# 2026 Physics Nobel Prize




Steve Boyd / Danny Steeghs
(*it wasn’t awarded to us, unfortunately.)

# Francis Halzen



- Awarded the 2026 Physics Nobel Prize
- Hilldale Professor at the University of Wisconsin
- Principle Investigator and Spokesperson for the IceCube experiment since 2001.



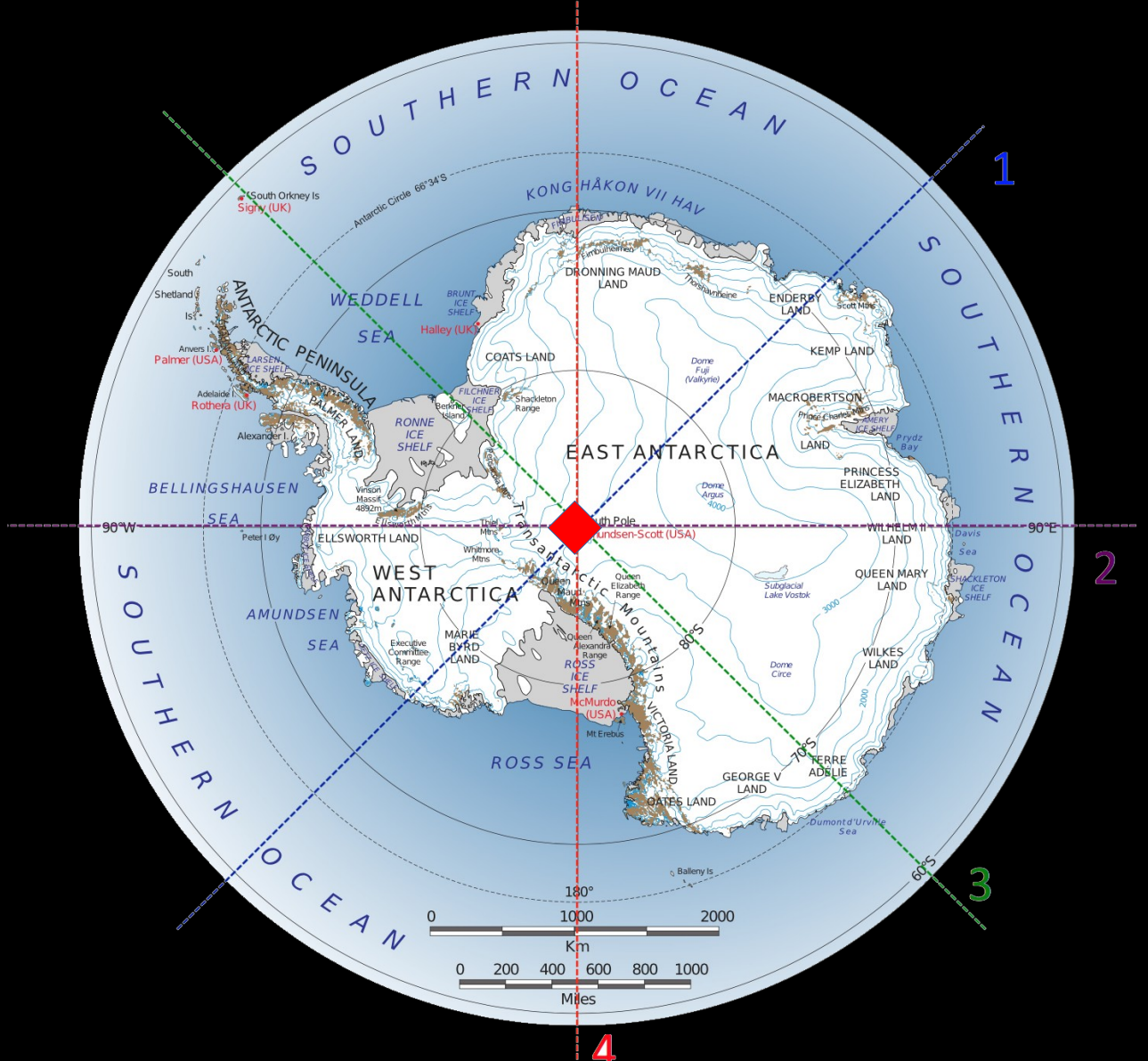
Scientific Background to the Nobel Prize in Physics 2026

# "FOR DECISIVE CONTRIBUTIONS TO THE ICECUBE NEUTRINO OBSERVATORY AND THE DISCOVERY OF HIGH-ENERGY NEUTRINOS OF ASTROPHYSICAL ORIGIN"

The Nobel Committee for Physics

- What is the IceCube optical array?
- Physics results from IceCube.
- What next?




SOUTHERN OCEAN
SOUTHERN OCEAN
SOUTHERN OCEAN
KONG HÅKON VII HAV
Antarctic Circle 66°34'S
South Orkney Is
Signy (UK)
South Shetland Is
Anvers I
Palmer (USA)
Adelaide I
Rothera (UK)
ANTARCTIC PENINSULA
PALMER LAND
LARSEN ICE SHELF
Alexander I
WEDDELL SEA
BRUNT ICE SHELF
Halley (UK)
FILCHNER ICE SHELF
Berkner Island
Shackleton Range
RONNE ICE SHELF
COATS LAND
DRONNING MAUD LAND
Thorshavnfjella
ENDERBY LAND
Scott Mtns
KEMP LAND
Dome Fuji (Valkyrie)
MACROBERTSON LAND
Prince Charles Mtns
AMERY ICE SHELF
Prydz Bay
EAST ANTARCTICA
PRINCESS ELIZABETH LAND
Dome Argus 4000
BELLINGSHAUSEN SEA
Vinson Massif 4892m
Ellsworth Mtns
Thiel Mtns
South Pole
Amundsen-Scott (USA)
90°W
90°E
Peter I Øy
ELLSWORTH LAND
Whitmore Mtns
WEST ANTARCTICA
Transantarctic Mountains
Queen Maud Mts
Queen Elizabeth Range
Subglacial Lake Vostok
3000
WILHELM II LAND
Davis Sea
SHACKLETON ICE SHELF
QUEEN MARY LAND
AMUNDSEN SEA
Executive Committee Range
MARIE BYRD LAND
Queen Alexandra Range
ROSS ICE SHELF
McMurdo (USA)
Mt Erebus
80°S
Dome Circe
2000
WILKES LAND
ROSS SEA
VICTORIA LAND
75°S
TERRE ADÉLIE
GEORGE V LAND
OATES LAND
Dumont d'Urville Sea
Balleny Is
60°S
180°
0 1000 2000
Km
0 200 400 600 800 1000
Miles
1
2
3
4

# IceCube: Exploring the High-Energy Universe

IceCube South Pole Neutrino Observatory

Using neutrinos to answer fundamental questions about the cosmos

NEUTRINOS REVEAL A DIFFERENT UNIVERSE

## 1. Identify the sources of high-energy cosmic neutrinos

Find and study astrophysical accelerators of cosmic rays, such as:

- Active galactic nuclei (AGN)
- Gamma-ray bursts (GRBs)
- Star-forming galaxies
- Supernova remnants
- Other extreme environments

*Neutrinos point back to their sources, carrying unambiguous information about the most energetic processes in the Universe.*

## 3. Search for new physics beyond the Standard Model

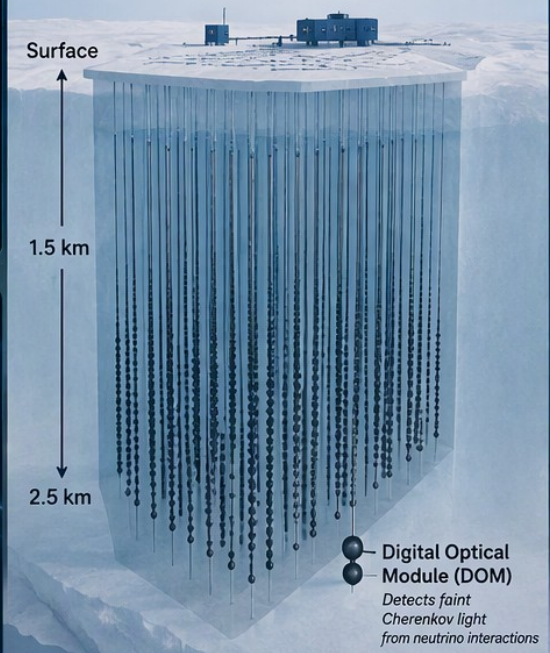
Look for signals of:

- Dark matter (e.g. WIMP annihilation)
- Neutrino decay or non-standard interactions
- Magnetic monopoles
- Lorentz invariance violation
- Extra dimensions and other exotic phenomena

*IceCube tests fundamental physics at the highest energies and in a unique environment.*

## IceCube at the South Pole

A cubic kilometre of ultra-pure ice instrumented with 5,160 optical sensors to detect Cherenkov light from neutrino interactions




## 2. Understand the origin of cosmic rays

Use neutrinos to probe the acceleration and interaction mechanisms of cosmic rays and to determine where they are produced.

*Neutrinos help solve the century-old mystery of where cosmic rays come from and how they reach such high energies.*

## 4. Study fundamental properties of neutrinos

Measure neutrino:

- Flavour composition ($\nu_e$, $\nu_\mu$, $\nu_\tau$)
- Energy spectrum
- Directional distribution
- Neutrino-nucleon cross-sections at unprecedented energies

*IceCube observes neutrinos over a wide energy range, from ~GeV to beyond 10 PeV, probing new regimes of neutrino physics.*

## 5. Conduct multi-messenger astronomy



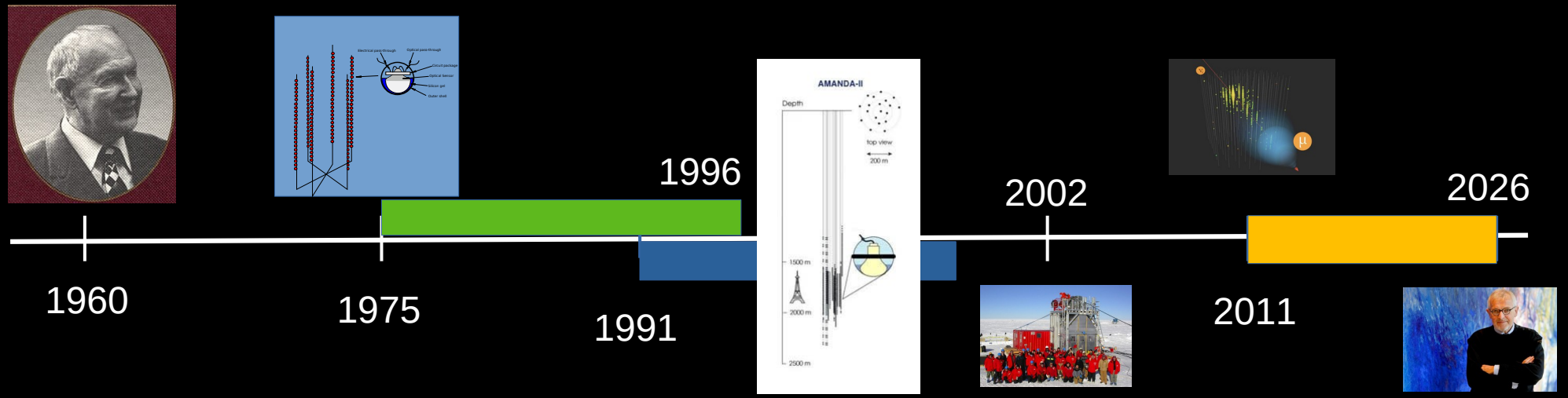

Combine neutrino observations with photons, gravitational waves and cosmic rays to obtain a complete picture of cosmic events.

*Neutrinos are a key messenger in the multi-messenger view of the Universe.*

A CLEARER VIEW OF A MORE ENERGETIC UNIVERSE

FROM THE SOUTH POLE TO NEW DISCOVERIES

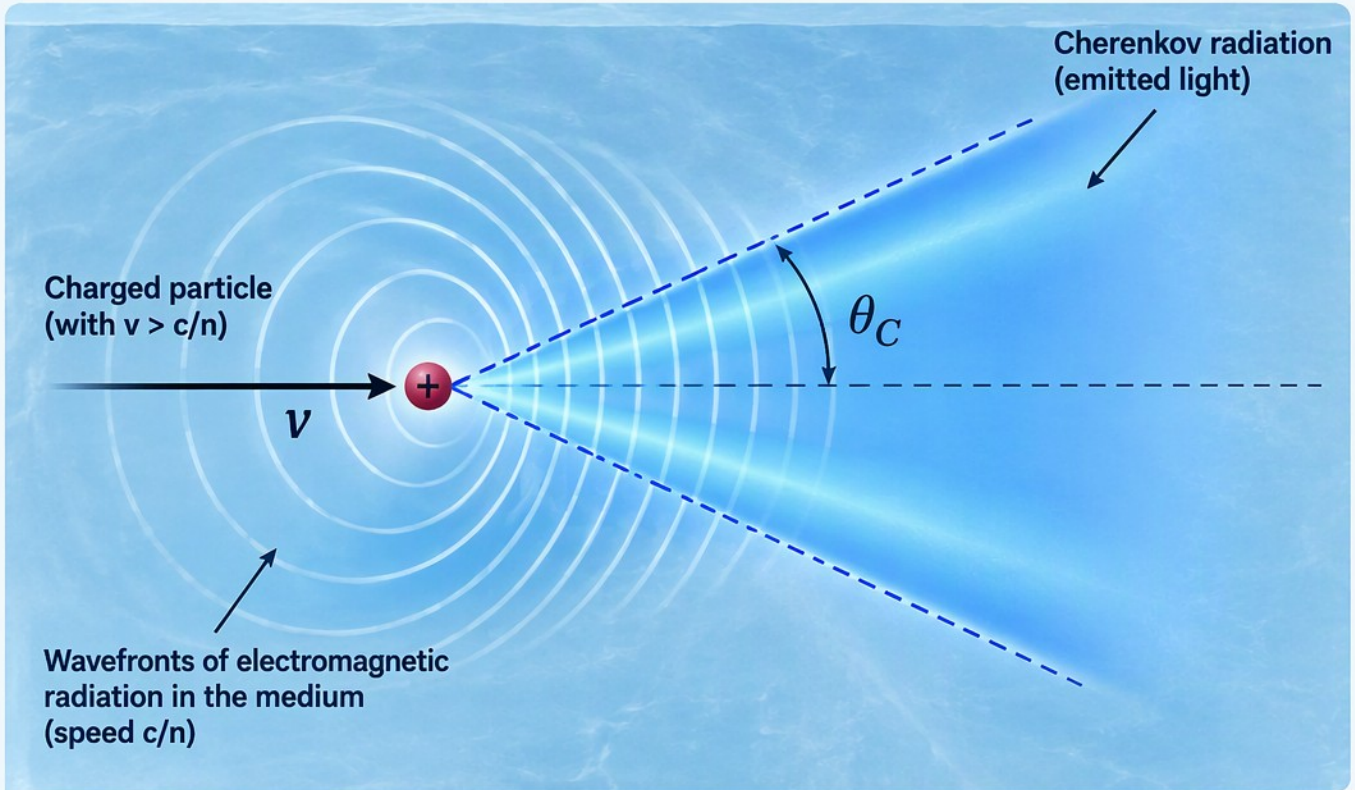
# IceCube History




1. DUMAND : Deep Underwater Muon And Neutrino Detector
2. AMANDA :  Antarctic Muon And Neutrino Detector Array

# Physics Principle : Cerenkov Radiation

A charged particle moving through a medium faster than the speed of light in that medium emits a cone of coherent electromagnetic radiation, called Cherenkov radiation.




