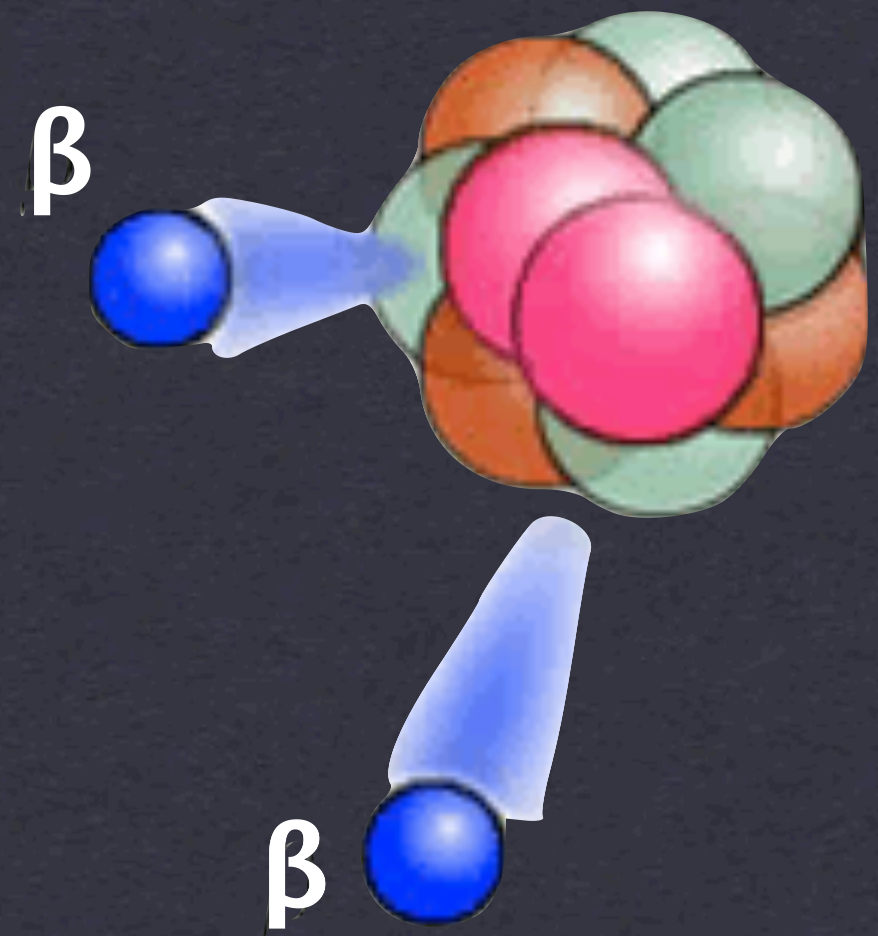
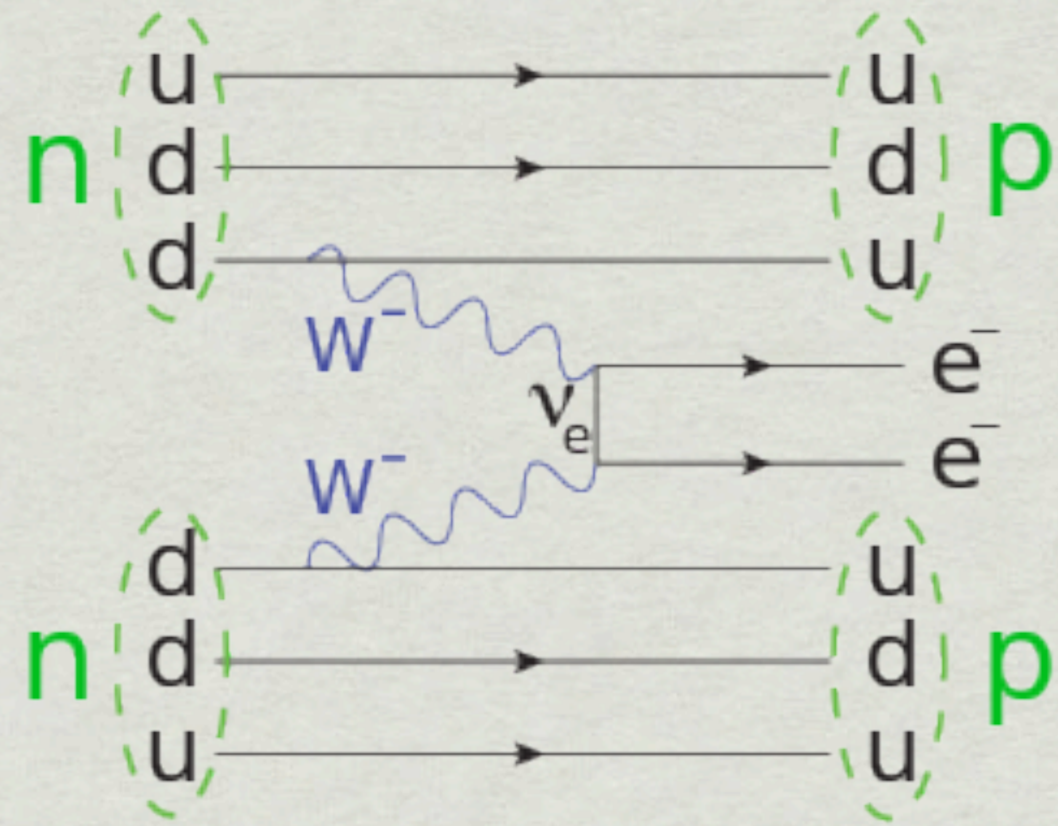


Neutrinoless Double-Beta Decay

Simon JM Peeters

Theoretical and experimental background

Neutrinoless double-beta decay ($0\nu\beta\beta$)



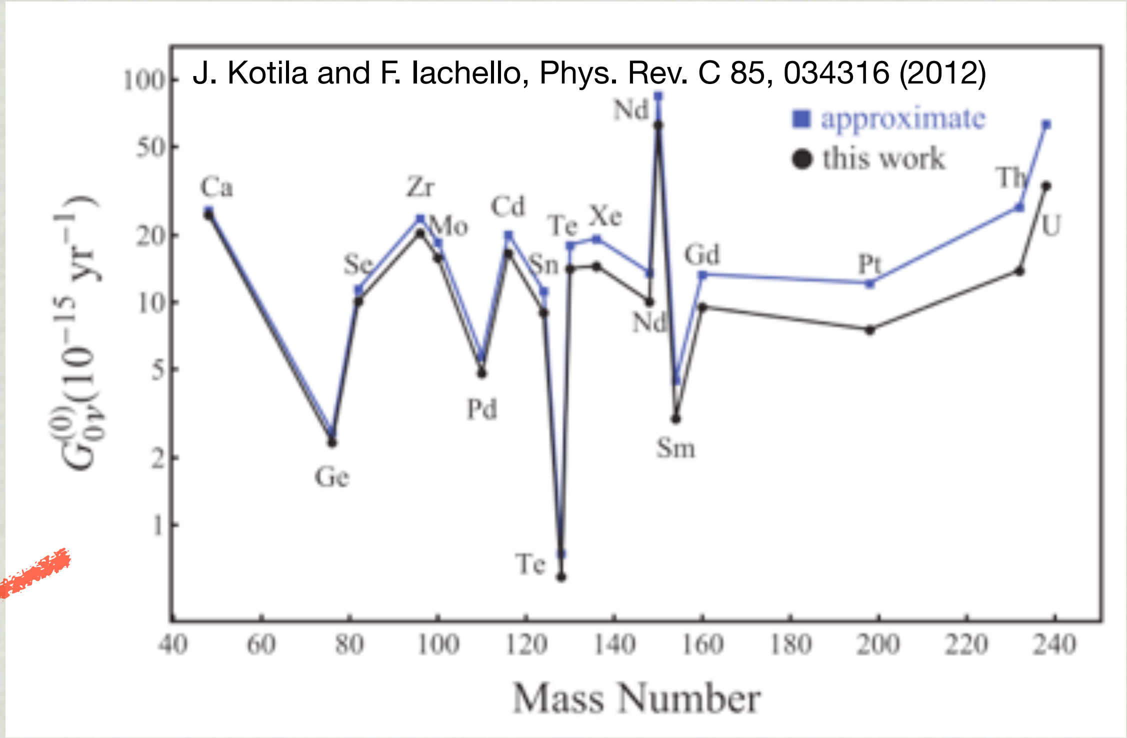
$$(A, Z) \to (A, Z+2) + 2e^-$$

Lepton flavour violation (by 2)!

Majorana nature of the neutrino
(Slechter and Valle, 1982)

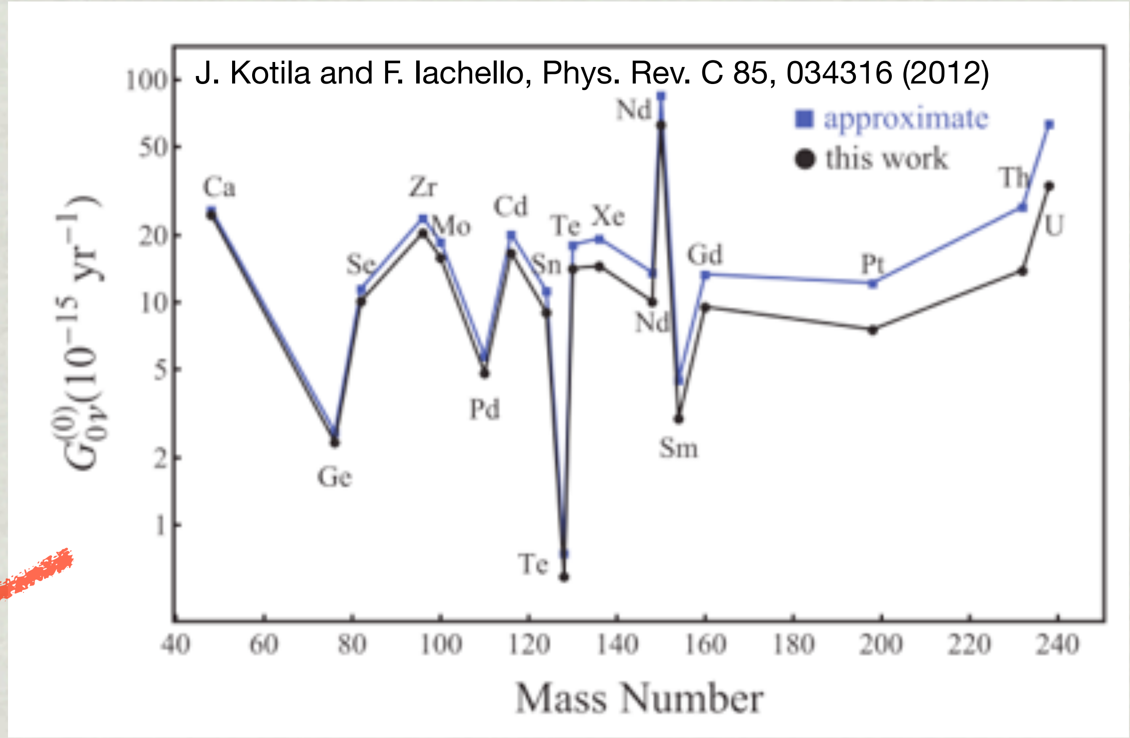
Provide information for:
Absolute neutrino mass scale
Neutrino mass hierarchy
The seesaw model:
help explain why neutrinos are so light
Leptogenesis:
the possible origin of the matter-antimatter asymmetry in the Universe

$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z) \left|M^{0\nu}\right|^2 \langle m_{ee} \rangle^2$$



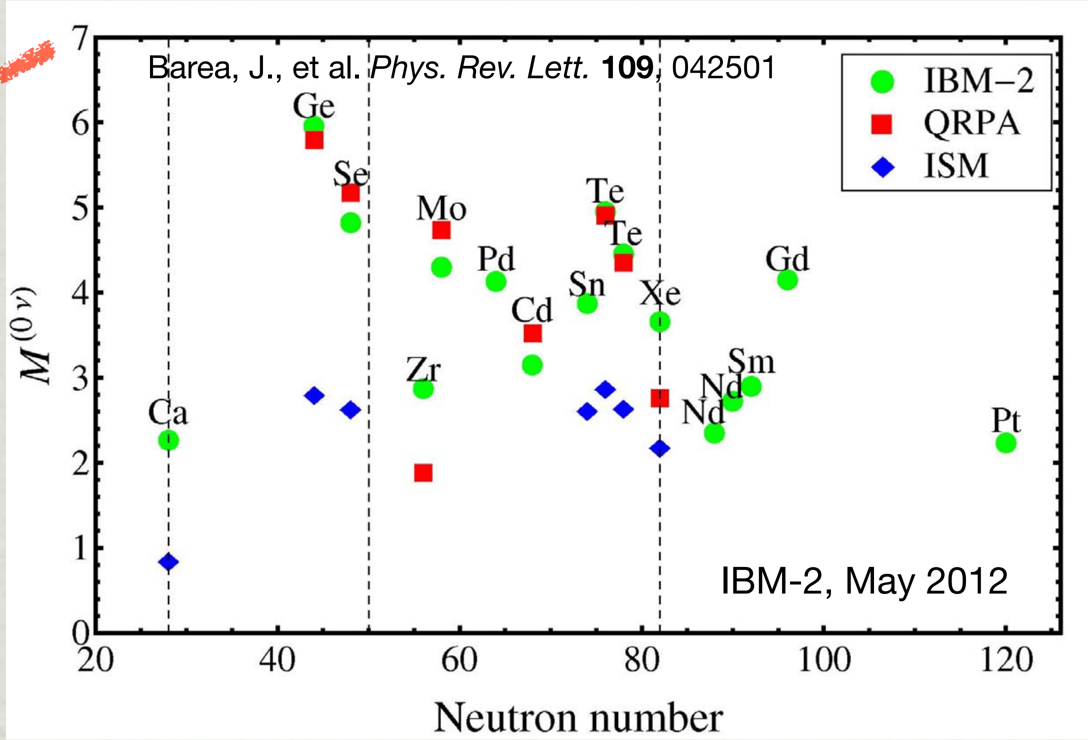
phase space factor

$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$



phase space factor

nuclear matrix element



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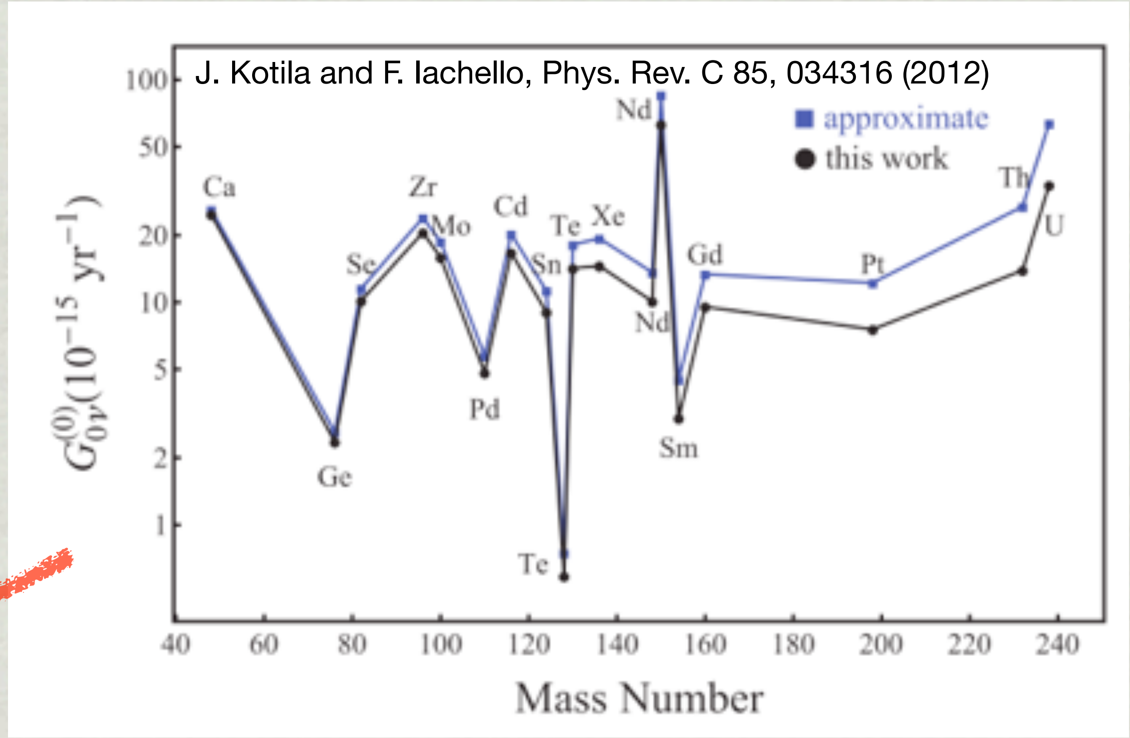

