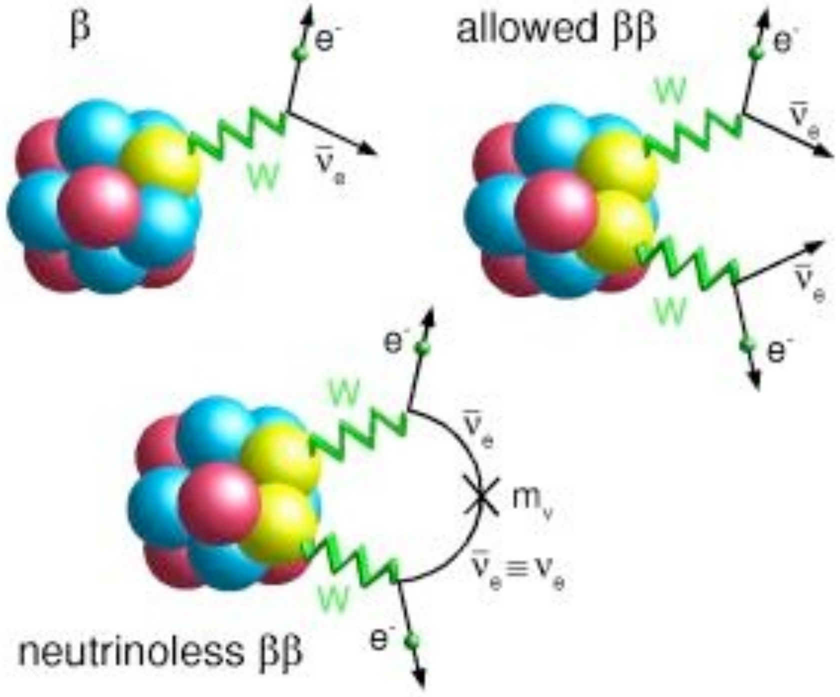
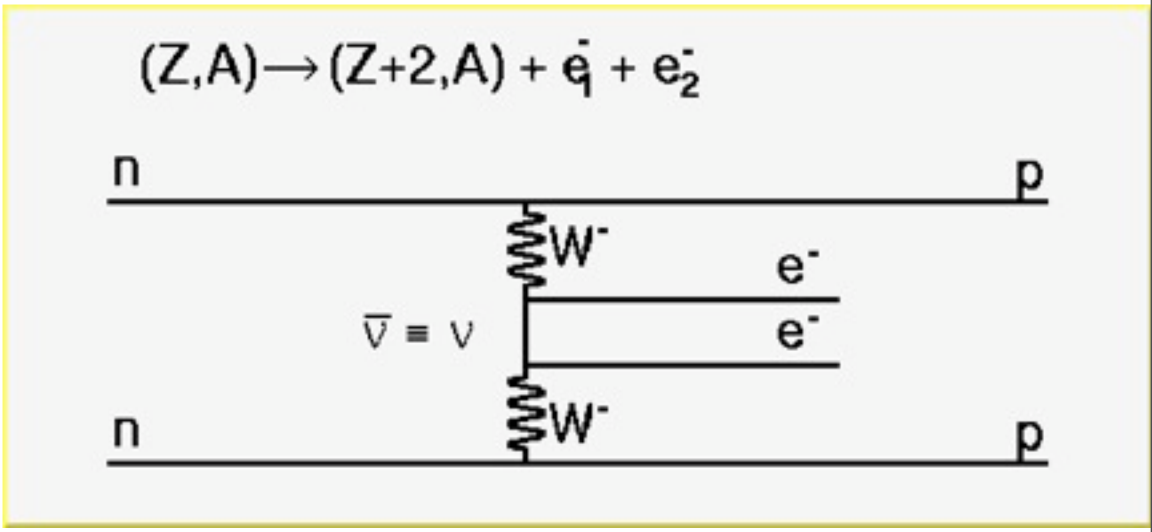




Neutrino mass and neutrinoless double beta decay (0νββ)

Ruben Saakyan (UCL)

Annual IOP HEPP Conference

Oxford

8 April 2009

Outline

- Double Beta Decay and neutrino mass
- Experimental techniques
- Current and Future projects
  - Weighted/biased by UK participation

Neutrinos are massive and they mix

What else do we want to know?

- Number of neutrinos: Are there sterile neutrinos?
- θ_{13}, Precision values of mixing angles and Δm^2's
- Absolute neutrino mass value. Only limits so far.
  Tritium: $m_{\bar{\nu}_e} < 2.3\ \mathrm{eV}$ Cosmology: $\sum m_{\nu_i} < 1\ \mathrm{eV}$
- 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 ($\nu = \text{anti-}\nu$) or Dirac ($\nu \neq \text{anti-}\nu$)?
  Full lepton number violation (required in
  most Grand Unification Theories) .

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

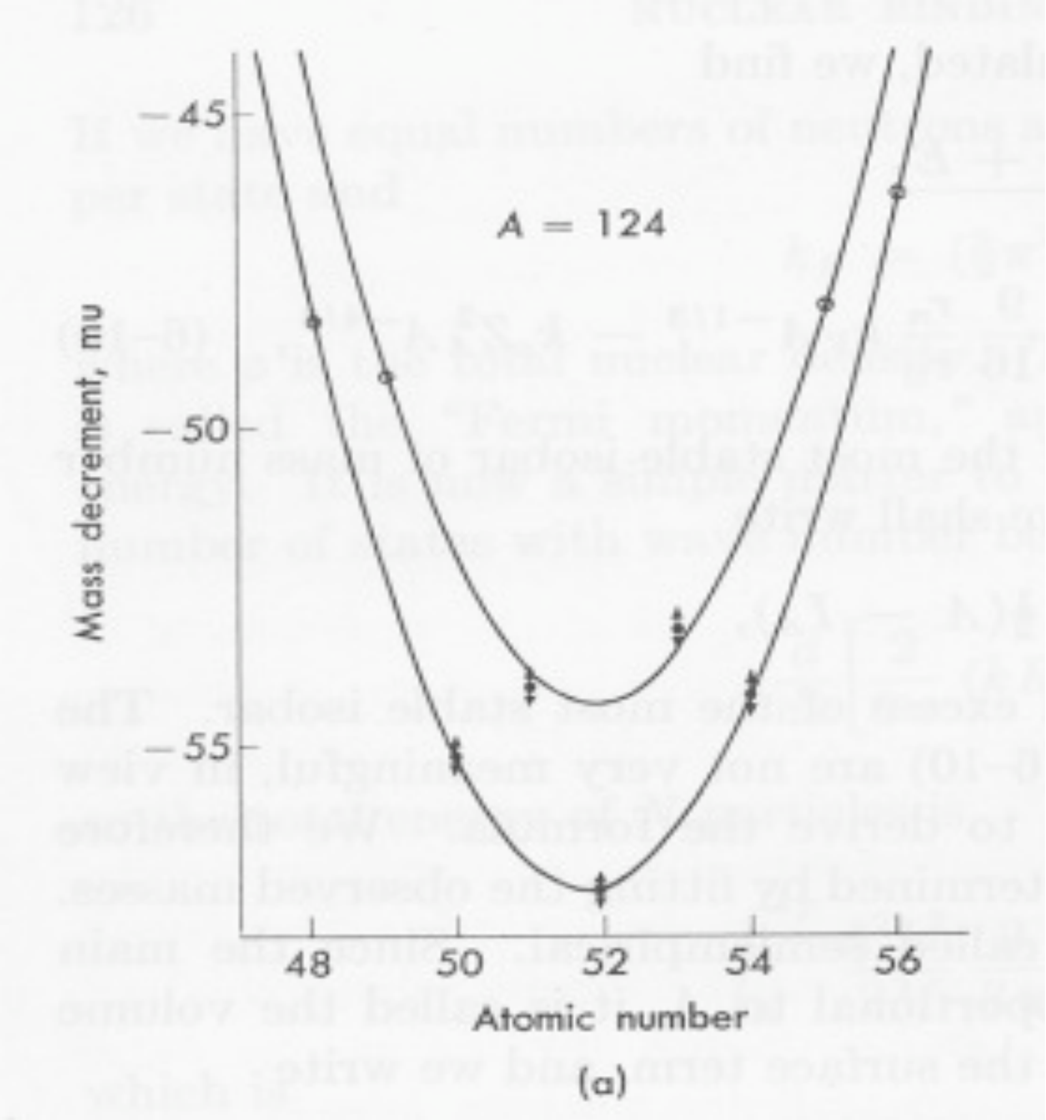
Nuclear Physics and Standard Model ββ decay

For most even-even nuclei only ββ decay is possible (recall pairing term in SEMF!)

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$$

$$(A,Z) \rightarrow (A,Z-2) + 2e^{+} + 2\nu_e$$

$$2e^{-} + (A,Z) \rightarrow (A,Z-2) + 2\nu_e$$



phase space

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

NME is **measured** in 2νββ

<u>NME</u>:
~~Nasty~~ Nuclear
Matrix
Element

^{76}Ge , ^{100}Mo, ^{82}Se, ^{116}Cd, ^{150}Nd, ^{48}Ca, ^{136}Xe ,^{96}Zr, ^{130}Te

Measured for 10 nuclei

Important input for 0νββ NME calculation!

Important to understand its background contribution

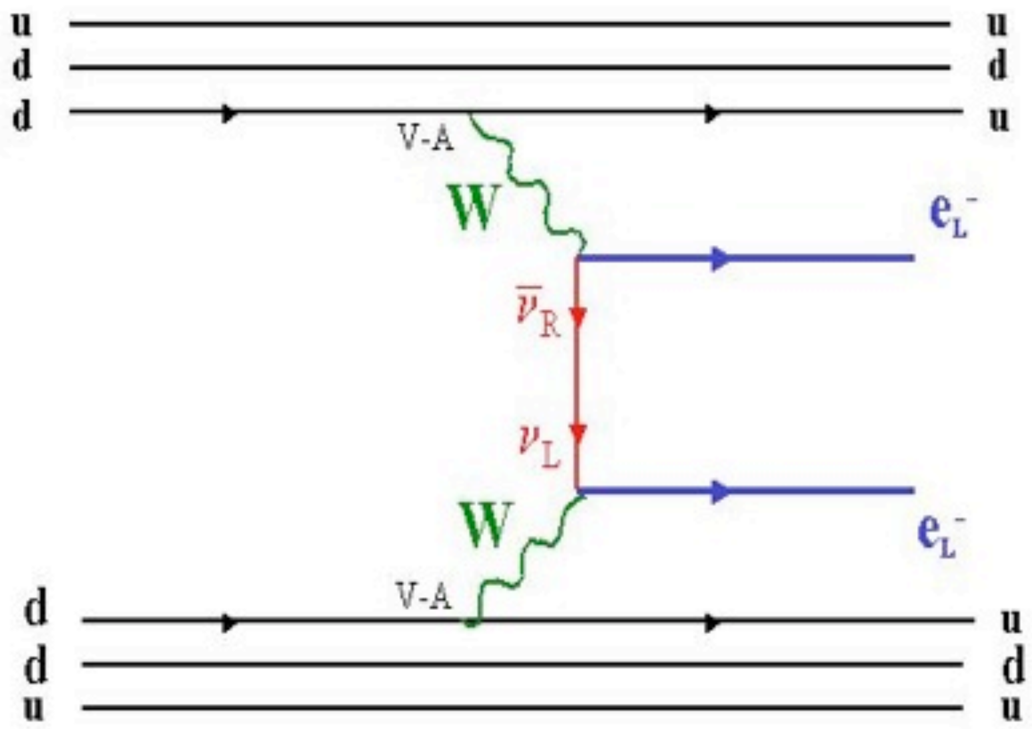
Neutrinoless double beta decay

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

(also $\beta^+\beta^+$ and 2K-capture possible)

$\Delta L = 2$

Lepton number violation!!!



Light neutrino exchange

→

Majorana neutrino ($\nu=\bar{\nu}$)

Access to absolute neutrino mass

Phase space factor

Nuclear matrix element

$$T^{-1}_{1/2} = F(Q^5_{\beta\beta},Z)\,|M^{0\nu}|^2\,\langle m_\nu\rangle^2$$

$$\langle m_\nu\rangle = m_1|U_{e1}|^2 + m_2|U_{e2}|^2.e^{i\alpha} + m_3|U_{e3}|^2.e^{i\beta}$$

|Uei|: mixing matrix elements

α and β: Majorana phases

Other possible process :

V+A current : $\langle m_\nu\rangle, \langle\lambda\rangle, \langle\eta\rangle$

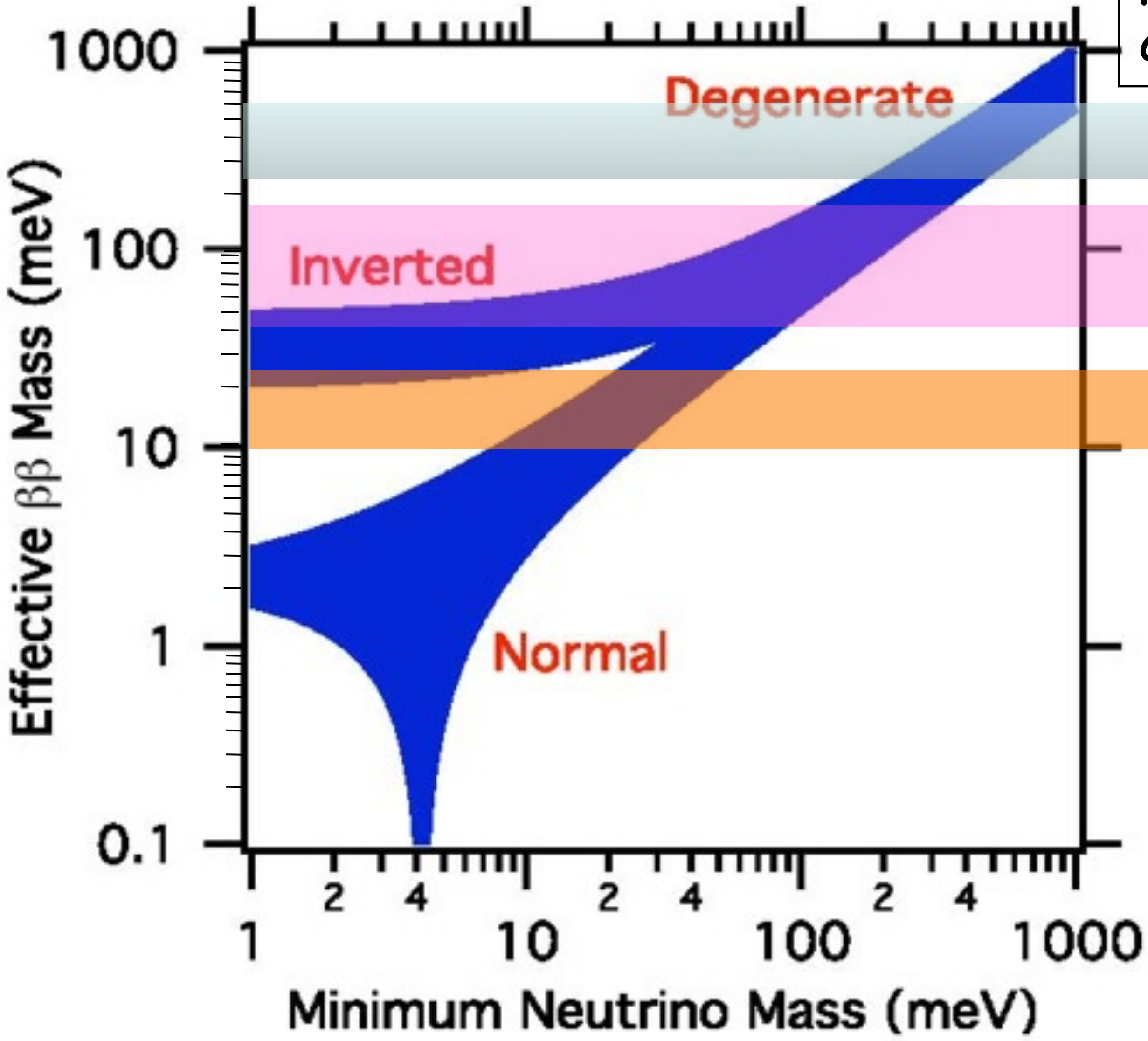
Majoron emission : $\langle g_M\rangle$

Supersymmetry : $\lambda'_{111},\ \lambda'_{113}$

Schechter-Valle theorem:

$\beta\beta(0\nu) \Longrightarrow$ **Majorana neutrinos**

NEMO3, CUORICINO running,
Complete verification by GERDA-I, SuperNEMO-Demonstrator



Klapdor et al. 0.24 - 0.58 eV

Coming up x100 kg experiments: SuperNEMO, CUORE, GERDA, EXO, SNO+,...

