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

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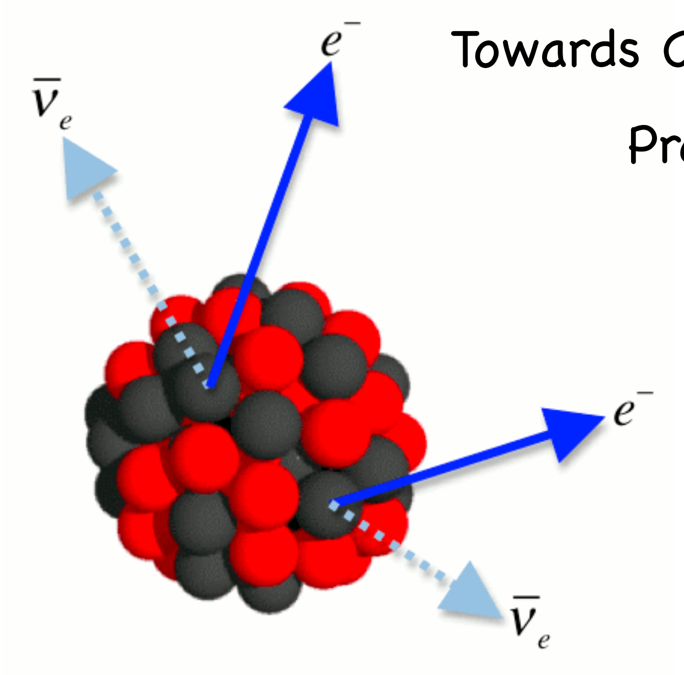
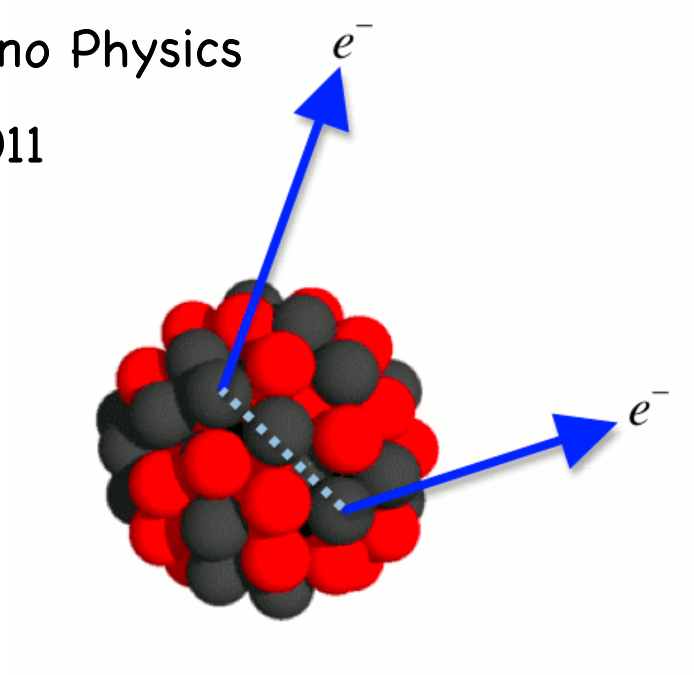
University College London

Towards CP Violation in Neutrino Physics

Prague, 7th October 2011





Key Questions in (No) Neutrino Physics

- Neutrinos have mass and they mix ➔ (see next talks)
- 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 :

$$m_{\bar{\nu}_e} < 2.3 \text{ eV (Tritium end-point)}$$

$$\Sigma m_{\nu_i} < 0.5 \text{ eV (Cosmology)}$$

- **Neutrino mass-hierachy** :
  - 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** : $\alpha_{21}, \alpha_{31} \neq 0, \pi$

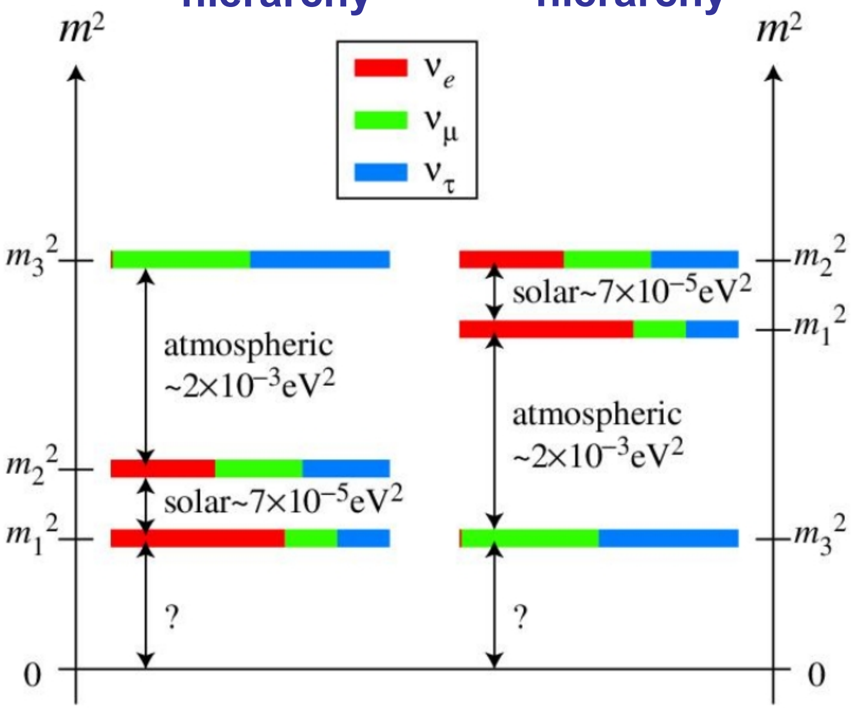
PMNS mixing matrix :

Majorana Phases

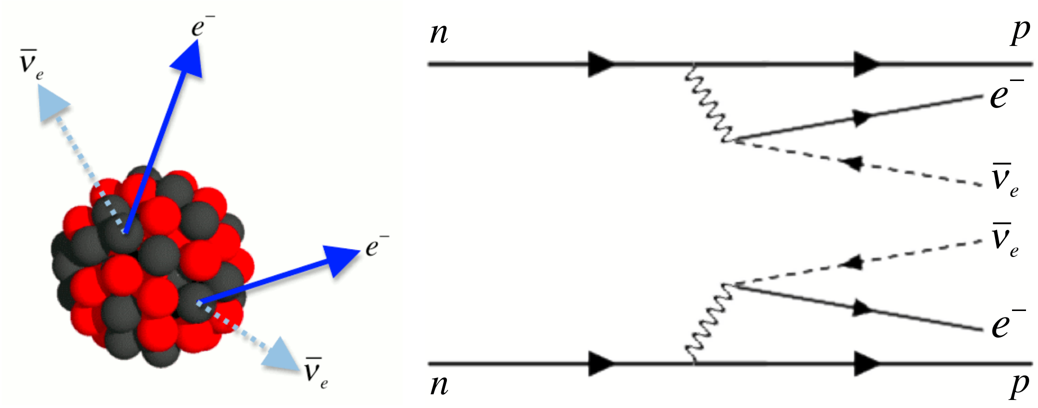
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

Normal hierarchy

Inverted hierarchy



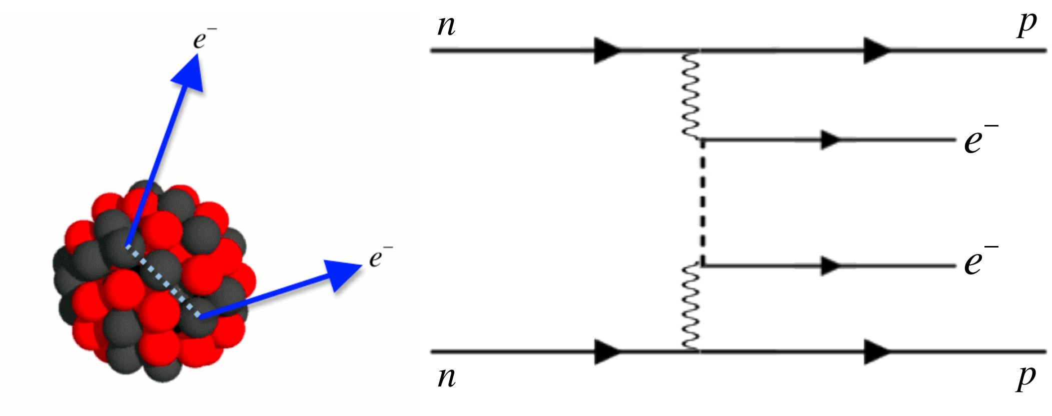
Double-Beta Decay



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 ~ $O\left(G_F^2\right)$



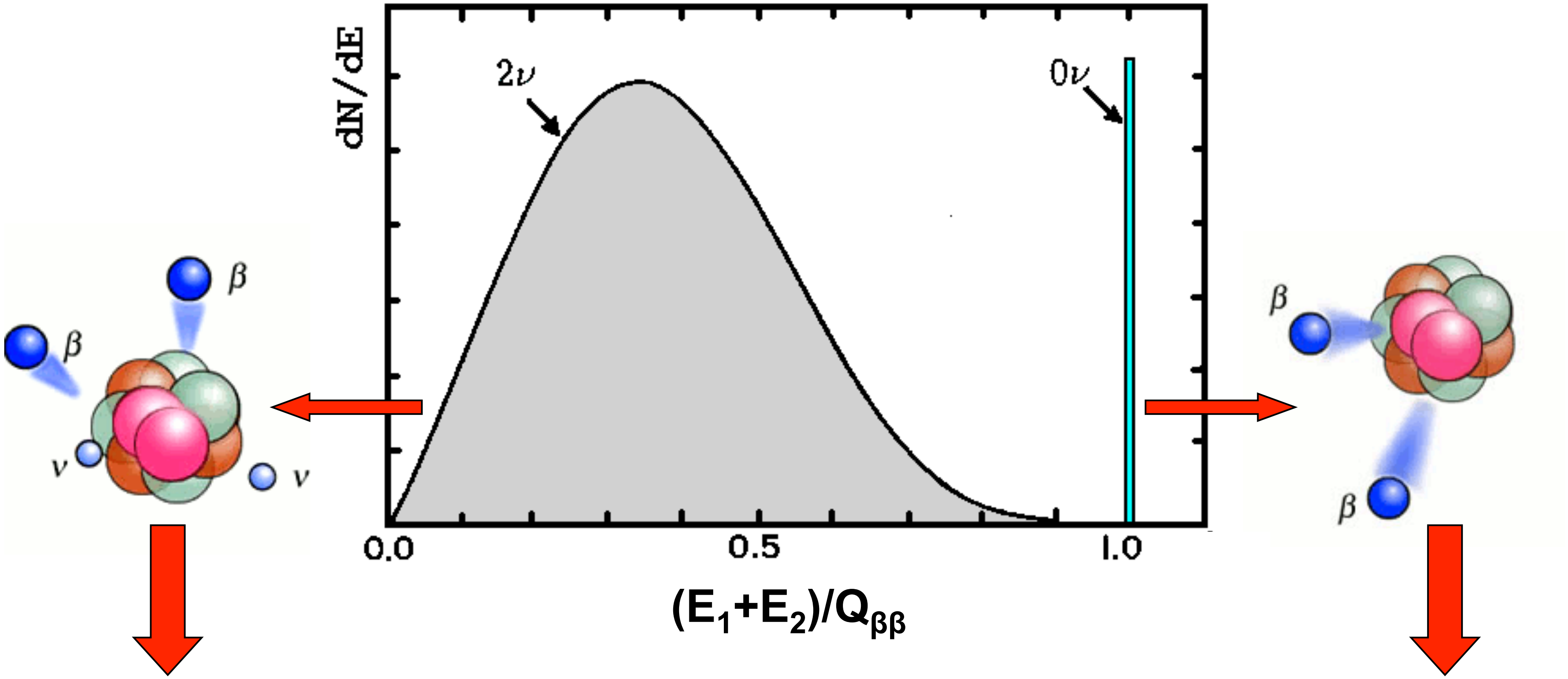
0-Neutrino Double Beta Decay

[Furry, 1939]

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

Double-Beta Decay : Basic Signature

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



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

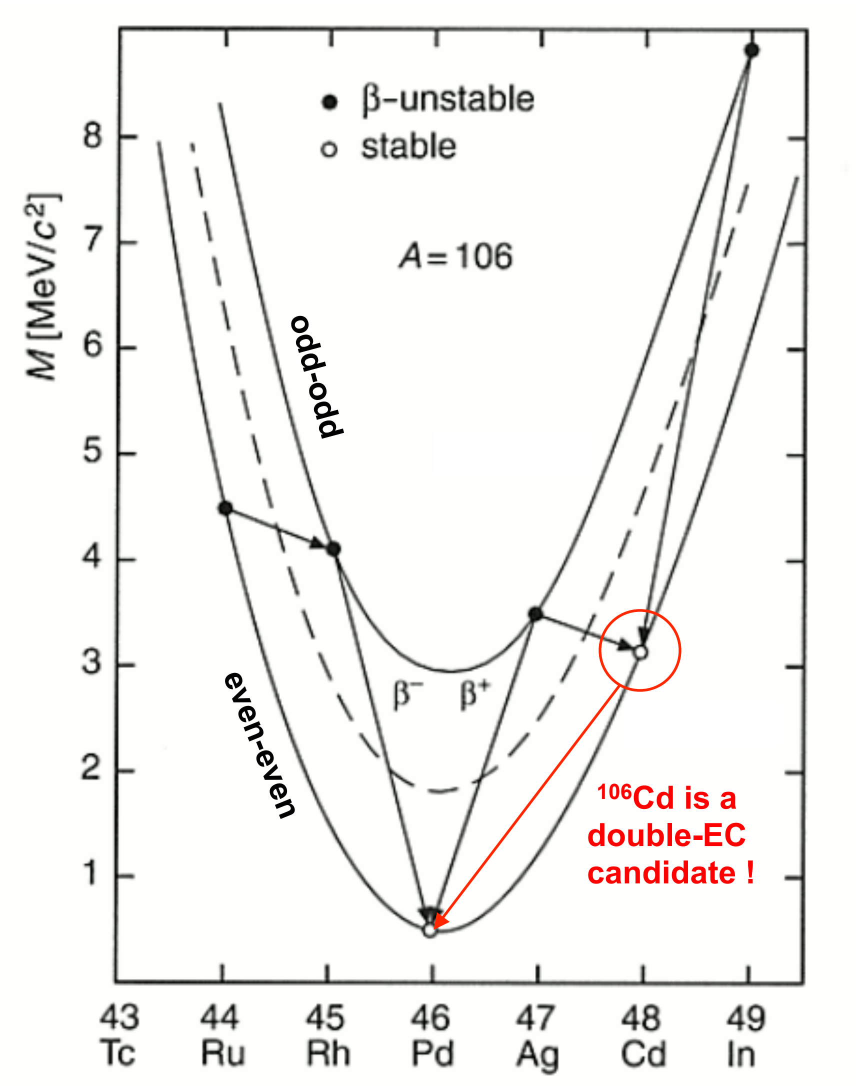
$$\left(E_1 + E_2\right)/Q_{\beta\beta} \approx 1$$

$[\otimes$ 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. 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

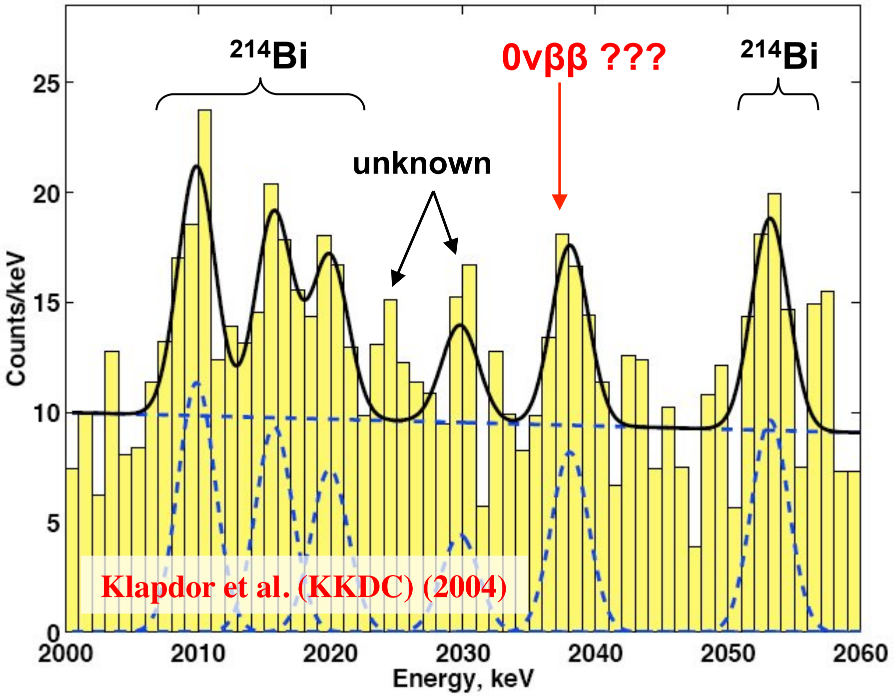
Signal in Heidelberg-Moscow experiment ?

- 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 :

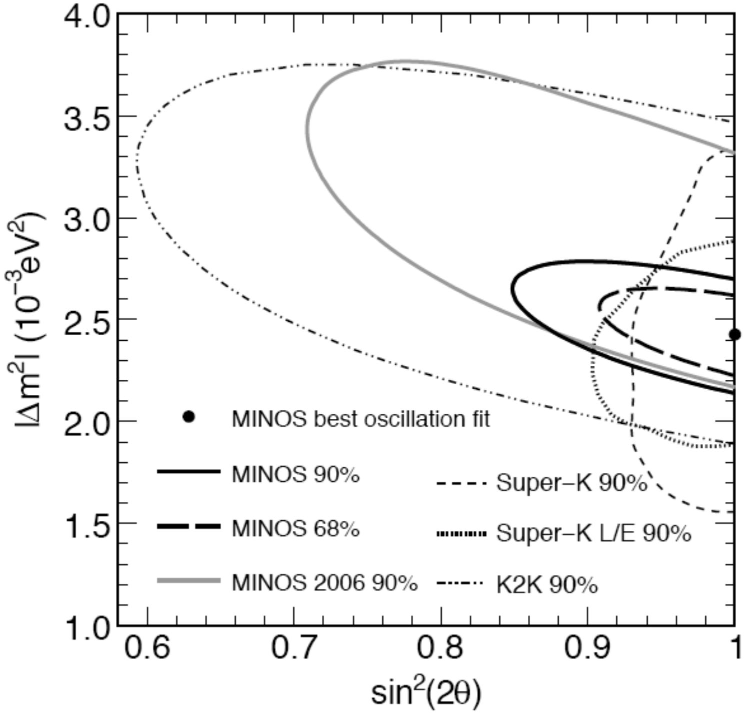
$$\langle m_\nu \rangle \sim 0.4 \text{ eV}$$



Neutrino Oscillations

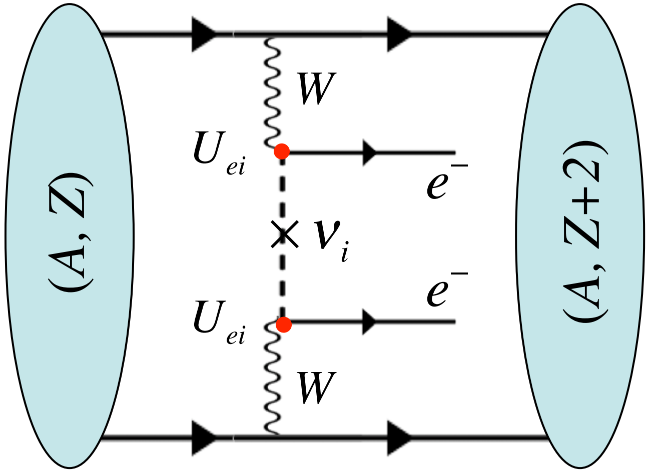
- Largest Δm^2 from "atmospheric" oscillations.
- Therefore there is at least one neutrino with :

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



Effective Neutrino Mass (Light Neutrino Exchange)

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



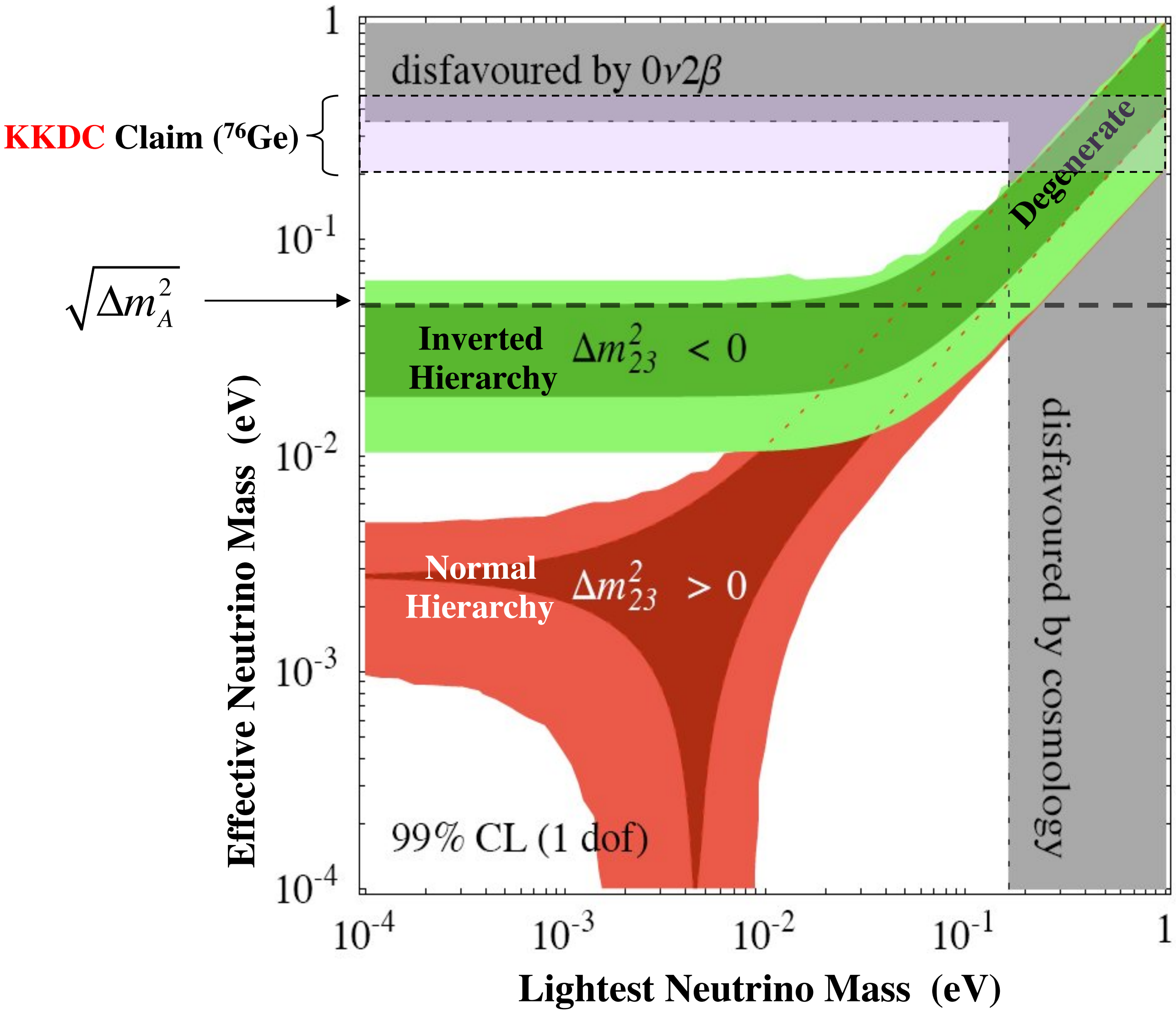
- Hence, experiments are sensitive to an *effective* 0νββ neutrino mass :

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

α_{21}, α_{31} = Majorana phases

Effective Neutrino Mass

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



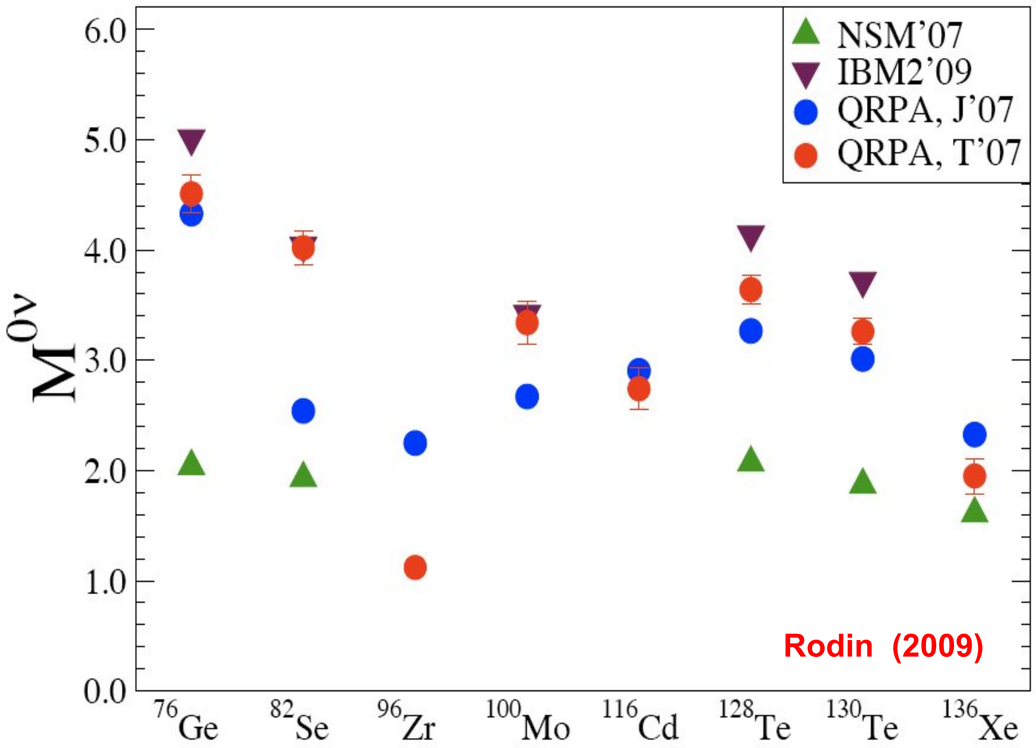
Strumia & Vissani (2006/2010)