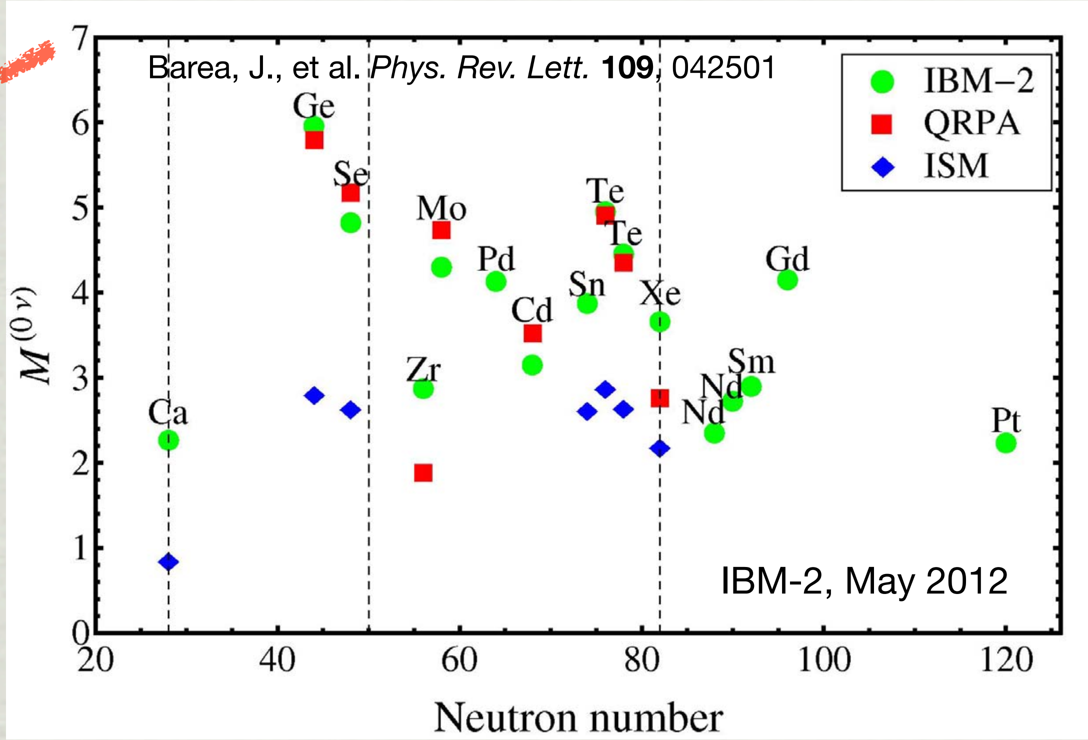

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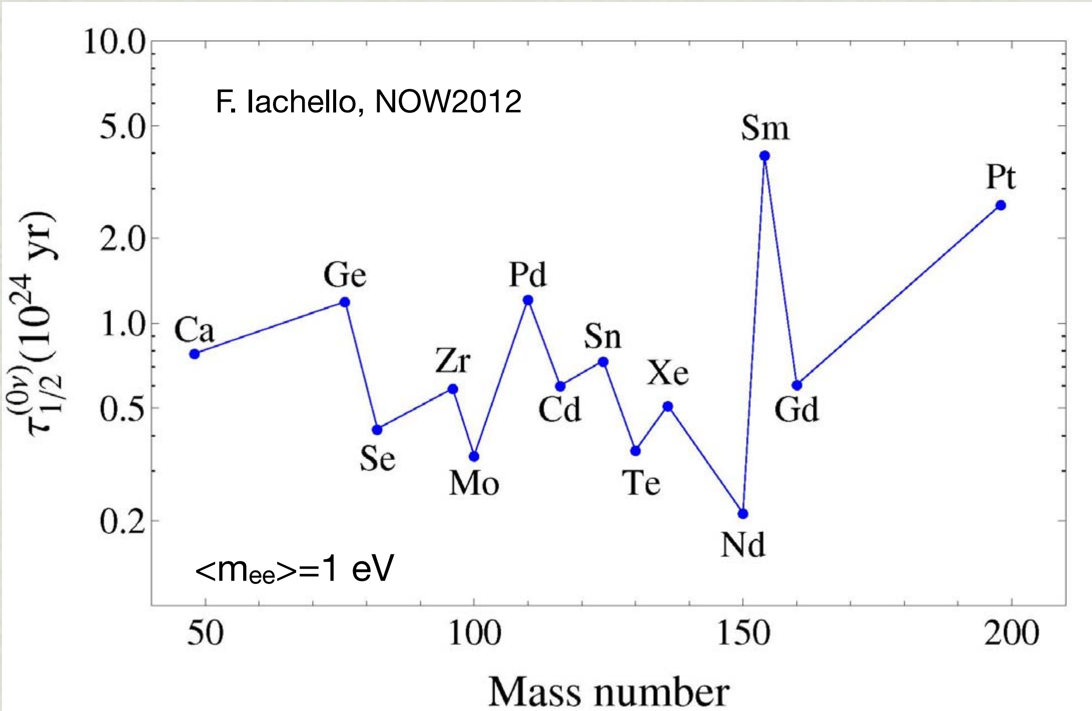
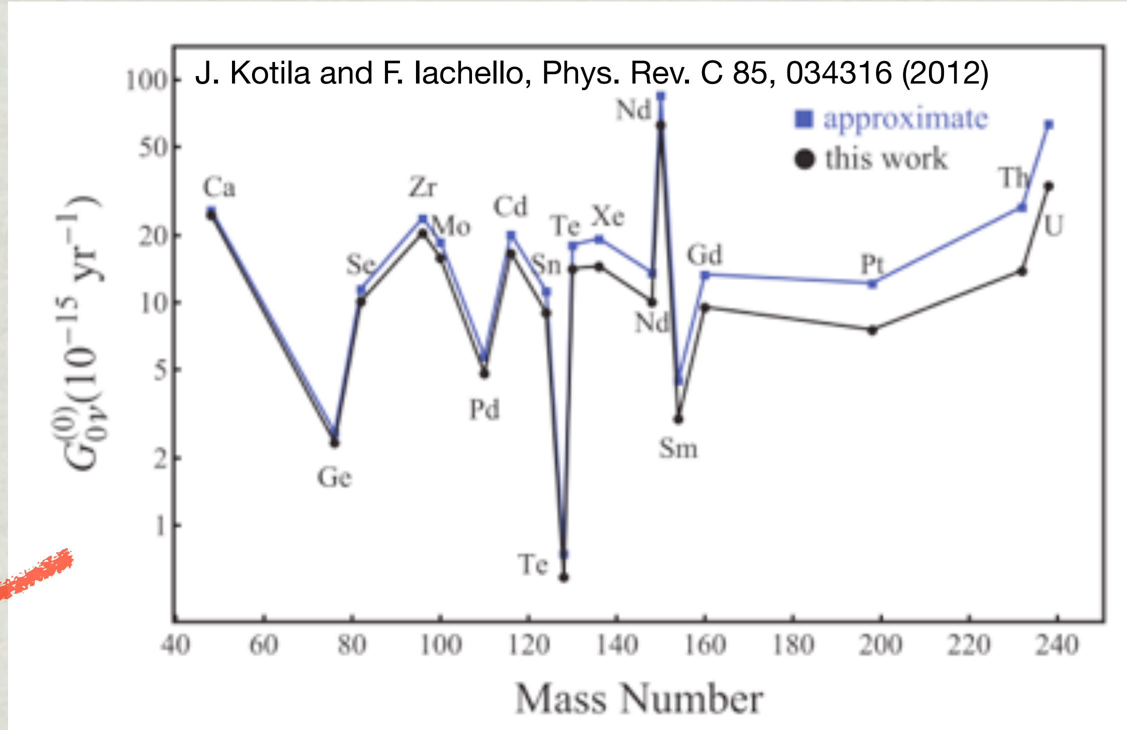
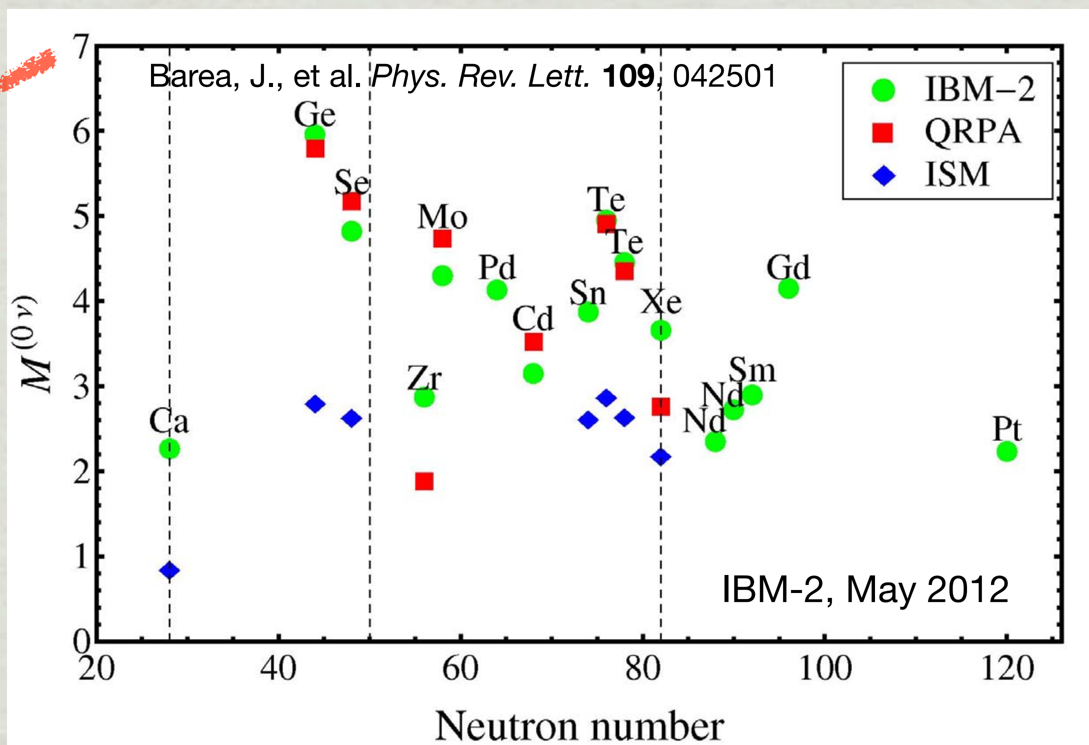
$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$

Towards a Resolution of the Double Beta Decay Problem (ECT, Trento) Sep 2012, with contributions from:

- Sean Freeman (nucleon transfer reactions, Manchester)
- Ben Kay (nucleon transfer reactions, York)







phase space factor

nuclear matrix element

$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$

neutrino mixing matrix

neutrino mass eigenvalues

$$\langle m_{ee}\rangle = \sum_k U_{ek}^2 m_k$$

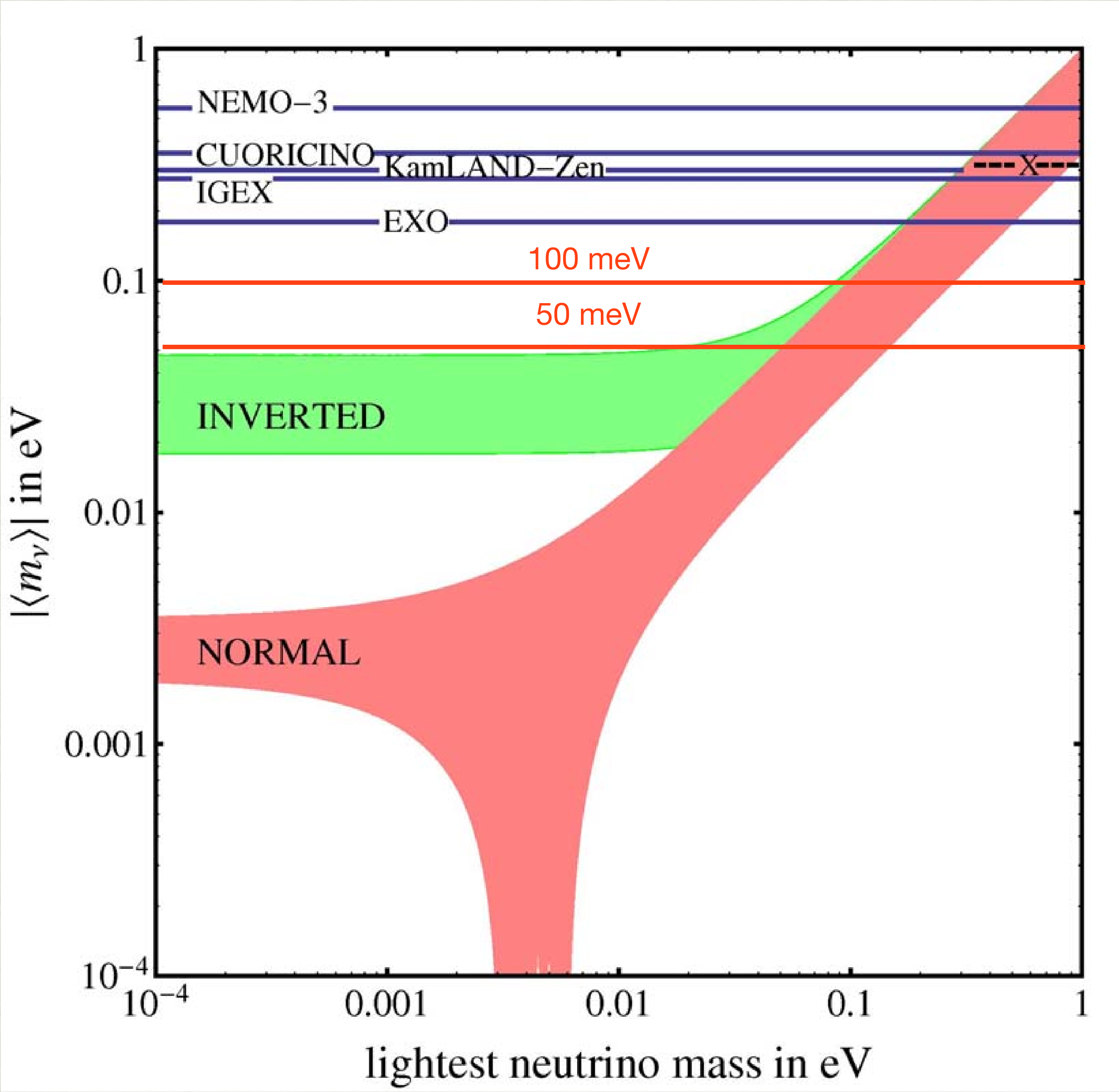
Towards a Resolution of the Double Beta Decay Problem (ECT, Trento) Sep 2012, with contributions from:

- Sean Freeman (nucleon transfer reactions, Manchester)
- Ben Kay (nucleon transfer reactions, York)

$$= \cos^2\theta_{12}\cos^2\theta_{13}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_2 + \sin^2\theta_{13}e^{i\beta}m_3$$

