Neutrinoless Double-Beta Decay

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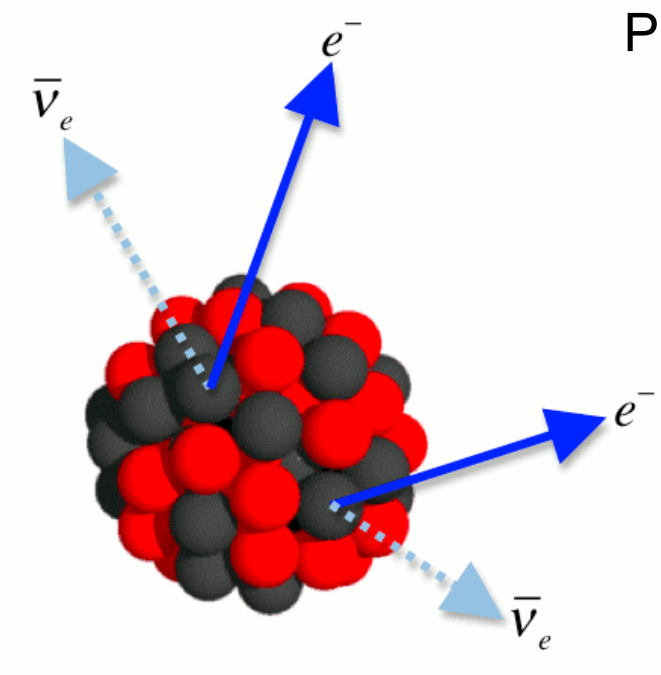
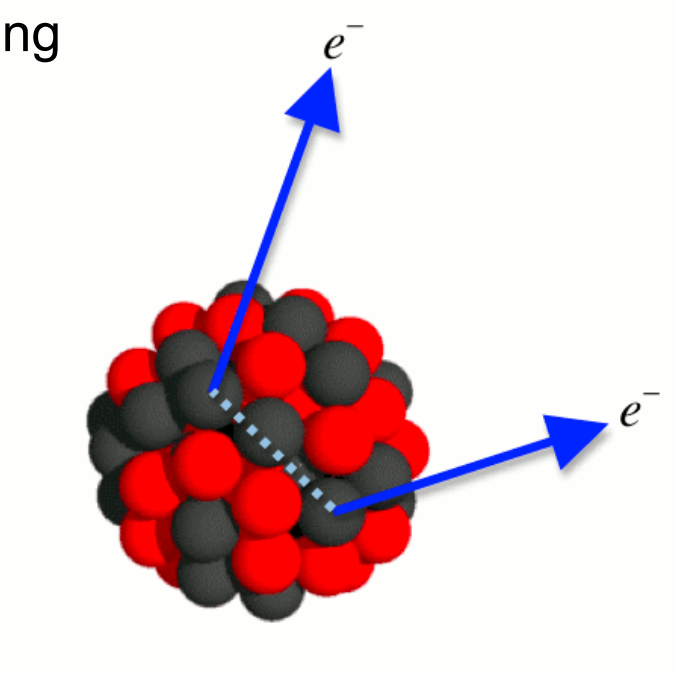
PPAP Community Meeting
RAL, 22nd July 2014



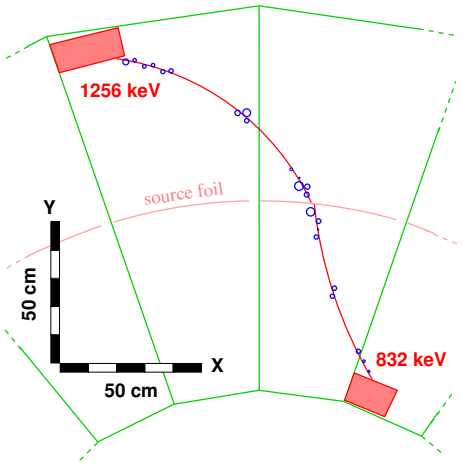


Why is it so Important ?

- **Nature of neutrinos** : Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}$)
  - ➡ See-saw mechanism, GUT scale physics, leptogenesis.
  - ➡ **0νββ is the only practical way of determining this.**

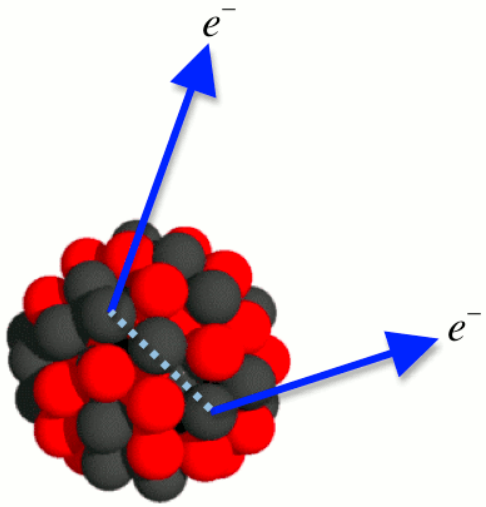
- **Absolute neutrino mass scale** : only limits so far :
  - ➡ $m_{\bar{\nu}_e} < 2.2$ eV (Tritium end-point)
  - ➡ $\Sigma m_{\nu_i} < 0.3$ eV (Cosmology)
  - ➡ **0νββ is the most sensitive (although not the most model-independent) technique.**

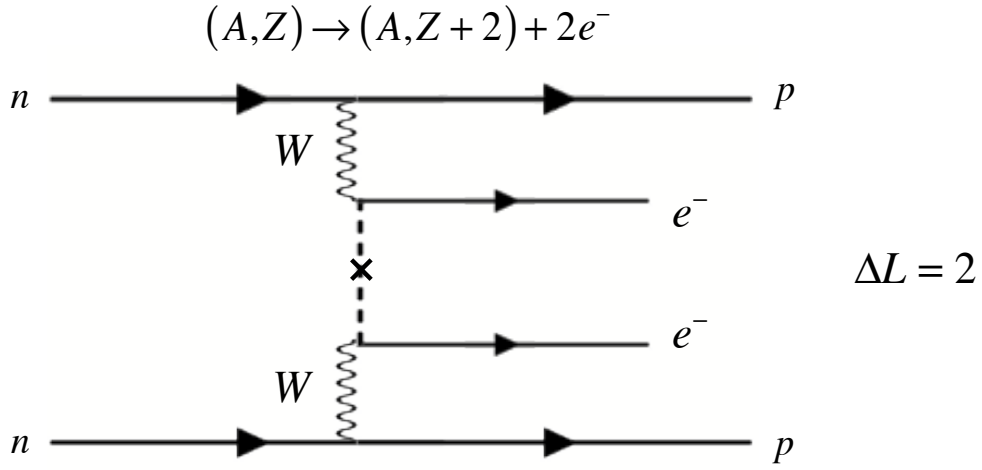
- **Leptonic CP-violation** :
  - ➡ Dirac phase (LBL)
  - ➡ Majorana phases : **0νββ is the only practical way of discovering these.**



What is Neutrinoless Double-Beta Decay ?

Neutrino-Antineutrino Transitions on Femtometre Baselines [Furry, 1939]





- Candidate isotopes have :
  - Single-β decay energetically forbidden or highly suppressed.
  - Large $Q_{\beta\beta}$-values (background separation).
  - Large natural abundance (or easily enriched).
  - Suitable physical properties (electrical, optical, mechanical, etc.)

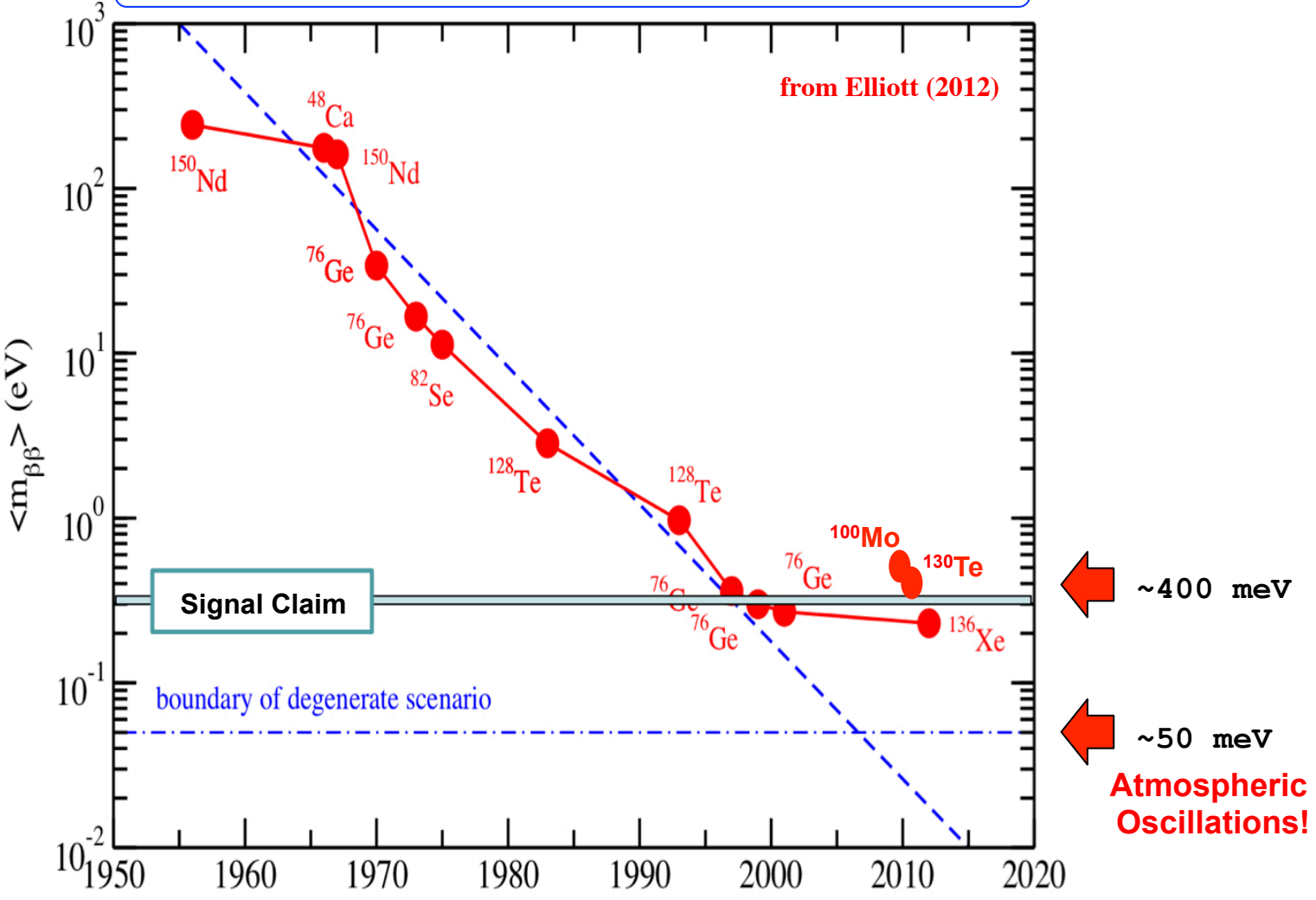
Isotope	$Q_{\beta\beta}$ (MeV)	Nat. Abund. (%)
^{48}Ca	4.272	0.187
^{76}Ge	2.039	7.8
^{82}Se	2.996	9.2
^{100}Mo	3.034	9.6
^{130}Te	2.528	34.5
^{136}Xe	2.459	8.9
^{150}Nd	3.371	5.6

