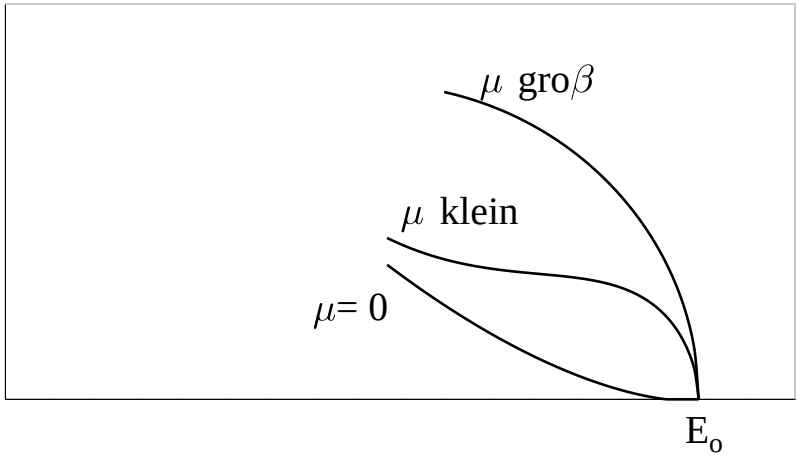
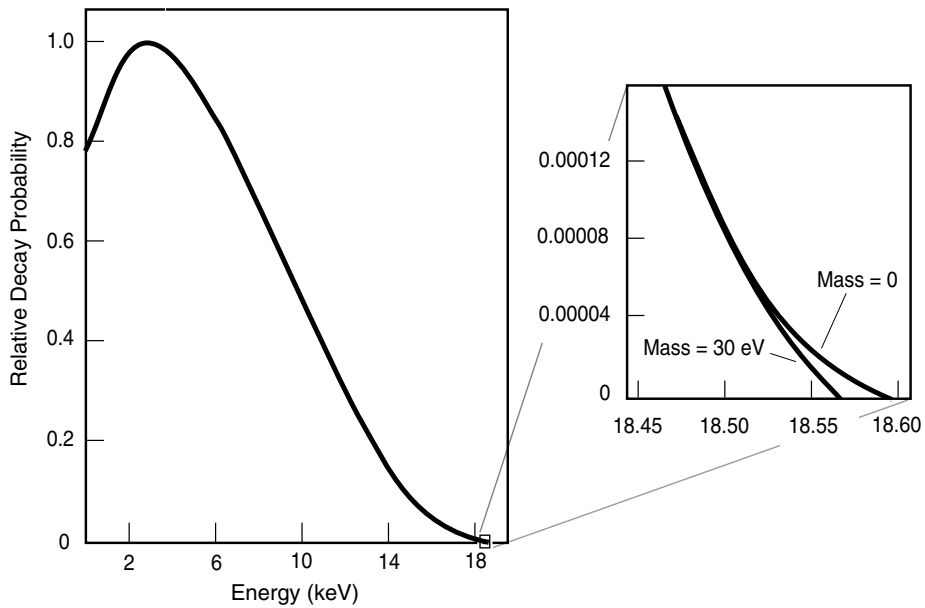
Direct measurements of neutrino masses

β decays: neutrino mass modify the electron spectrum shape close to the endpoint $E_\circ$.



Da E. Fermi, "Vershuch einer Theorie der beta-Strahlen", Z.Phys.88, 161-77 (1934)

A very tiny effect



Electron spectrum:

$$\frac{dN}{dE} = G_F^2 \frac{m_e^5 c^4}{2\pi^3 h^7} cos^2(\theta_C)|M|^2 F(Z,E) pE(E_\circ - E)[(E_\circ - E)^2 - m_\nu^2]^{1/2}$$

- max electron energy: $E_e^{Max} = E_\circ - m_\nu = M_s - M_e - m_\nu$
- M_s, M_e: atomic mass (start, end of the process)
- $F(Z,E)$: Coulomb correction
- Neutrino mass effects visible only close to $E_\circ$.
- Decay rate in a region ΔE close to $E_\circ$ depends from $Q = E_\circ - m_e$ and $\propto (\Delta E/Q)^3$.

Good nuclei candidates must have small Q and a high decay rate (lifetime “short”).

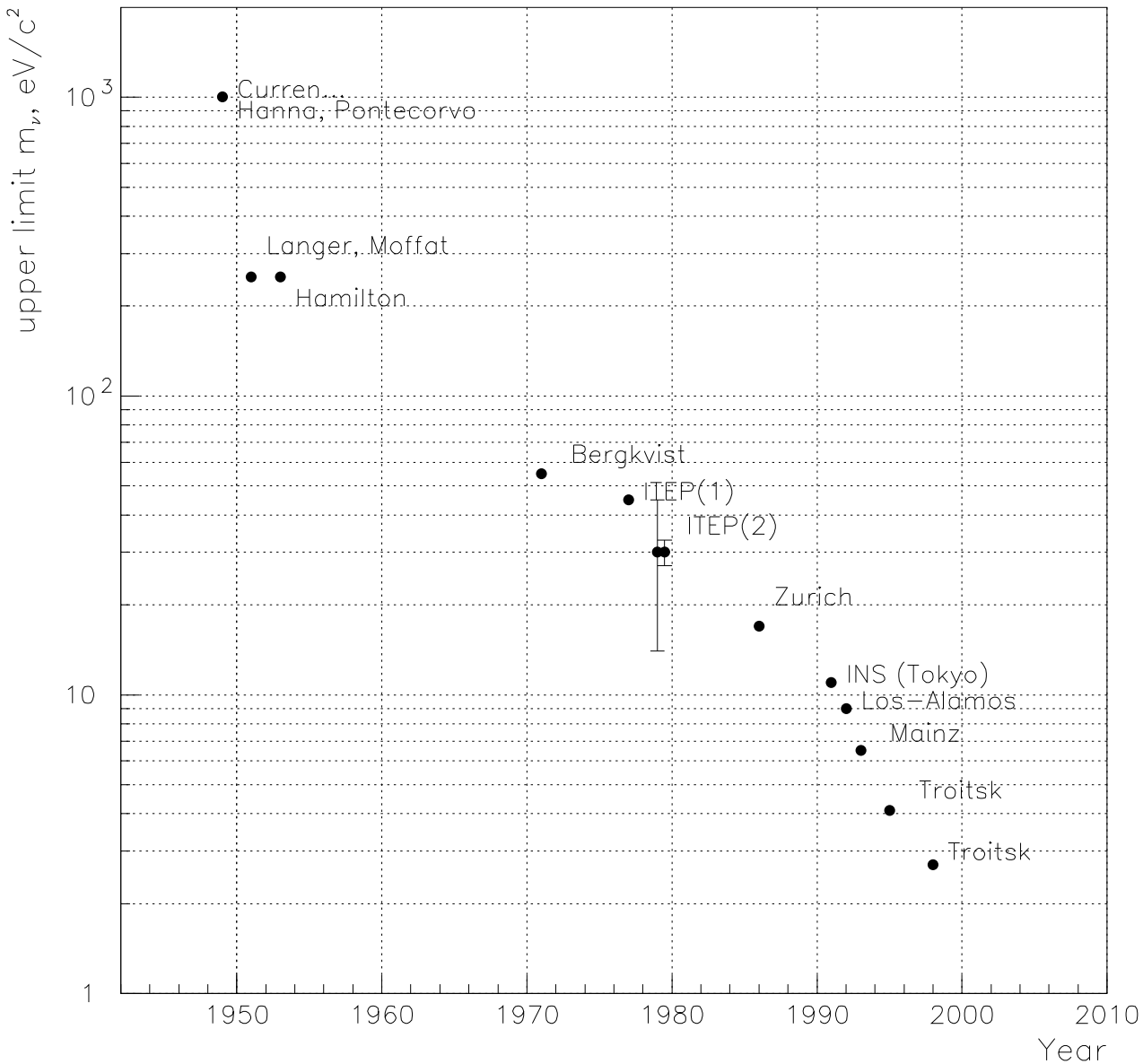
Best candidate: Tritium :

