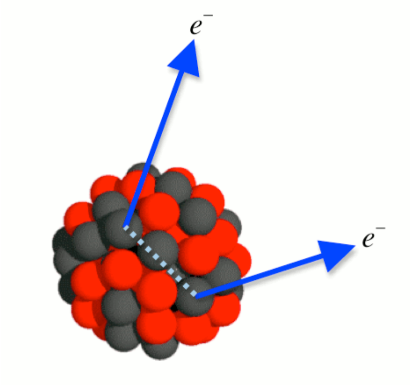
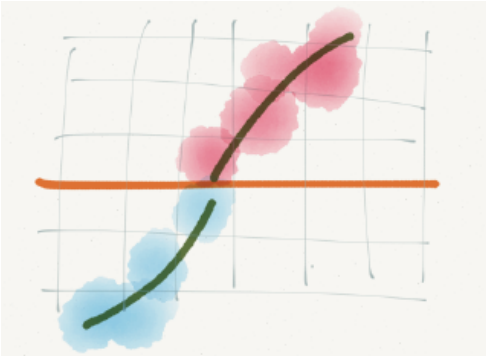
Neutrinoless Double Beta Decay





PPAP Community Meeting
Birmingham
26 July 2016

Ruben Saakyan (UCL)

Disclaimer:
No time for proper field overview
Therefore,
Focus on UK programme
and *latest* most *important* results

Outline

- $0\nu\beta\beta$ Introduction
- UK Funded projects
  - SuperNEMO Demonstrator
  - SNO+
- Current Landscape
- Way forward

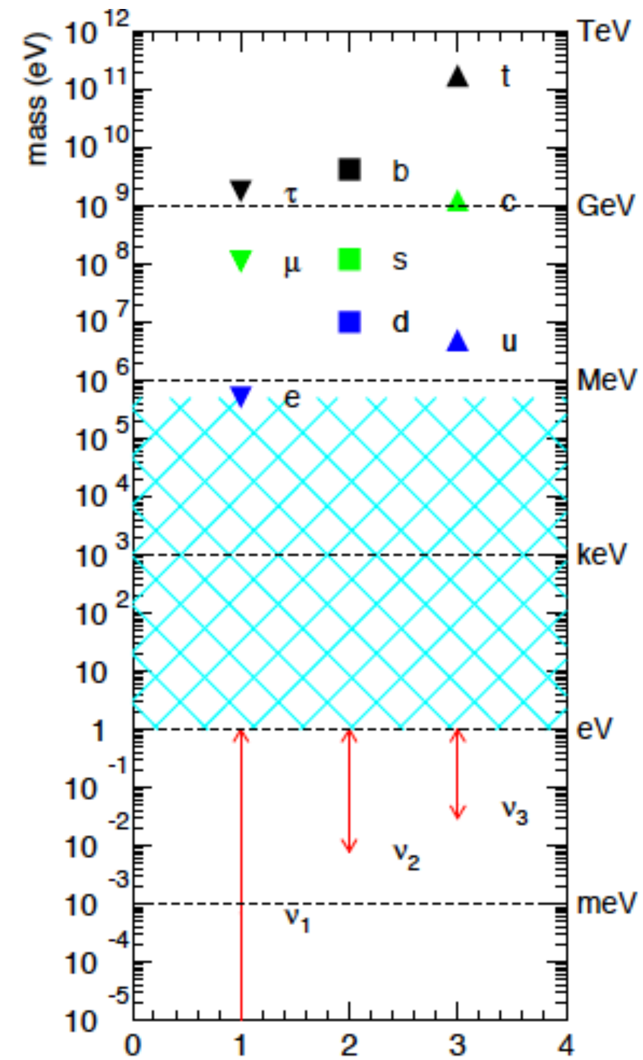
The "Big Picture"

- Neutrinos provide the only "particle physics evidence" beyond the SM
- Remaining Big Questions:
  - Neutrino mass ordering: normal vs inverted
  - CP- violation — Dirac phase

addressed by neutrino oscillations

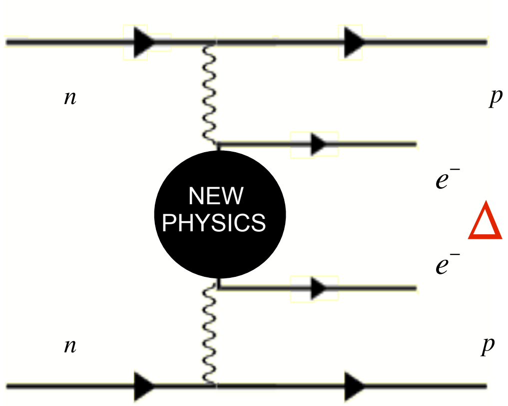
  - **Lepton number violation**
  - **Majorana vs Dirac — mass mechanism**
  - CP- violation — Majorana phase
  - Neutrino mass ordering: normal vs inverted

addressed by 0vbb



Impossible to answer key questions without 0νββ

Neutrinoless Double Beta Decay



$\Delta L = 2!$

phase space

NME — **N**uclear **M**atrix **E**lements

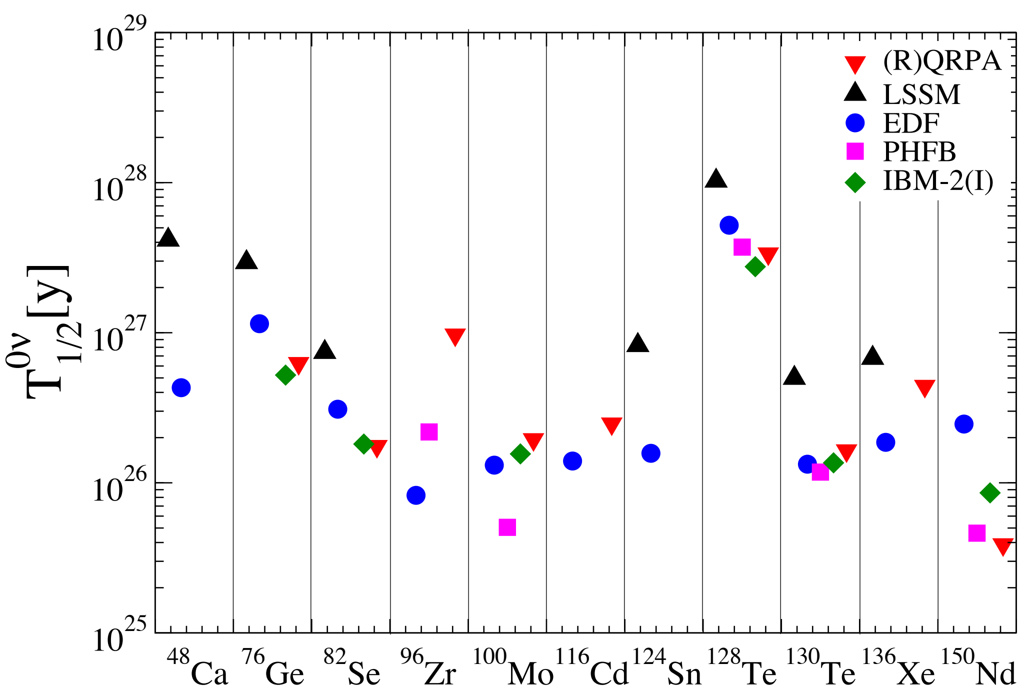
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z)\left|M^{0\nu}\right|^2 \eta^2 \longleftarrow$$ **Lepton number violating parameter**

Most popular mechanism — light Majorana neutrino mass $\langle m_\nu \rangle = \left|\sum U_{ei}^2 m_i\right| = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}\right|$

But other LNV mechanisms possible — important to be open-minded!

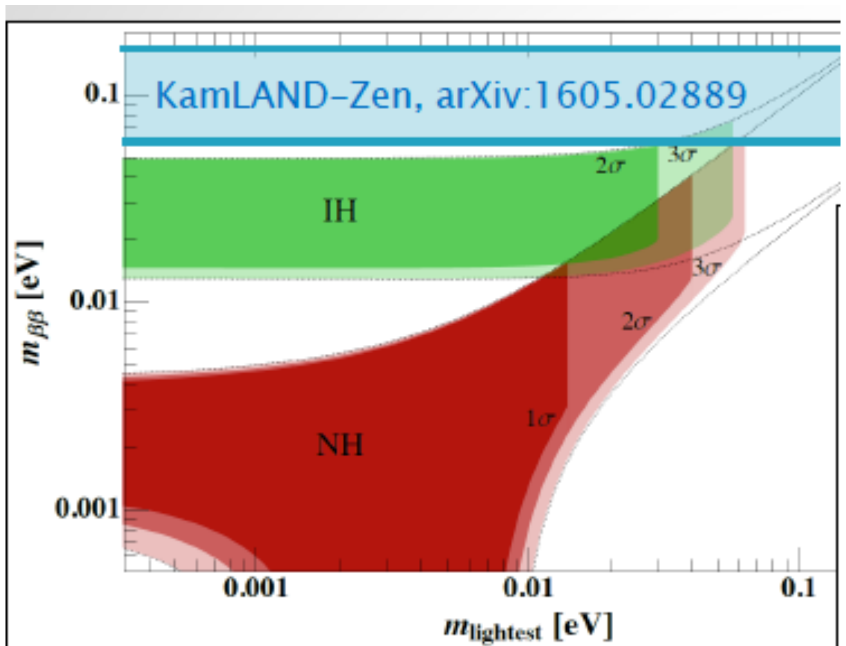
The Interpretation Problem

NME Uncertainties



We must :

- Search for $0\nu\beta\beta$ in many different isotopes to confirm mechanism. **(e.g. Deppisch & Pas 2007)**
- Challenge nuclear theory with as many "Standard Model" measurements as possible : $2\nu\beta\beta$, decays to excited states etc.



Dell'Oro, Marcocci, Viel, Vissani,
Adv.High Energy Phys. (2016) 2162659

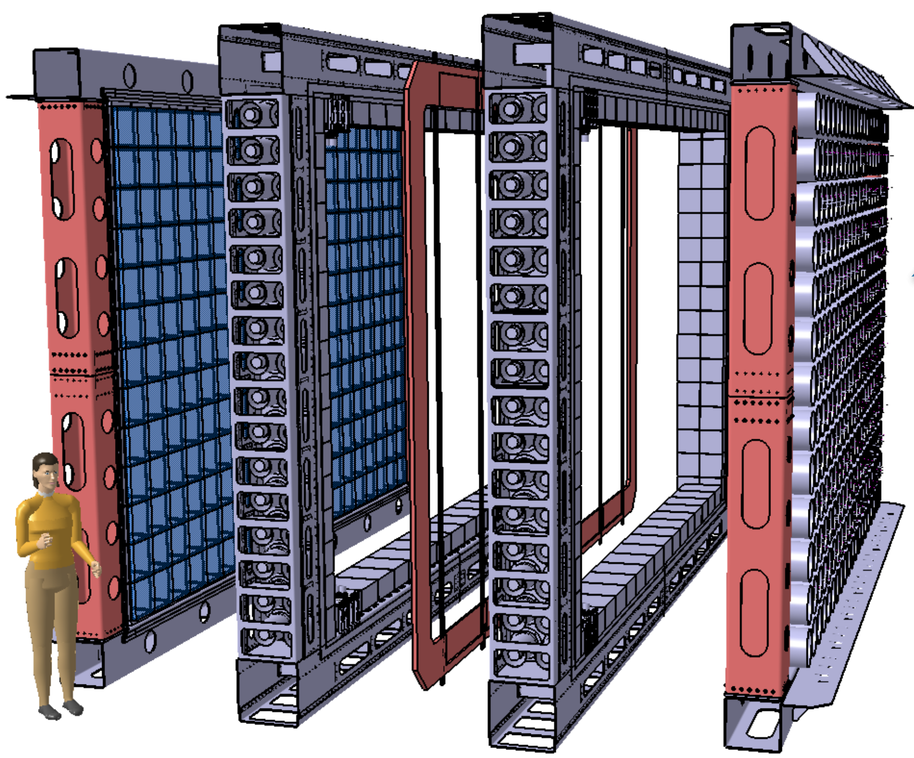
The Background Problem

$T_{1/2}$~10^{26}yr (<m_ν>~50-100 meV) with 100kg isotope — ~1 event/yr!

