Double Beta Decay

Jeanne R Wilson

25 – 9 – 2015

Remit: *Present the UK program on Double Beta decay and put it in context with world-wide efforts.*

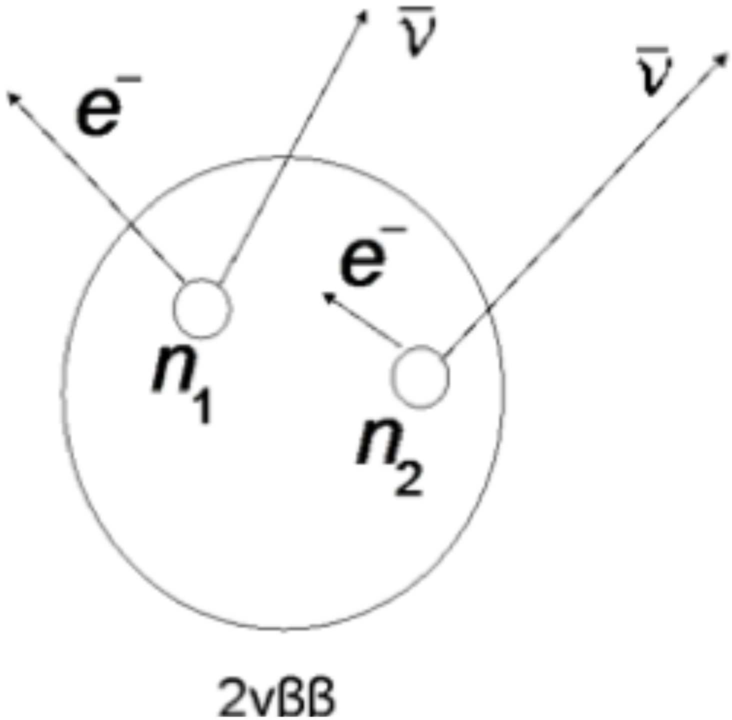
Thanks to: *D.Waters, S.Biller, S. Soldner-Rembold, P.Guzowski*

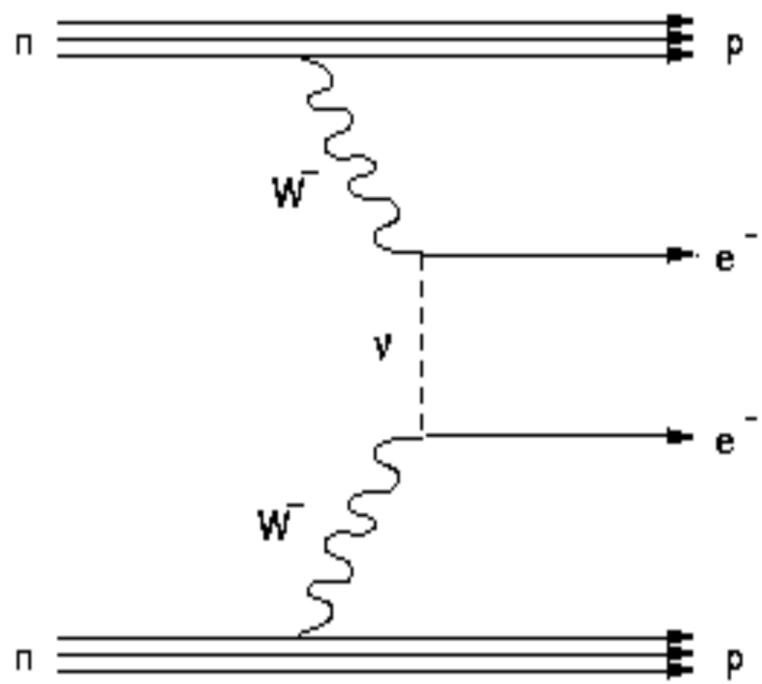
Contents

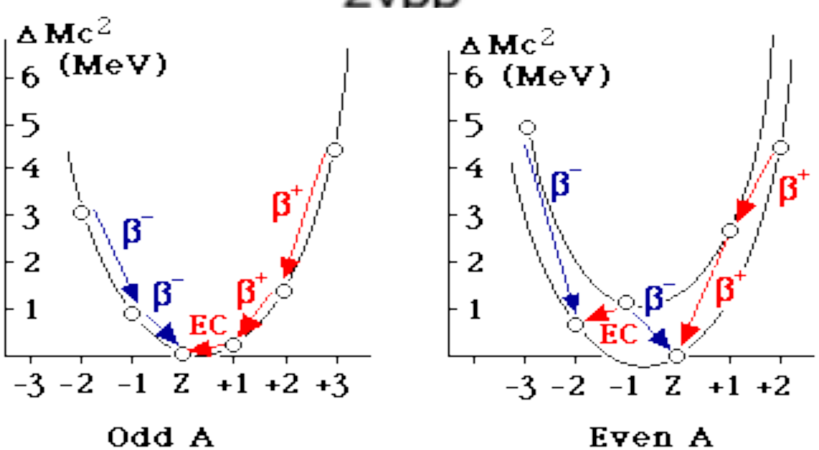
- Double Beta Decay in brief
- UK Experiments
- World-wide activity
  - ^{76}Ge: GERDA, Majorana
  - ^{130}Te: CUORE
  - ^{136}Xe: KamLAND-Zen, EXO

Double Beta Decay

$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}_e$ $(A,Z) \rightarrow (A,Z+2) + 2\,e^-$







- Only Observed if Majorana Neutrinos
  - GUTs and leptogenesis
- Rate proportional to absolute Neutrino Mass Scale

Neutrinoless Double Beta Decay

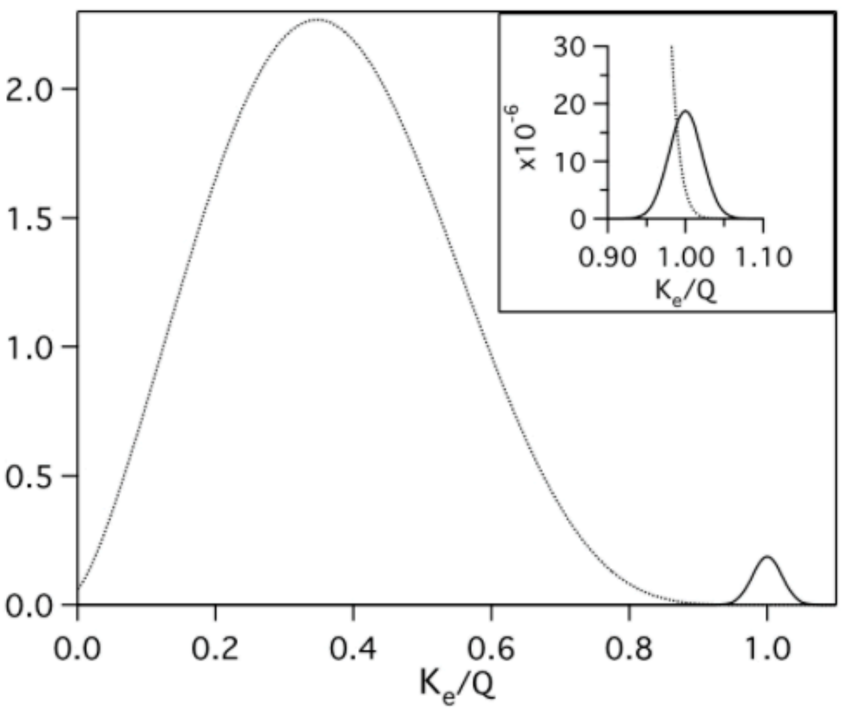
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Phase space → $G^{0\nu}$

Nuclear Matrix Element → $M^{0\nu}$

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$$

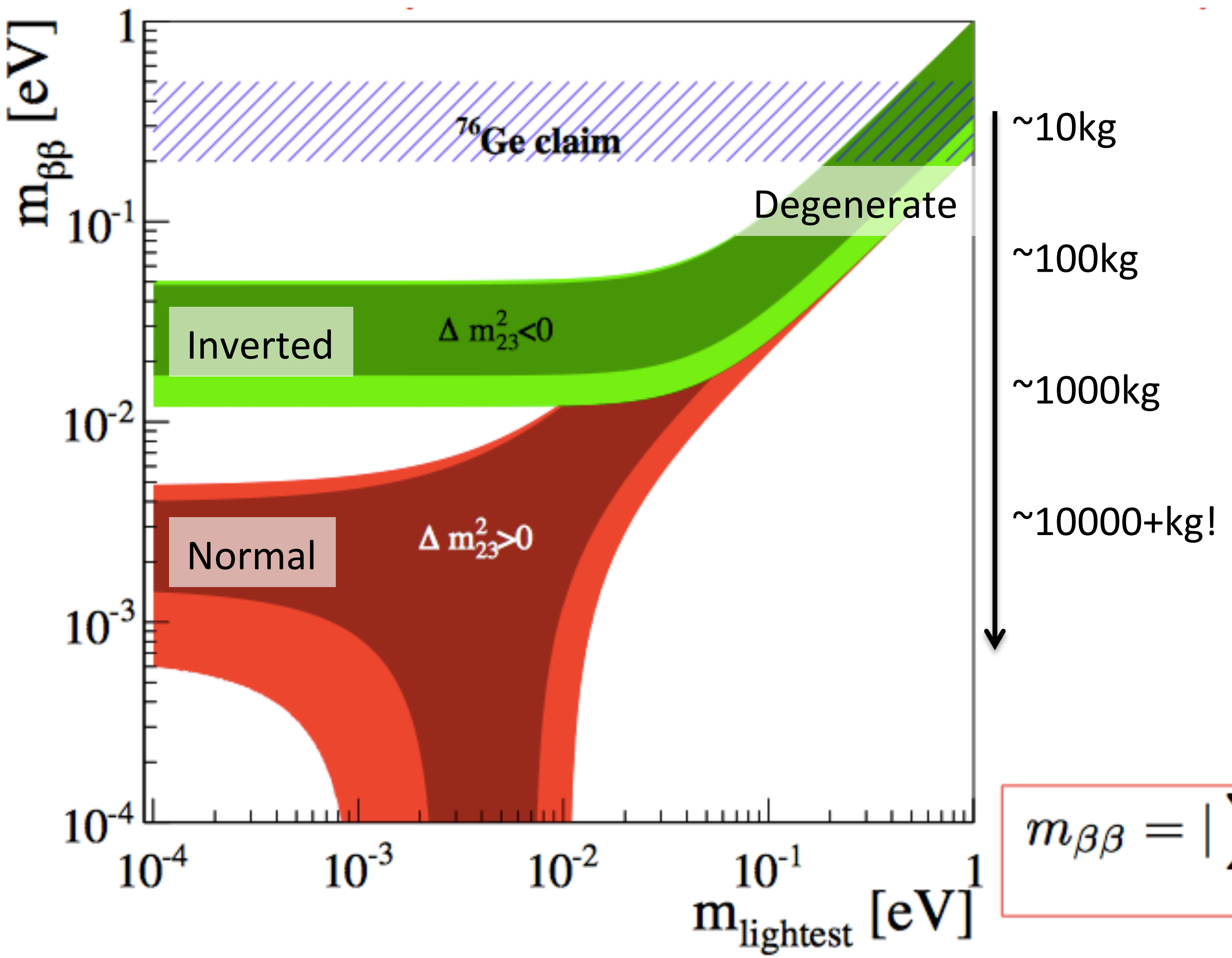
Sum of the electron kinetic energies, normalized to the endpoint Q.



<u>Experiment options</u>

- Select isotopes with favourable phase space
- Select isotopes with favourable matrix elements
    - Beware large uncertainty / differences between models
- Select isotopes with large abundance or good enrichment opportunity
- Good energy resolution
- Low Backgrounds in region of interest (ROI)

Experimental Sensitivity



$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

Massive detector provides self shielding from external backgrounds

^{130}Te

: Large natural isotopic abundance (34%), so no enrichment needed to deploy tonne-scale of isotope

: High half-life of 2ν mode (7.0×10^{20} yr) relative to possible 0ν transition compared to other isotopes

Liquid scintillator

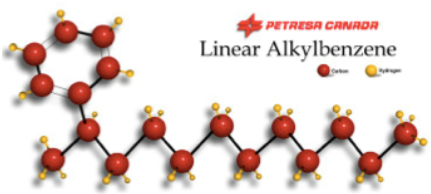
: Can be purified on-line

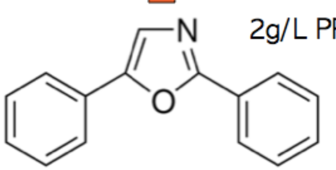
: Loading can be changed, scalable

: Fast timing allows rejection of several time-correlated radioactivity backgrounds

SNO+ Detector

- 12m diameter Acrylic Vessel
- 780 tonnes scintillator



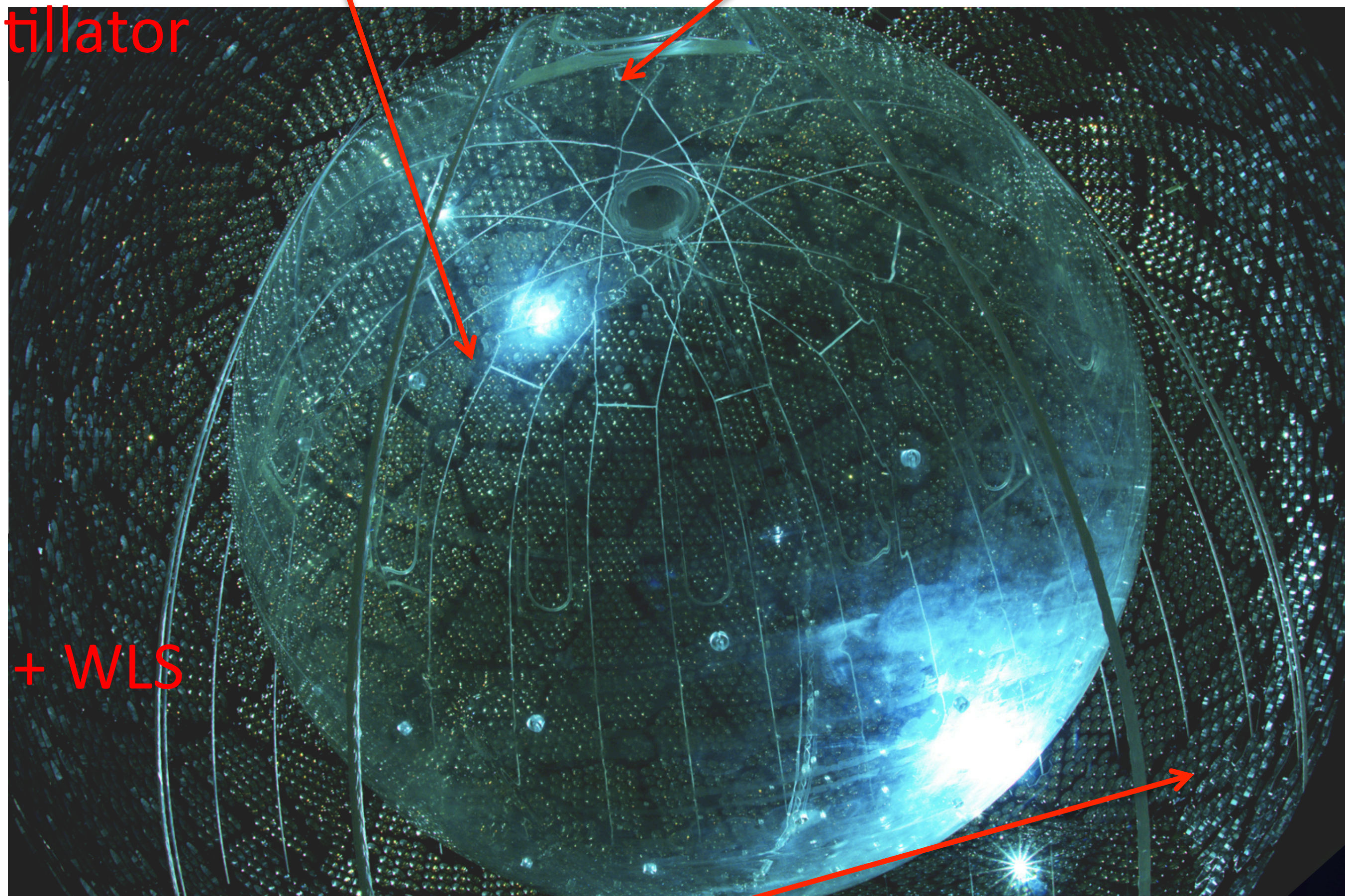


2g/L PPO

- + Telluric acid

+ H_20 + surfactant + WLS

Hold down rope net



- 7ktonnes water shielding
- ~9300 8inch PMT array

90 members, 6 countries, 23 institutions

Backgrounds co-coordinator
Analysis Co-coordinator
Calibration coordinator
Software co-cordinator