$^3H \rightarrow ^3He + e^- + \overline{\nu}_e$

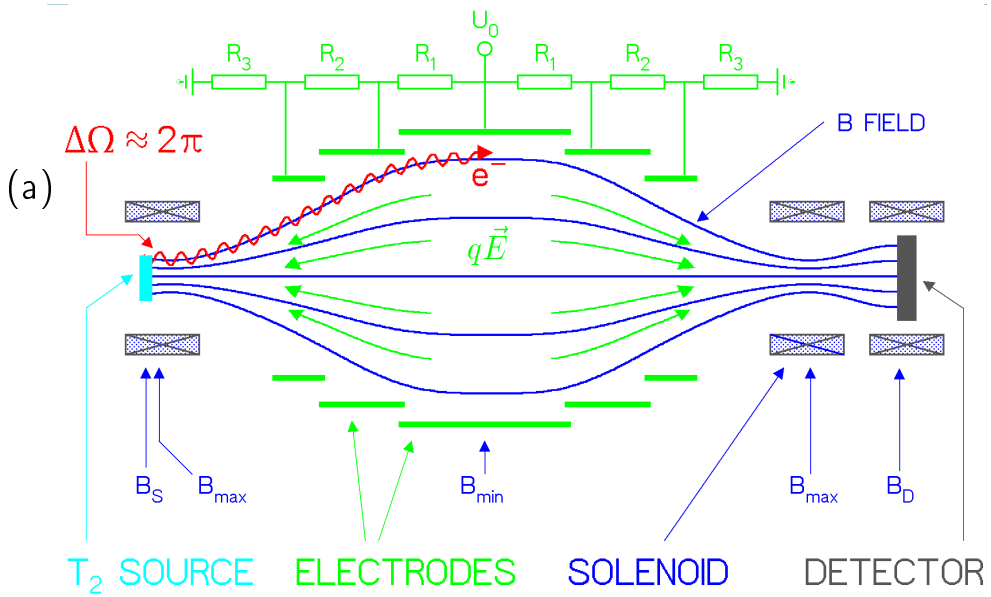
$E_\circ \simeq 18.6\, KeV$

Fraction of useful decays: $\sim 10^{-10}$.

Experimental progress of neutrino mass limits



Magnetic Adiabatic Collimation + Electrostatic Filter (MAC-E-Filter)



Electron kinetic energy in the solenoid:

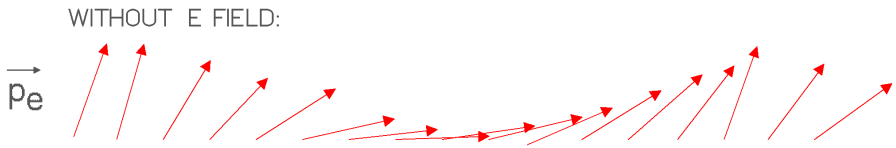
$$T = \frac{1}{2}mv^2 = \frac{1}{2}mv_\perp^2 + \frac{1}{2}v_z^2 = T_\perp + T_z = T_0 = cost$$

$$v_\perp = \omega r, \quad mv_\perp r = \text{cost} \Rightarrow$$

$$T_\perp = \frac{1}{2}mv_\perp^2 = \frac{1}{2}mv_\perp r\omega \propto B$$

$$B_1 = \frac{B_0}{5000}(\simeq 1.7\times10^{-3}T) \quad \Rightarrow \quad T_\perp(B_1) = \frac{T_\perp(B_0)}{5000}$$

(b)



⇒In the smallest B_T region the trajectory is almost longitudinal

⇒Applying an electrostatic potential $-U_0$: electrons transit if

$$T_z(B_1) = T_0 - 2\times10^{-4}T_\perp(B_0) \geq eU_0\,(= T_{min})$$

$$T_z(B_1) = T_0 - 2 \times 10^{-4} T_\perp(B_0) \geq eU_0 \, (= T_{min})$$

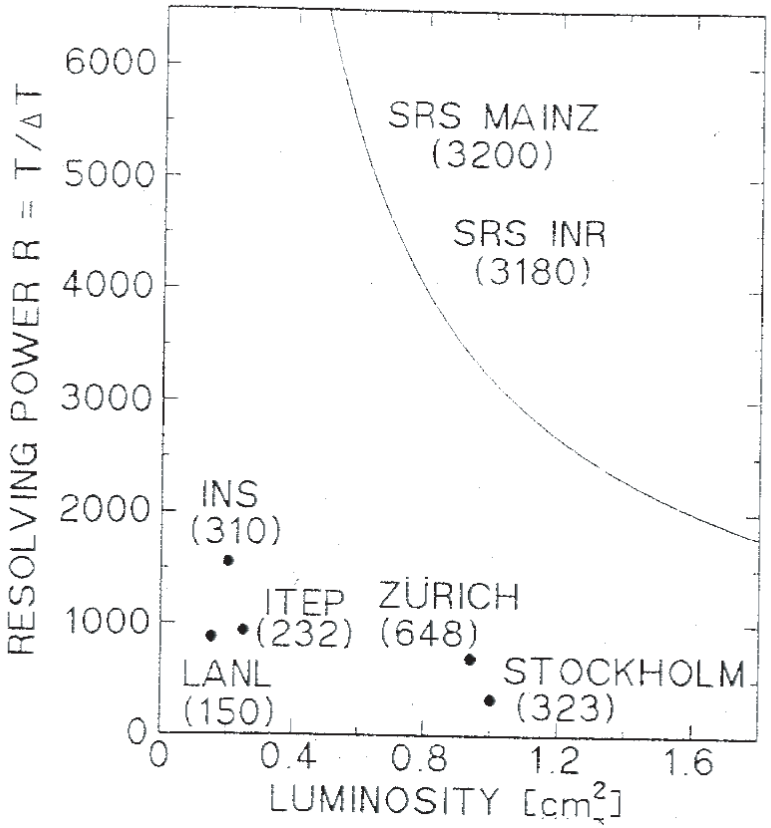
⇒Energy interval transmitted to the detector:

$$T \geq T_{min}(1 - 2 \times 10^{-4})$$

$$\Delta T = 2 \times 10^{-4} \, T_{min}$$

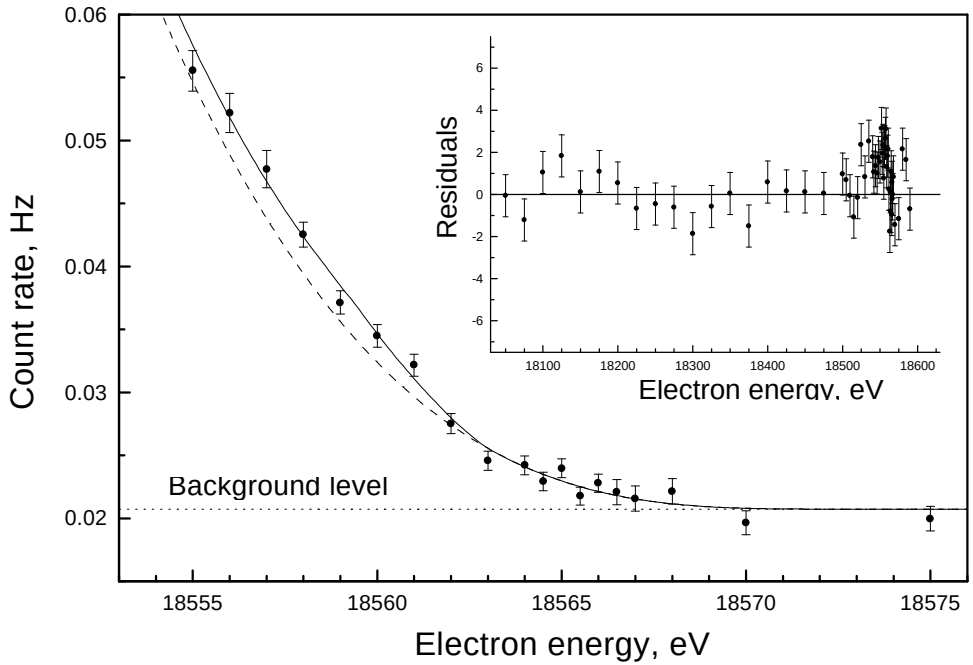
For $T_{min} = 18.6 \, KeV$ detector resolution is $\Delta T \simeq 3.7 \, eV$.

- Excellent energy resolution
- Large geometrical acceptance: great luminosity.
- INTEGRAL spectrometer: no direct spectral information.



The negative mass square problem

The first data of the two most sensitive experiments: Mainz and Troitsk, showed a count excess close to the end point: $\Rightarrow$ **fit to a negative m_ν^2**.



To solve the problem:

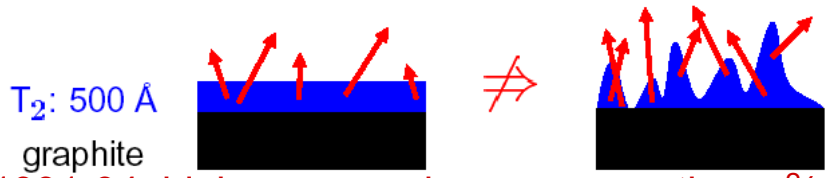
- Add additional arbitrary parameters to the fit
- Invoke new exotic physics to explain the problem
- Fix the experimental problem

Particle Data Book 1998: "...Unexpected effects have resulted in significantly negative m_ν in the new, precise tritium beta decay experiments. It is felt that a real neutrino mass as large as 10-15 eV would cause observable spectral distortions even in the presence of the end-point count excess.

Mainz: (final) neutrino mass results 1998-2001

detailed investigations of systematic effects

¥roughening transition of T_2 film

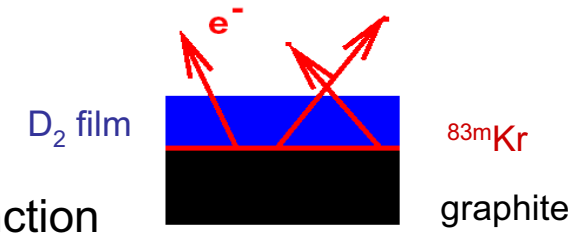


1991-94: higher energy losses _ negative $m^2(\nu)$

avoided by keeping film T < 2K

L. Fleischmann et al., J. Low Temp. Phys. **119** (2000) 615
L. Fleischmann et al., Eur. Phys. J. **B16** (2000) 521

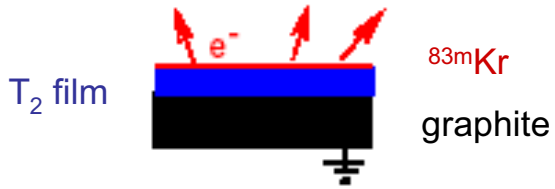
¥inelastic scattering in T_2 film



determination of cross section and energy loss function

V. Aseev et al., Europ. Phys. J. **D10** (2000) 39

¥self charging of T_2 film



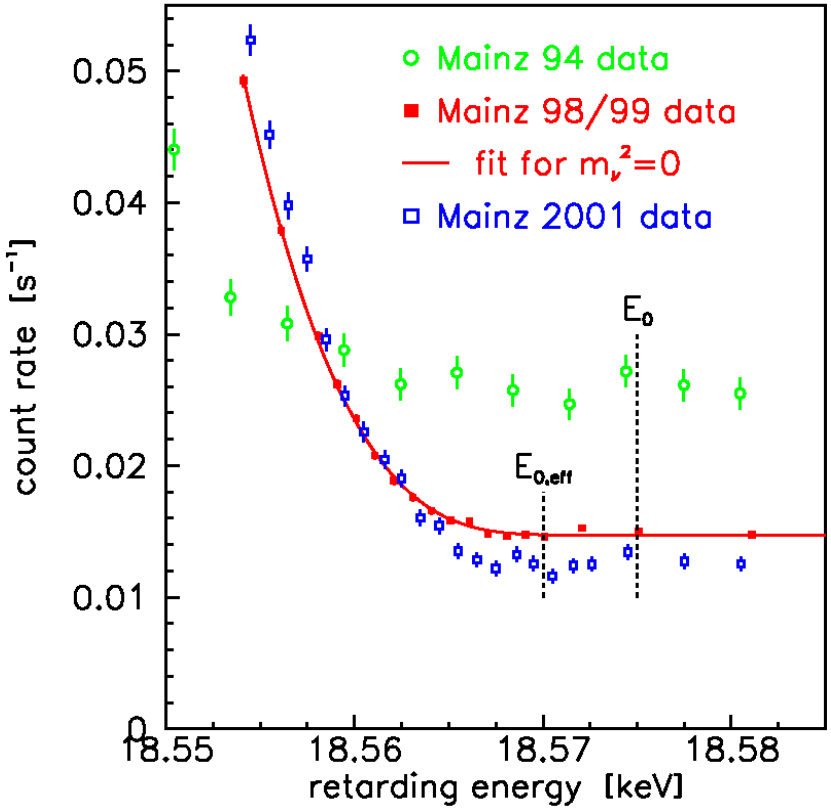
determination of critical field

B. Bornschein et al., J. Low Temp. Phys. **D10** (2000) 39

¥new: neighbour excitation amplitude fitted with data

agrees with calculations

Mainz: neutrino mass limits



fit range

lower boundary (variable)

upper boundary (fixed)

final ν-mass analysis from 1998-2001 measurements

(119 days, 6 runs: Q5-8,Q11,Q12)

