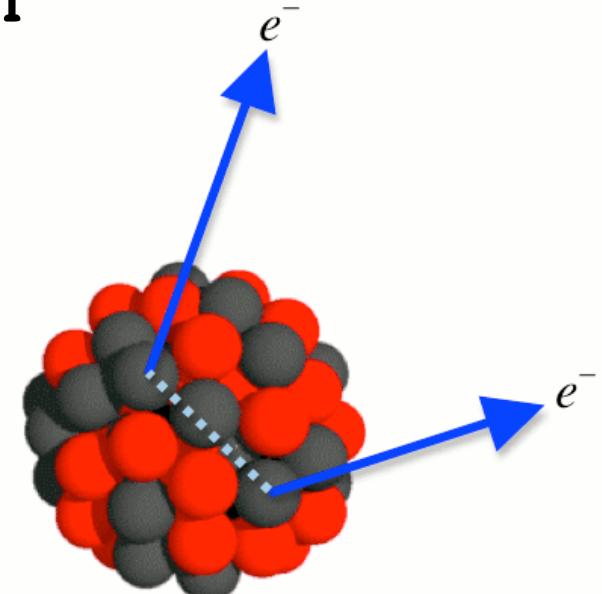
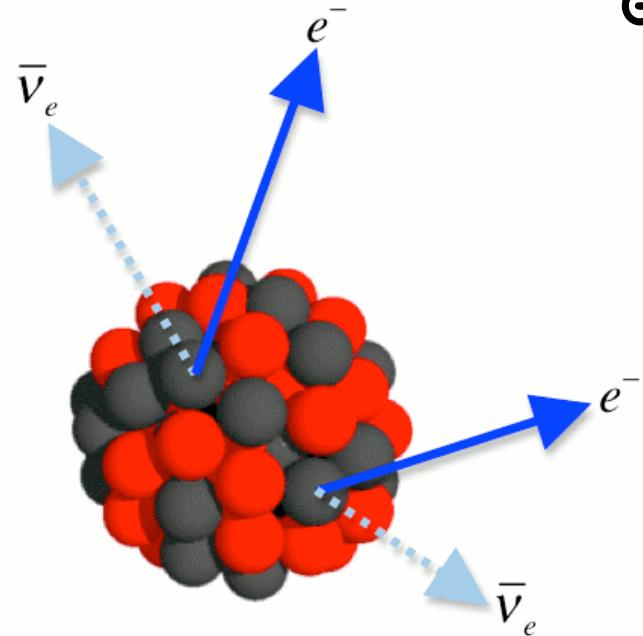


No-Neutrino Physics : The Search for Neutrinoless Double-Beta Decay

Dave Waters, UCL

IOP Nuclear & Particle Physics Divisional Conference

Glasgow, April 2011



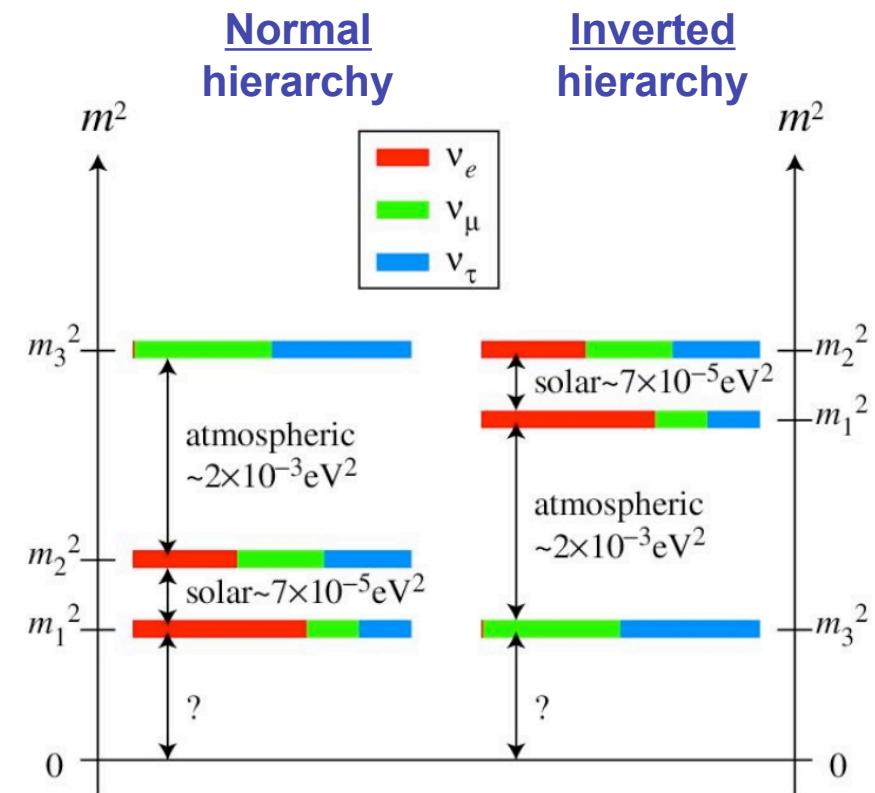
Key Questions in (No) Neutrino Physics

- Neutrinos have mass and they mix → (cf. previous talk).
- Precision measurements of mixing angles and Δm^2 . Is $\theta_{13} \neq 0$?
- **Nature of neutrinos** : Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}$)
- **Absolute neutrino mass scale** : only limits so far :
 - $m_{\bar{\nu}_e} < 2.3$ eV (Tritium end-point)
 - $\sum m_{\nu_i} < 0.5$ 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** : $\alpha_{21}, \alpha_{31} \neq 0, \pi$

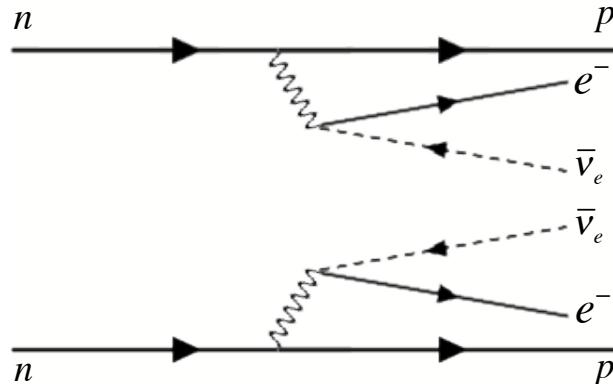
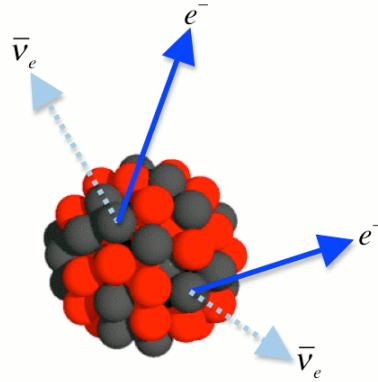
PMNS mixing matrix :

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

Majorana Phases



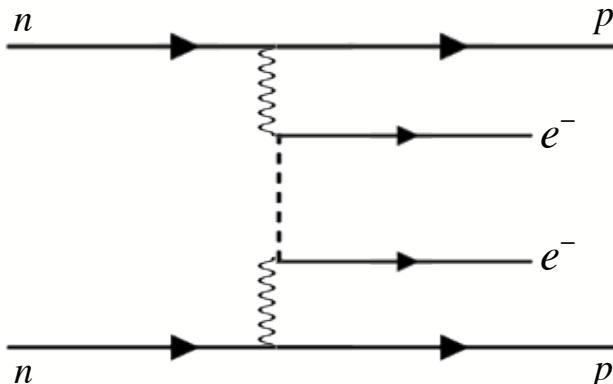
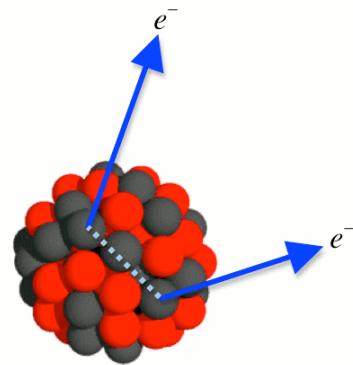
Double-Beta Decay



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 $\sim O(G_F^2)$



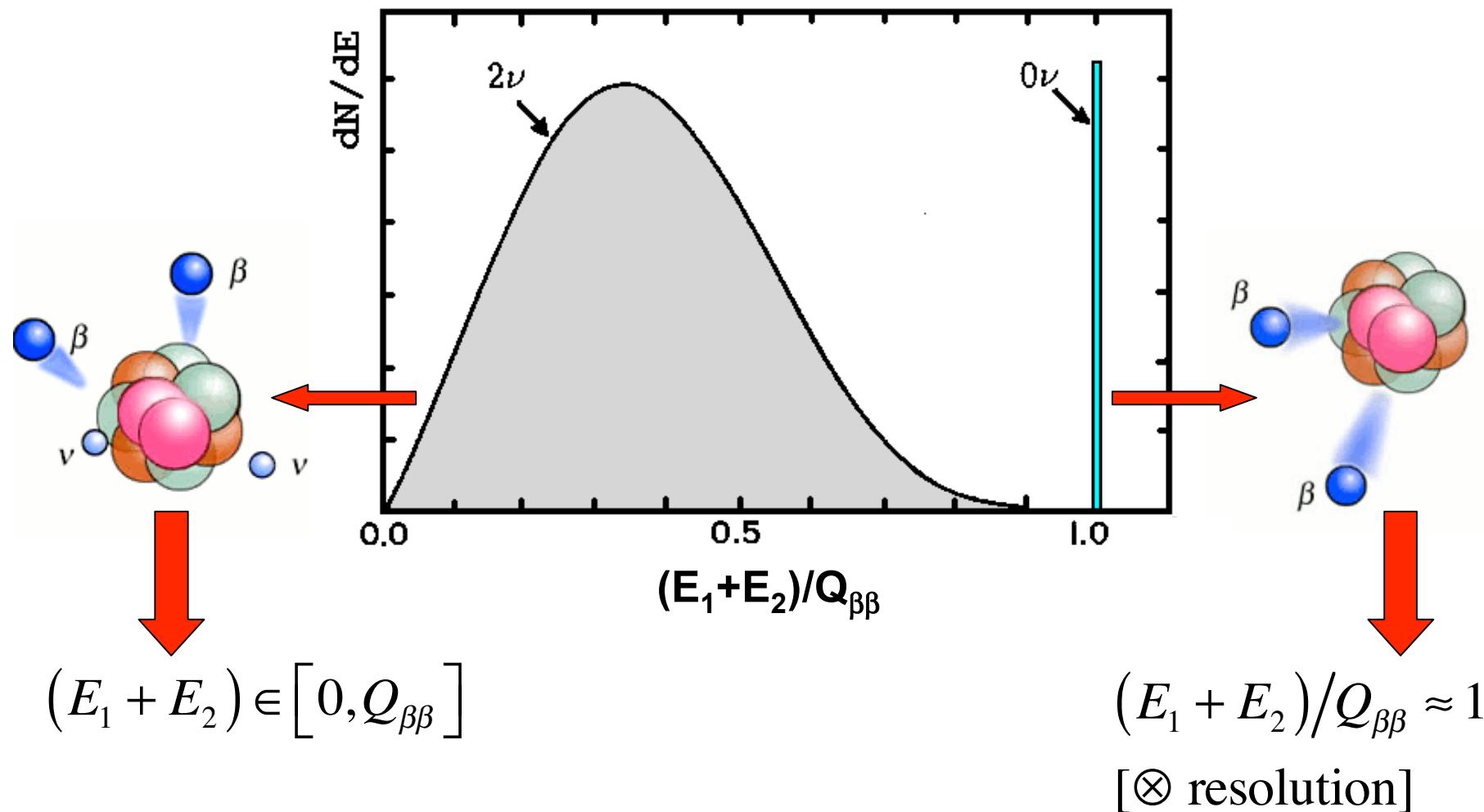
0-Neutrino Double Beta Decay

[Furry, 1939]

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

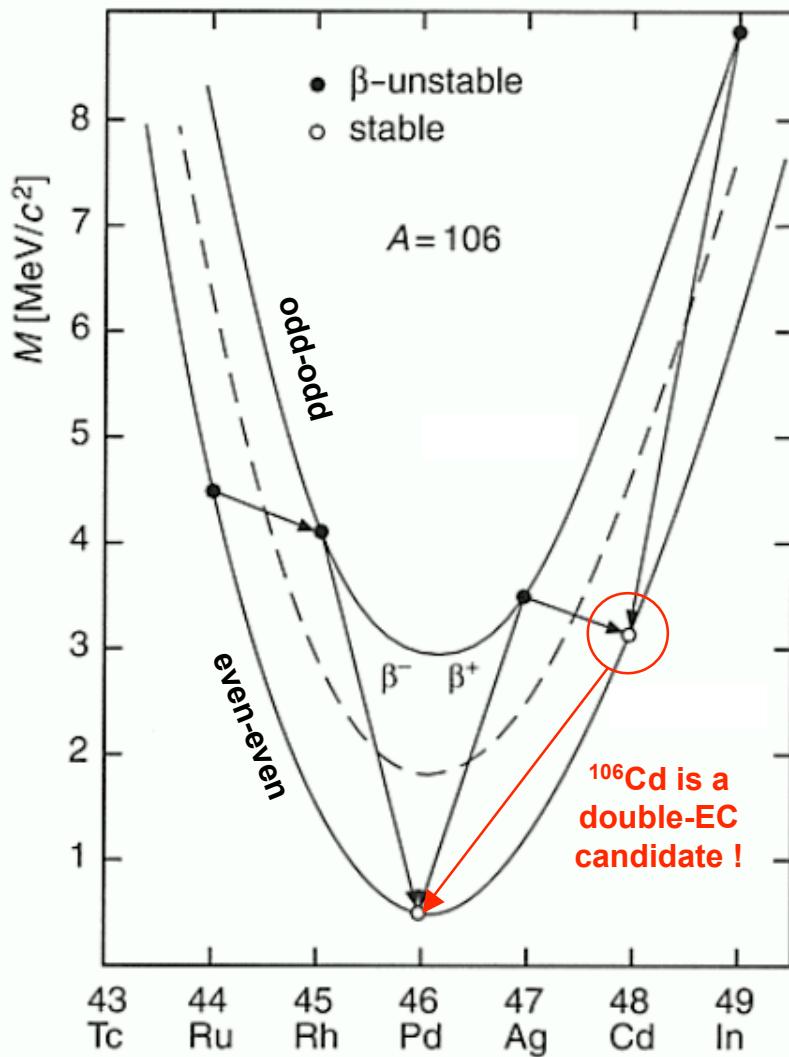
Double-Beta Decay : Basic Signature

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



Which Isotopes Can Double-Beta Decay ?

- Remember the pairing term in the SEMF!
- $\beta\beta$ candidates are all even-even nuclei.



Candidate isotopes :

| Isotope | $Q_{\beta\beta}$ (MeV) | Nat. Abundance (%) |
|-------------------|------------------------|--------------------|
| ^{48}Ca | 4.274 | 0.187 |
| ^{76}Ge | 2.039 | 7.8 |
| ^{82}Se | 2.996 | 9.2 |
| ^{96}Zr | 3.348 | 2.8 |
| ^{100}Mo | 3.035 | 9.6 |
| ^{110}Pd | 2.004 | 11.8 |
| ^{116}Cd | 2.809 | 7.6 |
| ^{124}Sn | 2.530 | 5.6 |
| ^{130}Te | 2.530 | 34.5 |
| ^{136}Xe | 2.462 | 8.9 |
| ^{150}Nd | 3.367 | 5.6 |

more energetic decay :
easier to separate from
background



enrichment often possible,
always expensive !

Neutrino Mass : Target Sensitivity

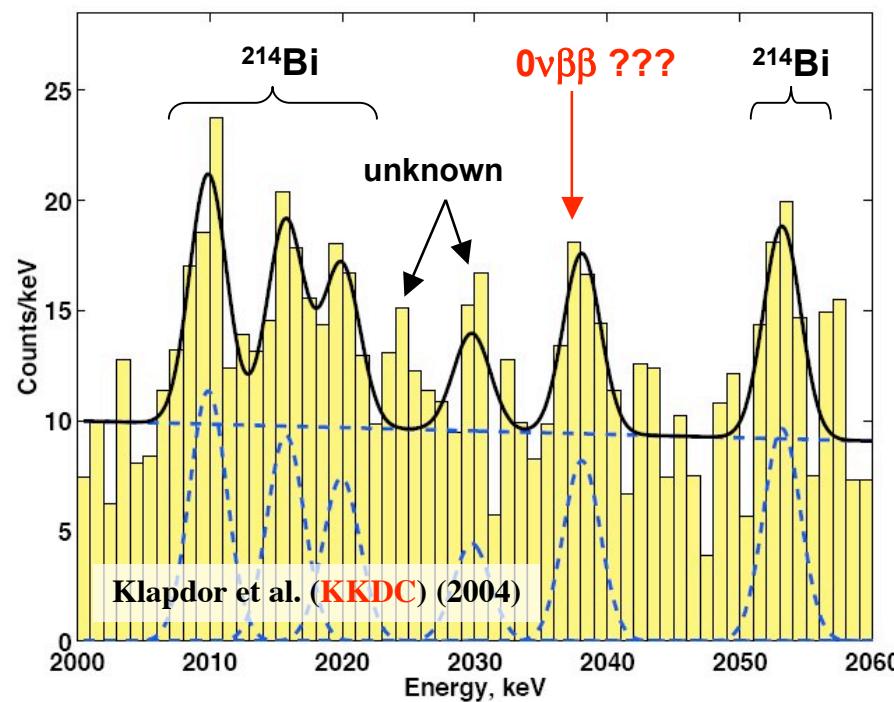
Signal in Heidelberg-Moscow experiment ?

