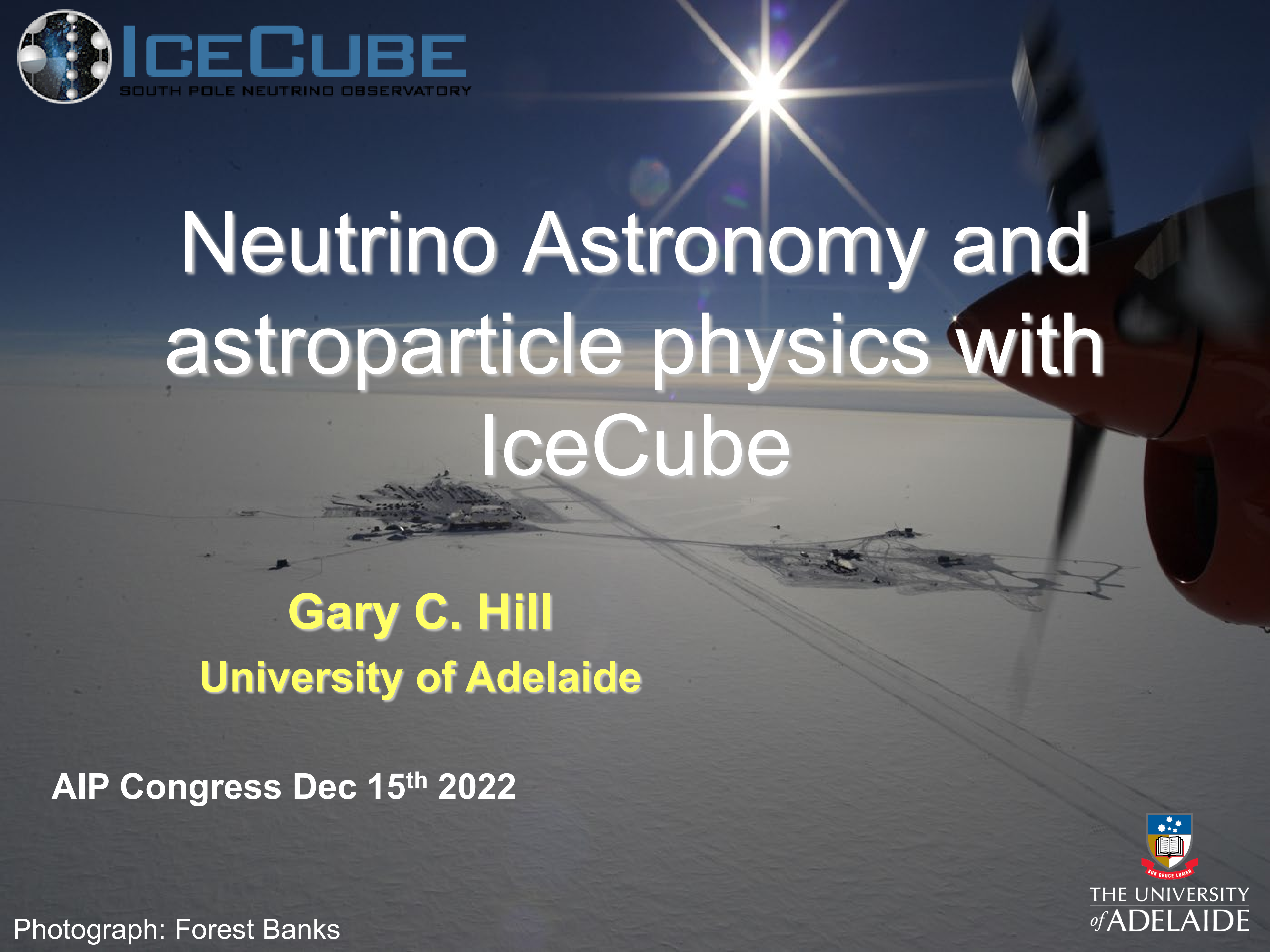


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Neutrino Astronomy and astroparticle physics with IceCube

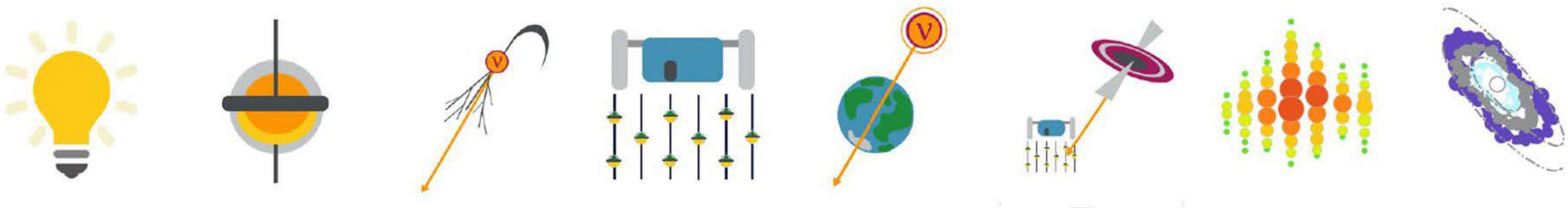
Gary C. Hill
University of Adelaide

AIP Congress Dec 15th 2022

THE UNIVERSITY of ADELAIDE

Photograph: Forest Banks

A History of Neutrino Astronomy in Antarctica



- **1988** — Telescope in the Ice Envisioned
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- **2001** — Atmospheric Neutrinos Detected
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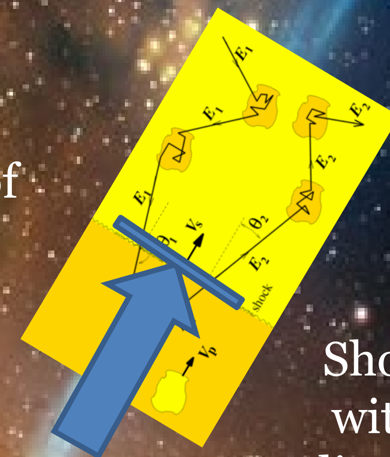
- **2013** — Astrophysical Neutrinos Discovered
- **2018** — First Source TXS 0506+056 Identified
- **2021** — Glashow Resonance Neutrino Identified
- **2022** — Second Source NGC 1068 Identified

An Active Galaxy,
or Quasar
Powered by a massive
black hole

Outflow of
material
in jets



Shock front
with speed
discontinuity

Many frequencies of light
– gamma-ray to radio

Acceleration site for
high-energy particles?

Fermi acceleration
in shocks?

Fermi acceleration as particles bounce back and forth across schock

- small boost in energy each crossing
- confinement by magnetised coulds

Neutrino and gamma production in cosmic ray accelerators?

The TeV gammas?

$$pp, p\gamma \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$

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

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

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

γ-rays also from electrons:

Bremsstrahlung
Inverse Compton

+

Let's look for these neutrinos!

Hadronic accelerator? – cosmic ray origin?

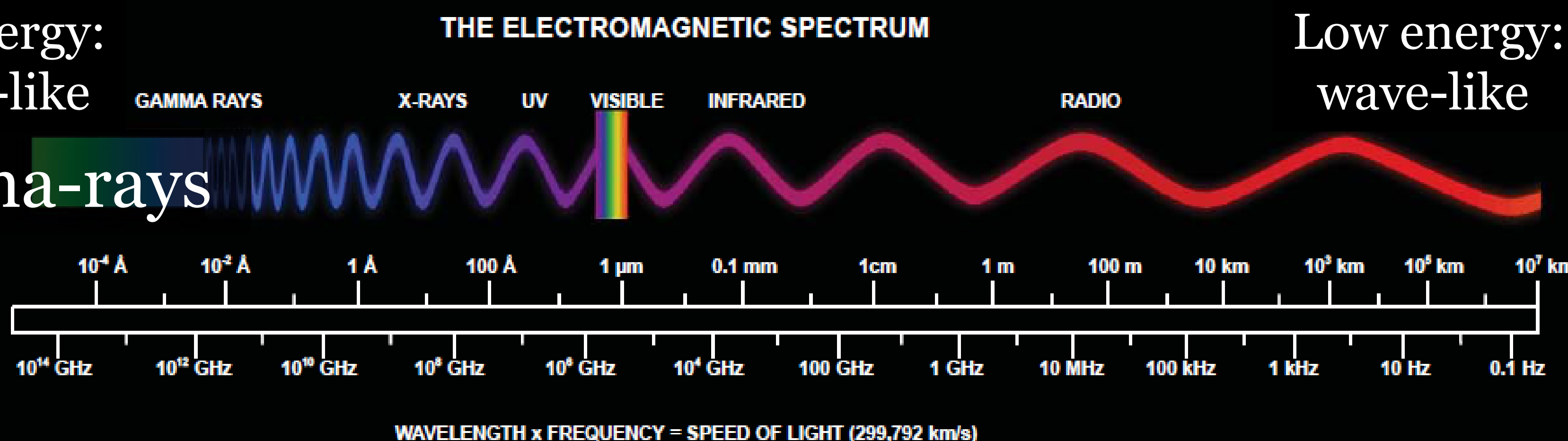
Astronomical messengers:

Light: the electromagnetic spectrum

High energy: particle-like

Low energy: wave-like

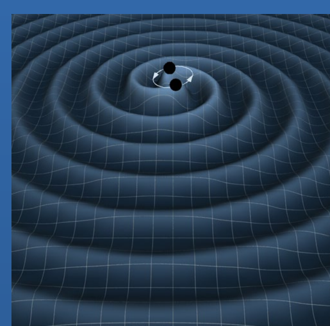
Gamma-rays



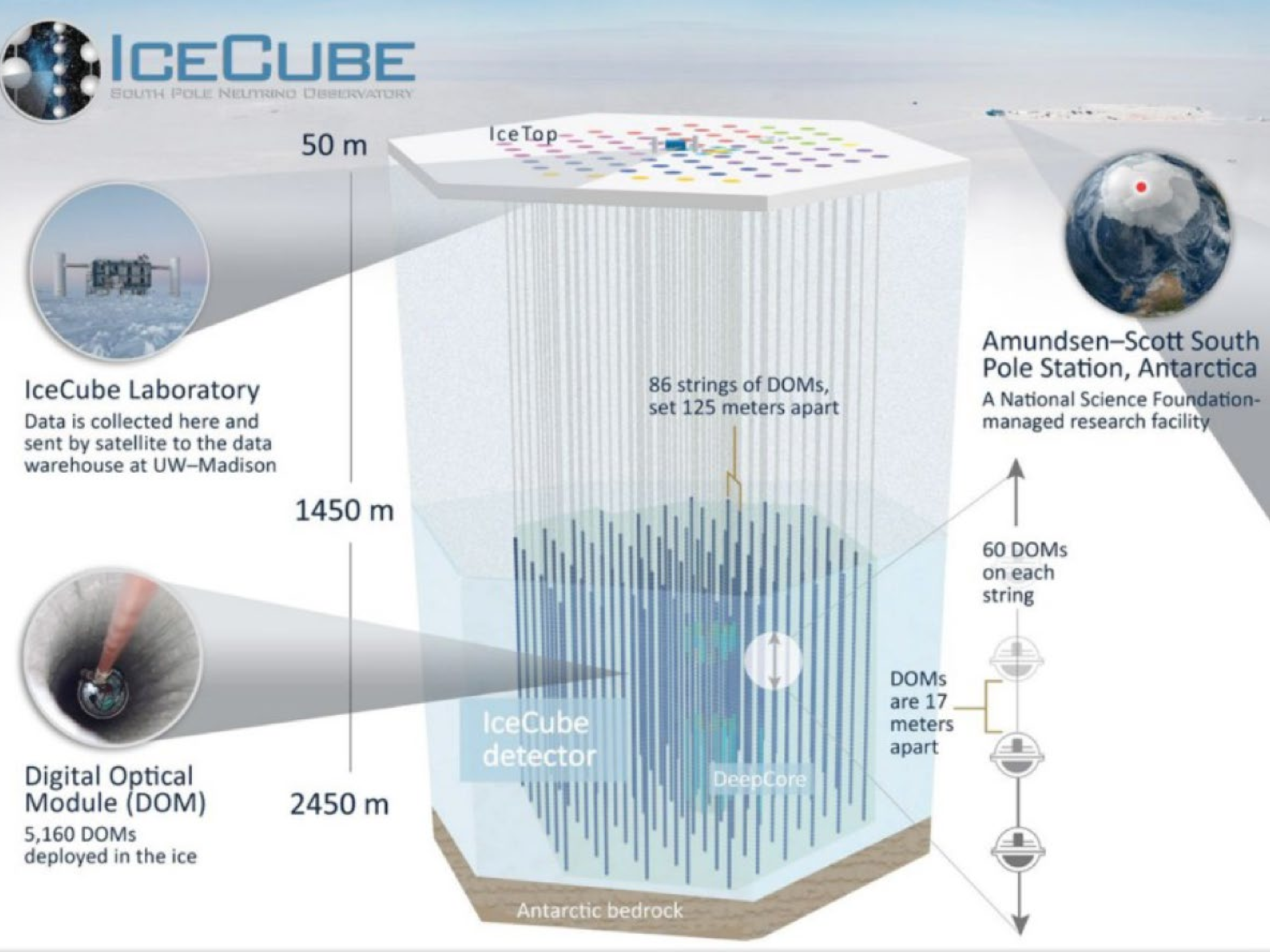
Not light: other messengers

Cosmic rays

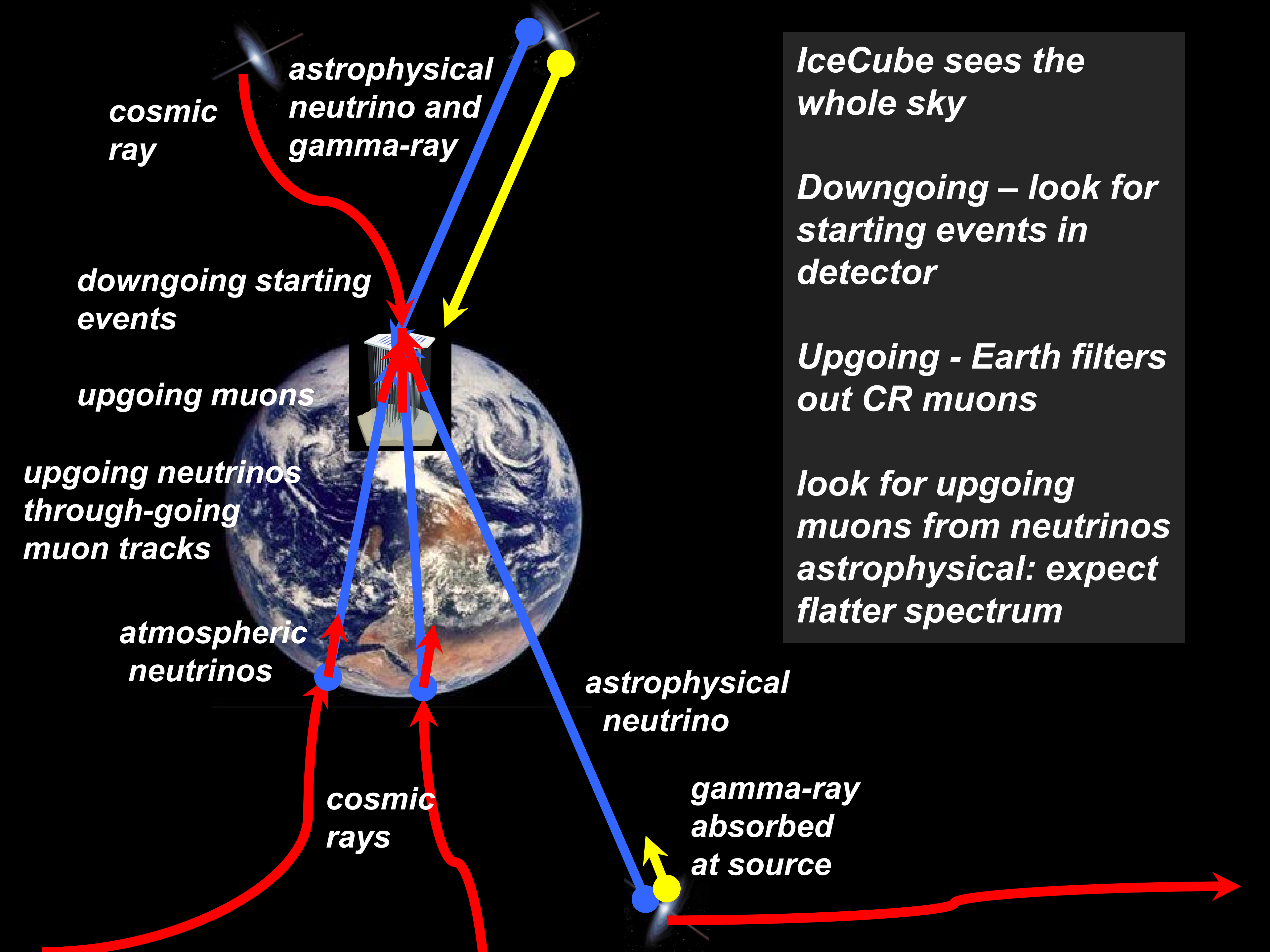
Neutrinos

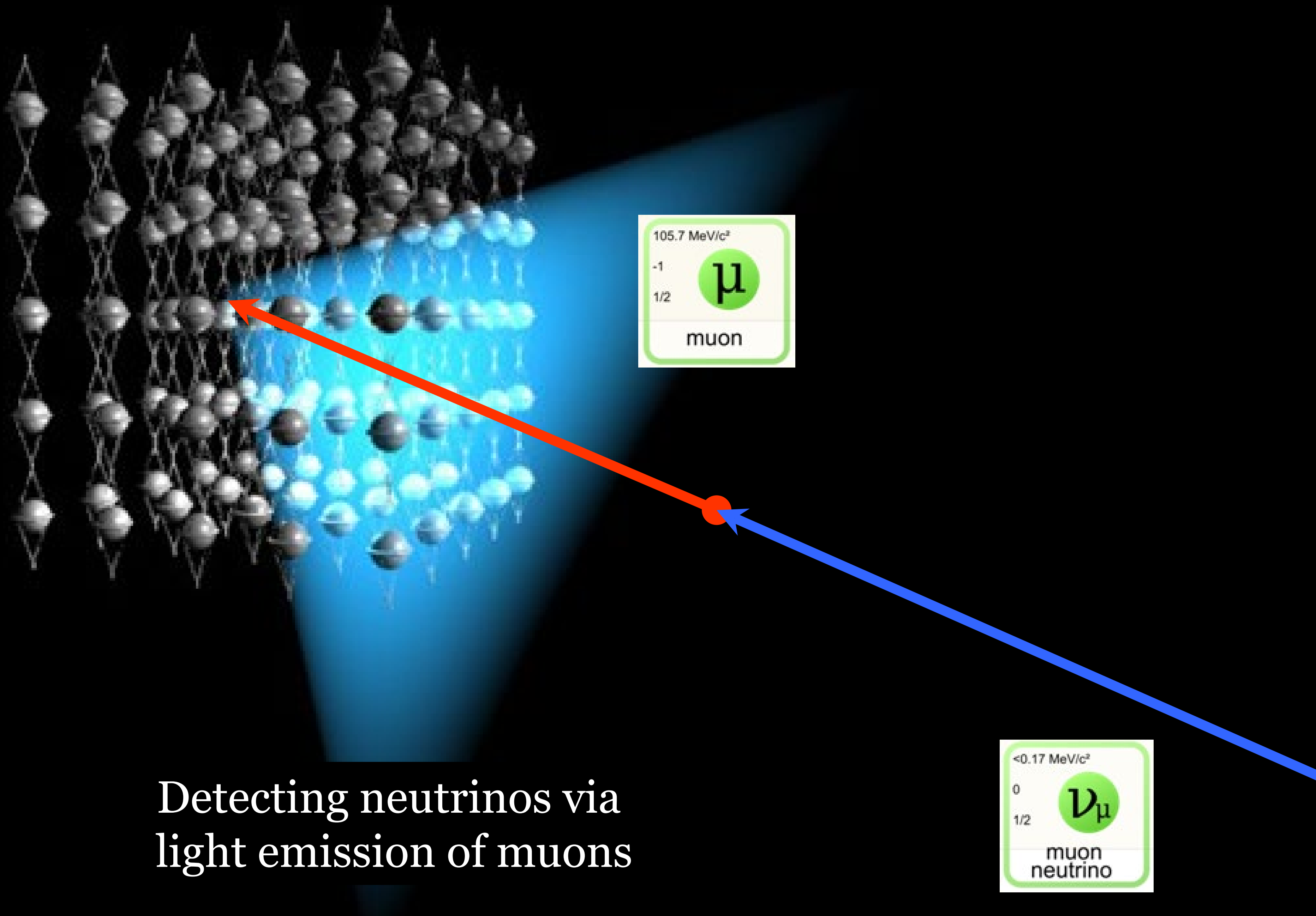


Gravitational waves


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock

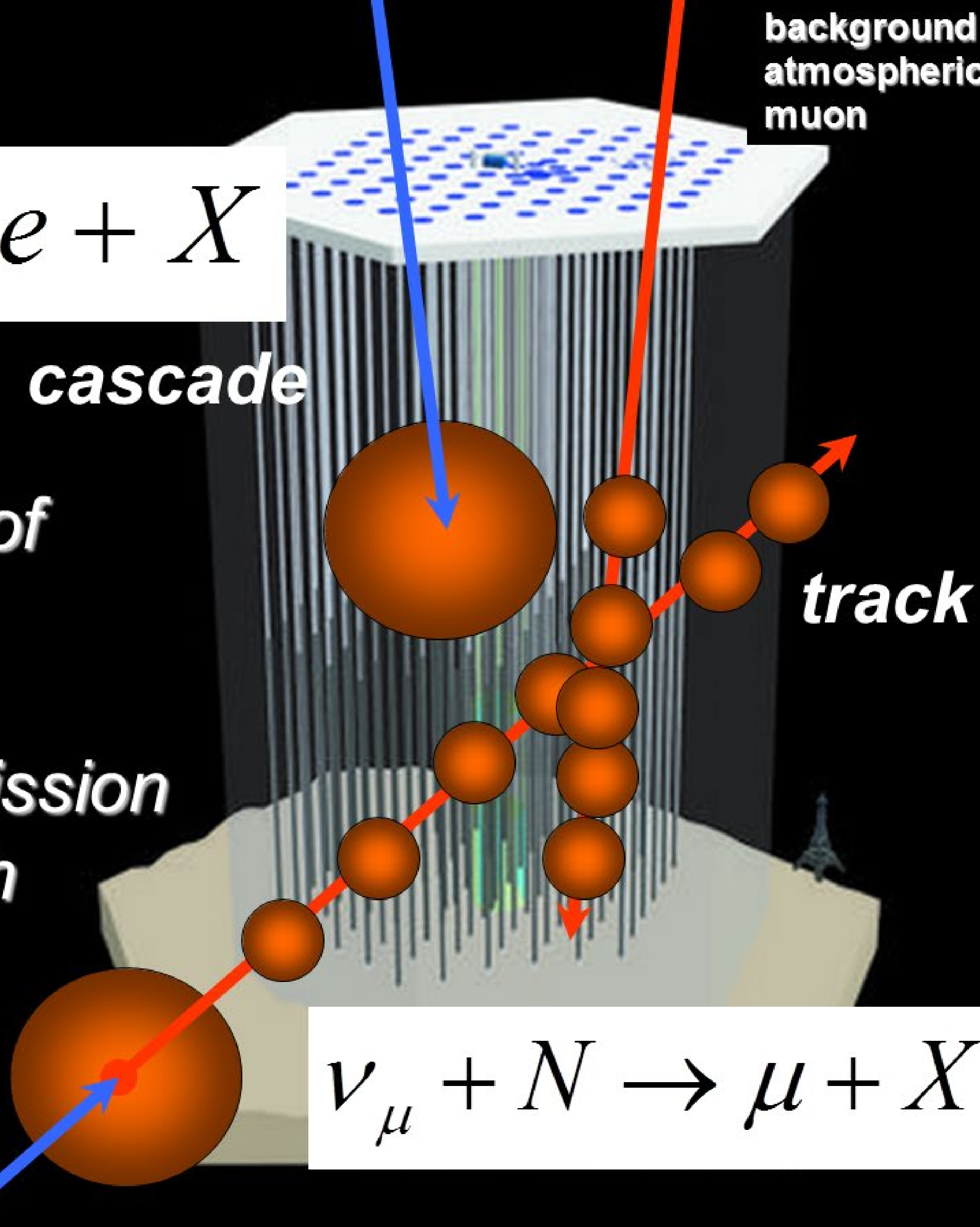

THE ICECUBE COLLABORATION
AUSTRALIA
University of Adelaide
BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster
JAPAN
Chiba University
NEW ZEALAND
University of Canterbury
REPUBLIC OF KOREA
Sungkyunkwan University
SWEDEN
Stockholms Universitet
Uppsala Universitet
SWITZERLAND
Université de Genève
UNITED KINGDOM
University of Oxford
UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University
FUNDING AGENCIES
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
ICECUBE
icecube.wisc.edu


cosmic ray
astrophysical neutrino and gamma-ray
downgoing starting events
upgoing muons
upgoing neutrinos through-going muon tracks
atmospheric neutrinos
astrophysical neutrino
cosmic rays
gamma-ray absorbed at source
IceCube sees the whole sky
Downgoing – look for starting events in detector
Upgoing - Earth filters out CR muons
look for upgoing muons from neutrinos astrophysical: expect flatter spectrum