Nuclear Matrix Elements

phase-space factor
(exactly calculable)

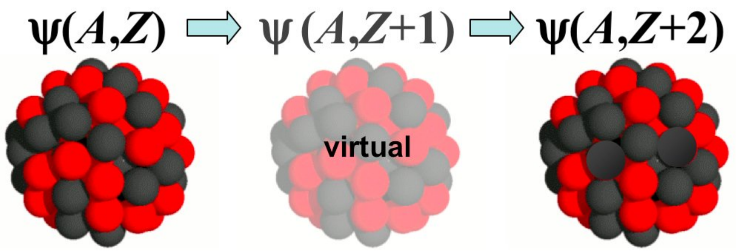
effective neutrino mass

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



Rodin (2009)

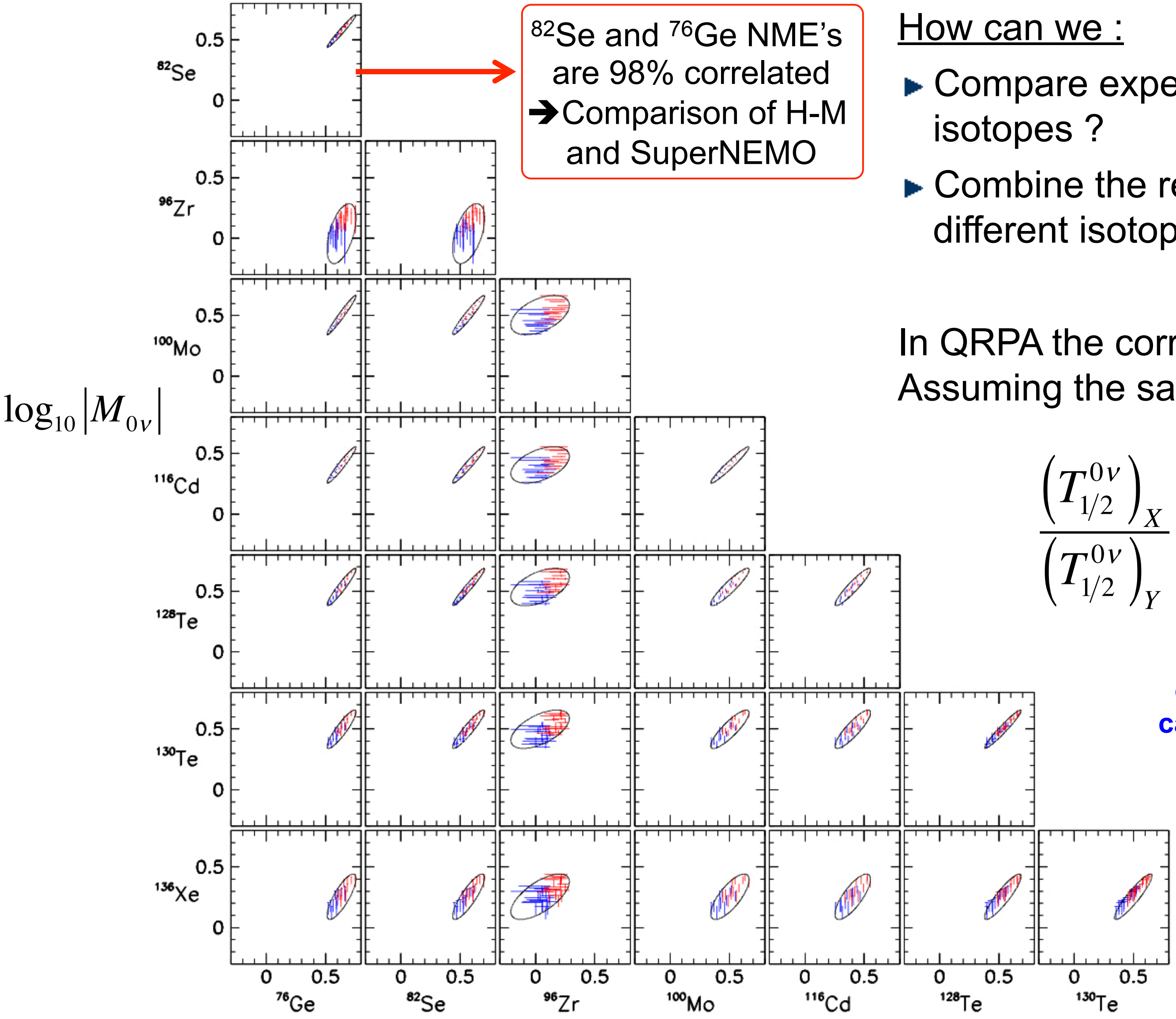
u**N**clear **M**atrix **E**lements



All is not lost :

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

NME : Correlations



^{82}Se and ^{76}Ge NME's are 98% correlated
➔Comparison of H-M and SuperNEMO

$\log_{10}|M_{0\nu}|$

Faessler et al. (2009)

How can we :

- Compare experiments using different isotopes ?
- Combine the results of experiments using different isotopes ?

In QRPA the correlations can be estimated. Assuming the same mechanism, then :

$$\frac{\left(T_{1/2}^{0\nu}\right)_X}{\left(T_{1/2}^{0\nu}\right)_Y} = \frac{G_{0\nu}^{Y}}{G_{0\nu}^{X}} \cdot \frac{\left|M_{0\nu}^{Y}\right|^2}{\left|M_{0\nu}^{X}\right|^2}$$

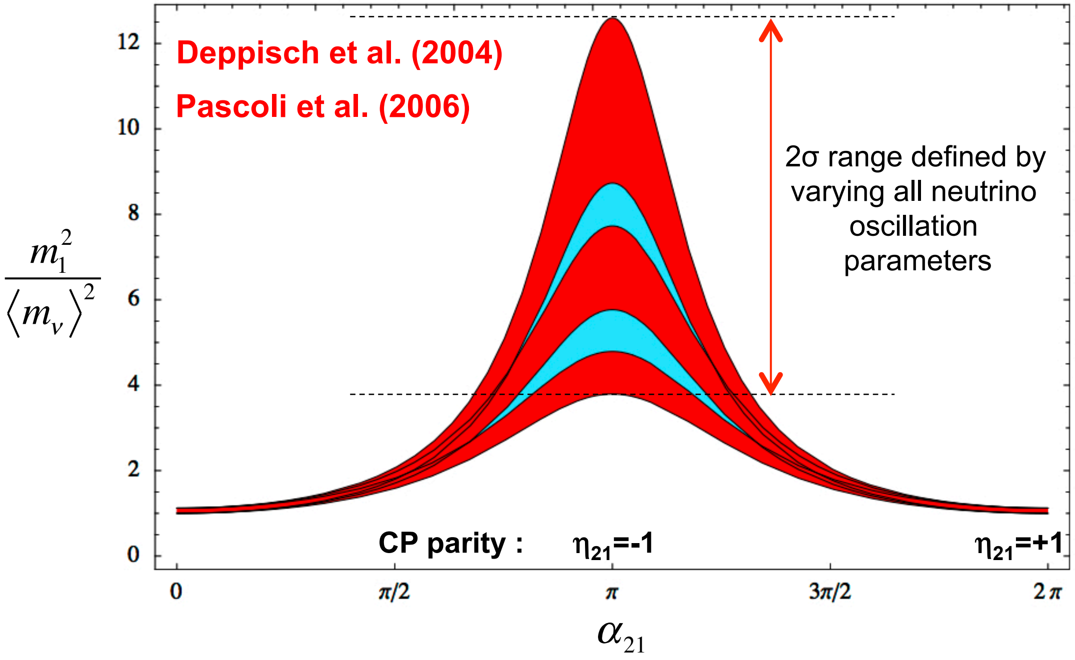
exactly calculable

ratio accurately predicted if NME's are highly correlated

CP Violation and 0νββ

- Neutrinoless double-beta decay is the only way to constrain the Majorana phases.
- As an example for small θ_{13} and in the quasi-degenerate mass region :

$$\langle m_\nu \rangle^2 \approx \left[1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\alpha_{21}}{2} \right) \right] m_1^2$$



- ***In principle*** the combination of a measurement of **$\langle m_\nu \rangle$** with **m_1** from β–decay end-point or cosmology can be used to constrain the Majorana phases.
- ***In practice*** this will be extremely difficult given likely uncertainties (e.g. on NME).

How To Build a ββ-Experiment

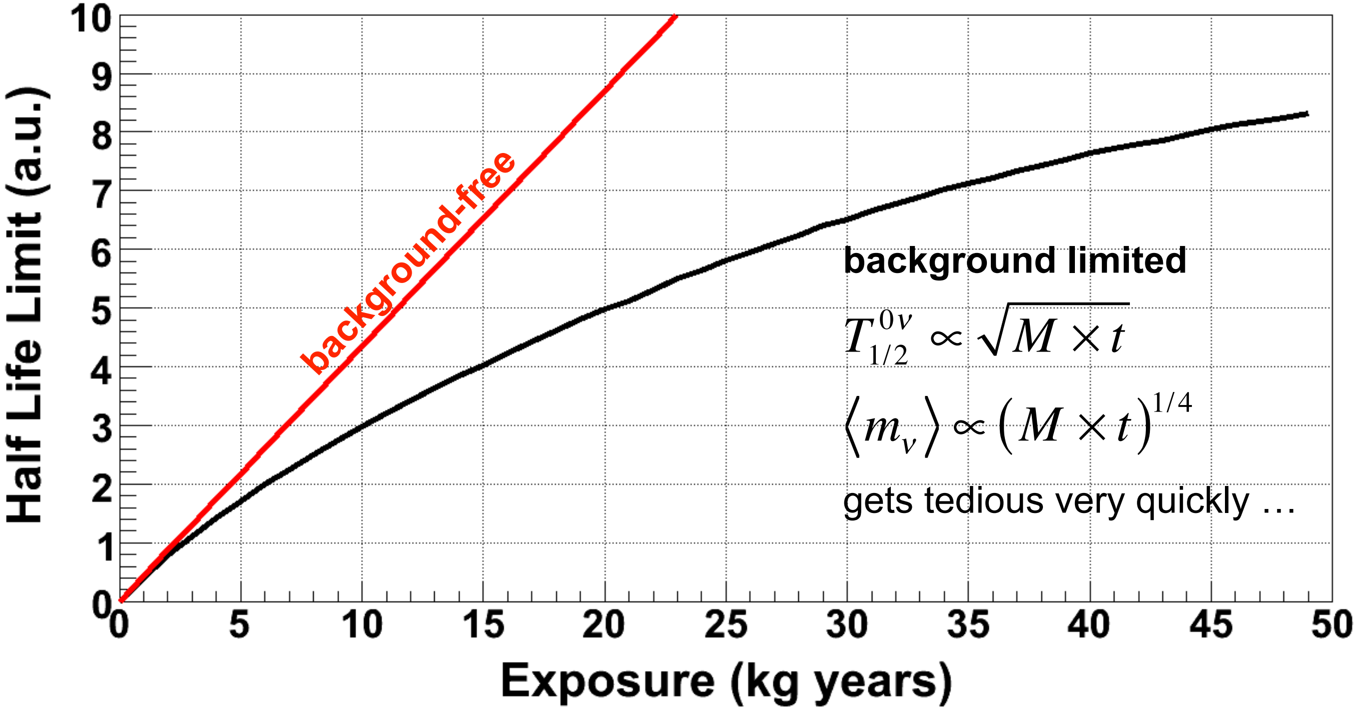
maximise efficiency (ε) & isotope abundance (*a*)

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

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

W = atomic weight

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



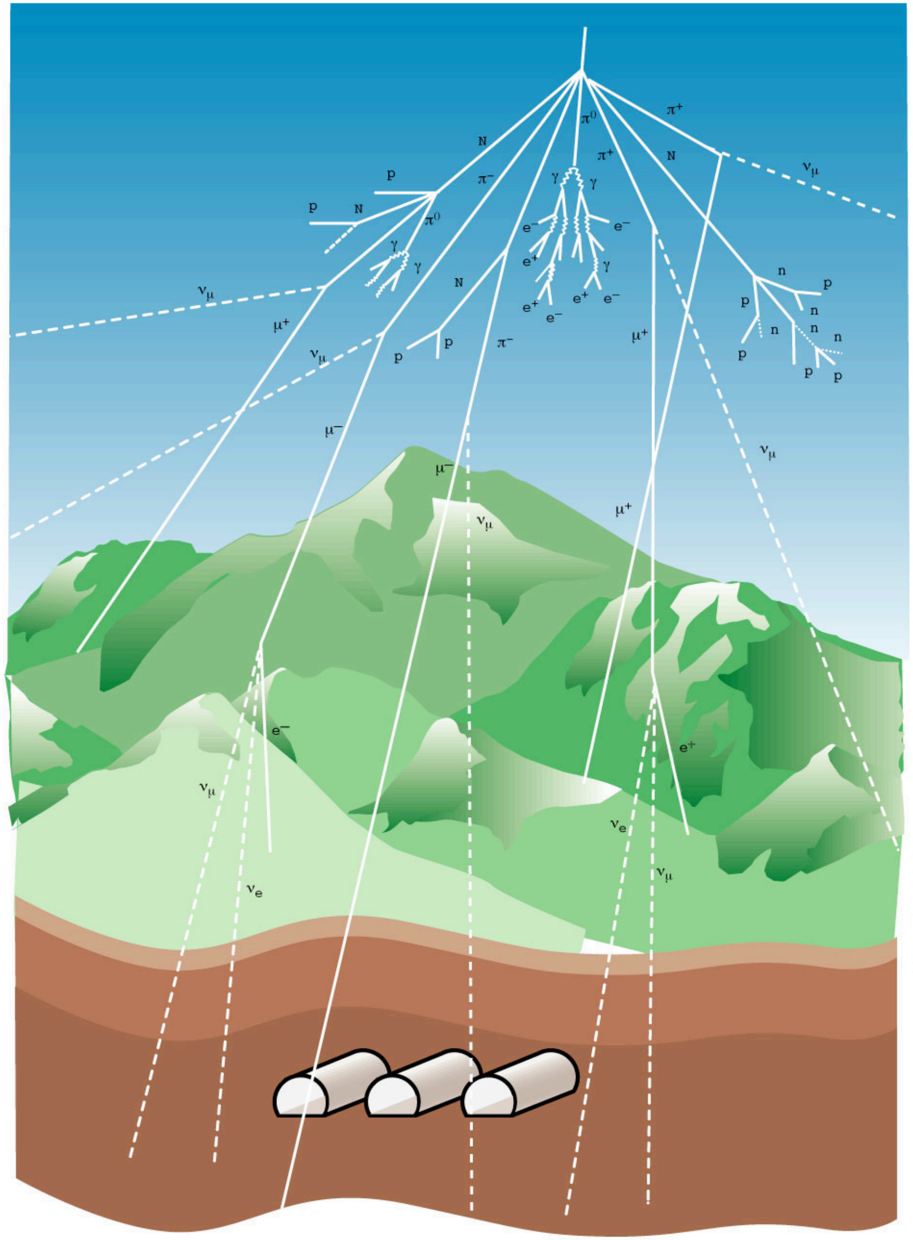
background limited

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

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

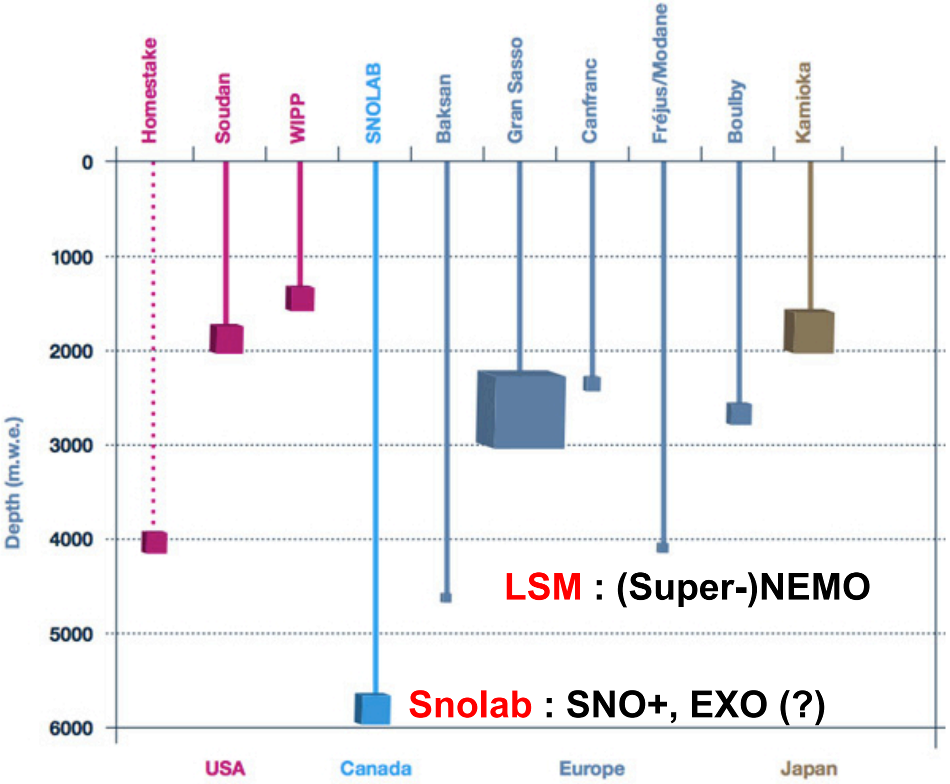
gets tedious very quickly …

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

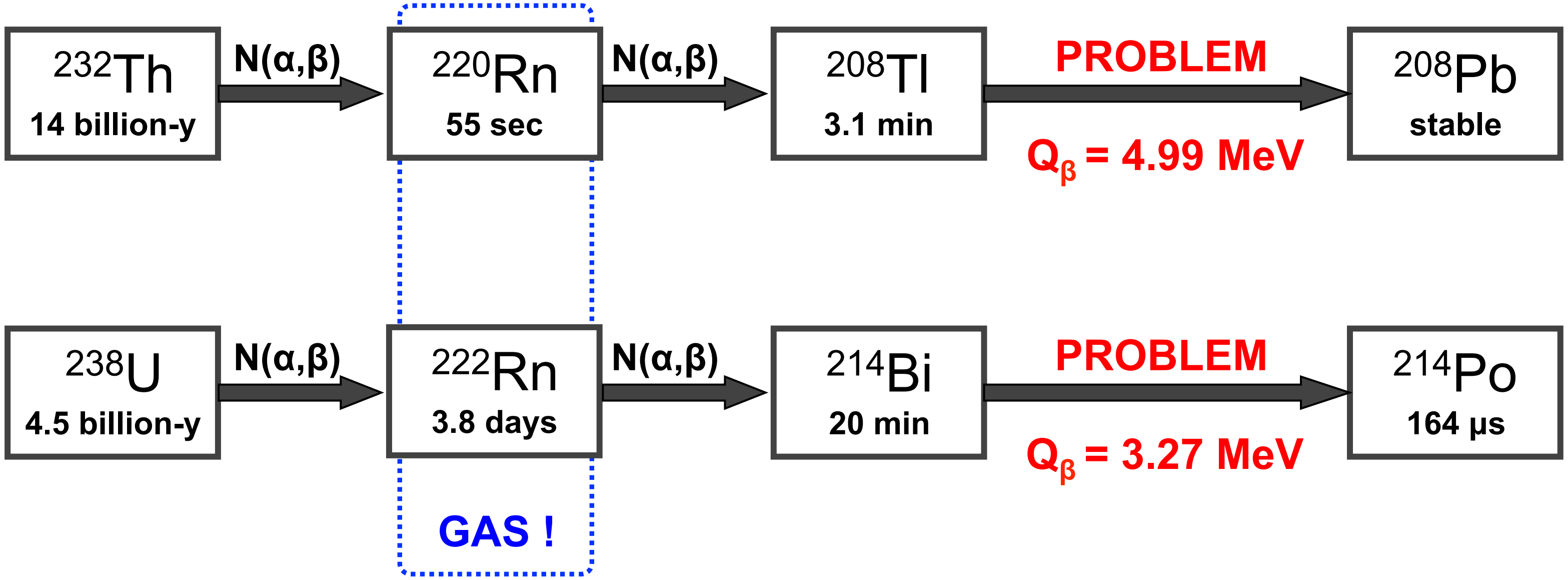


LSM : (Super-)NEMO

Snolab : SNO+, EXO (?)

Natural Radioactivity

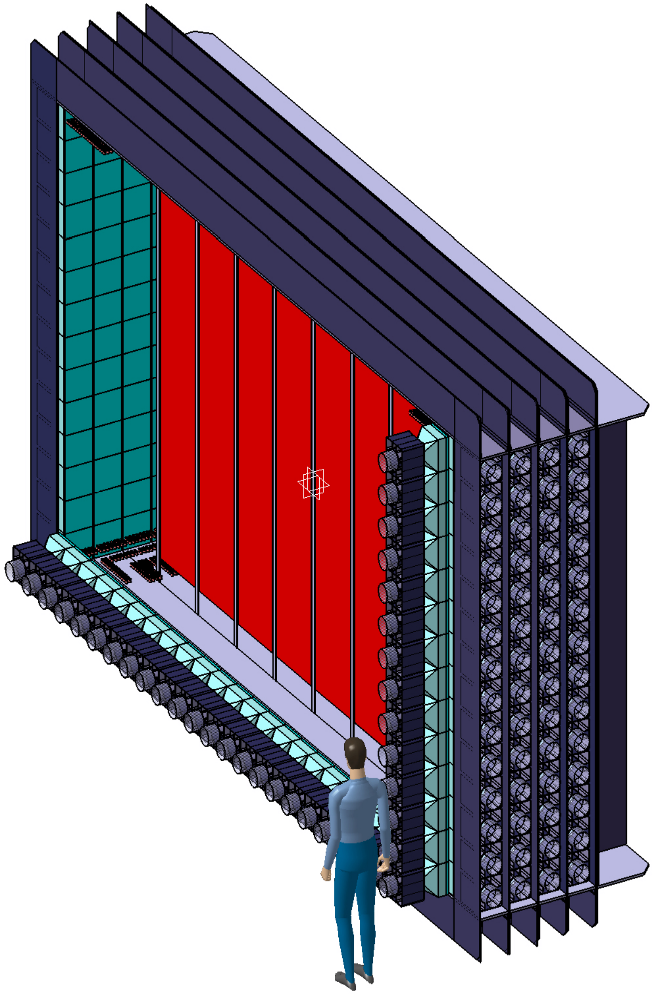
- Primarily Uranium and Thorium decay chain products, present in all materials.
  - **$T_{1/2}(^{232}Th, ^{238}U) \sim 10^{10}$ years**
  - **$T_{1/2}(0\nu\beta\beta) > 10^{25}$ years**



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

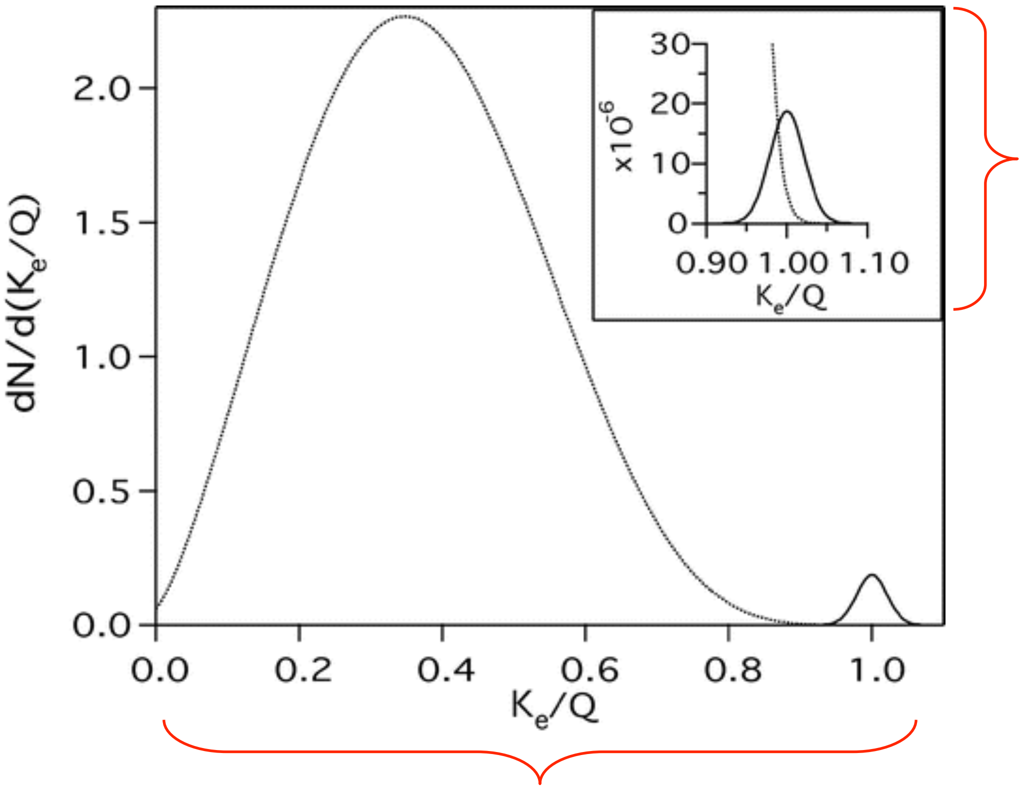
It's All About Backgrounds

SuperNEMO Demonstrator Module
20 tons
Radon emanation into tracker must be < 1.5 mBq



Brazil Nut
4 grams
400 mBq of Radium decays

Irreducible Background : 2νββ



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

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

- <u>What can be done ?</u>

▸ Improve energy resolution.

