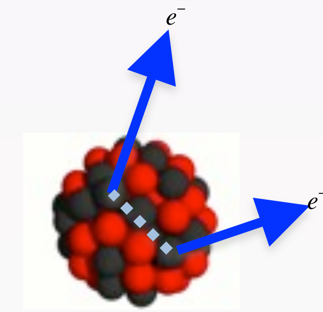
Topological detection of ββ-decay with NEMO-3 and SuperNEMO

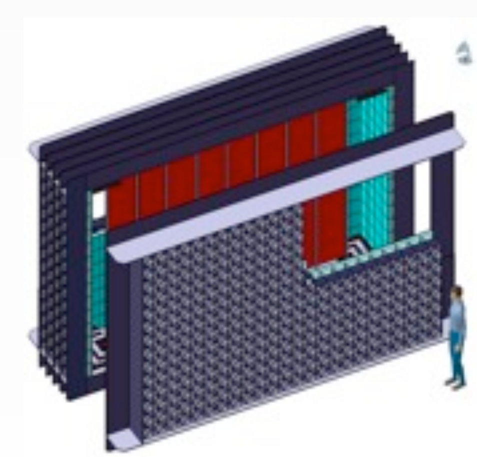
Ruben Saakyan
University College London
Particle Physics Seminar
University of Sussex
17 May 2012

- **Motivation and Concept**
  - ββ-decay and New Physics
  - Experimental approaches



- **NEMO-3**
  - Detector
  - Results

- **SuperNEMO**
  - Physics reach
  - R&D results
  - Demonstrator
  - Schedule



Neutrinos are massive and they mix

Different from quark sector. Can CP-violation in lepton sector address matter-antimatter puzzle?

PMNS matrix $= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$

$\Delta m_{23}^2 = \Delta m_{atm}^2 \approx 2.3\times10^{-3}eV^2$

$\theta_{23} \approx 45^\circ$ (maximal?)

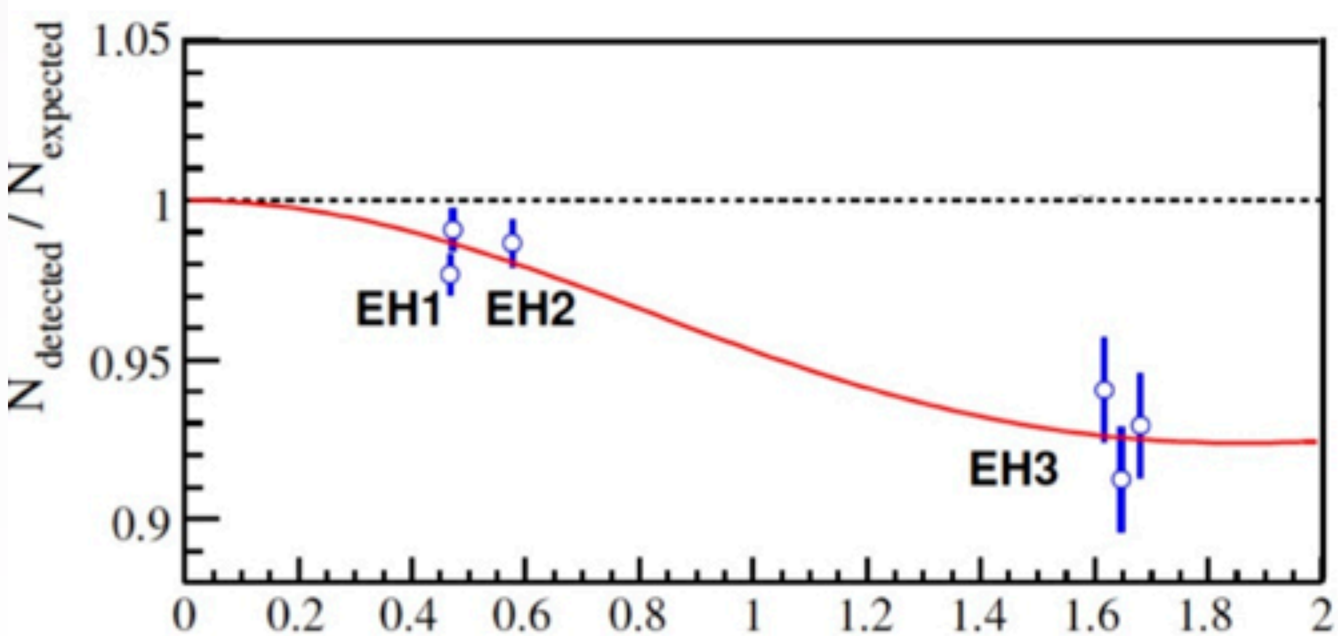
$\theta_{13} \approx 9^\circ$

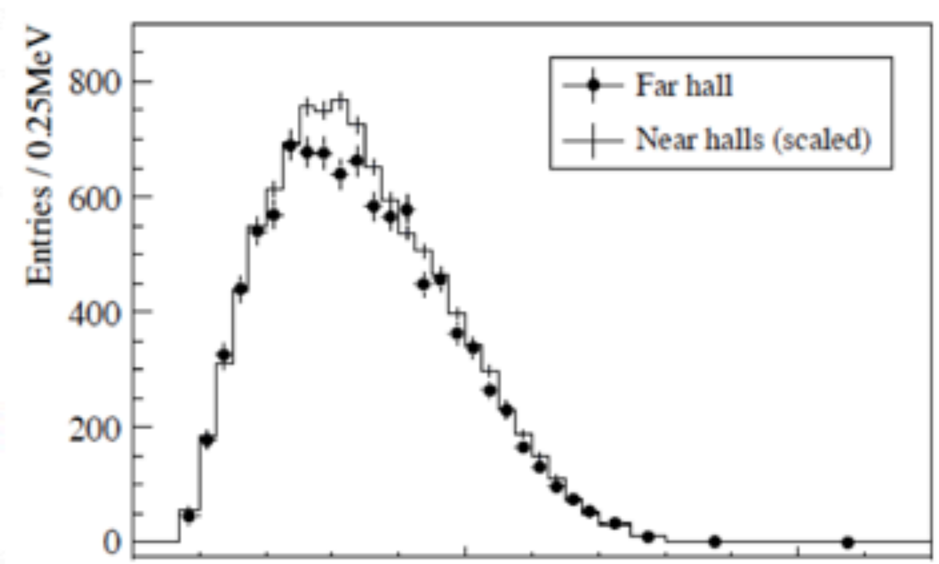
$\Delta m_{12}^2 = \Delta m_{sol}^2 \approx 7.7\times10^{-5}eV^2$

$\theta_{23} \approx 34^\circ$

Beautiful spring 2012!
Daya Bay and Reno results following hints from T2K, MINOS,D-Chooz

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$





Plots courtesy of
Daya Bay
Collaboration

Key Questions to Answer

- Number of neutrinos: Are there sterile neutrinos?
- *Precision* values of mixing angles and Δm^2's
- Absolute neutrino mass value. Only limits so far.
  Tritium: $m_{\bar{\nu}_e} < 2.3$ eV Cosmology: $\sum m_{\nu_i} < 1$ eV
- Neutrino mass spectrum: Normal ($m_1 < m_2 < m_3$)
  Inverted ($m_3 < m_1 < m_2$) or Quasi-degenerate ($m_1 \approx m_2 \approx m_3$)?
- Origin of matter-antimatter asymmetry.
  CP-violation in lepton sector: $\delta \neq 0,\pi$ and/or $\alpha,\beta \neq 0,\pi$?
- Nature of Neutrinos: Majorana (ν = anti-ν) or Dirac ($\nu \neq$ anti-ν)?
  Full lepton number violation (required in most Grand Unification Theories) .

addressed by $0\nu\beta\beta$ decay

Nature of Neutrinos: Majorana (ν = anti-ν) or Dirac (ν ≠ anti-ν)?

$\Delta L \neq 0$ $\Delta L = 0$

Directly related to fundamental symmetries of particle interactions

Provides important information on origin of neutrino mass

SEE-SAW

$$m_\nu \equiv m_M^L = \frac{m_D^2}{M} << m_D$$

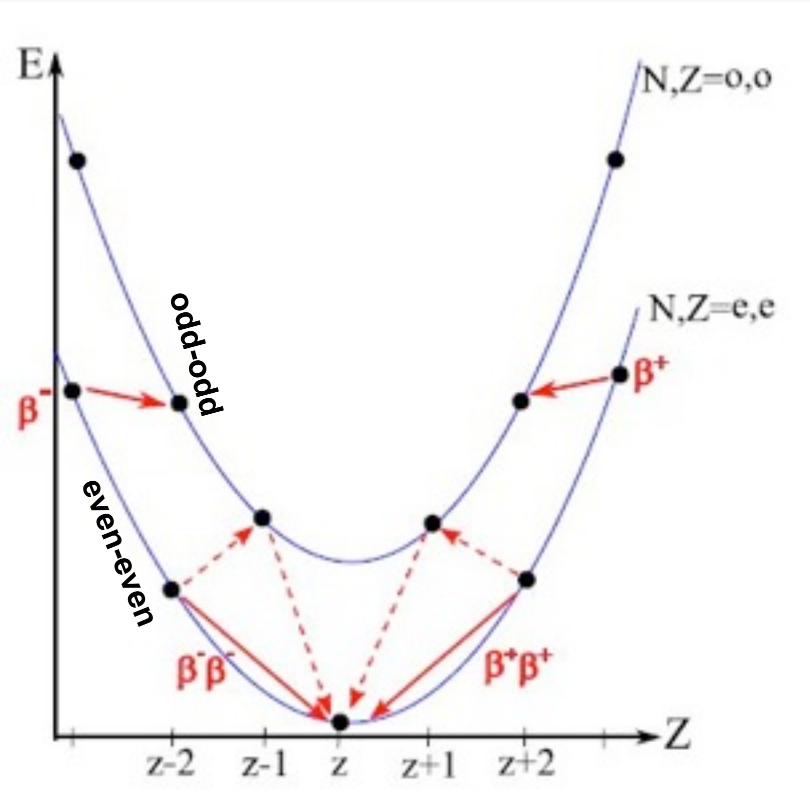
To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

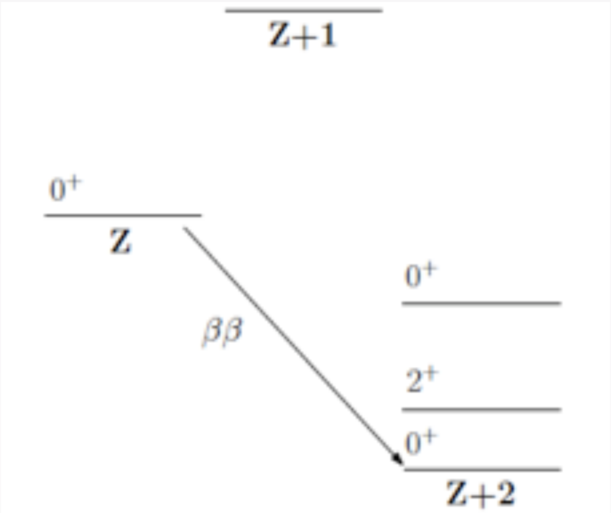
Lepton number violation is one of the key ingredients of **leptogenesis** as the mechanism to generate the baryon asymmetry of the Universe.

More matter than anti-matter!

Double Beta Decay in the Standard Model
(Goeppert-Mayer, 1935)

Recall pairing term in SEMF





M(A,Z) > M(A,Z+2)

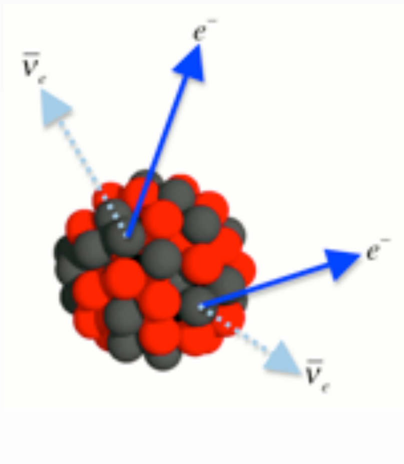
$Q_{\beta\beta}$ = M(A,Z) – M(A,Z+2)

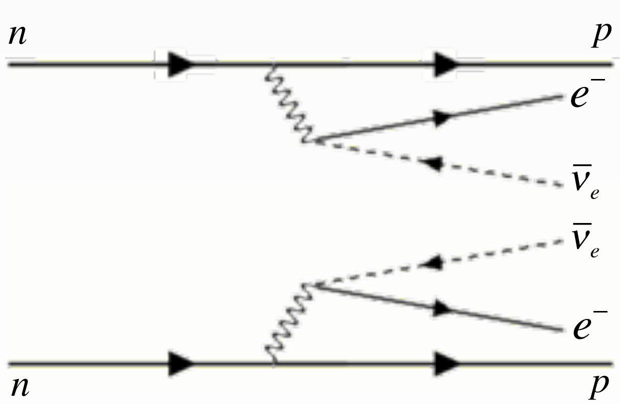
phase space

$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q_{\beta\beta}, Z)\left|M^{2\nu}\right|^2$$

NME: ~~Nasty~~ Nuclear Matrix Element

NME is **measured** in 2νββ



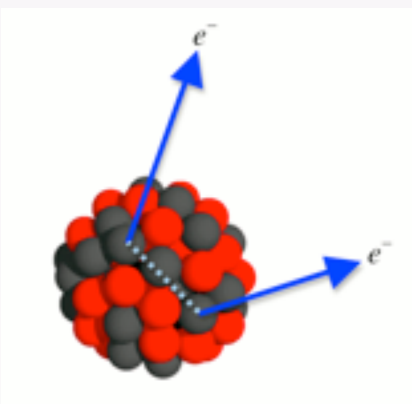


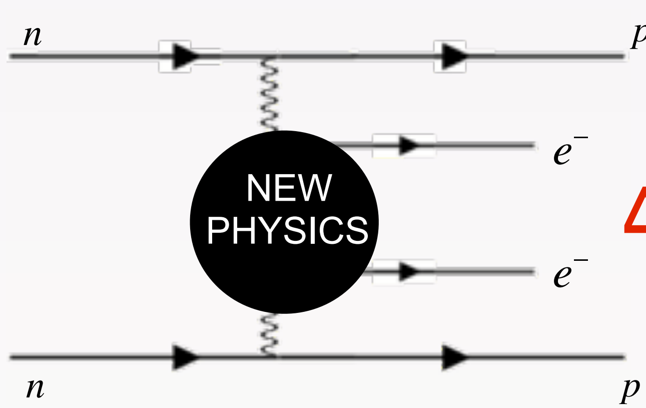
- Second order process ⇒ rare (~10^{19}-10^{21} yr)
- Nevertheless observed for 11 nuclei
- Experimental input for NME calculation

Double Beta Decay Beyond the Standard Model

↓

Neutrinoless Double Beta Decay (Furry, 1939).





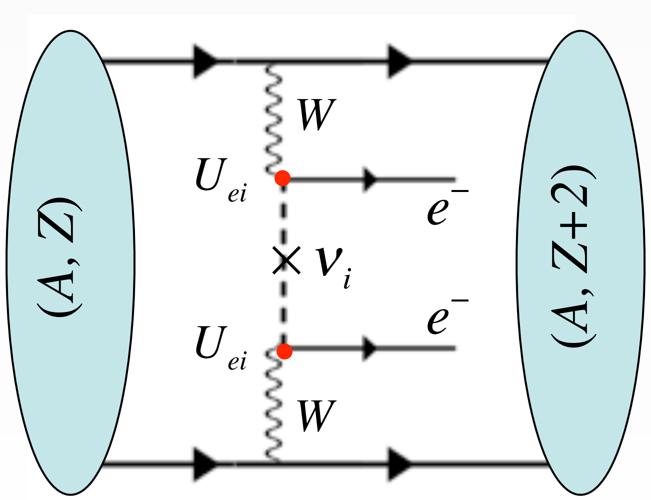
ΔL = 2!

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

Lepton number violating parameter

η can be due to $\langle m_\nu \rangle$, V+A, Majoron, SUSY, H^{--} or a combination of them

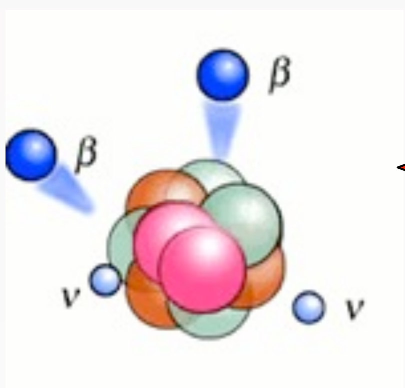
"Minimal" scenario - light Majorana mass

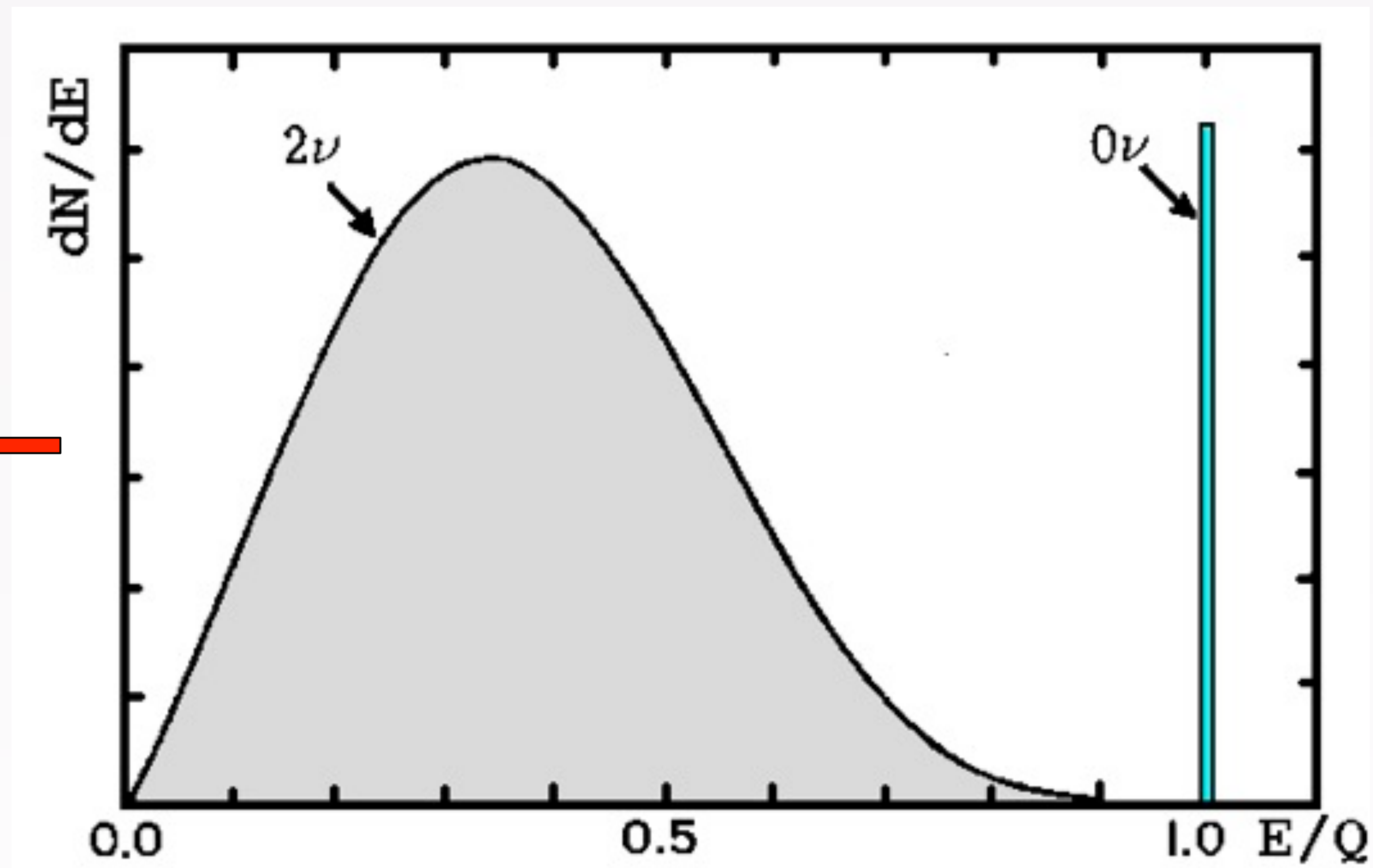


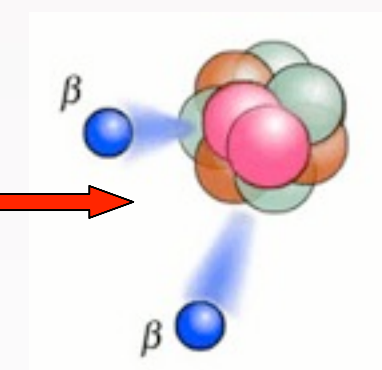
Coherent sum over neutrino amplitudes

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

Double Beta Decay. What is measured?







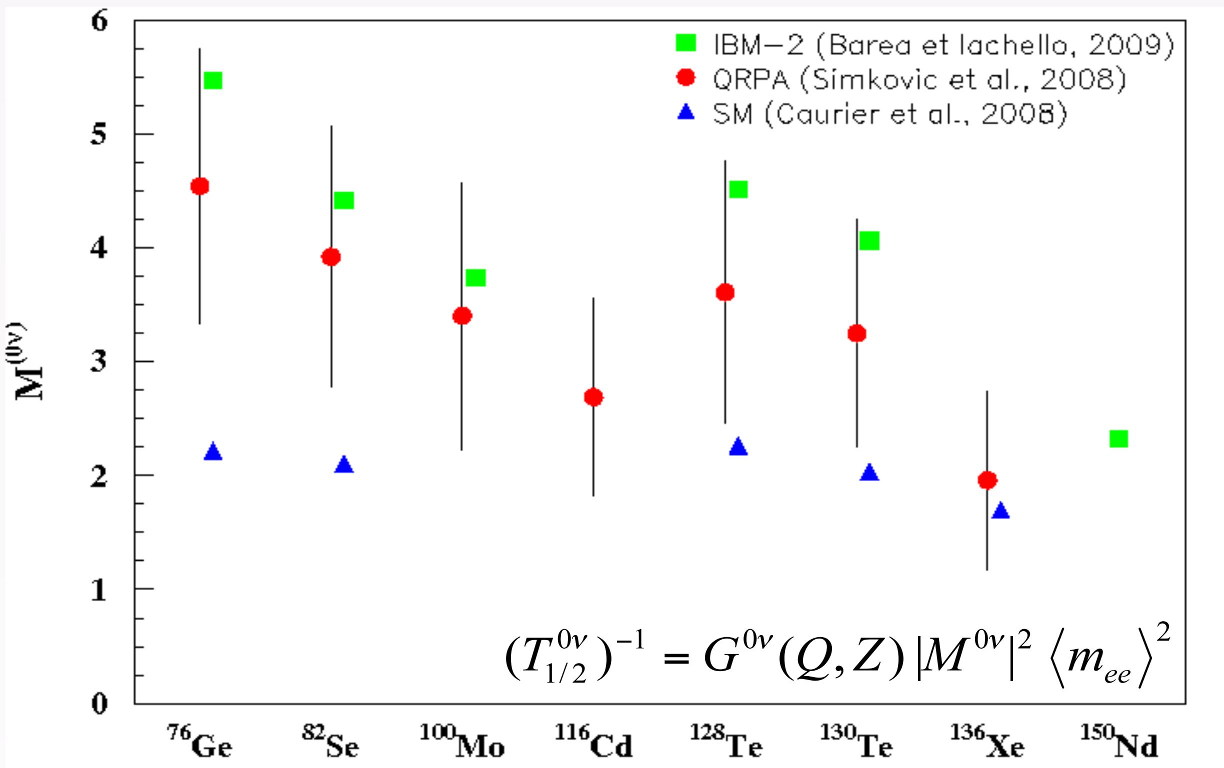
$$\left(E_1 + E_2\right) \in \left[0, Q_{\beta\beta}\right]$$

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

[⊗ resolution]

Double Beta Decay. Isotope Candidates.

