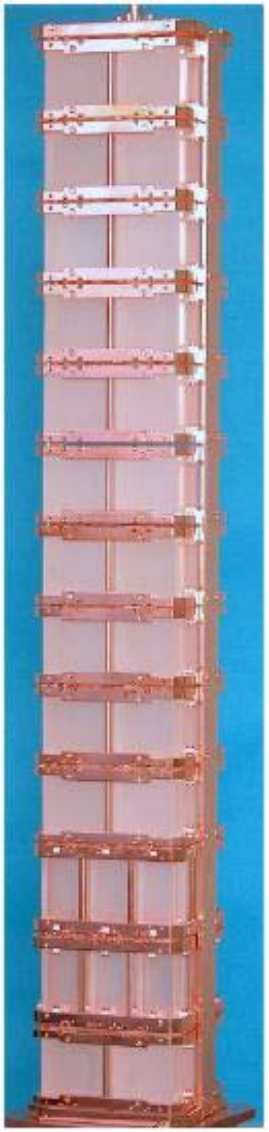
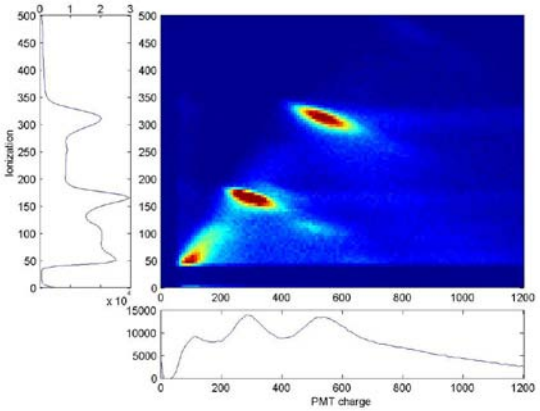
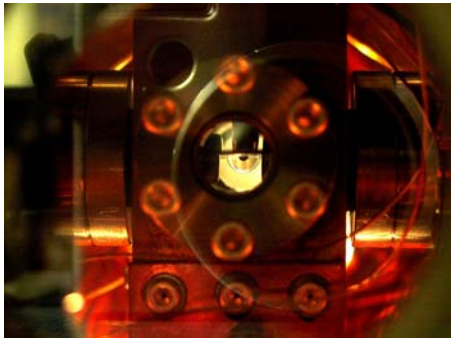
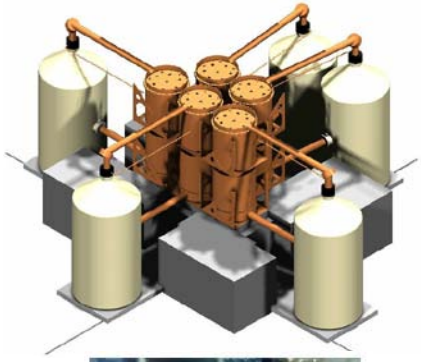


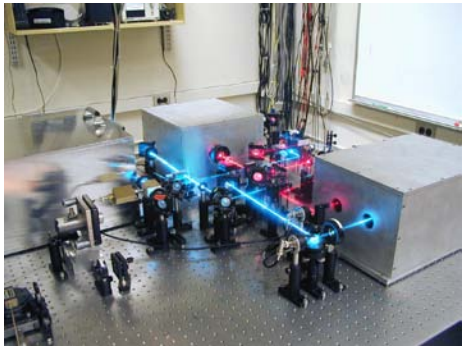


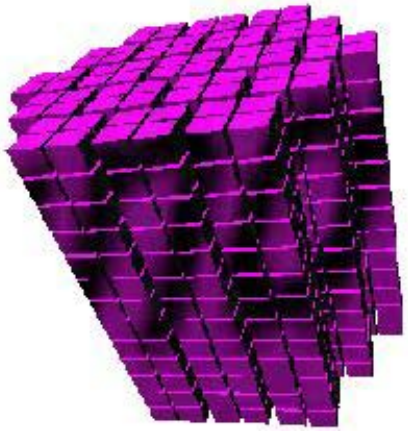




How can we search for double beta decay?

Carter Hall
University of Maryland

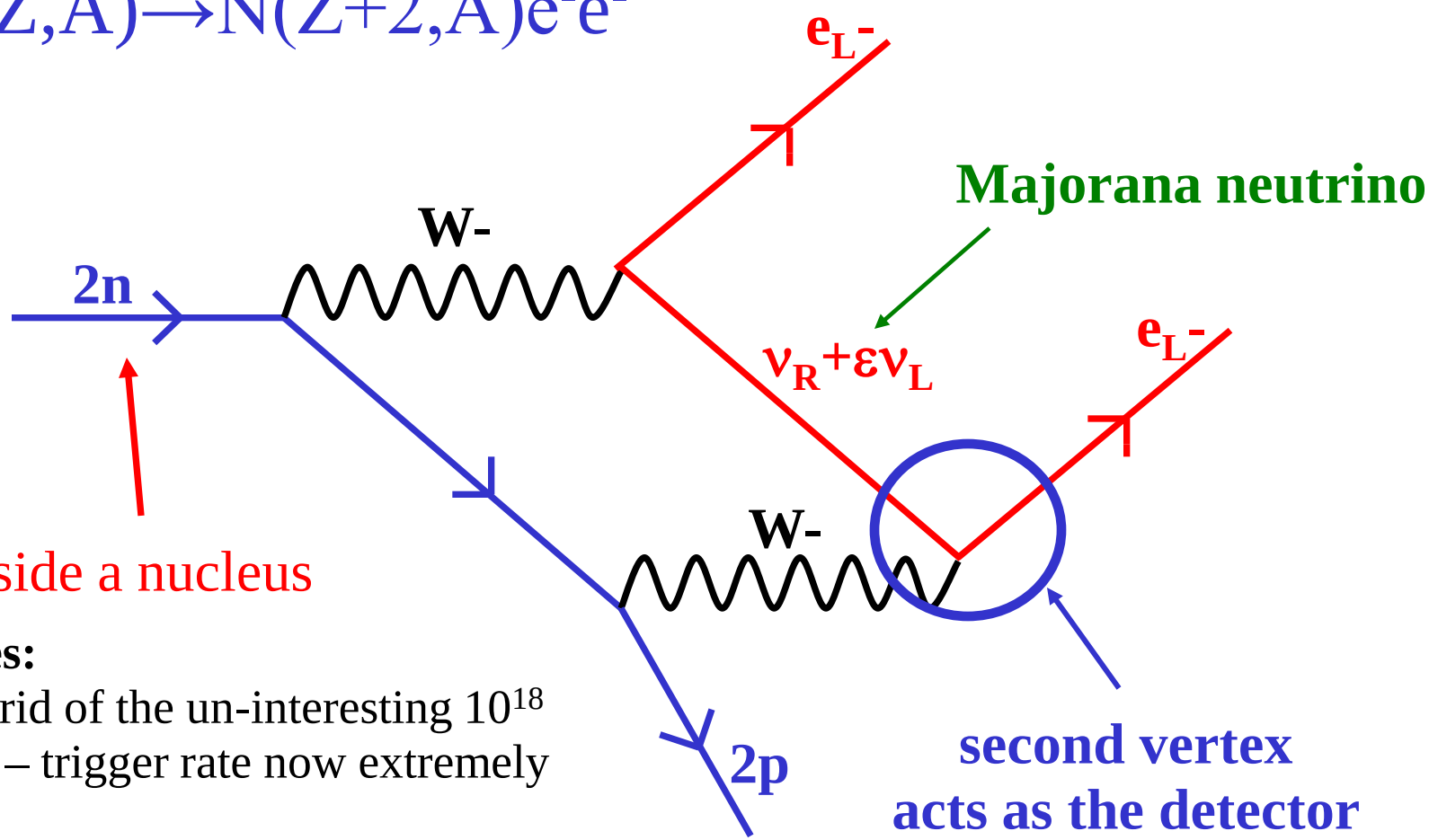




Neutrinoless Double Beta Decay ($\beta\beta0\nu$)

Forbidden if neutrino mass is Dirac only

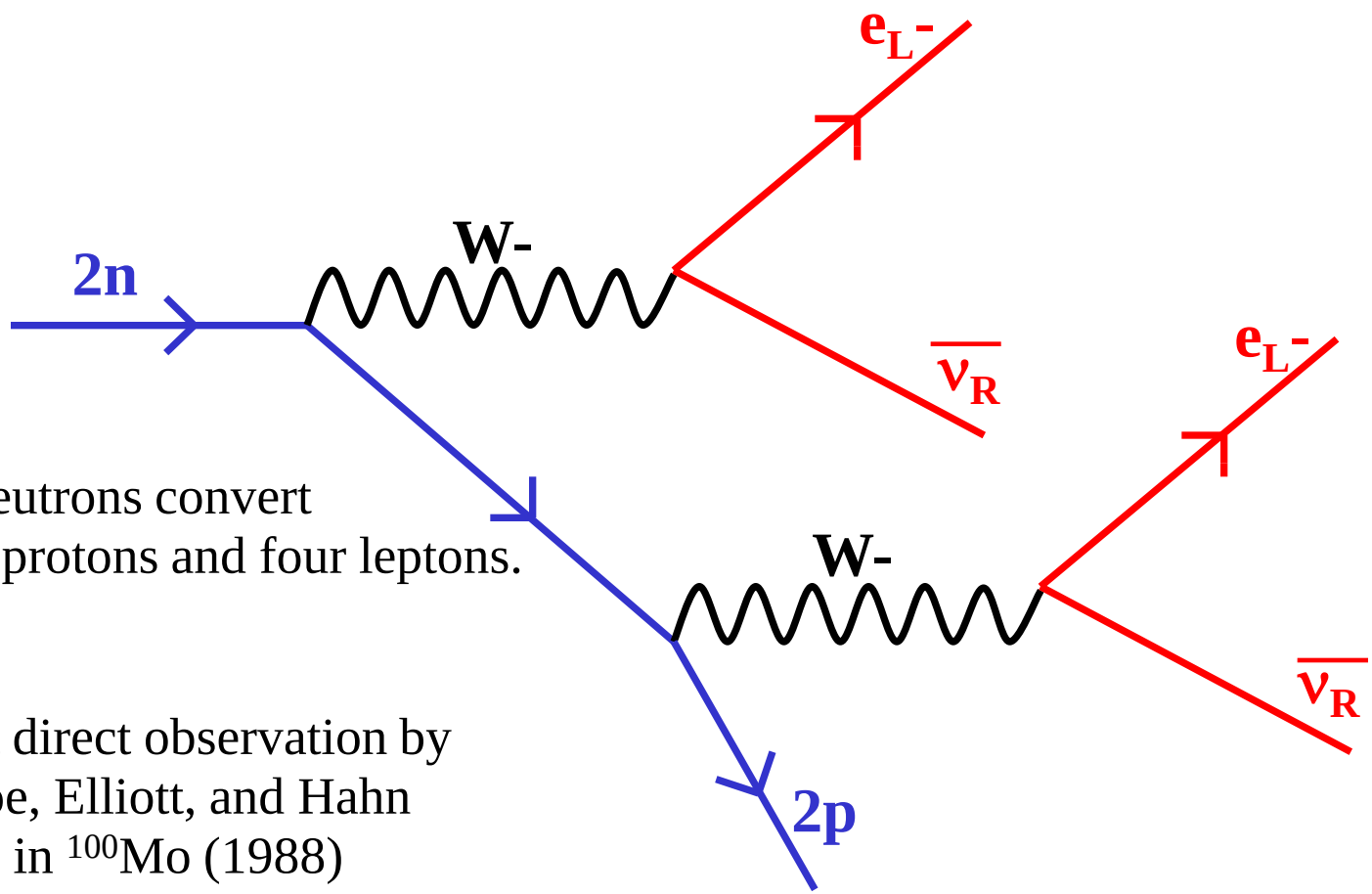
$N(Z,A) \rightarrow N(Z+2,A)e^-e^-$



Virtues:

- Gets rid of the un-interesting 10^{18} events – trigger rate now extremely small.
- Chiral suppression is still severe, but we can fight it with Avagadro's number

Two-Neutrino Double Beta Decay:

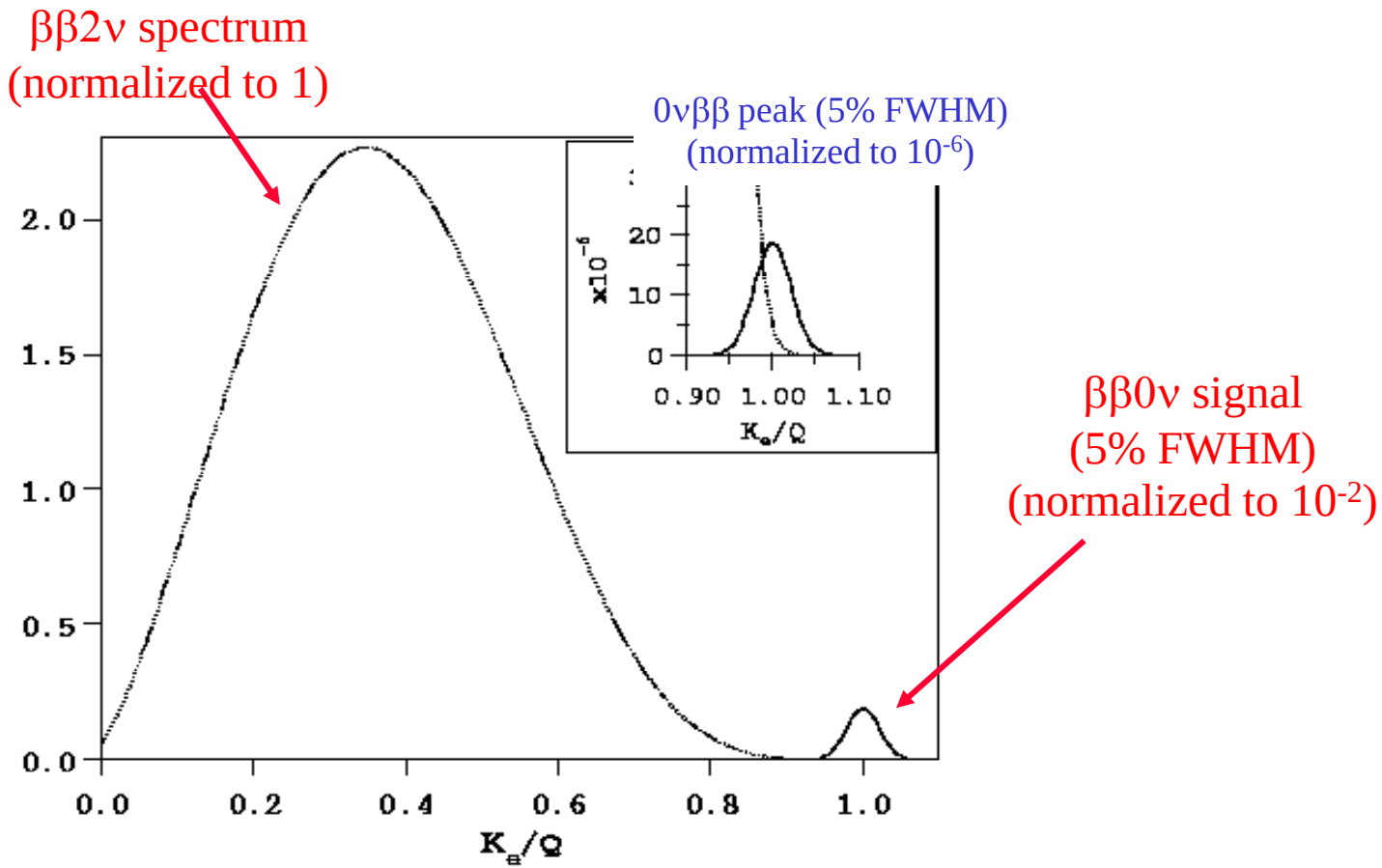


Two neutrons convert
to two protons and four leptons.

First direct observation by
Moe, Elliott, and Hahn
in ^{100}Mo (1988)

No direct implications for neutrino physics,
but useful for constraining the nuclear matrix element calculations

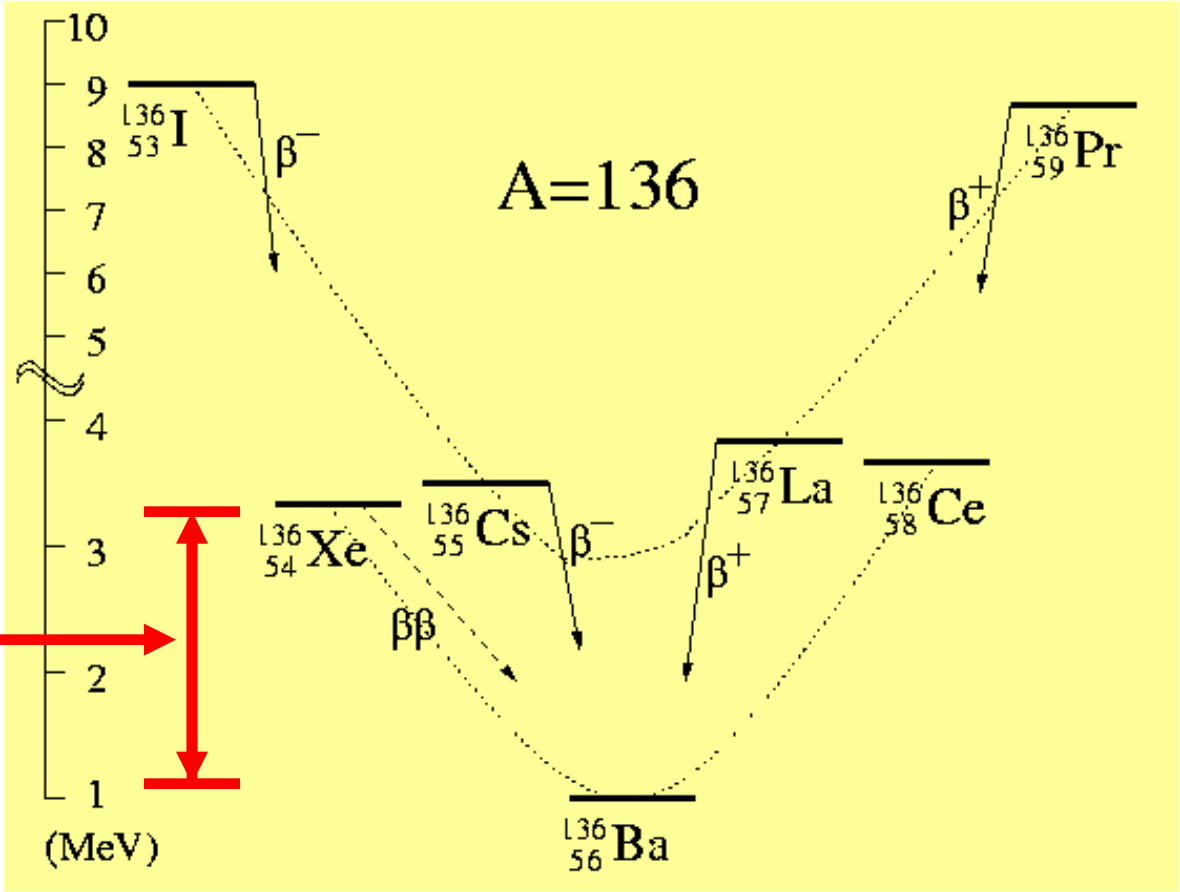
ββ0ν strategy: search for a peak in the summed electron energy spectrum at the known Q value



Summed electron energy in units of the kinematic endpoint (Q)

Choosing a double beta decay source isotope:

"Q value": how much KE is available



$N(Z,A) \rightarrow N(Z+2,A)e^-e^-$: daughter nucleus must have a smaller mass than the parent for the decay to occur.

Choosing a double beta decay source isotope

Decay candidate	Q value (MeV)	natural abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

$$N \rightarrow N' e^- e^-$$

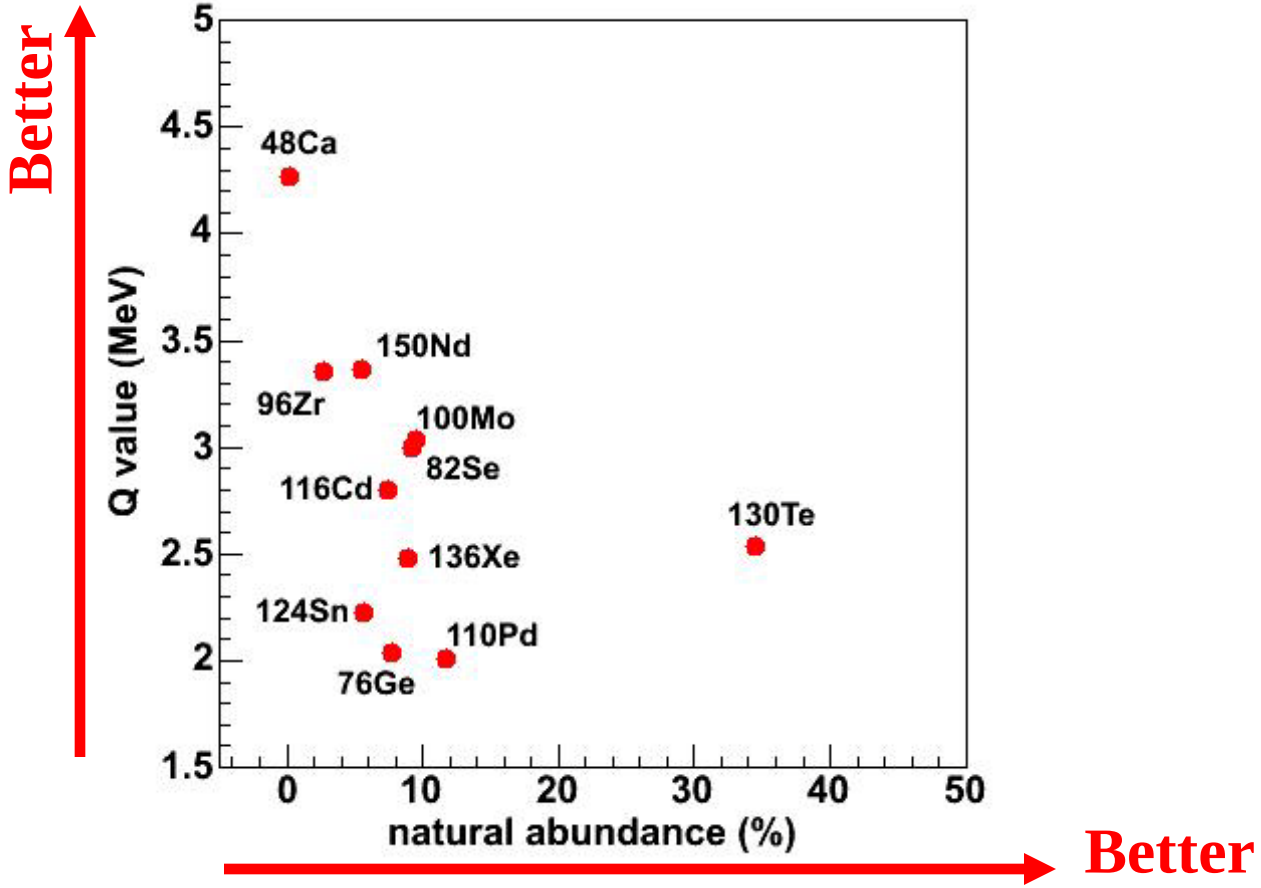
Q value = M(N) - M(N')

The electron energies must sum to the Q value by energy conservation

A large Q value is desirable because the decay rate is faster (larger phase space) and the radioactive backgrounds are smaller.

