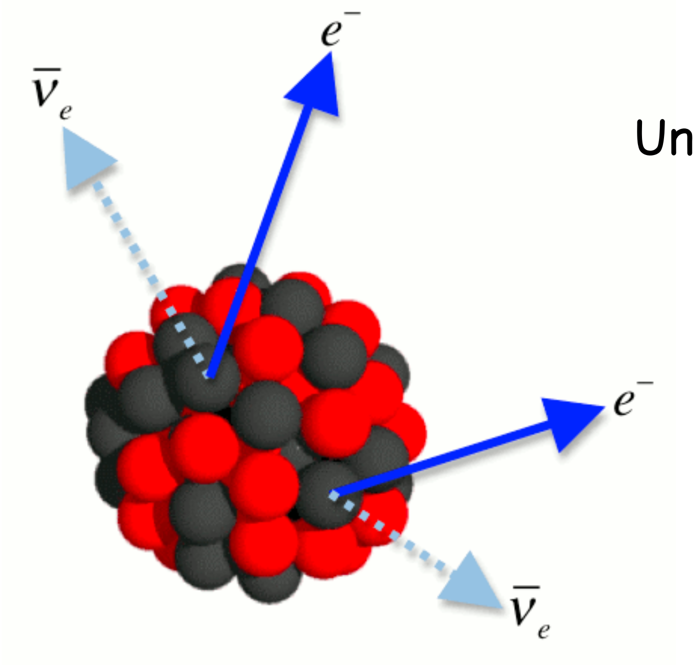
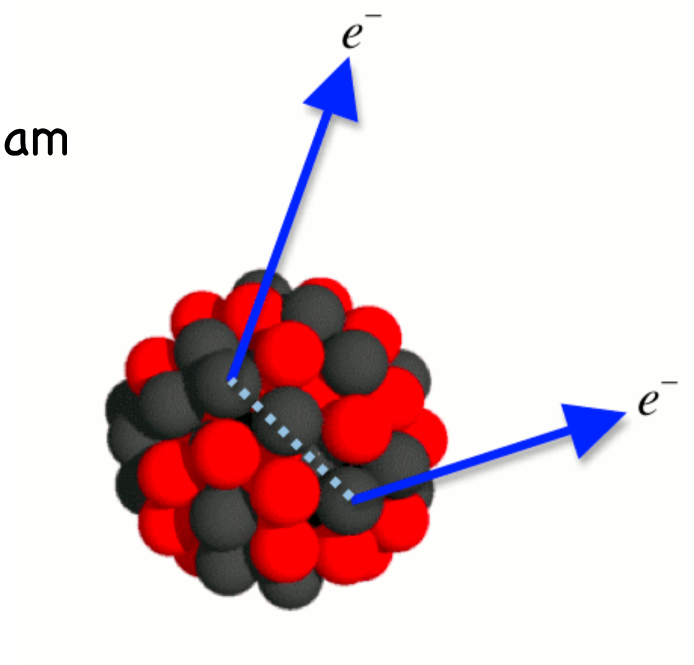
Neutrinoless Double-Beta Decay and SuperNEMO

Dave Waters
University College London



University of Birmingham
29th January 2014



Outline

- Measuring the Mass of the Neutrino
- Neutrinoless Double-Beta Decay
- How to Build a Neutrinoless Double-Beta Decay Experiment ?
- The SuperNEMO Experiment
- Latest Results From the Field

“The Most Tiny Quantity of Reality …” **F. Reines, ca. 1956**

- The most abundant matter particle in the universe. Important roles in :
  - Cosmology : BBN, CMB anisotropies & structure formation
  - Astrophysics : 99% of energy released in supernovae carried by neutrinos.
- Tiny but *non-zero* mass, very different in scale from the other fermions : $m_\nu / m_e \sim 10^{-7}$
- Could the very *small* neutrino mass be related to physics at extremely *high* energy scales ?

<u>“See-saw” mechanism :</u>

$$m_\nu \approx \frac{M_{\mathrm{EWK}}^2}{M_{\mathrm{GUT}}} \approx \frac{(100\ \mathrm{GeV})^2}{10^{15}\ \mathrm{GeV}} \approx 10\ \mathrm{meV}$$

- Is there CP violation in the lepton sector and could this be related to the observed matter-antimatter asymmetry in the universe ?

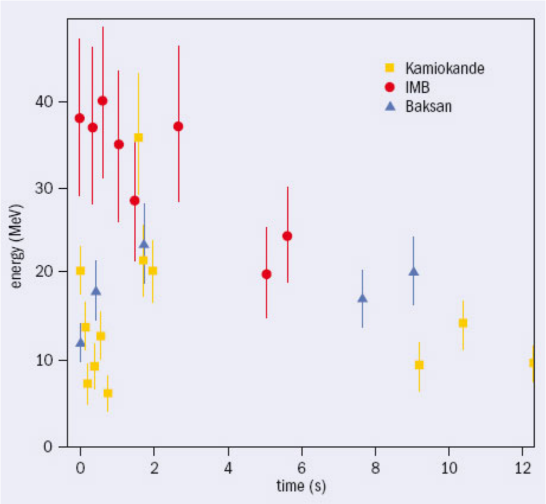
Measuring The Neutrino Mass

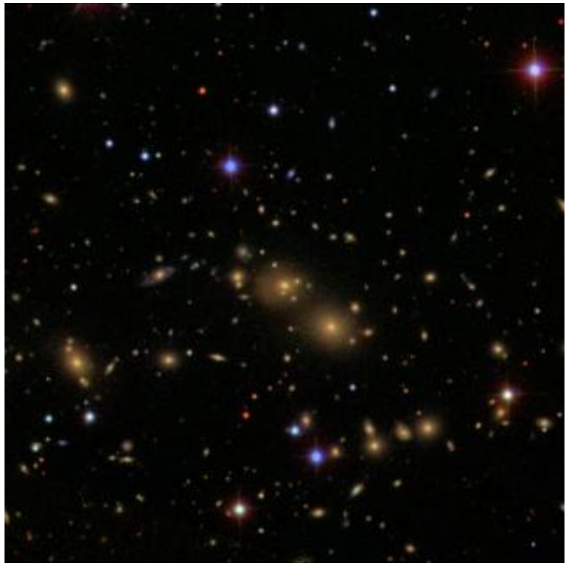
Supernova 1987A

Arnett & Rosner (1987)

The spread in arrival times for different energy neutrinos yields :

$$m_\nu \leq 15 \text{ eV}$$





Large Scale Structure

Thomas, Abdalla & Lahav (2010)

The growth of structure in the early universe was suppressed by free streaming neutrinos – depends on their velocity and hence mass.

$$\sum m_\nu \leq 0.28 \text{ eV} \quad (95\% \text{ C.L.})$$

Cosmological model dependence ?

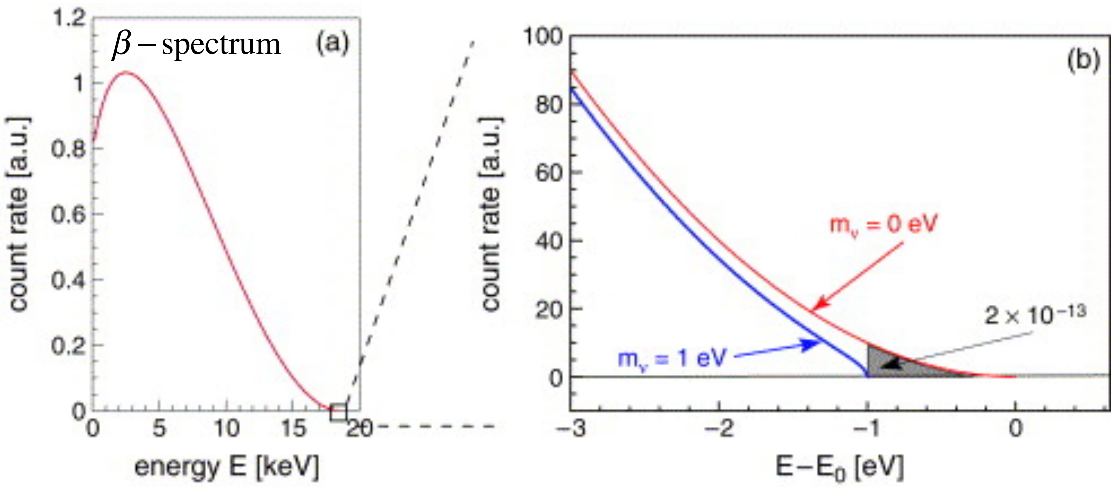
Measuring The Neutrino Mass

Tritium End Point Experiments

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_{e} + 18.6\ \ \mathrm{keV}$$

$$m_{\nu_e} \leq 2.2\ \mathrm{eV}\ \ (95\%\ \mathrm{C.L.})$$

Kraus et al. (2005), Aseev et al. (2011)



- Direct (relatively model independent) kinematic measurement.
- Extremely challenging experimentally.
- Next generation will reach ~0.2 eV

Key Questions in (No) Neutrino Physics

- Neutrinos have mass and they mix.
- Precision measurements of mixing angles and Δm^2.
- **Nature of neutrinos** : Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}$)
- **Absolute neutrino mass scale** : only limits so far :

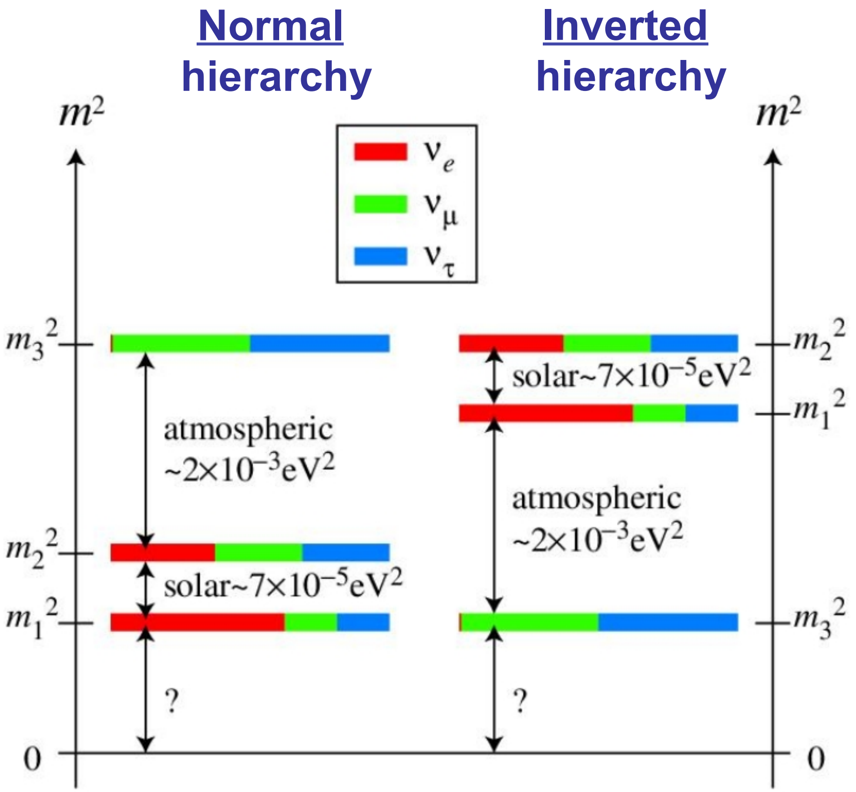
  $m_{\bar{\nu}_e} < 2.2$ eV (Tritium end-point)

  $\Sigma m_{\nu_i} < 0.3$ eV (Cosmology)
- **Neutrino mass-hierarchy** :
  - Normal : $m_1 < m_2 < m_3$
  - Inverted : $m_3 < m_1 < m_2$
  - Quasi-degenerate : $m_1 \approx m_2 \approx m_3$
- **CP-violation in neutrino sector** :
  - Dirac phase : $\delta \neq 0,\pi$
  - **Majorana phases** : $\alpha_{21},\alpha_{31} \neq 0,\pi$

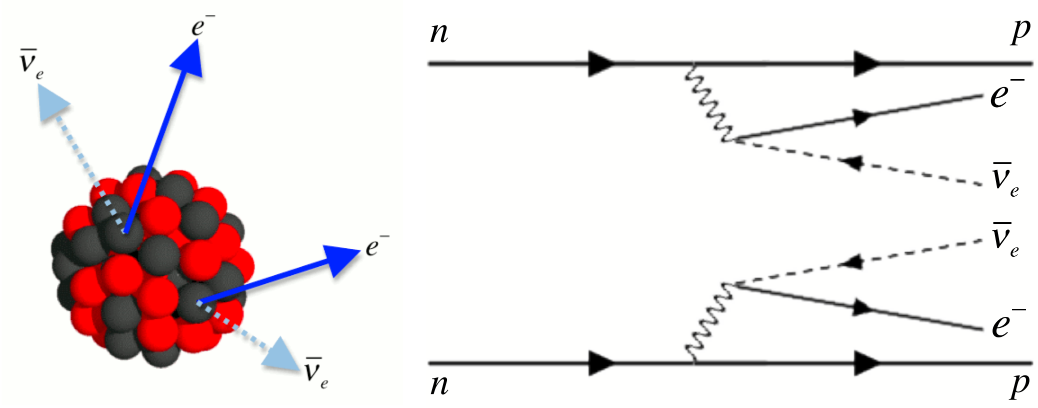
PMNS mixing matrix :

Majorana Phases

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$



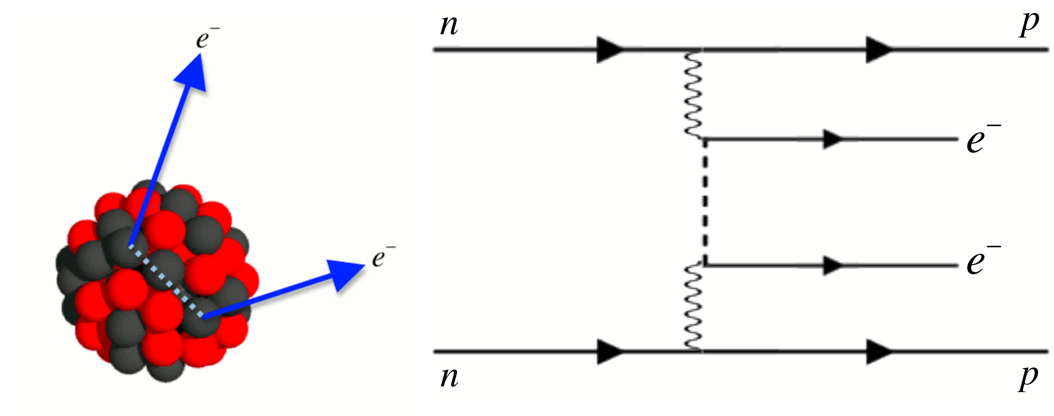
Double-Beta Decay



2-Neutrino Double Beta Decay

[Goeppert-Mayer, 1935]

- $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$
- Lepton number conserved.
- Allowed in Standard Model.
- Rate ~ $O\left(G_F^2\right)$



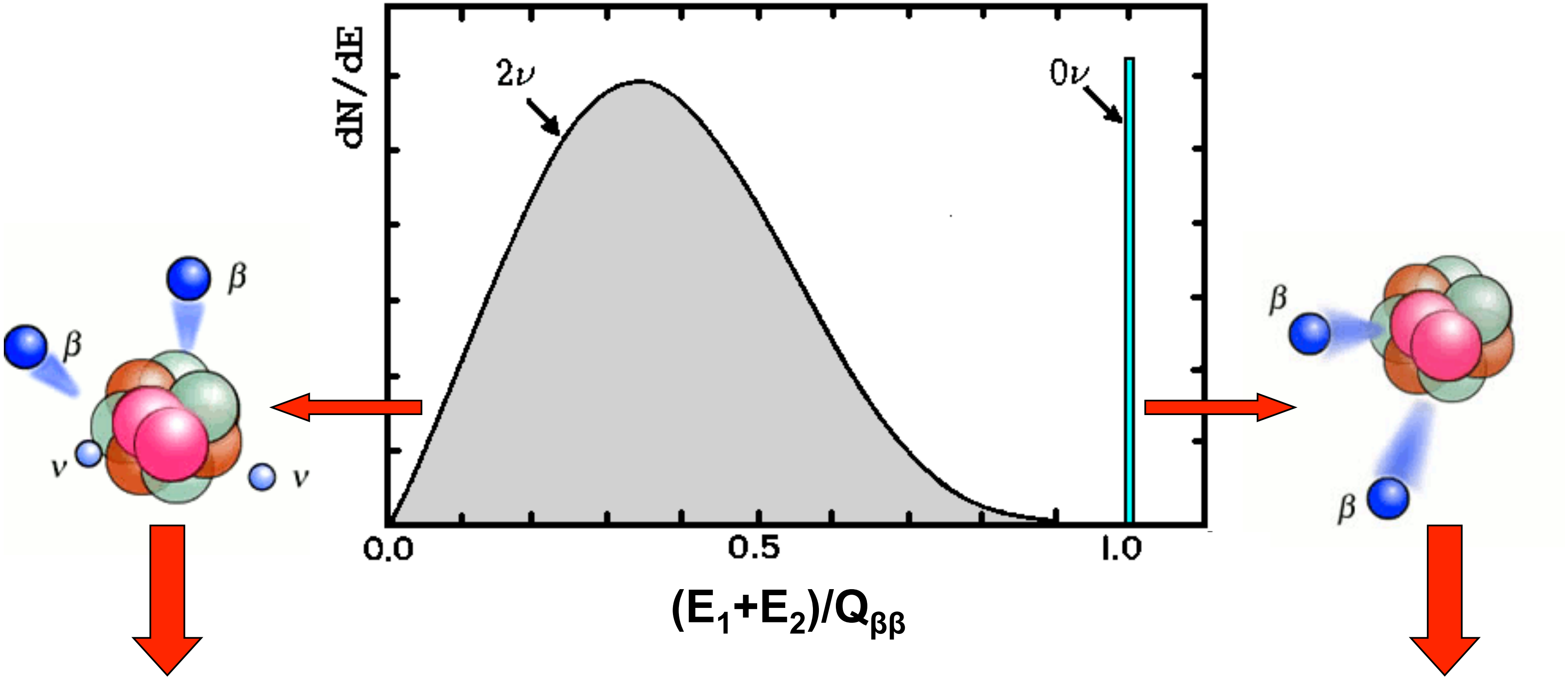
0-Neutrino Double Beta Decay

[Furry, 1939]

- $(A,Z) \rightarrow (A,Z+2) + 2e^-$
- Lepton number violation : $\Delta L = 2$
- Forbidden in Standard Model.
- $\mathrm{Rate}(0\nu\beta\beta) \ll \mathrm{Rate}(2\nu\beta\beta)$

Double-Beta Decay : Basic Signature

Measure the summed electron energy and compare to the energy of the transition :



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

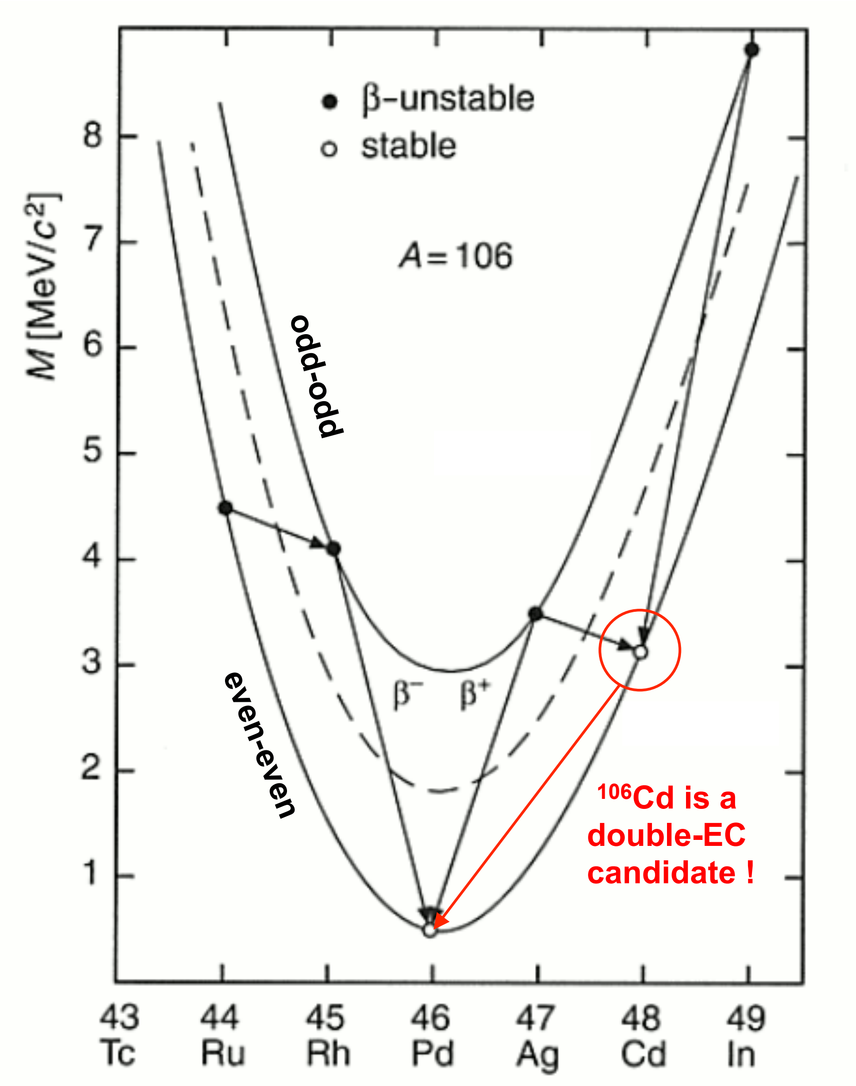
$$\left(E_1 + E_2\right) / Q_{\beta\beta} \approx 1$$

$[\otimes \text{ resolution}]$

Which Isotopes Can Double-Beta Decay ?