1998/99 : 15 weeks
2001: 5.5 weeks

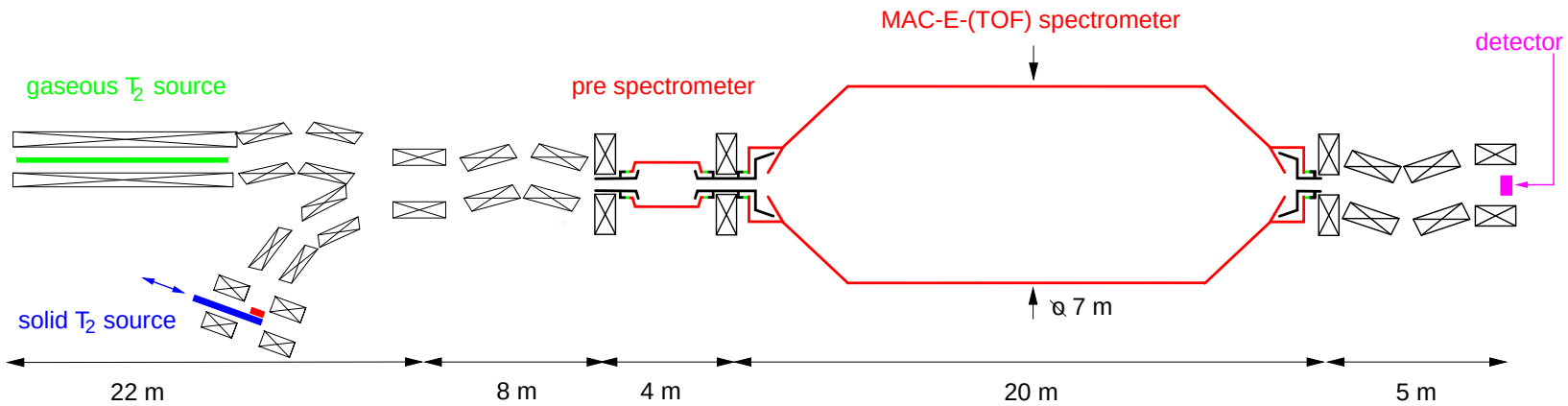
Signal: x5 improved

Background: x2 reduced

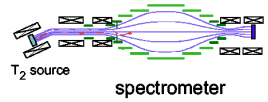
S/B ratio : x10 improved

detailed investigations: improvements for many systematic effects

Katrin Experiment (Karlsruhe, start in 2008)



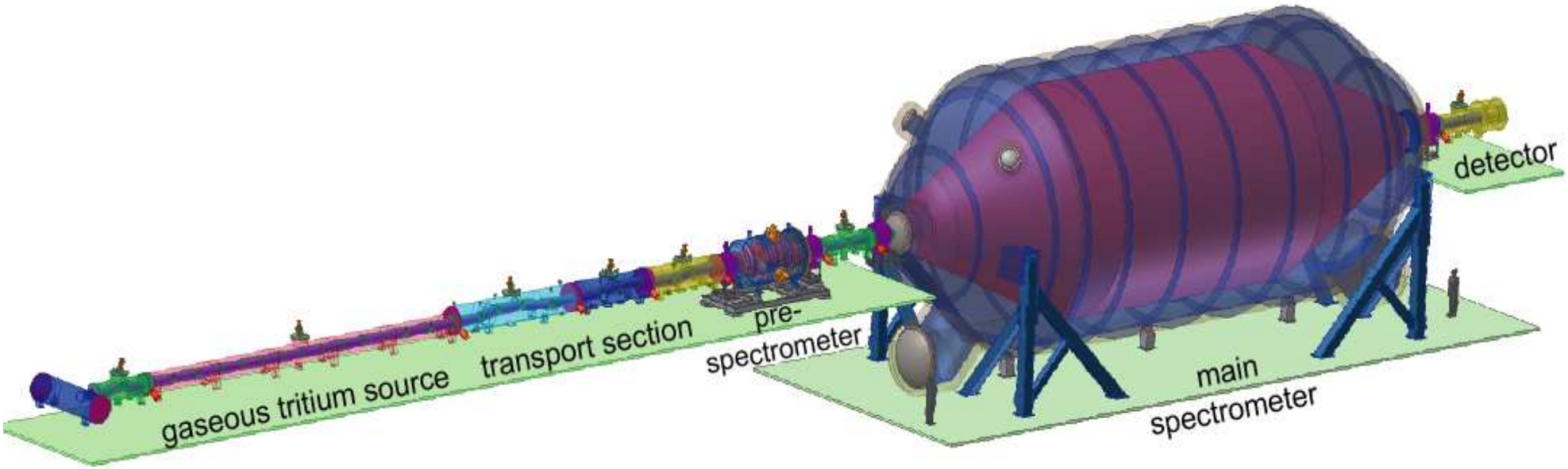
Present Mainz Setup :



Improve m_ν sensitivity by one order of magnitude (2 eV $\rightarrow$0.2 eV) $\Rightarrow$two orders of magnitude on m_ν^2 (4 ev^2 $\rightarrow$0.04 eV^2)
PROBLEM: endpoint count rate falls very rapidly ($\propto \delta E^3$)

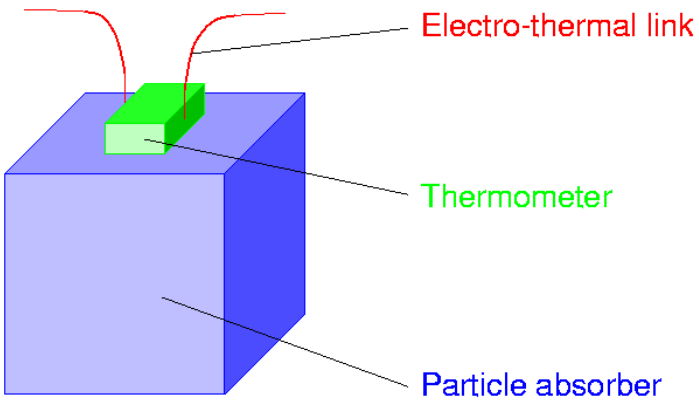
- Improve statistics: more powerful tritium source ($\times 80$) and longer running time (100 days $\rightarrow$1000 days)
- Improve energy resolution: Large electrostatic spectrometer with $\delta E = 1$eV ($\times 4$)
- Better control of systematics: two independent tritium sources (molecular and gaseous), decrease energy losses by one order of magnitudes.

The **KA**rlsruhe **TRI**tium **N**eutrino Experiment



A different approach: microbolometers

Measure total decay energy with (micro)bolometers instead that electron momentum with spectrometers



Good: No problem with nuclei final states: the whole energy is measured

Completely different systematic effects (no backscattering, energy losses in the source, solid state excitations ...)

Only limit on detector mass: how many microbolometers can be assembled

Bad: Slow detectors sensitive to all the decays $\Rightarrow$ pile-up problems

Energy dependent backgrounds

Worse resolution

Calibration and stability of all the detectors

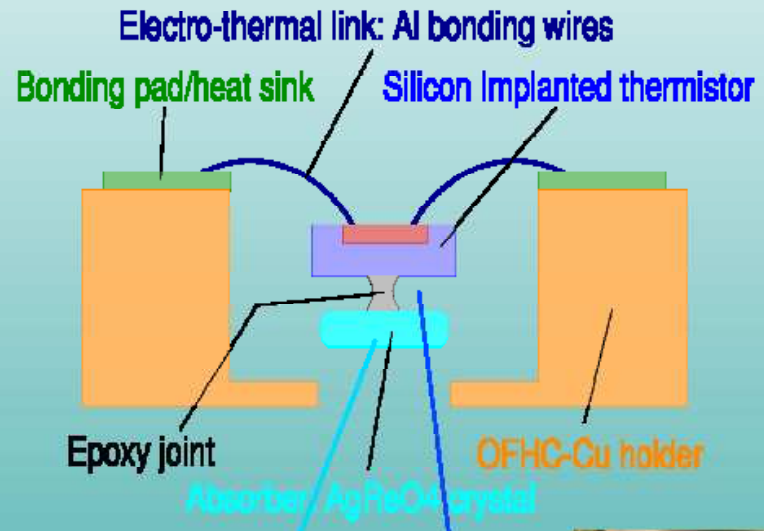
Microbolometers array, each sensor is $\sim 500\,\mu g$

Very low Q material: Rhenium (Q=2460 eV, $\tau_{1/2} = 4.3 \cdot 10^{10}$years).