Future 1 ton-scale experiments

Assumptions:

Majorana neutrinos
No cancellations

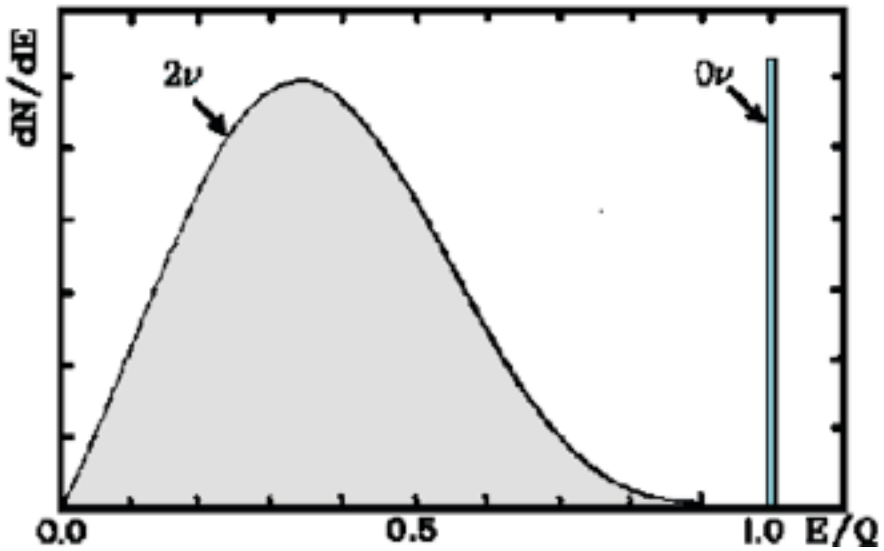
Plot from Avignone, Elliott, Engel arXiv:0708.1033 (2007)

depending on Majorana CPV phases:

$|\langle m_\nu \rangle| \simeq 0.1 - 0.5 \text{ eV}$ Quasi-degenerate hierarchy ($m_1 \approx m_2 \approx m_3$) - best case

$|\langle m_\nu \rangle| \simeq 0.02 - 0.05 \text{ eV}$ Inverted hierarchy ($m_3 < m_1 < m_2$) - tough but doable

$|\langle m_\nu \rangle| \simeq 0.0 - 0.006 \text{ eV}$ Normal hierarchy ($m_1 < m_2 < m_3$) - really tough



Experimental Observables/Signatures

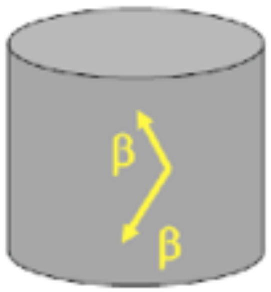
(1) Two coincident electrons from the
the same vertex

(2) $E_{e1} + E_{e2} = Q_{\beta\beta}$

(3) Angular distribution

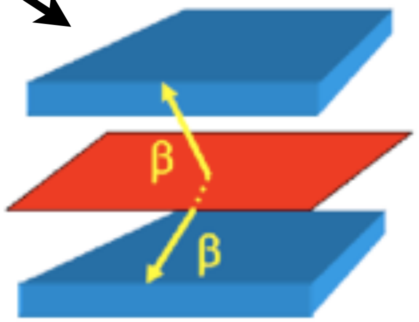
(4) Daughter nucleus ID (would be great)

Two Approaches



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

Lepton number violating parameter



Source = detector

(calorimeters)

Great ΔE/E

compact

η can be due to $\langle m_\nu \rangle$

V+A, Majoron, SUSY, H^{--} or
a combination of them

Source ≠ detector

(foil+tracking+calorimetry)

isotope flexibility

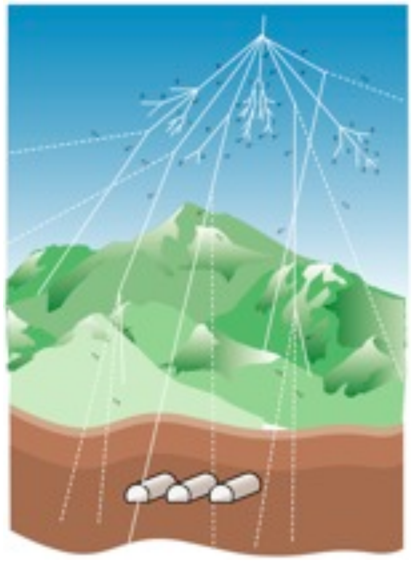
“smoking” gun

Topological bkg suppression

Need detectors which can probe different mechanisms (and different isotopes)

Backgrounds

Cosmic rays



Underground Lab is a must

Natural Radioactivity

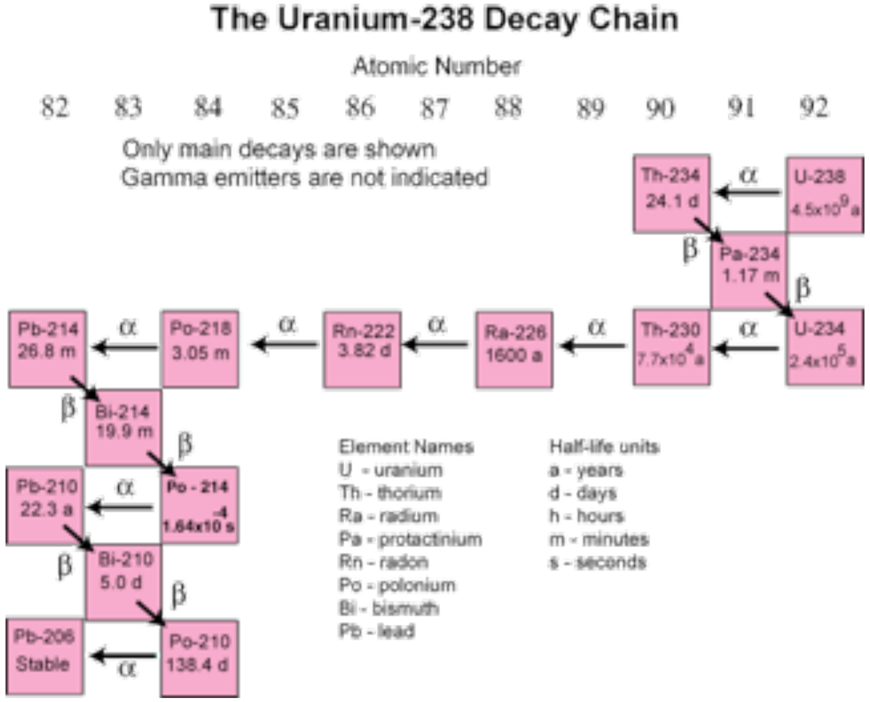
$T_{1/2}(^{238}\mathrm{U}, ^{232}\mathrm{Th}) \sim 10^{10}$ yr

$T_{1/2}(0\nu\beta\beta) > 10^{25}$ yr

Main threat from:

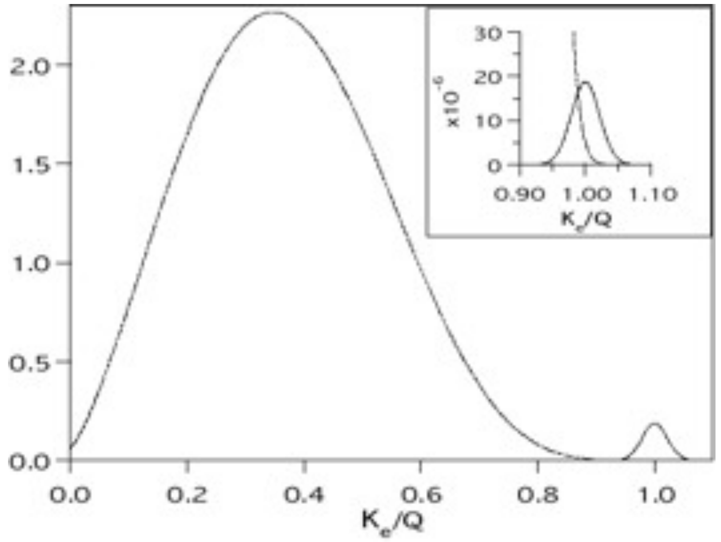
$^{214}\mathrm{Bi}$ (Q_β = 3.27 MeV)

$^{208}\mathrm{Tl}$(Q_β= 4.99 MeV)



Radio-purity and bkg identification

Standard Model $2\nu\beta\beta$



Irreducible bkg
Energy resolution
is the only
weapon here

Isotopes

Centrifuge enrichment well established
x100 kg production possible

Deuterium	2
Helium gas	3
Lithium	6 7
Carbon	13
Silicon	28 29 30
Sulphur	32 33 34 36
Chromium	50 52 54
Iron	54 56 57 58
Zinc /Depleted Zinc/	64 66 67 68 70
Gallium	69 71
Germanium	70 72 73 74 76
Selenium	74 76 77 78 80 82
Krypton	78 80 82 83 84 86
Molybdenum	96 97 98 100
Cadmium	108 110 111 112 113 114 116
Tellurium	122 123 124 128 130
Xenon	124 126 128-132 134 136
Osmium	184 186 187 188 189 190 192
Lead	204 206 207 20

High $Q_{\beta\beta}$ is important due to phase space and natural radioactivity considerations

Isotope	$Q_{\beta\beta}$ (MeV)	Abund (%)
$^{48}Ca \rightarrow {}^{48}Ti$	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

Unfortunately not possible for
^{150}Nd, ^{48}Ca, ^{96}Zr
Alternative for these isotopes: AVLIS (Atomic Vapour Laser Isotope Separation)
Interesting developments at the MENPHIS facility in France.

General Strategy

$$T^{0\nu}_{1/2}(y) > \frac{\ln 2 \,.\, N}{k_{C.L.}} \,.\, \frac{\varepsilon}{A} \sqrt{\frac{\mathbf{M} \,.\, \mathbf{t}}{\mathbf{N_{Bkg}} \,.\, \Delta \mathbf{E}}}$$

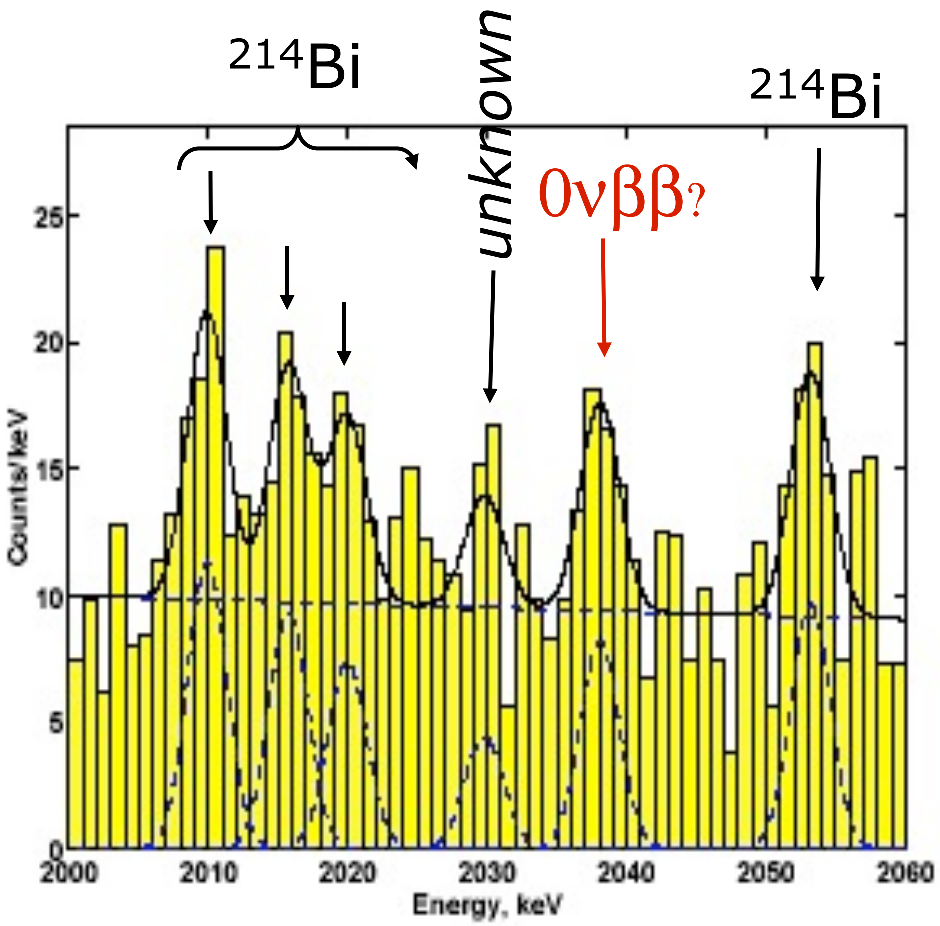
M: mass (kg)
ε : efficiency
$\mathbf{K_{C.L.}}$: Confidence level
N: Avogadro number
t: time (y)
$\mathbf{N_{Bckg}}$: Background events ($keV^{-1}.kg^{-1}.y^{-1}$)
ΔE: energy resolution (keV)

- Large mass (~100 kg to reach 0.05-0.1 meV level)
- High Efficiency
- Low $\mathbf{N_{Bkg}} \,.\, \Delta\mathbf{E}$ **Note:** The product is important when considering backgrounds
  - "Squeeze" **ΔE** - improve resolution
  - Lower $\mathbf{N_{Bkg}}$ - improve non ββ background rejection (topology, event ID etc)

The Claim

- HPGe detector (86% enriched)
- Full stat (71.71 kg y)
- Outstanding resolution 3.27 keV
- Unknown line at 2038 keV found
- I = 28.75 ± 6.86 events, 4.2σ
- $T_{1/2}$ = (0.69-4.18) 10^{25} y (3σ range, best fit = 1.19)

KKDC claim (subset of Heidelberg-Moscow collaboration)



$$< m_\nu >= 0.1 - 0.9\,\mathrm{eV}\ (\mathrm{KKDC,\ 2004})$$

Can not be dismissed out of hand

BUT

- Background under-estimated
- Relative intensities problem with ^{214}Bi lines
- Unknown line in the same region

- ^{56}Co by cosmic rays (γ 2034keV+6keV X-ray)
- ^{76}Ge(nγ)^{77}Ge (2038 keV)
- An unknown line
- A combination of the above

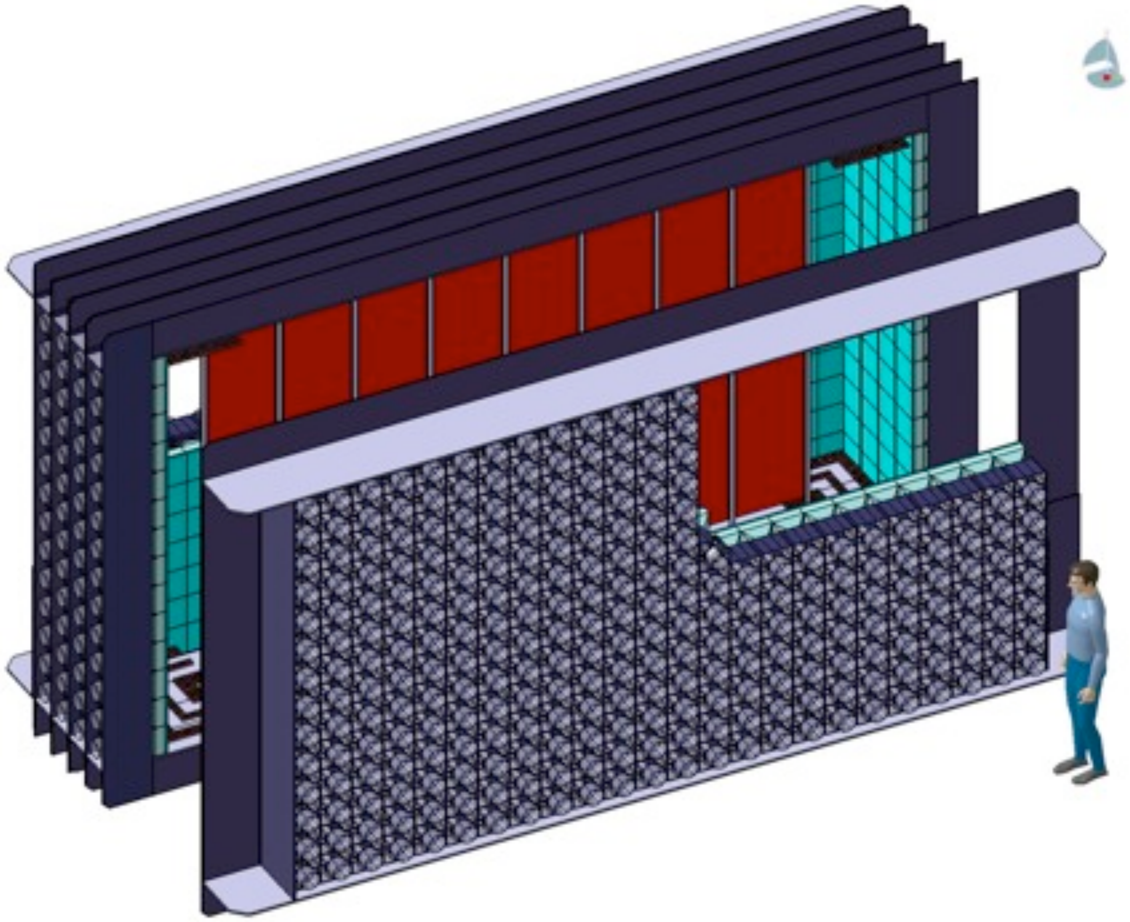
...

Tracking + Calorimetry, source ≠ detector

NEMO-III and SuperNEMO (~90 people)

NEMO-III

SuperNEMO



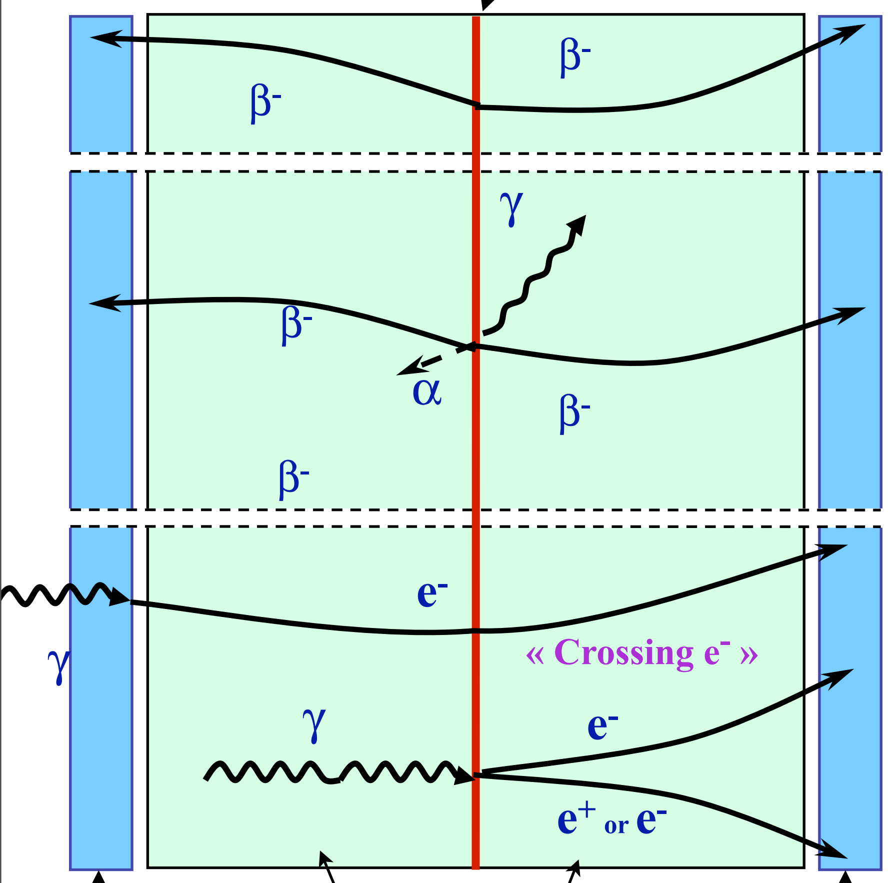
Major contribution from UK and France:
~80% shared equally

UK collaboration: UCL-HEP, UCL-MSSL, University of Manchester, IC.

