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

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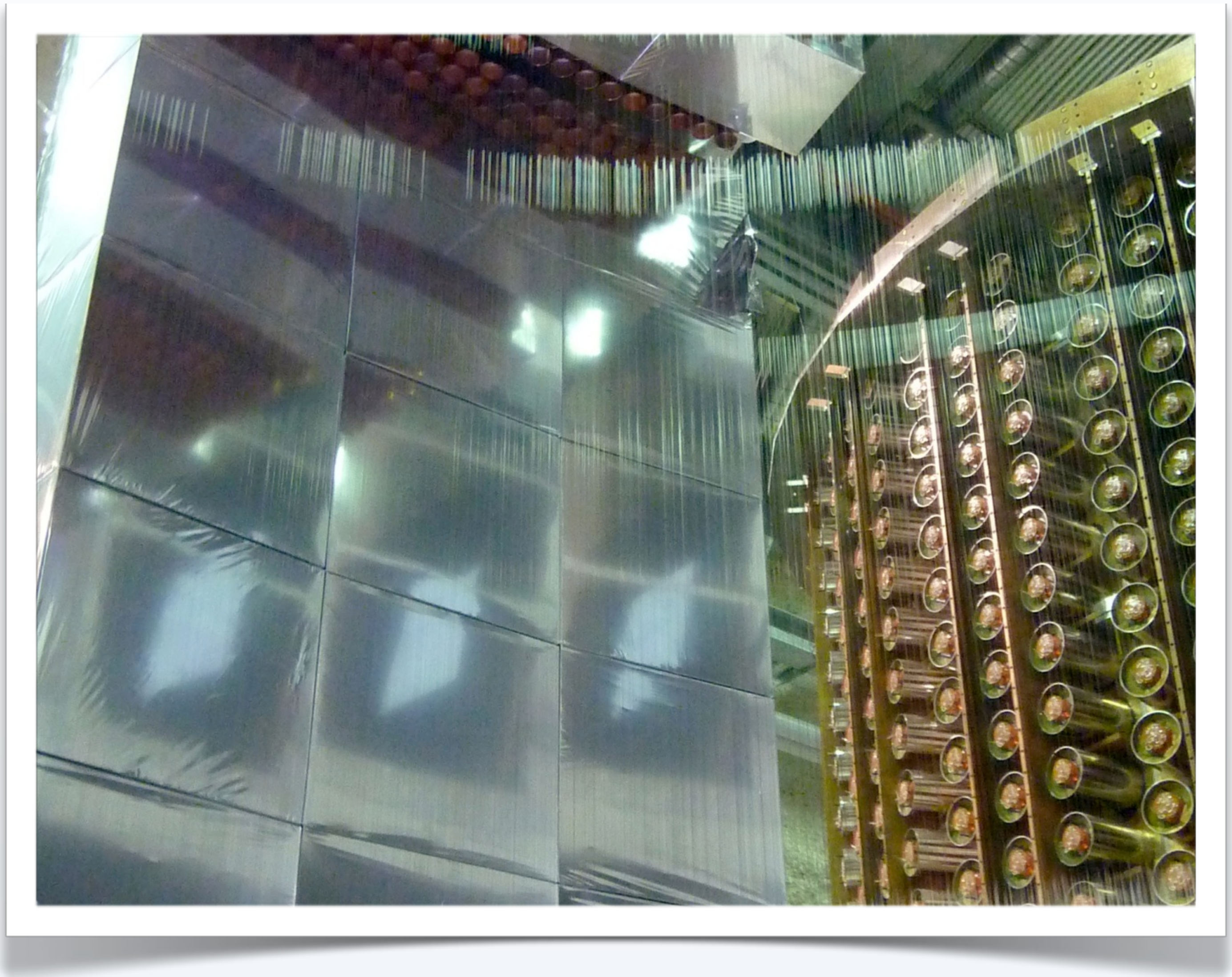
on behalf of the NEMO collaboration

XLIX[th] Rencontres de Moriond

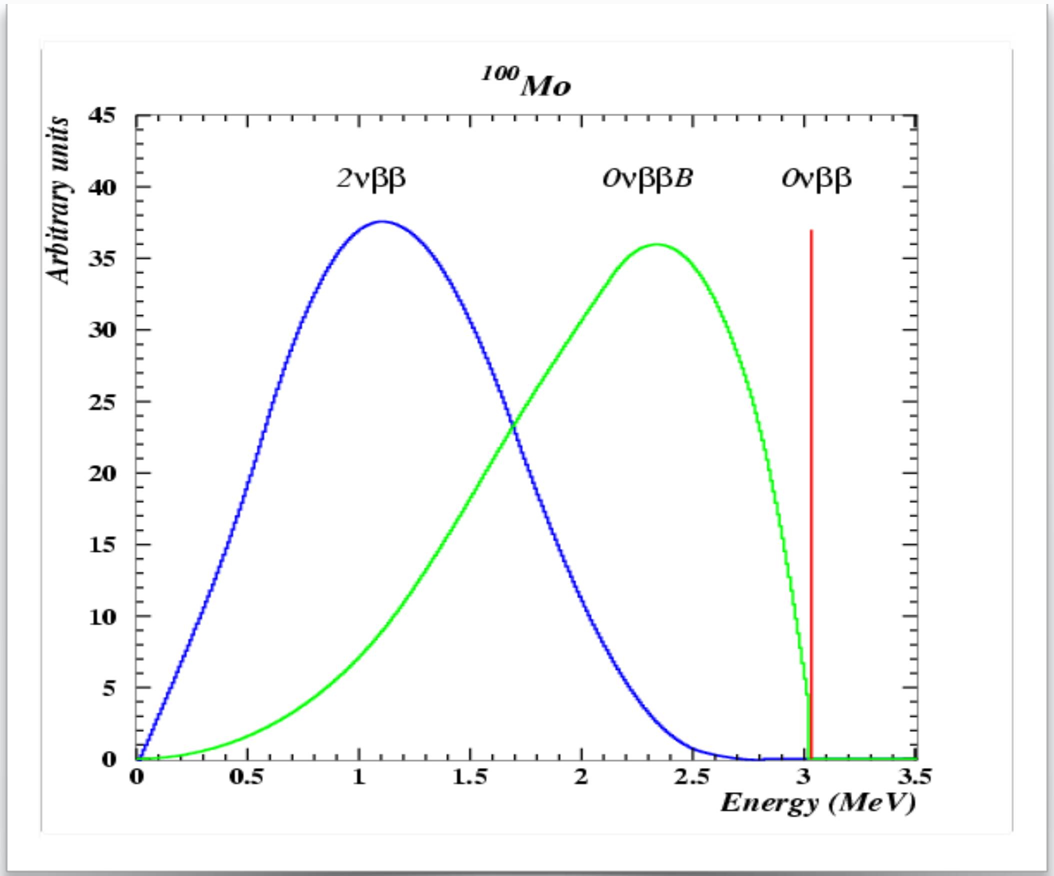
Electroweak Interactions and Unified Theories

La Thuile, 15[th]-22[nd] March 2014

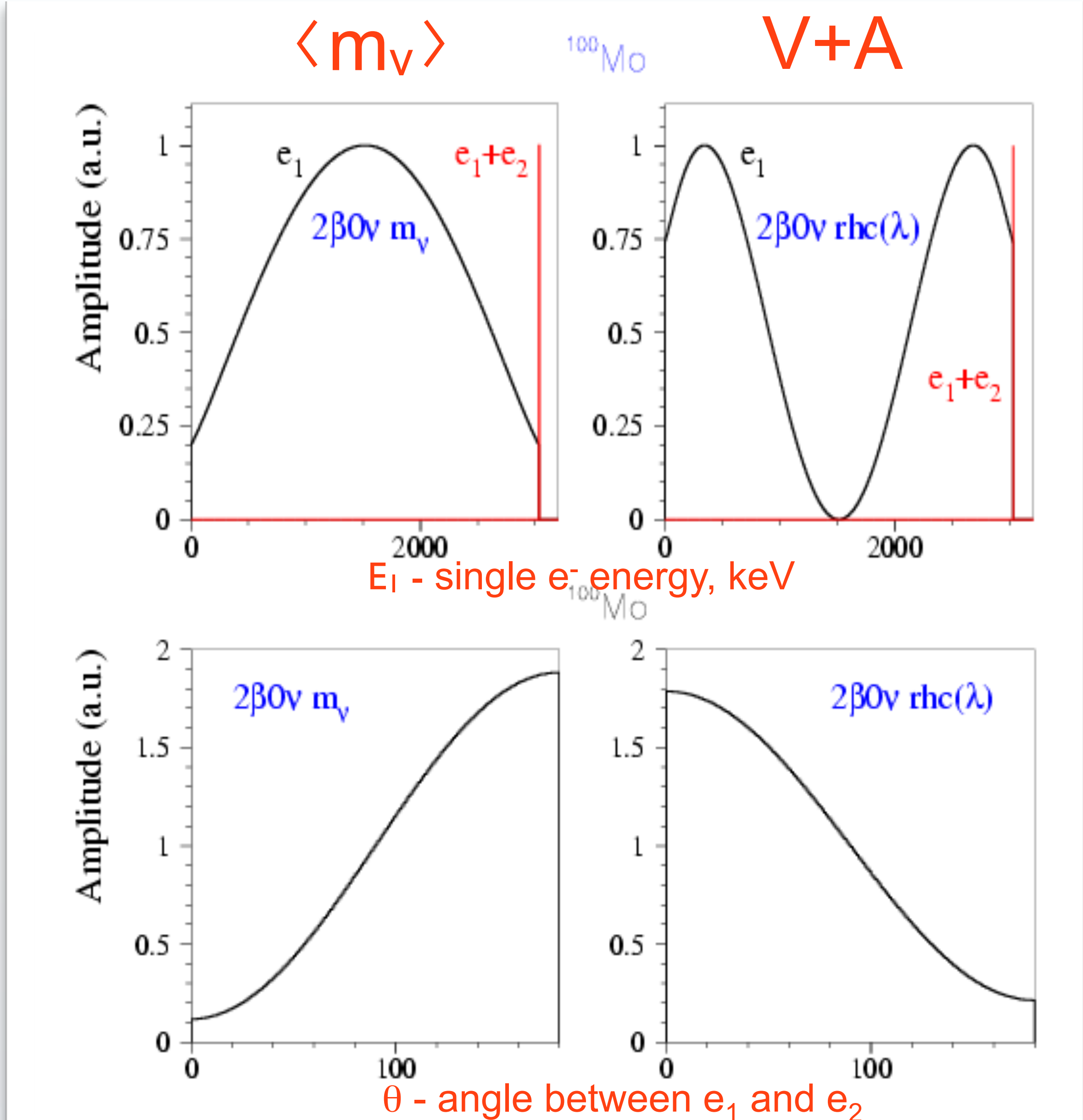


Which processes cause double beta decay?

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



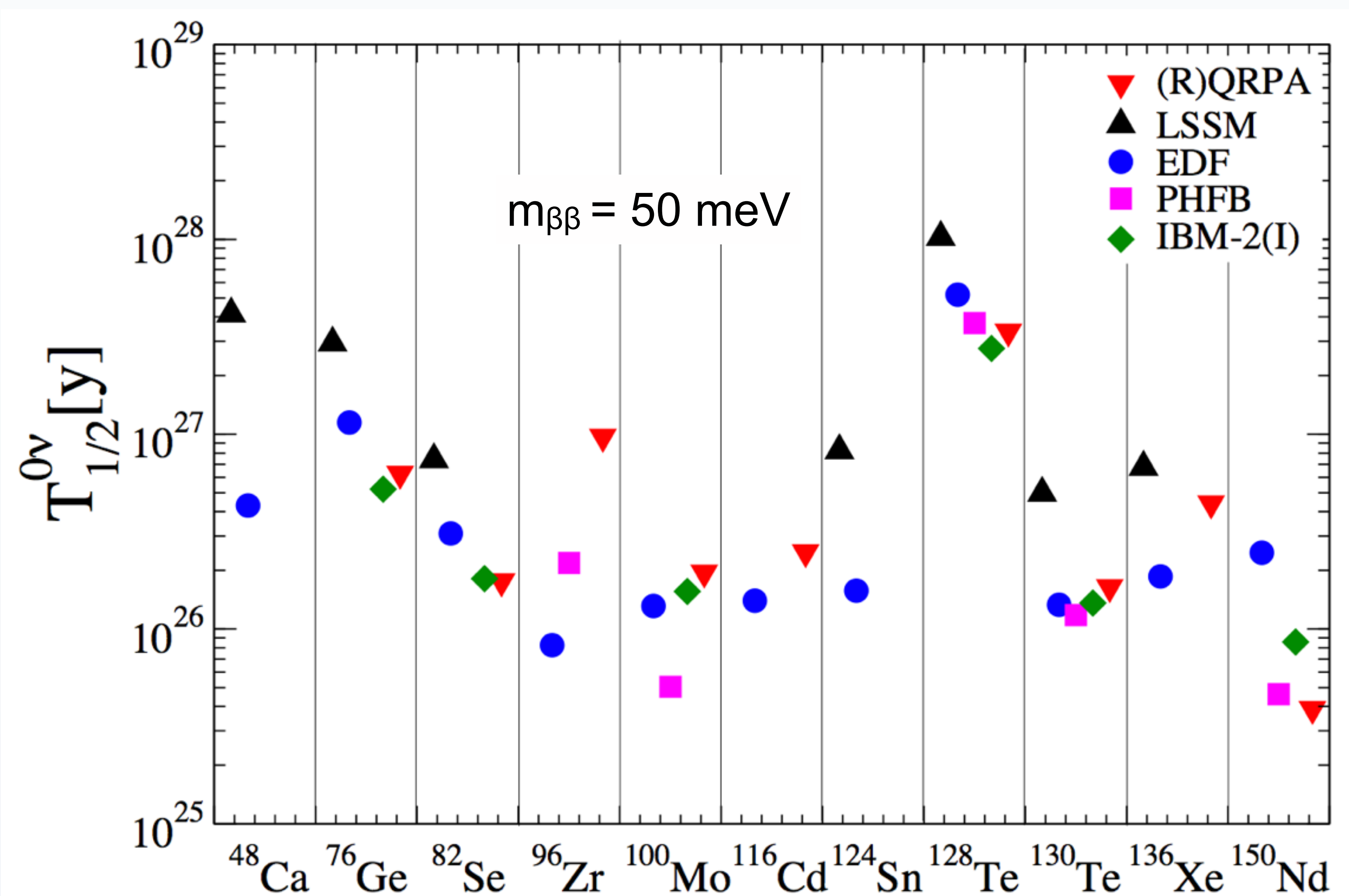
η can be due to mass mechanism, V+A, majoron, SUSY, ... with different topology in the final state



Measuring the Lepton Number Violating parameter

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

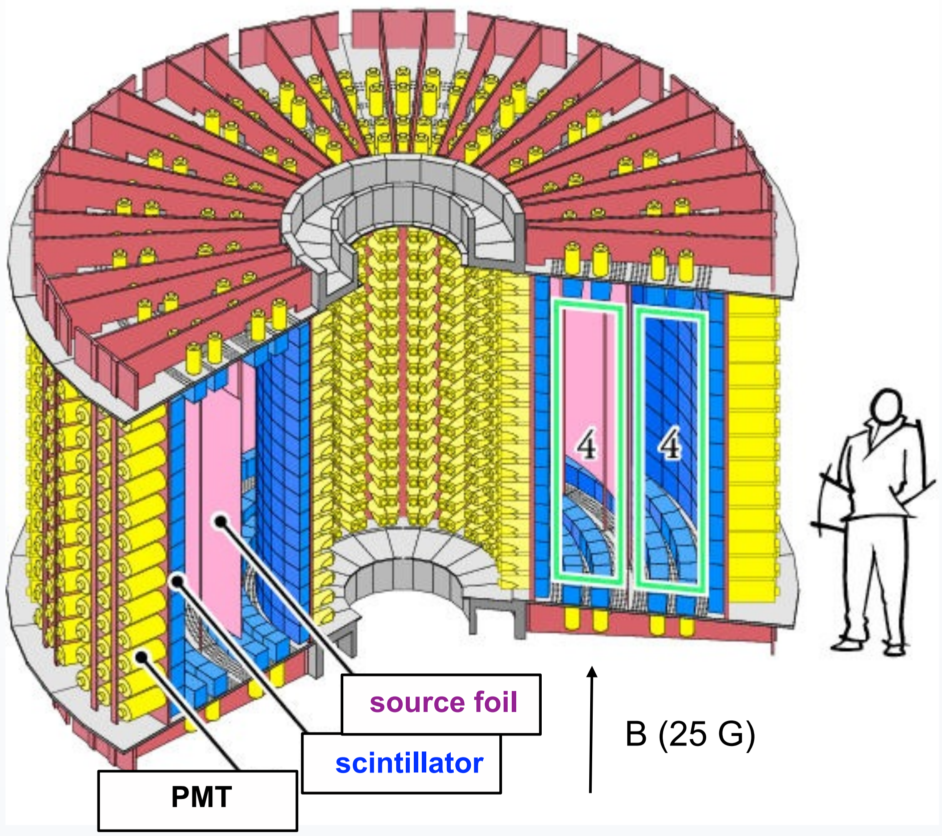
- need to know the Nuclear Matrix Element (NME)
- variation between models and isotopes
- combine measurements from as many isotopes as possible