- Remember the pairing term in the SEMF!

► ββ candidates are all even-even nuclei.



^{106}Cd is a double-EC candidate !

Candidate isotopes :

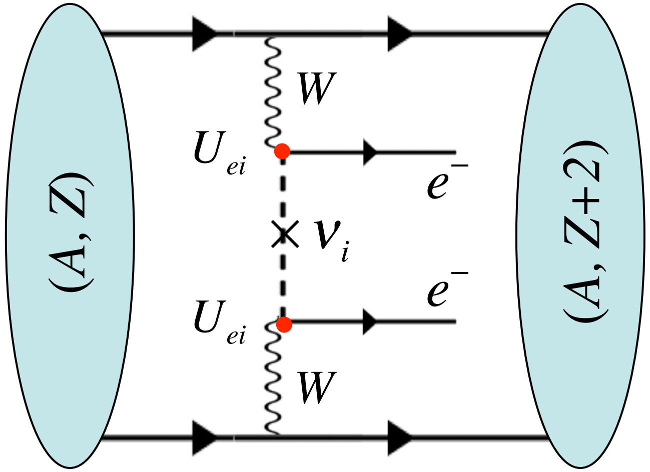
Isotope	**$Q_{\beta\beta}$ (MeV)**	**Nat. Abund. (%)**
^{48}Ca	4.272	0.187
^{76}Ge	2.039	7.8
^{82}Se	2.996	9.2
^{96}Zr	3.350	2.8
^{100}Mo	3.034	9.6
^{110}Pd	2.004	11.8
^{116}Cd	2.814	7.6
^{124}Sn	2.530	5.6
^{130}Te	2.528	34.5
^{136}Xe	2.459	8.9
^{150}Nd	3.371	5.6

more energetic decay : easier to separate from background

enrichment often possible, always expensive !

Effective Neutrino Mass (Light Neutrino Exchange)

- Which neutrinos participate in neutrinoless double-beta decay ?
- We must consider a *coherent* sum over neutrino amplitudes :

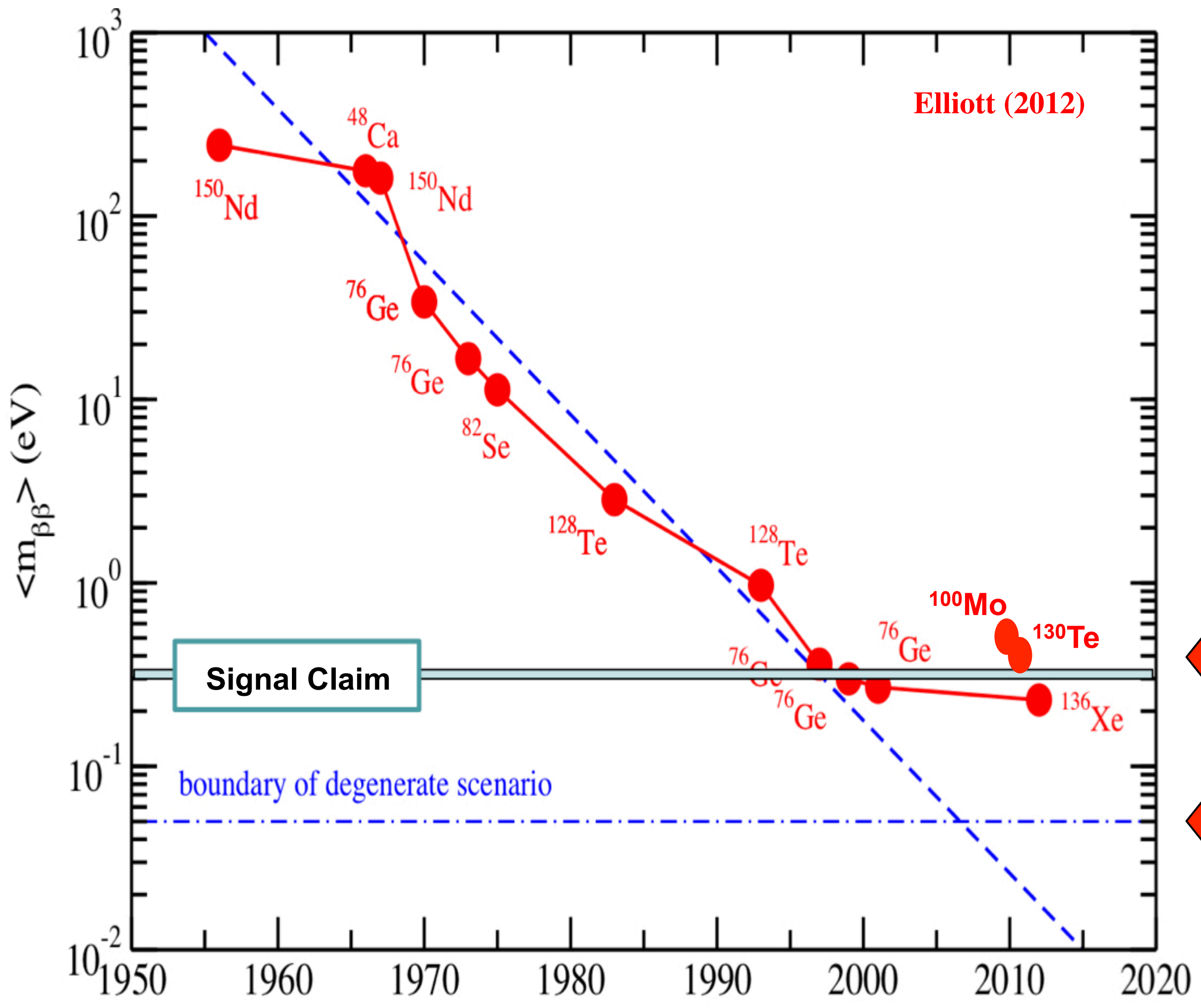


- Hence, experiments are sensitive to an *effective* $0\nu\beta\beta$ neutrino mass :

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

$\alpha_{21},\ \alpha_{31}$ = Majorana phases

The Historical Record



~400 meV

~50 meV

Neutrino Mass : Target Sensitivity

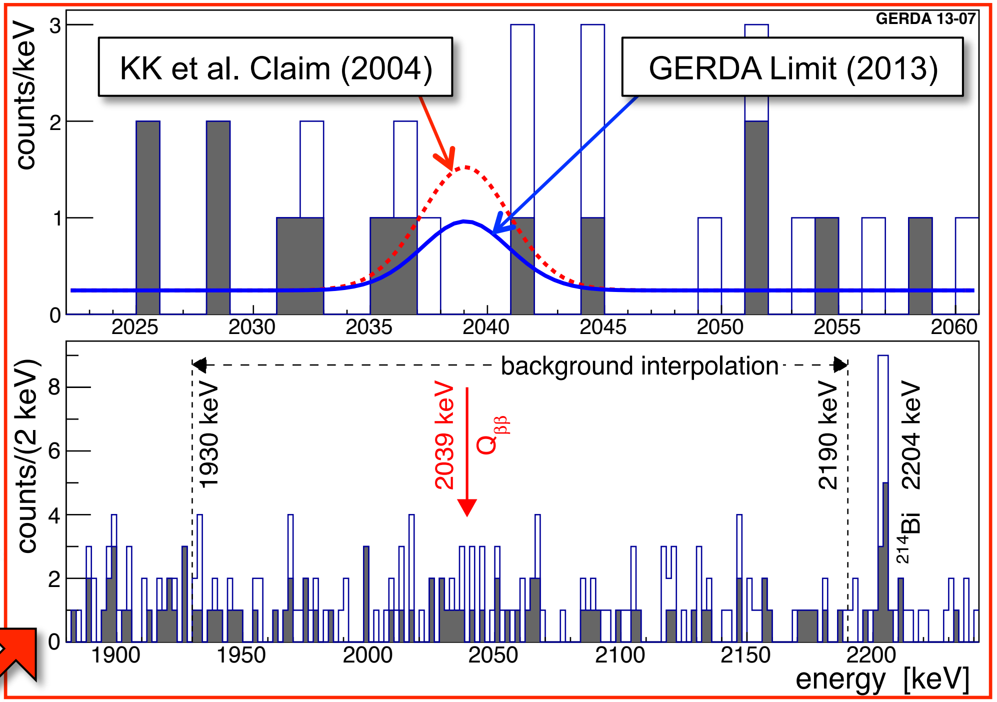
Signal in Heidelberg-Moscow experiment ?

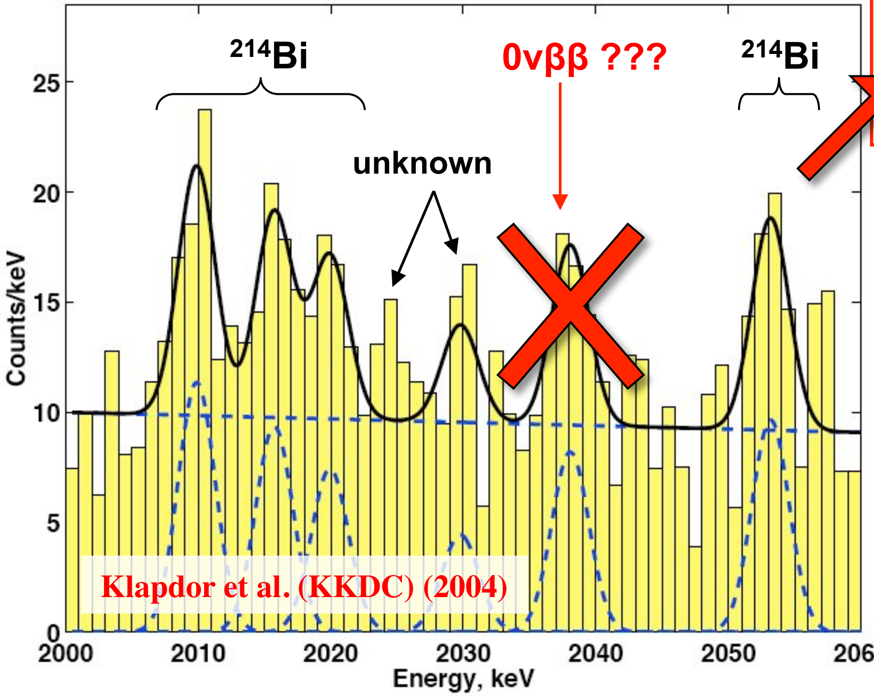
- HPGe detector enriched with 86% ^{76}Ge
- Peak observed in just the right place, but several unexplained spectral features.
- Half-life :

$$T_{1/2}^{0\nu} = (0.69 - 4.18) \times 10^{25} \text{ years } (3\sigma)$$

- Corresponding neutrino mass :

$$\langle m_\nu \rangle \sim 0.4 \text{ eV}$$





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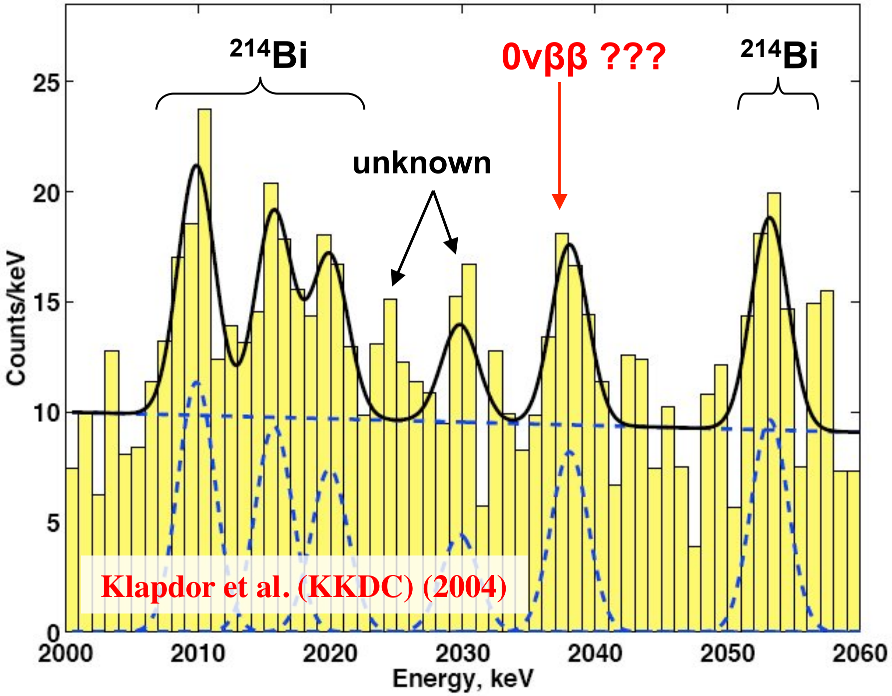
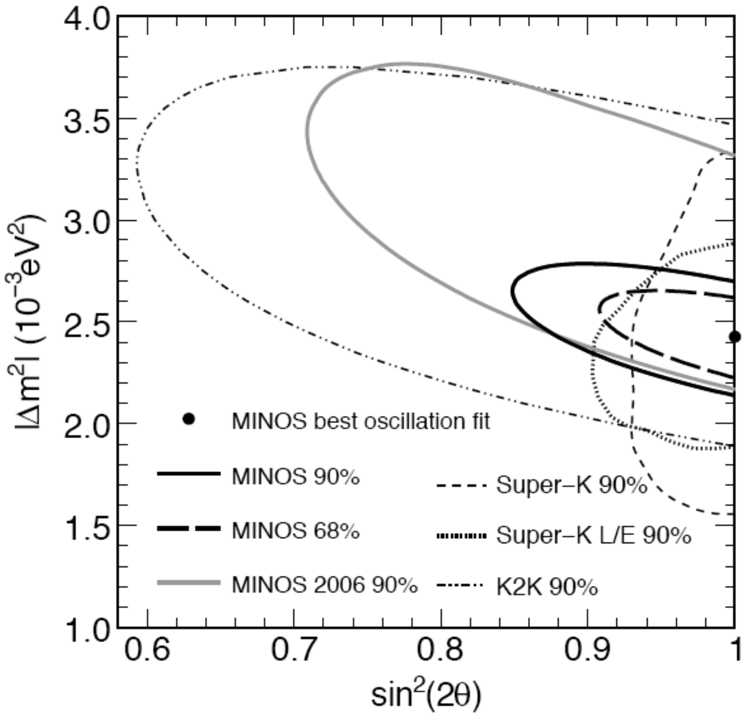


Neutrino Oscillations

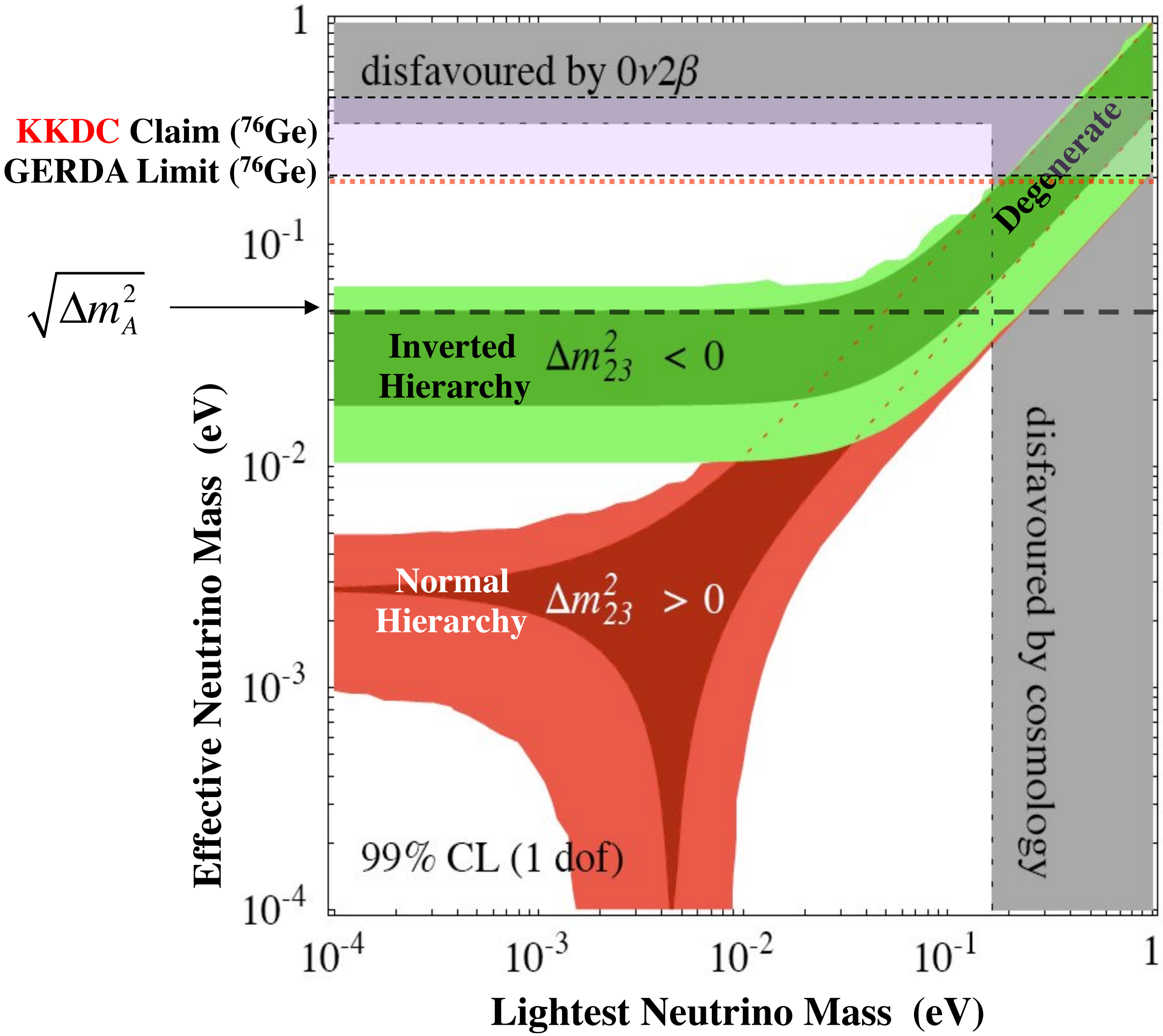
- Largest Δm^2 from "atmospheric" oscillations.
- Therefore there is at least one neutrino with :

$$m_\nu \sim \sqrt{\Delta m^2_{atm}} \sim 50 \text{ meV}$$



Effective Neutrino Mass

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



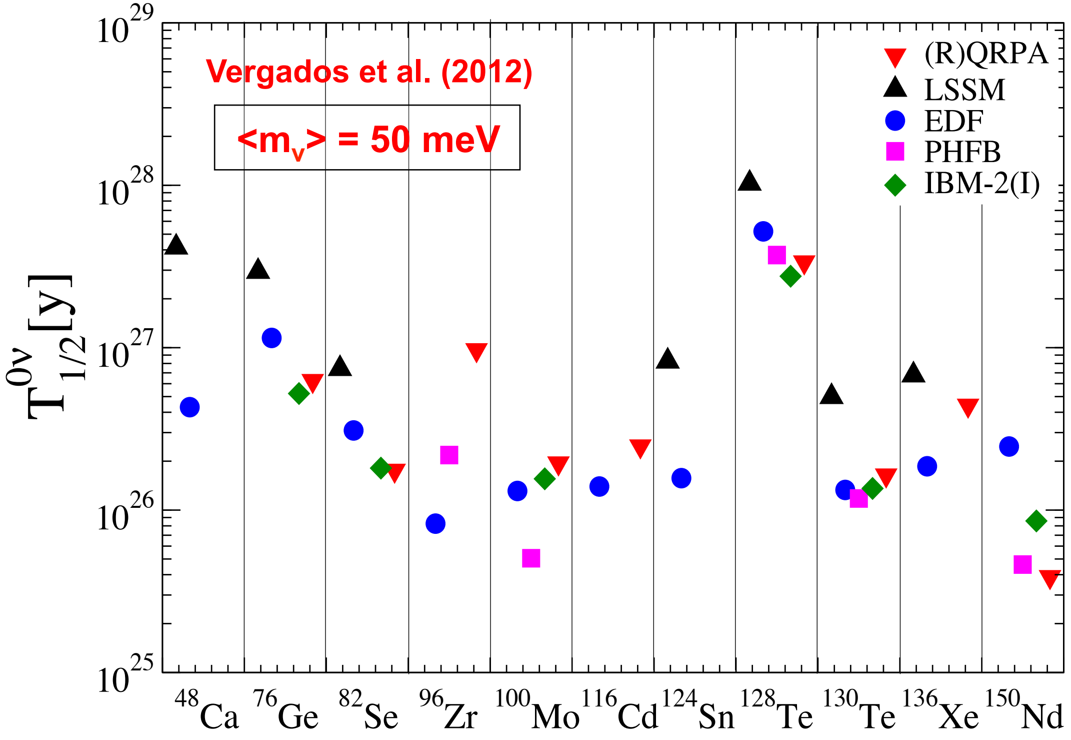
Strumia & Vissani (2006/2010)

