Neutrinoless Double Beta Decay

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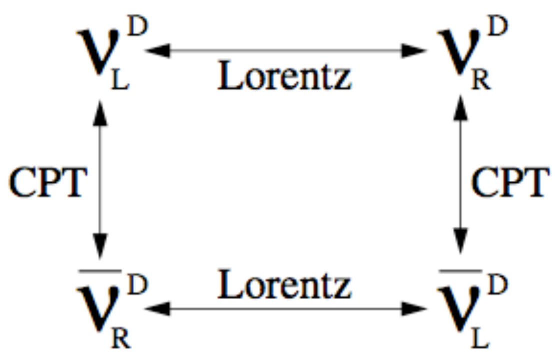
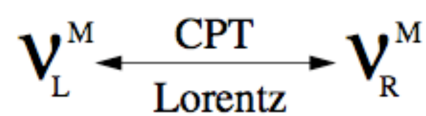
Flavor Physics and CP Violation *Torino 28/05/2010*

Dirac or Majorana?

- Neutrinos oscillation implies:
  - Lepton Flavour Violation (LFV)
  - $m_\nu \neq 0$
- Dirac mass term: $m_D^\nu \overline{\Psi_L} \Psi_R$
- SM symmetries & renormalizability allows a Majorana mass term: $m_M^\nu \overline{\Psi_R^c} \Psi_R$
  - Majorana conjecture: $\Psi = \Psi^C$



Dirac

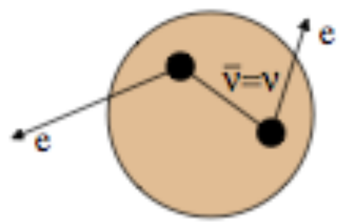


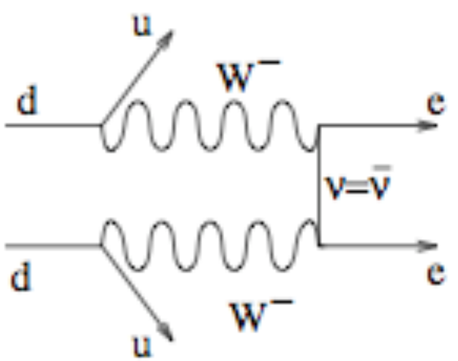
Majorana

- Massless neutrino DOES NOT allow testing of the Majorana nature
- Majorana neutrino implies Lepton Number Violation (LNV): $\Delta L=2$

Neutrinoless Double Beta

- The most sensitive LNV process: Neutrinoless Double Beta Decay ($0\nu\beta\beta$)
- Second order weak nuclear process: $(A,Z) \rightarrow (A,Z+2) + 2\,e^-$





Only if:

massive neutrinos → chirality flip

Majorana neutrino

$\Delta L=2$

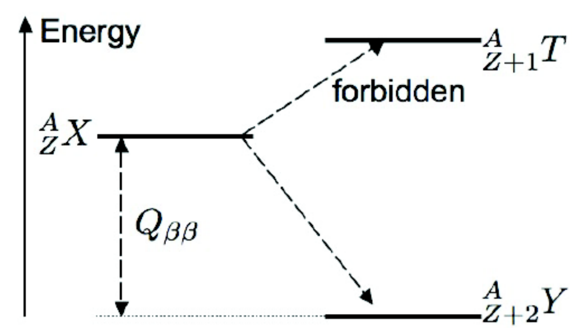
Many not SM diagrams can contribute

If observed → Majorana neutrino

Schetcher, Valle Phys. Rev. D25 2951 1982

- Possible only in few nuclei:

^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd



$0\nu\beta\beta \Leftrightarrow \nu$ mass

- The measurable quantity is the half life:

Phase space factor~Q^5 → $G(Q,Z)$

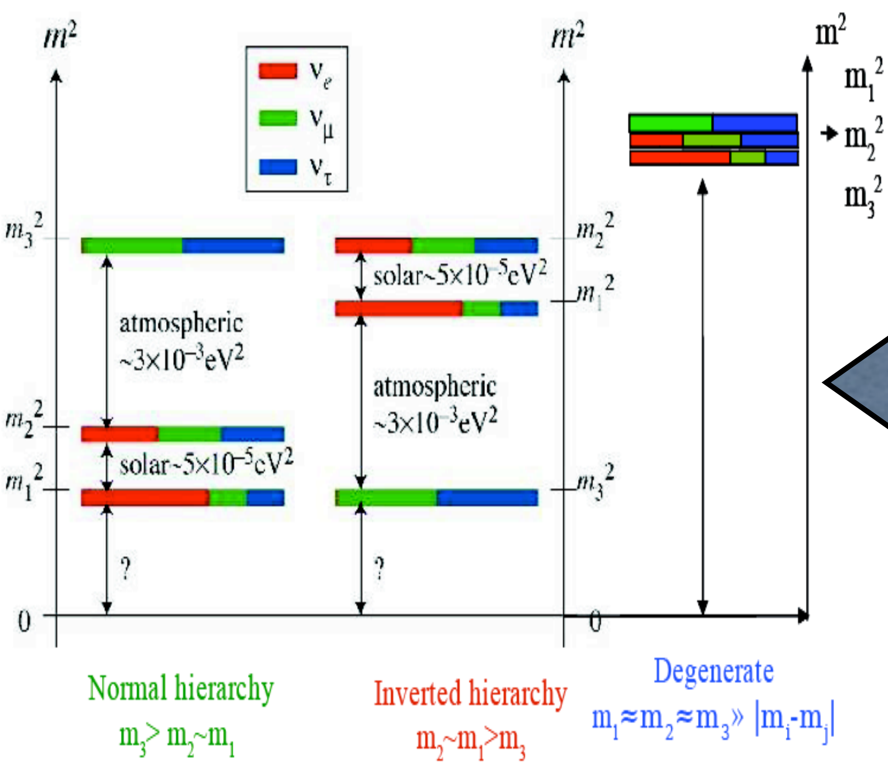
Nuclear Matrix Element → M_{nucl}

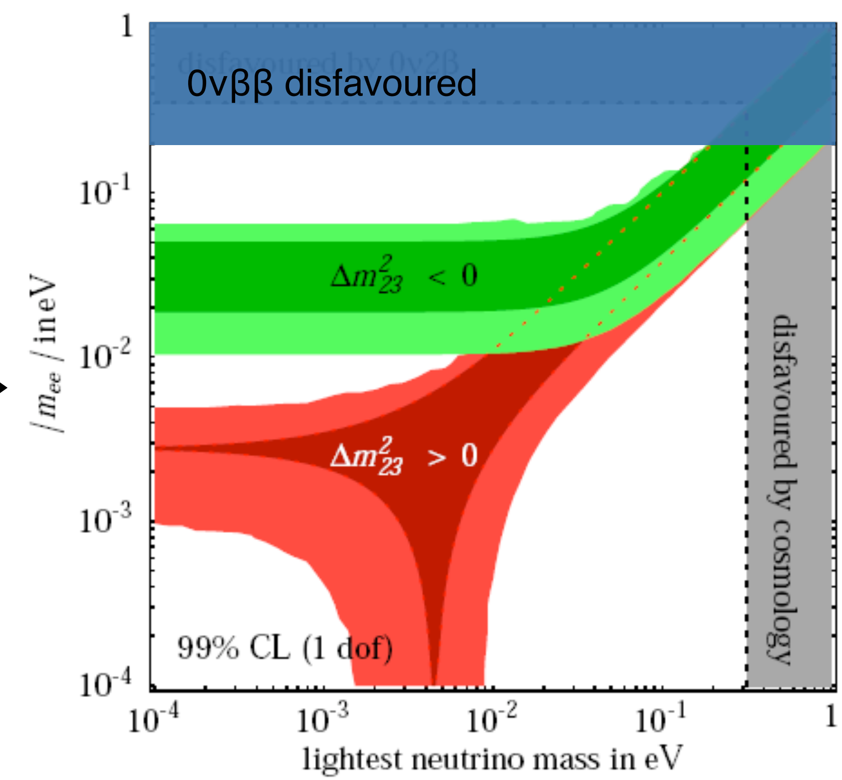
Effective neutrino mass → $m_{\beta\beta}$

$$(\tau^{0\nu}_{1/2})^{-1} = G(Q,Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

