Neutrino Physics in the UK

Mark Thomson

With thanks to: **Alfons Weber, Dave Wark, Ken Long, Ruben Saakyan, Steve Biller**

Theoretical Context

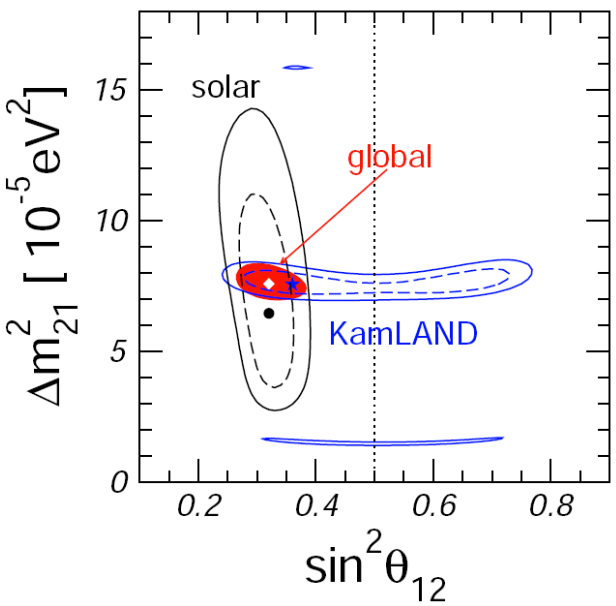
Neutrino Oscillations: Current Knowledge

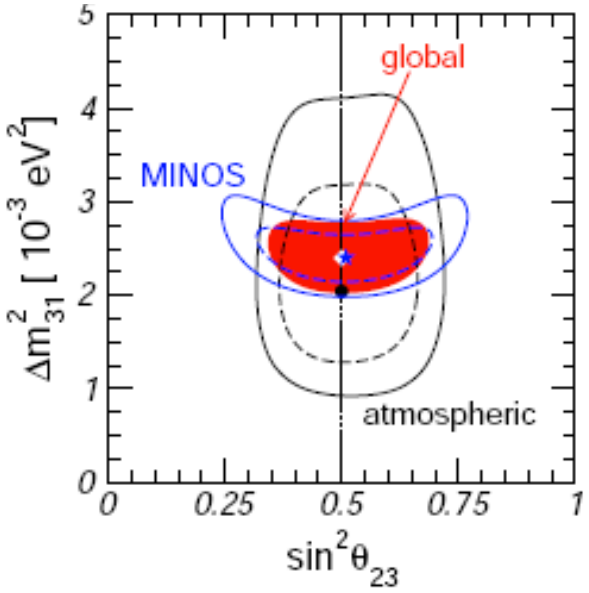
★ **Neutrino/Lepton-mixing sector parameterised by**

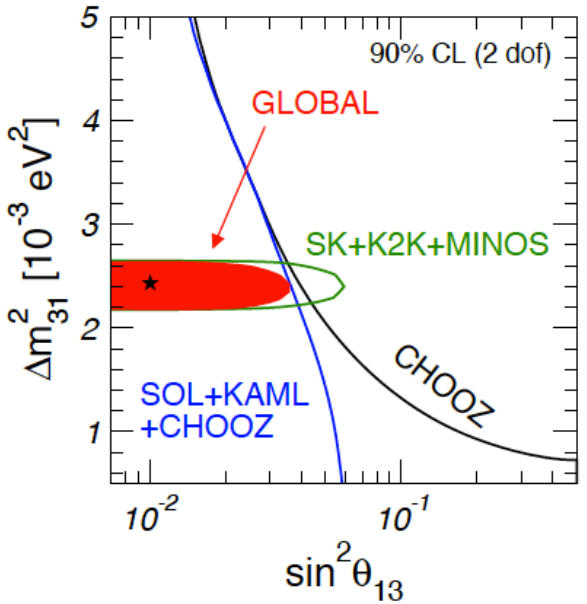
- **three neutrino masses** $\{m_1, m_2, m_3\}$
- **three mixing angles** $\{\theta_{12}, \theta_{23}, \theta_{13}\}$
- **a CP violating complex phase** δ

(+2 in case of Majorana neutrinos)

★ **Current neutrino oscillation results provide information on mass-squared differences and the mixing angles, e.g. global fit (Valle, Neutrino 2010):**







★ **In addition bounds from fits to cosmological data**

(WMAP + ΛQCD, Komatsu et al. 2010, Hannestad et al. 2010)

$$\sum m_\nu < 1.3\,\mathrm{eV}$$

What's Hot? The mixing angles…

★ Currently most burning issue is θ_{13}
- currently only know θ_{13} is "small", $\sin^2 2\theta_{13} \lesssim 0.15$
- need to know θ_{13} to estimate size of CP violating effects in lepton sector

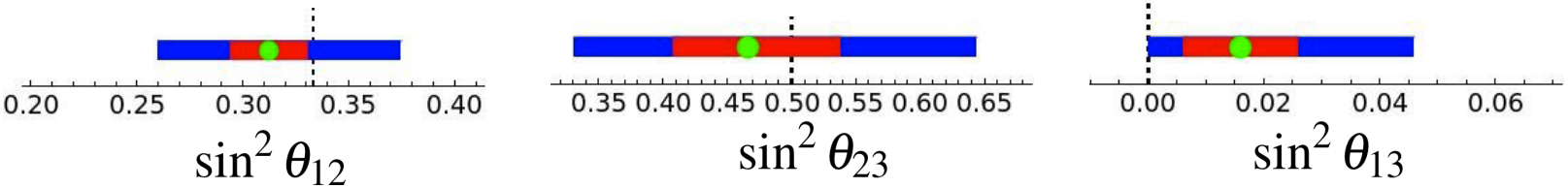
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- knowledge of θ_{13} essential to determine future neutrino programme

★ In addition, all mixing angles interesting in their own right
- hints of a flavour symmetry, e.g. $\sin^2 2\theta_{13} \sim 0 \quad \sin^2 2\theta_{23} \sim 1$
- current data (beware size of uncertainties) consistent with tri-bimaximal

$$U_{\mathrm{HPS}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Harrison, Perkins, Scott



