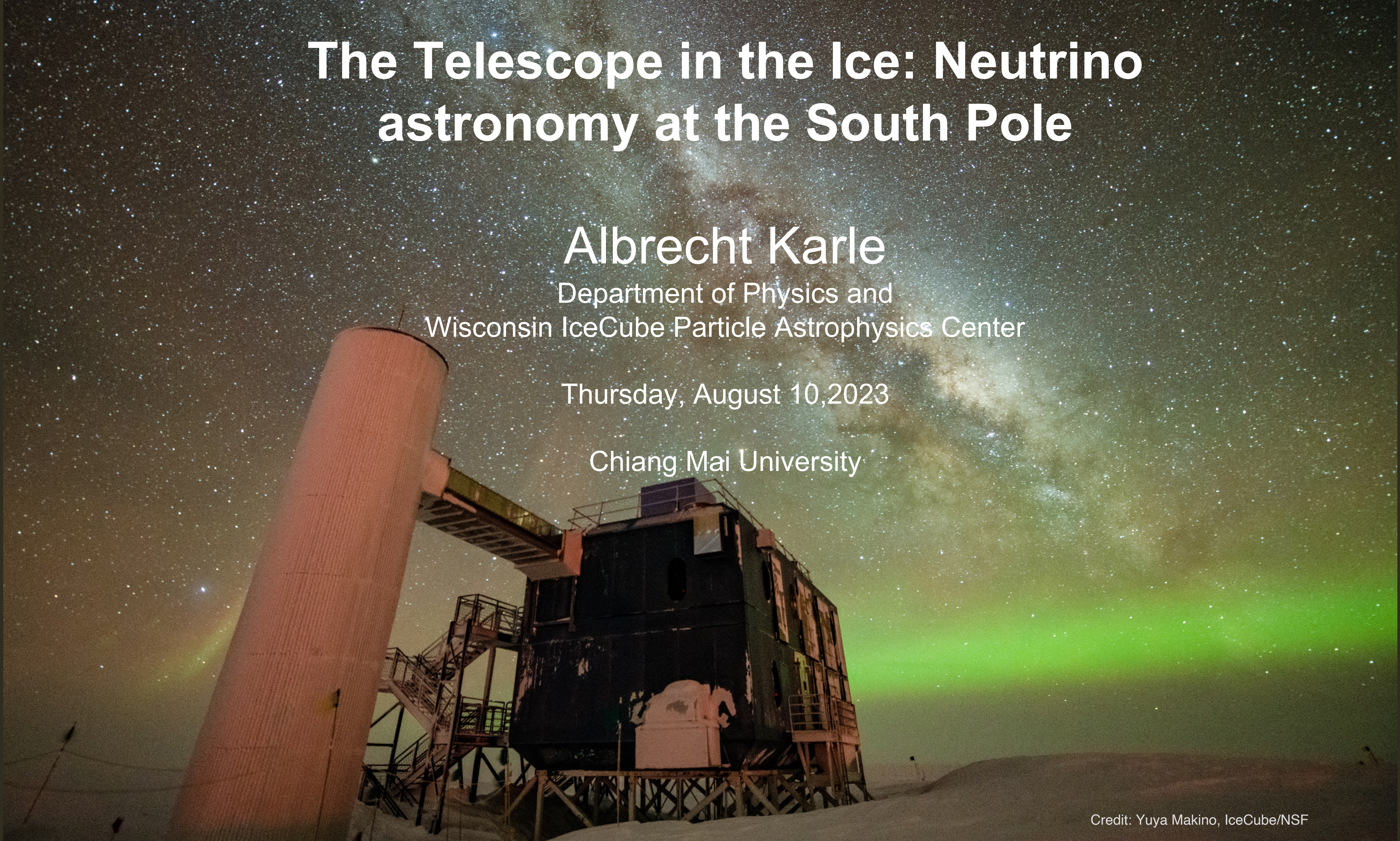
The Telescope in the Ice: Neutrino astronomy at the South Pole

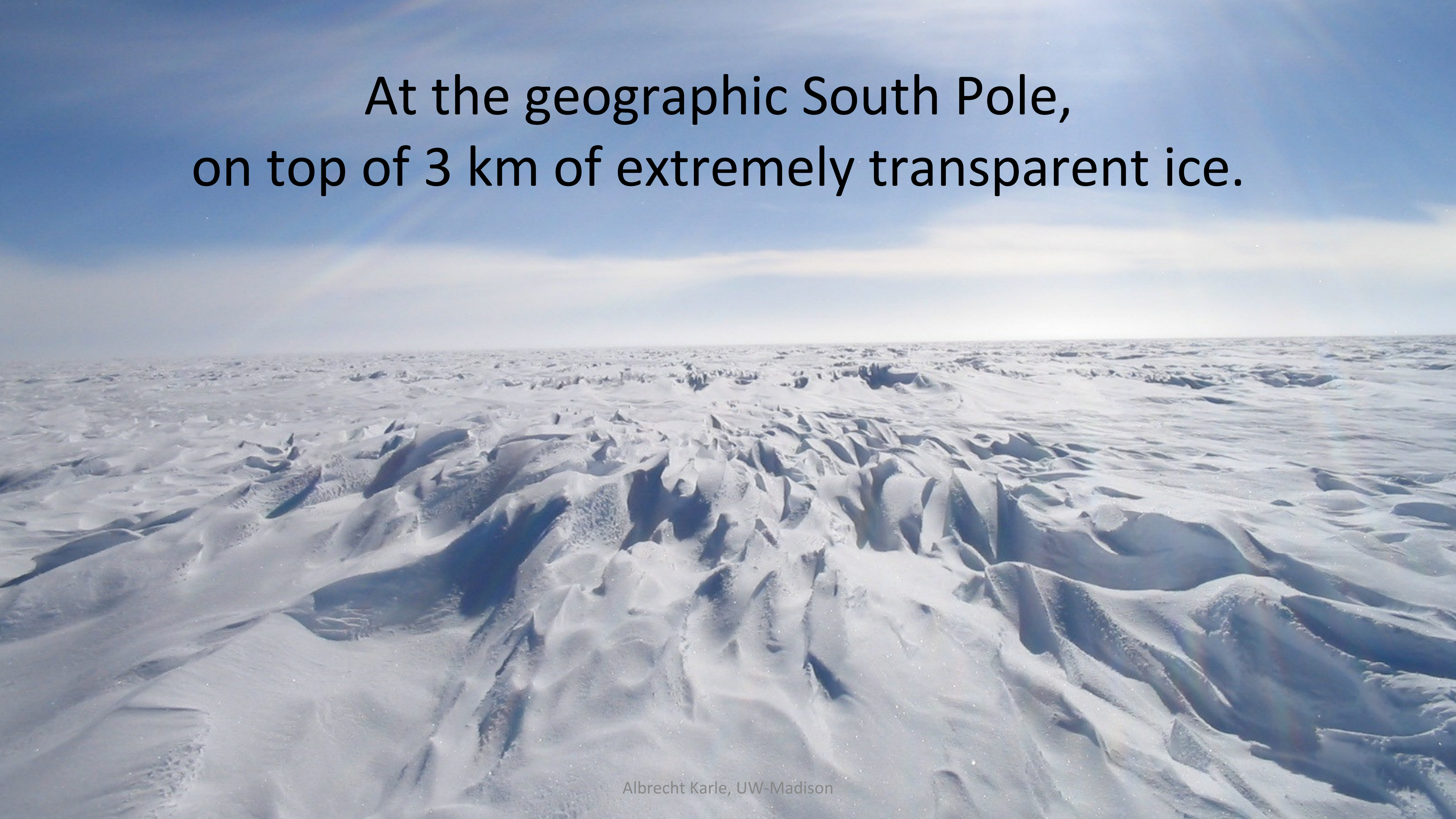
Albrecht Karle
Department of Physics and
Wisconsin IceCube Particle Astrophysics Center

Thursday, August 10,2023

Chiang Mai University



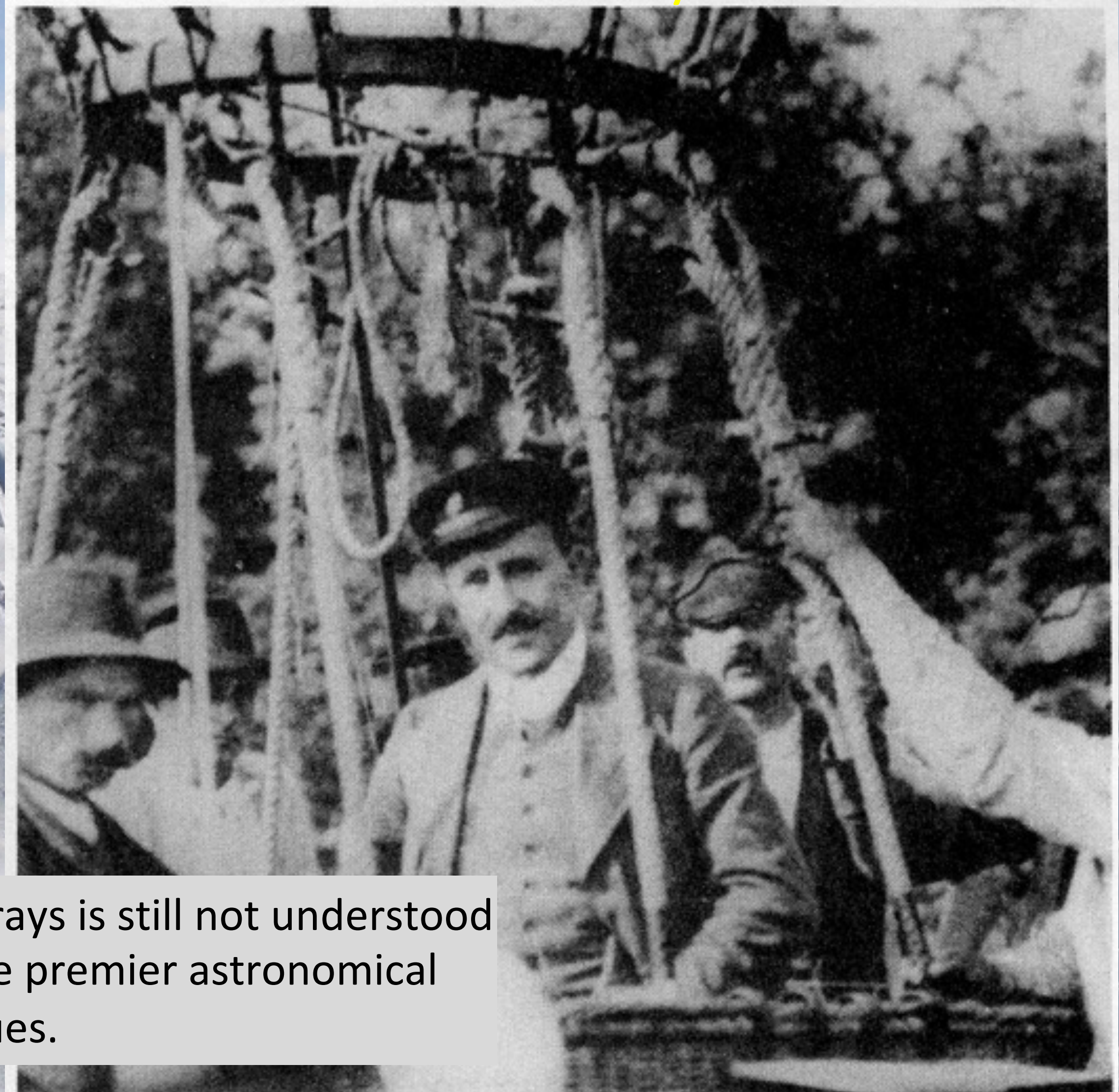
Credit: Yuya Makino, IceCube/NSF


At the geographic South Pole,
on top of 3 km of extremely transparent ice.
Albrecht Karle, UW-Madison

111 years ago

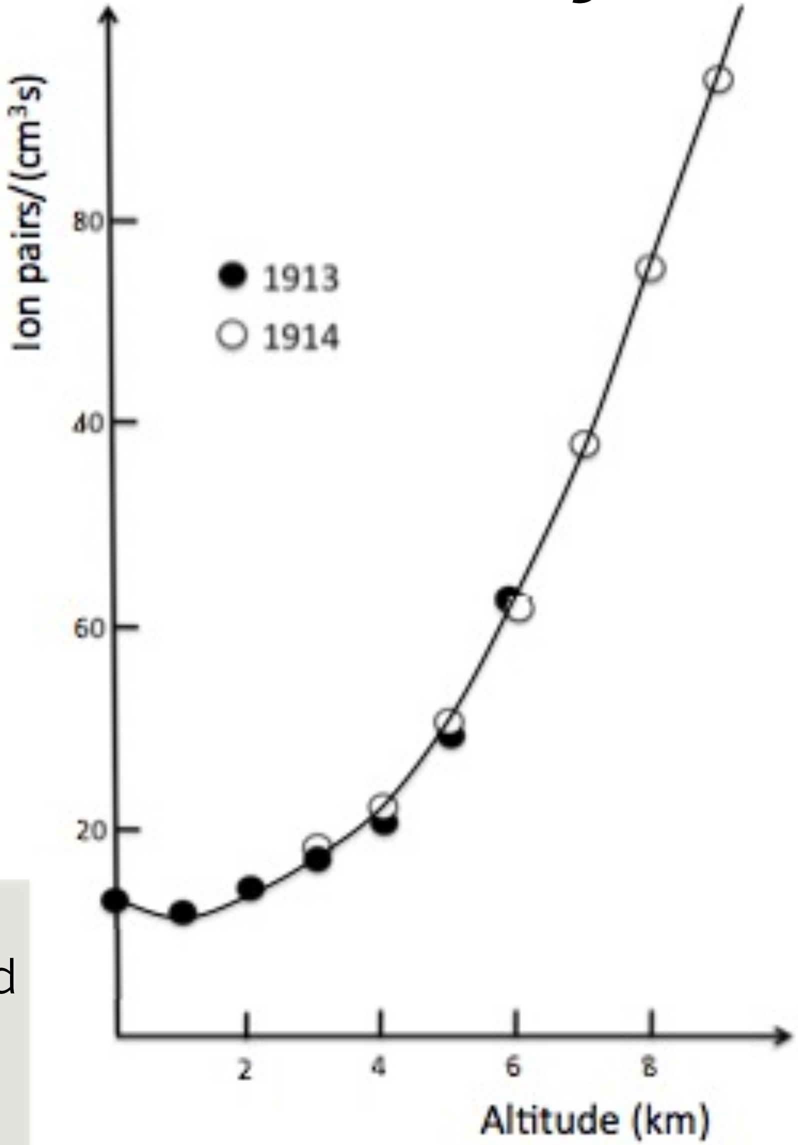
December 14, 1911:
Rould Amundson succeeds
to reach the South Pole

1911/1912:
Victor Hess discovers
Cosmic Rays



100 years later: The origin of cosmic rays is still not understood
The South Pole has become one of the premier astronomical laboratories which may give as the clues.

1912 - The discovery of cosmic rays

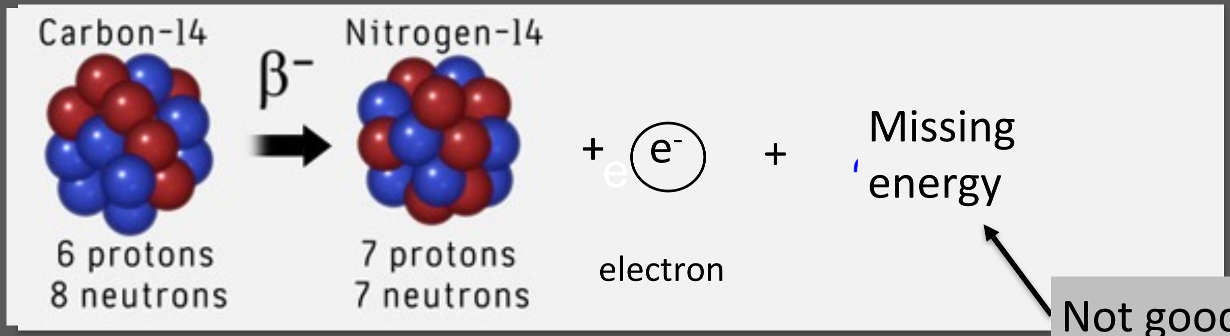


Data from Werner Kolhörster, 1913/14

"The discoveries revealed by the observations here given are best explained by assuming that radiation of great penetrating power enters our atmosphere from the outside" – Victor Hess, 1912

90 years ago

Radioactive decay:
1930: Experimental data are in severe conflict with theory.

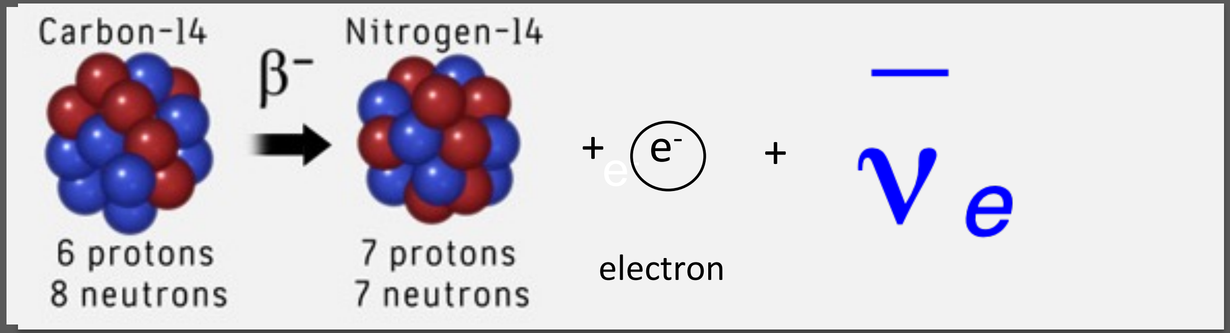


Not good.

That can't be true!
Energy must be conserved

90 years ago

Radioactive decay:
1930: Experimental data are in severe conflict with theory.



Wolfgang Pauli, 1930

Wolfgang Pauli:
In a „desperate way out“
postulates a new particle,
the neutrino:

“I have done a terrible thing, I have invented a particle that cannot be detected.”

It was not so "terrible":
26 years later,
In 1956 the neutrino is detected.

1956

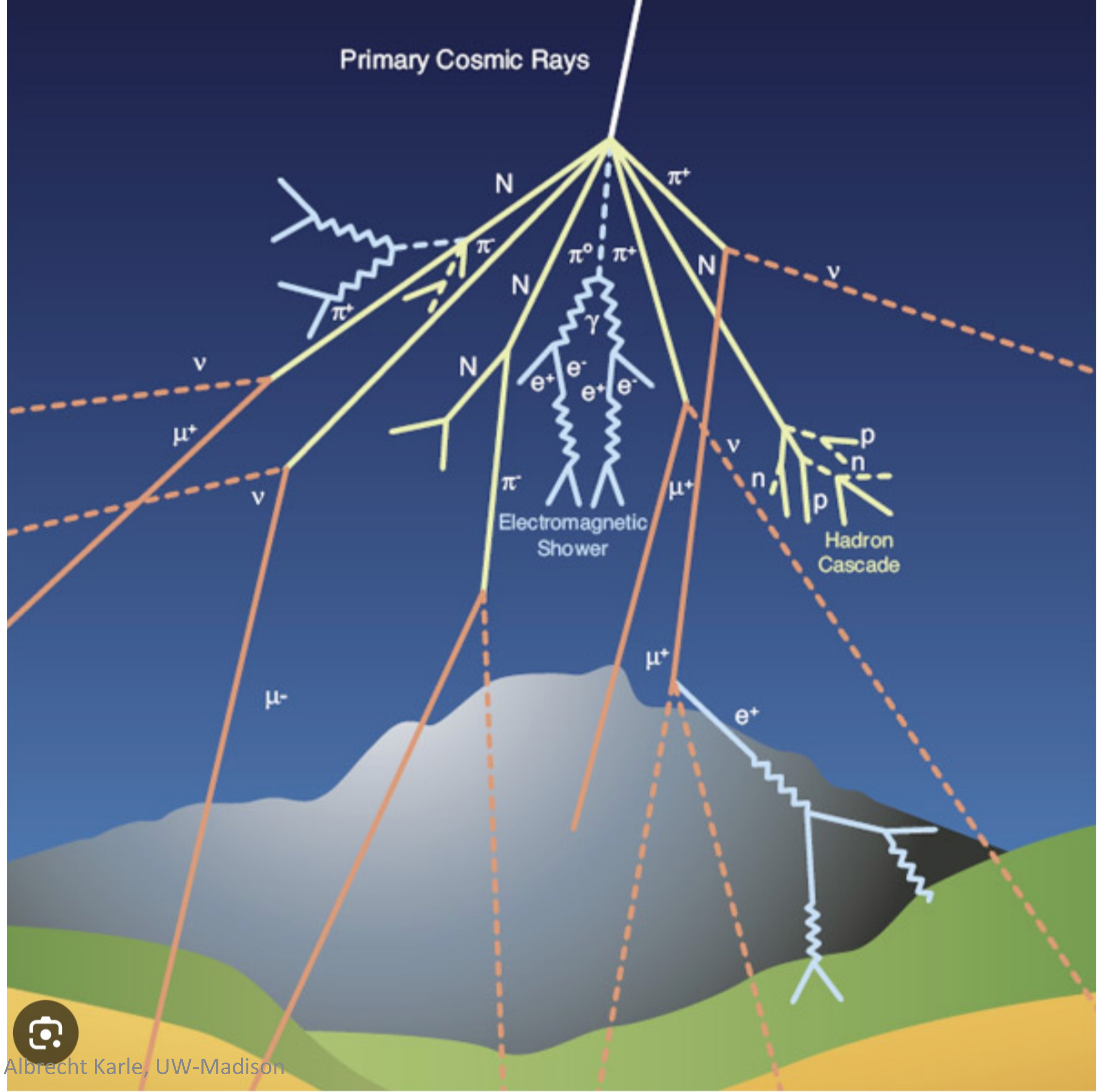
Researchers Reines and Cowan placed a detector of 1 m in size only 10 m near the core of a nuclear reactor.

10^16 neutrinos per second would pass through this detector,
and it was very hard to see just a few.

Reines receives Nobel prize in 1995

What are cosmic rays?

Can neutrinos help answer the question?



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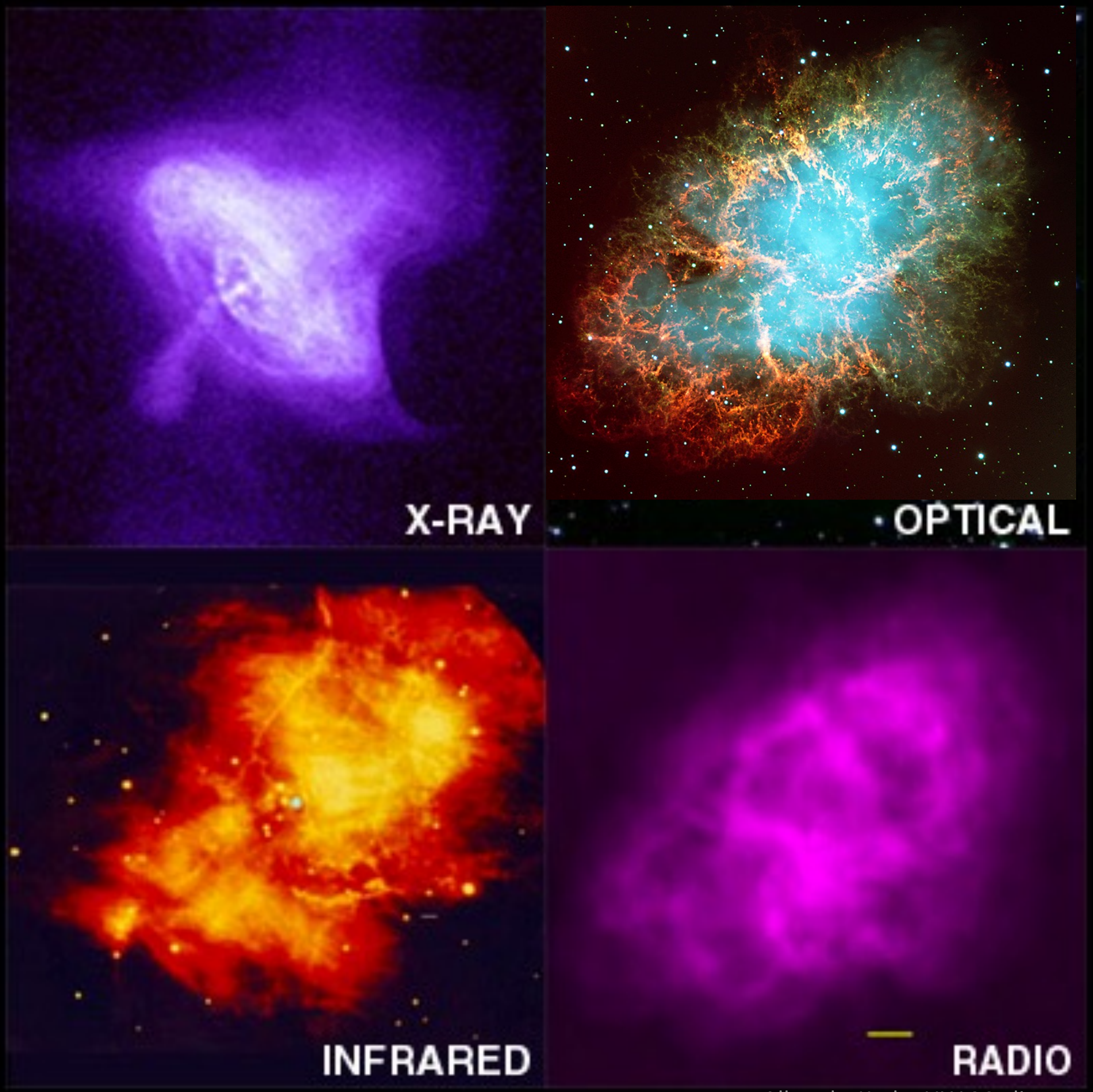
The Crab nebula

A star in our galaxy - the Milky Way - that exploded in 1054.

The event was documented by Chinese astronomers.