0νββ: a vibrant field

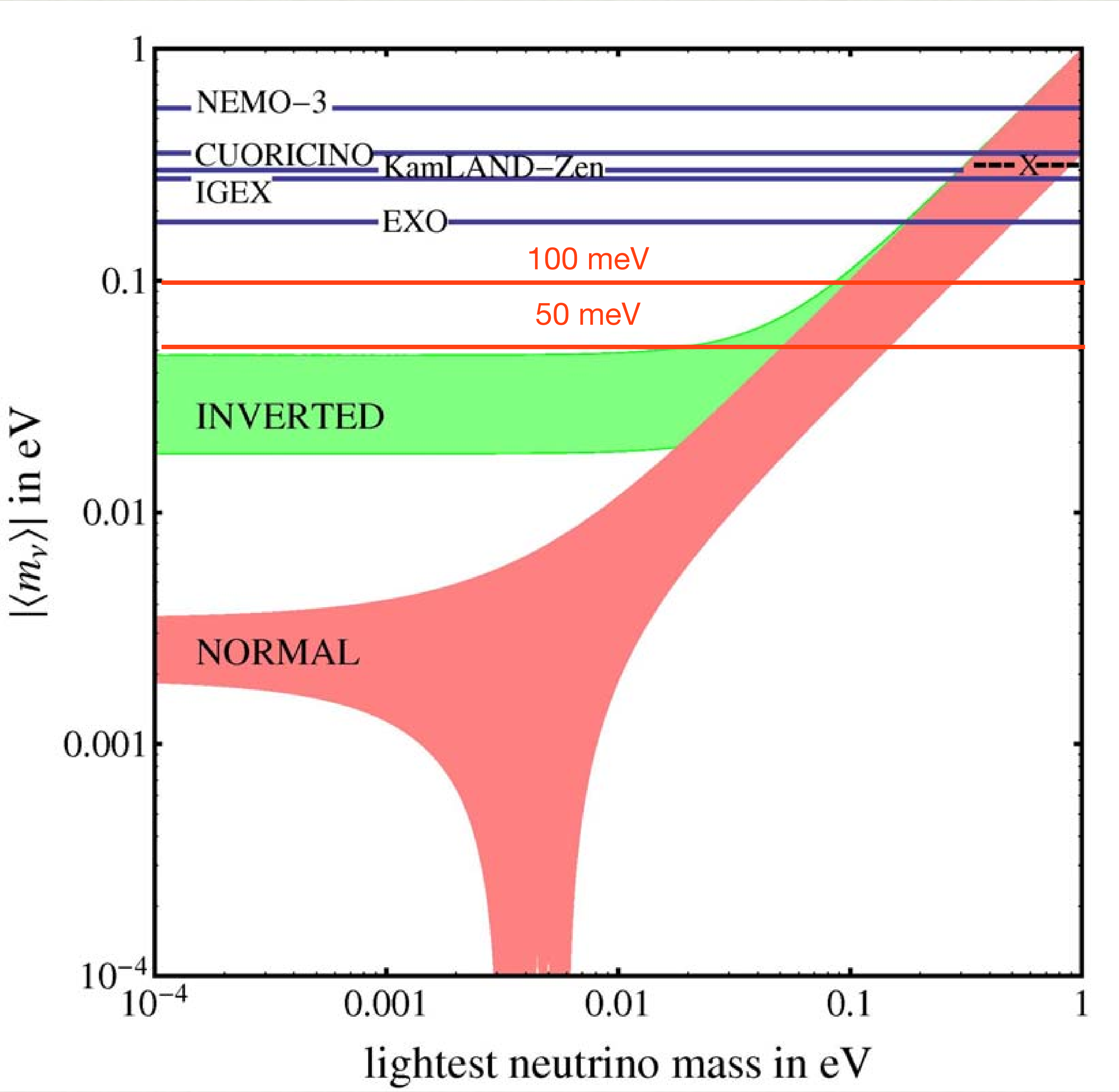
X: KK claim



Sensitivity

0νββ: a vibrant field

X: KK claim



Sensitivity

$$\tau_{0\nu}^{-1} \propto a\epsilon\sqrt{\frac{Mt}{B\Delta E}}$$

$$\tau_{0\nu}^{-1} \propto \langle m_{ee} \rangle^2$$

factor 2 in m_{ee} is a combined factor 16 of M x t x B x ΔE

0νββ: a vibrant field

X: KK claim

2012 highlights

EXO +

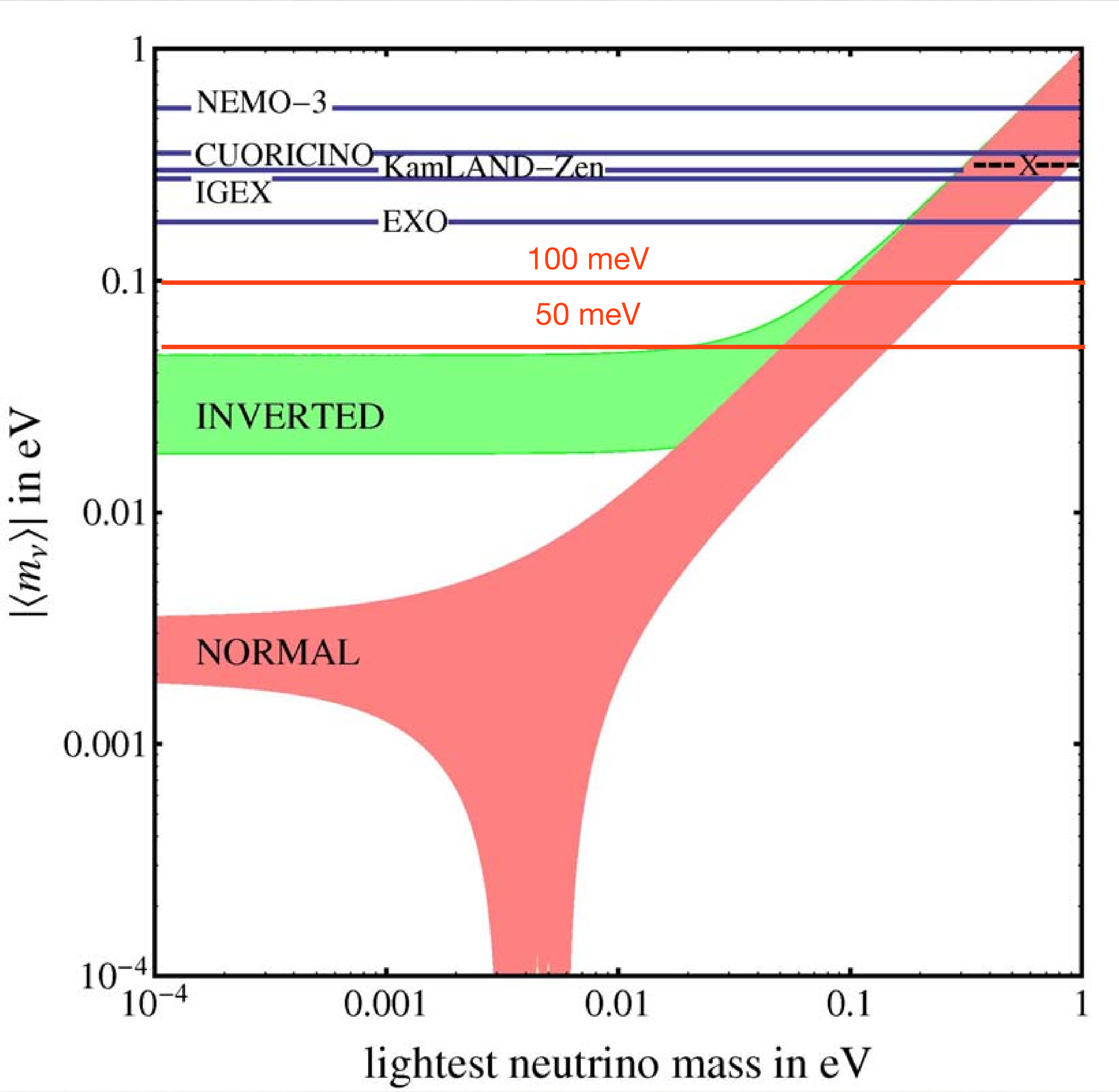
KamLAND-ZEN

2νββ results

EXO limit
at/below KK claim

GERDA started running

It has been an exciting year



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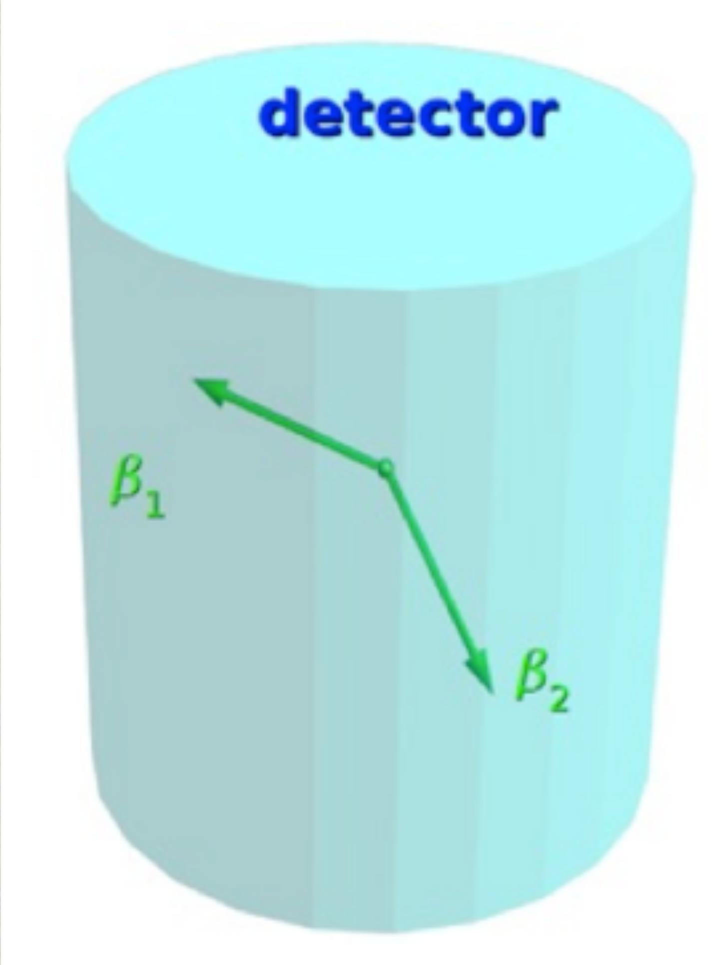
Experimental grouping

calorimeter

(oa scintillator)

+ Large mass

- Lower energy resolution

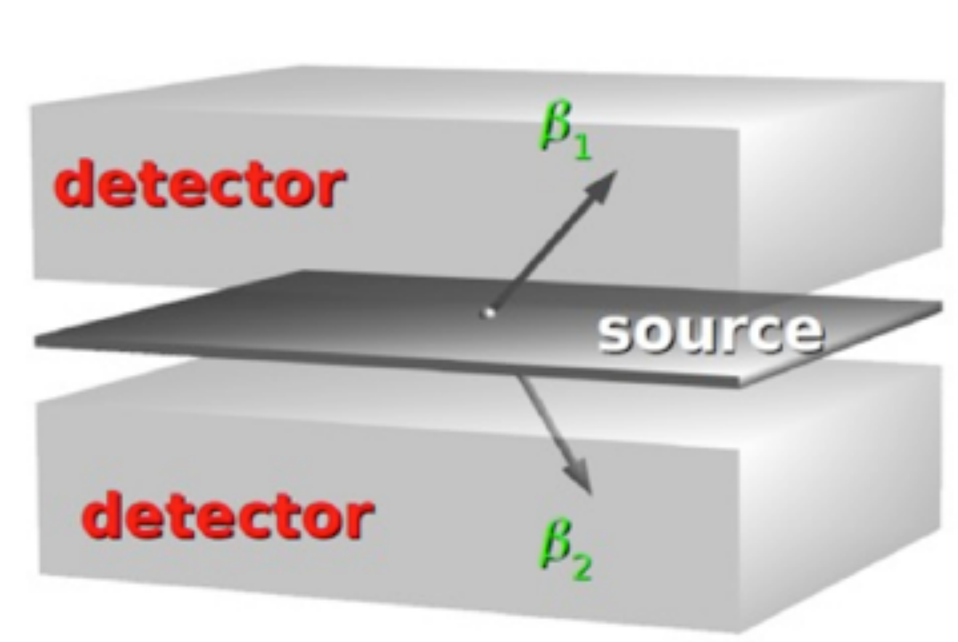


external source detectors

(oa gas TPC)

+ Event topology, leaving clean background (except 2νββ)

- Difficult to get large mass



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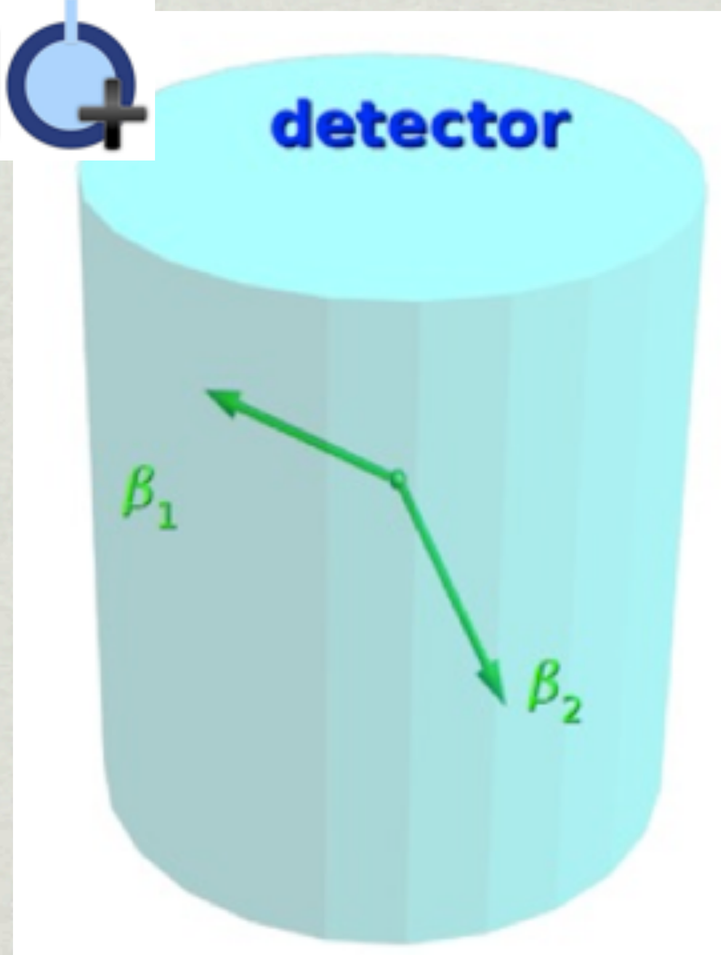

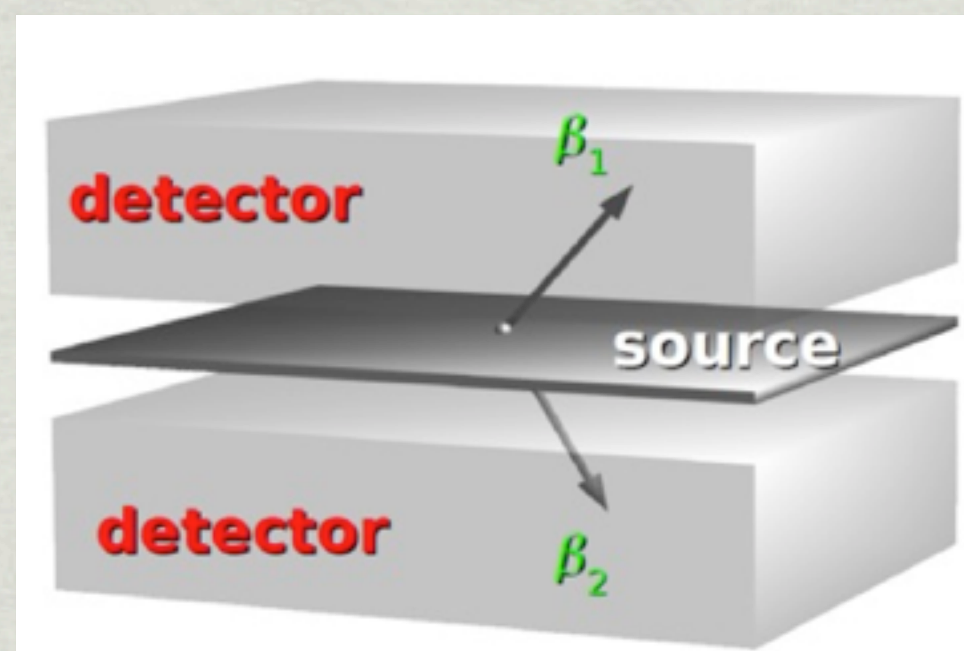

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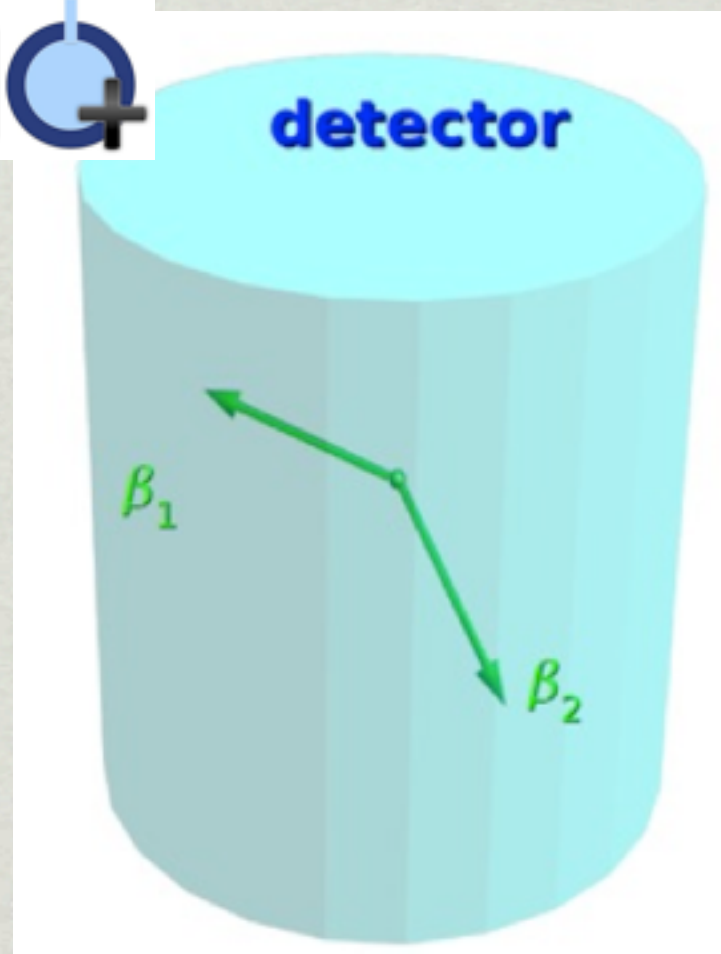

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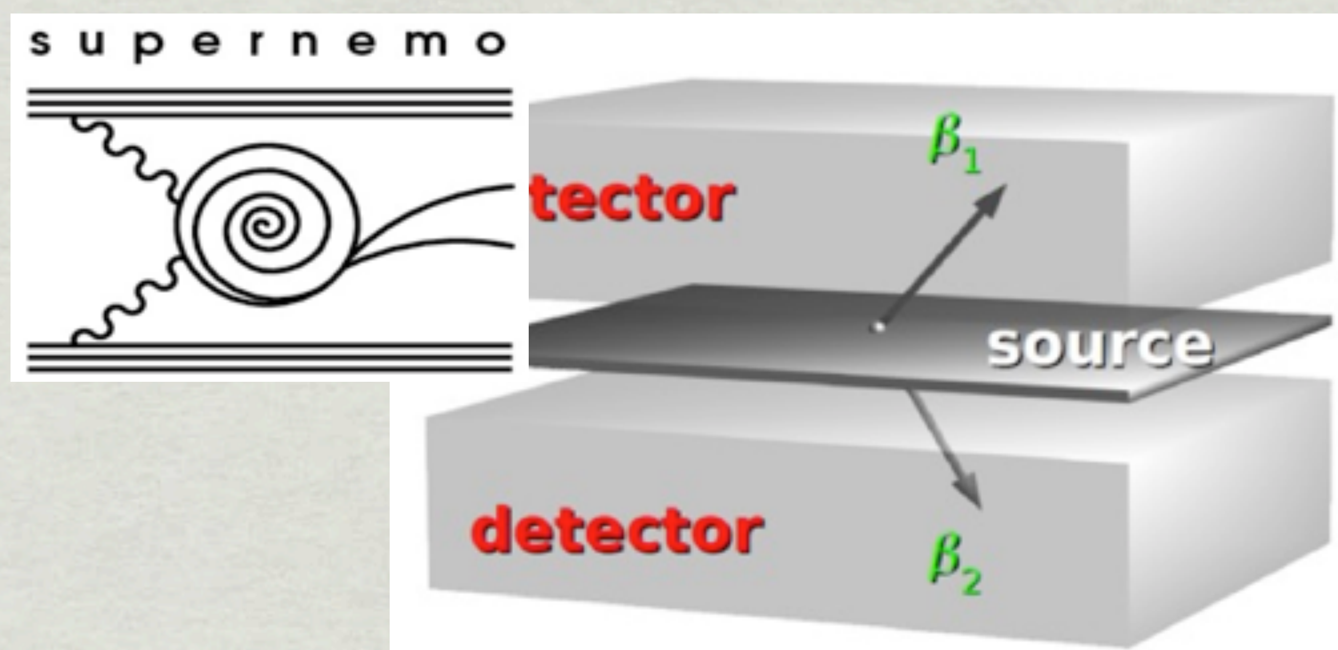


SLIDES PROVIDED BY DAVID WATERS

SuperNEMO

IMPERIAL, MANCHESTER, UCL,
UCL-MSSL, WARWICK
(~40% OF ENTIRE COLLABORATION)