Nuclear Matrix Elements

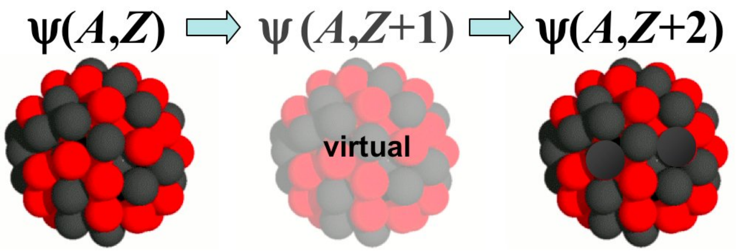
phase-space factor
(exactly calculable)

effective neutrino mass

$$0\nu\beta\beta \text{ Rate} \propto \frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}\left(Q_{\beta\beta}, Z\right)\left|M_{0\nu}\right|^2 \left\langle m_\nu \right\rangle^2$$



u**N**clear **M**atrix **E**lements

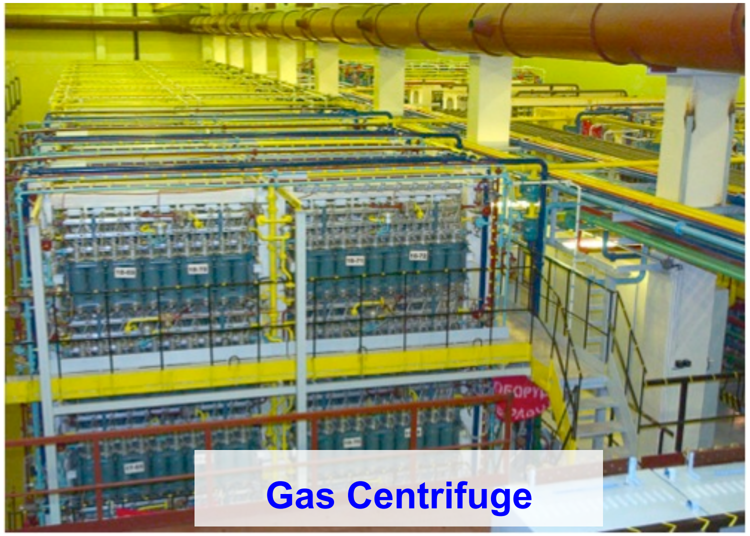

$\psi(A,Z) \Rightarrow \psi(A,Z+1) \Rightarrow \psi(A,Z+2)$

All is not lost :

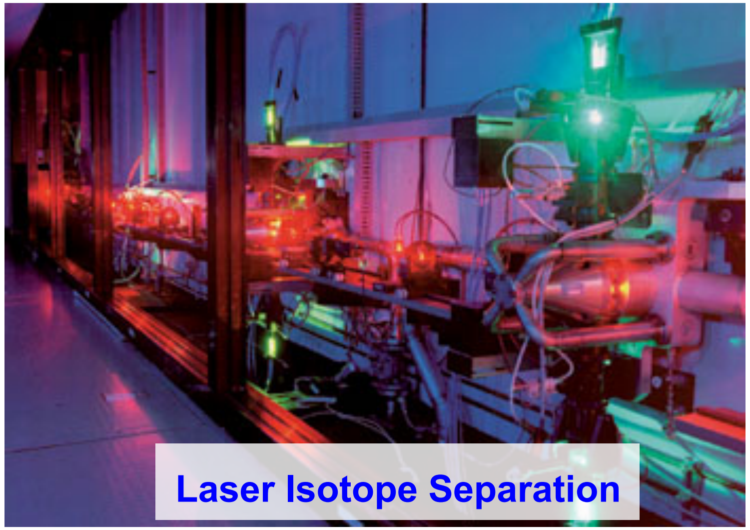
- Does not affect discovery potential
- Correlations between NME's can be exploited to compare experiments.

How To Build a ββ-Experiment

- Expected half-lives for 0νββ are in the range **10^{24} to 10^{27} years** for interesting $\langle m_\nu \rangle$
- The basic strategy is therefore :
  1. Collect N × Avogadro's number of nuclei of your chosen ββ isotope. **Enrichment** varies from relatively easy (^{136}Xe) to extremely difficult (^{48}Ca, ^{150}Nd). Natural Tellurium can be used.
  2. Purify the sample to remove trace radioactive contamination. **Radiochemistry** varies according to the isotope.
  3. Construct a detector able to detect 0νββ decays with maximum **resolution, efficiency** and **purity**.
  4. Wait quite a long **time** …



Gas Centrifuge



Laser Isotope Separation

How To Build a ββ-Experiment

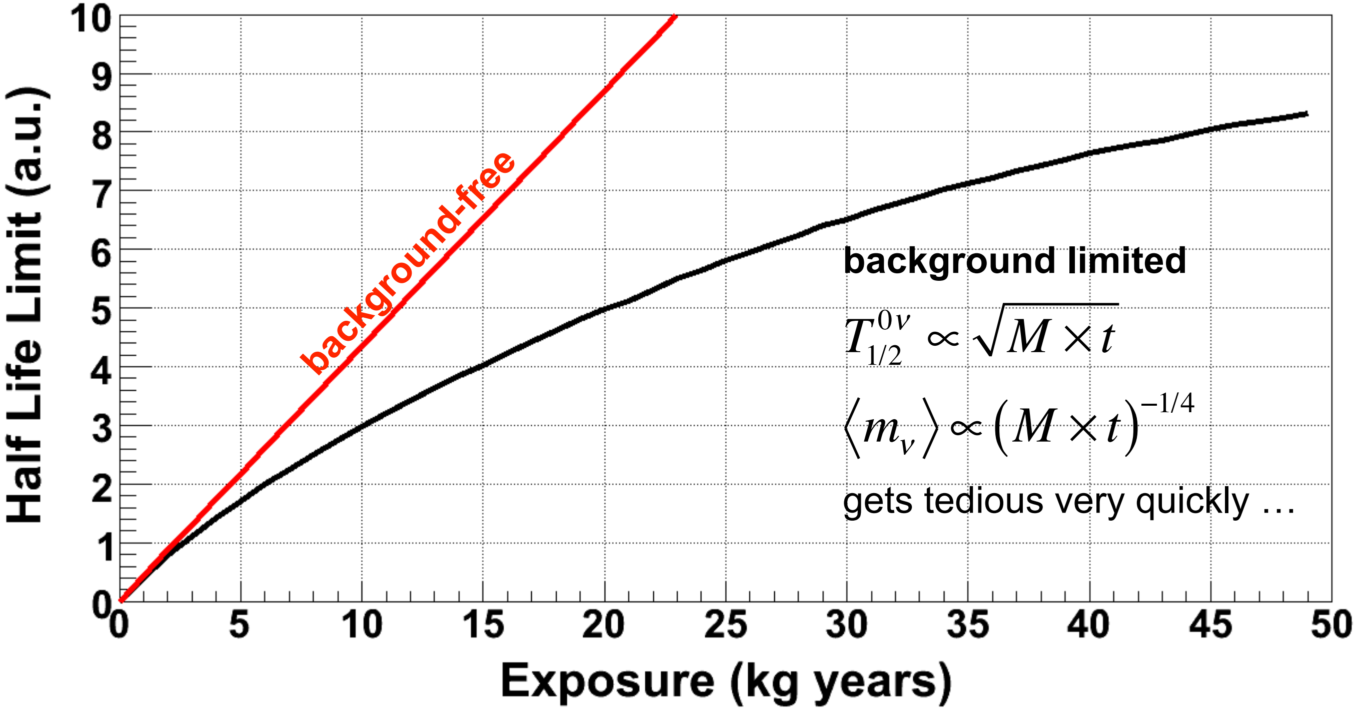
maximise efficiency (ε) & isotope abundance (*a*)

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

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

W = atomic weight

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



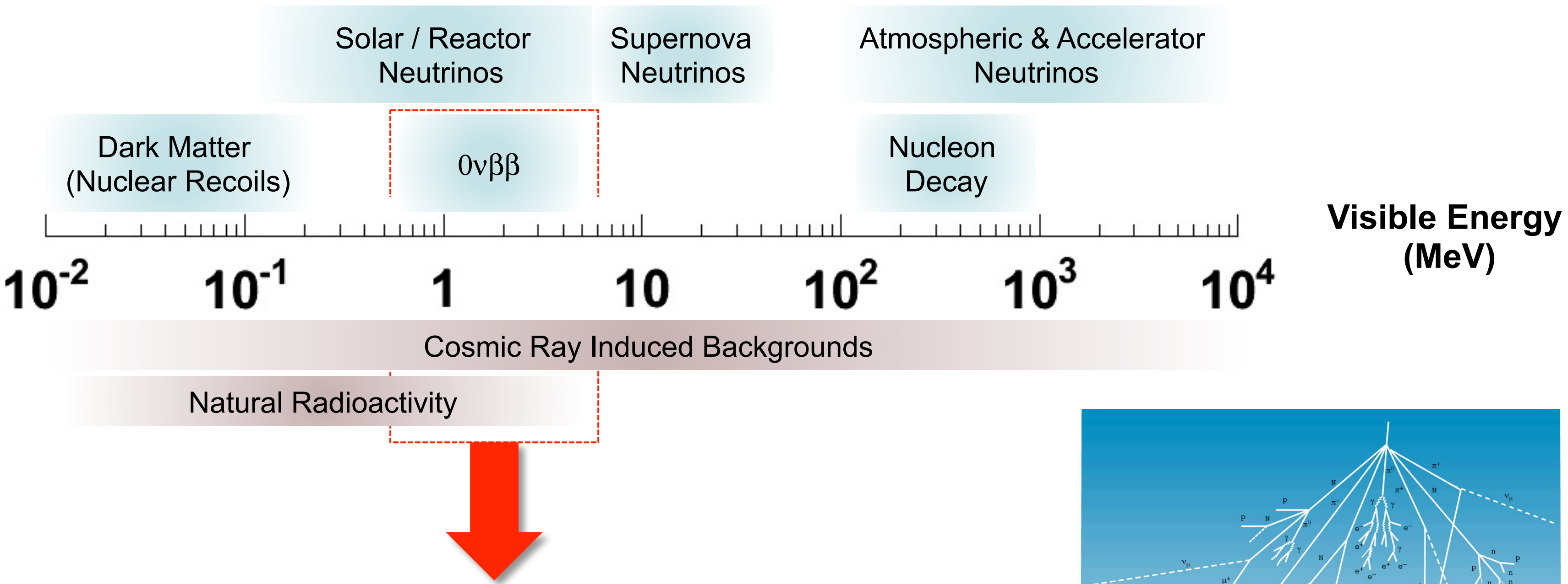
background limited

$$T_{1/2}^{0\nu} \propto \sqrt{M\times t}$$

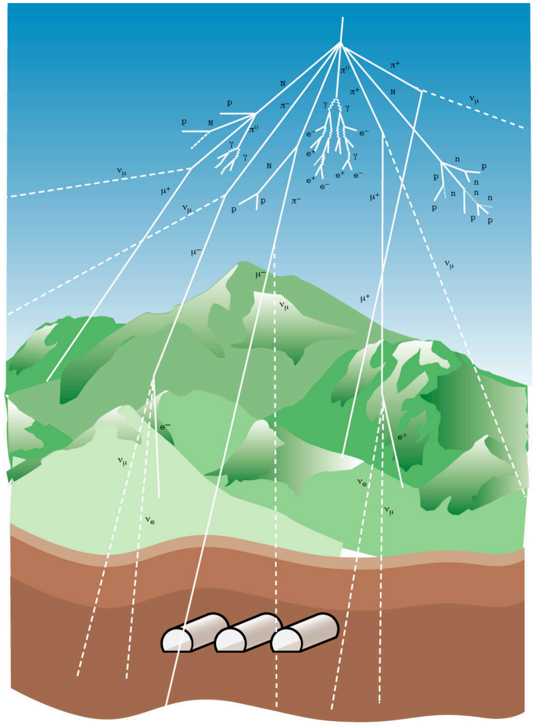
$$\langle m_\nu\rangle \propto (M\times t)^{-1/4}$$

gets tedious very quickly …

The Background Problem

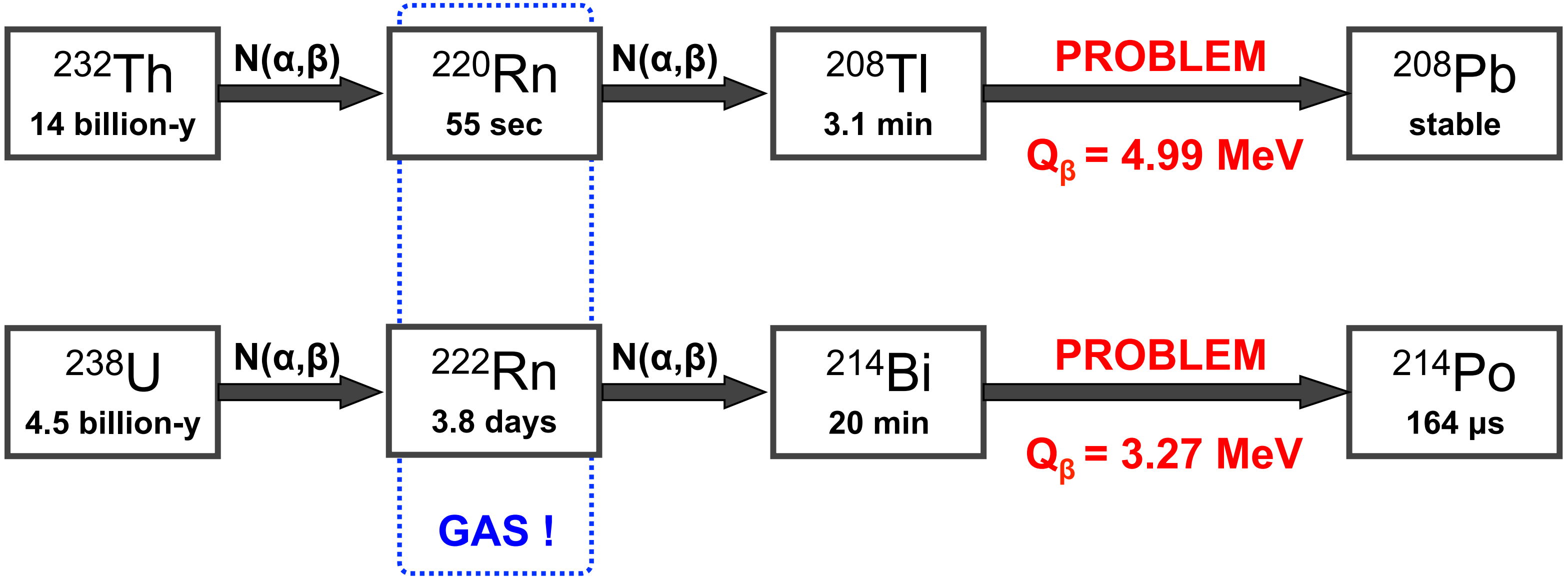


- Go underground (at least a few thousand meters of water equivalent)
- Suppress radioactive backgrounds, primarily Uranium and Thorium decay chain products which are present in all materials.
  - **$T_{1/2}(^{232}Th, ^{238}U) \sim 10^{10}$ years**
  - **$T_{1/2}(0\nu\beta\beta) > 10^{25}$ years**
- Background from $2\nu\beta\beta$: resolution and isotope choice.



Natural Radioactivity

- Most important culprits :



^{232}Th 14 billion-y $\xrightarrow{N(\alpha,\beta)}$ ^{220}Rn 55 sec $\xrightarrow{N(\alpha,\beta)}$ ^{208}Tl 3.1 min $\xrightarrow{\text{PROBLEM}}$ ^{208}Pb stable

$Q_\beta = 4.99$ MeV

^{238}U 4.5 billion-y $\xrightarrow{N(\alpha,\beta)}$ ^{222}Rn 3.8 days $\xrightarrow{N(\alpha,\beta)}$ ^{214}Bi 20 min $\xrightarrow{\text{PROBLEM}}$ ^{214}Po 164 μs

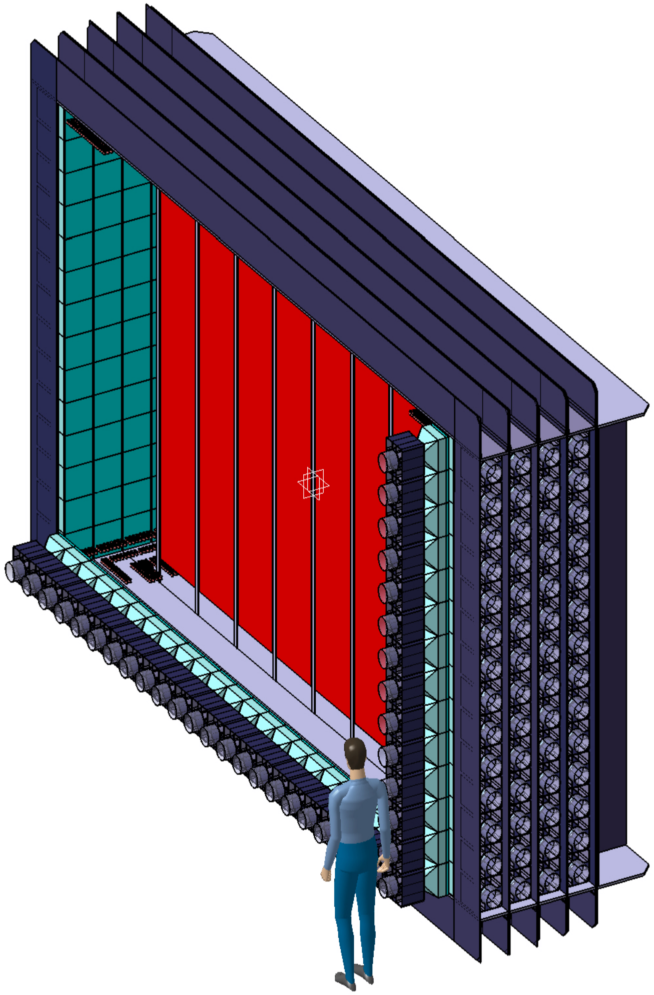
$Q_\beta = 3.27$ MeV

GAS !