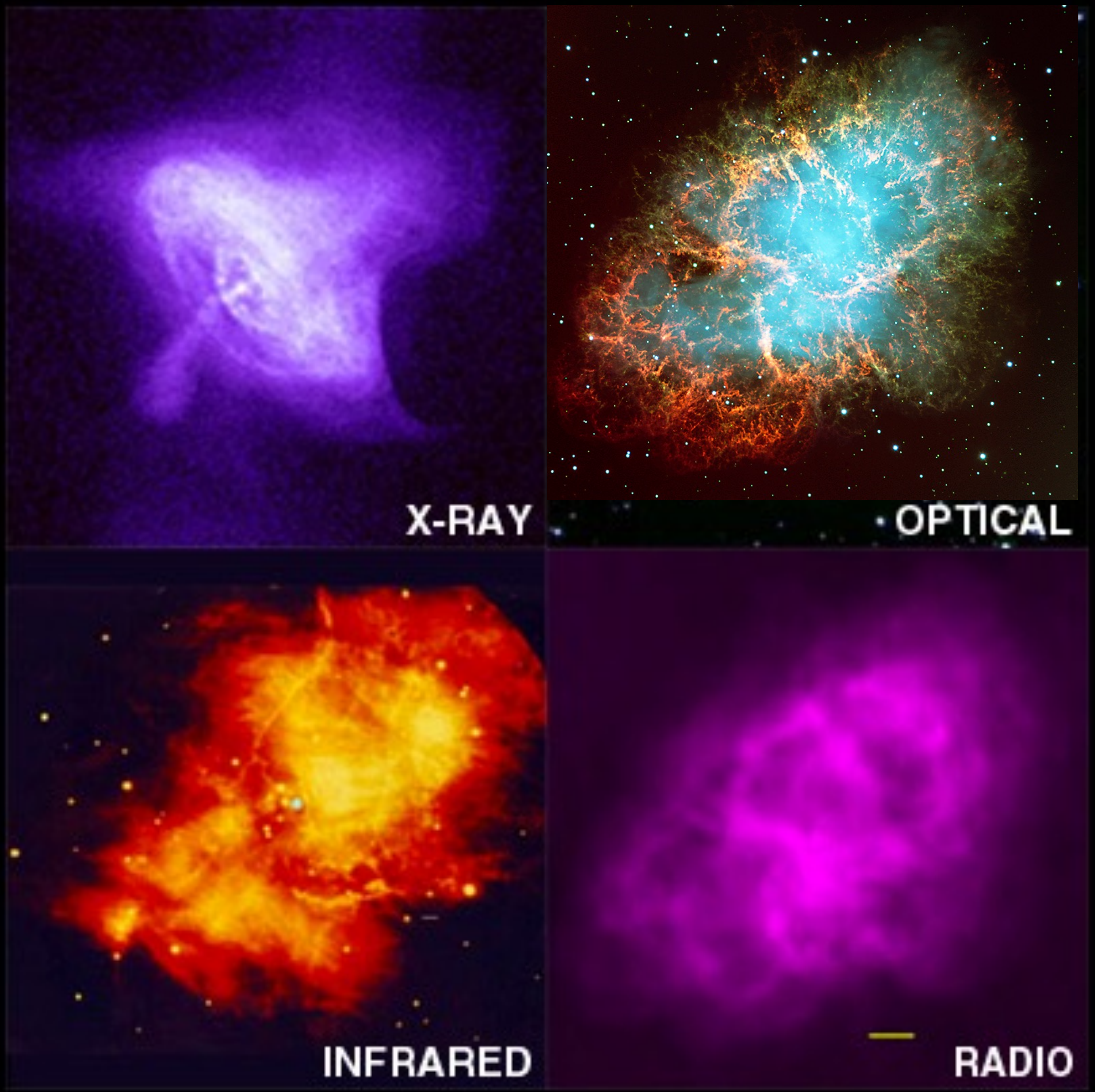
Today we know this kind of explosion as a "supernova".

Albrecht Karle, UW-Madison



Albrecht Karle, UW-Madison
Albrecht Karle, UW-Madison

The “Crab” is shown in different wavelengths – all photons.



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The “Crab” is shown in different wavelengths – all photons.

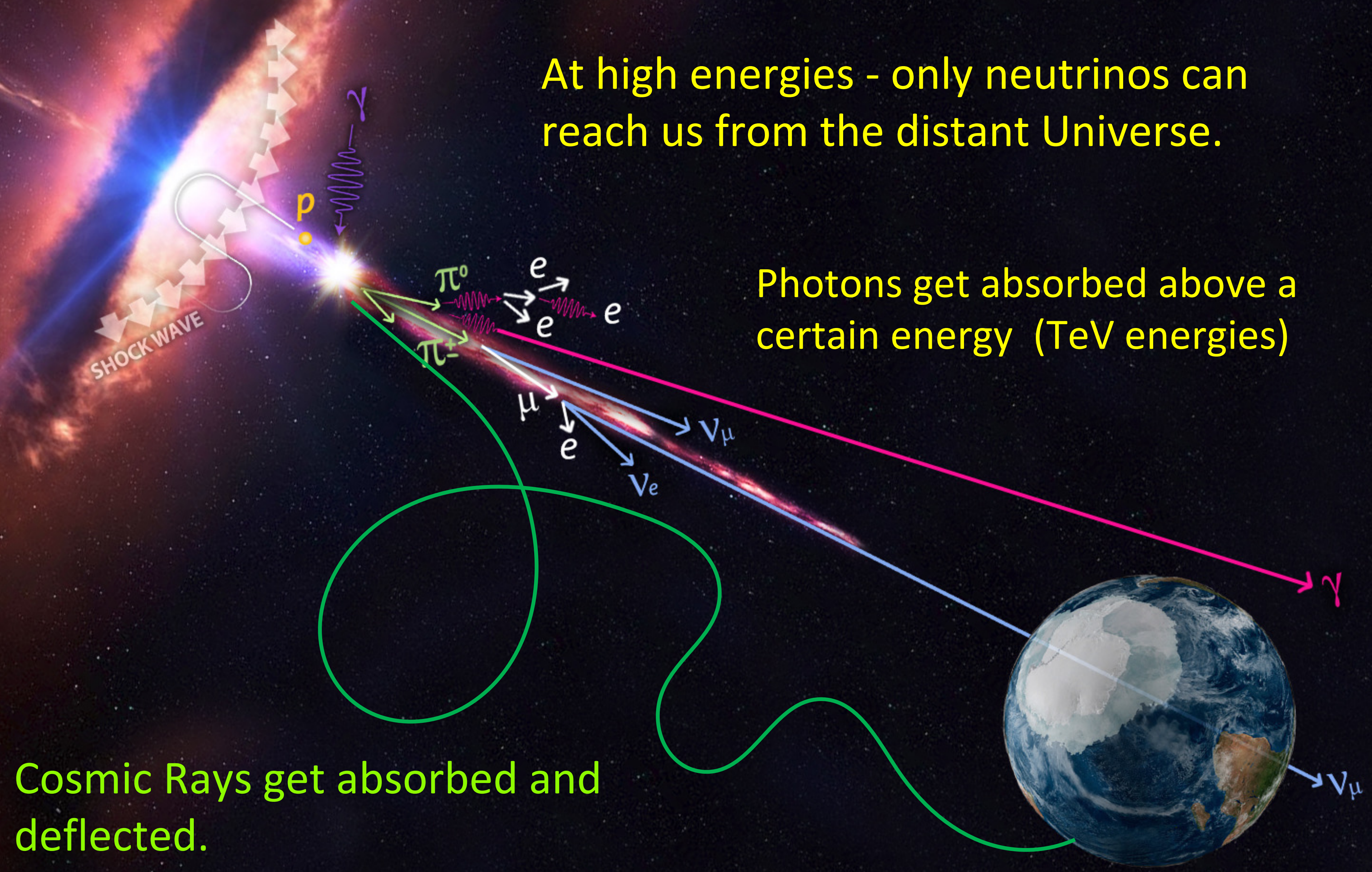
Neutrino?

Why neutrino astronomy?

Cosmic rays, gamma rays, and neutrinos from the cosmos

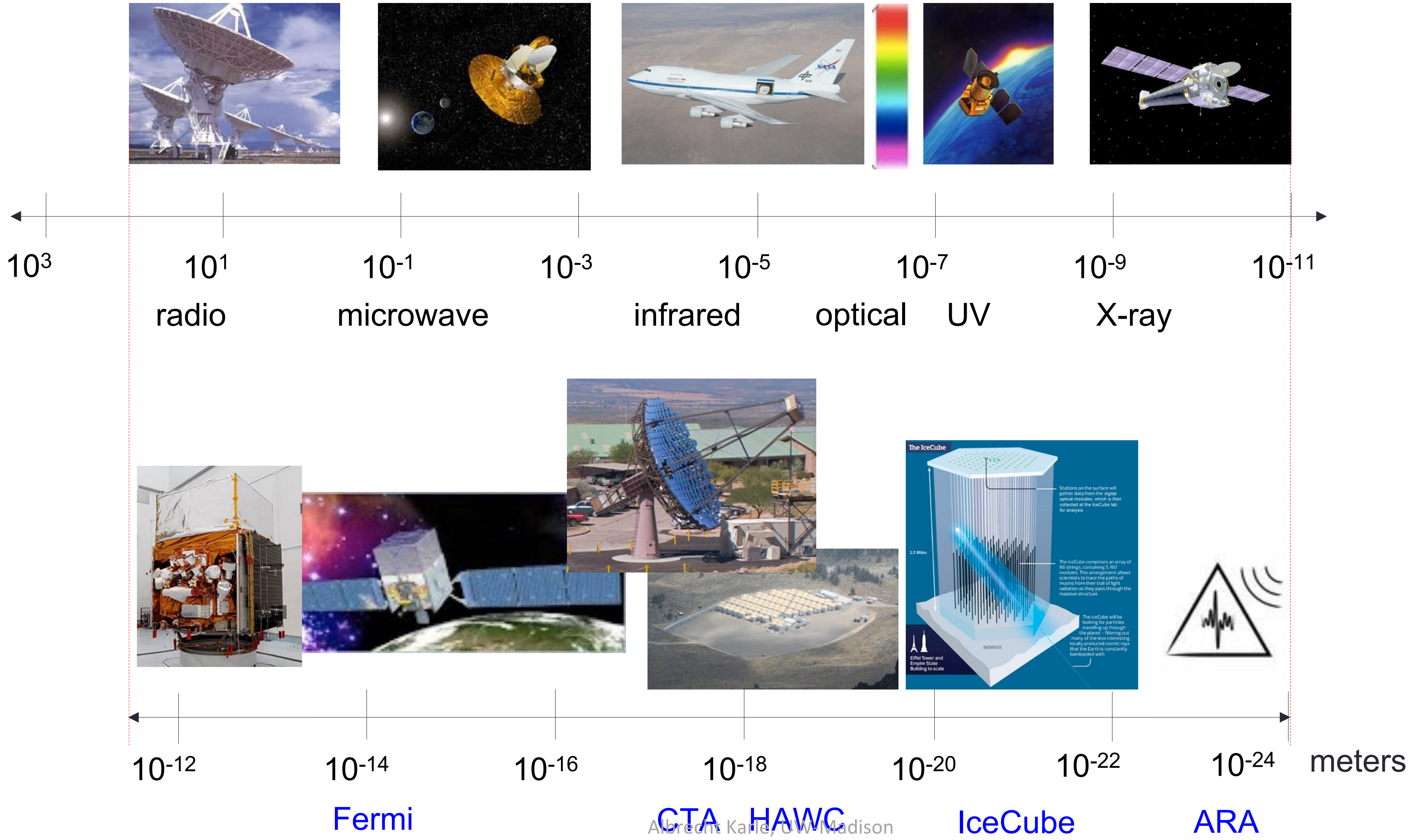
At high energies - only neutrinos can reach us from the distant Universe.

Photons get absorbed above a certain energy (TeV energies)



Cosmic Rays get absorbed and deflected.

Optical Telescopes —> Astro-Particle Telescopes



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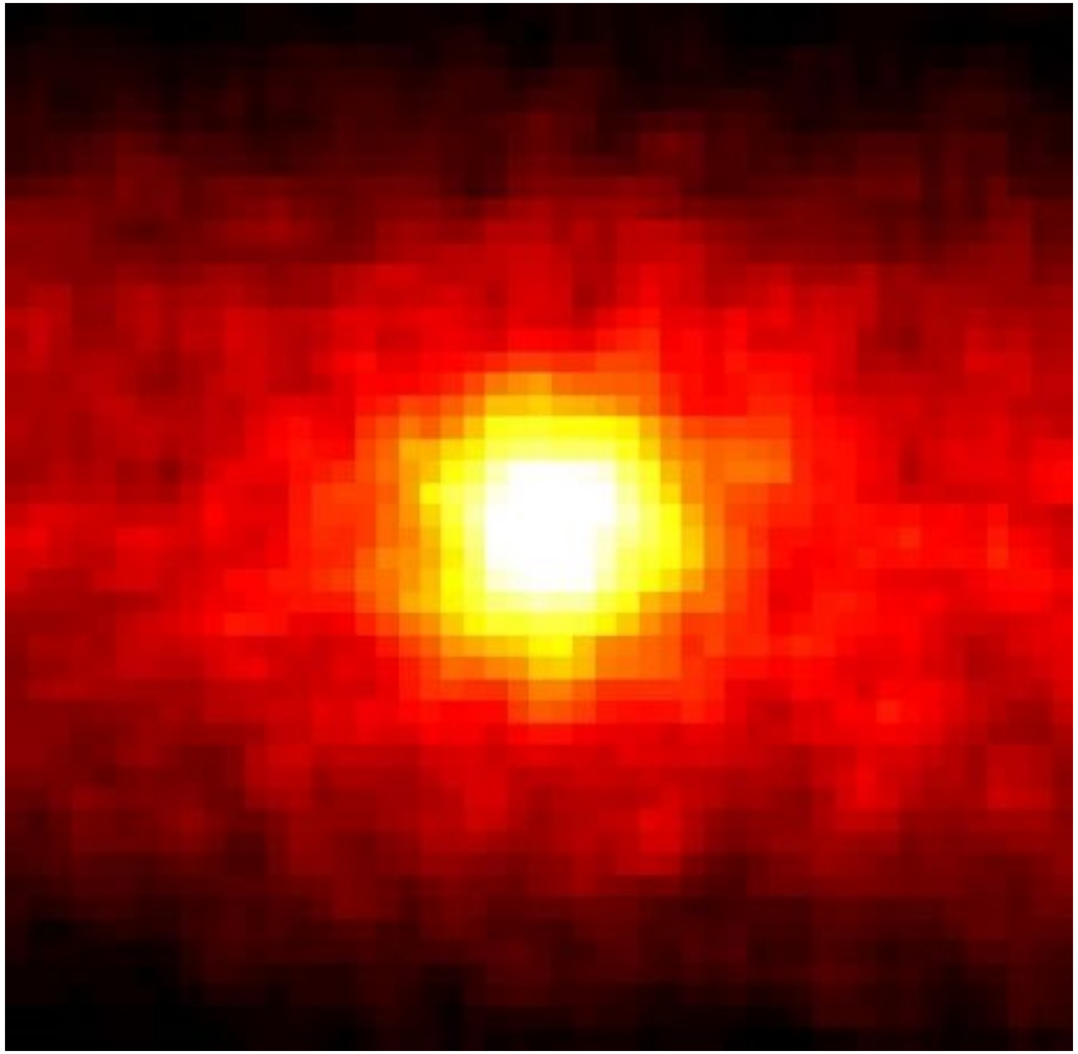
Neutrinos from the sun

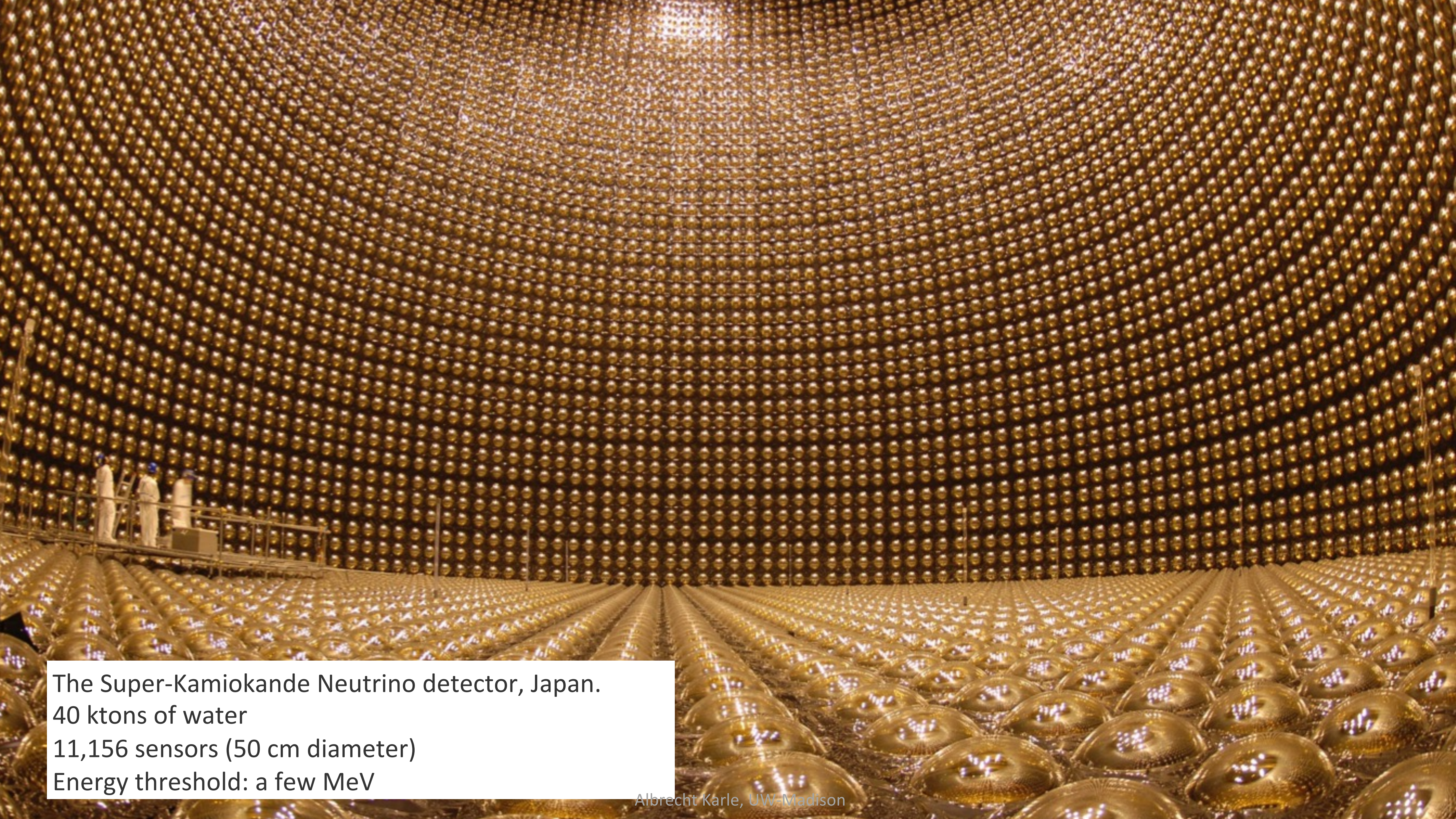
- The neutrinos are around us:
  - Sun: about 1 trillion neutrinos from the sun pass your thumb every second!
  - The can pass even through the Earth



Neutrino image of the (interior of the) sun.
Low energy neutrinos measured by the SuperK underground detector.

Neutrinos are direct evidence of nuclear fusion inside the sun

90˚x90˚



The Super-Kamiokande Neutrino detector, Japan.
40 ktons of water
11,156 sensors (50 cm diameter)
Energy threshold: a few MeV

Detecting Cosmic Neutrinos?

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

Theory:

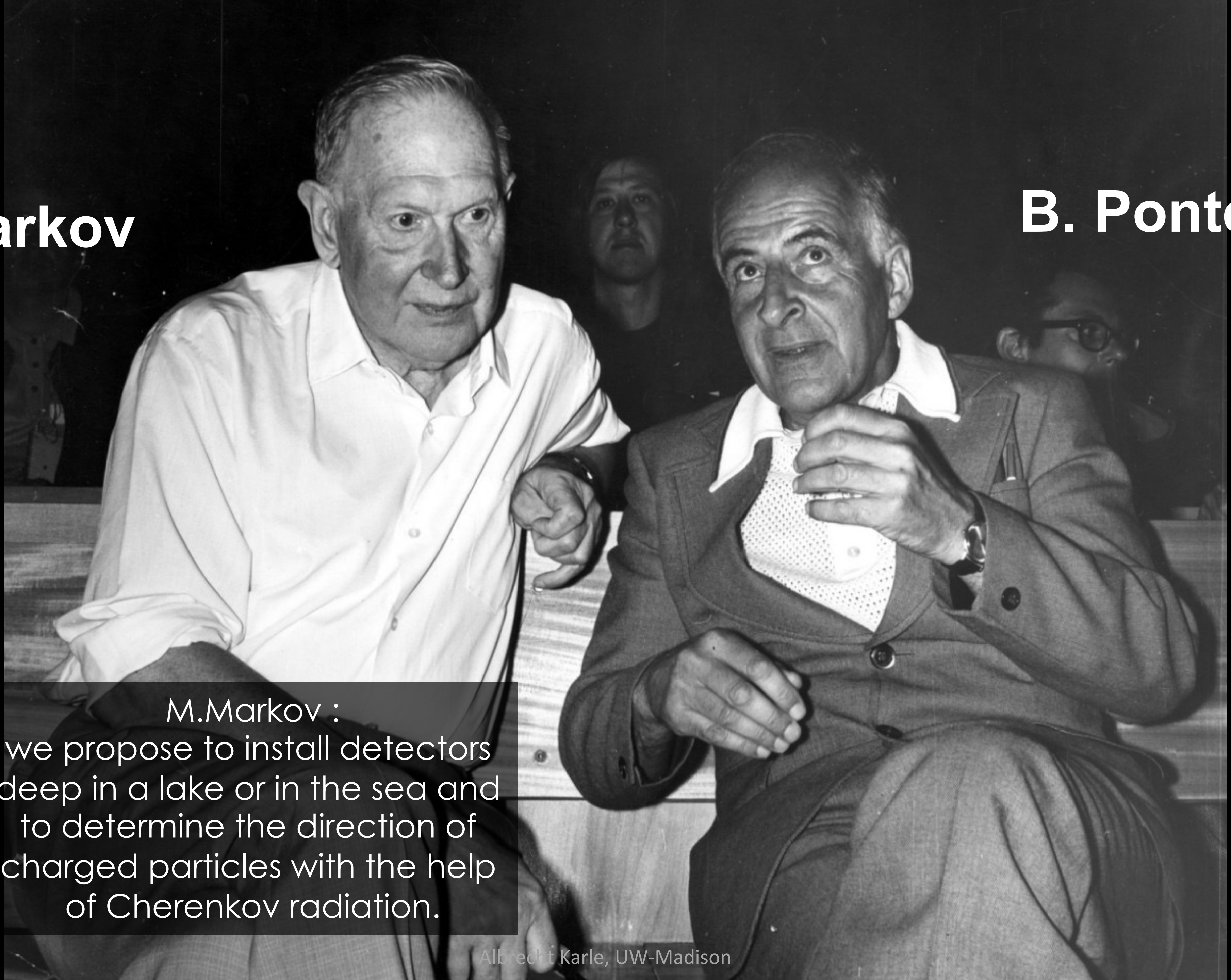
Need a very big detector:

target of 1 billion tons, - 1 km^3.

1960

M. Markov

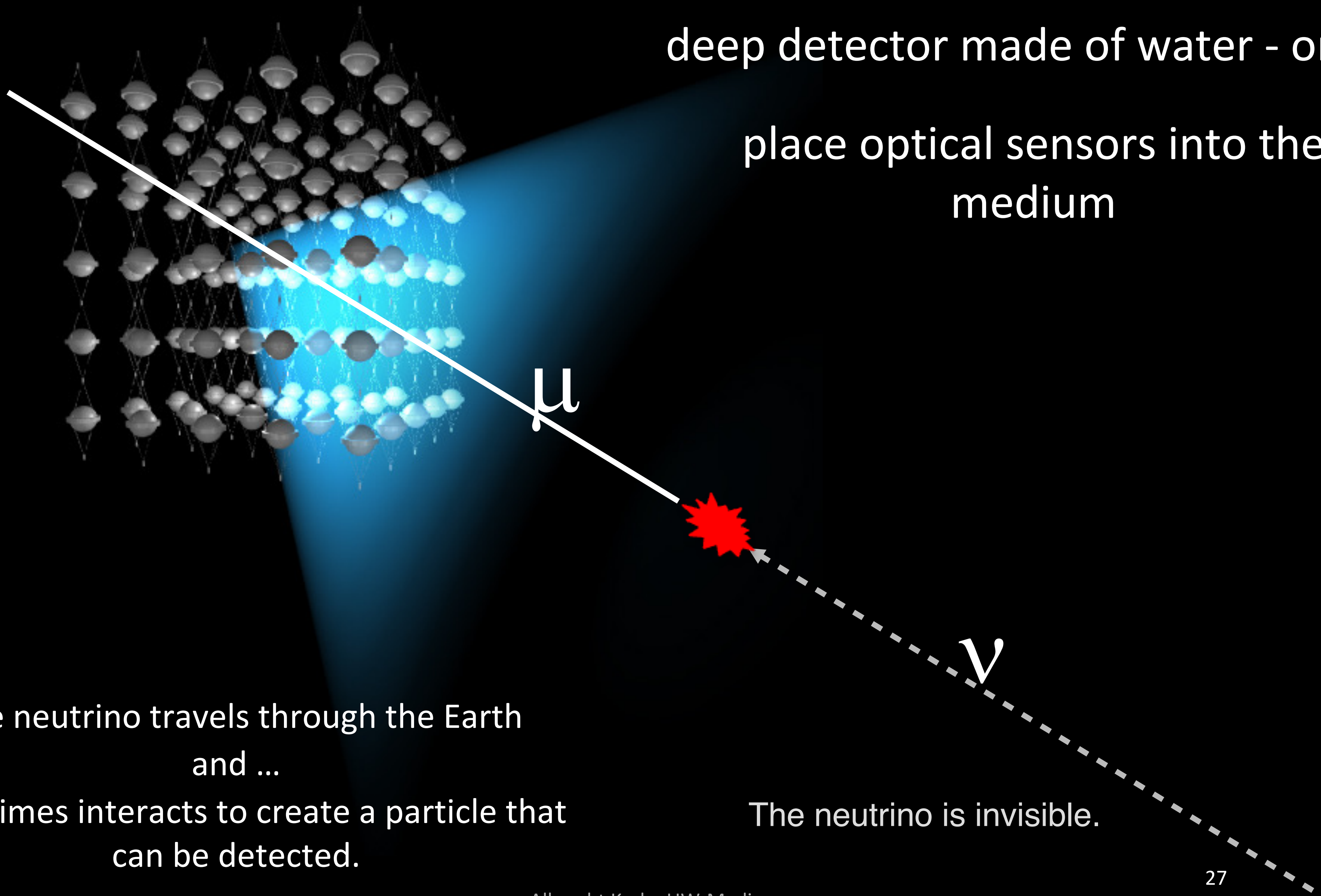
B. Pontecorvo



M.Markov :
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.

