Strategies for Next Generation Neutrinoless Double-Beta Decay Experiments

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General Theme

- I will not discuss the details of individual experiments.
- I will discuss the important parameters and how they impact the experimental techniques.
- The Parameters of interest are: $G^{0\nu}$, $\mathcal{M}^{0\nu}$, $\epsilon \equiv$ detection efficiency, Mass, Isotopic abundance, $b \equiv$ background rate, and $\delta E \equiv$ energy resolution.

Parameters of $T_{1/2}^{0\nu}$ Sensitivity

$$T_{1/2}^{0\nu} \simeq \frac{ln2Nt\epsilon}{\gamma\sqrt{bMt\,\delta E}}$$

$$T_{1/2}^{0\nu} \simeq \frac{ln2(A_0/W)\times 10^3(Mat\epsilon)}{\gamma\sqrt{bMt\,\delta E}}$$

$$T_{1/2}^{0\nu} \propto \frac{a\epsilon}{W}\sqrt{\frac{Mt}{b\,\delta E}}$$

$a \equiv isotopic\,abundance$

$b \equiv background\,rate\,in\,c/(keV \cdot kg \cdot y)$

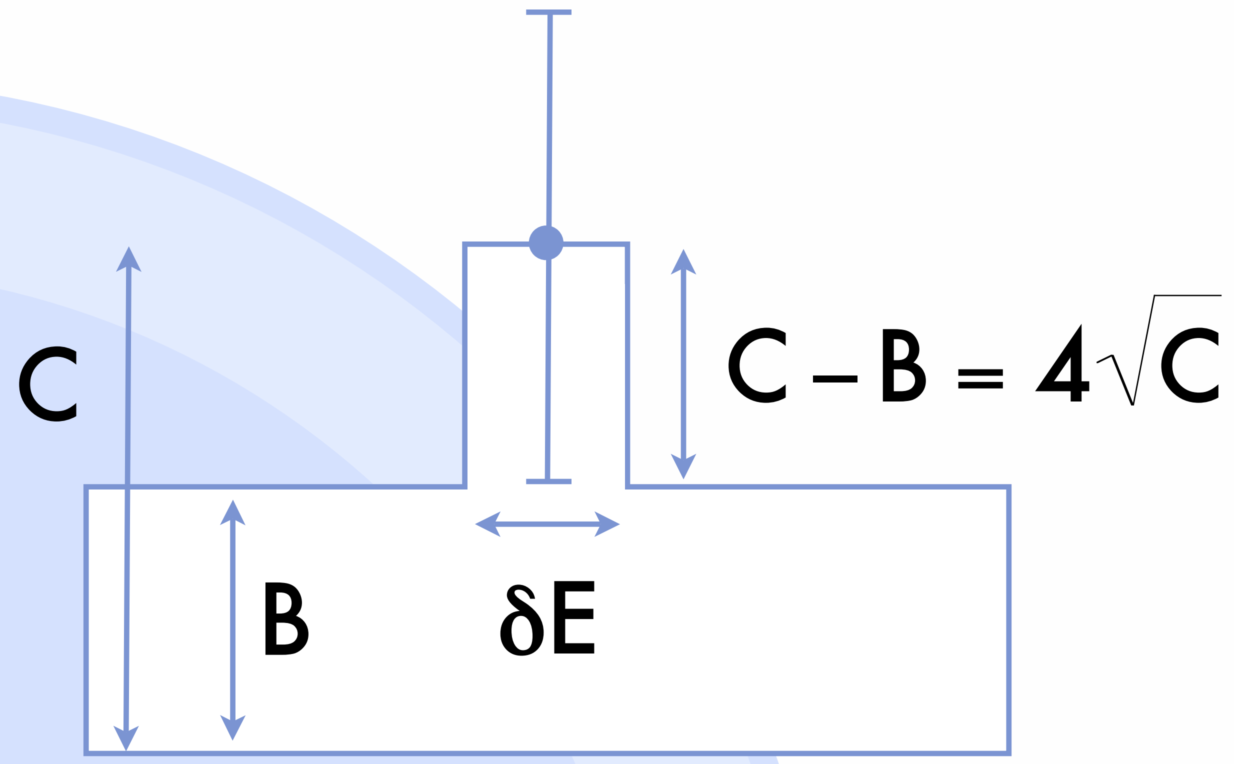
$M \equiv source\,mass$

$\delta E \propto energy\,resolution$

$\epsilon \equiv detection\,efficiency$

$W \equiv molecular\,weight$

Detection with a 4σ CL



$$T^{0\nu}_{1/2} \simeq 4.74 \times 10^{25} \frac{a\epsilon}{W} \sqrt{\frac{Mt}{b\,\delta E}}\ y$$

$a \equiv isotopic\ abundance$

$b \equiv background\ rate\ in\ c/(keV \cdot kg \cdot y)$

$M \equiv source\ mass$

$\delta E \propto energy\ resolution$

$\epsilon \equiv detection\ efficiency$

$W \equiv molecular\ weight$

Neutrinoless Double-Beta Decay

Experimental Figure of Merit

$$f \equiv \frac{\overline{\eta} a \epsilon}{W} \sqrt{\frac{M}{b \delta E}}$$

$$\eta \equiv G^{0\nu} |\mathcal{M}^{0\nu}|^2 \times 10^{13} = F_N \times 10^{13}$$

$$\overline{\eta} \equiv \langle \eta \rangle_{nuclear\ models}$$

Available Experimental Techniques

- Cryogenic Bolometry
- Ionization Detectors
- Scintillation Detectors
- Time Projection Chambers
- Tracking Chambers

Available Enriched Isotopes

- ^{48}Ca - AVLIS† (USA)
- ^{76}Ge - Centrifuge (Russia)
- ^{82}Se - Centrifuge (Russia)
- ^{100}Mo - Centrifuge (Russia) & AVLIS† (USA)
- ^{116}Cd - Centrifuge (Russia) & AVLIS† (USA)
- ^{130}Te - Centrifuge (Russia)
- ^{136}Xe - Centrifuge (Russia)
- ^{150}Nd - AVLIS† (USA)

† Technology available at LLNL. No known production program.

Average Theoretical Nuclear Structure Factors

Parent Isotope	$\langle F_N \rangle \equiv \left\langle G^{0\nu} \left| M^{0\nu} \right|^2 \right\rangle \; y^{-1}$
^{48}Ca	$(5.4^{+3.0}_{-1.4}) \times 10^{-14}$
^{76}Ge	$(7.3 \pm 0.6) \times 10^{-14}$
^{82}Se	$(1.7^{+0.4}_{-0.3}) \times 10^{-13}$
^{100}Mo	$(1.0 \pm 0.3) \times 10^{-12}$
^{116}Cd	$(1.3^{+0.7}_{-0.3}) \times 10^{-13}$
^{130}Te	$(4.2 \pm 0.5) \times 10^{-13}$
^{136}Xe	$(2.8 \pm 0.4) \times 10^{-14}$
^{150}Nd	$(5.7^{+1.0}_{-0.7}) \times 10^{-12}$

Table of Values of $\overline{\eta}$

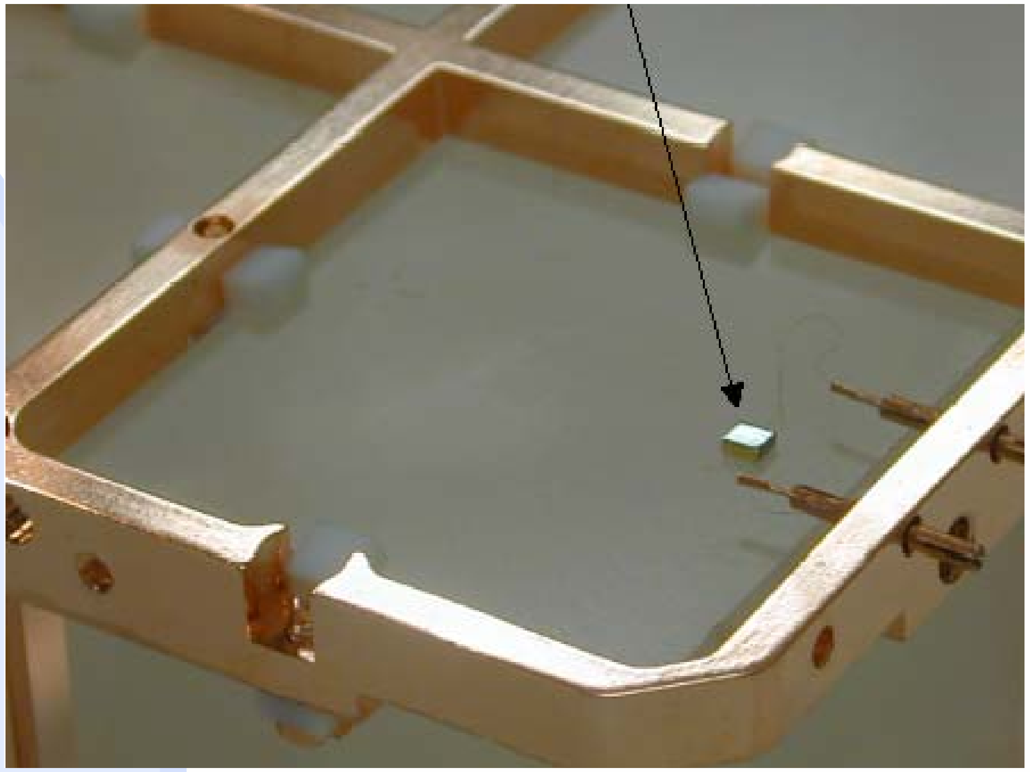
$$\overline{\eta} \equiv \langle G^{0\nu} |\mathcal{M}^{0\nu}|^2 \rangle \times 10^{13}$$

Isotope	$\overline{\eta}$
^{48}Ca	0.54
^{76}Ge	0.73
^{82}Se	1.70
^{100}Mo	10.0
^{116}Cd	1.30
^{130}Te	4.20
^{136}Xe	0.28
^{150}Nd	57.0