**Cherenkov angle**

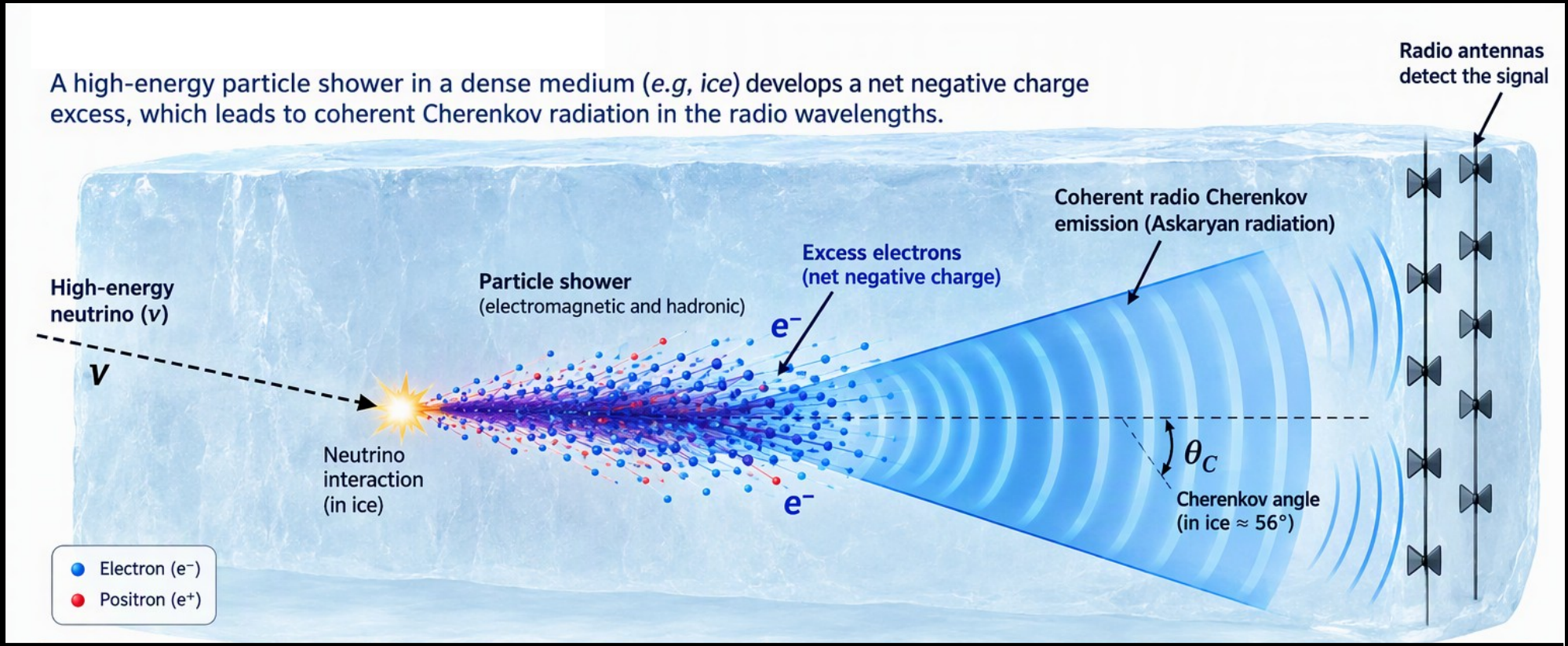
$$\cos\theta_C = \frac{1}{n\beta}$$

| | |
|---|---|
| $n$ | refractive index of the medium |
| $\beta = v/c$ | particle speed in units of $c$ |
| $\theta_C$ | Cherenkov angle (exists only if $\beta > 1/n$) |

**Condition for Cherenkov radiation:**

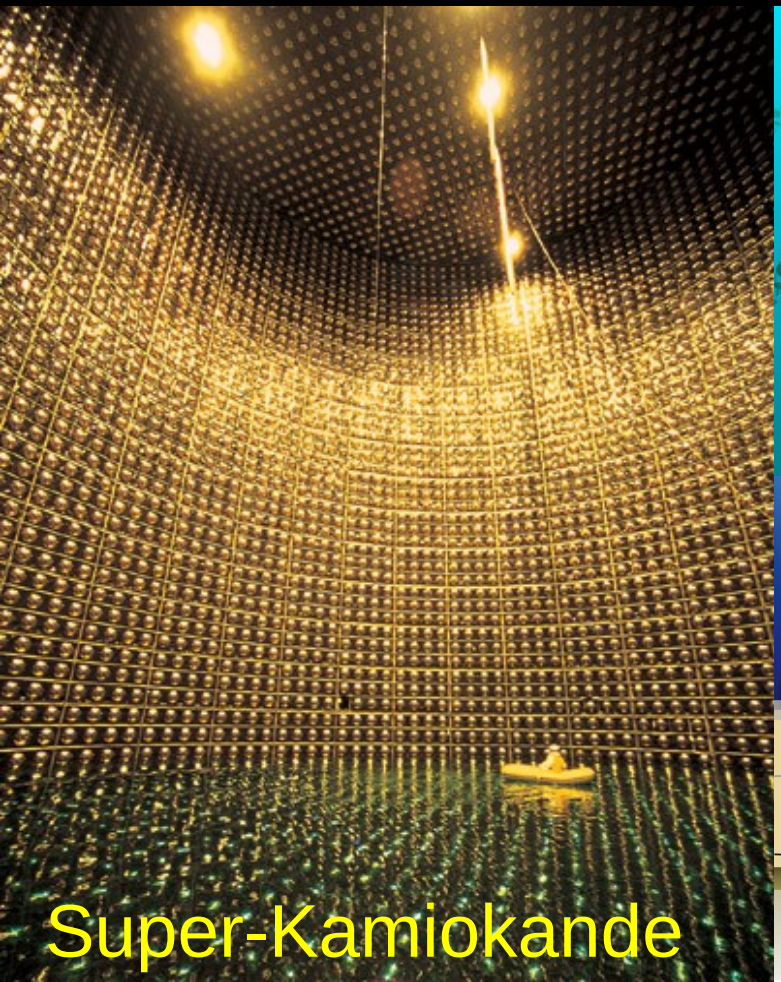
$$v > c/n$$

# Physics Principle : Askaryan Effect



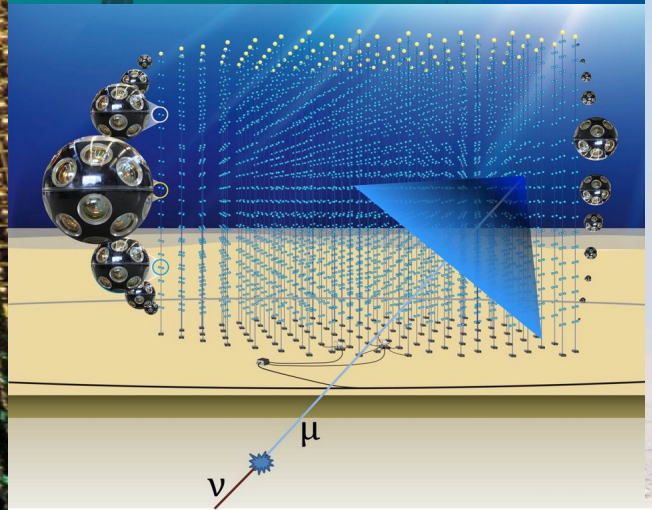

- Attenuation length of radio waves in ice ~ 1 km vs Cerenkov radiation ~ 100 m

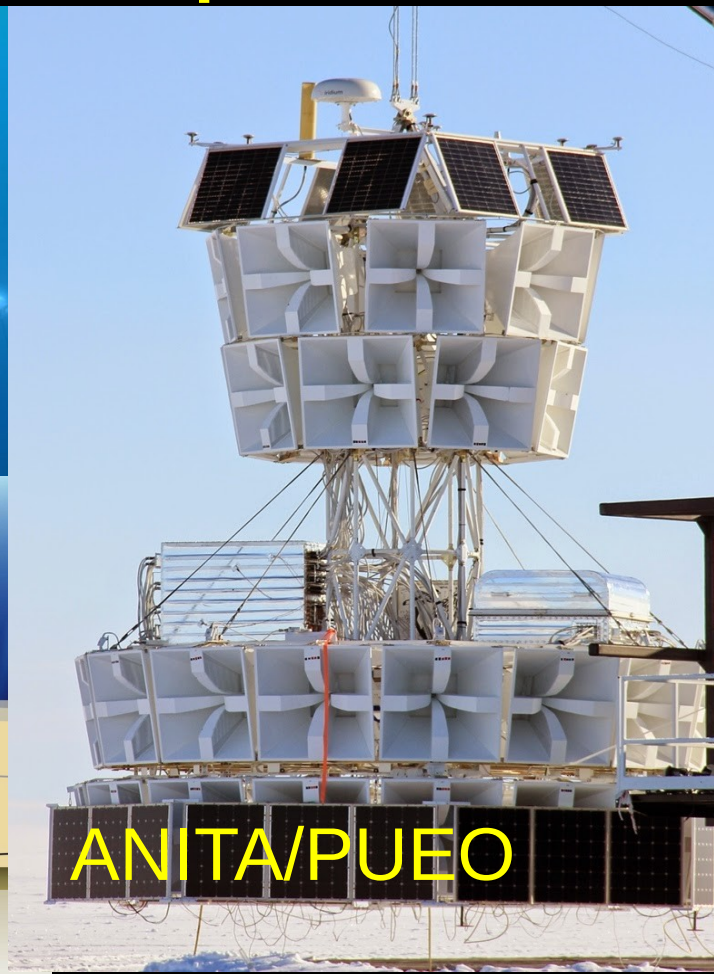
# IceCube : Working Principles

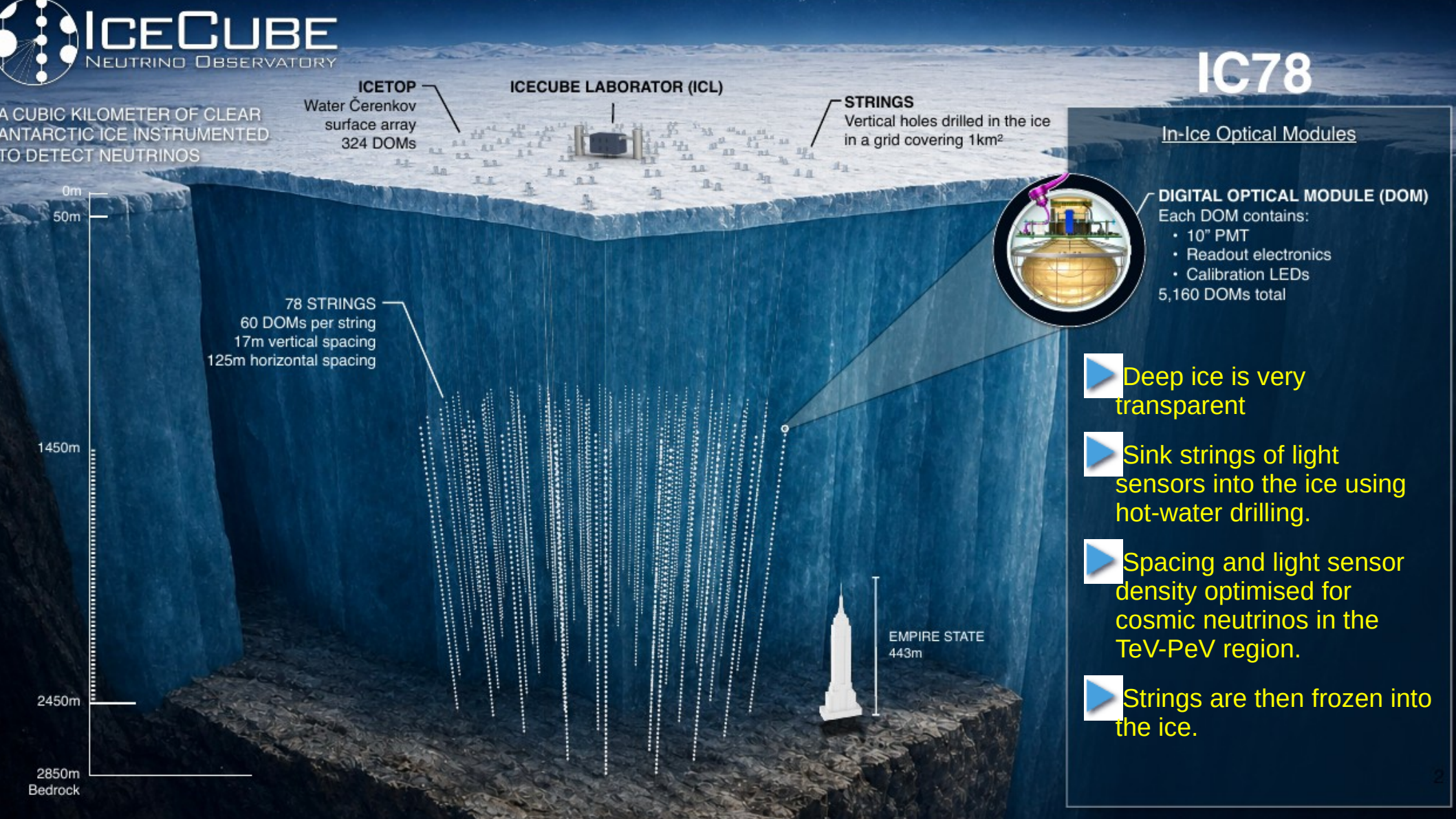


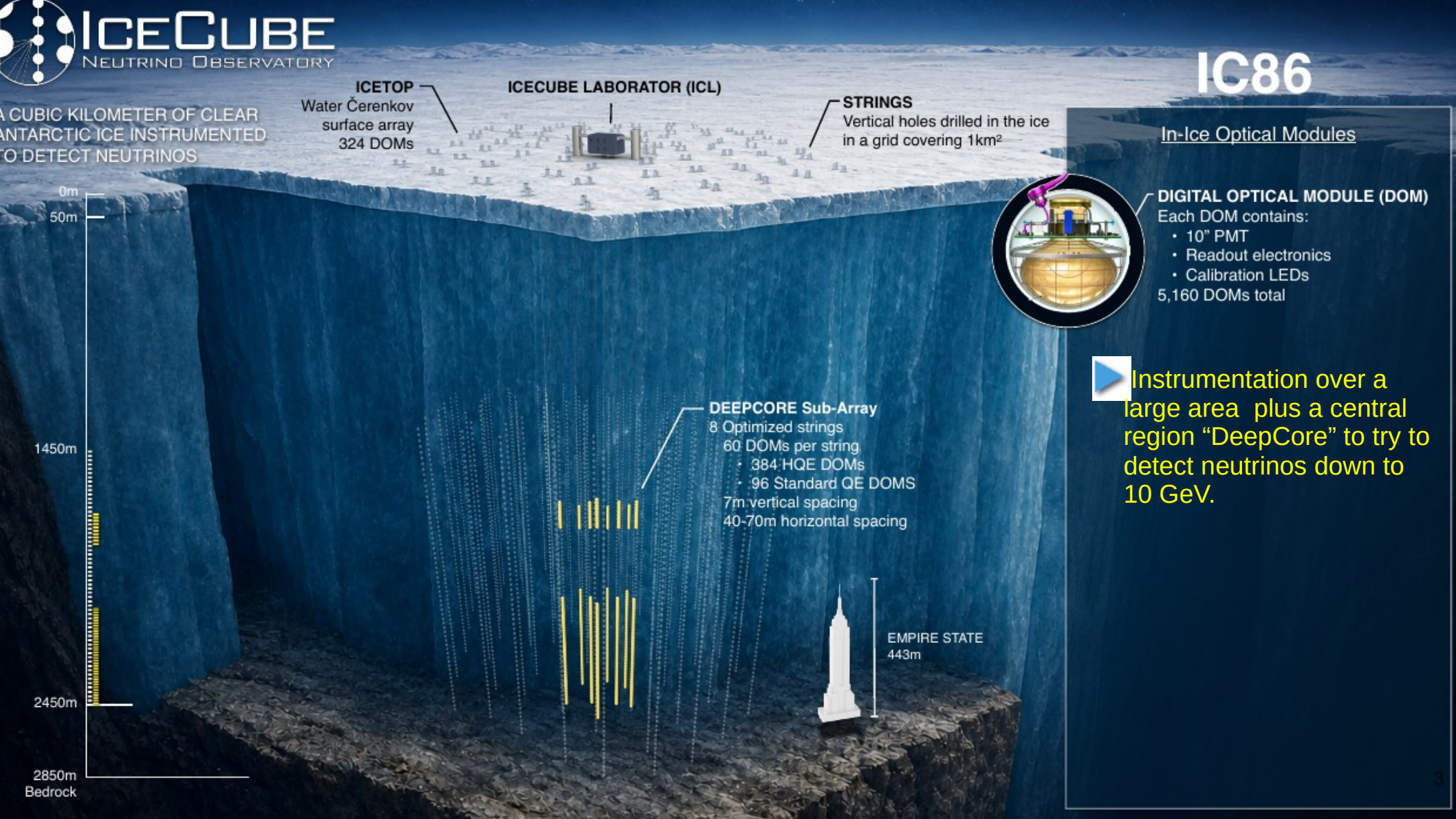






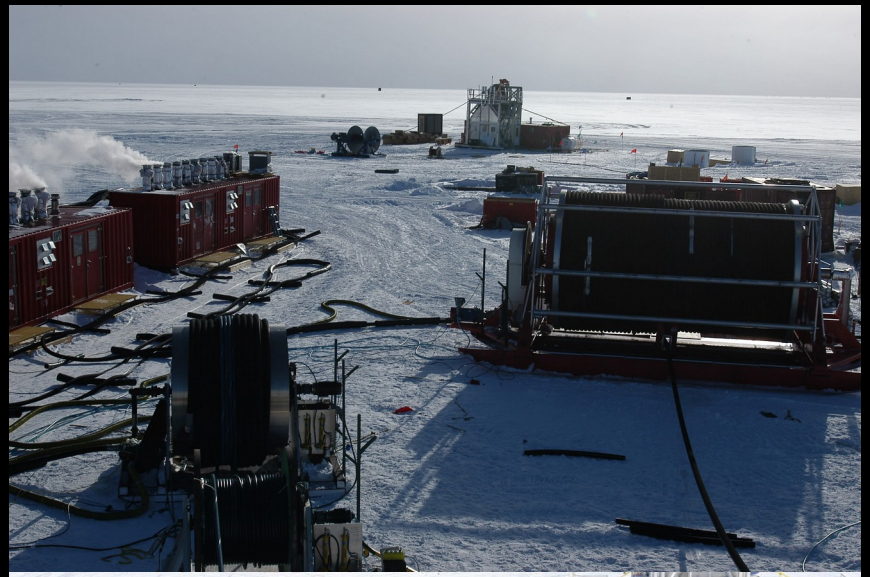




ICECUBE
NEUTRINO OBSERVATORY
A CUBIC KILOMETER OF CLEAR
ANTARCTIC ICE INSTRUMENTED
TO DETECT NEUTRINOS
ICETOP
Water Čerenkov
surface array
324 DOMs
ICECUBE LABORATOR (ICL)
STRINGS
Vertical holes drilled in the ice
in a grid covering 1km²
IC78
In-Ice Optical Modules
DIGITAL OPTICAL MODULE (DOM)
Each DOM contains:
• 10" PMT
• Readout electronics
• Calibration LEDs
5,160 DOMs total
0m
50m
1450m
2450m
2850m
Bedrock
78 STRINGS
60 DOMs per string
17m vertical spacing
125m horizontal spacing
EMPIRE STATE
443m
Deep ice is very transparent
Sink strings of light sensors into the ice using hot-water drilling.
Spacing and light sensor density optimised for cosmic neutrinos in the TeV-PeV region.
Strings are then frozen into the ice.