NEMO-III and SuperNEMO

Detection principle: reconstruct <u>topological signature</u>

Source foil



$\Delta t \sim 0$ ns Signal

$\Delta t \sim 0$ ns

Internal (e.g. ^{214}Bi)

Backgrounds

$\Delta t \geq 3$ ns

External (e.g. ^{208}Tl, neutrons)

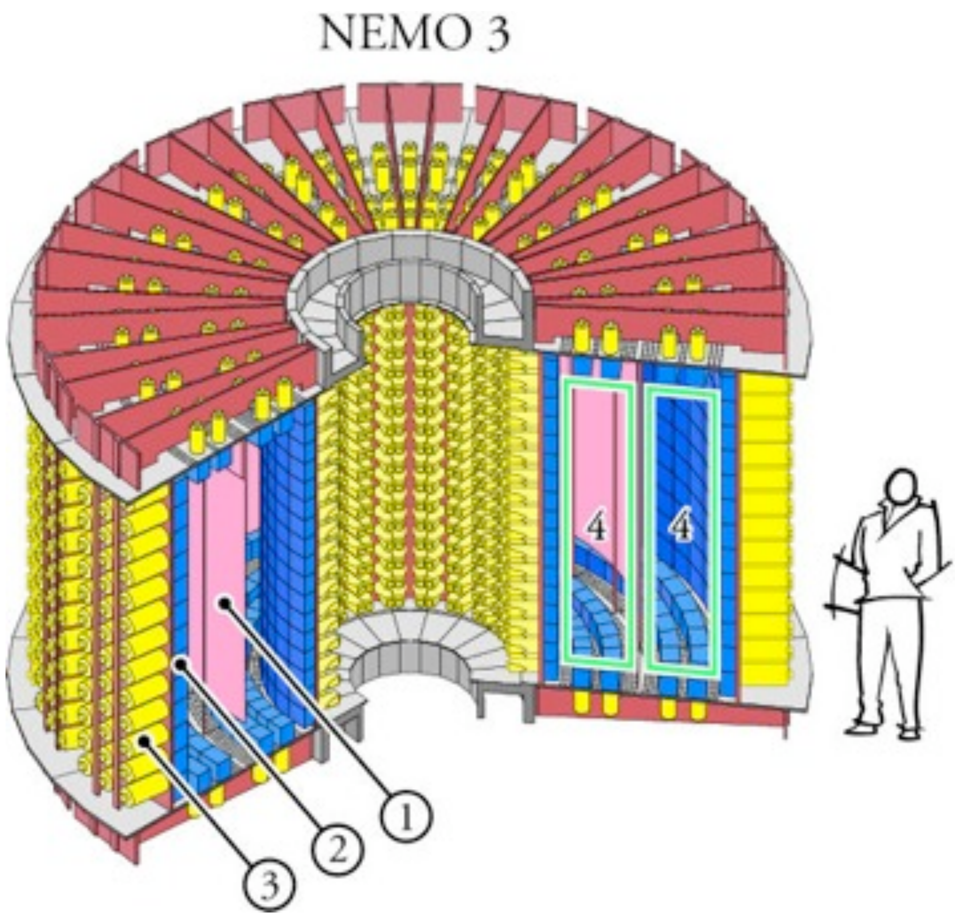
$\Delta t \sim 0$ ns

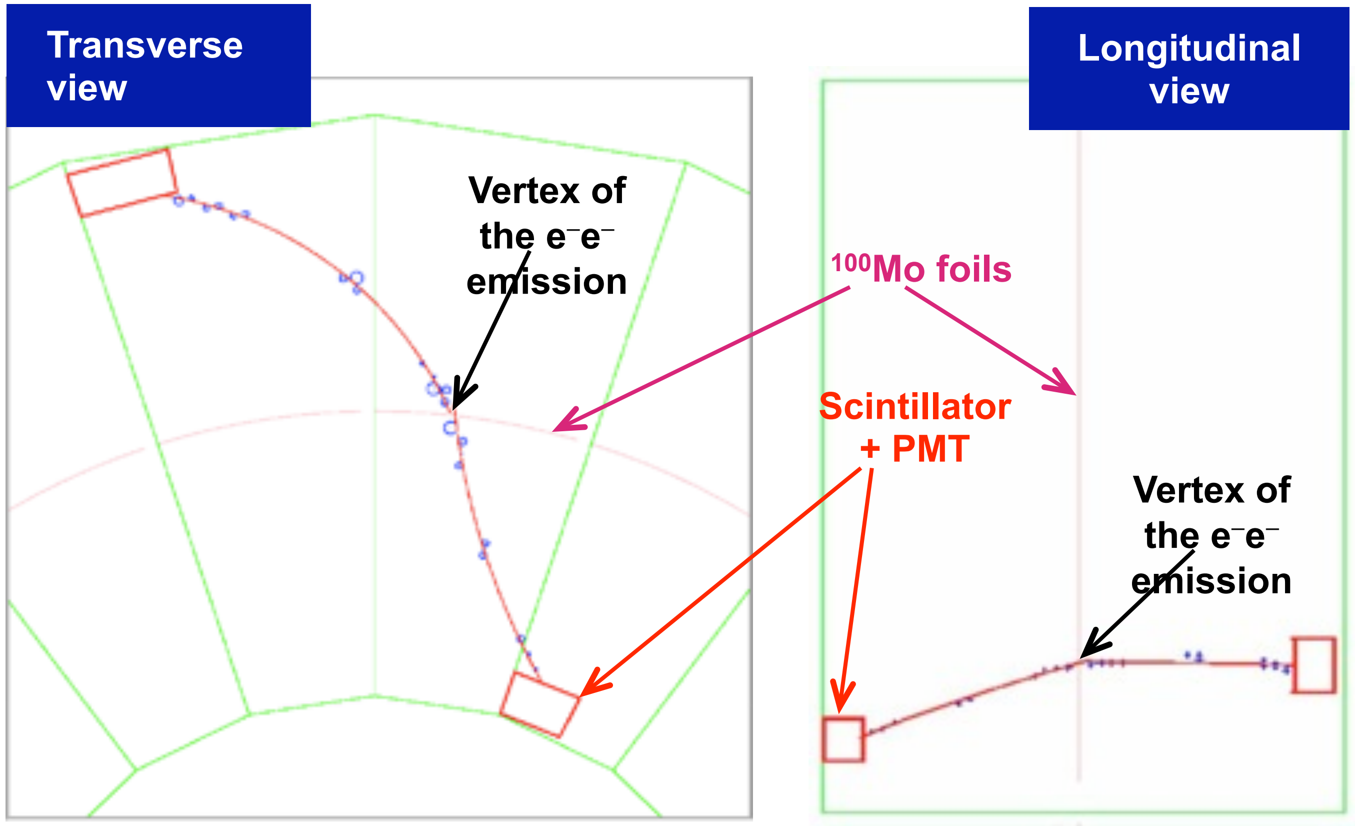
Geiger tracker
(95%He + 4% alcohol +1%Ar)

Calorimeter
(plastic scintillator)

- 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
- Background rejection through particle ID: e^-, e^+, α, γ

NEMO3/SuperNEMO approach. Calorimetry + Tracking





Sources separated from detector ⇒

⇒ can measure different isotopes

"Smoking gun" signature: ⇒

⇒ two e^- with **common** vertex

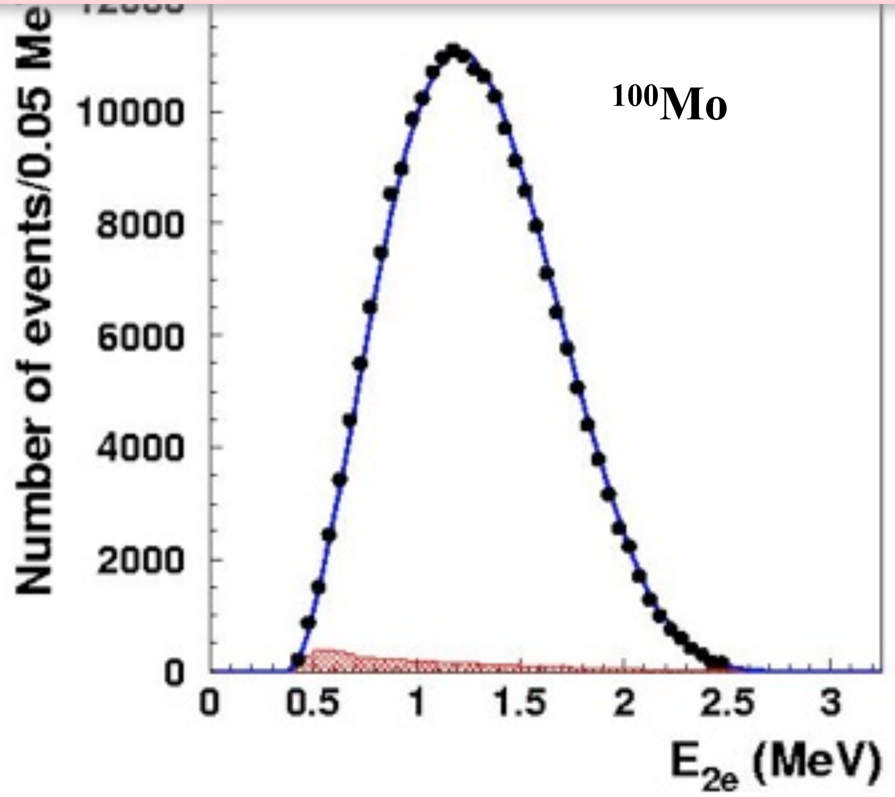
unique to NEMO

- Search for **any** lepton violating process including with continuum spectrum (e.g. Majoron)
- Attempt to disentangle the underlying physics mechanism through electron's angular distribution and individual energy analysis

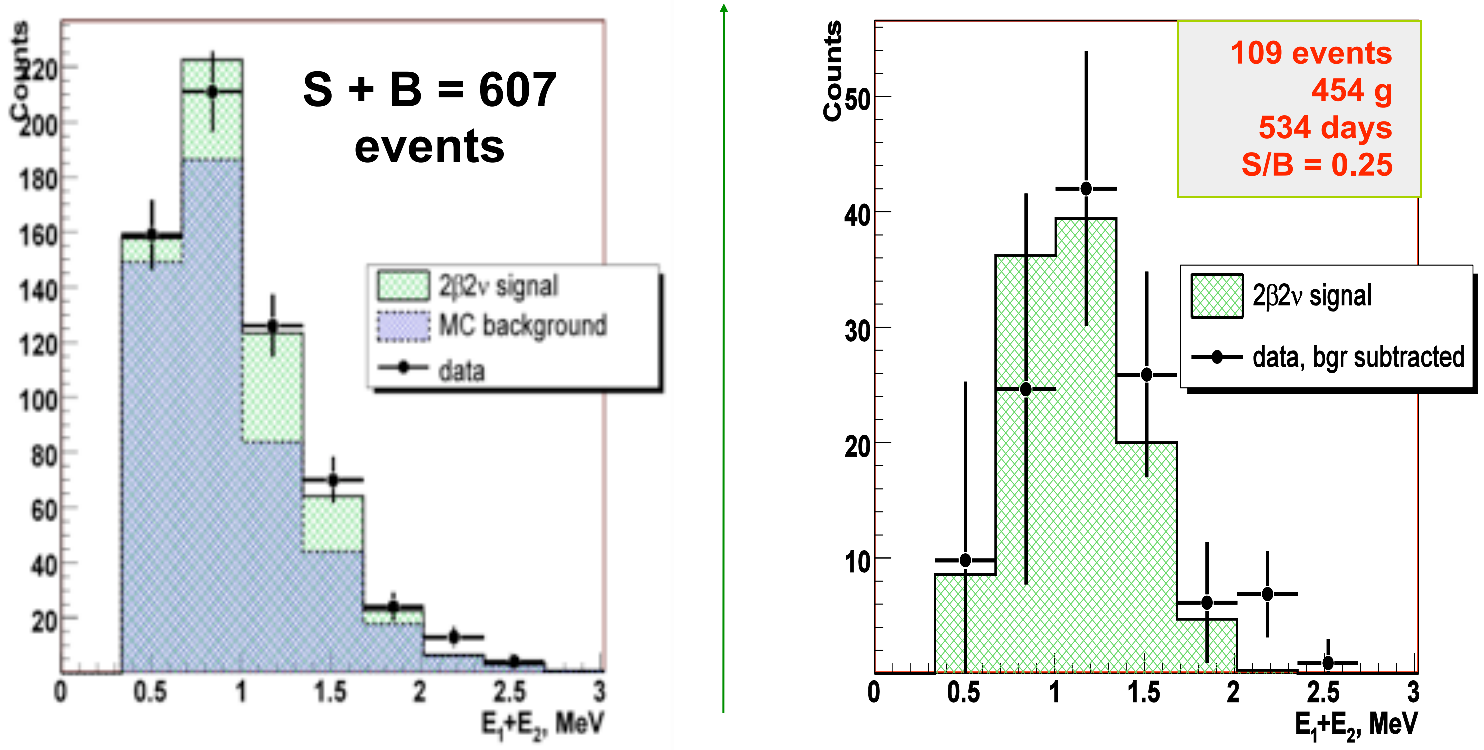
NEMO3 Results

Unprecedented accuracy of 2νββ measurements

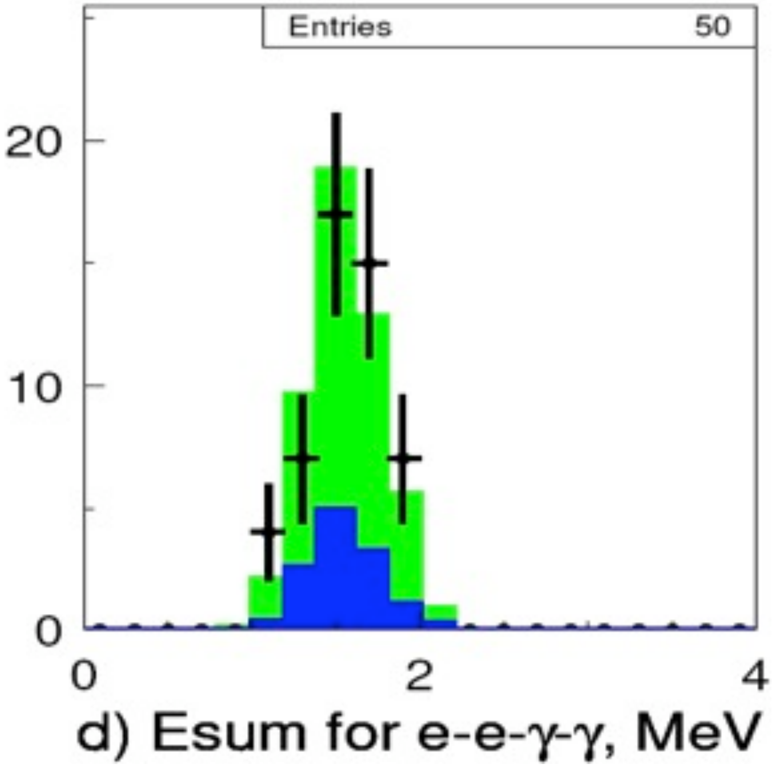
$T_{1/2}(\beta\beta 2\nu) = 7.11 \pm 0.02\ (\text{stat}) \pm 0.54\ (\text{syst}) \times 10^{18}$ yrs



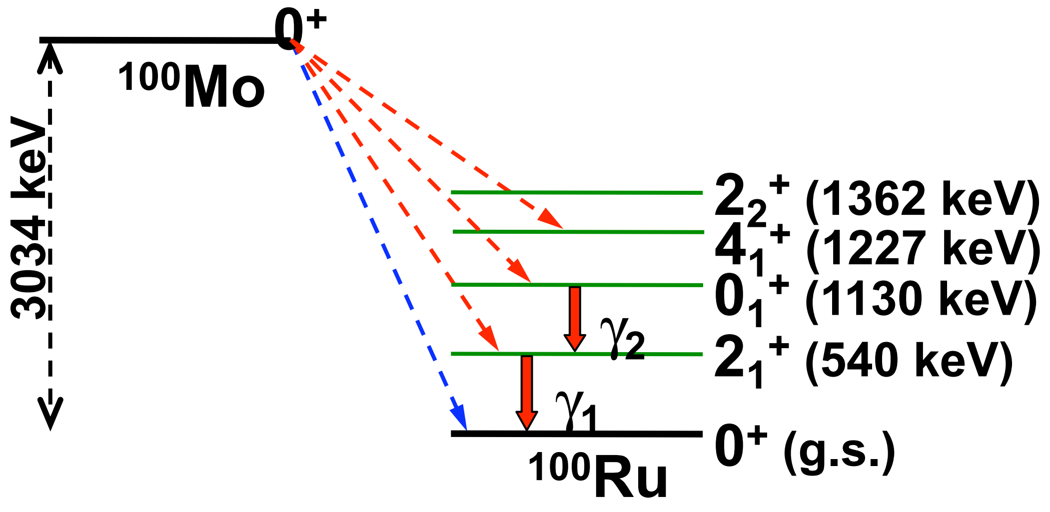
$T_{1/2} = [\,7.6 \pm 1.5\ (\text{stat}) \pm 0.8\ (\text{syst})\,] \times 10^{20}$ y (preliminary)



Long awaited ^{130}Te result



decay to excited states



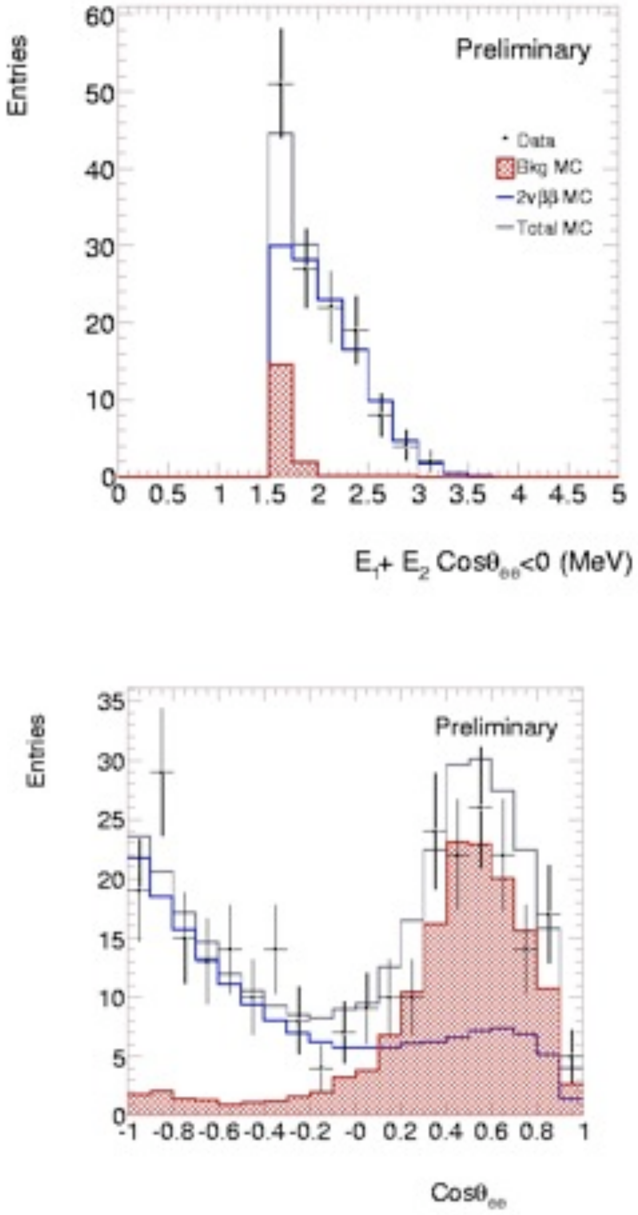
Also 2νββ measurements for ^{82}Se, ^{116}Cd, ^{150}Nd, ^{48}Ca, ^{96}Zr