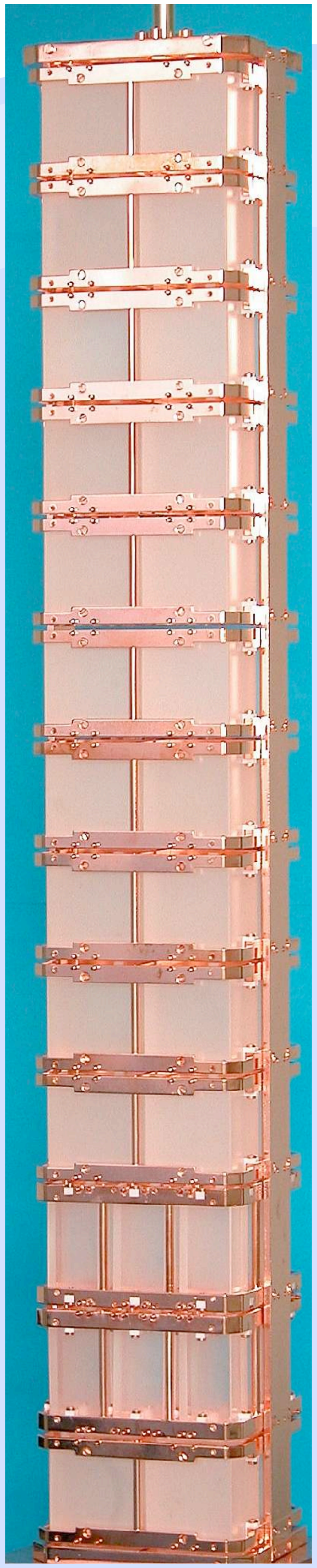
Cryogenic Detector

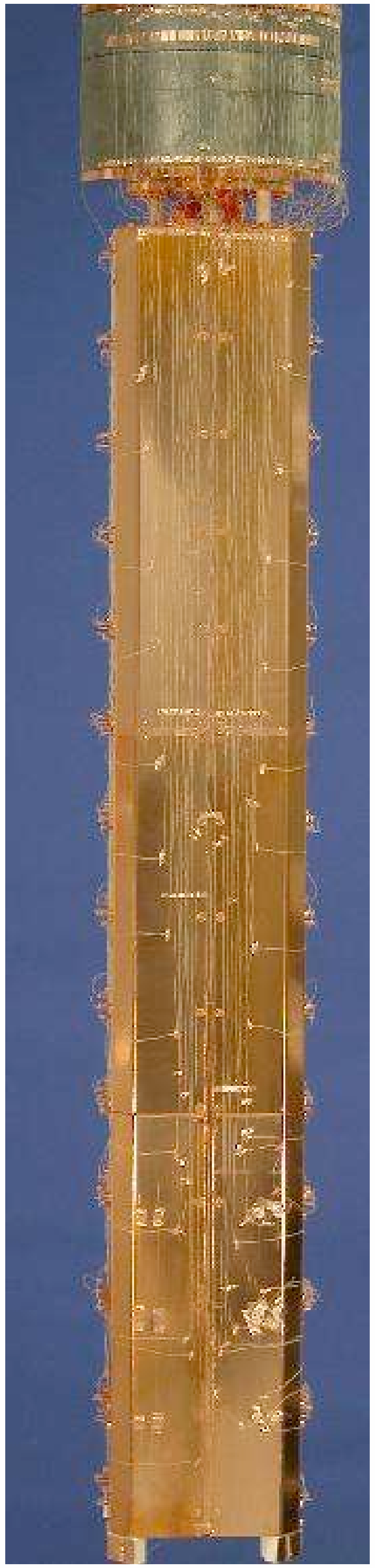
- CUORE/CUORICINO (Gran Sasso)
- 760 kg of TeO_2 (nat. abundance = 33.8%)
- 1000 bolometers at ~ 8 mK
- 25 Towers of 40 bolometers per tower
- CUORICINO ~ 1 tower, operated 03/04
  $T_{1/2}^{0\nu} \geq 7.5\text{x}10^{23}\,y$

CUORICINO



CUORICINO





Ionization Detectors

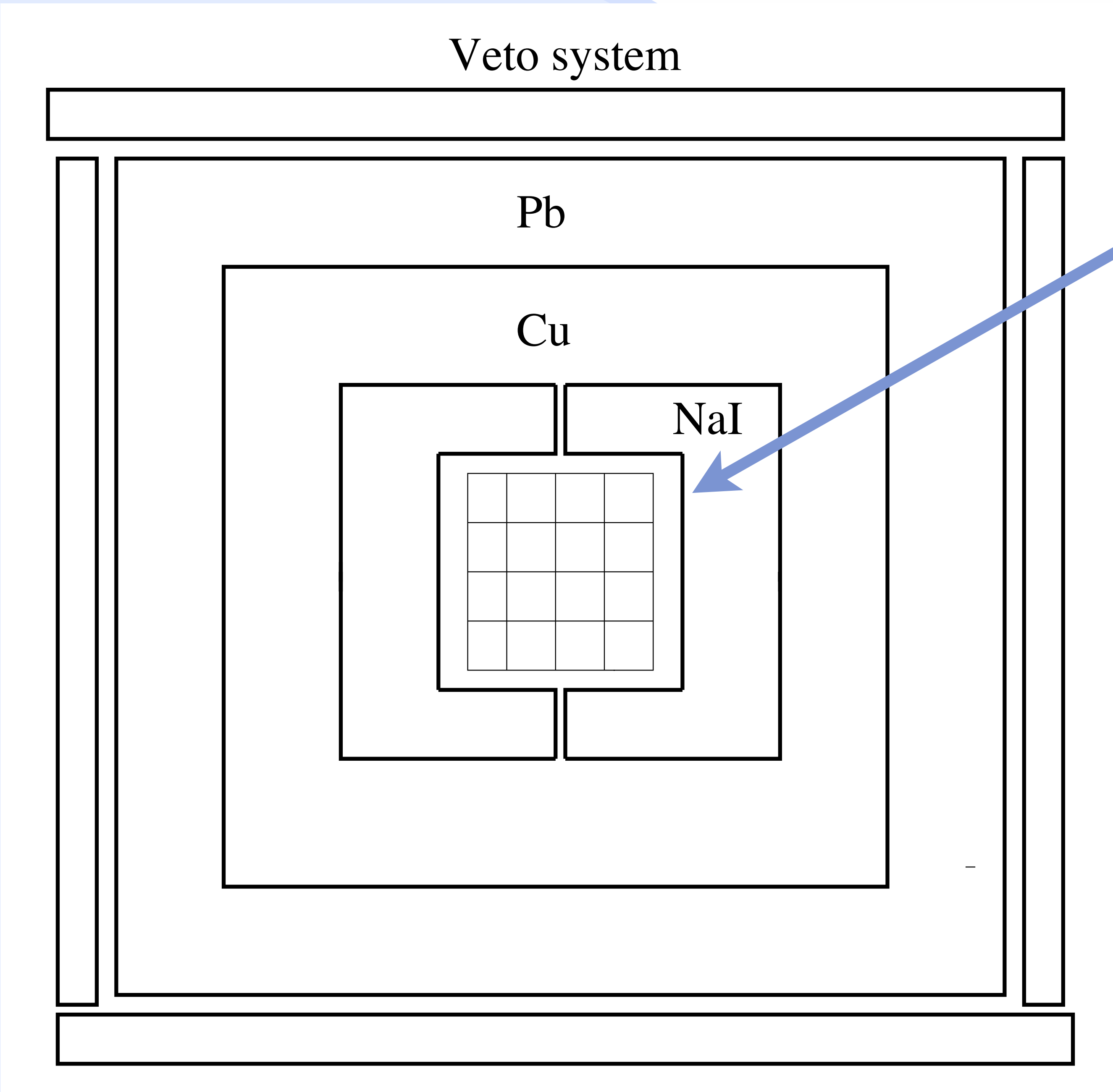
- COBRA - CdTe
- GEM - ^{76}Ge (Ge Crystals in LN)
- GENIUS - ^{76}Ge (Ge Crystals in LN)
- Majorana - ^{76}Ge (Ge Crystals in Cryostat)
- MPI - ^{76}Ge (Ge Crystals in LN)

COBRA

- 10 kg of CdTe (CdZnTe) Detectors
- Measure 7(9) double-beta isotopes at once
- Systematic studies of Cd and Te isotopes
- Rare beta decays of ^{113}Cd and ^{123}Te
- Dark matter search

Slide adapted from presentation of K. Zuber
at DESY Zeuthen, 19-21 June 2001

COBRA



CdTe - Array

1 ccm crystals

Option:

Pixel Detectors

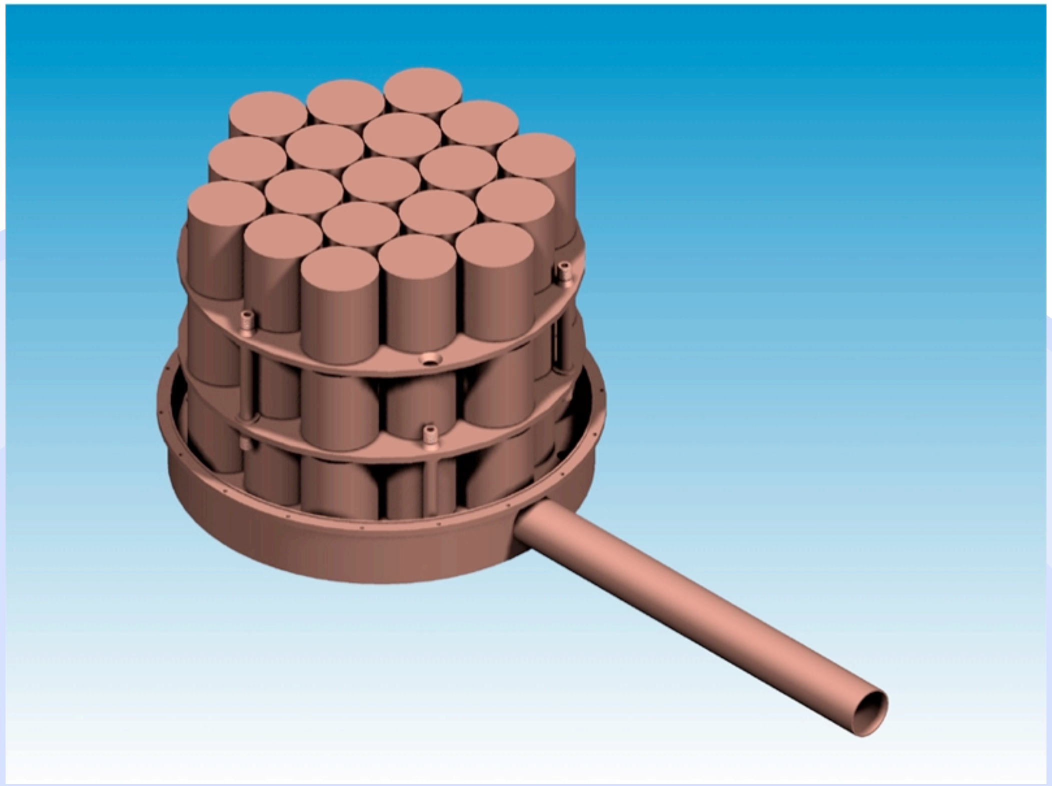
→ Tracking

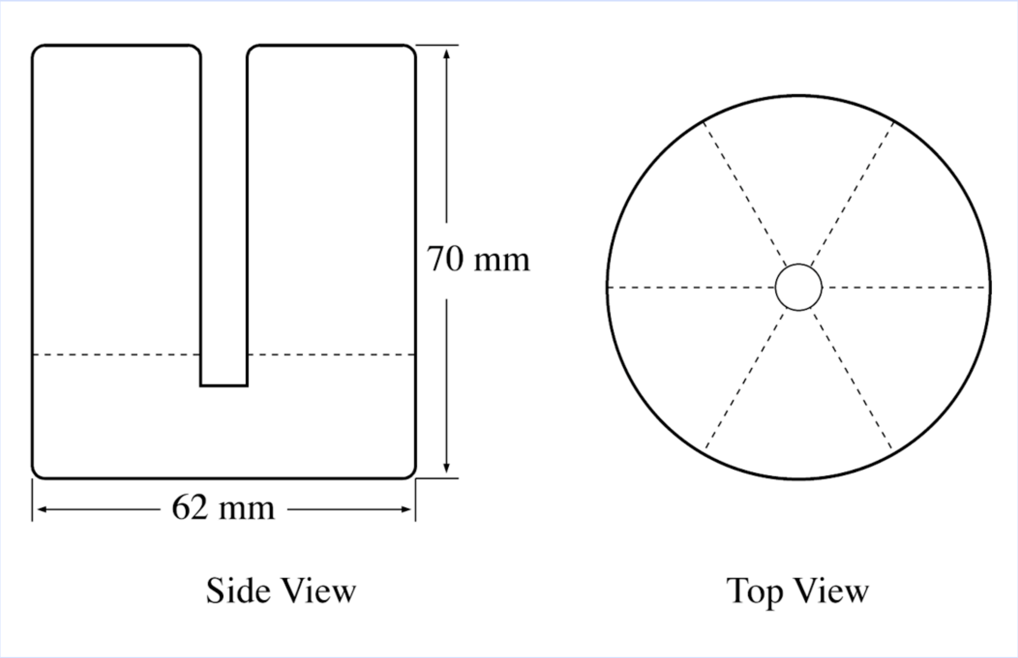
Slide adapted from presentation of K. Zuber at DESY Zeuthen, 19-21 June 2001

