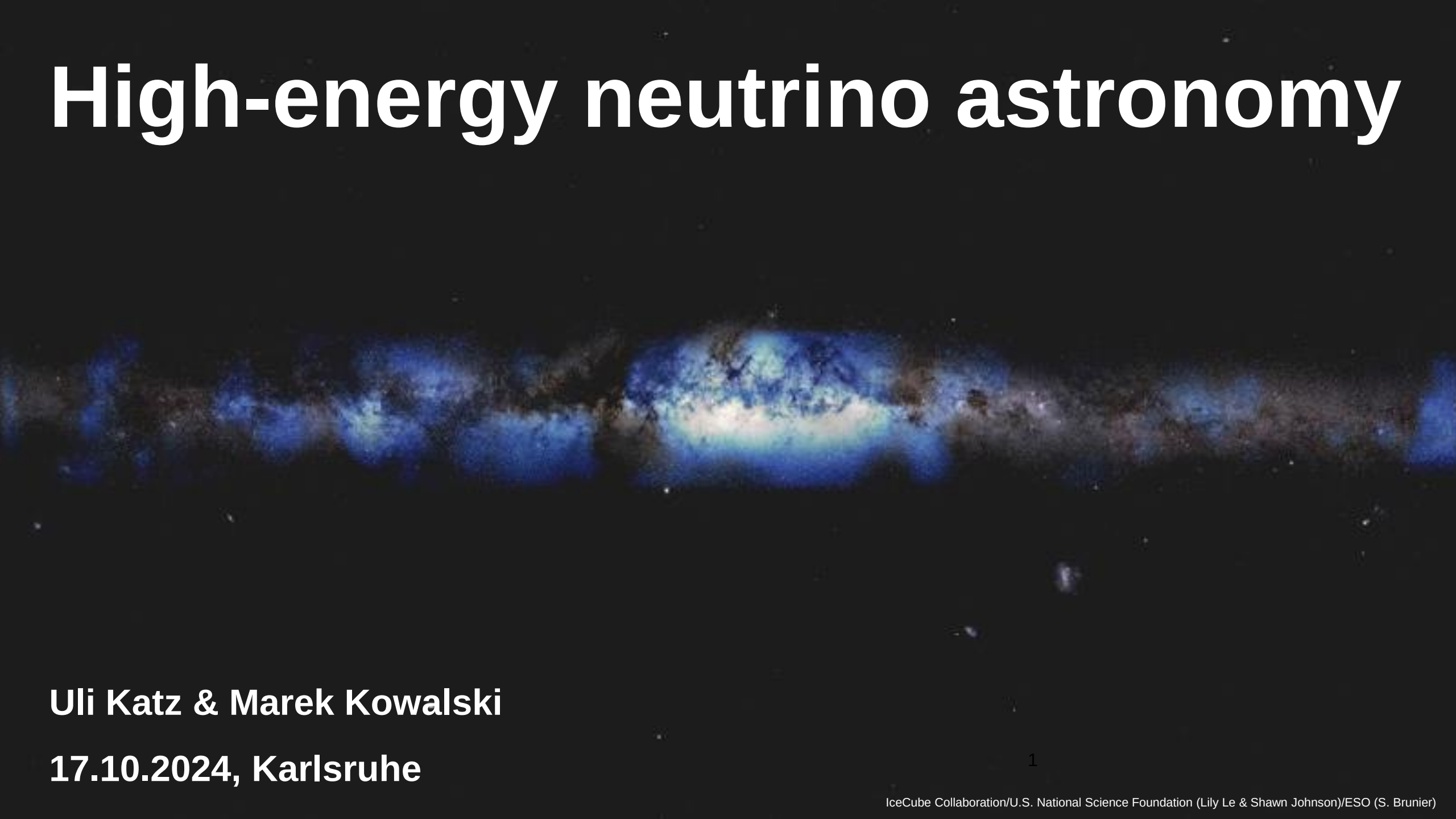
High-energy neutrino astronomy



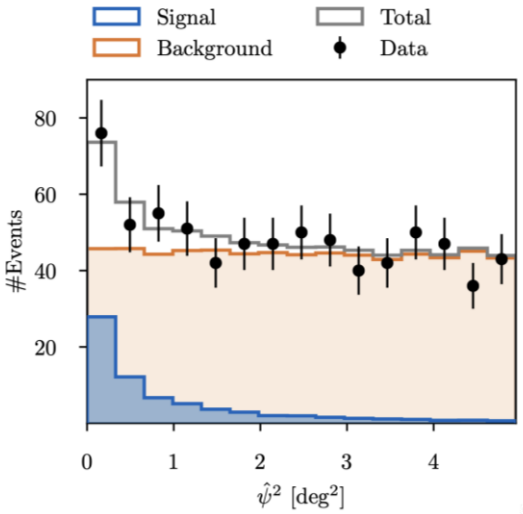
Uli Katz & Marek Kowalski

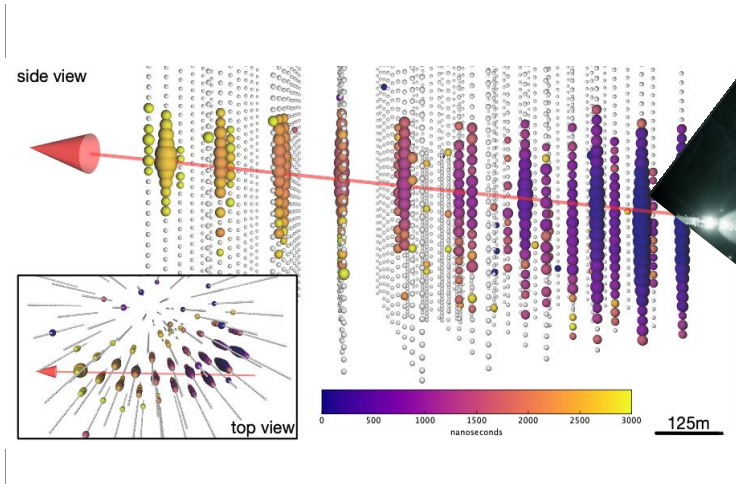
17.10.2024, Karlsruhe

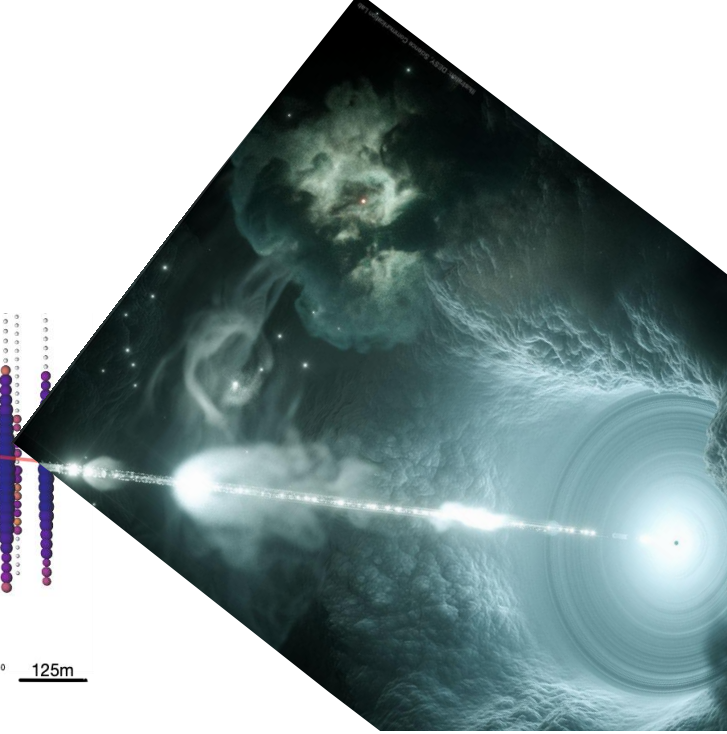
IceCube Collaboration/U.S. National Science Foundation (Lily Le & Shawn Johnson)/ESO (S. Brunier)

High-energy neutrino astronomy

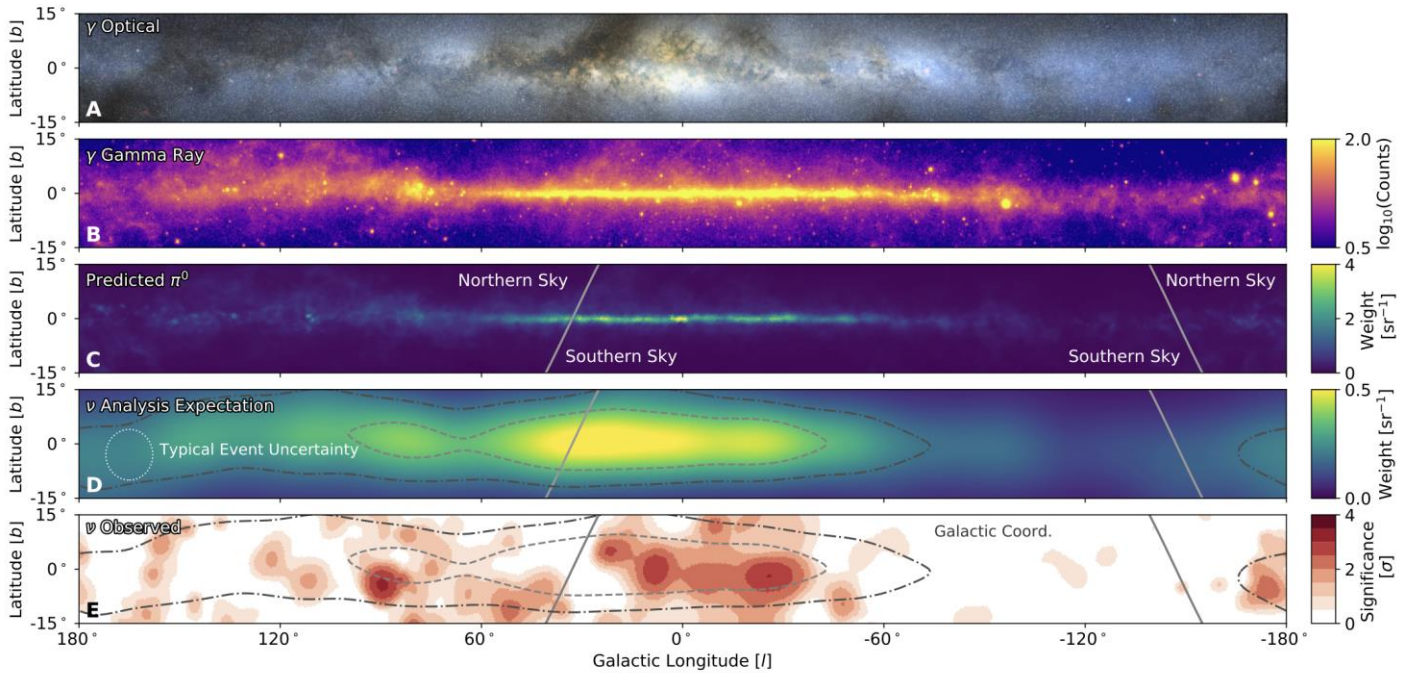
A new window to the Universe has been opened during the last decade!





