Double Beta Decay Experiments

Maura Pavan
Università di Milano Bicocca
Milano - Italy

Outline

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- introduction
- DBD and neutrino mass
- NME
- decay signature
- detector choice
- experimental sensitivity
- background sources

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- NEMO3
- Cuoricino

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- on-going: GERDA – CUORE – EXO ...
- proposed ...
- conclusions

Part1.

Double Beta Decay

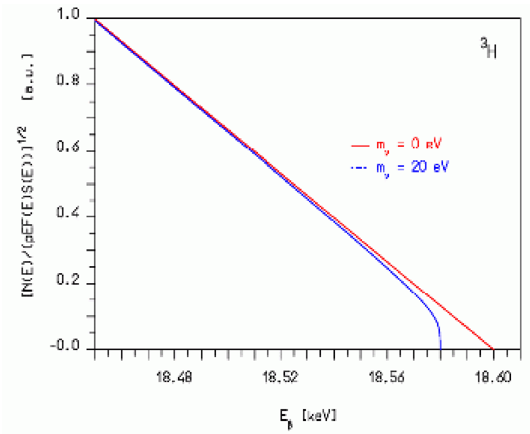
and Majorana neutrino

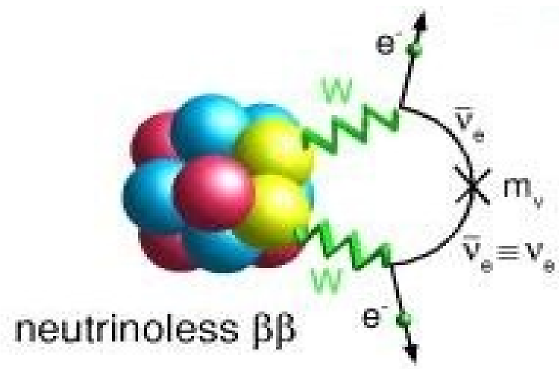
<< There are several categories of scientists in the world; those of second or third rank do their best but never get very far. Then there is the first rank, those who make important discoveries, fundamental to scientific progress. But then there are the geniuses, like Galilei and Newton. Majorana was one of these.

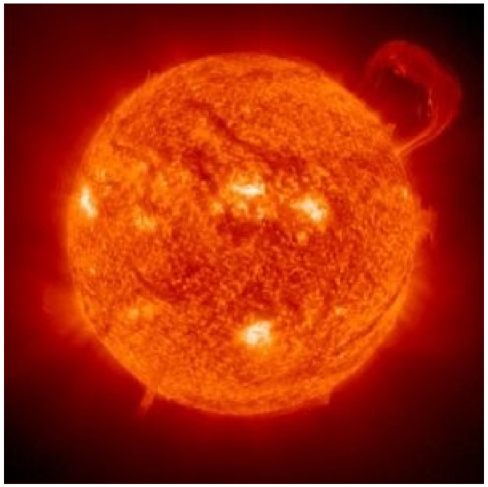
Majorana had what no-one in the world had. Unfortunately he lacked what other people generally have: common sense >>

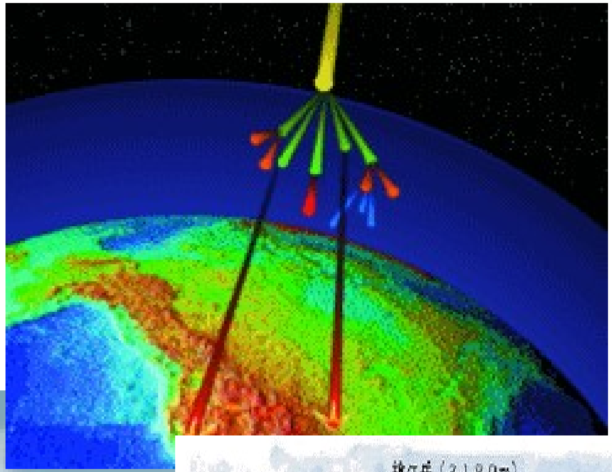
(Enrico Fermi)

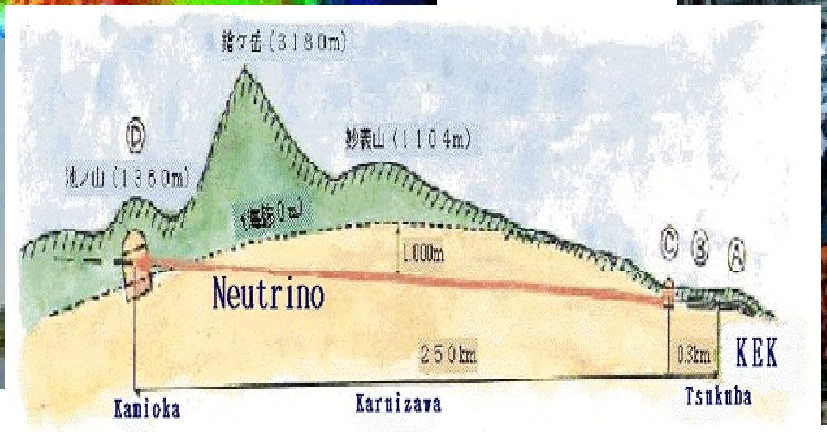
Introduction: *the "neutrino industry"*

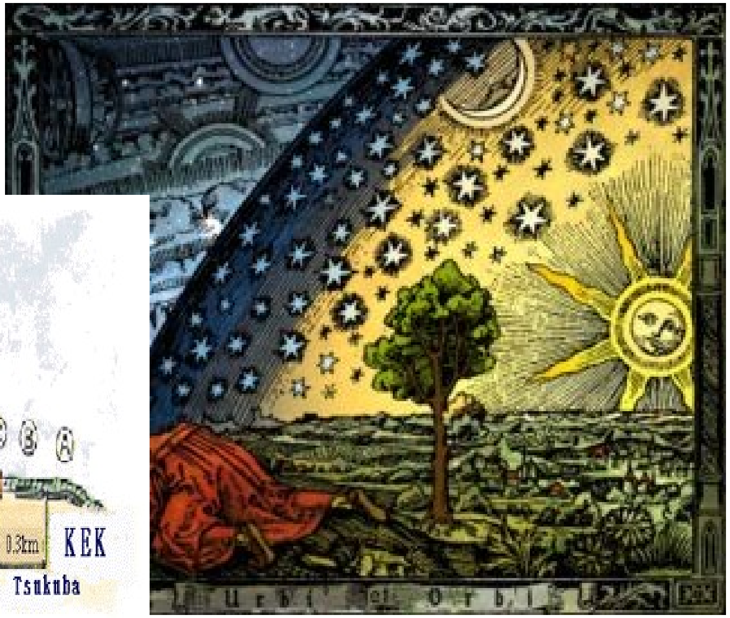












the "neutrino industry": proves mixing and masses

ν oscillations are a reality, we have distinguishable eigenvalues for:

flavor ν_e ν_μ ν_τ

mass ν_1 ν_2 ν_3

neutrino matrix is not diagonal:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

we can experimentally measure the values of the matrix elements

Atmospheric + K2K | Reactors (CHOOZ), Accelerators (JPARC) | Solar + Reactors

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

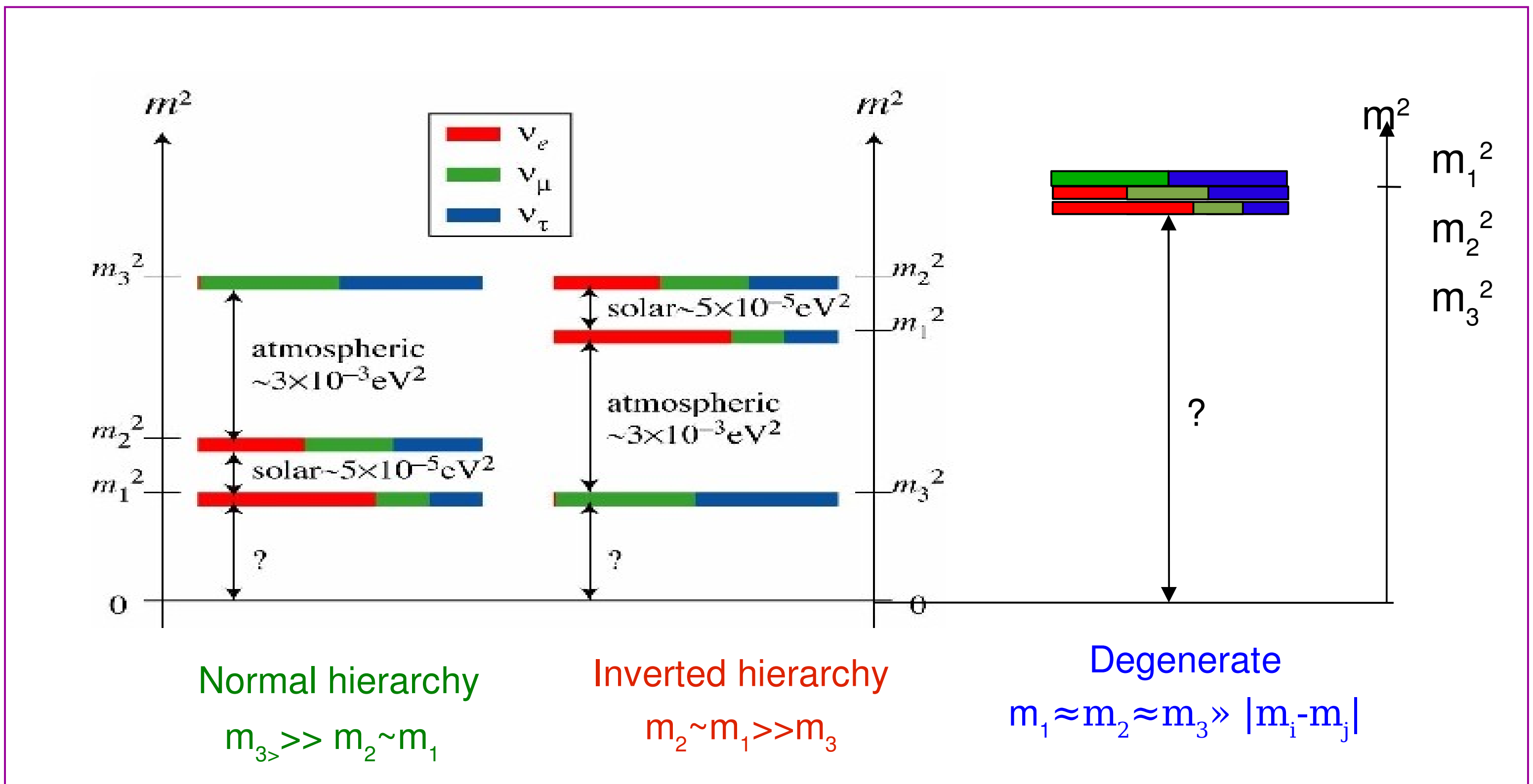
$\theta_{23} \sim 45°$ | $\theta_{13} <\sim 13°$ δ_{CP}= CP violation | $\theta_{12} \sim 30°$ | α,β : Majorana phase

the "neutrino industry": proves mixing and masses

... and measure Δm^2

$\nu_\mu \rightarrow \nu_\tau$ $\Delta m^2_{23} \sim 2.\ 10^{-3}\ eV^2$

$\nu_e \rightarrow \nu_\mu$ $\Delta m^2_{12} \sim 5.\ 10^{-5}\ eV^2$



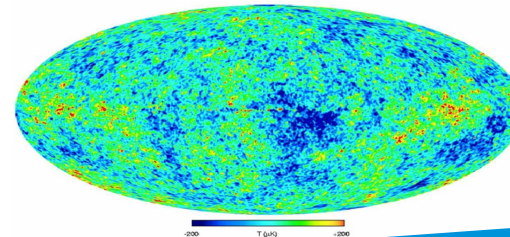
“how to measure the mass?”

Cosmology

$\Sigma = m_1 + m_2 + m_3$

simple sum

pure kinematic effect

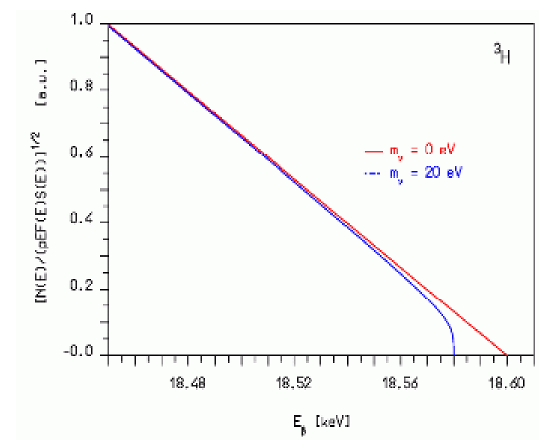


Beta decay

$m_{\nu e} = (\Sigma |U_{ei}|^2 m_i^2)^{1/2}$

incoherent sum

real neutrino



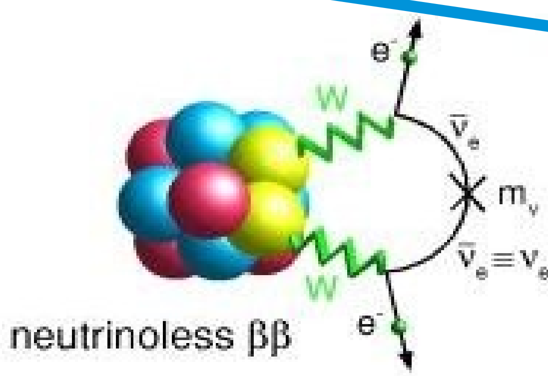
Double Beta Decay

$|<m_\nu>| = |\Sigma U_{ei}^2 m_i|$

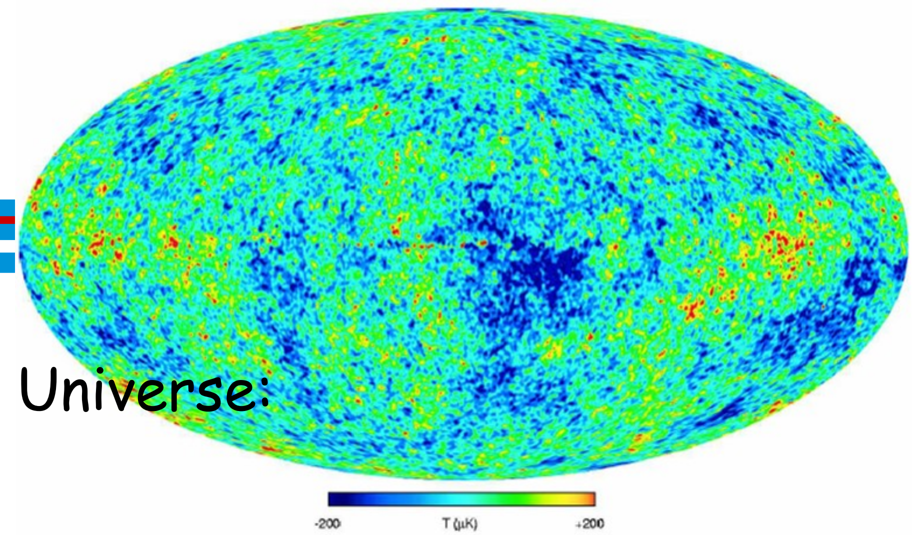
coherent sum

virtual neutrino

Majorana phases



Astrophysical bounds:



ν contribute to the energy density of our Universe:

$$O_\nu h^2 \sim \Sigma / 94 \text{ (eV)}$$

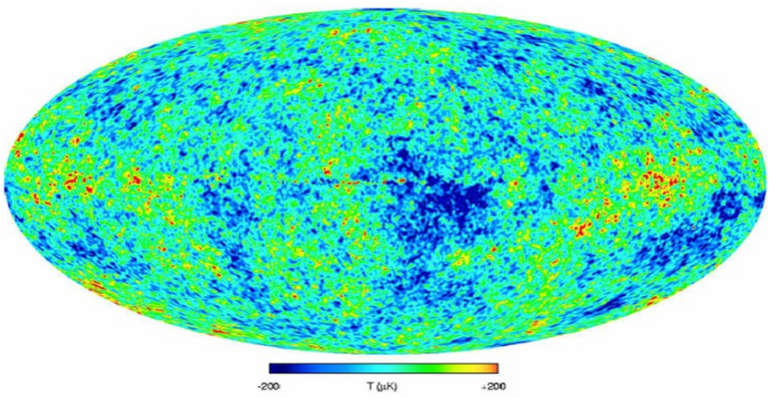
they influence various astronomical observables:

- CMB (Cosmic Microwave Background) power spectrum
- LSS (Large Scale Structures) matter distribution reconstructed by redshift survey of galaxies
- Ly-α (Lyman α) distant quasars light absorbed at Ly-α frequency by intervening matter
- ...

BUT

the upper bounds on Σ depend on data set included, priors and statistical treatments

Astrophysical bounds:



(1) Σ < 1:3 eV (WMAP5)

(2) Σ < 1:19 eV (WMAP5+ACBAR+VSA+CBI+BOOMERANG)

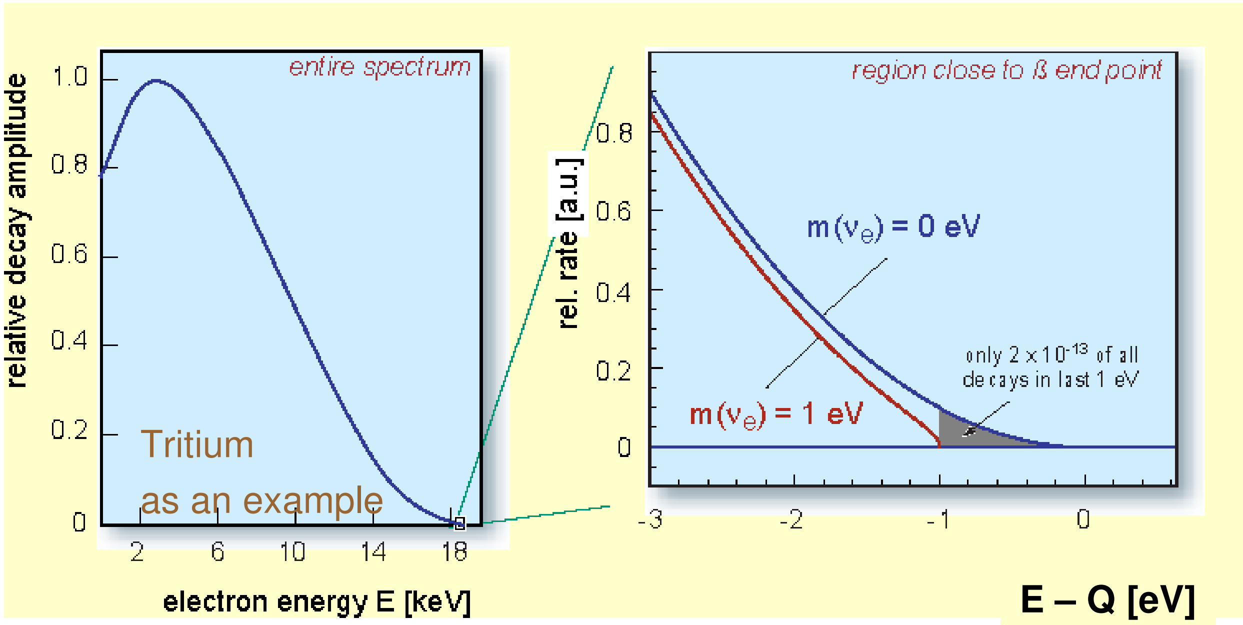
(3) Σ < 0:75 eV (CMB+HST+SN-Ia)

(4) Σ < 0:60 eV (CMB+HST+SN-Ia+BAO)

(5) Σ < 0:19 eV (CMB+HST+SN-Ia+BAO+Ly)

[Fogli et al., arXiv:0805.2517]

Direct measurements: deformation of Kurie plot



Tiny effect due to finite neutrino mass:

$\sim (m_\beta c^2/Q)^3$

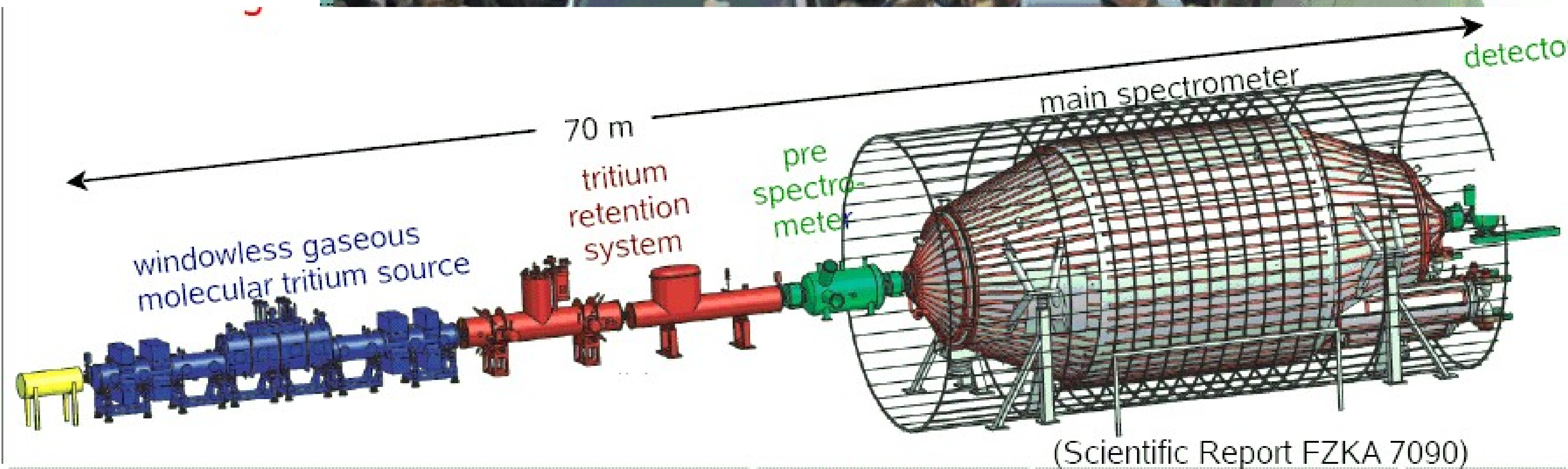
Mass sensitivity:

$m_\beta \sim \{Q^3 \Delta E / A\ T\}^{1/4}$

Present limit	= 2.3 eV (Mainz, Troitzk spectrometers)
Near future	= 0.2 eV (Katreen spectrometer)
Far future	= beyond 0.1 eV with bolometers ???

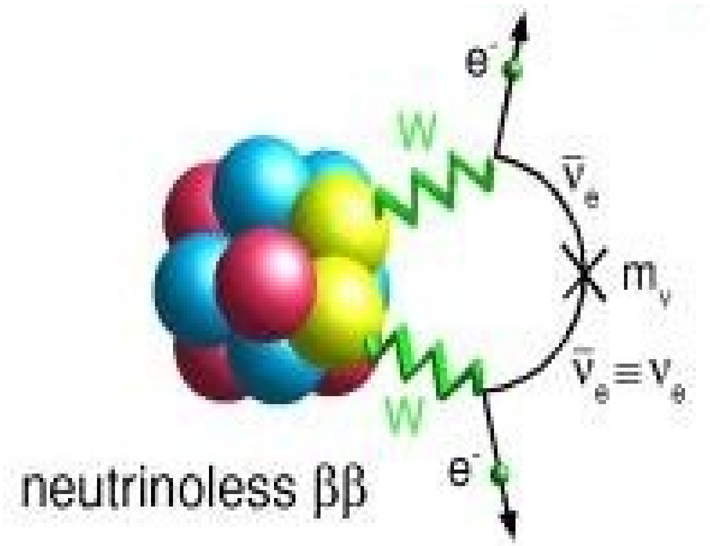
Bolometers use ^{187}Re (Q=2.47 keV τ=43 Gyr)
to go beyond 0.2 eV
they require technological improvement
accurate calculation of ^{187}Re beta spectrum

KATRIN


70 m
detecto
main spectrometer
pre
spectro-
meter
tritium
retention
system
windowless gaseous
molecular tritium source
(Scientific Report FZKA 7090)

Direct measurement: neutrinoless double beta decay

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



Phase space factor

Nuclear matrix element

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

Effective Majorana mass

$0\nu\beta\beta$ allow to study ν properties and measure n mass

BUT

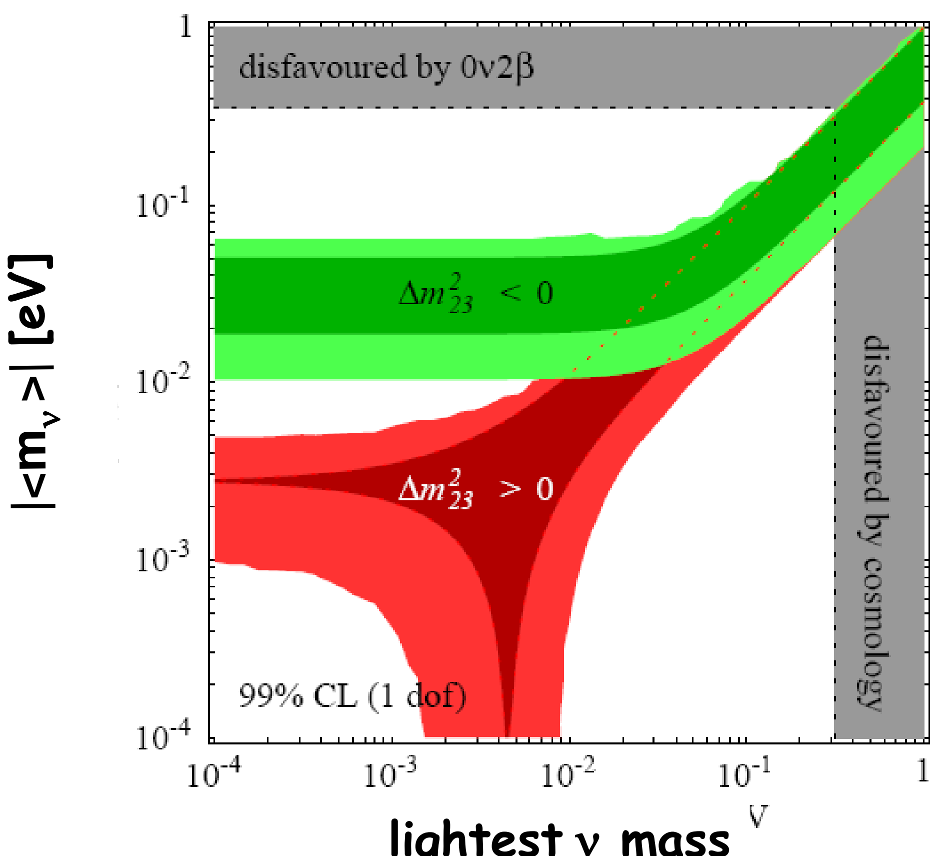
ν mass can be extracted from $T_{1/2}$ ONLY after $|M|^2$

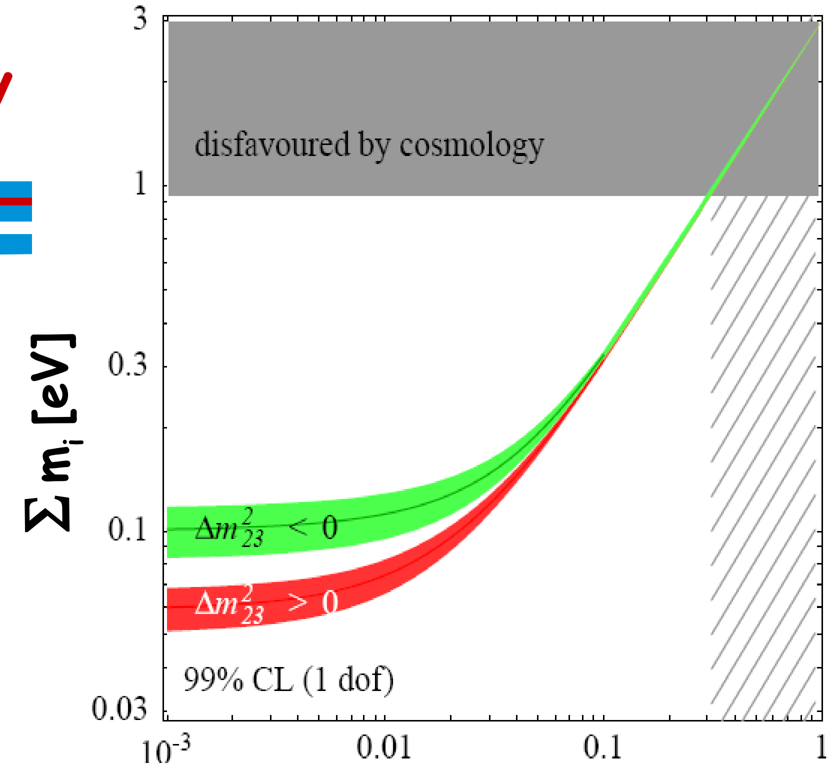
mass sensitivities compared: TODAY

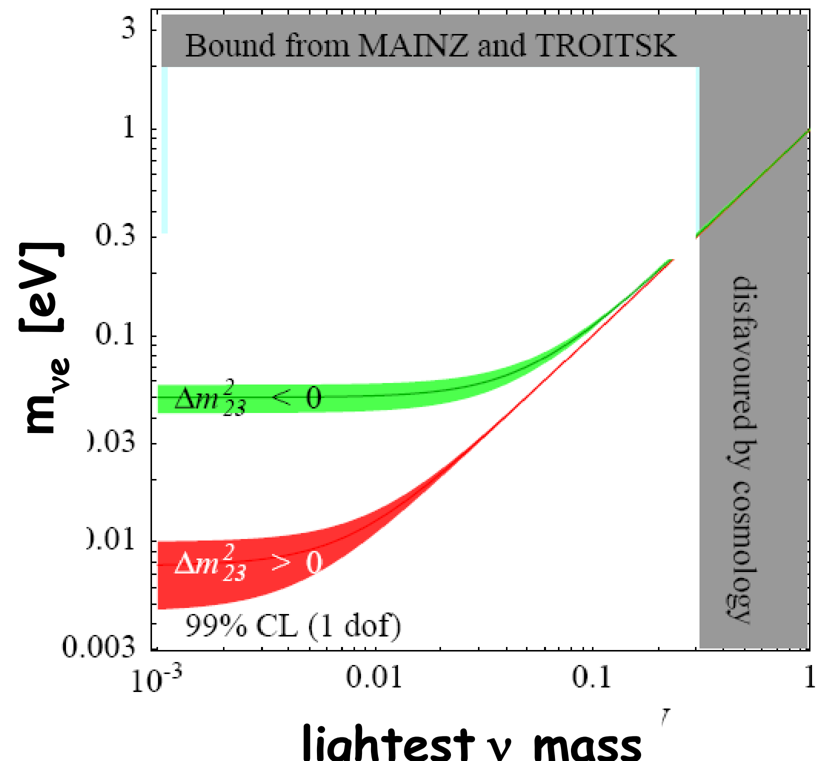
Cosmology $\Sigma m_i = m_1+m_2+m_3 \quad \leq 1$ eV