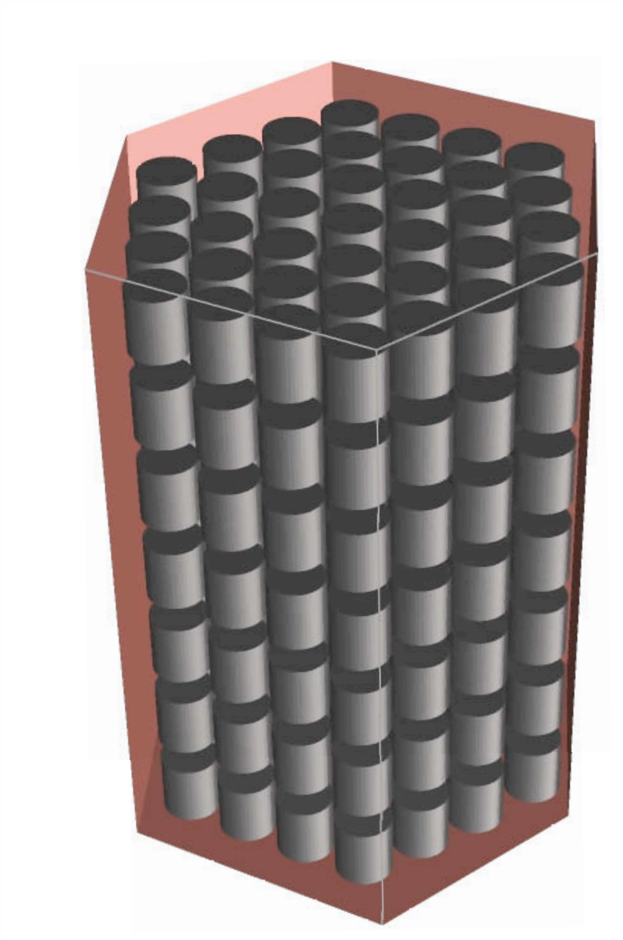
Majorana Proposal

- 500 kg of Ge (86% ^{76}Ge)
- Conventional Cryostat Technology
  - Could use GENIUS direct immersion in LN if feasible; cooperation with MPI
- Digital Electronics
- Pulse-Shape Discrimination

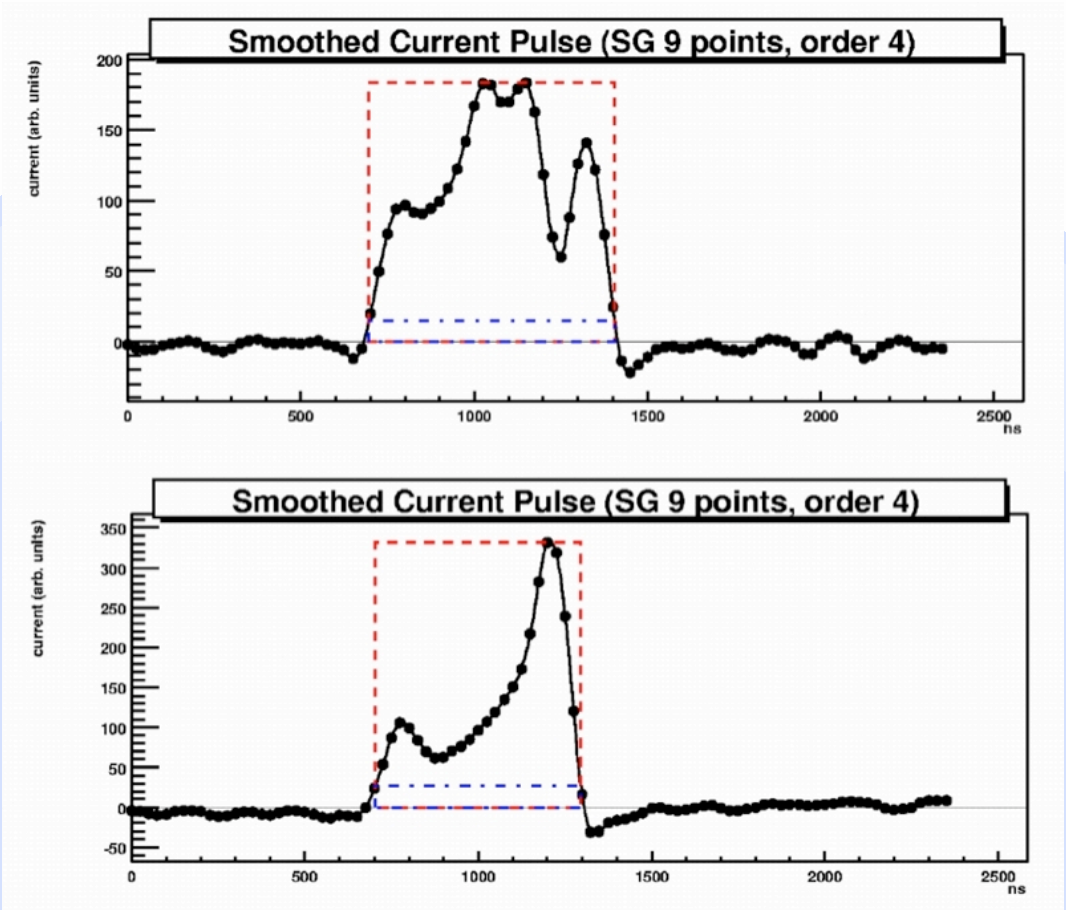
Majorana







Majorana



Smoothed Current Pulse (SG 9 points, order 4)
current (arb. units)
ns
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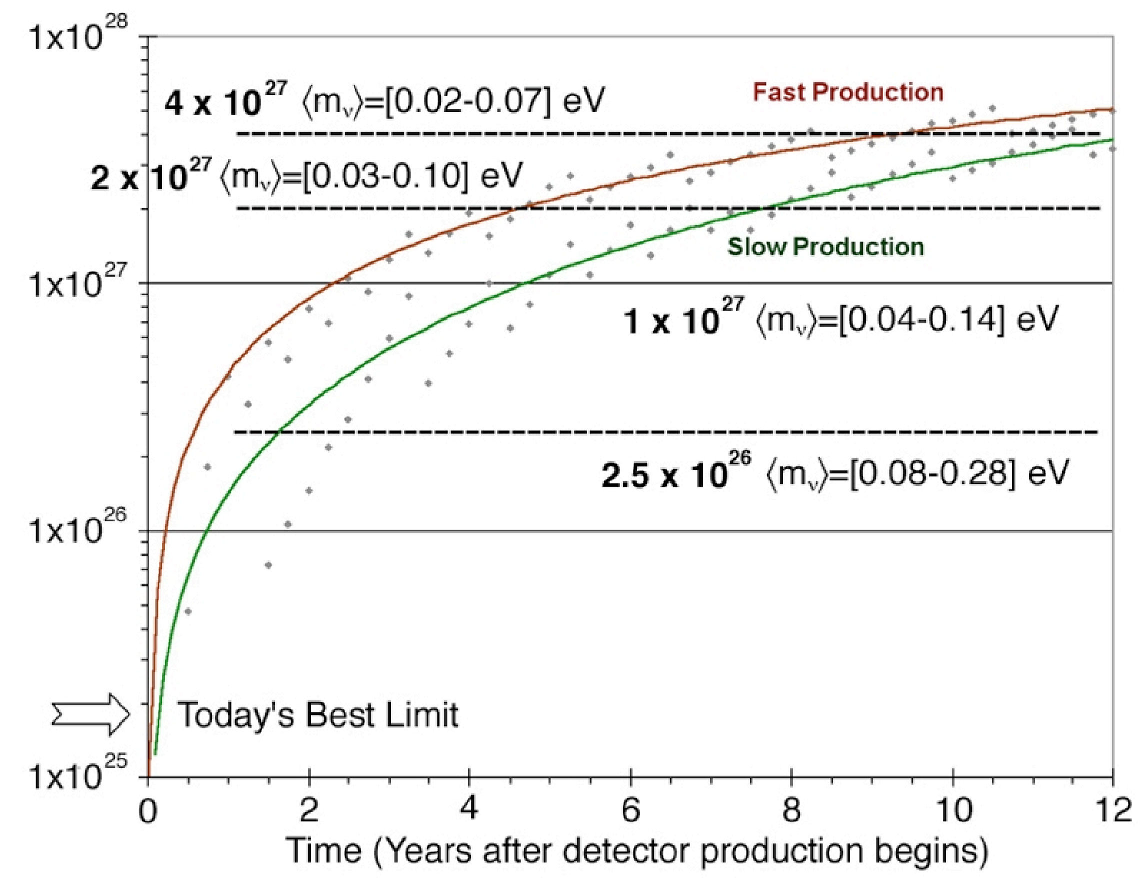
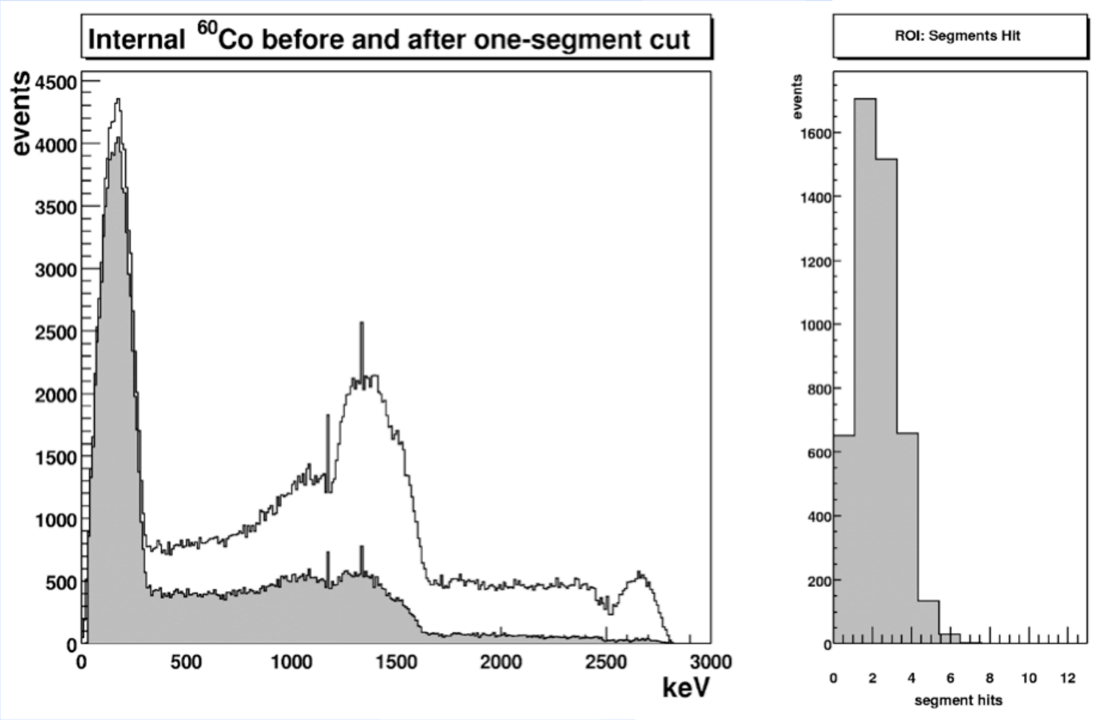
current (arb. units)
ns