- ▶ 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 :

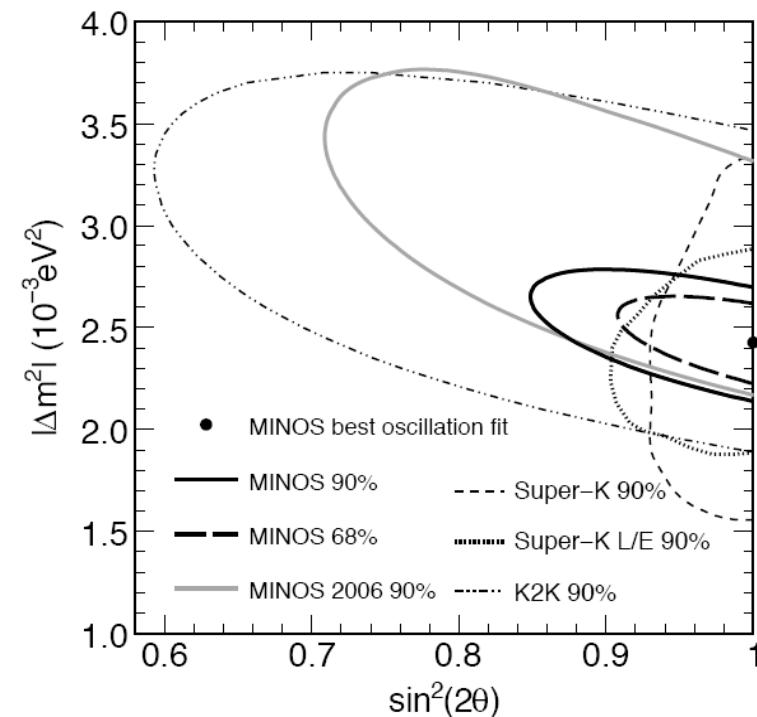
$$\langle m_\nu \rangle \sim 0.4 \text{ eV}$$



Neutrino Oscillations

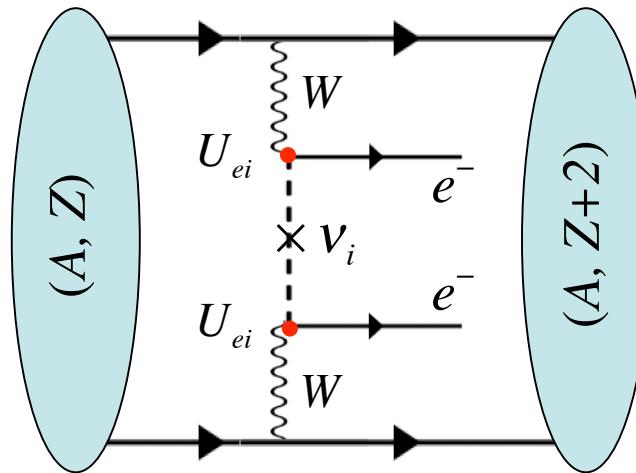
- ▶ Largest Δm^2 from “atmospheric” oscillations.
- ▶ Therefore there is at least one neutrino with :

$$\langle m_\nu \rangle \sim \sqrt{\Delta m_{atm}^2} \sim 50 \text{ meV}$$



Effective Neutrino Mass (Light Neutrino Exchange)

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



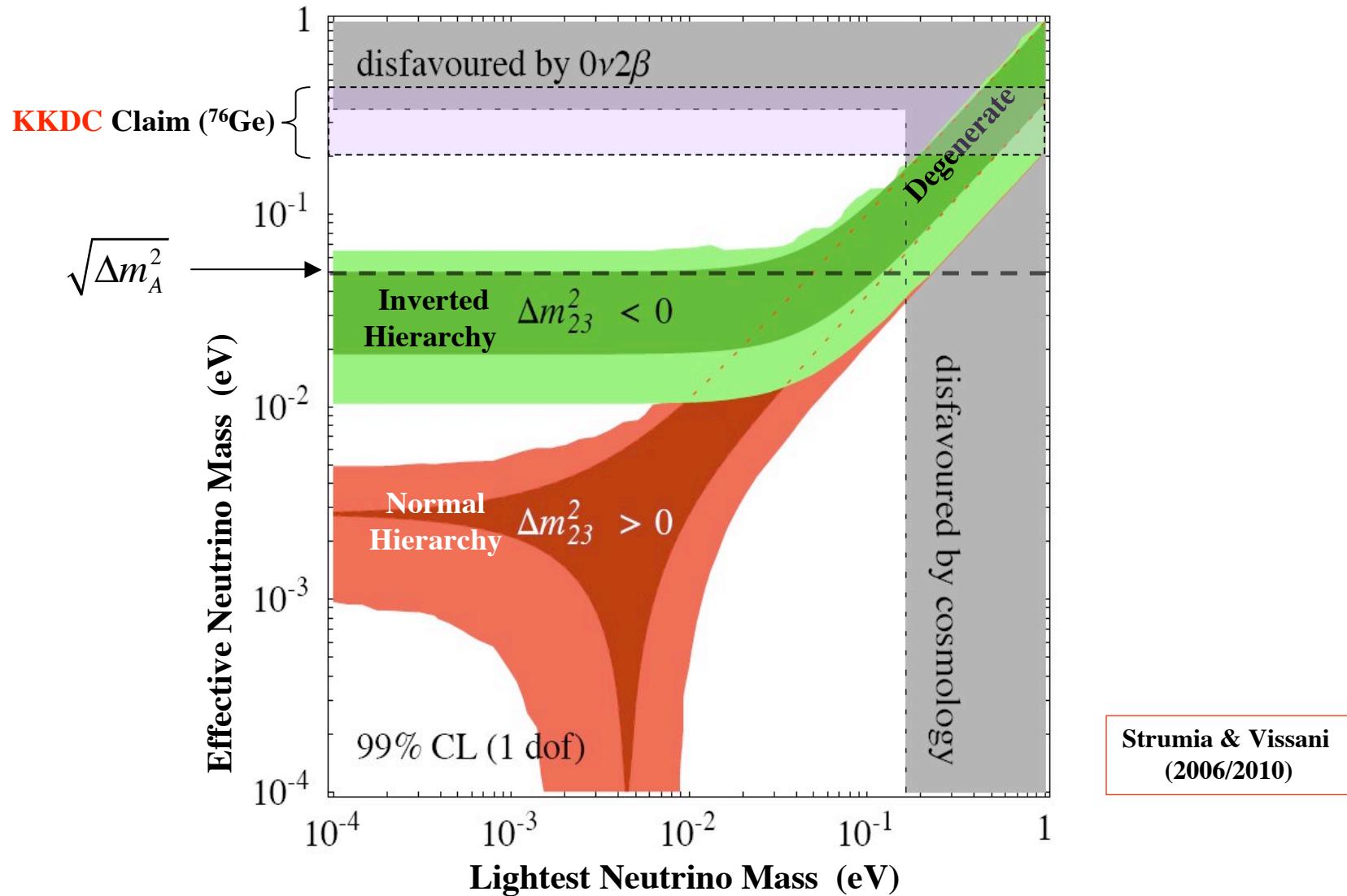
- Hence, experiments are sensitive to an **effective** $0\nu\beta\beta$ neutrino mass :

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

α_{21}, α_{31} = Majorana phases

Effective Neutrino Mass

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

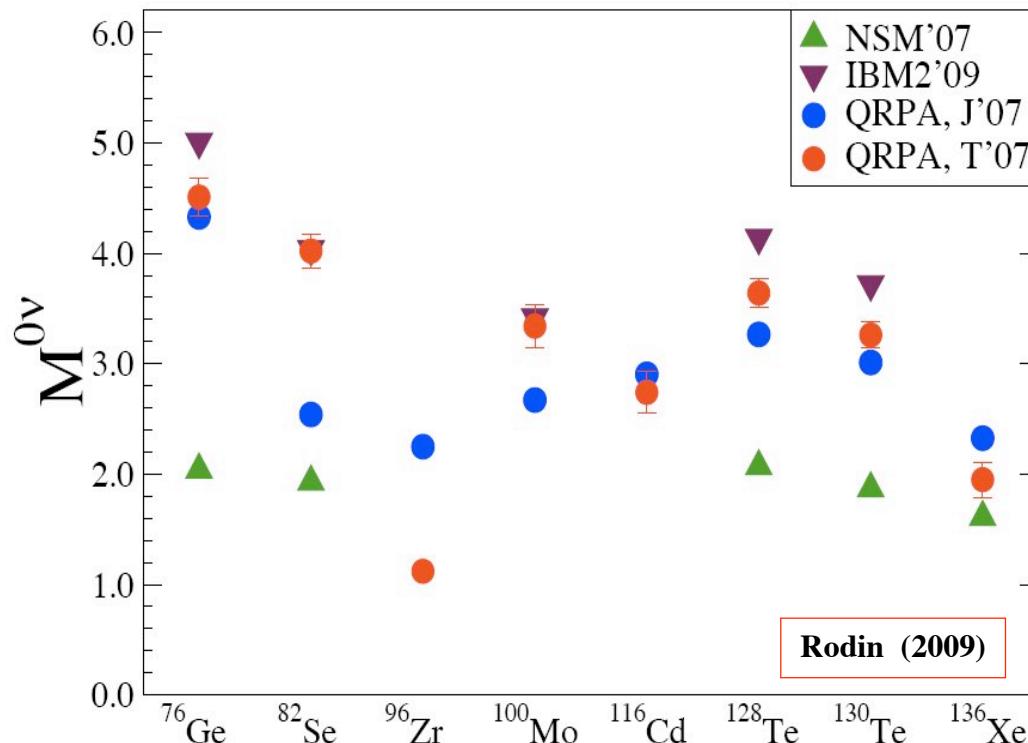


Nuclear Matrix Elements

phase-space factor
(exactly calculable)

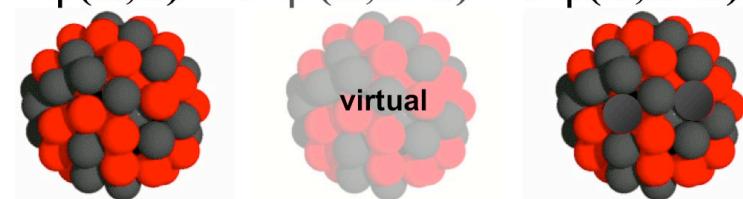
effective neutrino mass

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



uNclear Matrix Elements

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



All is not lost :

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

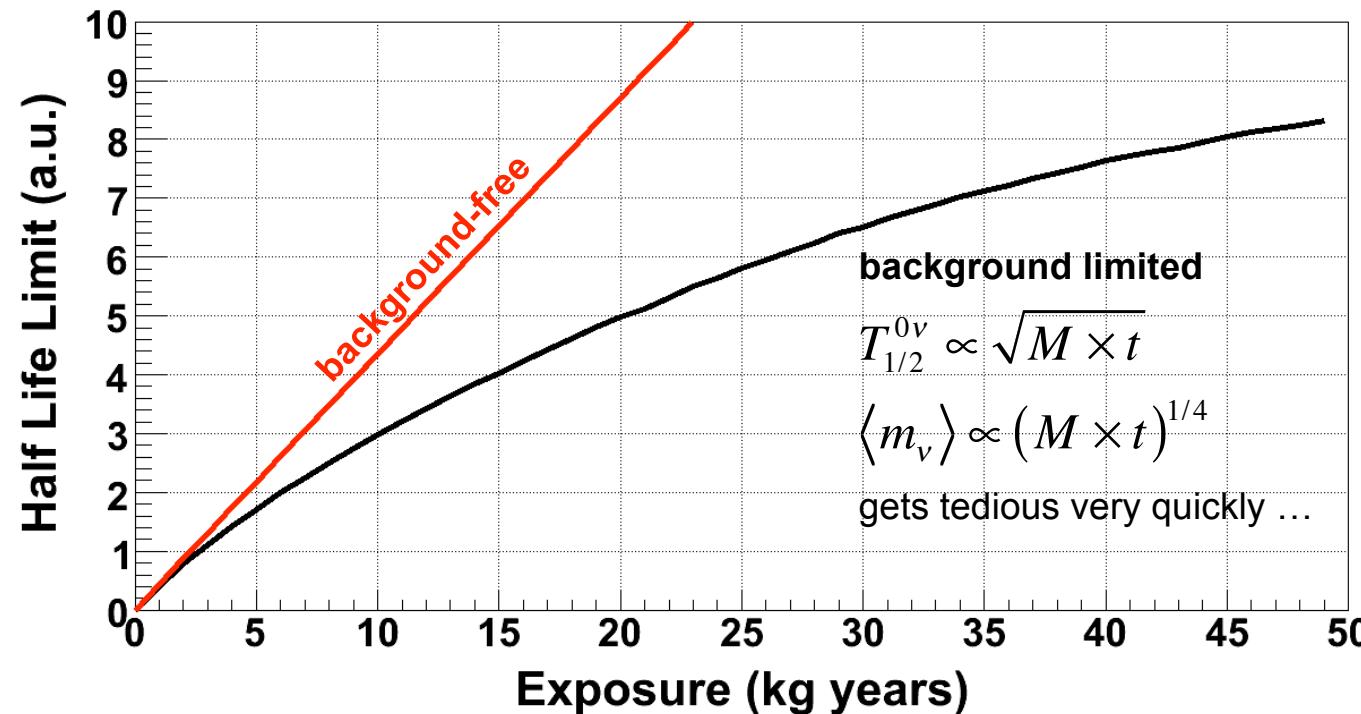
How To Build a $\beta\beta$ -Experiment

maximise efficiency & isotope abundance

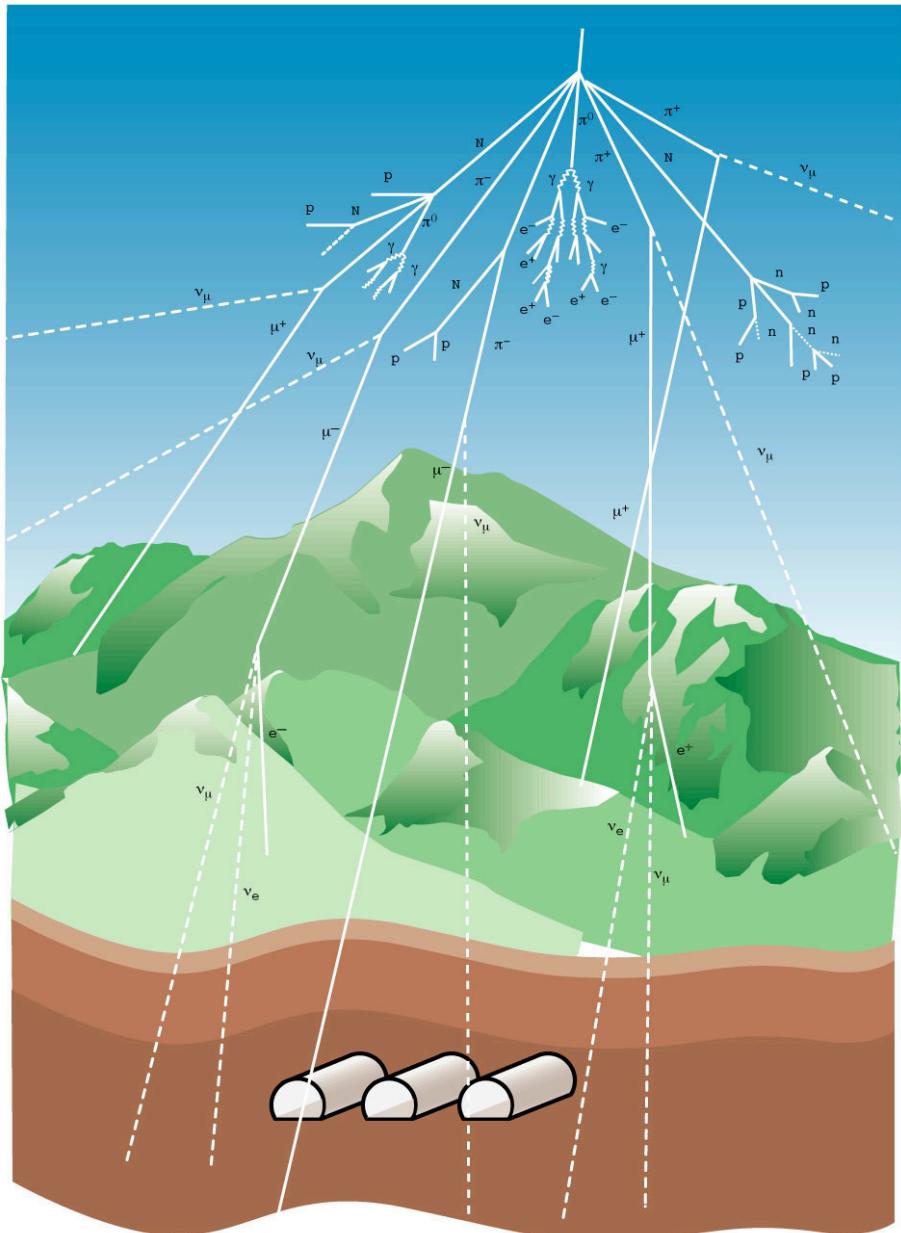
maximise exposure = mass \times time

$$T_{1/2}^{0\nu} (90\% \text{ C.L.}) = 2.54 \times 10^{26} \text{ y} \left(\frac{\varepsilon \times a}{W} \right) \sqrt{\frac{M \times t}{b \times \Delta E}}$$

minimise background & energy resolution



Ultra-Low Backgrounds



Essential to go deep underground

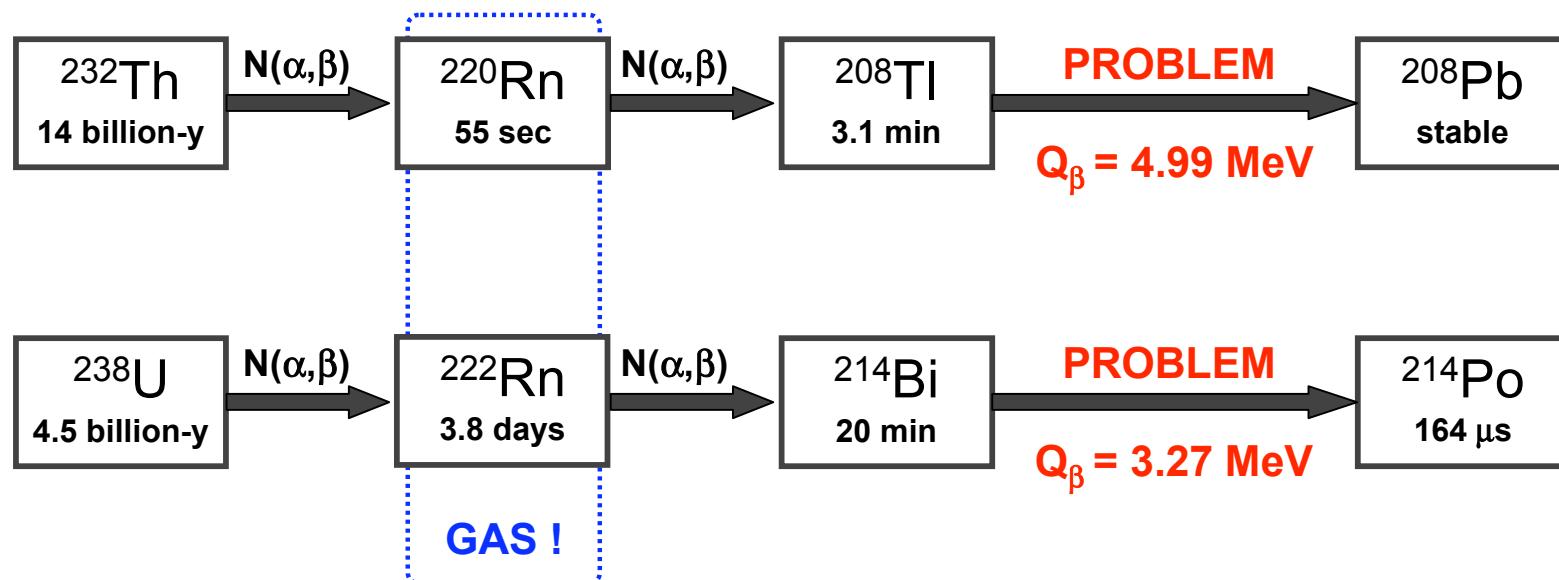
- Cosmic ray muon flux reduced by 10^{-6}
- Other important backgrounds are a function of depth and local geology :
 - ▶ Neutrons
 - ▶ γ 's
 - ▶ Radon