- Many other potential sources including cosmogenics, “degraded” alphas etc.
- Natural radioactivity falls very rapidly above ~3 MeV.
- What can be done ?
  - Extremely careful material selection.
  - Purification techniques.
  - Barriers against Radon penetration.
  - Vetos & active shielding.
  - Background tagging/identification techniques - e.g. single-site ($0\nu\beta\beta$) versus multiple-site (γ)

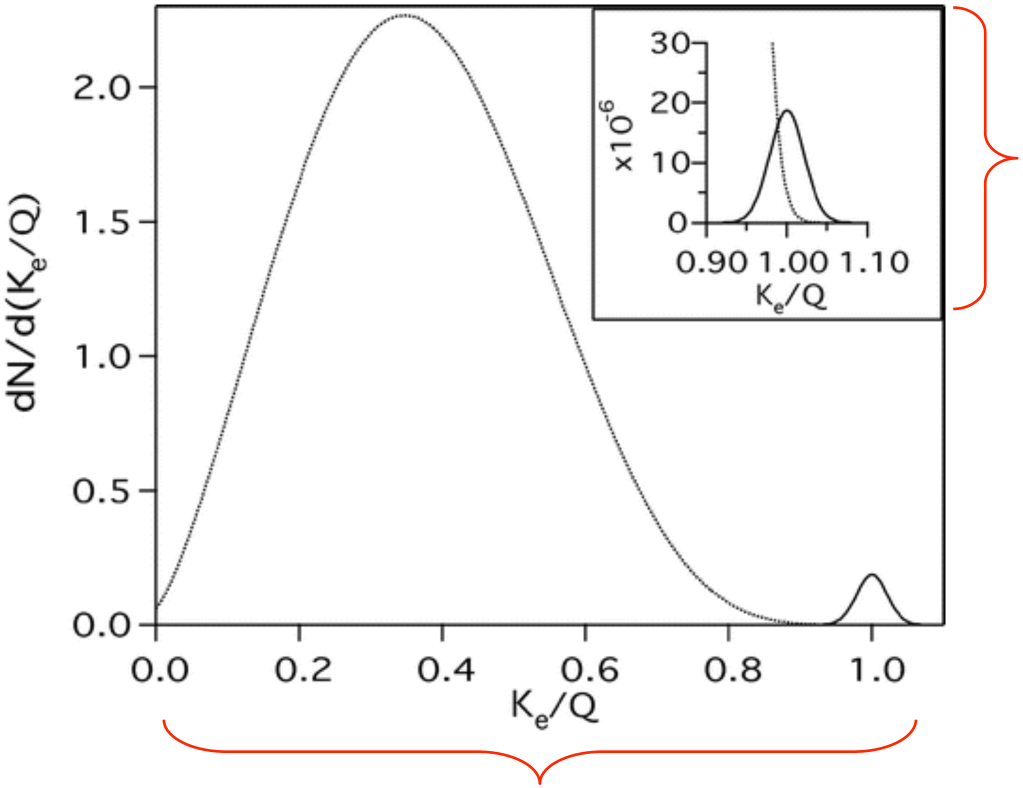
It's All About Backgrounds

SuperNEMO Demonstrator Module
20 tons
Radon emanation into tracker must be < 1.5 mBq
1 decay every ~10 minutes



Brazil Nut
4 grams
400 mBq of radium decays
1 decay every ~2 seconds

Irreducible Background : $2\nu\beta\beta$



Increase $\mathbf{T_{1/2}(0\nu\beta\beta)}$
by a factor 10,000

Well separated signal for small $\mathbf{T_{1/2}(0\nu\beta\beta)}$

- What can be done ?
- Improve energy resolution.
- Choose a different isotope with a more favourable ratio of $2\nu\beta\beta$ and $0\nu\beta\beta$:

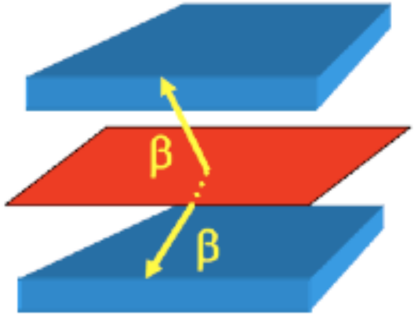
NEMO-3 ➔ SuperNEMO

^{100}Mo ➔ ^{82}Se

Experimental Approaches

Heterogenous

"tracking"



Advantages :

Full event topology information

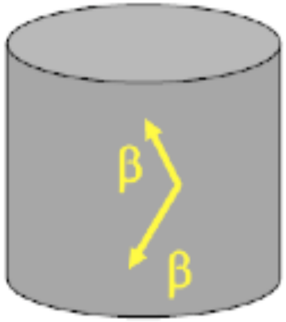
"Smoking-gun" signature for 0νββ

Can probe different mechanisms

Isotope flexibility

Homogenous

"source = detector"



Advantages :

Excellent ΔE/E

Compact

Techniques :

Semiconductor

Bolometer

(Liquid-) Scintillator

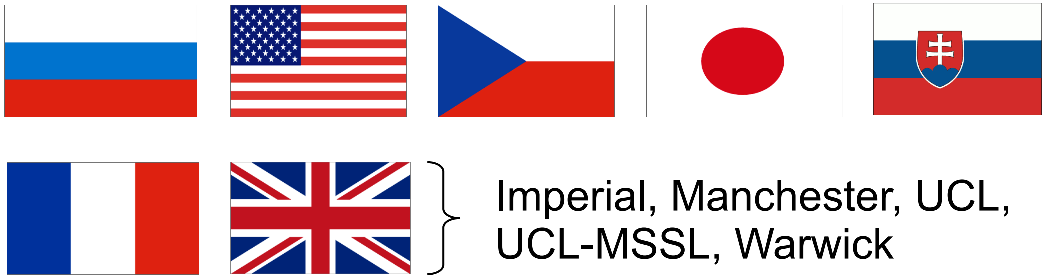
Elements of Both

Gaseous Xe TPC

Pixelated CdZnTe

(Super)-NEMO

supernemo collaboration



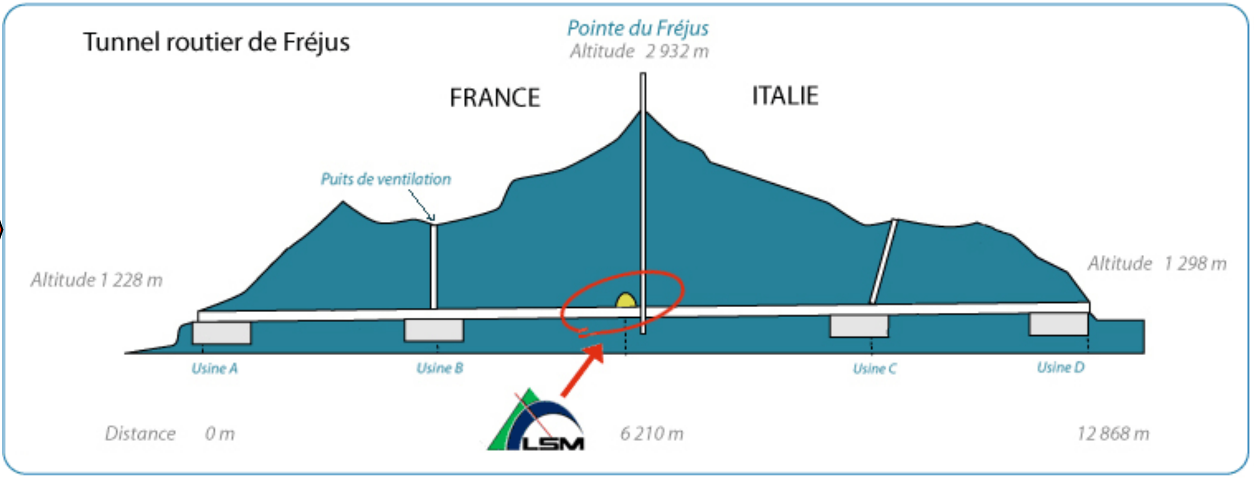
Imperial, Manchester, UCL, UCL-MSSL, Warwick

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 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.

Neutrino Ettore Majorana Observatory 3

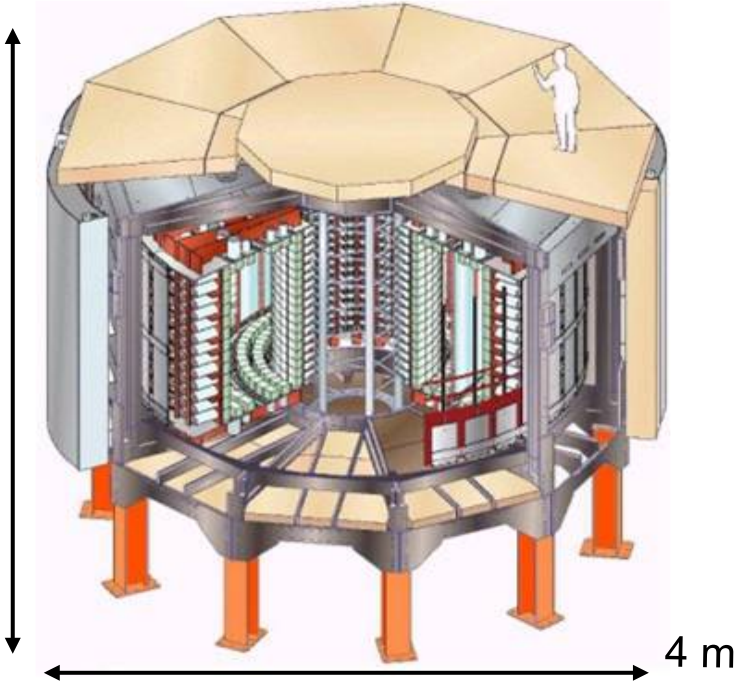
Laboratoire Souterrain de Modane (LSM) : 4800 M.W.E.



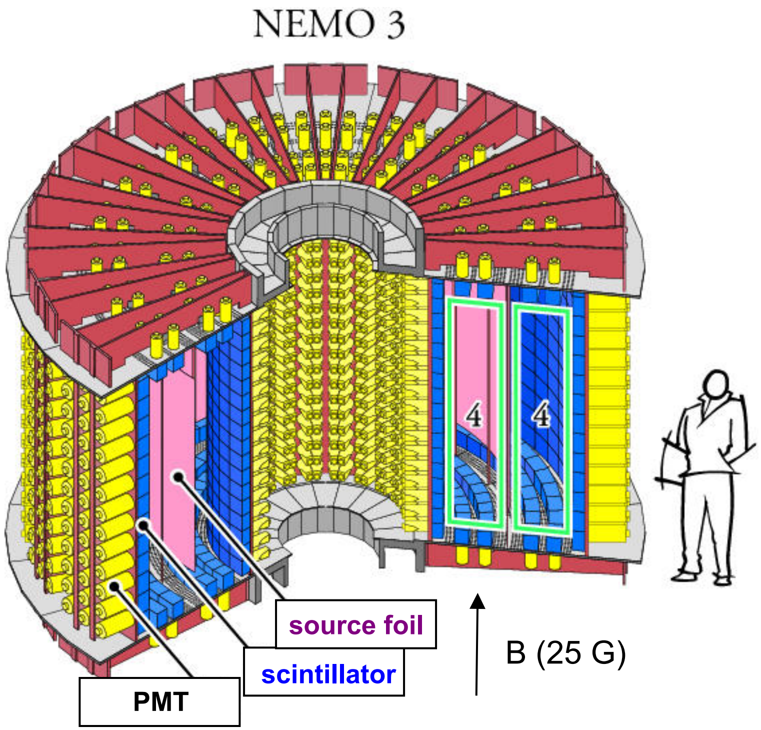
NEMO-3

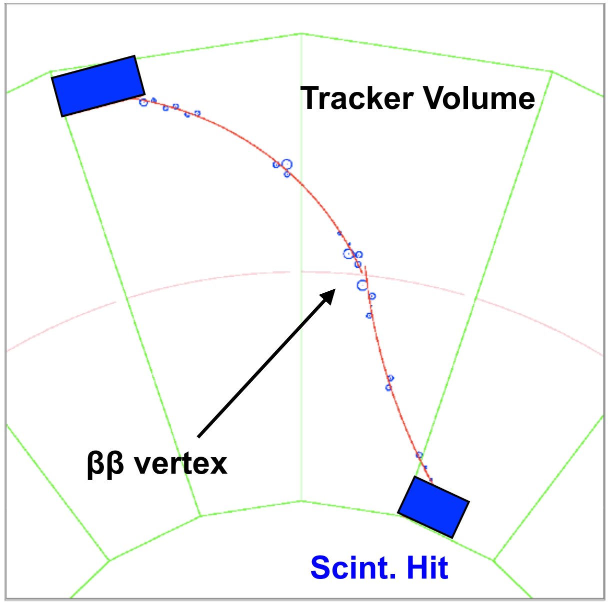
The world's biggest and cleanest Geiger counter

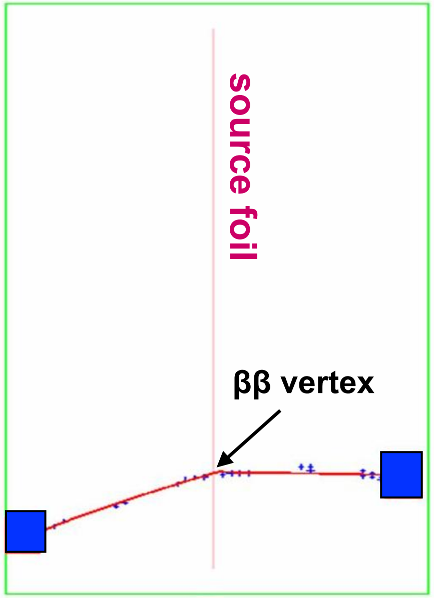
Ran from Feb. 2003 to Jan. 2011



NEMO-3




Transverse View


Longitudinal View

- The particle physicist's nuclear physics experiment.
- "Smoking gun" : complete event reconstruction for :
  - background rejection
  - signal characterisation (discovery!)

Isotopes

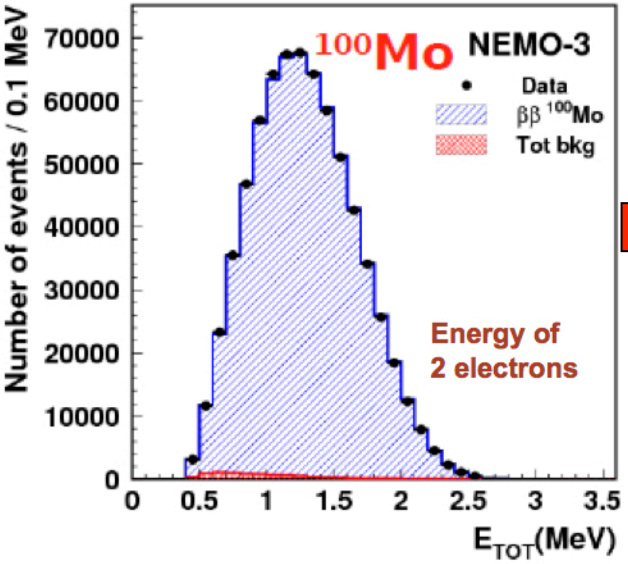
Large quantities: ^{100}Mo (7kg) ^{82}Se (1 kg)

Small quantities: ^{116}Cd ^{150}Nd ^{48}Ca ^{96}Zr ^{130}Te

All major isotopes except ^{76}Ge and ^{136}Xe

NEMO-3 : Physics Highlights ($2\nu\beta\beta$)

Isotope	mass, g	$Q_{\beta\beta}$ (keV)	$T_{1/2}(2\nu)$ (10^{19} yrs)	Comments
^{100}Mo	6914	3034	0.71 ± 0.05	World's Best !
^{82}Se	932	2996	9.6 ± 1.0	World's Best !
^{96}Zr	9.4	3350	2.35 ± 0.21	World's First (N2) & Best !
^{48}Ca	7	4272	4.4 ± 0.6	World's Best !
^{116}Cd	7.49	2814	2.8 ± 0.3	World's Best !
^{130}Te	454	2528	70 ± 14	World's Best & First (Direct) !
^{150}Nd	37	3371	0.9 ± 0.07	World's Best !



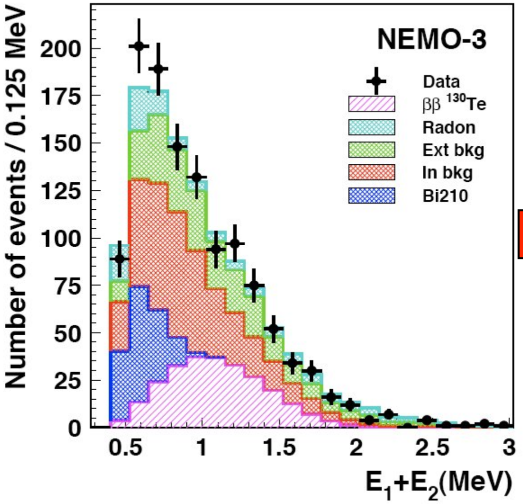
^{100}Mo : a double-beta decay Standard Candle

> 700,000 events

Signal/Background ~ 75

The rate of $2\nu\beta\beta$ is so large it's a problem for $0\nu\beta\beta$

Double–Beta Decay of ^{130}Te



Arnold et al. 2011

^{130}Te

454 g × 3.5 y

$T_{1/2} = 7.0 \pm 1.4 \times 10^{20}$ years

half-life > 10 billion × age of universe !

First high precision direct measurement of this lifetime.

Geochemical measurements :

- Measure integrated decay rate via abundance of daughter isotope
- Small M, large T

$$^{130}\mathrm{Te} \xrightarrow{\beta\beta} {}^{130}\mathrm{Xe}$$

$$^{128}\mathrm{Te} \xrightarrow{\beta\beta} {}^{128}\mathrm{Xe}$$

from mass spectrometry

Bernatowicz et al. 1993

Native Te (Colorado)

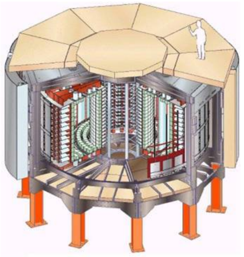
Sample Age ≈ 1.6 billion years

$T_{1/2} \approx 30 \times 10^{20}$ years

AuTe$_2$ (Colorado)

Sample Age ≈ 28 million years

$T_{1/2} \approx 9 \times 10^{20}$ years



Te Foil (LSM Lab)

Sample Age ≈ 0

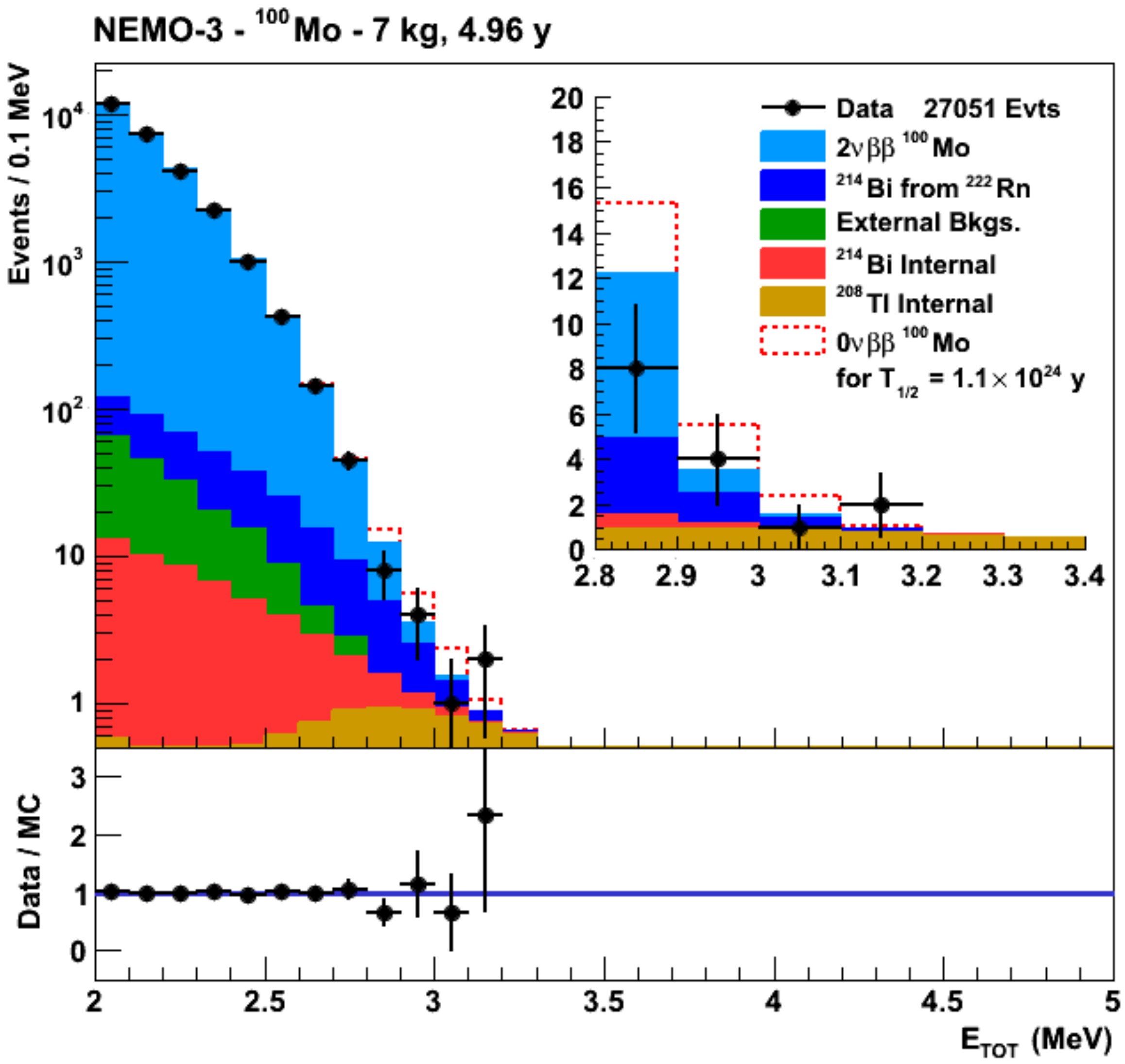
$T_{1/2} \approx 7 \times 10^{20}$ years

Time-varying decay rate ??

