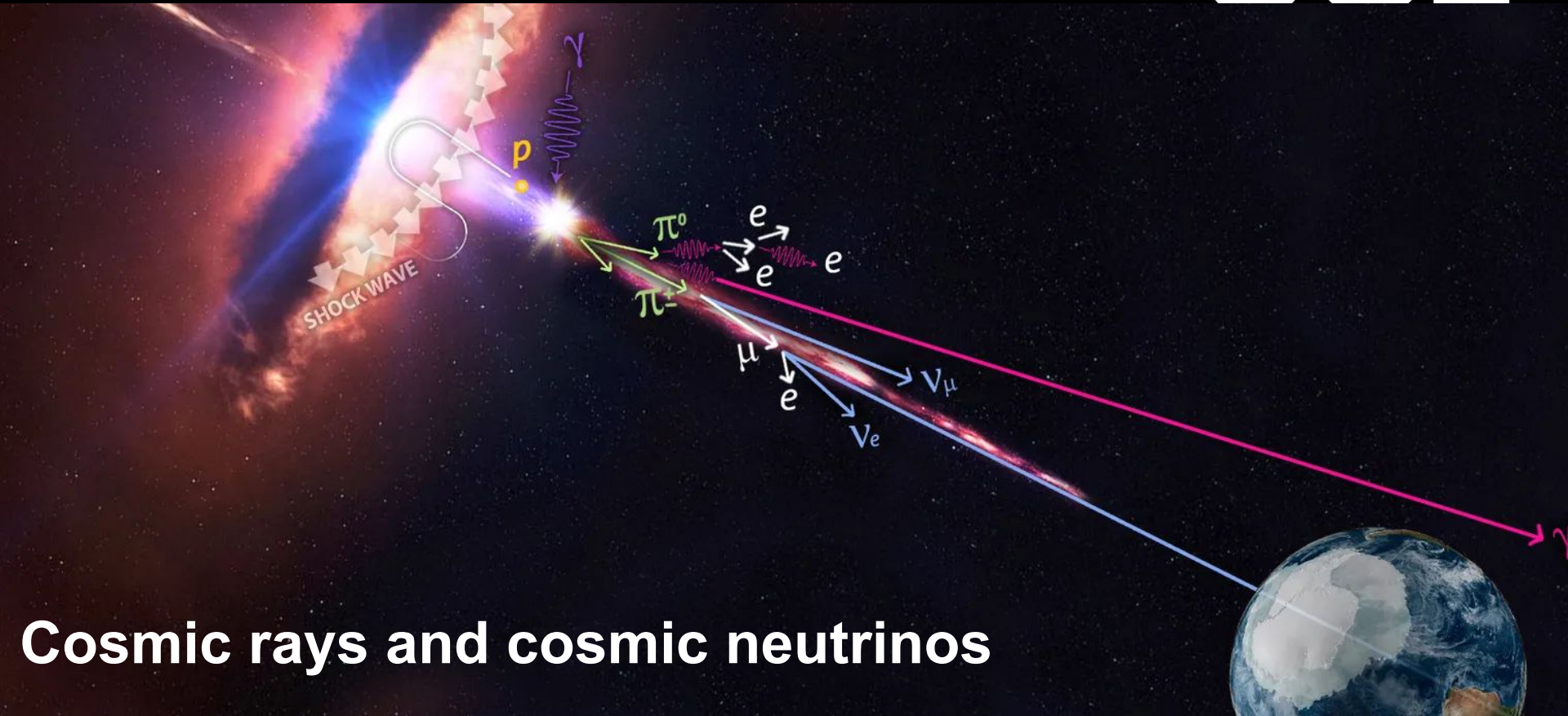


Cosmic rays and cosmic neutrinos

Cosmic Rays

When did we start looking for ‘cosmic rays’ from outer space?

A long time ago by flying balloons!

Image: Victor Hess before one of his balloon flights over Austria

Cosmic Neutrinos

When did we start looking for ‘cosmic neutrinos’ for outer space?

A long time ago by building detectors deep underground

Image: Ray Davis at the Homestake Mine during construction of his solar neutrino experiment.

Birth of Multimessenger Astronomy

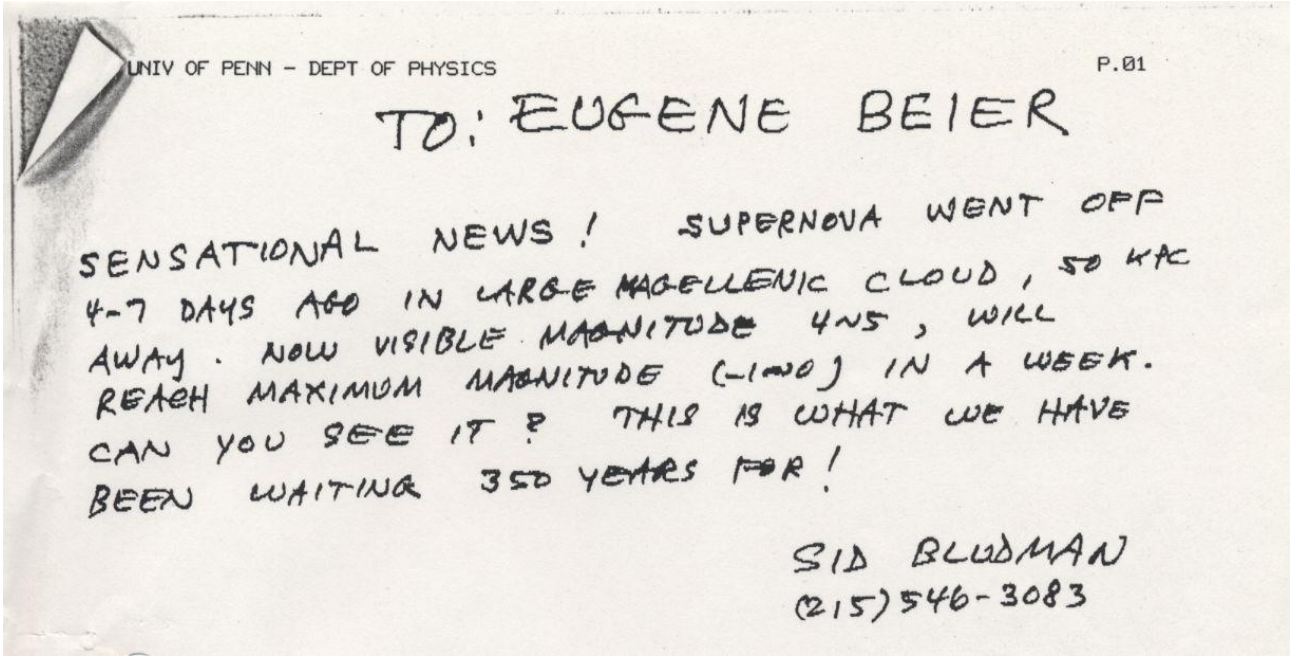
UCL

23rd February 1987 light from a nearby star exploding arrived at Earth

Image: Before (right) and after (left) images of SN1987A from the Anglo-Australian Observatory

Birth of Multimessenger Astronomy

25th February 1987
a fax sent to Japan



UNIV OF PENN - DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4N5, WILL REACH MAXIMUM MAGNITUDE (-1N0) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083

Image: The fax which was sent asking if the Kamiokande detector could see the supernova

Birth of Multimessenger Astronomy

28th February 1987 a printout of the first observation of neutrinos from outside our solar system

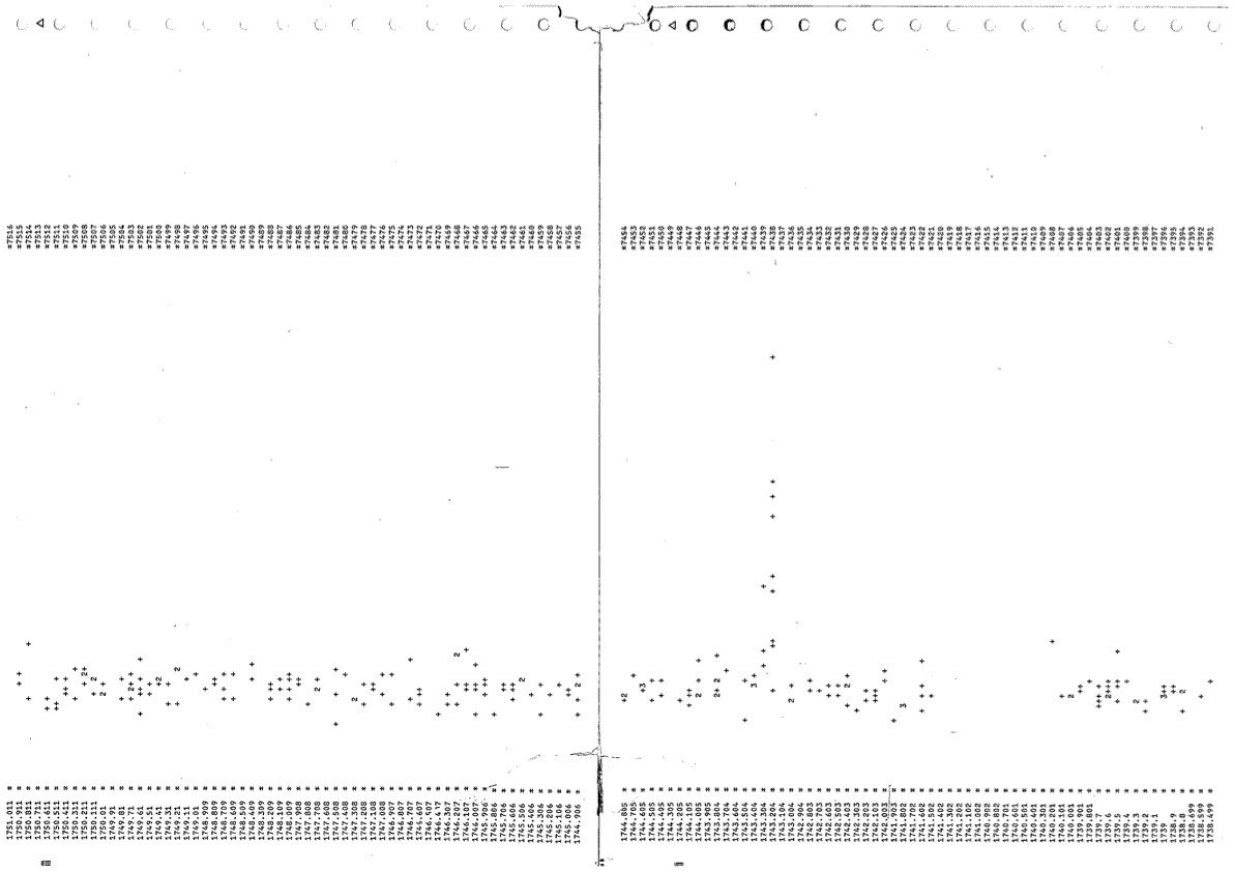
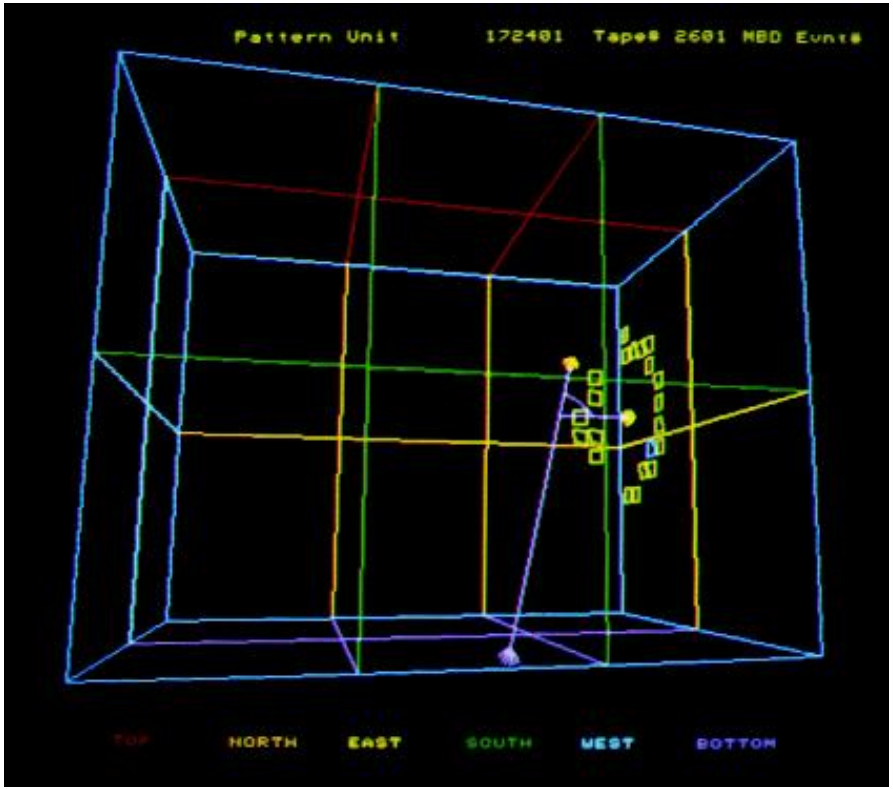


Image: A printout of number of photosensors vs time. Eventually determined 11 neutrinos were detected in 13 second span.