▸ Choose a different isotope with a more favourable ratio of 2νββ and 0νββ :

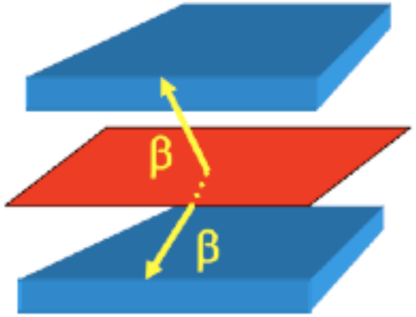
NEMO-3 ➔ SuperNEMO

^{100}Mo ➔ ^{82}Se

Experimental Approaches

Heterogenous

“tracking”



Advantages :

Full event topology information

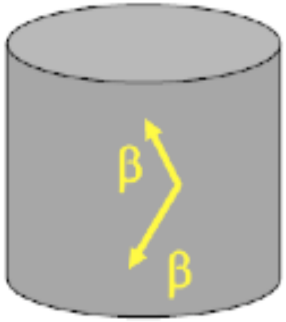
“Smoking-gun” signature for 0νββ

Can probe different mechanisms

Isotope flexibility

Homogenous

“source = detector”



Advantages :

Excellent ΔE/E

Compact

Techniques :

Semiconductor

Bolometer

(Liquid-) Scintillator

Elements of Both

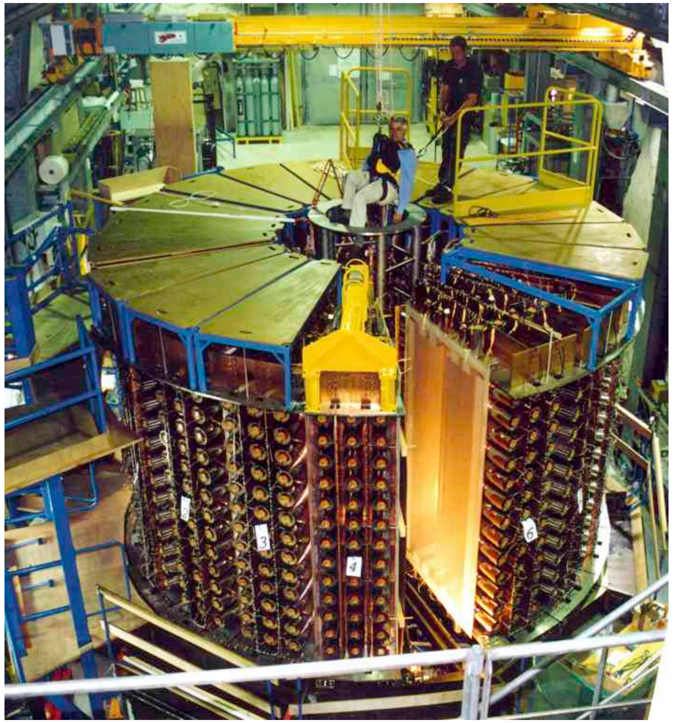
Gaseous Xe TPC

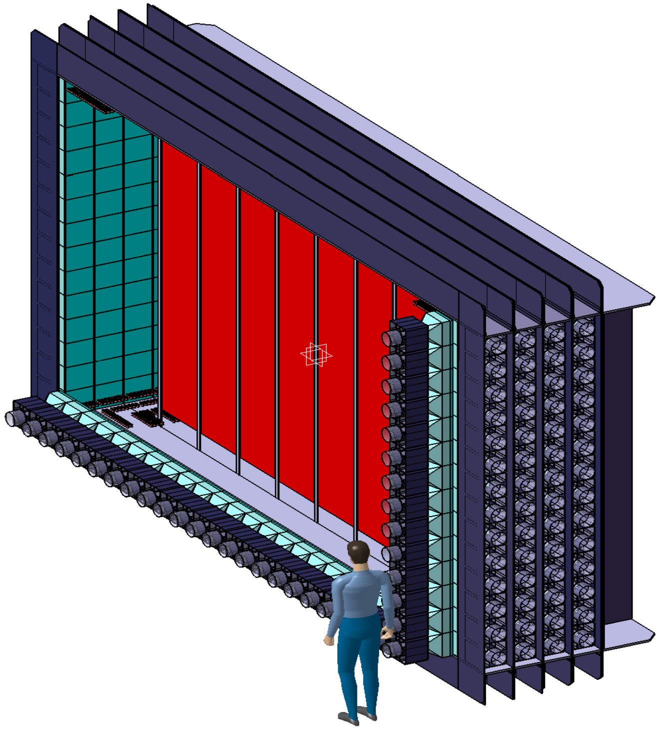
Pixelated CdZnTe

(Super-)NEMO

supernemo collaboration

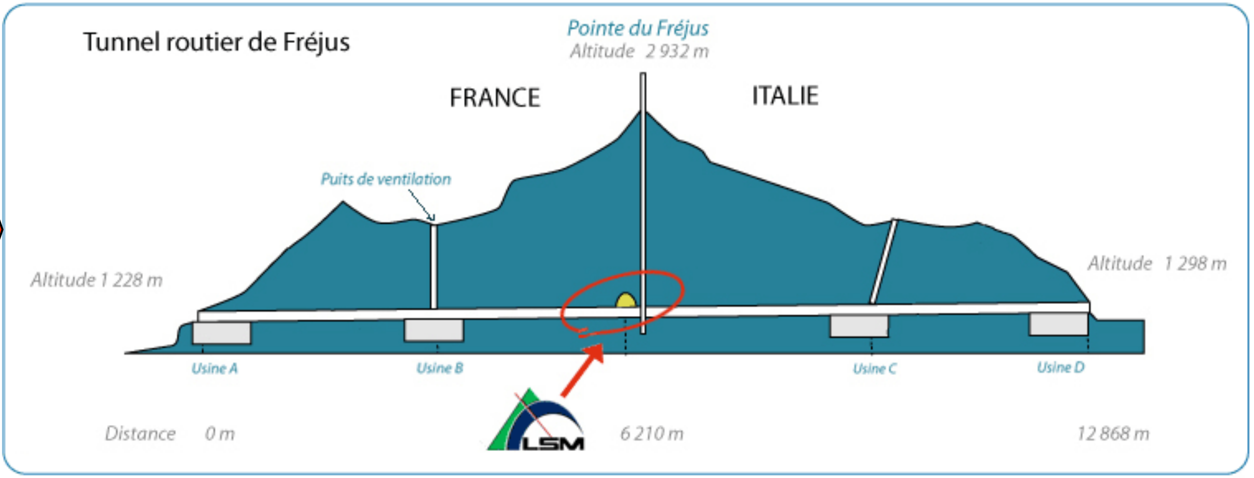
Czech Technical University
Charles University
Czech Republic Representative : Ivan Štekl





Neutrino Ettore Majorana Observatory 3

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

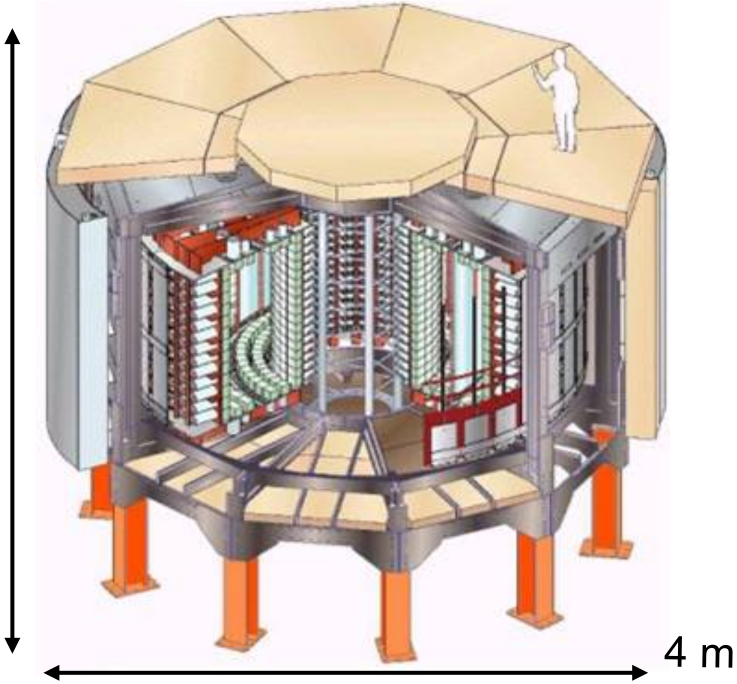


NEMO-3

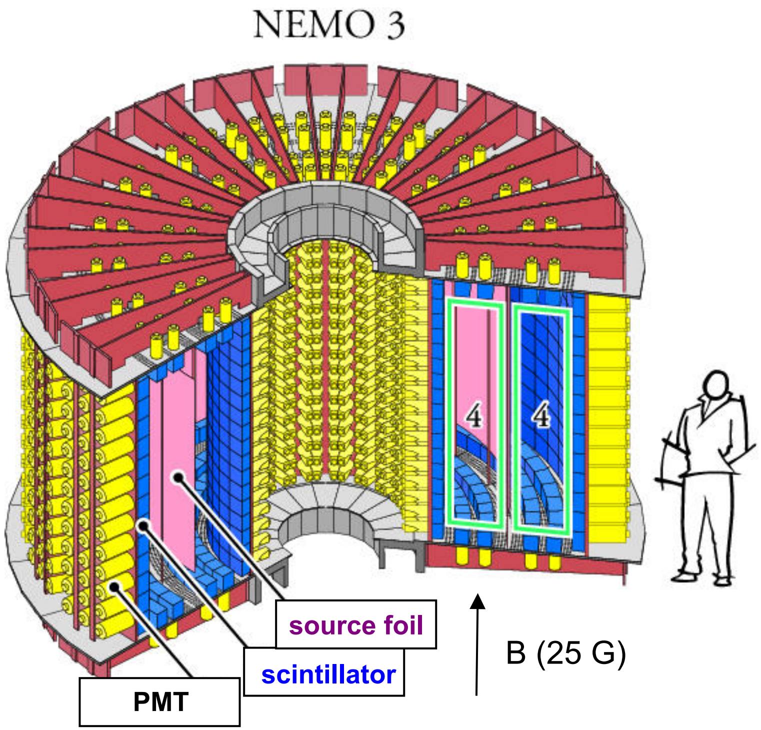
The world's biggest and cleanest Geiger counter

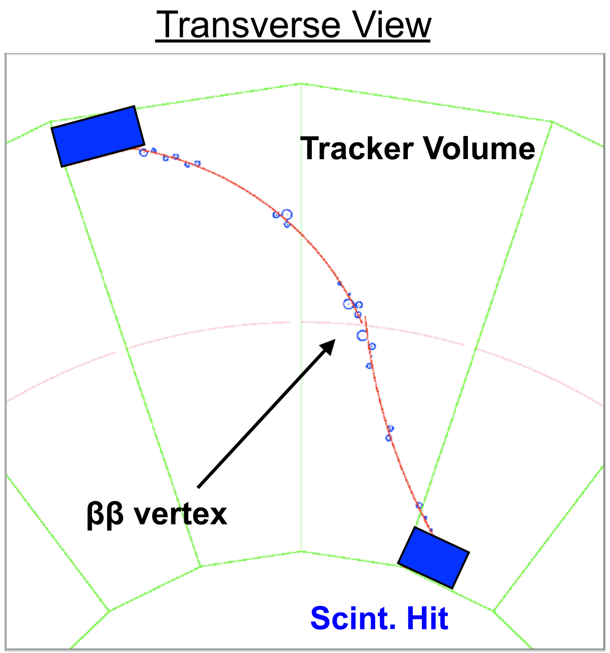
200 tons and ~1000 B
(cf. human body ~ 6000 Bq)

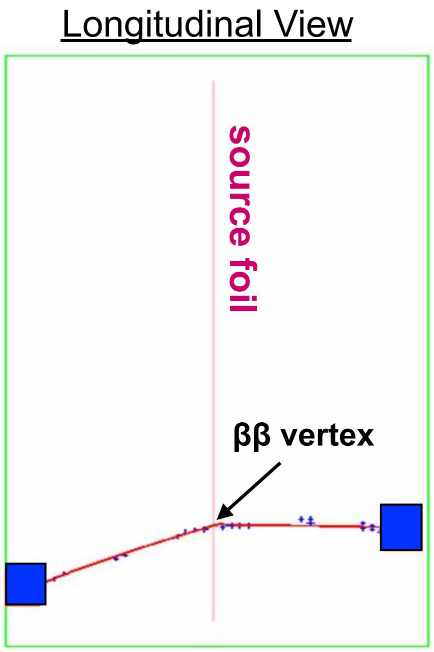
Ran from Feb. 2003 to Jan. 2011



NEMO-3







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

Isotopes

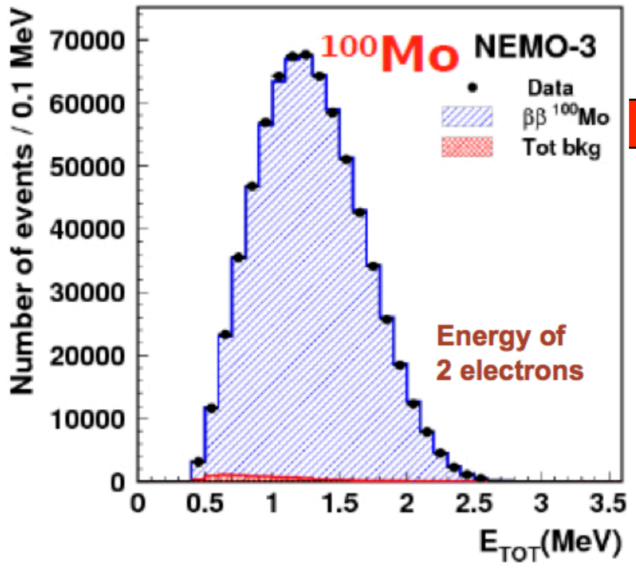
Large quantities: ^{100}Mo (7kg) ^{82}Se (1 kg)

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

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

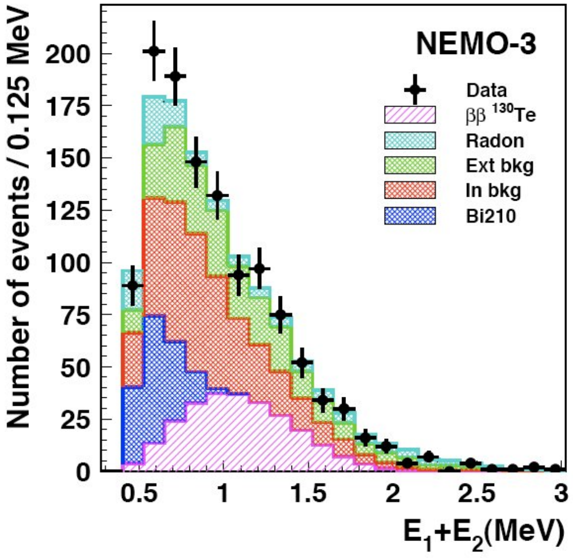
NEMO-3 : Physics Highlights ($2\nu\beta\beta$)

Isotope	mass, g	$Q_{\beta\beta}$ (keV)	$T_{1/2}(2\nu)$ (10^{19} yrs)	Comments
^{100}Mo	6914	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 ! (*ChU)**



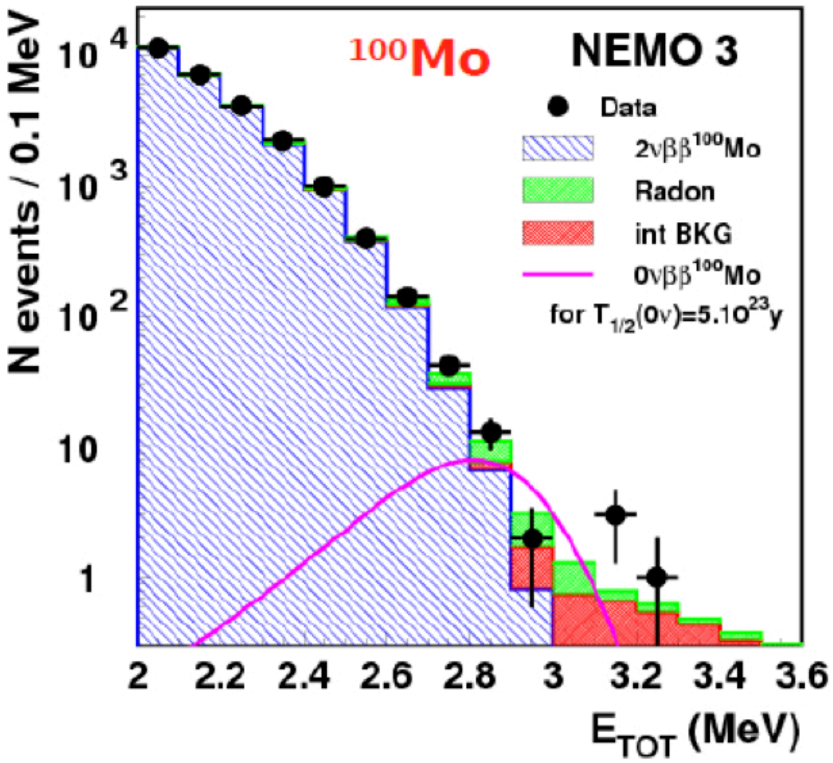
^{100}Mo
>700k 2-electron events
S/B ~ 75
(problem for $0\nu\beta\beta$)

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



NEMO-3 : Physics Highlights ($0\nu\beta\beta$)

^{100}Mo : 7kg × 4.5 years

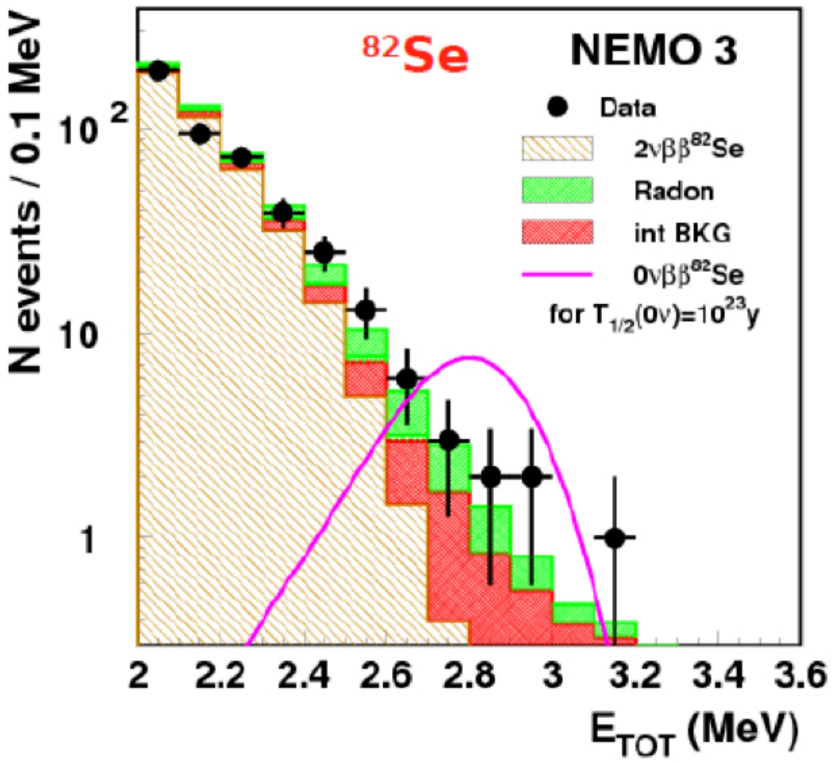


^{100}Mo : 31.5 kg-y

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

$$\langle m_\nu \rangle < (0.31 - 0.96)\ \text{eV}$$

^{82}Se : 1kg × 4.5 years

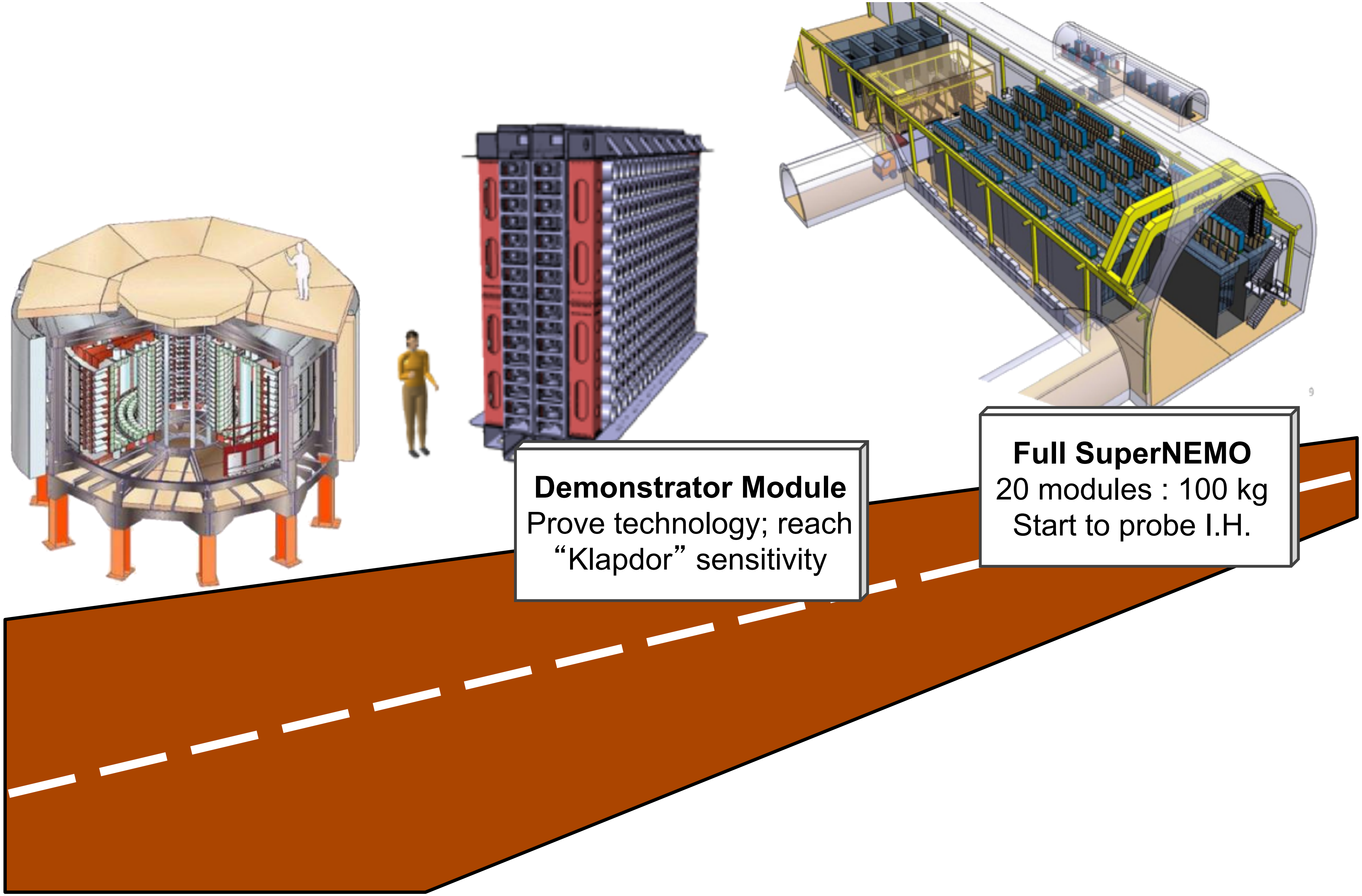


^{82}Se : 4.5 kg-y

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

$$\langle m_\nu \rangle < (0.94 - 2.6)\ \text{eV}$$

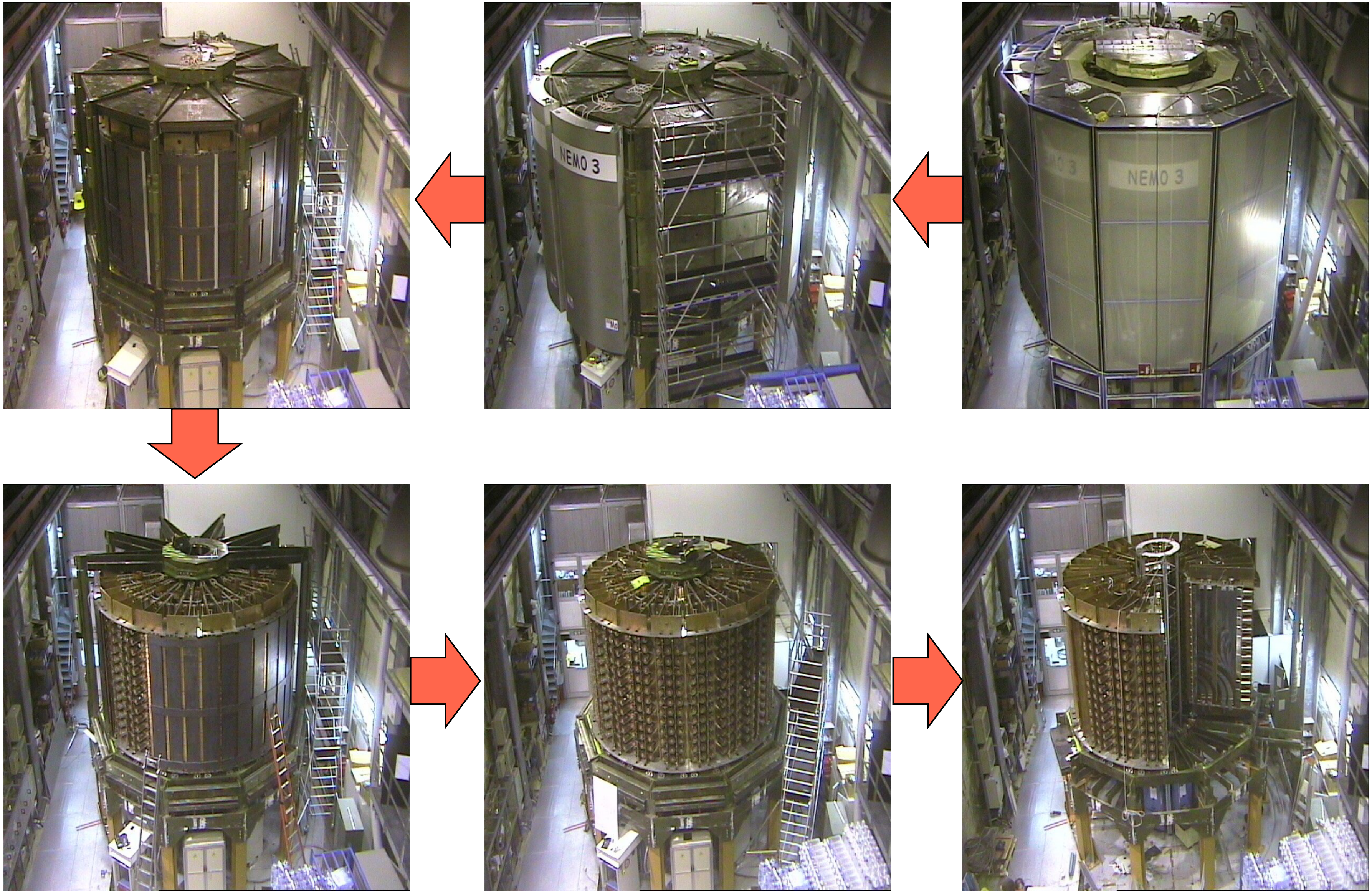
SuperNEMO : Road Map



Demonstrator Module
Prove technology; reach
“Klapdor” sensitivity

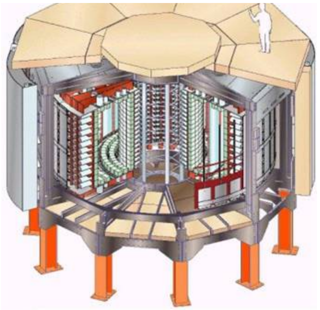
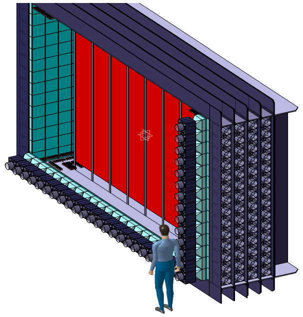
Full SuperNEMO
20 modules : 100 kg
Start to probe I.H.