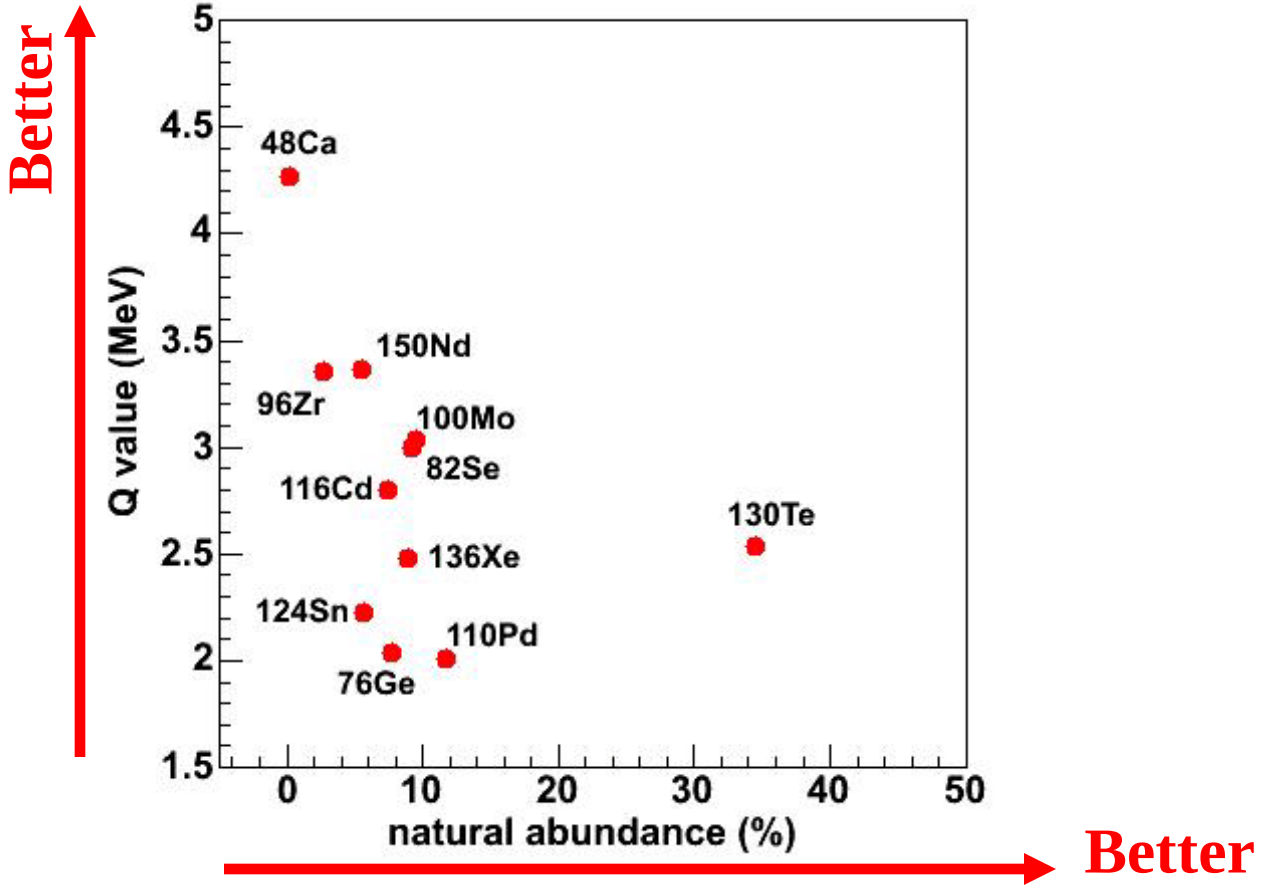
Large natural abundance make the experiment cheaper.

ββ0ν candidate isotopes:
Q value and natural abundance



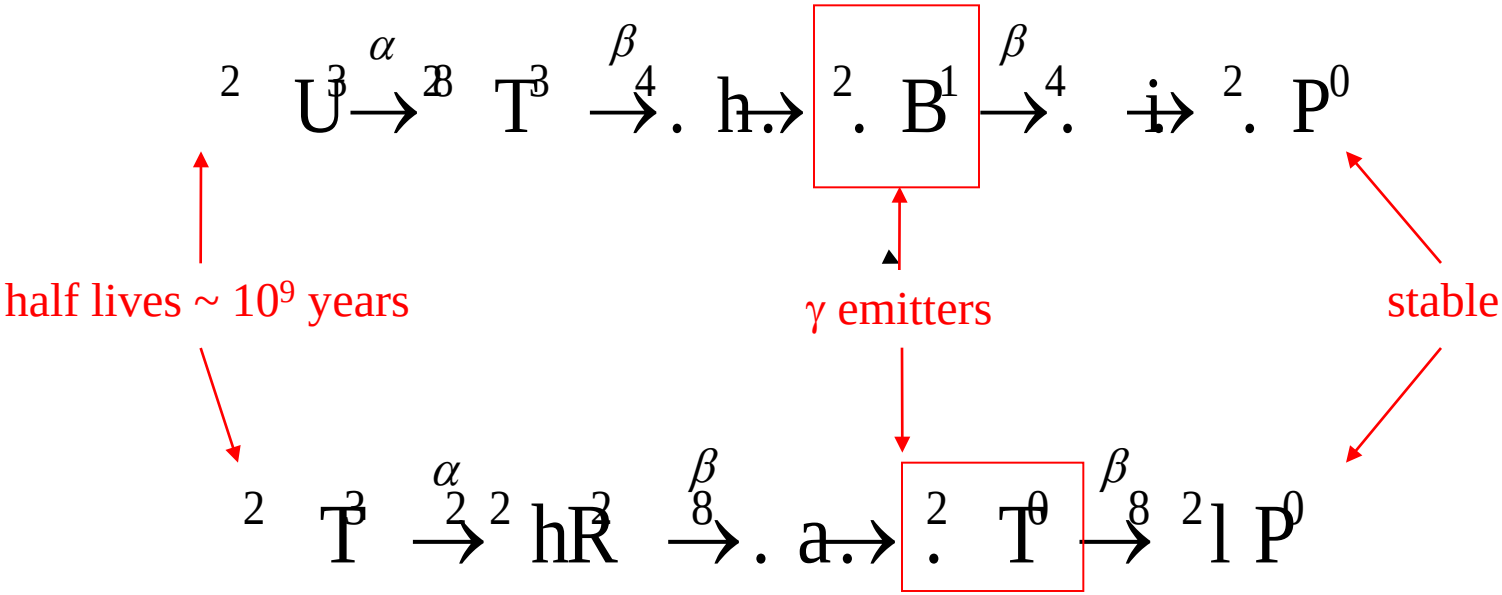
High Q value reduces backgrounds and increases the phase space & decay rate, large abundance makes the experiment cheaper.

ββ0ν candidate isotopes:
Q value and natural abundance



High Q value reduces backgrounds and increases the phase space & decay rate, large abundance makes the experiment cheaper.

Virtually all materials contain small amounts of radioactive isotopes:



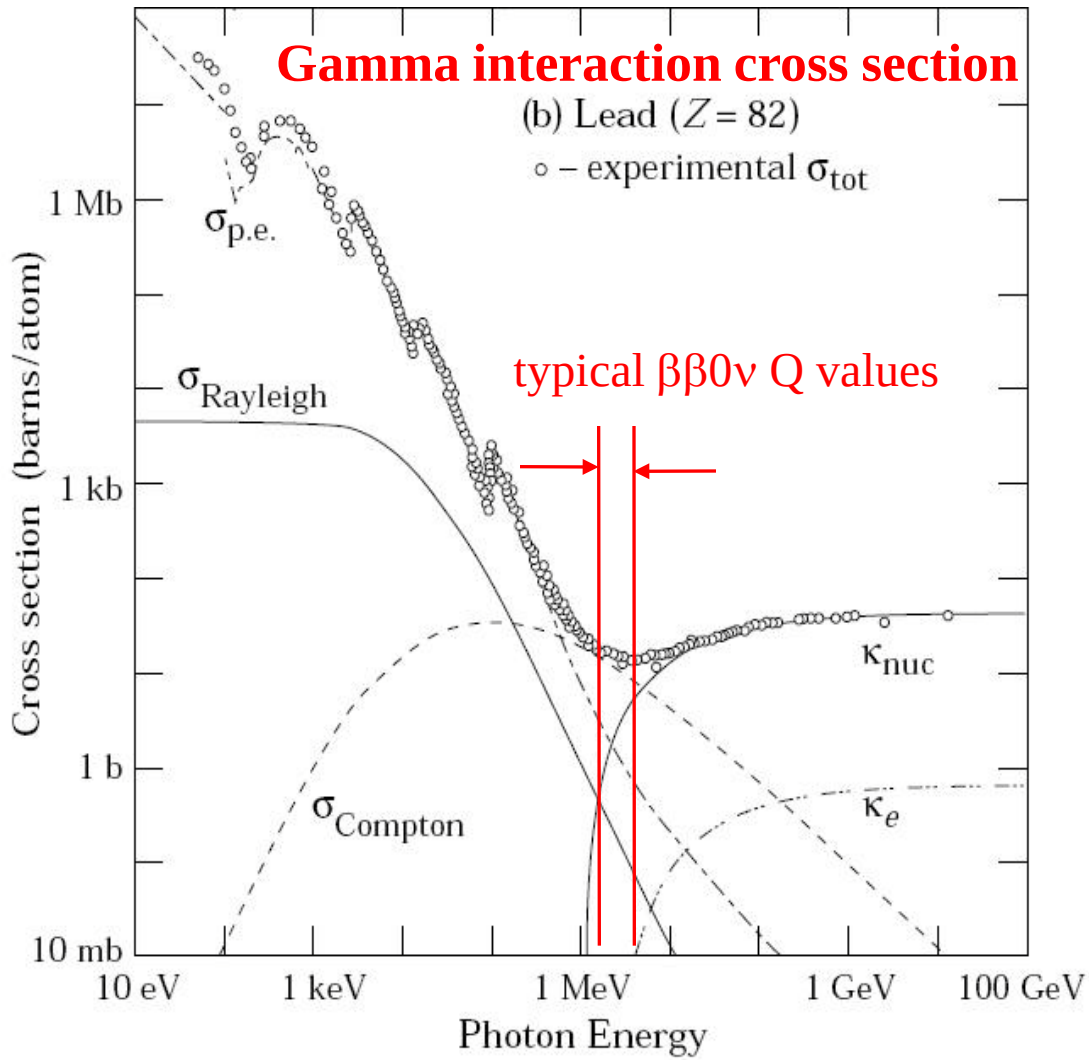
Natural radioactive decay chains

Compton scattering: $\gamma e^- \rightarrow \gamma e^-$ broad energy spectrum

Photoelectric effect: $\gamma e^- \rightarrow e^-$ monochromatic

Pair production: $\gamma \rightarrow e^+ e^-$ monochromatic

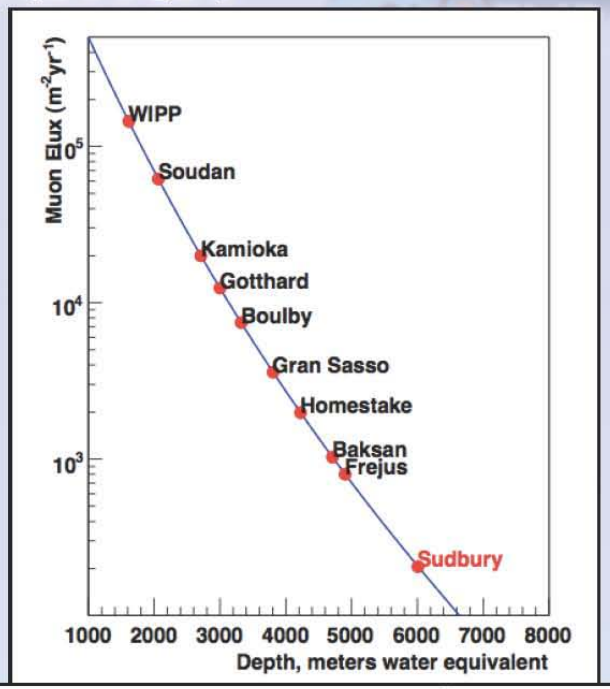
Shielding a detector from gammas is difficult because the absorption cross section is small.

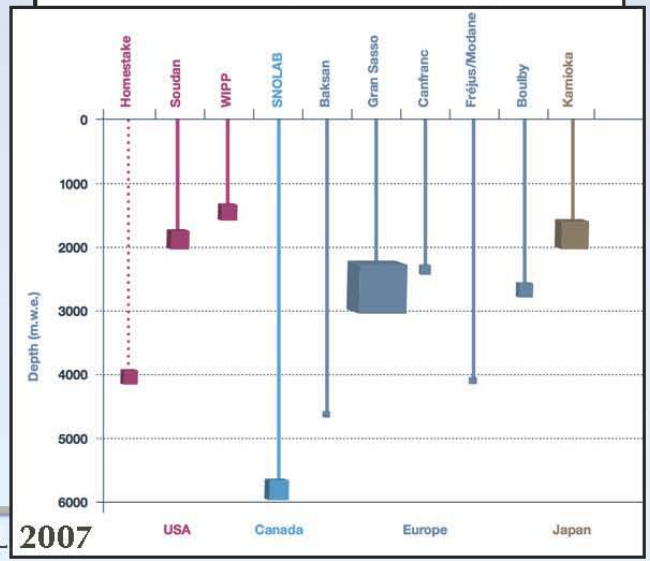


Example: γ interaction length in Germanium is 4.6 cm, comparable to the size of a germanium detector.

Why go underground?

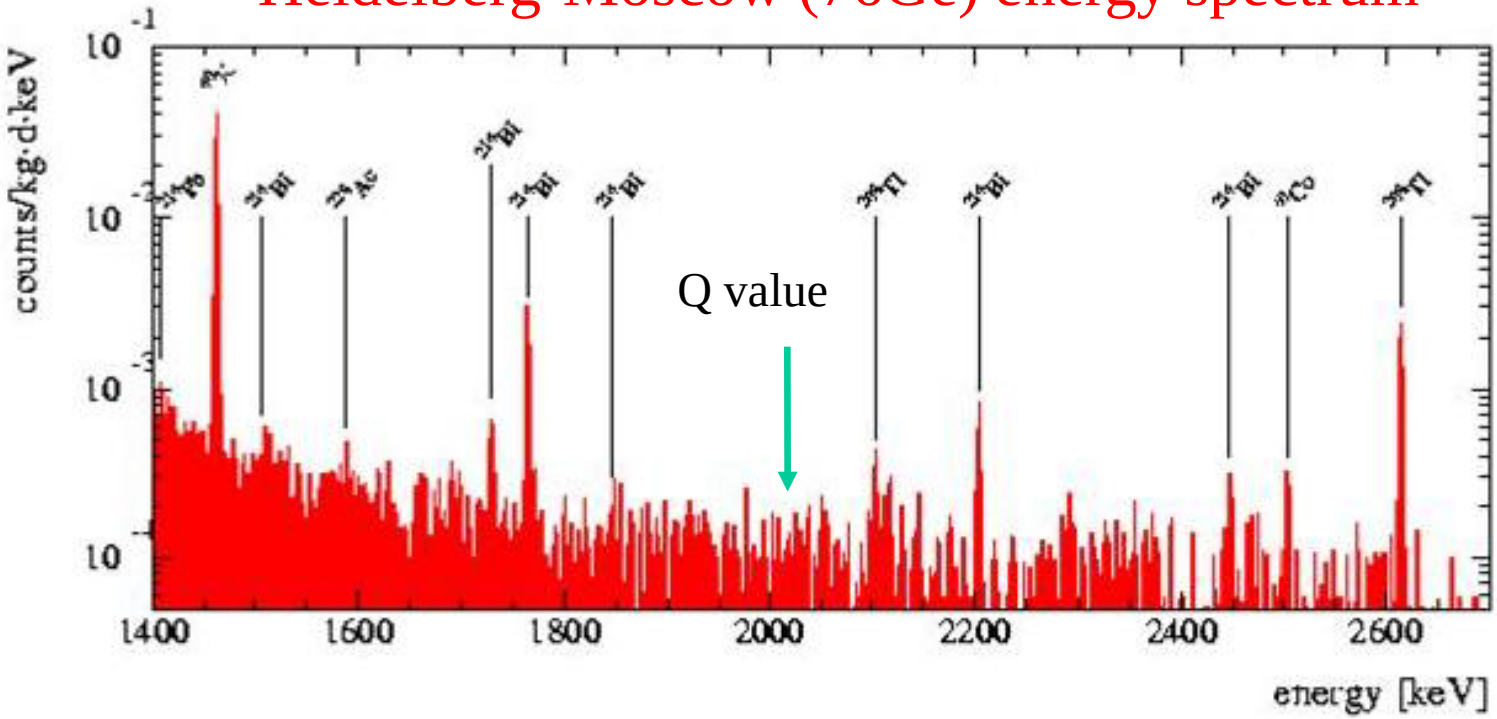
- Studies for rare events, either decays (eg proton or 0νββ) or weak interactions (dark matter, natural or generated neutrino), require very radio-quiet environments to undertake searches
- Deep underground facilities provide significant rock overburden and commensurate reduction in c.r. flux, and c.r.-spallation induced neutrons
  - Additional science programmes possible with such infrastructure - nuclear astrophysics, extreme biosystems, geology, geophysics, ...





The most sensitive double beta decay experiments to date are based on 76-Germanium.

Heidelberg-Moscow (76Ge) energy spectrum

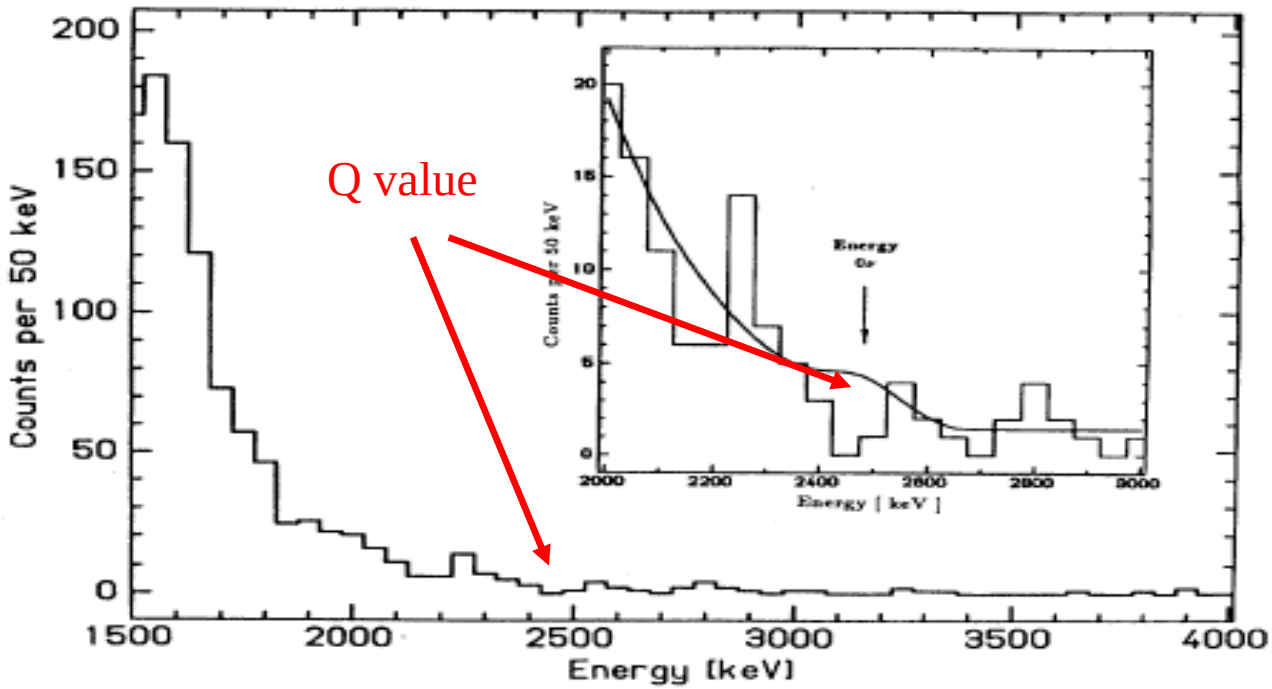


Half-life limit: 1.9 x 10^{25} years (H-M and IGEX)