The Historical Record

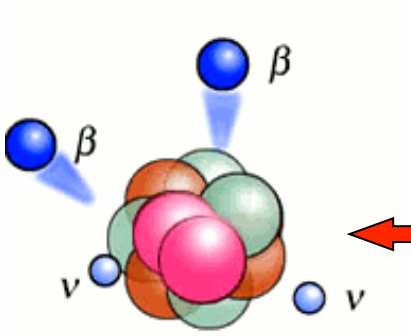
- 0νββ experiments constrain an effective neutrino mass (coherent sum over mass eigenstates)

$$\left\langle m_{\beta\beta} \right\rangle = \left| \sum U_{ei}^2 m_i \right| = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}} \right|$$

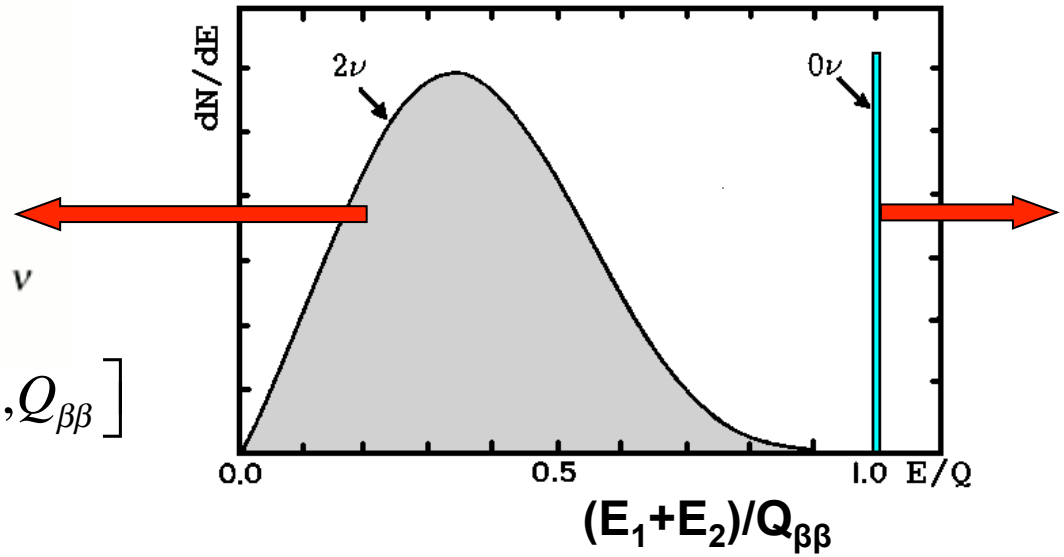
α_{21}, α_{31} = Majorana phases

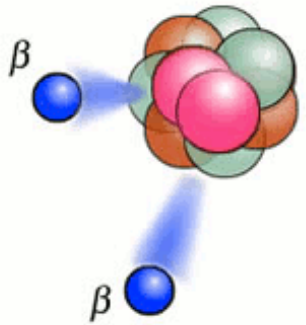


How To Build a ββ-Experiment



$(E_1 + E_2) \in [0, Q_{\beta\beta}]$

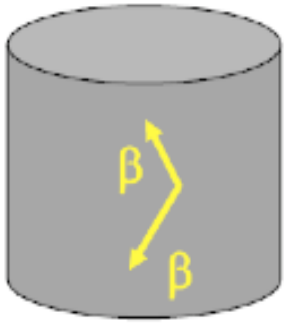




$(E_1 + E_2)/Q_{\beta\beta} \approx 1$

[⊗ resolution]

Homogenous "source = detector"



Semi-conductor, bolometer, LS.

Excellent ΔE/E Possible

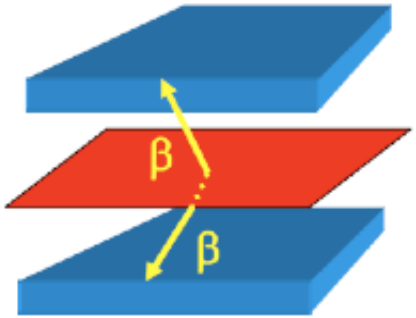
Large Masses Possible

Elements of Both

Gaseous Xe TPC

Pixelated CdZnTe

Heterogenous "source ≠ detector"



Tracking

Full event topology

Can probe different mechanisms

How To Build a ββ-Experiment

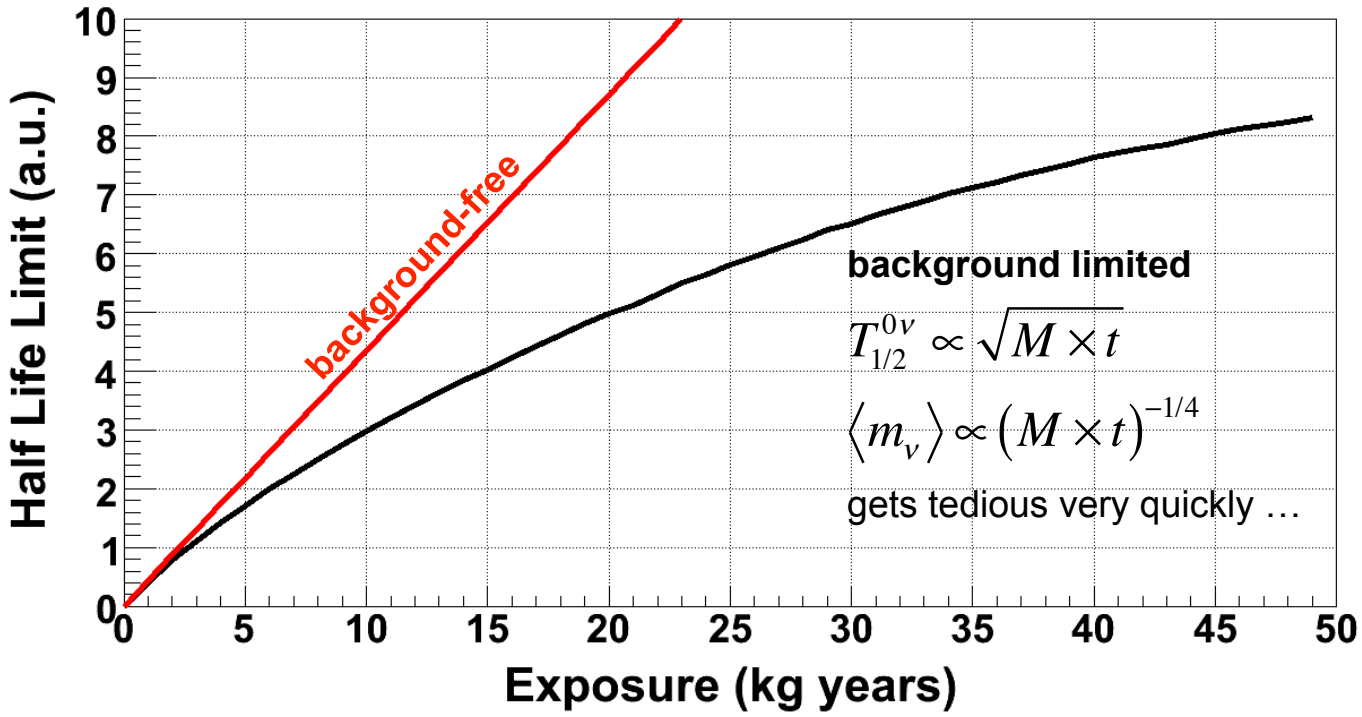
maximise efficiency (ε) & isotope abundance (*a*)

maximise exposure = mass (*M*) × time (*t*)

$$T_{1/2}^{0\nu}(90\%\ \text{C.L.}) = 2.54\times10^{26}\,\text{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

W = atomic weight

minimise background (*b*) & energy resolution (Δ*E*)



