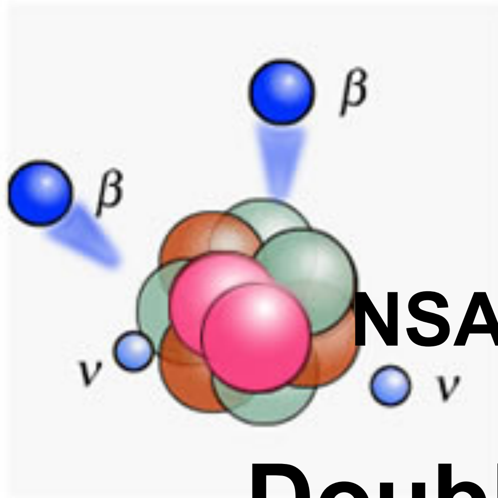
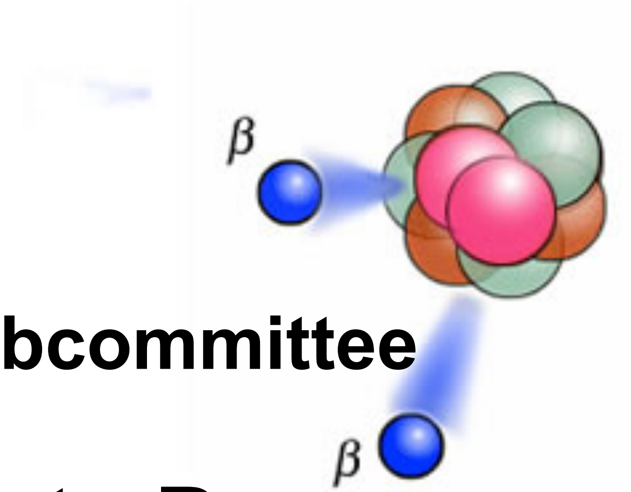




NSAC Subcommittee

Double Beta Decay Overview

Stuart Freedman

University of California, Berkeley
and
Lawrence Berkeley National Laboratory

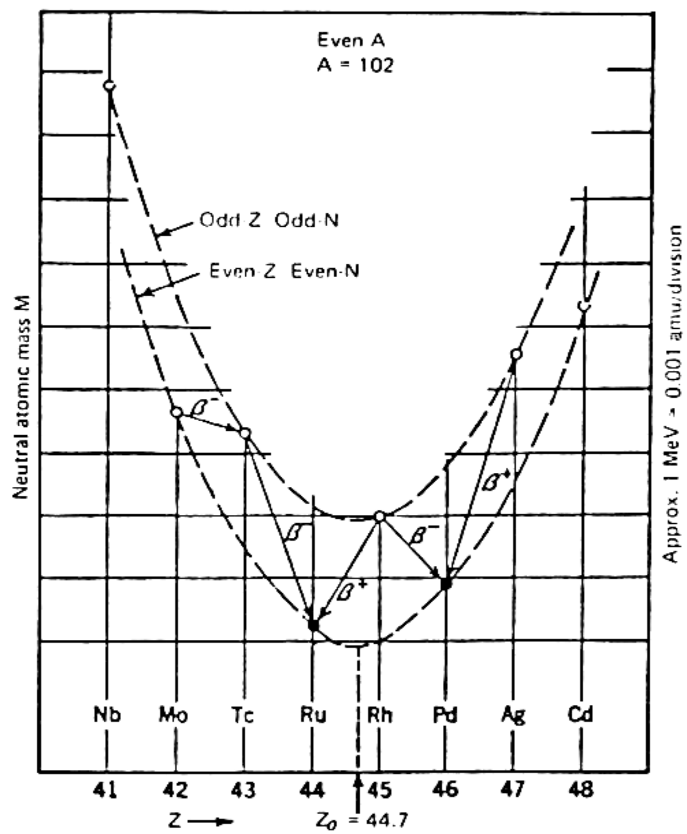
$2\nu\beta\beta$ Decay

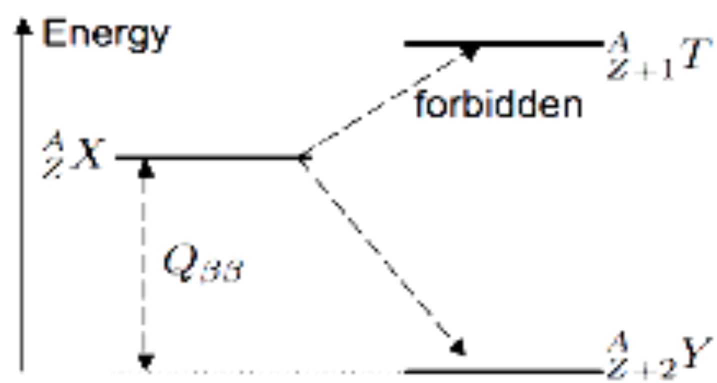
Bethe-Von Weizsacker semi-empirical mass relation

$$M(A,Z) = Zm_p + (A-Z)m_n - a_v A + a_s A^{2/3} + a_c Z^2 A^{-1/3} + a_a (A-2Z)^2 A^{-1} + \delta$$

$\delta = -a_p A^{-3/4}$ *(even,even) or* $+a_p A^{-3/4}$ *(odd,odd) or* 0 *(even,odd)*

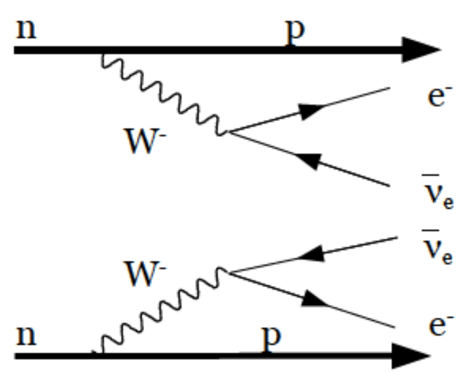
a_p *-> 33.5 MeV*

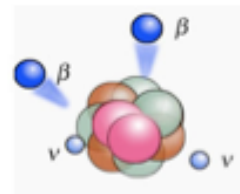




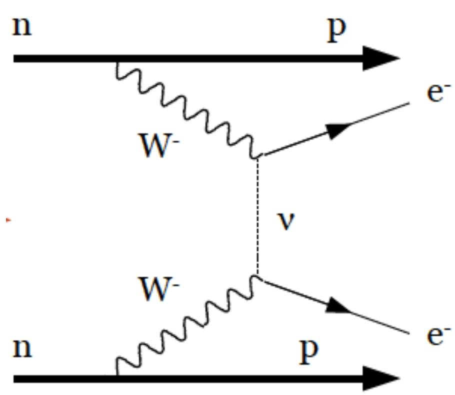
0νββ Decay

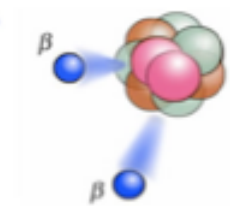
2νββ





0νββ



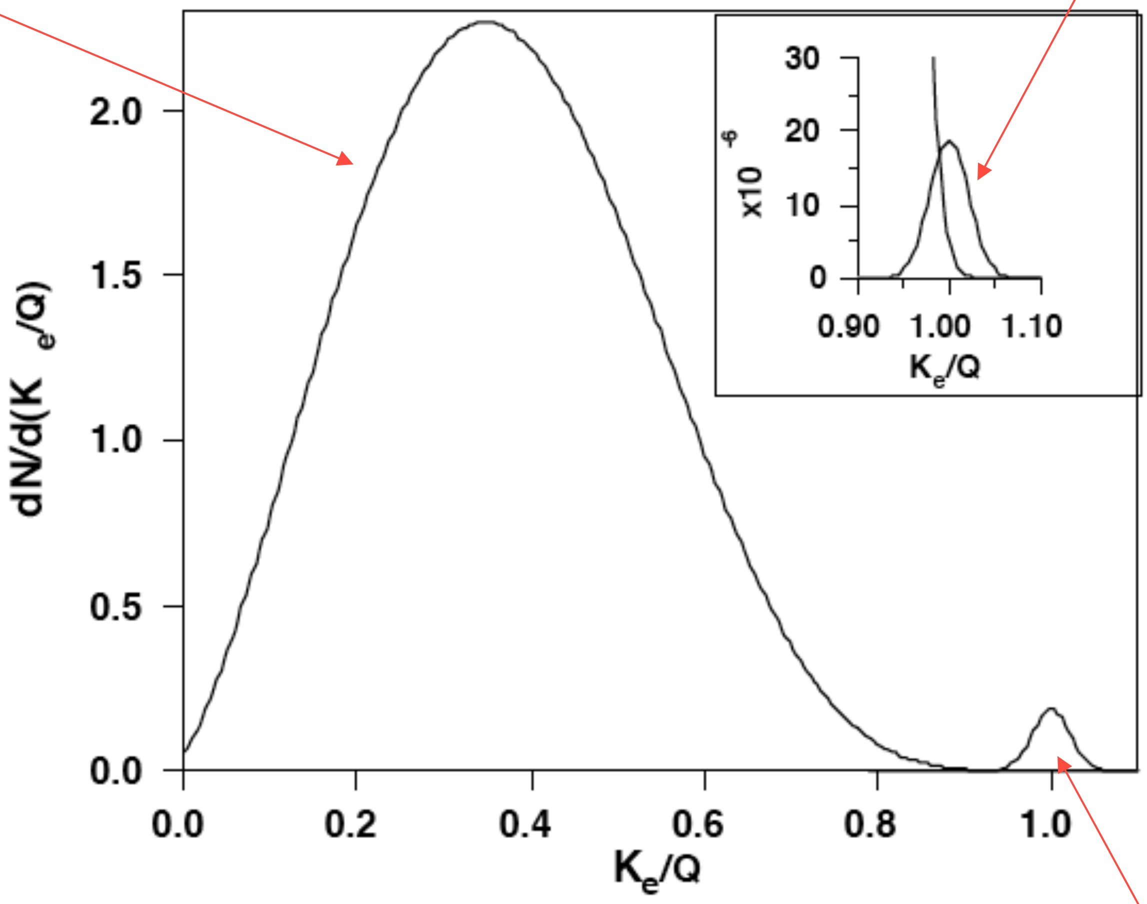


If 0νββ occurs then the neutrino is a Majorana particle and the neutrino and antiparticle are not distinct. Lepton number is not conserved!

Experimental Signal of Double Beta Decay

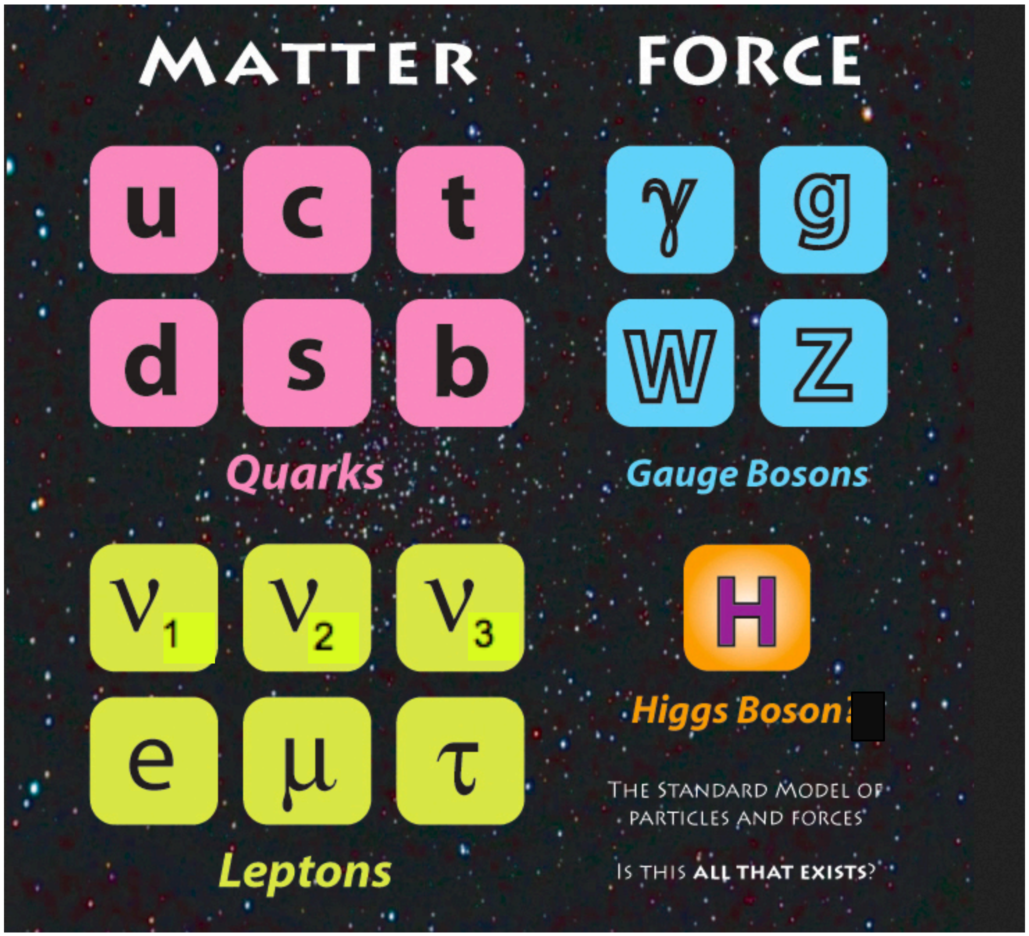
$$\frac{dN}{dE} \approx E(Q-E)^5\left(1+2E+\frac{4E^2}{3}+\frac{E^3}{3}+\frac{E^4}{30}\right)$$

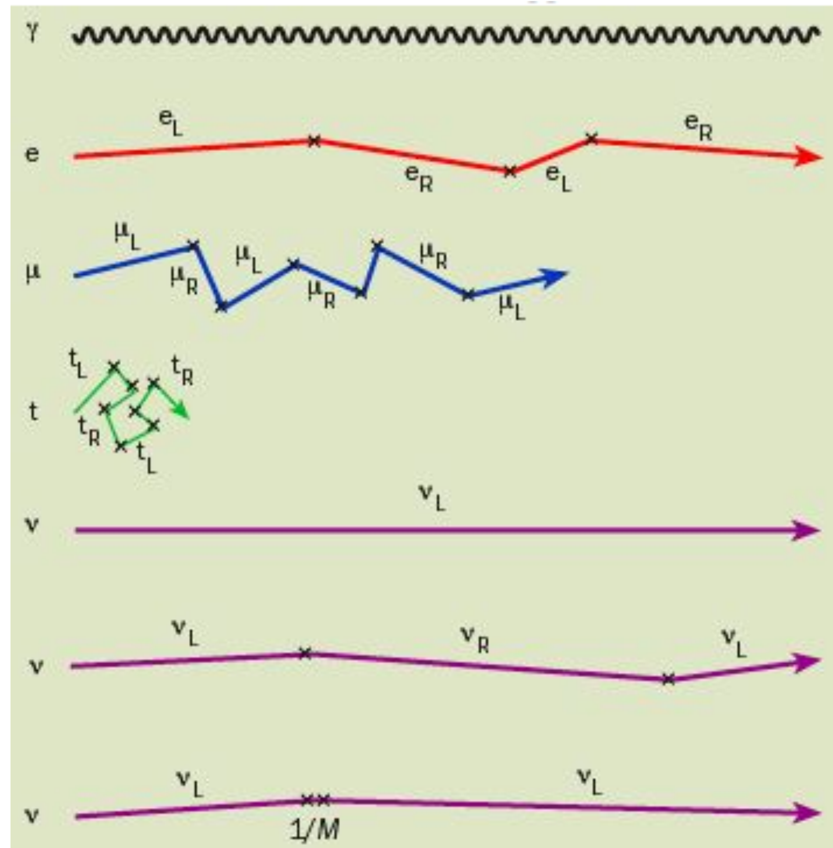
Experimental Resolution



$\Gamma_{0\nu} = G_{0\nu}(Q,Z)\ |M_{nucl}|^2 <m_{\beta\beta}>^2$

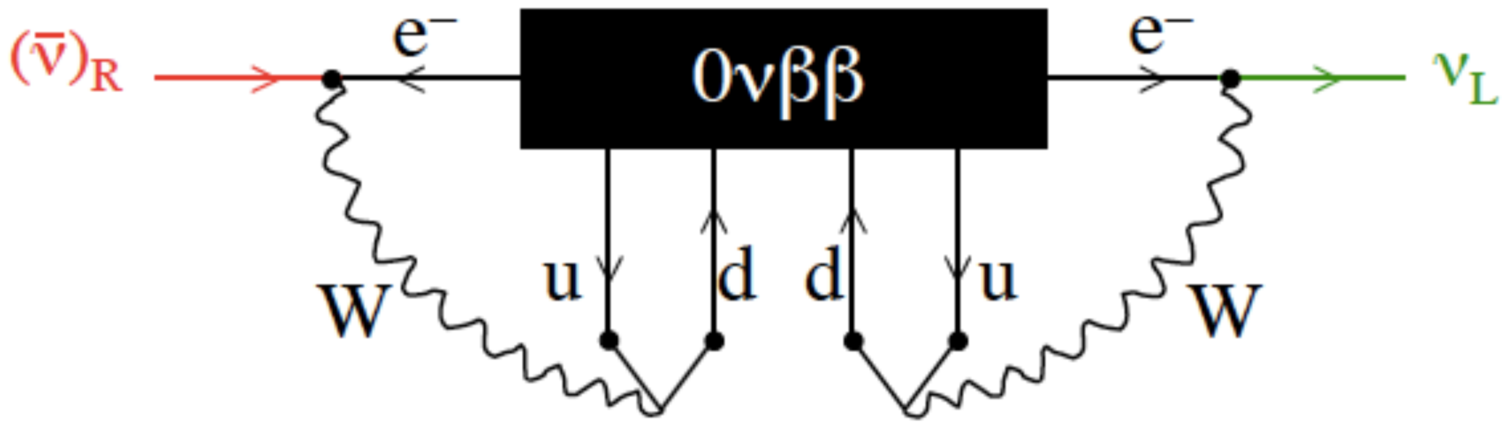
Higgs Boson, Majorana Mass and Lepton Number Conservation