Majorana neutrinos ruled out for masses greater than ~0.35-1.0 eV

Energy resolution of ββ0ν candidate isotopes

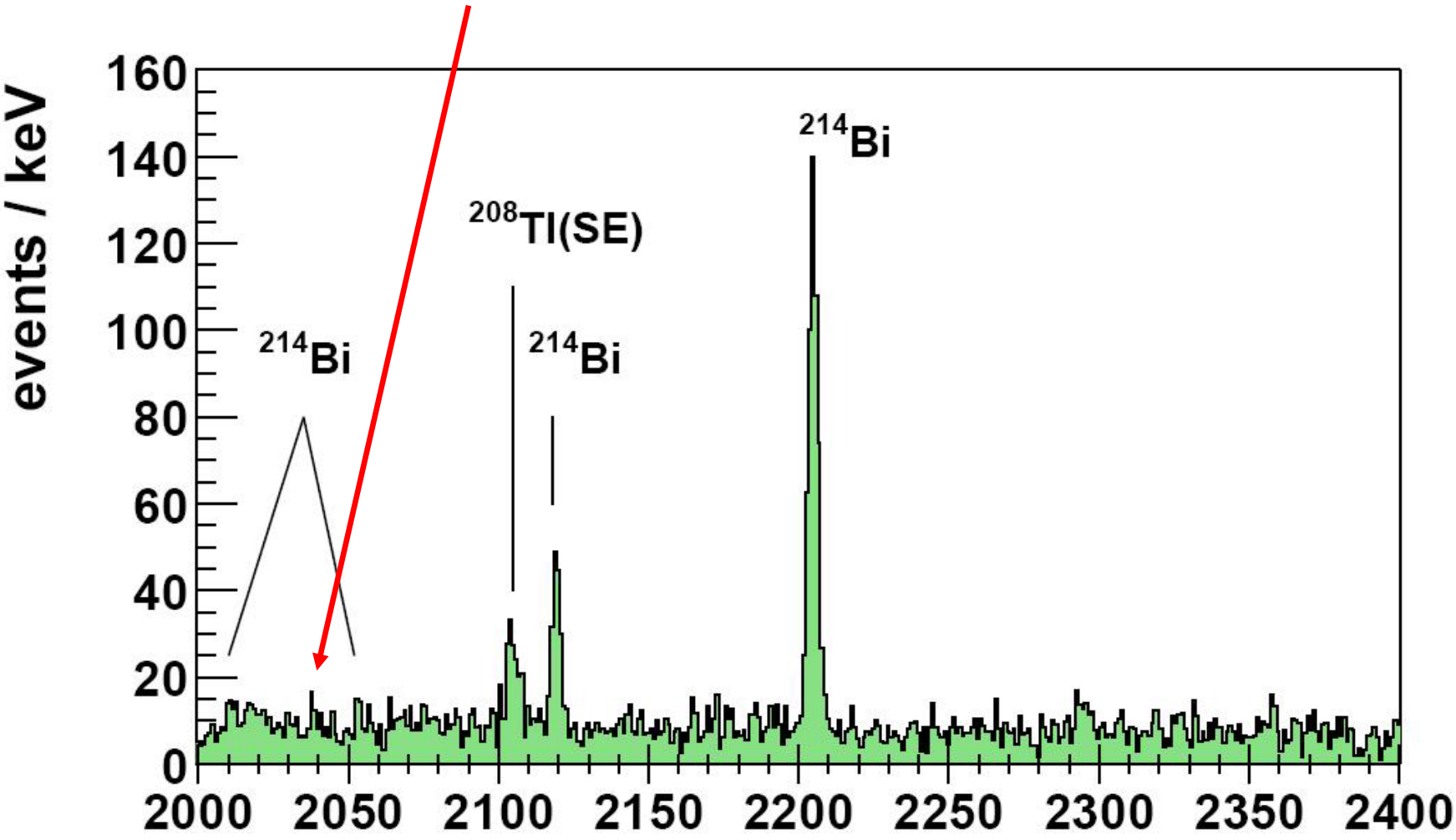
Gotthard TPC (136Xe) energy spectrum (1998)



Superior energy resolution:
76Ge (diode): 0.2% FWHM
130Te (bolometer): 0.4% FWHM

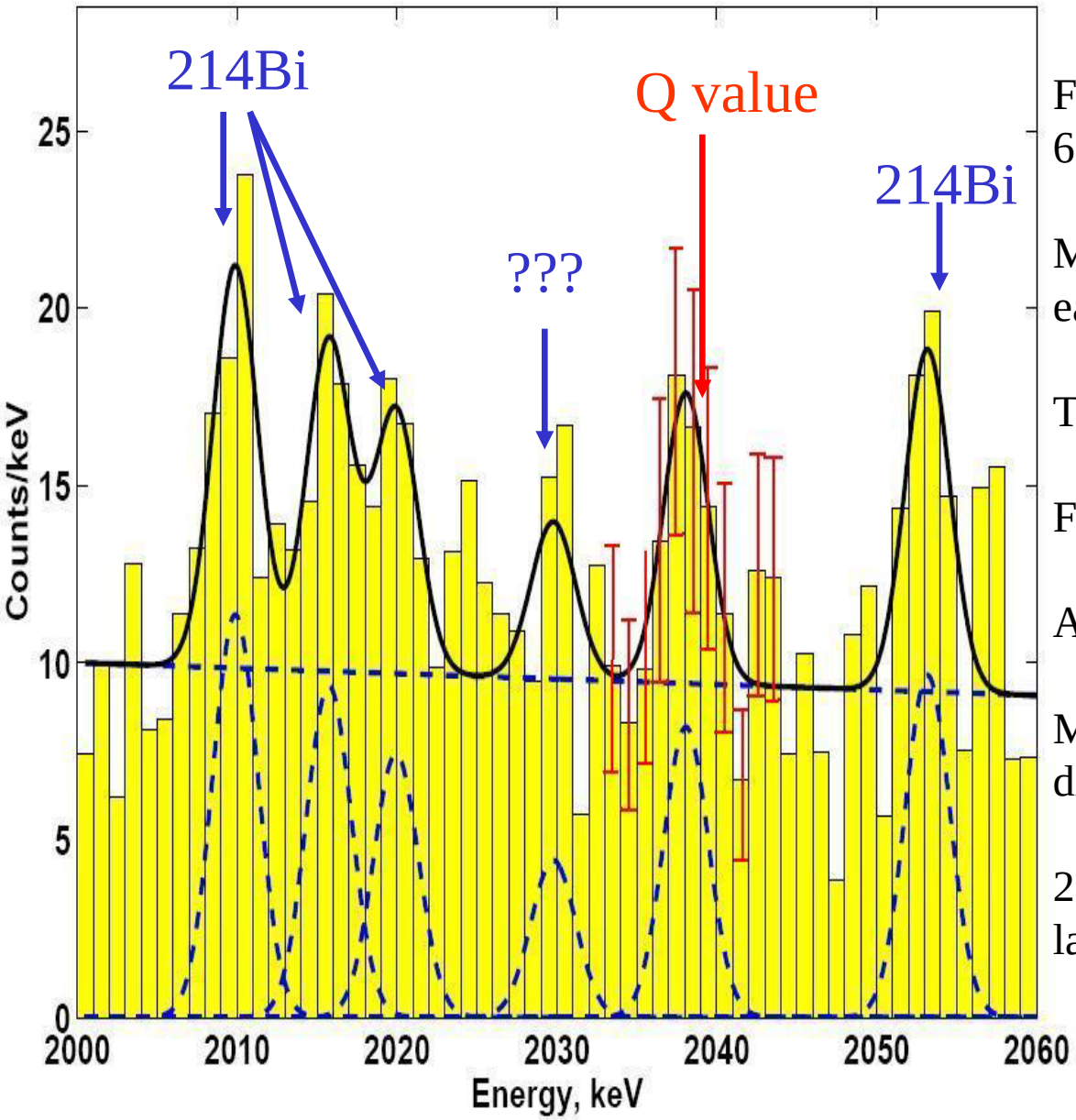
Modest energy resolution:
136Xe (liquid TPC): 3.3% FWHM
100Mo, 82Se (plastic scintillator): ~14% FWHM

ββ0ν discovery claim – 2001-2006



HV. Klapdor-Kleingrothaus, et. al,
Nuclear Instruments and Methods A **513** (2004) 371-406

ββ0ν discovery claim - 2004



Fit model:
6 gaussians + linear background.

Mean, width and intensity of each gaussian floats in the fit.

Total of 20 free parameters.

Fit intensity @ $Q_{\beta\beta}$ = 28.75 6.86.

Authors claim significance of 4.2 σ.

Mean value of ββ0ν candidate line displaced from $Q_{\beta\beta}$ by 2.1 σ.

214Bi intensity from fit is 2 – 2.5 σ larger than MC prediction.

Discovery of the Ω-

VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

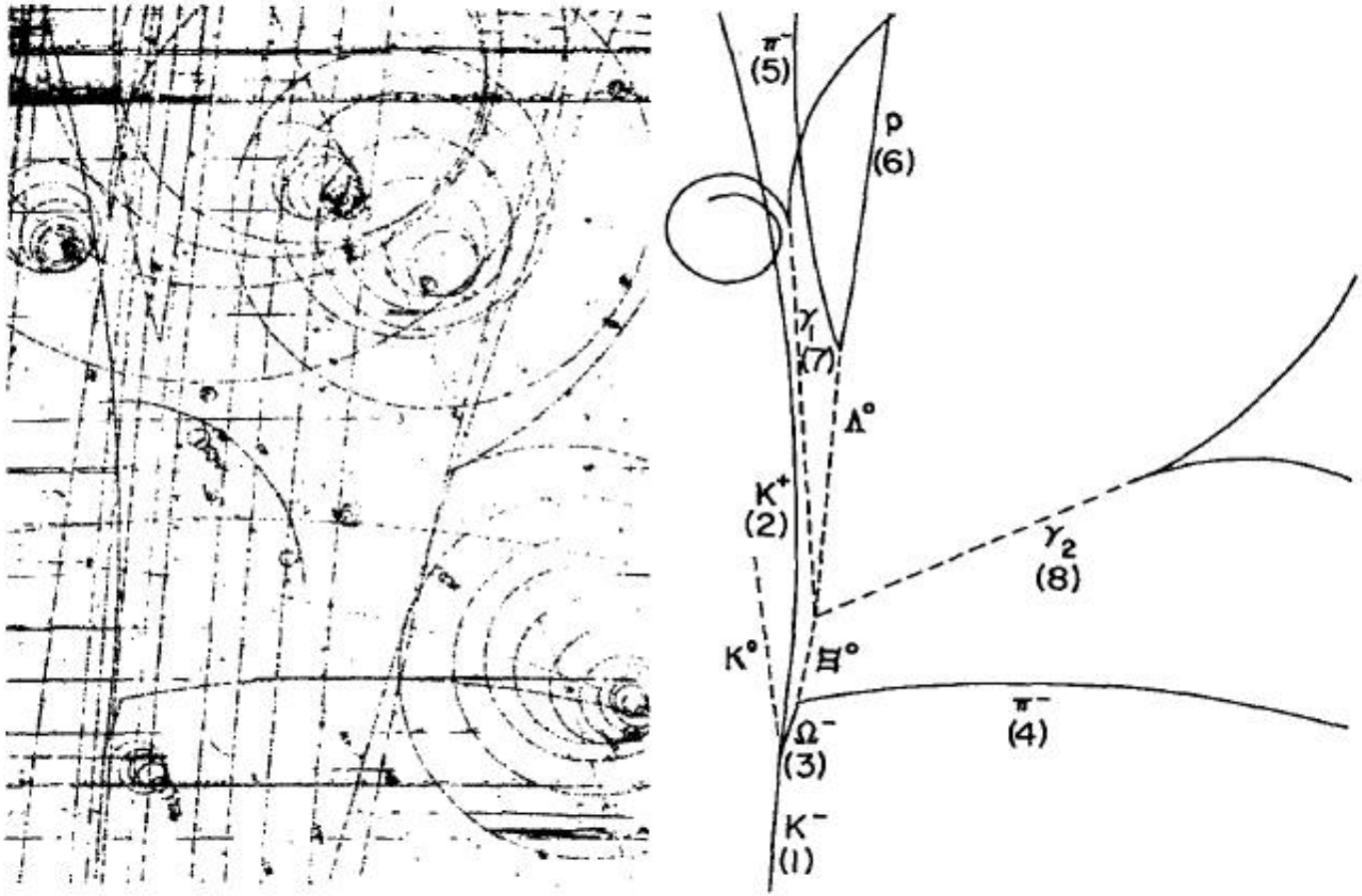
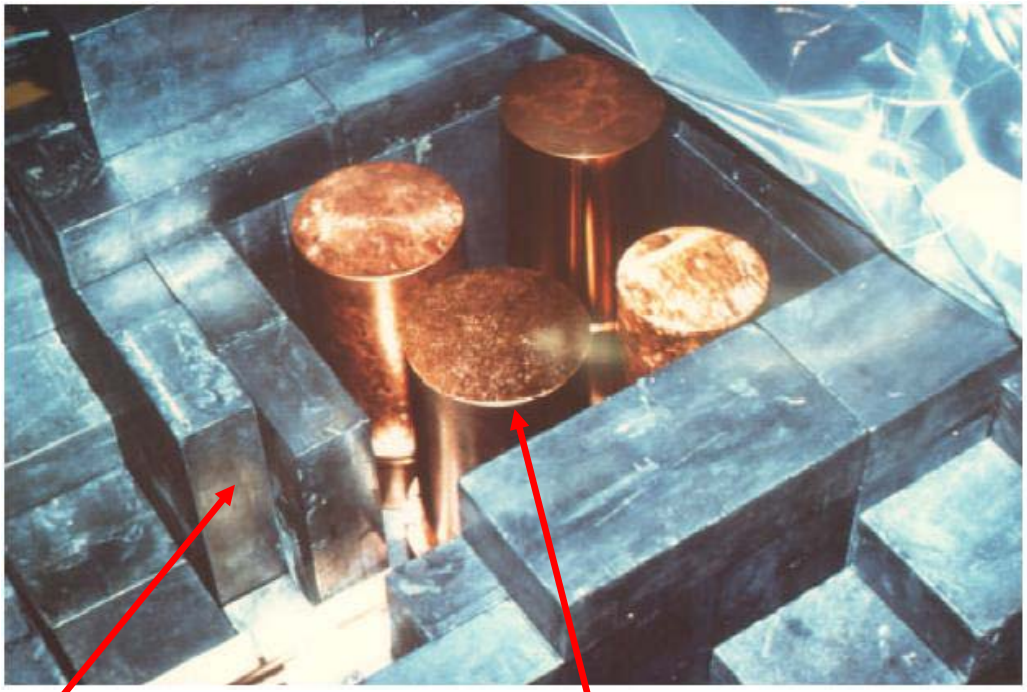


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

The statistical significance of a signal is determined by how strongly you reject the null hypothesis.

Germanium-76

Heidelberg-Moscow, IGEX, GERDA, MAJORANA experiments



2-3 kg Ge diodes,
80% ^{76}Ge

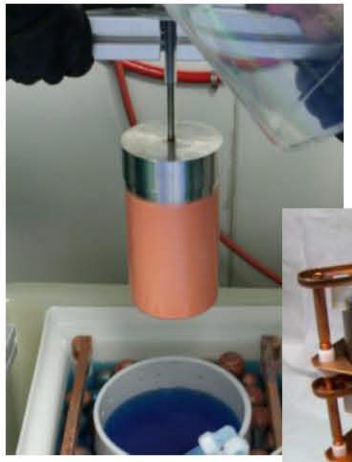
Lead shielding

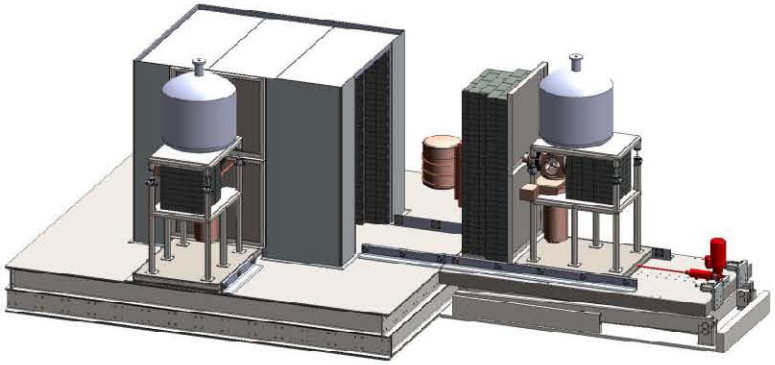
Cu cryostats

Fantastic energy resolution (4 keV FWHM).
Cooled with Liquid Nitrogen to suppress thermal noise.
Pulse shape analysis rejects multiple site events within a single crystal.
Suffers from low Q value (2039 keV), and cosmogenic activation of germanium and copper cryostats.

MAJORANA project status

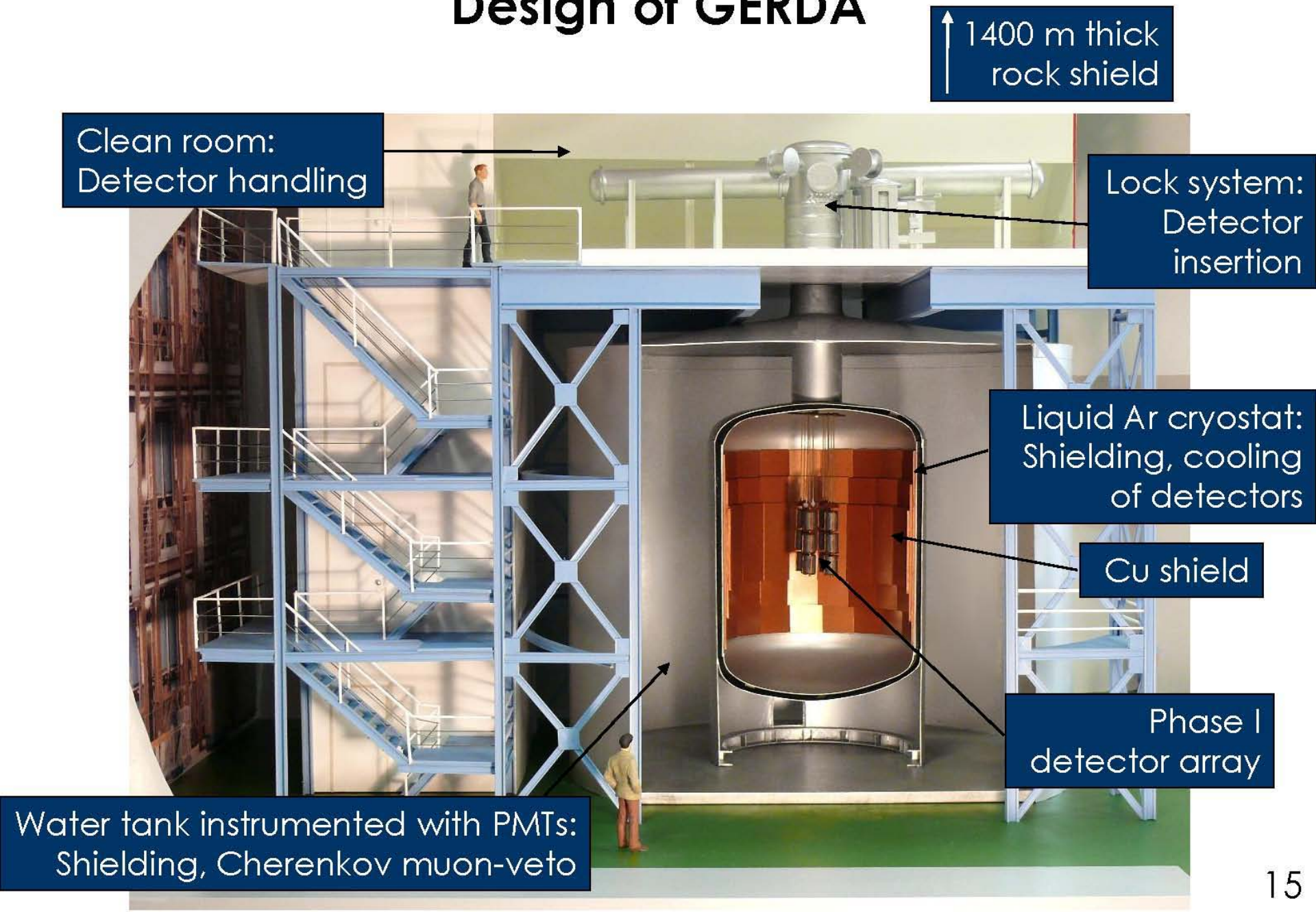
- **Demonstrator** approved for FY 2010-2013
  - 30 kg ^{nat}Ge & 30 kg ^{enr}Ge
  - Running 3 years (90 kg·y) → $T_{1/2} \geq 10^{26}$ y (90% CL))
  - B =10^{-3} cts/(kg·keV·y)
- **Objective**: Demonstrate background low enough to justify building a ton scale Ge experiment
- **Schedule**:
  - Start of Cu electroforming deep underground at DUSEL this year
  - First cryostat with 20 kg of ^{nat}Ge modified BEGe p-type detectors ready in fall 2011





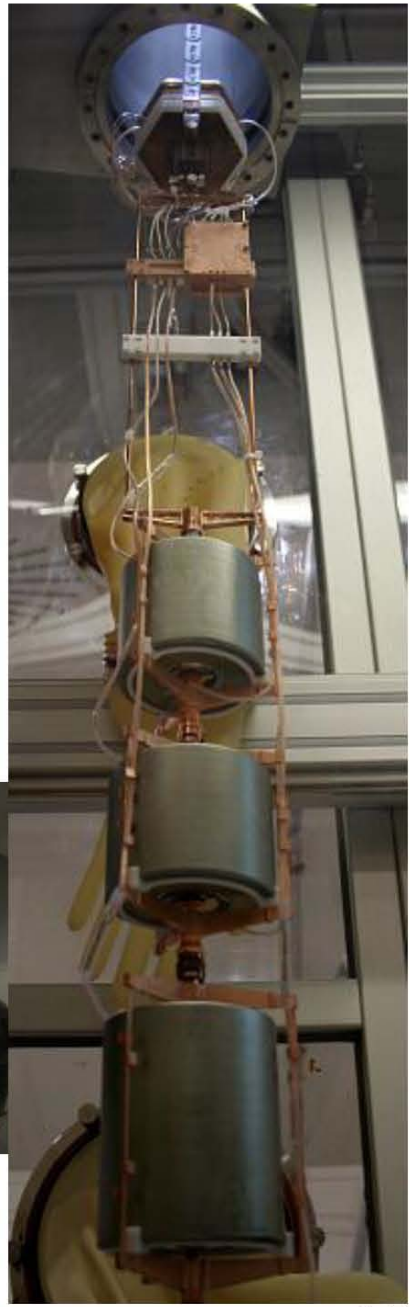
See posters 4, 95 & 120

Design of GERDA



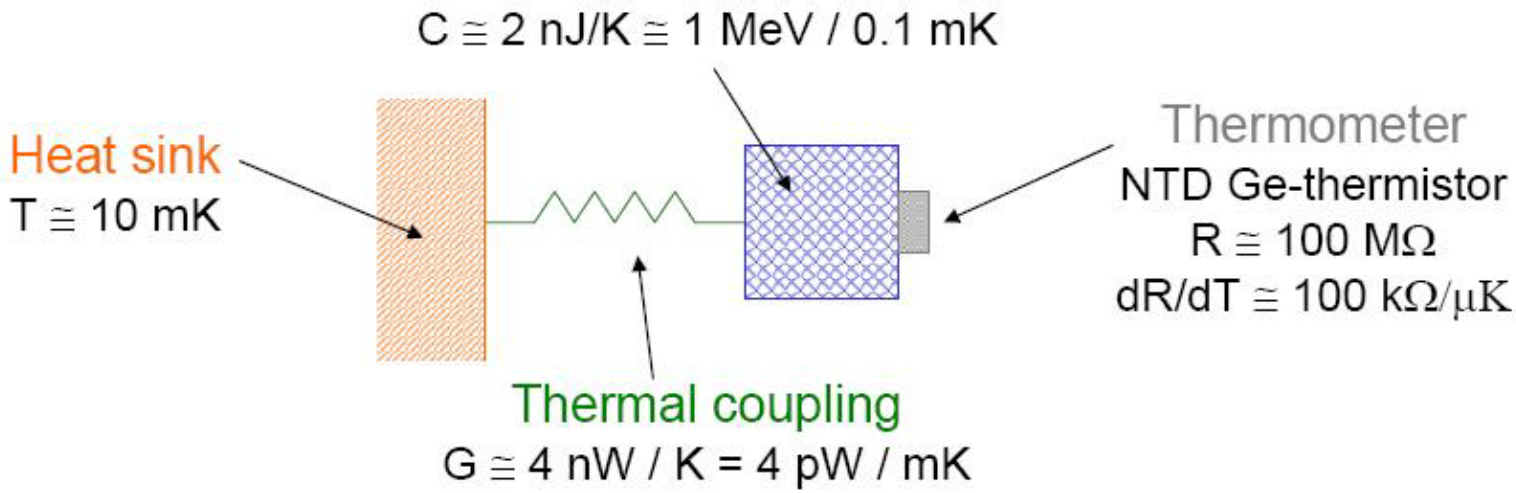
GERDA status

- Summer/autumn '09: Integration test of Phase I detector string, FE, lock, DAQ
- Nov/Dec.'09: Liquid argon filling
- Apr/May'10: Installation of 1-string lock in the GERDA cleanroom
- May '10: Deployment of FE & detector mock-up, followed by first deployment of a of non-enriched detector
- June '10: Water tank filling
- **June '10: Commissioning run with ^{nat}Ge detector string**



Tellurium basics: low temperature bolometers

Take advantage of tiny heat capacity of crystals at low temperature to measure energy deposition with a thermometer(!).