Sensitive test of $G_F(t)$

$0\nu\beta\beta$ 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 :

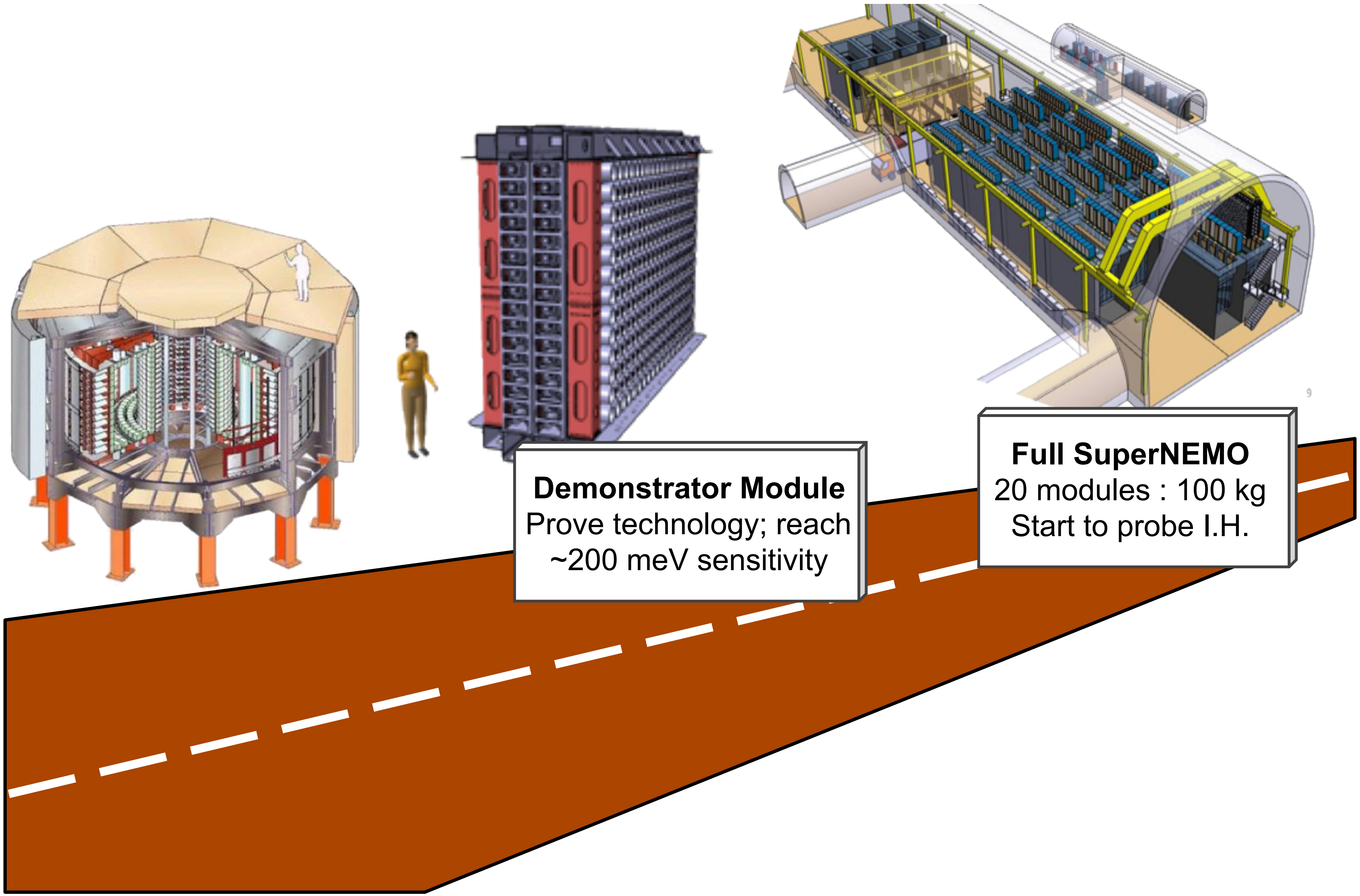
$$T_{1/2}^{0\nu\beta\beta} > 1.1\times10^{24}\ \text{yr (90\% C.L.)}$$

- For the Majorana mass mechanism this equates to :

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

- Also limits on RHC, $\cancel{R}_P$ SUSY etc.

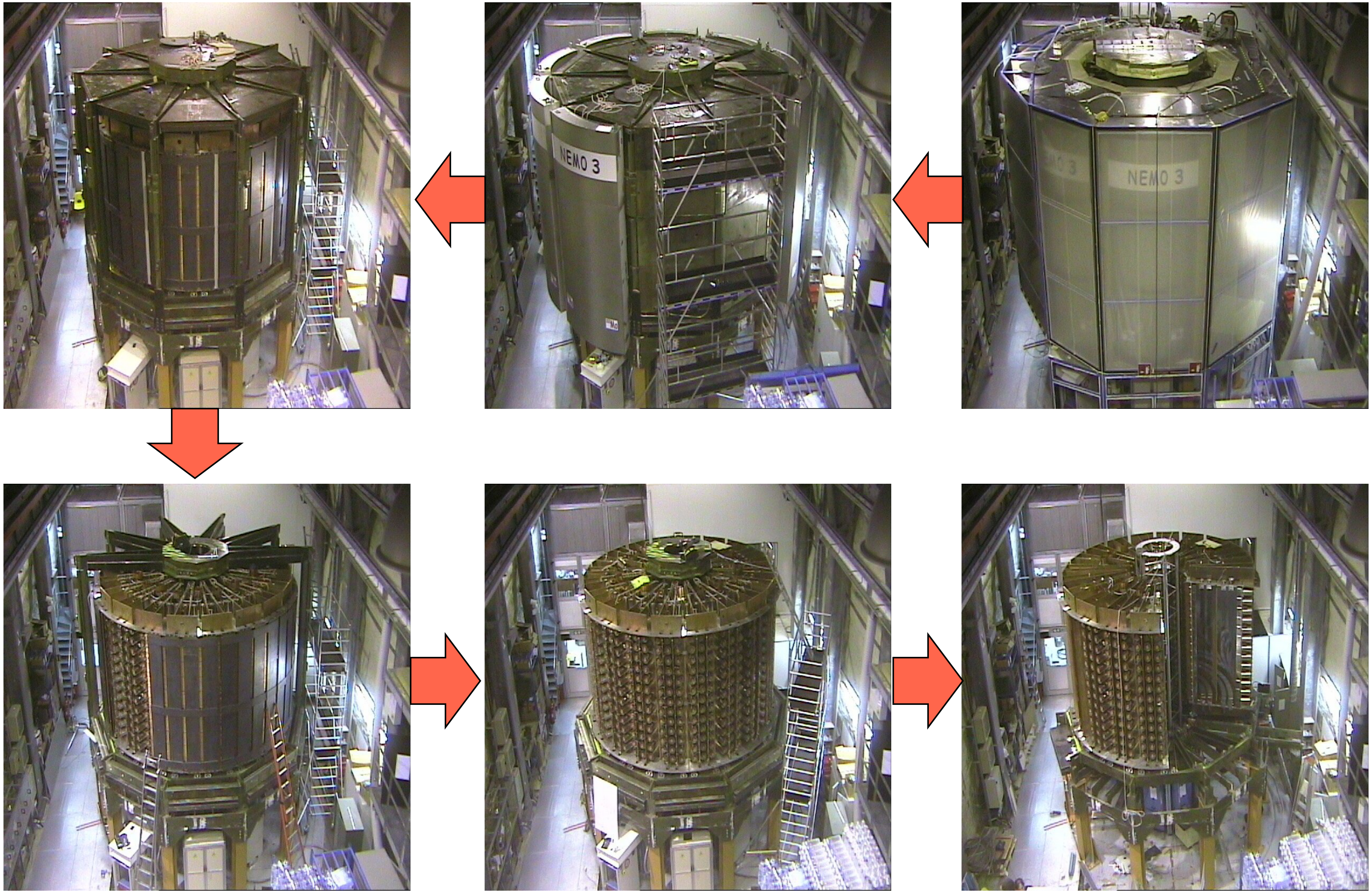
SuperNEMO : Road Map



Demonstrator Module
Prove technology; reach
~200 meV sensitivity

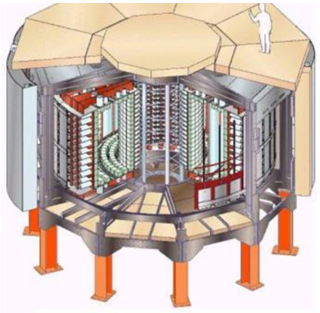
Full SuperNEMO
20 modules : 100 kg
Start to probe I.H.

NEMO-3 Dismantling

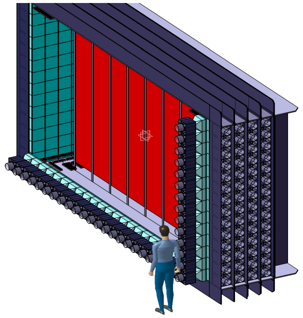


SuperNEMO : How to Get There ?

NEMO-3



SuperNEMO



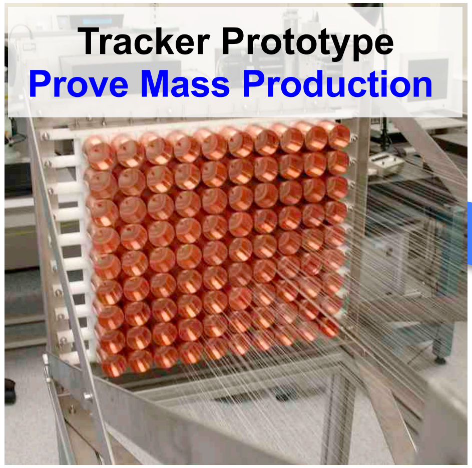
^{100}Mo	isotope	^{82}Se or other
7 kg	isotope mass	100+ kg
^{208}Tl: ~ 100 μBq/kg ^{214}Bi: ~ 300 μBq/kg Rn: ~ 5 mBq/m^3	internal contamination ^{208}Tl , ^{214}Bi in the ββ foil Rn in the tracker	^{208}Tl ≤ 2 μBq/kg ^{214}Bi ≤ 10 μBq/kg Rn ≤ 0.15 mBq/m^3
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV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

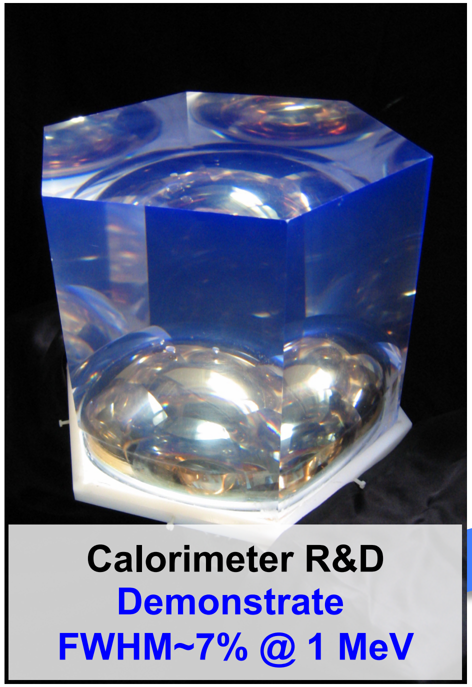
→ **factor ~100 in $T_{1/2}$**
factor ~10 in $\langle m_\nu \rangle$

SuperNEMO Demonstrator Module : Overview



Tracker Prototype

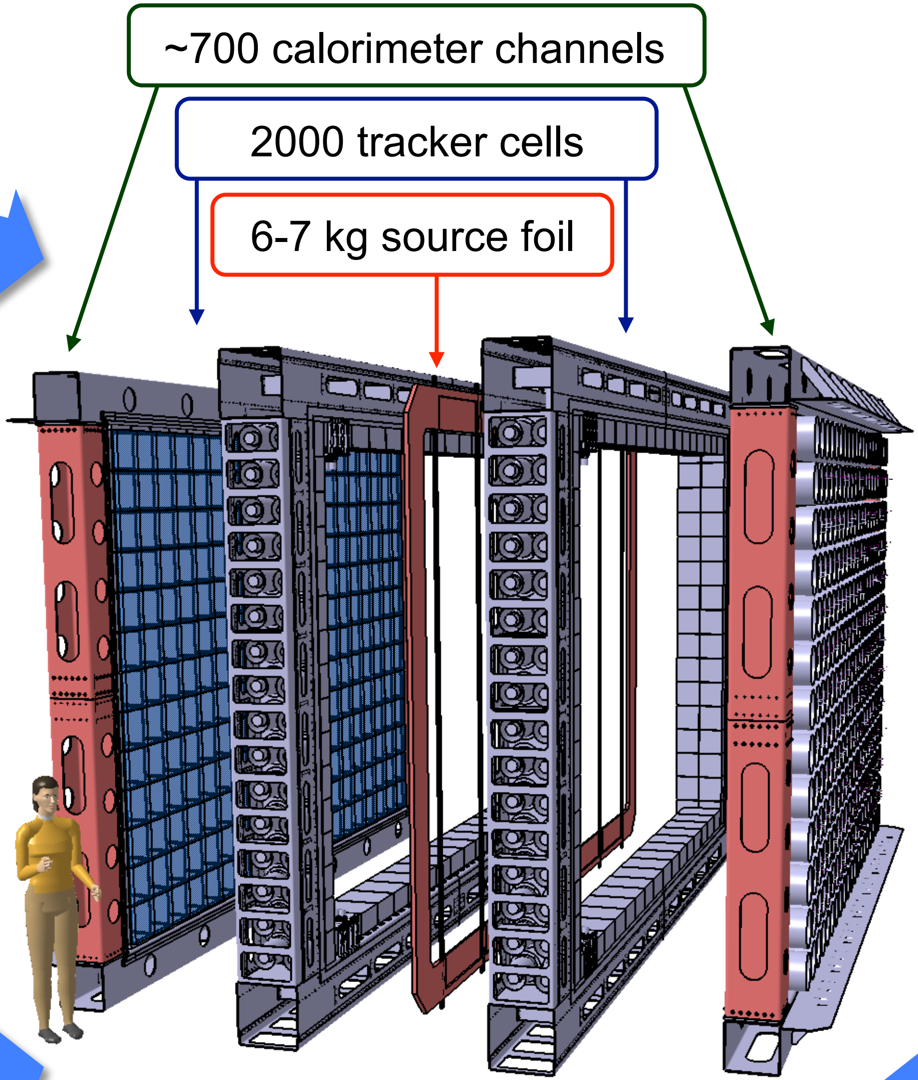
Prove Mass Production



Calorimeter R&D

Demonstrate

FWHM~7% @ 1 MeV



~700 calorimeter channels

2000 tracker cells

6-7 kg source foil

Demonstrator Module

Also :

- Change isotope ^{100}Mo → ^{82}Se
- Reduce radon in gas by factor 30
- Improved efficiency, calibration etc.

"BiPo" Detector

Measure source foil contamination to

^{208}Tl ≤ 2 μBq/kg

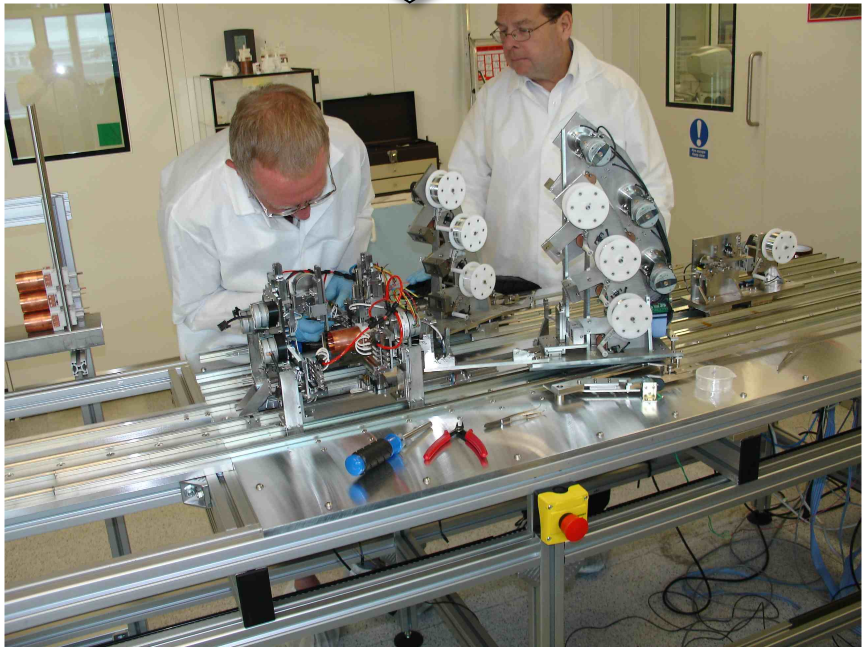
^{214}Bi ≤ 10 μBq/kg

SuperNEMO UK

Build a 2000 channel Geiger-mode tracking detector :

- Must reconstruct β−electron tracks with high efficiency and resolution.
- Must contribute zero background in the 0νββ 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.

