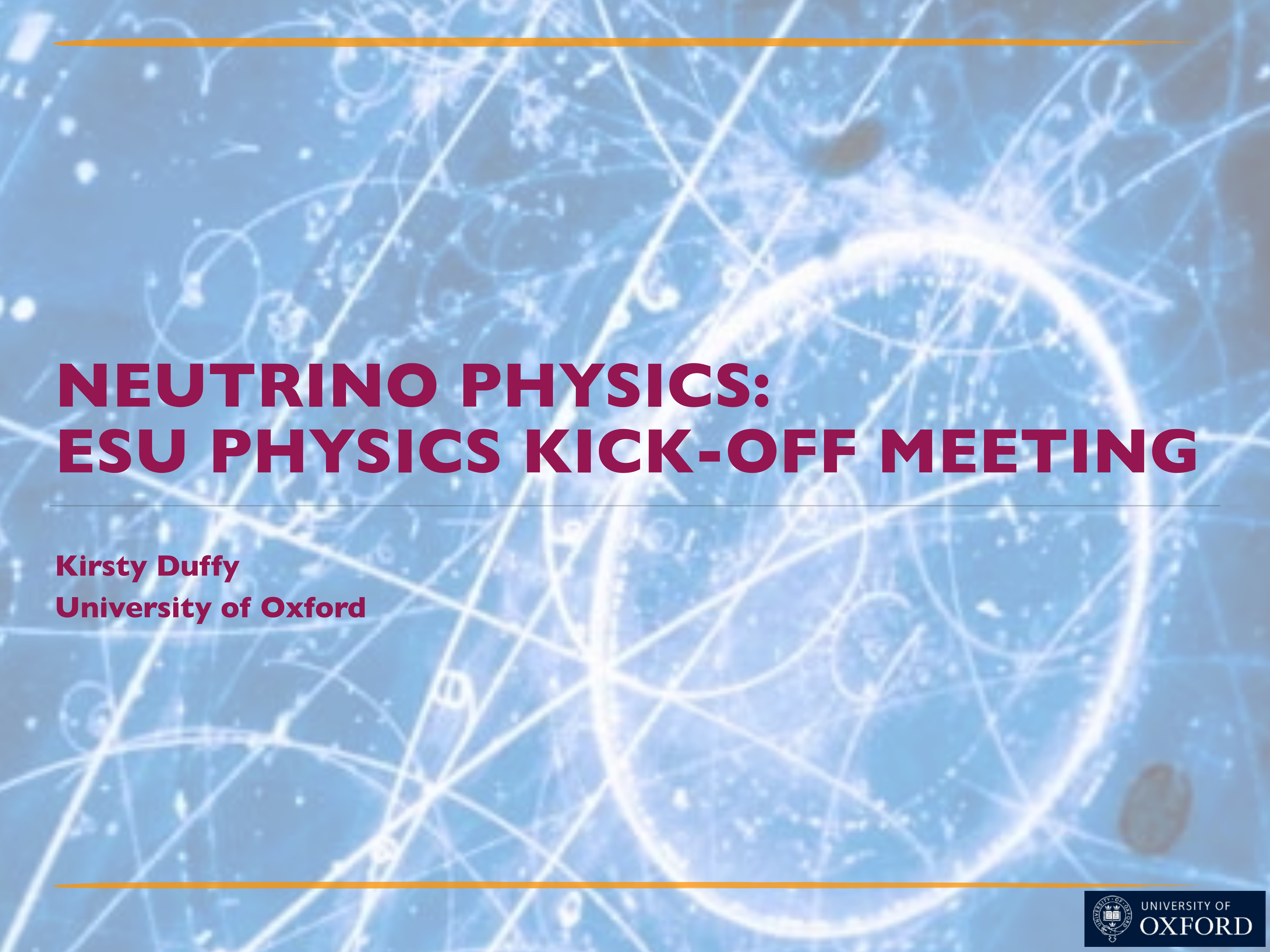


NEUTRINO PHYSICS: ESU PHYSICS KICK-OFF MEETING

Kirsty Duffy
University of Oxford

How many neutrinos are there?

How do neutrinos interact in the nuclear medium?

Which neutrino is heaviest? Which is lightest?

Is CP symmetry violated in neutrino oscillation?

Why is neutrino mixing so large?

How much do neutrinos weigh?

What else can neutrinos teach us?

Are neutrinos their own antiparticles?

Why are neutrino masses so much smaller than all other particles?

How many neutrinos are there?

SBND SHORT-BASELINE NEAR DETECTOR
μBooNE

How do neutrinos interact in the nuclear medium?

T2K
NOvA
SBND SHORT-BASELINE NEAR DETECTOR
νSTORM
MINERvA
μBooNE

Which neutrino is heaviest? Which is lightest?

P-ONE
T2K
NOvA
ICECUBE NEUTRINO OBSERVATORY
JUNO
HYPER K
DUNE

Is CP symmetry violated in neutrino oscillation?

T2K
NOvA
DUNE
JUNO
HYPER K
νSTORM

Why is neutrino mixing so large?

How much do neutrinos weigh?

QTNM Quantum Technologies for Neutrino Mass

What else can neutrinos teach us?

P-ONE
ICECUBE NEUTRINO OBSERVATORY
FASER

Are neutrinos their own antiparticles?

LEGEND
SNO+
supernemo collaboration

Why are neutrino masses so much smaller than all other particles?

How many neutrinos are there?

How do neutrinos interact in the nuclear medium?

Which neutrino is heaviest? Which is lightest?

The UK neutrino community is large and active

Senior leadership (Spokespersons, Physics Coordinators, IB Chairs…) in global flagship experiments across a comprehensive physics programme

Is CP sym violated in oscillat

much do os weigh?

What else can neutrinos teach us?

Are neutrinos their own antiparticles?

Why are neutrino masses so much smaller than all other particles?

Which neutrino is heaviest? Which is lightest?

P-ONE

NOvA

HYPER K

T2K

DUNE

ICECUBE
NEUTRINO OBSERVATORY

JUNO

Is neutrino oscillation different for neutrinos and antineutrinos?

LONG-BASELINE NEUTRINO OSCILLATION

Distance: L

Source

ν_μ

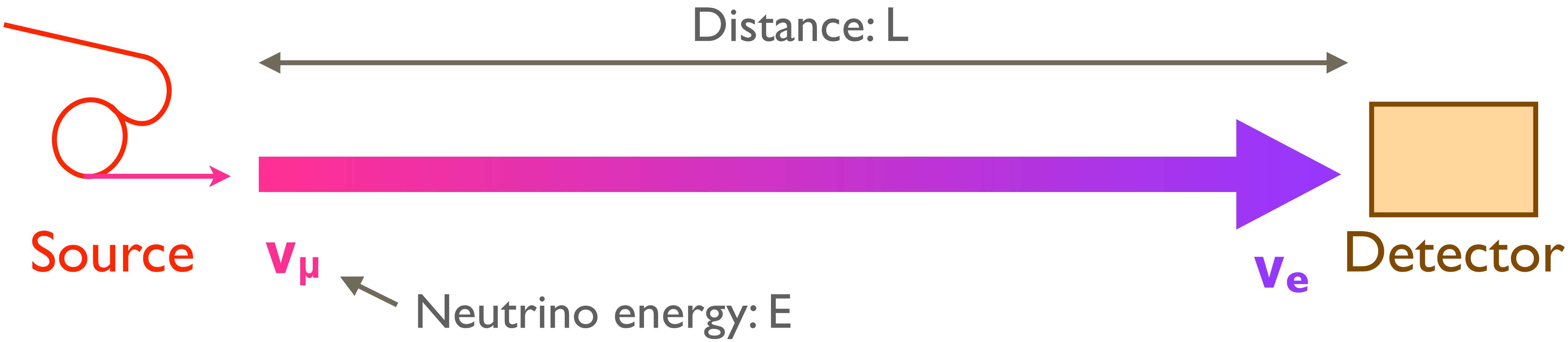
Neutrino energy: E

ν_e

Detector

Muon neutrino disappearance

Electron neutrino appearance



Probability to detect a neutrino of a given flavour **oscillates** as:

$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

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

$$\begin{aligned} P(\nu_\mu \to \nu_\mu) \simeq\ & 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \\ & \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32} L}{4E} \\ & + (\text{solar, matter effect terms}) \end{aligned}$$

THE MASS ORDERING

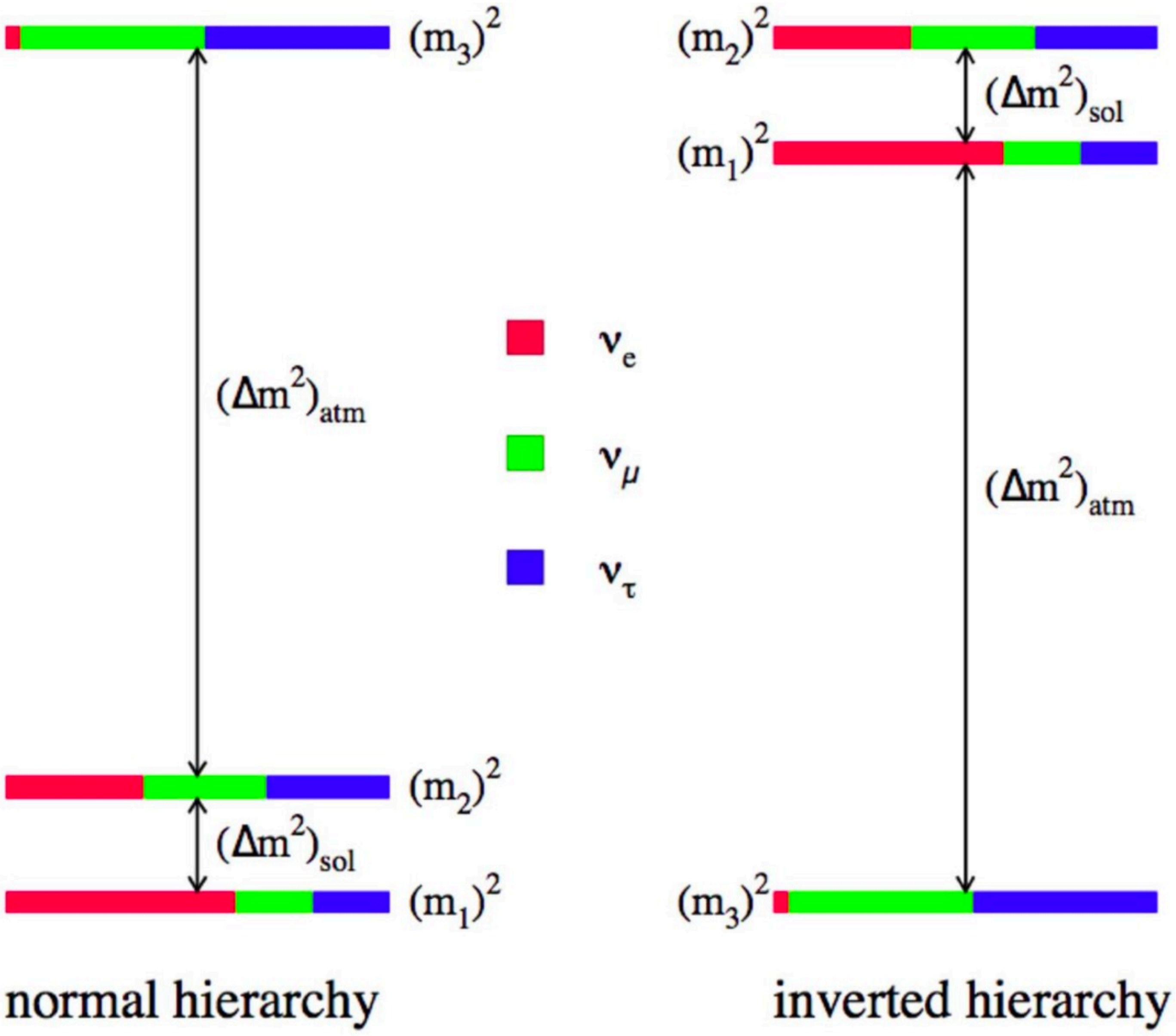
$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

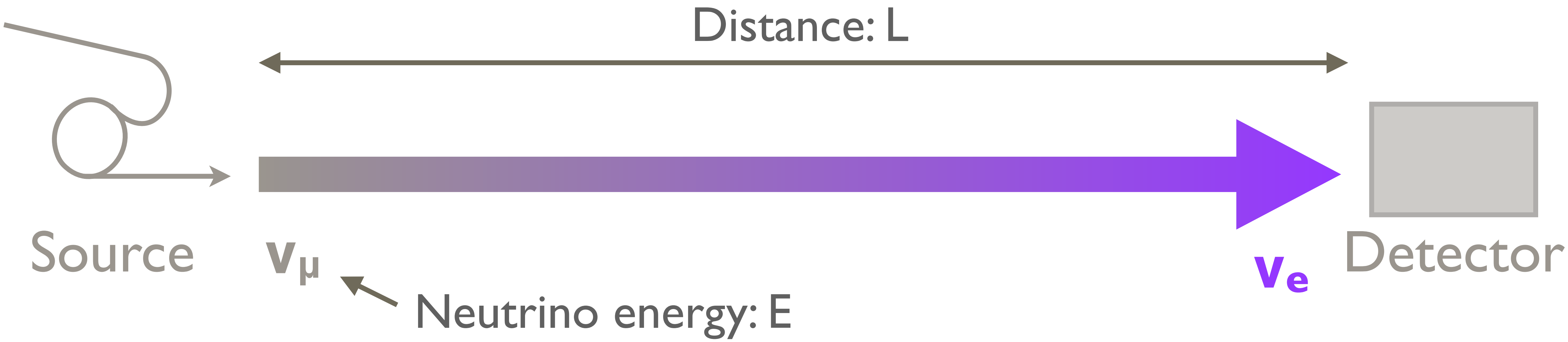
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Oscillation (in a vacuum) is only sensitive to the **size** of Δm², not the **sign**

→ We **know the sign of Δm^2_{21}** from solar neutrino measurements

→ We **do not know the sign of $|\Delta m^2_{32}|$**





Distance: L

Source

ν_μ

Neutrino energy: E

ν_e

Detector

Muon neutrino disappearance

Electron neutrino appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E}$$

$$(+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$

$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big]$$

$$+\ (\text{CP-even, solar, matter effect terms})$$

CP VIOLATION: LONG-BASELINE ACCELERATOR NEUTRINOS

	Current		**Next-generation**
Japan	T2K	→	HYPER K
US	NOvA	→	DUNE

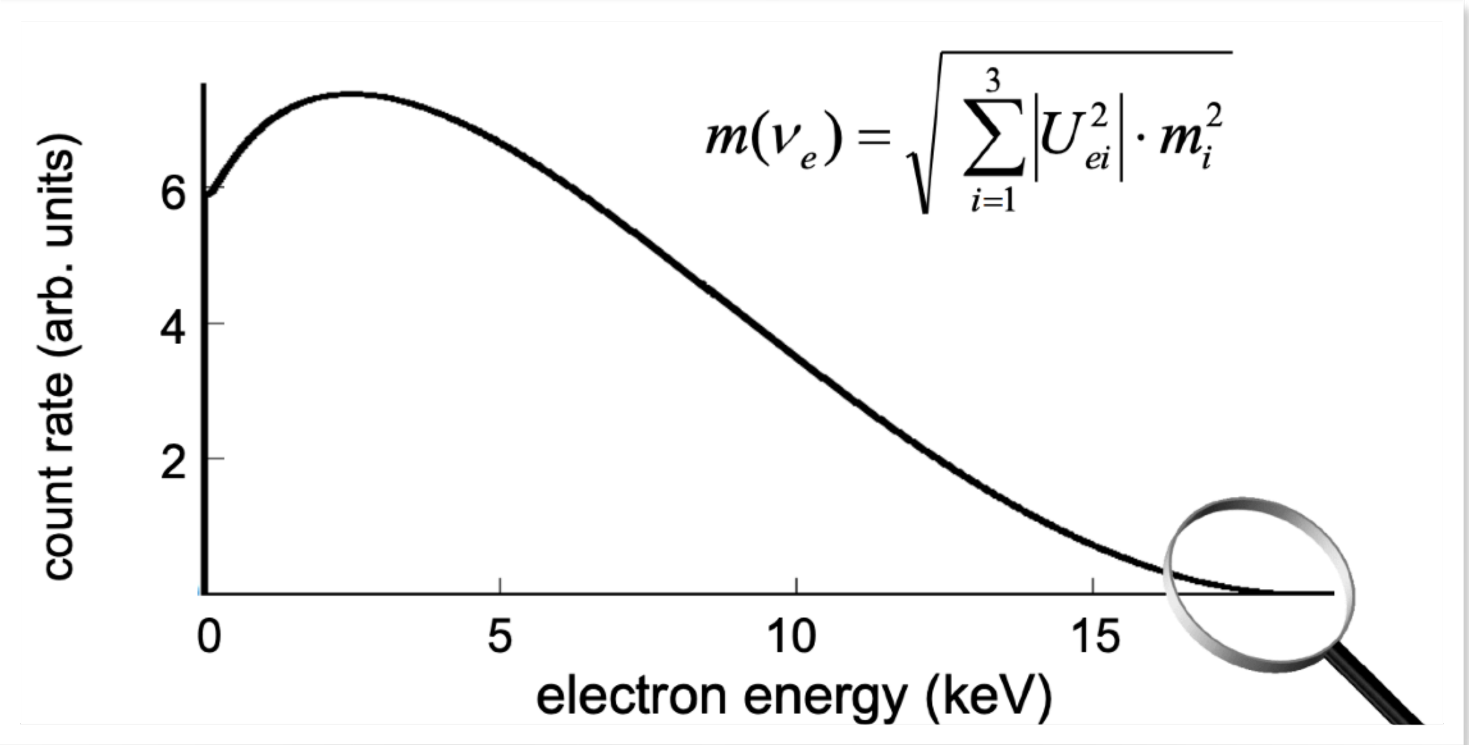
Both DUNE and Hyper-K will complete construction and move into physics exploitation over the period covered by the next ESU

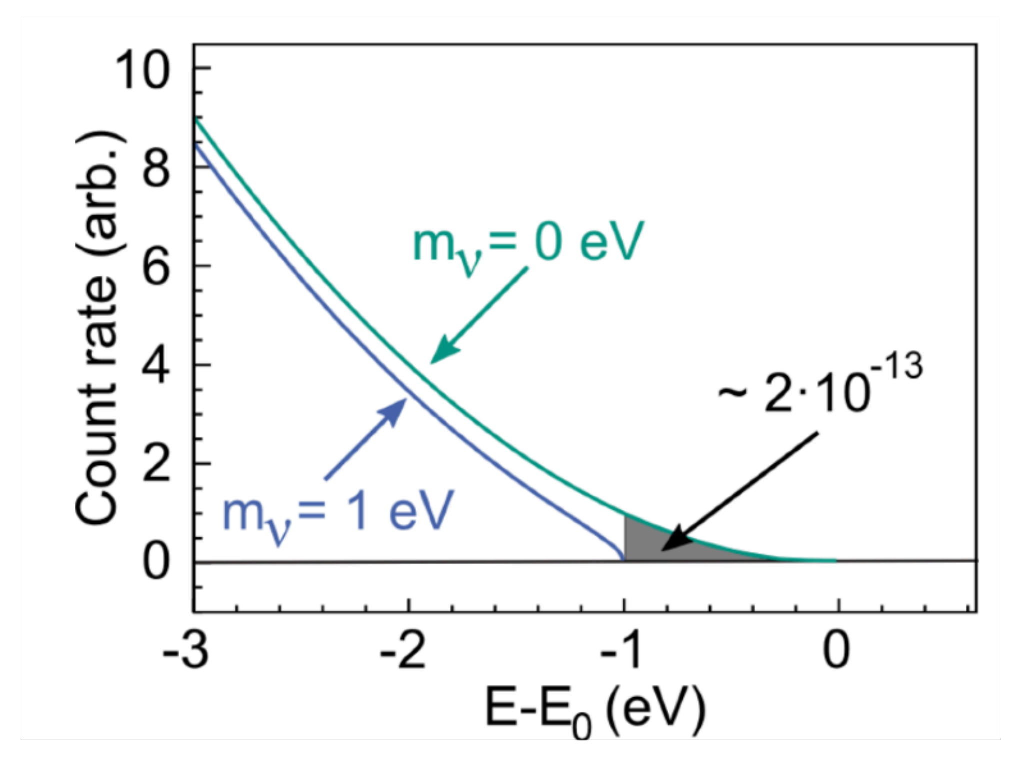
QTNM
Quantum Technologies for
Neutrino Mass

How much do neutrinos weigh?

