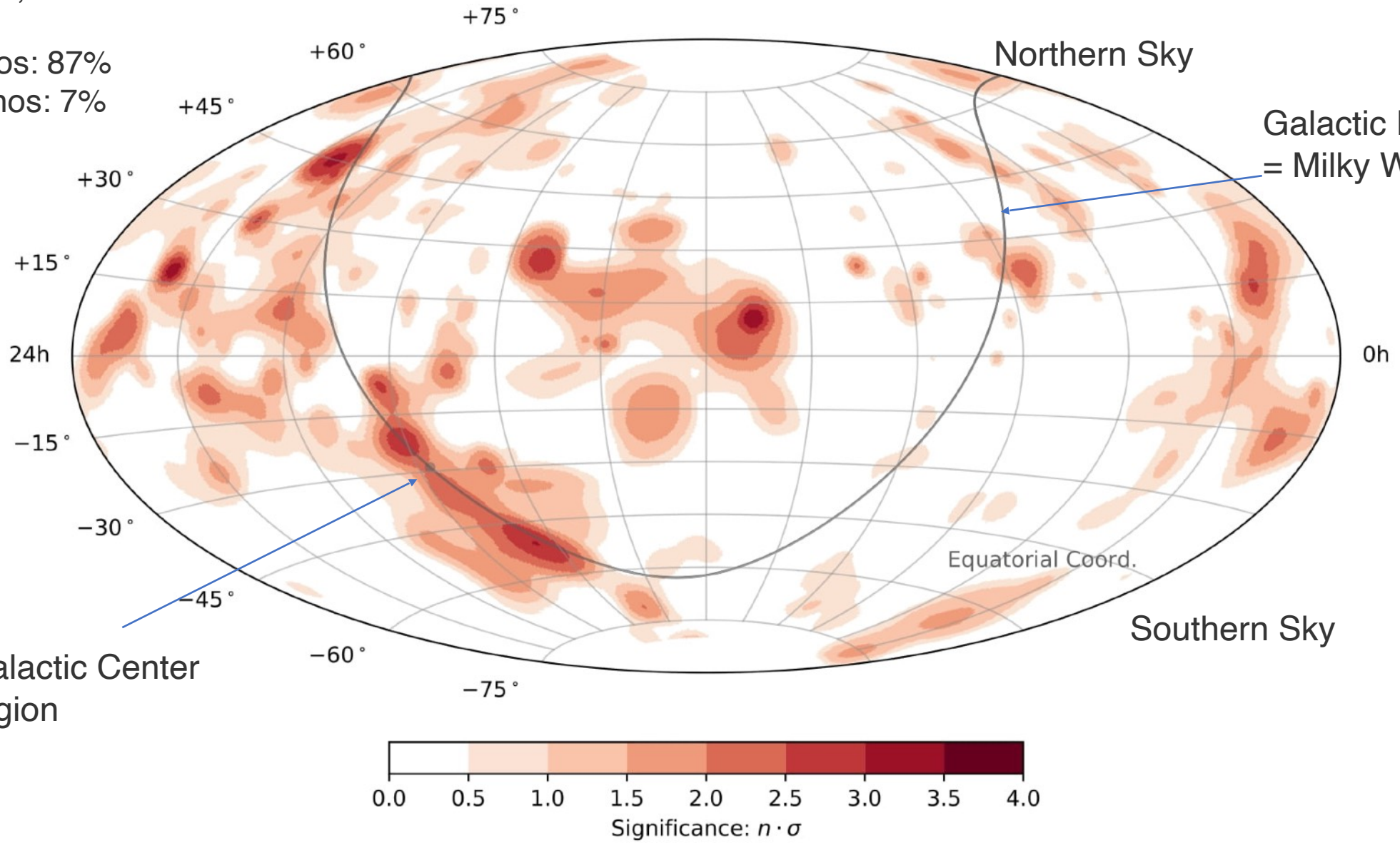
Neutrinos from the Milky Way



Credit: Yuya Makino, IceCube/NSF

IceCube Skymap of neutrinos optimized for the search for extended sources.

