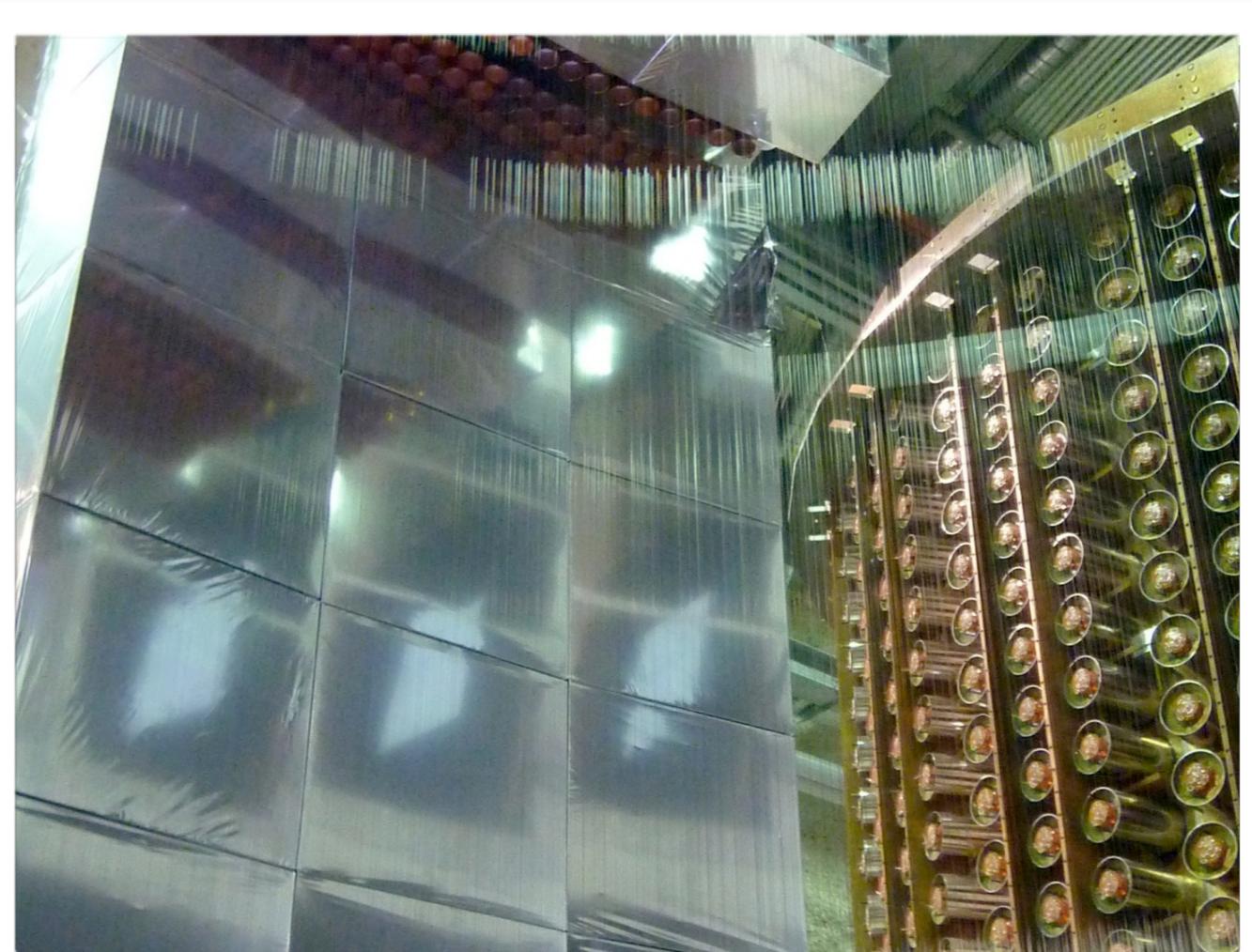


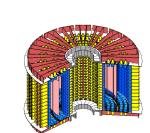
Search for Neutrinoless Double- β Decay of ^{100}Mo in the final NEMO-3 dataset

Stefano Torre
University College London

on behalf of the NEMO collaboration

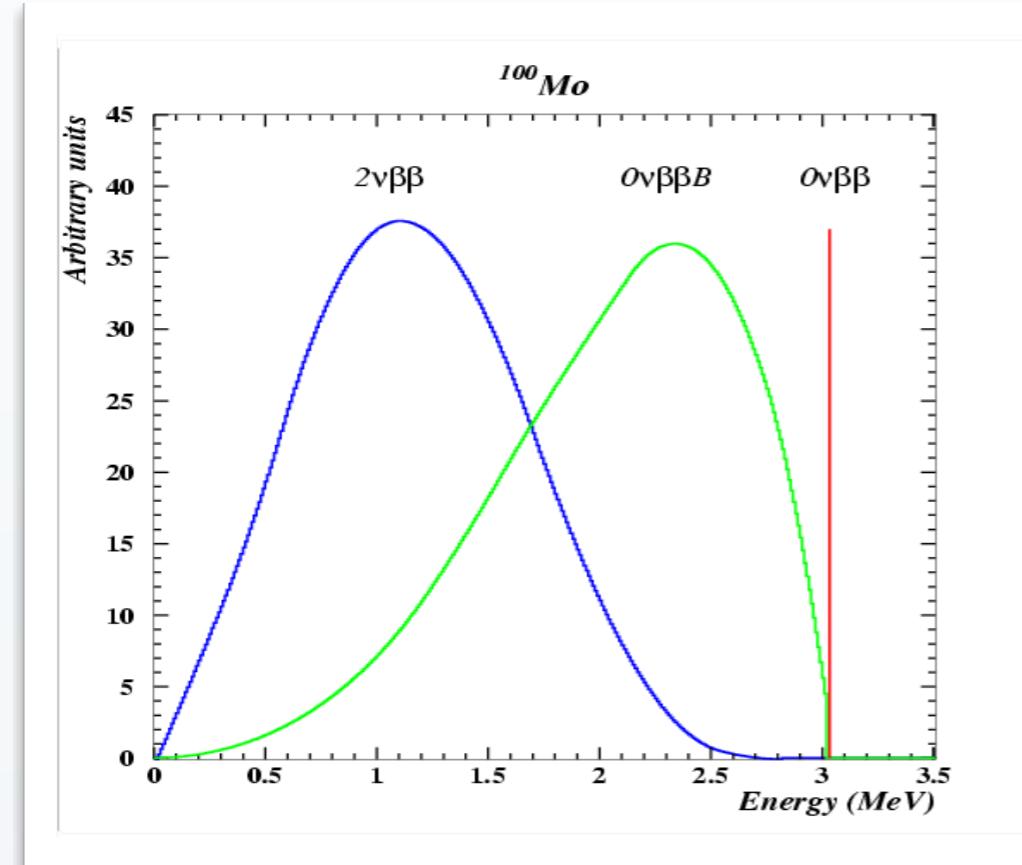
XLIXth Rencontres de Moriond
Electroweak Interactions and Unified
Theories
La Thuile, 15th-22nd March 2014



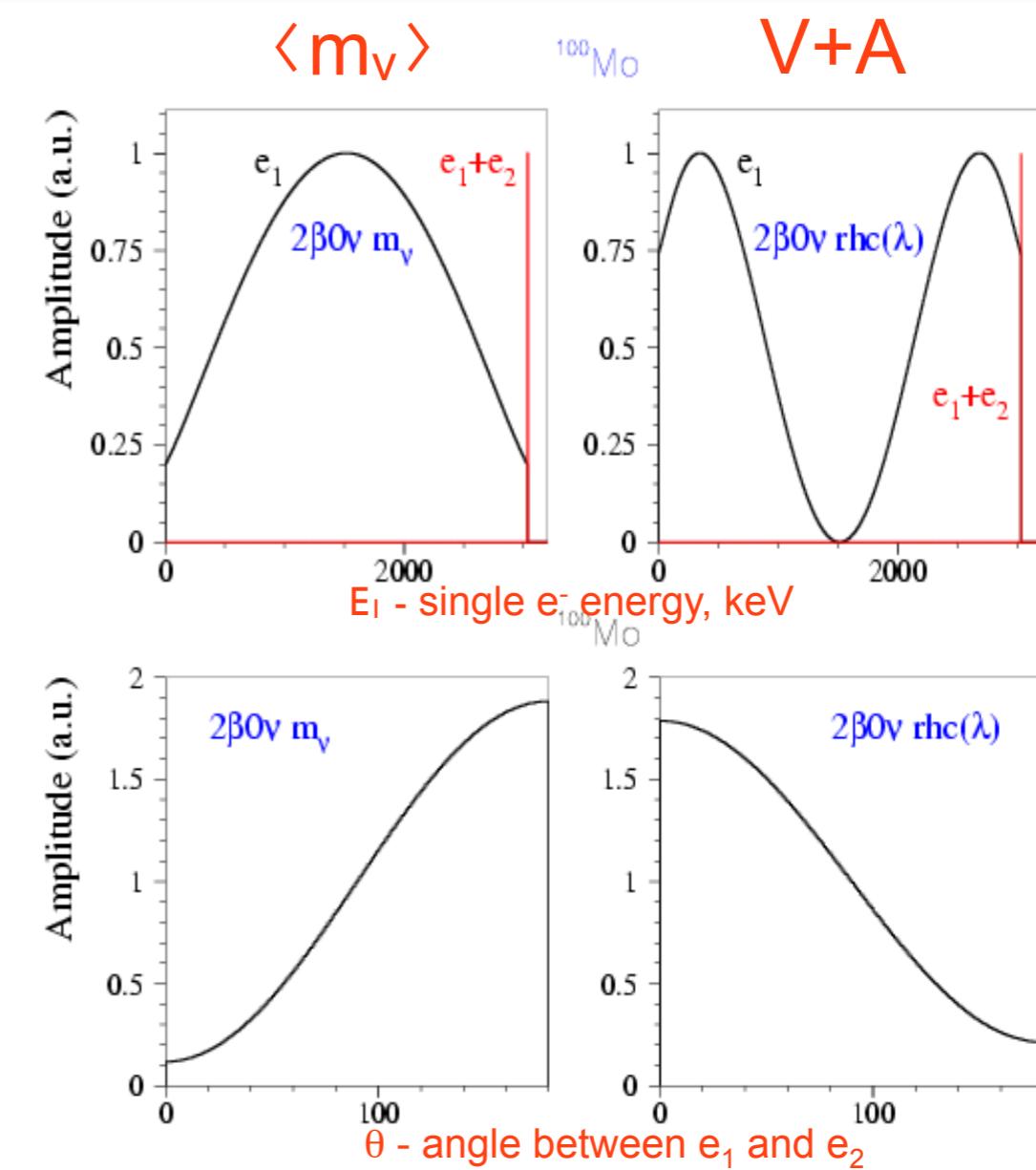


Which processes cause double beta decay?

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



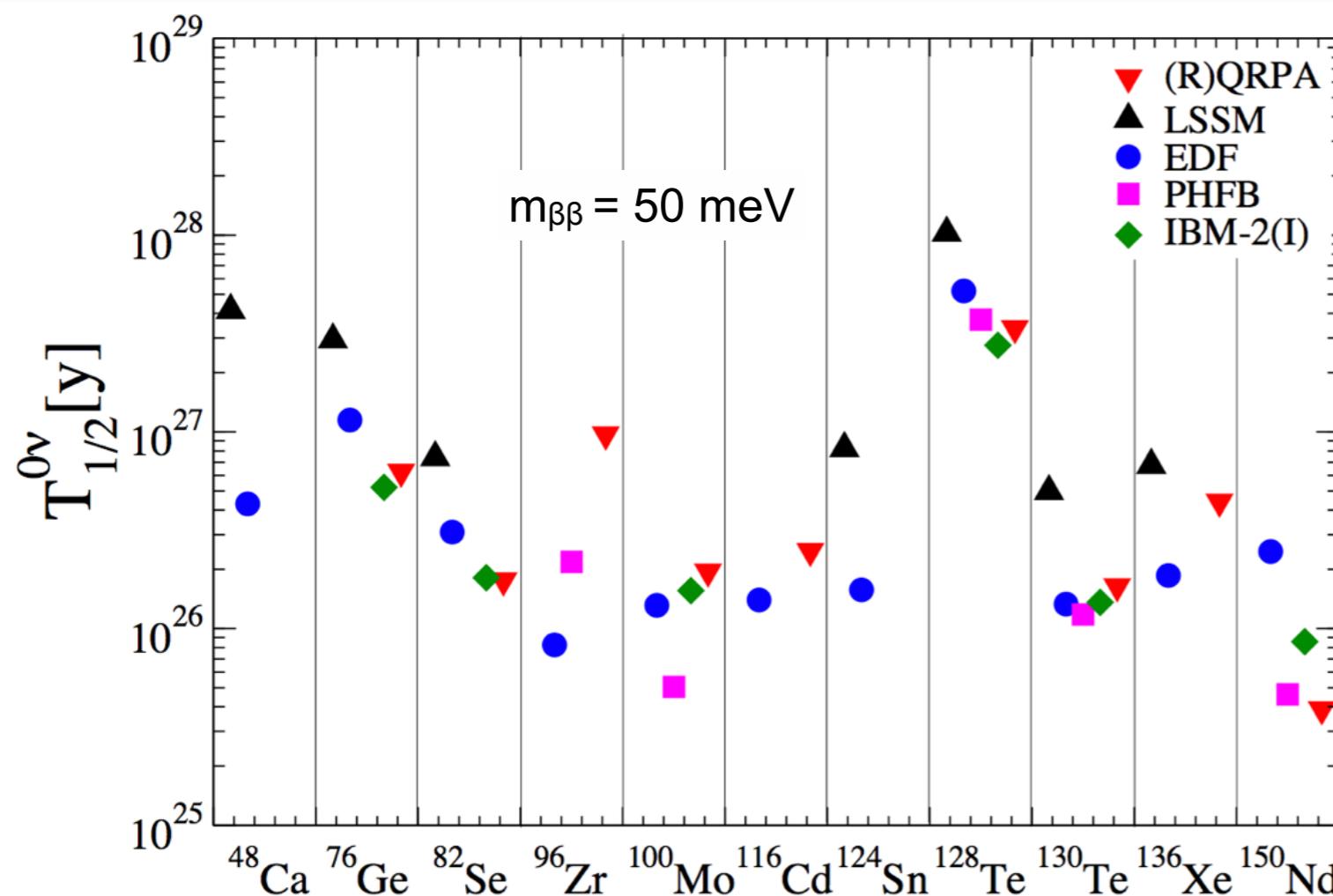
η can be due to mass mechanism, V+A, majoron, SUSY, ... with different topology in the final state



Measuring the Lepton Number Violating parameter

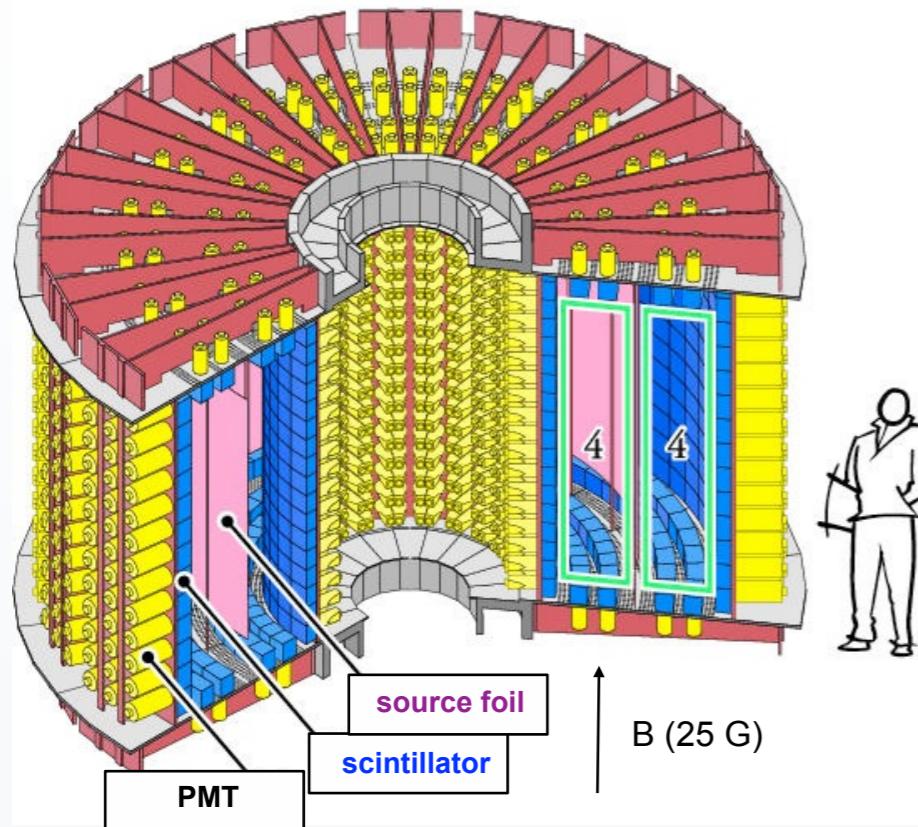
- need to know the Nuclear Matrix Element (NME)
- variation between models and isotopes
- combine measurements from as many isotopes as possible

