Experimental Neutrino Physics in the UK

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T2K e-like ring

ProtoDUNE-SP EM shower

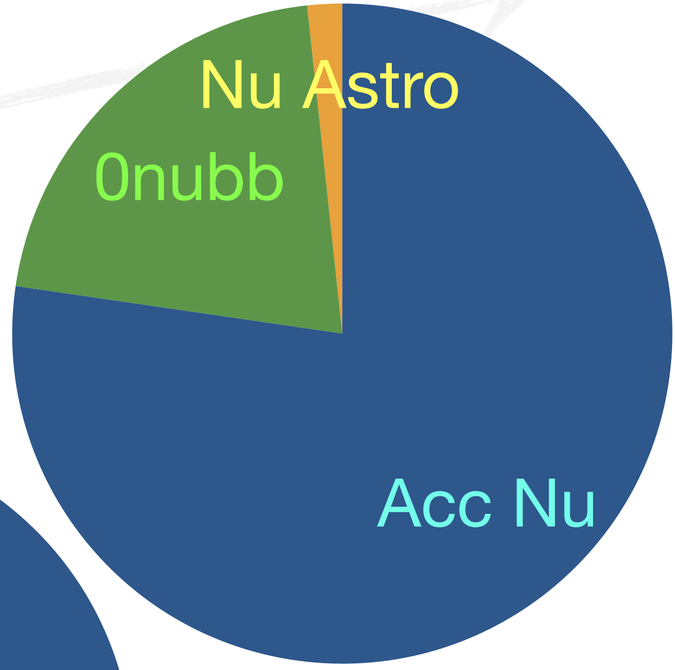
Overview of the field

- UK neutrino programme primarily focussed on masses and mixing
  - Oscillation measurements with accelerator based experiments (Acc Nu)
  - Majorana neutrino searches with neutrinoless double beta decay (0nubb)
- Also have small efforts using neutrinos as messengers and probes
    - High energy neutrino astronomy (Nu Astro)
      - Covered by Araújo
    - Neutrino-nucleus scattering
      - Now mainly an input to neutrino oscillation experiments
      - Measurements come from accelerator neutrino experiments
    - Nascent forward physics program at colliders
      - Covered by Barter and D’Onofrio

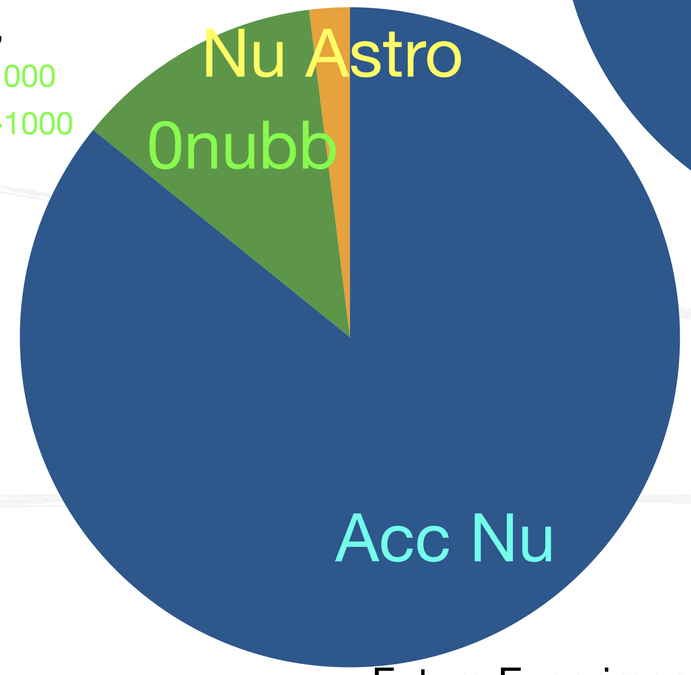
Broad UK participation in neutrino physics