- Suppress **radioactive backgrounds**, primarily Uranium and Thorium decay chain products which are 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**
- Go **underground** (at least a few thousand meters of water equivalent) to reduce cosmic background by x$O(10^6)$
- Background from $2\nu\beta\beta$: energy **resolution** and **isotope** choice.

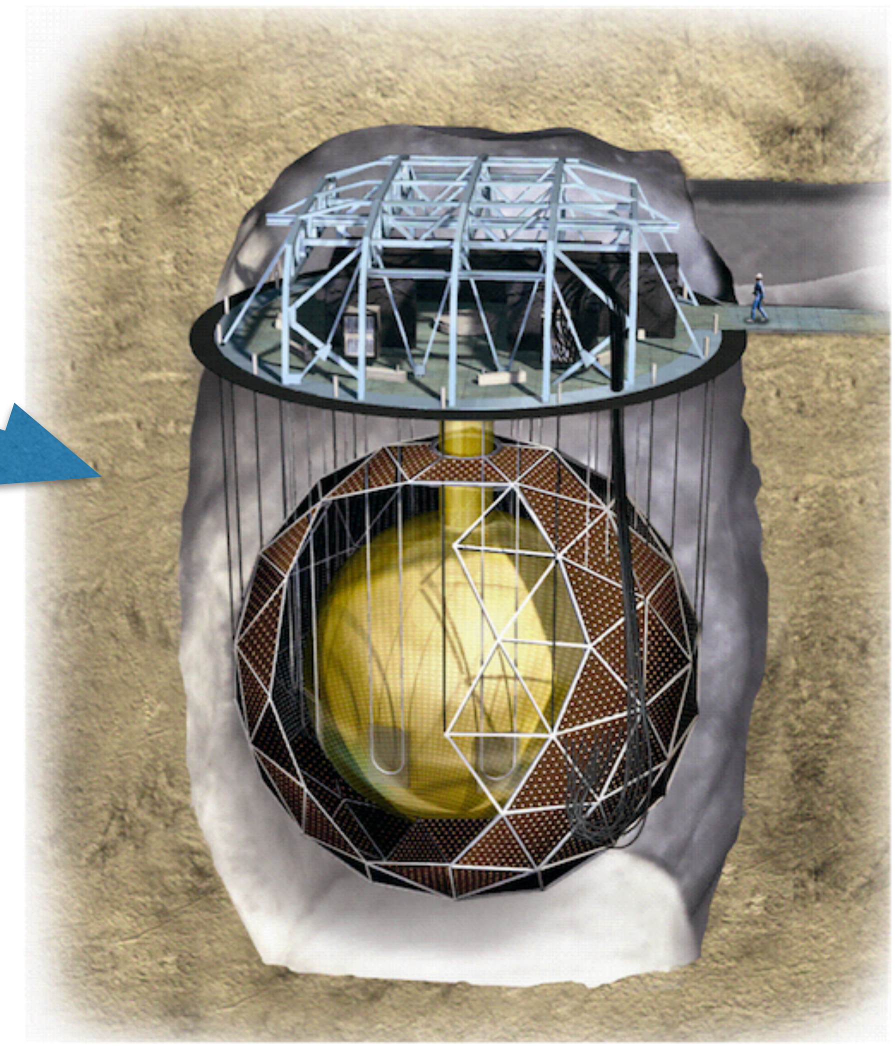
Consequently, the UK strategy so far

SuperNEMO



Isotope
Flexibility!

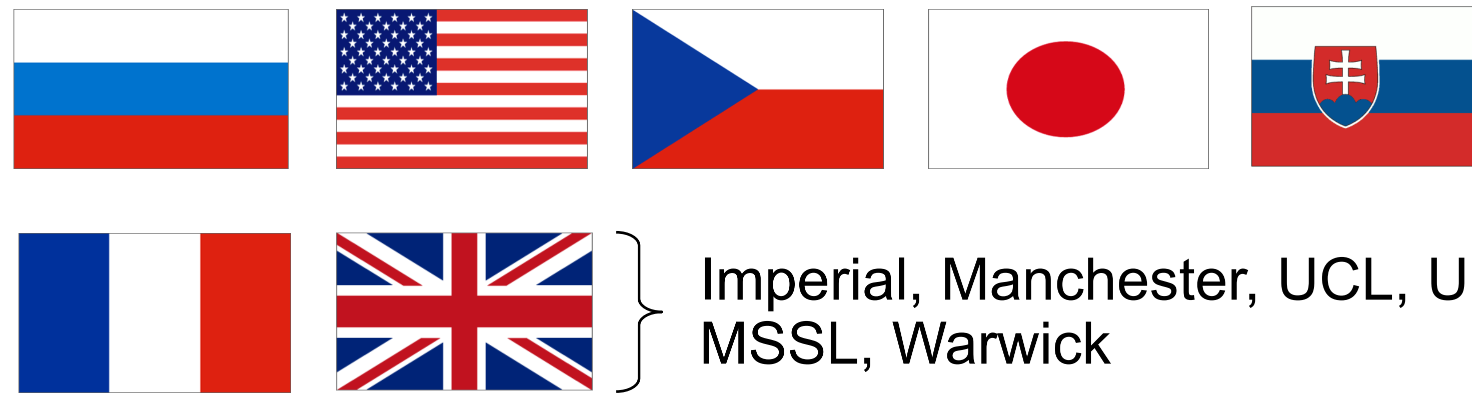
SNO+



Lowest background

Largest isotope mass

supernemo collaboration

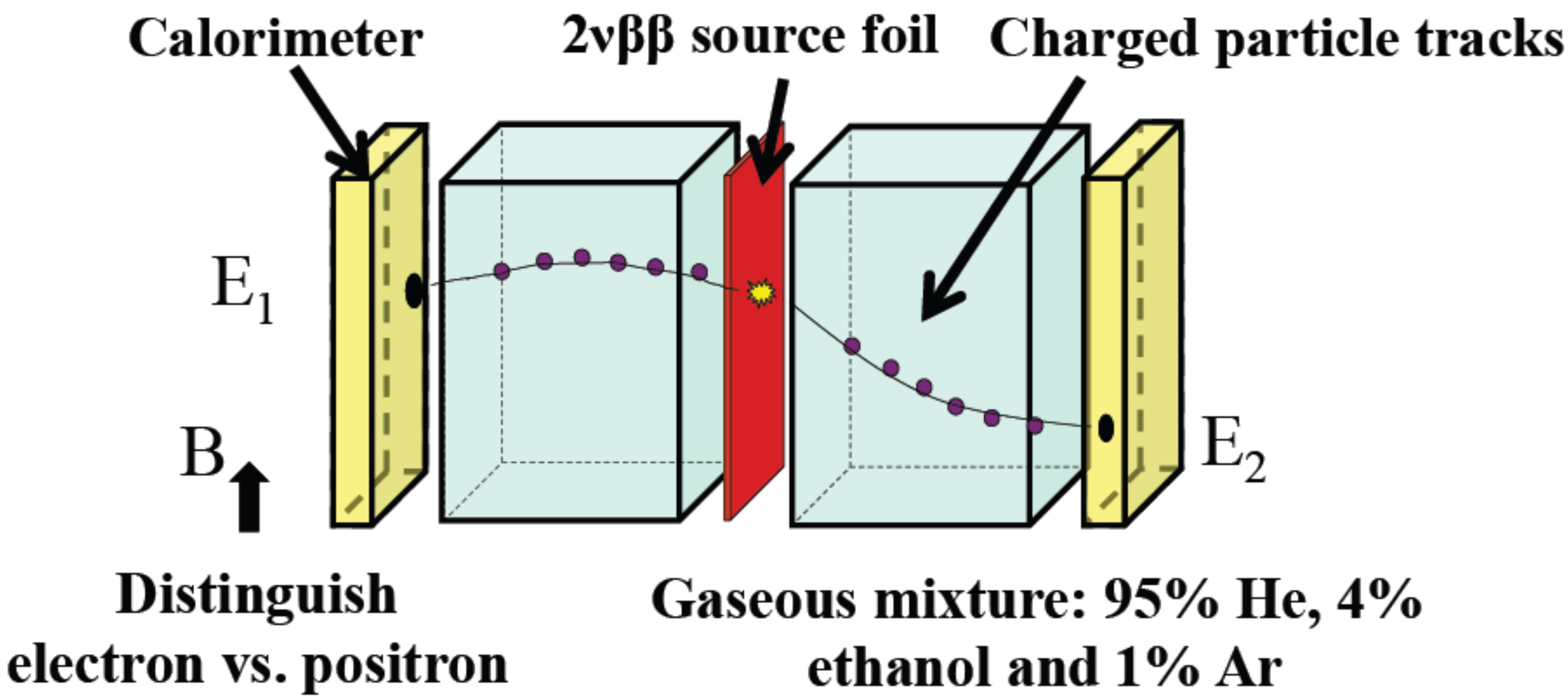


Imperial, Manchester, UCL, UCL-MSSL, Warwick

The goals of SuperNEMO :

1. Build on the experience of the extremely successful **NEMO-3** experiment.
2. Use the power of the **tracker-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.

SuperNEMO Detection Principle

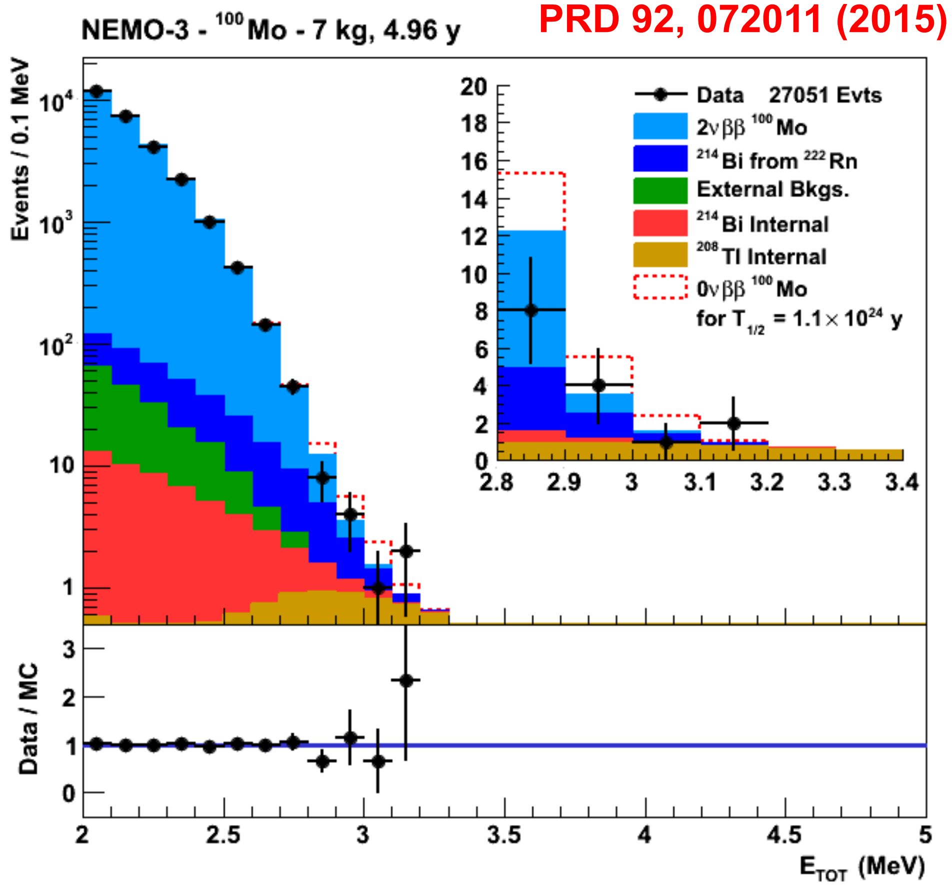


- Isotope **flexibility**
- Record breaking **background** index (**6×10^{-5}** count $keV^{-1}kg^{-1}yr^{-1}$ in RoI)
- Full **topology** reconstruction
- "Smoking gun" **signature**
- Sensitivity to **alternative** mechanisms of $0\nu\beta\beta$

NEMO-3 Result highlights presented at Neutrino 2016

(small subset)