Deepest Labs :

- Sudbury : SNO+
- LSM : (Super-)NEMO

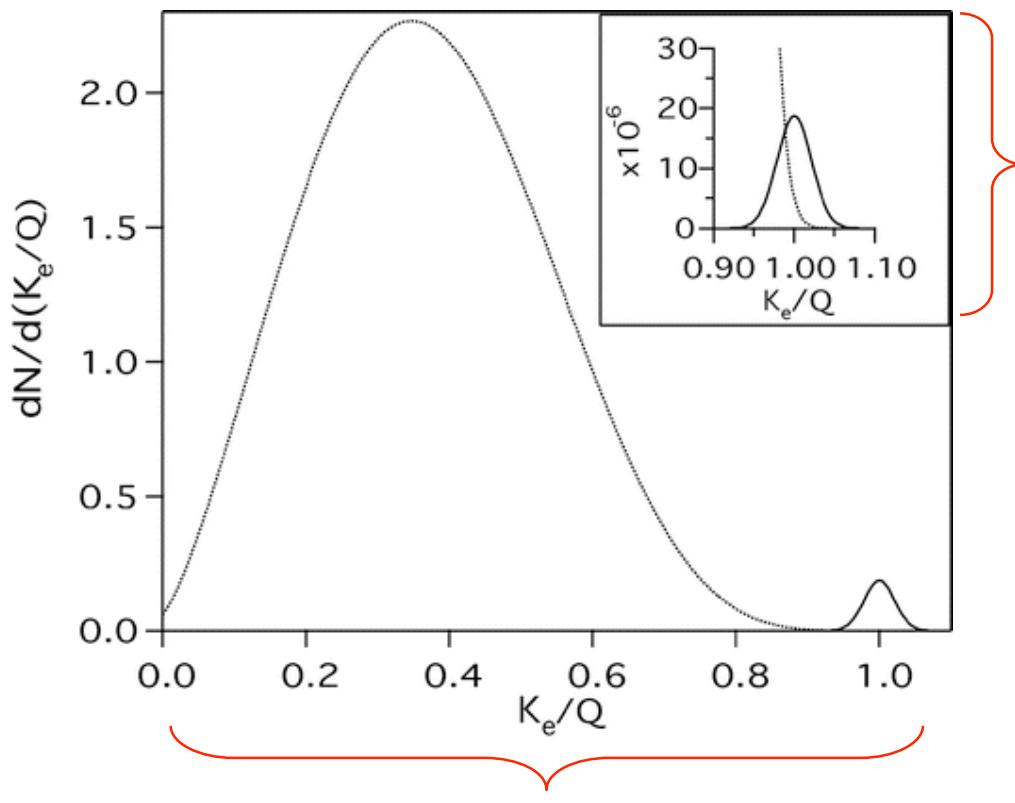
Natural Radioactivity

- Primarily Uranium and Thorium decay chain products, present in all materials.
 - ▶ $T_{1/2}(^{232}\text{Th}, ^{238}\text{U}) \sim 10^{10}$ years
 - ▶ $T_{1/2}(0\nu\beta\beta) > 10^{25}$ years



- What can be done ?
 - ▶ Extremely careful material selection.
 - ▶ Purification techniques.
 - ▶ Barriers against Radon penetration.
 - ▶ Background tagging/identification techniques.

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



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

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

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

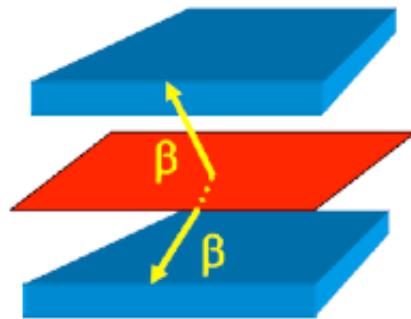
NEMO-3 → SuperNEMO



Experimental Approaches

Heterogenous

“tracking”

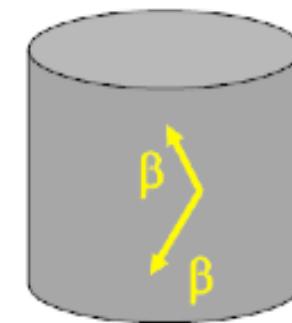


Advantages :

- Full event topology information
- “Smoking-gun” signature for $0\nu\beta\beta$
- Can probe different mechanisms
- Isotope flexibility

Homogenous

“source = detector”



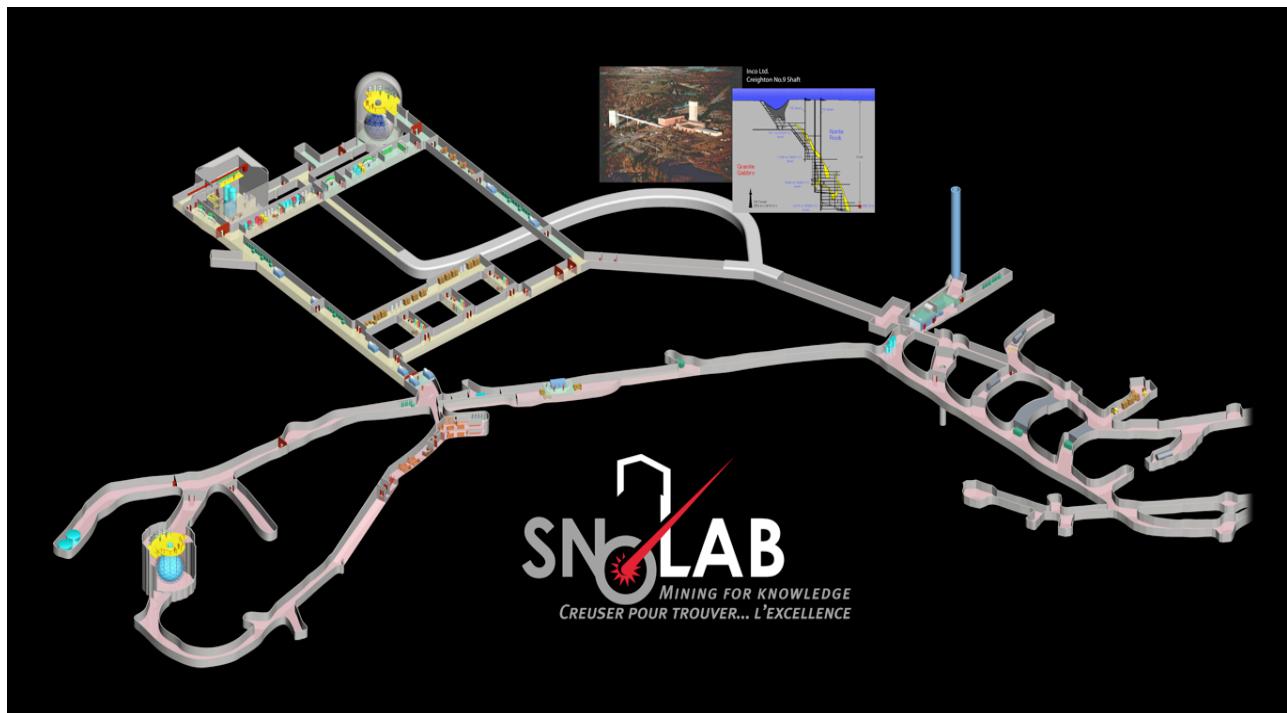
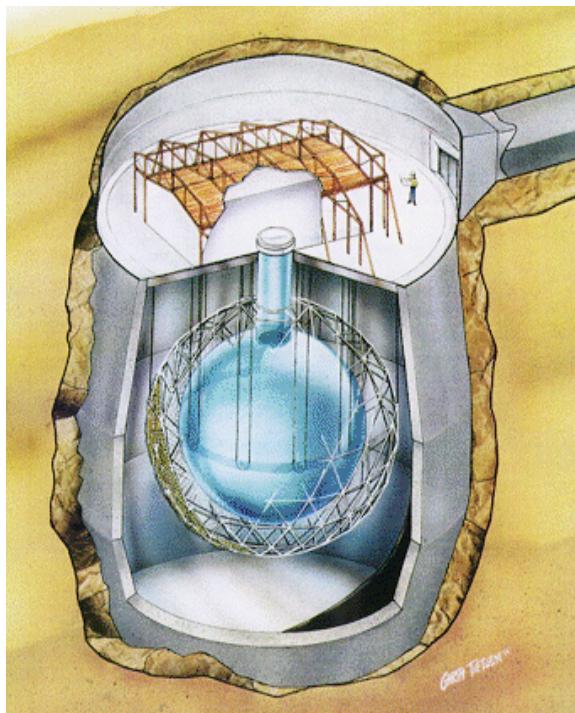
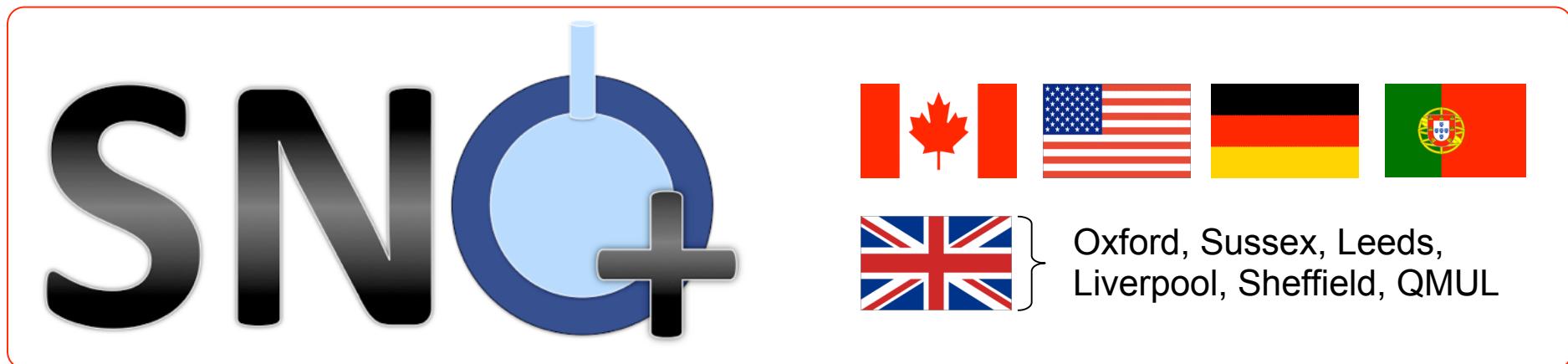
Advantages :

- Excellent $\Delta E/E$
- Compact

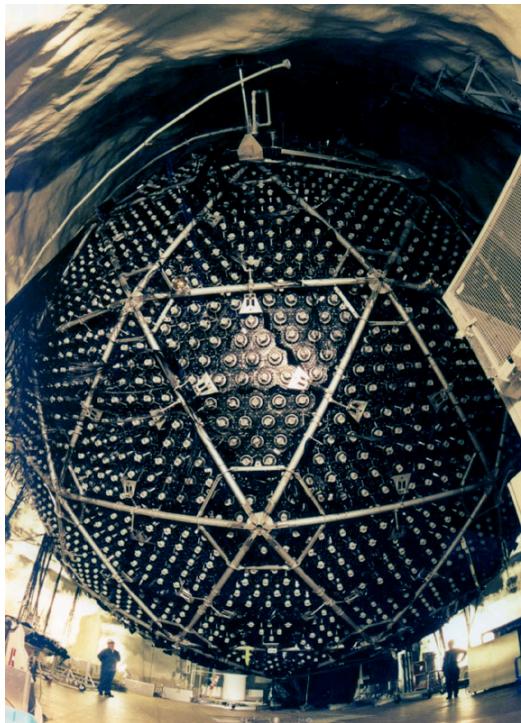
Techniques :

- Semiconductor
- Bolometer
- (Liquid-) Scintillator

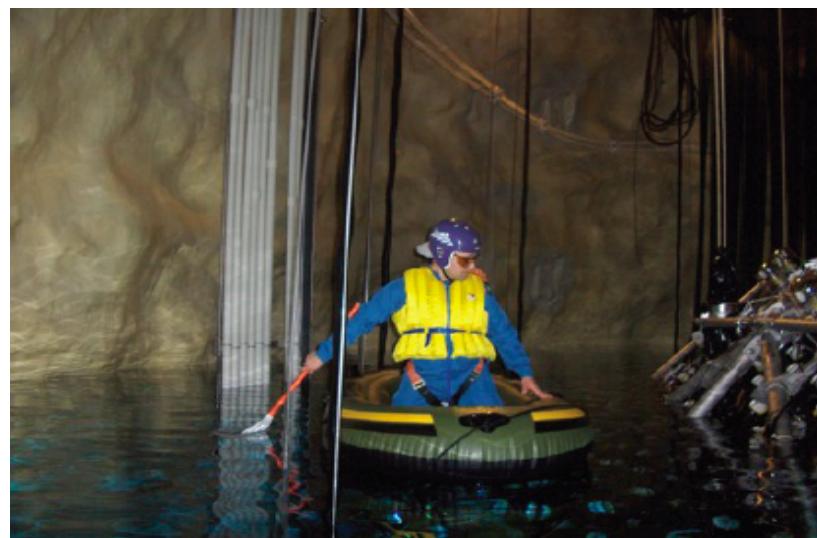
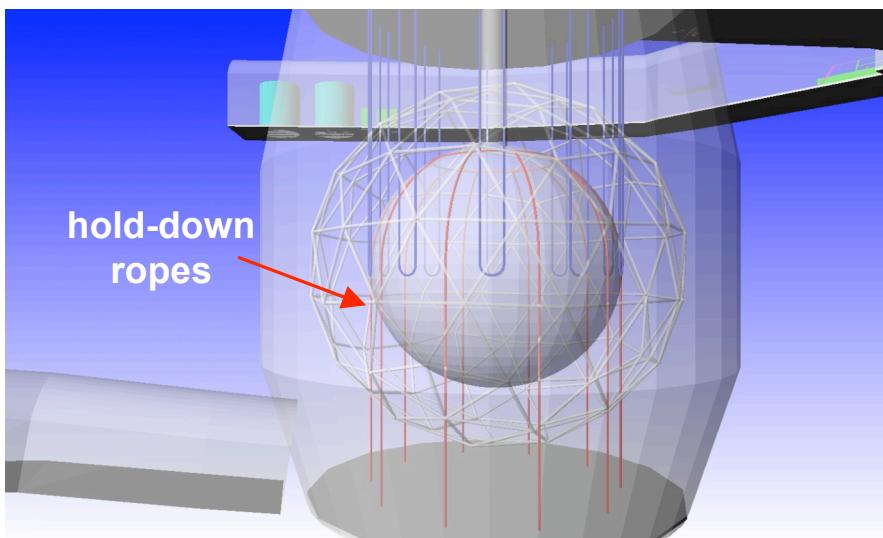
The SNO+ Experiment



