Recherche du neutrino de Majorana et de la ββ0ν

Xavier Sarazin   Séminaire LLR, Ecole Polytechnique, 30 Novembre 2009

Majorana Neutrino

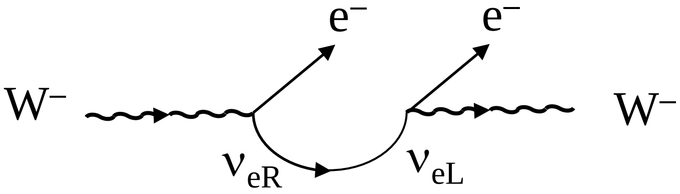
Neutrino is the only fermion with Q = 0

$\Rightarrow$ Neutrino might be a **Majorana particle** $\nu = \bar{\nu}$

Only two ν states:

$$|\nu_L, h = -1/2 > \xrightarrow{CPT} |\nu_R, h = +1/2 >$$

Massive Majorana neutrino $\Rightarrow$ Violation of the Leptonic Number



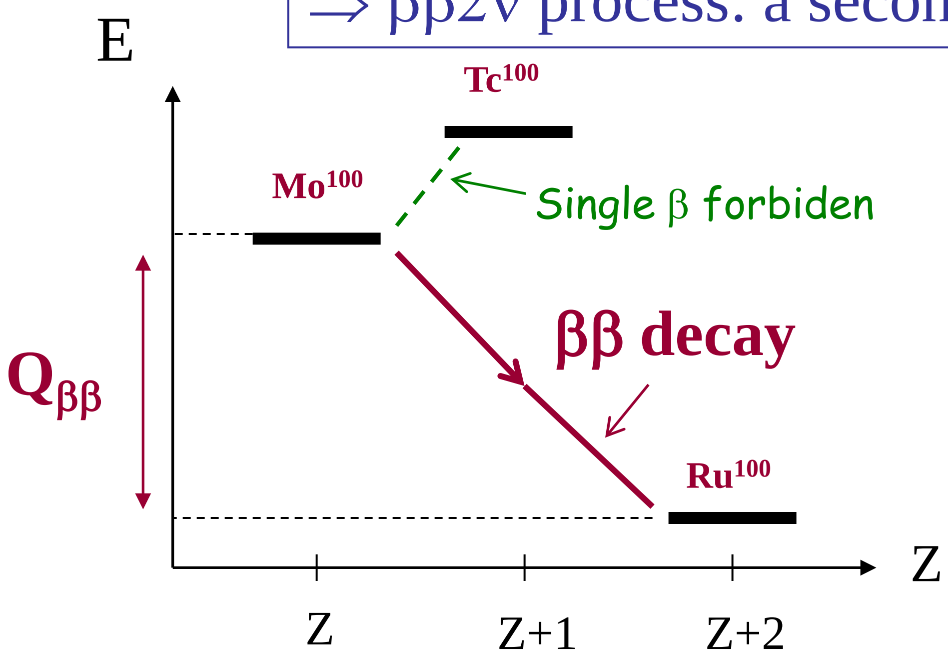
Theorists already uses the Majorana neutrino in mechanisms beyond the Standard Model:

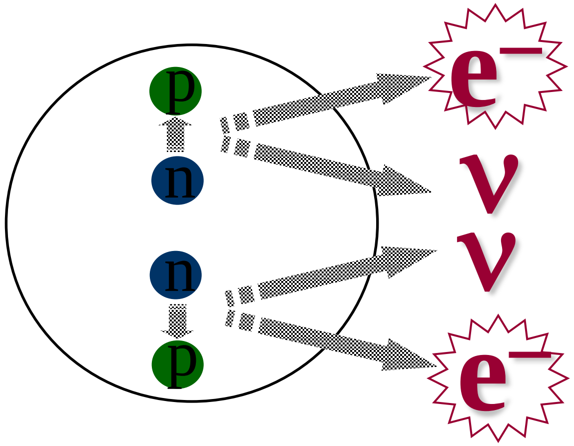
- Leptogenesis in the Early Univers through the Majorana neutrino to produce the observed Mater/AntiMater asymetry
- See-saw mechanism to explain the small mass of the neutrino

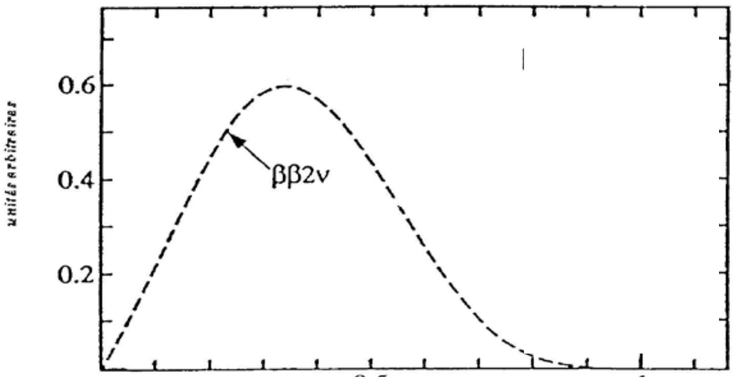
***Question:** if antigravity exists, what appends for the Majorana neutrino ????*

Standard ββ2ν decay

For few isotopes, the β-decay is forbiden
⇒ ββ2ν process: a second order β-decay



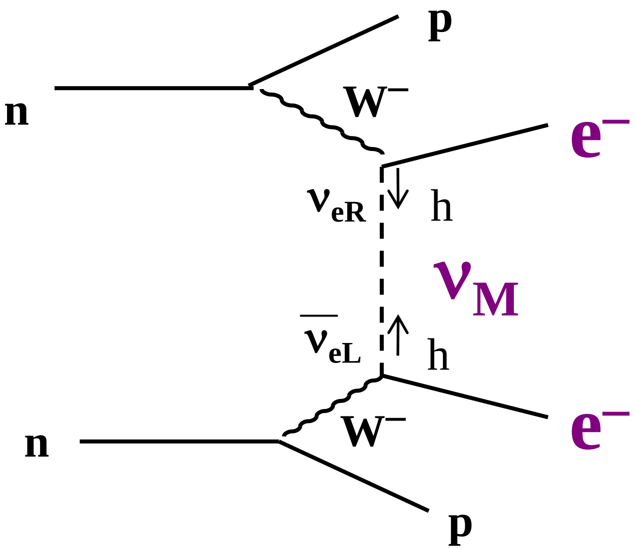




Energy Sum of the two electrons

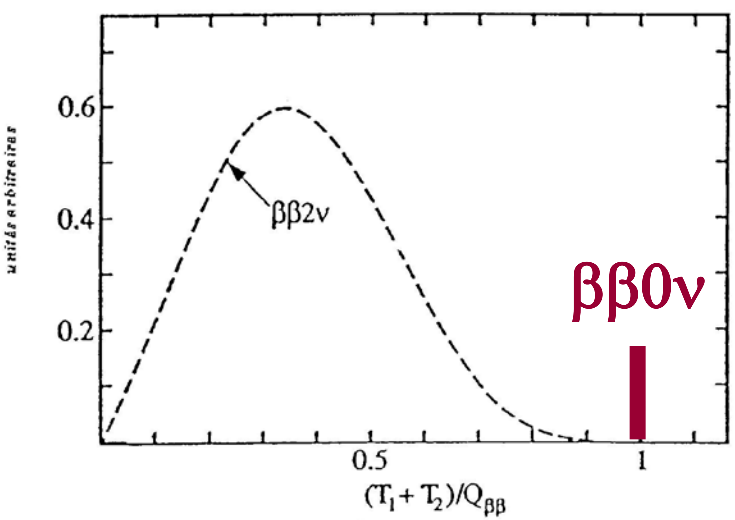
La désintégration ββ0ν

If neutrino is a Majorana particle ⇒ ββ0ν Process



Process ΔL = 2

- **Majorana neutrino exchange $\nu = \bar{\nu}$**
- Right Handed weak current
- Majoron production
- Exchange of SUSY particles



$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}\, M^2_{0\nu}\, \langle m_\nu \rangle^2$$

$G_{0\nu}$	Phase space factor
$M_{0\nu}$	Nuclear Matrix Element ⇒ Theoretical uncertainty
$\langle m_\nu \rangle$	Effective mass $\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$

List of isotopes used in the ββ experiments

Isotope	$Q_{\beta\beta}$ (MeV)	$G_{0\nu}$ (y^{-1})
^{48}Ca	**4.271**	2.44
^{76}Ge	2.040	**0.24**
^{82}Se	2.995	1.08
^{96}Zr	**3.350**	2.24
^{100}Mo	3.034	1.75
^{116}Cd	2.802	1.89
^{130}Te	2.528	1.70
^{136}Xe	2.479	1.81
^{150}Nd	**3.367**	**8.00**

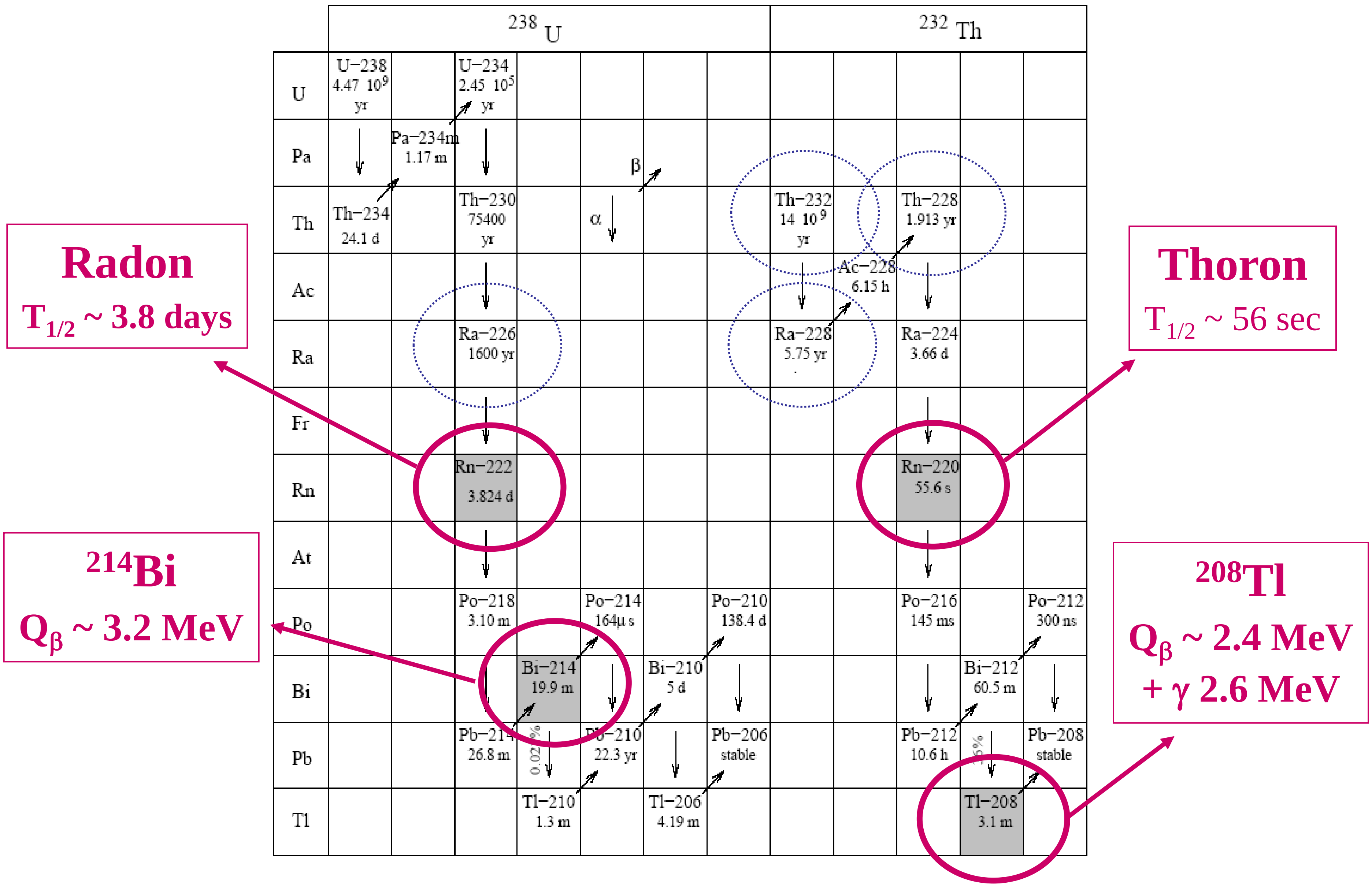
Criteria for the best isotope

- **High $Q_{\beta\beta}$** value for bkg suppression
  - $E_\gamma(^{208}Tl) = 2.6$ MeV
  - $Q_\beta(^{214}Bi) = 3.2$ MeV
- **High $G_{0\nu}$**
- **High $M_{0\nu}$**
  - $\Rightarrow$uncertainty in the calculations
- **High Mass**
  - capacity of **enrichment**
  - **Low** Atomic mass **A**
- **High efficiency of detection**

$$(T_{1/2})^{-1} = G_{0\nu} M_{0\nu}^2 \langle m_\nu \rangle^2$$

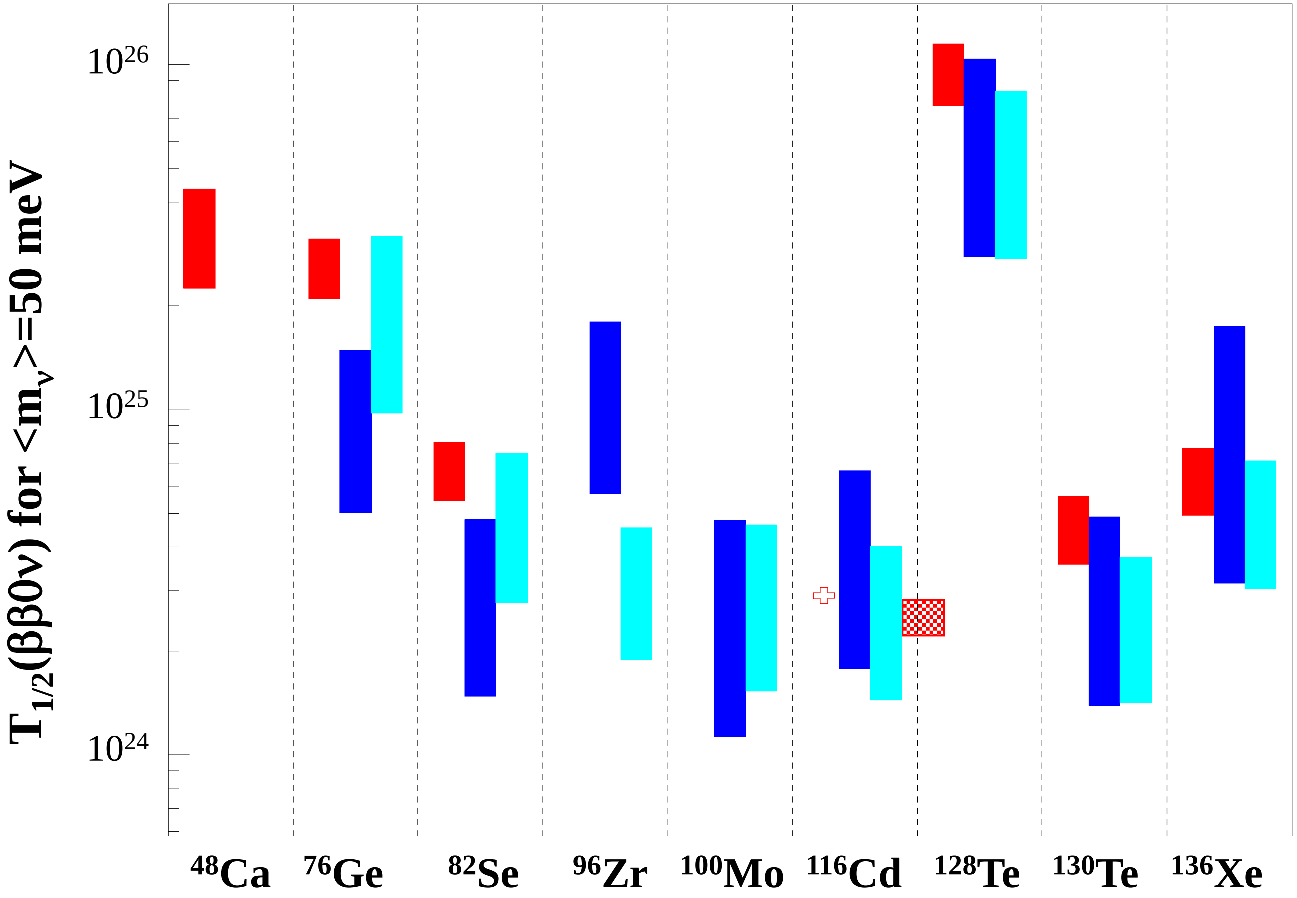
$$T_{1/2} = \ln 2 \; \frac{N_{ave}.Mass}{A} \; \varepsilon \; \frac{T_{obs}}{N_{excl}}$$

Natural radioactivity = Enemy of $\beta\beta0\nu$



Summary of the Nuclear Matrix Elements Calculation

Final Report of the N4 ILIAS Network (FP6 European Program)



$$(T_{1/2})^{-1} = G_{0\nu}\, M_{0\nu}\, \langle m_\nu \rangle^2$$

Shell Model
Caurier et al. PRL 100, 2008
Except Cd: Private Com.