PRD 92, 072011 (2015)

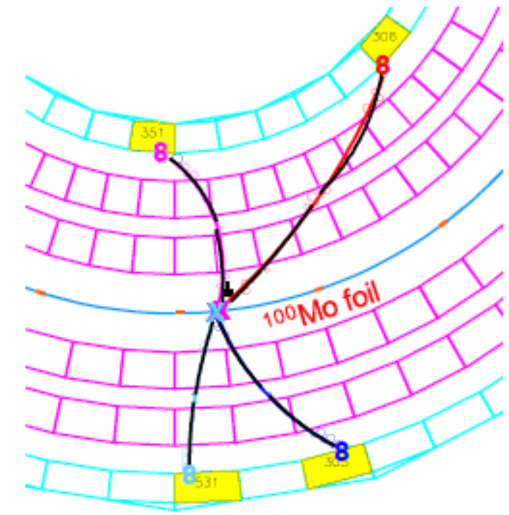


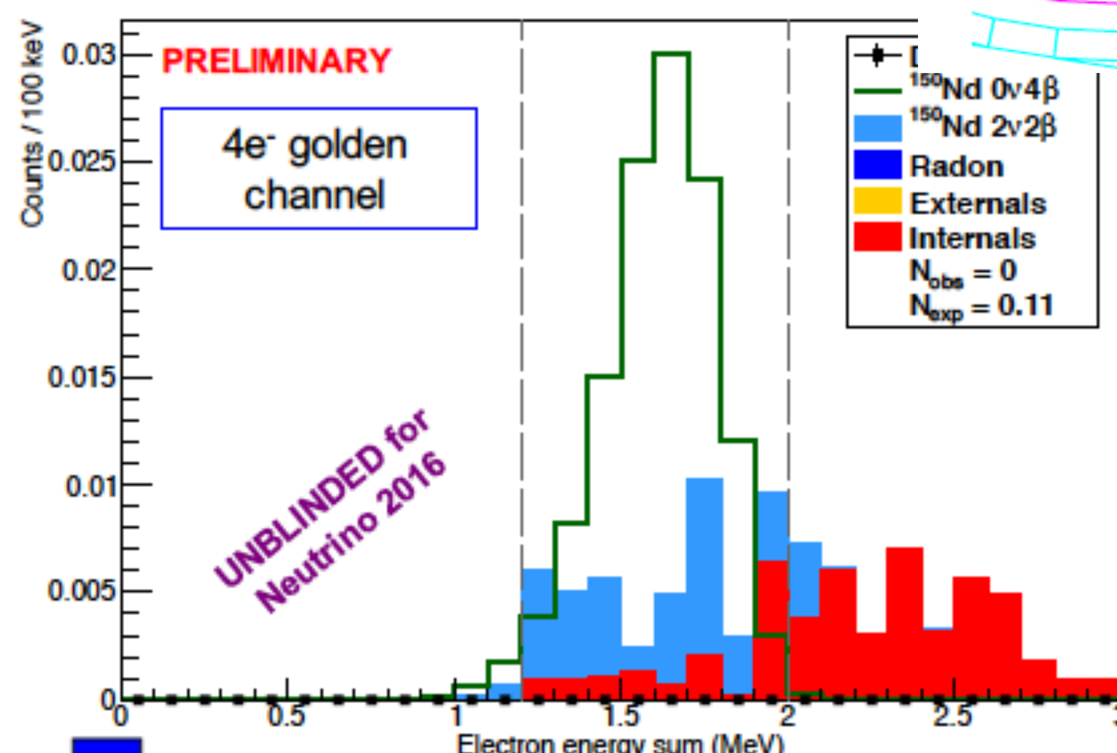
$$T_{1/2}^{0\nu\beta\beta} > 1.1\times10^{24}\ \text{yr (90\% C.L.)}$$
$$\langle m_\nu \rangle < 0.3 - 0.6\ \text{eV}$$

plots by D. Waters

0ν Quadruple Beta Decay of ^{150}Nd

$$^{150}\text{Nd} \xrightarrow{2.079\ \text{MeV}} {}^{150}\text{Gd} + 4e^-$$





$$T_{1/2}^{0\nu4\beta} > 2.6\times10^{21}\ \text{yr (90\% C.L.)}$$

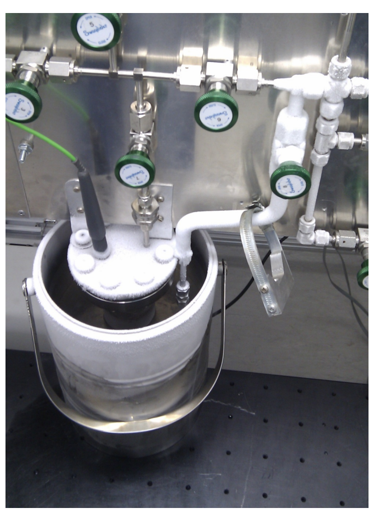
- *World's first limit on this process.*

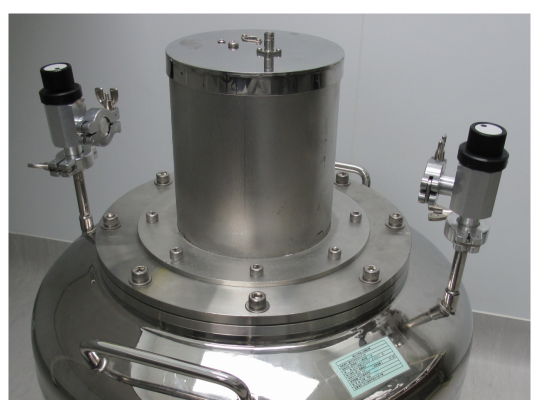
SuperNEMO Tracker Construction

Extensive Rn programme: emanation, gas purification, seals

~95% of tracker cell production complete (2034 cells, 15,000 wires)

On Schedule





Target Rn levels reached in fully instrumented tracker: 0.15mBq/m^3

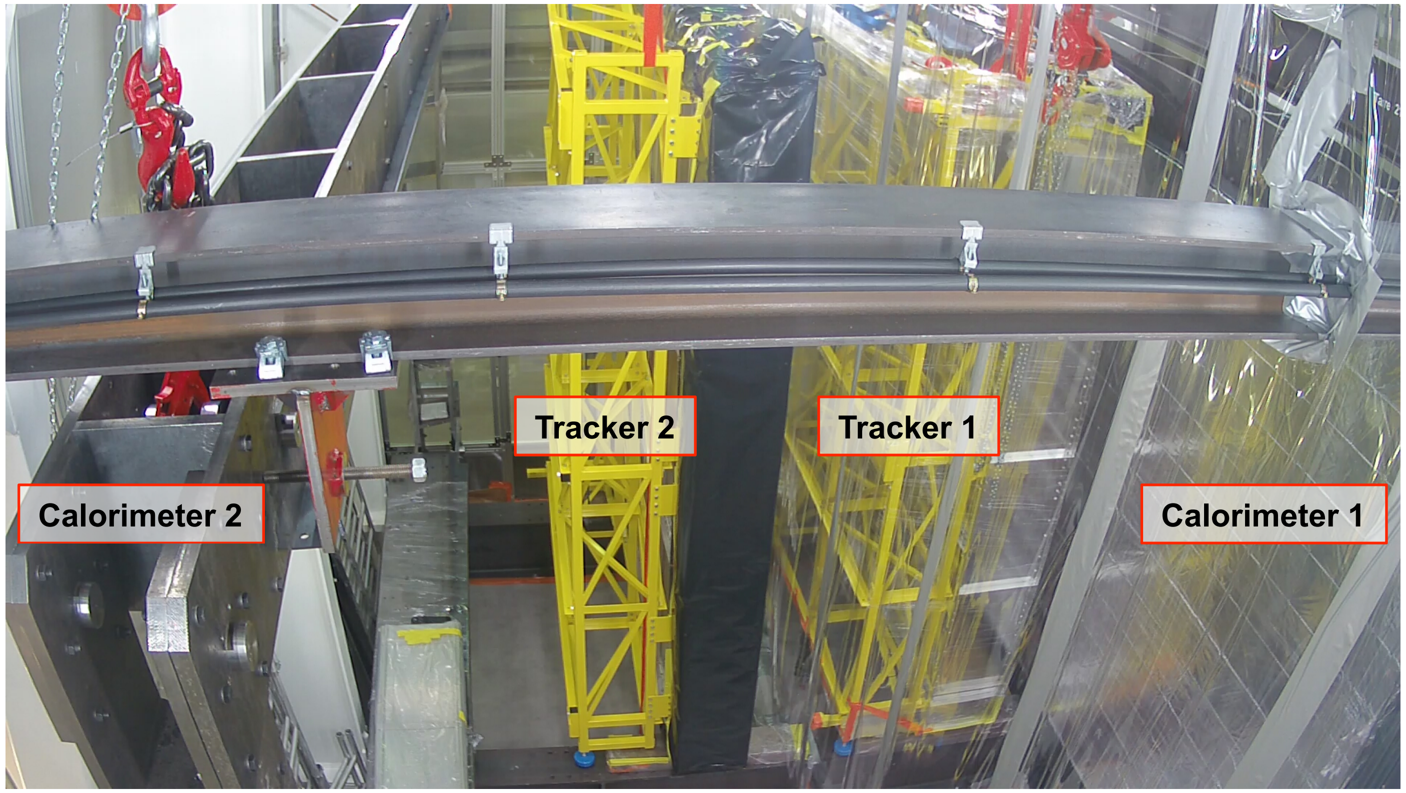
70 atoms of ^{222}Rn per m^3, 30 times better than NEMO-3

SuperNEMO Status

- ½ detector in place at LSM.
- Remaining sub-detectors delivered in next few months.
- Demonstrator Module complete by end 2016.

Laboratoire **S**outerrain de **M**odane, Frejus tunnel
4800 mwe

On Schedule



NEMO-3		SuperNEMO	Status
^{100}Mo	isotope	^{82}Se (or other, e.g. ^{150}Nd)	✓
7 kg	isotope mass	7 → 100 kg	✓
5 mBq/m³	radon	0.15 mBq/m³	✓
^{208}Tl: 100 μBq/kg ^{214}Bi: 300 μBq/kg	internal contamination	^{208}Tl ≤ 2 μBq/kg ^{214}Bi ≤ 10 μBq/kg	in progress
14% @ 1 MeV	FWHM	8% @ 1 MeV	✓

"Mothballed" "cheap and compact" SuperNEMO design being discussed in connection with new lab at Boulby

Demonstrator Module

17.5 kg.yr :

$$T^{0\nu}_{1/2} > 6.5 \times 10^{24} \text{ yr}$$

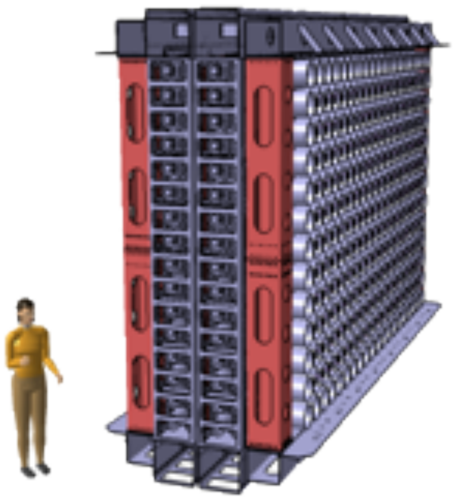
$$\langle m_\nu \rangle < 0.20 - 0.40 \text{ eV}$$