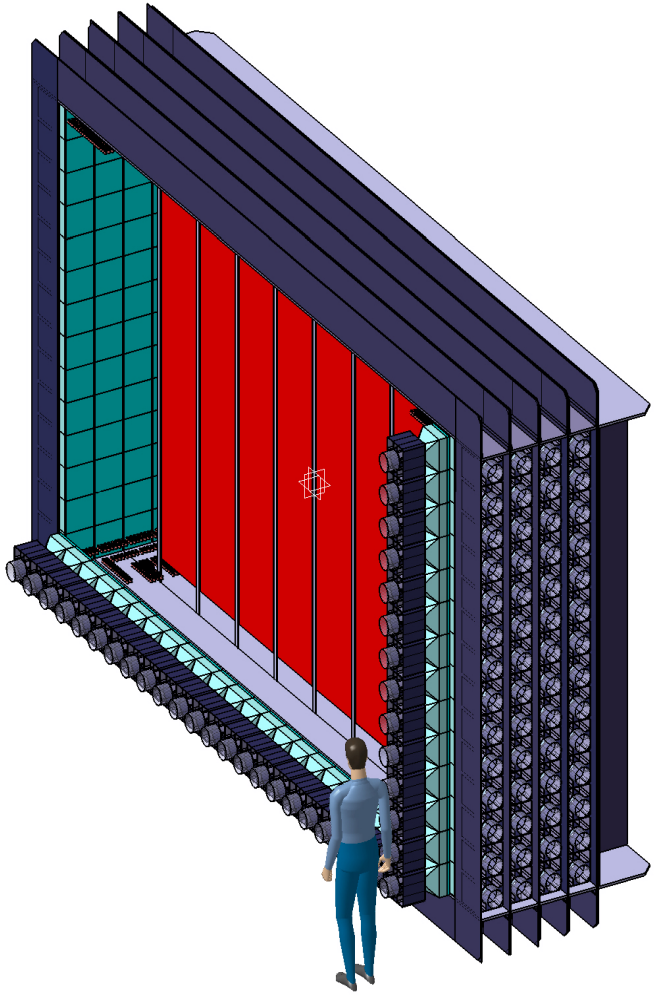
It's All About Backgrounds

SuperNEMO Demonstrator Module

20 tons

1000 radon atoms in the tracker

1 decay every ~10 minutes



Brazil Nut

4 grams

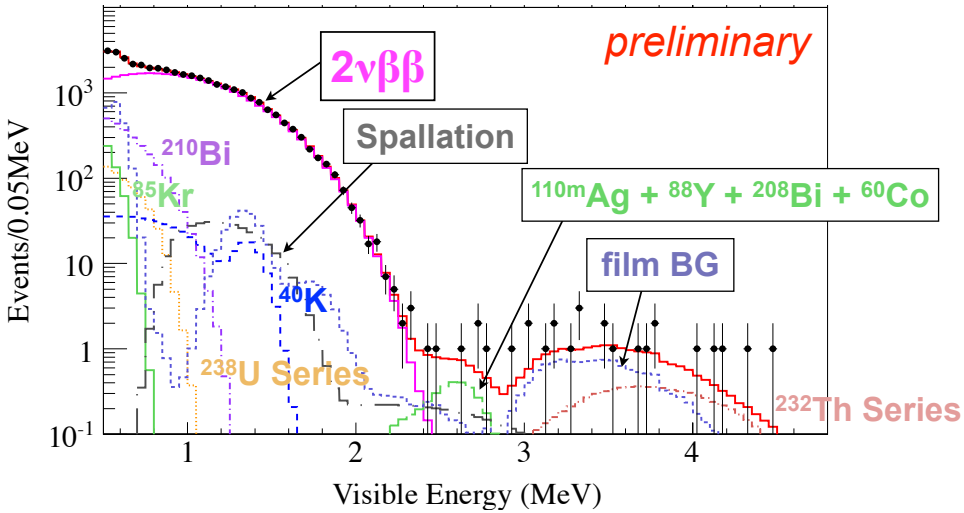
200,000 radon atoms

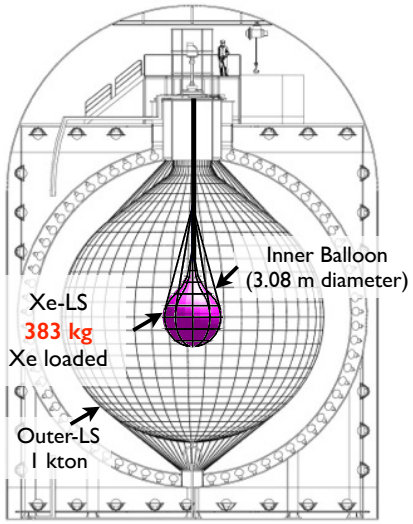
1 decay every ~2 seconds

- Cosmic rays. Work in underground labs (1000's m.w.e.)
- Naturally occurring radioactivity present in all materials :
  - **$T_{1/2}(^{232}Th,^{238}U) \sim 10^{10}$ years**
  - **$T_{1/2}(0\nu\beta\beta) > 10^{25}$ years**
- Background from $2\nu\beta\beta$: resolution and isotope choice.

^{136}Xe Experiments: EXO and KamLAND-Zen

KamLAND-Zen





~ 130 kg.yr

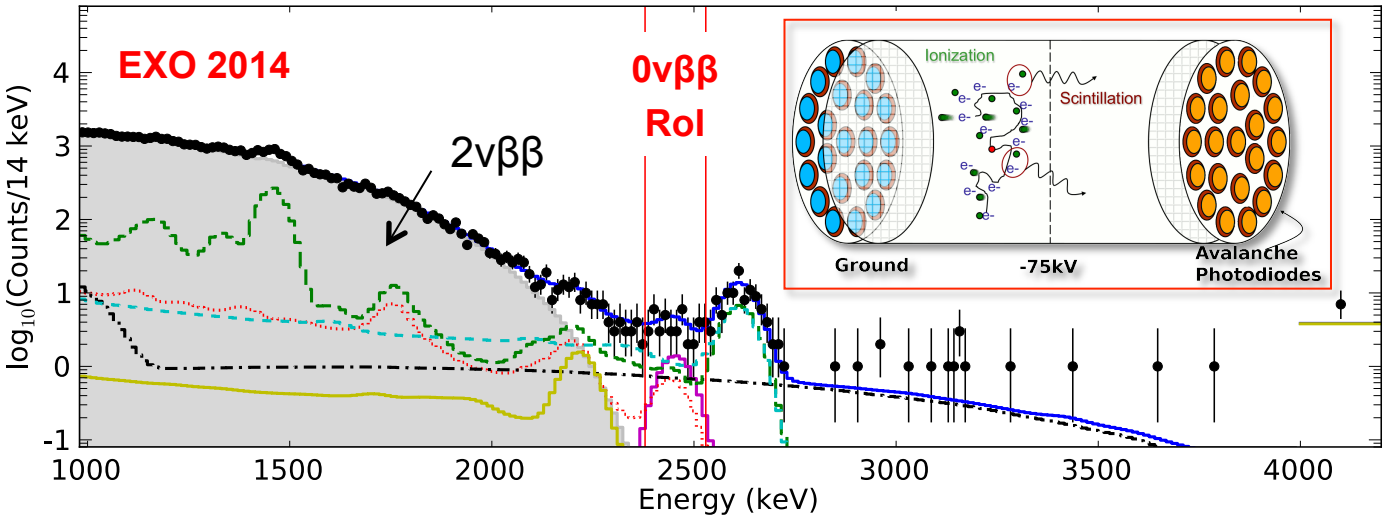
$T_{1/2}^{0\nu\beta\beta} > 2.6\times10^{25}$ yr

(90% C.L.)

$\langle m_\nu \rangle < 140 - 280$ meV

- Currently the best 0νββ limits.
- Background limited ?

Enriched Xenon Observatory



99.8 kg.yr

$T_{1/2}^{0\nu\beta\beta} > 1.1\times10^{25}$ yr

(90% C.L.)

$\langle m_\nu \rangle < 190 - 450$ meV

UK Strategy

Largest Isotope Mass

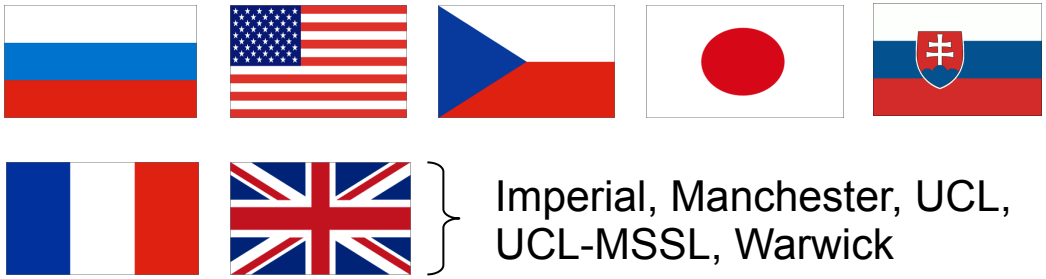
SNO+

Lowest Background

supernemo

Overview of SuperNEMO

supernemo collaboration



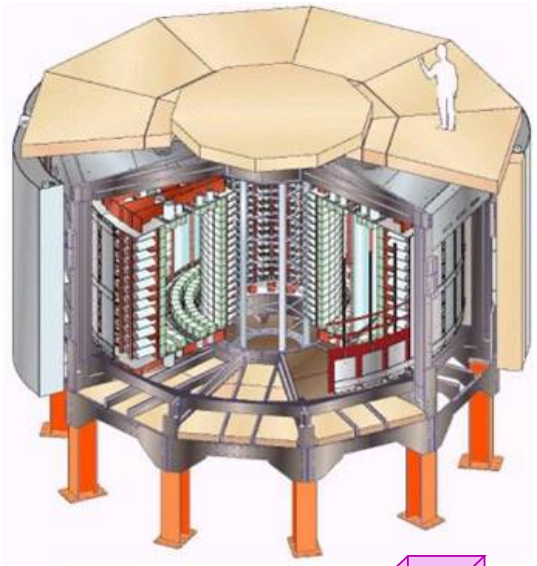
Imperial, Manchester, UCL, UCL-MSSL, Warwick