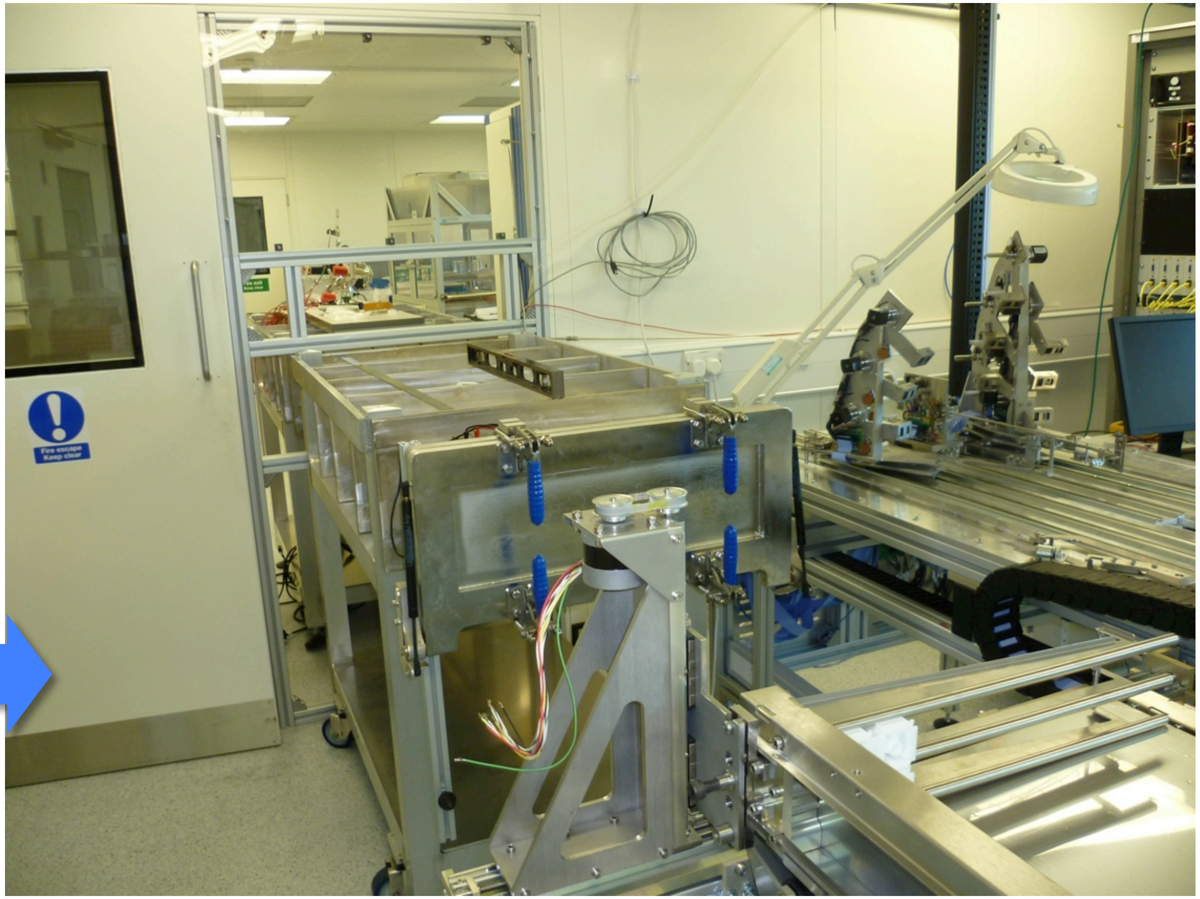
tracker robot being commissioned (Manchester)



optical module production line (UCL)

Tracker Production

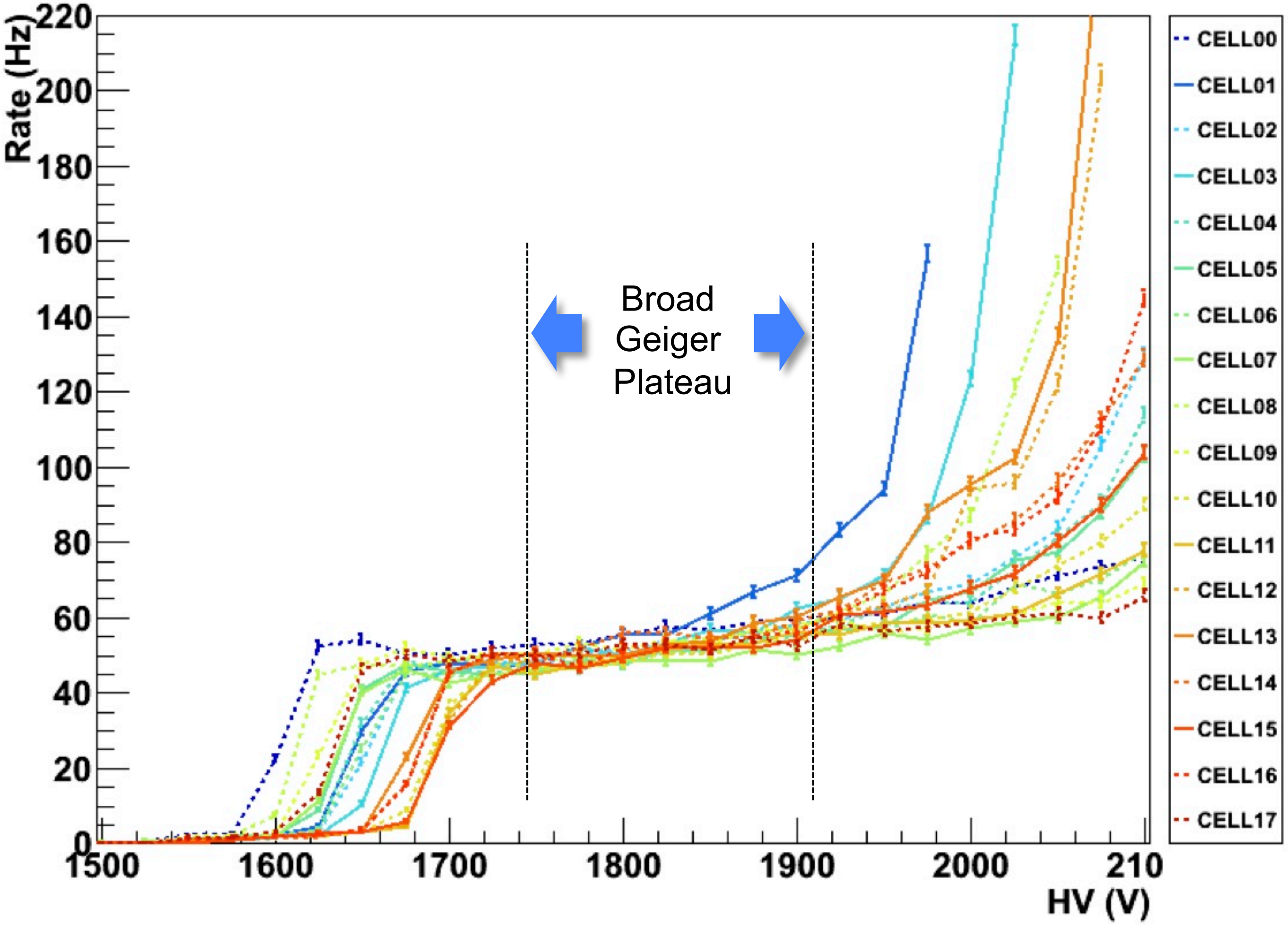
First 18-cell "cassette" produced automatically April 2013.



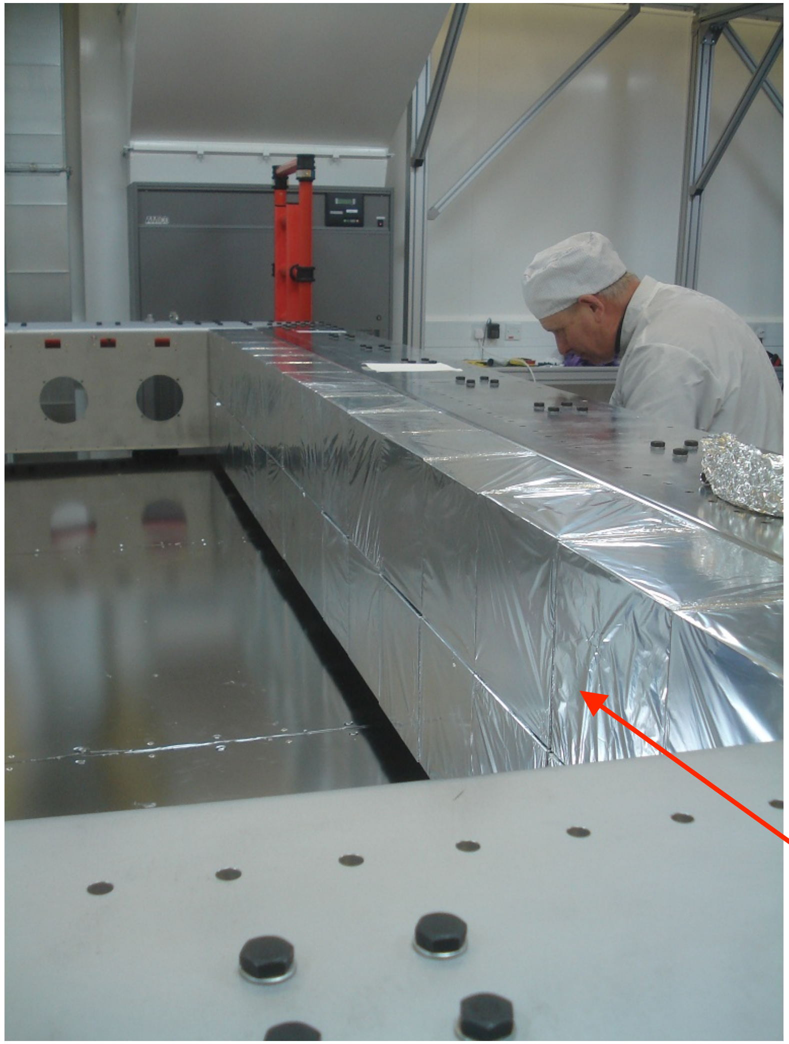
Each cassette is transferred to a test-tank for burn-in and testing.

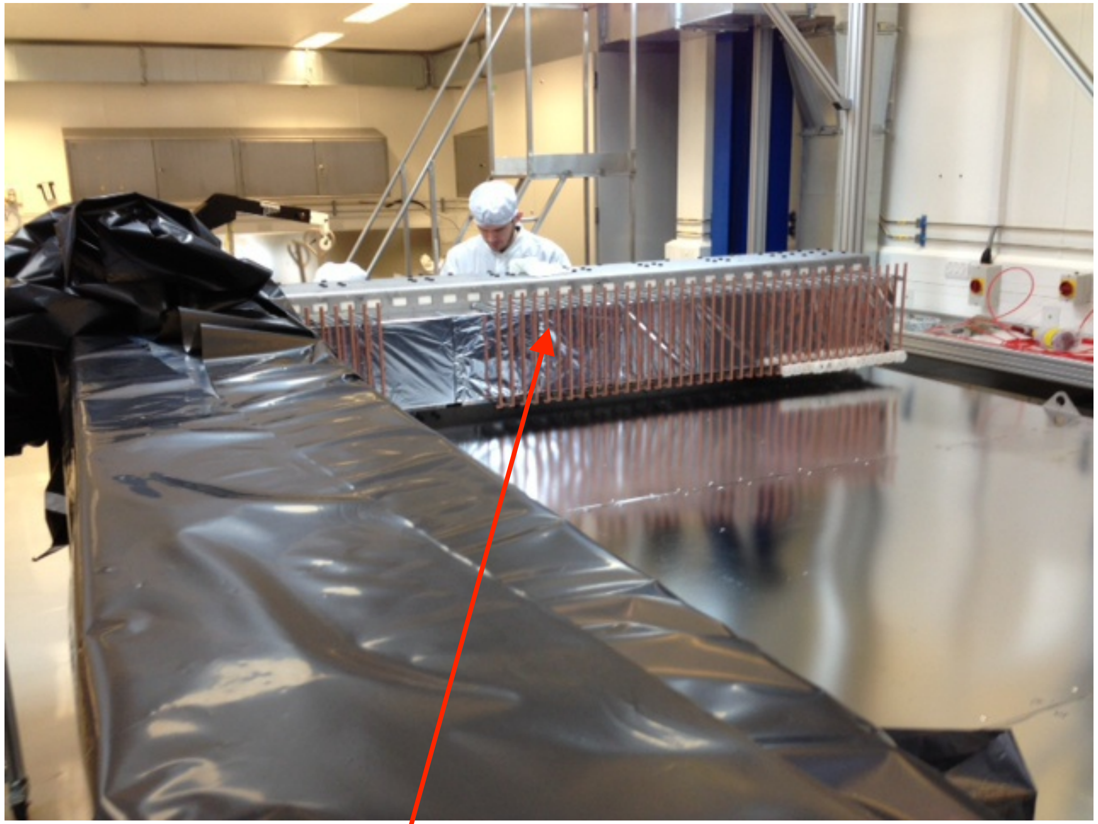
Tracker Production

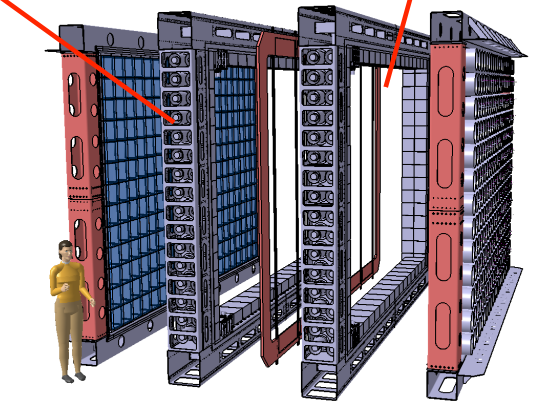
- Cassettes are now routinely passing all production quality requirements.



Tracker Frame

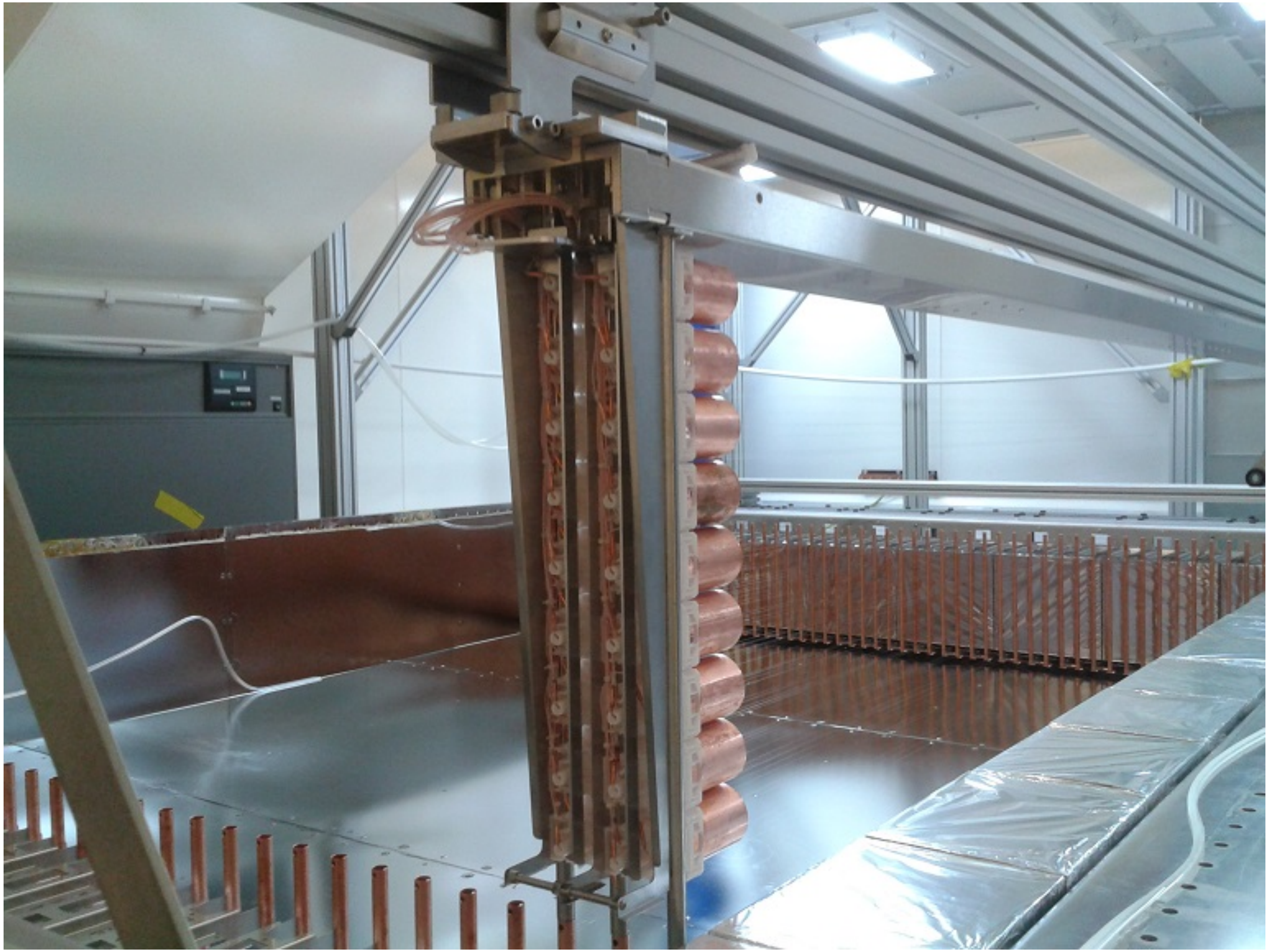




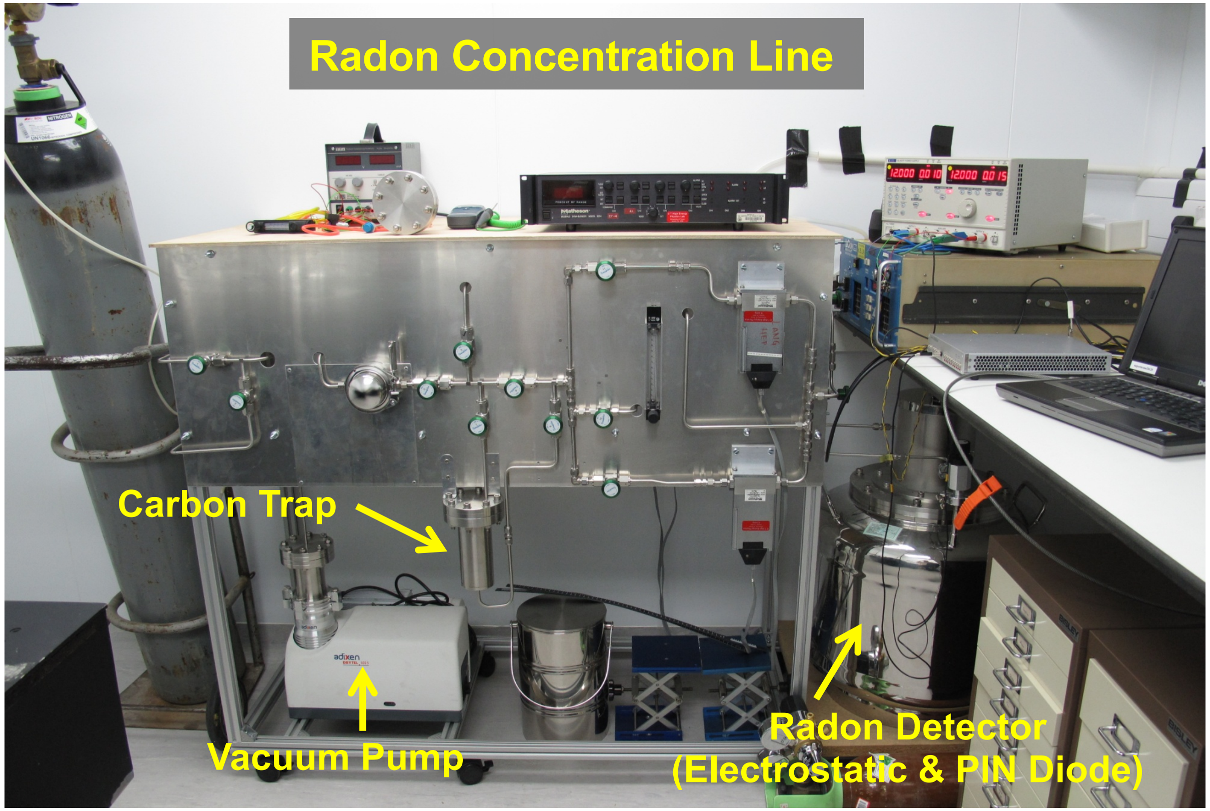


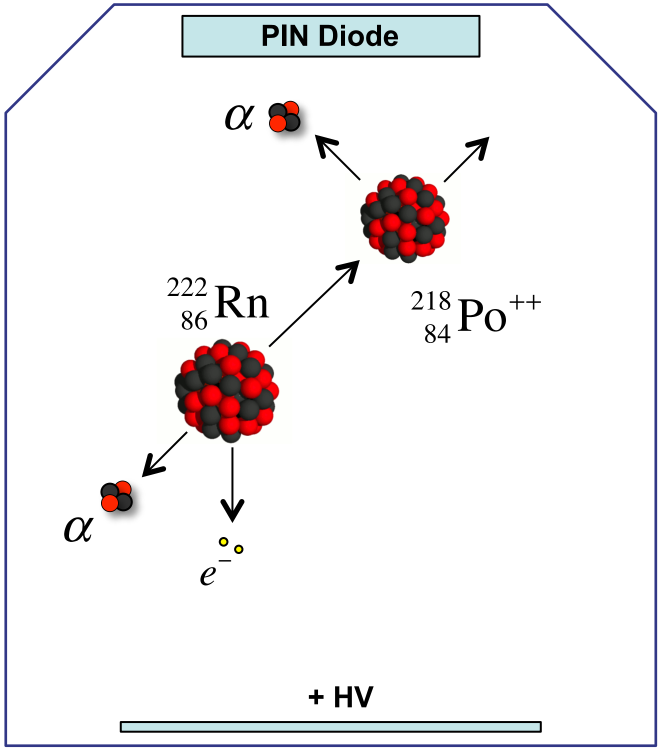
- Insertion of Optical Modules into tracker frame.
- Preparation of cell support structure.