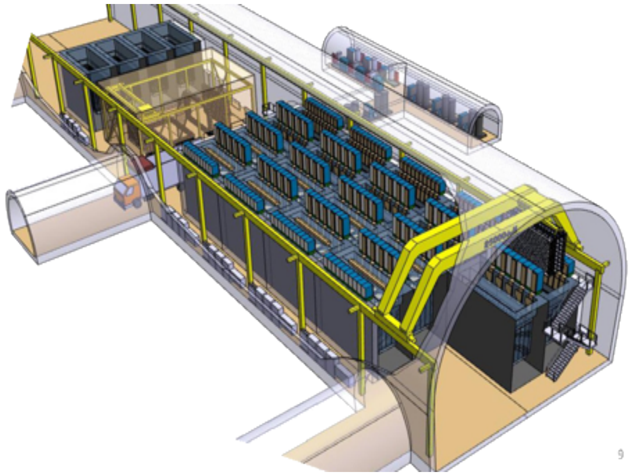
Full SuperNEMO

500 kg.yr :

$$T^{0\nu}_{1/2} > 10^{26} \text{ yr}$$

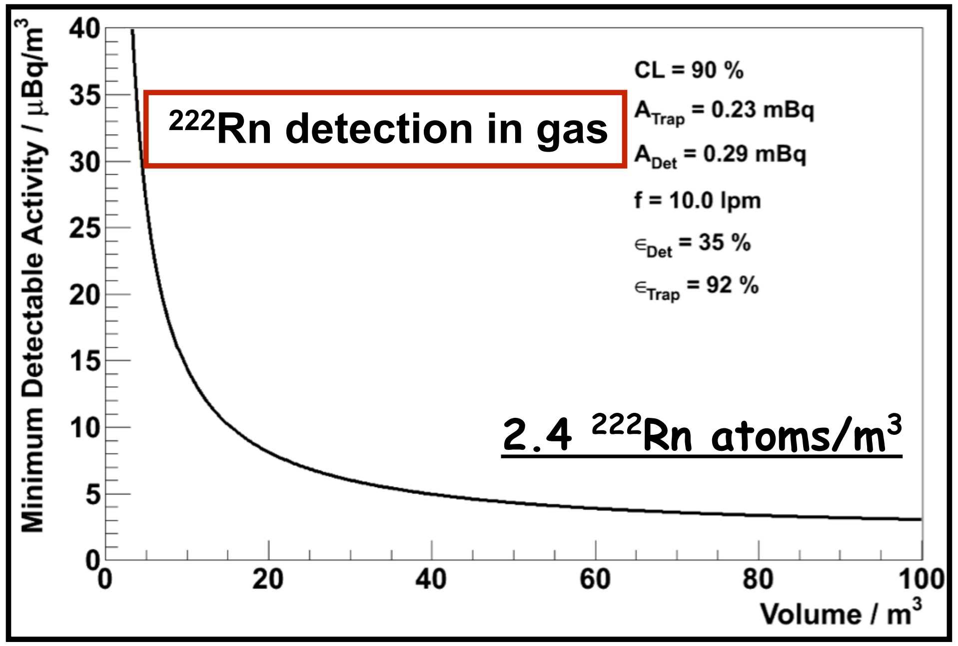
$$\langle m_\nu \rangle < 50 - 100 \text{ meV}$$





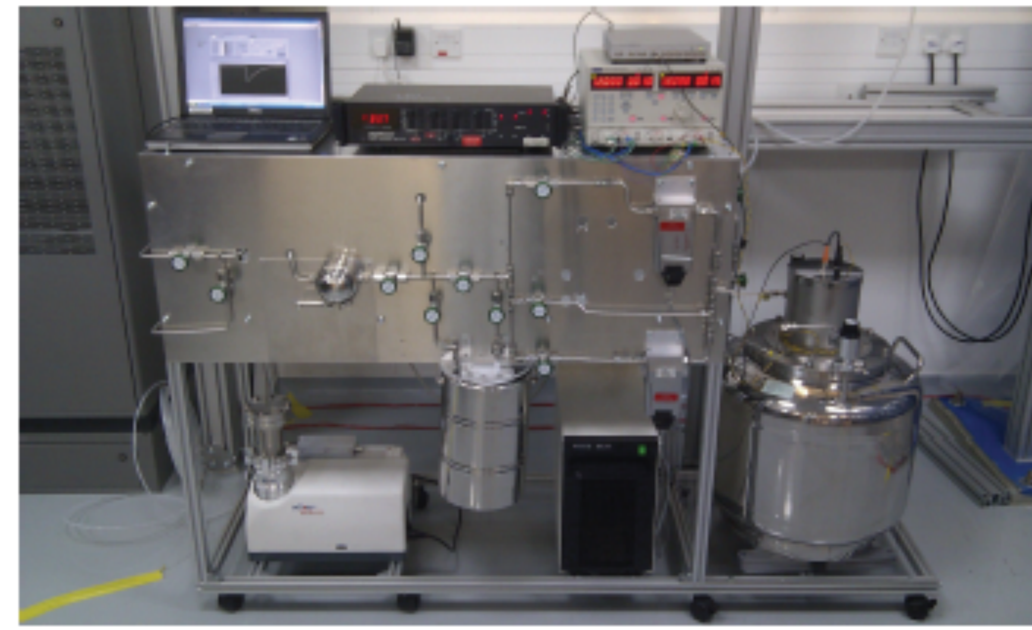
SuperNEMO “Technology Transfer”

Pushing low background technology boundaries

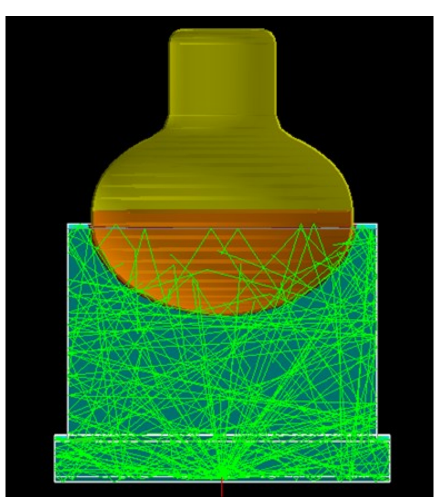


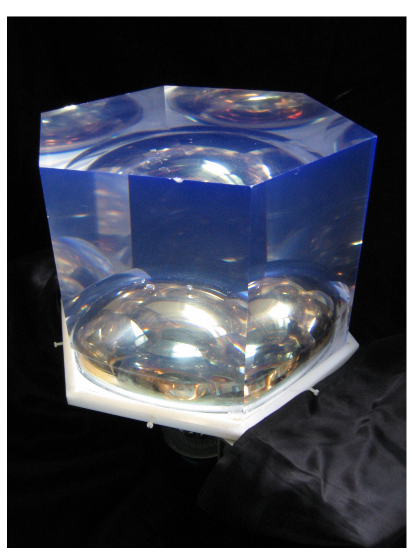
being used for Dark Matter
and other LB applications

Rn Concentration Line

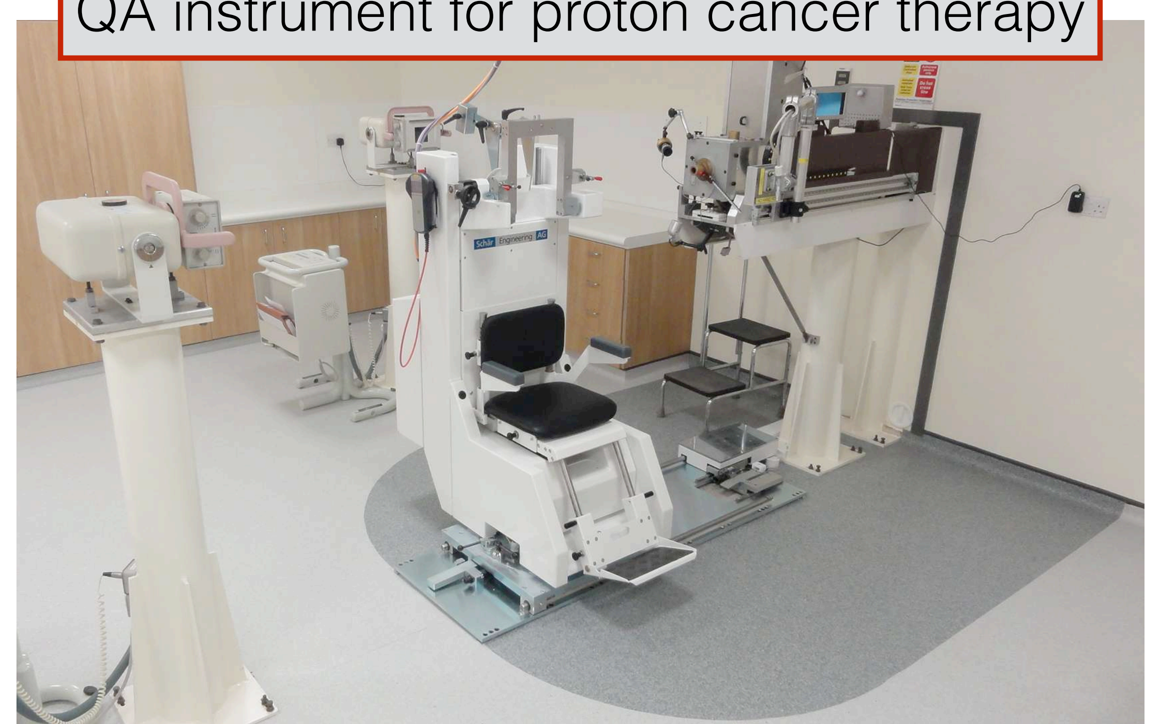


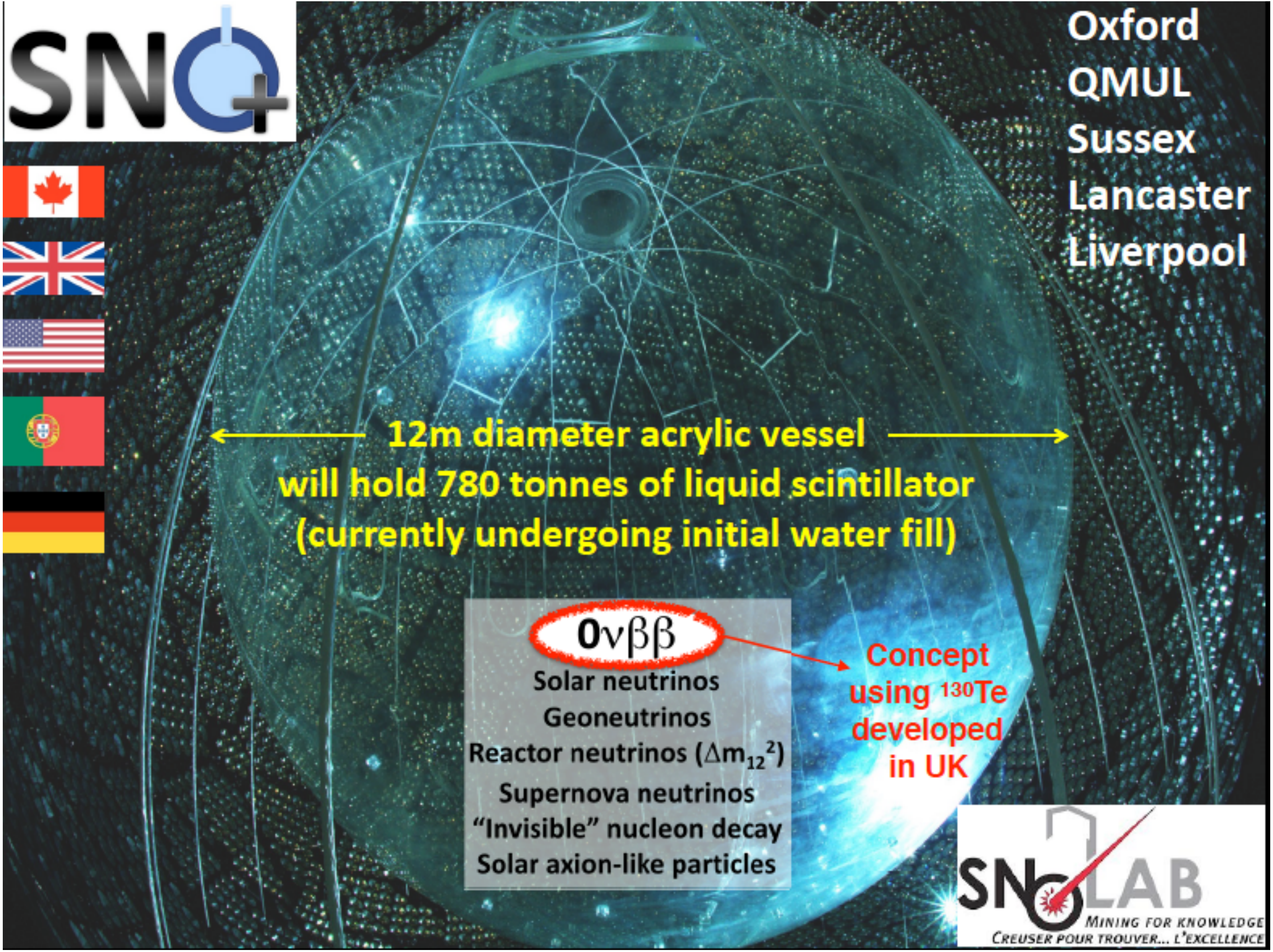
SuperNEMO Calorimeter Development





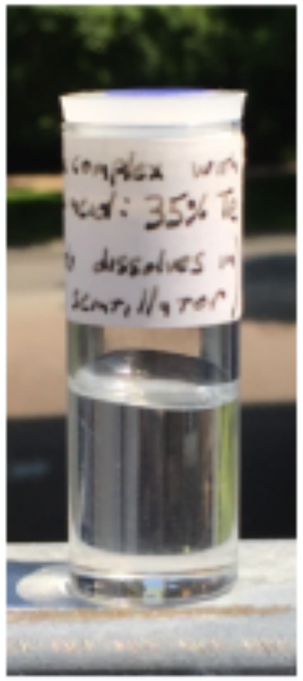
Mini-IPS grant to develop
QA instrument for proton cancer therapy