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

(light neutrino exchange mode)

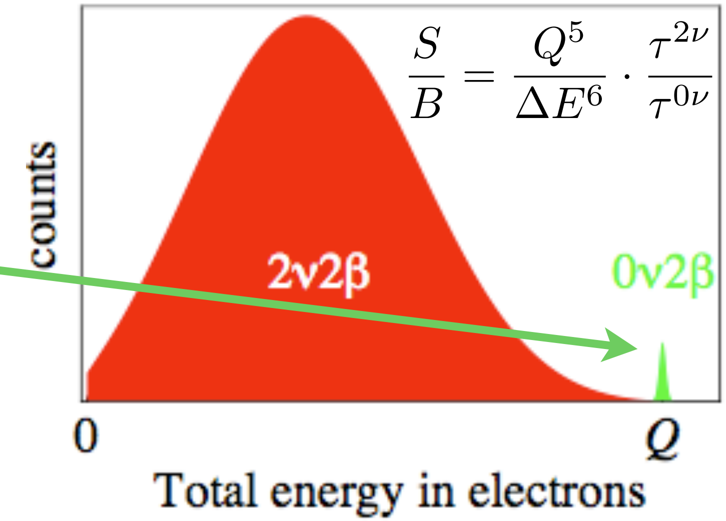




Strumia, Vissani hep/ph 0606054

0νDBD in Experiments

- Experiments measure the sum of the kinetic energies of the two emitted electrons
- Signature: monochromatic line at the Q-value of the decay (2-3 MeV)



$$S^{0\nu\beta\beta} = \ln 2 N_A \cdot \frac{a}{A} \left(\frac{Mt}{B \Delta E} \right)^{1/2} \cdot \epsilon$$

- Isotopic abundance → a
- Atomic mass → A
- Detector mass (kg) → M
- Measurement time (y) → t
- Background (counts/keV/kg/y) → B
- Energy Resolution (keV) → ΔE
- Efficiency → ϵ

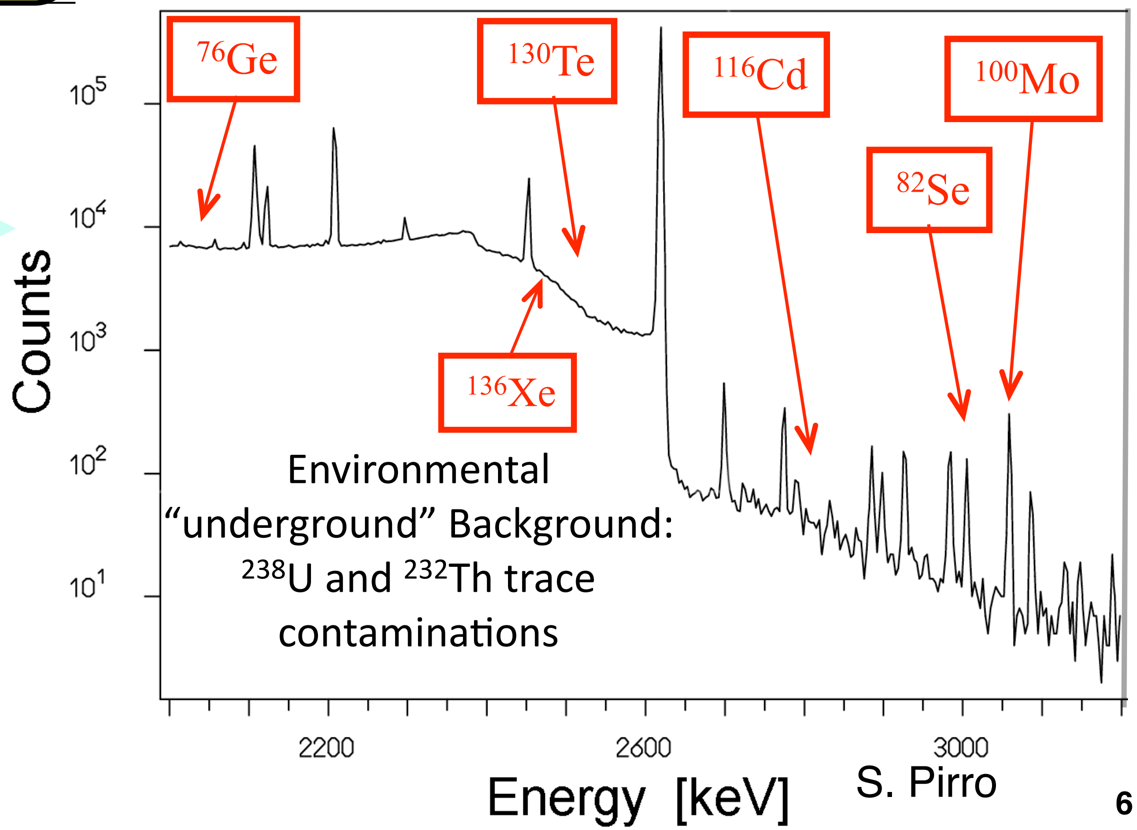
- Remember: $m_{\beta\beta} \propto (\tau^{0\nu})^{-1/2}$

The isotope choice

Parent Isotope	$Q_{\beta\beta}$ (KeV)	Ab(%)
^{48}Ca	4271	0.187
^{76}Ge	2039	7.8
^{82}Se	2995	9
^{100}Mo	3034	9.6
^{116}Cd	2902	7.5
^{130}Te	2530	33.9
^{136}Xe	2479	8.9
^{150}Nd	3367	5.6

Isotopic abundance:
<10% (only exception ^{130}Te)

Gain ~ 100
if
$Q_{\beta\beta}$ > 2615 keV
end of γ radioactivity (^{208}Tl)

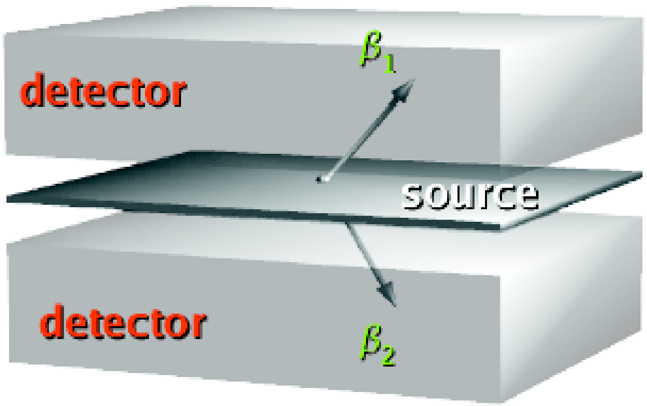


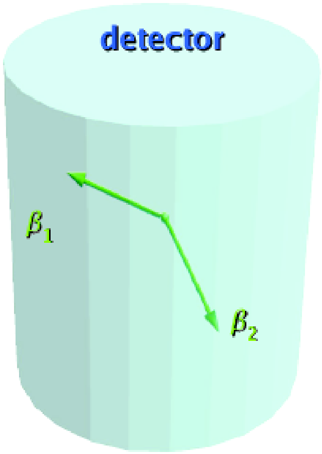
S. Pirro

Experimental strategies

source ≠ detector

source = detector





+++ Topology, Bkgd(2νββ exce.)

--- M, ΔE, ε

+++ M, ΔE, ε

--- Topology, Bkgd(2νββ exce.)