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

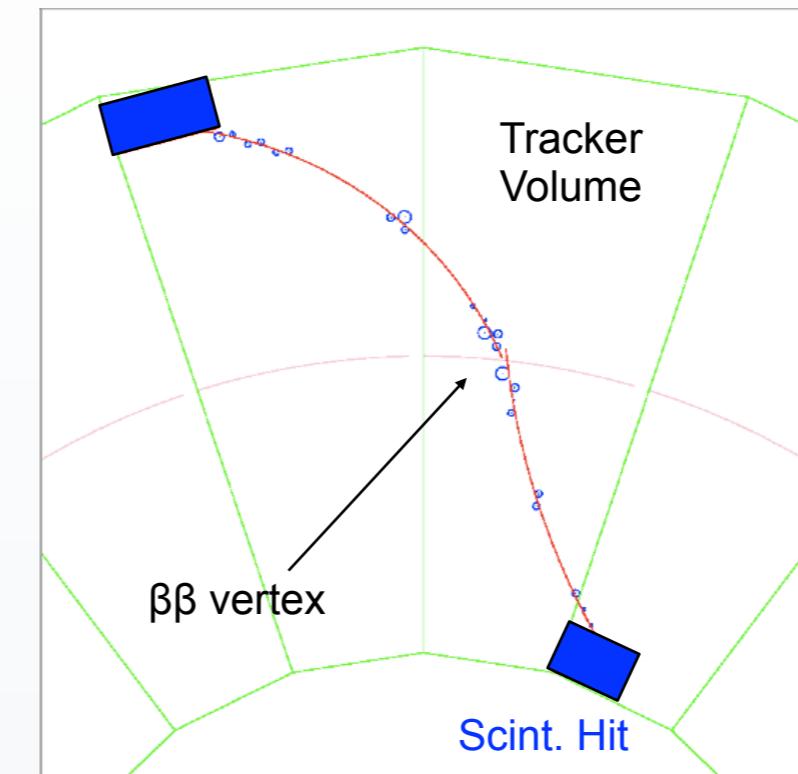


Isotope	Abundance (%)	$Q_{\beta\beta}$ (MeV)	$G^{0\nu}$ (10^{-14} y)
⁴⁸ Ca	0.19	4,276	7.15
⁷⁶ Ge	7.8	2,039	0.71
⁸² Se	9.2	2,992	3.11
¹⁰⁰ Mo	9.6	3,034	5.03
¹¹⁶ Cd	7.5	2,804	5.44
¹³⁰ Te	34.5	2,529	4.89
¹³⁶ Xe	8.9	2,467	5.13
¹⁵⁰ Nd	5.6	3,368	23.2

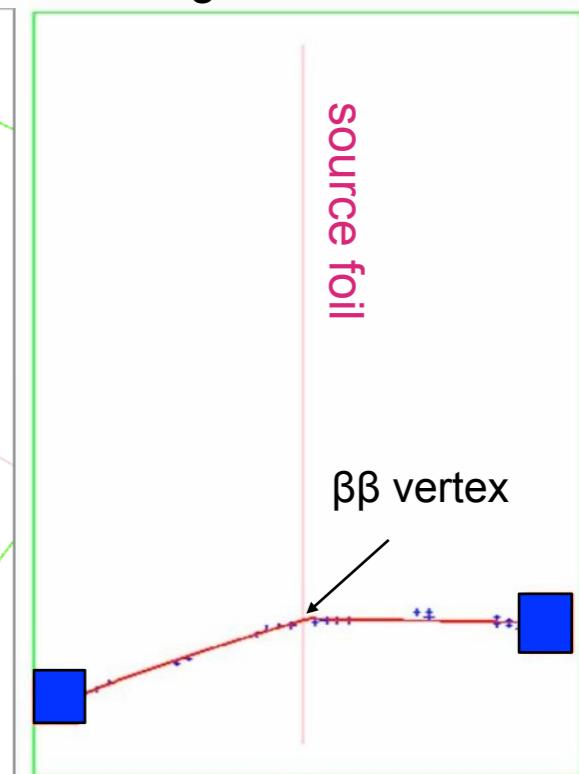
NEMO3



Transverse View



Longitudinal View



- The particle physicist's nuclear physics experiment.
- “**Smoking gun**” : complete event reconstruction for :
 - background rejection
 - signal characterization (discovery!)

Isotopes

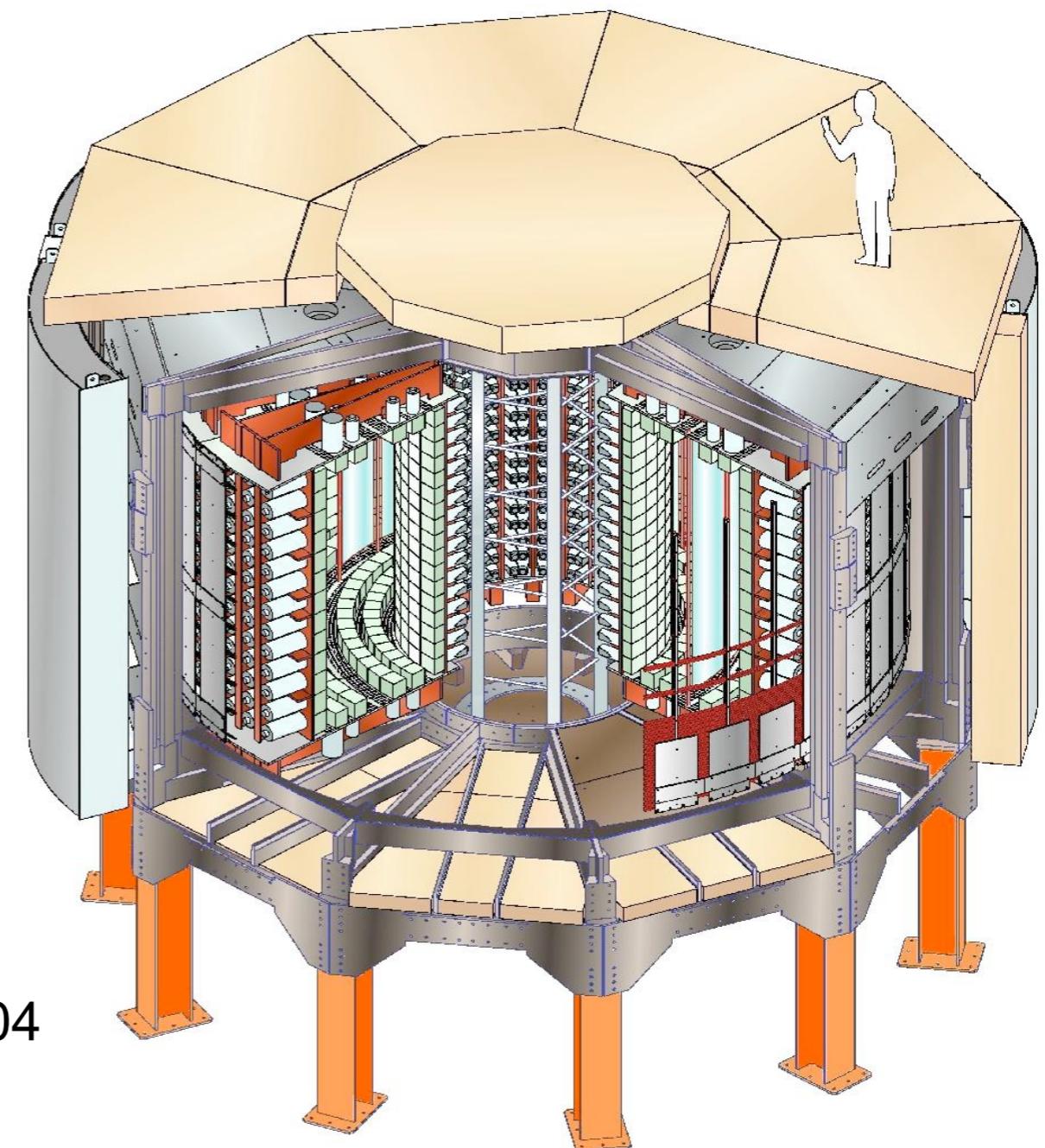
Large quantities: ^{100}Mo (7kg) ^{82}Se (1 kg)

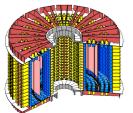
Small quantities: ^{116}Cd ^{150}Nd ^{48}Ca ^{96}Zr ^{130}Te

All major isotopes except ^{76}Ge and ^{136}Xe

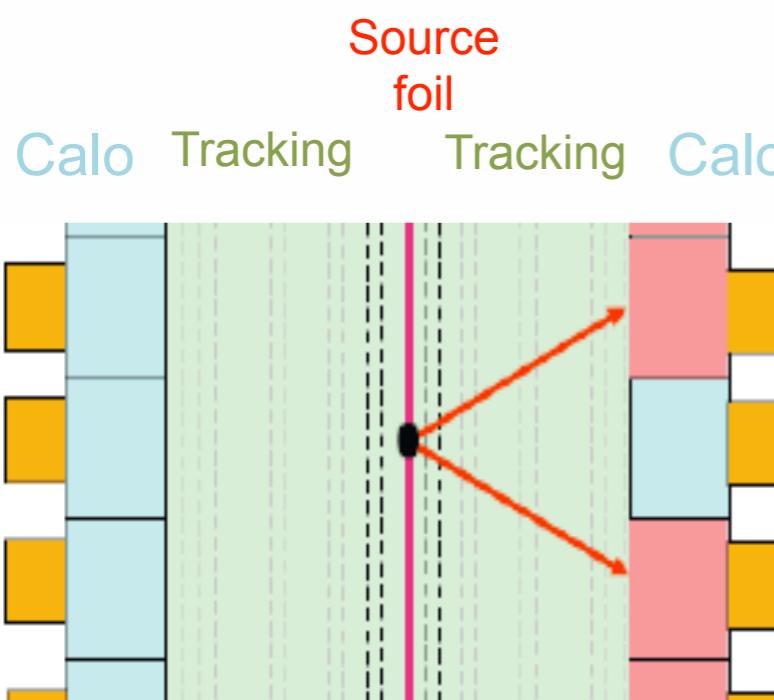
NEMO3

- source distributed on cylindrical surface
- 3D wire drift chamber operated in Geiger mode (6180 cells)
 - He + 4% ethyl alcohol + 1% Ar + 0.1% H₂O
- calorimeter made of 1940 plastic scintillators coupled to low radioactivity PMTs
- Magnetic field: 25 Gauss
- Gamma shield: iron
- Neutron shield:
 - 30cm borated water (external wall)
 - 40cm wood (top and bottom)
- Two separate runs:
 - Phase 1, “High” Rn: Feb, 2003 → Sep, 2004
 - Phase 2, “Low” Rn: Oct, 2004 → Jan, 2011

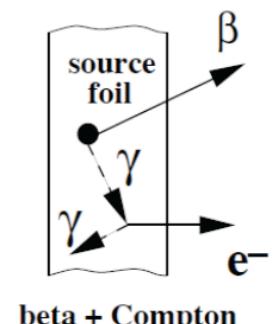
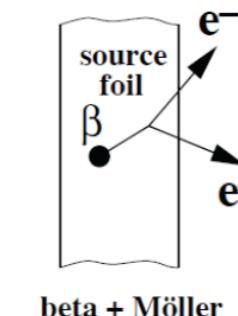
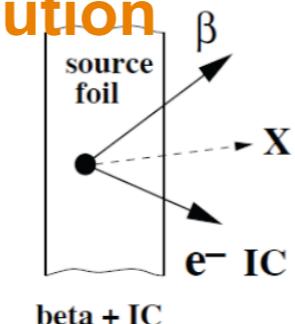




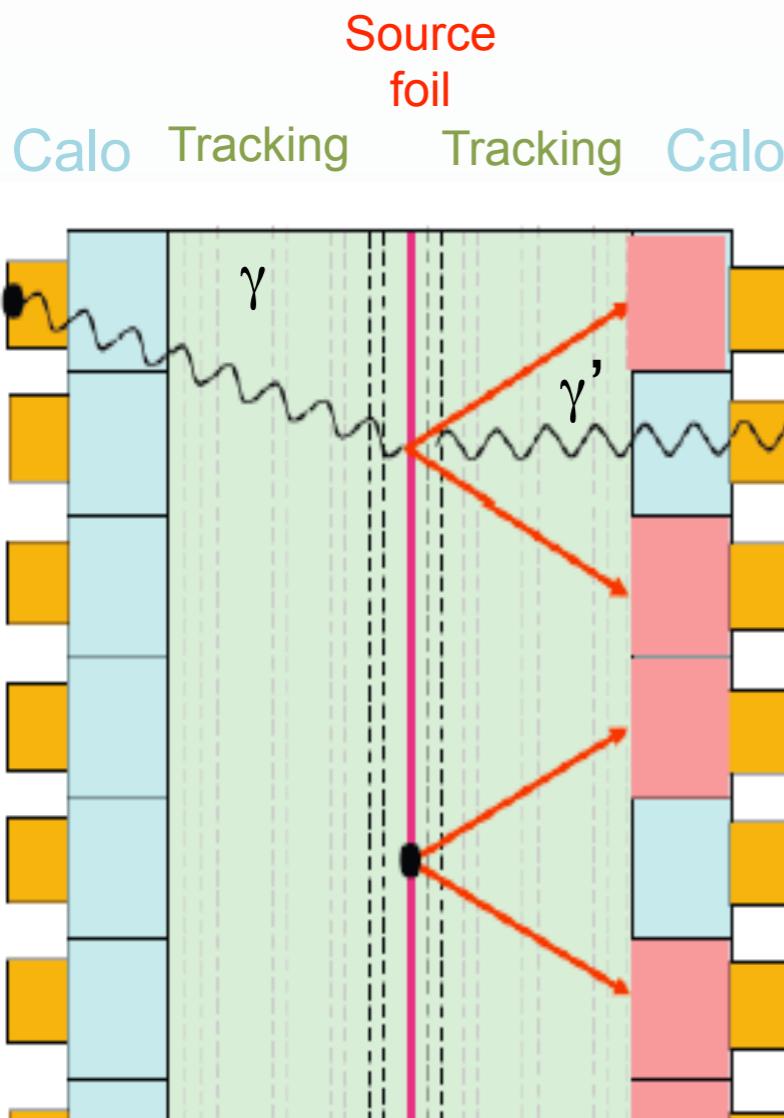
Backgrounds



In addition to $\beta\beta(2\nu)$, ^{214}Bi and ^{208}Tl
contribution
Internal
Background

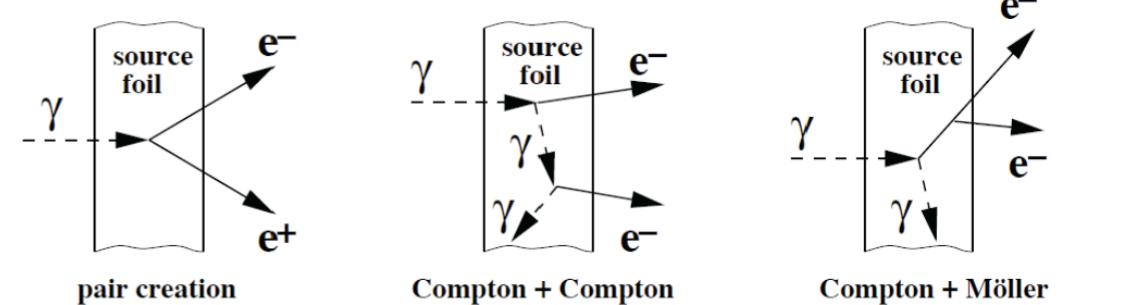


Backgrounds



External Background

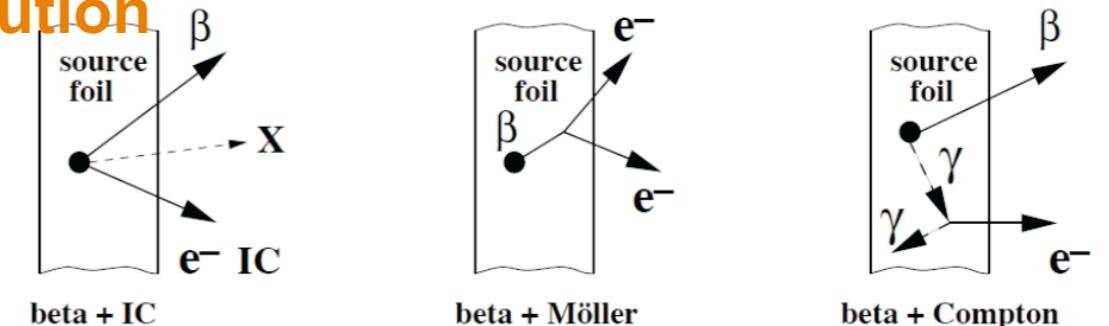
Radio-impurities in material, γ from (n,γ)
($n,n'\gamma$) and μ bremsstrahlung