Technique applicable to many isotopes – currently 130Te is used to take advantage of its high isotopic abundance (30%).

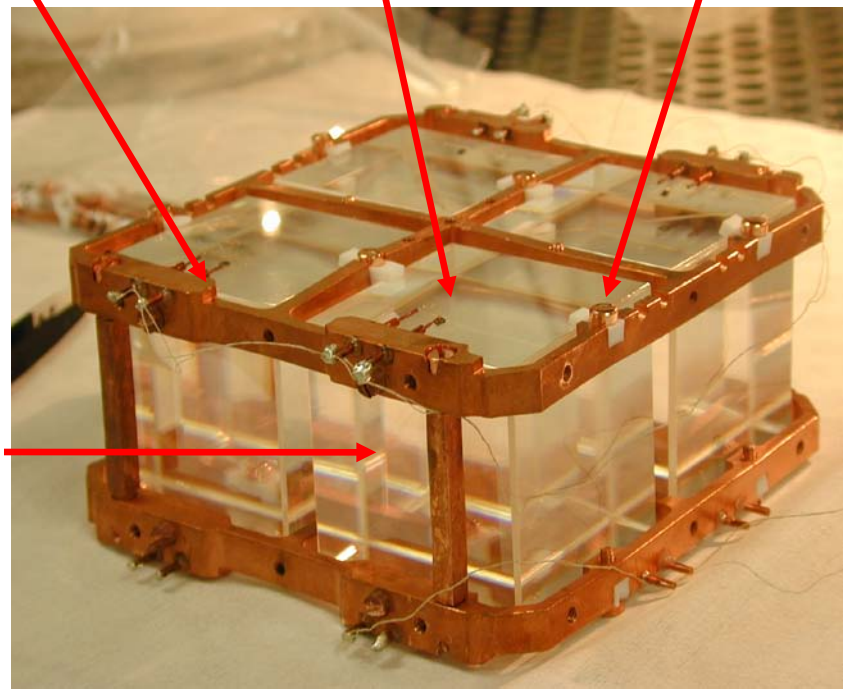
Drawbacks: no information beyond energy is available, like particle ID (α,β,γ), event location, or topology.

130Te : CUORICINO

Italy, US, Netherlands, Spain, at Gran Sasso, Italy

heat sink thermometer thermal link

TeO2 crystal



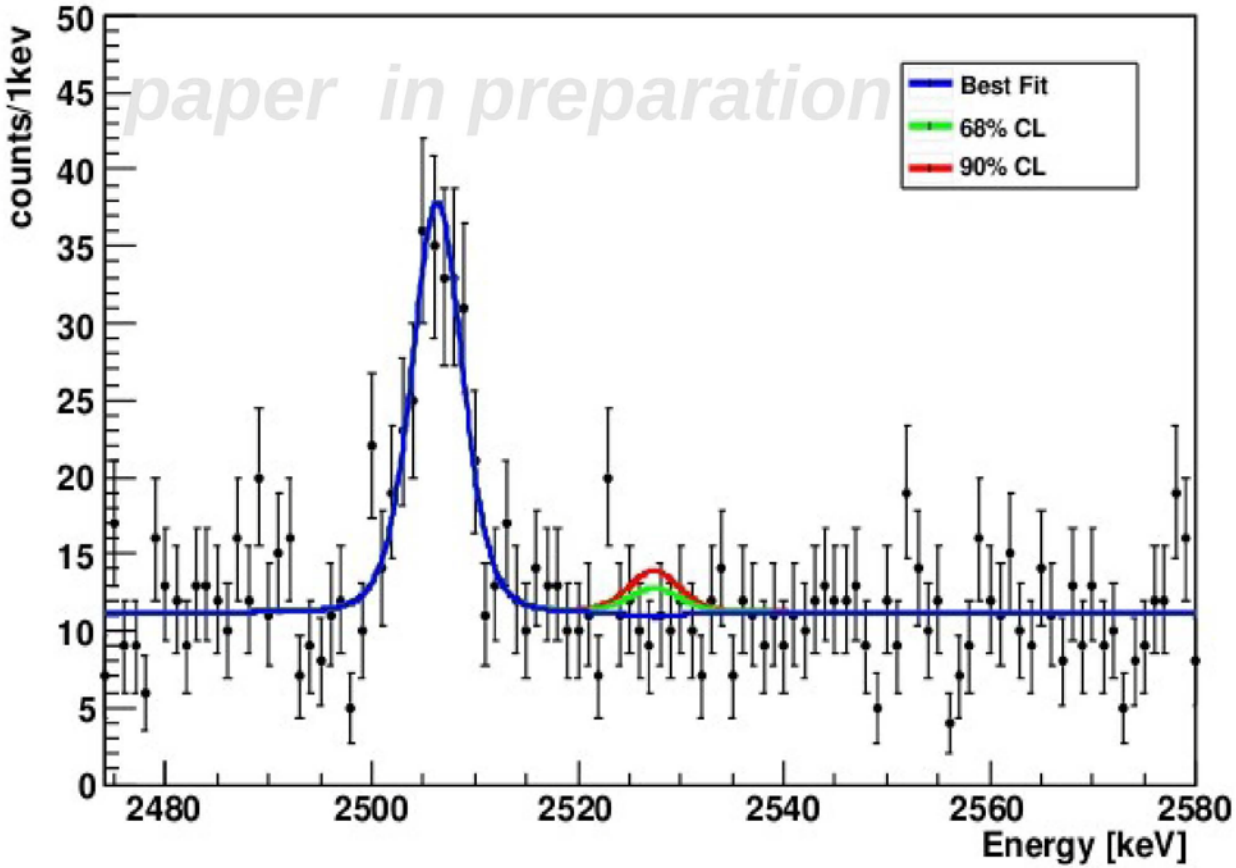
tower under construction

CUORICINO is a 40.7 kg tower of TeO2 crystals (34% 130Te) in operation at Gran Sasso.

CUORICINO: 0n DBD result

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

@ 90% C.L.
$\tau_{1/2}$ > 2.8 10^{24} [yr]
m_{ee} < 0.3÷0.7$^{1-4}$ eV

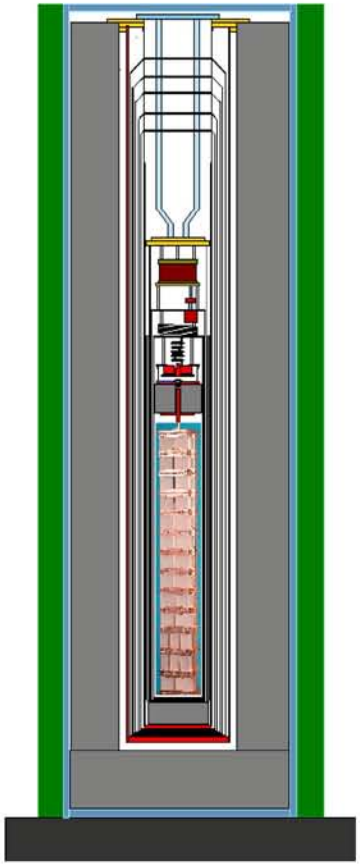


NME bibliography:

1 Šimkovic et al., PRC 77 (2008) 045503
2 Civitarese et al., JoP:Conference series 173 (2009) 012012
3 Menéndez et al., NPA 818 (2009) 139
4 Barea and Iachello, PRC 79 (2009) 044301

see POSTER – M. Carrettoni

From CUORICINO to CUORE
New Hardware

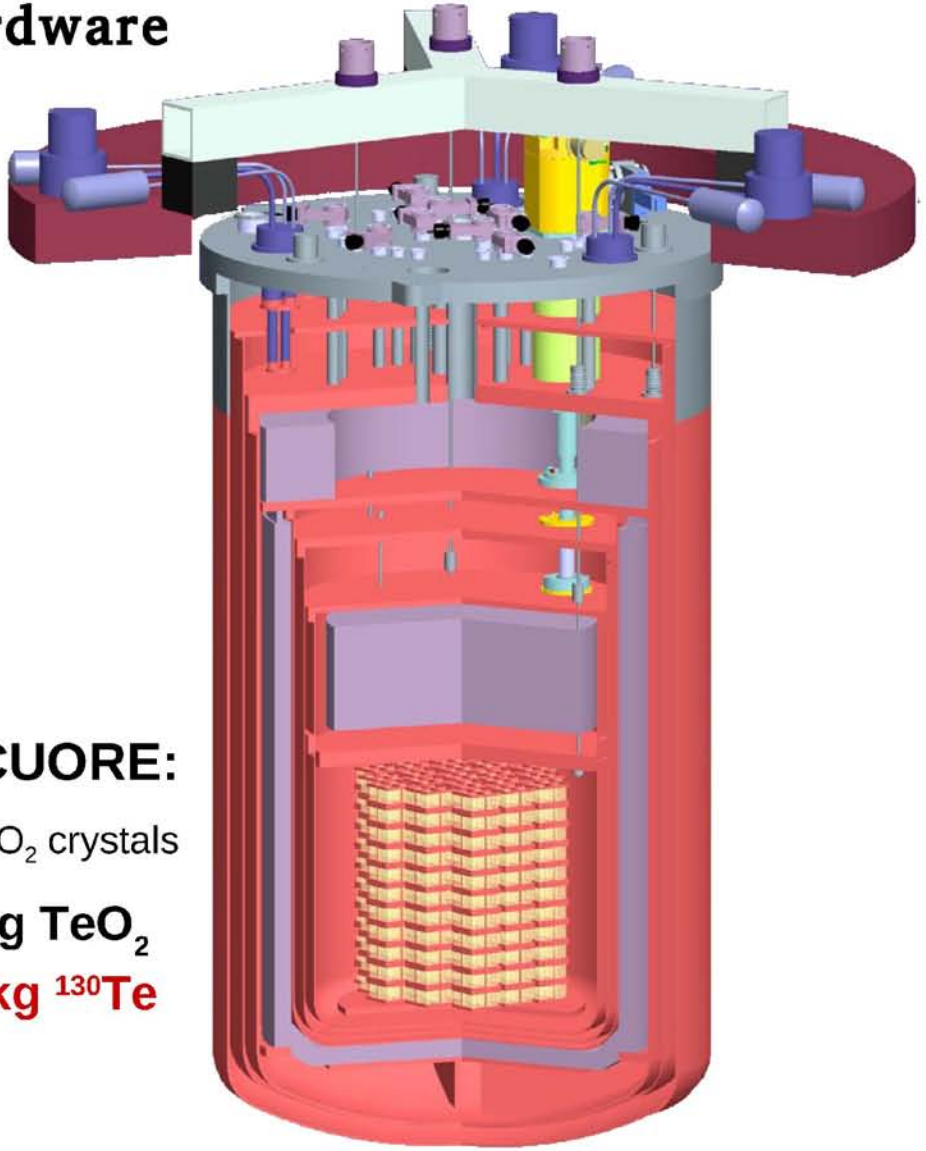


CUORICINO

44 5x5x5 cm^3 + 18 3x3x6 cm^3 TeO_2 crystals

1 TOWER: 40.7 kg TeO_2

11 kg ^{130}Te



CUORE:

988 5x5x5 cm^3 TeO_2 crystals

19 TOWER: 740 kg TeO_2

~200 kg ^{130}Te

CUORE goal
5 years sensitivity

Background [c/keV/kg/y]	ΔE_{FWHM} [keV]	$\tau_{1/2}^{0\nu}$ [y] @ 68%C.L.	m_{ee} [meV] R(QRPA)[1]	pn(QRPA)[2]	ISM[3]	IBM-2[4]
0.01	5	2.1×10^{26}	35÷66	41÷67	65÷82	41
0.001	5	6.5×10^{26}	20÷38	23÷38	37÷47	23

NME bibliography:

1 Šimkovic et al., PRC 77 (2008) 045503
2 Civitarese et al., JoP:Conference series 173 (2009) 012012
3 Menéndez et al., NPA 818 (2009) 139
4 Barea and Iachello, PRC 79 (2009) 044301

100Mo: NEMO-3

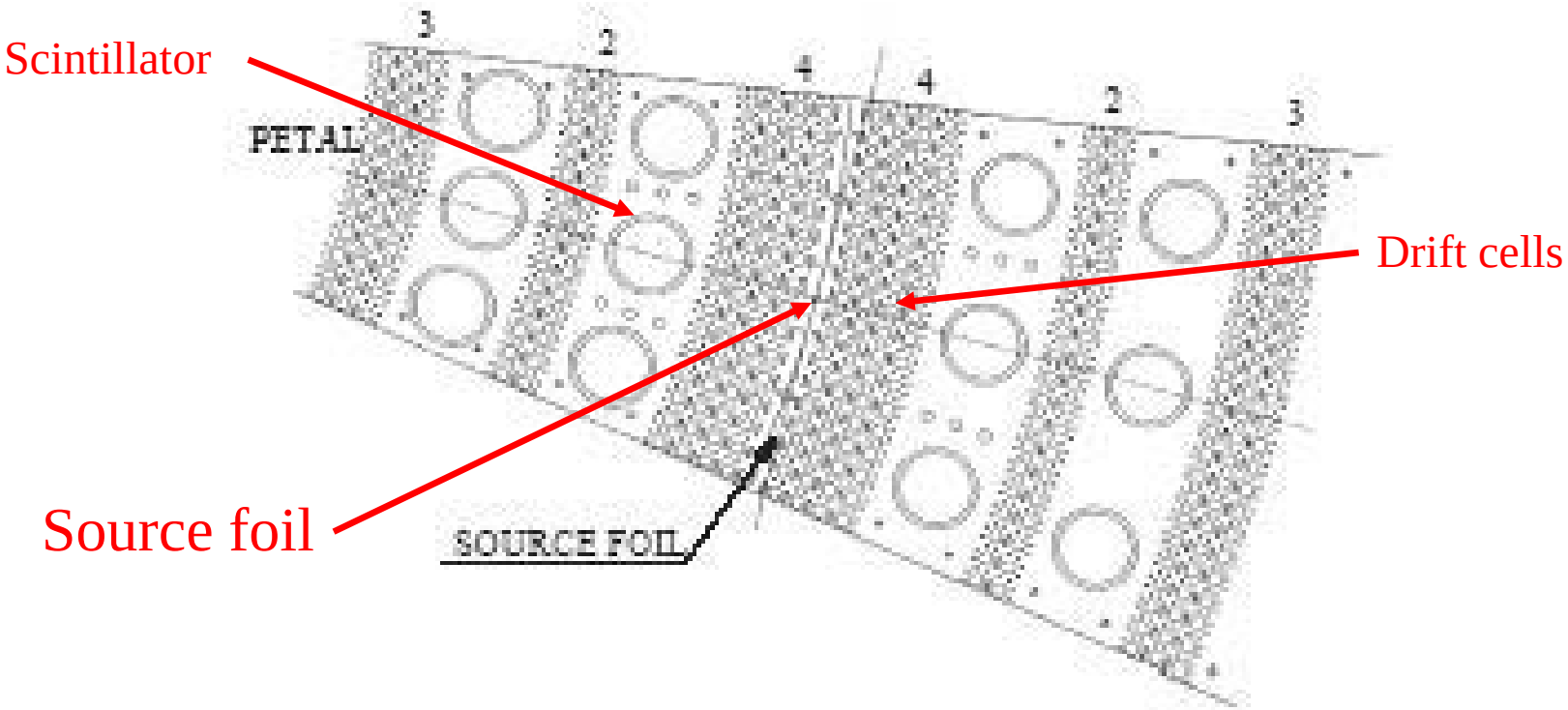
France, Russia, Japan, US, Czech Republic, currently taking data in Frejus, France.

Passive isotope on thin foils surrounded by Geiger mode drift cells for electron tracking and plastic scintillator for energy measurement

NEMO is designed to investigate the $\beta\beta0\nu$ mechanism:
multiple isotopes and electron angular distribution.

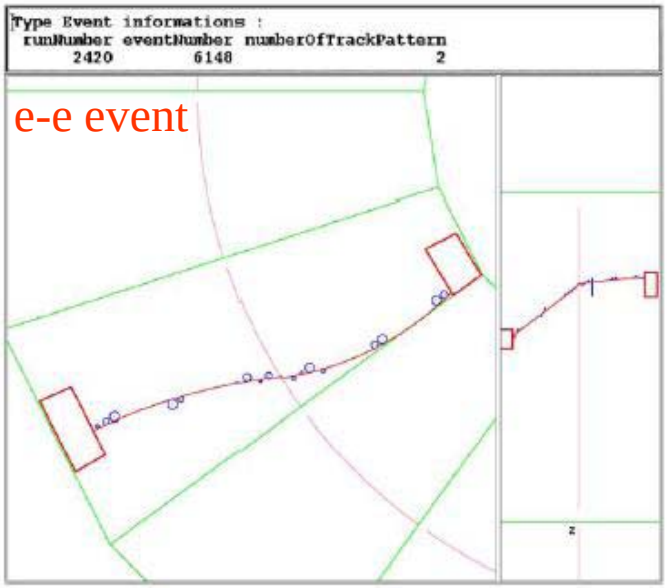
100Mo: NEMO-3

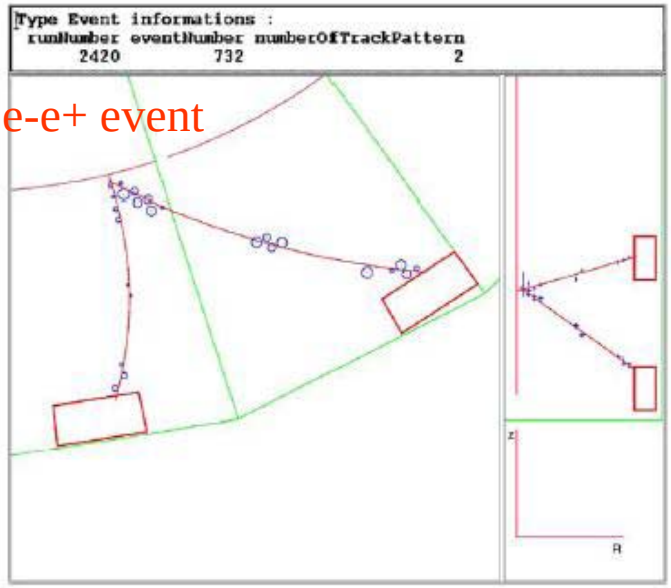
Tracking provides powerful background rejection



100Mo: NEMO-3

25 Gauss magnetic field measures β charge.





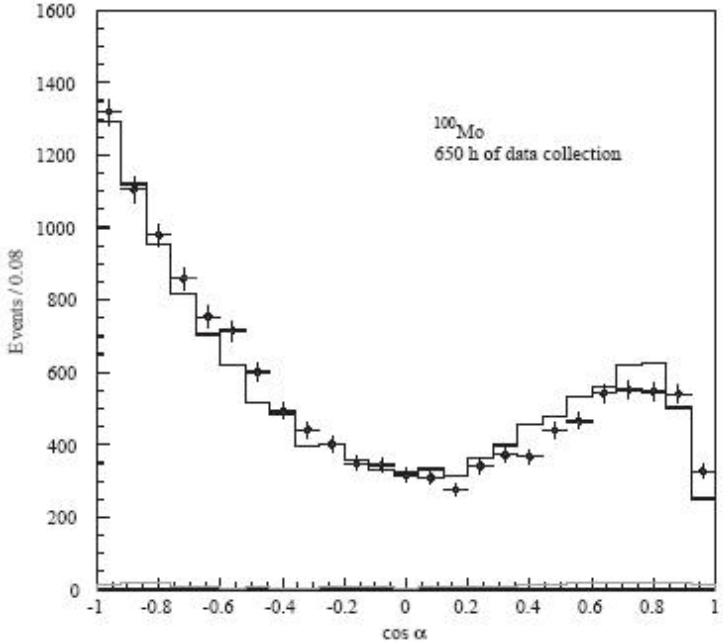
6.9 kg of 100Mo and 0.93 kg of 82Se for ββ0ν search.