Scintillator Development coordinator

Processing coordinators

Lancaster
Liverpool
Oxford
QMUL
Sussex

SNO+ Status

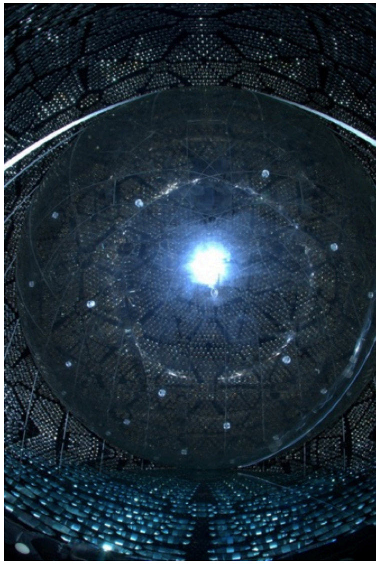
- Milestones
  - Scintillator plant main installation complete
  - Helium Leak checking complete
  - Cleaning and passivation ~done
  - Successfully tested loading on AV hold-down ropes
  - Electronics upgrades and PMT repairs
  - In-situ optical fibres for calibration (LED and laser)

    JINST Vol. 10, P03002 (2015)
  - Te loading and purification methods developed, can now all be accomplished underground

    S. Hans et al., NIMA795 (2015)
  - First tonne Te purchased, "cooling down" in SNOLAB (0.13% loading)
  - Additional Canadian funding will now allow us to go up to 0.5% loading in Phase I
  - New loading approach developed at Oxford is now being seriously considered - promises higher light yield, lower backgrounds, likely easier to implement.
    - Possible route to Phase II with PMT upgrade.

SNO+ Status

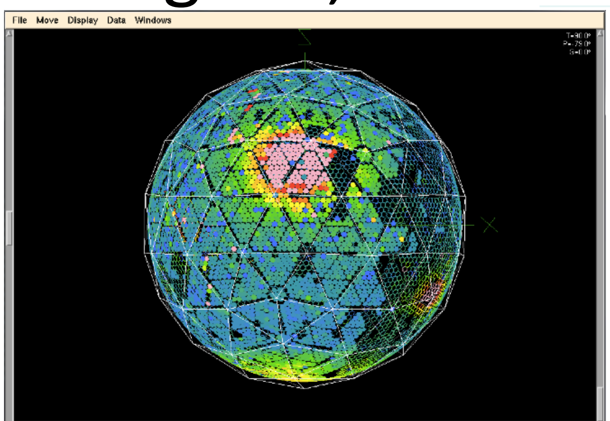
- Set-backs
  - Significant cavity water leak – currently lowering water level to identify and fix problem

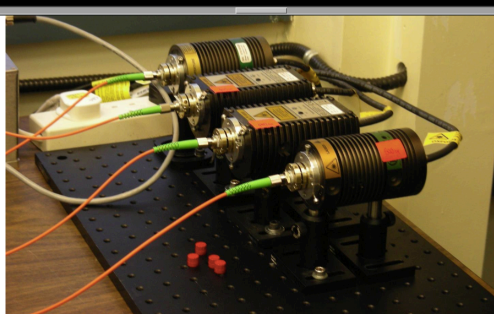


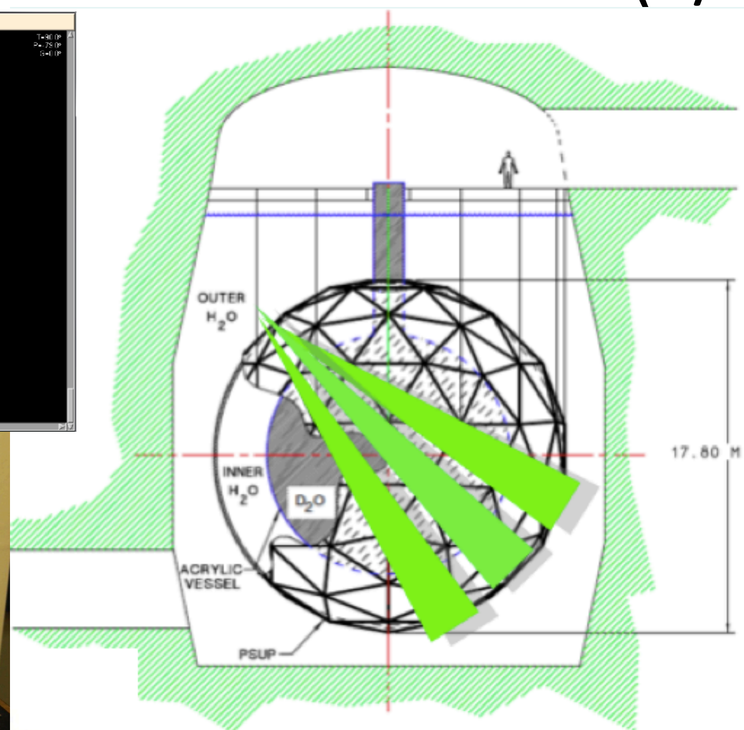
- Next Steps:
  - Commissioning detector with water
    - Optics, detector backgrounds
    - Nucleon decay, solar axions, anti-ν
  - Scintillator plant safety review and commissioning
    - ➢ Scintillator fill ~1 year from now
    - Calibrations, Background studies
    - Solar neutrino sensitivity, Supernova, Reactor, Geoneutrinos
  - Start Te deployment early 2017
    - **$0\nu\beta\beta$**, Supernova, Reactor, Geoneutrinos

Calibrations

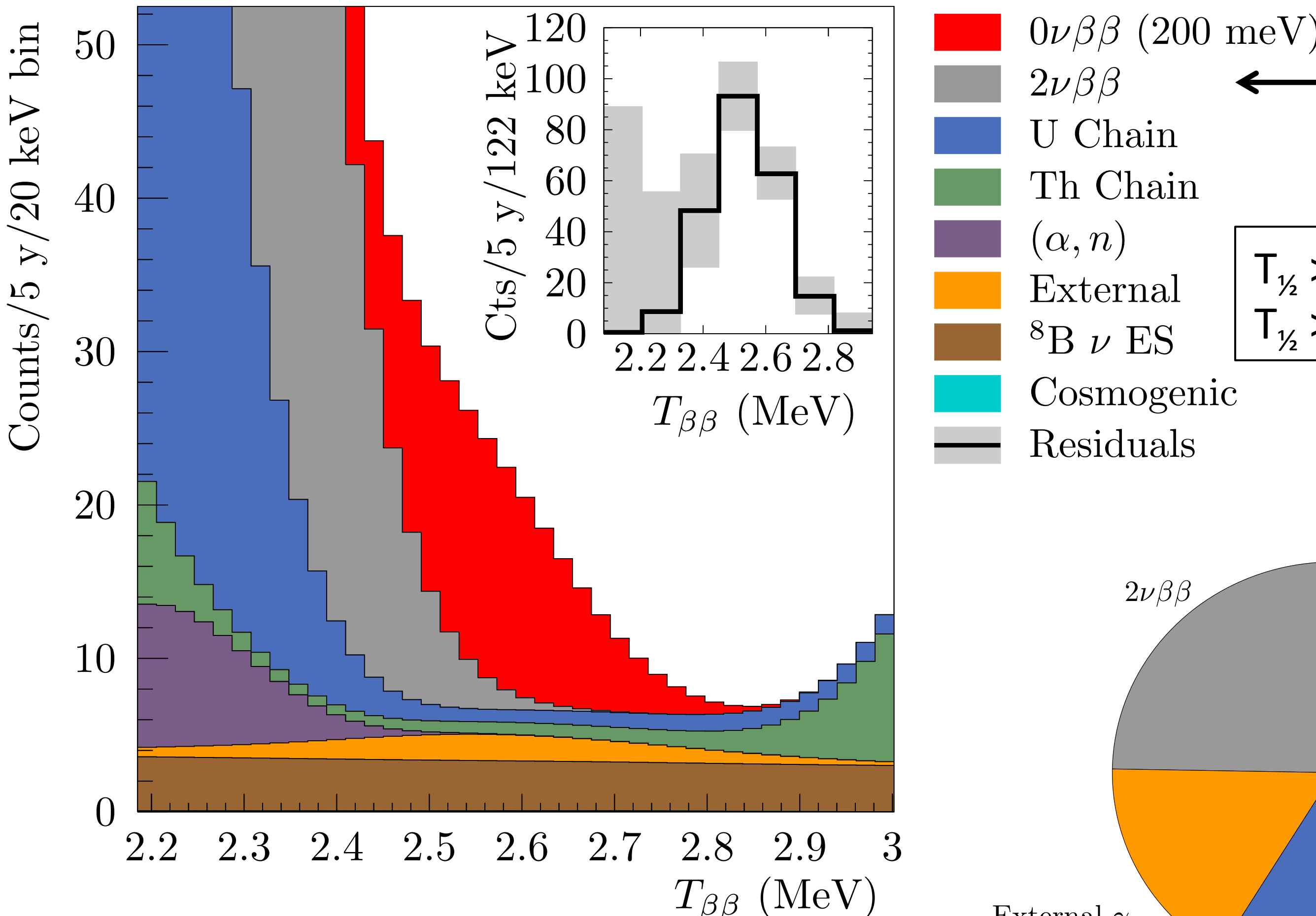
- ELLIE light injection system (UK + Portugal)
  - PMT timing calibration (TELLIE) LEDs
  - In-situ scattering measurement (SMELLIE) Lasers
  - Attenuation monitoring (AMELLIE) LEDs
- >100 fibres mounted on PMT support structure allows regular, non-invasive calibration (2/3 installed by boat)



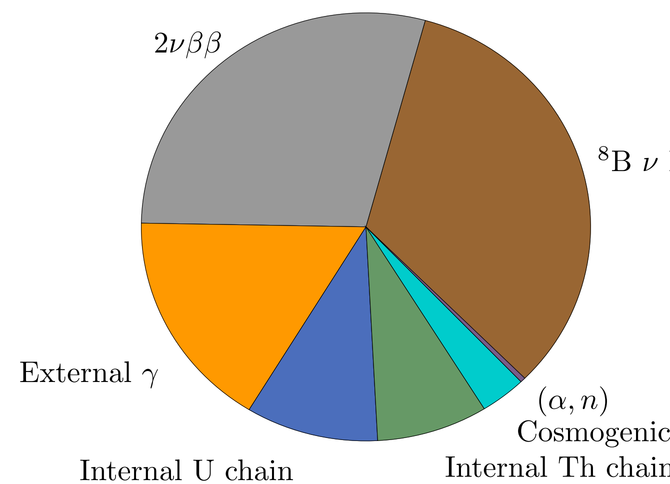




SNO+ (^{130}Te)