Number of events: 59,592
Cosmic rays: 6%
Atmospheric neutrinos: 87%
Astrophysical neutrinos: 7%



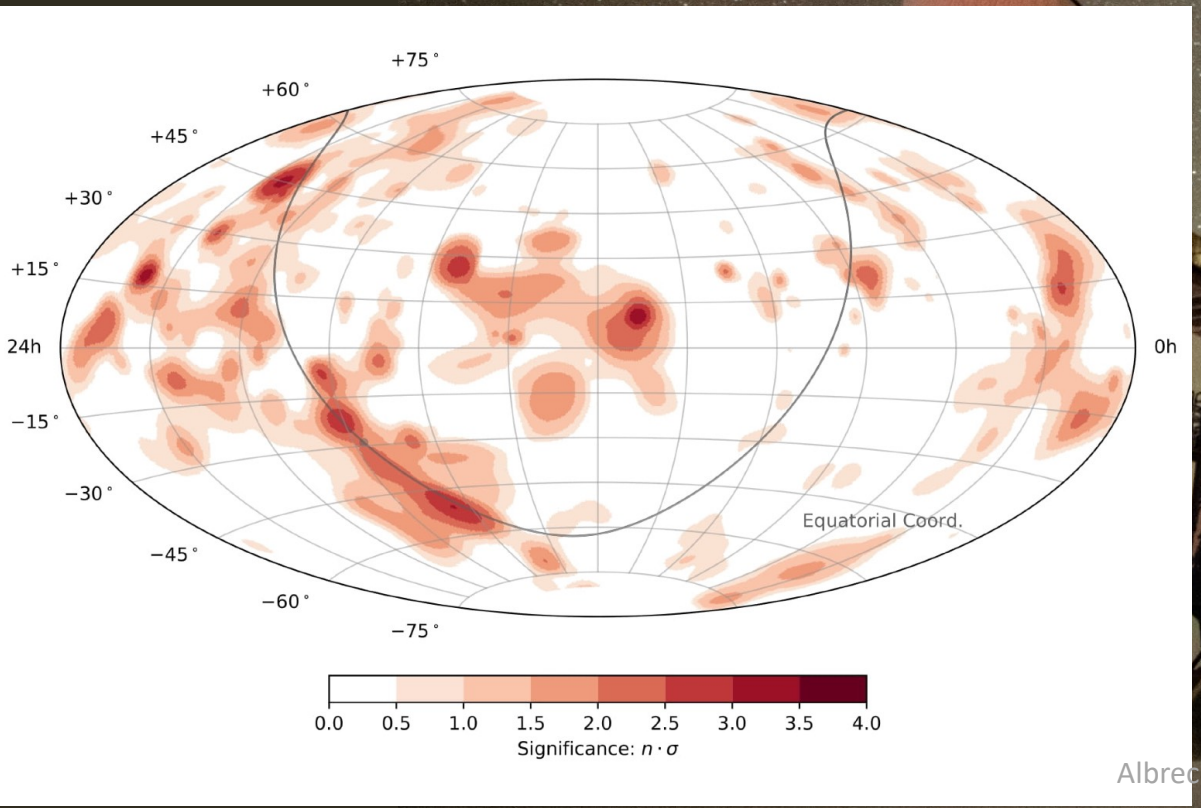
Northern Sky

Galactic Plane