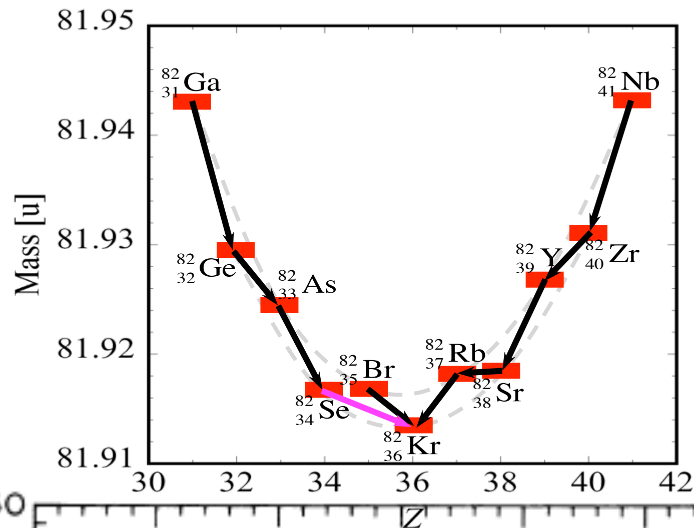


A Theorem

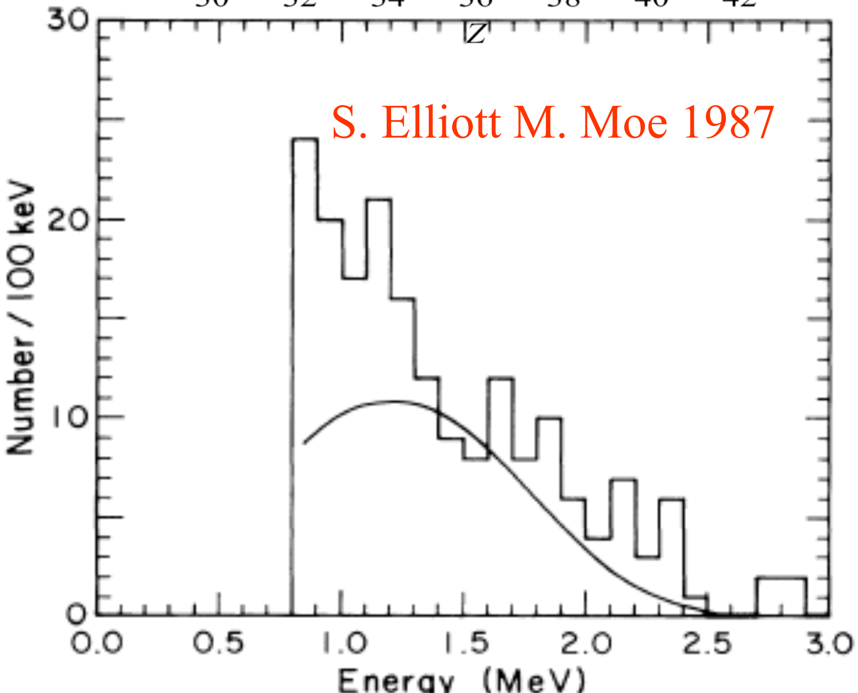
(Schechter and Valle)



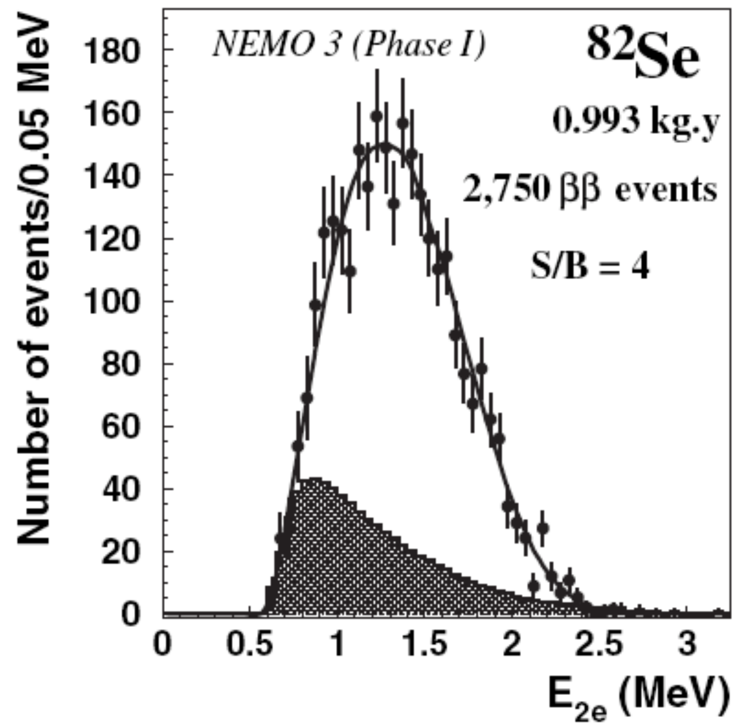
First direct detection of 2νββ



Mike Moe



^{82}Se, 35 events



Volume 25B, number 10 PHYSICS LETTERS 27 November 1967

A SEARCH FOR LEPTON NON-CONSERVATION IN DOUBLE BETA DECAY WITH A GERMANIUM DETECTOR

^{76}Ge

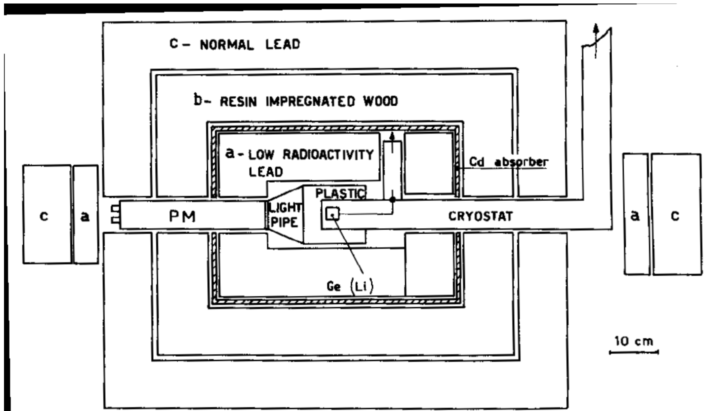


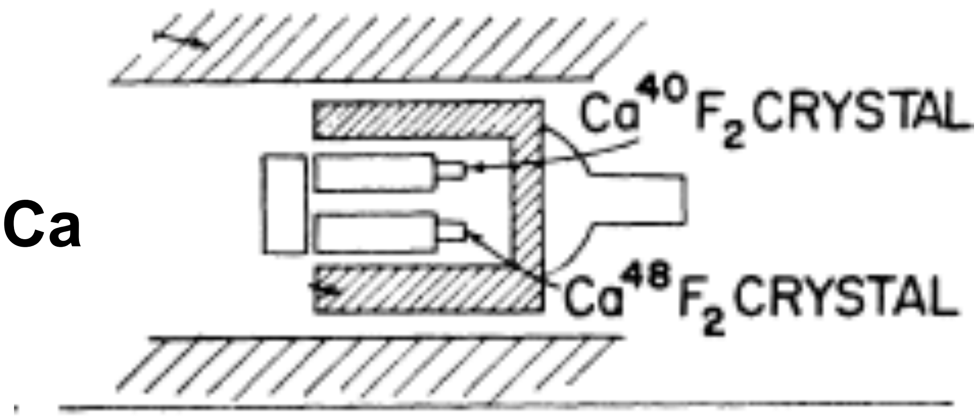
Fig. 1. Experimental setup.

≥ 3 x 10^{20} years

PHYSICAL REVIEW VOLUME 146, NUMBER 3 17 JUNE 1966

Limits for Lepton-Conserving and Lepton-Nonconserving Double Beta Decay in Ca^{48}†

^{48}Ca



≥ 2 x 10^{20} years

Claimed Observation of 0νββ in ^{76}Ge

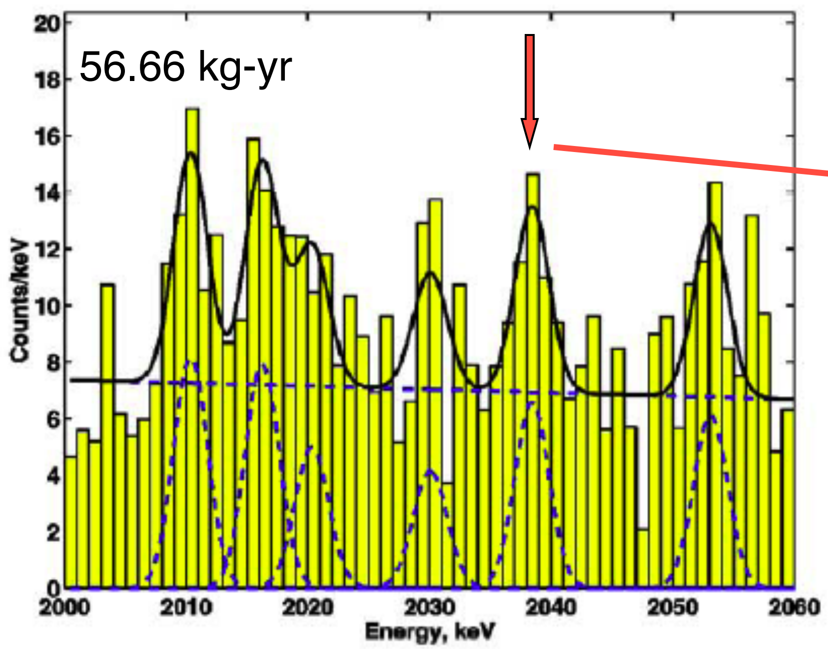
5 detectors of overall 10.96 kg enriched to 86%.
Most sensitive to date.

$T_{1/2}$ = (0.67 - 4.45) x 10^{25} *years* (99.73% *C.L.)*

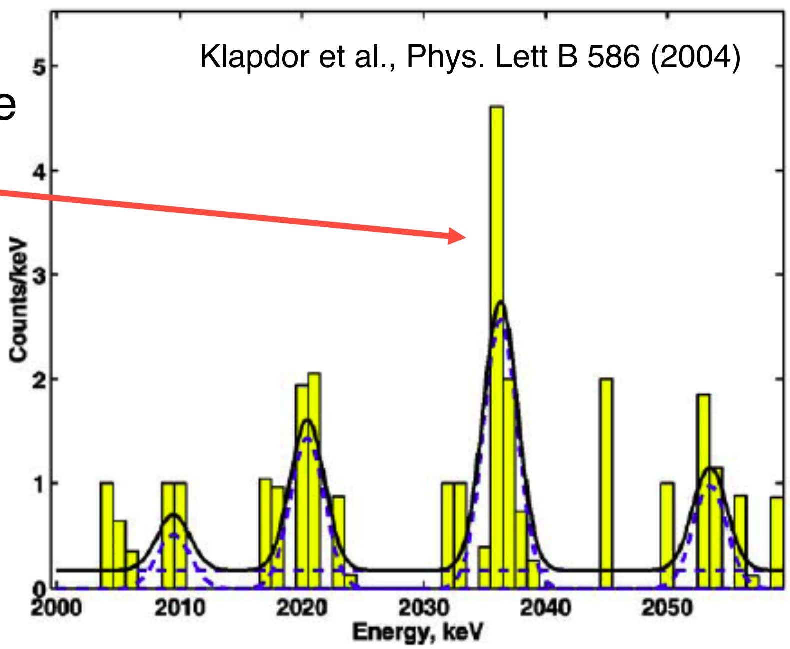
Majorana ν Mass

$<m_{\beta\beta}>$ = (0.1 - 0.9) eV (99.73% *C.L.*)

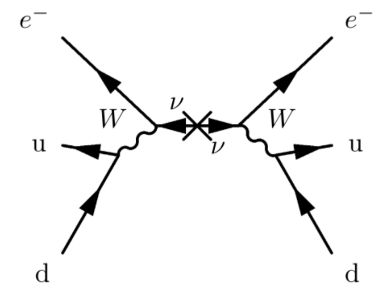
$<m_{\beta\beta}>_{best}$ = 0.45 *eV*



Pulse-shape selection



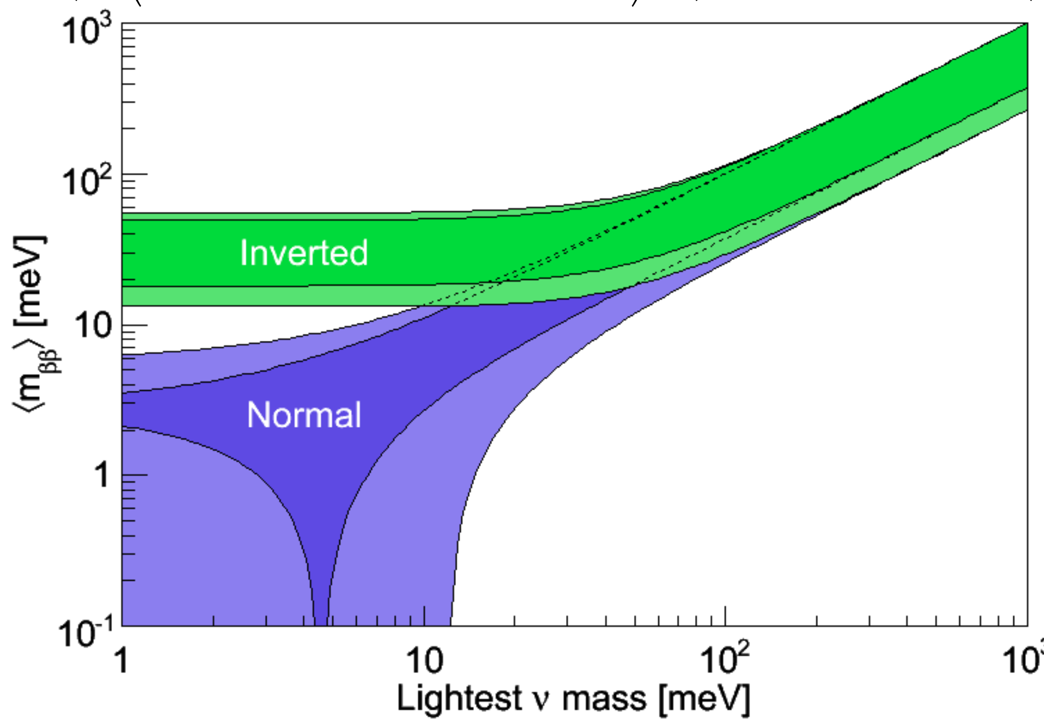
$$\Gamma_{0\nu} = G_{0\nu}(Q,Z)\,|M_{\mathrm{nucl}}|^2 <m_{\beta\beta}>^2$$