QRPA Tubingen
Simkovic et al. PRC 77, 2008

QRPA Jyvaskyla
Suhonen et al. IJMP E17, 2008

Except ^{76}Ge: recent calculation with neutron occupancies : Suhonen PLB 668, 2008

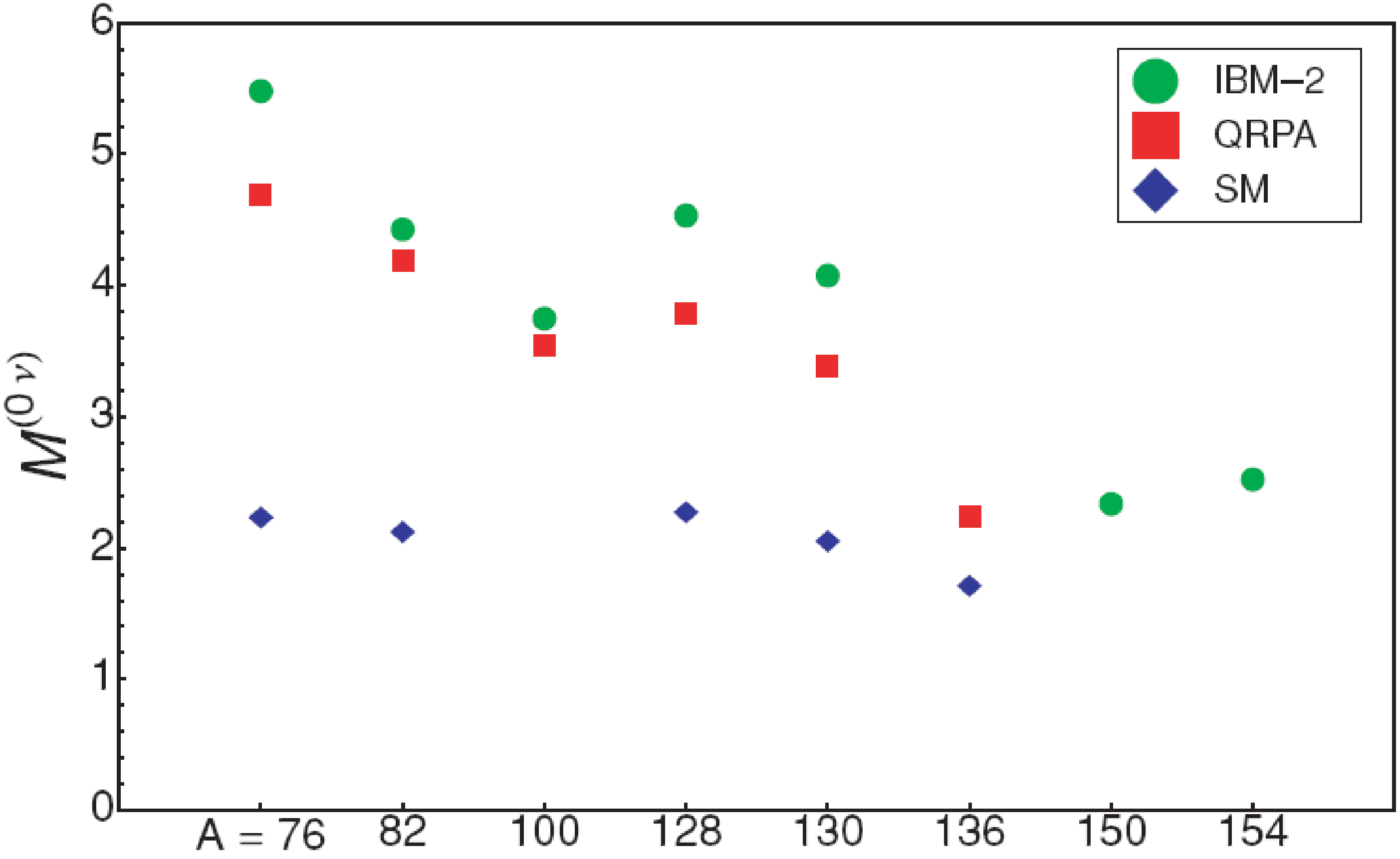
$M_{0\nu}$ strongly depends on g_A= coupling constant of the Gamow-Teller interaction ⇒ $T_{1/2}(0\nu) \sim (g_A)^{-4}$

For both QRPA: the **lower limit** always corresponds to the free value **g_A=1.25** and UCOM' short range corrections (s.r.c.) and the **upper limit** always corresponds to a strength quenched to **g_A=1.00** and Jastrow' s.r.c.

In β-decay, the strength is quenched to $g_A \sim 0.8 – 0.9$. ββ2ν decay rates indicate also $g_A \sim 0.8 – 0.9$

Recent calculation using a third and independant approach:
The Interacting Boson Model (IBM)

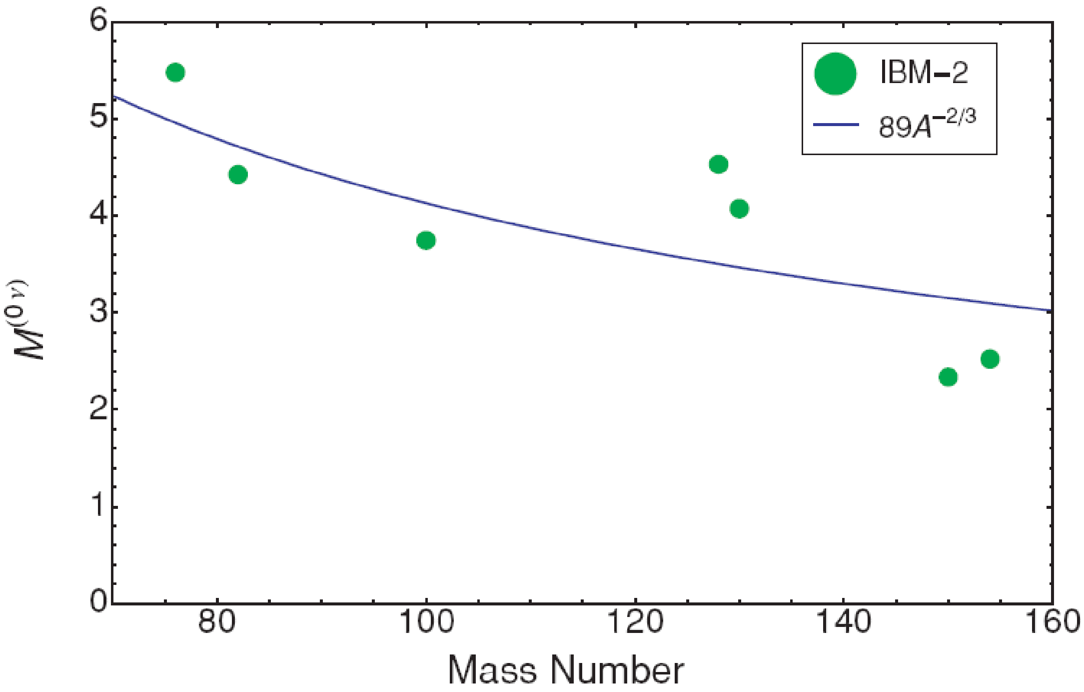
Barea and Iachello, Phys. Rev. C 79, 044301 (2009)



In agreement with QRPA…

They propose a very simple formulae for $M_{0\nu}$!

$$M_{0\nu} = 89\ A^{2/3}$$



Is it a real behaviour or a bias due to the theoretical model ?

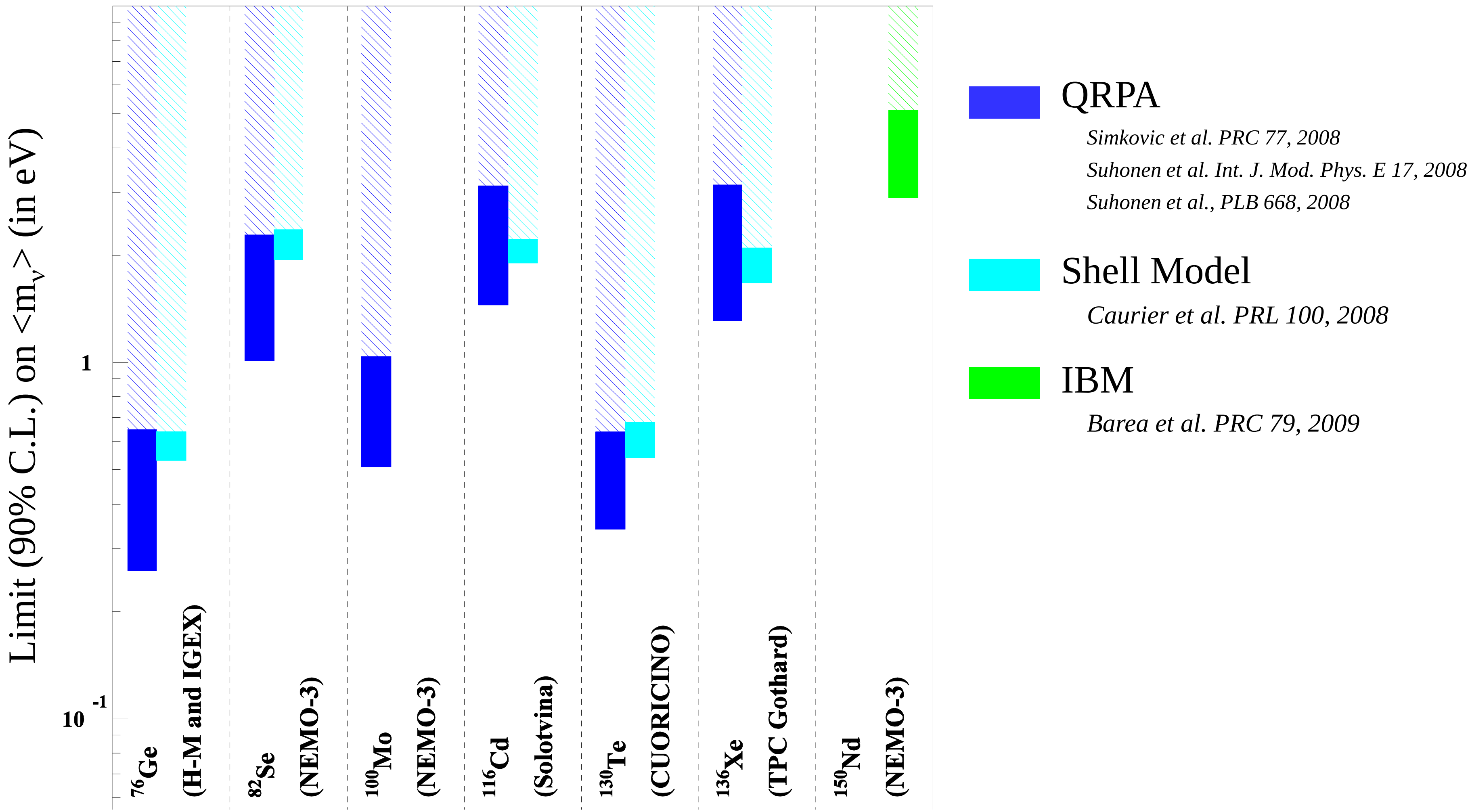
QRPA has similar dependence, Shell Model is independant of A

Current best limits in ββ0ν search

Isotope	Experiment	Technique	Mass of isotope	$T_{1/2}(0\nu)$ Limit (90%)	$<m_\nu>$ (eV) QRPA	Shell Model
^{48}Ca	NEMO-3	Tracko-calo	7 g	$> 1.3\ 10^{22}$	–	21 – 29
^{76}Ge	Heidel.-Mosc. IGEX	Germanium semicond.	11 kg	$> 1.5\ 10^{25}$	0.26 – 0.65	0.53 – 0.64
^{82}Se	NEMO-3	Tracko-calo	1 kg	$> 3.6\ 10^{23}$	1.01 – 2.28	1.94 – 2.36
^{100}Mo	NEMO-3	Tracko-calo	7 kg	$> 1.1\ 10^{24}$	0.51 – 1.04	–
^{116}Cd	Solotvina	$CdWO_4$ Crystal Scintillator	80 g	$> 1.7\ 10^{23}$	1.45 – 3.13	2.06
^{130}Te	CUORICINO	Bolometer	10 kg	$> 3.0\ 10^{24}$	0.34 – 0.64	0.54 – 0.68
^{136}Xe	TPC Gothard	Gas TPC Xe	3.4 kg	$> 4.4\ 10^{23}$	1.31 – 3.15	1.67 – 2.10
^{150}Nd	NEMO-3	Tracko-calo	37 g	$>1.8\ 10^{22}$	IBM: 2.9 – 5.1	

- Shell Model: *Caurier et al., Phys. Rev. Lett. 100 (2008)*
  Except ^{116}Cd preliminary results (no s.r.c. correction): *Private communication*
- QRPA Tubingen: *Simkovic et al., Phys. Rev. C 77 (2008)*
- QRPA Jyvaskyla: *Suhonen et al. Int. J. Mod. Phys. E 17 (2008) 1*
  Except ^{76}Ge: recent calculation with neutron occupancies: *Suhonen et al., Phys. Lett. B 668 (2008) 277*
- IBM: Barea et al., Phys. Rev. C. 79, 044301 (2009)

Current best limits in ββ0ν search

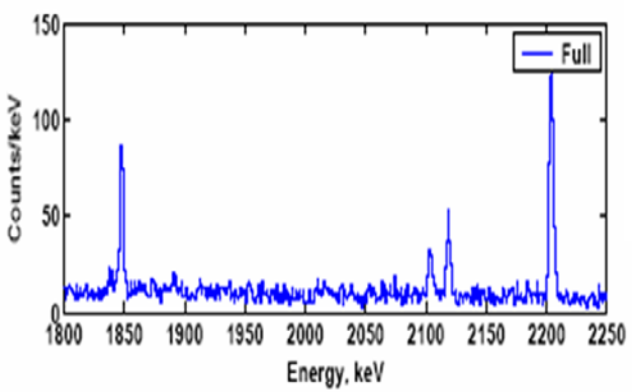


State-of-the-art: Limit … or claim ?

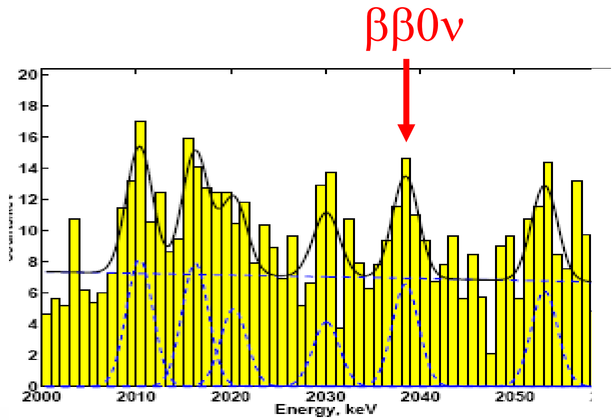
Heidelberg-Moscow experiment

- 5 HPGe crystal with enriched ^{76}Ge (~10 kg) running 1990 – 2003 ⇒ 71.7 kg.y
- Bkg ~ 0.11 cts/(keV.kg.y)
- ¨Part of the collaboration claims 4.2σ ββ0ν signal (NIM A 522 (2004) 371, PLB 586)

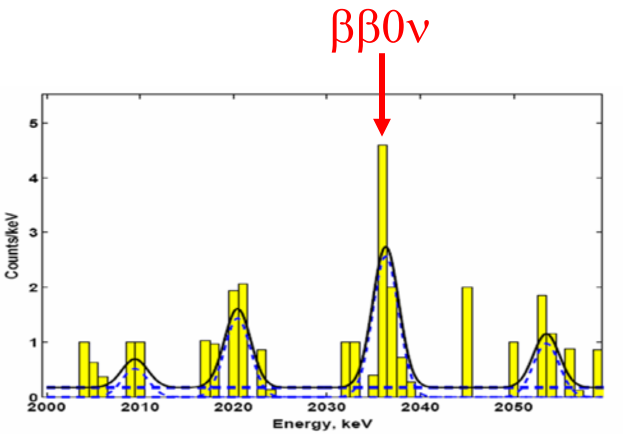
Best fit: $T_{½}(\beta\beta0\nu) = 1.2\ 10^{25}$ y



All data



Zoom at $Q_{\beta\beta}$ = 2039 keV



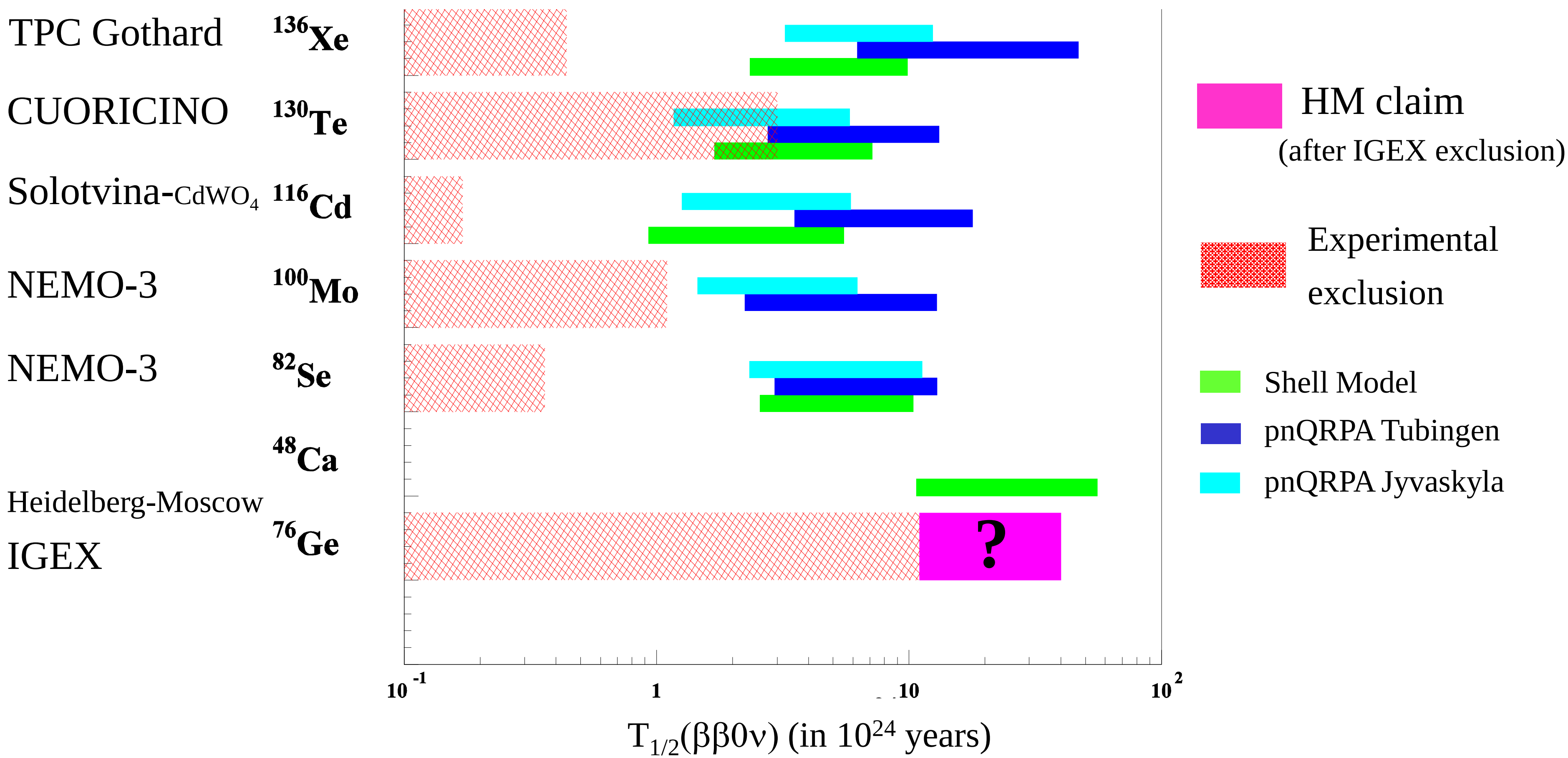
Pulse shape Analysis
(reject multi-compton events)

Significance and $T_{1/2}$ depends on background description

Recent analysis of the origin and description of background done by O. Chkvorets *(arXiv:0812.1206)*

Peak significant (without PSA) 1.3 σ
$T_{1/2}$= 0.4 – 4.0 10^{25} years (68% C.L.)

Ge claim and limits from other experiments



Heidelberg-Moscow claim: $T_{1/2}(\beta\beta0\nu) = 0.4 – 4.0\ 10^{25}$ y (68% C.L.)