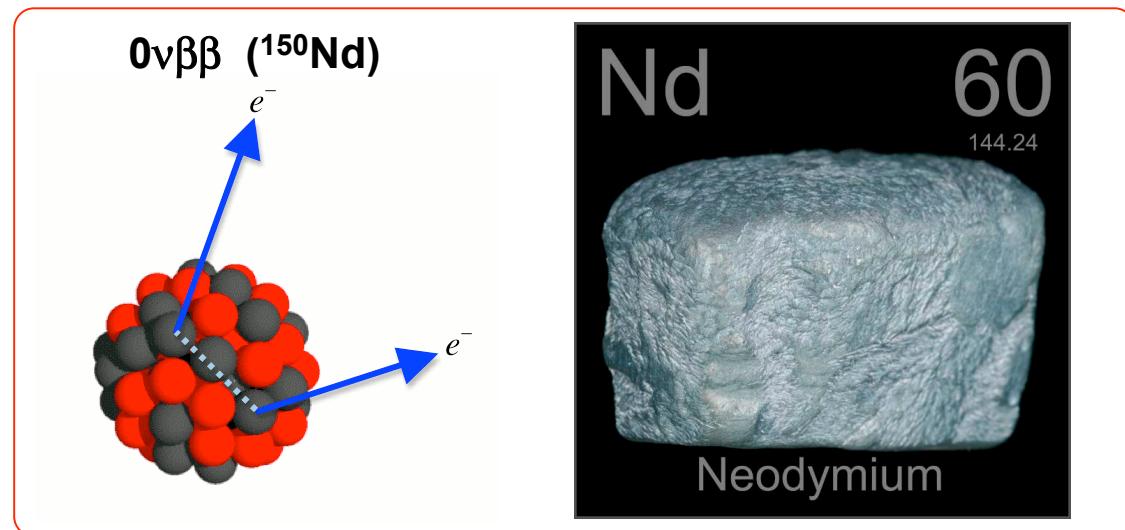
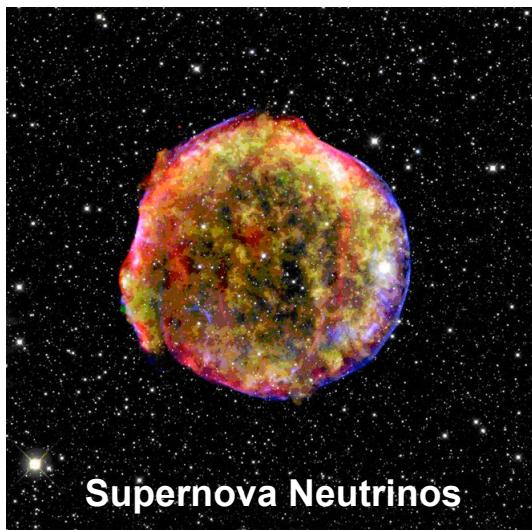
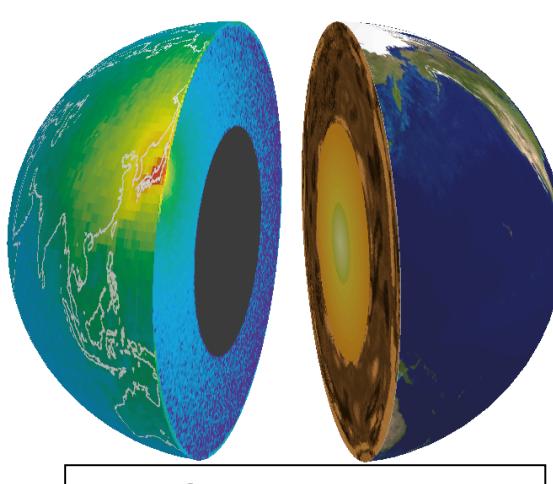
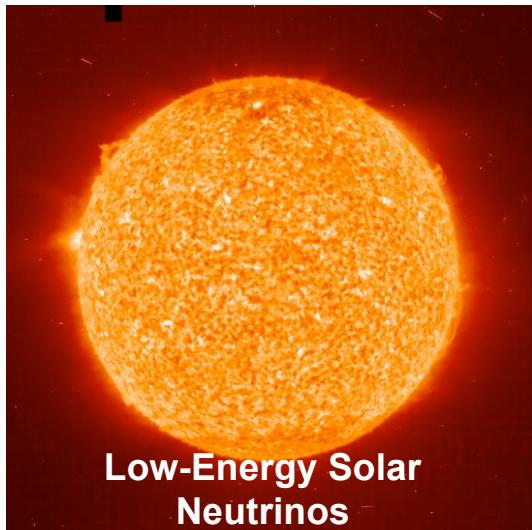
SNO+ : Basic Idea



- Re-use the existing SNO detector, which ceased heavy-water operation in 2006.
- Fill the acrylic vessel with 800 tonnes of liquid scintillator.
 - ▶ Linear **Alkyl-Benzene** + 2g/litre PPO fluor.
 - ▶ Hold-down the LAB rather than hold-up the D₂O
 - ▶ Development of techniques to achieve ultra-high radiopurity of both liquid scintillator and Ovββ source.
 - ▶ Cleaning (anti-radon), refurbished electronics & DAQ.
 - ▶ New calibration systems & software (**UK**) 



SNO+ : Physics Program



SNO+ : Double-Beta Decay

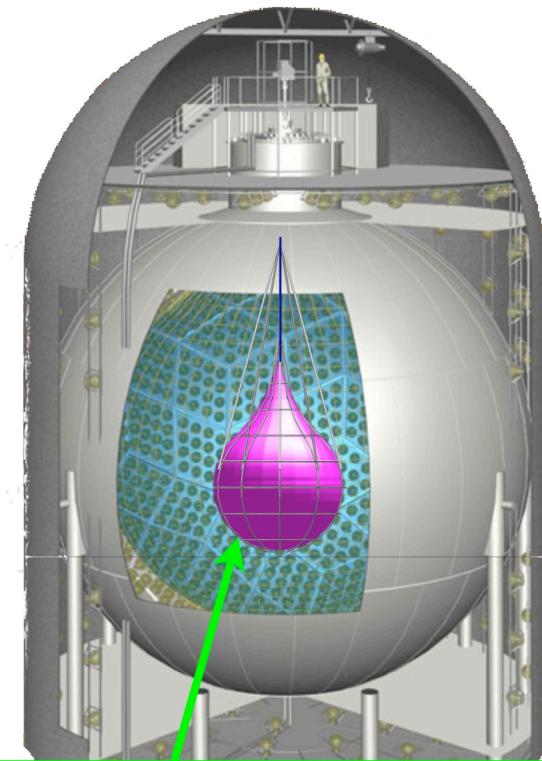
Isotope Choice : ^{150}Nd

- ✓ Large $Q_{\beta\beta} = 3.4 \text{ MeV}$ - above most radioactive backgrounds
- ✓ Very large phase space : 30 times larger than ^{76}Ge
- ✓ Chemistry compatible with dissolution in LAB
- ✓ Reasonably transparent to scintillation light
- ✓ Cheap !
- ✗ Natural abundance is low ~ 5.6%
- ✗ Difficult to enrich

Radiopurity Requirements

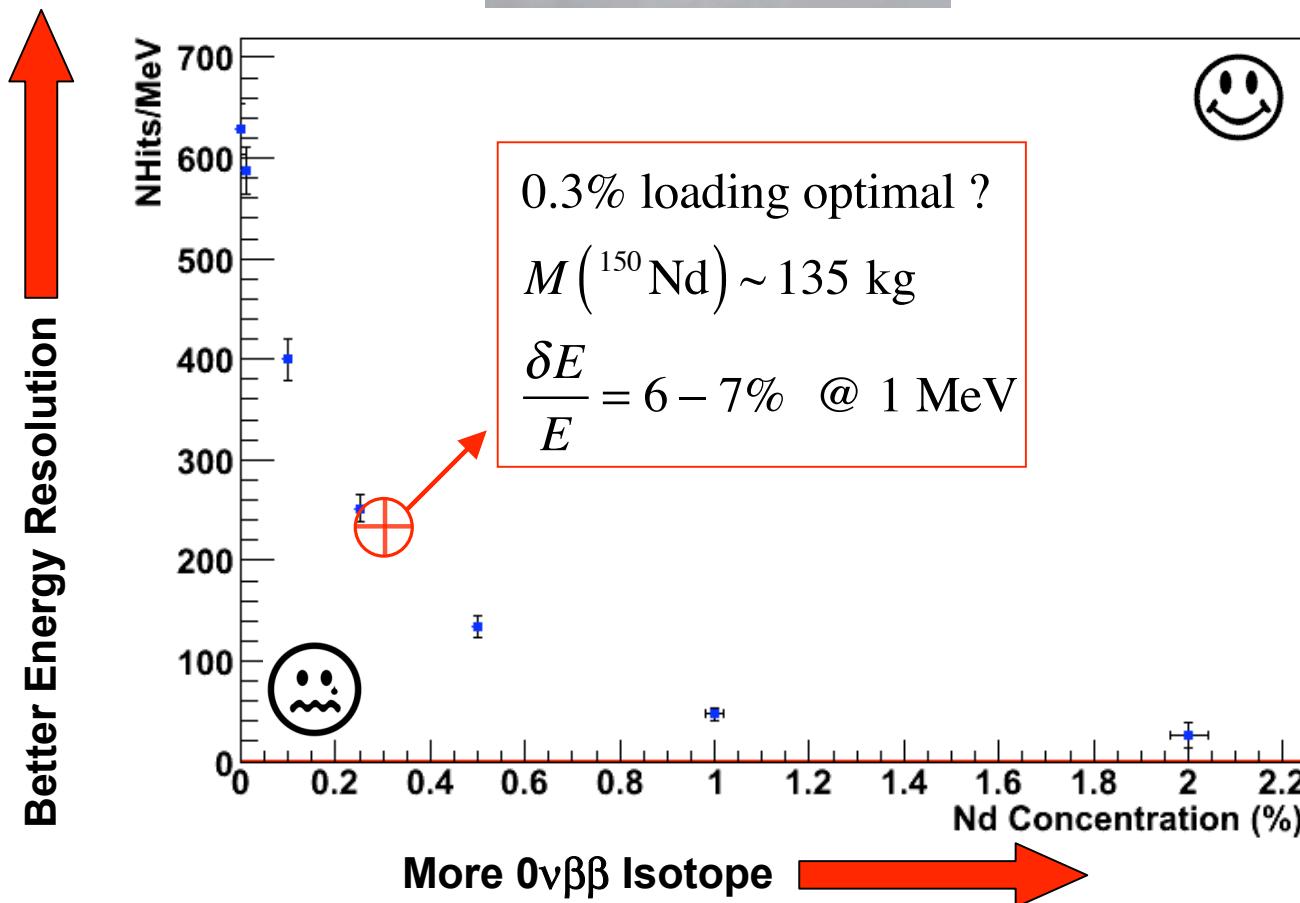
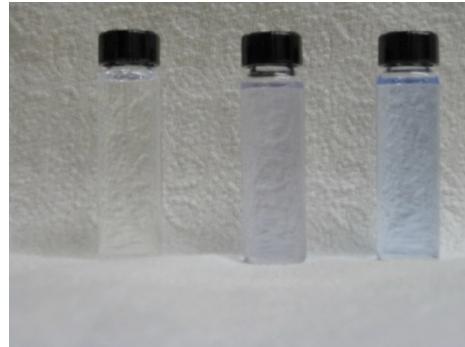
- ✗ Extremely stringent : $< 10^{-17} \text{ g } ^{228}\text{Ra}/^{228}\text{Th per g scintillator.}$
- ✗ The isotope compound (NdCl_3) must also be very radio-pure : $< 10^{-14} \text{ g } ^{228}\text{Ra}/^{228}\text{Th per g Nd}$
- ✓ Similar liquid scintillator purities have been demonstrated by Borexino and **Kamland**
- ✓ A lot of techniques developed for SNO/ D_2O should be applicable to purifying the Nd/solution.

Another liquid scintillator $0\nu\beta\beta$ proposal : **KamLAND-Zen**

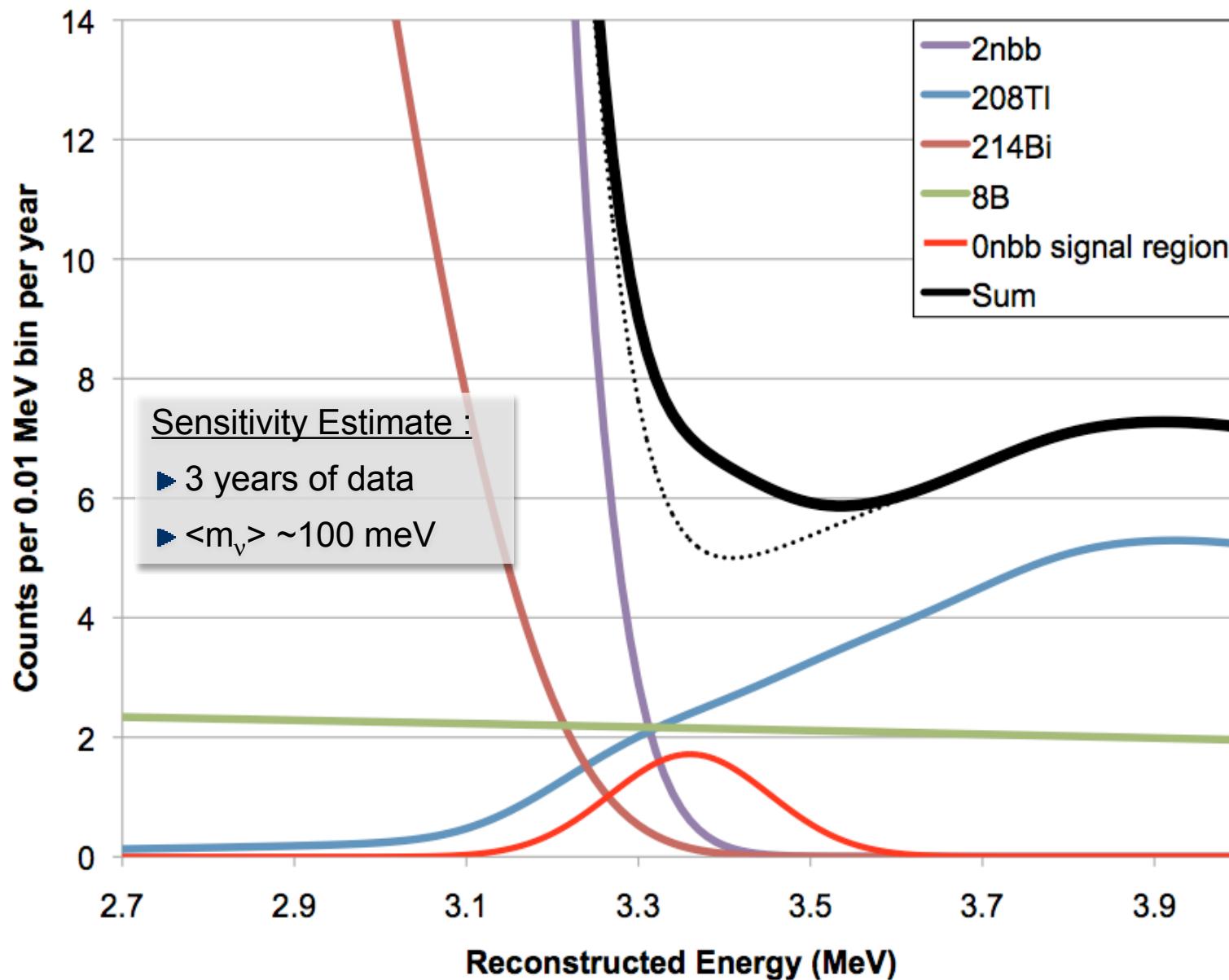


^{136}Xe 400 kg loaded LS
in mini-balloon, $R=1.7\text{m}$

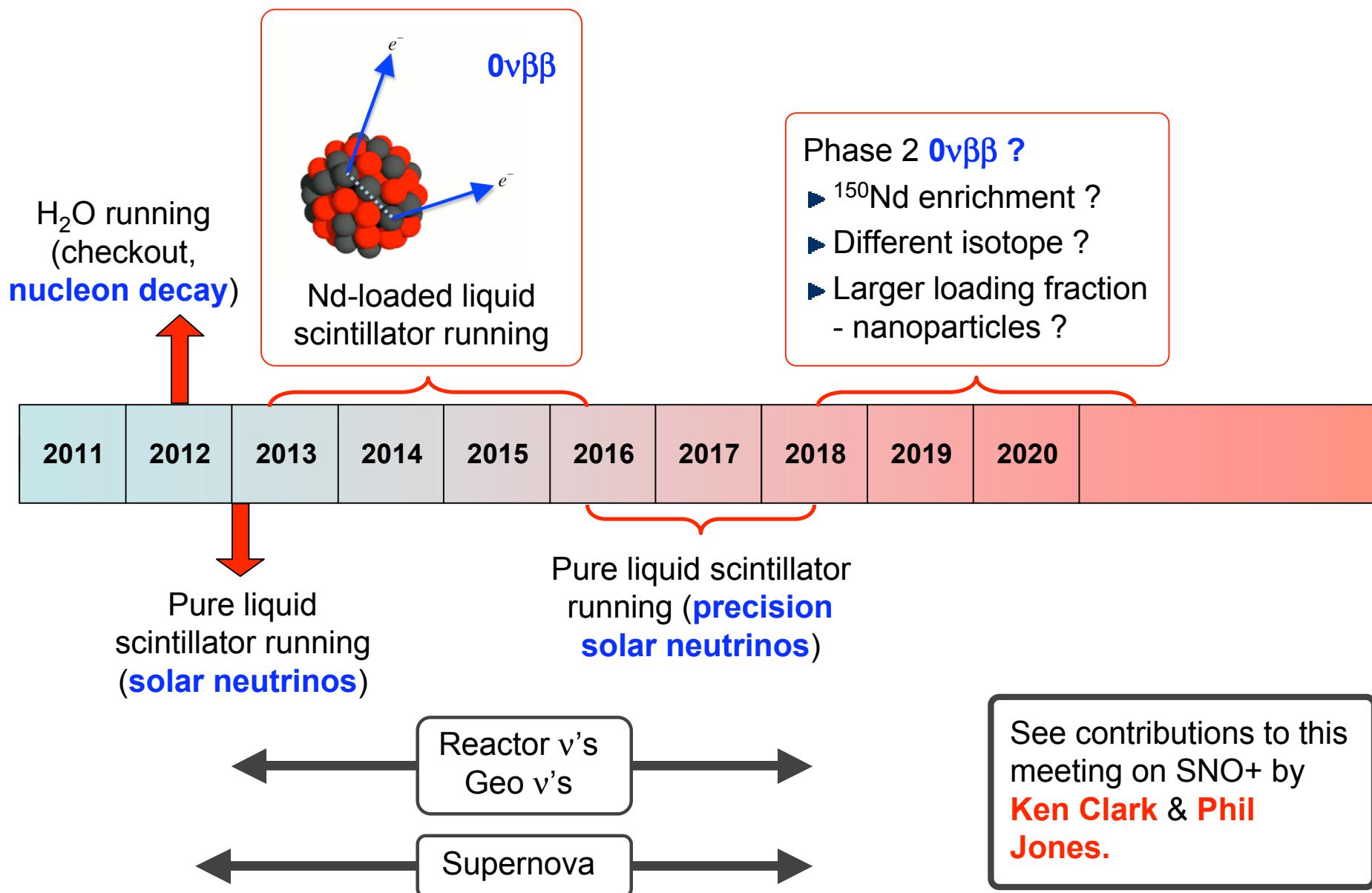
SNO+ : How Much Neodymium ?