Calo-tracko detectors
(NEMO, MOON,DCBA)

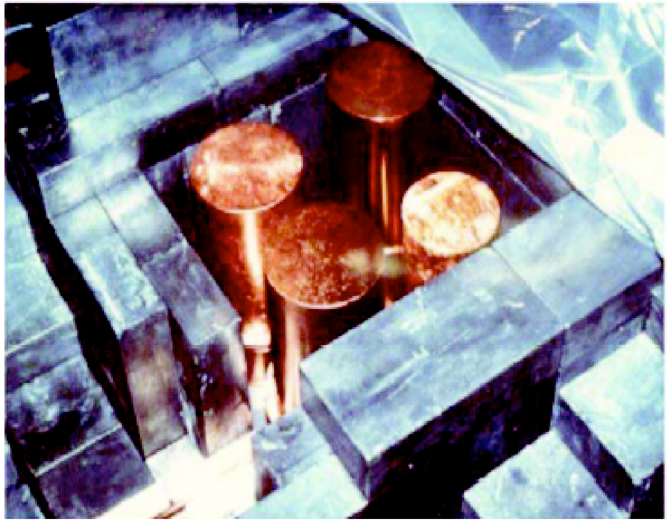
diodes (MAJORANA, GERDA)
bolometers (CUORE)
solid-state devices scintillators (COBRA)
solid scintillators(CANDLES)
liquid loaded scintillator(SNO++,Kamland)
Gaseous/Liquid TPC (EXO)

Heidelberg-Moscow: Klapdor claim

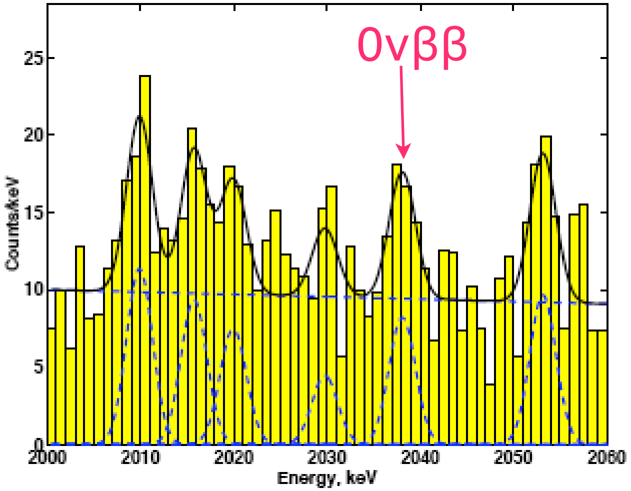
source = detector

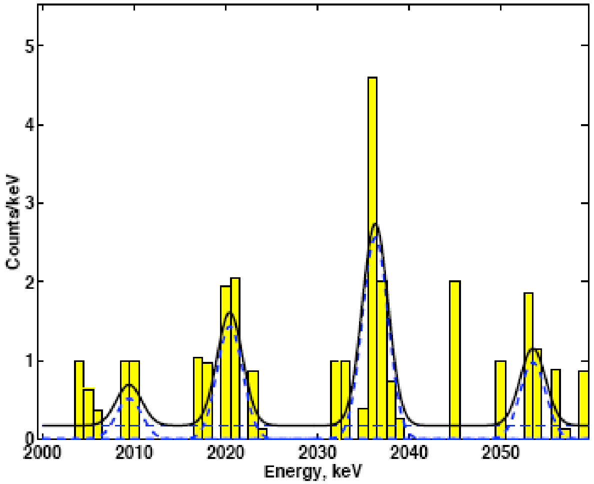
- 5 HP-Ge diodes: 10.9 kg (86% enriched ^{76}Ge)
- Exposure: 53.9 kg y (1990-2001)
- $\Delta E_{FWHM} \sim$ 4 keV @ $Q_{\beta\beta}$ ~2039 keV

$\tau^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ y $\Leftrightarrow$ $\langle m_{\beta\beta} \rangle < 0.35$ eV



Klapdor et al. Phys. Lett. B 586 (198) 2004





- Exposure: 71.7 kg y(1990-2003)
- Bkgd ~ 0.11 counts/keV/kg/y

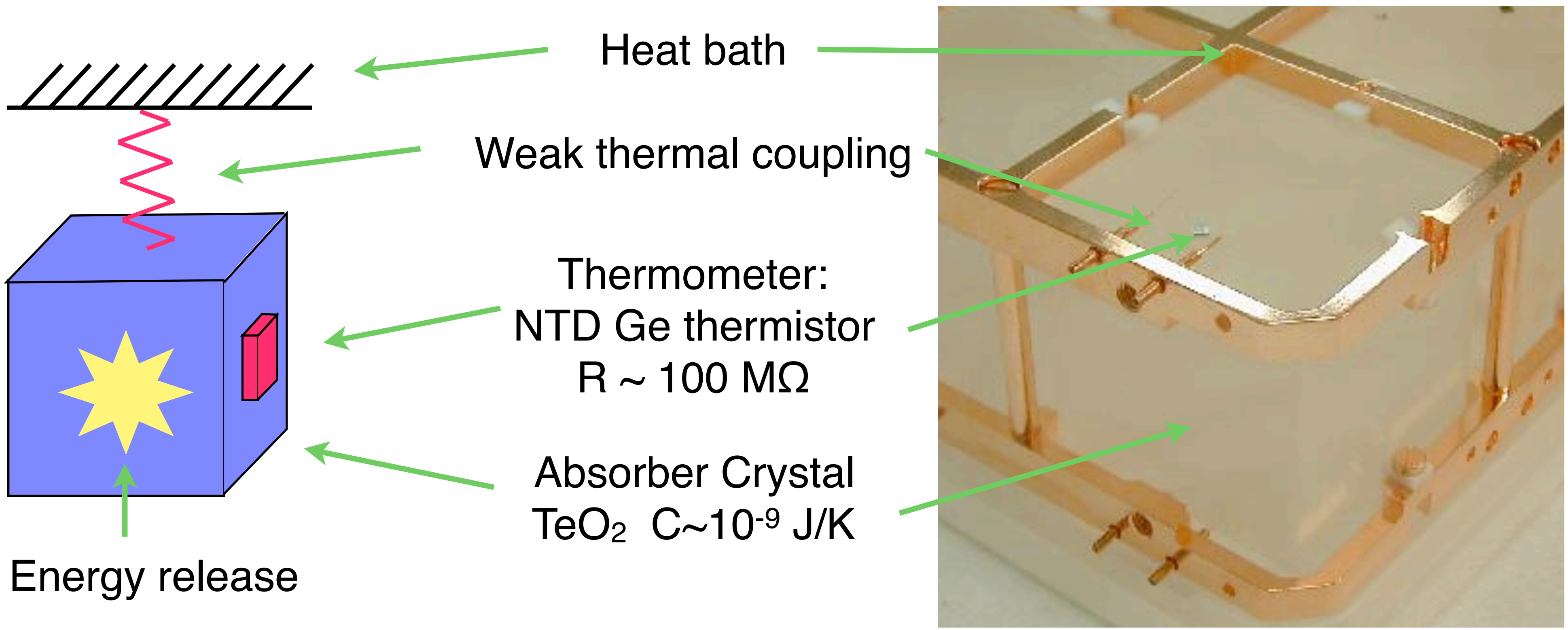
$\tau^{0\nu}_{1/2} = 1.2 \cdot 10^{25}$ y

$\Leftrightarrow$

$\langle m_{\beta\beta} \rangle = 0.44$ eV

Cuoricino

- Particle energy converted into phonons → temperature variation $\Delta T = E/C$
- Need very low heat capacity:
  crystals (dielectric, diamagnetic) @~8mK → TeO_2 source = detector