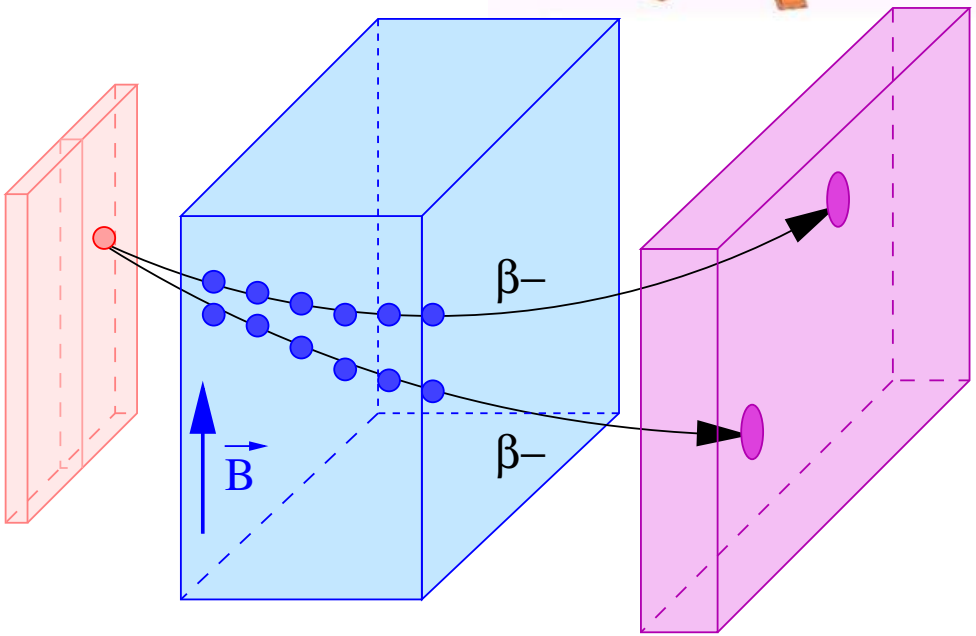
The goals of SuperNEMO :

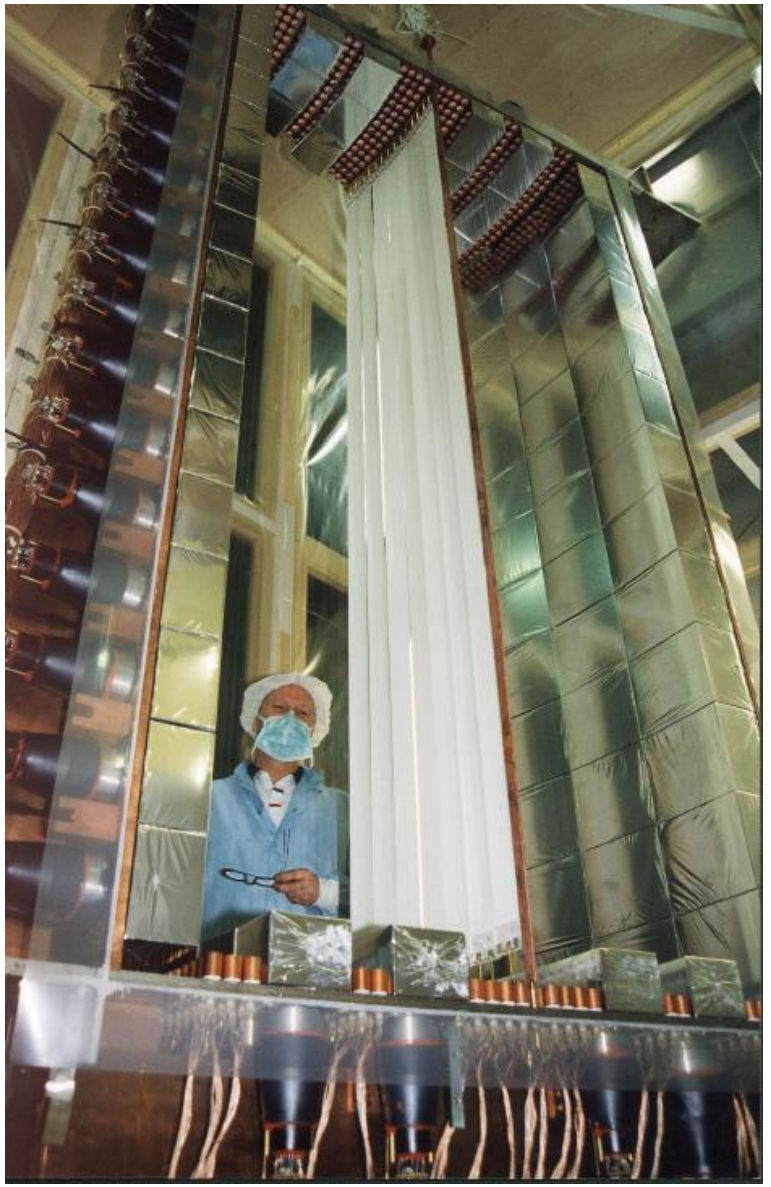
1. Build on the experience of the extremely successful NEMO-3 experiment.
2. Use the power of the tracking-calorimeter approach to identify and suppress backgrounds. This will yield a zero-background experiment in the first (Demonstrator Module) phase.
3. Prove that a 100 kg scale experiment can reach the inverted mass hierarchy (~50 meV) domain.
4. In the event of a discovery by any of the next-generation experiments, demonstrate that the tracking-calorimeter approach is by far the best one for characterising the mechanism of $0\nu\beta\beta$ decay.

NEMO-3 Overview

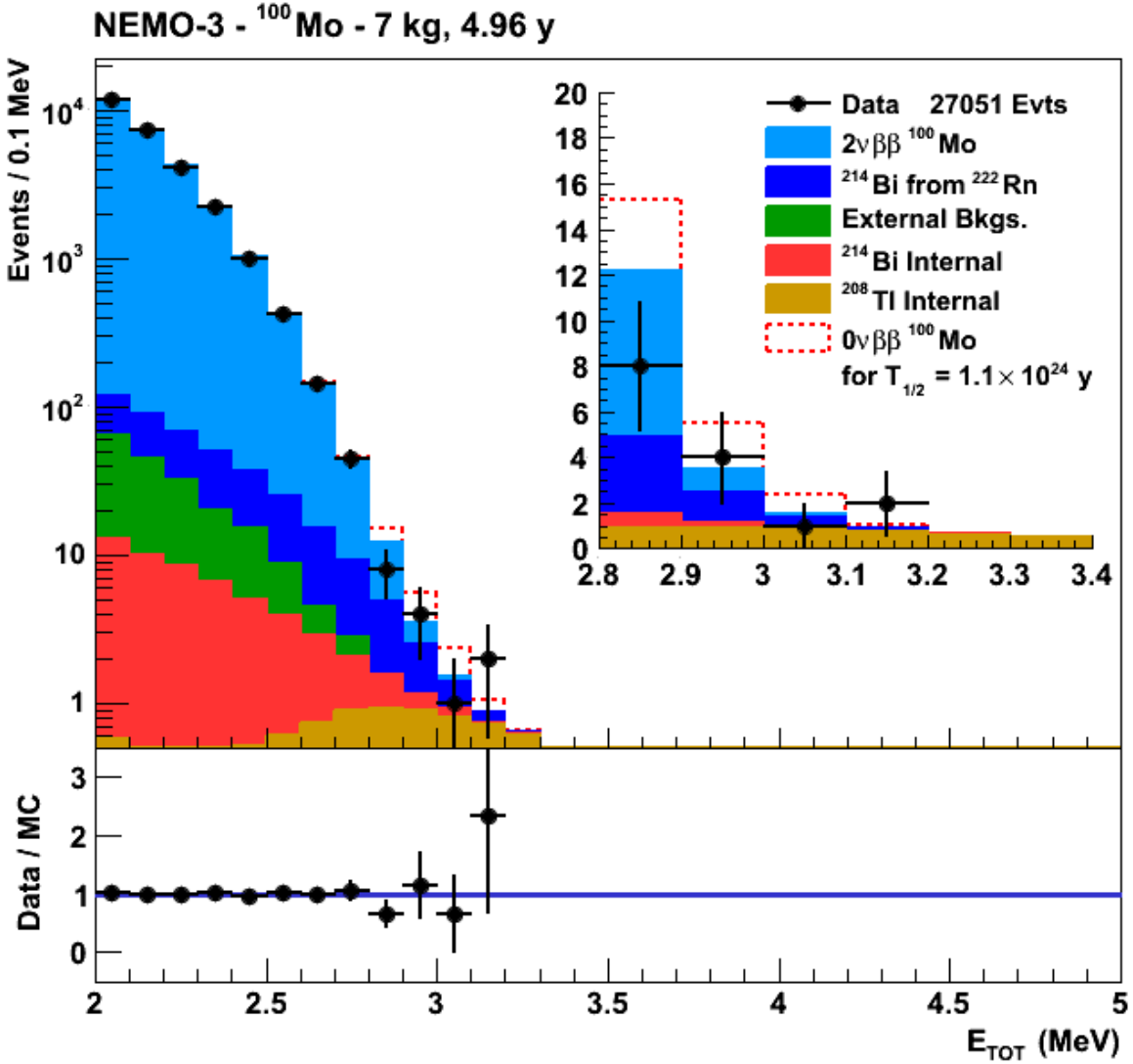
- Tracking-calorimeter detector.
- Situated in Laboratoire Souterrain de Modane (LSM) : 4800 M.W.E.
- Ran from 2003 – 2011
- Decommissioned to make space for the Demonstrator Module







0νββ Search with NEMO-3



New !