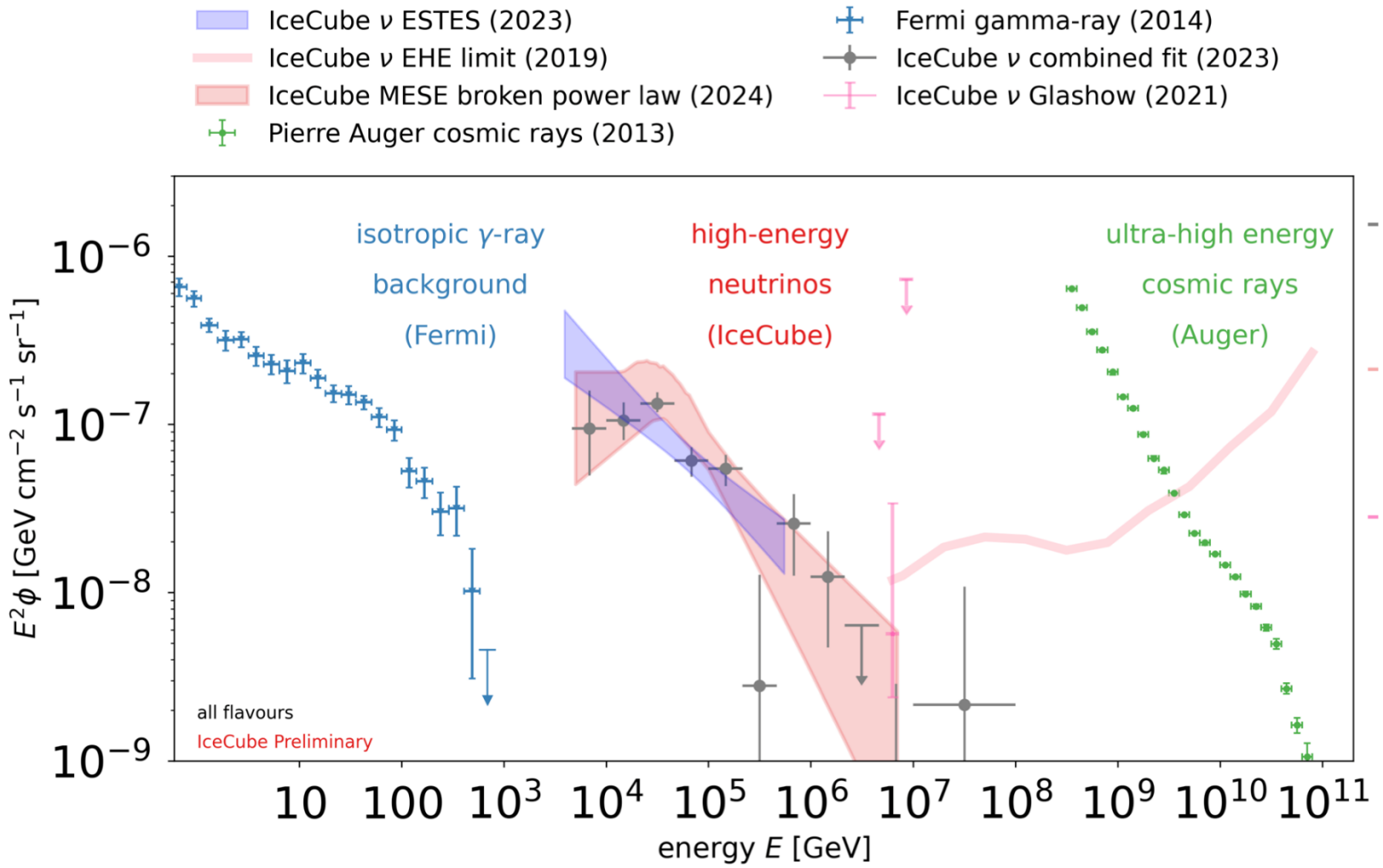


- 9+ sigma evidence for PeV energy cosmic neutrinos
- Strong evidence for first point sources (NGC1068, TXS 0506+056)
- Evidence for emission from the Galactic plane
- Glashow resonance & tau neutrino events observed
- ....



Selected science questions

Diffuse flux of high energy neutrinos

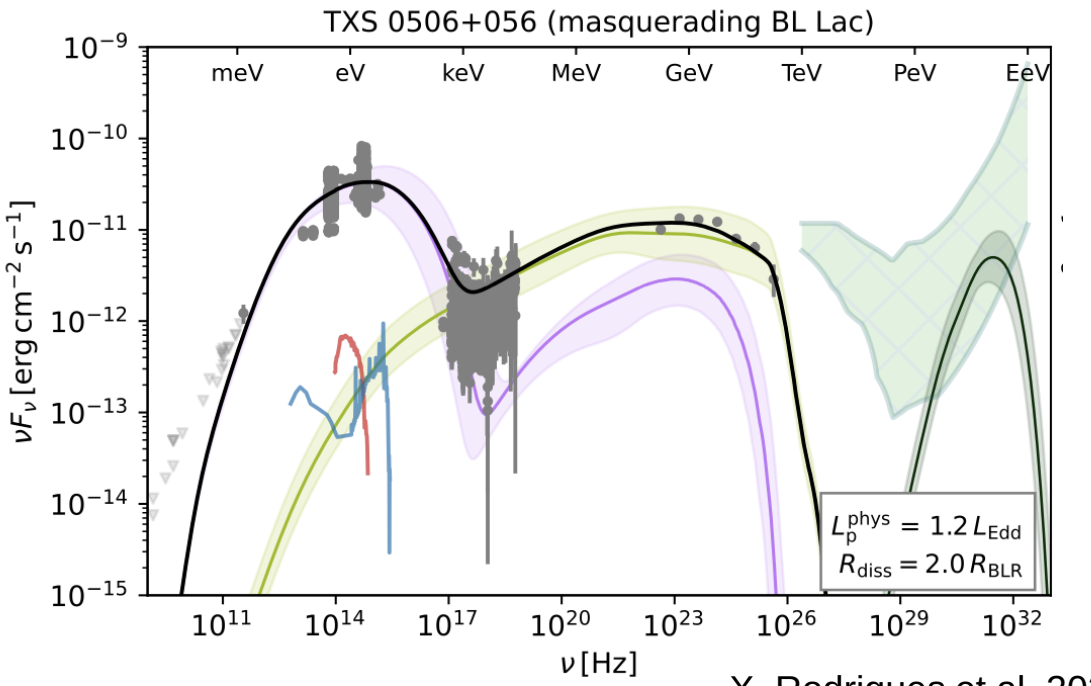


- **Combined fit**
  - Through-going tracks and contained cascades
- **MESE**
  - Starting tracks and contained cascades
- **PEPE**
  - Partially contained cascades

Evidence for a break (knee?) in the spectrum around 30 TeV. How does the spectrum continue towards EHE?