Beta decay $m_{\nu e} = (\Sigma\, |U_{ei}|^2\, m_i^{\,2})^{1/2} \quad < 2.3$ e

Double Beta Decay $|\langle m_\nu \rangle| = |\Sigma\, U_{ei}^{\,2}\, m_i| \quad \leq 2.3$ eV





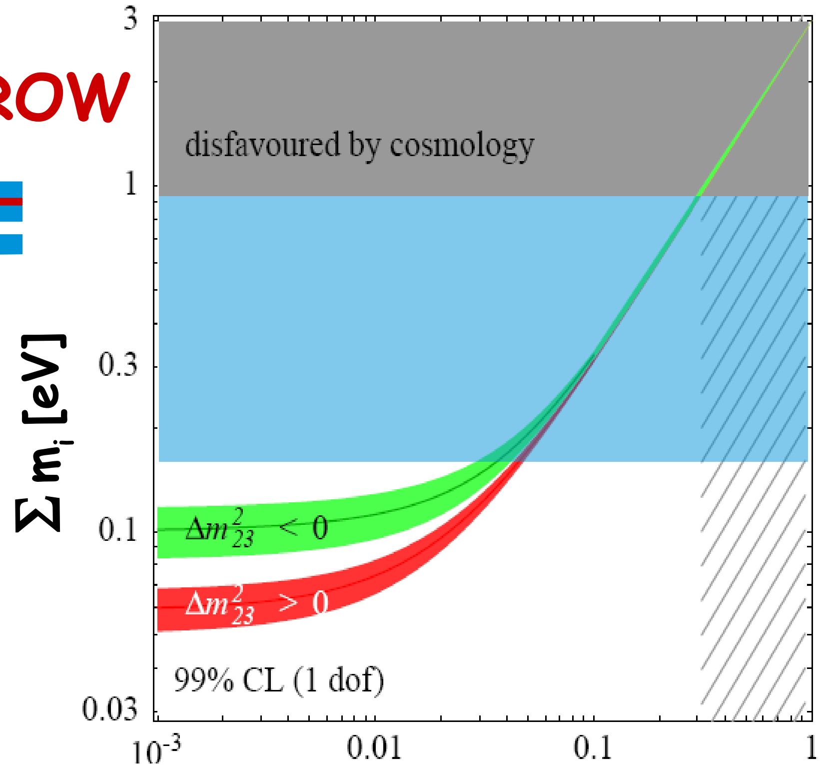


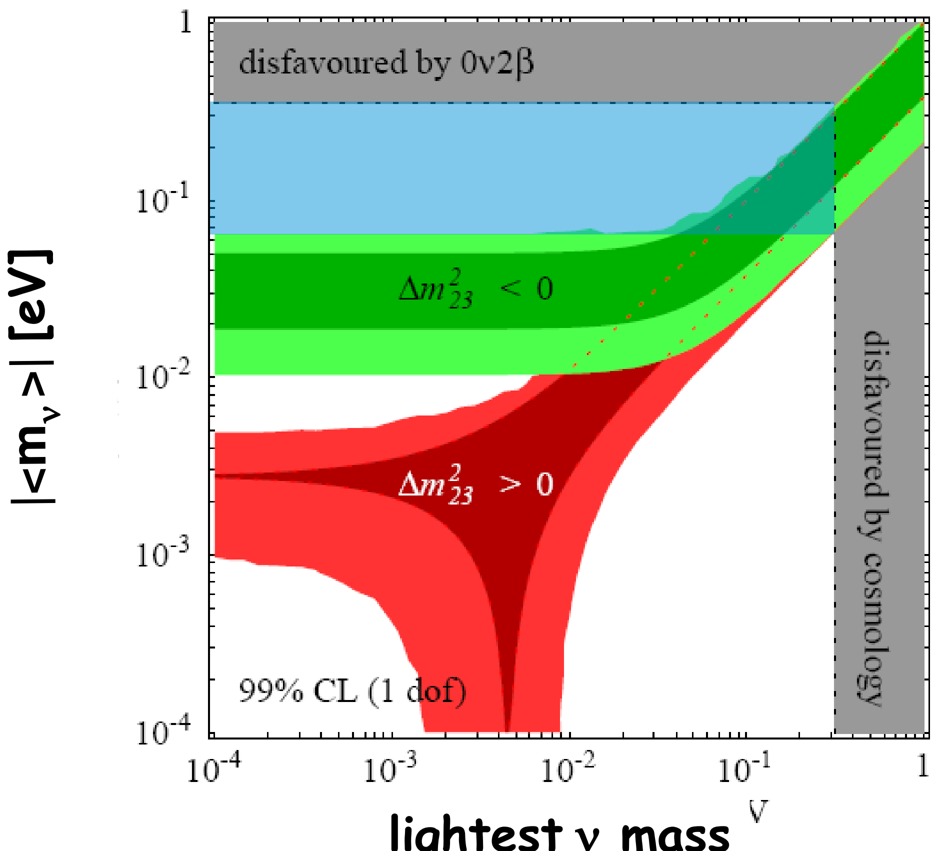
mass sensitivities compared: TOMORROW

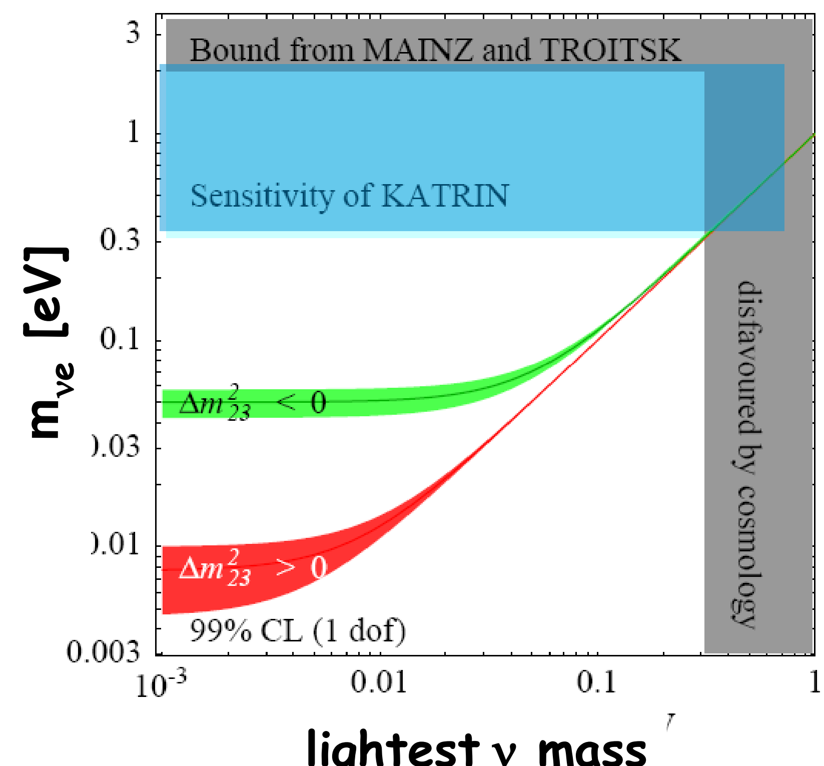
Cosmology $\Sigma m_i = m_1+m_2+m_3 \leq 0.1$ eV

Beta decay $m_{\nu e} = (\Sigma |U_{ei}|^2 m_i^2)^{1/2} < 0.3$ e

Double Beta Decay $|\langle m_\nu \rangle| = |\Sigma U_{ei}^2 m_i| \leq 0.05$ eV

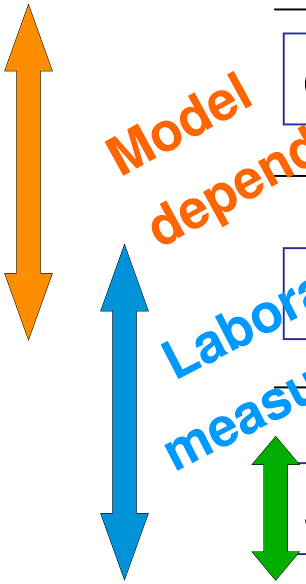






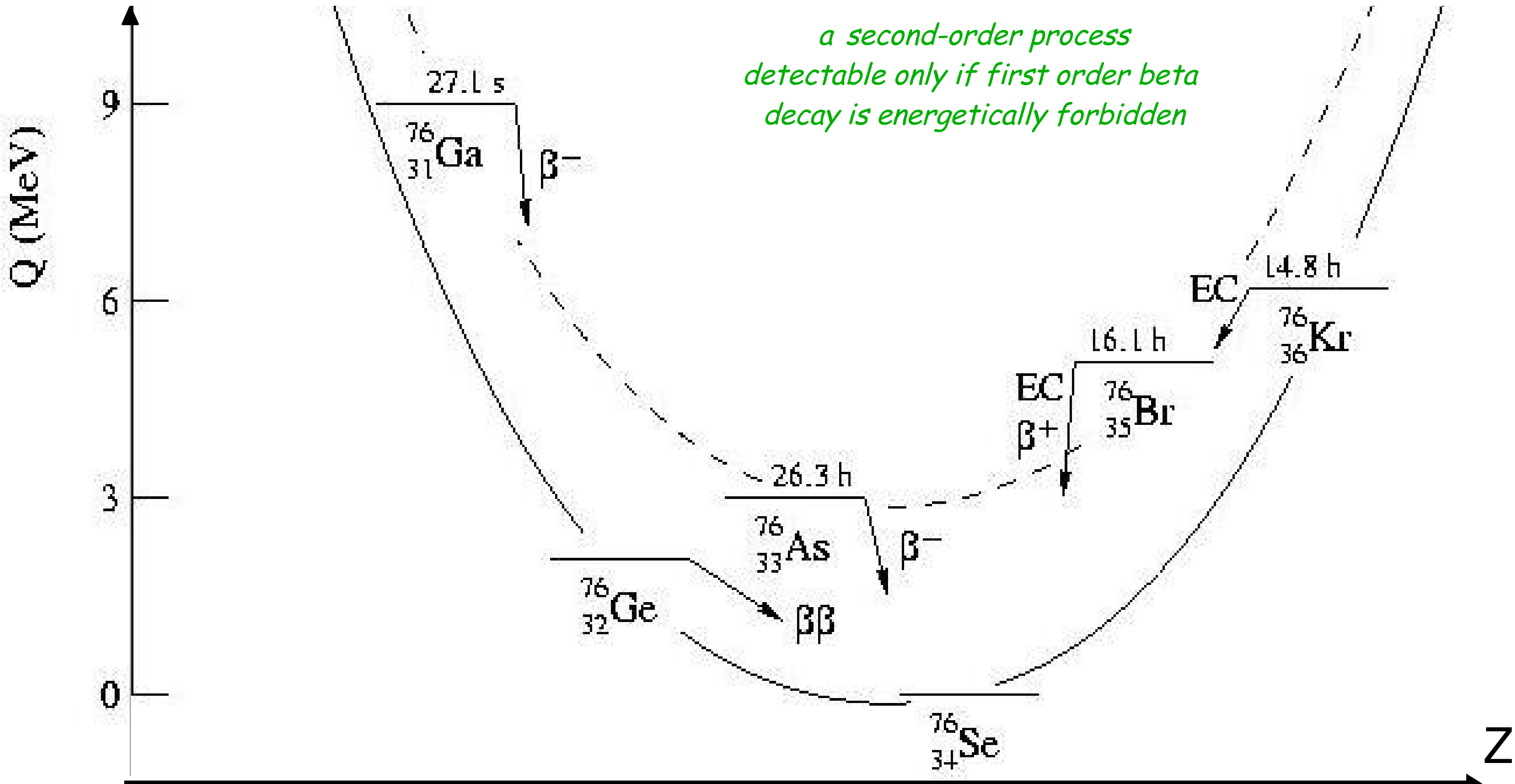
Tools for the investigation of the mass scale

Tools	Present sensitivity	Future sensitivity (a few year scale)
Cosmology (CMB + LSS)	0.7 - 1 eV	0.1 eV
Neutrinoless Double Beta Decay	0.5 eV	0.05 eV
Single Beta Decay	2.2 eV	0.2 eV



DBD and neutrino mass

even(A)-even(Z) nuclei whose single beta decay is energetically forbidden can however "double beta decay" on a lower mass isomer

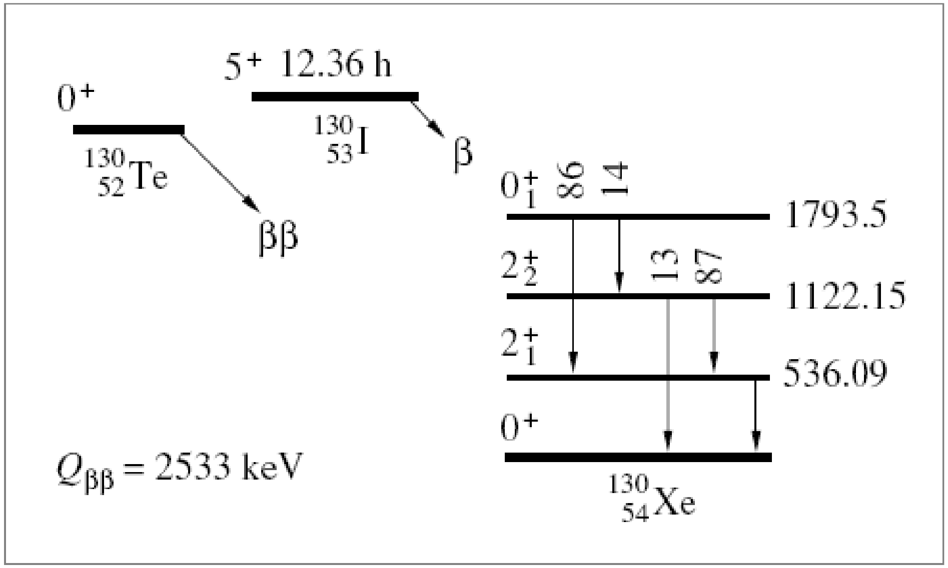


candidate nuclei with Q > 2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

all these nuclei decay by $\beta^-\beta^-$ emissions but also candidates decaying via $\beta^+\beta^+$ and EC EC do exist

the decay can be either on the 0+ ground state or on the excited state/s



decay processes

there is one SM allowed process:

$2\nu\beta\beta$ $(A,Z)\rightarrow(A,Z+2)+2\ e^- +2\nu$

two electrons sum energy $E_1+E_2 < Q$

and various energetically allowed but not standard 0ν processes:

$0\nu\beta\beta$ through <m> or RH currents or ....

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

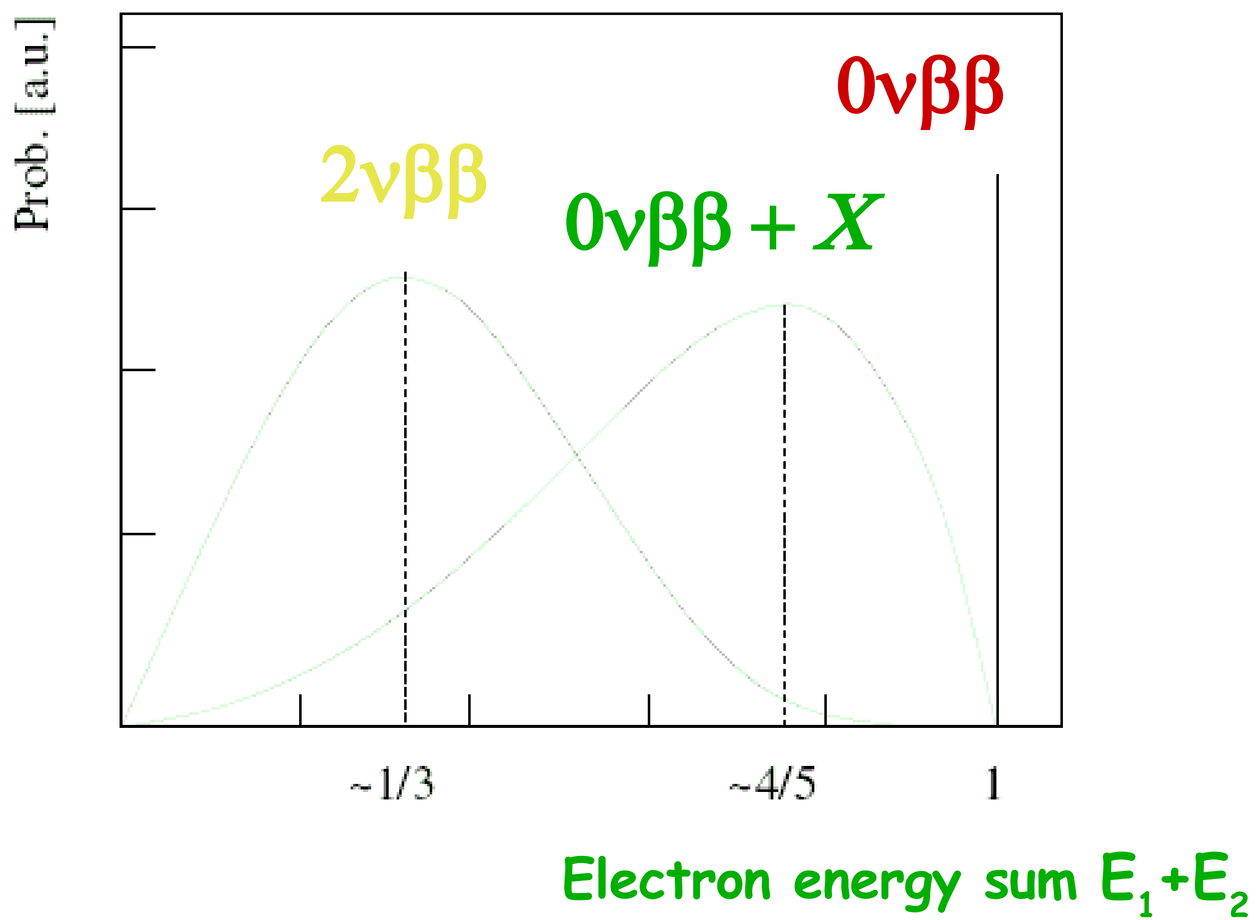
two electrons sum energy $E_1+E_2 = Q$

$0\nu\beta\beta$ + Majoron

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

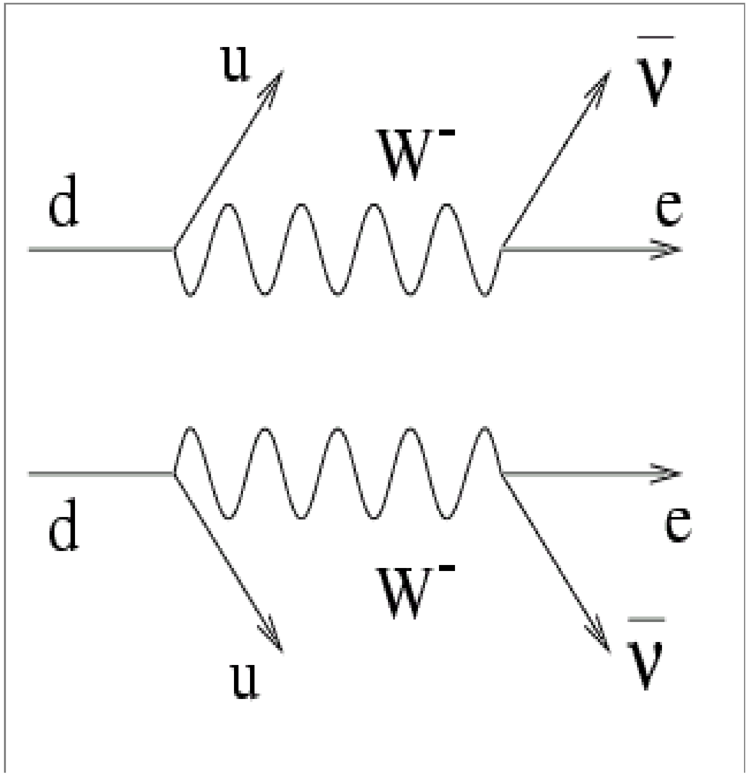
two electrons sum energy $E_1+E_2 < Q$

...


Prob. [a.u.]
0νββ
2νββ
0νββ + X
~1/3
~4/5
1
Electron energy sum E1+E2

two neutrino decay

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



this process is studied to get info concerning the NME

Isotope	Qββ (MeV)	Isotopic abundance (%)	Half life $T_{1/2}, 2\nu$ (y)
48Ca	4.27	0	~ $4.0\ 10^{19}$
76Ge	2.04	7.8	~ $1.4\ 10^{21}$
82Se	3	9.2	~ $0.9\ 10^{20}$
96Zr	3.35	2.8	~ $2.1\ 10^{19}$
100Mo	3.03	9.6	~ $8.0\ 10^{18}$
116Cd	2.8	7.5	~ $3.3\ 10^{19}$
128Te	0.87	31.7	~ $2.5\ 10^{24}$
130Te	2.53	34.5	~ $0.9\ 10^{21}$
136Xe	2.48	8.9	not observed yet
150Nd	3.37	5.6	~ $7.0\ 10^{18}$

neutrinoless decay: $(A,Z) \rightarrow (A,Z+2)+2e^-$

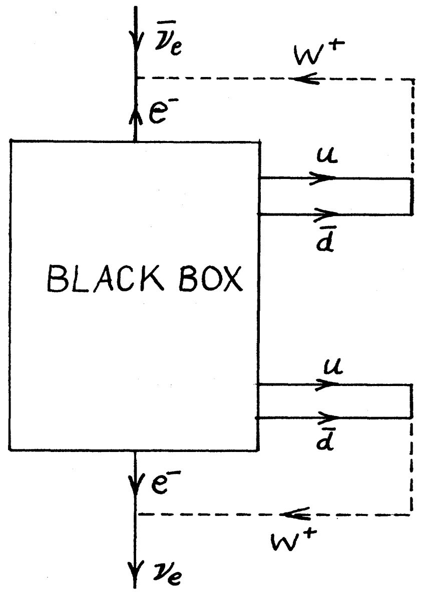


FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

Whatever processes cause 0νββ, its observation would imply the existence of a Majorana mass term"

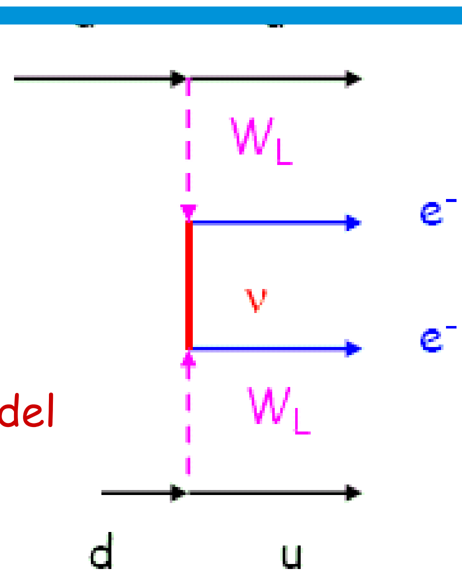
Schechter and Valle,

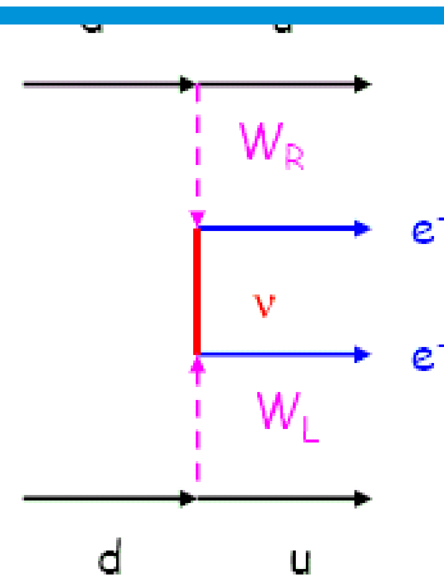
Phys. Rev. D, Vol.25 N.11, 1982

Hence observing the 0νββ decay guaranties that ν are massive Majorana particles.

neutrinoless decay: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

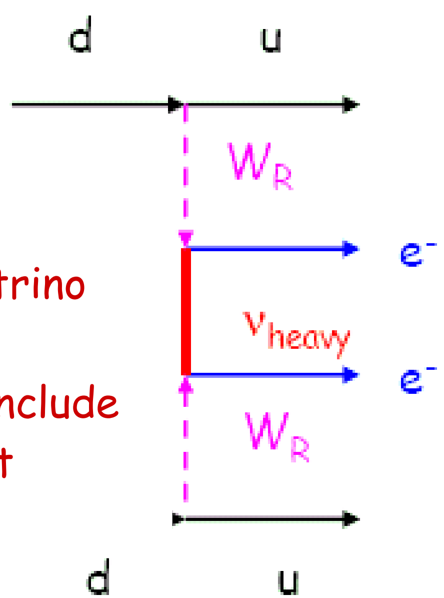
(I)
Light Majorana neutrino,
only Standard Model weak interactions

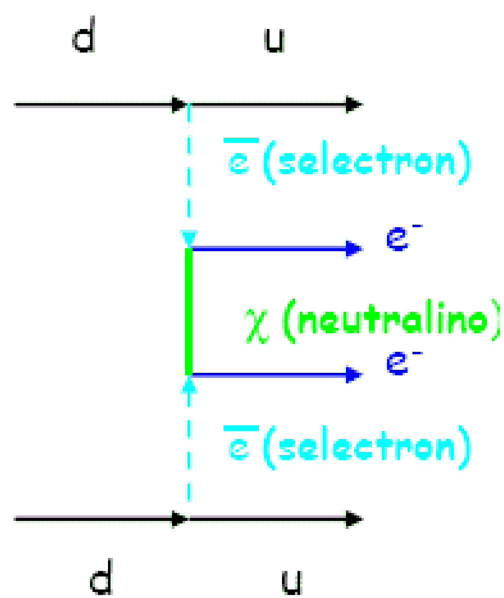




(II)
Light or heavy Majorana neutrino. Model extended to include right-handed WR.
Mixing extended between the left and right-handed neutrinos.

(III)
Heavy Majorana neutrino interacting with WR.
Model extended to include right-handed current interactions.



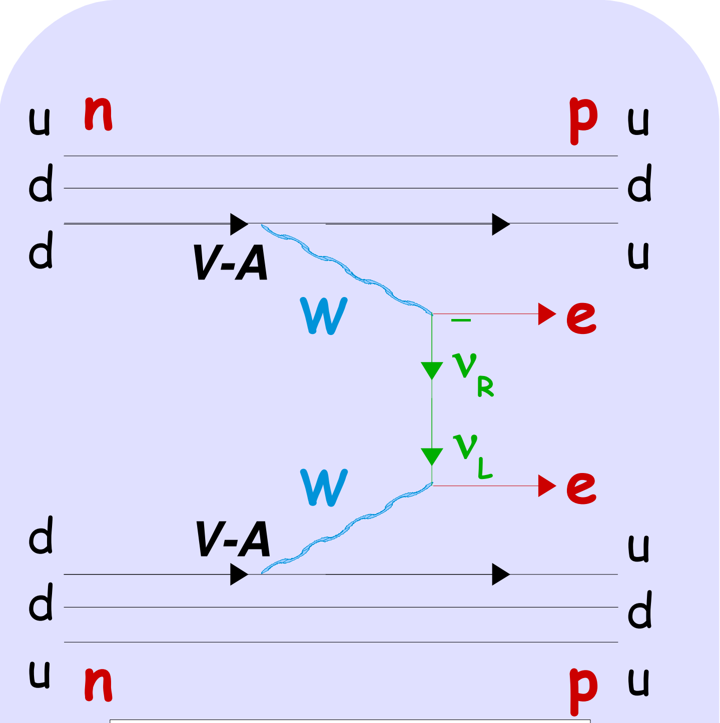


(IV)
Supersymmetry with R-parity violation. Many new particles invoked. Light Majorana neutrinos exist also.