NEMO-3 Dismantling



NEMO-3 Dismantling

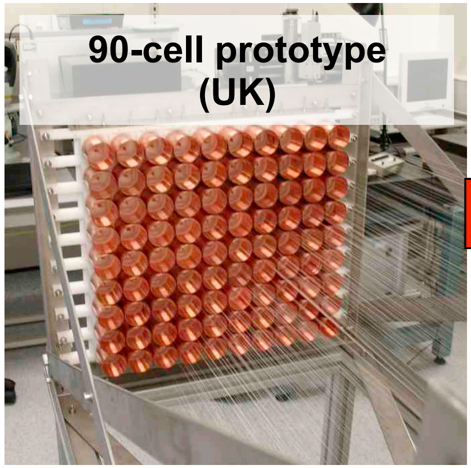
SuperNEMO : How to Get There ?

NEMO-3 		**SuperNEMO** 
^{100}Mo	isotope	^{82}Se or other
7 kg	isotope mass	100 kg
18 %	efficiency	~30 %
^{208}Tl: ~ 100 μBq/kg ^{214}Bi: < 300 μBq/kg Rn: 5 mBq/m^{3}	internal contaminations ^{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
$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{24}$ 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

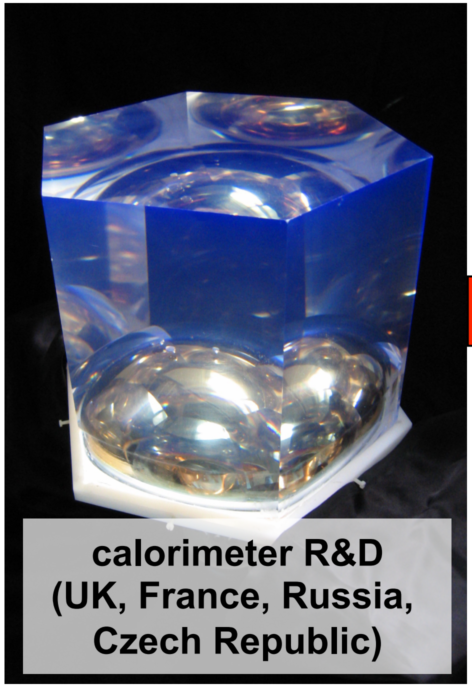
a ***background-free*** experiment

(at least for the demonstrator phase)

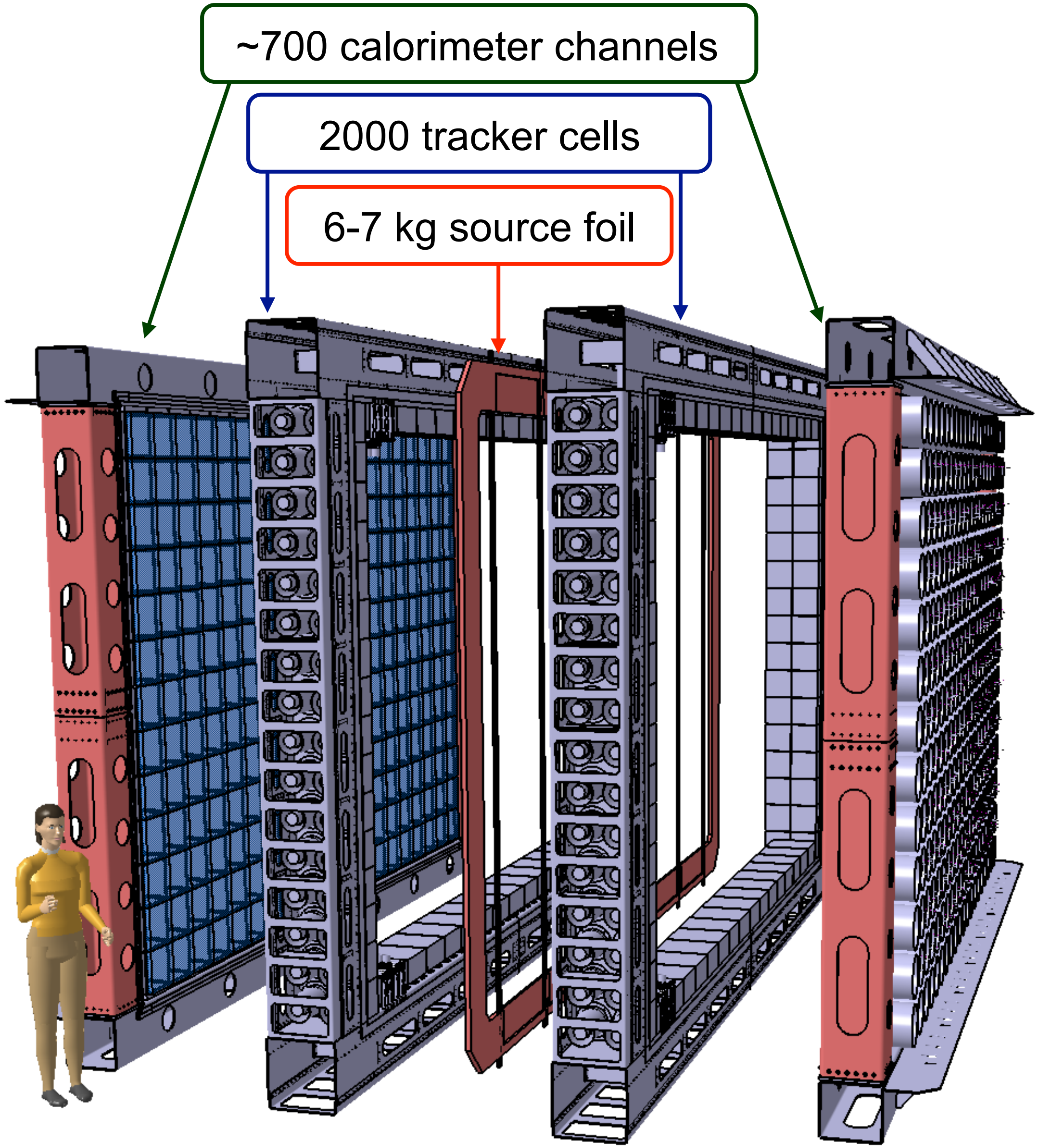
SuperNEMO Demonstrator Module : Overview



90-cell prototype (UK)



calorimeter R&D (UK, France, Russia, Czech Republic)

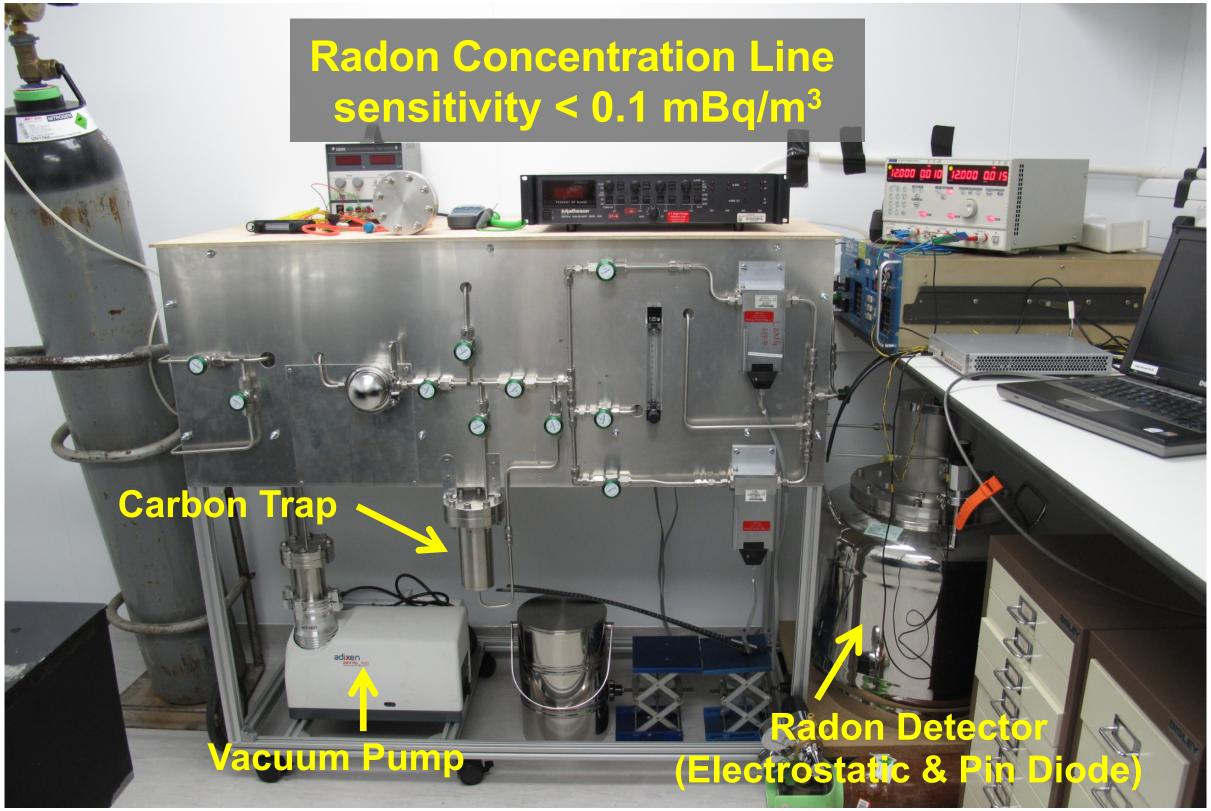


~700 calorimeter channels

2000 tracker cells

6-7 kg source foil

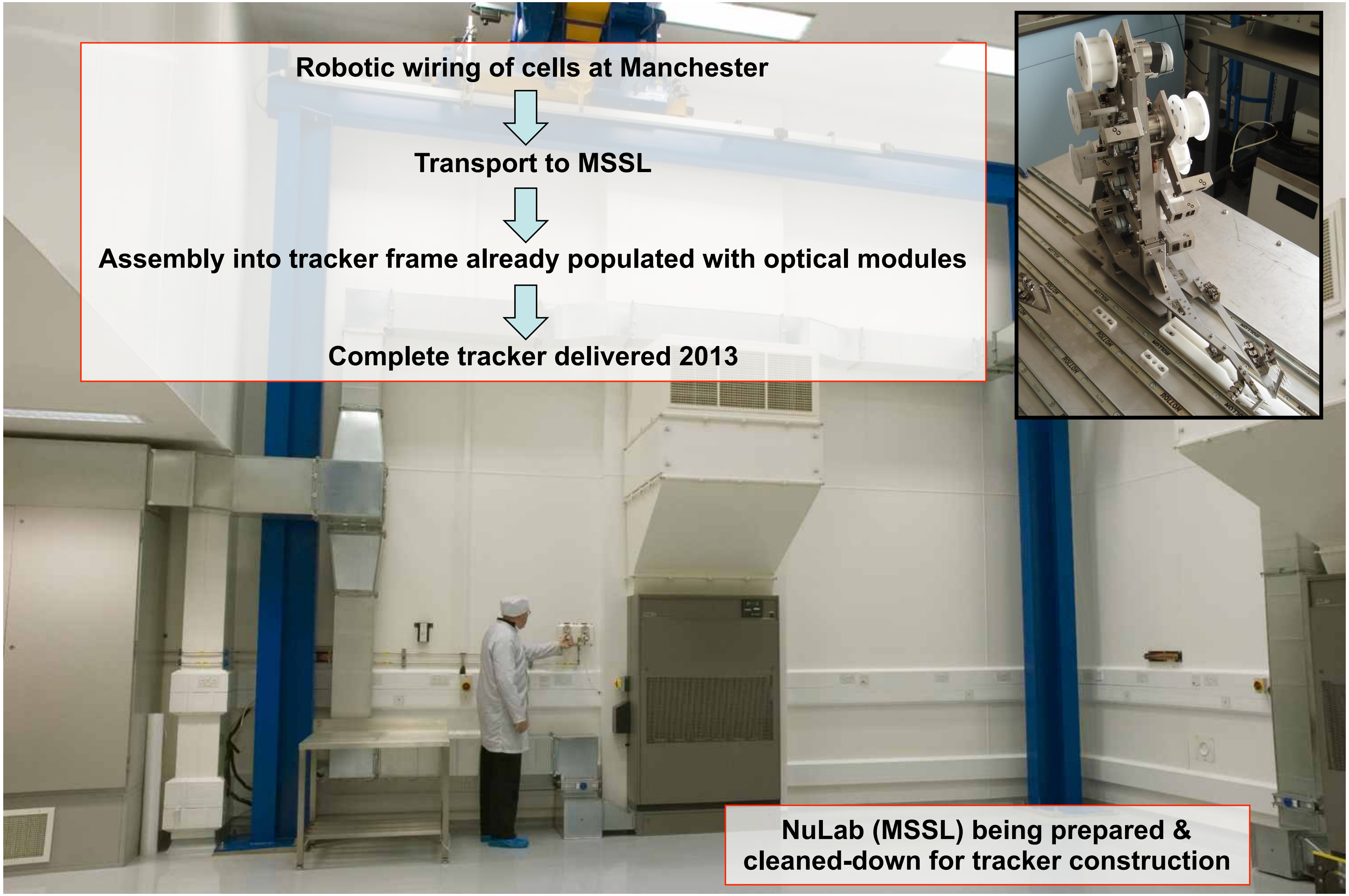
SuperNEMO : Overview of UK Activities



- Construction of robot for highly automated mass production of 2000 tracking cells
- Stainless-steel frame to hold tracker & associated mechanics
- Tracker readout electronics & internal/external cabling
- Software for tracking, simulations.

Imperial College London, Manchester University, UCL, UCL-MSSL, University of Warwick

SuperNEMO : Tracker Assembly



Robotic wiring of cells at Manchester

⇩

Transport to MSSL

⇩

Assembly into tracker frame already populated with optical modules

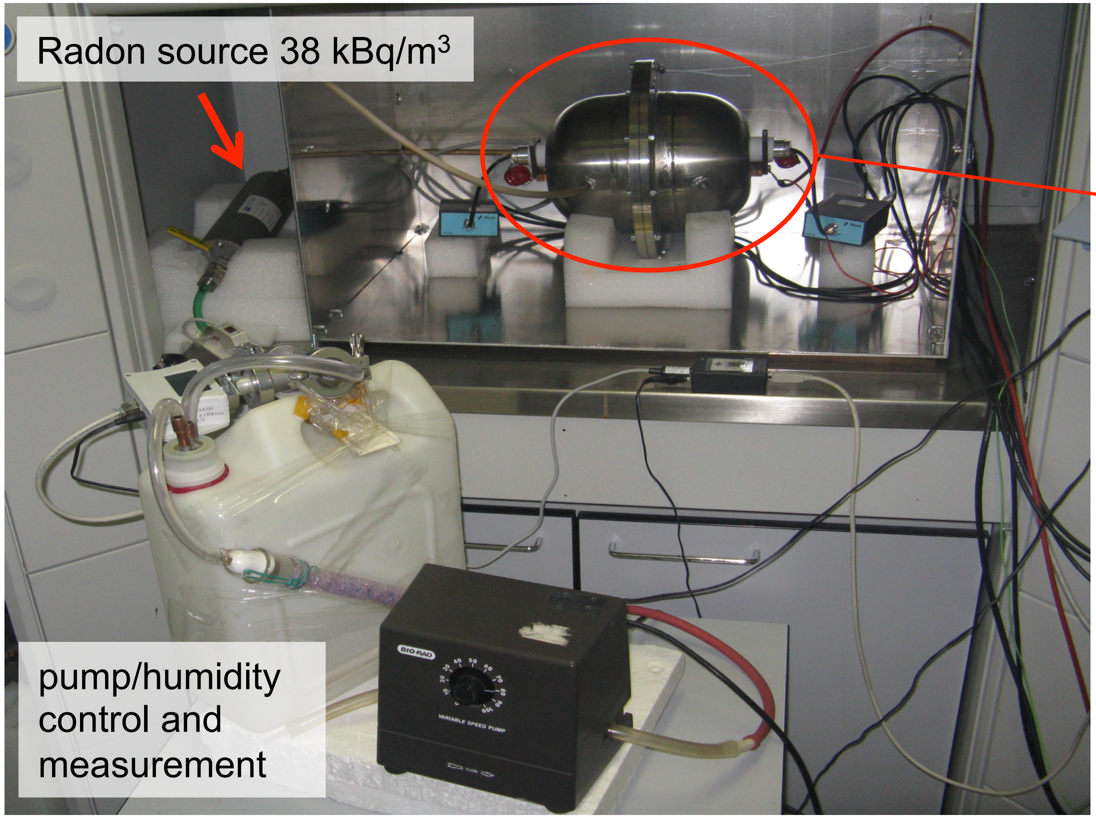
⇩

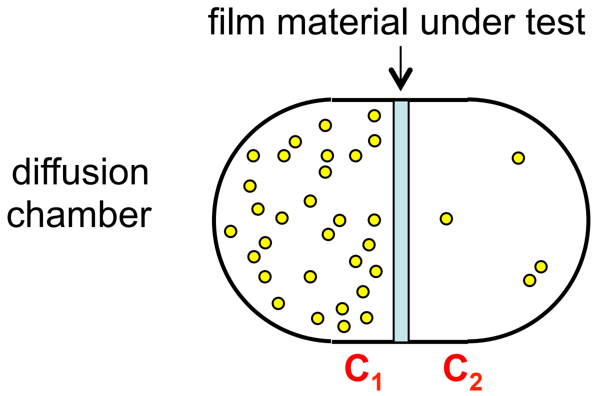
Complete tracker delivered 2013

NuLab (MSSL) being prepared & cleaned-down for tracker construction

SuperNEMO : Radon Diffusion Measurements

Czech Technical University
Institute of Experimental and Applied Physics
Pavel Čermák, Fadahat Mamedov,
Ivan Štekl, Karel Smolek





C_1/C_2 ➔ diffusion coefficient

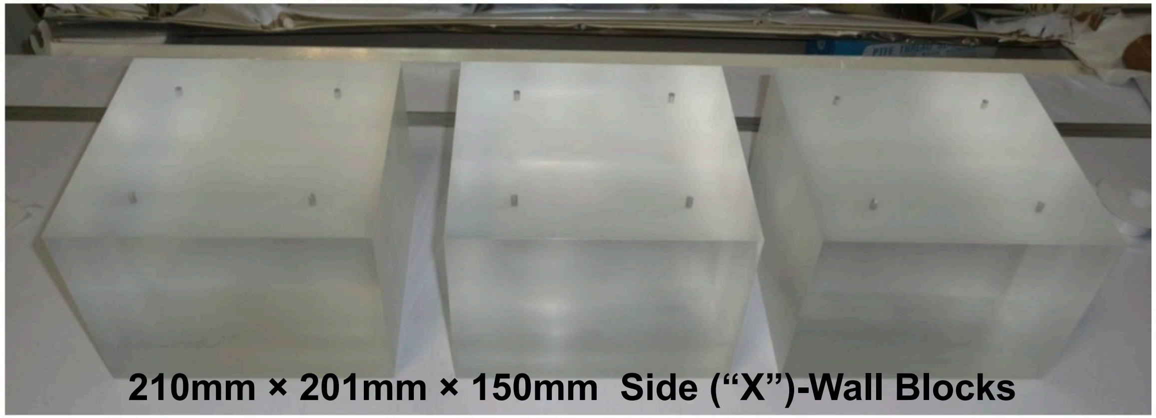
Possible radon seals:

RTV, silicone : $C_1 \sim C_2$ ➔ transparent!

Mylar/Tropac/PVA : $C_1/C_2 \geq\sim 10{,}000$

SuperNEMO : Scintillator Production & Characterisation

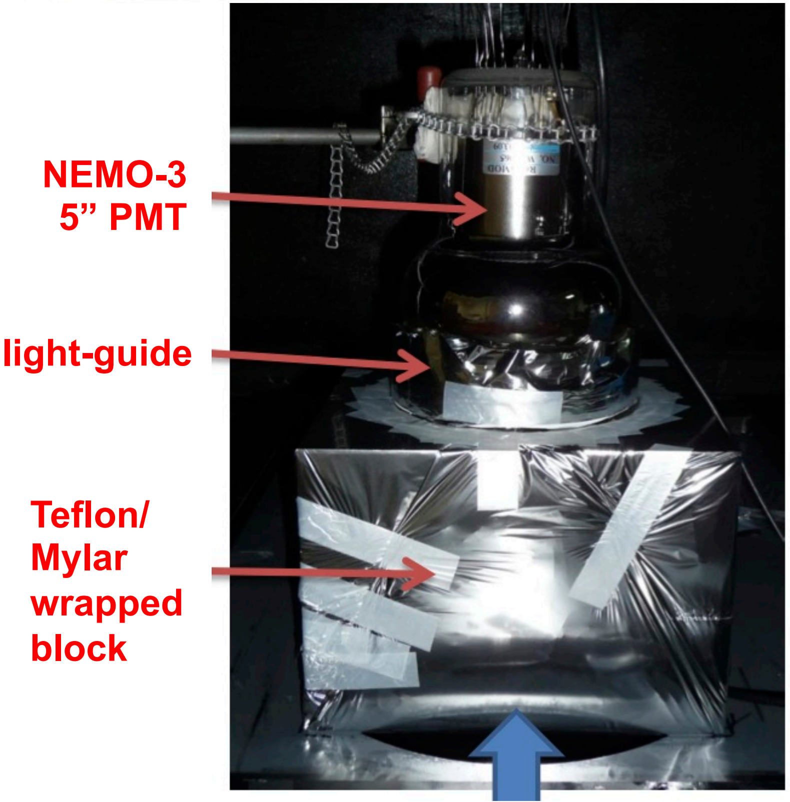
- Production of polystyrene scintillator blocks by Czech company **Envinet**.



210mm × 201mm × 150mm Side (“X”)-Wall Blocks

- It’s critical to measure the resolution and fully characterise each block prior to installation in the tracker frame.

IAEP CzechTechnical University	Ivan Štekl, Fadahat Mamedov
Charles University in Prague	Vít Vorobel, Aivaras Žukauskas
Envinet & JINR	



e$^-$ source (^{207}Bi /spectrometer)

SuperNEMO : Scintillator Production & Characterisation

Facilities under development at Charles University in Prague

Scanning electron spectrometer under development (CTU, Chu, JINR)

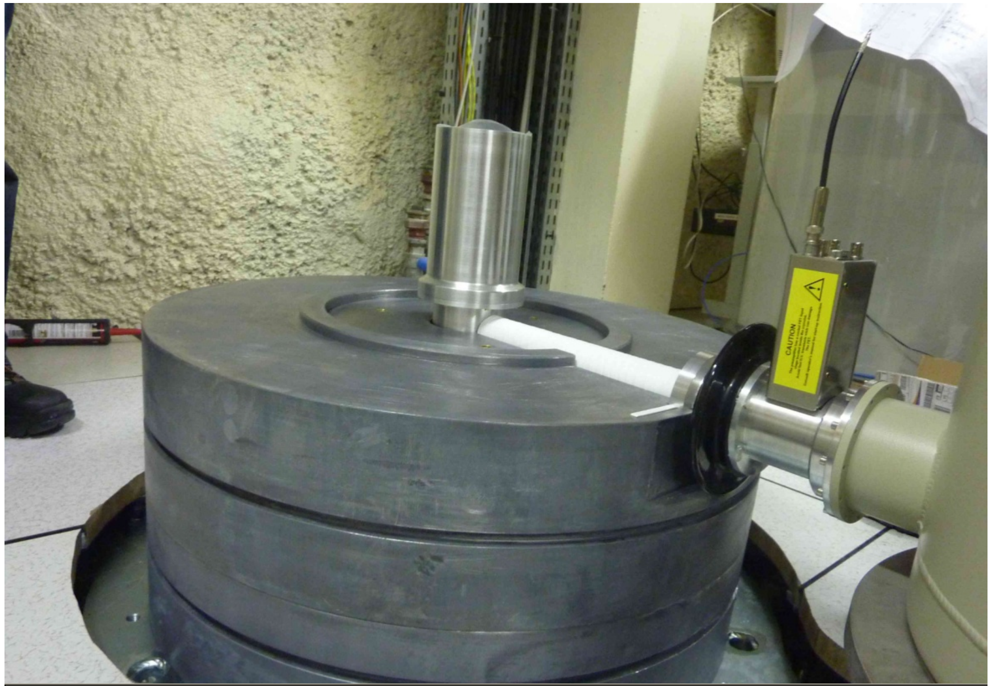
- 370 MBq ^{90}Sr source
- Requires careful setup and cross-calibration

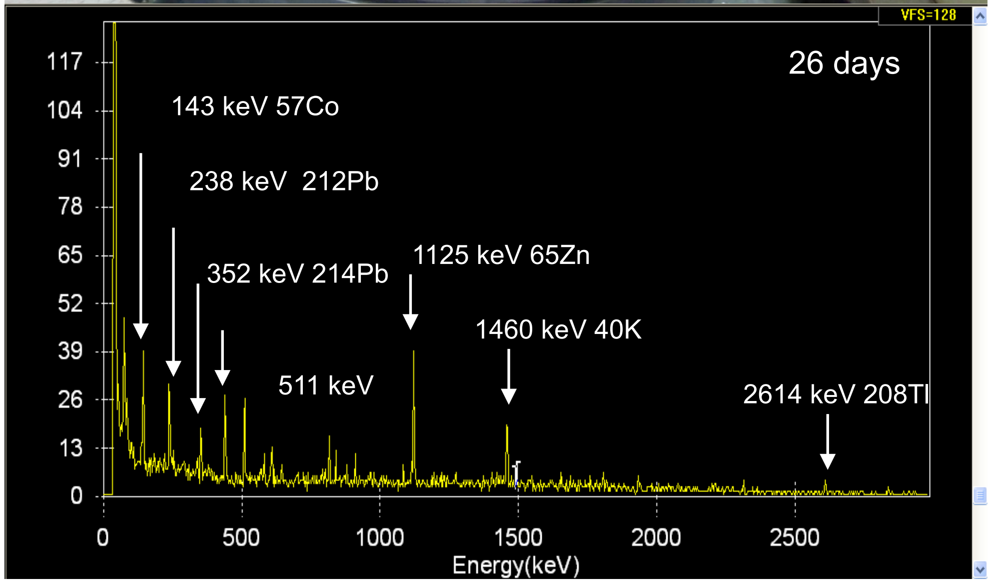
Clean room infrastructure

Minimise contamination during testing

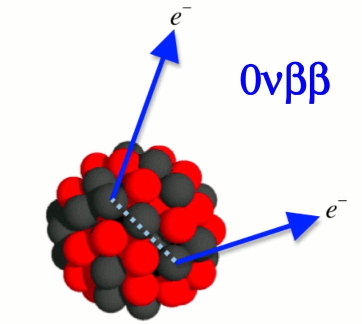
HPGe (IEAP CTU – JINR – LSM)

- 600 cm^3 HPGe detector in LSM
- Tests of ββ sources.
- Selection of pure construction materials - a *major issue* for SuperNEMO construction :
  - 10's of materials need testing
  - If the materials are dirty you know rather quickly, but if they are radio-pure it can take ≥ 1 month per sample.