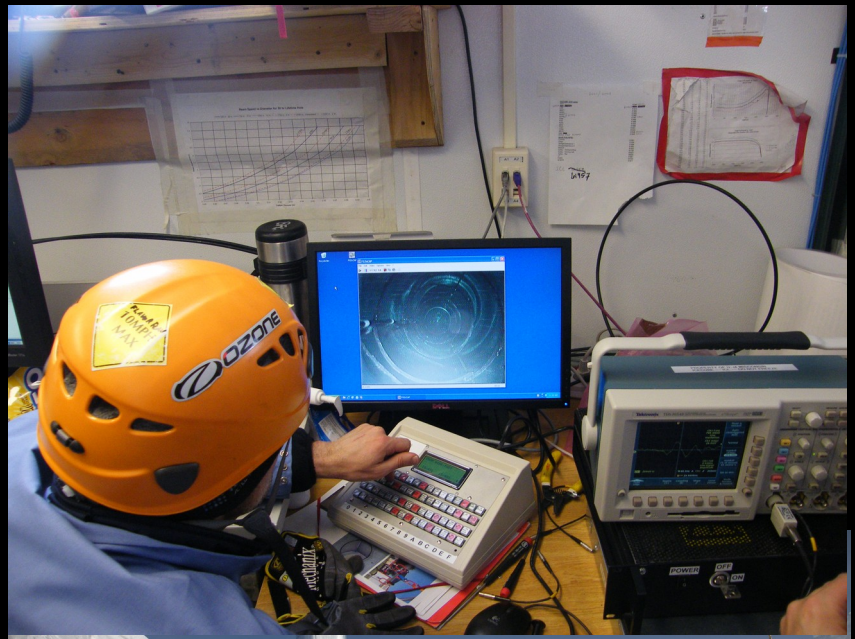

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In-Ice Optical Modules
DIGITAL OPTICAL MODULE (DOM)
Each DOM contains:
• 10" PMT
• Readout electronics
• Calibration LEDs
5,160 DOMs total
Instrumentation over a large area plus a central region "DeepCore" to try to detect neutrinos down to 10 GeV.
0m
50m
1450m
2450m
2850m
Bedrock
DEEPCORE Sub-Array
8 Optimized strings
60 DOMs per string
• 384 HQE DOMs
• 96 Standard QE DOMS
7m vertical spacing
40-70m horizontal spacing
EMPIRE STATE
443m

# Construction Challenges

- Construction could only happen during the Austral summer
- Ice drilling proved more difficult than expected. The top 50m is compacted snow, rather than ice, which required a different drilling solution than the ice.
- Holes would refreeze within 12 hours so an entire string had to be deployed before it was frozen-in, potentially in the wrong location or pointing in the wrong direction.
- Cabling : all signal, power and fibre cables have to be built for the cold and for pressure (if frozen in the ice holes)
- Logistics – there isn't a B&Q just down the road.









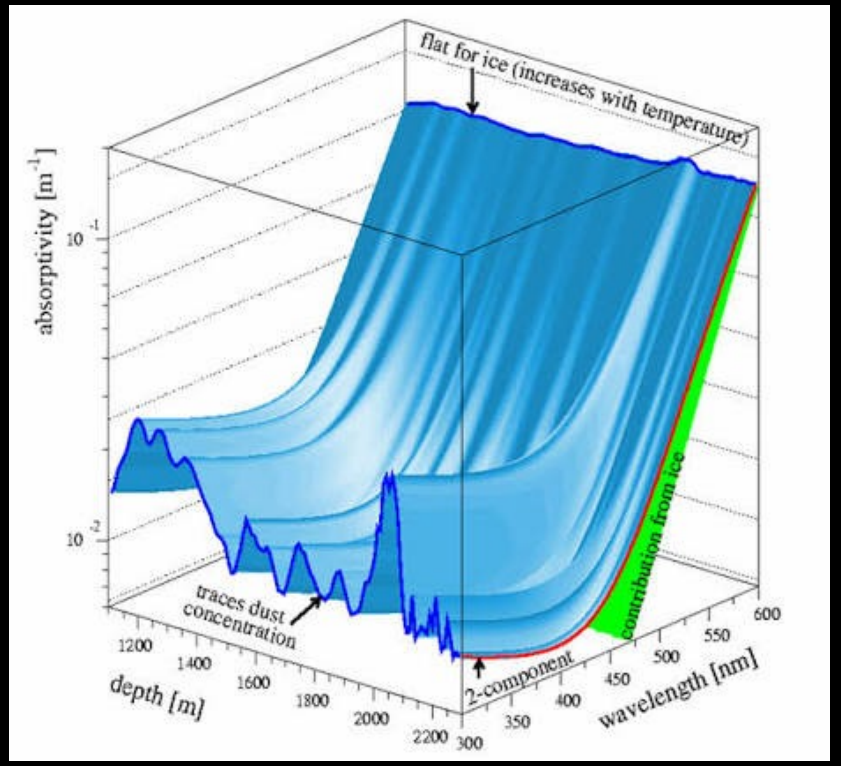

# Operational Challenges

- Winter isolation – skeleton crew (2) were effectively stranded from Feb to Oct. Everything needs to be stored over winter (e.g. fuel). Strict overall power budget.
- DOMs are frozen in and inaccessible. Repairs are not possible, so they had to be designed with extreme redundancy.
- No direct ethernet connection to the rest of the world. Data transfer relies on satellites with significant bottlenecks – data filtering reduction has to be done onsite with signficant onsite storage.
- Precision timing – GPS failure could halt the entire experiment.
- Frequent power interruptions when generators are services. IceCube can run without generators for only 10 minutes.

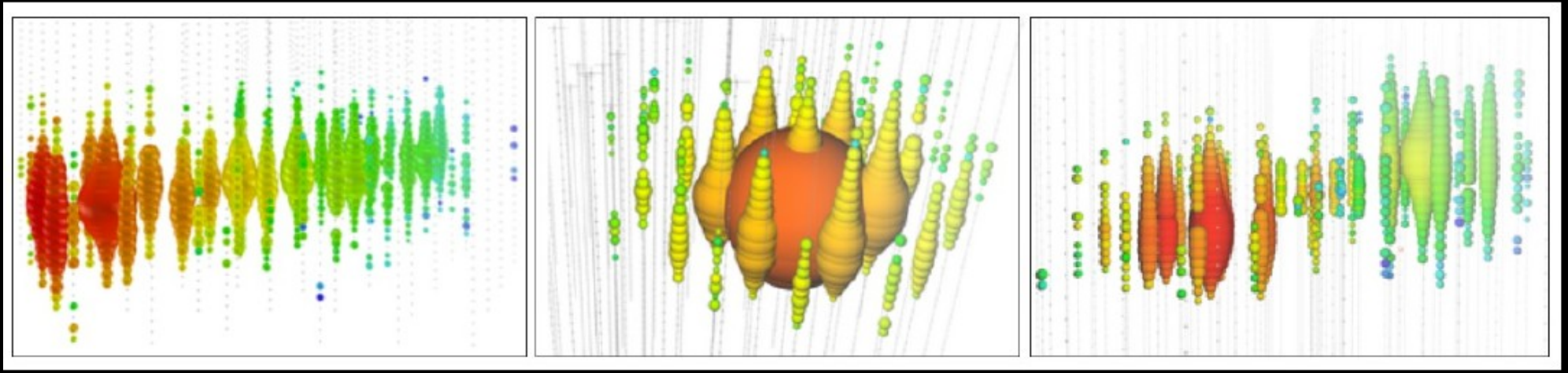
# Analysis Challenges

This sort of detector relies of precise understanding of light propagation in and around DOMS.

- Shadowing from other DOMs
- DOM hole ice has different properties
- Tilted dust/ash layers in the ice
- Bubbles in the ice
  - lead to depth variations in light scattering, and attenuation
- Ice flow changes the relative location of the DOMs over time.
- Ice is birefringent – different optical response in the direction of ice flow than in the direction transverse to flow.



# Neutrino Detection in IceCube



## Track

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

## Cascade

$\nu_e + N \rightarrow e + X$

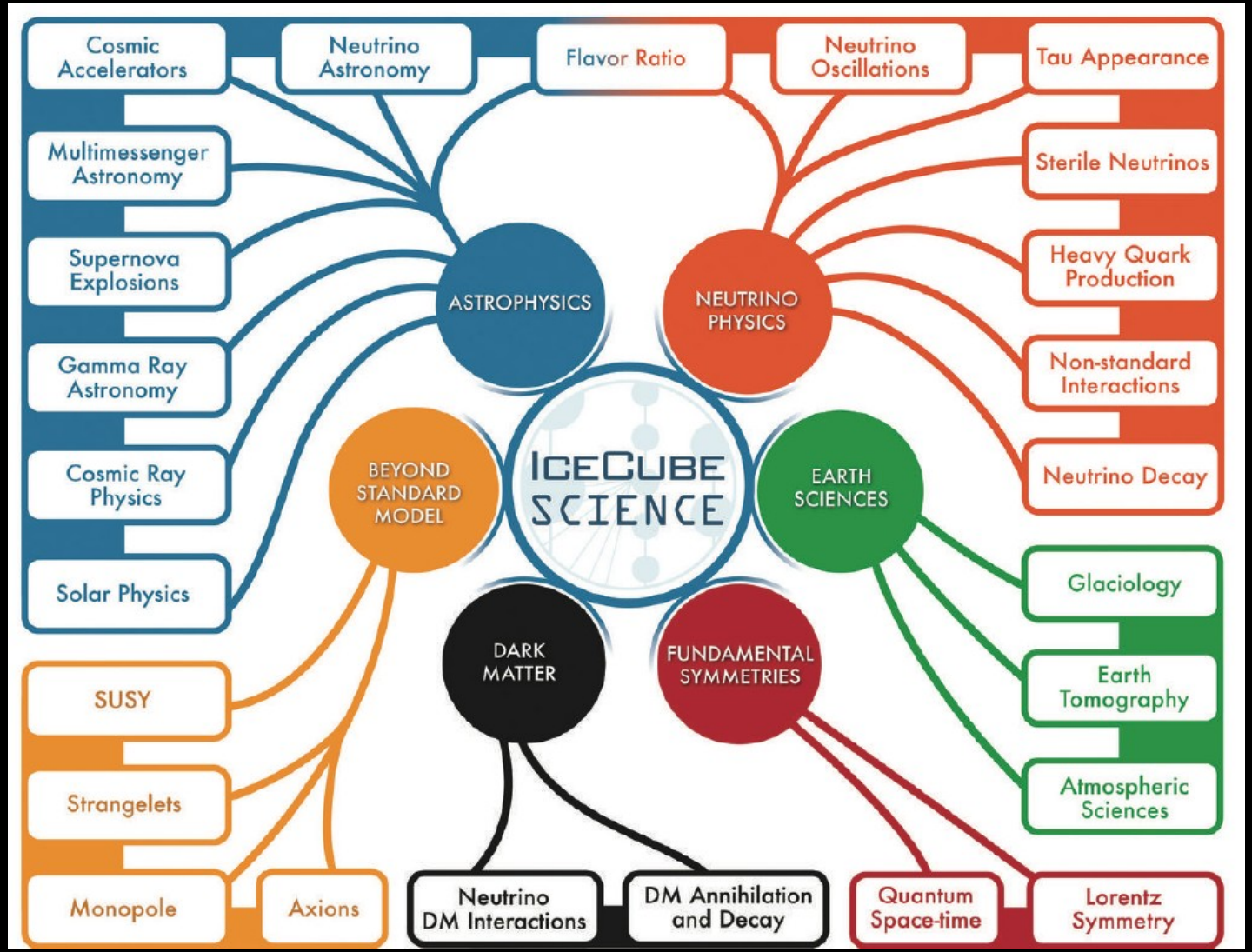
$\nu_\tau + N \rightarrow \tau + X$

$\nu_X + N \rightarrow \nu_X + X$

## Double Bang

$\nu_\tau + N \rightarrow \tau + X$

$\tau \rightarrow X'$


ICECUBE SCIENCE
ASTROPHYSICS
NEUTRINO PHYSICS
BEYOND STANDARD MODEL
EARTH SCIENCES
DARK MATTER
FUNDAMENTAL SYMMETRIES
Cosmic Accelerators
Neutrino Astronomy
Multimessenger Astronomy
Supernova Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
Neutrino Decay
Glaciology
Earth Tomography
Atmospheric Sciences
SUSY
Strangelets
Monopole
Axions
Neutrino DM Interactions
DM Annihilation and Decay
Quantum Space-time
Lorentz Symmetry

# Physics Results

# Messengers

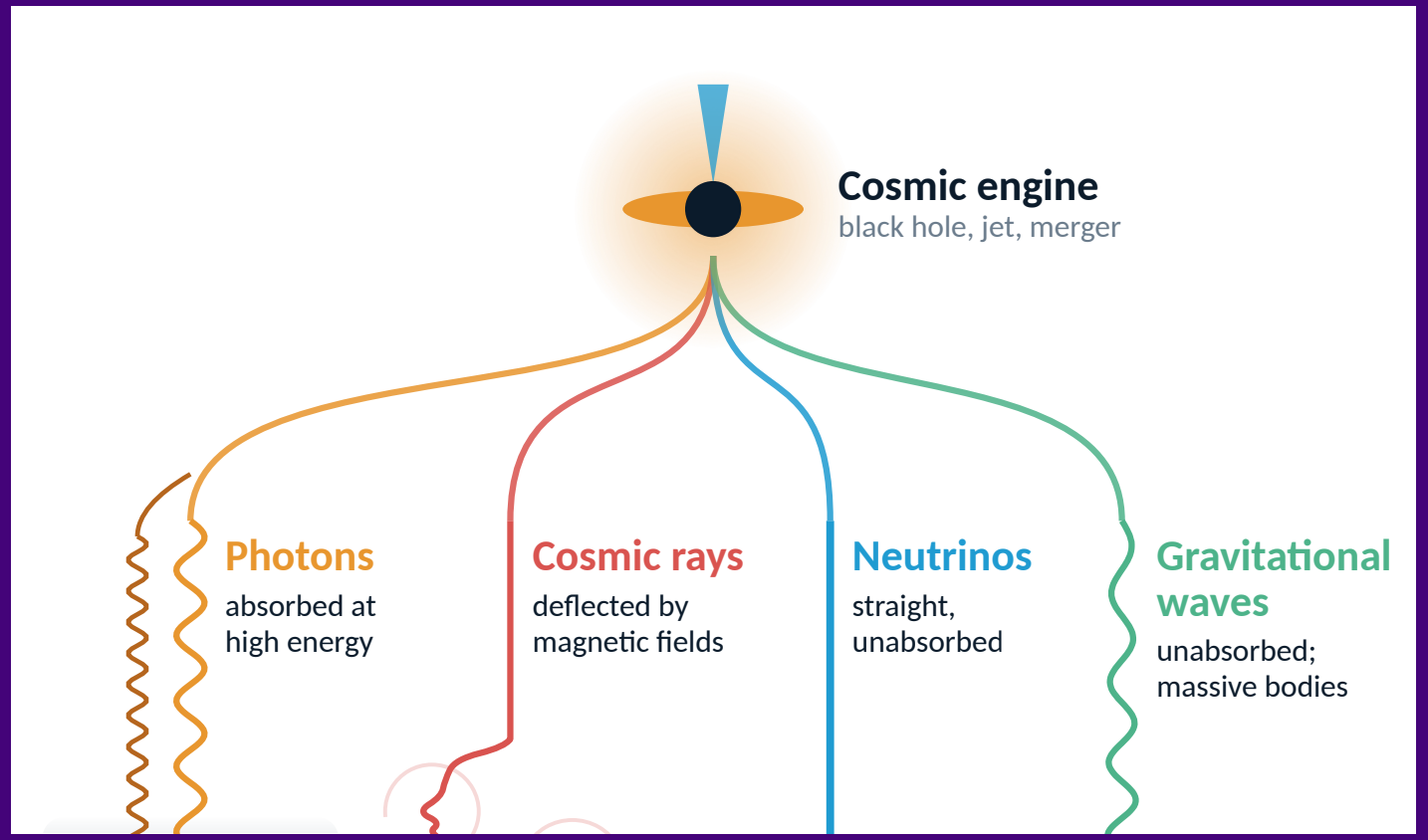
Multi-messenger astrophysics involves complementary carriers