deep detector made of water - or ice

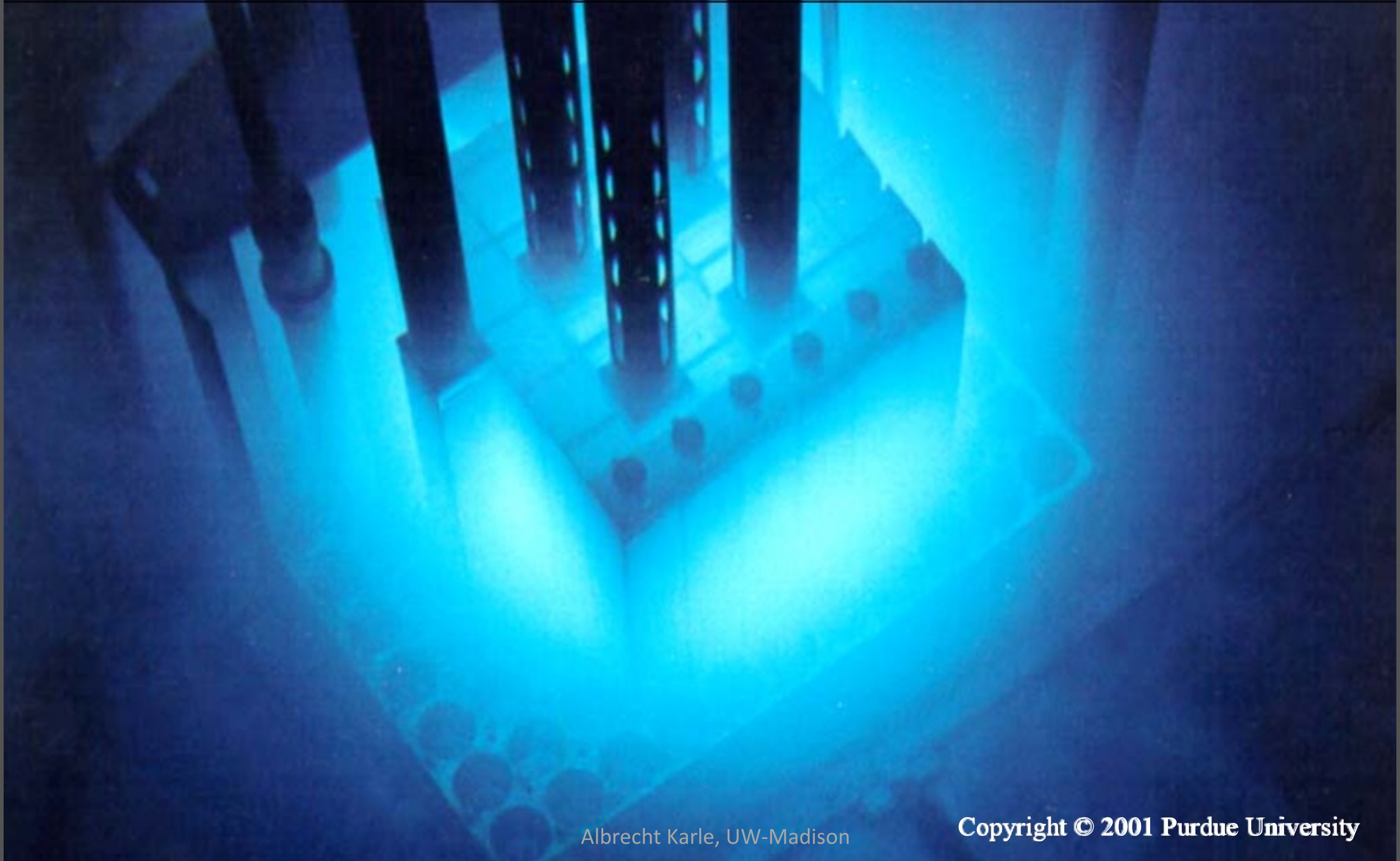
place optical sensors into the medium



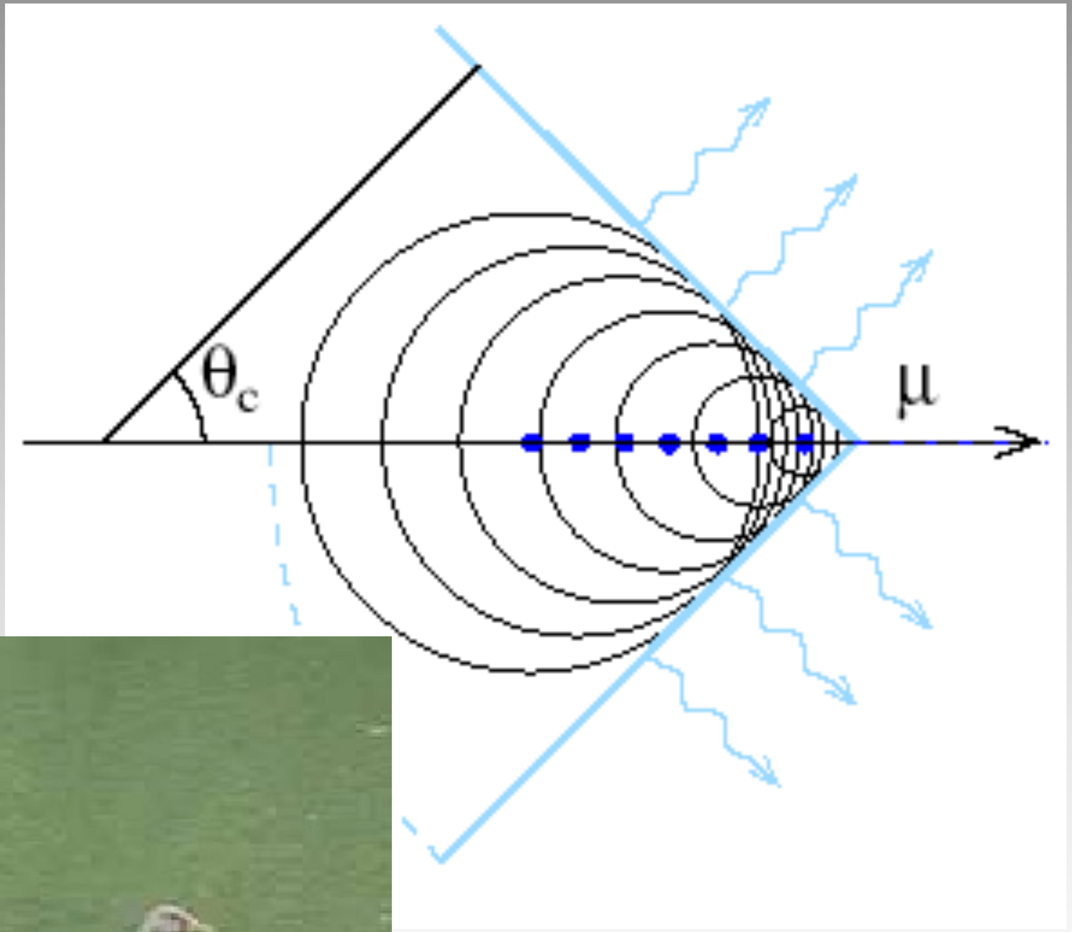
The neutrino travels through the Earth and …
sometimes interacts to create a particle that can be detected.

The neutrino is invisible.

Charged particles (from a nuclear reactor in the picture) produce blue light in water



Cherenkov radiation: muon travels faster than light in ice



Photomultiplier Tube

Principle:
Photoelectric effect
+ electron multiplication

Can detect single photons.

(Moonless nightsky: 10 billion photons / second mk^2)

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

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

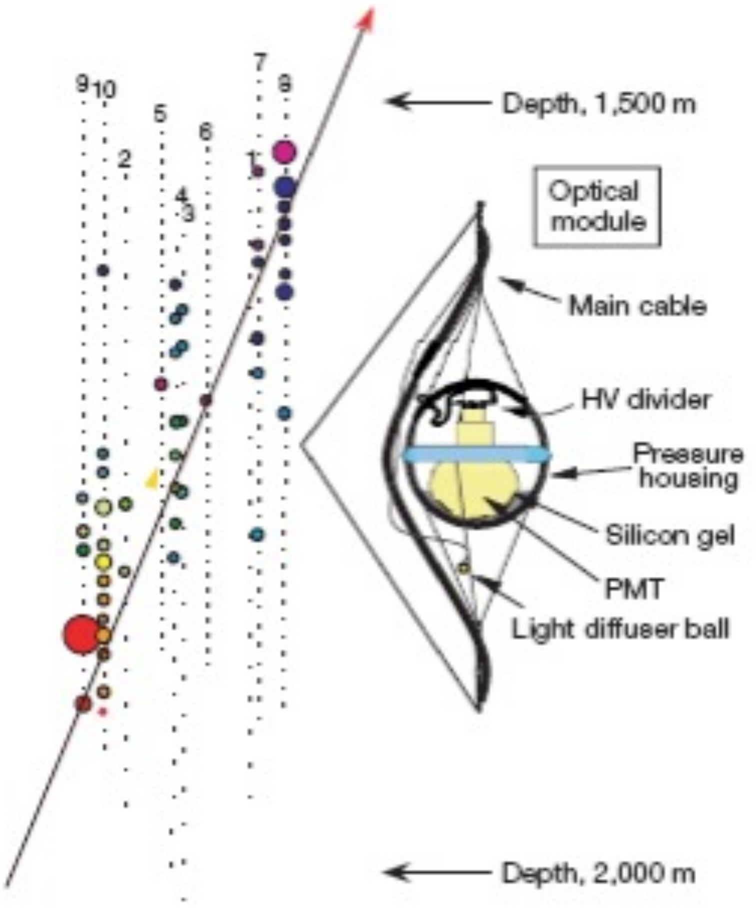
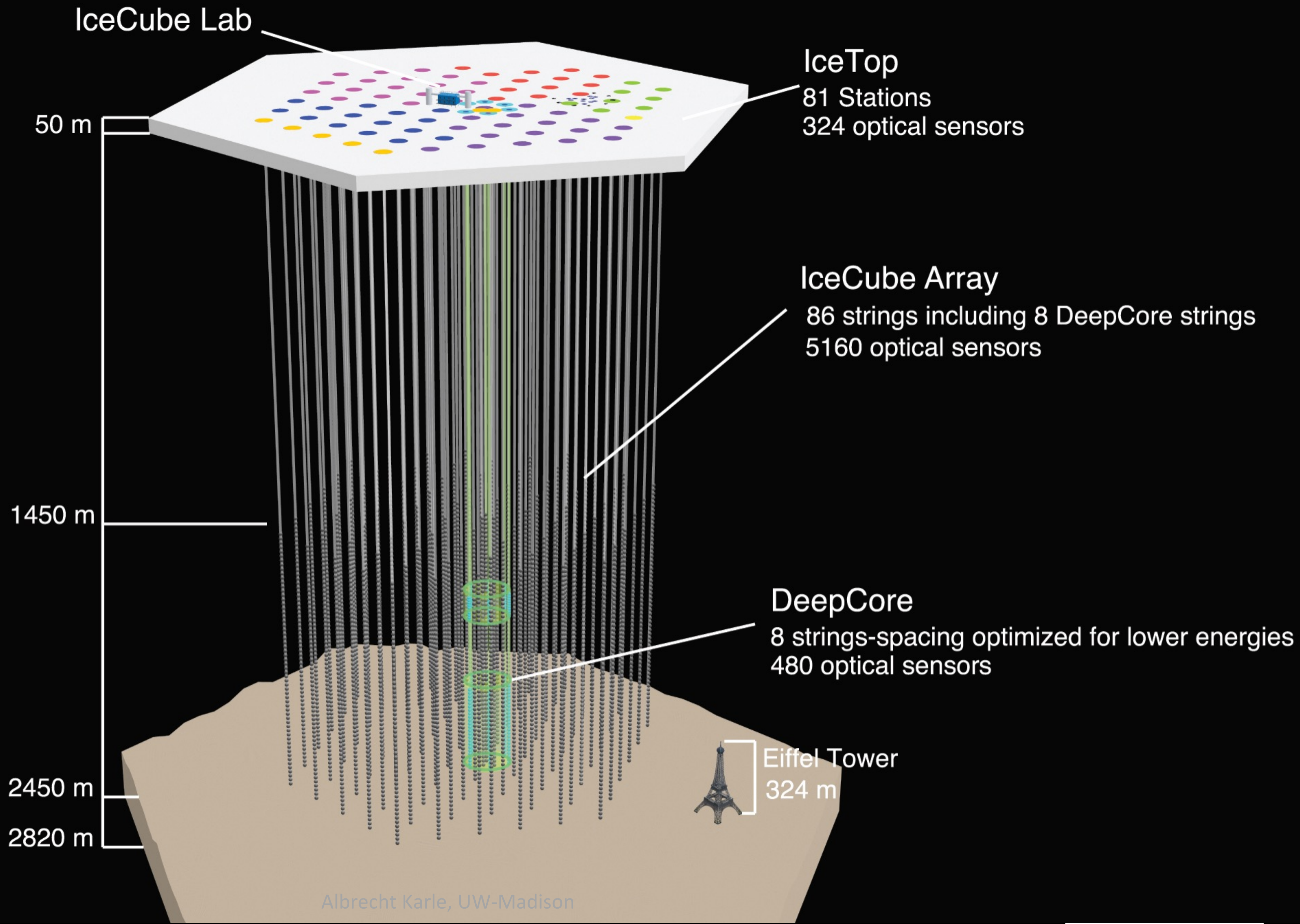
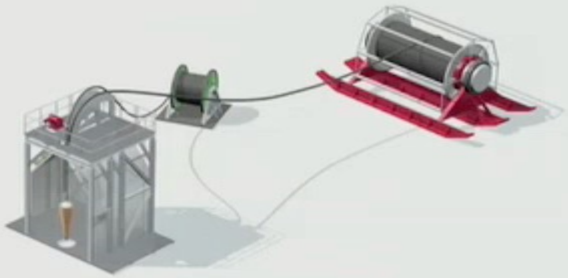


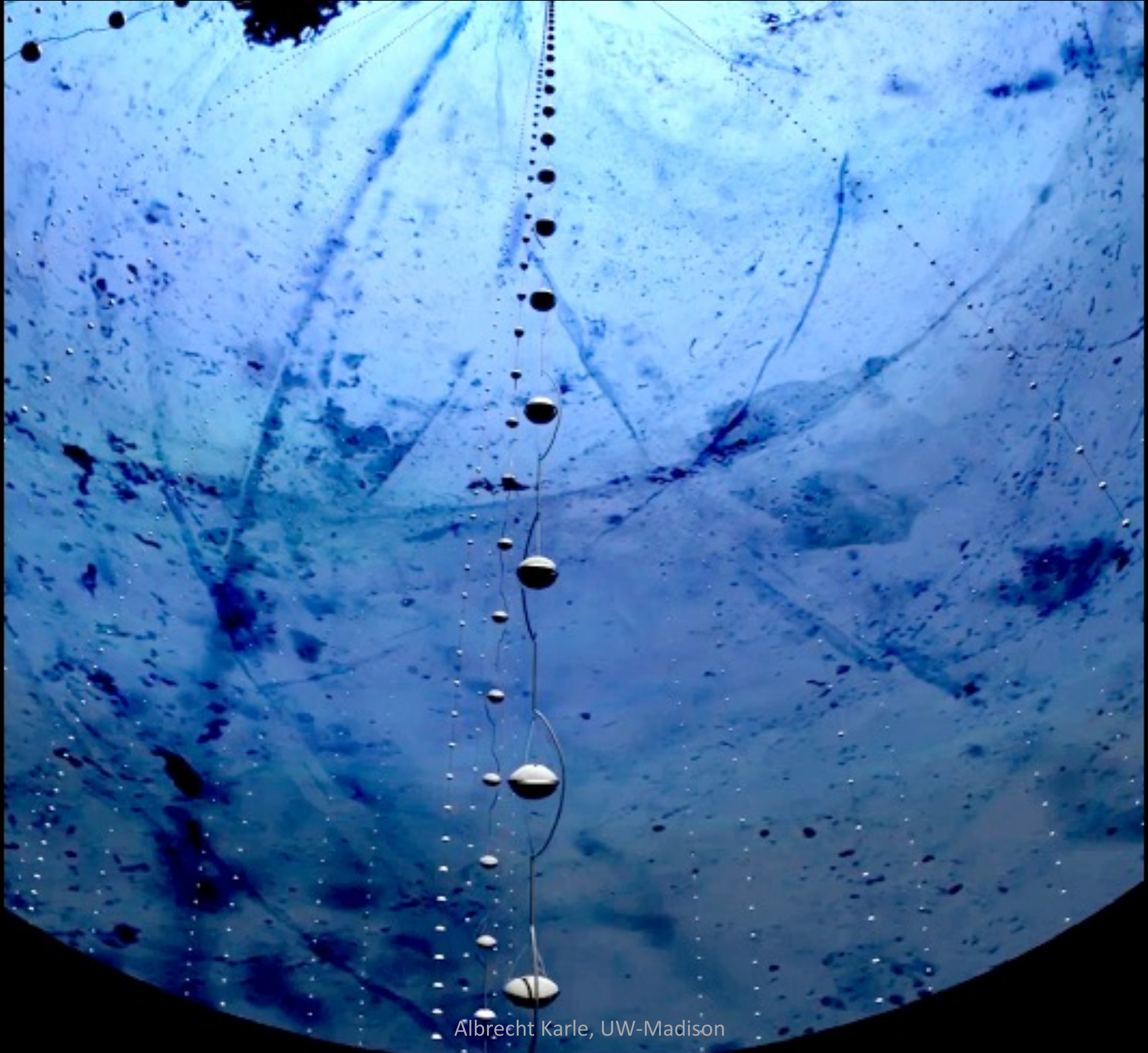
Figure 1 The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular event; the sizes of the circles indicate the amplitudes of the pulses and the colours correspond to the time of a photon's arrival. Earlier times are in red and later ones in blue. The arrow indicates the reconstructed track of the upwardly propagating muon.

IceCube Construction

The IceCube Neutrino Observatory







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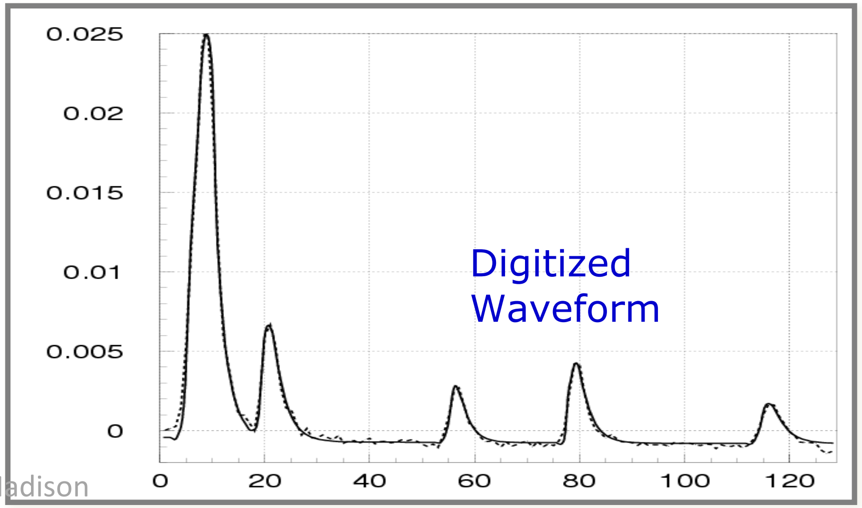
Digital Optical Module (DOM)

Each sensor is almost an independent detector

Converts the very faint light
signals - photons -
into electrical signals




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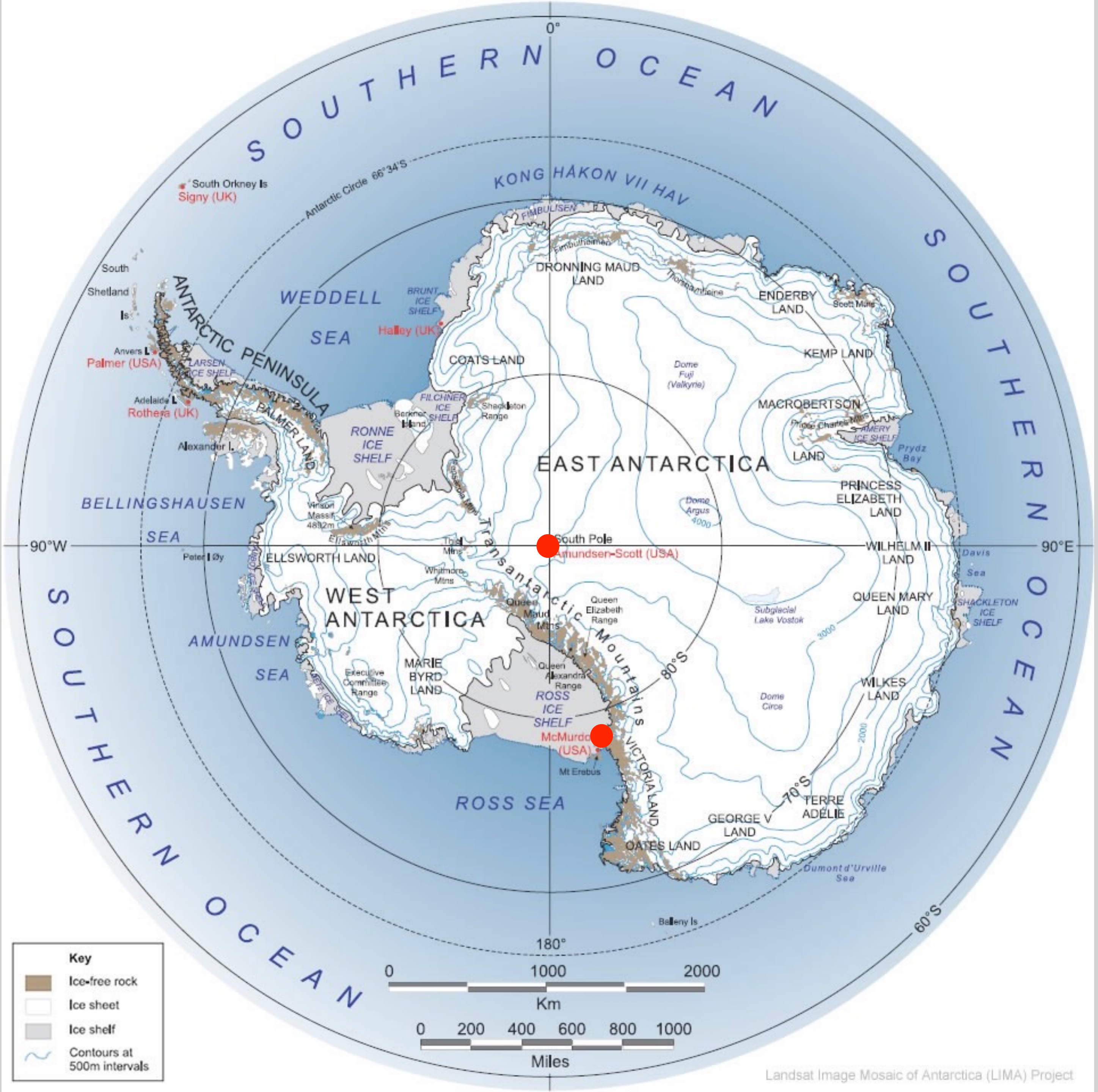
©2006
Goog

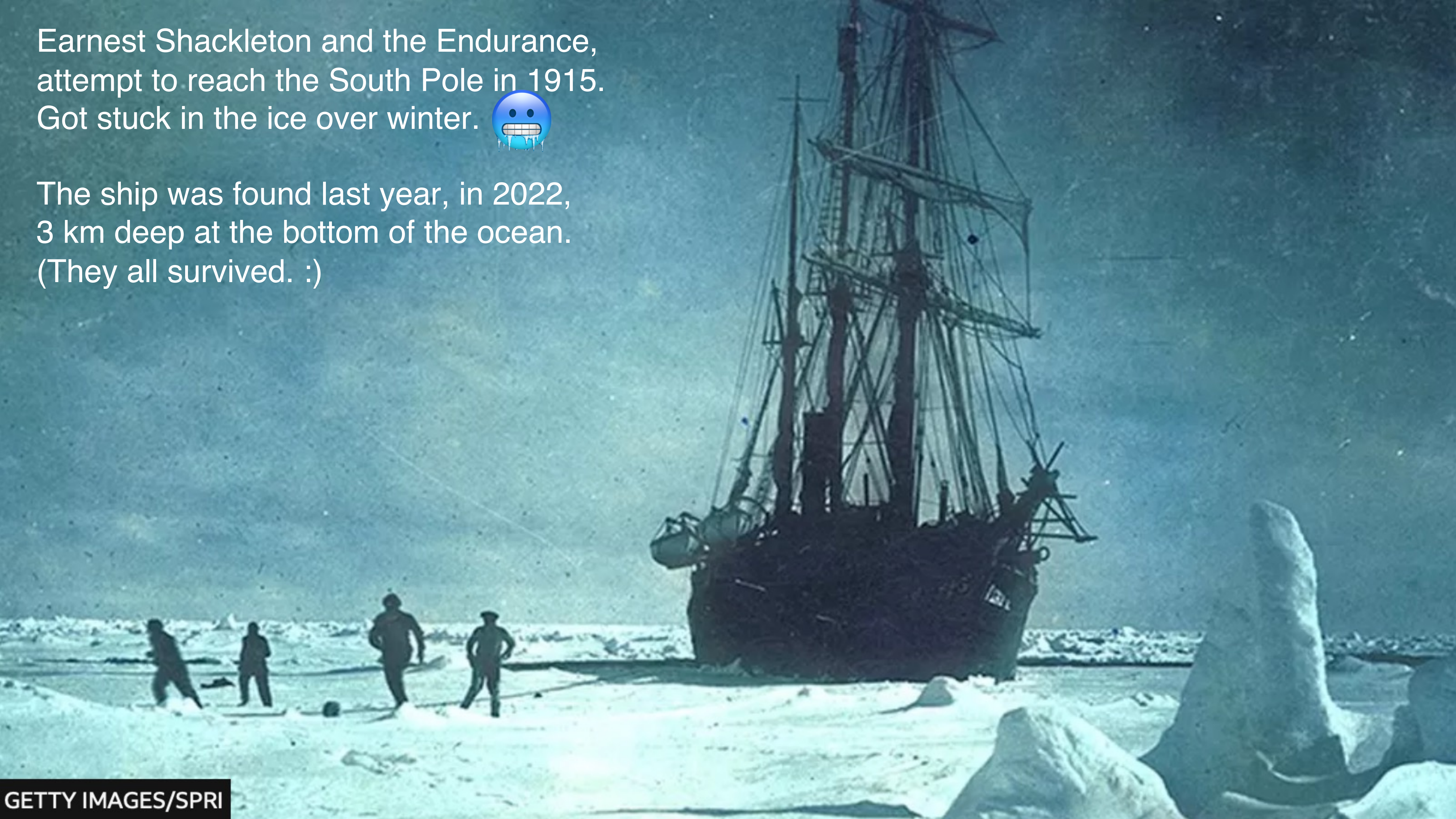

~ 40 lbs



SOUTHERN OCEAN
0°
90°W
90°E
180°
Antarctic Circle 66°34'S
KONG HÅKON VII HAV
South Orkney Is
Signy (UK)
South Shetland Is
Anvers I.
Palmer (USA)
Adelaide I.
Rothera (UK)
Alexander I.
ANTARCTIC PENINSULA
PALMER LAND
LARSEN ICE SHELF
WEDDELL SEA
BRUNT ICE SHELF
Halley (UK)
COATS LAND
FILCHNER ICE SHELF
Berkner Island
Shackleton Range
RONNE ICE SHELF
FIMBULISEN
DRONNING MAUD LAND
ENDERBY LAND
KEMP LAND
Dome Fuji (Valkyrie)
MACROBERTSON LAND
AMERY ICE SHELF
Prydz Bay
EAST ANTARCTICA
PRINCESS ELIZABETH LAND
Dome Argus
4000
BELLINGSHAUSEN SEA
Vinson Massif 4892m
Ellsworth Mtns
Peter I Øy
ELLSWORTH LAND
South Pole
Amundsen-Scott (USA)
WILHELM II LAND
Davis Sea
Whitmore Mtns
Transantarctic Mountains
WEST ANTARCTICA
Queen Maud Mtns
Queen Elizabeth Range
Subglacial Lake Vostok
3000
QUEEN MARY LAND
SHACKLETON ICE SHELF
AMUNDSEN SEA
MARIE BYRD LAND
Executive Committee Range
Queen Alexandra Range
80°S
ROSS ICE SHELF
Dome Circe
WILKES LAND
McMurdo (USA)
Mt Erebus
VICTORIA LAND
2000
ROSS SEA
70°S
TERRE ADÉLIE
GEORGE V LAND
OATES LAND
Dumont d'Urville Sea
Balleny Is
60°S
Key
Ice-free rock
Ice sheet
Ice shelf
Contours at 500m intervals
0 1000 2000
Km
0 200 400 600 800 1000
Miles
Landsat Image Mosaic of Antarctica (LIMA) Project

Earnest Shackleton and the Endurance,
attempt to reach the South Pole in 1915.
Got stuck in the ice over winter. 🥶

The ship was found last year, in 2022,
3 km deep at the bottom of the ocean.
(They all survived. :)




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


CREW CHIEF
MSGT DORISKI
WARNING
WITH CREW MEMBERS ABOARD THIS
DOOR WILL BE CLOSED AND OPENED
FROM THE INSIDE ONLY
CAUTION
ONLY ONE PERSON AT A TIME
ON THESE STEPS
LOCK
UNLOCK
ALBRECHT KARLE
South
Shetland
Is
Palmer (USA)
90°W
SOUTHERN
Key
Ice-free rock
Ice sheet
Ice shelf