Detecting neutrinos via
light emission of muons

$$\nu_e + N \rightarrow e + X$$

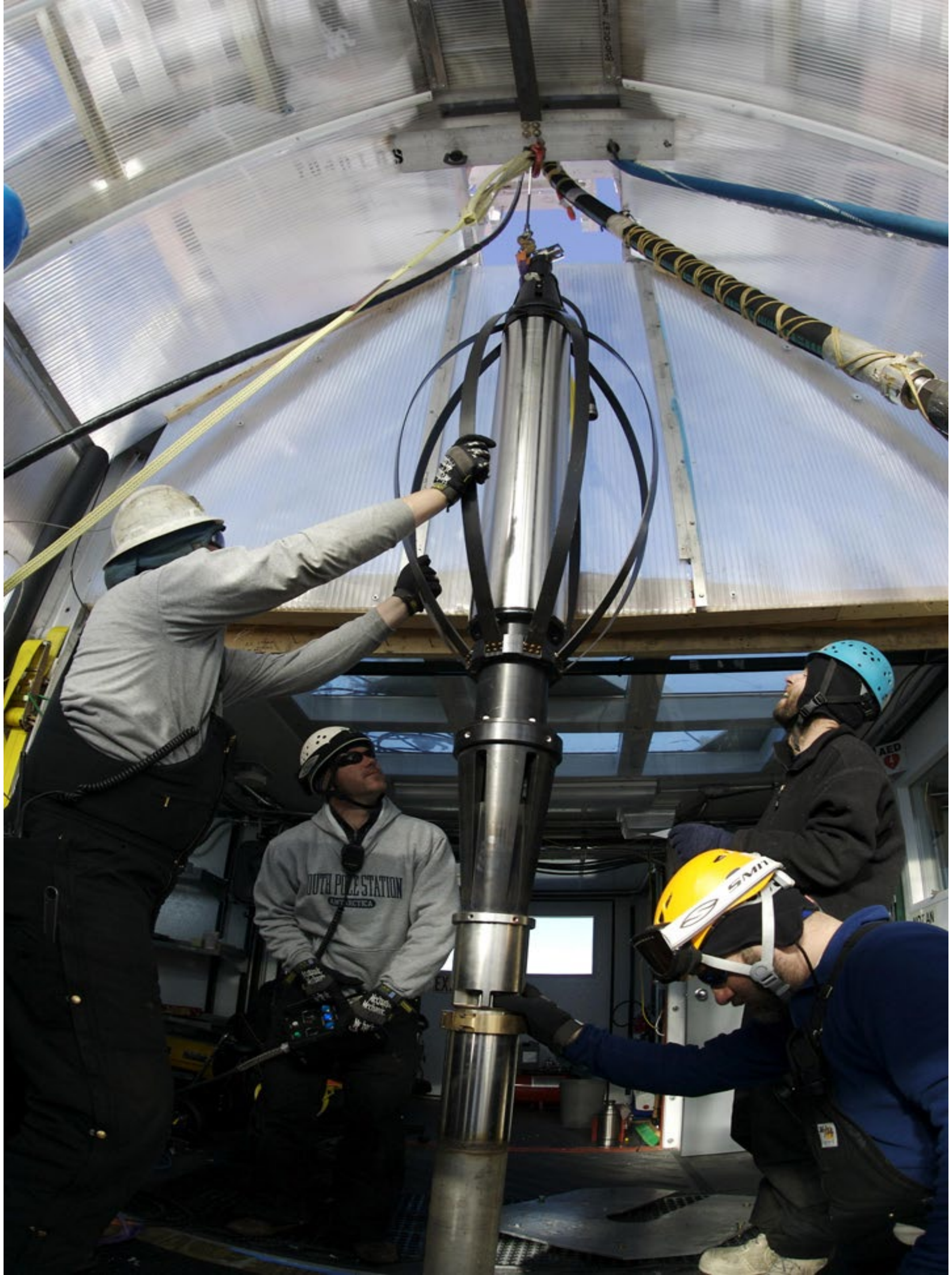


Direction:
Reconstruction of
Cerenkov cone

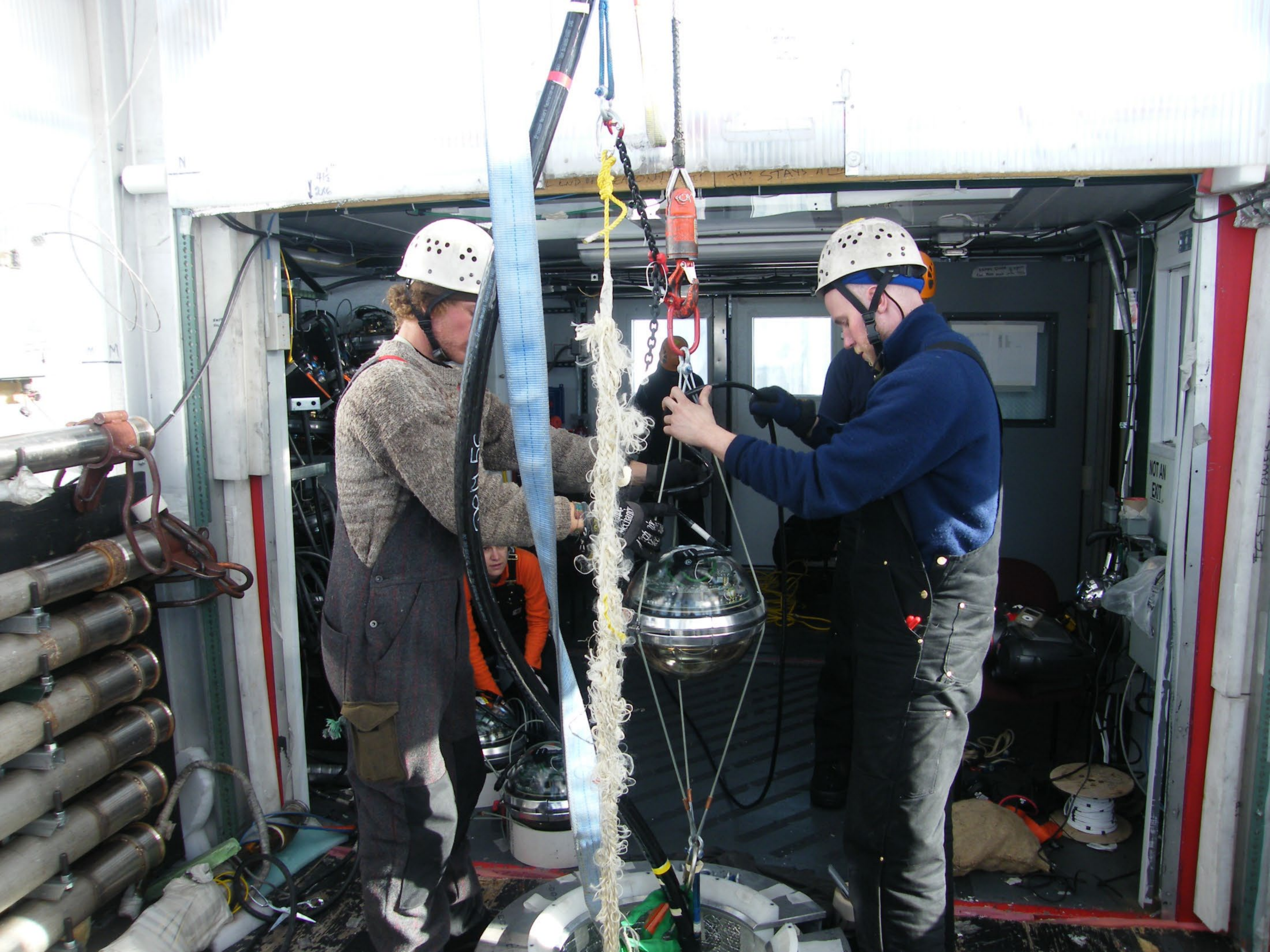
Energy:
Rate of light emission
along muon path

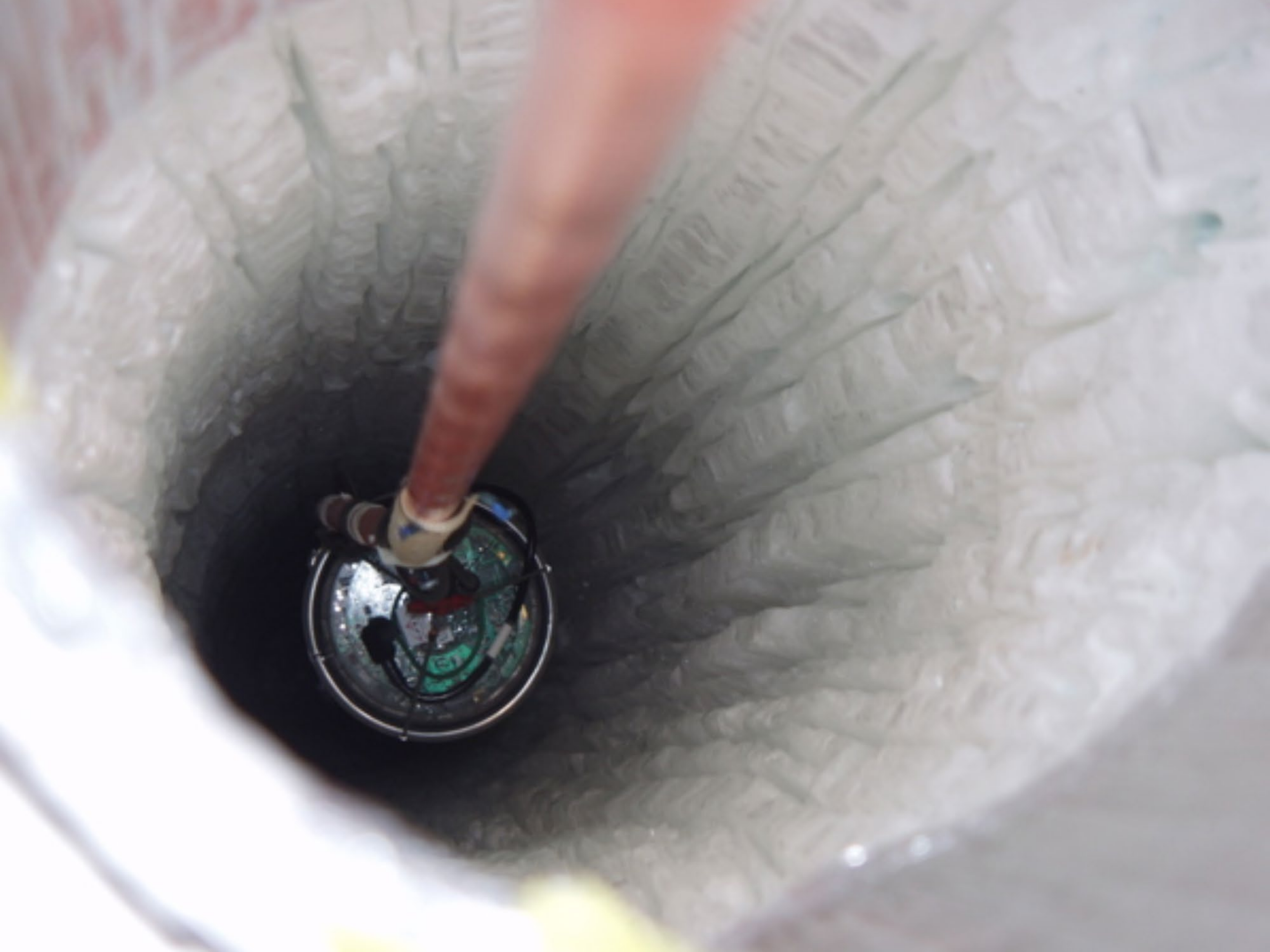
$$\nu_\mu + N \rightarrow \mu + X$$


Logistics
9 million pounds of Cargo and fuel
300 Hercules LC 130 missions

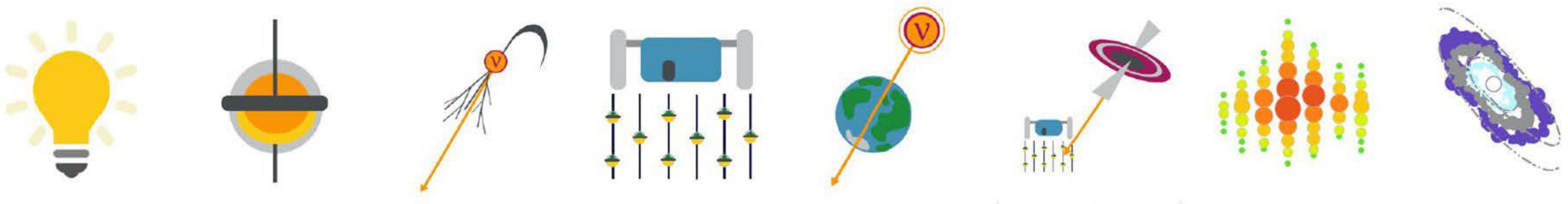

UTH POLE STATION
ANTARCTICA
AED


EXIT
TOS 1
2


NOT AN EXIT



A History of Neutrino Astronomy in Antarctica



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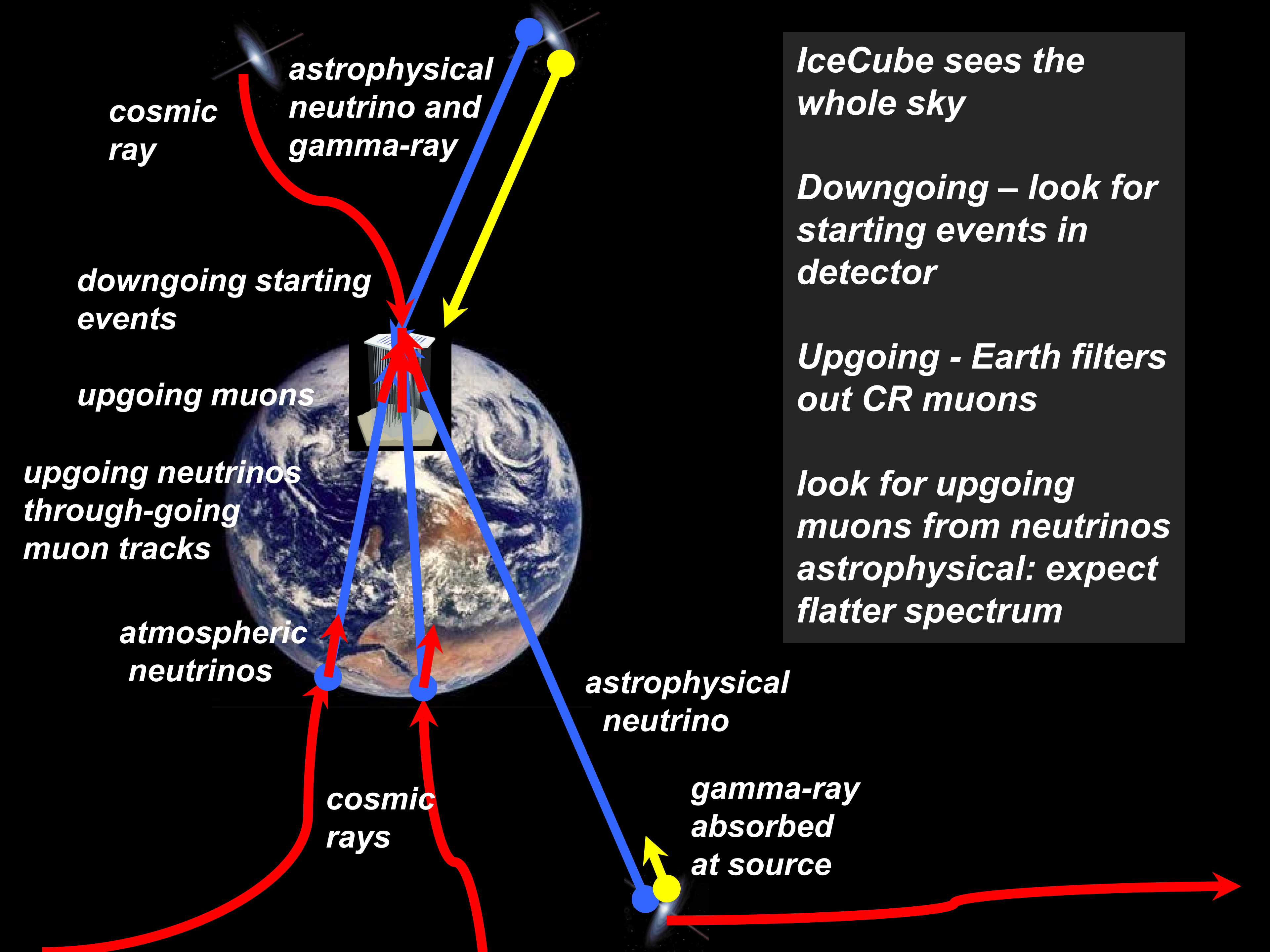
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cosmic ray
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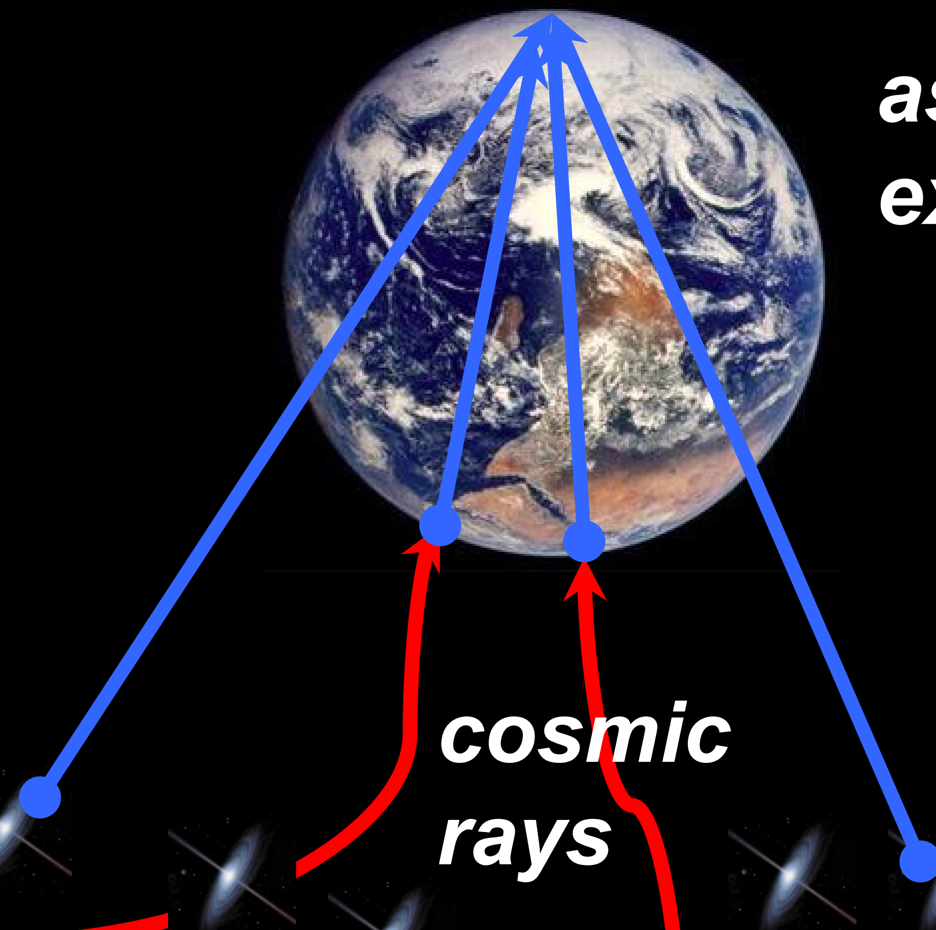
atmospheric neutrinos
astrophysical neutrino
cosmic rays
gamma-ray absorbed at source