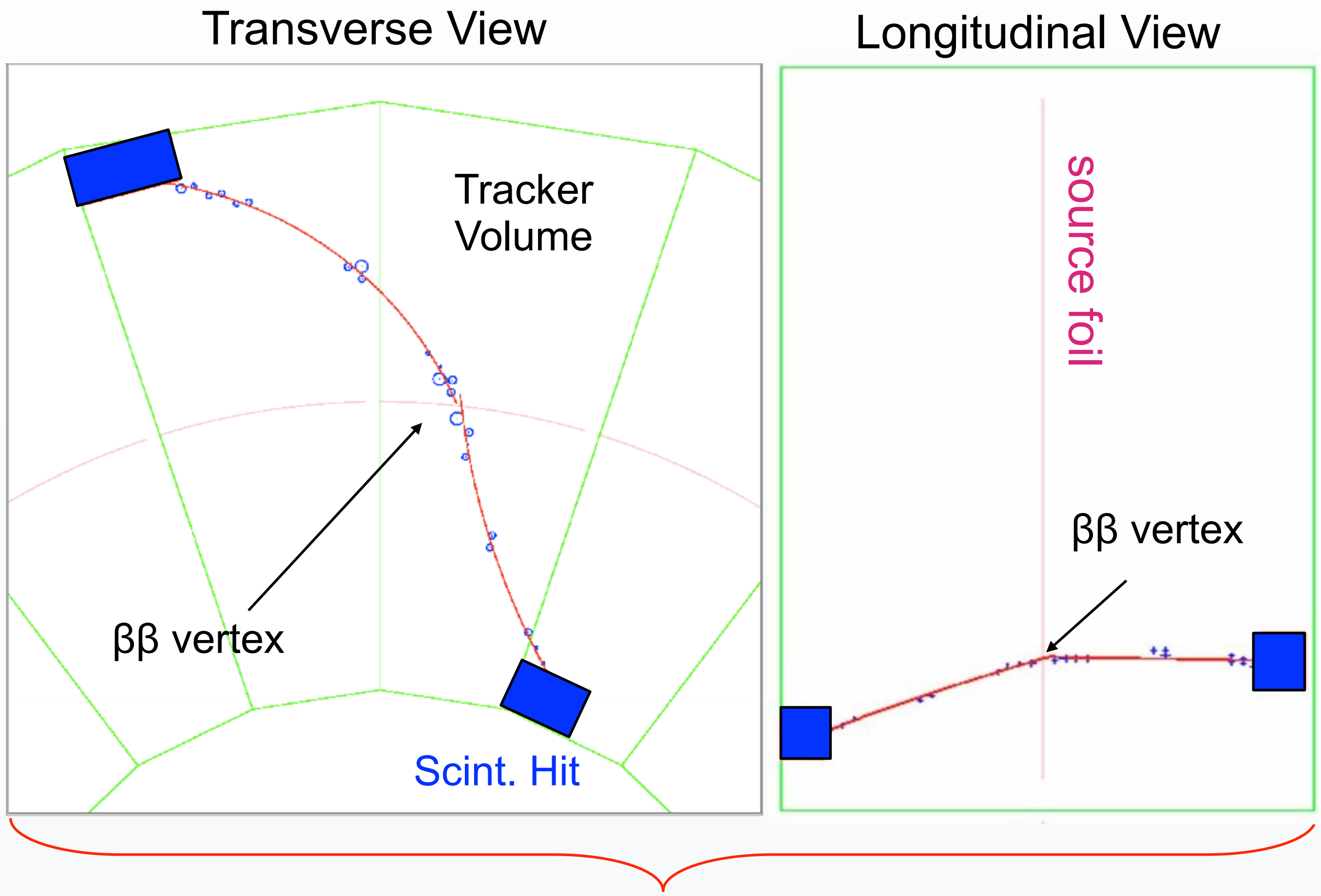


Isotope	Abundance (%)	$Q_{\beta\beta}$ (MeV)	$G^{0\nu}$ (10^{-14} y)
^{48}Ca	0.19	4,276	7.15
^{76}Ge	7.8	2,039	0.71
^{82}Se	9.2	2,992	3.11
^{100}Mo	9.6	3,034	5.03
^{116}Cd	7.5	2,804	5.44
^{130}Te	34.5	2,529	4.89
^{136}Xe	8.9	2,467	5.13
^{150}Nd	5.6	3,368	23.2

Vergados, J. D., et al., Phys.Scripta, 75, 106301 (2012)

NEMO3





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

Isotopes

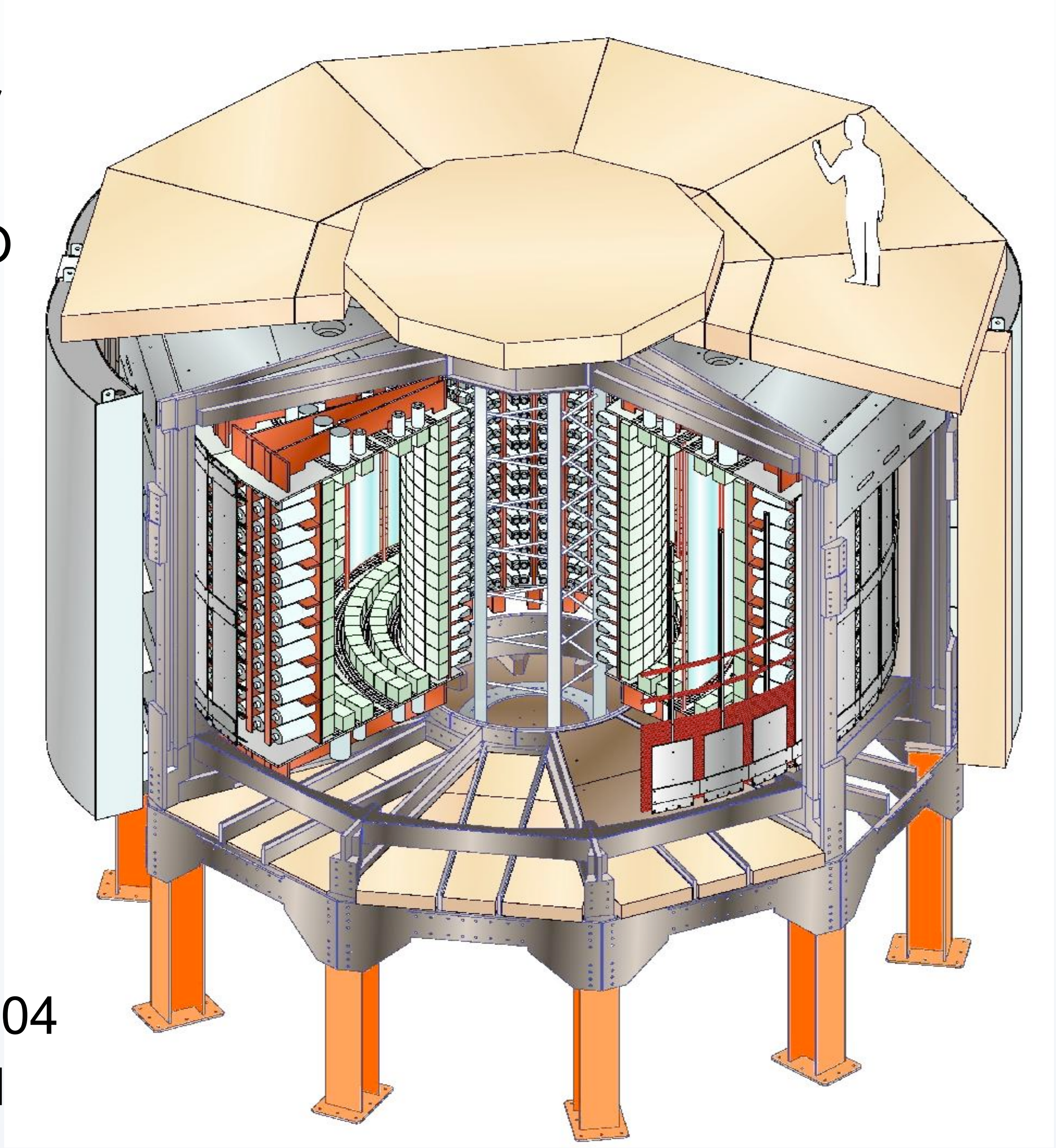
Large quantities: ^{100}Mo (7kg) ^{82}Se (1 kg)

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

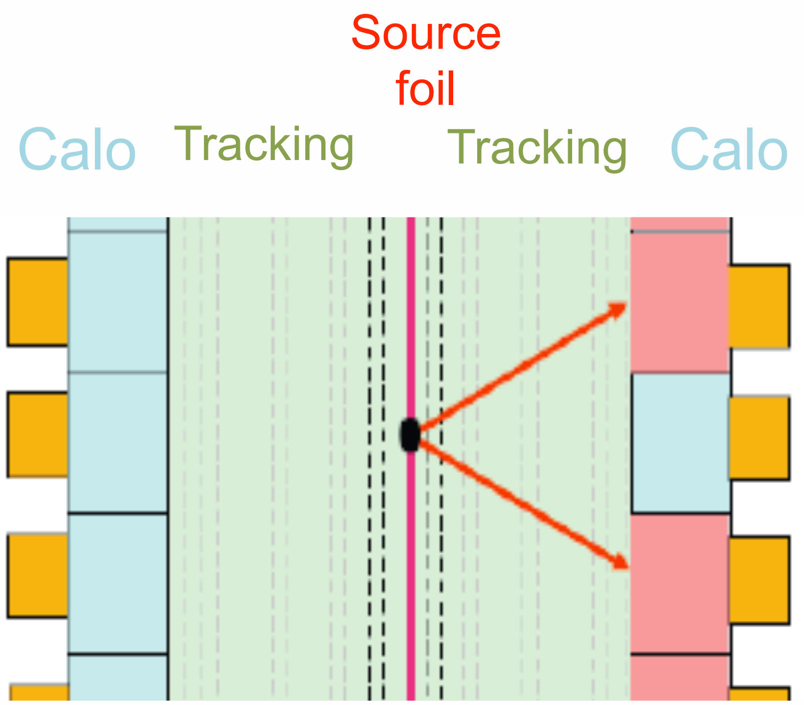
All major isotopes except ^{76}Ge and ^{136}Xe

NEMO3

- source distributed on cylindrical surface
- 3D wire drift chamber operated in Geiger mode (6180 cells)
  - He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O
- 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