NEMO3 Results

New results reported at Neutrino'08, Christchurch, New Zealand, May'08

^{48}Ca

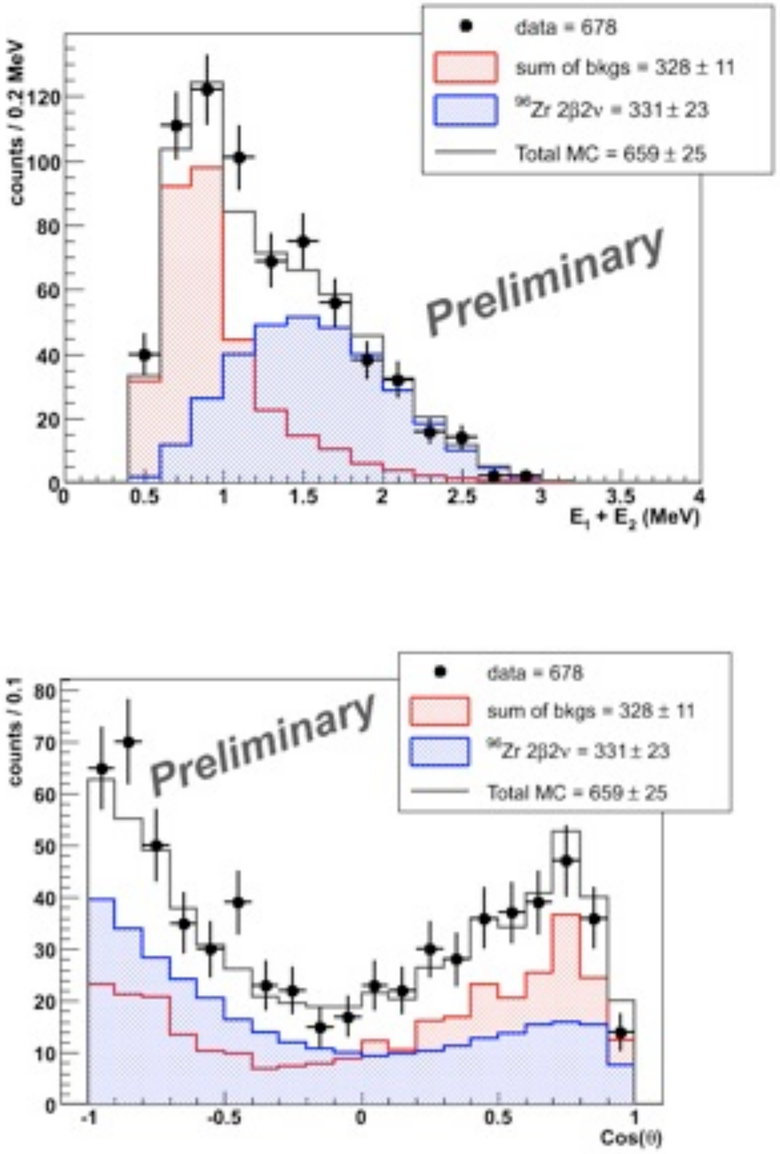
$T_{1/2}(2\nu\beta\beta) = [4.4\ ^{+0.5}_{-0.4}\ (\text{stat}) \pm 0.4\ (\text{syst})] \times 10^{19}$ y



paper in preparation

^{96}Zr

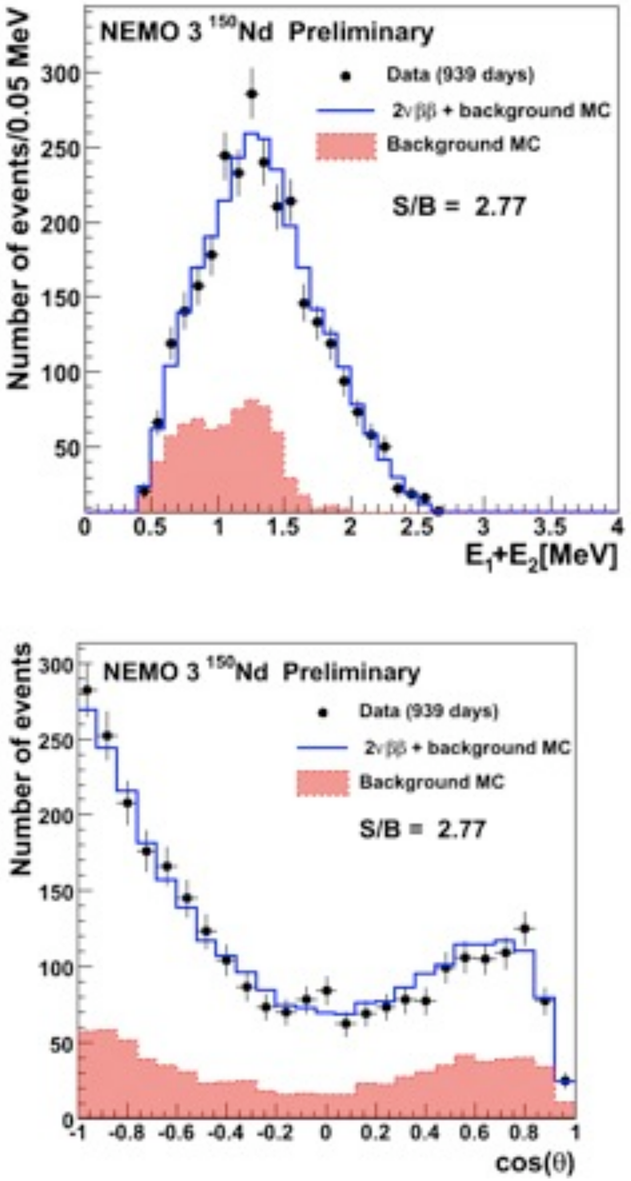
$T_{1/2}(2\nu\beta\beta) = [2.3 \pm 0.2(\text{stat}) \pm 0.3(\text{syst})] \times 10^{19}$ y



paper about to be submitted to Nucl. Phys. A

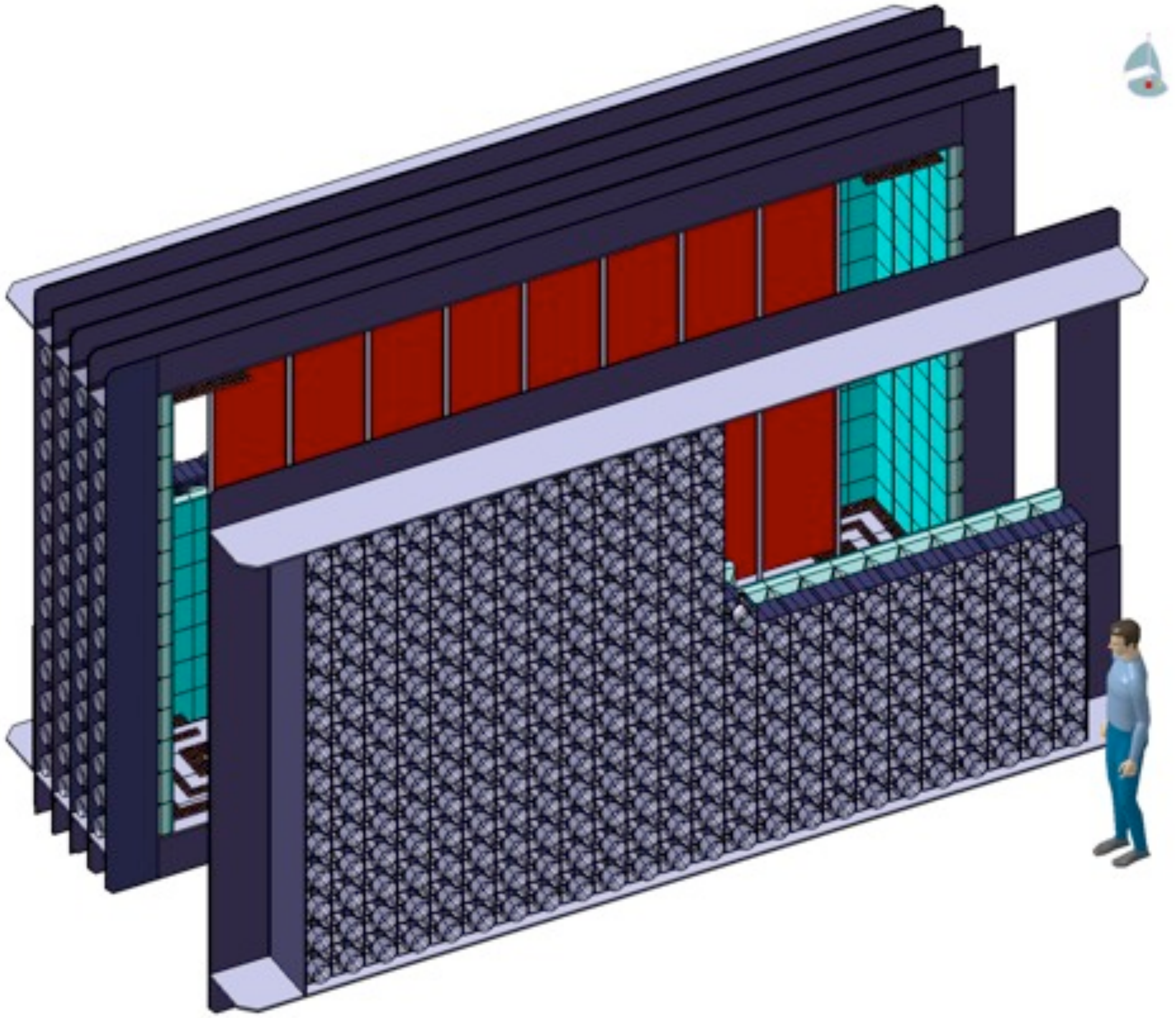
^{150}Nd

$T_{1/2}(2\nu\beta\beta) = [9.20\ ^{+0.25}_{-0.22}\ (\text{stat}) \pm 0.62\ (\text{syst})] \times 10^{18}$ y



submitted to PRL

SuperNEMO Detector



Planar and modular design:
~ 100 kg of enriched isotopes
(20 modules x 5 kg)

1 super-module:

Source (40 mg/cm^2)   4 x 3 m^2

Tracking : drift chamber

~2000 cells in Geiger mode

Calorimeter: scintillators + PMTs

- **~ 700 PMTs if scint. blocks**
- **~ 250 PMTs if scint. bars**

Modules surrounded by water passive shielding in an underground lab (new-LSM)

Funded Design Study
2006-2009

Calorimeter $\Delta E/E = 7\%/\sqrt{E}$ (MeV) $\Rightarrow$ 4% at $Q_{\beta\beta}$

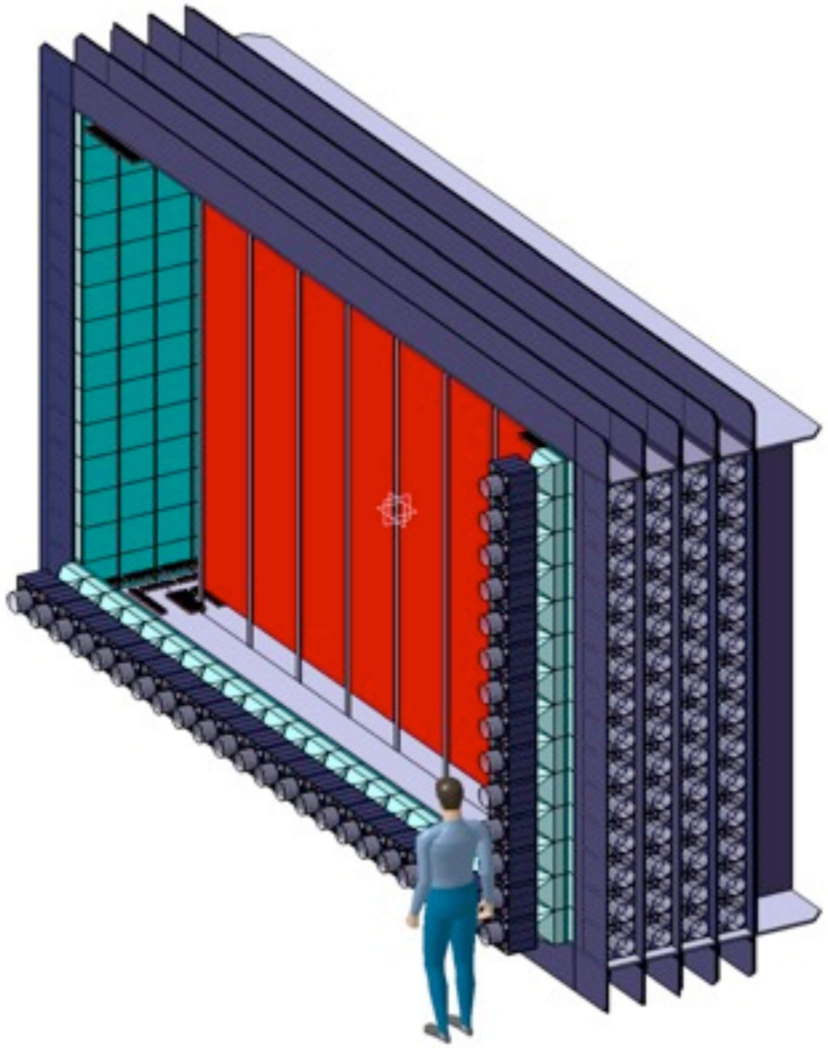
Source radiopurity: ^{208}Tl < 2 µBq/kg,
^{214}Bi < 10 µBq/kg (if ^{82}Se)

Tracker optimization – automated wiring

All deliverables on track to be completed by mid-2009

Next step: To build 1st SuperNEMO module - Demonstrator

Goals



- Demonstrate feasibility of large scale mass production
- To measure backgrounds especially from radon emanation
  - Only possible with a realistic super-module
- To finalise detector design
- To produce a competitive physics measurement

↓

Simple counting experiment: 0.3 bkg. events in R.O.I
with 7kg of ^{82}Se in 1.5 yr

$$T_{1/2}^{0\nu}(90\%CL) > \frac{M}{A} N_A \frac{\varepsilon \ln 2}{n_{90\%}} t = \frac{7kg \cdot 10^3}{82g} 6 \cdot 10^{23} \frac{0.3 \cdot 0.69}{2.4} 1.5 yr = 6.6 \cdot 10^{24}\, yr$$

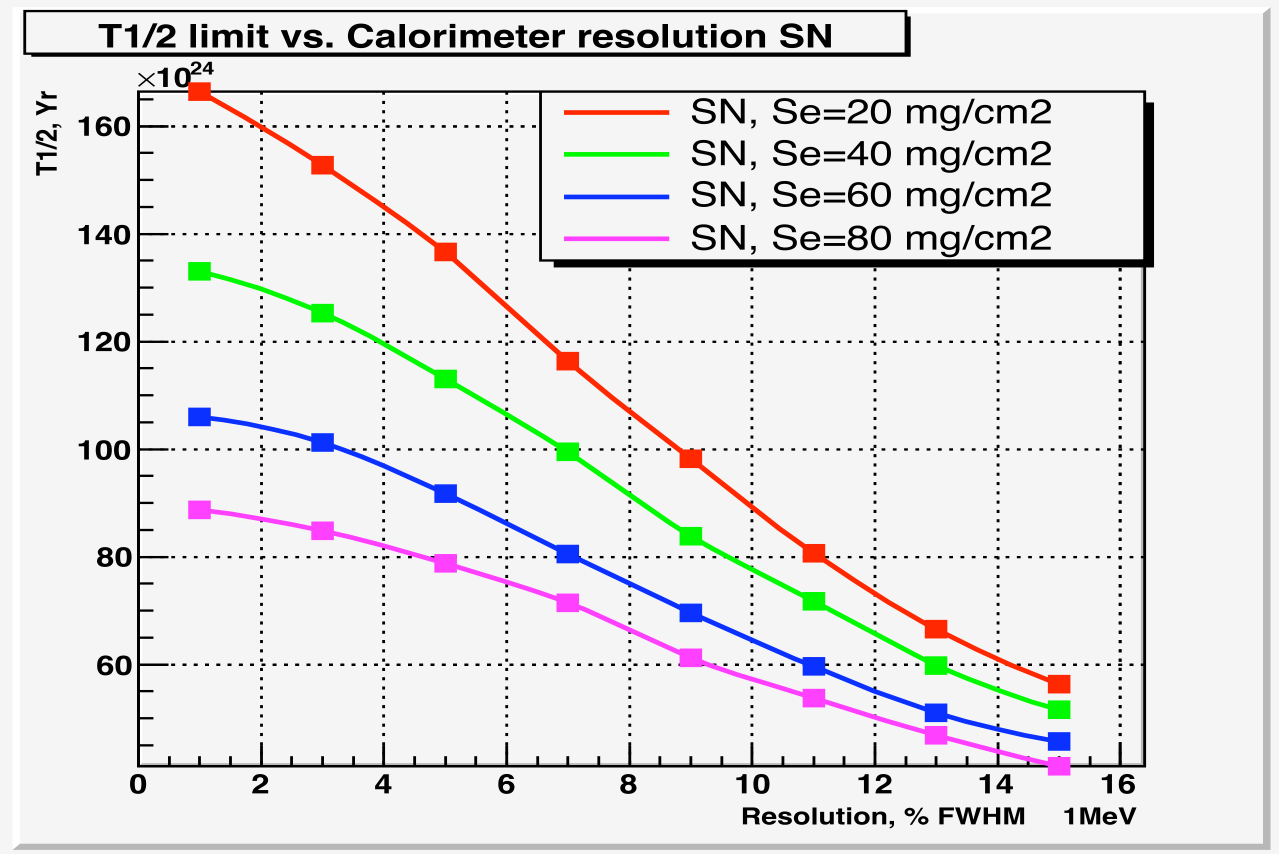
Assuming equal NMEs and known differences in phase space values,
it is equivalent to **$3 \cdot 10^{25}$ yr** for ^{76}Ge (GERDA-PhaseI)