Over 40 nuclei can undergo ββ-decay (including $\beta^+\beta^+$ and 2K-capture)
Only ~10 experimentally feasible



Isotope choice

- $Q_{\beta\beta}$
- $T_{1/2}(2\nu)$ (the longer the better)
- Isotope abundance
- Enrichment opportunities
- NME - Input from 2ν measurements is useful
- Phase space

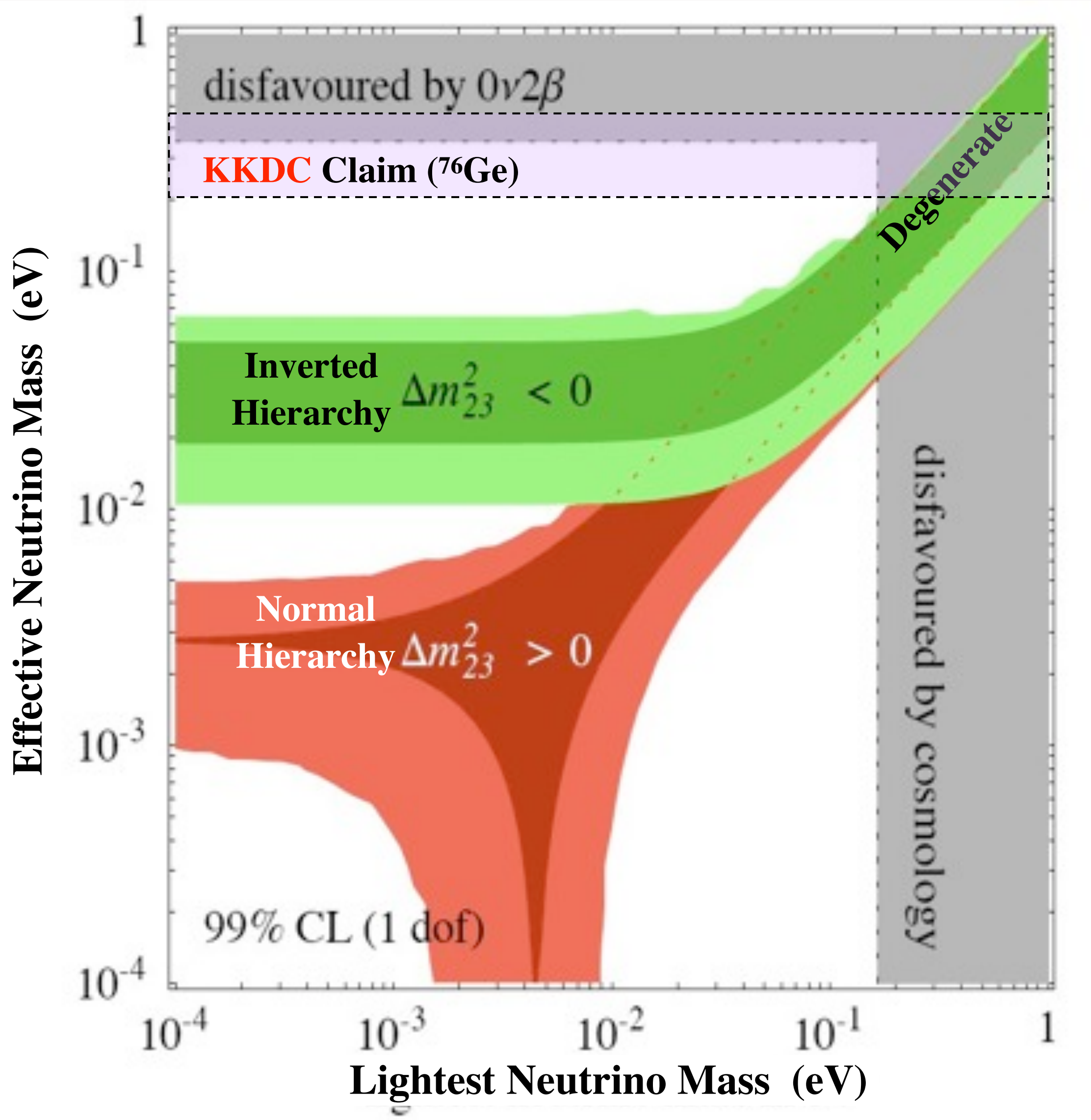
*J. Phys. G: Nucl. Part. Phys. 34 667 (2007)

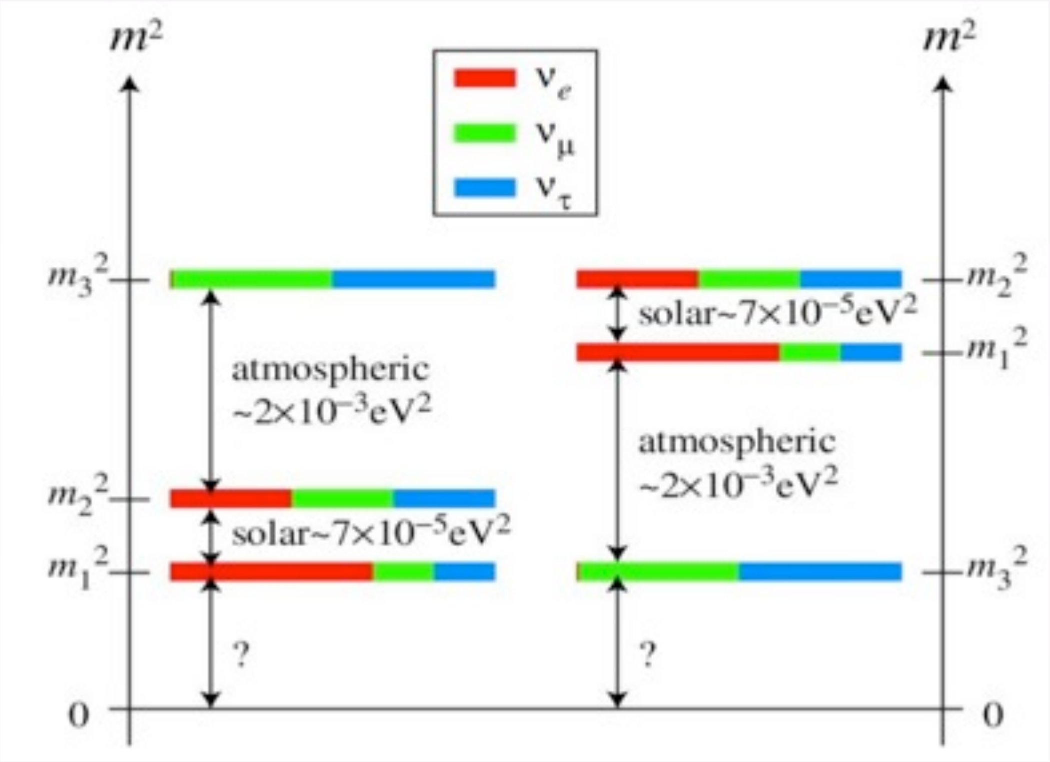
Isotope	Nat. Abundance (%)	Phase Space*, $G^{0\nu}\times10^{-15}yr^{-1}$	$Q_{\beta\beta}$ (MeV)
^{48}Ca	0.187	75.8	4.274
^{76}Ge	7.8	7.6	2.039
^{82}Se	9.2	33.5	2.996
^{96}Zr	2.8	69.7	3.348
^{100}Mo	9.6	54.5	3.035
^{116}Cd	7.6	58.9	2.809
^{130}Te	34.5	52.8	2.530
^{136}Xe	8.9	56.3	2.462
^{150}Nd	5.6	249	3.367

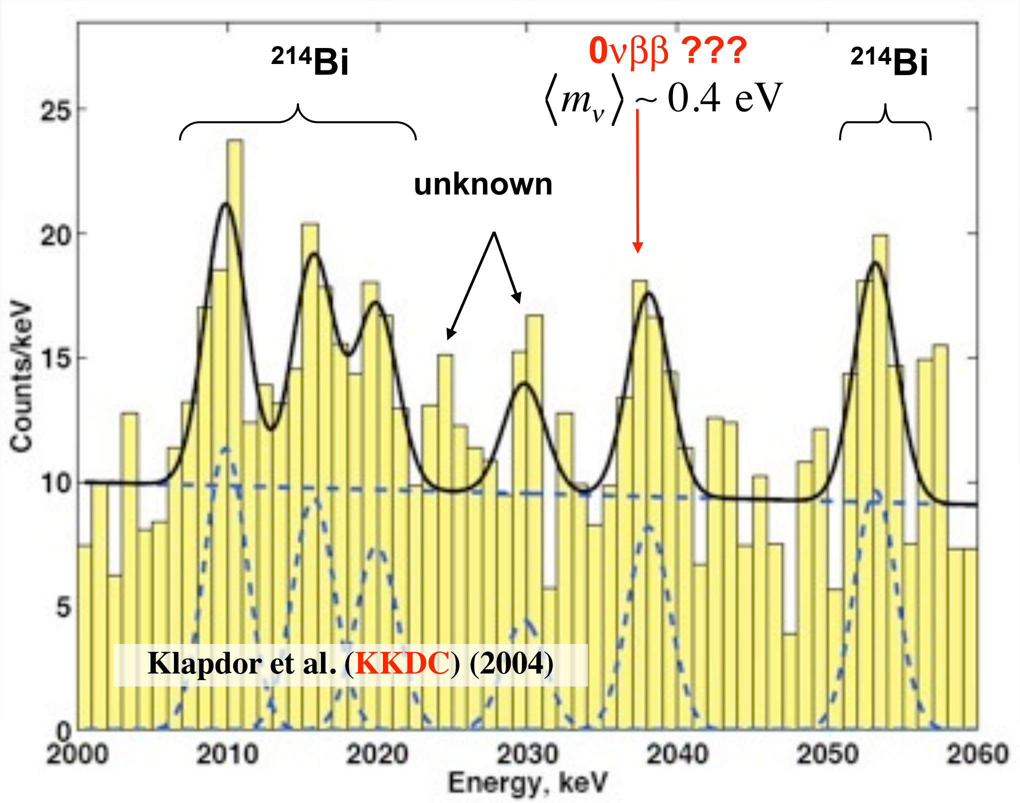
more energetic decay : easier to separate from background

enrichment often possible, always expensive !

Majorana Mass Physics Reach







Sensitivity Milestones

"Immediate" Future: ~0.1 eV to check K-K claim

Next step $\langle m_\nu \rangle \sim \sqrt{\Delta m^2_{atm}} \sim 0.05\,\mathrm{eV}$

And then ~ 0.01 eV to cover I.H.

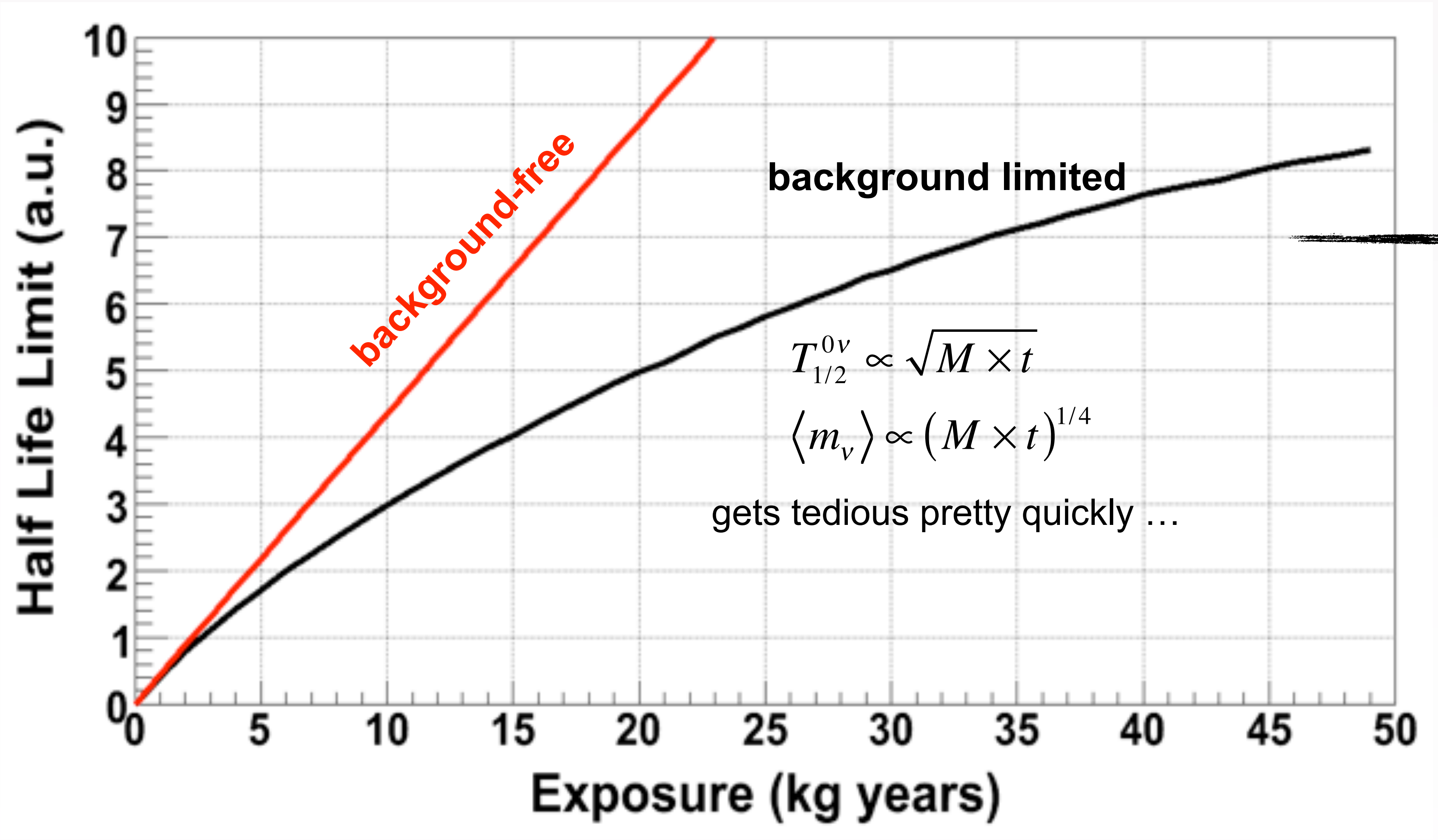
Experimental Sensitivity

maximise efficiency & isotope abundance

maximise exposure = mass × time

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

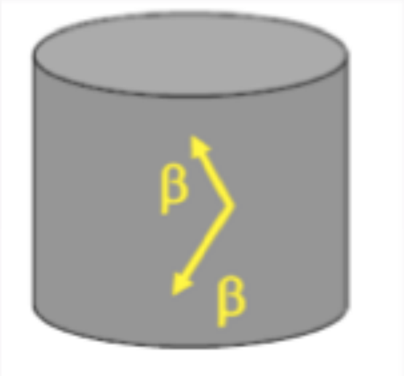
minimise background & energy resolution



ββ is about **background suppression!**

Experimental Approaches

Calorimeter-only. Source = Detector



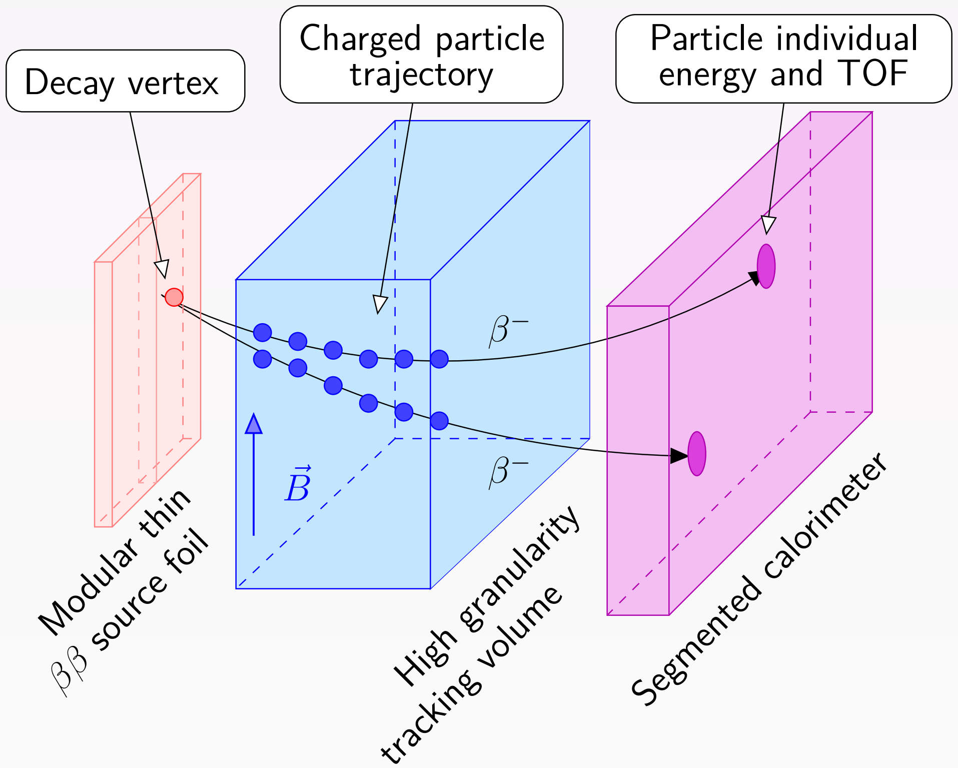
Main observable:
Deposited energy

Excellent ΔE/E
High efficiency
Relatively compact
Some particle ID capability

Main limiting factor: background

HPGe, Bolometers, (Liquid)-Scintillators, LXe.

Tracking + Calorimetry. Source ≠ Detector
(ala NEMO3 and SuperNEMO)



Full Topology Reconstruction

Strong background suppression and control
"Smoking gun" 0νββ signature. Any isotope can be studied.
Sensitivity to different physics mechanisms of 0νββ
Main limiting factor: efficiency

R&D on technologies that include elements of both
CdZnTe, HPXe TPC

A take-away message

- We need to measure different isotopes with different experimental approaches
  - NME uncertainties
  - Tiny signal - Huge Background. Will you ever trust a single positive measurement?
  - Disentangle underlying physics mechanism

↓

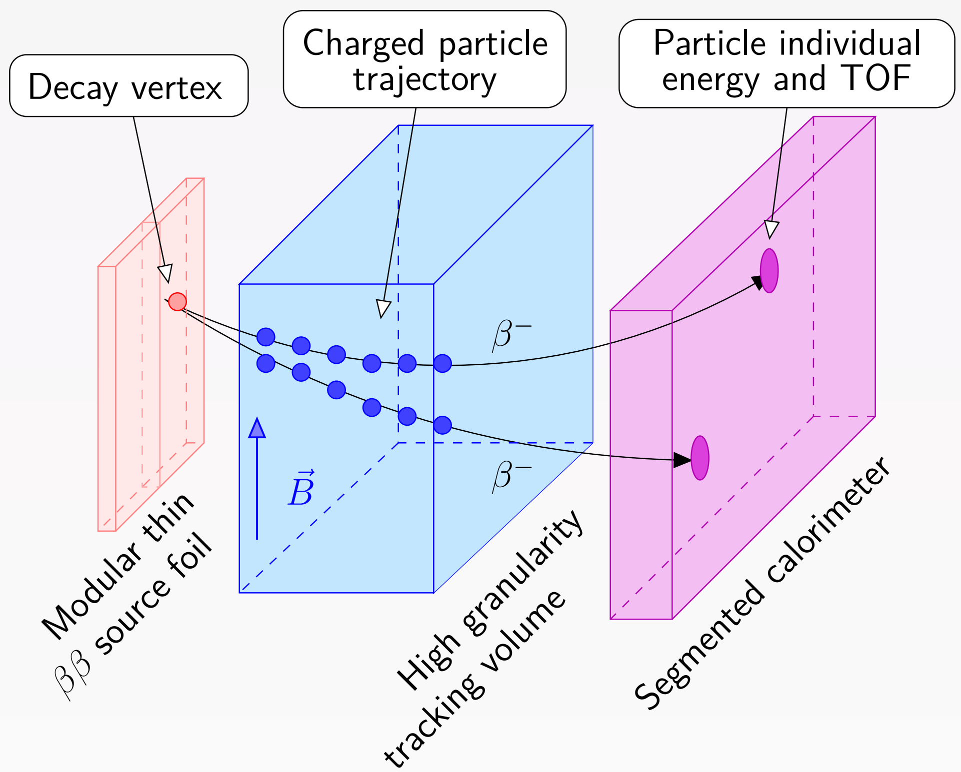
We need Diversity

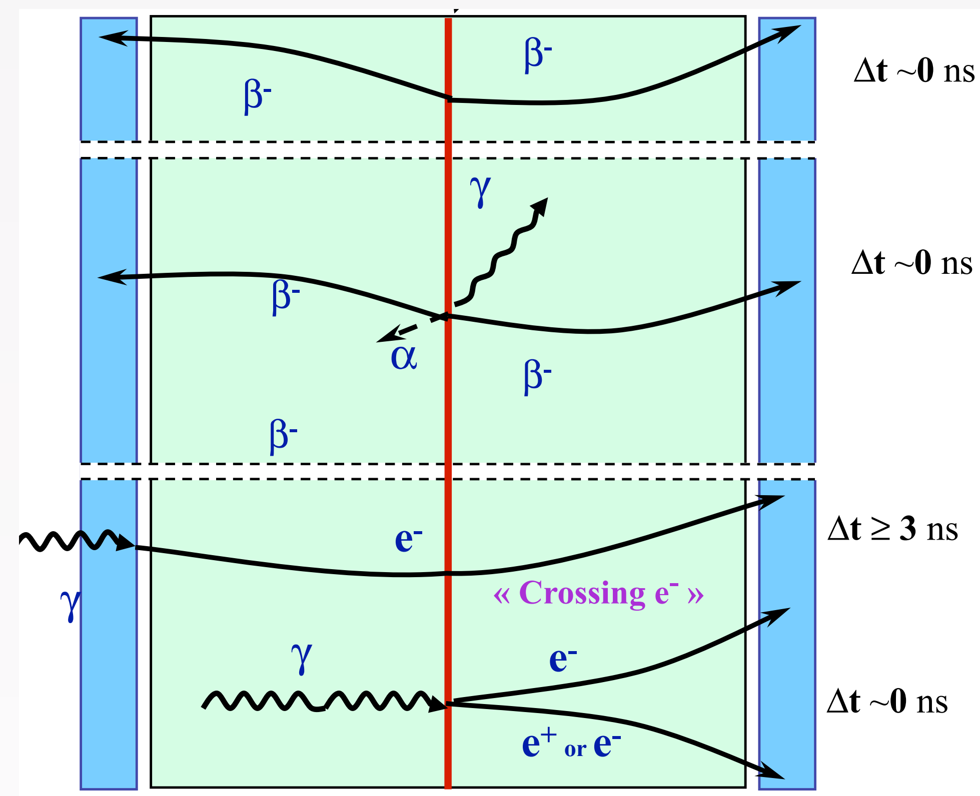
...and we have it!

Experiment	Isotope(s)	Technique	Main characteristics
NEMO-3	^{100}Mo, ^{82}Se, other	Tracking + calorimeter	Bckg rejection, isotope choice, topology
SuperNEMO	^{82}Se, ^{150}Nd, other	Tracking + calorimeter	Bckg rejection, isotope choice, topology
Cuoricino	^{130}Te	Bolometers	Energy resolution, efficiency
CUORE	^{130}Te	Bolometers	Energy resolution, efficiency
GERDA	^{76}Ge	Ge diodes	Energy resolution, eficiency
Majorana	^{76}Ge	Ge diodes	Energy resolution, efficiency
COBRA	^{130}Te, ^{116}Cd	CdZnTe semi-conductors	Efficiency, particle ID
EXO	^{136}Xe	TPC ionisation + scintillation	Mass, efficiency, particle ID
MOON	^{100}Mo	Tracking + calorimeter	Compactness, Bckg rejection
CANDLES	^{48}Ca	CaF_2 scintillating crystals	Efficiency, Active background vetoing
SNO++	^{150}Nd	Nd loaded liquid scintillator	Mass, efficiency
XMASS	^{136}Xe	Liquid Xe	Mass, efficiency
CARVEL	^{48}Ca	CaWO4 scintillating crystals	Mass, efficiency
Yangyang	^{124}Sn	Sn loaded liquid scintillator	Mass, efficiency
DCBA	^{150}Nd	Gaseous TPC	Bckg rejection
KamLAND-Zen	^{136}Xe	Xenon balloon	Mass, efficiency
NEXT	^{136}Xe	Gaseous TPC	Bckg rejection, efficiency

NEMO-3 and SuperNEMO

Unique Detection principle: reconstruct topological signature





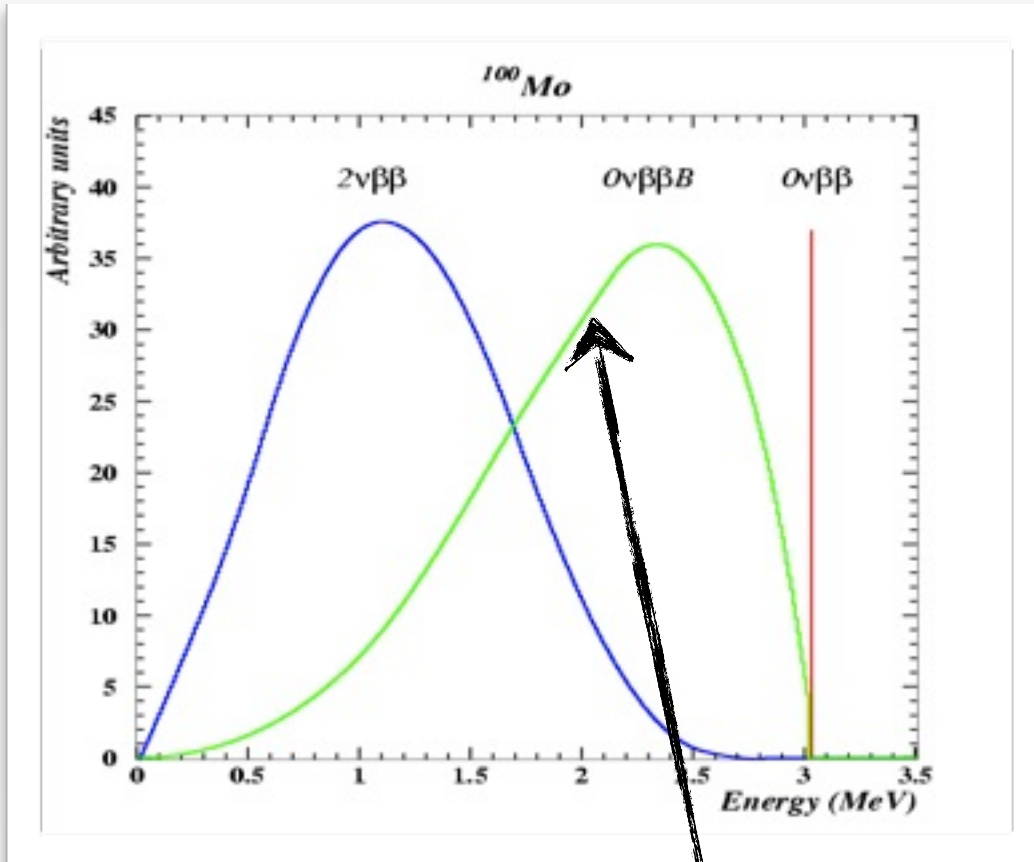
- **Reconstruct two electrons in the final state ($E_1+E_2 = Q_{\beta\beta}$)**
- **Measure several final state observables**
  - **Individual electron energies**
  - **Electron trajectories and vertices**
  - **time of flight**
  - **Angular distribution between electrons**
- **Powerful Background rejection through particle ID: e^-, e^+, α, γ**

➡ **"Smoking gun"** evidence for 0νββ

➡ **Open-minded** search for **any** lepton violating process

➡ Possibility to **disentangle** underlying **physics mechanism**

Topology reconstruction: Open-minded search for any 0νββ mechanism

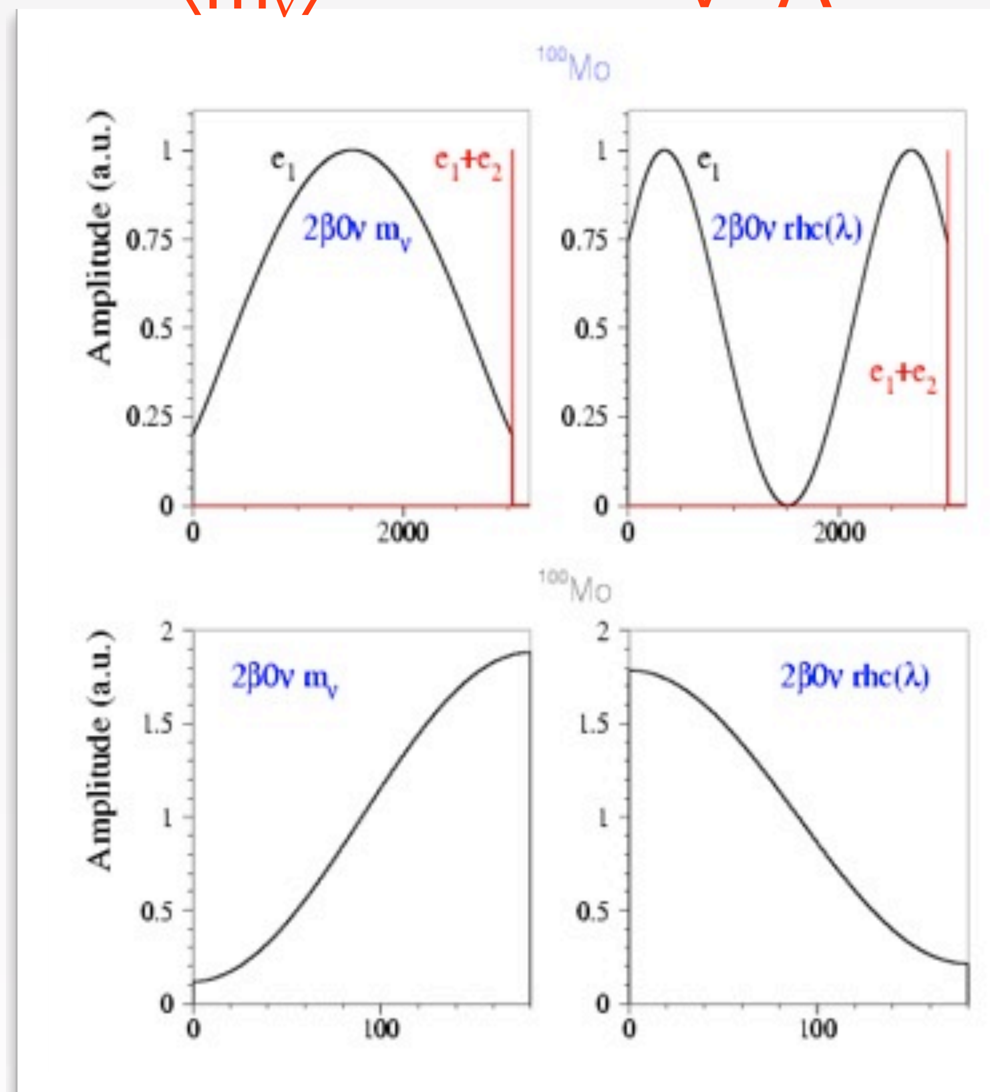


Majoron emission

$$\Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}\left|M^{0\nu}\right|^2 \chi^2$$