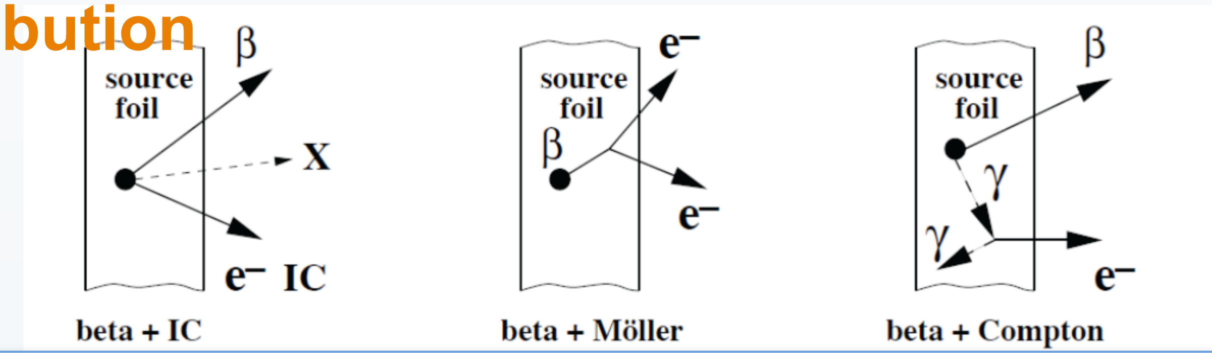


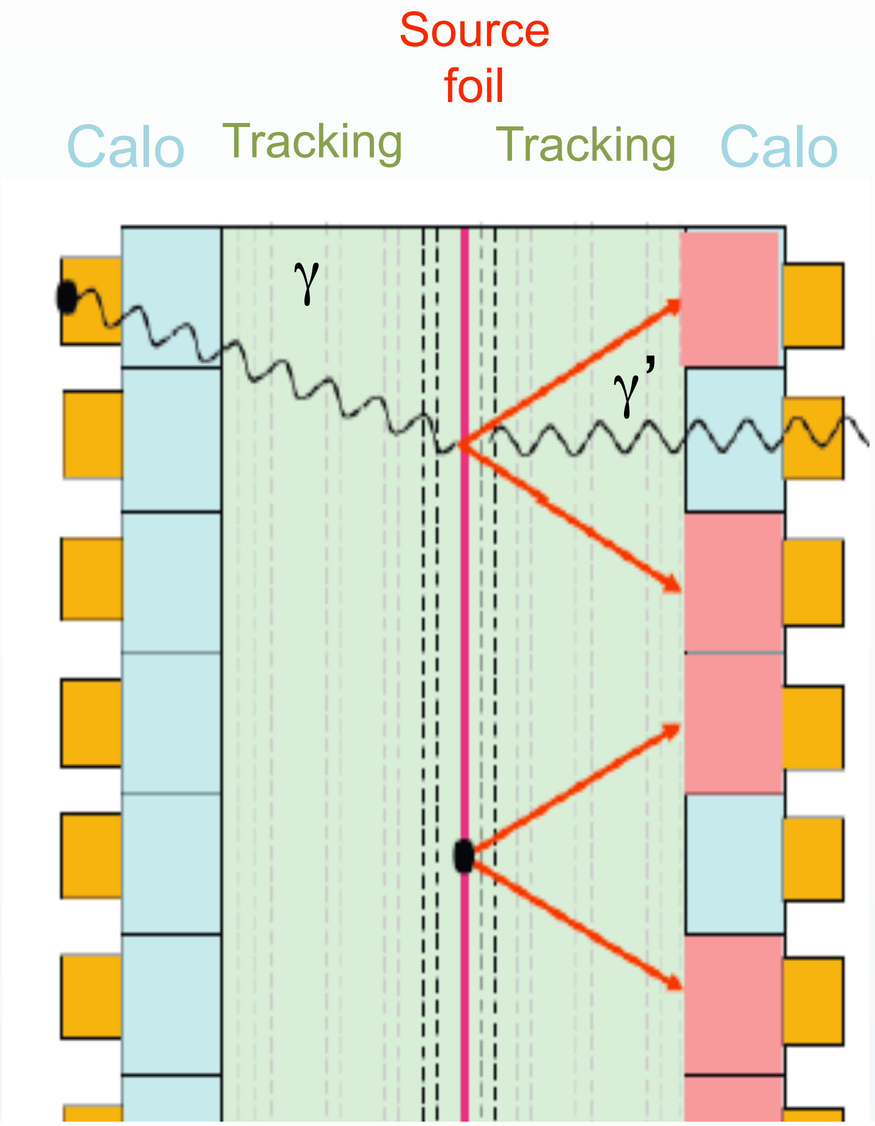
Backgrounds



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

Internal Background

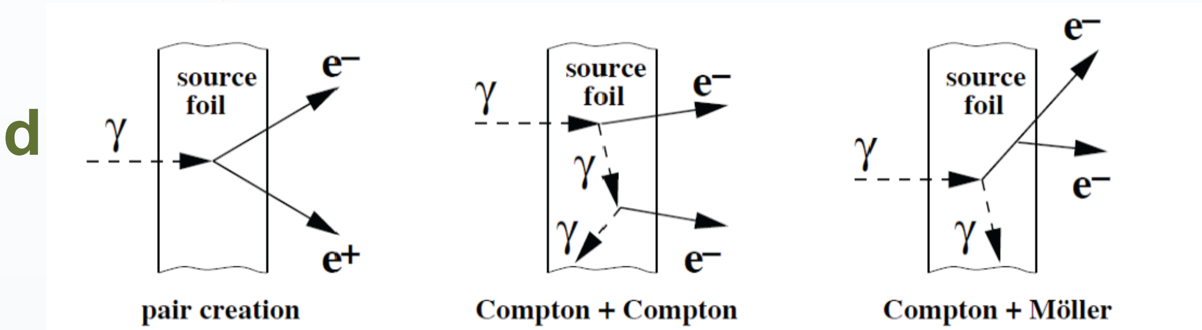




Backgrounds

Radio-impurities in material, γ from (n,γ) (n,n'γ) and μ bremstrahlung

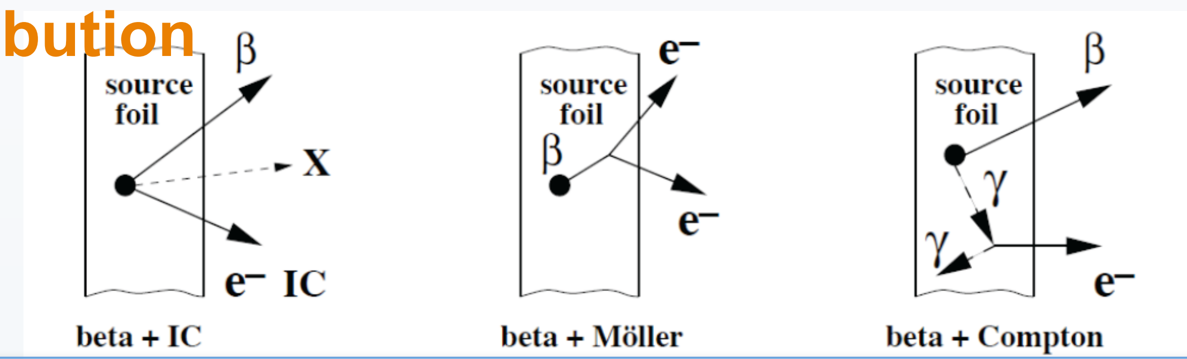
External Background



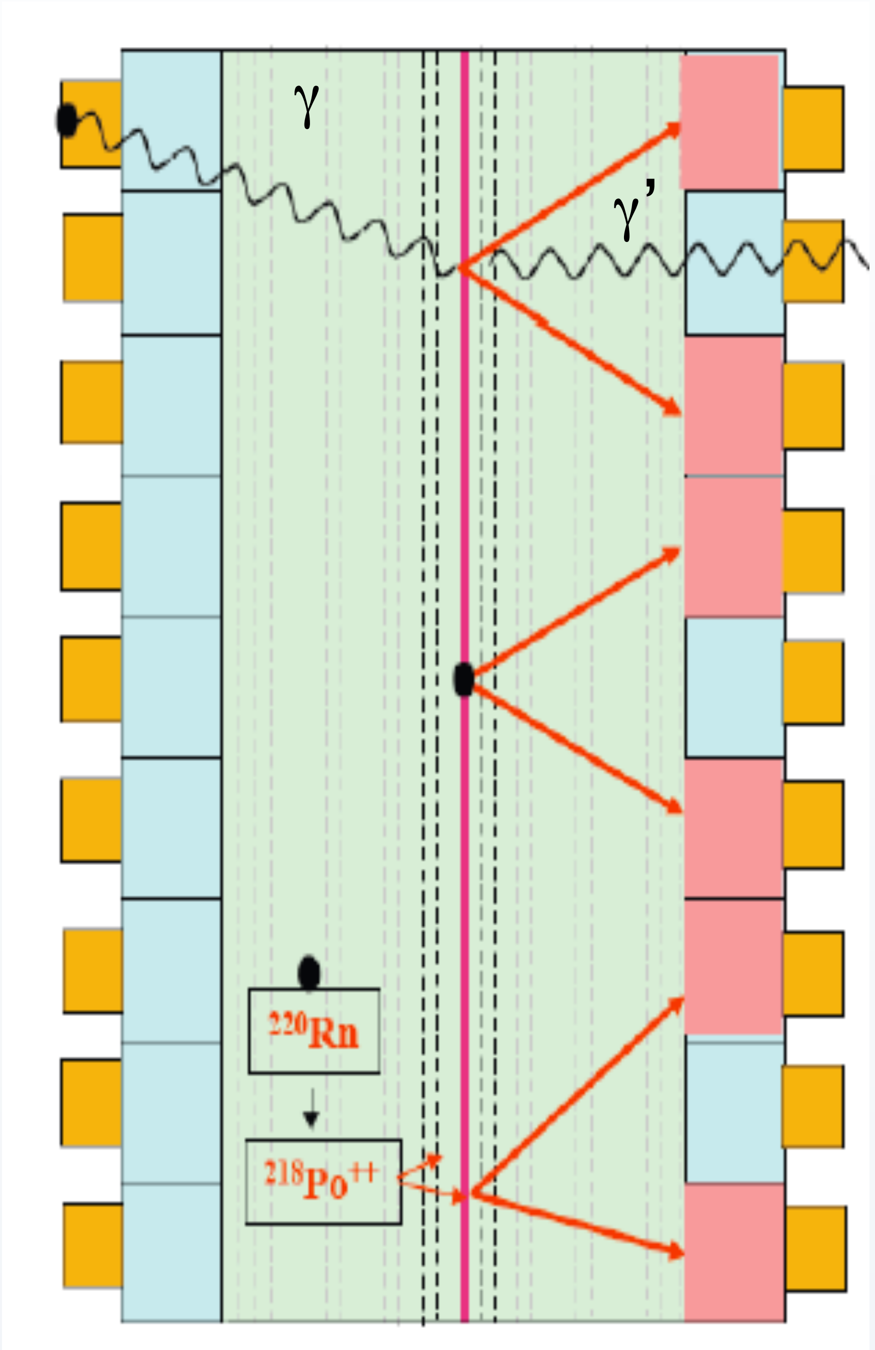
Reduction by a factor at least 100 compare to calorimeters

In addition to ββ(2ν), ^{214}Bi and ^{208}Tl contribution

Internal Background

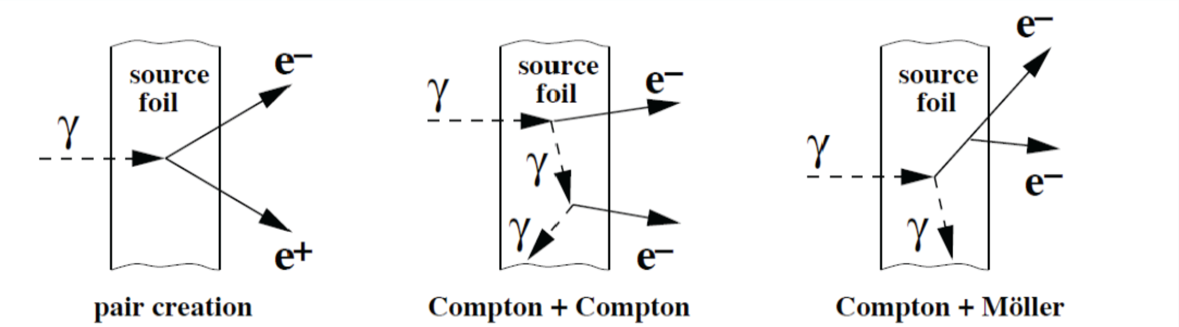


Backgrounds



External Background

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



Reduction by a factor at least 100 compare to calorimeters

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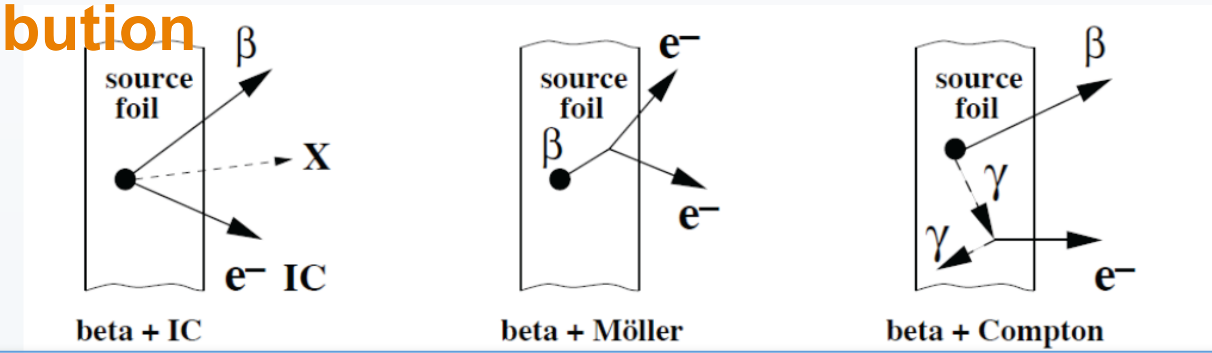
In addition to $\beta\beta(2\nu)$, ^{214}Bi and ^{208}Tl contribution



Radon Background

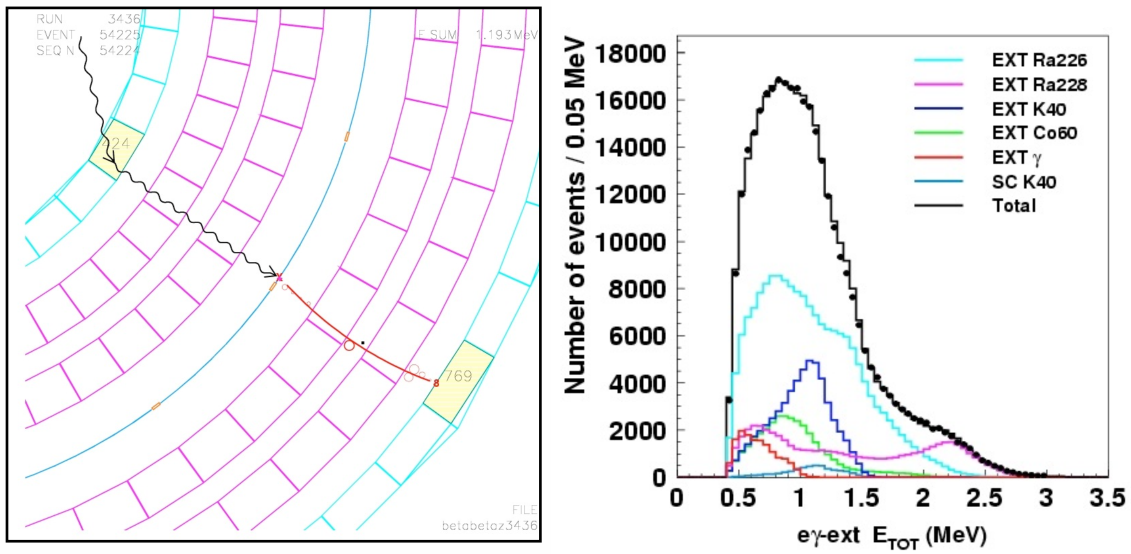
Radon daughter (^{214}Bi) deposited on the Source foil or near wires