or ~5 expected "golden events" if Klapdor is right

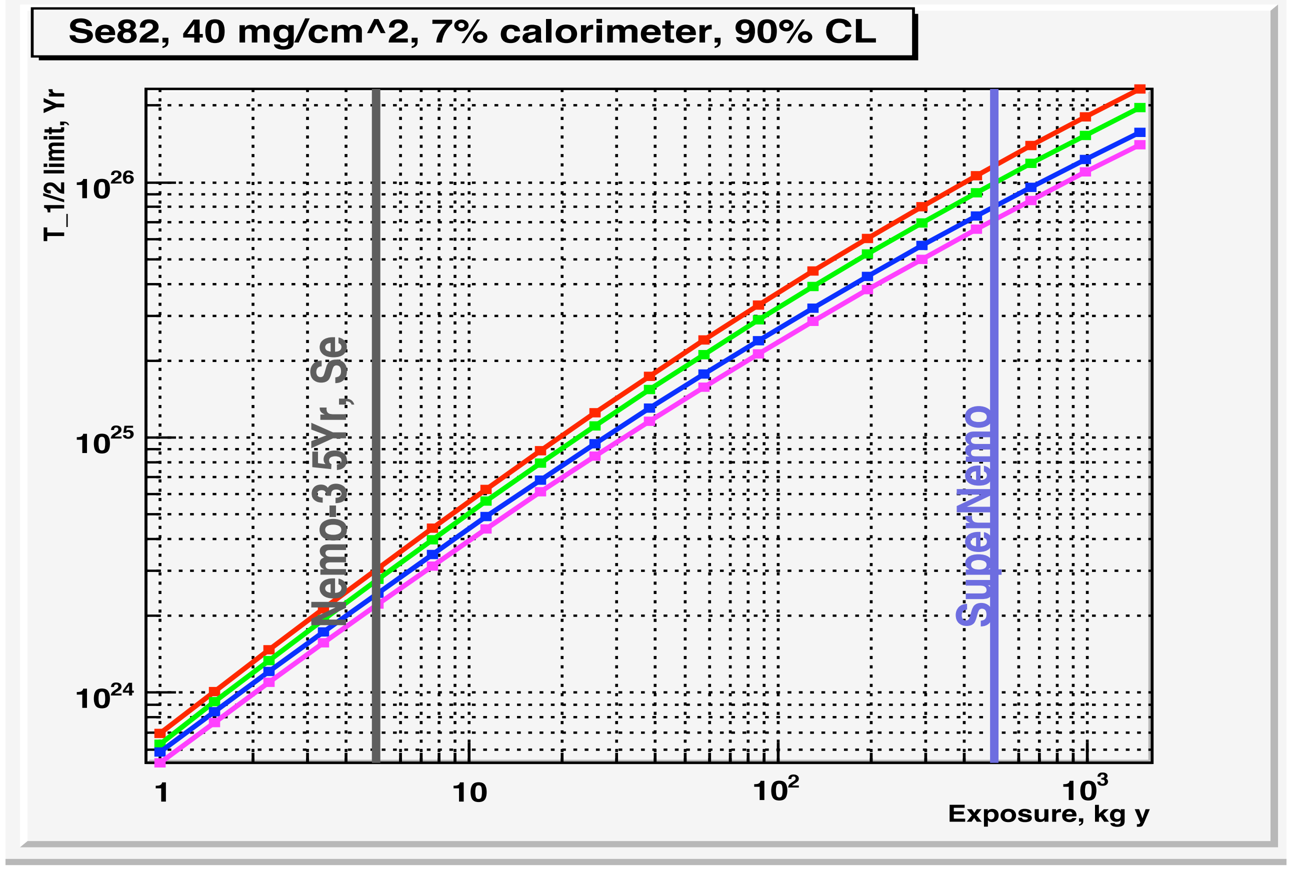
Proposal submitted to PPRP

SuperNEMO sensitivity:

500 kg x yr, target bkg levels (2 and 10 µBq/kg of ^{208}Tl and ^{214}Bi)



T1/2 limit vs. Calorimeter resolution SN



Se82, 40 mg/cm^2, 7% calorimeter, 90% CL

^{82}Se:

$T_{1/2}(0\nu) = 10^{26}$ yr

$<m_\nu> \leq 0.06 - 0.11$ eV

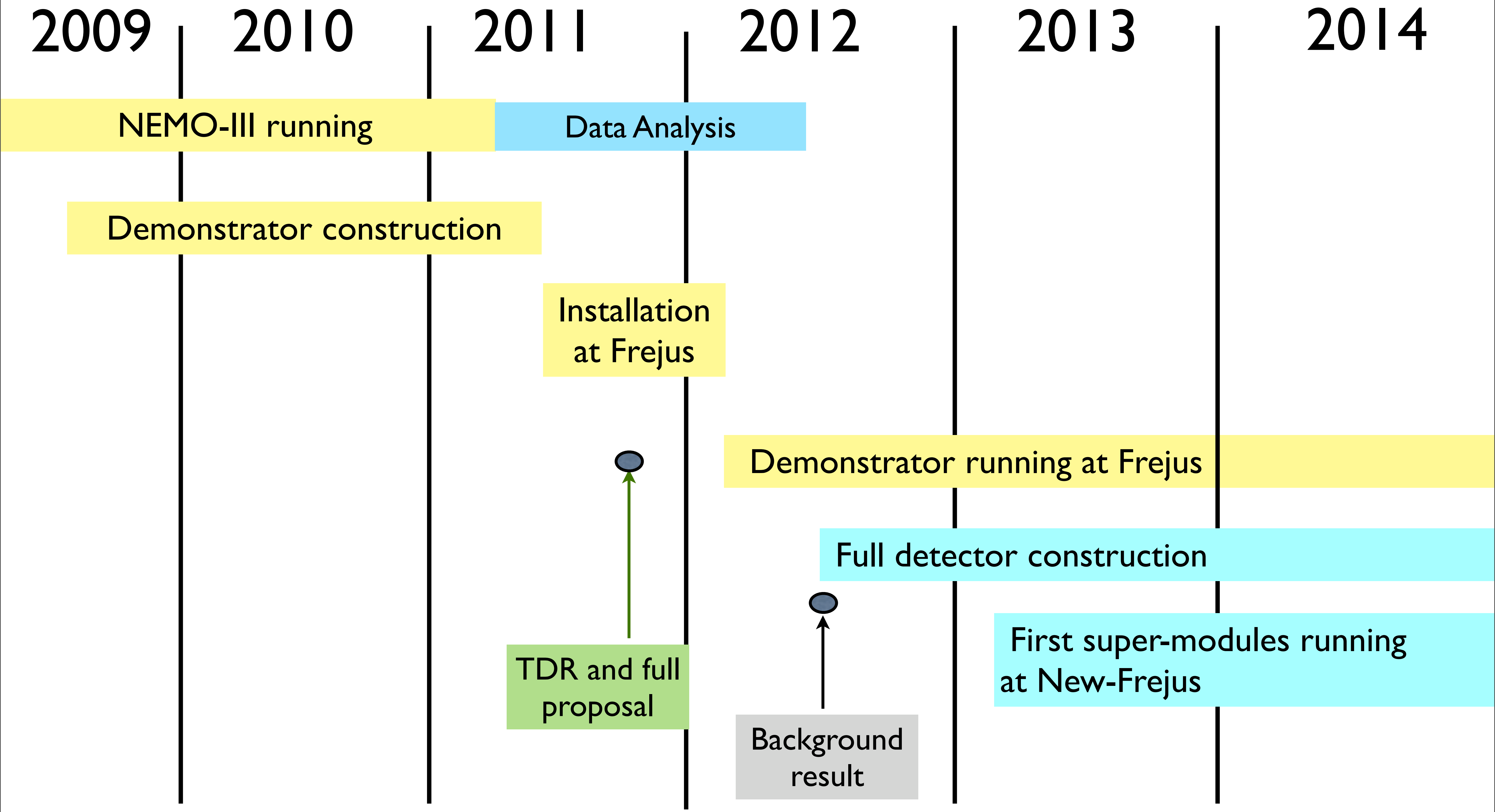
(range due to Nuclear Matrix Element uncertainties)

^{150}Nd:

$T_{1/2}(0\nu) = 5\ 10^{25}$ yr $<m_\nu> \leq 0.045$ eV

(but deformation **not** taken into account)

SuperNEMO schedule overview



2009 2010 2011 2012 2013 2014

NEMO-III running

Data Analysis

Demonstrator construction

Installation at Frejus

Demonstrator running at Frejus

Full detector construction

First super-modules running at New-Frejus

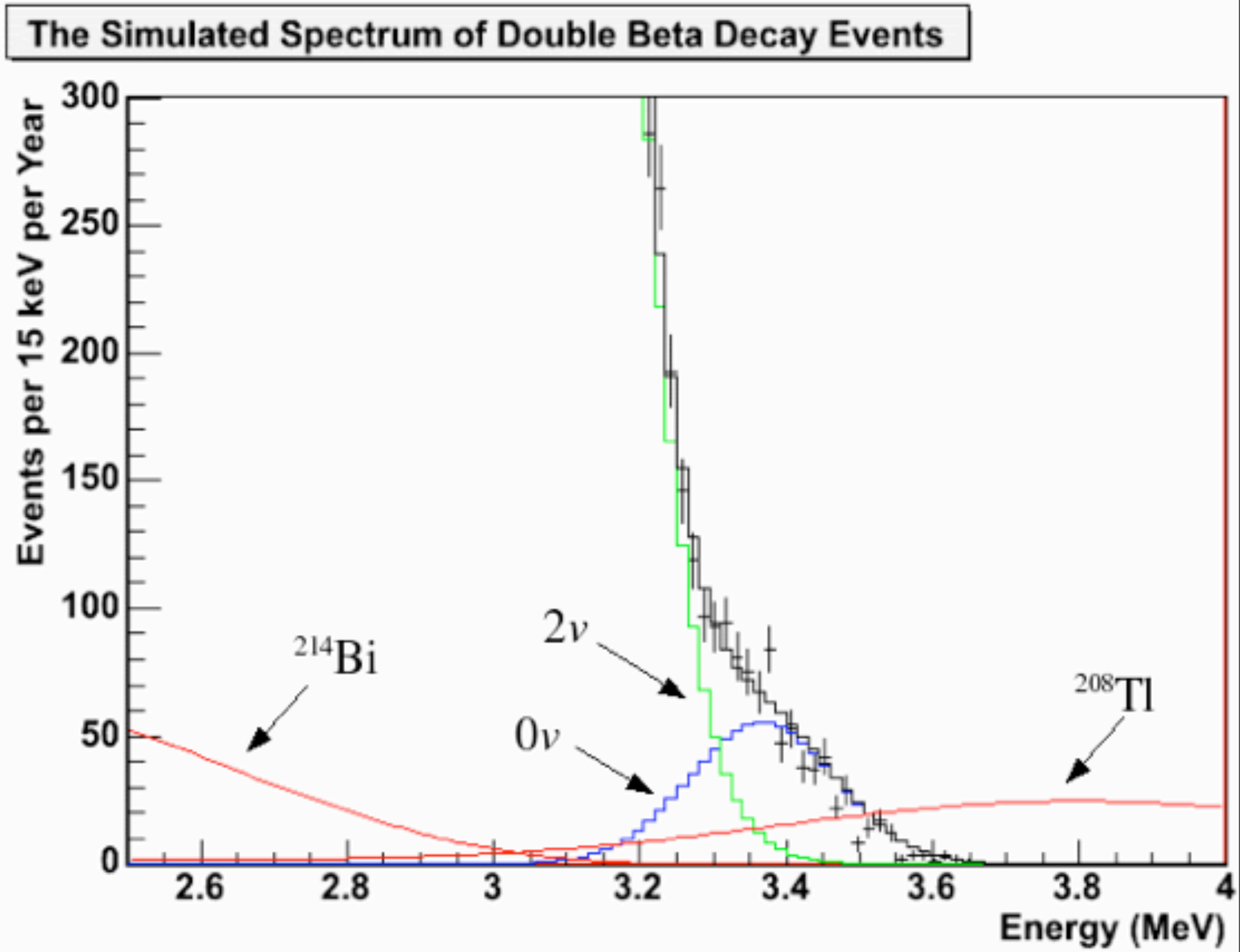
TDR and full proposal

Background result

Target sensitivity of 50-100 meV by 2018

SNO+

simulation of one year of data testing$\langle m_\nu \rangle$ = 150 meV (500kg of ^{150}Nd)



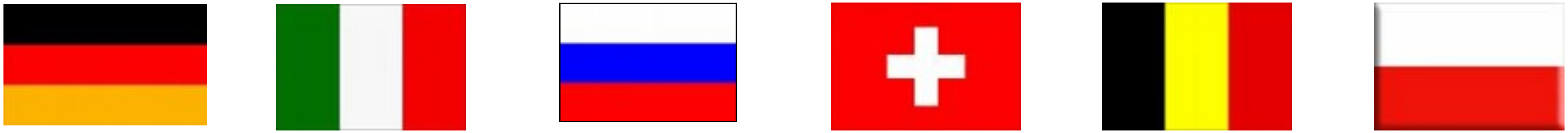
- **^{150}Nd double beta decays with an endpoint of 3.37 MeV (above most backgrounds).**
- **Poor energy resolution compensated by**
  - **little material near fiducial volume**
  - **meters of self-shielding**
  - **source in–source out capability**

- Nd-loaded liquid scintillator
- 0.1% ^{nat}Nd in 1000 t of liquid scintillator
  - 56 kg of ^{150}Nd
- 0.1 eV* sensitivity with ^{nat}Nd
  - Quick “turnaround”
  - ^{nat}Nd radio-purity is one of key questions (10^{-14} g/g in U and Th required)
- Possibility to enrich Nd with AVLIS (joint R&D with SuperNEMO)
- If enriched, 50 meV* sensitivity possible

UK participation proposal submitted to PPRP

*^{150}Nd deformation not taken into account in NME calculation

GERDA. ^{76}Ge



^{76}Ge – best way to check KKDC claim (free from NME uncertainties).

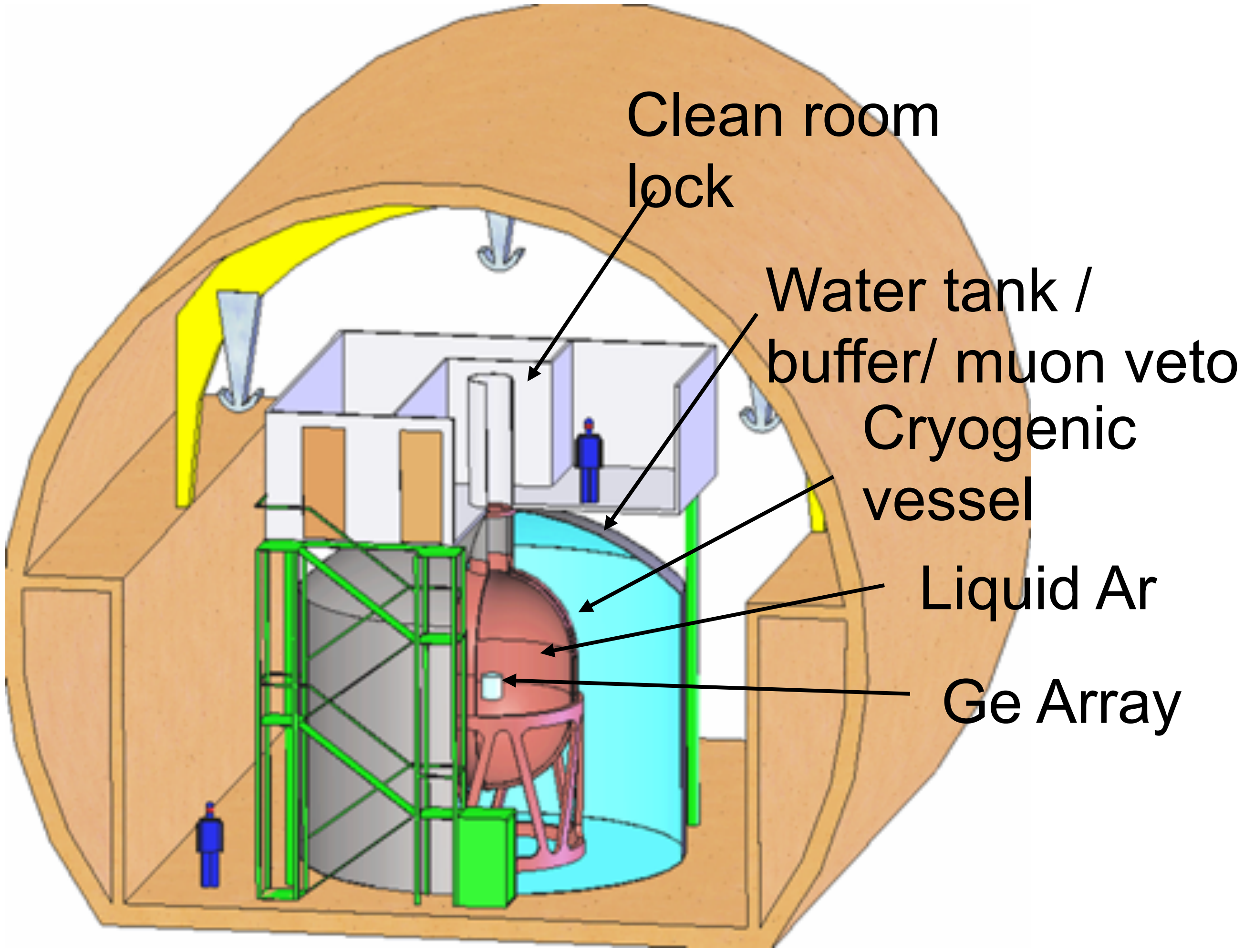
Naked enriched (86%) Ge-detectors
in LAr
Phased Approach.