= Milky Way

Southern Sky

Galactic Center
region

Neutrinos from the Milky Way

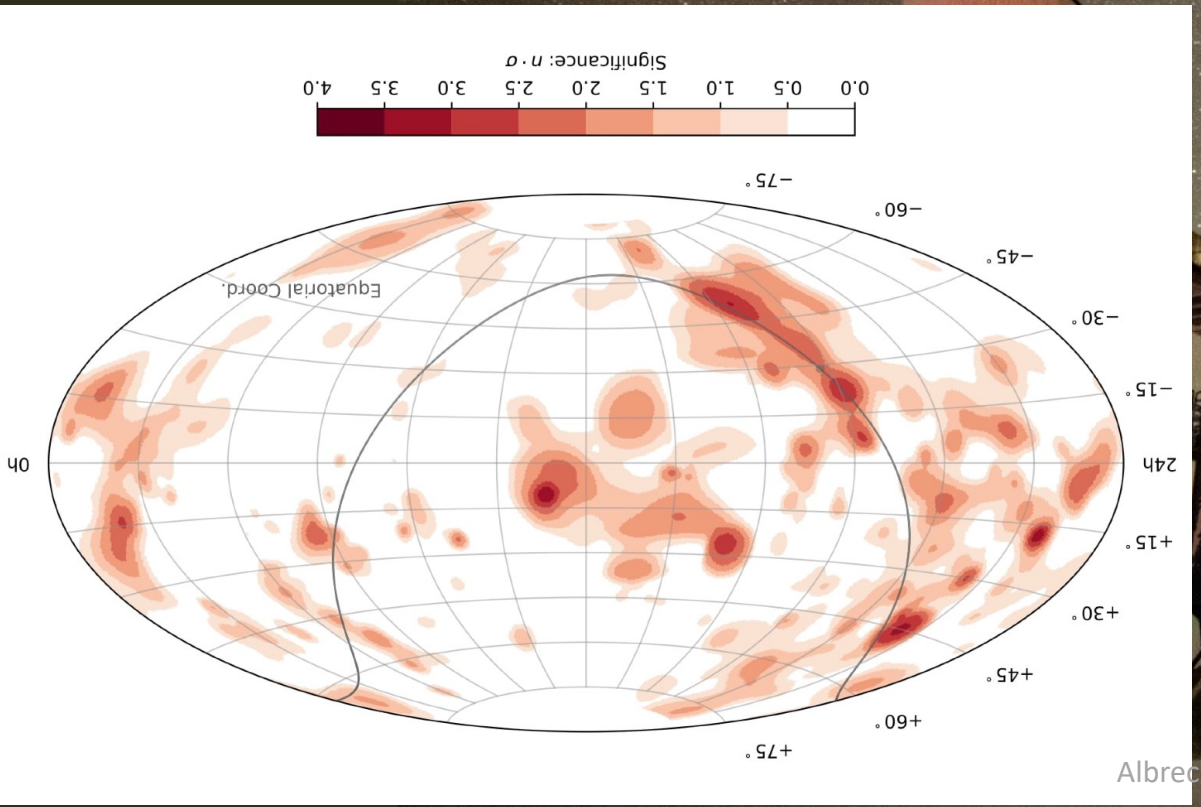


Credit: Yuya Makino, IceCube/NSF