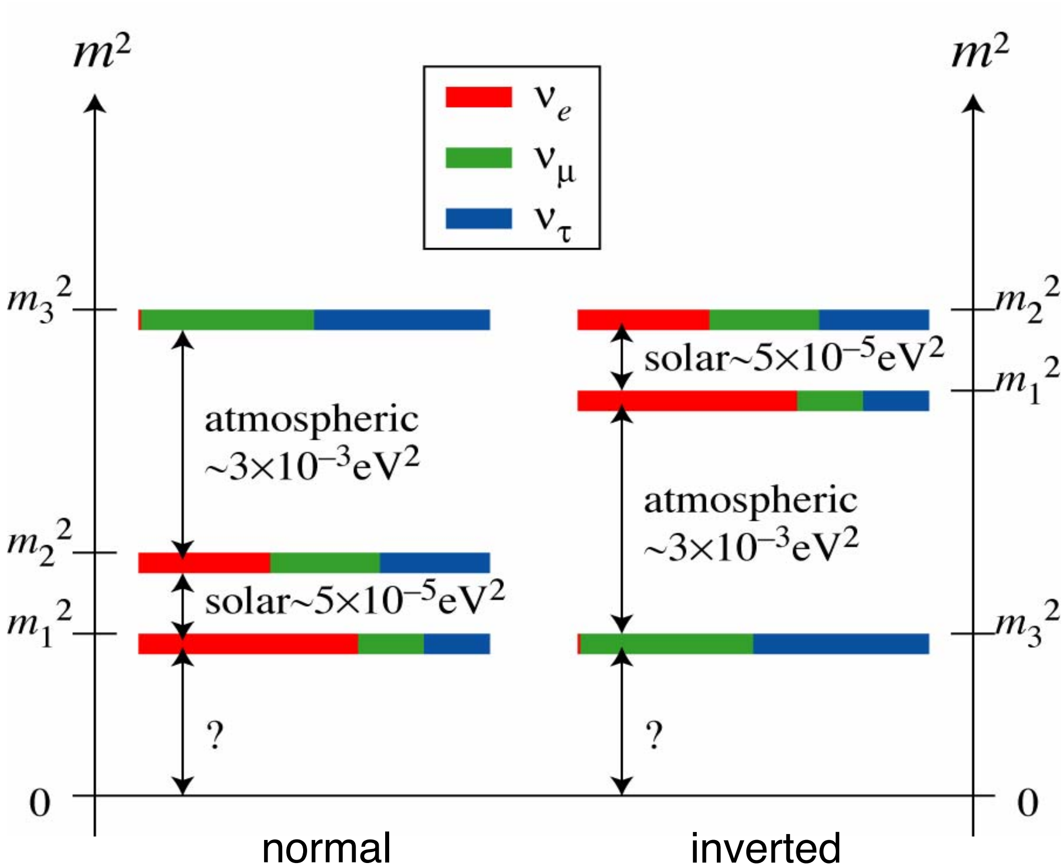
$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \varepsilon_i$$

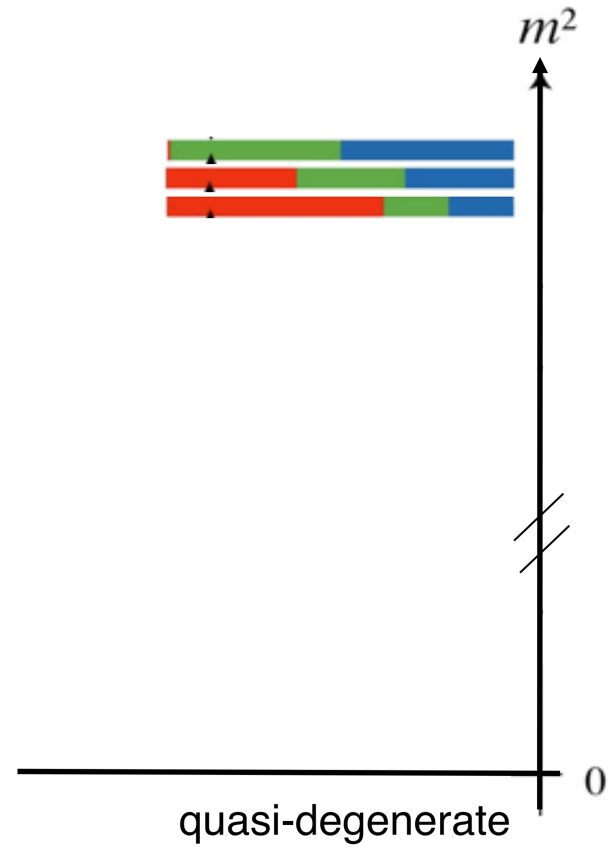
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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



Neutrino Mass Hierarchy





$\Delta m_{atm}{}^2$ $m_\nu > 40$ meV

$\Delta m_\odot{}^2$ $m_\nu > 8$ meV

Experimental Sensitivity

$$F_N \propto \varepsilon \frac{a}{A}\left[\frac{MT}{B\Gamma}\right]^{1/2}$$

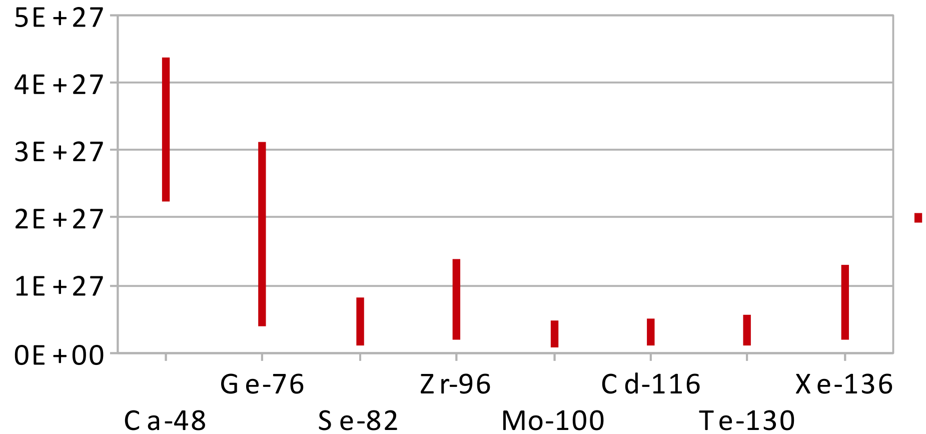
- Isotopic fraction (a)
- Detector efficiency (ε)
- Atomic mass (A)
- Detector Mass (M)
- Running time (T)
- Background (B)
- Detector resolution (Γ)

$$\langle m_{\beta\beta}\rangle \propto 1/\sqrt{T_{1/2}^{0\nu}} \propto 1/(MT)^{1/2}$$ **Background Free**

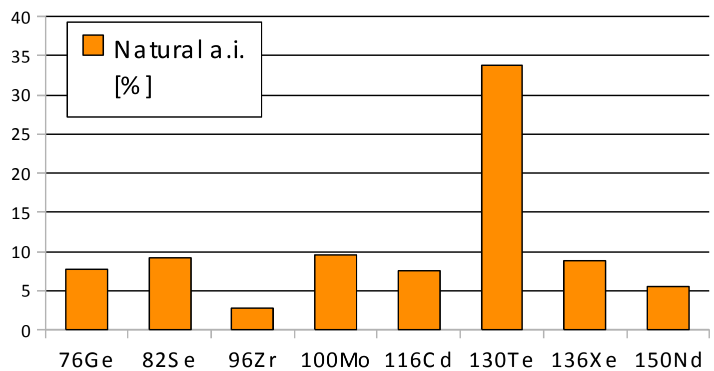
$$\langle m_{\beta\beta}\rangle \propto 1/\sqrt{T_{1/2}^{0\nu}} \propto 1/(MT)^{1/4}$$ **With Background**

Guide to selecting an experiment

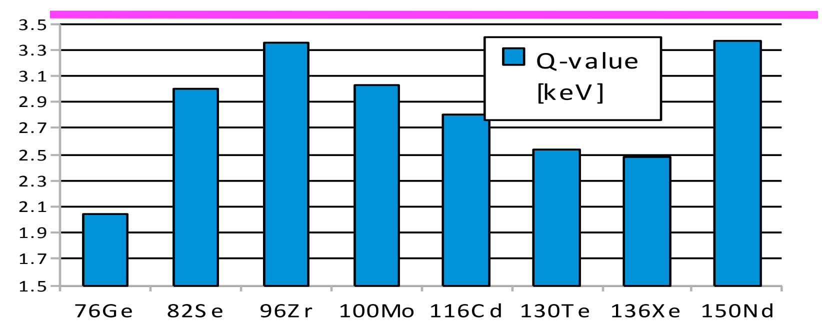
$$\Gamma_{0\nu} \sim G_{0\nu}(Q,Z)\ |M_{nucl}|^2$$



Nuclear Matrix Element

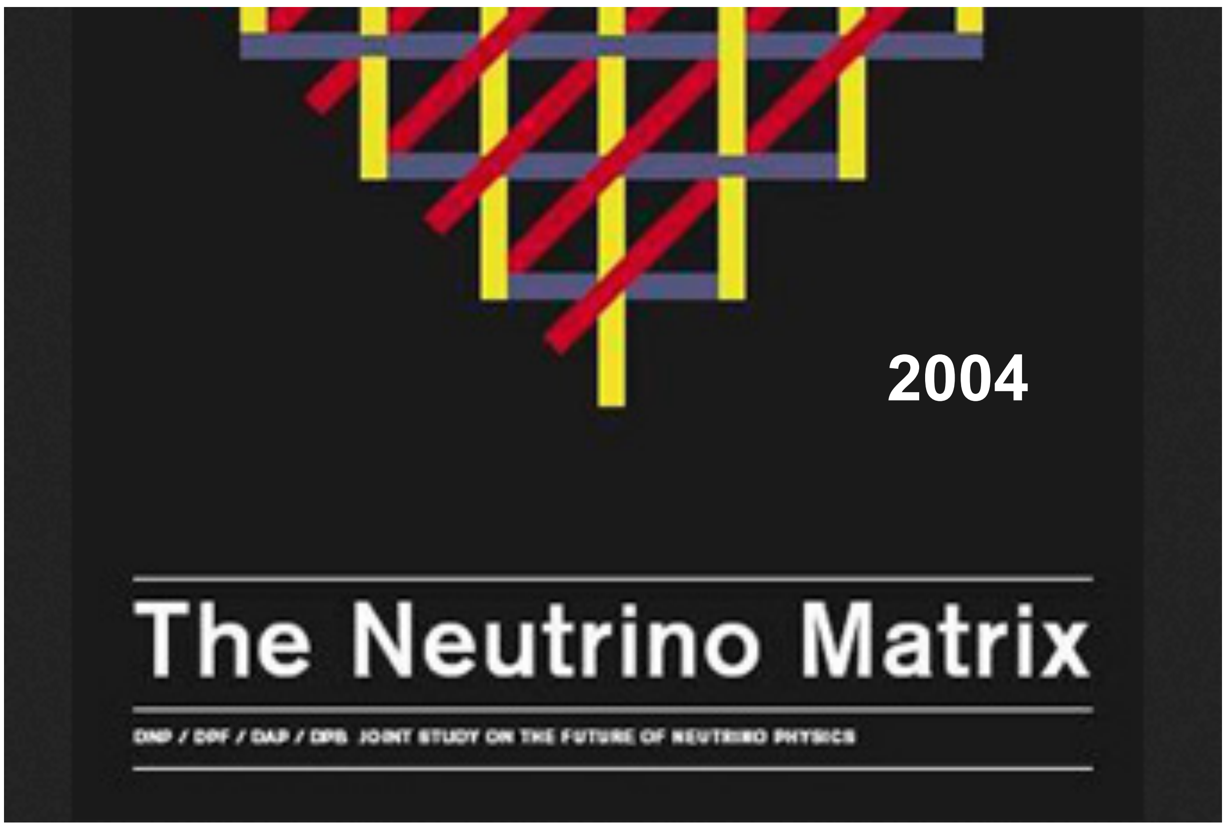


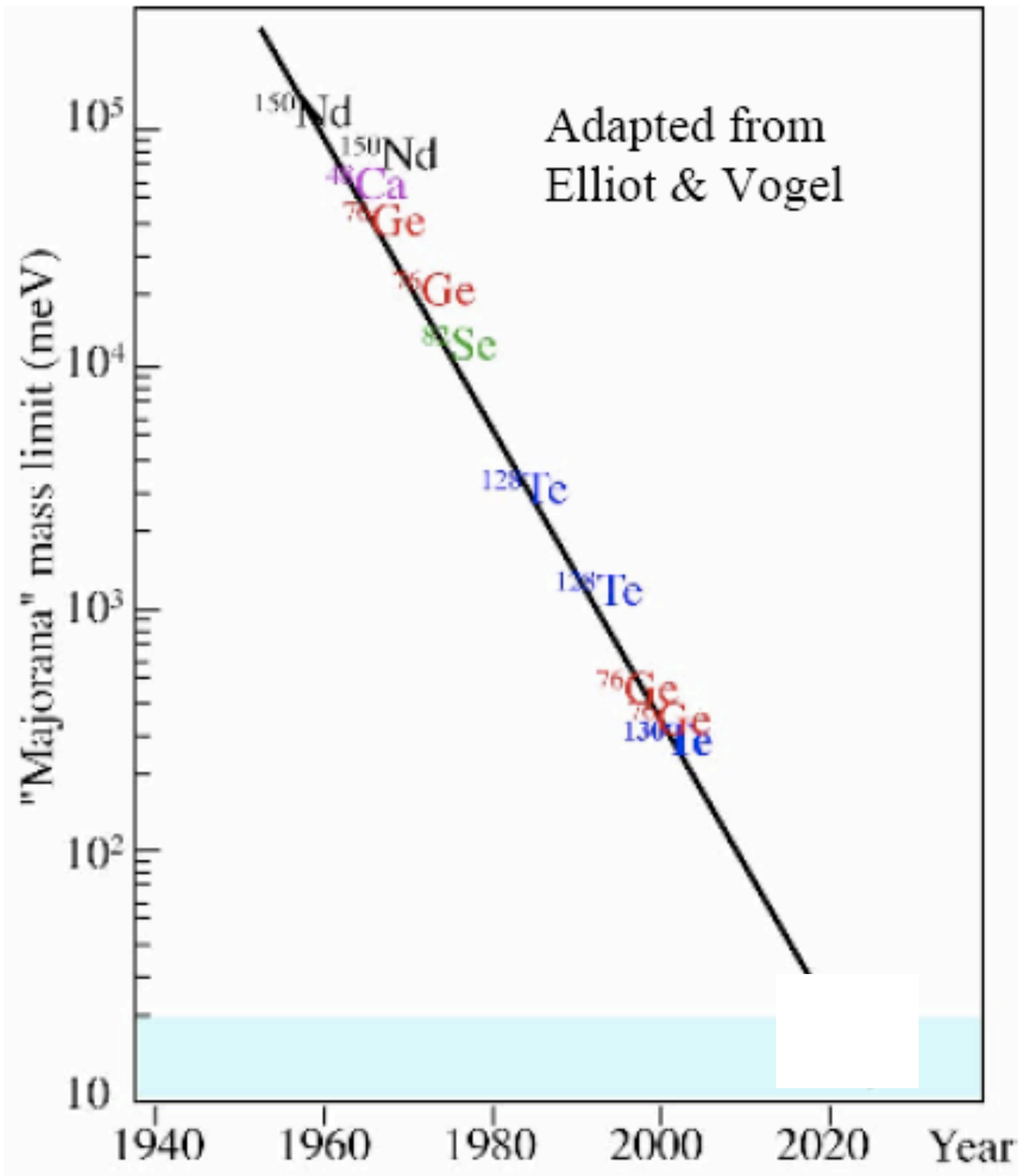
Natural Isotopic Abundance



Q-value

- We recommend, as a high priority, that a phased program of sensitive searches for neutrinoless nuclear double beta decay be initiated as soon as possible.