MEASURING THE NEUTRINO MASS

- Measurement of neutrino mass from the end-point of tritium beta decay spectrum
  - Requires excellent energy resolution
- **QTNM** (Quantum Technologies for Neutrino Mass) will use quantum technologies to carry out an experiment capable of measuring neutrino mass, even in the worst case scenario of it being ~10 meV
- Uses Cyclotron Radiation Emission Spectroscopy → measure frequency of EM radiation generated as a result of electron's motion in a magnetic field
- Technology demonstration funded through **QTFP: see Ian's talk!**





NOvA

T2K

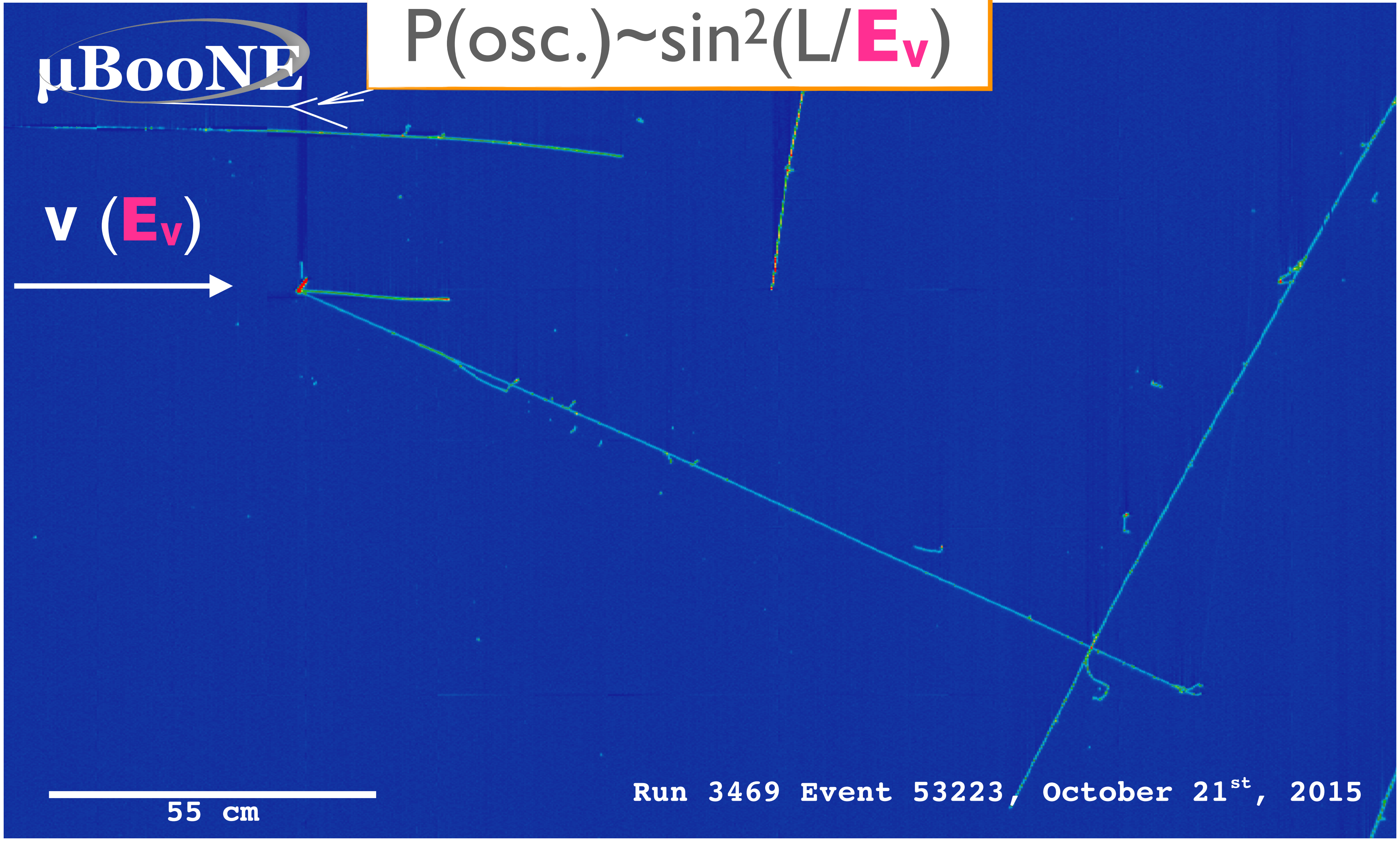
SHORT-BASELINE
SBND
NEAR DETECTOR

How do neutrinos interact in the nuclear medium?

MINERvA

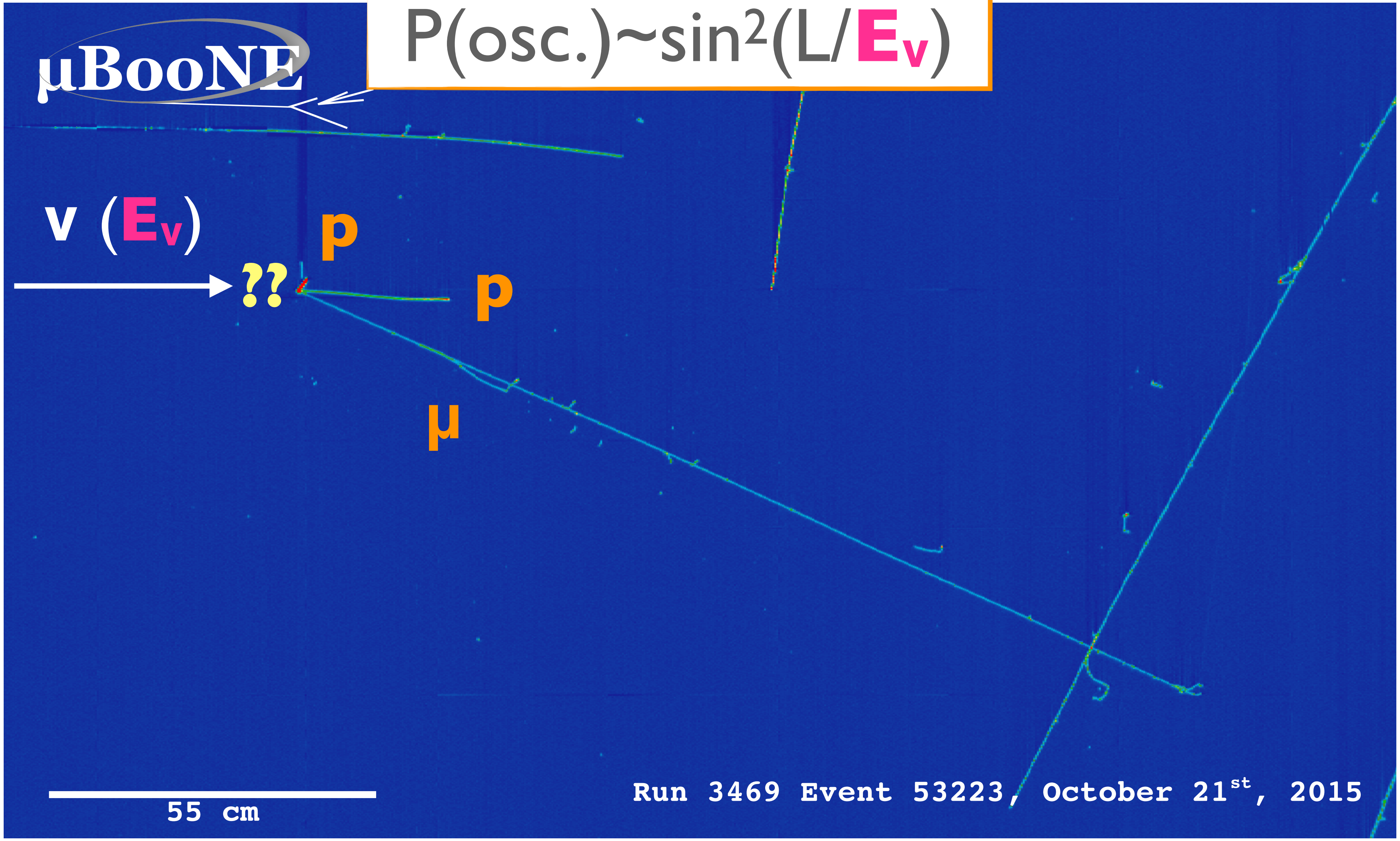
μBooNE

NEUTRINO INTERACTIONS



P(osc.)~$\sin^2(L/E_\nu)$

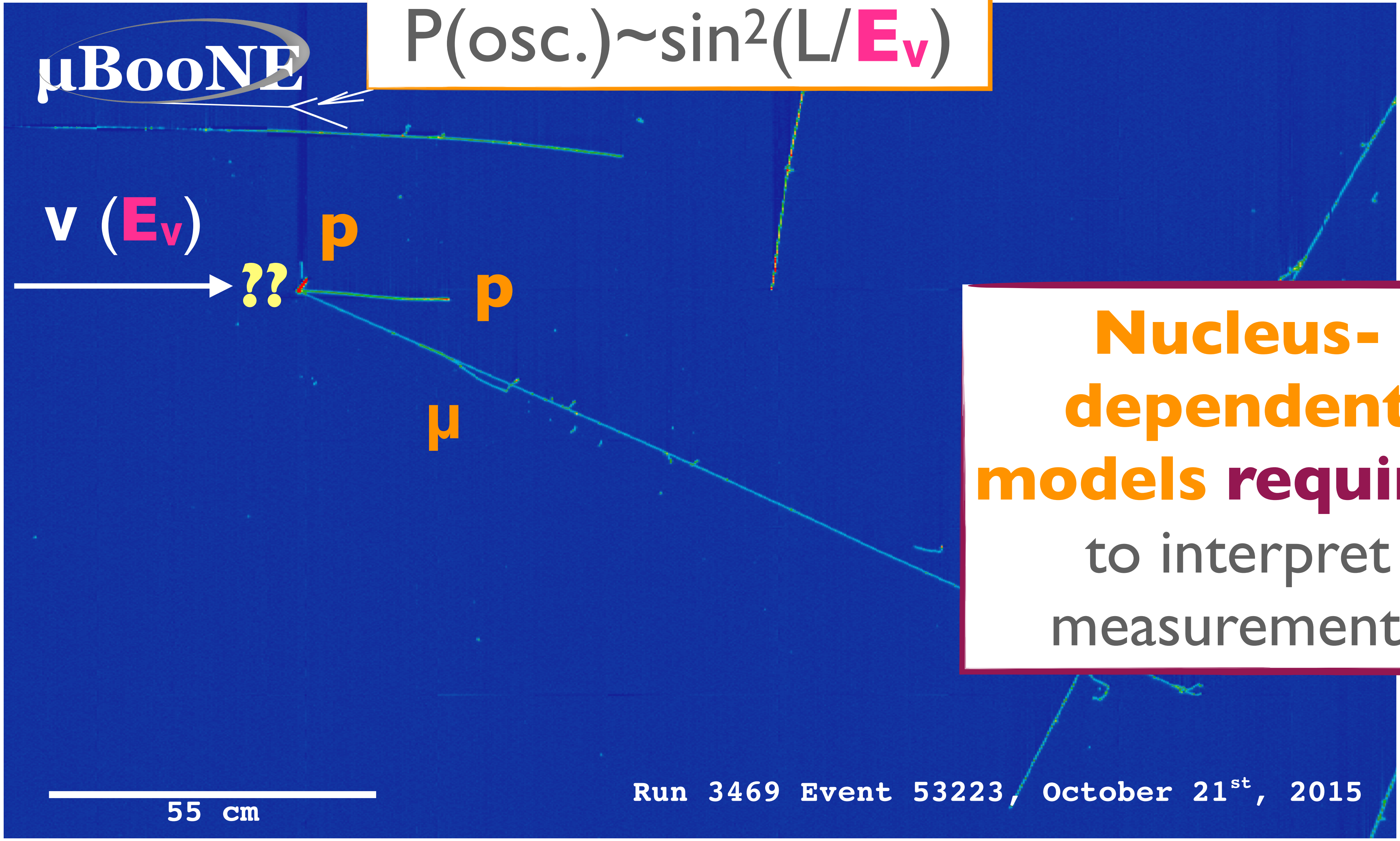
NEUTRINO INTERACTIONS



$P(osc.) \sim \sin^2(L/E_\nu)$

NEUTRINO INTERACTIONS

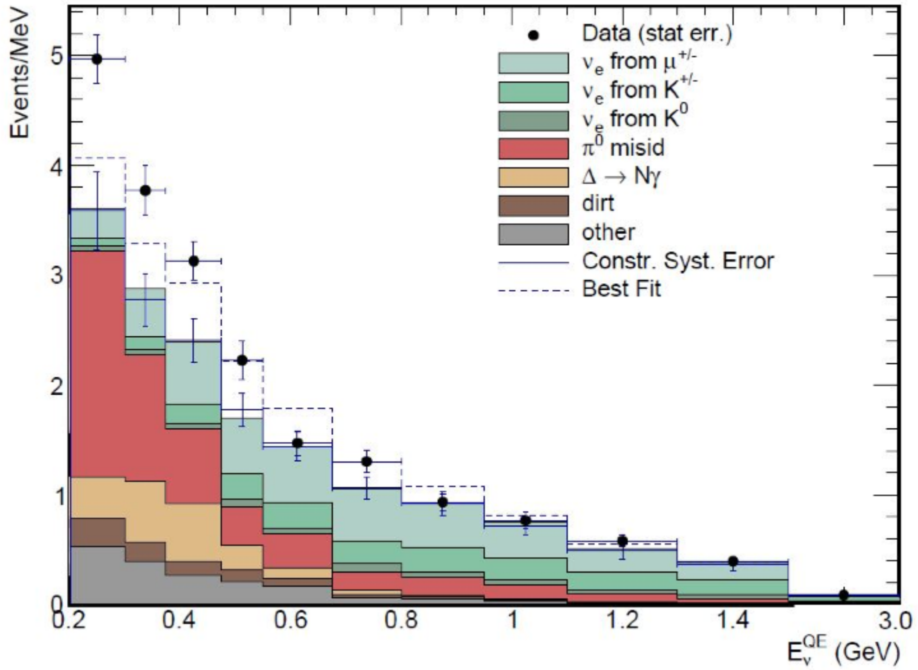
$P(\text{osc.}) \sim \sin^2(L/E_\nu)$

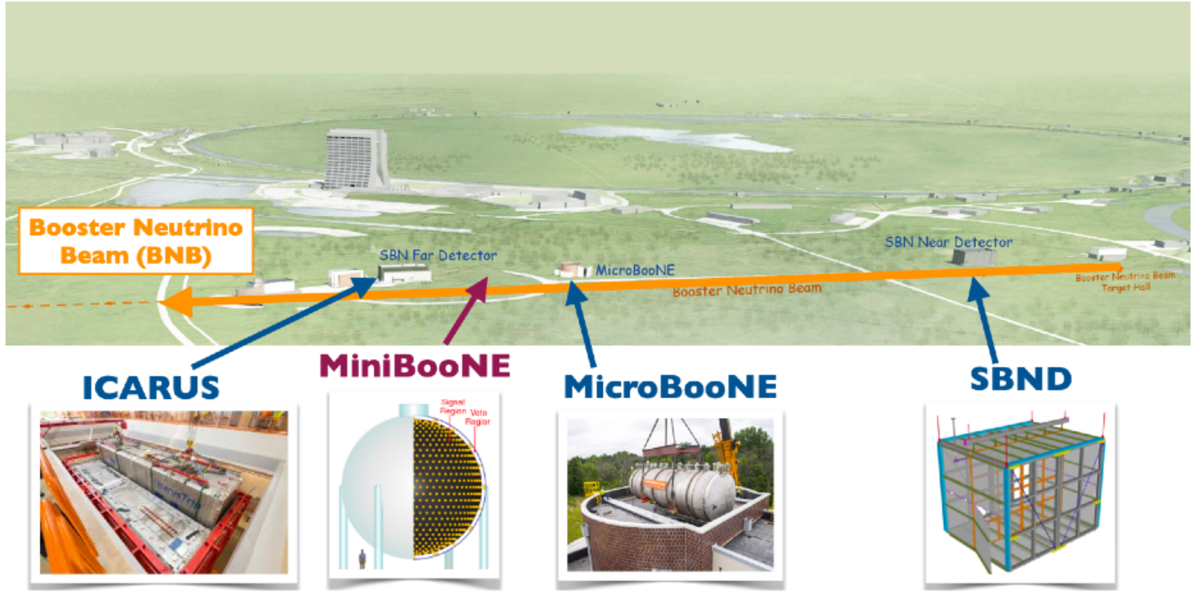


Nucleus-dependent models required to interpret measurements

How many neutrinos are there?

HOW MANY NEUTRINOS ARE THERE?