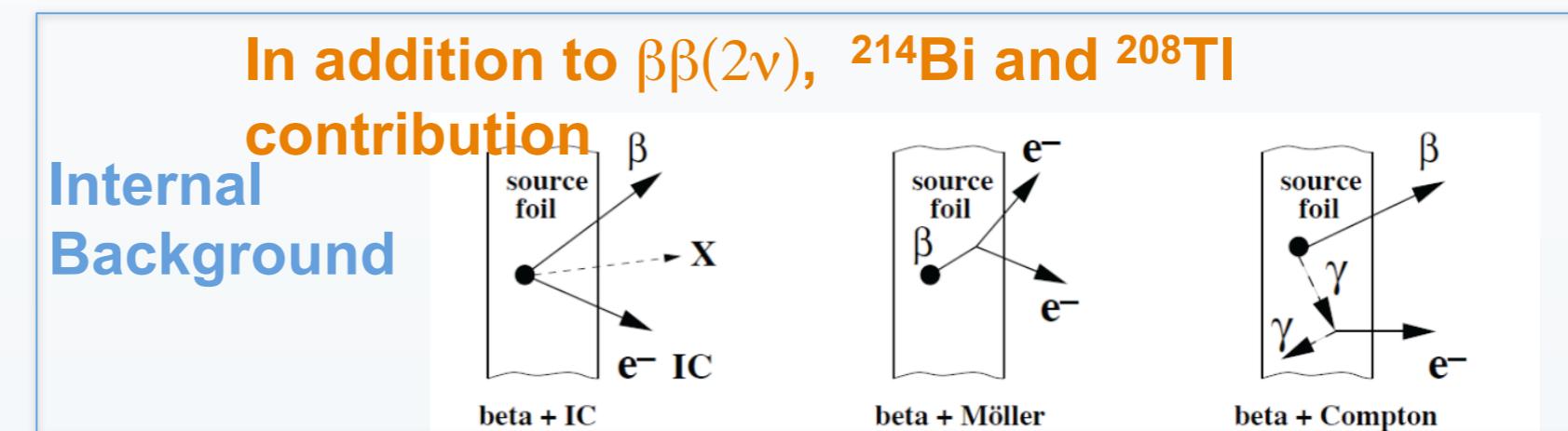
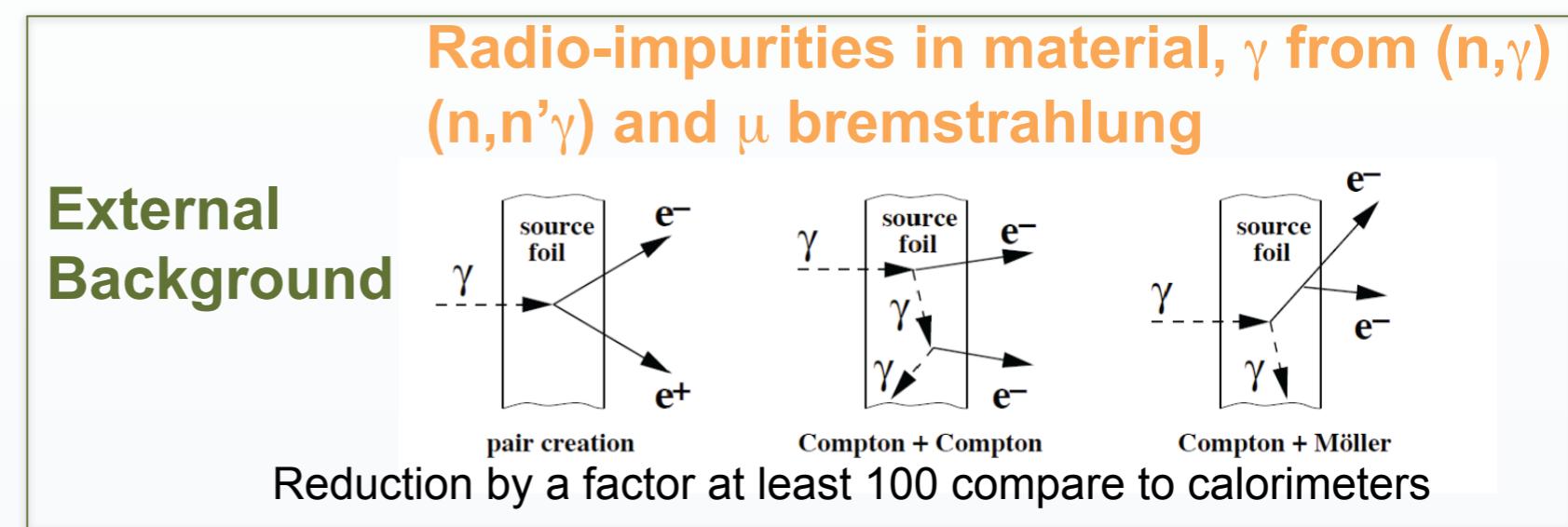
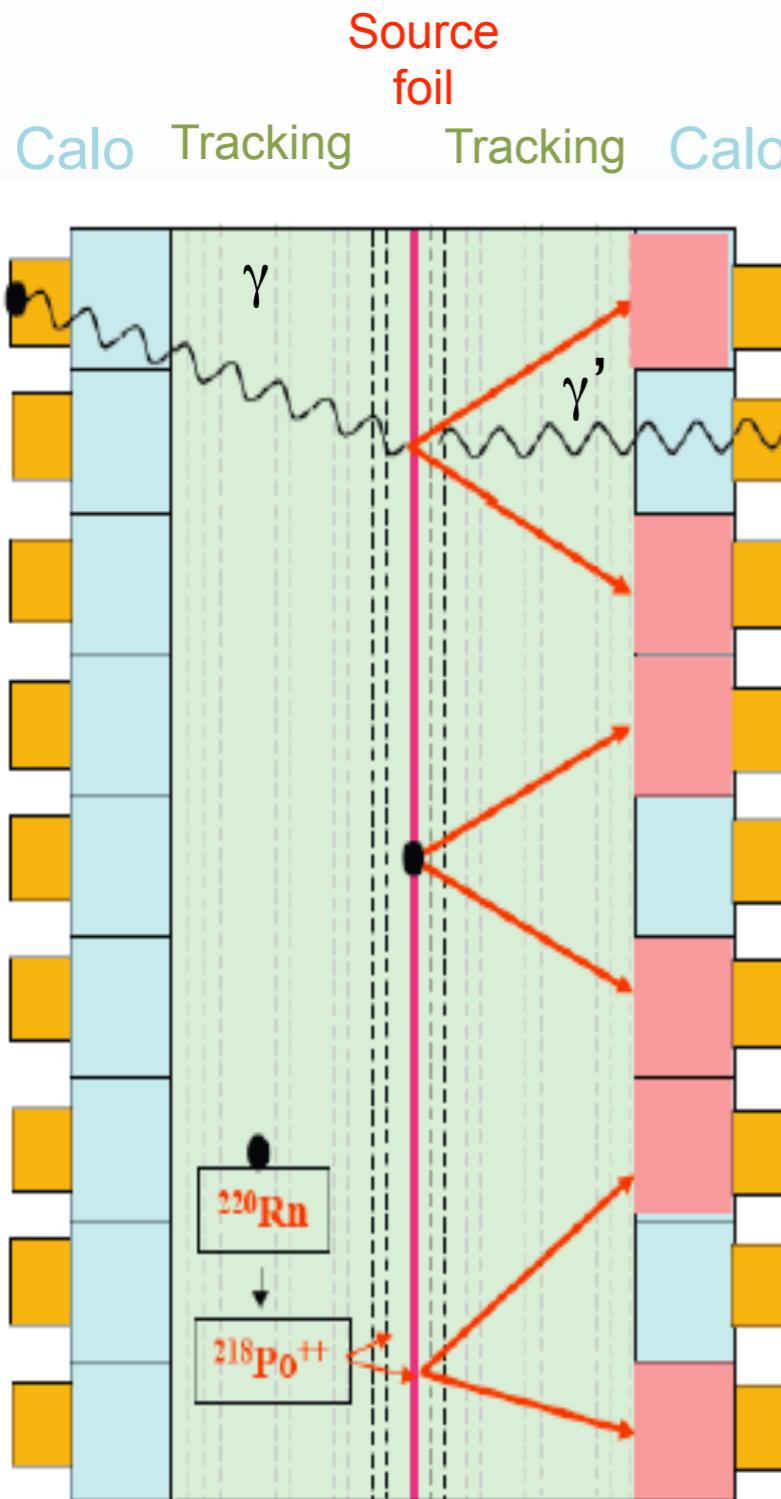
Reduction by a factor at least 100 compare to calorimeters

Internal Background

In addition to $\beta\beta(2\nu)$, ^{214}Bi and ^{208}Tl contribution



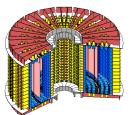
Backgrounds



Radon Background

Radon daughter (^{214}Bi) deposited on the Source foil or near wires

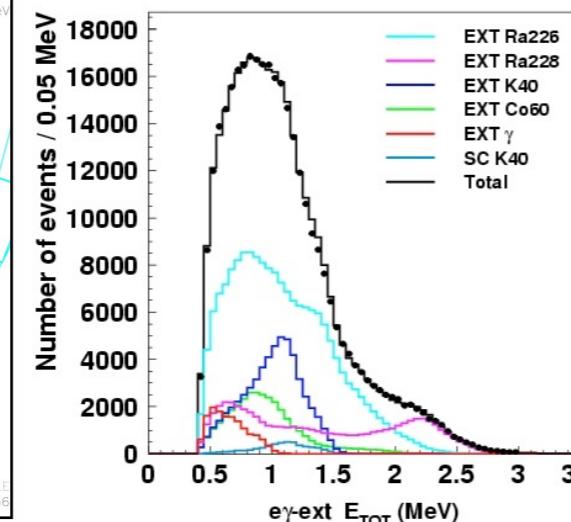
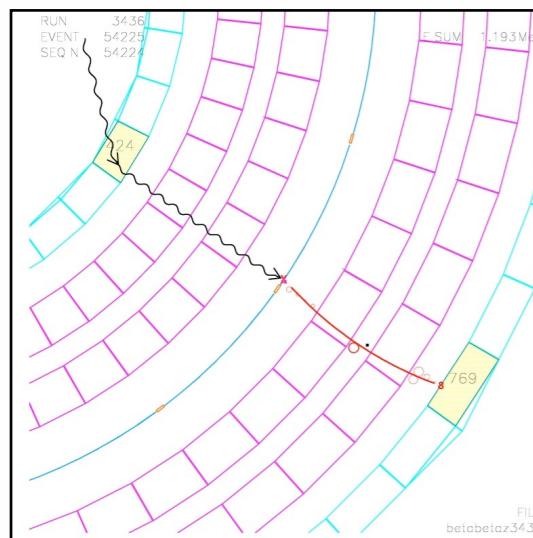
Some of these backgrounds are rejected by γ , X or delayed α detection



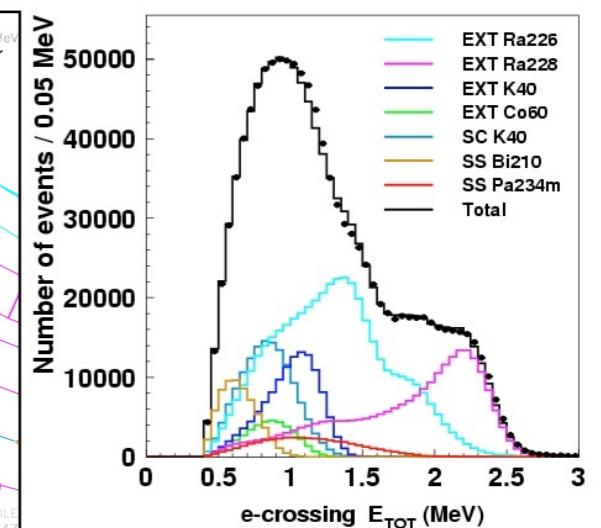
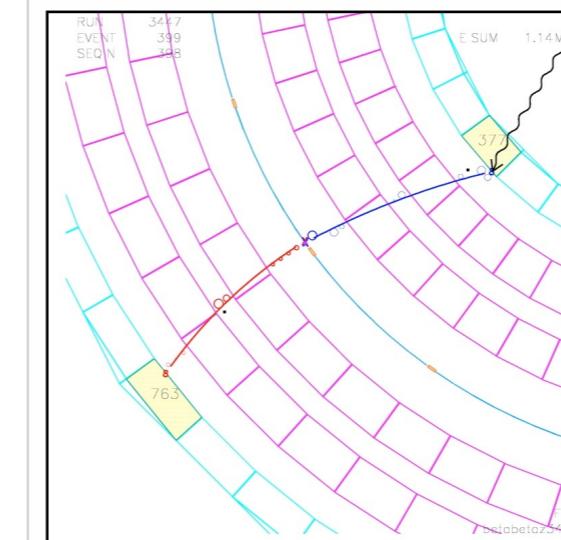
Backgrounds measurements

NIM A606 (2009) 449

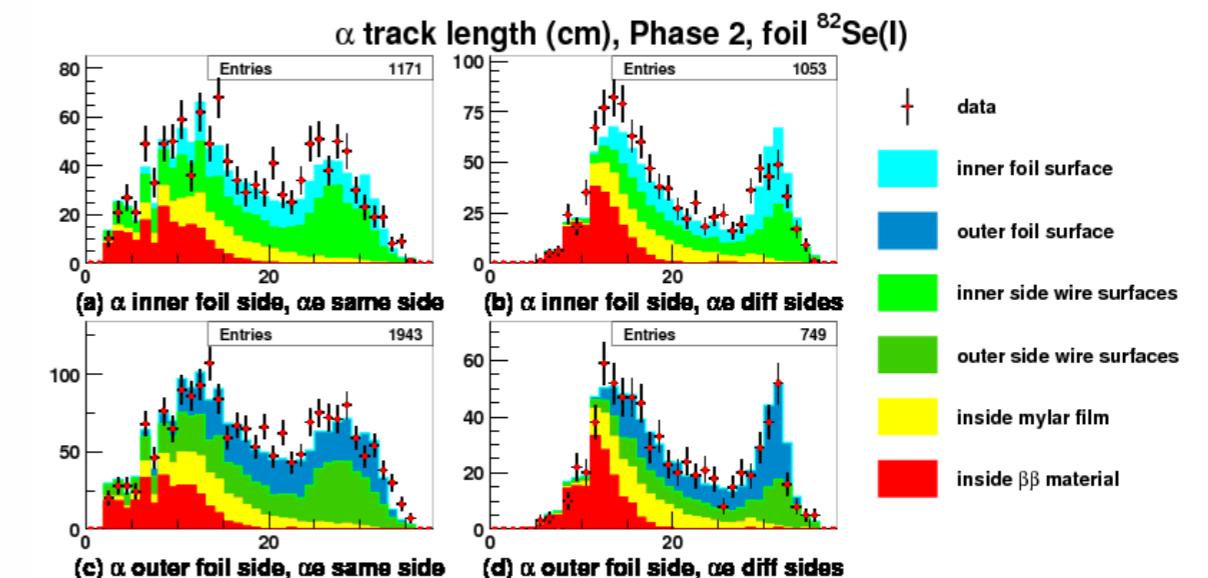
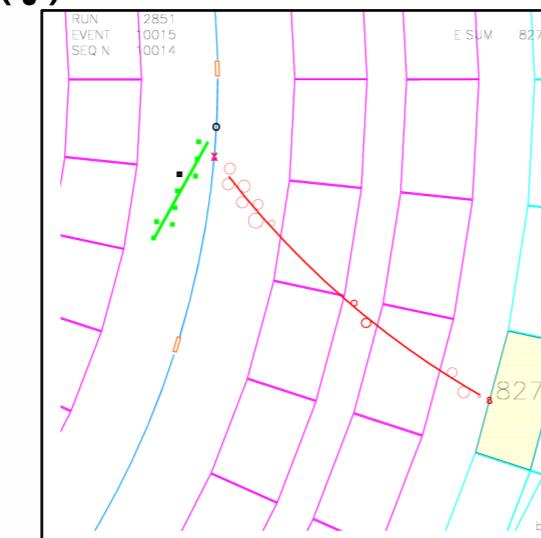
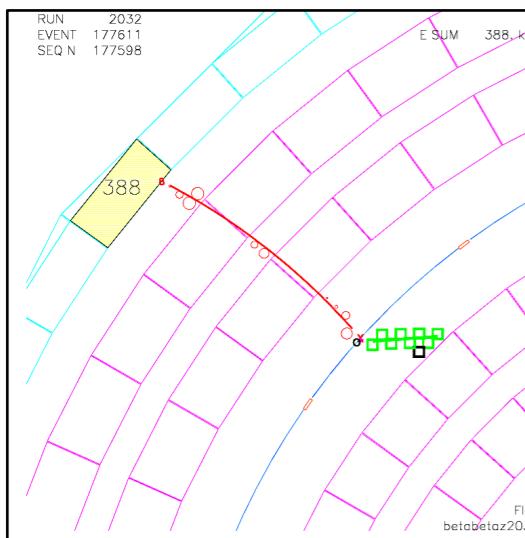
External background: e γ -external