4 x 10^27 ⟨m_ν⟩=[0.02-0.07] eV
Fast Production
2 x 10^27 ⟨m_ν⟩=[0.03-0.10] eV
Slow Production
1 x 10^27 ⟨m_ν⟩=[0.04-0.14] eV
2.5 x 10^26 ⟨m_ν⟩=[0.08-0.28] eV
Today's Best Limit
Time (Years after detector production begins)



Internal 60Co before and after one-segment cut
events
keV
ROI: Segments Hit
events
segment hits

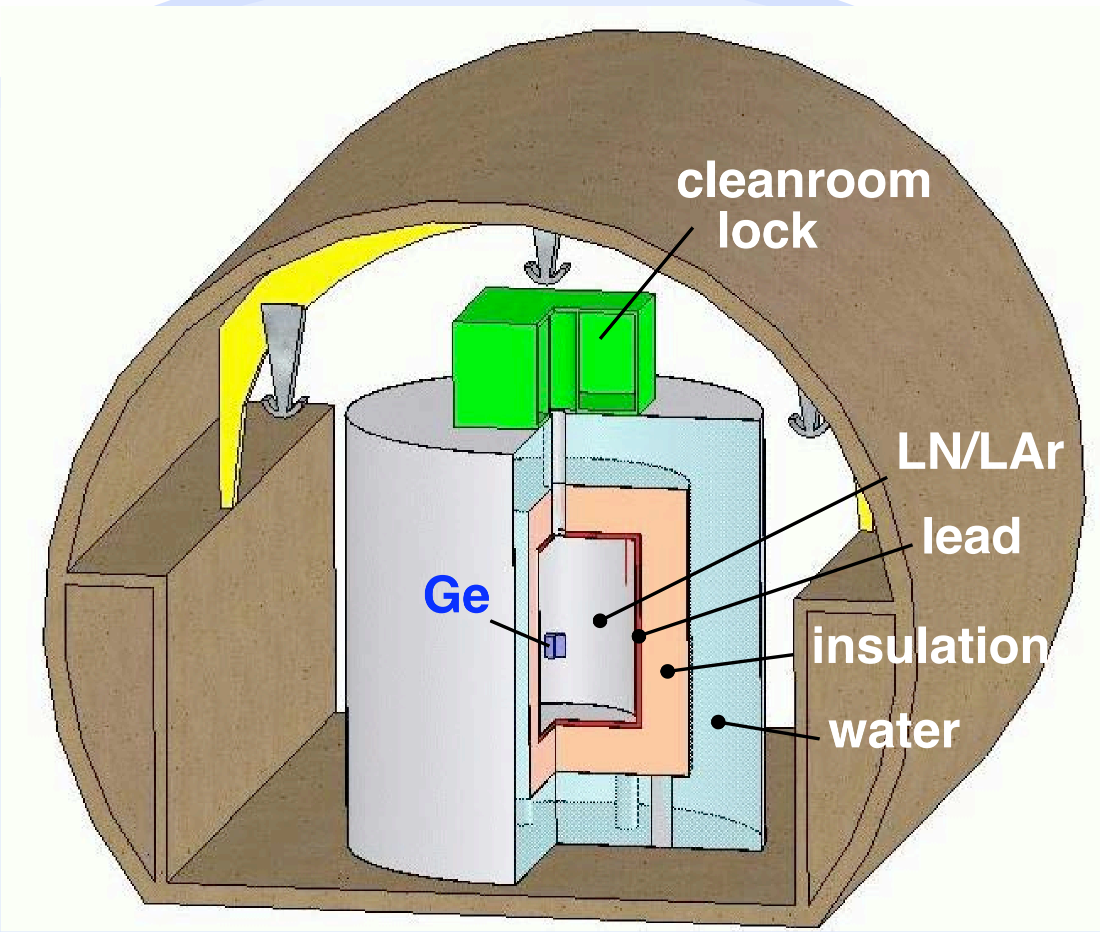
MPI ^{76}Ge Proposal for Gran Sasso

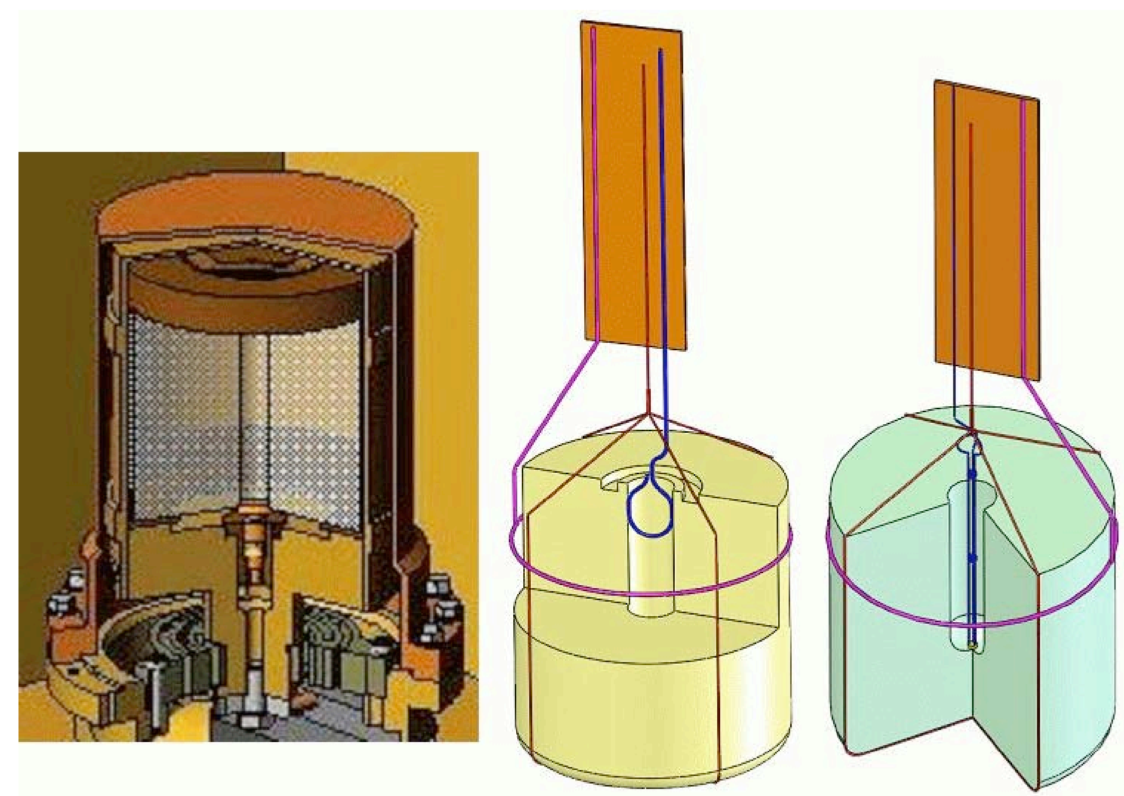
- Bare Ge detectors in pure LN/LAr
- Phase 1: ~ 20 kg, HM/IGEX; 86% ^{76}Ge
- Phase 2: Add 20 kg new enriched detectors

Physics Reach

- Phase 1: refute claim at 99.6% or confirm at 5σ
- Phase 2: 10% measurement if KKDK correct. Push limit to 2×10^{26} years if not.
- Start construction early 2005
- Begin data acquisition 2006