- Bristol: DUNE
- Brunel: NuSTORM, LEGEND-1000
- Cambridge: SBN, DUNE
- Durham: Trinity, LEGEND-1000
- Durham IPPP: NuSTORM
- Edinburgh: SBN, DUNE, SuperNEMO, LEGEND-1000
- Glasgow: SK, T2K, HK, FASERv, NuSTORM
- Hull: KM3NET, Trinity
- Imperial: SK, T2K, SBN, DUNE, HK, NuSTORM, SHiP
- King's: SK, T2K, HK,NuSTORM,SNO+,LEGEND-200 LEGEND-1000,IceCubeG2,
- Lancaster: SK, T2K, SBN,DUNE,HK,NuSTORM,SNO+,LEGEND-200, LEGEND-1000
- Liverpool: T2K,SBN,DUNE,HK,JUNO,NuSTORM,SNO+,LEGEND-200, LEGEND-1000
- Manchester: SBN,DUNE,NuSTORM,SuperNEMO, LEGEND-1000
- Oxford: T2K, SBN, DUNE, HK, SNO+, LEGEND-1000
- QMUL: NOvA,SBN,DUNE,NuSTORM
- RHUL: T2K, DUNE, FASERv
- Sheffield: T2K,SBN,DUNE,HK,FASERv,NuSTORM
- Southampton: LEGEND-1000
- STFC Boulby: LEGEND-1000
- STFC Daresbury : DUNE,LEGEND-200, LEGEND-1000
- STFC RAL PPD: SK, T2K, DUNE,HK,NuSTORM
- STFC RAL TD: T2K,DUNE,HK
- Sussex: NOvA, SBN, DUNE, SNO+, LEGEND-1000
- UCL: NOvA,DUNE,NuSTORM,SuperNEMO,LEGEND-200, LEGEND-1000,ANITA,PUEO,P-ONE,
- Warwick: T2K,SBN,DUNE,HK,JUNO,NuSTORM,LEGEND-200
- York: LEGEND-1000