Milano μ-calorimeters for ^{187}Re β decay study

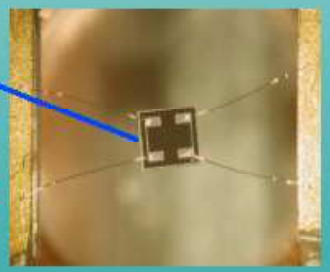
Neutrino mass measurement with arrays of 10 $AgReO_4$ μ-calorimeters. ⇨

- lower pile-up
- higher statistics



⇐ Bottom view

Top view ⇒



Absorbers

$AgReO_4$ single crystals

^{187}Re fraction ~0.32

$A_\beta \approx 5.4\times10^{-4}$ Hz/μg

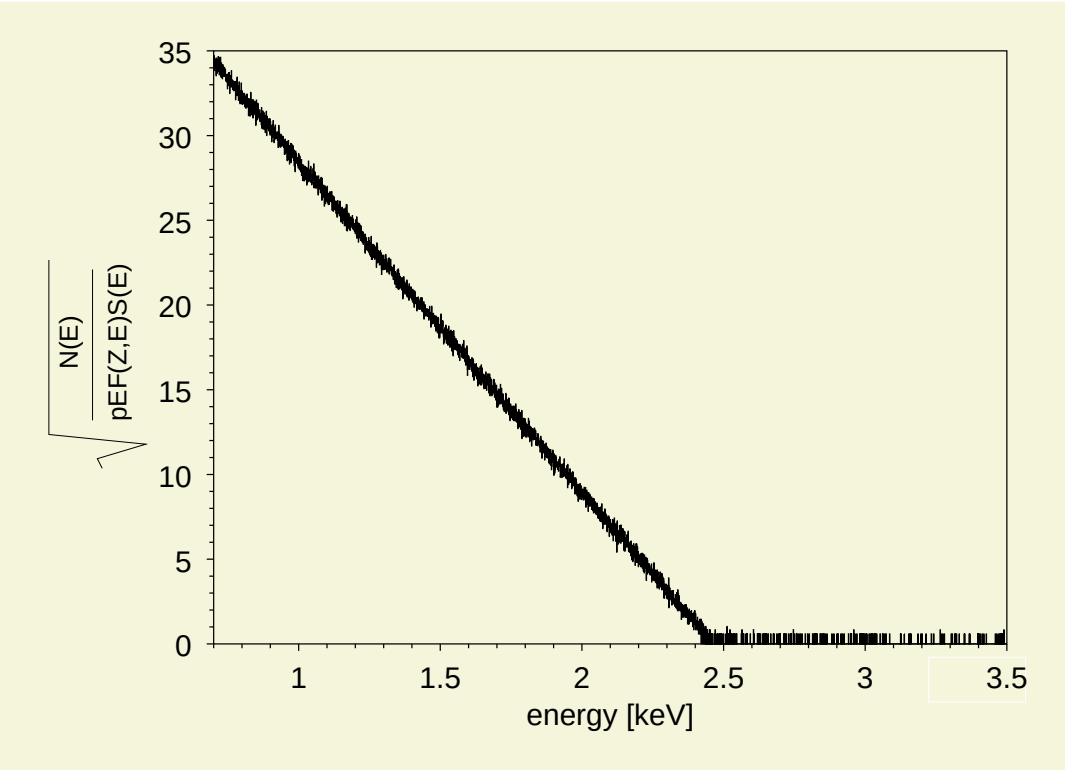
Mass 250 ~ 300 μg

Monica Sisti - TFAE 2004, Torino, April 14th - 16th 2004

MiBeta results

$6.2 \cdot 10^6$ ^{187}Re decays above 700 eV

8751 hours mg (of $AgReO_4$)



Fit with the following free parameters:

1. β end - point.
2. m_ν^2
3. spectrum normalization
4. pile-up normalization
5. background rate

RESULTS

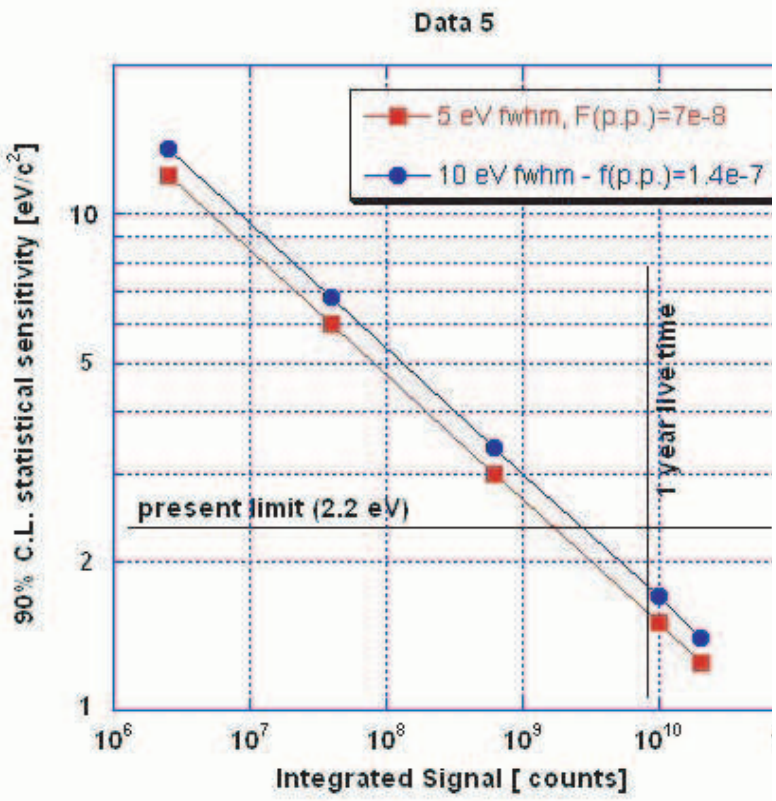
$$Q = 2465.3 \pm 0.5_{\text{stat}} \pm 1.6_{\text{sys}} \text{ eV}$$

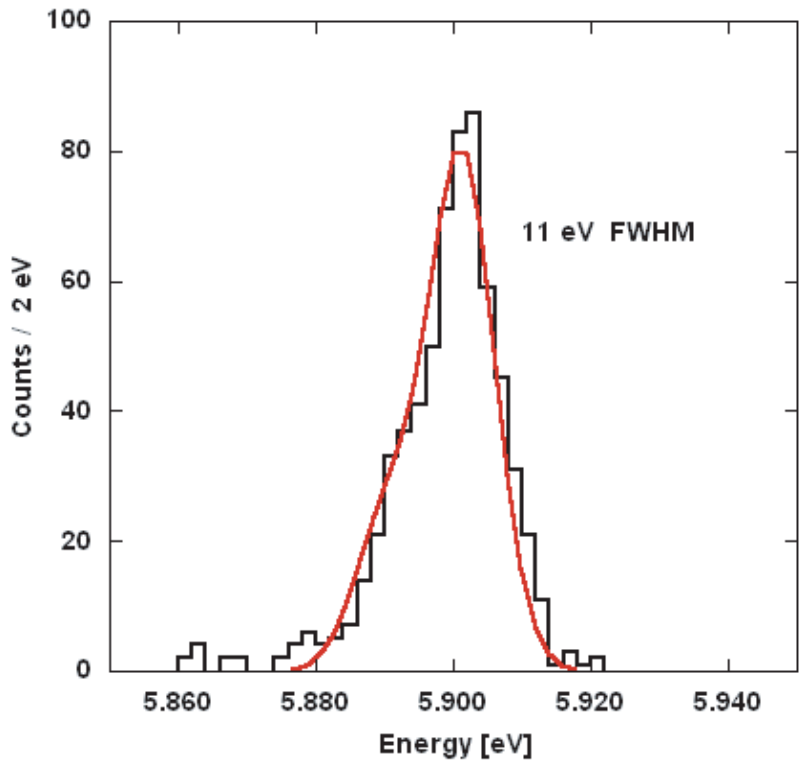
$$\tau_{1/2} = 43.2 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}} \text{ Gy}$$