**Photons**

**Protons (hadronic)**
**Electrons (leptonic)**
**…**

**Neutrinos**

**Gravitational Waves**




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# Messengers

Multi-messenger astrophysics involves complementary carriers

**Photons** ; can be absorbed, scattered, re-emitted (opacity)

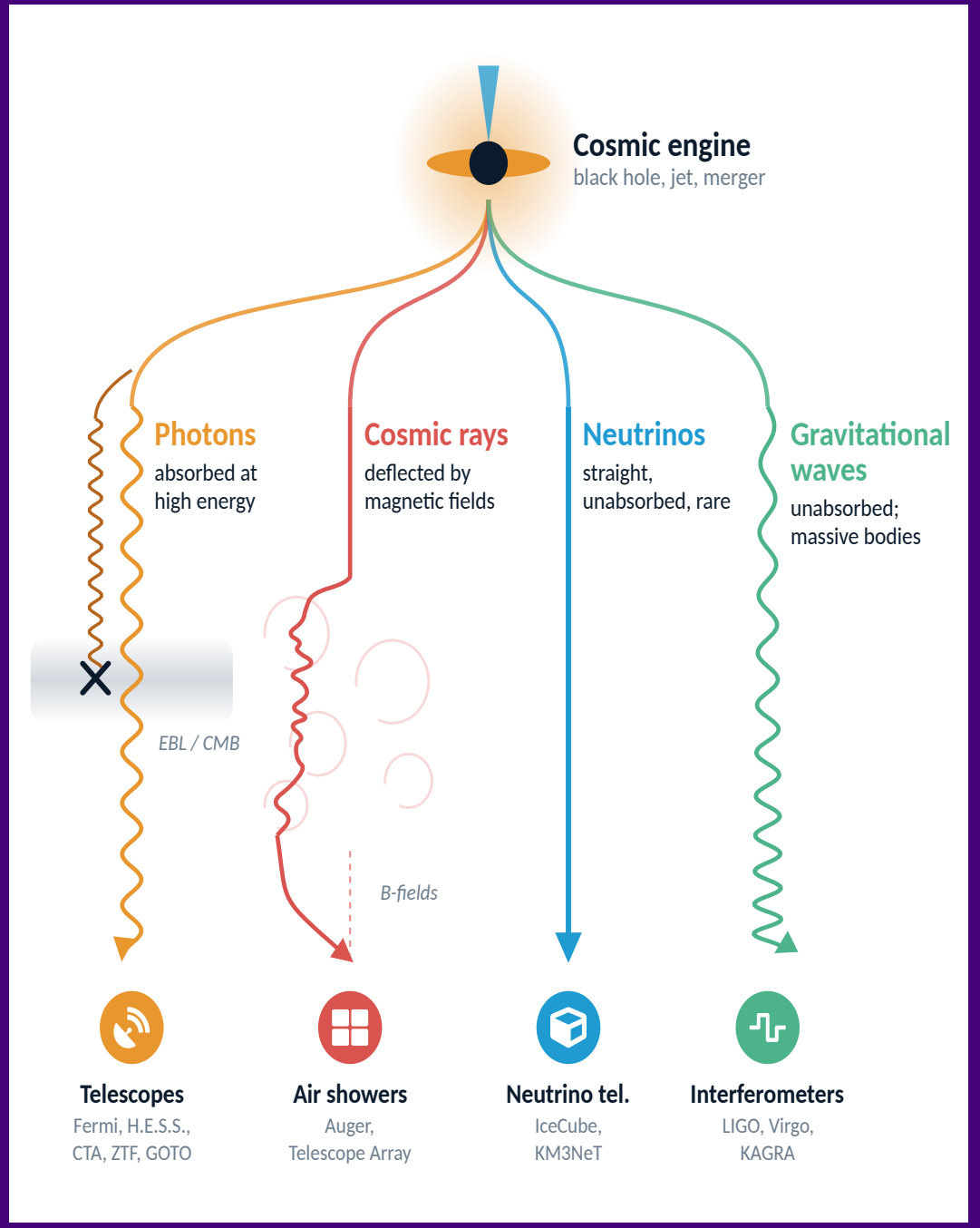
**Protons (hadronic)** ; many interactions, deflections (charged)
**Electrons (leptonic)** ; ditto, strong role in radiation fields
…

**Neutrinos** ; trace source locations (neutral), very low interaction

**Gravitational Waves** ; complementary (traces bulk motion)

PS: photons and neutrinos outnumber everything else by a lot

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# Messengers are coupled

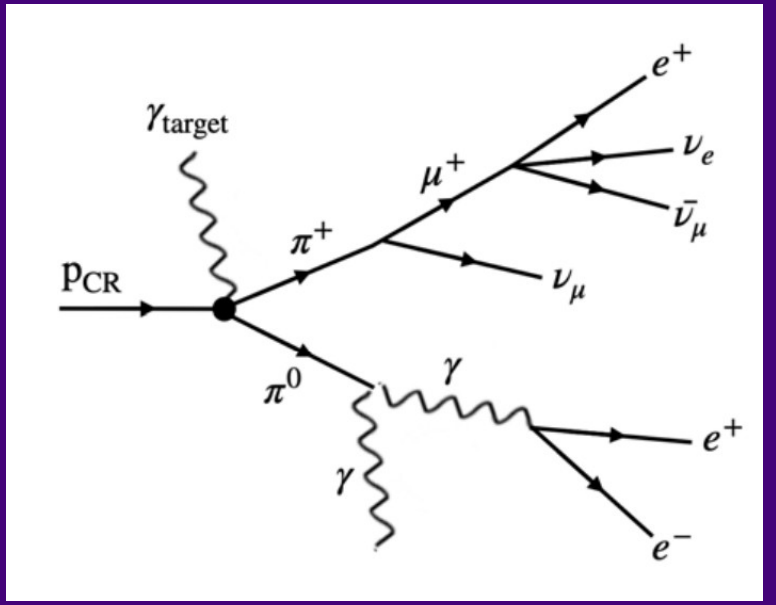
Photons and particles couple/interact strongly, so while this links potential sources, it also scrambles things on the way

Neutrinos are produced predominantly via channels involving protons: **proton-proton** (pp) and **proton-photon** (pγ)

So also coupled at source levels, but neutrinos a purer tracer

However, should see compatible populations of protons and photons to explain neutrinos

Understanding of neutrino sources is a **multi-messenger** subject




proton-photon channel for neutrinos (and gamma-rays)

[taken from Nobel Committee Scientific Background (2026)]

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# Cosmic Rays

Mostly protons and other charged particles

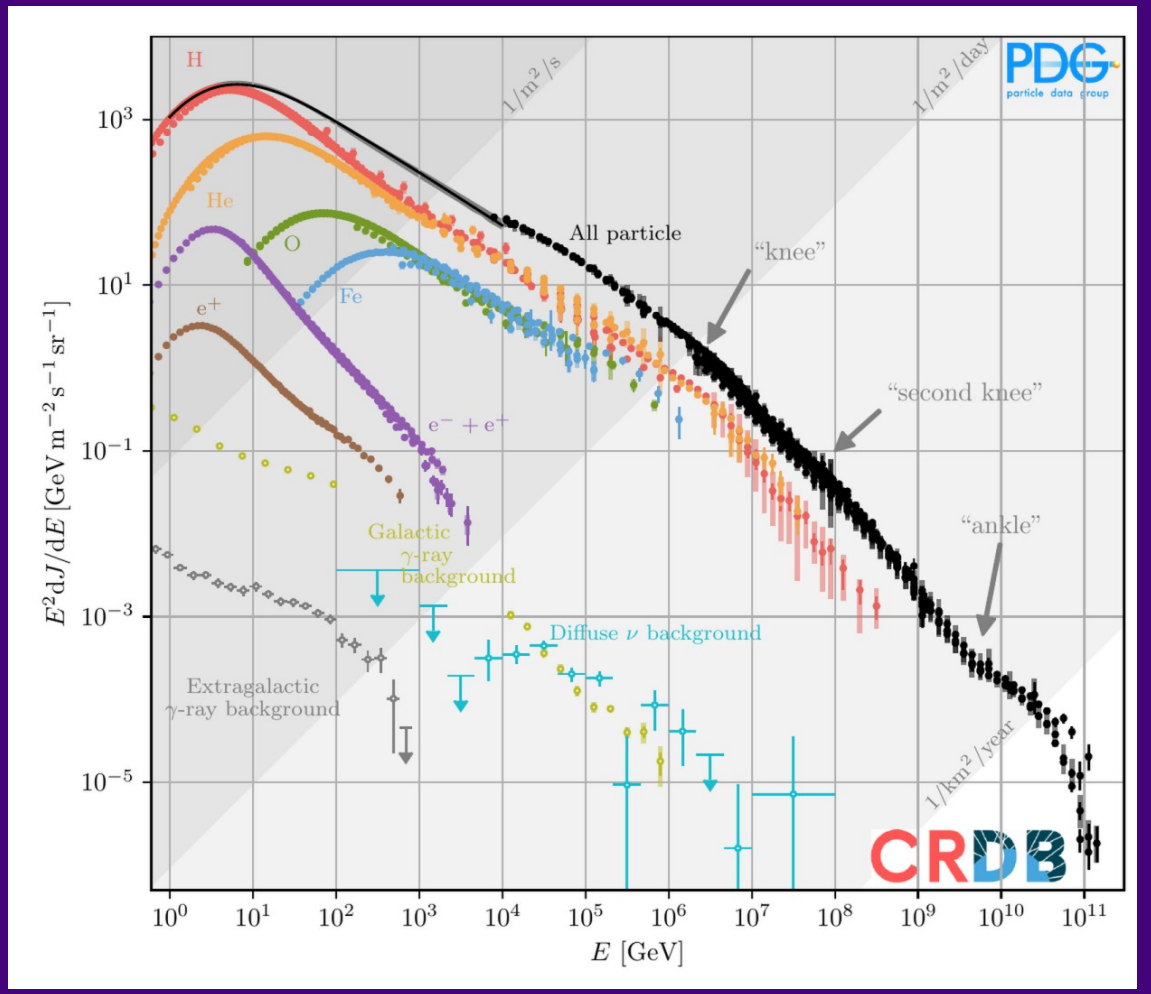
Can be deflected by magnetic fields

How to get to those extreme energies? (Lorentz factor $10^{10}$)

Shock acceleration, reconnection, stochastic



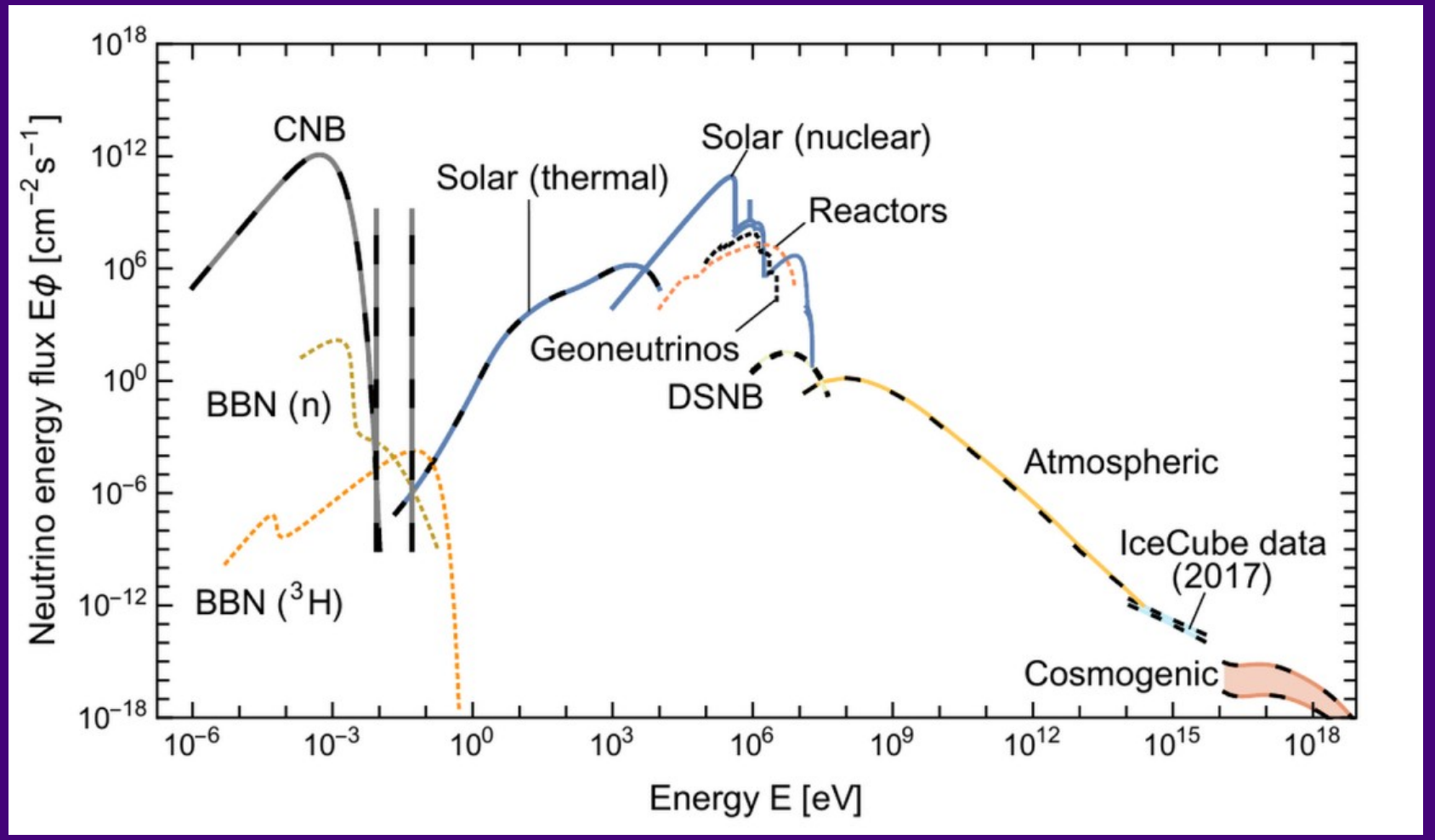
LST dishes / CTA



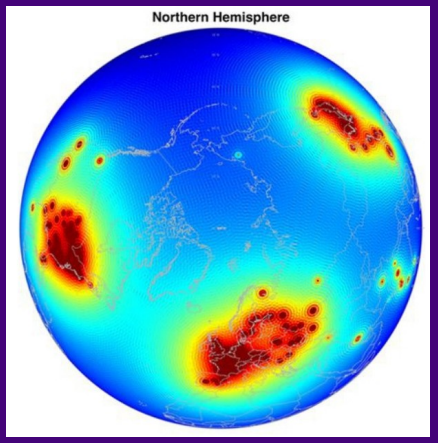

Alvarez-Muniz et al. PDG Review of Particle Physics (2026)

# Neutrino Spectrum

Grand Unified Neutrino Spectrum (GUNS):




Vitagliano, Tamborra & Raffelt (2020)




Earth view at 3 MeV (Usman et al. 2015)

Cosmic Neutrino Background at t=1s and (now) low energies

*to*

Cosmogenic Neutrinos at $10^{17}$ eV

Nuclear Reactors at MeV

Atmospheric neutrinos dominate above and out to ~100 TeV

# Supernovae

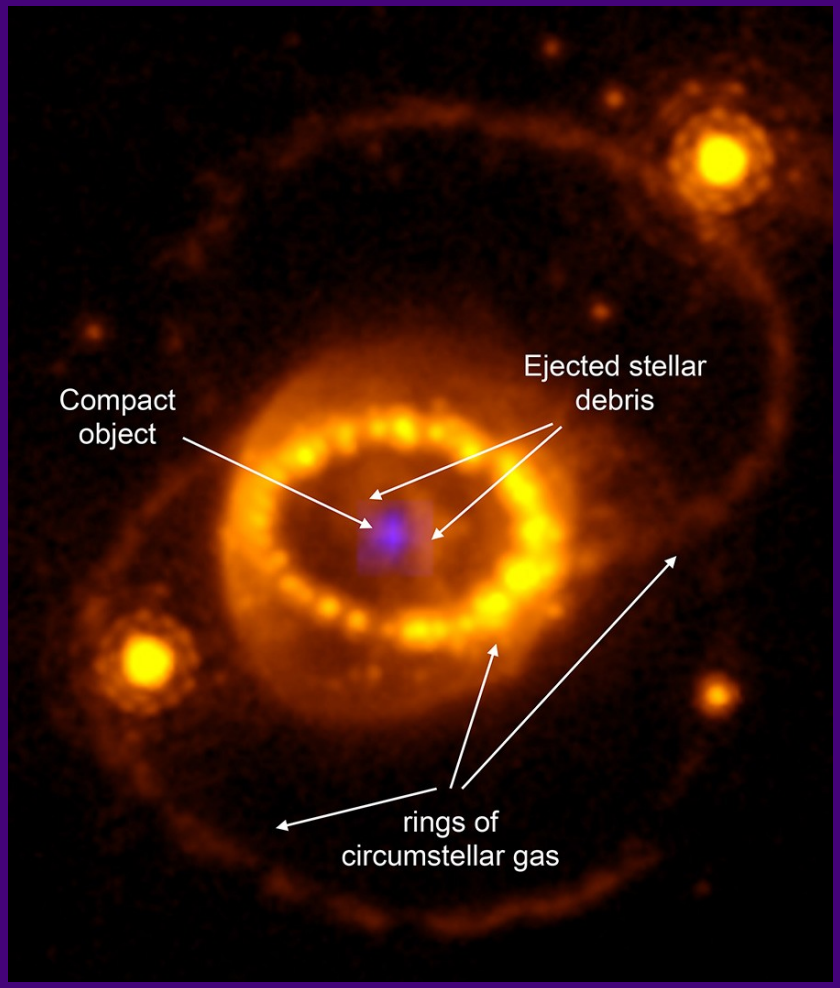
After detection of Solar neutrinos, first multi-messenger detection was of a nearby supernova