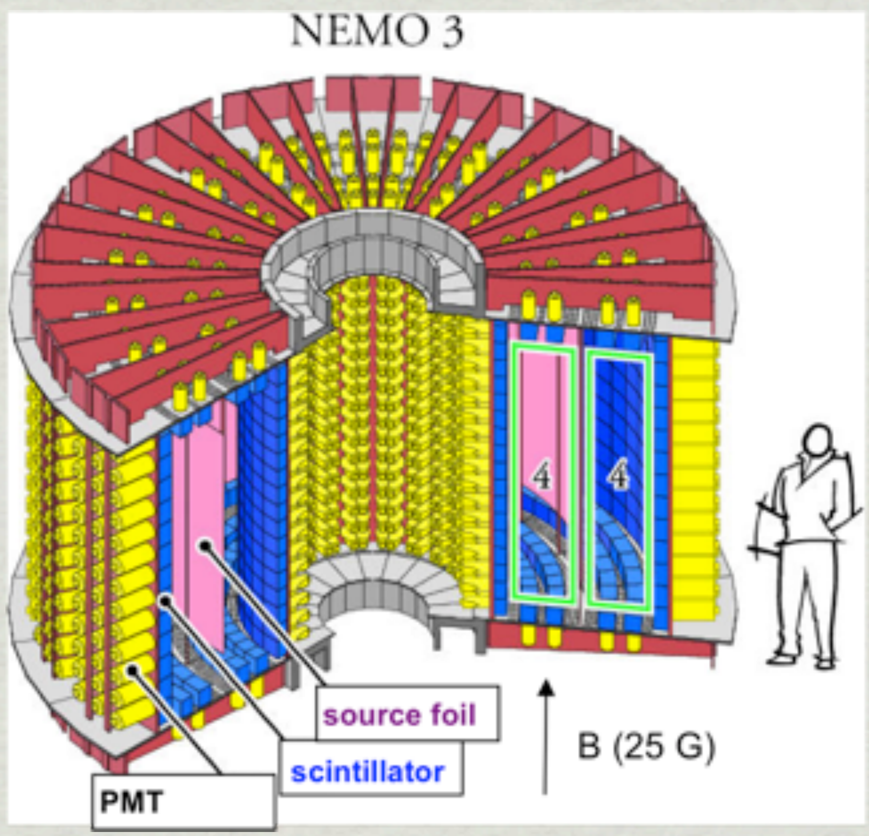
The goals of SuperNEMO :

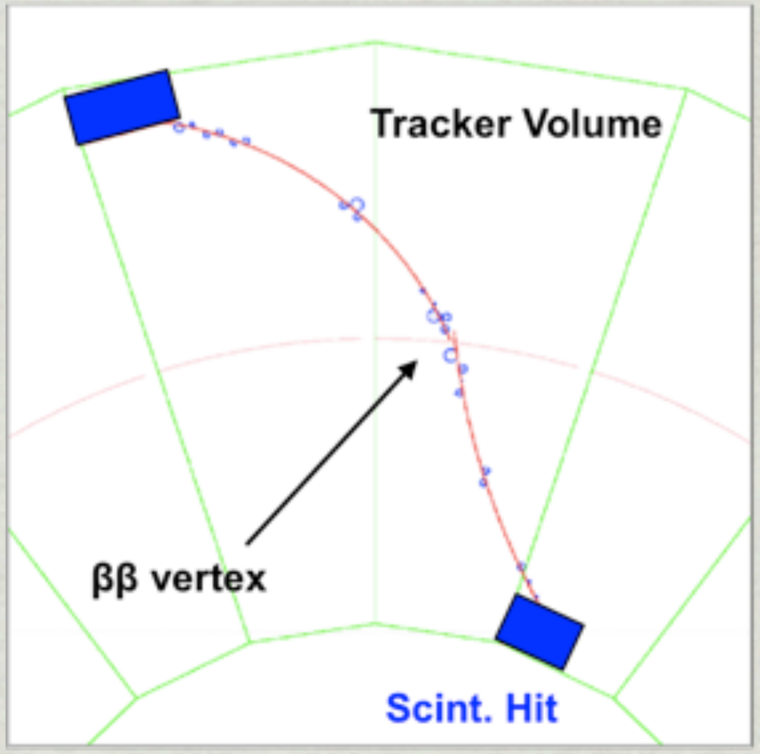
1. **Build on the experience of the extremely successful NEMO-3 experiment.**
2. **Use the power of the tracking-calorimeter approach to identify and suppress backgrounds. This will yield a zero-background experiment in the first phase.**
3. **Aim to reach the inverted mass hierarchy (~50 meV) region by the end of the decade.**
4. **In the event of a discovery by any of the next-generation experiments, the tracking-calorimeter approach is by far the best one for characterising the mechanism of** $0\nu\beta\beta$ **decay.**

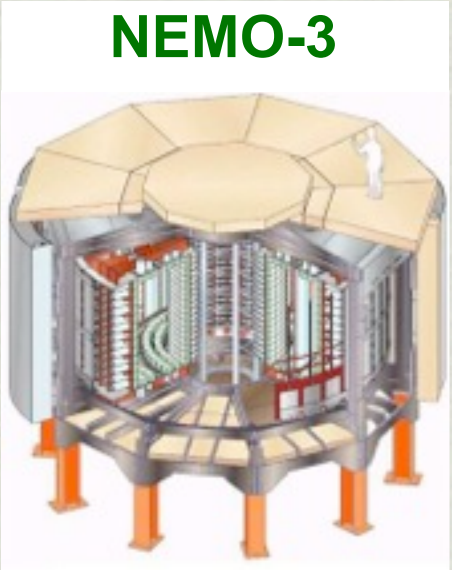
NEMO-3

Isotope	mass, g	$Q_{\beta\beta}$ (keV)	$T_{1/2}(2\nu)$ (10^{19} yrs)	Comments
^{100}Mo	6914	3035	0.71 ± 0.05	World's Best !
^{82}Se	932	2996	9.6 ± 1.0	World's Best !
^{96}Zr	9.4	3348	2.35 ± 0.21	World's First & Best !
^{48}Ca	7	4274	4.4 ± 0.6	World's Best !
^{116}Cd	405	2809	2.8 ± 0.3	World's Best !
^{130}Te	454	2530	70 ± 14	World's Best & First (Direct) !
^{150}Nd	37	3367	0.90 ± 0.07	World's Best !

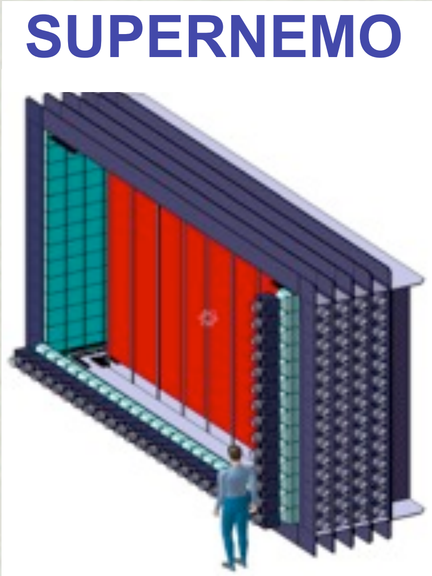
+ competitive $0\nu\beta\beta$ searches & many other results







SuperNEMO : How to get there ?



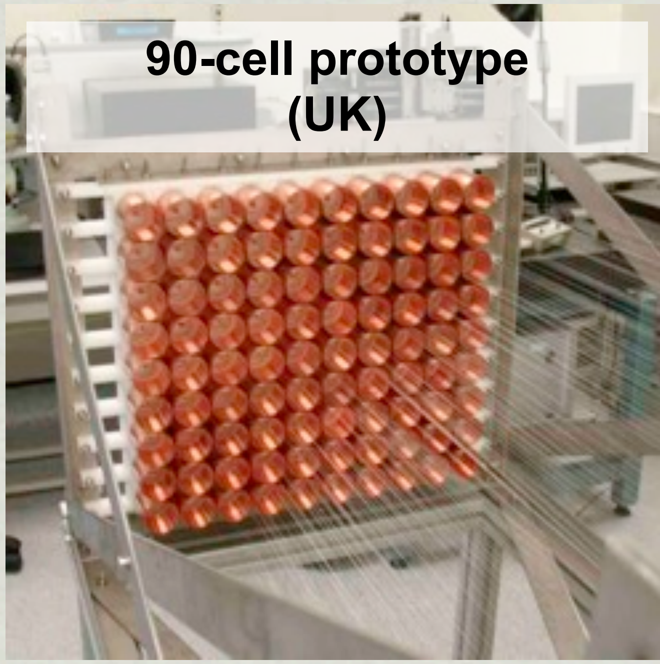
^{100}Mo	isotope	^{82}Se or other
7 kg	isotope mass	100+ kg
^{208}Tl: ~ 100 μBq/kg ^{214}Bi: ~ 300 μBq/kg Rn: ~ 5 mBq/m^3	internal contamination ^{208}Tl ,^{214}Bi in the ββ foil Rn in the tracker	^{208}Tl ≤ 2 μBq/kg ^{214}Bi ≤ 10 μBq/kg Rn ≤ 0.15 mBq/m^3
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2}(0\nu\beta\beta) > 1\text{-}2 \times 10^{24}$ y $\langle m_\nu \rangle < 0.3 – 0.9$ eV		$T_{1/2}(0\nu\beta\beta) > 1 \times 10^{26}$ y $\langle m_\nu \rangle < 0.04 - 0.11$ eV

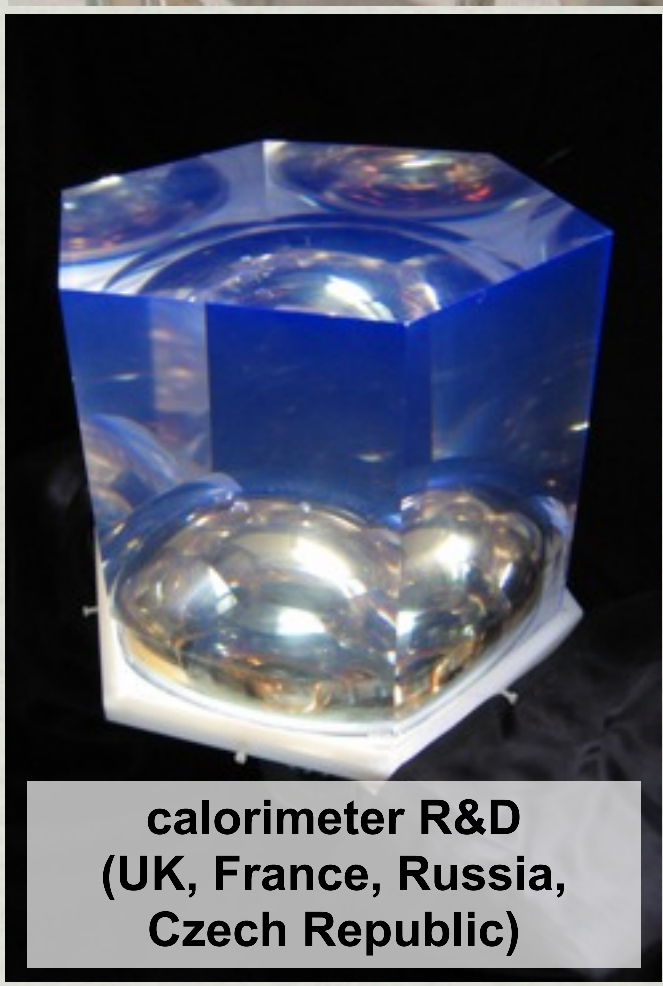
→ a ***background-free*** Demonstrator Module Phase 1

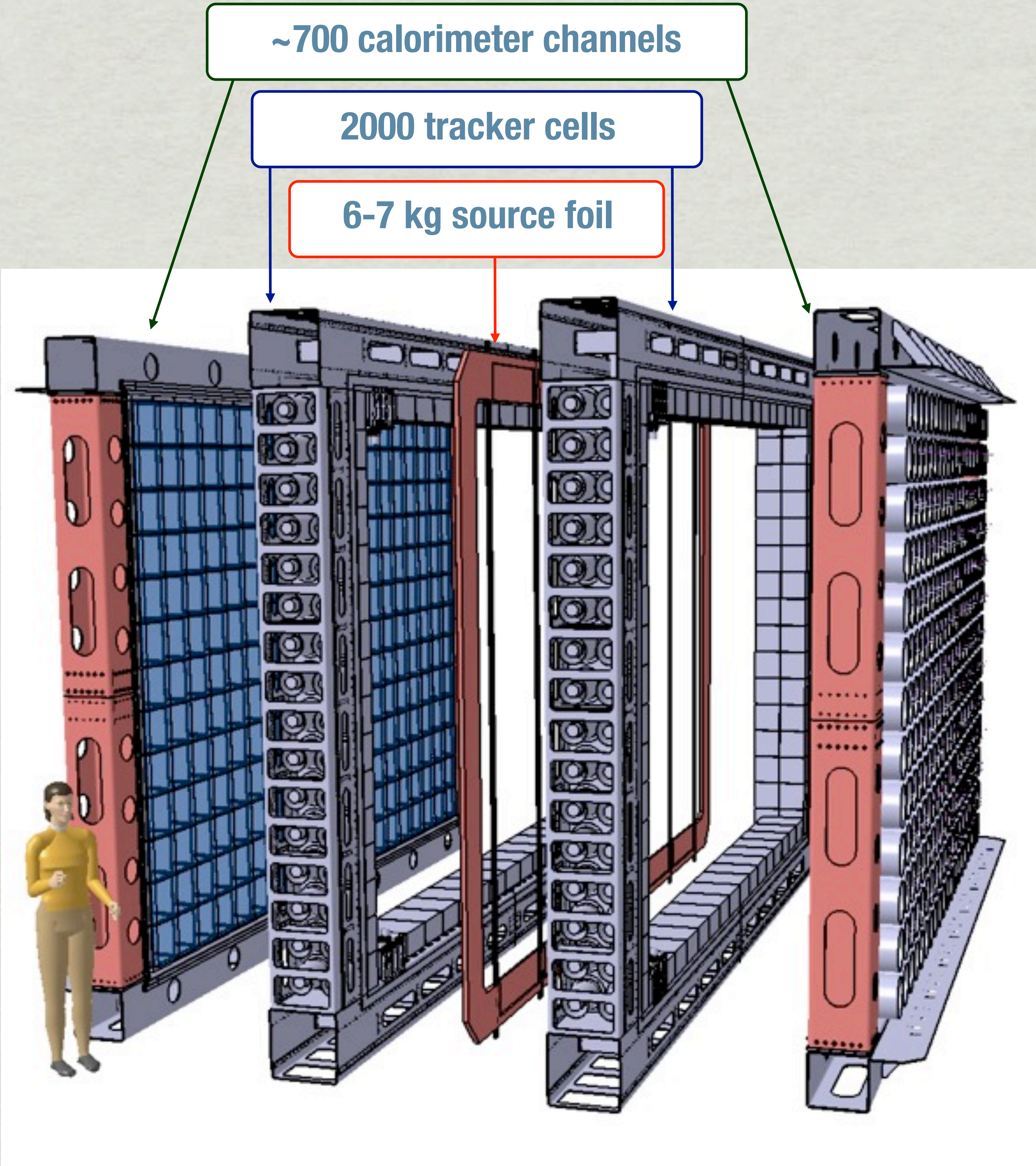
→ proven in UK R&D

→ factor ~100 in $T_{1/2}$
factor ~10 in $\langle m_\nu \rangle$

SuperNEMO Demonstrator Module : Overview







SuperNEMO Demonstrator Module : Goals

- ***Demonstrate backgrounds & sensitivity for full SuperNEMO.***
  - **This will take approximately 6 months from the start of running.**
  - **Full SuperNEMO construction can proceed after this initial demonstration phase.**

- ***Set the best limit on $0\nu\beta\beta$ for ^{82}Se and the best limit for a tracking-calorimeter experiment :***
  - **Half-life limit of 6.5×10^{24} yrs corresponding to $<m_\nu>$~ 200-300 meV after 2.5 yrs**

- ***Continue to study the most interesting isotopes for $0\nu\beta\beta$ searches (^{48}Ca, ^{150}Nd).***
  - **Isotope flexibility means that we can take advantage of the latest enrichment technologies.**

- ***Use the power of full event reconstruction to make measurements of double-beta decay processes with unprecedented sensitivity, e.g. :***

  $^{150}\mathrm{Nd} \xrightarrow{\beta\beta} {}^{150}\mathrm{Sm}^*\left(0_1^+\right) \rightarrow {}^{150}\mathrm{Sm} + 2\gamma$ **(only measured in HPGe to date)**
  - **Provide useful data for nuclear model-builders.**

- ***Continue to develop techniques to measure and control ultra-low backgrounds.***
  - **Including the UK-built Radon Concentration Line, able to measure Rn levels far lower than conventional detectors.**
  - **Applications to other areas : direct dark matter detection, and beyond.**

SuperNEMO UK

Build a 2000 channel Geiger-mode tracking detector :

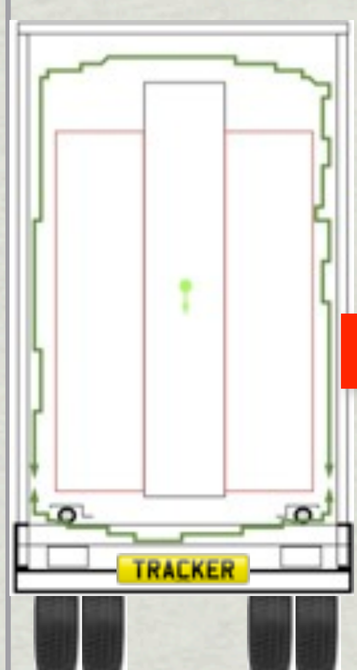
- Must reconstruct $\beta-$electron tracks with high efficiency and resolution.
- Must contribute zero background in the $0\nu\beta\beta$ analysis ➔ ultra-pure materials only.
- Must be impermeable to the diffusion of radon into the gas volume ➔ gas-sealing
- Robotic construction for accuracy, cleanliness and mass-production capability.
- Electronics, cabling, gas-system & software.

tracker robot being commissioned (Manchester)

optical module production line (UCL)