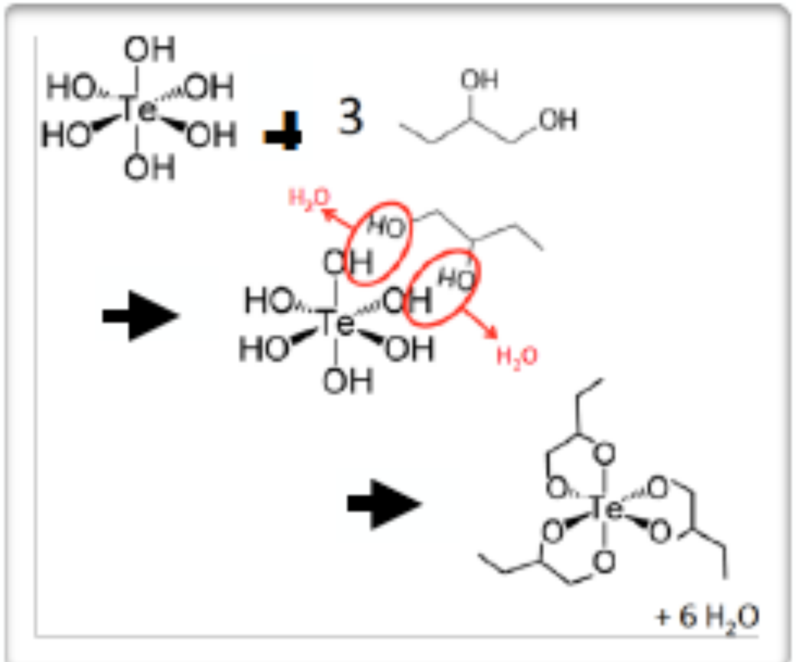




Slides by S. Biller

New loading technique developed at Oxford: Te-diol complex

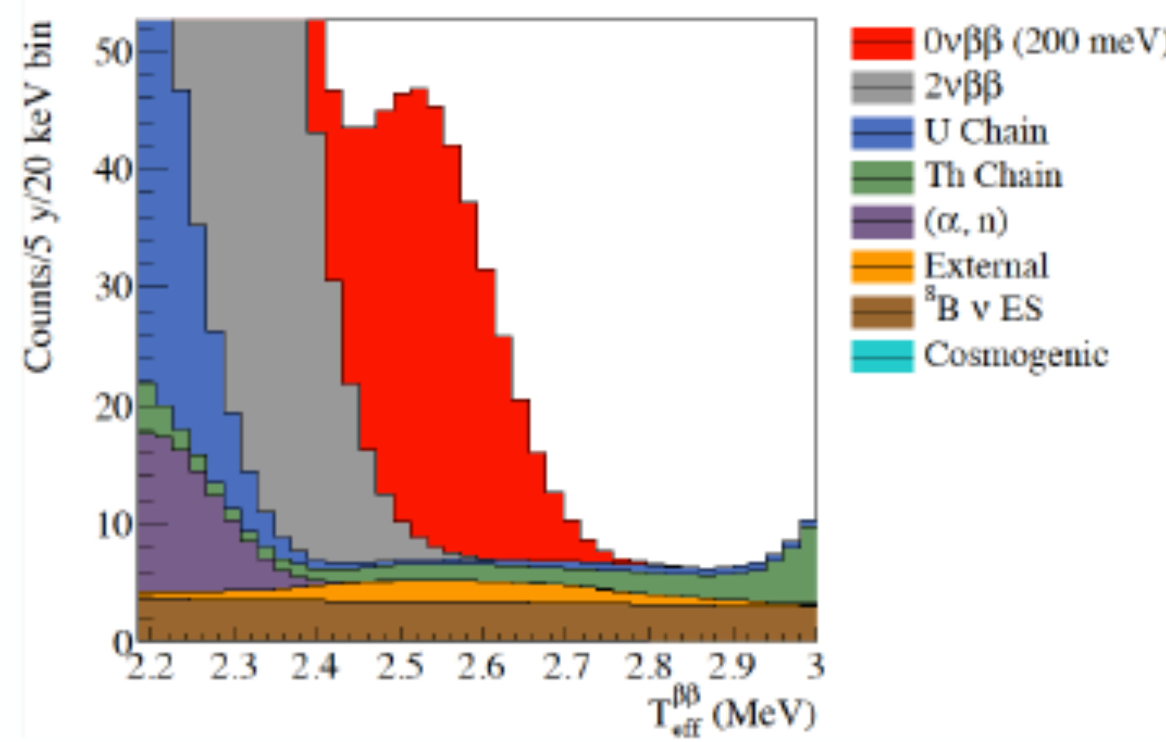




- Simple synthesis
- Single safe, distillable chemical
- Low radioactivity levels
- Minimal optical absorption
- High light levels at 0.5% loading

Selected Method for Phase I

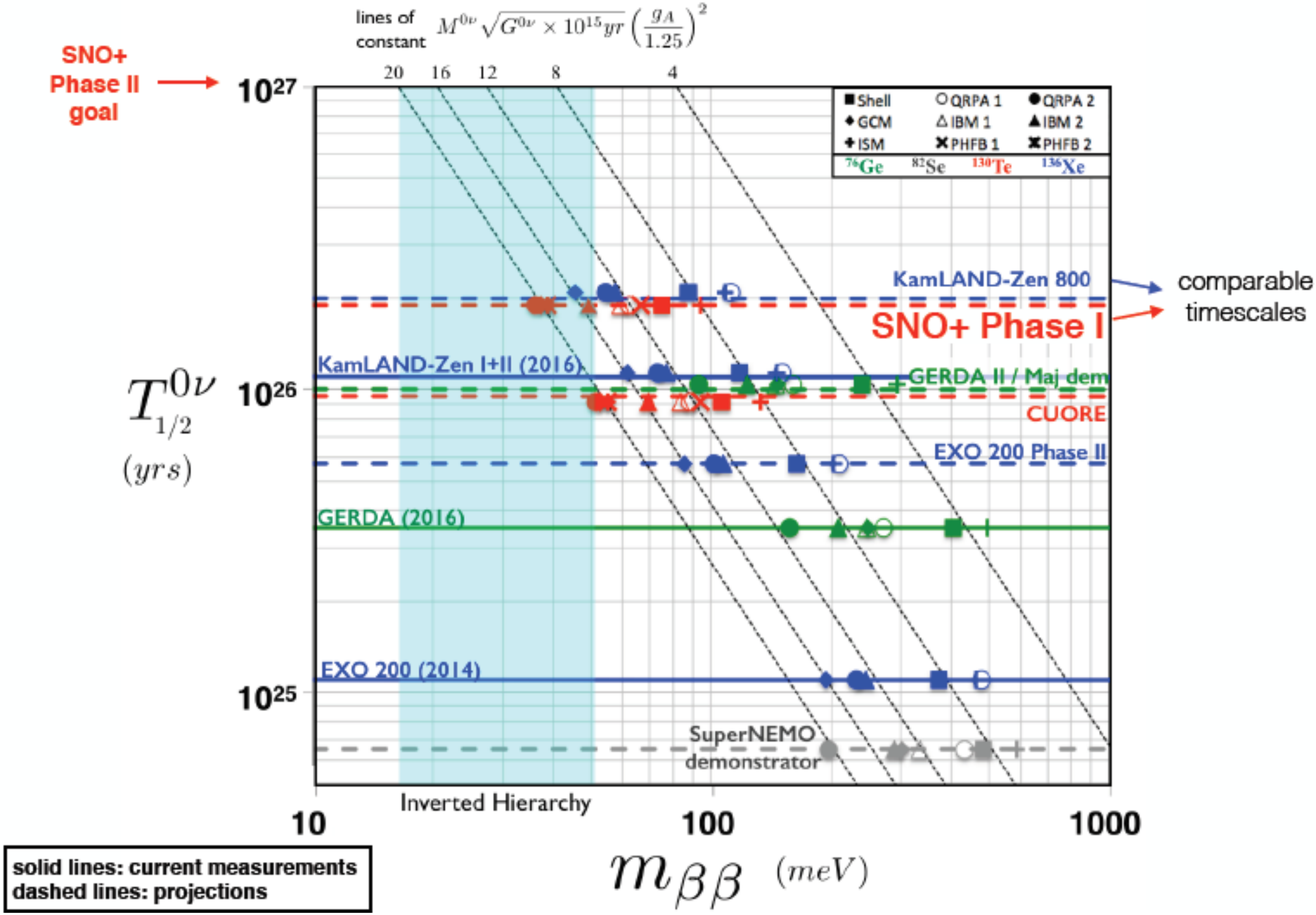
At 0.5% Te loading, the light output is quenched by the complex to ~65% that of pure scintillator. In the current detector, this corresponds to ~390 detected pe per MeV of deposited energy. A similar detected light level could be achieved for a ~2% Te loading and no further R&D by upgrading the PMT array with HQE tubes and improved concentrators. In addition, promising modifications of the loading technique that avoid quenching are under investigation, which could allow even higher loading with better energy resolution.



Promising approach for a sensitive, economic and timely coverage of the inverted mass hierarchy with a Phase II upgrade

Slides by S. Biller

Context relative to current and planned experiments



Slides by S. Biller

SNO+ Status

(Moving from commissioning phase to implementation/running over next year)

- Scintillator purification plant installed, commissioning under way
  - First LAB on site in a few months
  - Scintillator fill beginning spring 2017
- In the process of re-filling the detector with ultra-pure water
  - A few leaks in the cavity liner identified and repaired
  - New hold-down system for the acrylic vessel installed and fully tested
  - Making PMT repairs along the way
- Tellurium purification, installation underground beginning later this year
  - Loading system to follow in 2017
  - 1.8 T telluric acid (=1 T Te) stored underground for ~1 year now, 2.0 T telluric acid currently being shipped from supplier
- Tellurium loading early in 2018

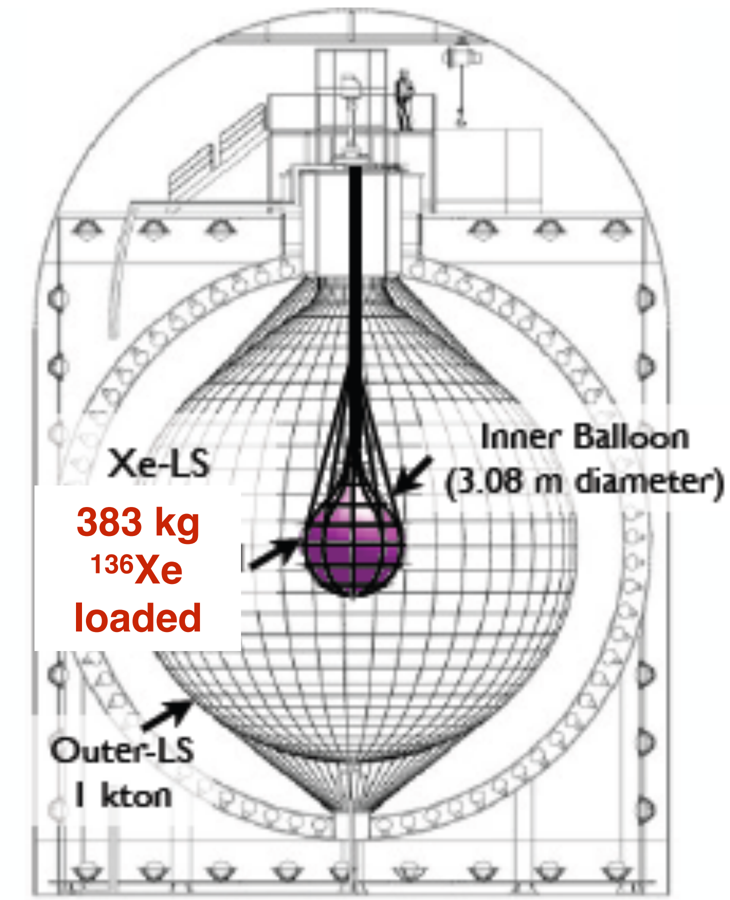
Originally projected to load by 2017 In last CG: slippage from completion of processing systems and cavity leak repair. Recent Canadian project review concluded that current schedule is under better control with major uncertainties retired.