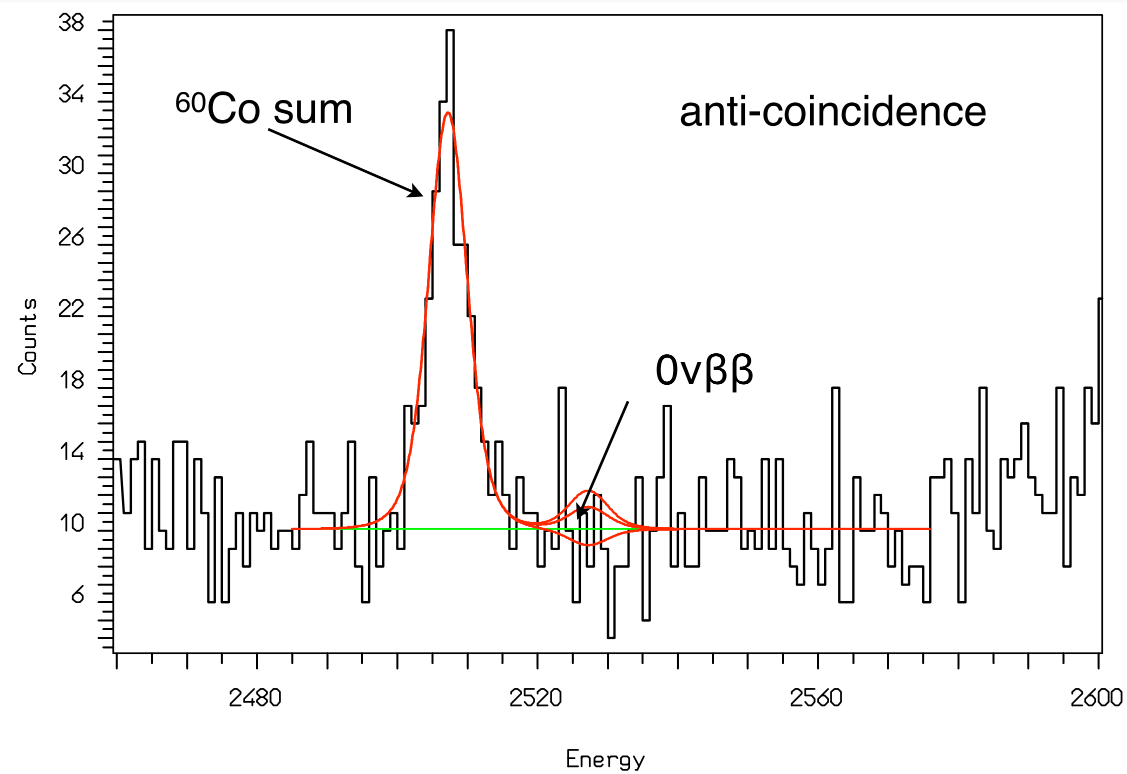


- Detector response in this configuration: ~ 0.2 mK / MeV~0.2 mV/MeV

Cuoricino Results

- Exposure (2003-2008):

$$M \cdot t = 18.14 \text{ kg } ^{130}\text{Te} \cdot \text{y}$$



- Background level:

$$(0.18 \pm 0.01)\text{counts/keV/kg/y}$$

  - ~50% from degraded α from inert material (Cu) facing crystals
  - ~40% from ^{208}Tl multi-Compton (cryostat contamination)

- ΔE_{FWHM}~ 7.5 keV @ $Q_{\beta\beta}$ ~2527 keV

$$\tau^{0\nu}_{1/2} > 2.94 \cdot 10^{24} \text{ y } @90\%CL \quad \Leftrightarrow \quad m_{\beta\beta} < 0.21 \div 0.72 \, \text{eV}$$

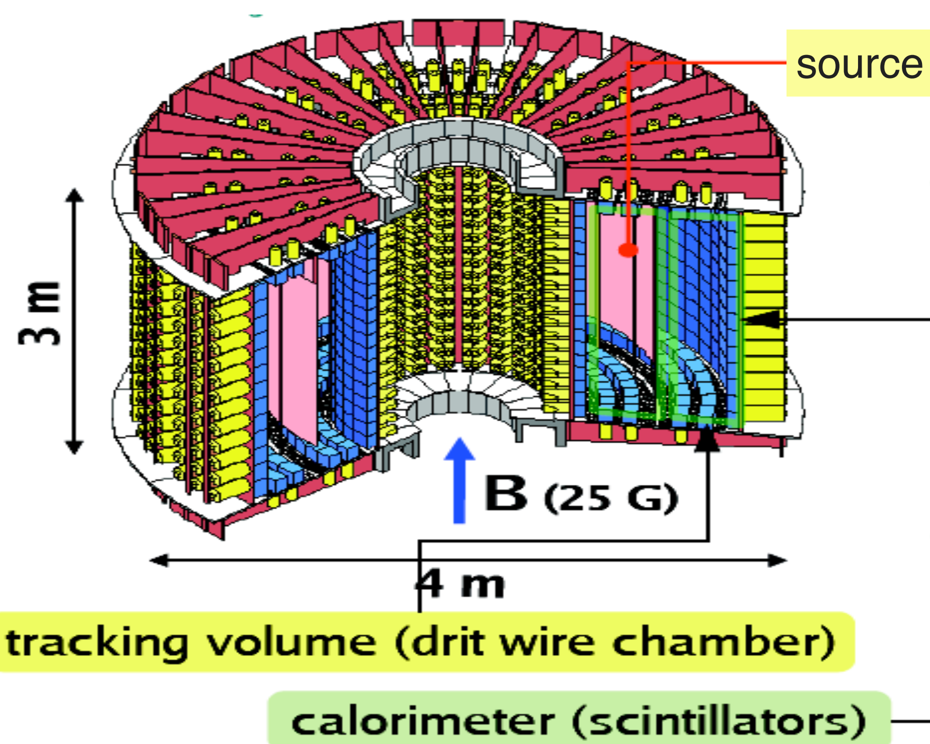
NEMO 3

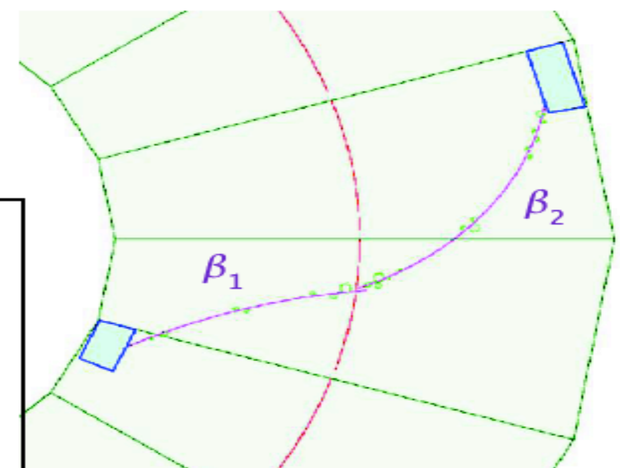
source ≠ detector

- Tracking detector: ~6000 Geiger mode drift chambers (95%He+4%alcohol+1%Ar)
- Calorimeter:~2000 plastic scintillators + PMTs
  - $\Delta E_{FWHM}/E$ ~ 8% @ 3MeV σ_T ~ 300 ps @ 1MeV
  - 3-5% charge confusion

Source	Mass	
^{100}Mo	6.9 kg	$0\nu\beta\beta$
^{82}Se	0.9 kg	
^{130}Te	0.45 kg	
^{116}Cd	0.4 kg	
^{150}Nd	37g	$2\nu\beta\beta$
^{96}Zr	9.4g	
^{48}Ca	7.0g	