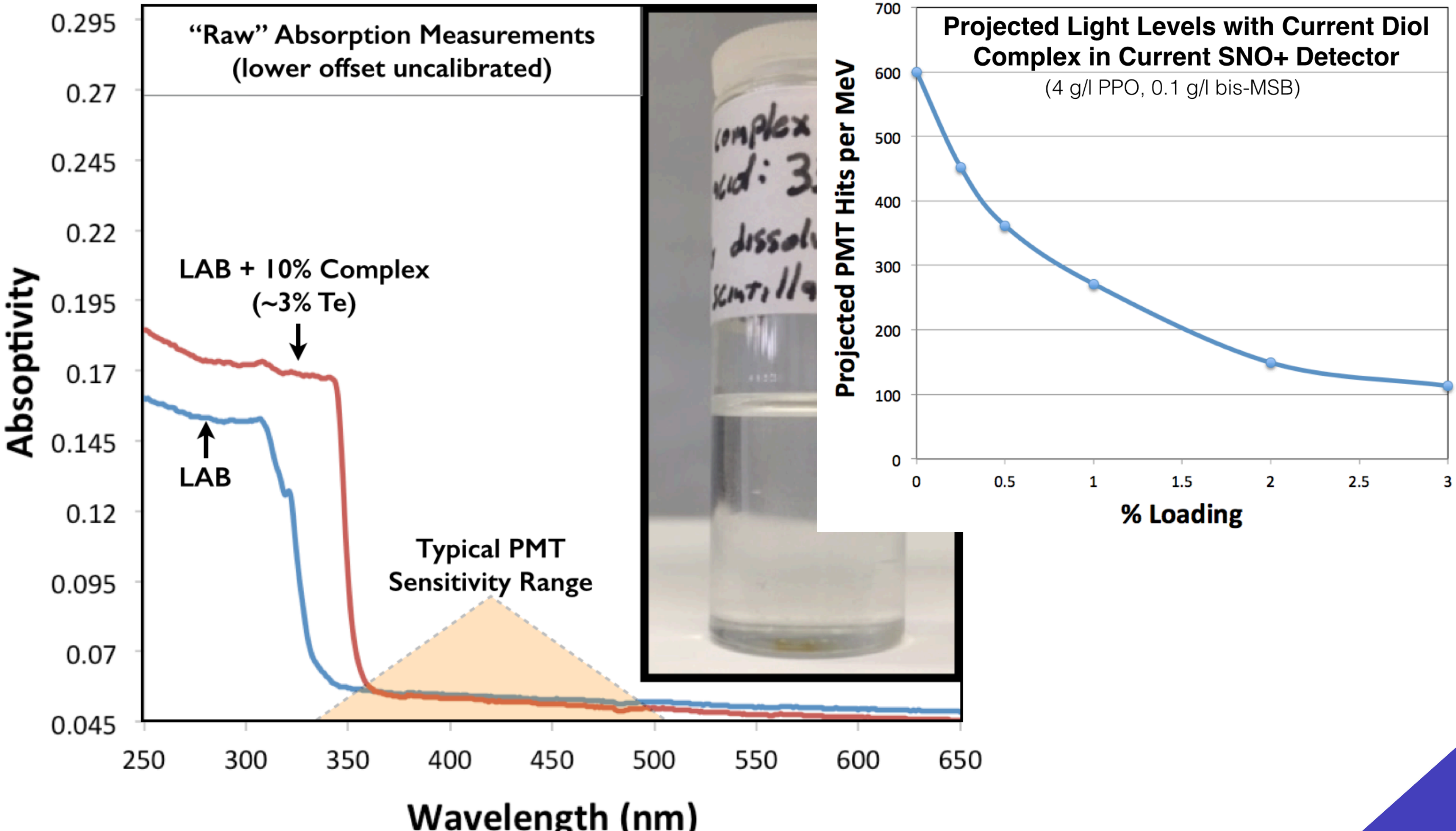


$T_{½} > 3.9 \times 10^{25}$ y (1 year,0.3%)
$T_{½} > 9.0 \times 10^{25}$ y (5 year,0.3%)



http://arxiv.org/abs/1508.05759

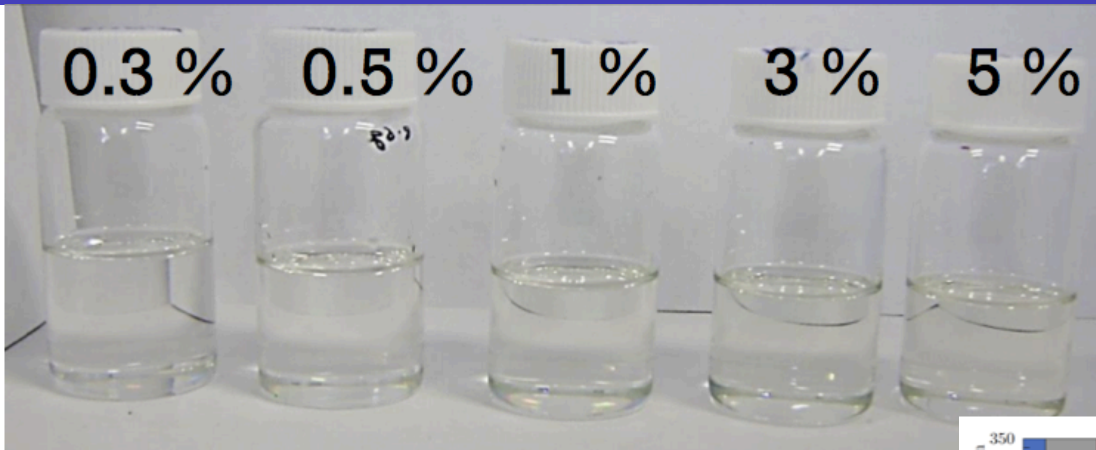
Diol Complexes

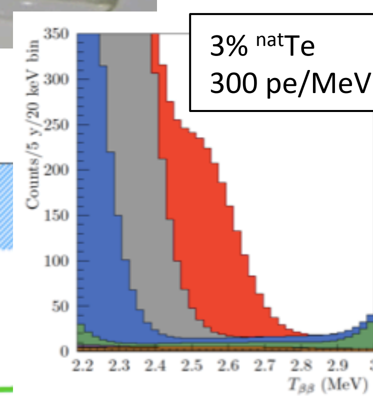


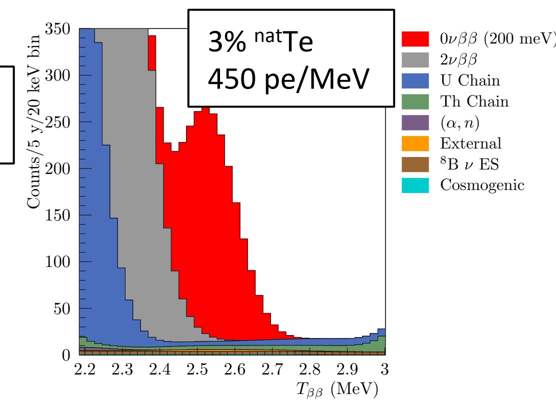
- Promises higher light yield, lower backgrounds, likely easier to implement.
- Quenching at ~% level but possible route to Phase II with PMT upgrade.

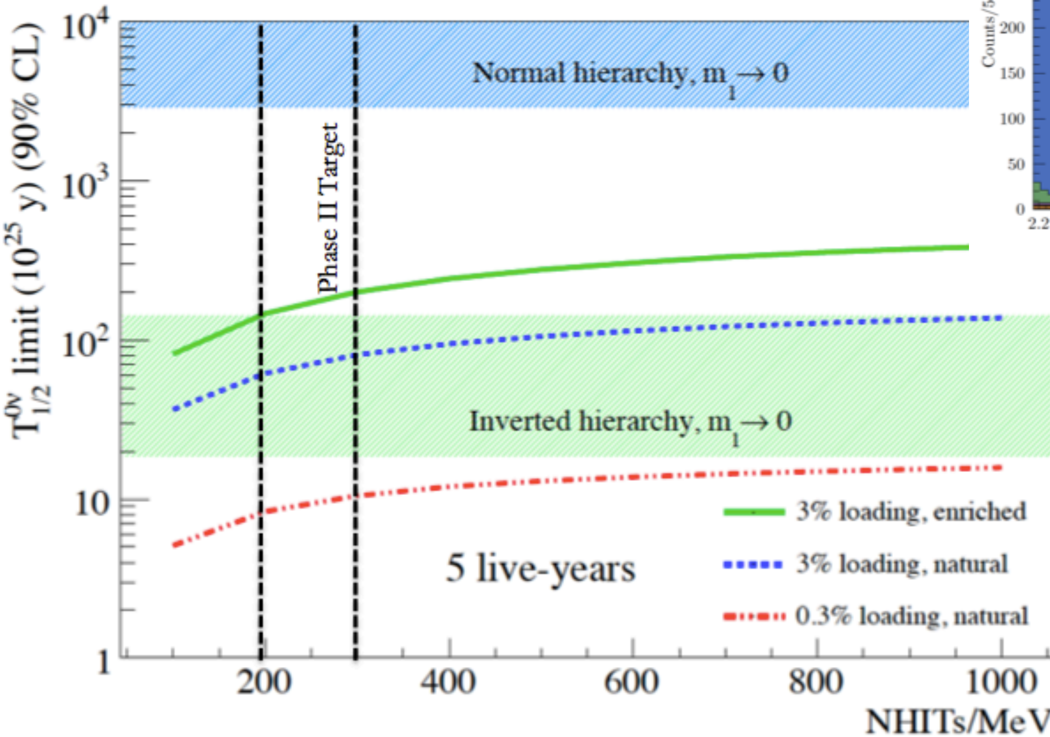
SNO+ future

	$T^{½}_{0\nu}$ sensitivity
0.3% Te, 1 yr	3.9×10^{25} yr
0.3% Te, 5 yr	9×10^{25} yr
3% Te, HQE PMTs	7×10^{26} yr





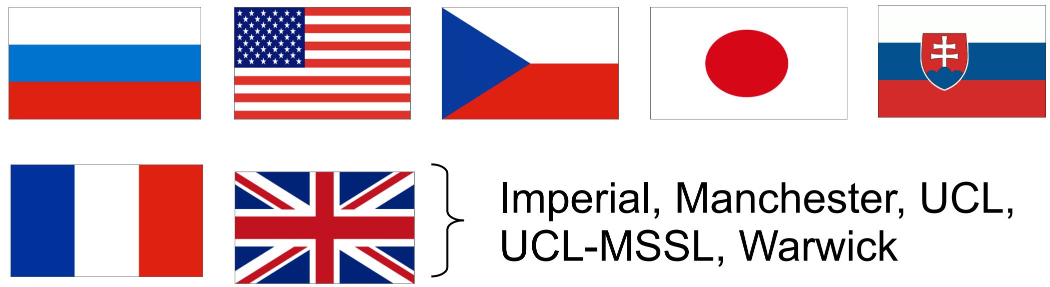




- R&D into surfactant + Cocktail developments to increase light yield, new surfactants, diols …
- Investigate bag to contain Te-loading to fiducial volume
- Upgrade to High QE PMT array

SuperNEMO

supernemo collaboration



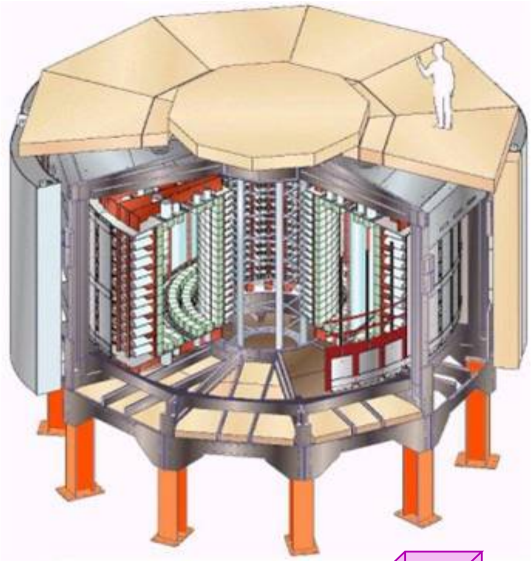
Imperial, Manchester, UCL, UCL-MSSL, Warwick

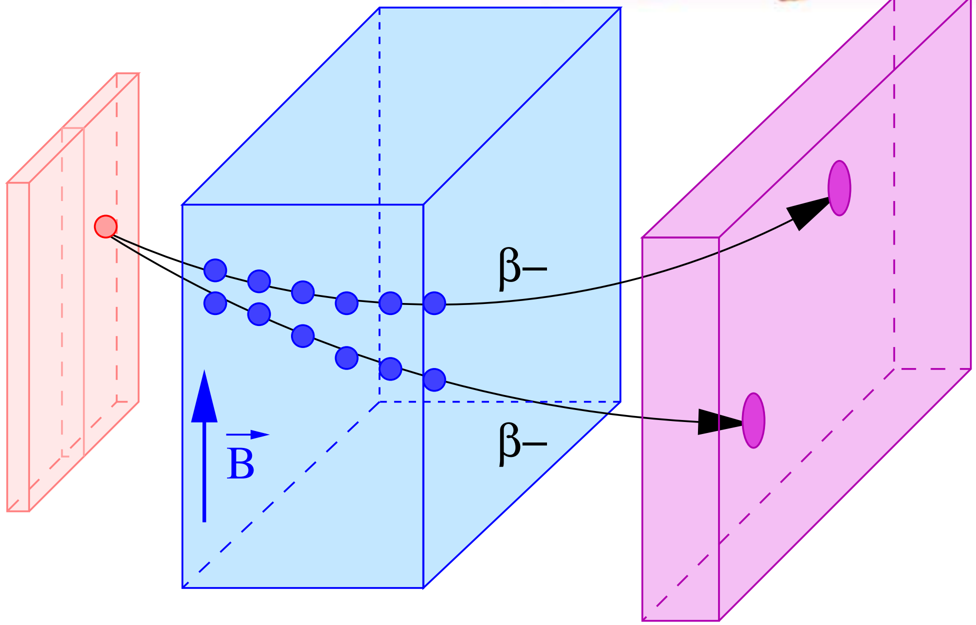
The goals of SuperNEMO :

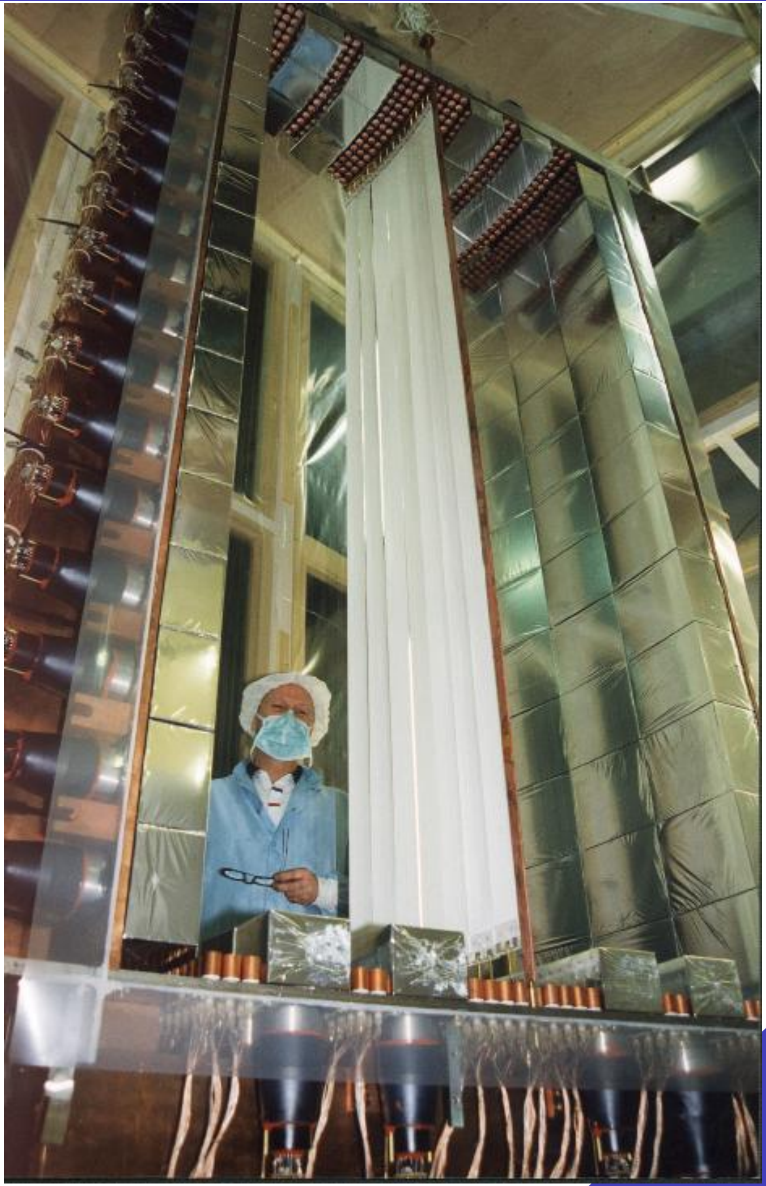
1. Build on the experience of the extremely successful NEMO-3 experiment.
2. Use the power of the tracking-calorimeter approach to identify and suppress backgrounds. This will yield a zero-background experiment in the first (Demonstrator Module) phase.
3. Prove that a 100 kg scale experiment can reach 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