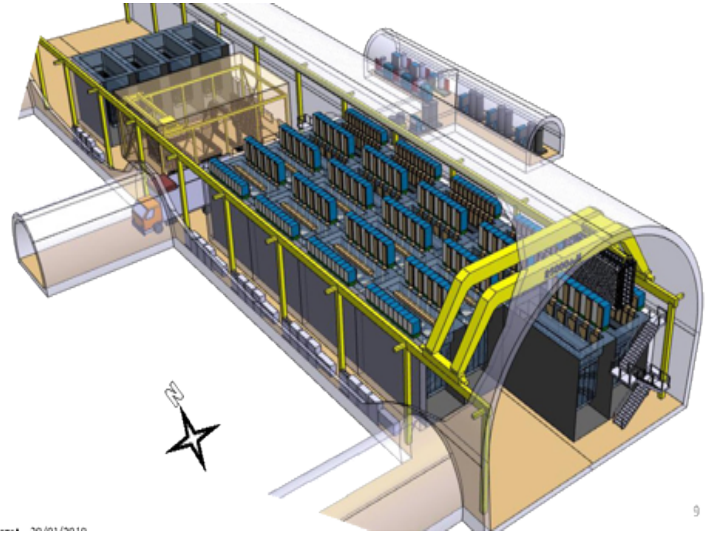




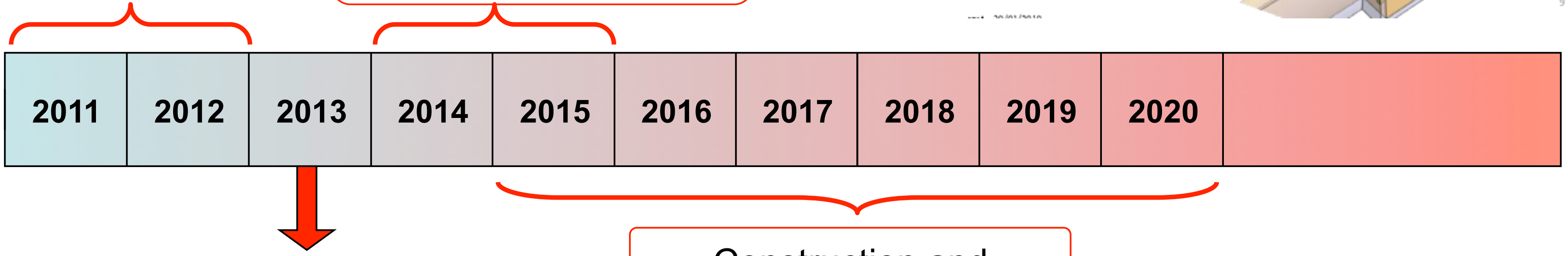
SuperNEMO : Timeline



Demonstrator Module running. “Klapdor” sensitivity end of 2015



Demonstrator Module construction and commissioning



Installation in LSM

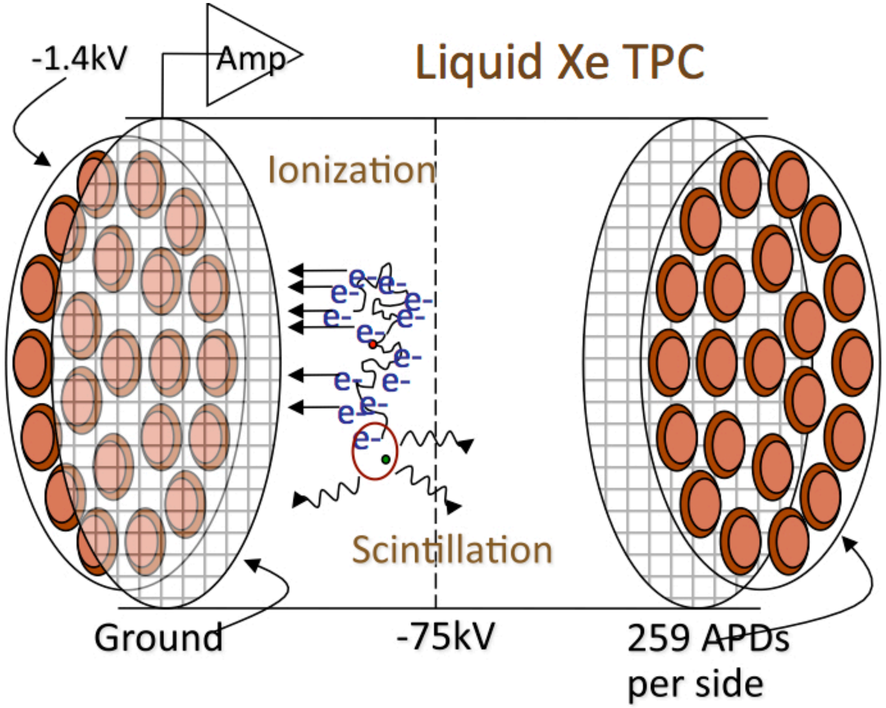
Construction and deployment of successive SuperNEMO modules

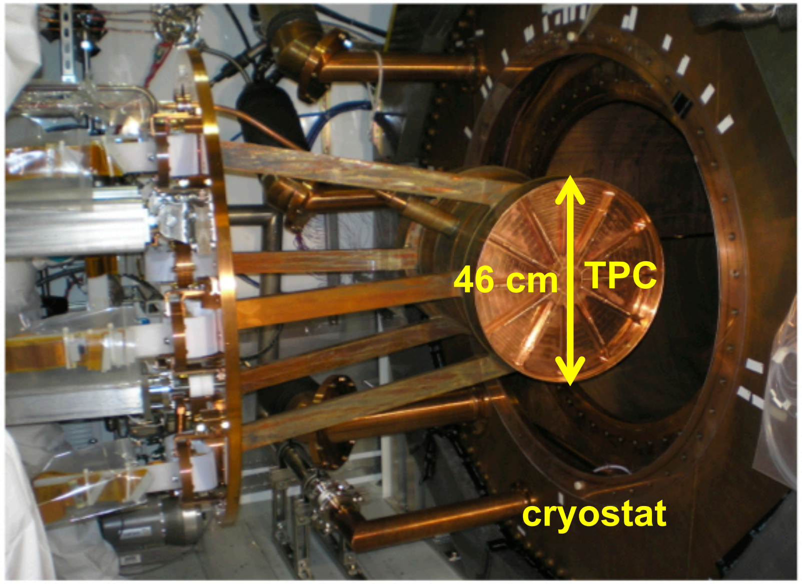
Continuous operation of ≥1 SuperNEMO module

Enriched Xenon Observatory

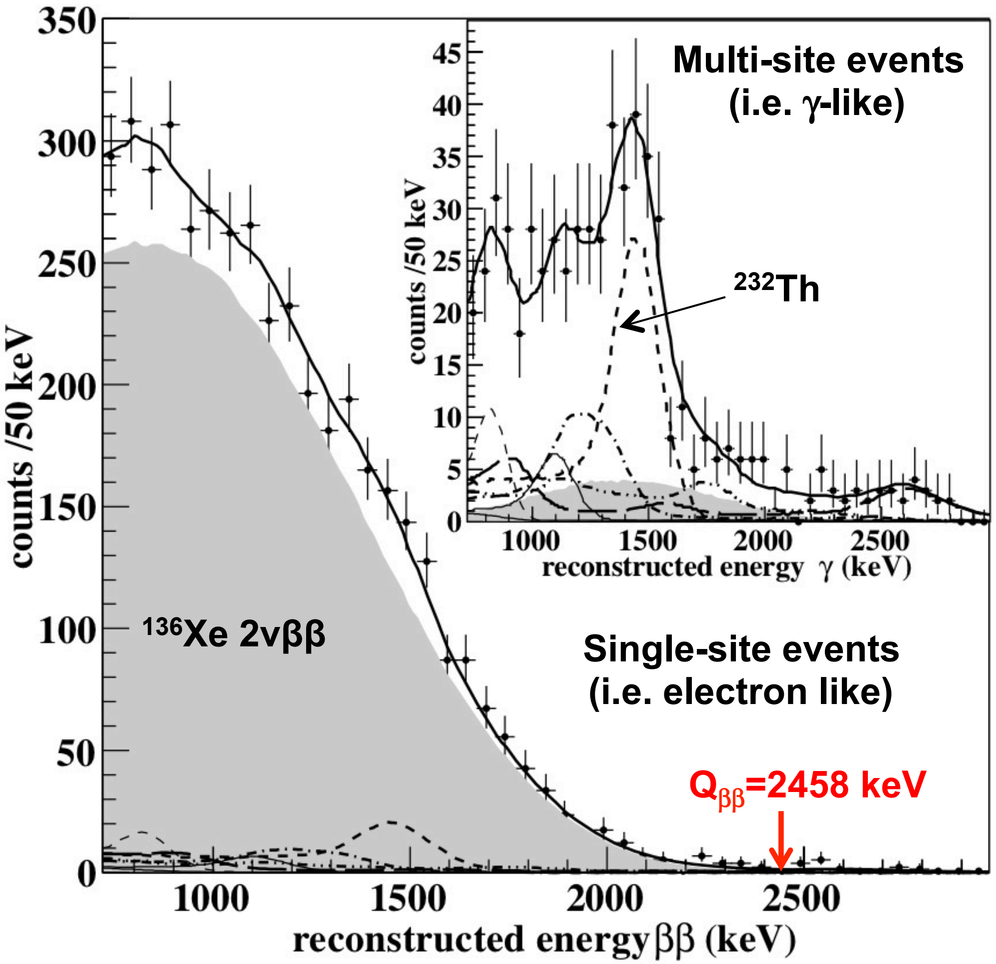
Liquid Xenon Time Projection Chamber

- Xenon enriched to 80.6% in ^{136}Xe
- Scintillation readout t_0 , (E)
- Ionisation readout : t_{drift}, x, y, E
- Energy resolution ~4% : can be further optimised by combining scintillation and ionisation readout.
- No topological event reconstruction but background rejection by fiducialisation and S_{scint}/S_{ion}.





Enriched Xenon Observatory



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

Ackerman et al., arXiv:1108.4193

First Measurement of $T_{1/2}(2\nu\beta\beta)$ in ^{136}Xe

- 752.66 hours of data taking
- Fiducial volume = 63 kg of ^{enr}Xe
- Electron lifetime > maximum drift time
- Calibration : ^{60}Co, ^{228}Th
- Systematics :
  - energy calibration : 1.8%
  - multiplicity assignment : 3.0%
  - fiducialisation : 9.3%
  - backgrounds : 0.6%

- Result is in tension with previous limits but looks very convincing.
- Matrix element (M = 0.019 MeV^{-1}) is the smallest amongst 2νββ emitters.

Future :

- Tagging of daughter ion :

$$^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}^{++} + 2e^{-}$$

- High pressure Xe gas (NEXT)

GERDA

Next-generation ^{76}Ge experiment

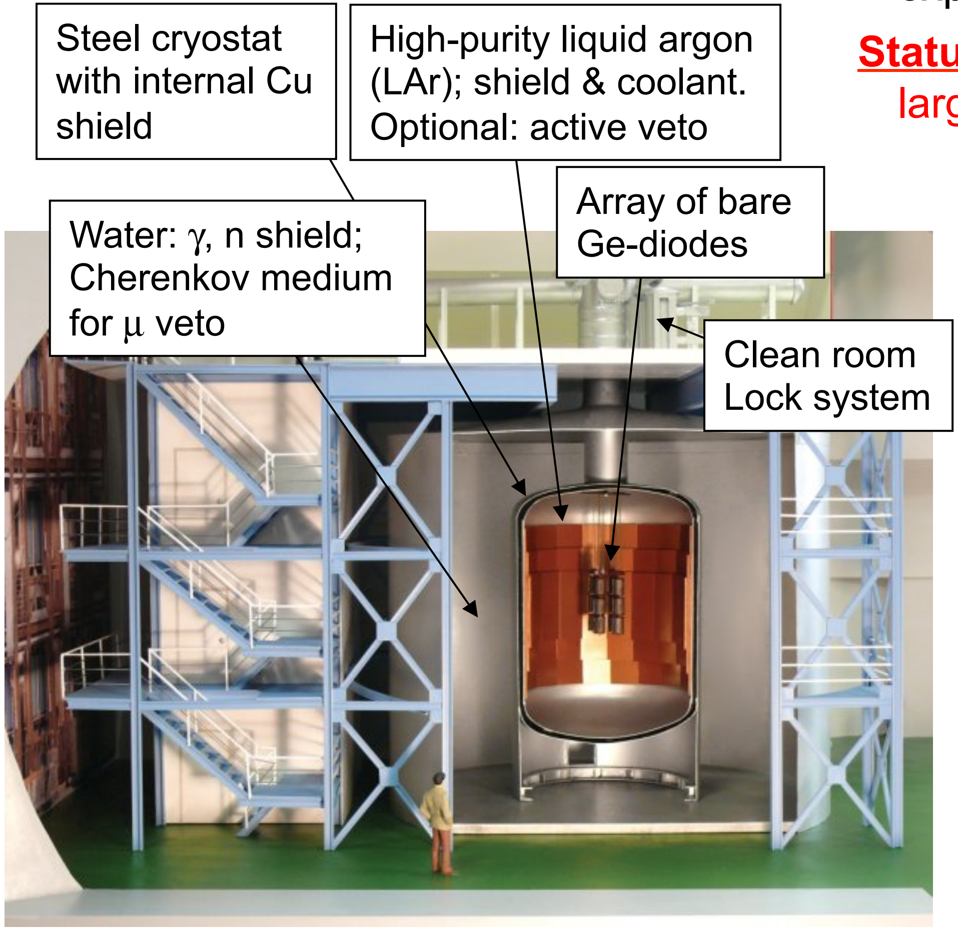
- Best way to directly check **KKDC** claim (no NME uncertainties)
- Location : Gran Sasso

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 : taking data since June 2010. Fighting larger than expected ^{42}Ar-^{42}K background.



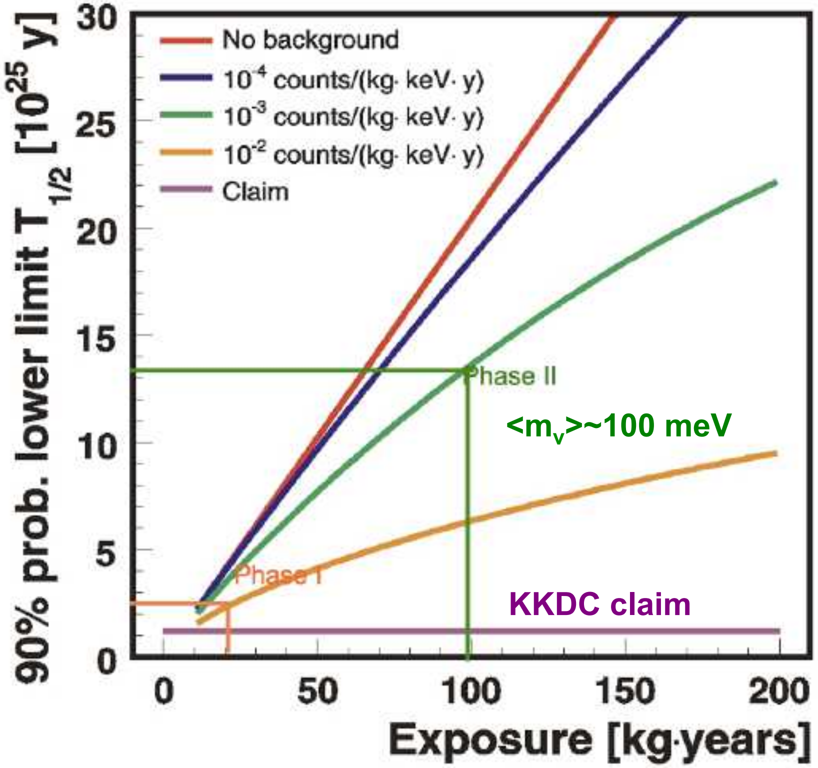
Steel cryostat with internal Cu shield

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

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

Array of bare Ge-diodes

Clean room Lock system

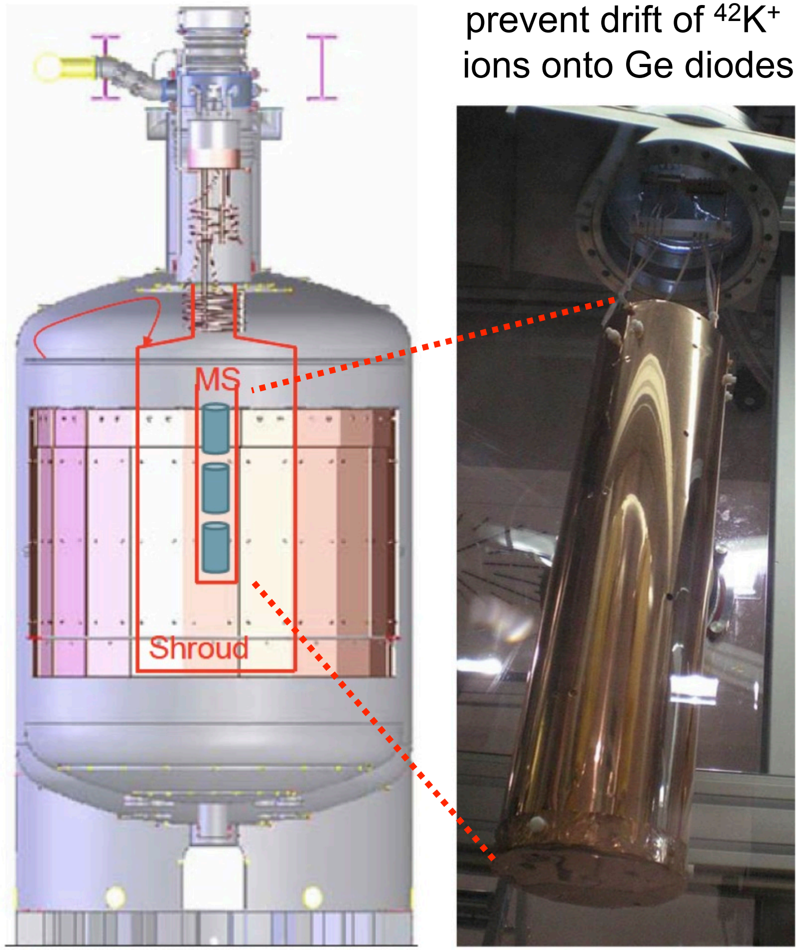


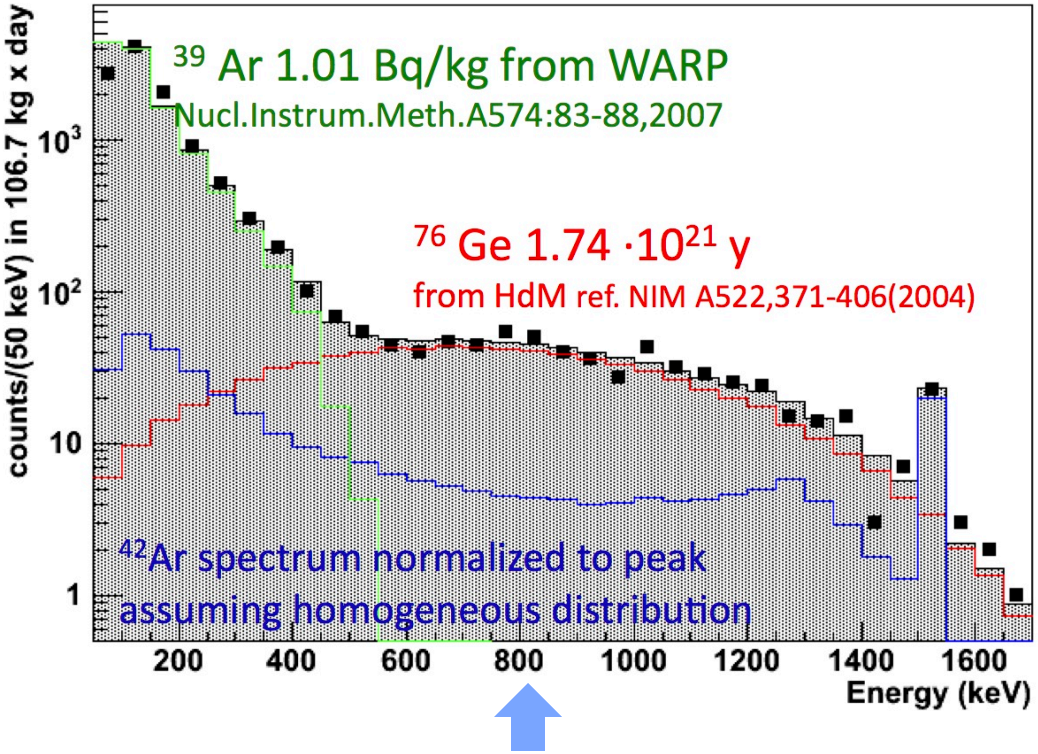
GERDA

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

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

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





First measurement of the $2\nu\beta\beta$ spectrum in GERDA string

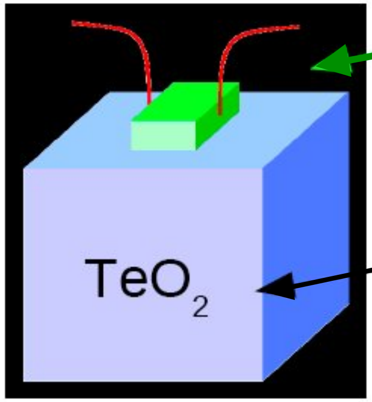
Next-steps :

- 2011 : start Phase 1 data-taking with 3 strings.
- BEGe detectors with better resolution and pulse-shape discrimination.
- Several handles on background remain.