Birth of Multimessenger Astronomy

UCL



VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud

R. M. Bionta,[12] G. Blewitt,[4] C. B. Bratton,[5] D. Casper,[2,14] A. Ciocio,[14] R. Claus,[14] B. Cortez,[16] M. Crouch,[9] S. T. Dye,[6] S. Errede,[10] G. W. Foster,[15] W. Gajewski,[1] K. S. Ganezer,[1] M. Goldhaber,[3] T. J. Haines,[1] T. W. Jones,[7] D. Kielczewska,[1,8] W. R. Kropp,[1] J. G. Learned,[6] J. M. LoSecco,[13] J. Matthews,[2] R. Miller,[1] M. S. Mudan,[7] H. S. Park,[11] L. R. Price,[1] F. Reines,[1] J. Schultz,[1] S. Seidel,[2,14] E. Shumard,[16] D. Sinclair,[2] H. W. Sobel,[1] J. L. Stone,[14] L. R. Sulak,[14] R. Svoboda,[1] G. Thornton,[2] J. C. van der Velde,[2] and C. Wuest[12]

[1]*The University of California, Irvine, Irvine, California 92717*
[2]*The University of Michigan, Ann Arbor, Michigan 48109*
[3]*Brookhaven National Laboratory, Upton, New York 11973*
[4]*California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California 91109*
[5]*Cleveland State University, Cleveland, Ohio 44115*
[6]*The University of Hawaii, Honolulu, Hawaii 96822*
[7]*University College, London WC1E 6BT, United Kingdom*
[8]*Warsaw University, Warsaw, Poland*
[9]*Case Western Reserve University, Cleveland, Ohio 44106*
[10]*The University of Illinois, Urbana, Illinois 61801*
[11]*The University of California, Berkeley, California 94720*
[12]*Lawrence Livermore National Laboratory, Livermore, California 94550*
[13]*The University of Notre Dame, Notre Dame, Indiana 46556*
[14]*Boston University, Boston, Massachusetts 02215*
[15]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[16]*AT&T Bell Laboratories, Summit, New Jersey 07910*

(Received 13 March 1987)

A burst of eight neutrino events preceding the optical detection of the supernova in the Large Magellanic Cloud has been observed in a large underground water Cherenkov detector. The events span an interval of 6 s and have visible energies in the range 20–40 MeV.

PACS numbers: 97.60.Bw, 14.60.Gh, 95.85.Sz

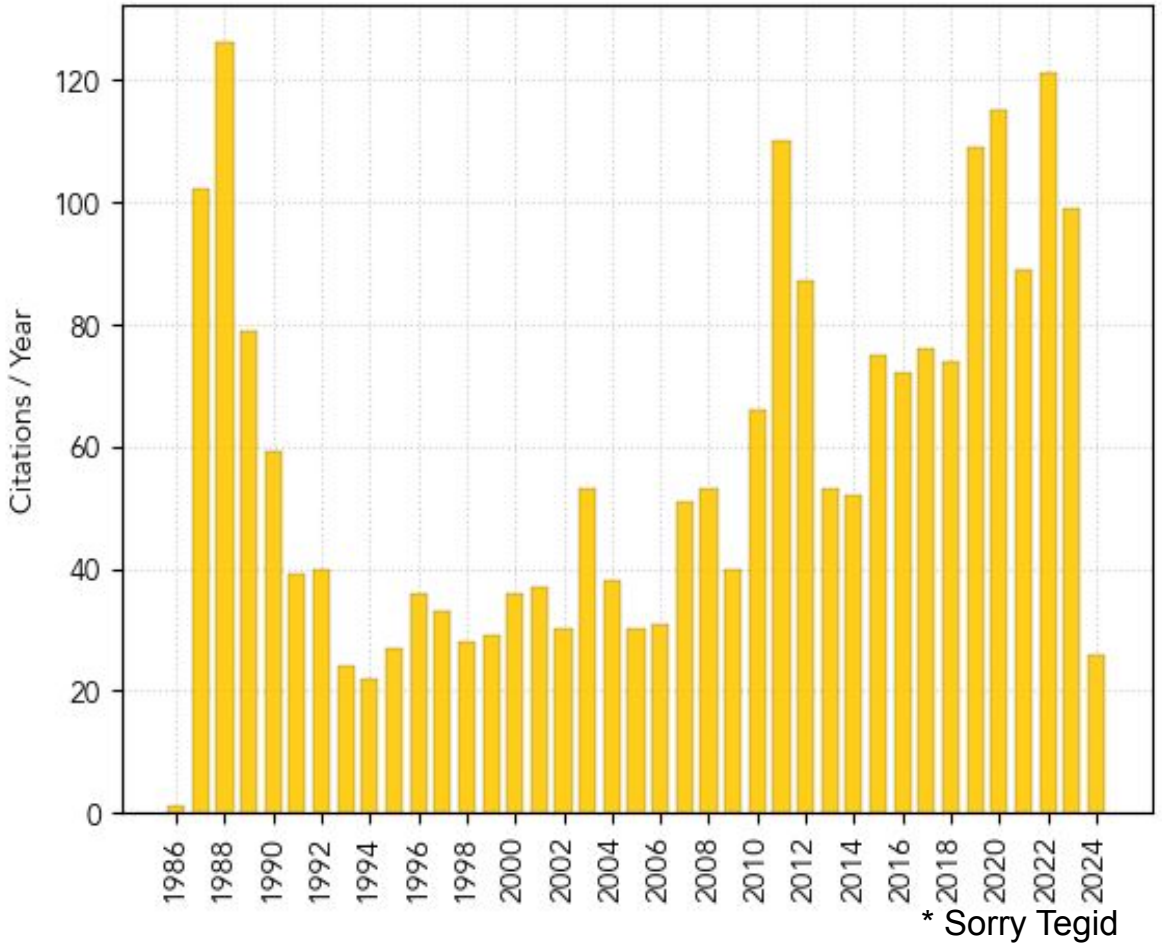
Also seen in the IMB experiment

Citations Kamiokande SN1987A

Our first actual measurement of astrophysical (defined for this slide as from outside the solar system)

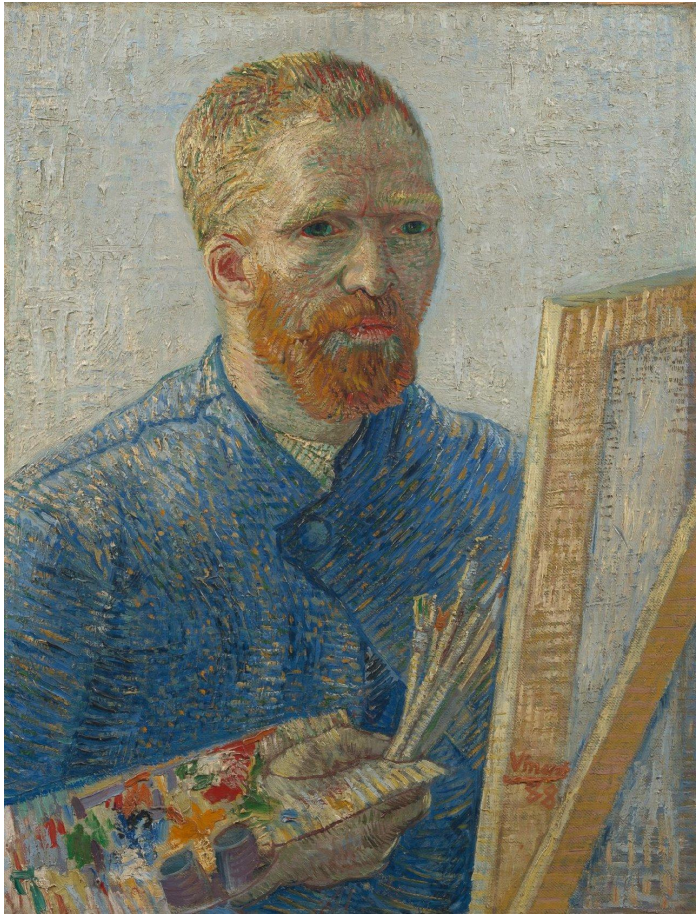
Plot: Shows citations per year for the Kamiokande-II* paper reporting the measurement of 11 (eleven) neutrinos from Supernova 1987A

Are these the most cited particles of all time?



* Sorry Tegid

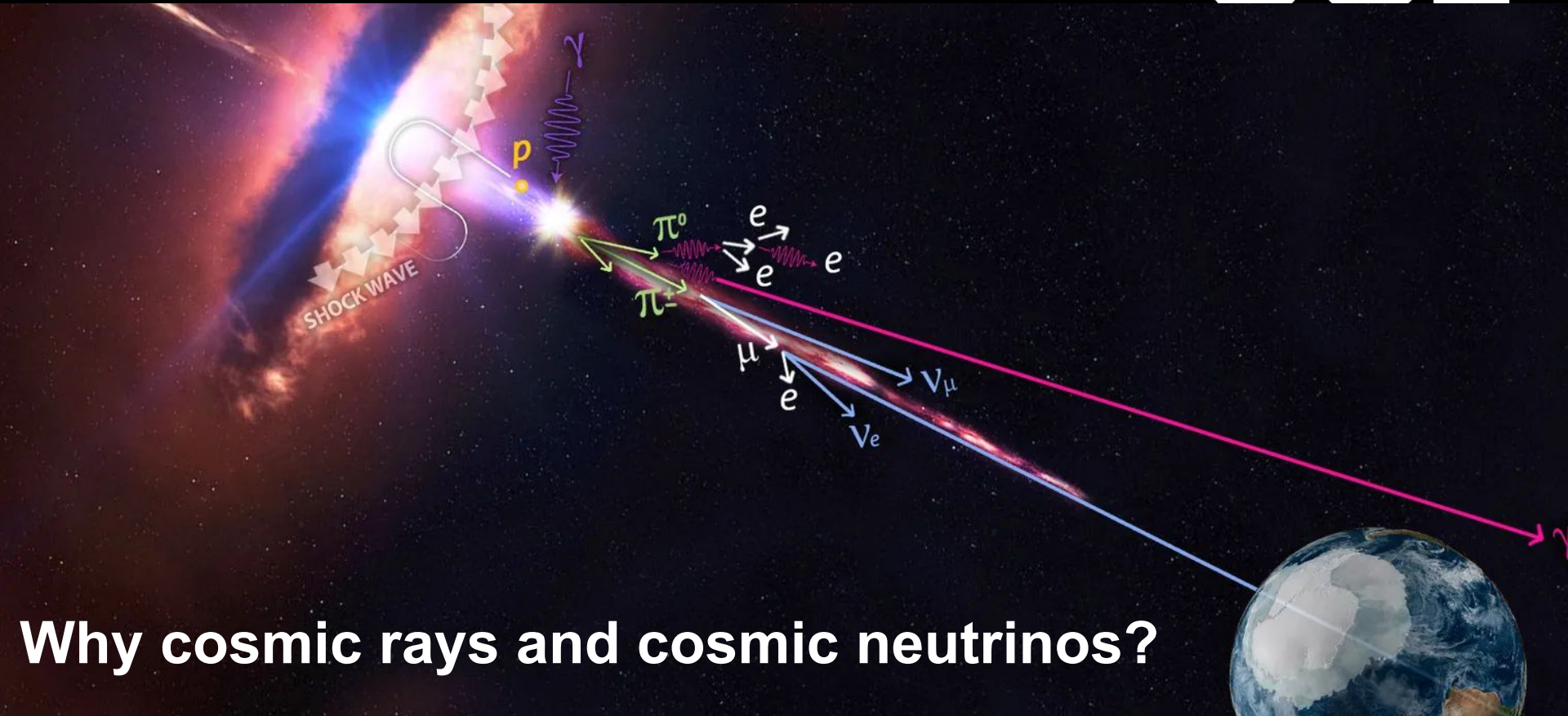
Why look for cosmic messengers?