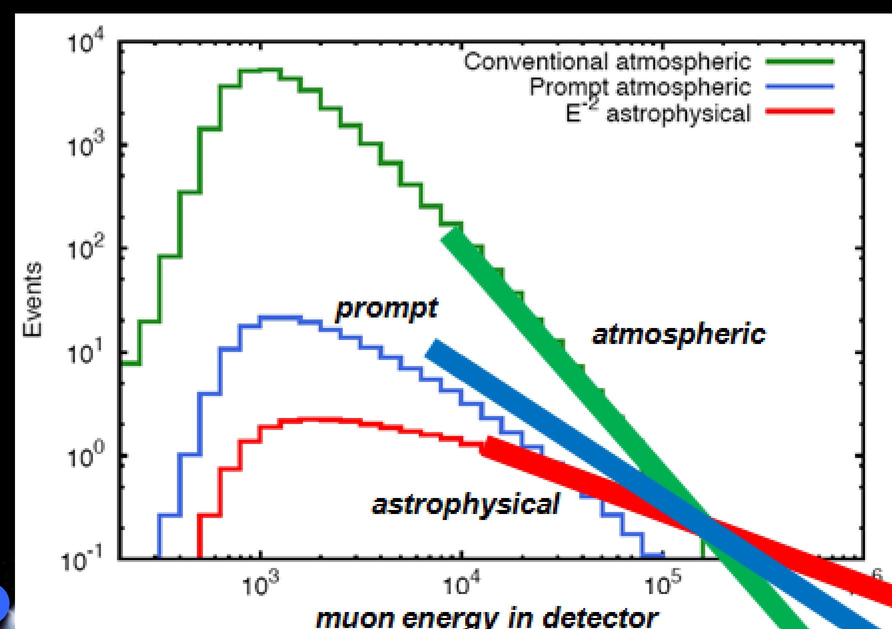
Looking down at the south pole into the northern sky

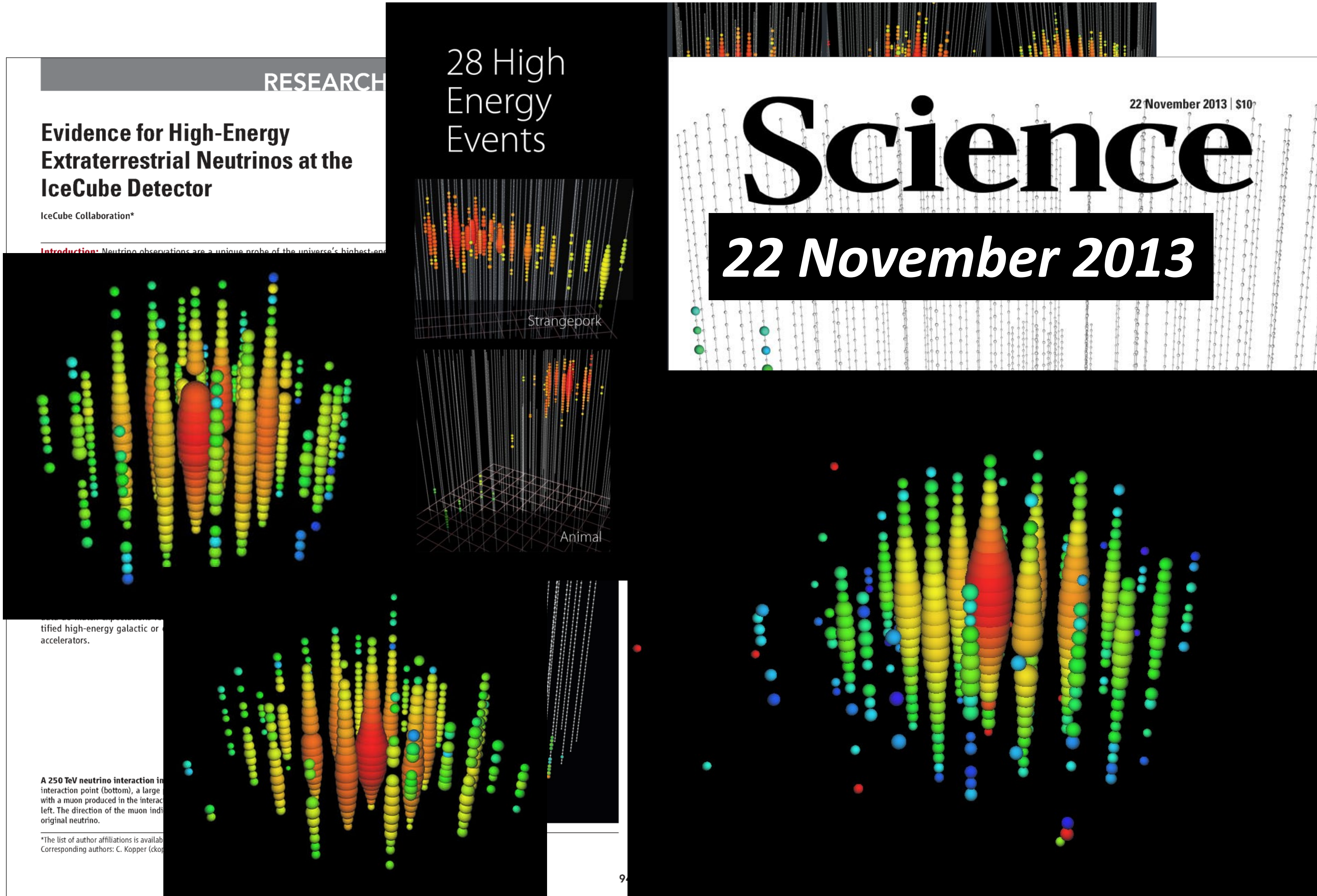
reject downgoing muons

upgoing neutrinos through-going muon tracks

astrophysical neutrino excess at high energy?



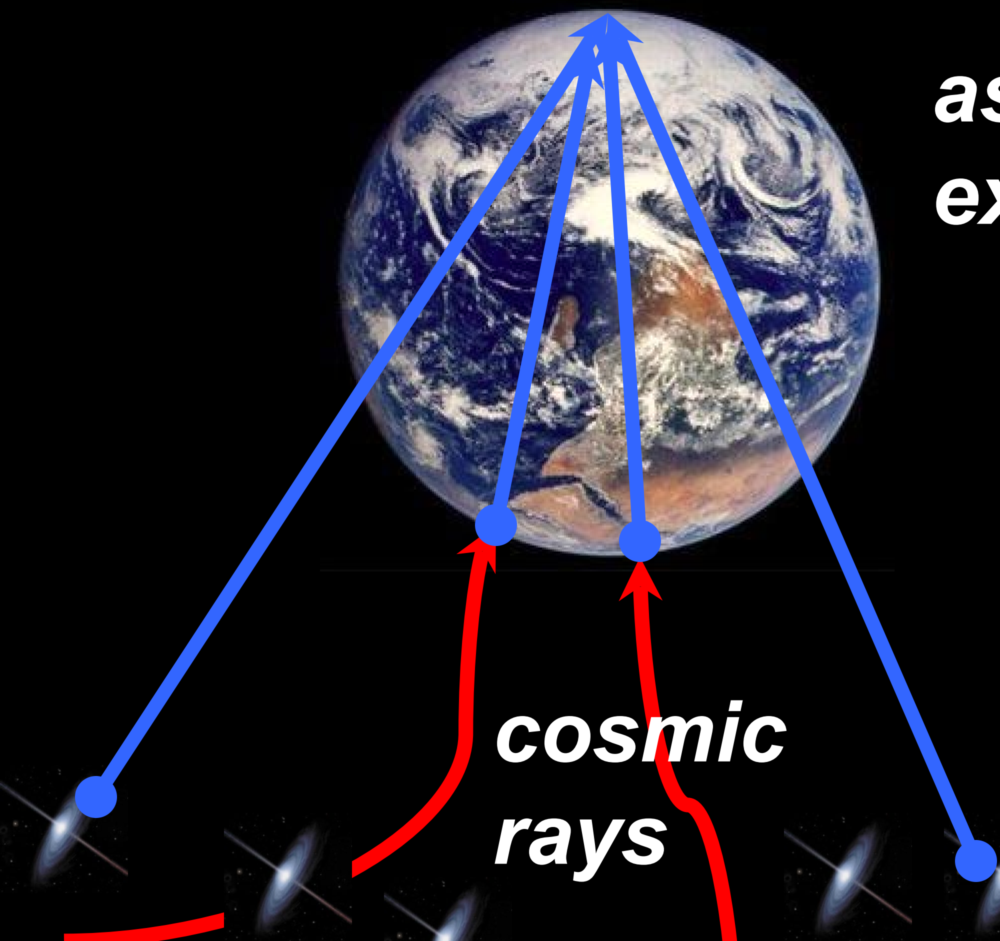



RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
IceCube Collaboration*
accelerators.
28 High Energy Events
Strangepork
Animal
Science
22 November 2013 | $10
22 November 2013

Looking down at the south pole into the northern sky

reject downgoing muons

upgoing neutrinos through-going muon tracks



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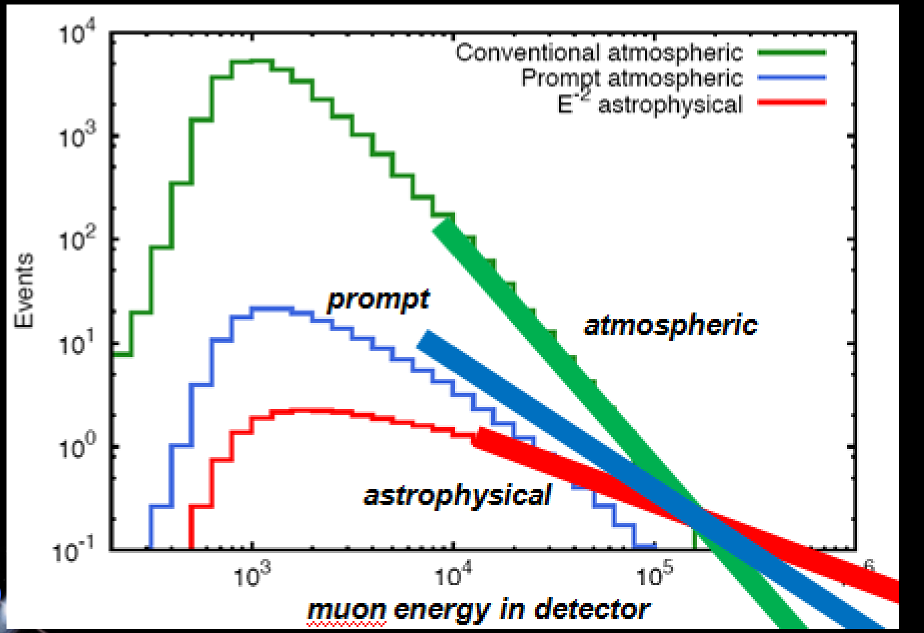
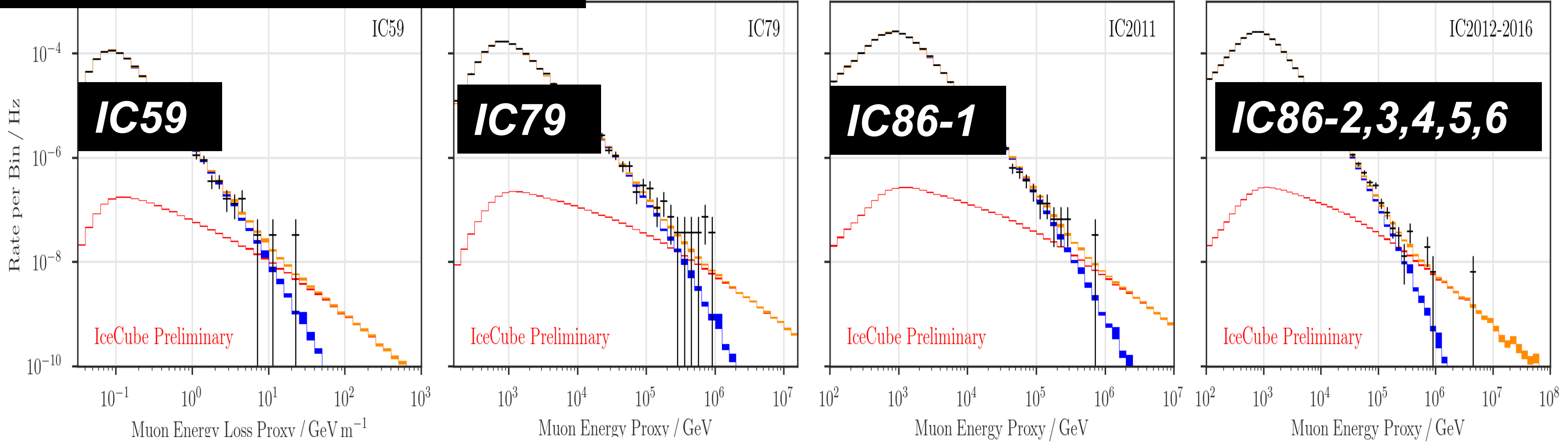
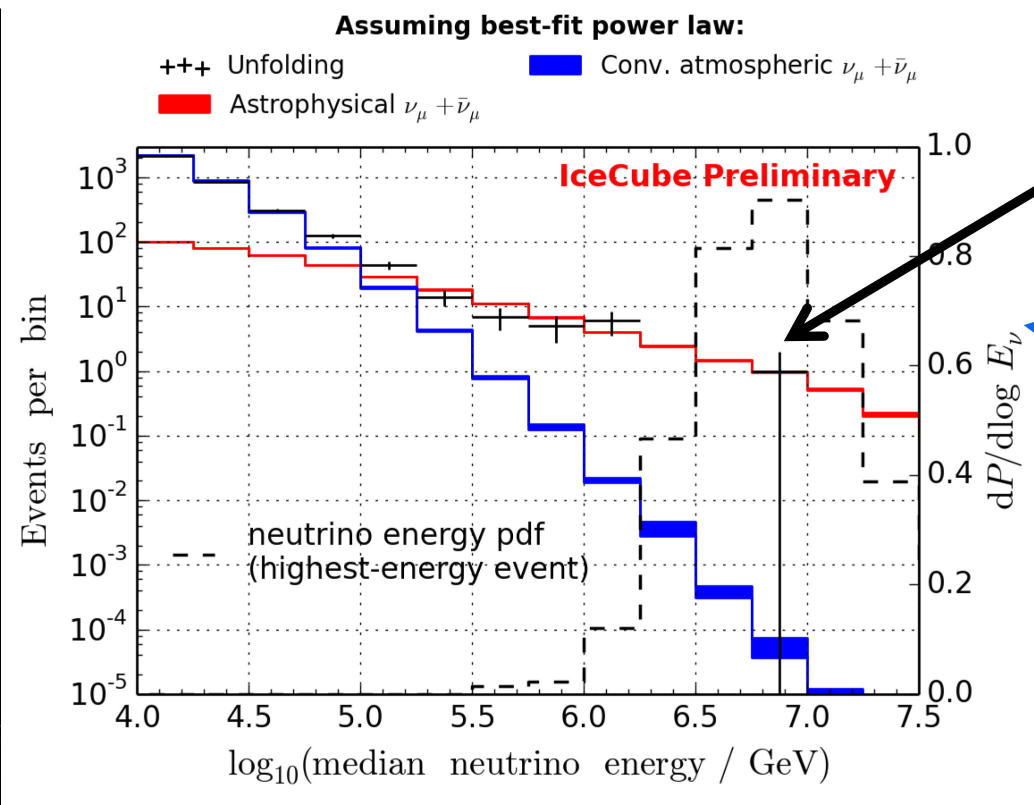
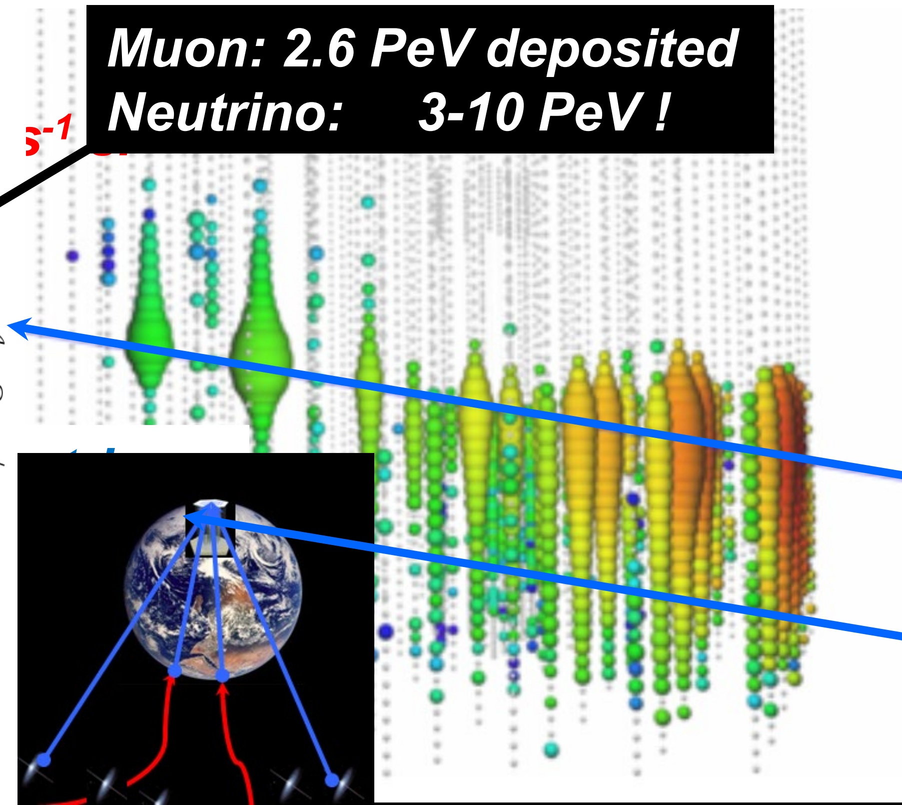


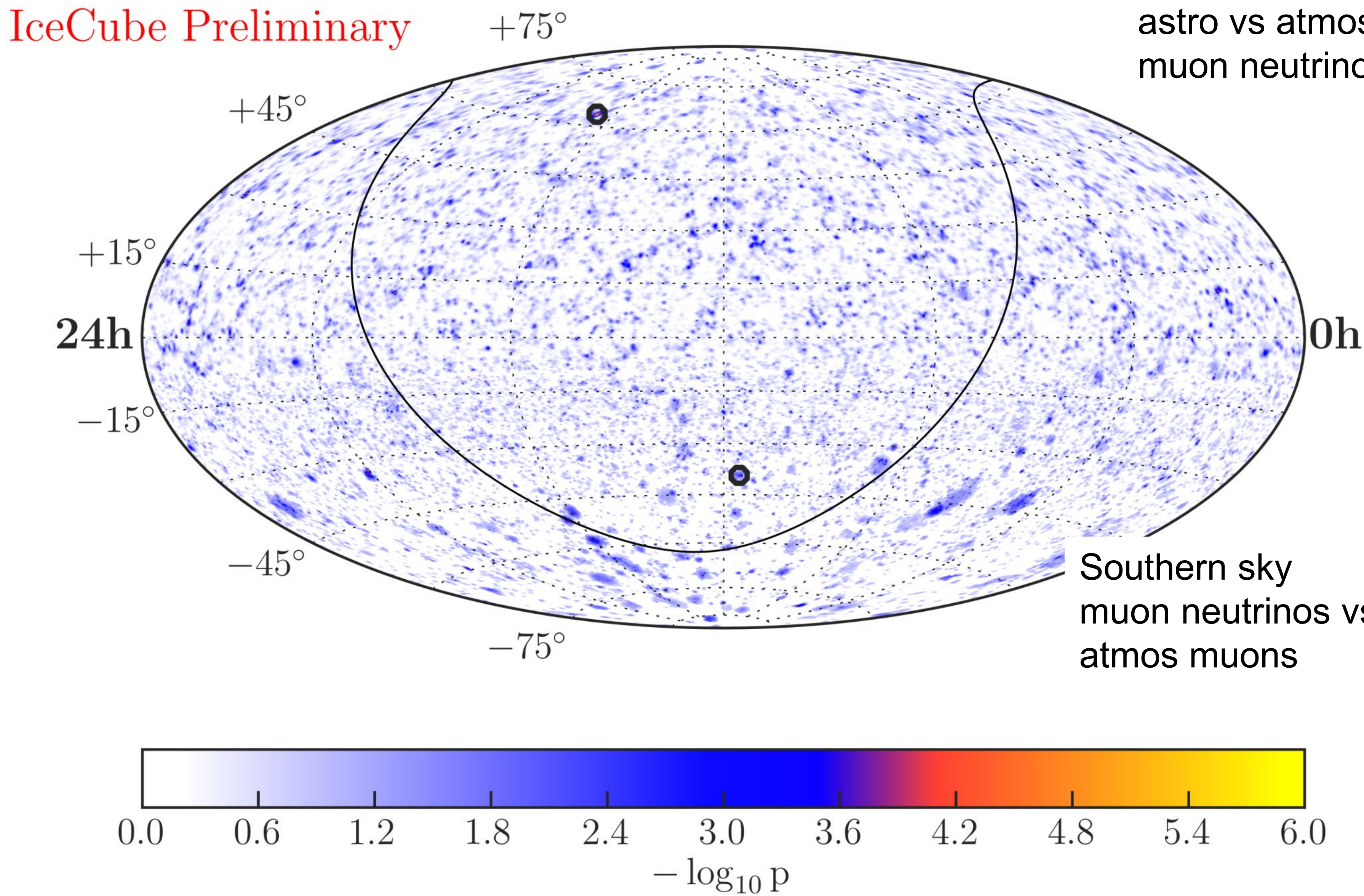
Upgoing diffuse 8 years







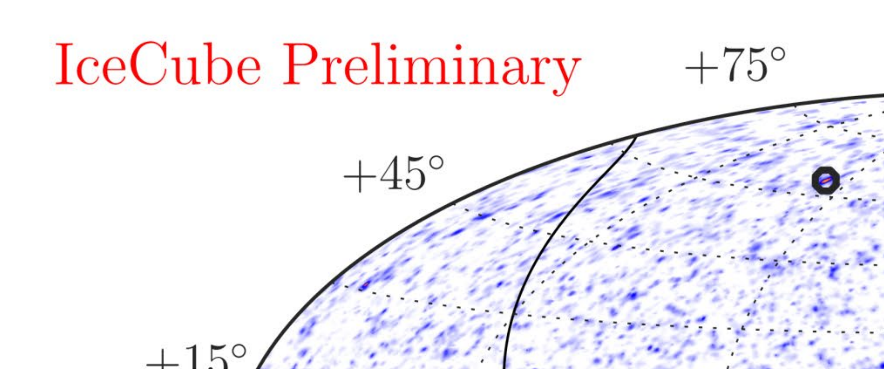
Results of (regular) 7 year clustering search (much less pure neutrino sample)