- A number of anomalous results (including MiniBooNE low energy excess) have led to renewed interest in possibility of sterile neutrinos

- Short-Baseline programme at Fermilab: 3 detectors (UK participates in 2: **MicroBooNE** and **SBND**)
  - Will resolve question of short-baseline neutrino oscillation (which would hint to existence of sterile neutrino)
  - Beam running approved until long shut-down in 2027; in discussion about resuming after that (particularly antineutrino beam)

- Also provides **cross-section measurements for neutrino interactions on argon** and **development of LArTPC technology** that will provide important input for DUNE

ICECUBE
NEUTRINO OBSERVATORY

FASER

What else can neutrinos teach us?

P-ONE

KM3NeT

NEUTRINO ASTRONOMY

Neutrinos are the only high-energy particles to explore the deep universe

- TXS0506+056: a nearby blazar
- NGC1068: a nearby galaxy
- Galactic plane: the nearest high-energy neutrino source

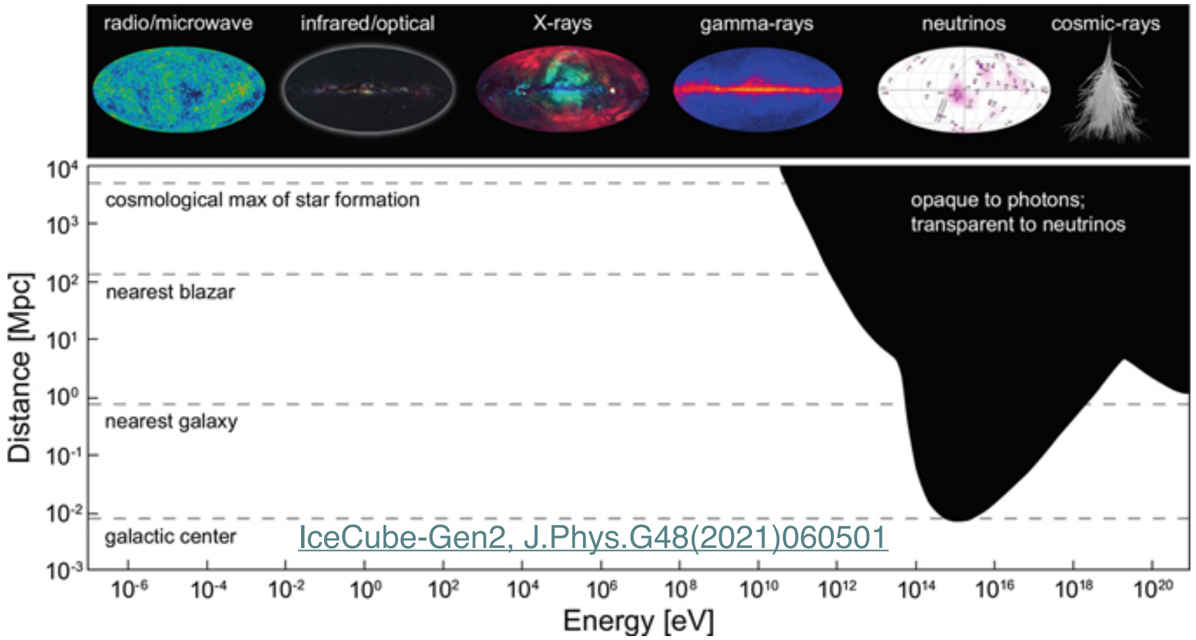
IceCube, Science380(2023)1338

All of these give new physics opportunities!

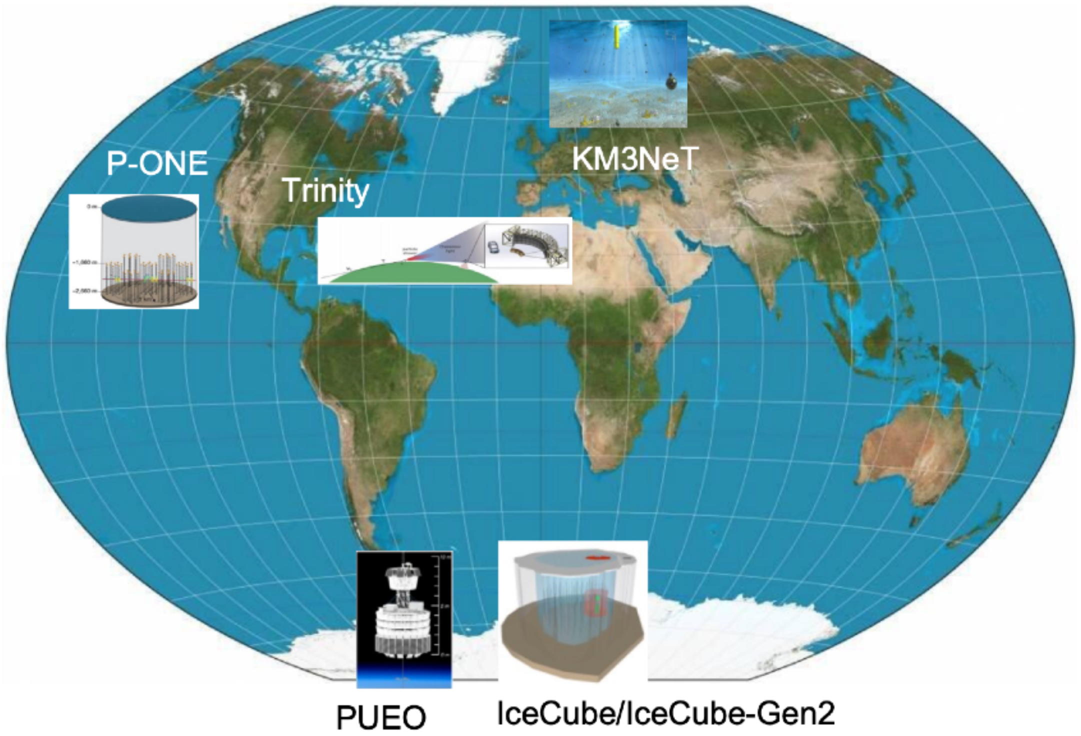
UK High-Energy Astrophysical Neutrino consortium

- IceCube, PUEO, P-ONE, KM3NeT, Trinity
  - Near term plan: exploit science from IceCube and PUEO
  - Long term plan: focus on a single future project (P-ONE is the leading candidate)
- Community building workshops planned this year (TBA)

The universe is opaque to high-energy gamma rays



IceCube-Gen2, J.Phys.G48(2021)060501



supernemo
collaboration

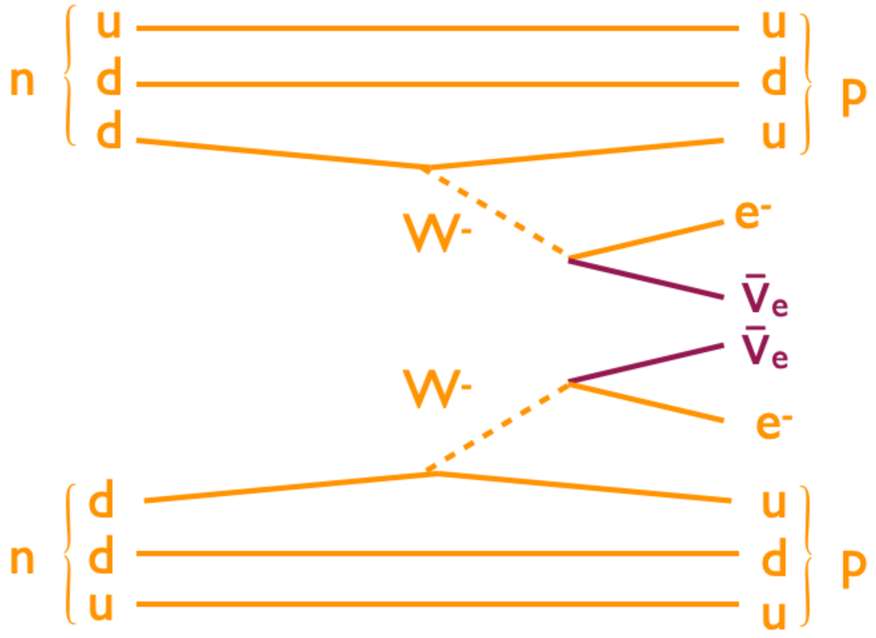
LEGEND

Are neutrinos their own antiparticles?

SNO+

ARE NEUTRINOS THEIR OWN ANTIPARTICLES?

- Uniquely in the Standard Model, neutrinos could be their own particles
  → Majorana fermions
- Could explain small neutrino mass
- Most promising way to search: neutrinoless double beta decay
- Neutrinoless double-beta decay UK community strategy released November 2023



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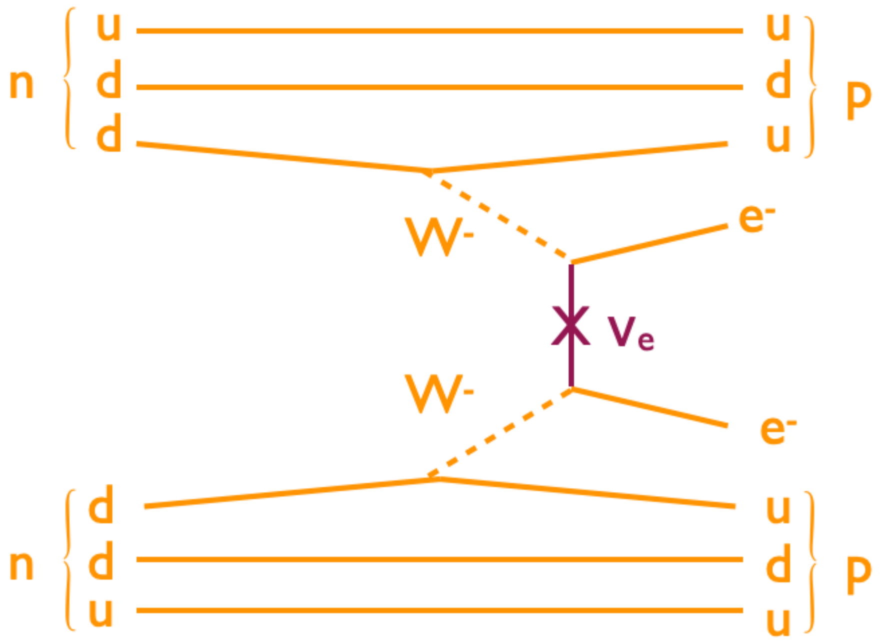
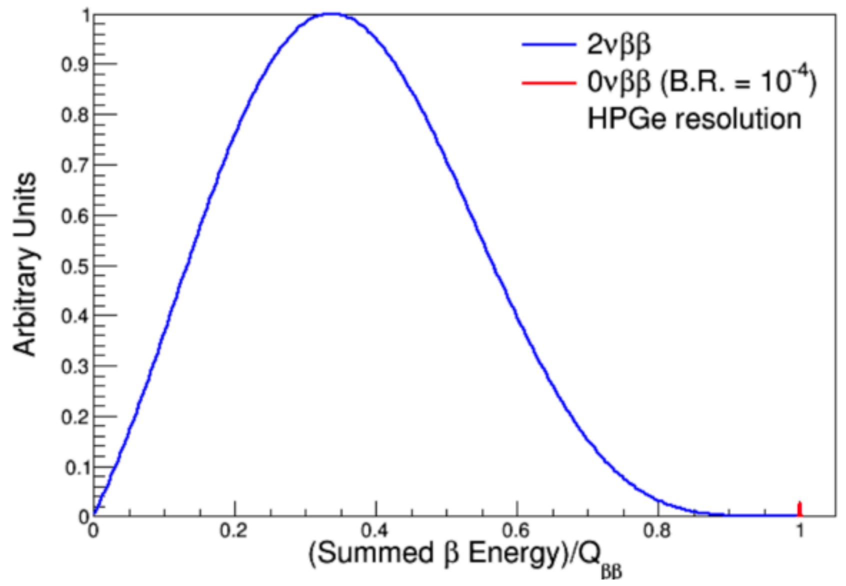


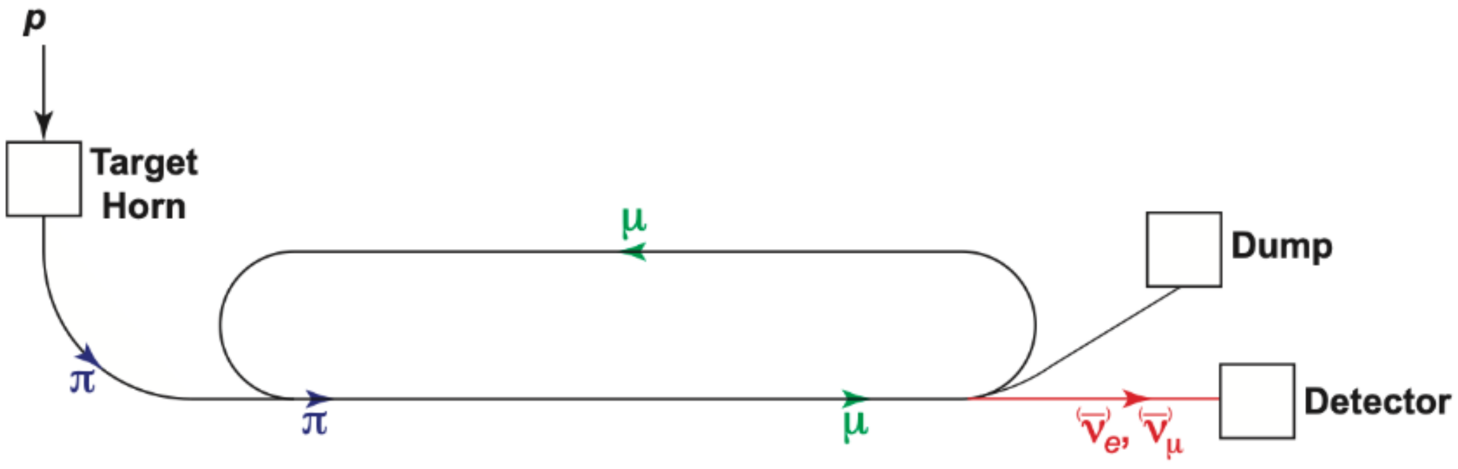


νSTORM

Future Facilities

NUSTORM

nuSTORM (Neutrinos from Stored Muons): proposed neutrino-beam facility based on a stored muon beam

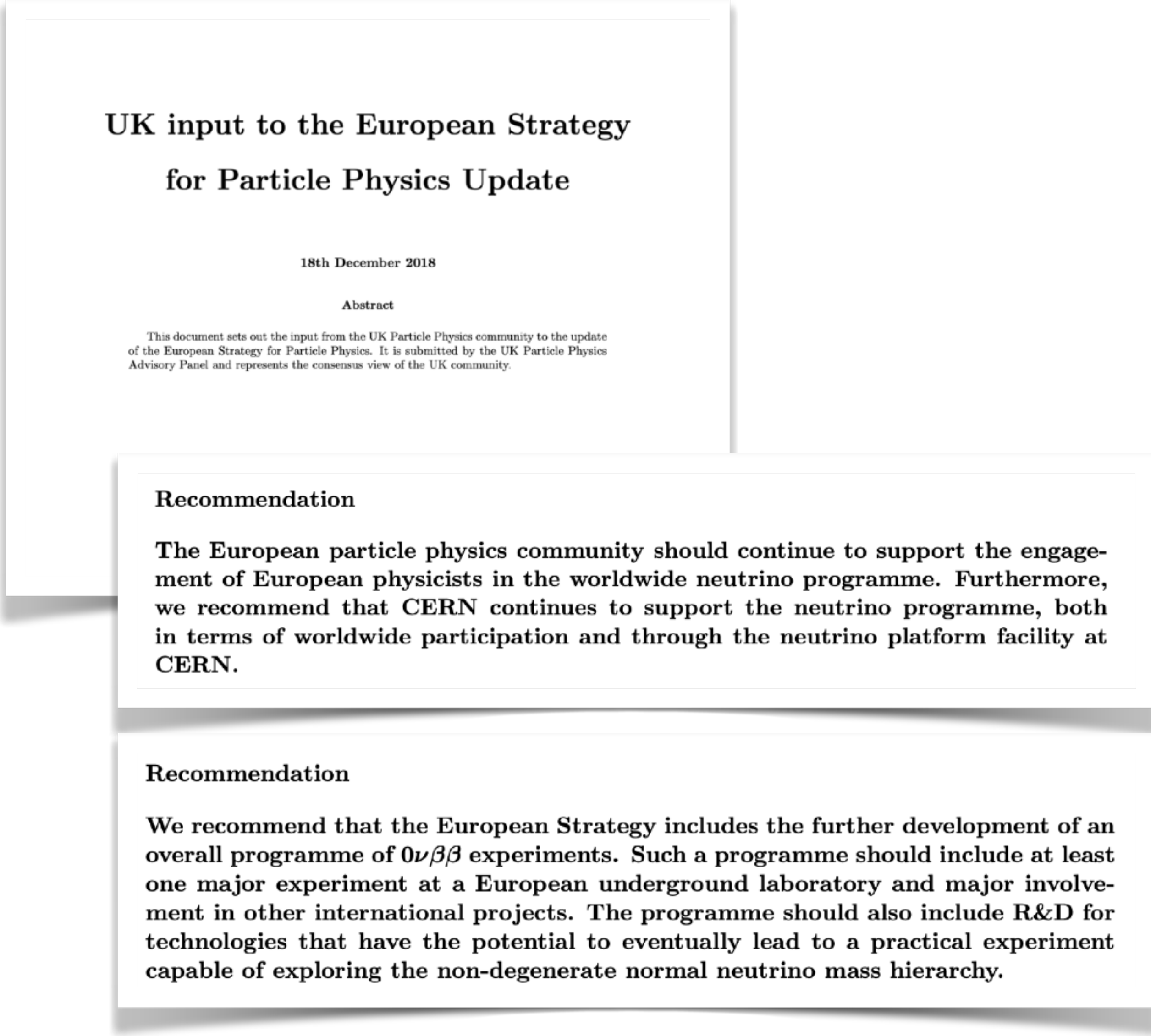


- %-level electron and muon neutrino cross sections
- Neutrino energy scan: spectrum at each point precisely known
- Exquisitely sensitive BSM and sterile neutrino searches
- A step towards a muon collider
    - Muon accelerator test bed
    - Proof of principle of high brightness stored muon beams
- Feasibility of executing nuSTORM at CERN established through Physics Beyond Colliders study

Opportunity for new studies for briefing book — participation welcomed!

NEUTRINOS IN 2020 ESU

- The 2020 Physics Briefing Book contained ~15 pages about neutrinos
- Covered neutrino oscillation, precision flux and cross section measurements, neutrinoless double beta decay, direct neutrino mass measurements, searches for sterile neutrinos, searches for heavy neutral leptons
- UK input included recommendations on supporting long-baseline neutrino physics and developing 0νββ experiments



UK input to the European Strategy
for Particle Physics Update

18th December 2018

Abstract

This document sets out the input from the UK Particle Physics community to the update of the European Strategy for Particle Physics. It is submitted by the UK Particle Physics Advisory Panel and represents the consensus view of the UK community.