Other isotopes for ββ2ν measurements and background studies.

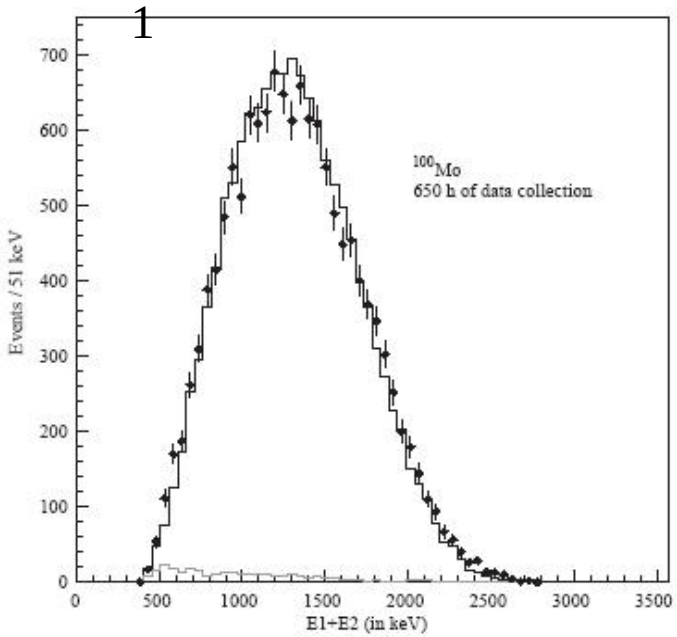
100Mo and 82Se: NEMO-3

Data for 100Mo ββ2ν agree beautifully with simulations .

100Mo ββ2ν angular distribution



100Mo ββ2ν energy spectrum



Super-NEMO: 100 kg with neutrino mass sensitivity of 50 meV.

From K. Nakamua, Neutrino 2010

SNO+

1000 t D_2O will be replaced by Nd loaded LS

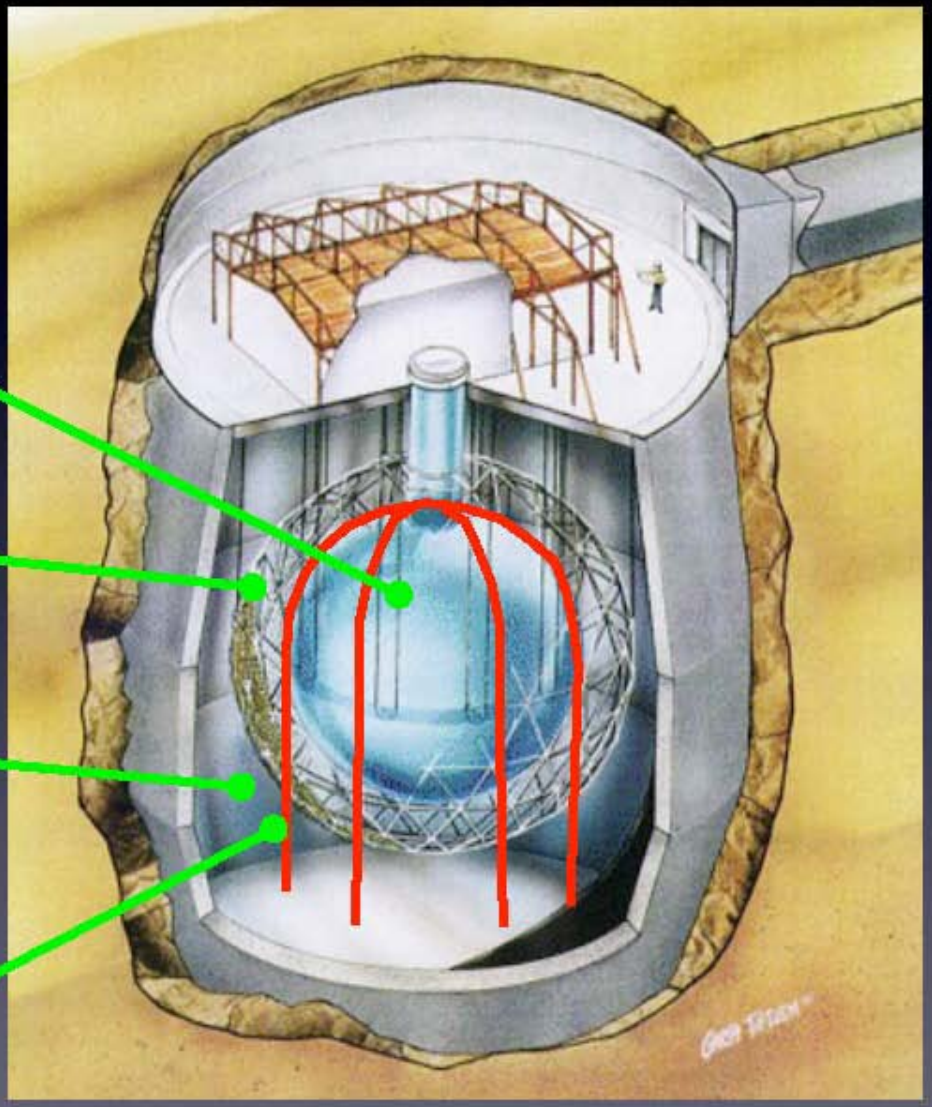
0.1 wt% = 780 kg Nd(natural)
= 44 kg Nd-150

9500 PMTs

Energy res = 5 %@1 MeV

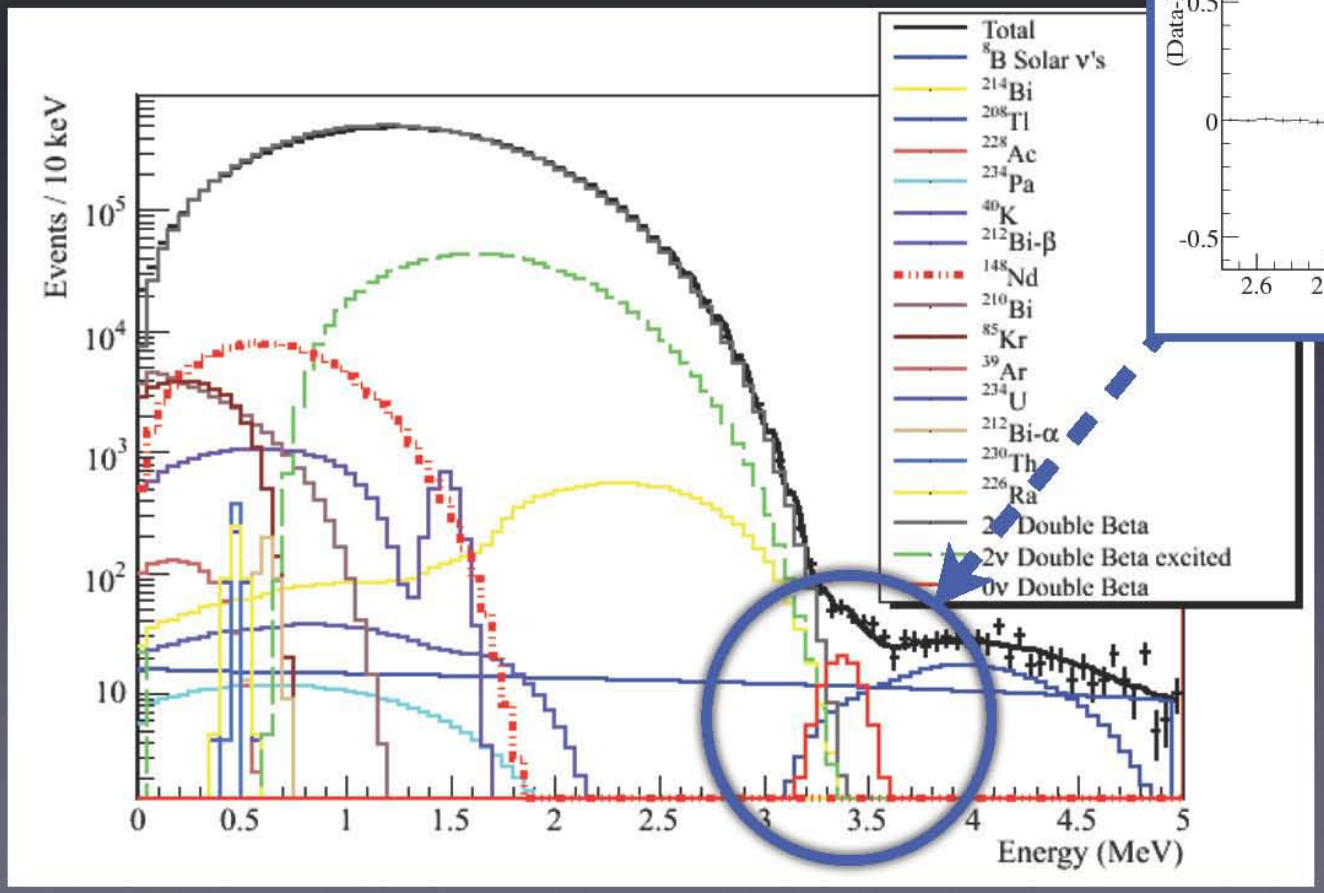
7000 t pure water shield

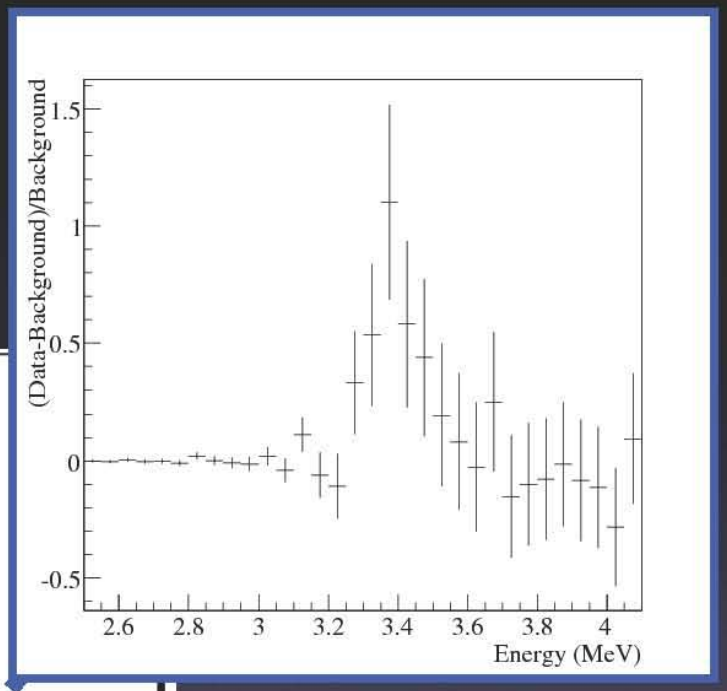
Hold down ropes will be installed



From K. Nakamua, Neutrino 2010

Double beta decay signal at the "KKDC level"

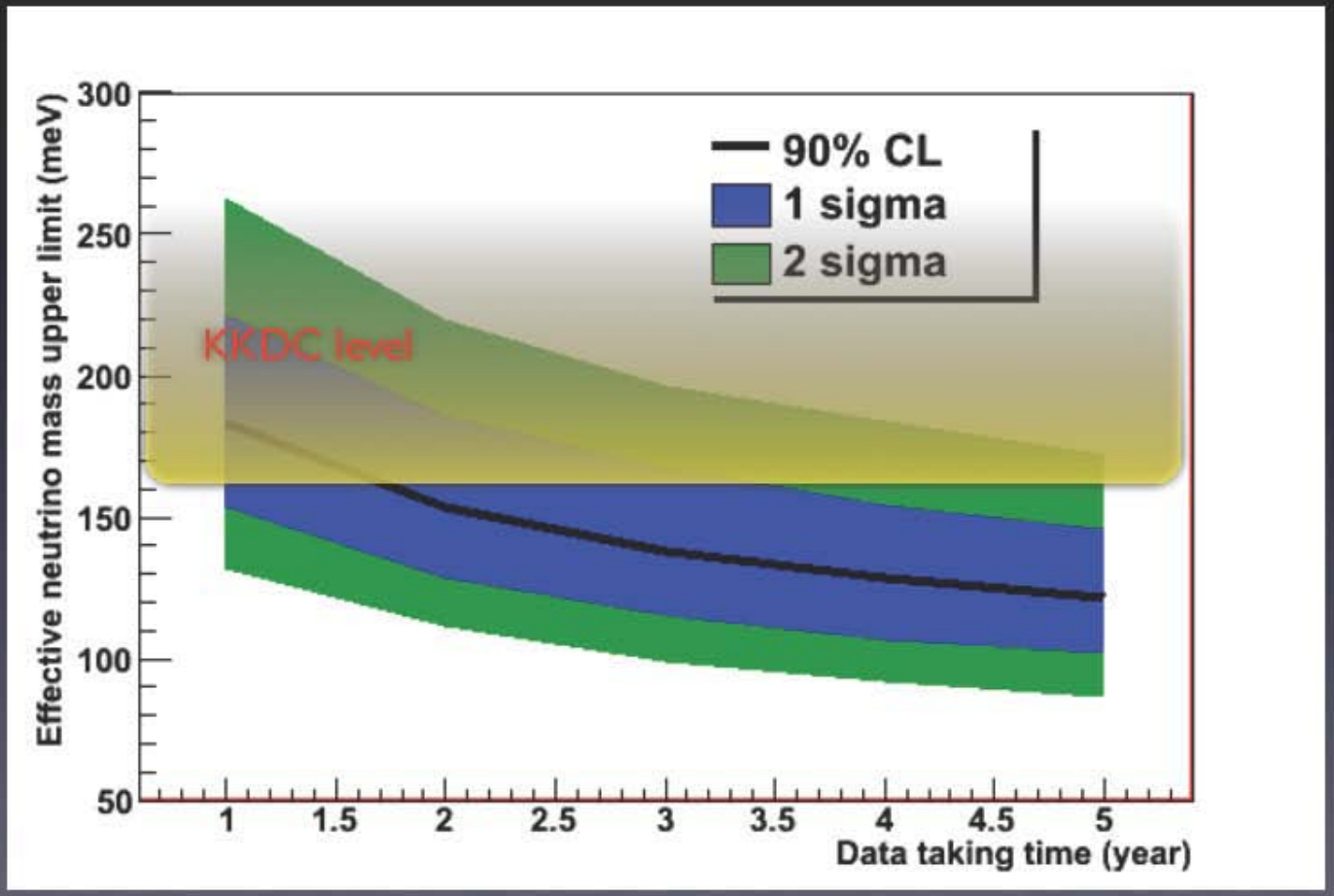




@1 year

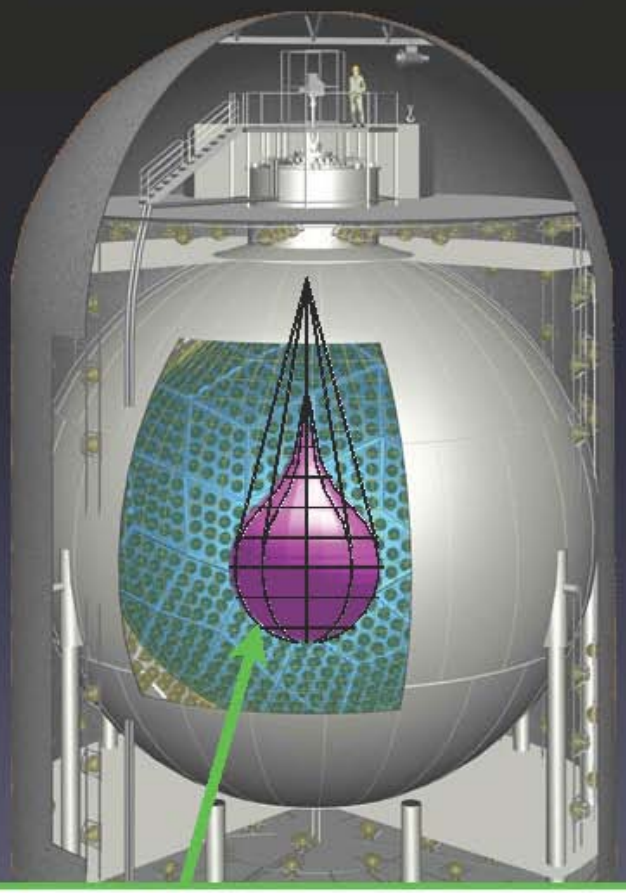
From K. Nakamua, Neutrino 2010

Sensitivity



From K. Nakamua, Neutrino 2010

KamLAND-Zen



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

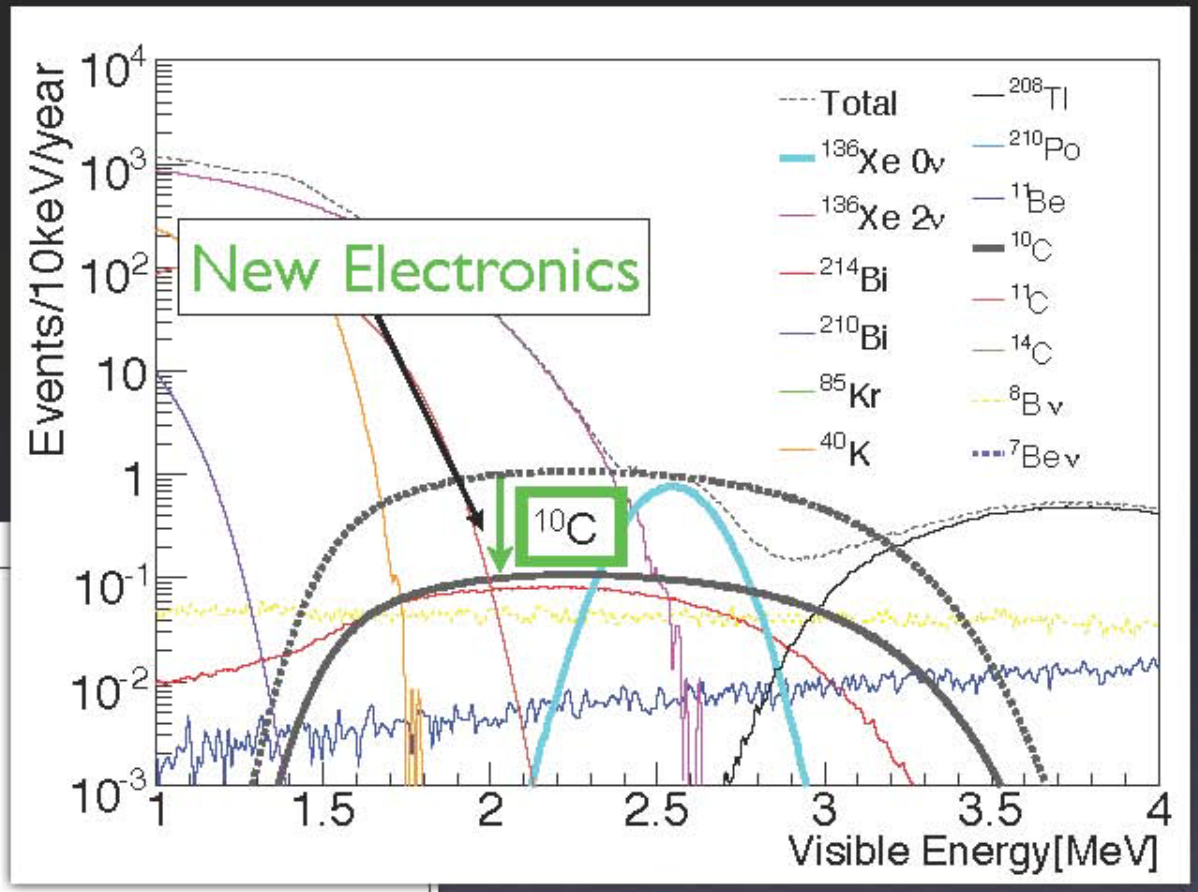
^{136}Xe 400 kg:

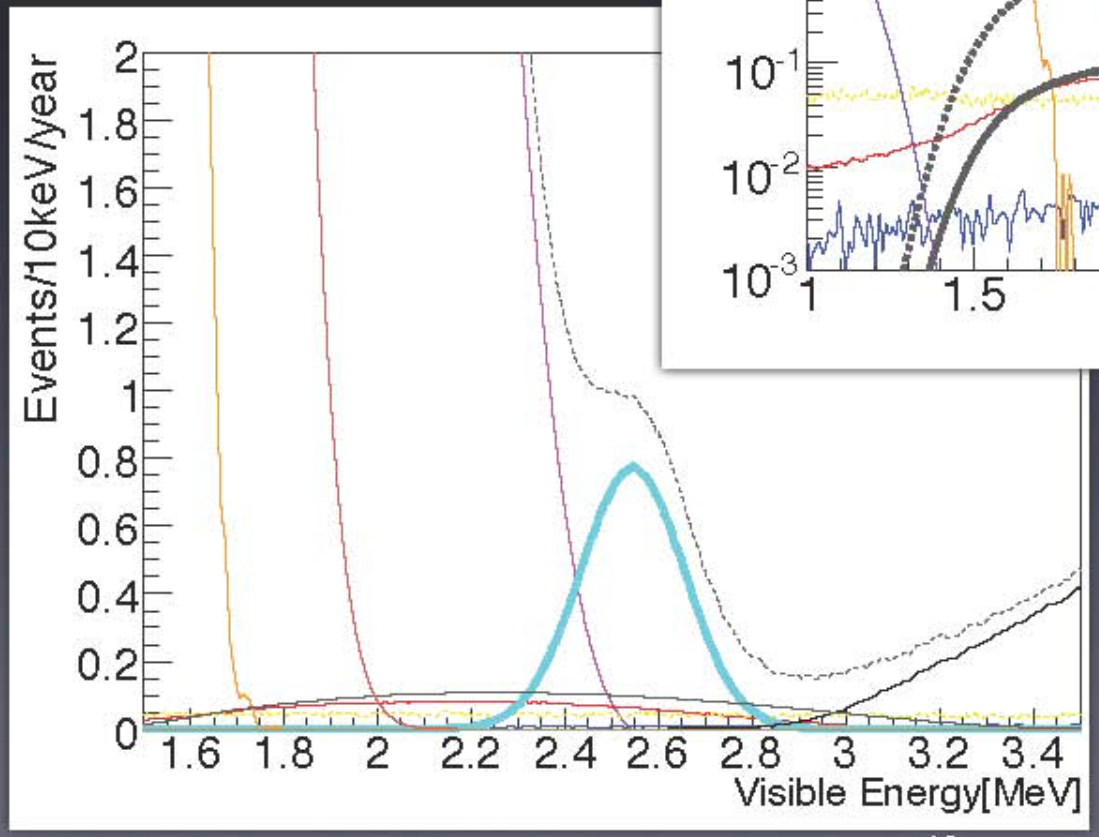
- 2.7 wt% dissolved into LS
- easy handling/ enrichment (90%)
- longer 2ν beta decay life time
- $T^{2\nu} > 10^{22}$ years (cf: ~$10^{19\text{-}20}$)