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

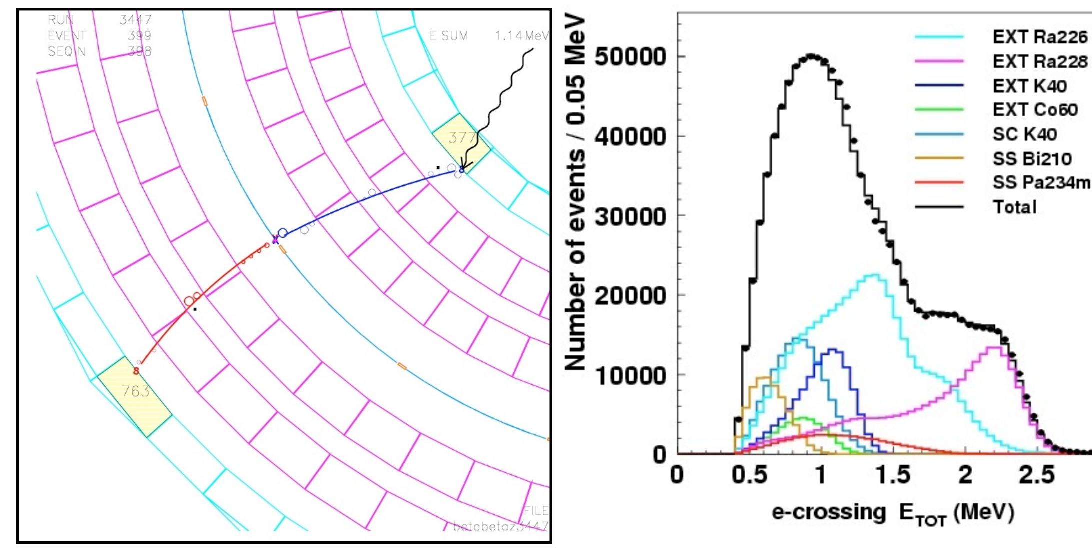
Backgrounds measurements

NIM A606 (2009) 449

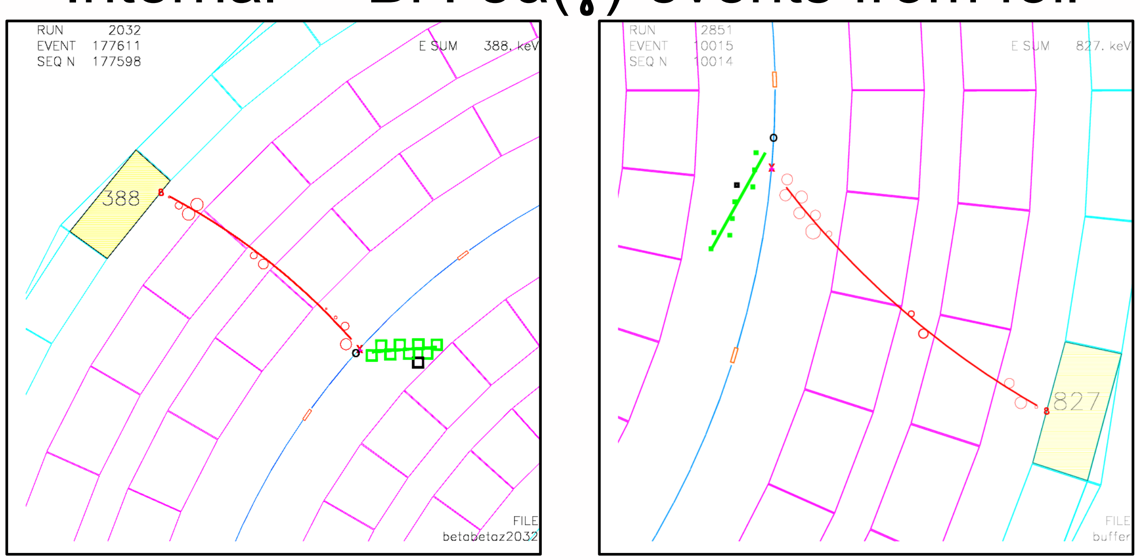
External background: eɣ-external

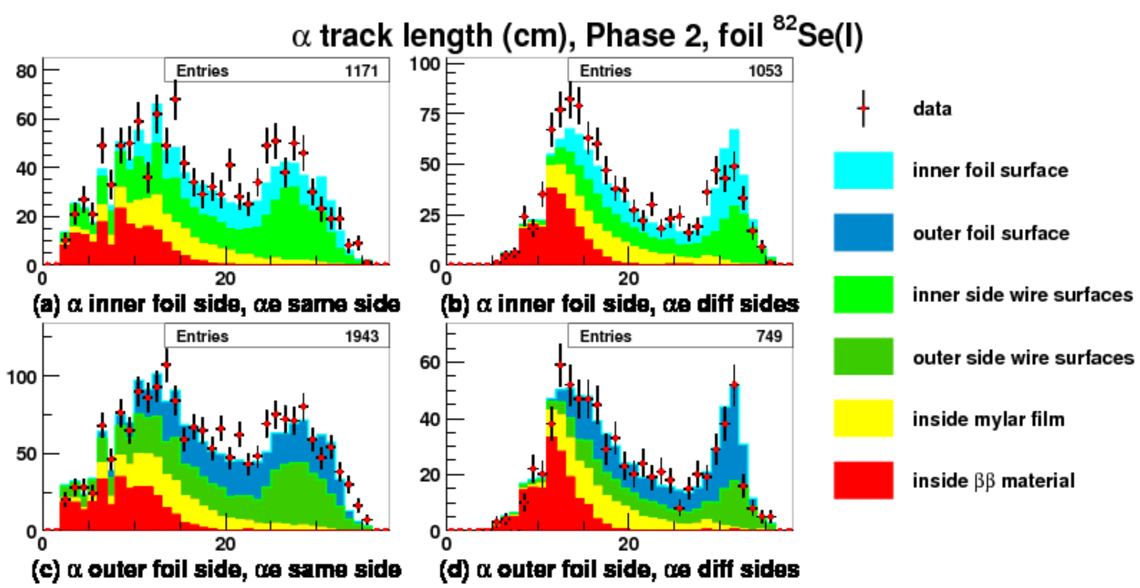


External background: e-crossing events

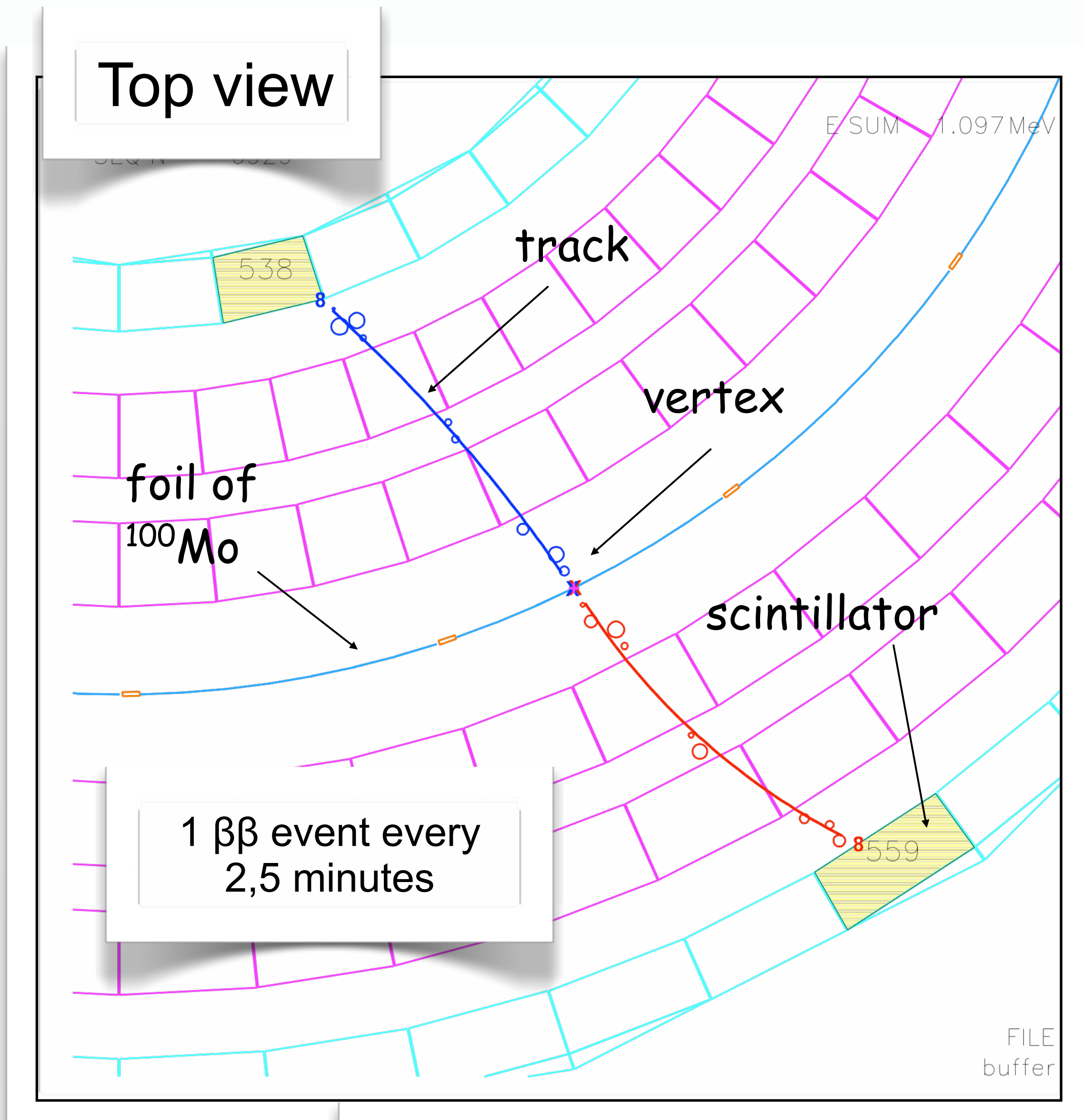


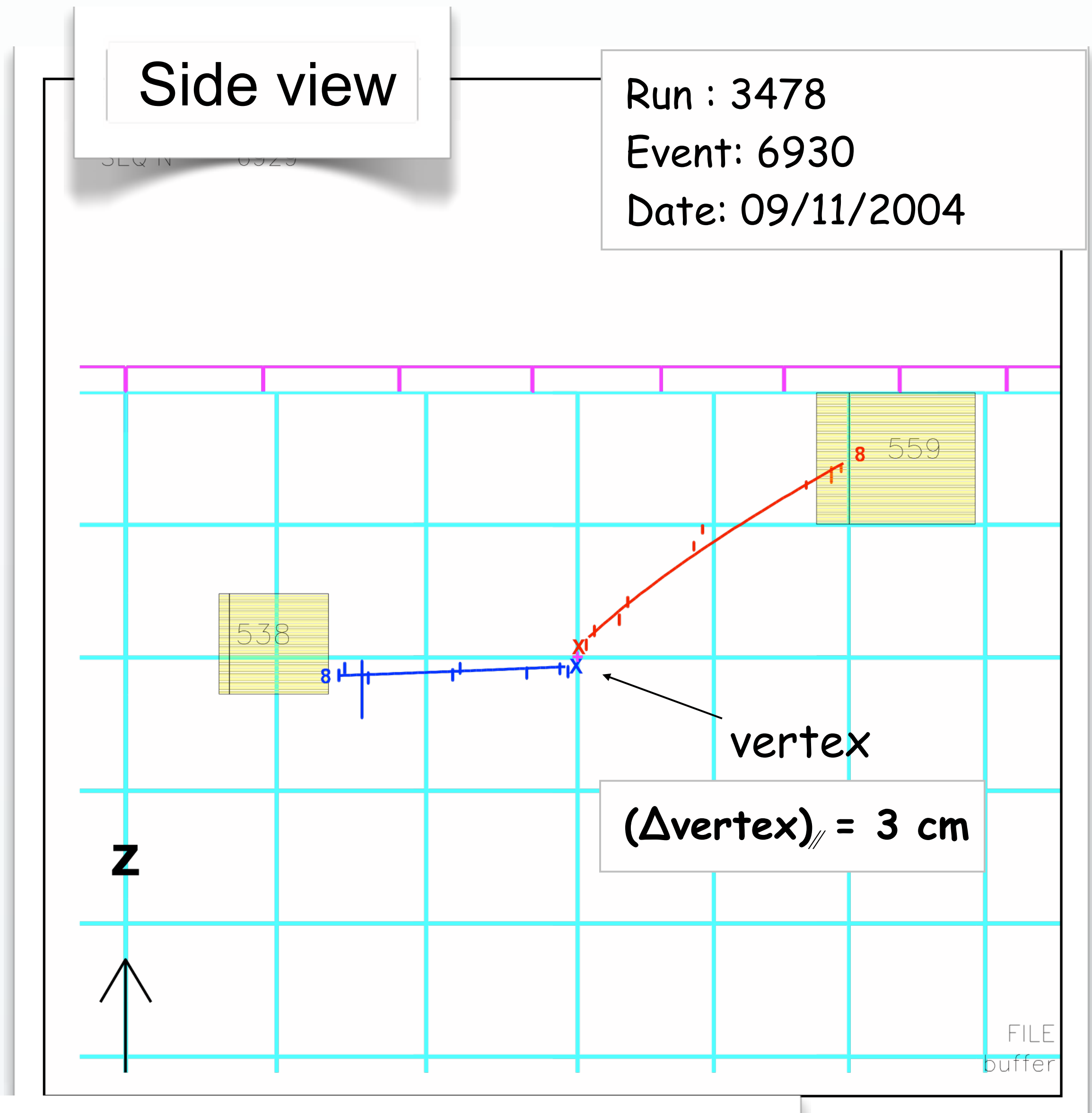
Internal ^{214}Bi : eα(ɣ)-events from foil





Selection of ββ events

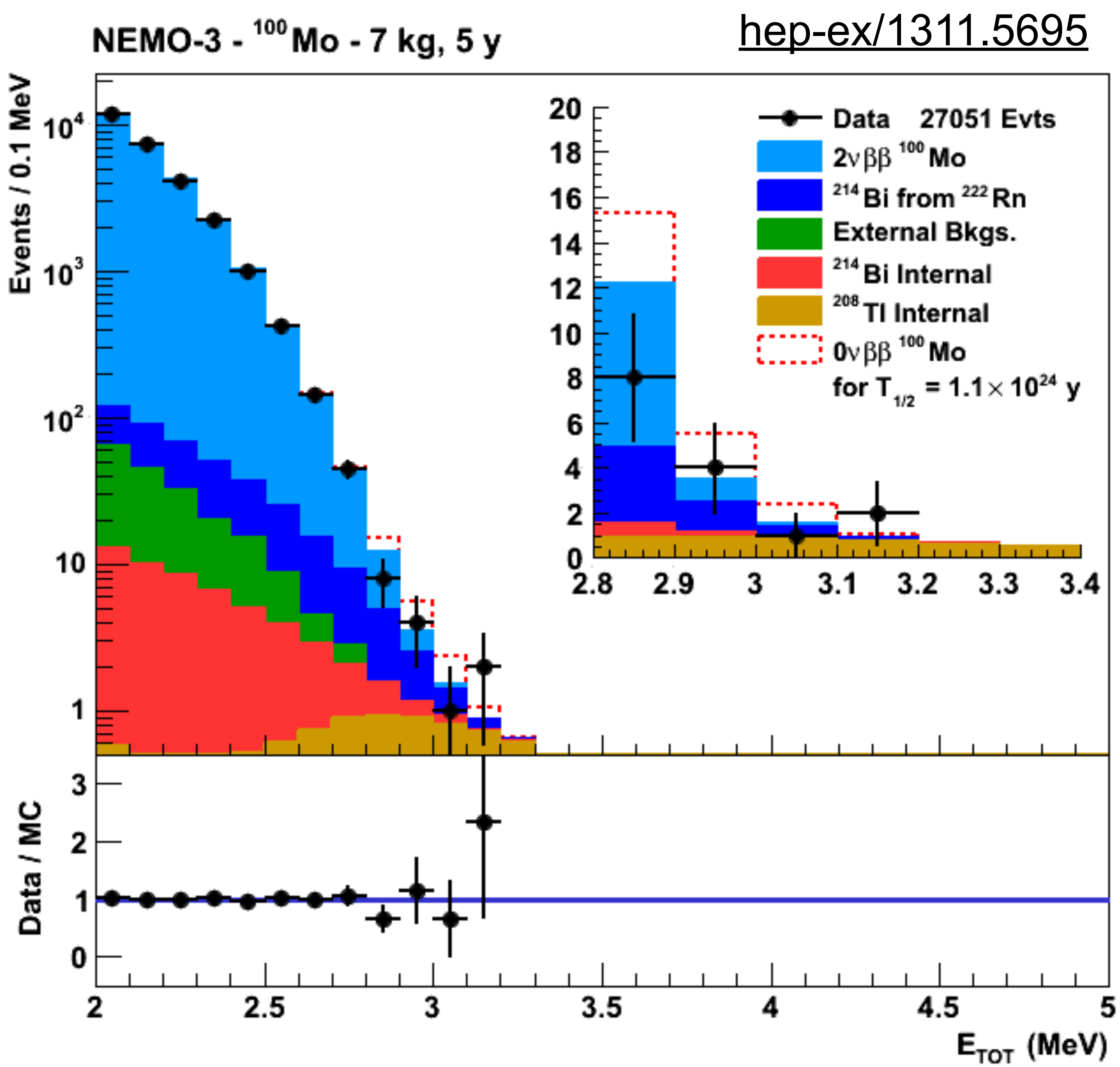




Criteria to select ββ events

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



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

Sample	Entries
External bkgs	< 0.2
^{214}Bi from ^{222}Rn	5.2 ± 0.5
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
$2\nu\beta\beta$	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

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

0νββ ^{100}Mo - Limits on the half-life

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

Systematics

0νββ reconstruction efficiency	7%
2νββ events in window	0.7%
^{208}Tl contamination	10%
^{214}Bi contamination	10%

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

0νββ process	Stat. Only	Systematics	Expected
Mass mechanism	1.1	1.1	1.0 [0.7, 1.4]
$q_{r.h.}$ - $l_{r.h.}$ coupling ⟨λ⟩	0.7	0.6	0.5 [0.4, 0.8]
$q_{r.h.}$ - $l_{l.h.}$ coupling ⟨η⟩	1.0	1.0	0.9 [0.6, 1.3]
Majoron	0.050	0.044	0.039 [0.027, 0.059]

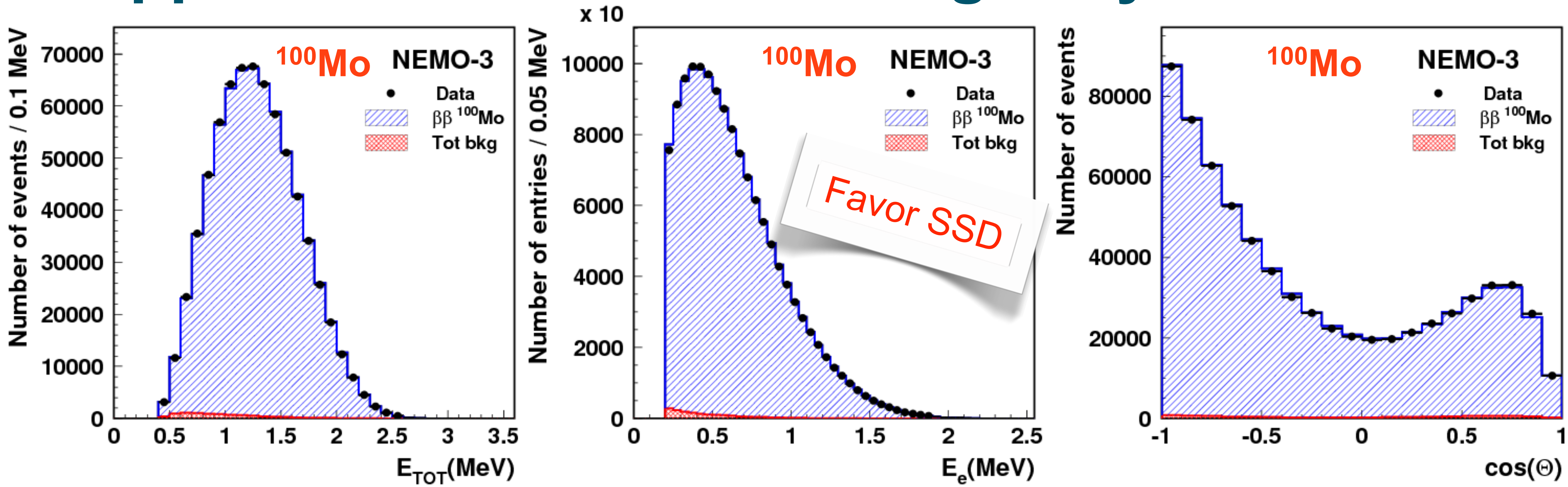
0νββ - Limits @ 90%C.L. on LNV parameters

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

Isotope	Exposure (kg·y)	Half life (10^{25} y) published	⟨m_ν⟩ (eV) published	⟨m_ν⟩ (eV) calculated	⟨λ⟩ (10^{-6}) published	⟨η⟩ (10^{-8}) published	λ'_{111}/f (10^{-2}) published	⟨g_{ee}⟩ (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

- ⟨m_ν⟩ limits recalculated using updated phase space and NME calculations see refs in [1] hep-ex/1311.5695
- $f = \left(\frac{M_{\tilde{q}}}{1\,\mathrm{TeV}}\right)^2 \left(\frac{M_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^{1/2}$

2νββ ^{100}Mo Phase 2 data - 7kg x 4 years



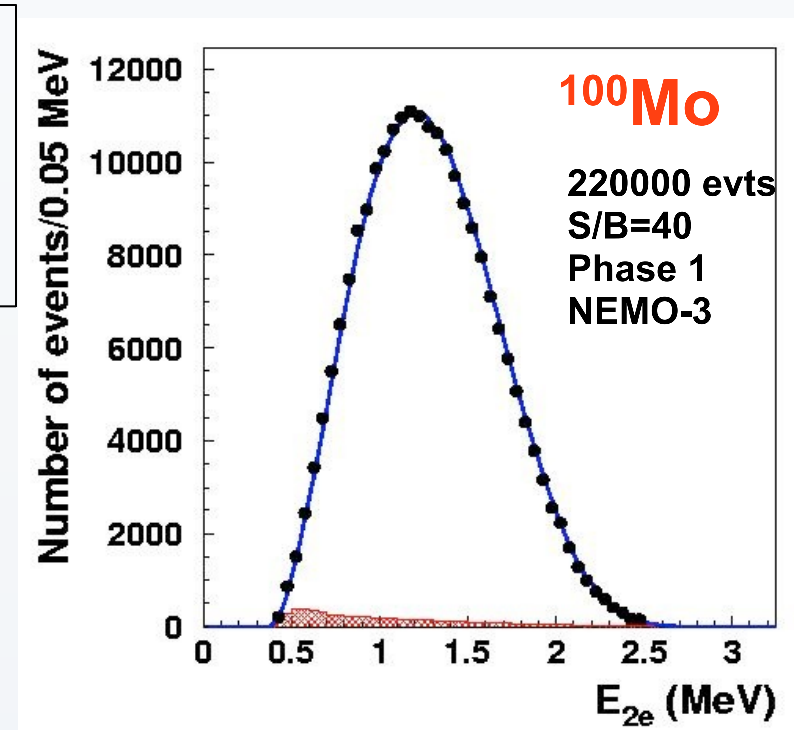
- 700000 two-electron events from ^{100}Mo foils
- S/B = 76
- $\varepsilon(2\nu2\beta) = 0.043$

  $T_{1/2}(2\nu2\beta) = [7.16 \pm 0.01 \text{ (stat)} \pm 0.54 \text{(syst)}]\ 10^{18}$ y   PRELIM.

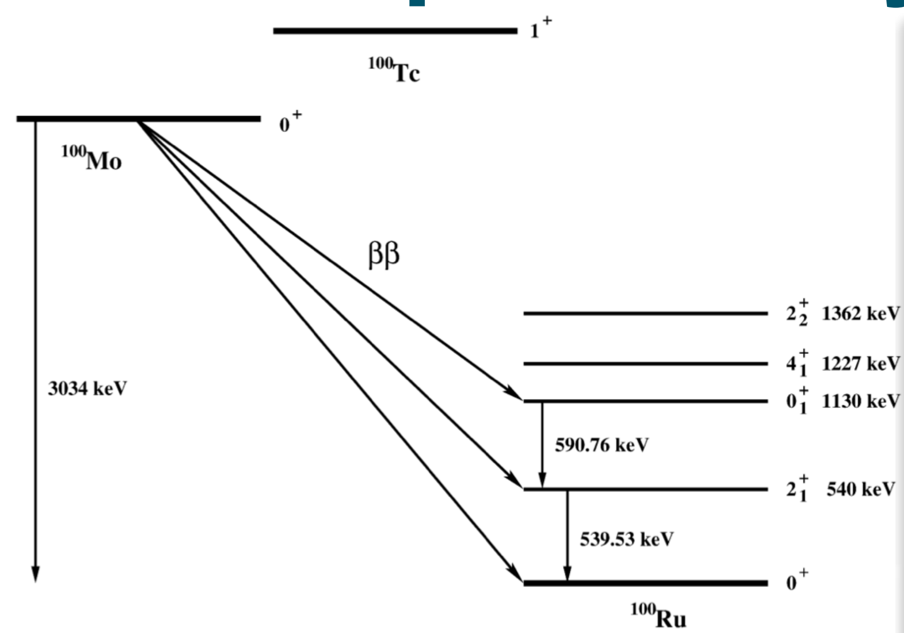
Consistent with the published NEMO-3 result obtained with Phase 1 data:

$T_{1/2} = [7.11 \pm 0.02\text{(stat)} \pm 0.54\text{(syst)}]\ 10^{18}$ y

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



^{100}Mo 2β2ν decay to excited states

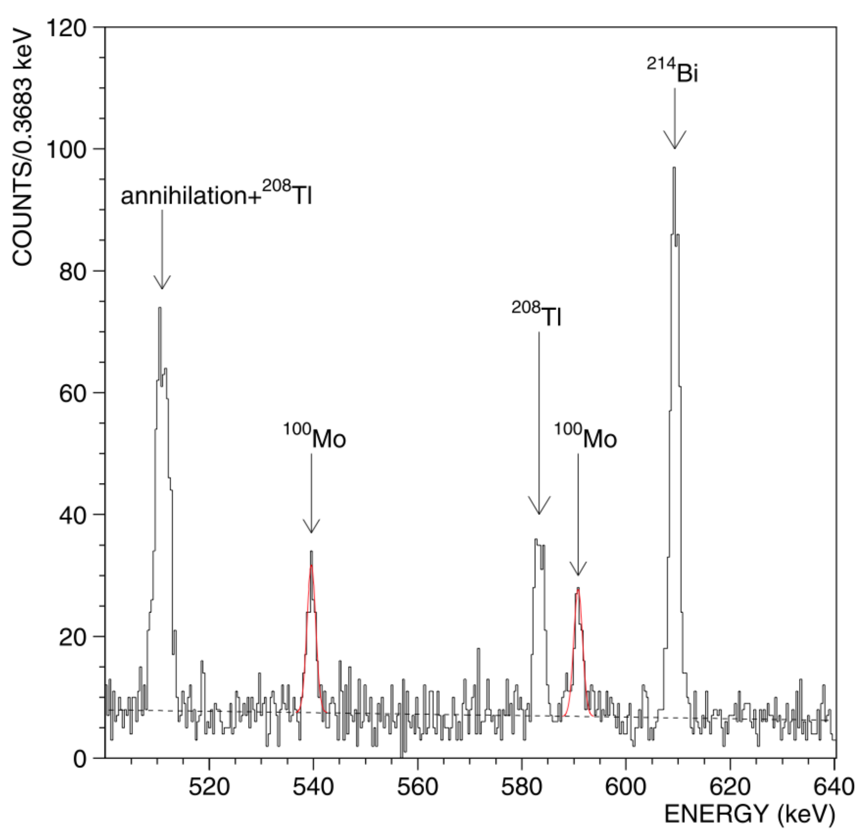


Decays to excited states have several photons in final state

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

$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9}$ (stat) ± 0.8 (syst) × 10^{20} y
$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22}$ y @ 90% C.L.
$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ y @ 90% C.L.
$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23}$ 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 detecto
- 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