Phase I:
Existing detectors (HM+IGEX)
17.9 kg enriched diodes
Bkg free proble of KKDC:
10^{-2} cts/kg keV yr

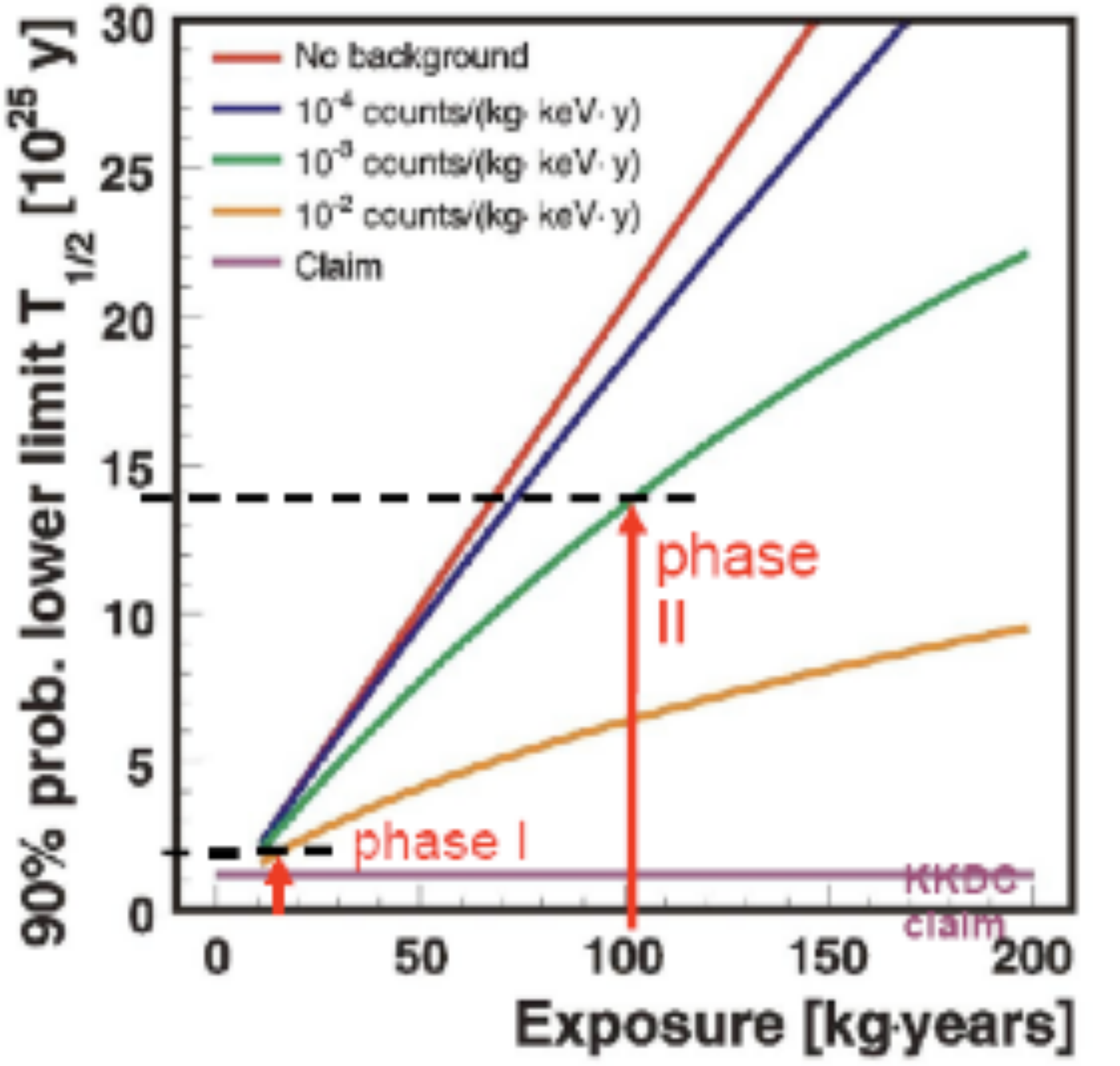
Phase II
Add new diodes (total: 40kg)
Bkg < 10^{-3} cts/kg keV yr

Both phases funded. Under construction

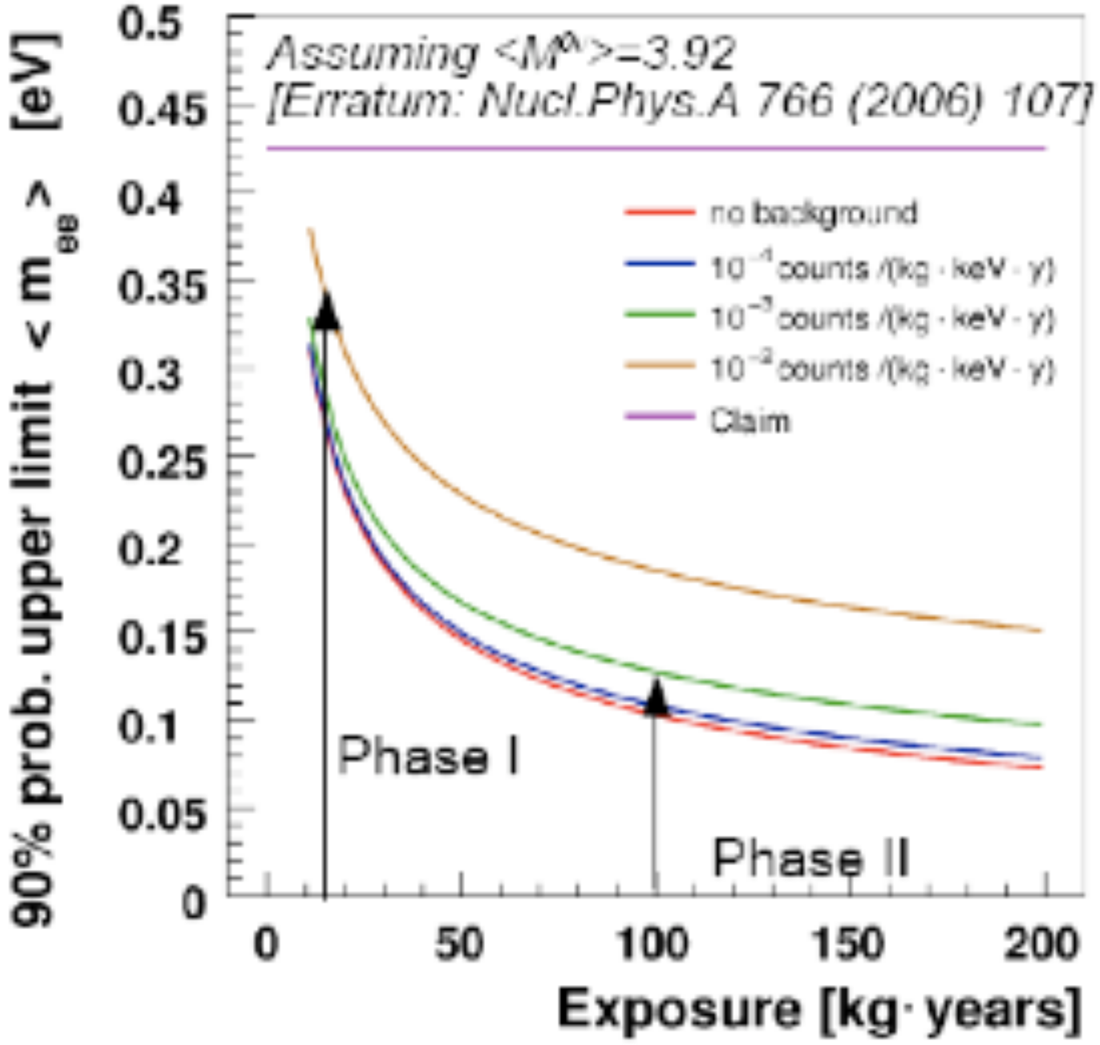
Location: Gran Sasso



Next step: GERDA + Majorana



assumed energy resolution: ΔE = 4 keV



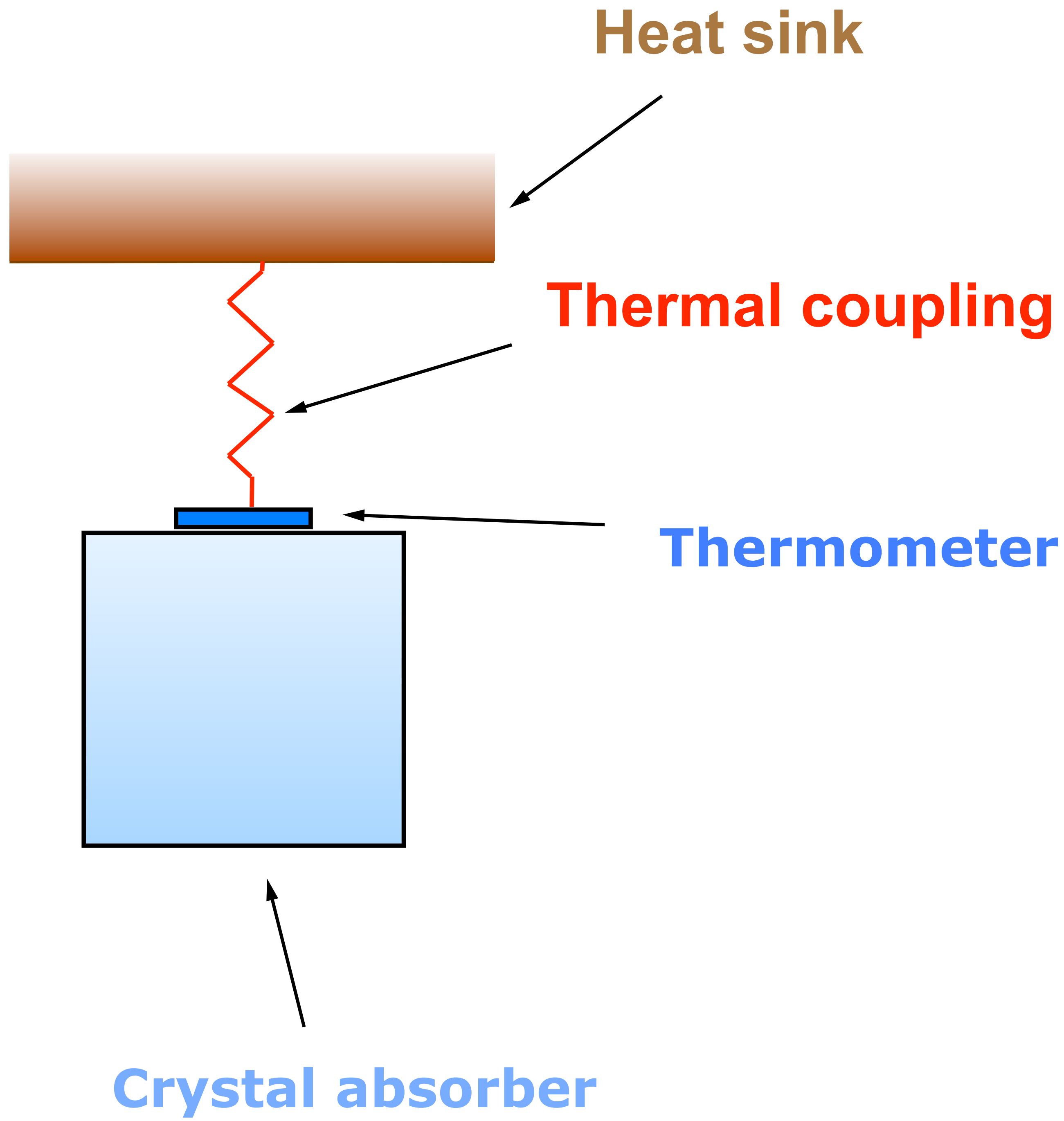
PhaseI (~15kg): Start data taking 2009

Phase III: GERDA + Majorana toward 1 ton detector

Depends heavily on background achieved in first two phases

CUORICINO Detection Principle (Bolometer)

CUORICINO and NEMO-III are the only running DBD experiments at the moment



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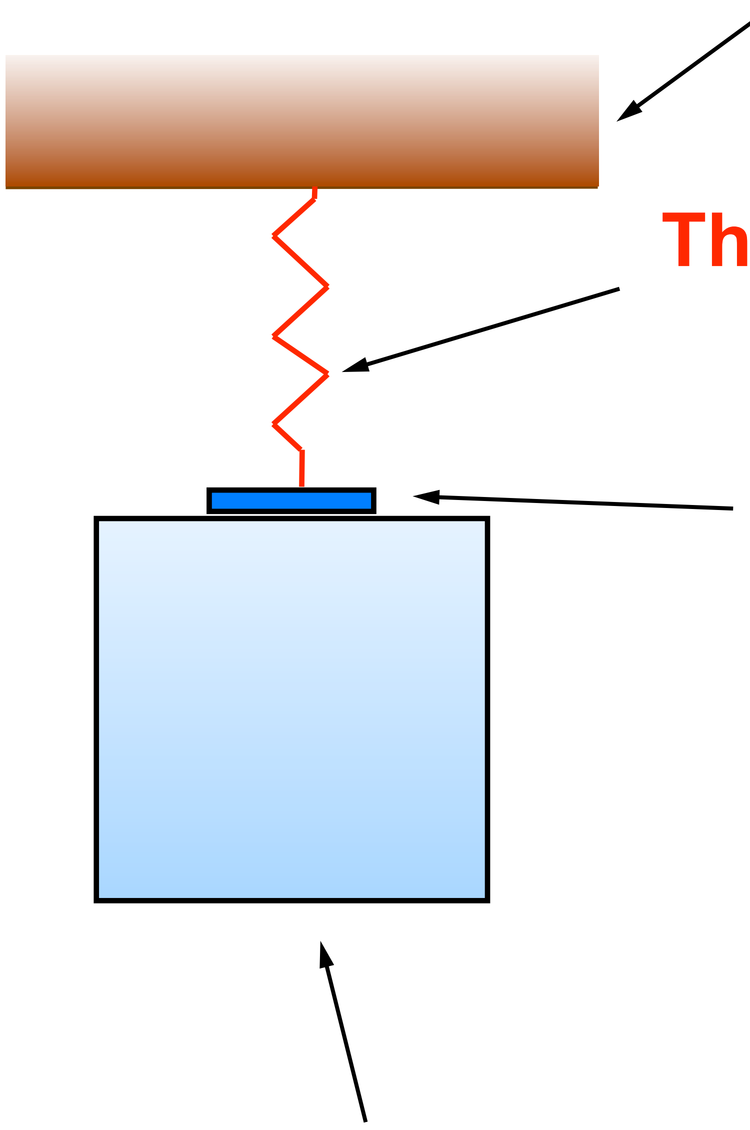
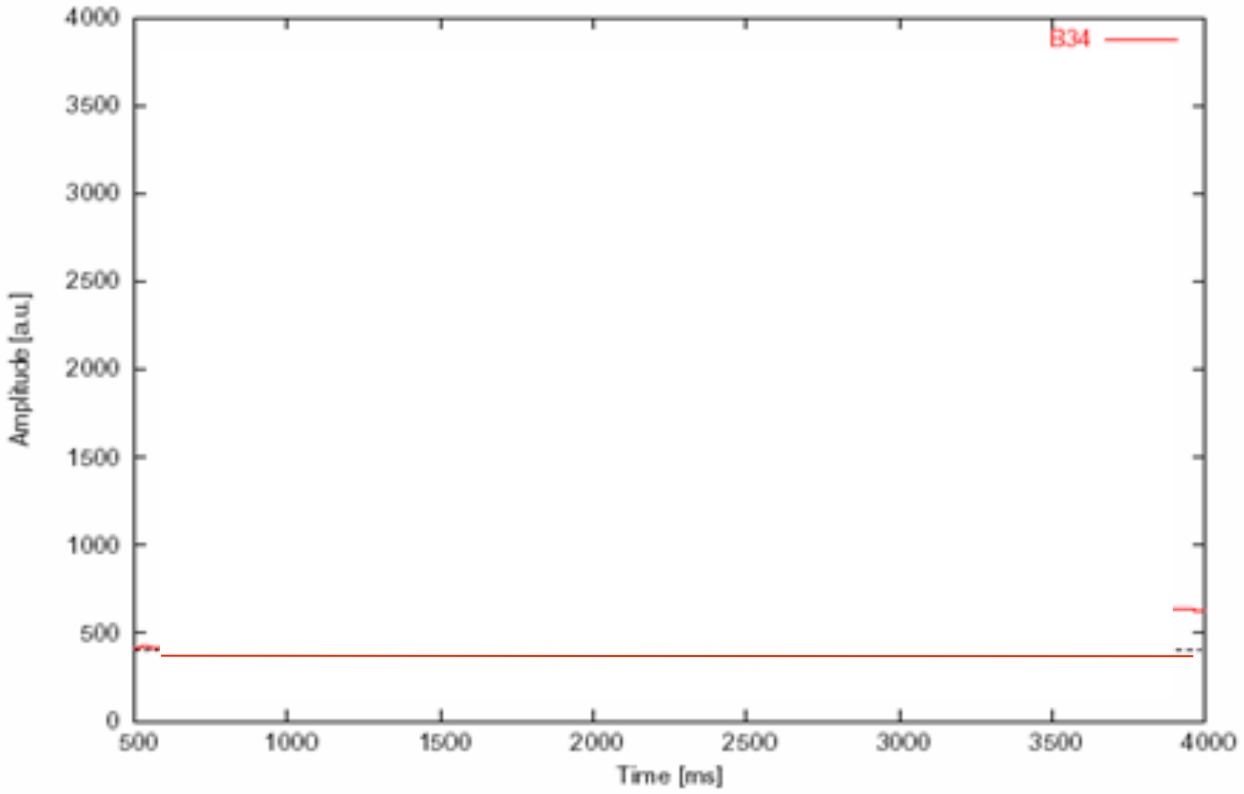


Heat sink

Thermal coupling

Thermometer

Crystal absorber



CUORICINO Detection Principle (Bolometer)

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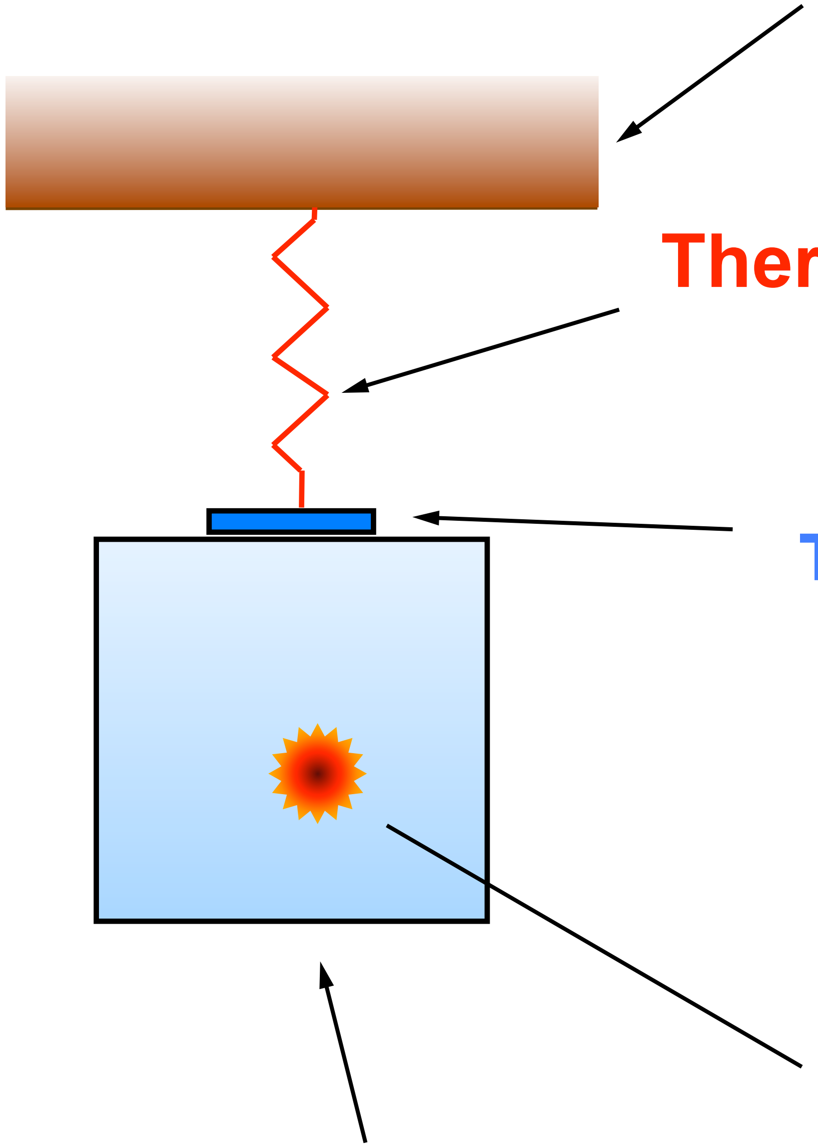