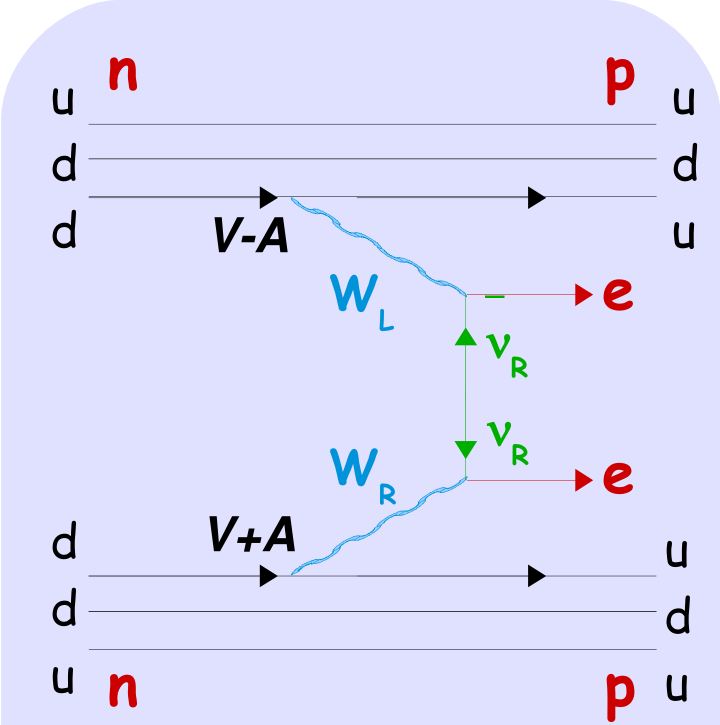
$(A,Z) \rightarrow (A,Z+2) + 2e^-$

the observation of this decay proves:

- Lepton number violation
- Majorana character of neutrinos
- measurement of the Majorana mass of neutrino
- infere the absolute mass scale and hierarchy
- test existence of RH currents



$0\nu\beta\beta$ through $\langle m_\nu \rangle$



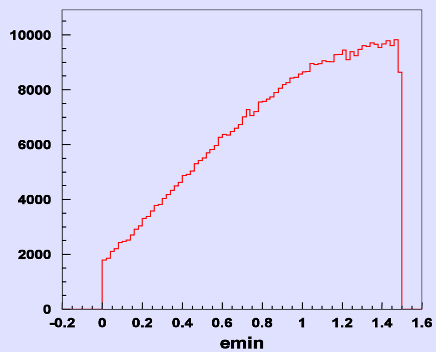
$0\nu\beta\beta$ through RH currents

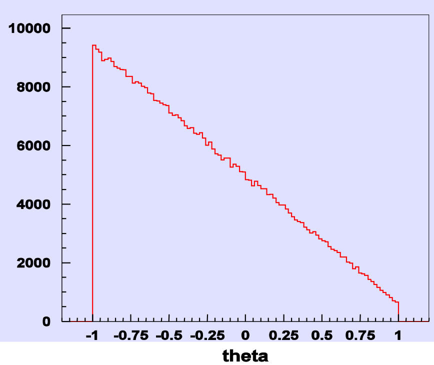
(A,Z) → (A,Z+2) + $2e^-$

Light neutrino exchange

$0\nu\beta\beta$ through $\langle m_\nu \rangle$

$$T_{1/2}^{-1} = F(Q_{\beta\beta}, Z)\,|M|^2\,\langle m_\nu \rangle^2$$

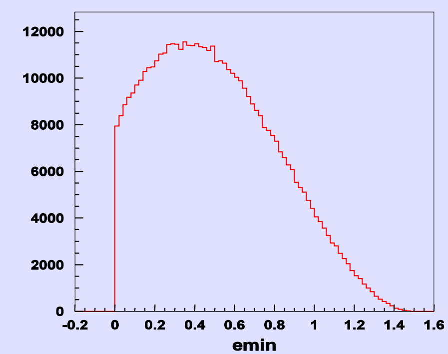


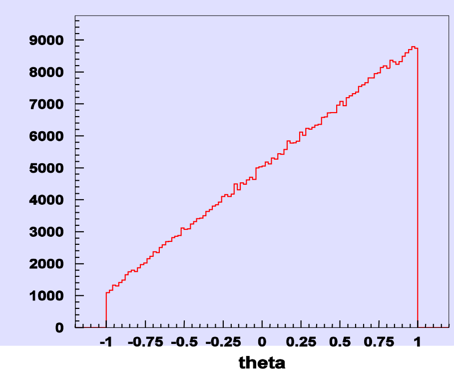


V+A current

$0\nu\beta\beta$ through RH currents

$$T_{1/2}^{-1} = C_1\,\langle m_\nu \rangle^2 + f(\langle m_\nu \rangle, \lambda, \eta)$$

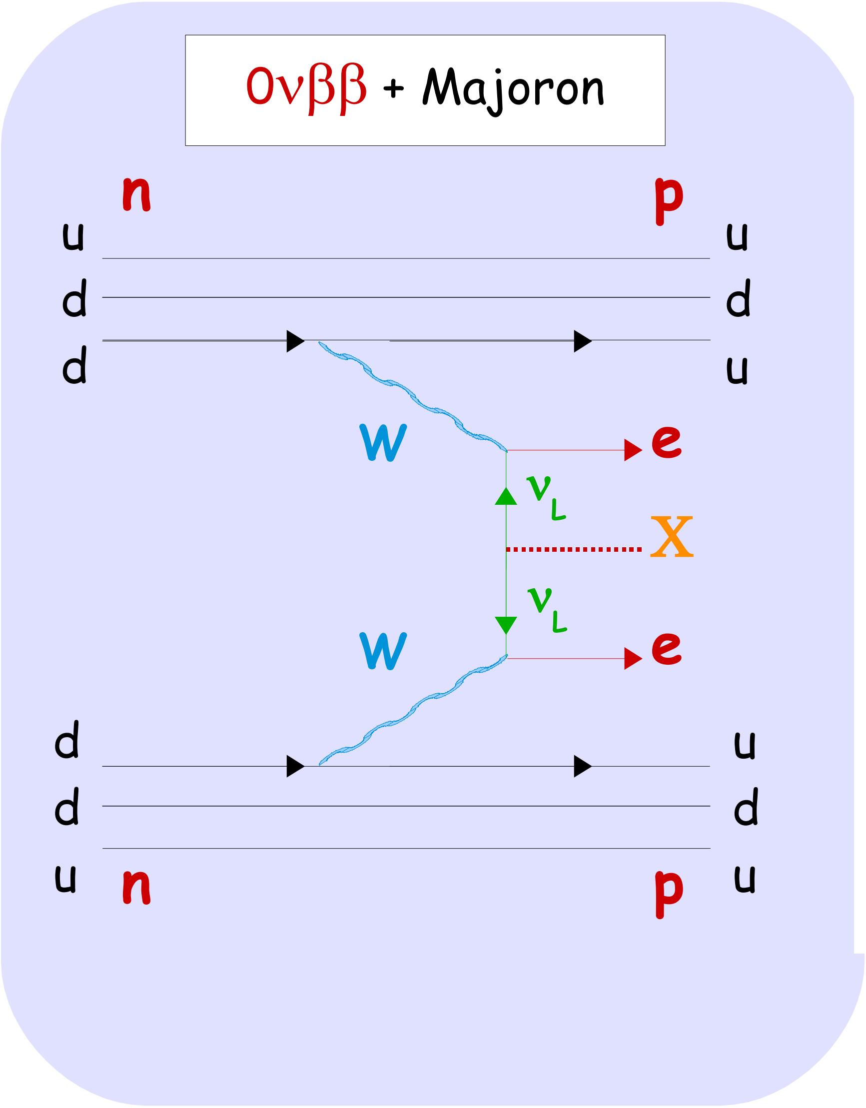




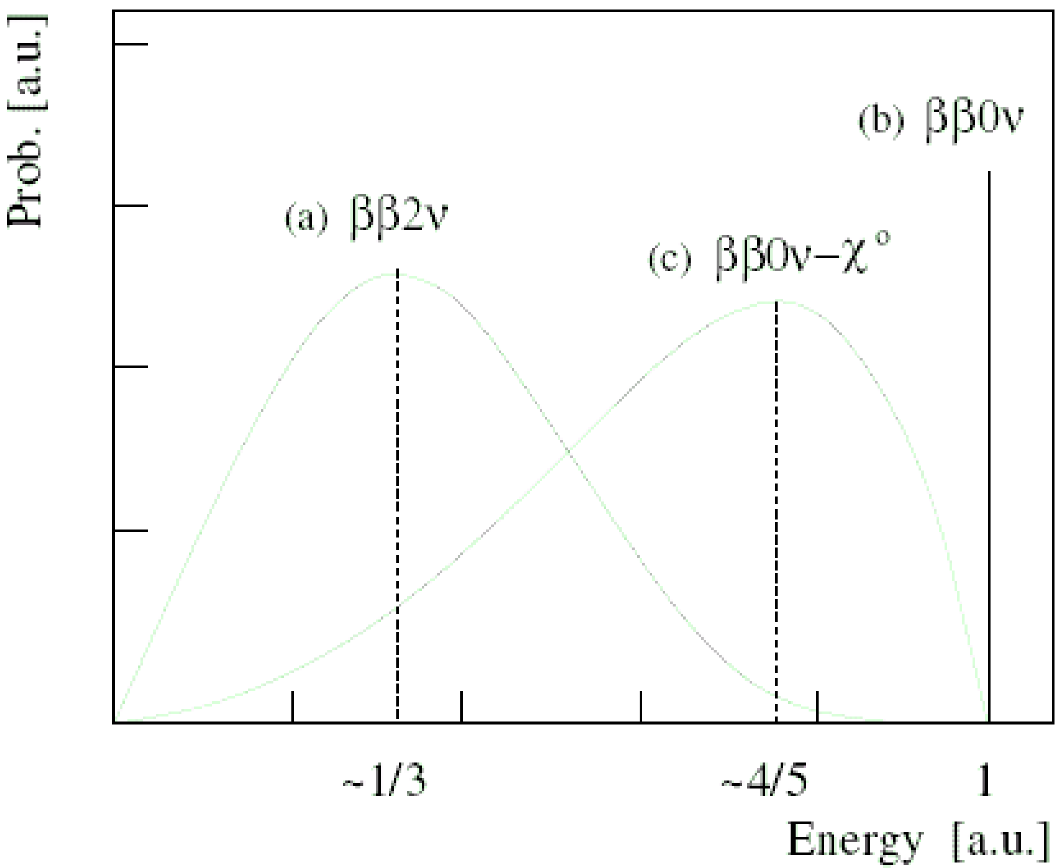
Minimum electron energy

Angular distribution betwen the 2 electrons

(A,Z) → (A,Z+2) + 2e⁻ + X



CP violation in leptonic sector



M. Pavan, Sept. 2008, Beijing "DBD Experiments"

$0\nu\beta\beta$ test lepton number conservation

A partial list of processes where the lepton number would be violated:

$0\nu\beta\beta$ decay:	$(Z, A) \rightarrow (Z\pm2, A) + 2e^{(\pm)}$	$T_{1/2} > \sim10^{25}$ y
Muon conversion:	$\mu^- + (Z, A) \rightarrow e^+ + (Z-2, A)$	$BR < 10^{-12}$
Anomalous kaon decays:	$K^+ \rightarrow \pi^-\mu^+\mu^+$	$BR < 10^{-9}$
Flux of ν_e from the Sun:		$BR < 10^{-4}$
Flux of ν_e from a nuclear reactor:		BR < ?

Observing any of these processes would mean that the lepton number is not conserved, and that neutrinos are massive Majorana particles.

It turns out that the study of the $0\nu\beta\beta$ decay is by far the most sensitive test of the total lepton number conservation.

$0\nu\beta\beta$ and neutrino mass *(assume diagram I dominates)*

$0\nu\beta\beta$ life-time is written as: $T_{1/2}^{-1} = F(Q_{\beta\beta},Z)\ |M|^2\ \langle m_\nu \rangle^2$

$F(Q_{\beta\beta},Z)$ = phase space
decay cinematic

$|M|^2$ = nuclear matrix element
theoretically evaluated (shell model, QRPA models …)
different results according to the nuclear model used

$$|\Sigma U_{ei}^2 m_i|^2 = \langle m_\nu \rangle^2 = \frac{1}{T_{1/2}\ F(Q_{\beta\beta},Z)\ |M|^2}$$

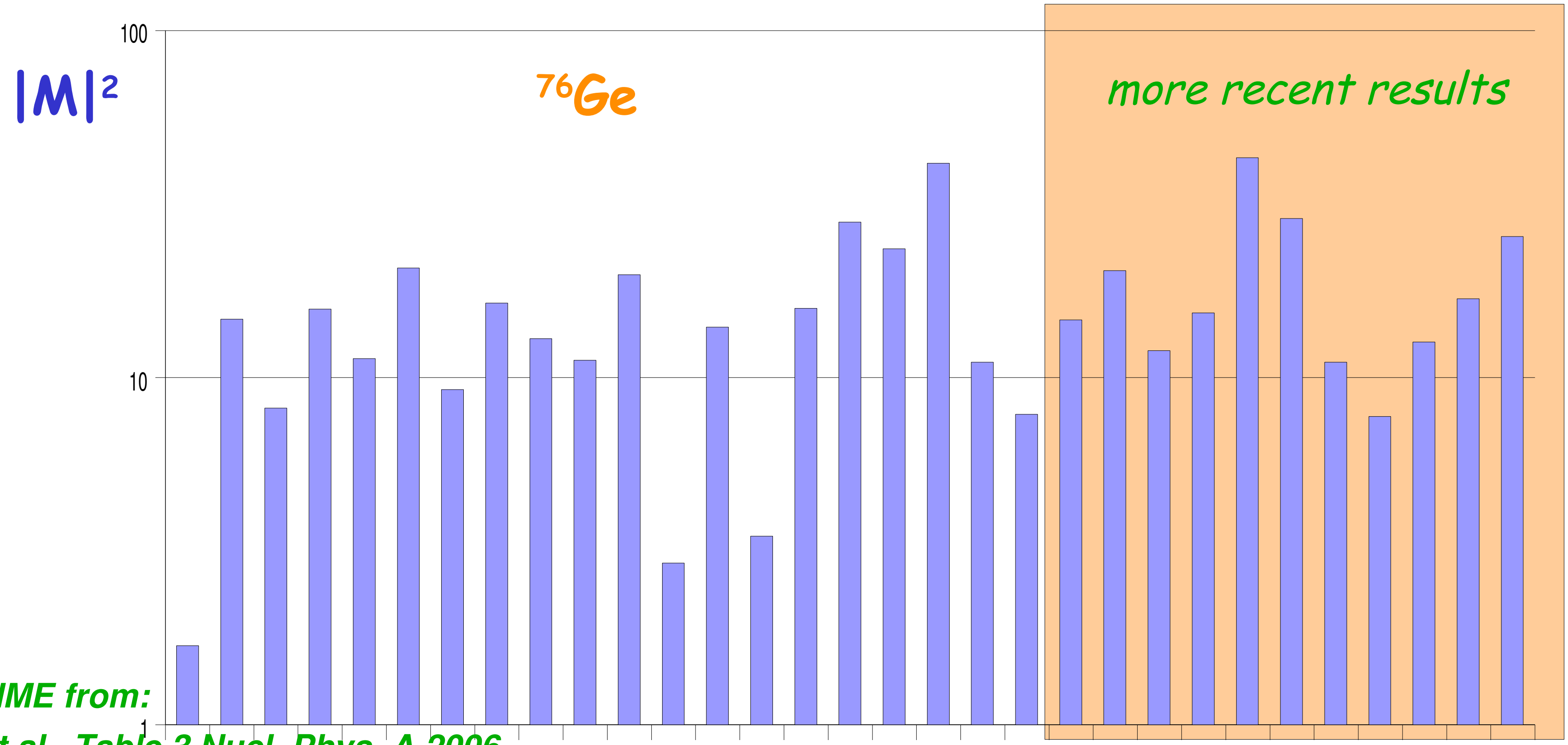
- $T_{1/2}^{-1}$ is experimentally measured → neutrino is Majorana particle
- $\langle m_\nu \rangle^2$ is extracted from the experimental value → mass absolute scale

however this ($\langle m_\nu \rangle^2$) result is model (NME) dependent !!!

Nuclear Matrix Element

Nuclear matrix elements are calculated using two models:

QRPA (RQRPA, SQRPA, …….), Shell model ...
with sometimes (particularly in the past) quite different results



QRPA NME from:
Rodin et al. Table 3 Nucl. Phys. A 2006
+ erratum nucl-th:0706.4304v1

selection of QRPA result

Nuclear Matrix Element

suggestion from Bahcall et al.

use the nuclear matrix range as an uncertainty: « Democratic approach »

BUT

does not take into account the improvements of the Models

does not help in the choice of the best candidate for an experiment

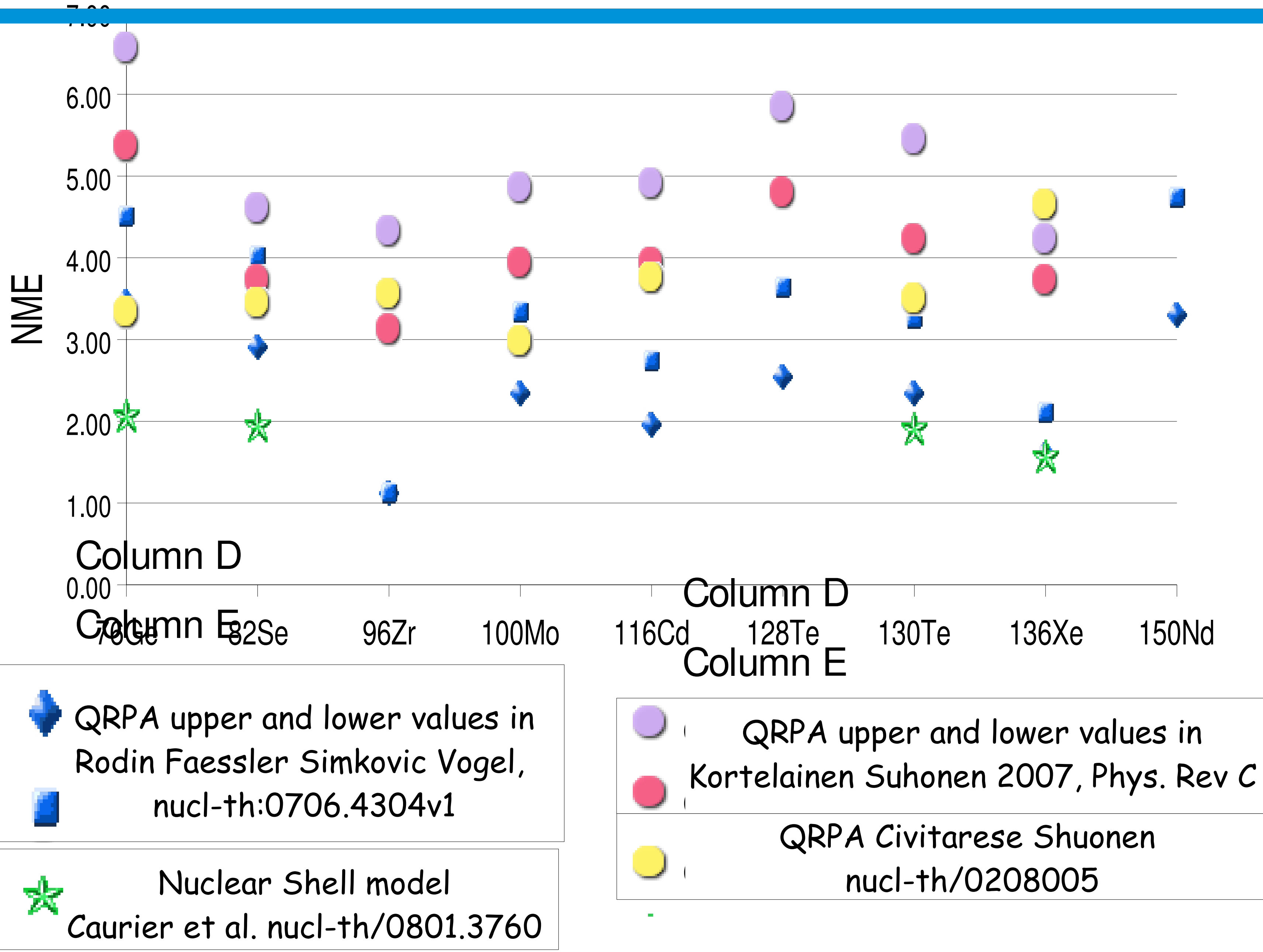
TODAY

exchanges between groups to understand discrepencies and evaluate errors

use of β and 2νββ decay data to fix parameters in QRPA, new results from Shell Model

new results are more similar than in the past !!!

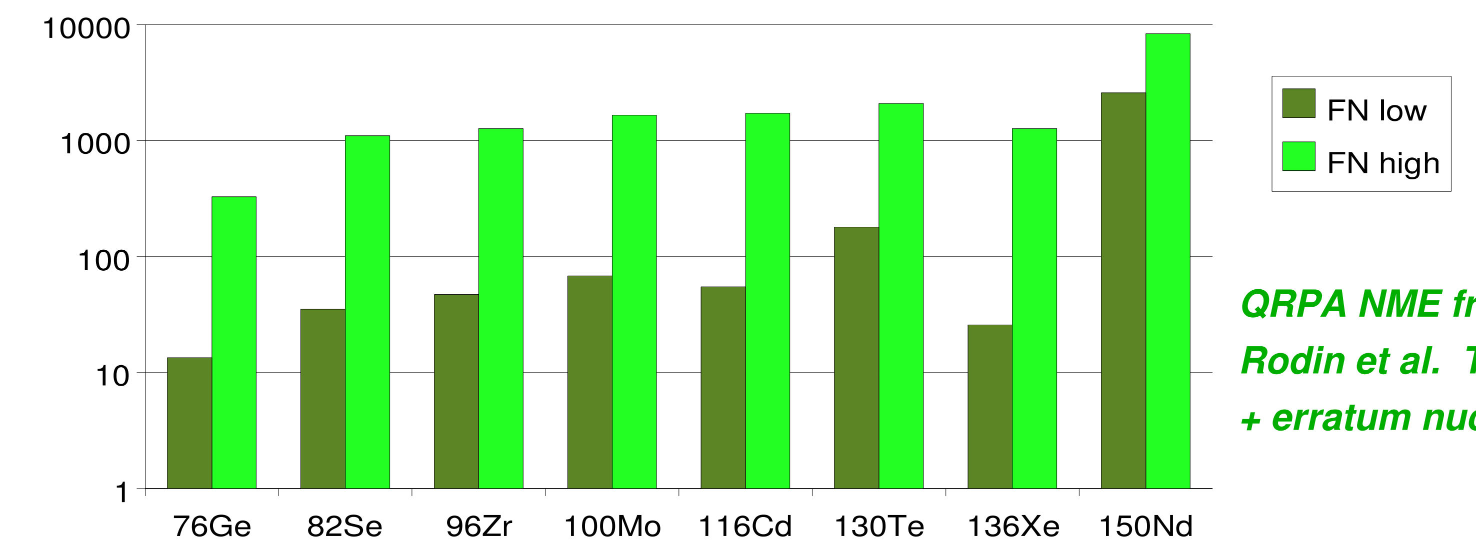
0νββ: Nuclear Matrix Evaluation



exctracting m_ν from $T_{1/2}^{0\nu\beta\beta}$

$$\langle m_\nu \rangle^2 = \frac{1}{T_{1/2} \, F(Q_{\beta\beta}, Z) \, |M|^2}$$

F_N nuclear factor of merit

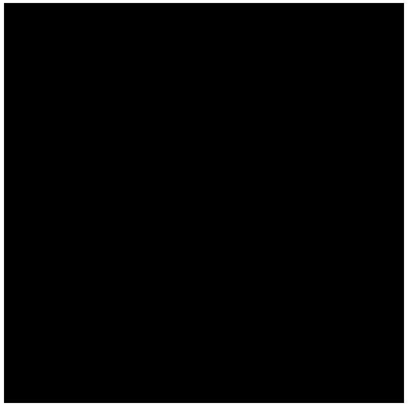


QRPA NME from:
Rodin et al. Table 3 Nucl. Phys. A 2006
+ erratum nucl-th:0706.4304v1

→ m_ν range: $\left(\frac{1}{T_{1/2}^{0\nu\beta\beta} \, F_{Nhigh}} \; ; \; \frac{1}{T_{1/2}^{0\nu\beta\beta} \, F_{Nlow}} \right)$

but which selection of NME values should be used? my solution for these slides was to quote the more recent results of the 2 QRPA "schools" and of the SM

Decay signature



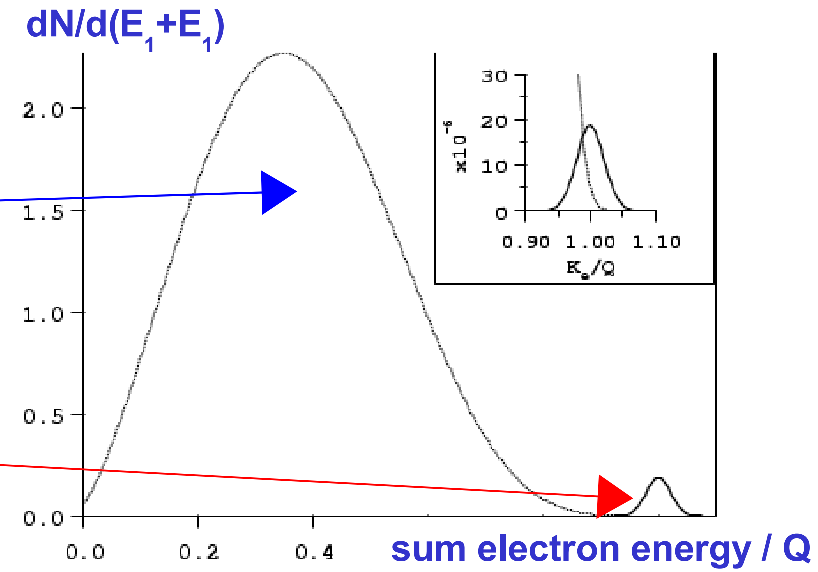
$(A,Z) \rightarrow (A,Z+2) + 2e^-$

search for the decay looking for the 2 e-

signature = the sum energy spectrum of the 2 e- is:

$2\nu2\beta$ =
a continuum with end point at Q-value

$0\nu2\beta$ =
a peak at Q-value, enlarged by det. res.



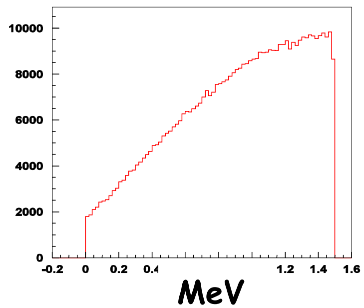
the ratio between the two half-life depends on the isotope !!