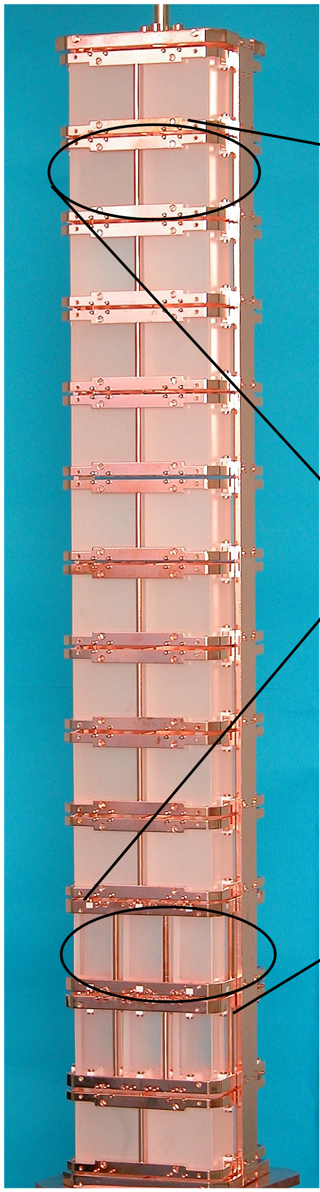


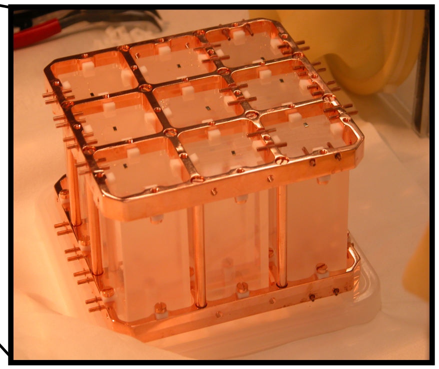


Adapted from
Elliot & Vogel
"Majorana" mass limit (meV)
Year
150Nd
150Nd
48Ca
76Ge
76Ge
82Se
128Te
128Te
76Ge
76Ge
130Te
10^5
10^4
10^3
10^2
10
1940
1960
1980
2000
2020

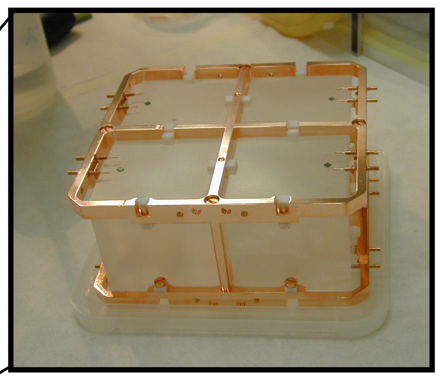
Cuoricino

Total detector mass: 40.7 *Kg* ⇒ **11.64 *Kg*** ^{130}**Te**

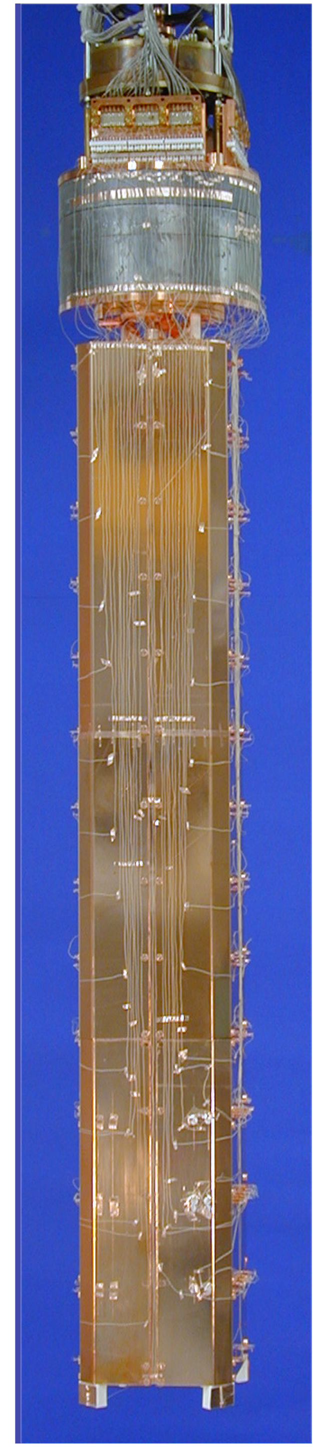




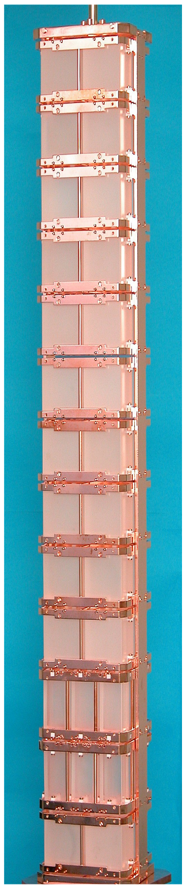
11 modules, 4 detector each
crystal dimension: **5x5x5 cm^3**
crystal mass: **790 *g***
44 x 0.79 = **34.76 *Kg* of TeO_2**



2 modules x 9 crystals each
crystal dimension: **3x3x6 *cm*^{3}**
crystal mass: **330 *g***
9 x 2 x 0.33 = **5.94 *Kg* of TeO_2**
(2 enriched in ^{128}Te @82.3%)
(2 enriched in ^{130}Te @75%)

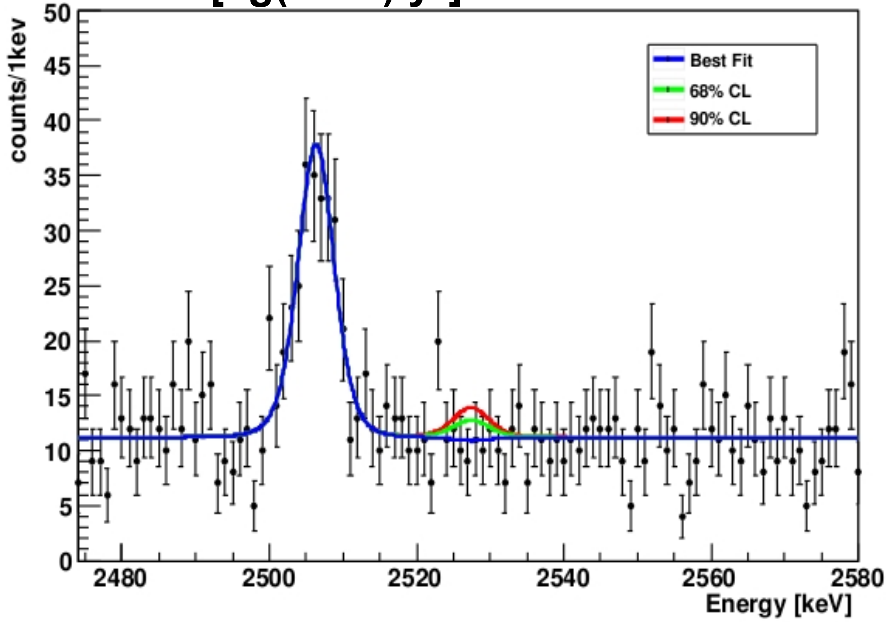


Cuoricino



TOTAL EXPOSURE
19.75 [kg(^{130}Te) yr]

Q-value =
2527.518 ± 0.013 keV



90% C.L.

$t_{1/2} > 2.8 \times 10^{24}$ [yr]

$\langle m_{\beta\beta} \rangle < 0.3 - 0.7$ eV

NuSAG 2005

For the region of degenerate neutrino masses, NuSAG recommends the following implementation strategy for the specific experiments. The following three experiments, listed in alphabetical order, have the highest priority for funding.

- **CUORE**: The CUORE ^{130}Te experiment has potential for good energy resolution and low background, provided the technology develops as planned. The high natural abundance of ^{130}Te results in a relatively low cost for a detector sensitive to the degenerate neutrino mass region. The cost of enriched ^{130}Te needed to extend the sensitivity is lower than for some other isotopes. The schedule presented by CUORE is timely. The panel is concerned that the requested budget share is not commensurate with the U.S. involvement in the project.

- **EXO**: The EXO-200 ^{136}Xe experiment is presently under construction and should continue to be supported. R&D for barium tagging is a priority as a step to a one ton scale $0\nu\beta\beta$ experiment. If barium tagging is successful, EXO may offer a unique and cost effective approach to a one ton or larger experiment.

- **Majorana**: The excellent background rejection achieved from superior energy resolution in past ^{76}Ge experiments must be extended using new techniques. The panel notes with interest the communication between the Majorana and GERDA ^{76}Ge experiments which are pursuing different background suppression strategies. The panel supports an experiment of smaller scope than Majorana-180 that will allow verification of the projected performance and achieve scientifically interesting physics sensitivity, including confirmation or refutation of the claimed ^{76}Ge signal. A larger ^{76}Ge experiment is a good candidate for a larger international collaboration due to the high cost of the enriched isotope.

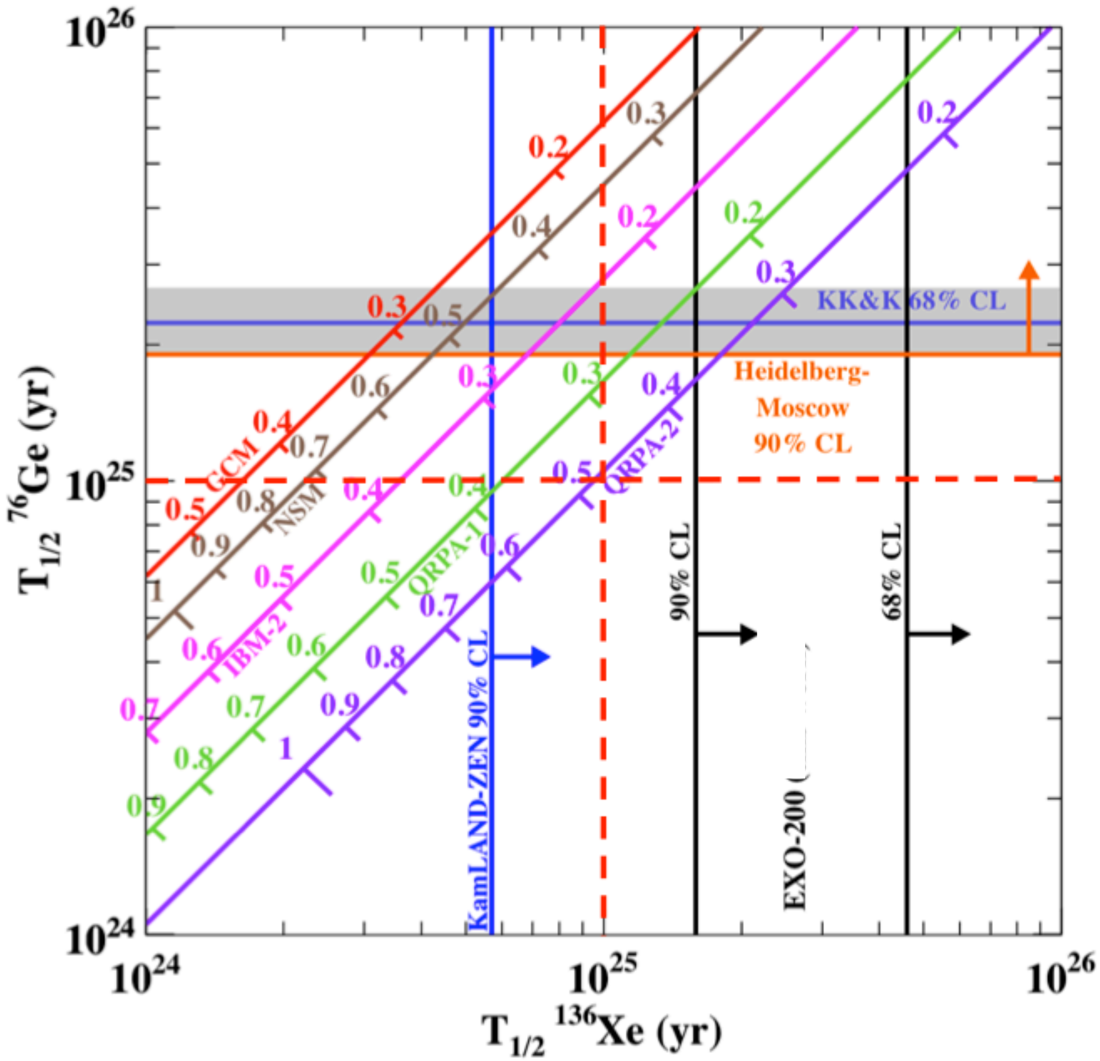
0βββν Experiments

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype - 2009	Kamioka
CARVEL	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
COBRA	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORICINO	^{130}Te	11 kg	TeO_2 bolometers	Complete - 2008	Gran Sasso
CUORE	^{130}Te	200 kg	TeO_2 bolometers	Construction - 2012	Gran Sasso
DCBA	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Kamioka
EXO-200	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Construction - 2009	WIPP
EXO	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal	DUSEL
GEM	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive	
GENIUS	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive	
GERDA	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Construction - 2009	Gran Sasso
GSO	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	
KamLAND	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Contruction - 2012?	Kamioka
MAJORANA	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Construction - 2011	SUL
MOON	^{100}Mo	1 t	^{enr}Mofoils/scint.	Development	
NEXT	^{136}Xe	80 kg	gas TPC	Development	Canfranc
SNO+	^{150}Nd	55 kg	Nd loaded liq. scint.	Construction - 2011	SNOLab
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Frejus
Xe	^{136}Xe	1.56 t	^{enr}Xe in liq. scint.	Development	
XMASS	^{136}Xe	10 ton	liquid Xe	Inactive for $\beta\beta$	Kamioka
HPXe	^{136}Xe	tons	High Pressure Xe gas	Development	

Experiments that can confront the existing claims about $0\nu\beta\beta$

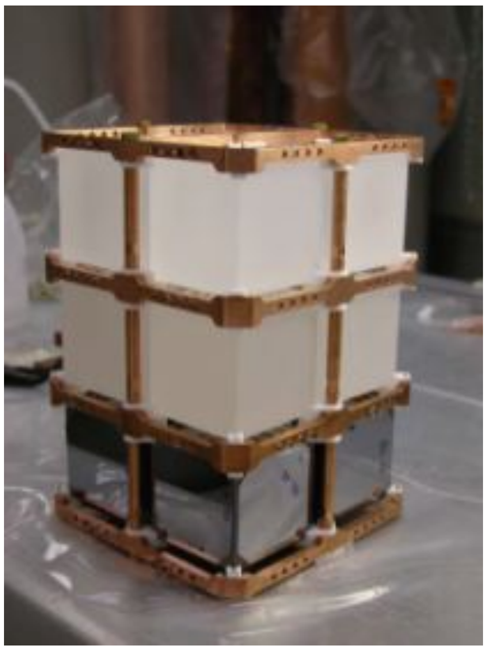
Experiment	Mass	Plan
CUORE0 CUORE	~10 Kg ~200 Kg	2012 2014
EXO-200	~200 Kg	2011
GERDA I/II	~34 Kg	2011/2013
KamLAND-Zen	~300 Kg	2012
MAJORANA	~30 Kg	2013
NEXT	~100 Kg	2014
SNO+	~60 Kg	2013
SuperNEMO	~7 Kg	2013