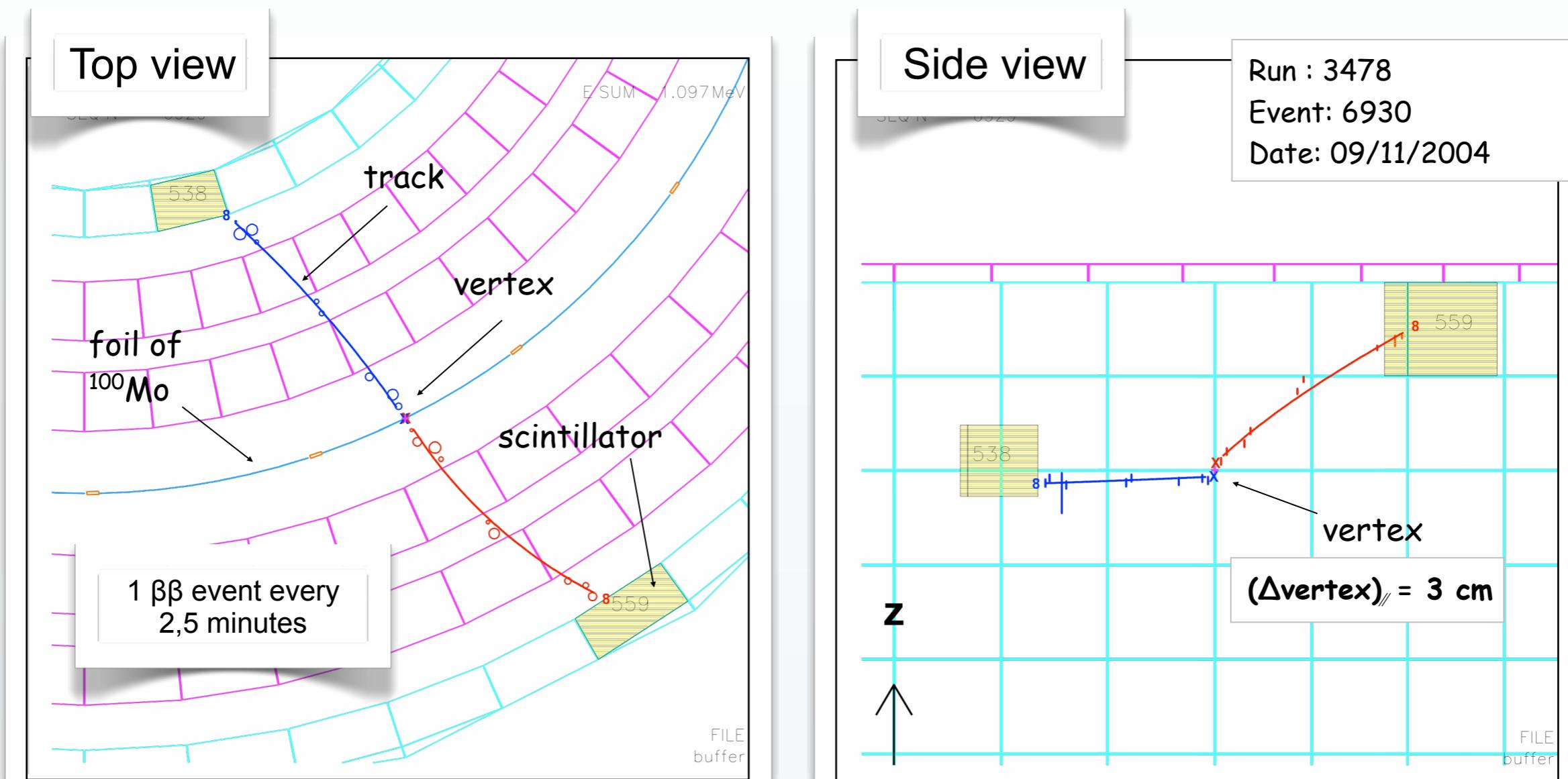
External background: e-crossing events



Internal ^{214}Bi : ea(γ)-events from foil



Selection of $\beta\beta$ events

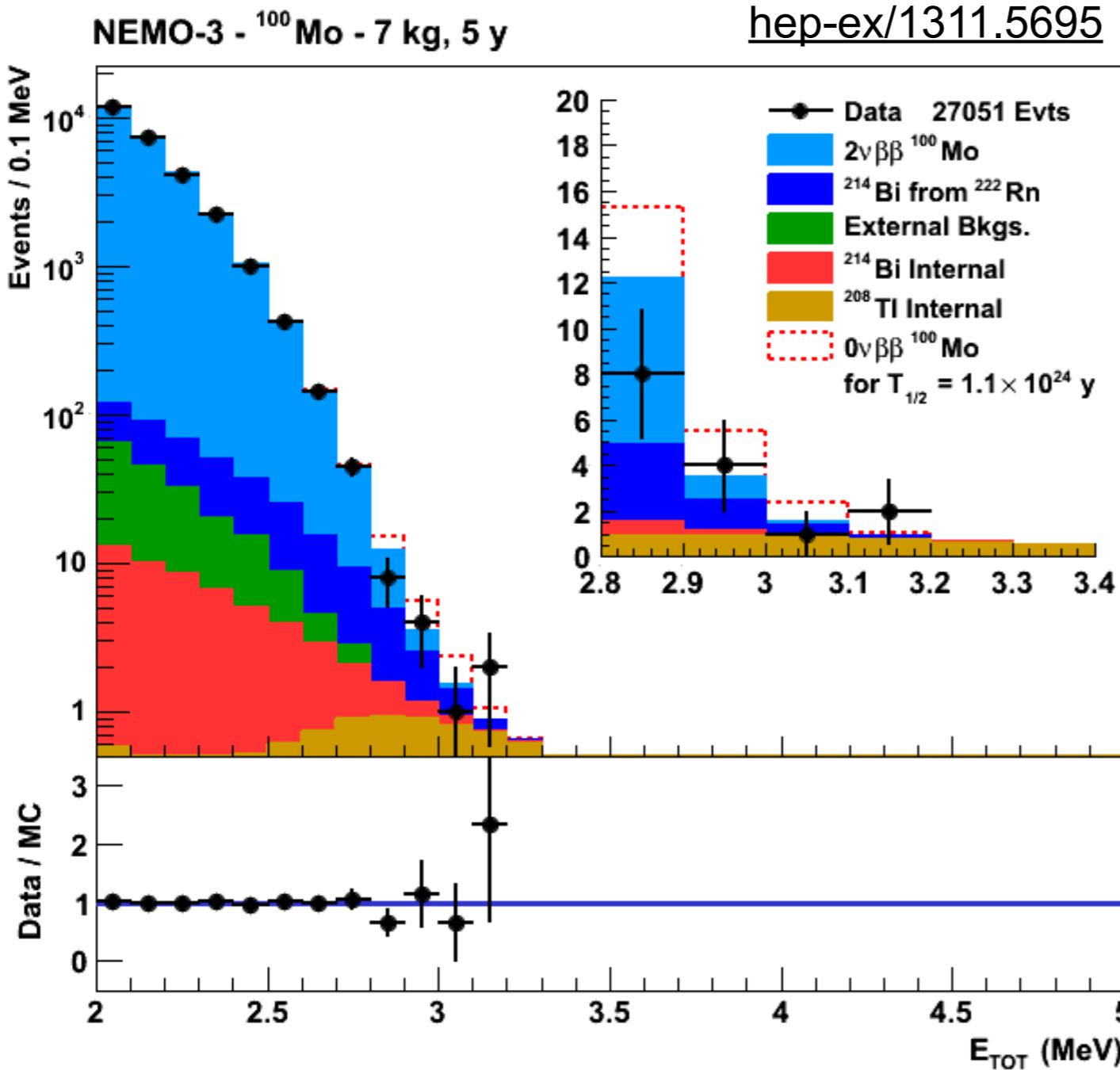


- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex

Criteria to select $\beta\beta$ events

- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track (^{214}Bi rejection)

$0\nu\beta\beta$ ^{100}Mo - Final sample



$E_{\text{TOT}} \in [2.8, 3.2] \text{ MeV}$

Sample	Entries
External bkgs	< 0.2
^{214}Bi from ^{222}Rn	5.2 ± 0.5
^{214}Bi internal	1.0 ± 0.1
^{208}Ti internal	3.3 ± 0.3
2v $\beta\beta$	8.45 ± 0.05
Total expected	18.0 ± 0.6
Observed events	15

Efficiency = 4.7%

Exposure = 34.7 kg·y

0 events observed in the range

$E_{\text{TOT}} \in [3.2, 10] \text{ MeV}$

$0\nu\beta\beta$ ^{100}Mo - Limits on the half-life

- modified frequentist analysis
- $E_{\text{TOT}} \in [2.0, 3.2] \text{ MeV}$
- account for statistical and systematic uncertainties and their correlations

Systematics

$0\nu\beta\beta$ reconstruction efficiency	7%
$2\nu\beta\beta$ events in window	0.7%
^{208}Tl contamination	10%
^{214}Bi contamination	10%

Limits at 90% C.L. in units of 10^{24}y

$0\nu\beta\beta$ process	Stat. Only	Systematics	Expected
Mass mechanism	1.1	1.1	1.0 [0.7, 1.4]
$q_{\text{r.h.}} - l_{\text{r.h.}}$ coupling $\langle\lambda\rangle$	0.7	0.6	0.5 [0.4, 0.8]
$q_{\text{r.h.}} - l_{\text{l.h.}}$ coupling $\langle\eta\rangle$	1.0	1.0	0.9 [0.6, 1.3]
Majoron	0.050	0.044	0.039 [0.027, 0.059]

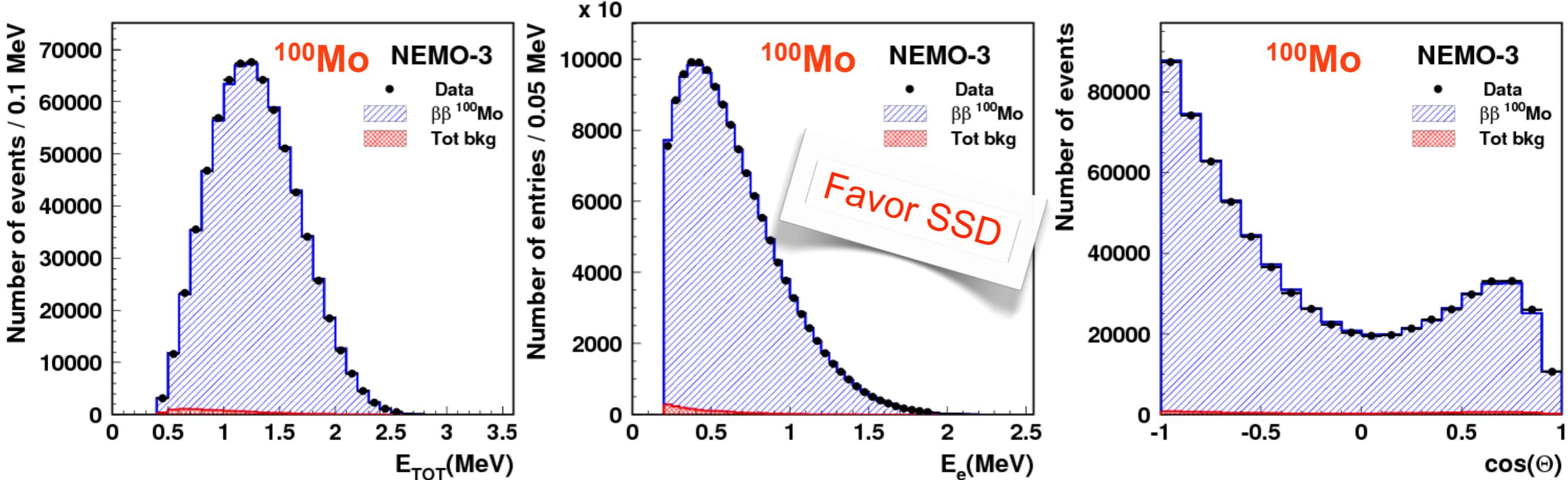
$0\nu\beta\beta$ - Limits @ 90%C.L. on LNV parameters

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

Isotope	Exposure (kg·y)	Half life (10^{25} y) published	$\langle m_\nu \rangle$ (eV) published	$\langle m_\nu \rangle$ (eV) calculated	$\langle \lambda \rangle$ (10^{-6}) published	$\langle \eta \rangle$ (10^{-8}) published	λ'_{111}/f (10^{-2}) published	$\langle g_{ee} \rangle$ (10^{-5}) published
^{100}Mo [1]	34.7	0.1	0.33 - 0.87	0.33 - 0.87	0.9 - 1.3	0.5 - 0.8	4.4 - 6.0	2 - 5
^{130}Te [2][3]	19.75	0.3	0.31 - 0.71	0.31 - 0.71	1.6 - 2.4	0.9 - 5.3		17 - 33
^{136}Xe [4][5]	89.5	1.9	0.14 - 0.34	0.14 - 0.34				
^{136}Xe [6]	99.8	1.1	0.19 - 0.45	0.19 - 0.45				
^{76}Ge [7]	21.6	2.1	0.2 - 0.4	0.26 - 0.62				
^{76}Ge [8]	35.5	1.9	0.4	0.27 - 0.65	1.1	0.6		8.1

- $\langle m_\nu \rangle$ limits recalculated using updated phase space and NME calculations see refs in [1] [hep-ex/1311.5695](#)
- $f = \left(\frac{M_{\tilde{q}}}{1 \text{ TeV}}\right)^2 \left(\frac{M_{\tilde{g}}}{1 \text{ TeV}}\right)^{1/2}$

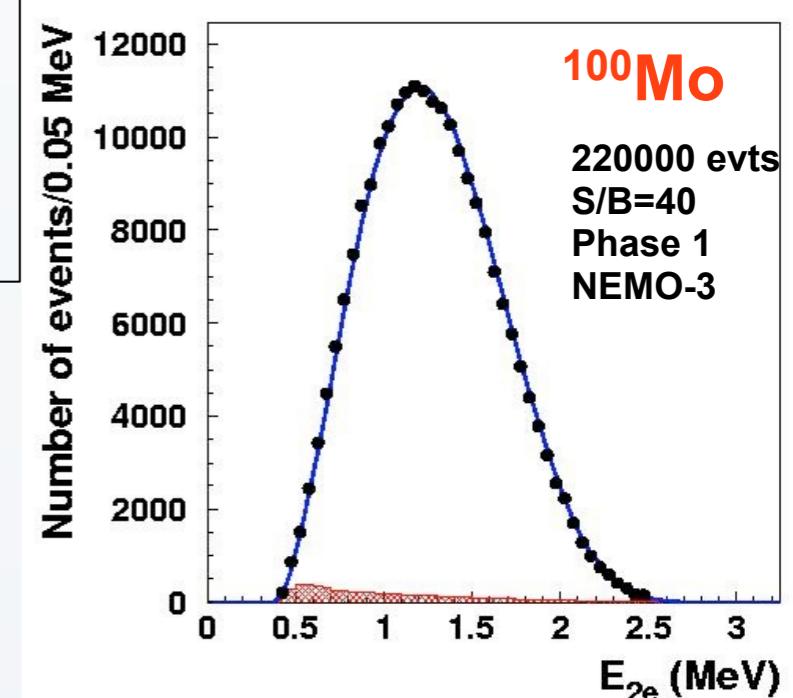
$2\nu\beta\beta$ ^{100}Mo Phase 2 data - 7kg x 4 years