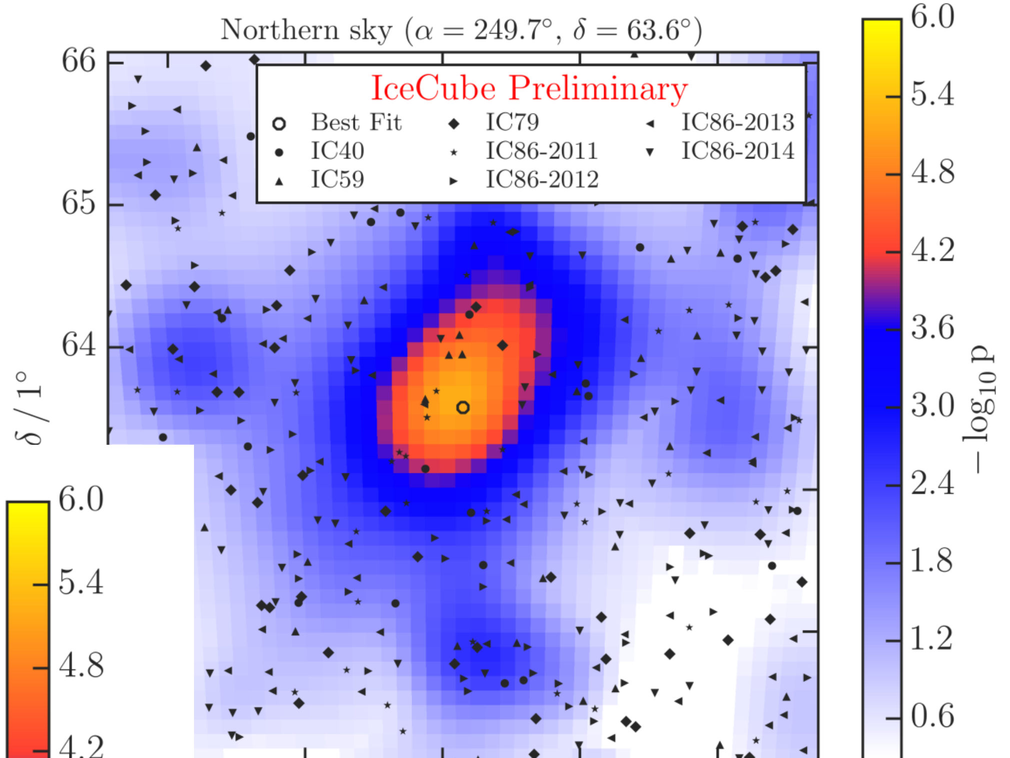


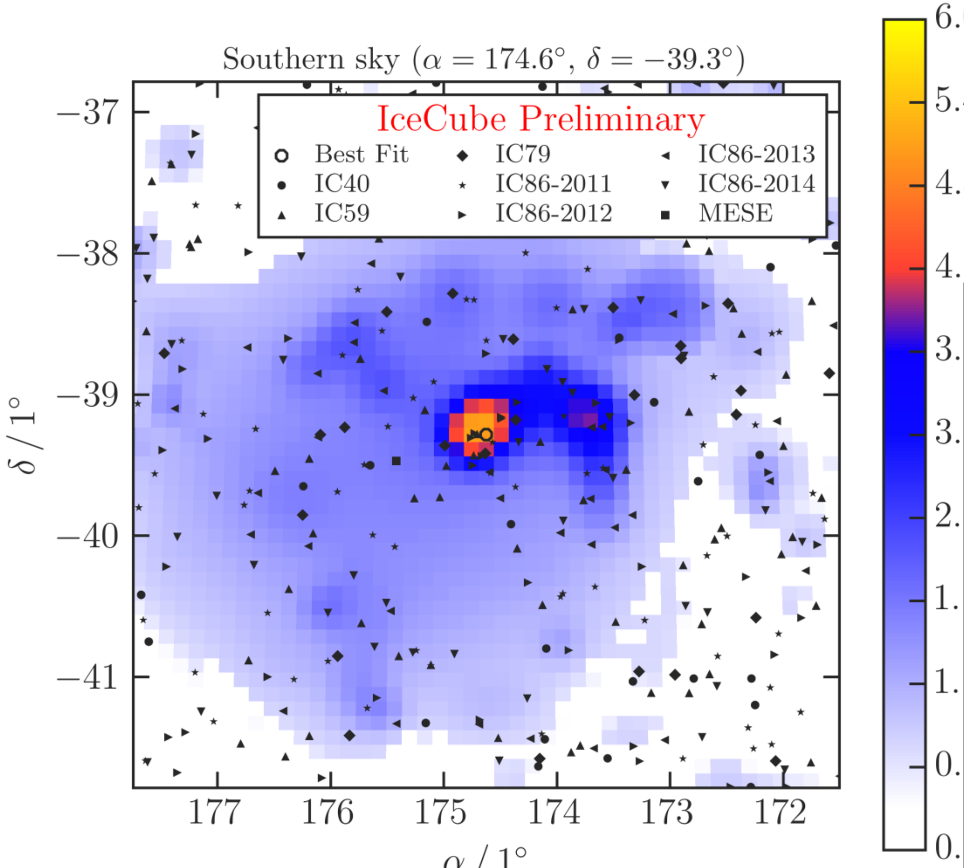
Northern sky astro vs atmos muon neutrinos

Southern sky muon neutrinos vs atmos muons

Resu







Hemisphere	North	South
N_Sources	27.22	15.54
Gamma	1.95	2.84
Test statistic	18.99	20.26
-log10(Pre-Trial P)	5.24	5.33
Post Trial P	44%	39%

IceCube Realtime Alert System arXiv:1612.06028

10 alerts in first year

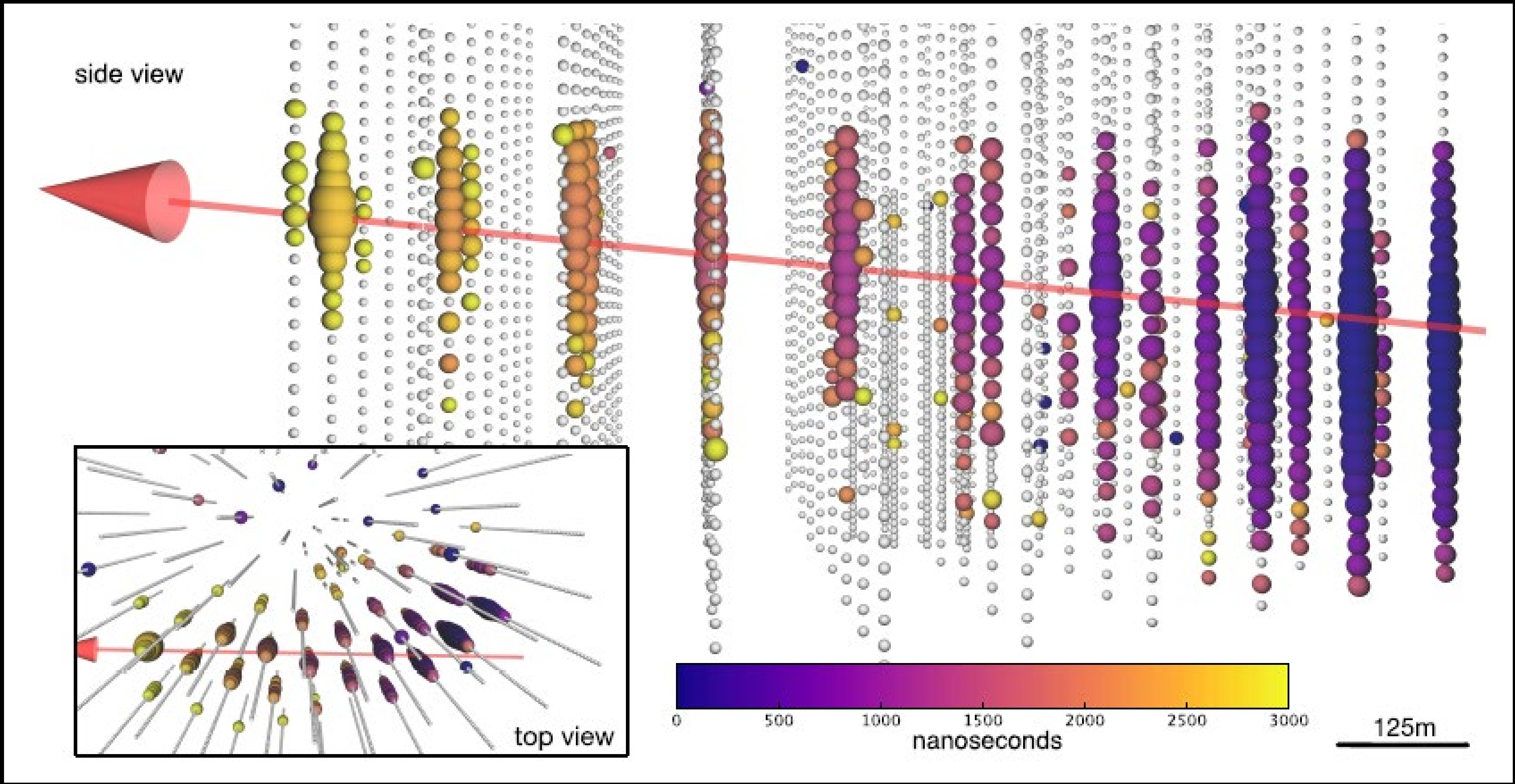
Multi-messenger astronomy

Expect (assuming $E^{-2.6}$ spectrum): 3.5 signal + 5.6 bkg per year

Time from event at South Pole to public alert: < 1 min

For highly signal-like events, many follow-up observations reported:

AGILE, ANTARES, FACT, Fermi-GBM, Fermi-LAT, HAWC, H.E.S.S., INTEGRAL, IPN, Konus-Wind, LCOGT, MAGIC, MASTER, Maxi/GSC, Pan-STARRS, PTF, Swift, VERITAS


side view
top view
0
500
1000
1500
2000
2500
3000
nanoseconds
125m

IceCube-170922A & TXS 0506+056

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17
FROM: E

Claudio Ko
report on I

On 22 Sep,
probability
Extremely
normal on

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; Y
K

Crede

Subjects: Gamma

Referred to by AT
10844, 10845, 10

Tweet | Rec

We searched for
neutrino event e
10787) with all-sk
ray Space Telesco
and also included
located inside the

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
*on **4 Oct 2017; 17:17 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet | Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of

September 22, 2017: a neutrino alert issued by IceCube
Fermi and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
Very active multi-messenger follow-up from radio to γ-rays


Chasing the ammonia economy p. 120
Time invested matters for mice, rats, and humans pp. 124 & 178
Two spindles are better than one pp. 128 & 189
Science
$15
13 JULY 2018
sciencemag.org
AAAS
NEUTRINOS
FROM A BLAZAR
Multimessenger observations of an astrophysical neutrino source pp. 115, 146, & 147

RESEARCH ARTICLE

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*†

Previous detections of individual astrophysical sources of neutrinos are limited to the Sun and the supernova 1987A, whereas the origins of the diffuse flux of high-energy cosmic neutrinos remain unidentified. On 22 September 2017, we detected a high-energy neutrino, IceCube-170922A, with an energy of ~290 tera–electronvolts. Its arrival direction was consistent with the location of a known γ-ray blazar, TXS 0506+056, observed to be in a flaring state. An extensive multiwavelength campaign followed, ranging from radio frequencies to γ-rays. These observations characterize the variability and energetics of the blazar and include the detection of TXS 0506+056 in very-high-energy γ-rays. This observation of a neutrino in spatial coincidence with a γ-ray–emitting blazar during an active phase suggests that blazars may be a source of high-energy neutrinos.

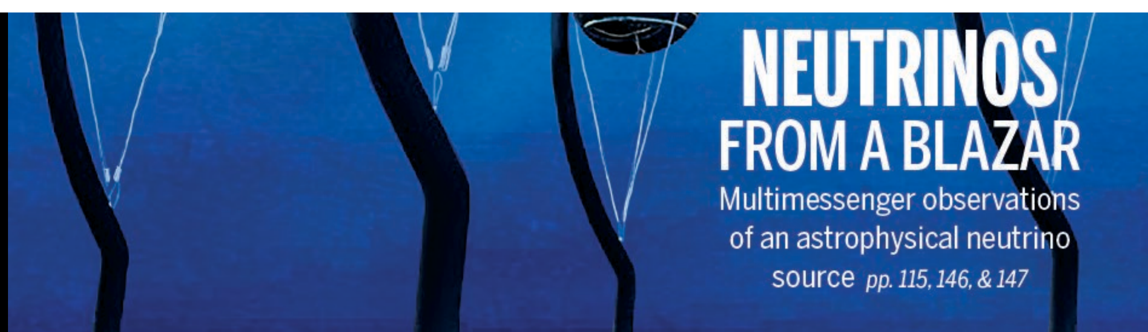
RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

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

IceCube Collaboration*†

A high-energy neutrino event detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056. Prompted by this association, we investigated 9.5 years of IceCube neutrino observations to search for excess emission at the position of the blazar. We found an excess of high-energy neutrino events, with respect to atmospheric backgrounds, at that position between September 2014 and March 2015. Allowing for time-variable flux, this constitutes 3.5σ evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode. This suggests that blazars are identifiable sources of the high-energy astrophysical neutrino flux.



RESEARC

NEUTRINO AS

Multin
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The IceCube Co
INTEGRAL, Ka
VERITAS, and

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direction was c
observed to be
ranging from ra
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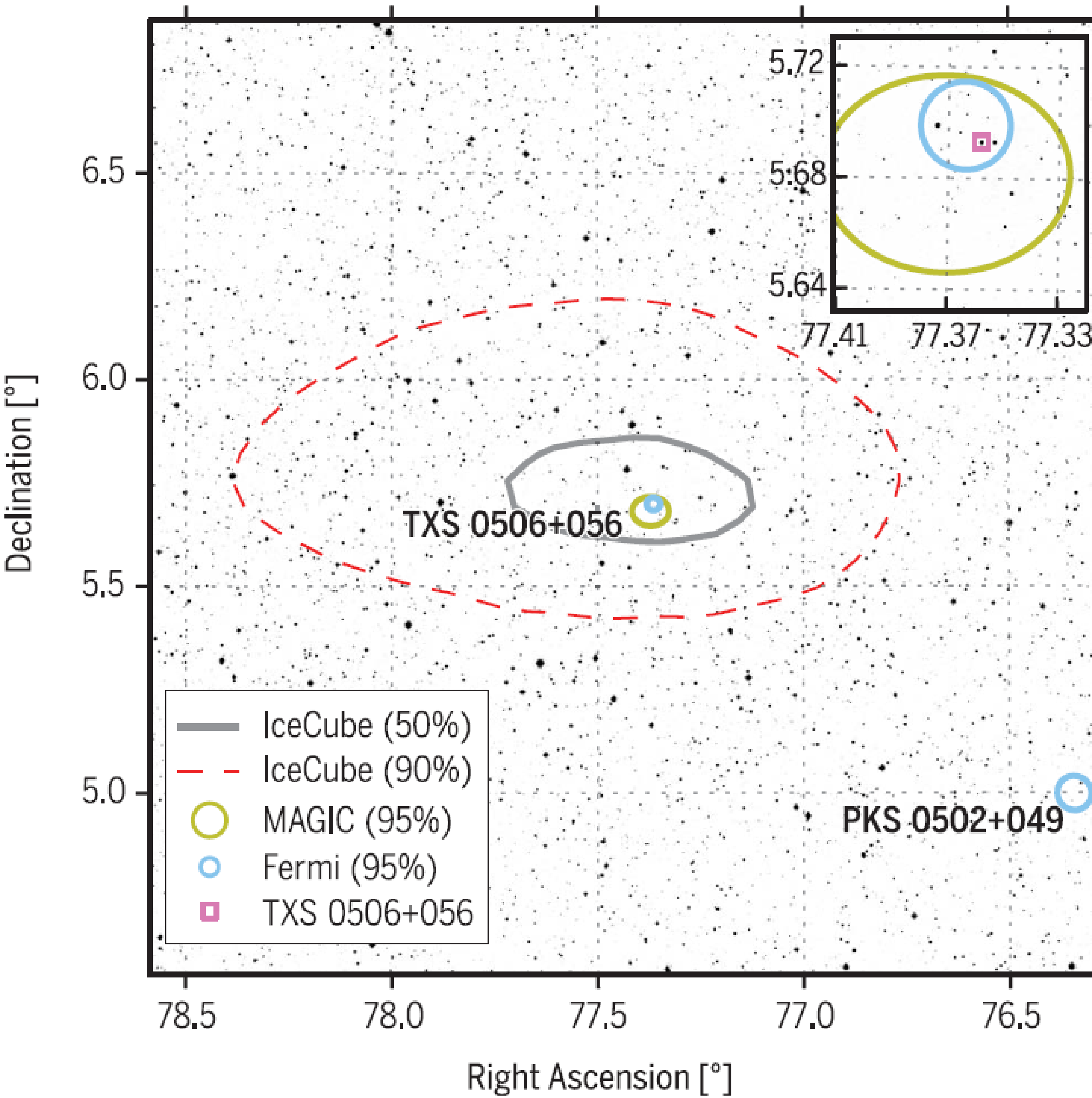

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or to

as coincident in
. Prompted by
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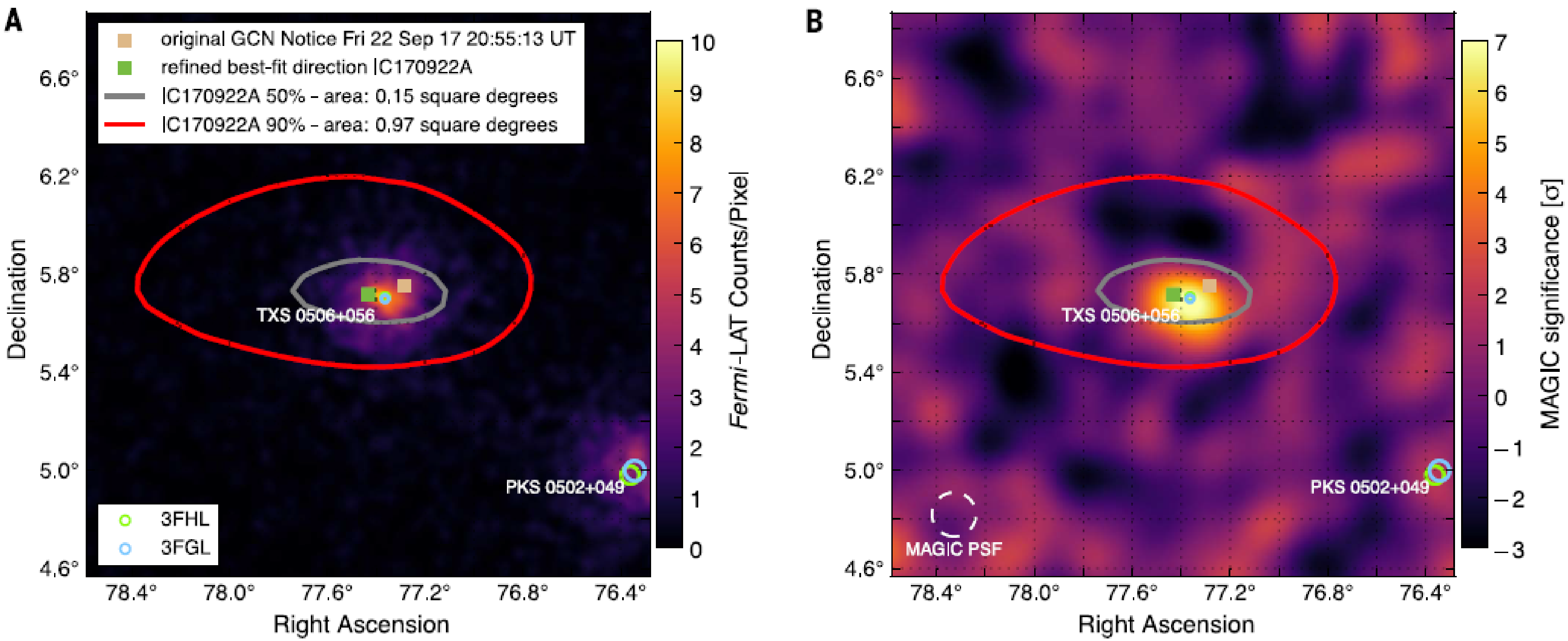


A
original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0,15 square degrees
IC170922A 90% - area: 0,97 square degrees
TXS 0506+056
PKS 0502+049
3FHL
3FGL
Declination
Right Ascension
6.6°
6.2°
5.8°
5.4°
5.0°
4.6°
78.4°
78.0°
77.6°
77.2°
76.8°
76.4°
Fermi-LAT Counts/Pixel
0
1
2
3
4
5
6
7
8
9
10
B
TXS 0506+056
PKS 0502+049
MAGIC PSF
Declination
Right Ascension
MAGIC significance [σ]
−3
−2
−1
0
1
2
3
4
5
6
7