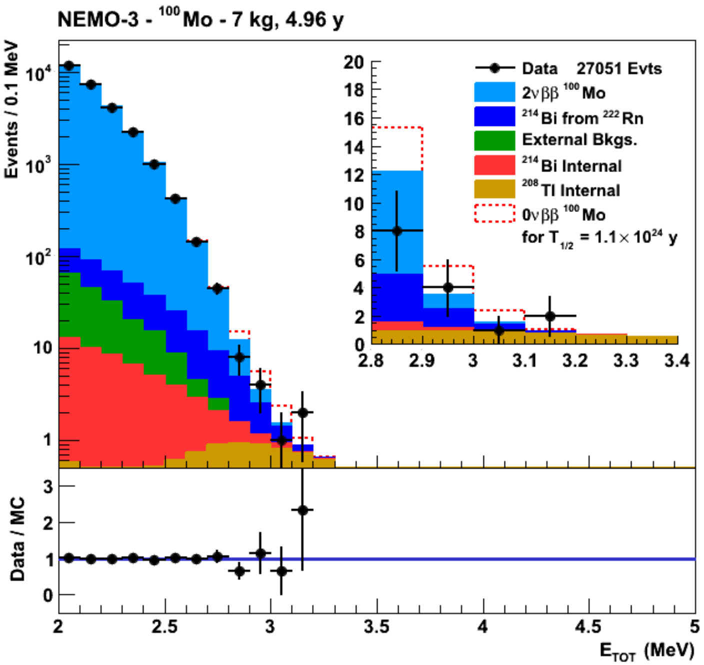
- Tracking-calorimeter detector.
- Situated in Laboratoire Souterrain de Modane (LSM) : 4800 M.W.E.
- Ran from 2003 – 2011
- Decommissioned to make space for the Demonstrator Module







Recent NEMO-3 Results: All Have Major Involvement



Final result with ^{100}Mo – 7kg

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

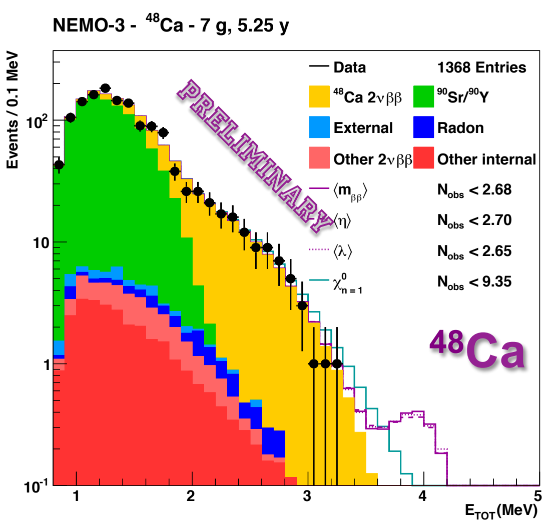
- For the Majorana mass mechanism :

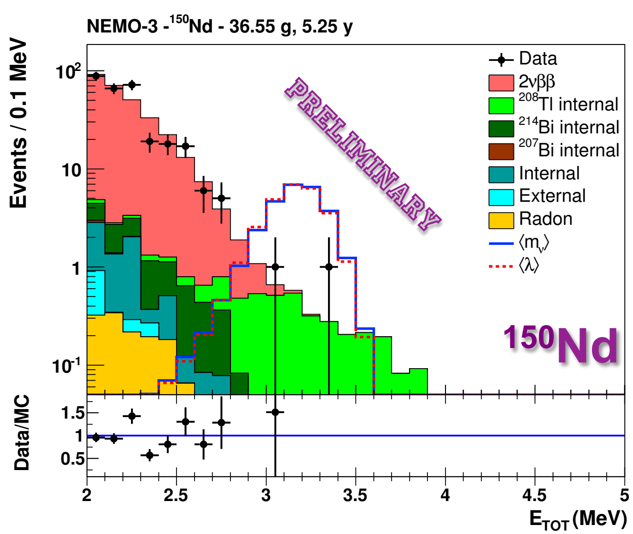
$$\langle m_\nu \rangle < 0.3-0.6 \text{ eV}$$

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

Phys.Rev. D**89** (2014) 11, 111101

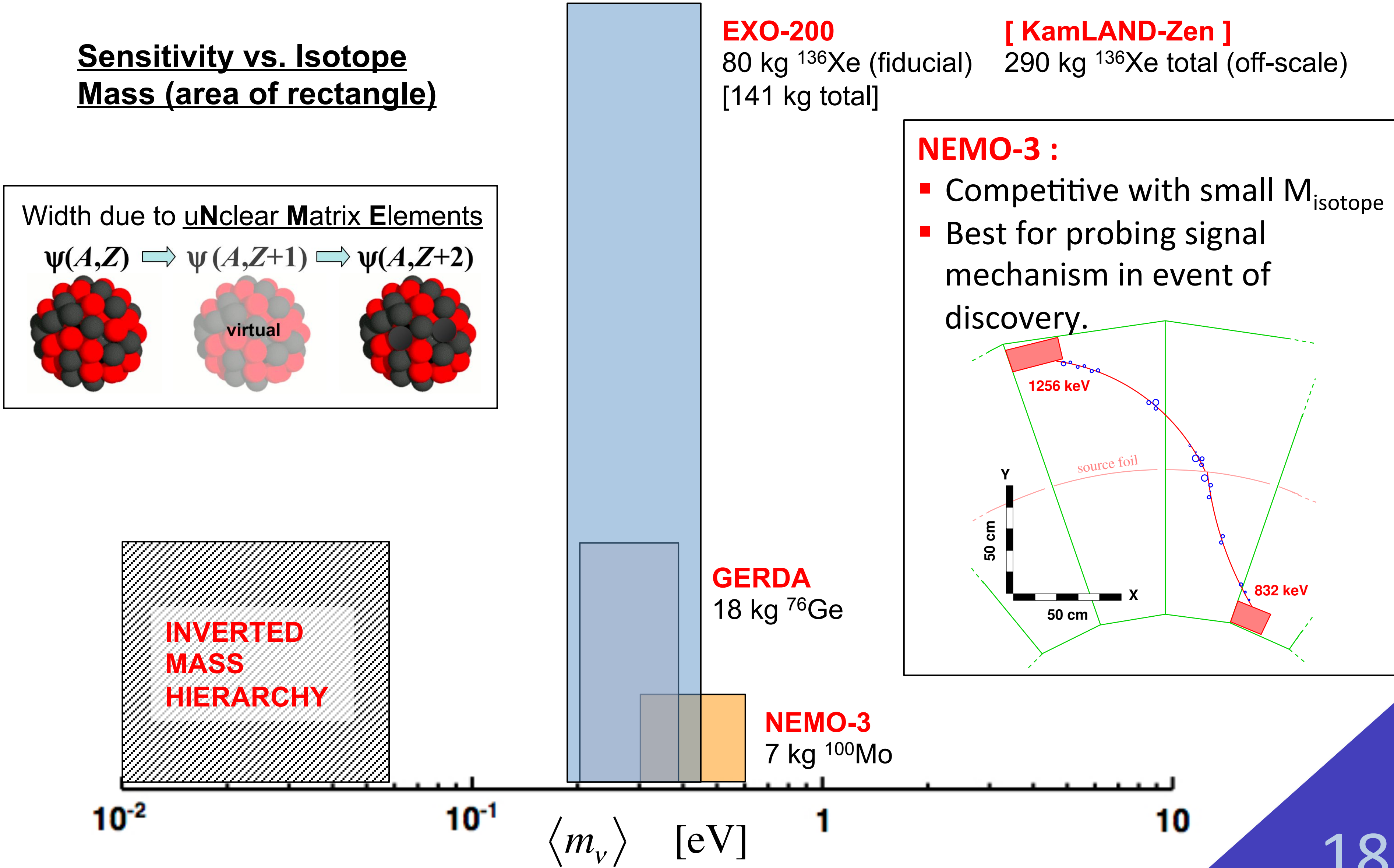
arXiv:1506.05825





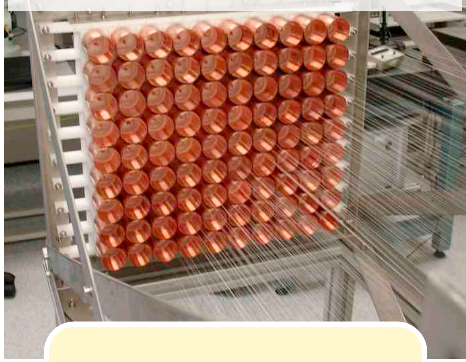
- Final analyses of NEMO-3 data currently being published : more than 50% are UK led.
- Two PhDs completed since the last PPAP meeting in 2014.

World's Best Limits



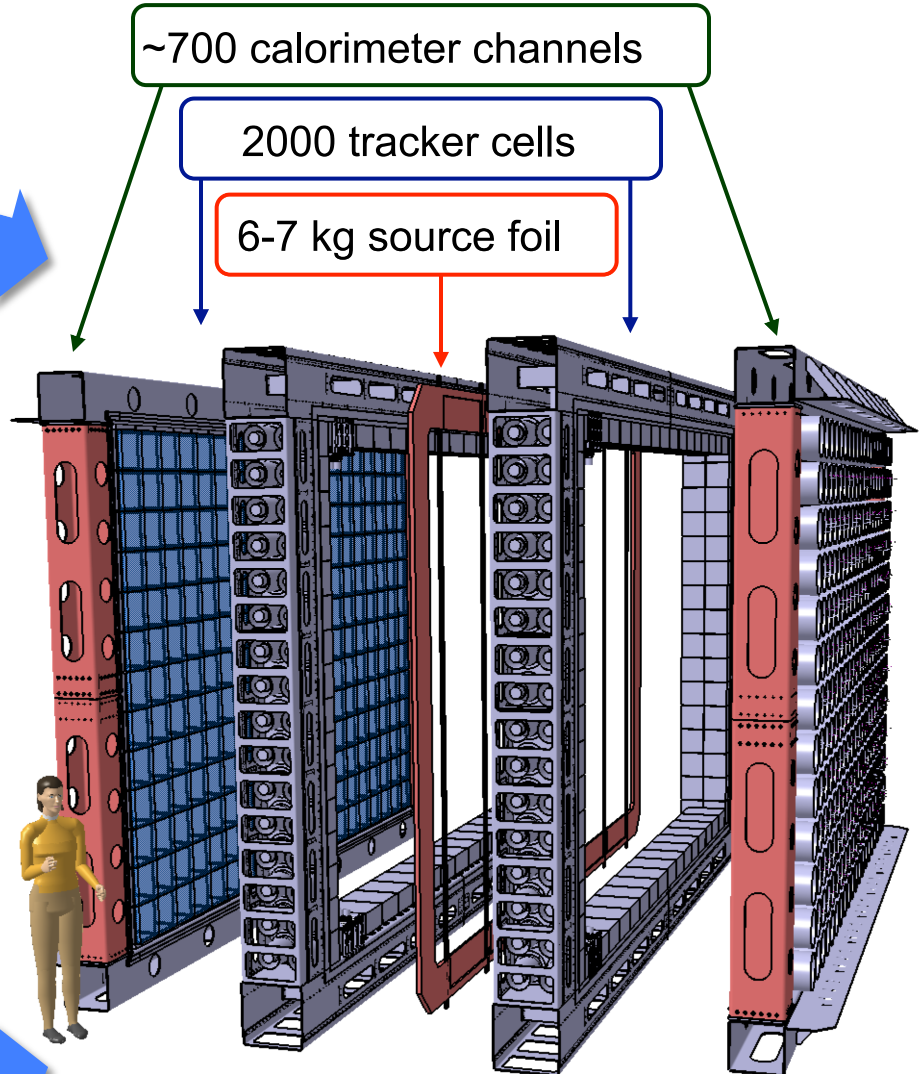
SuperNEMO Demonstrator Module: Overview

Tracker Prototype
Prove Mass Production



UK R&D

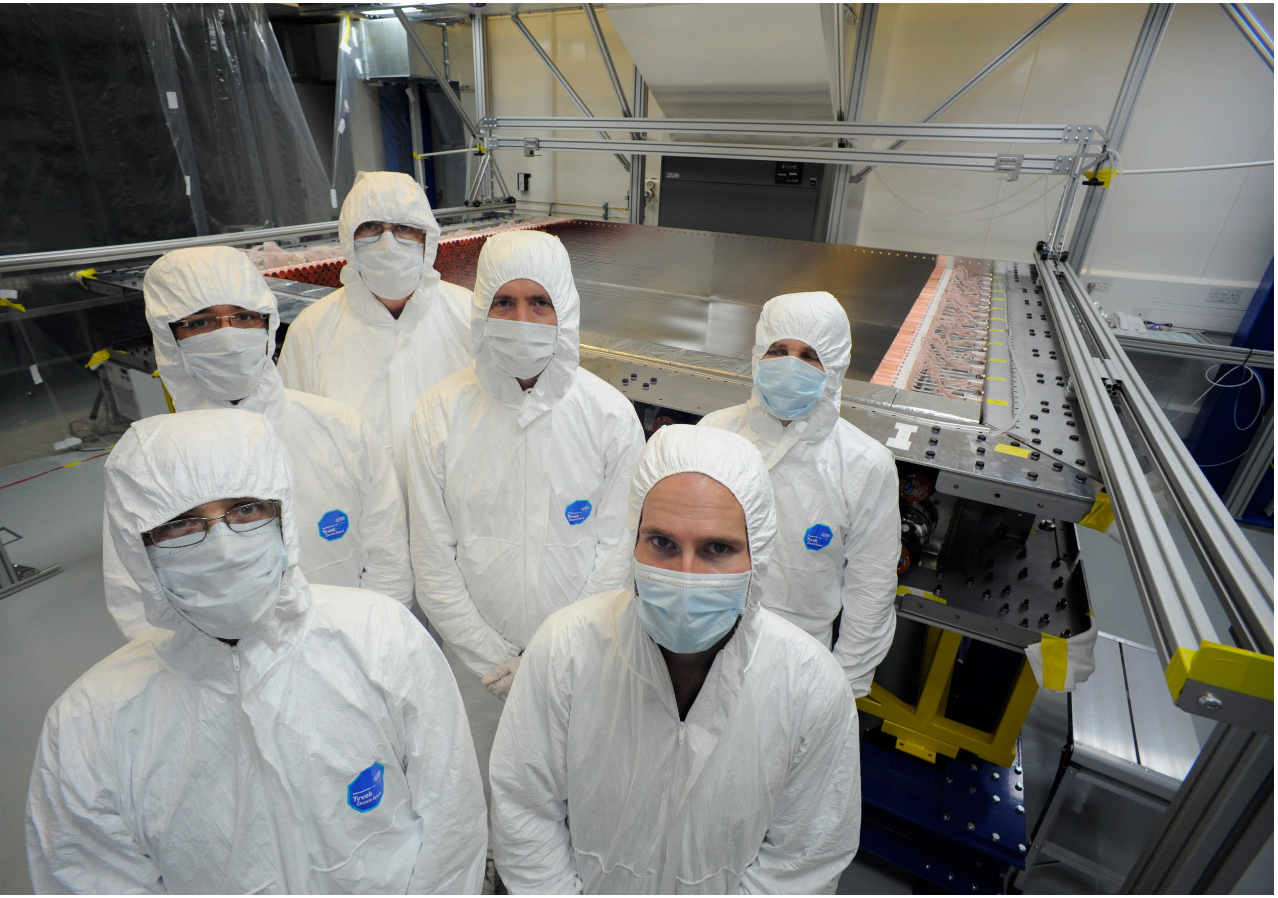
Calorimeter R&D
Demonstrate
FWHM~7% @ 1 MeV