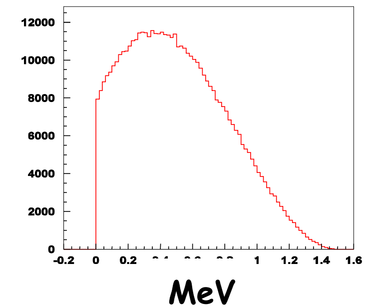
other observables

Light neutrino exchange

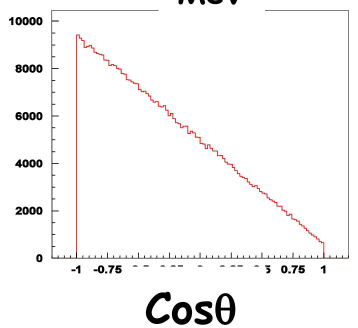
V+A current

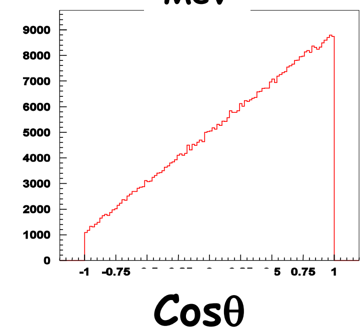
Available only in tracking experiments





Minimum electron energy





Angular distribution betwen the 2 electrons

further signatures:

Novel techniques under development

the signal is due to electrons = charge -1

short range particle “single site”

the daughter nucleus

what does happen if you find the signal?

in most experiments the signature of the decay will be rather poor, it is unlikely – but possible - that background event can mimic all the observables of $0\nu\beta\beta$

it is commonly accepted by the "$\beta\beta$ community" that the discovery of $0\nu\beta\beta$ would require:

the decay shows up
- in more than one experiment
- for more than one isotope

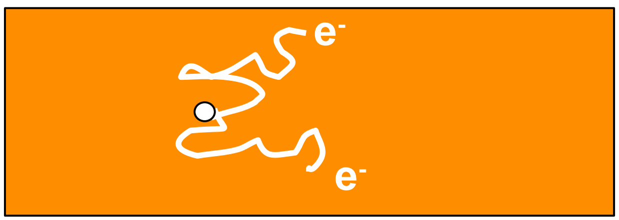
the comparison of experiments studying the same isotope is trivial (so it is possible to clearly state that a certain result is confirmed or not, however this does not prove that the observed events are due to $0\nu\beta\beta$ and not to some background source)

in the case of different isotopes the comparison goes through the NME (only observing the decay in different isotopes we can be reasonably confident that $0\nu\beta\beta$ decay have been discovered)

Detector choice

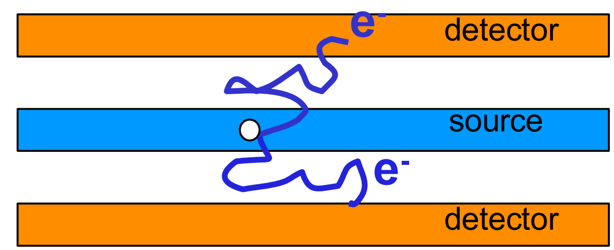
two electrons each with a continuous spectrum

and a monochromatic sum energy



Source ≡ Detector

(calorimetric technique)



Source ≠ Detector

semiconducting devices Ge, CdTe

scintillators

solid CaF_2, $CdWO_4$

liquid/gas Xe

bolometers

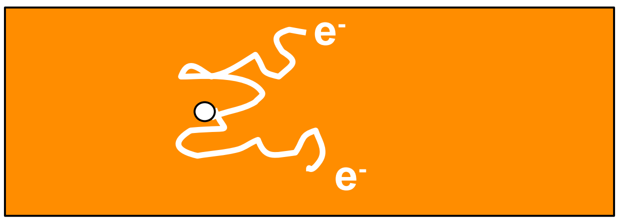
TeO_2, $CdWO_4$, CaF_2, $MoWO_4$ ...

very thin sheets containing the source

ionization detectors for tracking and energy measurement

almost any candidate

source = detector



Source = **Detector**

(calorimetric technique)

constraints on detector materials

very large masses are possible
demonstrated: up to ~ 50 kg
proposed: up to ~ 1000 kg

with proper choice of the detector,
very high energy resolution

Ge-diodes
bolometers

BUT

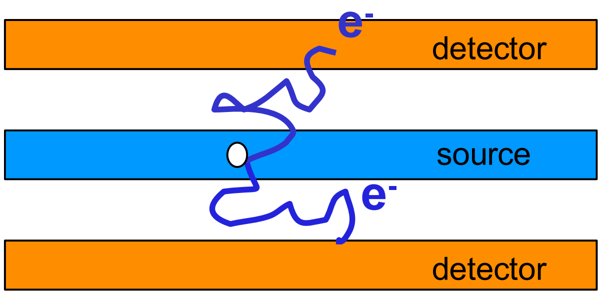
no event topology
no or limited event identification

in gaseous/liquid Xenon detector,
indication of event topology
and event identification

BUT

poor energy resolution

source ≠ detector



Source ≠ Detector

- neat reconstruction of event topology (allow to study the decay mechanism)
- it is difficult to get large source mass
- several candidates can be studied with the same detector
- generally poor energy resolution ($2\nu\beta\beta$ could be the dominant background)

experimental sensitivity $S_{0\nu}$ [years]

half-life corresponding to the minimum detectable number of events above background at a given C.L

$$T_{1/2}^{0nbb} = \frac{ln2 \cdot N_{0nbb}}{rate_{0nbb}}$$

b= background counting rate in the ROI (Region Of interest) [counts/keV/kg/y]

FWHM ~ size of the ROI [keV]

M = mass of the ββ isotopes in the source [kg]

counts in the ROI = 0

90% upper limit on the rate

$$rate_{0nbb} = \frac{N_{Poisson}(90\%)}{time}$$

$$S_{0n} \sim M\ time$$

counts in the ROI≠0

statistical fluctuation of bkg in the ROI

$$rate_{0nbb} = \frac{\sqrt{b \cdot time \cdot FWHM}}{time}$$

$$S_{0n} \sim \sqrt{\frac{M\ time}{FWHM\ \ b}}$$

fighting for sensitivity

$$S_{0n} = ln2 \cdot N \cdot i.a. \cdot \sqrt{\frac{time}{(bgk \cdot FWHM)}} \cdot eff.$$

i.a. = isotopic abundance of the ββ candidate

Nature or Money

N = number of nuclei

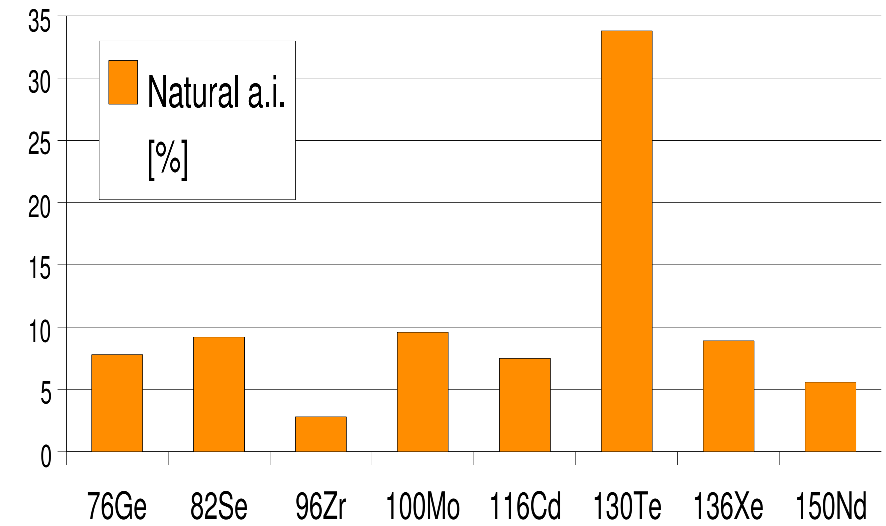
time = experiment live time

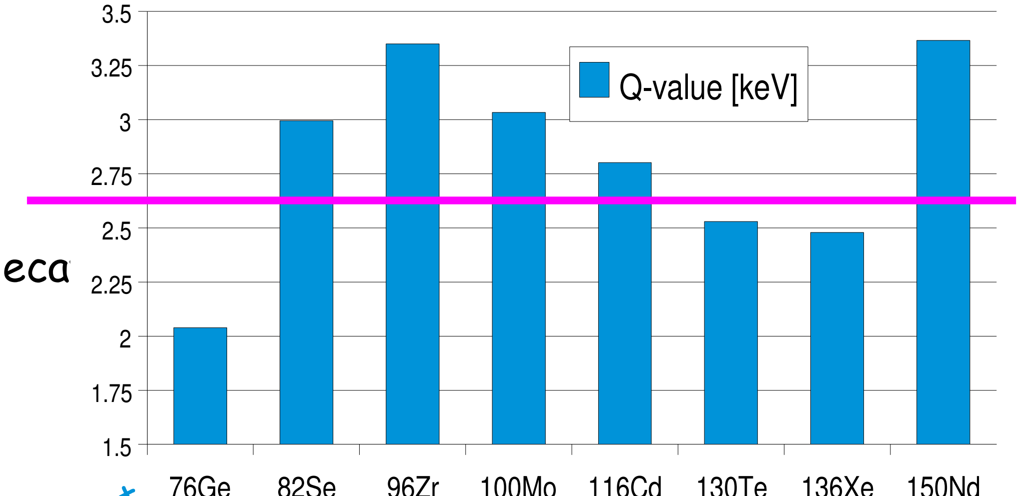
eff. = % of 0nbb decay detected

Detector choice

FWHM = measures detector capability to distinguish a 0νββ event from a bkg event

bkg = background of events capable of mimic a 0νββ deca





Q-value is a rather good indicator for bkg,
"the higher the Q value, the lower the bkg"
most natural γ radioactivity is negligible above 2.6 MeV
location underground and deep to shield from cosmic rays

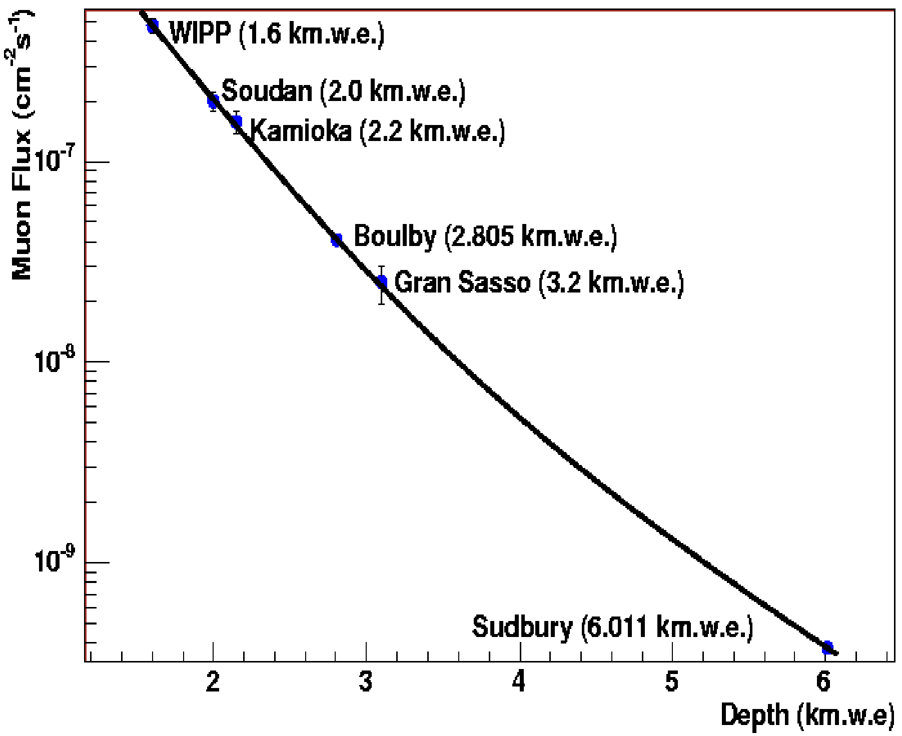
Detector choice +
Location + Shielding
terial selection

The enemy: background sources able to mimic a 0νββ event

from the Universe: cosmic rays

→ deep underground laboratories

here only muons survive muon energy and flux depends on the lab depth



μ direct interaction in the apparatus

→ veto

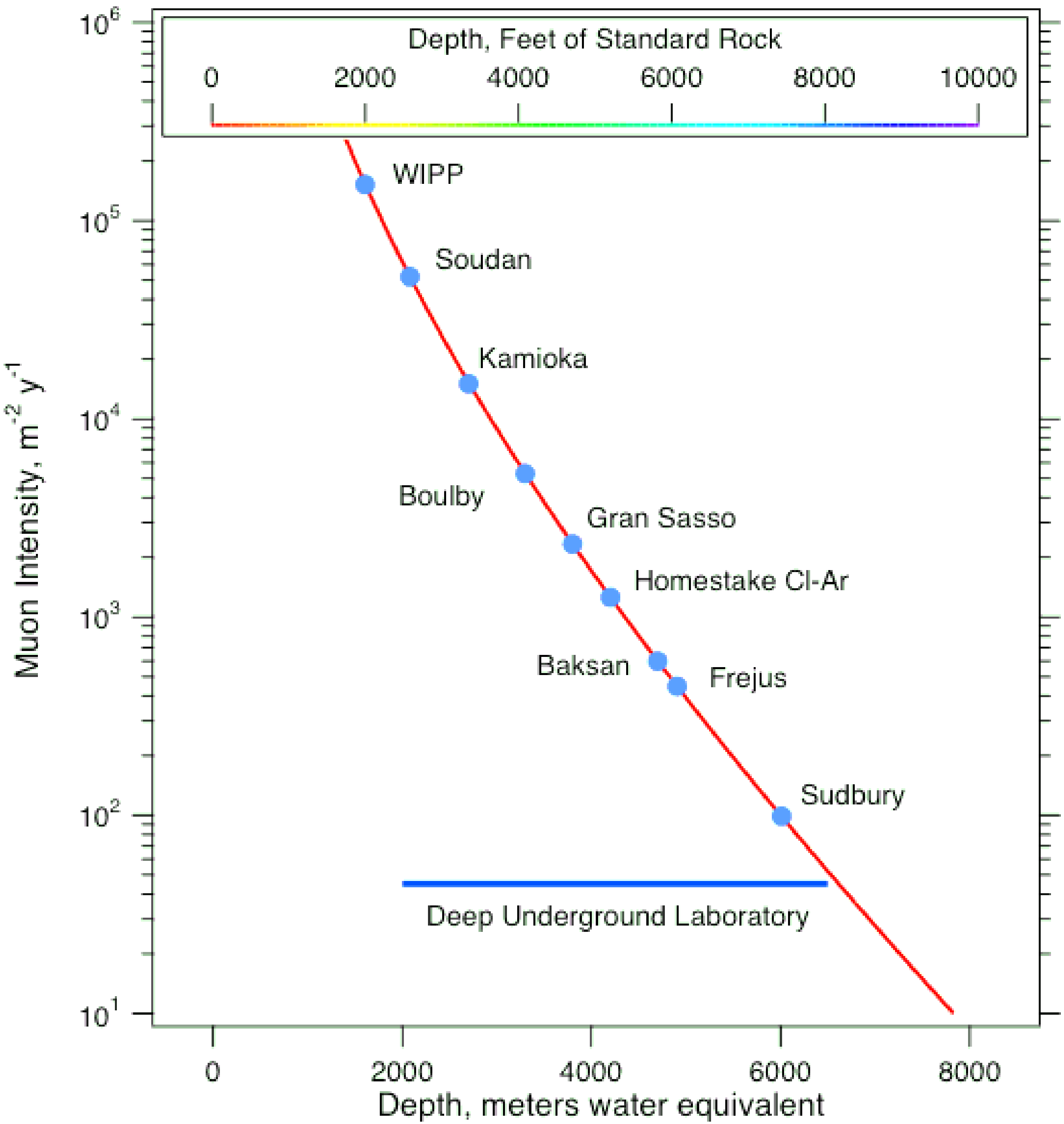
surround the exp. apparatus with a μ detector
NOTE: does not solve the problem of metastable nuclei produced by μ interaction in the materials

μ interaction in the rock, relevant secondaries are gammas, neutrons

→ shields

these have an harder spectrum than the one due to radioactivity (but extremely low fluxes)

if veto and shields are not enough the only solution is a deeper location



Depth, Feet of Standard Rock
0
2000
4000
6000
8000
10000
WIPP
Soudan
Kamioka
Boulby
Gran Sasso
Homestake Cl-Ar
Baksan
Frejus
Sudbury
Deep Underground Laboratory
Muon Intensity, m-2 y-1
10^6
10^5
10^4
10^3
10^2
10^1
0
2000
4000
6000
8000
Depth, meters water equivalent

Radioactivity

natural long living isotopes (U, Th, K ...) α, β, γ **and n**

n are produced by (α, n) reactions and spontaneous fission, they have E < 10 MeV

cosmogenically activated isotopes β **and** γ

anthropogenic (nuclear explosions, nuclear plants , industry, medical ...) β **and** γ

radioactivity of the rock:

γ and **n** → <u>shield the apparatus</u>

<u>labs located in mountains with low radioactivity rock (salt mines)</u>

radioactivity of the apparatus:

γ, **n** and also α and β (when emitted near to the active volume)

→ <u>material selection</u>

<u>avoid cosmic ray activation</u> (underground storage of materials)

<u>develop active rejection technique</u>

(pulse shape rejection, double reading, coincidences ...)

fighting background

a typical experimental apparatus is

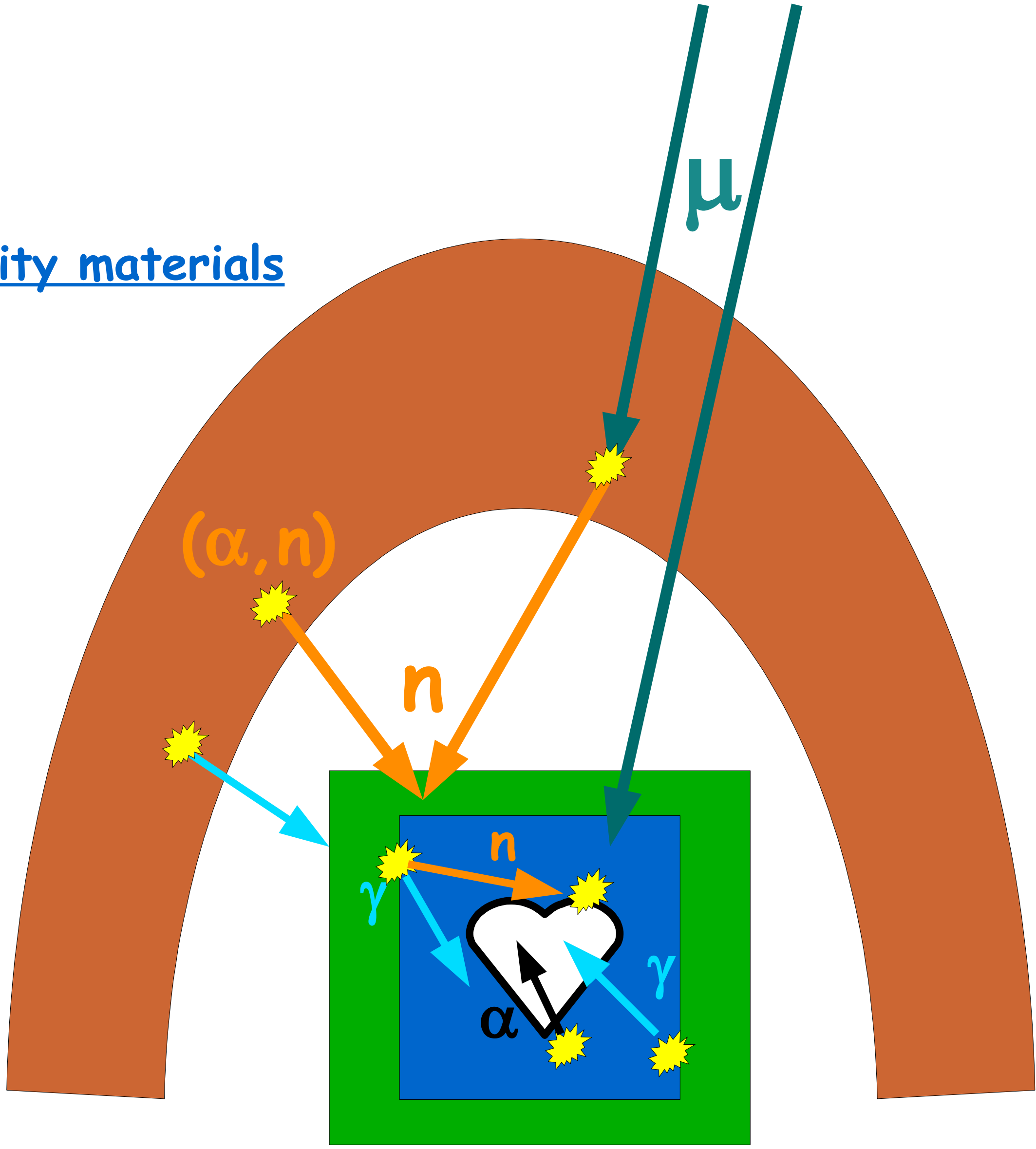
deep underground
shielded against gamma and neutrons
built with specially selected low activity materials

tools useful for the study of background components

MonteCarlo simulation
--> require several exp. inputs
--> validation

μ and n flux measurements
(or simulation)

HPGe, ICPMS, n activation ...
--> material selection



Part2.

Present and Past Experiments

"prehistory"

- 1948 – first counter experiment (Geiger counters, $T_{1/2}(0\nu) > 3 \cdot 1015$ y)
- 1950 – first evidence for $2\beta2\nu$ decay of ^{130}Te in first geochemical experiment: $T_{1/2} \sim 1.4 \cdot 10^{21}$ y
- 1950-1965 – a few tens experiments with sensitivity ~ 10^{16}-10^{19} y

“history”

- $T_{1/2}(^{76}Ge) > 5\cdot10^{21}$ y; Ge(Li) detector, 1973 (E. Fiorini et al.)
- $T_{1/2}(^{48}Ca) > 2\cdot10^{21}$ y; streamer chamber + magnetic field + plastic scint., 1970 (C. Wu et al.)
- $T_{1/2}(^{82}Se) > 3.1\cdot10^{21}$ y; streamer chamber + magnetic field + plastic scint., 1975 (C. Wu et al.)
- Geochemical experiments with ^{130}Te, ^{128}Te, ^{82}Se (“positive” results)

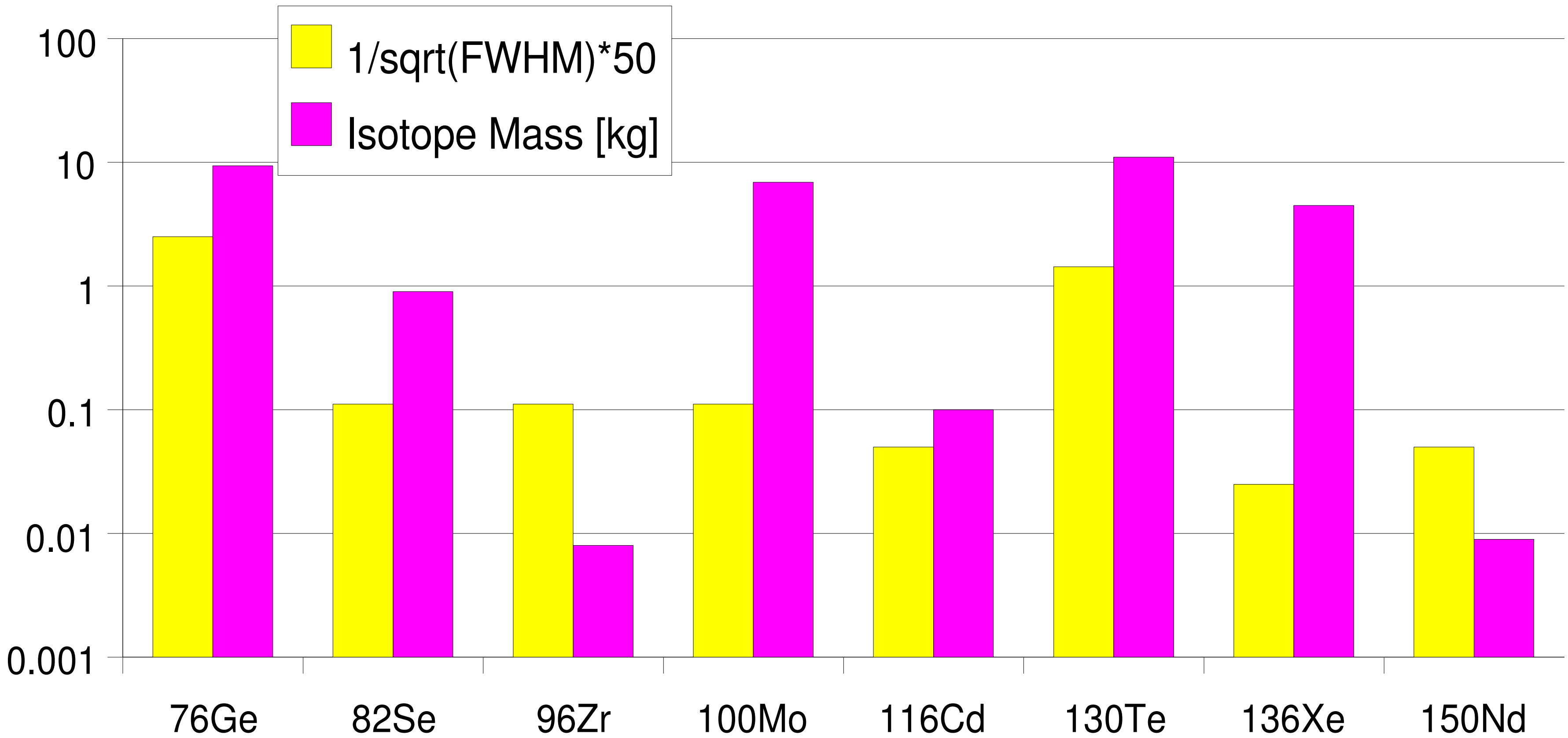
yestarday

Emitter	Experiment	$T^{0\nu}_{1/2} >$	C.L.%
^{48}Ca	ELEGANT VI	1.4×10^{22} y	90
^{76}Ge	MPIH/KIAE	1.9×10^{25} y	90
	IGEX	1.6×10^{25} y	90
^{82}Se	UCI	2.7×10^{22} y	68
	NEMO 3	4.7×10^{22} y	90
^{96}Zr	NEMO 2	1.3×10^{21} y	90
^{100}Mo	LBL/MHC/UNM	2.2×10^{22} y	68
	UCI	2.6×10^{21} y	90
	Osaka	5.5×10^{22} y	90
	NEMO 3	6×10^{22} y	90
^{116}Cd	Kiev	1.7×10^{23} y	90
	Osaka	2.9×10^{21} y	90
	NEMO 3	1.6×10^{22} y	90
^{130}Te	Milano	2.1×10^{23} y	90
	CUORICINO	1×10^{24} y	90
^{136}Xe	Caltech/UN/PSI	4.4×10^{23} y	90
^{136}Xe	Rome	1.2×10^{24} y	90
^{150}Nd	UCI	1.2×10^{21} y	90
	NEMO 3	1.4×10^{21} y	90

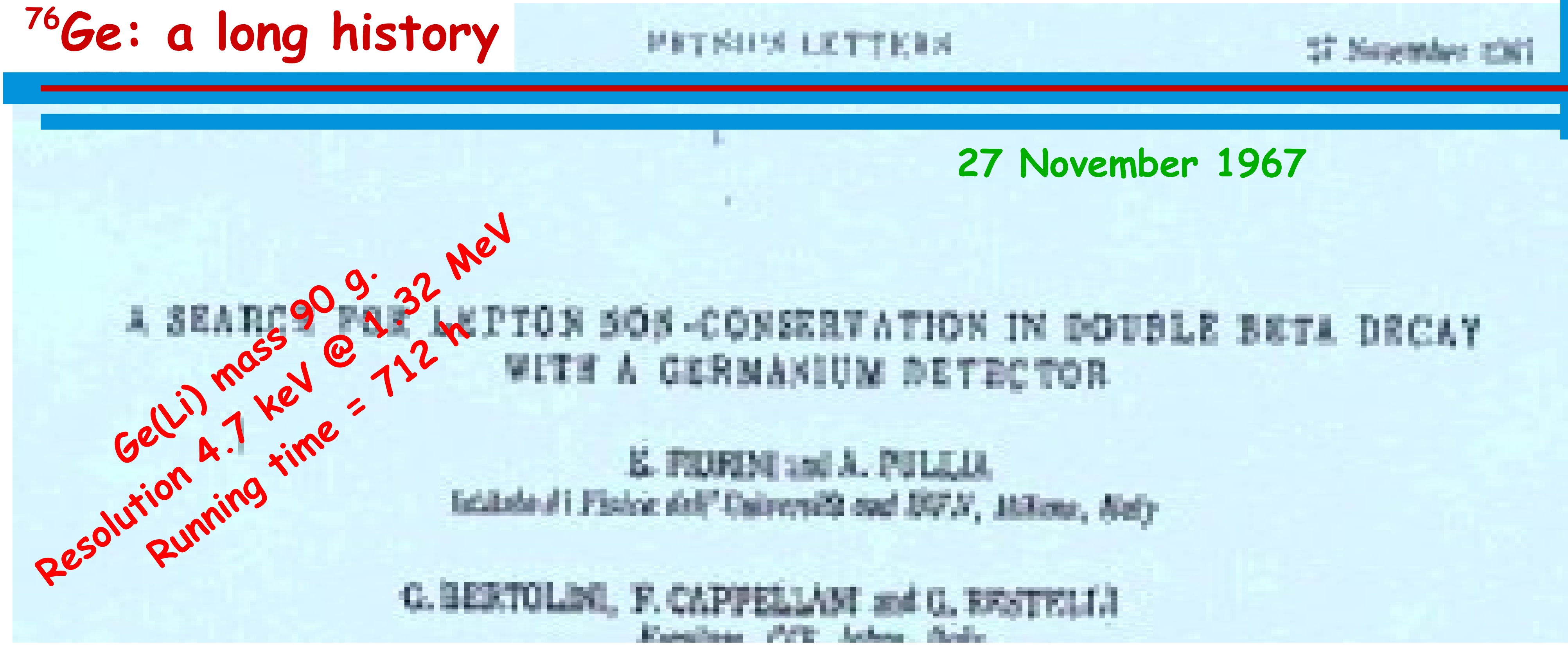
Table 1.4: *Limits on Neutrinoless Decay Modes*

a selection of present/past experiments:

$$S_{0n} = \ln 2 \cdot N \cdot ai \cdot \sqrt{\frac{time}{(bgk \cdot FWHM)}} \cdot eff.$$



^{76}Ge: a long history



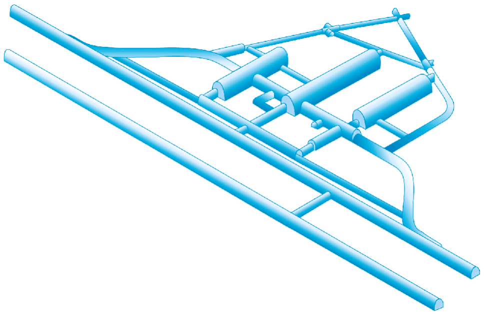
27 November 1967

A SEARCH FOR LEPTON NON-CONSERVATION IN DOUBLE BETA DECAY WITH A GERMANIUM DETECTOR

Why ββ searches of ^{76}Ge have so long history?