At South Pole

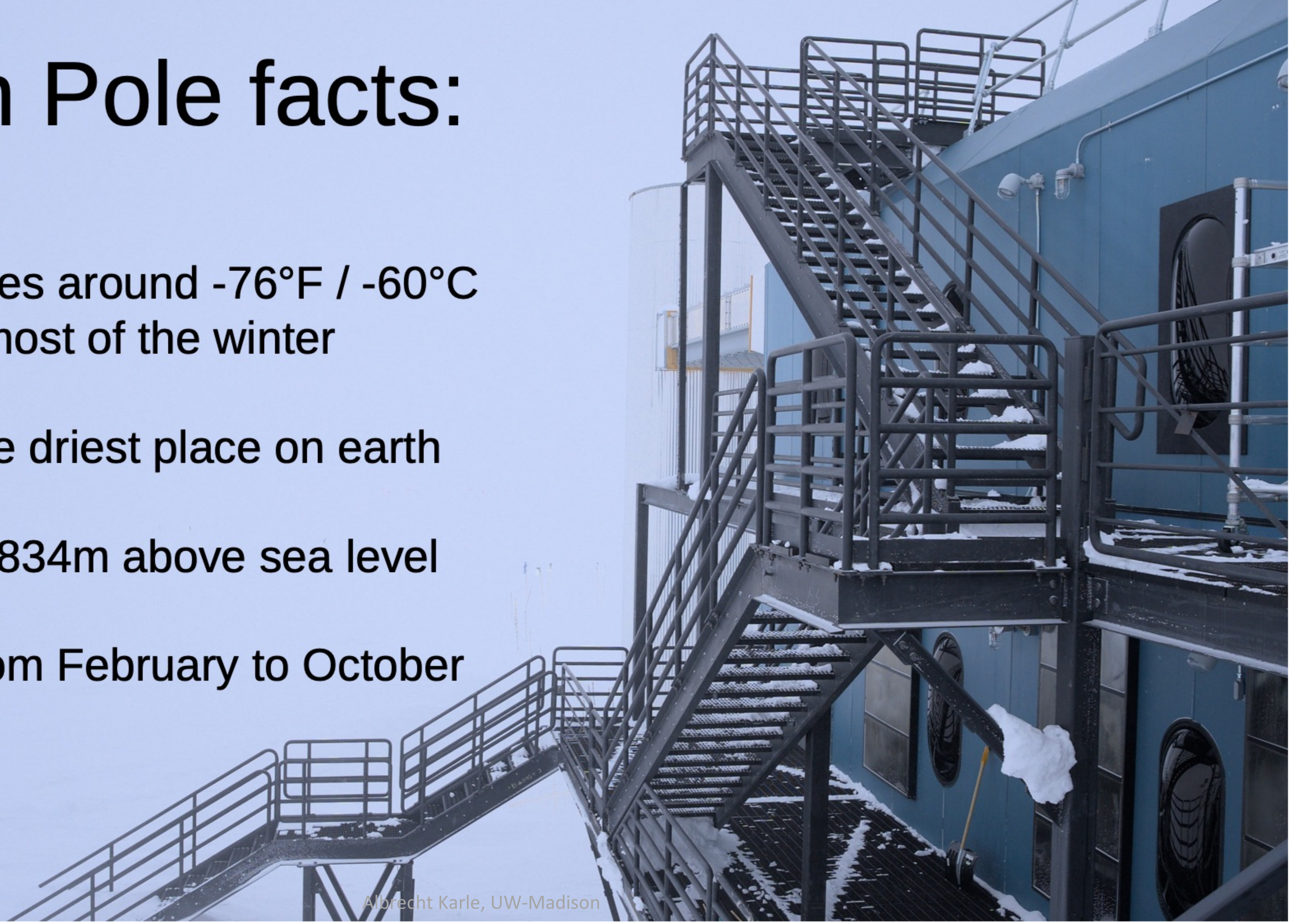
South Pole facts:

Temperatures around -76°F / -60°C
for most of the winter

One of the driest place on earth

9300ft / 2834m above sea level

Isolated from February to October



Construction

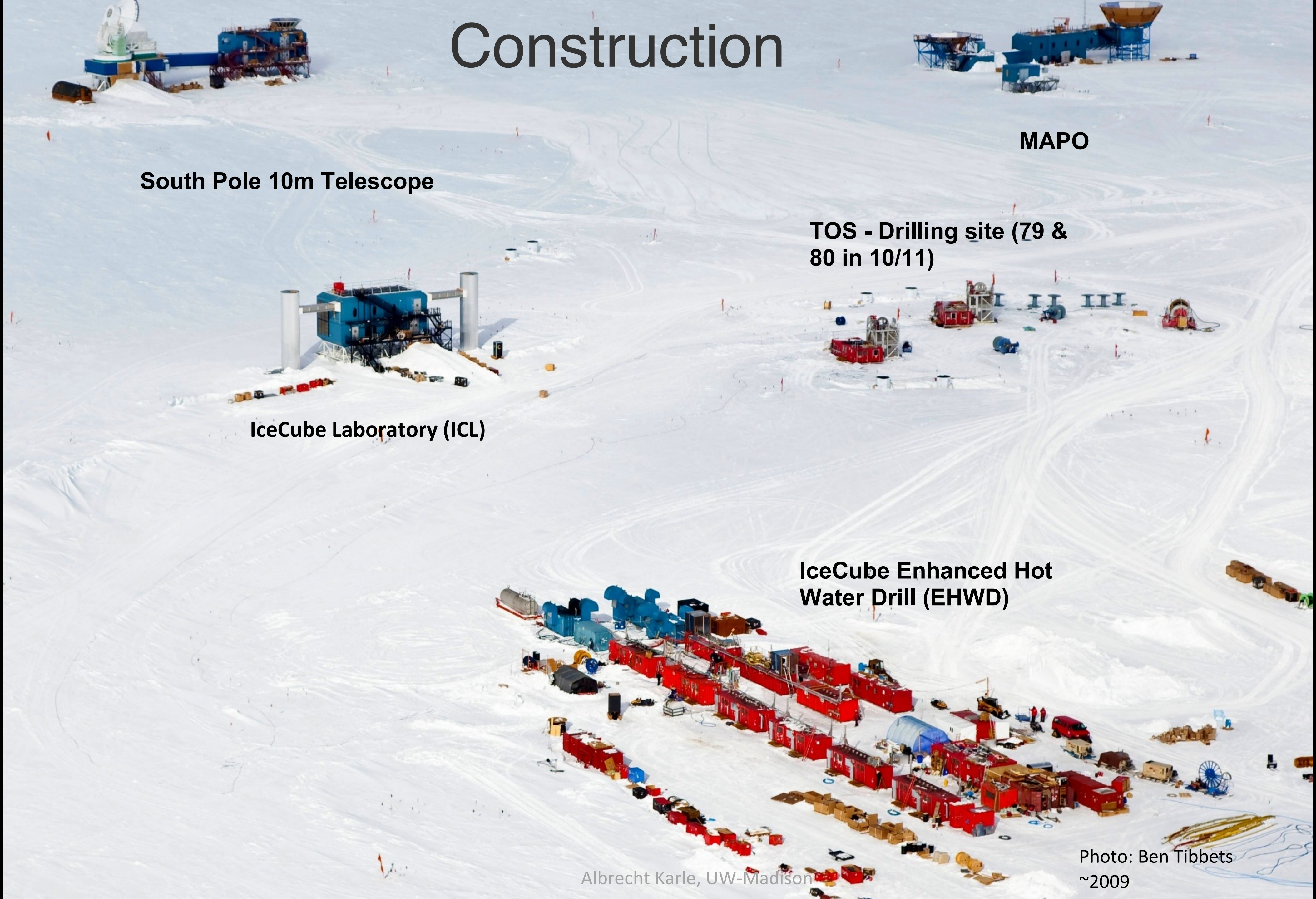
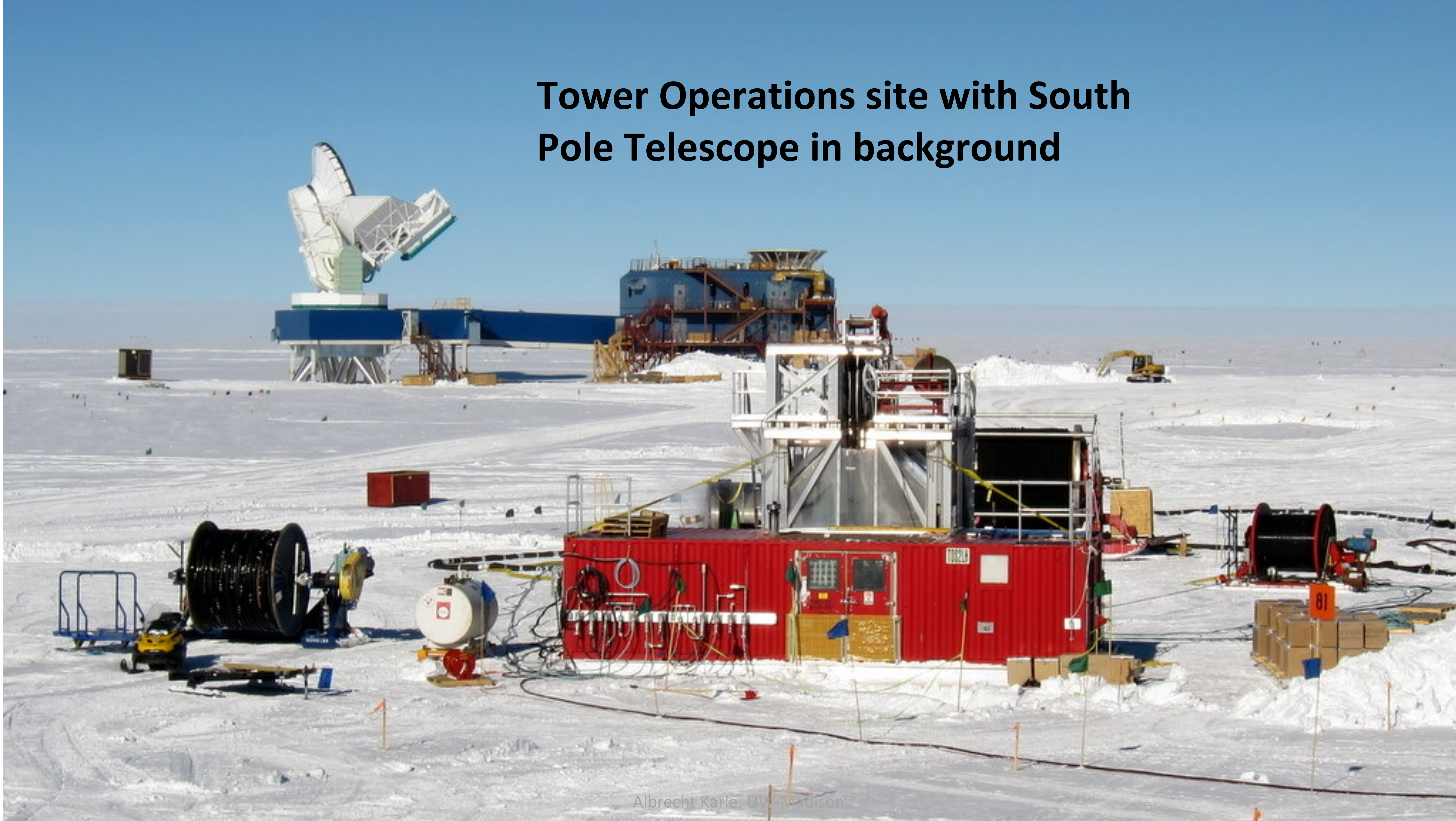


Photo: Ben Tibbets
~2009

Tower Operations site with South Pole Telescope in background

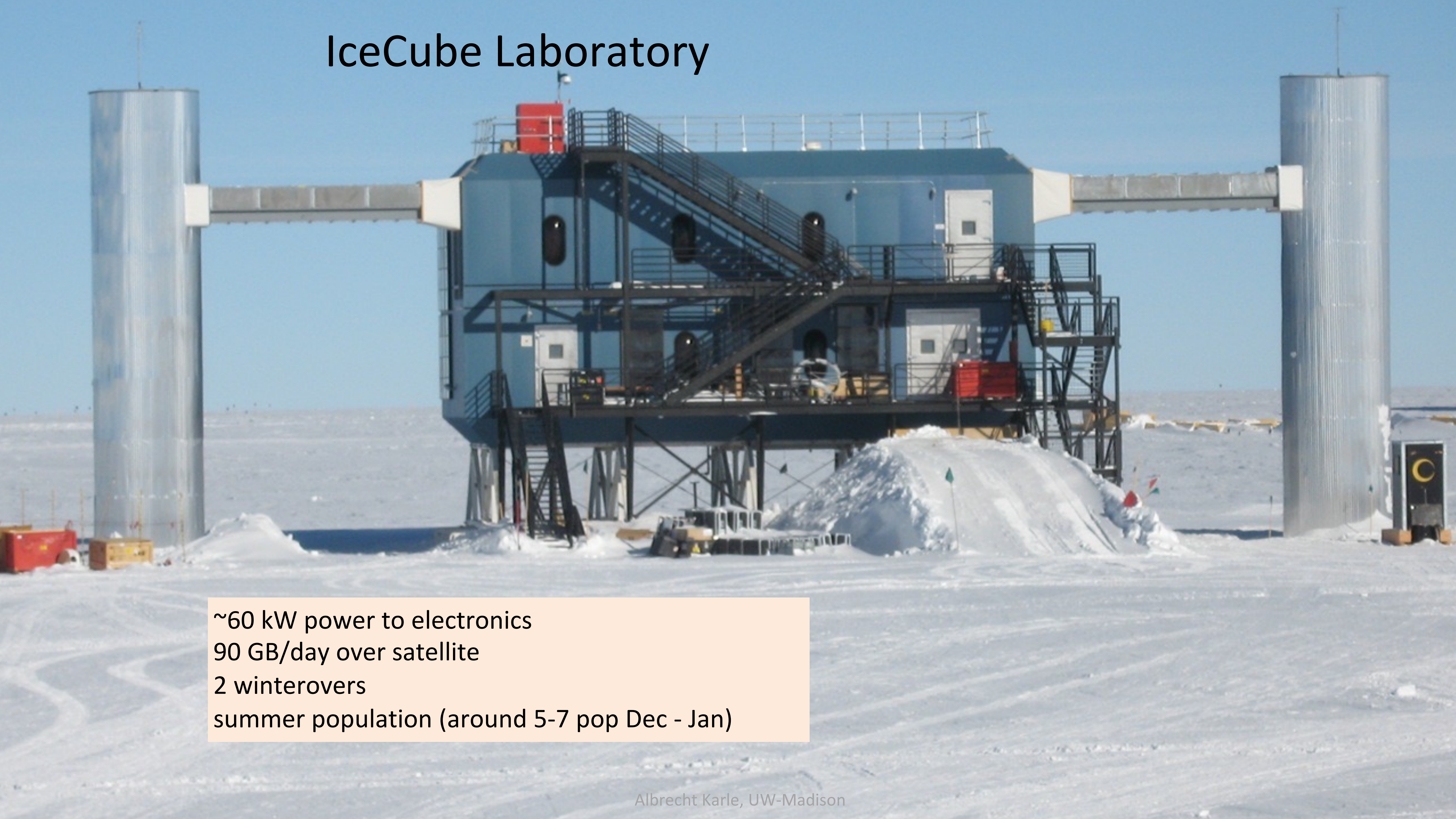


… not always easy

5160 sensors are deployed to a depth between 1500 and 2500m.

The last sensor gets a signature.

IceCube Laboratory

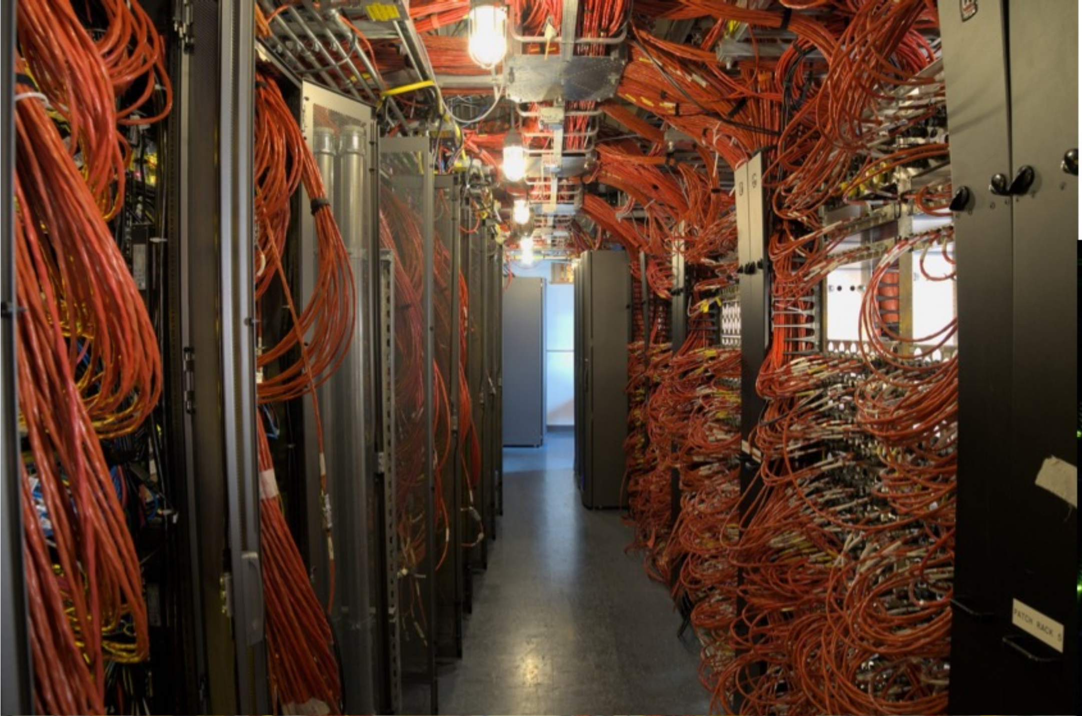


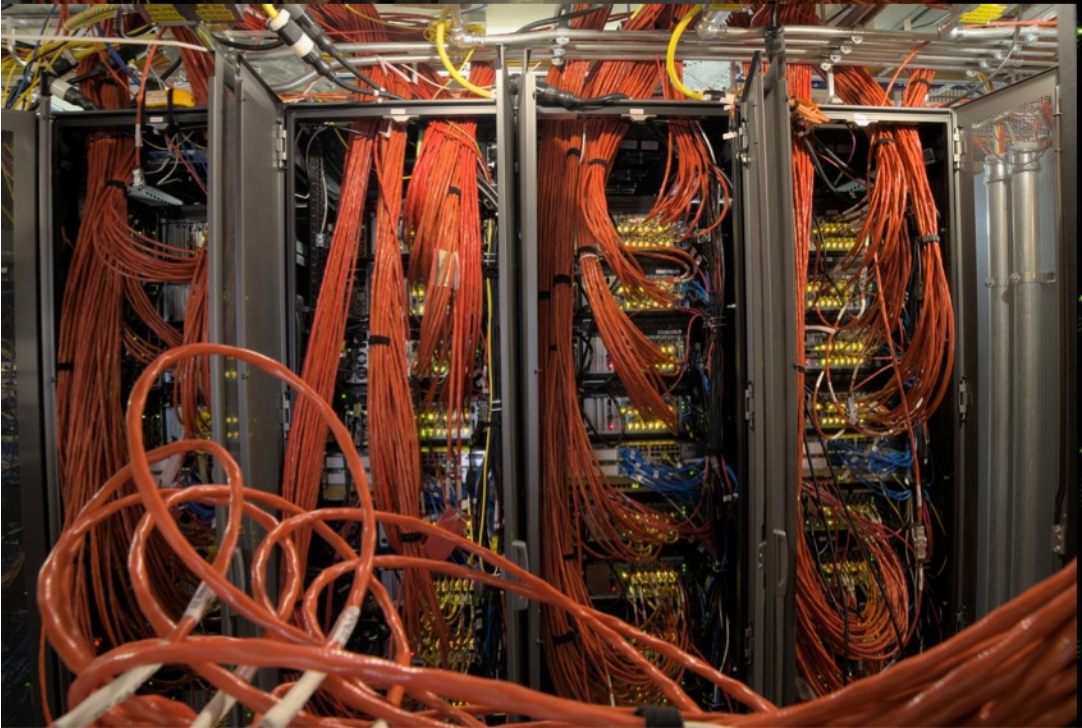
~60 kW power to electronics
90 GB/day over satellite
2 winterovers
summer population (around 5-7 pop Dec - Jan)

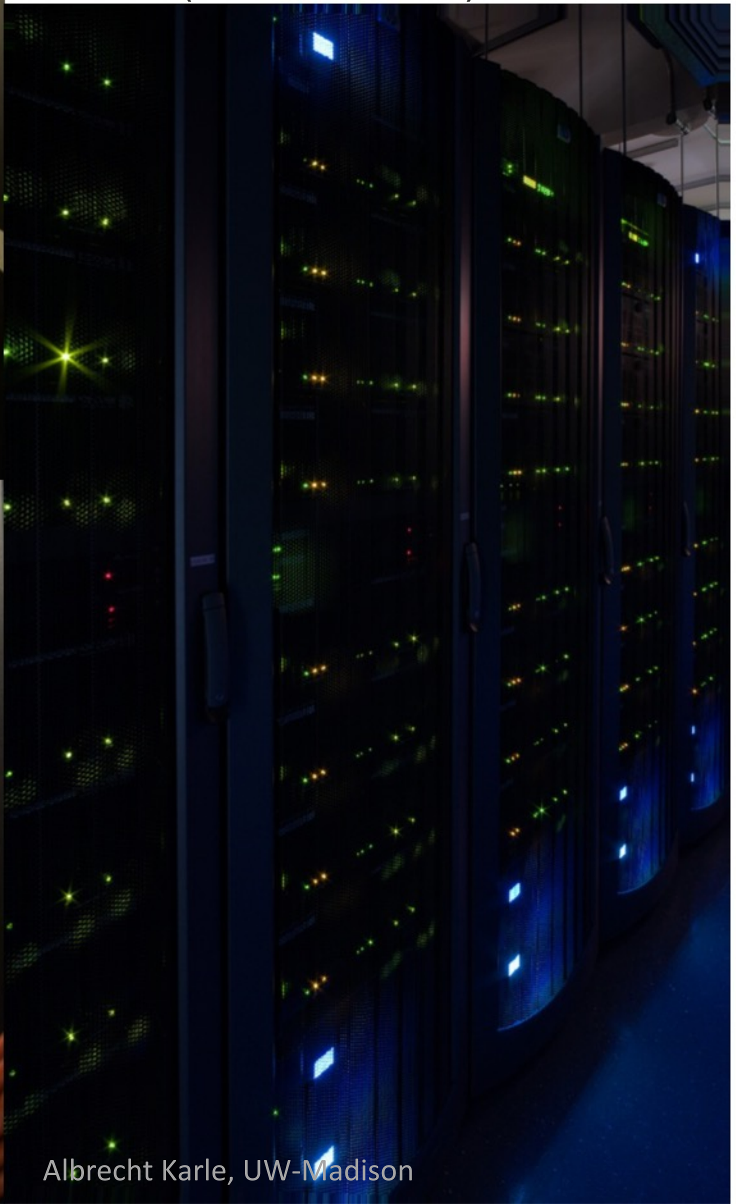

Albrecht Karle, UW-Madison

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 …

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
Queen's University
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
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University of Rochester
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University of Utah
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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 NEUTRINO OBSERVATORY
icecube.wisc.edu

Chiang Mai University (Prof. Waraporn) is Associate Member of IceCube since 2021.

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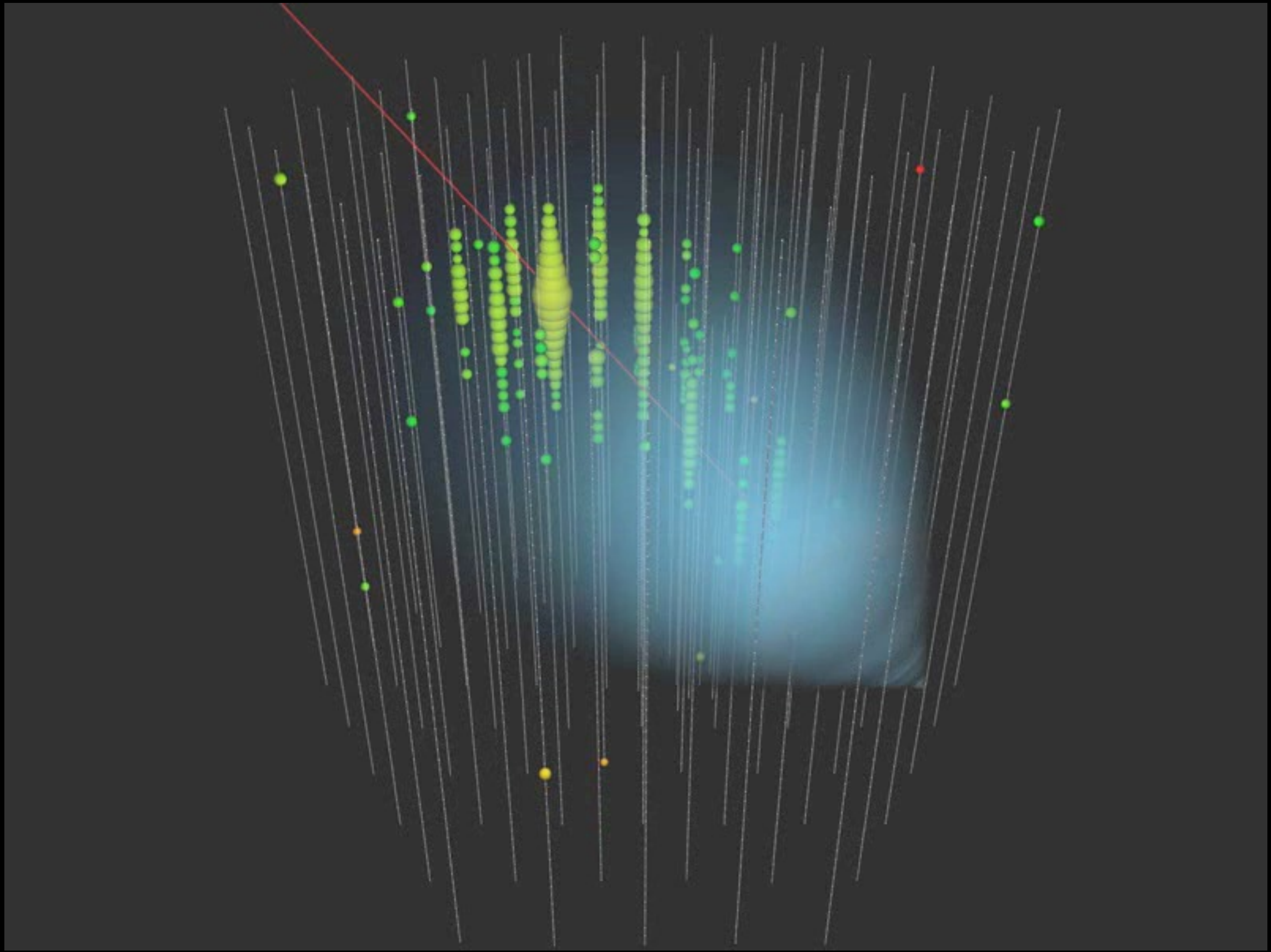

muon track: color is time; number of photons is energy

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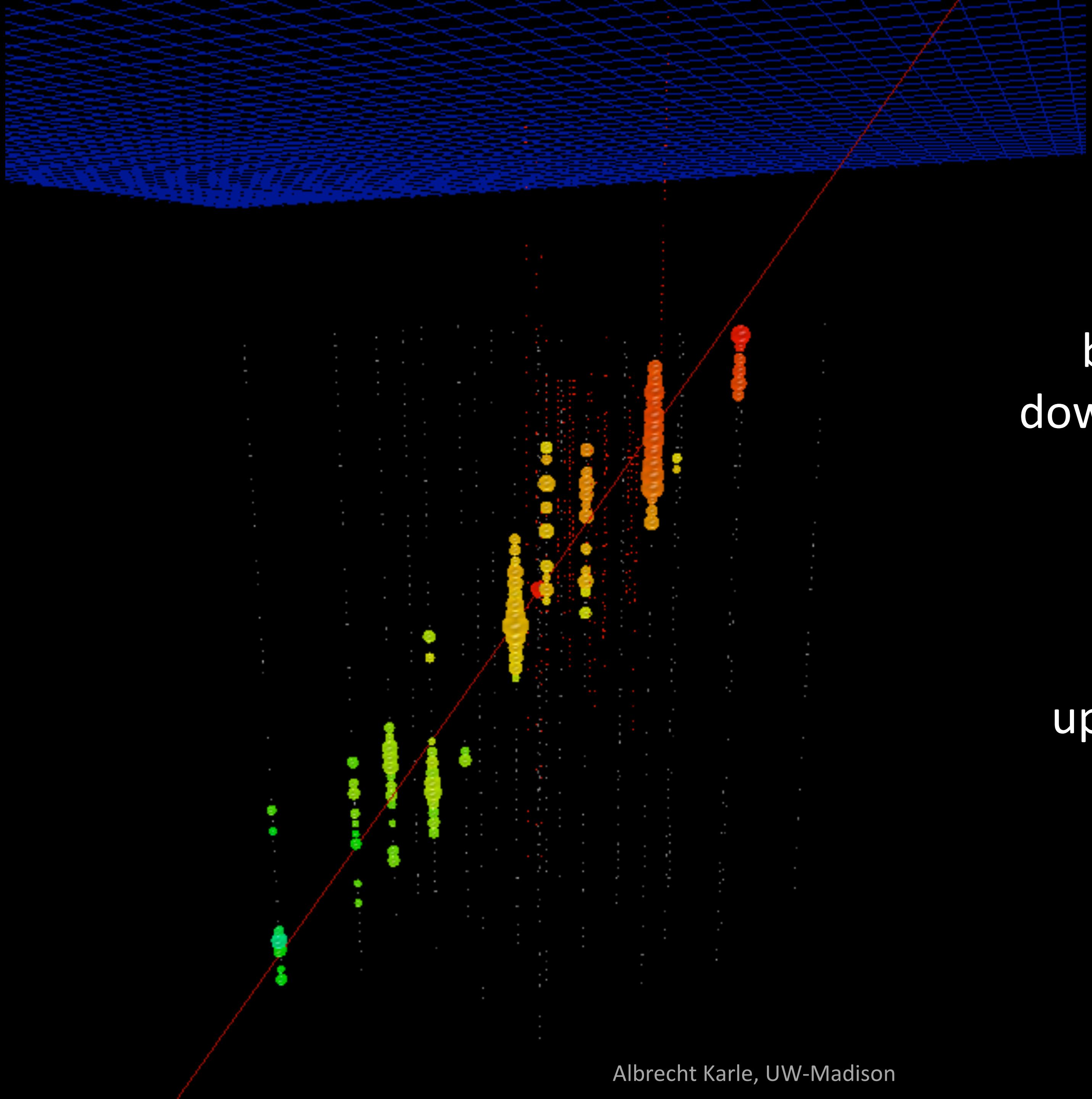