Selected science questions

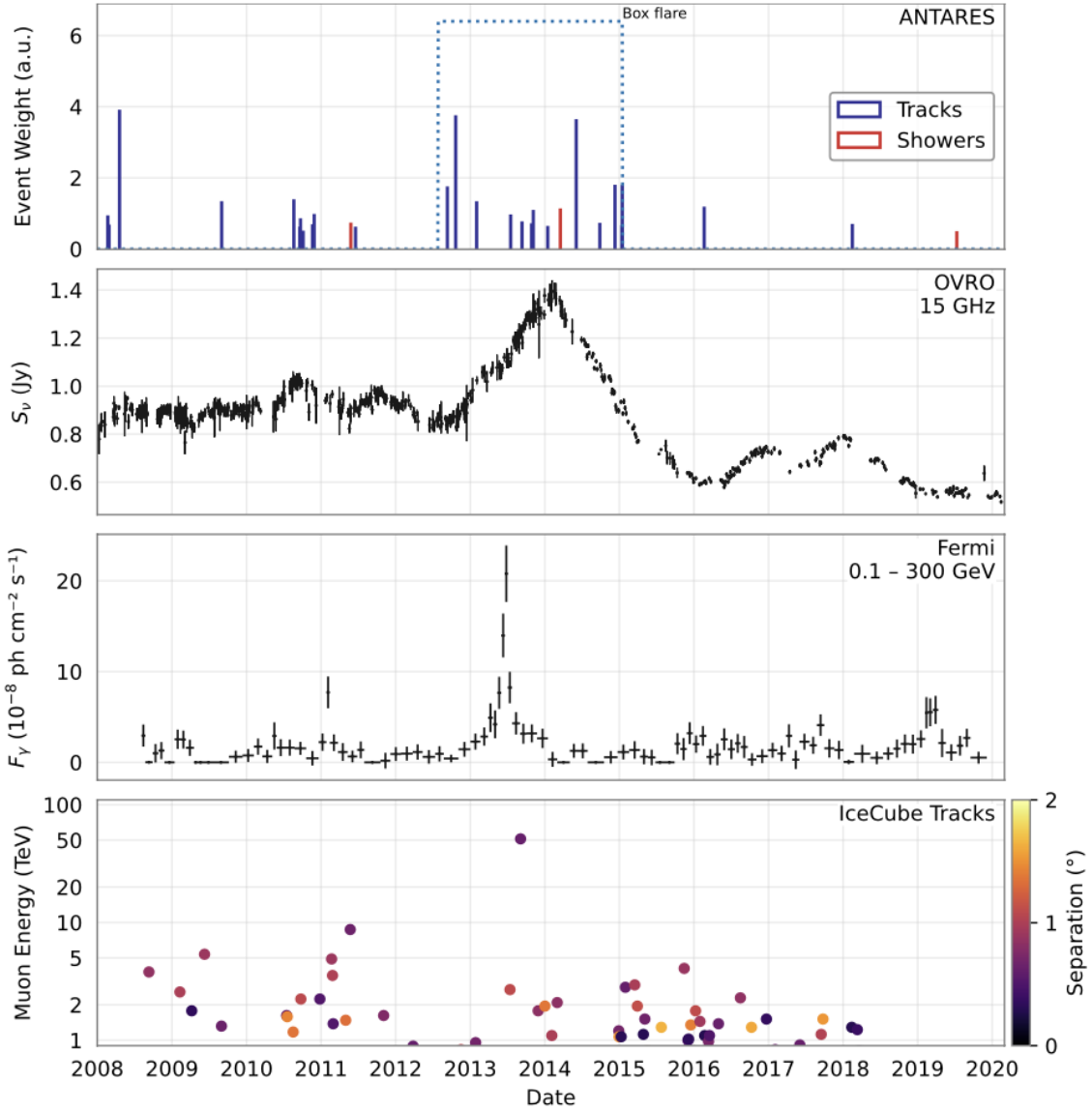
What are the sources of the observed neutrino flux?



X. Rodrigues et al, 2024

Learning about (prospective) neutrino sources from multi-messenger observations!

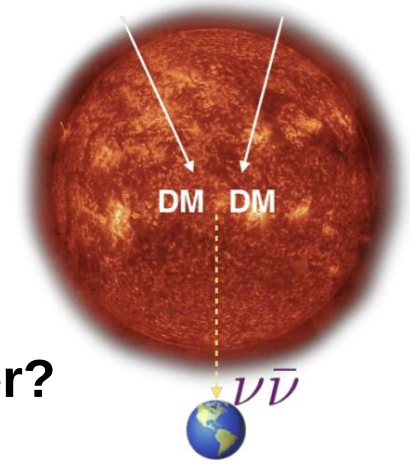
Lots of activity within the Germany IceCube Community, but also outside (e.g. see ERC grants by Yuri Kovalev and Sara Buson)



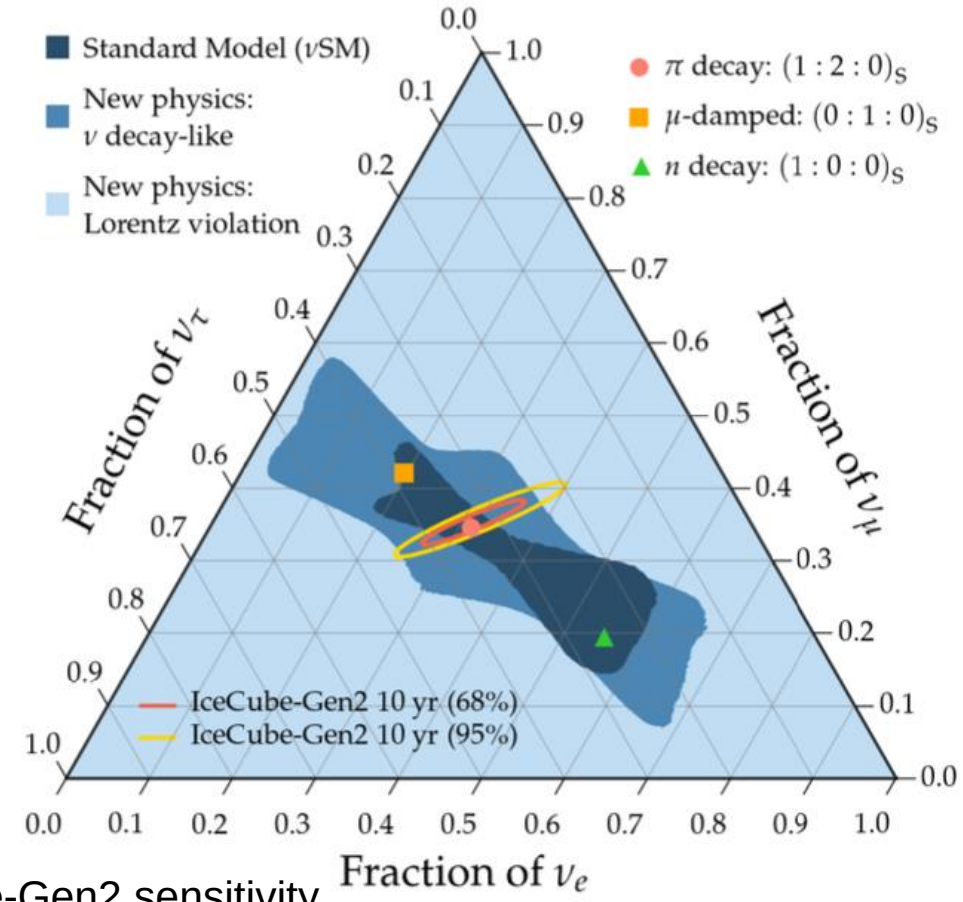
Albert, A., et al., 2024, ApJ, 964, 3

Selected science questions

Physics beyond the standard model

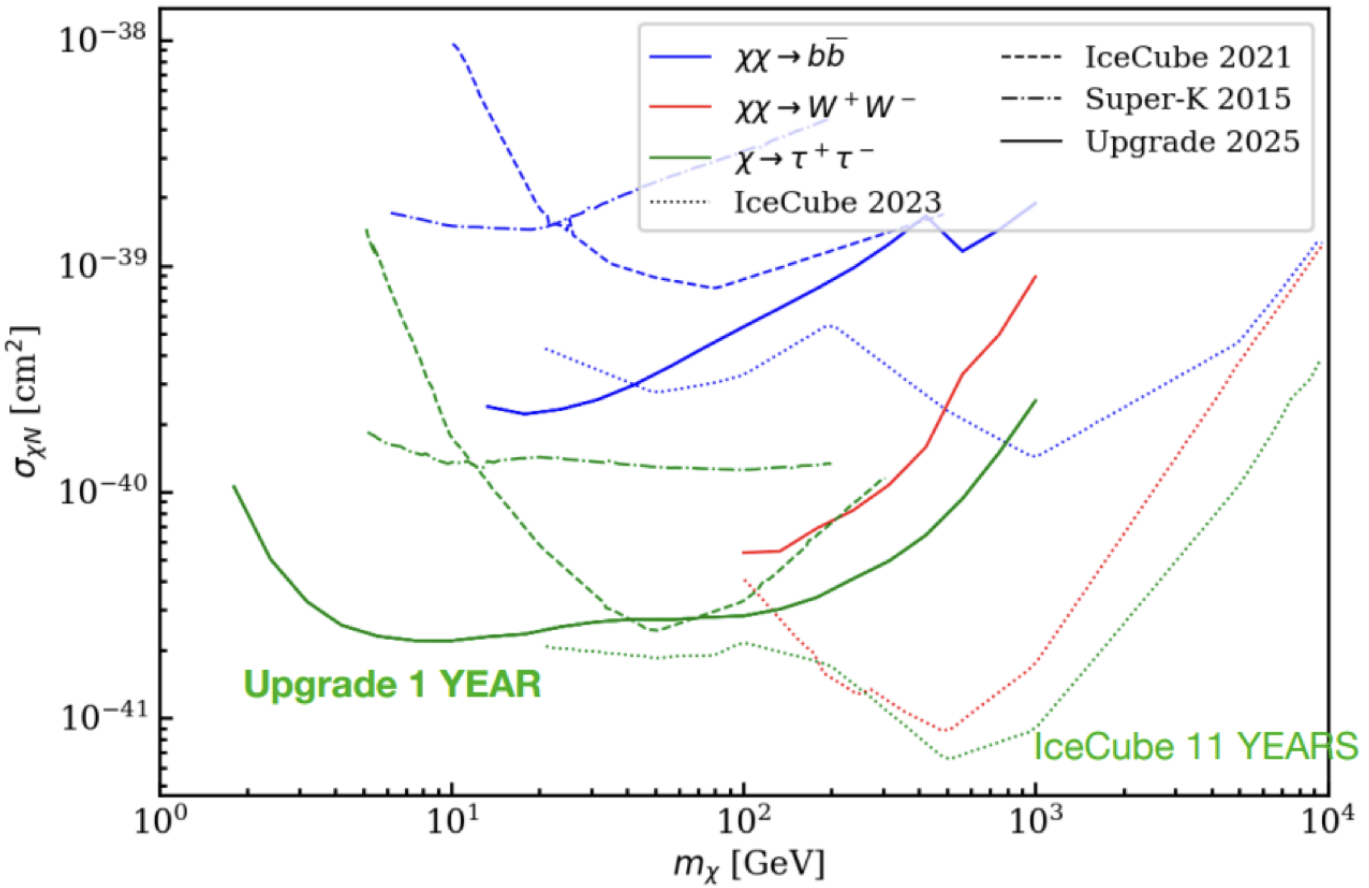


How do neutrino mix on cosmic baseline?



IceCube-Gen2 sensitivity

What is the nature of dark matter?