Recommendation

The European particle physics community should continue to support the engagement of European physicists in the worldwide neutrino programme. Furthermore, we recommend that CERN continues to support the neutrino programme, both in terms of worldwide participation and through the neutrino platform facility at CERN.

Recommendation

We recommend that the European Strategy includes the further development of an overall programme of $0\nu\beta\beta$ experiments. Such a programme should include at least one major experiment at a European underground laboratory and major involvement in other international projects. The programme should also include R&D for technologies that have the potential to eventually lead to a practical experiment capable of exploring the non-degenerate normal neutrino mass hierarchy.

P5 RECOMMENDATIONS ON NEUTRINOS

Exploring the Quantum Universe

- As the **highest priority independent of the budget scenarios, complete construction projects and operations of ongoing experiments and research to enable maximum science**. This includes…**the first phase of DUNE**

- Construct a **portfolio of major projects** that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future
  - Re-envisioned **second phase of DUNE** with an early implementation of an enhanced 2.1MW beam as the definitive long-baseline neutrino oscillation experiment
  - **IceCube-Gen2** for the study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter

- Create an **improved balance between small-, medium-, and large-scale projects**

- Support a **comprehensive effort to develop the resources essential to our 20-year vision for the field**. This includes an aggressive R&D program that…could yield **revolutionary accelerator designs** that chart a realistic path to a 10 TeV pCM collider. In particular, the **muon collider option** builds on Fermilab strengths and capabilities and supports our aspiration to host a major collider facility in the US

Neutrino Factory (e.g. nuSTORM) is a step on the way to this!

SUMMARY

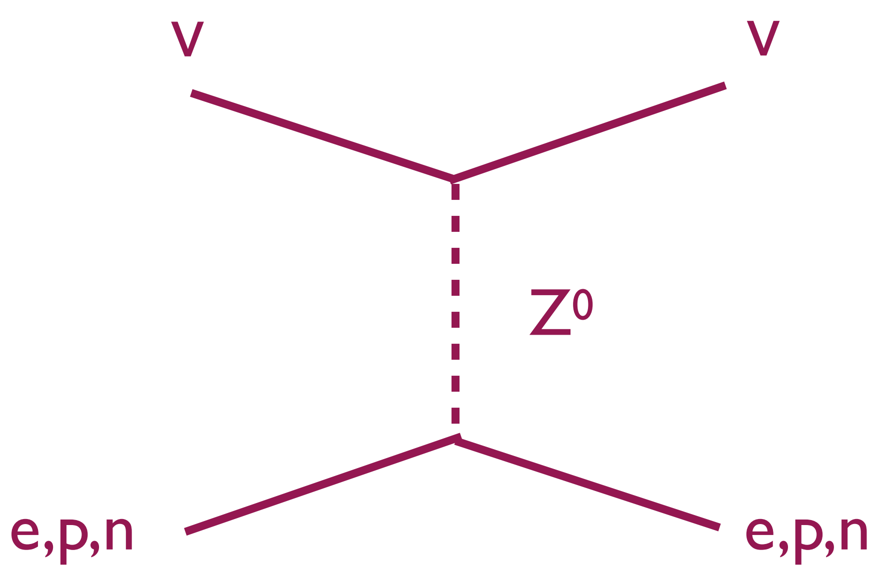
Much more detail about projects and UK contributions in backup slides

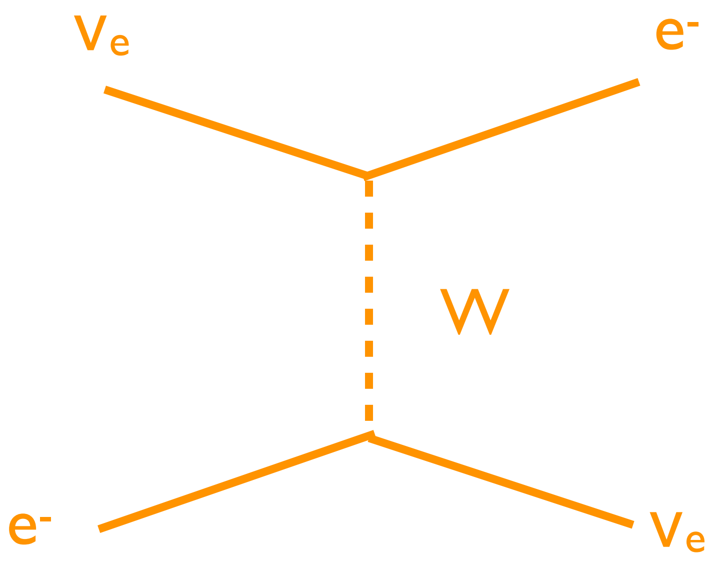
- UK neutrino community is large. Many international projects have UK leadership, so we are poised to capitalise on neutrino physics output in the next generation of experiments
- CERN Neutrino Platform has been extremely valuable for neutrino physics
  - Provided a subdetector for T2K near detector upgrade, cryostats for DUNE far detectors, ProtoDUNE
  - So we should engage strongly with this strategy update!
- For many of the larger projects, expect status to be similar to last ESU, or to follow recent community strategic plans (e.g. P5, $0\nu\beta\beta$, astrophysical neutrinos)
- Synergy with other groups in this process e.g. QTFP, FASER
- There are likely also new efforts (some not on these slides) that we should include in this process
- **Please get in touch if you would like to contribute or have new ideas!**

BACKUP SLIDES

MEASURING THE MASS ORDERING: MATTER EFFECTS

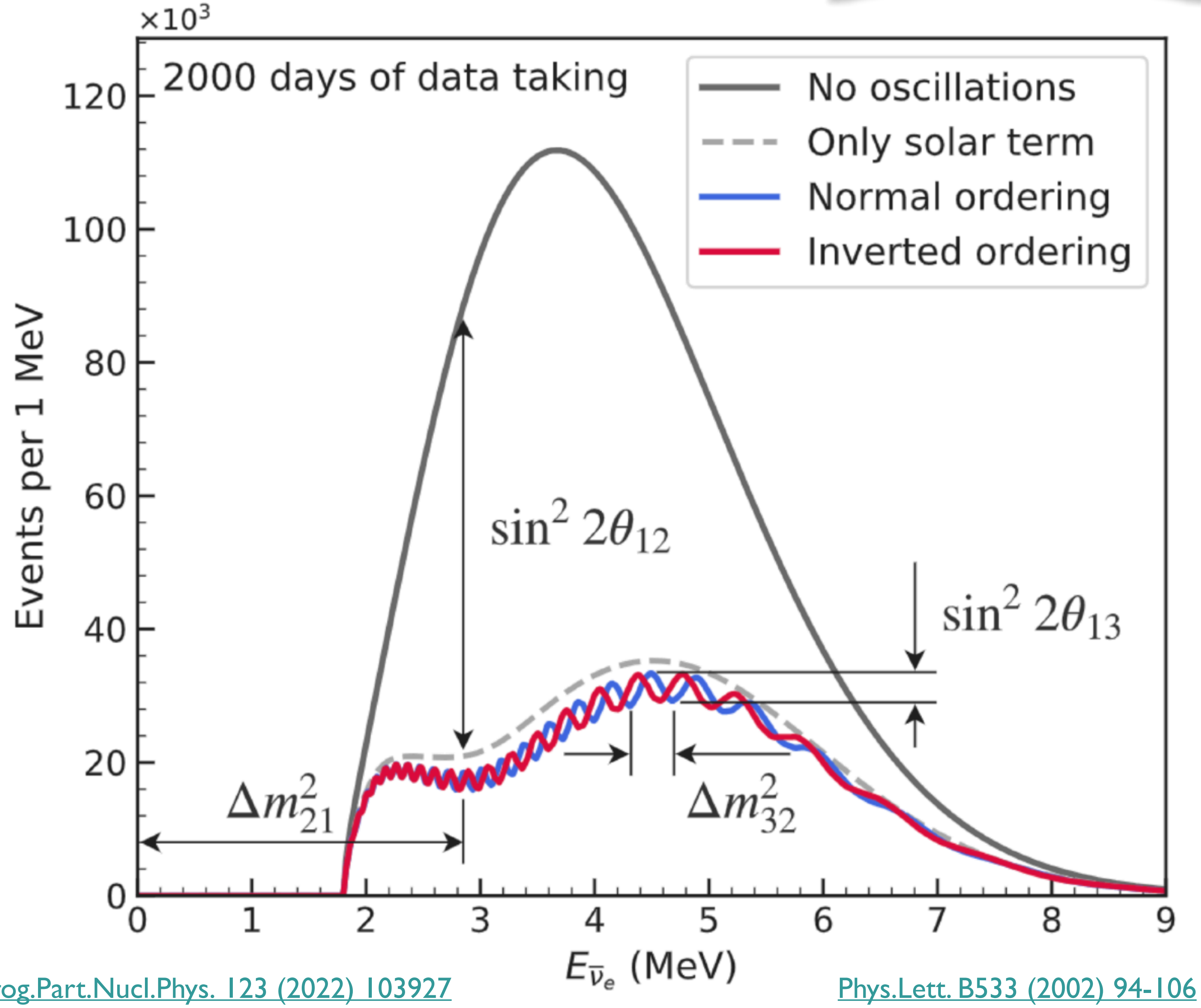
- Long-baseline experiments are **sensitive to the mass hierarchy via matter effects**
- Additional charged-current interactions in matter for ν_e, not available to ν_μ, ν_τ
- → **“extra potential”** for ν_e breaks mass-hierarchy symmetry (depending on which mass state contains the most ν_e)





MEASURING THE MASS ORDERING: JUNO

- Reactor neutrino experiment: $\bar{\nu}_e$ disappearance at baseline ~50 km
- Sensitive to both oscillations according to Δm^2_{21} and Δm^2_{32} → **interplay of both** gives sensitivity to mass hierarchy
- Requires extremely precise energy resolution

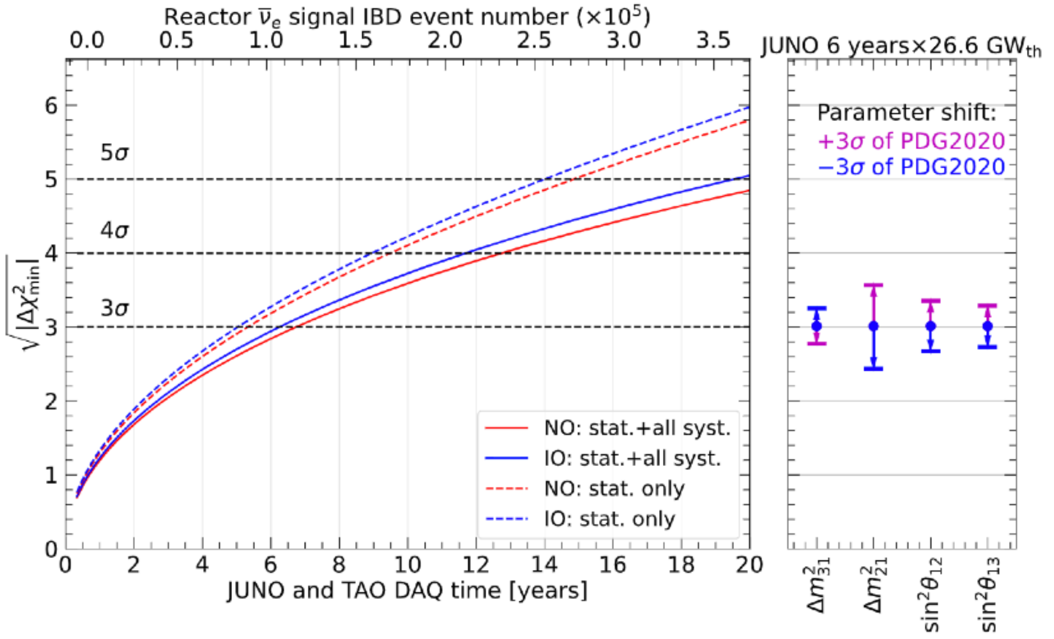


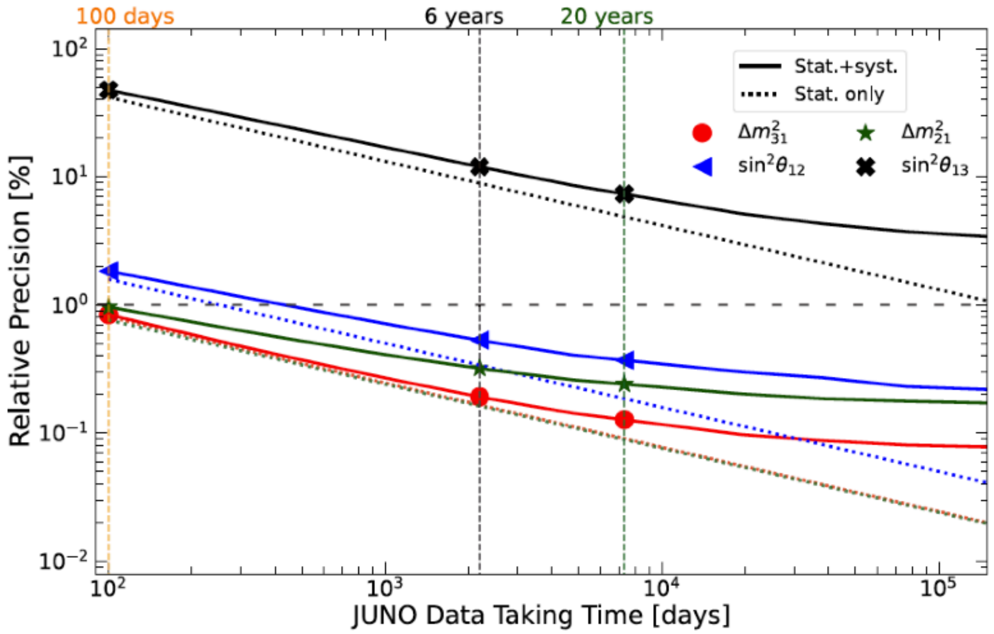
Prog.Part.Nucl.Phys. 123 (2022) 103927

Phys.Lett. B533 (2002) 94-106

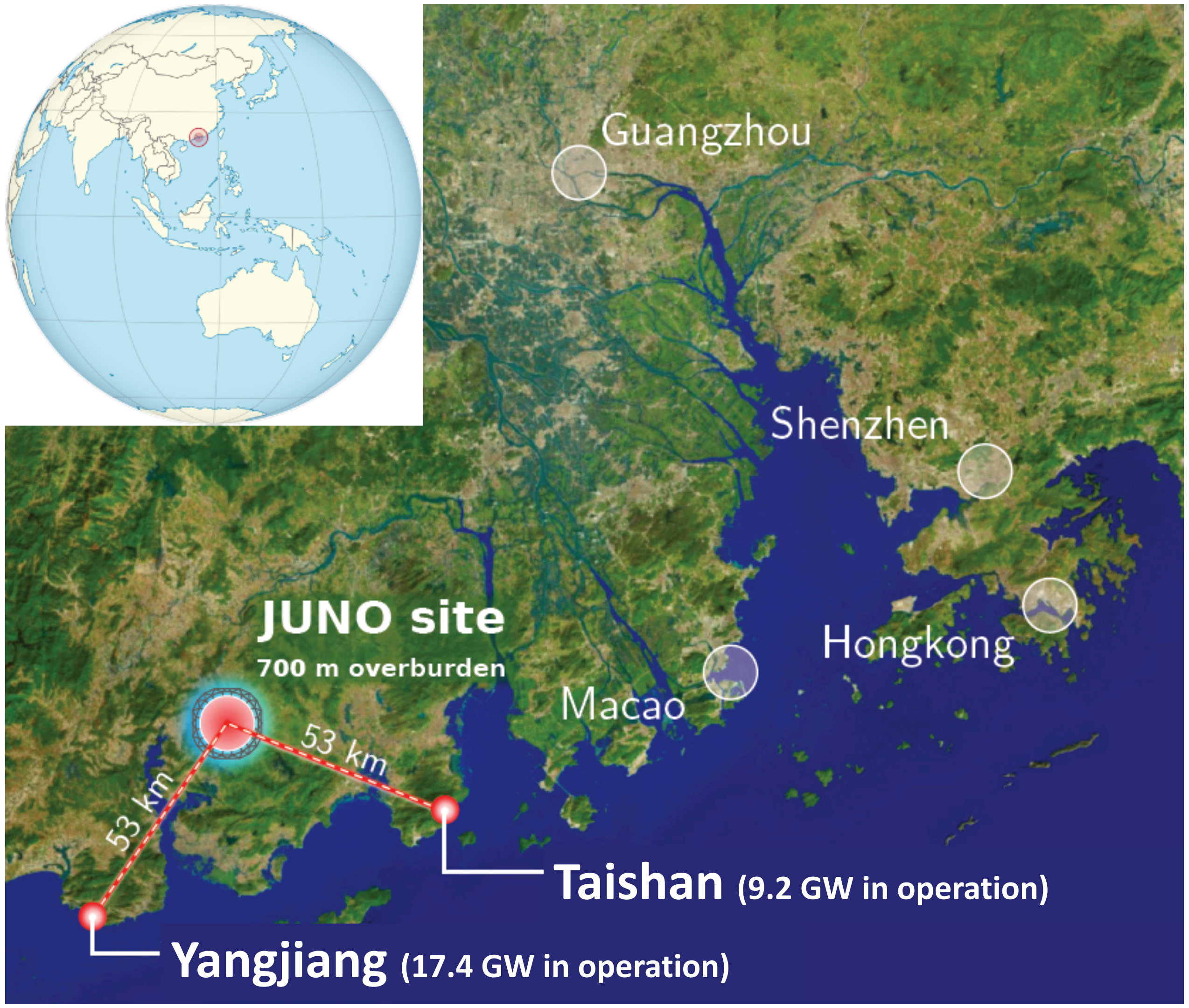
JUNO

- Goals
  - detect neutrinos from nuclear power plants to determine the neutrino mass ordering
    - 3 sigma in 6 years w/ reactor data only
    - Combination w/ atmospheric neutrinos could enhance the mass ordering sensitivity
  - and measure three-oscillation parameters
    - better than 0.5% precision in 6 years
  - also study solar & supernova neutrinos, geo-neutrinos, and nucleon decays.
- Timeline
  - Approved 2013
  - Civil construction 2015-2021
  - Detector construction 2021-2024
  - Data-taking 2025
- **UK involvement**
  - Warwick 2021 (Lu), Liverpool 2023 (Andreopoulos)
  - Funding sources: ERF/UKRI, University fundings, CSC/ China.
  - Activities: atmospheric neutrino oscillation analyses and ML based event selection, event generators for GeV physics, GENIE/VALOR/Reweigh framework.
  - Leadership: Neutrino Interaction Working Group Convener 2022.