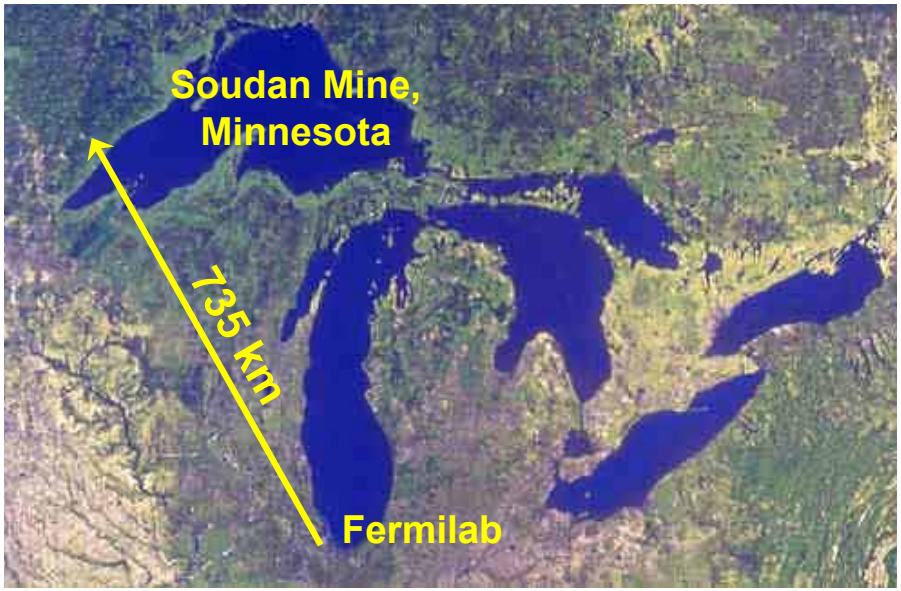
Fogli et al

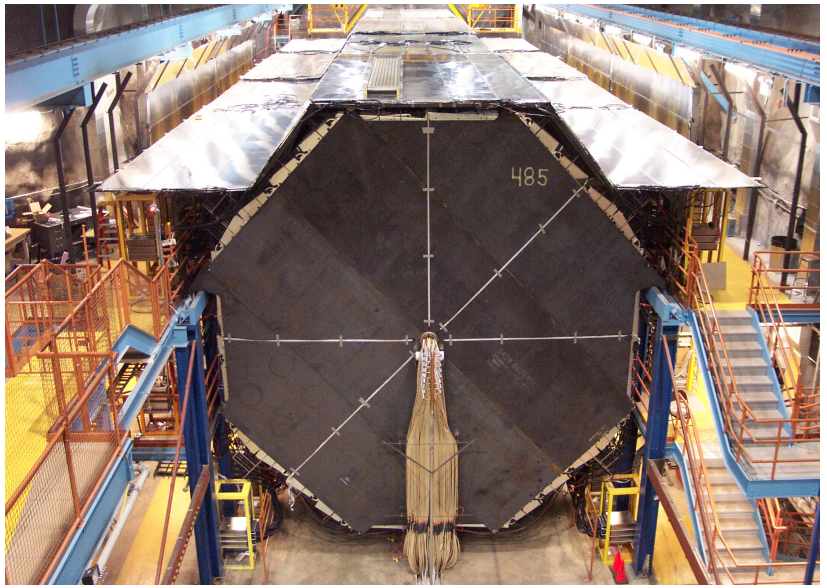
The UK Experimental Programme

- Current long-baseline experiments
- R&D for future neutrino oscillation experiments
- Neutrinoless Double Beta Decay

Current Long Baseline Experiments

MINOS



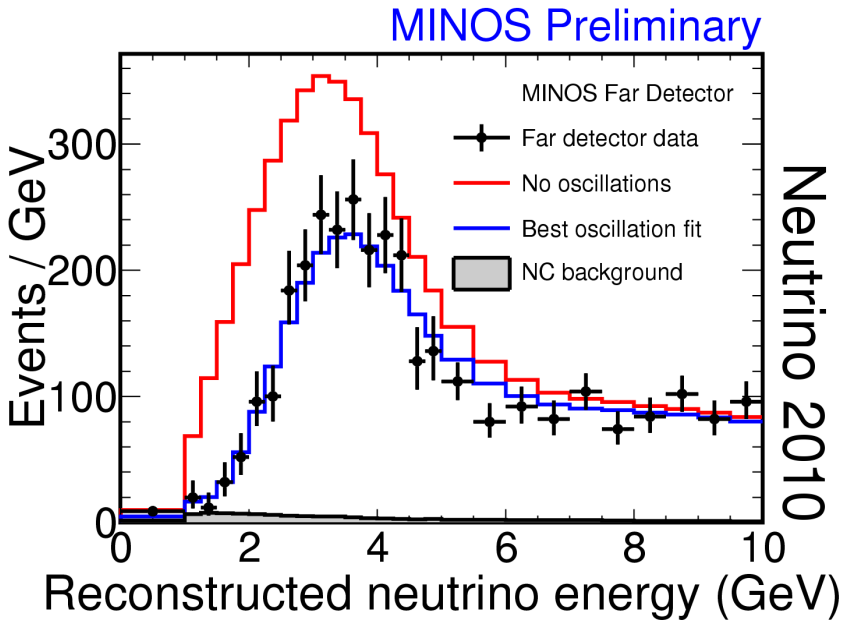


Overview

- ★ Long baseline neutrino oscillation experiment based on a ν_μ beam
- ★ Beam operational since **2005** – now routinely operating at design perf.
- ★ Main physics goals:
  - Precise (5%) measurement of $|\Delta m^2_{32}|$ from ν_μ disappearance
  - Precision tests of oscillation hypothesis (vs. decay/decoherence)
  - Sensitivity to $\sin^2 2\theta_{13} \sim 0.1$ from search for ν_e appearance
  - …

MINOS: Recent Results

★ **Several world leading results (each with major UK contributions), e.g.**



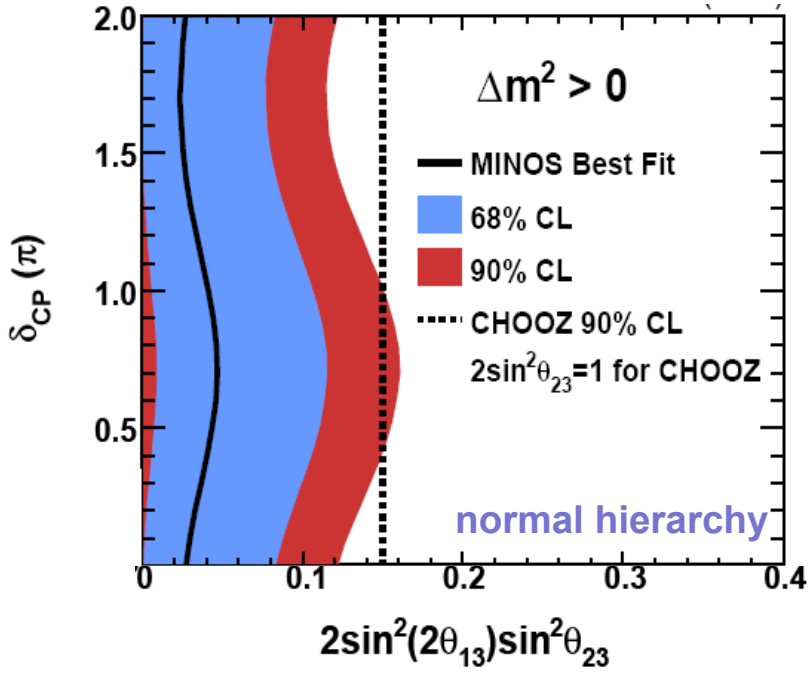
$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta > 0.91\,(90\%\,\mathrm{C.L.})$$