Slides by S. Biller

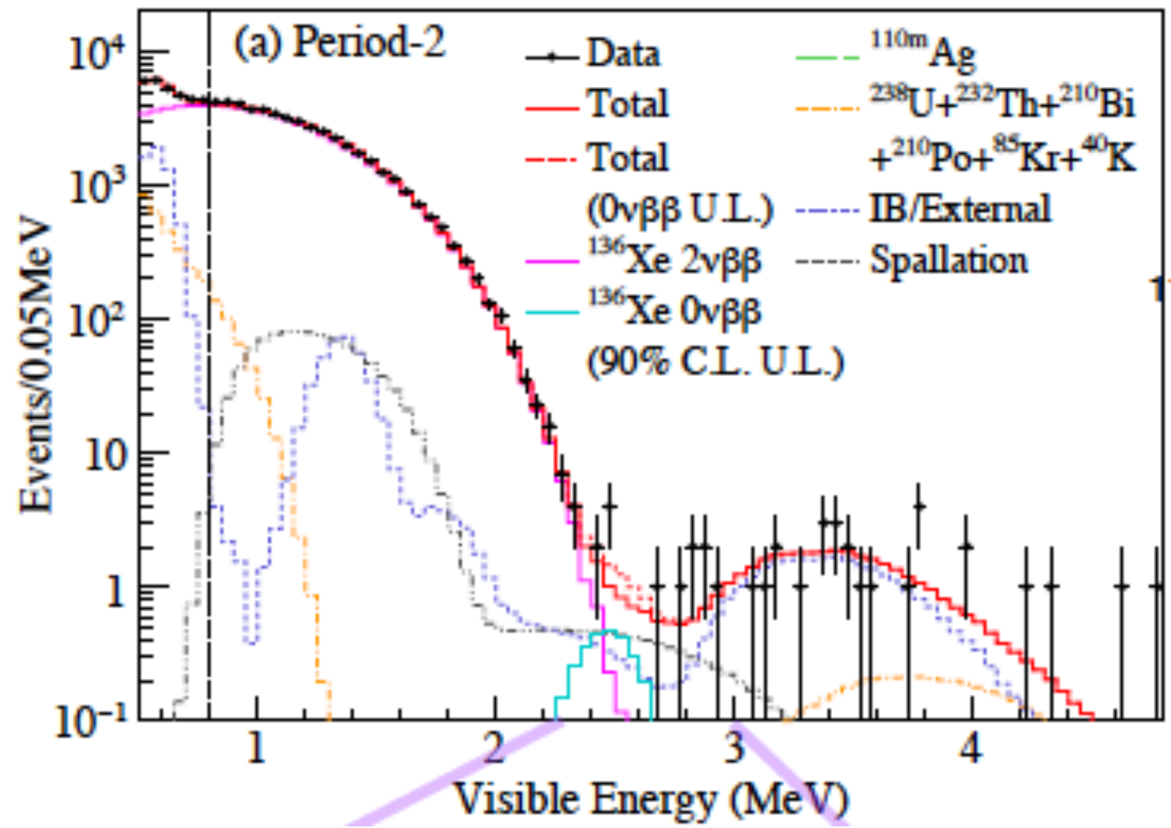
International Context

Latest Results

KamLAND-Zen, ^{136}Xe
(Plots from J. Shirai, Neutrino 2016)



504 kg-yr exposure!



Successful ^{110m}Ag removal

First published in May 2016, arXiv:1605.02889v1[hep-ex], slightly corrected at Neutrino-2016:

Limits (90%C.L.)

$$T^{0\nu}_{1/2} > 1.07\times10^{26}\ \text{yr}$$

$$\langle m_{\beta\beta}\rangle < (61\text{-}\ 165)\ \text{meV}$$

Latest Results

GERDA, ^{76}Ge (Plots from M. Agostini, Neutrino 2016)

- GERDA Phase II is running stable
- 3-4 keV energy resolution at $Q_{\beta\beta}$
- lowest background in ROI ever achieved:

$35^{+21}_{-15} \cdot 10^{-4}$ cts/(keV· kg· yr) for Coax

$7^{+11}_{-5} \cdot 10^{-4}$ cts/(keV· kg· yr) for BEGe

- combined Phase I+II sensitivity:

$T^{0\nu}_{1/2} > 4.0 \cdot 10^{25}$ yr (90% C.L.)*

- blind analysis, no $0\nu\beta\beta$ signal:

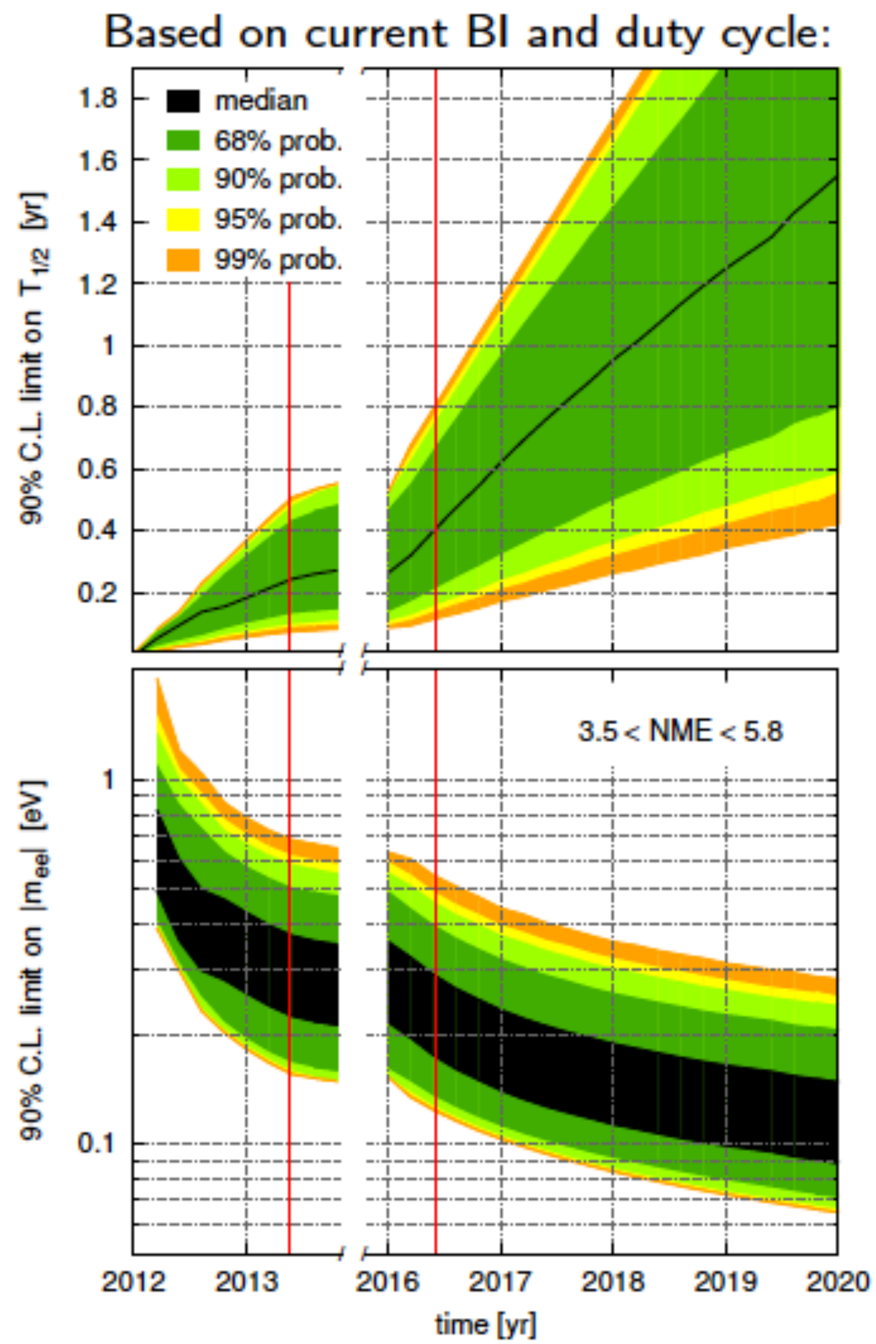
$T^{0\nu}_{1/2} > 5.2 \cdot 10^{25}$ yr (90% C.L.)*

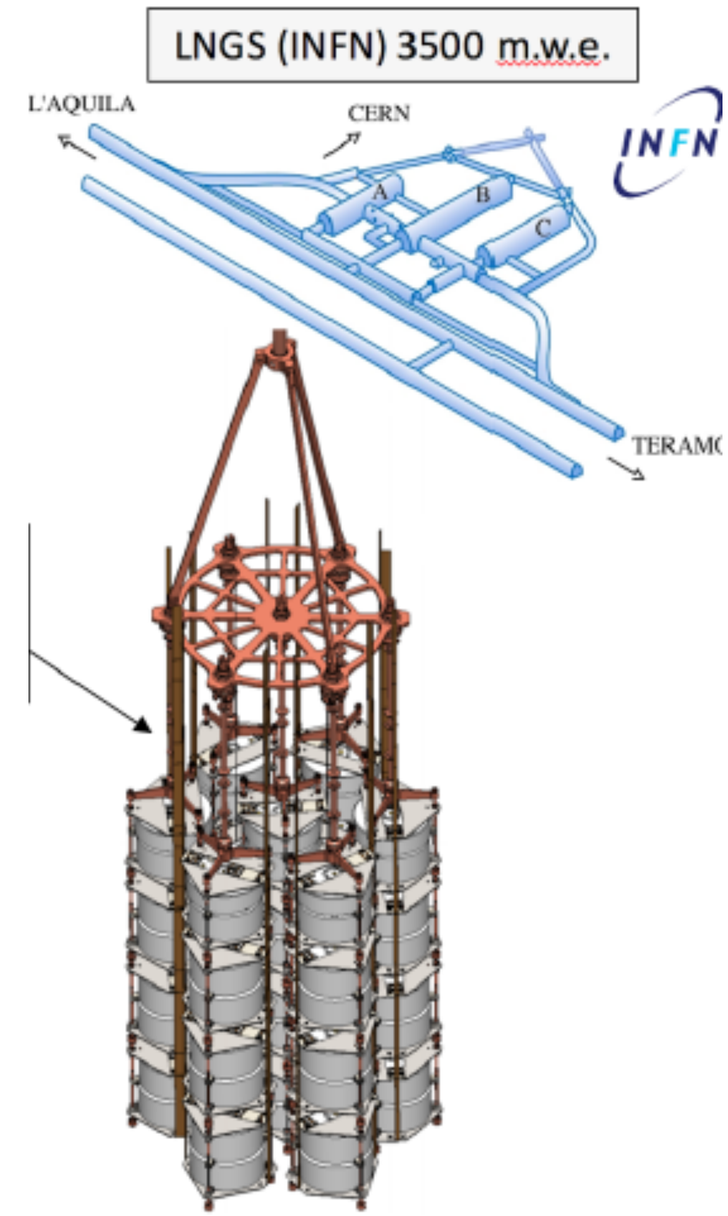
$|m_{ee}| <$ [160,260] meV (90% C.L.)*

(* preliminary, ϵ^{PSD}_{coax} to be finalized)