IGEX limit: $T_{1/2}(\beta\beta0\nu) \geq 1.1\ 10^{25}$ y

Overview of experiments

Name	Nucleus	Mass*	Method	Location	Time line
Operational & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48	tbd	scintillation	Solotvina	
COBRA	Cd-116, Te-130	tbd	ionization	LNGS	
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	

The GERDA Experiment

Next generation ^{76}Ge ββ experiment at Gran Sasso
Under installation – Commissioning Jan. 2010

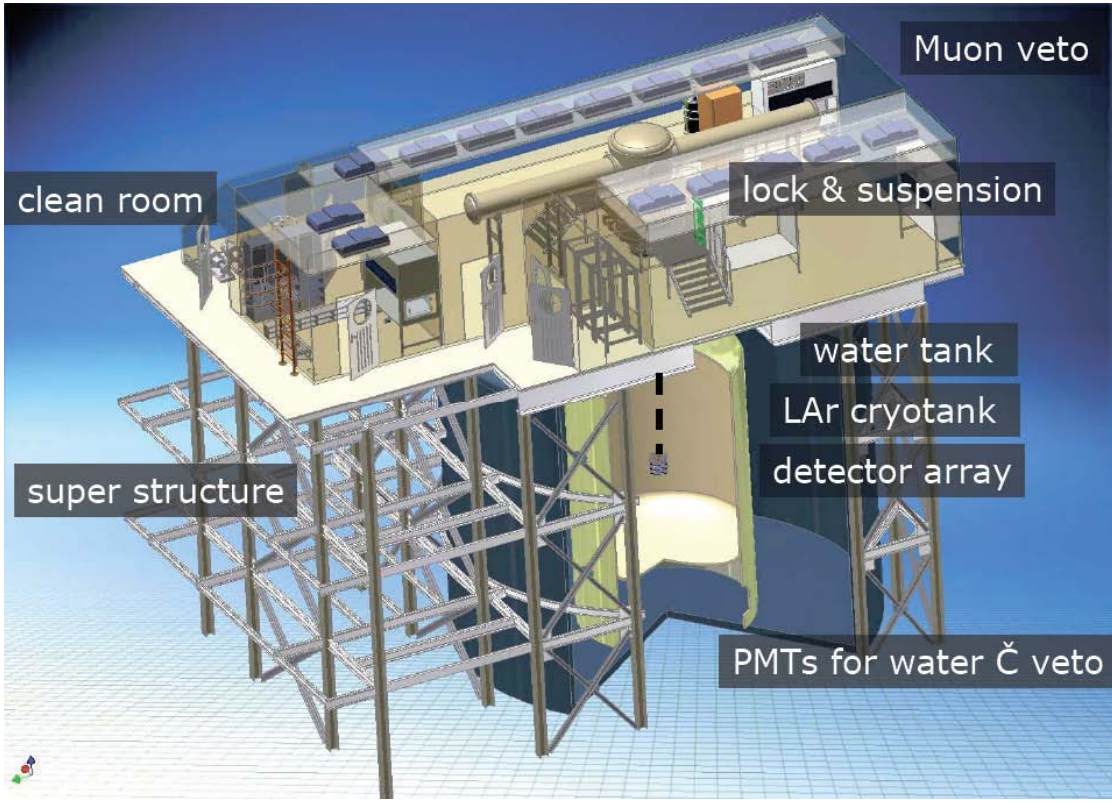
- **Operation of bare ^{76}Ge diodes in ultrapure cryogenic liquid Argon**

- **Background rejection**

• Heidelberg-Moscow:
bkg~0.1 cts/(keV.kg.y)

• This bkg seems to be produced by external γ

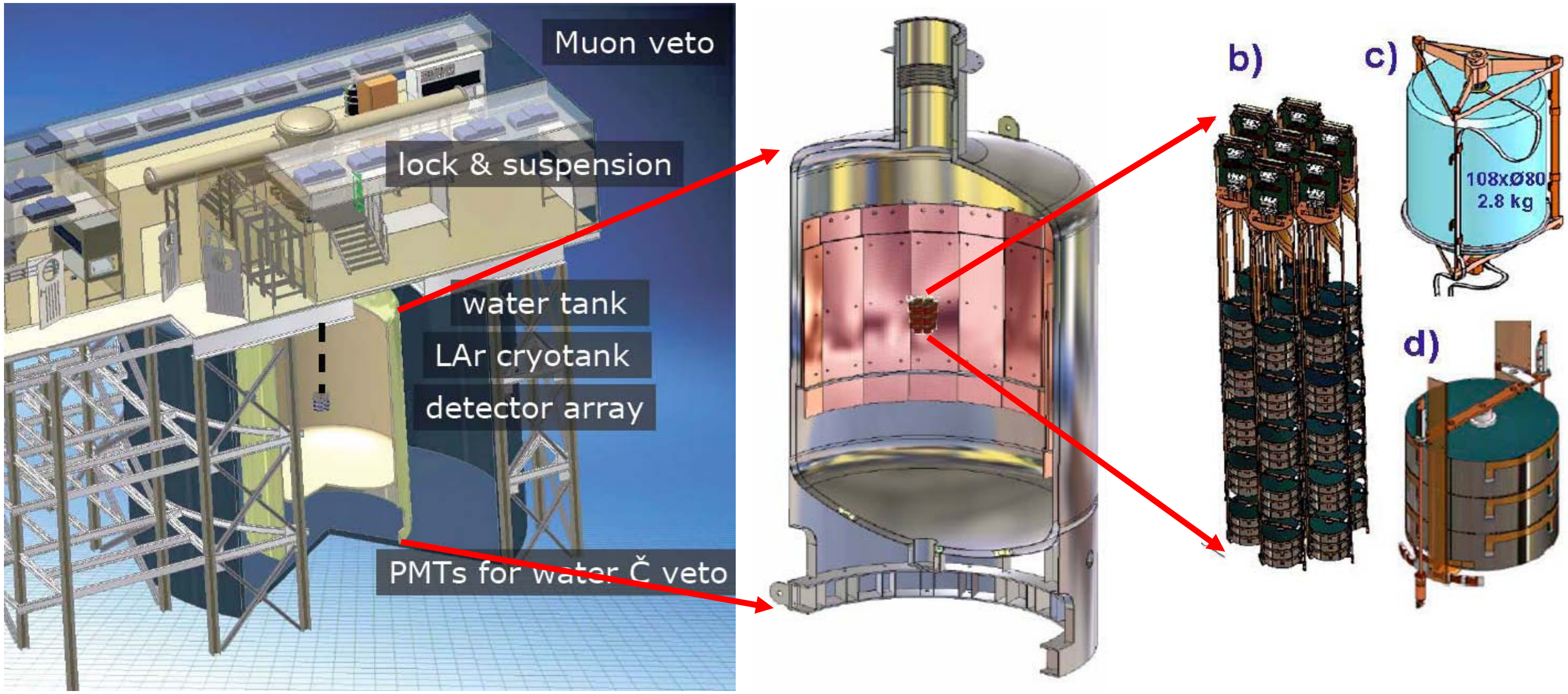
• Goal of GERDA: achieve an ultimate bkg ~ 0.001 cts/(keV.kg.y)



The GERDA Experiment

A stainless steel cryostat (25 t, U/Th≤5 mBq/kg)
with **internal Cu shield** (20 t, U/Th≤16 μBq/kg)
will contain **100 tones of LAr, ^{222}Rn = ≤1 μBq/m^3.**
The cryostat is immersed in a water tank **(590 t of water)**

The Ge detector array is made up of individual detector strings and is situated in the central part of the **cryostat**



Phase I

- All **8 existing and reprocessed enriched detectors** from previous Heidelberg-Moscow and IGEX experiments ⇒ **In total 18 kg of ^{76}Ge**
- And 6 reprocessed natural HPGe detectors ⇒ **In total 15 kg of ^{Nat}Ge**

Phase II

- **The new BeGe (or segmented) detectors** with PSA bkg rejection, made from recently produced enriched ^{76}Ge material added (> 20kg of ^{76}Ge) ⇒ **In total 40 kg of ^{76}Ge + 15 kg of ^{Nat}Ge**

The GERDA Experiment

Phase III ~ 100 kg

10 y of exposure

LAr active veto with PMTs

bkg ~ 1 cts/(keV.ton.y)

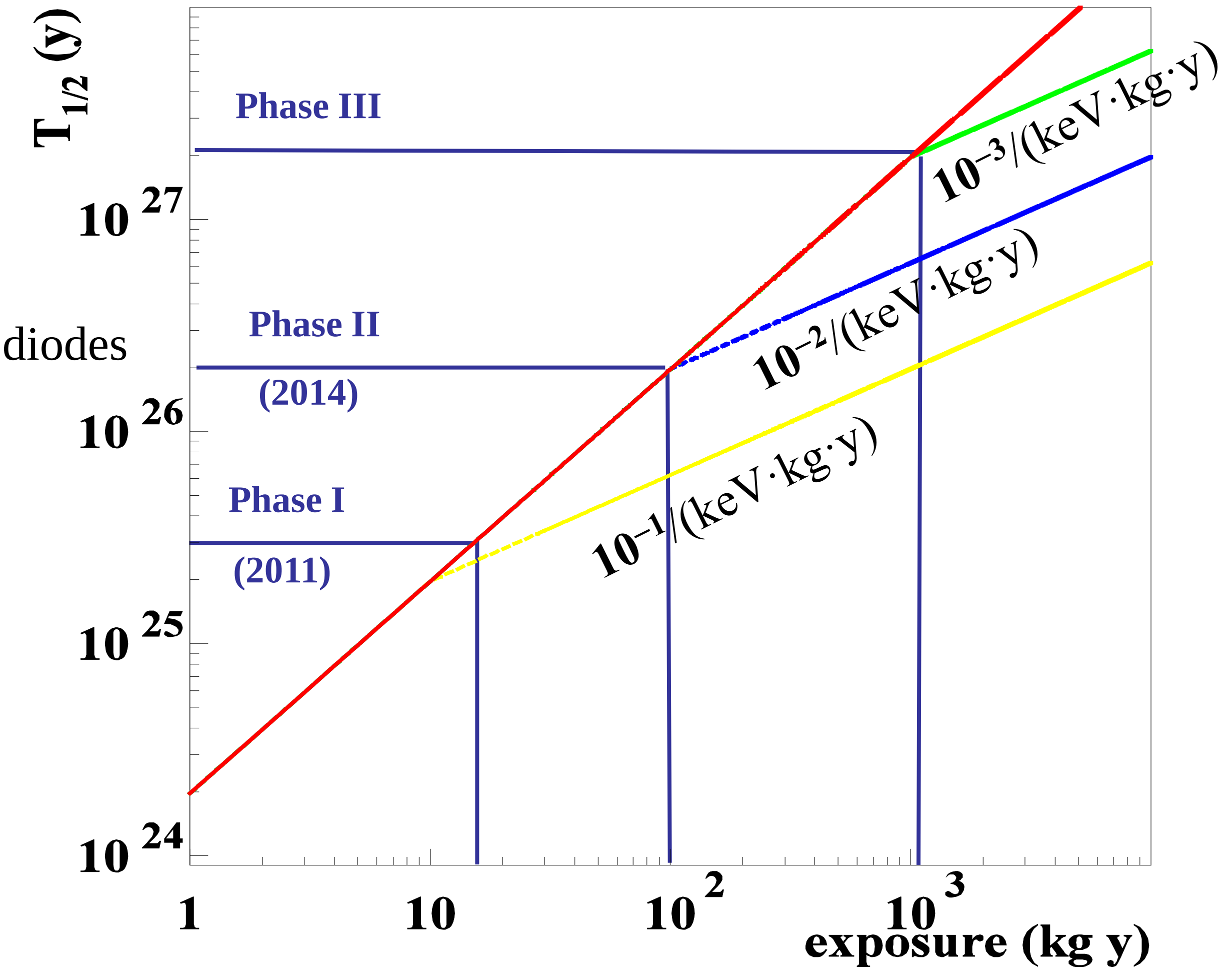
Phase II ~ 40 kg ^{76}Ge

- Add new (segmented ?) ^{76}Ge diodes
- bkg rejection with PSA
- bkg ~ 0.01 cts/(keV.kg.y)

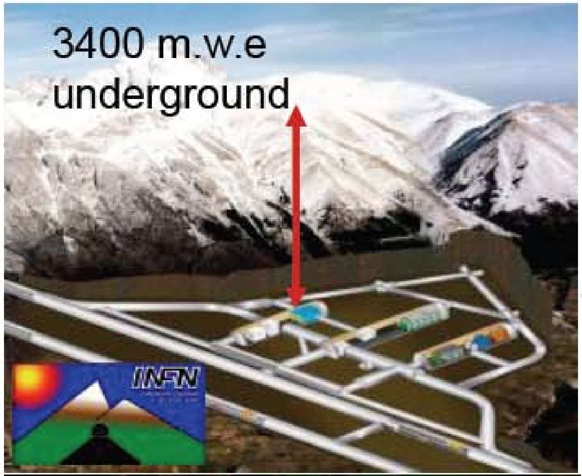
Phase I ~ 18 kg ^{76}Ge

- Use available ^{76}Ge diodes from HdM and IGEX
- bkg ~ 0.1 cts/(keV.kg.y)
- Can reach $T_{1/2}$=3.10^{25} y in 1 year

Will validate claim's ?



The GERDA Installation @ LNGS



Start Commissioning: Beginning 2010

Detector string
Glove box & lock
Clean room
Cryostat & μ-veto
Heat exchanger & pipes

The GERDA R&D

Testing of naked HPGe detectors in Liquid Argon

Long-term stability tests (3 HPGe detectors in LN2/LAr during 2 years)

tested in liquid Argon
FWHM ~2.5keV (at 1332keV),
leakage current stable

Problems reported from GENIUS-TF
[H.V.Klapdor-Kleingrothaus end I.Krivosheina, NIM A556 (2006) 472]

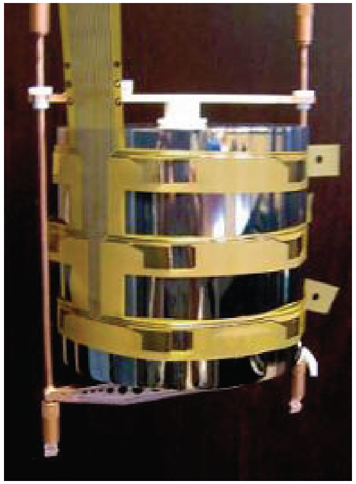
have been overcome by GERDA.

Long term stability for > 1 year.
Detector performances are stable in LAr !

The GERDA R&D

Novel Ge-detectors with advanced 0νββ-signal recognition & background suppression

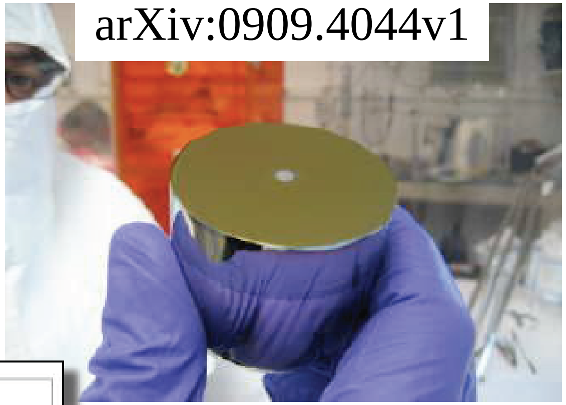
Segmented detectors



n-type detectors with 18-fold segmented electrodes

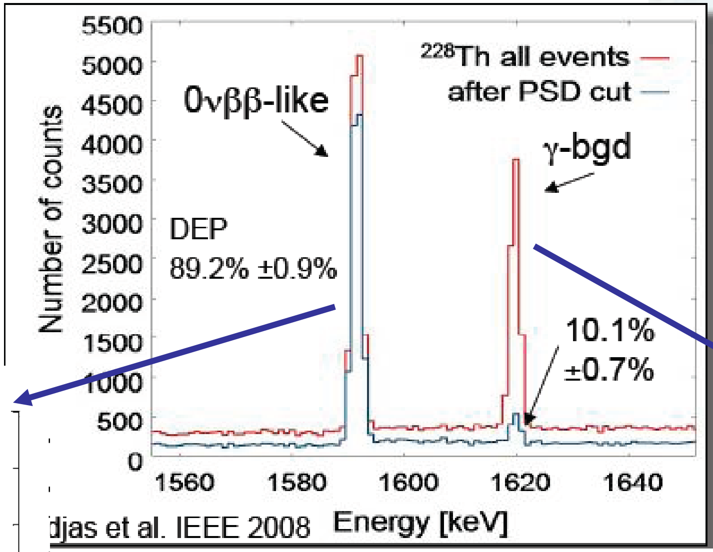
BeGe detectors

arXiv:0909.4044v1

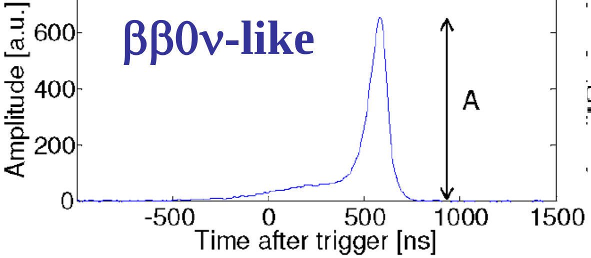


p-type with small readout electrode; Similar performance with thick-window BEGe detectors

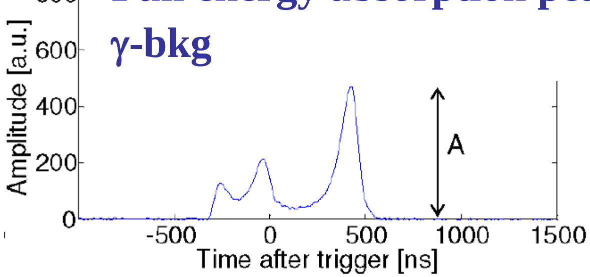
- **0νββ:** point-like events
- **Bgd:** multi-site or partial energy deposition outside crystal
- LAr scintillation read out



Double-escape peak
ββ0ν-like



Full energy absorption peak
γ-bkg



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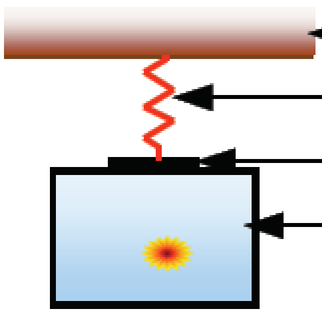
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	

CUORICINO Bolometers

TeO_2 Bolometer: Source = Detector

Te natural: 34% of ^{130}Te



Heat sink: Cu structure (8 mK)

Thermal coupling: Teflon (G = 4 pW/mK)

Thermometer: NTD Ge-thermistor (dR/dT ≅ 100 kΩ/μK)

Absorber: TeO_2 crystal (C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

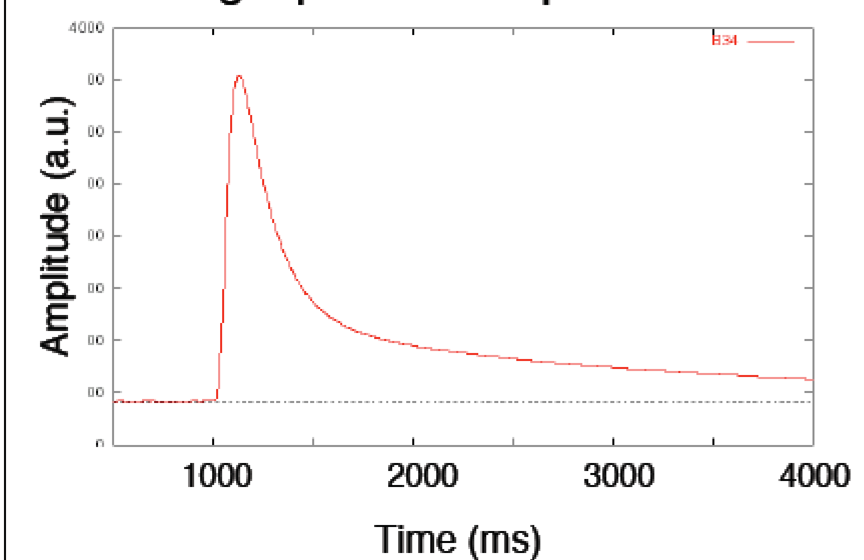
For E = 1 MeV:

- **$\Delta T = E/C \cong 0.1$ mK**
- **Signal size: 1 mV**

Time constant:

- **$\tau = C/G = 0.5$ s**

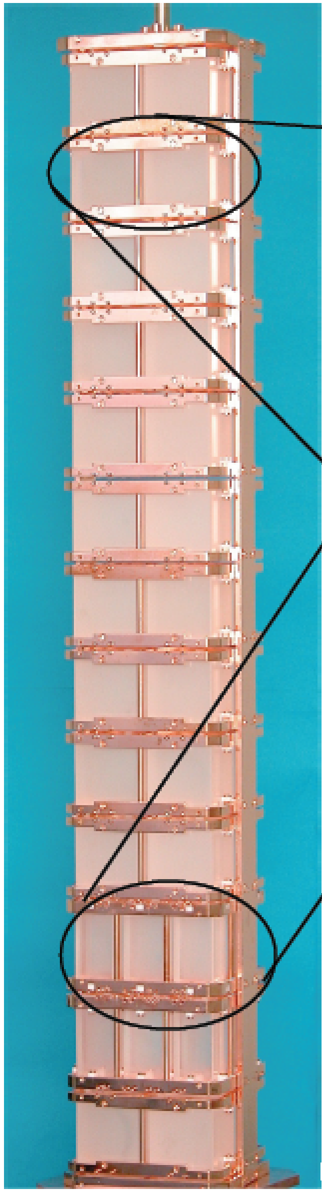
Energy resolution (FWHM) ~ 5-10 keV at 2.5 MeV

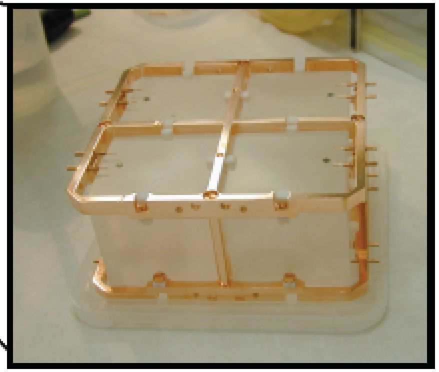


CUORICINO detector

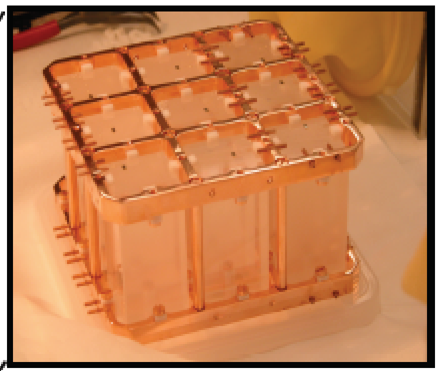
Gran Sasso Underground Laboratory (Italy), 3500 m.w.e.