CUORICINO

^{130}Te Bolometer Experiment

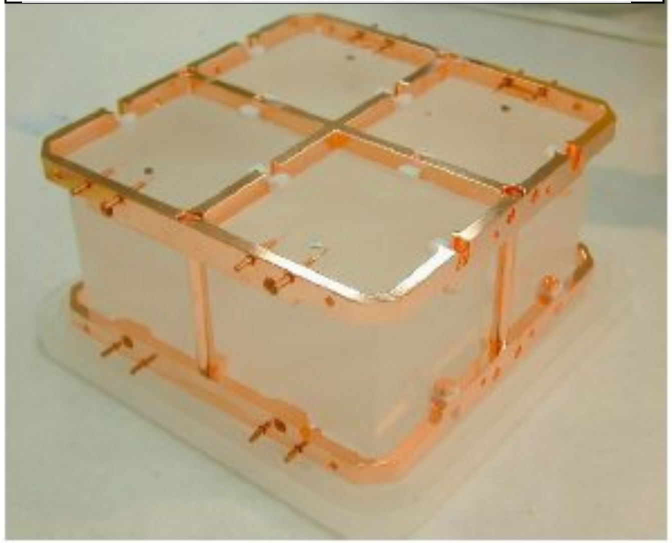
- ^{130}Te has high natural abundance (34%) (no enrichment necessary)
- TeO_2 crystals have low heat capacity, high intrinsic radio-purity.
- Operated at 8-10 mK

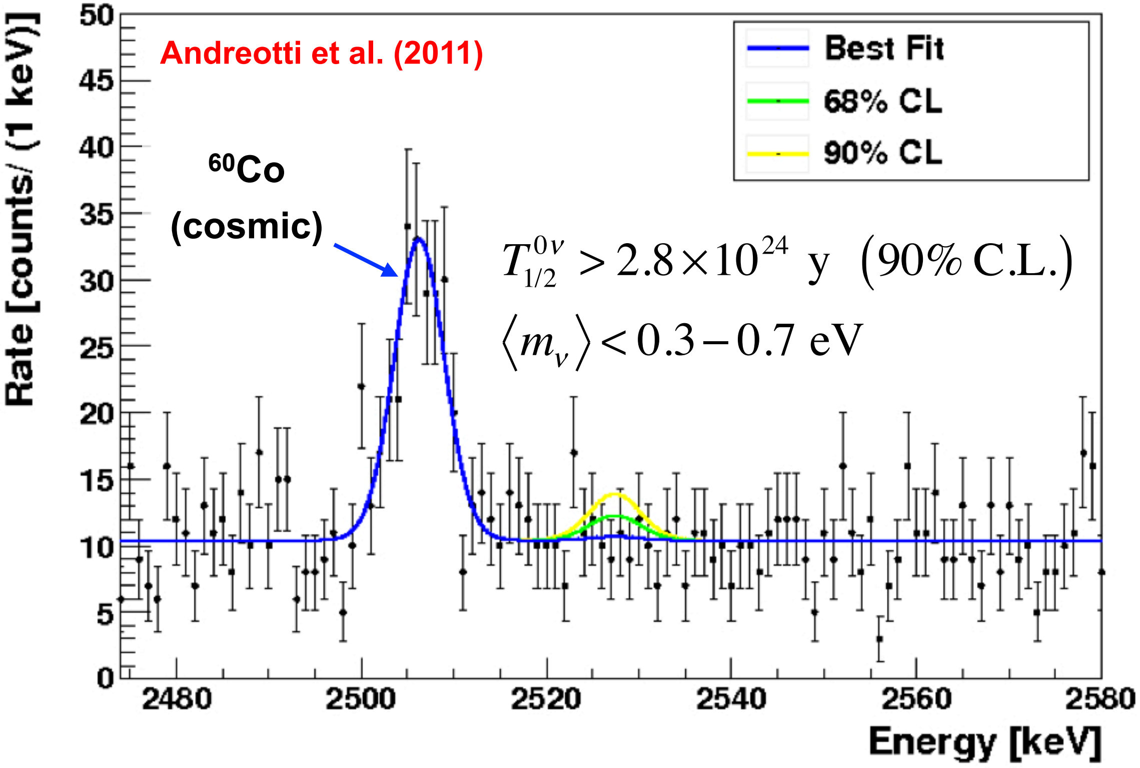


Temperature Sensor :
NTD Thermistor

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

Single-Module (× 13)
11.3 kg ^{130}Te total





$$T_{1/2}^{0\nu} > 2.8\times10^{24}\ \mathrm{y}\ \ (90\%\ \mathrm{C.L.})$$
$$\langle m_\nu \rangle < 0.3-0.7\ \mathrm{eV}$$

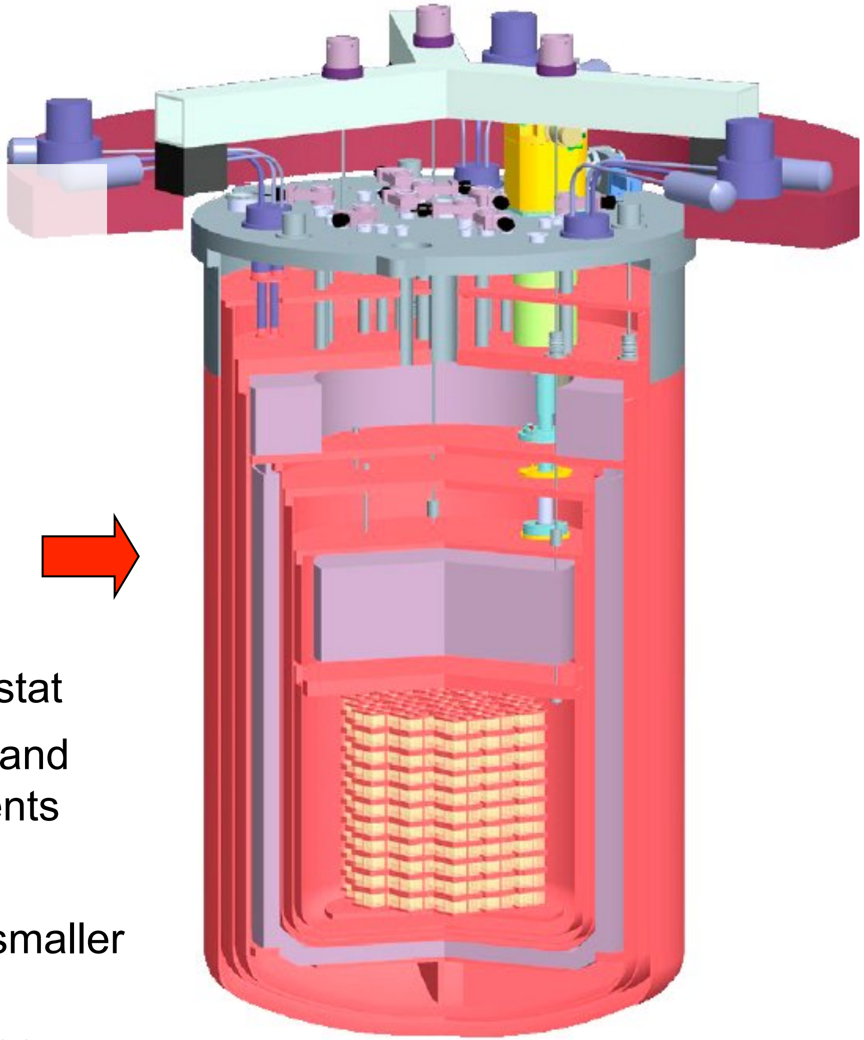
CUORE

CUORE-0

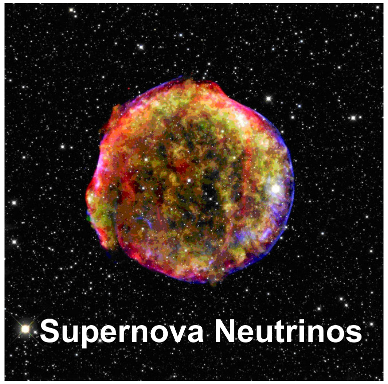
- 2011-2014
- ~11 kg ^{130}Te

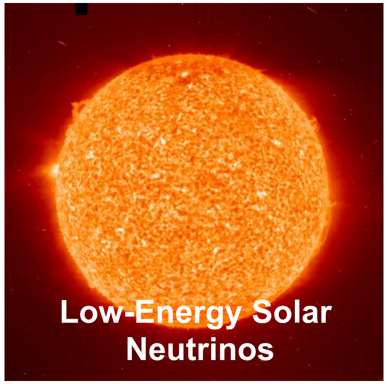
CUORE

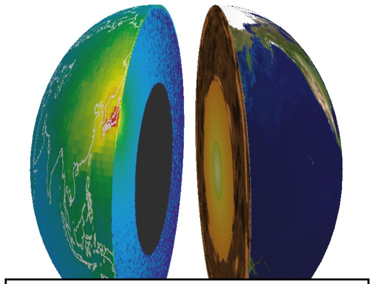
- 2013-2018
- 19 towers in new cryostat
- Many (self-) shielding and radiopurity improvements
- ~200 kg ^{130}Te
- Backgrounds 10-100 smaller than CUORICINO
- 5 years : $<m_\nu>$ ~ 40-100 meV

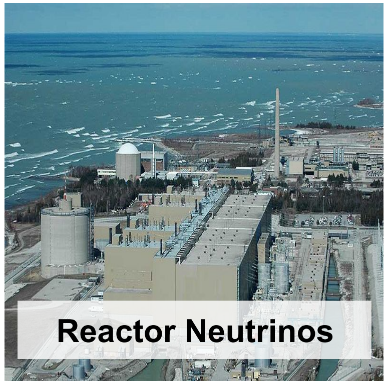


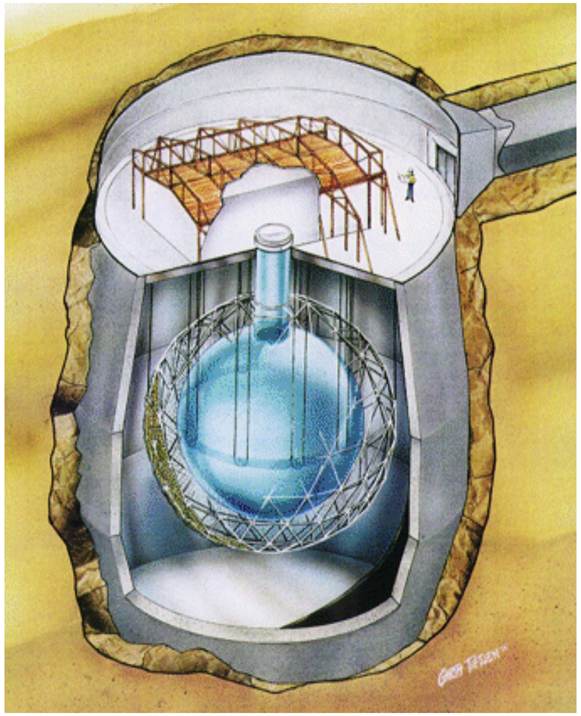
SNO+

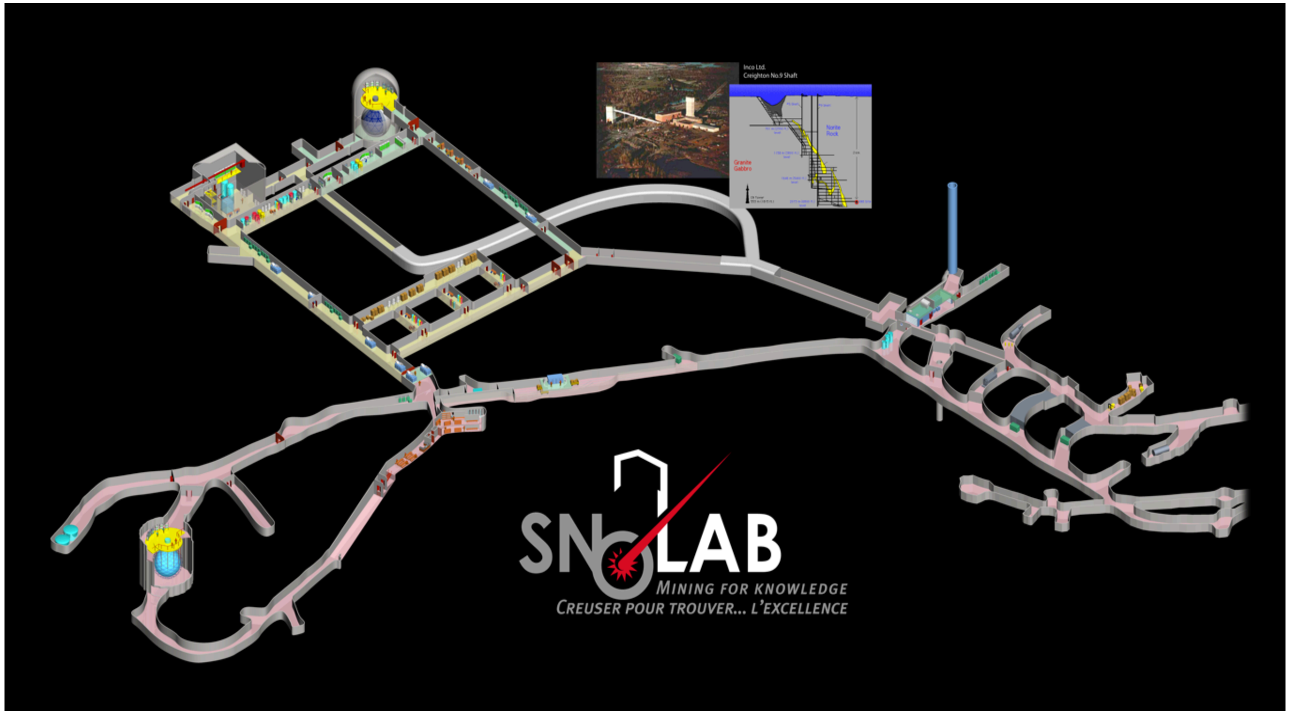

Supernova Neutrinos


Low-Energy Solar Neutrinos

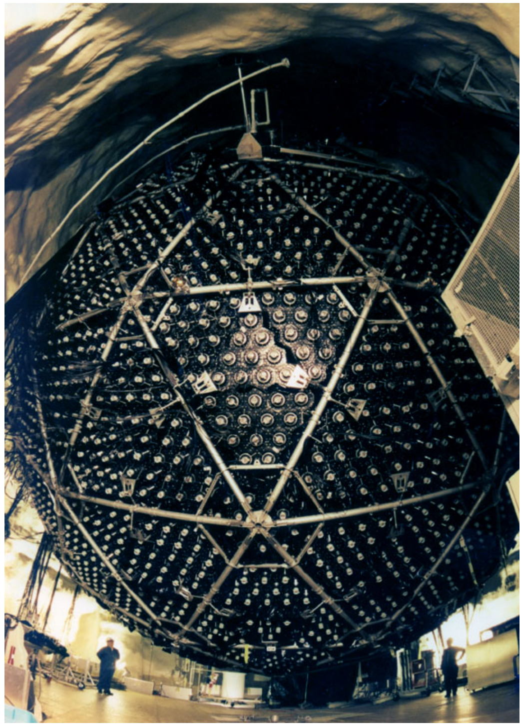

Geo-Neutrinos


Reactor Neutrinos

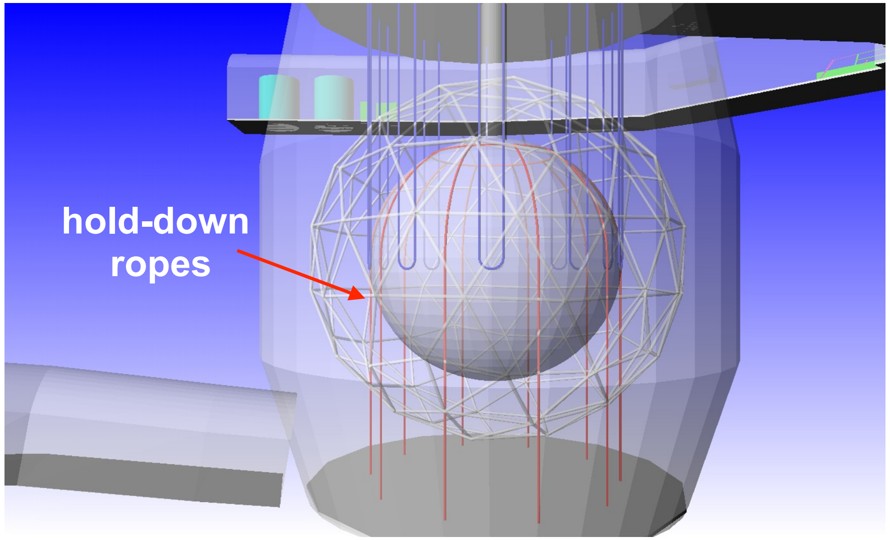




SNO+ : Basic Idea



- Re-use the existing SNO detector, which ceased heavy-water operation in 2006.
- Fill the acrylic vessel with 800 tonnes of liquid scintillator, loaded with ^{150}Nd :
  - **L**inear **A**lkyl-**B**enzene + 2g/litre PPO fluor.
  - Hold-*down* the LAB rather than hold-*up* the D_2O
  - Development of techniques to achieve ultra-high radiopurity of both liquid scintillator and $0\nu\beta\beta$ source.
  - Cleaning (anti-radon), refurbished electronics & DAQ.
  - New calibration systems.



SNO+ : Double-Beta Decay

Isotope Choice : ^{150}Nd

✓ Large $Q_{\beta\beta}$= 3.4 MeV - above most radioactive backgrounds

✓ Very large phase space : 30 times larger than ^{76}Ge

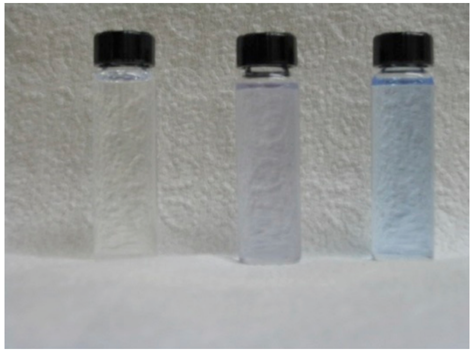
✓ Chemistry compatible with dissolution in LAB

✓ Reasonably transparent to scintillation light

✓ Cheap !

✗ Natural abundance is low ~ 5.6%

✗ Difficult to enrich



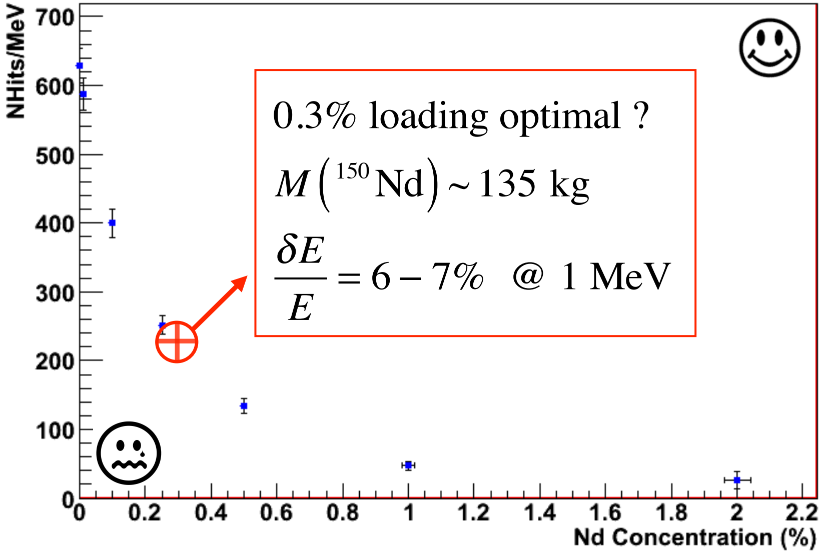
Radiopurity Requirements

✗ Extremely stringent : **< 10^{-17}g ^{228}Ra/^{228}Th per g scintillator**.

✗ The isotope compound ($NdCl_3$) must also be very radio-pure : **< 10^{-14}g ^{228}Ra/^{228}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.

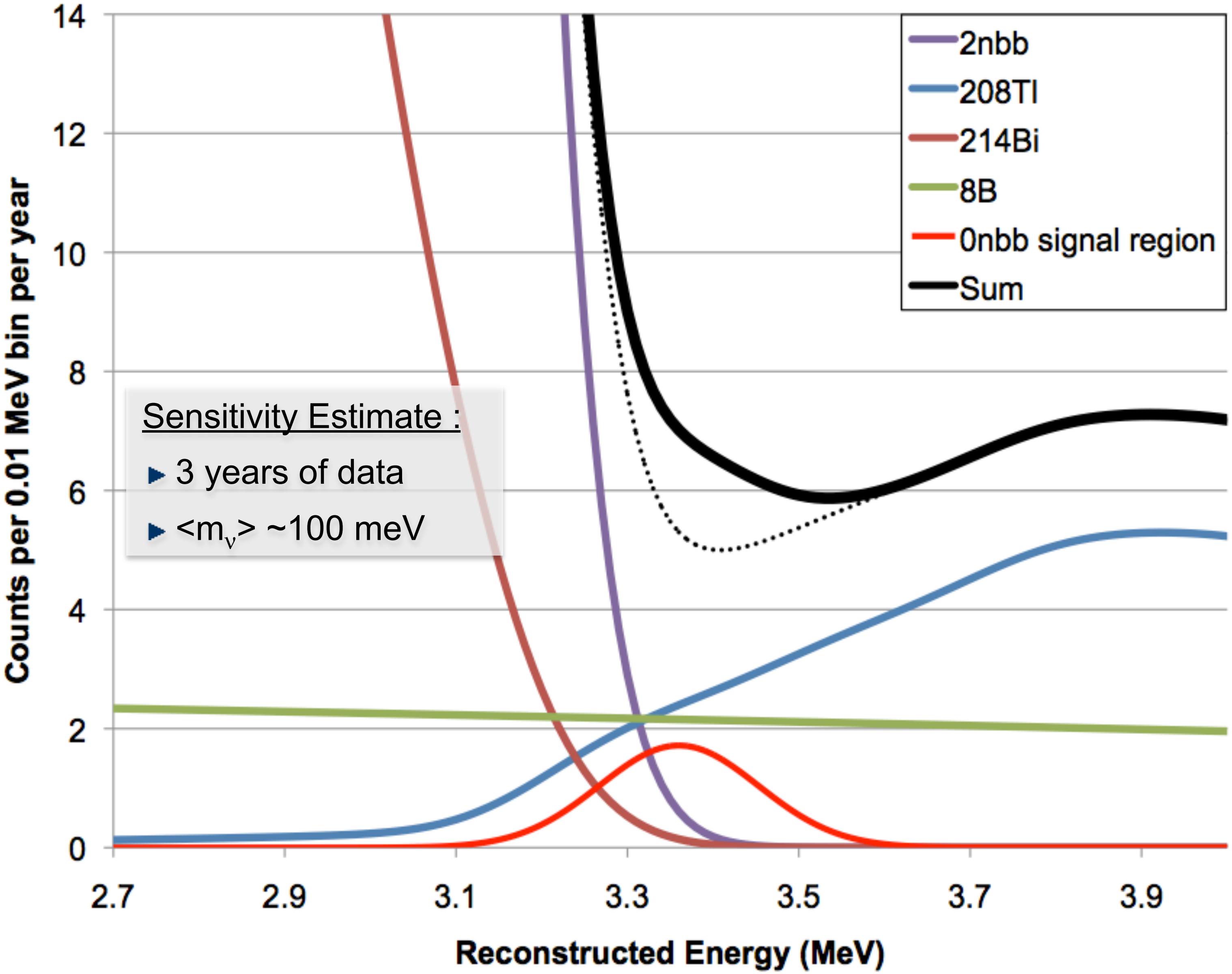


0.3% loading optimal ?

$M\left({}^{150}\mathrm{Nd}\right) \sim 135$ kg

$\frac{\delta E}{E} = 6 - 7\% \quad @ \ 1$ MeV

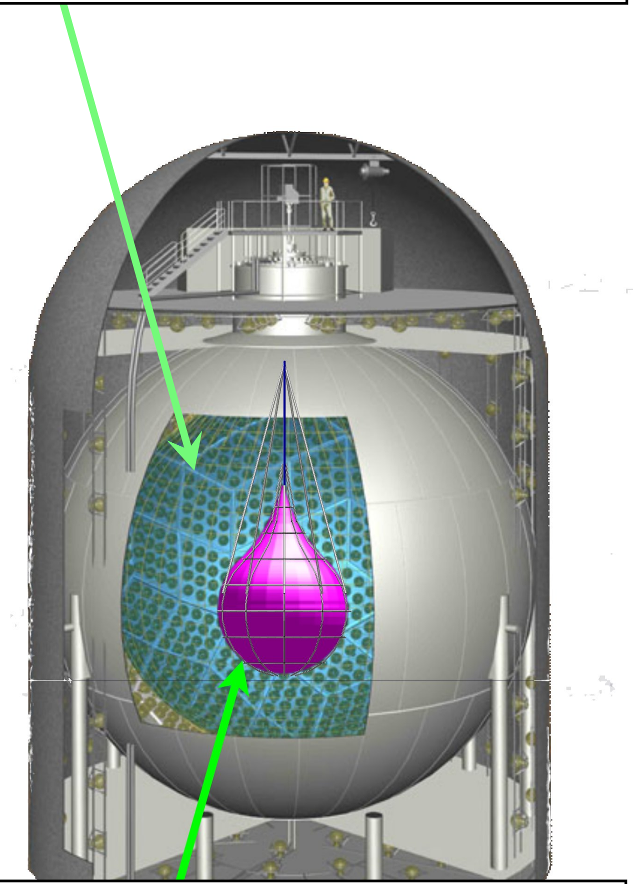
SNO+ : $0\nu\beta\beta$ Prospects



Sensitivity Estimate :

- 3 years of data
- $\langle m_\nu \rangle$ ~100 meV

KamLAND-Zen



Existing KamLAND LS and shielding

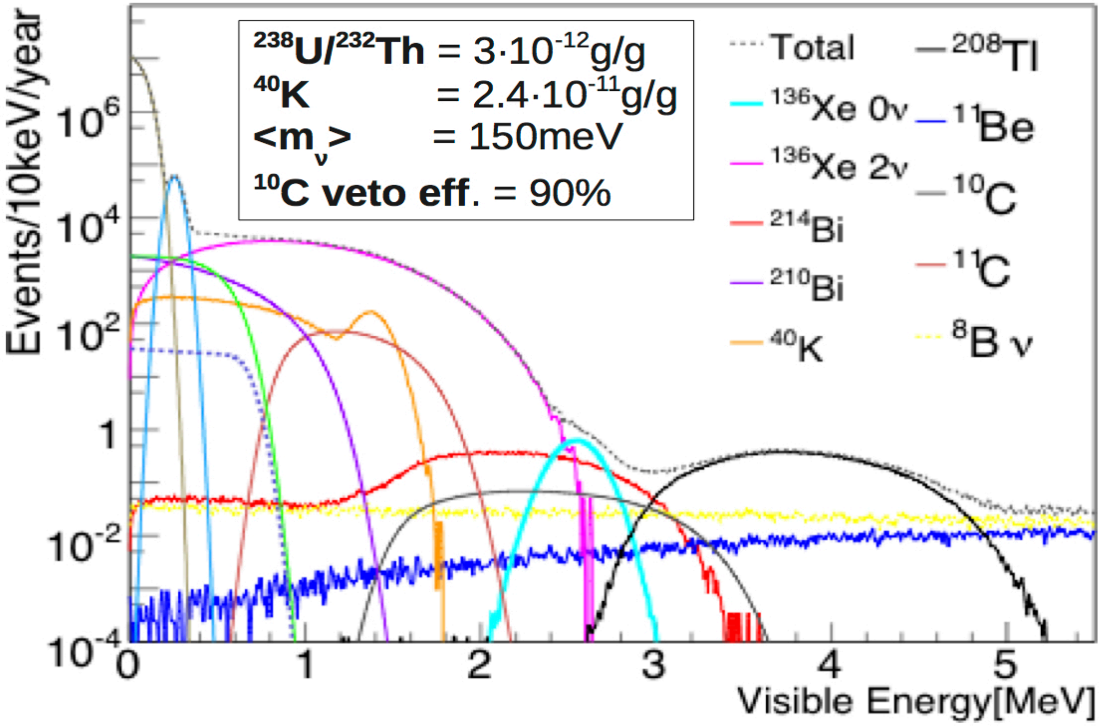
400 kg ^{136}Xe loaded LS mini-balloon, R=1.7m
Density well matched to outer LS

25µm Nylon balloon under test

Expected performance :

$$\sigma_E = 6.8\%/\sqrt{E}\,(\mathrm{MeV})$$

- Sophisticated cosmogenic rejection.
- Start probing I.H. after few years.
- Scalable ?