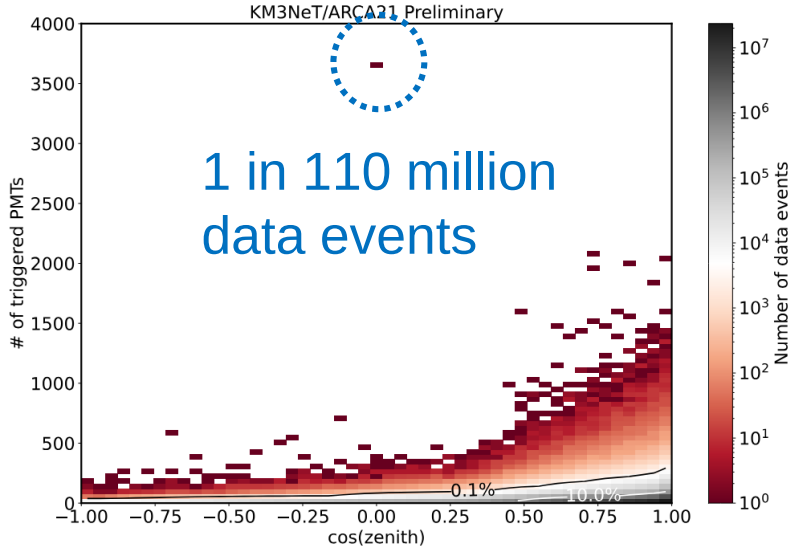


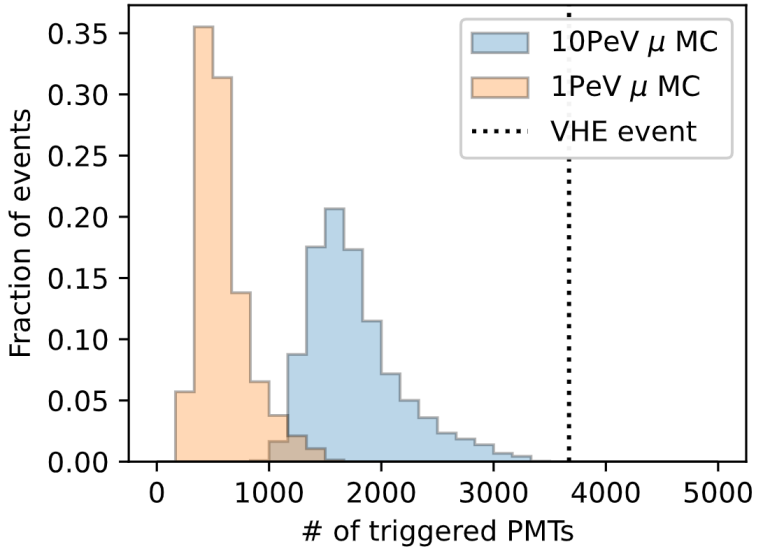
IceCube-Upgrade sensitivity

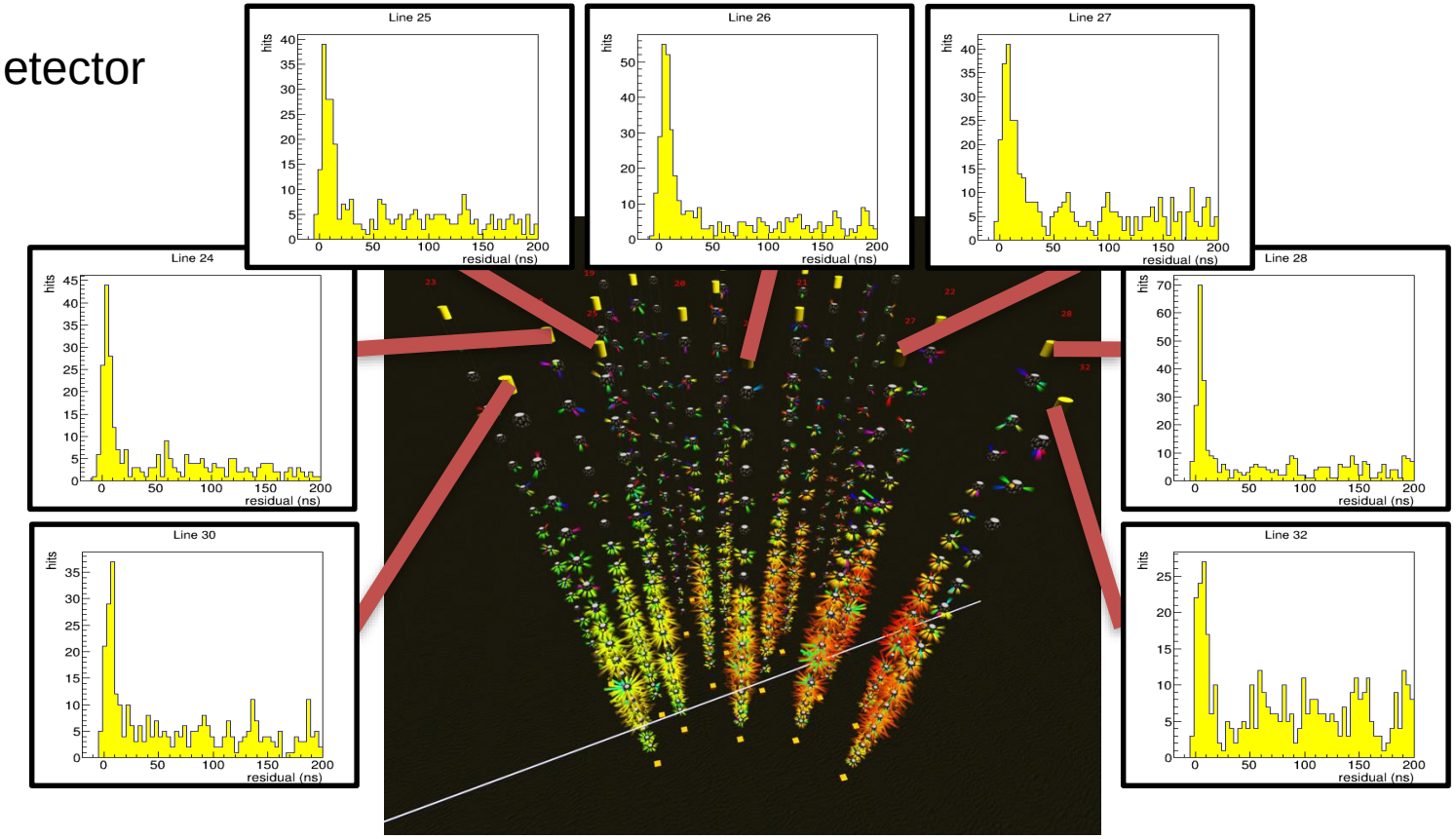
Selected science questions: KM3NeT news

ARCA: Very-high Energy Event

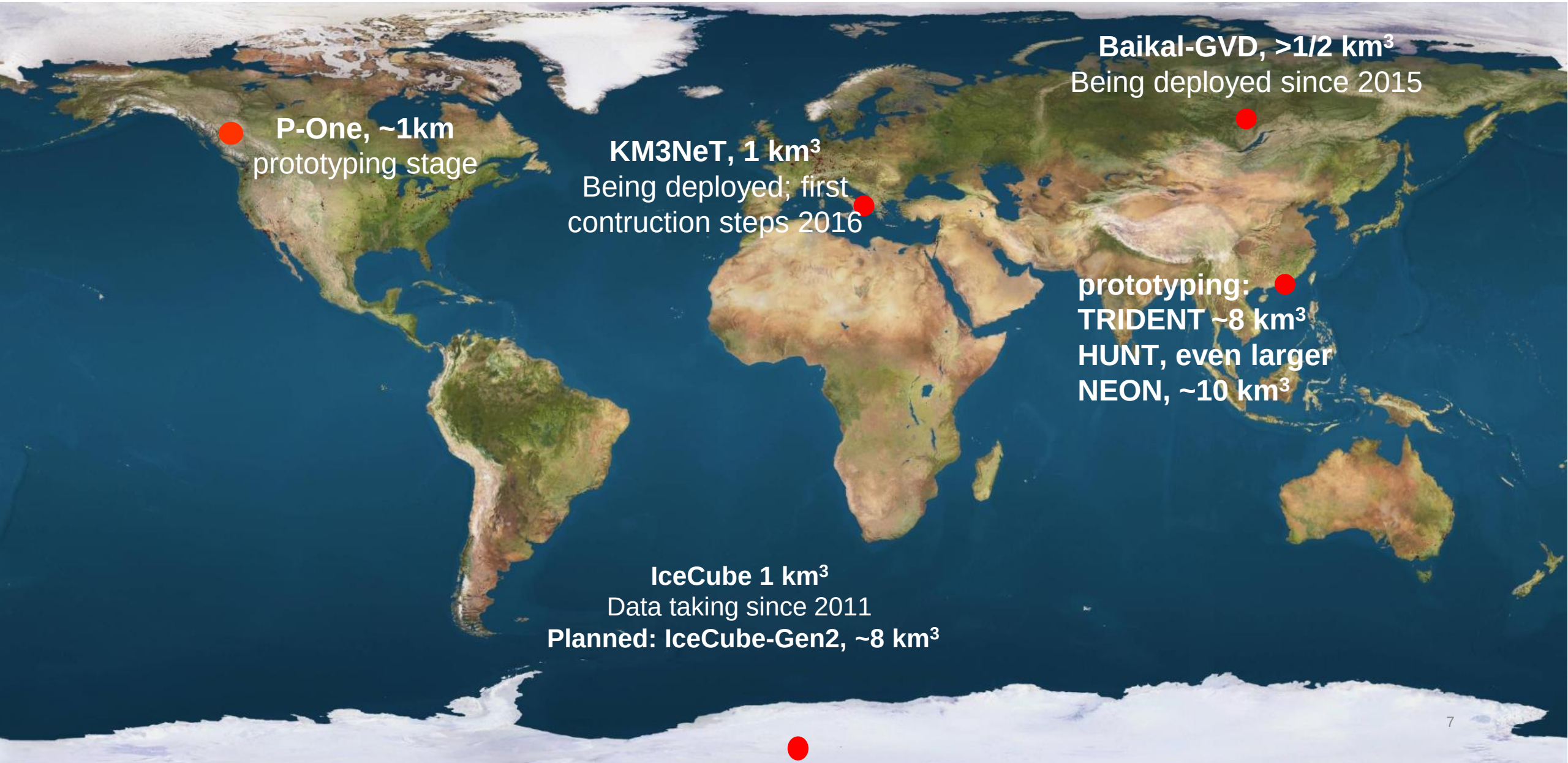
- Significant event observed with huge amount of light, reconstructed as muon with three sub-showers
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light