KamLAND exists:

- ultra pure environment (U/Th~10^{-17} g/g)
- LS techniques
- Balloon experience
- LS Density control techniques
- Reactor/Geo neutrino

From K. Nakamua, Neutrino 2010





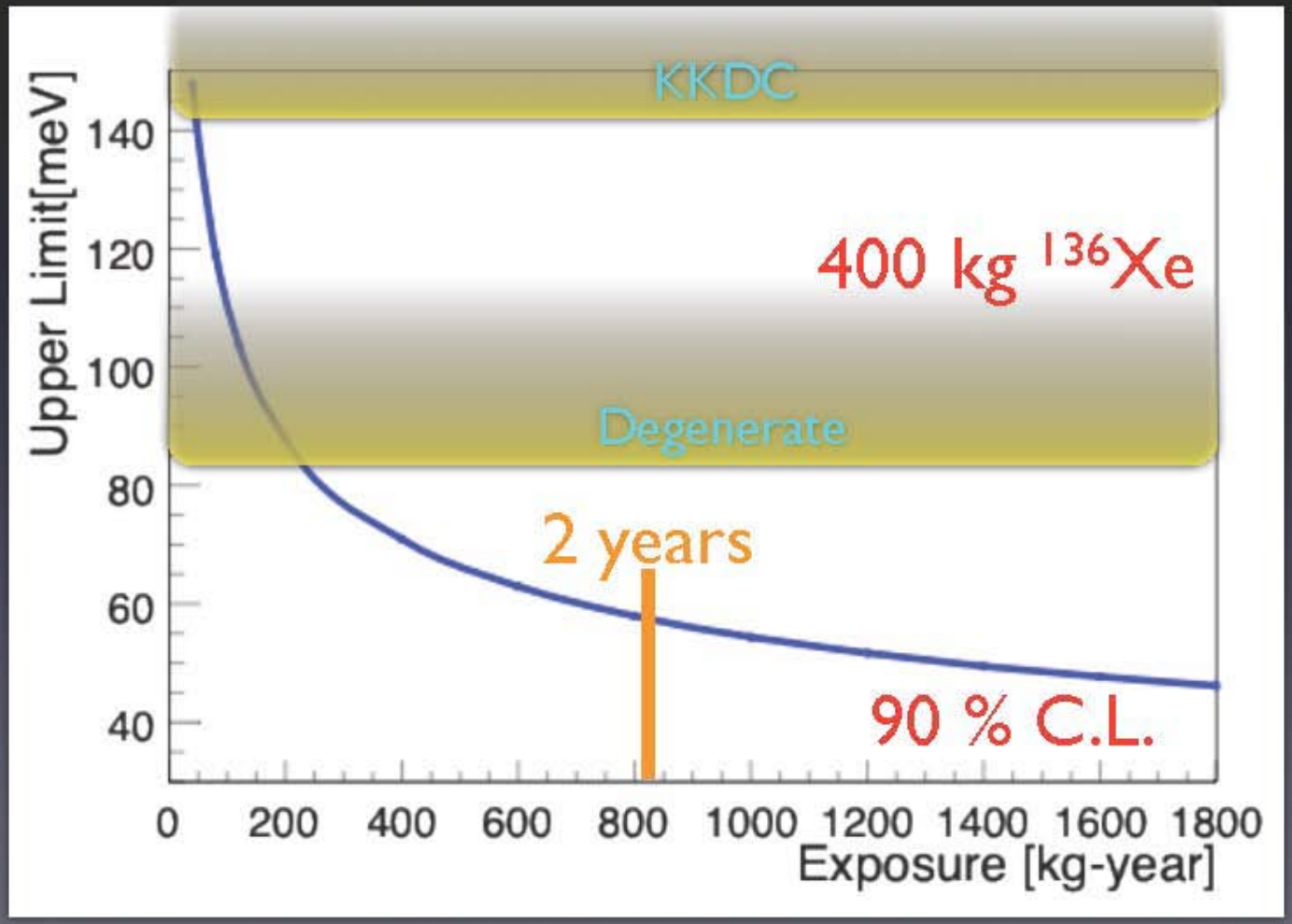
$\langle m_\nu \rangle$ = 0.15 eV (minimum KKDC)

$T_{1/2}$ (0ν) = 9.8 × 10^{25} y

$T_{1/2}$ (2ν) = 1.0 × 10^{22} y

From K. Nakamua, Neutrino 2010

Sensitivity



uni NEUCHÂTEL

SLAC
STANFORD LINEAR ACCELERATOR CENTER

Carleton UNIVERSITY
Canada's Capital University

LELAND STANFORD JUNIOR UNIVERSITY
DIE LUFT DER FREIHEIT WEHT
1891

ITEP
ИТЭФ

Enriched Xenon Observatory

EXO

for double beta decay

UCI
University of California, Irvine

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

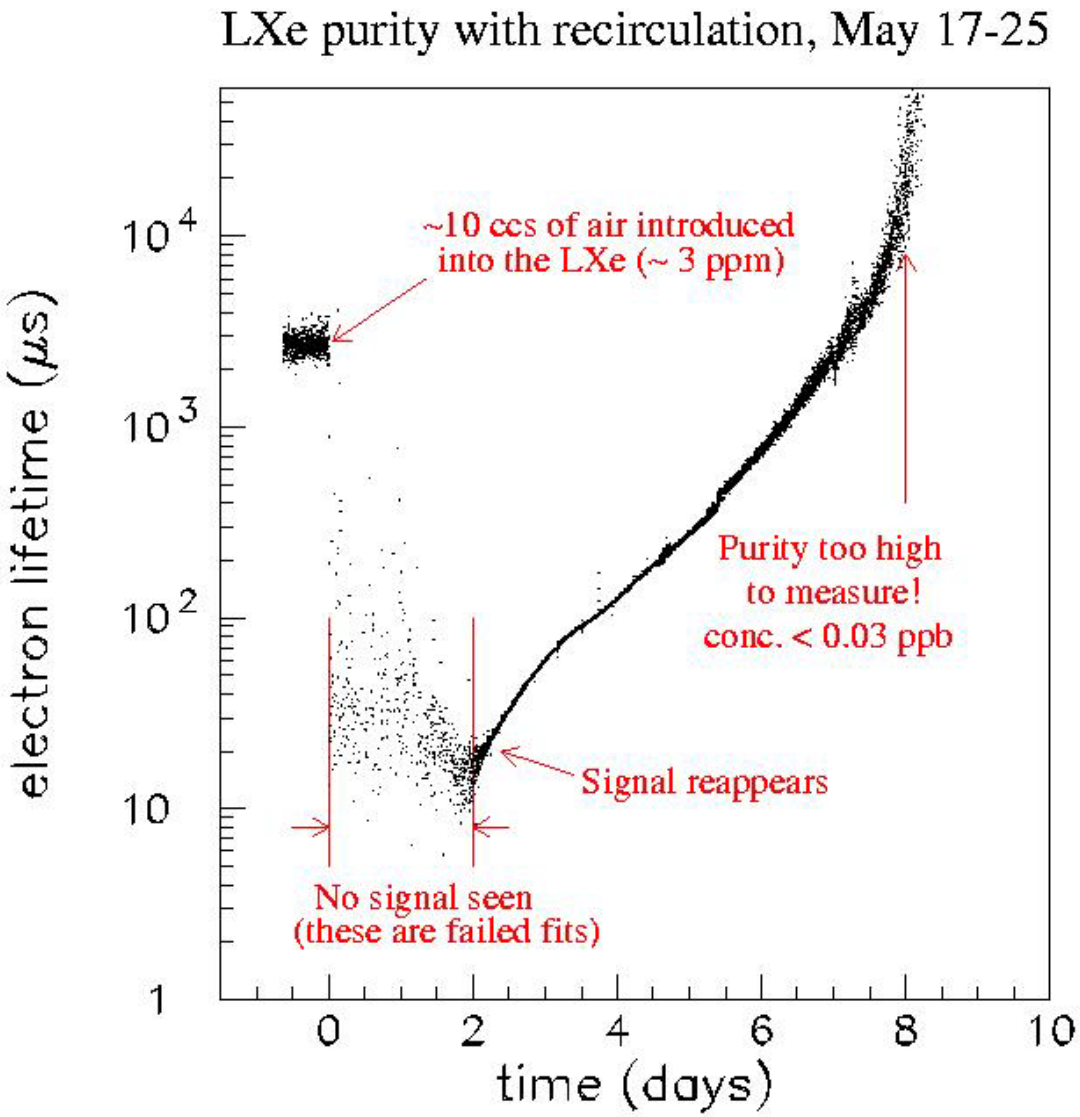
Waste Isolation Pilot Plant
WIPP

Colorado State University
Knowledge to Go Places

Laurentian UNIVERSITY•UNIVERSITÉ Laurentienne

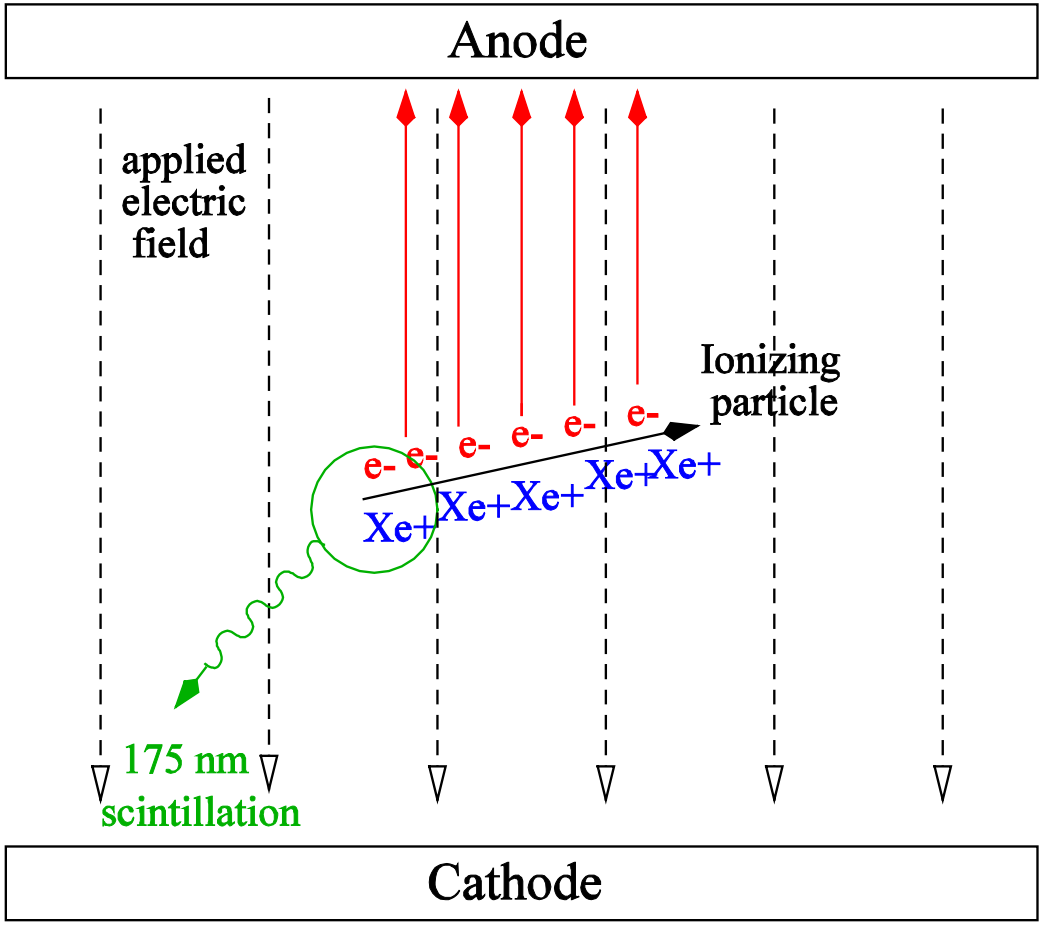
THE UNIVERSITY OF ALABAMA
1831

Xenon can be continuously purified of chemical and radioactive contaminants



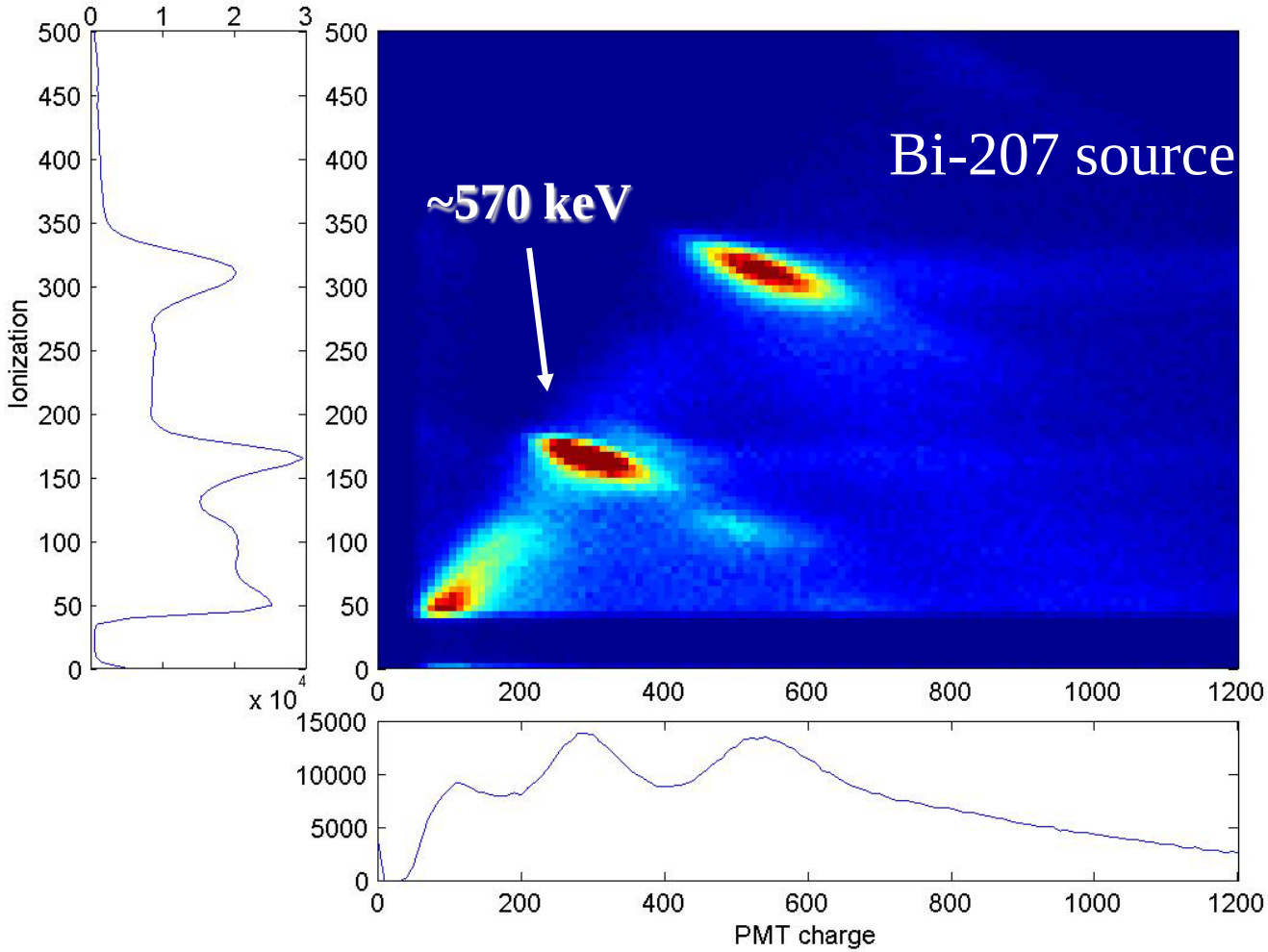
Fluids often have extraordinarily low radioactivity, and noble gases are particularly simple to purify.

Liquid xenon calorimetry



Measure the event energy by collecting the ionization on the anode and/or observing the scintillation.

Liquid xenon data show an anti-correlation between ionization and scintillation



Energy resolution: 3.0% @ 570 keV or 1.4 % @ Q(ββ)

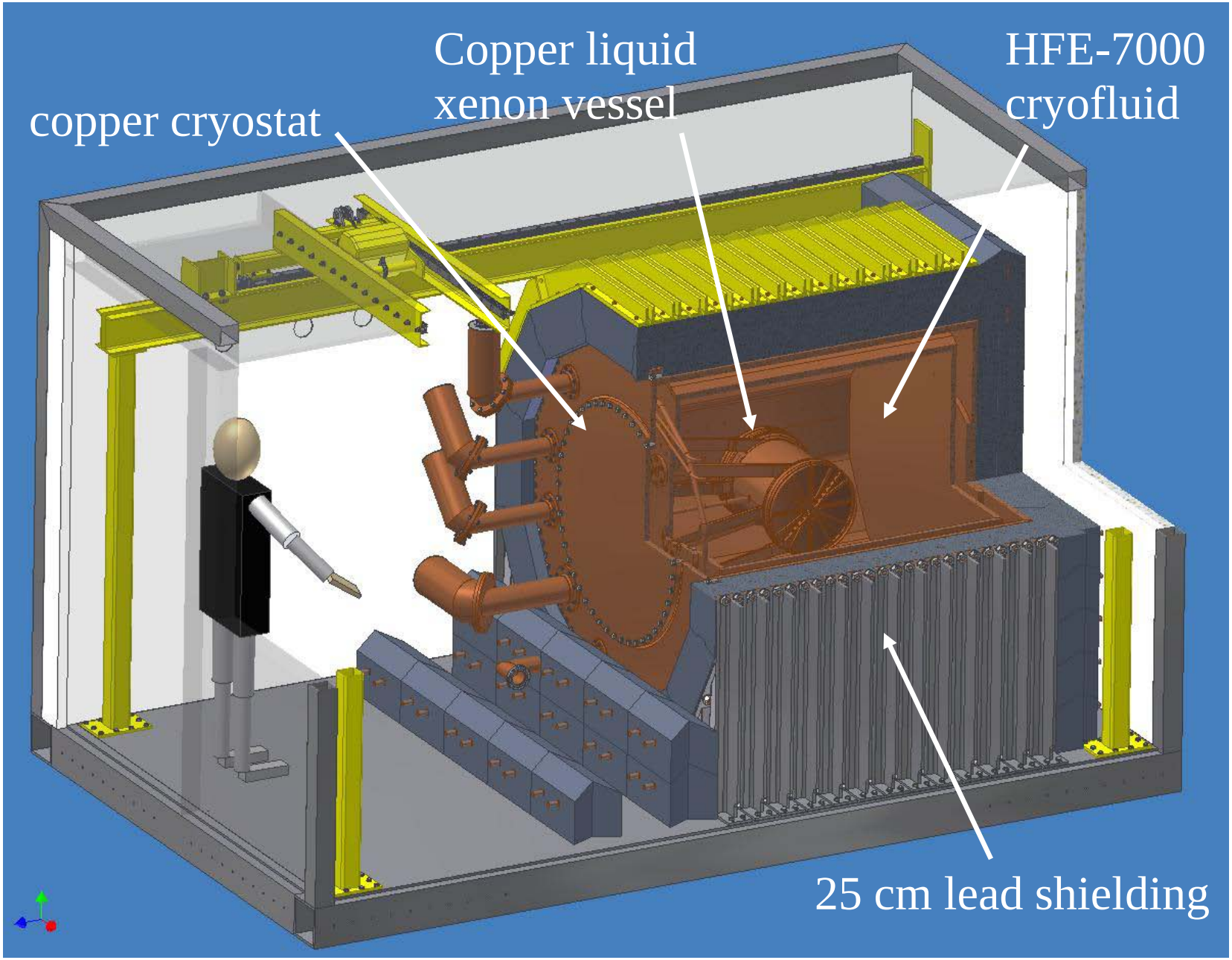
Factor of two better than most recent Xe experiment

The crown jewels of EXO

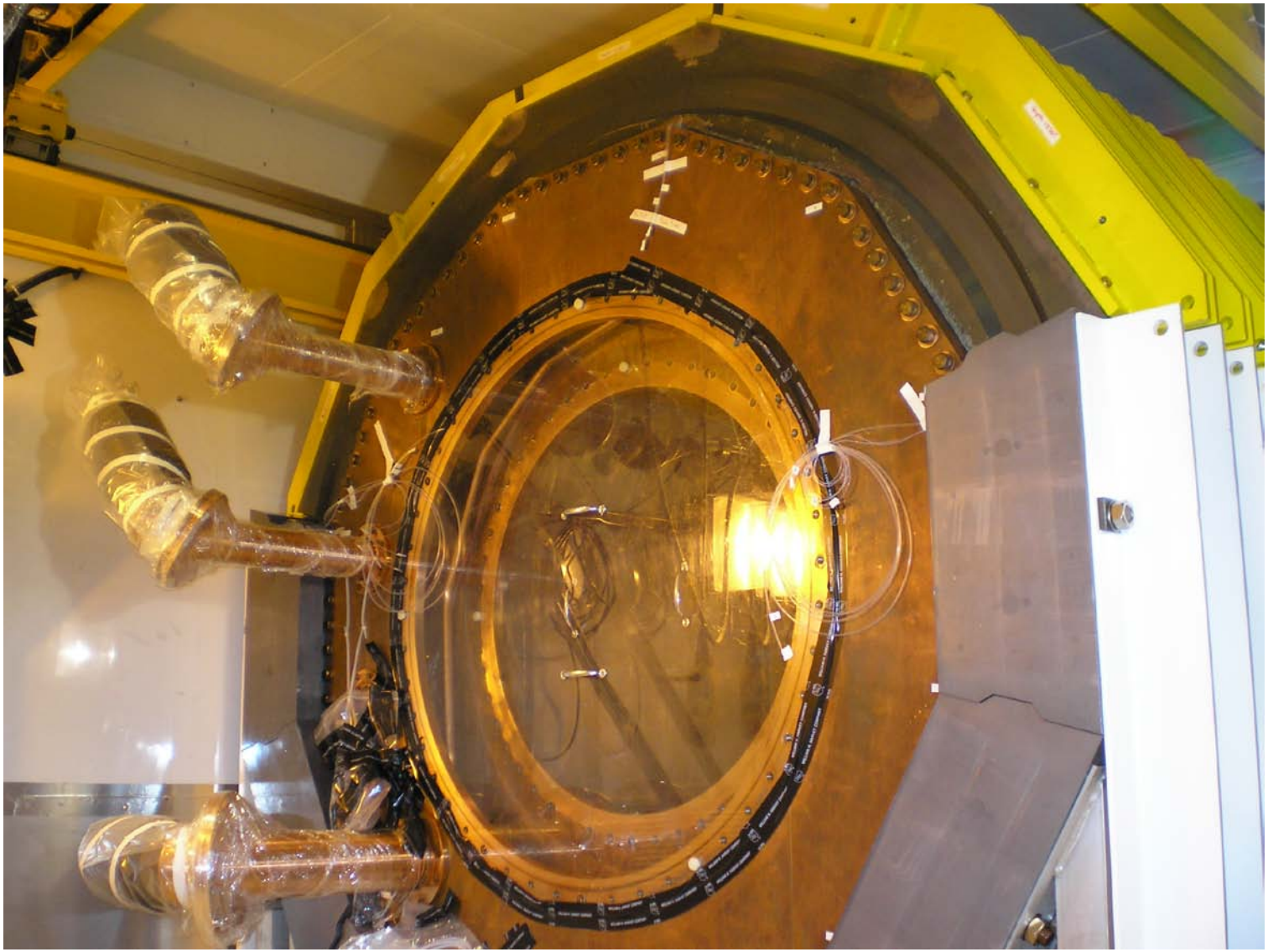
200 kg of xenon enriched to 80% in ^{136}Xe:

11 times larger than previous double beta decay experiments.