Double Electron-Capture : Experimental Signature

Neutrinoless Mode

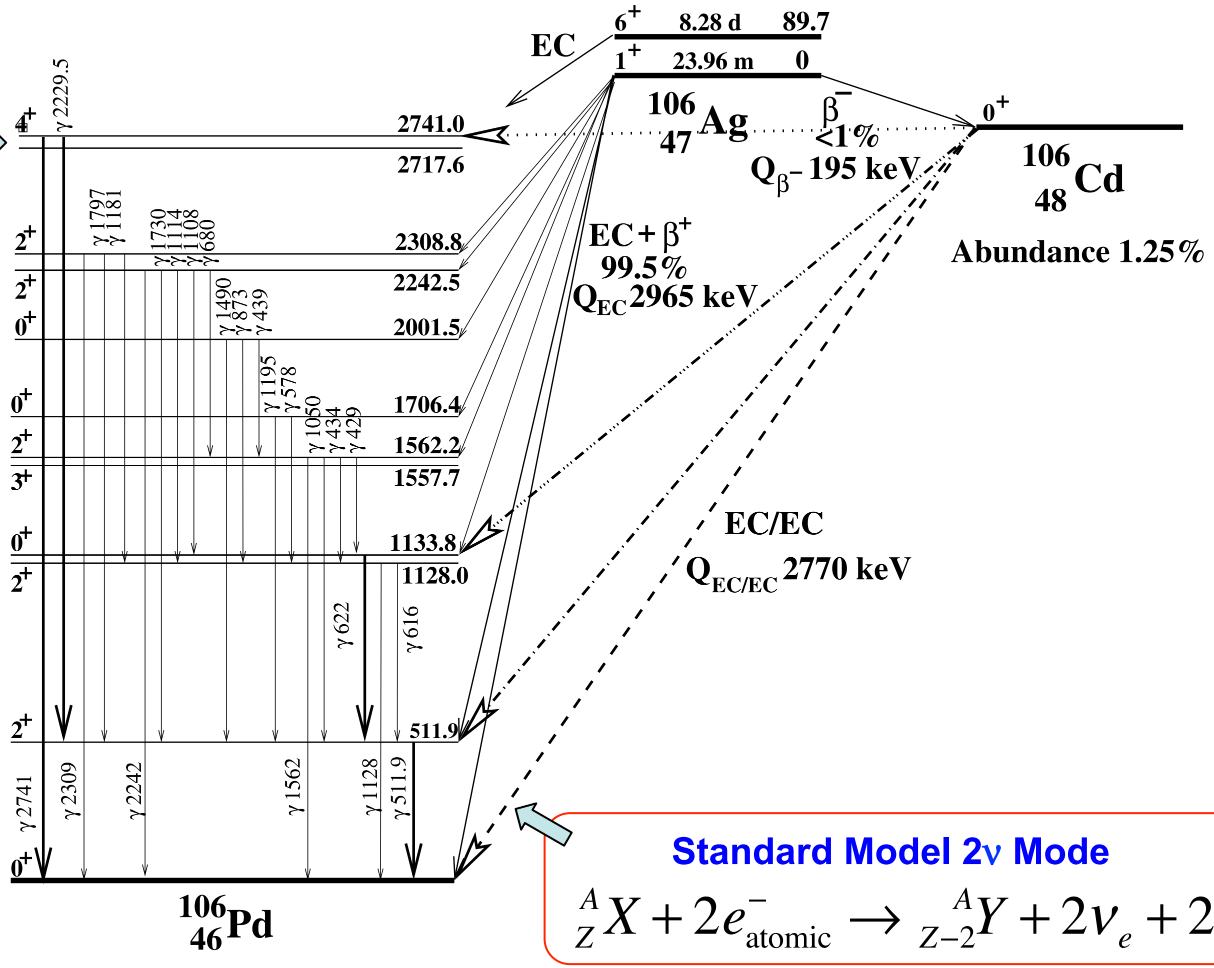
$$ {}^{A}_{Z}X + 2e^{-}_{\text{bound}} \rightarrow {}^{A}_{Z-2}Y^{*} + 2x $$

Decay of excited daughter nucleus:

$$ \Sigma E_{\gamma} = \Delta M_{X,Y} - \varepsilon_1 - \varepsilon_2 $$

Resonance condition :

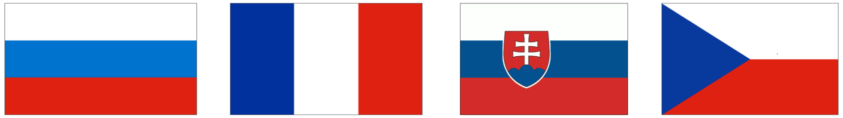
$$ \Delta M_{X,Y} - \varepsilon_1 - \varepsilon_2 \approx E\left(Y^{*}\right) $$



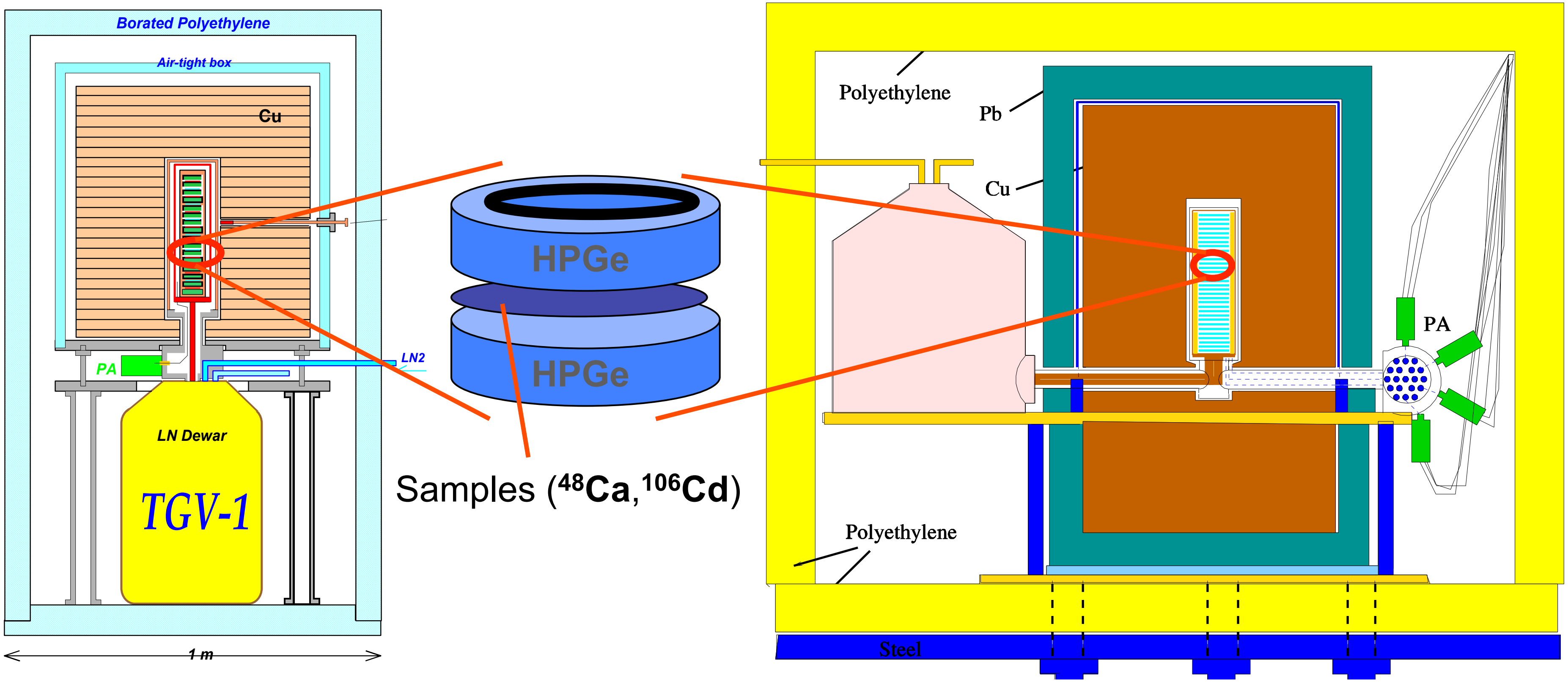
Standard Model 2ν Mode

$$ {}^{A}_{Z}X + 2e^{-}_{\text{atomic}} \rightarrow {}^{A}_{Z-2}Y + 2\nu_e + 2x $$

Telescope Germanium Vertical Array



Czech Technical University (Ivan Štekl)



TGV I (1996-200)

1.08g of ^{48}**Ca** (nat➔78% enrich.)

16 × HPGe [1200mm^2×6mm]

$$T_{1/2}^{2\nu\beta\beta}\left({}^{48}\mathrm{Ca}\right) = \left(4.2\,^{+3.3}_{-1.3}\right)\times 10^{19}\ \mathrm{yr}$$

PLB 495 (2000) 63

TGV II (2004-2010)

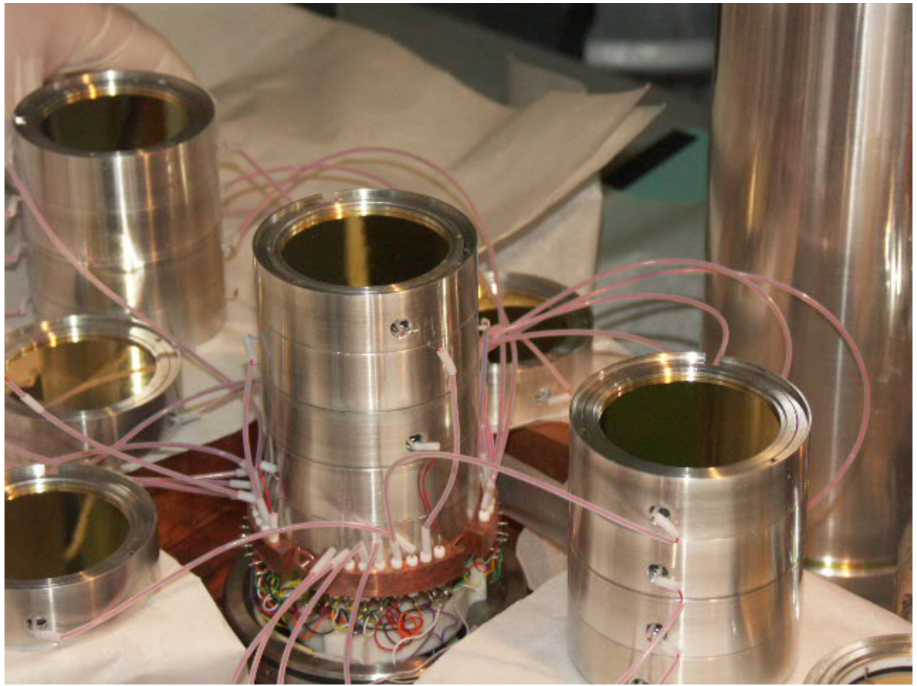
13.6g of ^{106}**Cd** (75% enrich.)

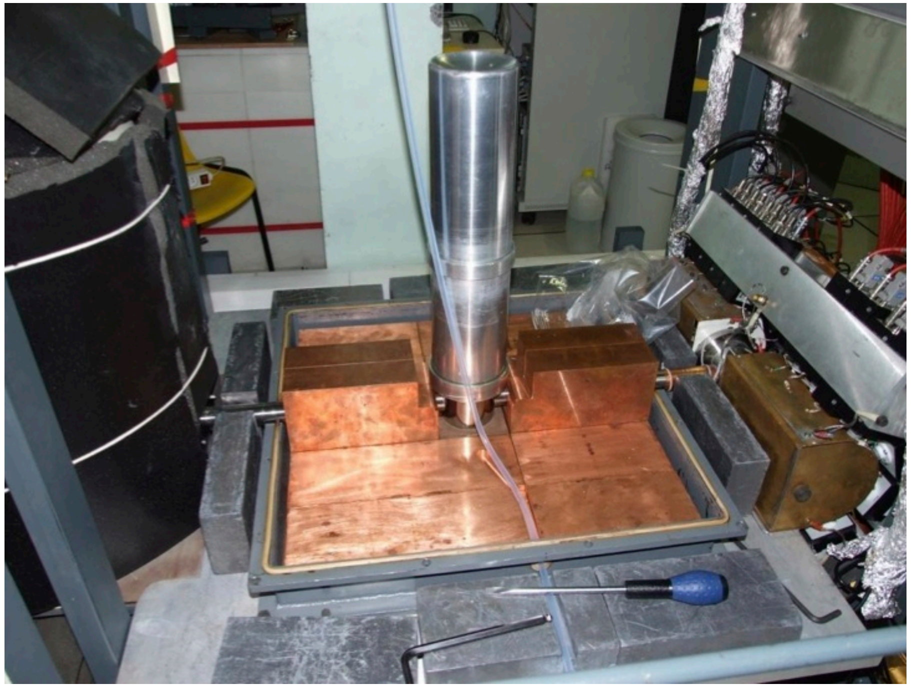
32 × HPGe [2040mm^2×6mm]

$$T_{1/2}^{2\nu\mathrm{ECEC}}\left({}^{106}\mathrm{Cd}\right) > 4.2\times 10^{20}\ \mathrm{yr}\ (90\%\ \mathrm{CL})$$

NPA 852 (2011) 197

Telescope Germanium Vertical Array





Detectors:

- 32 HPGe Ø 60 mm x 6 mm
- Sensitive volume 20.4 cm^2 x 6 mm
- Total sensitive volume ~ 400 cm^3
- Total mass ~3 kg

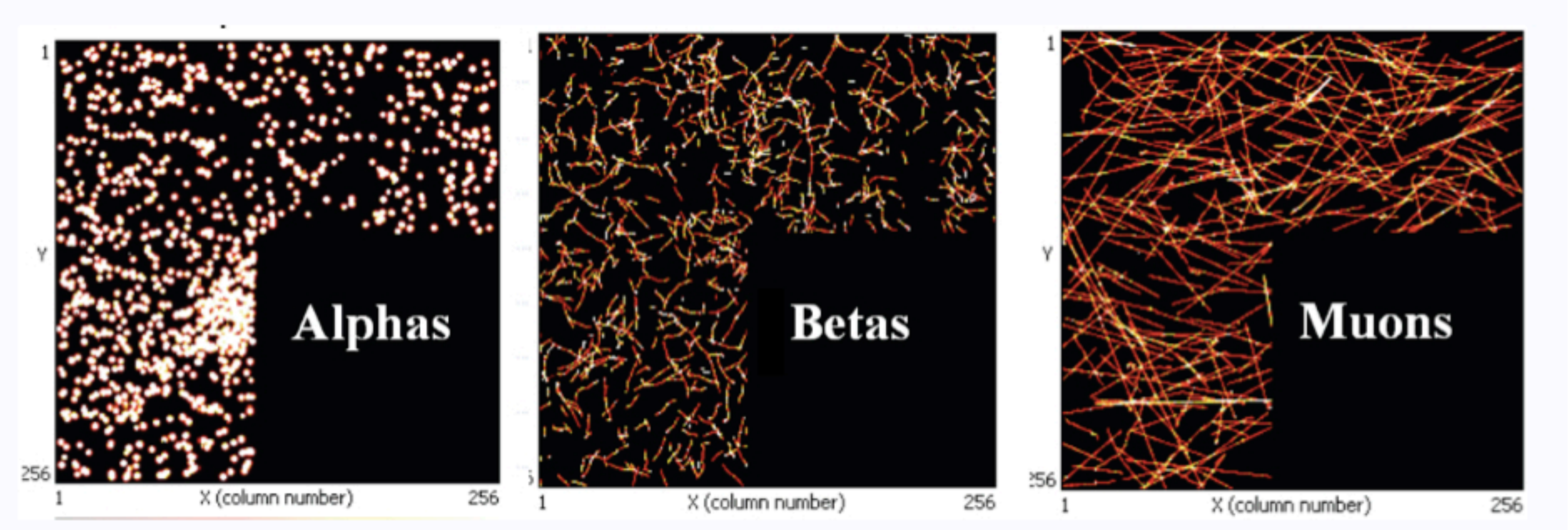
Cryostat and Shielding

Future ➔ pixel detectors & TGV-III

Double-Beta Decay with Pixel Detectors

Solid-state TPC concept

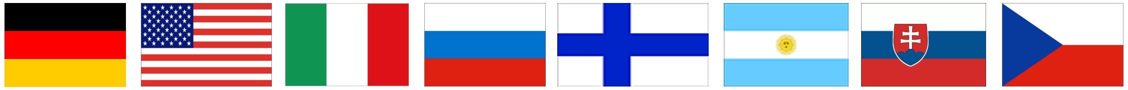
- **50-100 µm** pixel size enables microscopic particle identification.
- In principle combines benefits of solid-state detectors (i.e. resolution) and tracking detectors (spatial & topological background rejection).



Options for fabricating such detectors :

- Take advantage of existing/developing silicon pixel technology ➔ source ≠ detector
- Pixelate CdZnTe ➔ source = detector

Double-Beta Decay with Pixel Detectors



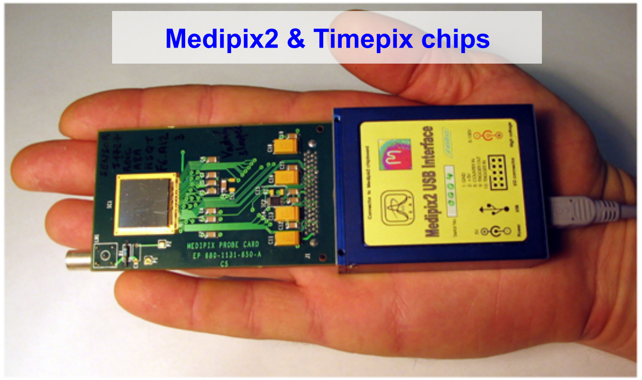
Czech Technical University

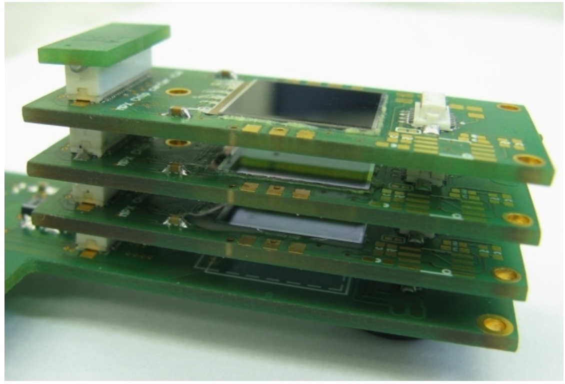
COBRA extension

- Segmented CdZnTe pixel detectors (with enriched Cd)
- Signature = two tracks of electrons from one pixel, Bragg peak
- Particle identification / rejection (alpha, electrons, photons)

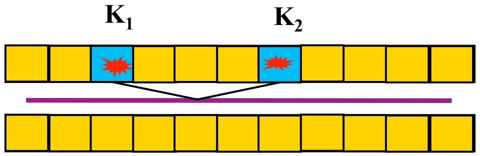
TGV III (EC/EC)

- Si pixel detectors in coincidence mode
- Thin foil of enriched isotope
- Signature = two hit pixels with X-rays of precise energy
- Efficiency (x2 compared with TGV II)
- Particle identification (alpha, electrons)

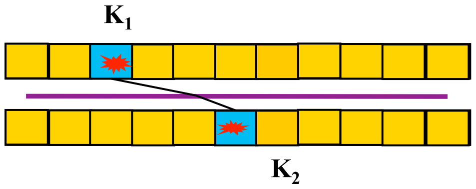




Single-sided event

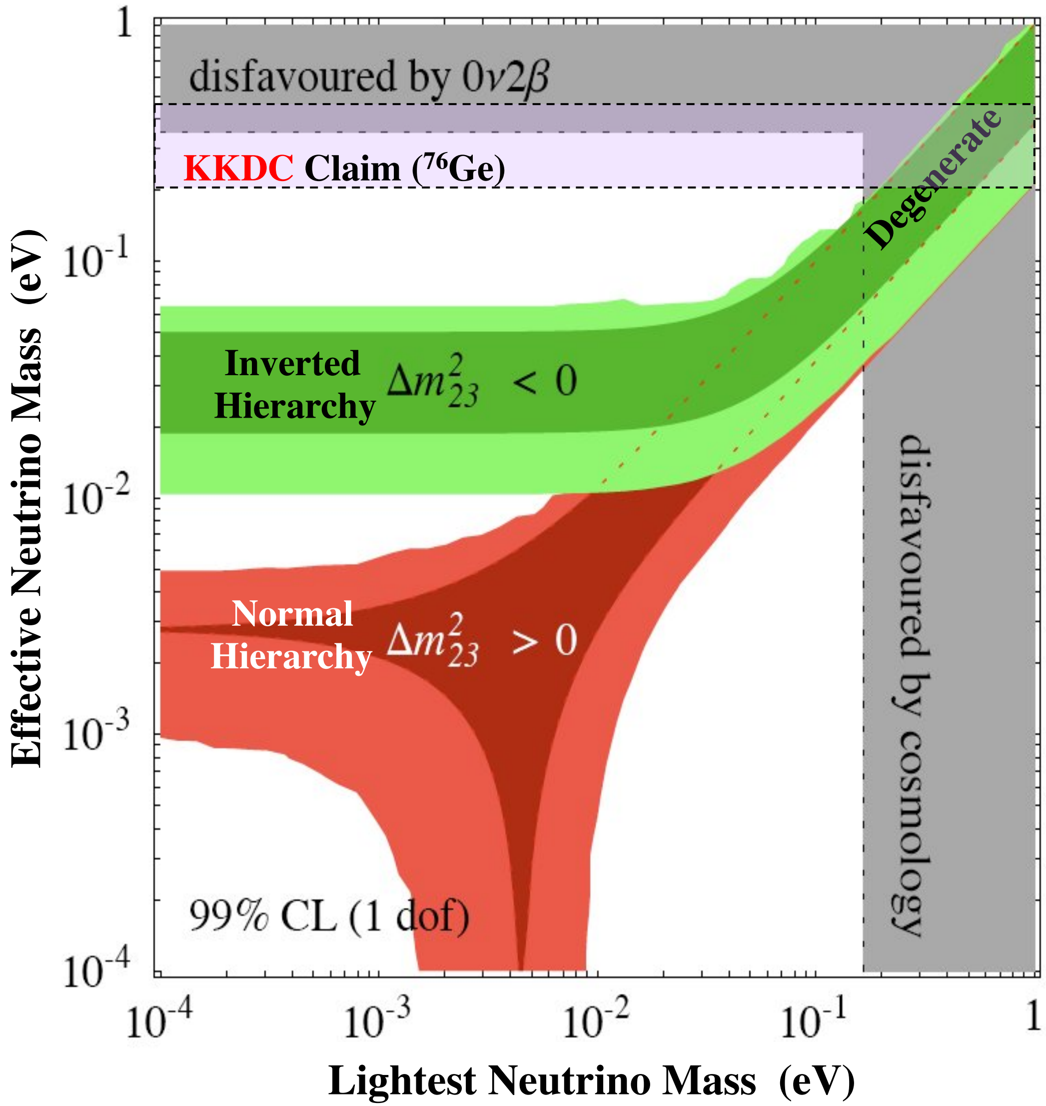


2 × 21 keV X-rays from ^{106}Pd daughter



Double-sided event

Summary



2012-2015
SuperNEMO Demonstrator
SNO+ Phase 1
GERDA Phase 1
CUORE (0)
Others

2015-2020
SuperNEMO
SNO+
GERDA
CUORE
Others

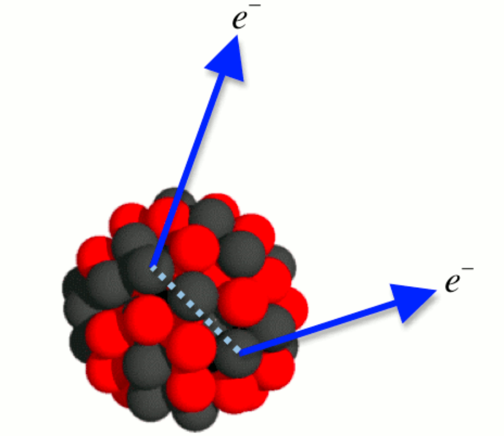
Multi-ton Experiments
Scalability of existing techniques ?
New ideas ?