Global neutrino telescope landscape (TeV-PeV)



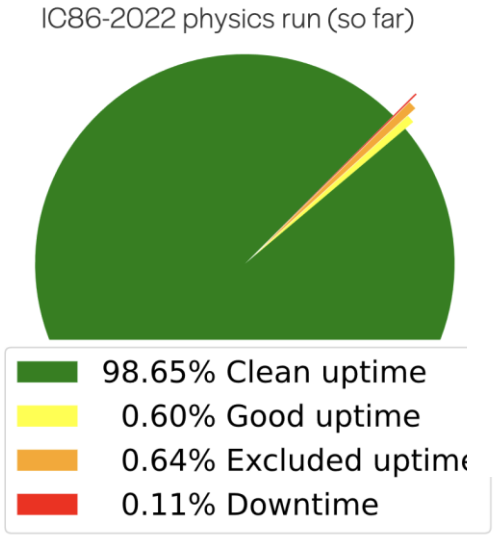
Strategy in Germany

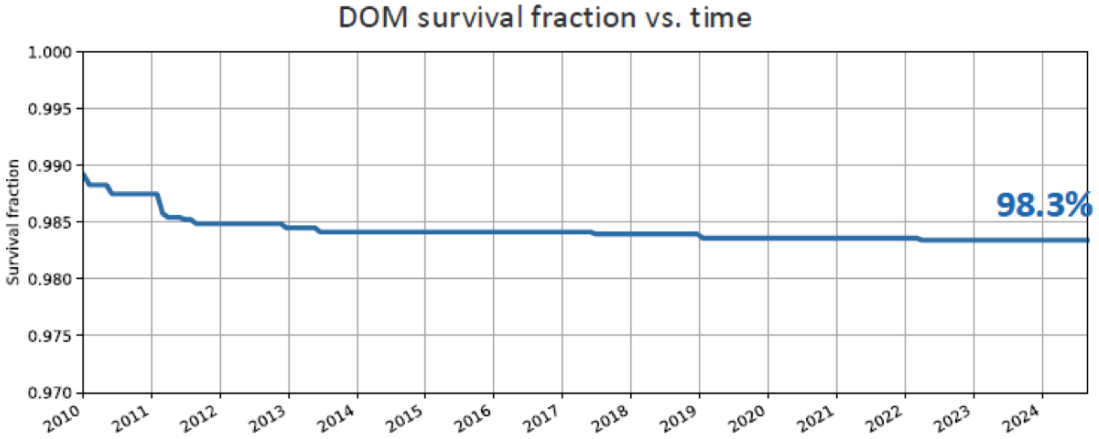
Remaining in a leading position in a quickly developing field

- The German high-energy neutrino community is fully committed to continuing the effort at the South Pole (IceCube and IceCube Upgrade) and is a driving force behind the design of IceCube-Gen2, an eight cubic kilometre optical array complemented by a large radio array to increase the sensitivity of IceCube by an order of magnitude and the detection range beyond 10 PeV.
- German groups are also engage in alternative/complementary paths towards reaching the science goals. They participate in KM3NeT neutrino telescope in the Mediterranean, lead a new effort called P-ONE from the Canadian coast to the Pacific Ocean, and are installing a radio neutrino facility called RNO-G in the Greenland ice sheet. Each of these international efforts offer opportunities for synergy. They create a seed for operating in a distributed manner and covering almost the entire sky with an ideal exposure and energy range of cosmic neutrinos.

IceCube

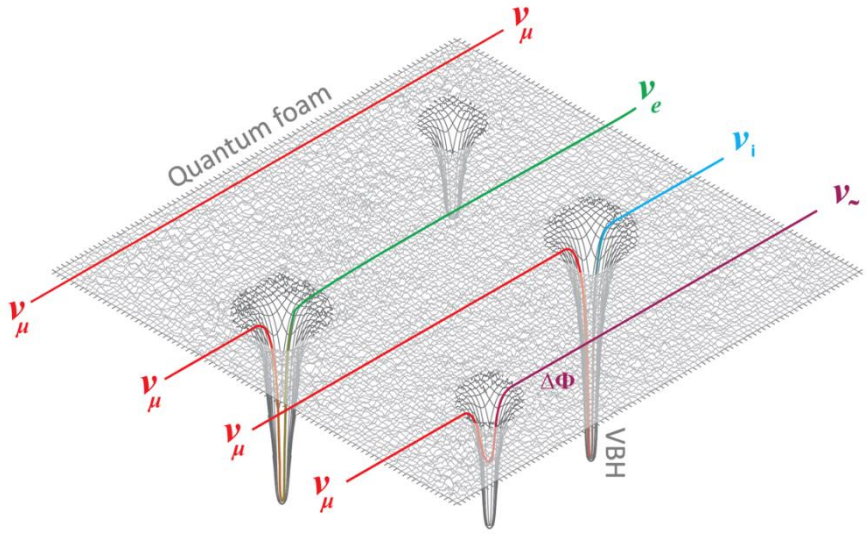
The first cubic kilometer neutrino detector operating since 2010



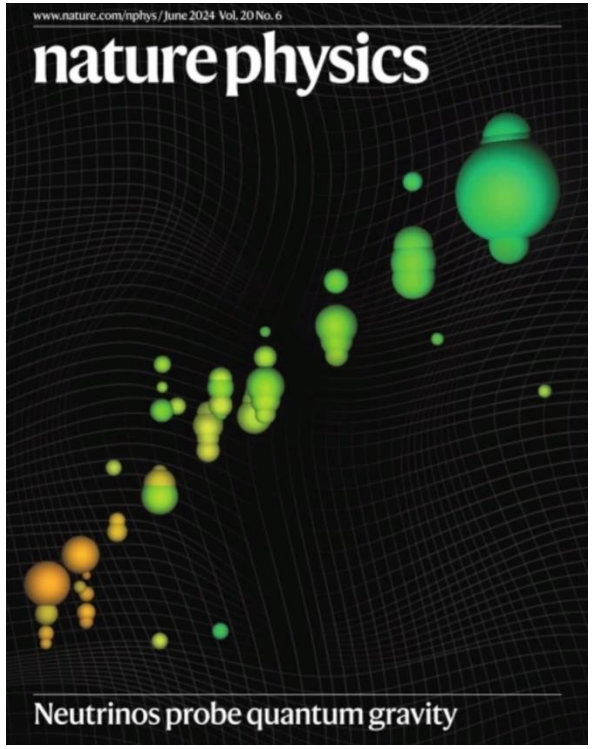


- No DOM failures since March 2022
  - 4 DOM fails in the past 10 years

- IceCube runs extremely smoothly, with no signs of aging.
- Continuous improvements in performance through better calibration, simulations and reconstructions.
- Steady stream of high-impact results, from astrophysics to physics, expected to continue



Search for quantum decoherence among 300.000 atmospheric neutrino events, [Nat. Phys. 2024]



IceCube-Upgrade

The next step for IceCube

Scope and time line:

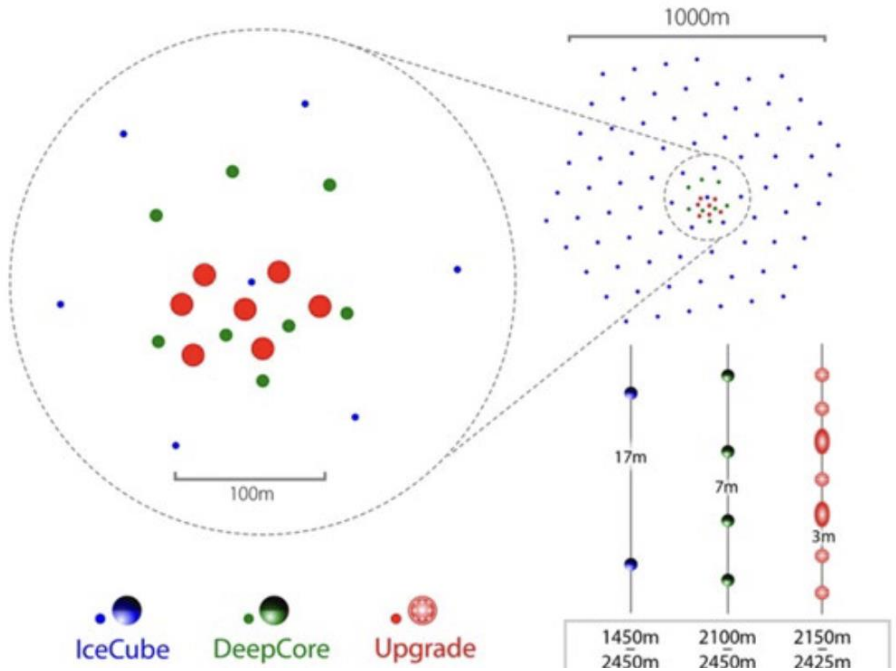
- Dense in-fill array consisting of seven strings, equipped with a new generation of optical sensors and an array of new calibration devices
- Construction on going, on track for deployment in 2025/26