$$m_\nu^2 = -112 \pm 207_{\text{stat}} \pm 90_{\text{sys}} \text{ eV}^2$$

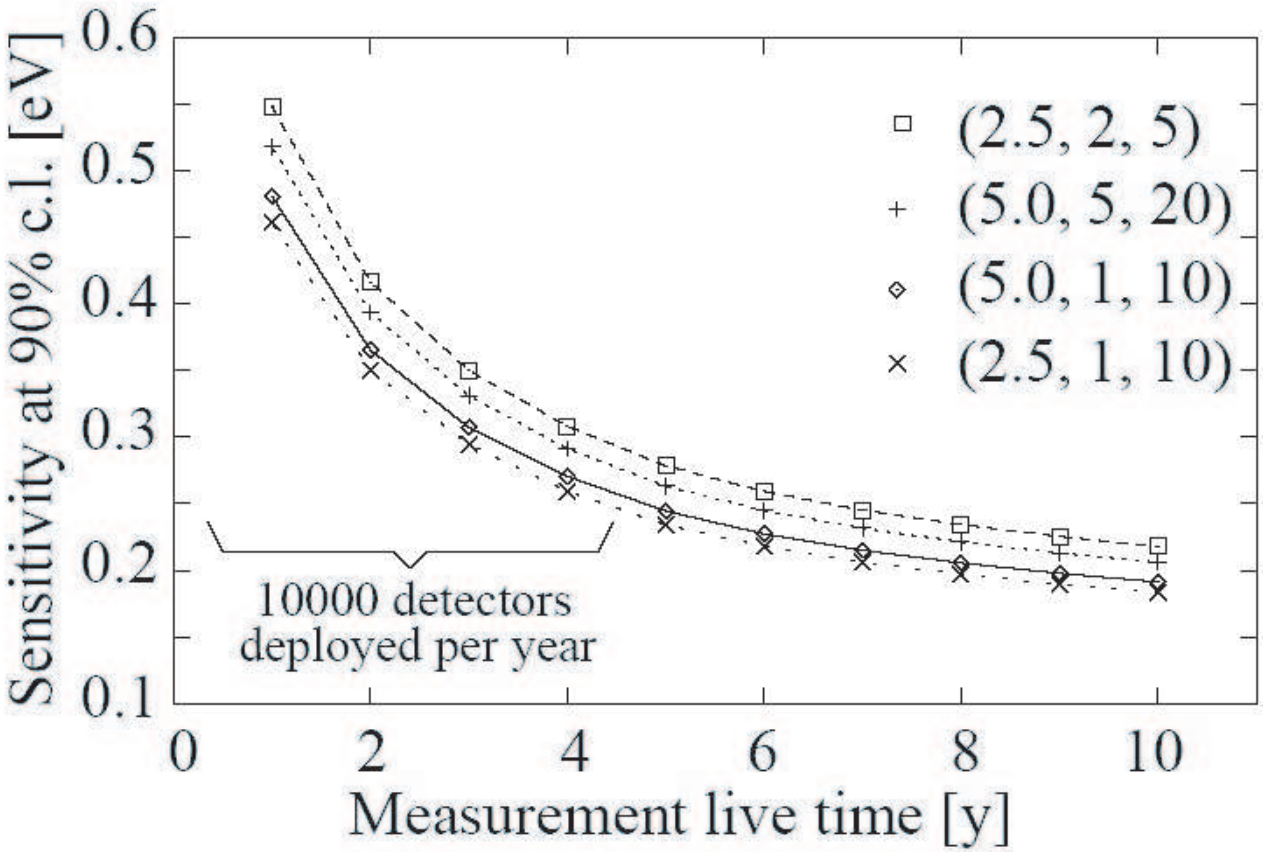
$$m_\nu < 15\text{eV } (90\% \text{ CL})$$