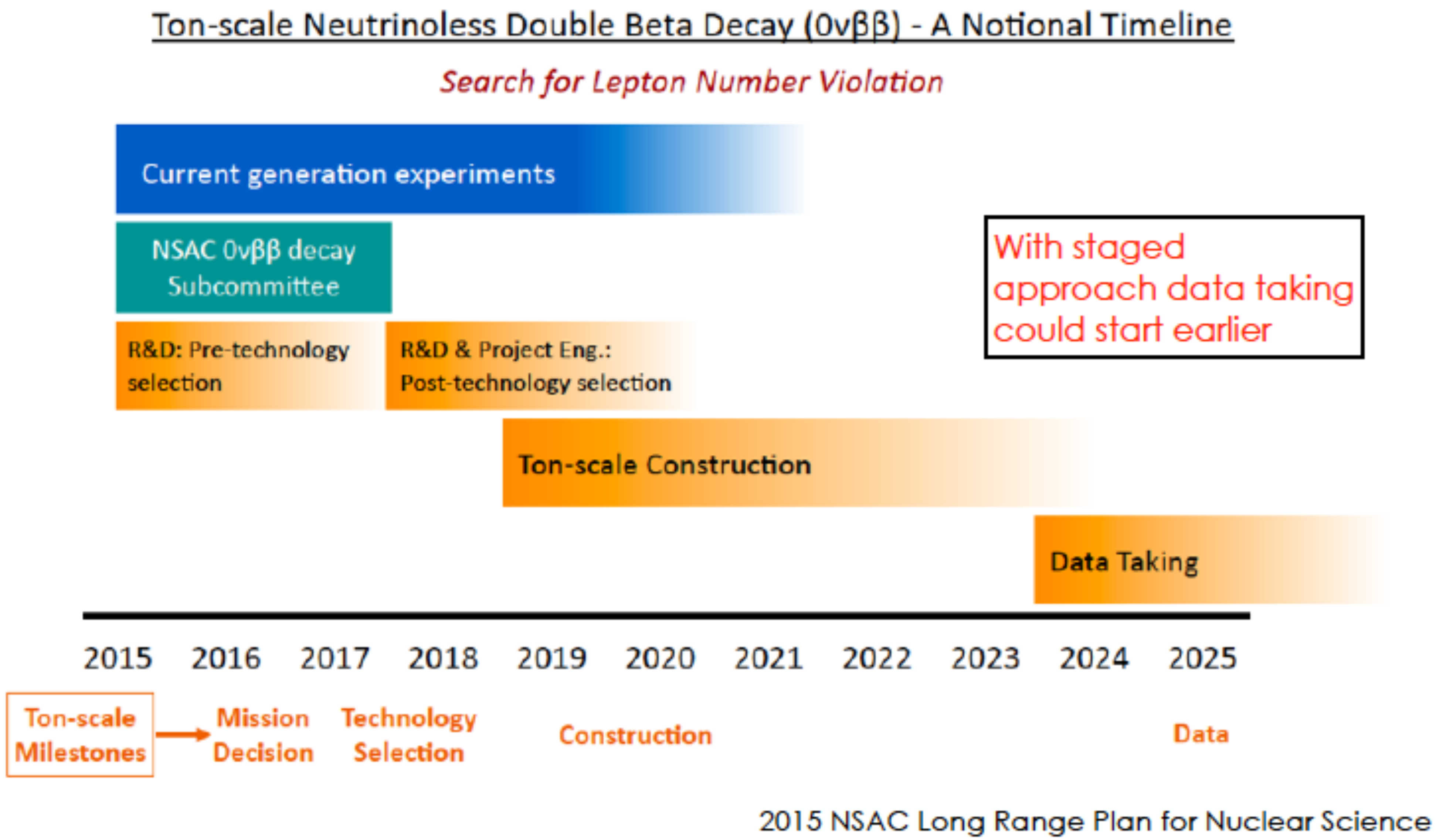
GERDA Phase II is the high-resolution and background-free experiment!

[see poster on next gen ^{76}Ge exp: P4.057]





US Down-Select Process



- down-select two technologies by ~2018
- 1 with leading US participation, 1 with significant contribution
- Significant funds “earmarked”

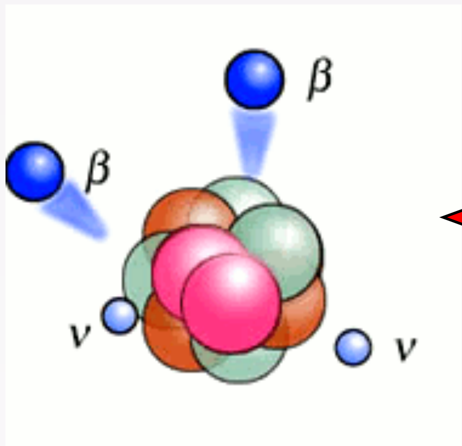
Personal view: LXe (nEXO) and 1t Ge (Gerda+Majorana) are two likely candidates

Concluding Remarks

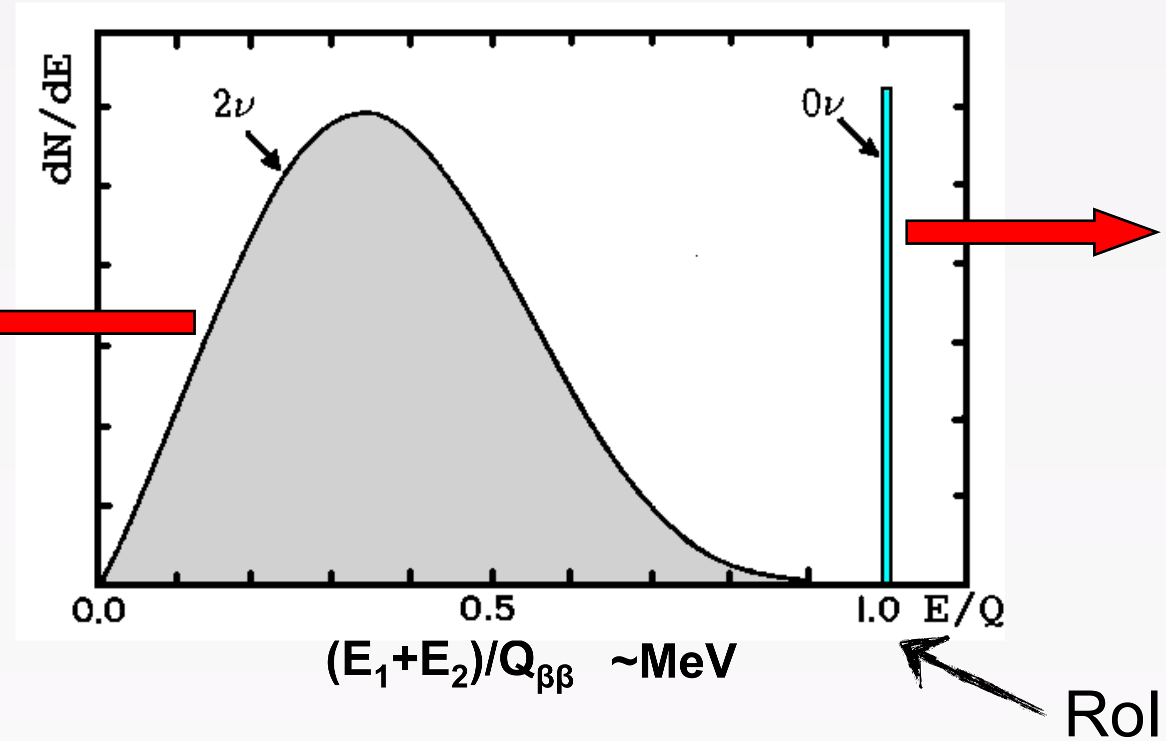
- **NDBD** is and **must remain** a key element of the **UK neutrino programme**
- **UK** lead two worldwide efforts and have **expertise** to continue to play a lead role in **NDBD**
- SuperNEMO and SNO+ UK teams started a joint evaluation of the best way forward for **future UK NDBD programme**
  - Joint meeting held
  - Discussions on joint PRD aimed at future UK NDBD programme
- Consultation with major international partners as they gear up towards next generation experiments are also in progress
- Need better exploit **synergies** and **expertise** with Dark Matter
  - UK leads low background WPs in SuperNEMO and LZ
  - New low background facilities at Boulby

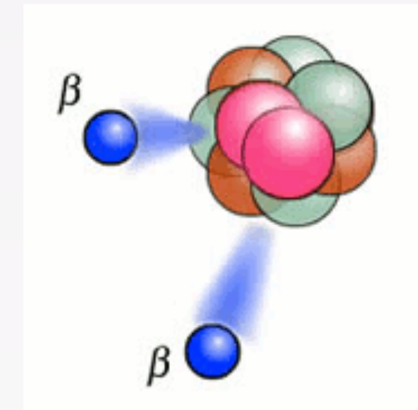
BACKUP

Design of a ββ experiment



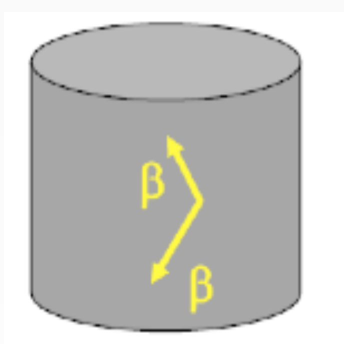
$(E_1 + E_2) \in [0, Q_{\beta\beta}]$





$(E_1 + E_2)/Q_{\beta\beta} \approx 1$
[⊗ resolution]

Homogenous “source = detector”



Semi-conductor, bolometer, LS.

Observable E_{12} ($=E_1+E_2$)

Excellent ΔE/E Possible

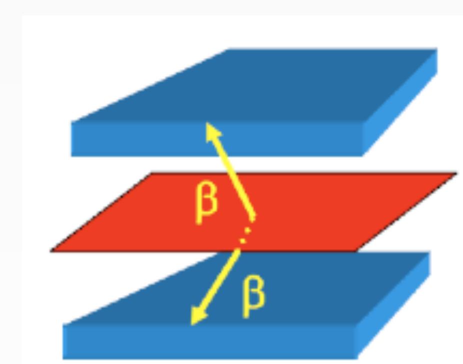
Large Masses Possible

Elements of Both

Gaseous Xe TPC

Pixelated CdZnTe

Heterogenous “source ≠ detector”