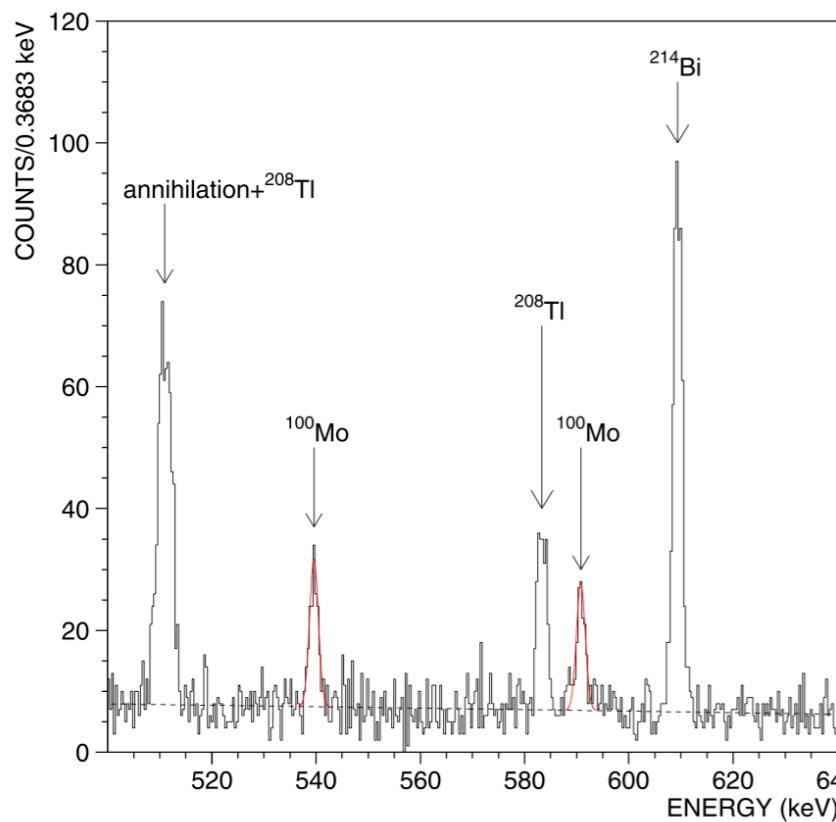
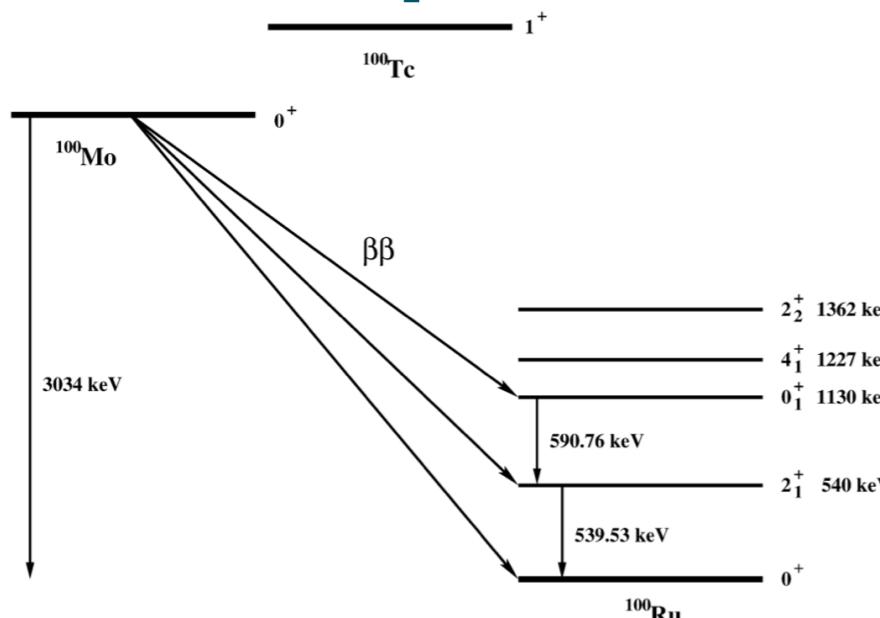
- 700000 two-electron events from ^{100}Mo foils
- S/B = 76
- $\epsilon(2\nu 2\beta) = 0.043$
- $T_{1/2}(2\nu 2\beta) = [7.16 \pm 0.01 \text{ (stat)} \pm 0.54 \text{ (syst)}] 10^{18} \text{ y}$ PRELIM.

Consistent with the published NEMO-3 result obtained
with Phase 1 data:
 $T_{1/2} = [7.11 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)}] 10^{18} \text{ y}$

Phys. Rev. Lett. 95, 182302 (2005)



^{100}Mo $2\beta 2\nu$ decay to excited states



Decays to excited states have several photons in final state

With NEMO3 after 7 kg·yr of exposure (Phase1):

$$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9} \text{ (stat)} \pm 0.8 \text{ (syst)} \times 10^{20} \text{ y}$$

$$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22} \text{ y @ 90% C.L.}$$

$$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21} \text{ y @ 90% C.L.}$$

$$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23} \text{ y @ 90% C.L.}$$

[Nuclear Physics A781 \(2007\) 209-226](#)

[Nuclear Physics A 925 \(2014\) 25-36](#)

- Measure the γ lines using low background HPGe detector
- 2518g of ^{100}Mo in metallic foils from NEMO3 detector
- Data collected over 2288 hours
- Use ^{238}U , ^{152}Eu and ^{138}La calibrations source: data/MC discrepancy < 7%

**NEW
RESULT**

$$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 7.5 \pm 0.6 \text{ (stat)} \pm 0.6 \text{ (syst)} \times 10^{20} \text{ y}$$

most precise measurement

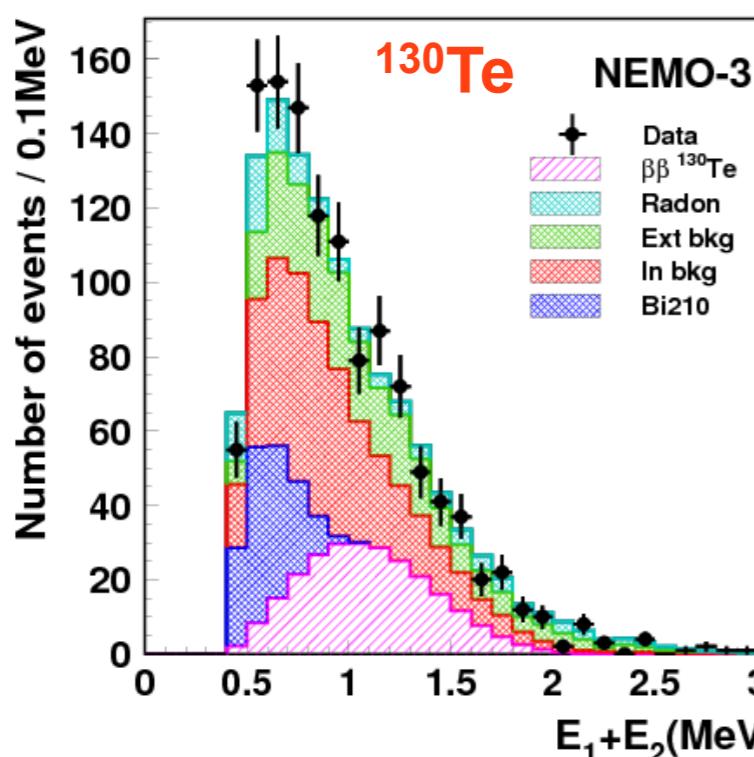
$$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 2.5 \times 10^{21} \text{ y @ 90% C.L.}$$

best limits on all other transitions to excited states were set

$M_{2\nu}(\text{g.s.})/M_{2\nu}(0^+_1) \sim 1.25$ independently on the NME chosen

2νββ Results

Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)	$T_{1/2}(2\nu)$ (10^{19} yrs)	S/B	Comment	Reference
^{82}Se	932	2996	9.6 ± 1.0	4	World's best!	Phys.Rev.Lett. 95 (2005) 182302
^{116}Cd	405	2809	2.8 ± 0.3	10	World's best!	
^{150}Nd	37	3367	0.90 ± 0.07	2.7	World's best!	Phys. Rev. C 80, 032501 (2009)
^{96}Zr	9.4	3350	2.35 ± 0.21	1	World's best!	Nucl.Phys.A 847(2010) 168
^{48}Ca	7	4271	4.4 ± 0.6	6.8 (h.e.)	World's best!	
^{100}Mo	6914	3034	0.71 ± 0.05	80	World's best!	Phys.Rev.Lett. 95 (2005) 182302
^{130}Te	454	2533	70 ± 14	1	First direct detection!!!	Phys. Rev. Lett. 107, 062504 (2011)

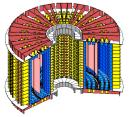


First direct observation: 7.7σ significance

Indirect observations:

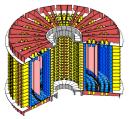
- $\sim 2.7 \times 10^{21}$ yrs in 10^9 yr old rocks
- $\sim 8 \times 10^{20}$ yrs in 10^7 - 10^8 yr old rocks

Indication from MIBETA Coll in isotopically enriched crystals: $6.1 \pm 1.4(\text{st})^{+2.9}_{-3.5}(\text{sy}) \times 10^{20}$ yrs



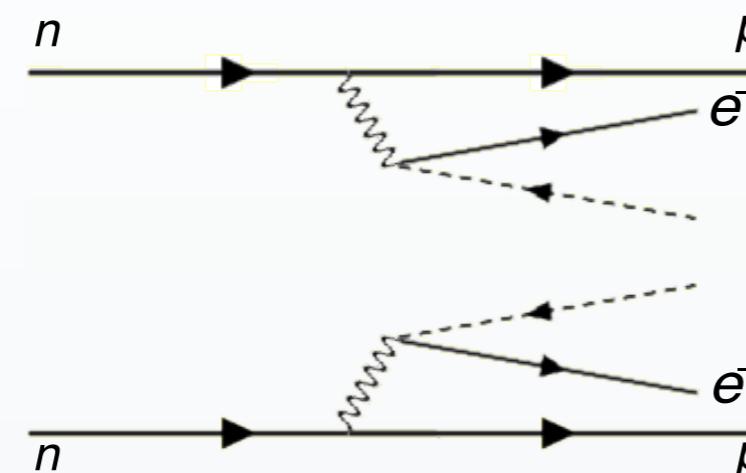
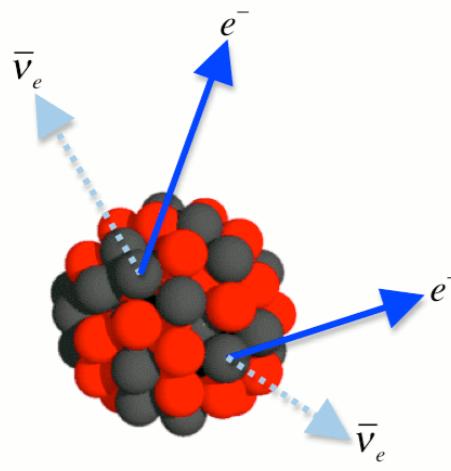
Conclusions

- The unique design of NEMO3 allowed for
 - unique background rejection capabilities
 - measurement of the details of $2\nu\beta\beta$ in several isotopes
- Search of $0\nu\beta\beta$ of ^{100}Mo in the full data set has lead to the best limit on the half-life of this process
 - limits on the effective Majorana neutrino mass are in the range currently constrained using other isotopes
 - world best limits on several other mechanisms are also provided



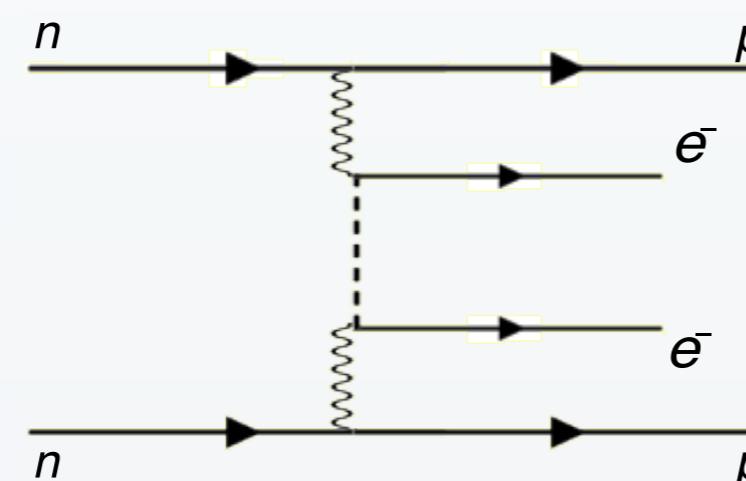
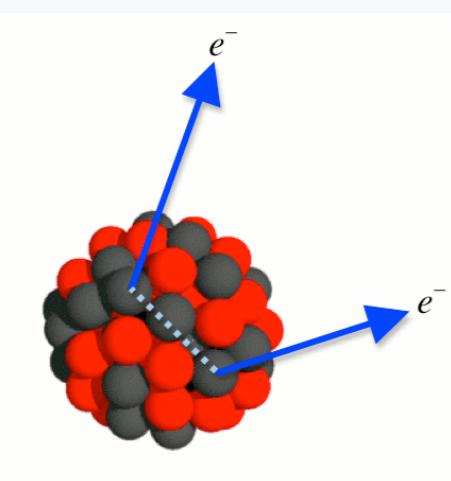
Backup

Double-Beta Decay



2-Neutrino Double Beta Decay

- Lepton number conserved.
- Allowed in Standard Model.
- Rate $\mathcal{O}(G_F^2)$

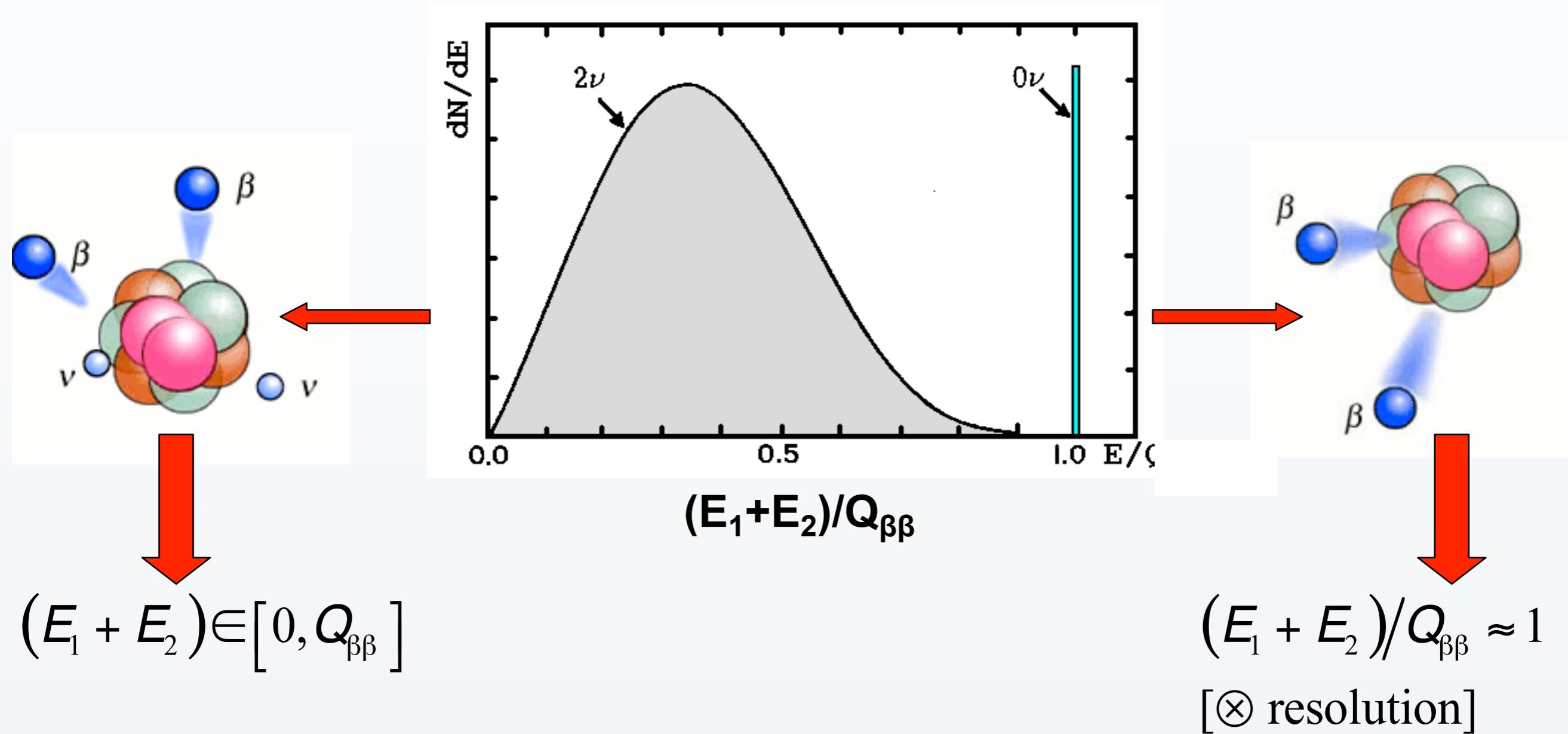


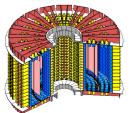
0-Neutrino Double Beta Decay

- Lepton number violation :
- Forbidden in Standard Model: $\Delta L = 2$
- Rate($0\nu\beta\beta$) \ll Rate($2\nu\beta\beta$)