- Germanium ha high intrinsic purity (required also by other application
- Ge diodes detector is a well established technology
- source = detector high efficiency!
- ^{76}Ge isotopic abundance = 7.44%, but enrichment of ^{76}Ge possible at centrifuge up to >80%.
- Ge density = 5.3 g cm^{-3} compact setup
- low Atomic Weight (1 kg of ^{76}Ge = 13.1 Moles = 7.9 x 10^{24} nuclei)

^{76}Ge: Heidelberg-Moscow experiment



Location = **Lab. Naz. del Gran Sasso - Italy**

Countries = **Germania + Russia**

source=detector experiment

- ***tech. suggested in '60 by E. Fiorini, dominating this field since now***
- ***exp. started in 1990***

detector = 5 Ge diodes

source = 10.9 kg diodes

enriched in ^{76}Ge (i.a. 86%)

Q - value = 2039 keV

The experiment is closed but can be considered the precursor (together with IGEX) of the next generation expt. GERDA and Majorana

^{76}Ge: Heidelberg-Moscow experiment

statistics=

53.9 kg y, with PSA = 35.5 kg y

performances =

4.2 keV FWHM resolution at DBD Q-value

background in 0νββ region =

0.19 +/- 0.01 c/keV/kg/y

0.06 +/- 0.01 c/keV/kg/y with PSA

Pulse Shape Analysis, used to identify and reject multi-site events (gamma background)

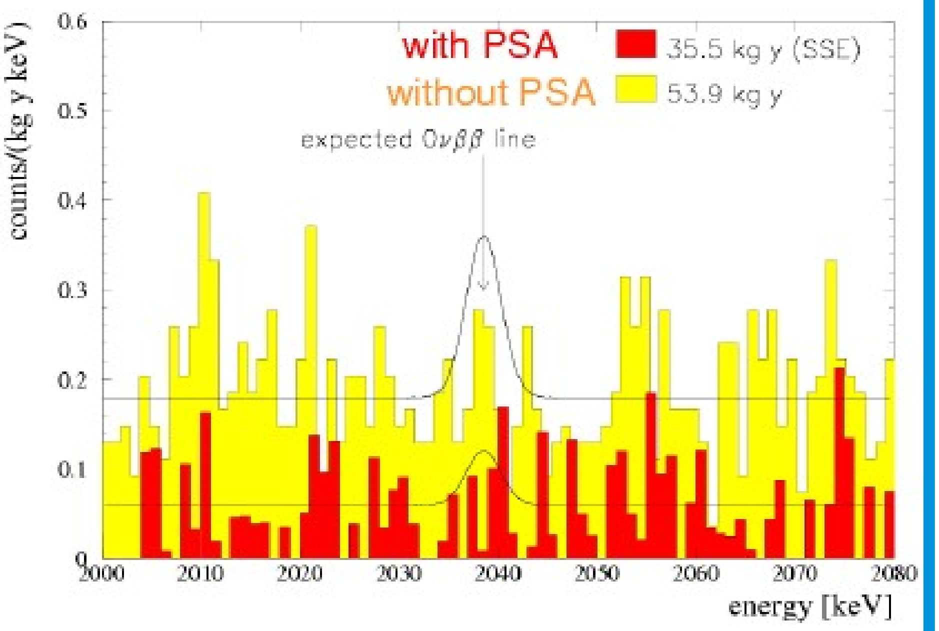
the entire collaboration (14 authors):

Klapdor-Kleingrothaus et al.

Eur. Phys. J. 12 (2001) 147

$\tau_{1/2}^{0n} > 1.9\ 10^{25}$ y at 90% C.L.

$\langle m_\nu \rangle < 0.35$ eV *



* *using nuclear calculations of Staudt et al.*

Europhys. Lett 13 (1990) 31

^{76}Ge: Heidelberg-Moscow experiment a controversial result

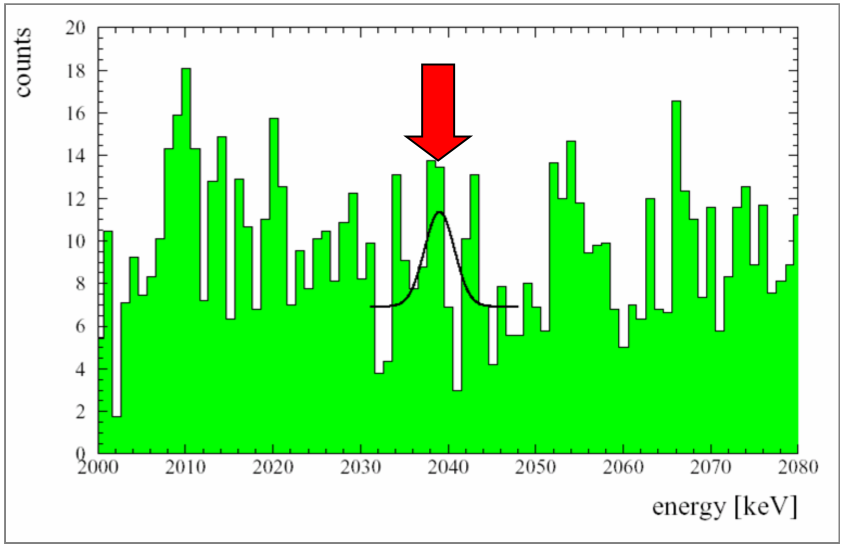
2001: a re-analysis by part of the collaboration (4 authors):

"Evidence for Neutrinoless DBD"

Klapdor-K. et al. Mod. Phys. Lett. A 16 (2001) 2049

$\tau_{1/2}^{0n}$ = (0.8 - 18.3) 10^{25} y @ 95% C.L.

➡ $<m_\nu>$ = 0.11 - 0.56 eV

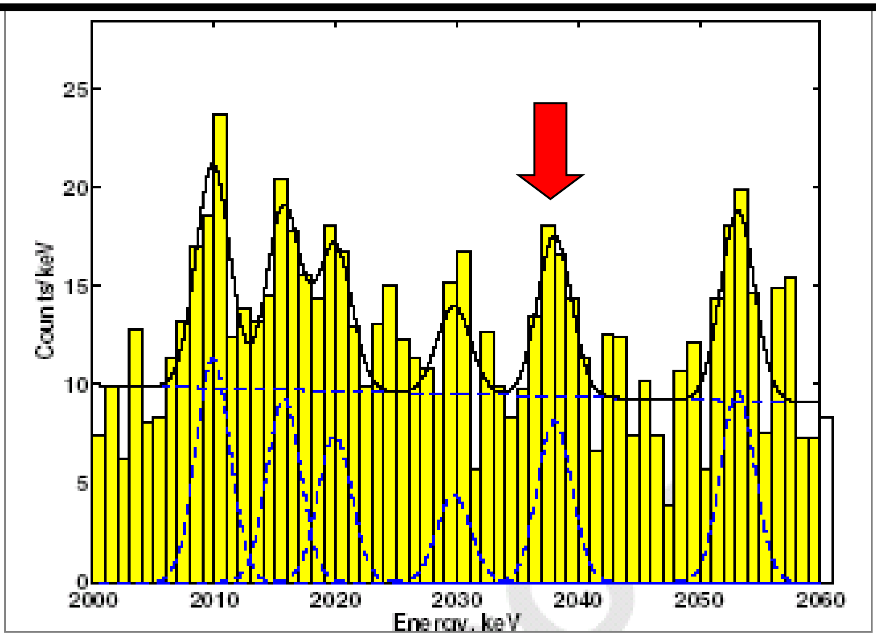


2004: data with higher statistics and with better quality show an increase of the statistical significance of the "peak":

Klapdor-K et al. Phys. Lett. B 586 (2004) 198-212

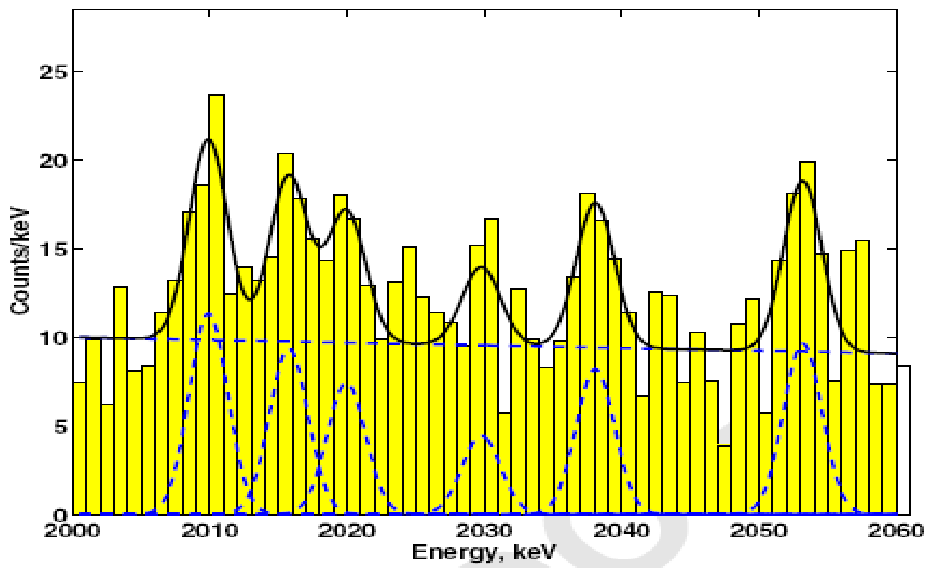
$\tau_{1/2}^{0n}$ = (0.69 - 4.18) 10^{25} y (3σ)

➡ $<m_\nu>$ = 0.24 - 0.58 eV



^{76}Ge: Heidelberg-Moscow experiment a controversial result

skepticism in DBD community



comments and reanalysis:

Aalseth CE et al. , Mod. Phys. Lett. A 17 (2002) 1475

Feruglio F et al. , Nucl. Phys. B 637 (2002) 345

Zdezenko Yu G et al., Phys. Lett. B546(2002)206

replies:

Klapdor-Kleingrothaus HV hep-ph/0205228

H.L. Harney, hep-ph/0205293

- One peak not explained
- Looking at a larger range, many structures resemble the DBD “peak” and need to be explained
- The statistical significance depends on the flat component of the background

$<m_\nu>$ [eV]	
0.2-0.6	QRPA Rodin Faessler Simkovic Vogel, nucl-th:0706.4304v1
0.1-0.4	QRPA Kortelainen Suhonen 2007, Phys. Rev C
0.3-0.7	QRPA Civitarese Shuonen , nucl-th/0208005
0.4-1.1	Nuclear Shell model, Caurier et al. nucl-th/0801.3760

^{76}Ge: IGEX

Collaboration: (ITEP,INR,U.South Carolina; PNNL, U. of Zaragoza, Yerevan)
Location: Canfranc UL (Spain)
Detectors: two enriched Ge diodes

Pulse shape discrimination
117 mol . y = 8.9 kg . y

Bkg at 2 Mev
~ 0.1 (with PSA)
~ 0.2 (without PSA) [cts/(keV. y)]

$T_{1/2}$ > 1.57 10^{25}y with PSA

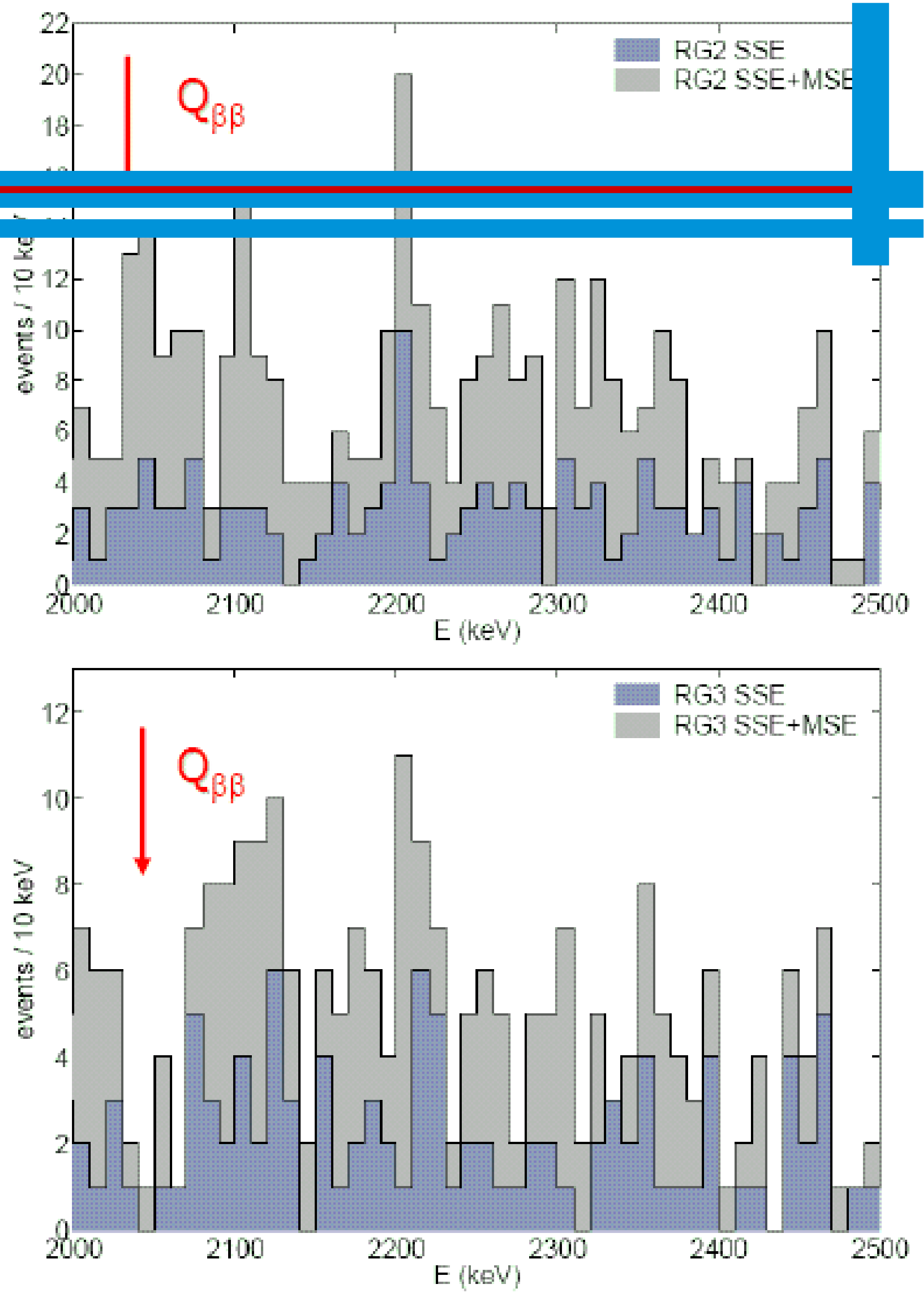


Figure 10: Background spectra before and after the PSD based on the counting of the number of lobes for detectors RG2 (top) and RG3 (bottom).

What if not Ge?

There are several reasons to study more than one isotope. The "Ge way" was the easiest and natural one: this detector is based on a very well known technology,with several different application justifing large efforts in its technical improvement (in purity, size, resolution).

How to choose an isotope/detector/experiment?

These are the ingredients:

NME
isotopic abundance
total mass
Q value
energy resolution

detector technology

I tell you the unusual story that gave birth to bolometers

"bolometer tale"

Once upon a time ... searching for the best DBD candidate a physicist discovered how Nature had been kind with ^{130}Te :

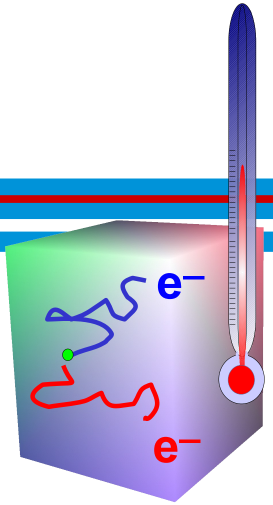
- a good F_N
- a rather high Q-value
- a high i.a. (quite relevant for the empty pockets of the experimentalist).

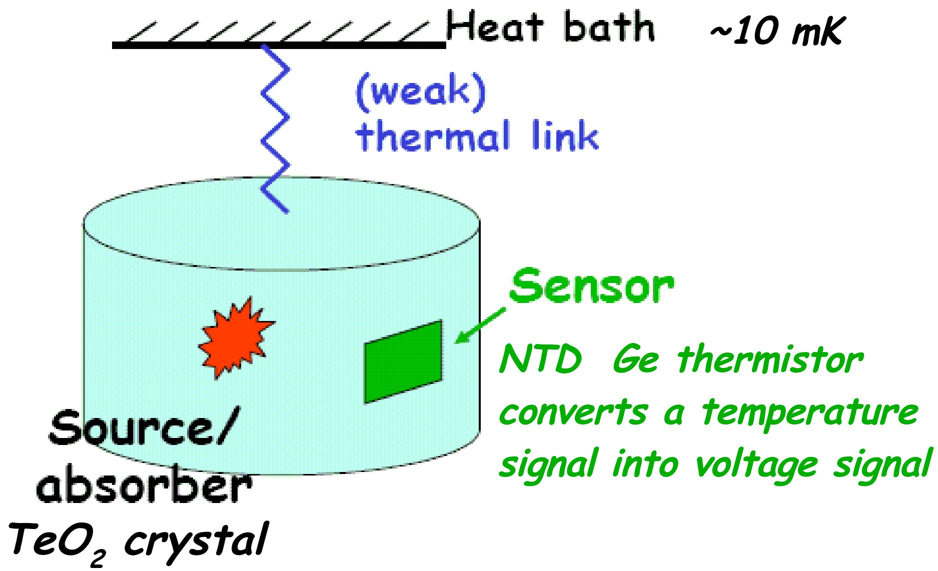
At that time the best DBD experiments used ^{76}Ge diodes, ^{130}Te was/is in principle better ^{76}Ge, the only (not negligible) point was that at that time no solid state detector – made of Te - with performances competitive with Ge diodes did exist.

The solution: **JUST "INVENT" IT (this looked like a DREAM)**

that is build a bolometric detector (at that time - '80 – maximum size was ~ grams) and reach energy resolution and masses as good as HPGe

bolometers





bolometers = low temperature calorimeters

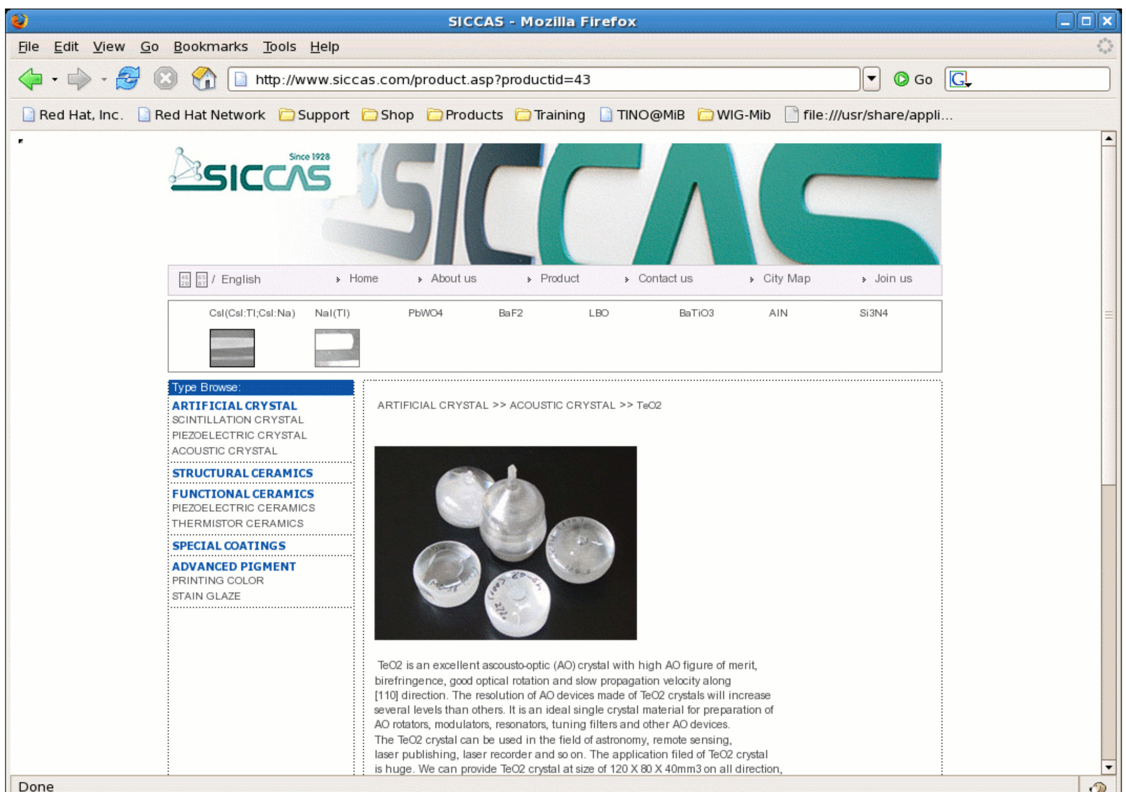
the energy released by the particle interaction in the absorber (calorimetric mass) is read-out after thermalization by a temperature transducer (thermometer)

- wide choice of materials
- detectors with an energy resolution
- (comparable with that of Ge diodes)

- tech. suggested in 1985 by E. Fiorini and T.O. Niinikoski
- the first Te detector worked in 1989
- first bolometric DBD experiment in 1997
- predecessor of CUORICINO : 20 crystal array (MiDBD)
- other applications: Dark Matter detection (CDMS, Edelweiss, CRESST)

"bolometer tale"

Our physicist it well known to be a lucky man and he happened to be told during a meeting that there was a crystal producer in China that was growing beautiful TeO_2 crystals.



TeO_2 has good thermal, mechanical, radioactive properties

- easy to grow large size crystals (up to 6x6x6 cm^3 =1.2 kg)
- good intrinsic radiopurity (better than 10^{-13} g/g in U and Th)
- extremely good bolometric performances

  (FWHM at the ^{130}Te DBD transition energy ~ 7 keV)

extensively tested by the Milano group during the last 10 years

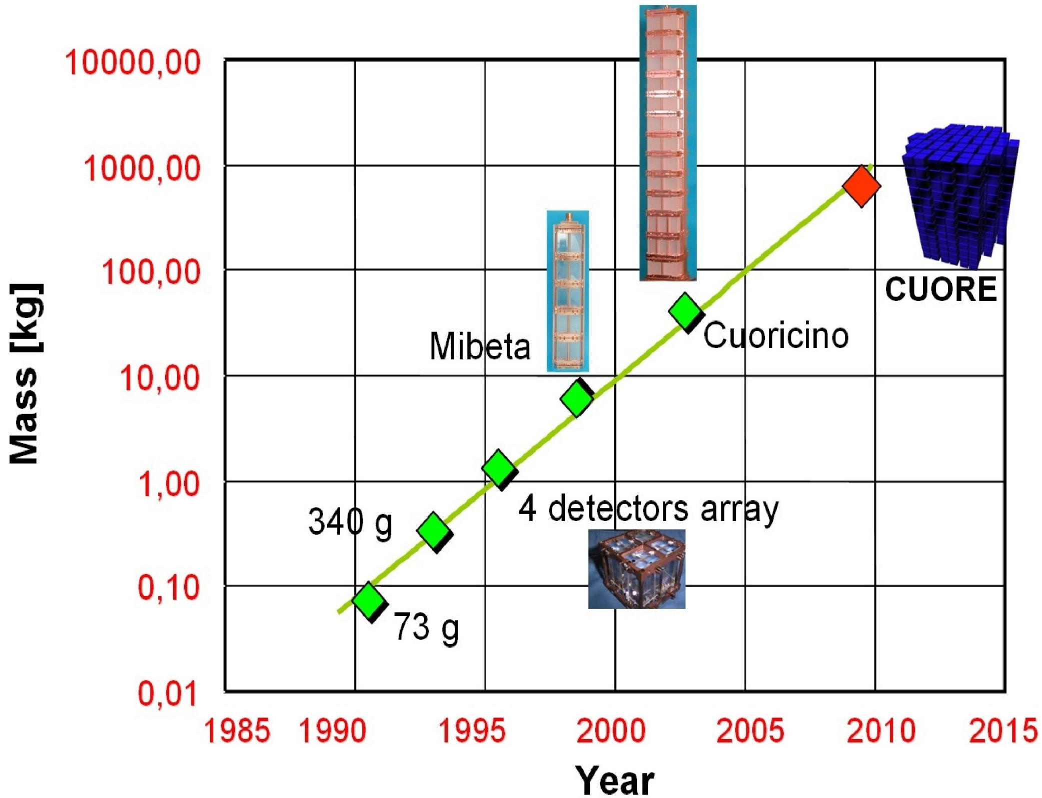
standard production by SICCAS (Shanghai China)

"bolometer tale"

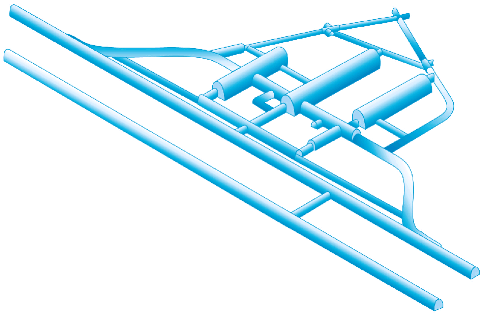
... AND THE REALITY OVERCAME THE DREAM ...

- the detector did work very well
- in the years detectors growing in size without showing deterioration of performances (resolution)
- the bulk radio-purity of these crystals have always be extremely high
- our physicist is now the spokesperson of a big collaboration (CUORE)

The Moore's law of TeO_2 bolometers



^{130}Te: Cuoricino



Lab. Naz. del Gran Sasso - Italy

source=detector experiment

- *tech. suggested in 1985*
  by E. Fiorini and T.O. Niinikoski
- *first experiment in 1997*

source ~ 40 kg natural TeO_2

(^{130}Te i.a. 33.8 % => ~ 11 kg ^{130}Te)

The experiment was recently closed (June 2008).

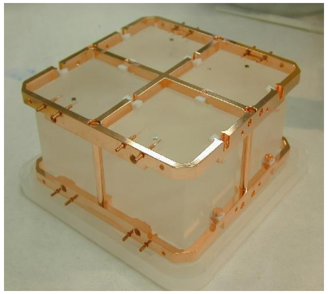
A 1 ton experiment (CUORE) is under construction

Cuoricino detector

40.7 kg TeO_2 ~ 11 kg ^{130}Te

44 TeO_2 crystals 5x5x5 cm^3

+ 18 TeO_2 crystals 3x3x6 cm^3



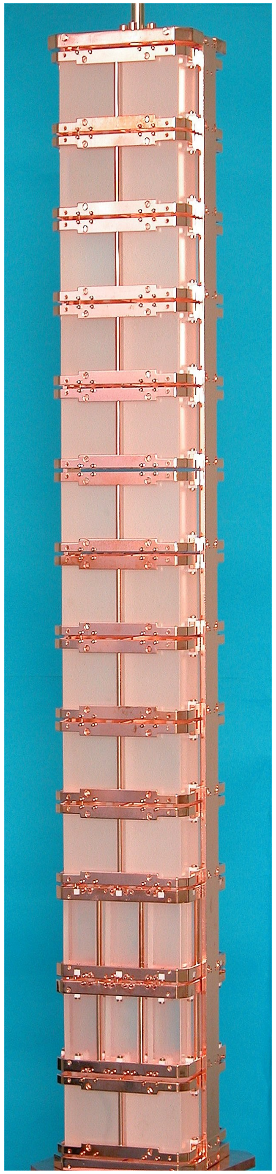
11 modules, 4 detector each,
crystal dimension 5x5x5 cm^3
crystal mass 790 g