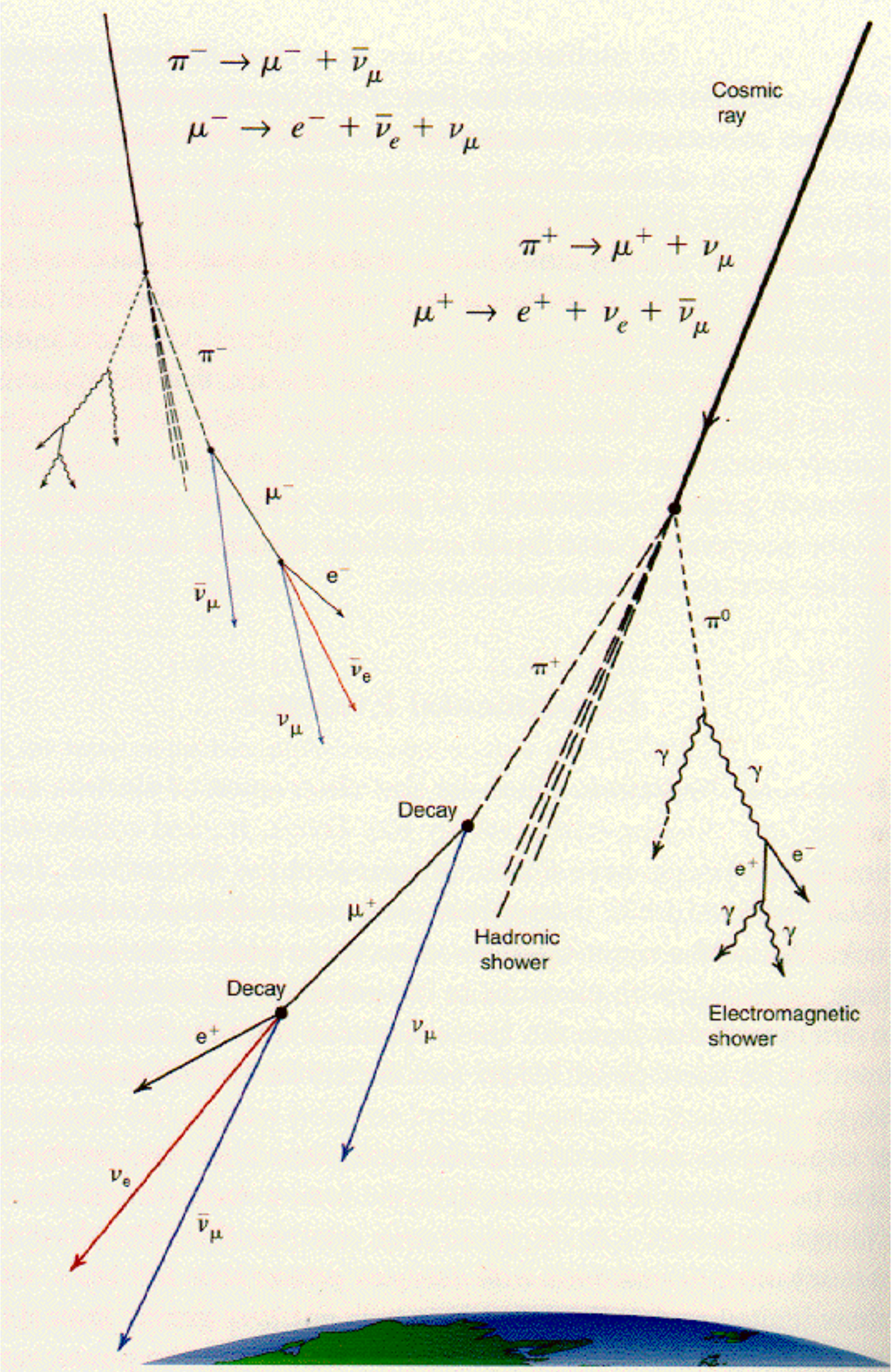
background:
downgoing cosmic
ray muons

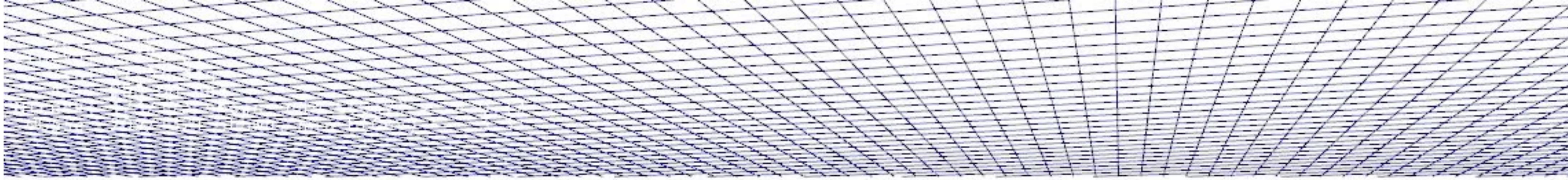
signal:
upgoing muons
initiated by
Neutrinos

Neutrinos and cosmic rays in the atmosphere

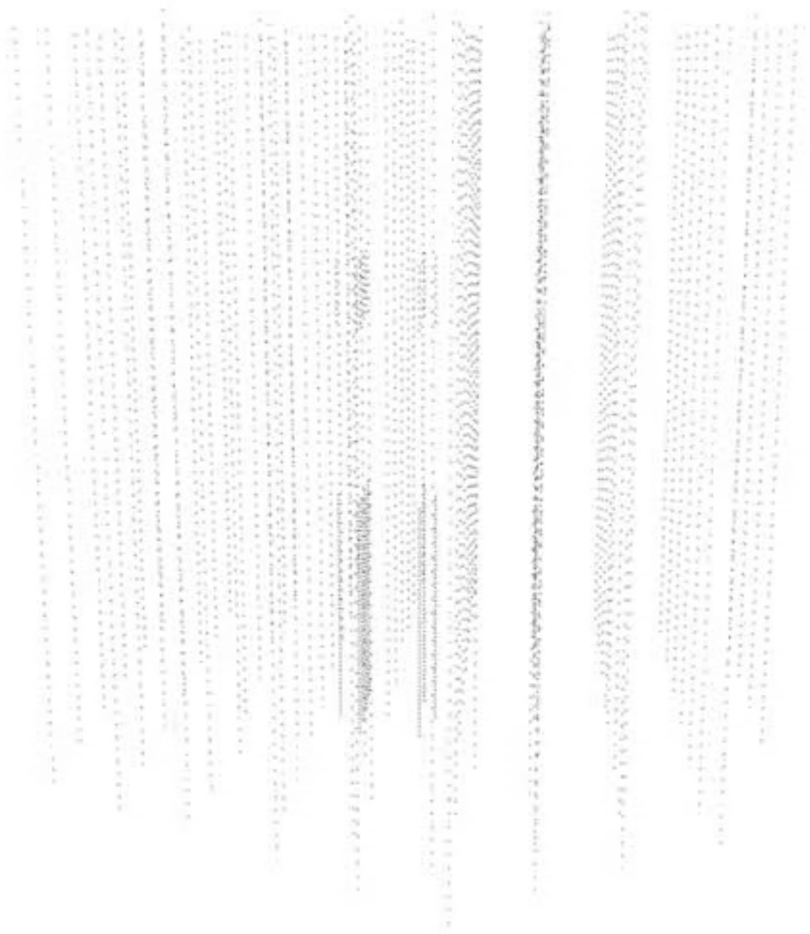
a constant rain of
muons and neutrinos
is produced by
cosmic rays
crashing into
the atmosphere

IceCube measures
200 billion "events" (mostly muons)/year
and
50,000 neutrinos/year generated by the rain of cosmic rays hitting the Earth.





Simulation: 1 ms of μ’s and noise

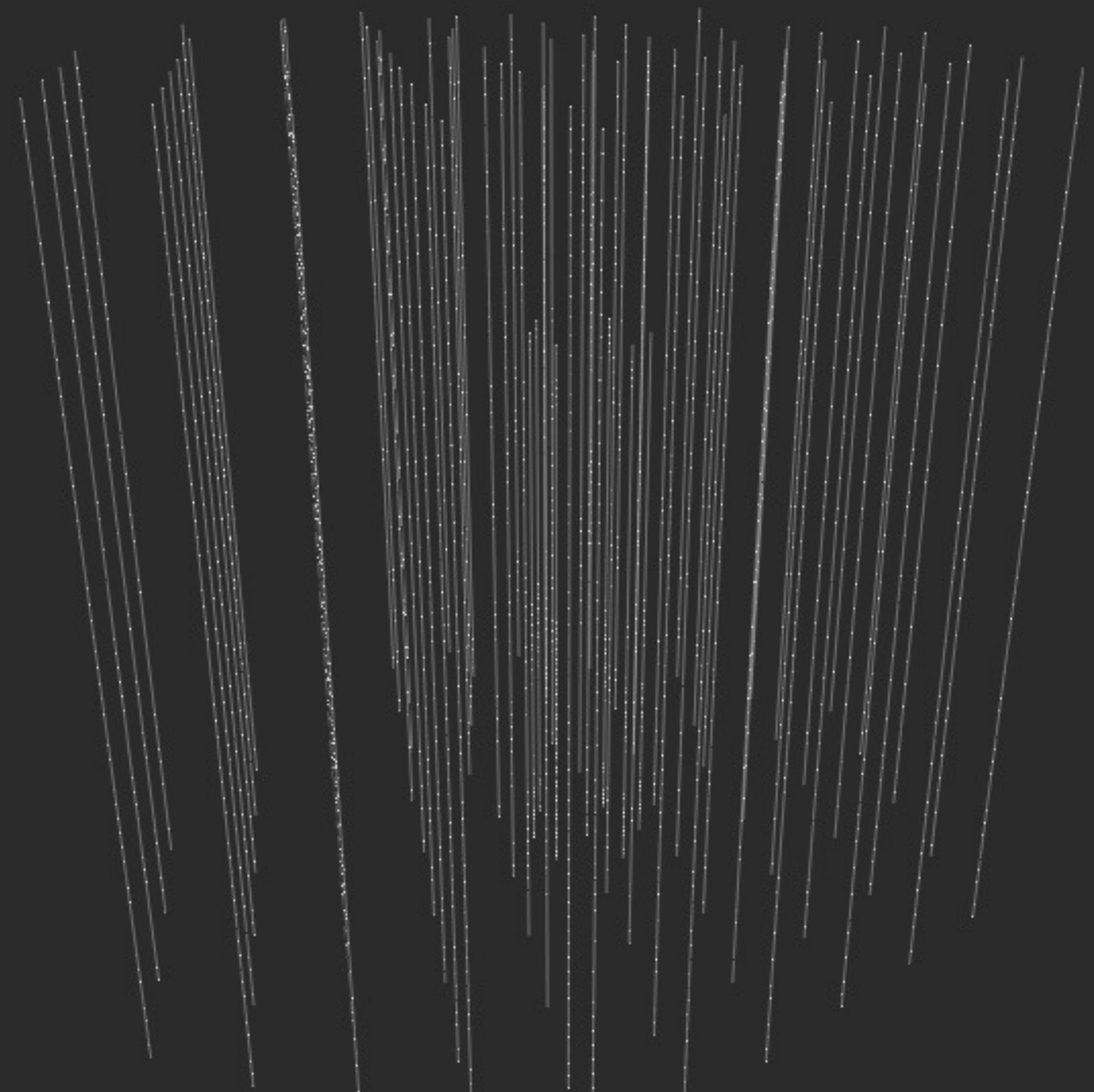


Trigger rate: 3000 particles per second (muons)
Shown are also muons that will not form a trigger
noise rate: only 300 photoelectrons/s (at -30°C)

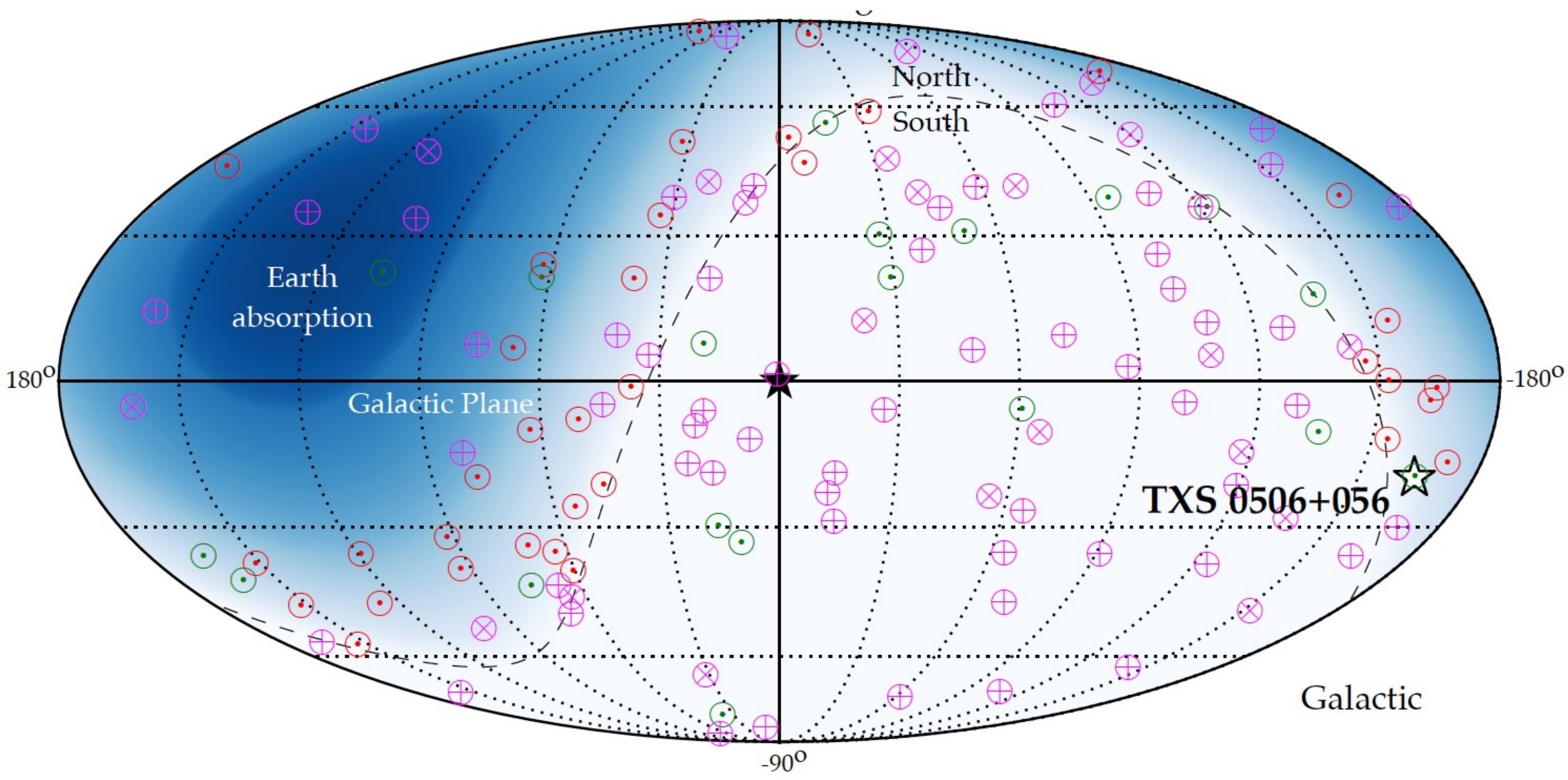
"Dr. Strangepork"

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

Neutrino interaction inside the detector.



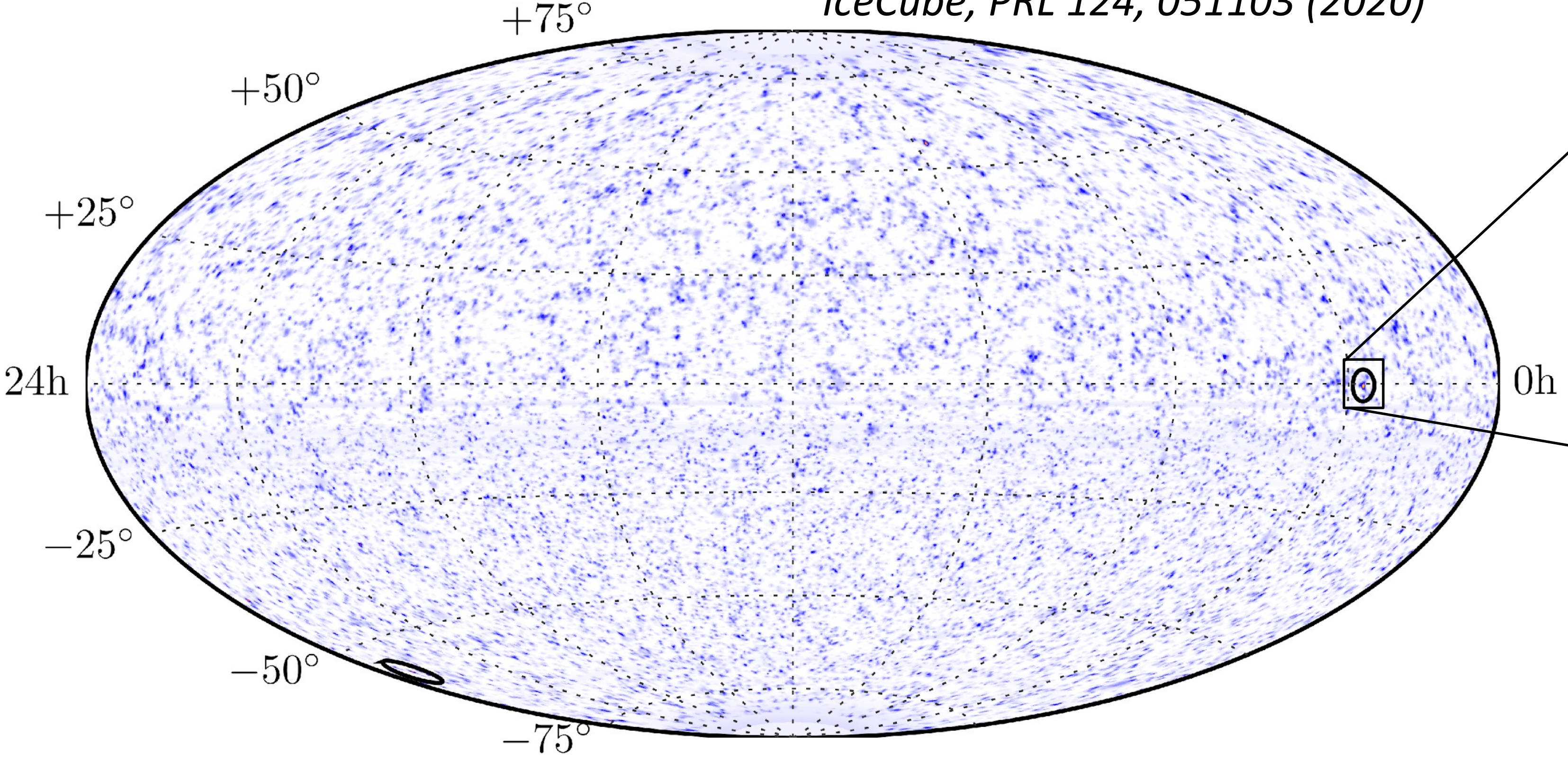
10 years of IceCube: The high energy neutrino sky

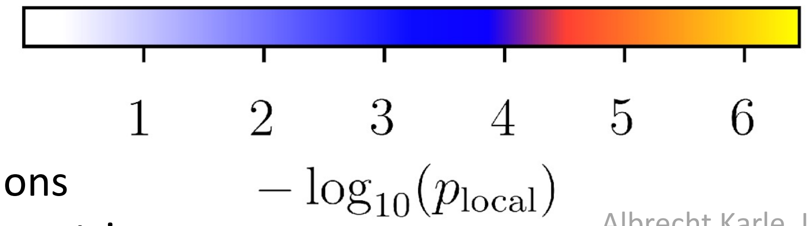


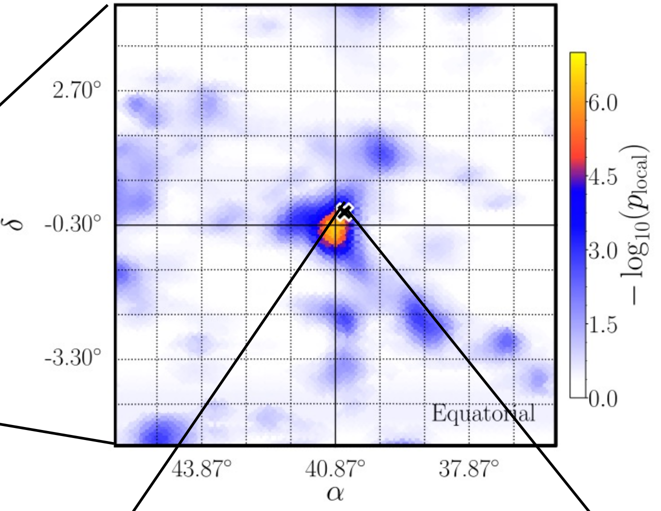
High energy events only (> 100 TeV)

2020 skymap: Most significant position on sky consistent with the location of a nearby galaxy (2.9 σ)

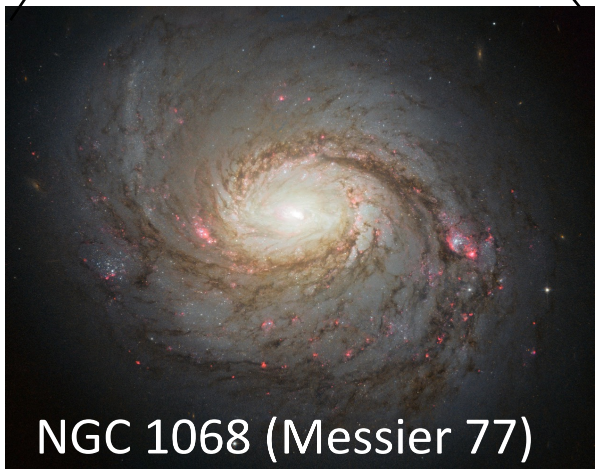
IceCube, PRL 124, 051103 (2020)







50 neutrinos



Per year:
90 billion atmospheric muons
80 thousand atmospheric neutrinos

Two years later: With better calibration and a little more statistics:

Science Magazine — Nov. 4, 2022

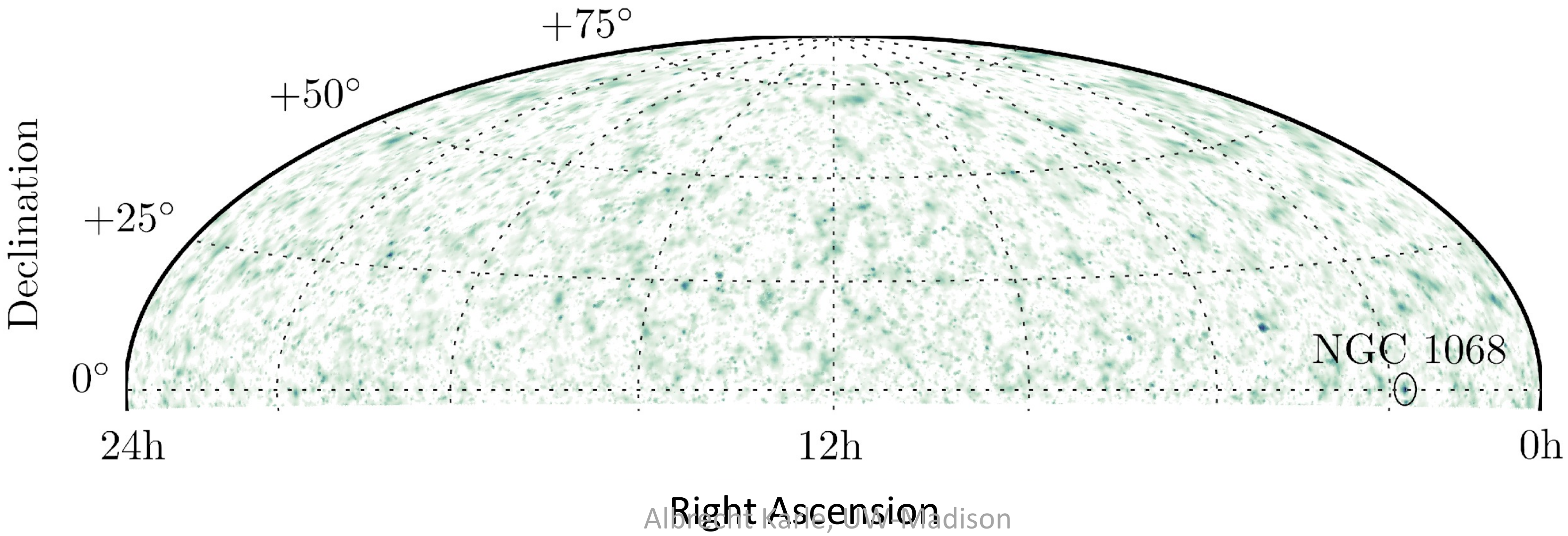
RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