26 institutes participating in
18 collaborations



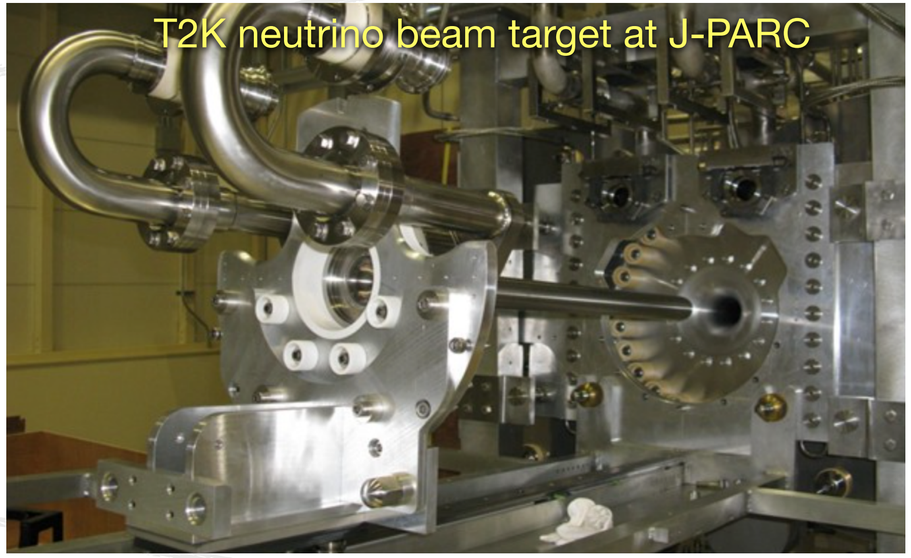
Operating Experiments

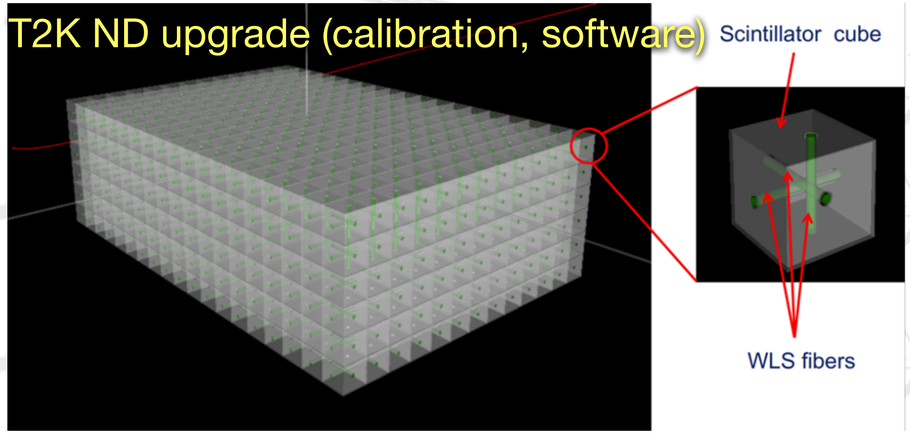


Future Experiments

Long baseline experiments, current

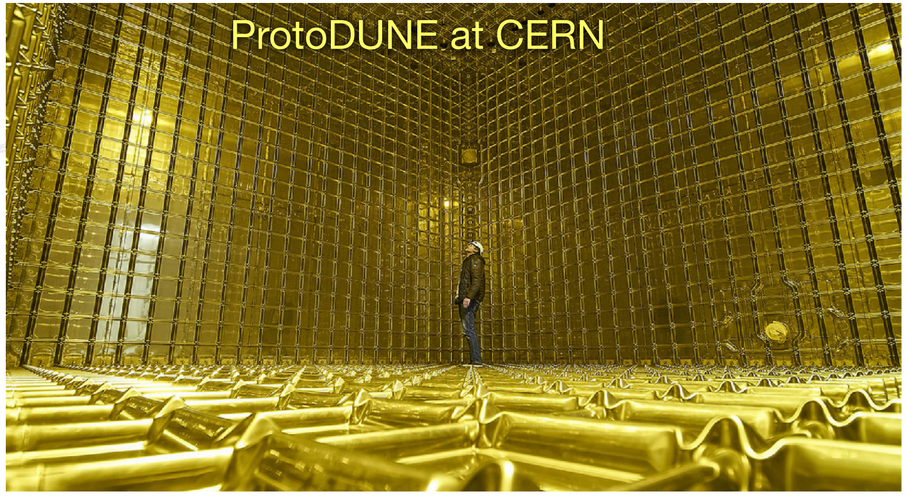
- UK has delivered major components for neutrino beams and detectors in many experiments
- (Many important contributions to MINOS)
- T2K (98 people)
  - Neutrino beam target(s)
  - ECAL
  - ND280 electronics (3/6 subdetectors)
  - ND280 DAQ (3/6 + global)
  - ND280 upgrade DAQ (2 new subdetectors +)
  - ND280 Recon software
- NOvA (21 people)
  - Recon software, operations coordination
- Also now have separate SK membership (20 people)





Long baseline experiments, future

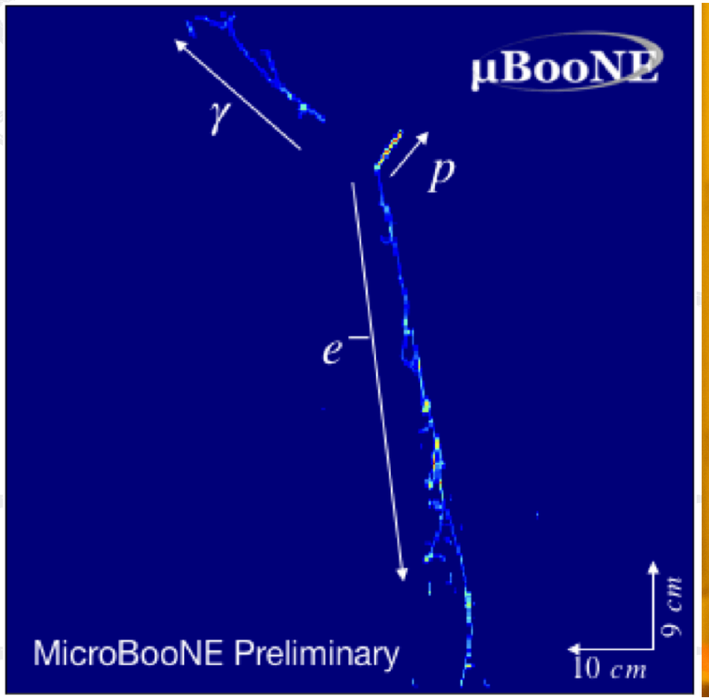
- LBNF/DUNE (172 people)
  - PIP-II RF cavities
  - Neutrino beam target
  - DUNE FD LArTPC APAs (HD module)
  - DUNE FD DAQ for (2 modules)
  - DUNE Recon software and computing
- HK (80 people)
  - ID DAQ & calibration
  - Outer detector
  - ND (IWCD) calibration
- CERN Neutrino platform playing important role in both experiments
  - ProtoDUNEs essential for DUNE FD development
    - Hardware, DAQ, software, physics
  - HK IWCD prototype crucial for innovative PMTs