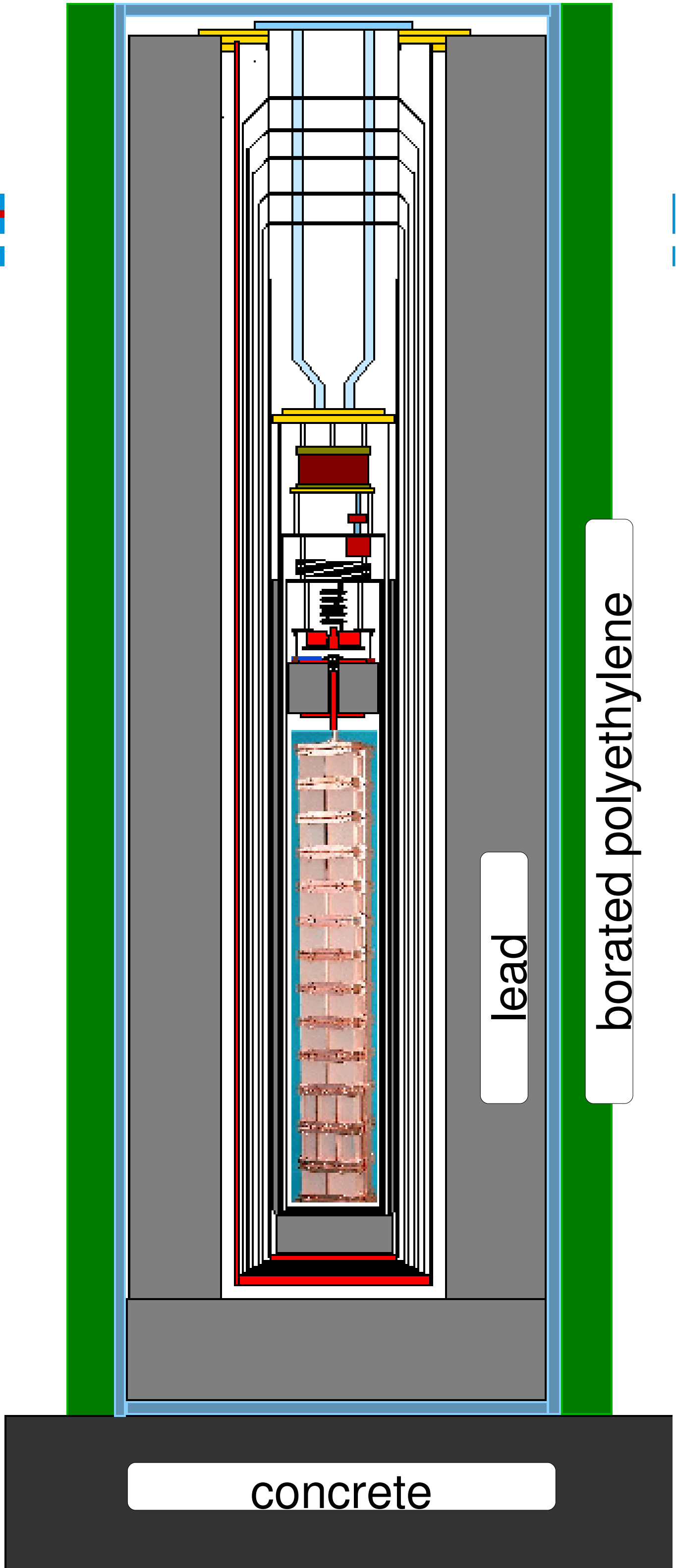
4 x 11 x 0.79 = 34.76 kg of TeO_2

2 modules, 9 detector each,
crystal dimension 3x3x6 cm^3
crystal mass 330 g

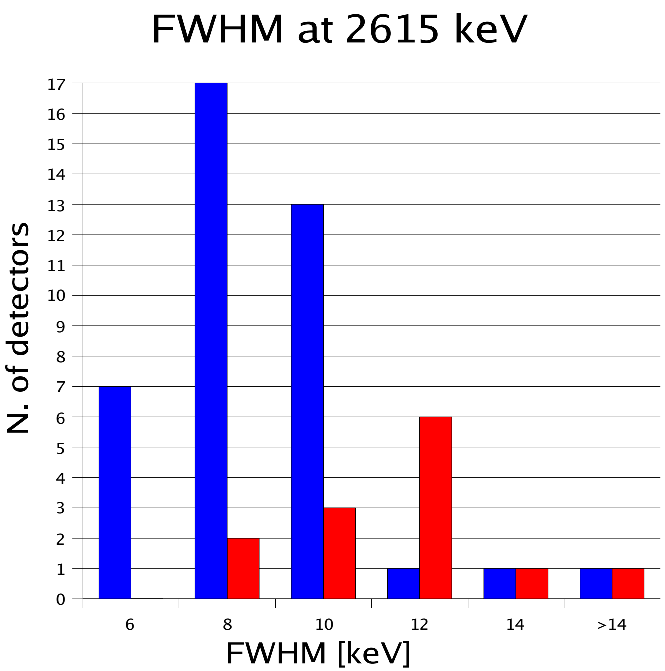
9 x 2 x 0.33 = 5.94 kg of TeO_2

two small crystals enriched in ^{130}Te
two small crystals enriched in ^{128}Te



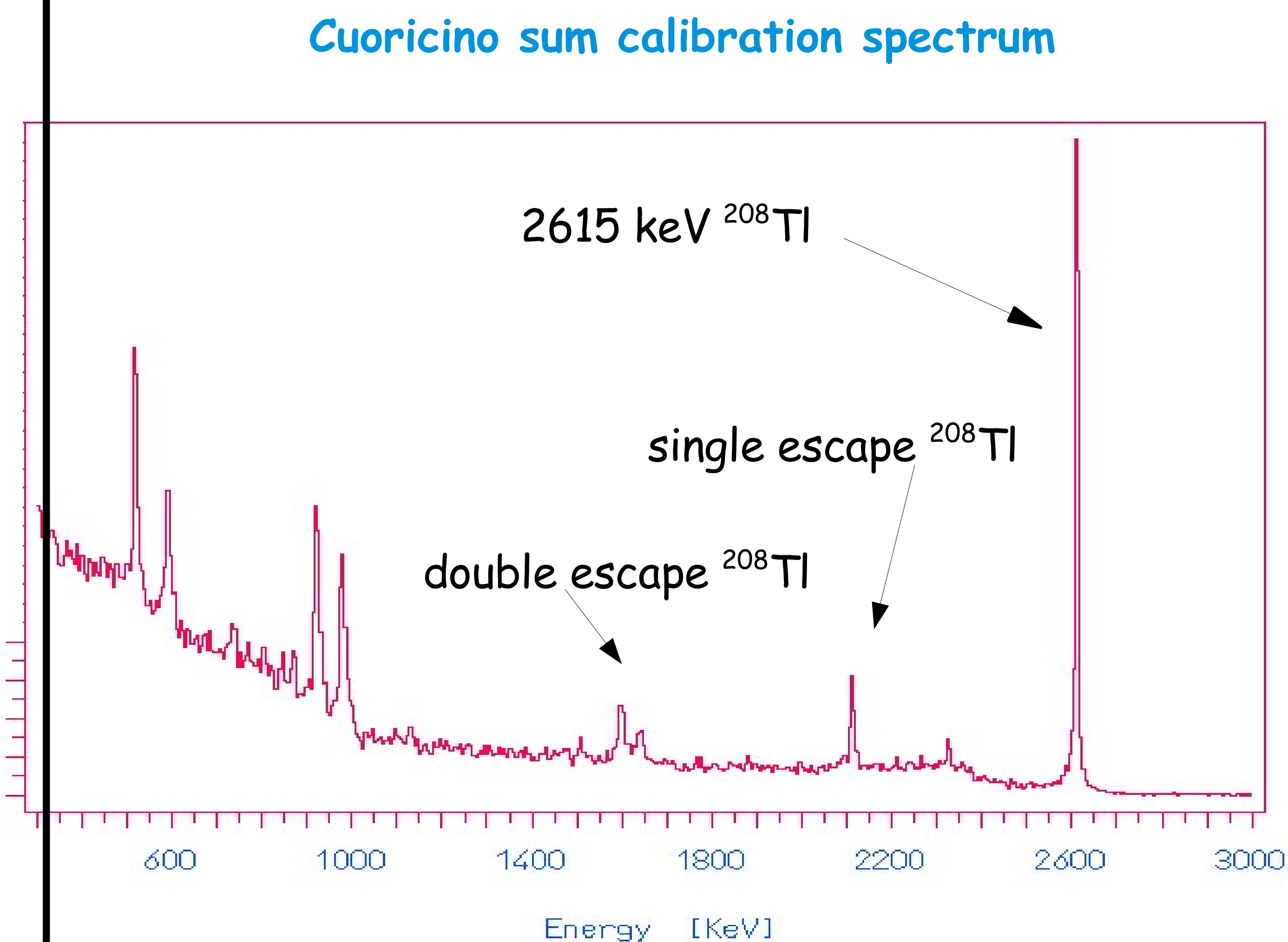


an array behaving as a single detector:

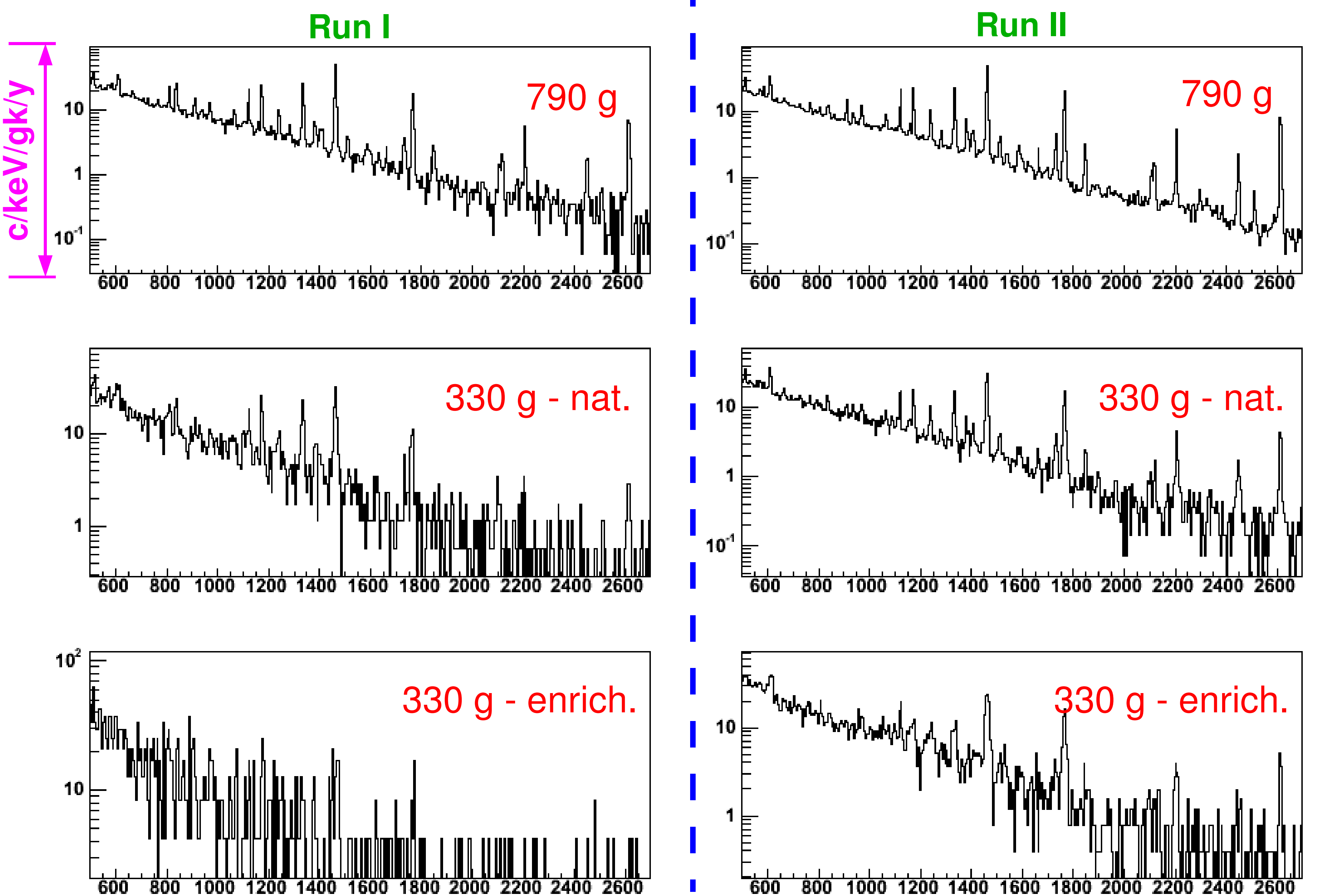


5x5x5 crystals
<FWHM> 7.5 +/- 2.9 keV

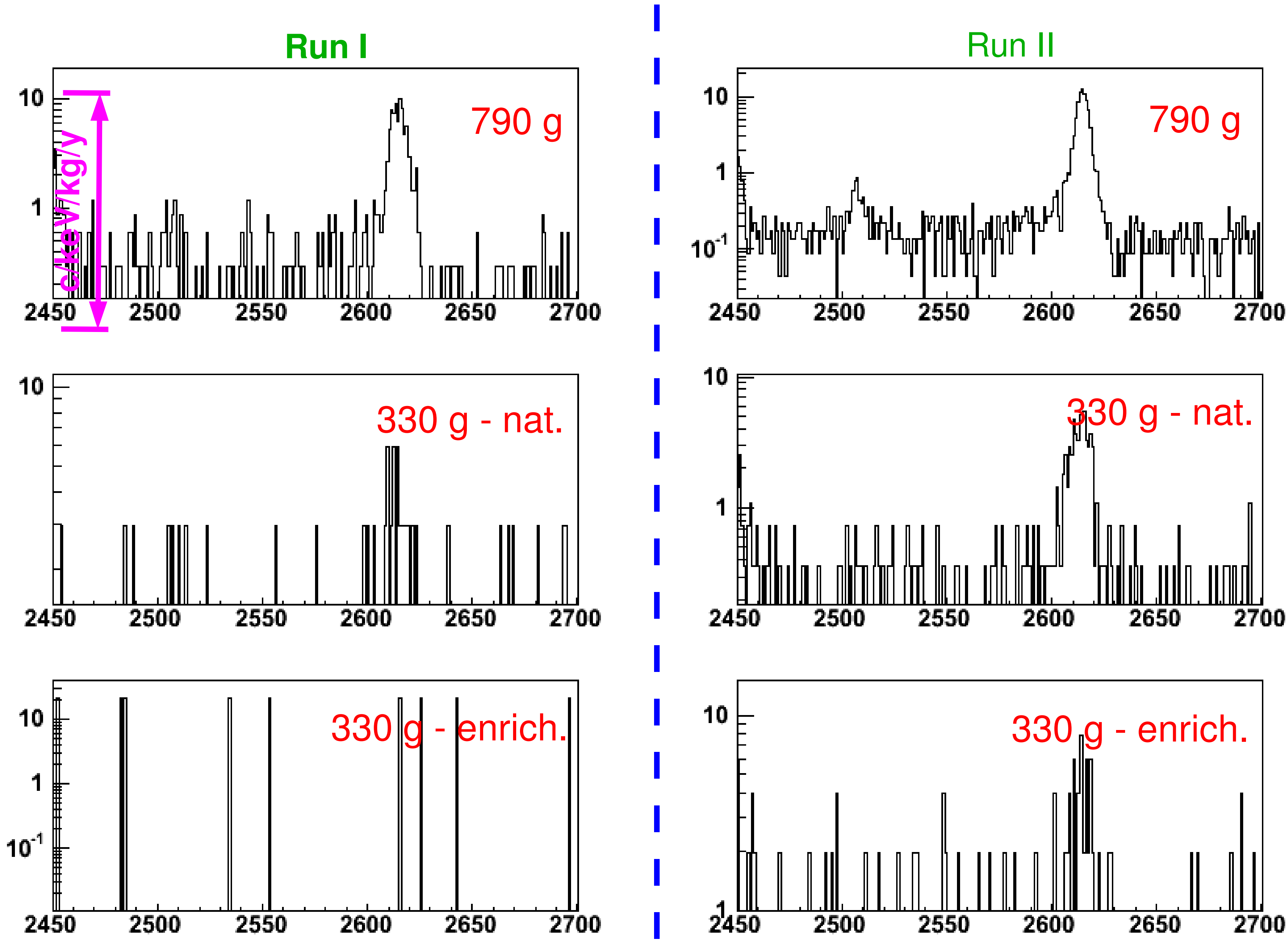
3x3x6 crystals
<FWHM> 9.6 +/- 2.5 keV



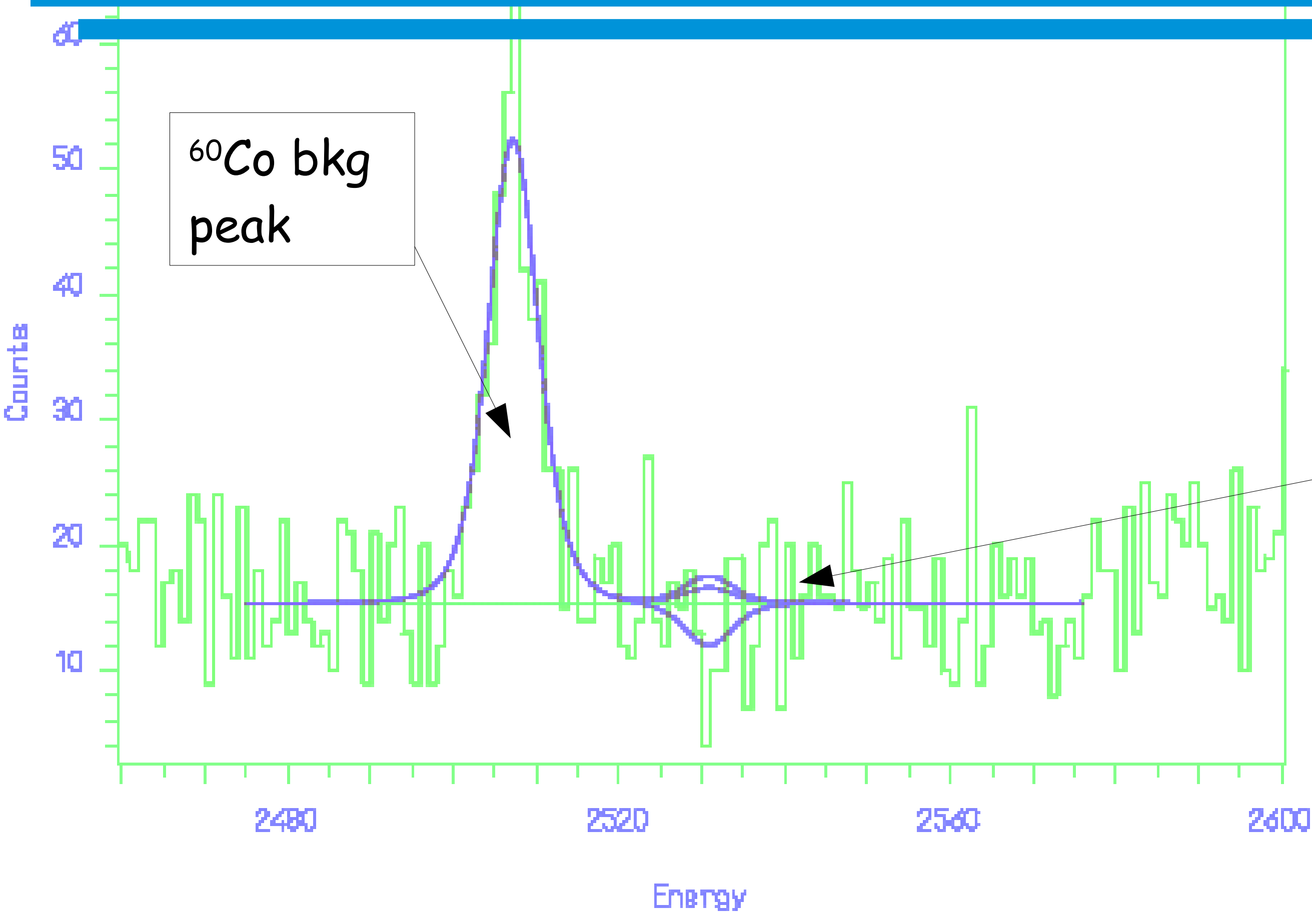
Cuoricino: sum spectra in the γ region



Cuoricino: sum spectra in the $\beta\beta$ region



Cuoricino $0\nu\beta\beta$ result:



background in the $\beta\beta$ region
~ 0.18 evts/y/kg/keV at $Q_{\beta\beta}$

^{130}Te $\beta\beta$ Q-value
2530 keV

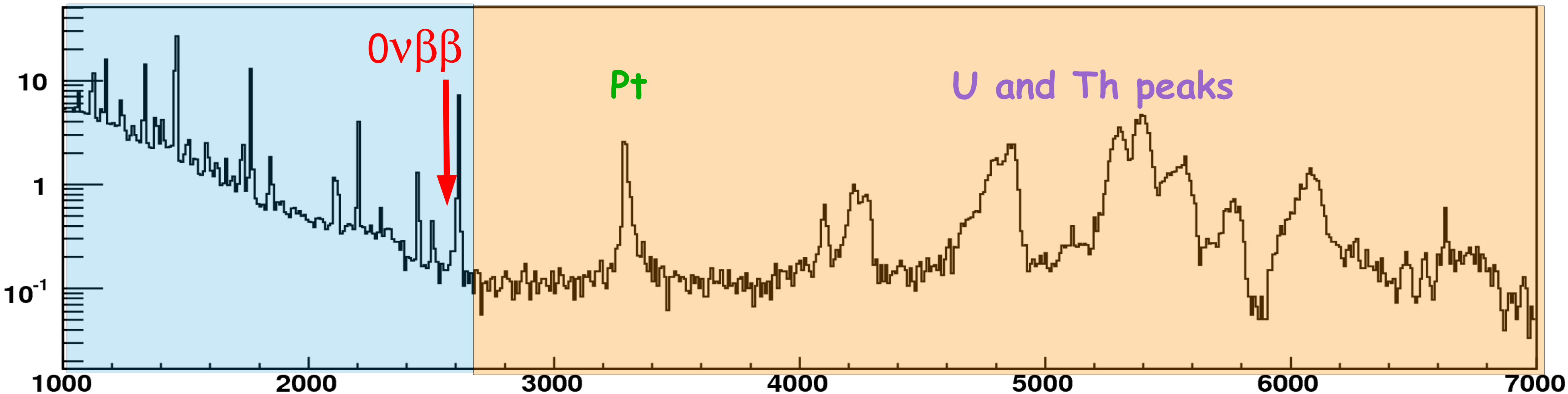
90%C.L. limit
68%C.L. limit
best fit (negative)

$\tau_{1/2} > 3.1\ 10^{24}$ [y] @ 90% C.L.

$<m_n> <$ (0.2– 0.98) [eV]

to be published
previous result Phys. Rev. C 78 (2008) 035502

Cuoricino background



γ region

α region (internal or surface contaminations)

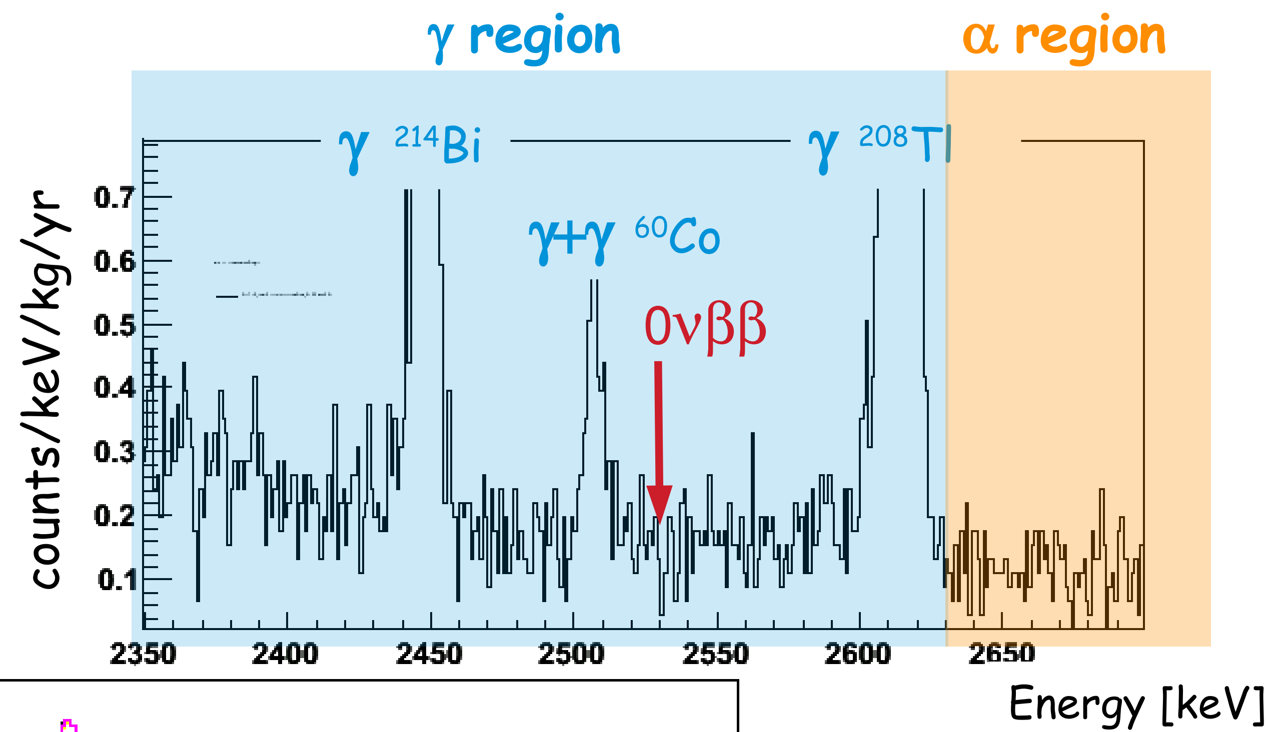
peaks are due to
- ^{238}U, ^{232}Th contaminations in the cryostat
- ^{60}Co cosmogenic activation of Cu
- ^{40}K ? no info on its location

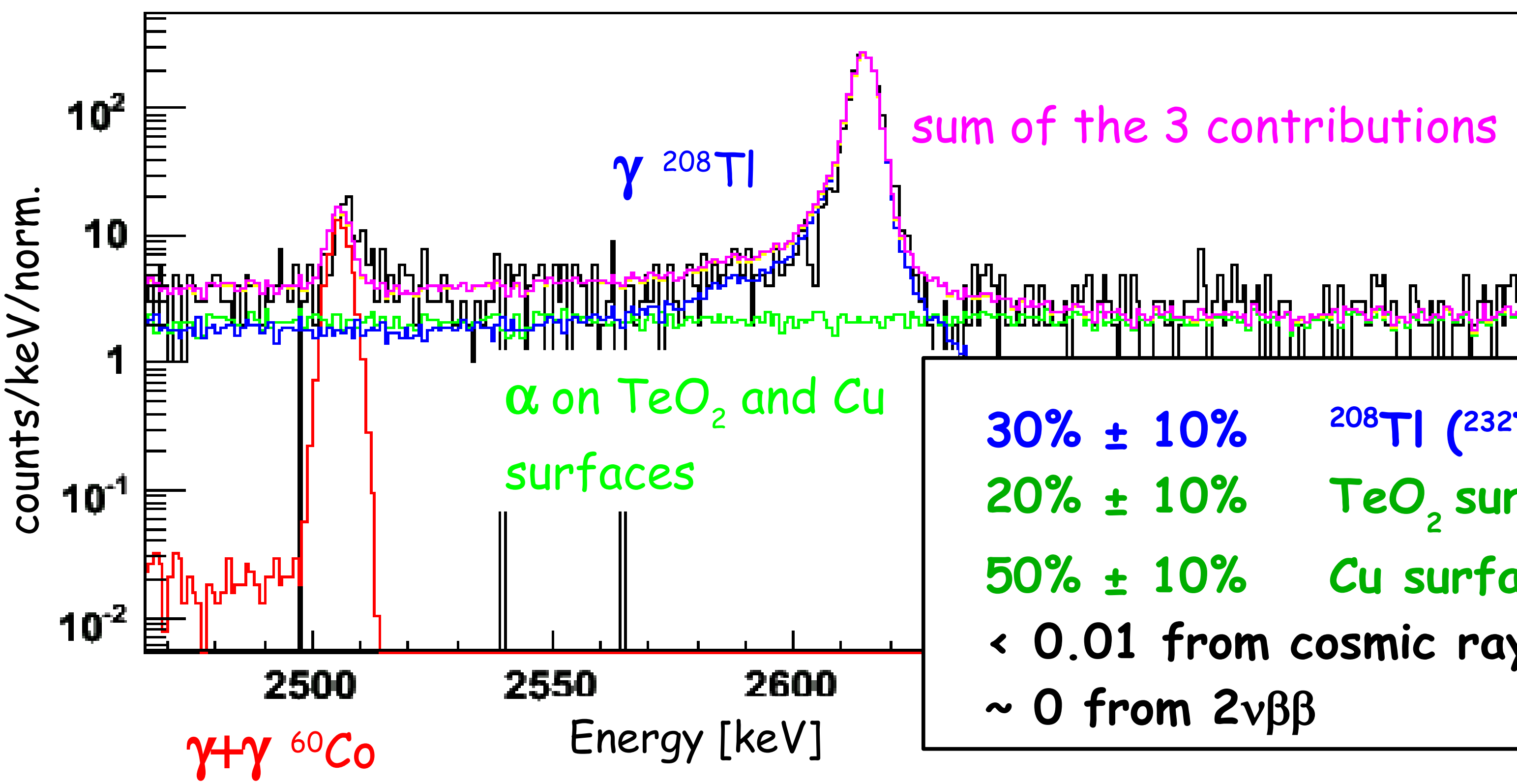
continuum accounted for by
- degraded γ

peaks are due to
- ^{238}U, ^{232}Th surf. contam of TeO_2 crystals
- ^{190}Pt bulk contam. of TeO_2
- minor contribution form ^{238}U, ^{232}Th bulk. contam of TeO_2 crystals

continuum accounted for by
- degraded α (surf. contam. of Cu?)