Timeline of all follow-ups

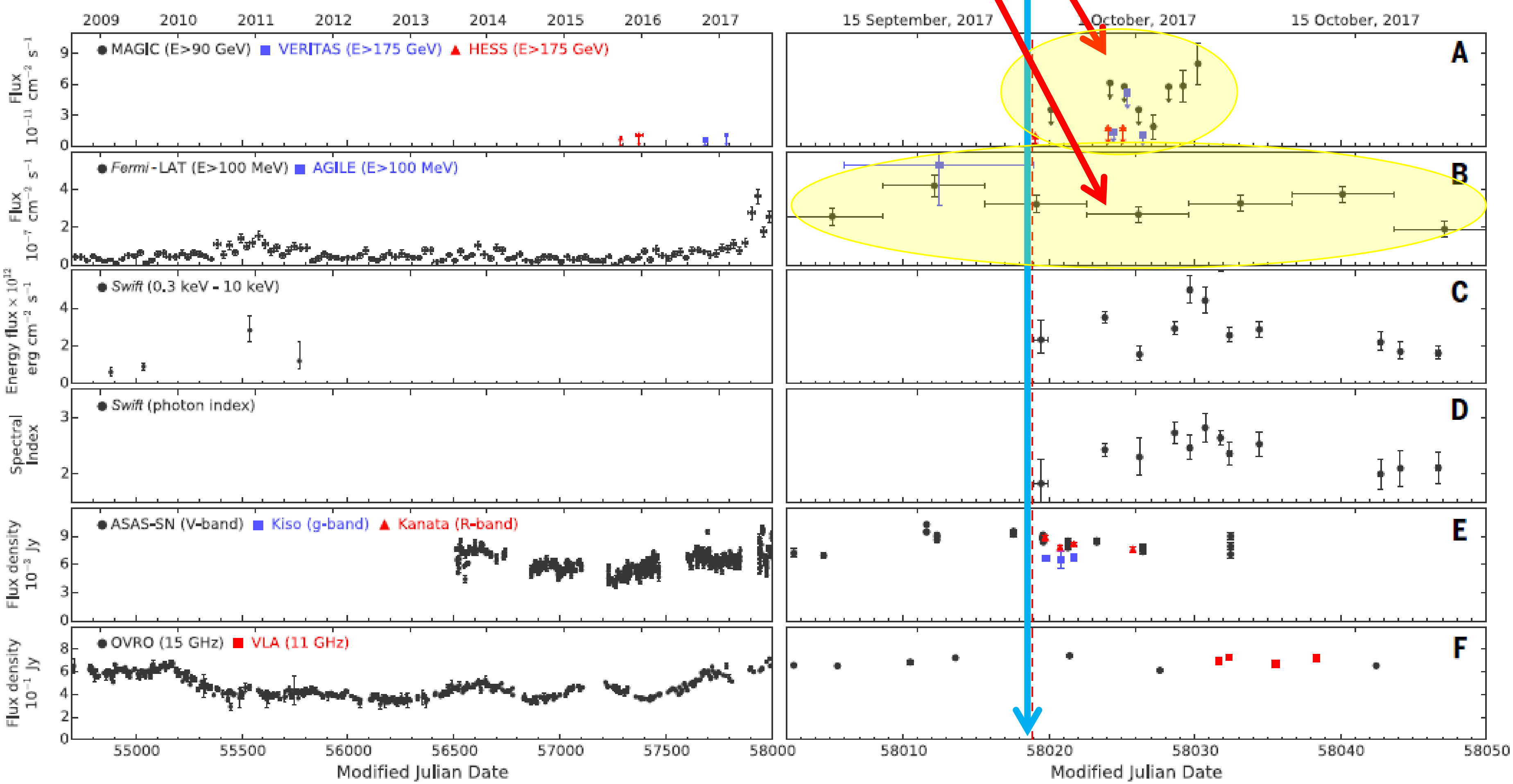
Neutrino arrival time (Sep 2017)

High gamma ray activity

Neutrino-gamma correlation significance: 3 sigma

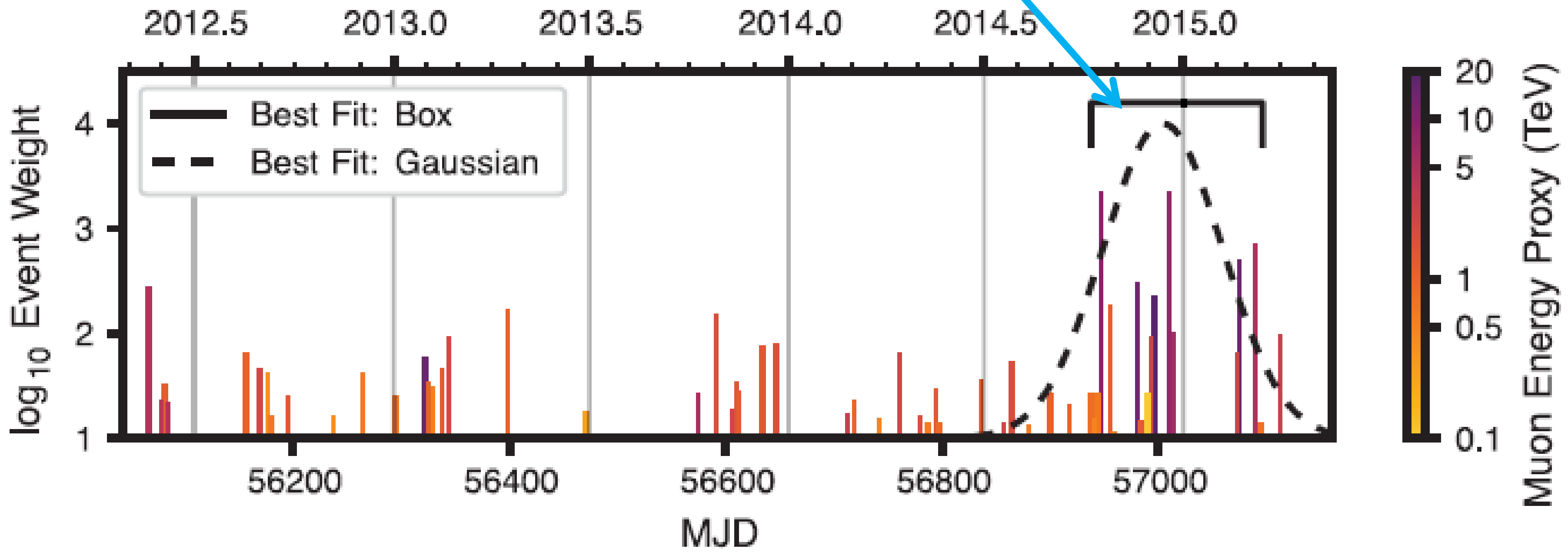
Fermi

MAGIC



Also, looking back in time: there was a burst of neutrinos over 6 months back in 2014/2015

Neutrino time-clustering significance: 3.5 sigma



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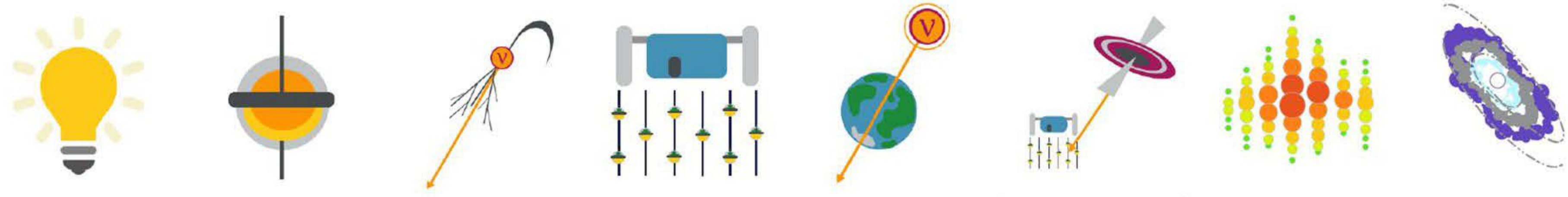

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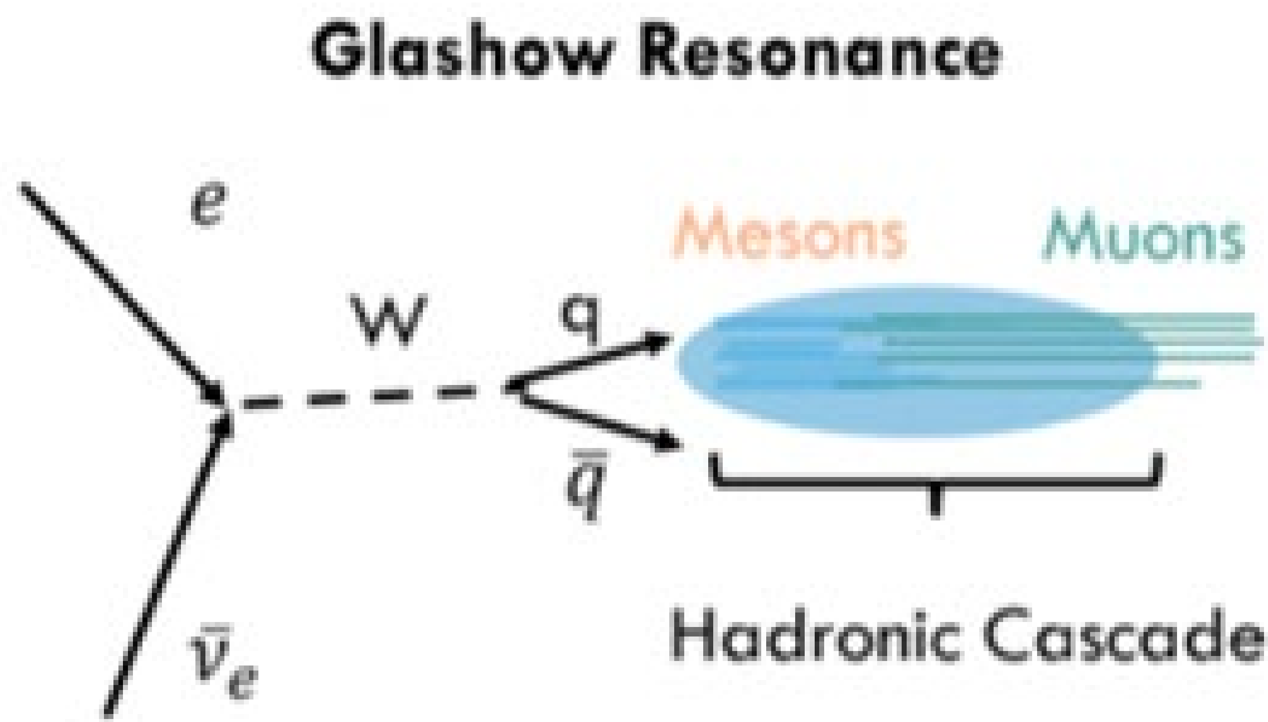
PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Resonant Scattering of Antineutrinos

SHELDON L. GLASHOW*
Institute for Theoretical Physics, Copenhagen, Denmark
(Received October 26, 1959)

The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e \rightarrow \bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have K-meson mass, the resonance occurs at an incident antineutrino energy of $\sim 2\times 10^{12}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.



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The interaction responsible for muon decay also permits an inelastic scattering of antineutrinos by electrons,

$$\bar{\nu}+e\rightarrow\bar{\nu}+\mu^-.$$

With the conventional four-Fermion form of decay interaction, the cross section for this process is

$$\sigma_0=(E/m_e)1.5\times10^{-45}\text{ cm}^2,$$

where E is the energy of an antineutrino incident upon a stationary electron. However, if muon decay is mediated by a charged, unstable boson, this cross section becomes radically altered. The process will occur by the sequence

$$\bar{\nu}+e\rightarrow Z^-\rightarrow\bar{\nu}+\mu^-,$$

and at some antineutrino energy there will be a resonance, occasioned by the real production of an intermediary boson. The cross section, in this case, assumes a typical resonance form,

$$\sigma=\sigma_0\frac{E_0^2}{(E-E_0)^2+\Gamma^2},$$

in which the incident antineutrino energy at the resonance is $E_0=m_Z^2/2m_e$ and Γ denotes its width, $\Gamma=(m_Z/m_e)(1/\tau_Z)$ in terms of the lifetime, τ_Z, of the Z meson. Although σ_0 is proportional to the fourth power of the coupling constant of Z mesons to leptons, the average cross section near the resonance,

$$\frac{1}{2\Delta}\int_{E_0-\Delta}^{E_0+\Delta}\sigma(E)dE\cong\frac{\pi}{4}\left(\frac{E_0}{\Delta}\right)\left(\frac{E_0}{\Gamma}\right)\sigma_0,$$

depends only upon its square. If the Z-meson mass is not much greater than that of the nucleon, this enhanced cross section is not necessarily beyond experimental reach. We shall consider only values of the Z-meson mass such that $m_K\leqslant m_Z\leqslant m_N$, since smaller values of m_Z would prohibit the use of the Z meson to mediate K-meson decays.

The principal decay modes of the Z meson are expected to be $Z^-\rightarrow e+\bar{\nu}$ and $Z^-\rightarrow\mu^-+\bar{\nu}$. With coupling strengths of the Z meson to muon and electron currents chosen equal (in accordance with universality) and of magnitude determined by the muon lifetime, we find

$$\tau_Z=(m_N/m_Z)^3 10^6 m_N^{-1}\hbar c^2\text{ sec.}$$

With $m_Z=m_N$, the energy of the incident antineutrino energy at the resonance is 9×10^{11} ev and the width of the resonance is 2×10^6 ev, while with $m_Z=m_K$, $E_0=2.3\times10^{11}$ ev and $\Gamma=1.5\times10^5$ ev.

Although the natural width of the resonance is quite small, a significant broadening is produced by the spread in velocity of the target electrons. In a collision with an electron of velocity βc along the direction of incidence, the resonance occurs at the antineutrino energy

$$E_0'=(1+\beta)^{-1}E_0.$$

Thus the experimental width of the resonance will be approximately $(\mathfrak{z}/137)E_0$, where $\mathfrak{z}$ is the mean atomic number of the target material. Upon earth, antineutrinos of energies within the resonance should have a mean free path of some hundreds of kilometers, corresponding to a cross section of 10^{-32} cm^2.

The only known source of antineutrinos of sufficiently great energies is the decay of cosmic-ray pions and K mesons. Practically all such antineutrinos are produced in association with muons, consequently their intensity and energy spectrum may be deduced from the known sea-level flux of muons.[1] We estimate that at 9×10^{11} ev the antineutrino flux is 10^{-11} cm^{-2} sec^{-1} Bev^{-1}, and at 2.3×10^{11} ev it is 10^{-9} cm^{-2} sec^{-1} Bev^{-1}. Exposed to these antineutrino fluxes, each target electron will act as a source of 4×10^{-40} muon per second if $m_Z=m_N$, or 10^{-38} muon per second at the lower value of $m_Z=m_K$.

With a muon-sensitive area of one square meter, placed underground, the experimenter might anticipate a counting rate of two per day (at $m_Z=m_K$) or of 0.1 per day (at $m_Z=m_N$) independently of the depth at which the experiment is performed. The counting rate should be relatively insensitive to the orientation of the experimental apparatus with respect to the vertical, since the muons should be produced isotropically in the upper hemisphere. A positive result to this experiment would be evidence both for the existence of an intermediary boson and for the absence of a selection rule that prevents those neutrinos produced in association with muons from interacting with electrons.

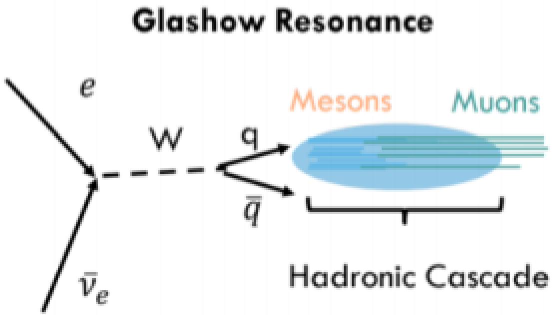
* National Science Foundation Post-Doctoral Fellow.

[1] A. Subramanian and S. D. Verma, Nuovo cimento 8, 572 (1959).

ACKNOWLEDGMENTS

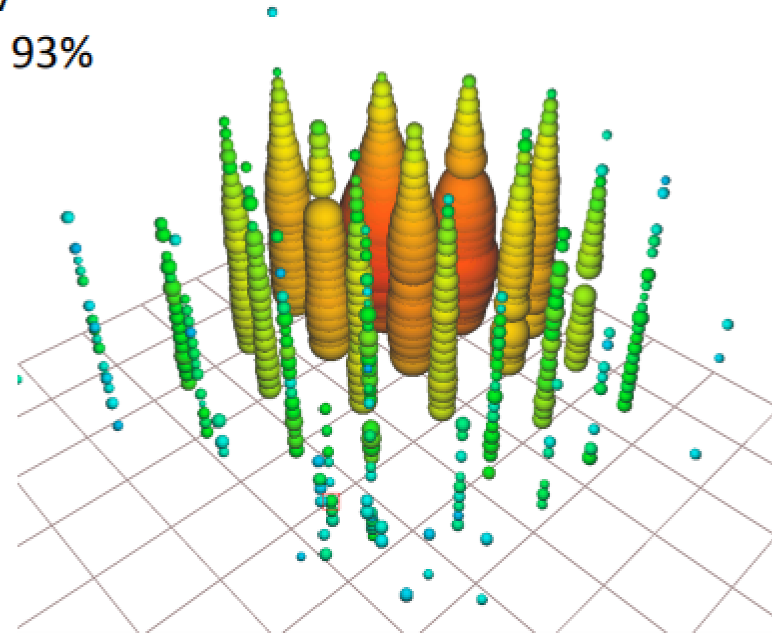
I am grateful to Professor A. Bohr and Professor B. Peters for valuable discussions, and to Professor Niels Bohr for the hospitality that has been extended to me at his Institute.

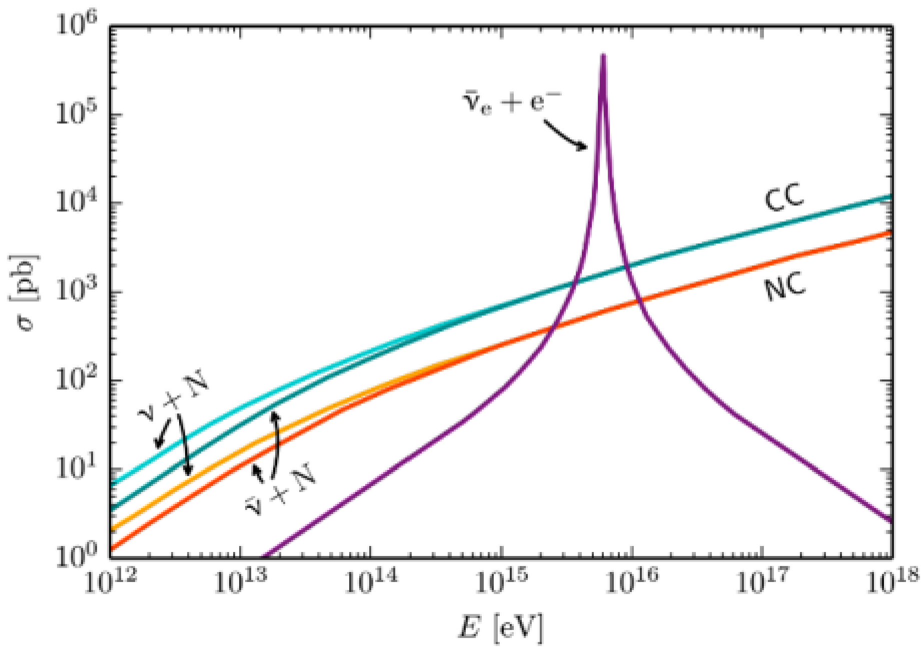
A 5.9 PeV event in IceCube



Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%

Work in progress





Event identified in a partially-contained PeV search (PEPE)

Deposited energy: 5.9±0.18 PeV (stat only)

ICRC 2017 arXiv:1710.01191

Potential hadronic nature of this event under study

Article

Detection of a particle shower at the Glashow resonance with IceCube

https://doi.org/10.1038/s41586-021-03256-1

Received: 28 July 2020

Accepted: 18 January 2021

Published online: 10 March 2021

Check for updates

The IceCube Collaboration*

The Glashow resonance describes the resonant formation of a W^- boson during the interaction of a high-energy electron antineutrino with an electron[1], peaking at an antineutrino energy of 6.3 petaelectronvolts (PeV) in the rest frame of the electron. Whereas this energy scale is out of reach for currently operating and future planned particle accelerators, natural astrophysical phenomena are expected to produce antineutrinos with energies beyond the PeV scale. Here we report the detection by the IceCube neutrino observatory of a cascade of high-energy particles (a particle shower) consistent with being created at the Glashow resonance. A shower with an energy of 6.05 ± 0.72 PeV (determined from Cherenkov radiation in the Antarctic Ice Sheet) was measured. Features consistent with the production of secondary muons in the particle shower indicate the hadronic decay of a resonant W^- boson, confirm that the source is astrophysical and provide improved directional localization. The evidence of the Glashow resonance suggests the presence of electron antineutrinos in the astrophysical flux, while also providing further validation of the standard model of particle physics. Its unique signature indicates a method of distinguishing neutrinos from antineutrinos, thus providing a way to identify astronomical accelerators that produce neutrinos via hadronuclear or photohadronic interactions, with or without strong magnetic fields. As such, knowledge of both the flavour (that is, electron, muon or tau neutrinos) and charge (neutrino or antineutrino) will facilitate the advancement of neutrino astronomy.