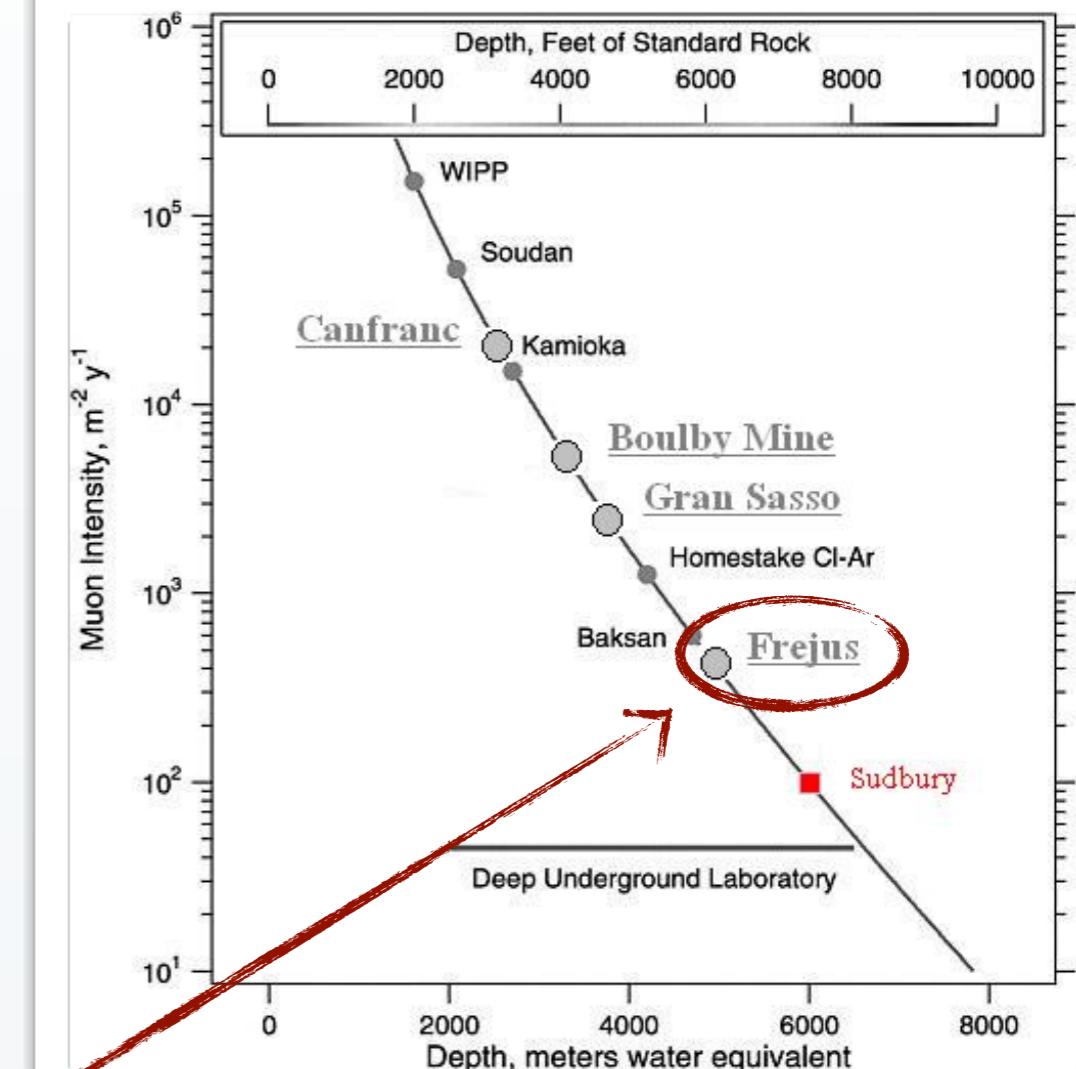
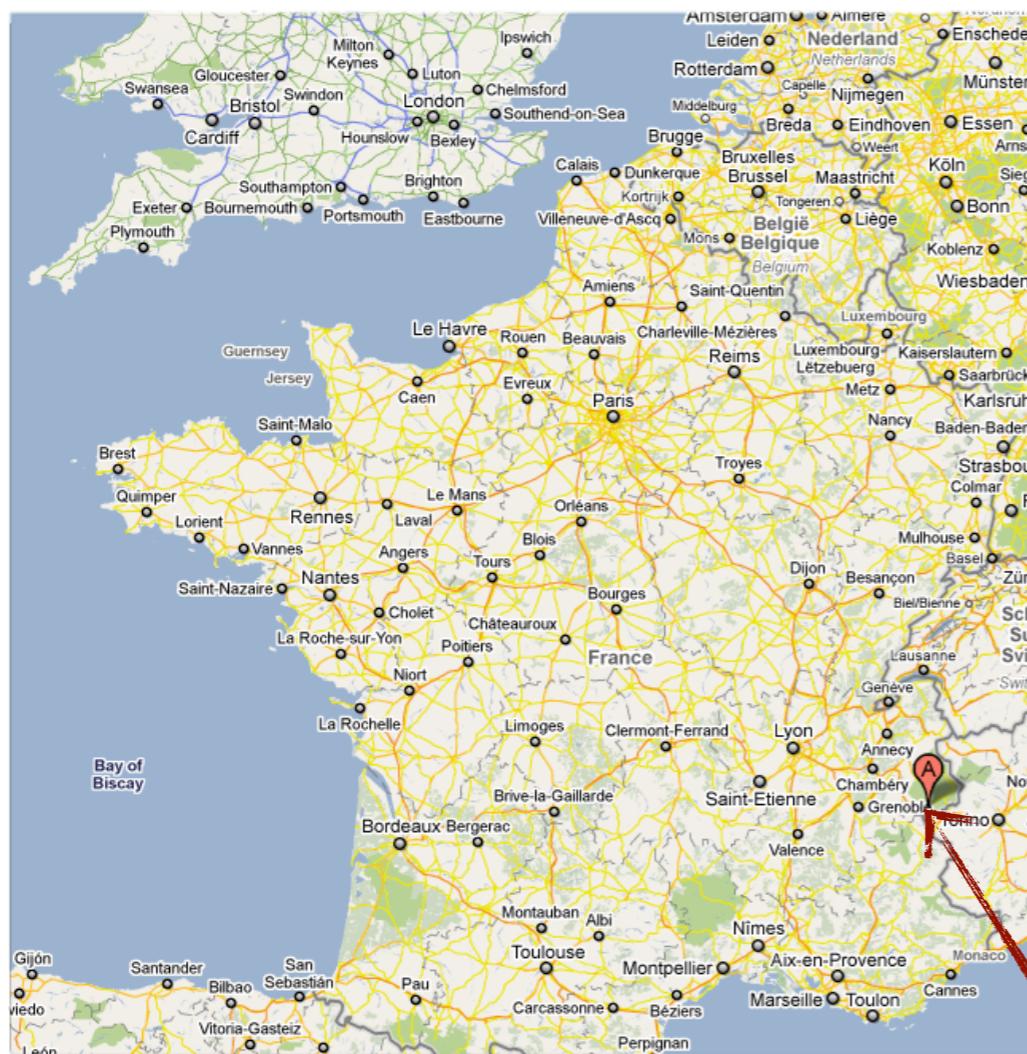
Double-Beta Decay : Basic Signature

Measure the summed electron energy and compare to the energy of the transition :



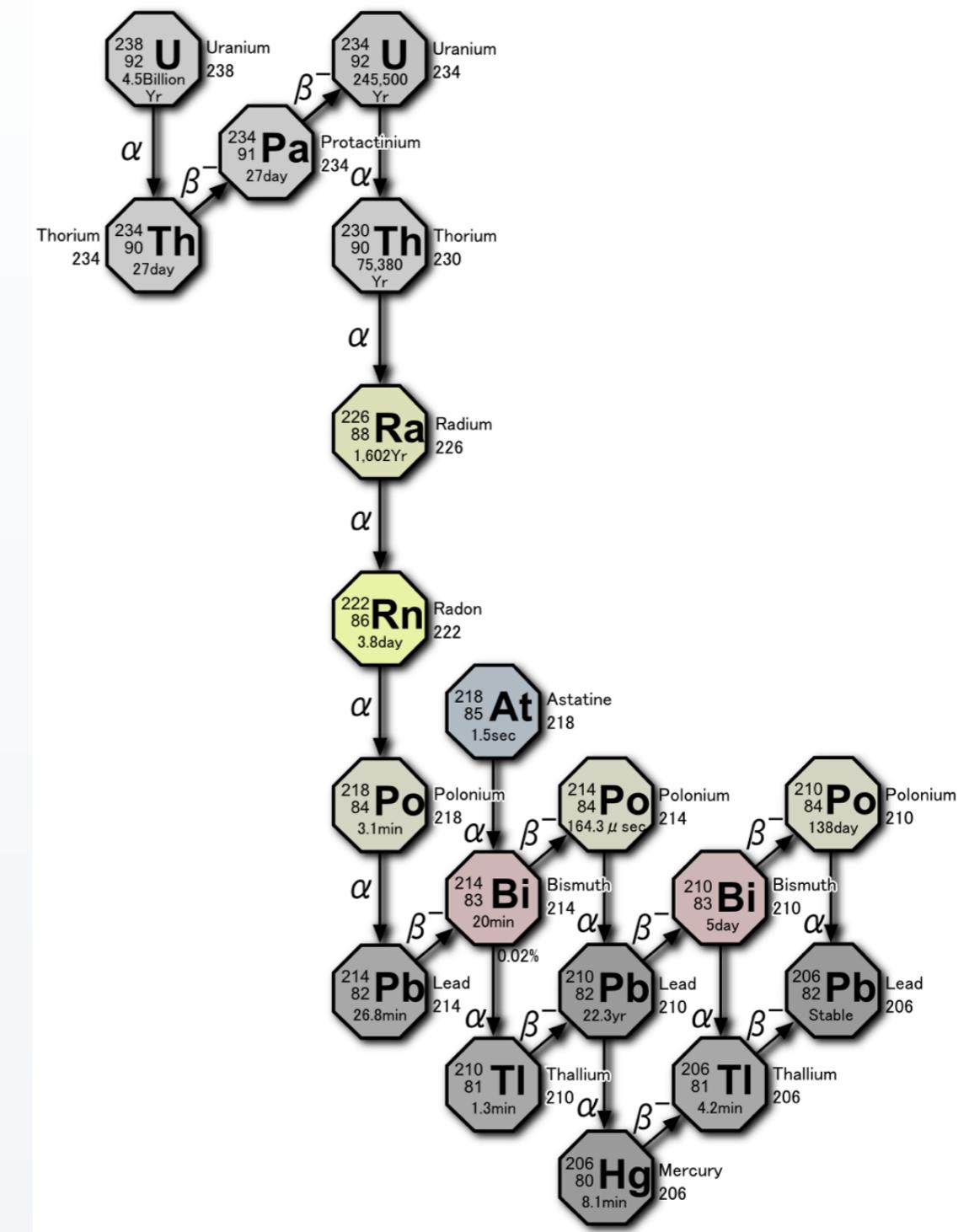
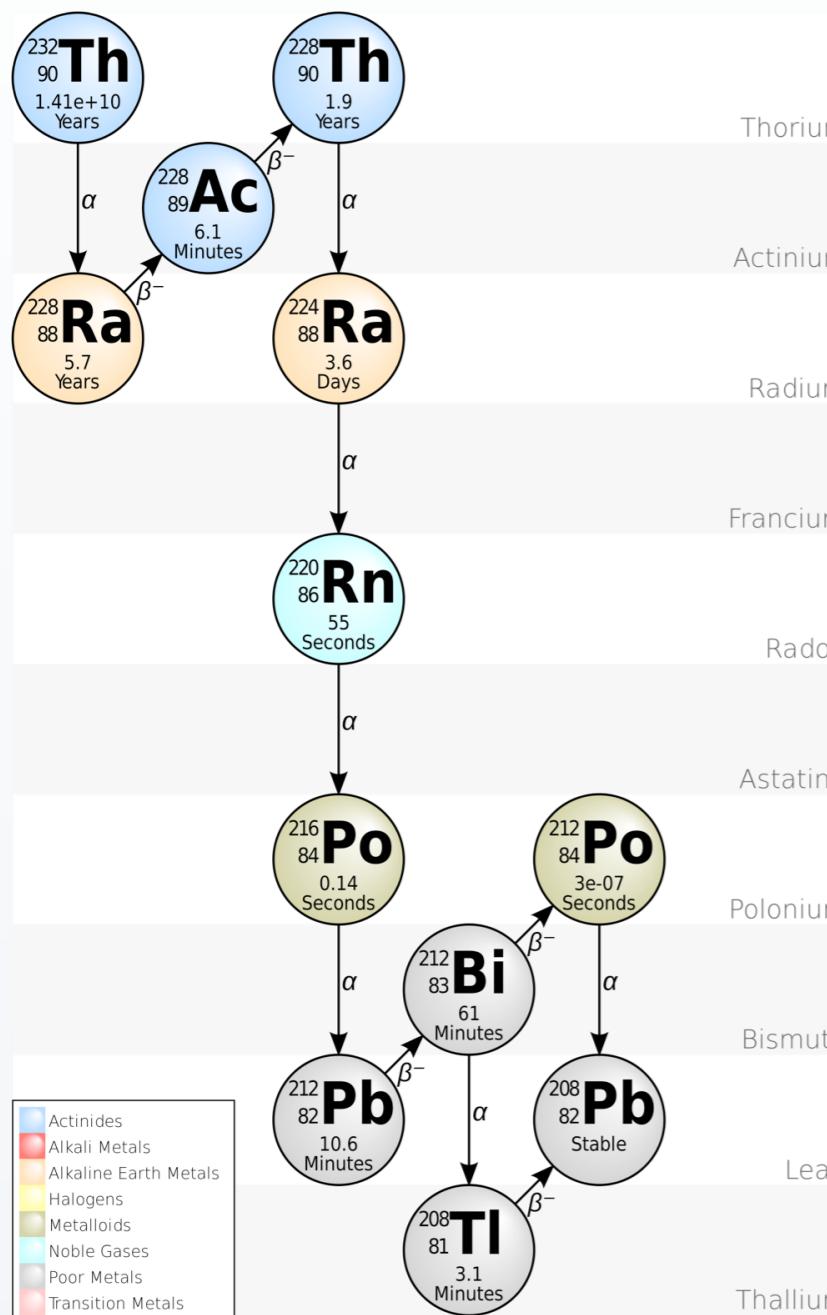


NEMO3



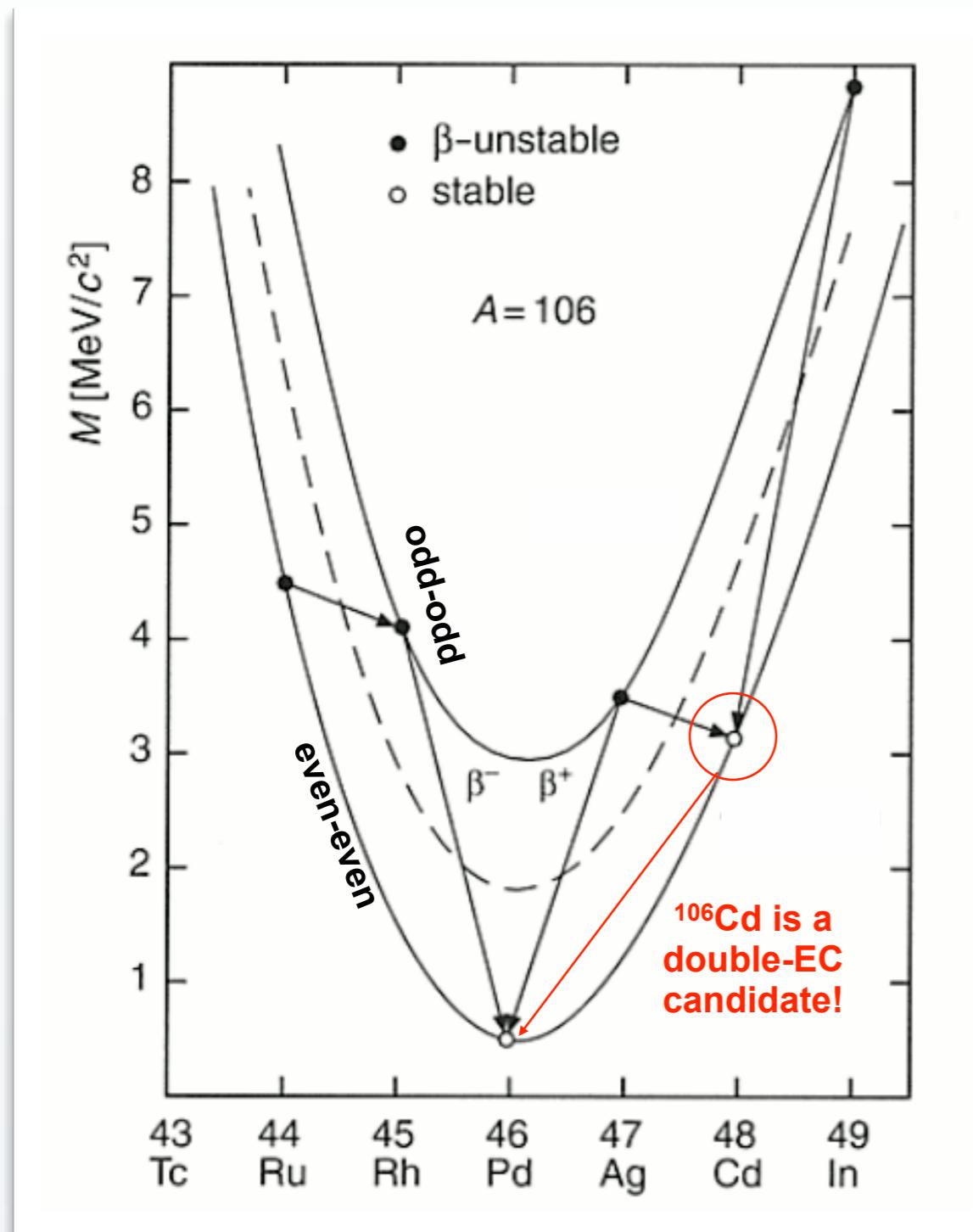
LSM Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

Th and U chains



Candidate isotopes :

Which Isotopes Can Double-Beta Decay ?