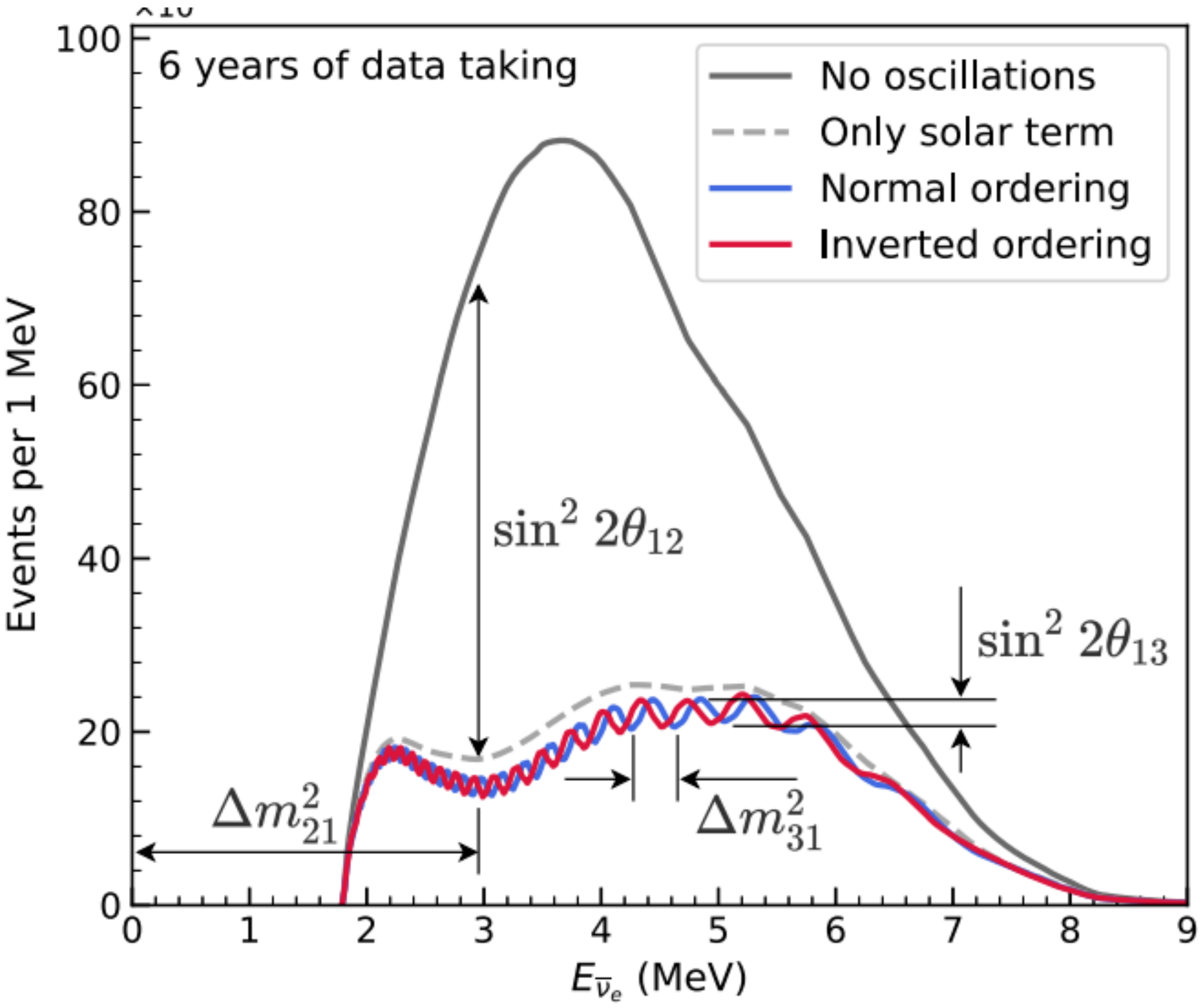




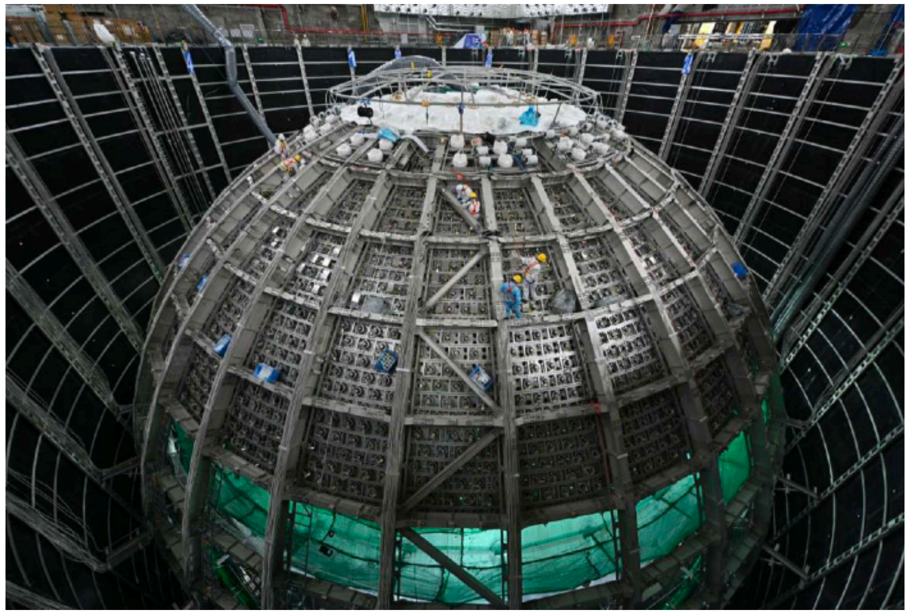
Angel Abusleme *et al* [JUNO] 2022 *Chinese Phys. C* **46** 123001

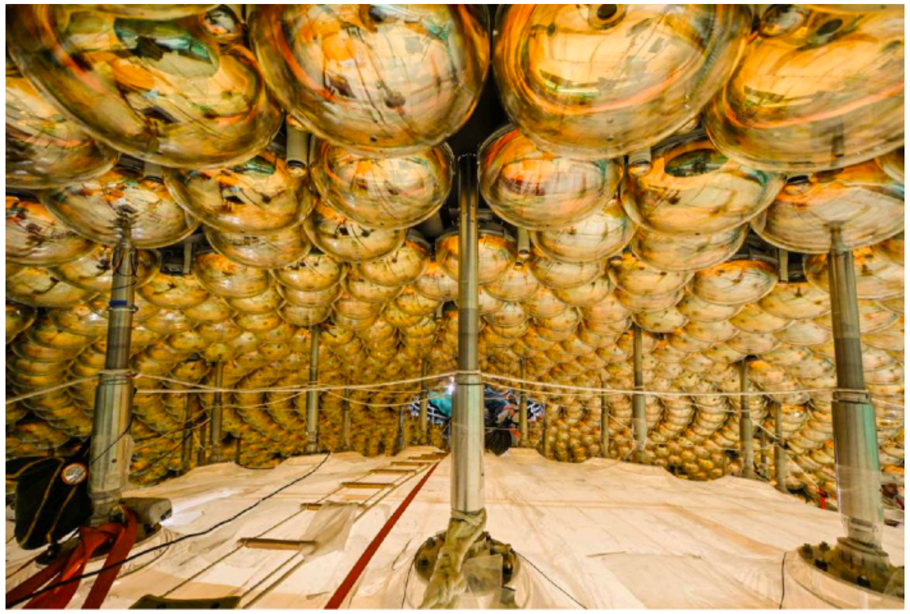


Primary goal: neutrino mass ordering measurement

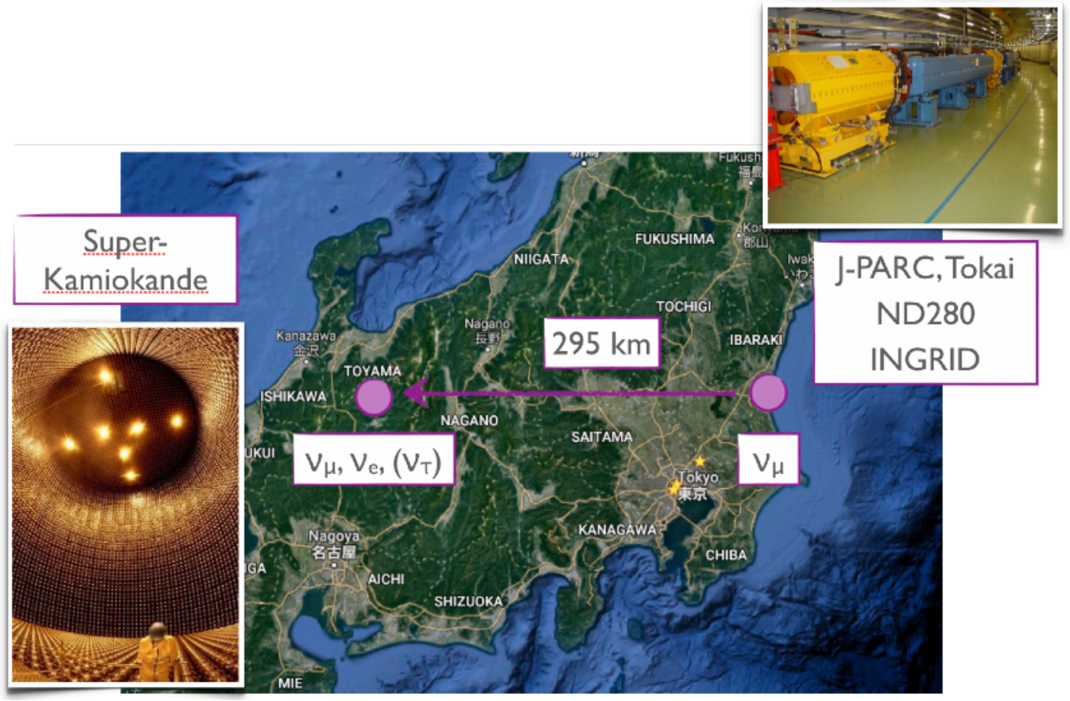


PMT installation, June 2023





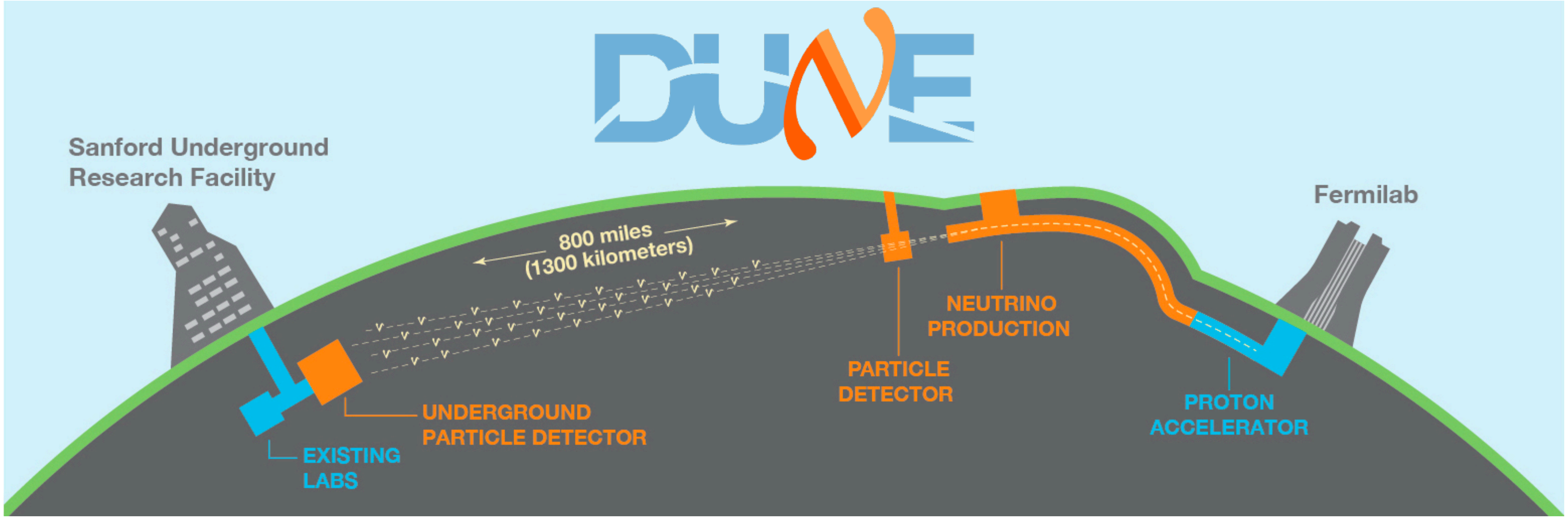
CP VIOLATION: LONG-BASELINE ACCELERATOR NEUTRINOS

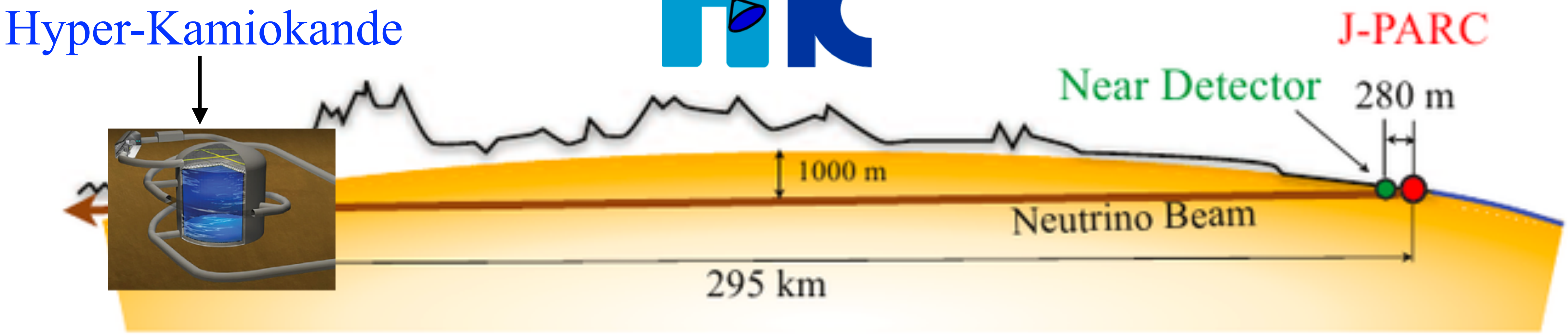


Oxford, RAL, Lancaster, Warwick, Imperial, King's, RHUL, Glasgow, Liverpool, Sheffield,

Sussex, UCL, QMUL

Joint T2K+NOvA analysis released this year with UK leadership from QMUL, Imperial


DUNE
Sanford Underground Research Facility
Fermilab
800 miles (1300 kilometers)
NEUTRINO PRODUCTION
PARTICLE DETECTOR
PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS

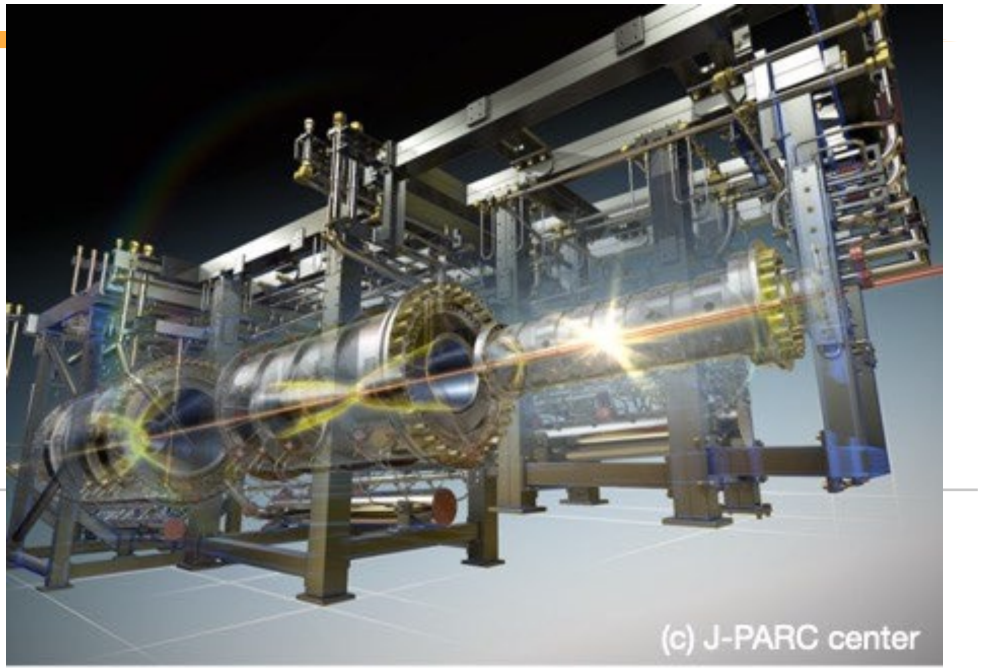

Hyper-Kamiokande
J-PARC
Near Detector
280 m
1000 m
Neutrino Beam
295 km

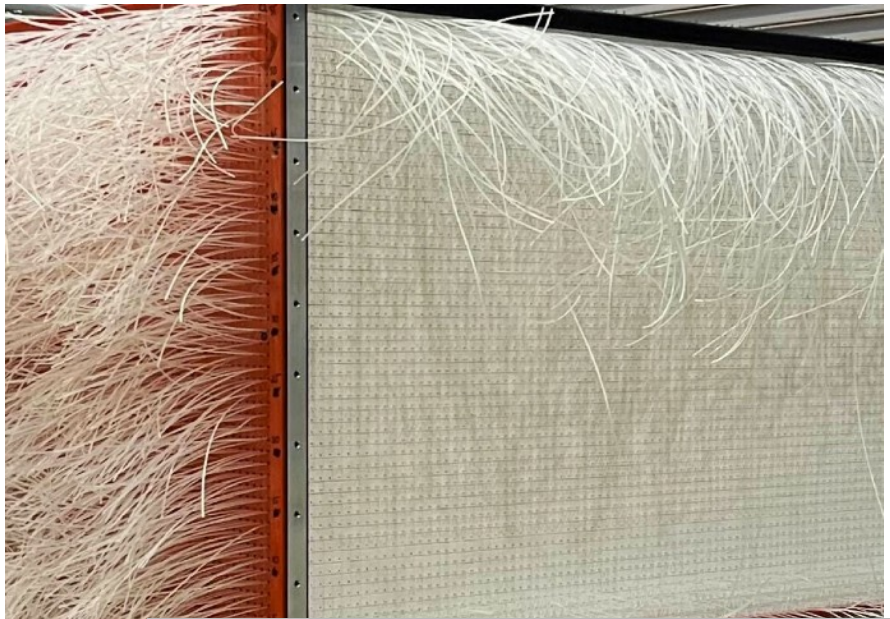
T2K

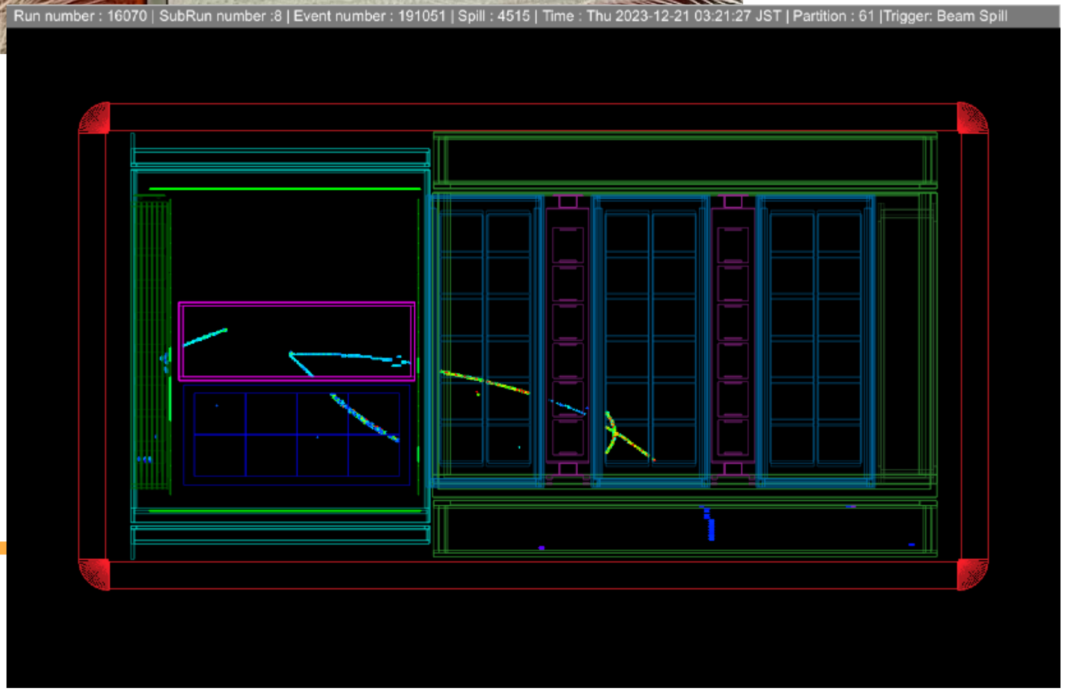
- T2K resumed data-taking in December 2023 with a significantly upgraded neutrino beam producing about half as many more neutrinos than before, with major UK contributions to improvements to beam targetry, monitoring, and modelling