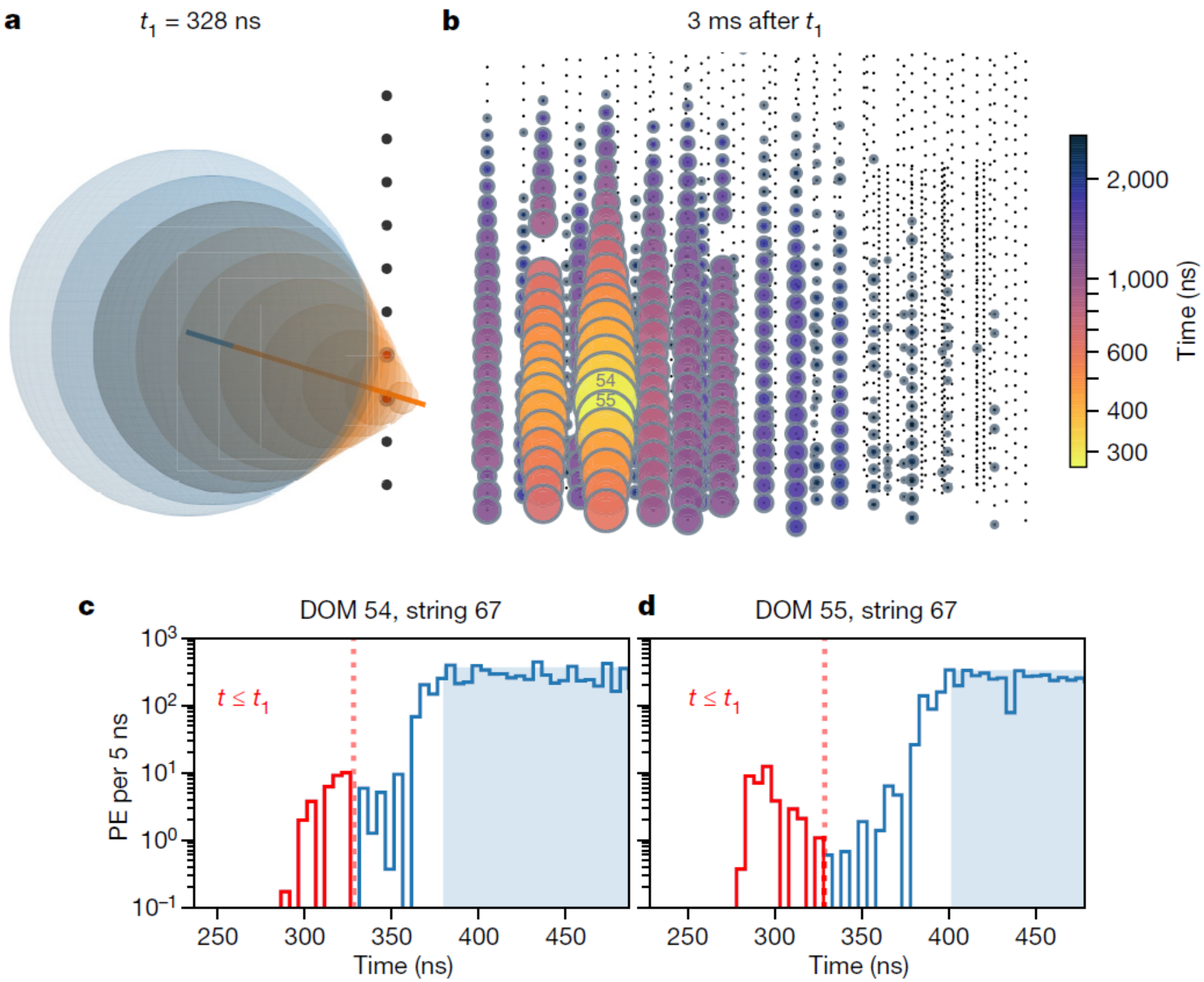
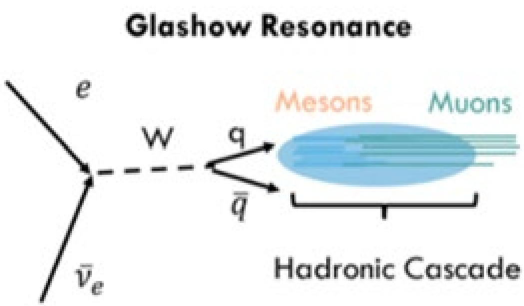
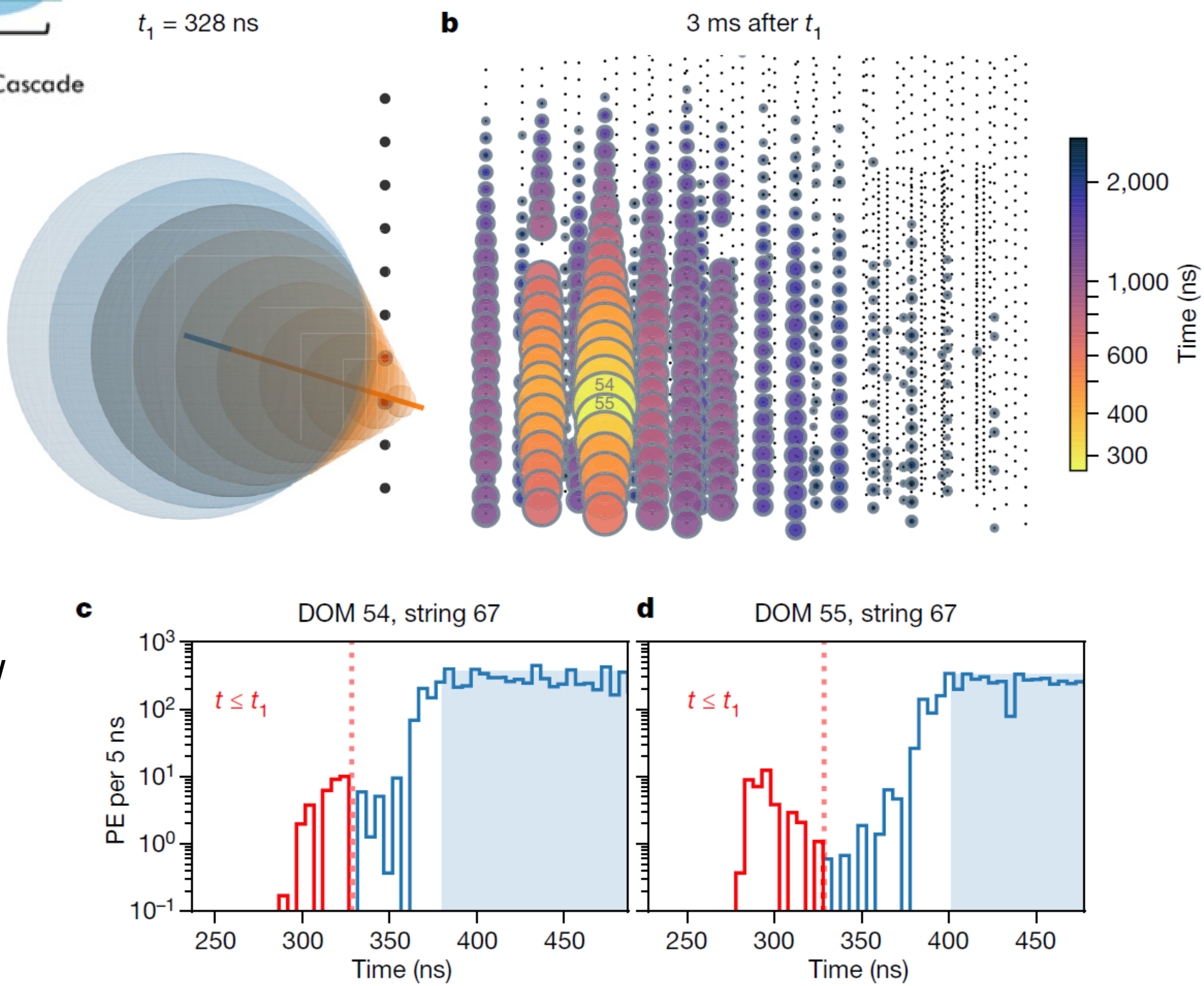


Fig. 1 | Visualization of detected photons at different times and distribution of early pulses. a, Schematic of an escaping muon travelling at faster than the speed of light (in ice) and its Cherenkov cone (orange). The muons reach the nearest modules (DOMs 54 and 55 on string 67) ahead of the Cherenkov photons produced by the EM component of the hadronic shower (blue) as these travel at the speed of light in ice. The blue line is associated with the average distance travelled by the main shower, while the orange line extends further and is associated with the muons. Each black dot arranged vertically is a DOM on the nearest string, with the two (slightly larger) dots inside the orange cone the first two to observe early pulses. The time t_1 indicates the approximate time elapsed since the neutrino interaction at which this snapshot graphic was taken. **b**, Event view, showing DOMs that triggered across IceCube at a later time. Each bubble represents a DOM, with its size proportional to the deposited charge. Colours indicate the time each DOM first triggered, relative to our best knowledge of when the initial interaction occurred. The small black dots are DOMs further away that did not detect photons 3 ms after t_1. **c**, **d**, Distributions of the deposited charge over time on the two earliest hit DOMs, 54 (**c**) and 55 (**d**). The dotted red line is at t_1 = 328 ns, the instant shown in **a**. The histogram in red (blue) shows photons arriving before (after) t_1, and the blue shaded region denotes saturation of the photomultiplier tube.





The structure of the measured photons in the detector matches well to the hypothesis of a W decay into a shower and muons!

New results from the IceCube Neutrino Observatory

Thursday, November 3, 1:00 PM CDT

Master of Ceremony
Albrecht Karle, University of Wisconsin–Madison

Opening Remarks
Denise Caldwell, National Science Foundation
Steve Ackerman, University of Wisconsin–Madison

Presentations
Justin Vandenbroucke, University of Wisconsin–Madison
Elisa Resconi, Technical University of Munich
Hans Niederhausen, Michigan State University and Technical University of Munich
Ignacio Taboada, Georgia Institute of Technology

Question & Answer Session

Credit: Martin Wolf, IceCube/NSF

ICECUBE

NSF

Science — Nov. 4, 2022

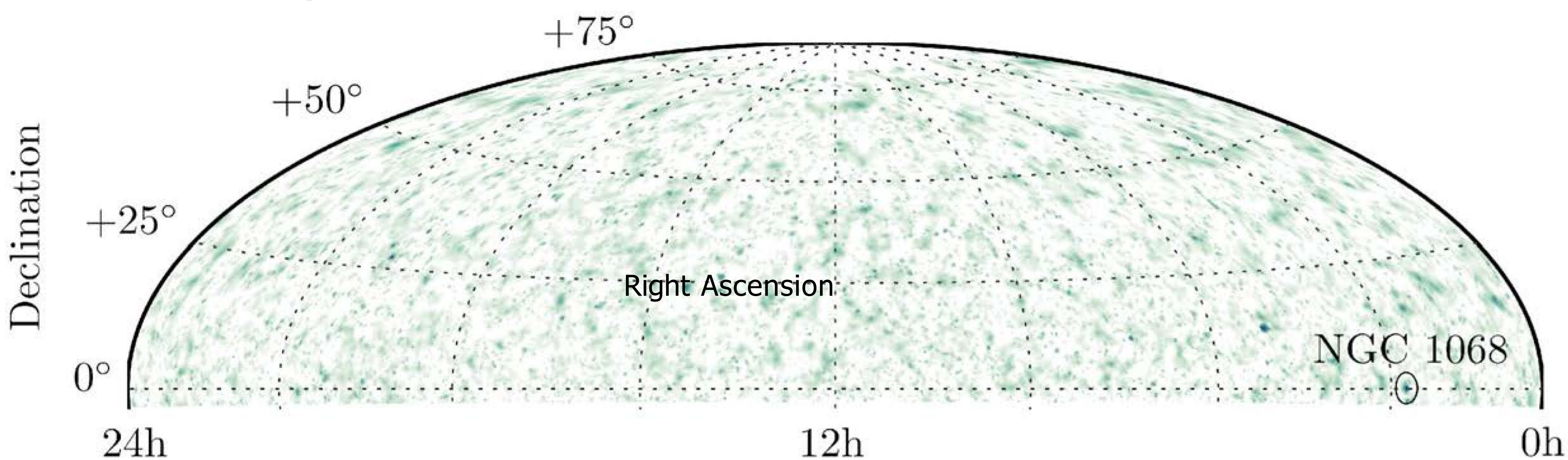
RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

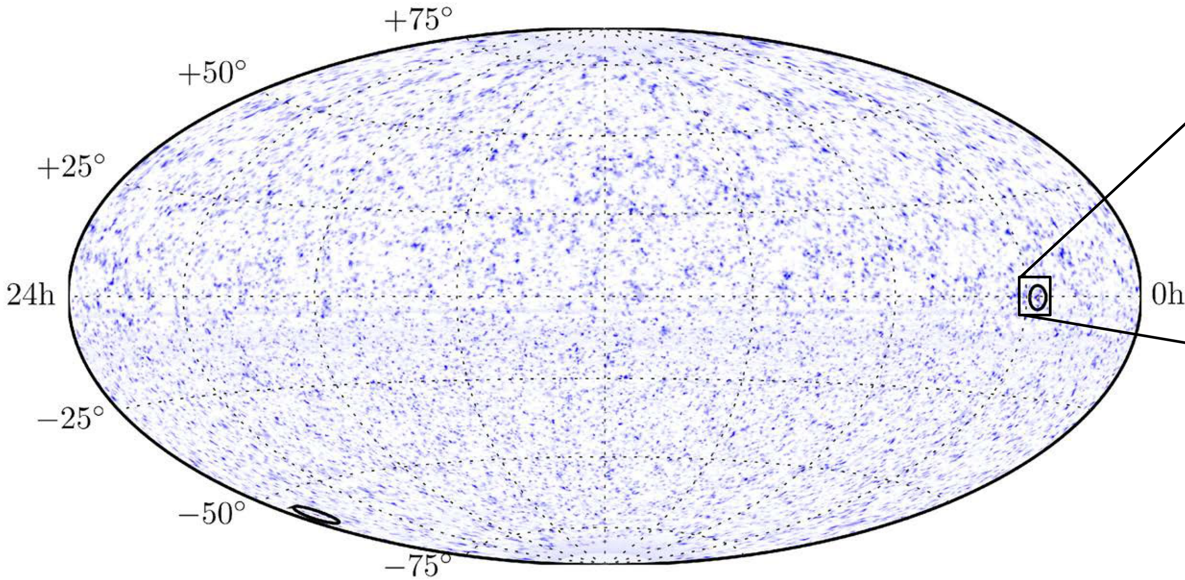
Evidence for neutrino emission from the nearby active galaxy NGC 1068

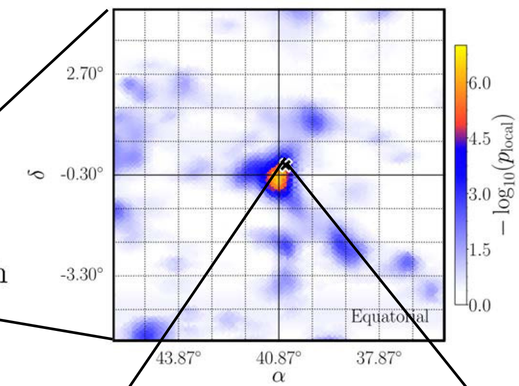
IceCube Collaboration*†



Previous analysis:

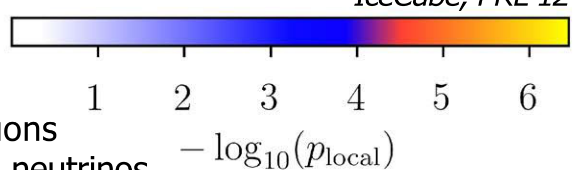
Most significant position on sky: consistent with NGC 1068 (Messier 77), a Seyfert Ⅱ galaxy (2.9 σ)





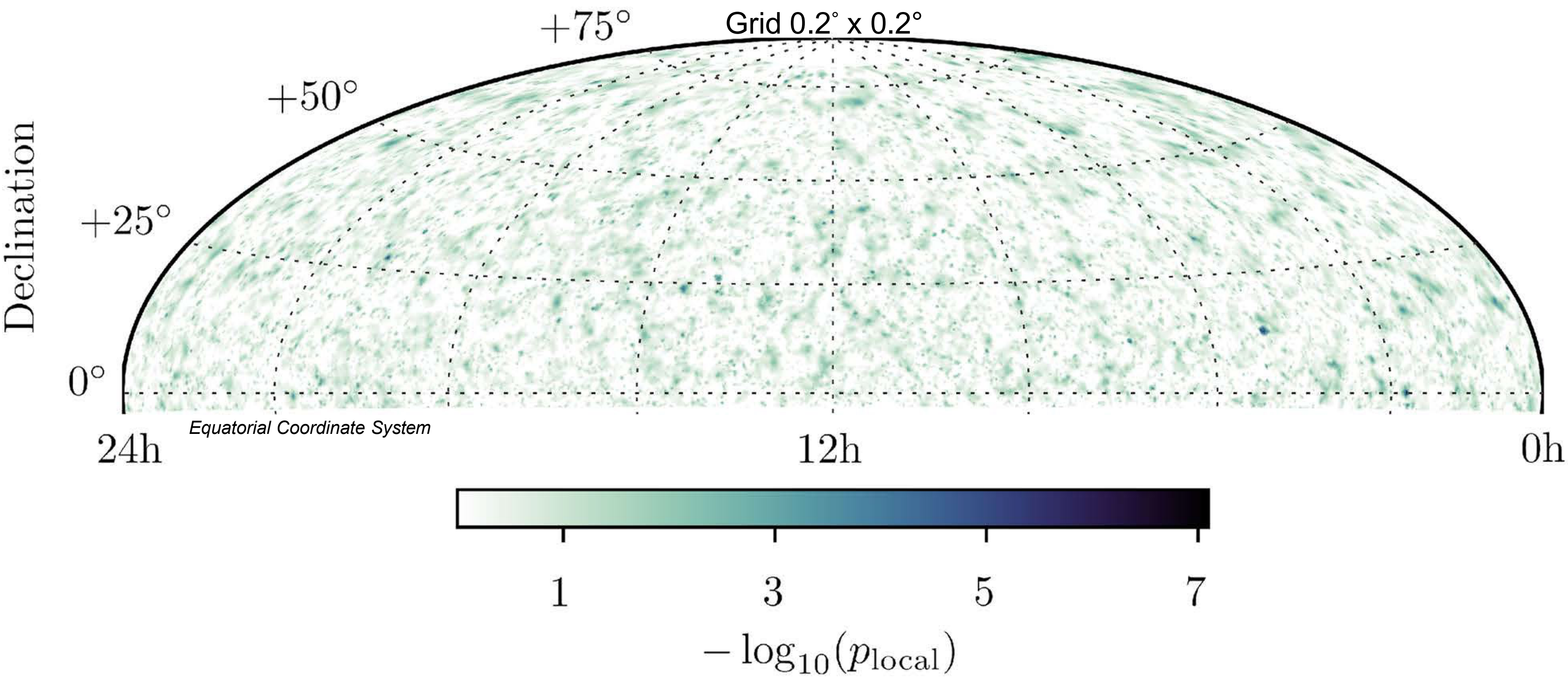
50 neutrinos

IceCube, PRL 124, 051103 (2020)

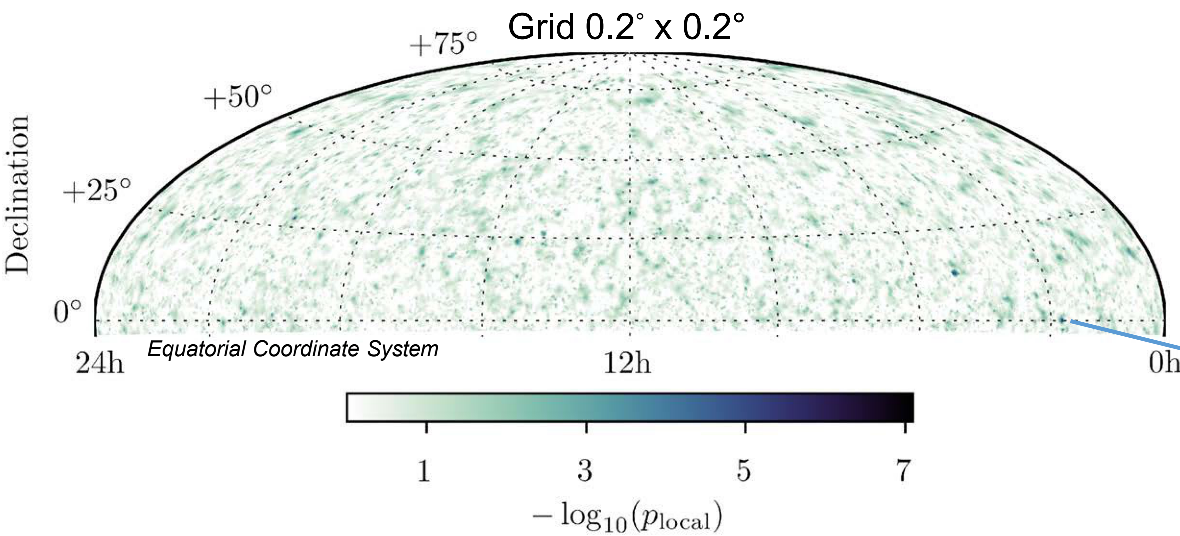


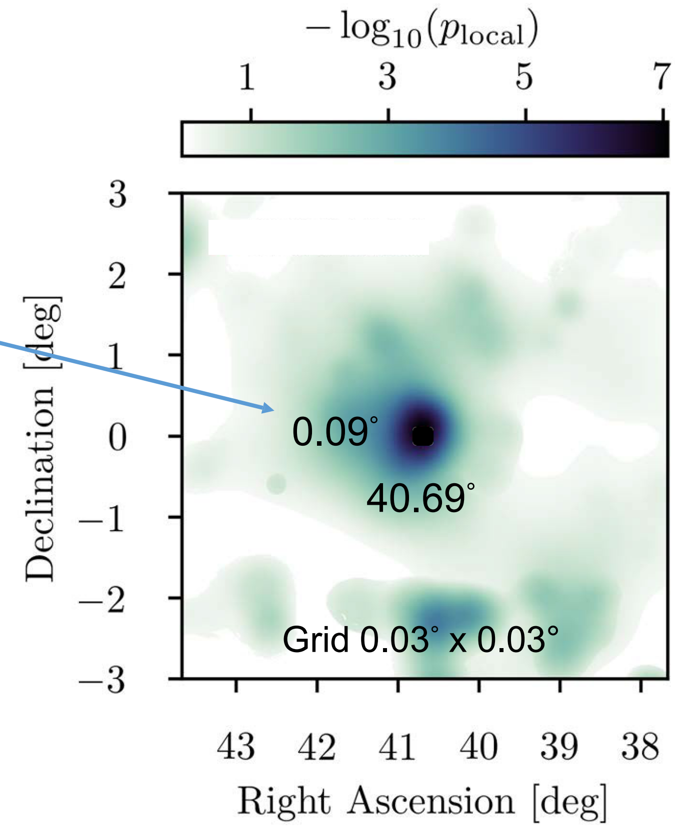
Per year:
90 billion atmospheric muons
80 thousand atmospheric neutrinos

The new IceCube neutrino map (improved processing, directional and energy reconstruction)