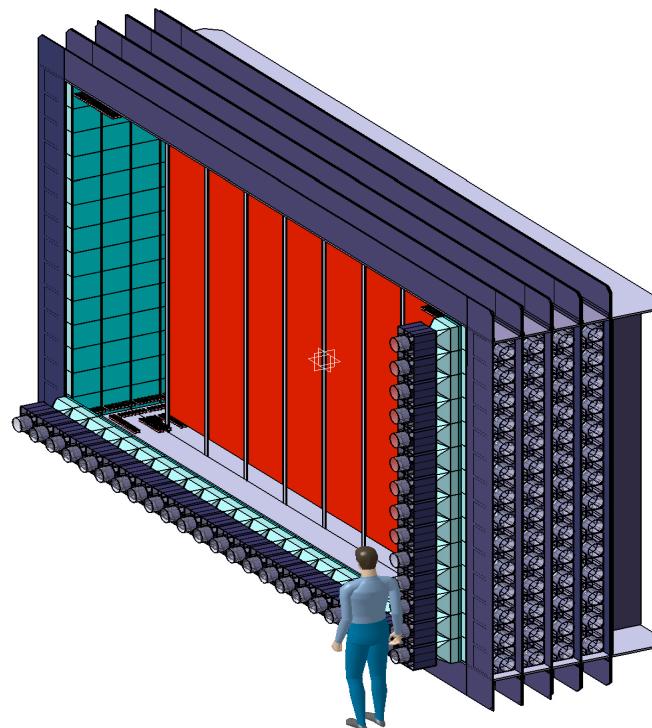
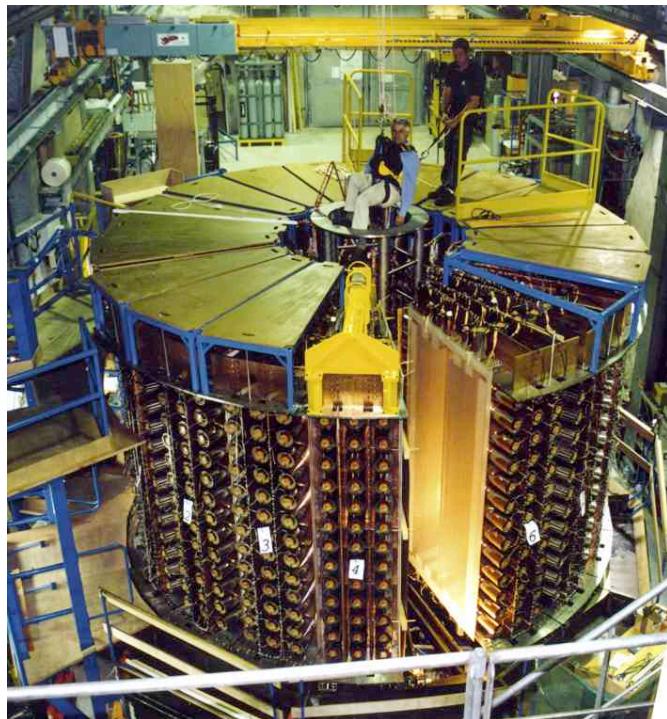
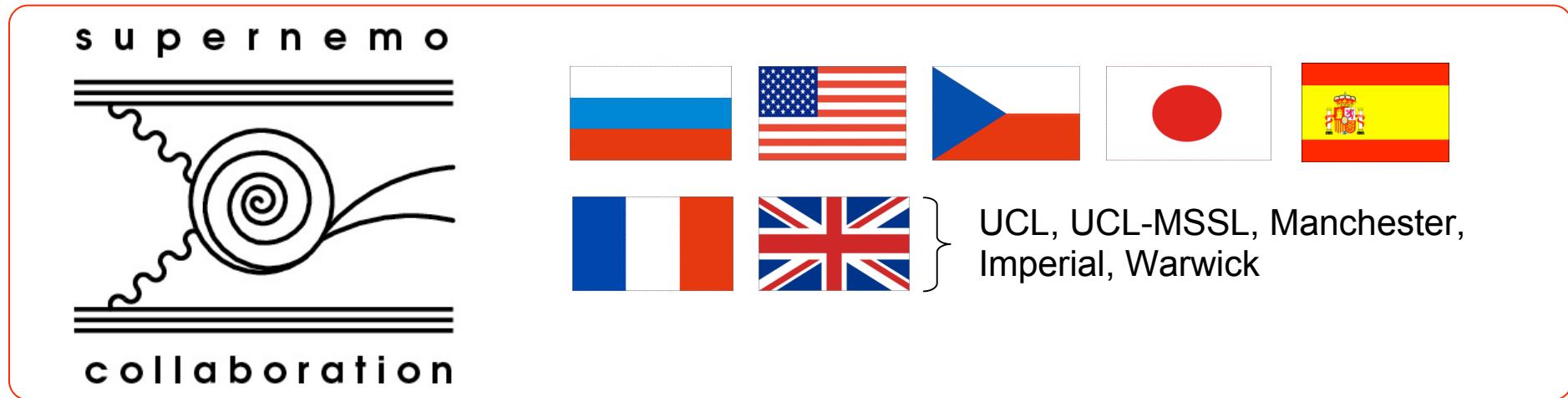
SNO+ : $0\nu\beta\beta$ Prospects



SNO+ : Timeline



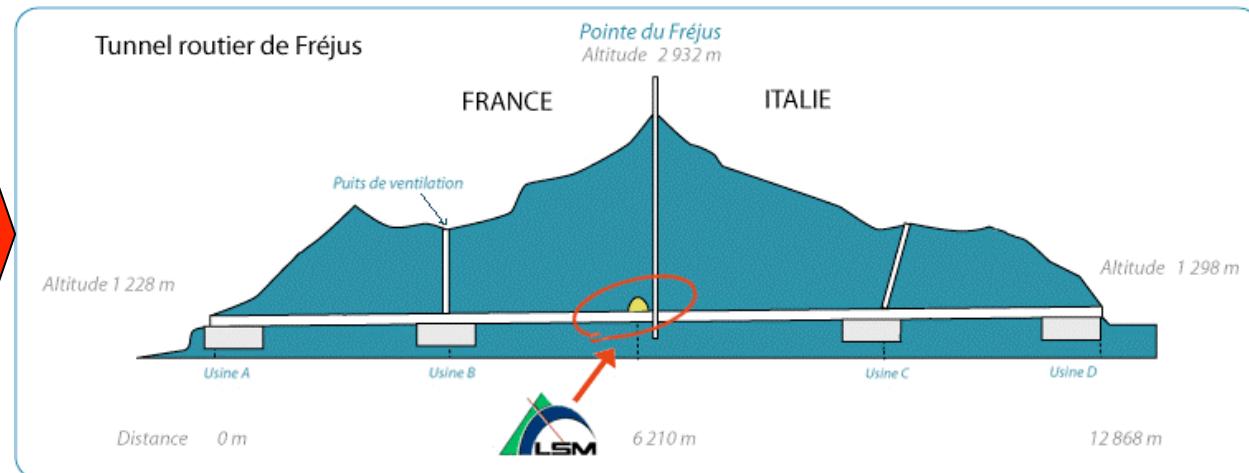
(Super-)NEMO



Neutrino Ettore Majorana Observatory 3



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

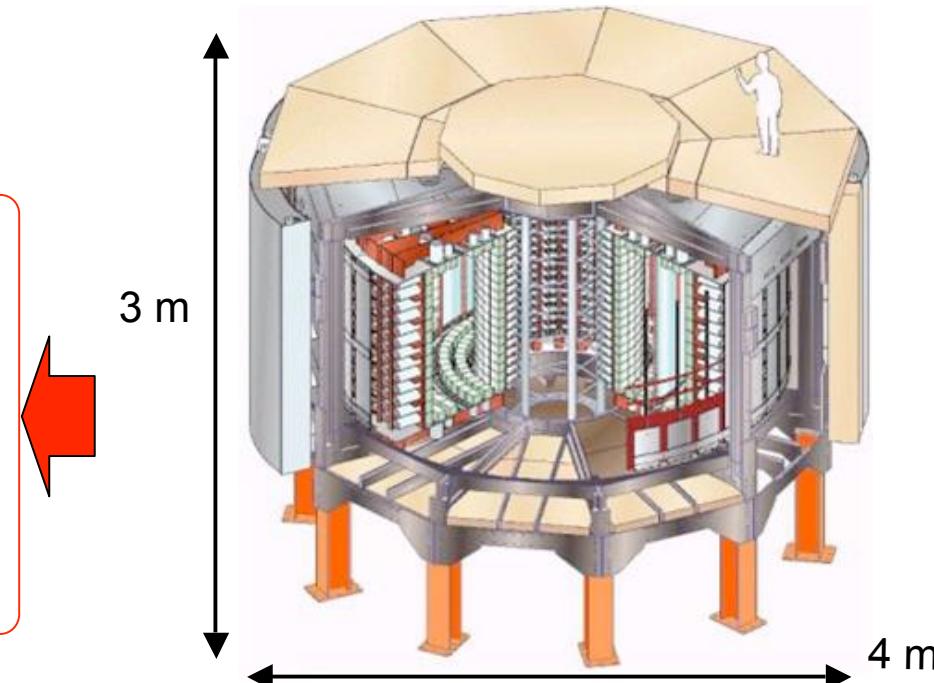


NEMO-3

The world's biggest and cleanest
Geiger counter

200 tons and ~1000 Bq
(cf. human body ~ 6000 Bq)

Ran from Feb. 2003 to Jan. 2011



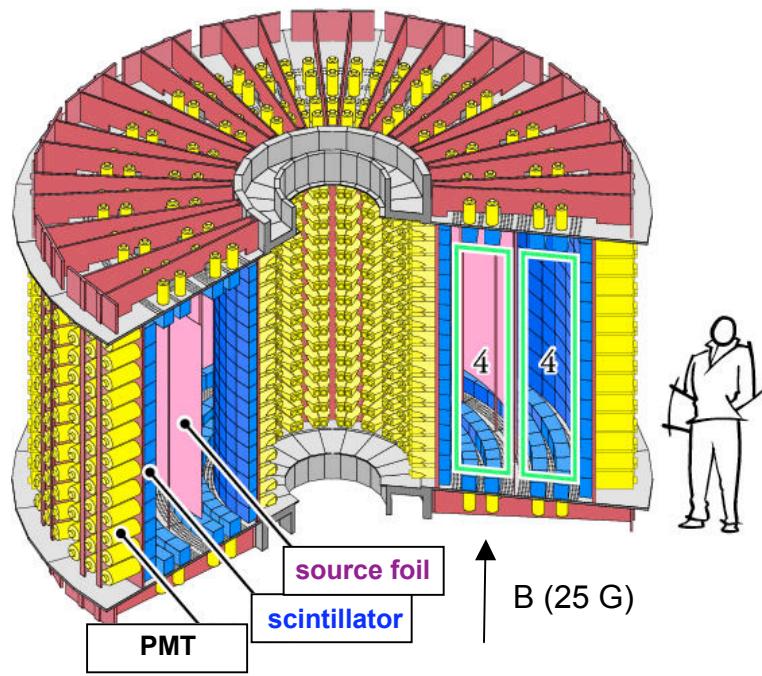
NEMO-3



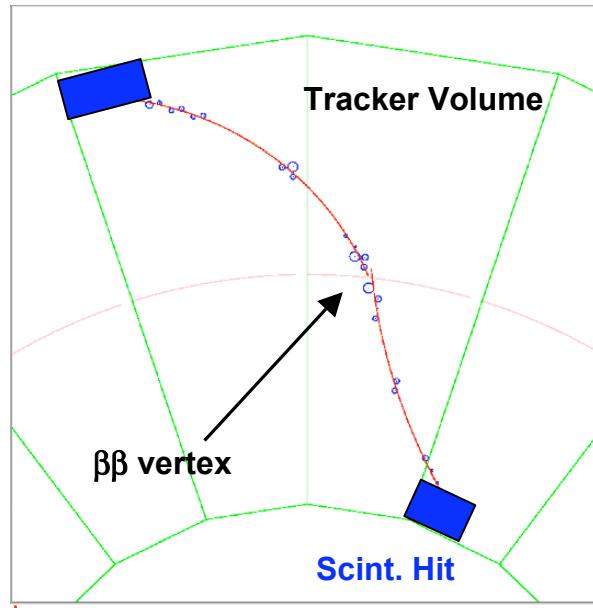
NEMO-3 is currently being dismantled to make way for SuperNEMO

NEMO-3

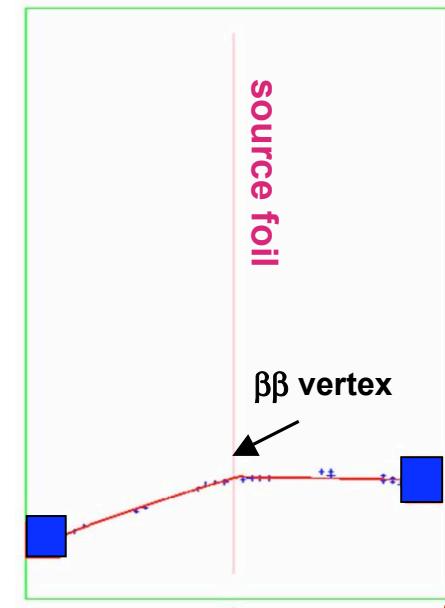
NEMO 3



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)

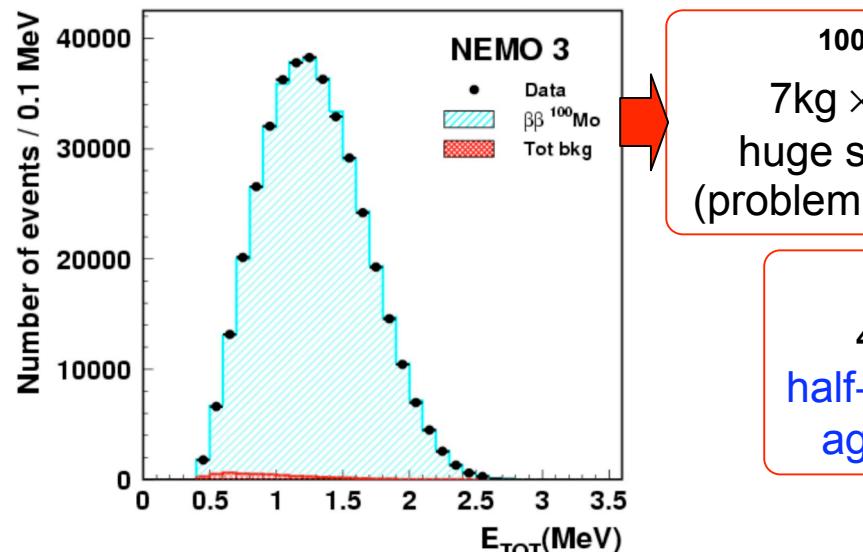
Small quantities: ^{116}Cd ^{150}Nd ^{48}Ca ^{96}Zr ^{130}Te

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

See talk on ^{48}Ca by **Ben Richards** in PP parallel session 3.2 (Wednesday morning)

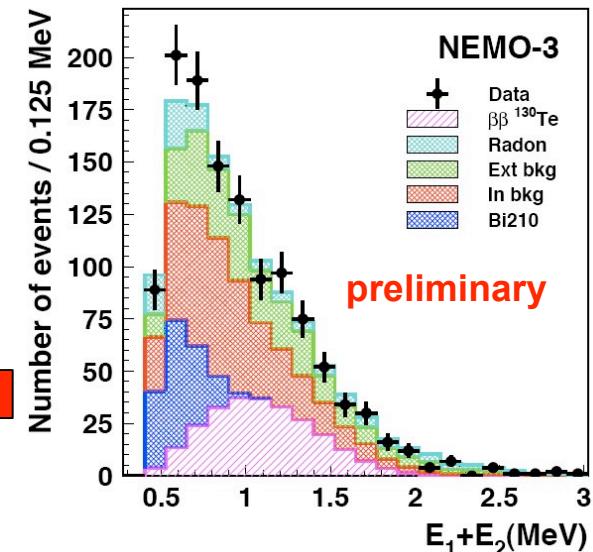
NEMO-3 : Physics Highlights ($2\nu\beta\beta$)

| Isotope | mass, g | $Q_{\beta\beta}$ (keV) | $T_{1/2}(2\nu) (10^{19} \text{ yrs})$ | Comments |
|-------------------|---------|------------------------|---------------------------------------|---------------------------------|
| ^{100}Mo | 6914 | 3035 | 0.71 ± 0.05 | World's Best ! |
| ^{82}Se | 932 | 2996 | 9.6 ± 1.0 | World's Best ! |
| ^{96}Zr | 9.4 | 3348 | 2.35 ± 0.21 | World's First & Best ! |
| ^{48}Ca | 7 | 4274 | 4.4 ± 0.6 | World's Best ! |
| ^{116}Cd | 7.49 | 2809 | 2.8 ± 0.3 | World's Best ! |
| ^{130}Te | 454 | 2530 | 70 ± 14 | World's Best & First (Direct) ! |
| ^{150}Nd | 37 | 3367 | 0.9 ± 0.07 | World's Best ! |

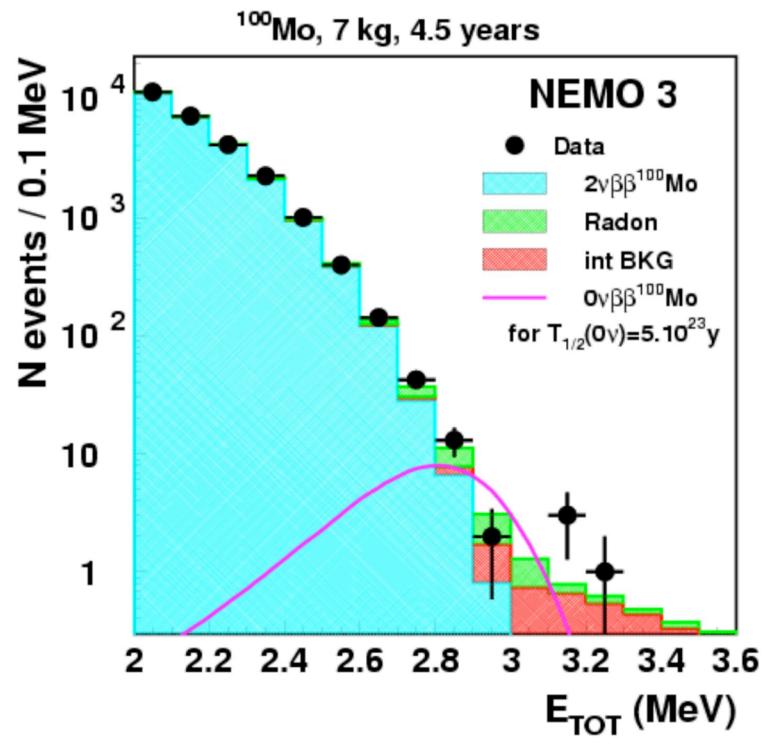


^{100}Mo
7kg \times 3.5 y
huge statistics
(problem for $0\nu\beta\beta$)

^{130}Te
454 g \times 3.5 y
half-life $>$ 10 billion \times
age of universe !