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

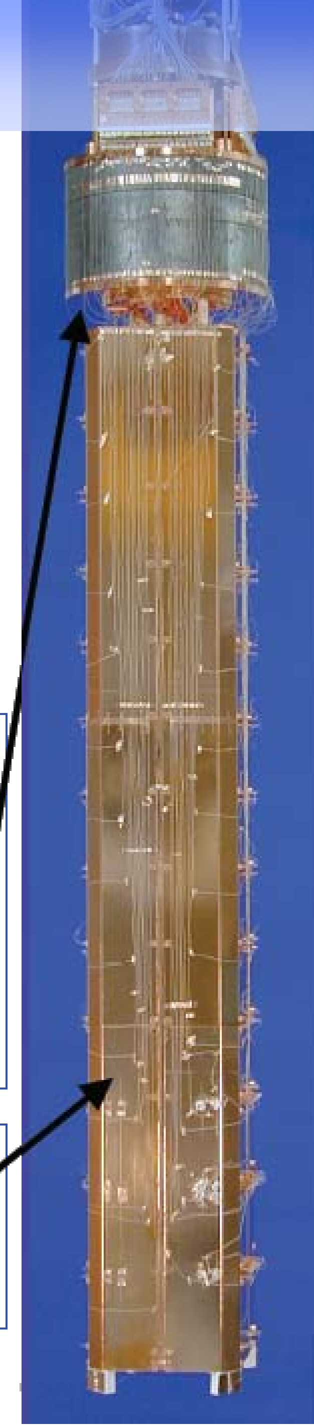




11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 790 g
44 x 0.79 = **34.76 kg of TeO_2**



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%)



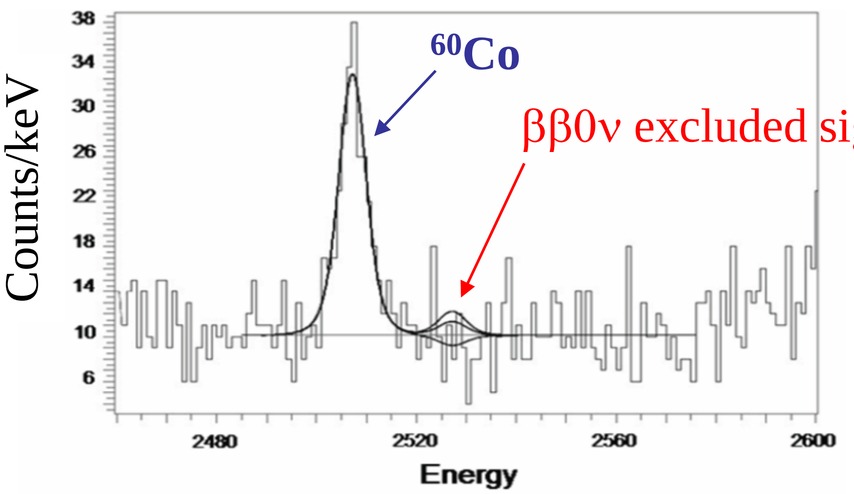
Shielding:

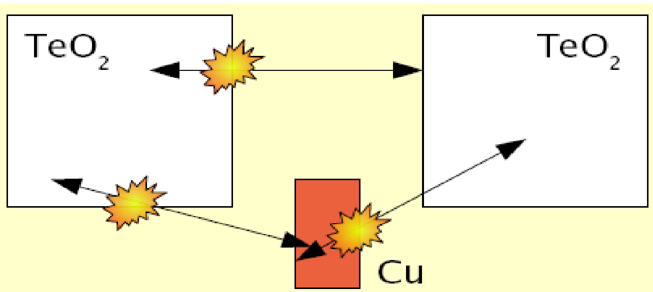
- Cu box + Roman Pb inside cryostat
- 20 cm Pb & 10 cm borated polyethylene outside

CUORICINO results

- **Total exposure: 18 kg.y of ^{130}Te**
- **Bkg: 0.18 cts/(keV.kg.y)**
- **FWHM at 2615 keV: ~ 8 keV**

$$T_{1/2}(\beta\beta0\nu) \geq 3.10^{24}\ y\ \ (90\%\ C.L.)$$





Model of background

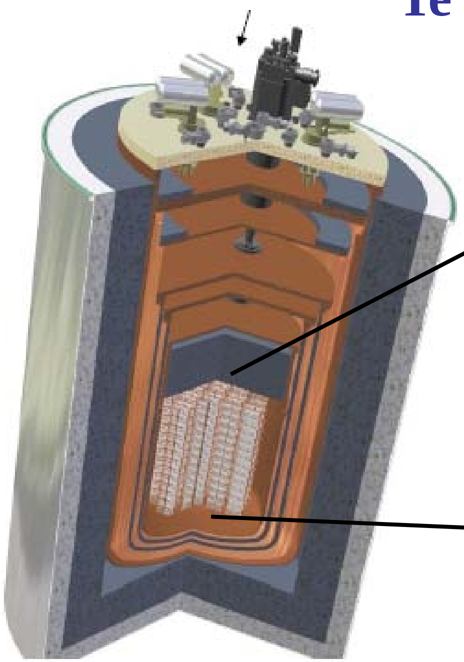
Source	^{208}Tl	$\beta\beta_{0\nu}$	3-4 MeV
U/Th on TeO_2 surface	-	20%	20%
U/Th on Cu surface	15%	50%	80%
Th from external γs	85%	30%	-

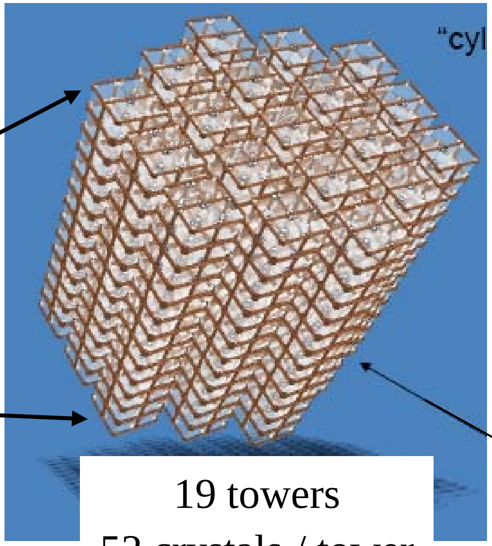
Origin of Background: ^{238}U or ^{232}Th contamination on the surface of crystal and Cu structure facing the detectors

CUORE experiment

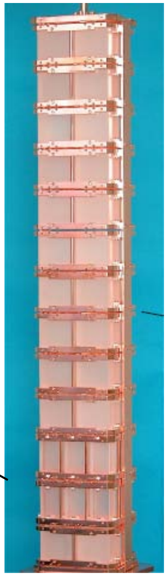
Assembling **19 towers** similar as CUORICINO $\Rightarrow$ Total = **988 crystals**

Te natural → 741 kg $^{nat}TeO_2$ = ~ **200 kg ^{130}Te**





19 towers
52 crystals / tower



- 5 years of data collection
- FWHM = 5 keV @ 2528 keV
- **Bkg = 0.01 cts/(keV.kg.year)**

⇓

Expected Sensitivity:

$T_{1/2}(\beta\beta0\nu) > 2.1 \times 10^{26}$ y

CUORICINO bkg = 0.18 cts/(keV.kg.y)

⇓

CUORE Target bkg = 0.01 cts/(keV.kg.y)

Reduction factor = 20

⇒

Reduce background by:

- Material selection and proper handling
- Shielding
- **Surface cleaning crystals and Cupper**
- Avoid recontamination
- Improve detector design

CUORE bkg prediction

First test results (Hall C) on cleaning crystals and copper surfaces:

- reduction of crystal surface contamination of a factor ~5
- reduction of continuum background in 3-4 MeV region of a factor ~2

Measured contaminations projected (Montecarlo) on CUORE

SOURCE	BACKGROUND @ 2.5 MeV (10^{-3} counts/keV/kg/y)
TeO_2 crystal bulk	< ~1.3
TeO_2 crystal surface	< ~7
Detector mounting bulk	< ~1
Detector mounting surface	< ~25
Experimental set-up gamma	~ 2
Environmental gamma	~ 0.002
Environmental neutrons	< ~0.1
Environmental muons (no veto)	~ 0.4

target background:

< 0.01 c/kg/kev/y

presently projected bkg:

< 0.04 c/kg/kev/y

... STILL WORKING TO IMPROVE THESE NUMBERS!

→ special efforts devoted to crystal production and copper surface cleaning

CUORE-0: the first CUORE tower

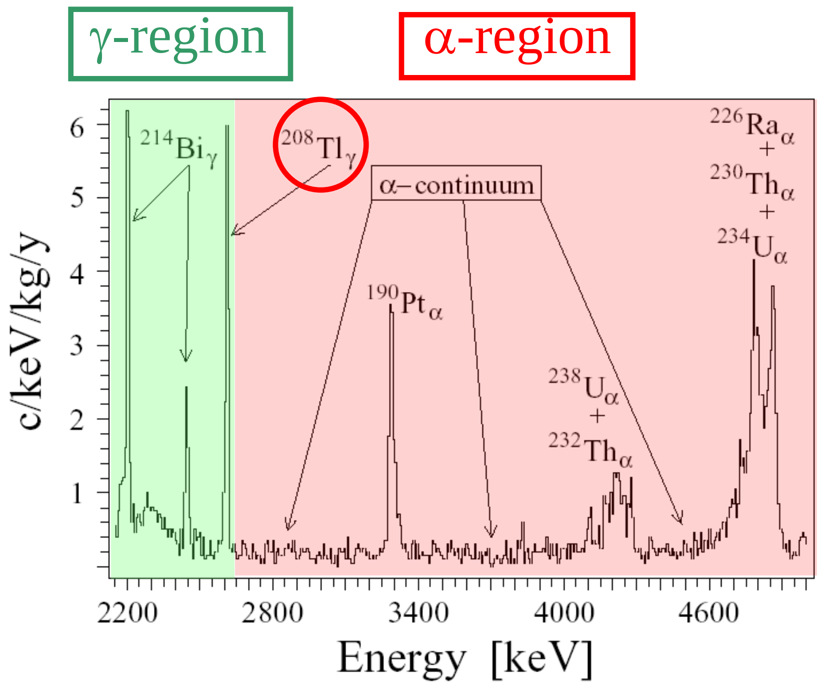
- **CUORE-0: first tower under assembly, will be installed in CUORICINO cryostat in 2009/2010**
  – will demonstrate the assembly procedure improved during R&D years (gluing, holder, NTD…)
  – will demonstrate the bkg reduction obtained from R&D
  Mostly: improvement of Cu surface cleaning
  – 52 crystals (750 g each) already arrived and sefely stored in LNGS
  – Bolometric test is presently starting in CUORICINO experimental facility

⇒ Target: 0.01 cts/keV/kg/y

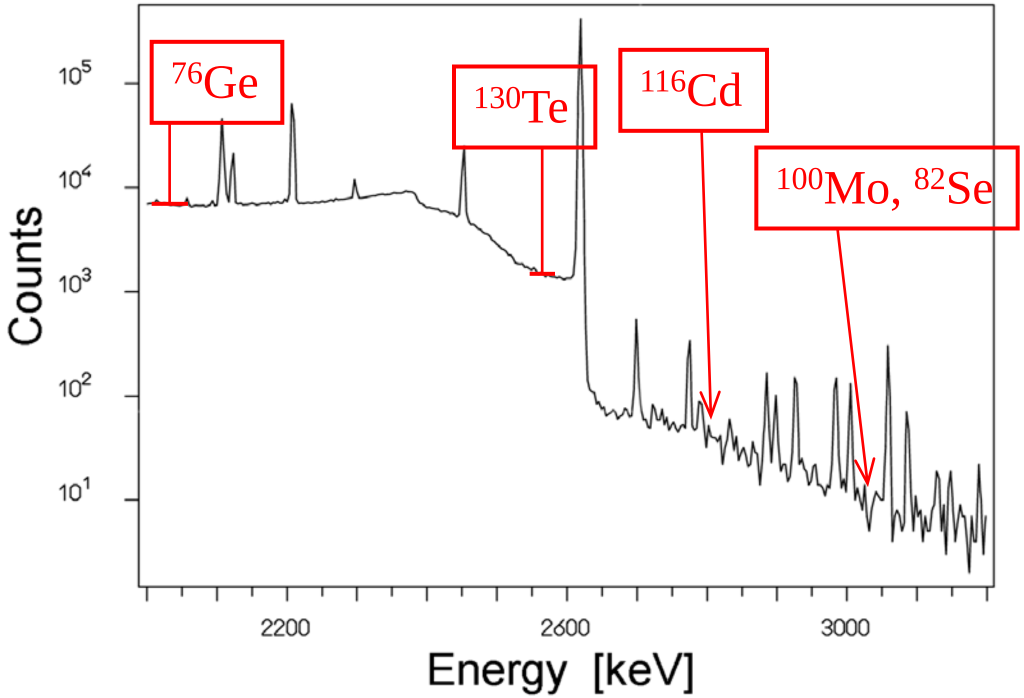
- **Full CUORE detector: commissioning is forseen in 2012:**
  – 1000 crystals funded by INFN and DoE
  – CUORE Hut has been installed in LNGS
  – Cryostat assembly under progress

Scintillating bolometers

Above 2.6 MeV, BKG dominated by α from surface contamination !



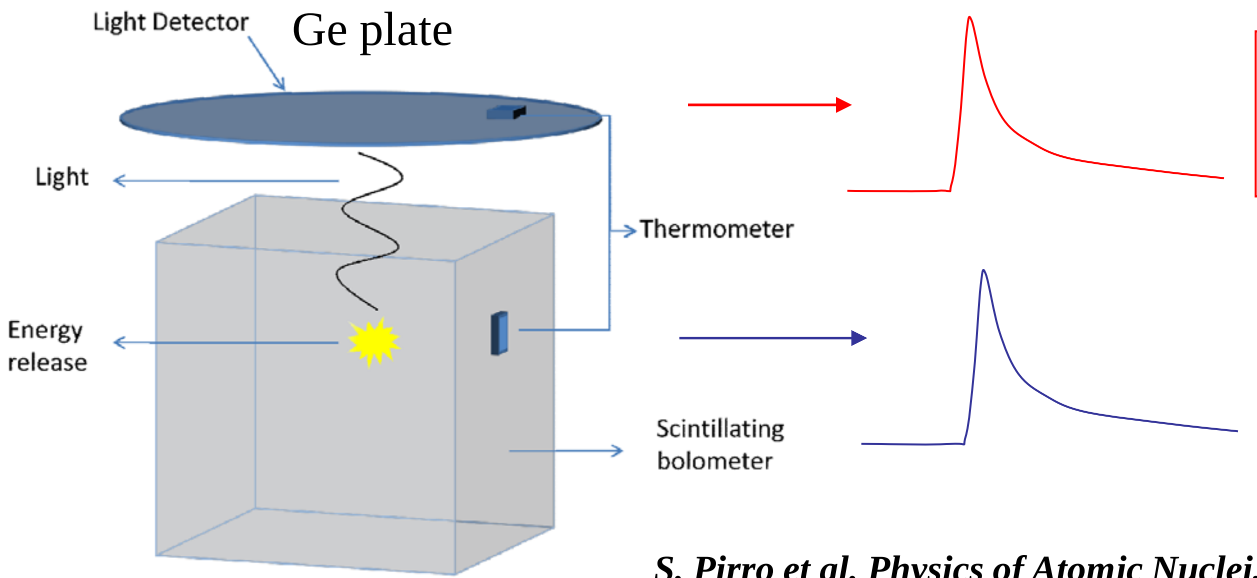
CUORICINO α Background



Environmental "underground" Background:
^{238}U and ^{232}Th trace contaminations

Furthermore a not negligible part of the background can arise from high energy neutrons from μ-spallation