**SN1987A** in the Large Magellanic Cloud (Feb 1987)

Two dozen neutrinos detected

Can't wait for a galactic one (~1/century)

Universe rate is ~1/second




SN1987A with HST/JWST (courtesy NASA)

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# Supernovae

Neutrinos key to explosion physics and evolution of a core-collapse in a SN

Carry away 99% of the binding energy

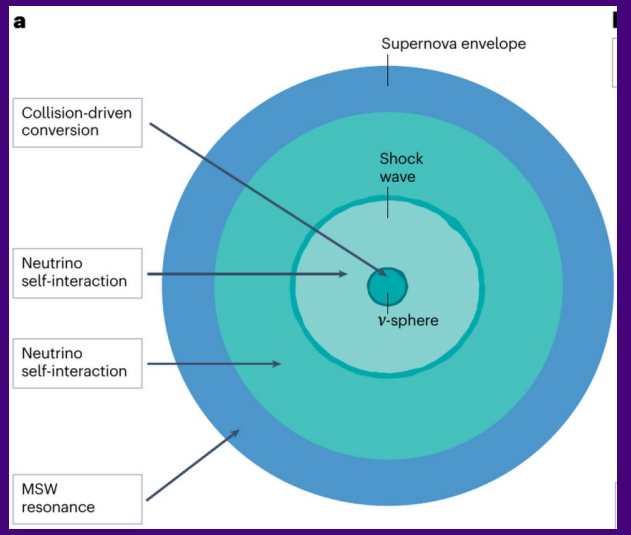
But mostly around **10 MeV**

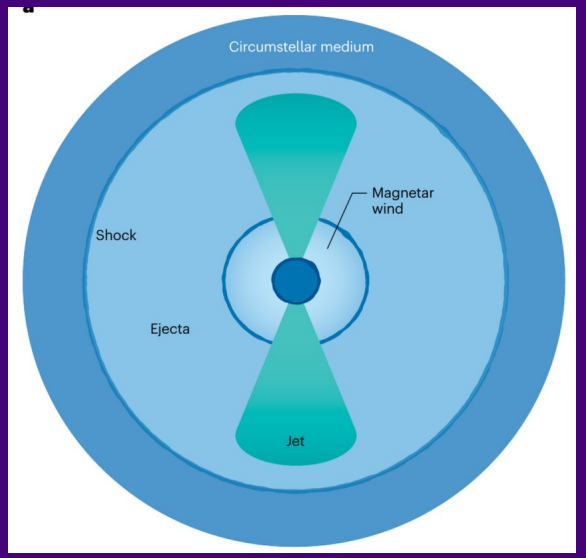
The collective signal is a **diffuse SN background** component

**Non-thermal neutrinos** also produced via the mentioned *pp* or *pγ* channels in the outflows from the SN (shocks and jets)

The post-SN stellar remnant can also produce high-E neutrinos (**pulsar/magnetar**)

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Tamborra (2025)

# IceCube Highlights: diffuse emission

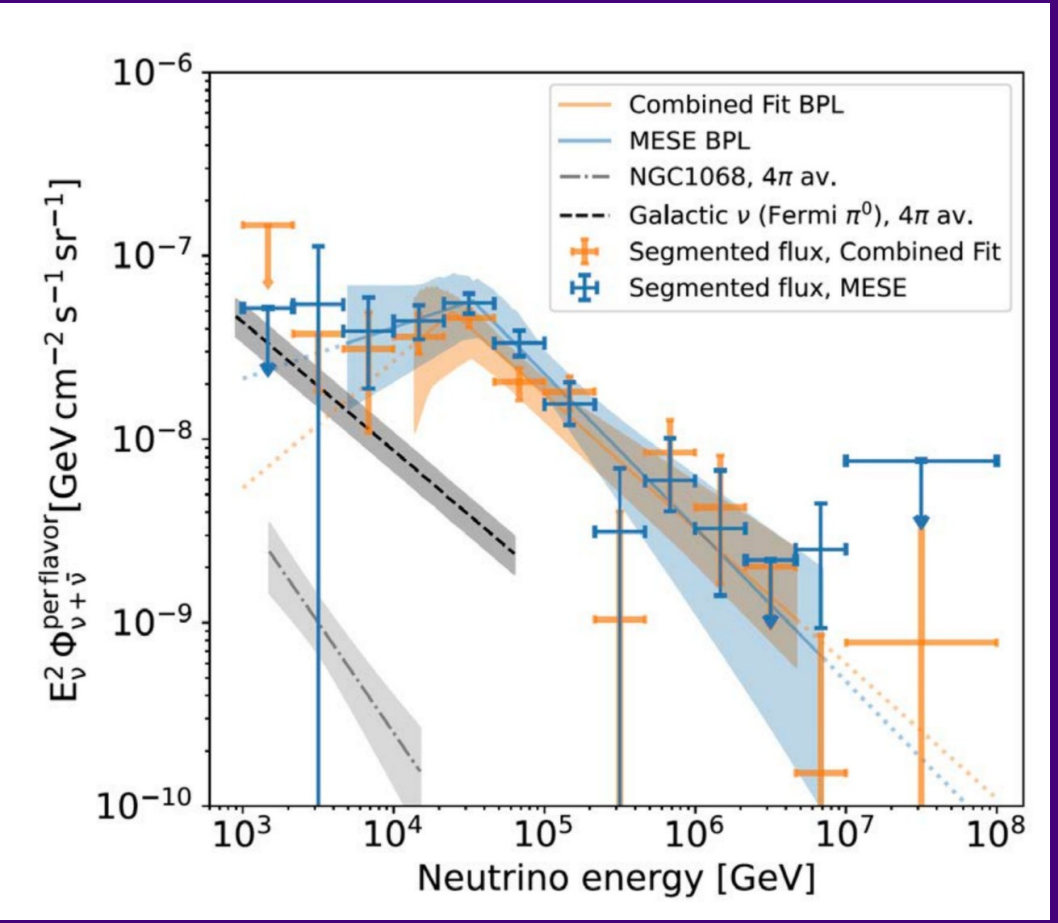
Detection of PeV neutrinos in early stages of operation (Bert, Ernie, Big Bird)

Steady accumulation of detections since 2013

A few dozen/year typically

Apparently isotropic, producing the *diffuse neutrino background* in the TeV to PeV range

Spectral slope steeper at high-E




IceCube collaboration (2026)

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# Active Galactic Nuclei

Galaxies harbour central super-massive black holes that feed from their surroundings

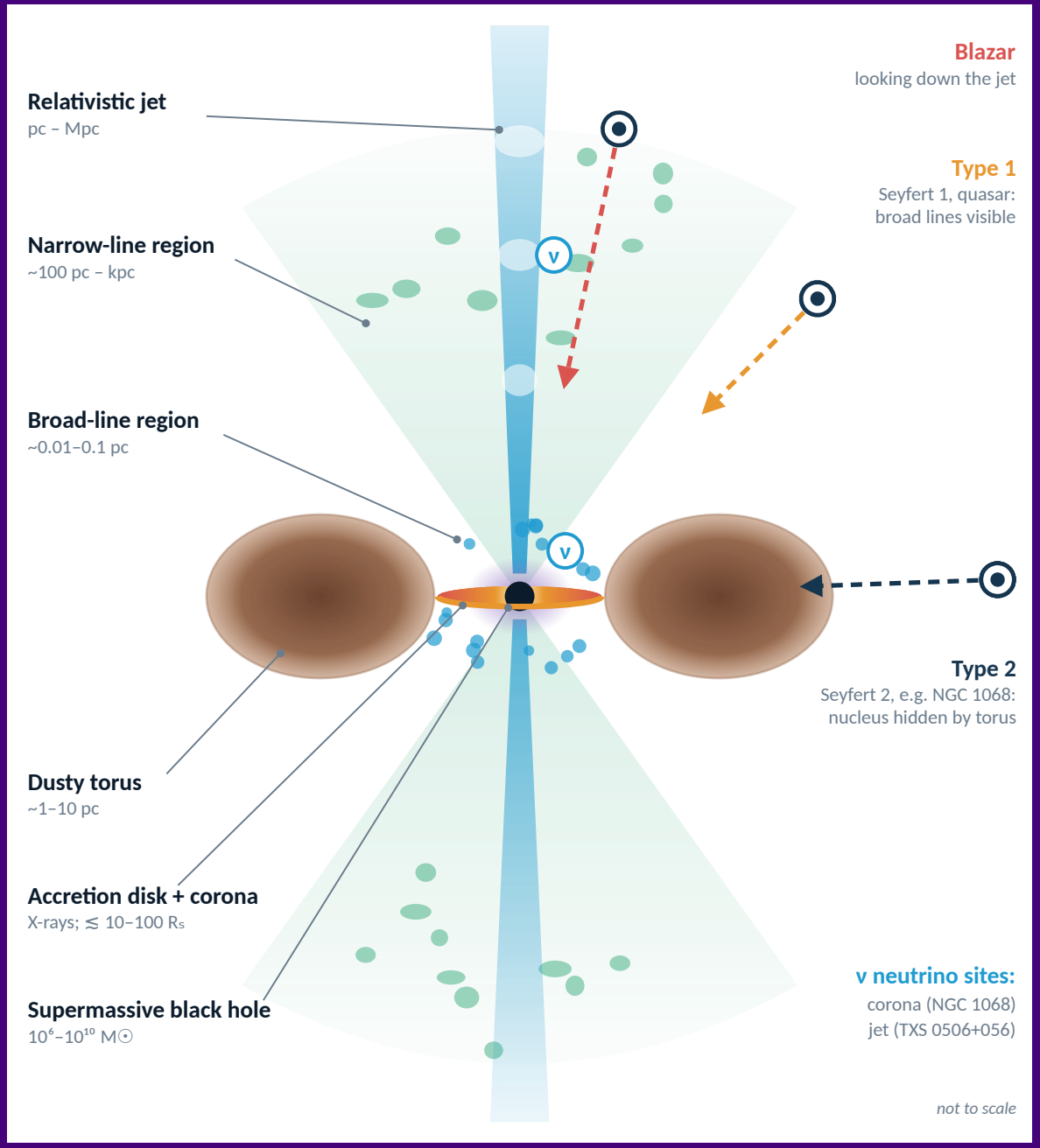
Complex structures around this BH: accretion disk, thick torus, line region, corona, jets

Unified picture in light of viewing angle

**Blazars** are active galaxies with the jet pointing at us

Jets are the best particle accelerators we know of. Accretion can drive relativistic jets.

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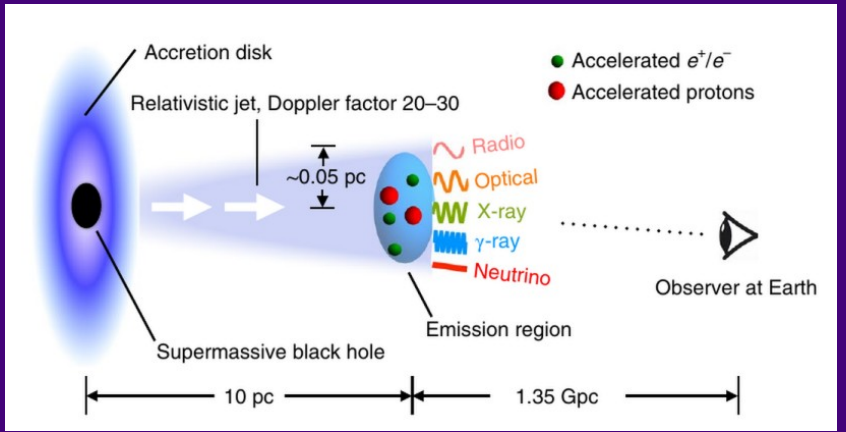
# IceCube Highlights: coincident

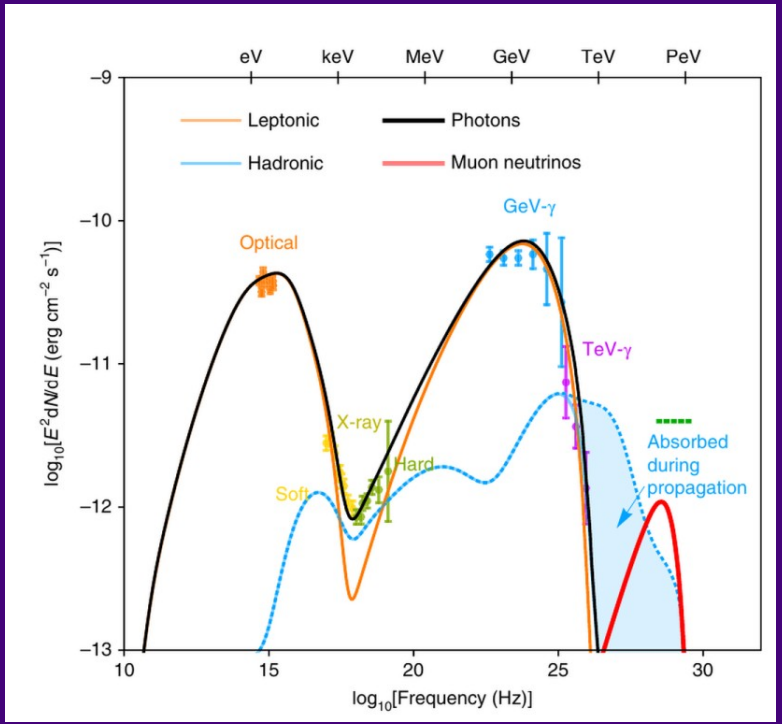
2017: coincident detection of a neutrino and a gamma-ray flare in the **blazar TXS0506+056**

Multi-messenger ; need to explain the neutrinos as well as the gamma-rays and lower-E emission components

Followed by excess of neutrinos consistent with a known source, **NGC1068 (Seyfert II)**

AGN **jets** and coronae the currently favoured source population; **environments of particle acceleration**




TXS0506+056 Gao et al. (2019)

# Other things with jets?

**Neutron-star mergers** ; no neutrinos from GW170817

**Gamma-ray bursts** ; no coincident detections despite ~1000 GRBs in IceCube period

**Tidal disruption events** ; star ripped apart as it approaches a black hole

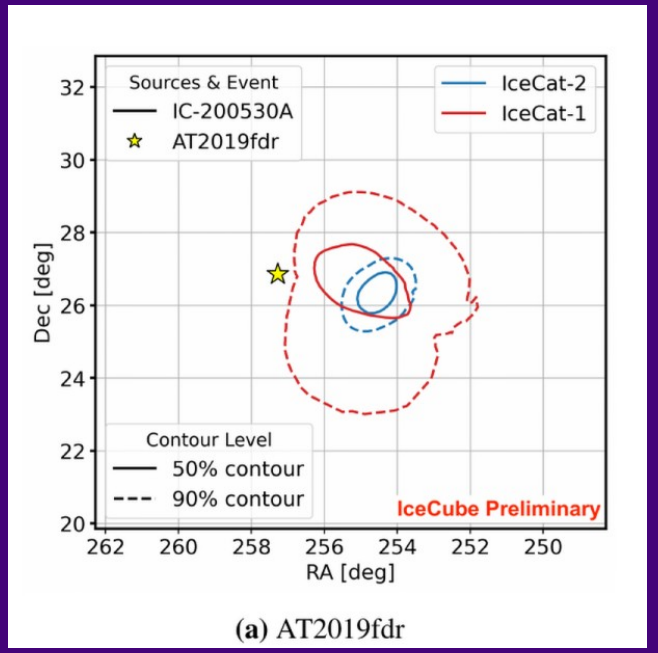
Some coincidences claimed, but no statistically significant correlation when looking at sample of TDEs

Updated reconstructions no longer positionally coincident

*Real-time coincident multi-messenger searches can be very constraining*

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(a) AT2019fdr

IceCube Collaboration (2025)

# The haul so far: IceCat-2

365 alerts ( ~27/yr)

~10/year gold category (50% chance)

Localisations typically to 1-2 deg$^2$

Consistent with isotropy

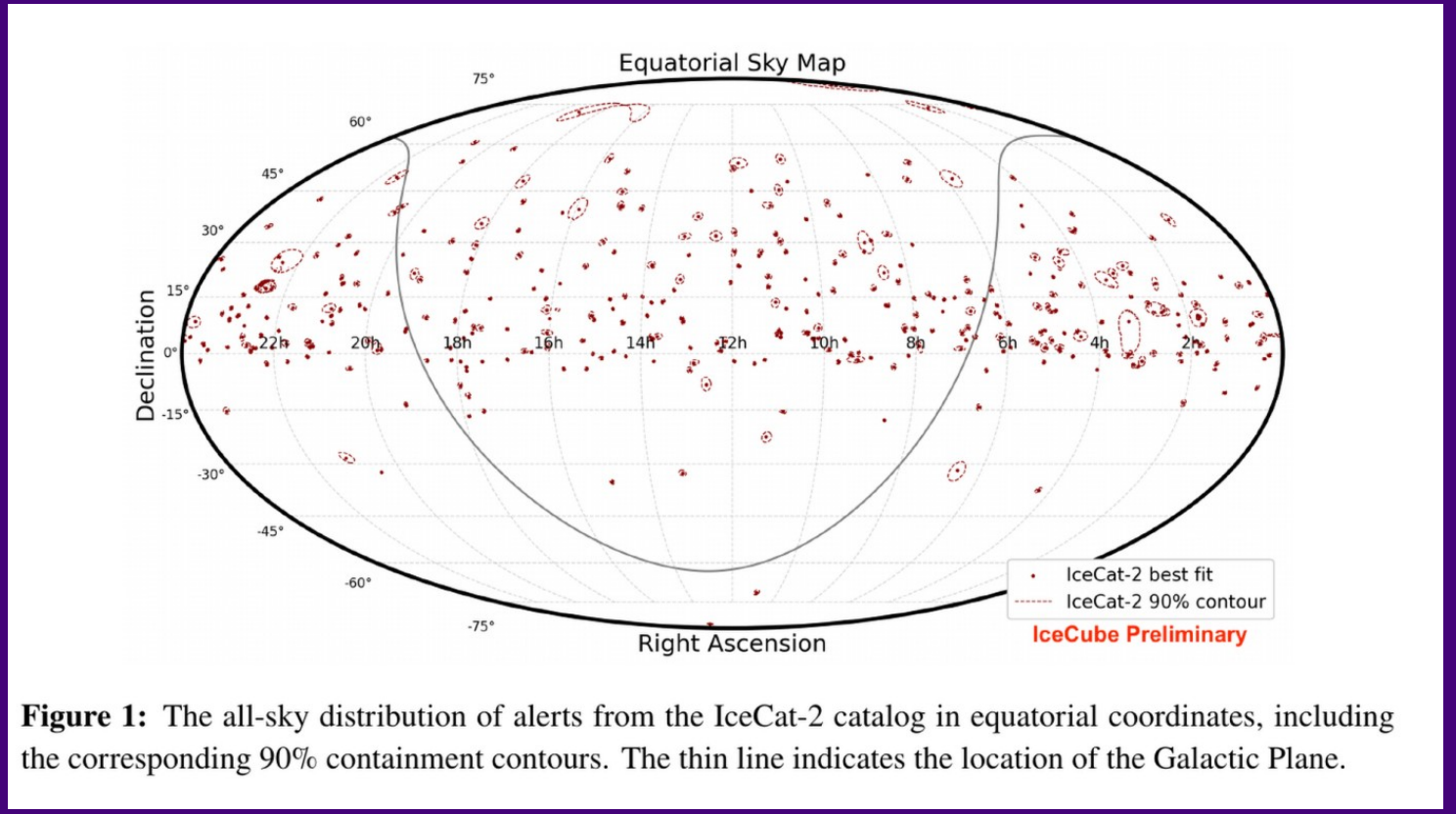



**Figure 1:** The all-sky distribution of alerts from the IceCat-2 catalog in equatorial coordinates, including the corresponding 90% containment contours. The thin line indicates the location of the Galactic Plane.