- New detectors have been deployed in the ND280 near-detector complex, with key UK contributions, which will improve the detail with which it can observe neutrino interactions, and will also give it a much broader geometrical acceptance

- Over the next several years, these improvements, combined with Super-K, which now has neutron-tagging capabilities from the Gadolinium that has been added to the water in the detector, will allow T2K to continue to produce world-leading data on neutrino oscillations, leading into the era of physics with Hyper-K

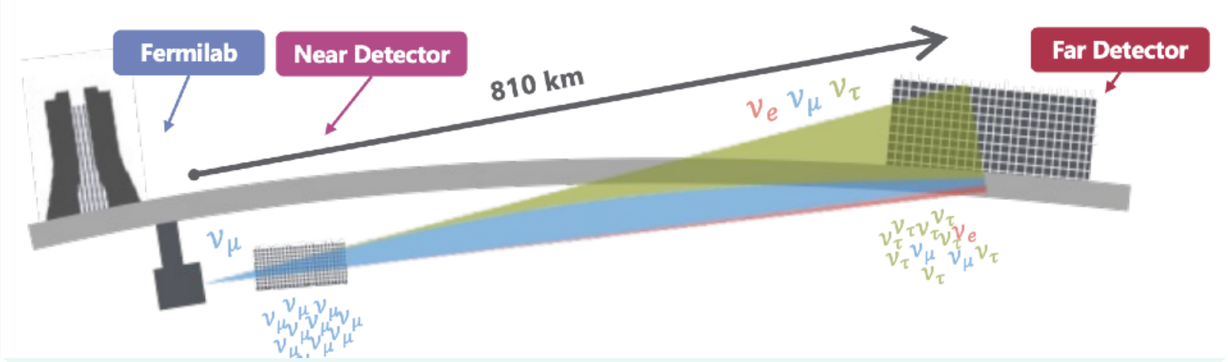

(c) J-PARC center




Run number : 16070 | SubRun number :8 | Event number : 191051 | Spill : 4515 | Time : Thu 2023-12-21 03:21:27 JST | Partition : 61 |Trigger: Beam Spill

NOvA UK

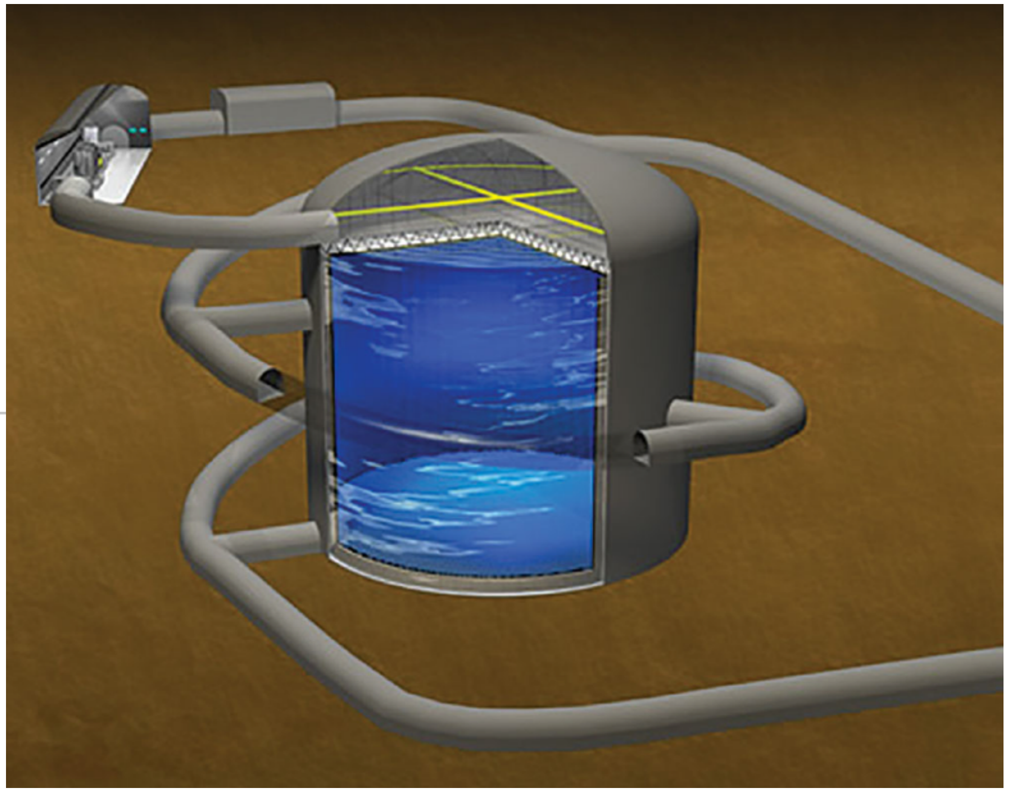
- The NOvA long-baseline neutrino oscillation experiment uses the NuMI (anti)neutrino beam at Fermilab and two low-Z, tracking calorimeters optimised for identifying electron neutrinos.
- NOvA has sensitivity to all the remaining questions in standard 3-flavour neutrino oscillation physics:
    - the mass hierarchy,
    - CP violation,
    - whether θ_{23} is non-maximal (and if so its octant).
- Our broad physics programme includes neutrino interactions, sterile neutrinos, and exotics searches.
- The collaboration is made up of 260 scientists and engineers from 49 institutions in eight countries.



- The three UK groups (Sussex, QMUL, and UCL) make up around 8% of the collaboration (with 7 academics, 6 PDRAs, and 8 PhD students) but provide 22% of the leadership roles, including:
    - The physics analysis coordinator (Hartnell from 2019 to 2022 and Cremonesi since then).
    - Convenors of the following groups:
        - 3-flavour oscillation (Nichol),
        - test-beam analysis (Asquith),
        - reconstruction and deep learning (Booth),
        - detector systematics (Waldron),
        - beam flux (Thomas and Shorrock),
        - production (Cicala), and
        - data quality (Singh).
- The UK also provides the Institutional Board Chair (Nichol), two members of the Executive Committee (Cremonesi, Nichol), an Equality, Diversity and Inclusion Chair (Asquith), and NOvA-T2K joint analysis leadership team member (Cremonesi).
- UK groups have made strong leading contributions to:
    - 3-flavour oscillations
    - neutrino cross-section analyses
    - Test beam programme
    - Computing groups
    - Detector calibration
    - Operations

HYPER-K

- The Hyper-Kamiokande experiment is well advanced in construction and should begin taking data in 2027/28 using the J-PARC neutrino beam, which recently began running again after upgrades
- Backed by a £15.5M investment from the UKRI infrastructure funds and additional funds from STFC, the UK has secured significant roles in Hyper Kamiokande including major contributions to the software and computing, DAQ hardware and software, calibration systems, elements of the Outer Detector, and continuing involvement in the neutrino beamline
- These contributions will enable UK physicists to participate in the broad physics programme of Hyper Kamiokande, including (but not limited to) the search for CP violation in neutrino oscillations, more precise determinations of neutrino mixing parameters and interaction properties, the search for nucleon decay, the study of atmospheric and solar neutrinos, the study of relic and burst supernova neutrinos, and much more



Excavation of Dome Section Completed!

69-m diameter x 21-m height

Photo by Takenaga-san

- Excavation of the dome section completed including rock supports on October 3, 2023.
- Already started the excavation of the 1st bench of the barrel section and will finish it by November 15, 2023, to install overhead crane.

2

DUNE UK

- **PiP-II:** UK delivering 3 cryomodules for the last stage of the PiP-II chain, high beta 650 MHz, with each module comprising 6 cavities. The first cavities have been produced already and the first complete cryomodule assembly is scheduled for Jan '26 (ready for cryogenic testing at FNAL), with the 3rd ready by Nov '26

- **High-power targets:** UK delivering a target for 1.2 MW LBNF running, a remote target exchange system, and the helium plant. This phase is funded and scheduled to complete by 2027. There is also R&D underway to investigate materials/designs that can accommodate a beam upgrade to 2.4 MW, to be ready for around 2031

- **APAs:** The UK is building 137 of the 150 Anode Plane Assemblies (APAs) for the DUNE horizontal-drift far-detector module. These are the primary charge-redout elements of the horizontal-drift TPC

- Production of APAs has started and the assembly factory in Daresbury is being adapted/developed to deliver a high rate production run that will complete by the end of 2027, in time for installation in SURF in 2028.

- The CERN Neutrino Platform has been a very valuable part of developing the DUNE detector. 6 APAs were tested in ProtoDUNE-SP, and four more APAs of the final production design will be tested in ProtoDUNE-2 this summer. ProtoDUNE-2 will be commissioned over the next few weeks (filling is completing this week)

DUNE UK: DAQ

- **DAQ:** UK is responsible for a large fraction of the DUNE Far Detector DAQ
  - Timing, Readout, Trigger, DQM, and Control/Configuration/Monitoring
- Software-based DAQ system using commodity hardware
  - Custom electronics for timing/synchronisation only
  - Extensive use of common standards and open source cloud technology
- System requirements and challenges driven by:
  - High resolution detectors on vast scale
  - High readout data throughput - O(TB/s) per module
  - High uptime for supernova detection, requiring extremely robust system with automated anomaly detection and correction
- Working DAQ required by 2026, to validate detector operation and performance during detector installation

Reconstruction Software and Distributed Computing

Current

- The RS&DC project is developing the advanced reconstruction software and computing workflows that DUNE needs to enable data-taking at its Far Detector
- The project harnesses the Pandora toolkit for advanced particle-flow reconstruction, and exploits the established UK expertise in distributed computing
- The project is one of the key ways in which the UK is working at the forefront of AI/ML software for the Intensity Frontier

Future

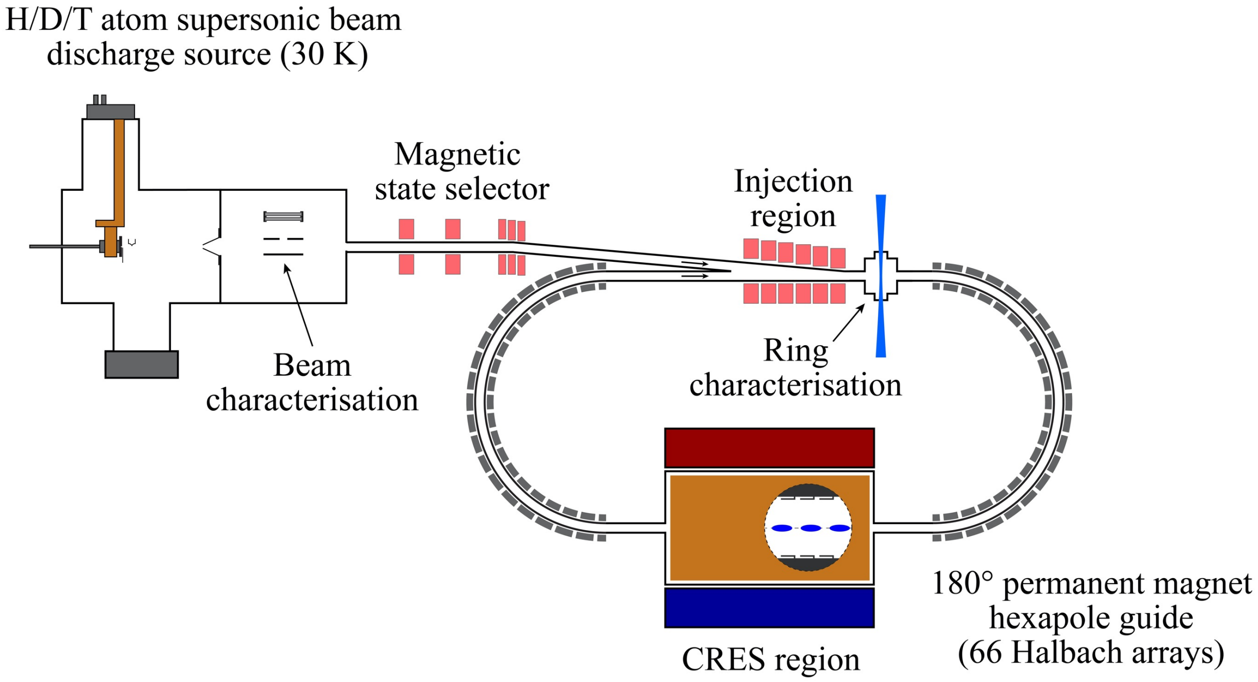
- We should support software and computing into the DUNE exploitation era as part of a strong UK-led physics programme
- The continued development of cutting-edge event reconstruction technologies for DUNE is critical for retaining scientific leadership and maximising science outputs

Last ESU highlighted the importance of data science, calling out HL-LHC in particular. Aim to include DUNE in the highlights this time around.

QTNM

Quantum Technologies for
Neutrino Mass

CRESDA = CRES Demonstration Apparatus



Goal

Neutrino mass measurement from atomic ^{3}H β-decay via Cyclotron Radiation Emission Spectroscopy using latest advances in quantum technologies.

Current project (QTFP Wave 1, 2021-2025)

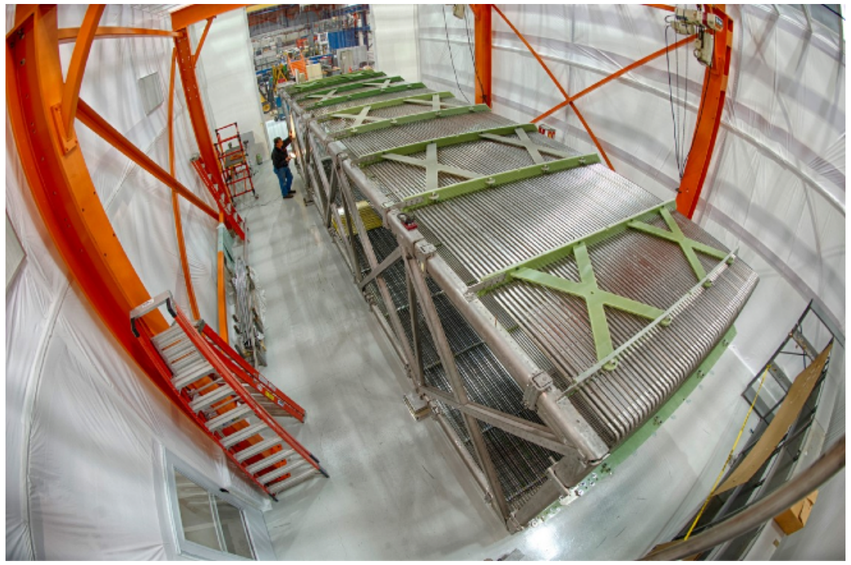
Technology Demonstration

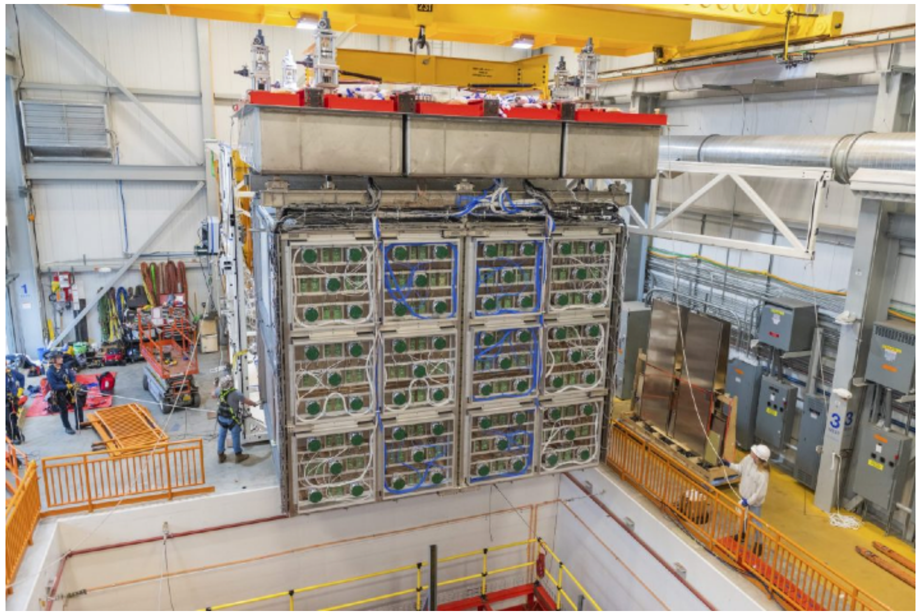
- Quantum noise limited microwave sensors at TRL7/8 for CRES at ~18GHz
- 3D B-field mapping with $\lesssim 1\ \mu$T precision, using H-atoms as quantum sensors (Rydberg Magnetometry)
- Production and confinement of H-atoms, $\geq 10^{12}$ cm^{-3}