MANU-2: sensitivity

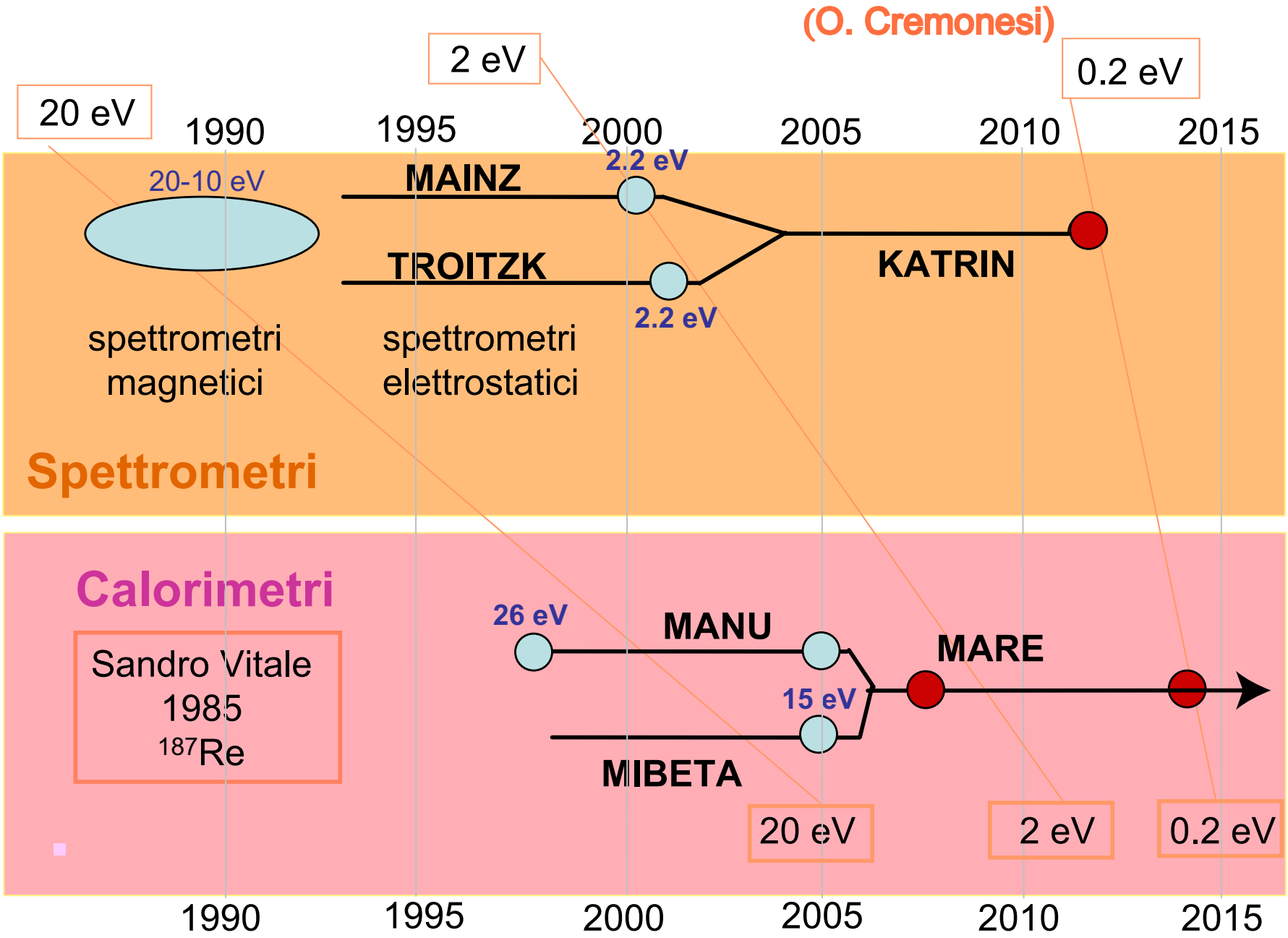




Proposal MARE, down to 0.2 eV

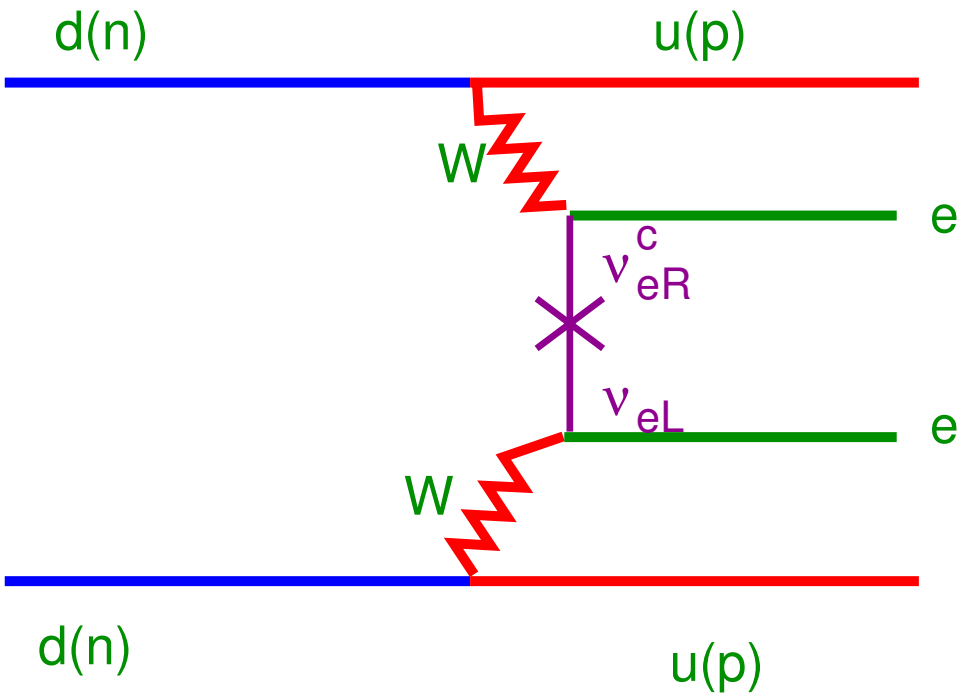


mν in the future



Neutrinoless Double Beta Decays

Another way to measure neutrino mass:



$\beta\beta0\nu$: (A,Z) $\rightarrow$(A,Z+2)+$e^- + e^-$

$$\left(T^{0\nu}_{1/2}\right) = G^{0\nu}(E_\circ, Z)|M^{0\nu}_{GT}\frac{g_V^2}{g_A^2}M^{0\nu}_F|^2\langle m_\nu\rangle 2$$

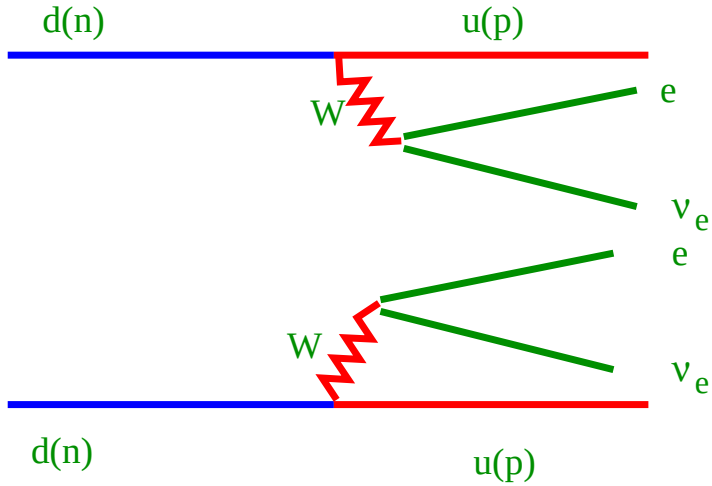
To happen it needs:

- Violate by 2 units lepton number conservation ($\Delta L = 2$)
- Majorana neutrinos: neutrino = antineutrino.
- Massive neutrinos

Similar processes are allowed:

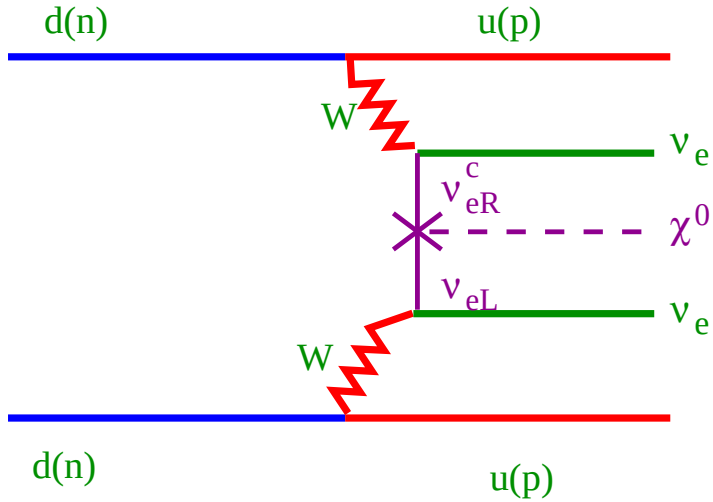
$\beta\beta 2\nu$: (A,Z) $\rightarrow$(A,Z+2)+$e^- + e^- + \nu_e^c + \nu_e^c \quad (\Delta L = 0)$

$$\left(T_{1/2}^{2\nu}\right) = G^{2\nu}(E_\circ, Z)|M_{GT}^{2\nu}|^2$$

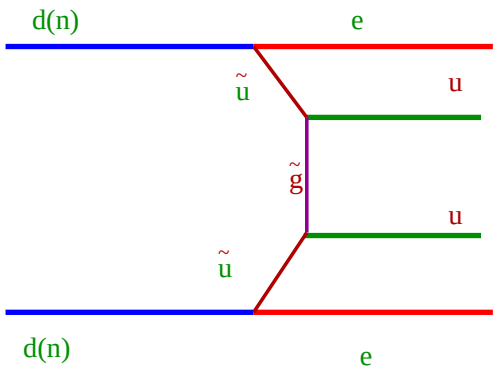


$\beta\beta\chi^\circ$: (A,Z) $\rightarrow$(A,Z+2)+$e^- + e^- + \chi^\circ$

$$\left(T_{1/2}^{\chi^\circ}\right) = G^{\chi^\circ}(E_\circ, Z)|M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu}|^2 < g_{eff}^2$$