Pure decay/decoherence excluded

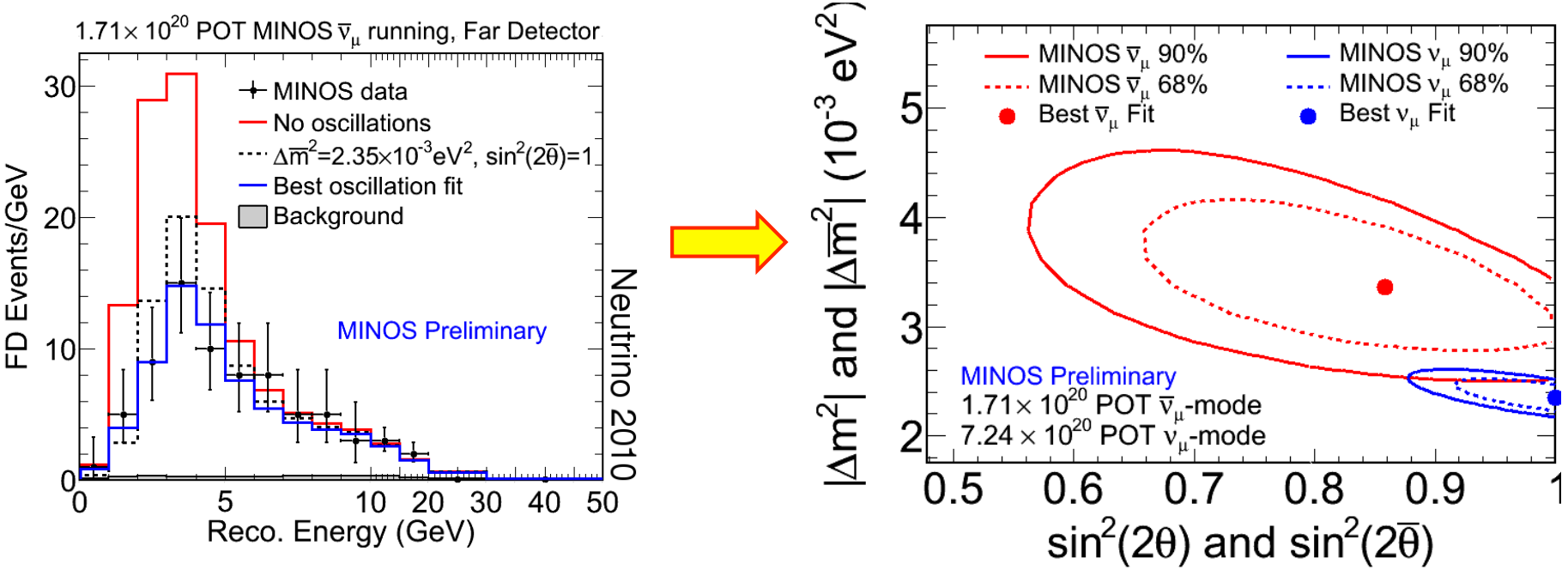
Search for $\nu_\mu \rightarrow \nu_e$

- **Search for electron-like events**
- **Expect (bgnd.): 49.1 ± 2.7(sys.)**
- **Observe: 54 events in the FD**
- **Competitive limits on θ_{13}**



MINOS: Recent Results cont.

★ At end 2009, switched to reversed horn current to produce $\overline{\nu}_\mu$ beam
- Allows measurement of oscillation parameters for anti-neutrinos
- UK led initiative + measurement is unique to MINOS
- First results (based on relatively small data) sample:



★ Tension between neutrino and anti-neutrino results: **~5 % chance prob.**
- Generating a lot of interest
- Most likely a statistical fluctuation
- But it is a genuinely new measurement…

MINOS: Impact of Cuts

- ★ MINOS was drastically cut by the PPGP and PPAN prioritisation
  - originally at 8-9 FTE
  - now at 4.7 FTE and will drop to 1 FTE in 12/13
- ★ All groups hit badly - RAL and Sussex almost eliminated
- ★ Main losses
  - DAQ effort (a UK responsibility) – transferred to Fermilab
  - No further MC production in UK (was up to 50%)
  - Calibration effort (a UK responsibility)
  - PDRA analysis effort
- ★ Some mitigation via STFC/Fermilab strategic partnership:
  - STFC funds 3 PDRAs at 50%
  - Transfer of MINOS knowledge to LBNE (see later)
- ★ Future of MINOS
  - MINOS will run until October 2011
  - MINOS is planning 2-4x10^{20} PoT of anti-neutrinos
  - this would be end of data taking for UK
    (maybe end of MINOS ND continues as part of Minerva)
  - Final combined analysis through to 2013

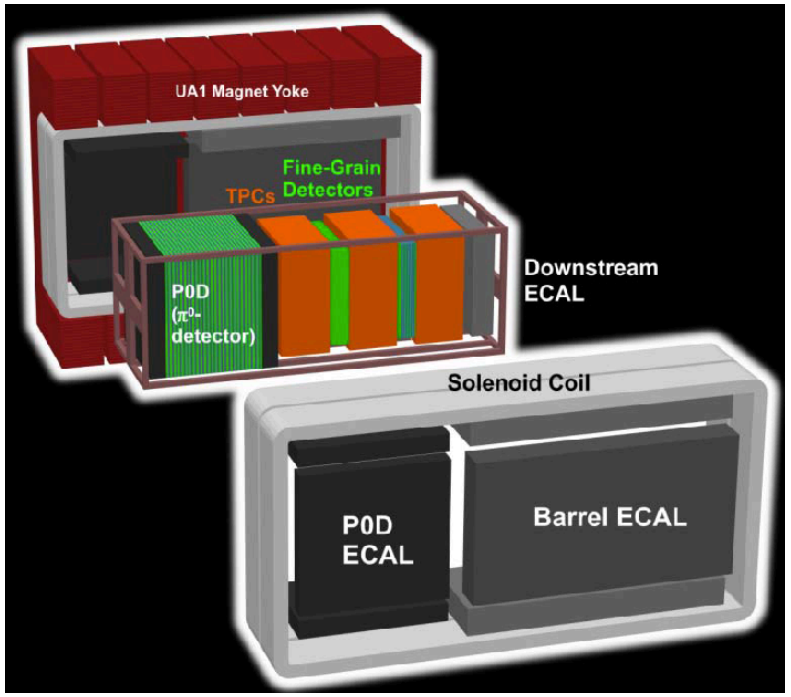
T2K

Overview

- ★ First off-axis long baseline neutrino oscillation experiment
- ★ Intense ν_μ beam (ultimately 0.75 MW)
- ★ Main physics goals:
  - Discovery of ν_e appearance ⇨ θ_{13}
    - Opens up possibility of studying CP in neutrino sector
    - $\sin^2 2\theta_{13} \sim 0.01$ Order of magnitude improvement on current limit
  - Precision measurements of ν_μ disappearance
    - Is θ_{23} really maximal?
    - $\sin^2 2\theta_{23} \sim 0.01$ Order of magnitude improvement on current limit
- ★ Potential for major breakthroughs…

T2K: UK Contribution

Two major capital contributions



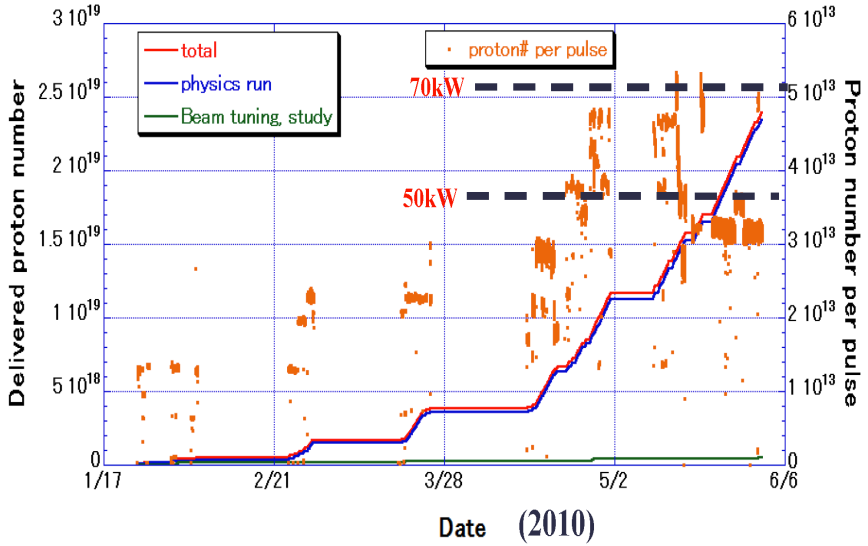
★ **Near Detector (ND280)**
- ECAL
- Electronics
- DAQ
- Final ECAL modules due to be installed by end of Summer