The Artist

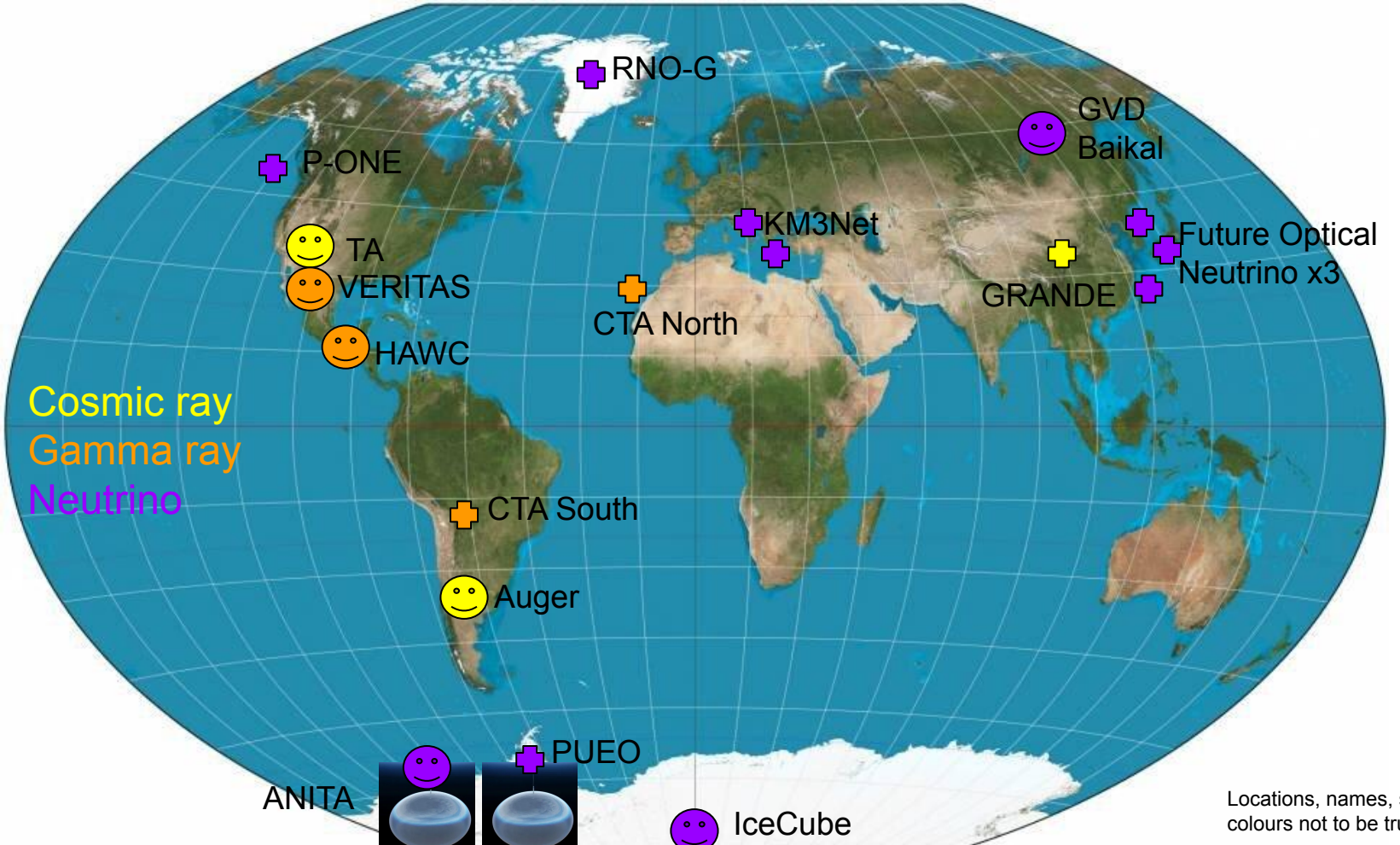
The Mountain Climber

UCL



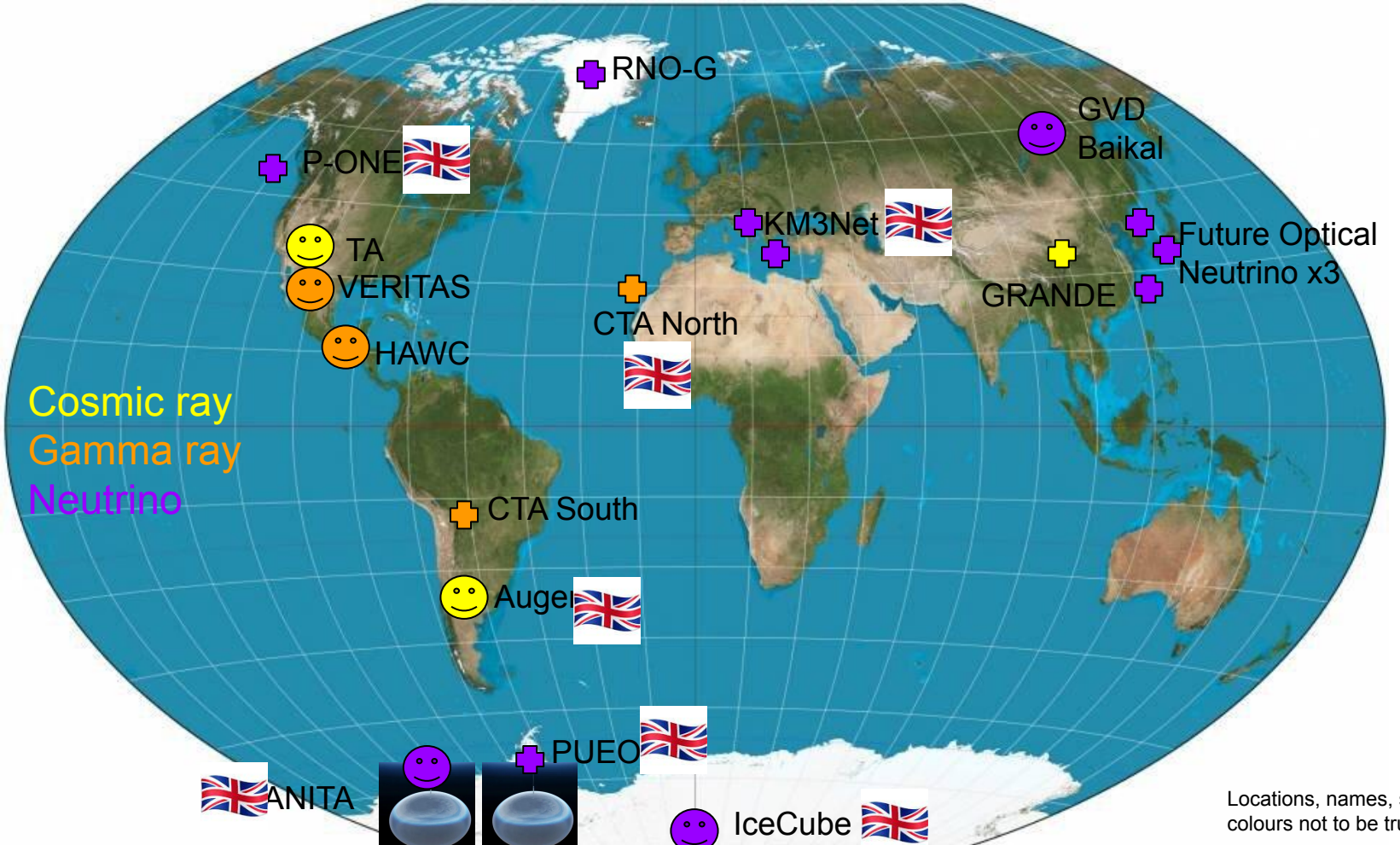
Why cosmic rays and cosmic neutrinos?

Where do we look for them?



Locations, names, shapes, and colours not to be trusted.

Where do we look for them?



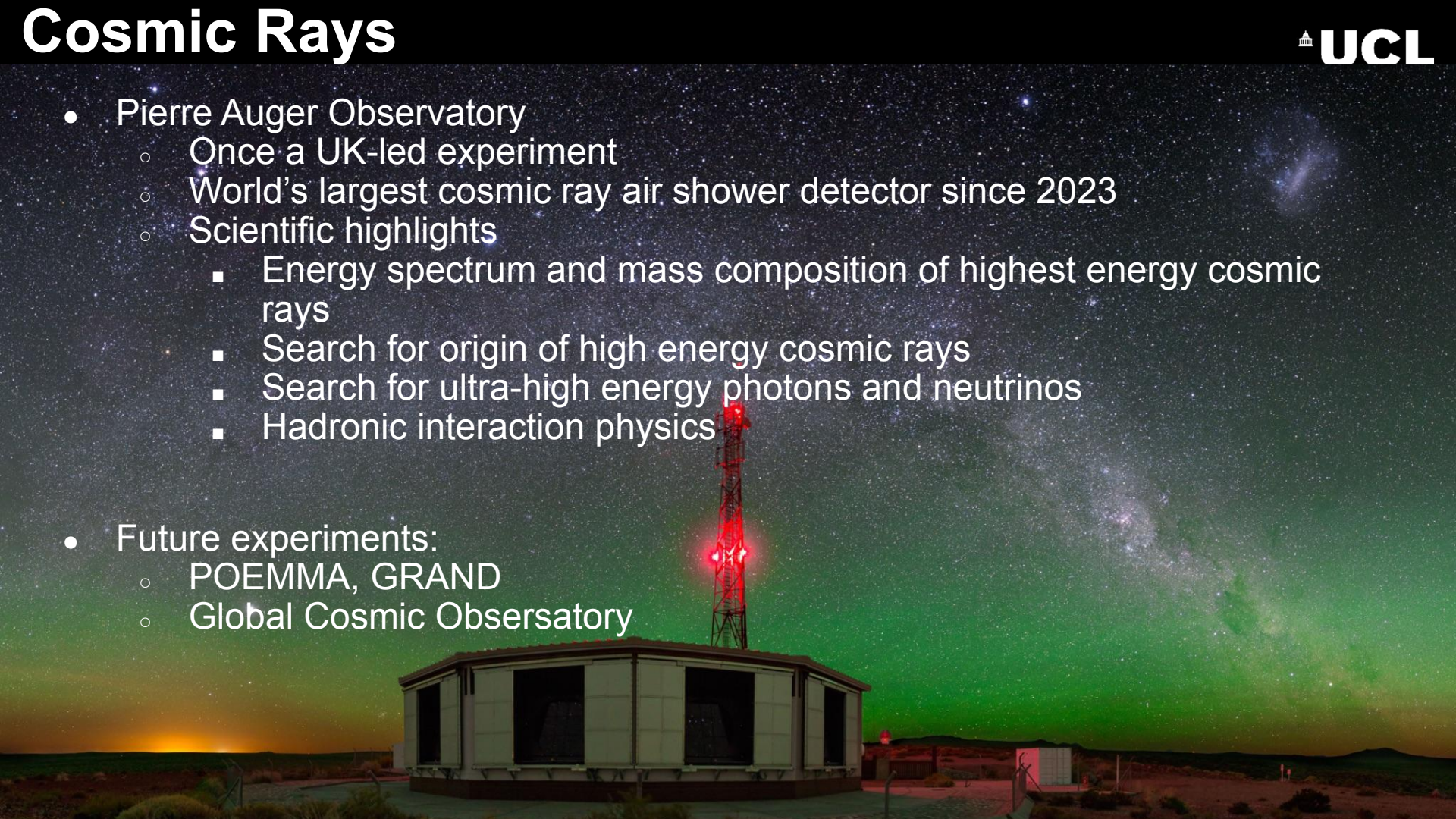
Locations, names, shapes, and colours not to be trusted.

Cosmic Rays

UCL

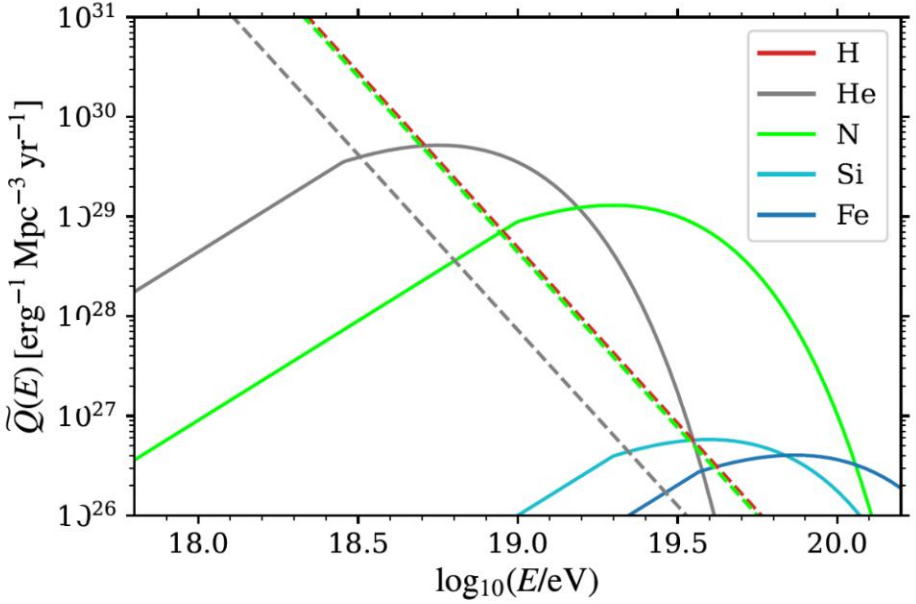
- Pierre Auger Observatory
  - Once a UK-led experiment
  - World's largest cosmic ray air shower detector since 2023
  - Scientific highlights
    - Energy spectrum and mass composition of highest energy cosmic rays
    - Search for origin of high energy cosmic rays
    - Search for ultra-high energy photons and neutrinos
    - Hadronic interaction physics

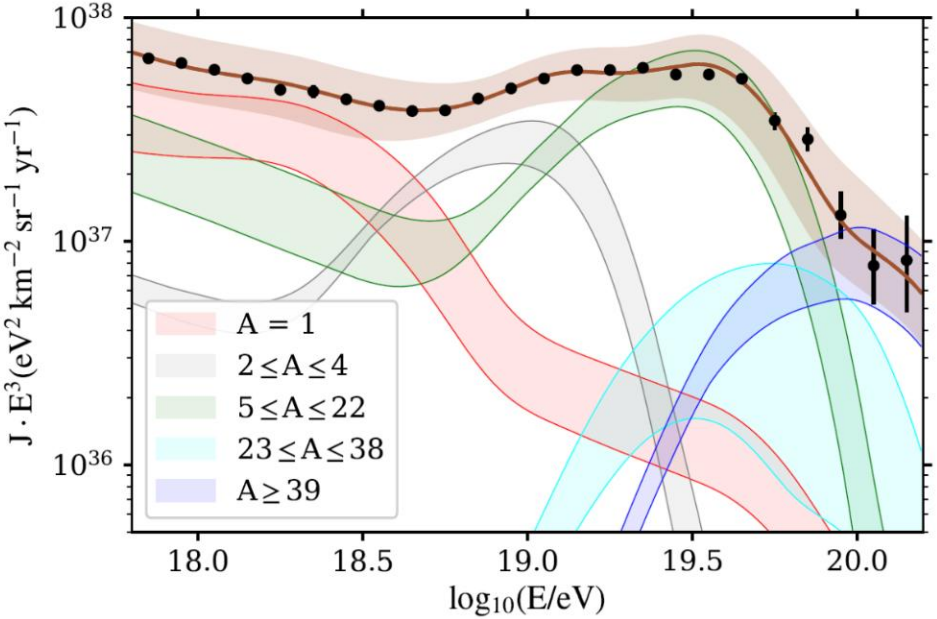
- Future experiments:
  - POEMMA, GRAND
  - Global Cosmic Obsersatory