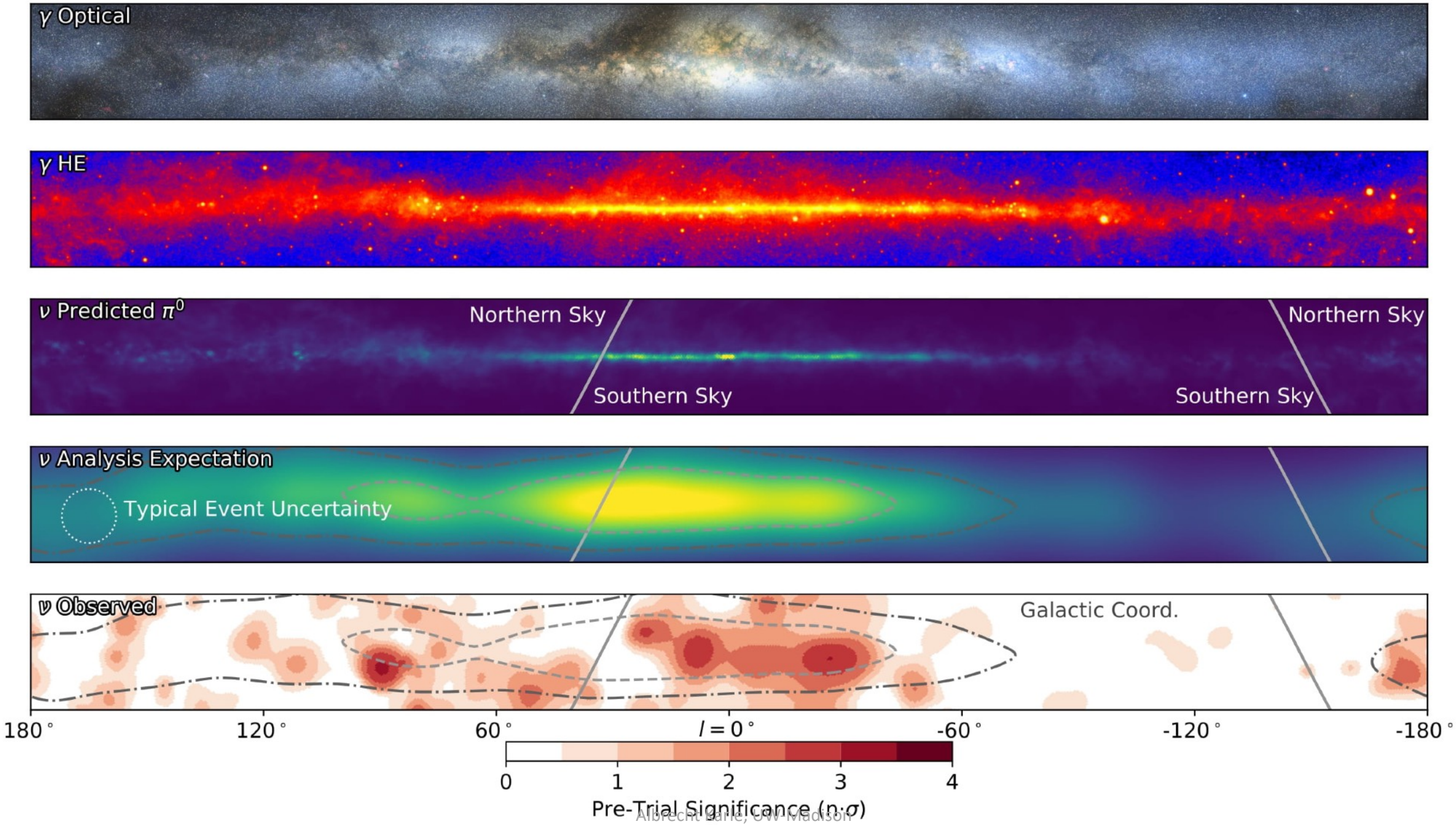
Neutrinos from the Milky Way

Neutrino flux in Milky Way less than average in the Universe?

“Is the Milky Way a neutrino desert?”