Final results with ^{100}Mo

- Updates to background model and analysis techniques.
- Half-life limit from fit to E_{TOT} distribution :

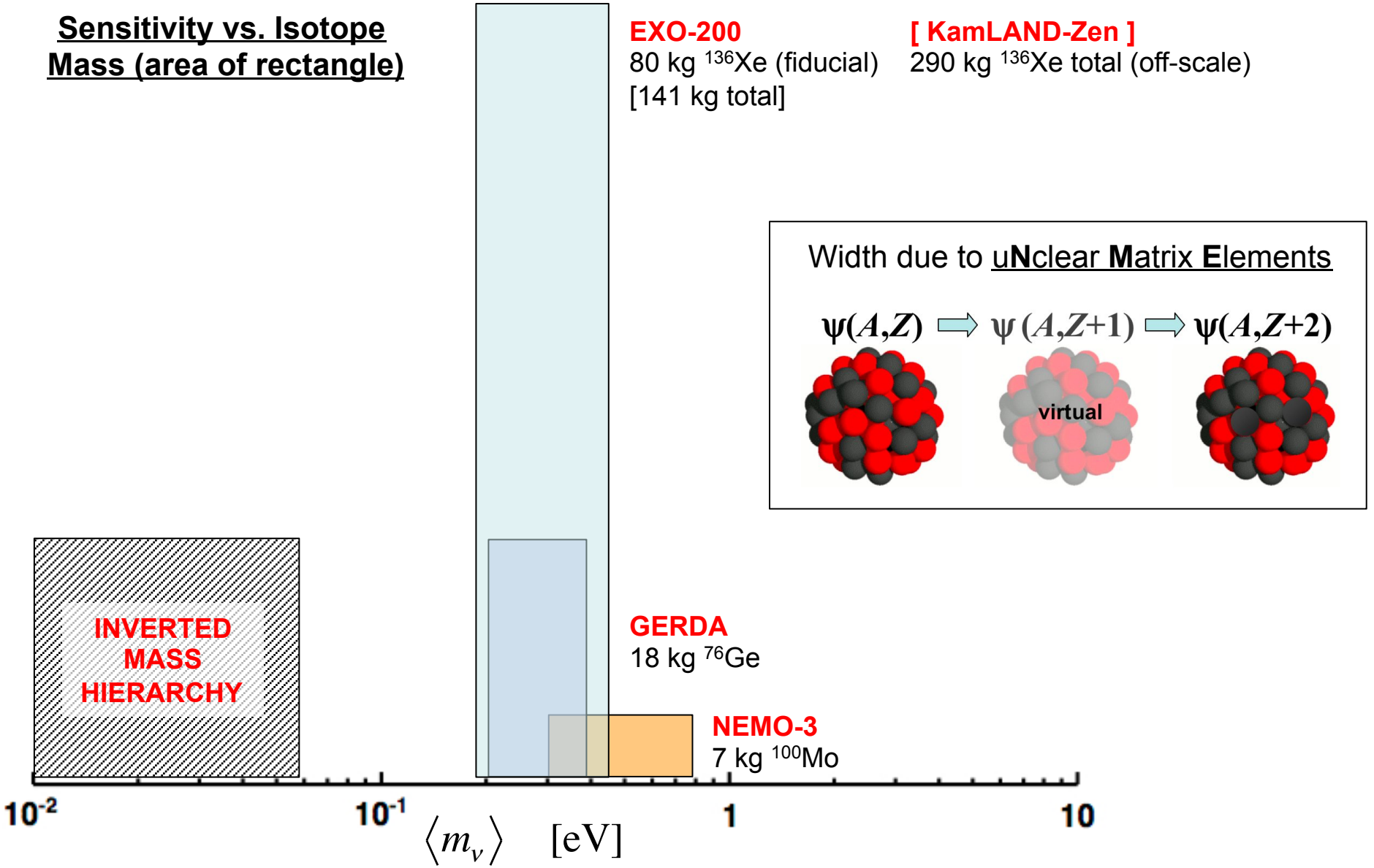
$$T_{1/2}^{0\nu\beta\beta} > 1.1\times10^{24} \text{ yr (90\% C.L.)}$$

- For the Majorana mass mechanism this equates to :

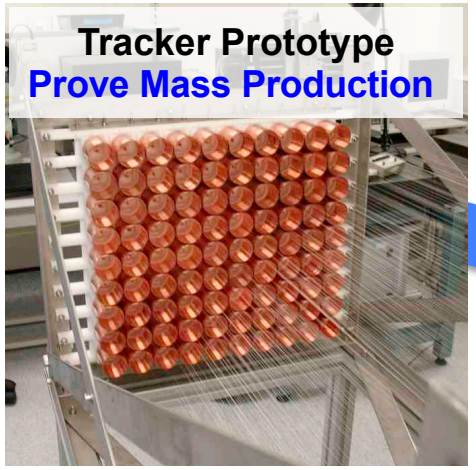
$$\langle m_\nu \rangle < 0.3 - 0.8 \text{ eV}$$

- Also limits on RHC, $\not{R}_P$ SUSY etc.

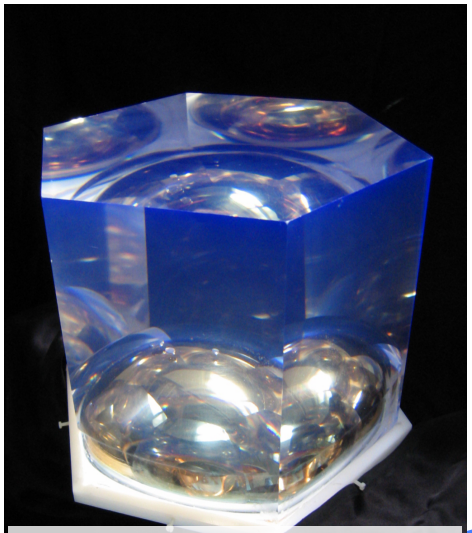
World's Best Limits



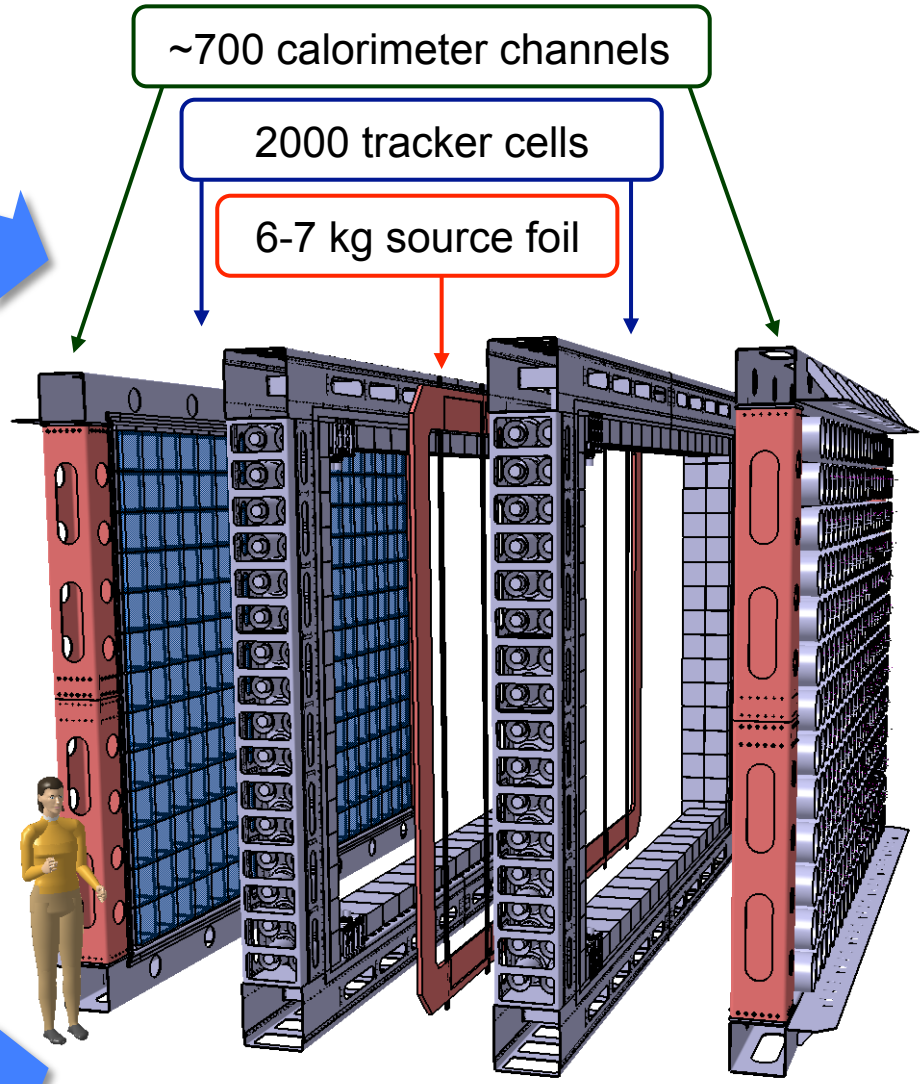
SuperNEMO Demonstrator Module : Overview