MPI ^{76}Ge Proposal

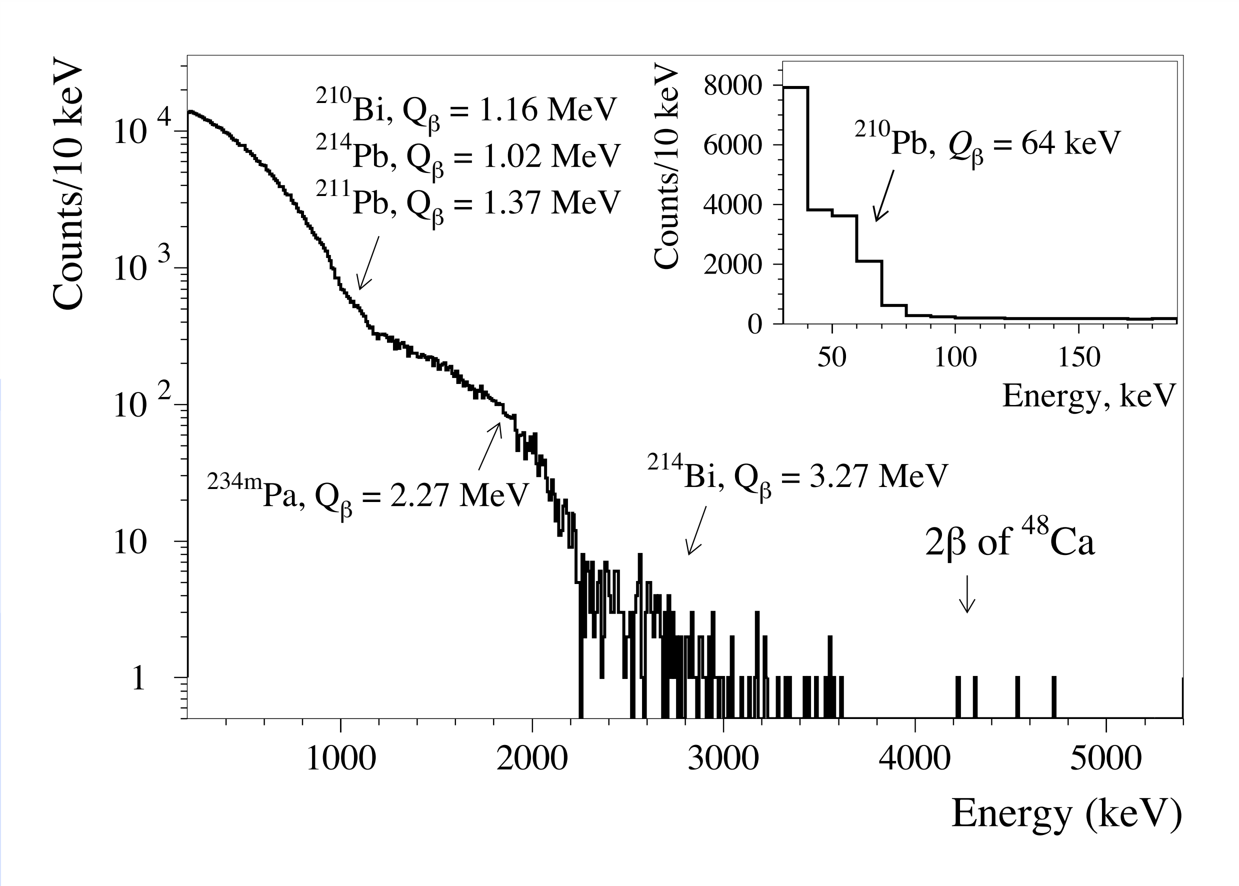




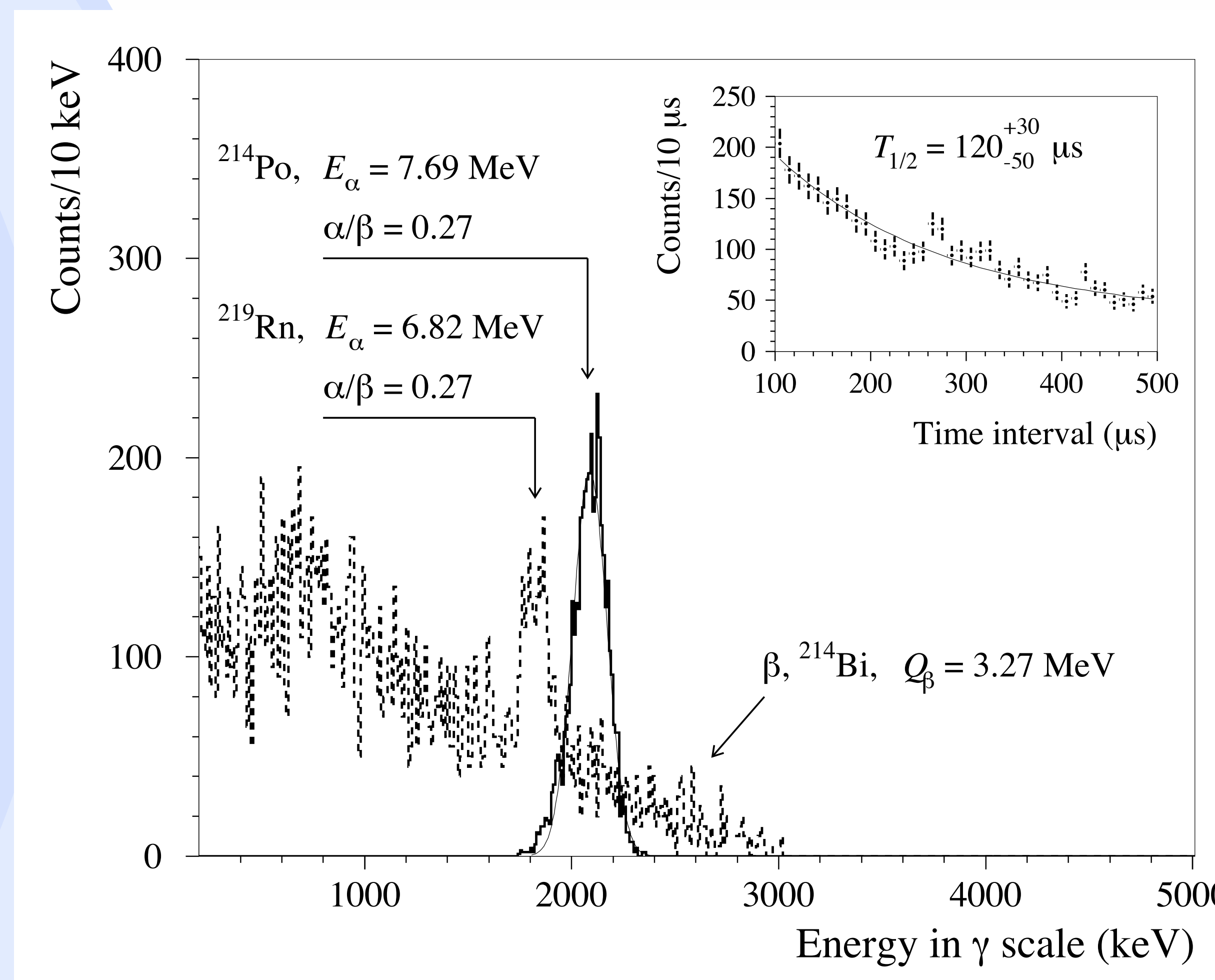
Scintillation Detectors

- CAMEO - ^{116}Cd ($CdWO_4$ crystals in liq. scint.)
- CANDLES - ^{48}Cd (CaF_2 crystals in liq. scint.)
- CARVEL - ^{48}Cd ($CaWO_4$ scintillators)
- GSO - ^{160}Gd (Gd_2SiO_4 crystals in liq. scint.)
- Xe - ^{136}Xe (Xe dissolved in liq. scint.)

Carvel

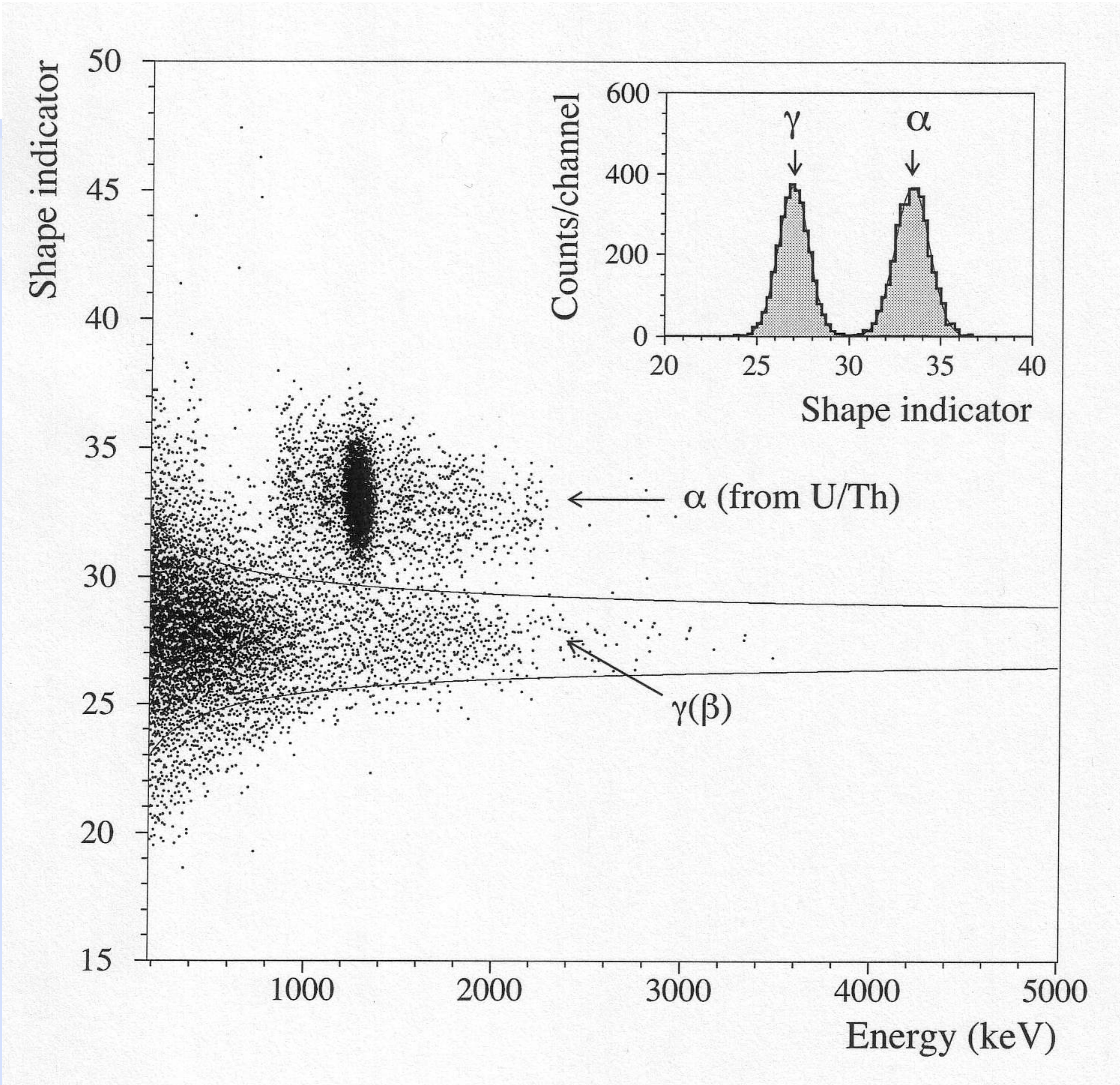


Counts/10 keV
Energy (keV)
^{210}Bi, Q_β = 1.16 MeV
^{214}Pb, Q_β = 1.02 MeV
^{211}Pb, Q_β = 1.37 MeV
^{234m}Pa, Q_β = 2.27 MeV
^{214}Bi, Q_β = 3.27 MeV
2β of ^{48}Ca
^{210}Pb, Q_β = 64 keV
Energy, keV



Counts/10 keV
Energy in γ scale (keV)
^{214}Po, E_α = 7.69 MeV
α/β = 0.27
^{219}Rn, E_α = 6.82 MeV
α/β = 0.27
β, ^{214}Bi, Q_β = 3.27 MeV
Counts/10 μs
$T_{1/2} = 120^{+30}_{-50}$ μs
Time interval (μs)

Carvel



Shape indicator
50
45
40
35
30
25
20
15
1000
2000
3000
4000
5000
Energy (keV)
α (from U/Th)
γ(β)
Counts/channel
600
400
200
0
γ
α
20
25
30
35
40
Shape indicator

Time Projection, Tracking , & Drift Chambers

- DCBA - ^{150}Nd (Nd foils in a drift chamber)
- MOON - ^{100}Mo (Mo foils in plastic scint. - tracking chamber)
- NEMO/Super NEMO - ^{82}Se (Se foils in a magnetic tracking chamber)
- EXO - ^{136}Xe (Gas or liquid Xe TPC with ^{+}Ba identification)