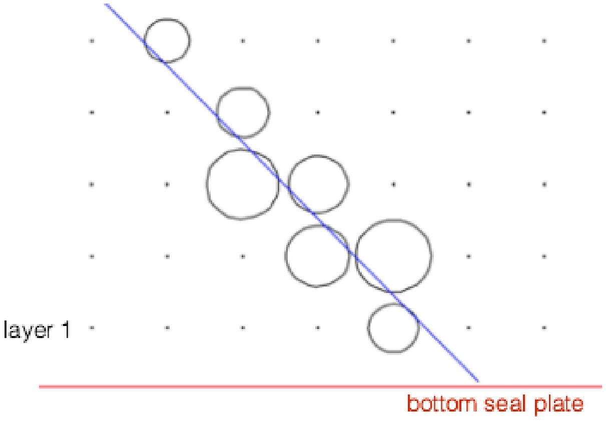


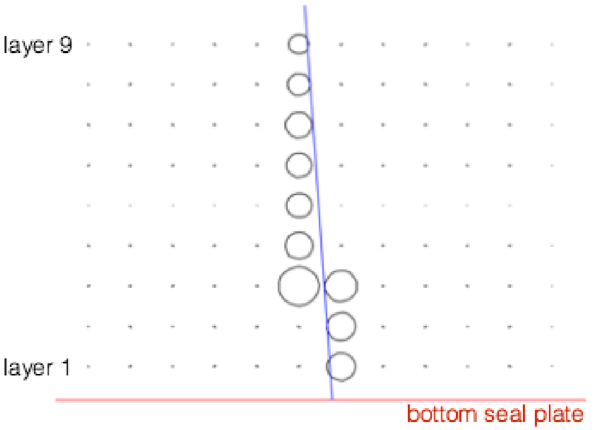
Demonstrator Module

- Change isotope $^{100}Mo \longrightarrow {}^{82}Se$ (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 Status



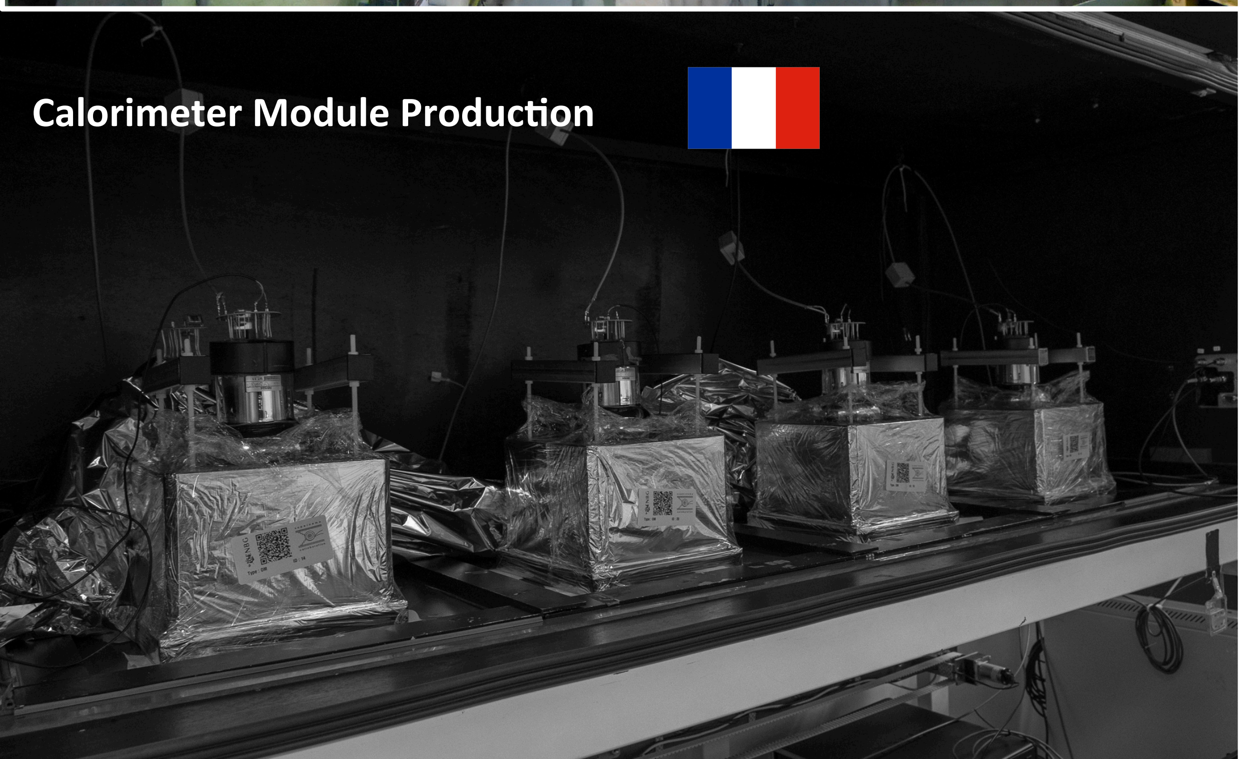




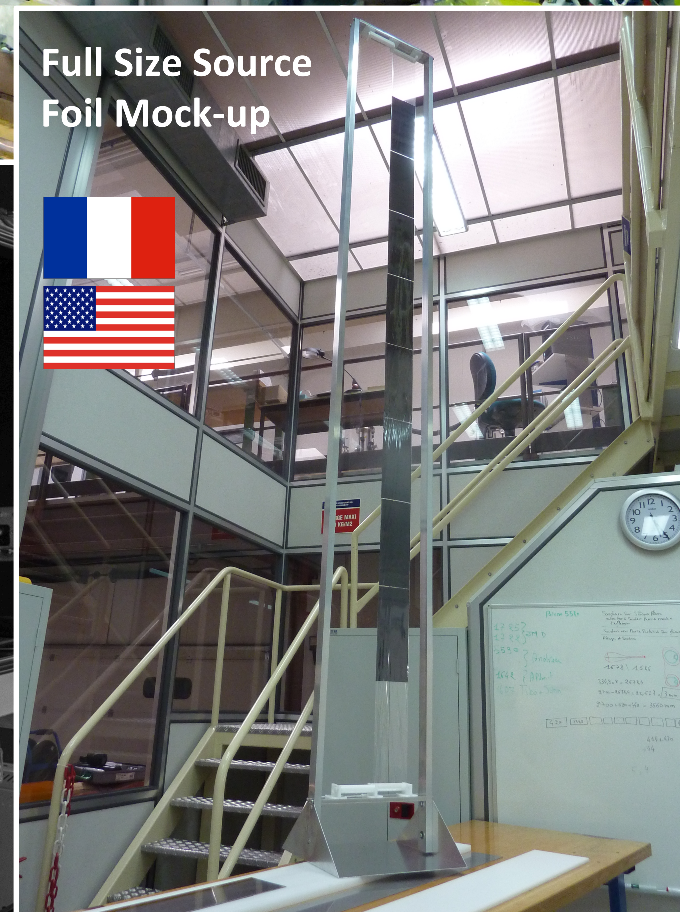
- First tracker module completed October 2014.
- Fully tested and commissioned with cosmics : > 98% good channels.
- Meets background (radon) requirements.

SuperNEMO Construction Status

Support Structure & Clean-Tent at LSM



Calorimeter Module Production



Full Size Source
Foil Mock-up

SuperNEMO Construction Status

Transport Container

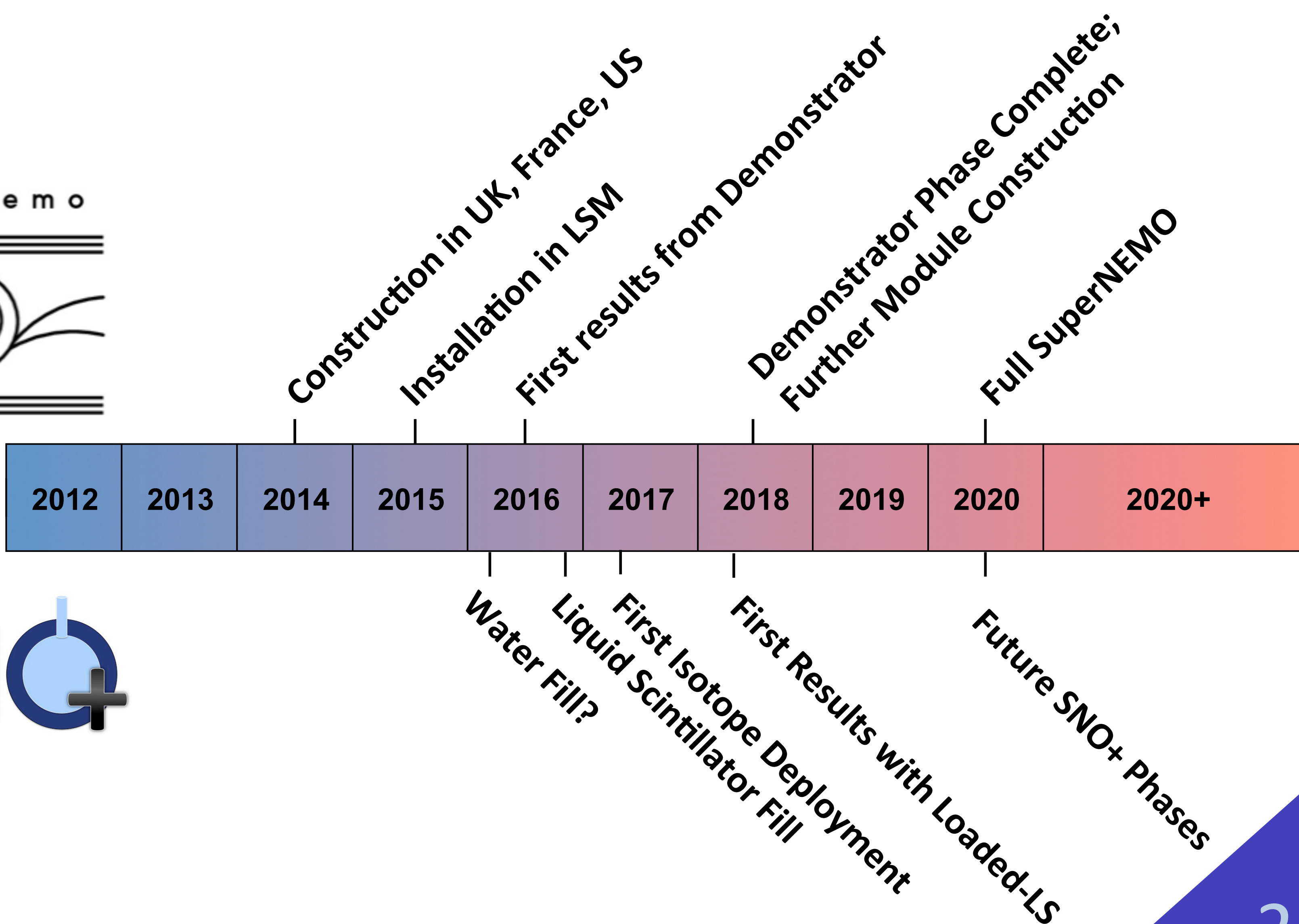
Transport Clean Bag

- Second module completed June 2015, 3rd / 4 underway

  -> construction of trackers for demonstrator more than 50% complete.

- *The first module is leaving for the LSM tomorrow !*
- On track to complete the Demonstrator Module construction & assembly in 2016.