Topology detection is a more sensitive method for phenomena with continuous spectra, e.g. 2νββ, 0νββχ (Majoron)

⟨mν⟩ V+A

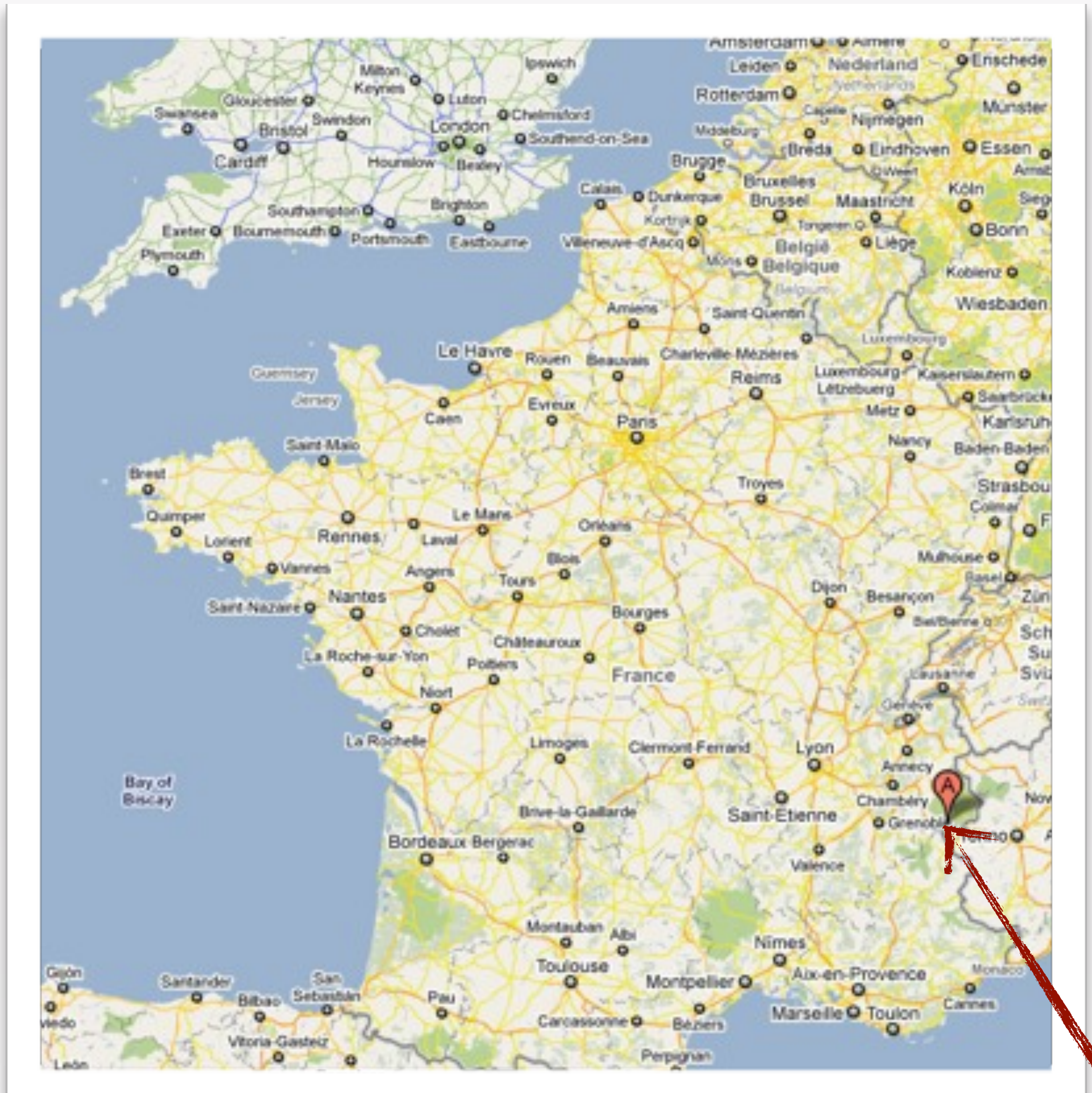


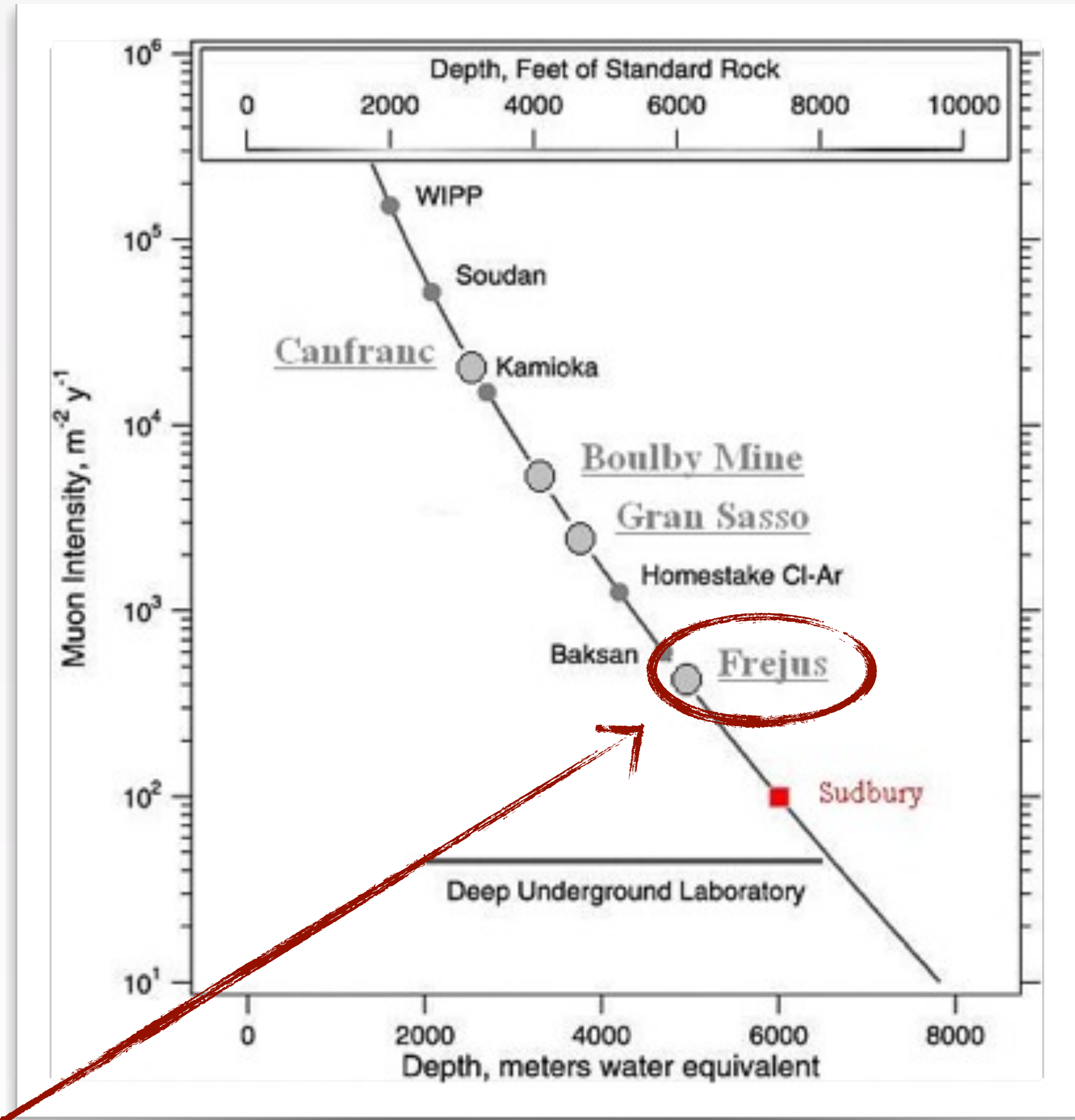
$$\Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}\left|M^{0\nu}\right|^2 \lambda_{V+A}^2$$

Topology can be used to disentangle underlying physics mechanism

Neutrino Ettore Majorana Observatory 3

Data taking: Feb'03 - Jan'11

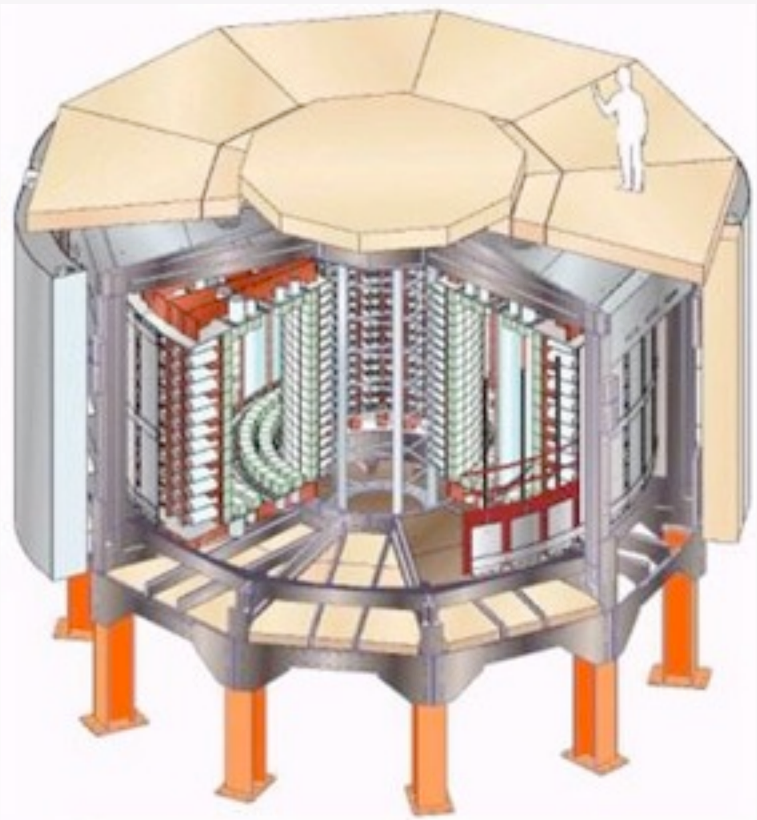




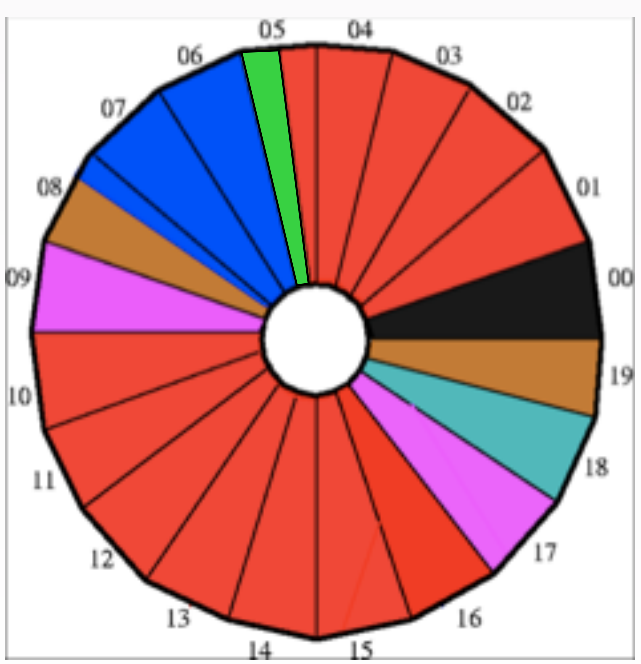
Laboratoire Souterrain de Modane (LSM)
Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

> 10^6 suppression factor for cosmic muons!

NEMO-3 - 20 sectors with ~10 kg of isotopes



- Magnetic field: 25 Gauss
- Gamma shield: 18 cm of pure iron
- Neutron shield:
  - 30cm borated water (external wall)
  - 40cm wood (top and bottom)
- Anti-Radon "factory" and "tent"



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

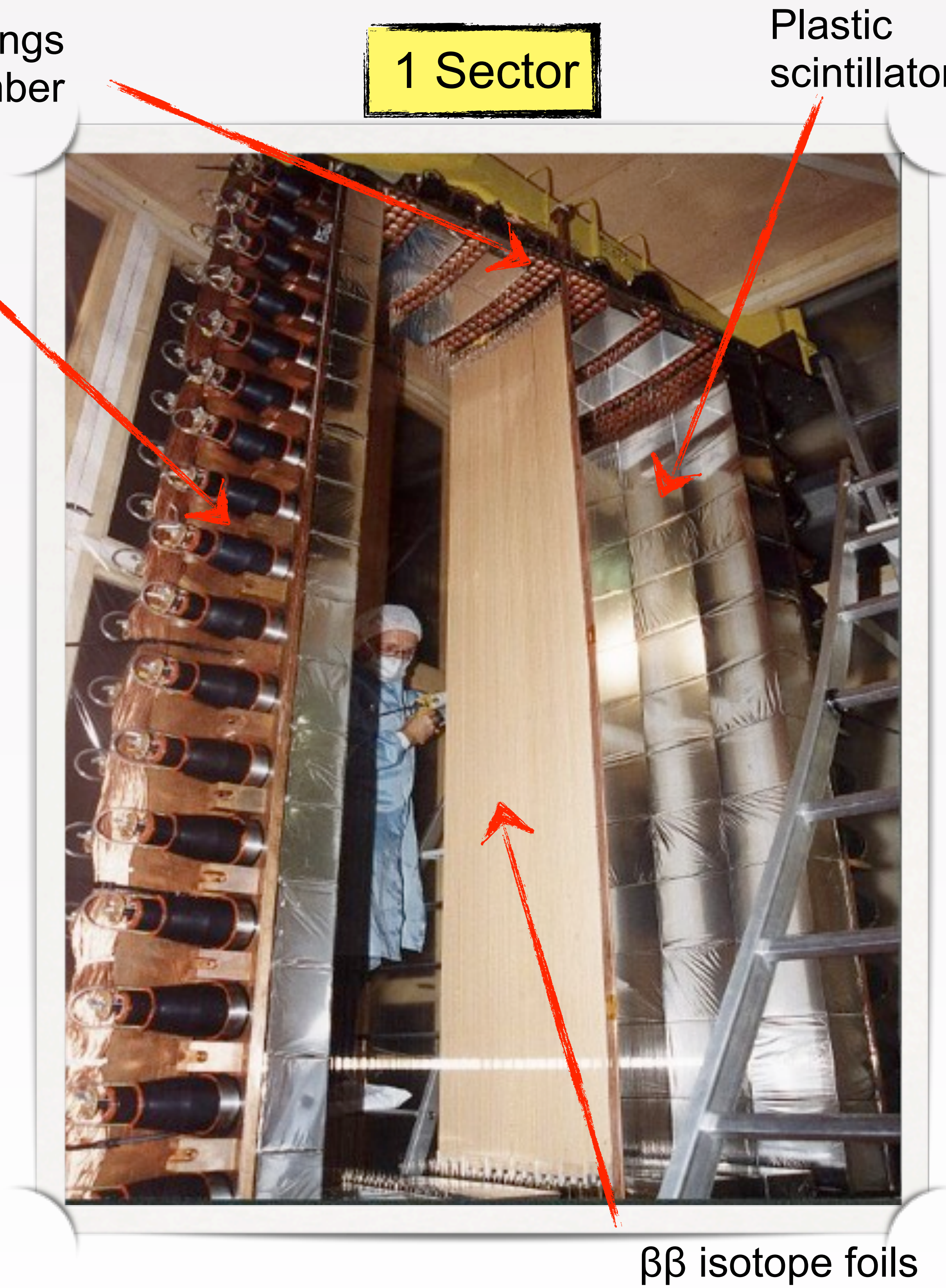
^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te 491 g

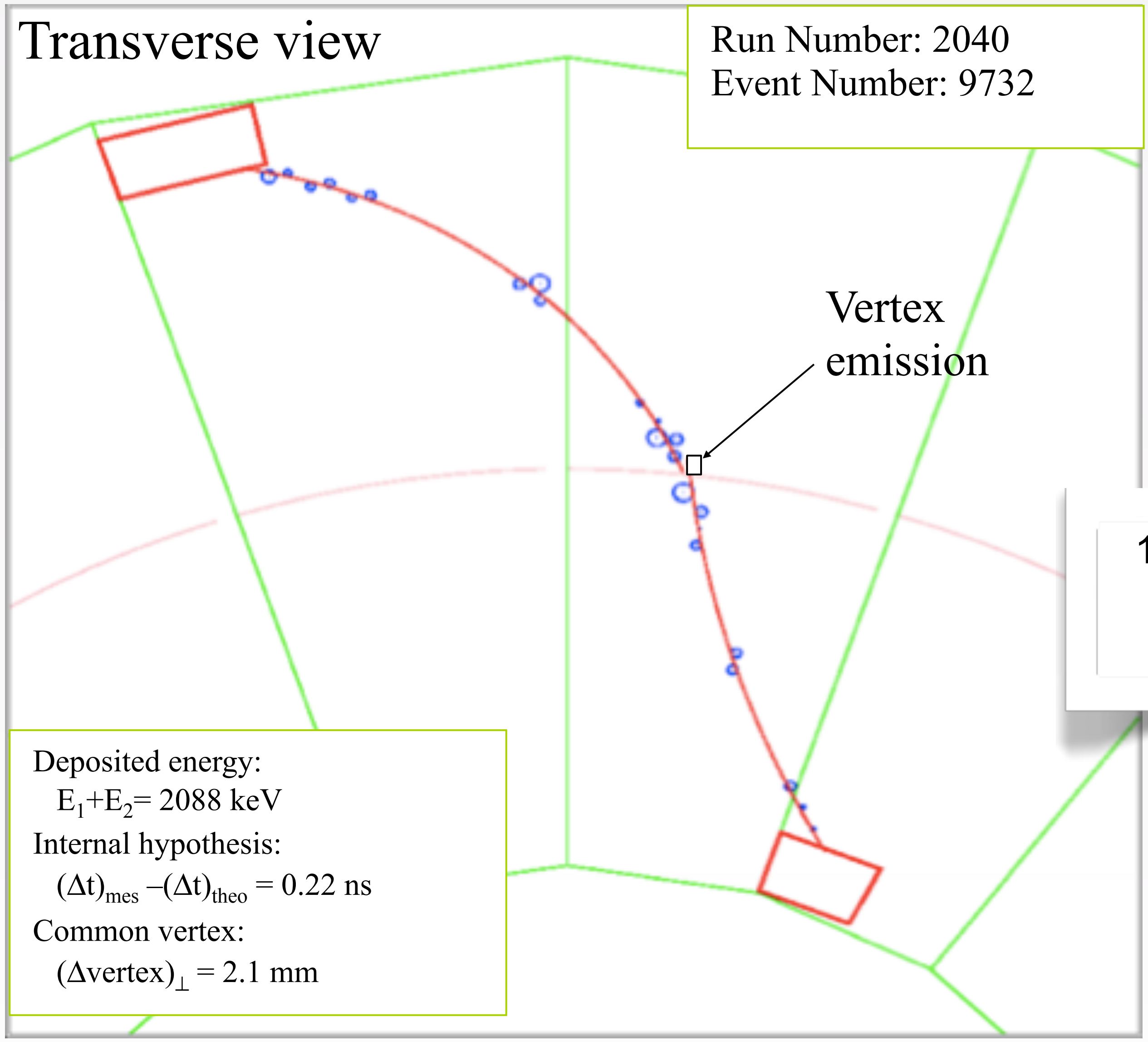
Cu 621 g

NEMO-3 design

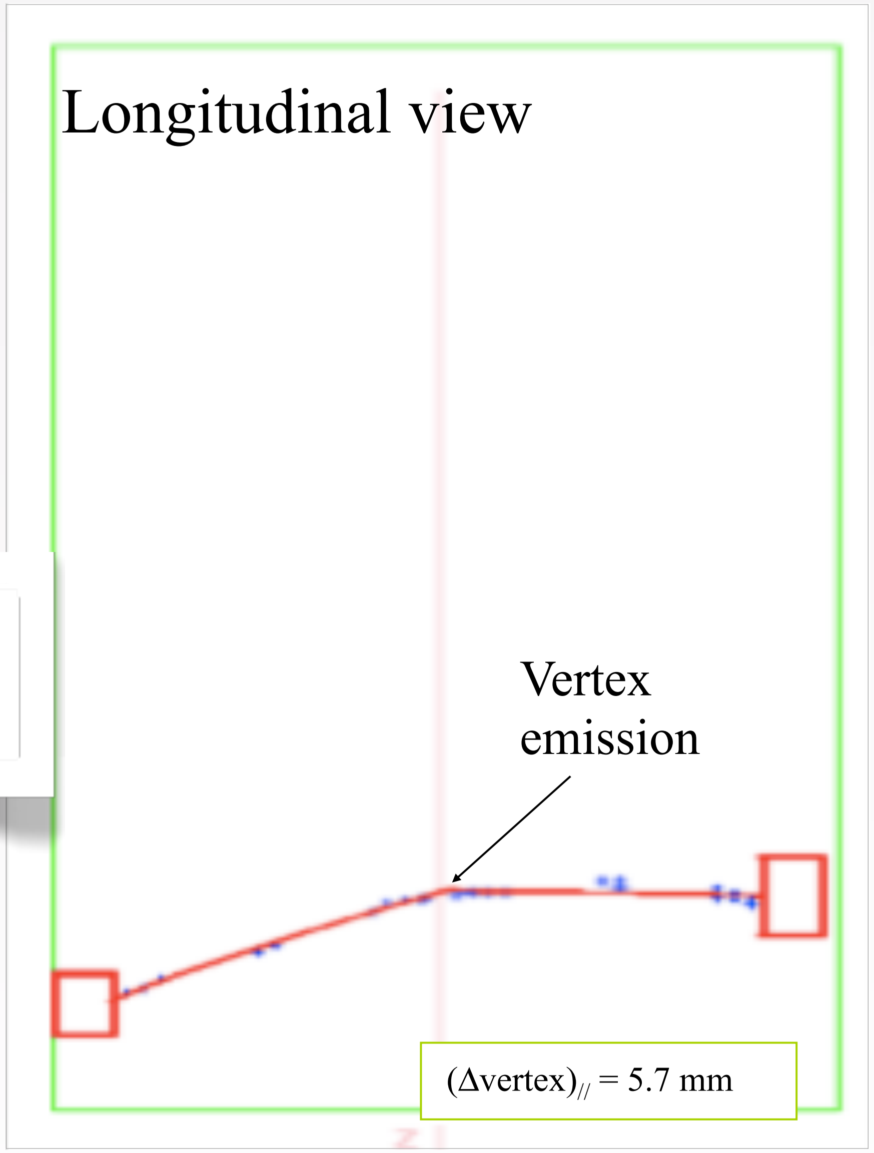
- Tracker for full event reconstruction
  - 6180 drift cells in Geiger mode: Helium + 4% ethyl alcohol + 1% Ar + 0.1% H_2O
- Calorimeter for energy and time measurement
  - 1940 scintillator blocks coupled to low radioactivity PMTs
- Identify e^-, e^+, γ, α
- Identify external and internal events



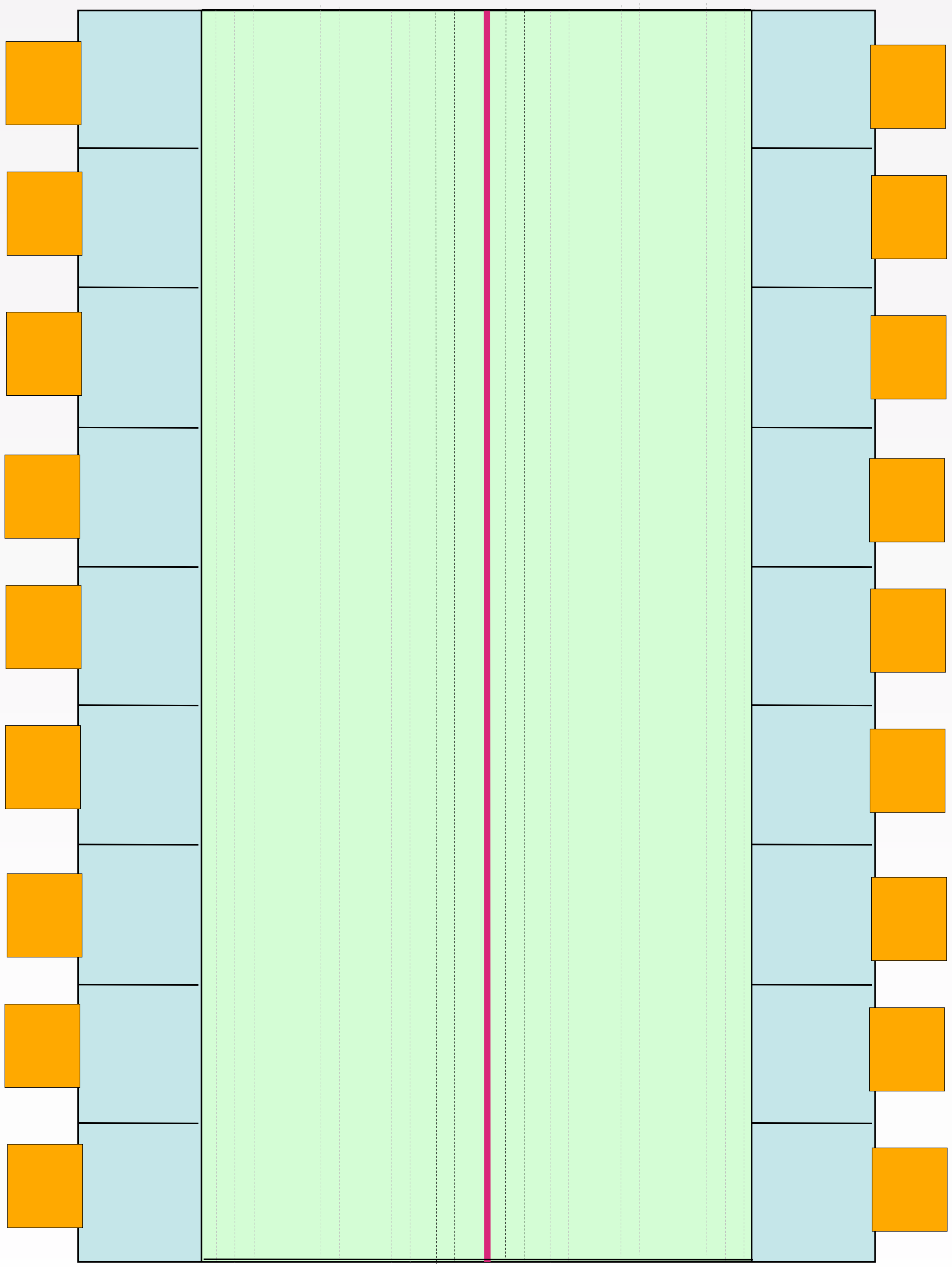
NEMO-3 ββ event selection



1 ββ event every 2,5 minutes! (in ^{100}Mo)



- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex
- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track (^{214}Bi rejection)

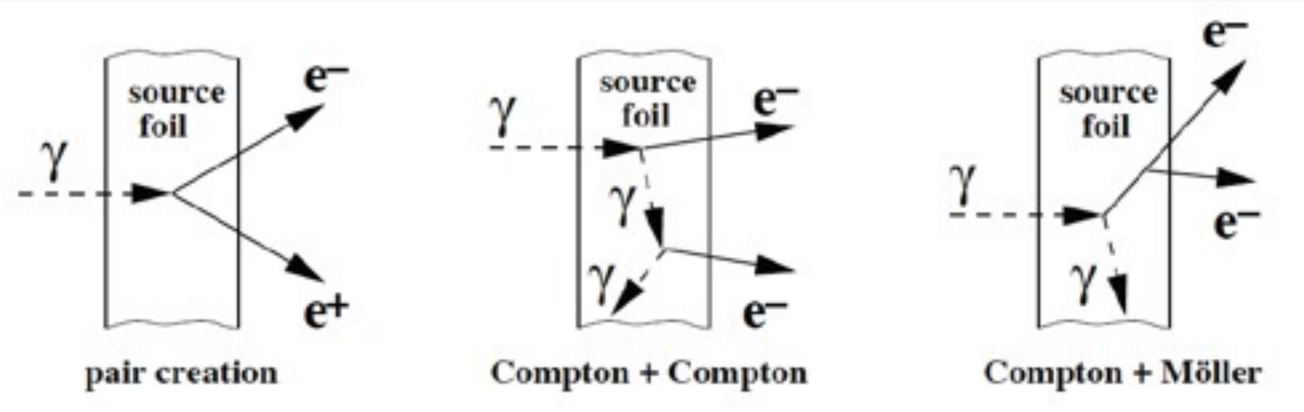


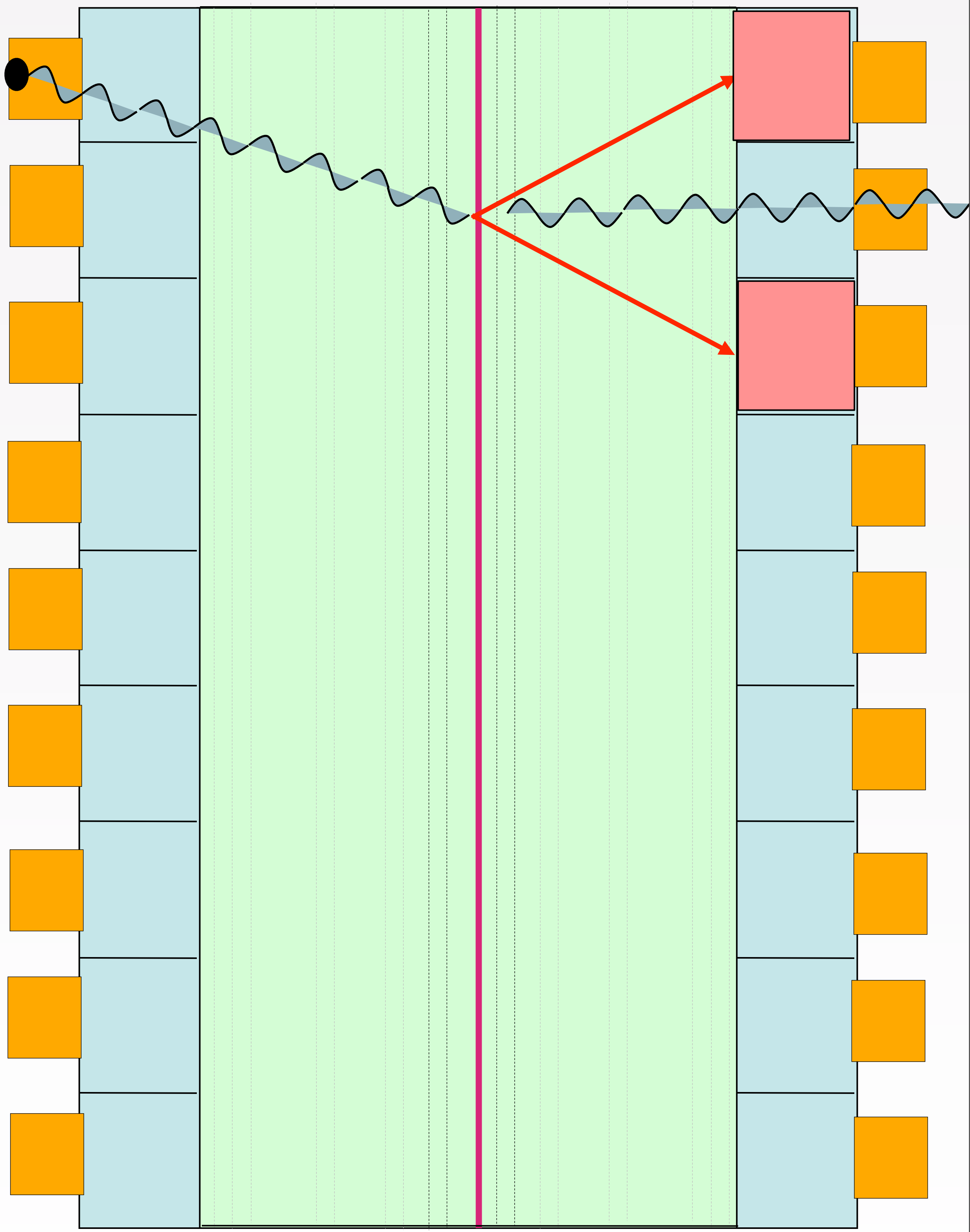
- **External** γ (if the γ is not detected in the scintillators)

  Origin: natural radioactivity of the detector or neutrons

  Major bkg for $2\nu\beta\beta$ but small for $0\nu\beta\beta$

  (^{100}Mo and ^{82}Se $Q_{\beta\beta}$~ 3 MeV > $E\gamma(^{208}Tl)$ ~ 2.6 MeV)



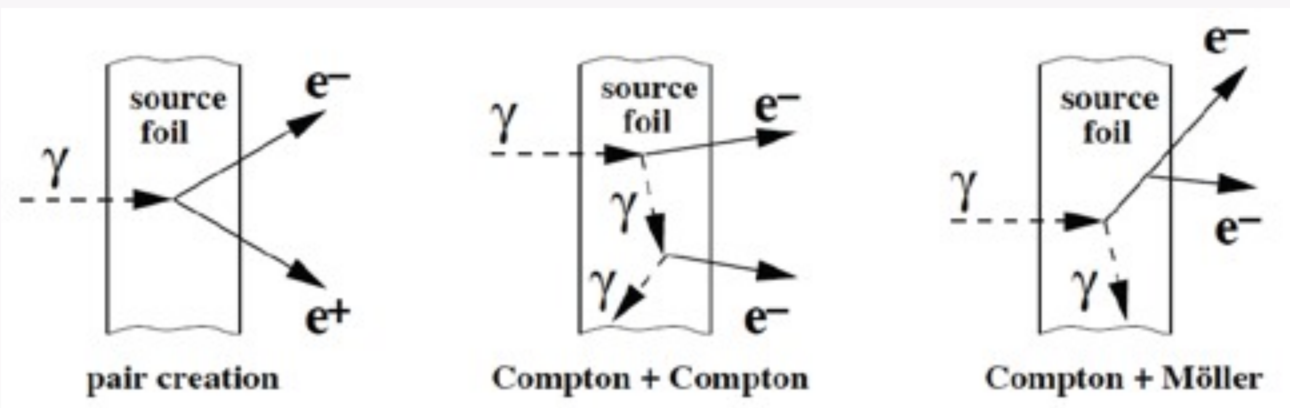


- **External γ** (if the γ is not detected in the scintillators)

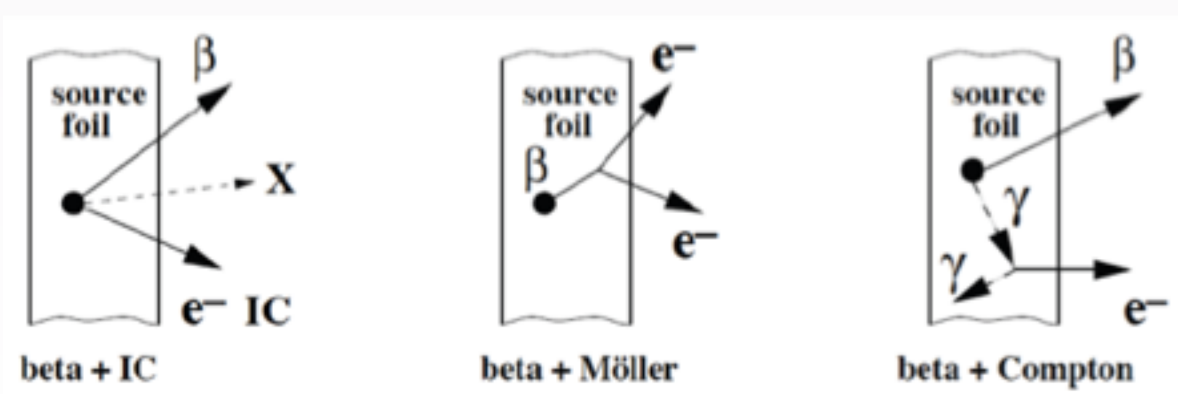
  Origin: natural radioactivity of the detector or neutrons

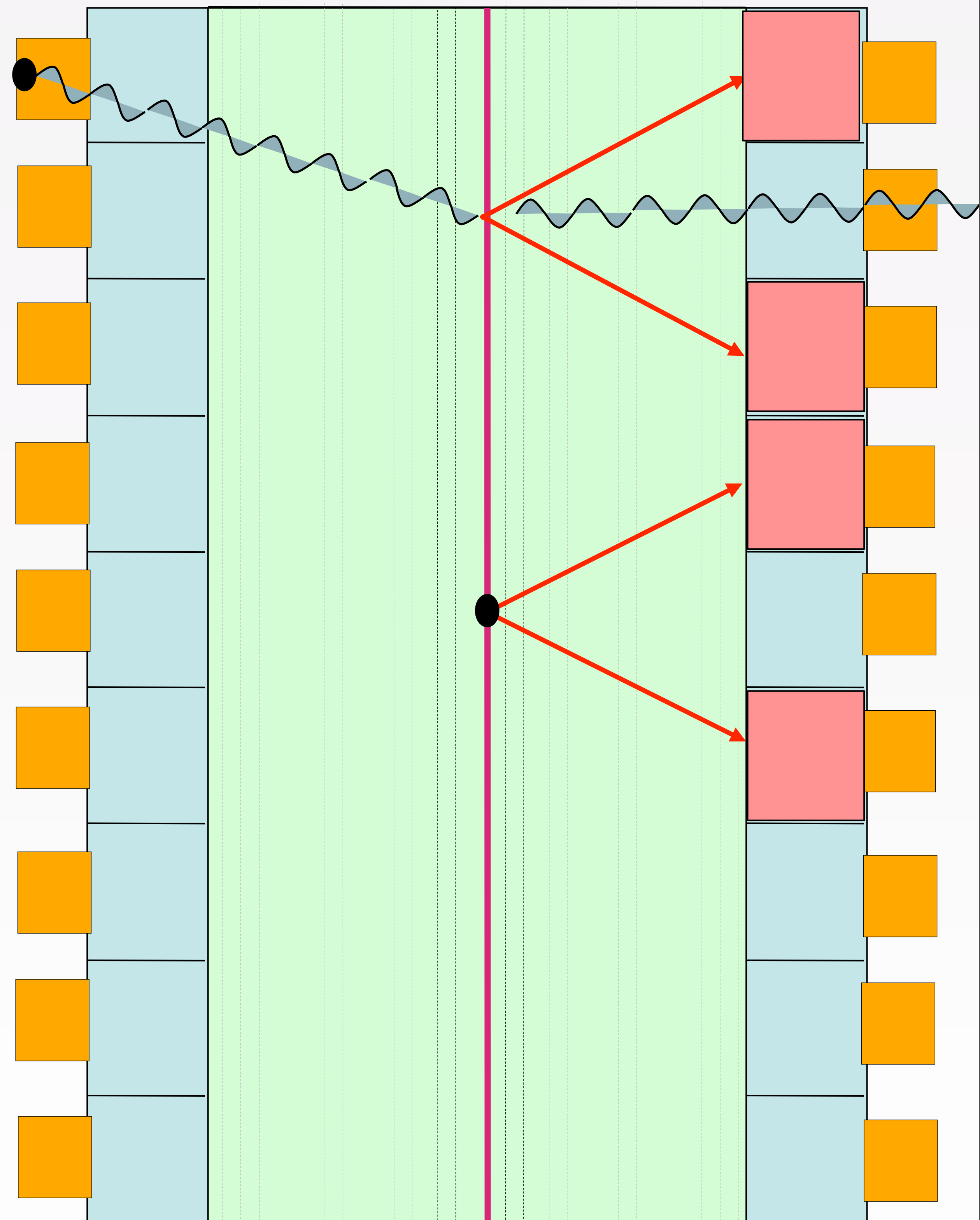
  Major bkg for 2νββ but small for 0νββ

  (^{100}Mo and ^{82}Se $Q_{\beta\beta}$~ 3 MeV > Eγ(^{208}Tl) ~ 2.6 MeV)

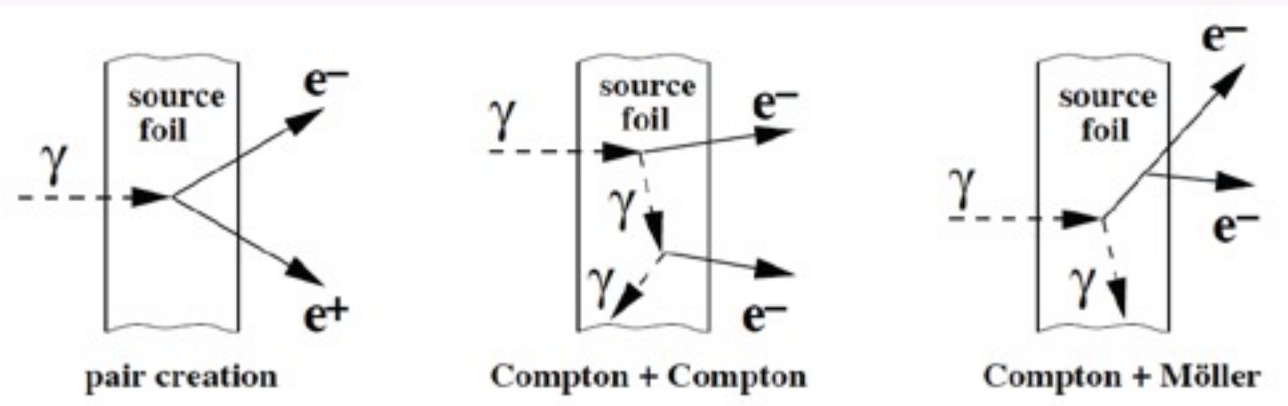


- **^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi) contamination inside the ββ source foil**

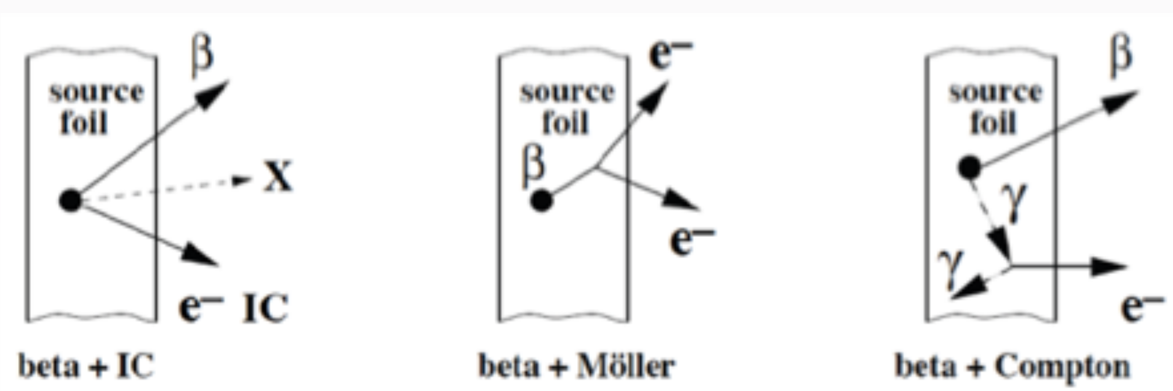




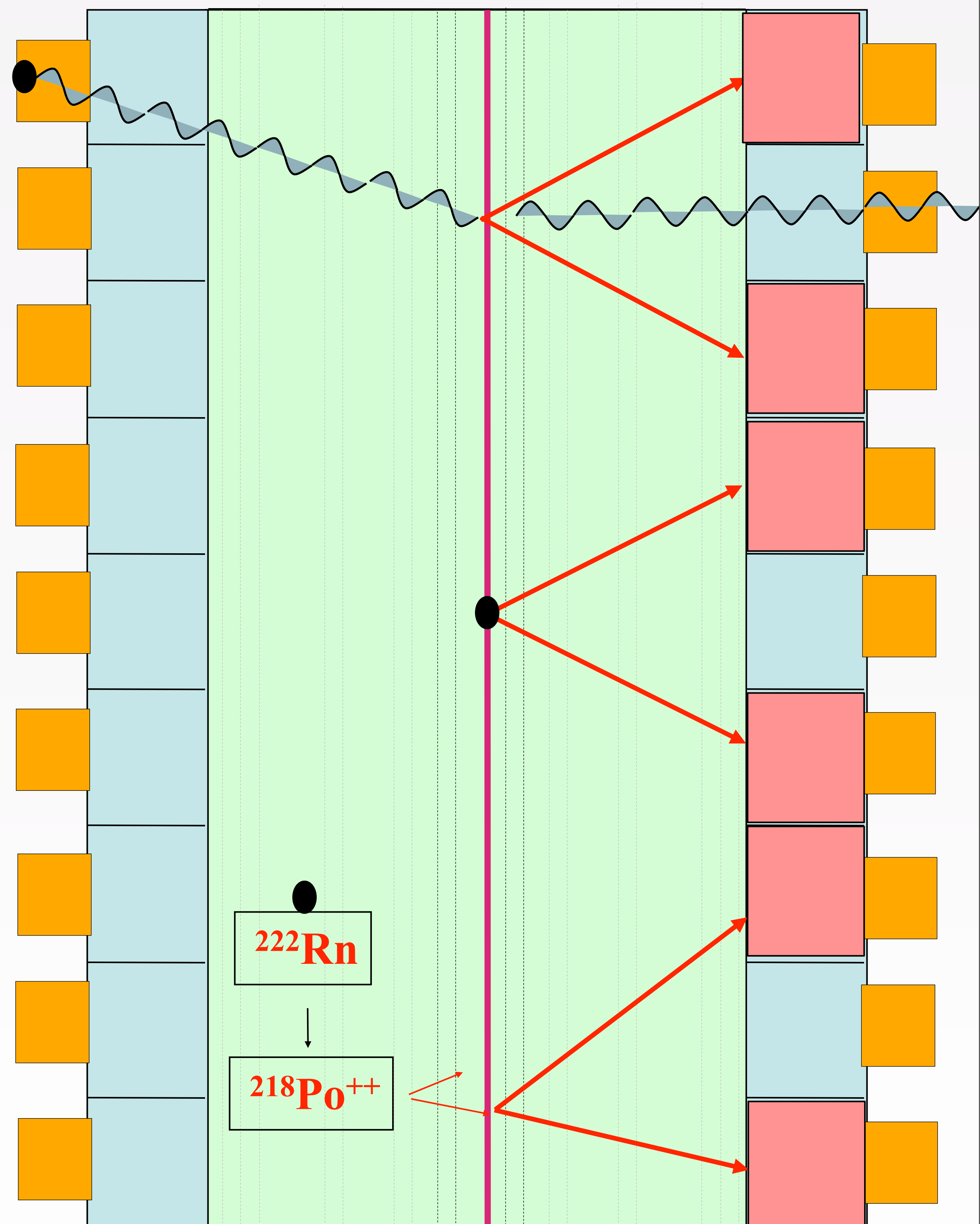
- **External γ** (if the γ is not detected in the scintillators)
  Origin: natural radioactivity of the detector or neutrons
  Major bkg for 2νββ but small for 0νββ
  (^{100}Mo and ^{82}Se $Q_{\beta\beta} \sim 3$ MeV > Eγ(^{208}Tl) ~ 2.6 MeV)



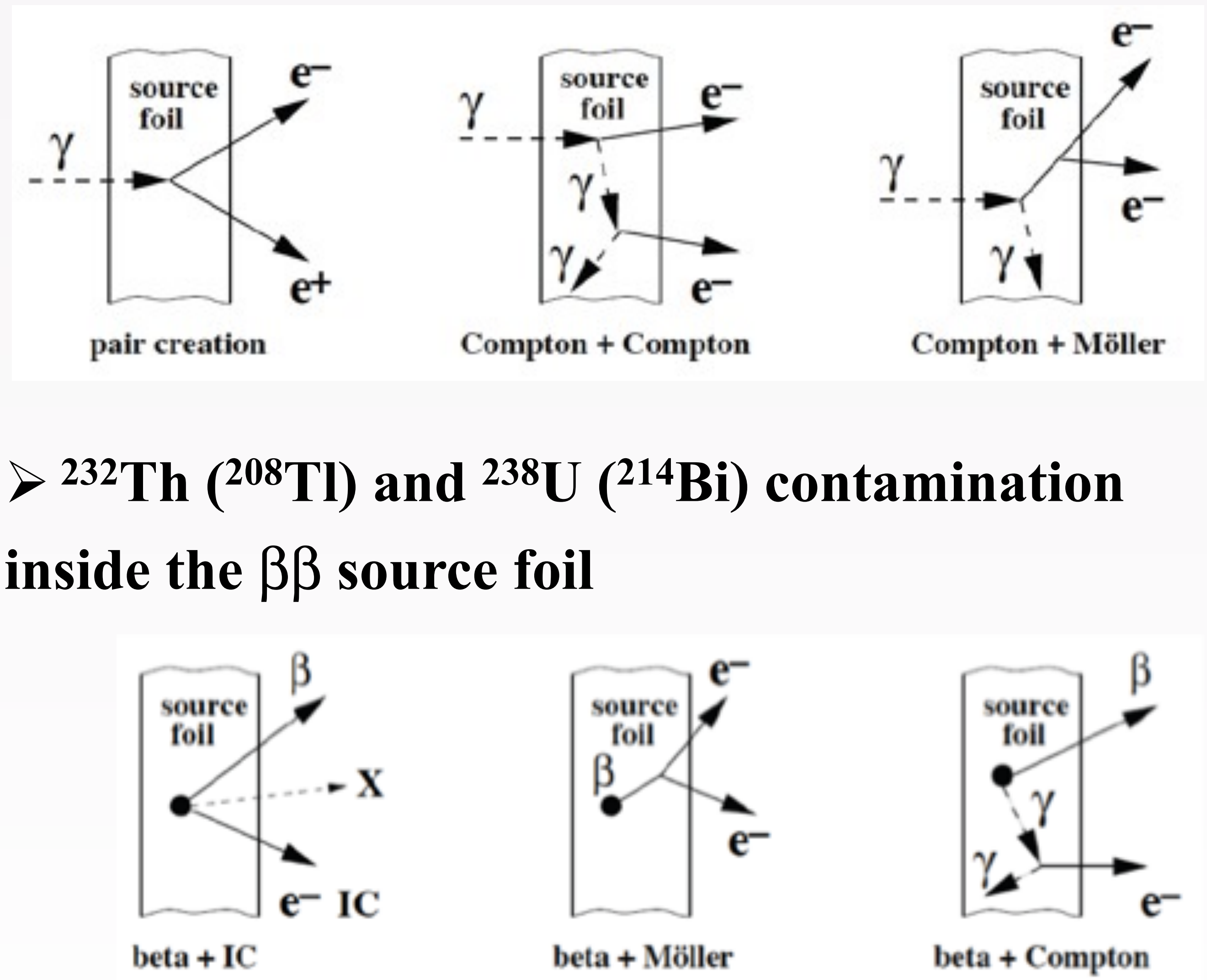
- **^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi) contamination inside the ββ source foil**



- **Radon (^{214}Bi) inside the tracking detector**
  - deposits on the wire near the ββ foil
  - deposits on the surface of the ββ foil