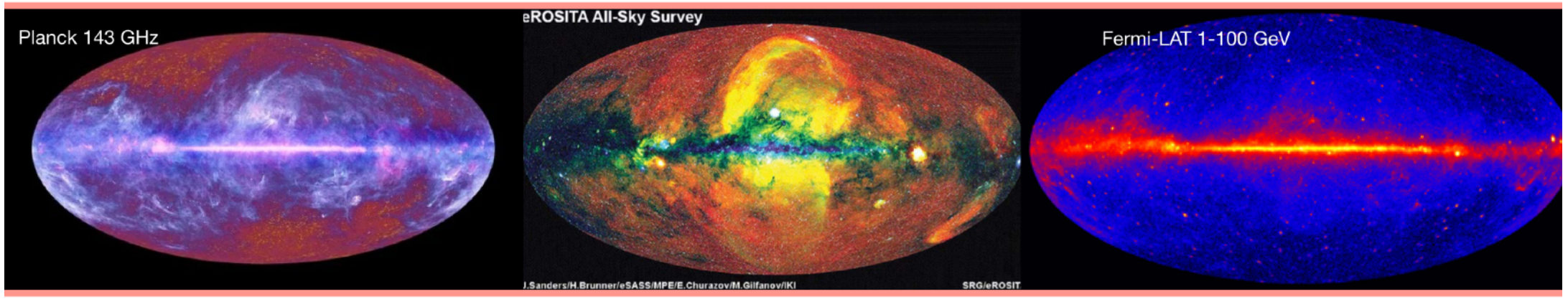


Credit: Yuya Makino, IceCube/NSF

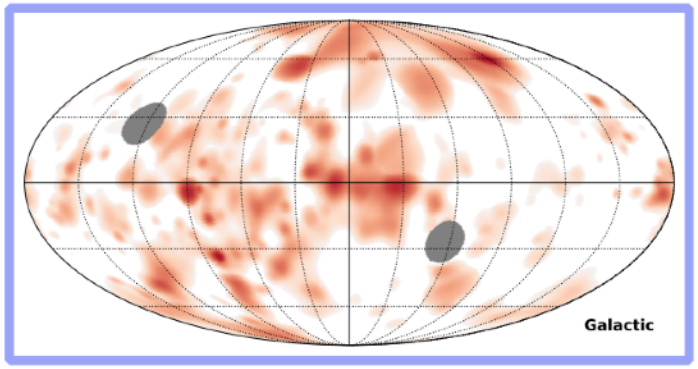


Albrecht Karle, UW-Madison

The Universe in Radio, X-ray, Gamma-ray Lights



The Universe in Neutrino



IceCube Collaboration, *Science (2023)*

The IceCube Observatory detects the Milky Way in 2023. In **neutrino**, the Galactic Plane is not much brighter than the extragalactic background, as it is in **photon.**

Neutrino flux in Milky Way less than average in the Universe by an order of magnitude.

The “Milky Way as neutrino desert” **Halzen, Gallagher, Fang, Nature Astronomy, 2023**