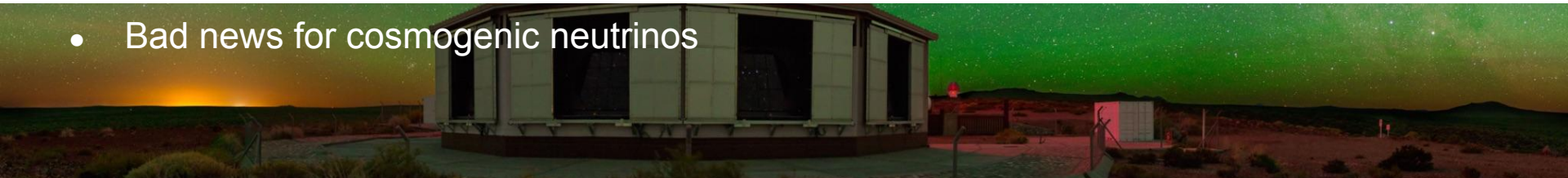
Cosmic Rays

- Cosmic ray mass composition





- Bad news for cosmogenic neutrinos



UCL

High-Energy Gamma Rays

- Covers large energy range with different observatories
- Satellites (Fermi, AMEGO (launch 2029), ASTROGAM)
- Imaging Air Cherenkov Telescopes (H.E.S.S., Veritas, MAGIC)
- Ground-based arrays (GRAPES, TAIGA, HAWC, LHAASO, SWGO)
- Main future project within APPEC: CTA (ESFRI)

APPEC

VERITAS

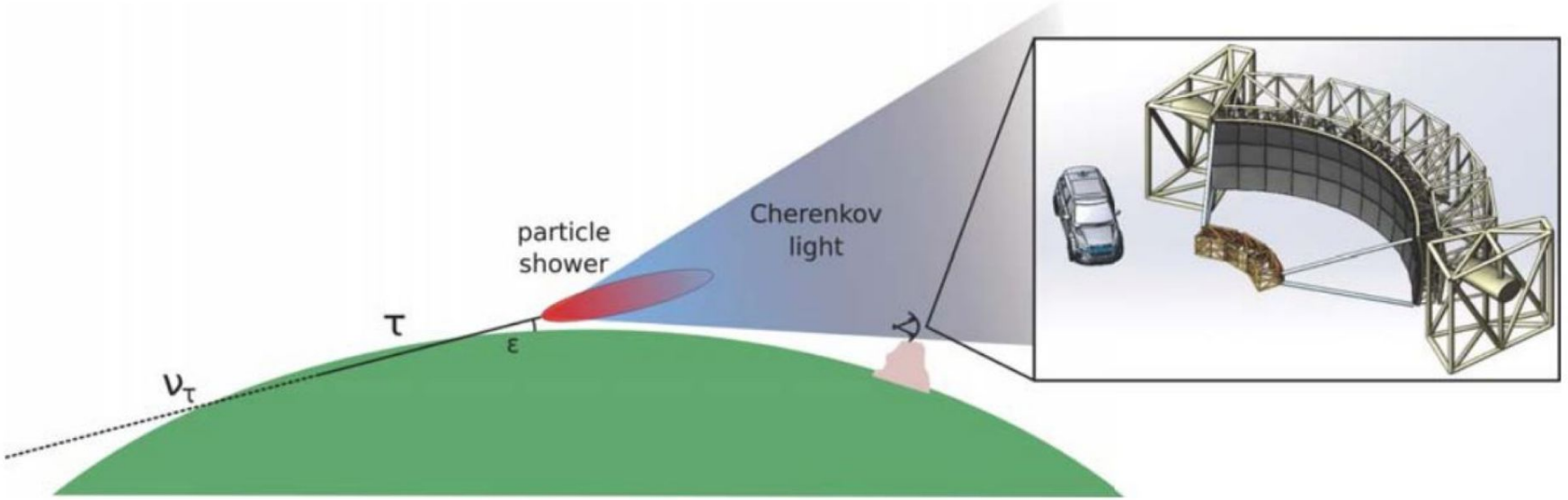
MAGIC

H.E.S.S.

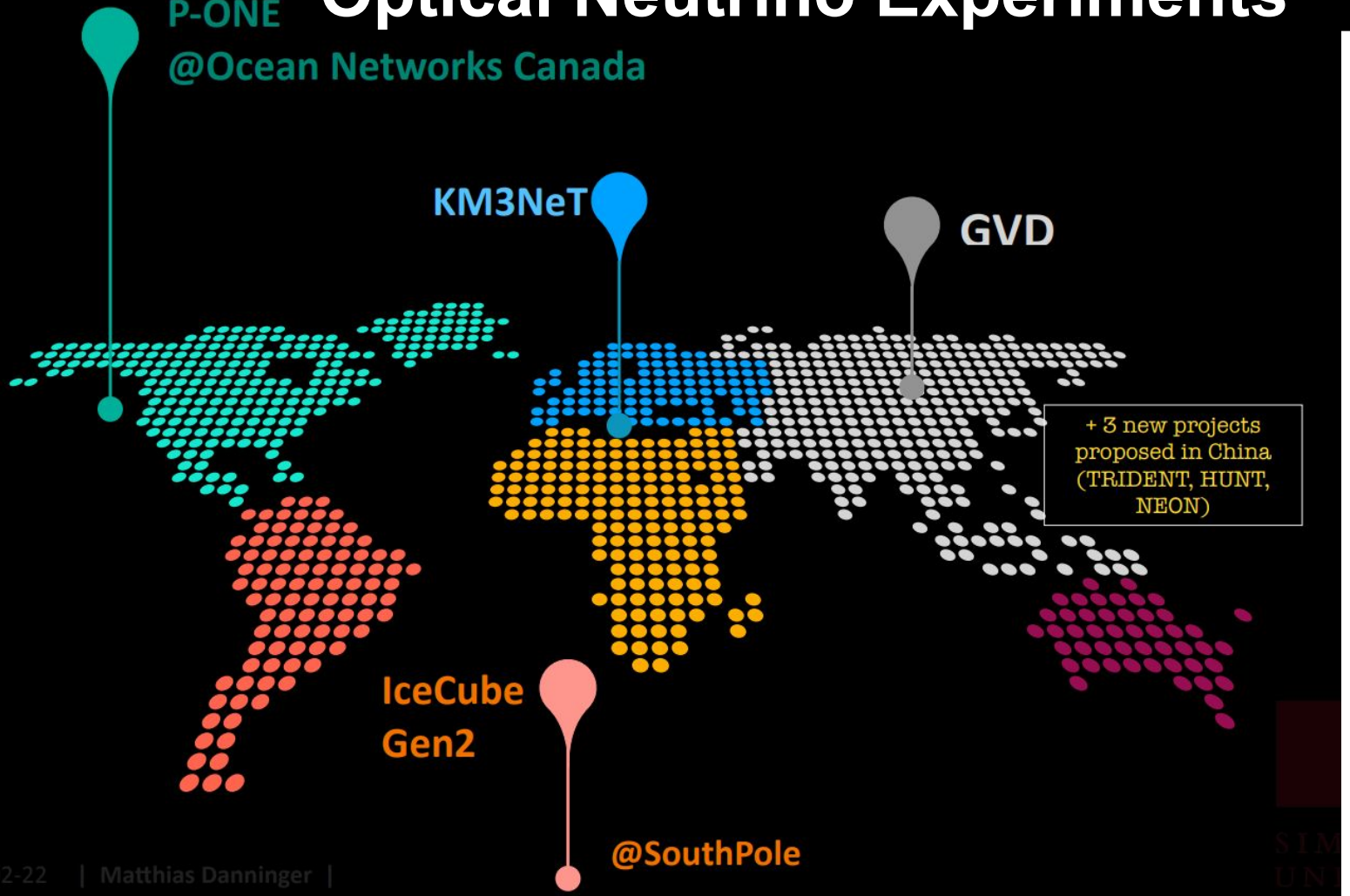
LHAASO

HAWC

Turn air shower detector into neutrino detector

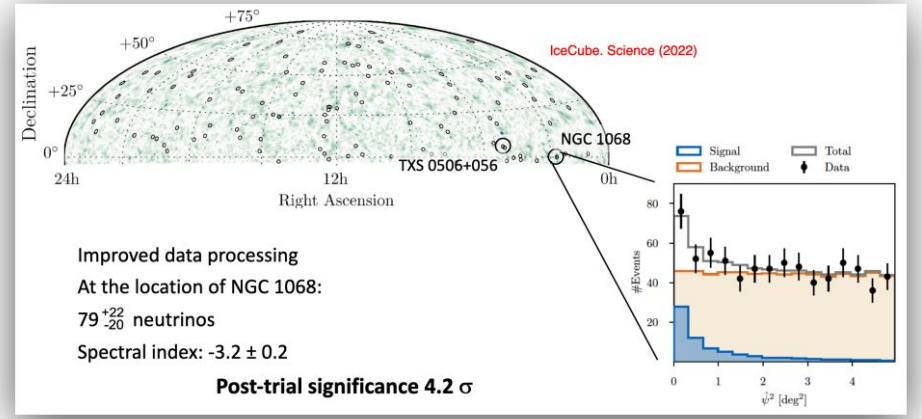


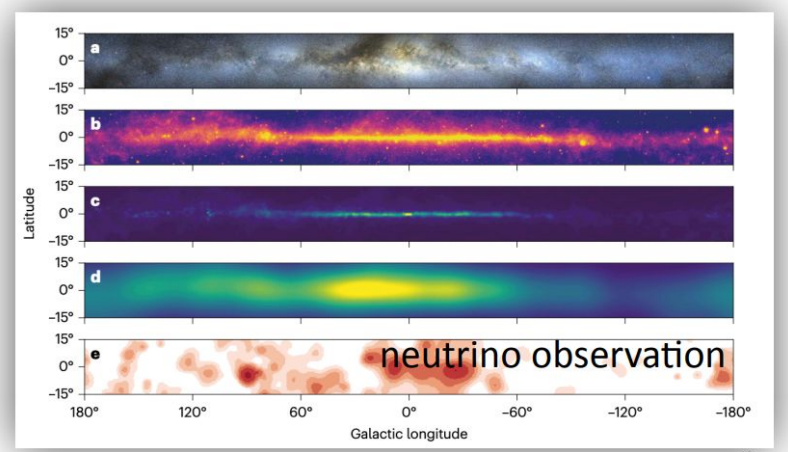
Optical Neutrino Experiments

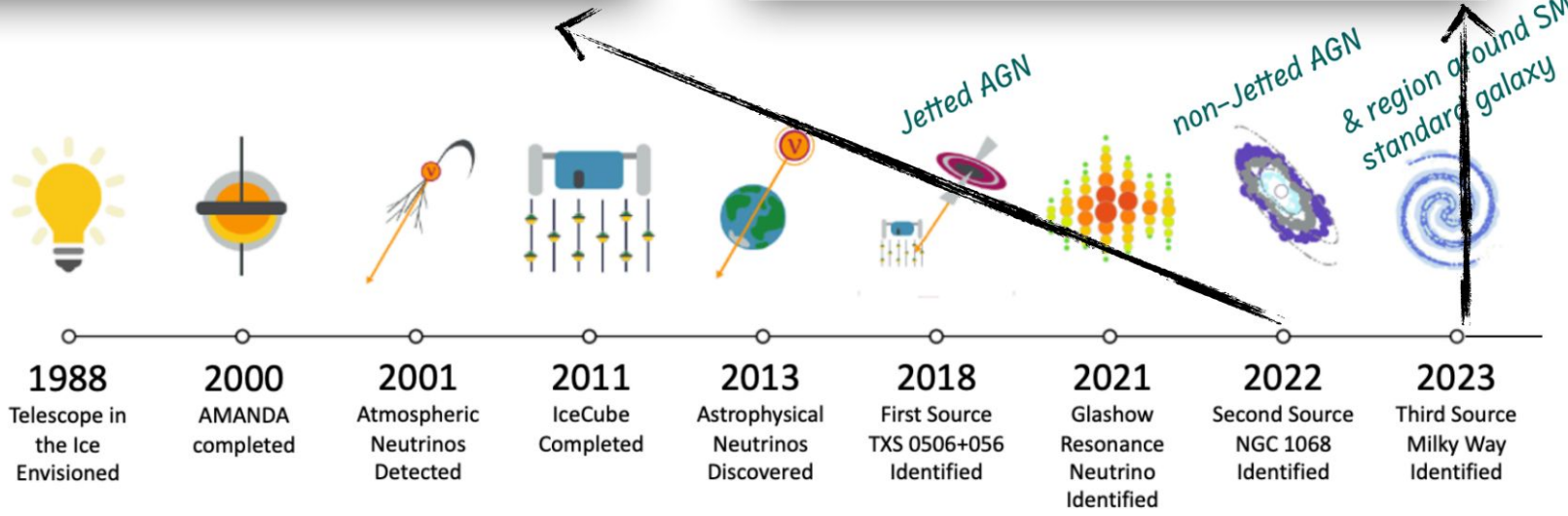


IceCube

UCL


IceCube. Science (2022)
Declination
+75°
+50°
+25°
0°
24h
12h
0h
Right Ascension
NGC 1068
TXS 0506+056
Signal
Background
Total
Data
#Events
80
60
40
20
0
1
2
3
4
ψ^2 [deg^2]
Improved data processing
At the location of NGC 1068:
79^{+22}_{-20} neutrinos
Spectral index: -3.2 ± 0.2
Post-trial significance 4.2 σ


a
b
c
d
e
15°
0°
−15°
Latitude
180°
120°
60°
0°
−60°
−120°
−180°
Galactic longitude
neutrino observation

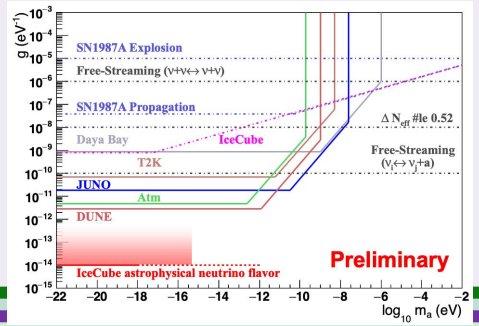

Jetted AGN
non-Jetted AGN
& region around SMBH
standard galaxy
1988
Telescope in the Ice Envisioned
2000
AMANDA completed
2001
Atmospheric Neutrinos Detected
2011
IceCube Completed
2013
Astrophysical Neutrinos Discovered
2018
First Source TXS 0506+056 Identified
2021
Glashow Resonance Neutrino Identified
2022
Second Source NGC 1068 Identified
2023
Third Source Milky Way Identified