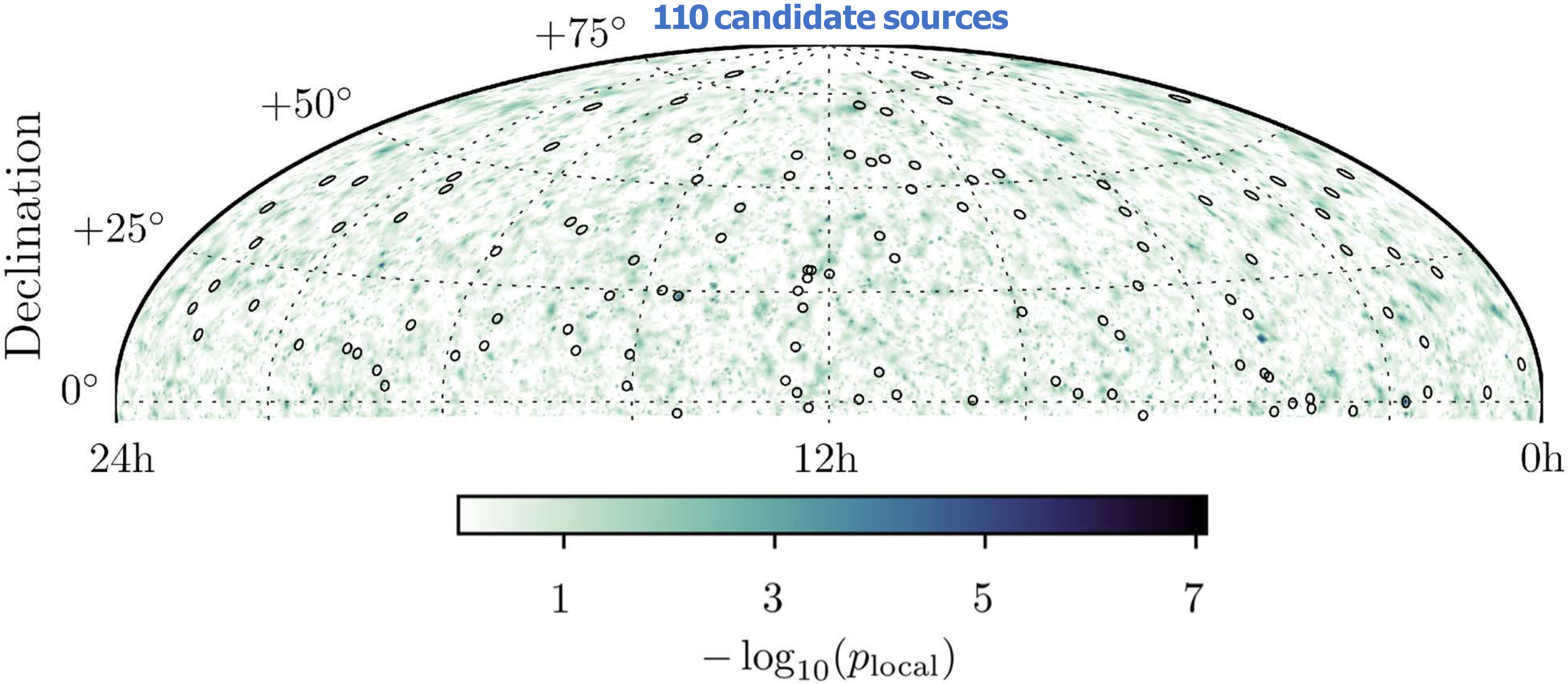
Identified 'hot' spot



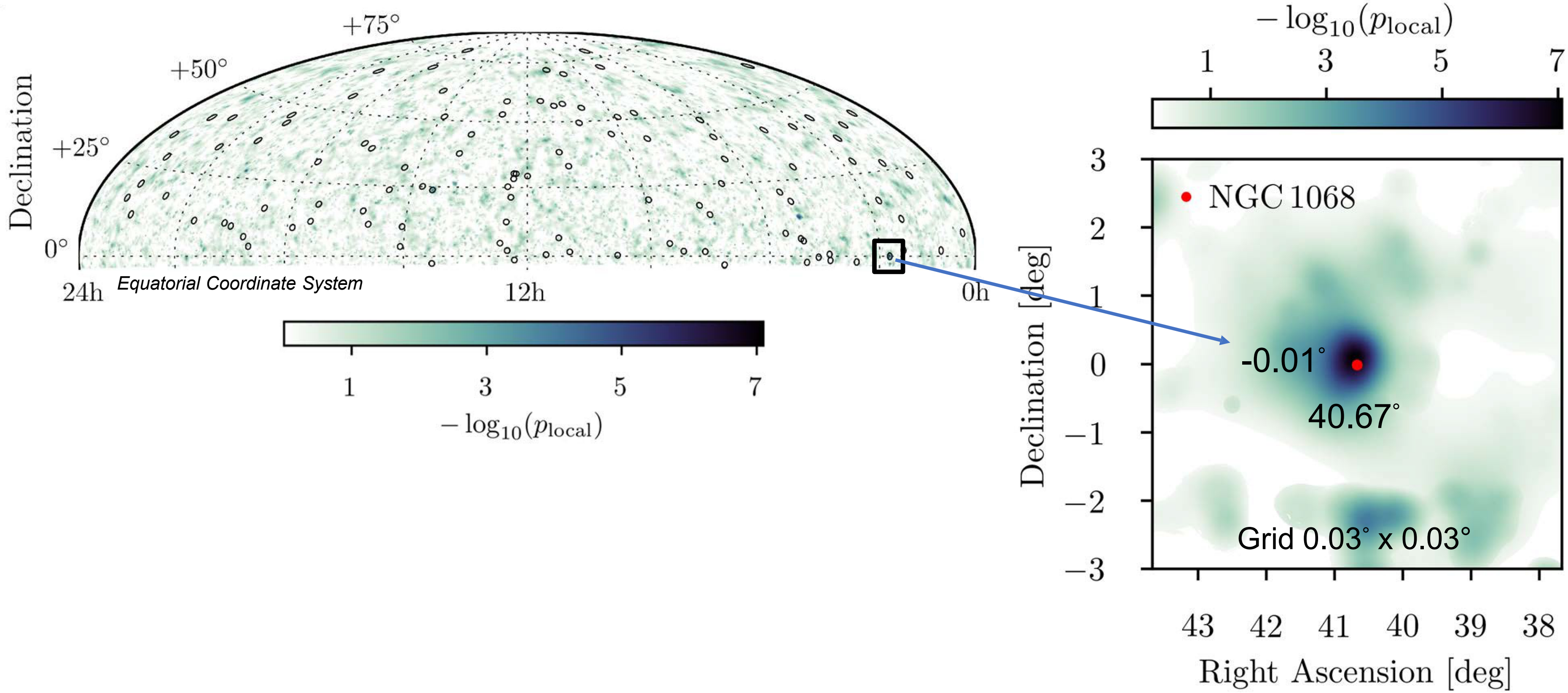


At the brightest location in full sky scan:
Mean astrophysical neutrino events = 81
Mean spectral index = 3.2

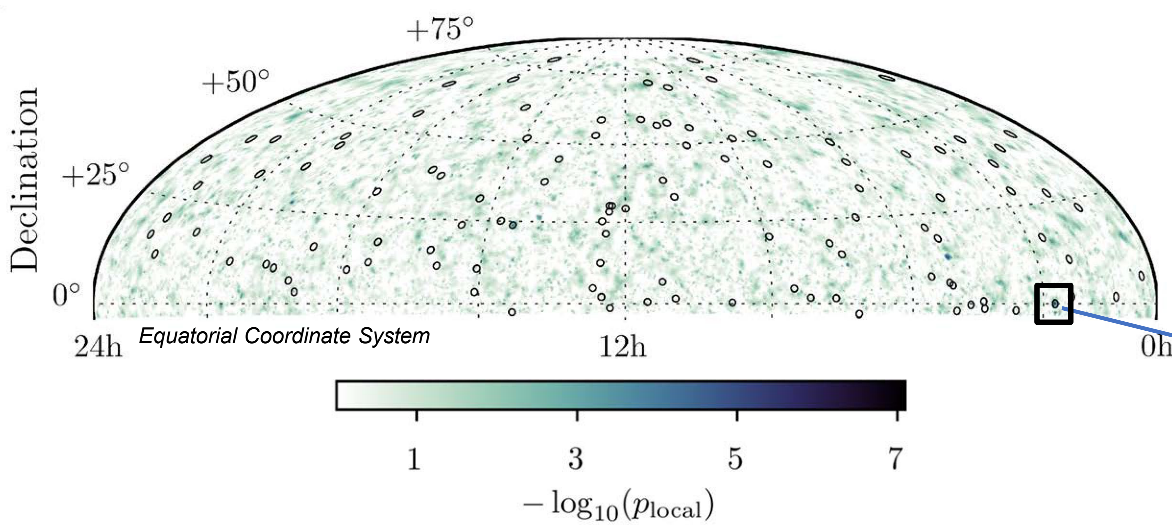
Is the ‘hot’ spot in coincidence with an object?

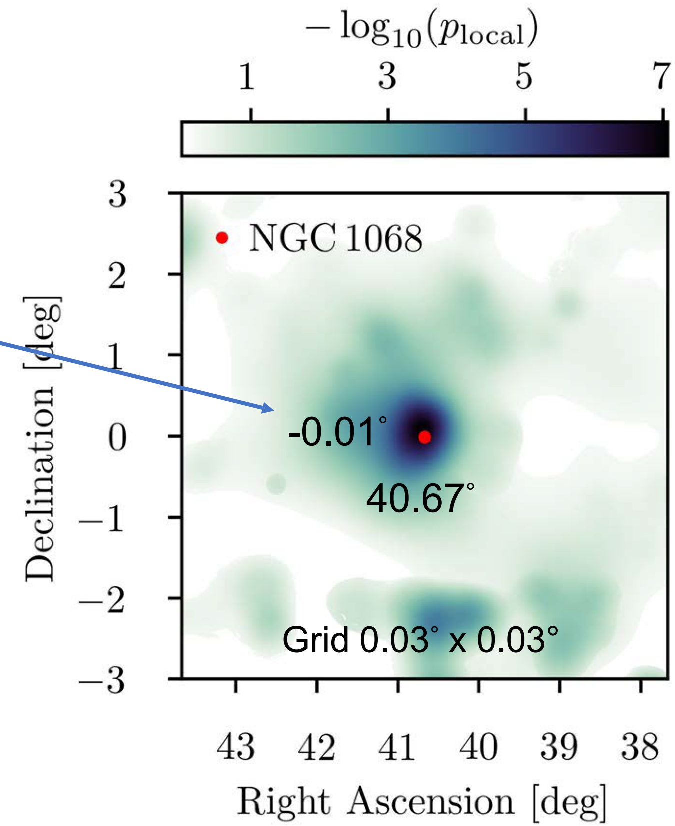


Hottest spot coincides with NGC 1068



Hottest spot coincides with NGC 1068



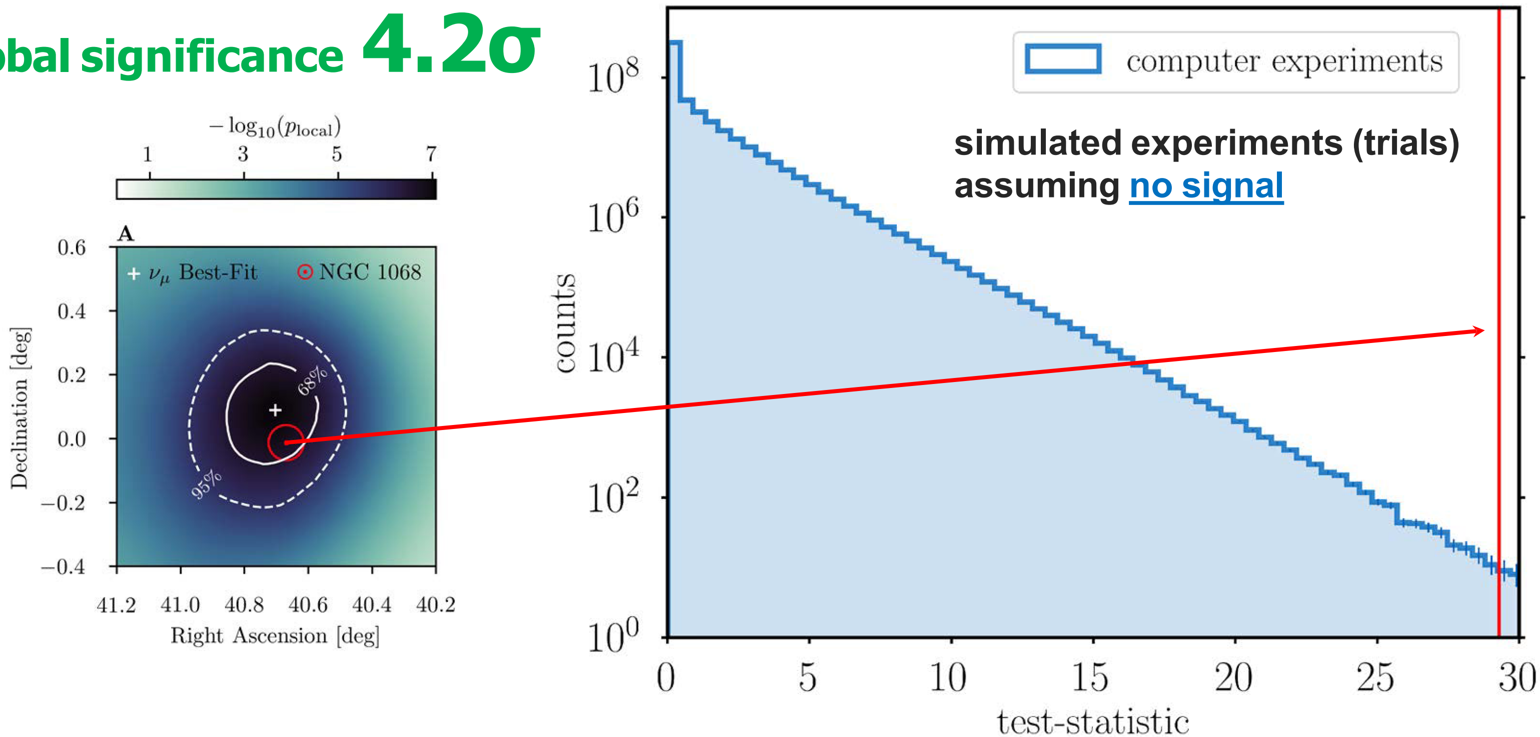


At the NGC 1068 location:

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

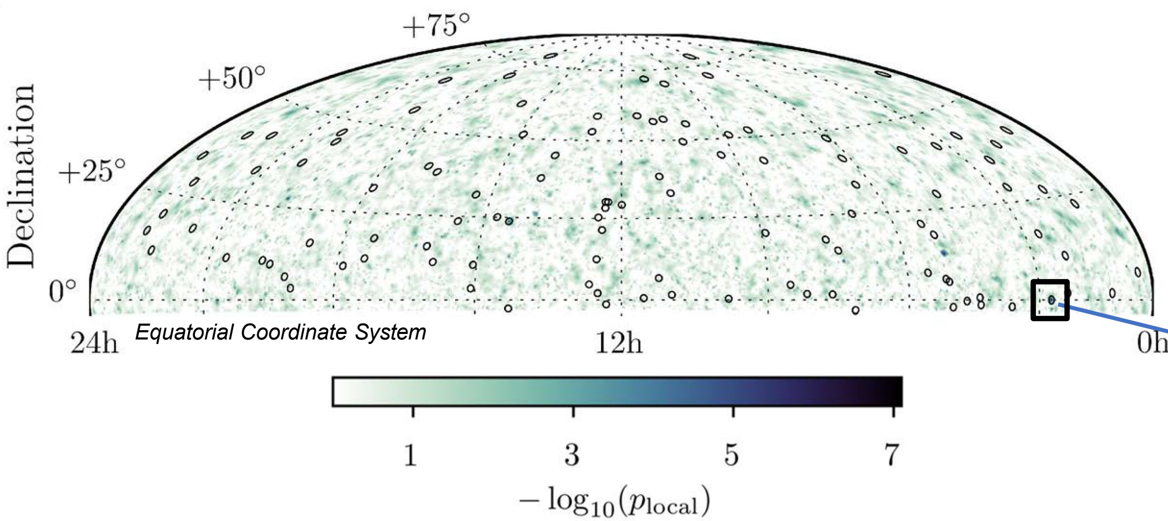
Spectral index = 3.2 ± 0.2

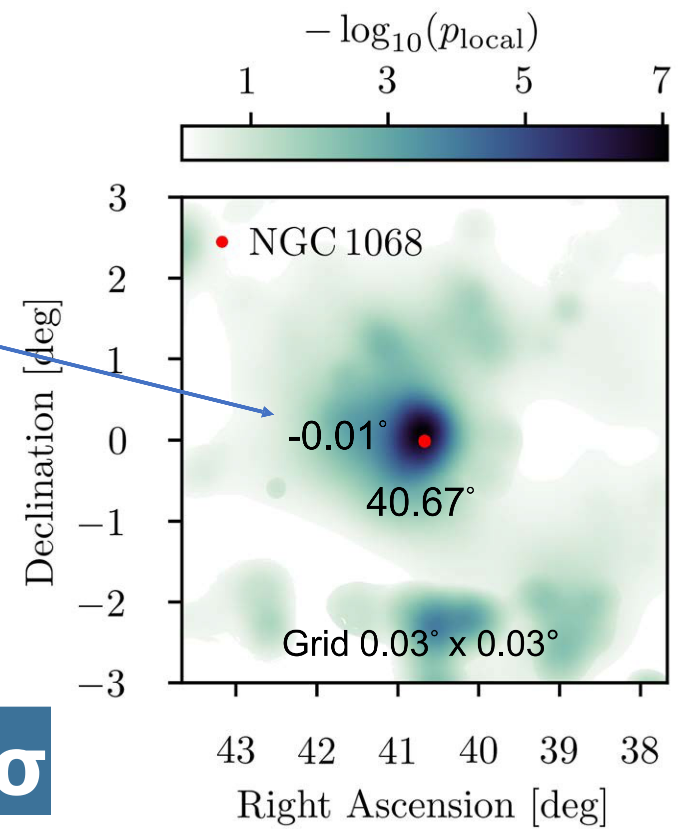
... global significance 4.2σ



using 500×10^6 computer experiments assuming no signal
and accounting for catalog size (110 candidate sources) yields $p \sim 1.1 \times 10^{-5}$

Evidence for neutrino emission from NGC 1068





At the NGC 1068 location:
Astrophysical neutrino events = 79 $^{+22}_{-20}$
Spectral index = 3.2 ± 0.2

Global significance **4.2σ**

An improved track dataset

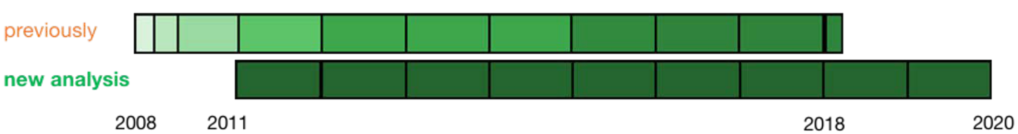
data: May 2011 to May 2020

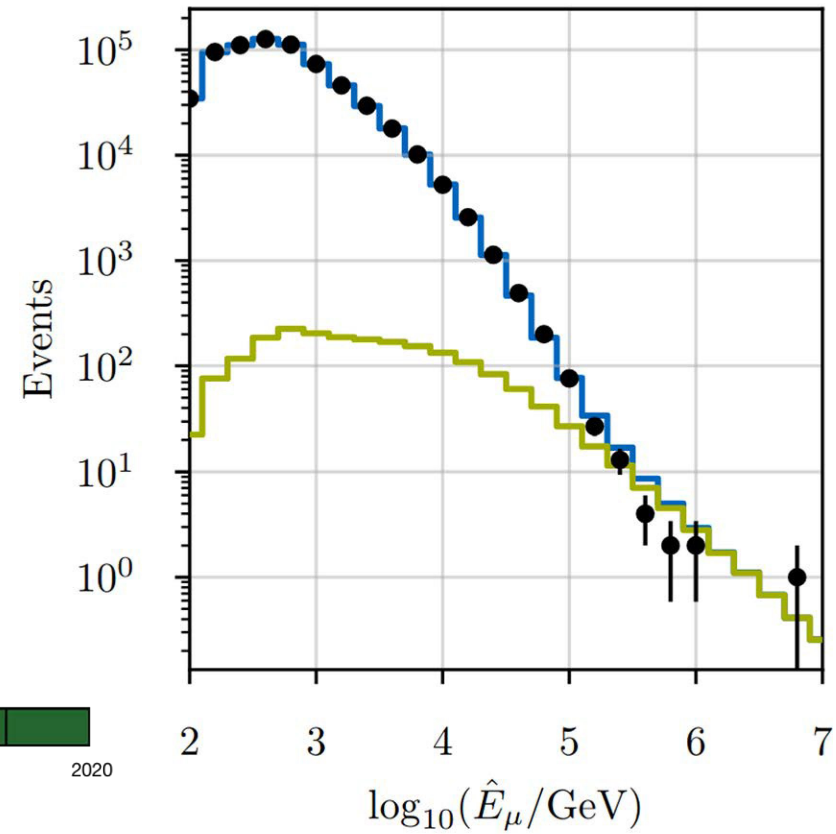
~99% detector uptime

~670,000 neutrinos selected (99.7% purity)
out of ~1 trillion events recorded

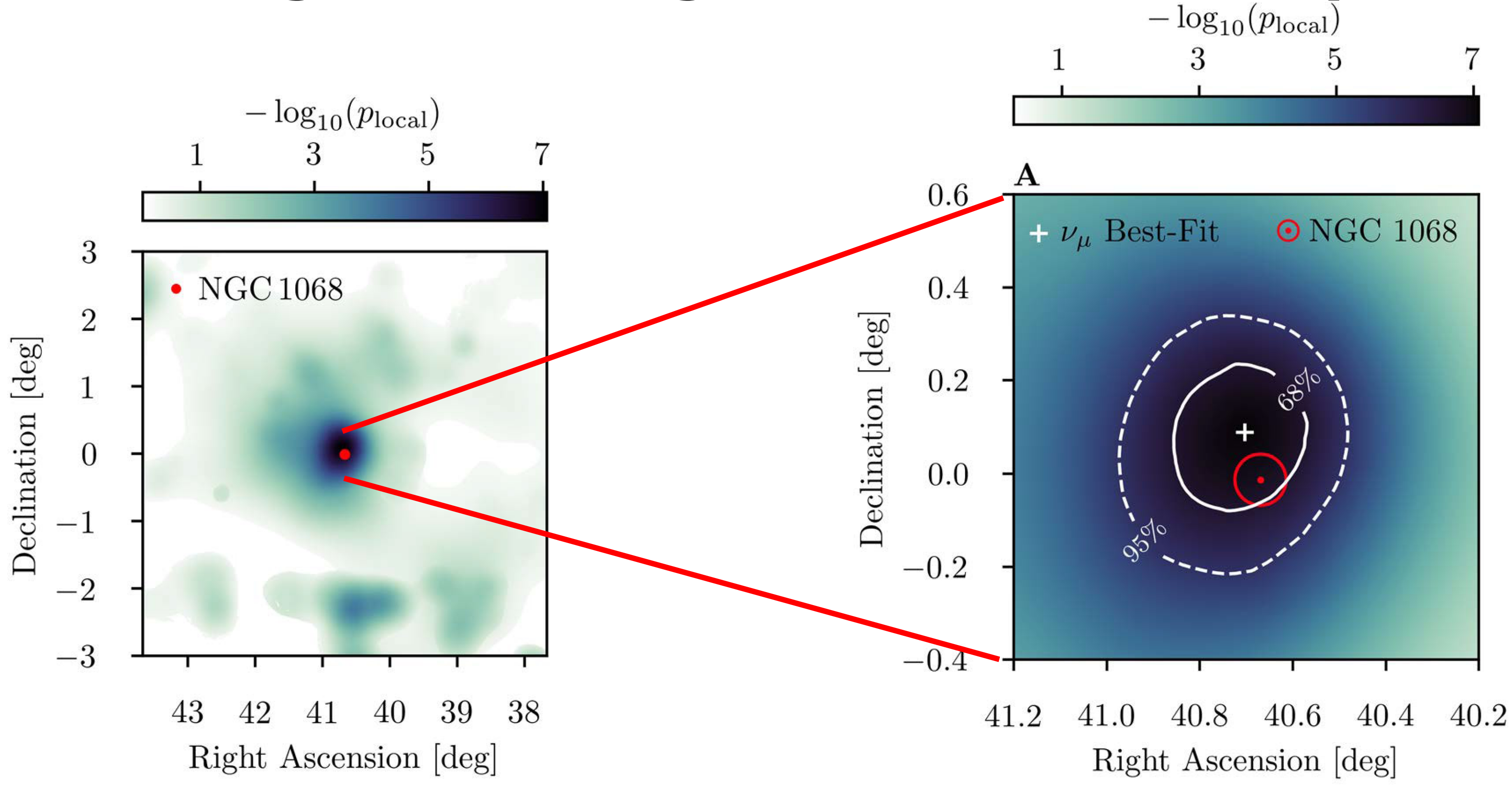
multiple improvements
detector calibration, data filtering and processing applied to entire dataset (all ~1 trillion events)