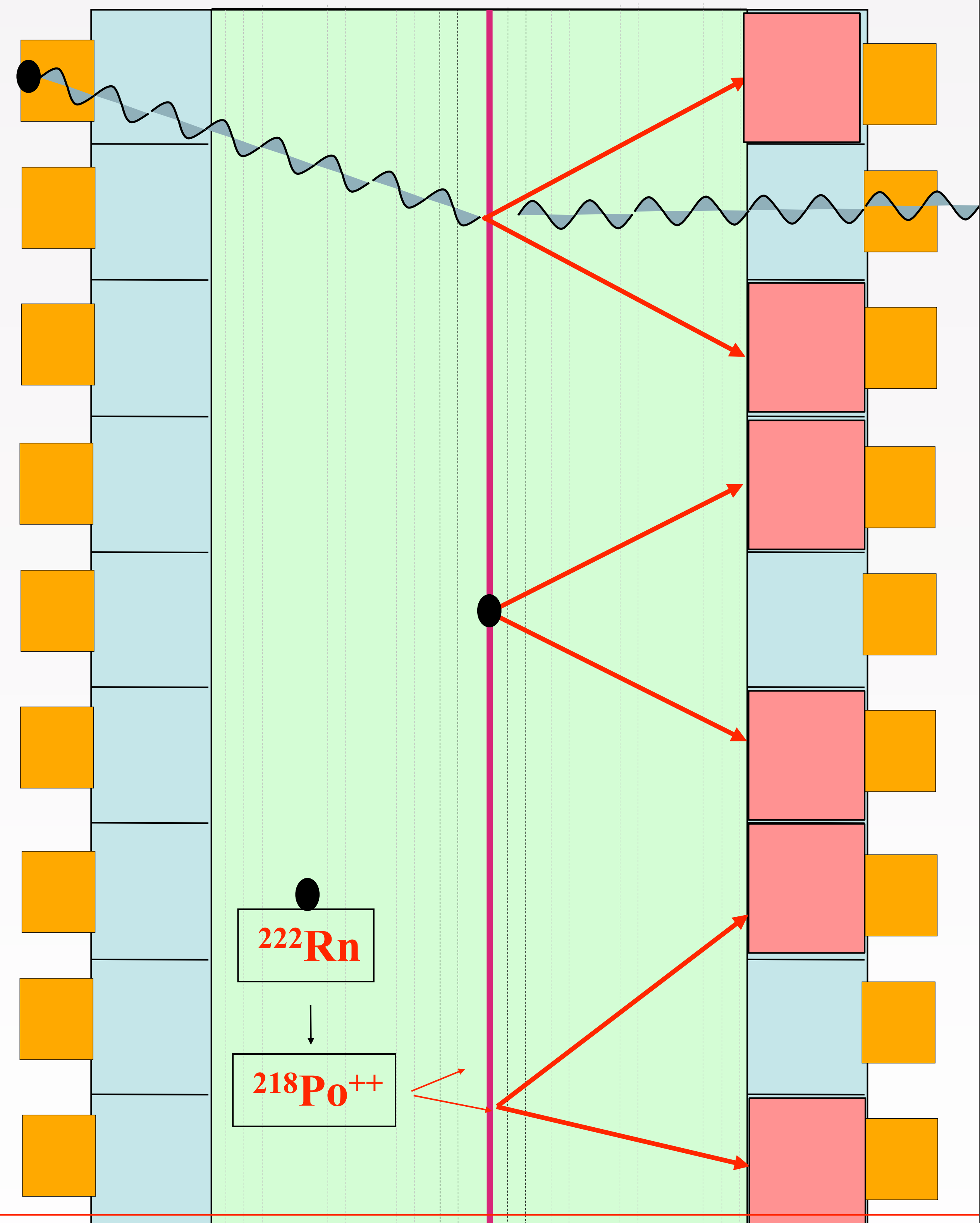


- **External** γ (if the γ is not detected in the scintillators)
  Origin: natural radioactivity of the detector or neutrons
  Major bkg for $2\nu\beta\beta$ but small for $0\nu\beta\beta$
  (^{100}Mo and ^{82}Se $Q_{\beta\beta}$~ 3 MeV > Eγ(^{208}Tl) ~ 2.6 MeV)

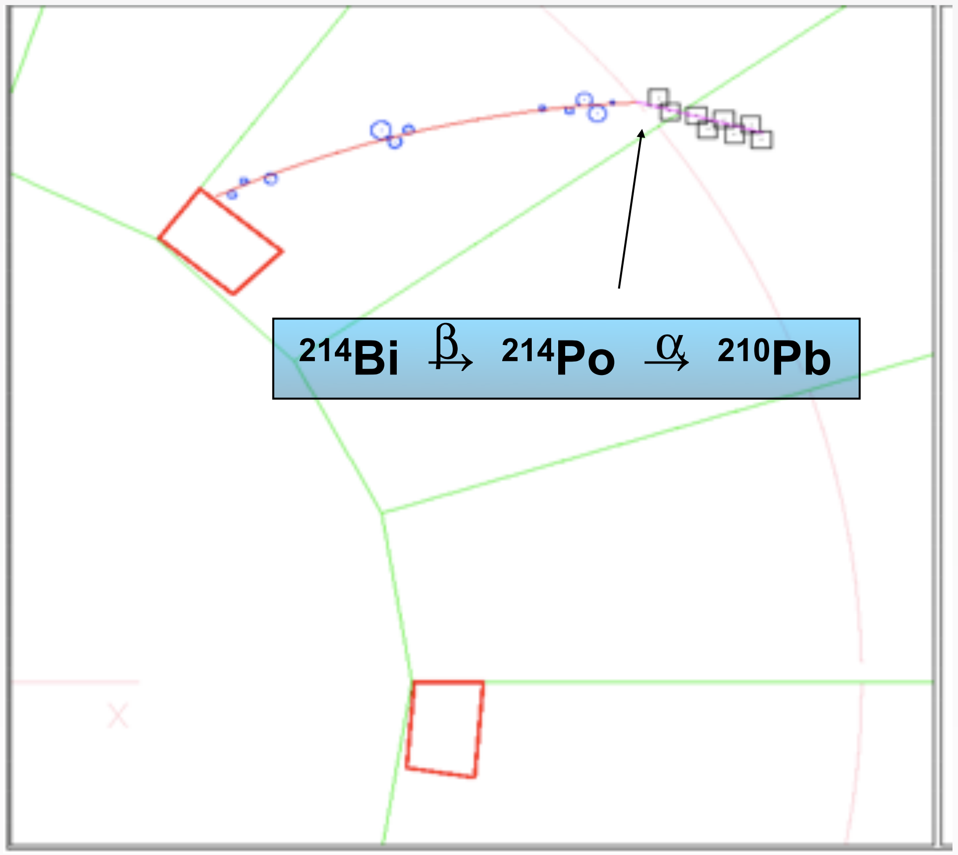


- **^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi) contamination inside the $\beta\beta$ source foil**

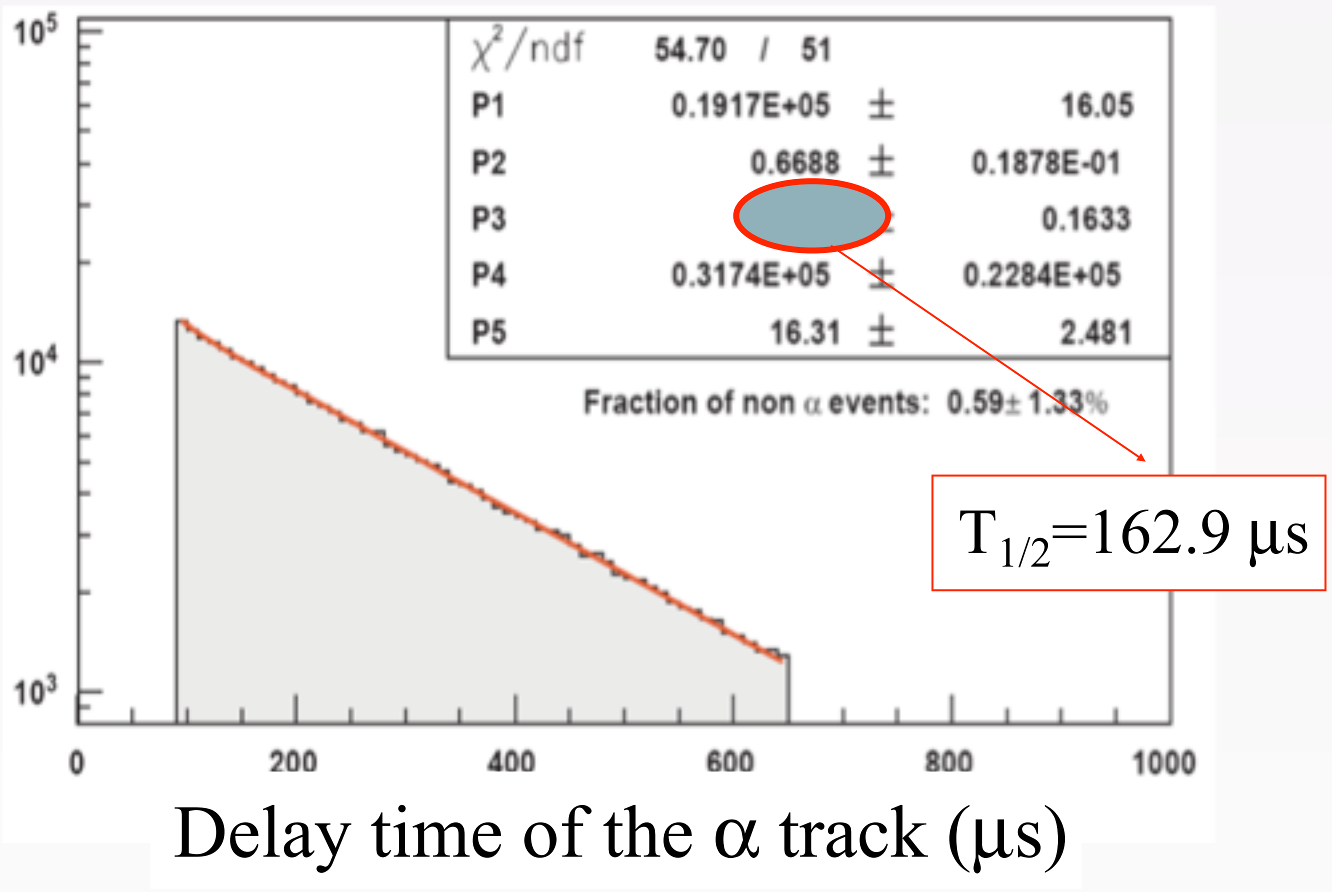
- **Radon (^{214}Bi) inside the tracking detector**
  - deposits on the wire near the $\beta\beta$ foil
  - deposits on the surface of the $\beta\beta$ foil



Each bkg is measured using the NEMO-3 data



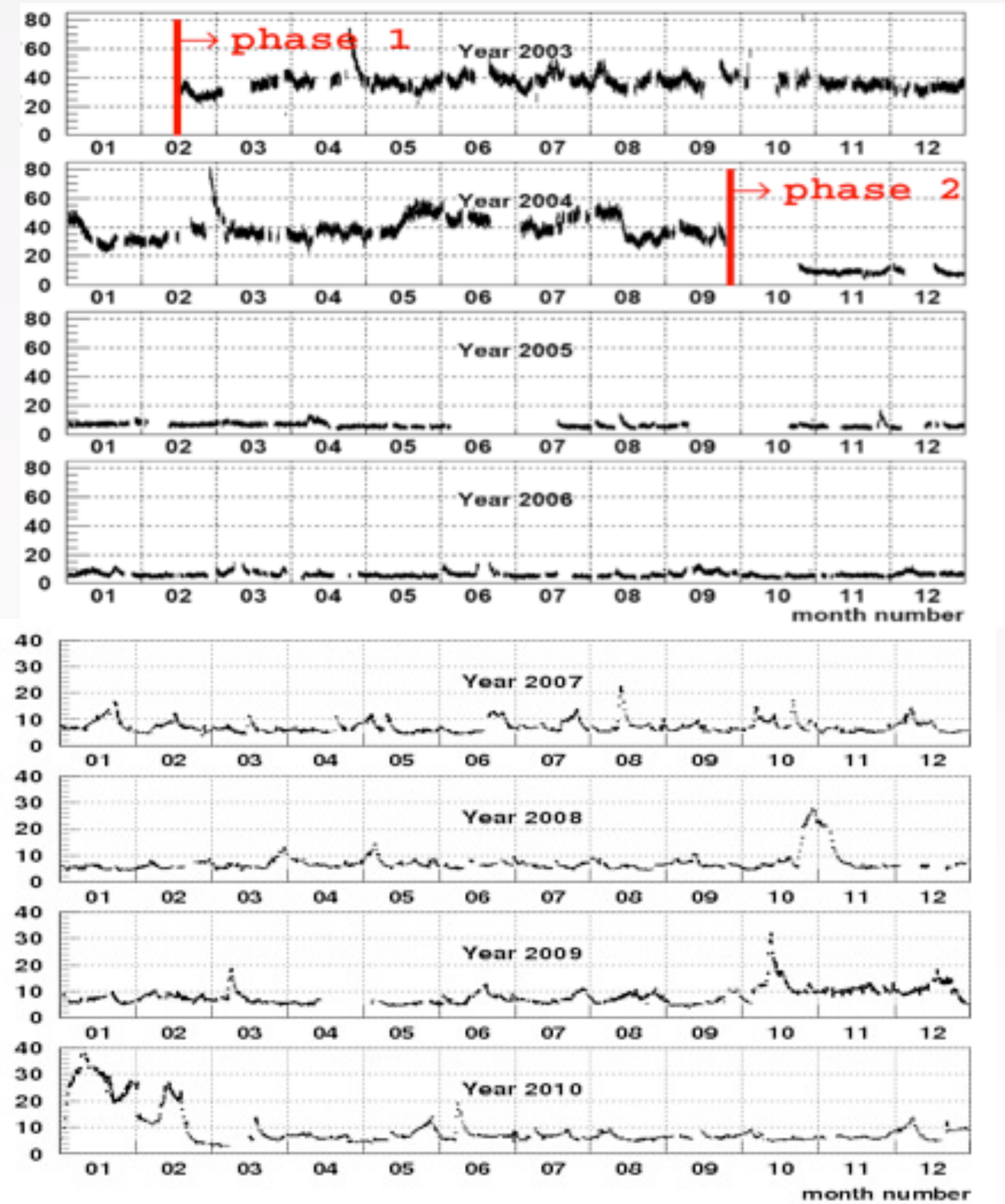
Pure sample of $^{214}Bi - ^{214}Po$ events



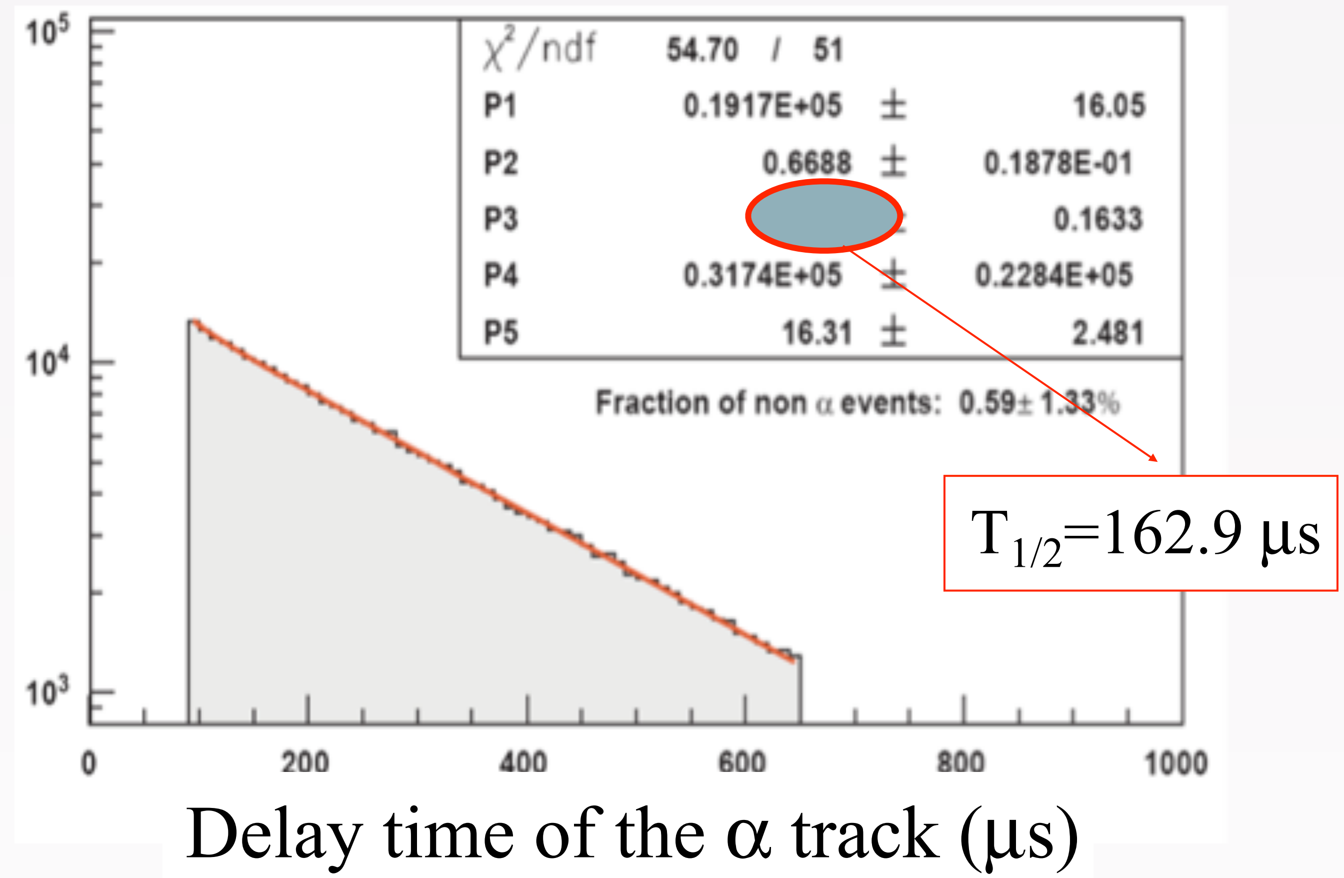
Radon

Anti-radon "factory" - trapping Rn in cooled charcoal. A must for a low-background lab.

Measurements of ^{222}Rn activity in the gas of tracker (mBq/m^3)



Pure sample of $^{214}Bi - ^{214}Po$ events



Anti-Rn factory: Input=15Bq/m^3 →Output 15mBq/m^3

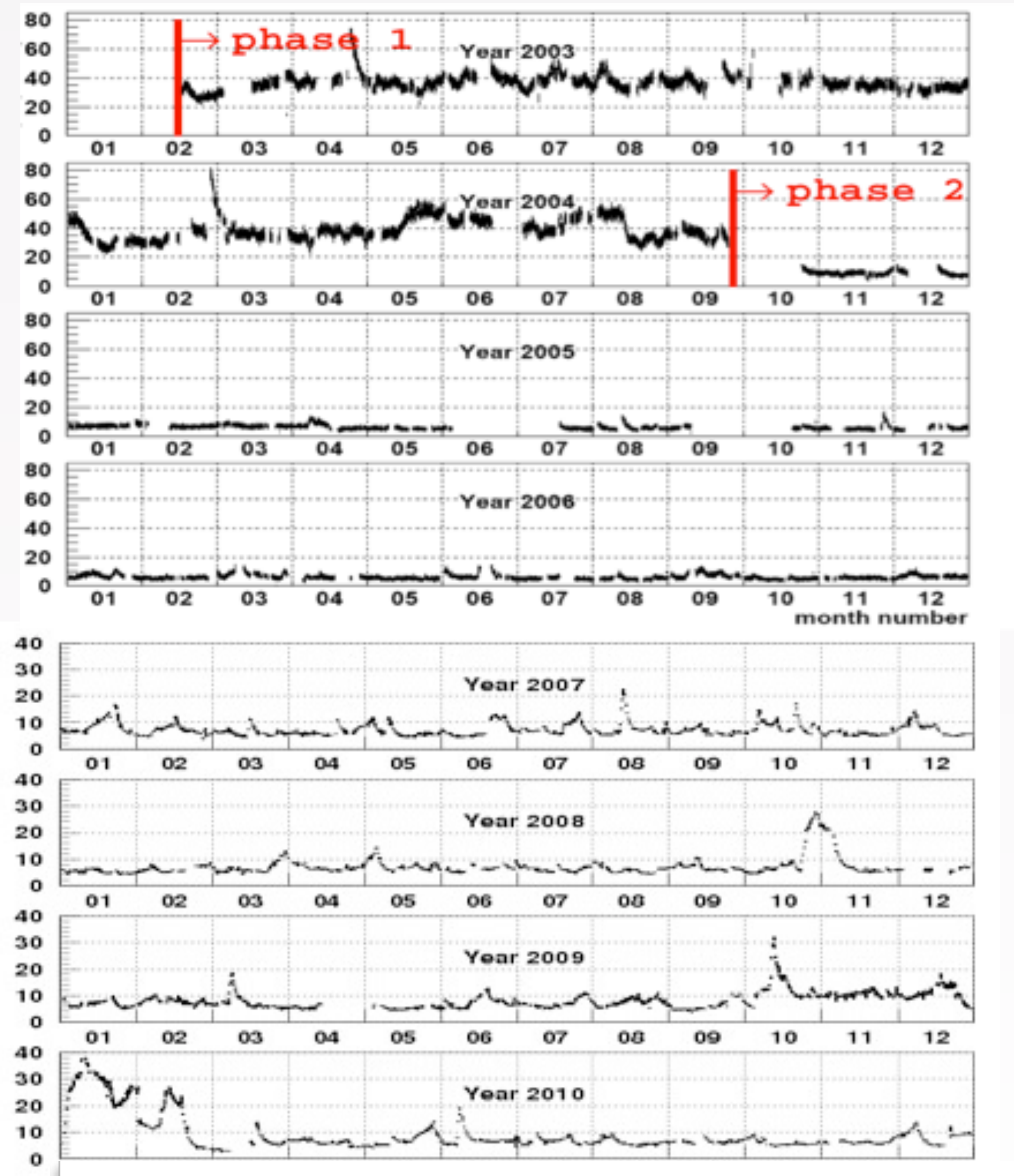
Inside the detector:

- Phase 1: Feb'03 → Sep'04
  A(Radon) ≈ 40 mBq/m^3
- Phase 2: Dec. 2004 → Jan'11
  A (Radon) ≈ 5 mBq/m^3

Radon

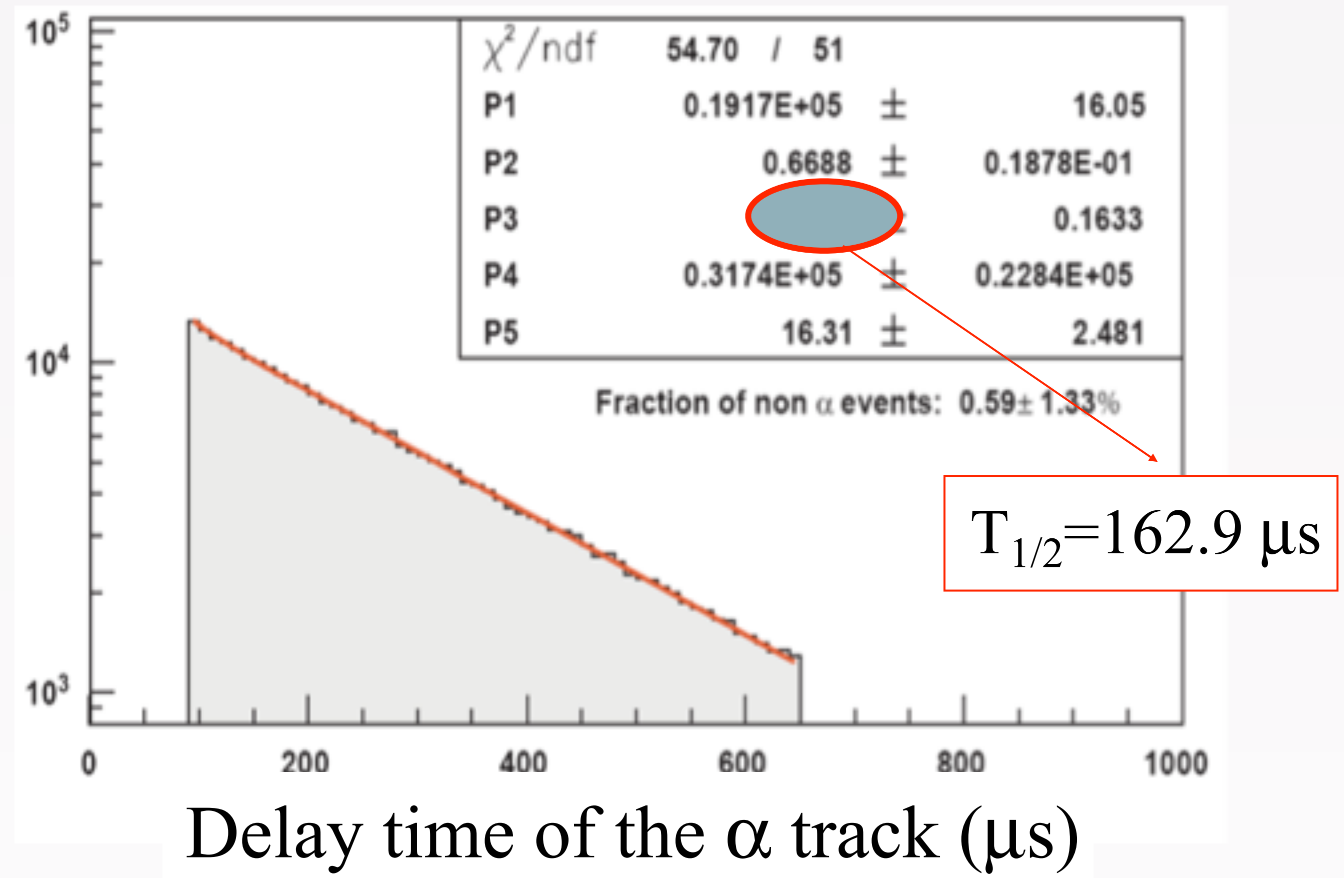
Anti-radon "factory" - trapping Rn in cooled charcoal. A must for a low-background lab.

Measurements of ^{222}Rn activity in the gas of tracker (mBq/m^3)



"Handbook" on backgrounds for ββ experiments:
Background measurement in NEMO3:
NIM A 606 (2009) pp. 449-465.