★ **Beamline components**
- Target and beam dump design
- Target window, remote handling
- Beam dump design
- All beam components working flawlessly
- UK is now a world-leader in high intensity target design

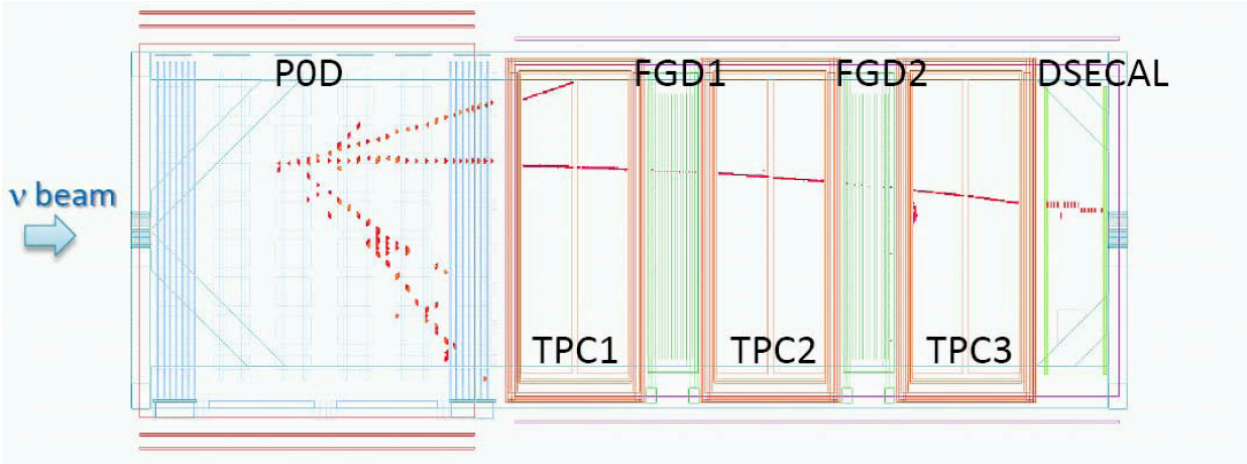
★ **Total UK contribution to construction, including RG effort, £14.4M**
- essentially on budget
- money spent before prioritisation…

T2K: Status

★ Beam commissioned in first half of 2010
- Operated upto 70 kW
- From November restart at 100 kW
- Gradual increase to design intensity



★ Neutrino events seen in both near (ND280) and far (Super-K) detectors
- ND280 used to characterise background in FD based on detailed event information



★ T2K moving into exploitation phase

T2K: Impact of Cuts

- ★ Over last few years the numbers of PDRAs have been significantly reduced
- ★ Current effort
  - 12 PDRAs (not all STFC funded, not all working 100 % on T2K)
  - 20 Academics
  - 16 Students
- ★ With current effort challenging to continue to lead physics analyses and to meet operational responsibilities
  - Detector commissioning
  - DAQ and detector operations
  - Calibration

Main Concern (?)

- ★ The future…
- ★ Anticipated JPARC beam line upgrade to **1.7 MW** (middle of decade)
  - possible route to CP violation in neutrino sector
  - requires new target – area of UK expertise
  - The UK FJNE (Future JPARC Neutrino Project) programme was killed
  - R&D proposal for liquid Argon detector R&D also killed (see later)

Future Neutrino Oscillation Experiments

⇨ **Targeting CP Violation**

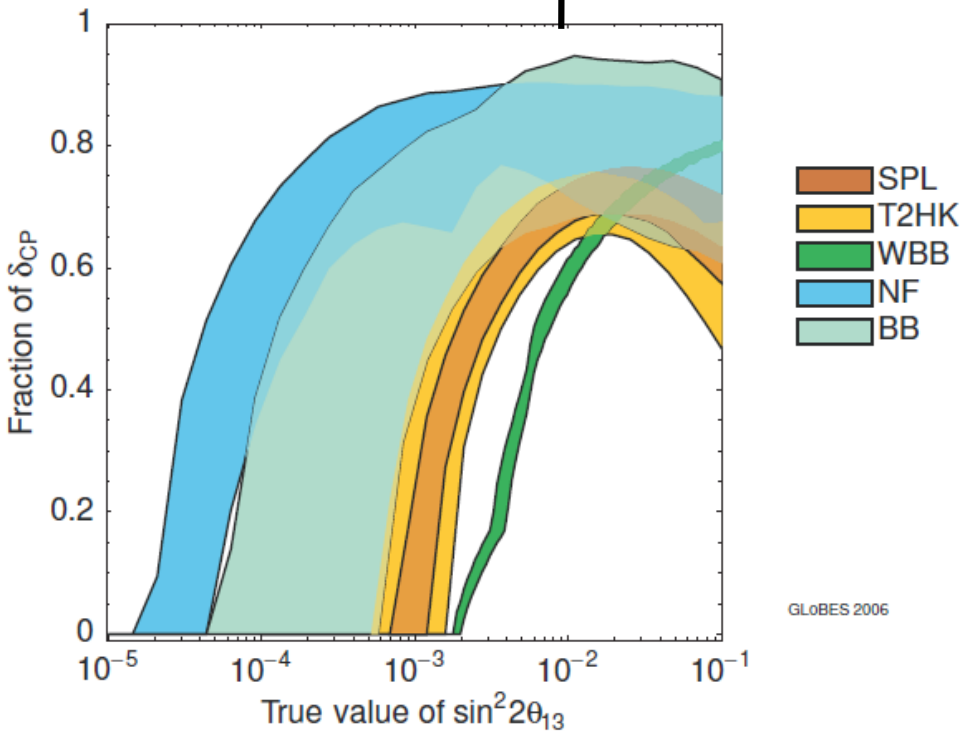
Future Long Baseline Programme

★ **Ability to observe CP violation depends on θ_{13}**

- **CP violating effects enter as $U_{e3} = \sin\theta_{13} e^{-i\delta}$**
- **If θ_{13} is small "conventional" neutrino beams not sufficient**

Neutrino Factory
Beta beams

"Conventional"