Short baseline experiments

- MicroBooNE and SBND (68 people)
- MicroBooNE in exploitation phase, SBND in commissioning phase
- Providing crucial experience of LArTPC analysis for UK physicists
- The UK provides significant leadership in many areas of the SBN programme, including significant senior leadership in both MicroBooNE and SBND
- UK led Installation and Assembly of SBND
- HV feedthroughs for SBND


MicroBooNE members at IOP




SBND assembly

UK Accelerator neutrino achievements

- UK scientists have held key leadership roles in all accelerator experiments
  - T2K: 2 Spokes, Exec Com, 6 Osc Ana conveners, all committees, &more
  - NOvA: Ana Coord, analysis inc. Osc Ana, IB Chair, Exec Comm
  - SBN: uB Spokes, uB & SBND Phys Coord, SBND IB Chair, Exec Board
  - DUNE: 2 Spokes, Leads in all relevant Consortia, Resource Board Chair, ProtoDUNE coordinator, several working groups, and more
  - HK: Spokes, Exec Comm, many working group convenerships
- T2K members shared 2016 Breakthrough Prize
- Recent scientific highlights include pioneering efforts to exploit the substantial complementarity and independence of the LBL experiments:
  - NOvA-T2K joint analysis, led & performed by UK groups
  - SK-T2K joint analysis, led & performed by UK groups

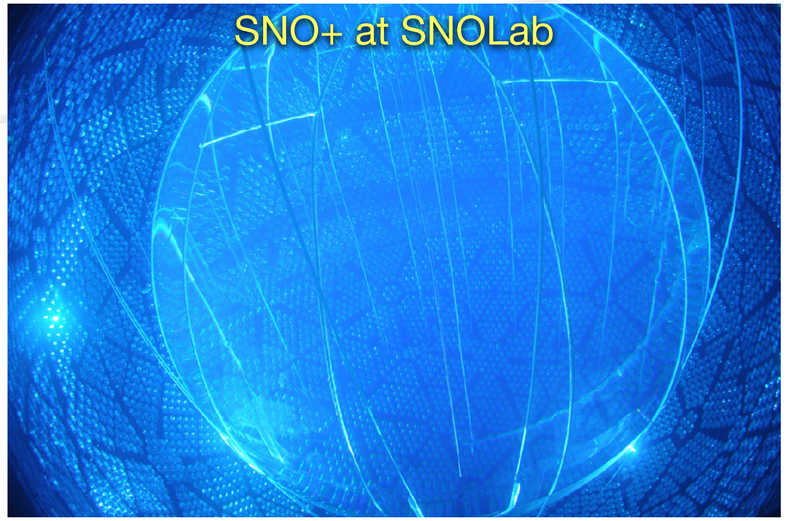
Accelerator neutrino expts c.2024

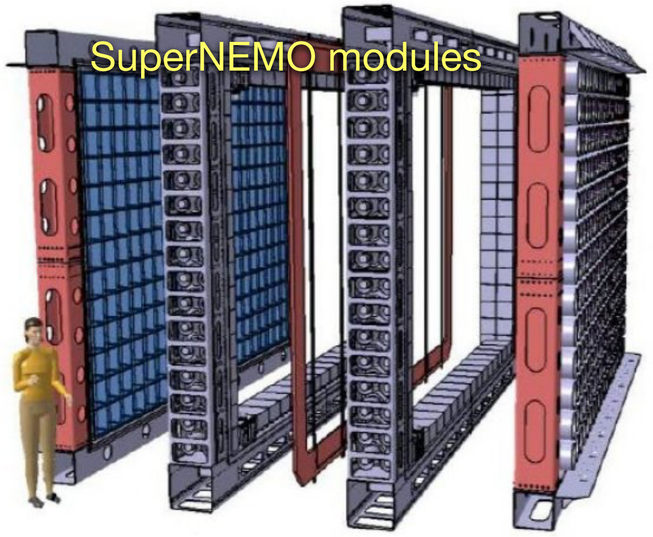
Collaboration	Data start (year)	Institutes	Senior members	PhD students	Technical staff	Funding	Main Sources
T2K	Operating	10	63	32	3	£350k/y	STFC CG
NOVA	Operating	3	14	7	0		STFC, RS, others
SBN	Operating	11	41	27	-		STFC CG
HK	Construction	9	55	10	15	~£18M	STFC Project
LBNF/DUNE	Construction	18	109	20	43	~£80M	STFC Project