Scintillating bolometers



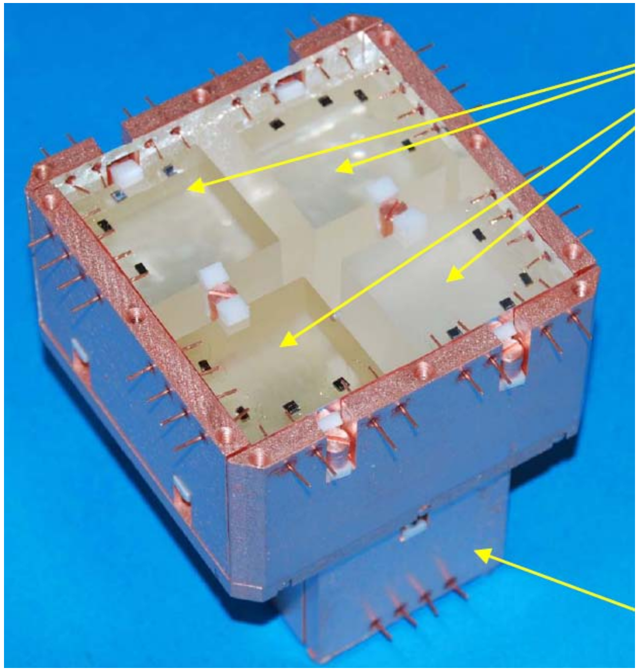
Scintillation signal

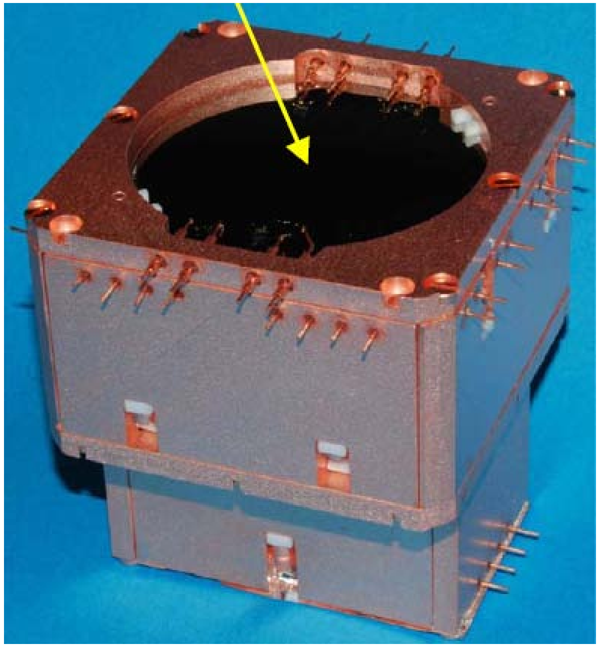
α / (e⁻,γ) discrimination

Heat signal

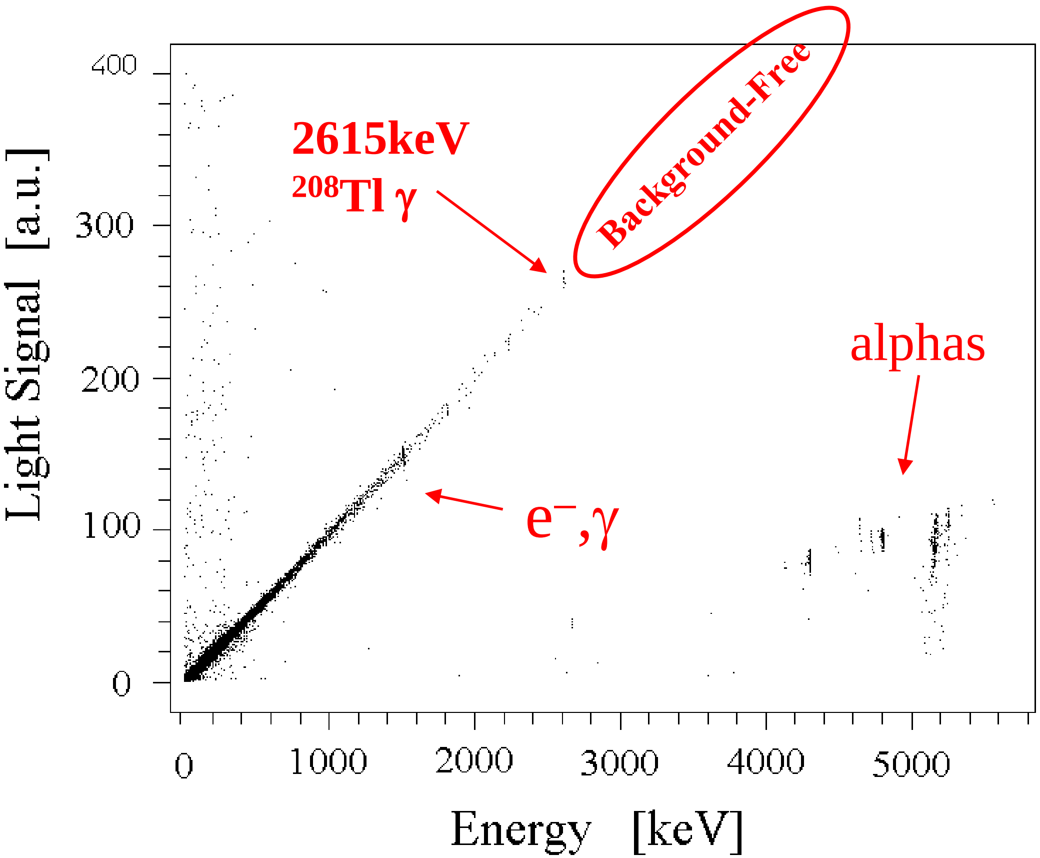
Energy measurement

S. Pirro et al. Physics of Atomic Nuclei, 69, 2109–2116 (2006)





Background measurement with CdWO4 crystal



Pirro et al., Optical Materials 31 (2009) 1388–1392

Large $CdWO_4$ crystal
$3\times3\times6$ cm^3, ~ 400 g
44 days of measurement

Test done in the Test Facility Cryostat
⇒ Not an ultra radiopure setup !…

No count observed
above 2.6 MeV !!!

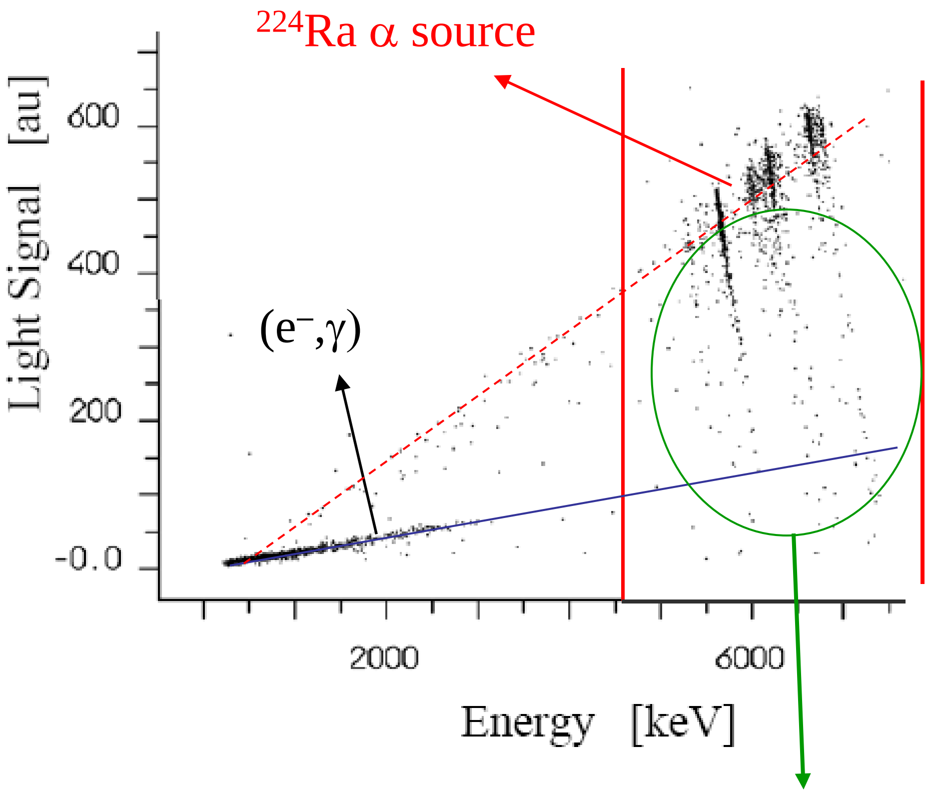
Ultimate bkg:
- U/Th contamination on the surface of the crystal (and α escapes the crystal)
- Th contamination in the mechanical frames: pile-up of the 2 γ's (2615 + 583 keV)
- Neutrons (from μ-spallation)

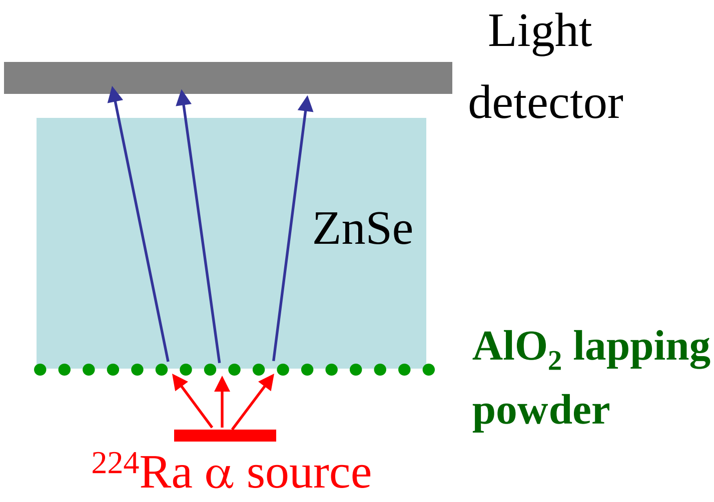
Using CUORICINO/CUORE measured contaminations (crystal and Copper surface), the expected bkg, calculated with GEANT4 is: **bkg ~ 10^{-4} cts/(keV.kg.y) !!!**

ZnSe (^{82}Se) an extremely interesting crystal

Many tests with different productions of large ZnSe crystals

For all crystals, **inverted quenching for α** has been always observed !





Several experimental tests have shown that **α events with lower amount of scintillation light are due to residual lapping powder** (AlO_2 non scintillating) on the surface of the crystal

Scintillating Bolometers: a very promising technique !

Positive results have been also obtained with:

- **^{100}Mo: $ZnMoO_4$**, $PbMoO_4$, $CaMoO_4$, $SrMoO_4$
- **^{48}Ca: CaF_2**, $CaMoO_4$
- **^{82}Se: ZnSe** (scint. quenching for α is < 1 ⇒ sensitive to surface quality)

But NO scintillation light with $Te0_2$…

Very promizing technique:

- High bkg rejection efficiency
- High ββ0ν efficiency
- Can study several isotopes: ^{116}Cd, ^{82}Se, ^{100}Mo and ^{48}Ca
- Compact detector

Expected sensitivity with CUORICINO-like experiment

Assuming:

- 5 years data
- bkg = 10^{-3}cts/keV/kg
- FWHM=10 keV

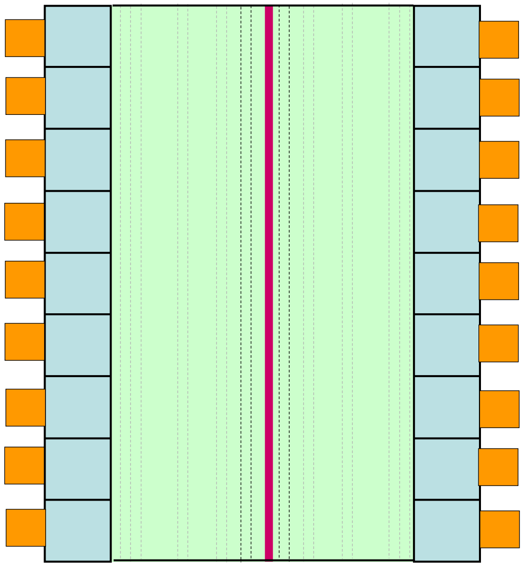
Crystal	Isotope	M_{tot} (kg) Crystals	**$M_{\beta\beta}$ (kg)**	Bkg cts/FWHM/y	$T_{1/2}(\beta\beta0\nu)$ 90% C.L.
$CdWO_4$	^{116}Cd	51.1	**14.8**	0.5	**$0.6\ 10^{26}$**
$ZnMoO_4$	^{100}Mo	27.2	**11.8**	0.3	**$0.6\ 10^{26}$**
ZnSe	^{82}Se	34.0	**19.0**	0.3	**10^{26}**
CUORICINO	*^{130}Te*	*38.8*	*10.48*	*56*	*$0.06\ 10^{24}$*

Larger scale test with enriched isotope must be performed

Overview of experiments

Name	Nucleus	Mass*	Method	Location	Time line
Operational & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48	tbd	scintillation	Solotvina	
COBRA	Cd-116, Te-130	tbd	ionization	LNGS	
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	

NEMO: a tracko-calo detector



➢ Source in form of thin foil, separated to the detector

➢ Detector combines :

- a tracking detector to reconstruct the two e^- tracks
- a calorimeter to measure the energy

⇒ A complementary technique which allows to identify directly the two emitted electrons

The NEMO-3 detector

Modane Underground Laboratory : 4800 m.w.e.

Source: 10 kg of ββ isotopes

cylindrical, S = 20 m^2, e ~ 60 mg/cm^2

Tracking detector:

drift wire chamber operating in Geiger mode (6180 cells)

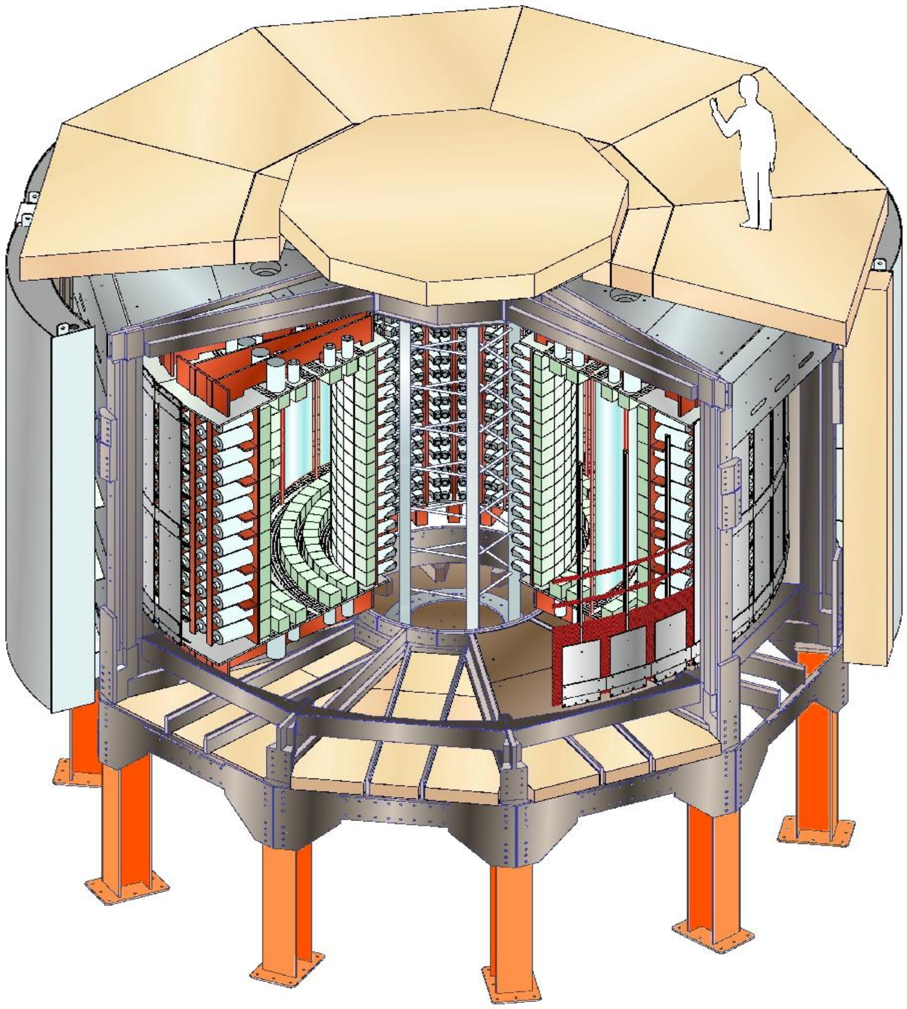
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:

1940 plastic scintillators coupled to low radioactivity PMTs

The NEMO-3 detector

Modane Underground Laboratory : 4800 m.w.e.



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Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (e = 18 cm)
Neutron shield: 30 cm water (ext. wall)
40 cm wood (top and bottom)
(since march 2004: water + boron)

The NEMO-3 detector

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40 cm wood (top and bottom)

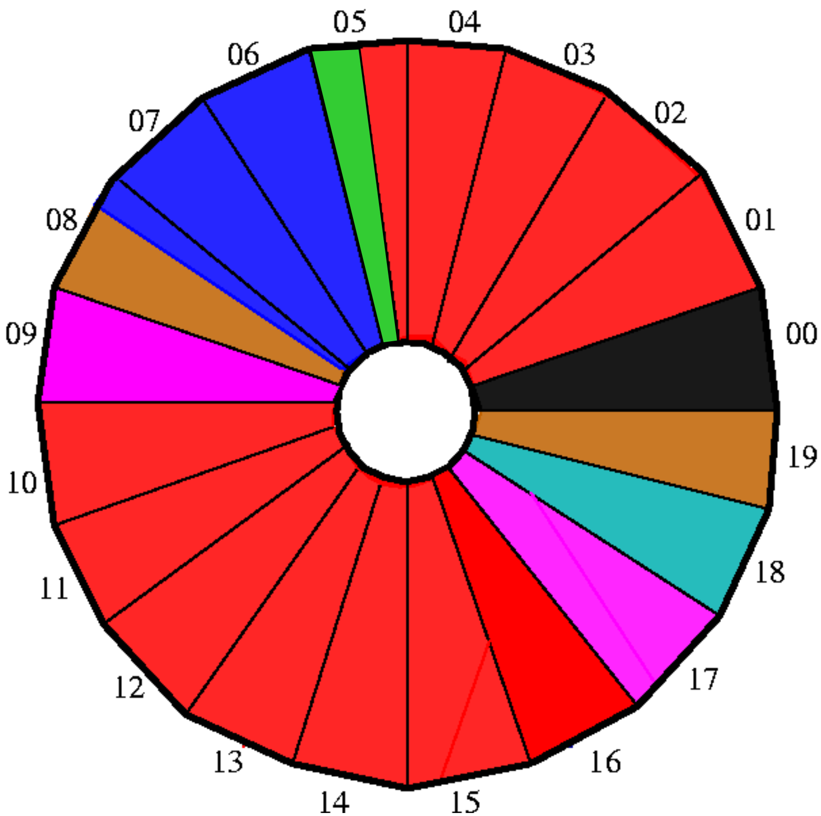
(since march 2004: water + boron)

Radon-free air around the detector

- Phase I (Feb 2003 oct. 2004): High Radon
- Phase II (Dec 2004 today): Low Radon

(Radon cont. reduced by factor 6)