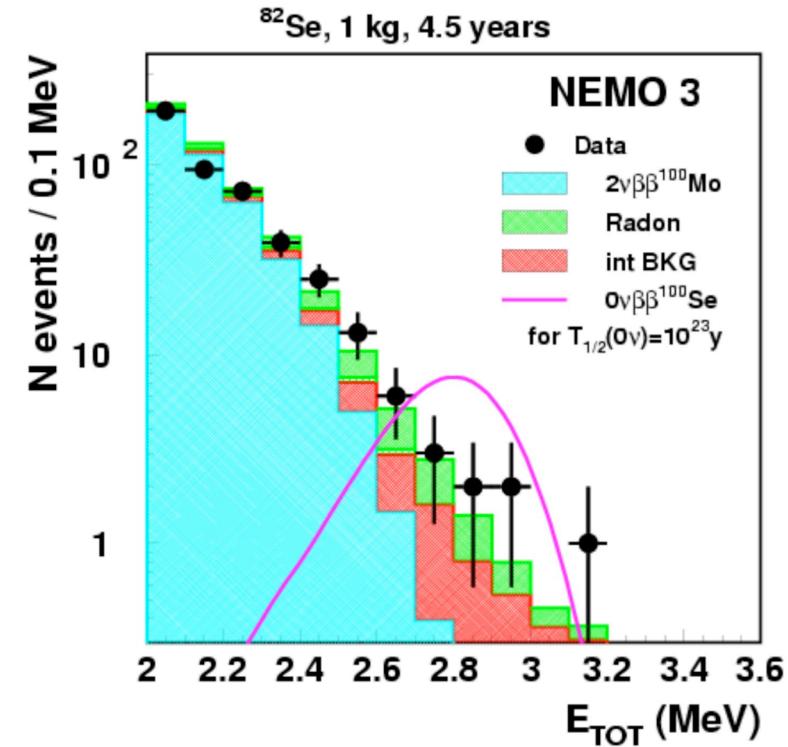
NEMO-3 : Physics Highlights (0νββ)



100Mo : 31.5 kg-y

$T_{1/2}^{0\nu} > 1.0 \times 10^{24} \text{ y } (@90\% \text{ C.L.})$

$\langle m_\nu \rangle < (0.47 - 0.96) \text{ eV}$

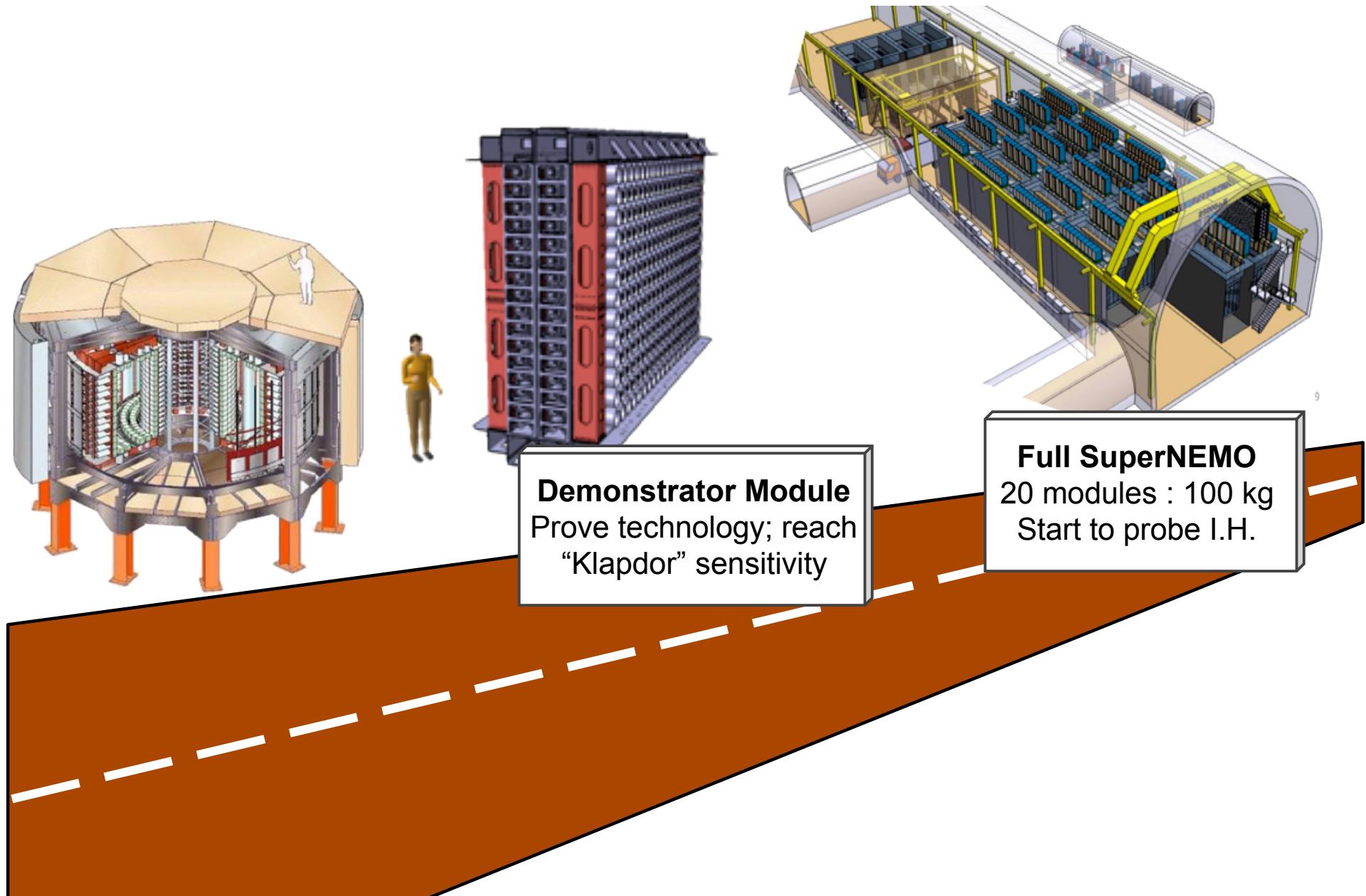


82Se : 4.5 kg-y

$T_{1/2}^{0\nu} > 3.2 \times 10^{23} \text{ y } (@90\% \text{ C.L.})$

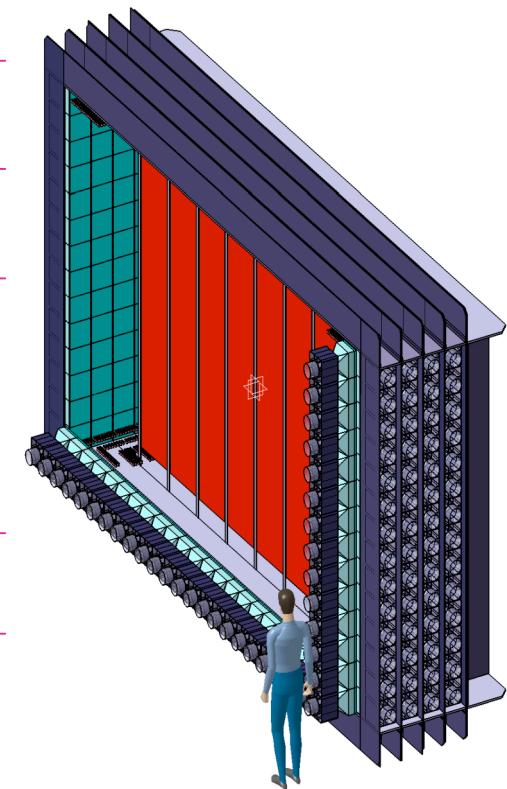
$\langle m_\nu \rangle < (0.94 - 2.5) \text{ eV}$

SuperNEMO : Road Map

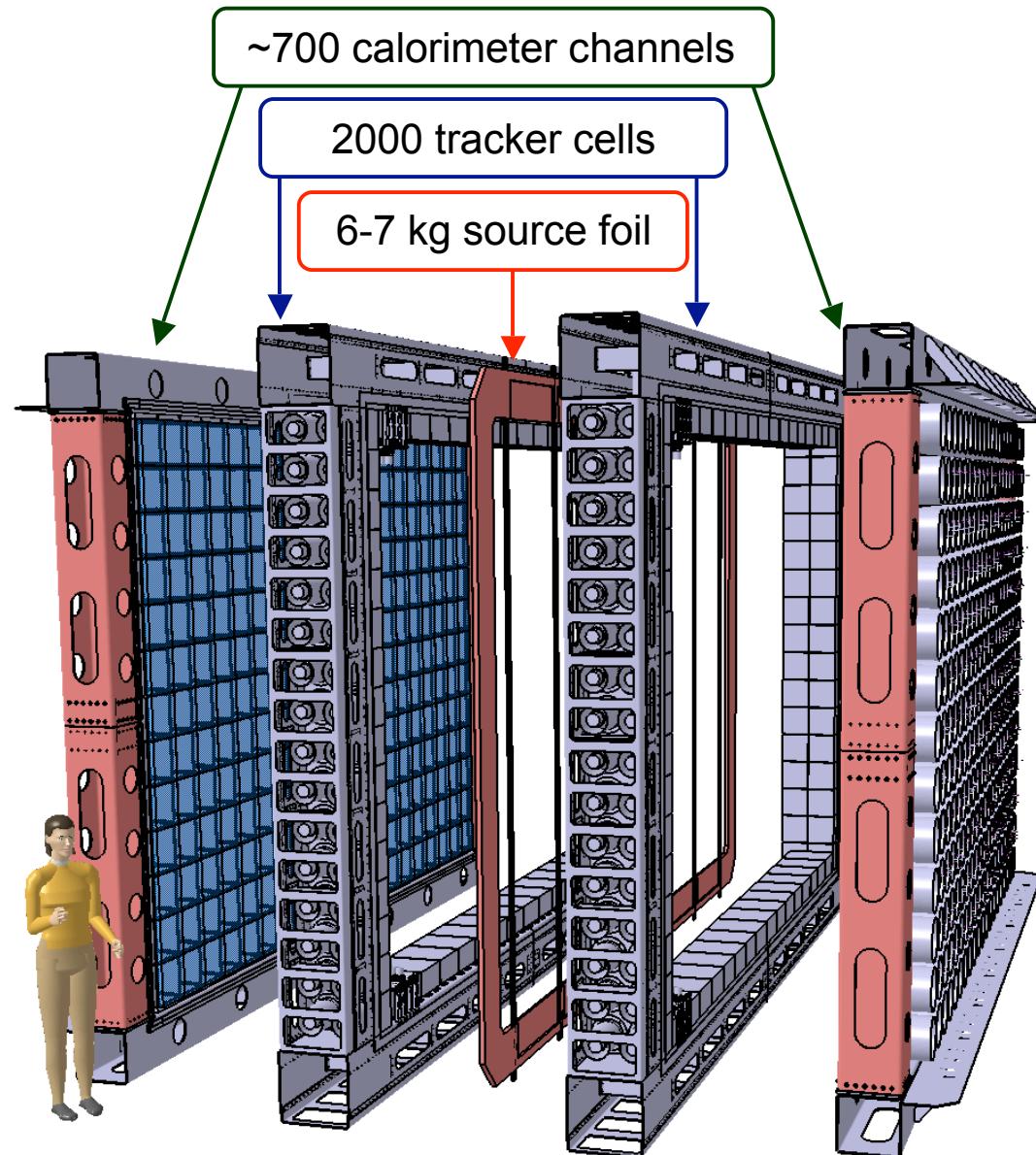
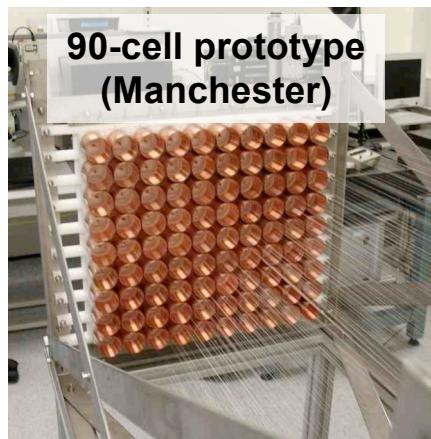


SuperNEMO : How to Get There ?

| NEMO-3 | | SuperNEMO |
|---|--|---|
| ^{100}Mo | isotope | ^{82}Se or other |
| 7 kg | isotope mass | 100 kg |
| 18 % | efficiency | ~30 % |
| ^{208}TI : ~ 100 $\mu\text{Bq}/\text{kg}$ | internal contaminations | $^{208}\text{TI} \leq 2 \mu\text{Bq}/\text{kg}$ |
| ^{214}Bi : < 300 $\mu\text{Bq}/\text{kg}$ | ^{208}TI , ^{214}Bi in the $\beta\beta$ foil | $^{214}\text{Bi} \leq 10 \mu\text{Bq}/\text{kg}$ |
| Rn: 5 mBq/m ³ | Rn in the tracker | $\text{Rn} \leq 0.15 \text{ mBq}/\text{m}^3$ |
| 8% @ 3MeV | energy resolution (FWHM) | 4% @ 3 MeV |
| $T_{1/2}(\beta\beta 0\nu) > 2 \times 10^{24} \text{ y}$ | | $T_{1/2}(\beta\beta 0\nu) > 1 \times 10^{26} \text{ y}$ |
| $\langle m_\nu \rangle < 0.3 - 0.9 \text{ eV}$ | | $\langle m_\nu \rangle < 0.04 - 0.11 \text{ eV}$ |