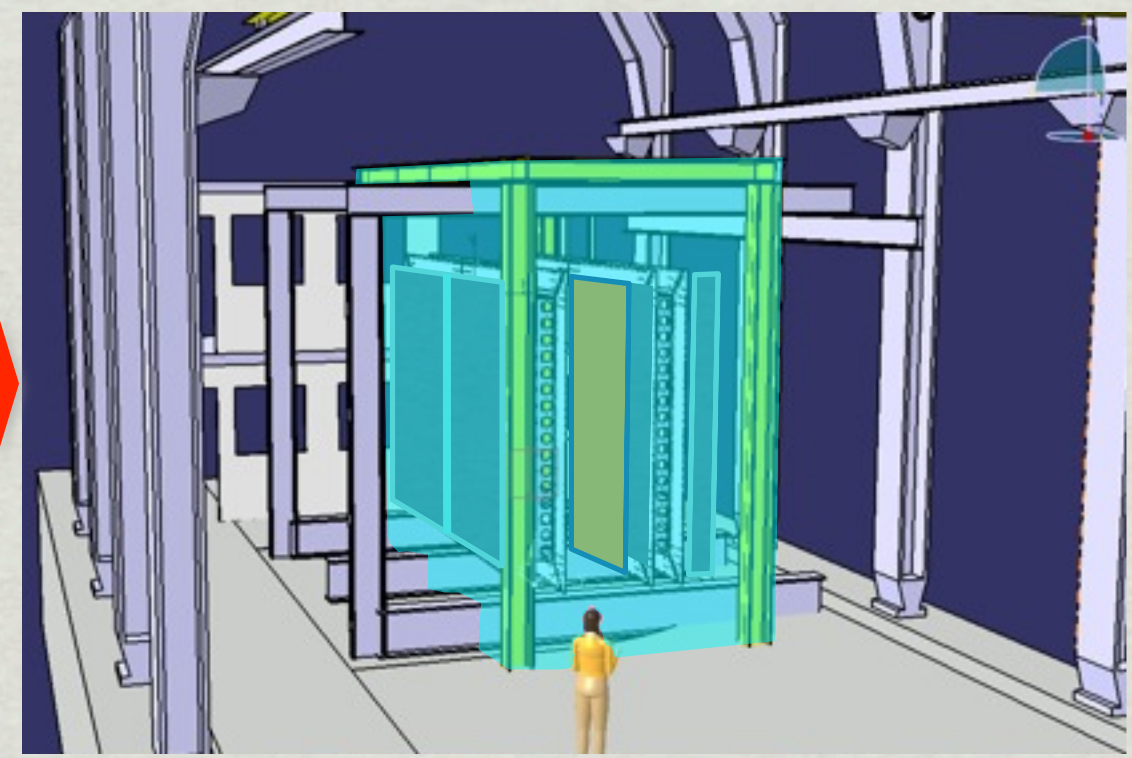
SuperNEMO UK : Next 3 Years

- Complete the construction of the tracker in the UK (**2013**).
- Transport and install in the LSM (**2013/2014**)
- Integrate the tracker with the other Demonstrator Module components – calorimeter and source foil (**2014**)
- Commission the Demonstrator Module (**2014**)
- Perform an initial 6-month long sensitivity run (**2014/2015**)

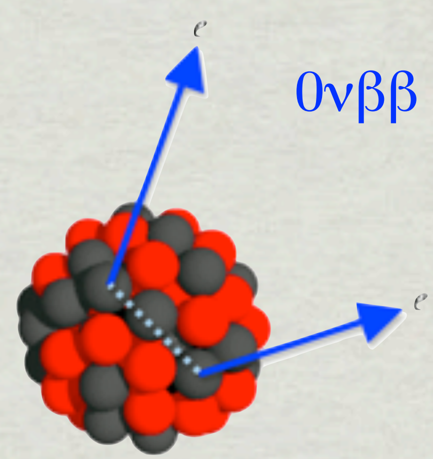


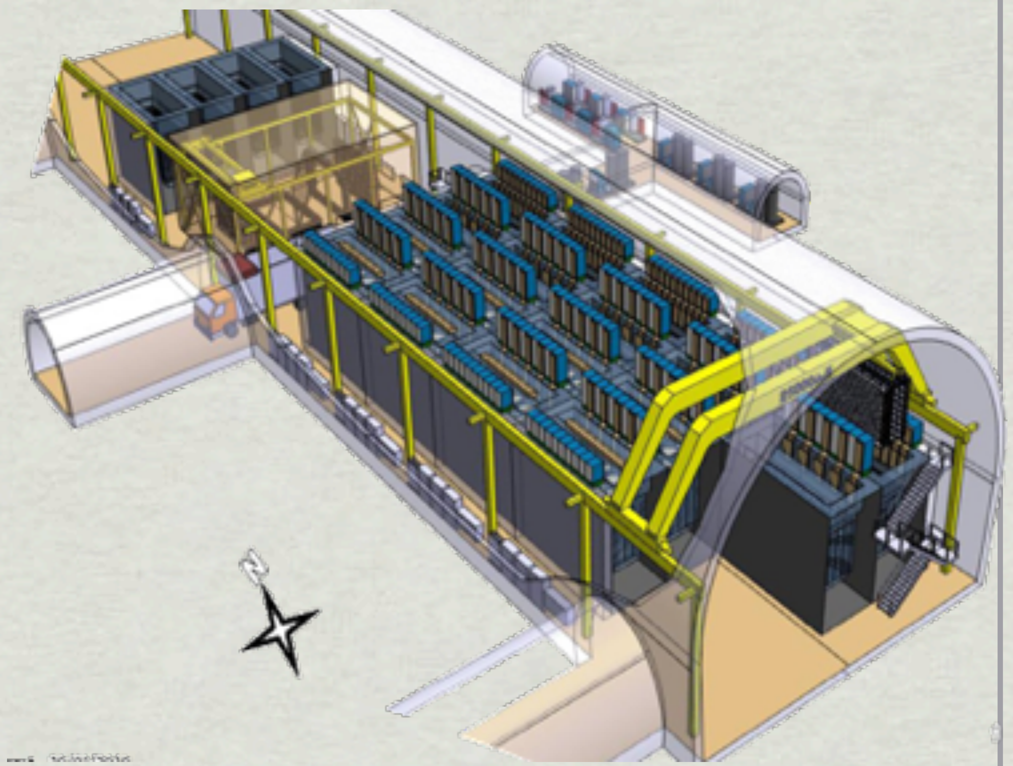
Existing LSM Hall (ready for SuperNEMO Demonstrator Module)

Integrated Demonstrator Module



SuperNEMO : Full Timeline





Demonstrator Module construction and commissioning

Demonstrator Module running. Sensitivity reaches 6.5×10^{24} yr.

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

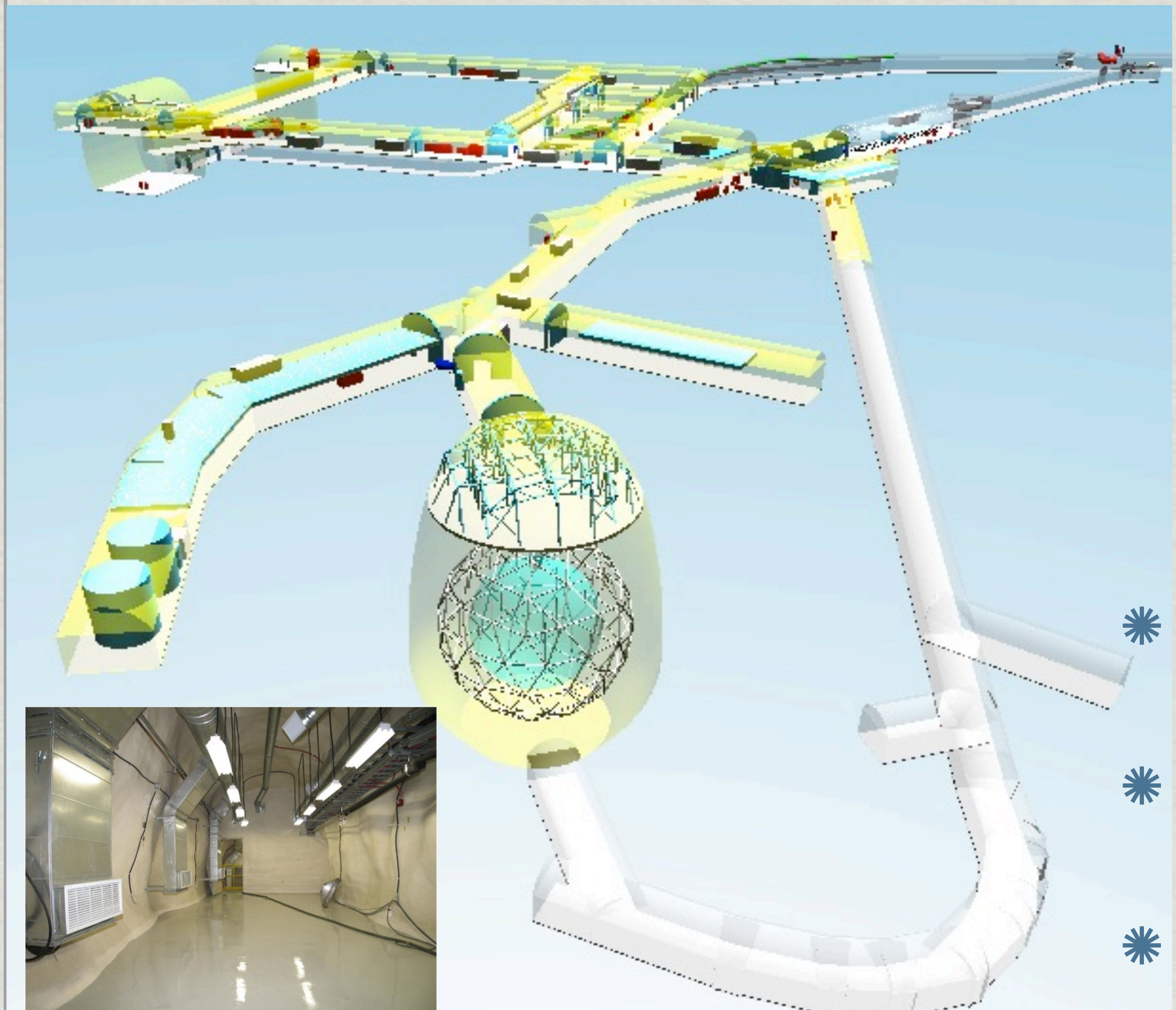
SuperNEMO Sensitivity Demonstration

Construction and deployment of successive SuperNEMO modules

CONTINUOUS OPERATION OF ≥1 SUPERNEMO MODULE

SNO+

SNO detector @ SNOLAB

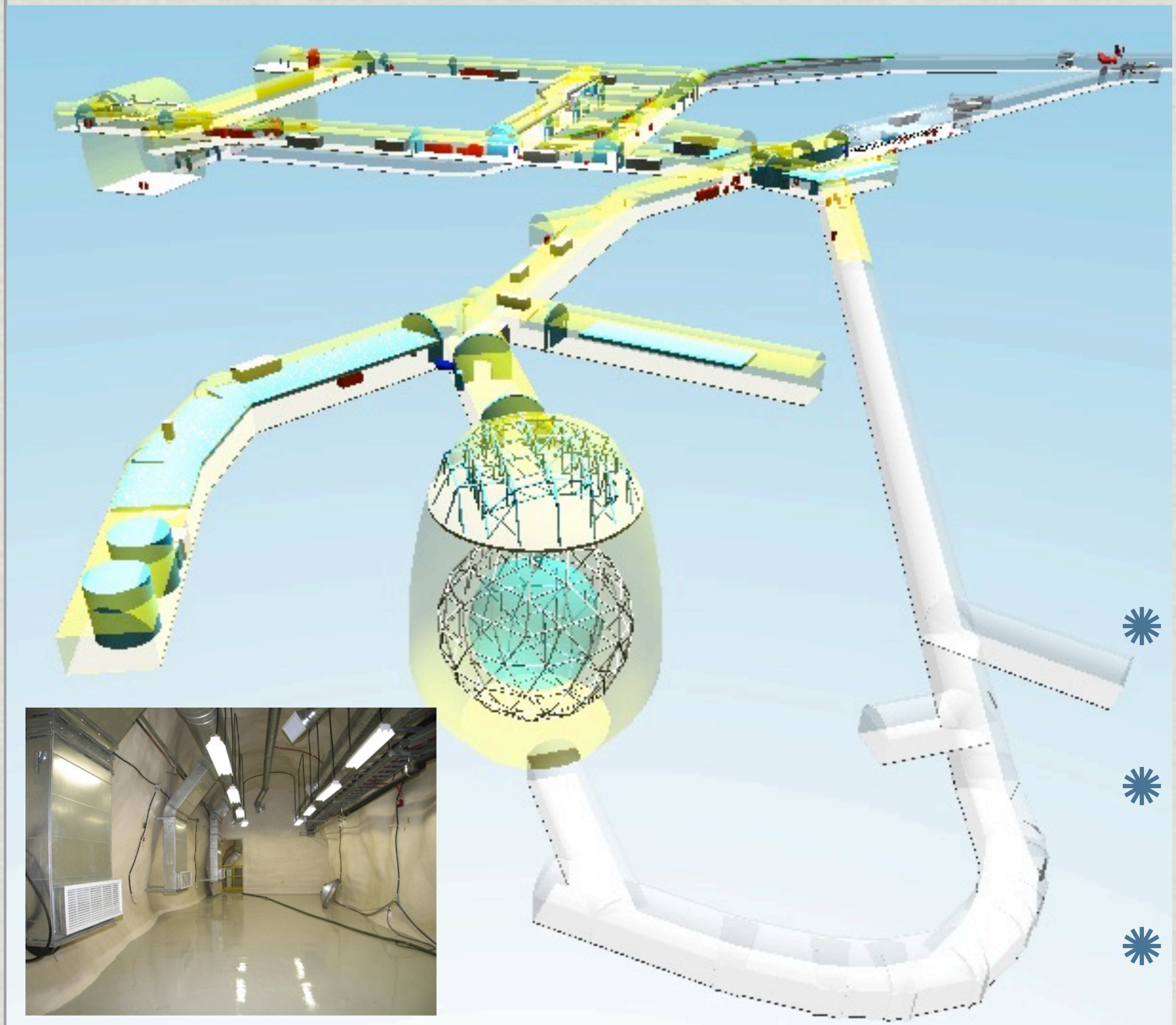


DEEPEST AND CLEANEST LARGE-SPACE INTERNATIONAL FACILITY IN THE WORLD

NEAR SUDBURY, ONTARIO, CANADA (350 KM NORTH OF TORONTO)

- 12 m diameter acrylic vessel
- 9000 PMTs with light collectors
- 7 ktonne UPW shield:
- Cavities (urylon liner)

SNO detector @ SNOLAB



DEEPEST AND CLEANEST LARGE-SPACE INTERNATIONAL FACILITY IN THE WORLD

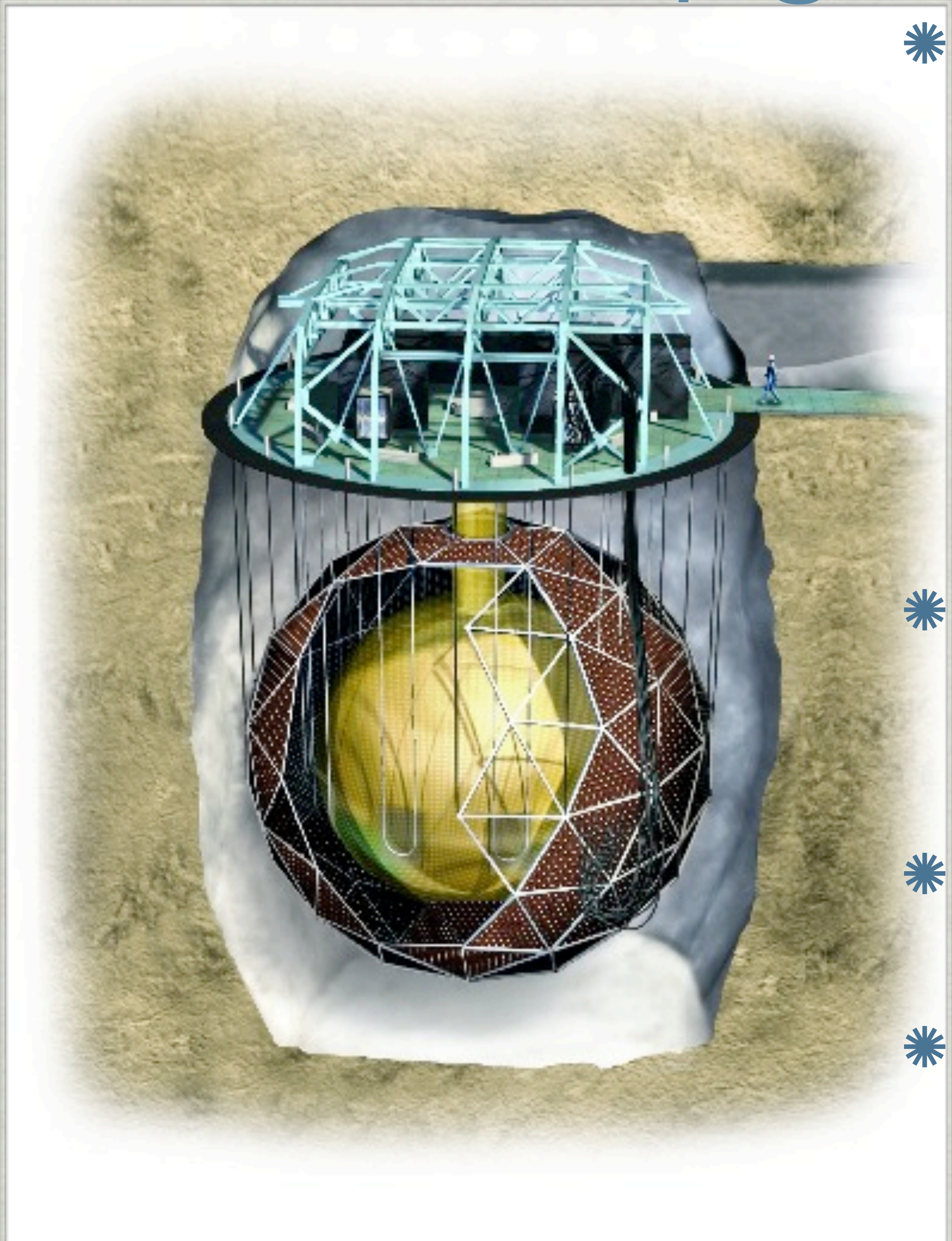
NEAR SUDBURY, ONTARIO, CANADA (350 KM NORTH OF TORONTO)