ββ decay isotopes in NEMO-3 detector



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν measurement

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te 491 g

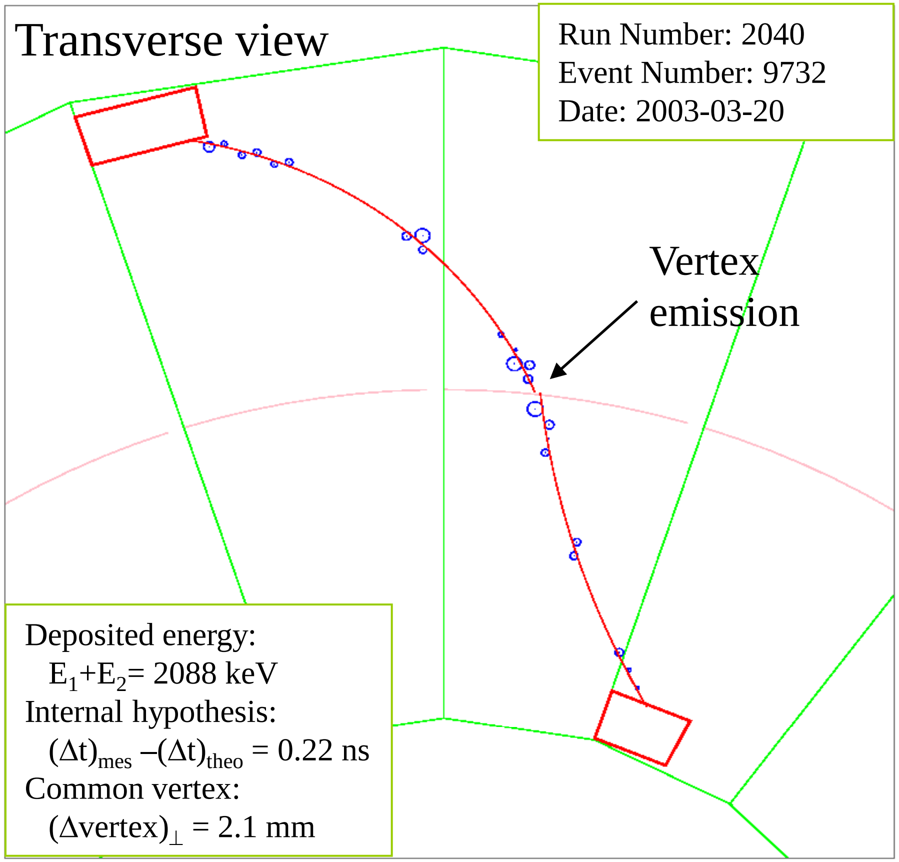
Cu 621 g

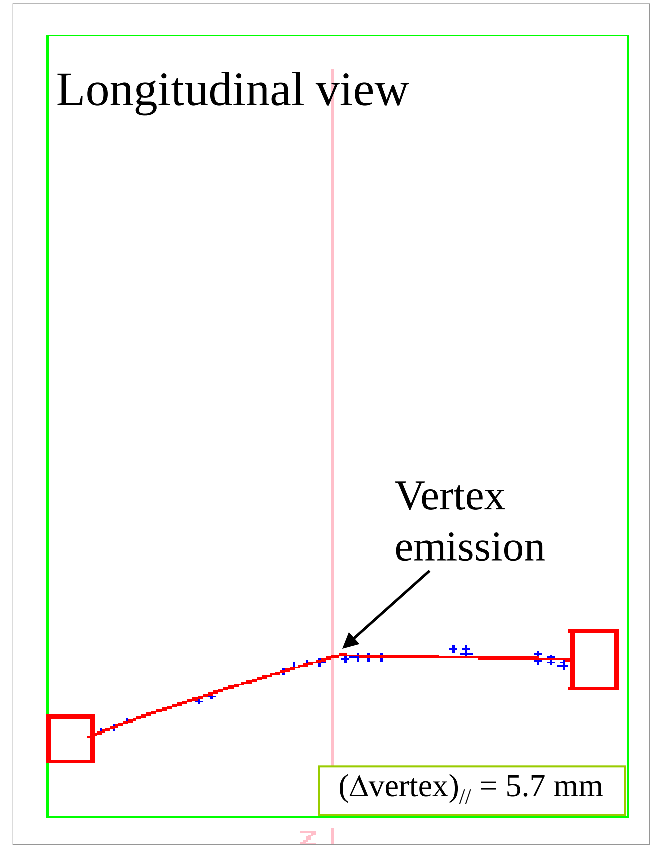
External bkg measurement

(Enriched isotopes produced by centrifugation in Russia)

ββ event in NEMO3

Typical ββ2ν event observed from ^{100}Mo





Trigger: 1 PM > 150 keV

3 Geiger hits (2 neighbour layers + 1)

Trigger Rate ~ 5.5 Hz

ββ evts: 1 event every 2 minutes

ββ events selection

- 2 tracks with charge < 0
- 2 PM, each E> 200 keV
- PM-track association
- Common vertex
- Internal hypothesis Δt~0ns
- No isolated PM (γ rejection)
- No delayed track (^{214}Bi rejection)

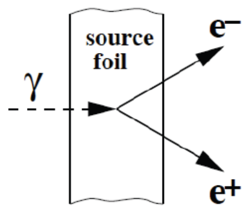
NEMO-3 Backgrounds Measurement *NIM A606 (2009) 449-465)*

➢ **External γ** (if the γ is not detected in the scintillators)

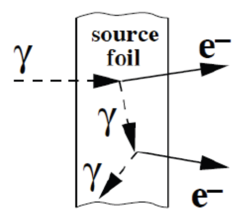
Origin: natural radioactivity of the detector or neutrons

Main bkg for ββ2ν but negligeable for ββ0ν

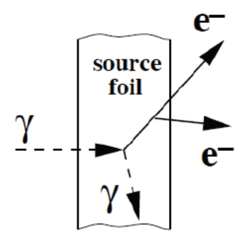
(^{100}Mo and ^{82}Se $Q_{\beta\beta}$ ~ 3 MeV > Eγ(^{208}Tl) ~ 2.6 MeV)



pair creation

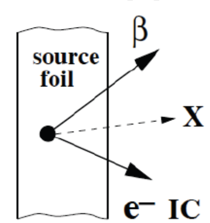


Compton + Compton

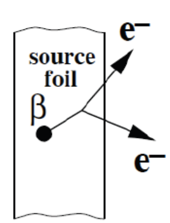


Compton + Möller

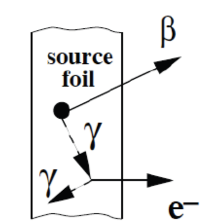
➢ **^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi) contamination inside the ββ source foil**



beta + IC



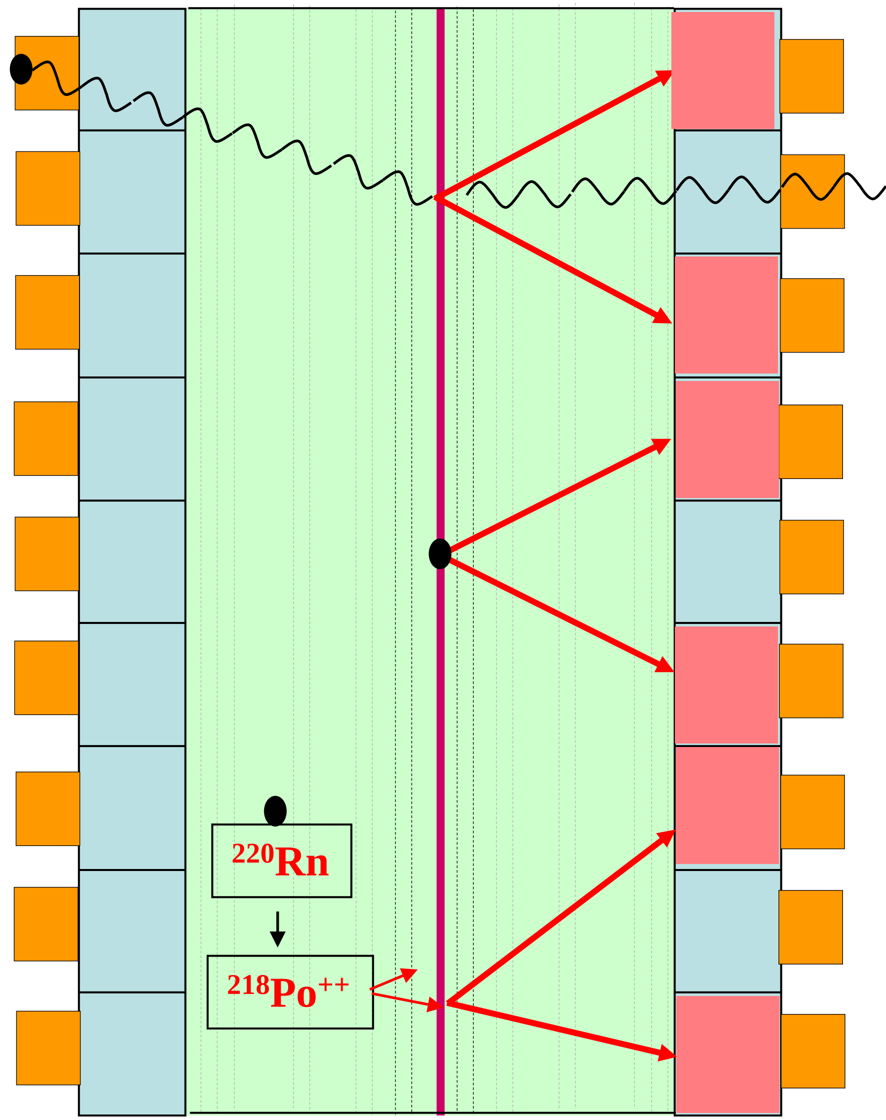
beta + Möller



beta + Compton

➢ **Radon (^{214}Bi) inside the tracking detector**

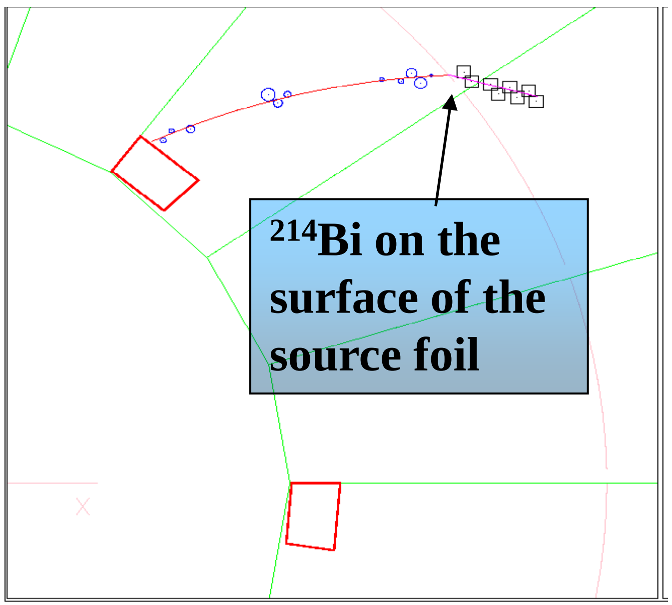
- deposits on the wire near the ββ foil
- deposits on the surface of the ββ foil



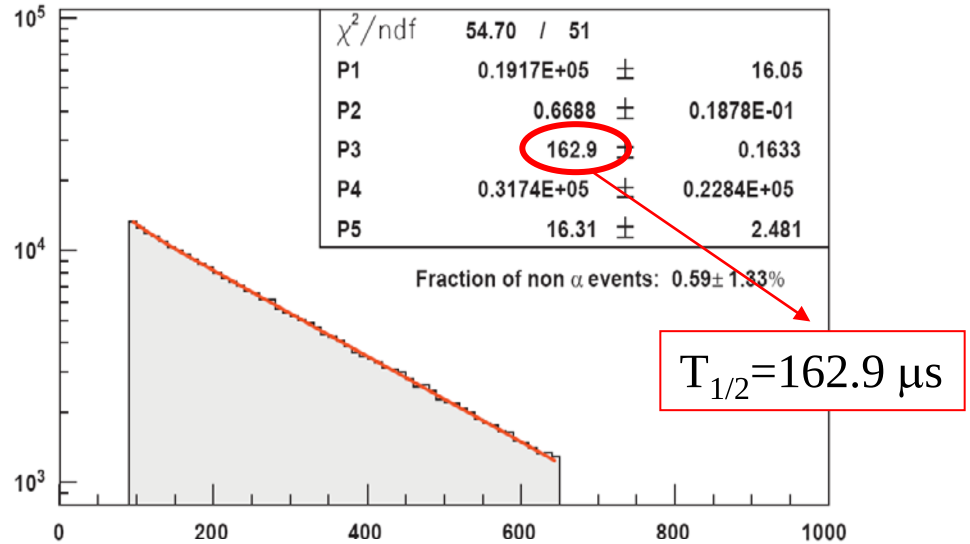
Each bkg is measured using the NEMO-3 data

Measurement of the Radon inside the tracking detector

$^{214}Bi \xrightarrow{\beta} {}^{214}Po \xrightarrow{\alpha} {}^{210}Pb$
(164 μs)

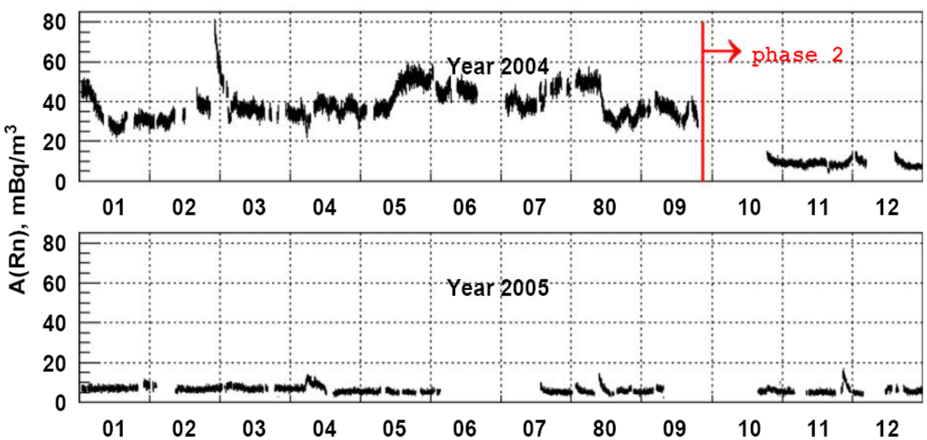


Pure sample of ^{214}Bi – ^{214}Po events



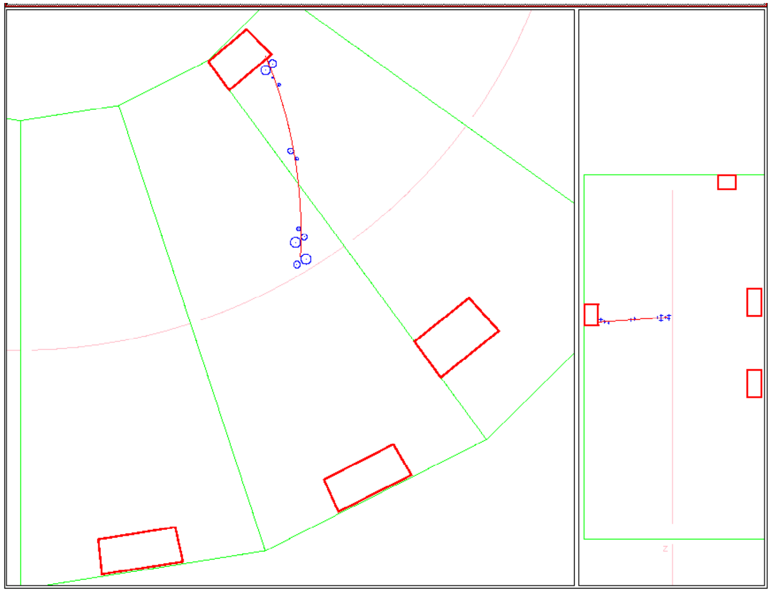
Delay time of the α track (μs)

Monitoring of the Radon bkg every day



- Phase 1: Feb. 2003 → Sept. 2004
  Radon Contamination
- Phase 2: Dec. 2004 → Today
  A (Radon) ≈ 5 mBq/m³

Measurement of the ^{208}Tl (^{232}Th) inside the ββ source foil



^{208}Tl contamination inside the ββ source foils is measured using **internal (e^-,γ,γ) or (e^-,γ,γ,γ) channels**

ββ material	*N*	A (mBq/kg)	A_{HPGe} (mBq/kg)
^{100}Mo(m)	666	0.11 ± 0.01	$<0.13; <0.1; <0.12^*$
^{100}Mo(c)	1628	0.12 ± 0.01	<0.17
^{82}Se(I)	446	0.34 ± 0.05	<0.670
^{82}Se(II)	507	0.44 ± 0.04	$0.4 \pm 0.13^{**}$
^{48}Ca	42	1.15 ± 0.22	$<2.$
^{96}Zr	158	2.77 ± 0.25	$<10.; <5.^*$
^{150}Nd	1002	9.32 ± 0.32	$10. \pm 1.7$
^{130}Te	448	0.23 ± 0.05	<0.5
^{nat}Te	495	0.27 ± 0.04	<0.08
^{116}Cd	196	0.17 ± 0.05	$<0.83; <0.5^*$
Cu	66	0.03 ± 0.01	<0.033

Agreement with HPGe measurements

^{208}Tl contamination in the Mo foils:

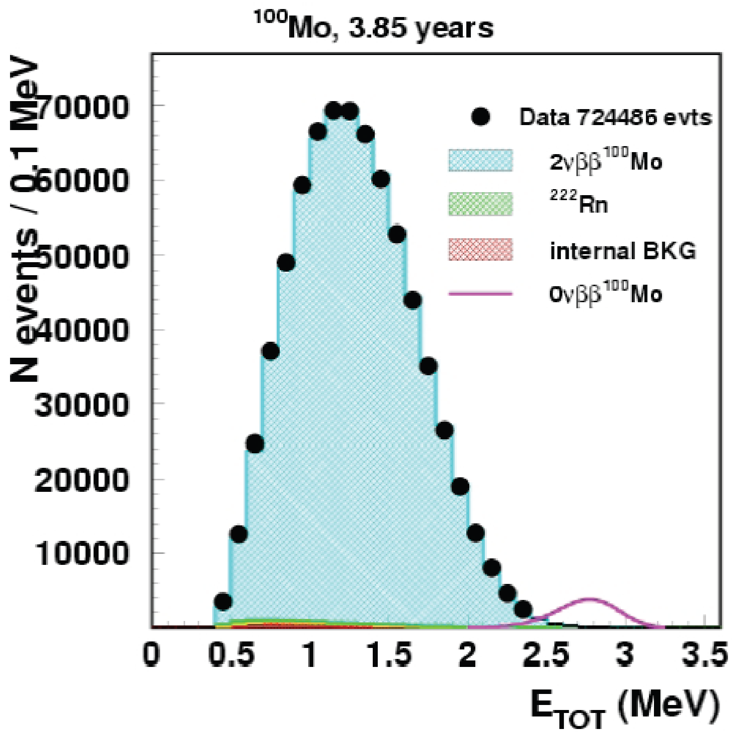
A(^{208}Tl) ~ 100 μBq/kg

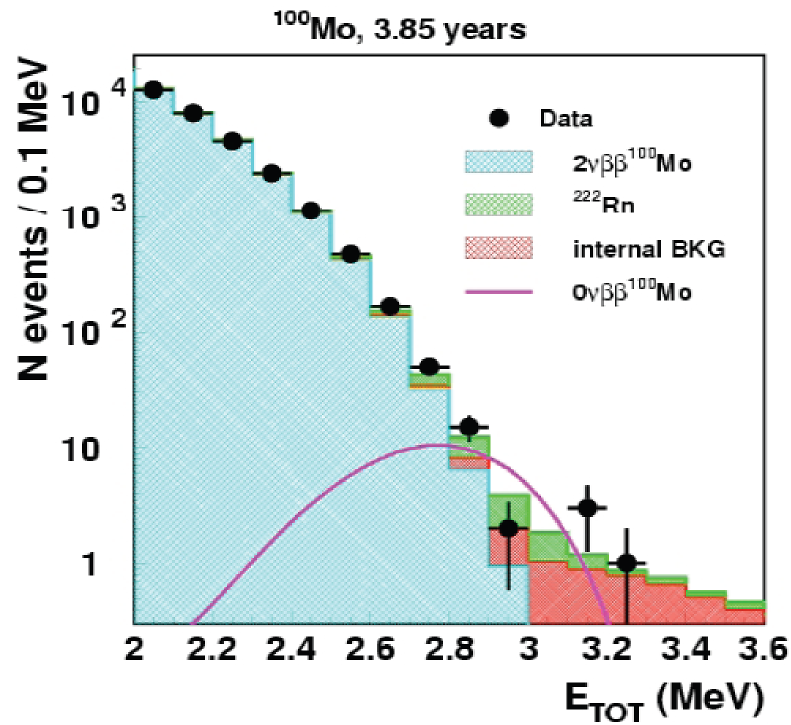
⇒ ^{100}Mo foils should be measured later inside the BiPo detector