IceCube Collaboration (2025)

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# GOTO Follow-up of IceCube events

Automated machine-readable alerts issued since few yrs

Permits real-time follow-up, ideal for robotic telescopes like our ***Gravitational wave Optical Transient Observer***

Popular sources such as blazars bright enough, localisation much smaller than GOTO field of view

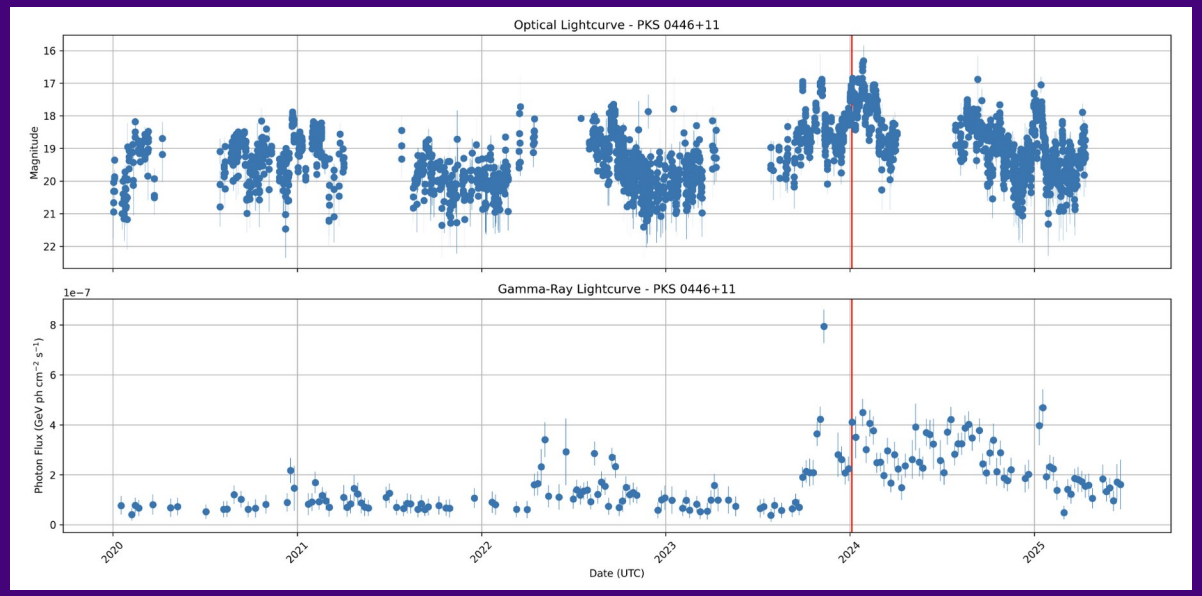
We point at both *Gold* and *Bronze* events

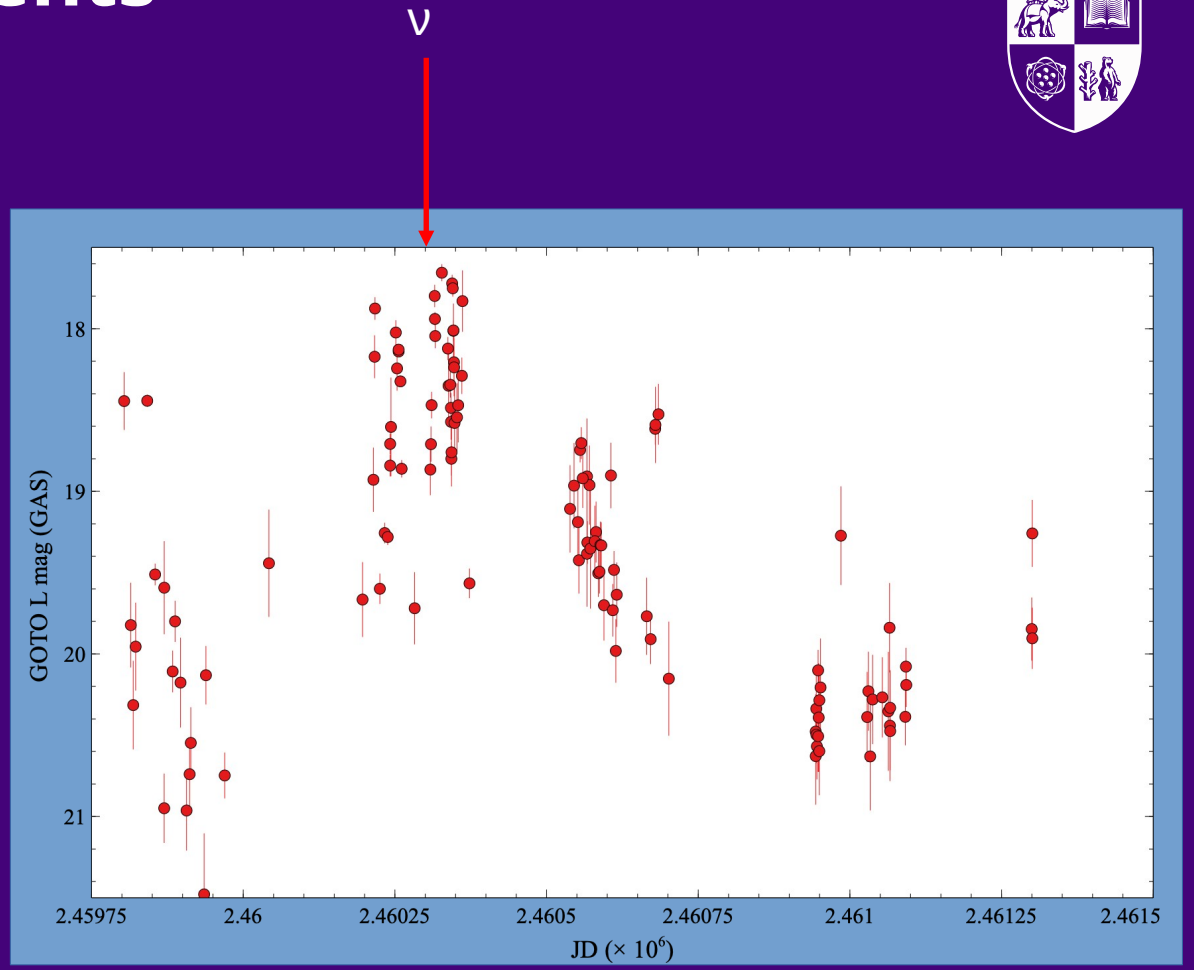
Mostly Northern → La Palma / GOTO-North




UNIVERSITY OF WARWICK

# GOTO Follow-up of IceCube events




Courtesy Klaas Wiersema, Anas Ahmad & Devi Krishnamurthy (Herts)
*preliminary*

# Astro Summary

Isotropic neutrino flux implies mostly extra-galactic source population

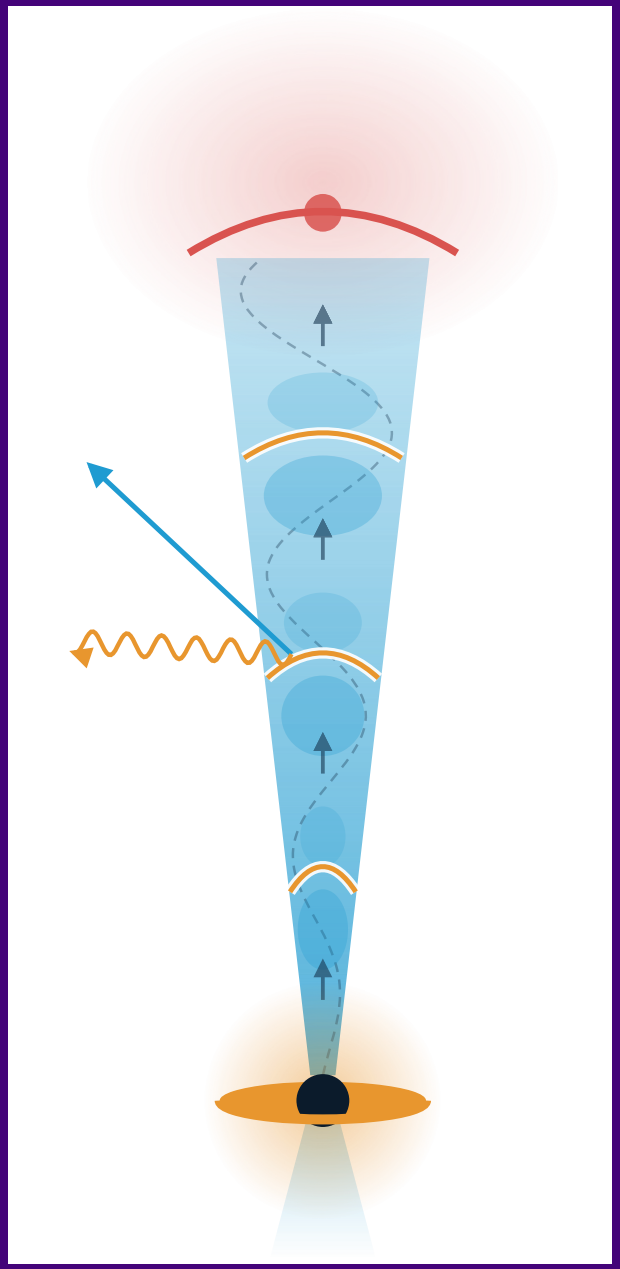
Expected links to gamma-rays and cosmic rays are there, but devil in the details

Active Galaxies a favoured class, but many other sources can produce TeV to PeV neutrinos

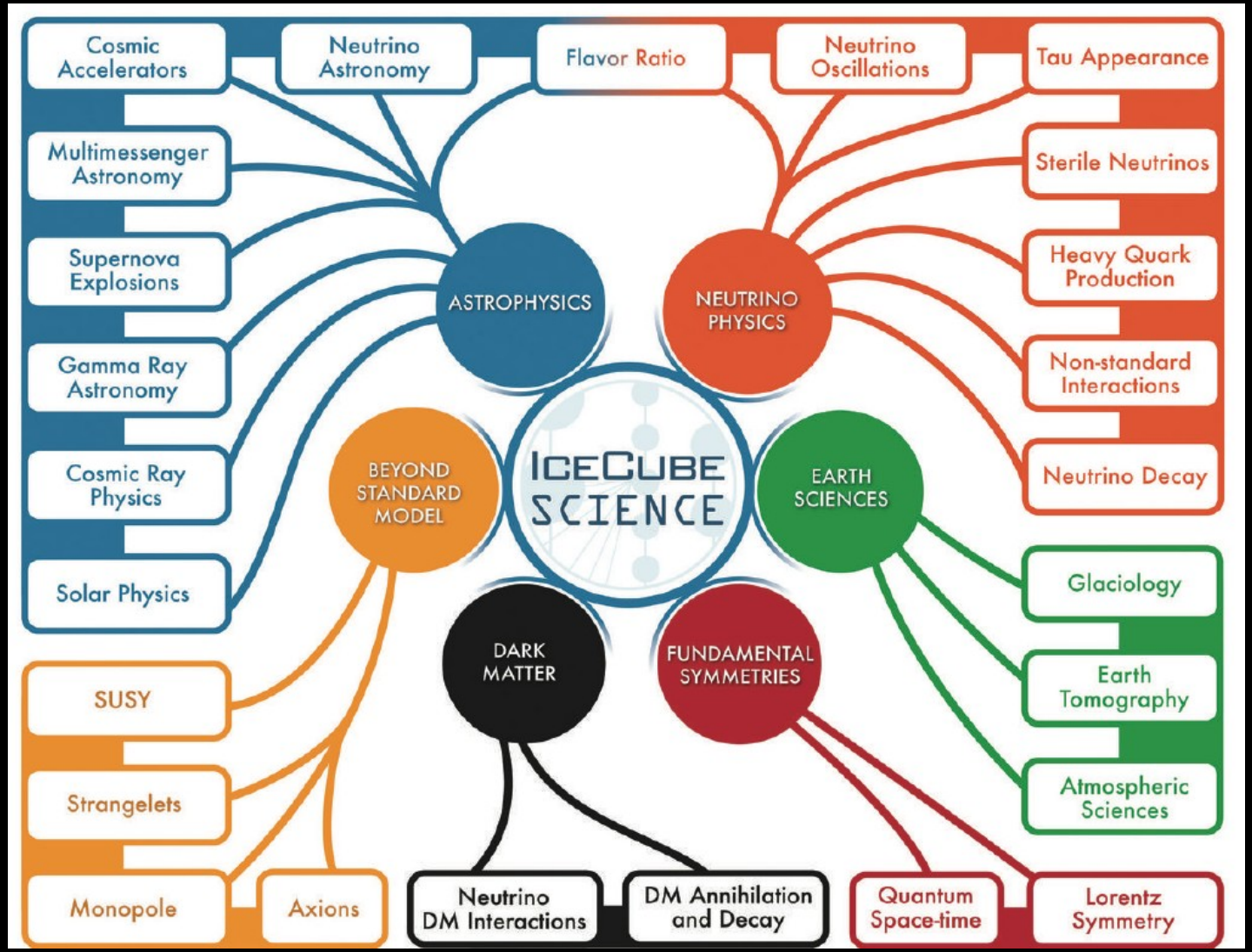
The specific contributions from various source types still unclear/weakly constrained. Jets are likely key.