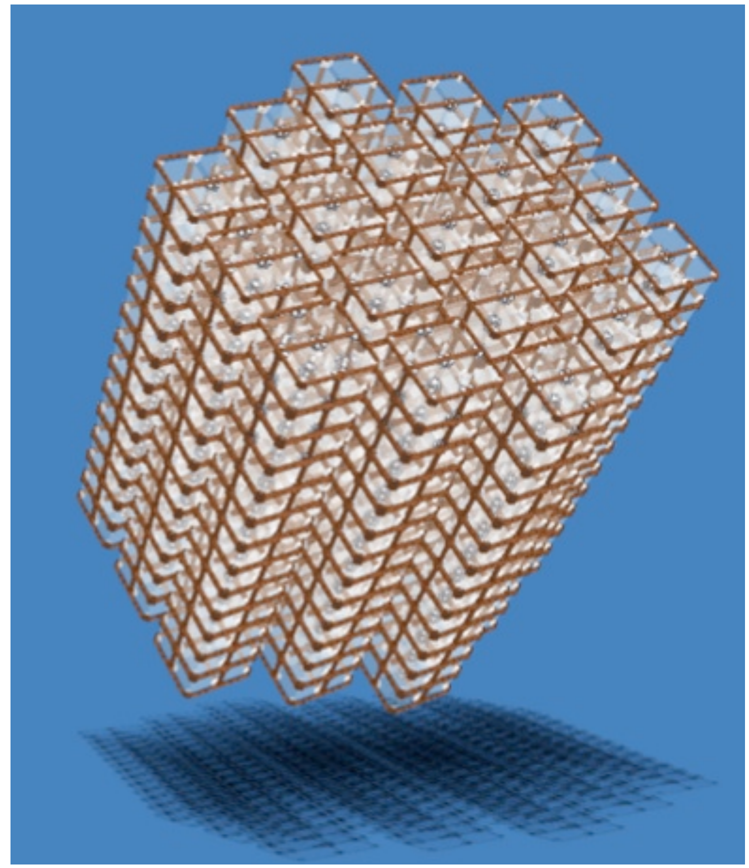
Recent results from ^{136}Xe



CUORE

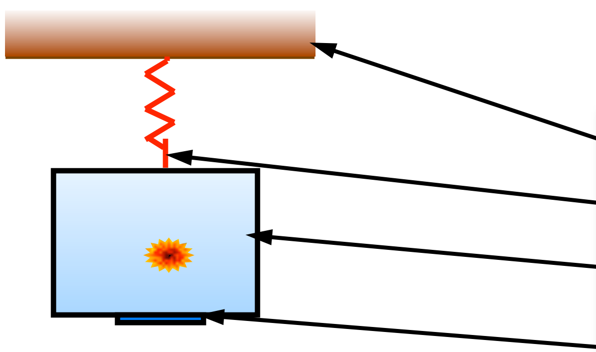
Cryogenic Underground Observatory for Rare Events



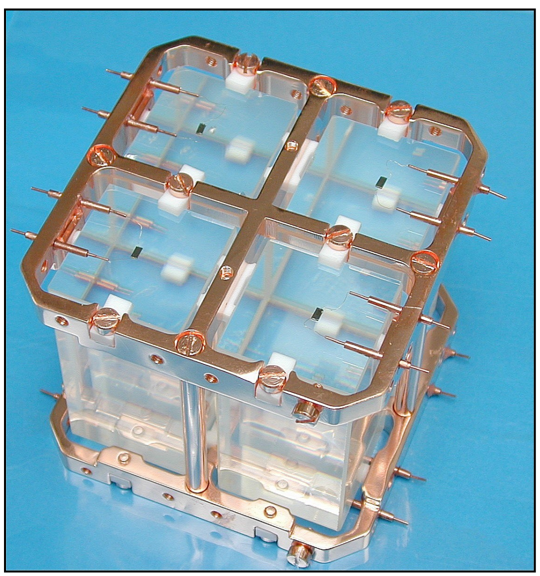


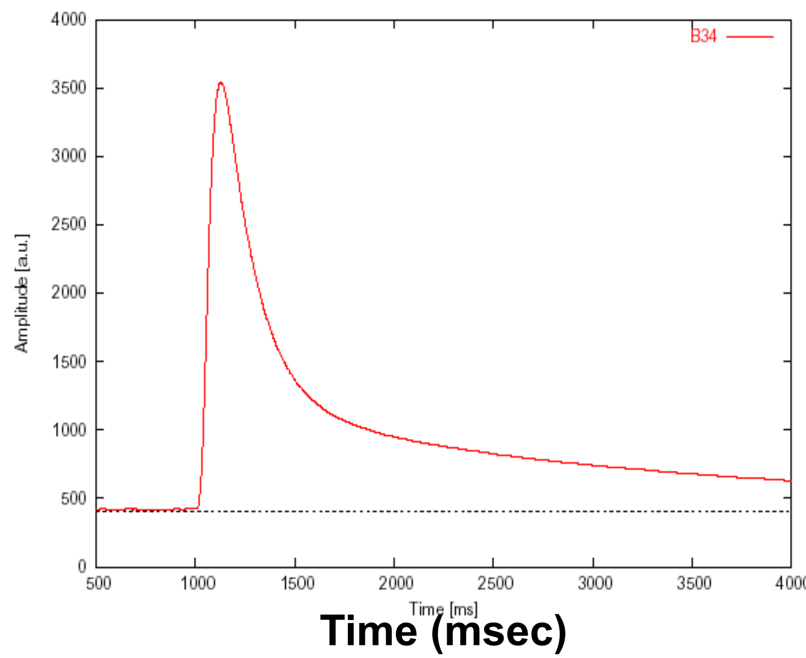
CUORE Bolometer

TeO_2 Bolometer: Source = Detector



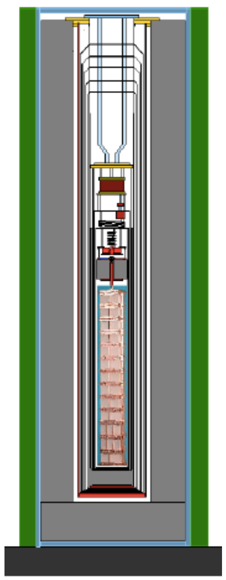
Heat sink: ~8 mK
Thermal coupling: Teflon
Absorber: TeO_2 crystal
Thermometer: NTD Ge thermistor



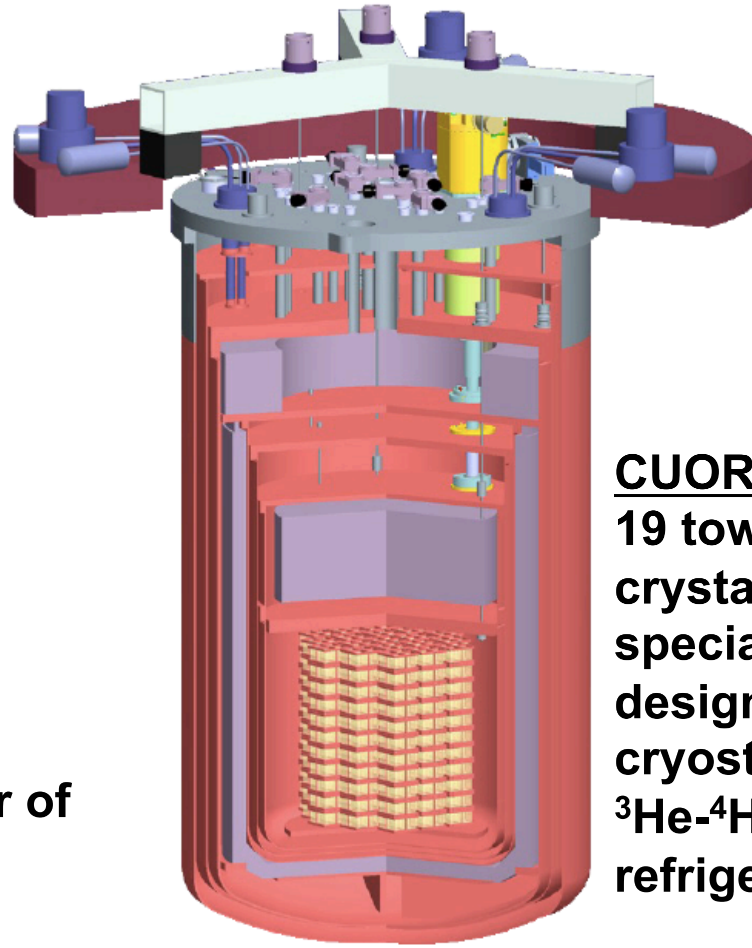


CUORE and CUORE0

Single tower:
52 5x5x5 cm^3
crystals

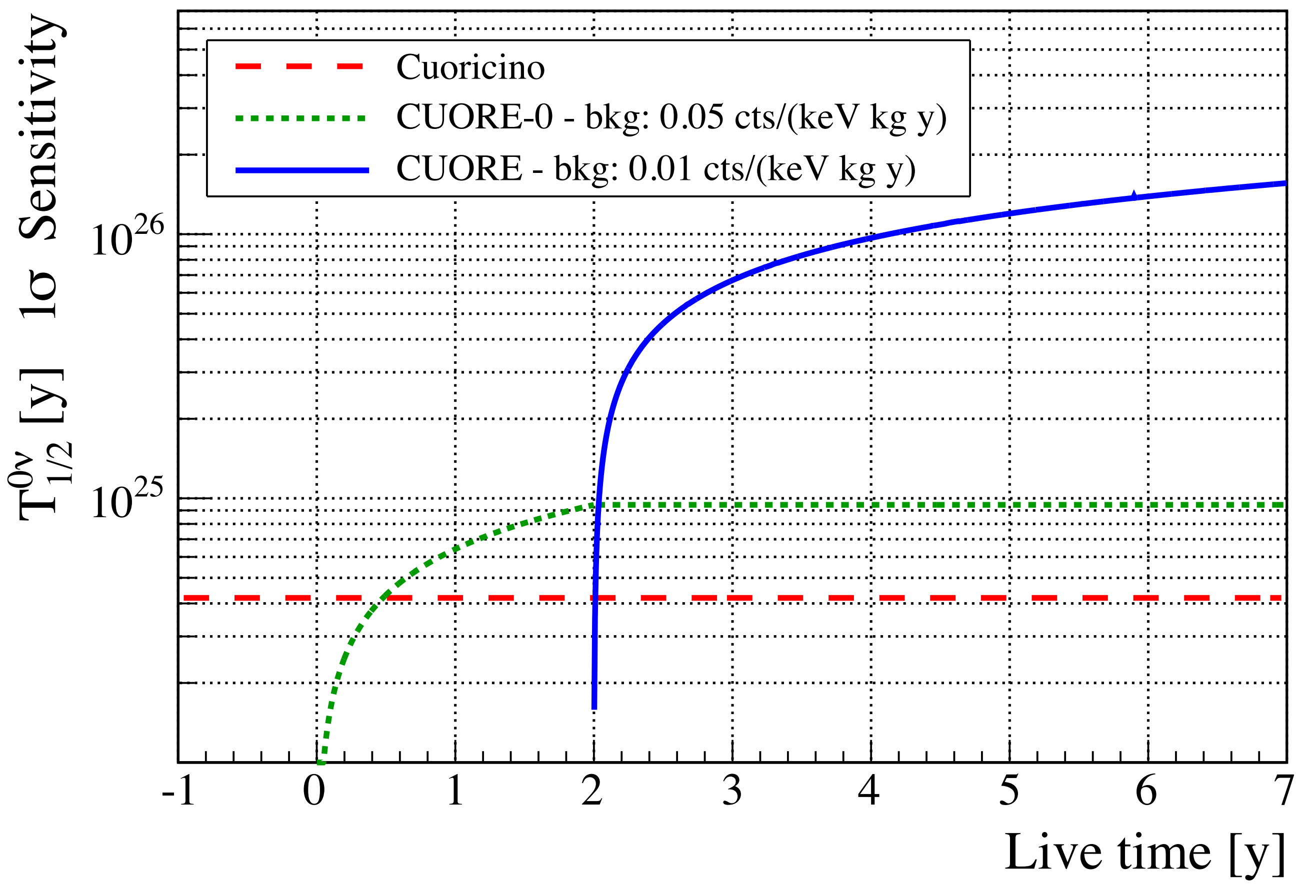


CUORE0:
A single tower of
CUORE in the
Cuoricino
cryostat



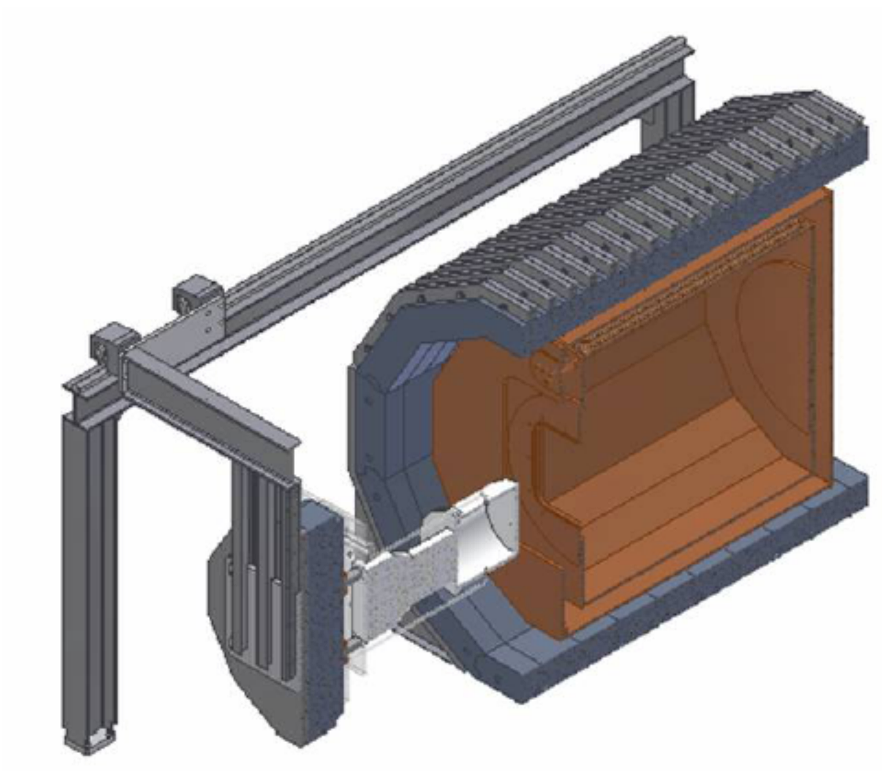
CUORE:
19 towers of 52
crystals each In a
specially
designed
cryostat and
^{3}He-^{4}He dilution
refrigerator