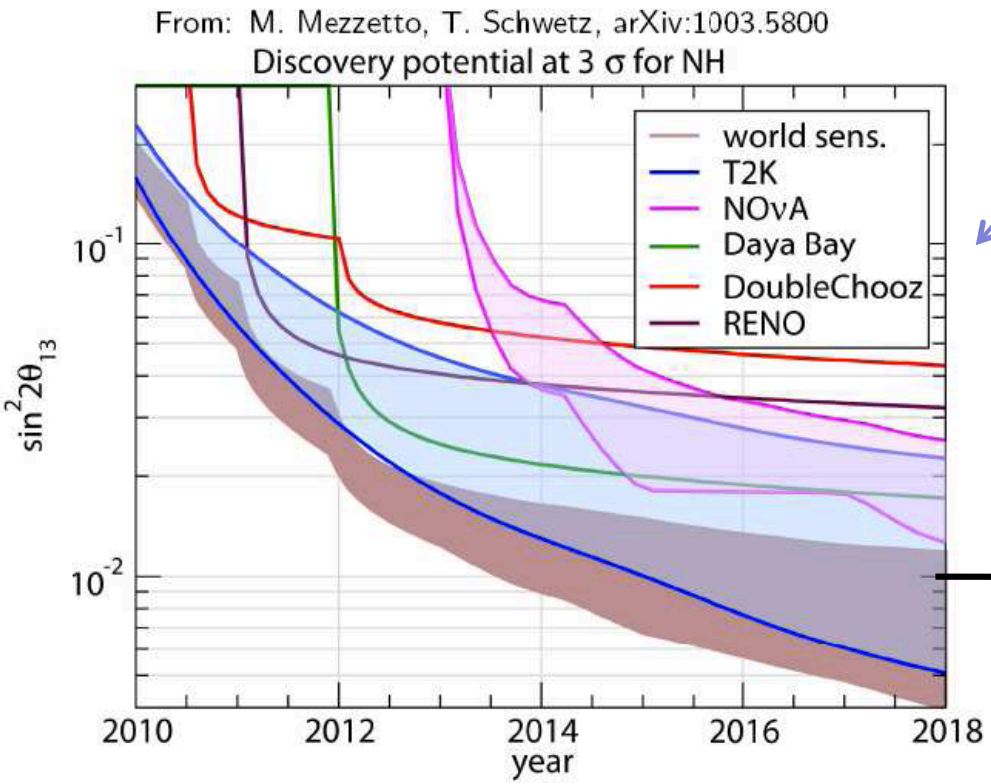


★ **"Conventional" = SuperBeam, i.e. MW proton beam – challenging…**

Updated θ_{13} Timeline

★ θ_{13} is the focus of a number of experiments:

- Long-baseline (off-axis): T2K, NOνA
- Reactor: Double Chooz, Daya Bay, RENO



Probably need to shift most lines by one year

Super-Beams

Neutrino Factory
Beta beam

★ If $\sin^2 2\theta_{13} > 0.01$ should know by ~2016

The next generation (?): Super-Beams

Japan: J-PARC

- ★Upgrade to **1.7 MW** proton beam
- ★Two options for far detector options being considered
  - 540 kton Water Cherenkov or 50 kton Liquid Argon TPC

LBNE: Fermilab to DUSEL Gained significant momentum in US

- ★Wide band **0.7 MW** beam, then **2.3 MW** with **Project X**
- ★Two options for far detector options being considered
  - 300 kton Water Cherenkov or 50 kton Liquid Argon TPC
- ★ Significant funding already committed
  - Total of **$31M** from DoE (Jan 2010) and NSF (Oct 2009)
  - Total project cost (beam + detectors) ~ **$750-1000M**
- ★ Things moving rapidly
  - Conceptual Design Review (CD1) in **Dec. 2010**
  - Preliminary Design (CD2) in **2012/2013**
  - Possible construction **2015-2019**

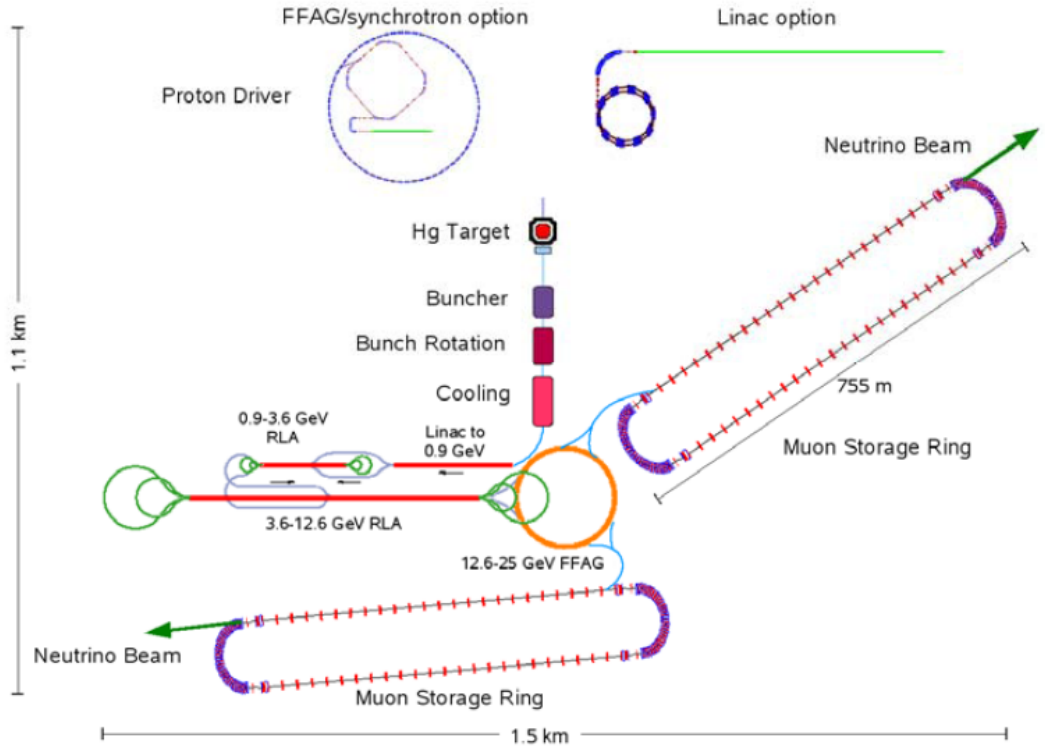
CERN

- ★ Proposed proton beam from proposed SPL
- ★ SPL no longer central to CERN accelerator complex upgrade…

Only minimal UK involvement

The next-to-next generation: Neutrino Factory

- ★ The neutrino factory is the ultimate neutrino physics
- ★ Conceivably could be hosted in **UK**
- ★ Impressive physics reach demonstrated in the (**UK initiated, UK led**) International Scoping Study (**ISS**) which delivered the baseline design



Neutrino Factory: International Context

- ★ Current activities geared around International Design Study (IDS)
  - Deliver the neutrino factory reference design by 2012/2013
  - UK has significant leadership roles
- ★ International support
  - EUROnu (coordinator Rob Edgecock)
    - FP7 Design Study for super beams, beta-beams and Neutrino Factory
    - Reports to Strategy Session of CERN Council in 2012
  - US "Muon Accelerator Programme", MAP
    - Significant US initiative
      - real momentum and cash (FY10 = $10M, FY11 = $15^{+}M)
    - Focuses on muon collider but strong connection to NF
    - IDS-NF and MICE are central to muon acceleration