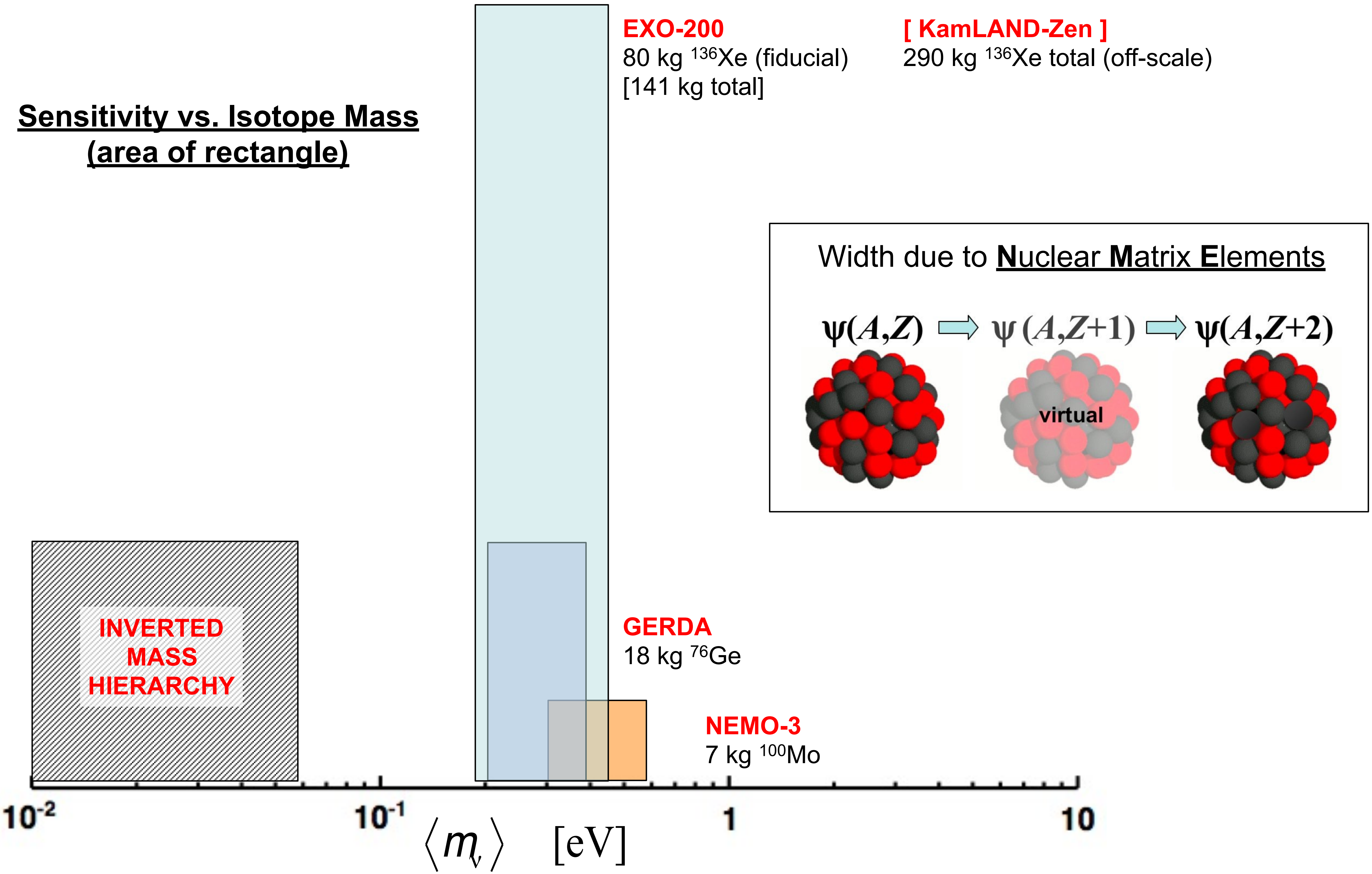


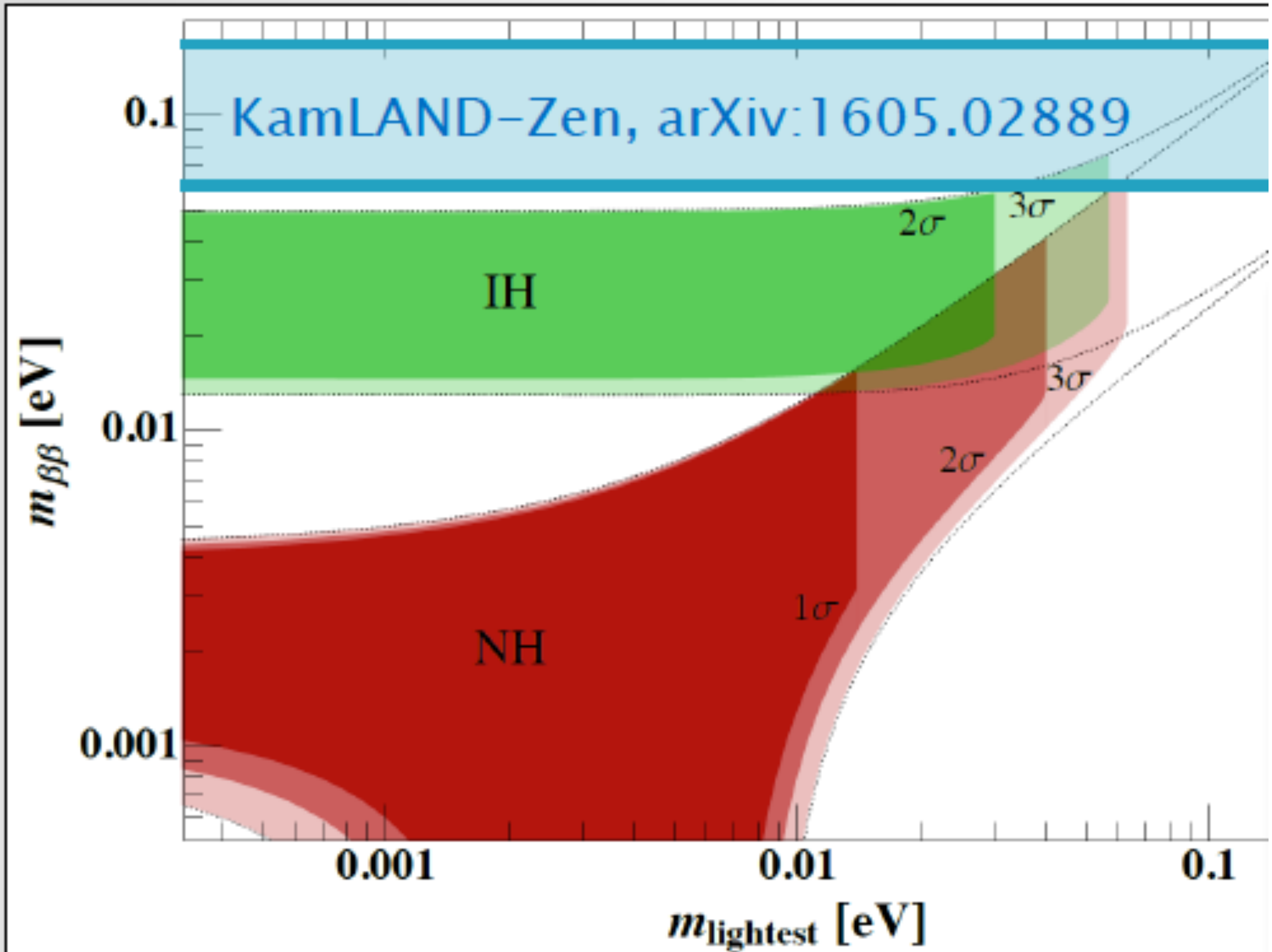
Tracking

Observables: E_{12}, E_1, E_2, cosθ

Full event topology

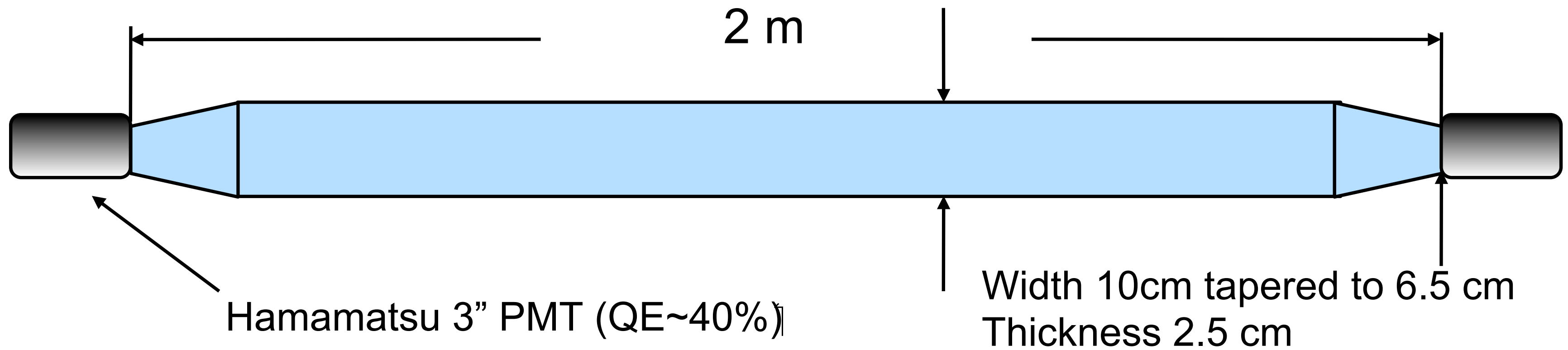
Can probe *different mechanisms*


Sensitivity vs. Isotope Mass
(area of rectangle)
EXO-200
80 kg ^{136}Xe (fiducial)
[141 kg total]
[KamLAND-Zen]
290 kg ^{136}Xe total (off-scale)
Width due to Nuclear Matrix Elements
$\psi(A,Z)$
$\psi(A,Z+1)$
$\psi(A,Z+2)$
virtual
INVERTED
MASS
HIERARCHY
GERDA
18 kg ^{76}Ge
NEMO-3
7 kg ^{100}Mo
10^{-2}
10^{-1}
1
10
$\langle m_\nu \rangle$ [eV]



Dell'Oro, Marcocci, Viel, Vissani,
Adv.High Energy Phys. (2016) 2162659

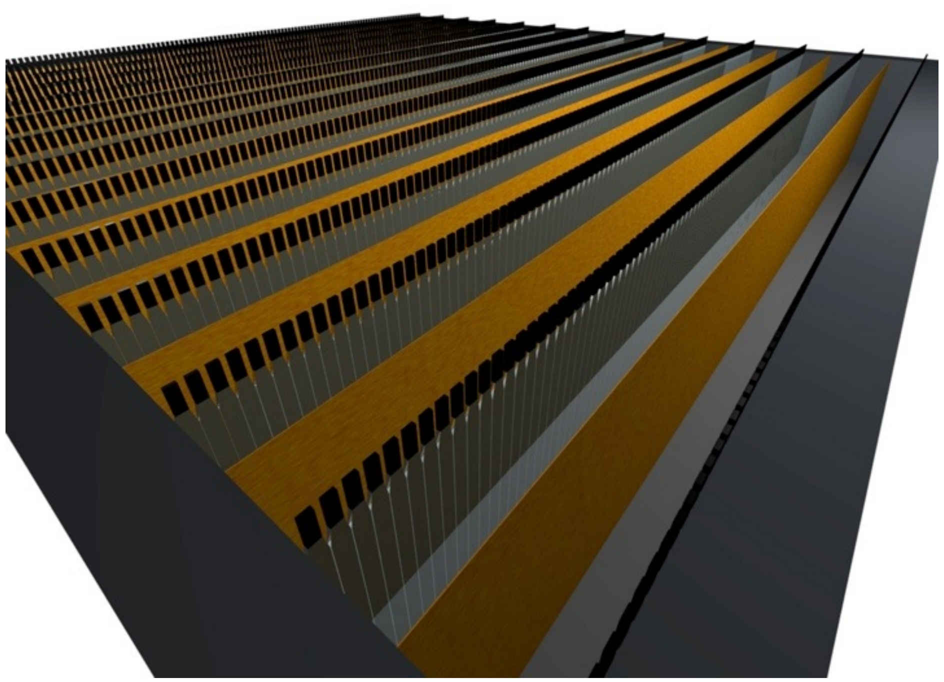
SuperNEMO design with scintillator bars



Main ideas of scintillator bars design

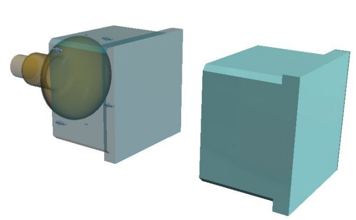
- Fewer much cheaper PMTs
- Lower radioactivity from PMTs
- Compact design (14m x 14m x 2.5m)
- Very high (close to ~100%) efficiency of γ tagging
- No B-field. Tagging e+ with 511 keV γ's $\Rightarrow$ better efficiency

Lower background



But worse energy resolution — 2v background

FWHM(3 MeV) = 4.5%



FWHM(3 MeV) = 5%

New Underground Lab at Boulby

- Large Experimental Hall: 45m(L) x 7m(W) x 6.5m(H). Class < 10,000 cleanroom throughout.
- Low background screening laboratory: < 1,000 cleanroom
- 10T lifting capacity
- Transportation capacity: 2m x 2.1m x 2.1m in manshaft cage. Up to 8m long items with a week notice. Larger than in SNO and Homestake
- Uninterrupted Power Supply, 100-1000 Mbps internet
- Low natural Rn, 2.5 Bq/m^3
- **Essentially ready for beneficial occupancy**