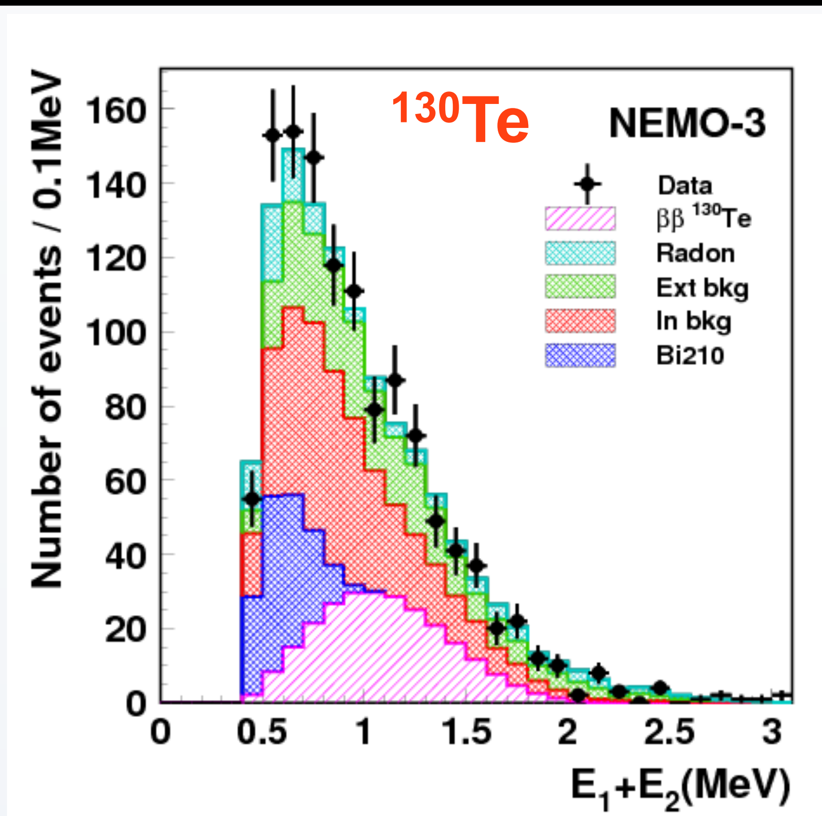
$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 7.5 \pm 0.6$ (stat) ± 0.6 (syst) × 10^{20} y
$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 2.5 \times 10^{21}$ y @ 90% C.L.
best limits on all other transitions to excited states were set

most precise measurement

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

2vββ Results

Isotope	Mass (g)	$Q_{\beta\beta}$(keV)	$T_{1/2}$(2v) (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:
- ~2.7 x 10^{21} yrs in 10^9 yr old rocks
- ~8 x10^{20} yrs in 10^7-10^8 yr old rocks

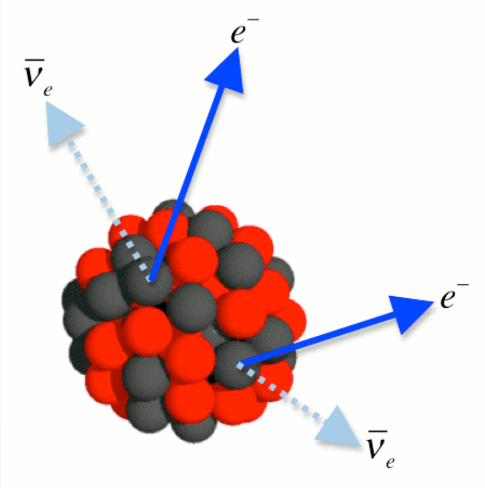
Indication from MIBETA Coll in isotopically enriched crystals: 6.1 ± 1.4(st) $^{+2.9}_{-3.5}$(sy) x10^{20} yrs

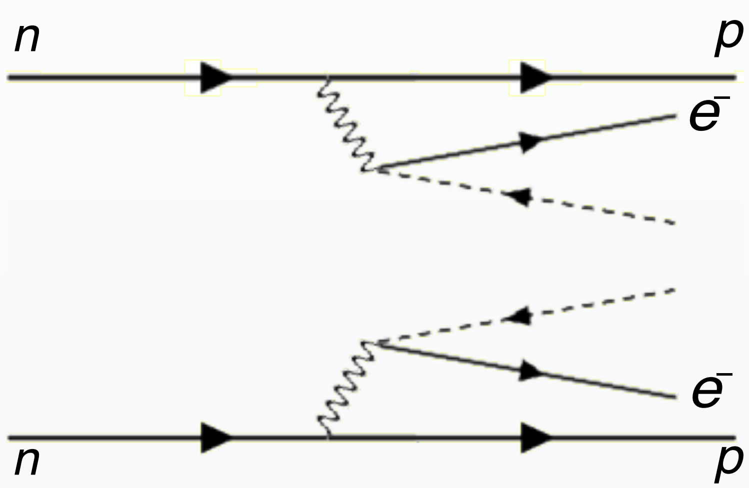
Conclusions

- 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

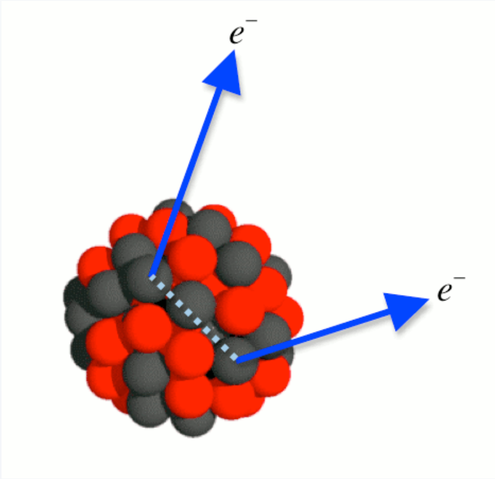
Double-Beta Decay

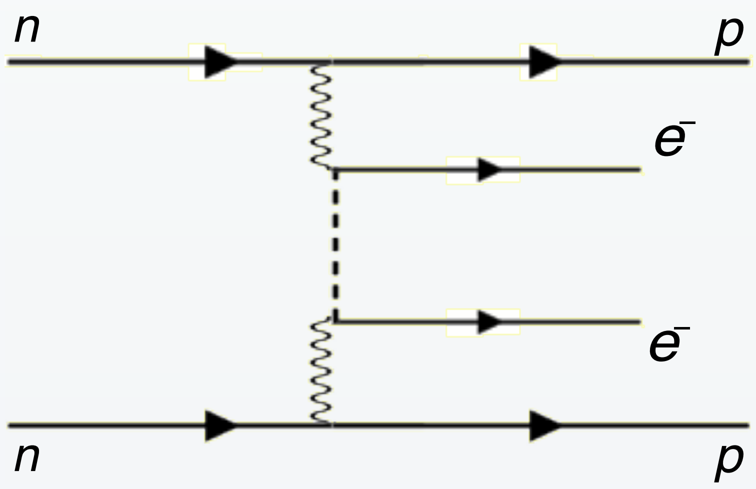




2-Neutrino Double Beta Decay

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



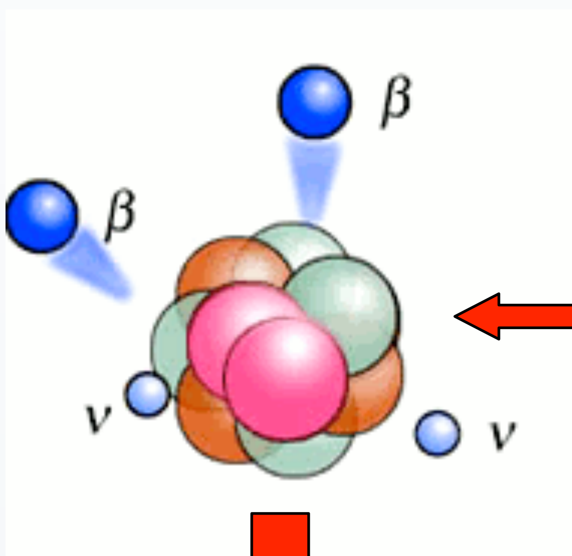


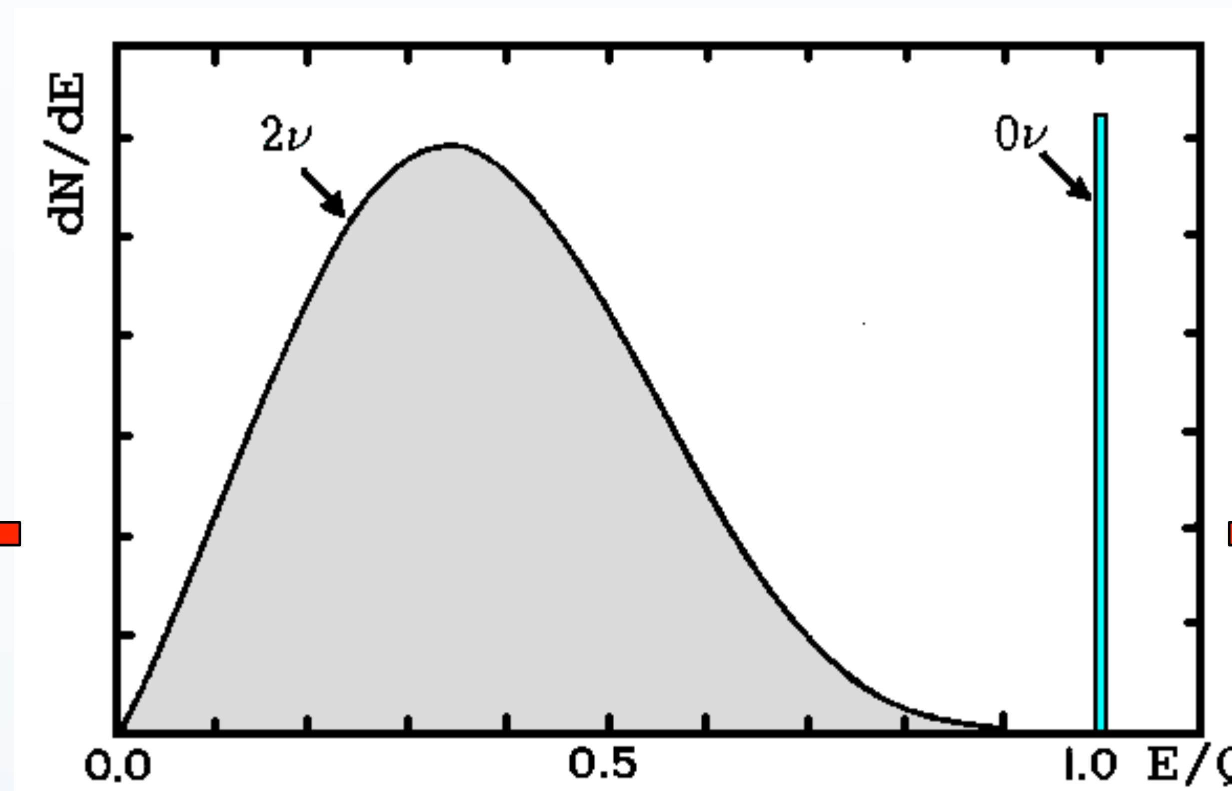
0-Neutrino Double Beta Decay

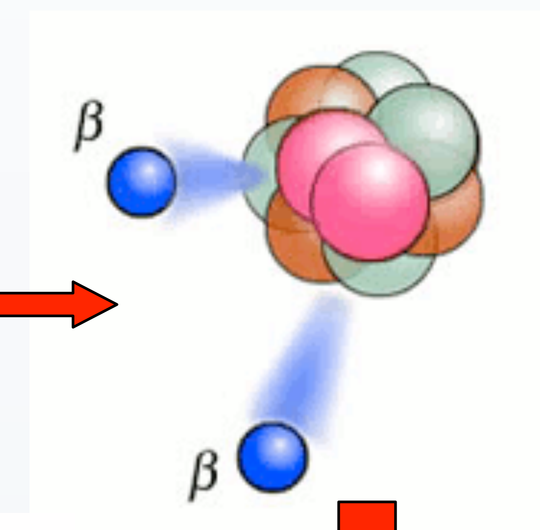
- Lepton number violation :
- Forbidden in Standard Model: $\Delta L = 2$
- Rate($0\nu\beta\beta$) « Rate($2\nu\beta\beta$)

Double-Beta Decay : Basic Signature

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







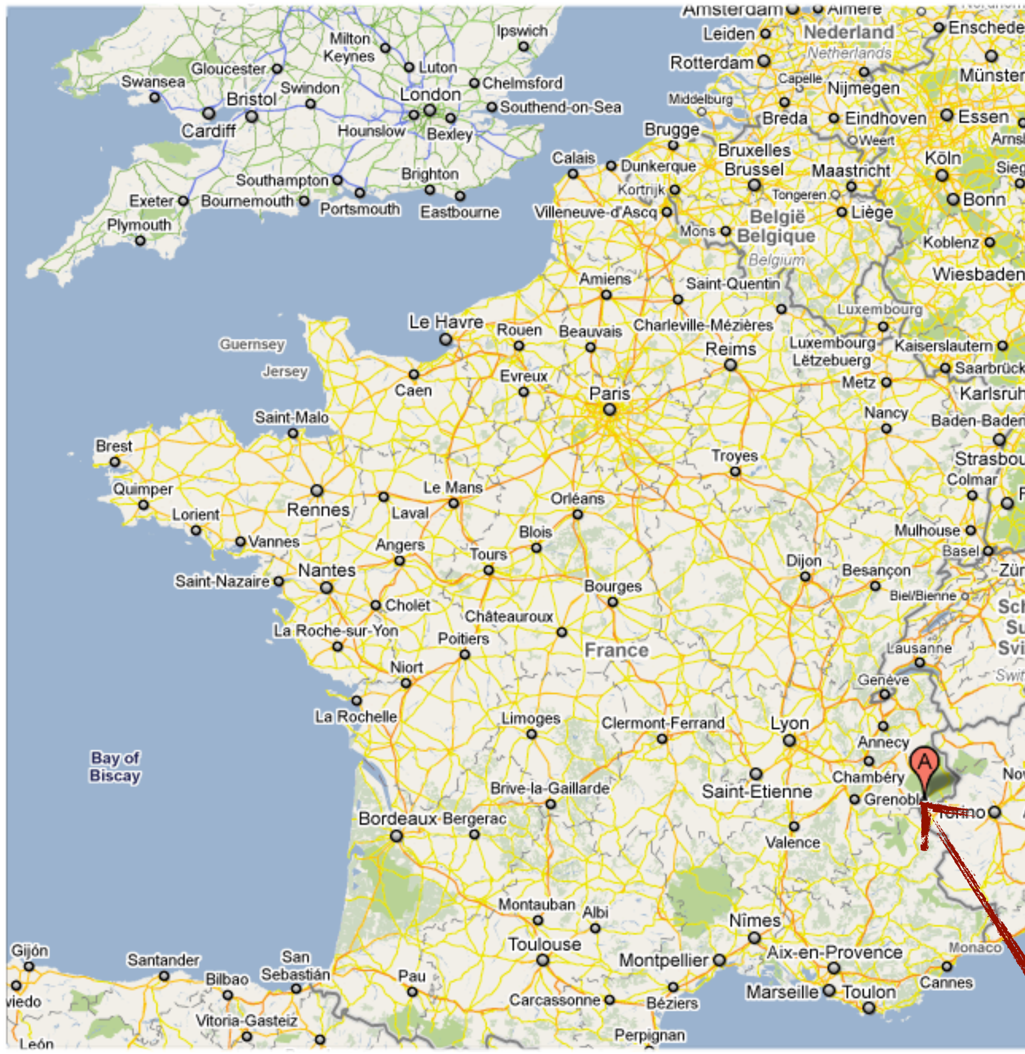
$(E_1+E_2)/Q_{\beta\beta}$

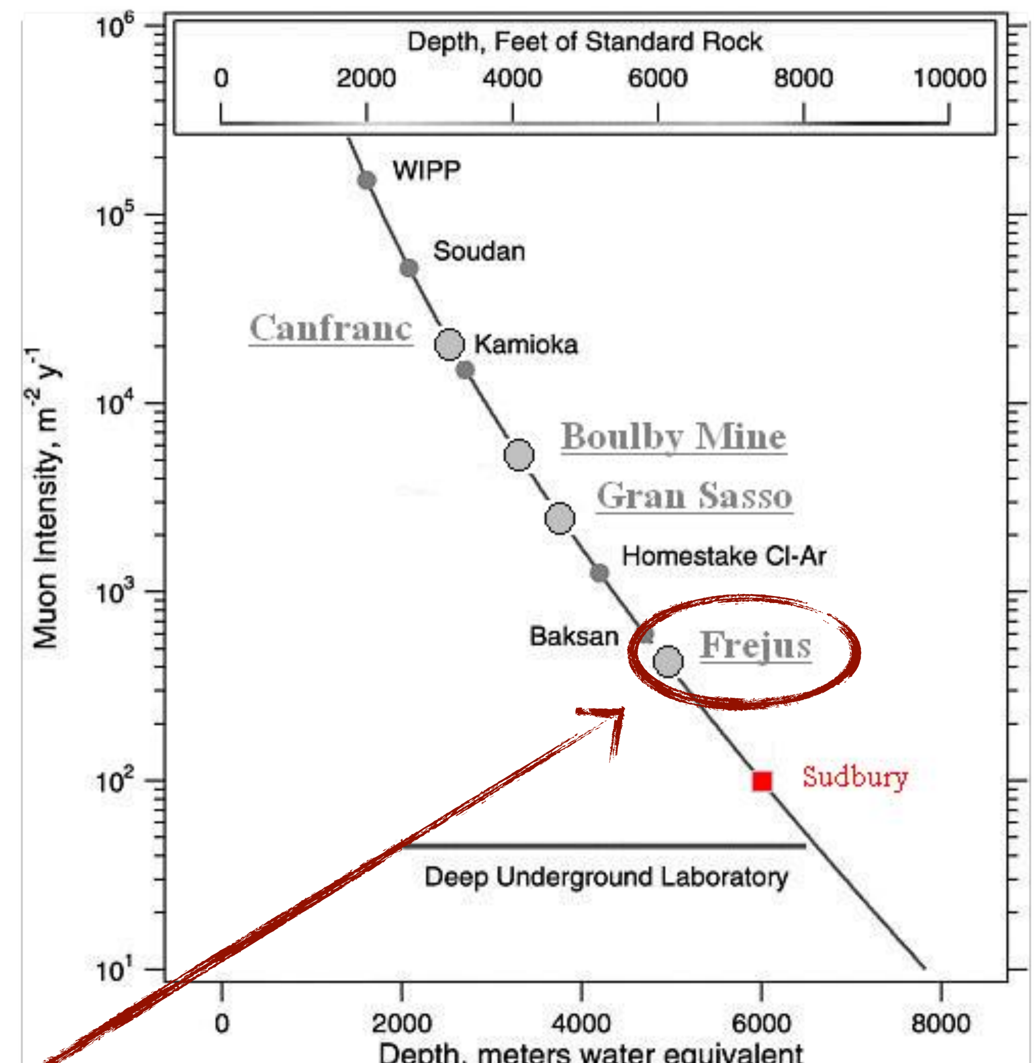
$$\left(E_1+E_2\right)\in\left[0,Q_{\beta\beta}\right]$$