Neutrino Factory: UK R&D

★ Two main aspects of UK R&D programme

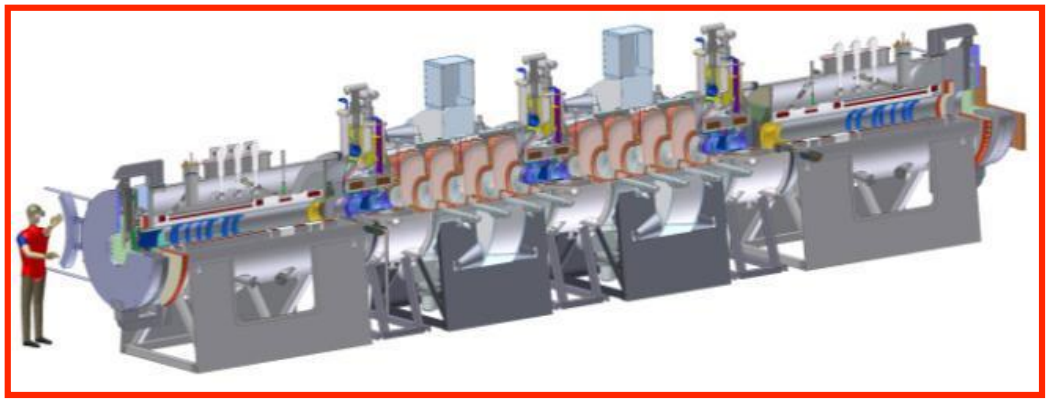
- UKNF specific: (i.e. specific to NF rather than site specific)
  - Conceptual design (as part of IDS-NF)
  - MICE – single largest part
- UKNF generic: (i.e. accelerator R&D applicable more widely than 'just' NF)
  - Proton-driver front-end test stand (FETS)
  - Target studies
  - Development of high-gradient cavities
  - Rapid acceleration – EMMA (funded through Basic Technology Fund)

★ STFC funded programme used to leverage external funds:

- UKNF Conceptual design work:
  - Matching funds for EUROnu
  - Leverage resources from US (MAP) and elsewhere
- UKNF FETS:
  - Leverages resources from Spain
- UKNF target studies:
  - Matching funds for EUROnu
- UKNF cavity work:
  - Matching funds for SC cavity work within EUCARD

MICE Status

- ★ MICE is designed to demonstrate muon cooling, central the the NF
- ★ A major Particle Physics project based in UK (RAL)
- ★ Significant contributions from international collaborators (US, …)



- ★ Currently STEP I (of VI) installed and operational

UKNF/MICE: Impact of cuts

UKNF

- ★ Cuts have led to reduction in range and scope activities
- ★ Partly protected by external funds (EU etc.)
- ★ Future programme (from **2012**) uncertain:
  - Will require negotiation/proposals in light of new accelerator centre

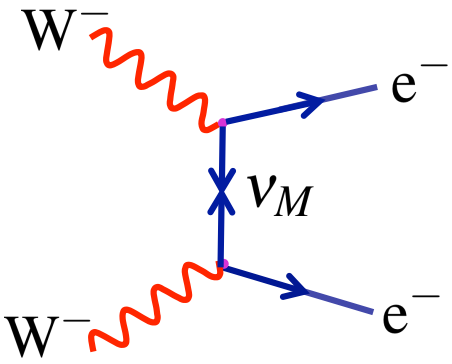
MICE

- ★ Cash flow problems relating to prioritisation/STFC finances
- ★ In addition, MICE-UK asked to bear some costs previously considered host-lab costs
- ★ Despite this, **still possible to implement the experiment,** but likely to lead to a slip in the schedule.

Neutrinoless Double Beta Decay

Neutrinoless Double Beta Decay: Context

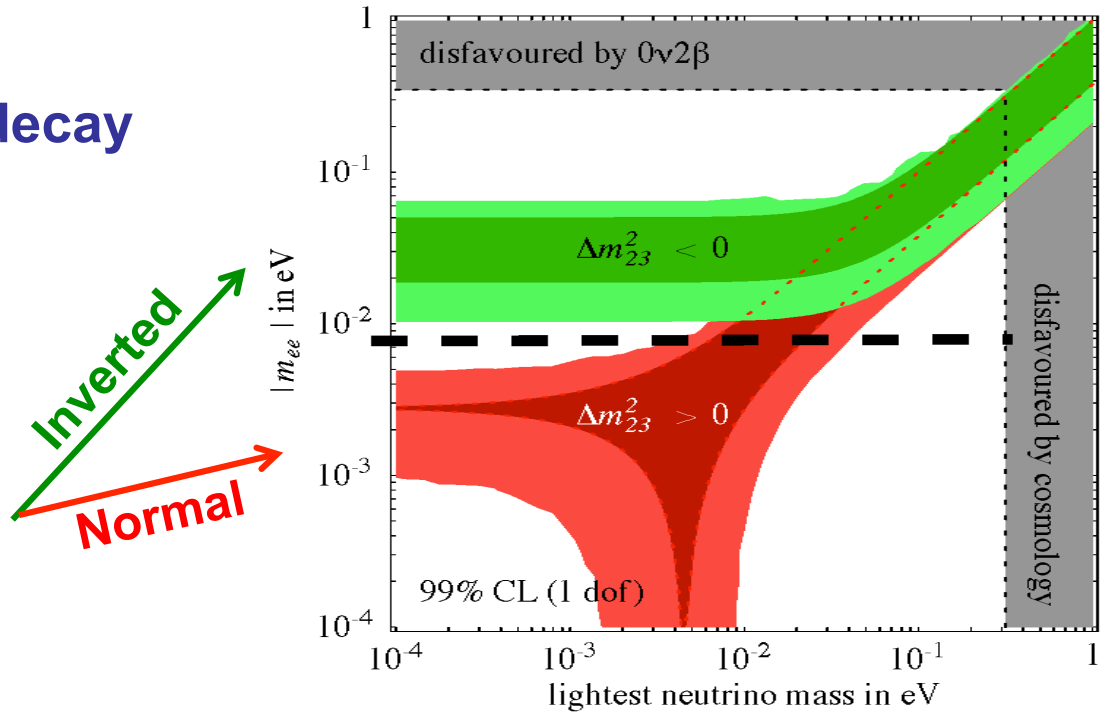
- ★ Are neutrinos Majorana or Dirac particles
- ★ Theoretical prejudice favours Majorana neutrino
- ★ Consequences:
  - neutrinos are there own anti-particles
  - $\Delta L = 2$ leading to neutrinoless double β decay



- ★ Neutrinoless double beta decay sensitivity depends on:

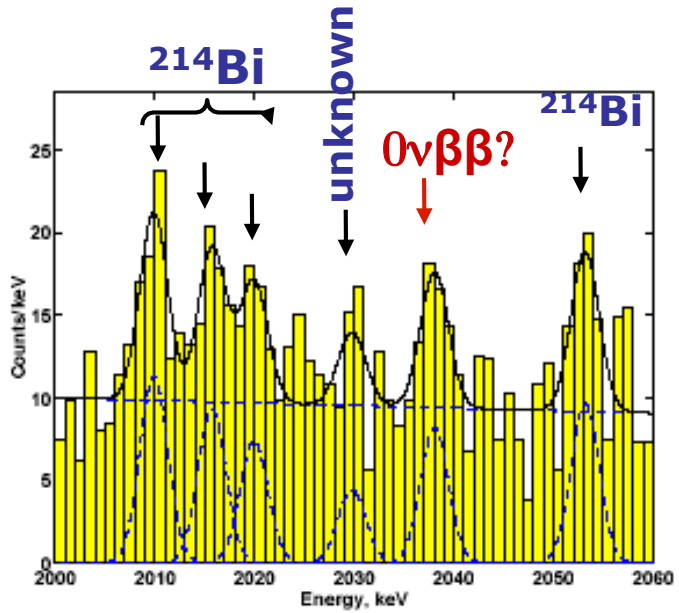
$$\langle m_{\beta\beta} \rangle = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