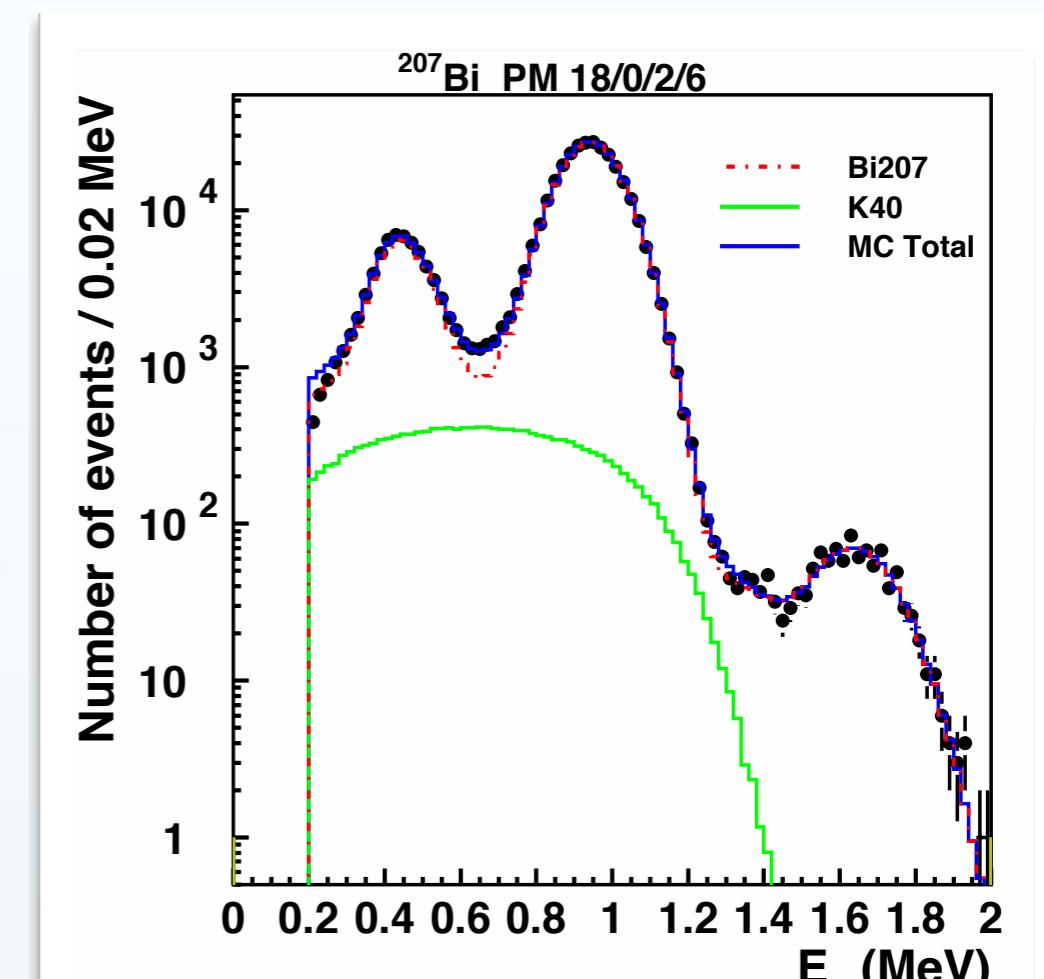
Isotope	$Q_{\beta\beta}$ (MeV)	Abundance (%)
^{48}Ca	4.276	0.19
^{76}Ge	2.039	7.8
^{82}Se	2.992	9.2
^{96}Zr	3.348	2.800
^{100}Mo	3.034	9.6
^{110}Pd	2.004	11.800
^{116}Cd	2.804	7.5
^{124}Sn	2.530	5.600
^{130}Te	2.529	34.5
^{136}Xe	2.467	8.9
^{150}Nd	3.368	5.6

more energetic decay:
easier to separate from
background

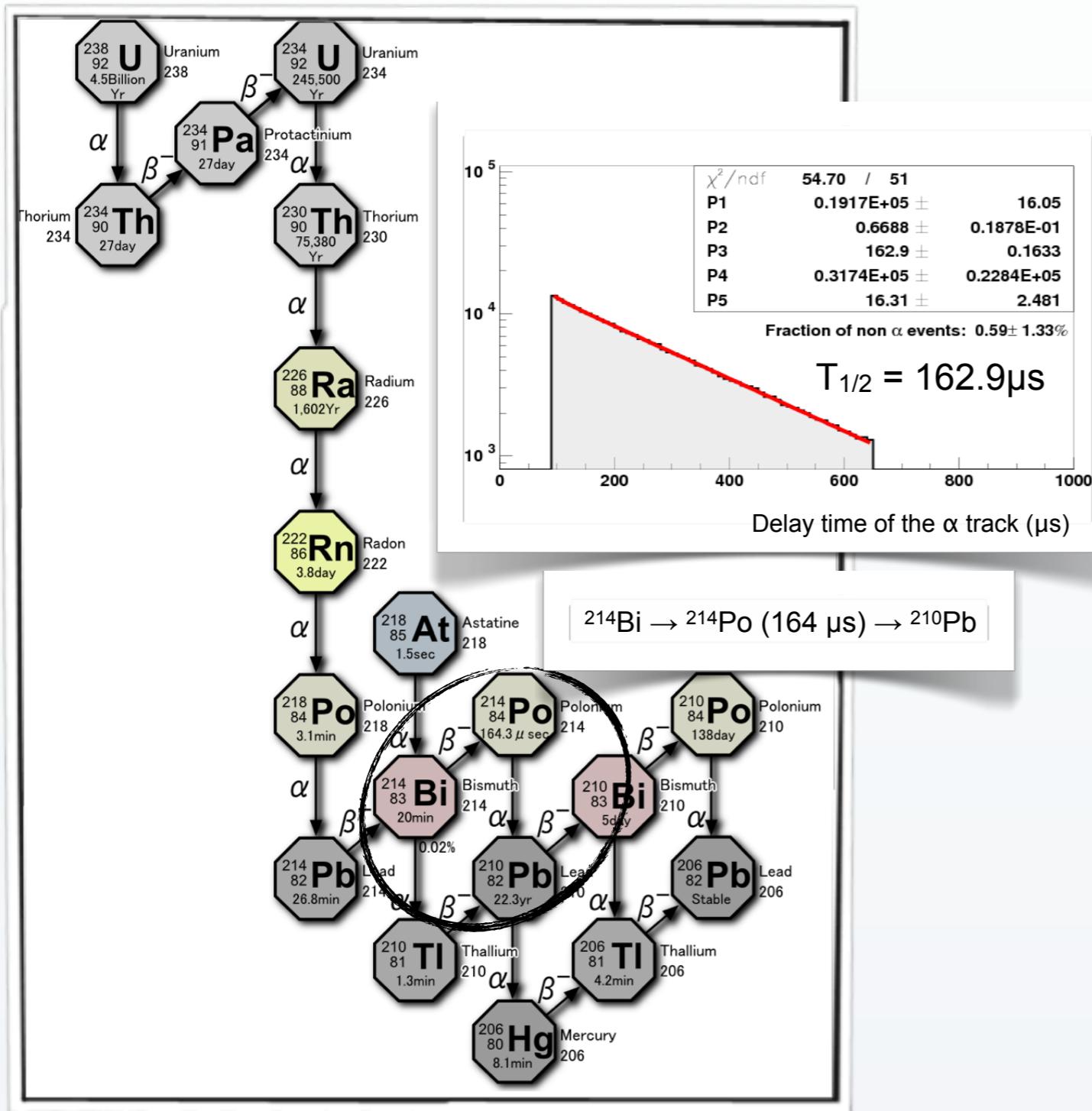
enrichment often possible,
always expensive !

Calibrations

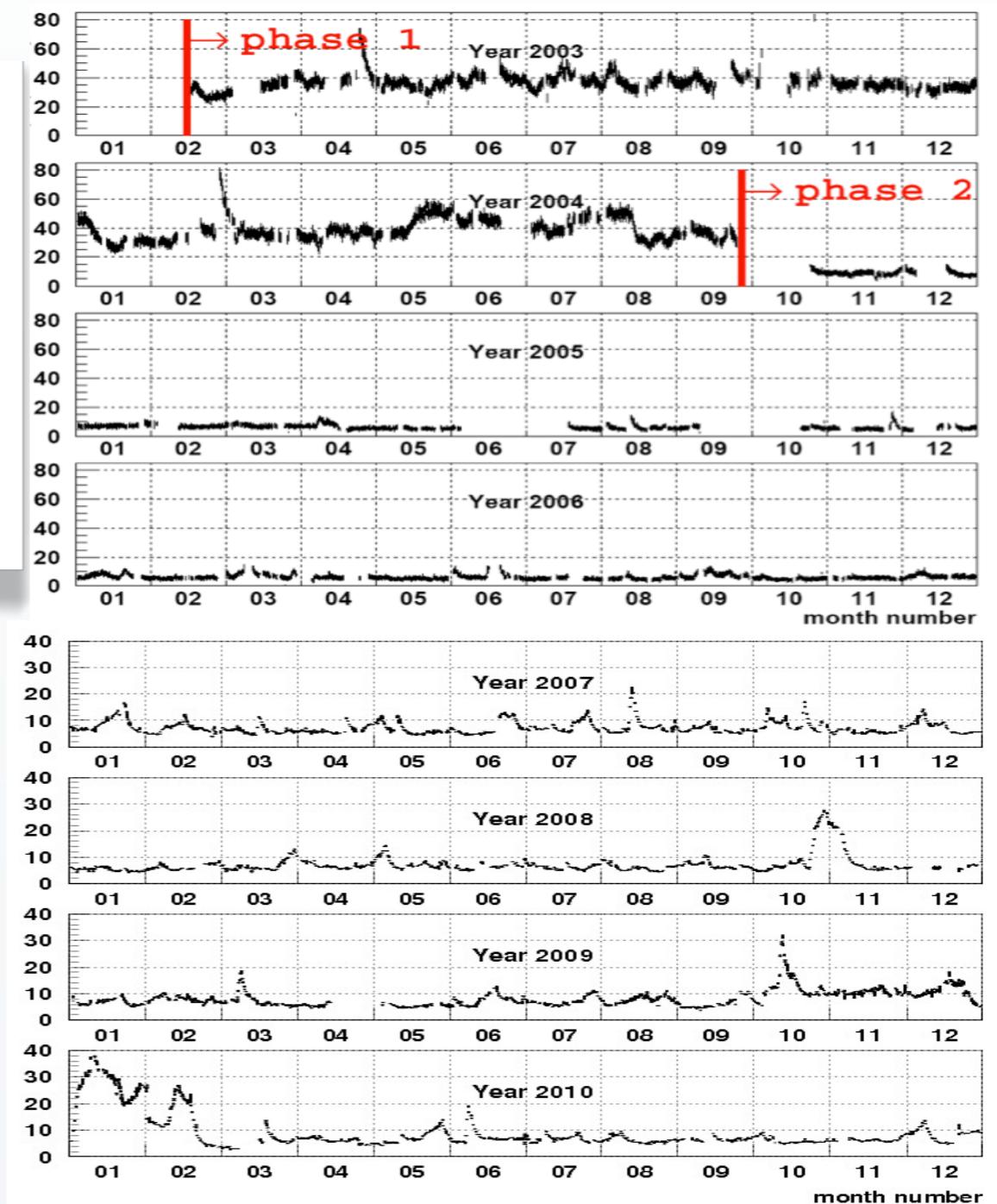
- ^{207}Bi sources
 - position of 1682 keV peak used for energy scale uncertainty
 - data-MC discrepancy < 0.2%
 - energy scale known @ 2% or PMT is removed
 - systematics on 2e^- reconstruction efficiency: 7%
- ^{232}U sources: systematics on the reconstruction of ^{208}TI in the foil: 10%
- gain variations are monitored during the day using light injection system, PMT showing large fluctuations are rejected



Background: Rn activity

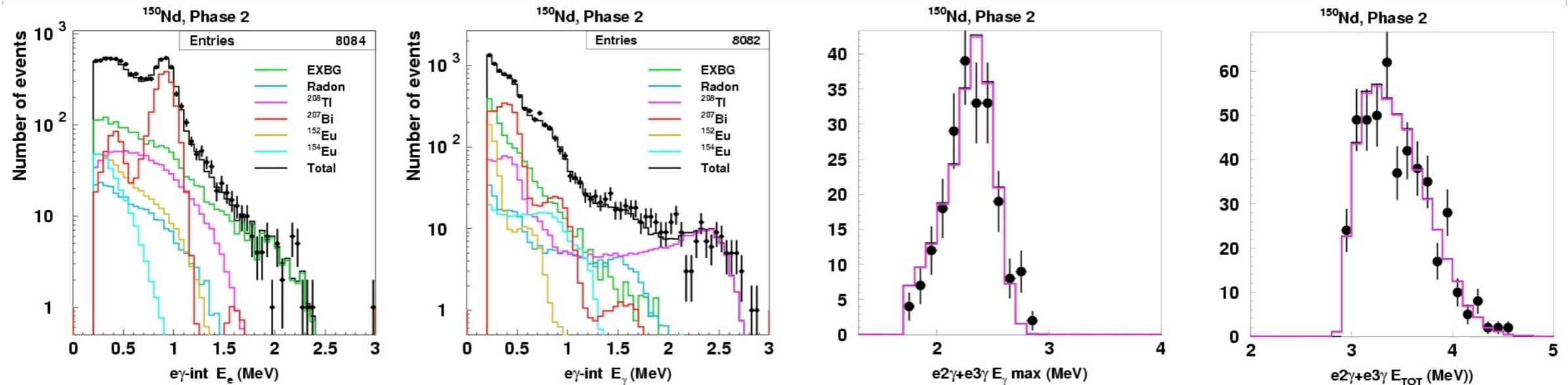


Measurements of ^{222}Rn activity in the gas of tracker (mBq/m³)