$$\left(E_1+E_2\right)/Q_{\beta\beta}\approx 1$$

[⊗ resolution]

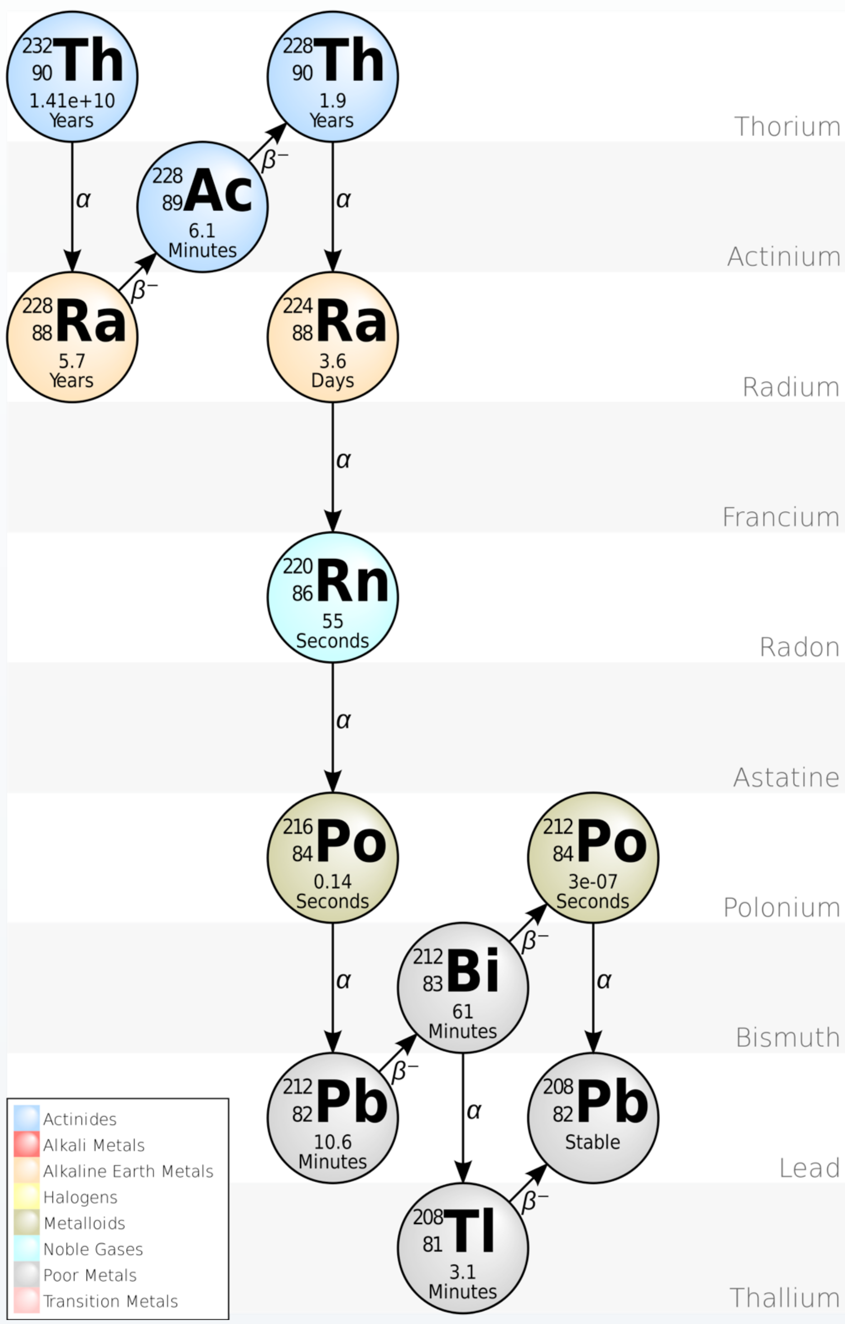
NEMO3

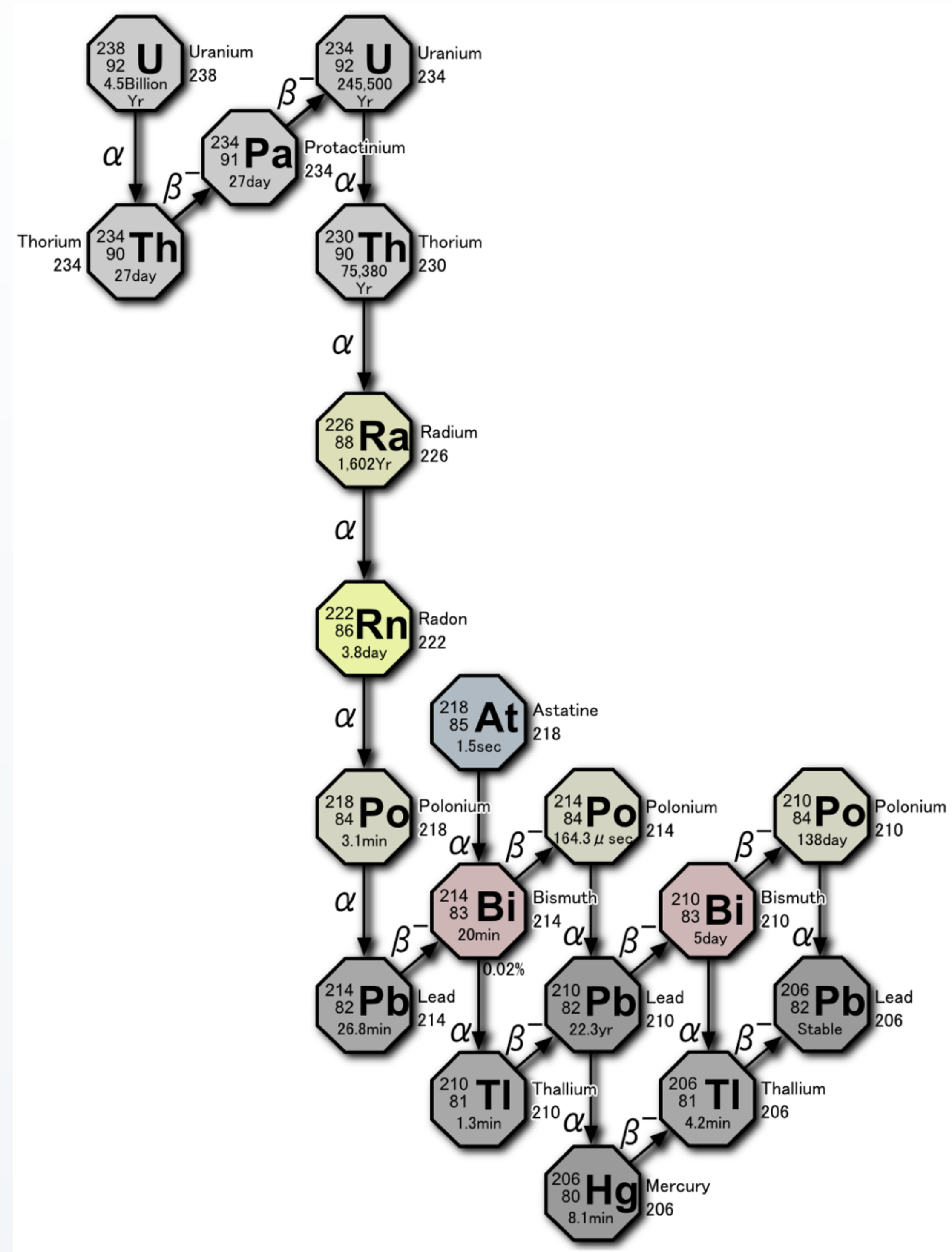




LSM Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

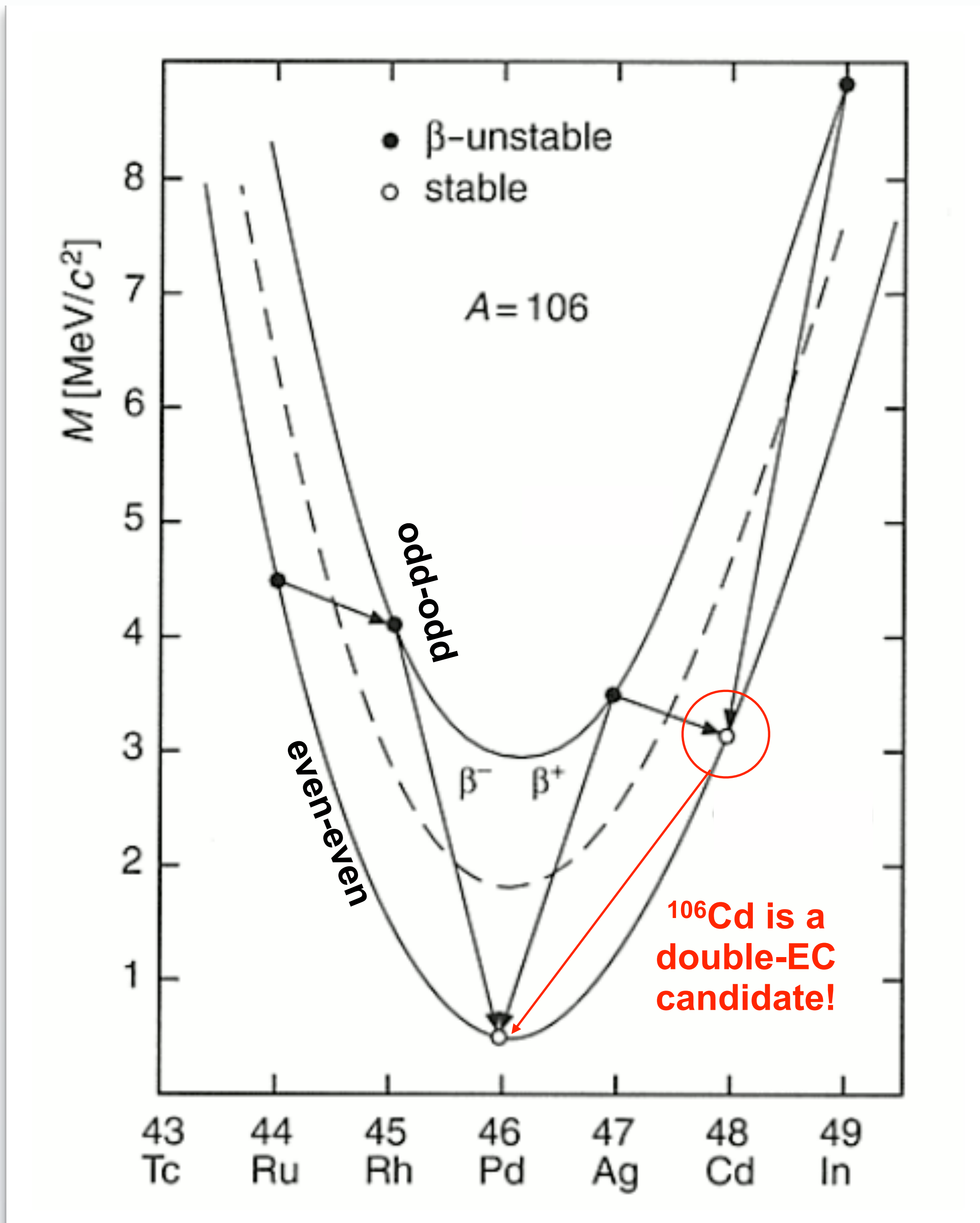
Th and U chains





Candidate isotopes :

Which Isotopes Can Double-Beta Decay ?



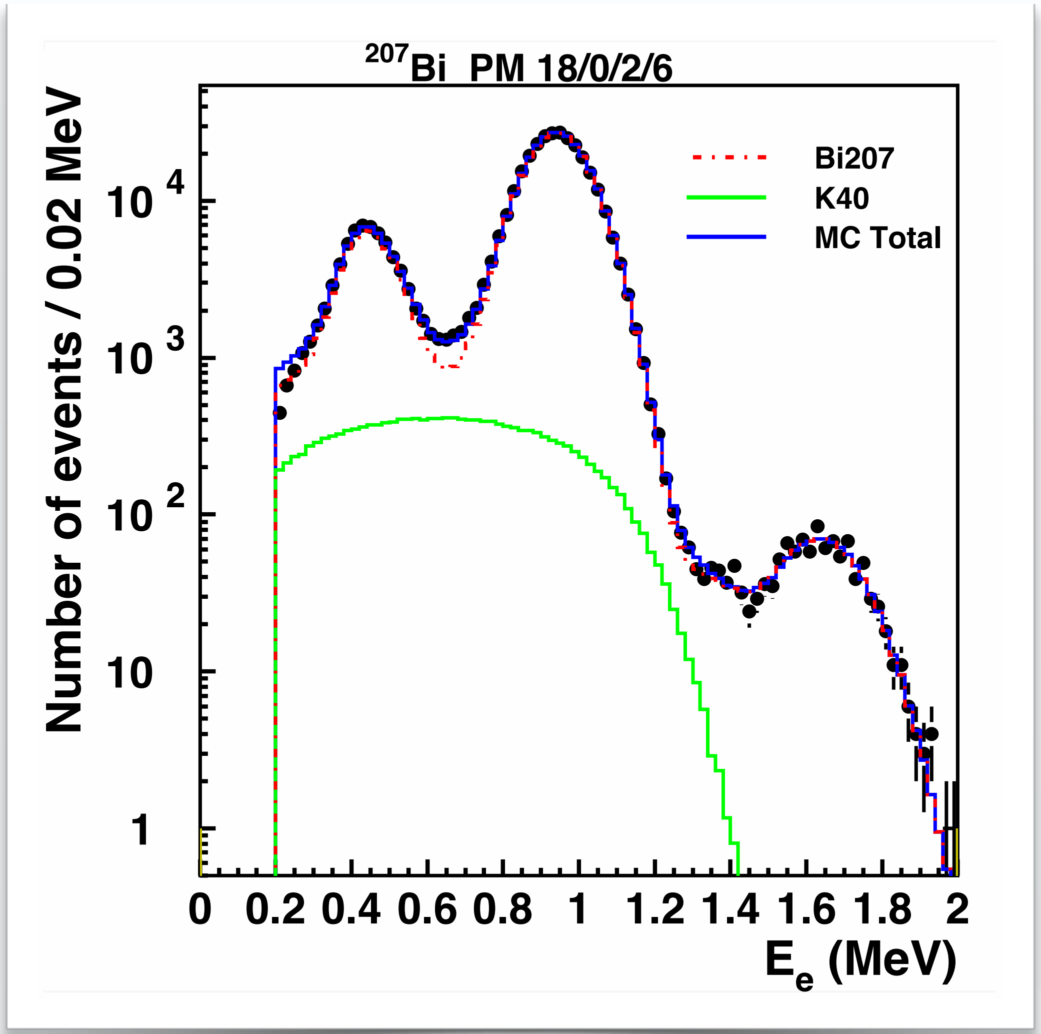
Isotope	$Q_{\beta\beta}$ (MeV)	Abundance (%)
^{48}Ca	4.276	0.19
^{76}Ge	2.039	7.8
^{82}Se	2.992	9.2
^{96}Zr	3.348	2.800
^{100}Mo	3.034	9.6
^{110}Pd	2.004	11.800
^{116}Cd	2.804	7.5
^{124}Sn	2.530	5.600
^{130}Te	2.529	34.5
^{136}Xe	2.467	8.9
^{150}Nd	3.368	5.6