source in foils 40-60 mg/cm2

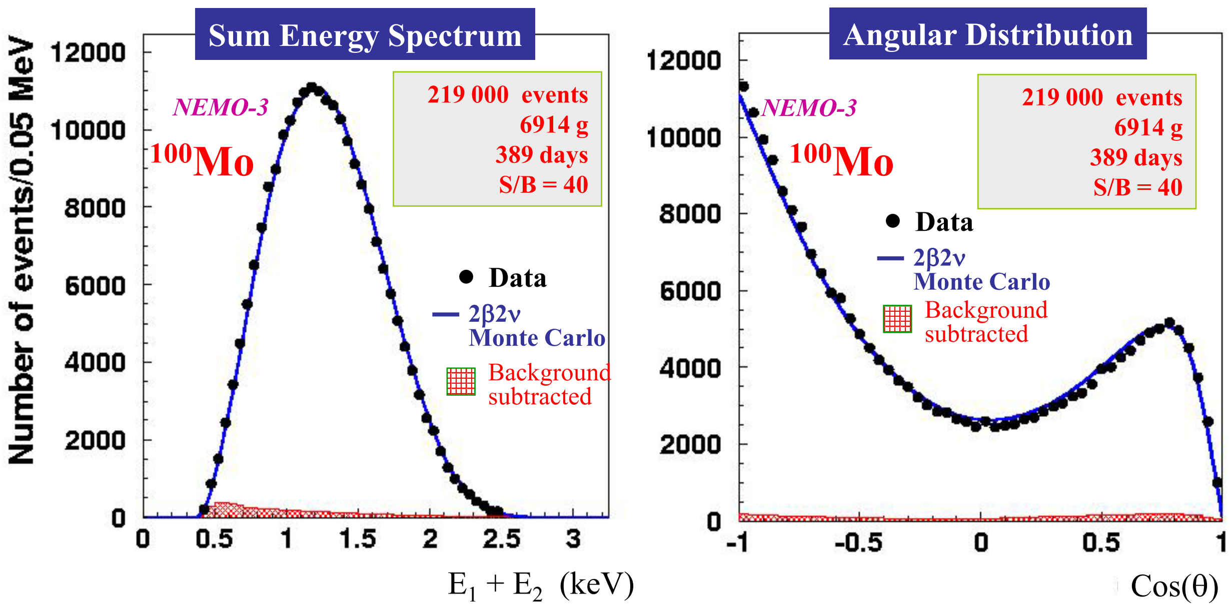


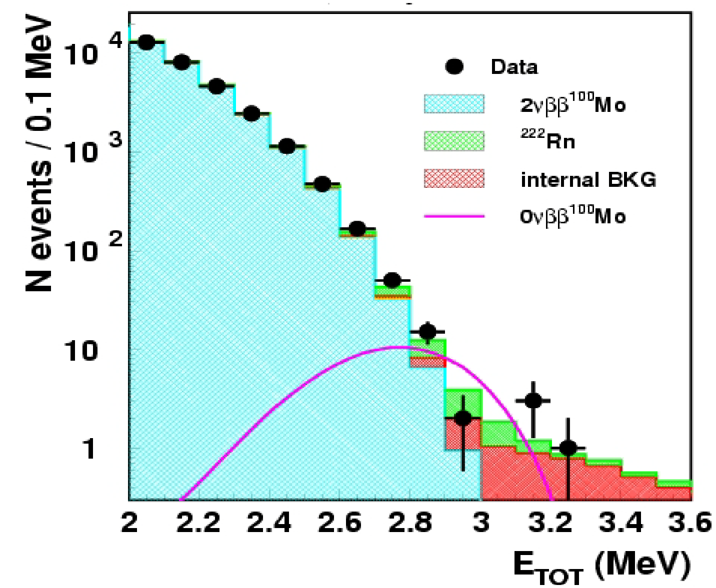


NEMO 3 results

^{100}Mo: $\tau^{2\nu}_{1/2}$ =(7.11±0.02±0.54)·10^{18} y

^{100}Mo: $\tau^{0\nu}_{1/2}$ >1.1·10^{24} y





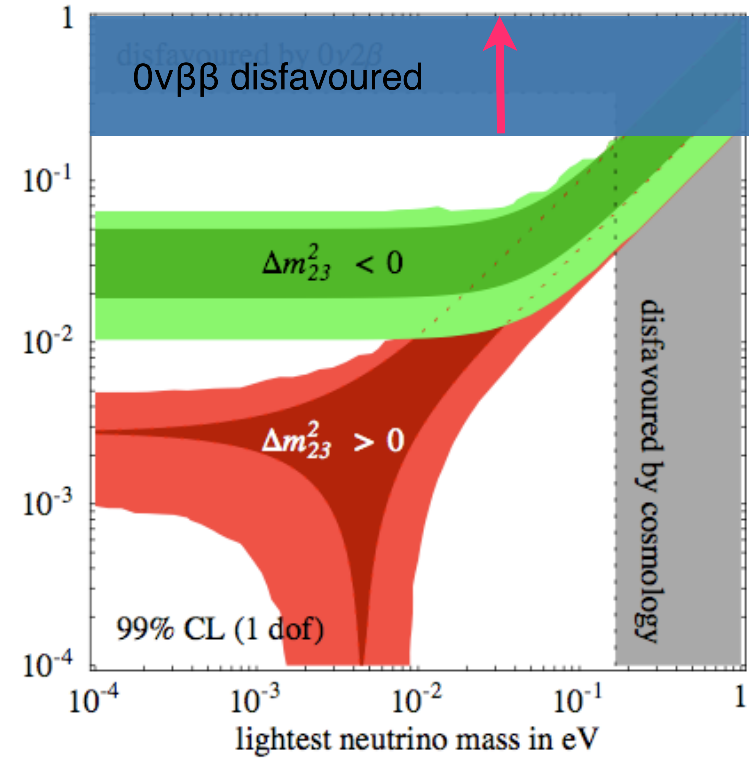
Isotope	Exposure (kg·y)	$T_{1/2}(0\nu\beta\beta)$, y	$\langle m_\nu \rangle$, eV [NME ref.]
^{100}Mo	26.6	> 1.1 · 10^{24}	< 0.45 – 0.93 [1-3]
^{82}Se	3.6	> 3.6 · 10^{23}	< 0.9 – 1.6 [1-3]; < 2.3 [7]
^{150}Nd	0.095	> 1.8 · 10^{22}	< 1.7 – 2.4 [4,5] ;< 4.8 – 7.6 [6]
^{130}Te	1.4	> 9.8 · 10^{22}	< 1.6 – 3.1 [2,3]
^{96}Zr	0.031	> 9.2 · 10^{21}	< 7.2 – 19.5 [2,3]
^{48}Ca	0.017	> 1.3 · 10^{22}	< 29.6 [7]

Bkgd: natural radioactivity,
mainly ^{214}Bi et ^{208}Tl, Rn,
neutrons (n,γ), muons

Isotope	S/B	(2νββ), y (NEMO 3)
^{100}Mo	40	(7.11 ± 0.02(stat)±0.54(syst))·10^{18} (SSD favoured) [1]
^{100}Mo(0^+_1)	3	(5.7$^{+1.3}_{-0.9}$(stat))±0.8(syst))·10^{20} [2]
^{82}Se	4	(9.6± 0.3(stat)±1.0(syst))·10^{19} [1]
^{116}Cd	7.5	(2.8± 0.1(stat)±0.3(syst))·10^{19} [3]
^{130}Te	0.35	(6.9± 0.9(stat)±1.0(syst))·10^{20} [6]
^{150}Nd	2.8	(9.11$^{+0.25}_{-0.22}$(stat)±0.63(syst))·10^{18} [4]
^{96}Zr	1.0	(2.35± 0.14(stat)±0.16(syst))·10^{19} [5]
^{48}Ca	6.8	(4.4$^{+0.5}_{-0.4}$(stat)±0.4(syst))·10^{19} [6]

Future strategies

$$S^{m_{\beta\beta}} = \left(\frac{A}{\ln 2 N_A a \epsilon G}\right)^{1/2} \frac{1}{|M_{nucl}|} \left(\frac{B\Delta E}{Mt}\right)^{1/4}$$



- Enrichment: difficult and expensive
- To start to explore(cover) inverted hierarchy:
  - M~0.1(1) Ton
  - B~10^{-2}(10^{-3}) counts/keV/kg/y
- Background sources:
  - natural radioactivity: U, Th(τ~10^{10} y) in detector and surroundings

    contamination ~10^{-13} g/g (close or below detectability of HPGE, NAA, ICPMS)
  - neutrons: from radioactivity and muon-induced
  - cosmic rays: (in)direct interaction and activation