2026: High-energy neutrino emission from the Milky Way

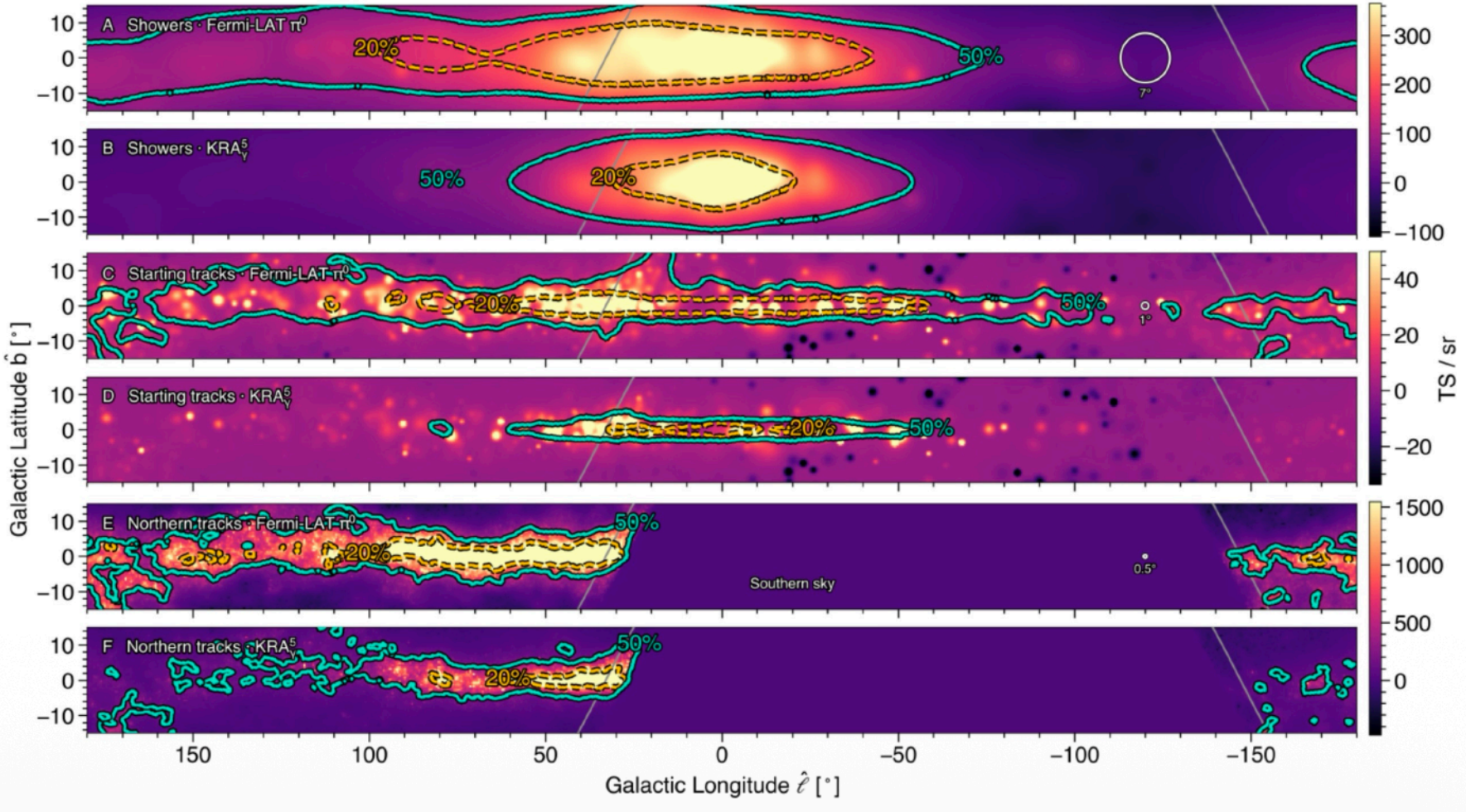
arXiv:2607.25966

5.7 σ Observation of the Galactic Plane

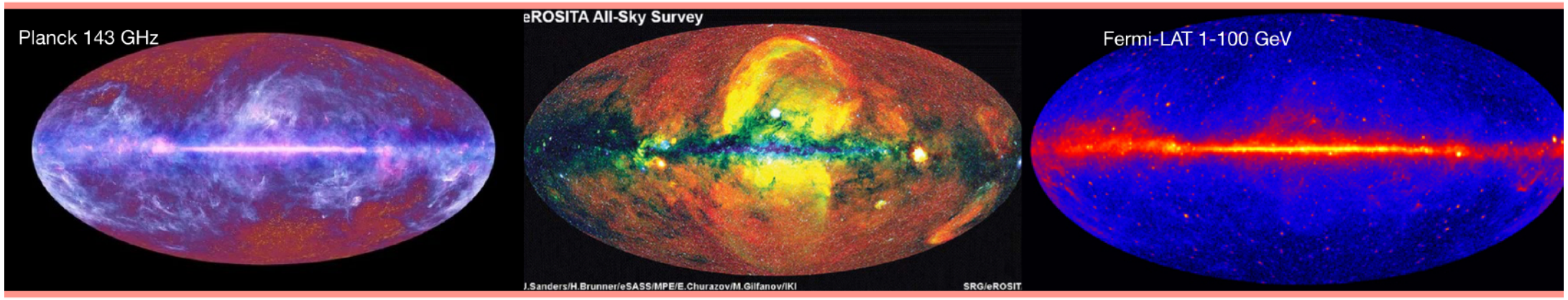
Larger sample combining:
- Cascades (showers)
- Starting Tracks (S Sky)
- Tracks (N Sky)

Four different templates of galactic plane neutrino emission tested (shown here, Fermi-LAT π^0, KRA_γ^5 for each data sample)