Pure sample of $^{214}Bi - ^{214}Po$ events



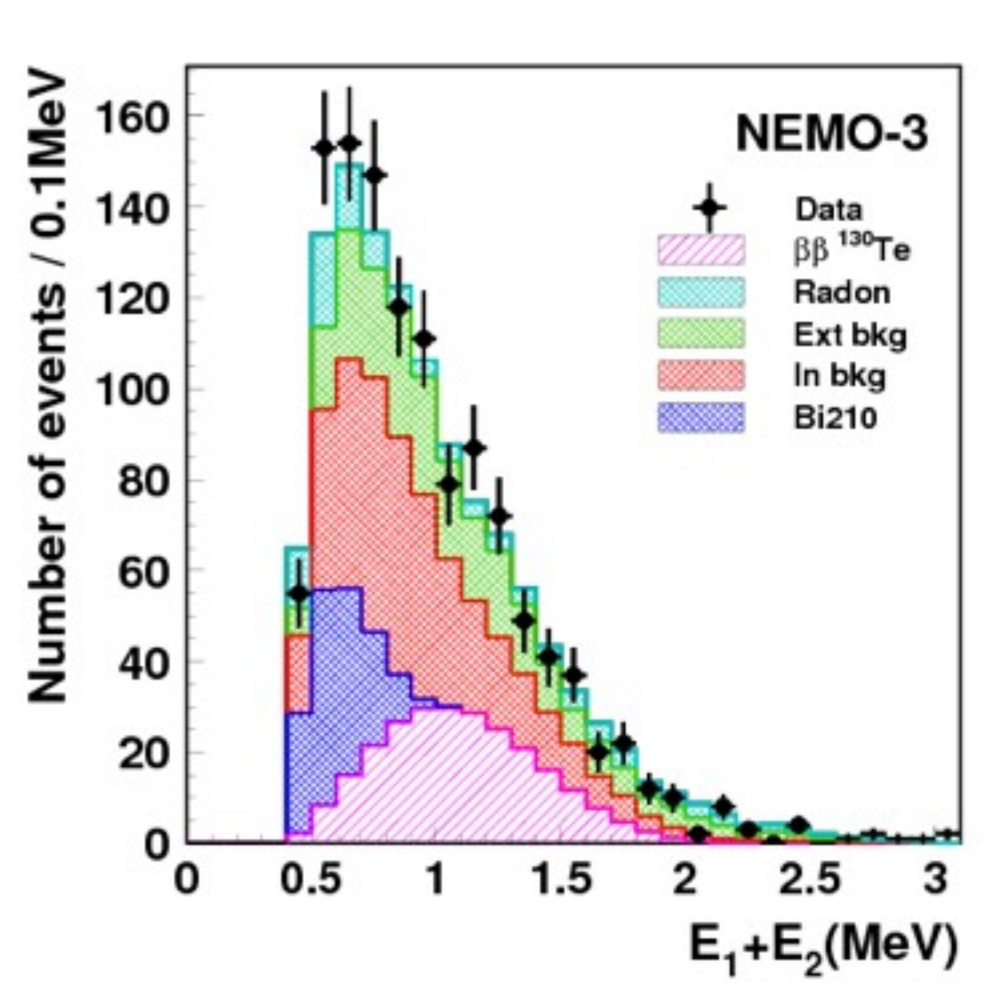
Anti-Rn factory: Input=15Bq/m^3 →Output 15mBq/m^3

Inside the detector:

- Phase 1: Feb'03 → Sep'04
  A(Radon) ≈ 40 mBq/m^3
- Phase 2: Dec. 2004 → Jan'11
  A (Radon) ≈ 5 mBq/m^3

NEMO-3 recent results (2011)

661 g of ^{130}Te



1275 days

N(2νββ) = 178 ± 23

$$T_{1/2}^{2\nu} = [7.0 \pm 0.9(stat) \pm 1.1(syst)] \times 10^{20} \text{ yr}$$

Phys. Rev. Lett. 107, 062504 (2011)

c.f.

Indirect observations (geochemistry):
- ~2.7 x 10^{21} yrs in 10^9 yr old rocks
- ~8 x10^{20} yrs in 10^7-10^8 yr old rocks

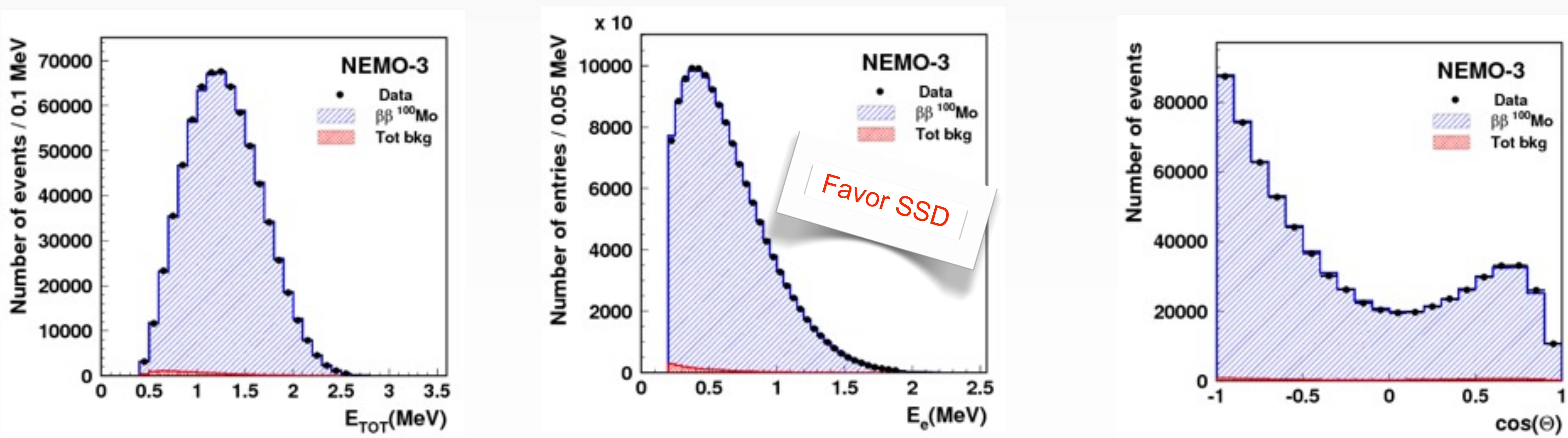
Indication from MIBETA

$$T_{1/2}^{2\nu} = [6.1 \pm 1.4(stat)^{+2.9}_{-3.5}(syst)] \times 10^{20} \text{ yr}$$

$2\nu\beta\beta$ Results

Isotope	Mass (g)	$Q_{\beta\beta}$(keV)	$T_{1/2}(2\nu)$ (10^{19}yrs)	S/B	Comment	Reference
^{82}Se	932	2996	9.6 ± 1.0	4	World's best	Phys.Rev.Lett. 95(2005) 483
^{116}Cd	405	2809	2.8 ± 0.3	10	World's best	
^{150}Nd	37	3367	0.9 ± 0.07	2.7	World's best	Phys. Rev. C 80, 032501 (2009)
^{96}Zr	9.4	3350	2.35 ± 0.21	1	World's best	Nucl.Phys.A 847(2010) 168
^{48}Ca	7	4271	4.4 ± 0.6	6.8 (h.e.)	World's best	
^{100}Mo	6914	3034	0.71 ± 0.05	80	World's best	Phys.Rev.Lett. 95(2005) 483
^{130}Te	454	2533	70 ± 14	0.5	First direct detection	Phys. Rev. Lett. 107, 062504 (2011)

Unprecedented accuracy with ^{100}Mo

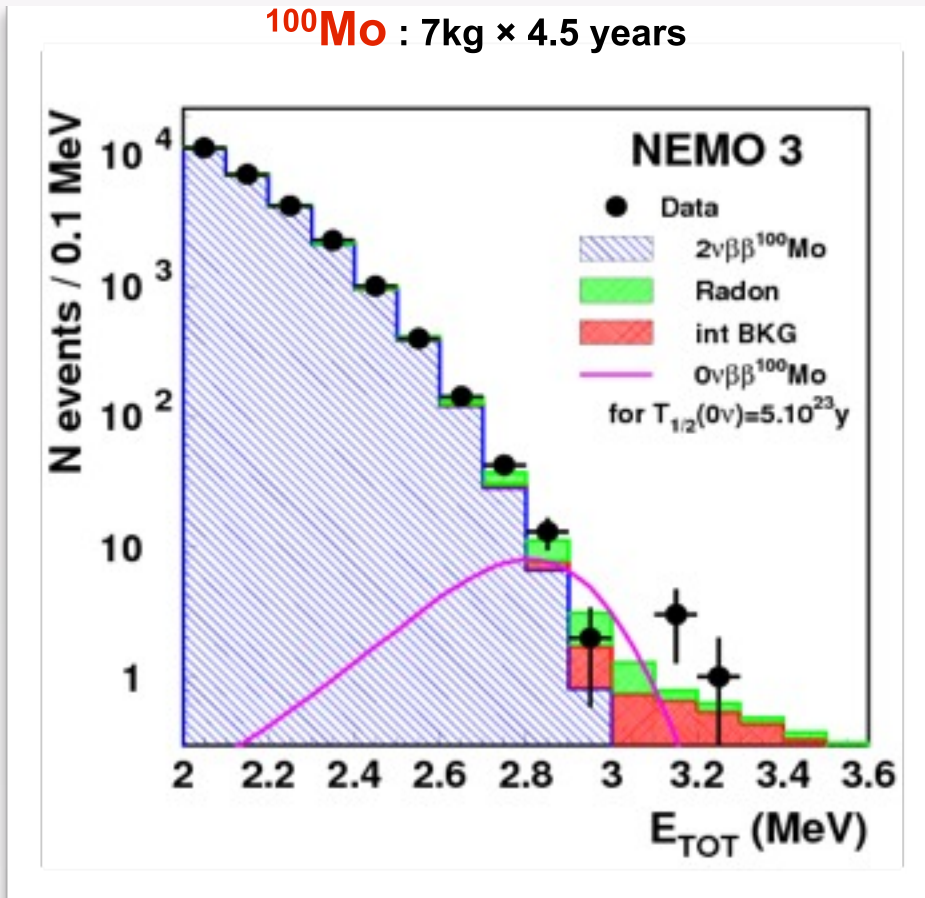


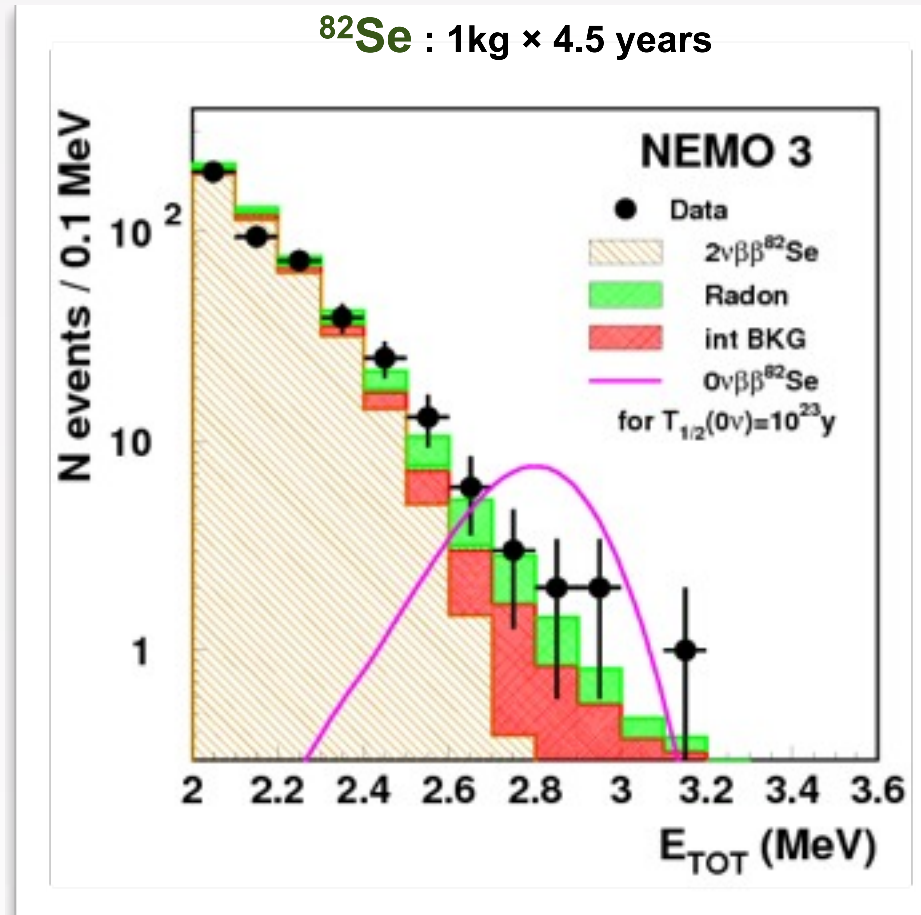
Crucial experimental input for 1) NME calculations

2) Ultimate background characterisation for 0ν

Search for 0νββ

Data period: Feb'03 - Dec'09





[2.8-3.2] MeV: DATA = 18; MC = 16.4±1.4

$T_{1/2}(0\nu) > 1.0\times10^{24}$ yr at 90%CL

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

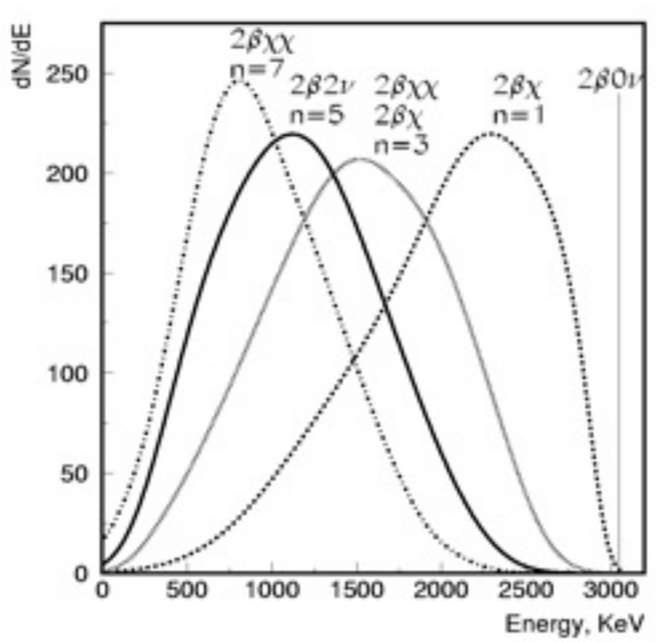
[2.6-3.2] MeV: DATA = 14; MC = 10.9±1.3

$T_{1/2}(0\nu) > 3.2\times10^{23}$ yr at 90%CL

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

c.f. CUORICINO: $\langle m_\nu \rangle < (0.3 - 0.7)$ eV; Combined H-M/IGEX $\langle m_\nu \rangle < (0.22 - 0.41)$ eV

Other 0νββ modes



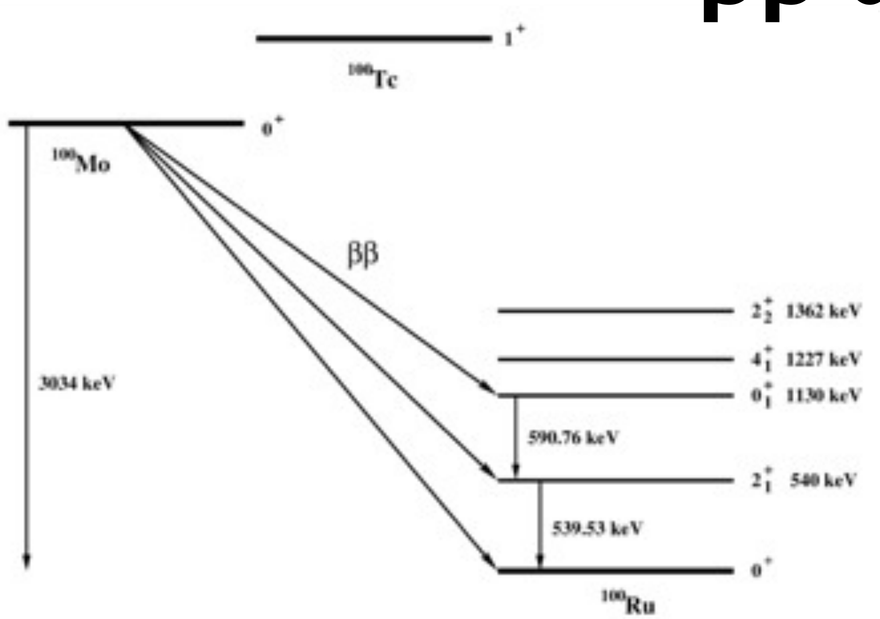
Majoron emission would distort the shape of the energy sum spectrum

	V+A*	n=1**	n=2**	n=3**	n=7**
Mo	$>5.7\cdot10^{23}$ $\lambda<1.4\cdot10^{-6}$	$>2.7\cdot10^{22}$ **$G_{ee}<(0.4-1.8)\cdot10^{-4}$**	$>1.7\cdot10^{22}$	$>1.0\cdot10^{22}$	$>7\cdot10^{19}$
Se	$>2.4\cdot10^{23}$ $\lambda<2.0\cdot10^{-6}$	$>1.5\cdot10^{22}$ $G_{ee}<(0.7-1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{21}$	$>5\cdot10^{20}$

n: spectral index, limits on half-life in years
* Phase I+Phase II data (including 2008)
** Phase I data, ***R.Arnold et al. Nucl. Phys. A765 (2006) 483***

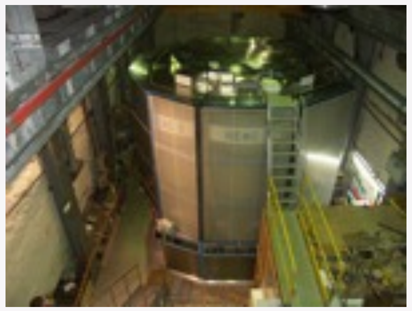
World's best

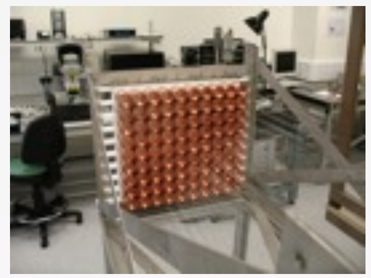
ββ decays to excited states

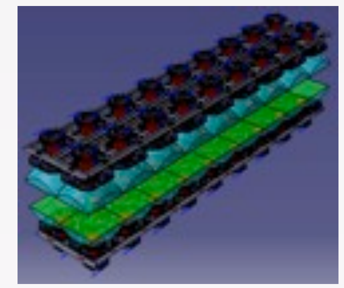


$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9}$ (stat) ± 0.8 (syst) × 10^{20} y
$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22}$ y @ 90% C.L.
$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ y @90% C.L.
$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23}$ y @ 90% C.L.
Nuclear Physics A781 (2006) 209-226.

From NEMO-3 to SuperNEMO





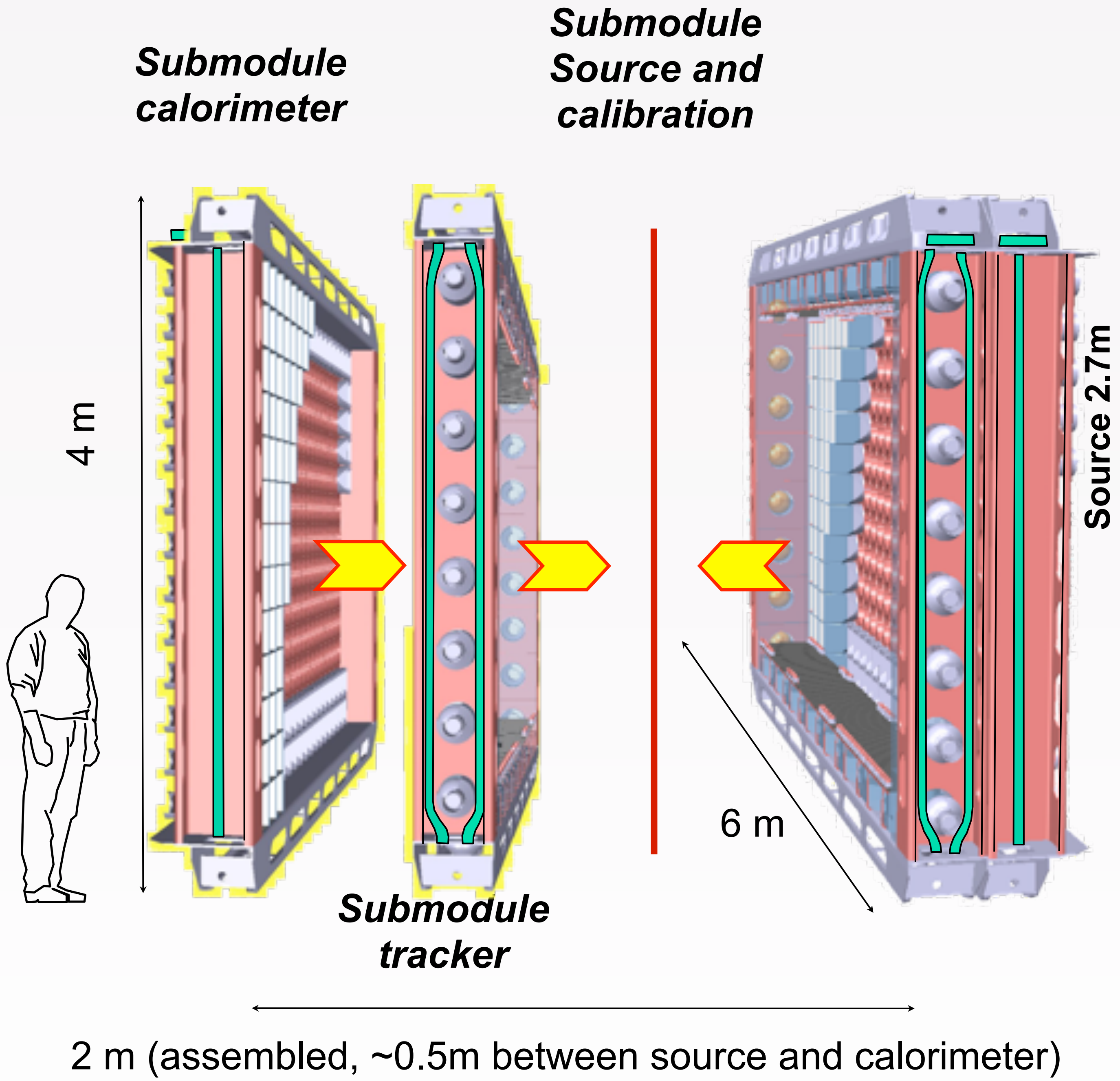


supernemo collaboration

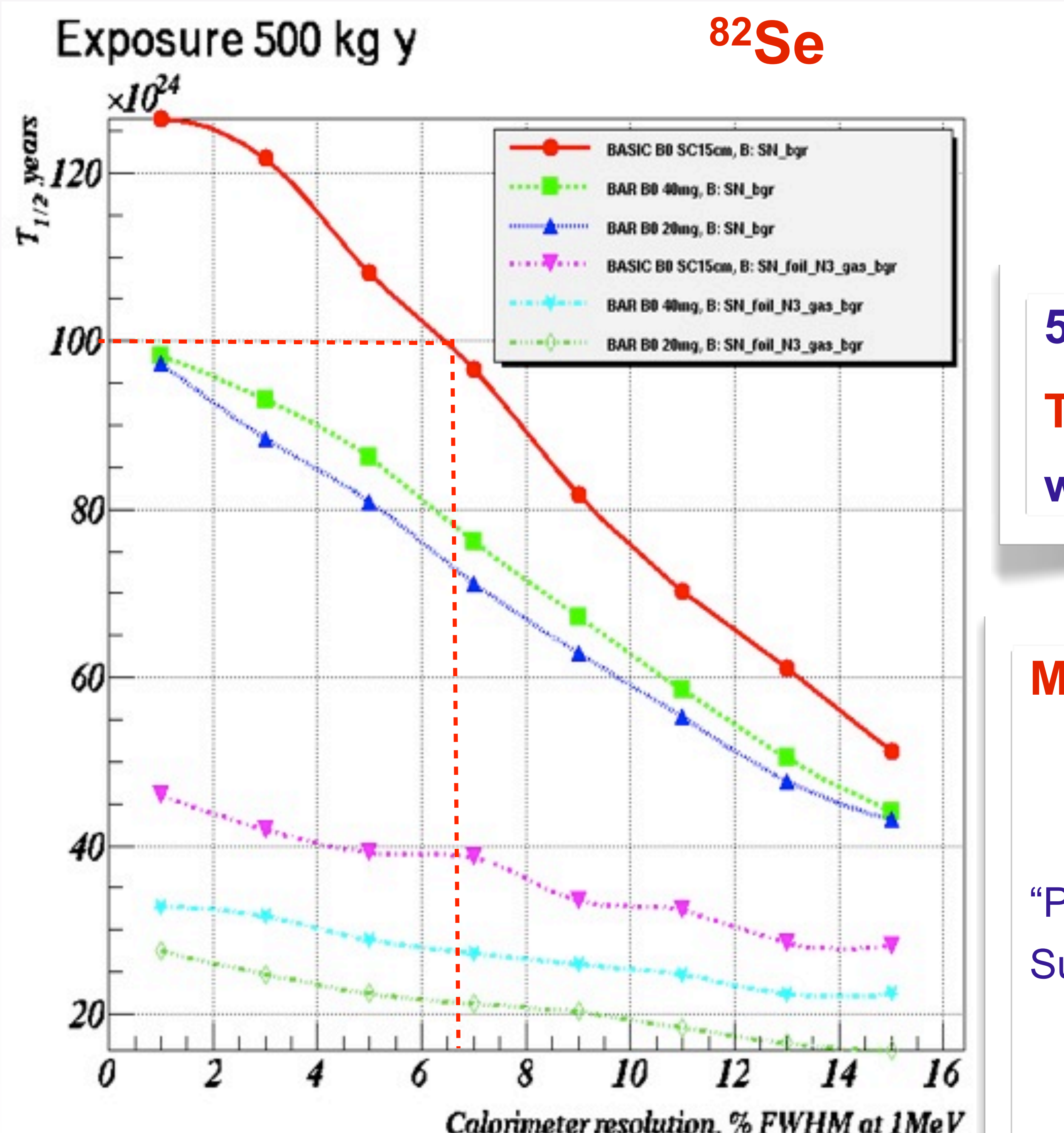
R&D since 2006 →

NEMO-3		SuperNEMO
^{100}Mo	Isotope	^{82}Se (or ^{150}Nd or ^{48}Ca)
7 kg	Isotope mass M	100+ kg
^{208}Tl: ~ 100 μBq/kg ^{214}Bi: < 300 μBq/kg	Contaminations in the ββ foil	^{208}Tl ≤ 2 μBq/kg ^{214}Bi ≤ 10 μBq/kg
Rn: 5 mBq/m^3	Rn in the tracker	Rn ≤ 0.15 mBq/m^3
8% @ 3MeV	Calorimeter energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2}(\beta\beta0\nu) > 1÷2 \times 10^{24}$ y $<m_\nu> < 0.3 – 0.9$ eV	Sensitivity	$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y $<m_\nu> < 0.04 - 0.1$ eV

- Modular design
  - 20 modules, each with 5kg of isotope
- Each Module:
  - Source: (40mg/cm^2) 4x2.7m^2
    - ^{82}Se (High $Q_{\beta\beta}$, long $T_{1/2}(2\nu)$, proven enrichment technology)
    - ^{150}Nd, ^{48}Ca being looked at
  - Tracking
    - drift chamber ~2000 cells in Geiger mode
  - Calorimeter:
    - 550 PMTs + scintillators
  - Module surrounded by passive shielding (water)



SuperNEMO Physics Studies



Full chain of GEANT-4 based software + detector effects + backgrounds + **NEMO3 experience**

5 yr with 100kg of ^{82}Se:

$T_{1/2} > 10^{26}$ yr, $<m_\nu> < 50\text{-}100$ meV at 90%CL

with target detector parameters

Much more than 1 result!