Cuoricino background in the ββ region





30% ± 10% ^{208}Tl (^{232}Th cryostat)

20% ± 10% TeO_2 surfaces (α ^{232}Th or ^{238}U)

50% ± 10% Cu surfaces (α ^{232}Th or ^{238}U)

< 0.01 from cosmic rays (n and μ)

~ 0 from 2νββ

Cuoricino result vs. HM claim of evidence:

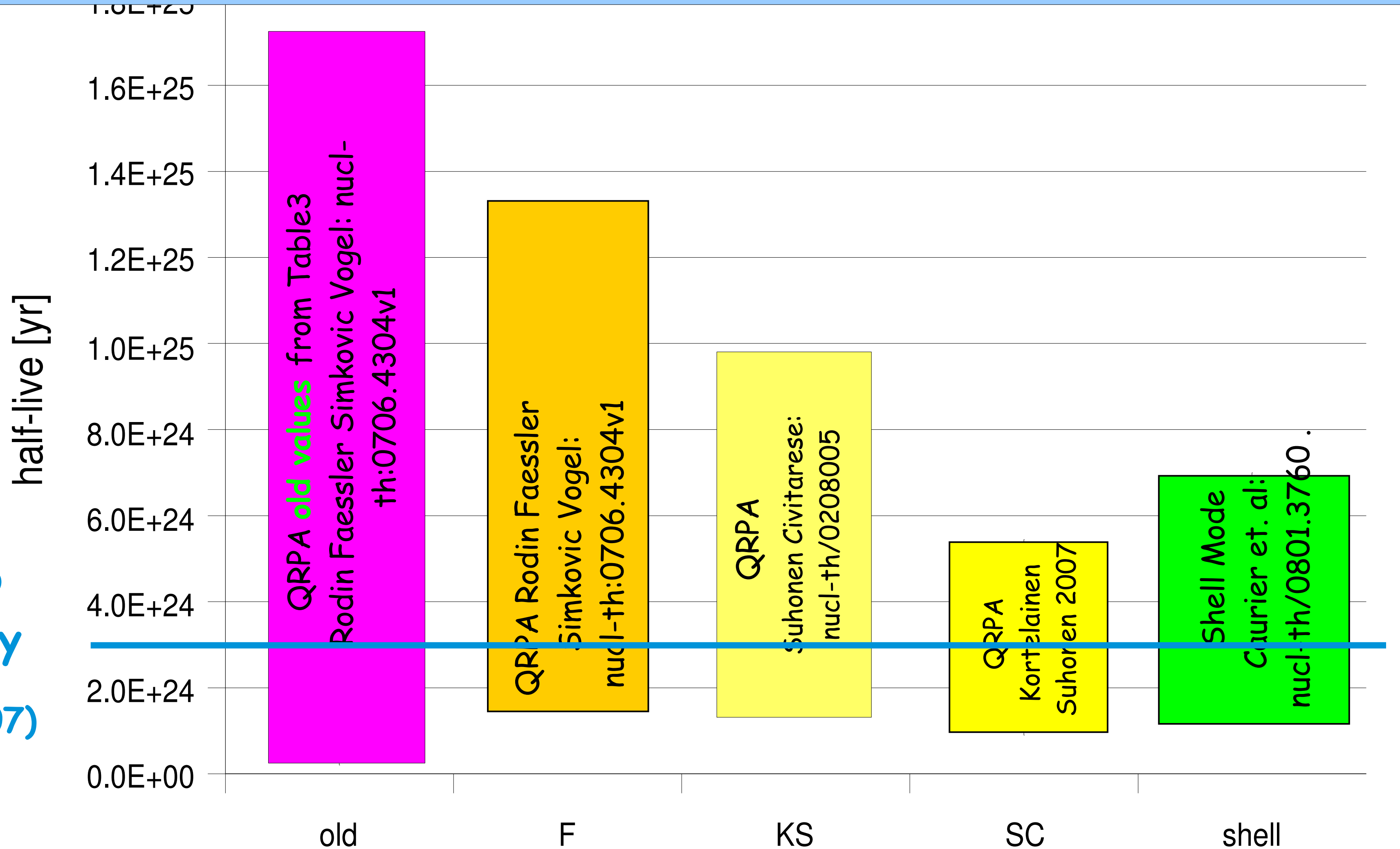
HM claim of evidence:

$T_{1/2}^{0\nu}$ (y) = (0.69-4.18) × 10^{25} (3σ range)

$T_{1/2}^{-1} = F(Q_{\beta\beta},Z)\ |M|^2\ \langle m_\nu \rangle^2$

^{130}Te predicted

$T_{1/2}^{0\nu}$ (y) range

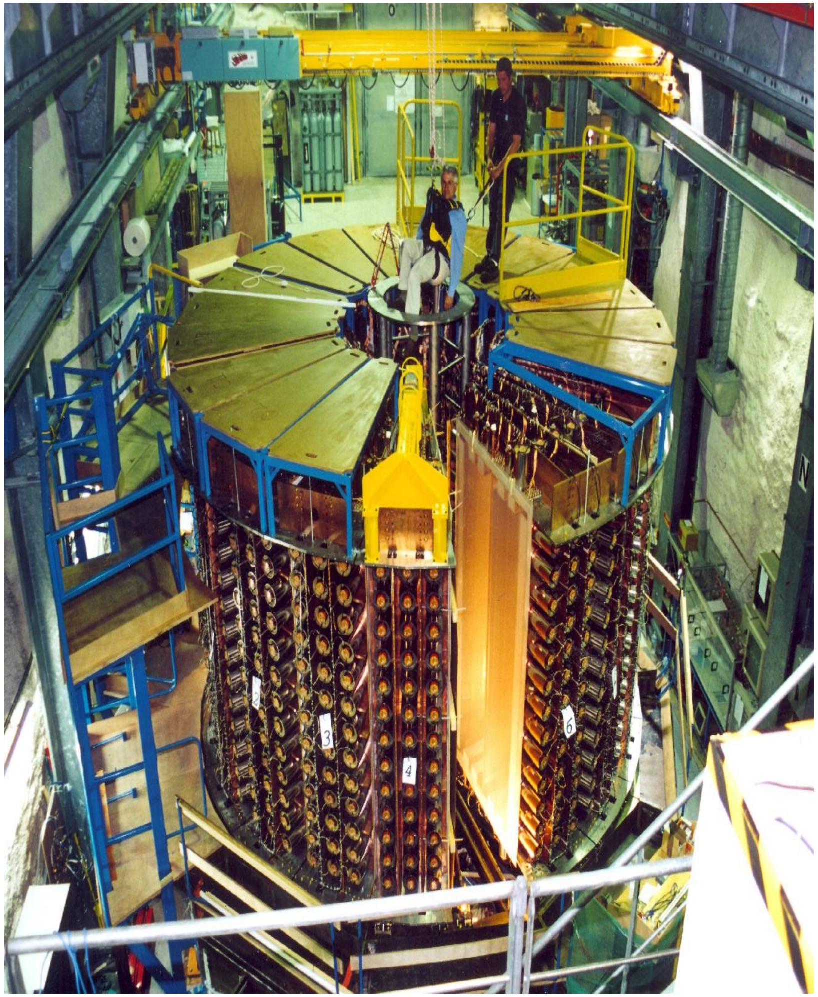


Cuoricino

3.1x10^{24} y

(summer 2007)

NEMO3: Neutrino ettore Majorana Observatory



LS Modane, FR
Tunnel Frejus

4800 m.w.e

During installation AUGUST 2001

F. Piquemal (CENBG)

NEMO3 detector

tracking detector He + 4% ethil alcohol + Ar

6180 vertical drift cells operated in Geiger mode

each cell has an optagonal shape and is 2.7 m long, 3D tracking is accomplished with the arrival time of the signals on the anode wires and the plasma propagation times to the ends of the drift cells

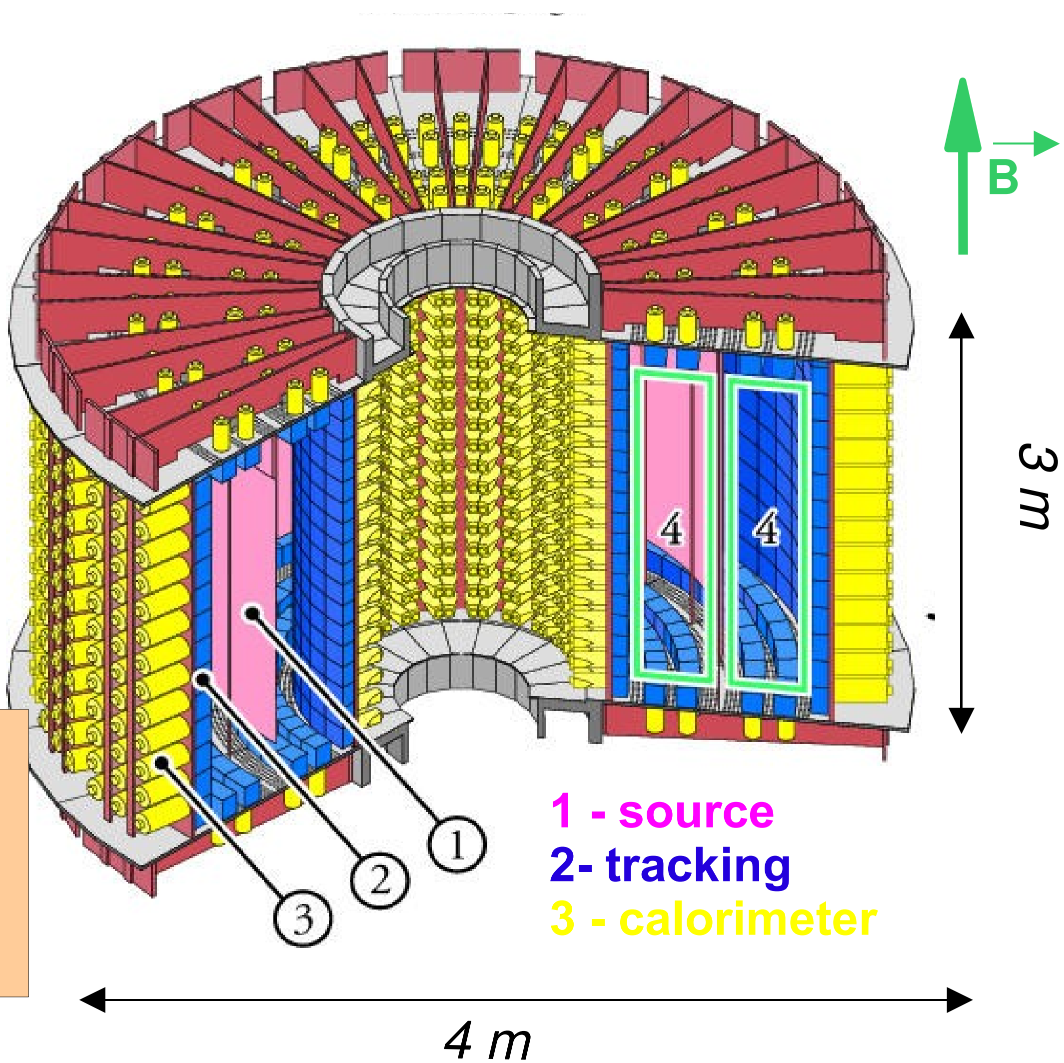
calorimeter

1940 plastic scintillators + PMTs

for energy and TOF measurement

magnetic field B=25 G

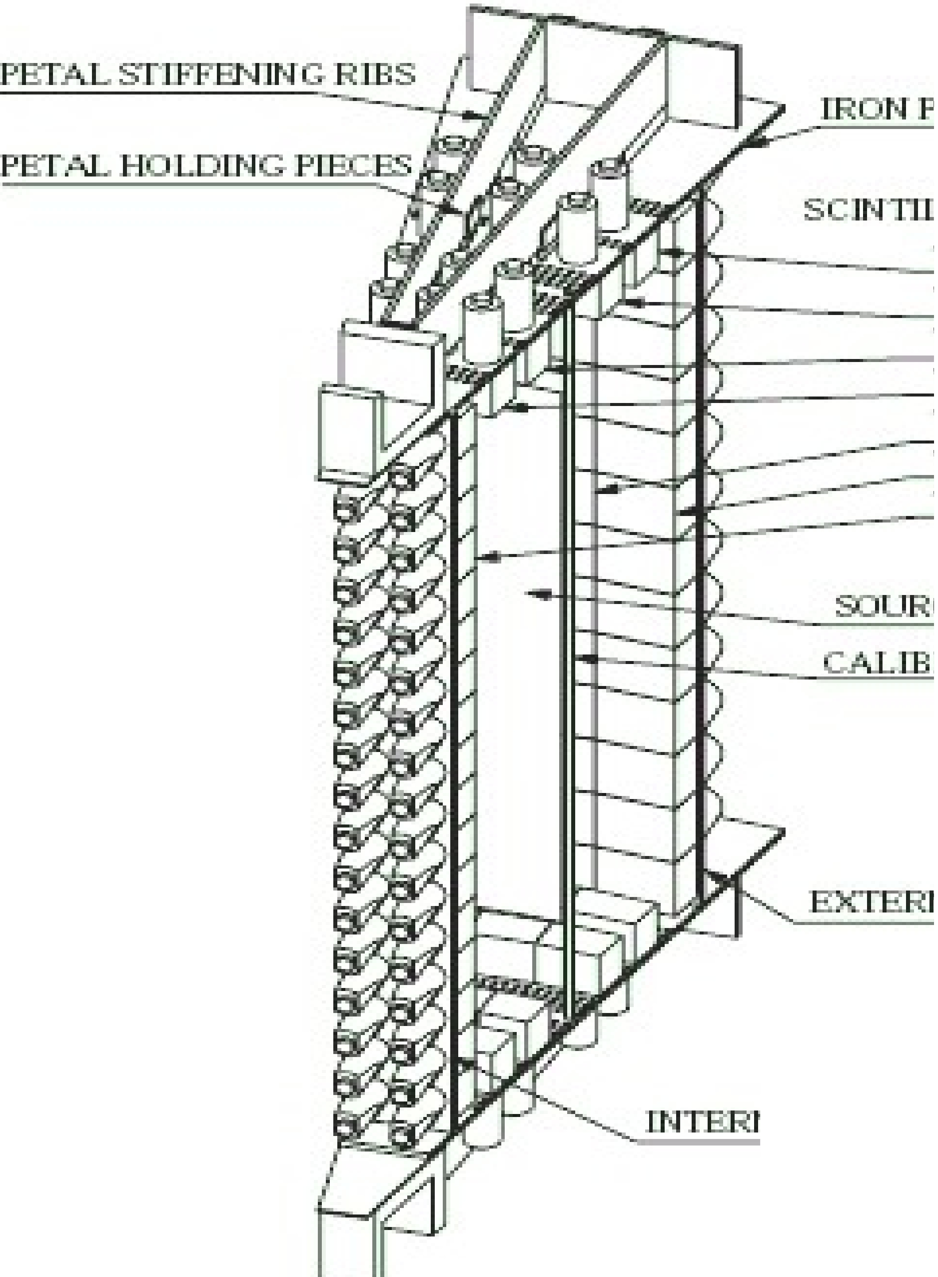
for charge identification

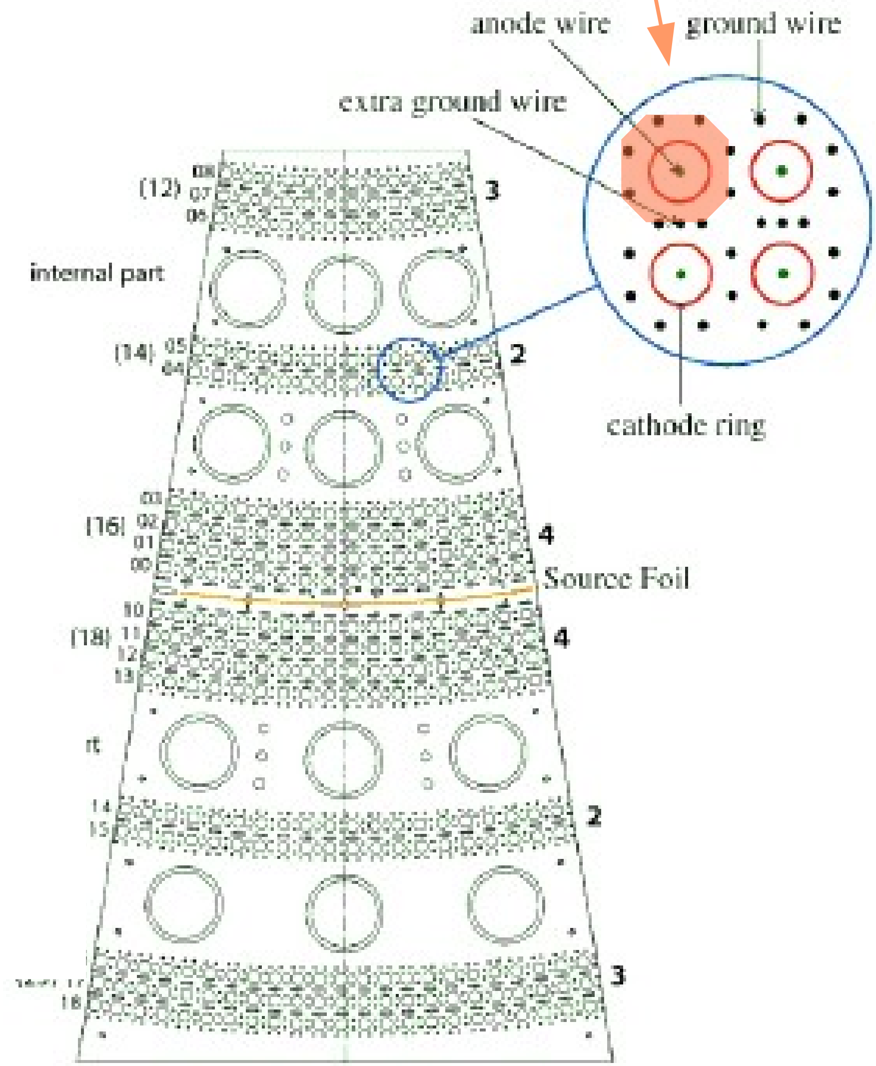


provides:

- track reconstruction
- energy resolution σ_E\E ~ 3% at 3 MeV
- particle identification

top view of a drift cell=
1 anode wire + 9 ground wires
a cathode ring

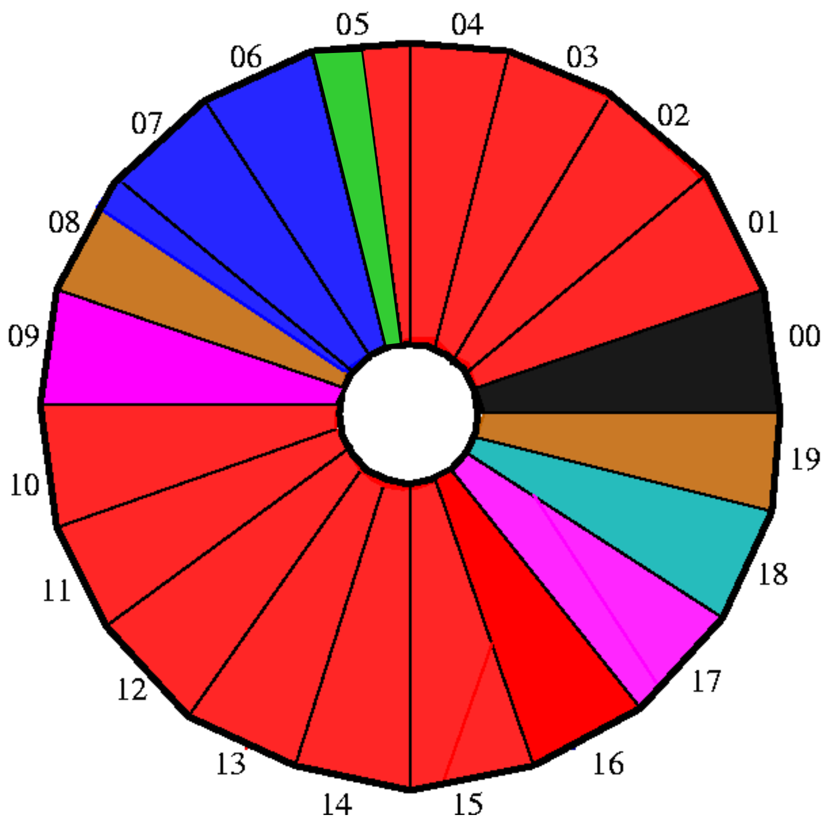




NEMO3 detector: a sector

NEMO3: the sources

sources are foils (30-60 mg/cm2) of different material forming a cylindrical patchwork inserted in the middle of the 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

^{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

(All enriched isotopes produced in Russia)

NEMO3: detector

PMTs

scintillators

ββ isotope foils

Cathodic rings

Wire chamber

Calibration tube

NEMO3: shields

top/bottom wood shield

40 cm thick

moderates/absorbs neutrons

water tank

lateral, 30 cm thick

moderates/absorbs neutrons

since 2004 added boron

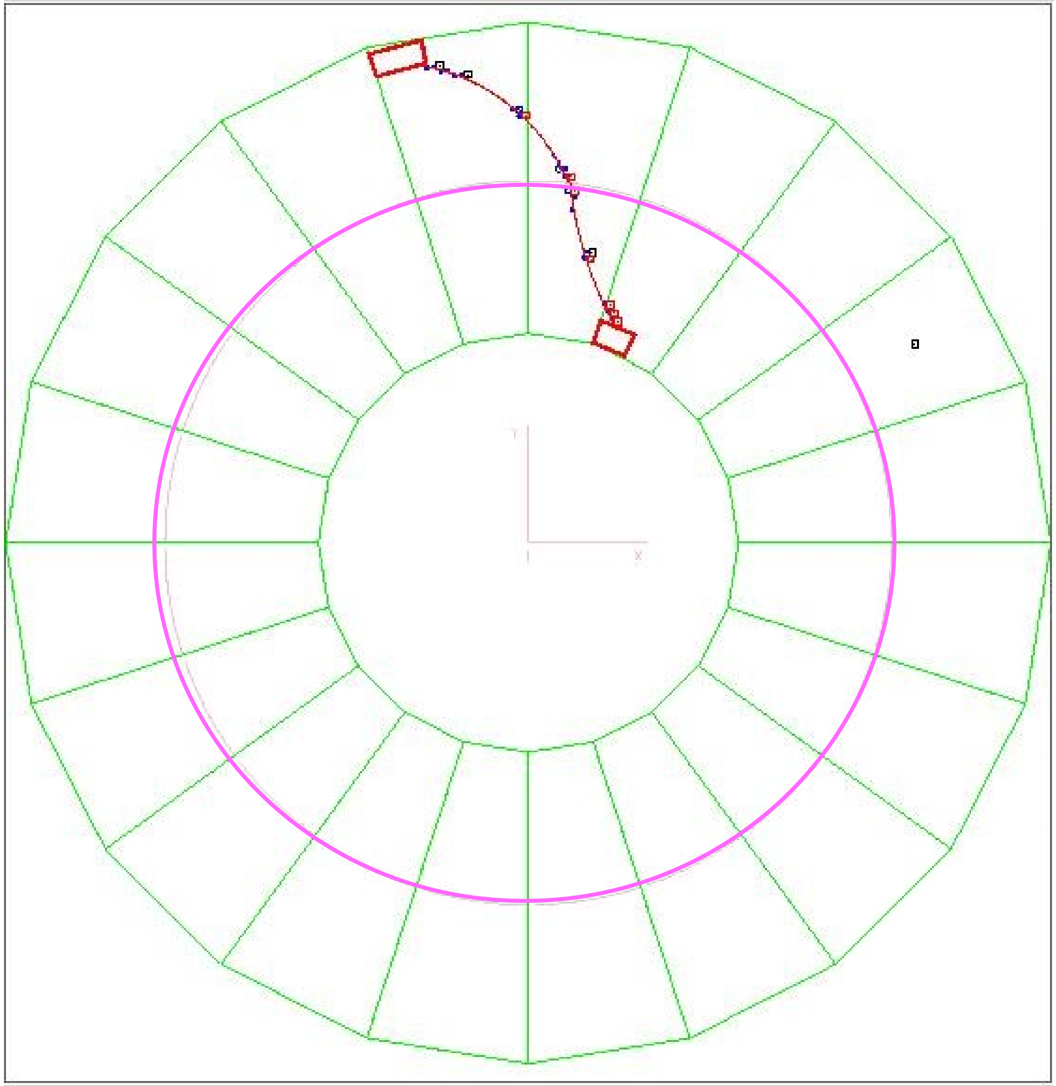
iron shield

18 cm thick

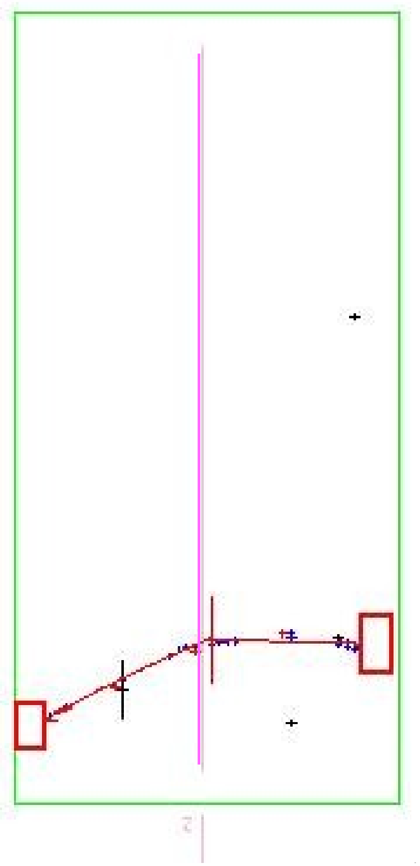
shields from

environmental γ's

NEMO3: a ββ event

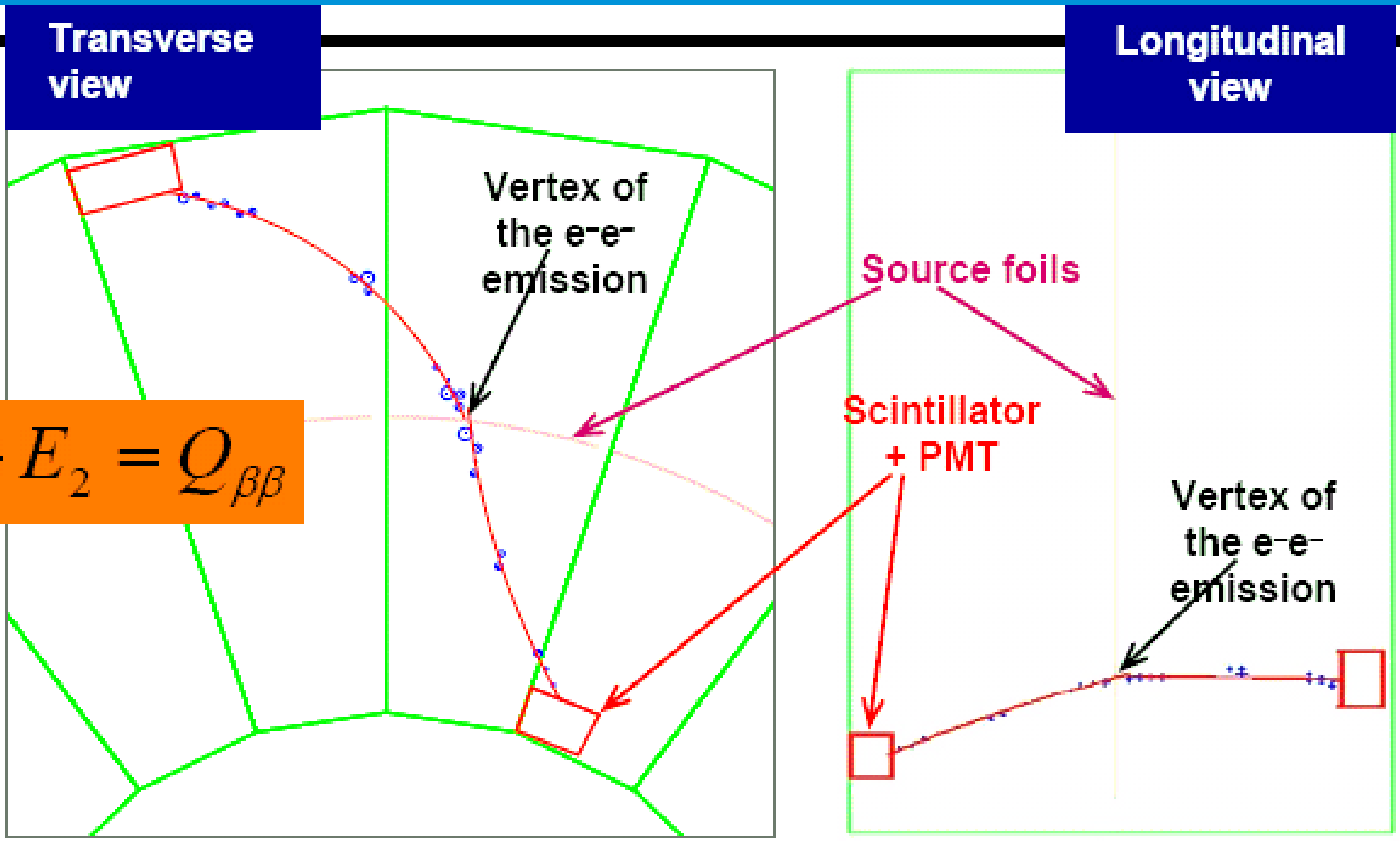


Top view



Side view

NEMO3: a ββ event



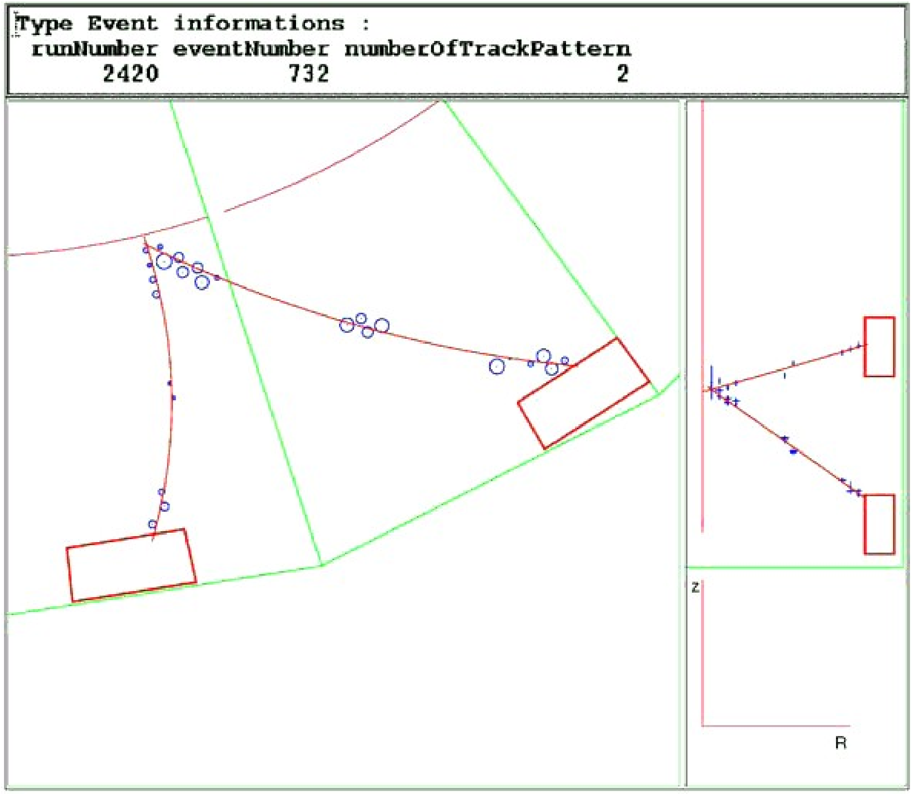
$$E_1 + E_2 = Q_{\beta\beta}$$

Observables of the final state

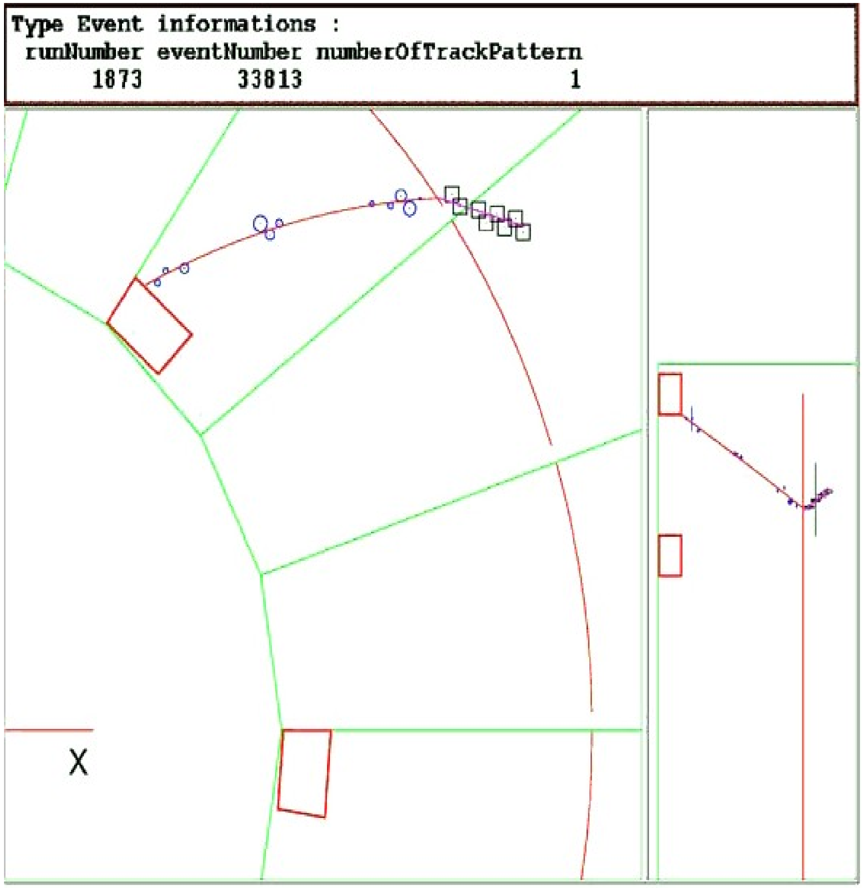
- Trajectories of the 2 electrons
- Energies of the 2 electrons
- Time of flight
- Curvature of the tracks in a B-field (+ or -).