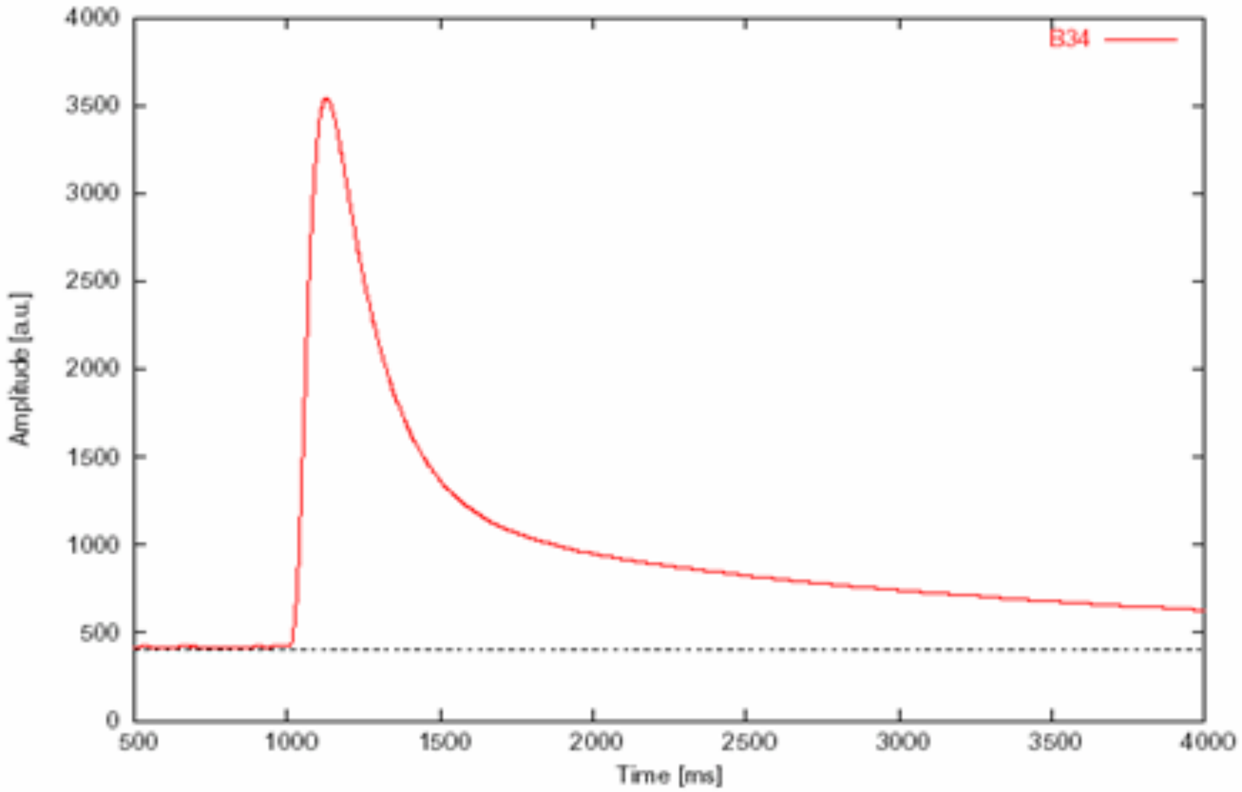
Heat sink

Thermal coupling

Thermometer

incident particle

Crystal absorber



CUORICINO Detection Principle (Bolometer)

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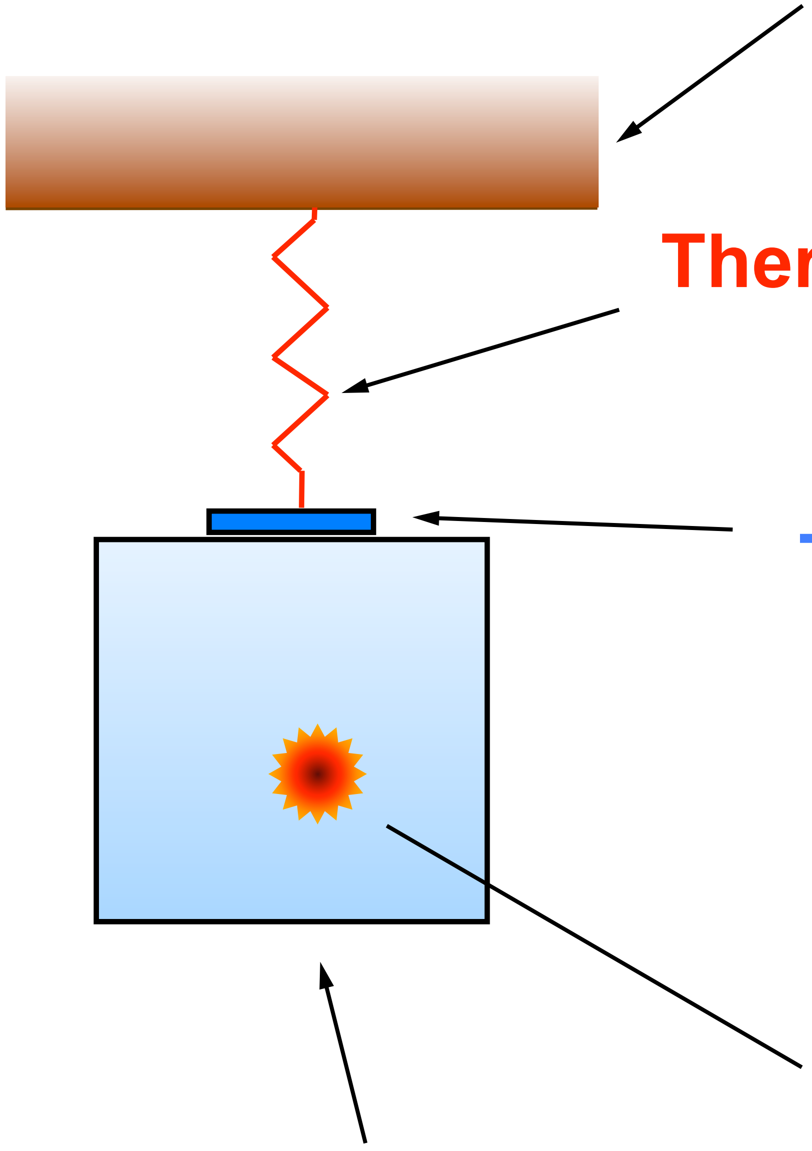


Heat sink

Thermal coupling

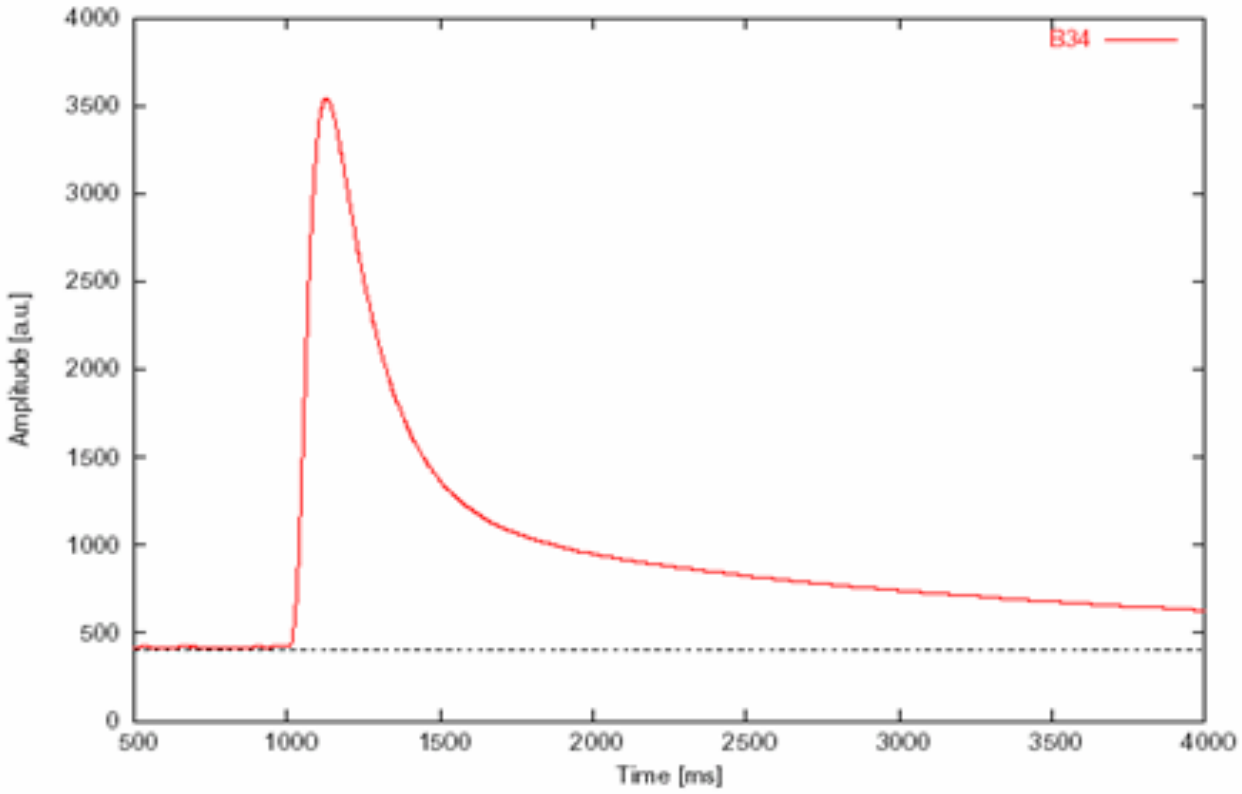
Thermometer

incident particle

Crystal absorber

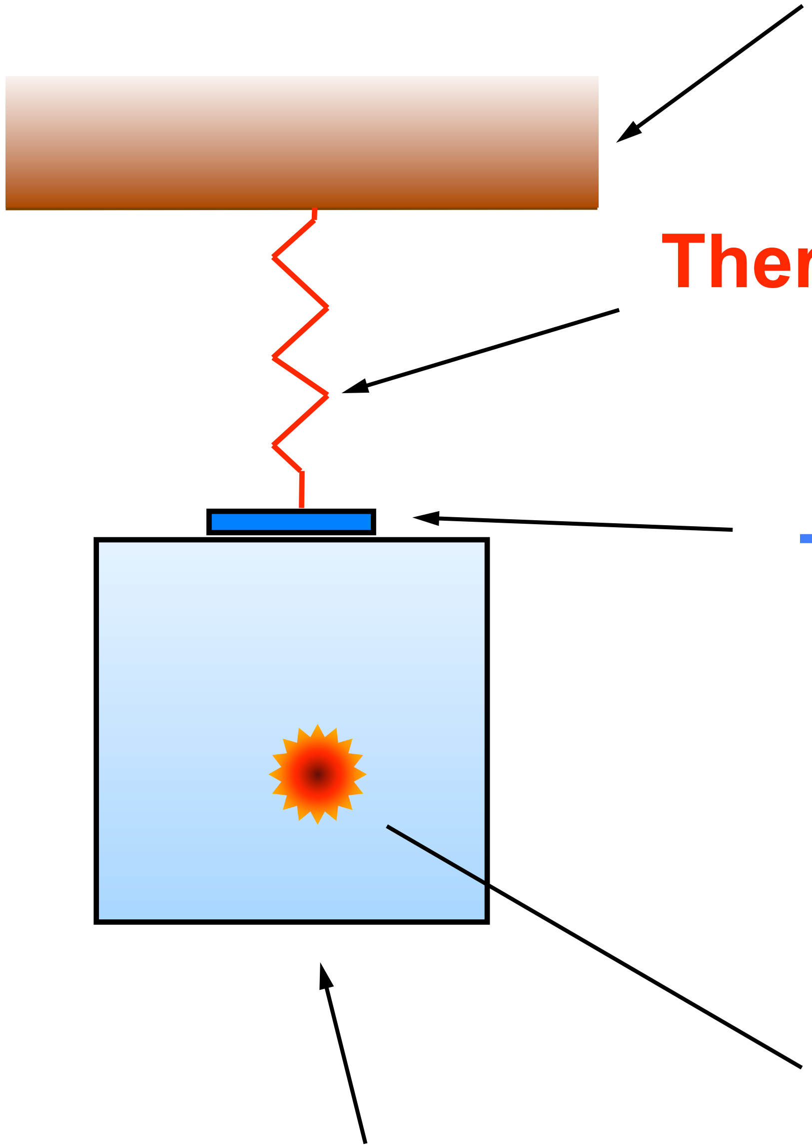
In a monolithic thermal model:
thermal signal

$$\boxed{\Delta T = E/C}$$



CUORICINO Detection Principle (Bolometer)

CUORICINO and NEMO-III are the only running DBD experiments at the moment



Heat sink

Thermal coupling

Thermometer

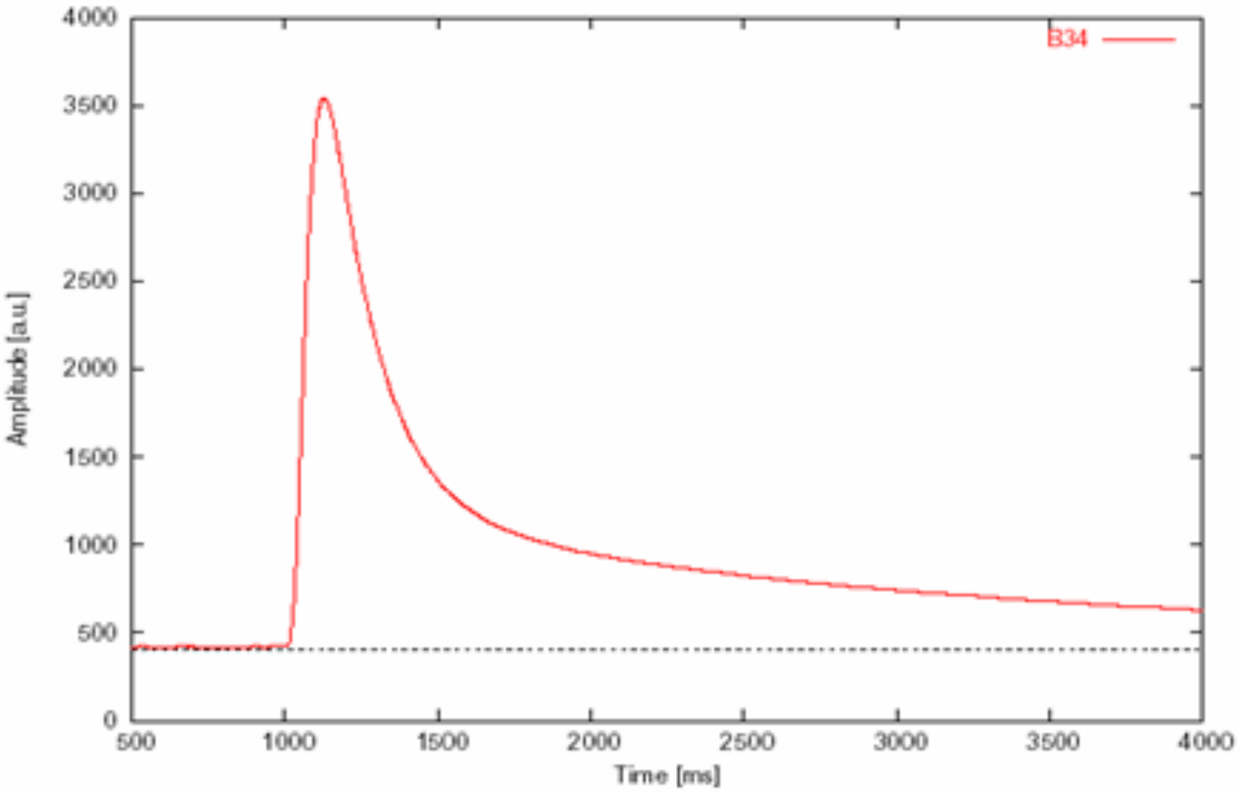
incident particle

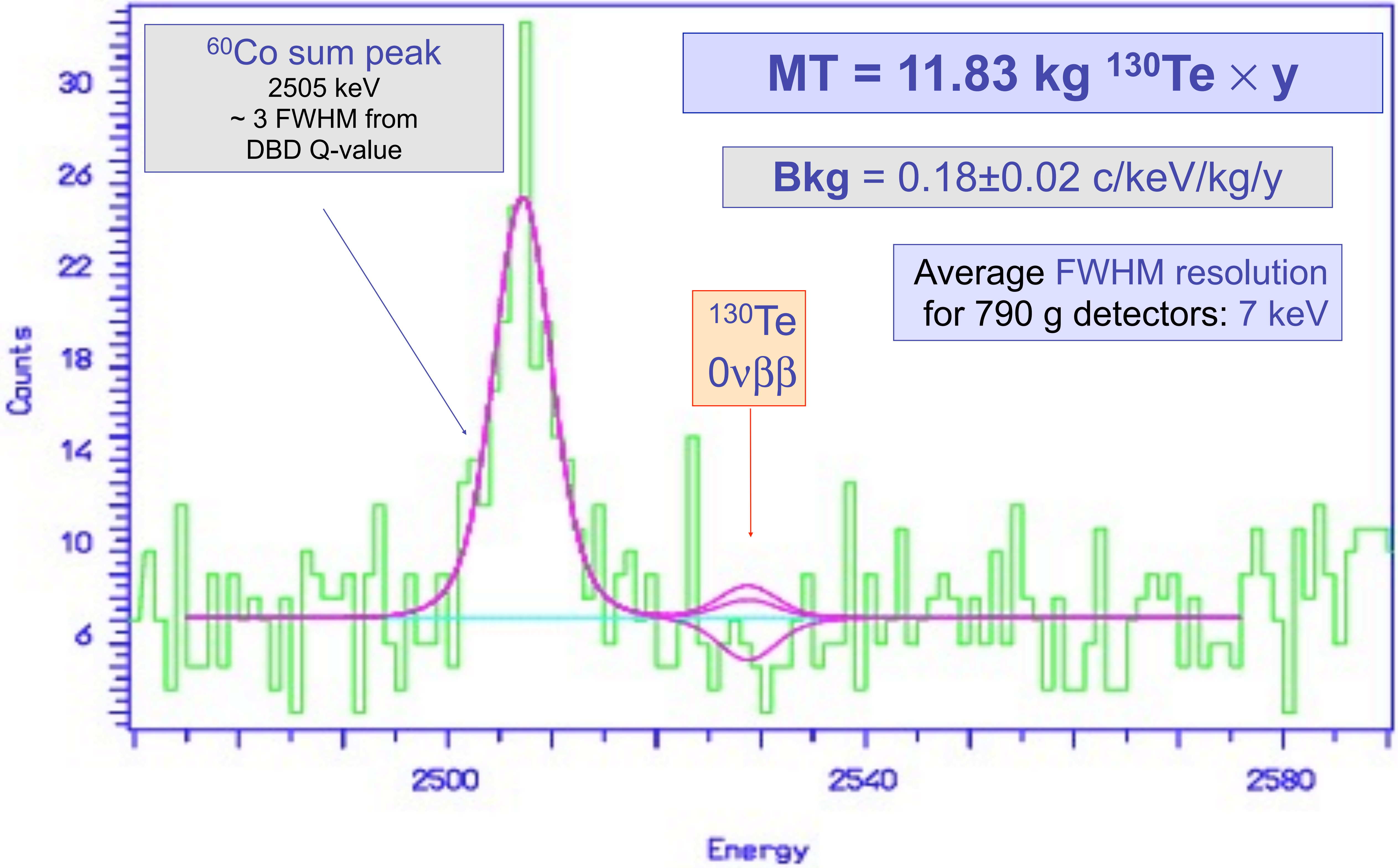
Crystal absorber

In a monolithic thermal model: thermal signal

$$\boxed{\Delta T = E/C}$$

The detector has to work at low temperature (10 mk) in order to develop high pulses