EXISTING UK INVESTMENT

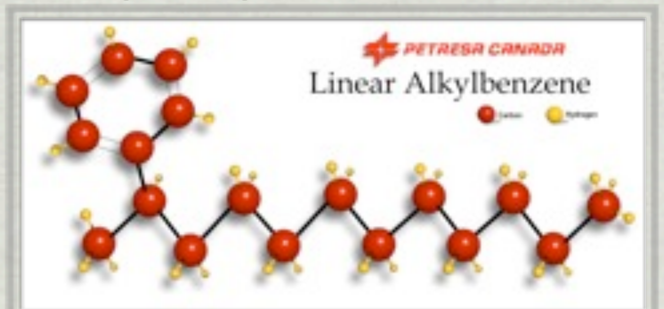
UK EXPERTISE RECOGNISED

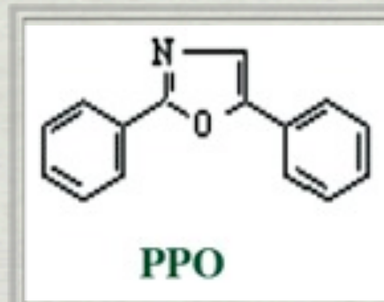
- 12 m diameter acrylic vessel
- 9000 PMTs with light collectors
- 7 ktonne UPW shield:
- Cavities (urylon liner)

Upgrade to SNO+



- 780 tonne liquid scintillator
  (LAB + PPO)
  - compatible with acrylic
  - safe
  - high light yield



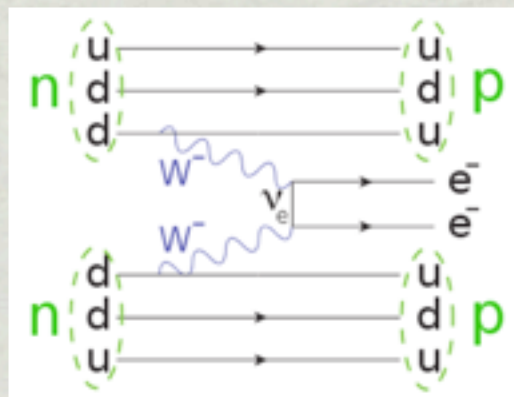


- Nd-loaded to 0.3%
  (2240 kg of natural Nd)
  - loading has been demonstrated to be stable of long time periods
- New rope system to hold down the acrylic vessel
- Upgrade of many aspects of the detector
  - refurbishment project

world leading neutrino physics

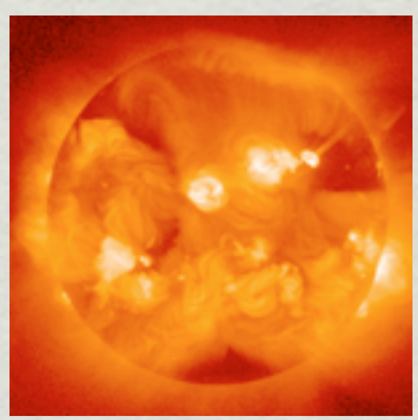
Neutrinoless Double Beta decay

Observation of this process would gives us important information about the nature of the neutrino.
(and help to understand why there is more matter than anti-matter in the universe).

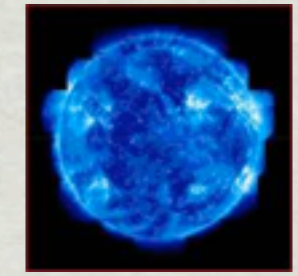


Measurement of pep solar neutrinos

Thanks to its deep location, SNO+ is the only experiment that will be able to observe these neutrinos.
These neutrinos would provide a unique probe of Non-Standard Interactions.

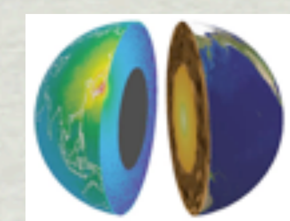


And much more:



- Observe CNO neutrinos
  SNO+ has the sensitivity to do the first measurement of CNO neutrinos. This could resolve the solar composition problem.

- Observe SN neutrinos
  Sensitivity to SN within our galaxy. Tests Supernova and is sensitive to neutrino mass hierarchy and θ_{13}.
  Part of SNEWS, the SN Early Warning System.

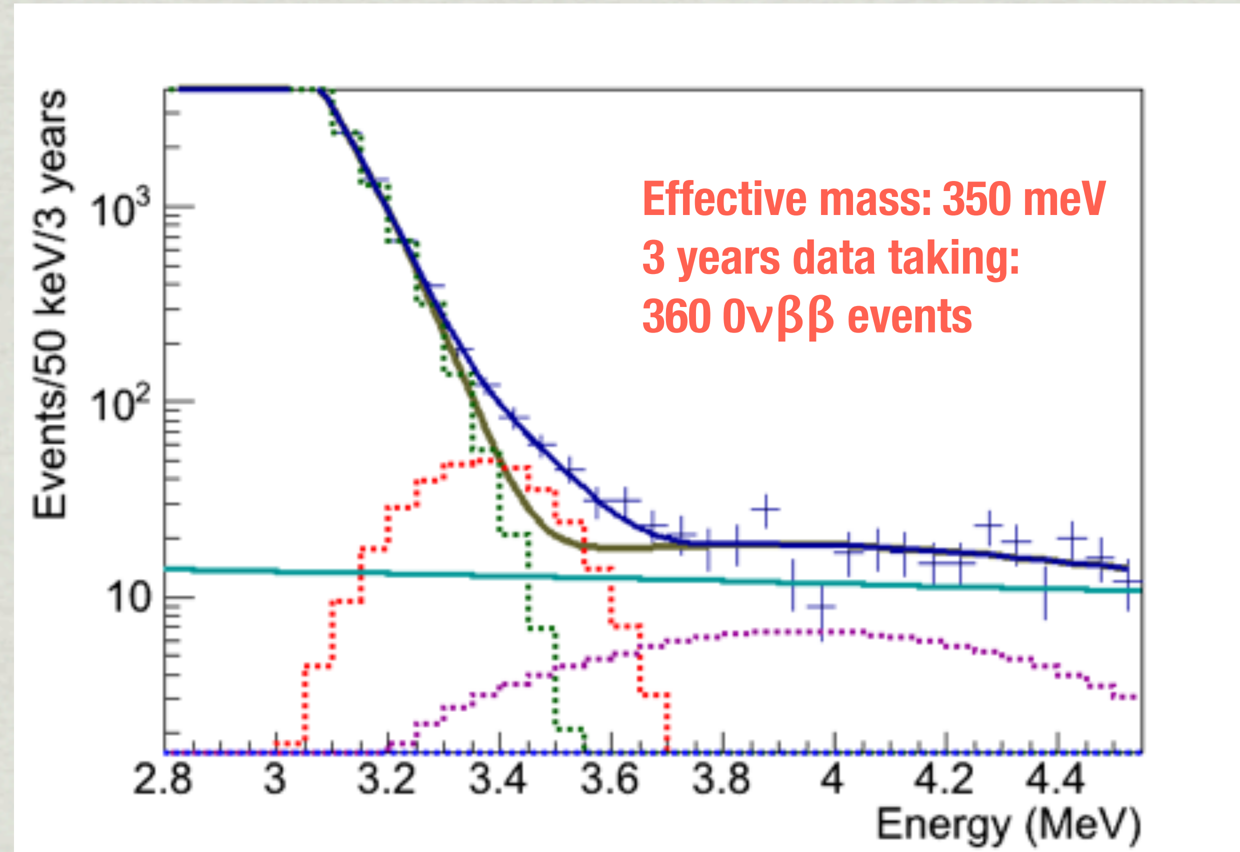


- Geo-neutrinos
  Contribute to the geological understanding of the earth.

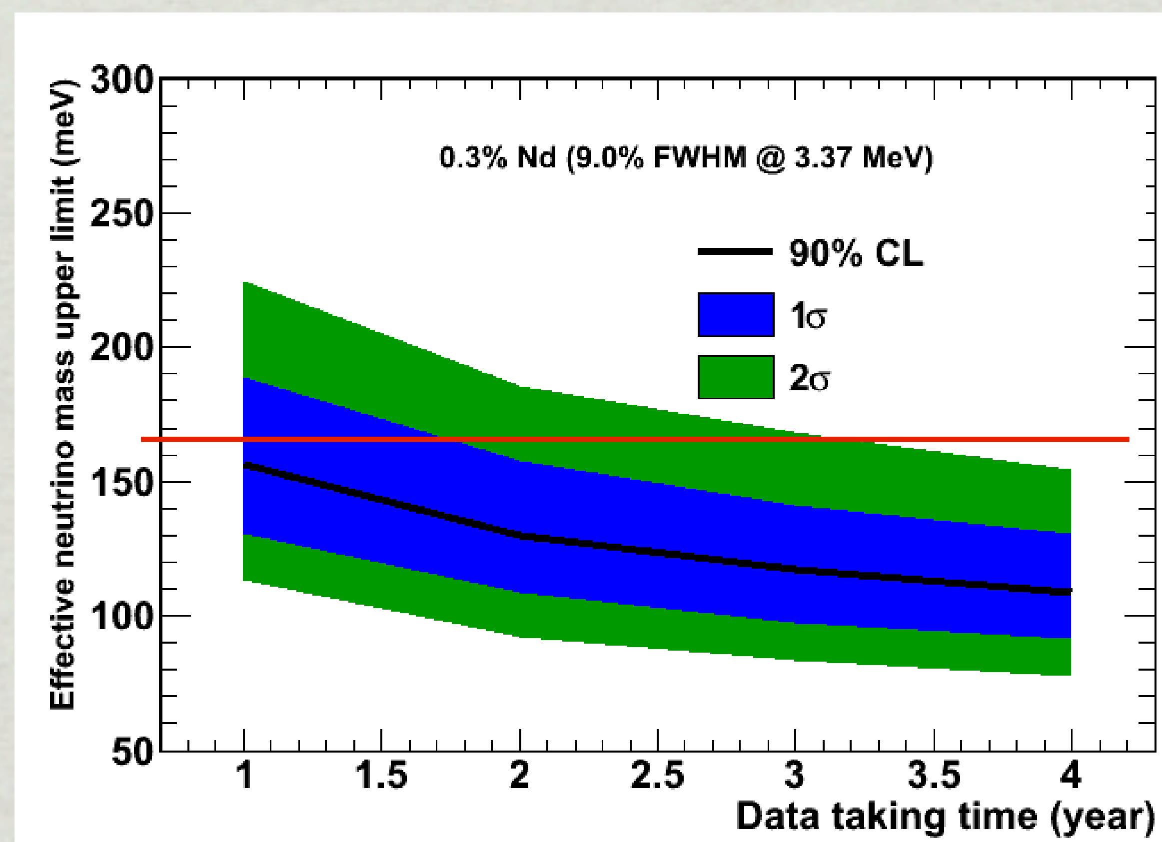
- Reactor neutrinos
  Independent measurement of Δm_{12}^2
- Nucleon decay
  Unique sensitivity to invisible mode

0νββ sensitivity

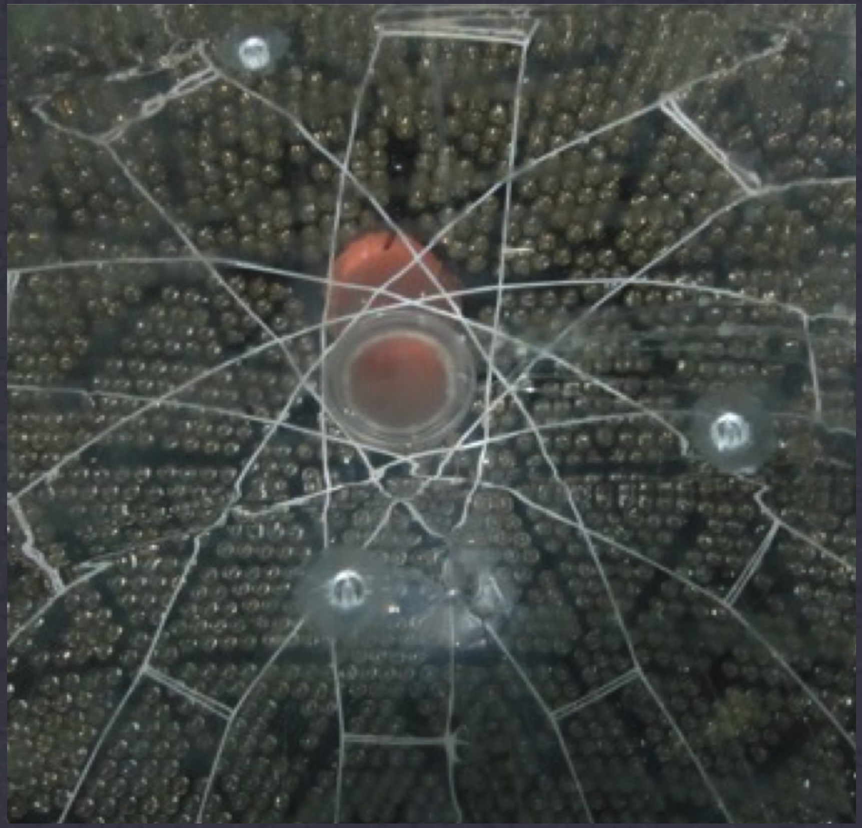
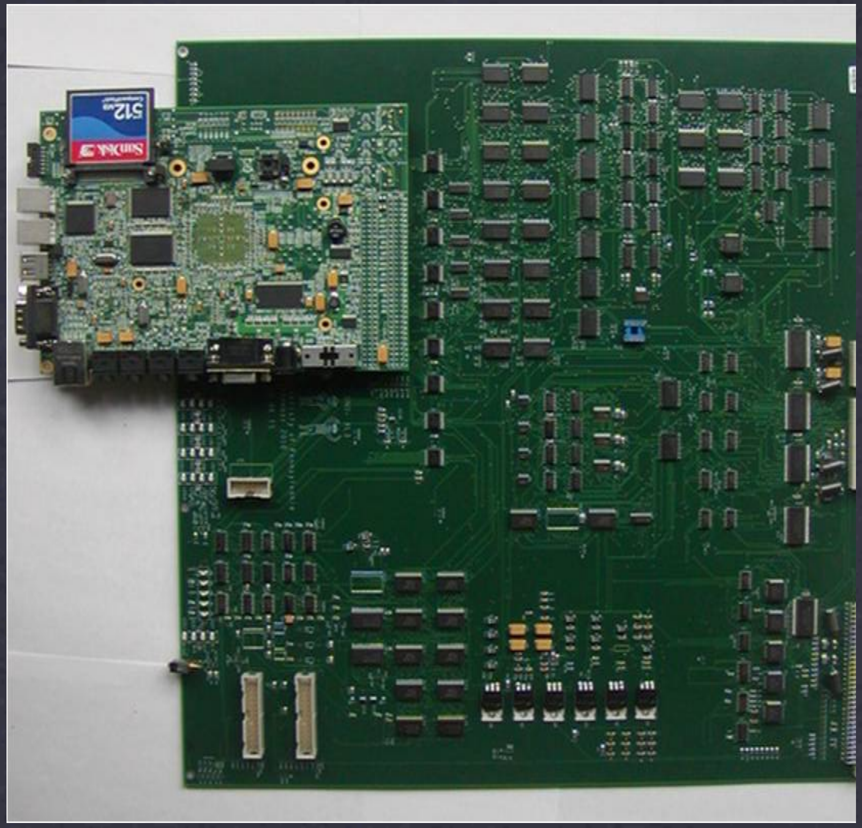
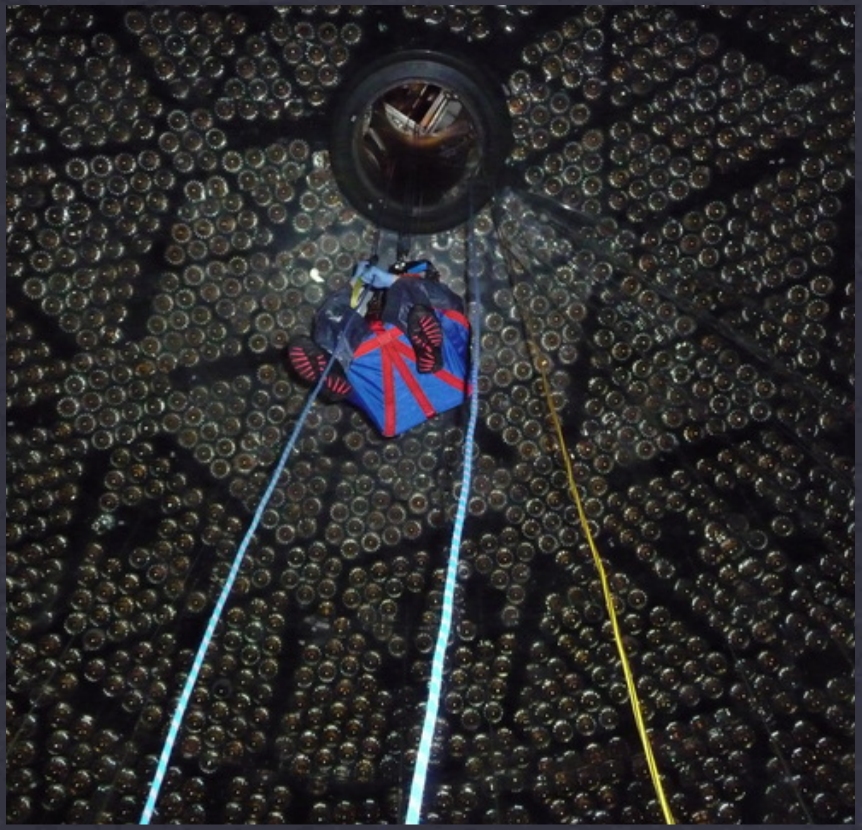
- 0.3% loading of ^{150}Nd
- Nuclear matrix element: IBM-2
  (Barea & Iachello, Phys. Rev. C 79 (2009))
  (matrix element 2.5, phase space factor 2.69 x 10^{-13})
- Fiducial volume: 50%
- 80% livetime
- Main backgrounds:
  - Solar ^{8}B
  - ^{150}Nd 2νββ
  - ^{214}Bi
    (tagged and removed 99.98% efficiency)
  - ^{208}Tl
    (tagged and removed 90% efficiency)