Sensitivity of CUORE0 and CUORE



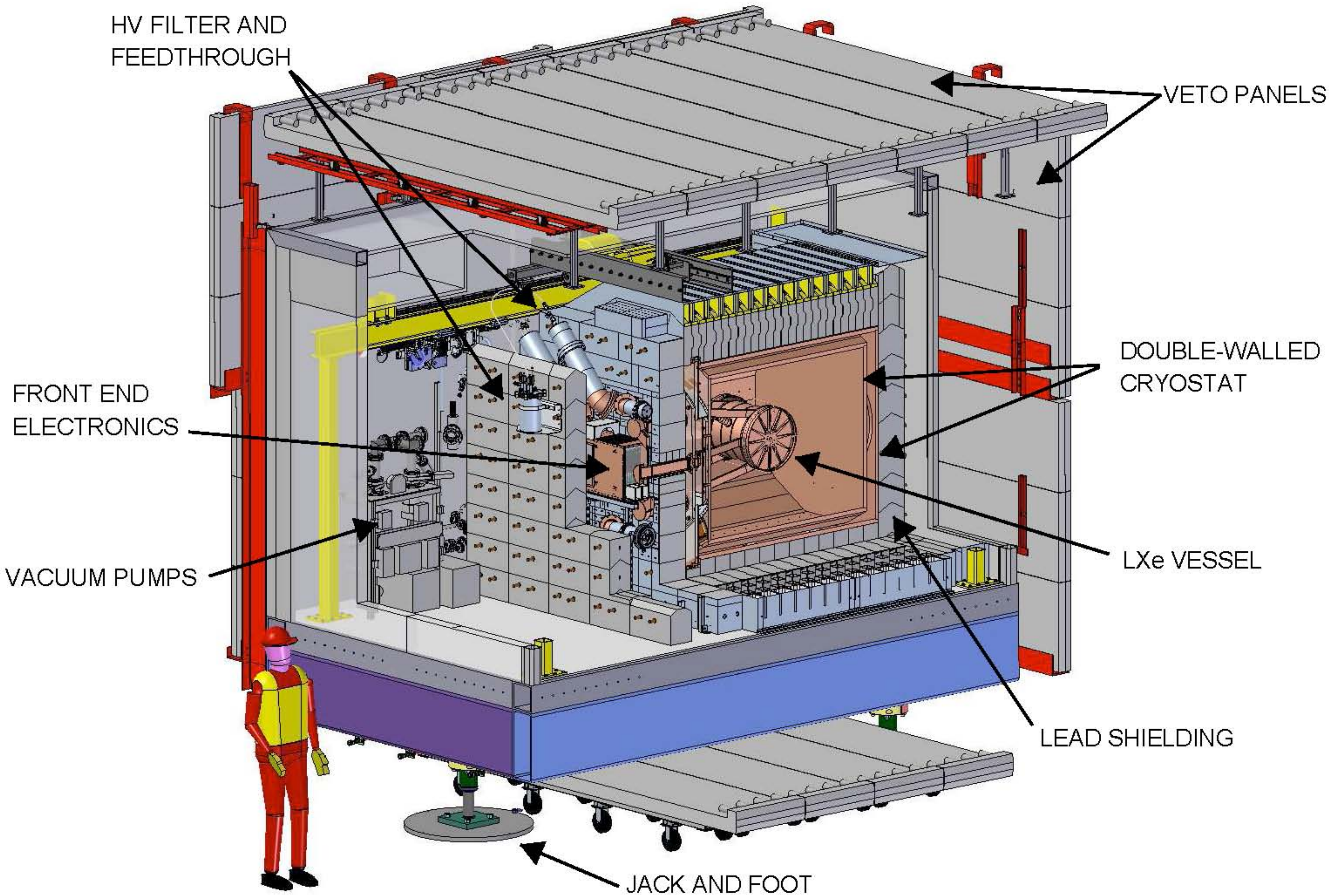
EXO - Enriched Xenon Observatory

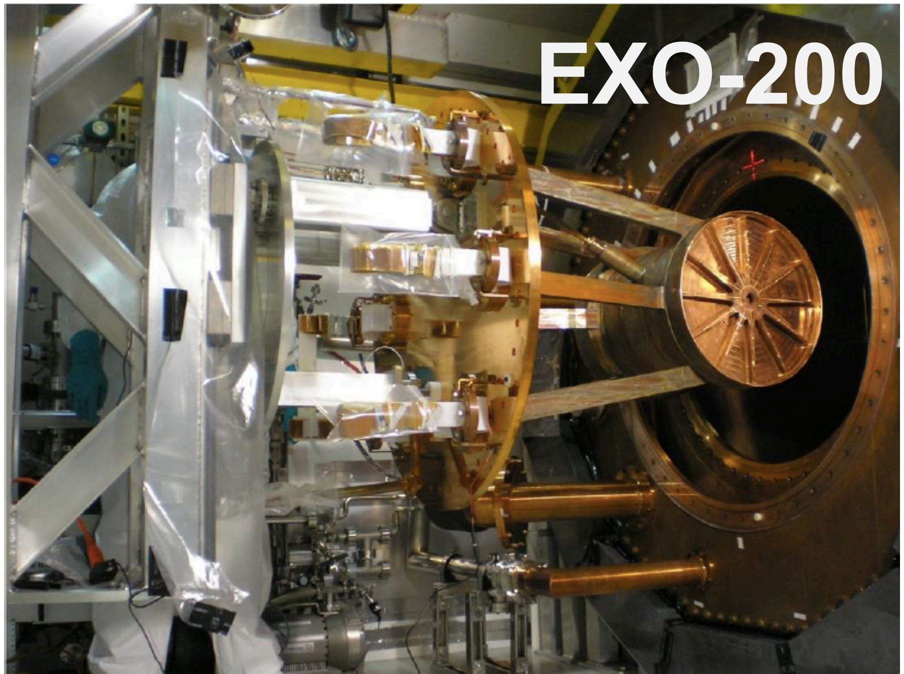
$^{136}Xe \rightarrow ^{136}Ba^{++} + 2\,e^{-}$ (Q = 2.4 MeV)

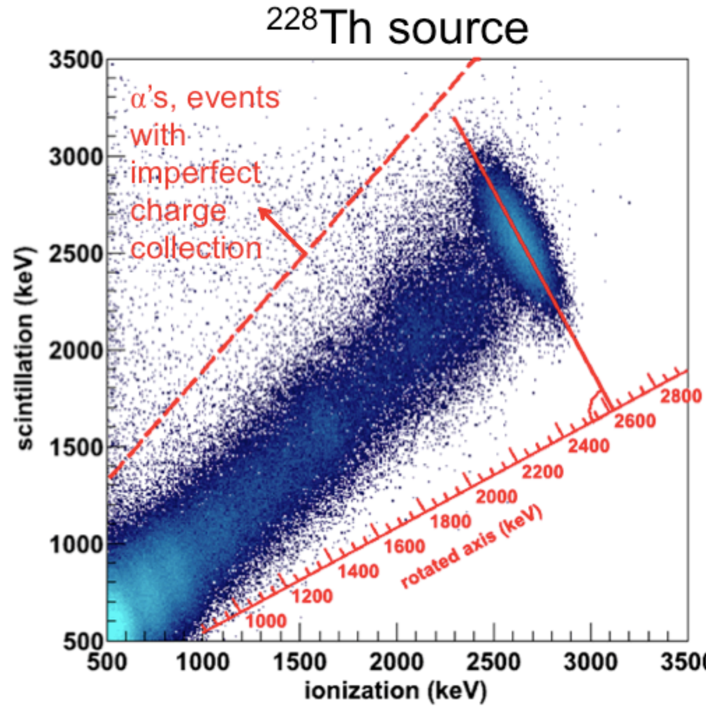


- LXe time projection chamber (TPC) with liquid ^{136}Xe
- Eventual Ba tagging

EXO-200


HV FILTER AND
FEEDTHROUGH
VETO PANELS
DOUBLE-WALLED
CRYOSTAT
FRONT END
ELECTRONICS
LXe VESSEL
VACUUM PUMPS
LEAD SHIELDING
JACK AND FOOT





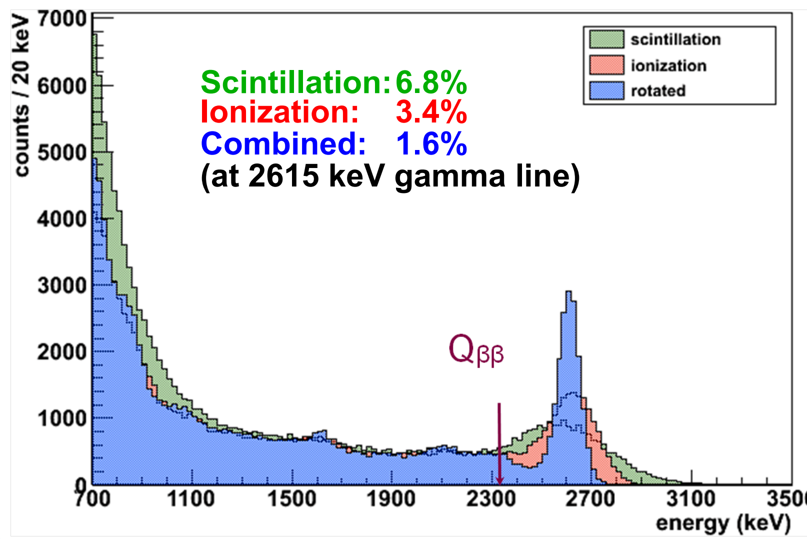
The TPC

• Cylindrical Cu vessel (1.37 mm wall thickness), 110 kg of liquid Xenon (enriched to 80.6% ^{136}Xe) in active volume. 175 kg Xe are in liquid phase.

• HV cathode in the middle. 2D event reconstruction by crossed wires. Third coordinate from time.

• Light read-out via 234 avalanche photodiodes per side.

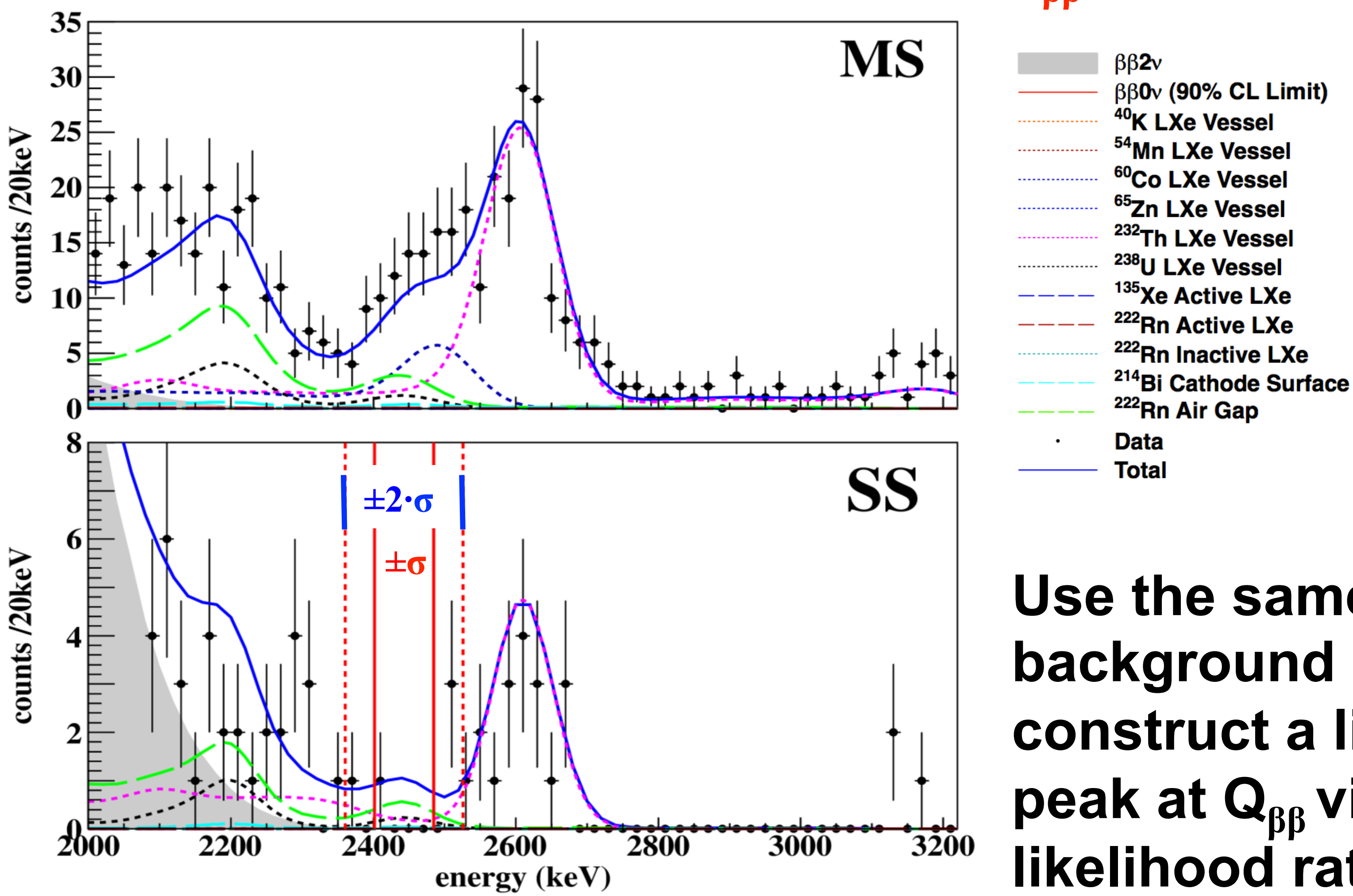
→ This design allows <u>full</u> 3-dim event reconstruction.



Active background rejection in EXO-200:

• 3D tracking discriminates single from multi site events (β/γ).
• Ratio of charge and scint. signals discriminates α from β/γ.
• Position sensitivity finds decays on electrodes and walls.

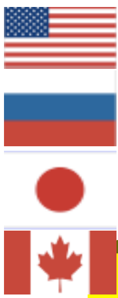
No peak observed at $Q_{\beta\beta}$.

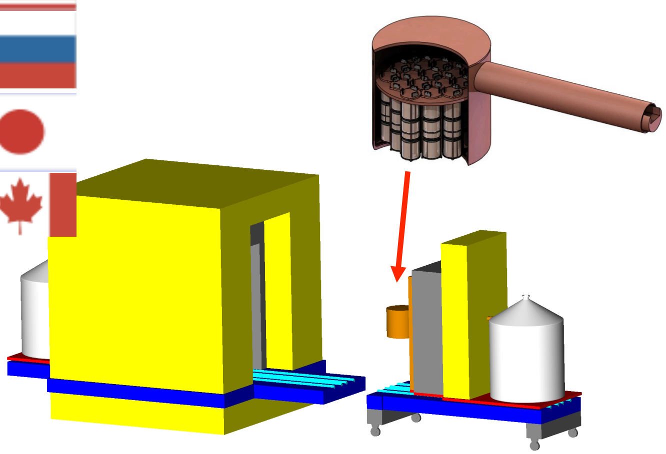


Use the same background model to construct a limit for peak at $Q_{\beta\beta}$ via a likelihood ratio hypothesis test.

MAJORANA - GERDA

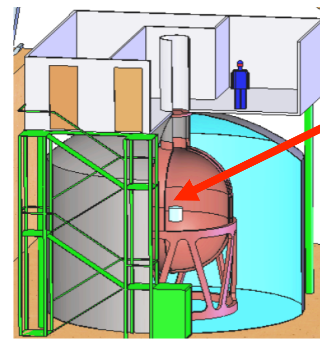
MAJORANA

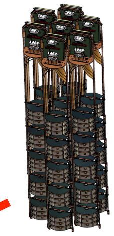




SURF

GERDA



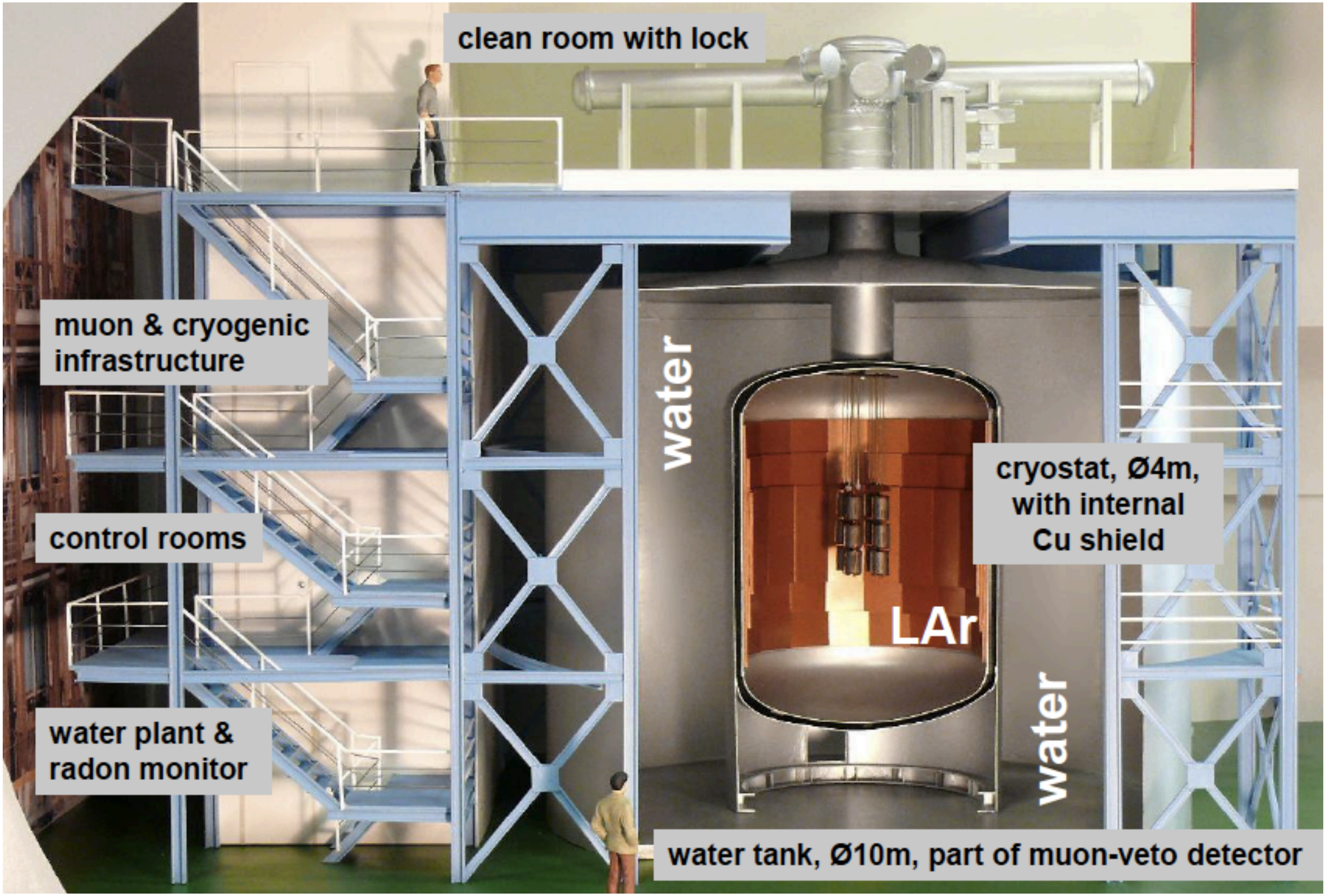


Gran Sasso

- **Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat**
- **Shield: electroformed copper / lead**
- **Initial phase: R&D demonstrator module: Total ~60 kg (30 kg enr.)**