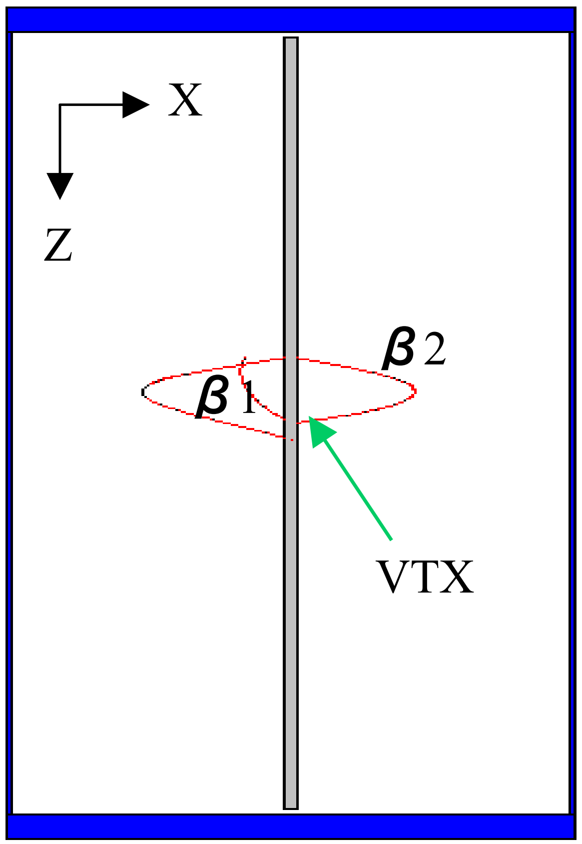
DCBA

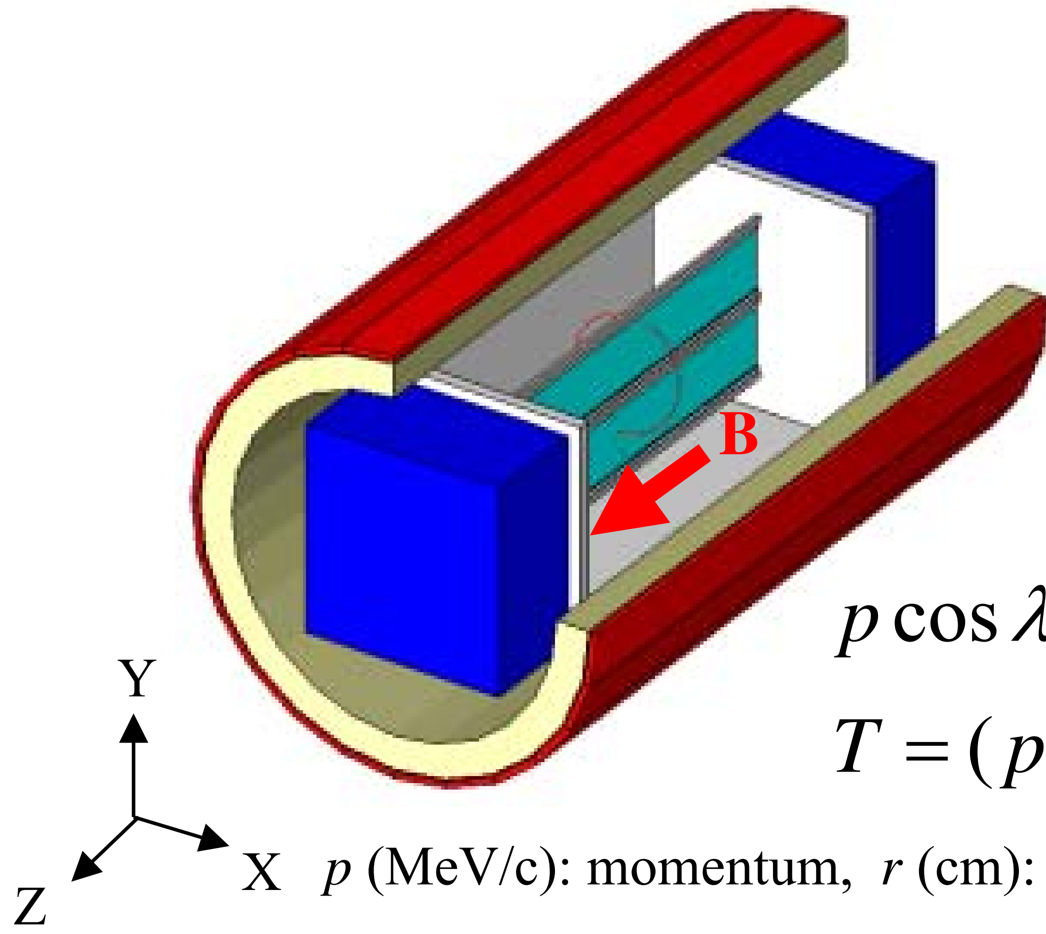
Drift Chamber Beta-ray Analyzer

- DCBA-T (Test apparatus for technical development)
- DCBA-I (4xDCBA-T - Standard Module (SM) with natural Nd source)
- DCBA-II(1) (100-SM with natural Nd - 7.7 mol ^{150}Nd)
- DCBA-II(2) (100-SM with 124 mol ^{150}Nd enriched source)
  - Sensitivity to effective neutrino mass ~0.05eV

Slide adapted from presentation of N. Ishihara at NDM03 Nara, 9-14 June 2003

DCBA





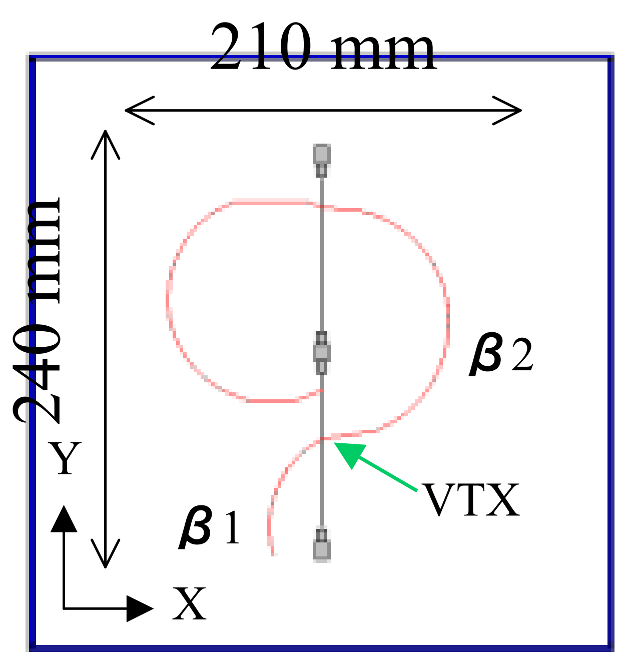
DCBA-T

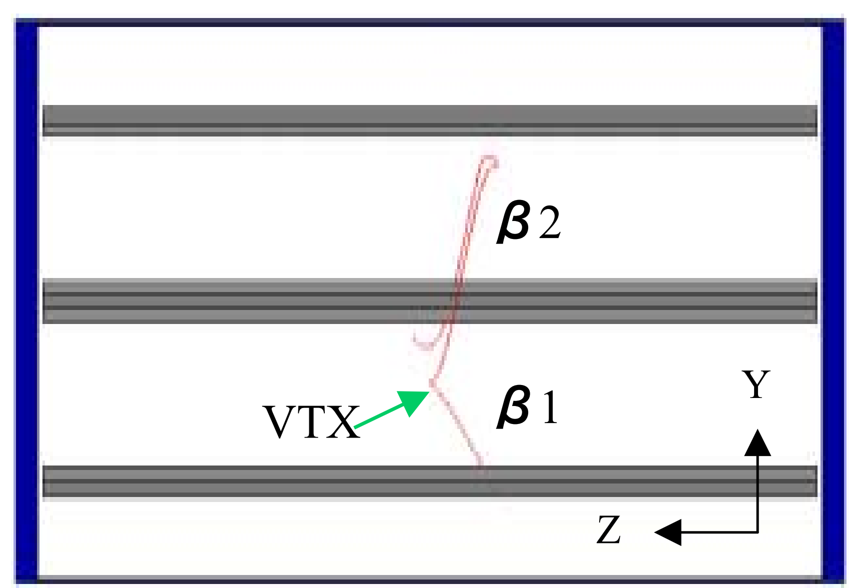
$$p\cos\lambda = 0.3rB,$$

$$T = (p^2 + m_e^2)^{1/2} - m_e$$

p (MeV/c): momentum, r (cm): radius, λ: pitch angle

B (kG): mag. field, m_e (MeV/c^2): electron mass

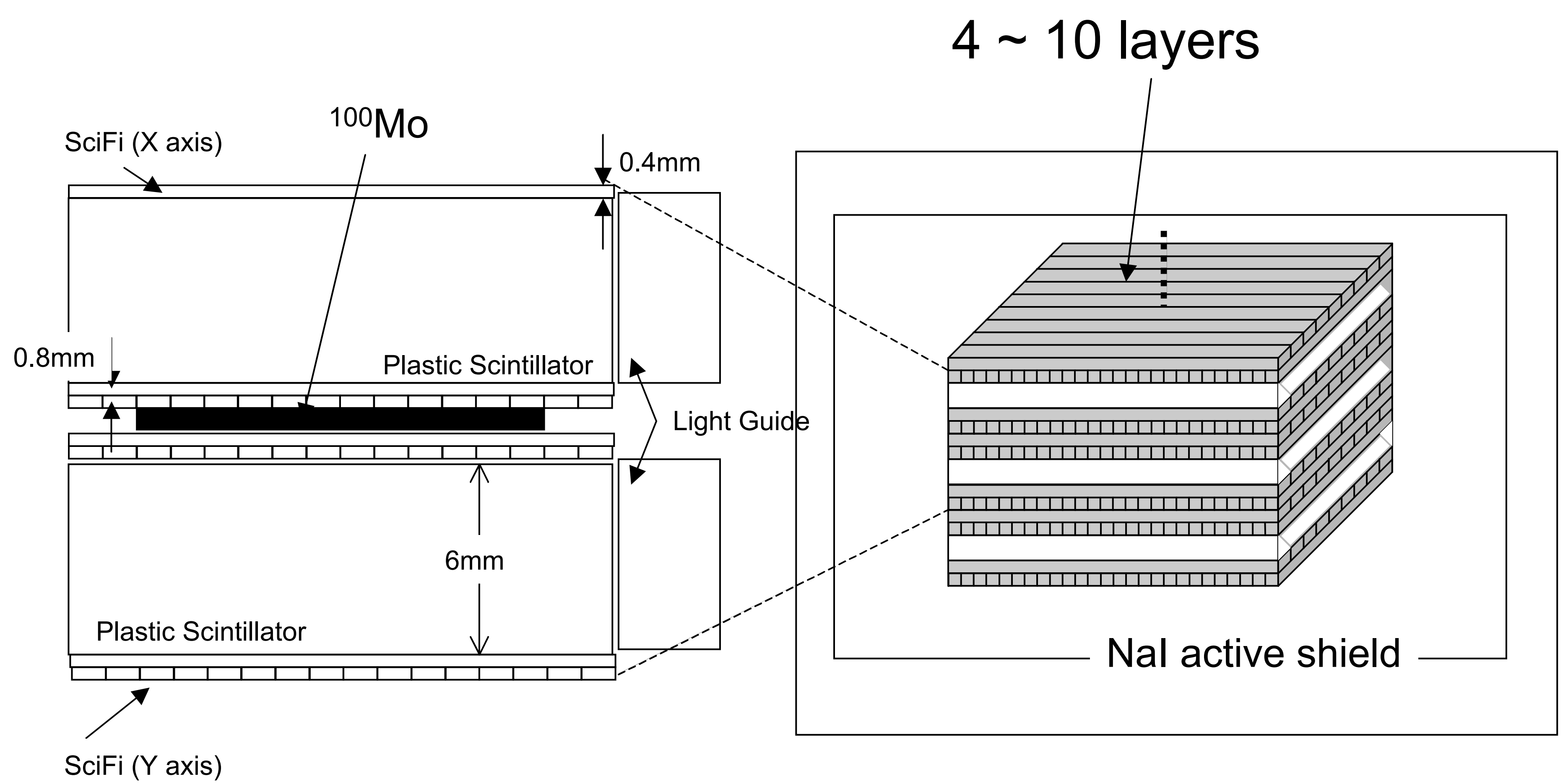




Slide from presentation of N. Ishihara at APPI 2004 Iwate, 16-20 February 2004

Molybdenum Observatory Of Neutrinos (MOON)