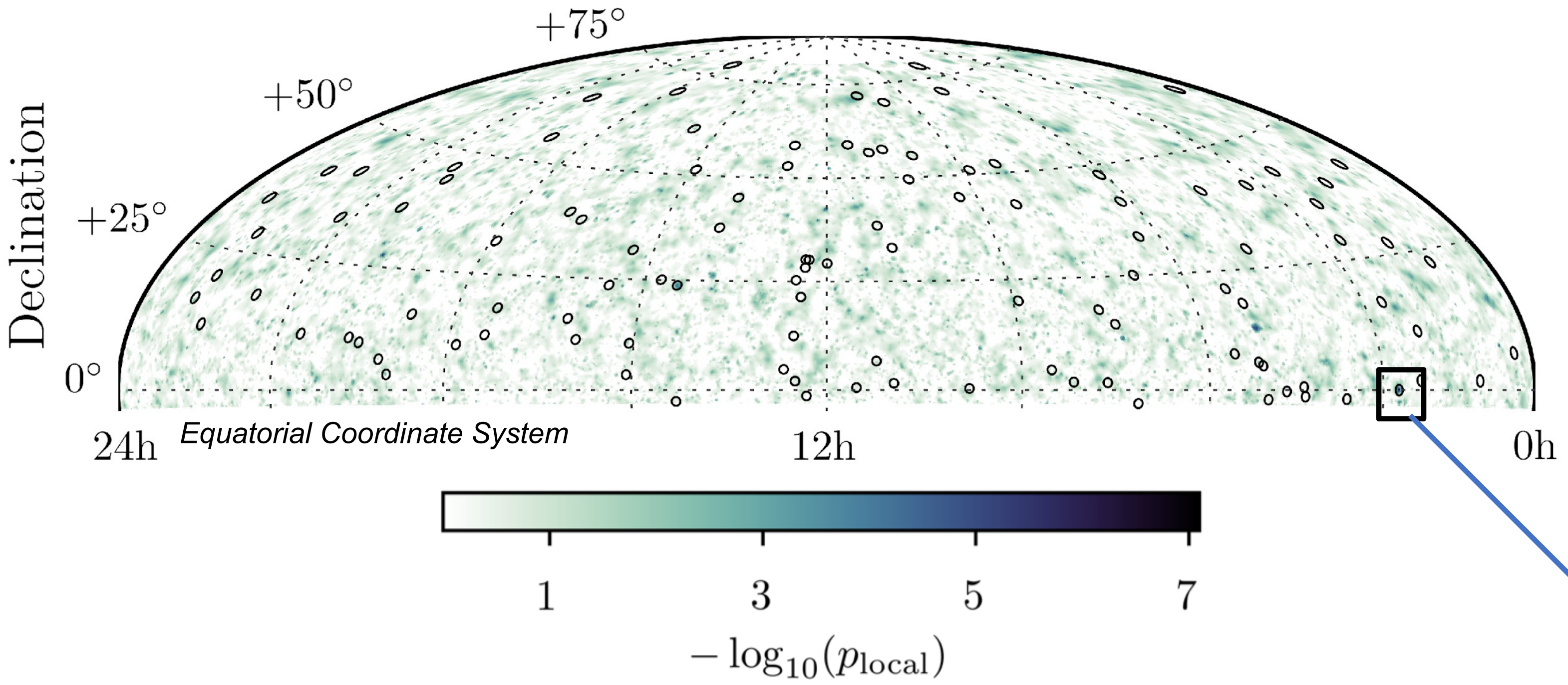
IceCube Collaboration*†

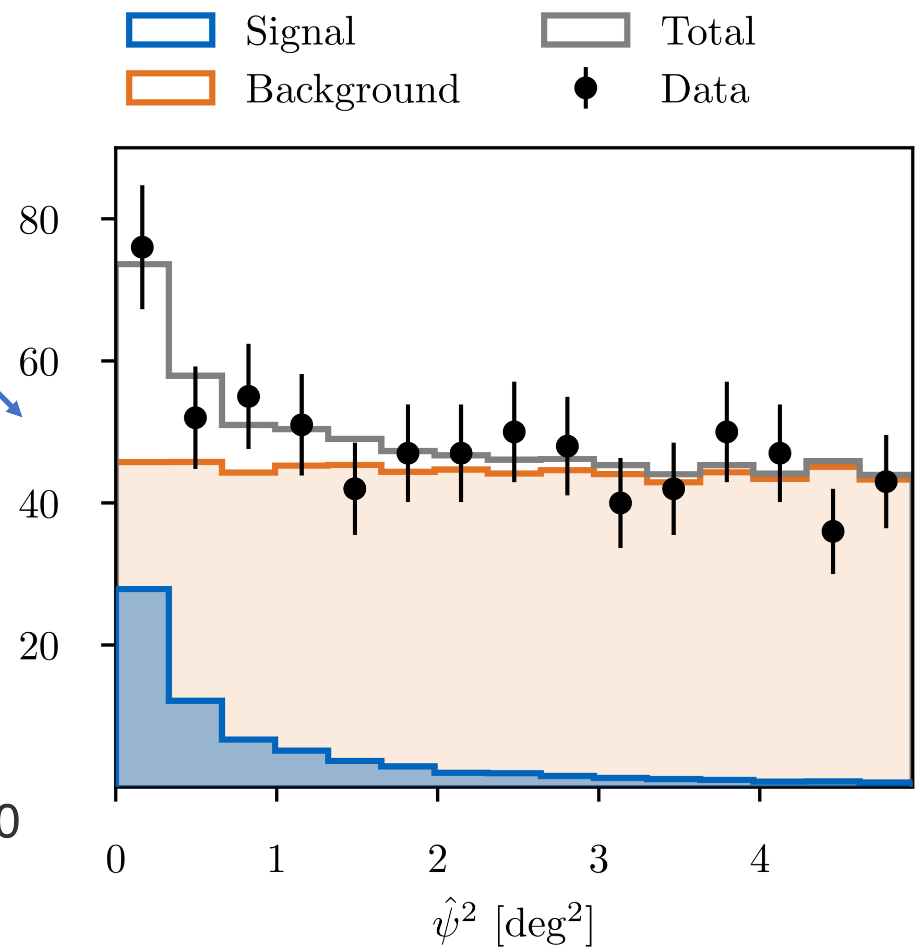


Evidence for neutrino emission from the nearby active galaxy NGC 1068 (M 77)

Science — Nov. 4, 2022

Analysis with improved calibrations





At the NGC 1068 location:

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

Out of a total of 1 trillion events (10^12).

Spectral index = 3.2 ± 0.2

... significance 4.2σ

p-value: 1:100,000
(what is this?)

What is NGC 1068?

A galaxy with a massive black hole in the center.

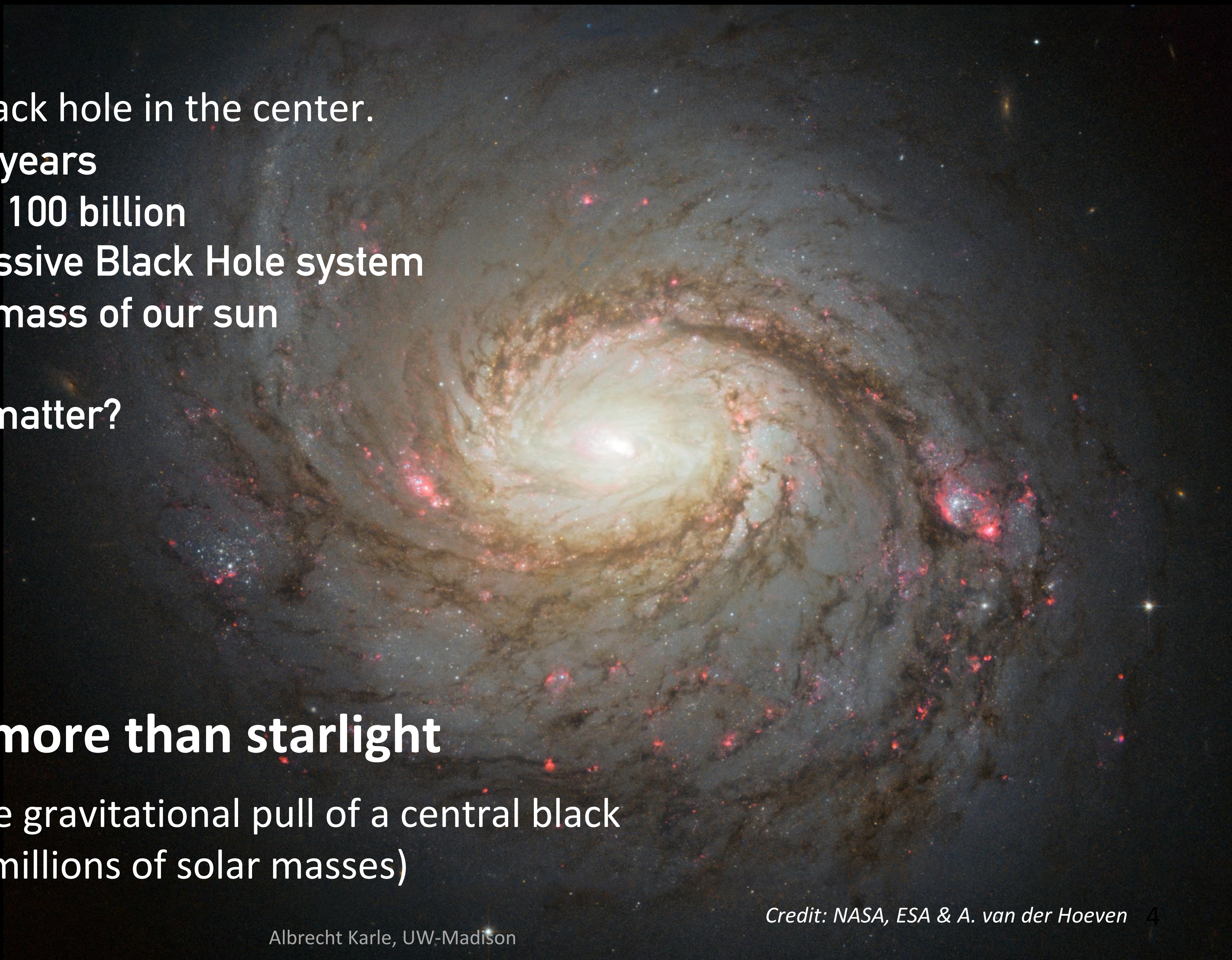
Distance: 50 million light years

Number of stars: of order 100 billion

In the center: A super massive Black Hole system

~20 million times the mass of our sun

Why does the black hole matter?



Galaxies: much more than starlight

Emission powered by a the gravitational pull of a central black hole (tens of millions of solar masses)

Credit: NASA, ESA & A. van der Hoeven

NGC 1068

(insert: artist conception)

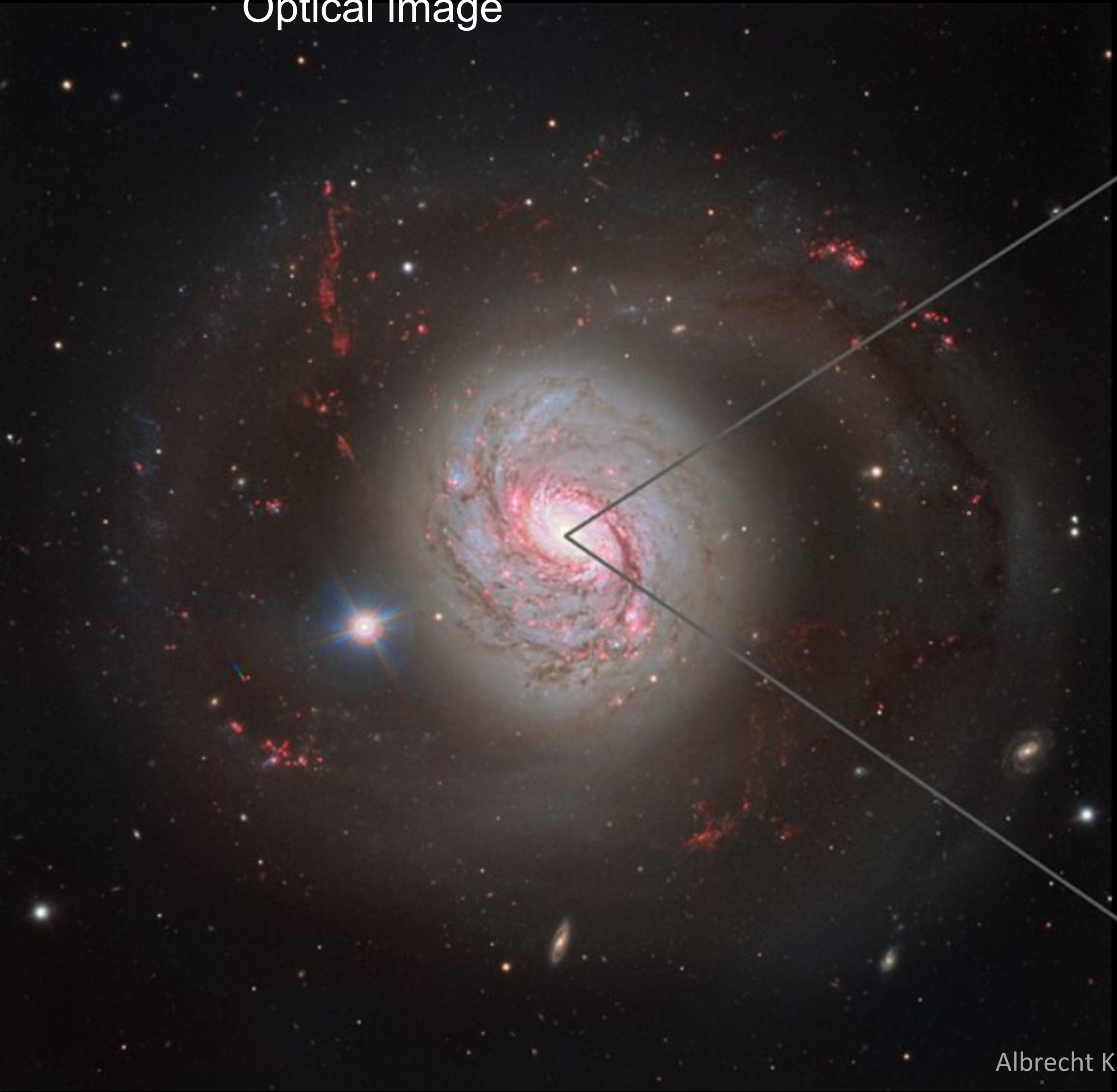
Credit: NASA/JPL-Caltech

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

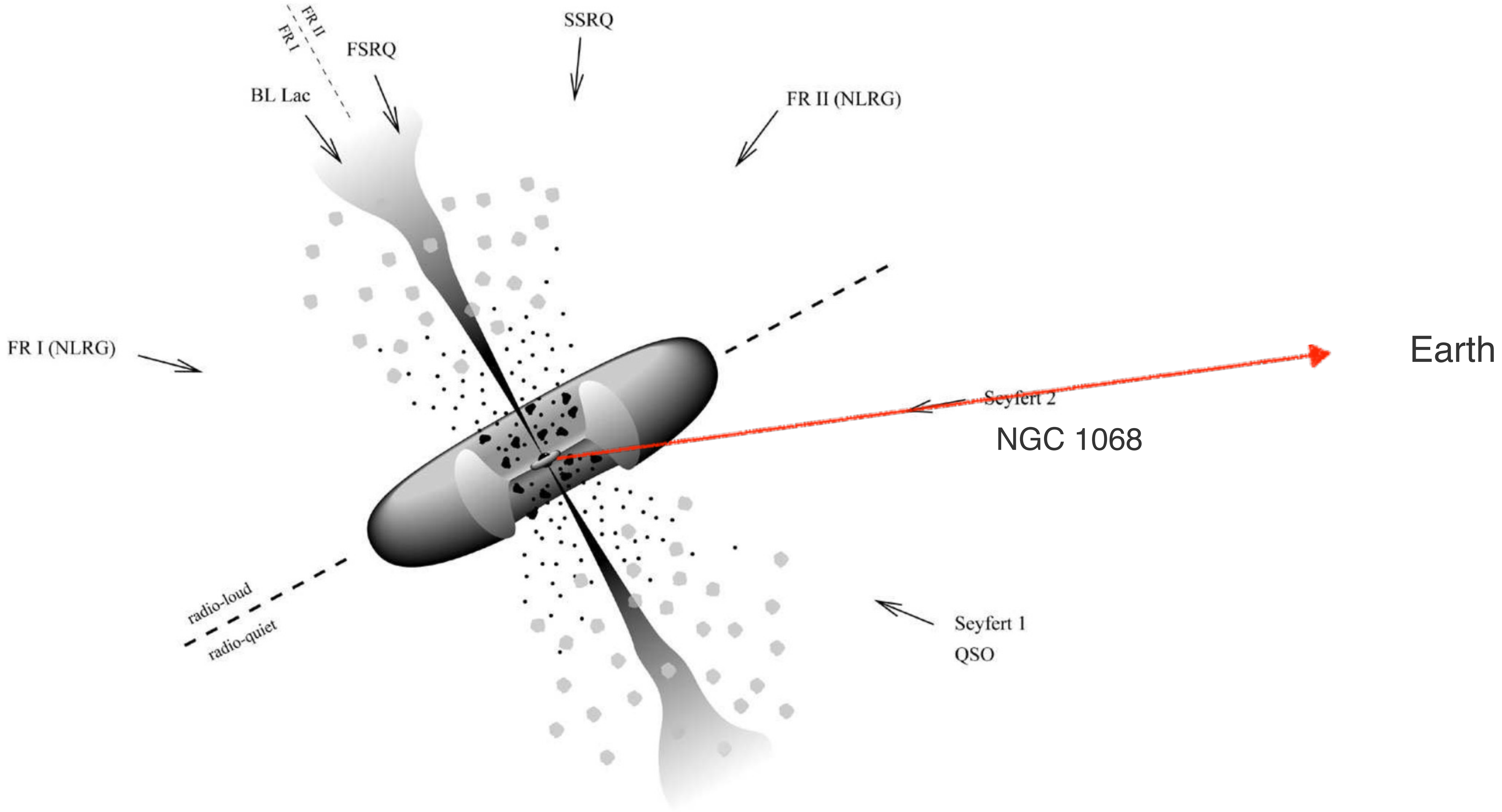
Infrared image confirms dust cloud surrounding black hole

(Neutrinos don't care about dust.)

Optical image



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


FR II
FR I
FSRQ
SSRQ
BL Lac
FR II (NLRG)
FR I (NLRG)
Earth
Seyfert 2
NGC 1068
radio-loud
radio-quiet
Seyfert 1
QSO

How are neutrinos produced in non-jetted AGNs?

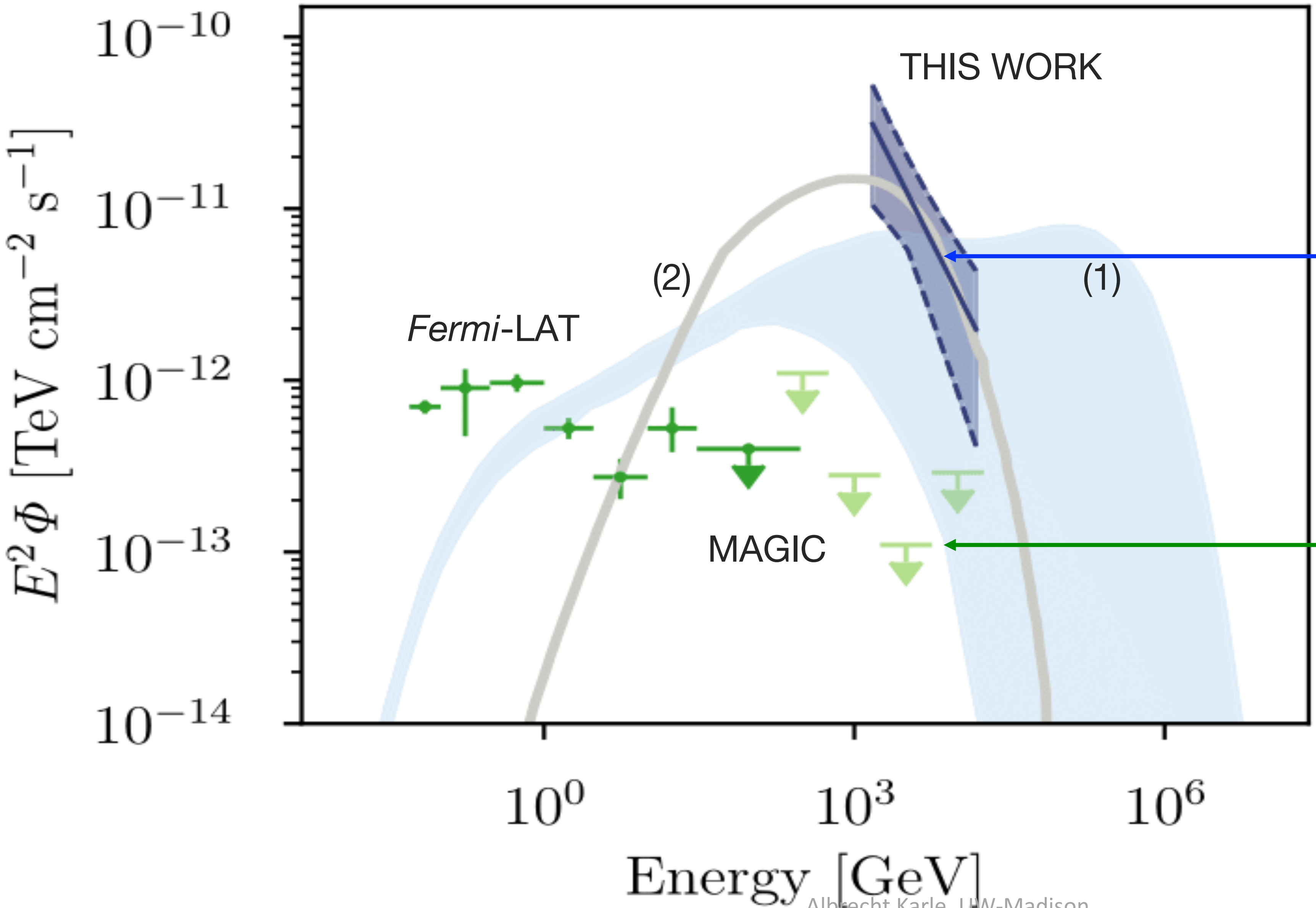
We conclude that active galactic nuclei are powerful sources for
accelerating particles to cosmic ray energies. The bulk of meta-
galactic cosmic rays is likely to ori
particular, in the Virgo supercluster
NGC 4151 and NGC 1068 are likely to b
"local" metagalactic cosmic rays, inc
the ultra-high energy ($E \gtrsim 10^{19}$ 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

Gamma Rays (photons) and Neutrinos



We know that neutrinos and gamma rays are produced together

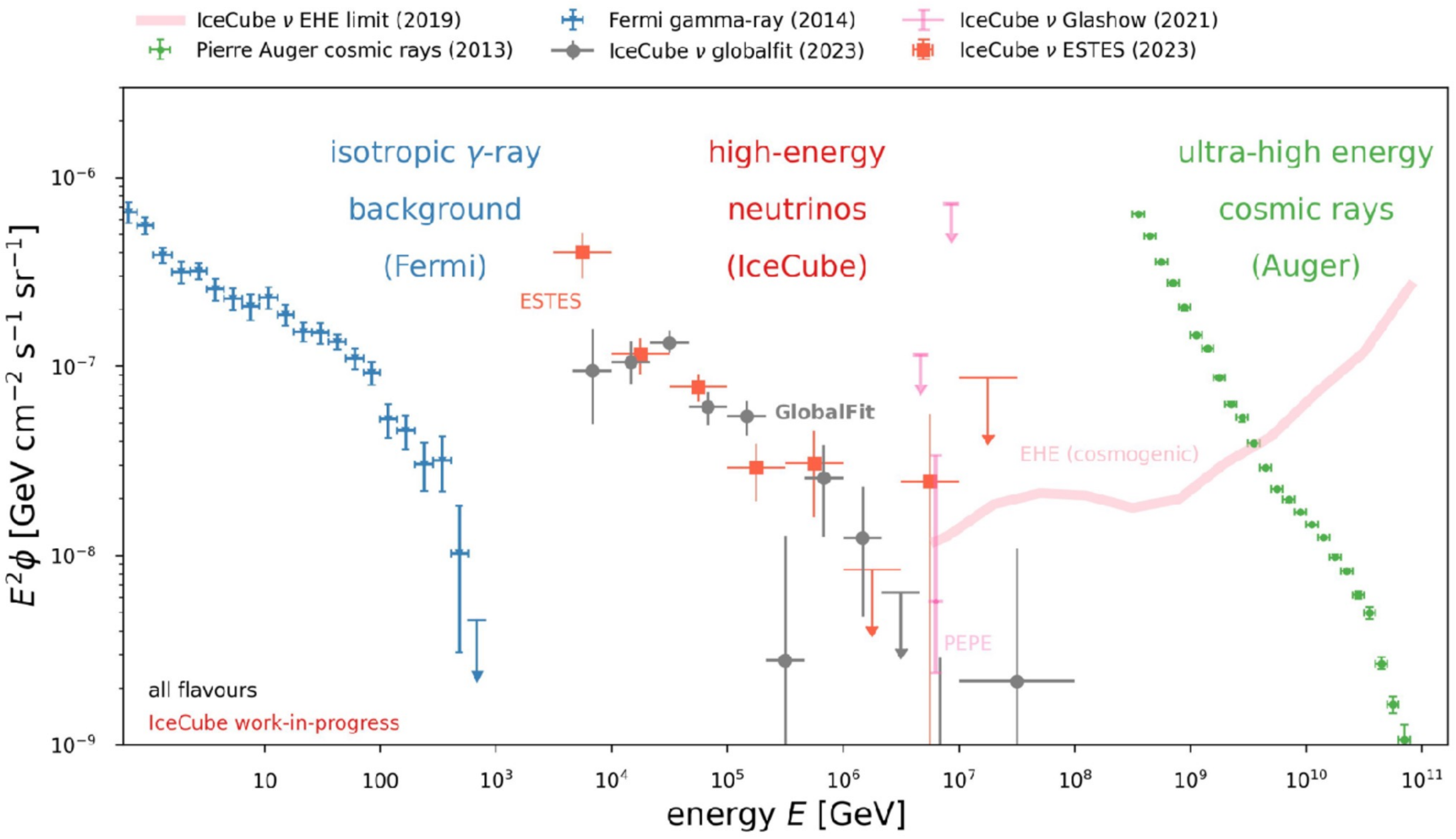
Neutrinos are coming out

Gamma rays are missing
- and it is not a surprise.

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

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

Neutrinos and cosmic rays over the entire sky: they carry similar total energy in the Universe



IceCube is pushing towards lower energies, where systematics and backgrounds become increasingly important.
Interpretation and significance of low-energy “tension" between ESTES and “GlobalFit" is unclear.