Tracker Prototype
Prove Mass Production



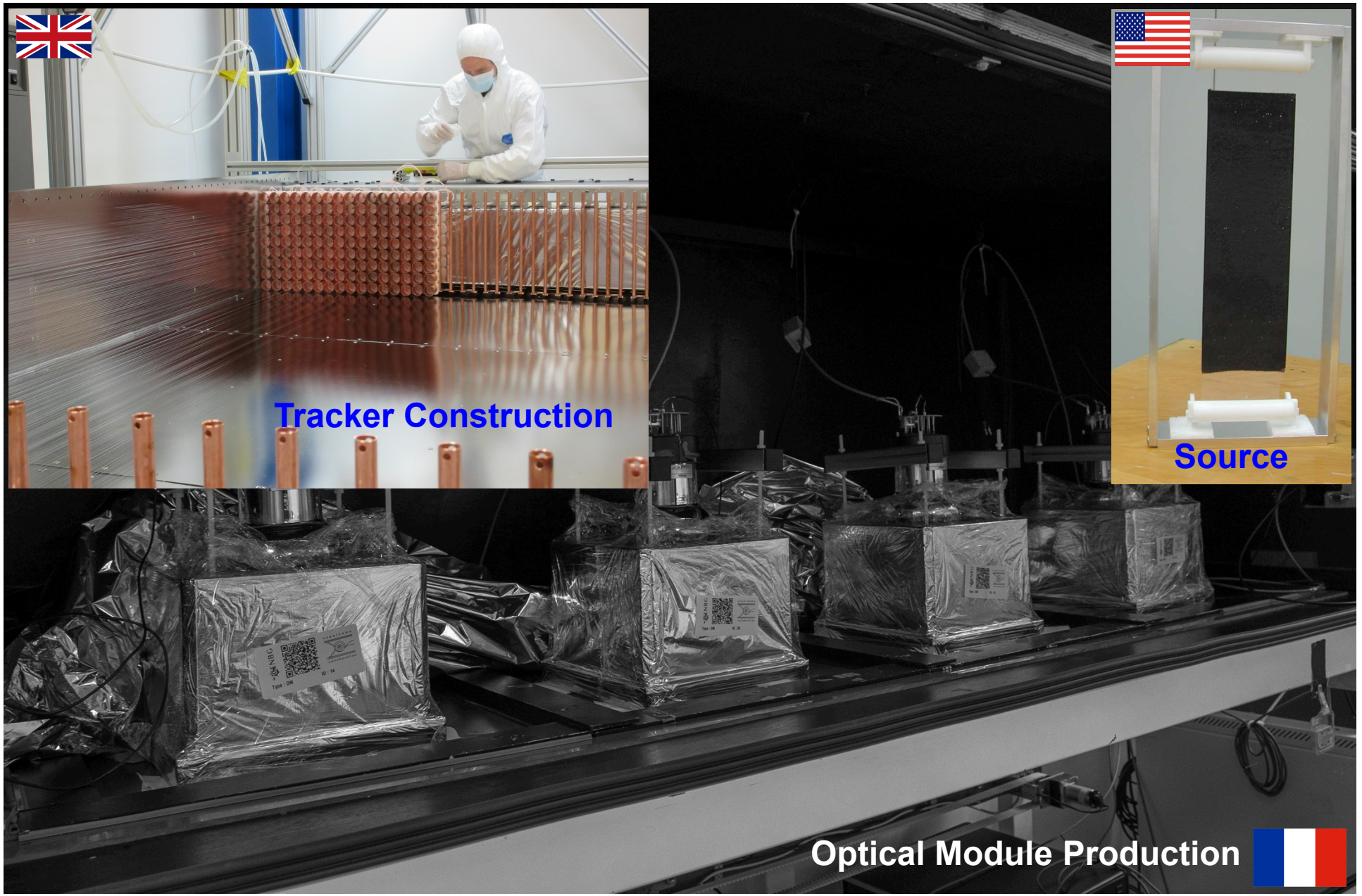
Calorimeter R&D
Demonstrate
FWHM~7% @ 1 MeV



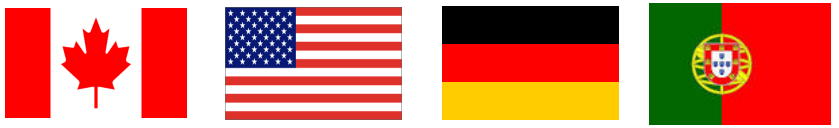
Demonstrator Module

- Change isotope $^{100}Mo \rightarrow {}^{82}Se$ (longer $T_{1/2}^{2\nu\beta\beta}$)
- ^{214}Bi and radon reduced by a factor of 30.
- ^{208}Tl reduced by a factor of 50.
- Halve the calorimeter resolution to 4% at $Q_{\beta\beta}$.
- Improved efficiency, calibration etc.

SuperNEMO Construction Progress



SNO+



Oxford, Sussex, QMUL,
Liverpool, Sheffield, Lancaster

The goals of SNO+ :

1. Cost-effective repurposing of SNO as a giant liquid-scintillator detector.
2. Pursue a broad physics programme of 0νββ, solar neutrinos, geo-neutrinos and SN.
3. Load the liquid scintillator with O(1 tonne) of isotope.
4. Have sensitivity to the inverted mass hierarchy region on a competitive timescale.

SNO+

Acrylic vessel (AV)
12 m diameter

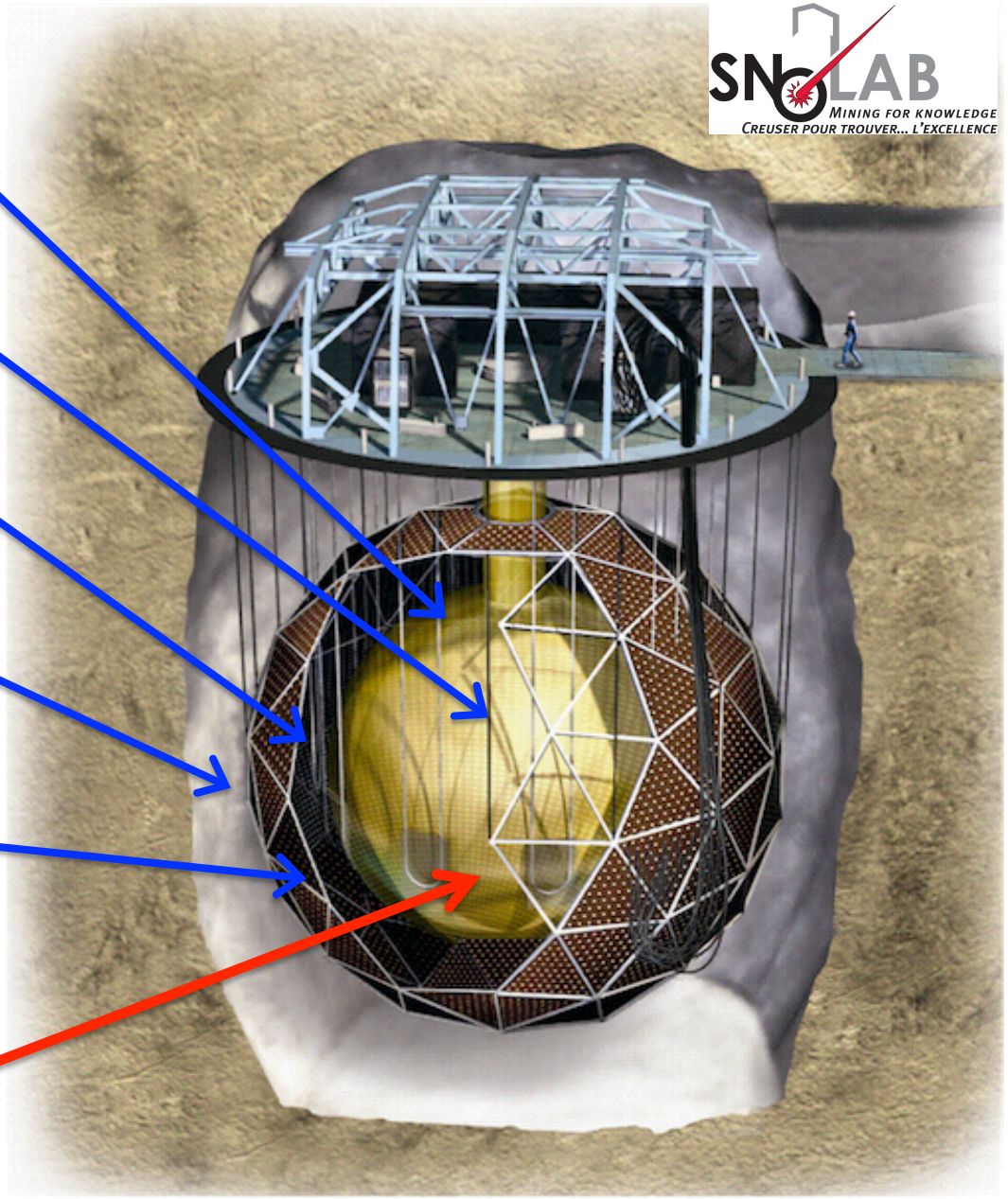
780 tonnes of LAB LS
Borexino & KamLAND-Zen have shown that LS can be extremely pure.