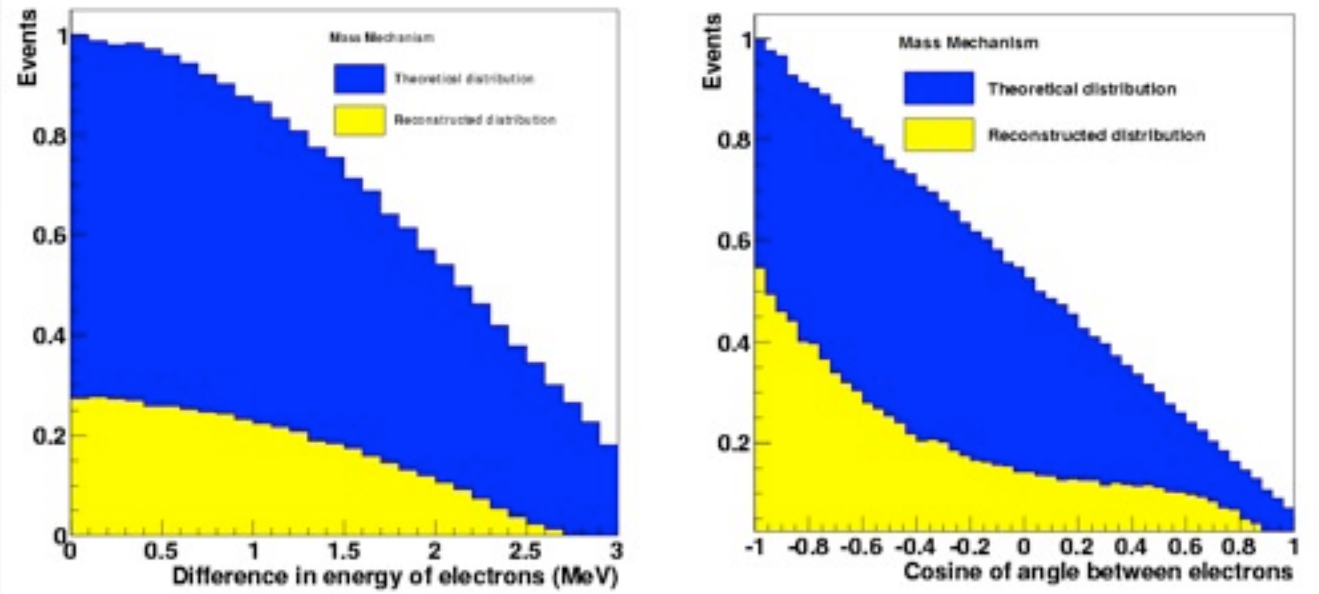
- **Other mechanisms: V+A, Majoron, etc**
- **Disentangling $<m_\nu>$ and V+A**

"Probing new physics models of 0νββ with SuperNEMO", EPJ C (2010) 70, 972-943. (next slide)

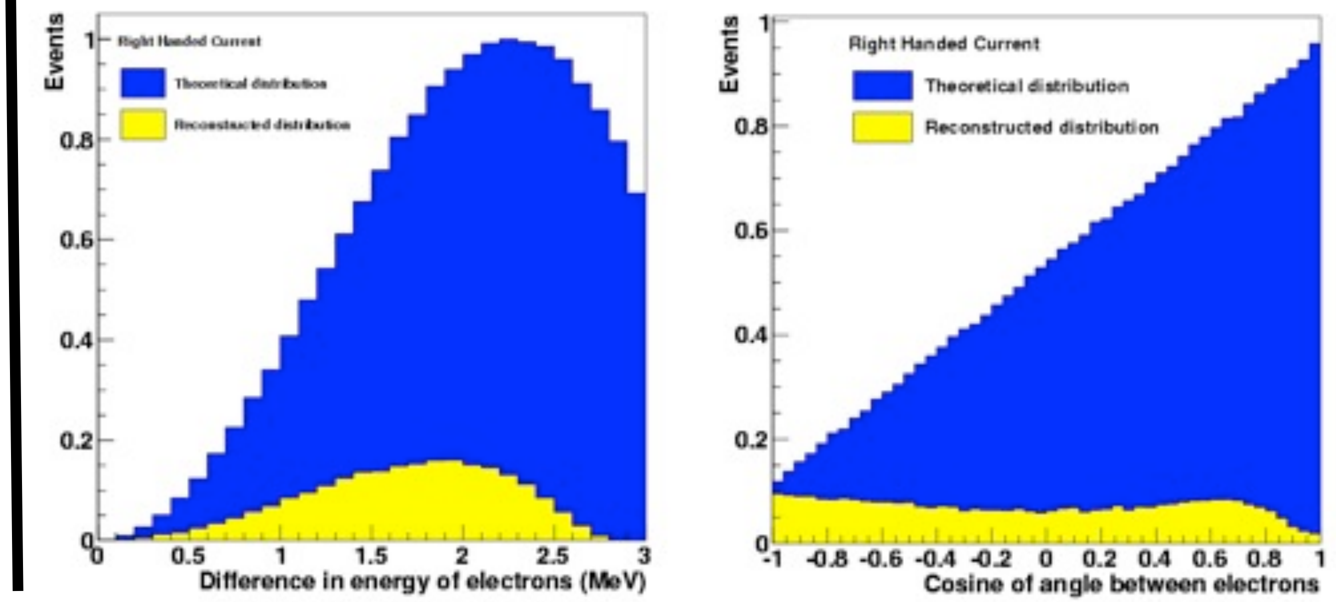
- **ββ0ν(and 2ν) to excited states**
- **Other isotopes**

"Probing new physics models of $0\nu\beta\beta$ with SuperNEMO", EPJ C (2010) 70, pp. 972-943.

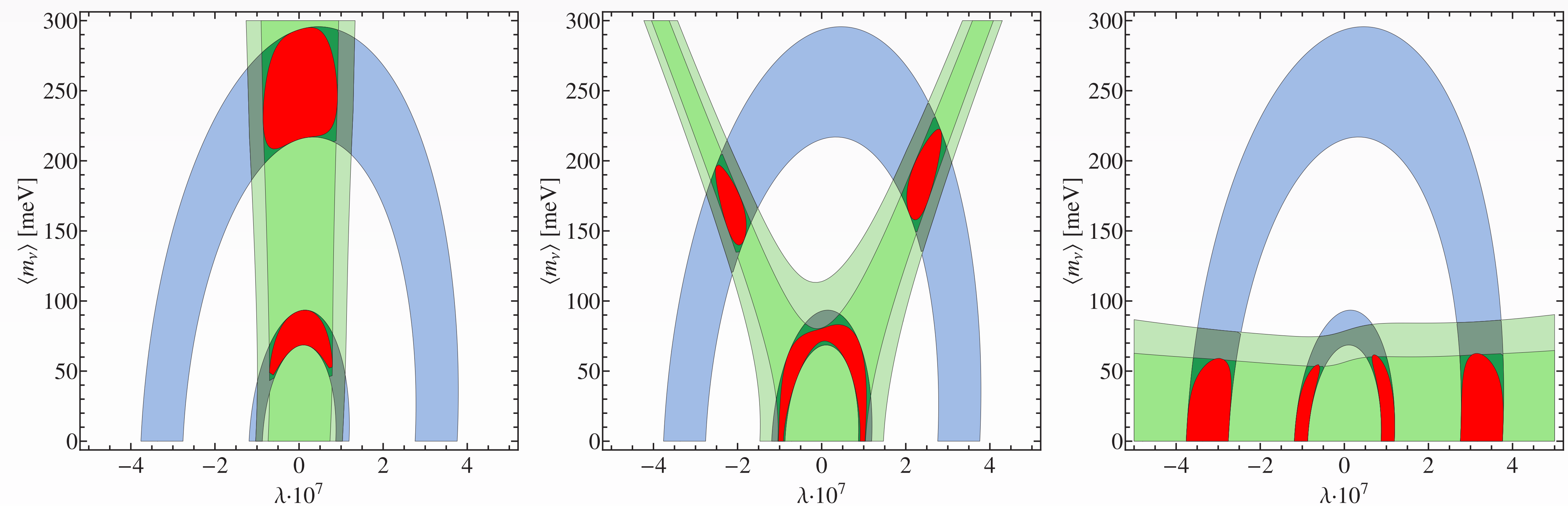
$\langle m_\nu \rangle$



V+A

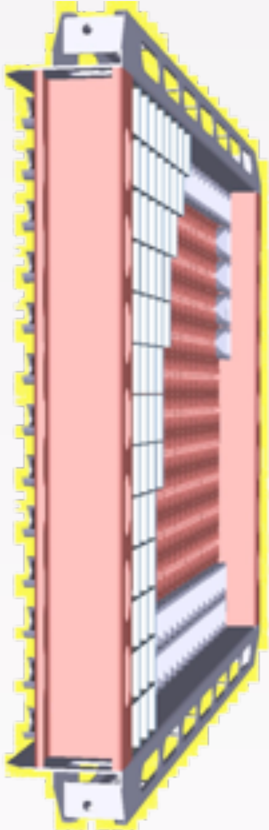


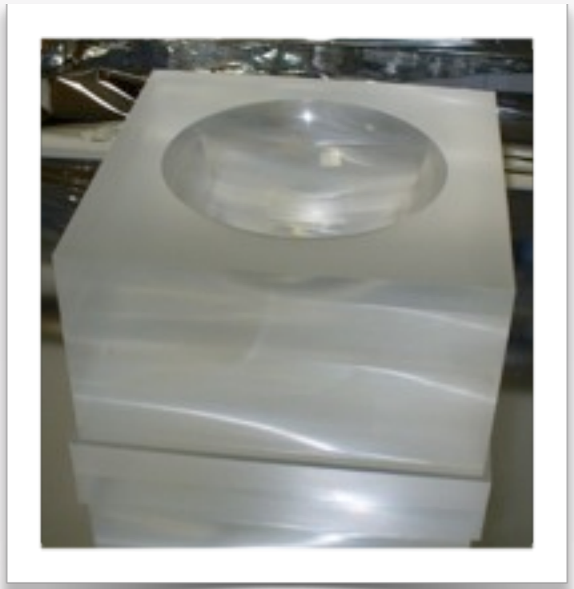
Exploit topological reconstruction available in SuperNEMO (angular distributions and individual electron energies) to disentangle/constrain new physics

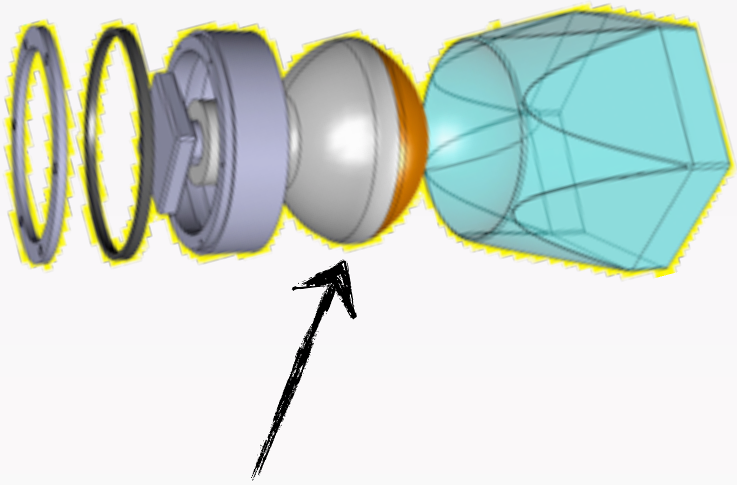


If K-K claim is correct, O(100) events with virtually no background (2-3 expected BG events)

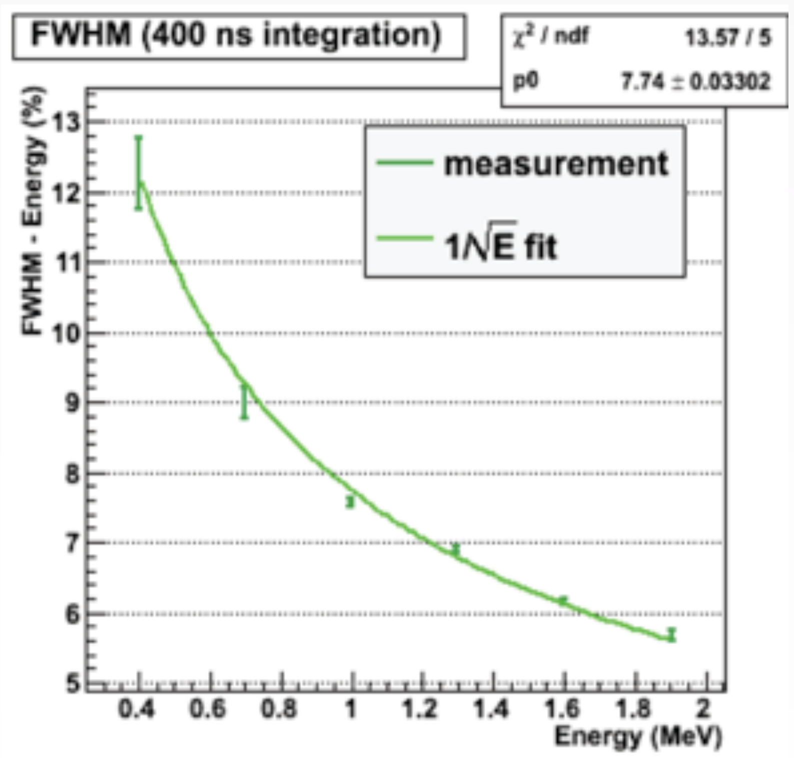
Main Calorimeter Wall







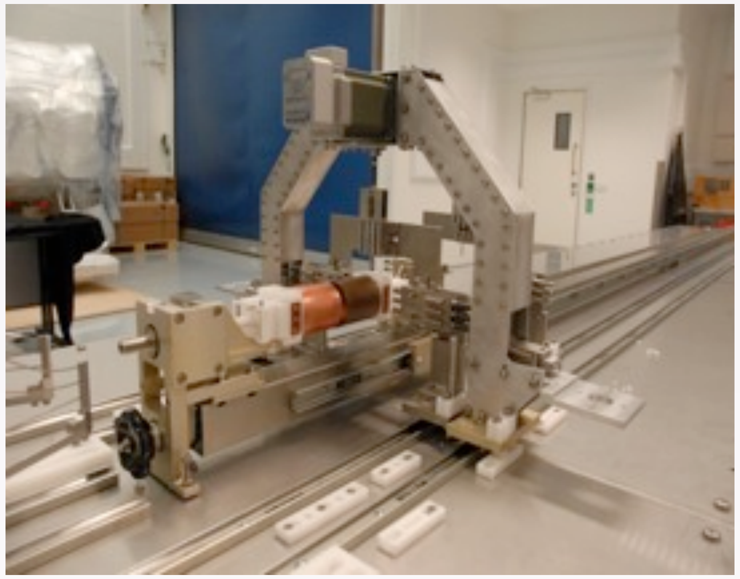
8” High-QE PMT:
Hamamatsu R5912MOD

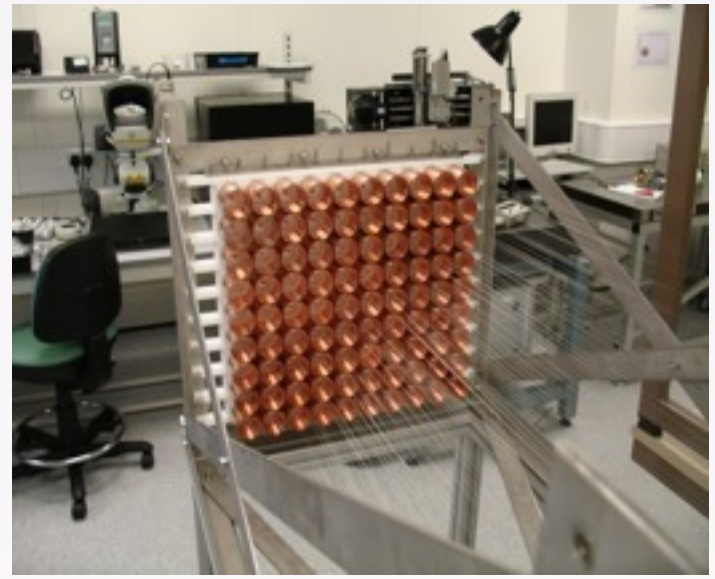


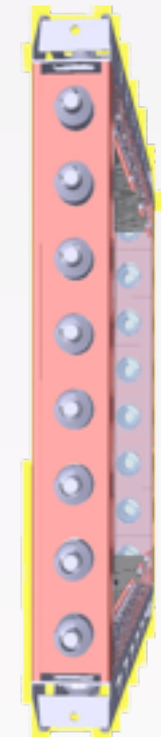
ΔE/E ~ 7.2% (FWHM) at 1 MeV equiv. to 4% @ $Q_{\beta\beta}$ = 3 MeV

Target resolution has been reached with hexagonal and cubic blocks

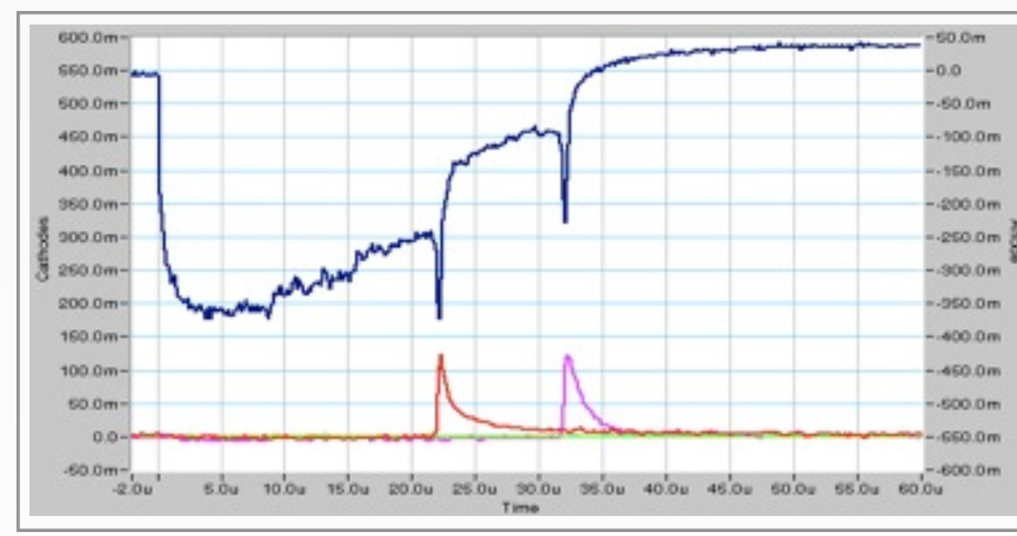
SuperNEMO Tracker







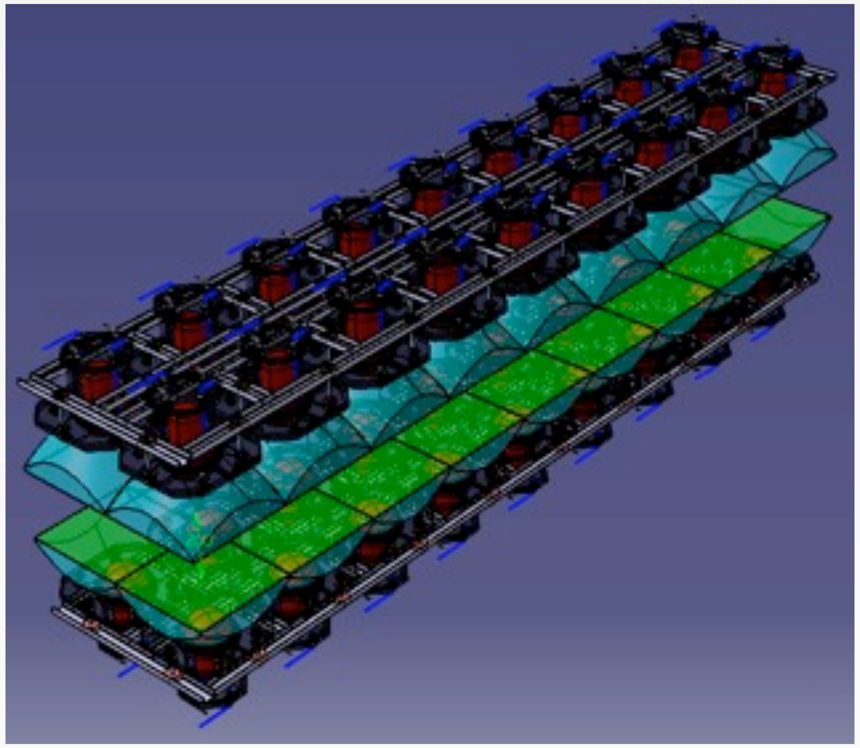
- Automated wiring robot design to mass produce under ultra low background conditions
  - 500,000 wires to be strung, crimped and terminated
- Basic design developed and verified with several prototypes
  - Resolution: 0.7mm transverse, 1cm longitudinal
  - Cell efficiency > 98%
- Readout electronic being developed:
  - Allow for single and double-cathode readout
  - Differentiate anode signal



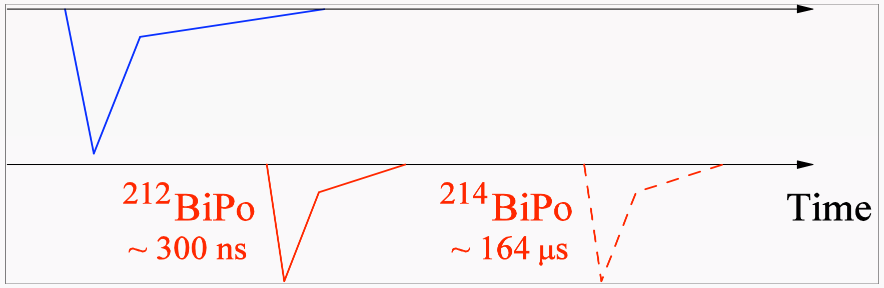
Source Radiopurity

- ~2.7m "composite" foil strips of 40-50 mg/cm^2 (~80 μm)
- Radiopurity (^{82}Se)
  - ^{208}Tl < 2 μBq/kg
  - ^{214}Bi < 10 μBq/kg

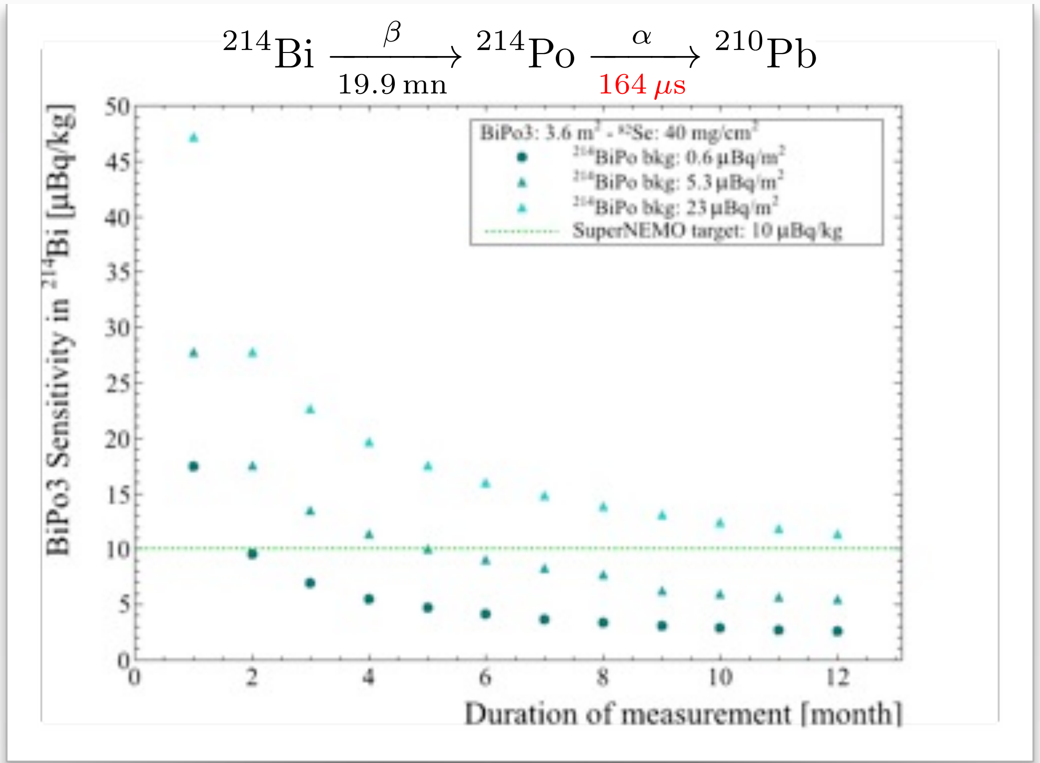
→ HPGe detectors are used for screening but not sufficient to reach required levels

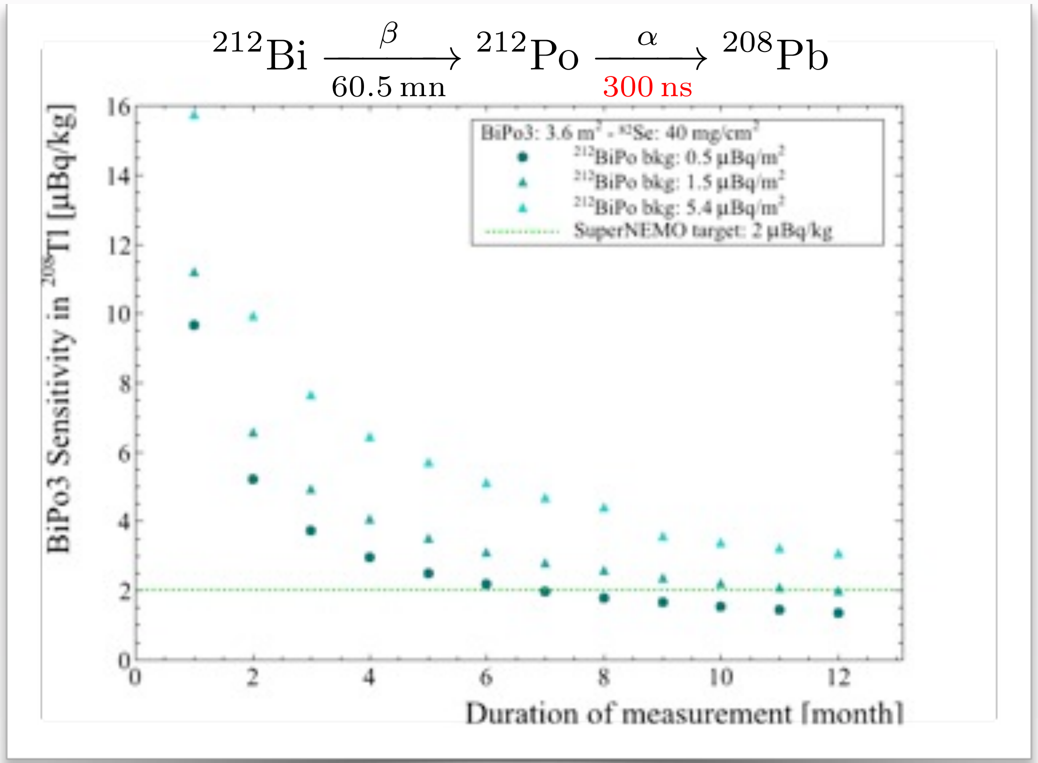


BiPo signature



Dedicated **BiPo** detector developed and installed in Canfranc (running in 2012)