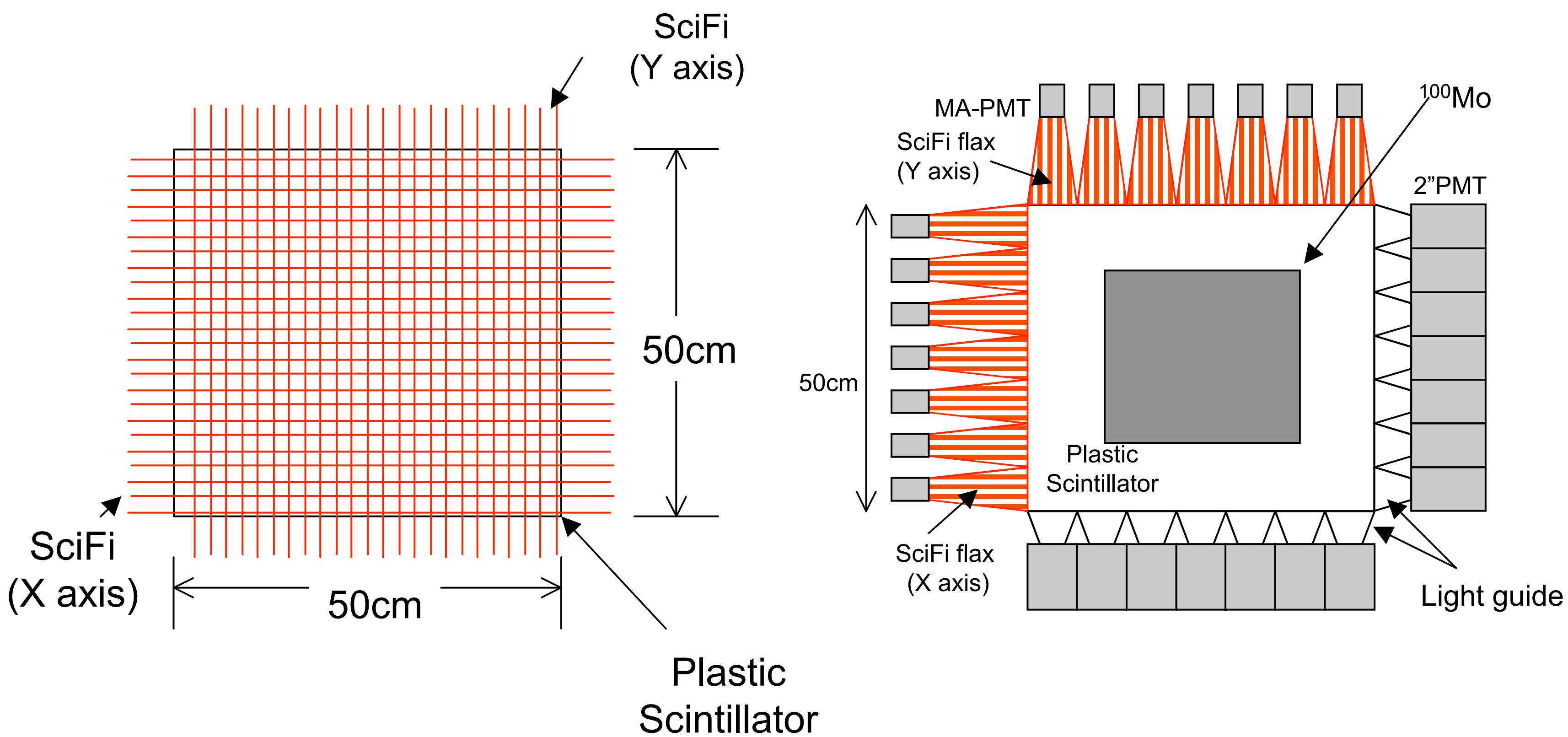
- Molybdenum foils between plastic scintillators for energy readout optical fibers for position readout
- MOON-I: 1 kg, 3 y, $T_{1/2}$~$6x10^{25}$ y (m$_{ee}$~0.1 eV)
- MOON-II: 250 kg, 3 y, $T_{1/2}$~$8x10^{26}$ y (m$_{ee}$~0.03 eV)
- MOON III: 750 kg, 7 y, $T_{1/2}$~$3x10^{27}$ y (m$_{ee}$~0.02 eV)
- Tracking with angular resolution



Size ; Plastic Scintillator ~ 50cm X 50cm

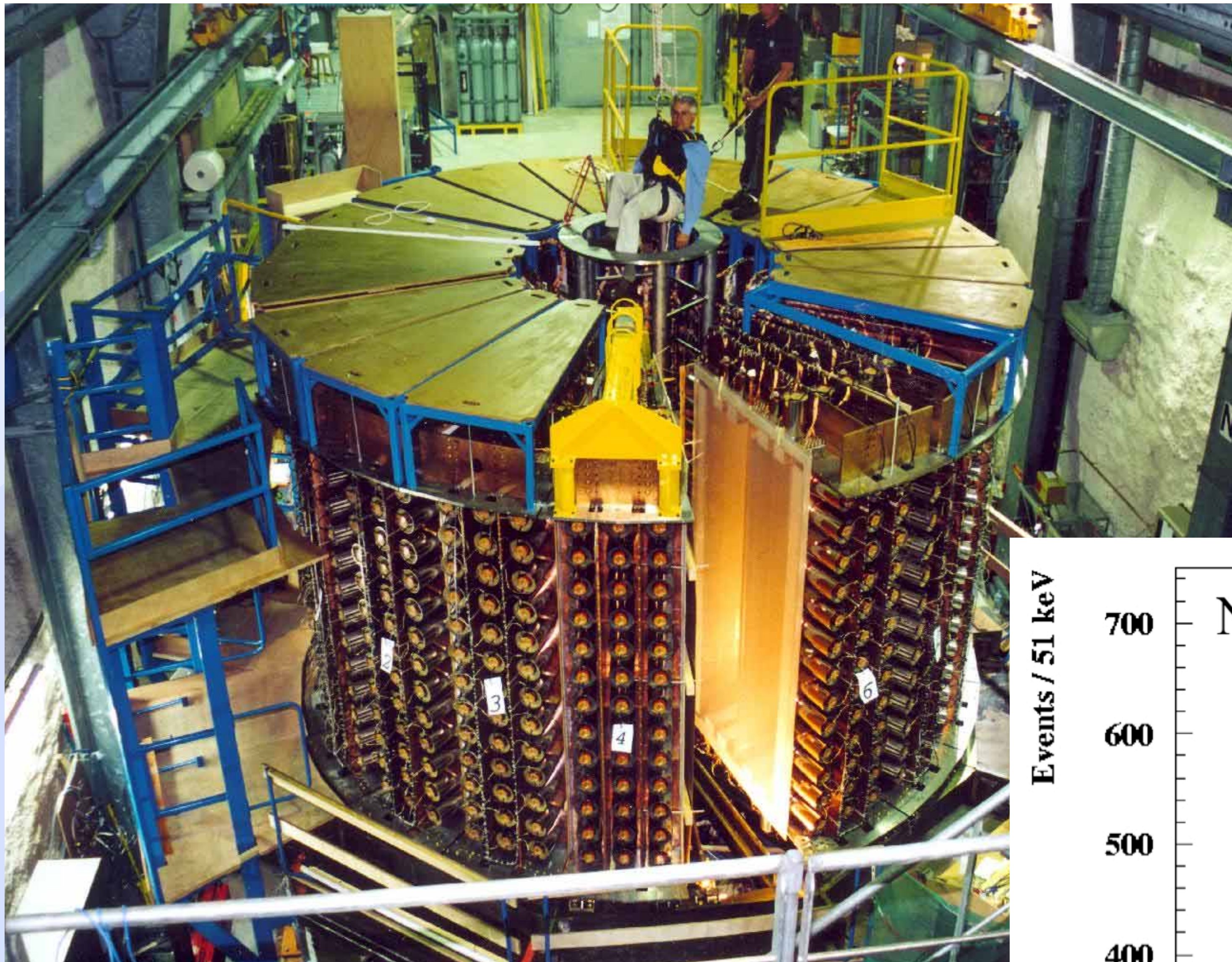
^{100}Mo foil ~ 30cm X 30cm

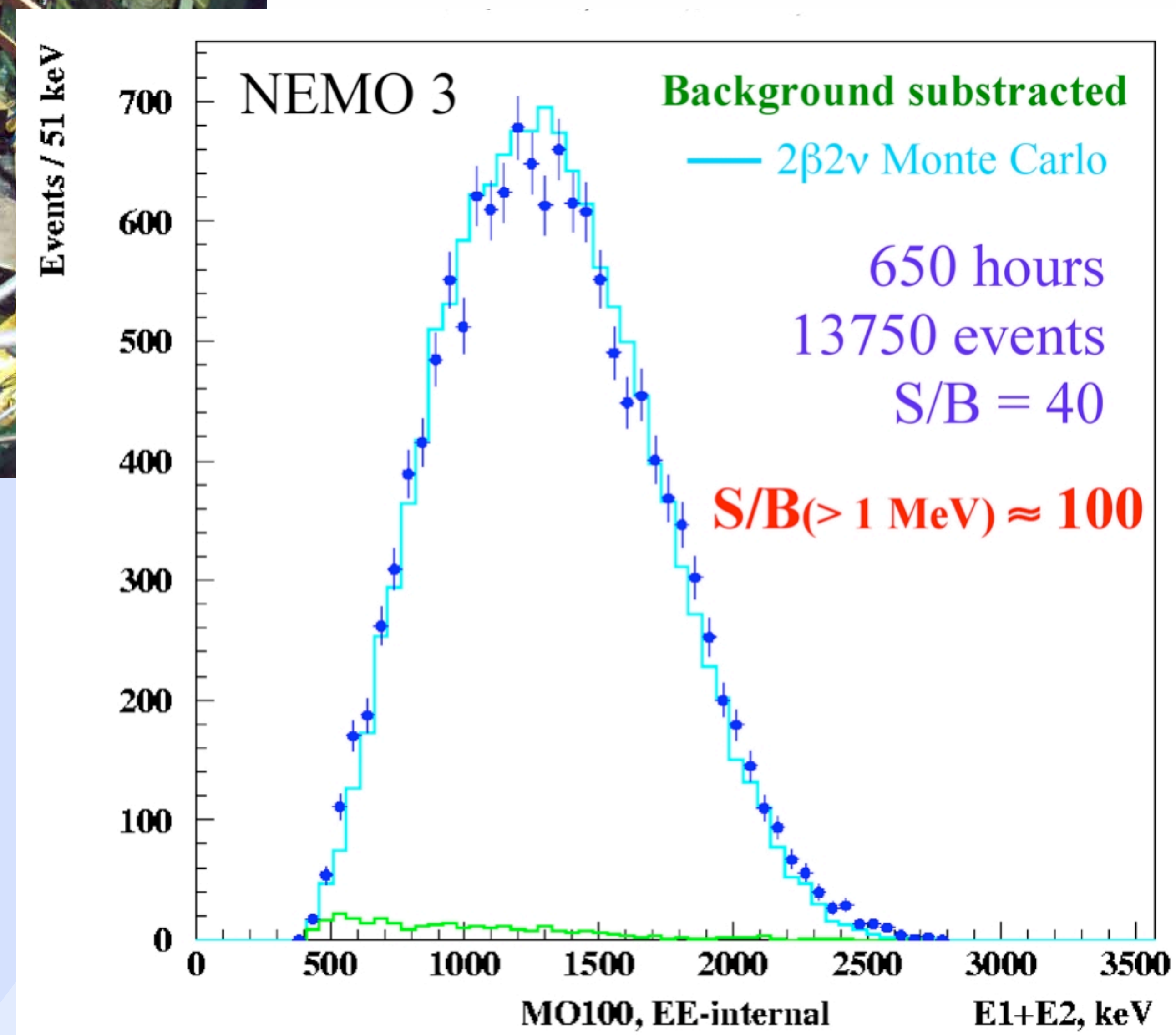
MOON



SciFi
(Y axis)
50cm
SciFi
(X axis)
50cm
Plastic
Scintillator
MA-PMT
SciFi flax
(Y axis)
100Mo
2"PMT
50cm
Plastic
Scintillator
SciFi flax
(X axis)
Light guide