Timescales


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+
Water Fill?
Liquid Scintillator Fill
First Isotope Deployment
First Results with Loaded-LS
Future SNO+ Phases

Other Experiments

^{130}Te

CUORE:

TeO crystal Bolometers

(Cuoricino -> CUORE-0 -> CUORE -> CUPID)

^{136}Xe

KamLAND-Zen:

Enriched ^{136}Xe loaded LS in Bag

EXO:

^{136}Xe liquid TPC (EXO-200 -> nEXO)

^{76}Ge

GERDA:

HPGe array, Lar cryogenic shield

Majorana:

HPGe, high purity Cu shield

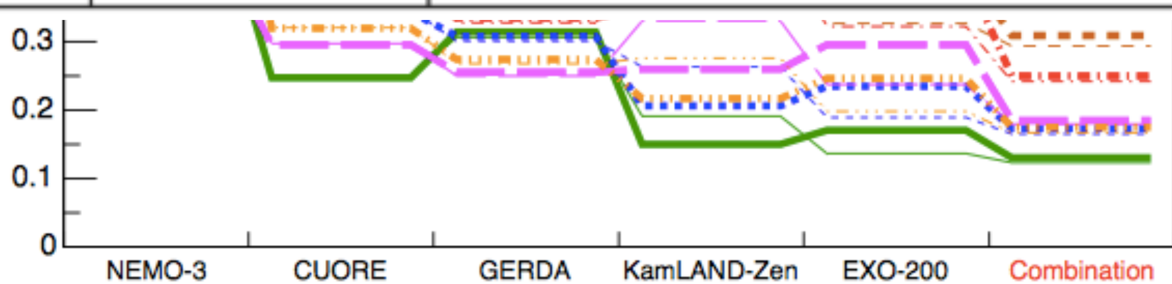
Summary Table

Experiment	Isotope/Method	$T^{1/2}_{0\nu}$ Limits (90% CL) Predicted / Solo / combined	Future	Predicted Sensitivity (5 years)*
SNO+	^{130}Te liquid scintillator	3.9×10^{25} y (0.3% loading, 1 year)	SNO++ (3% loading, HQE PMTs)	7×10^{26} y
NEMO-3 SuperNEMO	^{100}Mo ^{82}Se Source foils and tracking	1.1×10^{24} y 6.5×10^{24} y (7kg demonstrator)	Full 100kg	1×10^{26} y
GERDA	^{68}Ge HPGe	2.1×10^{25} y 3.0×10^{25} y	Future ^{76}Ge	3.2×10^{27} y
Majorana	^{68}Ge HPGe	1×10^{25} y (30kg.y)	"	"
Cuoricino CUORE-0 CUORE	^{130}Te bolometers	2.8×10^{24} y 2.7×10^{24} y 4.0×10^{25} y	CUPID	(2-5) $\times 10^{27}$ y (*10 years)
KamLAND-Zen	^{136}Xe liquid scintillator	2.6×10^{25} y	KamLAND2-Zen	10^{26}- 10^{27} y (*20meV)
EXO200	^{136}Xe TPC	1.1×10^{25} y	nEXO	6.6×10^{25} y

Combining Results

- Phys Rev D **92**, 012002, & P Guzowski, TAUP2015
- Experiments measure half-life
- Combined limits on $m_{\beta\beta}$ dependent on NME

Isotope	Phase Space Factor $G^{0\nu}$ $(10^{-14} y^{-1})$	Nuclear Matrix Element							
					RQRPA				
		GCM	IBM	NSM	A-old	A-new	B-old	B-new	QRPA
^{76}Ge	0.615	4.60	5.42	2.30	5.812	5.157	6.228	5.571	4.315
^{100}Mo	4.142	5.08	3.73	—	5.696	5.402	6.148	5.850	3.184
^{130}Te	3.699	5.13	4.03	2.12	4.306	3.888	4.810	4.373	3.148
^{136}Xe	3.793	4.20	3.33	1.76	2.437	2.177	2.735	2.460	1.795



Combining Results

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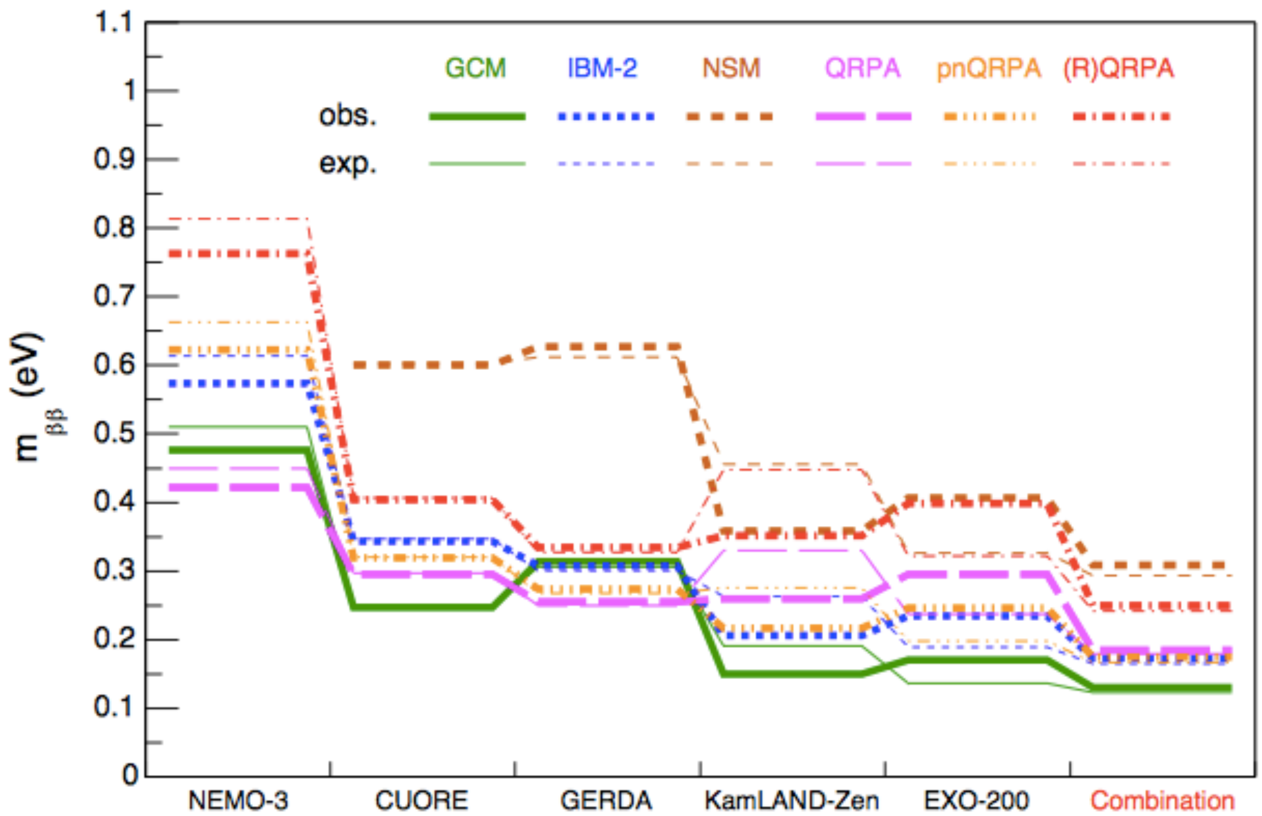
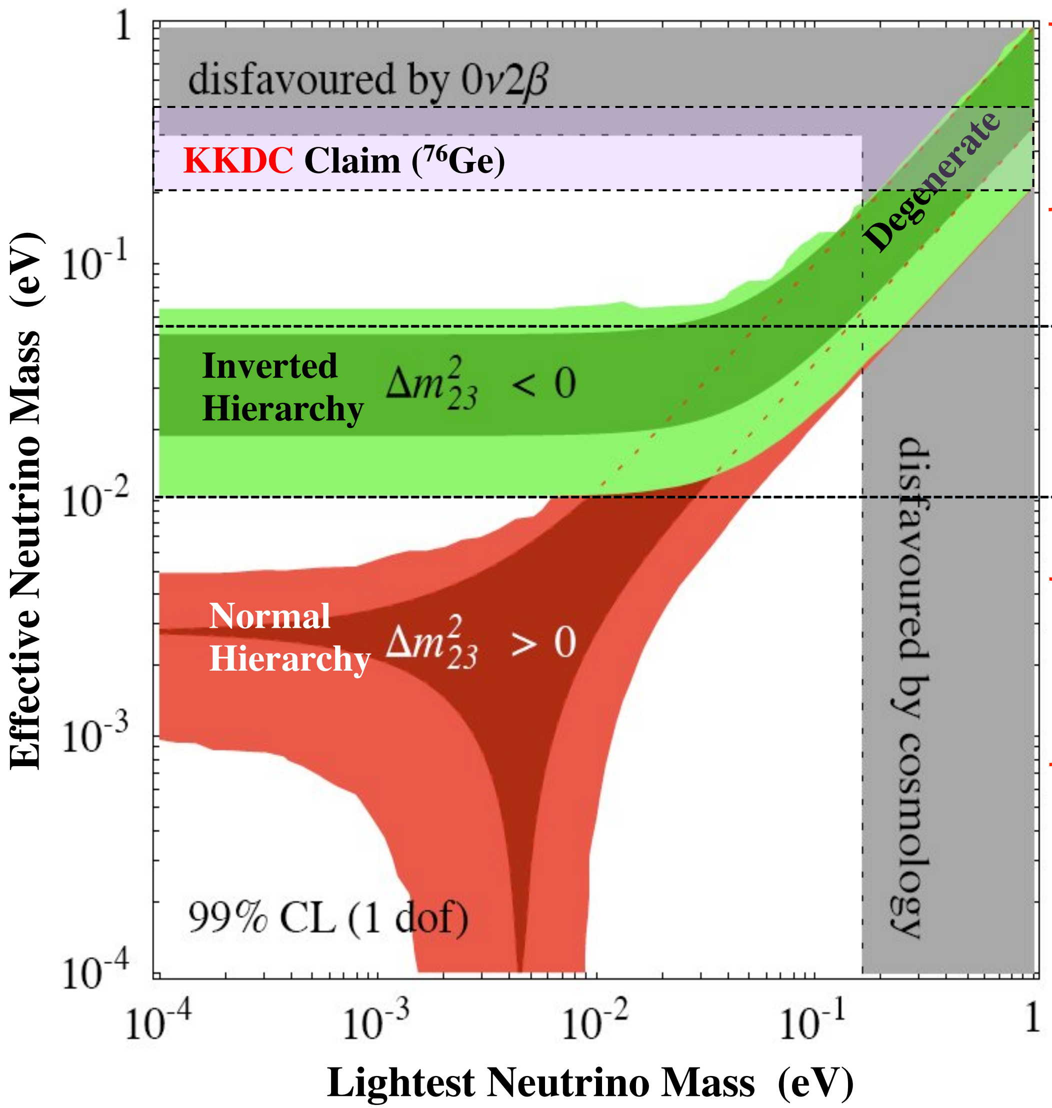
- Experiments measure half-life
- Combined limits on $m_{\beta\beta}$ dependent on NME



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.....
Biller, Physical Review D, 071301R

Summary

- UK heavily involved in two major 0νββ experiments
- Different isotopes, Different methodologies

Enriched ^{82}Se
Tracking -> Zero Background
Probe Mechanism

Large Mass -> Scalability
natural Te loading
(^{130}Te)

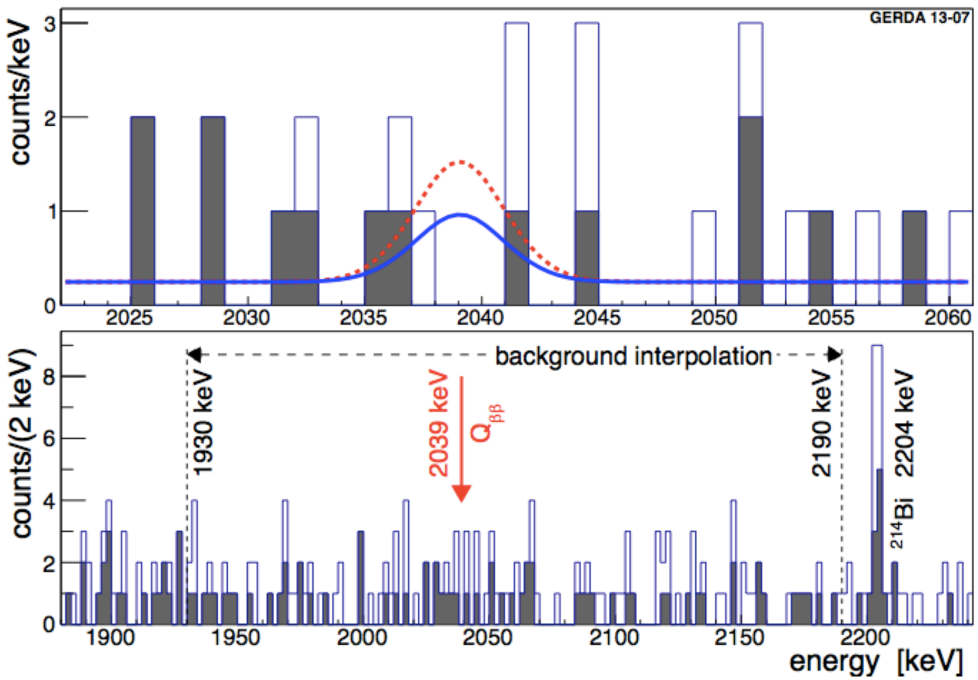
Backups

76 Germanium

GERDA

Phys. Rev. Lett 111 (2013) 122503
arXiv:1307.4720

- Enriched HPGe array
- LAr active cryogenic shield
- 18 kg of enriched 76Ge (Phase I)
- 40 kg of enriched 76Ge (Phase II)



<u>Phase 1 results</u>

21.6 kg·yr exposure

0.01 cts/(keV·kg·yr) after pulse shape discrimination

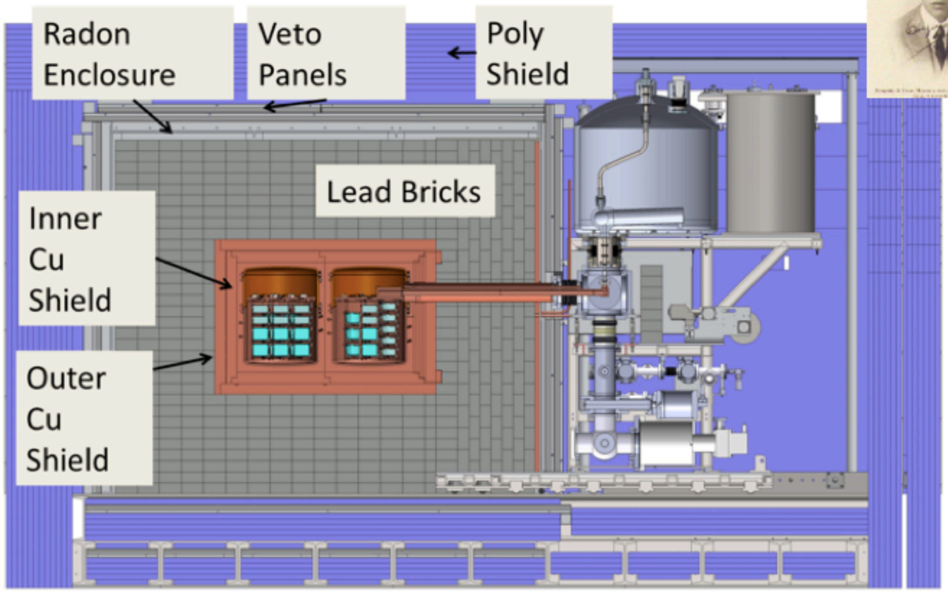
$T^{1/2}_{0\nu}$ > <u>2.1 · 10^{25} yr (90 % CL)</u>

+IGEX+HM = $T^{1/2}_{0\nu} > 3.0 \cdot 10^{25}$ yr (90 % CL)

Majorana

<u>Demonstrator:</u>

- 30kg (87%)enriched ^{76}Ge
- 15kg natural Germanium
- Sandford lab
- High-purity electroformed Cu shield (compact)
- arXiv:1501.03089



- Require <3 count/tonne/year in 4meV ROI
- ➔<1count/tonne year in ROI for tonne-scale experiment