0nubb experiments

- The UK has long involvement in 0nubb experiments, with strong leadership and technical contributions
- SNO+
  - Te development, Detector calibration and operations, Software management, Analysis coordinator
  - First observation of solar nus on ^{13}C
- SuperNEMO
  - 3 Spokes, Ana Coord,
  - World-first measurements of ^{150}Nd and ^{100}Mo decays
- LEGEND-200
  - 2 IB Chairs, Ana Coord, several committees

- Future plans: UK groups have converged on joining LEGEND-1000 for the far future. An SoI has been submitted to STFC.



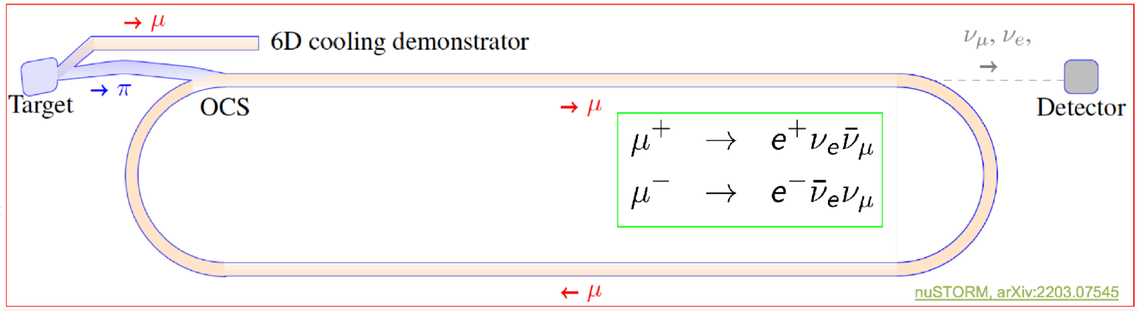


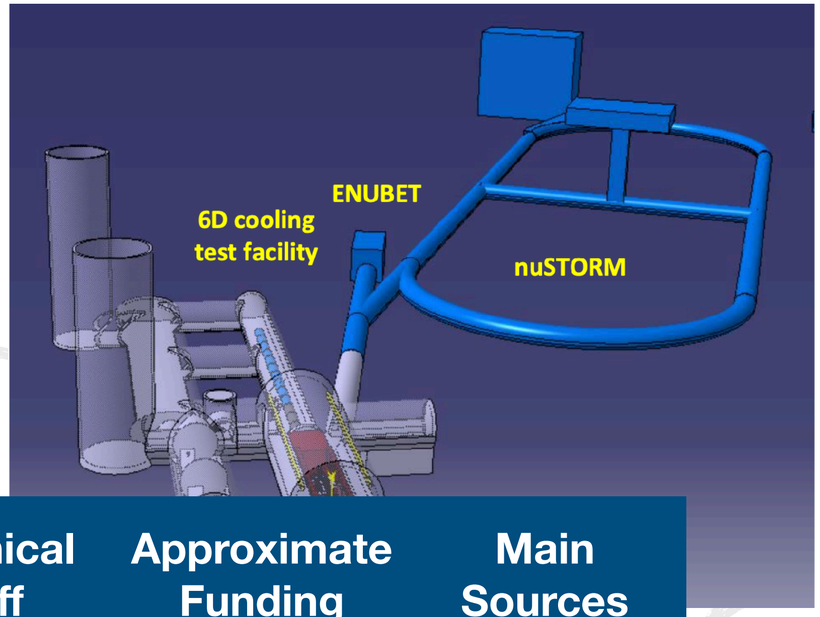
0nubb expts c. 2024

Collaboration	Status	Institutes	Senior members	PhD students	Technical staff	Approximate Funding	Main Sources
SuperNEMO	Operating	2	7	3	~1	£72k/y	STFC CG
SNO+	Operating	5	13	7	-	~£50k/y	STFC Project+CG
LEGEND-200	Operating	6	14	4	-	~£45k/y	STFC Project+CG
LEGEND-1000	Future	12	37	-	-	-	SoI to STFC