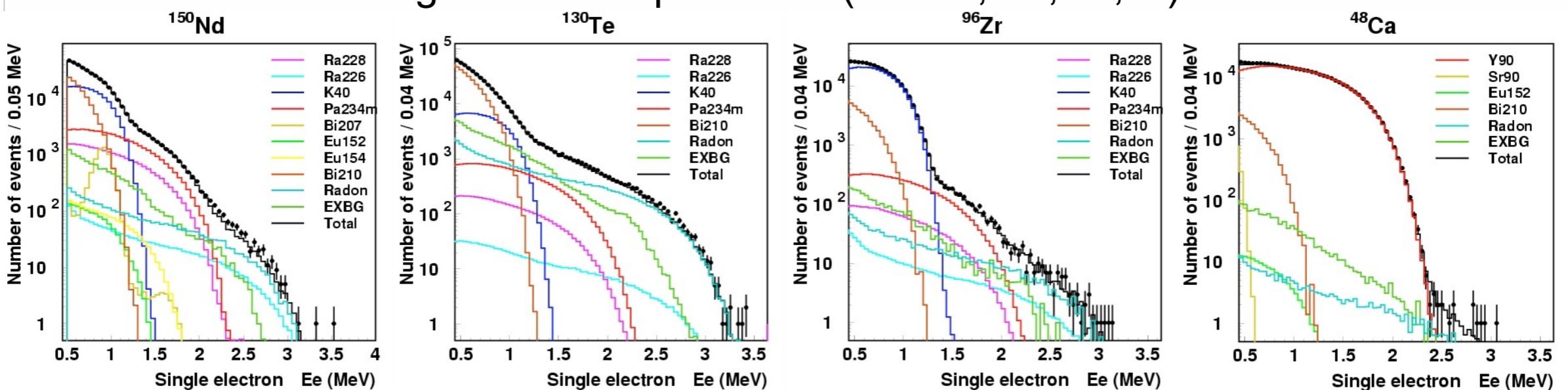


Internal Backgrounds measurements

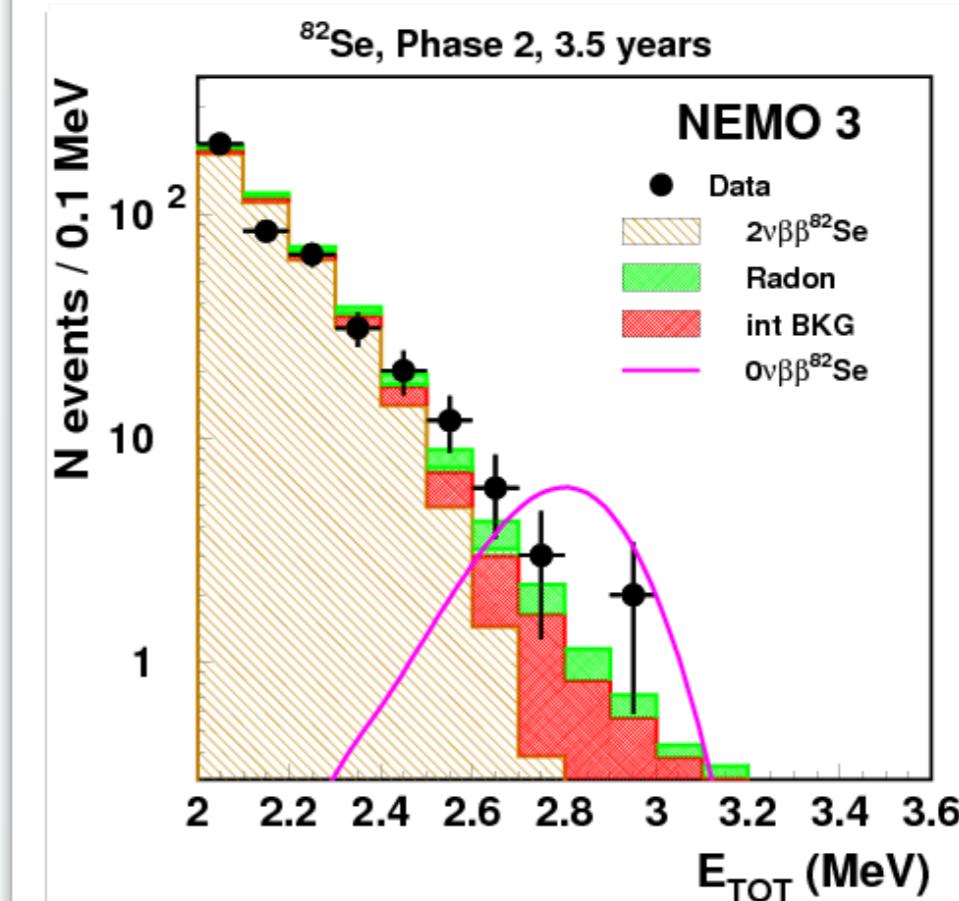
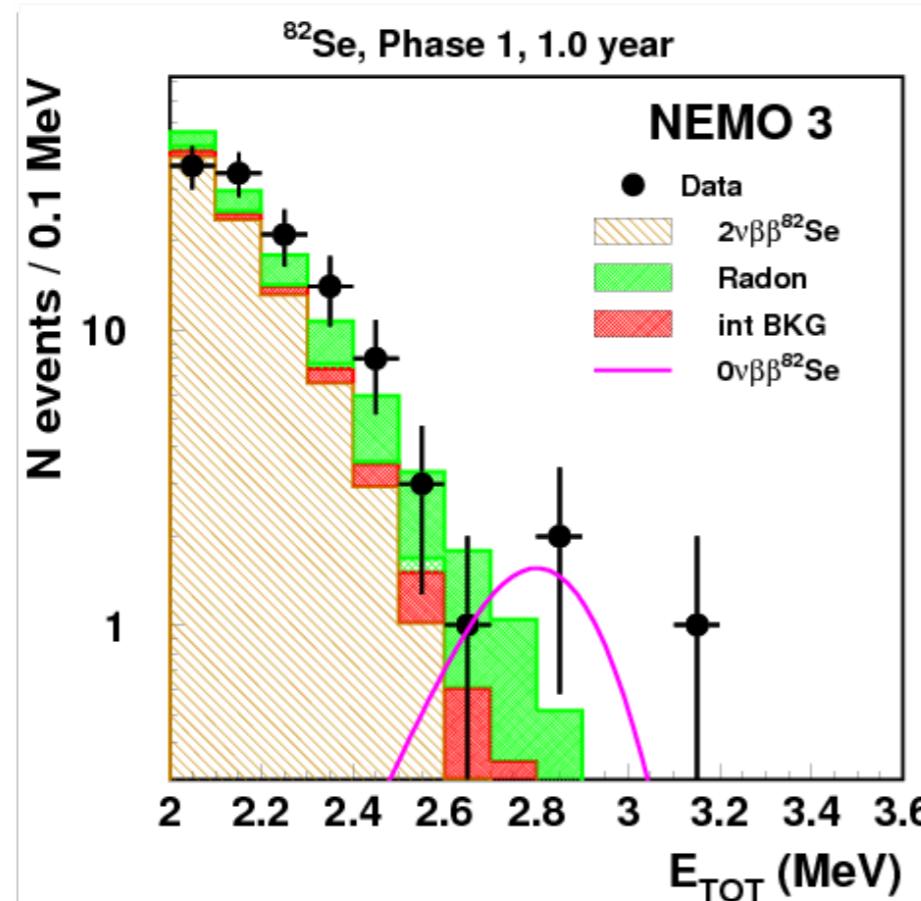
Internal background from γ -emitters(^{208}TI , ^{207}Bi ,...): ($e\gamma, e\gamma\gamma, e\gamma\gamma\gamma$)-events



Internal background from β -emitters(^{234m}Pa , ^{40}K , ^{90}Y ,...): 1e-events



Search for $0\nu\beta\beta$ with ^{82}Se



[2.6 , 3.2] MeV:

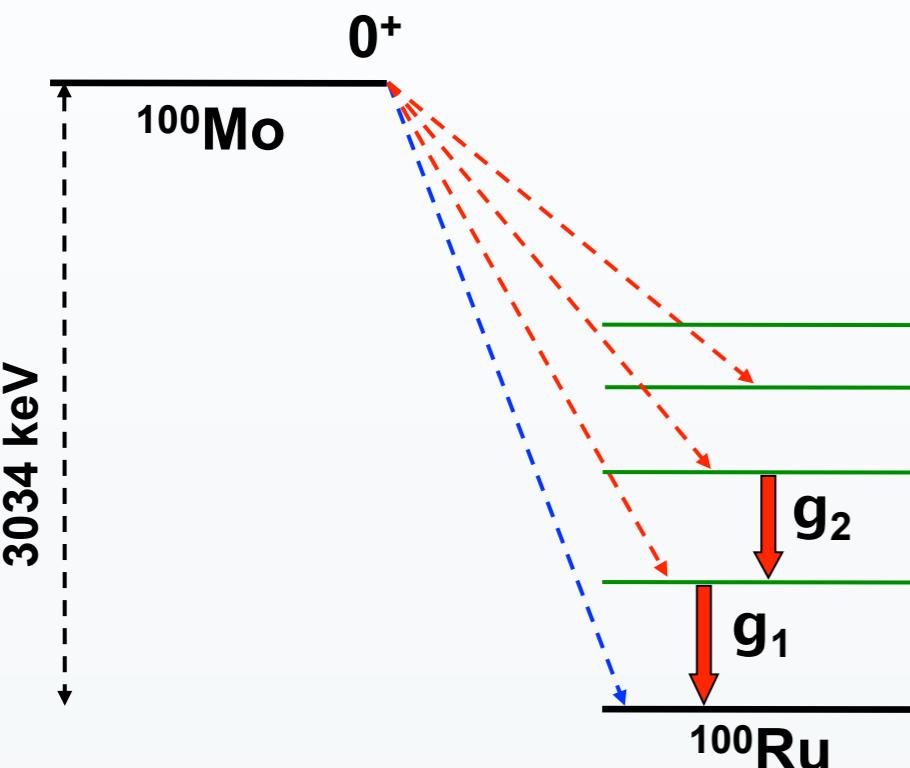
$\epsilon(0\nu) = 0.105$
 Tot MC= 3.8 ± 0.5 , Data: 4 events
 $MC\ 2\nu\beta\beta = 0.4 \pm 0.1$
 $MC\ \text{radon} = 2.4 \pm 0.4$
 $MC\ \text{int bkg}=1.0 \pm 0.2$ ($^{214}\text{Bi}=0.55, ^{208}\text{Tl}=0.42$)

[2.6 , 3.2] MeV:

$\epsilon(0\nu) = 0.118$
 Tot MC= 7.3 ± 0.8 , Data: 10 events
 $MC\ 2\nu\beta\beta = 1.5 \pm 0.4$
 $MC\ \text{radon} = 2.0 \pm 0.3$
 $MC\ \text{int bkg}=3.8 \pm 0.6$ ($^{214}\text{Bi}=2.2, ^{208}\text{Tl}=1.6$)

[2.6,3.2]MeV in 4.5 years 14 events observed, 11.1+1.3 expected

^{100}Mo $2\beta 2\nu$ decay to excited states



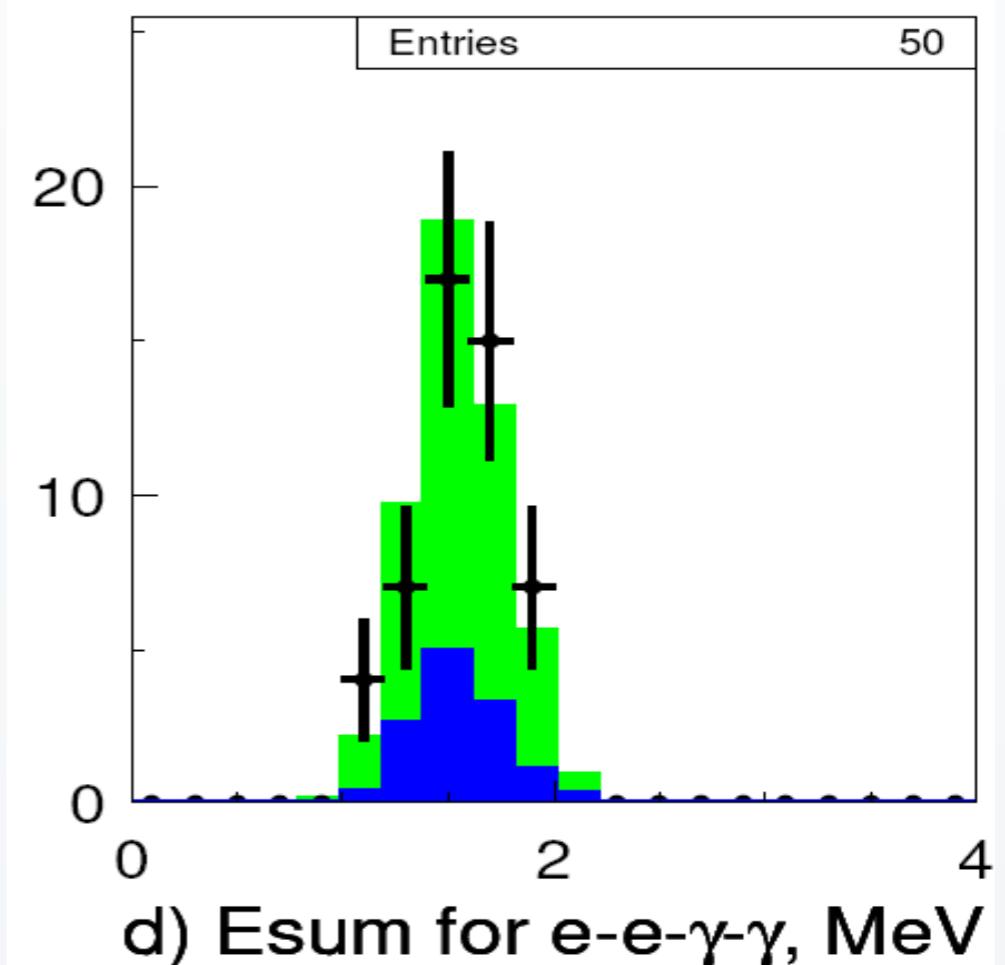
$$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9} \text{ (stat)} \pm 0.8 \text{ (syst)} \times 10^{20} \text{ y}$$

$$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22} \text{ y @ 90% C.L.}$$

$$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21} \text{ y @ 90% C.L.}$$

$$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23} \text{ y @ 90% C.L.}$$

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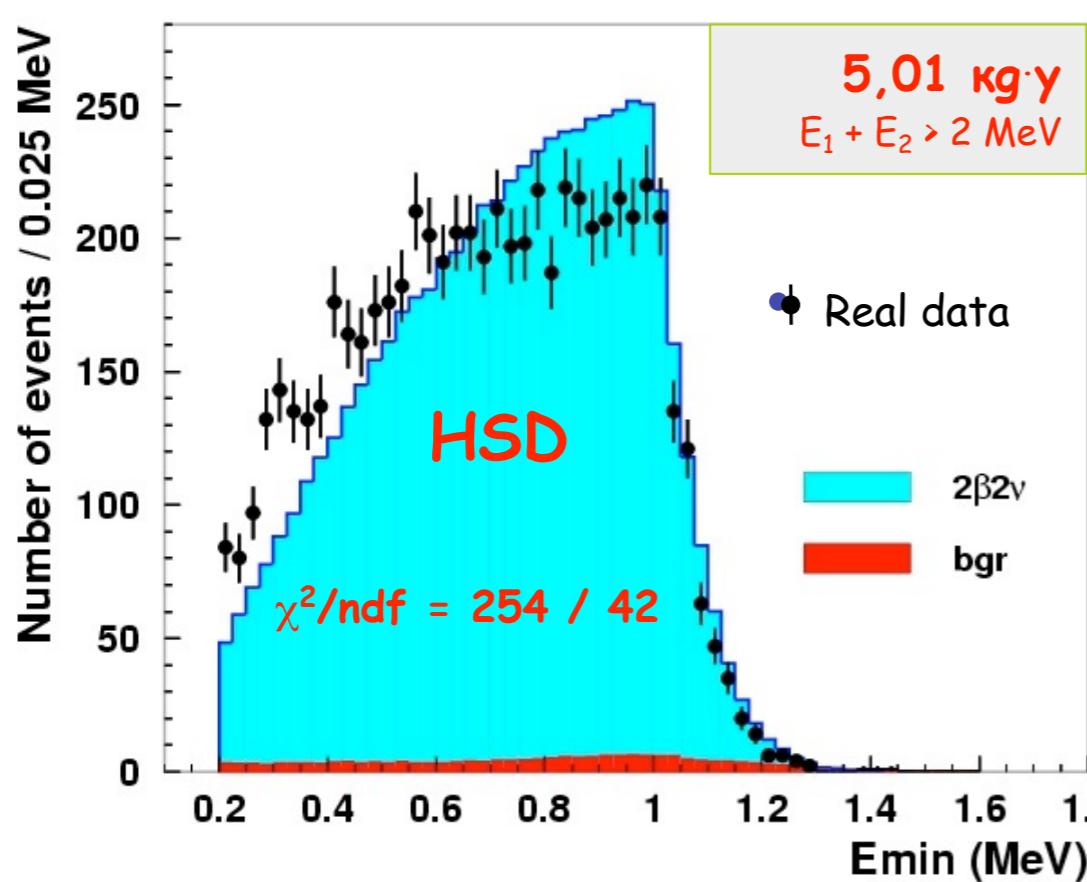
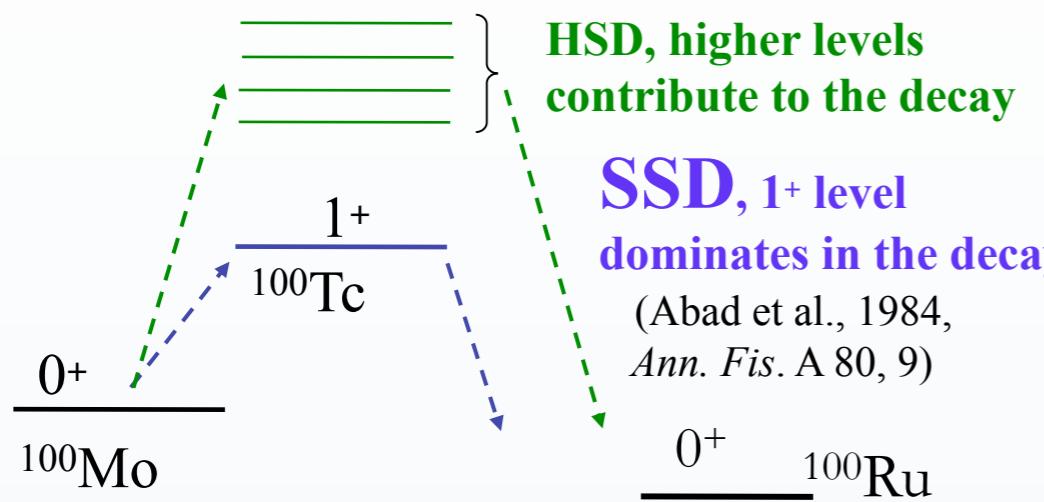


Event topology:

0_1^+ : 2e⁻ + 2g in time & energy and TOF cuts

2_1^+ : 2e⁻ + 1g in time & energy and TOF cuts

SSD/HSD $2\nu\beta\beta$ (^{100}Mo)



Electron energy distribution in $2\nu\beta\beta$ decay of ^{100}Mo is in favour of Single State Dominance (SSD)

Single electron spectrum different between SSD and HSD