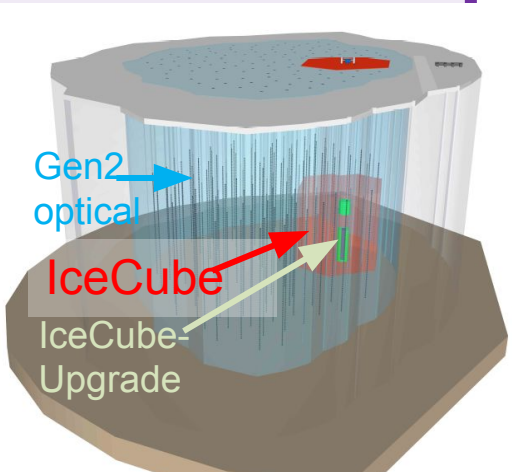
IceCube Science

KING'S College LONDON

Beyond-the-Standard Model Physics

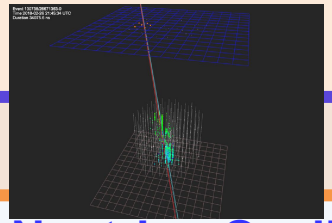
- Astrophysical neutrino flavour physics for new physics
- Quantum Gravity [Nature Physics 18(2022)1287]
- Lorentz violation [CPT2022.59]
- Ultra-light dark matter [PoS(ICRC2023)1225]





Detector R&D

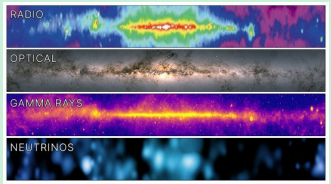
- In-Ice scintillator detector R&D for Gen2 [icecube/202311002]
- Multi-PMT R&D synergy with HyperK, P-ONE, KM3NeT



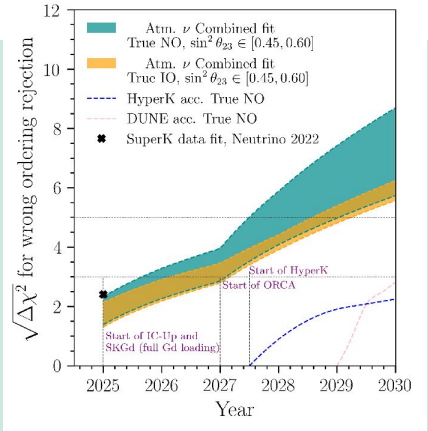
[PoS(ICRC2023)1183]

Astrophysical Neutrinos

- New astrophysical neutrino sample (2024) [PoS(ICRC2023)1007]
- High-energy neutrinos from the galactic plane† [Science 380(2023)1338]



† no direct involvement from IceCube-King's groups



Neutrino Oscillations

- IceCube-Upgrade under construction
- Neutrino interaction systematics study
- First 3σ neutrino mass ordering result in 2027 [PRX 13(2023)041055]
- Joint 5σ NMO result in 2029

Tau Neutrino Observation

UCL

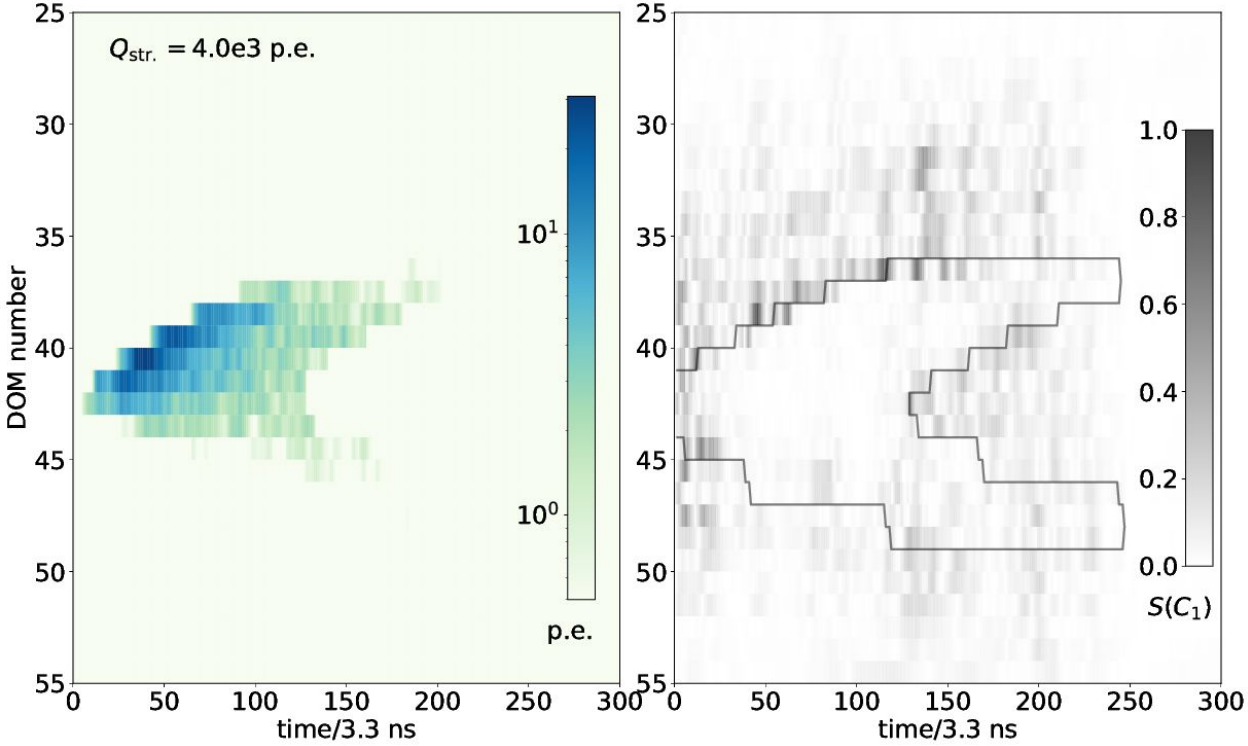
Observation of Seven Astrophysical Tau Neutrino Candidates with IceCube

IceCube Collaboration • R. Abbasi Show All(403)

Mar 4, 2024

e-Print: 2403.02516 [astro-ph.HE]

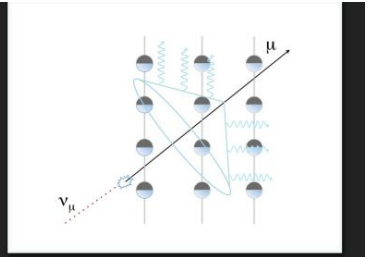
Slightly fake ‘UK’ result as Doug Cowen (Penn State) has been on sabbatical over here