KKDC (~170-350 meV)
IBM-2 calculation





SOME HIGHLIGHTS OF THE REFURBISHMENT OF SNO

UK contributions

6 institutions: Oxford, Sussex, QMUL, Liverpool, Leeds and Sheffield (25% of collaboration)

12 academic faculty, 8 PhD students, 4 RAs (two externally funded plus two temporary posts leveraged from University/sub-department funds), and roughly 1 FTE of technical support

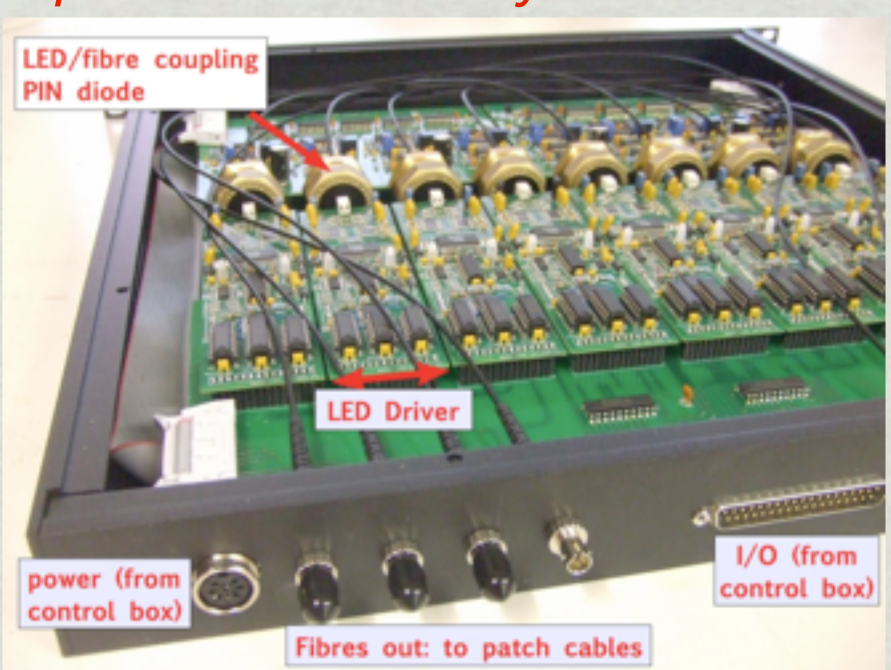
Leadership roles

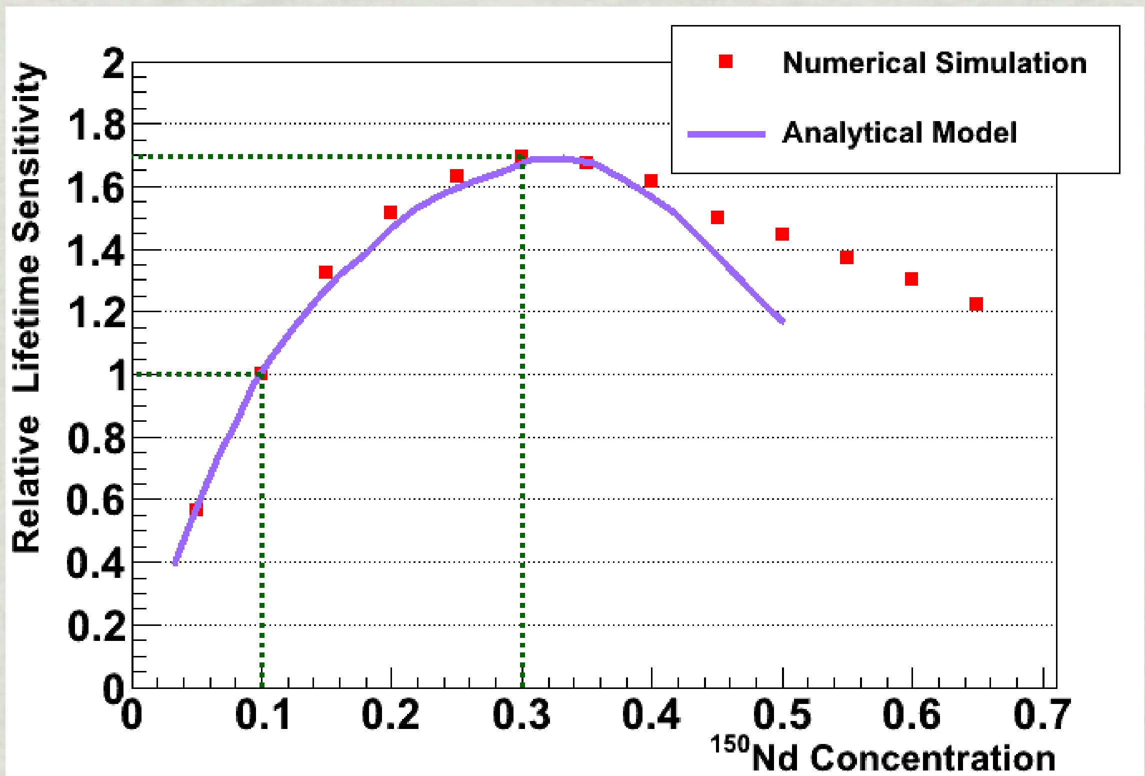
Analysis co-ordinator
Calibration co-ordinator
Leaders of the Data Flow group,
Monte-Carlo group,
Reconstruction group,
Anti-neutrino group,
SuperNova group
Leading the investigation for improved sensitivity

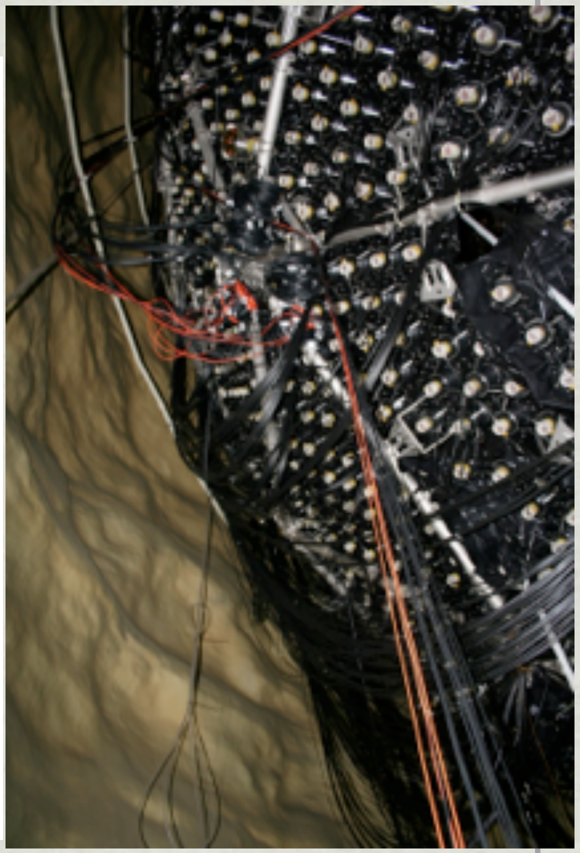
Highlights of recent achievements

- *Improved sensitivity due to loading studies, tagged background analysis, improved fitters, PID*
- *Installed 1/3 of an external optical calibration system with innovative LED drivers.*

Commissioning run next month: first SNO+ data

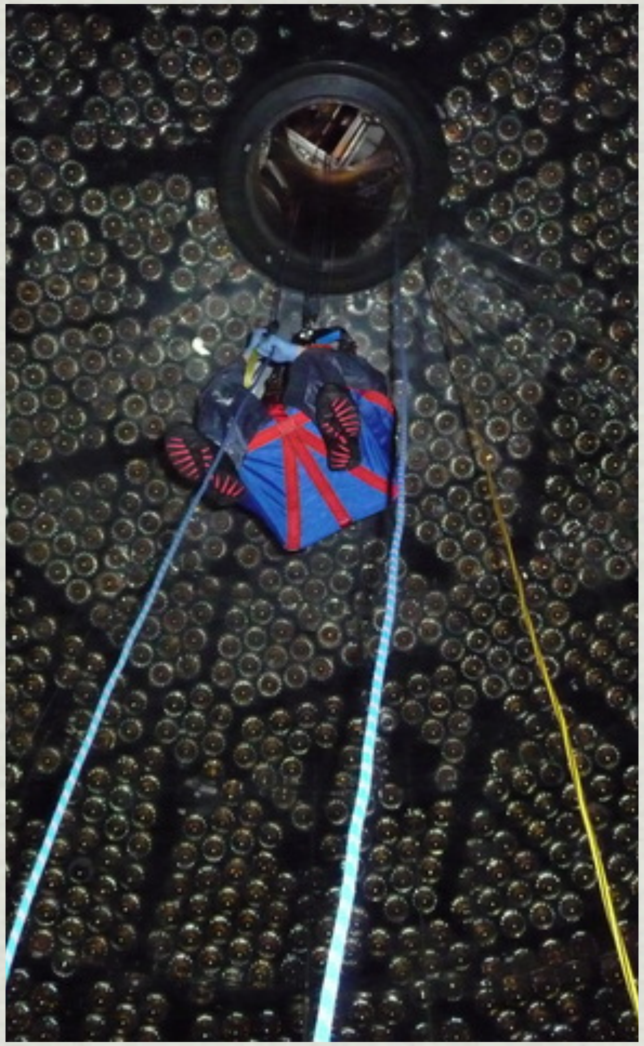






Timeline

- **2012**
  - Finish work in cavity
  - Process system construction
- **2013**
  - Water phase
  - Scintillator filling
- **2014**
  - Isotope introduced
  - First Neutrinoless Double-Beta Decay phase



After a successful first phase, demonstrating the technique, a second phase is planned to take the search down to 50 meV and beyond.

Under investigation, avenues that are being explored are:

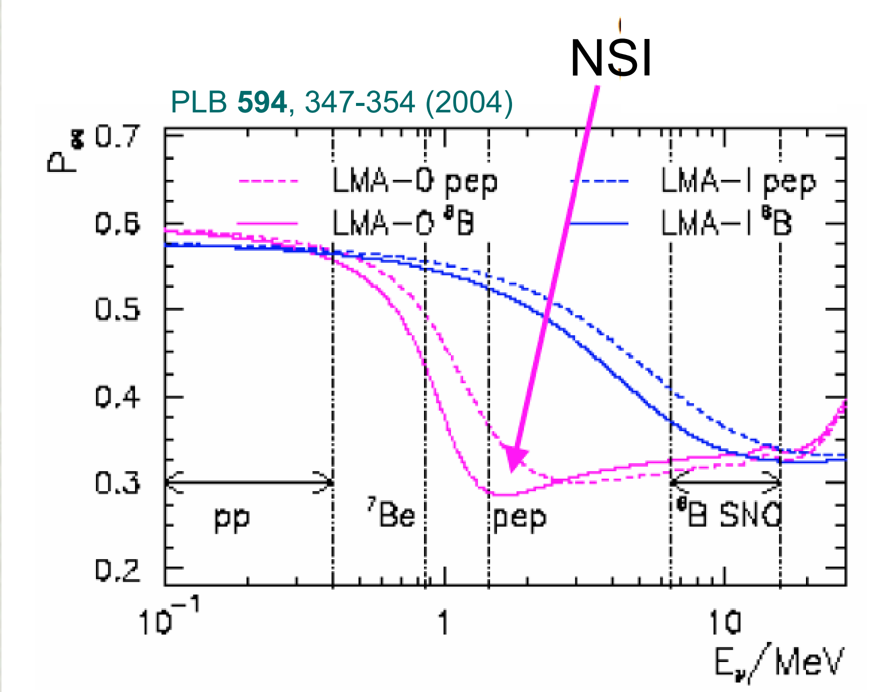
Further optimisations, enrichment of Nd, alternative (enriched) isotopes