SuperNEMO Demonstrator Module : Overview

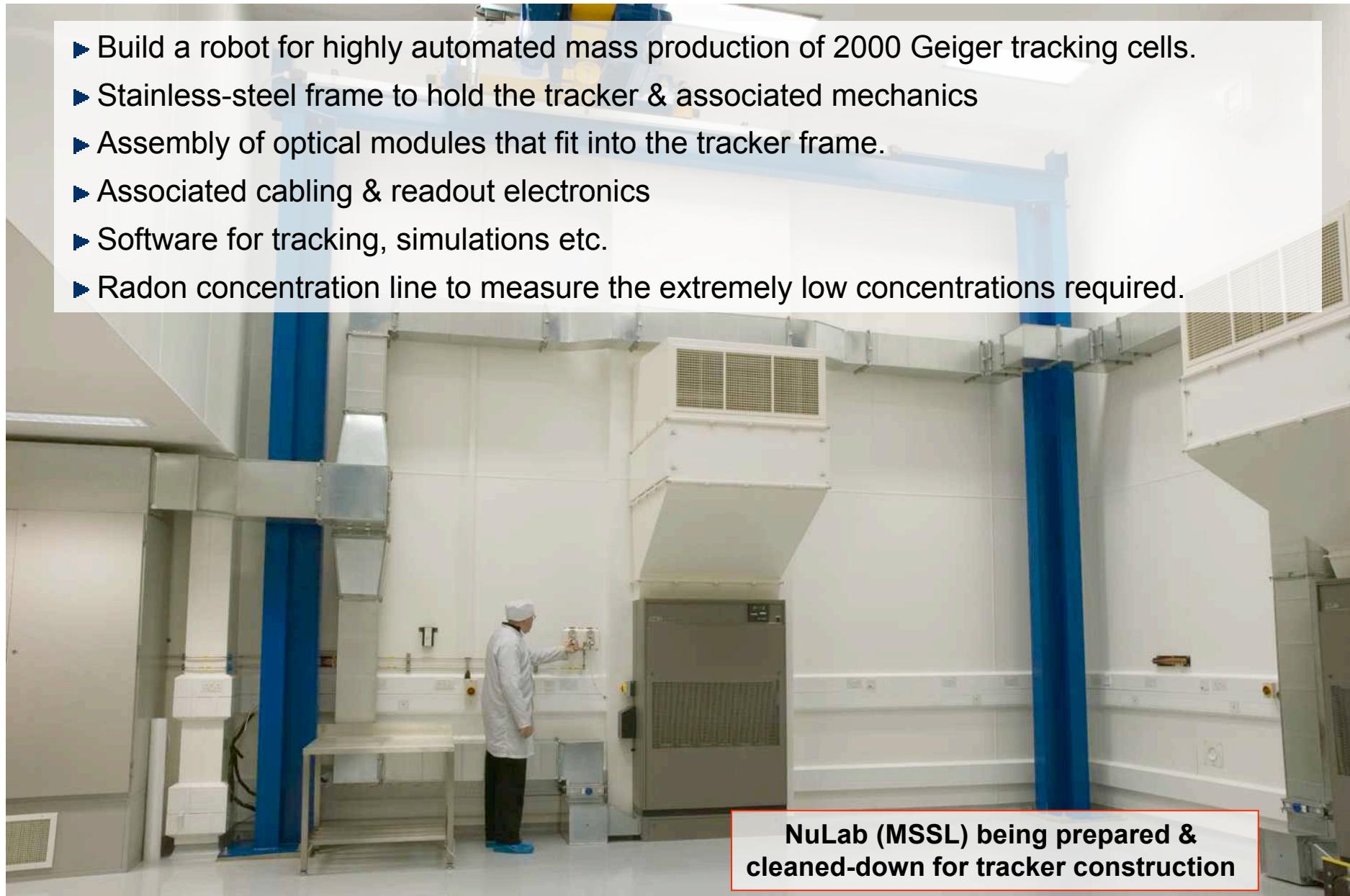




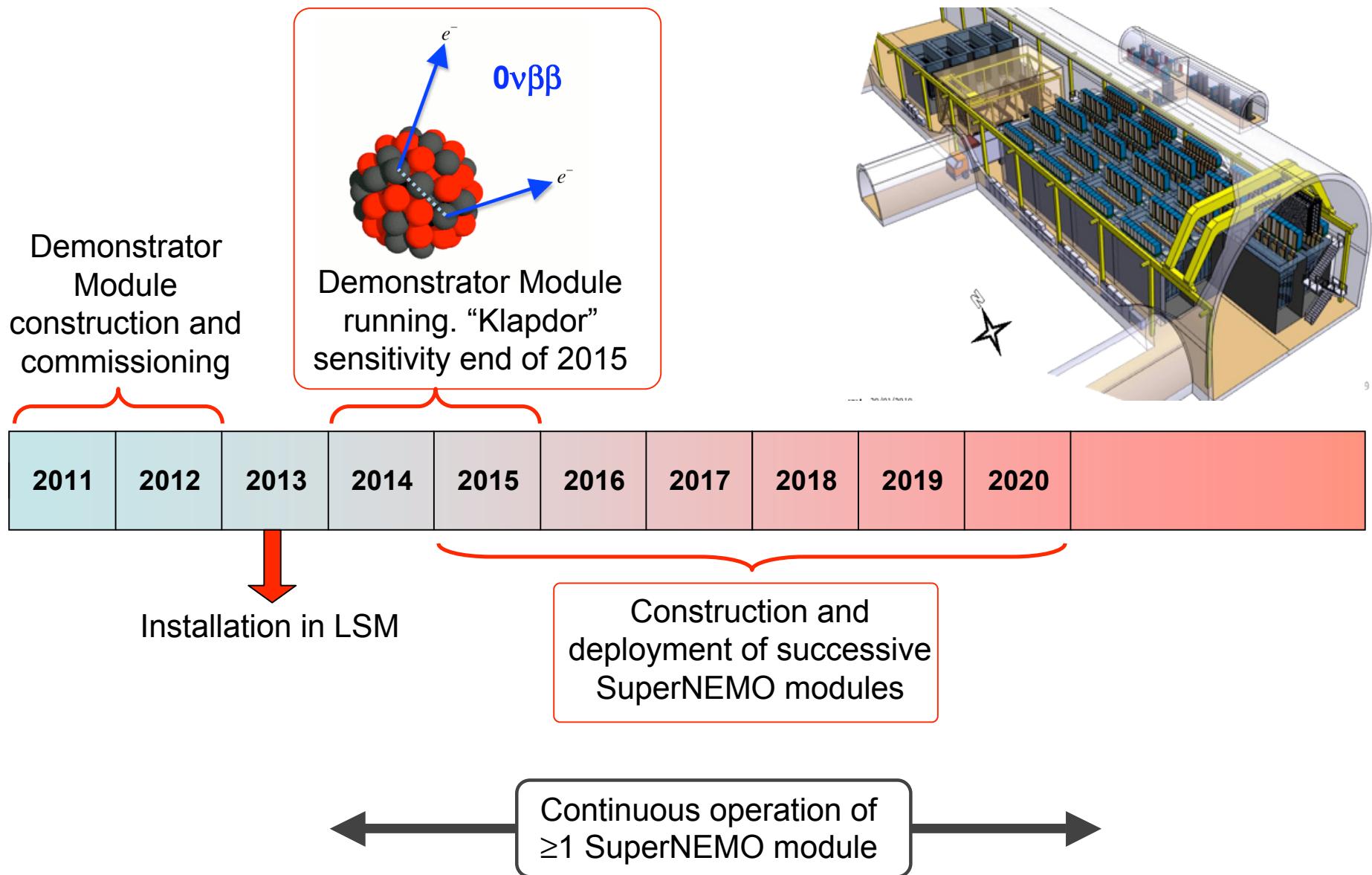
SuperNEMO UK : Tracker Construction



- ▶ Build a robot for highly automated mass production of 2000 Geiger tracking cells.
- ▶ Stainless-steel frame to hold the tracker & associated mechanics
- ▶ Assembly of optical modules that fit into the tracker frame.
- ▶ Associated cabling & readout electronics
- ▶ Software for tracking, simulations etc.
- ▶ Radon concentration line to measure the extremely low concentrations required.

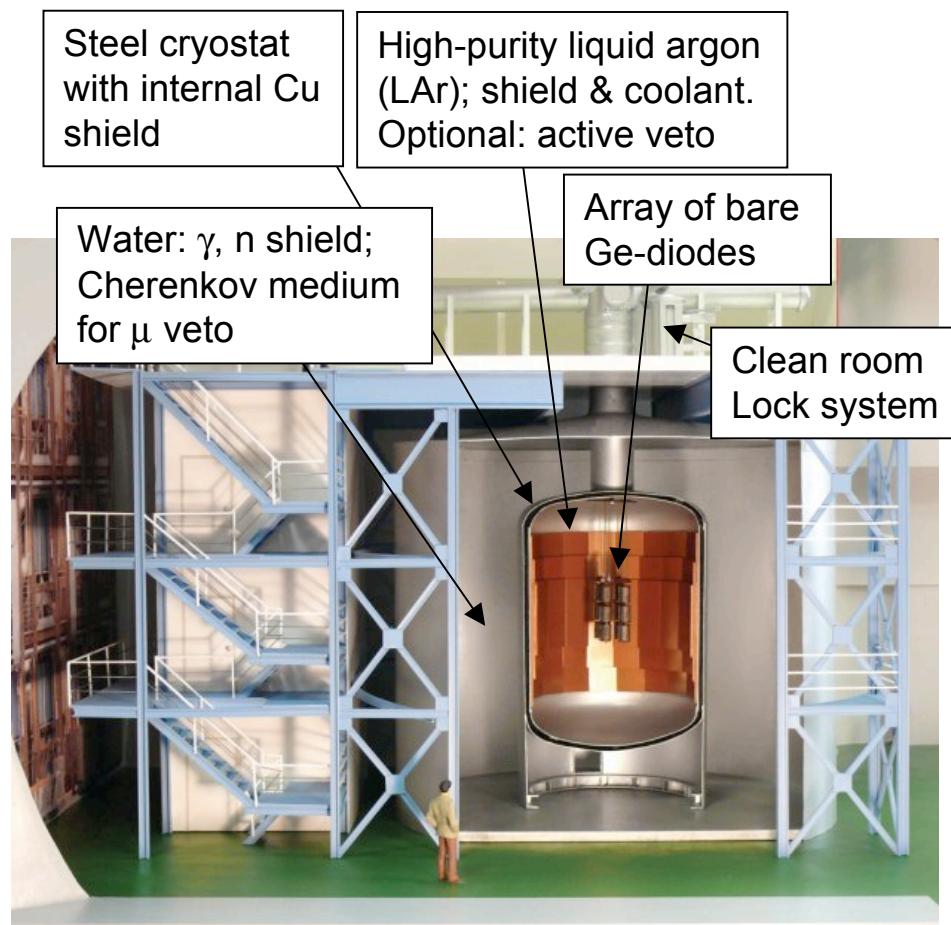


SuperNEMO : Timeline



Next-generation ^{76}Ge experiment

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

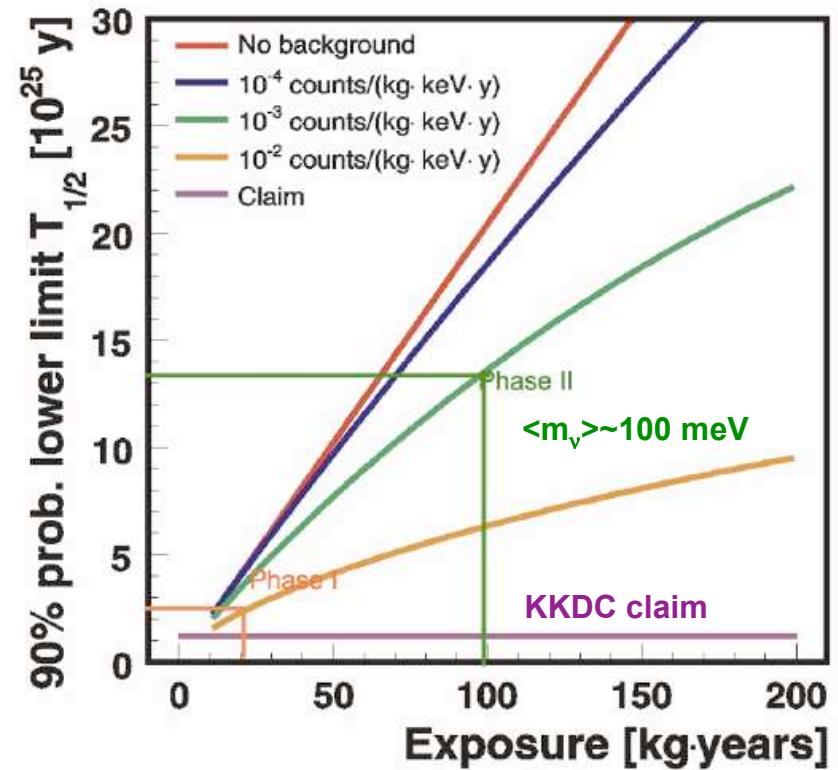


Phase I : 18 kg of 86% enriched detectors, background 100 times smaller than H-M.

Phase 2 : 40 kg of enriched detectors, background 1000 times smaller .

Future : 1-ton experiment (with Majorana) to fully explore inverted hierarchy.

Status : physics running to begin imminently !

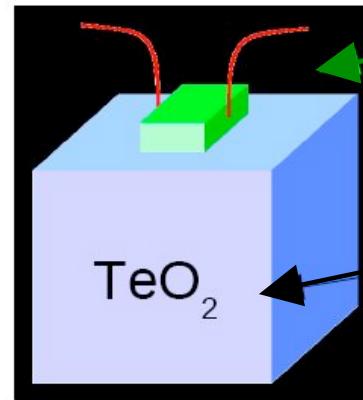




CUORICINO

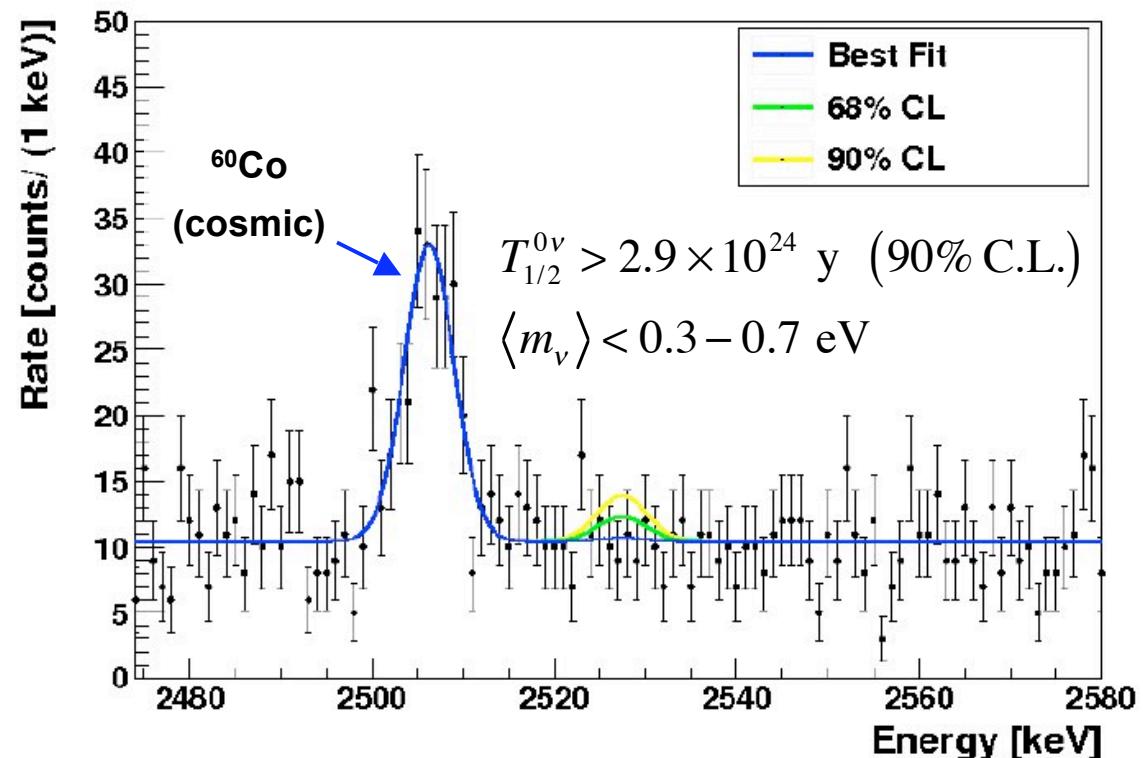
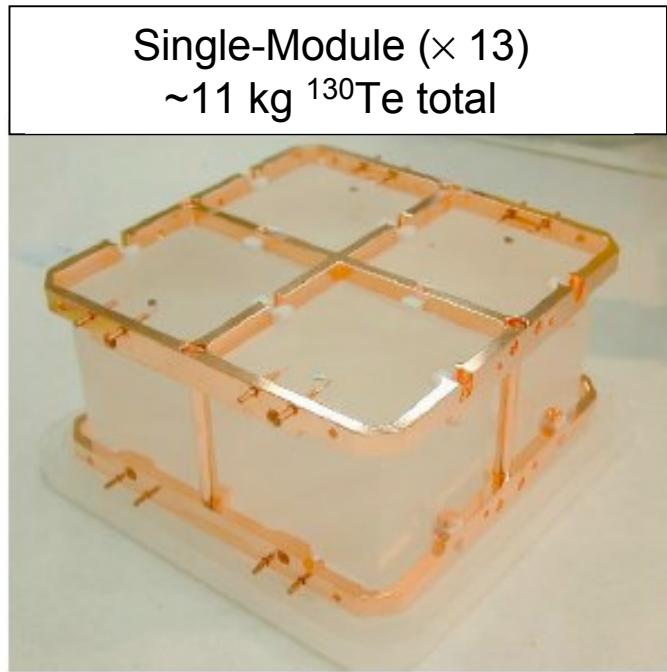
^{130}Te Bolometer Experiment

- ▶ ^{130}Te has high natural abundance (34%)
(no enrichment necessary)
- ▶ TeO_2 crystals have low heat capacity,
high intrinsic radio-purity.
- ▶ Operated at 8-10 mK



Temperature Sensor :
NTD Thermistor

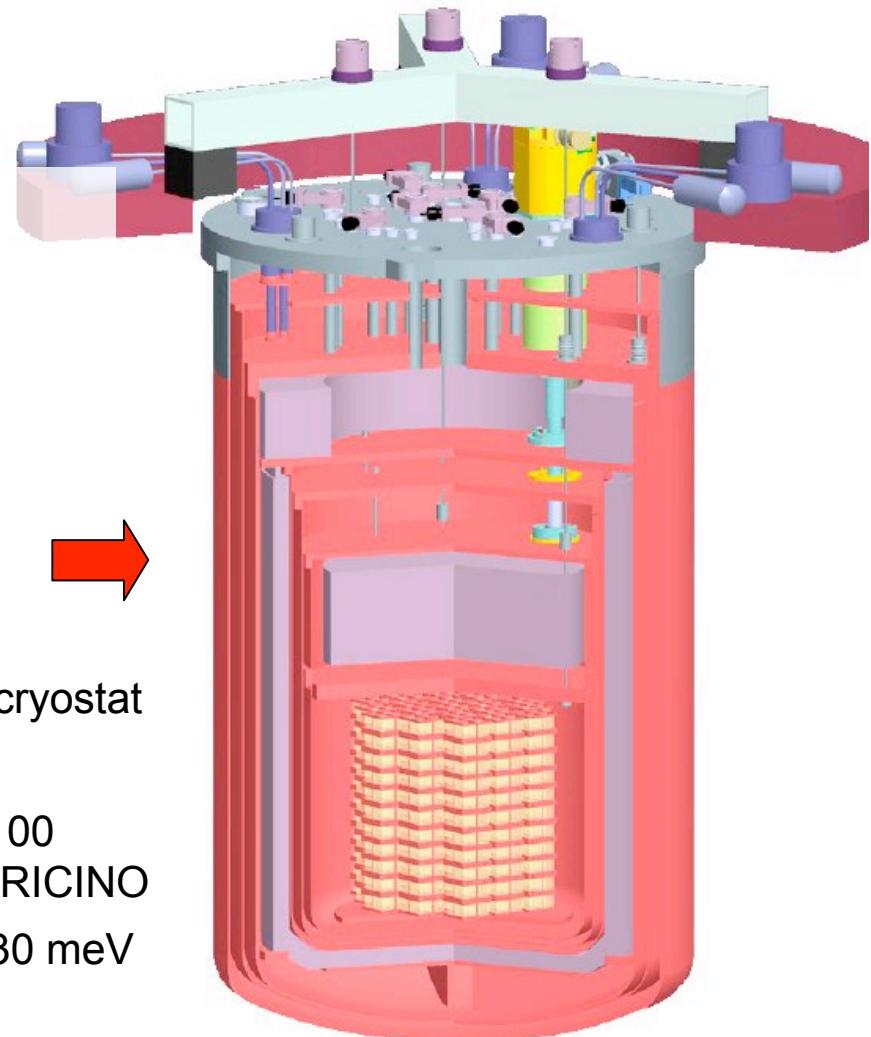
Absorber :
 $E \rightarrow \Delta T \sim E/C(T)$