Farther future

- Beyond DUNE and HK, exploration of PMNS matrix probably requires a muon based neutrino beam
- UK hosted and led MICE, which successfully demonstrated ionisation cooling
- NuSTORM studies for CERN ongoing with leadership of Imperial and Durham IPPP
- Discussion with ENUBET for combined facility
- Largest neutrino flux also produced by muon collider
  - Paper in preparation studying flux of tau neutrinos from muon collider detected by P-ONE





Collaboration	Status	Institutes	Senior members	PhD students	Technical staff	Approximate Funding	Main Sources
NuSTORM	Future	13	52 (8)	2	-	-	STFC CG/ MuCol

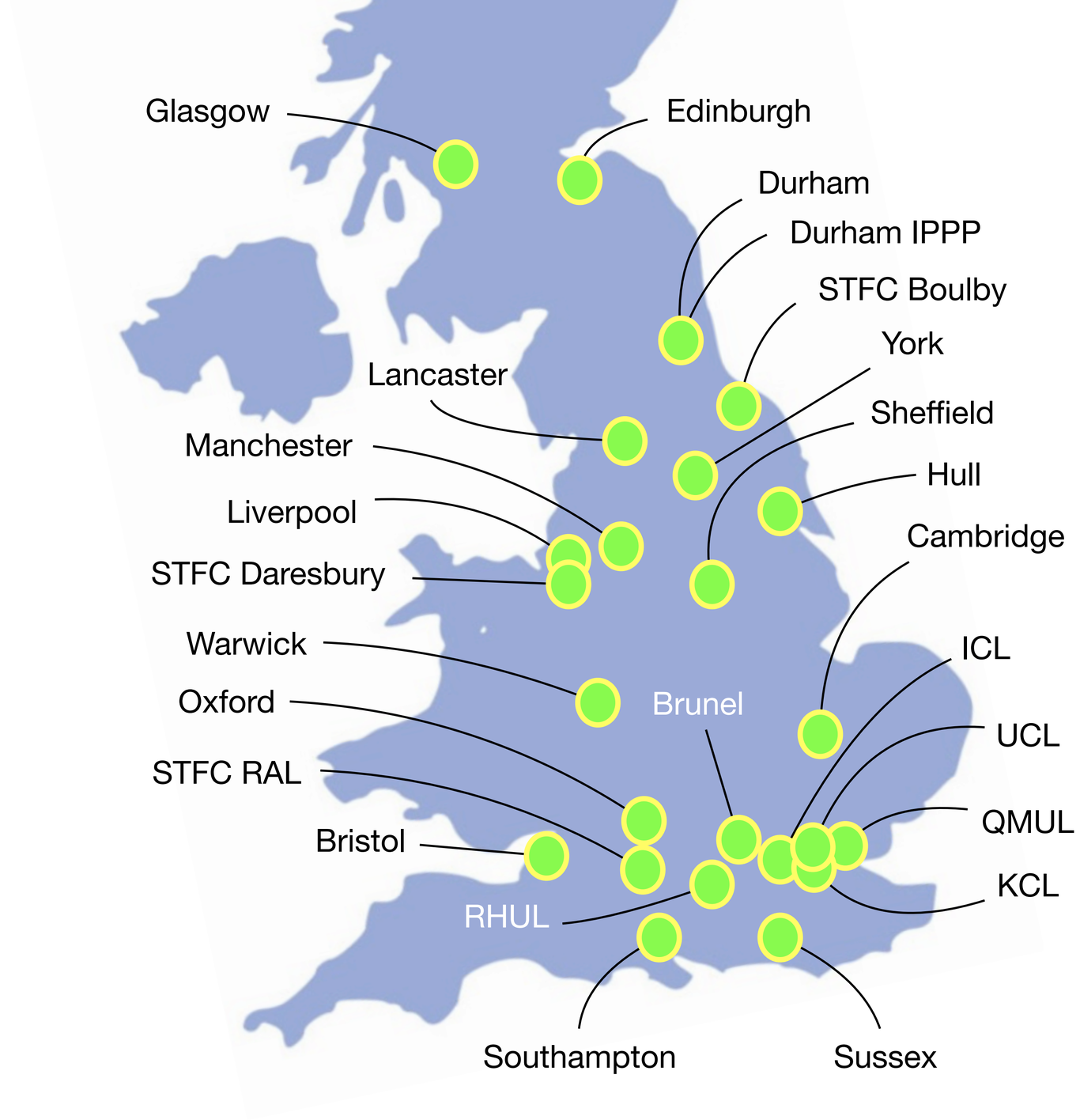
Culture and ECR development

- UK members have played important roles in neutrino collaboration ECR groups
  - Inter-collaboration communication via university groups and summer schools spreads ideas and interest
- UK members have led development of Codes of Conduct for all our accelerator neutrino experiments
  - Recently getting improved engagement from FNAL and KEK management on issues related to professional conduct
  - Further work on these topics is warranted