ββ0ν results with ^{100}Mo

T_{obs} = 3.85 years
M(^{100}Mo) = 6.914 kg

Data until the end of 2008





[2.8 , 3.2] MeV:
Data: 20 events, Expected: 18.6 events
Excluded at 90% C.L. 9.6 events
Efficiency ε= 0.0726

MCLIMIT : [2.0, 3.2] eV
18 events excluded
Total mean 0ν efficiency ε = 0.174

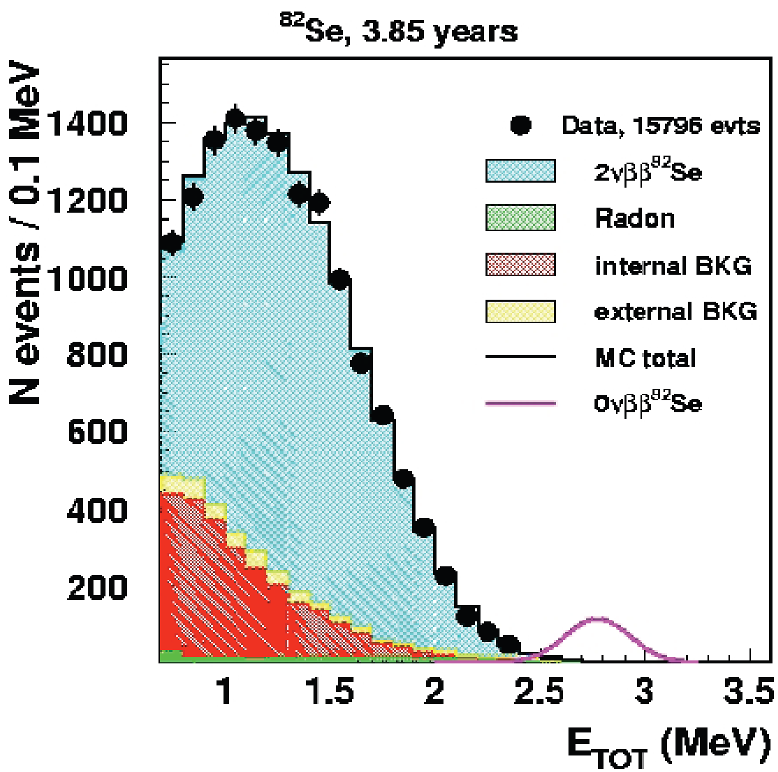
Both simple counting and likelihood methods are consistent

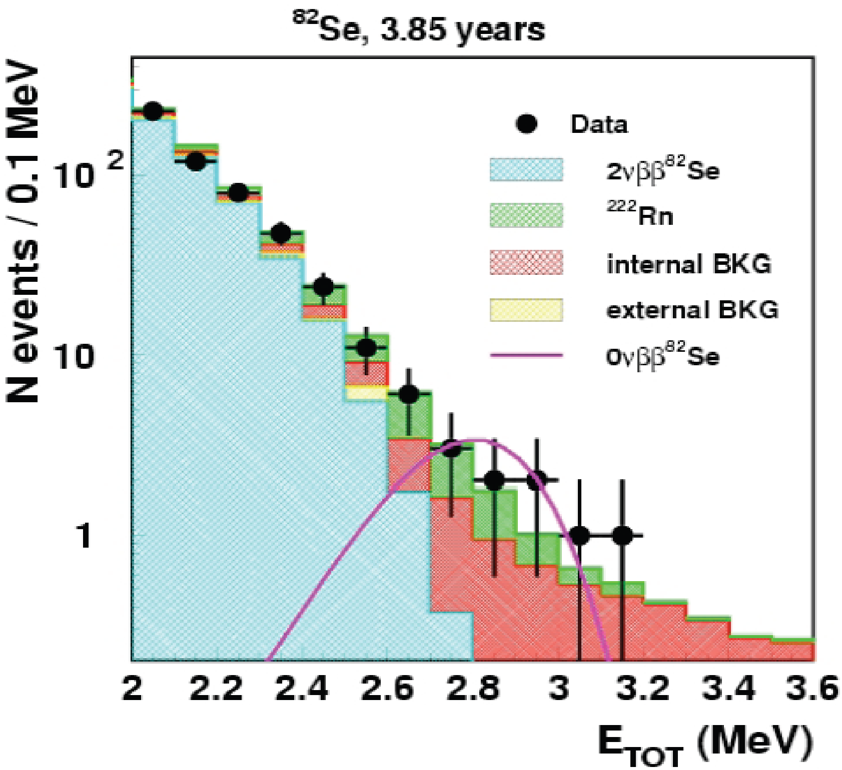
$T_{1/2}$ (0νββ) > 1.1 x 10^{24} y @ 90% C.L.
$\langle m_\nu \rangle$ < 0.45 – 0.93 eV

ββ0ν results with ^{82}Se

T_{obs} = 3.85 years
M(^{82}Se) = 932 g

Data until the end of 2008





[2.6 , 3.2] MeV:
Data: 15 events, Expected: 13.2 events
Excluded at 90% C.L. 8.9 events
Efficiency ε= 0.151

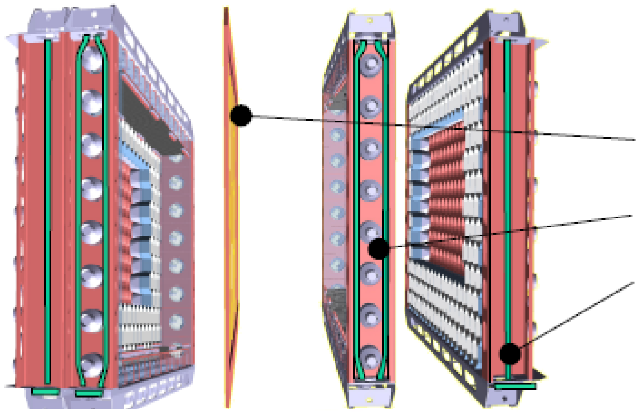
MCLIMIT : [2.0, 3.2] MeV
9.8 events excluded
Total mean 0ν efficiency ε = 0.182

$T_{1/2}$ (0νββ) > 3.6 x 10^{23} y @ 90% C.L.
<m_ν> < 0.89 – 1.61 eV

SuperNEMO Project

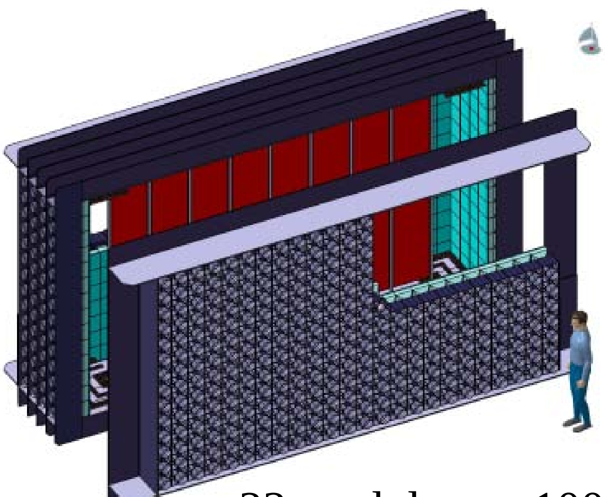
Extrapolation of NEMO-3 detector ⇒ 100 kg of ^{82}Se

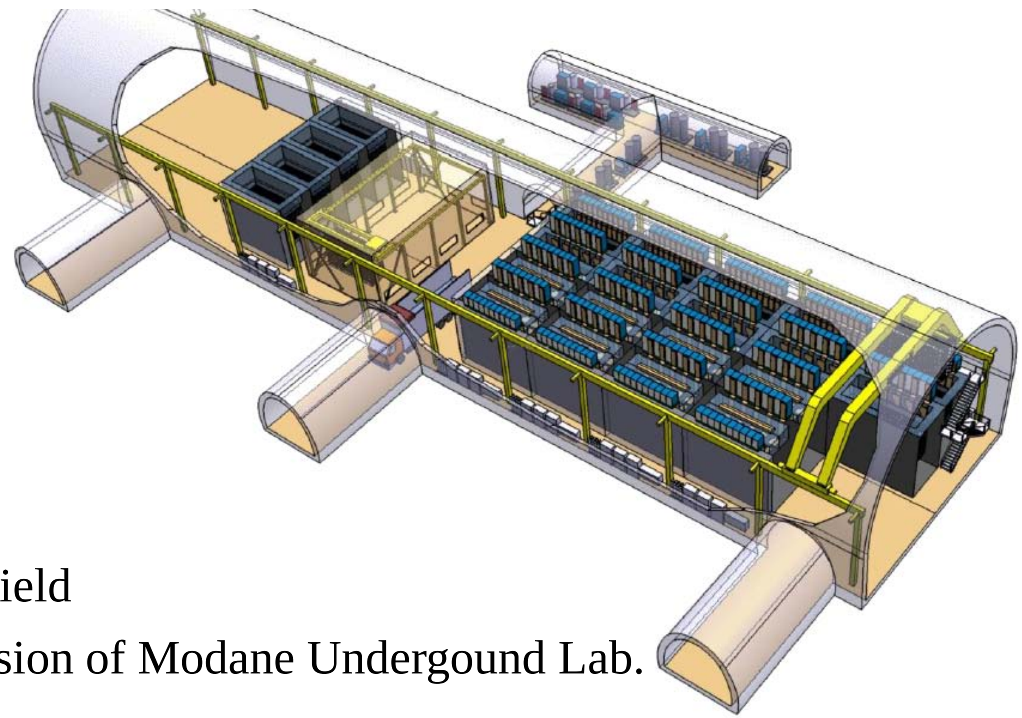
⇒ to reach $T_{1/2}(\beta\beta0\nu) \geq 10^{26}$y



Modular detector with a planar geometry

- source : 4 x 3 m² foil (40 mg / cm²)
- tracking : drift cells in Geiger mode
- calorimeter : **PVT hexa scintillator + 8" low radioactive PMTs**





22 modules ⇒ 100 kg of ^{82}Se

Modules surrounded by water shield

To be installed in the futur extension of Modane Undergound Lab.

Three main R&D challenges for SuperNEMO

In order to reach $T_{1/2}(\beta\beta0\nu) \geq 10^{26}$ y with 100 kg of ^{82}Se,

the R&D targets are:

NEMO-3

- **Reduce $\beta\beta2\nu$ background**
  - $T_{1/2}(\beta\beta2\nu)$ = **10^{20} y for ^{82}Se** ---------- **^{100}Mo 7.10^{18} y**
  - Energy resolution Calorimeter FWHM = 7% @ 1 MeV ---------- **14% @ 1 MeV**

- **Reduce ^{208}Tl and ^{214}Bi contamination inside $\beta\beta$ source foils**

  $A(^{208}Tl)$ < **2 μBq/kg** ---------- **A=100 μBq/kg**

  $A(^{214}Bi)$ < 10 μBq/kg

- **Reduce Radon and Thoron contamination inside the detector**

  A(Radon) < **0.1 mBq/m^3** ---------- **A= 5 mBq/m^3**

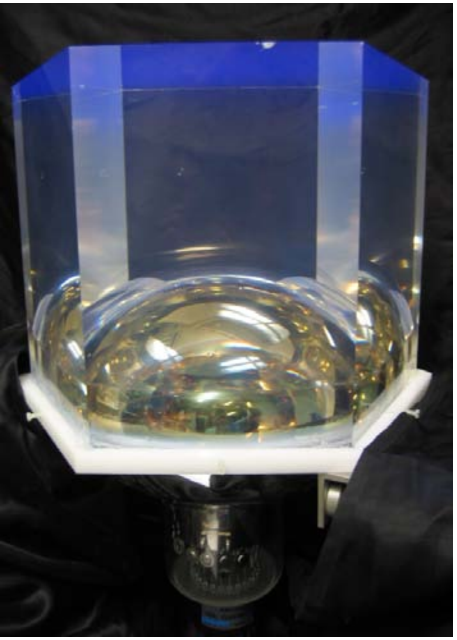
  A(Thoron) < 15 μBq/m^3 ---------- **A= 150 μBq/m^3**

Energy Resolution

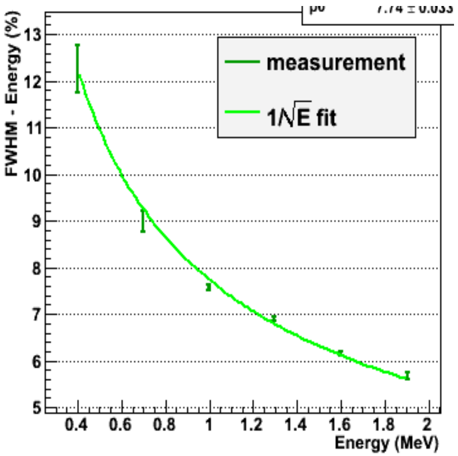
- PMT 8” Photonis QE = 45% with dedicated dynodes
- Plastic Scintillator: PVT EJ200 (~ BC408)
- Hexagonal design
- Wrapped with ESR teflon and aluminized mylar on the entrance face

Measured with ^{90}Sr spectrometer at CENBG
Crosscheck with ^{207}Bi at UCL London

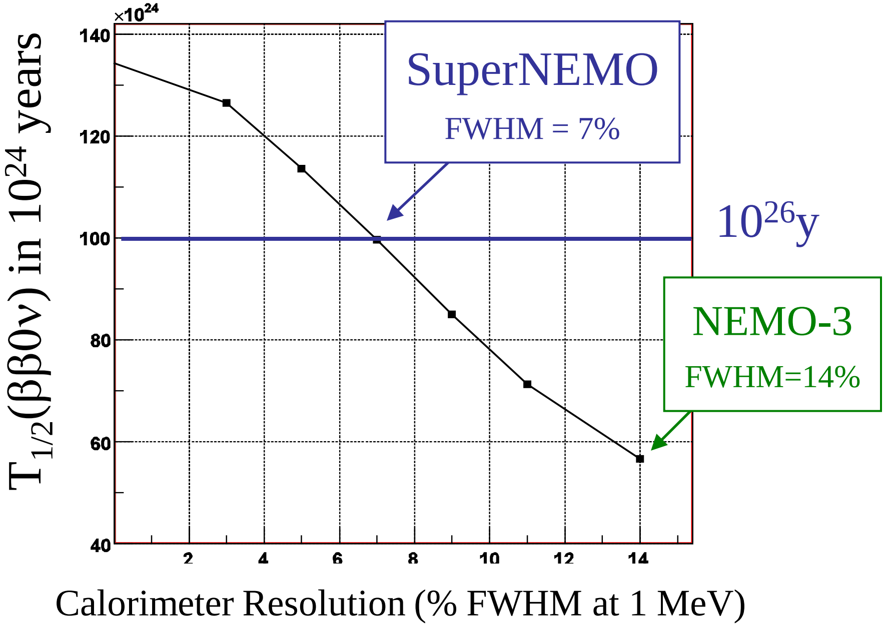
⇨ **FWHM @ 1 MeV = 7.1 %**



Results with Spectrometer



SuperNEMO Simulations



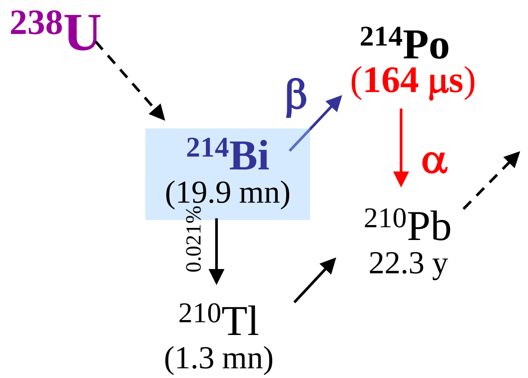
BiPo detector

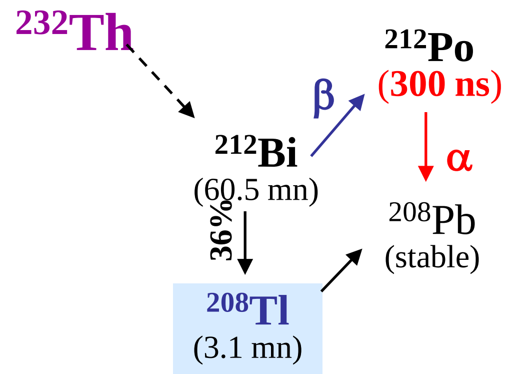
Measure the purity in ^{208}Tl and ^{214}Bi of the SuperNEMO ββ source foils

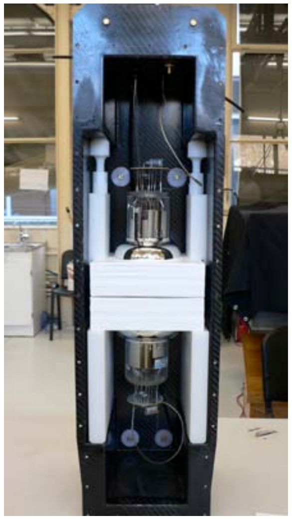
Goal: To **measure ~10 m^2 of foils (40 mg/cm^2) in ~ 1 month** with a sensitivity of:

^{208}Tl < 2 μBq/kg and ^{214}Bi < 10 μBq/kg

Detect the BiPo decay cascade: beta + delay alpha

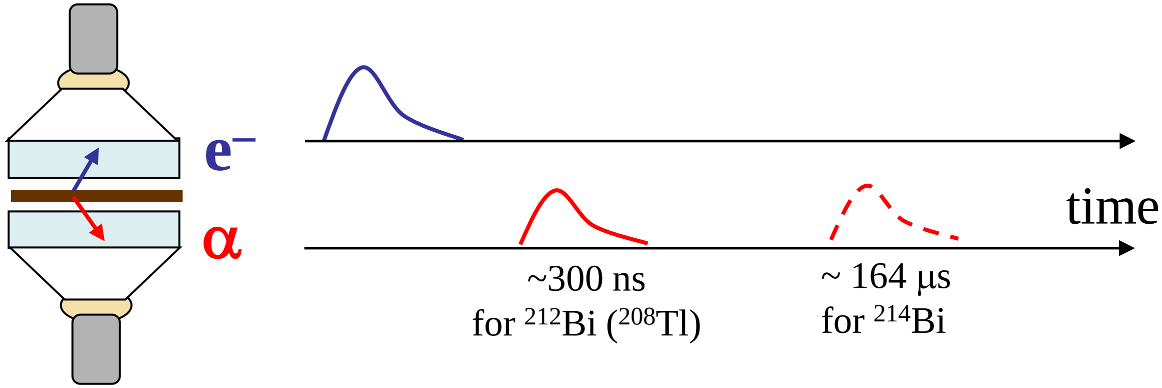




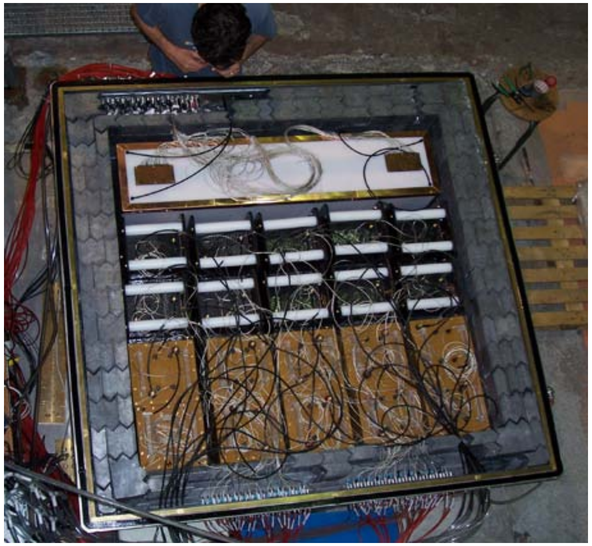


Sandwich of two low radioactive thin polystyrene plastic scintillators

Time topology signature: 1 hit + 1 delay hit (and no coincidence)