Beyond IceCube

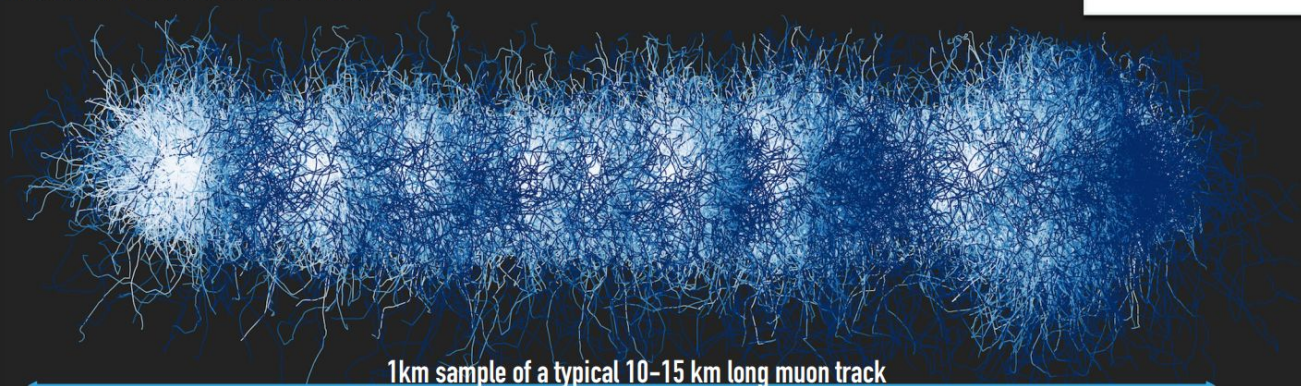
UCL

HORIZONTAL HIGH ENERGY MUONS: THE SIGNATURE



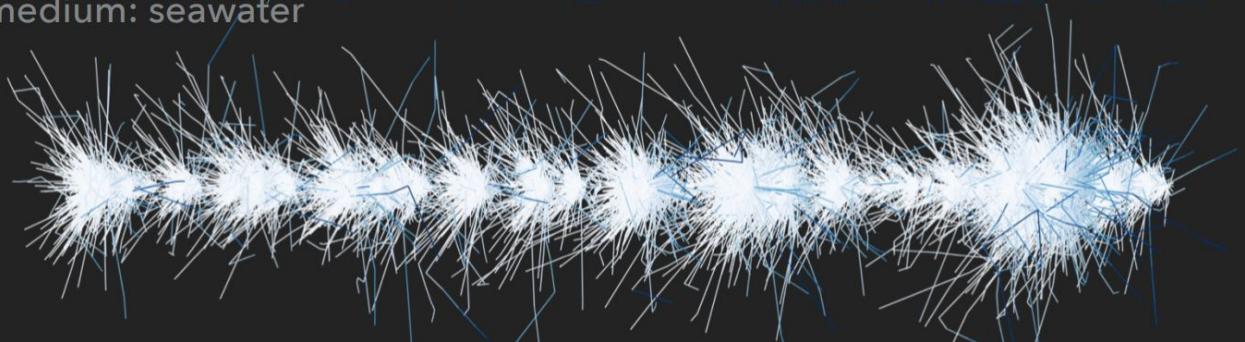
1 PeV horizontal muon

medium: IceCube ice

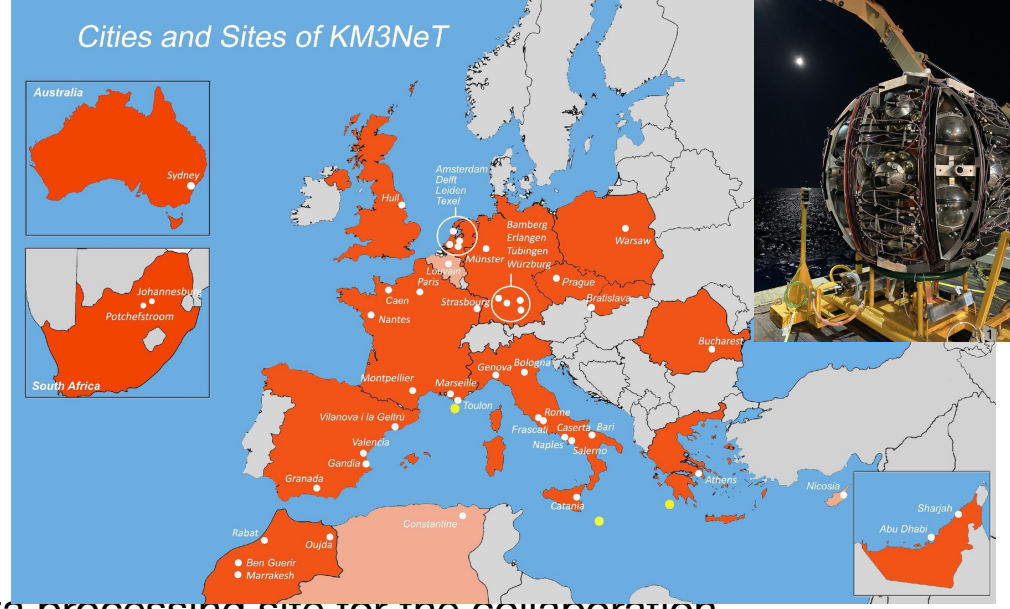


1km sample of a typical 10–15 km long muon track

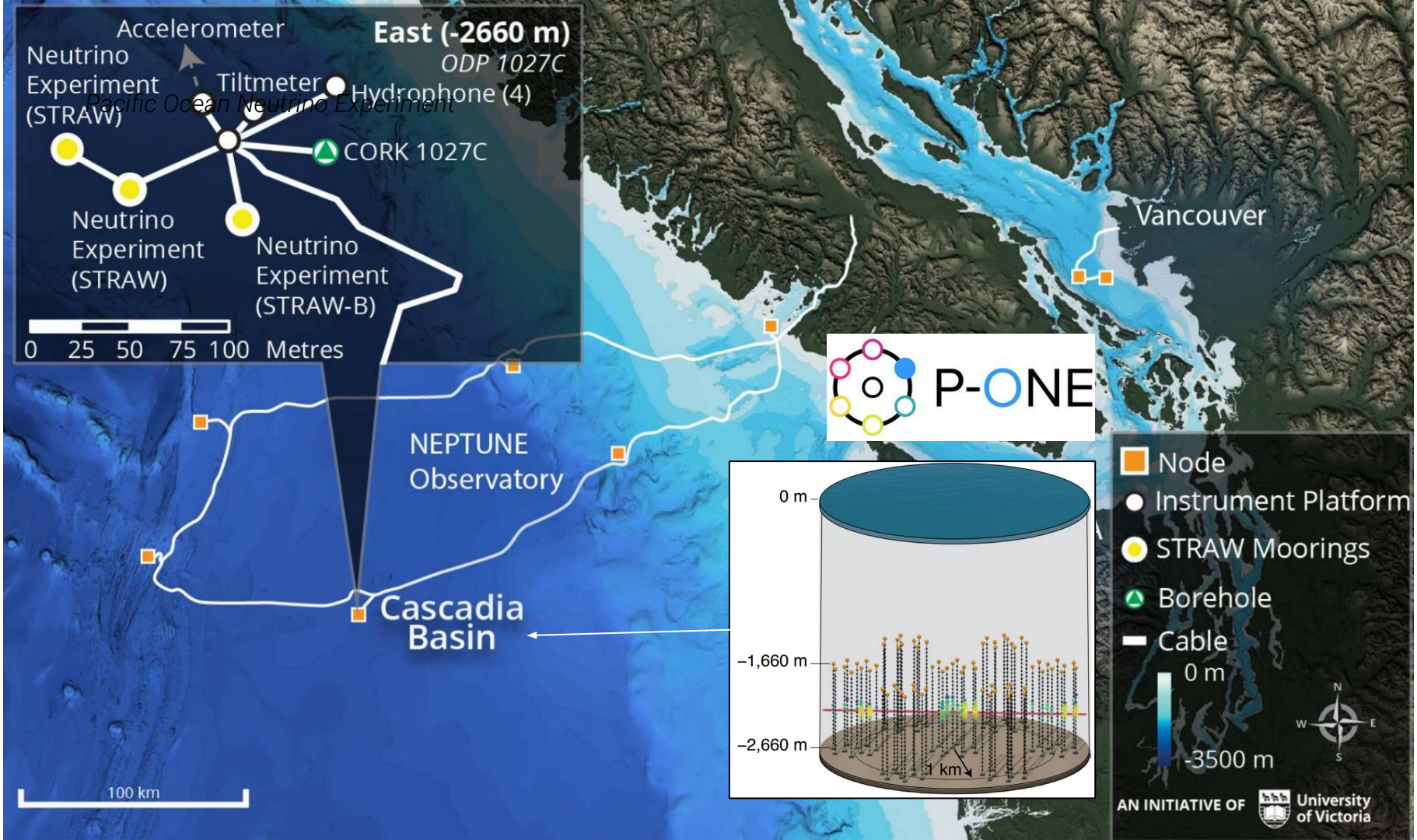
medium: seawater



Current KM3NeT activities @ Hull



- **ML/AI** workgroup looking at better event classification
- **Data workflow and processing** of event data from shore stations
  - Hull HPC to become Tier-1 KM3NeT data processing site for the collaboration
- **Neutrino oscillation** studies using quantum computing techniques to develop faster models
- **Outreach**: KM3NeT-focussed exhibits at the Deep submarium in Hull
- **Astronomy**: Supporting efforts aimed at real-time detection of CC SNe neutrinos and their use in discriminating between models


Accelerometer
East (-2660 m)
ODP 1027C
Neutrino Experiment (STRAW)
Tiltmeter
Hydrophone (4)
Pacific Ocean Neutrino Experiment
CORK 1027C
Neutrino Experiment (STRAW)
Neutrino Experiment (STRAW-B)
0 25 50 75 100 Metres
Vancouver
P-ONE
NEPTUNE Observatory
Cascadia Basin
0 m
–1,660 m
–2,660 m
1 km
100 km
Node
Instrument Platform
STRAW Moorings
Borehole
Cable
0 m
-3500 m
N
W
E
S
AN INITIATIVE OF
University of Victoria

P-ONE

Pacific Ocean Neutrino Experiment

[Agostini et al., Nature Astronomy 4 (2020)]

What's P-ONE?

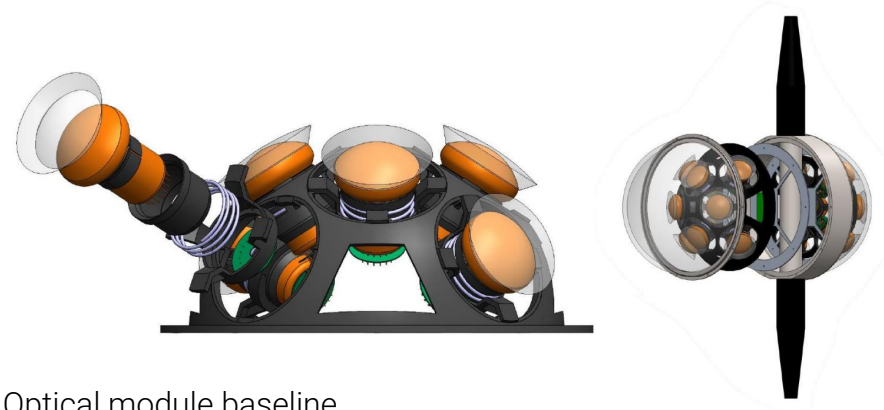
- km^3-scale water Cherenkov detector
- optimized for cosmic neutrinos (100 TeV- PeV)
- opening the northern sky, view on Milky Way centre

Building on consolidated technology

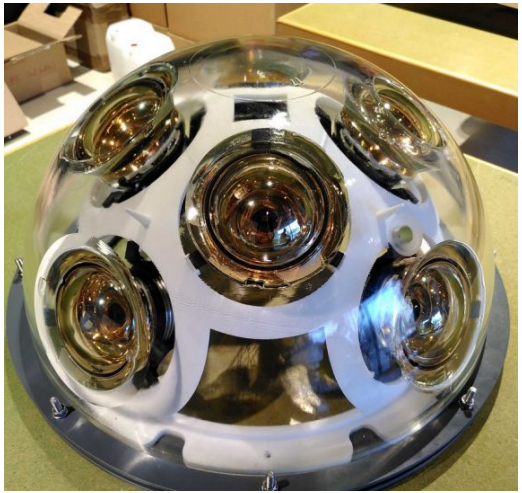
- array of instrumented vertical lines (IceCube)
- multi-PMT optical sensors (KM3Net)
- clustered deployment (GVD)

Innovations and breakthroughs

- new cutting-edge line concept
- integrated in large scale oceanographic infrastructure
- focus on modular and scalable design



Optical module baseline design with 16 Hamamatsu R14374-10



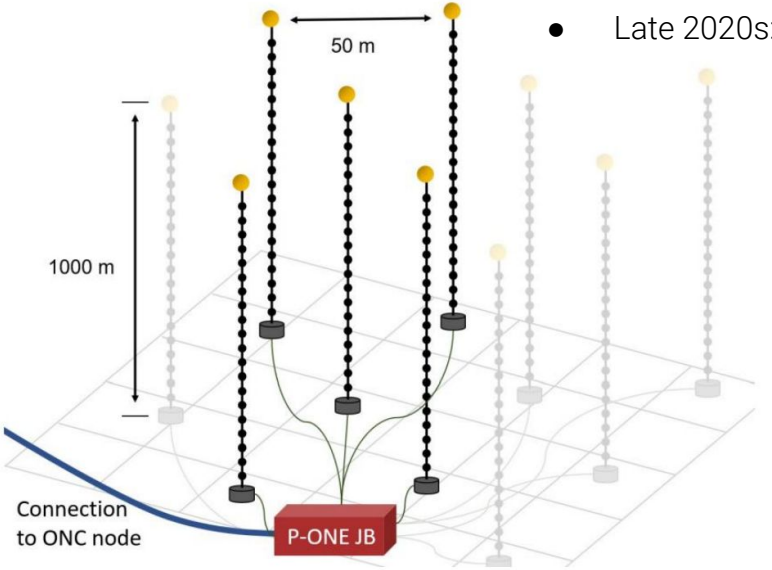
P-ONE module in integration testing

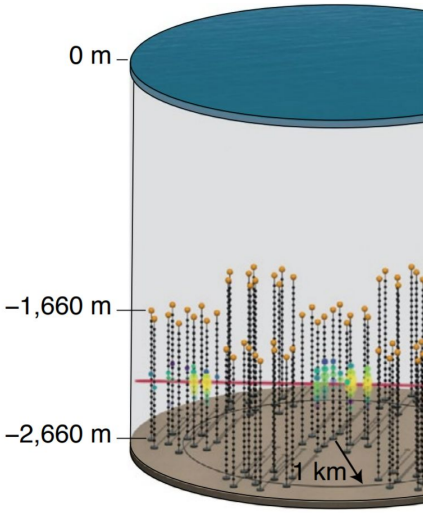
P-ONE

Pacific Ocean Neutrino Experiment

Timeline:

- 2018-present: site validation
- 2020-2022: cable/infrastructure design
- 2021-2024 module technical design
- 2025: pilot string deployment
- 2025-2028: demonstrator
- Late 2020s: full detector construction

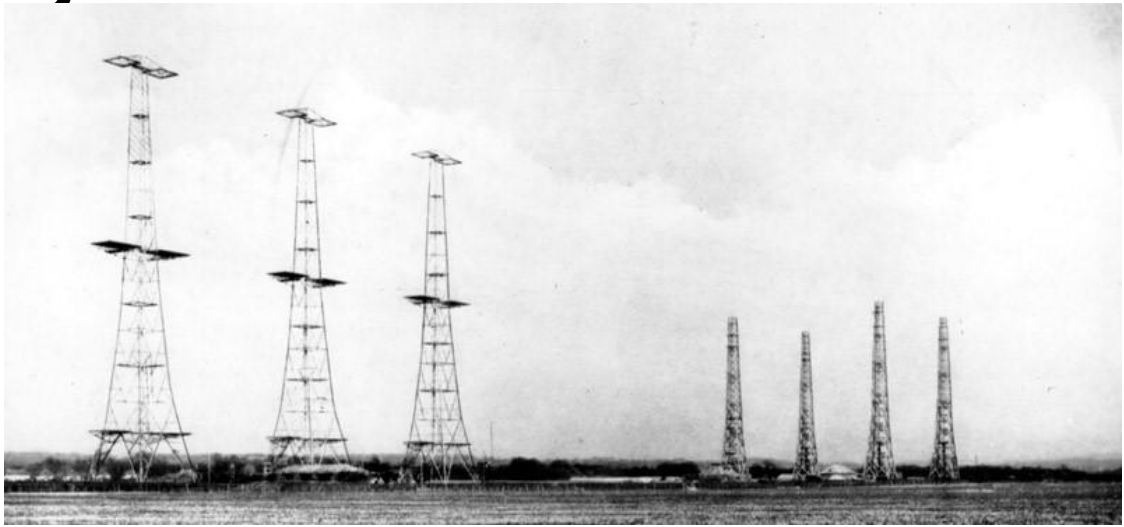




P-ONE pilot string
2025

P-ONE demonstrator
2025-2028

Radar & Particle Physics



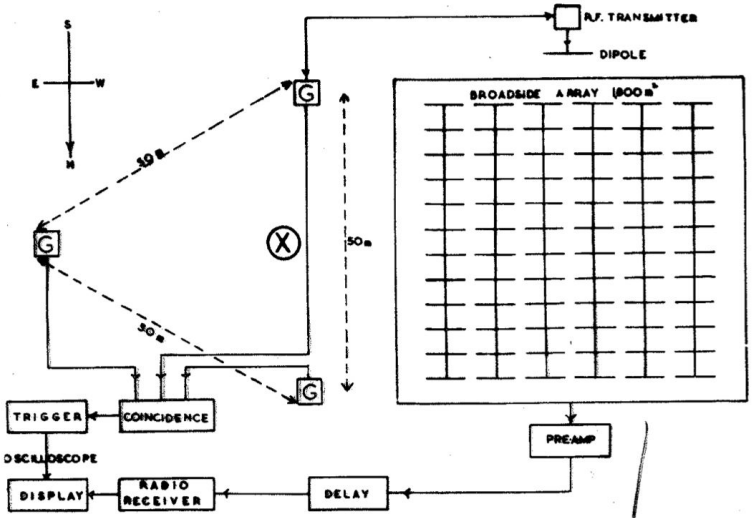
Radio echoes and cosmic ray showers

By P. M. S. Blackett, F.R.S., and A. C. B. Lovell

(*Received* 22 *October* 1940)

Watch Bernard Lovell discussing this https://www.webofstories.com/people/bernard.lovell/22?o=SH

Radio detection of cosmic rays



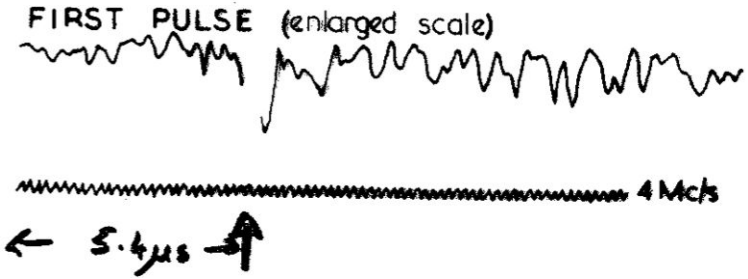
4 sections,
3 wλ by 3λ
Area ~ 1,700
T~ 450°K