Summary

- 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 for important projects I have not covered :

AMoRE	**^{100}Mo**	**$CaMoO_4$ cryogenic**
CANDLES	**^{48}Ca**	**CaF_2 scintillator**
DCBA/MTD	**^{100}Mo/^{150}Nd**	**Magnetic tracking**
MAJORANA	**^{76}Ge**	**Semiconductor**
MOON	**^{100}Mo**	**Tracking calorimeter**
NEXT	**^{130}Xe**	**HPXe TPC**
XMASS	**^{130}Xe**	**Scintillation**



Backup Slides

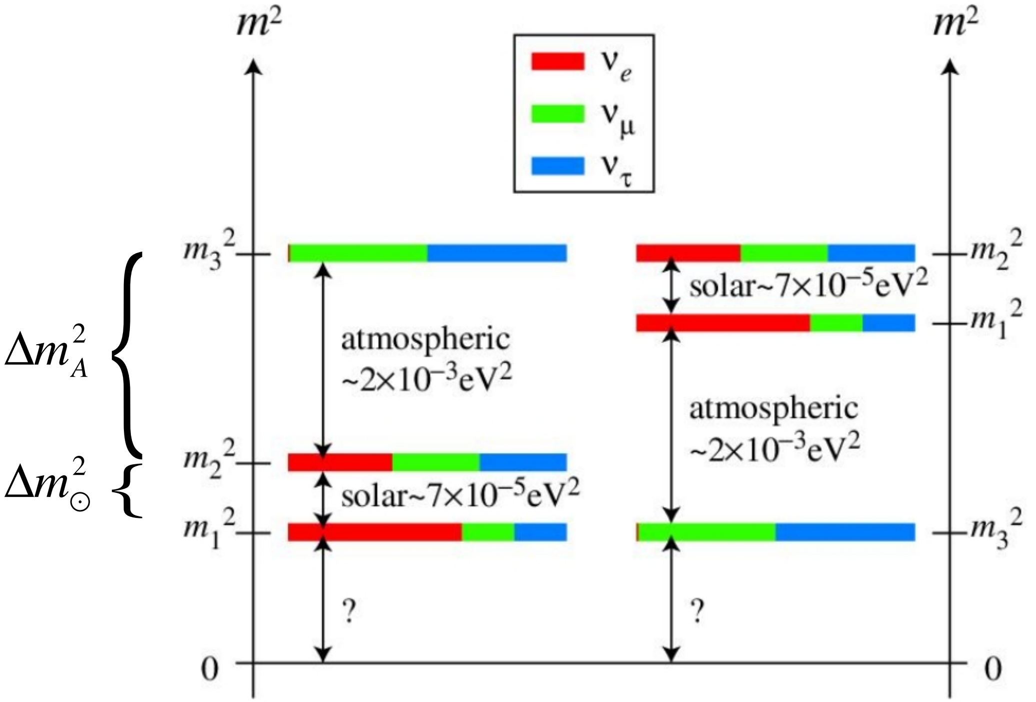
Table of Neutrinoless Double-Beta Decay Experiments

Experiment	Isotope	Technique
AMoRE	^{100}Mo	$CaMoO_4$ cryogenic scintillation/phonon
CANDLES	^{48}Ca	CaF_2 scintillator
COBRA	$^{116/106}$CdZn^{130}Te	Semiconductor
CUORE	^{130}Te	Bolometer
DCBA/MTD	^{100}Mo/^{150}Nd	Magnetic tracking
EXO	^{130}Xe	Liquid TPC
GERDA	^{76}Ge	Semiconductor
KamLAND-Zen	^{130}Xe	Liquid scintillator
MAJORANA	^{76}Ge	Semiconductor
MOON	^{100}Mo	Tracking calorimeter
NEXT	^{130}Xe	High-pressure gas TPC
SuperNEMO	^{82}Se	Tracking calorimeter
SNO+	^{150}Nd	Liquid scintillator
XMASS	^{130}Xe	Scintillation

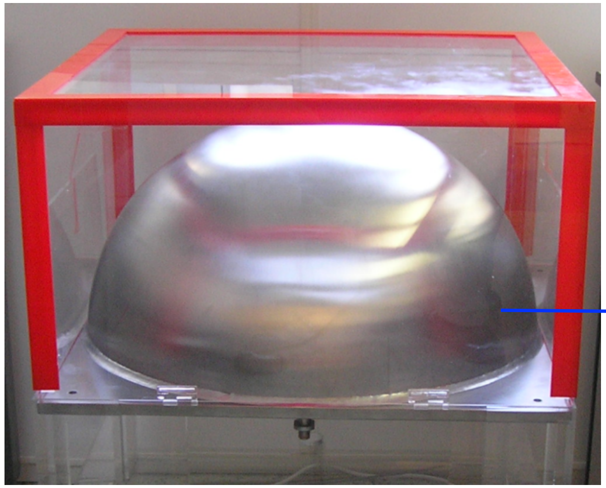
Neutrino Mixing & Masses

PMNS mixing matrix :

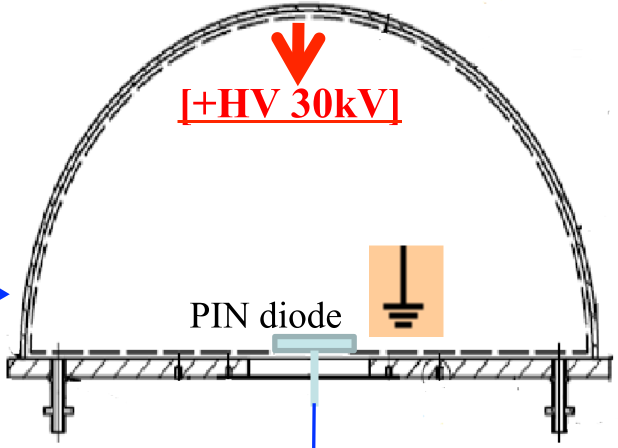
$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}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



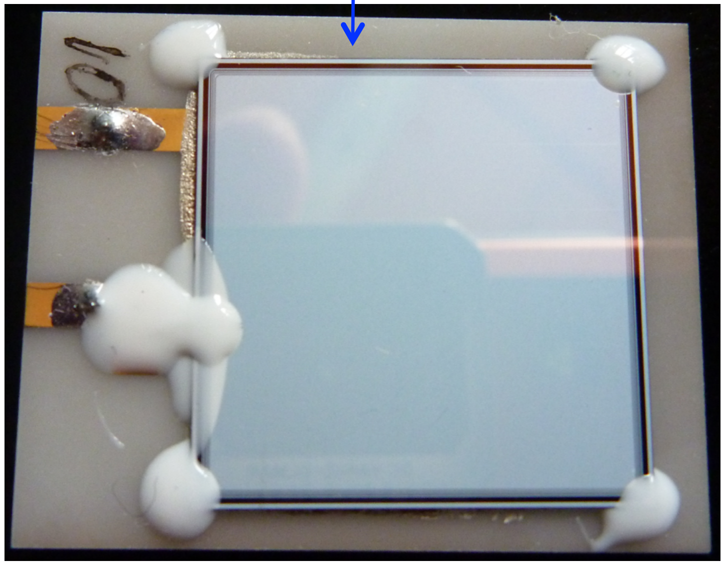
SuperNEMO : Ultra-low Radon Background Measurements

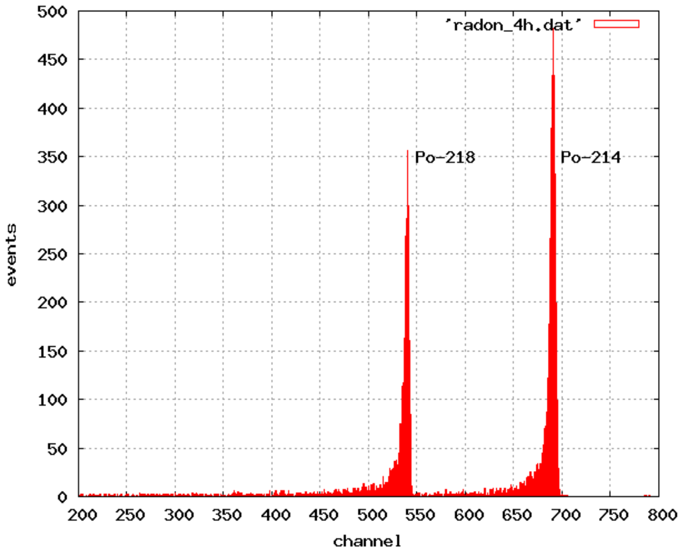


drift radon progeny under HV

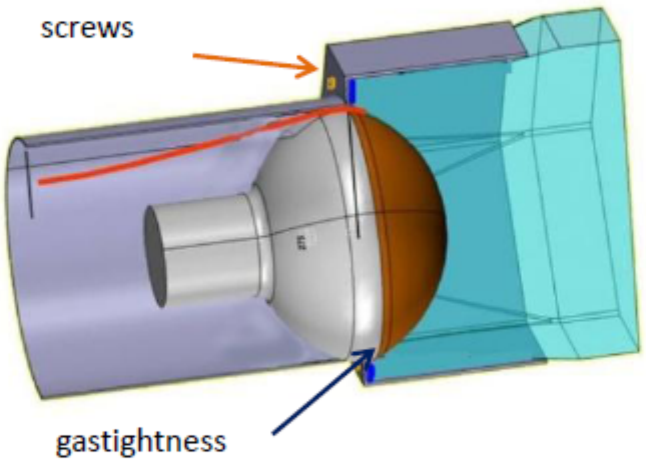


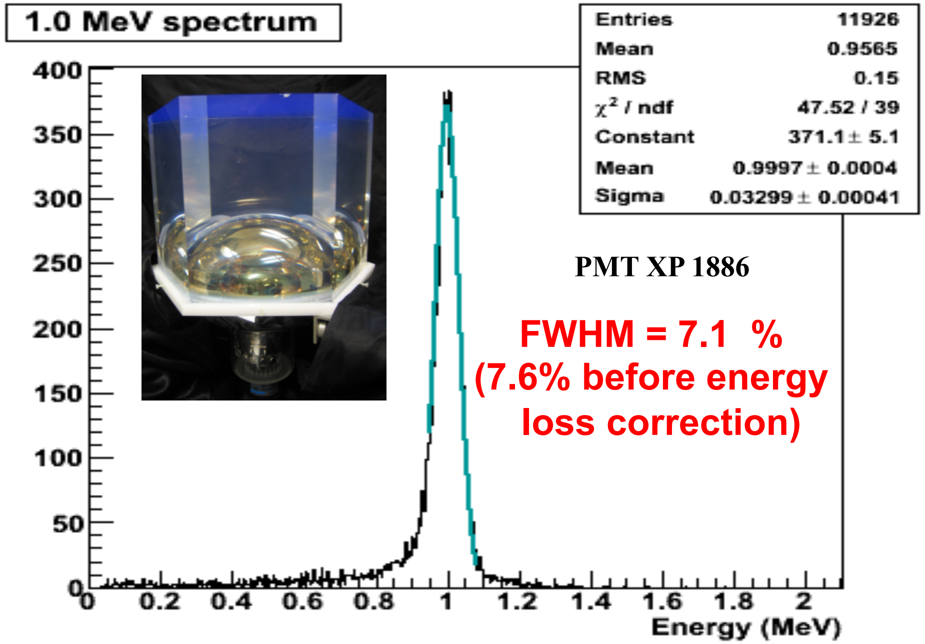
complementary to radon concentration line work @ UCL





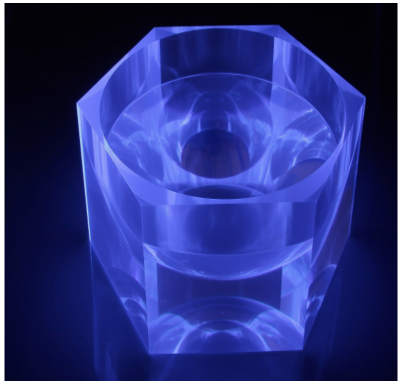
SuperNEMO Calorimeter R&D





PMT XP 1886

FWHM = 7.1 %
(7.6% before energy loss correction)



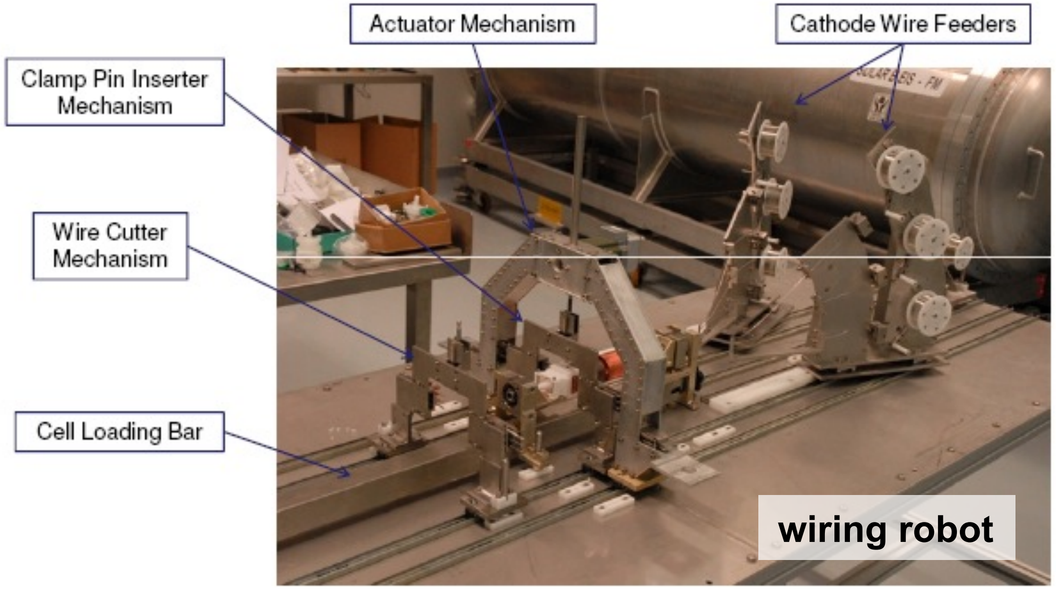
Volume: 8 lit. (cf. NEMO3 4 lit.)
8” PMT (cf. NEMO3 5” PMT)
ΔE/E ~ 6.5 – 8 %
➔ Factor 2 smaller than NEMO3

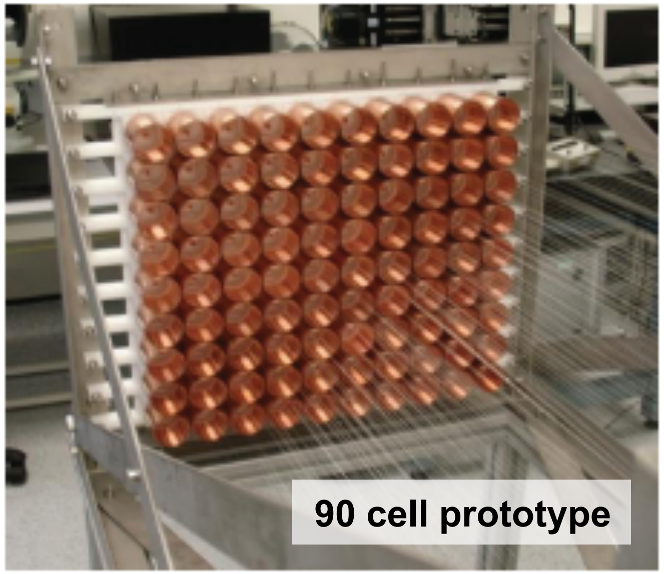
Mechanics much simpler with a cubic geometry :

- Material : PVT
- Size: 256 × 256 mm (face), ≥120 mm (depth)
- PMT : 8”
- Resolution :

FWHM = 7.3% @ 1 MeV
FWHM = 4.2% @ 3 MeV

SuperNEMO Tracker R&D





Dimensions of individual Geiger cell :

- ø = 44mm
- L = 3.7mm

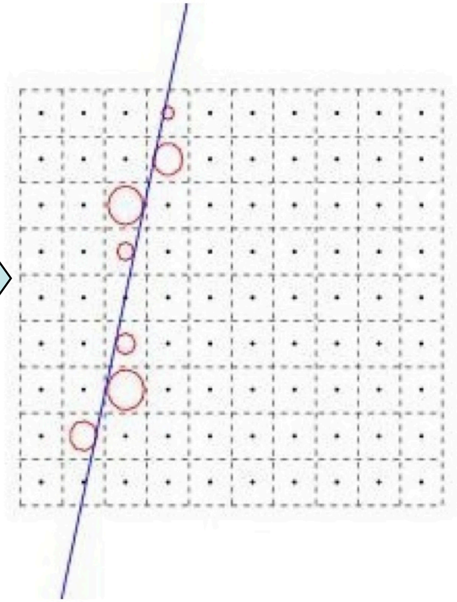
Performance:

$\sigma_T \sim 0.7$ mm

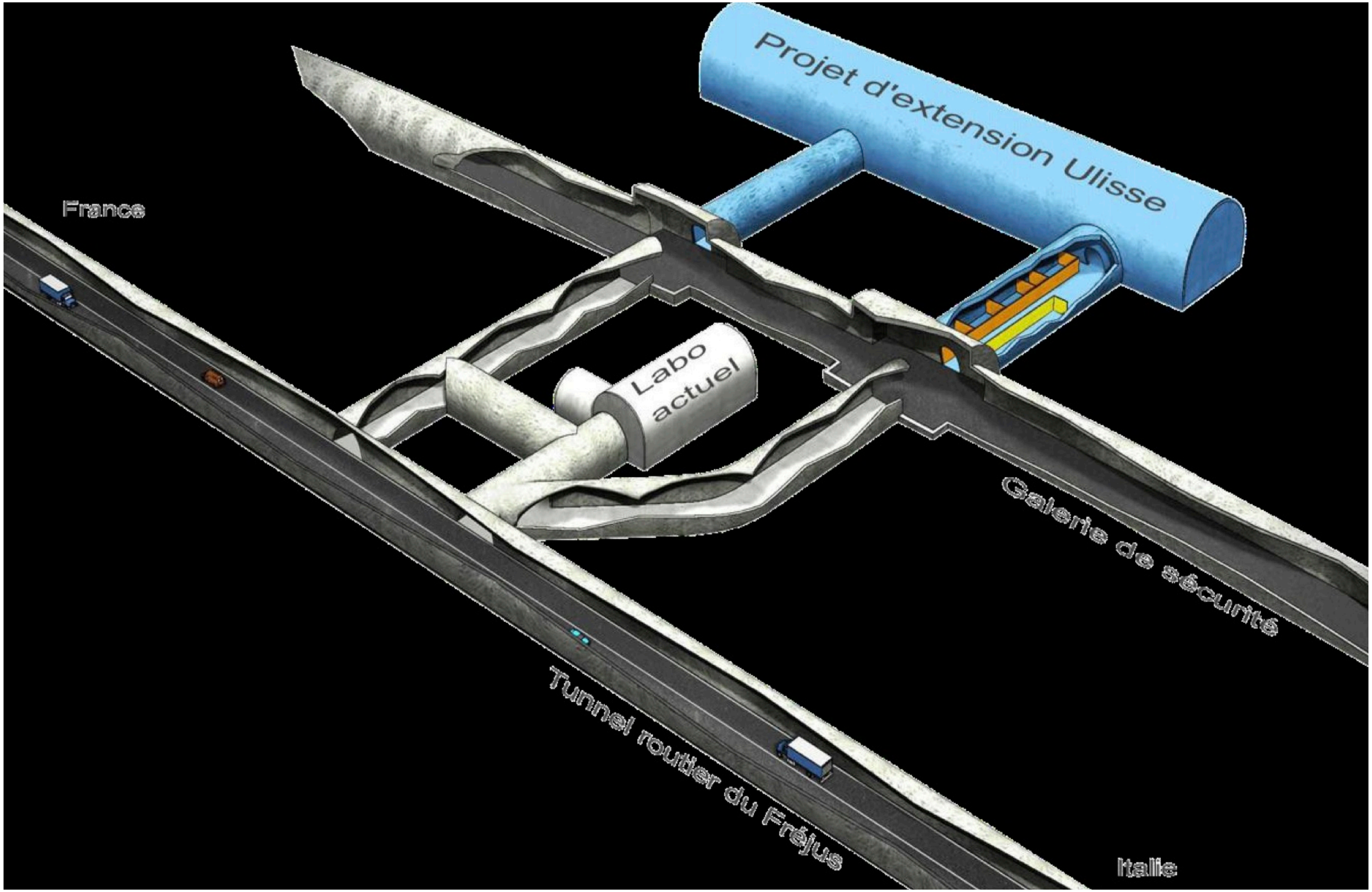
$\sigma_L \sim 1.0$ cm

$\varepsilon_{Geiger} > 98\%$

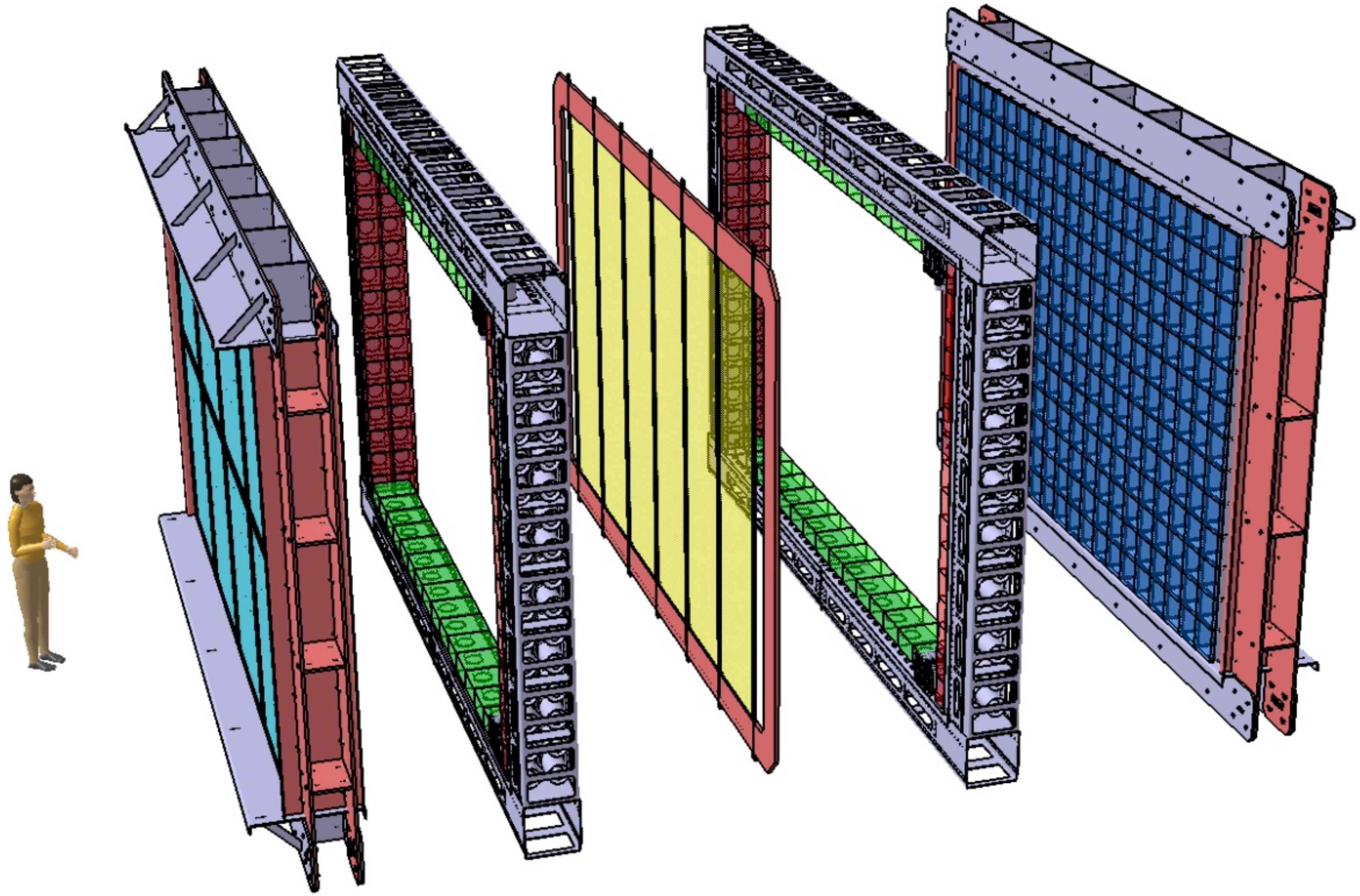
90 cell prototype cosmic-ray data



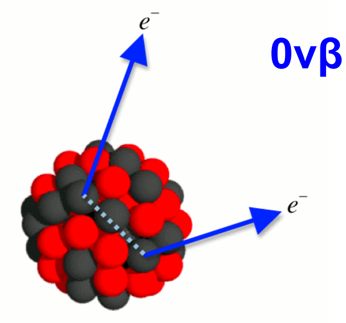
LSM Extension



SuperNEMO Blow-Up

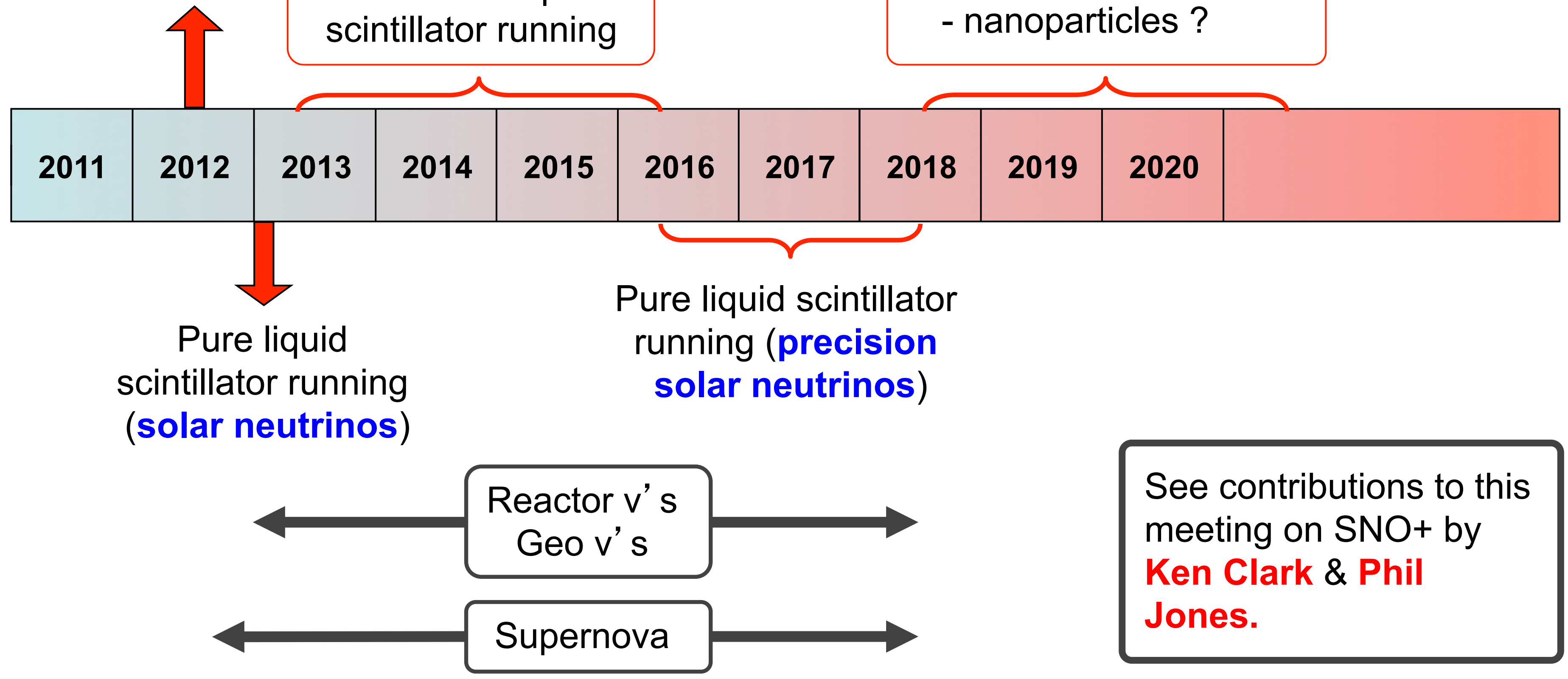


SNO+ : Timeline



0νββ

Nd-loaded liquid scintillator running



H_2O running (checkout, **nucleon decay**)

Phase 2 **0νββ ?**

- ^{150}Nd enrichment ?
- Different isotope ?
- Larger loading fraction - nanoparticles ?

Pure liquid scintillator running (**solar neutrinos**)

Pure liquid scintillator running (**precision solar neutrinos**)

Reactor ν's
Geo ν's

Supernova

See contributions to this meeting on SNO+ by **Ken Clark** & **Phil Jones.**