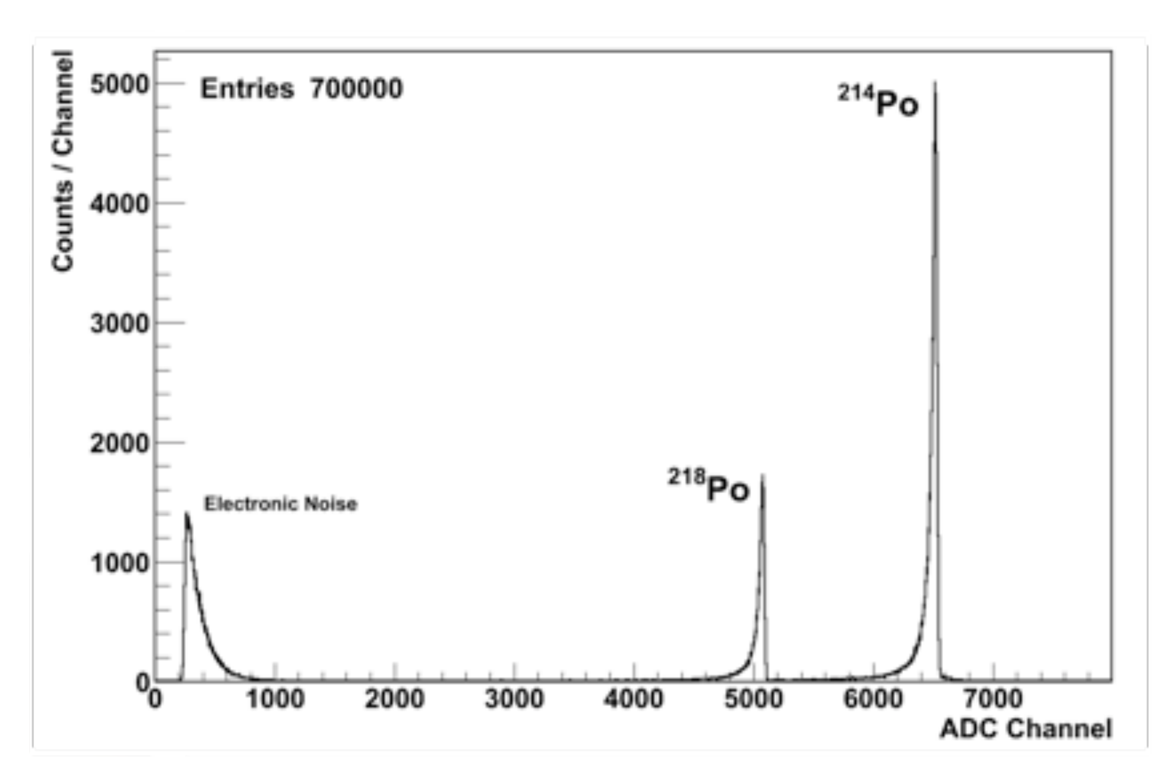




Radon activity measurement

Requirement: Rn activity inside tracker < 150 μBq/m^3

Radon Concentration Line sensitivity < 50 μBq/m^3 (90%CL)



- Measurements of Rn emanation from materials
- Rn permeability measurements through membranes/seals

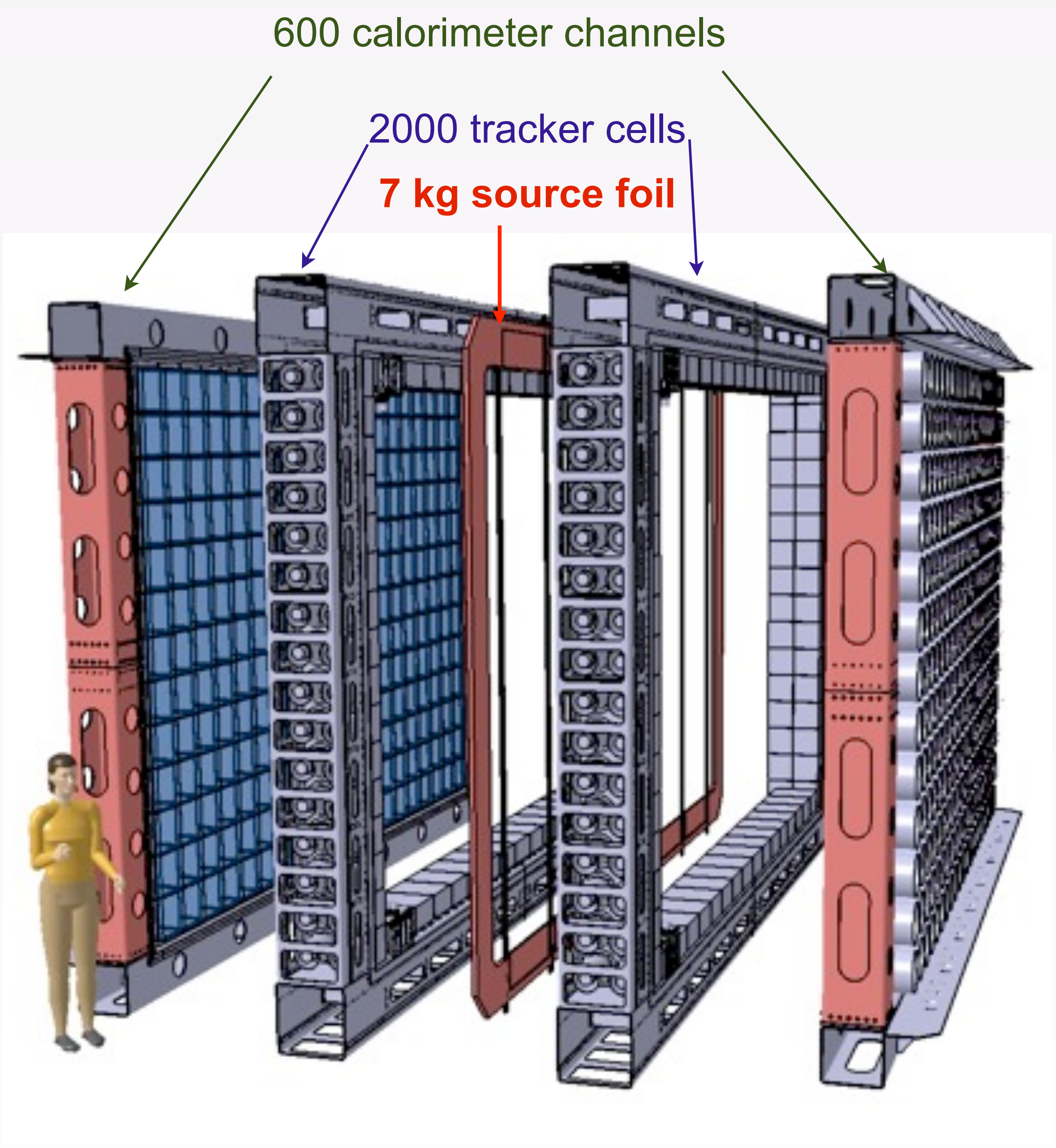
SuperNEMO Demonstrator

Technology
Ultimate proof of BG levels
Physics
Sensitive to K-K claim

7kg of ^{82}Se (5 kg in hand)
Bgrd ≤ 0.06 events/yr in the RoI

A Zero-Background Experiment

$$T_{1/2}^{0\nu}(90\%CL) = 2.56\times 10^{24}\times t\ \ \text{yrs}$$



Gerda-I sensitivity in 2.5 years -
6.5×10^{24} yr (equivalent to 3×10^{25}yr with ^{76}Ge)

SuperNEMO Demonstrator Construction has started

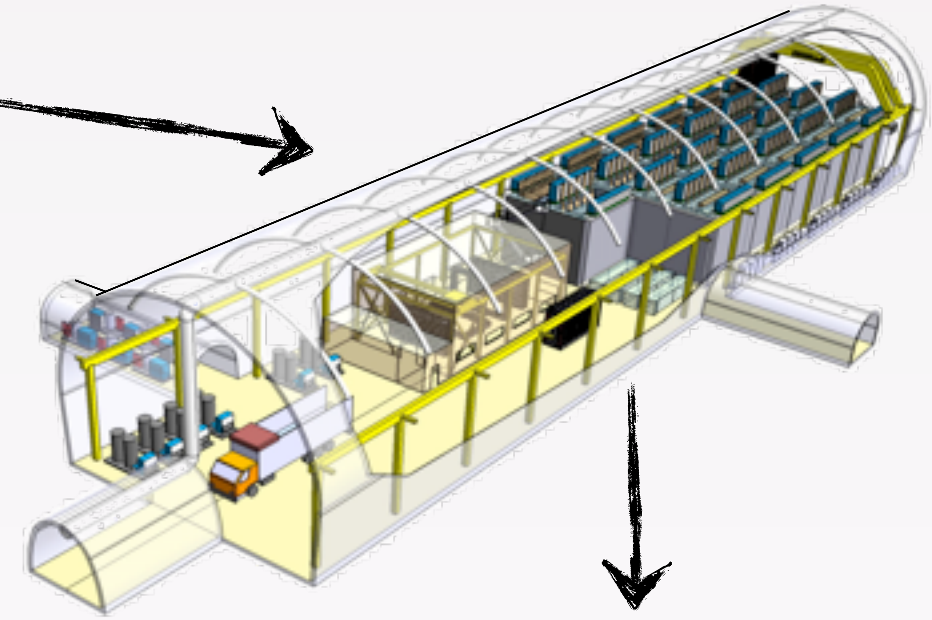
Construction of optical modules for tracker frame

Assembly hall prepared for tracker integration and commissioning

NEMO3 dismantled and removed to free underground space at LSM for Demonstrator

SuperNEMO Schedule

SuperNEMO in planned LSM extension



Modularity of SuperNEMO makes distributed location in different underground labs possible and even beneficial (provided resources availability).

Demonstrator running

Demonstrator Module construction and commissioning

K-K claim probed

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	

Installation in LSM

Construction, deployment and running successive SuperNEMO modules

Continuous operation of ≥1 SuperNEMO module

Figure of Merit

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

$$FOM = T_{1/2}^{0\nu}(90\%CL)\times\frac{G^{0\nu}}{G^{0\nu}_{^{76}Ge}}$$

Phase-space factor normalised to ^{76}Ge

Normalised to exposure **500 kg yr** and assuming the **same NMEs**

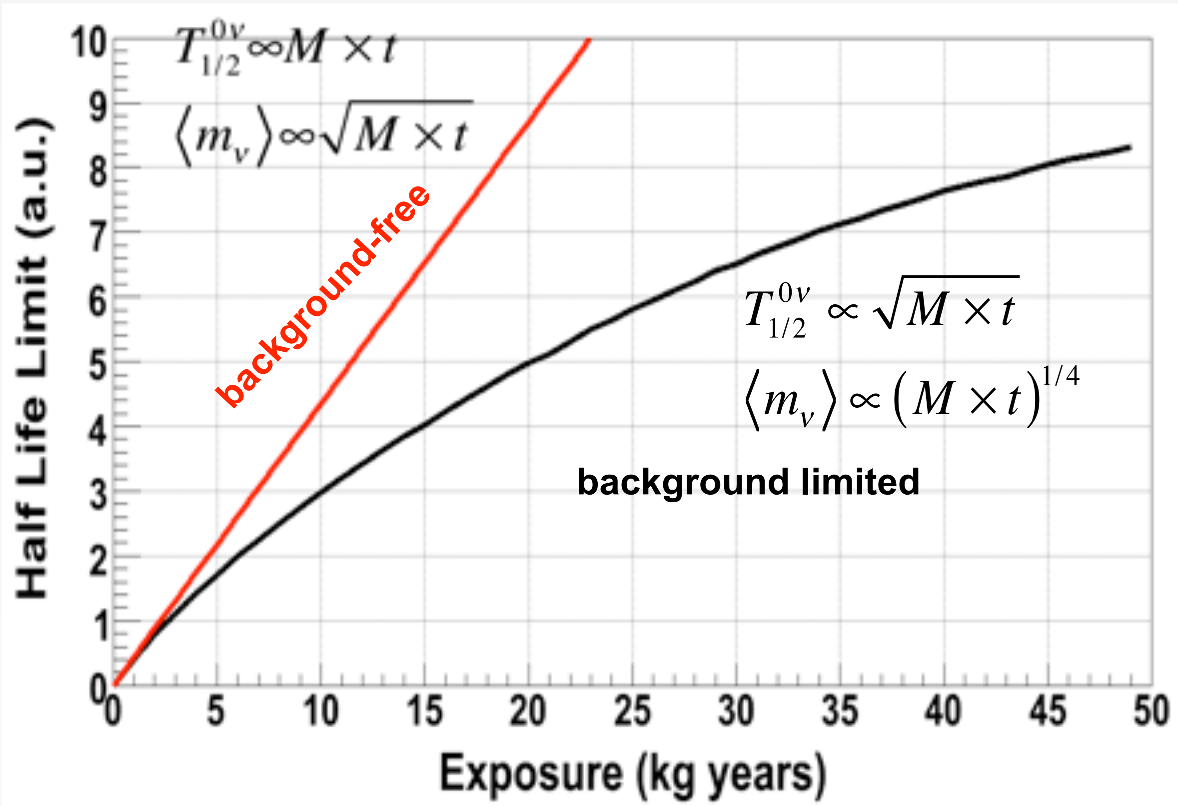
Project	Isotope	ε in $Q_{\beta\beta}$ window	b [cnts $kg^{-1}keV^{-1}$ yr^{-1}]	FWHM keV	Total B, counts	$T_{1/2}$ (90%CL) yr	$\frac{G^{0\nu}}{G^{0\nu}_{^{76}Ge}}$	F.O.M yr
GERDA	^{76}Ge	80%	0.01	4	40	2.1×10^{26}	1	2.1×10^{26}
Super-NEMO	^{82}Se	17%	6×10^{-5}	120	7	1×10^{26}	4.4	4.4×10^{26}
CUORE	^{130}Te	80%	0.01	5	185	5.7×10^{25}	6.9	4×10^{26}
EXO200	^{136}Xe	70%	6.3×10^{-4}	94	73	7.6×10^{25}	7.4	5.6×10^{26}
SNO+	^{150}Nd	70%	7.5×10^{-4}	300	3996	9.4×10^{24}	32.8	3.1×10^{26}

Reliability of expected performance numbers is **not** taken into account

Ton-experiment, 10 meV and other speculations

UCL

- O(100kg) generation will reach FOM ~ **4×10^26 yr** by **2018-2020**. <m_ν> = **50-100 meV**
- To **exclude IH**, i.e. to get **10-20 meV**, we need FOM = **~10^28 yr**.
- Example: A ^{76}Ge experiment even with ambitious b = 0.001 cnts/(kg keV yr) would need **30 tons** (!) of enriched (!!) **^{76}Ge** measured over 5yr! Similar for other projects.
- Thus for **10 meV** stage we should try to find a **"background-free" solution**



- Example: **150kg** x 5 yrs of **^{48}Ca**, if **no background** and ε~40% , gives required FOM =**10^28 yr**.
  - NEMO-3 had virtually no background in this region after 8 years of running!
  - But we need to learn how to enrich ^{48}Ca (0.19% nat. abundance)

Future "Ton" experiments

^{222}Rn poses serious challenge (How to control **~1atom/N×m^3** contamination?)
Future may belong to **"Big Three"**

^{48}Ca	**^{96}Zr**	**^{150}Nd**
4.27 MeV	3.4 MeV	3.4 MeV

to break away from ^{222}Rn progeny

^{214}Bi
3.27 MeV

Summary

- **0νββ** is the **only way** to answer questions on Full **Lepton Number violation** and nature and **mechanism** behind **neutrino mass**
- Reach **interplay** with **other areas**
  - Neutrino mass from end-point β-decay, cosmology, neutrino oscillations
- Several next generation experiments **starting** in the **next few years**
  - K-K "claim" tested
  - Benchmark sensitivity of 50 meV
- **NEMO-3** demonstrated feasibility of **topological** detection of **ββ**
  - Competitive **0νββ** result with open-minded approach to **mechanism of LNV**
  - **2νββ** measurements with **unprecedented accuracy**. Many more results.
- **SuperNEMO** will probe **50 meV** region with a **unique topological detection** approach
  - **Different isotopes** can be probed. Possibility to **disentangle** underlying **physics** if $<m_\nu> \geq 100$ meV.
  - Excited states, precision SM ββ-studies
- Need a **common strategy** to get down to **10 meV** (and lower?).
- **Topological ββ detection** could provide an **alternative to (multi)ton**-scale **detectors** if enrichment of **high-$Q_{\beta\beta}$** isotopes proves feasible

BACKUP

The Roadmap

UCL

Scenario 1

$$\langle m_\nu \rangle \sim 0.1 \text{ eV}$$

2012 —— 2015 —— 2020

Measurements with several isotopes. Possibility to disentangle LNV physics mechanism (almost background free with e.g SuperNEMO). Possibility to access Majorana CP phases.

Scenario 2

$$\langle m_\nu \rangle \ll 0.1 \text{ eV}$$

2012 —— 2015 —— 2020

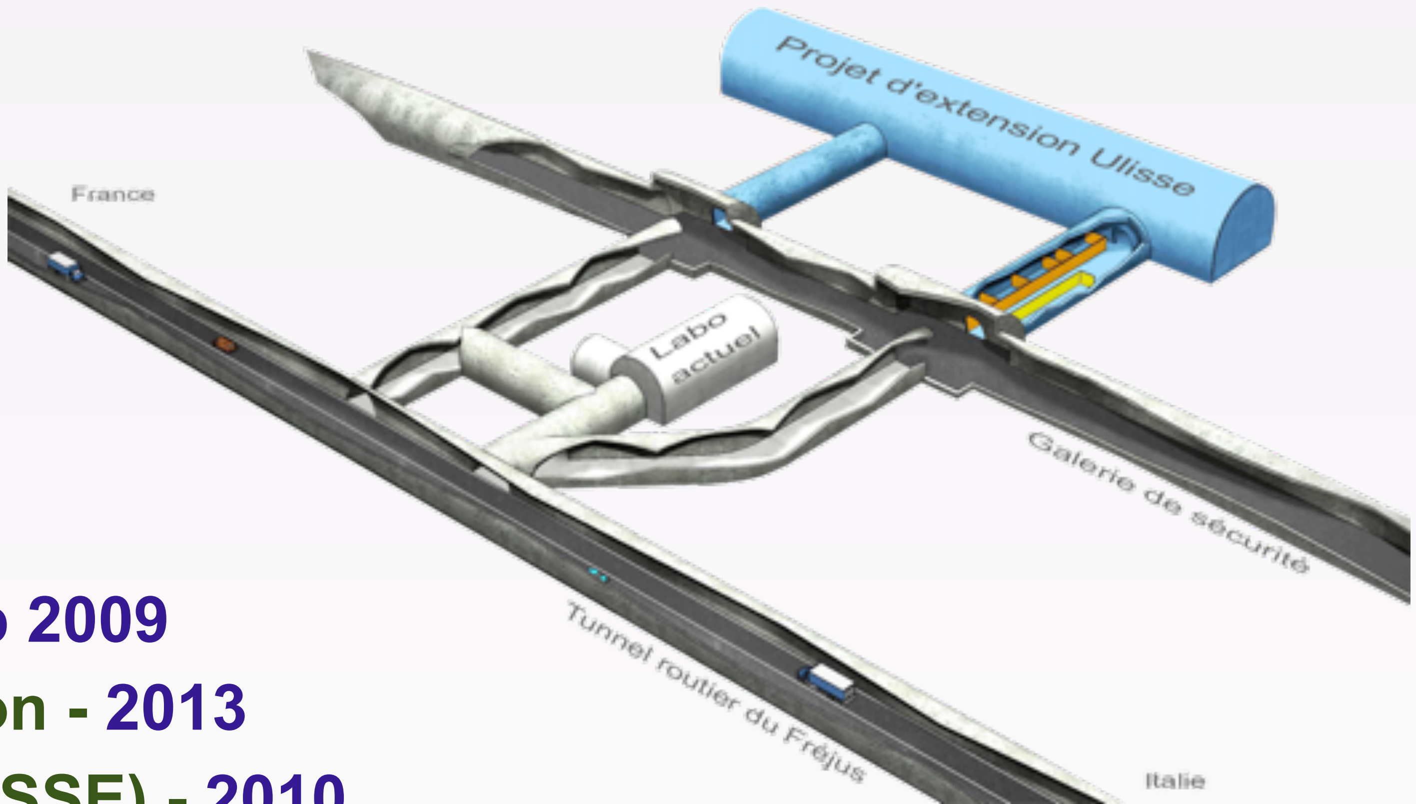
Understanding backgrounds and limiting factors (Radon?) with *O*(100kg) experiments
Isotope enrichment technology.

→ "Background-free" detector technology and isotope(s) choice.

→ *"Ton"* detector construction

"Ton" Experiment must have the sensitivity to establish or exclude the IH

LSM Extension



Provisional Schedule

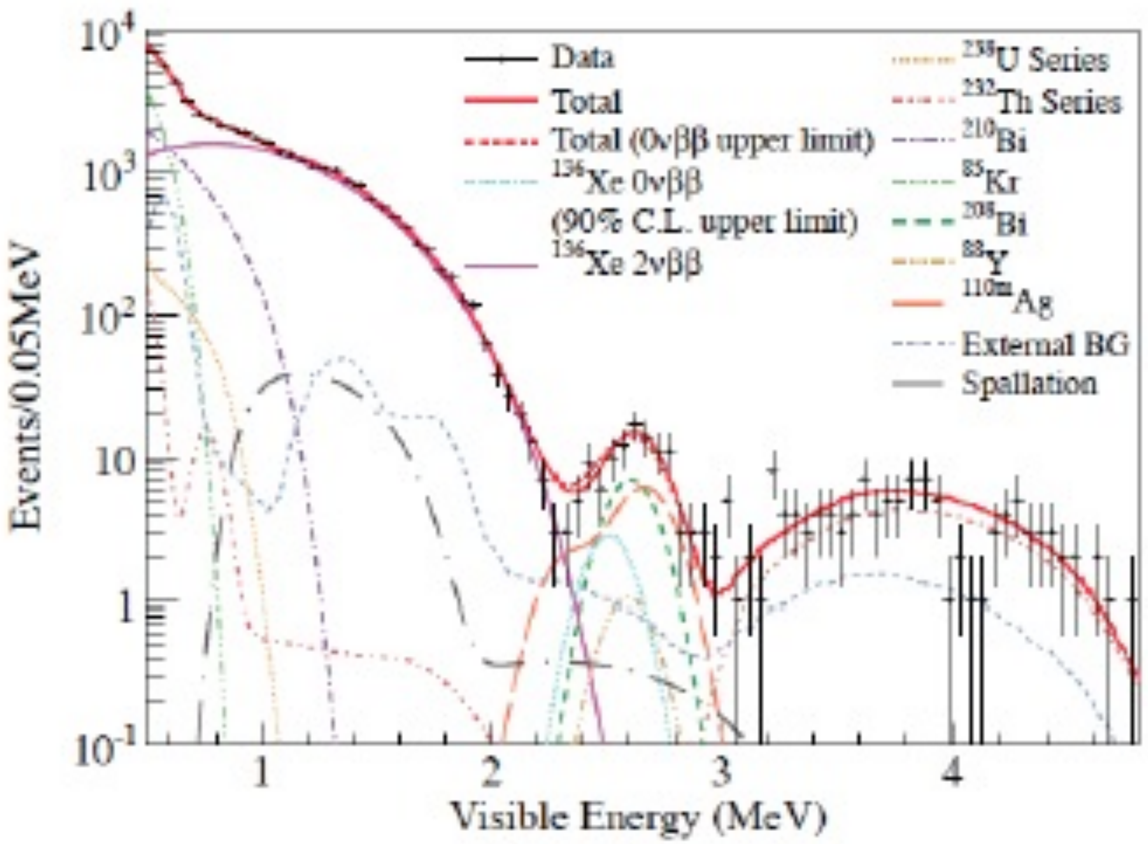
- Safety tunnel construction start - Sep 2009
- Safety tunnel, end of civil construction - 2013
- Detailed study of LSM extension (ULISSE) - 2010
- Deadline for final decision/money commitment - 2012
- Excavation of new Lab completed - 2014
- Outfitting completed, Lab ready to host experiments - 2015

17,500m^3 (50m long), 7M€ excavation + 3M€ outfitting

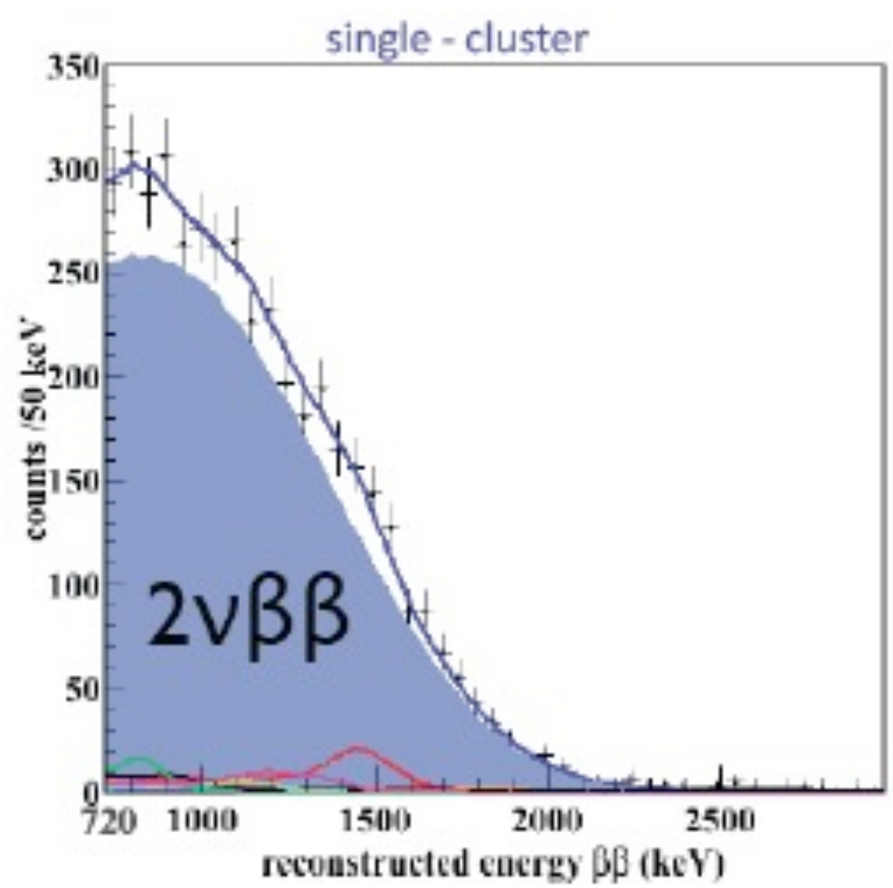
2^d ULISSE workshop in October'09. 11 LOIs received.

New Xe136 result

KamLAND-ZEN 2012



EXO-200 2011



$$T_{1/2}^{2\nu}(^{136}Xe) = (2.1 - 2.4) \times 10^{21}\ yr$$

Longest lifetime ever measured!