Tracker Cell Insertion



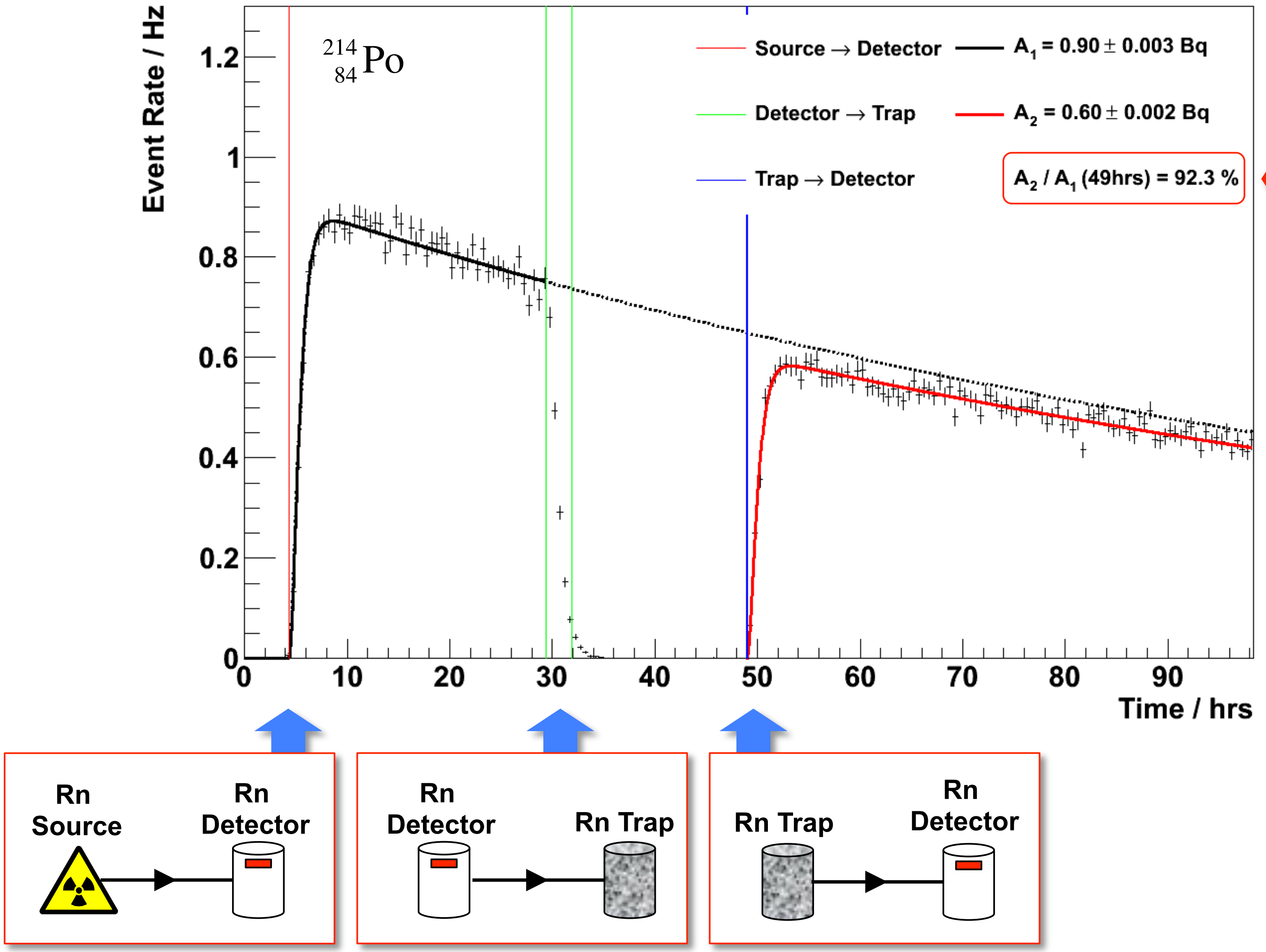
Low Background Measurements





- Radon concentration in ordinary air is 10-100 Bq/m^3
- We need to be able to measure concentrations down to 0.1 mBq/m^3 : 100,000 times smaller.
- Latest results indicate that we have achieved the required sensitivity.

Radon Concentration Line Calibration



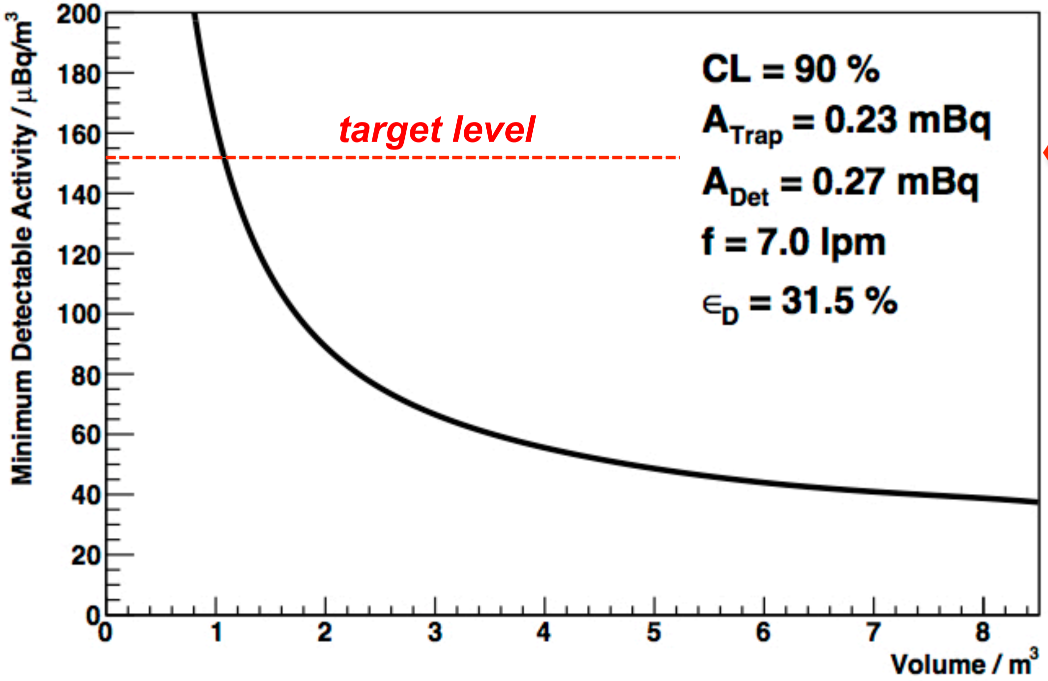
Rn Source → Rn Detector

Rn Detector → Rn Trap

Rn Trap → Rn Detector

high efficiency

Radon Concentration Line Sensitivity

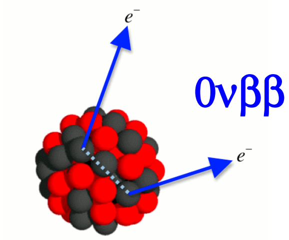


- Sensitivity of the RnCL as a function of volume of gas sampled, under realistic conditions.
- This is far in excess of our target of 150 µBq/m^3

- Tests of the first tracker C-section are ongoing.
- "Anti-Radon" tent providing a high flux of N_2 is visible.
- Main difficulty is obtaining clean enough input gas for the test.

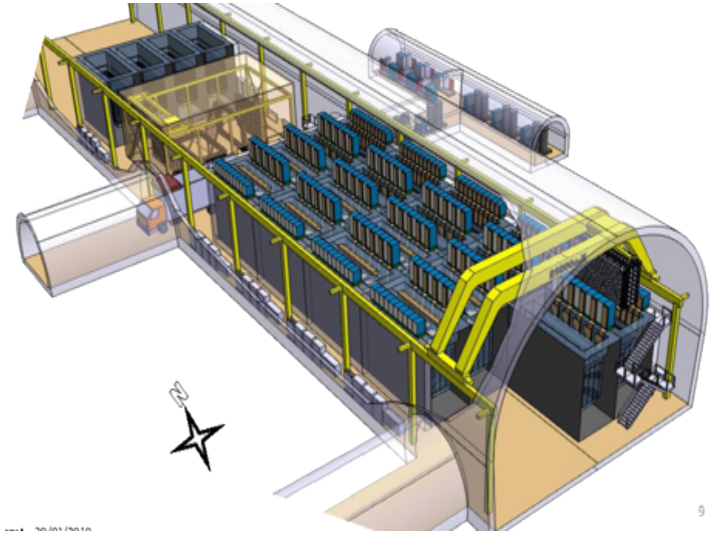
SuperNEMO : Timeline

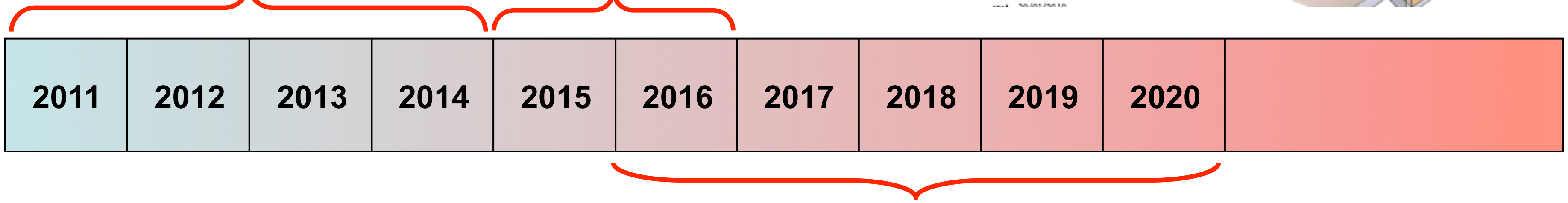
Demonstrator Module
construction and
commissioning



Demonstrator Module Running :

- Prove $B \sim 10^{-4}$ cts/keV/kg/yr : amongst best of *any* experiment.
- Limit on $T_{1/2} \sim 6.5 \times 10^{24}$ yr.
- Unique ββ measurements.





Construction and deployment of successive SuperNEMO modules

Sensitivity with 100 kg :

$T_{1/2}(0\nu\beta\beta) \sim 10^{26}$ yr $\longrightarrow$ $\langle m_\nu \rangle \sim$ 40-110 meV

Continuous operation of ≥1 SuperNEMO module

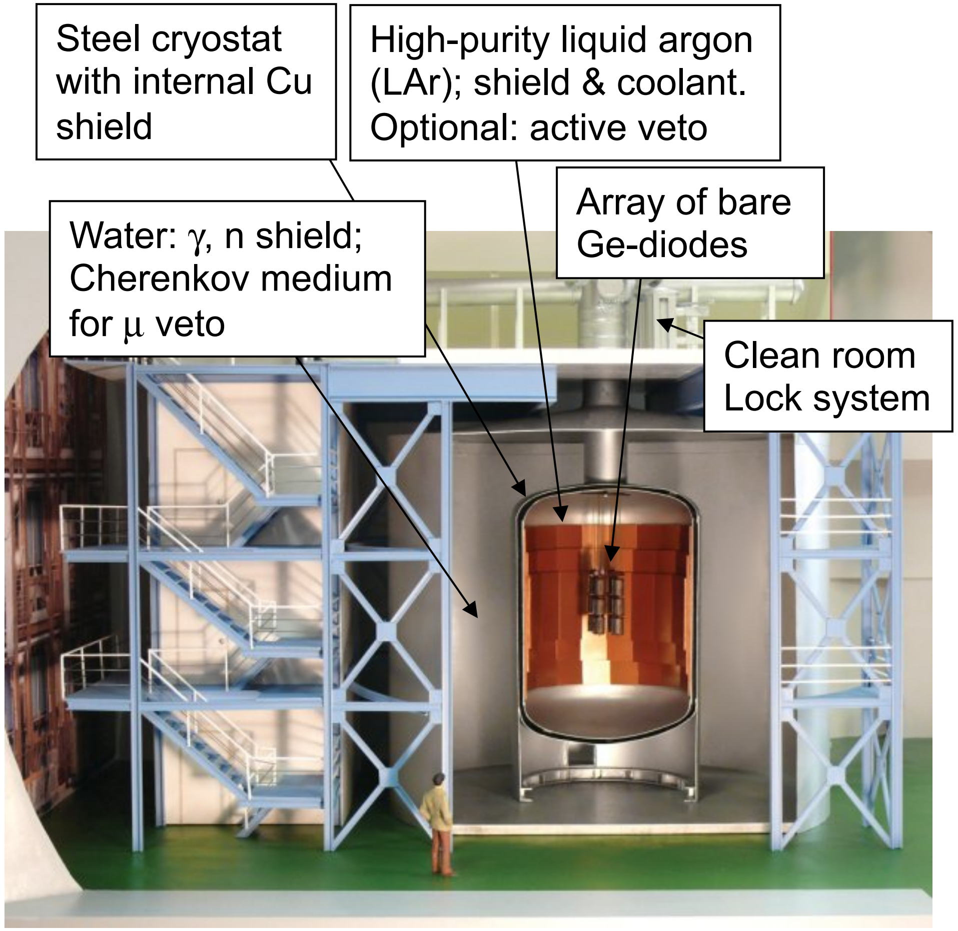
GERDA

Next-generation ^{76}Ge experiment

- Best way to directly check **KKDC** claim (no NME uncertainties)
- Location : Gran Sasso

$$^{42}\text{Ar} \xrightarrow[33y]{\beta^-} {}^{42}\text{K} \xrightarrow[12h]{\beta^-} {}^{42}\text{Ca}$$

creates a background at $Q_{\beta\beta}(^{76}\text{Ge})$



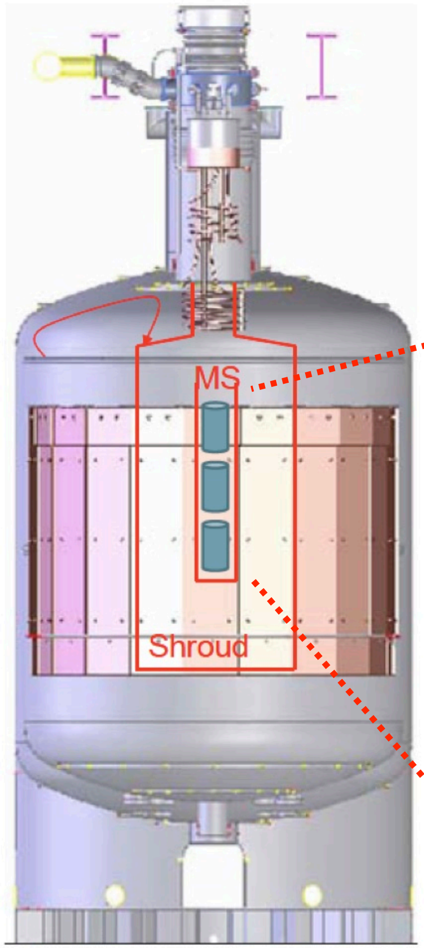
Steel cryostat with internal Cu shield

High-purity liquid argon (LAr); shield & coolant. Optional: active veto

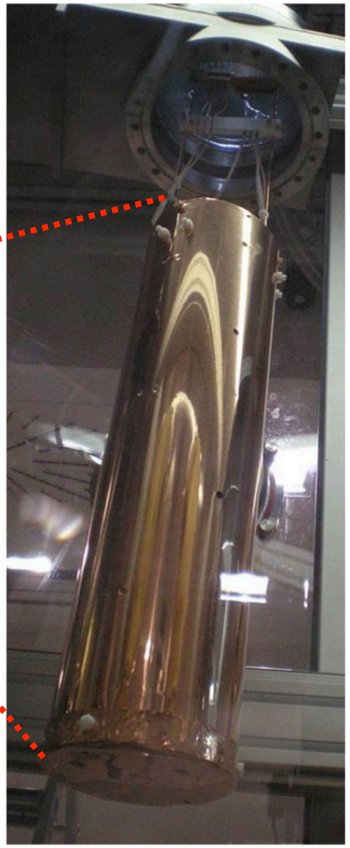
Array of bare Ge-diodes

Water: γ, n shield; Cherenkov medium for μ veto

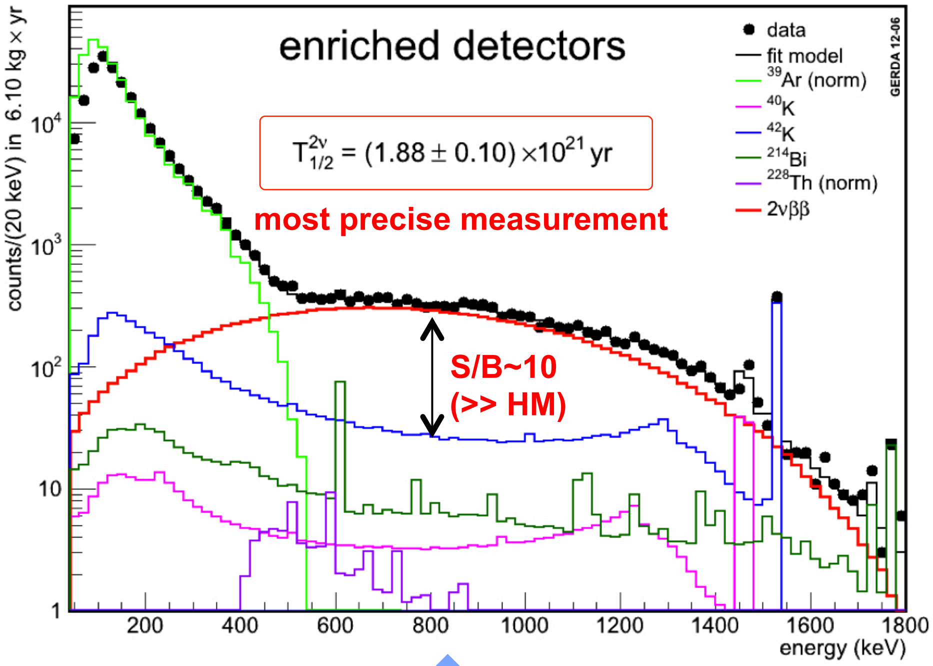
Clean room Lock system



Cu “mini-shroud” to prevent drift of $^{42}\text{K}^+$ ions onto Ge diodes

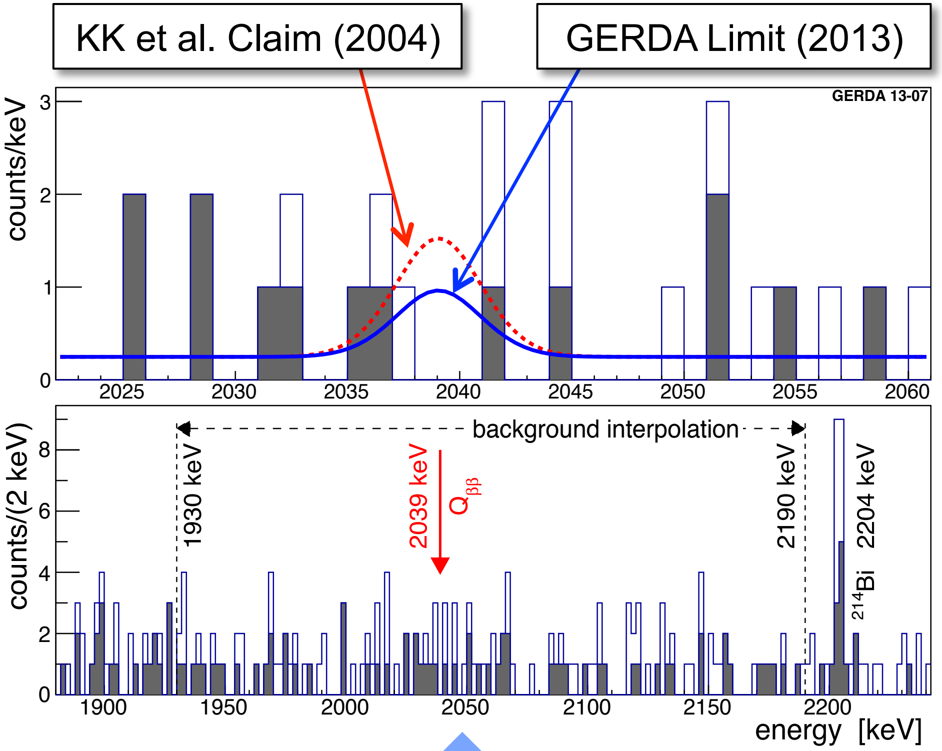


GERDA



most precise measurement

S/B~10 (>> HM)



KK et al. Claim (2004)

GERDA Limit (2013)

Measurement of the 2νββ half-life.

$$T_{1/2}^{2\nu\beta\beta} = (1.88 \pm 0.10) \times 10^{21}\,\text{yr}$$

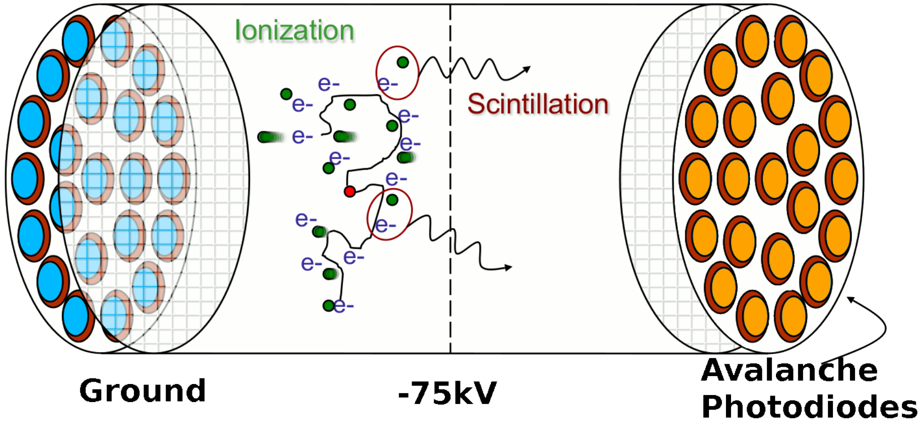
Agostini et al. (2012)

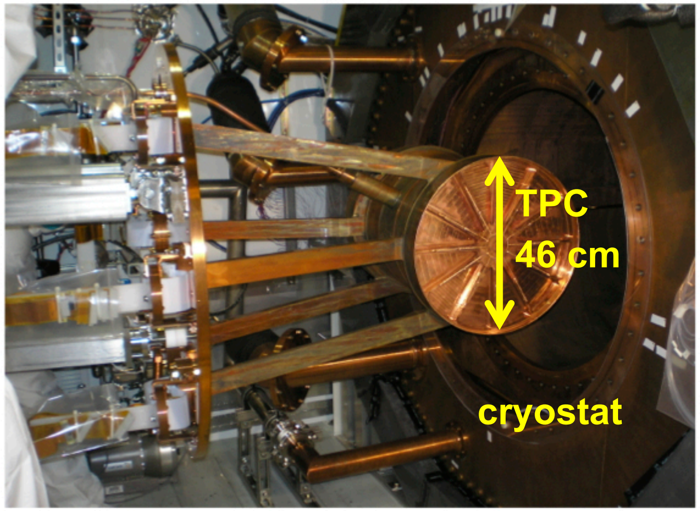
Unblinding of the the 0νββ region of interest.

$$T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{25}\ \text{yr (90\% C.L.)}$$

Agostini et al. (2013)

Enriched Xenon Observatory





- Liquid-xenon TPC with ionisation & scintillation readout
- Fiducial mass of 79.4 kg of ^{136}Xe for the $0\nu\beta\beta$ search.