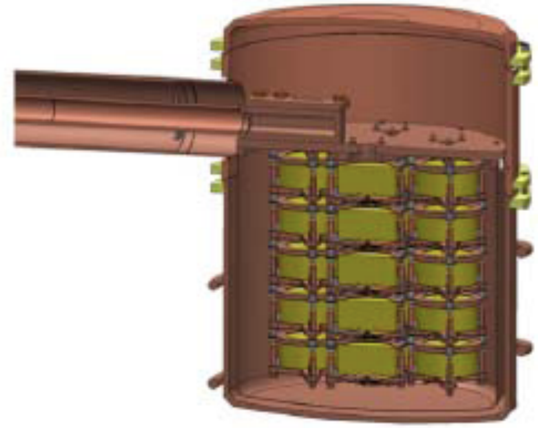
- **'Bare' ^{enr}Ge array in liquid argon**
- **Shield: high-purity liquid Argon / H_2O**
- **Phase I: ~18 kg (HdM/IGEX diodes)**
- **Phase II: add ~20 kg new detectors - Total ~40 kg**

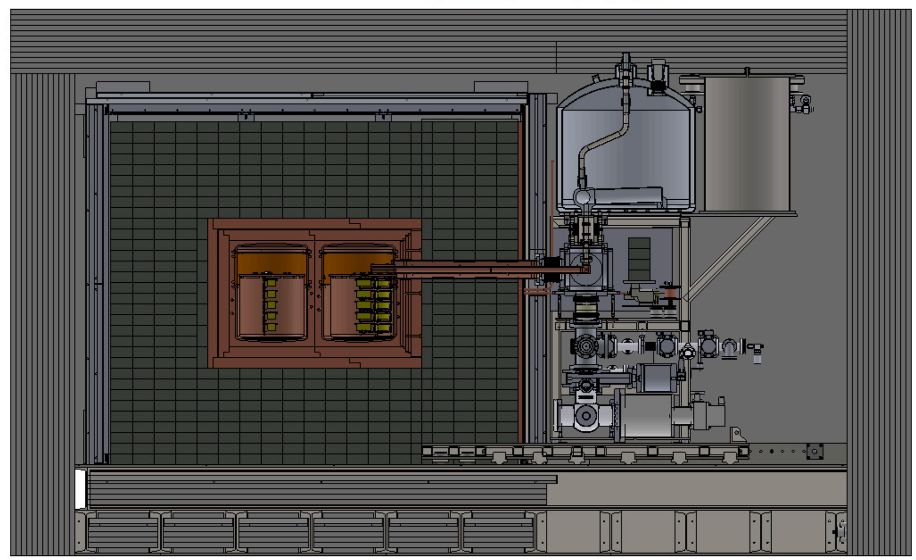
GERDA


clean room with lock
muon & cryogenic infrastructure
control rooms
water plant & radon monitor
water
water
LAr
cryostat, Ø4m, with internal Cu shield
water tank, Ø10m, part of muon-veto detector

MAJORANA DEMONSTRATOR (MJD)

- Located underground at 4850' Sanford Lab in SD
- 40 kg of HPGe detectors:
  - 30 kg of 86% enriched ^{76}Ge crystals
  - 10 kg of natural Ge crystals
- 2 independent cryostats
  - Ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - Scalable design
- Compact shield
  - Low background passive Cu and Pb shield
  - Active muon veto

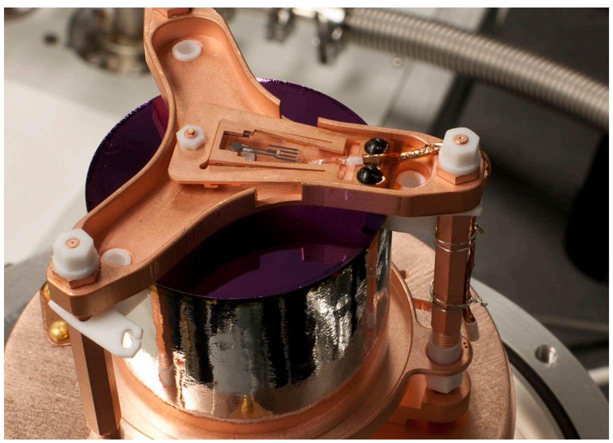


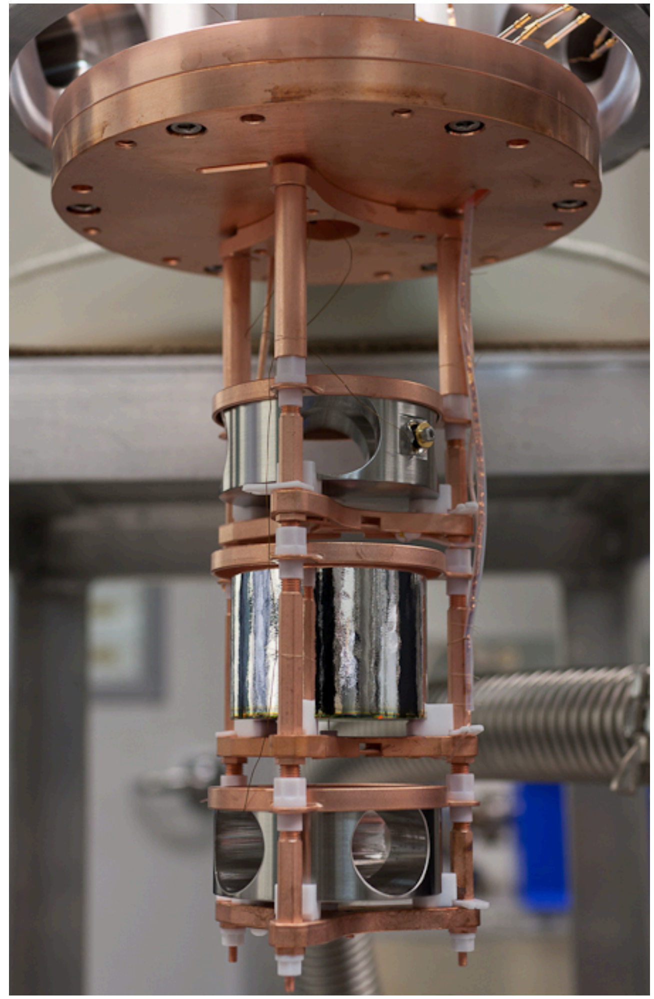


Background Goal in the 0vββ peak ROI (4 keV at 2039 keV):
~ 3 count/ROI/t-y after analysis cuts (scales to 1 count/ROI/t-y for tonne expt.)

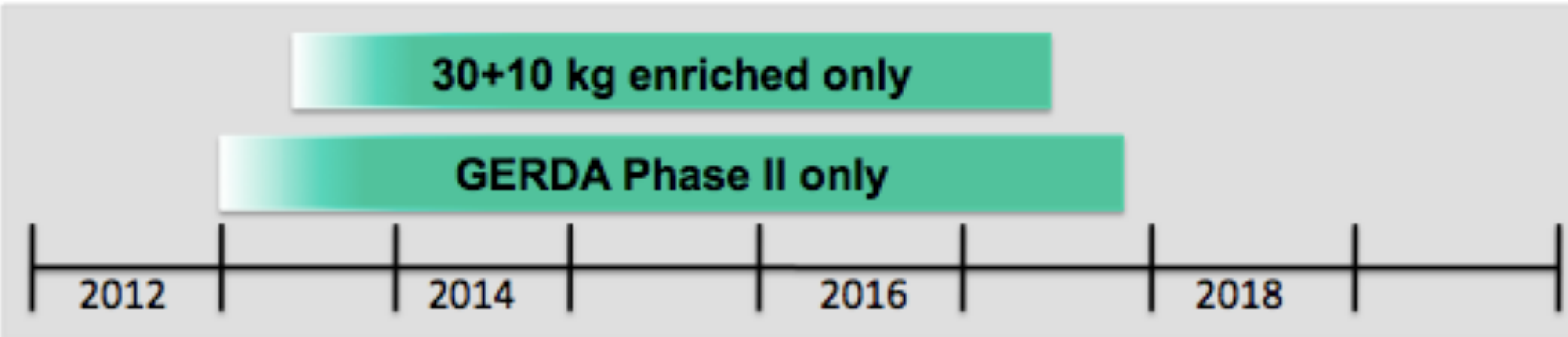
Status: Detectors

- 20 kg of ^{nat}Ge detectors ("modified BEGe detectors" by Canberra) in hand, and are stored underground at SURF.
- ORTEC selected to produce ^{enr}Ge detectors.
- ORTEC has produced a detector from natural Ge purified by ESI. ^{enr}Ge detector production begins in Fall 2012.
- Detector mounts and signal processing electronics for prototype cryostat in good shape.

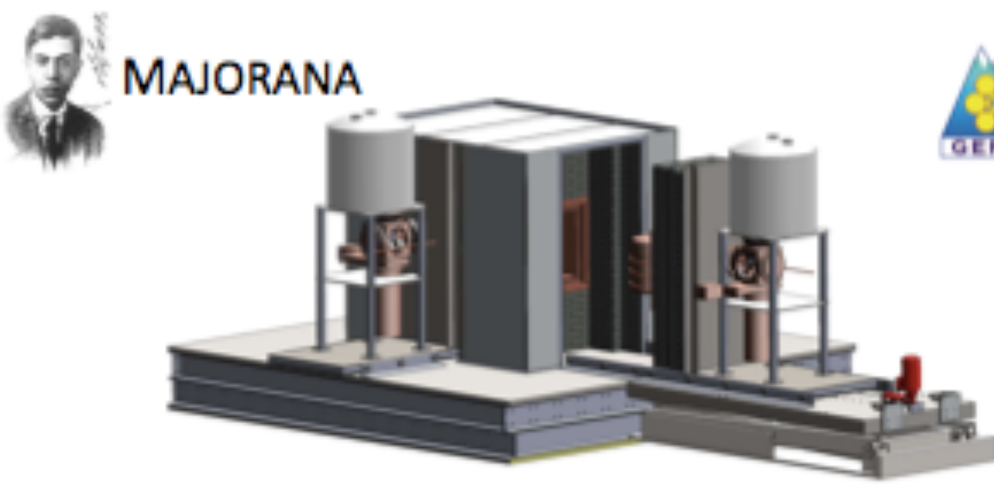




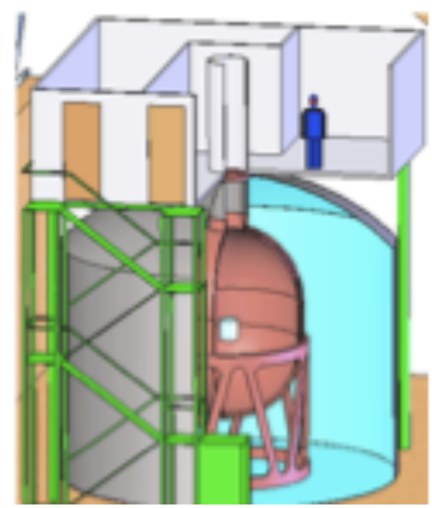
Reaching 100 kg-y Exposure



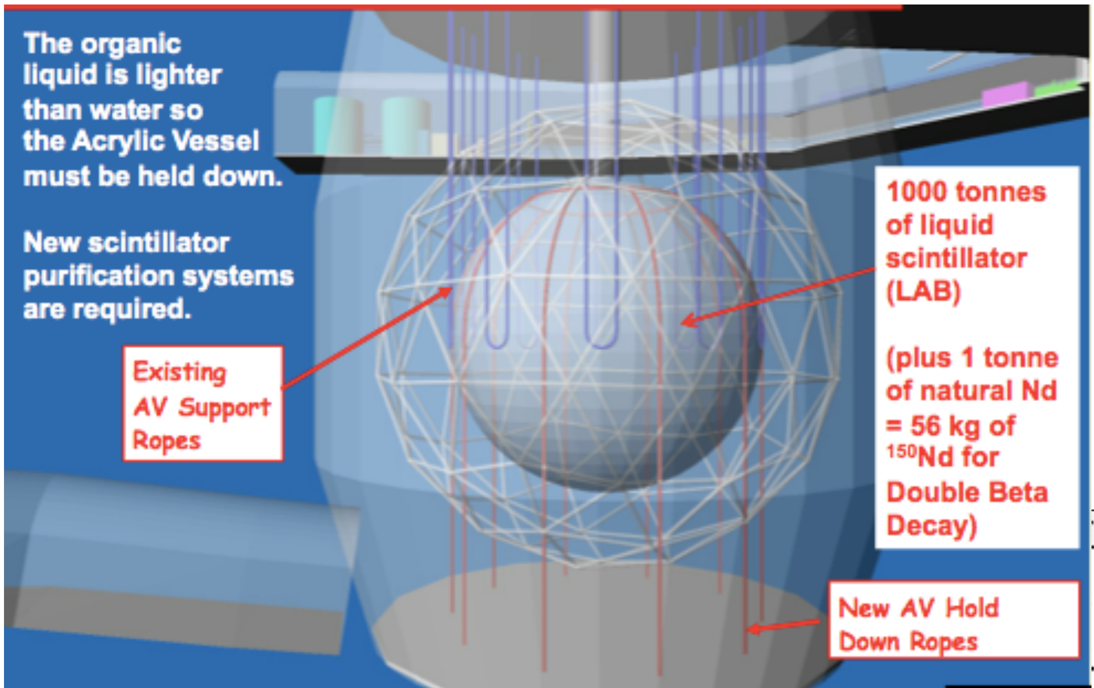
- With 30 kg ^{enr}Ge and 10 kg ^{nat}Ge, MJD is competitive with GERDA Phase II in total exposure.
- Both projects aim to demonstrate the feasibility of a tonne-scale ^{76}Ge experiment, which will require a background level of 1 count/ROI/t/y.