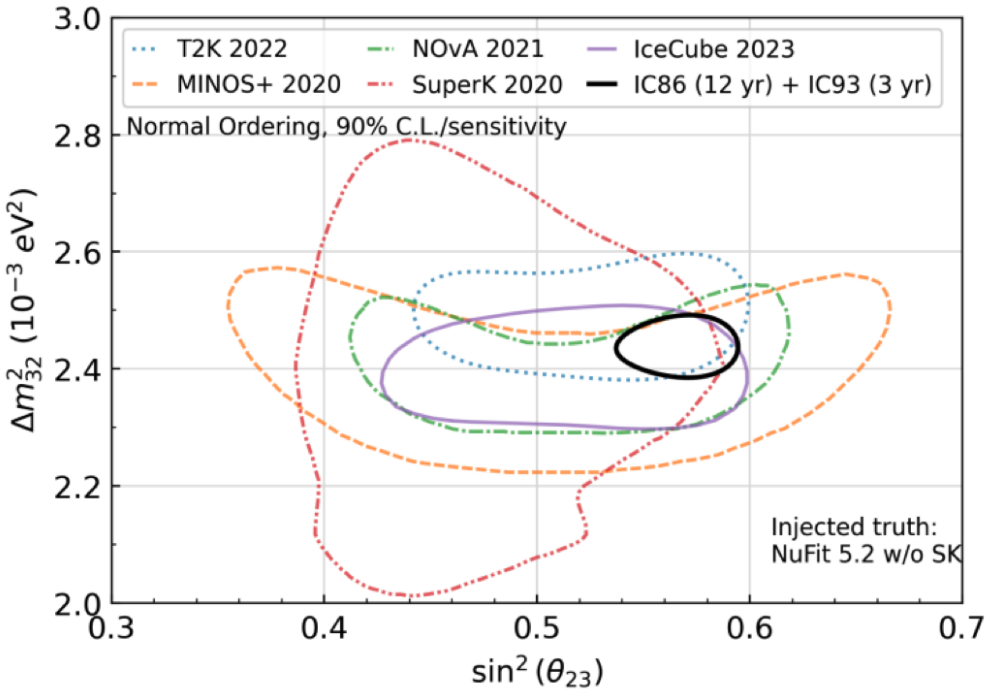
Science goals:

- High precision atmospheric neutrino oscillation measurements
- Better calibration of new and existing detector modules and ice, including previously unexplored depths

German contribution:

- Design & production of the mDOM (8 institutions effort!)
- Several calibration devices

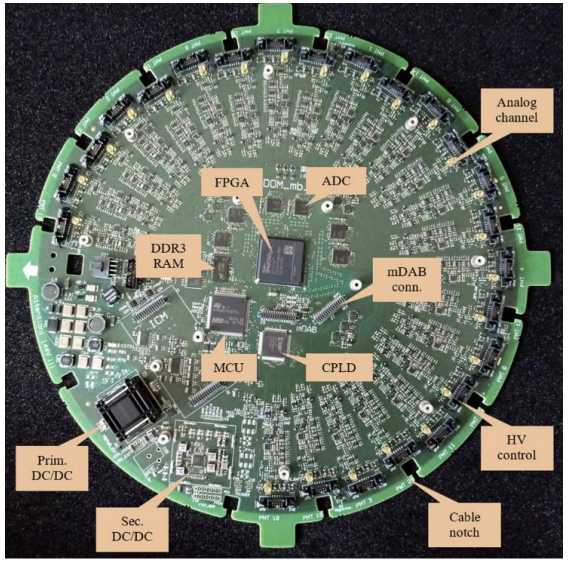




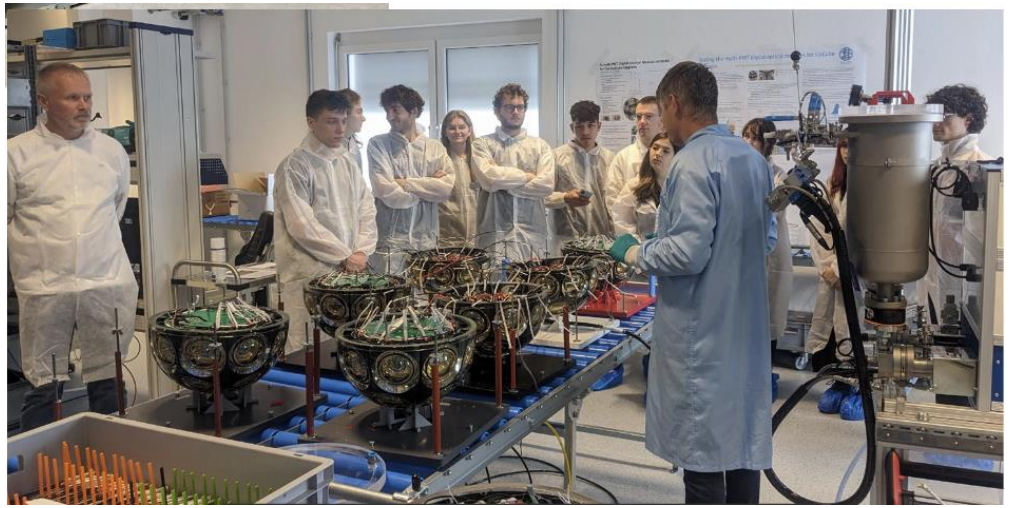
IceCube-Upgrade

Selected hardware activities in Germany

Acoustic module: position calibration



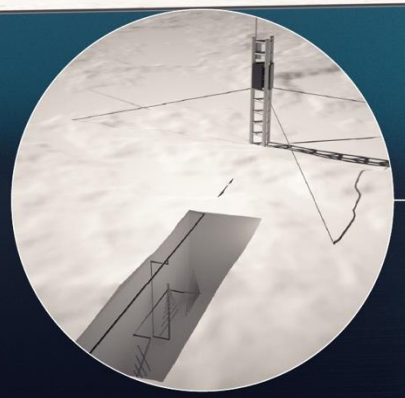
mDOM mainboard



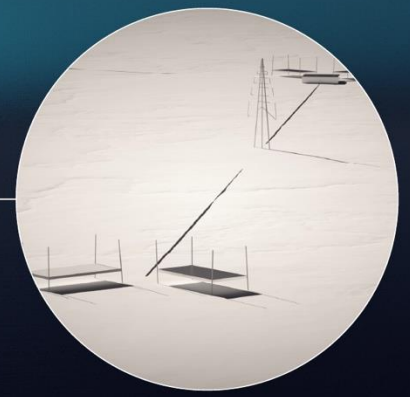
POCAM for ice and energy calibration

mDOM production: first 128 mDOMs send to South Pole. identical facility now also operating at MSU.
Check out production video

IceCube Gen2

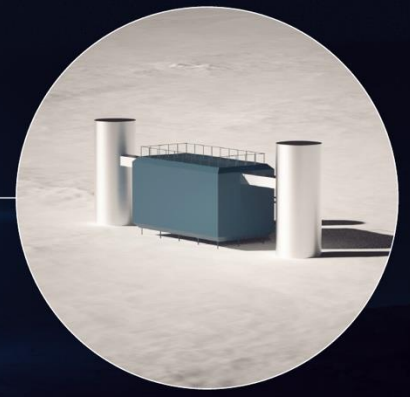


Radio Array | Station



Surface Array | Station

Optical Array | Sensor



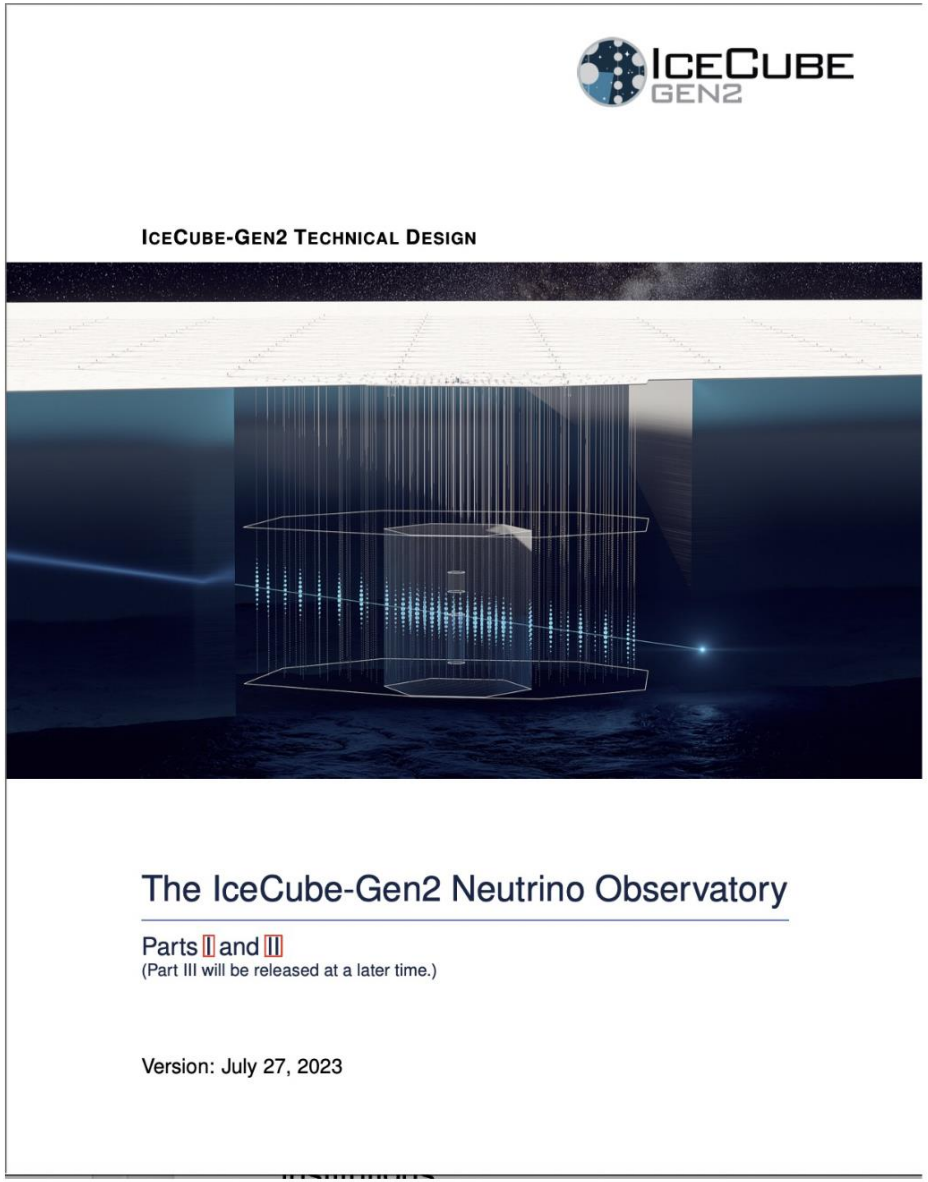
IceCube | Laboratory

Credit: DESY & SciComLab

IceCube-Gen2

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

- Multipurpose neutrino (and cosmic ray) observatory with unique discovery potential from 10^9 to 10^{20} eV
- International collaboration of 400+ scientists from 14 countries
- Germany is the second strongest partner after the USA (DESY+KIT+10 German universities, ~25% of all authors)
- Costs: ~500Mio $ (US accounting) of which German groups are planning for a 55 Mio € in-kind contribution
- Project was favorably evaluated in various international roadmap processes, including in Astro 2020 US Decadal Survey, the Particle Physics Project Prioritization Panel (P5 panel), the Japanese MEXT, and the European APPEC roadmap.
- Construction could start as soon as 2028/9 with an 10 year construction phase.