NEMO


2
3
4
6


NEMO 3
Background substracted
2β2ν Monte Carlo
650 hours
13750 events
S/B = 40
S/B(> 1 MeV) ≈ 100
Events / 51 keV
0
100
200
300
400
500
600
700
0
500
1000
1500
2000
2500
3000
3500
MO100, EE-internal
E1+E2, keV

The Super-NEMO Double-Beta Decay Expression of Interest

- At least 10 times the capacity of NEMO-3
  - ~ 100 kg of enriched isotopes
- Sensitivity $\langle m_{\nu} \rangle \sim 30$ meV
- ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe

Super-NEMO Proposed Schedule

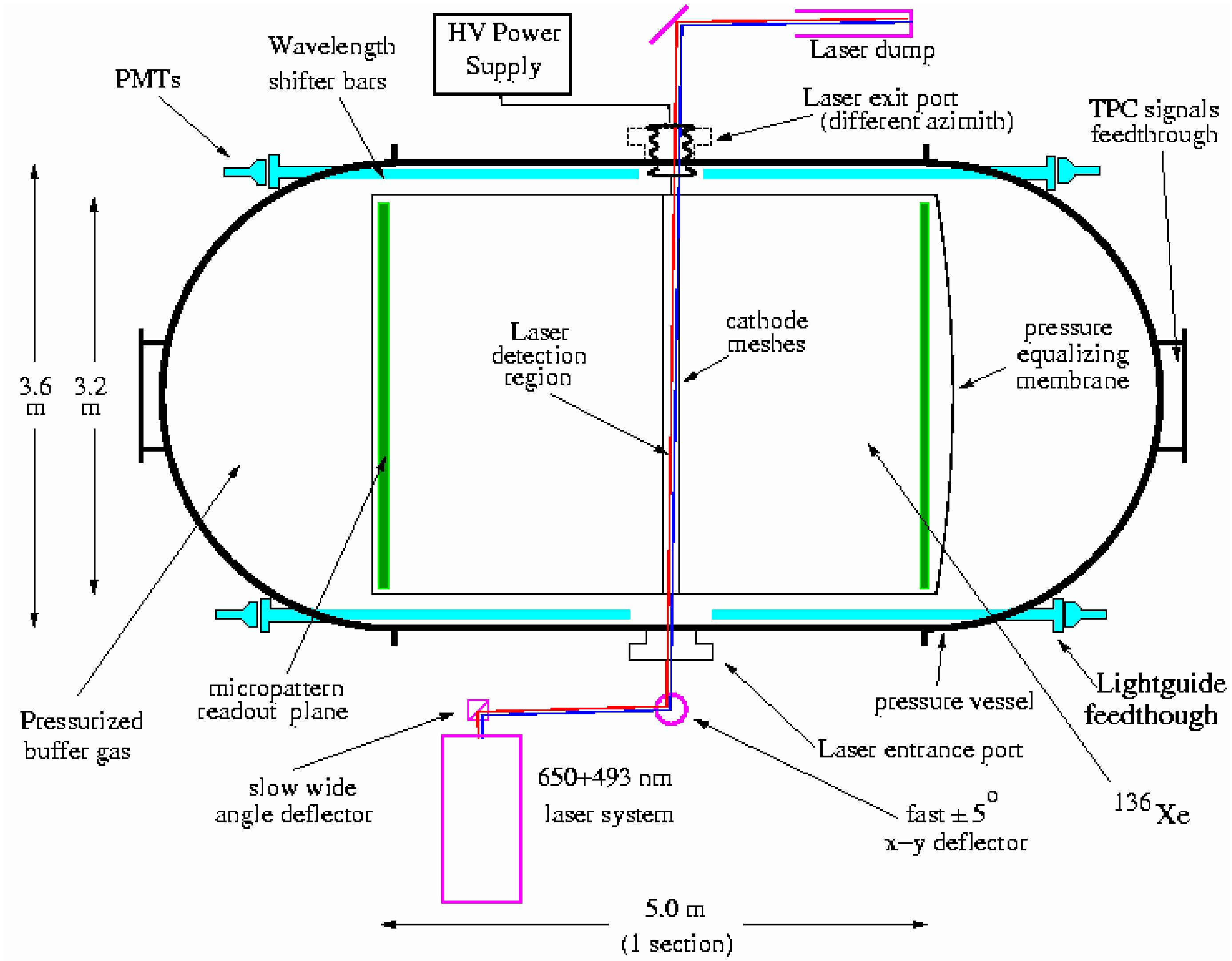
- Phase 1. (2004 - 2006) Feasibility Studies
- Phase 2. (mid 2006 - 2007) Engineering, Design, and Acceptance
- Phase 3. (2008 - end 2010) Construction
- Phase 4. (2011-) Operation

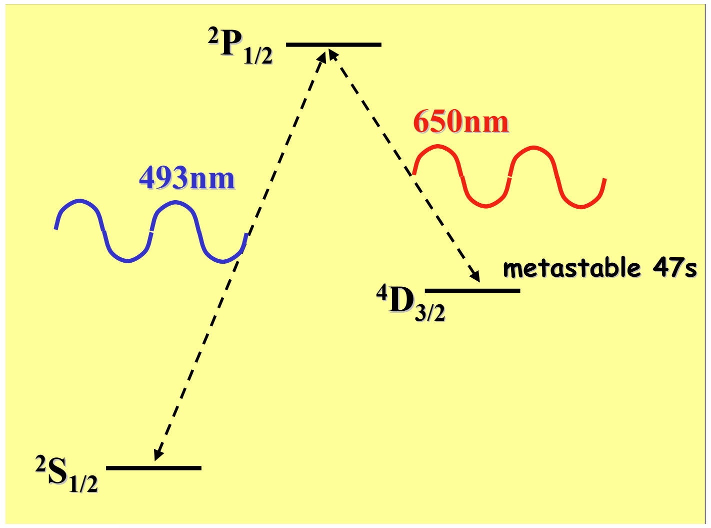
Enriched Xenon Observatory

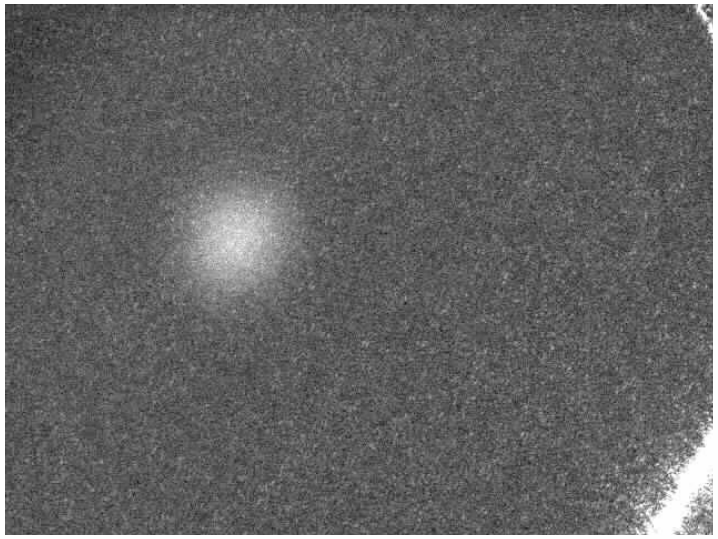
- ^{136}Xe - 40 m^3 at 10 Atm. (2000 kg)
- 80% ^{136}Xe (Xe is a good scintillator.)
- Energy resolution ~2% at 2.5 MeV
- Possible Liquid Version
- R&D on tagging ^{+}Ba daughter ion
- 200 kg Prototype (no tagging) was approved and is funded. It will be located in the DOE WIPP site in Carlsbad, New Mexico.

EXO

Conceptual scheme of a high pressure Xe gas TPC with laser tagging







Sample Figures of Merit

- 500 kg of Ge enriched to 86% ^{76}Ge
- $$\epsilon = 0.8 \qquad b = 0.005$$
- $$f = \frac{(0.73)(0.86)(0.8)}{76}\sqrt{\frac{500}{(0.005)(4)}} \simeq 1.05$$
- 760 kg of TeO_2 nat. ab. 33.8% ^{130}Te
- $$\epsilon = 0.84 \qquad b \simeq 0.01 \qquad f = 0.89$$
- 122 kg of TeO_2 enriched to 85% ^{130}Te

$$\epsilon = 0.84 \qquad b \simeq 0.01 \qquad f = 0.90$$

Large Tracking Detector (Super NEMO?)

$$M = 100\ kg \quad a = 0.9 \quad \epsilon = 0.3 \quad b = 0.003 \quad \delta E = 125\ keV$$

$$f = \frac{\overline{\eta} a \epsilon}{W} \sqrt{\frac{M}{b\, \delta E}} = \frac{\overline{\eta}}{W}(4.4)$$

^{82}Se: $\frac{\overline{\eta}}{W} = \frac{1.7}{82} = 0.002$ $\quad f \simeq 0.09$

^{150}Nd: $\frac{\overline{\eta}}{W} = \frac{57}{150} = 0.38$ $\quad f \simeq 1.7$

Target Half-Lives for $\langle m_\nu \rangle = 0.04$ eV

Isotope	$T_{1/2}^{0\nu}$
^{48}Ca	3.0×10^{27}
^{76}Ge	2.3×10^{27}
^{82}Se	9.4×10^{26}
^{100}Mo	1.6×10^{26}
^{116}Cd	1.3×10^{27}
^{130}Te	3.9×10^{26}
^{136}Xe	5.8×10^{27}
^{150}Nd	2.9×10^{25}

Conclusions

- Large value of $G^{0\nu}|\mathcal{M}^{0\nu}|^2$ (linear) $\overline{\eta}$
- High Efficiency (linear) ϵ
- High Isotopic Abundance (linear) a
- Large Source Mass $\sqrt{M}$
- Good Energy Resolution $\sqrt{\delta E}$
- Low Background $\sqrt{b}$
- Cost Feasibility $

$$f \equiv \frac{\overline{\eta} a \epsilon}{W} \sqrt{\frac{M}{b\, \delta E}}$$