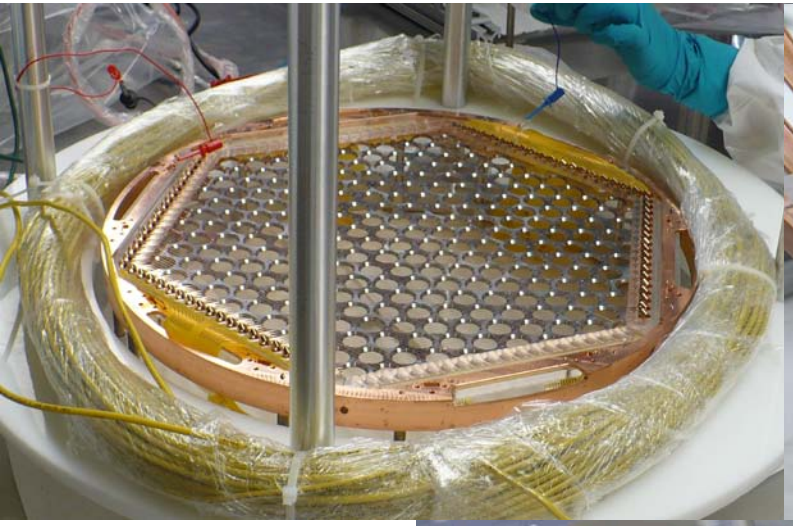
EXO-200: the first 200 kg ββ0ν experiment

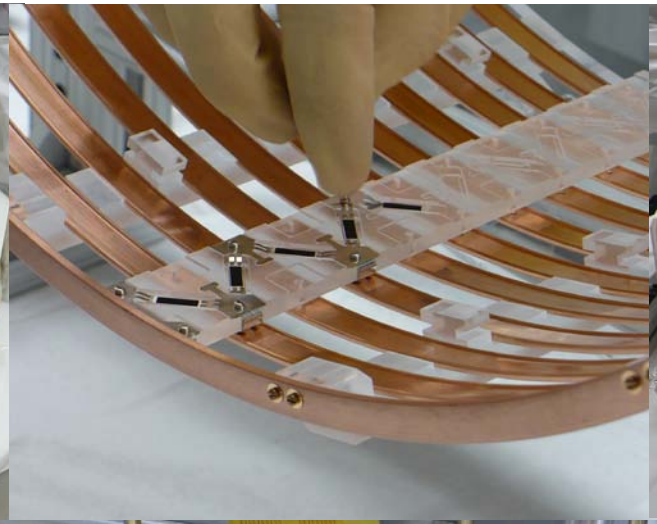


EXO-200 Cryostat & Lead (March 2008)

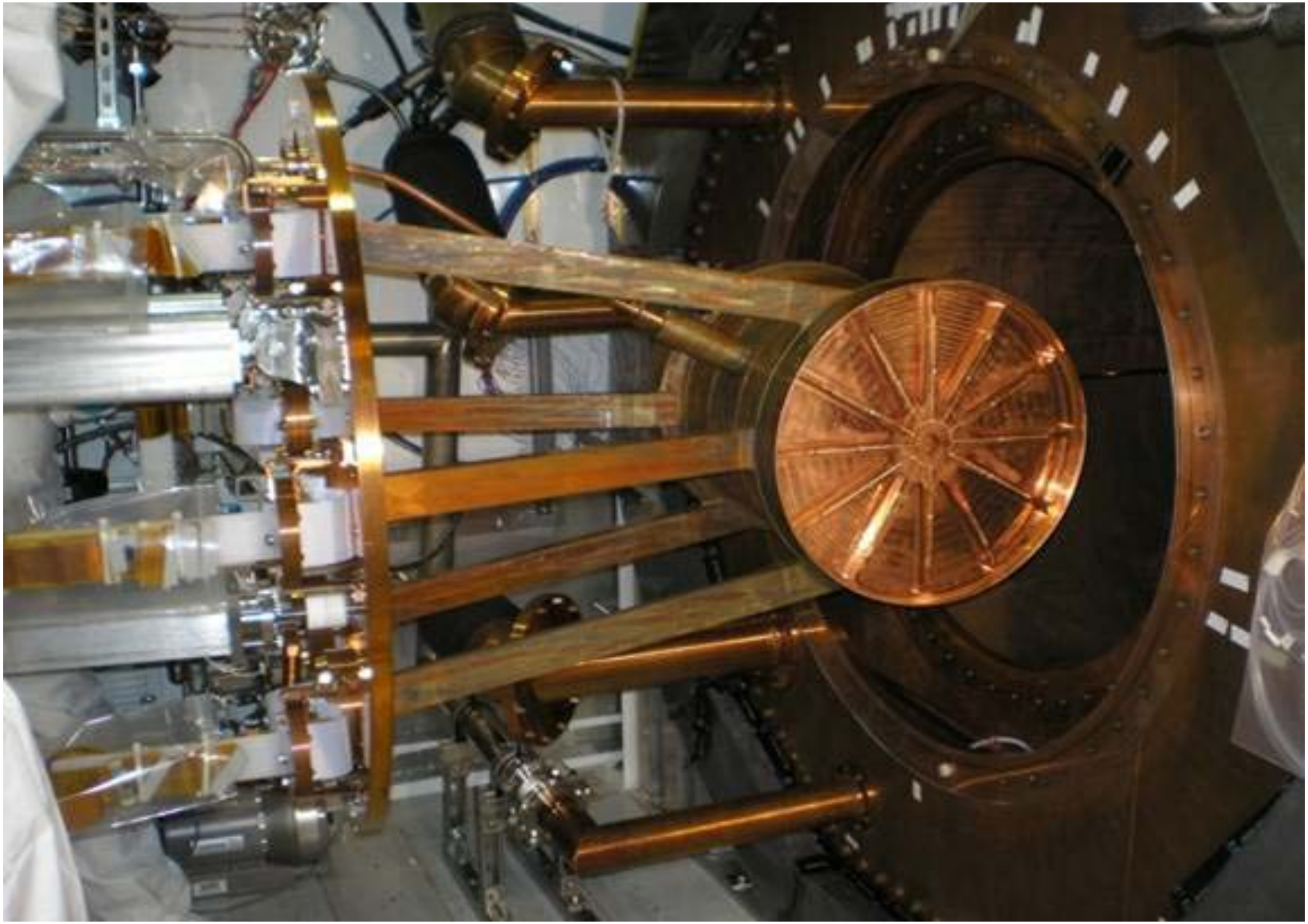


EXO-200 TPC Construction

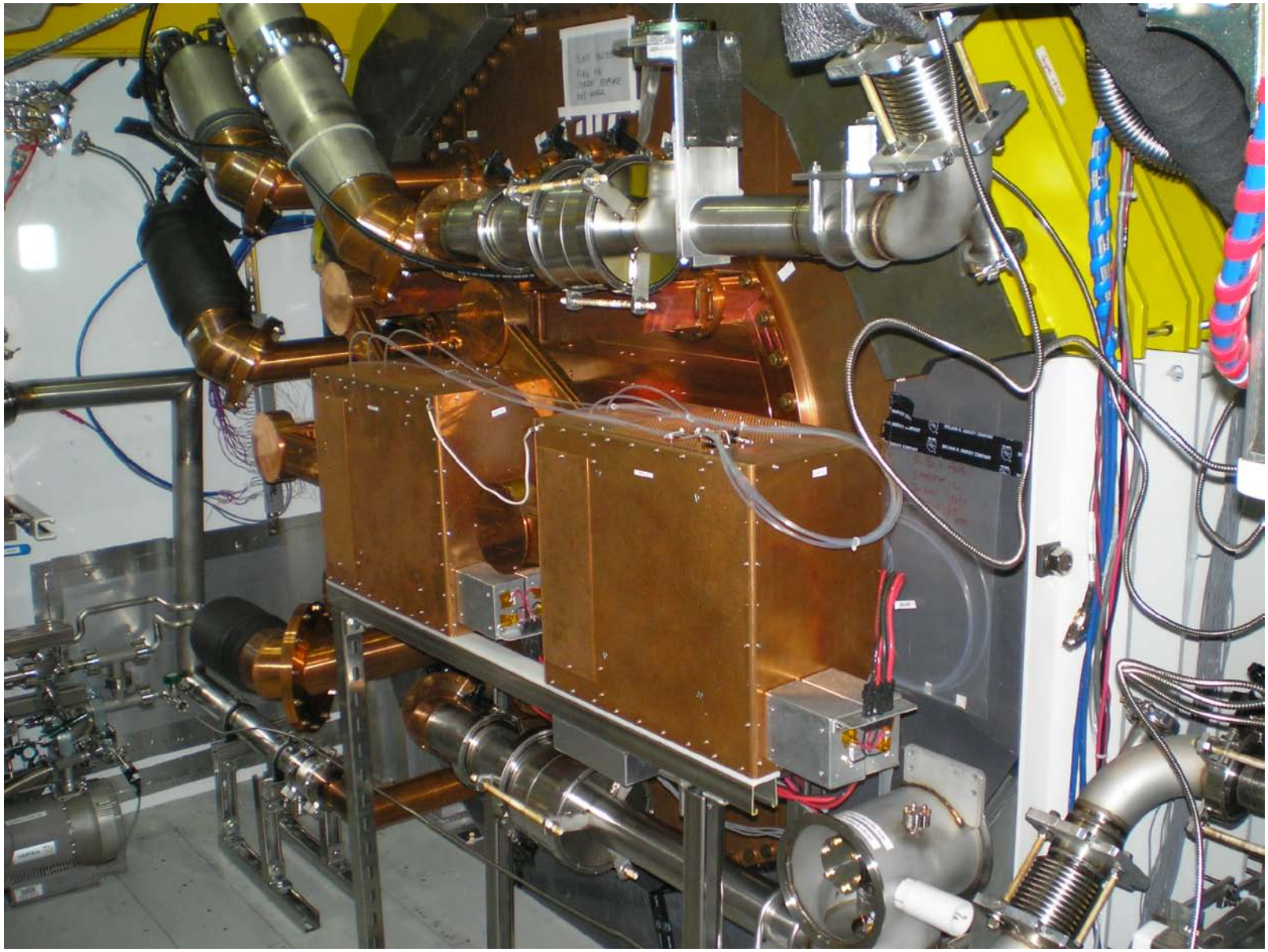




EXO-200 – Final TPC installation in January 2010



EXO-200: First data expected in September



Sensitivity of EXO-200

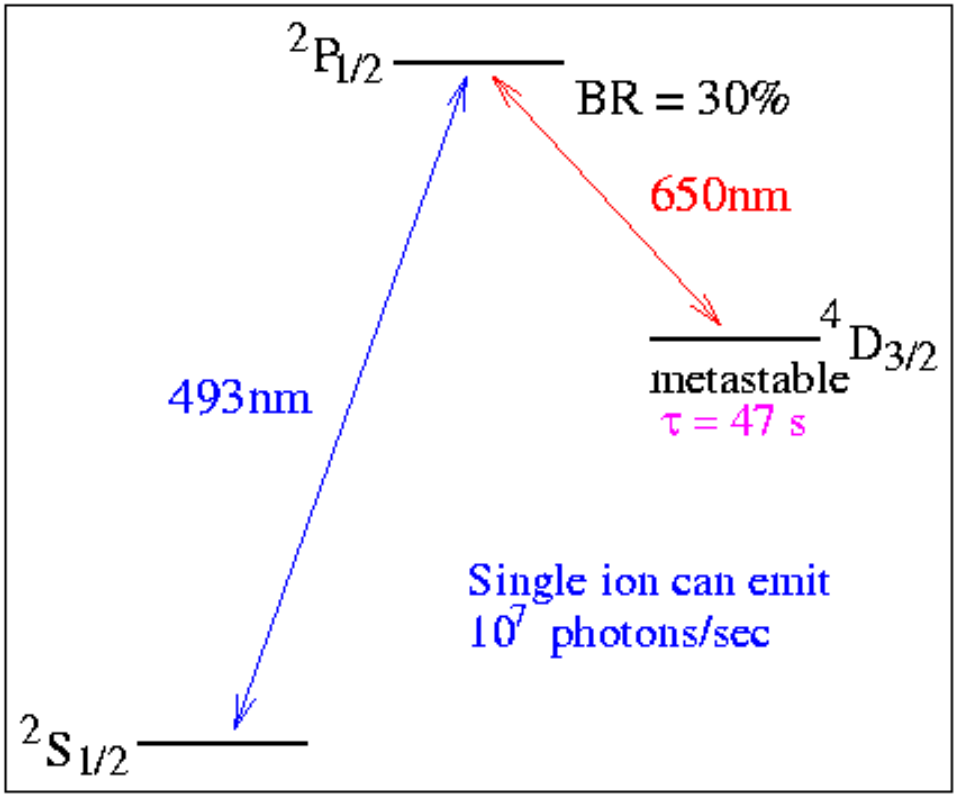
Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV)	
							QRPA[1]	NSM[2]
EXO-200	0.2	70	2	1.6*	40	$6.4*10^{25}$	109	135

1) Simkovic et al. Phys. Rev. C**79**, 055501(2009) (use RQRPA and g_A= 1.25)
2) Menendez et al., Nucl. Phys. A**818**, 139(2009), (use UCOM results)

Xe offers a new tool to reduce background:

$^{136}Xe \rightarrow {}^{136}Ba^{++}$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)

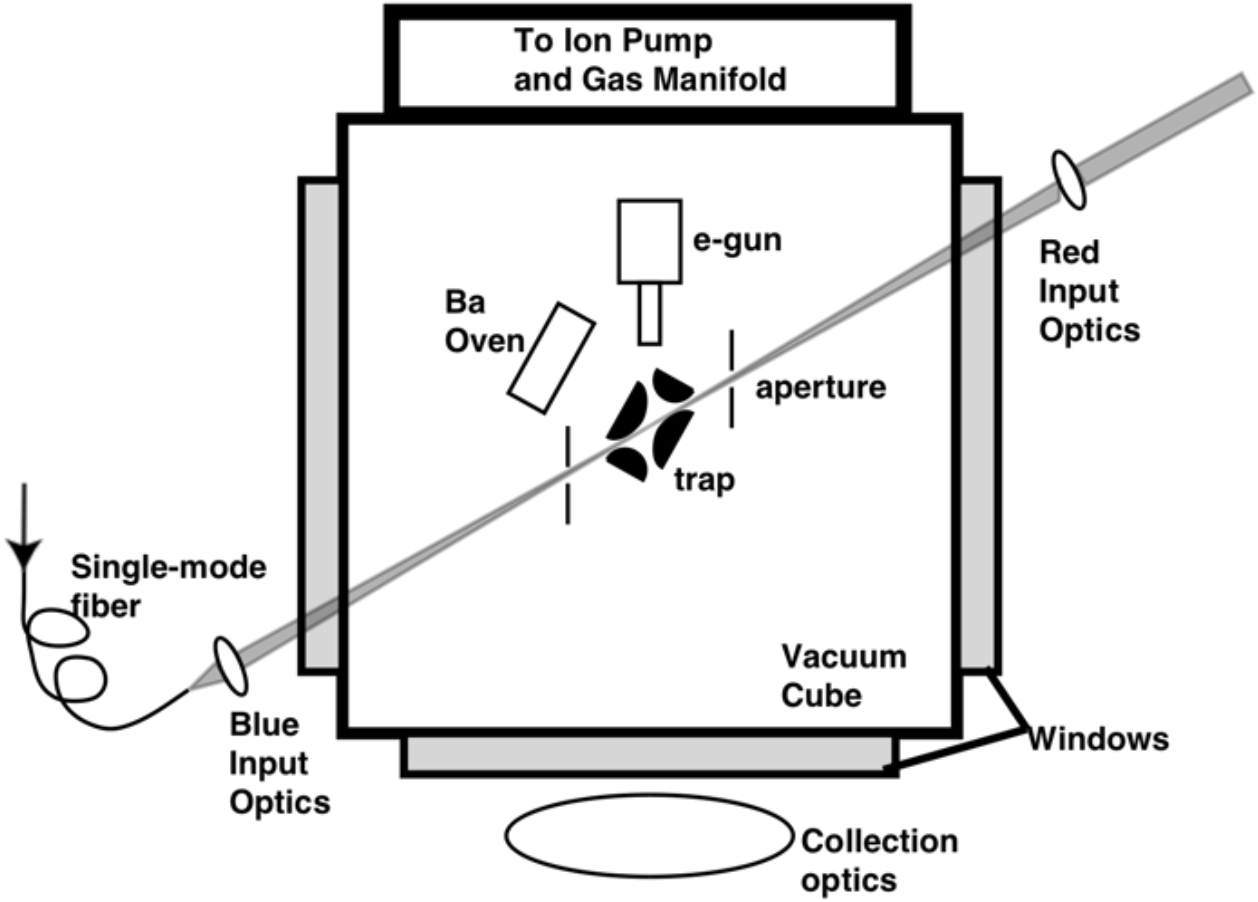
Ba^{+} system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)
Very specific signature "shelving"
Single ions can be detected from a photon rate of 10^{7}/s



Level structure for Ba^{+}

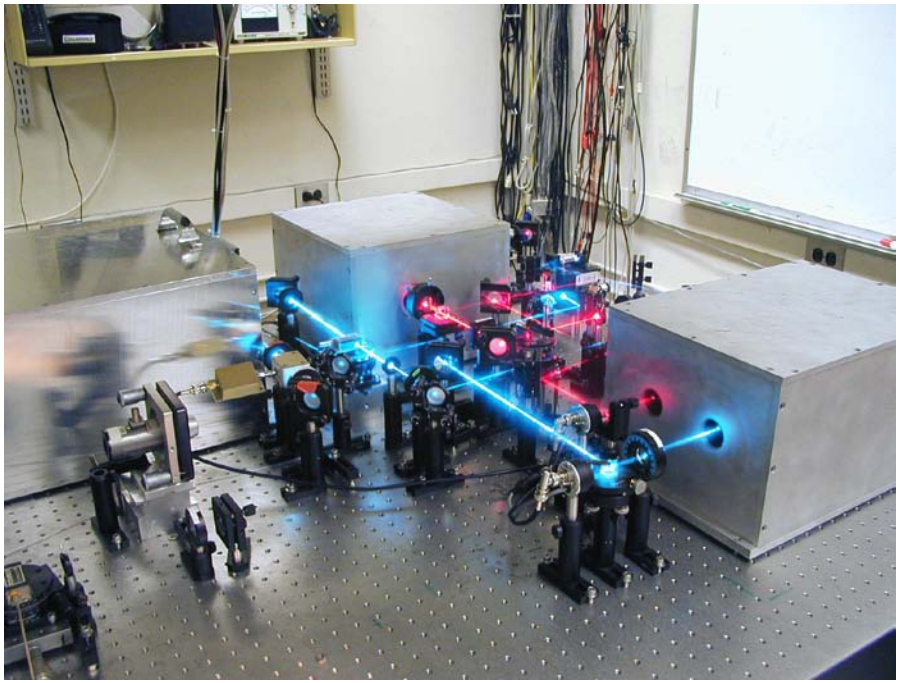
Barium tagging would eliminate all radioactive backgrounds, leaving only 2νββ.