IceCube-Gen2 Technical Design Report completed: Parts I and II covering science and detector released in July 2023, Part III covering construction and logistics released June 2024 (370 pages) [1].

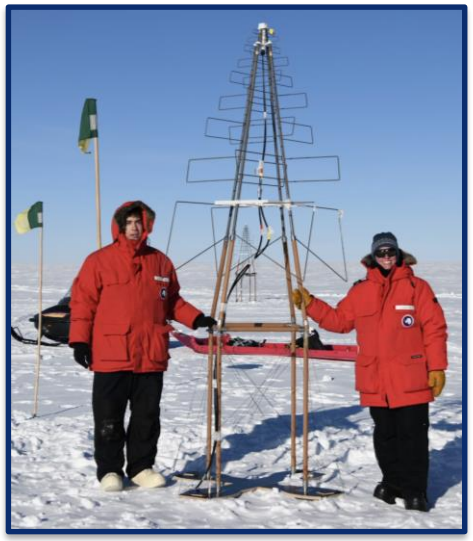
Developments towards IceCube-Gen2

Building on experience and new technology

IceCube Installation

Operating sensors in the ice since 2006

New surface technology

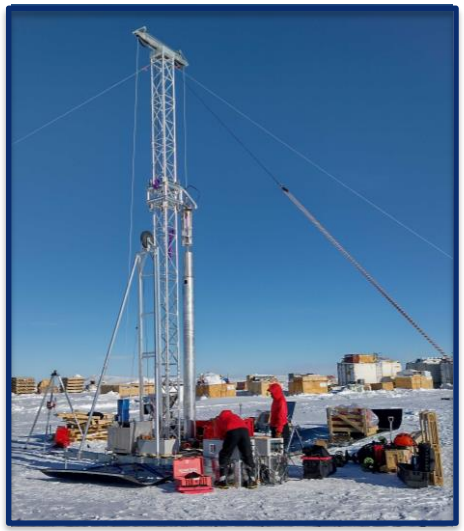


Scintillator / radio station deployed at South Pole (2019)

IceCube Upgrade

Deployment of next generation sensors (mDOM/dEgg)

Radio-Tests in Greenland



RNO-G radio technology deployed in Greenland (2021)

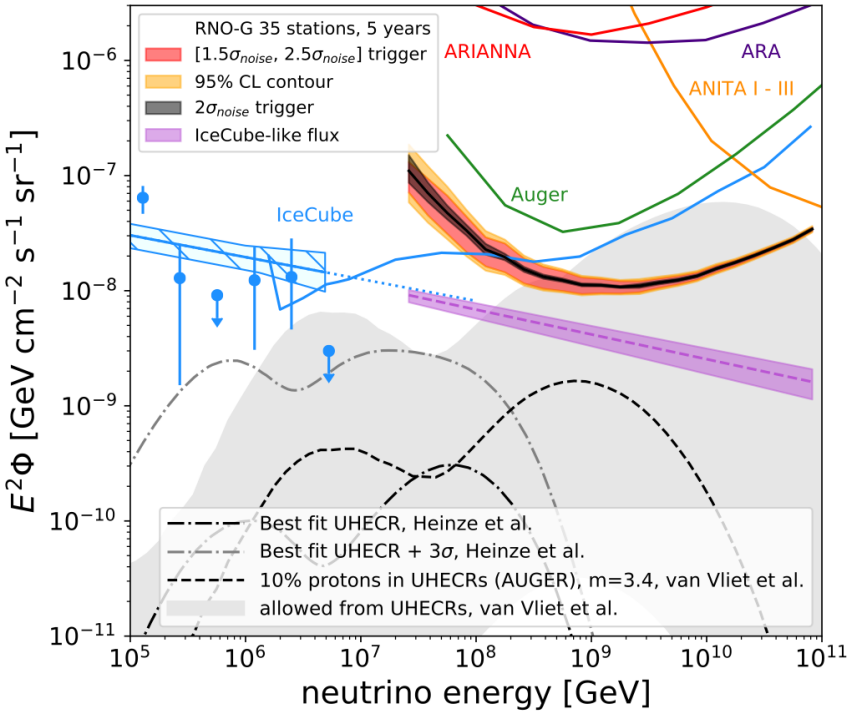
IceCube GEN2

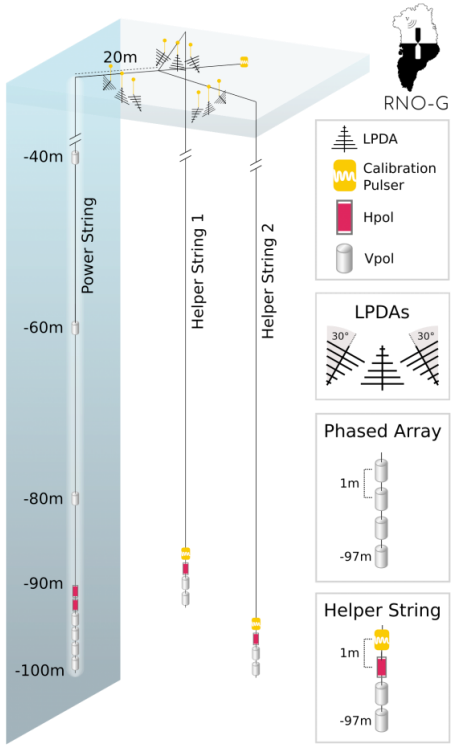
The Radio Neutrino Observatory Greenland (RNO-G)

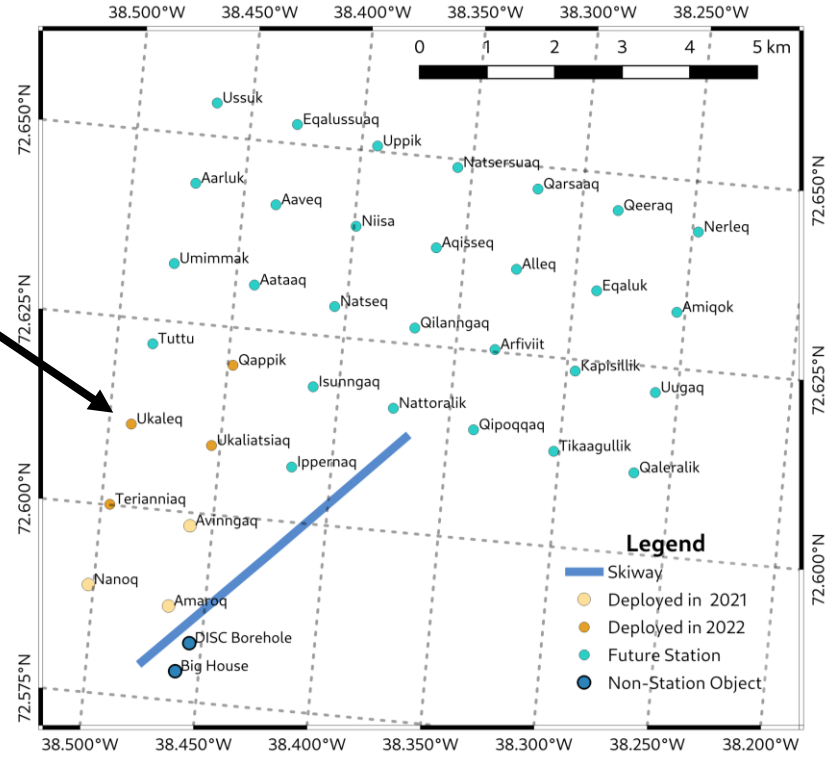
Construction of 35 stations: 2021 - 2028

- Targets the energy range in which neutrinos are expected from the interaction of ultra-high energy cosmic rays and the CMB (>10 PeV): Discovery experiment
- Partners: Germany (FAU + DESY, Funding: Emmy-Noether, ERC), US, Belgium, Sweden
- Several proposed competitors in this energy range, RNO-G currently the only one funded