Strategy: Phased Approach

$$\underbrace{\underline{\textbf{CRESDA0}}}_{\textit{current}} \rightarrow \underbrace{\textbf{CRESDA-Tritium} \rightarrow \textbf{100 meV} \rightarrow \textbf{50 meV} \rightarrow O(\textbf{10 meV})}_{\textit{Culham Centre for Fusion Energy}}$$

SHORT-BASELINE NEUTRINO PROGRAMME





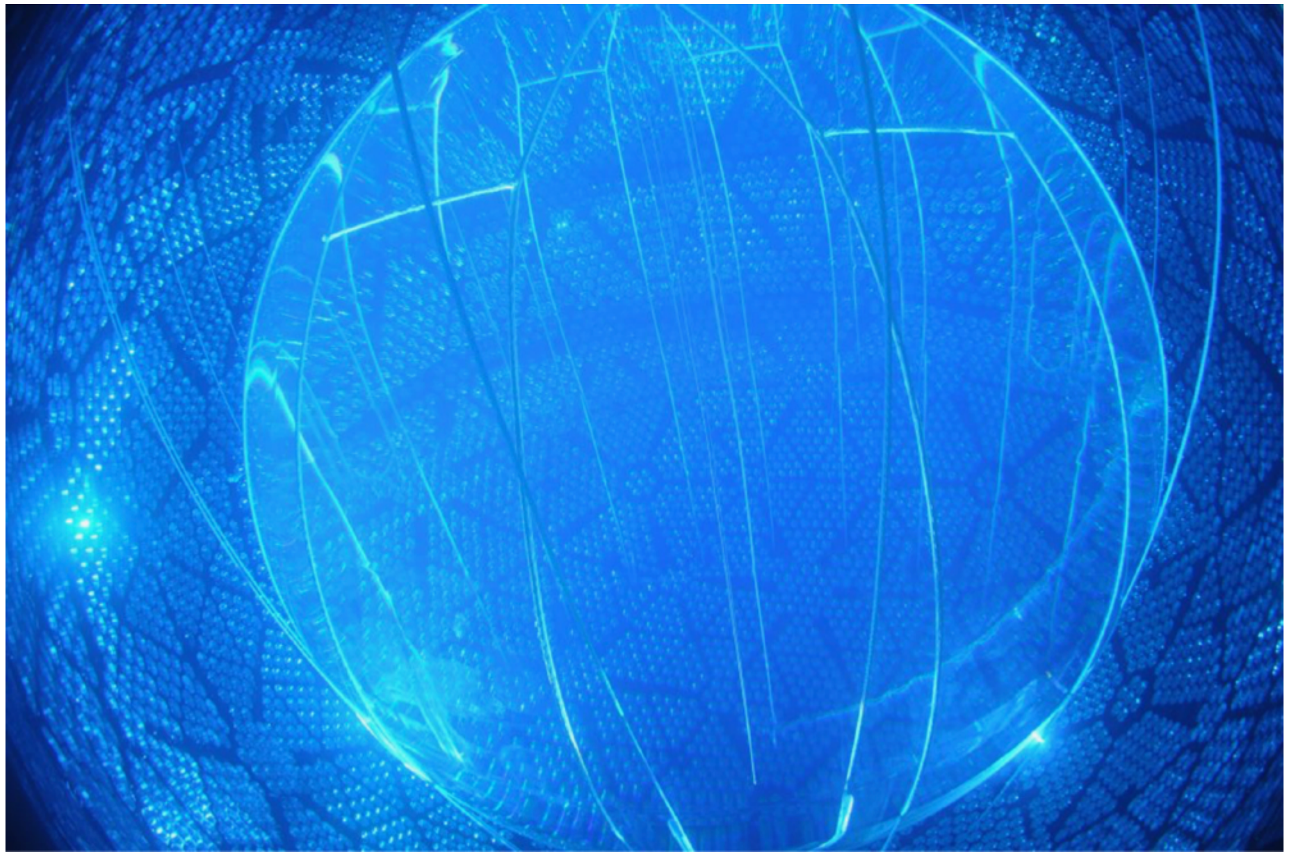
- 11 institutes across the UK: Liverpool, Oxford, Lancaster, Manchester, Sussex, Sheffield, Warwick, Edinburgh, Cambridge, Imperial, QMUL
- MicroBooNE
  - Finished data-taking: fully in analysis phase
  - First search for LEE published, more results anticipated this summer.
  - UK leading updated LEE analysis, BSM analyses, many xsec measurements
  - UK spokesperson, Physics Coordinator, many conveners
- SBND
  - Currently in commissioning phase
  - UK led construction of key elements, including 50% of wire planes and all Anode Plane Assemblies
  - UK Physics Coordinators, IB chair, Executive Committee members, many conveners

ARE NEUTRINOS THEIR OWN ANTIPARTICLES?

Neutrinoless double-beta decay UK community strategy released November 2023:

1. Continued support for exploitation of **LEGEND-200**, **SNO+**, and **SuperNEMO Demonstrator**, recognising the unique near-term physics programmes of each experiment and building on substantial prior UK investment
2. Support construction of **LEGEND-1000** in the near term as the highest priority project in the USA and Europe, ensuring **UK leadership in an experiment that will have >3σ discovery sensitivity** for Majorana neutrinos in the inverted mass ordering range in the medium term
3. Support development and implementation of **higher loading phases of SNO+**, which will provide complementary sensitivity with a different isotope in the medium term and lay foundations for a technique that might be extended to the normal mass ordering in the longer term
4. Exploit **cross-field scientific and technological synergies with the XLZD dark matter community** and explore **strategic R&D opportunities** offered by complementary technologies, such as NEXT, to further strengthen the main programme in the medium term, while continuing to support **blue-skies R&D into new technologies** able to reach sensitivities beyond the inverted mass ordering in the long term

SNO+



2025 final commissioning

2026 Te deployment

2027 Phase I data taking

2028 increase Te loading

2029 Phase II higher loading data taking

SNO+: Te-loaded Liquid Scintillator

- Highly scalable
- Isotope readily available & inexpensive (no need for enrichment)
- Broad physics programme

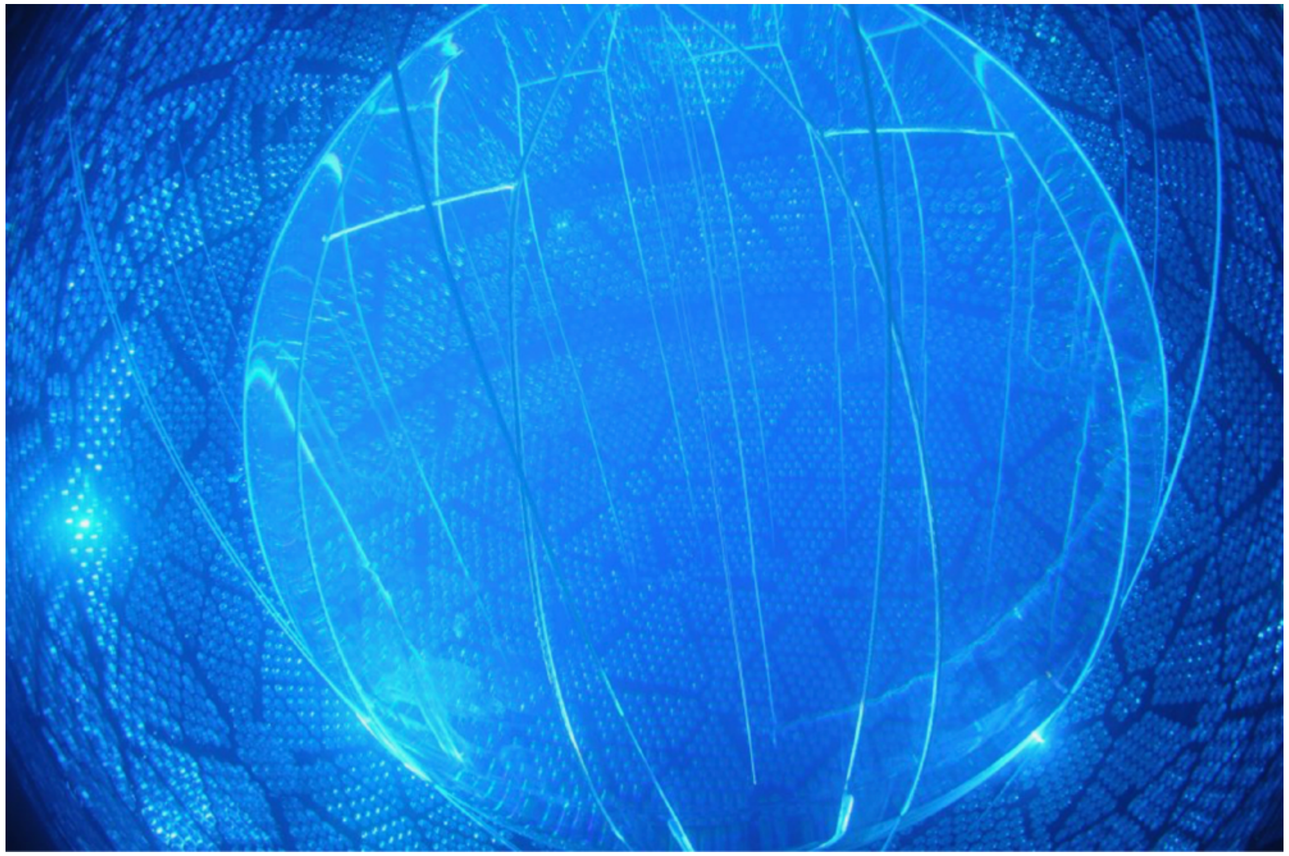
Recent results (several other analyses also in progress):

- 1st detection of anti-nus from distant reactors in pure water (PRL)
- 1st directional reconstruction of 8B solar neutrinos in pure scintillator (PRD)
- Prelim geo & reactor measurement (publications in progress) [expected to overtake current dm12^2 precision in ~2 years]

Te status:

- Test batch operations currently underway for Te systems (smooth running so far!)
- Initial 0.5% Te deployment planned to begin next year (will start probing inverted mass ordering)
- Canadian grant application to be submitted this year to treble loading, starting 2027 (will be able to cover majority of inverted mass ordering with good sensitivity)

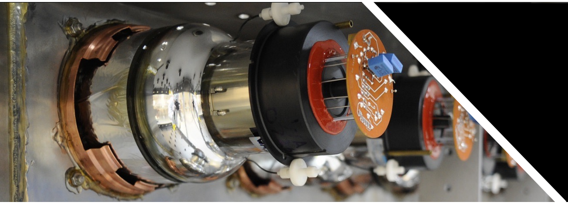
SNO+



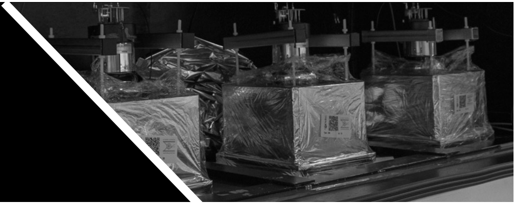
Participating Countries
Canada
China
Germany
Mexico
Portugal
UK
US

Current UK SNO+ Institutions
King's College London
Lancaster University
Liverpool University
Oxford University
Sussex University

Particular UK Leadership Roles Include:
Tellurium Development for 0nbb
Analysis Coordination
Energy & Optics
Laser & LED-based calibration systems
In-situ BiPo calibrations
Data quality & run selection
Solar neutrinos
Supernova neutrinos
Simulation & overall software management
Event reconstruction

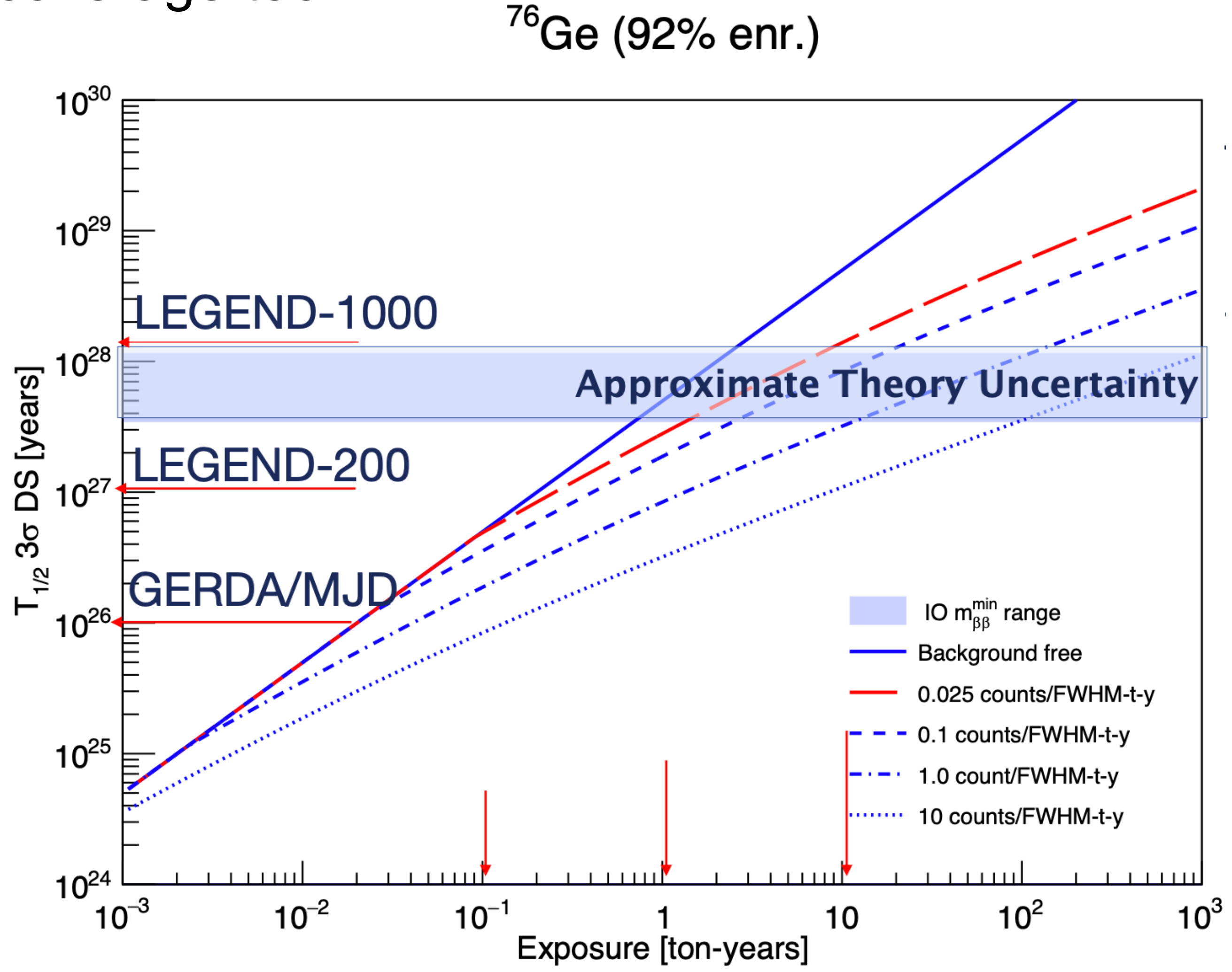


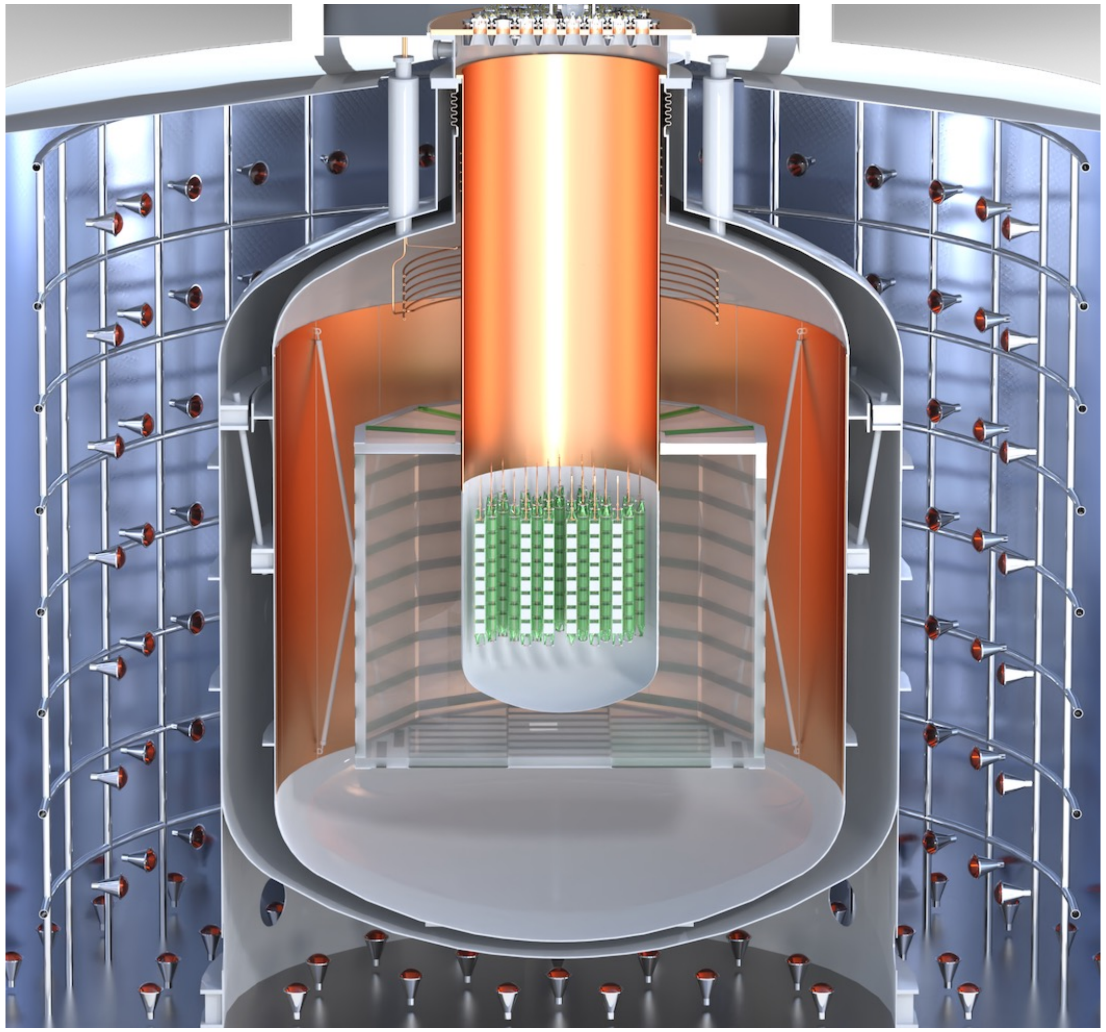
LEGEND $0\nu\beta\beta$ Experiment



Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay

- Uses technologies demonstrated in GERDA, MJD and new innovations such as large detector mass.
- LEGEND-200 running now!
- LEGEND-1000 completely covers the IO region even for pessimistic NMEs. Substantial NO coverage too.