Difficulties and limitations

- Difficulty balancing current/operating experiments against future/under construction experiments. In neutrinos, this often means entirely different collaborations, possibly in different countries.
- Funding management issues:
  - Short term: travel for experiments has been curtailed substantially. UK is demonstrably losing visibility at international meetings. This was noted especially by SBN and DUNE.
  - Mid-term: lack of funding in this timeframe is stifling opportunities for new projects, for example LEGEND-1000 in particular.
  - International currency fluctuations mean costs to travel outside of Europe can fluctuate substantially.
  - Can funders reserve funds for such problems?
- Could benefit from stronger engagement with international agencies and labs to mitigate problems with project schedules and decisions.
- There is no mechanism for people in particle physics community and astronomy community work together. Large impact on neutrino astronomy (and all astroparticle physics).

Backup slides


Glasgow
Edinburgh
Durham
Durham IPPP
STFC Boulby
York
Lancaster
Sheffield
Manchester
Hull
Liverpool
Cambridge
STFC Daresbury
Warwick
ICL
Oxford
Brunel
UCL
STFC RAL
QMUL
Bristol
KCL
RHUL
Southampton
Sussex

Timelines

T2K

> Group dimensions: Number of members (doctoral students, senior members, technicians, engineers, etc.)

Number of T2K-UK members: 98, of which

27 Academics (IC: 5, Glas: 2, KCL: 3, Lancs: 4, Liv: 4, Ox: 3, RAL: 0, RHUL: 1, Shef: 2, War: 3)
12 Staff Physicists (IC: 2, Glas: 0, KCL: 0, Lancs: 1, Liv: 2, Ox: 0, RAL: 6, RHUL: 0, Shef: 0, War: 0)
3 Engineers (IC: 0, Glas: 0, KCL: 0, Lancs: 0, Liv: 0, Ox: 0, RAL: 3, RHUL: 0, Shef: 0, War: 0)
24 Postdocs and Fellows (IC: 6, Glas: 2, KCL: 3, Lancs: 3, Liv: 3, Ox: 3, RAL: 0, RHUL: 1, Shef: 1, War: 2)
32 PhD Students (IC: 9, Glas: 2, KCL: 4, Lancs: 3, Liv: 3, Ox: 5, RAL: 0, RHUL: 2, Shef: 3, War: 1)

> Group financing: Details of funding over the last 7 years

Approximately GBP 350k per year, in addition to academic salaries etc.

> Group responsibilities: Key roles in collaborations and significant results from recent years

T2K Management roles held by UK members

- T2K Co-Spokesperson
- T2K Executive Committee
- Run Coordination
- Publications Board
- Speakers Board
- Shift Coordinator
- Public Webpage Committee
- Authorship Committee
- Safety Committee
- Elections Committee

Super-K roles held by UK members

- Steering Board
- UK Light Injection
- Outer Detector Monitoring
- Deuterium-Tritium Generator
- Pre-supernova trigger

T2K / ND280 Convenerships held by UK members

- ND280
- Cross Section
- Cross Section Sub-Groups
- Selection Development
- Electron-Neutrino and EM interactions
- Pion Physics
- CC-Pionless
- Neutrino Interactions WG
- Selections Cross-Section
- Oscillation Analysis
- Software
- Computing
- ND280 Calibration
- ECal
- ND280 Data Acquisition
- WAGASCI/BabyMIND
- T2K+Super-K-Atmospherics
- T2K+NOvA Liaison
- T2K Neutrino Beam MC