Coincident searches very powerful (odds ratio of correlations in both space and time)

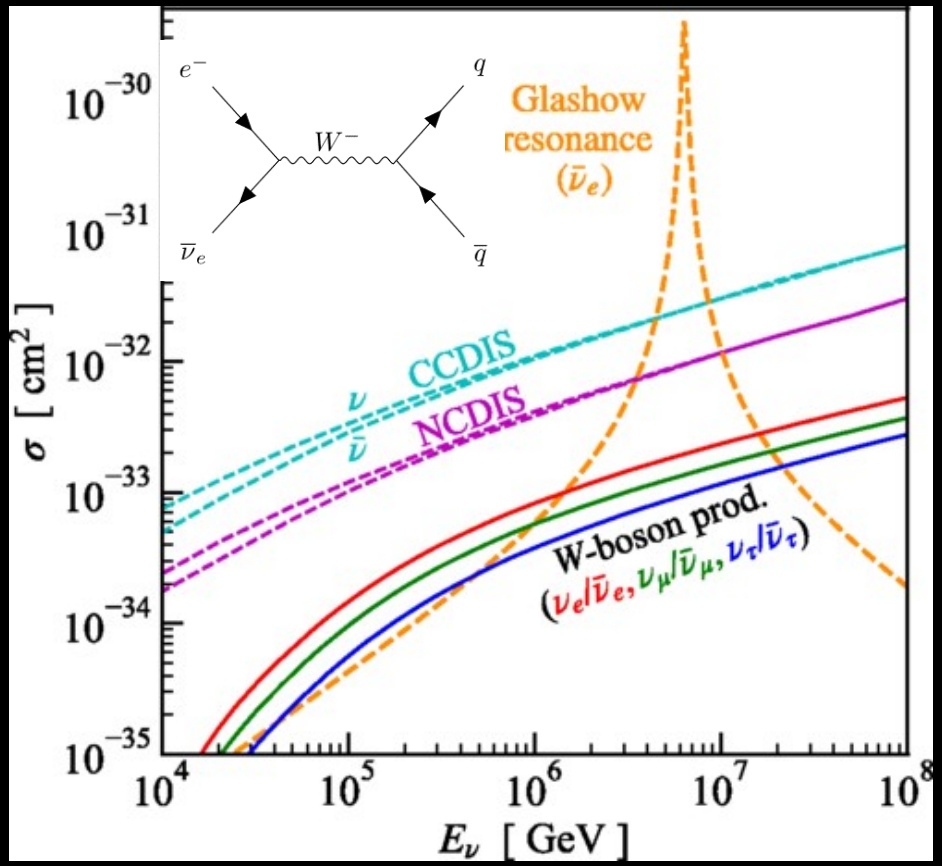
Need better telescopes and better models



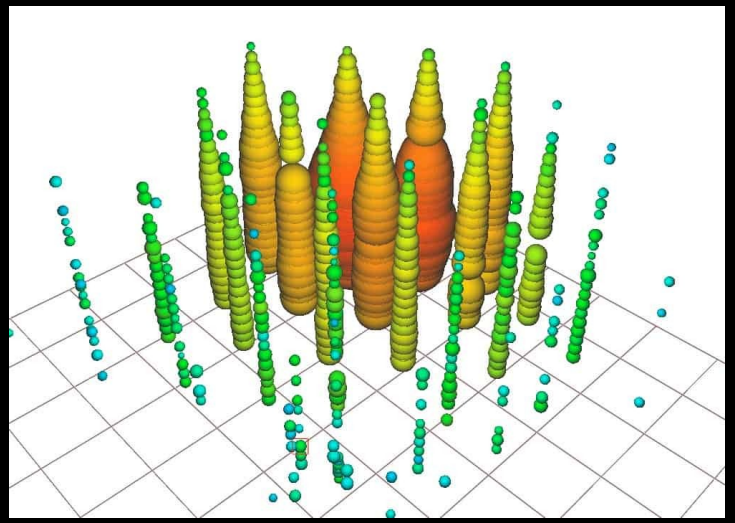
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ICECUBE SCIENCE
ASTROPHYSICS
NEUTRINO PHYSICS
BEYOND STANDARD MODEL
EARTH SCIENCES
DARK MATTER
FUNDAMENTAL SYMMETRIES
Cosmic Accelerators
Neutrino Astronomy
Multimessenger Astronomy
Supernova Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
Neutrino Decay
Glaciology
Earth Tomography
Atmospheric Sciences
SUSY
Strangelets
Monopole
Axions
Neutrino DM Interactions
DM Annihilation and Decay
Quantum Space-time
Lorentz Symmetry

# Glashow resonance




- Very high energy electron antineutrino collides with an electron in the ice creating an on-shell W-boson which decays to a high energy hadronic cascade.
- 6.3 PeV threshold
- First observation in 2021



# Neutrino Flavour Oscillations

- Neutrinos produced in the atmosphere travel through the earth and can change flavour due to neutrino flavour oscillations.

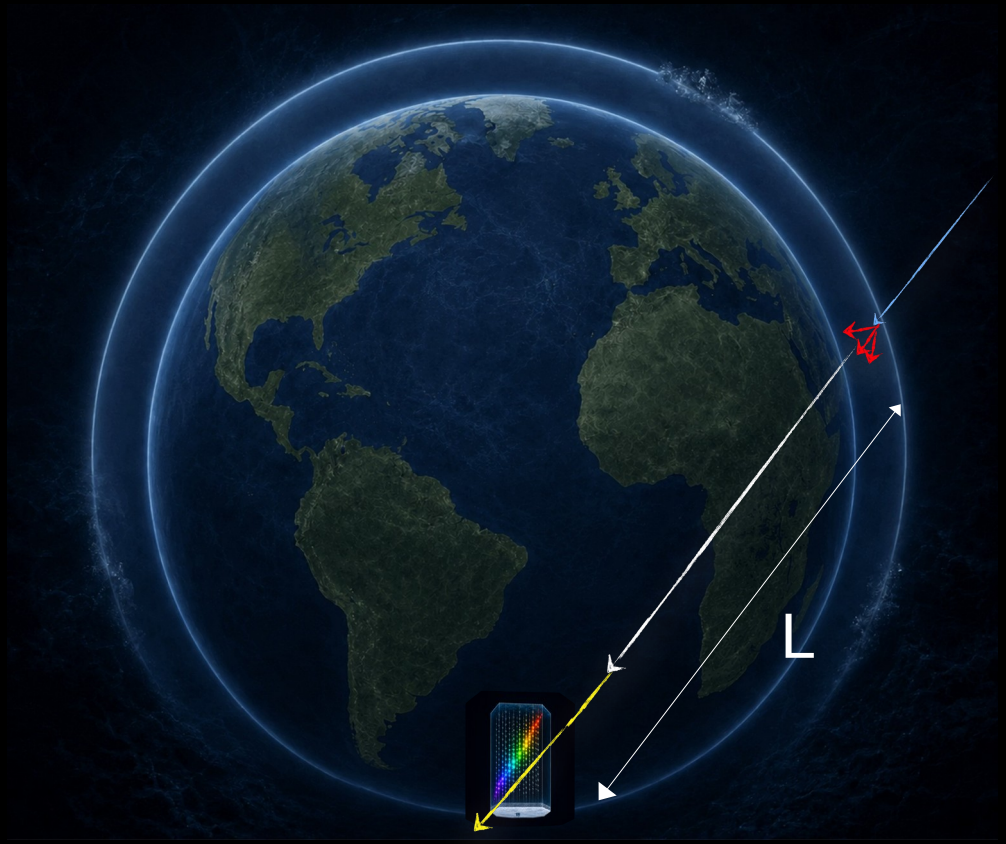
- IceCube is sensitive to neutrino flavour and can therefore measure neutrino oscillations

- $$P(\nu_\mu \rightarrow \nu_\tau) \sim \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)$$

Mixing angles

Mass splitting

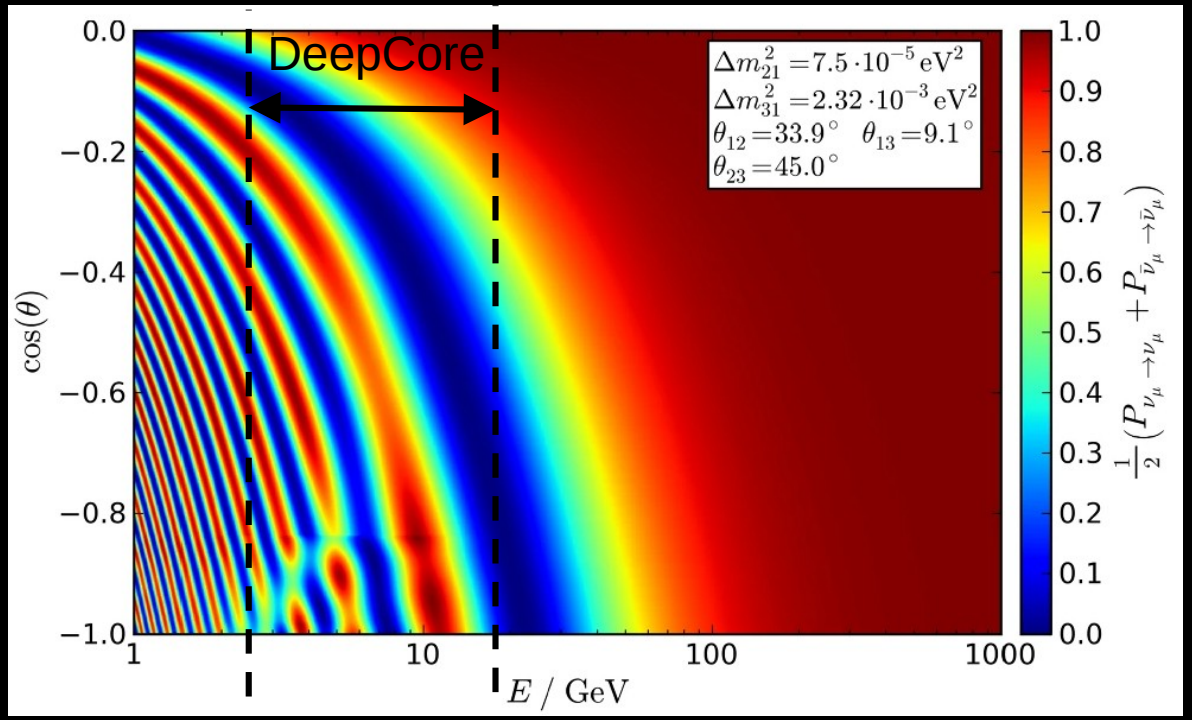
$$\Delta m^2_{ij} = m^2_i - m^2_j$$



# Oscillogram

Horizon

Cos(Zenith angle)

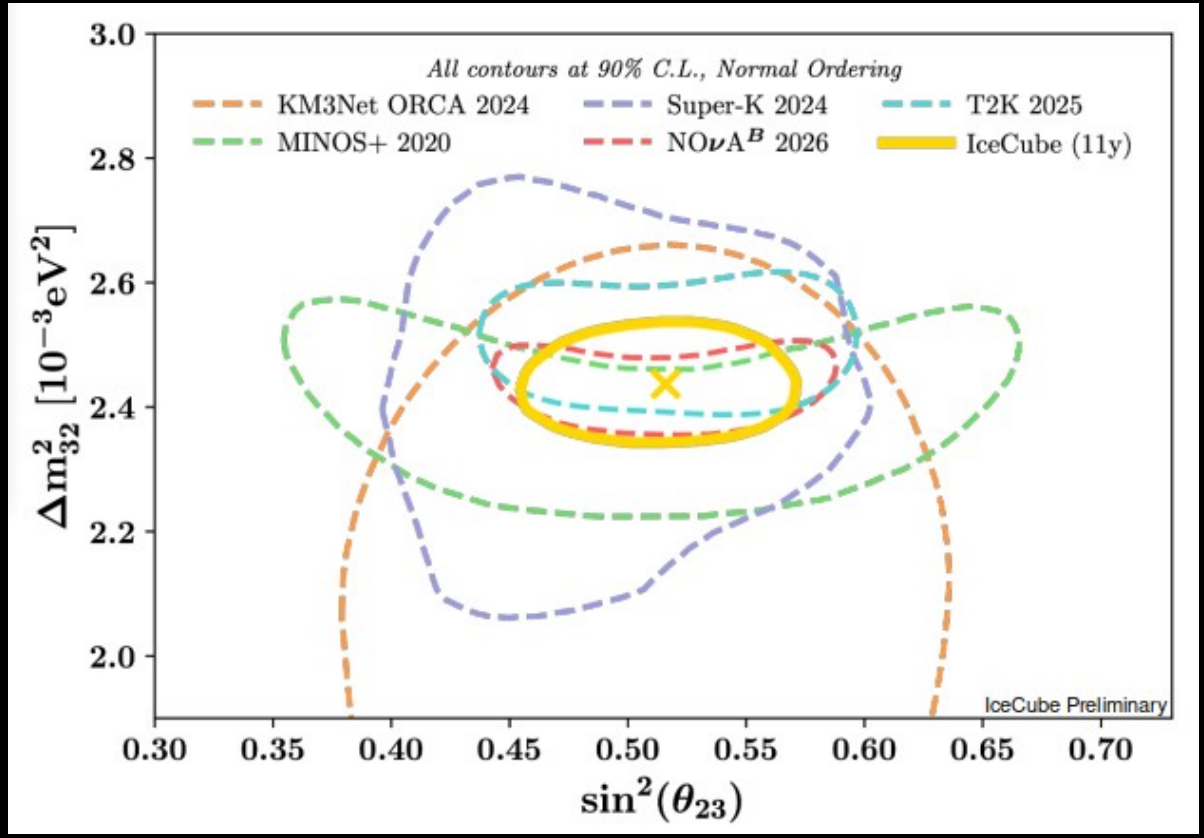



Below

Survival Probability

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m^2_{23}(2 R_e \cos\theta_z)}{4E}\right)$$

# Atmospheric Oscillation Results




S. Axani for the IceCube Collaboration,Neutrino 2026

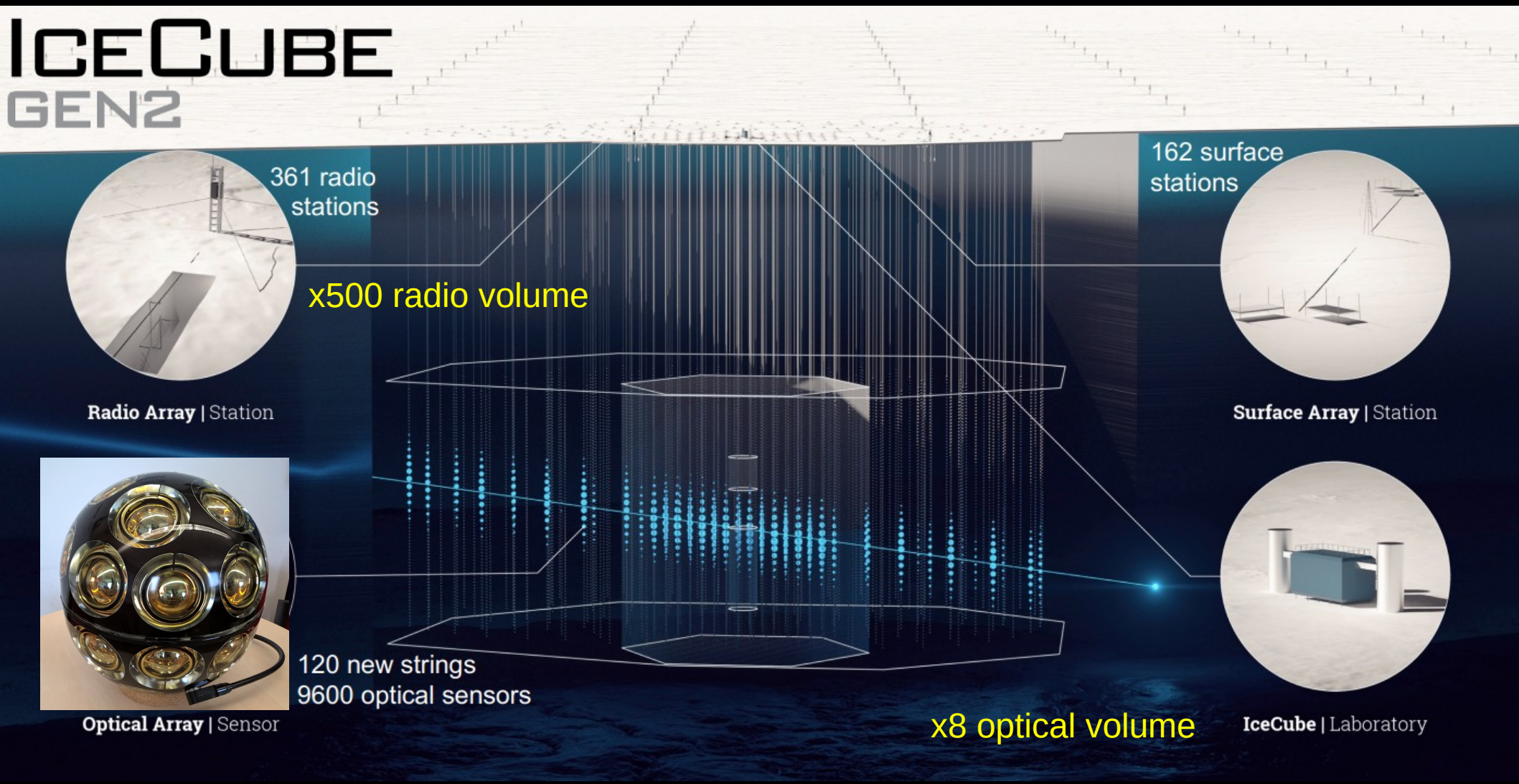
“Francis Halzen has made pivotal contributions to IceCube as Principal Investigator – from its invention and conceptual design, through the technically audacious construction, to routine science operations.

Through his visionary leadership, Halzen created and nurtured an international collaboration, which was able to transform theoretical ideas on neutrino detection into precise observations and a vibrant experimental field.

The use of high-energy neutrinos in multi-messenger astronomy will be fully capitalised on during the next decade with a global network of next-generation neutrino telescopes with instrumented volumes exceeding a cubic-kilometre.”