^{136}Xe $2\nu\beta\beta$ measurement :

$$T_{1/2}^{2\nu\beta\beta} = 2.11 \pm 0.04(\text{stat.}) \pm 0.21(\text{syst.}) \times 10^{21}\ \text{yr}$$

Ackerman et al. (2011)

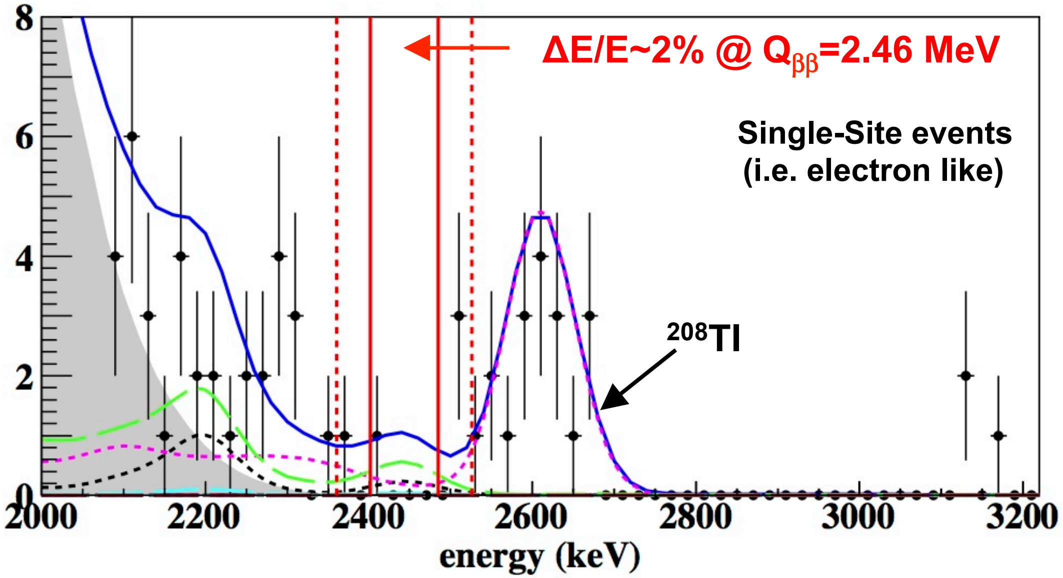
1 event observed in 1σ RoI around $Q_{\beta\beta}$ vs. 4.1 background events expected.

33 kg.yr B~0.0015 cts/keV/kg/yr

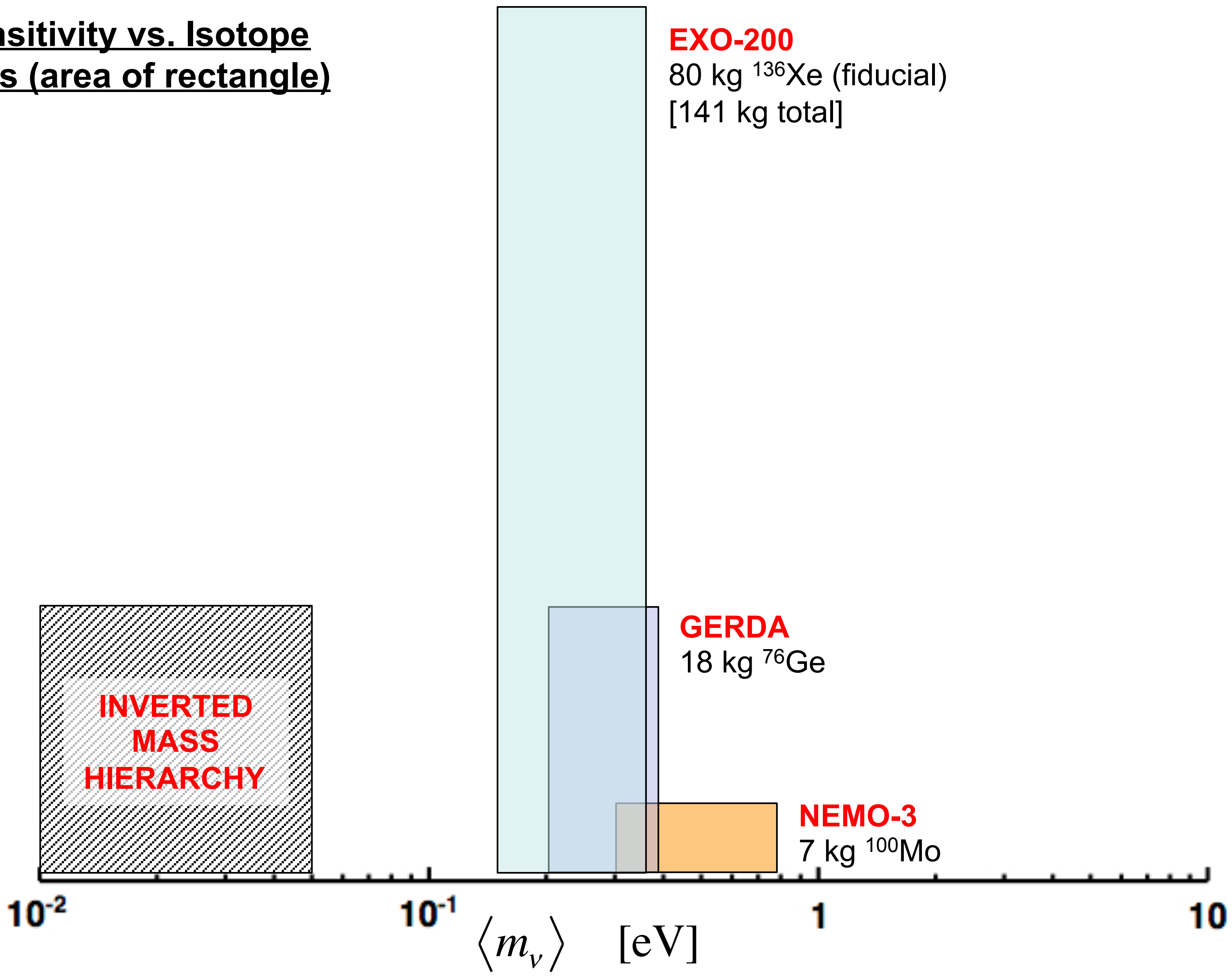
$$T_{1/2}^{0\nu\beta\beta} > 1.6 \times 10^{25}\ \text{yr} \ \ @\ 90\%\ \text{C.L.}$$

$$\langle m_\nu \rangle < 140 - 380\ \text{meV}$$

Auger et al. (2012)

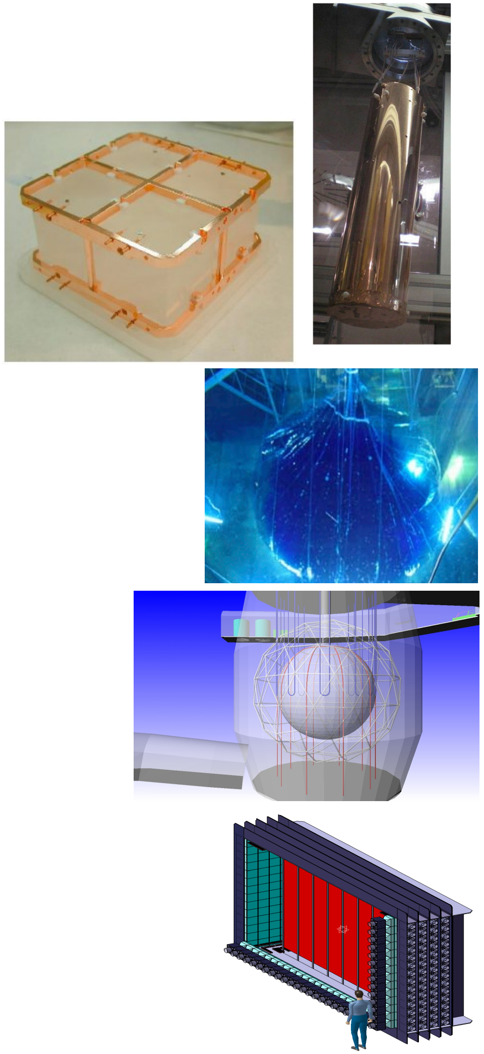


Comparison of Recent Limits

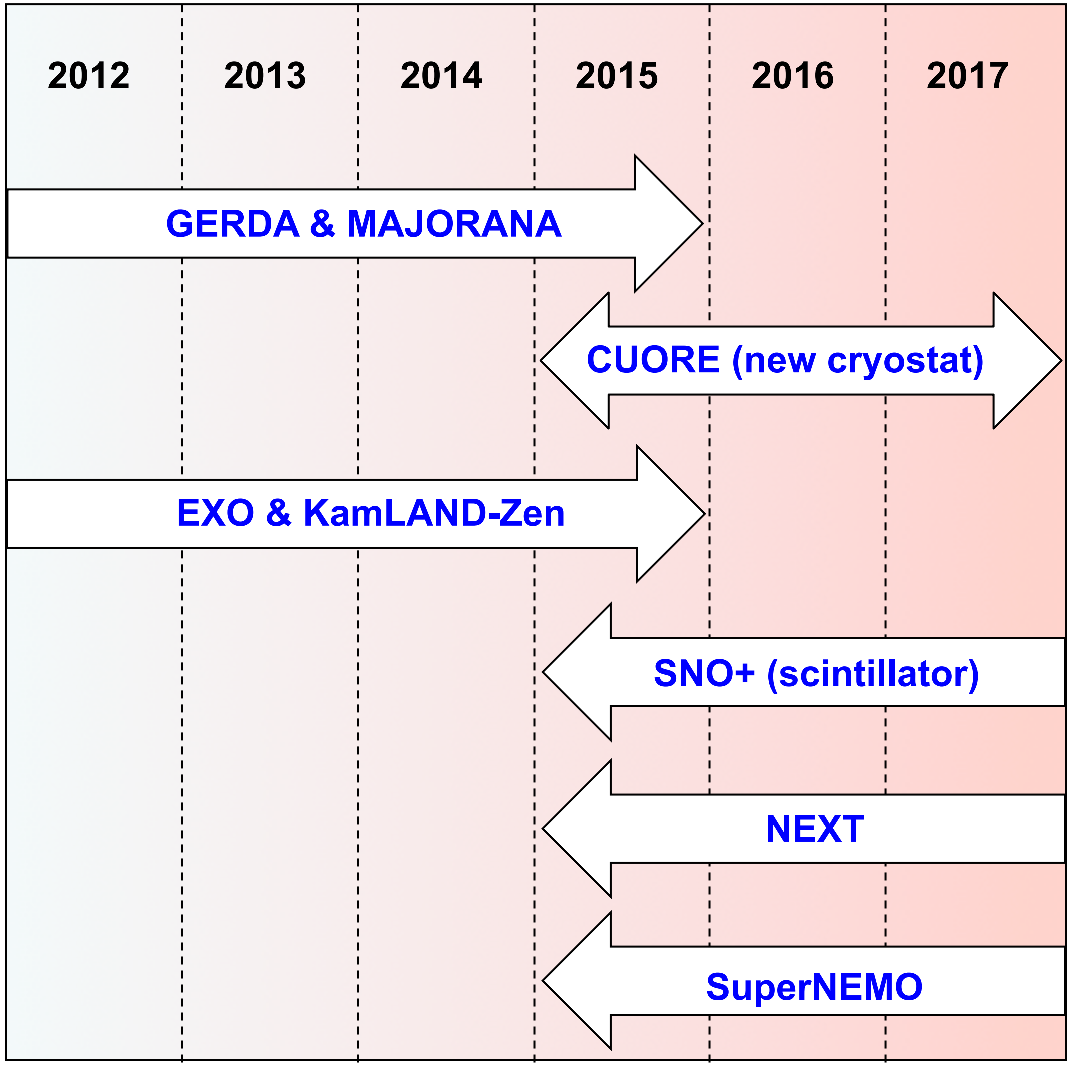


Timescales

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



Selected Experiments Only



2012 2013 2014 2015 2016 2017

GERDA & MAJORANA

CUORE (new cryostat)

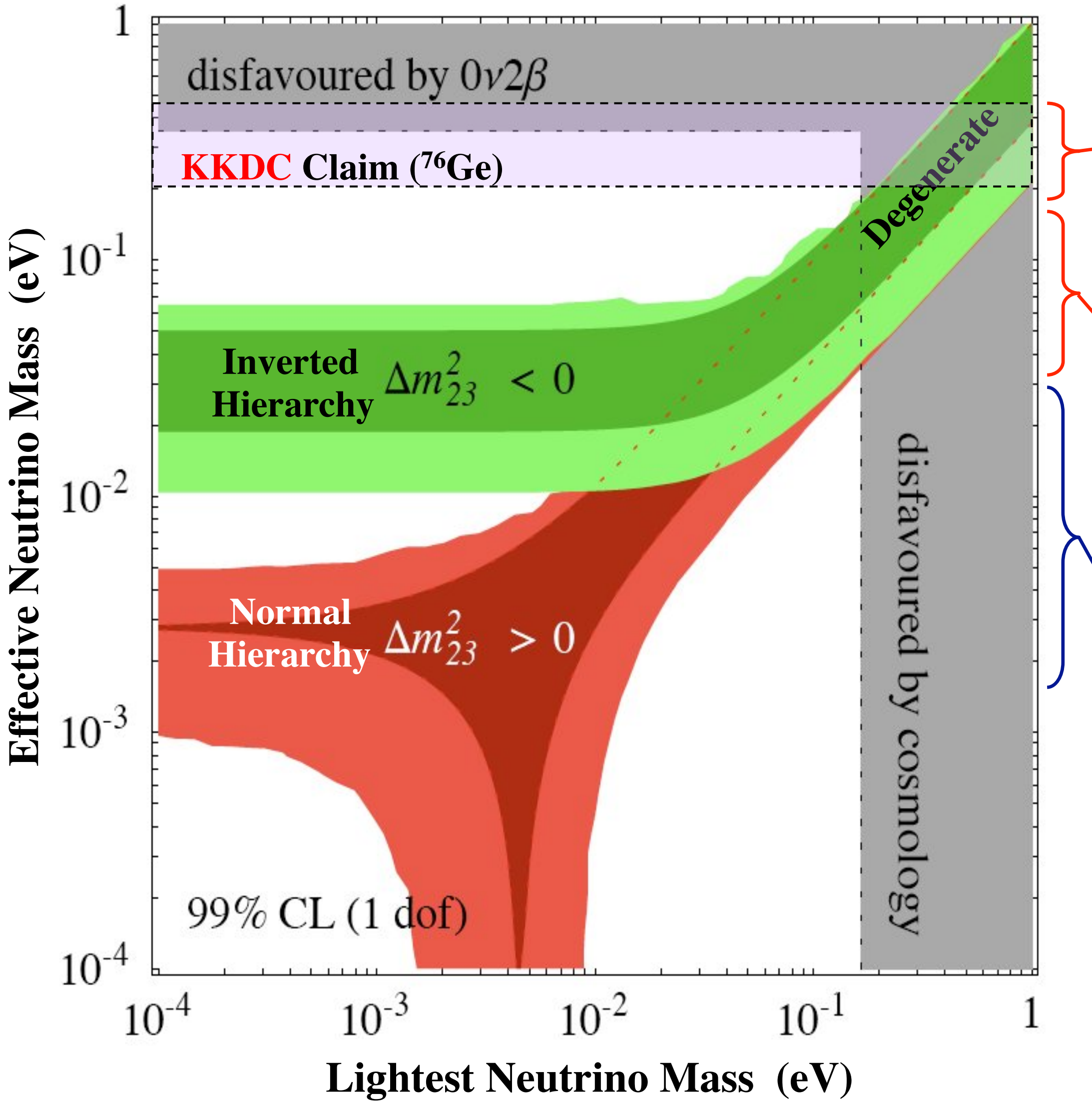
EXO & KamLAND-Zen

SNO+ (scintillator)

NEXT

SuperNEMO

Summary



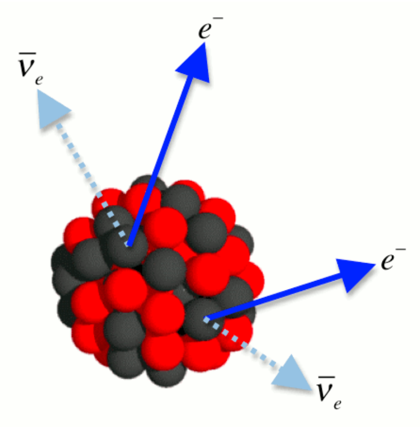
2012-2015
SuperNEMO Demonstrator
EXO & Kamland-Zen
SNO+ Phase 1
GERDA Phase 1
CUORE (0)
Others

2015-2020
SuperNEMO
SNO+
GERDA
CUORE
Others

Multi-ton Experiments
Scalability of existing techniques ?
New ideas ?

Summary

- We are compelled to search for $0\nu\beta\beta$: it is the only way to address fundamental questions in neutrino physics.
- Several next-generation experiments are under construction, using a variety of techniques that span the [mass/background] space.
- Strengths of the SuperNEMO approach are :
    - Comparable sensitivity to other experiments for much smaller isotope masses.
    - Isotope flexibility : if any *ton-scale* experiment discovers a signal, then SuperNEMO with *few(100) kg* can feasibly explore the signal with several different isotopes.
    - In the event of a discovery, a tracking experiment is by far the best approach to determine the mechanism of neutrinoless double-beta decay.
- Construction of the SuperNEMO Demonstrator Module is well advanced.



supernemo
collaboration