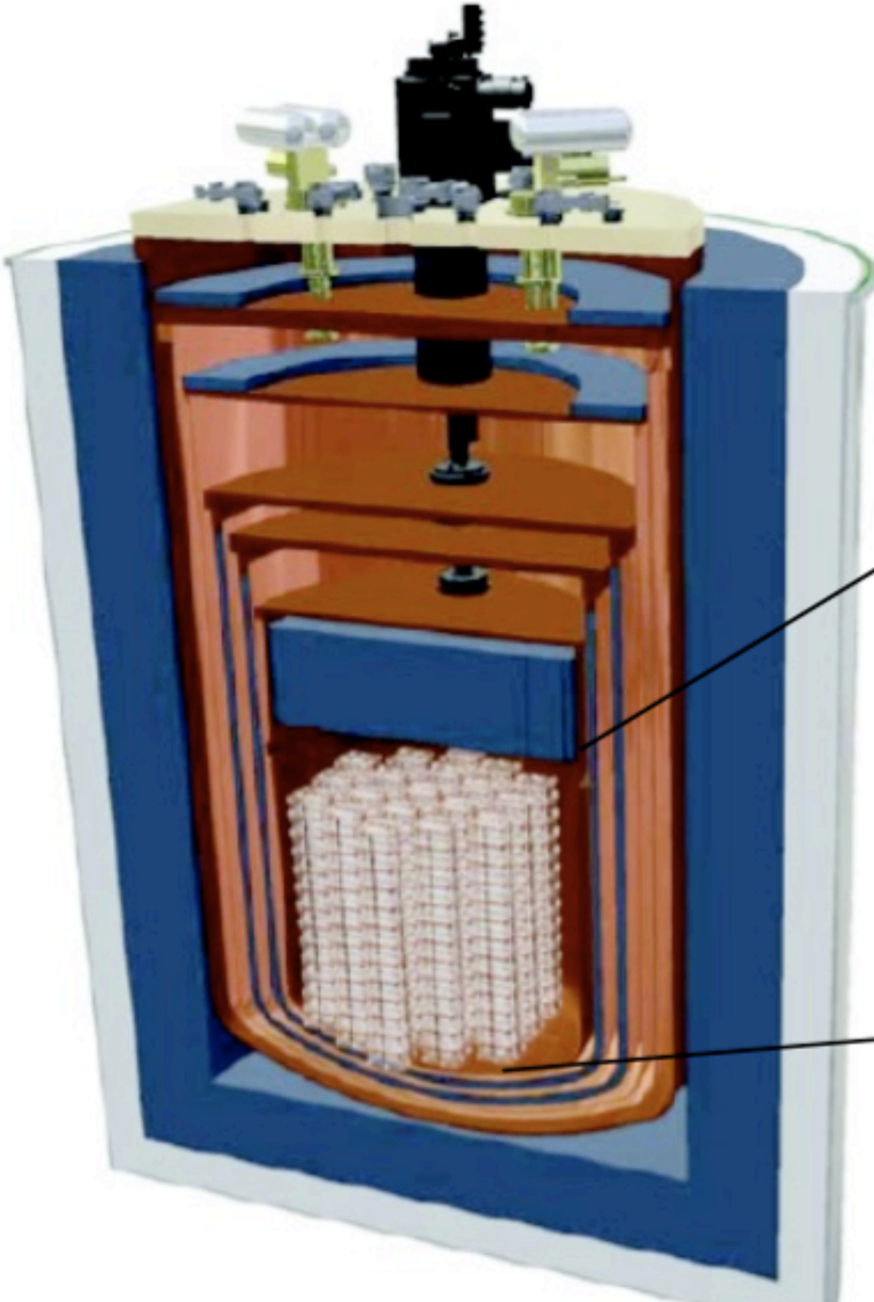
CUORE

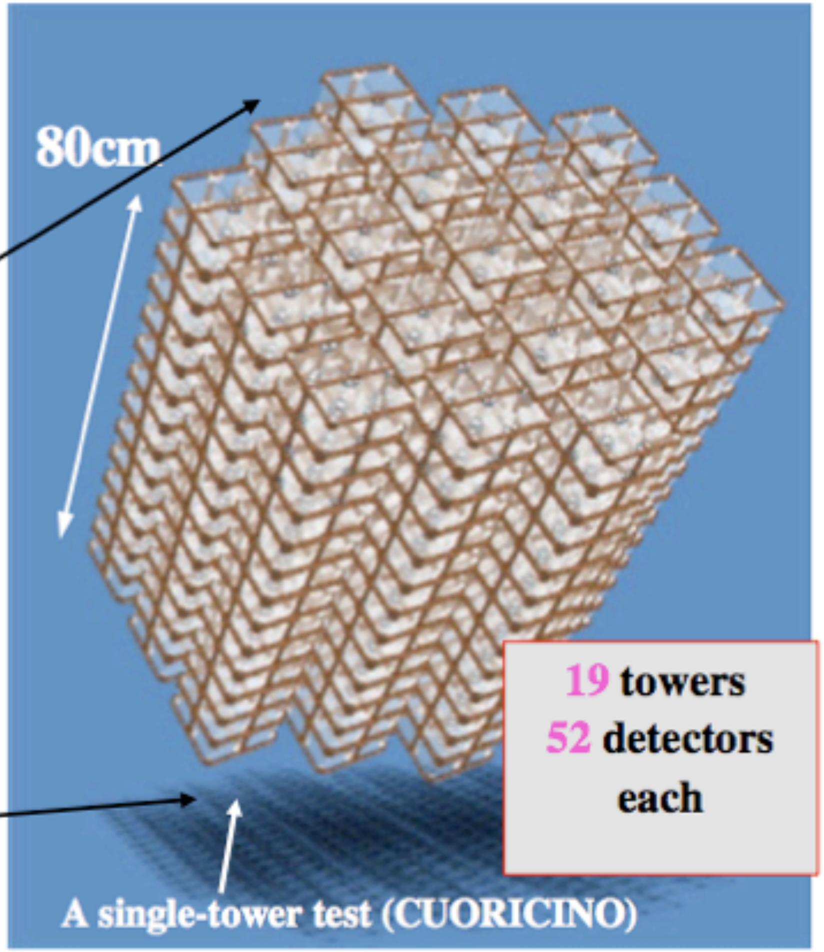
source = detector

Single dilution refrigerator ~10mK

Closed packed array of 988 TeO_2 crystals
compact structure⇒ active shielding

741 kg TeO_2: 204 Kg ^{130}Te ~10^{27} nuclides





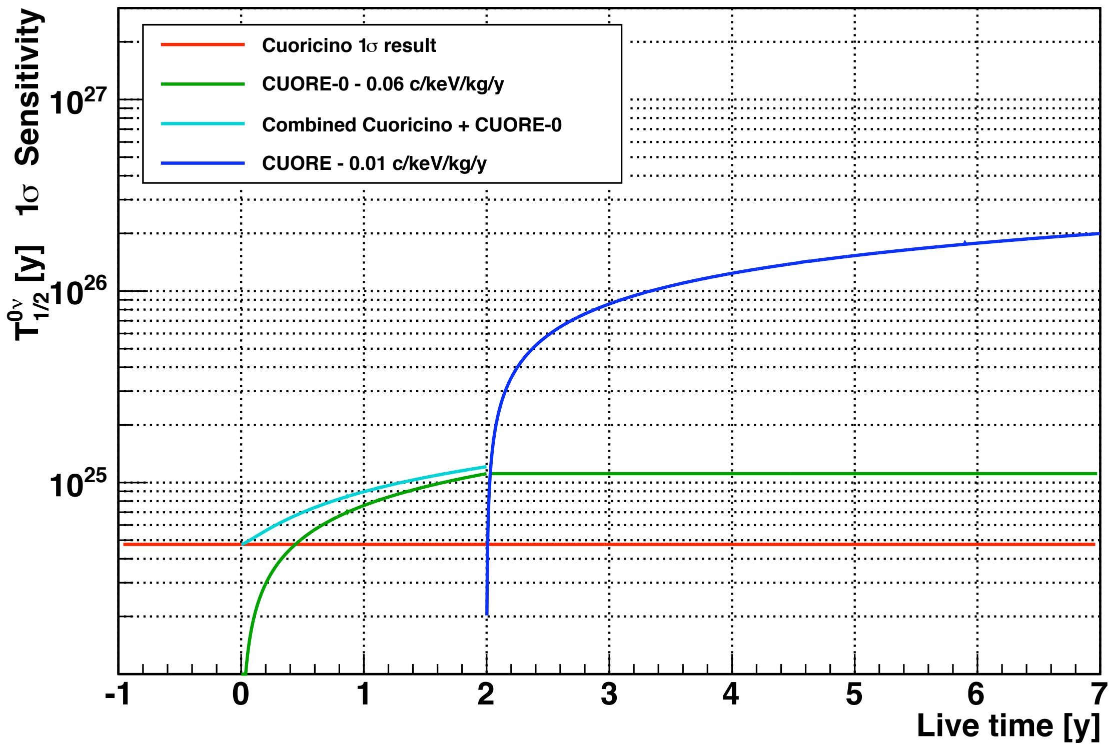
CUORE status

- The First CUORE Tower (CUORE-0) will be assembled and operated in 2010
  - test new procedures on gluing, holder, wires, zero contact approach
  - expected background: 0.06 counts/keV/kg/y (limited by cryostat contamination)
  - $\Delta E_{FWHM} \sim 5$ keV @ $Q_{\beta\beta} \sim 2527$ keV