- Need 30 kg.y exposure to test HM claim

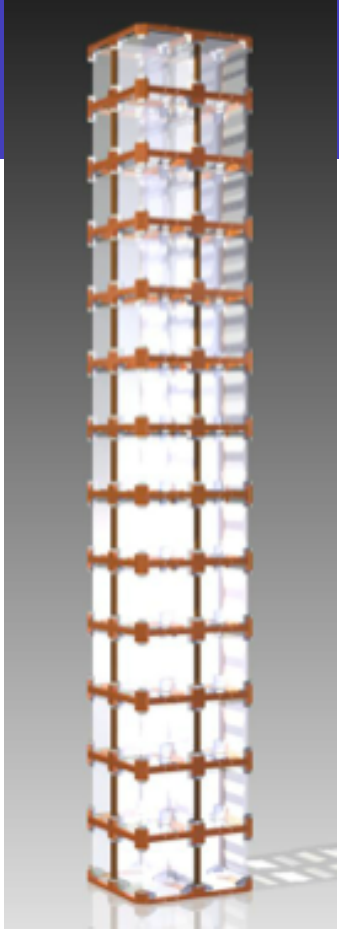
Future ^{76}Ge

- Majorana + GERDA → single international ^{76}Ge 0νββ Collaboration
- Tentative down-select 2017
- Stepwise implementation towards 1000kg
- 5 year 90% CL sensitivity $T^{½}_{0\nu} > 3.2\times10^{27}$ yr

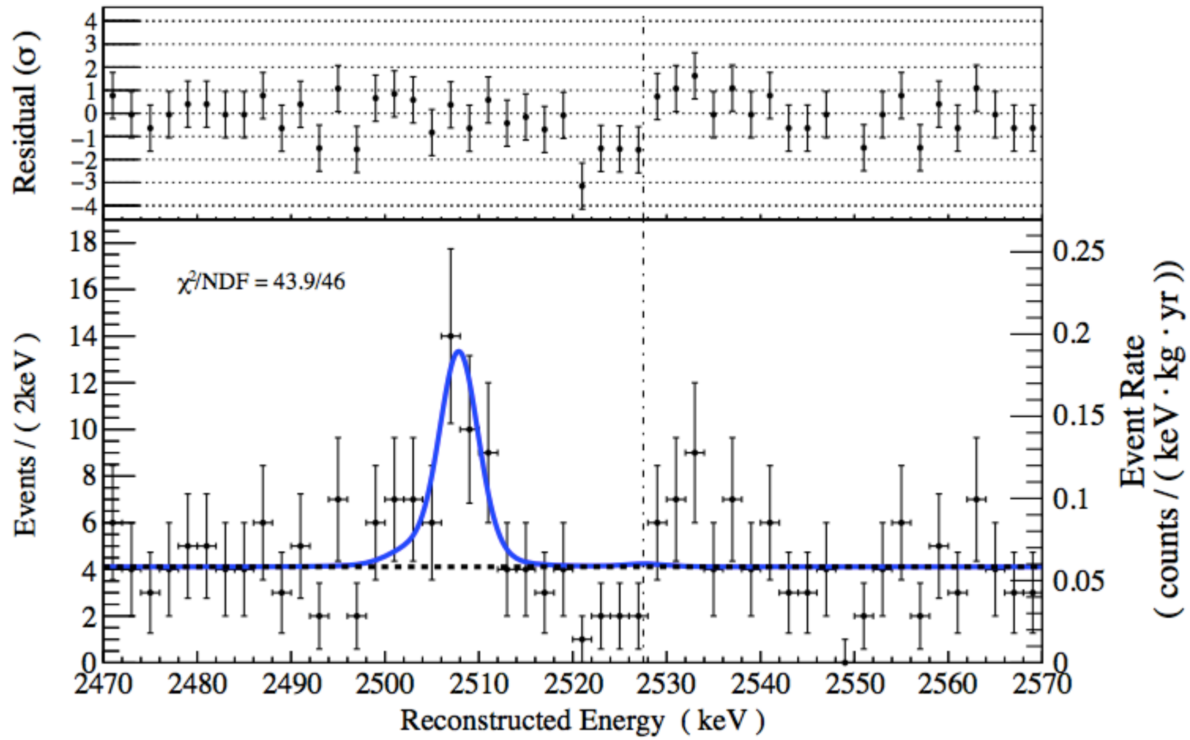
http://science.energy.gov/~/media/np/nsac/pdf/docs/2014/NLDBD_Report_2014_Final.pdf

130 Tellurium

CUORE-0



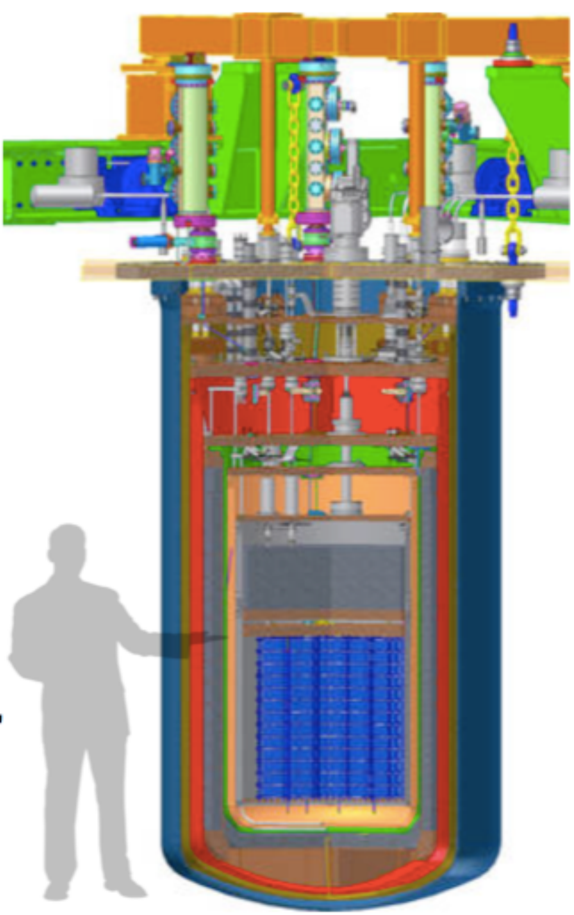
1 tower
52 crystals
10.9kg ^{130}Te



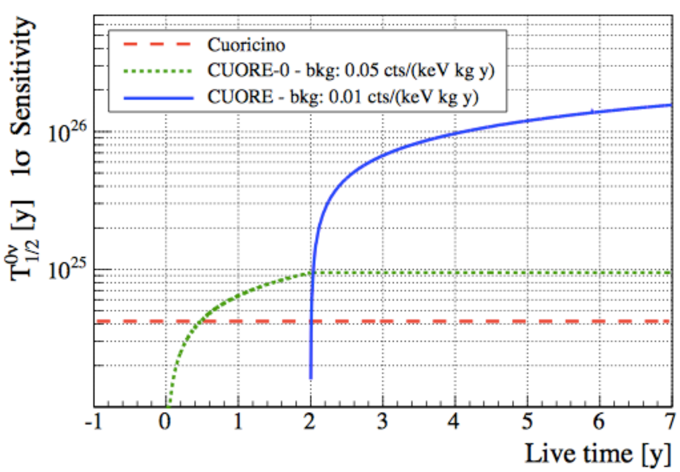
$T^{1/2}_{0\nu}$ > <u>2.7 × 10^{24} yr (90 % CL)</u> arXiv:1504.02454 (PRL)

- 11kg ^{130}Te operating 2013-2015 TeO_2 Cryogenic bolometers
- Energy resolution = 5.1 ± 0.3 keV (FWHM)
- Background = 0.058 ± 0.004 (stat.) ± 0.002(syst.) counts/(keV·kg·yr)
- In combination with Cuoricino: $T^{1/2}_{0\nu}$ > 4.0×10^{24} yr (90% CL)

CUORE future



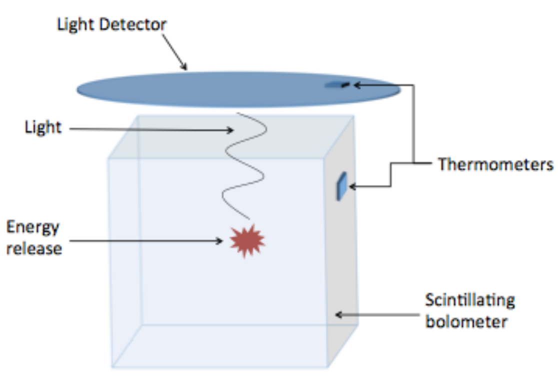
- 2015 – 2020, 206kg ^{130}Te in array of 988 crystal bolometers.
- All towers assembled and underground
- Cryostat and dilution unit under commissioning (reached 6mK base T)
- Expect to start operations by end of year
- 5 year sensitivity: $T^{1/2}_{0\nu} > 9.5\times10^{25}$yr



2020++: CUPID (Eur.Phys.J. C74, 3096 (2014))

- CUORE with PID
- 10 year sensitivity

$T^{1/2}_{0\nu} > 2\text{-}5\times10^{27}$yr



136 Xenon

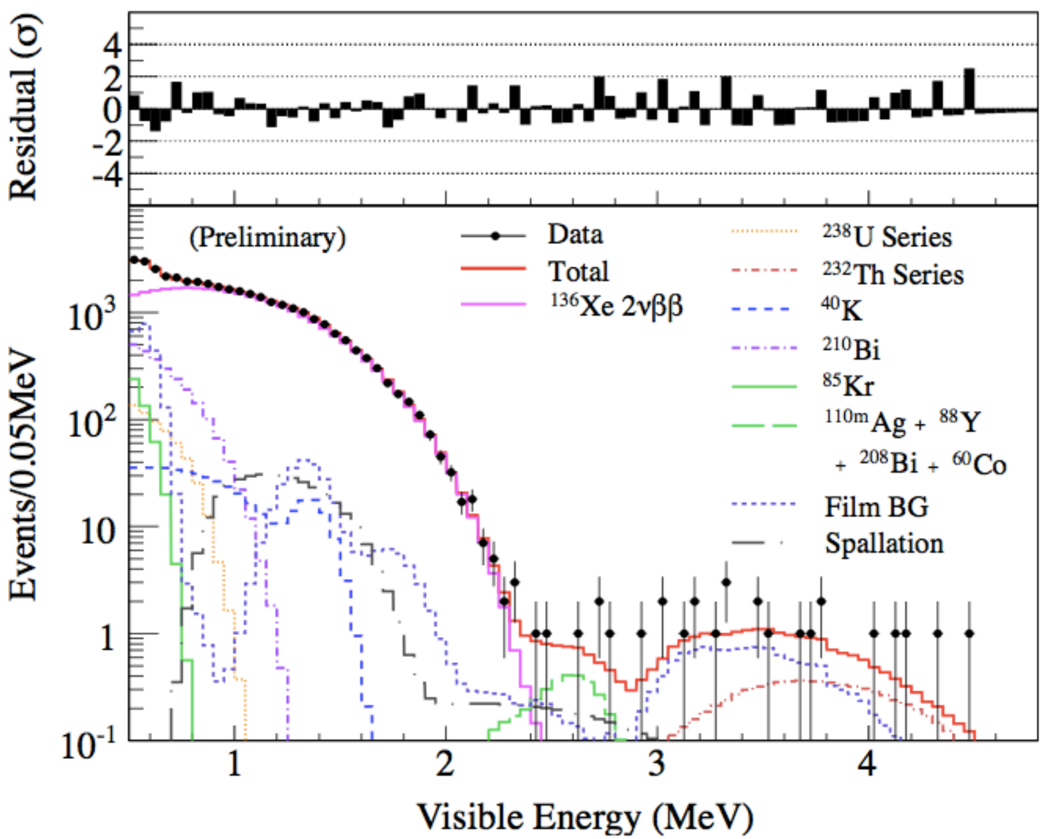
KamLAND-Zen

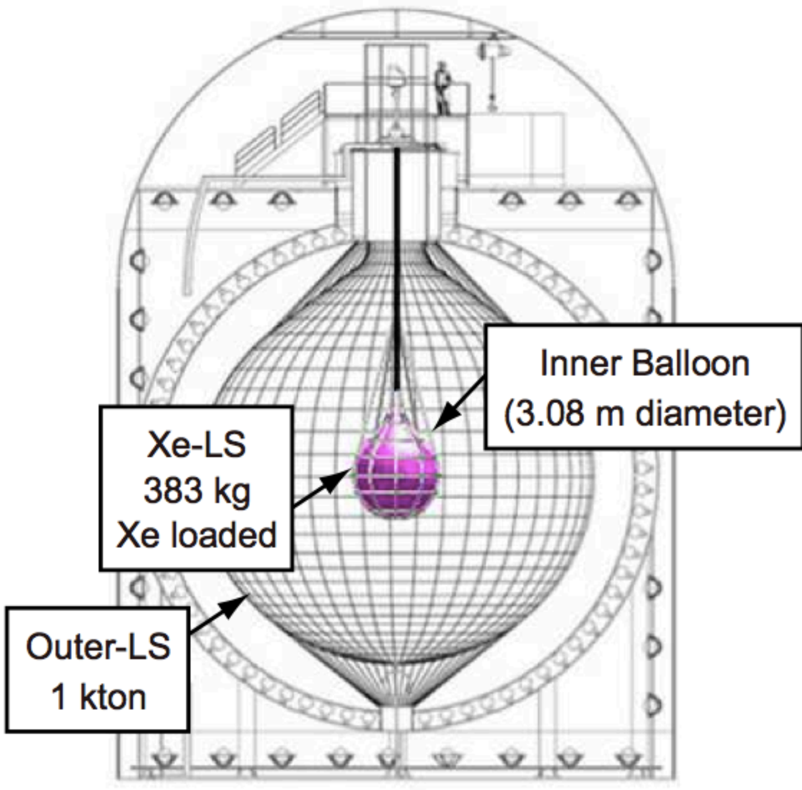
arXiv: 1409.0077

114.8 live days ➔ 27.6 ^{136}Xe kg-yr

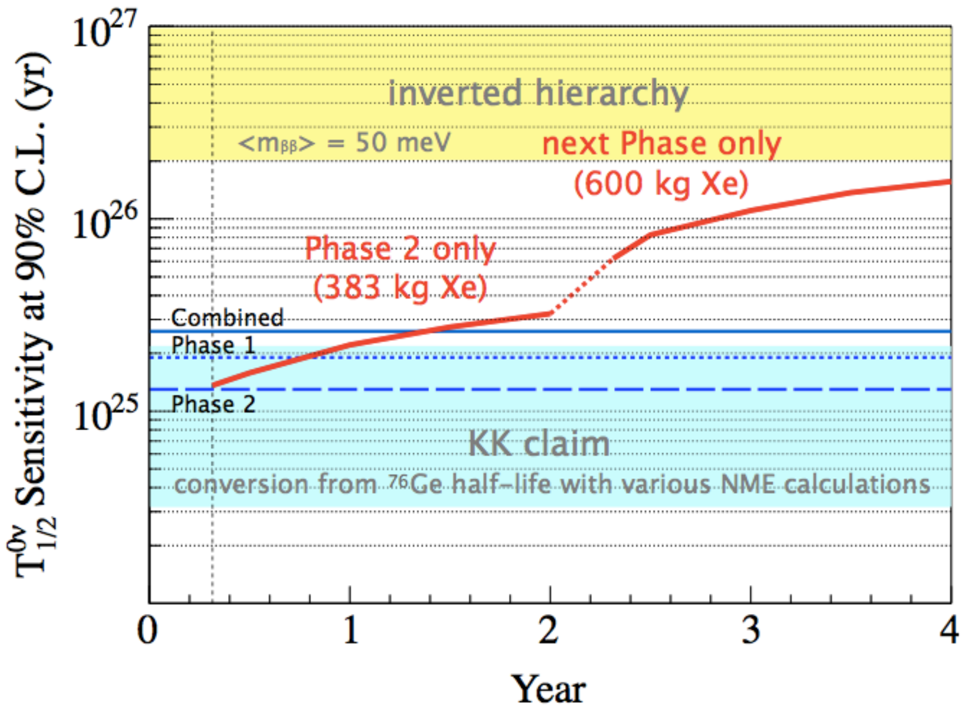
^{110m}Ag reduced > factor of 10

$T^{1/2}_{0\nu}$ > 2.6 × 10^{25} years (90%CL)