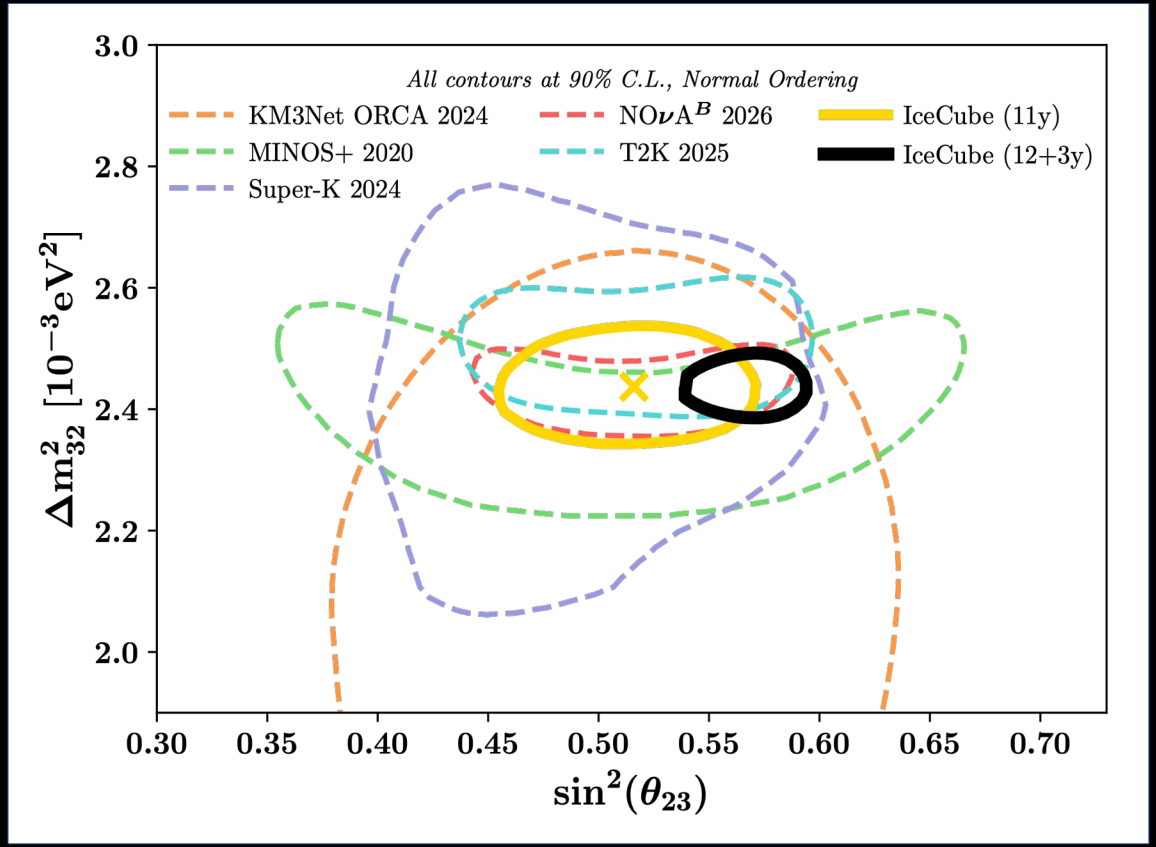
Summary of scientific background to the Nobel Prize 2026

# IceCube Gen2



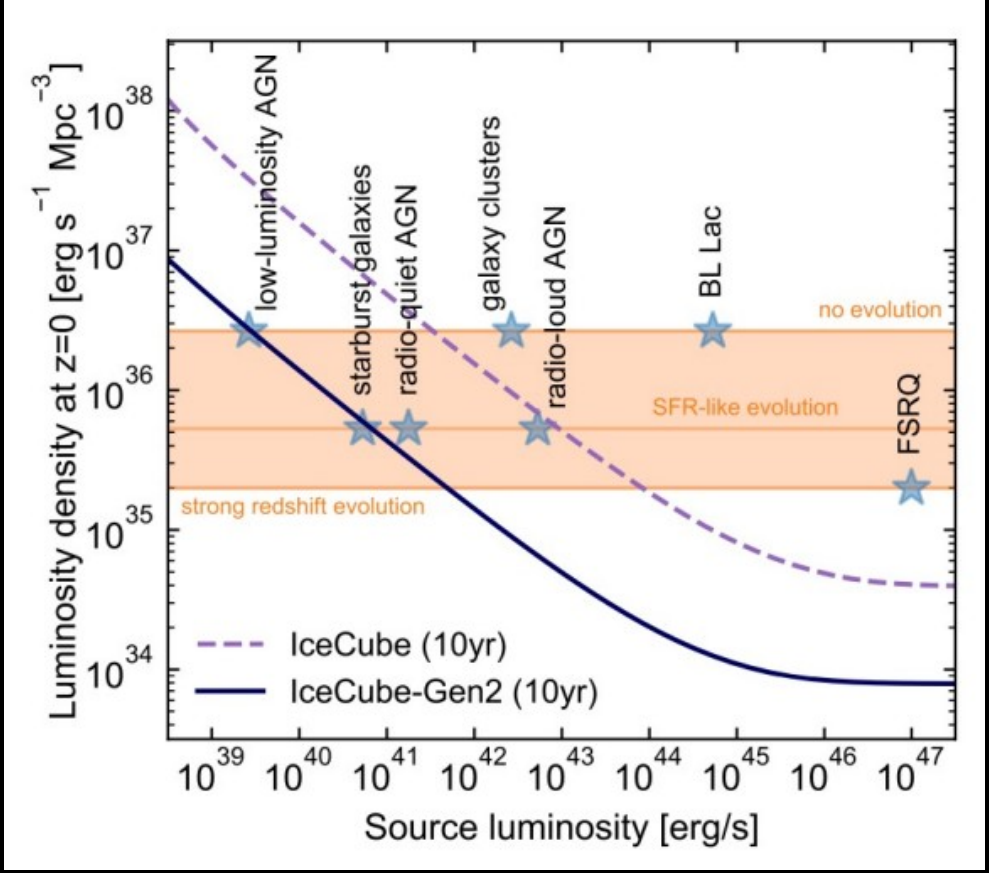

Project funding approved; Pre-construction tasks occurred in Austral summer

# Atmospheric Oscillation Sensitivity




IceCube-Gen2 technical design report

# Exploring the high energy sky

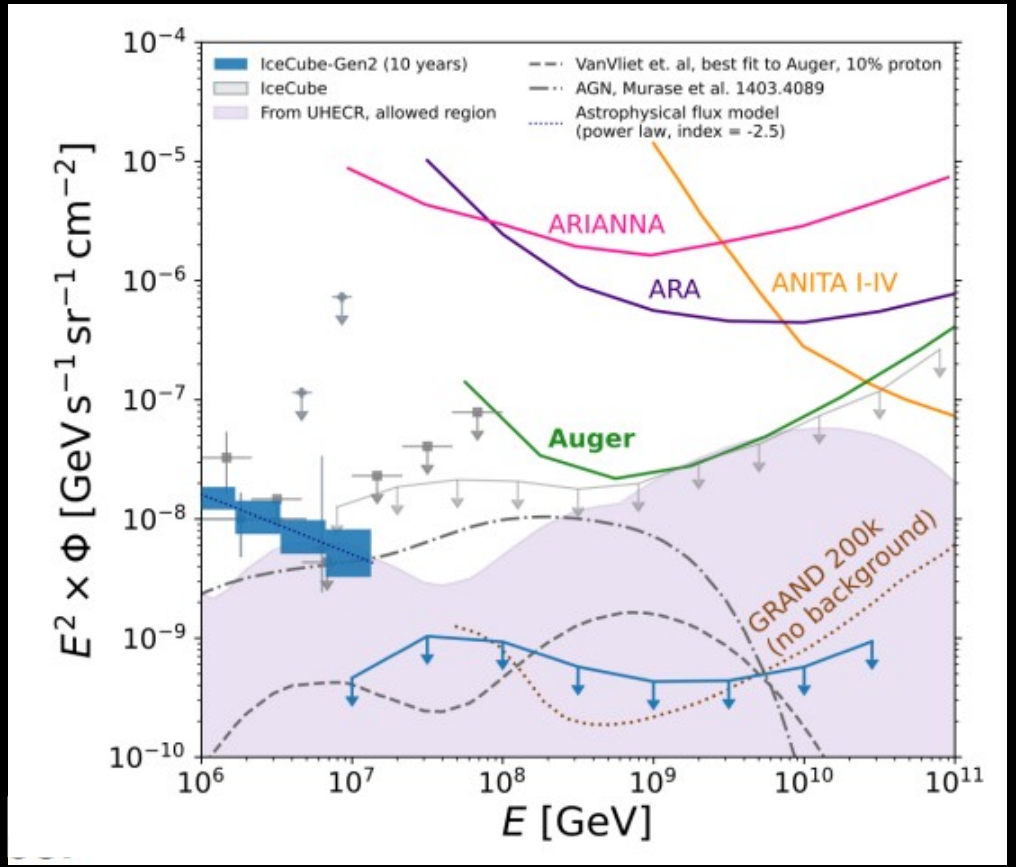



- Factor of 10 increase in the number of observed sources
- Factor 5 increase in point source position sensitivity

IceCube-Gen2 technical design report

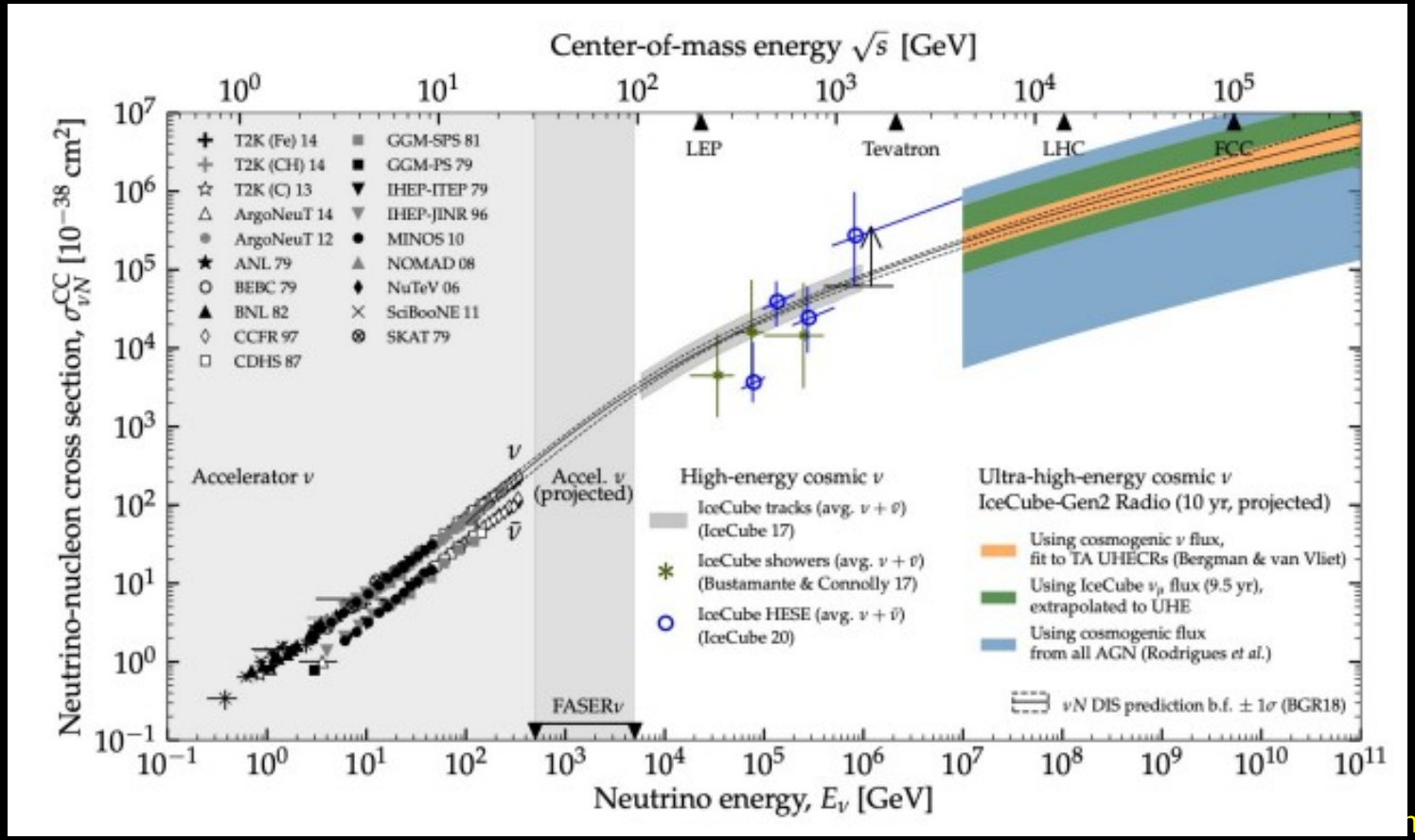
# Accessing EHE neutrino flux

- High energy cascades can emit radio pulses within the Cerenkov cone (Askaryan effect)
- Huge increase in radio sensitive volume can increase sensitivity to extremely high energy neutrinos by a factor of 10 or more.




IceCube-Gen2 technical design report

# Neutrino cross sections




nical design report

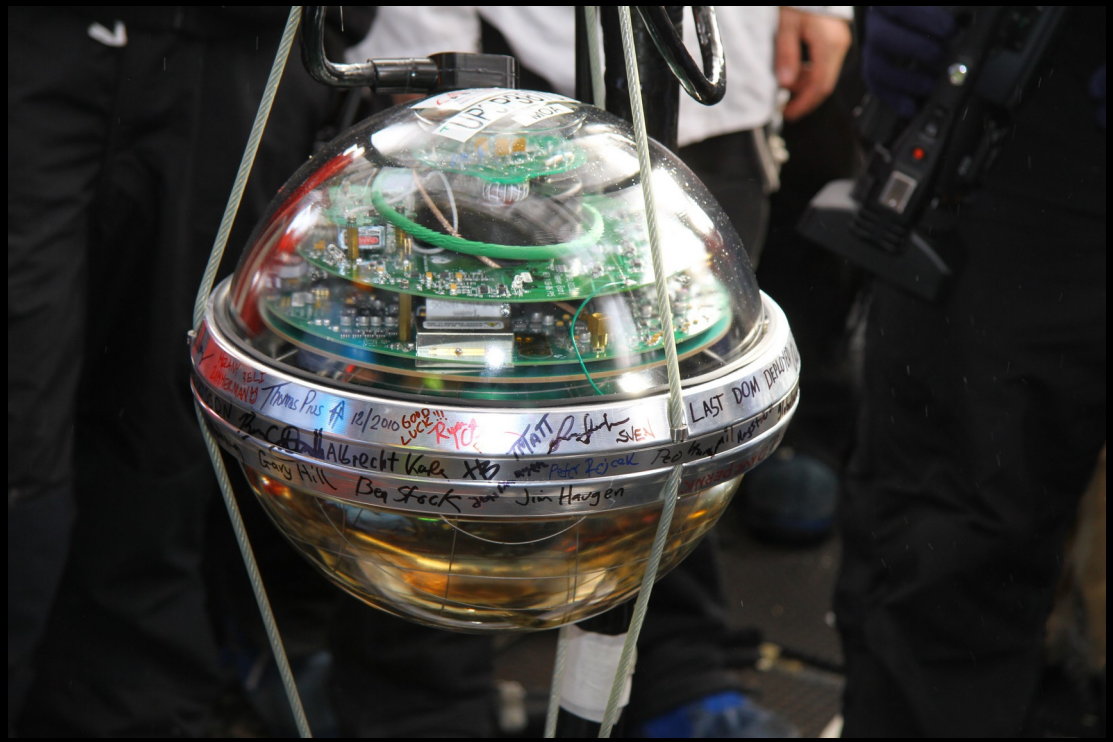
# Encouraging Words

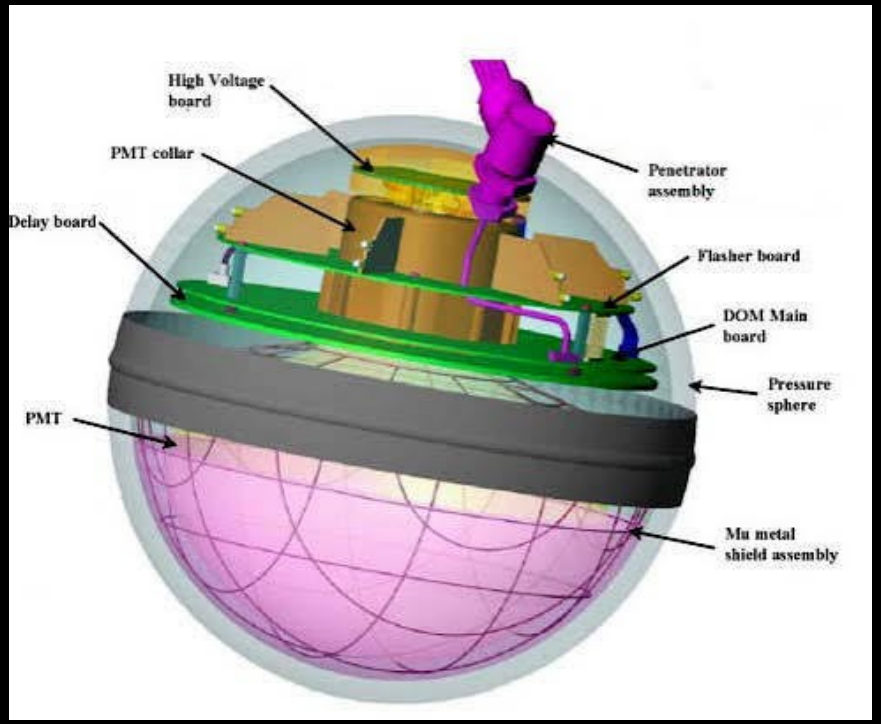
“When we started this project, everybody realised this was maybe a good idea, but very few thought it would work, including myself.”

Francis Halzen, Nobel Prize Press Conference

# Backup

# Digital Optical Modules (DOMs)






Failure rate around 1 DOM / year