RNO-Coll; arXiv:2010.12279



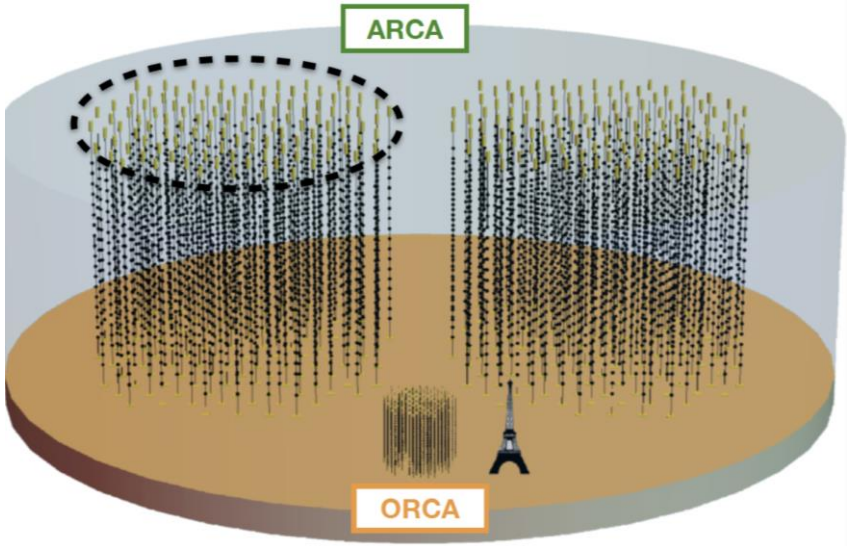




KM3NeT

ARCA & ORCA

- Two sub-detectors: ORCA (densely instrumented, ~10 Mton, lower energies, neutrino physics) and ARCA (sparsely instrumented, 1 Gton, higher energies, neutrino astronomy);
- Science objectives: Neutrino astronomy, neutrino physics, as well as marine sciences, geology, environmental sciences.
- Installation is complete to ~20% (ORCA) and >15% (ARCA), respectively. Operation of the detector modules installed so far confirms performance even beyond expectation.
- KM3NeT priority in the APPEC Roadmap and also in Italy, Netherlands and France. German involvement: Erlangen, Würzburg, Münster. **MPIfR**, **Bonn new full member.**
- Costs: 250-300 M€ (t.b.c.), with major contributions from Italy, France and Netherlands. No significant German invest contribution.



For more information, check out

web page & letter of intent.

KM3NeT

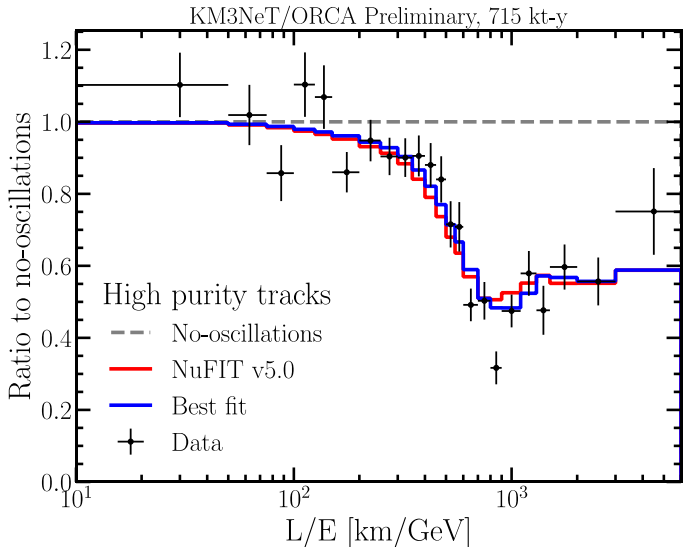
ORCA: Oscillation Measurement

- New measurement uses 715 kt-y of data (65% increase over 2023 dataset)
- Clear oscillation pattern in L/E
- Slight preference for Inverted Ordering (IO)

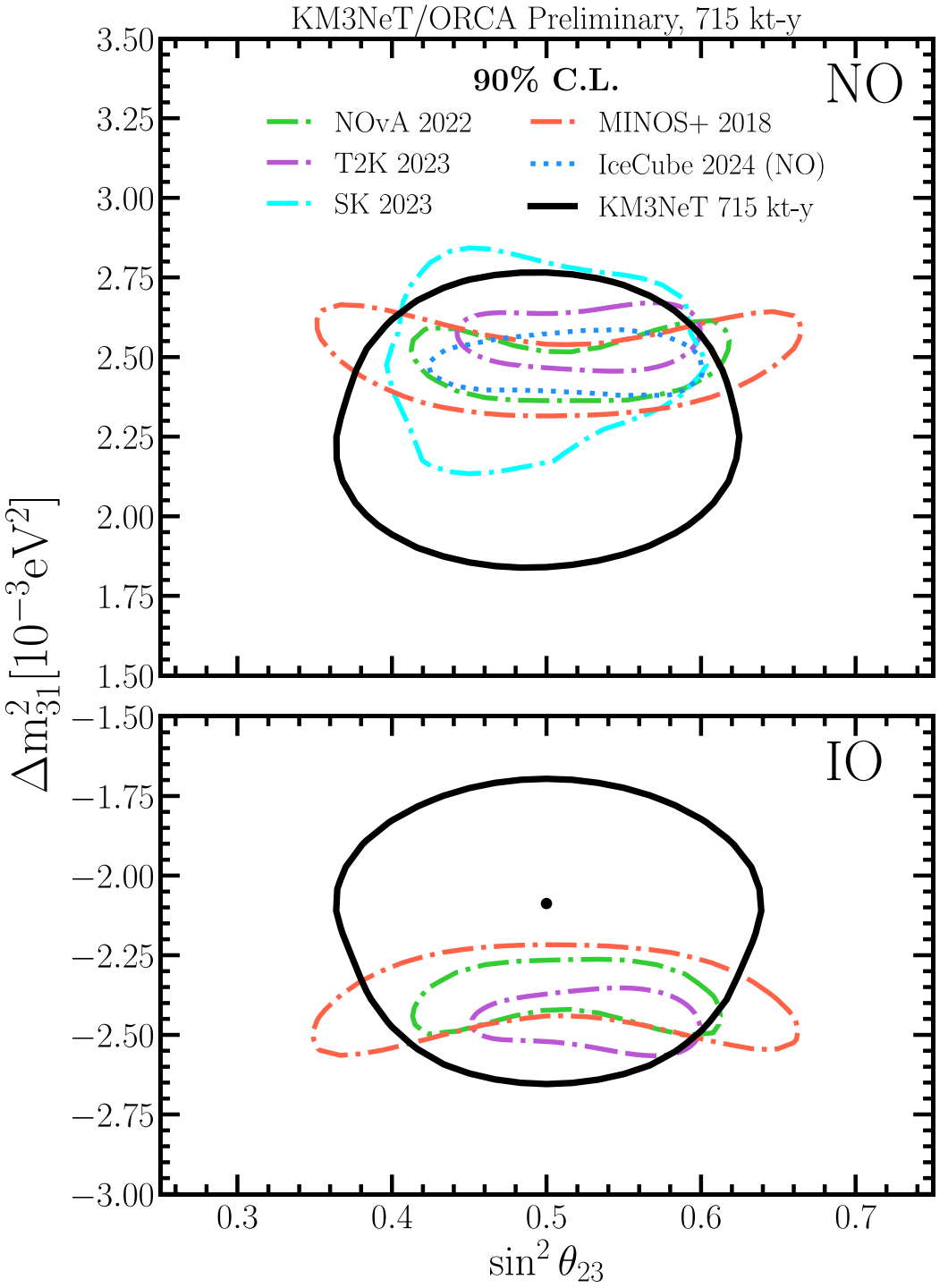
$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\text{eV}^2, & \text{IO} \\ [2.10, 2.37] \times 10^{-3}\text{eV}^2, & \text{NO} \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$

$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$



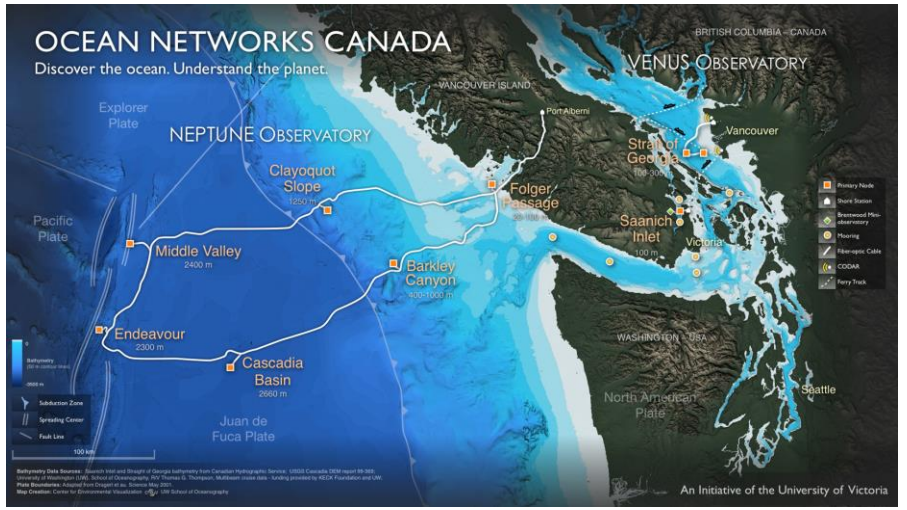
arXiv:2408.07015,
accepted by JHEP.



P-ONE

Pacific Ocean Neutrino Experiment in Canada

- The Pacific Ocean Neutrino Experiment (P-ONE) is a novel initiative for a large-volume (multi-km^3) neutrino telescope based within the existing oceanographic infrastructure operated by Ocean Networks Canada (ONC).
- Two pathfinder missions (STRAW and STRAW-b) with several years of successful operation in water. Funds secured for the P-ONE Demonstrator phase (~10 lines).
- Full completion of P-One requires O(100MEuro) invest for a duration of 5 years (starting 2028)
- Funding/roadmaps: Cluster of Excellence ORIGINS, SFB1258, ERC, APPEC Midterm, Canadian Subatomic Physics Long-Range Plan, Roadmap for UK particle astrophysics 2022.



Conclusion

- IceCube has established high-energy neutrino astronomy, with key contributions by the German community.
- KM3NeT is now delivering first high-profile results!
- Construction of IceCube Upgrade in full swing, on track to be deployed 2025/26.
- Several new initiatives are being developed to harvest the science potential around the globe, both in terms of sky coverage, as well as in energy.
- Most experimental groups in Germany involved in IceCube/Upgrade and committed to IceCube-Gen2, but a diverse set of other initiatives provide many interesting opportunities as well.