KamLAND-Zen next generation



....to reach $<m_{\beta\beta}>$ ~20meV in 5 years running ➔ KamLAND2-Zen

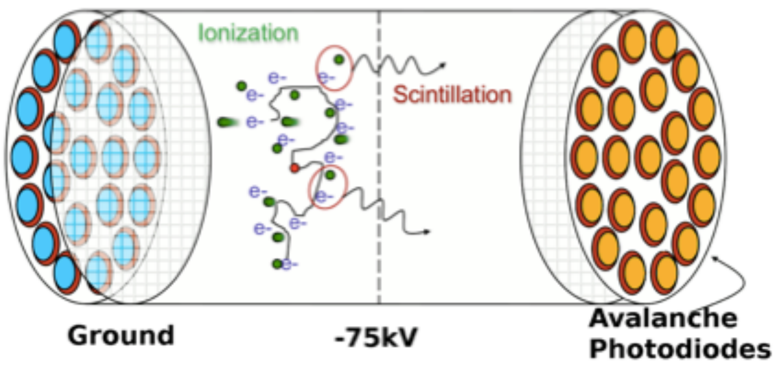
Increase light yield ➔Energy Resolution <2.5% at Q-val (from 4.0%)

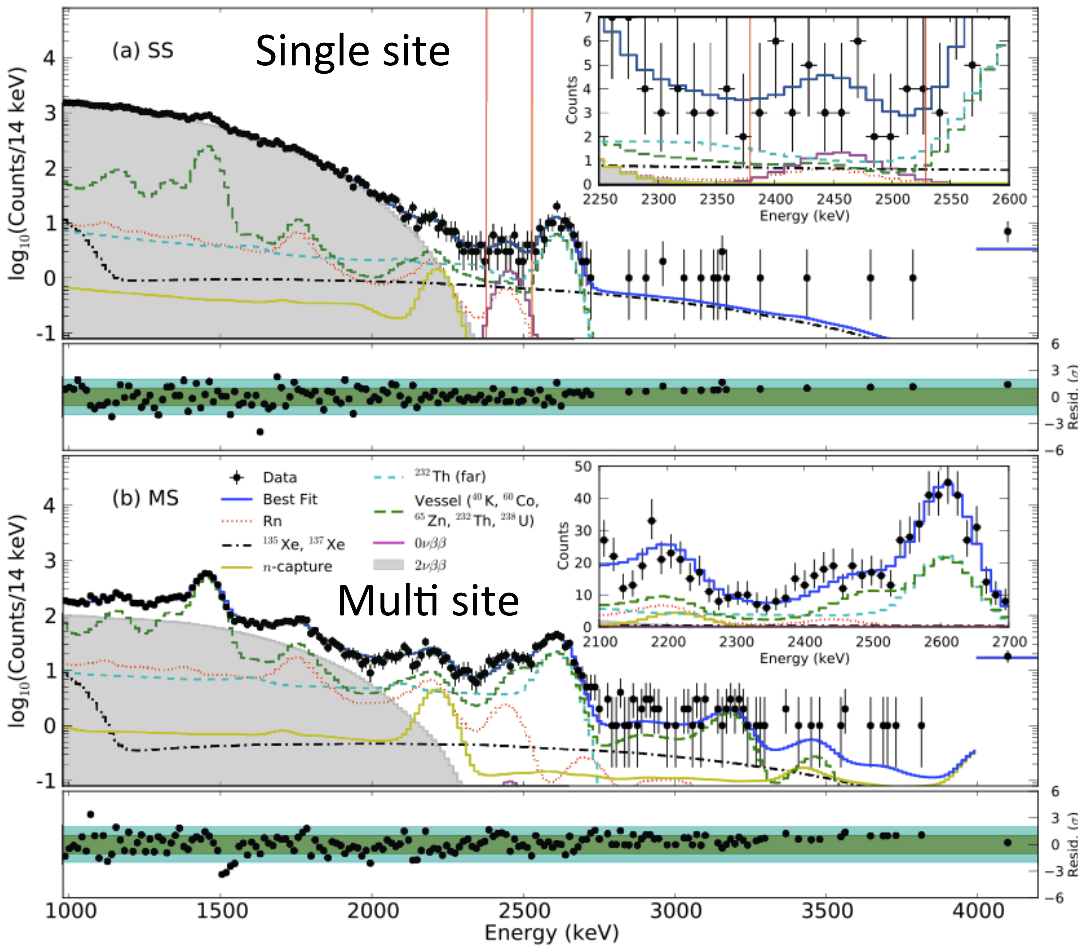
- light collective mirrors (×1.8 light yield)
- Brighter LS (×1.4 light yield)
- High QE PMTs (×1.9 light yield)

Increase mass ➔ 1000kg ^{136}Xe

- Enriched Xe

EXO-200





Nature 510, 229-234, arXiv: 1402.6956

$T^{1/2}_{0\nu} > \underline{1.1 \times 10^{25}\ \text{yr (90\% CL)}}$

200kg Single phase liquid Xenon Detector (enriched 80.6% ^{136}Xe)

100kg-yr ^{136}Xe exposure

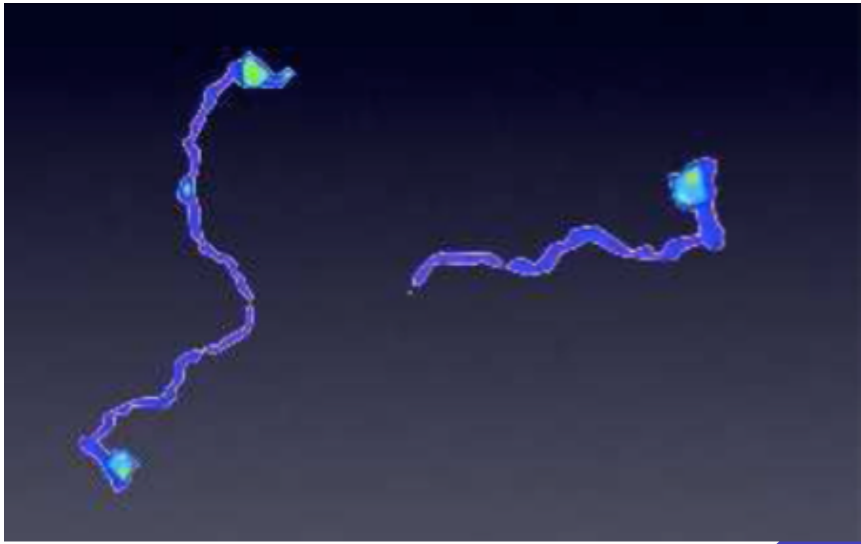
Energy resolution = σ/E = 1.53%

EXO next Generation

- 5 tonnes enriched ^{136}Xe
- nEXO 5yr 90% CL sensitivity: $T^{½}_{0\nu} > 6.6 \times 10^{27}$yr
- LXe homogeneous imaging TPC similar to EXO200:
  - baseline: install at SNOLAB (cosmogenic background reduced wrt EXO200)
  - simultaneous measurement: energy, spatial extent, location, particle ID
  - Multi-parameter approach improves sensitivity: strengthens proof in case of discovery
  - inverted hierarchy covered with a well proven detector concept
  - possible later upgrade for Ba retrieval/tagging: start accessing normal hierarchy

Next Generation ^{136}Xe

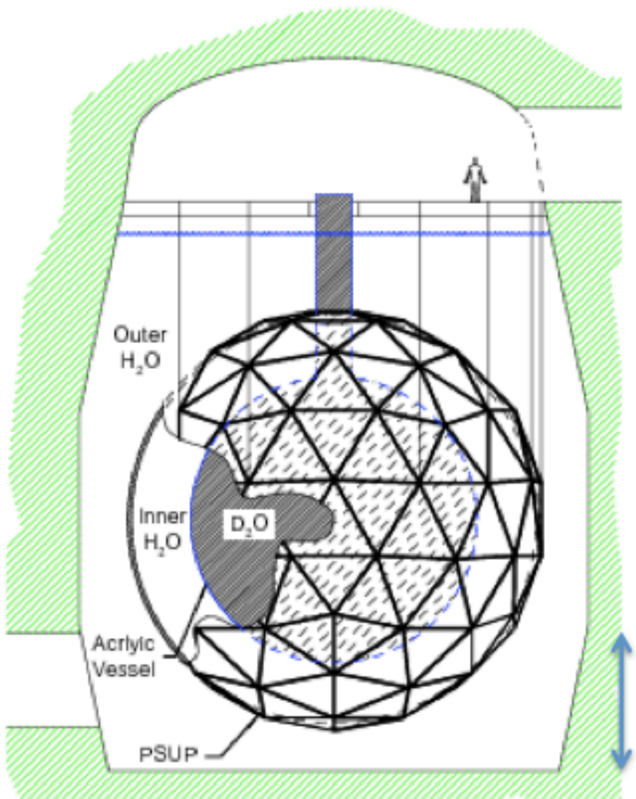
- NEXT: electroluminescent high-pressure xenon gas TPC filled with 100 kg of enriched Xe
- Energy resolution better than 1% at $Q_{\beta\beta}$
- Topological information gives signal: background rejection
- NEXT (Spain)
  - 100kg detector ~2017
- PANDA-X III (China)
  - 200kg detector ~2017



SNO+ Water Leak

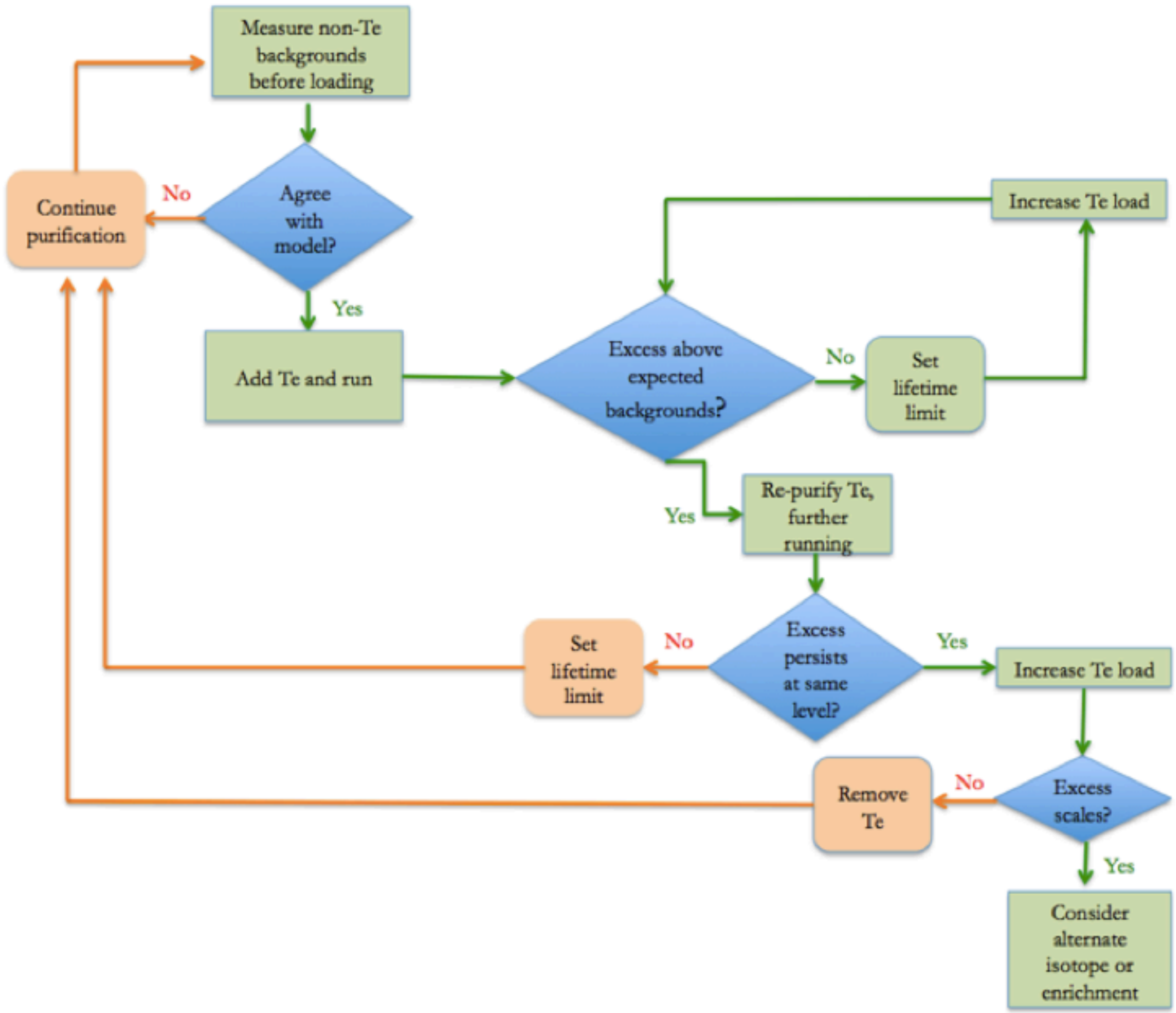
Cavity Water Leak

- As water filled cavity, high leak rate seen both in sump and water level
- Consistent with leak at 20' level but could be lower
- Extensive campaign to find source; one hole repaired but small effect



Range of heights where leak may be

SNO+: What if we see a Bump?



Global Landscape (USA Perspective)