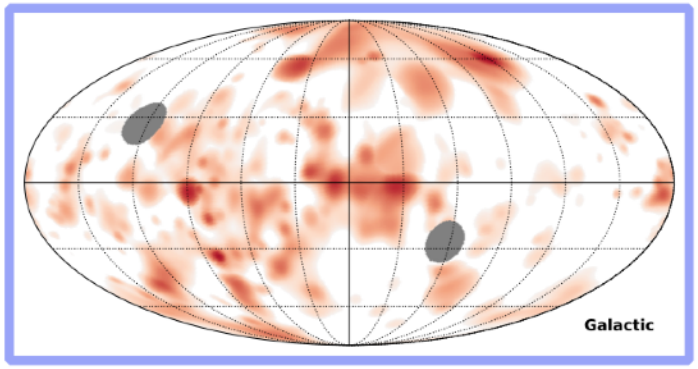
Results for all templates above 5 sigma



The Universe in Radio, X-ray, Gamma-ray Lights



The Universe in Neutrino



IceCube Collaboration, *Science (2023)*

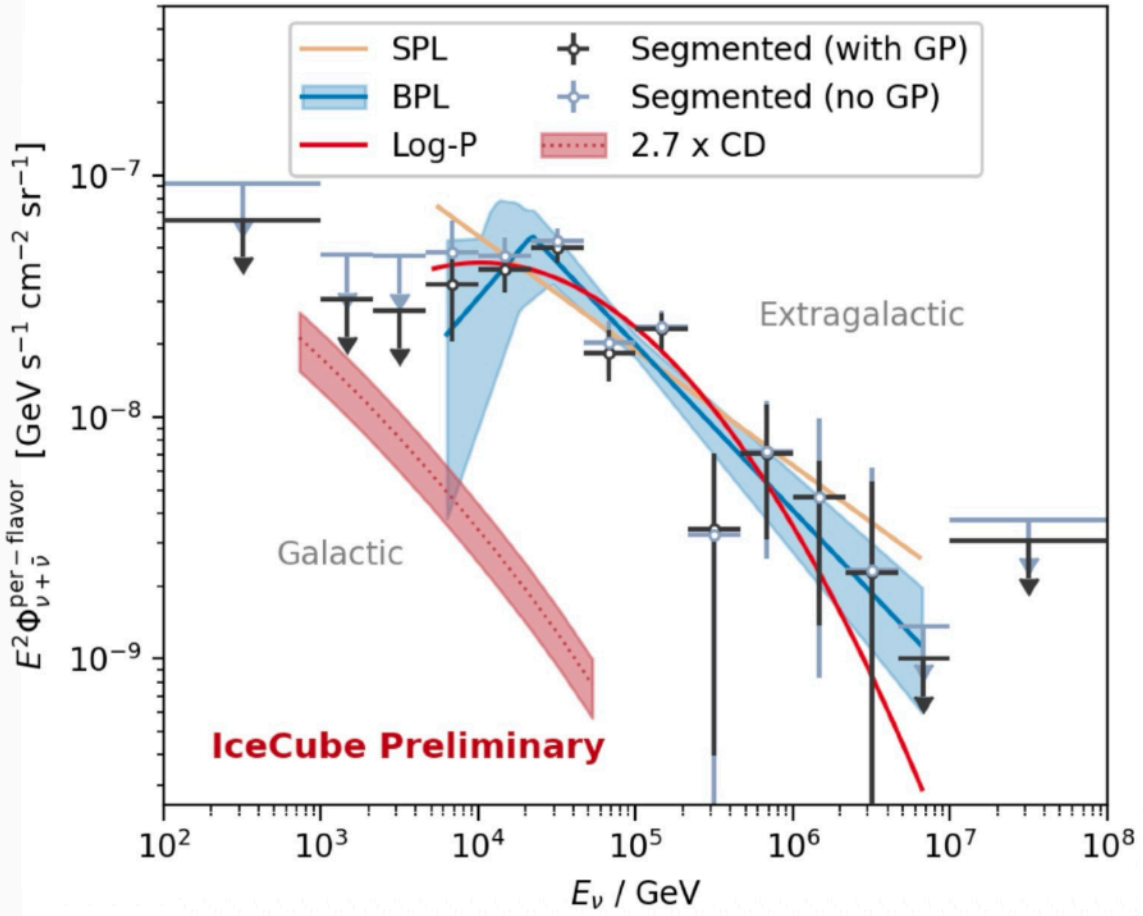
The IceCube Observatory detects the Milky Way in 2023. In **neutrino**, the Galactic Plane is not much brighter than the extragalactic background, as it is in **photon.**

Neutrino flux in Milky Way less than average in the Universe by an order of magnitude.

The “Milky Way as neutrino desert” Halzen, Gallagher, Fang, Nature Astronomy, 2023