Selected Results from Recent Years

- Results from the T2K+NOvA Joint Analysis; to be published
- First joint oscillation analysis of Super-Kamiokande atmospheric and T2K accelerator neutrino data; https://arxiv.org/pdf/2405.12488
- Measurements of neutrino oscillation parameters from the T2K experiment using 3.6E21 protons on target; Eur.Phys.J.C 83 (2023) 9, 782
- Scintillator ageing of the T2K near detectors from 2010 to 2021; JINST 17 (2022) 10, P10028
- Search for Electron Antineutrino Appearance in a Long-baseline Muon Antineutrino Beam; Phys.Rev.Lett. 124 (2020) 16, 161802
- Measurements of νμ-bar and νμ-bar+νμ charged-current cross-sections without detected pions or protons on water and hydrocarbon at a mean anti-neutrino energy of 0.86 GeV; PTEP 2021 (2021) 4, 043C01
- First T2K measurement of transverse kinematic imbalance in the muon-neutrino charged-current single-π+ production channel containing at least one proton; Phys.Rev.D 103 (2021) 11, 112009
- First Measurement of the Charged Current antinumu Double Differential Cross Section on a Water Target without Pions in the final state, Phys.Rev.D 102 (2020) 1, 012007
- Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations; Nature 580, 339–344 (2020)

> Scientific output: Number and relevance of publications, coordination positions in collaborations, theses, etc.:

62 journal articles, 23 articles with over 100 citations, including

- Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam; Phys.Rev.Lett. 107 (2011) 041801, 1800 citations
- Observation of Electron Neutrino Appearance in a Muon Neutrino Beam; Phys.Rev.Lett. 112 (2014) 061802, 732 citations
- Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations; Nature 580 (2020) 7803, 339-344, 578 citations
- Measurements of neutrino oscillation in appearance and disappearance channels by the T2K experiment with 6.6×10^20 protons on target Phys.Rev.D 91 (2015) 7, 072010, 439 citations
- T2K neutrino flux prediction; Phys.Rev.D 87 (2013) 1, 012001, 394 citations from Muon Neutrino Disappearance in an Off-Axis Beam Phys.Rev.Lett. 112 (2014) 18, 181801, 361 citations

SBN

SBN UK members:
11 groups: Oxford, Liverpool, Lancaster, Manchester, Sussex, Sheffield, Warwick, Edinburgh, Cambridge, Imperial, QMUL
21 academics
20 PDRAs
27 current PhD students (31 additional students graduated with PhD theses on SBN since 2018)

Funding (last 7 years):
Predominantly funded through Consolidated Grant funding - the SBN-UK project covers UK activities on both MicroBooNE and SBND as part of the broader SBN programme
1 FLF (which includes 2 FTE of PDRA funding)
Two ERFs
Some of the groups are part of the EC INTENSE grant which allows more collaboration travel.

SBN UK responsibilities:
The UK provides significant leadership in many areas of the SBN programme, including significant senior leadership in both MicroBooNE (Spokesperson, Physics Coordinator, members of Spokespersons' Advisory Board) and SBND (Physics Coordinator, IB Chair, members of Executive Board)

UK PDRAs lead or have led the SBN Release and Code Validation group, and many UK students have served as coordinators for the early career groups on both MicroBooNE and SBND.

SBN UK members:
Scientific output:
MicroBooNE has published 65 papers, of which 19 were UK-led measurements and a further 32 were performed under UK leadership and coordination. The majority of MicroBooNE physics results, including the flagship low-energy excess searches, have been led by UK scientists and enabled through the work of PDRAs and postgraduate students (I can send more on this if useful!)
SBND has recently entered the commissioning stage, and the UK has been instrumental in building and commissioning the detector for physics (see leadership roles above). In particular, a UK colleague was L2 Manager for Assembly and Installation, leading this work for the collaboration, with significant contributions from UK students on LTA at Fermilab to both the TPC and Photon Detection System assembly, installation, and quality assurance measurements.
The UK led construction of the key elements of SBND, including 50% of the wire planes and all Anode Plane Assembly frames, and is now leading the commissioning.

Difficulties and limitations:
Travel funding allocated to the experiments in previous CG rounds has been limiting, particularly because of the expansion of the groups and obtaining key senior leadership roles which require the holders to attend all meetings. We have been forced to limit the attendance of SBN members to overseas collaboration meetings in more than one case.
The SBN programme is an important step in developing the technology and UK expertise in running LArTPC detectors ahead of DUNE. These experiments provide opportunities for hands-on experience with LArTPC operations and data. As we move closer to the start of DUNE, it is important to still prioritise the physics and training opportunities afforded by these experiments and ensure the best return on the datasets collected.