more energetic decay: easier to separate from background

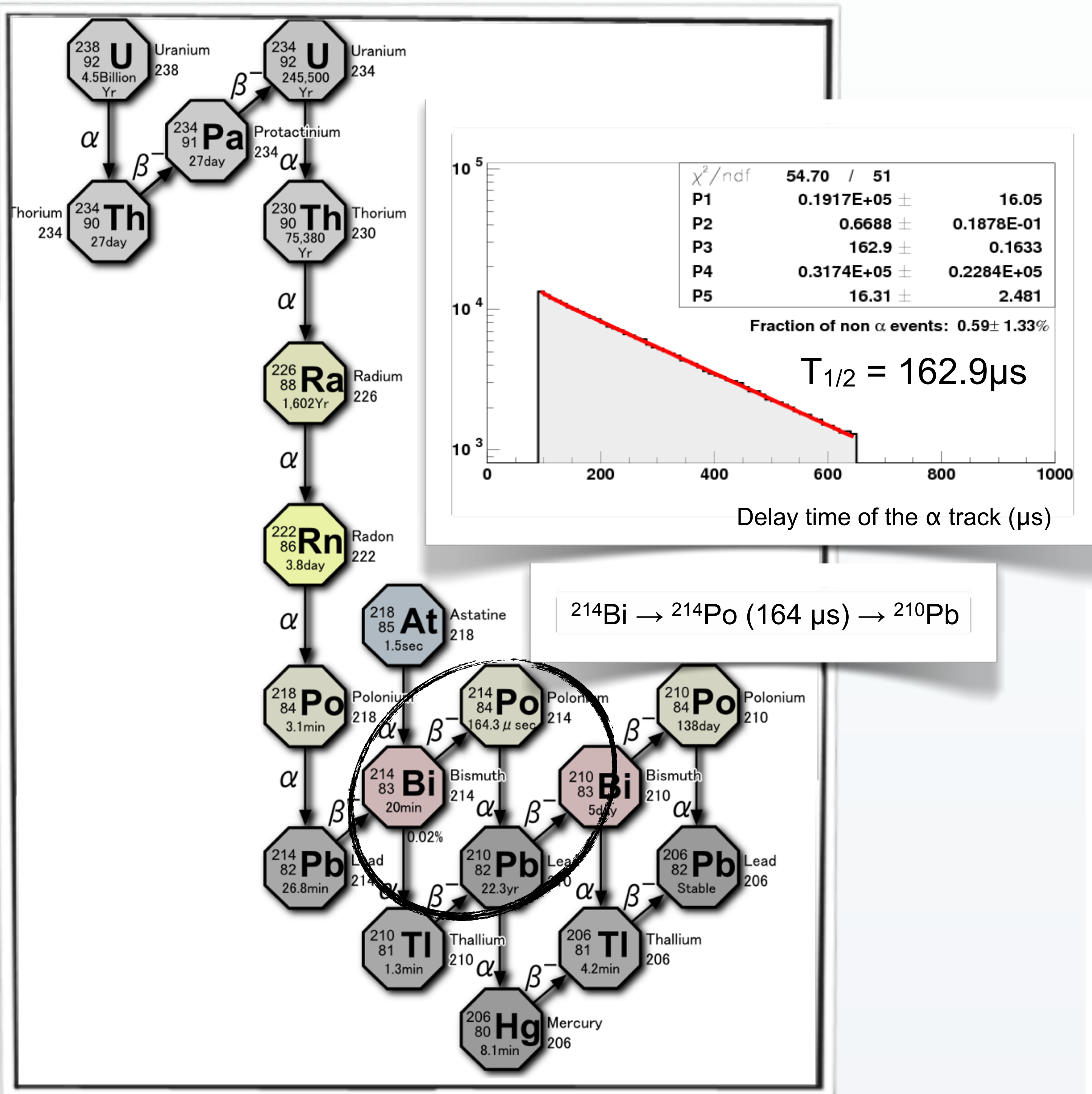
enrichment often possible, always expensive !

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}Tl in the foil: 10%
- gain variations are monitored during the day using light injection system, PMT showing large fluctuations are rejected

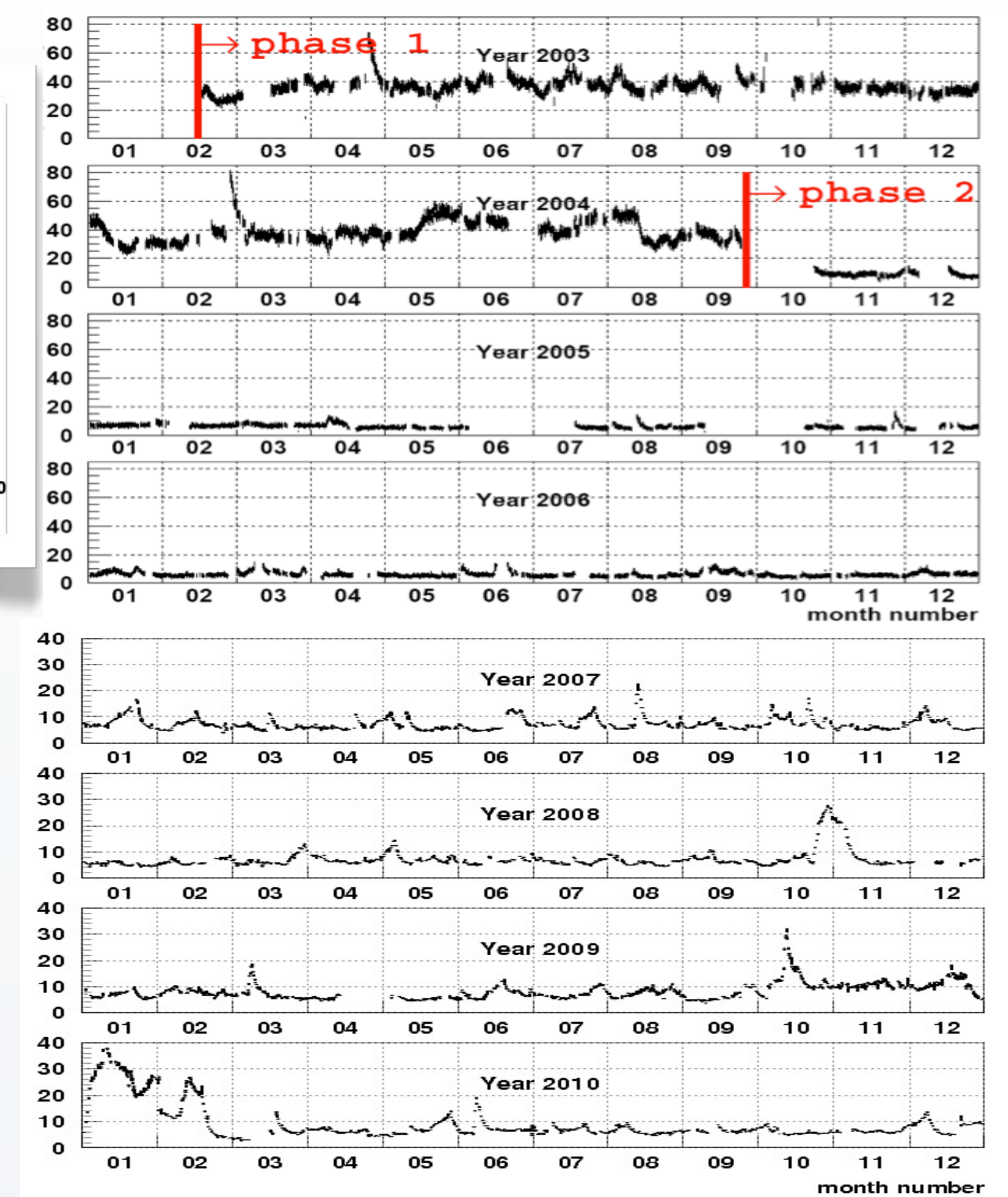


Background: Rn activity



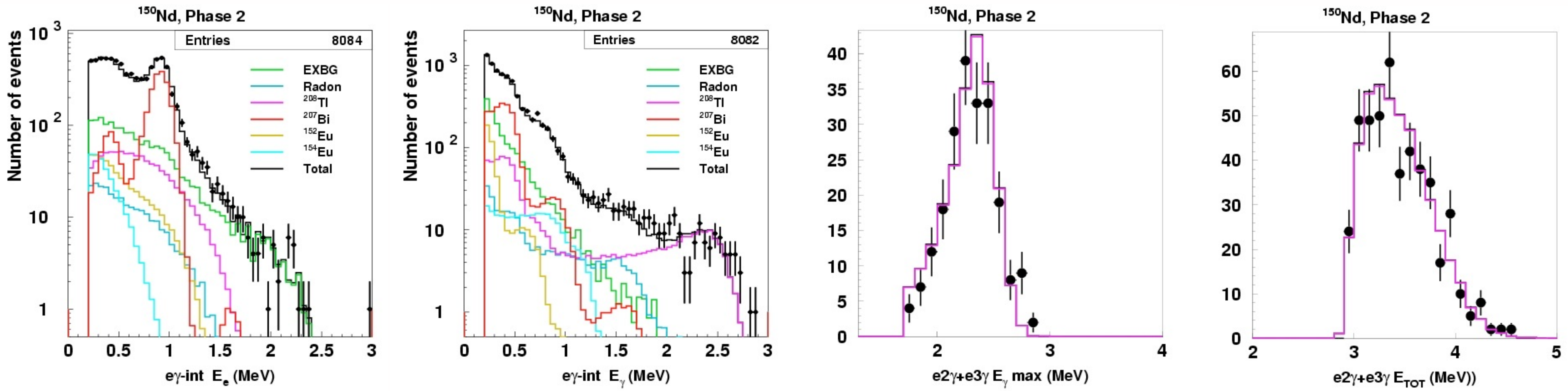
^{214}Bi → ^{214}Po (164 μs) → ^{210}Pb

Measurements of ^{222}Rn activity in the gas of tracker (mBq/m^3)

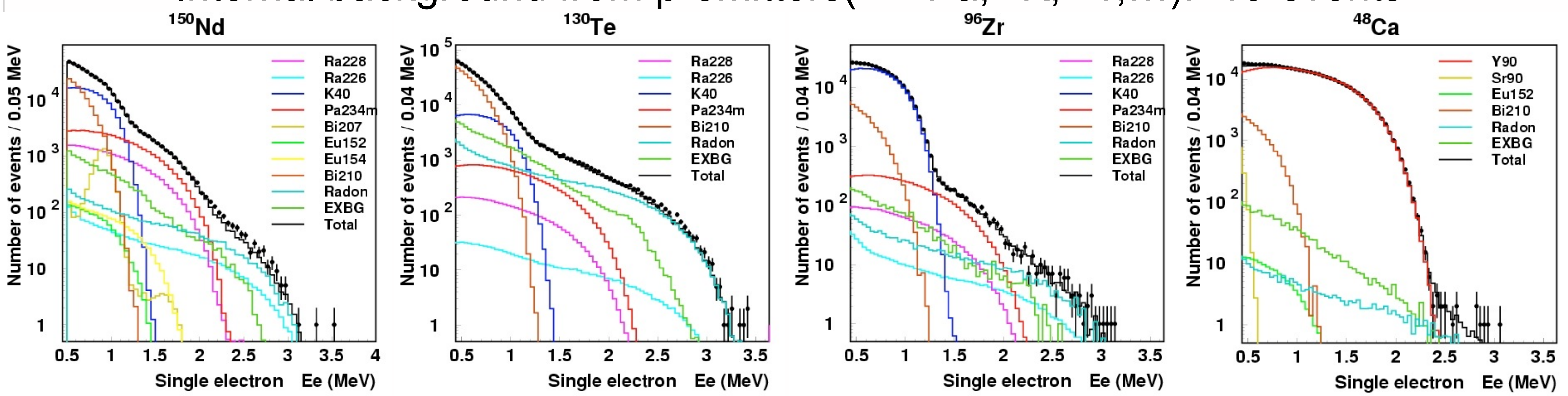


Internal Backgrounds measurements

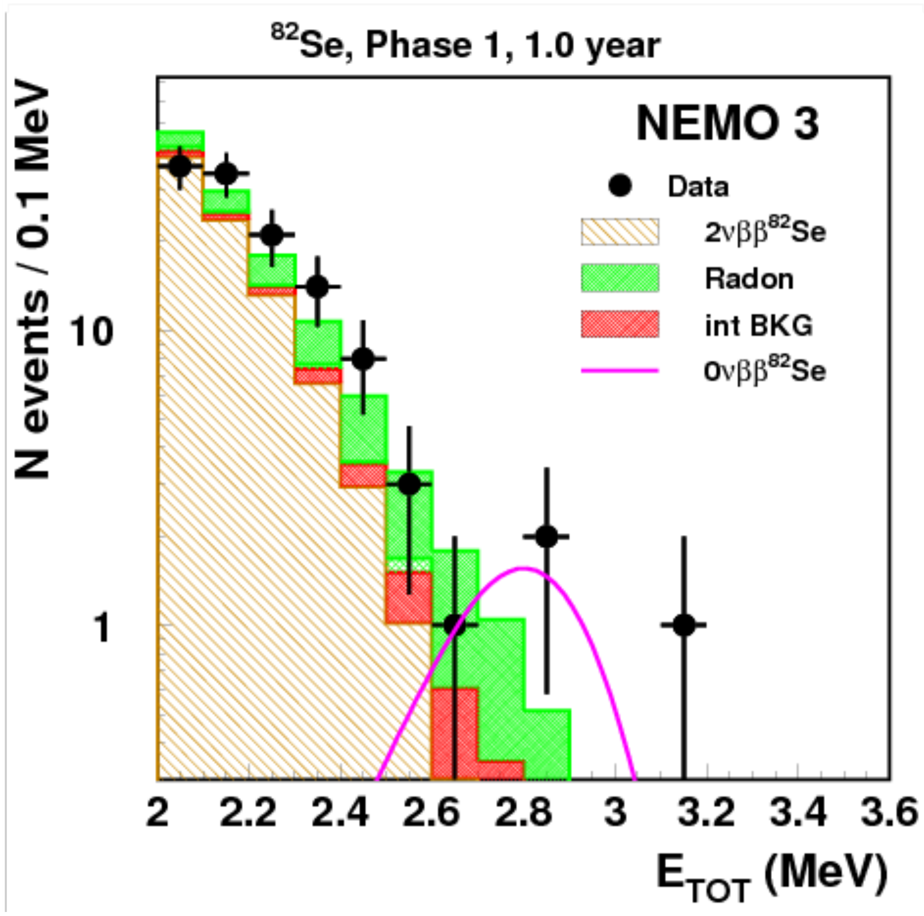
Internal background from ɣ-emitters(^{208}Tl,^{207}Bi,…): (eɣ,eɣɣ,eɣɣɣ)-events

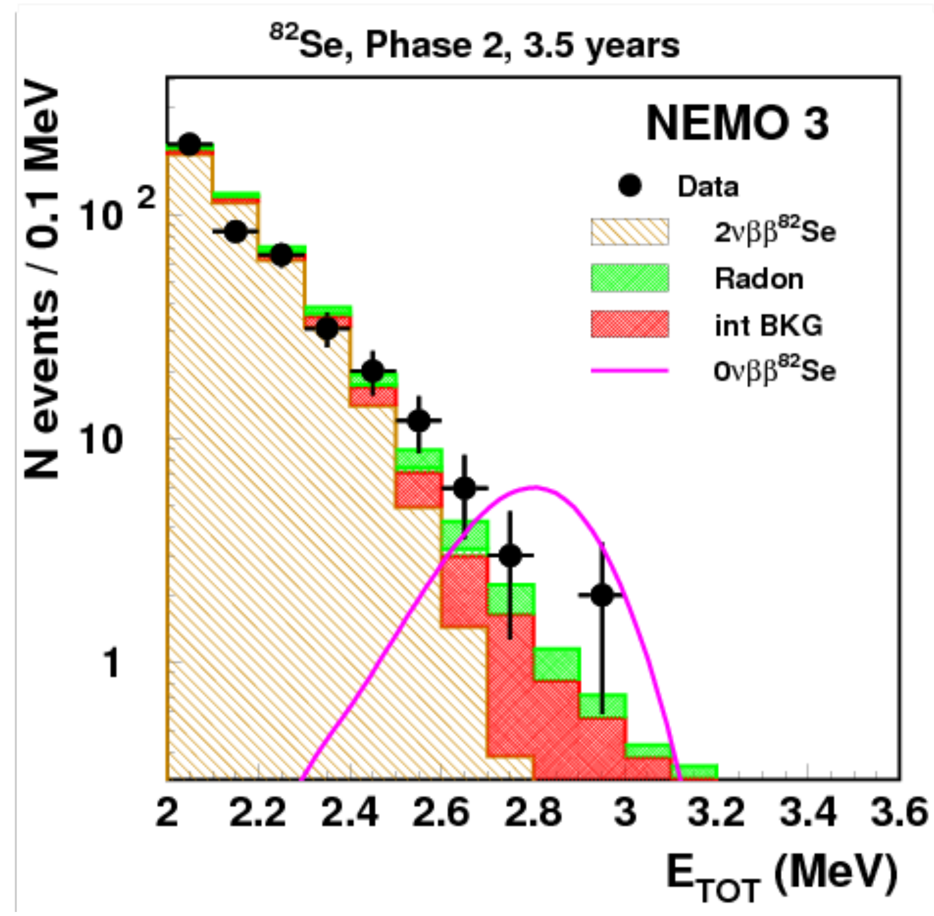


Internal background from β-emitters(^{234m}Pa,^{40}K,^{90}Y,…): 1e-events



Search for 0νββ with ^{82}Se





[2.6 , 3.2] MeV:
ε(0ν) = 0.105
Tot MC= 3.8±0.5 , Data: 4 events
MC 2vbb = 0.4±0.1
MC radon = 2.4±0.4
MC int bkg=1.0±0.2 (^{214}Bi=0.55,^{208}Tl=0.42)