CUORE-0

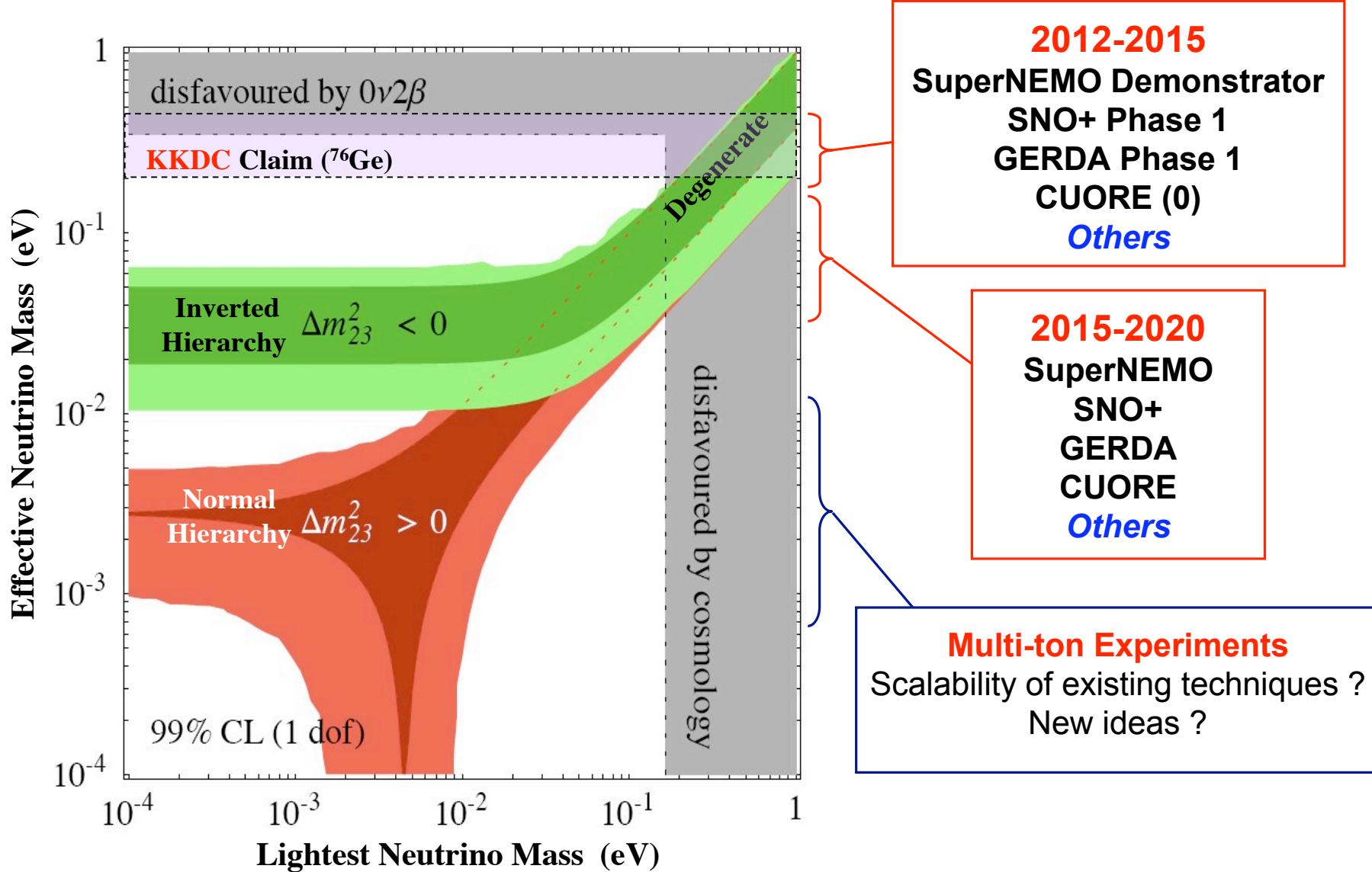
- ▶ 2011-2014
- ▶ $\sim 11 \text{ kg } ^{130}\text{Te}$



CUORE

- ▶ 2013-2018
- ▶ 19 towers in new cryostat
- ▶ $\sim 200 \text{ kg } ^{130}\text{Te}$
- ▶ Backgrounds 10-100 smaller than CUORICINO
- ▶ 5 years : $\langle m_\nu \rangle \sim 30 \text{ meV}$

Summary

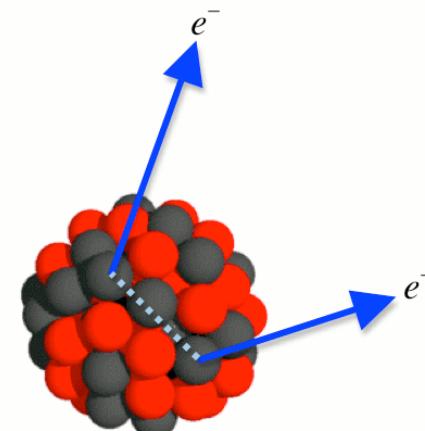


Summary

- Neutrinoless double-beta decay is a unique way to address fundamental questions in neutrino physics.
- We are entering a very interesting time with several next generation experiments starting in the next few years.
- Rich interplay with other areas :
 - ▶ Neutrino mass determinations from **β -decay end-point** experiments
 - ▶ Neutrino mass determinations from **cosmology**
 - ▶ Neutrino **oscillation** experiments
- There is the real possibility of a major discovery in the next 3-10 years.

Apologies :

- ▶ **Majorana** (^{76}Ge)
- ▶ **EXO** (liquid Xenon)
- ▶ **NEXT** (gaseous Xenon)
- ▶ **COBRA** (CdZnTe semi-conductor - very interesting idea with UK R&D)
- ▶ **CANDLES** ($^{48}\text{CaF}_2$ scintillator)
- ▶ ...

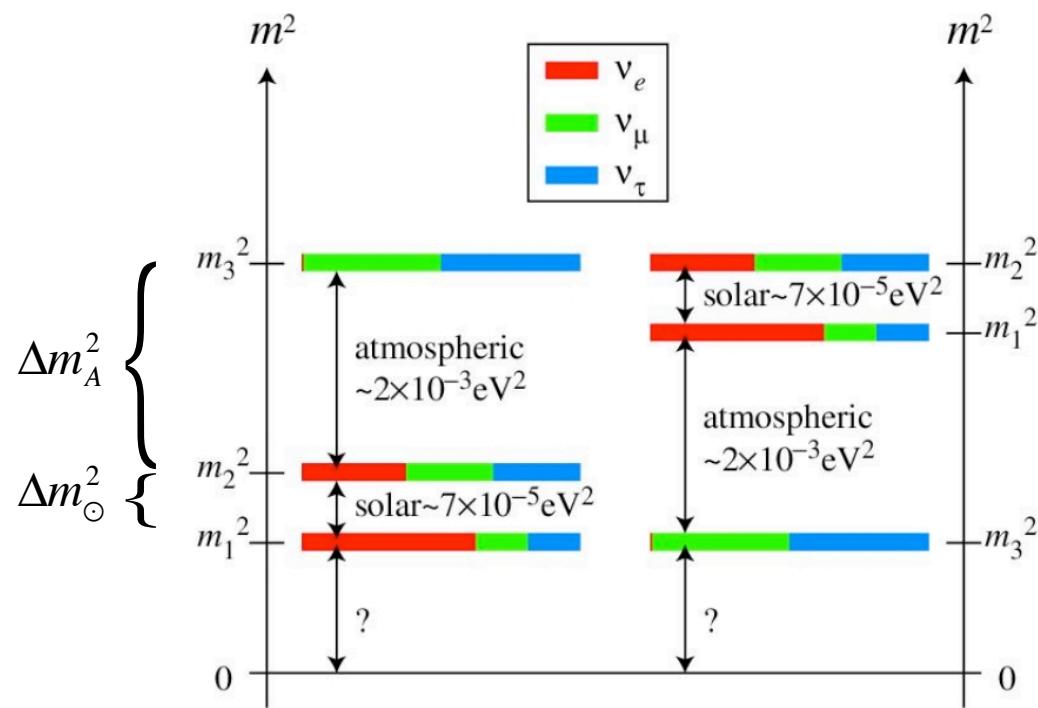


Backup Slides

Neutrino Mixing & Masses

PMNS mixing matrix :

$$U = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$



Current UK SNO+ Involvement

Oxford University:

Steve Biller, Nick Jelley, Armin Reichold, Phil Jones, Ian Coulter
(UK Spokesperson &
Head of Event Reconstruction)

& Ken Clark*

(Canadian postdoc "on-loan")

Sussex University:

Elisabeth Falk, Jeff Hartnell, Simon Peeters,
(Co-Head of Data Flow) (Head of Calibration)

Shak Fernandes, James Sinclair, Gwen Lefevre

Leeds University:

Stella Bradbury, Joachim Rose

Queen Mary University of London:

Jeanne Wilson
(Analysis Coordinator)

Liverpool University

Neil McCauley
(Co-Head of Data Flow)

University of Sheffield

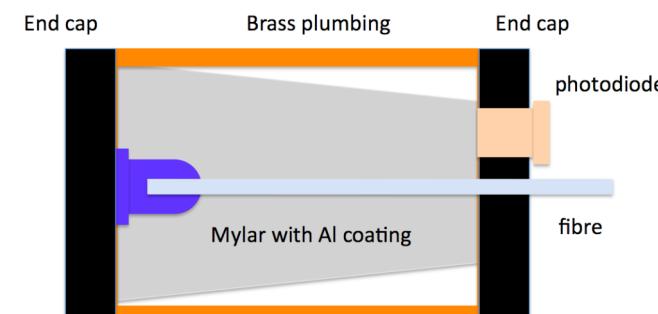
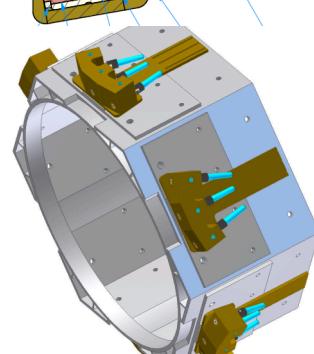
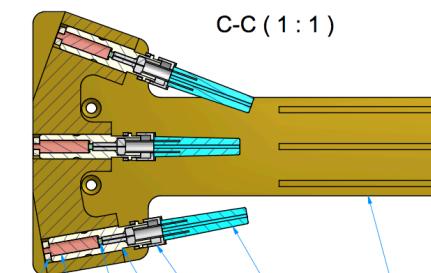
John McMillan



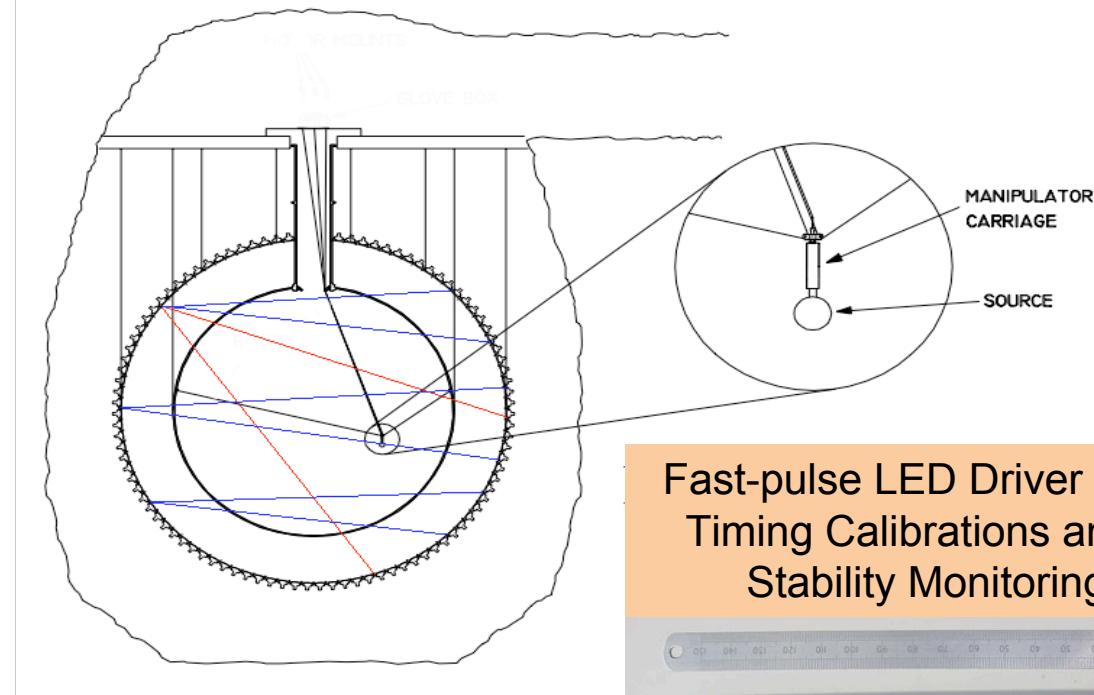
Software

- Scintillator & PMT modelling and simulations.
- Sensitivity studies, including optimal ^{150}Nd loading of liquid scintillator.

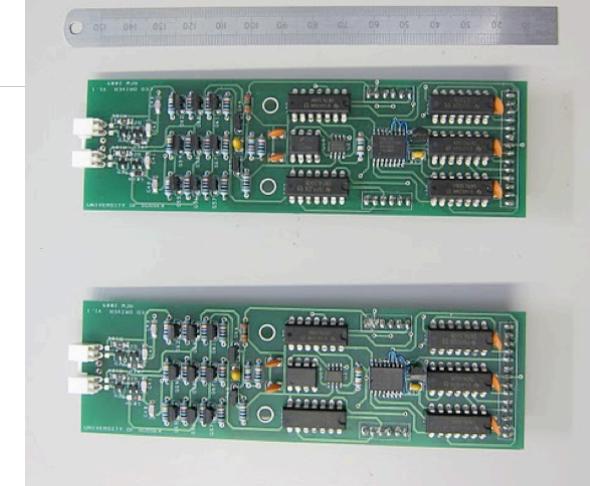
Collimator for laser-based scattering measurements



Embedded Fibre Optic Calibration System



Fast-pulse LED Driver for Timing Calibrations and Stability Monitoring





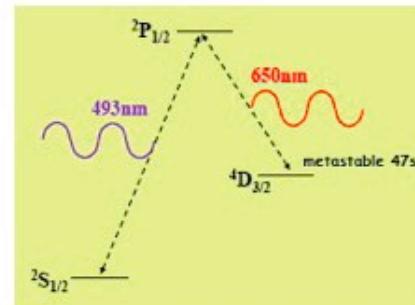
Enriched Xenon Observatory

Liquid Xe TPC

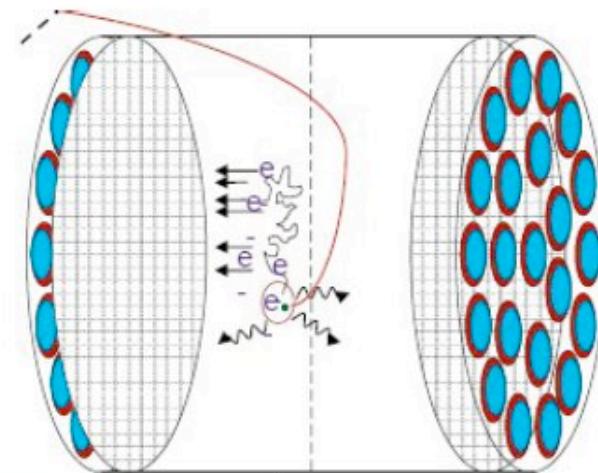
Energy measurement by ionization + scintillation

Tagging of Barium ion ($^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2 e^-$)

Optical spectroscopy with Ba+



Ion Grabber/mover



| Case | Mass (ton) | Eff. (%) | Run Time (yr) | $\sigma_E/E @ 2.5\text{MeV}$ (%) | $2\nu\beta\beta$ Background (events) | $T_{1/2}^{0\nu}$ (yr, 90%CL) | Majorana mass (meV) | QRPA [#] | NSM [#] |
|--------------|------------|----------|---------------|----------------------------------|--------------------------------------|------------------------------|---------------------|-------------------|------------------|
| Conservative | 1 | 70 | 5 | 1.6* | 0.5 (use 1) | $2*10^{27}$ | 50 | 68 | |
| Aggressive | 10 | 70 | 10 | 1† | 0.7 (use 1) | $4.1*10^{28}$ | 11 | 15 | |