Carlos Argüelles — ICRC Neutrino Rapporteur Talk 2023

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

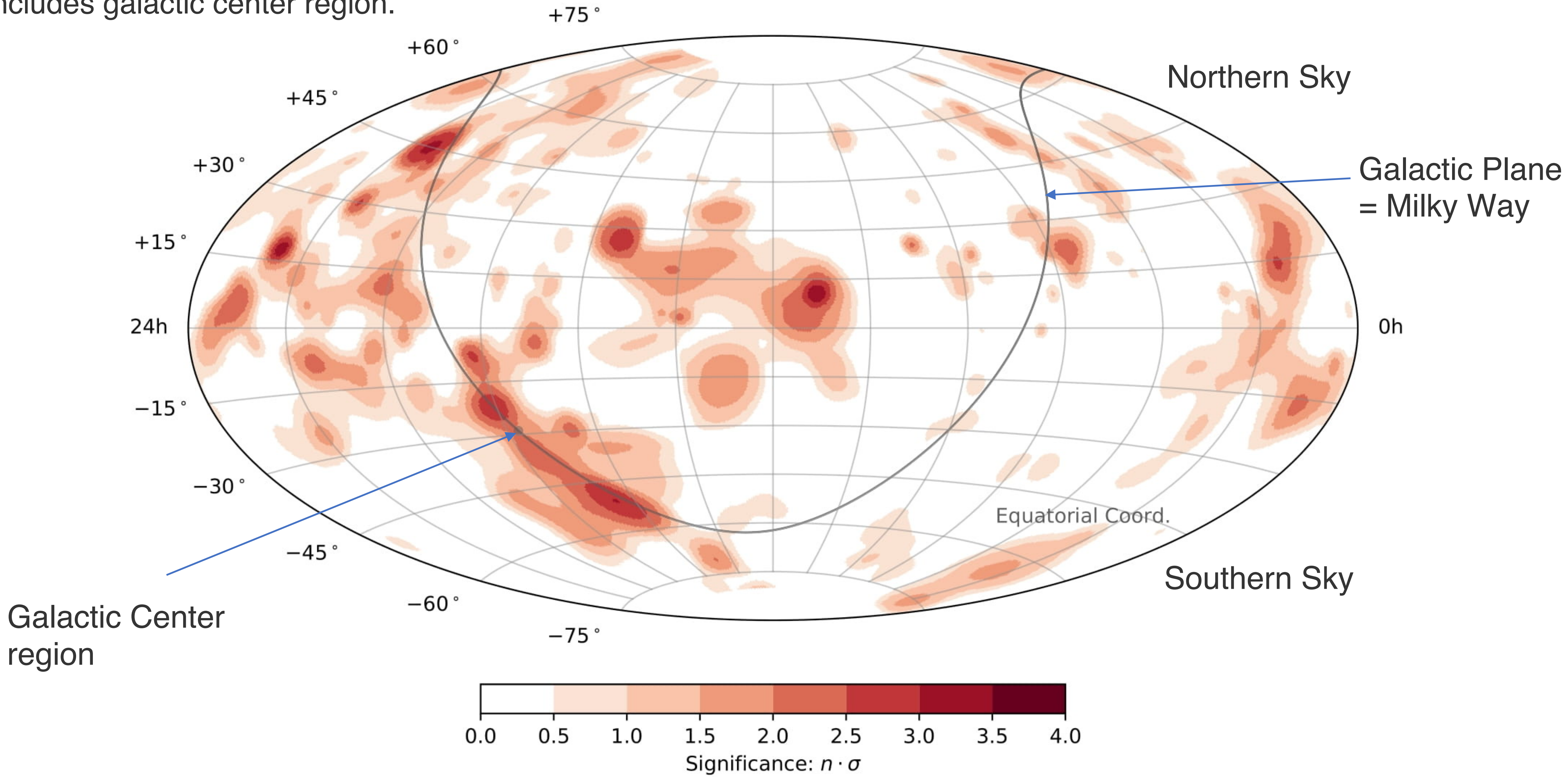
Neutrinos from the Milky Way

Albrecht Karle, UW-Madison

Credit: Yuya Makino, IceCube/NSF

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

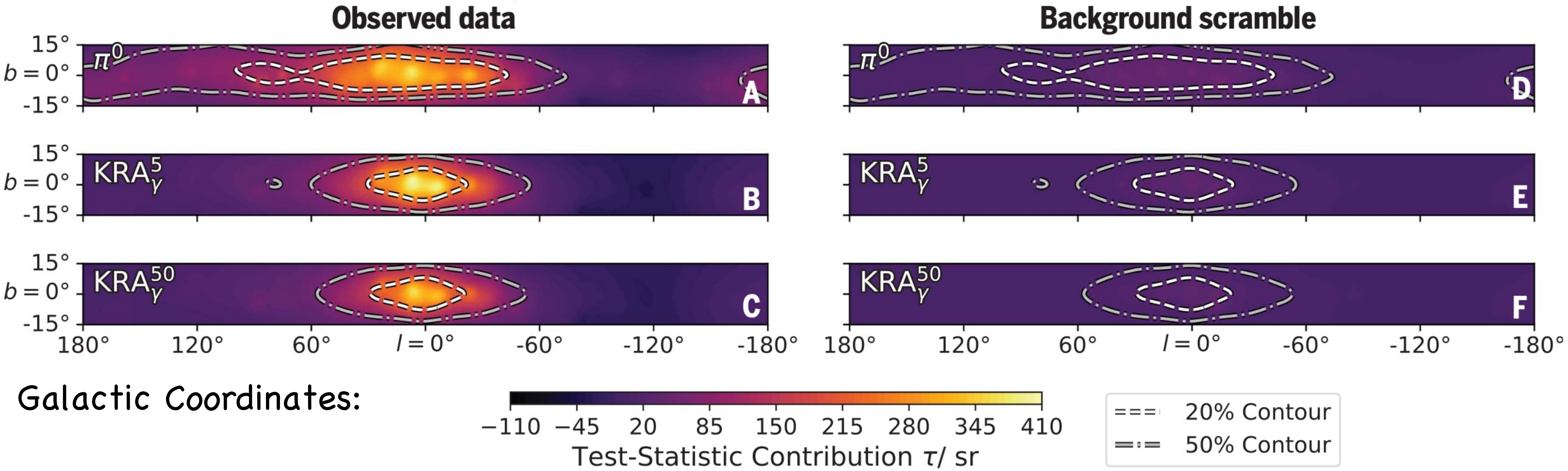
Features: Low background, high sensitivity in the Southern hemisphere, includes galactic center region.



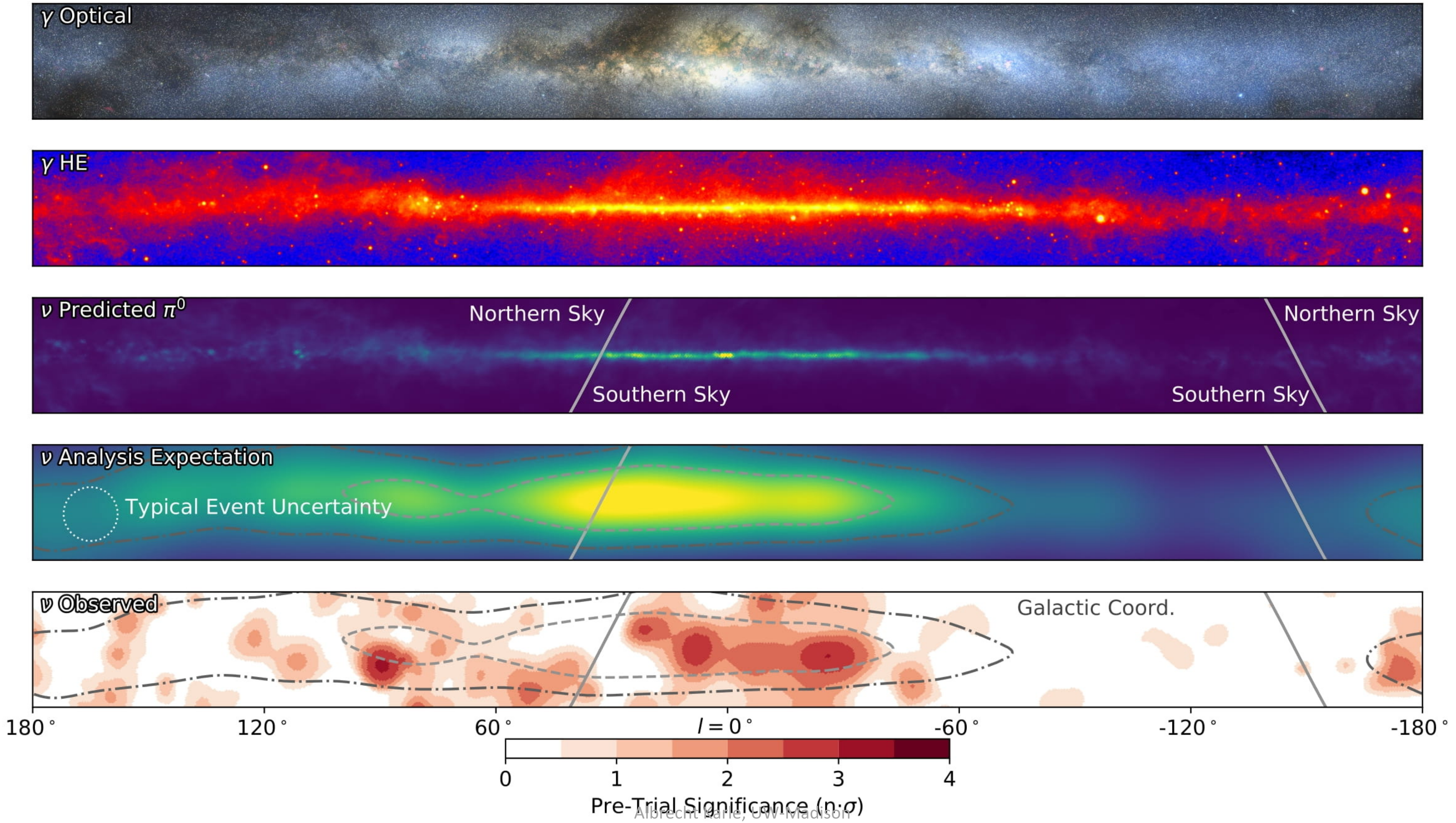
Neutrinos from the Milky Way

Significant observation: 4.3 sigma

Testing different Models for neutrino emission.

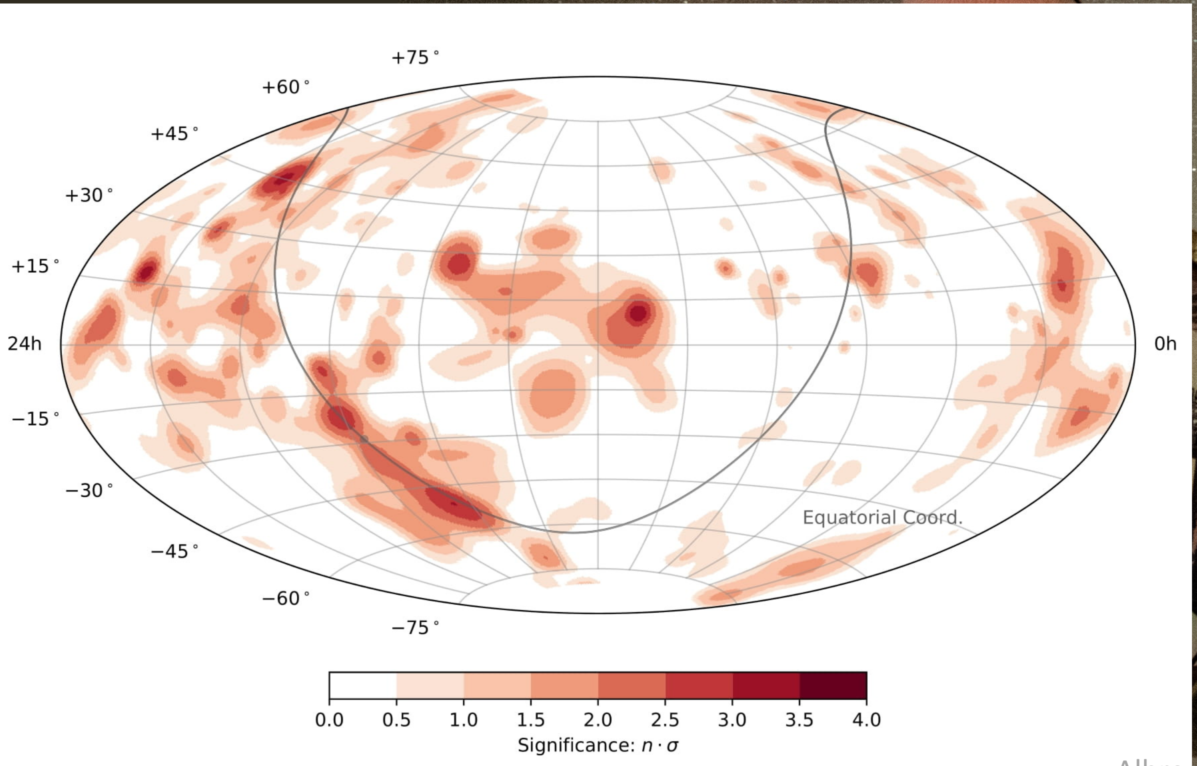


Galactic Coordinates:

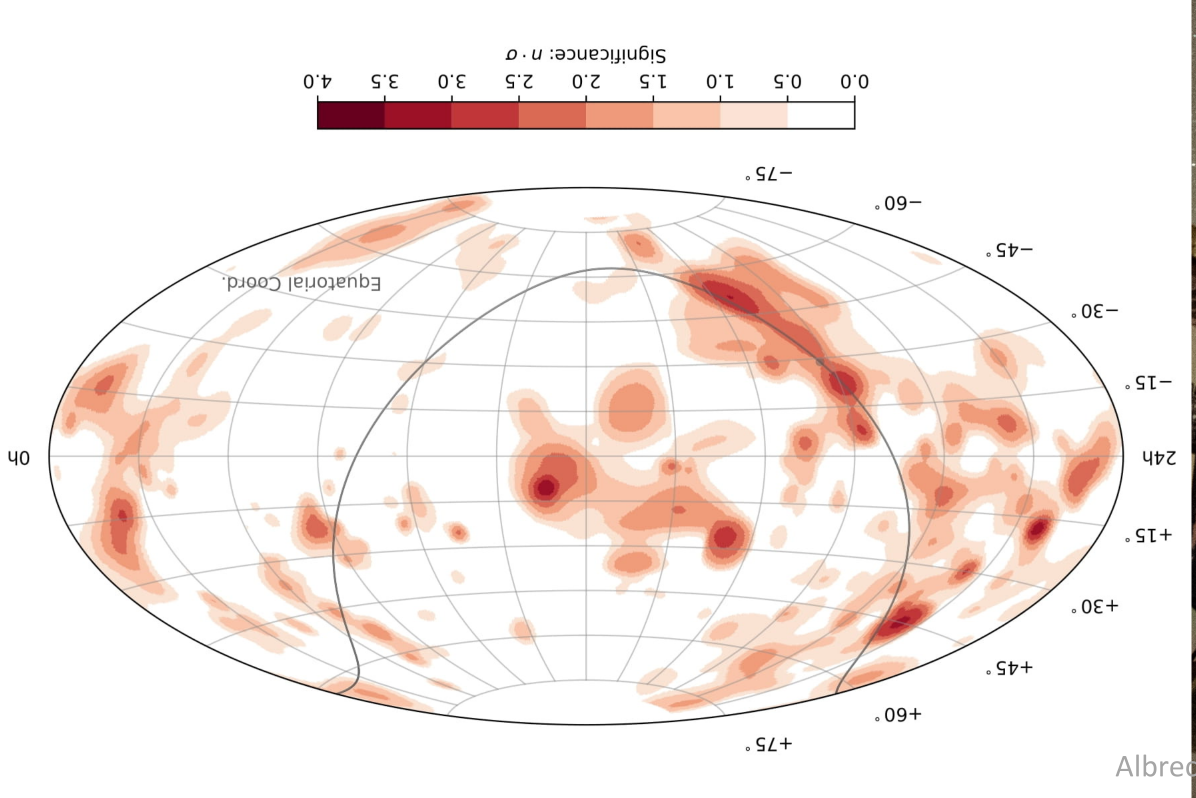


γ Optical
γ HE
ν Predicted π⁰
Northern Sky
Southern Sky
Northern Sky
Southern Sky
ν Analysis Expectation
Typical Event Uncertainty
ν Observed
Galactic Coord.
180°
120°
60°
l = 0°
-60°
-120°
-180°
0
1
2
3
4
Pre-Trial Significance (n·σ)

Neutrinos from the Milky Way



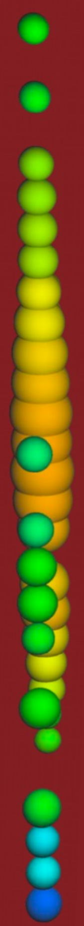
Neutrinos from the Milky Way



Albrecht Karle, UW-Madison

Credit: Yuya Makino, IceCube/NSF

Future Plans ....



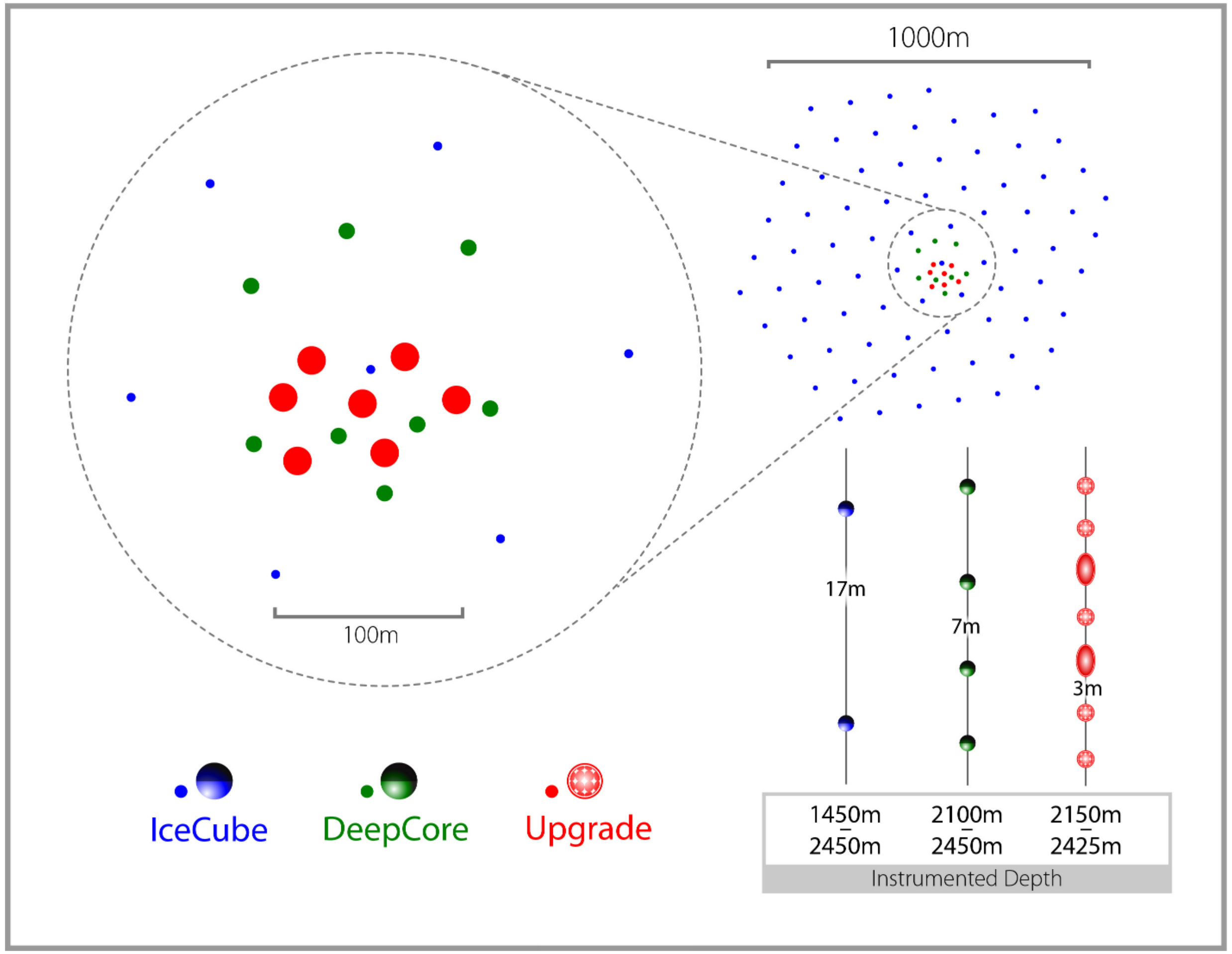
The IceCube-Upgrade

In progress

Scope:
Add 7 new strings, 700 sensors, densely packed in the center of IceCube.

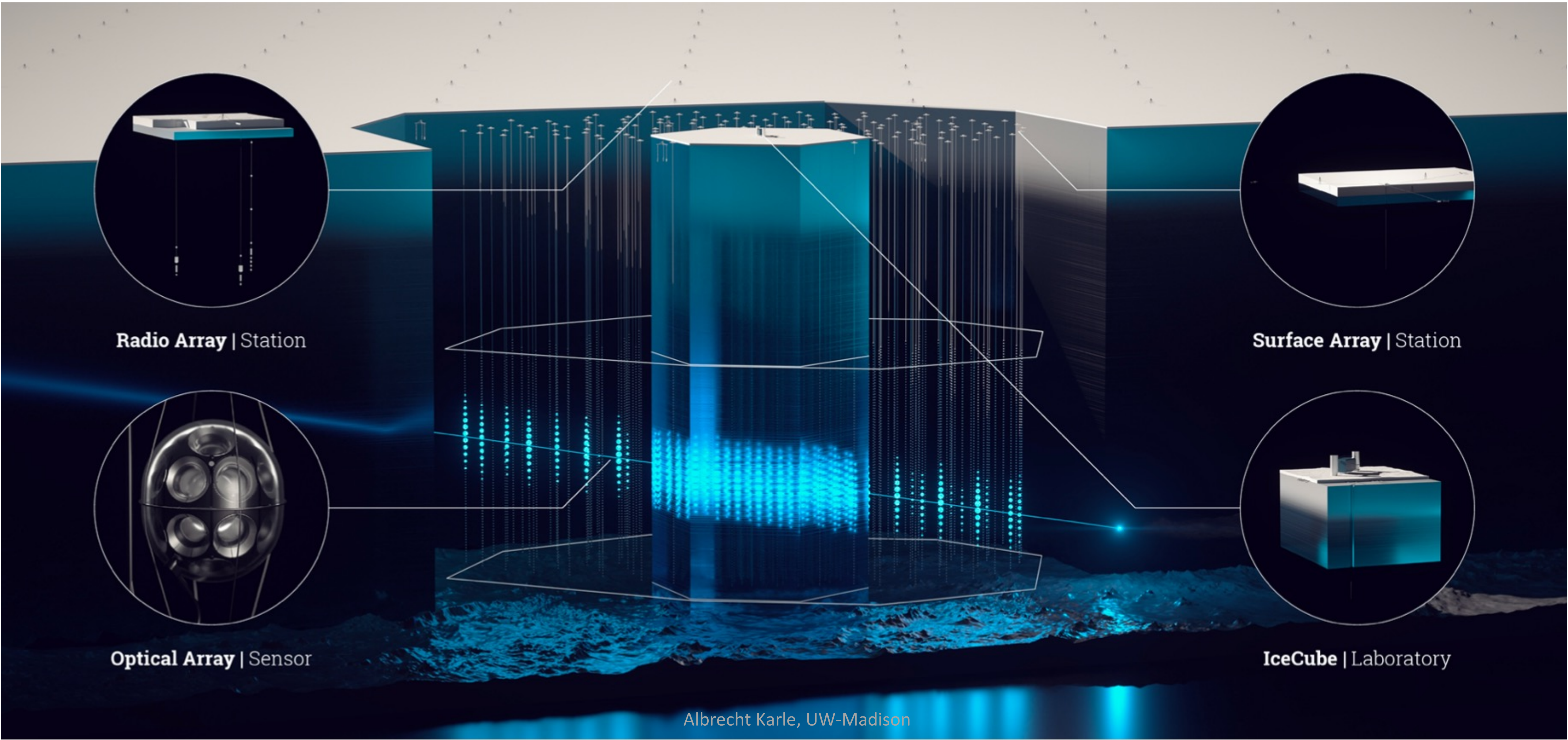
Instrumented volume: 2 Mt
Energy threshold: ~ 1 GeV

Science goals:
- Fundamental neutrino properties
- Improved calibration
- R&D, new instruments.

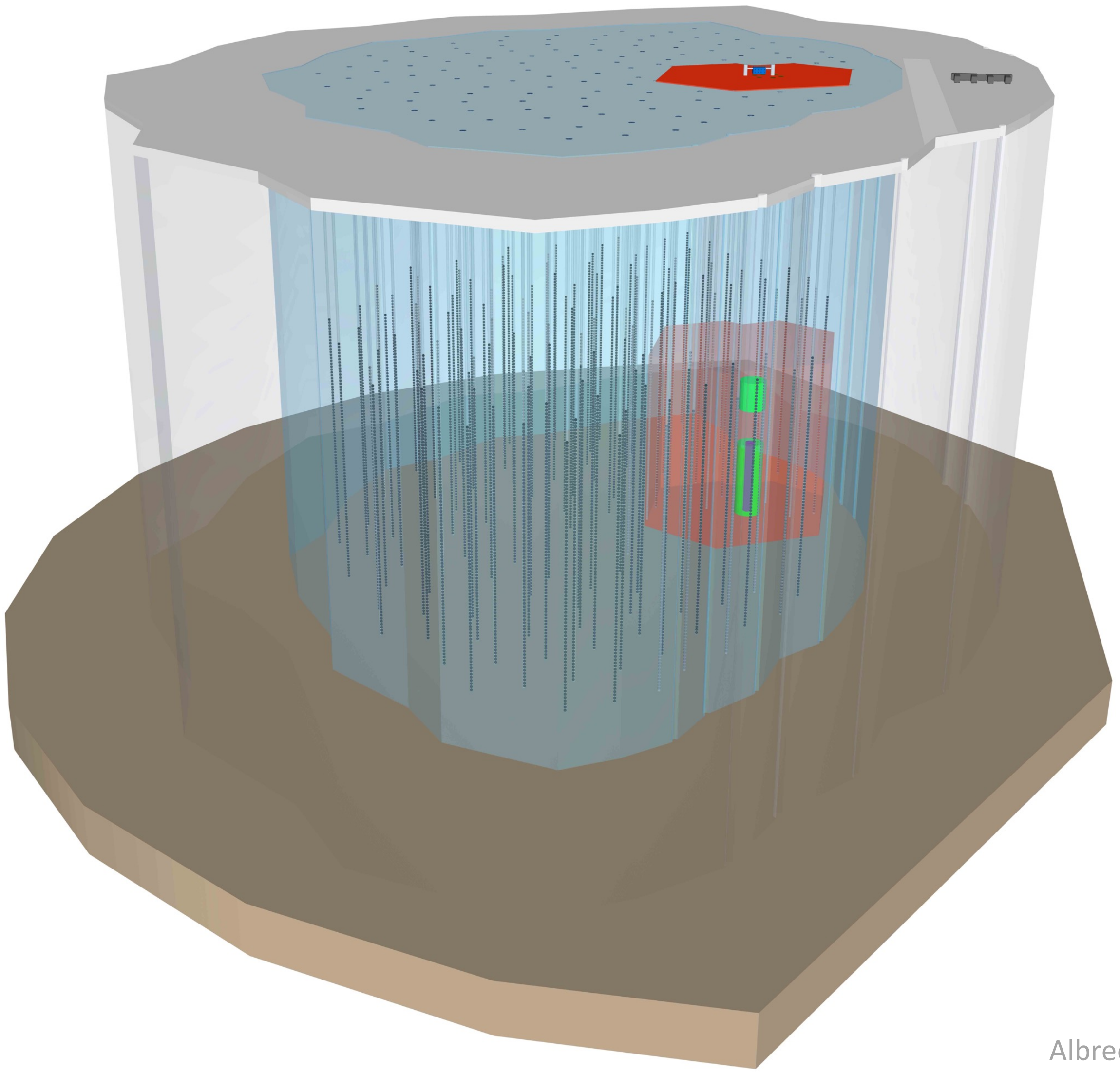


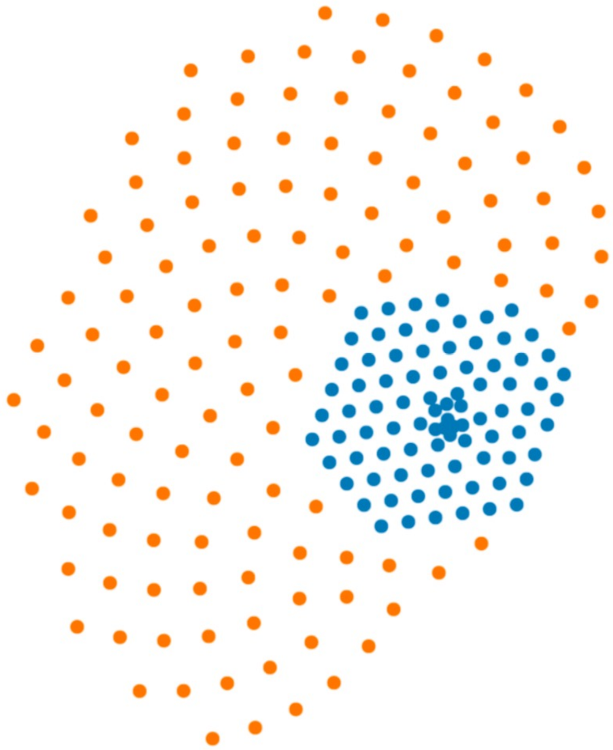
Installation: 2025/26 South Pole season.