1700 tonnes H_20
inner shielding

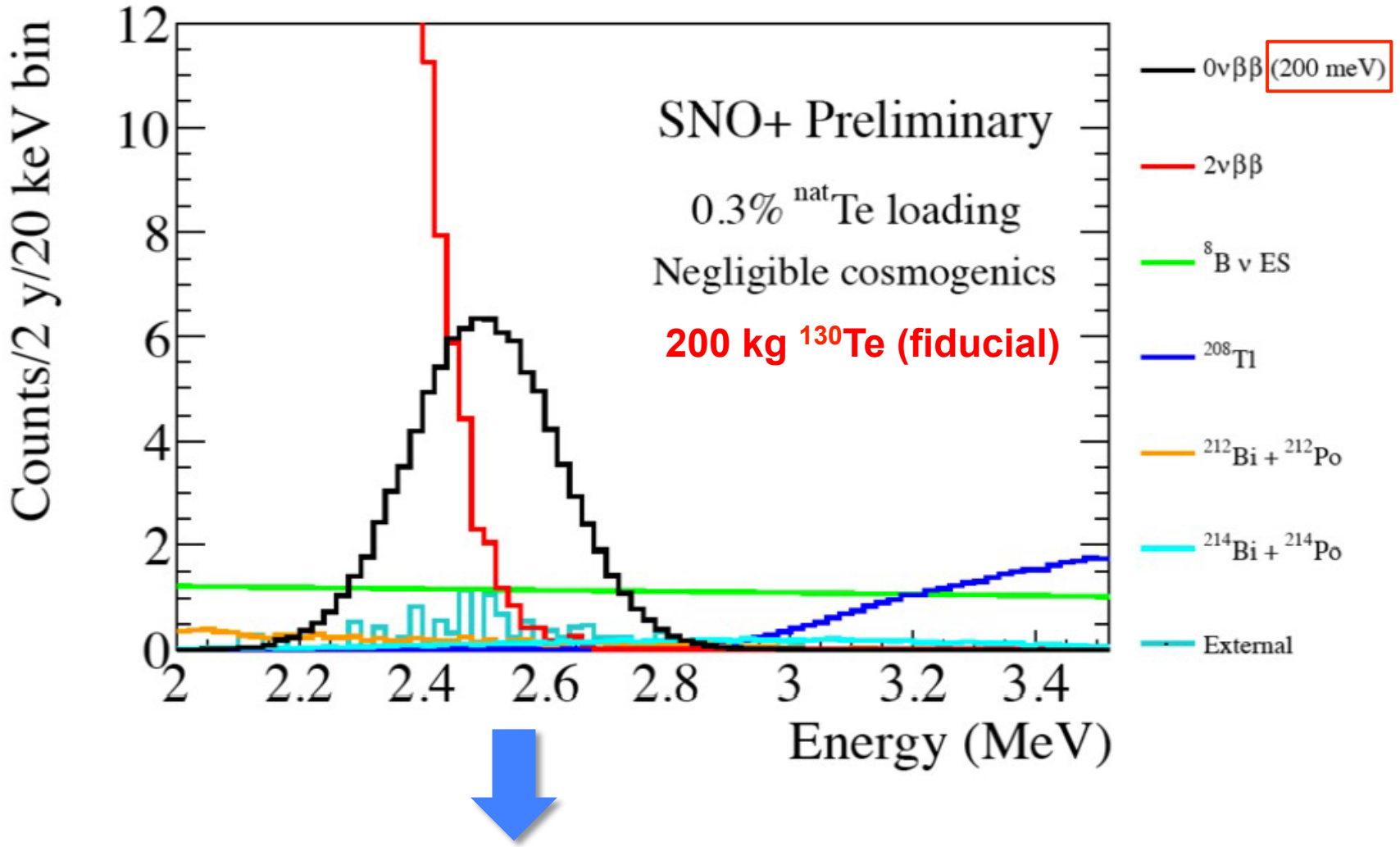
5700 tonnes H_20
outer shielding

~9500 PMTs

O(tonne) 0νββ isotope
Flexibility regarding choice of isotope and loading fraction



SNO+ : Basic Idea

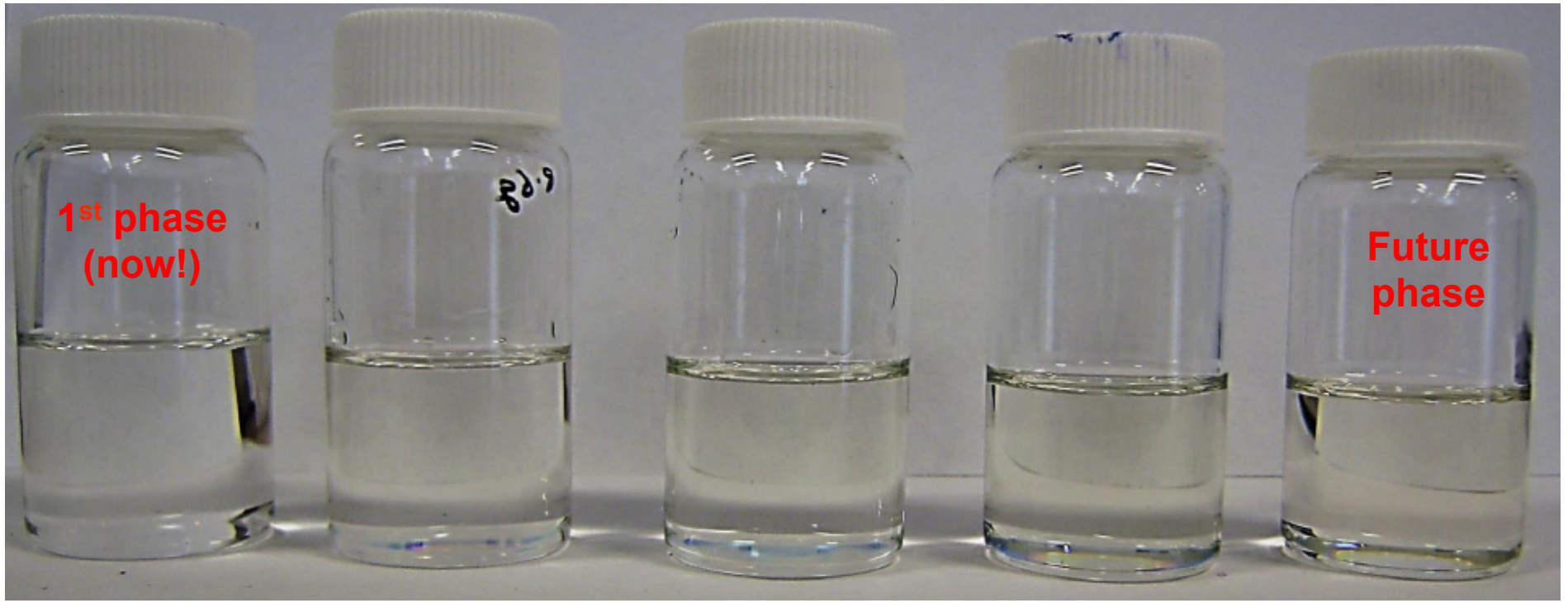


- Compensate modest resolution with large isotope mass.
- Increase loading fraction to reduce background index.

SNO+ : Future

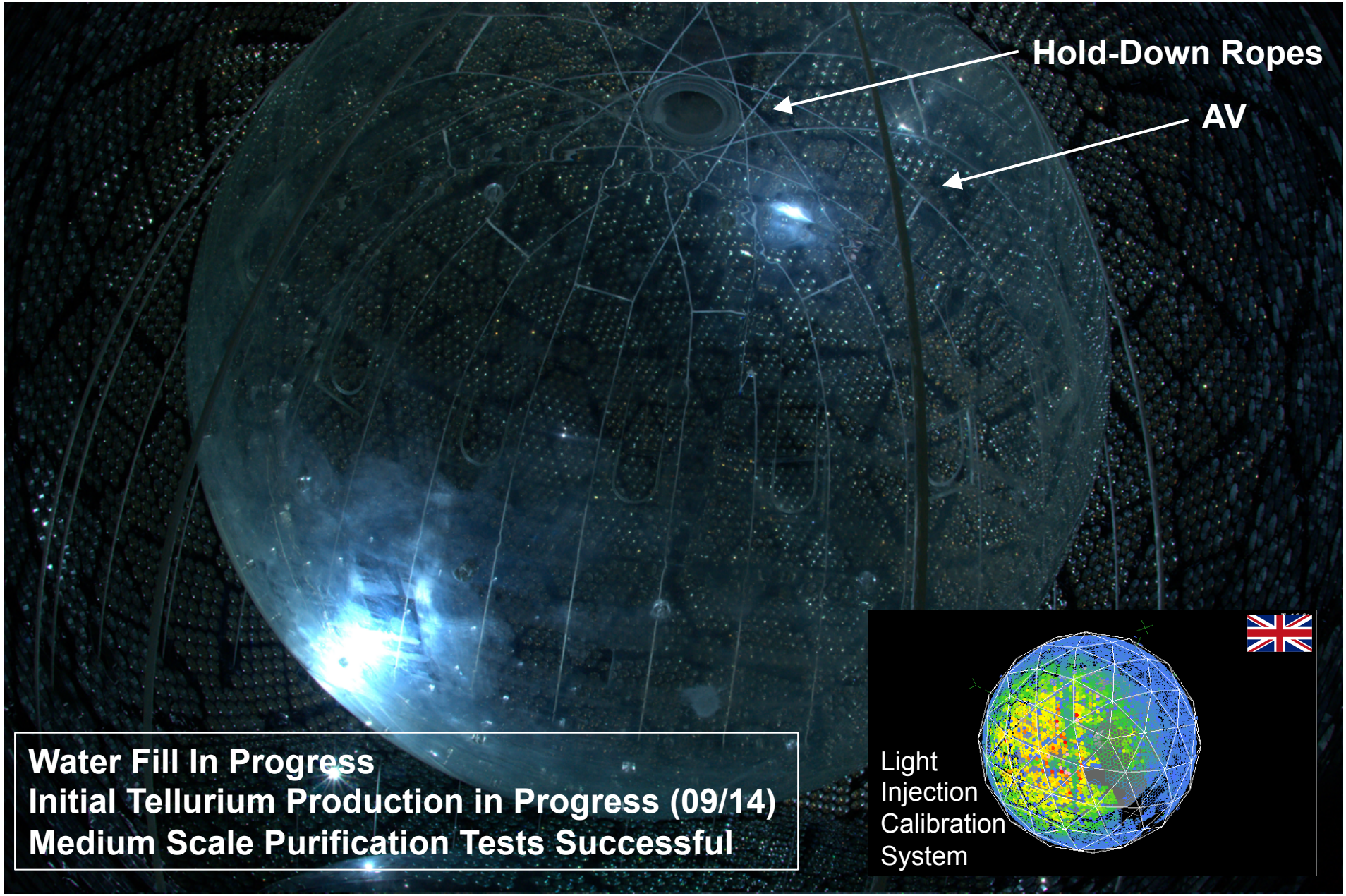
Higher Loading Fractions :

- Multi-tonne isotope mass.
- Studies ongoing to confirm no degradation of optical properties.