^{60}Co sum peak
2505 keV
~ 3 FWHM from
DBD Q-value

MT = 11.83 kg ^{130}Te × y

Bkg = 0.18±0.02 c/keV/kg/y

Average FWHM resolution
for 790 g detectors: 7 keV

^{130}Te
$0\nu\beta\beta$

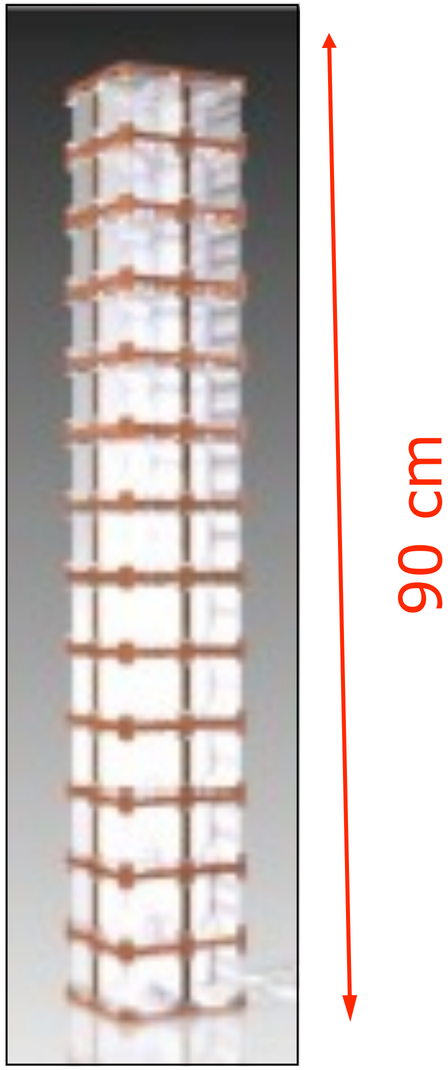
$\tau_{1/2}^{0\nu}$ (y) > 3.0 × 10^{24} y (90% c.l.)

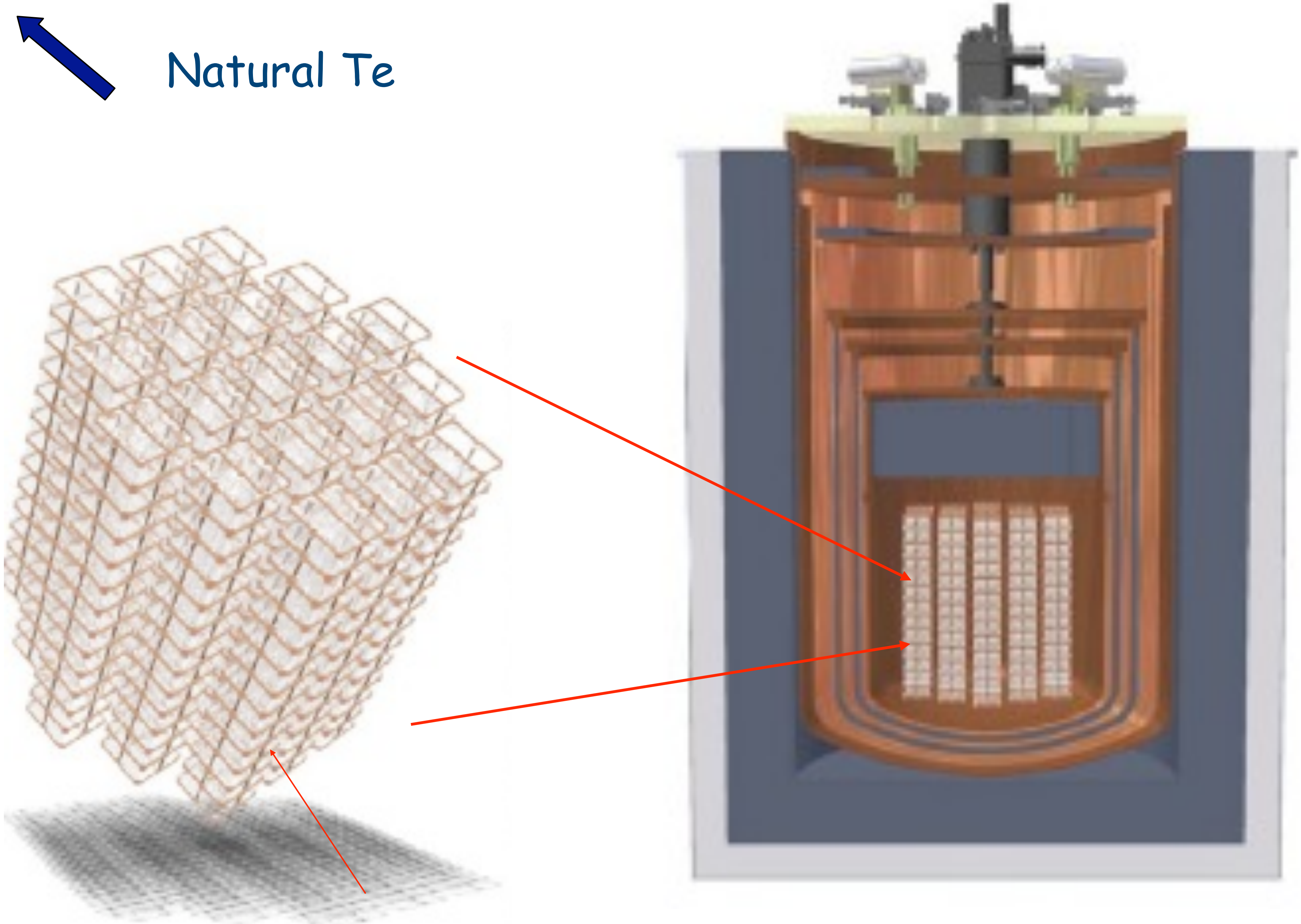
$\langle M_{\beta\beta} \rangle < 0.20 - 0.98$ eV

CUORE. ^{130}Te

Array of 988 detectors:
19 Cuoricino-like towers.
⇒ M = 0.741 ton of TeO_2
⇒ M = 600 kg of Te
⇒ M = 203 kg of ^{130}Te

Natural Te





19 CUORICINO-like towers

Main background: Surface contamination close to fiducial volume
(Recall CUORICINO background level 0.18±0.02 c/keV/kg/y)

Two-pronged approach to tackle this background:
Passive ⇒ surface cleaning
Active ⇒ event ID:

- Surface sensitive bolometers
- Scintillating bolometers

Enrichment is also possible

Expected sensitivities (5 years of data)

"Baseline" scenario	**"Aggressive" scenario**
$N_{bckg}=0.01$ cts.keV^{-1}.kg^{-1}.yr^{-1}	$N_{bckg}=0.001$ cts.keV^{-1}.kg^{-1}.yr^{-1}
$T_{½} > 2.1\ 10^{26}$ yr	$T_{½} > 6.6\ 10^{26}$ yr
$<m_\nu> < 0.03 - 0.17$ eV	$<m_\nu> < 0.015 - 0.1$ eV

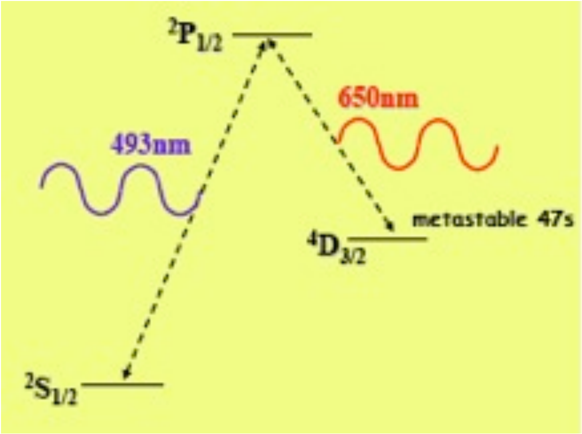
Planned start-up: 2011

Liquid Xe TPC

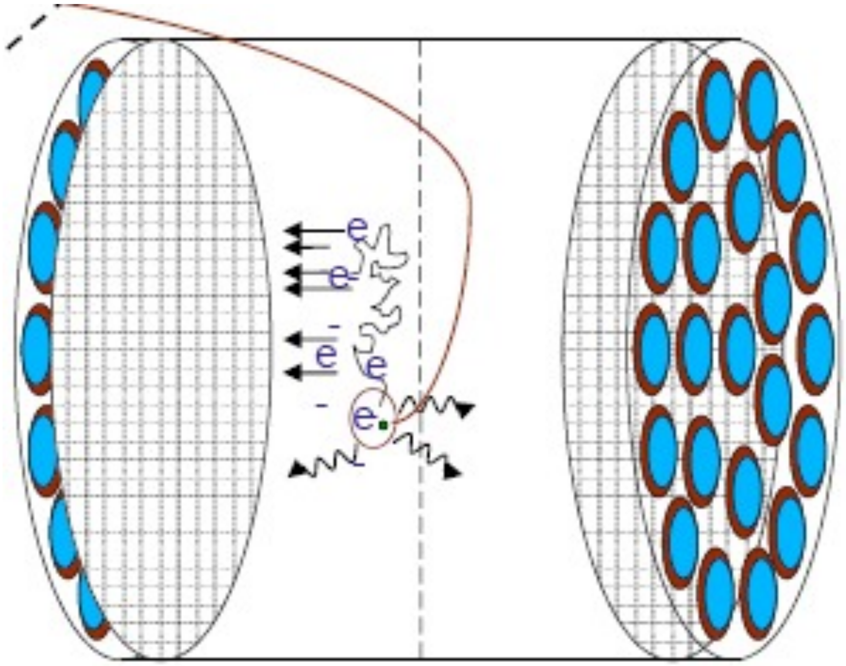
Energy measurement by ionization + scintillation

Tagging of Barium ion ($^{136}Xe \rightarrow {}^{136}Ba^{++} + 2\ e^-$)

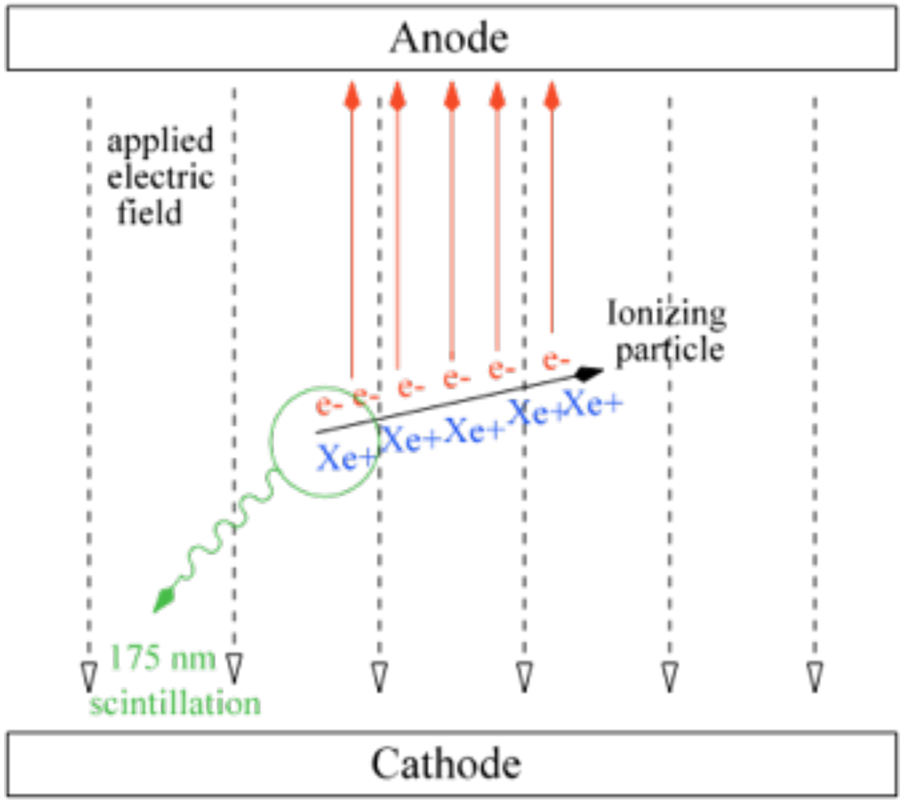
Optical spectroscopy with Ba+



Ion Grabber/mover



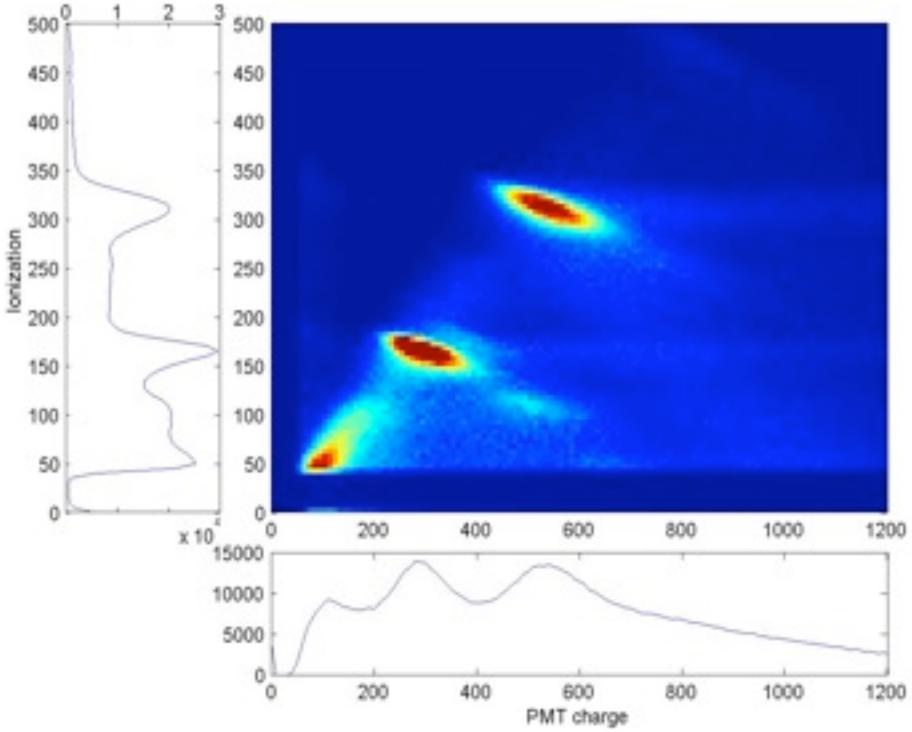
Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV)	
							QRPA‡	NSM#
Conservative	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	50	68
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	11	15



200 kg of LXe (80% enriched ^{136}Xe in hand)

No Ba+ tagging

Ionization + scintillation to improve $\Delta E/E$ and detect apha (BiPo bkg suppression)



Being installed in WIPP (New Mexico)

Physics run to start in 2009

Goals:

- Measure $2\nu\beta\beta$ of ^{136}Xe
- Search for $0\nu\beta\beta$ in ^{136}Xe with competetive
- sensitivity
  - $T_{1/2}^{0\nu} > 6.4\ 10^{25}$ y (after 2y)
- Understand the operation of a large LXe detector
  - Backgrounds
  - Resolution, Xe purification and handling

Apologies to

- Majorana
  - – US-based 76Ge experiment (segmented Ge detectors). Close collaboration with Ge. Merger between the two to go towards 1t.
- COBRA
  - – R&D with CdZnTe semi-conductor detectors (room-ish temperature). Very interesting potential with pixelated detectors. Main isotopes ^{116}Cd and ^{130}Te
- CANDLES
  - – Undoped CaF_2 scintillator crystal detectors. Isotope: ^{48}Ca. Start with natural, look into possibilities of enrichment in the future
- ....

Experiment	**Isotope**	**kg**	**$T_{1/2}$ yr, 90% CL**	**m_ν*, meV**	**Start-up timescale**	**Status**
HM	^{76}Ge	15	$>1.9\ 10^{25}$	230-560	1990	finished
KDHK claim	^{76}Ge	15	$(0.7\text{-}4.2)\ 10^{25}$ (3σ)	150-920	1990	finished
NEMO 3	^{100}Mo	7	$2\ 10^{24}$ (expect. 2010)	340-590	2003	running
CUORICINO	^{130}Te	11	$>3\ 10^{24}$ (current)	260-610	2002	running
CUORE	^{130}Te	210	$1.3\ 10^{26}$	40-92	2011	approved
GERDA, Phase I	^{76}Ge	15	$3\ 10^{25}$	180-440	2009	approved
Phase II	^{76}Ge	~31	$2\ 10^{26}$	70-170	2011	approved
EXO 200	^{136}Xe	160	$6.4\ 10^{25}$	270-380	2009	approved
EXO 1t	^{136}Xe	800	$2\ 10^{27}$	50-68	2015	R&D
SuperNEMO	**^{82}Se/^{150}Nd**	**100**	**$1\ 10^{26}$**	**45-110**	**2012**	**Design Study**
COBRA	^{116}Cd	151	$1.5\ 10^{26}$	38-96	?	R&D
SNO+	^{150}Nd	500	$(1\text{-}5)\ 10^{25}$	50-100 (?)	2012?	R&D

** Matrix elements from MEDEX'07*
or provided by experiments

Summary

- $0\nu\beta\beta$ is the only practical way to establish neutrino mass nature (Majorana vs Dirac) and understand if $\Delta L \neq 0$.
- Vibrant and rapidly growing field
- Results will come in from several x100kg experiments in near-ish future
  - Big potential for a major discovery
  - Necessary step to converge on 1-2 ton-scale detector technology(ies)