The big vision: IceCube-Gen2



IceCube-Gen2: the optical array





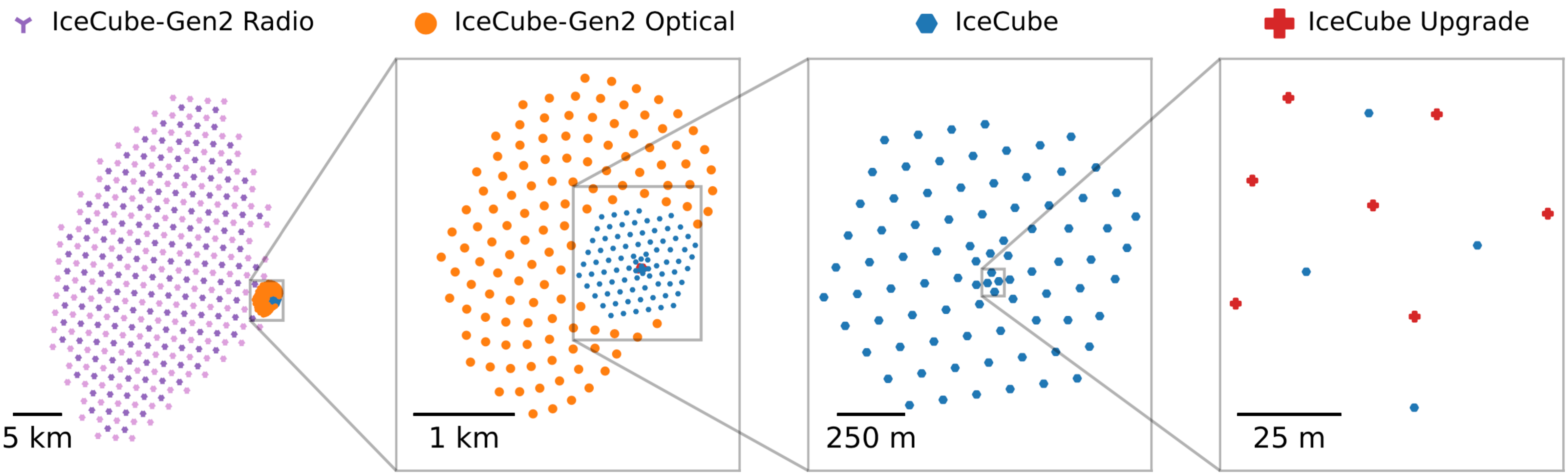
Surface Area: ~6.5km^2 (0.9)
Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km^3

Order of magnitude increase

9600 optical sensors
120 strings

IceCube and IceCube-Gen2 — scales and energie ranges



>10 PeV **> 5 TeV** **>0.5 TeV** **few GeV**

Summary

Neutrinos give us new insights to the high energy Universe.

IceCube has discovered cosmic neutrinos and also the first sources of neutrinos.

One is a supermassive black hole not too far away.

We also have seen the Milky Way - much closer to home.
One more step to understand our place in the Universe.

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.

Thank you very much to our hosts, Prof. Fhon Waraporn and her team, who came for a research visit to Madison this summer.
I and the other three visitors from IceCube are enjoying to support the ThaisCube Workshop.
Thank you also to Chiang Mai University for the support of our scientific collaboration.

Albrecht Karle, UW-Madison

From the South Pole

to the Milky Way

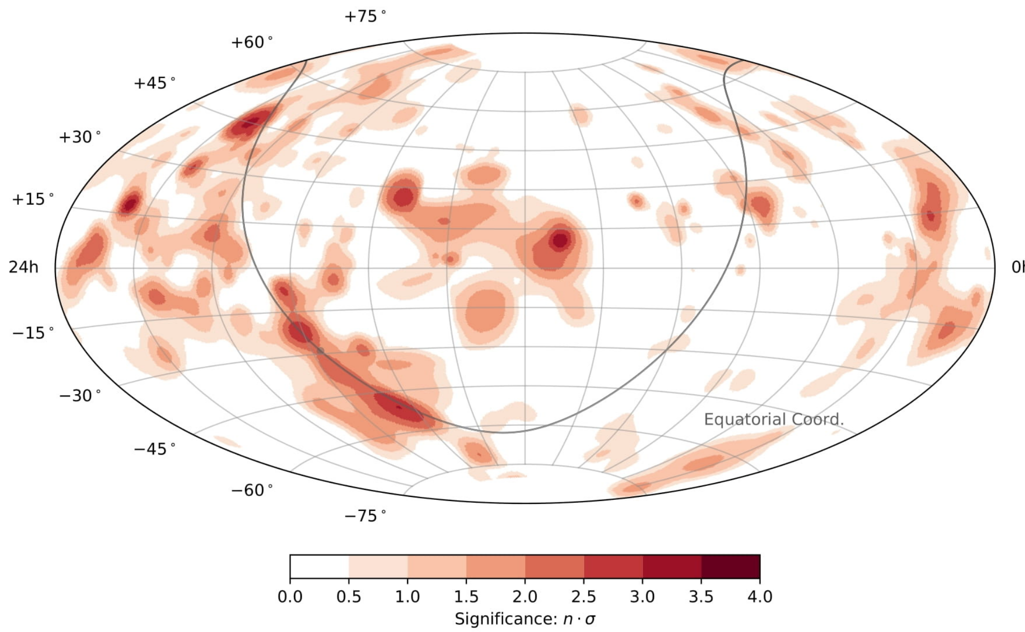
- the journey continues …

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

Thank you and greetings from the penguins!

Questions?

Neutrinos from the Milky Way



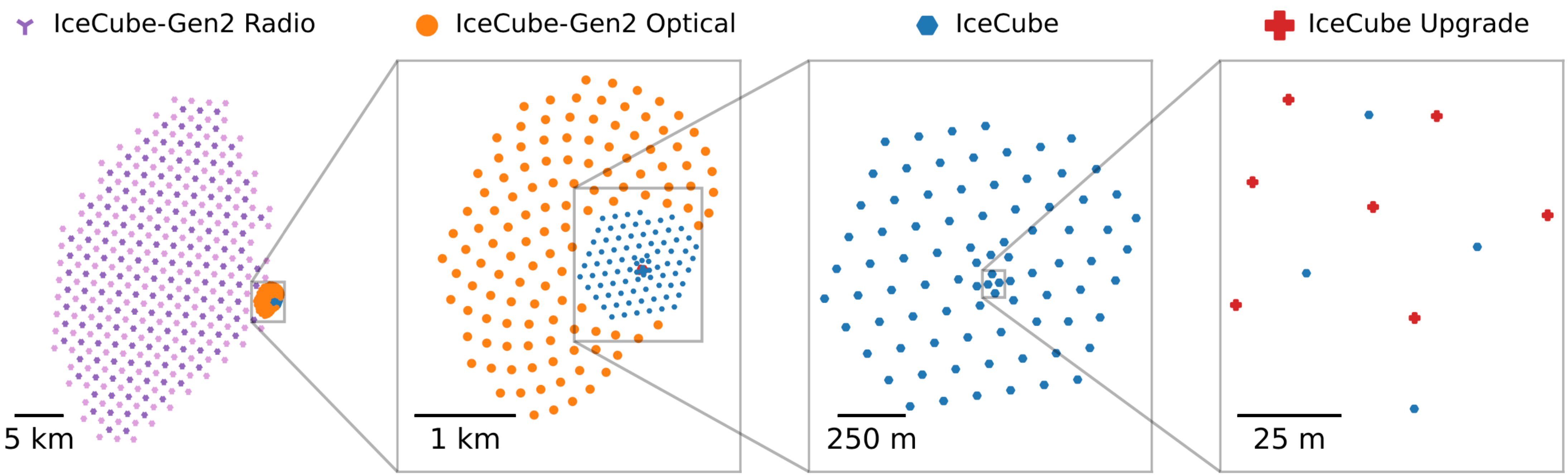
Possible origins for the neutrinos from the Milky Way:

1.) Cosmic Rays collide with other particles in the Milky Way.
There is not much interstellar matter or radiation, but there is some.
Remember what energetic protons do when they collide ....
2.) Galactic particle accelerators produce direct signals when the protons hit a target, eg dust or radiation.

Need more data and analysis to give the answer.

IceCube-Gen2: A wide-band observatory

Optimizing scales for leading sensitivity from 10^9 to 10^{20} eV



>30 PeV

> 3 TeV

>0.5 TeV

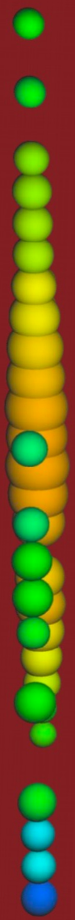
competed in 2011

> GeV

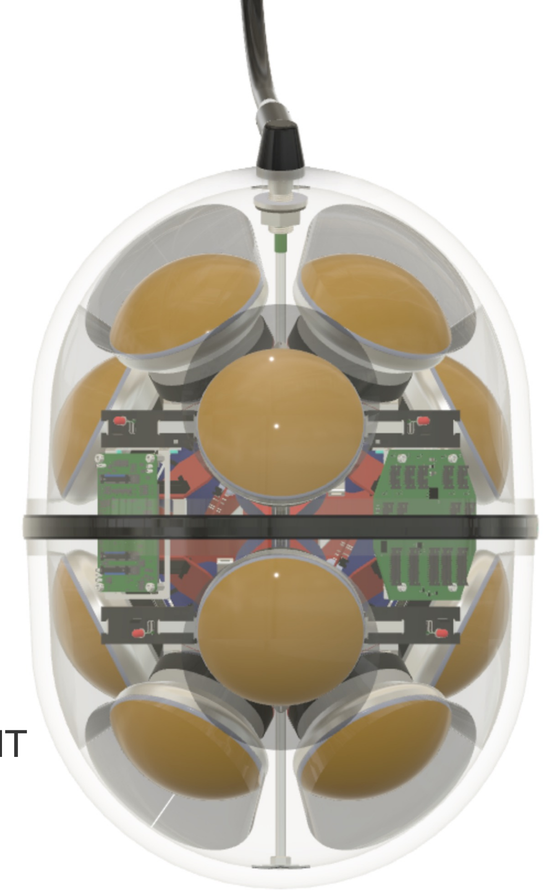
under construction,
deployment in Dec. 2025

Closed Caption box size

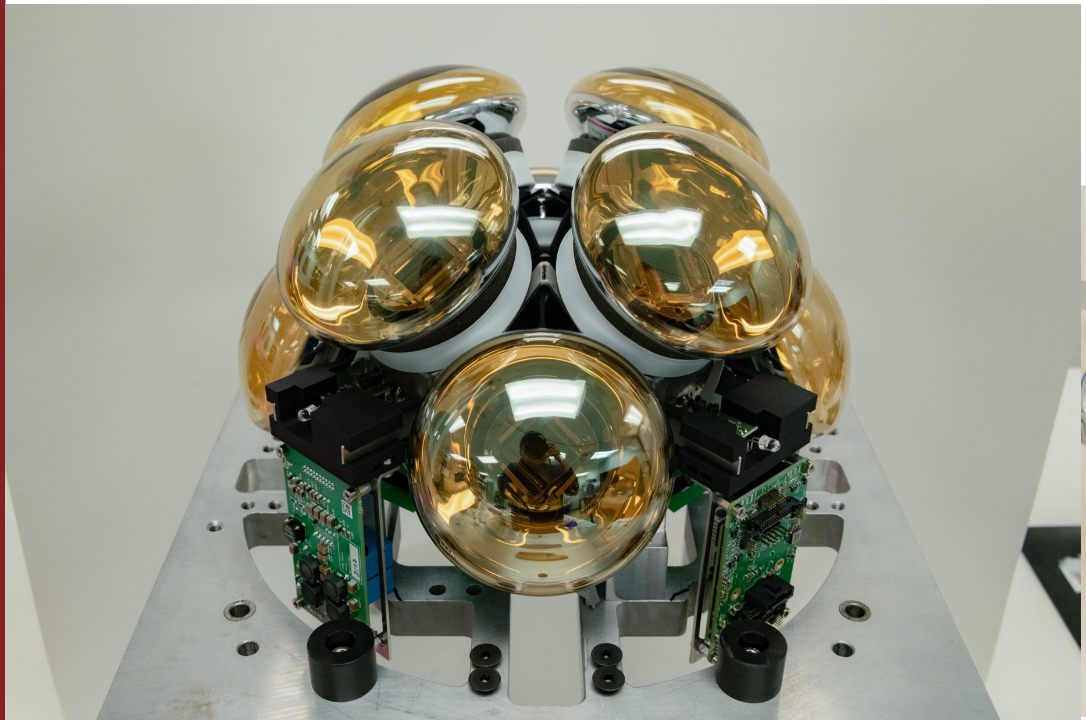
Sensor and Electronics



- **4-inch PMTs developed for IceCube-Gen2**
- **>3 x sensitivity**
- **>100 times dynamic range**
- **Less power**
- **Cost per photoelectron: <1/2 IceCube**



16 or 18 x 4 inch PMT
Diameter: 31 cm



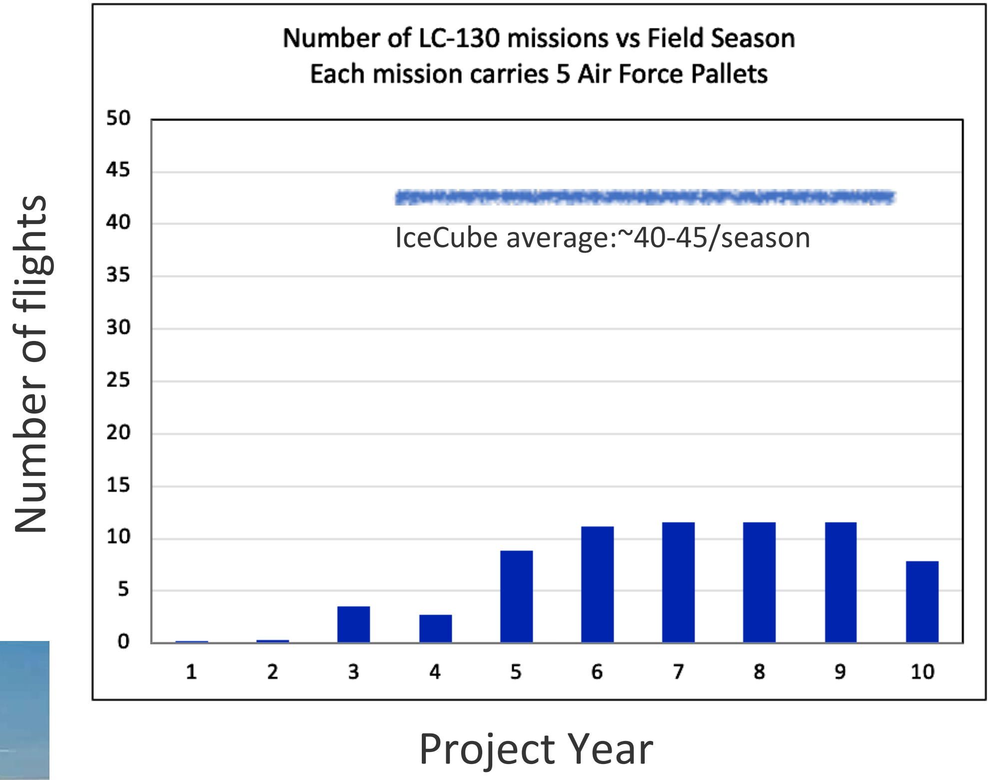
160,000 PMT

Closed Caption box size

Logistical Support Example: LC-130 flights

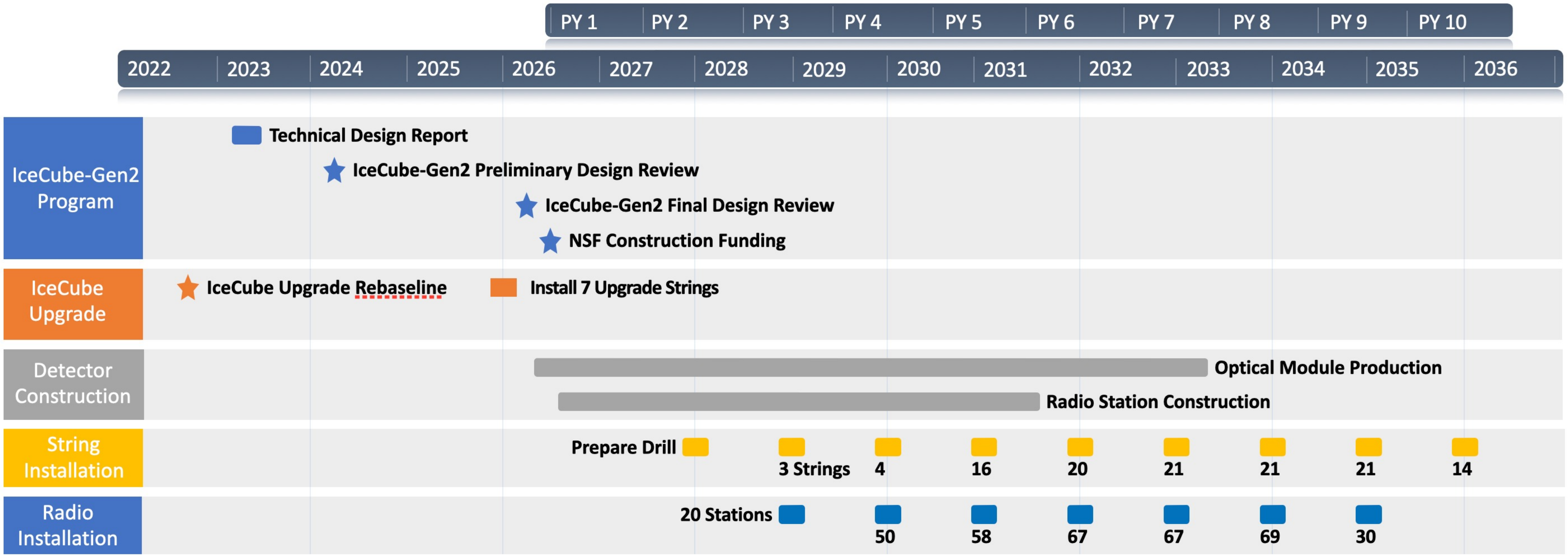
LC 130 aircraft

Overland traverse



Closed Caption box size

Schedule (Technically Driven)



<u>Technically Driven Schedule:</u> These are the dates the Project would be ready to move through the MREFC process

- Preliminary Design Review in 2024, Final Design Review and Construction Funding Start in 2026

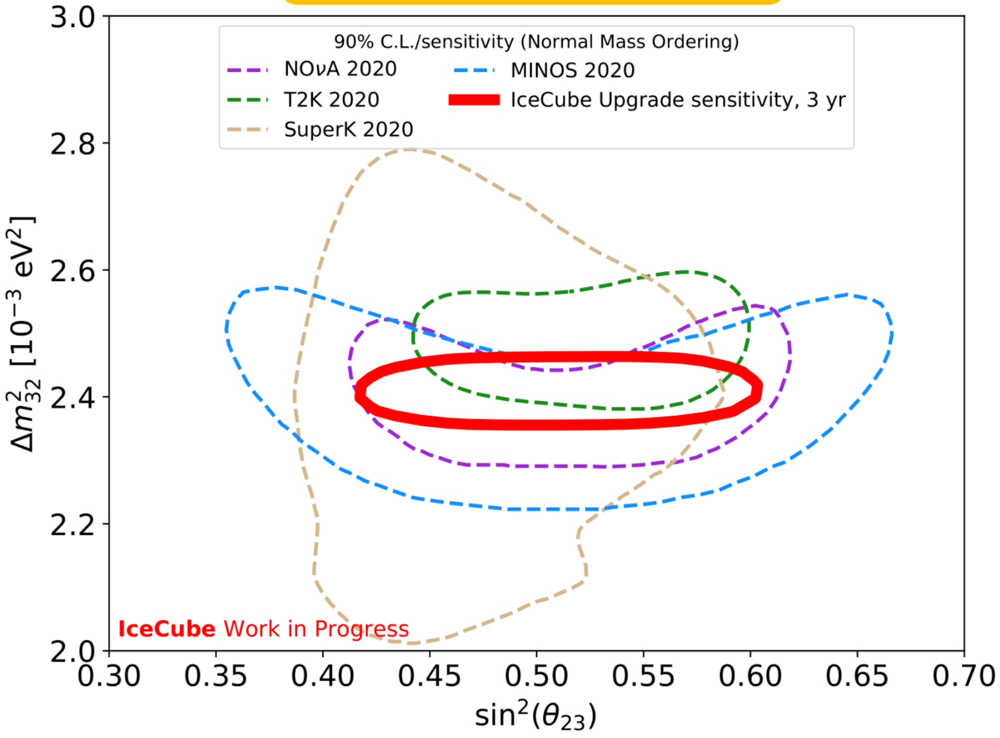
<u>Project Year:</u> Project Year starts with Construction Funding Start

— in our schedule this could be as early as June, 2026

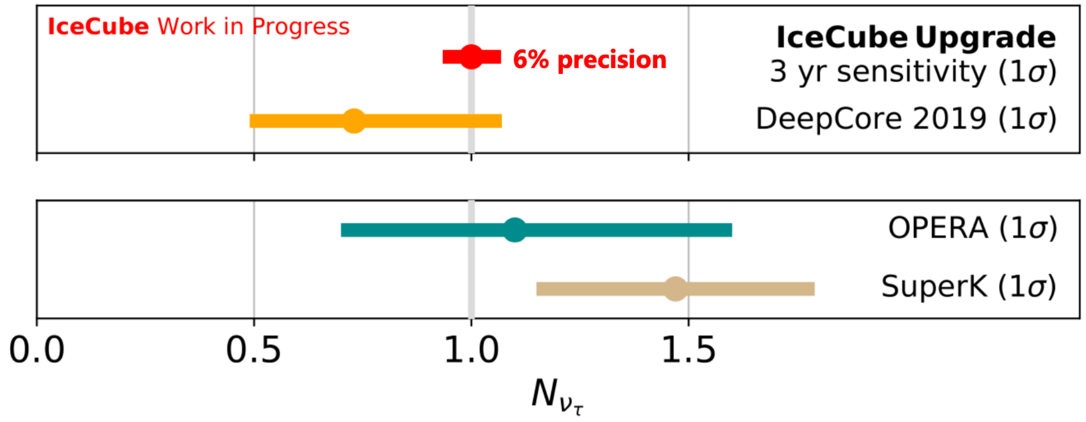
IceCube-Upgrade

IceCube Upgrade sensitivity after only 3 years

ν_μ disappearance



ν_τ appearance

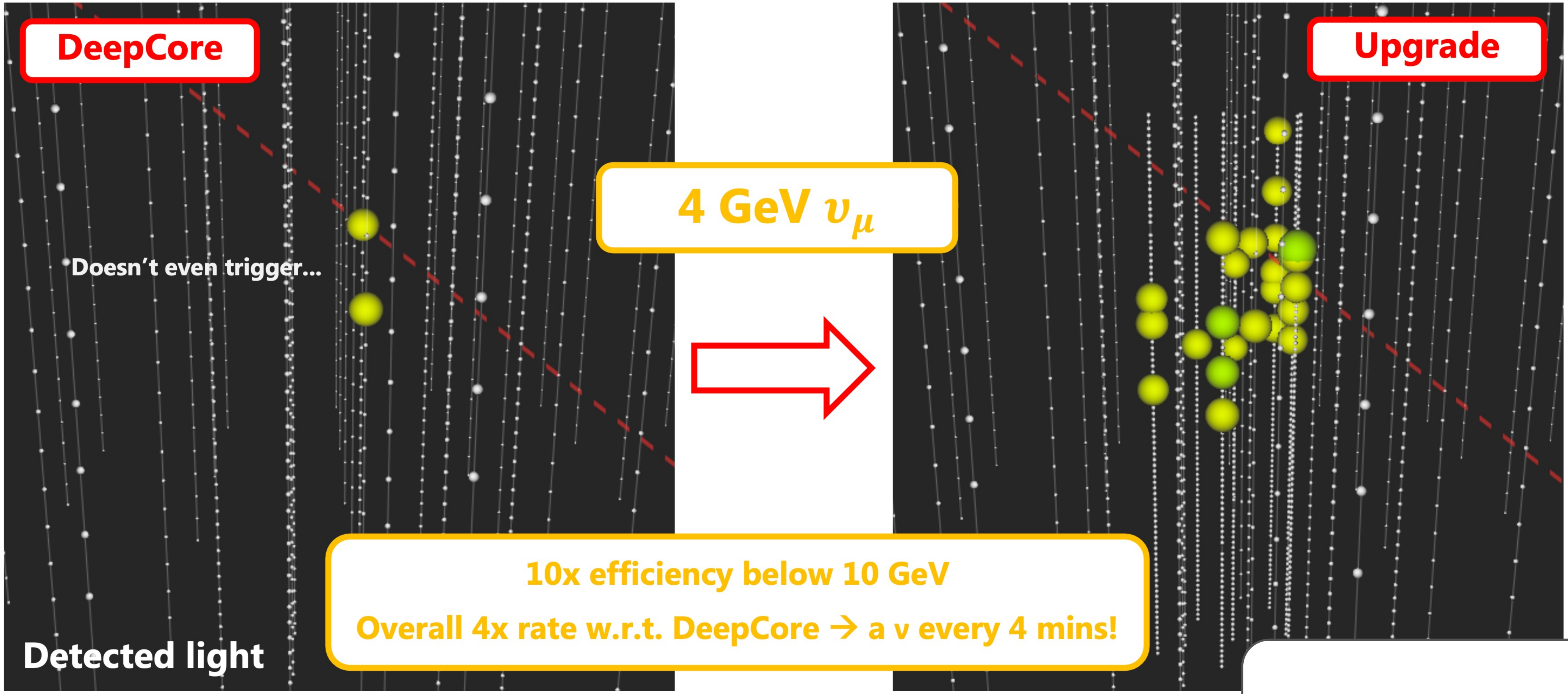


Closed Caption box size

IceCube-Upgrade

Dense instrumentation in 2 Mton core

- Large increase in photocathode density → sensitive down to ~**1 GeV neutrinos**



Closed Caption box size

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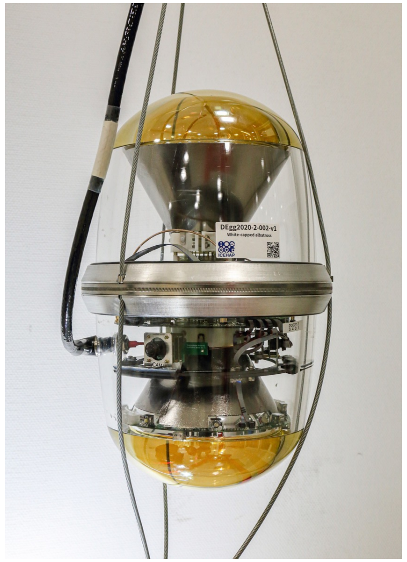

Science example:
Atmospheric tau neutrino appearance