2026: Joint Characterization of Galactic and Extragalactic Neutrino Fluxes

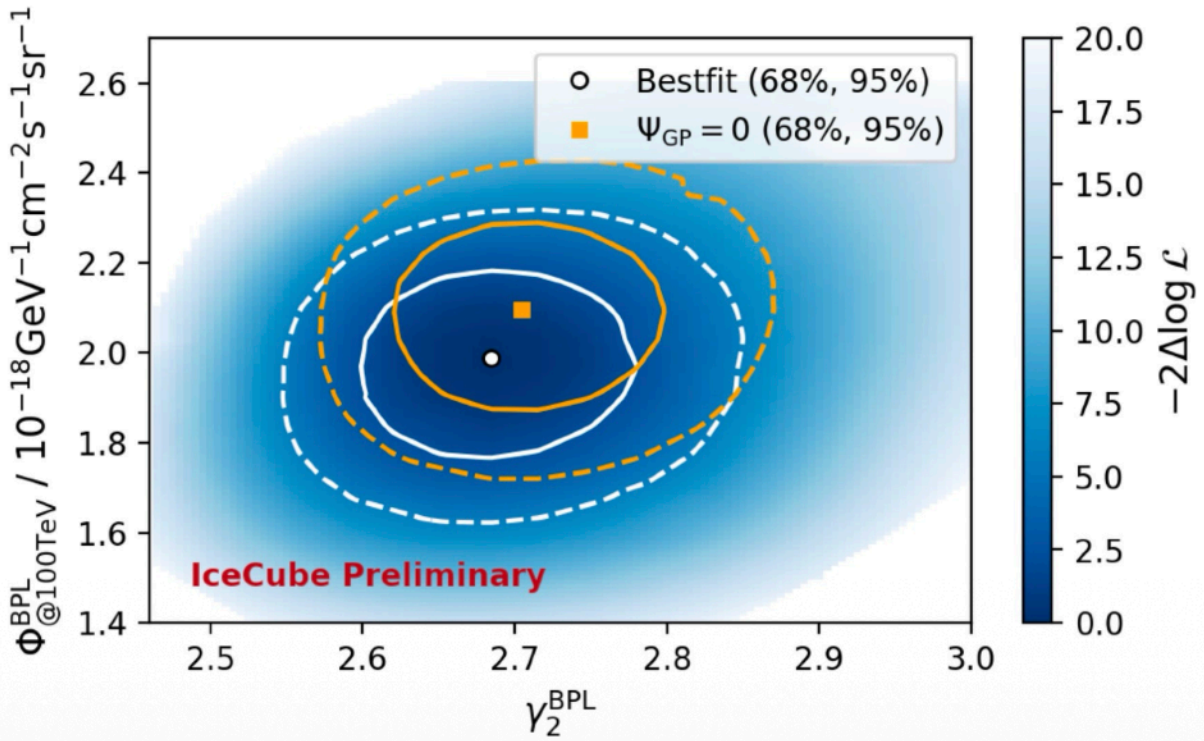
Presented last week at TeVPA



Break in power-law, reported previously in PRL 136, 121002 (2026), observed at > 5 **σ** preference over single power-law

Analysis of the isotropic extragalactic neutrino flux ("diffuse flux") relies on simulation (No on-source, off-source possibility).

Additional presence of GP neutrinos now accounted for in first joint GP-diffuse analysis



https://indico-icehap.phys.s.chiba-u.ac.jp/event/3/contributions/426/attachments/300/581/TeVPA2026_pfuerst.pdf

A History of Neutrino Astronomy in Antarctica



1988 — Telescope in the Ice Envisioned

2000 — AMANDA Completed

2001 — Atmospheric Neutrinos Detected

2011 — IceCube Completed

2013 — Astrophysical Neutrinos Discovered

2018 — First Source TXS 0506+056 Identified

2021 — Glashow Resonance Neutrino Identified

2022 — Second Source NGC 1068 Identified

2023 — Third Source Milky Way Identified

New developments

IceCube Upgrade
optimized for low energy
5 new strings in operation;
IceCube-Gen2
— > next talk

Summary

Neutrinos have become an important messenger from the High Energy Universe.

There is a cosmic neutrino flux from TeV to beyond 10 PeV

NGC 1060 Active Galaxy with a supermassive black hole. Population of x-ray bright sources.
Neutrinos from the Milky Way now at 5.7 sigma. Can now start to make more precise measurements of spectrum and topology.

There are many more things IceCube can do which I leave out today.

Neutrino astronomy has just started. There is much more to do in the future.

From the South Pole

to the Milky Way

- the journey continues …

Thank you



Photo: Yuya Makino, IceCube/NSF
2022 IUPAP100 Photo Contest Winner