- ★ Expectation depends on mass hierarchy
- ★ Long-term goal **~10 meV**



0νββ Decay: Experiments

★ To date only one (hotly disputed) claim for a signal



Heidelberg-Moscow Experiment

klapdor-kleingrothaus interpretation

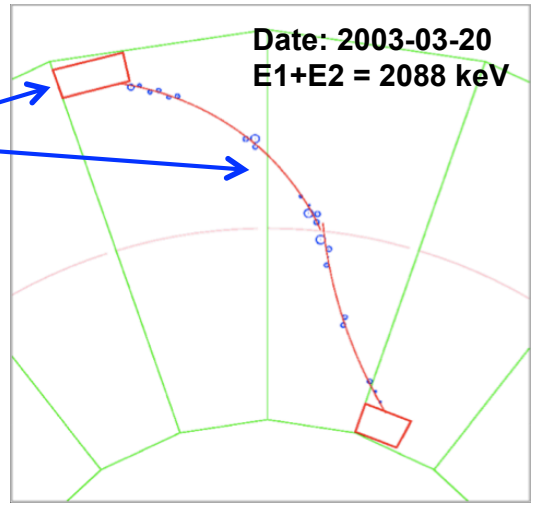
$$200 < \langle m_{\beta\beta} \rangle < 500\,\mathrm{meV}$$

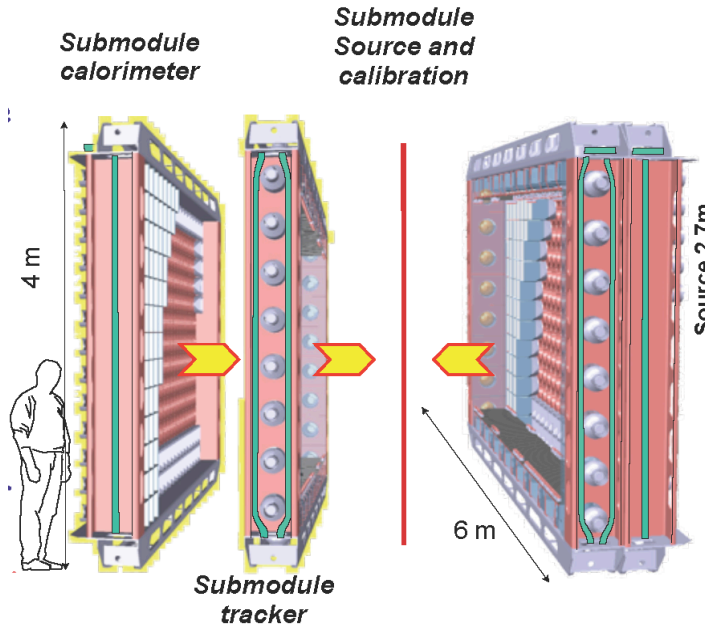
★ This is one of the hot topics in physics

- ~7 experiments coming online
- UK involvement Super-Nemo and SNO+

Super-NEMO

- ★ Builds on **NEMO-III** approach
  - observe both electrons in tracker
  - measure energy in ECAL
  - unambiguous signal
- ★ **Super-NEMO**
  - planar and modular design
  - 100 kg enriched isotopes
    (5kg x 20 modules)
  - UK and France contribute 70-80% of total cost (shared equally)





1 module:

Source ^{82}Se first but almost any isotope possible

Tracking : 2000 cells in Geiger mode

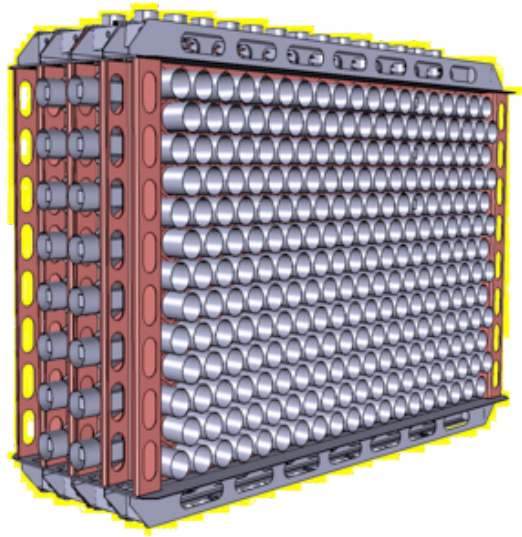
Calorimeter: 550 PMTs + scint. blocks

Modules surrounded by water

passive shielding

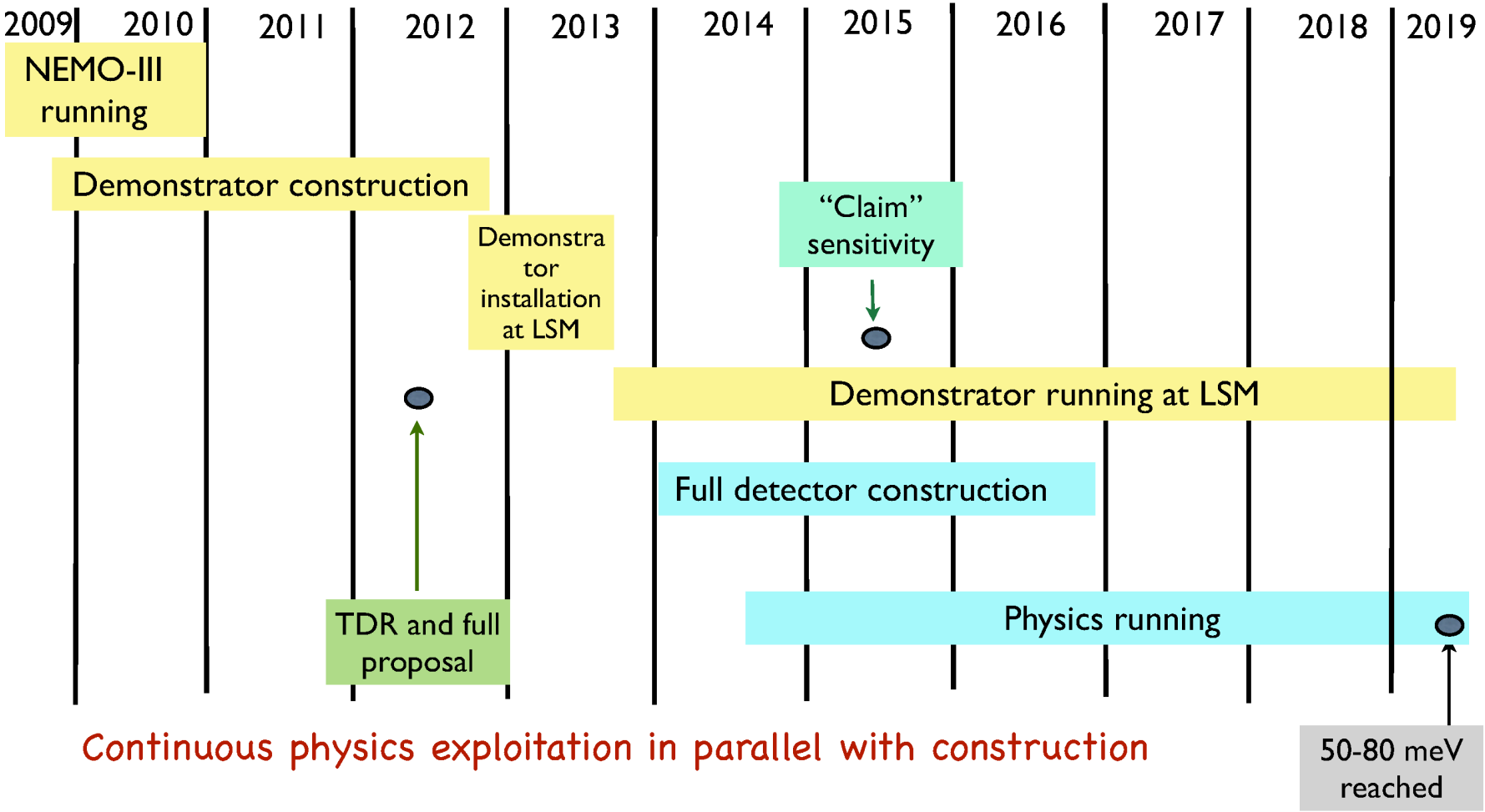
Super-NEMO Demonstrator Module

- ★ Build first Super-NEMO module as **a demonstrator** prior to full TDR
- ★ Aims:
  - Demonstrate feasibility of large scale mass production
  - Measure backgrounds
  - finalise detector design
  - Competitive physics measurement
    - sensitivity to Klapdor claim by 2015



- ★ UK Super-NEMO funding is currently limited to demonstrator module
- ★ Impact of financial situation
  - Original request: ~ **£5M**
  - **£3M** (funded) over **2009-2012**
  - Work-packages not-funded:
    - ASIC-based Tracker readout
    - Calorimeter
    - Calibration

Super-NEMO: Looking Forward

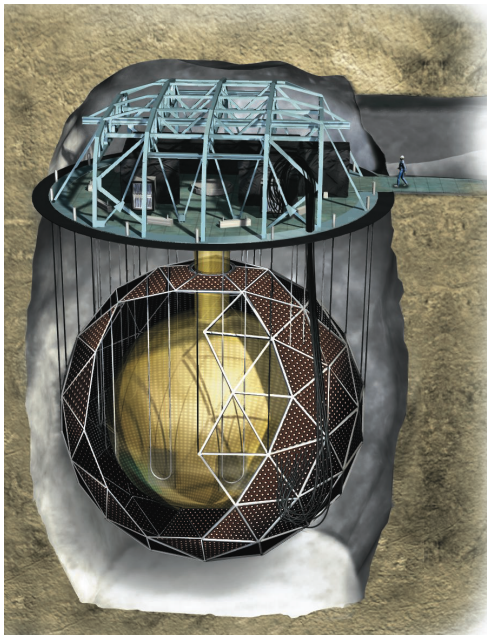


NOTE:

★ **Full proposal for Super-NEMO ~ 2012**

SNO+

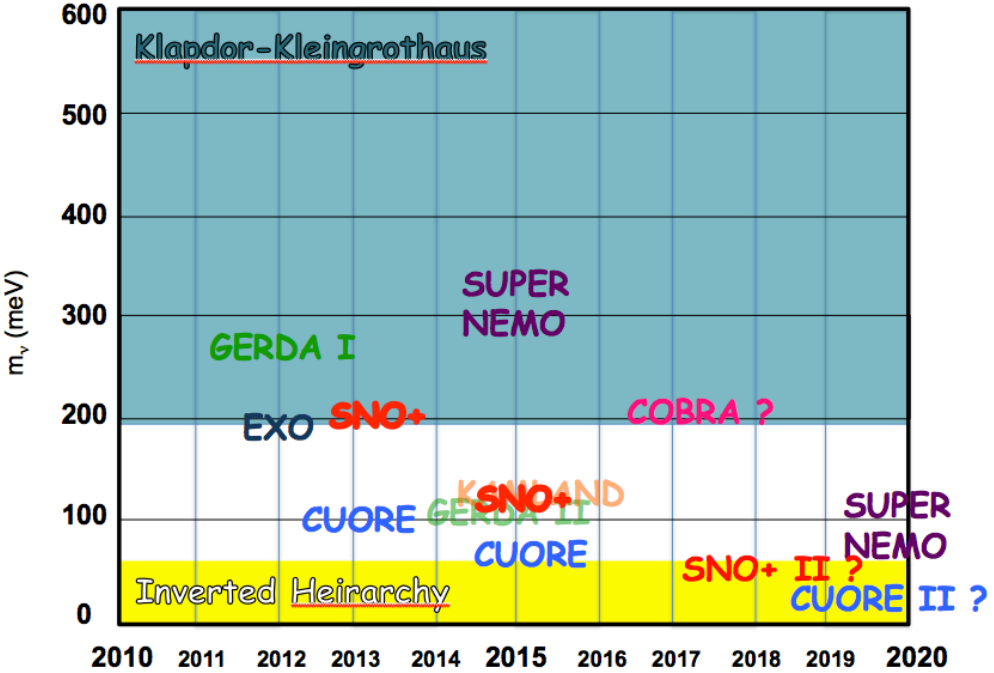
- ★ Replace D_20 with Neodymium-loaded liq. scint.
- ★ Primary interest $0\nu\beta\beta$
  - cost-effective and extremely competitive
  - fully operational by **2012**
- ★ In addition, broad physics programme
  - Solar neutrinos
  - Geo-neutrinos
  - 240 km baseline reactor ν oscillations
  - Supernova neutrinos
  - …



- ★ UK Perspective:
  - Capitalising on over 20 year of UK investment in SNO
  - Already a very high UK impact
    - Filling key roles with 30% of academics on collaboration
  - Canada providing some support
  - STFC is providing "minimal bridging funds" for next 2 years
    - but no post-doc support

0νββ Outlook

★ Notional sensitivities and timescales for 0νββ experiments



- **2013:** KK claim may be ruled out by multiple experiments
- **2015:** *if* KK claim true, may have firm evidence from Super-NEMO
- **By 2015:** neutrino mass above $\langle m_{\beta\beta} \rangle \sim 100\,\mathrm{meV}$ will either be established or ruled out by multiple experiments (**GERDA, EXO, CUORE, SNO+**) using different isotopes

★ From the UK perspective: **circa 2012**

- Funding request for full proposal for **Super-NEMO**
- **SNO+** will be fully operational, will need "more official" UK support, including post-docs.

My Conclusions

- ★ The revolution in our understanding of the neutrino sector continues
  - anticipate a number of truly significant results in next decade
- ★ The good news: the UK still has a neutrino programme
- ★ But, the post-prioritisation cuts have hurt:
  - MINOS exploitation: continues (with FNAL support)
  - T2K exploitation: UK in decent position despite lack of PDRAs
  - UKNF: world-leading (in part due to external support), but next funding request not so far away…
  - MICE: now operational (step I) but potentially significant delays due to current financial constraints
  - Super-NEMO: demonstrator funded (at a reduced level c.f. request)
  - SNO+: surviving on academic effort thanks to STFC "bridging funds"

- ★ Viable near-term programme (**MINOS**, **T2K**, **$0\nu\beta\beta$**)
- ★ Significant effort towards long-term programme (**MICE**, **UKNF**)
- ★ But, lack of a medium term programme is a real concern:
  - UK JPARC Future Neutrino Project (high power targetry etc.) not funded
  - Liquid Argon detector development project not funded

Final Words

- ★ Over the past 15 years the UK has built up a vibrant and well-focused neutrino programme
- ★ The recent round of cuts are more than just a flesh wound
  - – they had a real impact
- ★ Must defend our science, further cuts could have a devastating impact…

2010

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2010