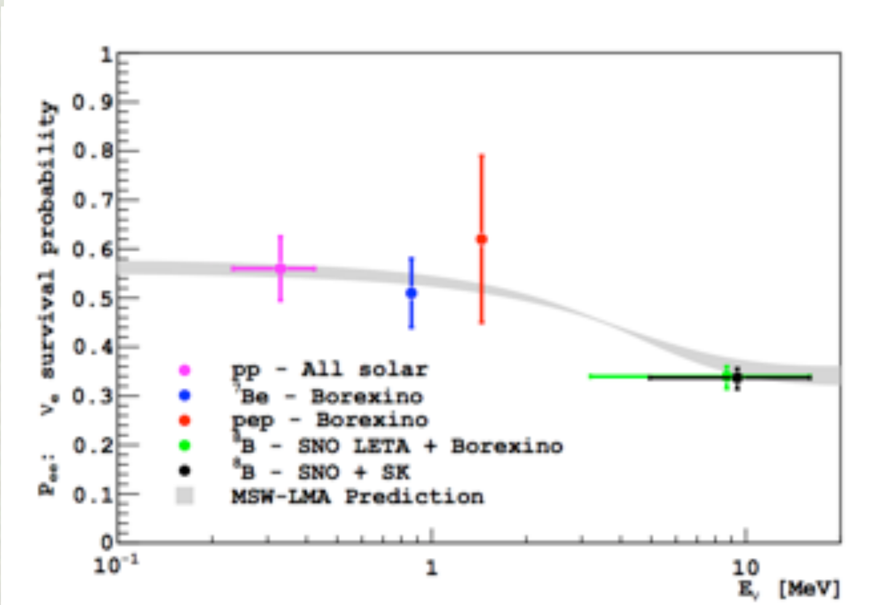
SNO+

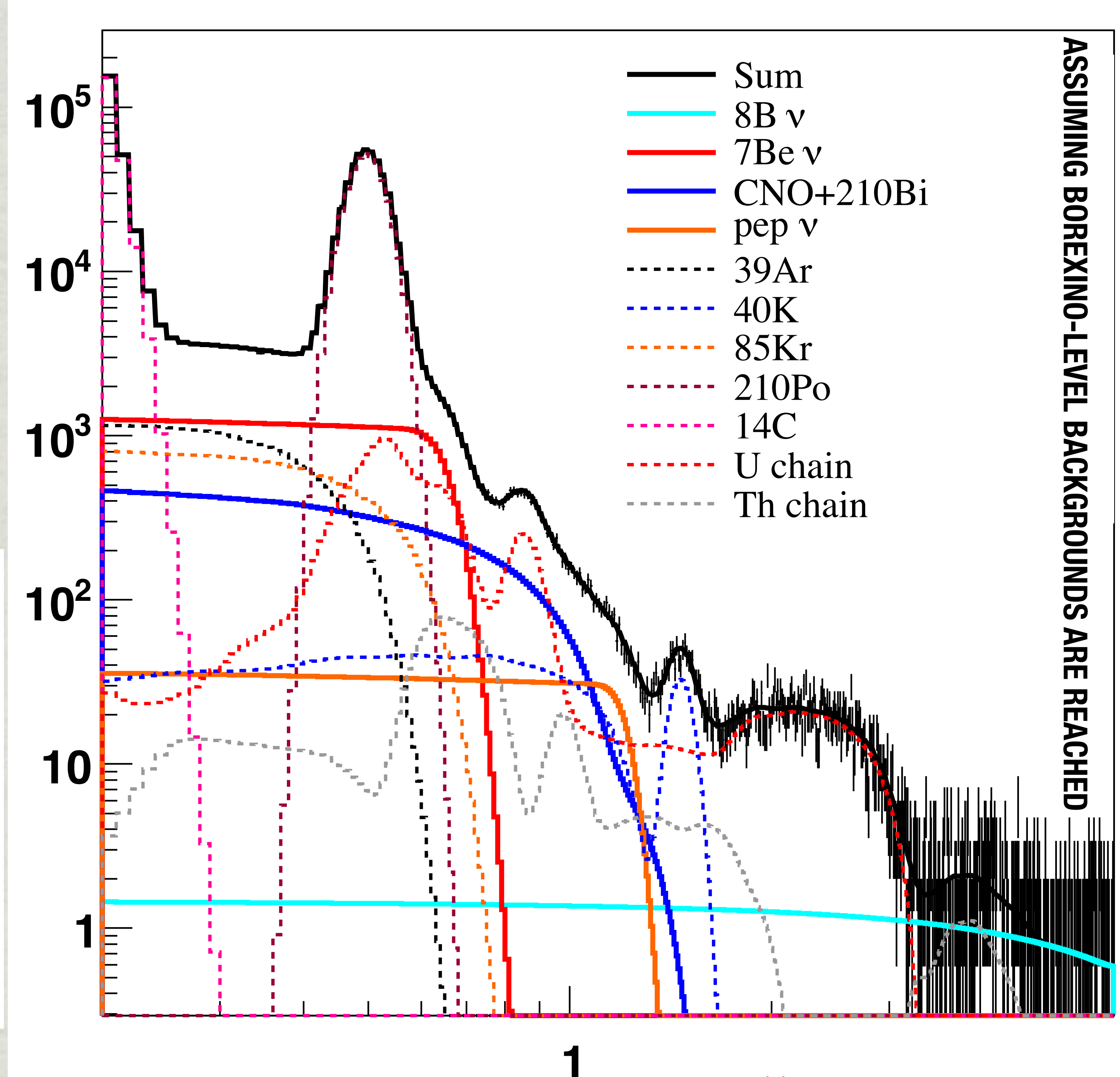
Solar neutrinos

Solar neutrinos

1 YR DATA
50% FIDUCIAL VOLUME





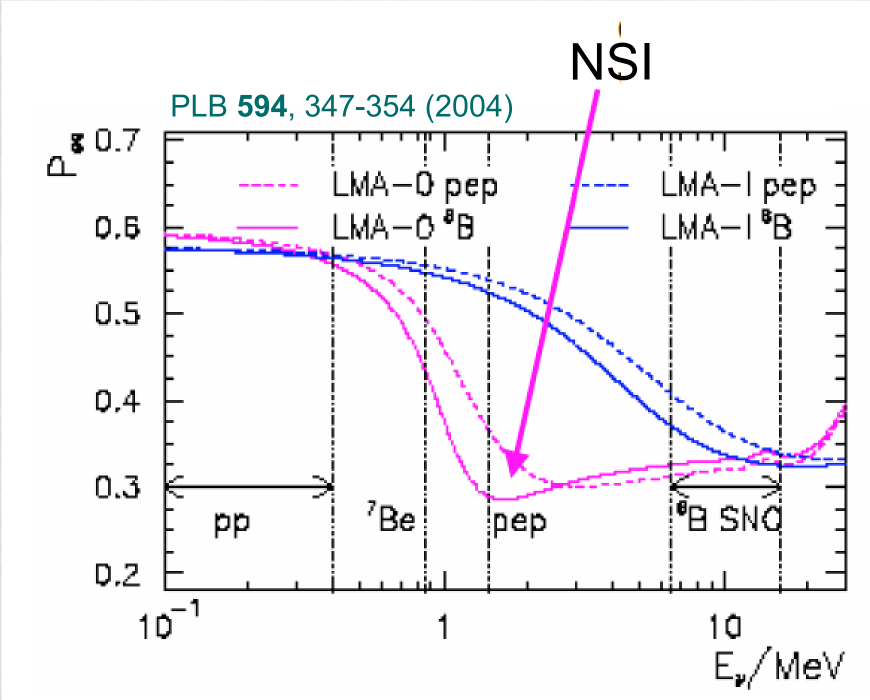


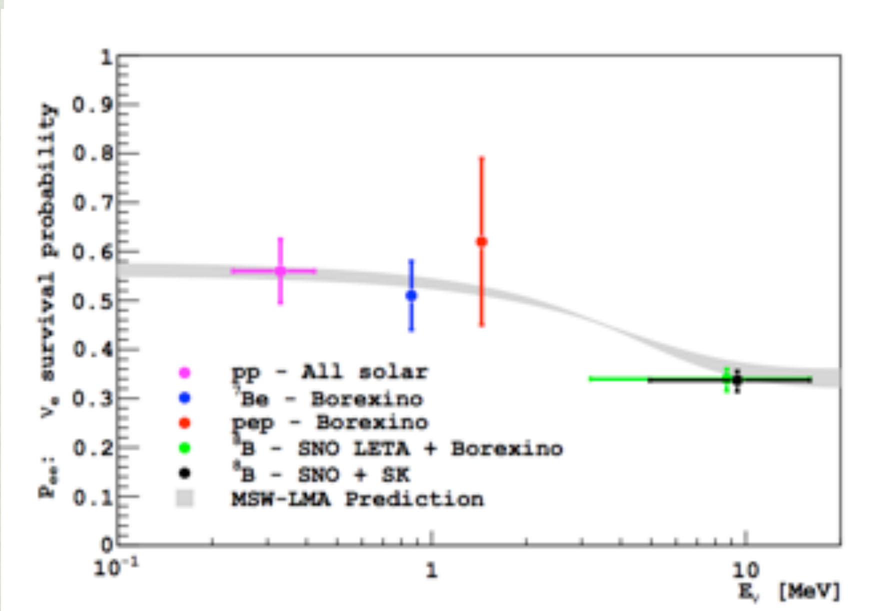
SNOLAB is very deep: very low muon flux, and thus insignificant ^{11}C background

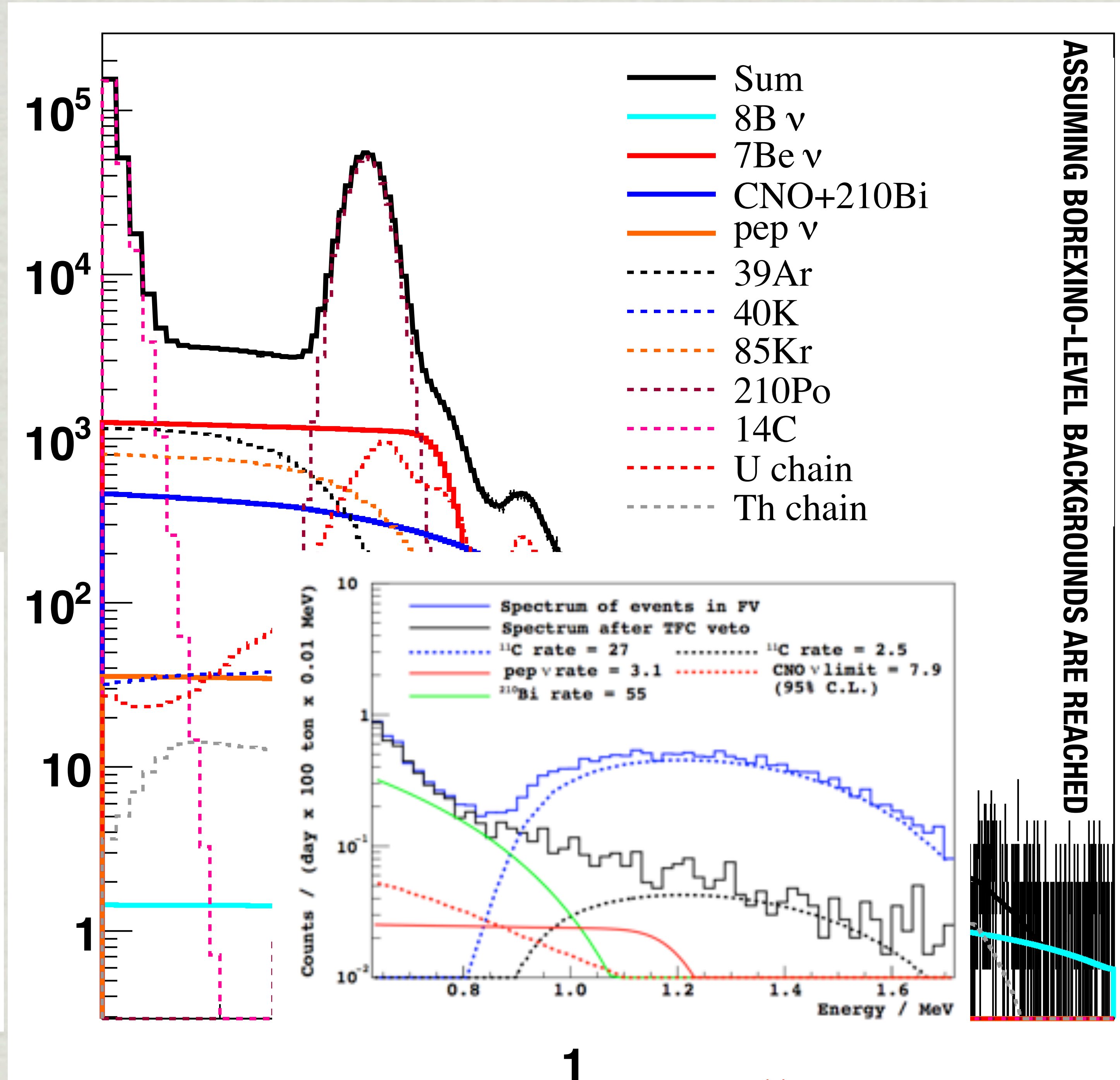
- Precise measurement of pep flux and improvement on θ_{12} measurement (future thoughts on intermediate baseline reactor experiments)
- CNO neutrinos - probe of metallicity problem
- Dark Matter and LBL experiments

Solar neutrinos

1 YR DATA
50% FIDUCIAL VOLUME







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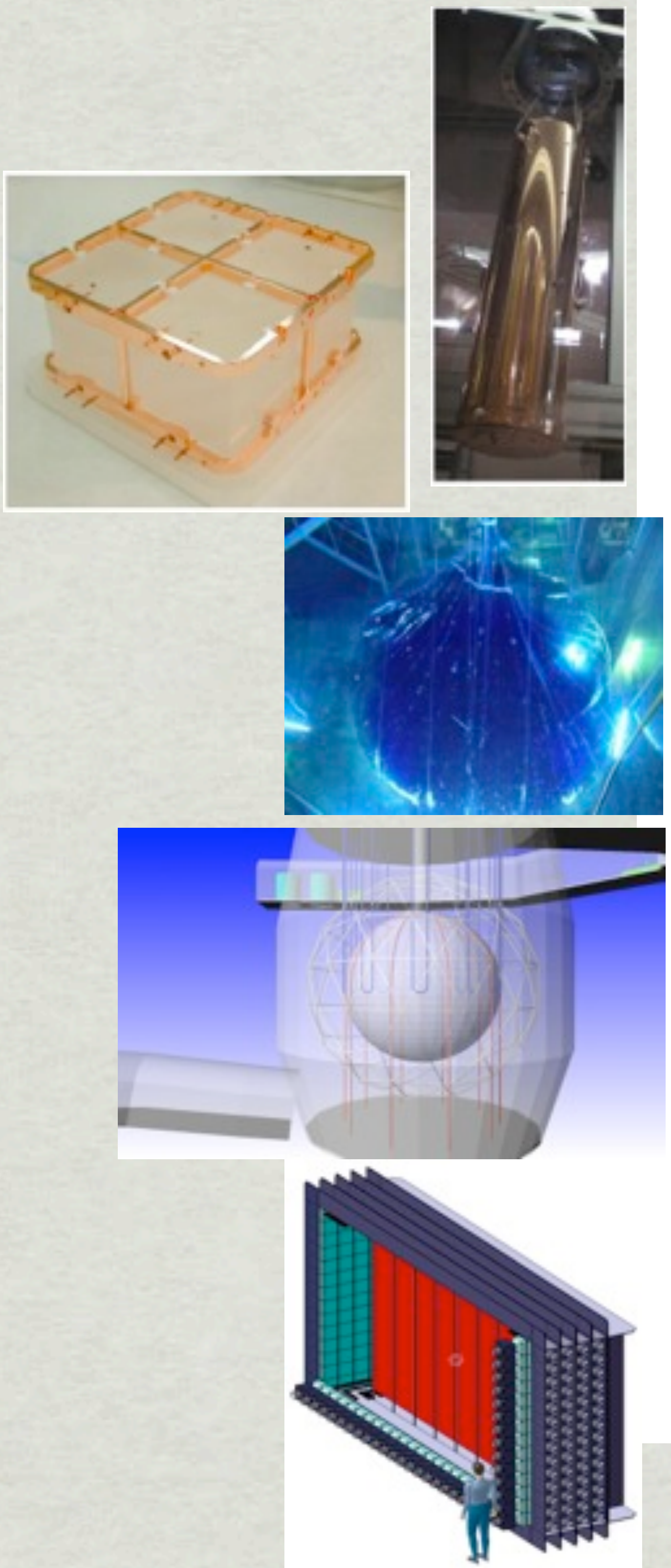
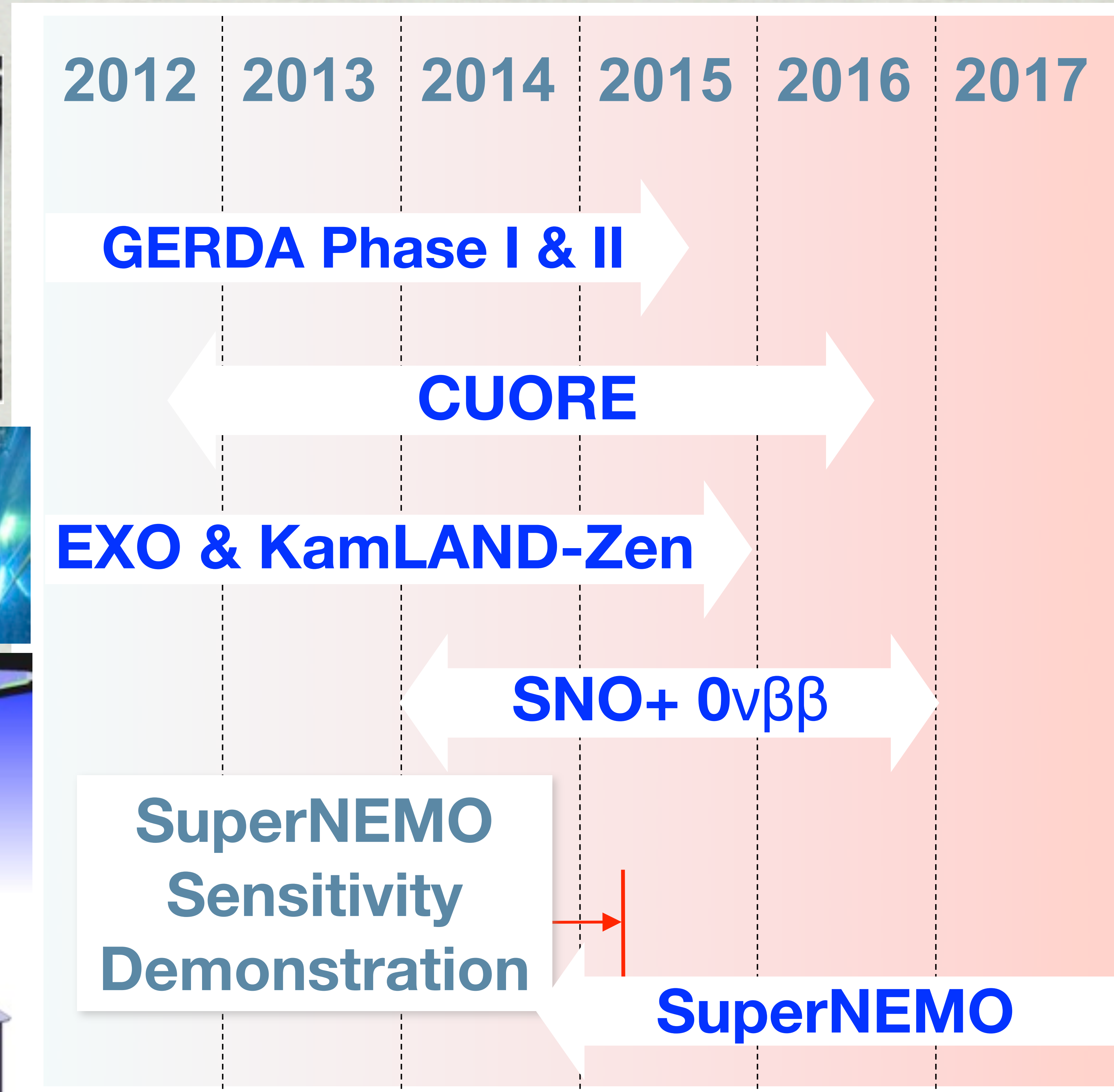
Conclusions

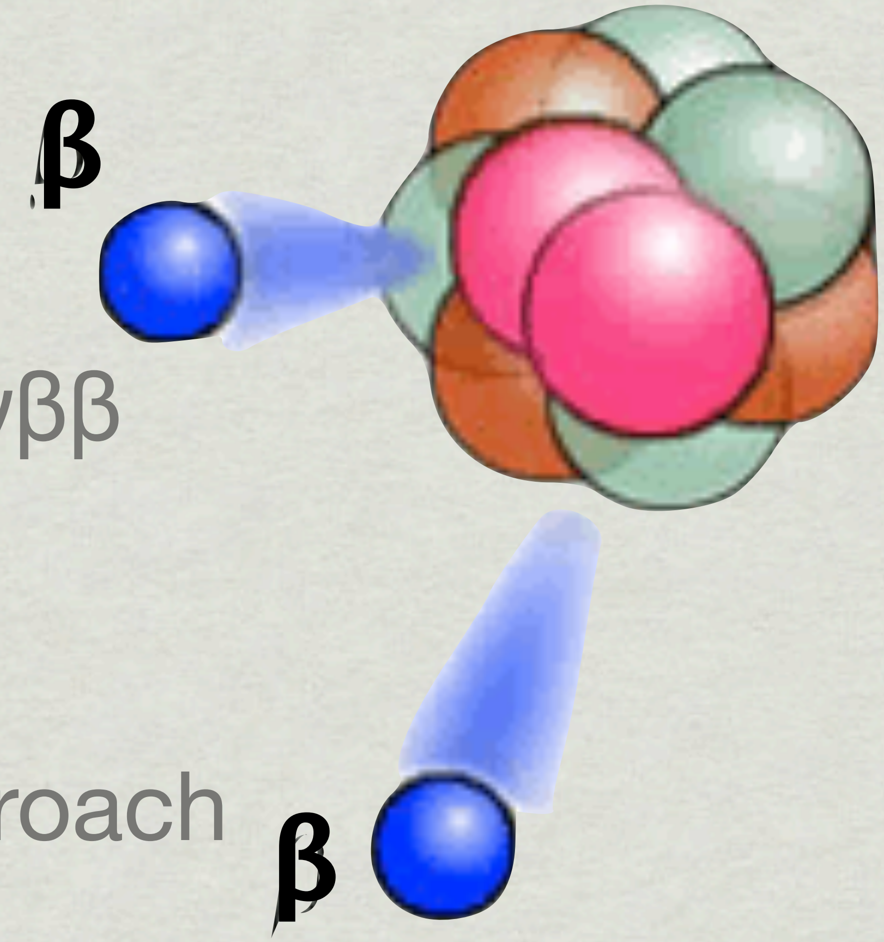
Major $0\nu\beta\beta$ Experiments and Timescales

- Currently running/planned experimental phases, reaching $\langle m_\nu \rangle$ ~100 meV :





Summary



- UK has a leading role in the two main experimental approaches in $0\nu\beta\beta$
  - SuperNEMO - improving NEMO3
  - SNO+ - promising innovative approach

    which should be maintained.
- Exciting times:
  ground breaking particle physics results could be around the corner
- Through SNO+, the UK continues to play a dominant role in solar neutrino physics