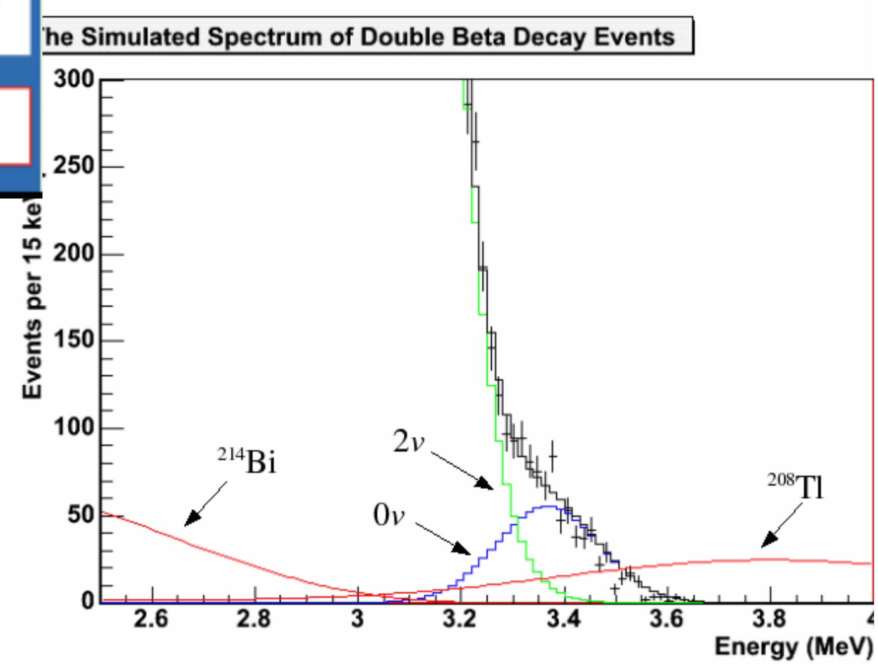


GERDA

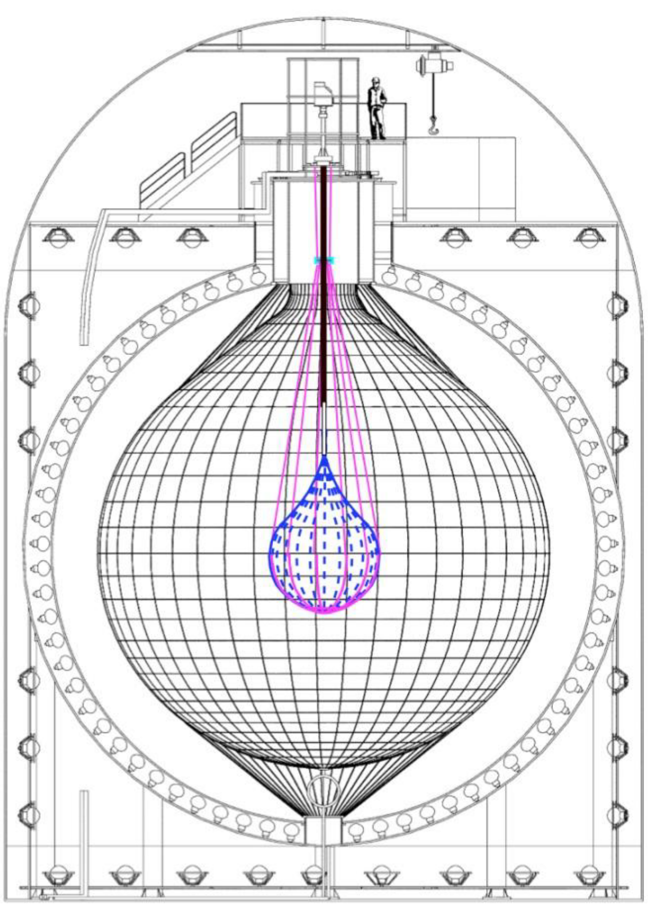


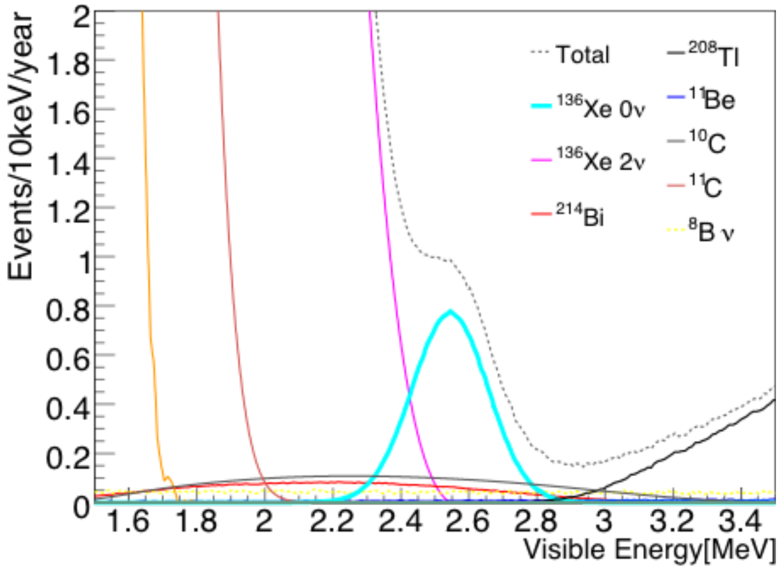
SNO+ ‘repurposed SNO’



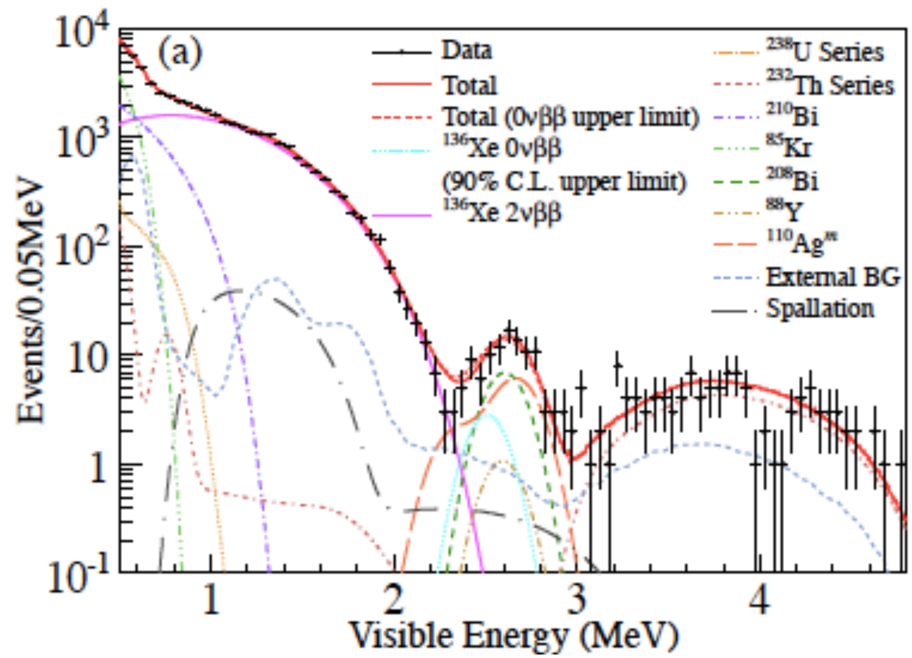


KamLAND Zen – ‘repurposed KamLAND’



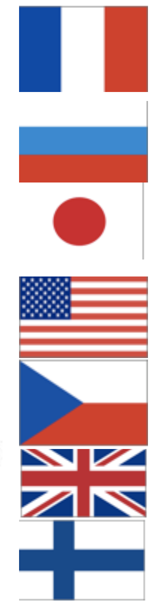


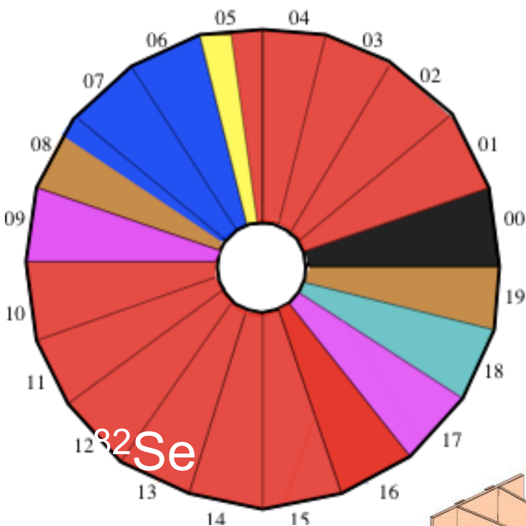
3.0wt% Xe(390kg)
90% enriched 136Xe
<m>=150meV
Baloon : 25μm
Rballoon : 1.7m
232Th, 238U : 10-12g/g
10C : 95% tag



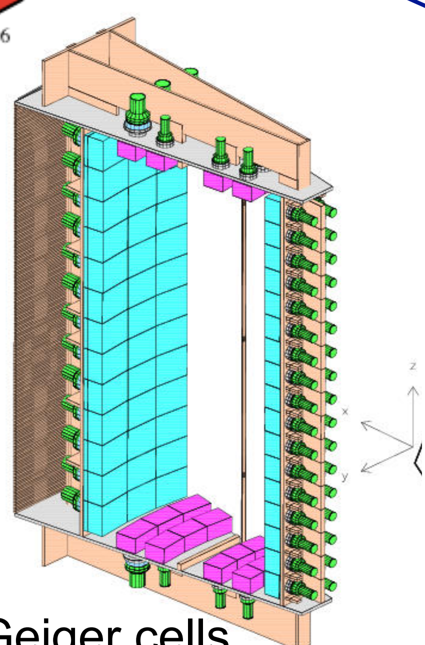
NEMO Experiment at Modane

Neutrino Ettore Majorana Observatory

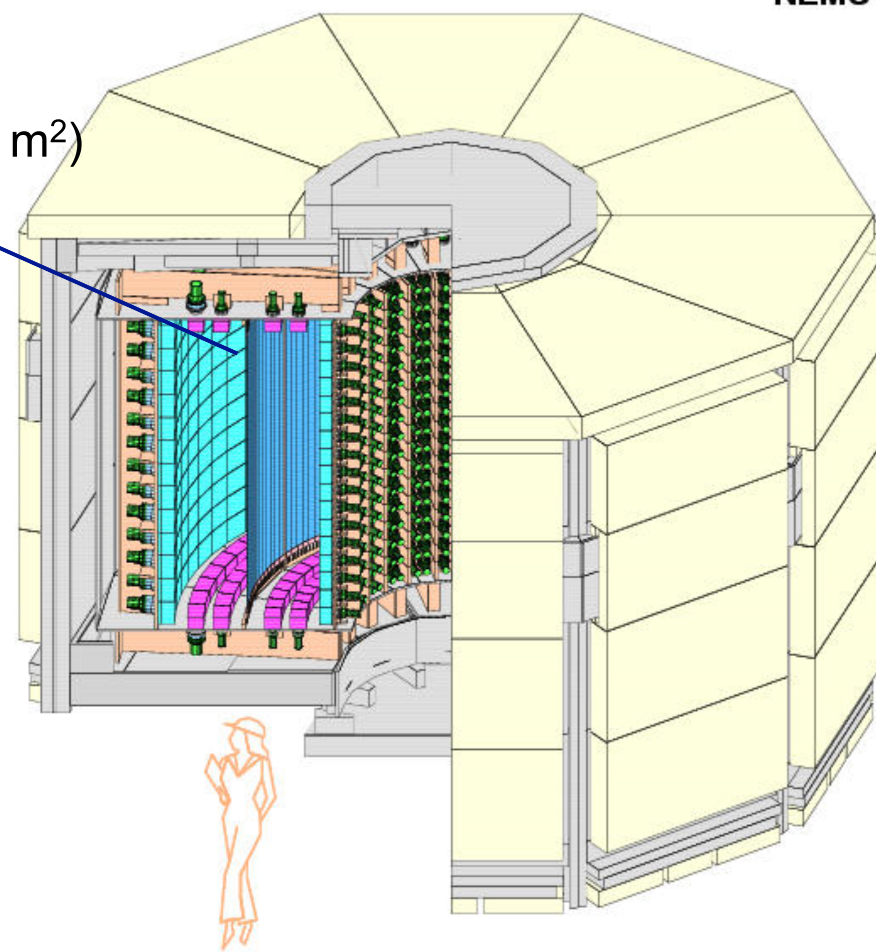




source-foils
(d=50 μm A=20 m^2)



NEMO 3



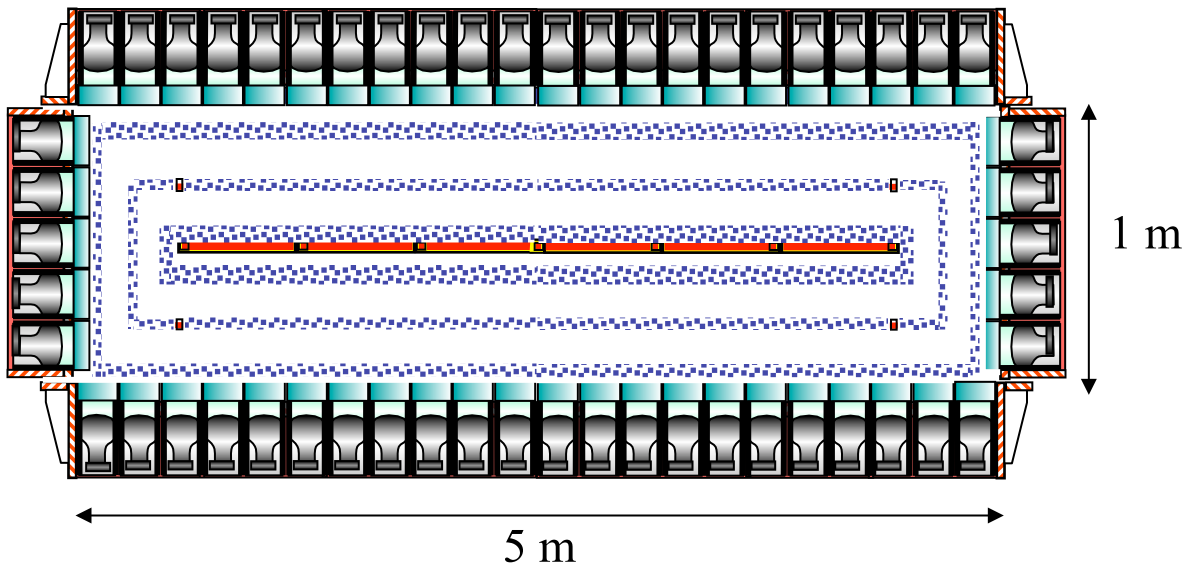
6180 octogonal Geiger cells
1940 plastic scintillators (d=10 cm)

SuperNEMO preliminary design

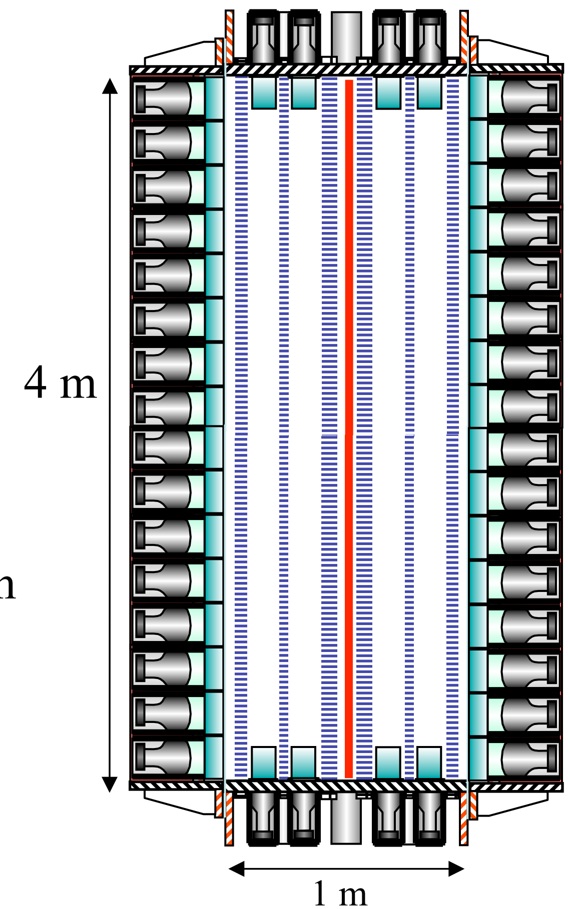
Plane and modular geometry: ~5 kg of enriched isotope per module

1 module: Source (40 mg/cm2) 4 x 3 m^2
Tracking volume: drift wire chamber in Geiger mode, ~ 3000 cells
Calorimeter: scintillators + PMTs

20 modules: 100 kg of enriched isotope
~ 60 000 channels for drift chamber
~ 20 000 PMT if scint. block
~ 2 000 PMT if scint. bars



Top view



Side view