=> IceCube Pass 2 data



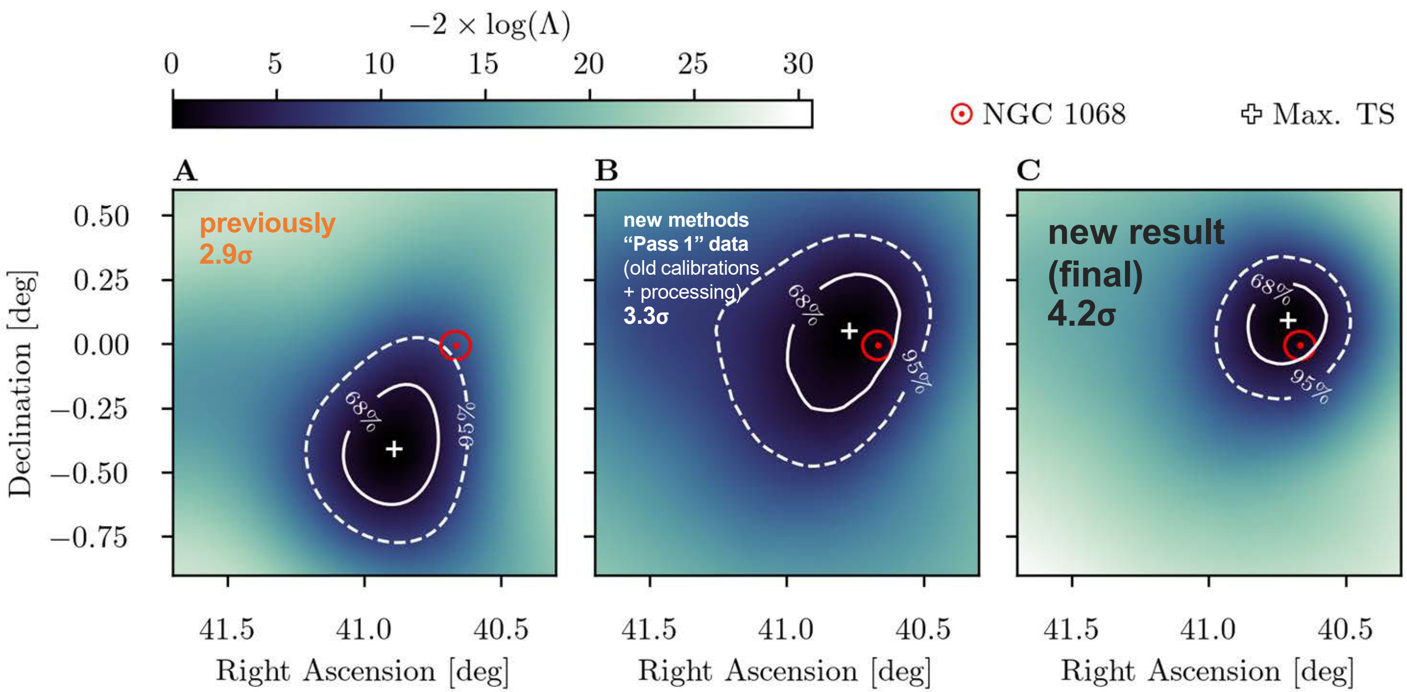


NGC 1068 is consistent with location of strongest clustering of neutrinos in the sky



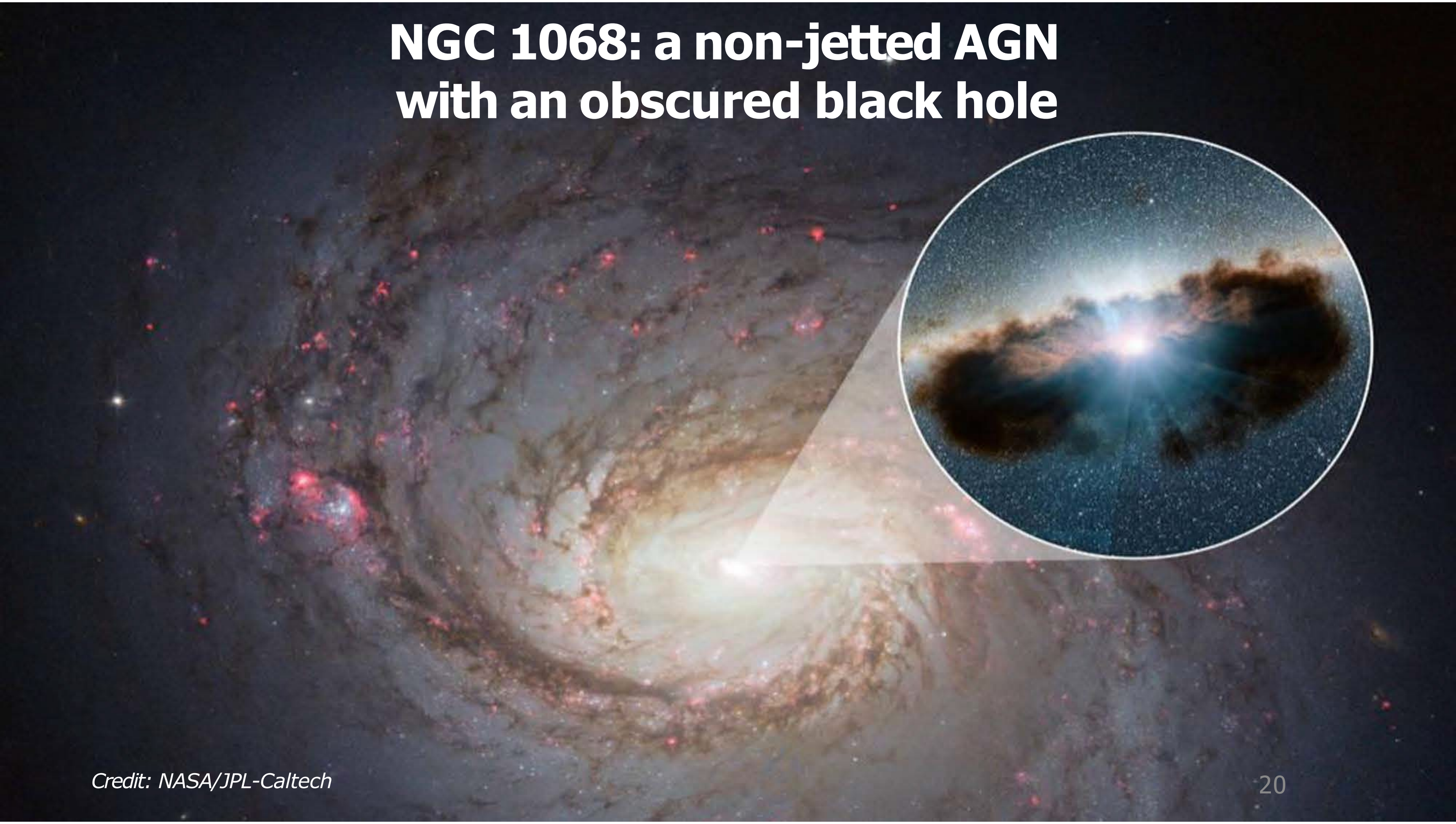
Improvements made new results possible

1) Improvements in data quality (updated calibrations, uniform processing) "Pass2"
2) Improved statistical methods and directional and energy reconstructions

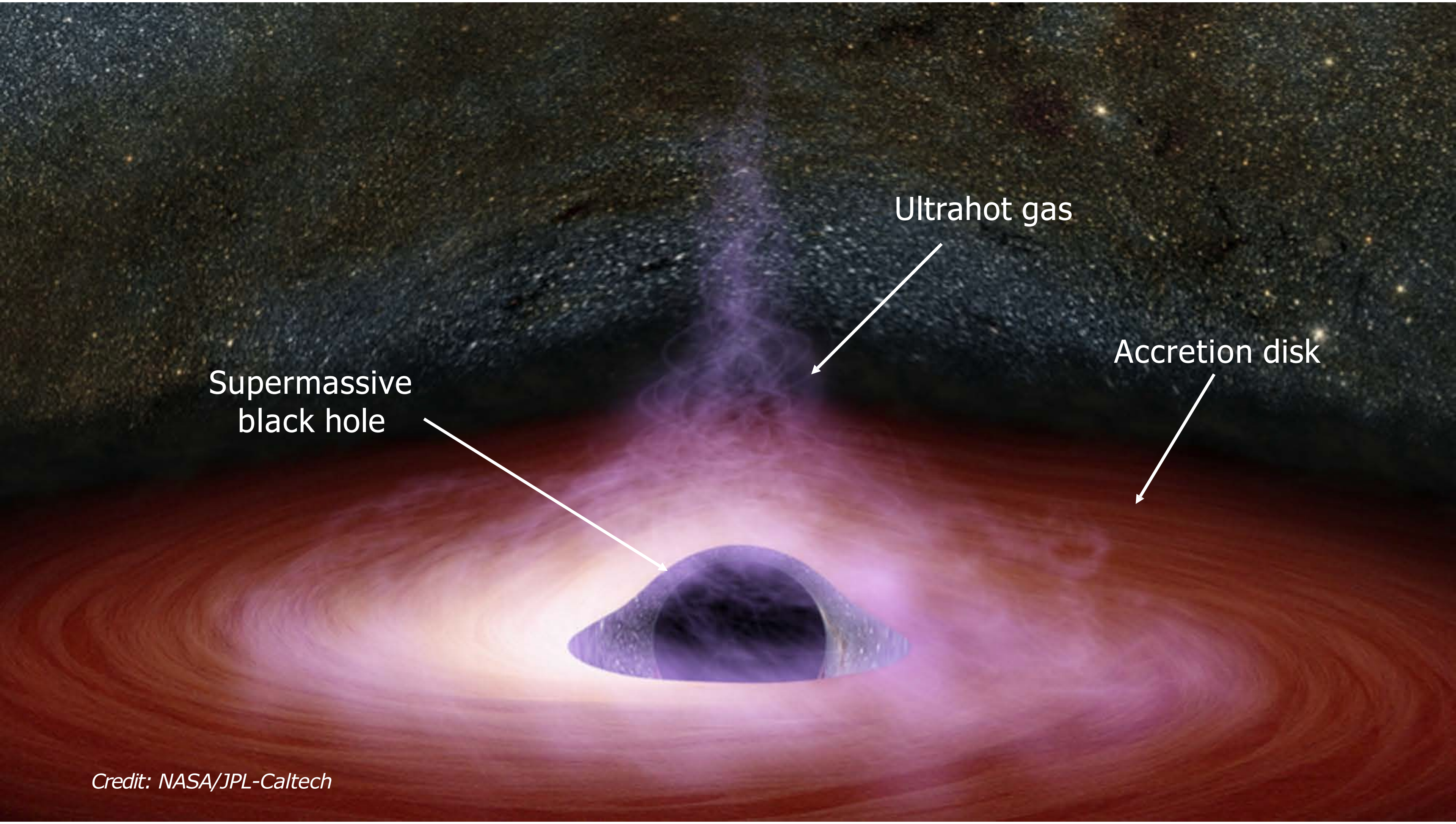


(new processing + old methods: 3.8σ)

NGC 1068: a non-jetted AGN with an obscured black hole



Credit: NASA/JPL-Caltech



Ultrahot gas
Accretion disk
Supermassive
black hole
Credit: NASA/JPL-Caltech

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 ($E \gtrsim 10^{19}$ 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 ~ 1 MeV, and from a spinar, above ~ 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

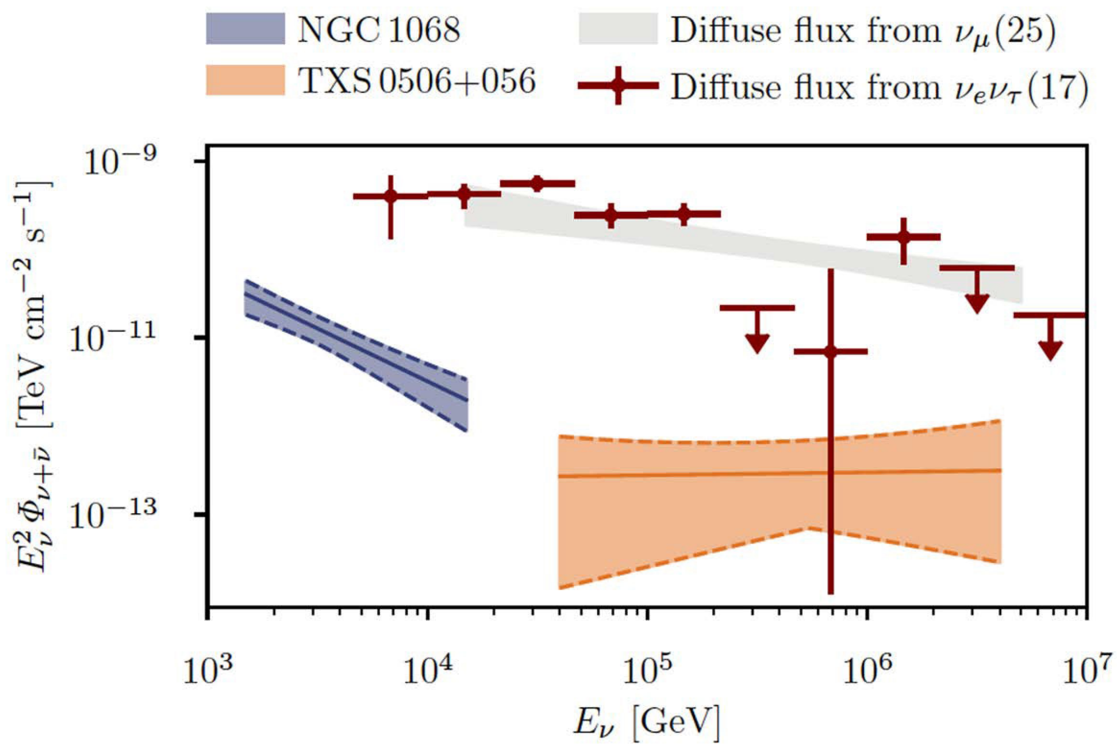
1982

Implications of the NGC 1068 neutrino observation

Active galaxies may contribute to significant fraction of extragalactic neutrino flux.

NGC 1068 is opaque to high-energy gamma-rays

NGC 1068 and TXS 0506+056 are different.



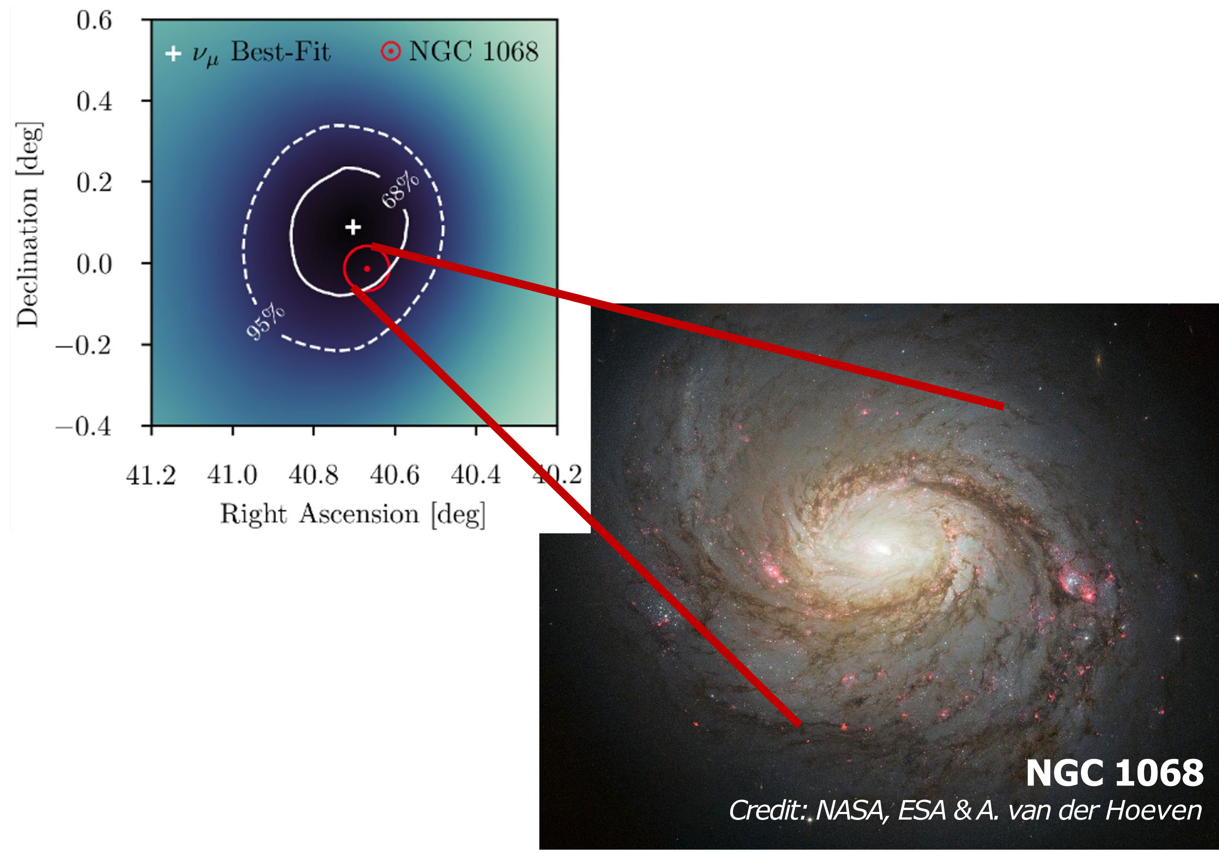
[25] IceCube. ApJ 928, 50 (2020)
[17] IceCube. PRL. 125, 121104 (2020)

IceCube is getting better – and we are not finished

More to IceCube than “adding more years of data”

New instrumentation in 2025/2026 will improve angular resolution

The future IceCube-Gen2 will have even better sensitivity than IceCube

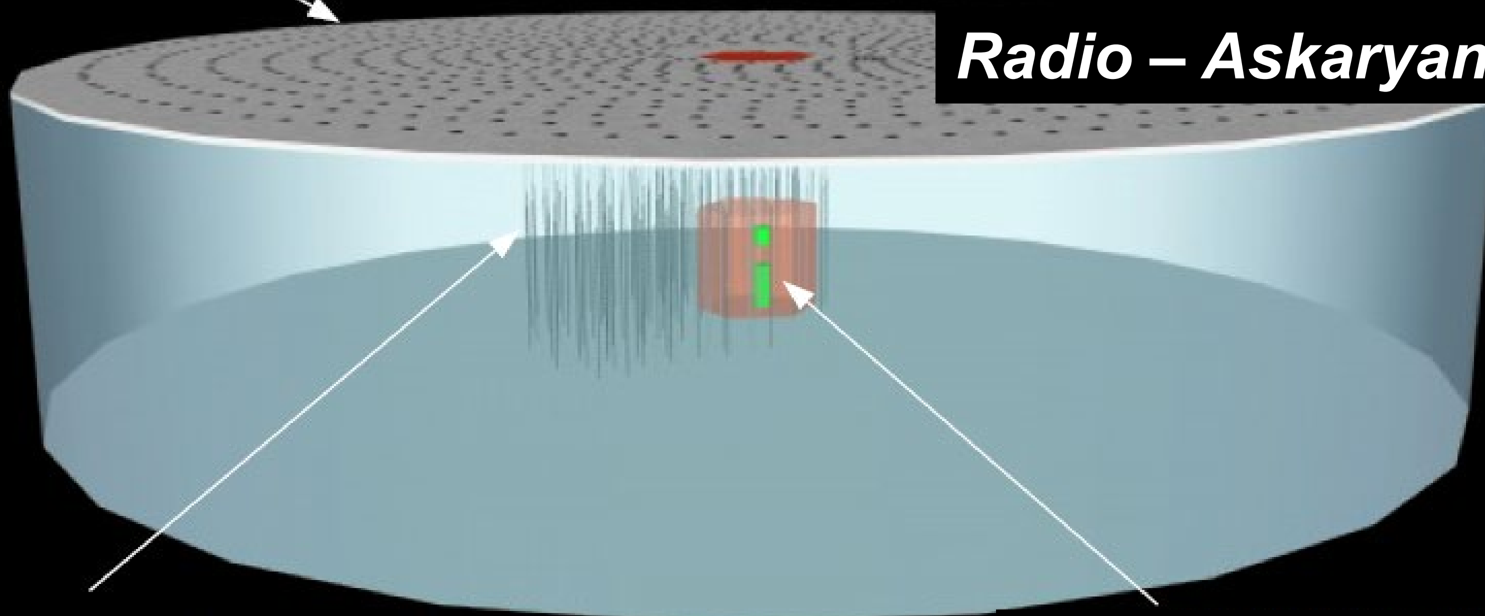


IceCube- Gen2

Extended surface array for veto

IceAct- Air Cherenkov telescope

Radio – Askaryan Effect



100 new strings with 240 m spacing

IceCube Upgrade
7 strings – 2025/26