EXO Ba+ trapping Experiment



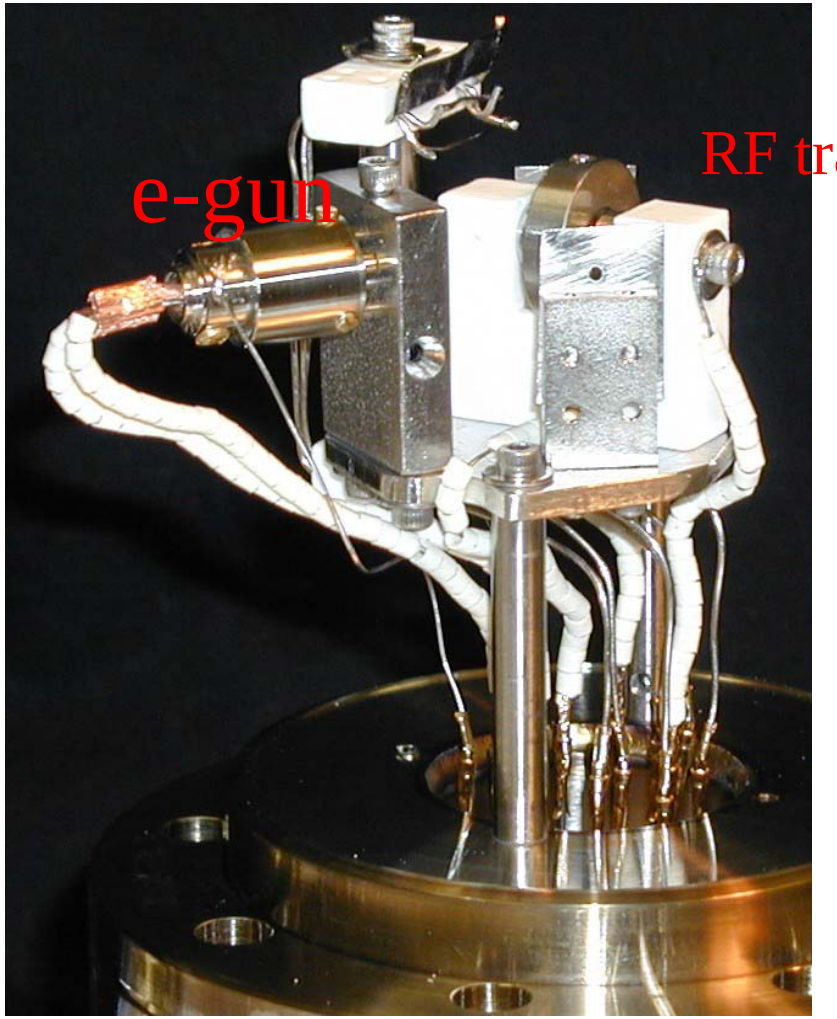
RF quadrupole trap loaded in UHV from a Ba dispenser and e-beam ionizer.
Xe can be injected while observing the ions at pressures from 10^{-10} torr to 0.1 torr=

EXO spectroscopy lab



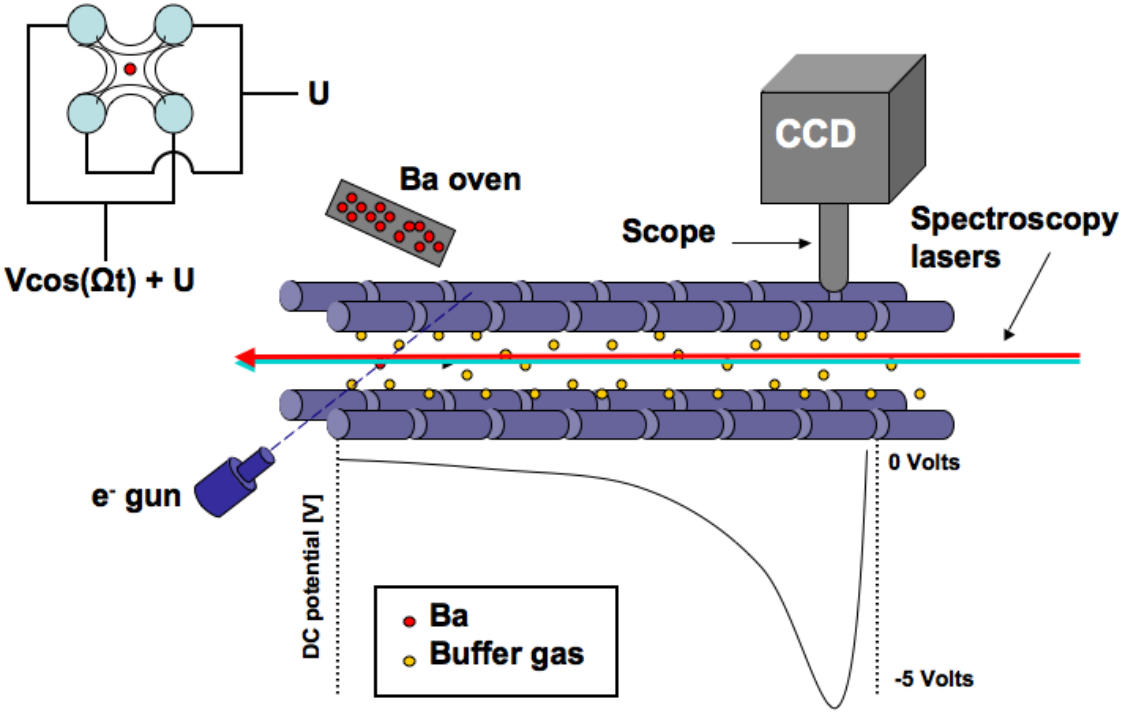
650 nm: External Cavity Diode Laser (ECDL)

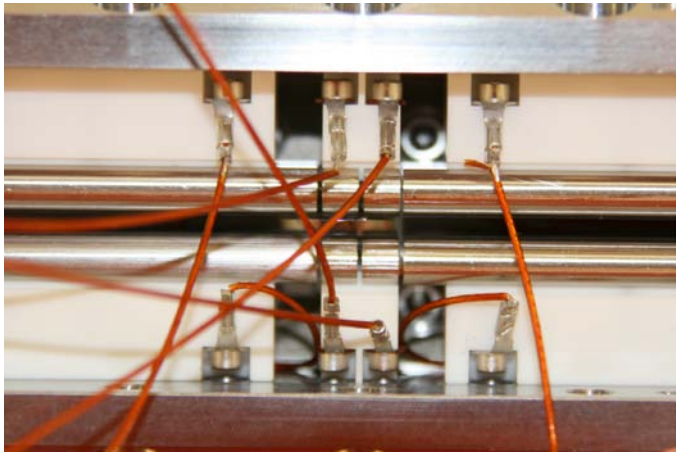
493 nm: Frequency doubled 986 nm

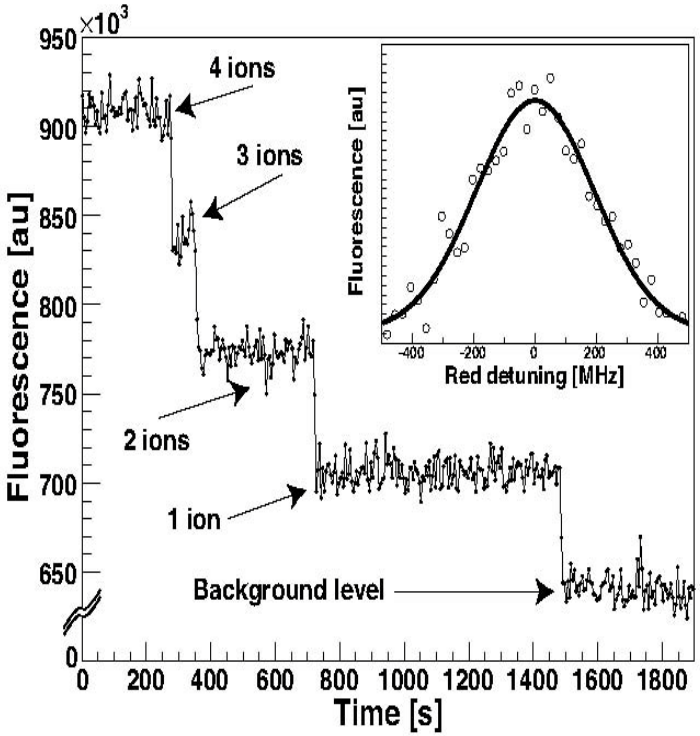


Ba^+ Tagging: Ion Trap + fluorescence

QuickTime™ and a decompressor are needed to see this picture.







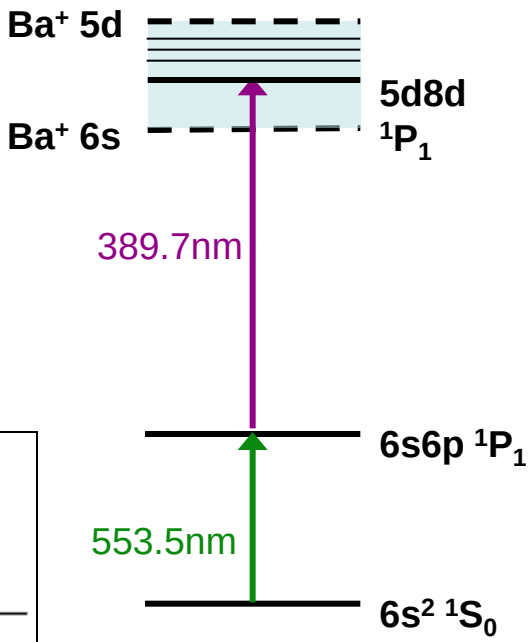
~9σ discrimination in 5s integration

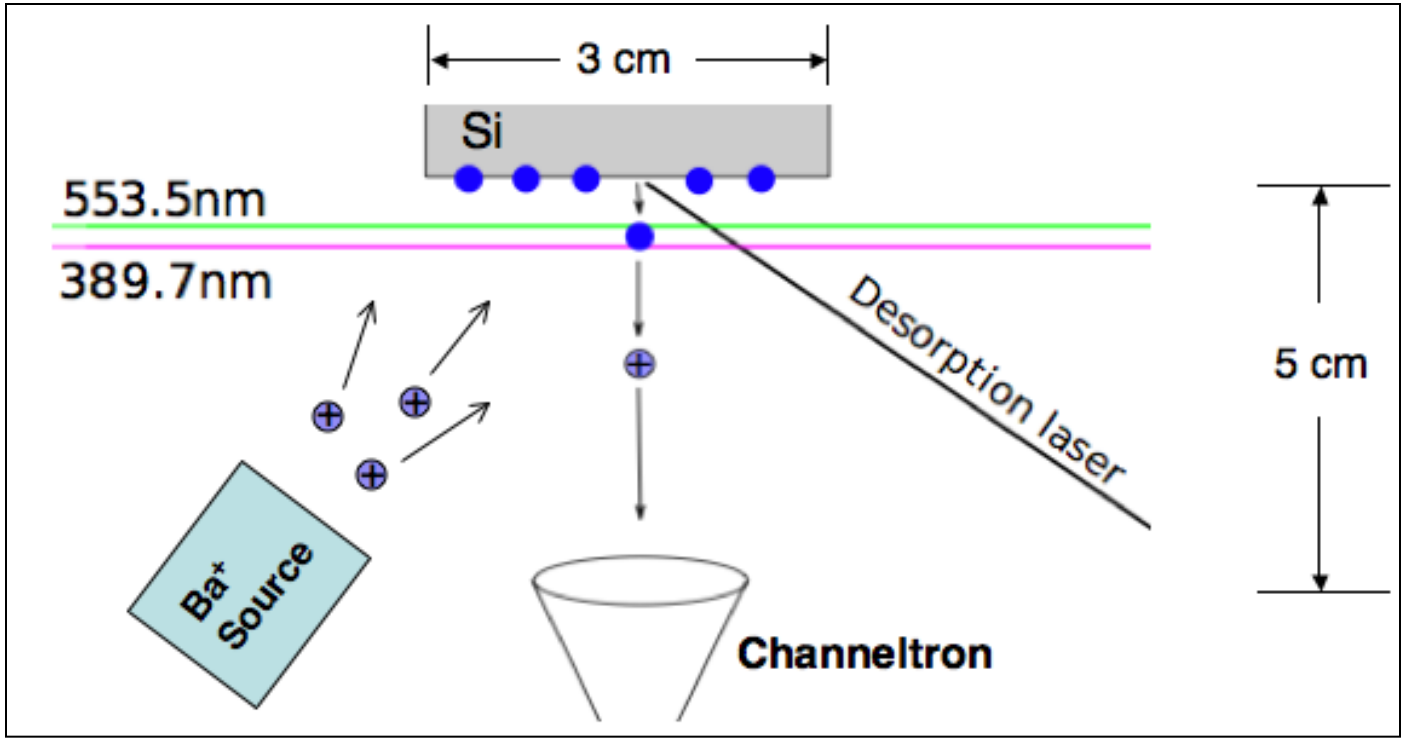
M.Green et al., *Phys Rev* A**76** (2007) 023404
B.Flatt et al., *NIM* A**578** (2007) 409

Ba^+ Tagging: RIS

QuickTime™ and a decompressor are needed to see this picture.

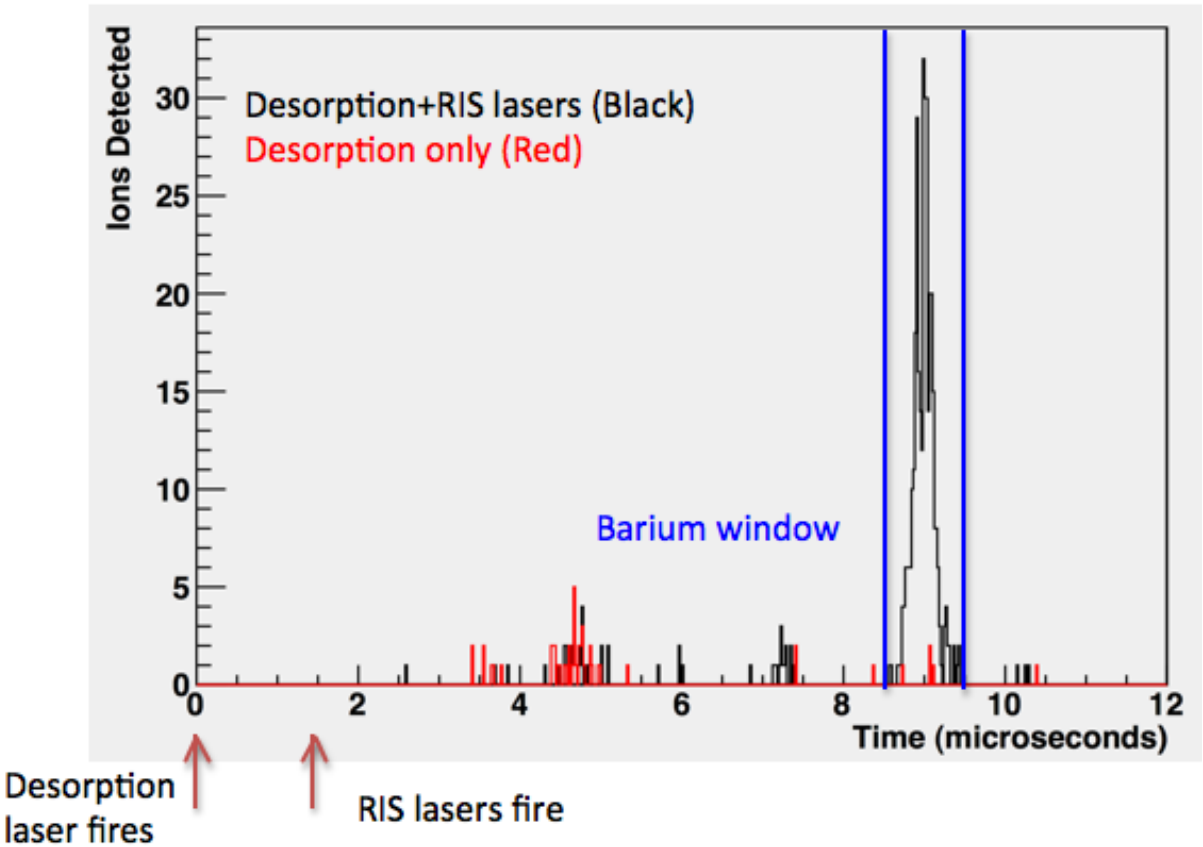
- Resonant Ionization Spectroscopy uses lasers tuned to atomic resonances to first *excite* and then *ionize* specific atoms.
- We use pulsed dye lasers at 553.5 nm and 389.7 nm.
- Autoionization: The 5d8d $^1P_1$ state decays to a lower energy ionized state, allowing use of the high cross section of the resonance to achieve ionization.

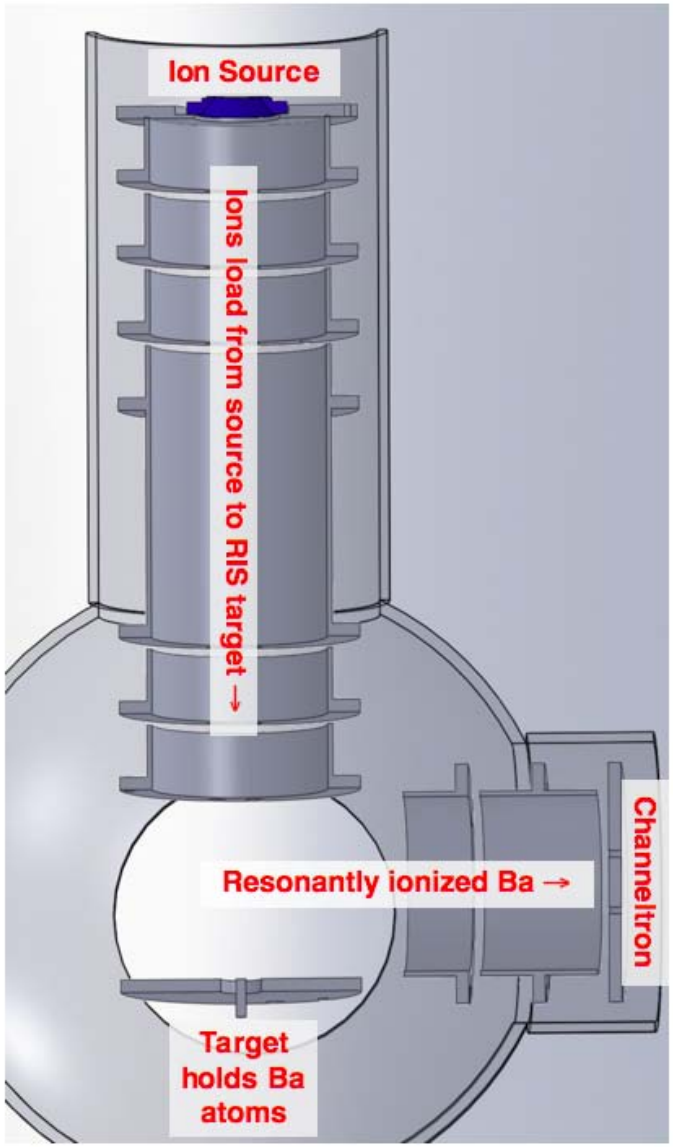




Ba^+ Tagging: RIS

QuickTime™ and a decompressor are needed to see this picture.





Efficiency of ~10^{-3} in "bulk mode" setup. New "single ion mode" setup about to start taking data.

Sensitivity of ton-scale EXO with barium tagging

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA[1]	NSM[2]
Conservative	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	19	24
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	4.3	5.3

1) Simkovic et al. Phys. Rev. C**79**, 055501(2009)
2) Menendez et al., Nucl. Phys. A**818**, 139(2009)

What to expect in the next decade

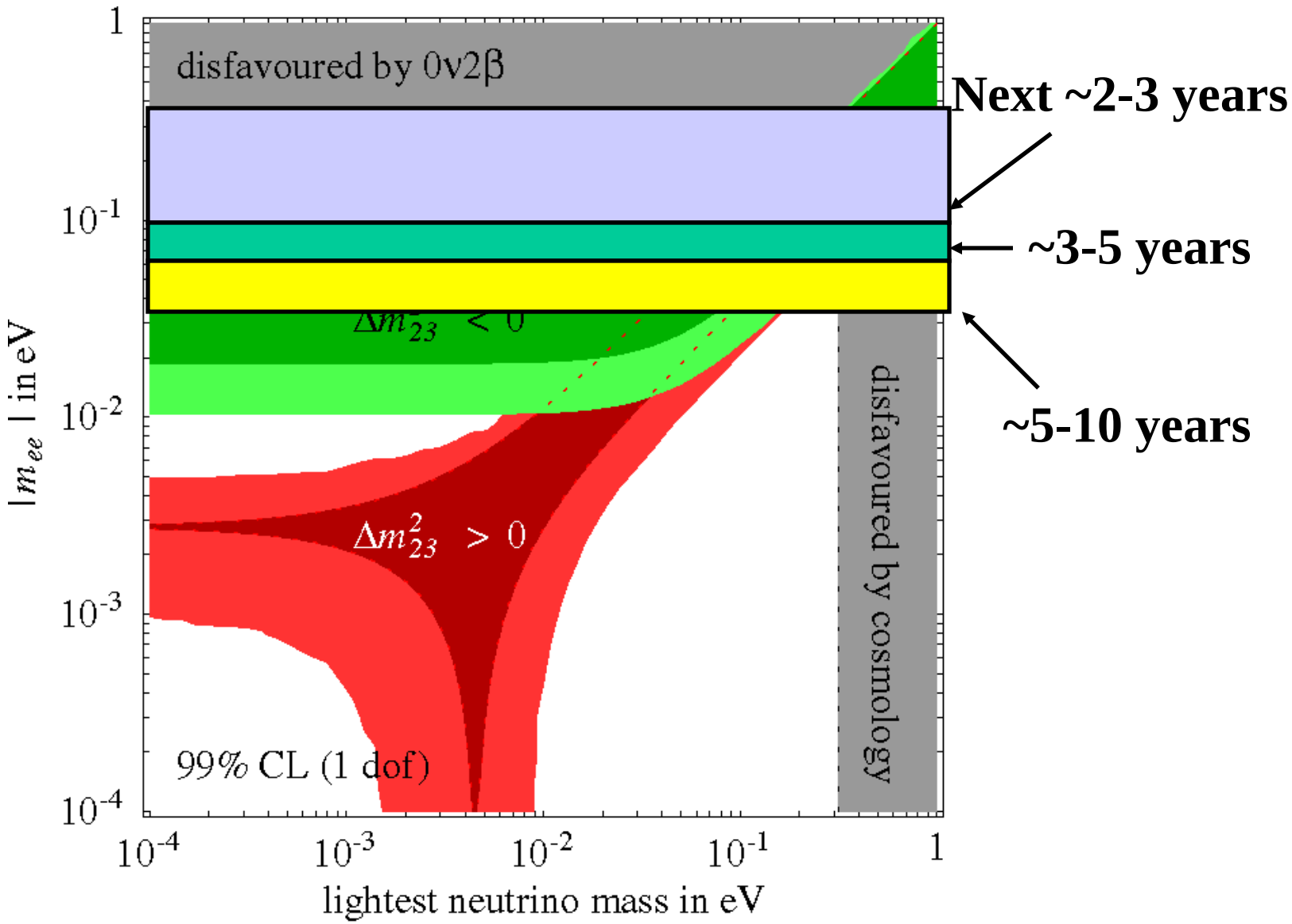


Figure from Strumia & Vissani, Nucl. Phys. B **726** 294 (2005)