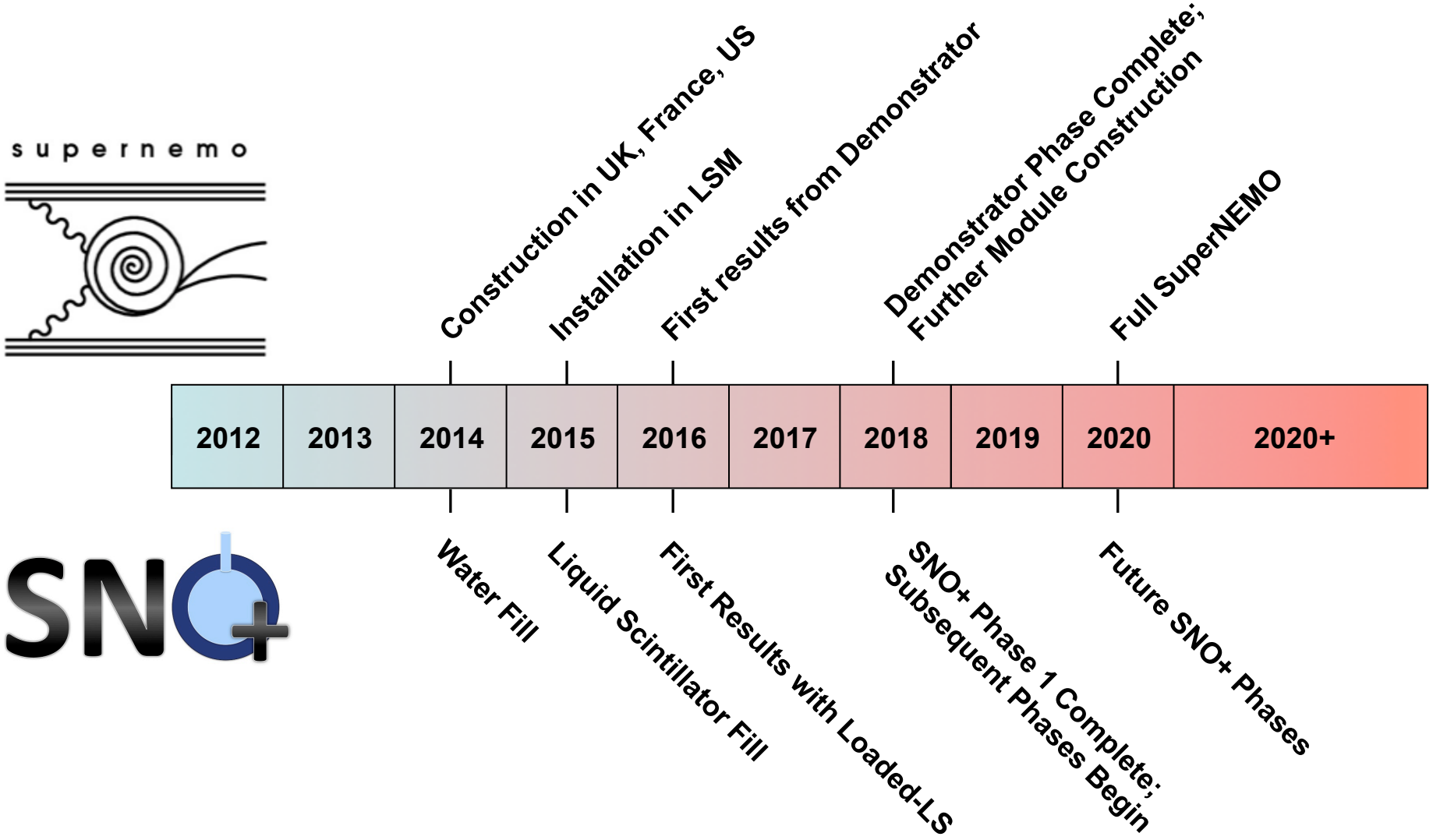


0.3% 0.5% 1% 3% 5%

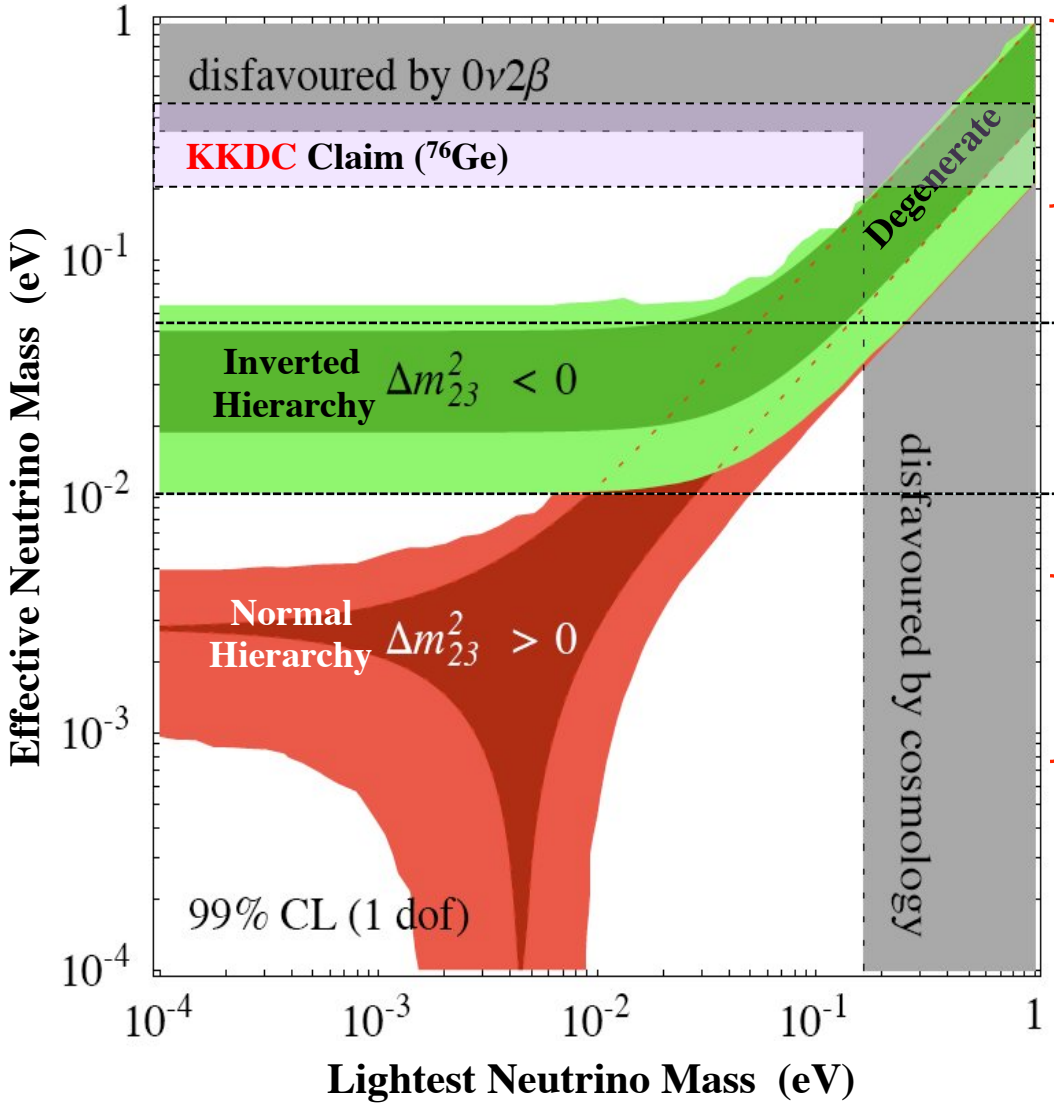
SNO+ : Construction Progress



Timescales


supernemo
Construction in UK, France, US
Installation in LSM
First results from Demonstrator
Demonstrator Phase Complete;
Further Module Construction
Full SuperNEMO
2012
2013
2014
2015
2016
2017
2018
2019
2020
2020+
SNO+
Water Fill
Liquid Scintillator Fill
First Results with Loaded-LS
SNO+ Phase 1 Complete;
Subsequent Phases Begin
Future SNO+ Phases

Timescales & Sensitivity



Best Current Limits
(**EXO**, **KLZ**, **Gerda**, **NEMO-3**)

Current Target Level
(**SNO+ Phase 1**, **CUORE**, **EXO+**, **GERDA+**, **KLZ+**, **Full SuperNEMO**)

Inverted Hierarchy Explorers
(**SNO+ Phase 2/3** (?) **nEXO** (?), **Super-KLZ** (?))

There Be Dragons …
Or maybe enormous LS or bolometer detectors.

Summary

- A summary of the field of neutrinoless double-beta decay :
  - It's really important.
  - It's really difficult.
  - There's no reason to think we will not have to search for 0νββ, whatever the outcome of neutrino oscillation or other experiments.
  - The UK is leading two of several worldwide efforts, and has the expertise to continue leading the field.
  - We need as many hands on deck as possible …

Thanks !