- CUORE data taking foreseen in 2013
  - bkgd: 10^{-2} counts/keV/kg/y

$\tau^{0\nu}_{1/2} = 2.0 \cdot 10^{26}$ y

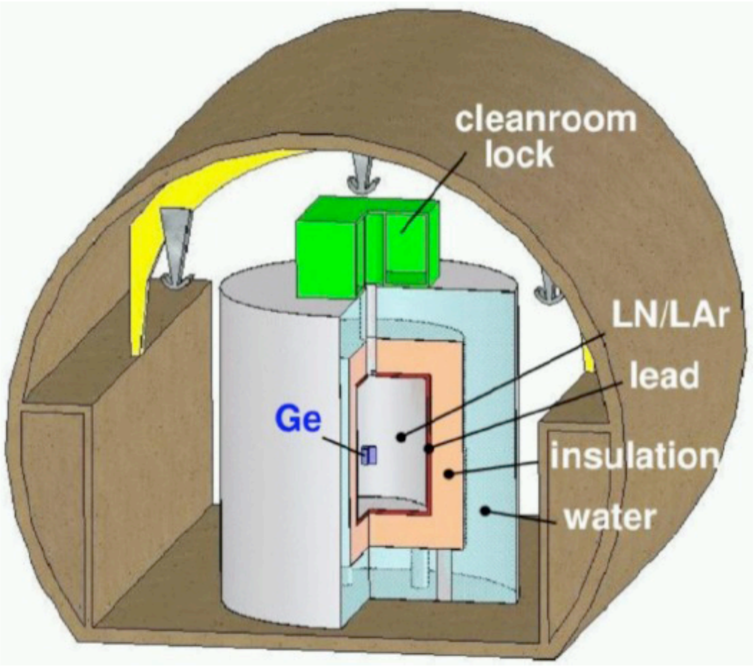
$\langle m_{\beta\beta} \rangle = 44\text{-}87$ meV



GERDA

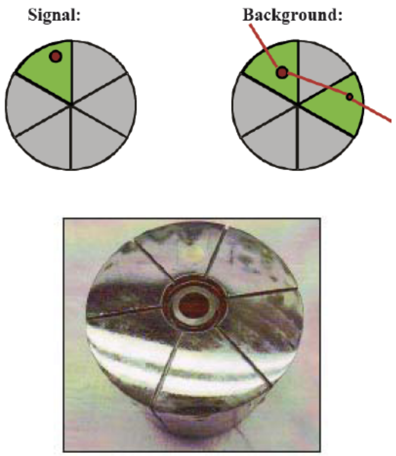
source = detector

- HM-KK bkgd: detector surroundings & Ge cosmogenic activation
- Phase 1:
  - 18 kg bare (HM+IGEX) ^{76}Ge diodes in LAr
  - Background ~10^{-2} counts/keV/kg/y
  - Scrutinize KK-HM claim in 1 year
  - Detector commissioning in fall 2010



- Phase 2:
  - 40 Kg enriched segmented diodes
  - Background ~10^{-3} counts/keV/kg/y
  - Sensitivity: $\tau^{0\nu}_{1/2}$~$2\cdot10^{26}$ y

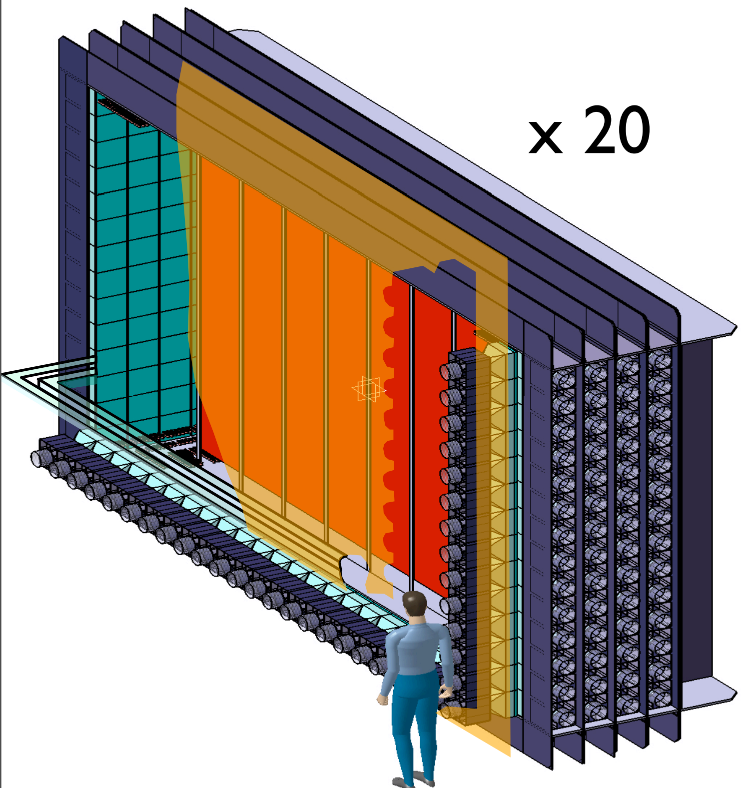
    $\langle m_{\beta\beta}\rangle$ <90-200 meV



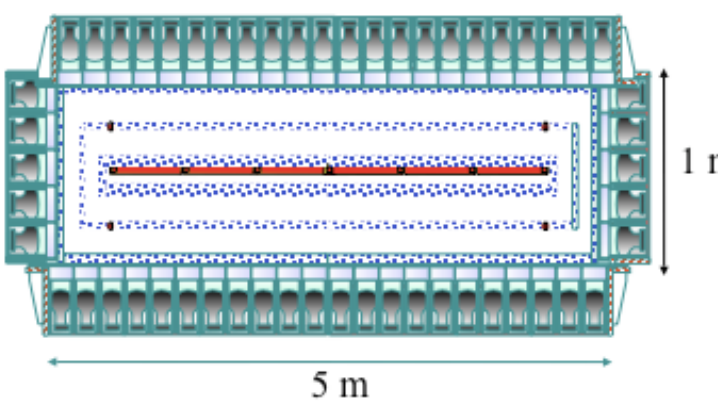
SuperNEMO

source ≠ detector

First prototype module in 2011



x 20



NEMO-3		SuperNEMO
^{100}Mo $T_{1/2}(\beta\beta2\nu) = 7.\ 10^{18}$ y	Choice of isotope	^{82}Se (and/or ^{150}Nd) $T_{1/2}(\beta\beta2\nu) = 10^{20}$ y
7 kg	Isotope mass M	100 - 200 kg
$\varepsilon(\beta\beta0\nu) = 8\ \%$	Efficiency ε	$\varepsilon(\beta\beta0\nu) \sim 30\ \%$
$^{214}Bi < 300\ \mu Bq/kg$ $^{208}Tl < 20\ \mu Bq/kg$ (^{208}Tl, ^{214}Bi) ~ 1 evt/ 7 kg /y	N_{exclu} = f(BKG) *Internal contaminations* *^{208}Tl and ^{214}Bi in the ββ foil*	$^{214}Bi < 10\ \mu Bq/kg$ $^{208}Tl < 2\ \mu Bq/kg$ (^{208}Tl, ^{214}Bi) ~ 1 evt/ 100 kg /y
FWHM(calo)=8% @3MeV	2νββ	FWHM(calo)=4% @3MeV
$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ y $\langle m_\nu \rangle < 0.3 – 0.7$ eV	SENSITIVITY	$T_{1/2}(\beta\beta0\nu) > 2\ 10^{26}$ y $\langle m_\nu \rangle < 50$ meV

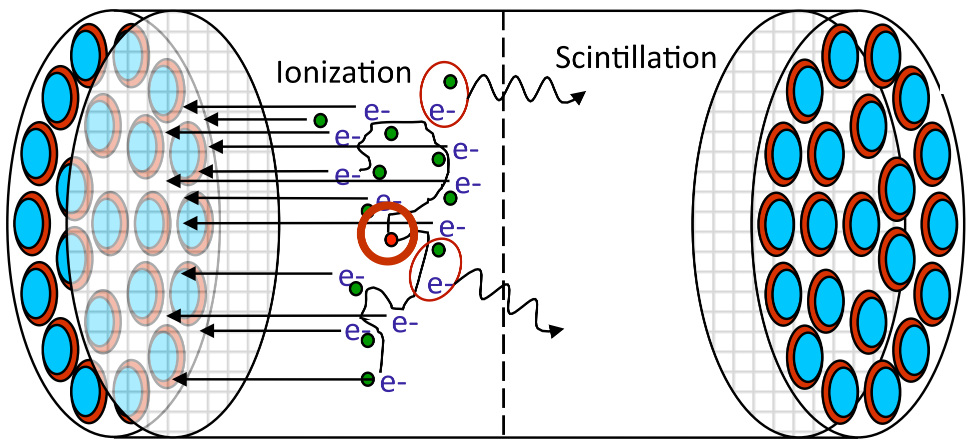
1) ββ source production **2) Energy resolution**