NEMO3: background

most background sources produce events quite different fromthose due to a ββ decay



e⁺ e⁻ background event



Decay of some internal contamination producing a single electron event coming from a molybdenum source foil (sector 02) followed by a delayed alpha particle, which is the short straight track represented by open squares. Note the presence of one gamma-ray

NEMO3: background events that can mimic a 0νββ decay

^{100}Mo 0νββ decay - number of events in the $2.8 < E_1+E_2 < 3.2$ MeV window

External Background ^{208}Tl (PMTs)

~ 10^{-3} ββ0ν-like events year^{-1} kg^{-1}

External Neutrons and High Energy gamma

~ 0.02 ββ0ν-like events year^{-1} kg^{-1}

^{208}Tl impurities inside the foils

~ 0.06 ββ0ν-like events year^{-1} kg^{-1}

^{214}Bi impurities inside the foils

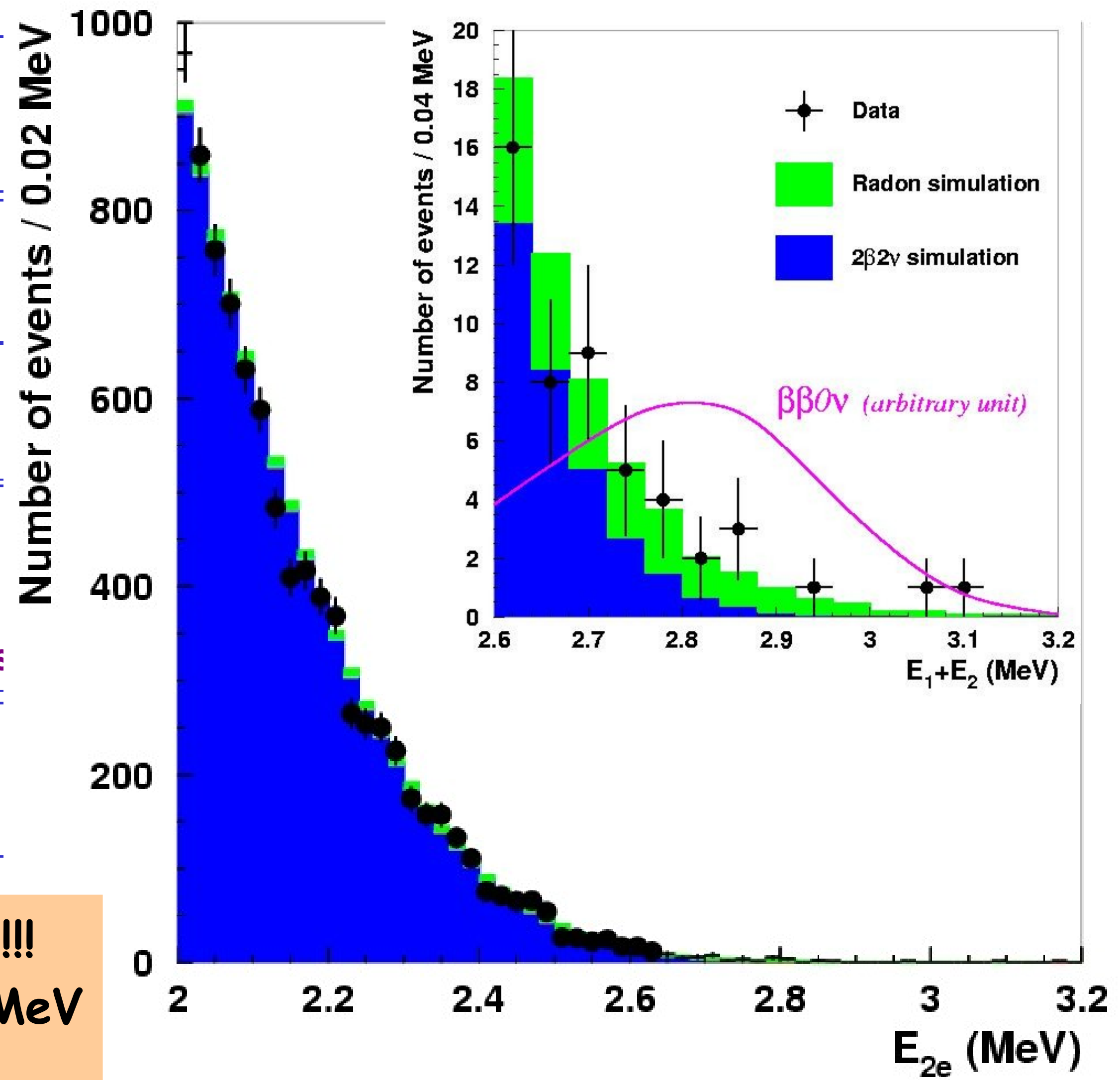
< 0.1 ββ0ν-like events year^{-1} kg^{-1}

Dominated by radon in first period, Radon supress

^{100}Mo ββ2ν decay $T_{1/2} = 7.14\ 10^{18}$ y

~ 0.3 ββ0ν-like events year^{-1} kg^{-1}

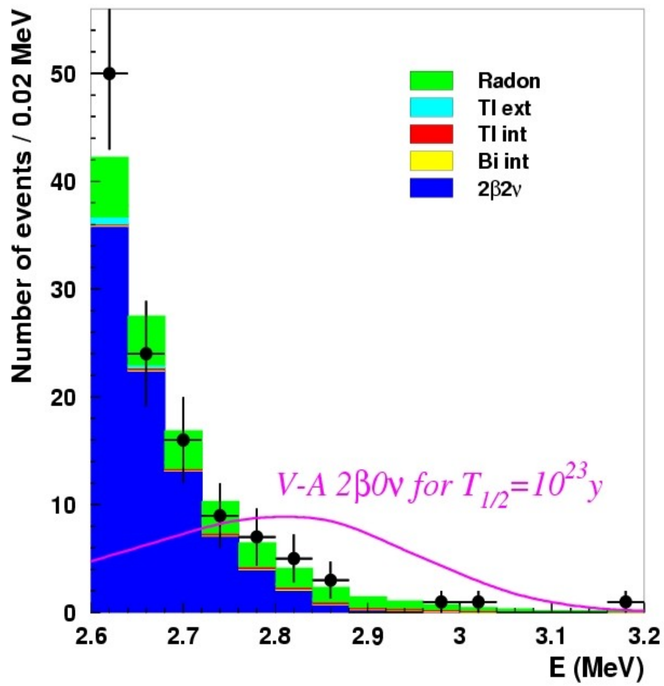
the ultimate bkg comes from 2νββ !!!
(energy resolution FWHM ~ 8% at 3 MeV = 240 keV !!!)



NEMO3 0νββ results (V-A):

^{100}Mo

$T_{1/2}(\beta\beta0\nu) > 5.8\ 10^{23}$ (90 % C.L.)



m_ν < (0.5 - 2.5) eV

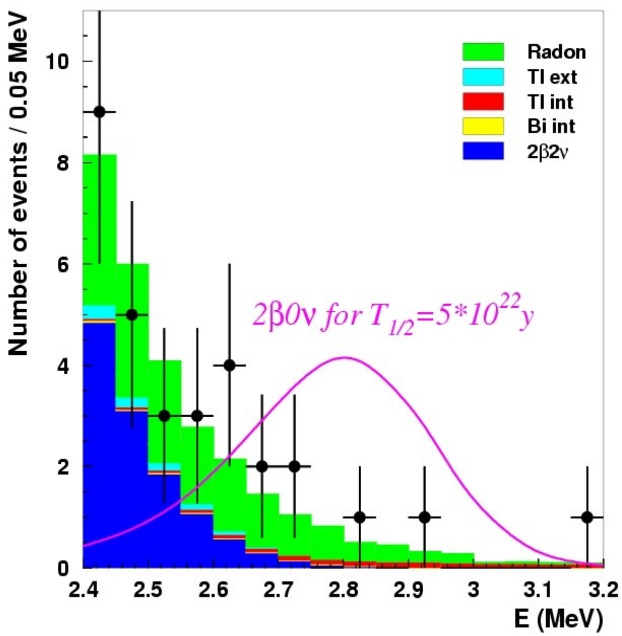
Phase I + II

693 days

^{82}Se

$T_{1/2}(\beta\beta0\nu) > 2.1\ 10^{23}$ (90 % C.L.)

(evts y^{-1} kg $^{-1}$ [2.8-3.2] MeV)



m_ν < (1- 5.9) eV

NEMO3 $0\nu\beta\beta$ results (V+A) and Majoron:

old values to be updated

Limit on Majoron

^{100}Mo: $T_{1/2}(\beta\beta0\nu M) > 1.8\ 10^{22}$ y

$g_M < (5.3 - 8.5)\ 10^{-5}$ (best limit)

Simkovic (1999), Stoica (1999)

^{82}Se: $T_{1/2}(\beta\beta0\nu M) > 1.5\ 10^{22}$ y

$g_M < (0.7 - 1.6)\ 10^{-4}$

Simkovic (1999), Stoica (2001)

Limit on V+A

^{100}Mo: $T_{1/2}(\beta\beta0\nu\ V{+}A) > 2.3\ 10^{23}$ y

$\lambda < (1.5 - 2.0)\ 10^{-6}$

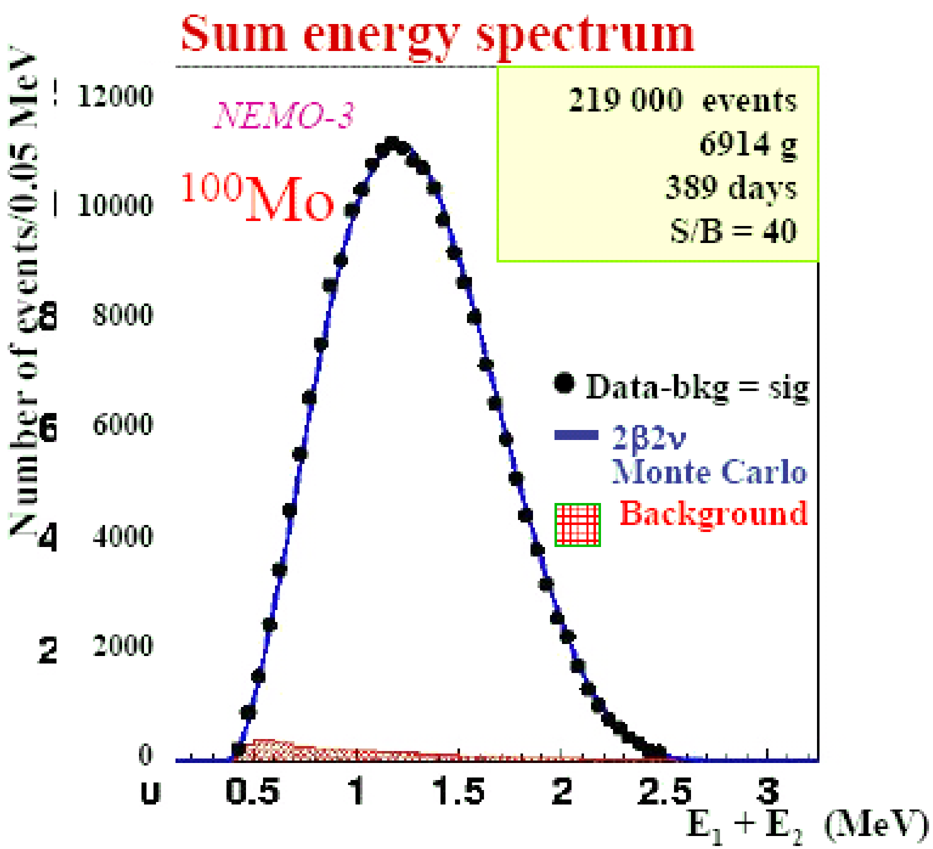
Tomoda (1991), Suhonen (1994)

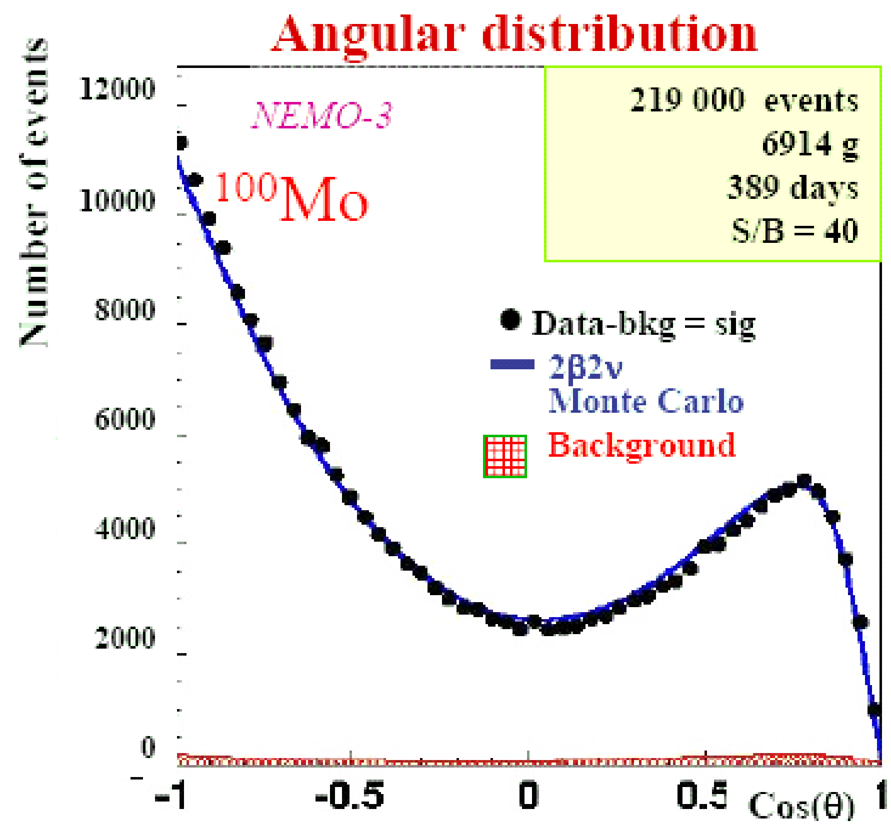
^{82}Se: $T_{1/2}(\beta\beta0\nu\ V{+}A) > 1.0\ 10^{23}$ y

$\lambda < 3.2\ 10^{-6}$

Tomoda (1991)

NEMO3 2νββ results ^{100}Mo 2νββresults





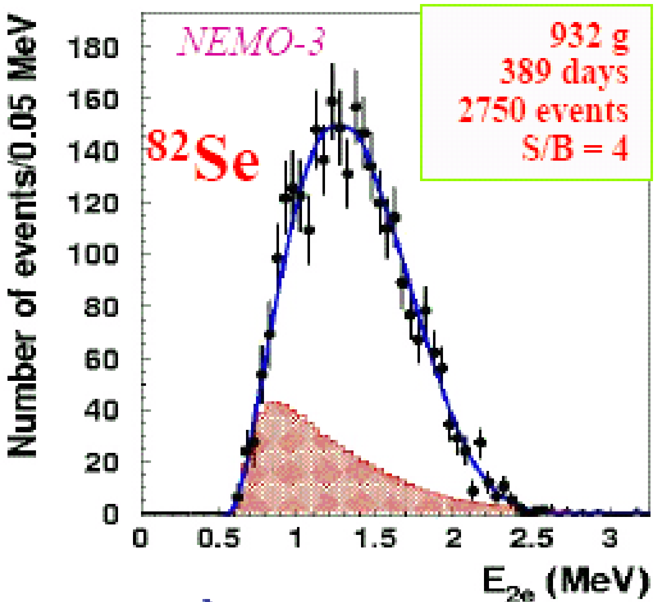
$T_{1/2}(2\nu\beta\beta) = 7.11 \pm 0.02\ (\text{stat}) \pm 0.54\ (\text{syst}) \times 10^{18}$ years

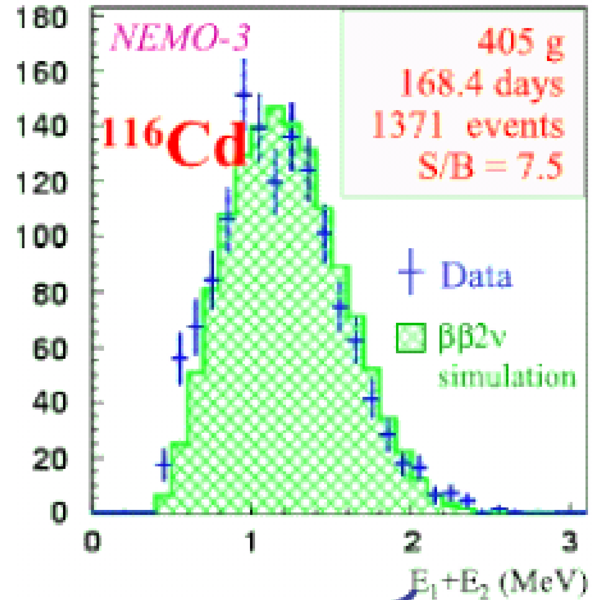
Phase 1: Feb. 2003 – Dec. 2004
"High Radon"

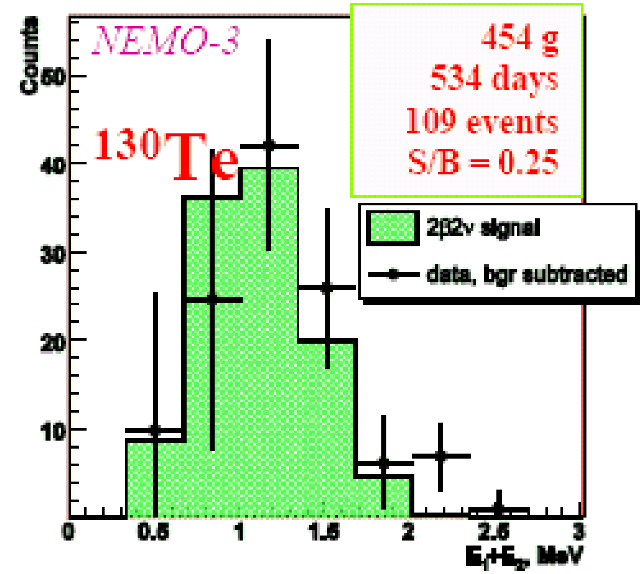
Phys. Rev. Lett. 95 182302 (2005)

Now have in excess of 0.5M events and will update later this year.

NEMO3 2νββ results







Results for Phase I data. Additional statistics are being analysed and to be published soon.

^{82}Se:

$T_{1/2}$ = [9.6 ± 0.3 (stat) ± 1.0 (syst)] × 10^{19} y

^{116}Cd:

$T_{1/2}$ = [2.8 ± 0.1 (stat) ± 0.3 (syst)] × 10^{19} y

Preliminary:

Result for Phase 1 and 2 data.

^{130}Te:

$T_{1/2}$ = [7.6 ± 1.5 (stat) ± 0.8 (syst)] × 10^{20} y

2νββ is important: 1) Experimental input to NME calculation
2) Ultimate background for 0νββ

NEMO3 result vs. HM claim of evidence:

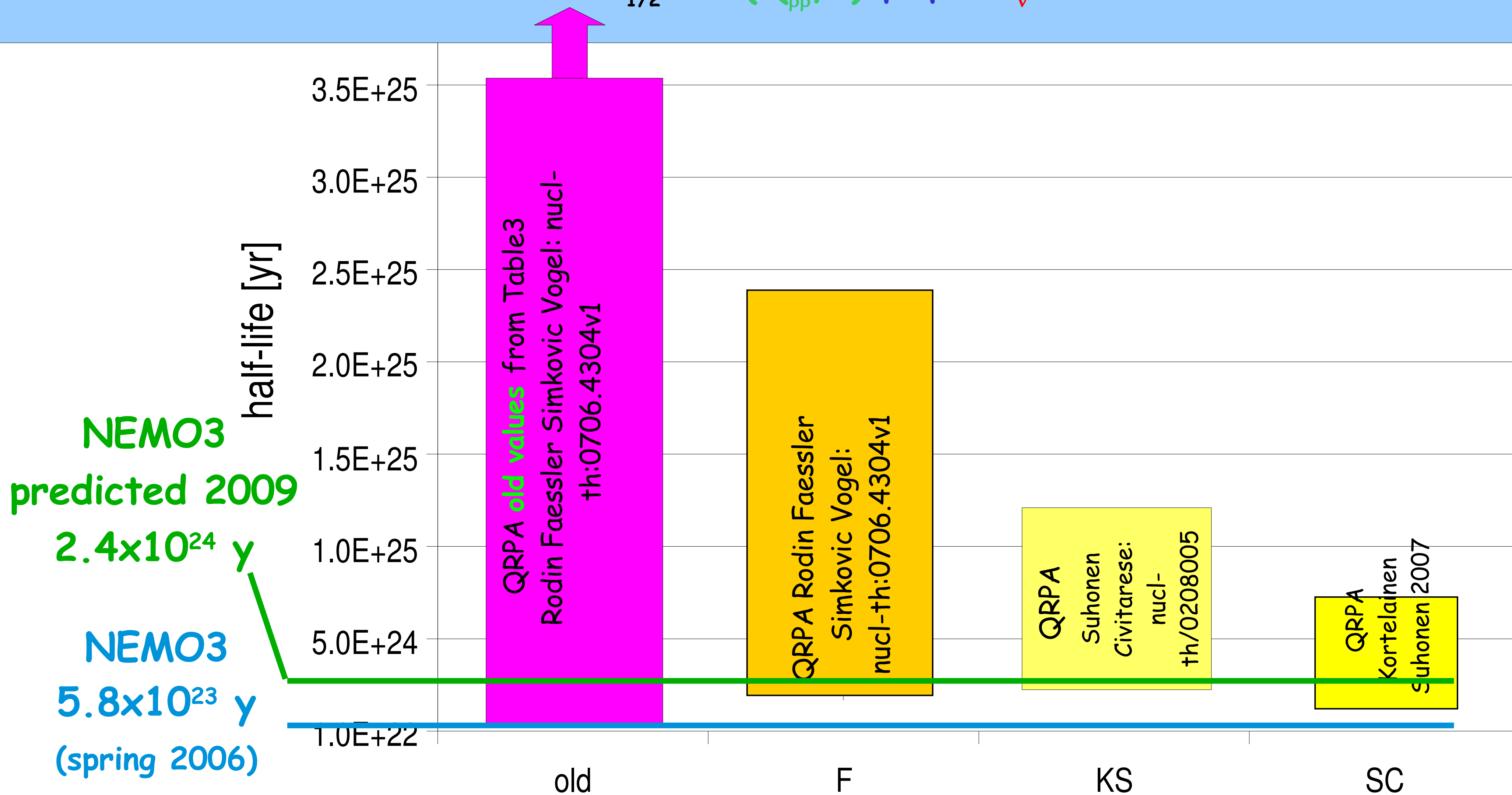
HM claim of evidence:

$T_{1/2}^{0\nu}$ (y) = (0.69-4.18) × 10^{25} (3σ range)

^{100}Mo predicted

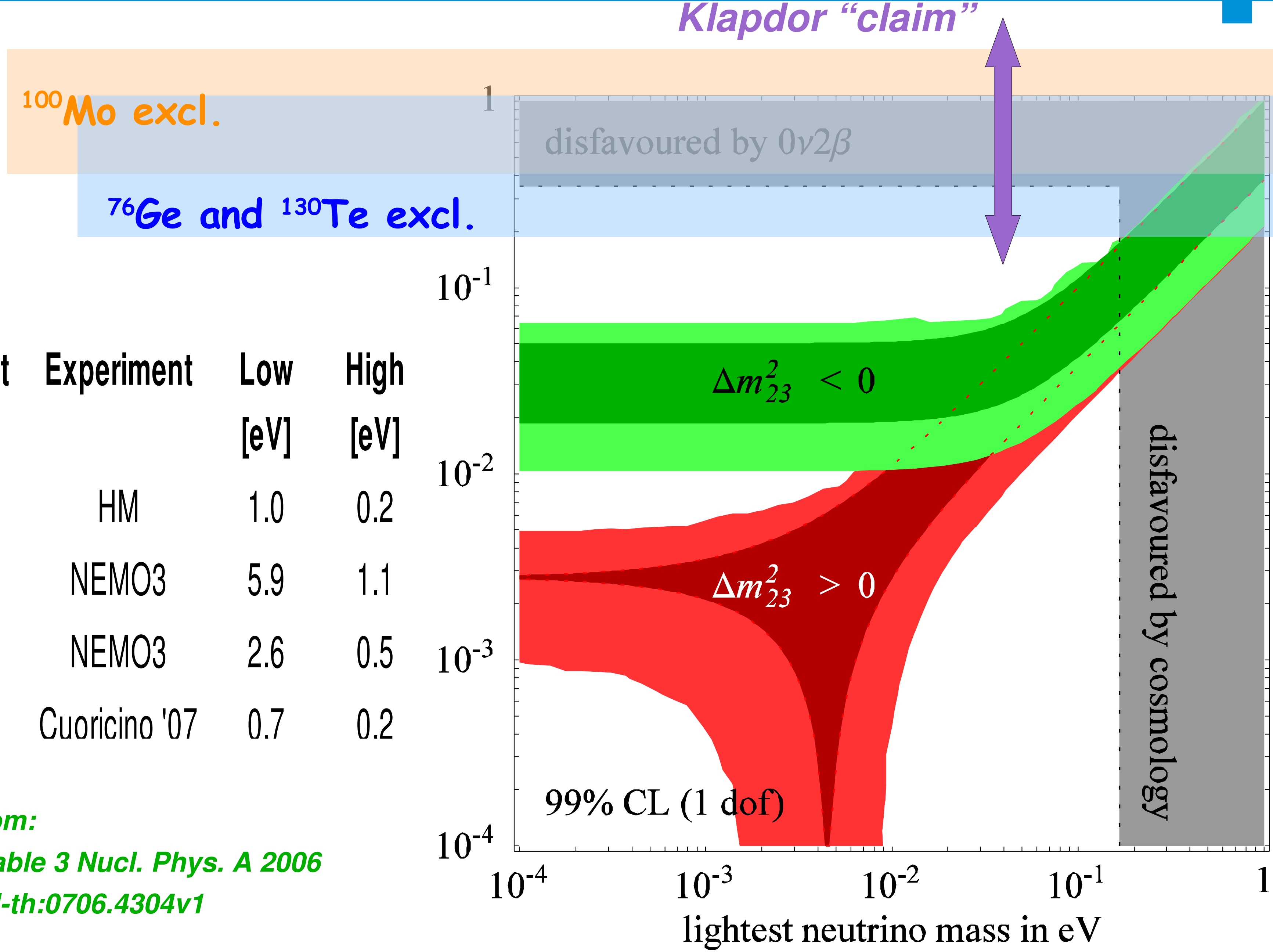
$T_{1/2}^{0\nu}$ (y) **range**

$$T_{1/2}^{-1} = F(Q_{\beta\beta}, Z)\ |M|^2\ \langle m_\nu \rangle^2$$



Past/Present experiments

NME uncertainty



Isotope	τ 90% limit [y]	Experiment	Low [eV]	High [eV]
^{76}Ge	1.9E+25	HM	1.0	0.2
^{82}Se	1.2E+23	NEMO3	5.9	1.1
^{100}Mo	5.8E+23	NEMO3	2.6	0.5
^{130}Te	3.0E+24	Cuoricino '07	0.7	0.2

QRPA NME from:
Rodin et al. Table 3 Nucl. Phys. A 2006
+ erratum nucl-th:0706.4304v1

Bibliography

several slides adapted from talks at:

Neutrino 2006

http://neutrinosantafe06.com/

Neutrino 2008

http://www2.phys.canterbury.ac.nz/~jaa53/

Varenna school 2008

http://www.sif.it/SIF/en/portal/activities/fermi_school/mmviii_en

NOW 2008

http://www.ba.infn.it/~now2008/