Setting Up at Jodrell Bank, July, 1964

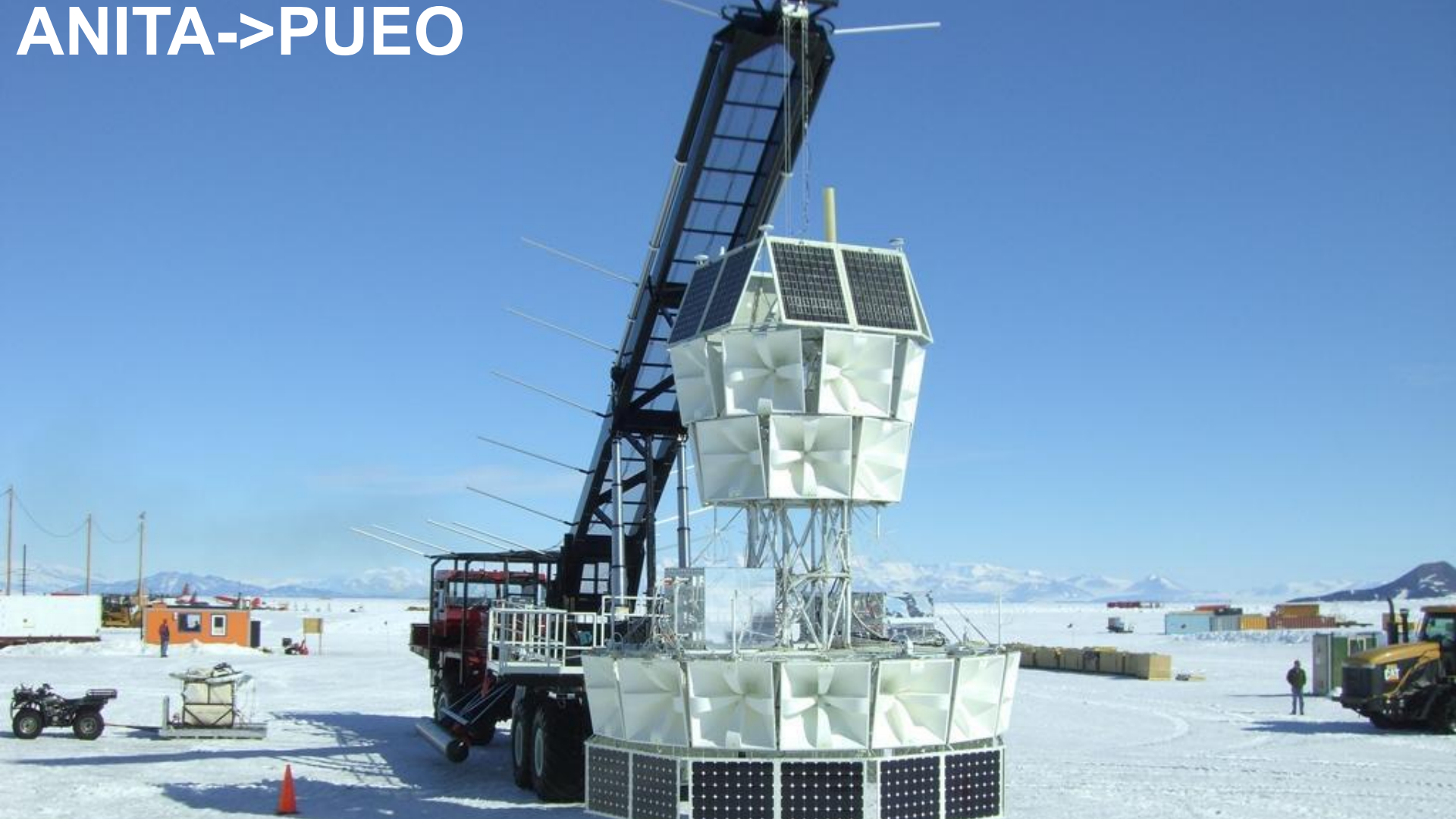
RADIO PULSES FROM EXTENSIVE COSMIC-RAY AIR SHOWERS

By Dr. J. V. JELLEY and J. H. FRUIN
Atomic Energy Research Establishment, Harwell
Prof. N. A. PORTER and T. C. WEEKES
University College, Dublin
AND
Prof. F. G. SMITH and R. A. PORTER
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank

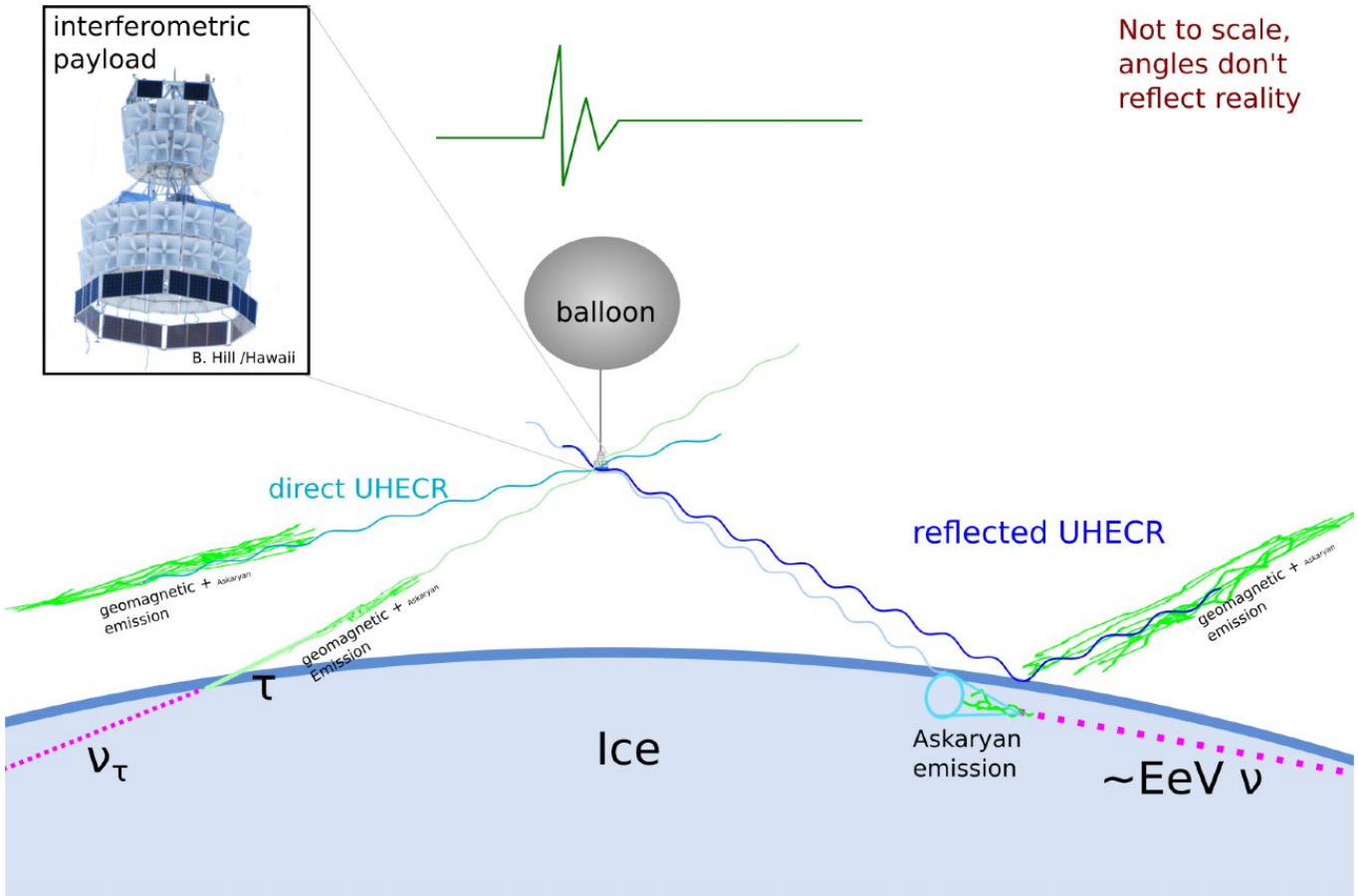
The First Event



ANITA->PUEO



Concept


interferometric payload
B. Hill /Hawaii
Not to scale, angles don't reflect reality
balloon
direct UHECR
reflected UHECR
geomagnetic + Askaryan emission
geomagnetic + Askaryan Emission
geomagnetic + Askaryan emission
τ
ν_τ
Ice
Askaryan emission
~EeV ν

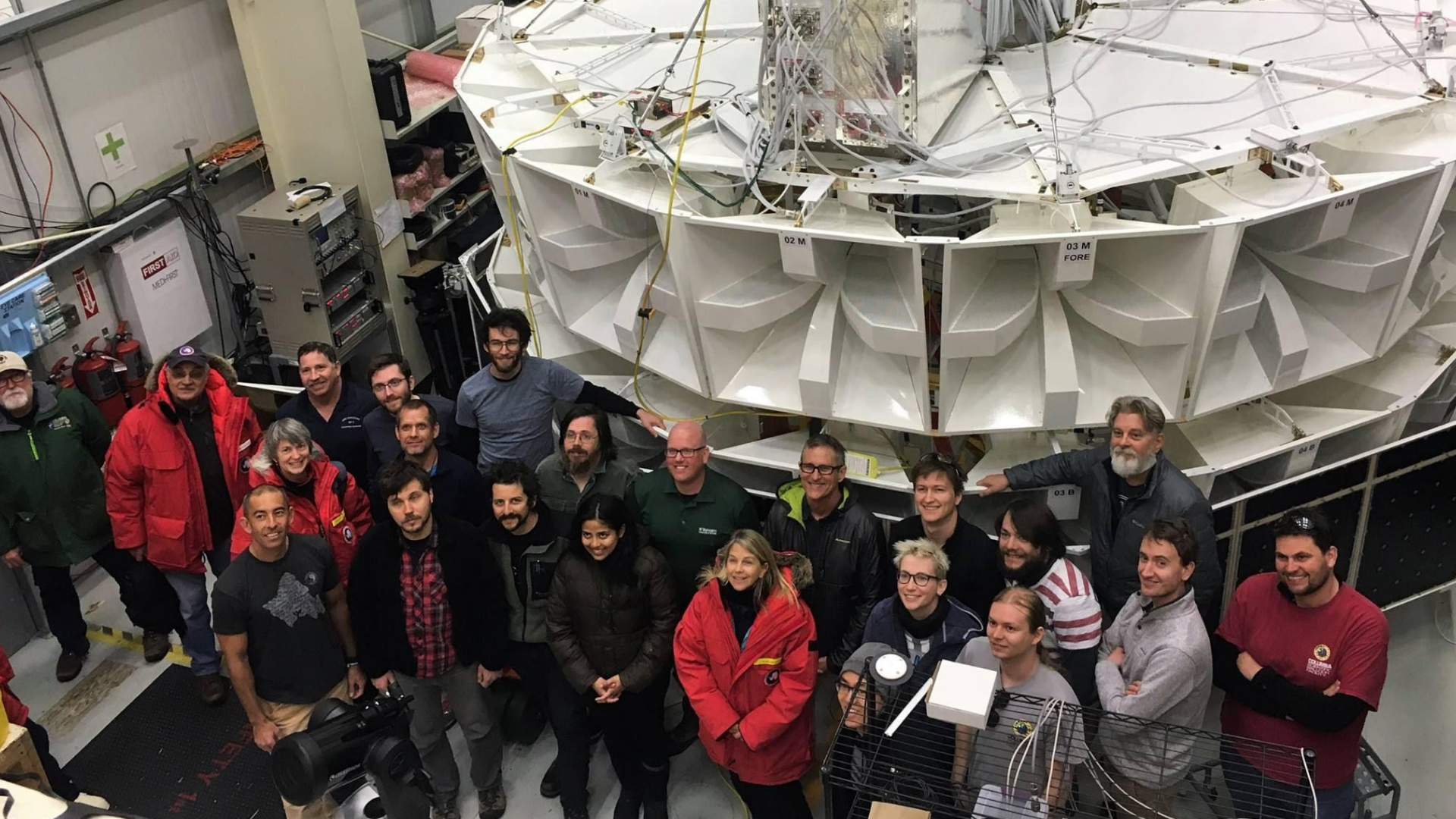
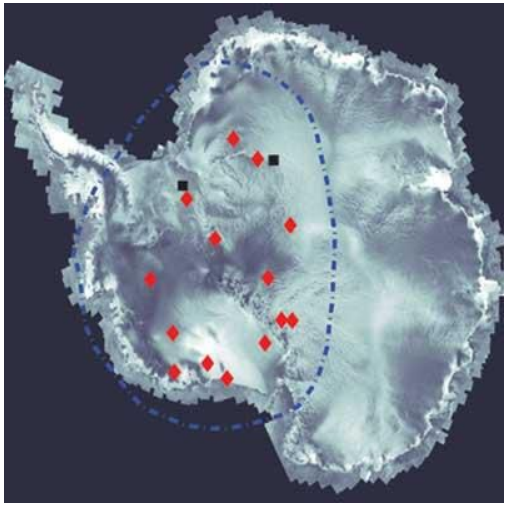
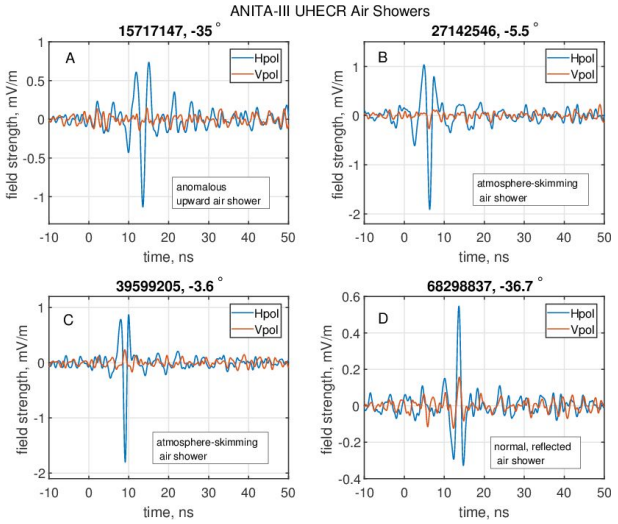

02 M
03 M
FORE
04 M
03 B
04 B
FIRST
MIDFIRST

Image: Christian Miki, University of Hawaii

ANITA results



No neutrinos but lots of cosmic rays…. including some that are going the wrong way



Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANIT

P. W. Gorham,[1] B. Rotter,[1] P. Allison,[2] O. Banerjee,[2] L. Batten,[3] J. J. Beatty,[2] K. Bechtol,[4] K. Belov,[5] D. Z. Besson,[6,7] W. R. Binns,[8] V. Bugaev,[8] P. Cao,[9] C. C. Chen,[10] C. H. Chen,[10] P. Chen,[10] J. M. Clem,[9] A. Connolly,[2] L. Cremonesi,[3] B. Dailey,[2] C. Deaconu,[4] P. F. Dowkontt,[8] B. D. Fox,[1] J. W. H. Gordon,[2] C. Hast,[11] B. Hill,[1] K. Hughes,[2] J. J. Huang,[10] R. Hupe,[2] M. H. Israel,[8] A. Javaid,[9] J. Lam,[12] K. M. Liewer,[5] S. Y. Lin,[10] T.C. Liu,[10] A. Ludwig,[4] L. Macchiarulo,[1] S. Matsuno,[1] C. Miki,[1] K. Mulrey,[9] J. Nam,[10] C. J. Naudet,[5] R. J. Nichol,[3] A. Novikov,[6] E. Oberla,[4] M. Olmedo,[1] R. Prechelt,[1] S. Prohira,[6] B. F. Rauch,[8] J. M. Roberts,[1] A. Romero-Wolf,[5] J. W. Russell,[1] D. Saltzberg,[12] D. Seckel,[9] H. Schoorlemmer,[1] J. Shiao,[10] S. Stafford,[2] J. Stockham,[6] M. Stockham,[6] B. Strutt,[12] G. S. Varner,[1] A. G. Vieregg,[4] S. H. Wang,[10] and S. A. Wissel[13]

A Sterile Neutrino Origin for the Upward Directed Cosmic Ray Showers Detected by ANITA

John F. Cherry[1] and Ian M. Shoemaker[1]

[1]*Department of Physics, University of South Dakota, Vermillion, SD 57069, USA*

(Dated: 8-23-2018)

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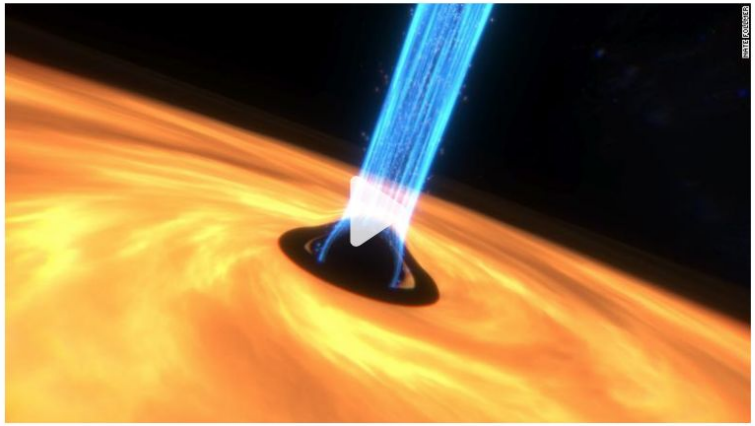
SPACE SCIENCE

Scientists didn't detect a parallel universe in Antarctica. But they are learning more about mysterious, ghostly neutrinos

By Ashley Strickland, CNN

Updated 1544 GMT (2344 HKT) May 27, 2020



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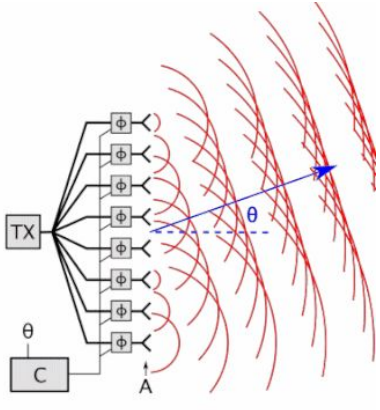
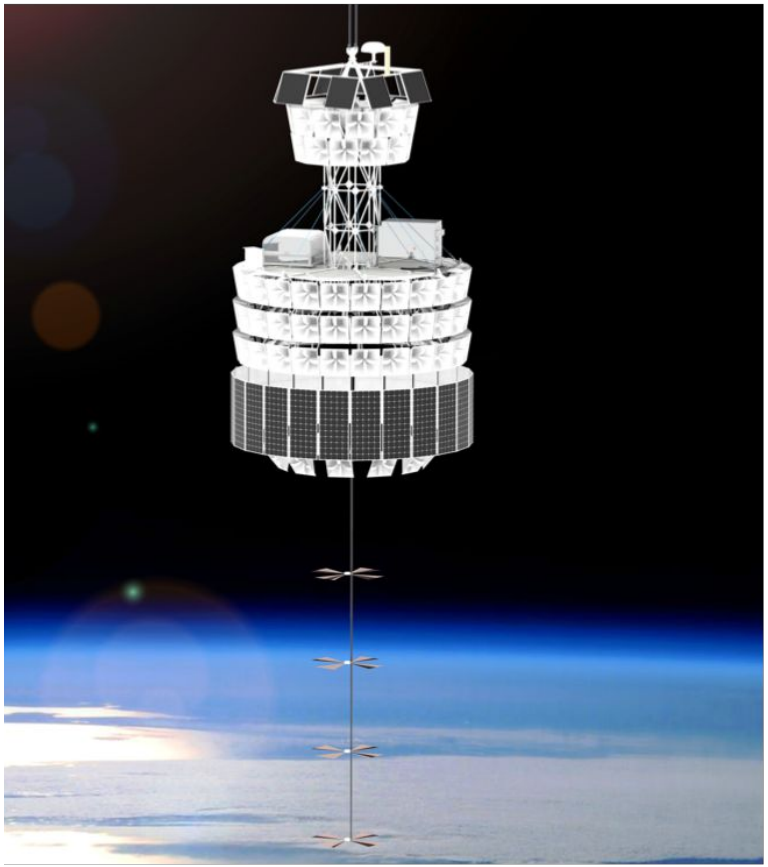
(Elen11/iStock/Getty Images Plus)

...erious Neutrinos Back to ...les

PUEO: Payload for Ultrahigh Energy Observations

- A new name and a new paradigm
  - Embracing the technological advances to implement a trigger based on high-bandwidth digital filtering and beam forming
  - Prototype digitisation system based on XILINX RFSoC under development at UCL



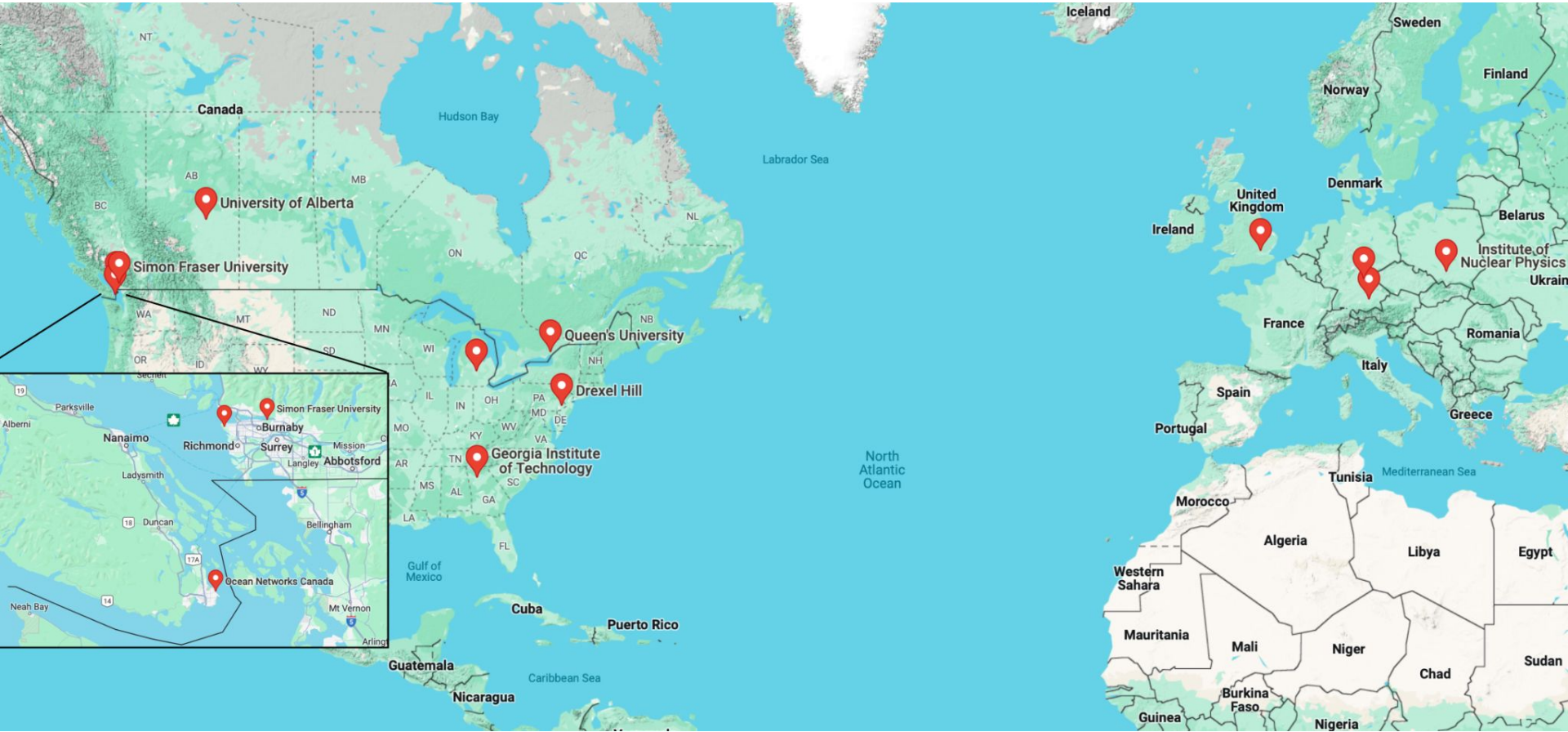


- We have entered the era of multi-messenger astronomy
- Shedding new ‘light’ not only on astrophysics but also particle physics
- PUEO scheduled to fly next year
- Next decade will see the turn on of the next generation of cosmic observatories (CTA, P-ONE, etc.)

P-ONE

Pacific Ocean Neutrino Experiment

12 institutions, ~60 members



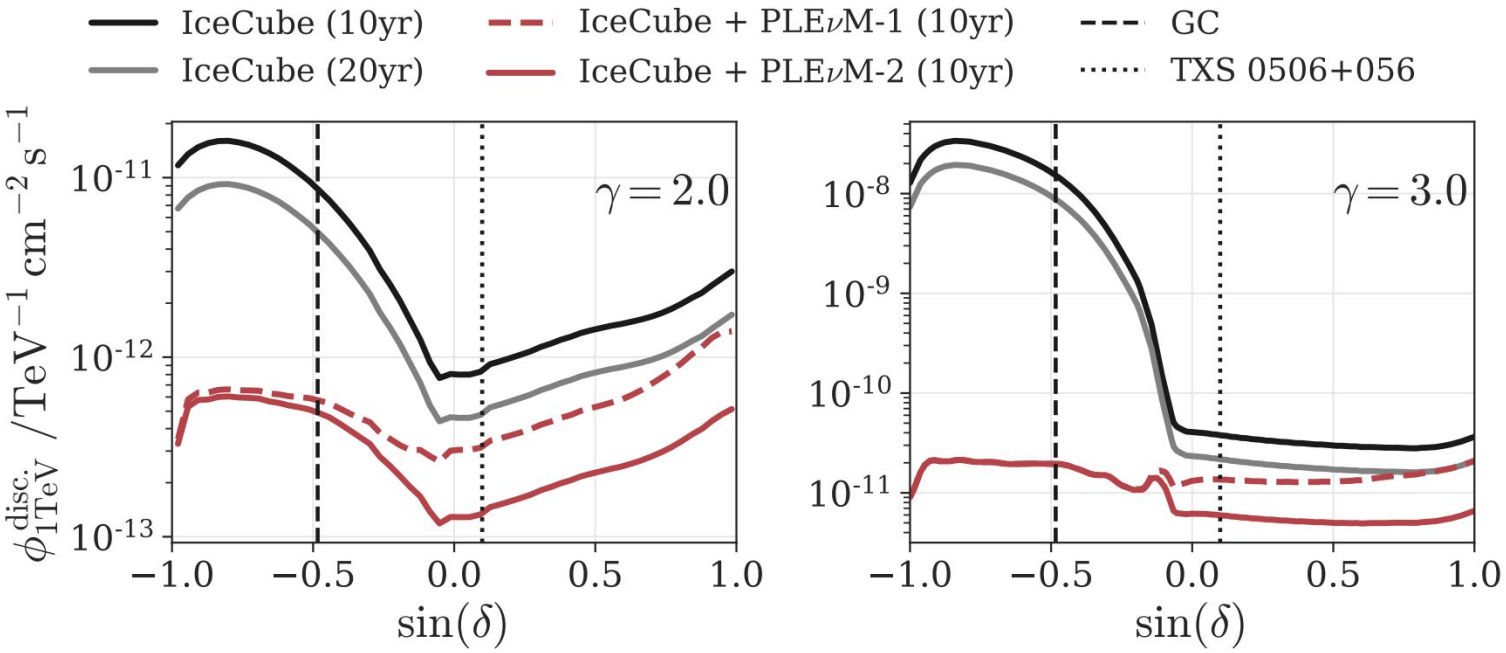


Figure 3: Comparison of discovery potentials (DP) for two spectral indices: $\gamma = 2.0$ (left) and $\gamma = 3.0$ (right). The DP is calculated for an neutrino flux per source with a spectrum of $\mathrm{d}\Phi/\mathrm{d}E = \Phi^{\rm disc.} \cdot (E/1\,\mathrm{TeV})^{-\gamma}$ at 1 TeV. Shown are the DPs based on the 10yr PS analysis by IceCube [3] (black), an estimate with a livetime of 20 yrs (gray), PLEνM-1 including IceCube (dashed red) and PLEνM-2 including IceCube $\times$7.5 (solid red).