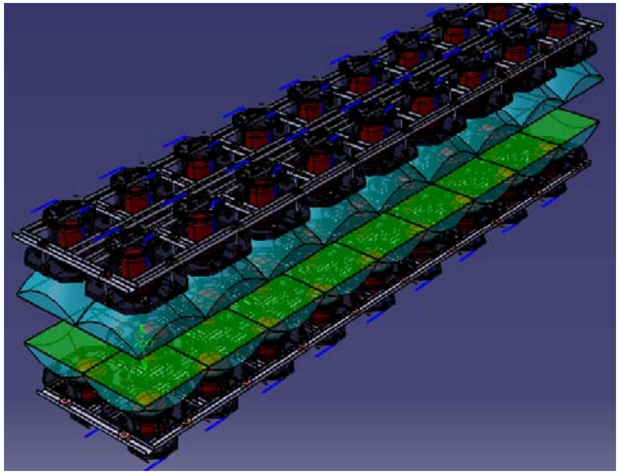
From the BiPo-1 prototype to the BiPo-3 detector



➢ BiPo-1 prototype of 0.8 m^2

- Prototype of **0.8 m^2 running in LSM Modane**
  (20 modules of 20×20×0.3 cm^2 scintillators)
- **Goal: Measurement of the backround level**
  (surface radiopurity of the scintillators)
- **Results:** 32 BiPo events detected after 420 days of data collection

➡ **Bkg level A(^{208}Tl) = 1.5 μBq/m^2**



➢ Next step: a BiPo detector of 3.5 m^2

(construction in 2010)

- Goal: To measure 3.5 m^2 of ^{82}Se ββ source foils
  (thickness=40 mg/cm^2)
- Assuming a background A(^{208}Tl) = 1 μBq/m^2 (as in BiPo-1), one can achieve a sensitivity of

➡ **A(^{208}Tl) < 3 μBq/kg (90% C.L.) after 6 months of measurement**

SuperNEMO demonstrator

- First SuperNEMO module in Modane
- 7 kg of ^{82}Se
- Expected sensitivity :

  $T_{1/2}(\beta\beta0\nu) > 4.10^{24}$ years per year of data collection

  Bkg ~ 0.1 cts/FWHM/year at $Q_{\beta\beta}$

- Goal : demonstrate the control of the background

  Foil purity: A(^{208}Tl) < 2μBq/kg & A(^{214}Bi) < 14μBq/kg

  Gas purity inside the detector: A(Radon)<0.1 mBq/m^3 & A(Thoron)<15μBq/m^3

- Installation expected in 2013 in Modane

Overview of Experiments

Name	Nucleus	Mass*	Method	Location	Time line
Operational & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48	tbd	scintillation	Solotvina	
COBRA	Cd-116, Te-130	tbd	ionization	LNGS	
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	

SNO+ *(Sudbury, Canada)*

- **Uses existing SNO detector**
  Heavy water replaced by liquid scintillator (1 kton) loaded with ^{150}Nd
  1% natural Nd-loaded liquid scintillator in SNO
  = 56 kg of ^{150}Nd (before fiducial cut)

- **Modest resolution** (compensated by high statistical accuracy ?)

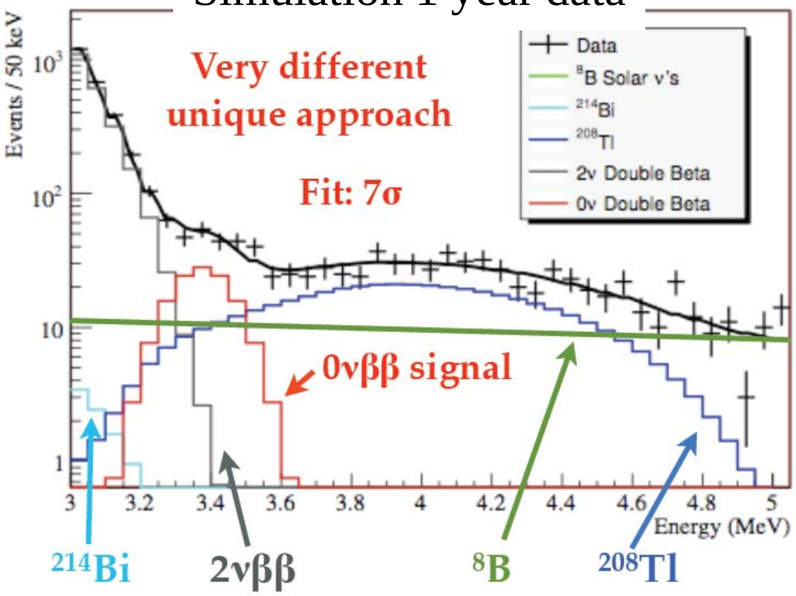
- Liquid scintillator: **Linear Alkylbenzene (LAB)**
  - Compatible with acrylic, undiluted
  - High light yield, long attenuation length
  - Safe: high flash point, low toxicity
  - Cheaper than other scintillators

- **Requires engineering for acrylic vessel hold down and purification plant.**
  ⇒ Technologies already developed.

- **Start filling with scintillator in early 2011**

^{Nat}Nd-loaded Liq. Scint.

Simulation 1 year data



Expected Sensitivity: $T_{1/2}(\beta\beta 0\nu) \sim 5.10^{24}$ yr after 1 year of data
Large uncertainty on Nuclear Matrix elements
However largest phase space factor (= 32 times more favorable than ^{76}Ge !)

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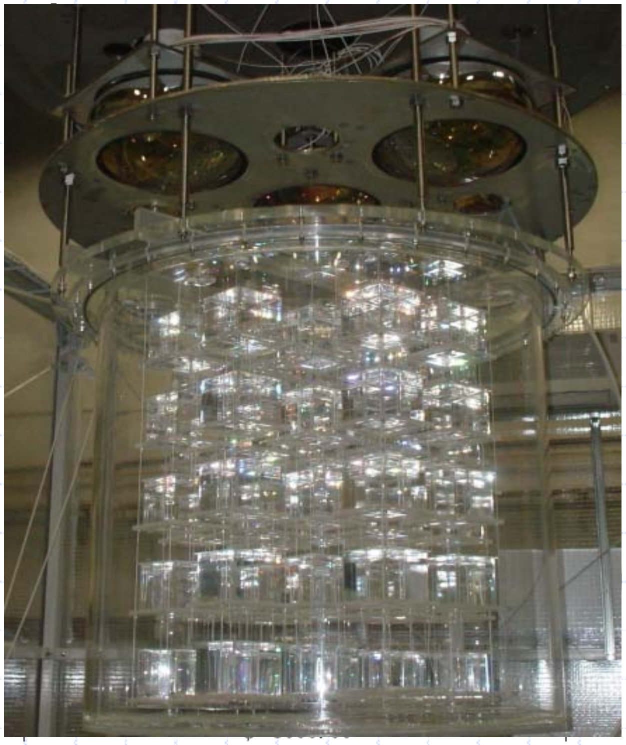
MOON	Mo-100	tbd	tracking	Oto	

CANDLE-III *(Kamioka, Japan)*



- undoped CaF_2 (CaF_2(pure))
  - ^{48}Ca ($Q_{\beta\beta}$=4.27 MeV)
  - Attenuation length > 10 m
  - Low radioactive impurities
- Low background detector
  - 4π active shield (LS)
  - Passive shield (Water, LS)
  - Pulse shape information → { CaF2 pure ~μs; Liq. Scint. ~10ns }
- Good energy resolution
  - large photo-coverage
  - Two phase LS system

  ⇒ FWHM ~ 5% @ 4.2 MeV

96 crystals ^{nat}CaF2 (10^3 cm^3) : Total Mass = 305 kg

⇒ only ~ 350 g of ^{48}Ca (natural abundance = 0.187%)

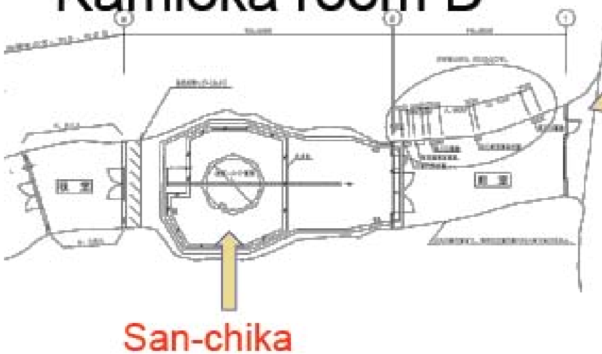
Enrichment R&D

- Current R&D: enrichment using chromatography and Ca-doped Crown Ether
- Korean group also started an R&D program to enrich ^{48}Ca by laser separation
  ⇒ In 2012: Demonstrator for ^{48}Ca enrichment 1 kg/year…
- If enriched ^{48}Ca becomes available in the future, CANDLE would become a competitive experiment

CANDLE-III *(Kamioka, Japan)*

….will illuminate Kamioka

Kamioka room D



305 kg (96 x 10^3 cm^3 crystals) of natural-CaF_2
⇒350 g of Ca-48

First PMT was installed at 24 June, 2009.

S. Schönert, TAUP 2009

Overview of Experiments

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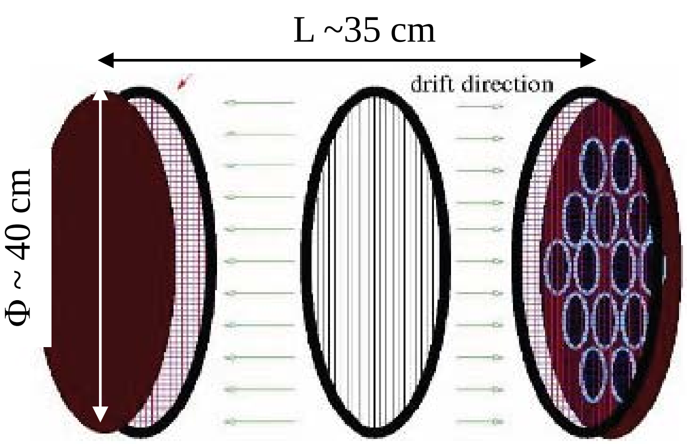
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	

EXO-200 *(WIPP, USA)*

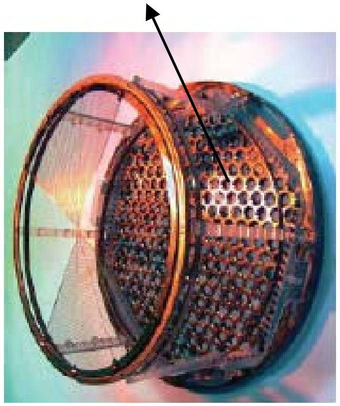
- A liquid ^{136}Xe TPC ⇒ compact detector: L ~ 35 cm, Φ ~ 40 cm
- 200 kg 80% enriched ^{136}Xe already produced
- $Q_{\beta\beta}$=2479 keV
- ββ2ν has not yet been observed $T_{1/2}(\beta\beta 2\nu)$
- It combine ionization charge & Scintillation light readout

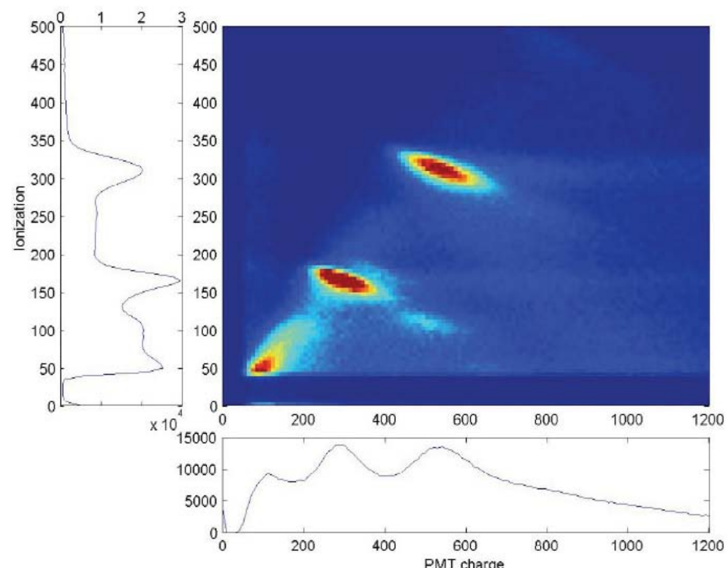
  ⇒ FWHM = 3.4% @ $Q_{\beta\beta}$= 2479 keV

Eff.	Run Time	Background Cts/FWHM	$T_{1/2}(\beta\beta 0\nu)$ (90% C.L.)	$\langle m_\nu \rangle$ *(NME N4-ILIAS)*
70%	**2 yr**	**40**	**6.4 10^{25} yr**	**0.11 – 0.26 eV**



250 large area APD plane





EXO-200 goes underground…

…and commissioning will start end of 2009

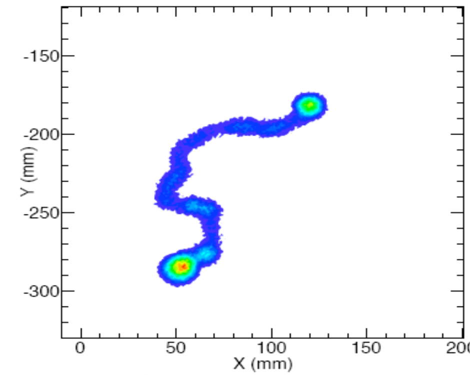
EXO-200 at WIPP

NEXT-100 *(Canfranc, Spain)*

- A High Pressure Gaseous ^{136}Xe TPC (HPG-TPC) with 100 kg of ^{136}Xe
- Pressure ~ 10 bars (e^- with energy ~ $Q_{\beta\beta}$ traverses ~ 30 cm of gas)

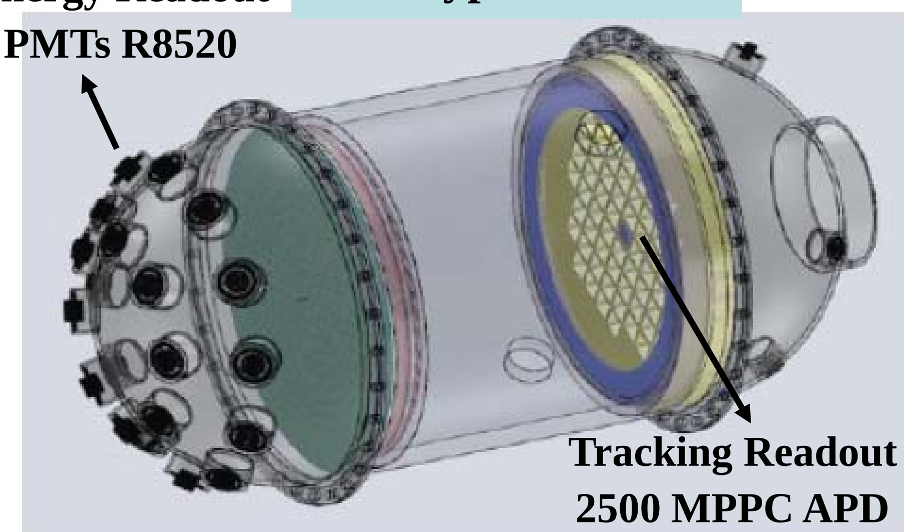
  Size of the NEXT-100 TPC: L ~140 cm, F ~ 140 cm
- Reconstruct the topology of ββ events: a track that ends in two "blobs" of energy
- Electroluminescence (EL) TPC for a better energy resolution

  Target: FWHM ~ 1% @ $Q_{\beta\beta}$= 2479 keV (already achieved at lower energy with small EL TPC)
- Advantage: Gas Xe potential of providing event topology + very good energy resolution
- Challenge: Low density provides limited self shielding

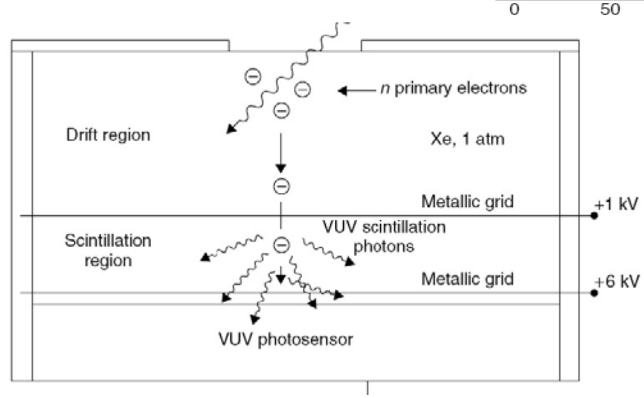


Energy Readout
PMTs R8520

Prototype NEXT-10



EL TPC



SUMMARY - Overwiev of ββ experiments

Project	Isotope	Mass (in kg)	FWHM @ $Q_{\beta\beta}$	Bkg Cts/ (keV.kg.y)	Bkg Cts/ (FWHM.y)	$T_{1/2}(\beta\beta0\nu)$ limit	$\langle m_\nu \rangle$ (in meV)	Time line *Start - results*
Construction / Commissioning								
GERDA I **GERDA II** **GERDA III**	^{76}Ge	18 40 100	4 keV	10^{-2} 10^{-3} 10^{-3}	0.7 0.2 0.4	**3.10^{25}** **2.10^{26}** **2.10^{27}**	**200 - 500** **80 - 200** **25 - 65**	*2010-2011* *2011-2013* *?*
CUORE	^{130}Te	200	5 keV	10^{-2}	37	**2.10^{26}**	**40 – 85**	*2012-2017*
EXO-200	^{136}Xe	200	40 keV	$2.5\ 10^{-3}$	20	**6.10^{25}**	**110 - 260**	*2010-2012*
SNO+	^{150}Nd	56	~200keV	-	~ 80	**-**	**~ 100**	*2011-2013*
Substantial R&D funding / prototyping								
CANDLE 3	^{48}Ca	0.35	210 keV	-	-	-	-	*2010 - ?*
SuperNEMO	^{82}Se	100	210 keV	10^{-4}	~ 2	**10^{26}**	**60 – 140**	*2013-2020*
NEXT-100	^{136}Xe	100	25 keV			**6.10^{25}**	**110 – 260**	*2014-2019*
R&D								
Scintillating **Bolometers** **1 tower**	^{82}Se ^{116}Cd ^{100}Mo	19 15 12	10 keV	$\leq 10^{-3}$	≤ 0.3	**10^{26}** **6.10^{25}** **6.10^{25}**	**60 – 140** **75 – 165** **65 - 130**	*?*