3) Radiopurity **4) Tracking**

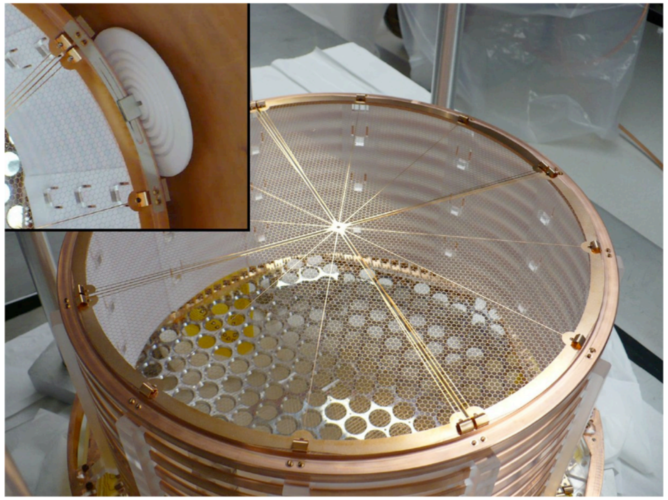
EXO-200

source = detector

- 200 kg Liquid (80% ^{136}Xe) Xe TPC + scintillation: $^{136}Xe \rightarrow\ ^{136}Ba^{++} + 2e^{-} (+ 2\nu_e)$



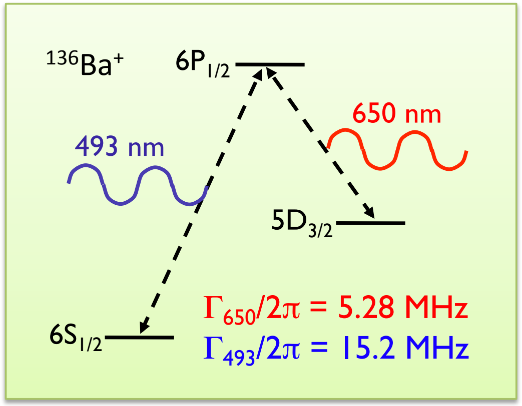
Data taking foreseen in Sep 2010



Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu\beta\beta}$ (yr, 90%CL)	$m_{\beta\beta}$ (meV)
0.2	70	2	1.6	40	6.4×10^{25}	133-186

- Full EXO ~Ton scale gas or liquid TPC
- Single Ba^{+} tagging in real time
  - Ion extraction from TPC and trapping
  - Ion identification with Laser Induced Fluorescence

$^{136}Ba^{+}$ level structure



Loaded Liquid Scintillators

- Poor resolution but hugh mass and low background compensate

source = detector

data taking foreseen in 2011

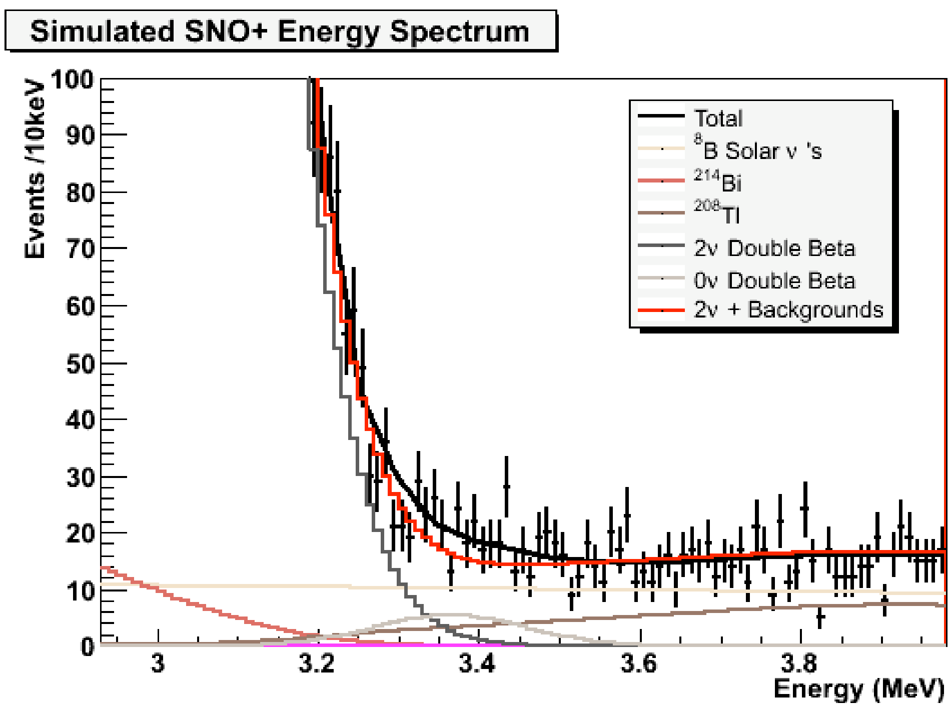
SNO++

^{150}Nd (i.a.=5.6%)

0.1% natural load Nd ~56 kg ^{150}Nd

ΔE_{FWHM}~ 6.4% @ 3367 keV

sensitivity(3y): $\langle m_{\beta\beta} \rangle$ ~100 meV



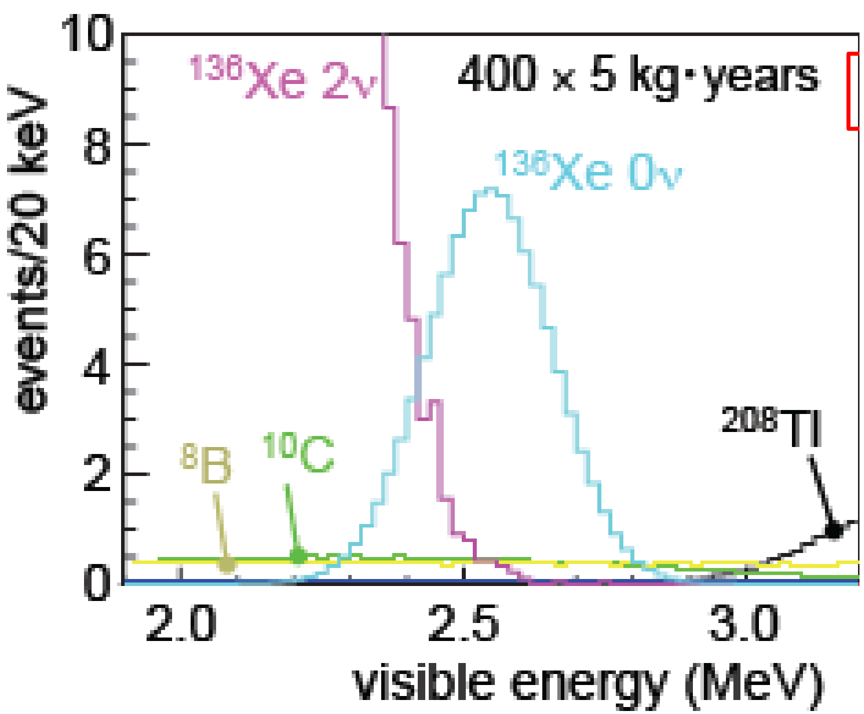
Kamland

^{136}Xe (i.a.=8.9%)

200-400 kg enriched ^{136}Xe

ΔE_{FWHM}~ 5% @ 2479 keV

sensitivity(5y): $\langle m_{\beta\beta} \rangle$ <150 meV



Conclusions

- Neutrinoless Double Beta Decay is unique tool to study neutrino properties:
  - neutrino nature: Majorana or Dirac
  - Lepton number violation: $\Delta L=2$
  - measurement of the absolute ν mass (with some caveats...)
- Second Generation experiment ready to data taking with improved sensitivity
  - HH-KK ^{76}Ge claim will be tested in 2011
  - If the effective neutrino mass is $m_{\beta\beta}$~100 meV, Majorana neutrino will be discoverd in the next 5 years.