[2.6 , 3.2] MeV:
ε(0ν) = 0.118
Tot MC= 7.3±0.8 , Data: 10 events
MC 2vbb = 1.5±0.4
MC radon = 2.0±0.3
MC int bkg=3.8±0.6 (^{214}Bi=2.2,^{208}Tl=1.6)

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

^{100}Mo 2β2ν decay to excited states

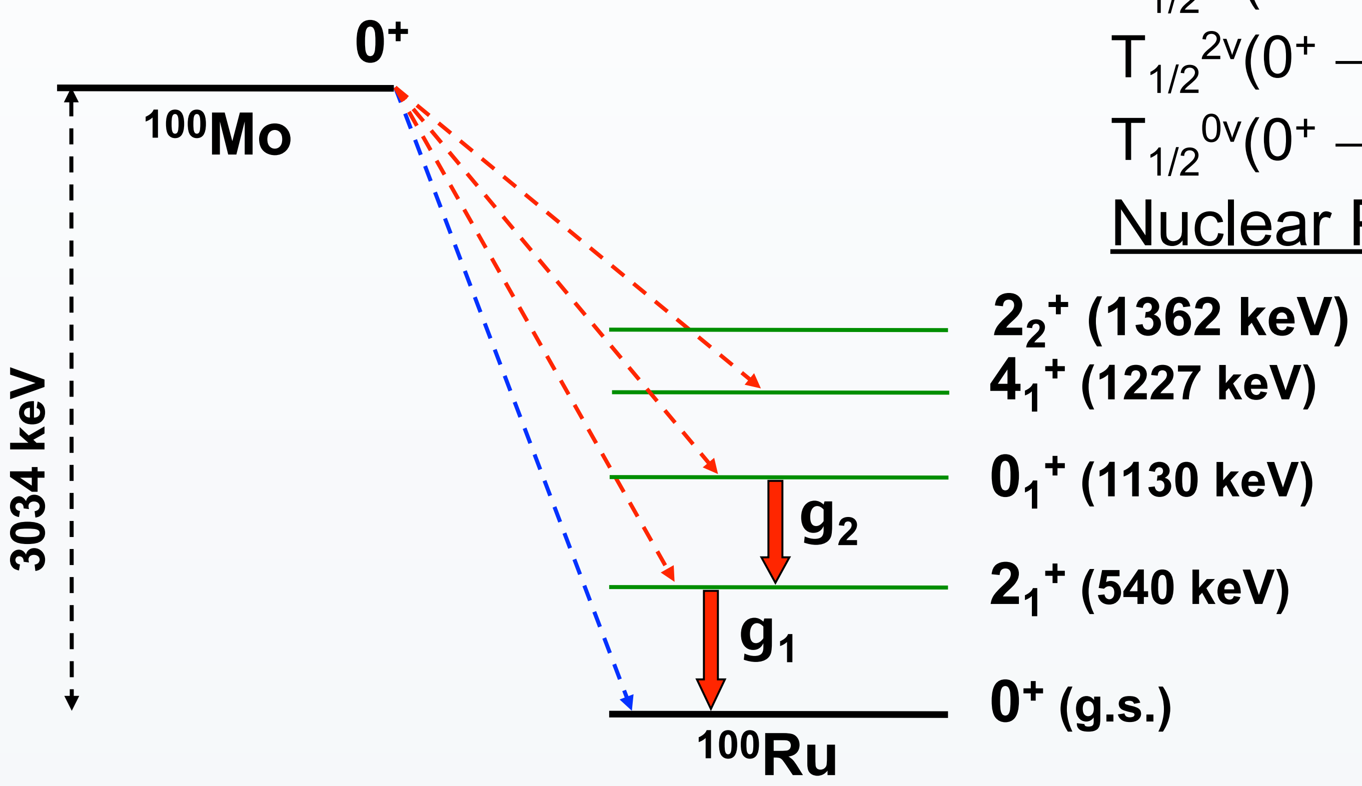
$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1)$ = $5.7^{+1.3}_{-0.9}$ (stat) ± 0.8 (syst) × 10^{20} y

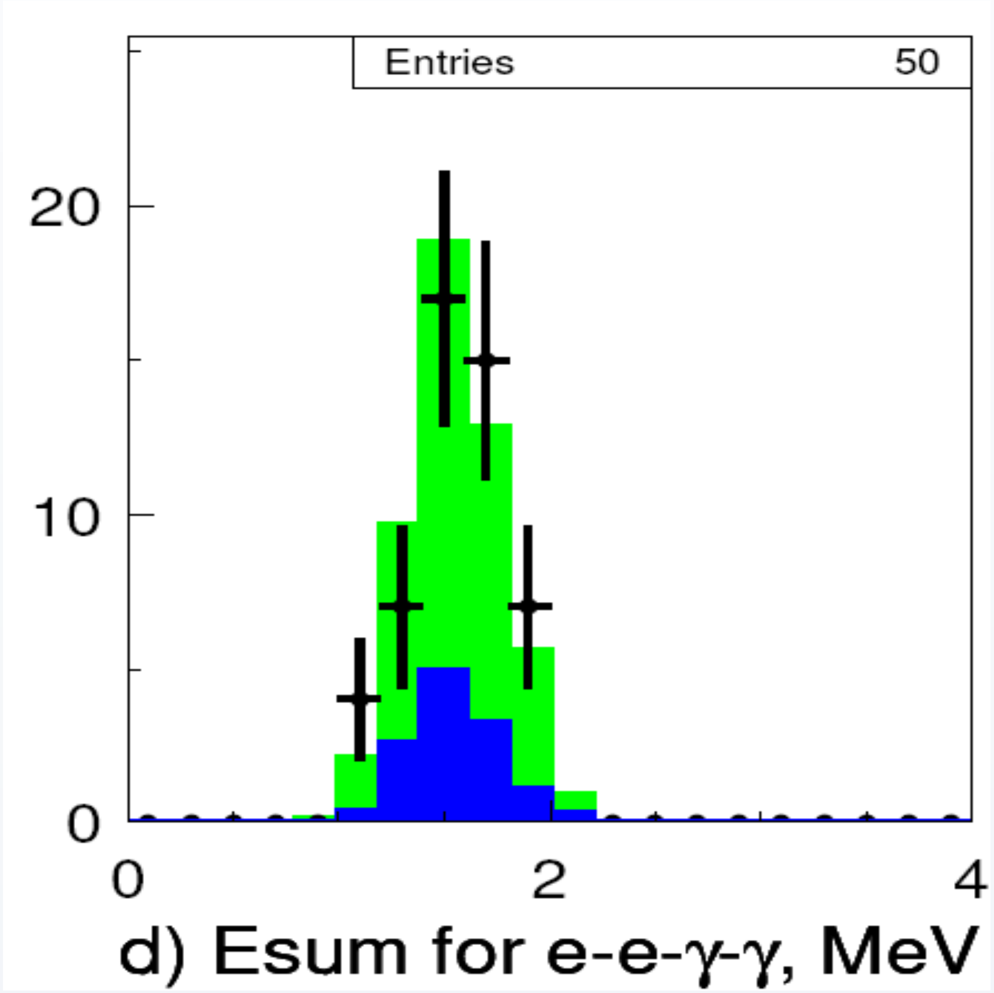
$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1)$ > 8.9 x 10^{22} y @ 90% C.L.

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

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

Nuclear Physics A781 (2007) 209-226.



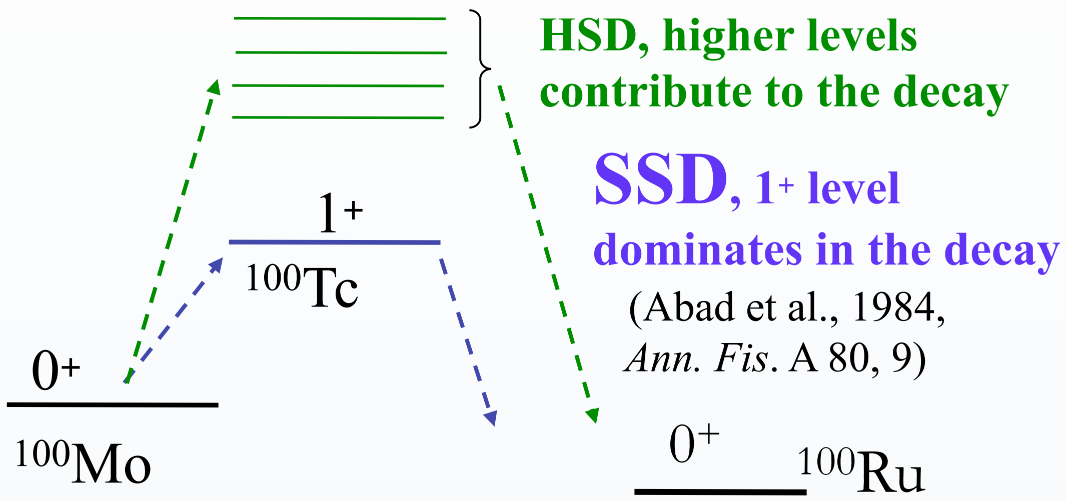


Event topology:

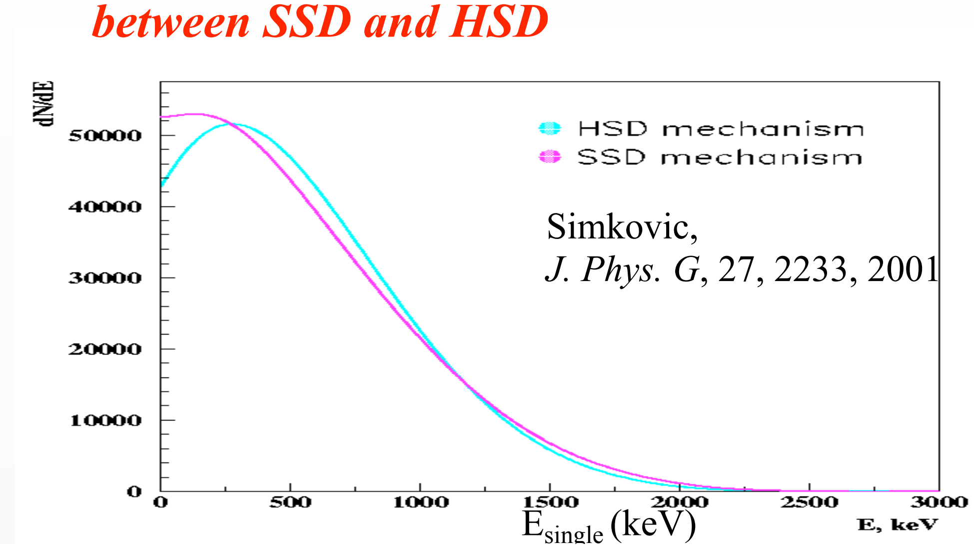
0_1^+: $2e^-$ + 2g in time & energy and TOF cuts

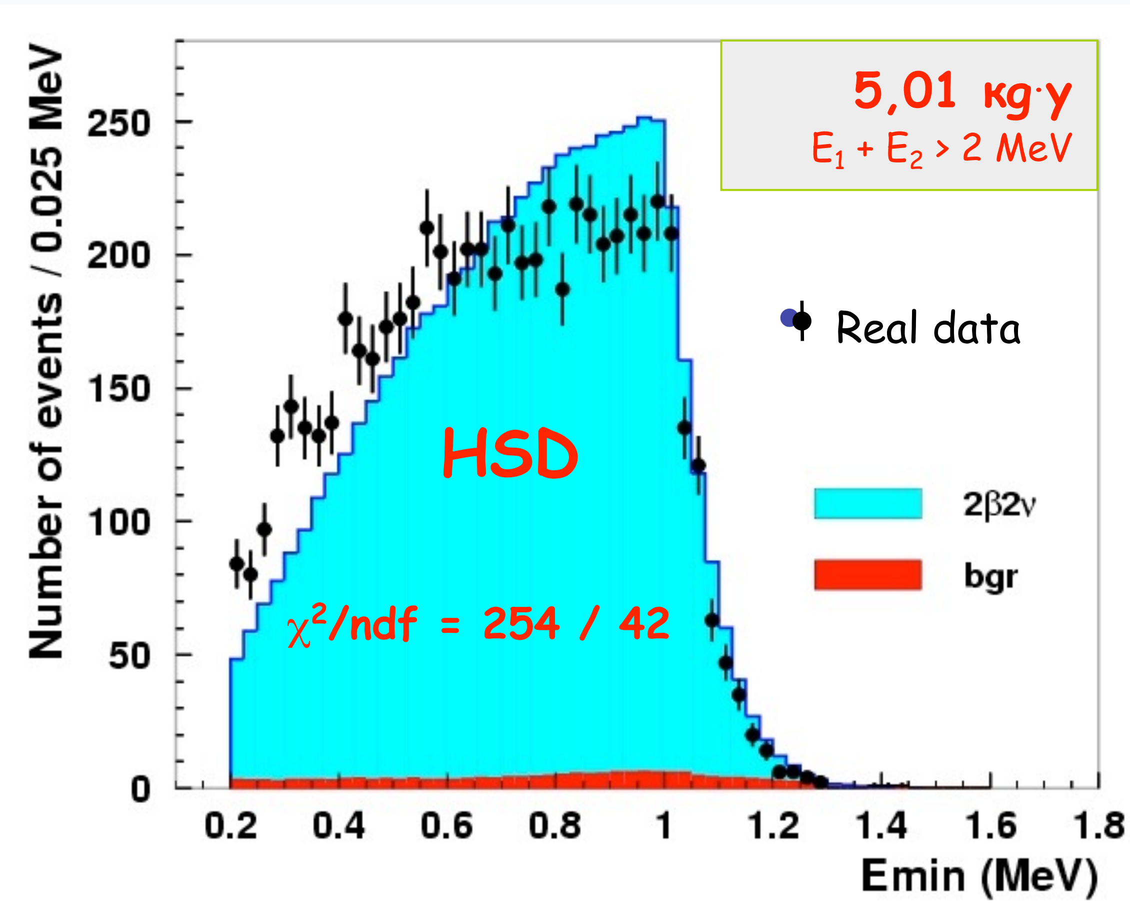
2_1^+: $2e^-$ + 1g in time & energy and TOF cuts

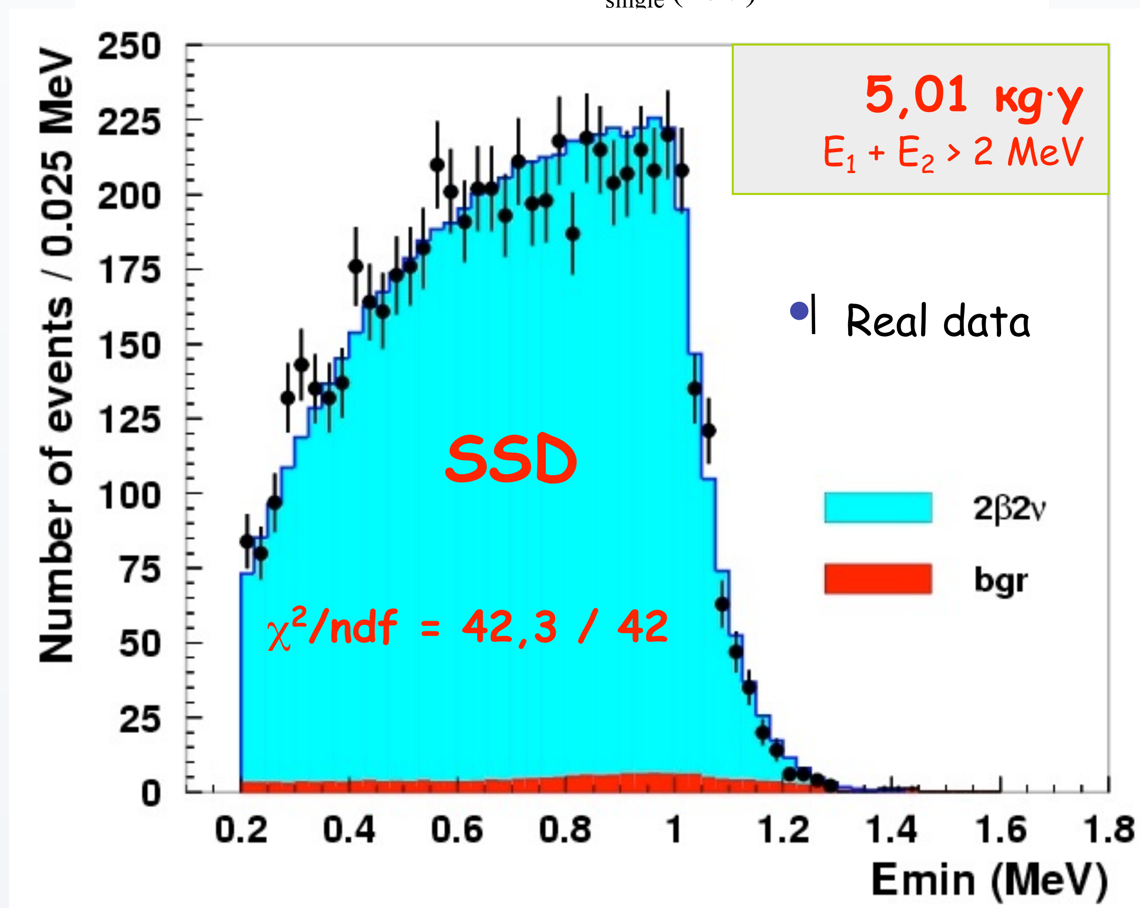
SSD/HSD 2νββ (^{100}Mo)



Single electron spectrum different between SSD and HSD







Electron energy distribution in 2β2ν decay of ^{100}Mo is in favour of Single State Dominance (SSD)