LEGEND-1000 (running by 2030)

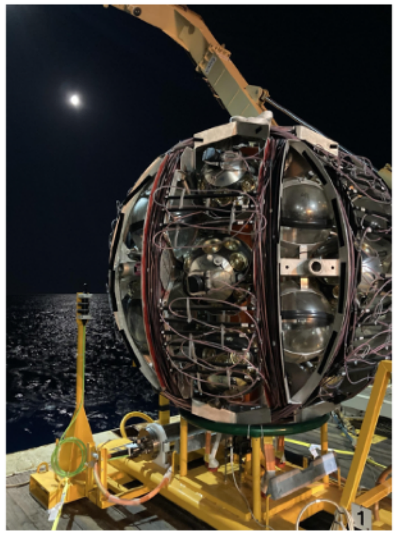
- Innovations (e.g. U-LAr) to remain in quasi-background free regime.
- Highest priority project in the US with DOE and NSF proposals in progress.
- Highlighted for support by APPEC.
- LNGS baseline site, with engineering design and CDR well advanced.

UK Astrophysical Neutrinos

Exploitation

Construction

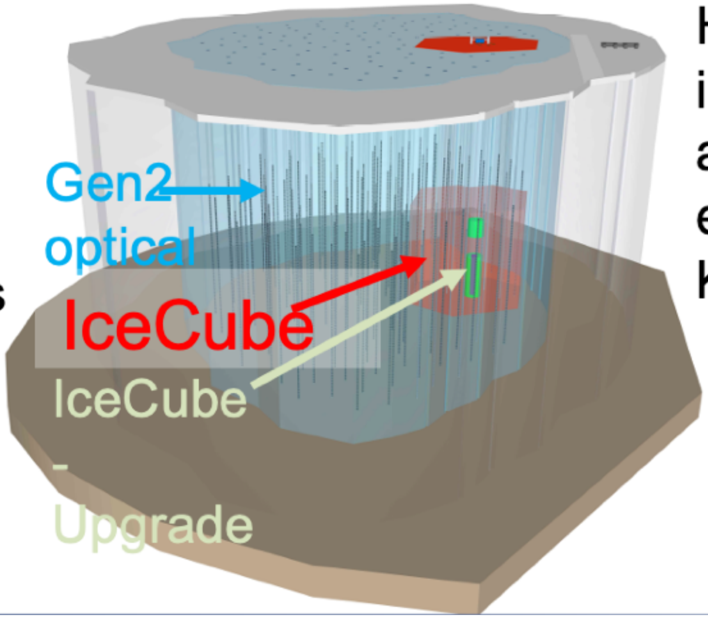
ANITA -> PUEO
Next flight
December 2025.
UCL+QMUL
delivering storage
’black box’ and
online software



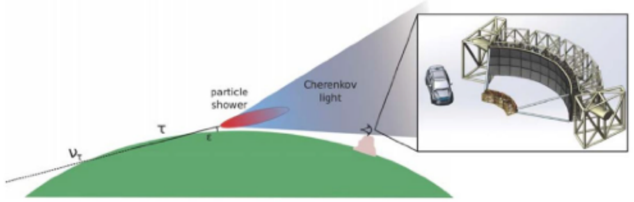
UK Astrophysical Neutrino community are combining efforts to focus on a single large scale construction project in the next decade. Community building meetings coming this year

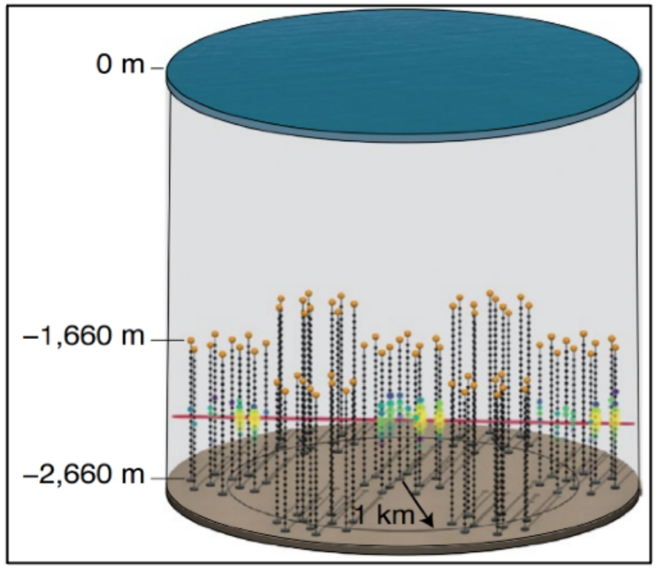
P-ONE is the leading candidate, dependent on successful demonstrator phase

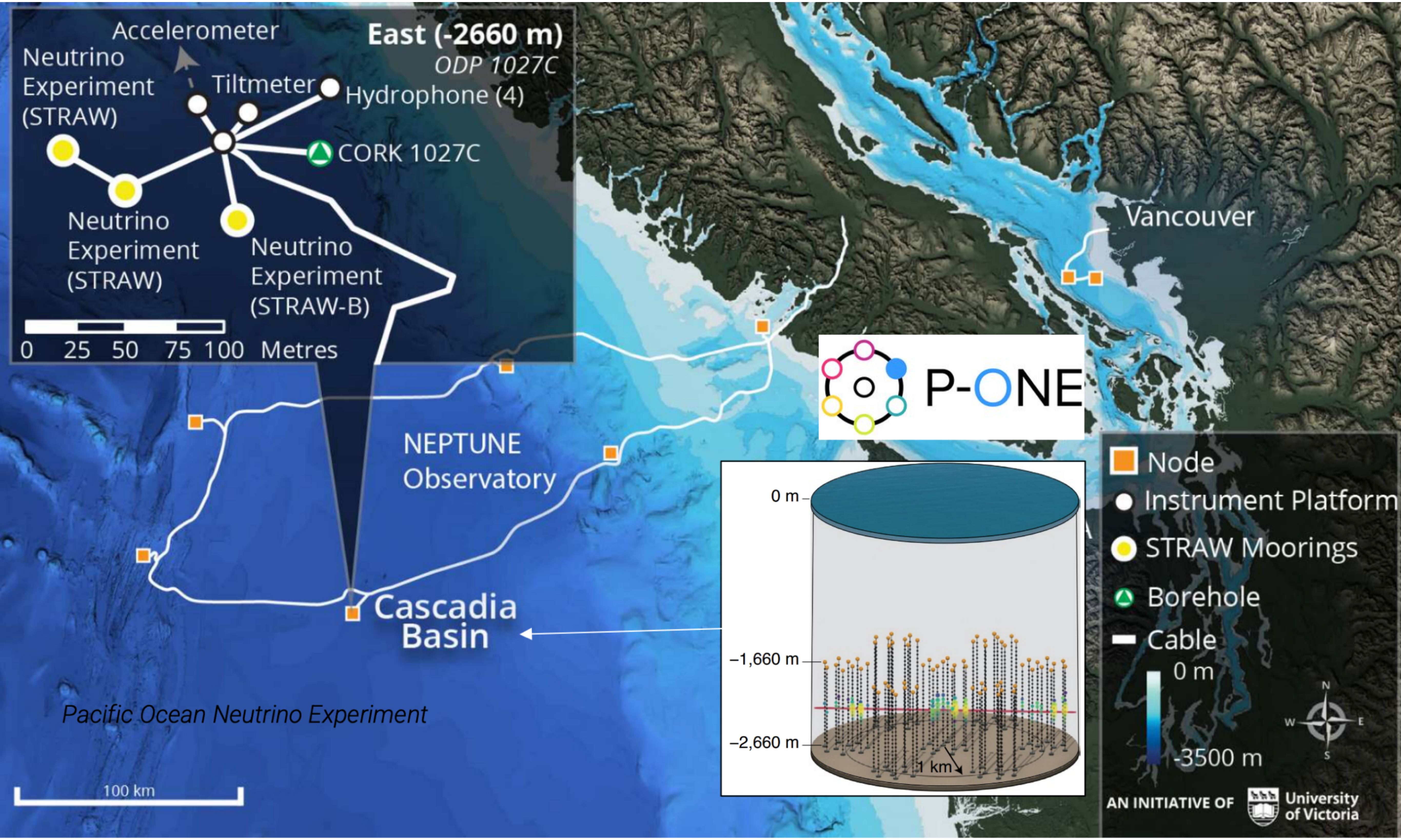
Kings +
Manchester
associated
members: physics
analysis from
oscillations to
ultra-high energy
Lorentz violation



Hull + Durham
interested in
astronomy
exploitation of
Km3Net data






Accelerometer
East (-2660 m)
ODP 1027C
Neutrino Experiment (STRAW)
Tiltmeter
Hydrophone (4)
CORK 1027C
Neutrino Experiment (STRAW)
Neutrino Experiment (STRAW-B)
0 25 50 75 100 Metres
Vancouver
P-ONE
NEPTUNE Observatory
Cascadia Basin
Pacific Ocean Neutrino Experiment
100 km
0 m
–1,660 m
–2,660 m
1 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?

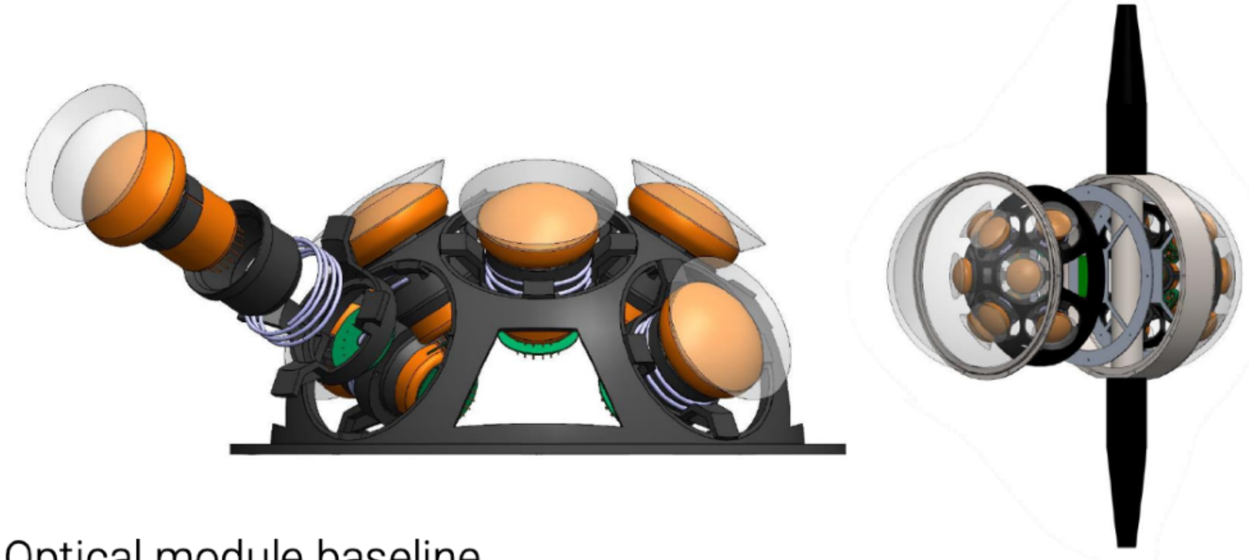
- km^3-scale water Cherenkov detector
- optimized for cosmic neutrinos (100 TeV- PeV)
- opening the northern sky, view on Milky Way centre

Building on consolidated technology

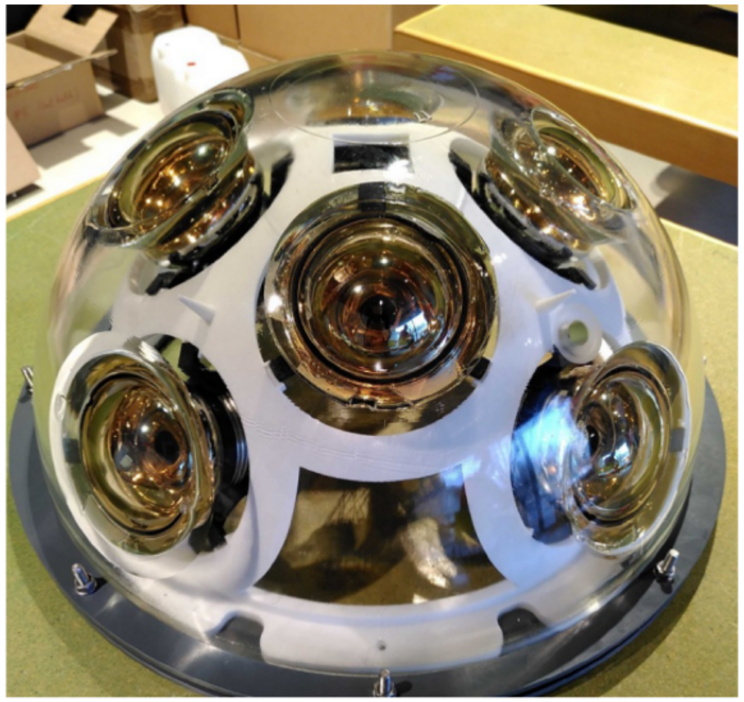
- array of instrumented vertical lines (IceCube)
- multi-PMT optical sensors (KM3Net)
- clustered deployment (GVD)

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

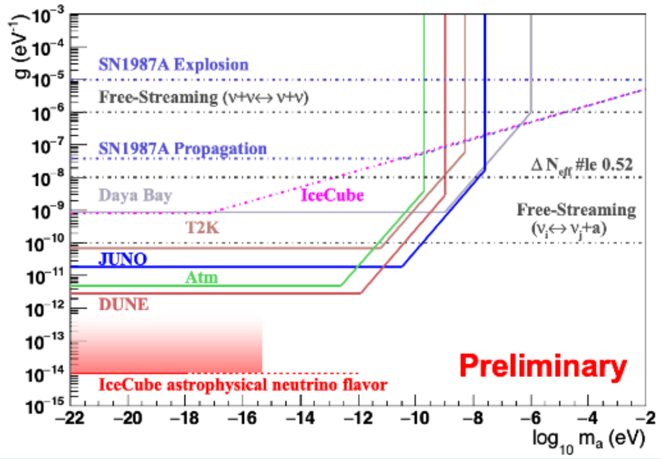


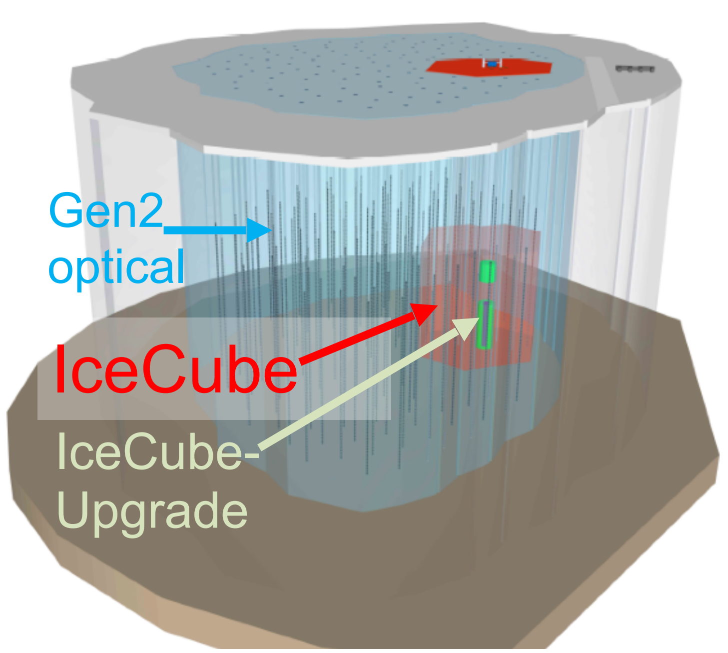
P-ONE module in integration testing

IceCube Science

Beyond-the-Standard Model Physics

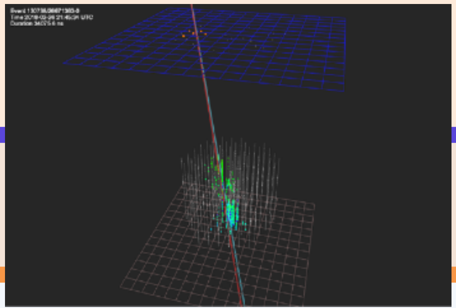
- Astrophysical neutrino flavour physics for new physics
- Quantum Gravity Nature Physics 18(2022)1287
- Lorentz violation CPT2022,59
- Ultra-light dark matter PoS(ICRC2023)1225





Detector R&D

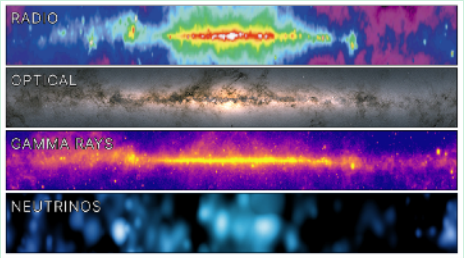
- In-Ice scintillator detector R&D for Gen2 icecube/202311002
- Multi-PMT R&D synergy with HyperK, P-ONE, KM3NeT



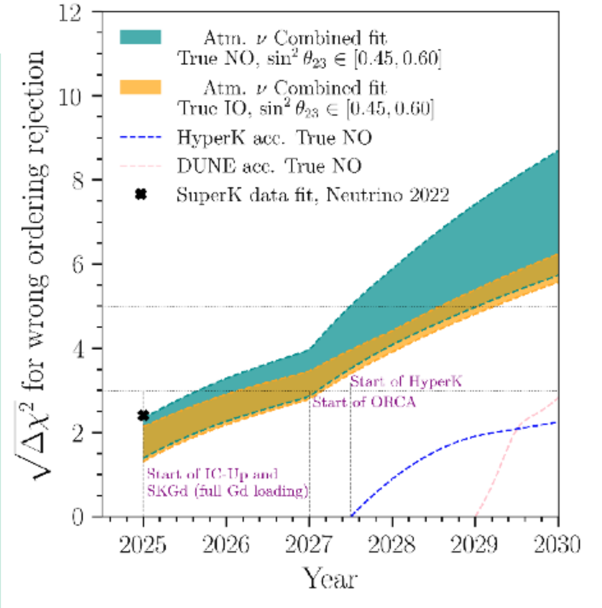
PoS(ICRC2023)1183

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