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

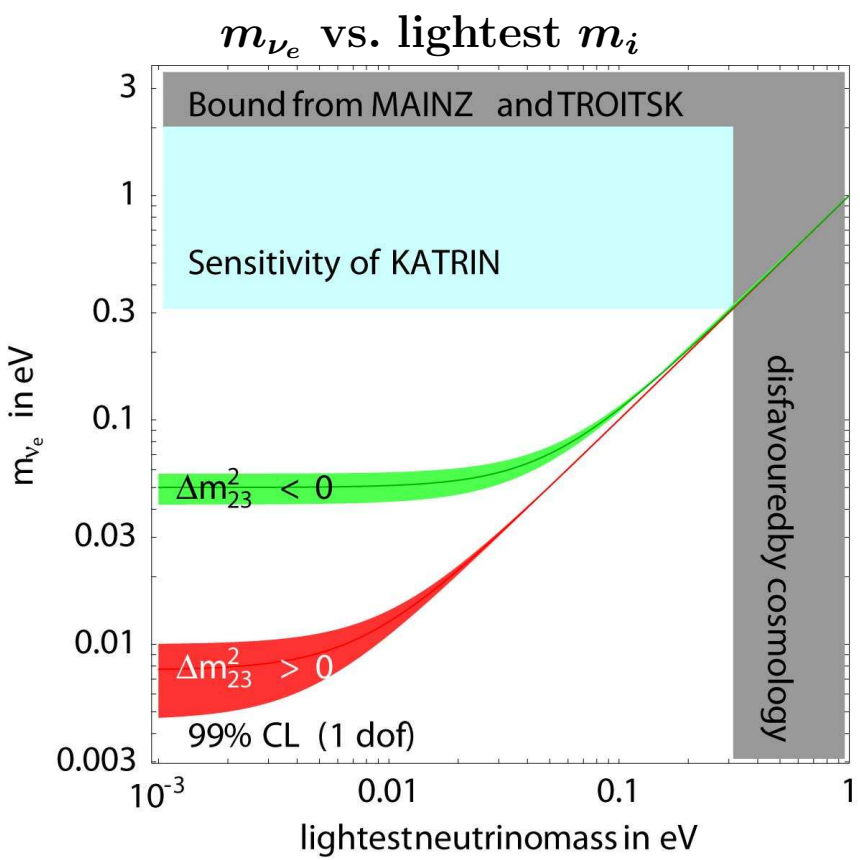


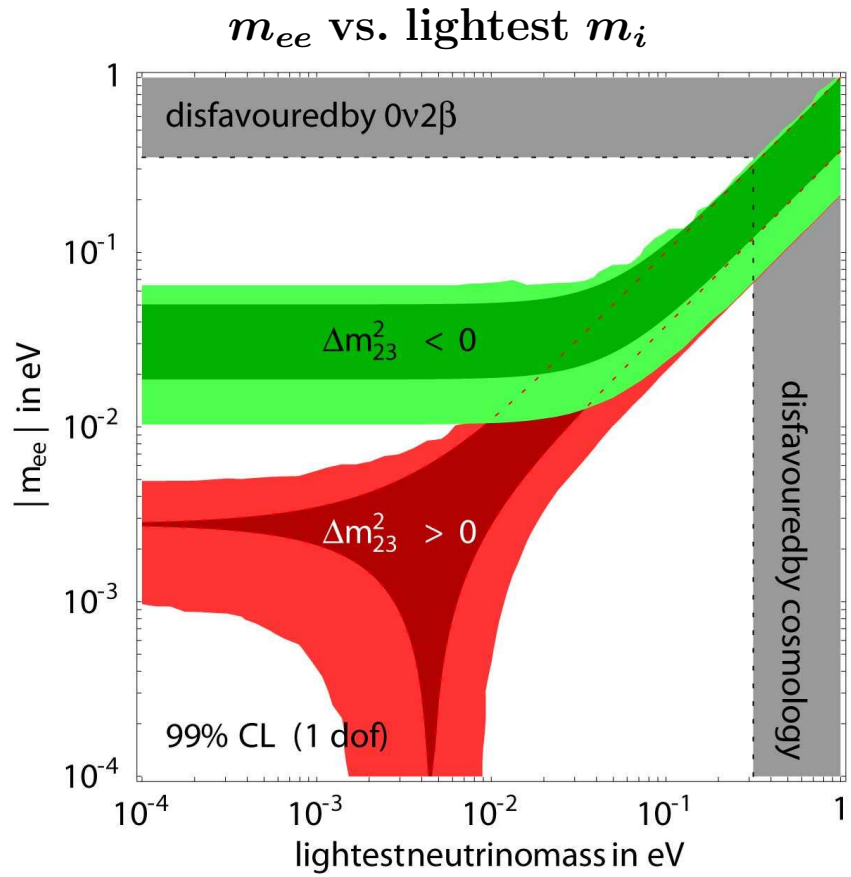
Beta and Double Beta mass measurement interplay

β and $0\nu2\beta$ observables in terms of the mass eigenstates m_i, the mixing angles θ_{ij} and the Majorana phases α e β:

$$m_{\nu_e} = \left(\sum_i |V_{ei}^2|\, m_i^2\right)^{1/2} = \left(\cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2 sin^2\theta_{12}) + m_3^2 sin^2\theta_{13}\right)^{1/2} \quad (1)$$

$$|m_{ee}| = \left|\sum_i V_{ei}^2\, m_i\right| = \left|\cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 e^{2i\beta} sin^2\theta_{13}\right|. \quad (2)$$

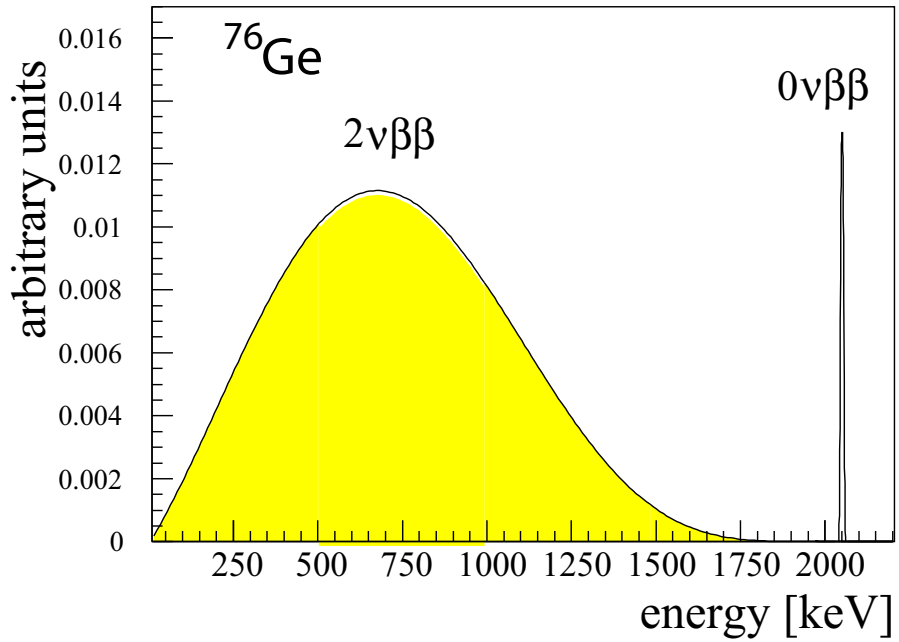




0ν and 2ν $\beta\beta$ decays have different electron spectra.

Nuclei are needed where:

- Single beta decays are suppressed
- $0^+ \rightarrow 0^+$ transitions
- Abundant isotopes in nature.



Experimental merit factor

:

$$T^{0\nu}_{1/2} \propto \frac{a}{A}\sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \cdot \epsilon$$

a: isotopic abundance

A: atomic mass

M: mass

t: running time

B: background rate

ϵ: efficiency

ΔE: energy resolution

Extremely rare process: $T^{0\nu}_{1/2} > 10^{24}$ years for $\langle m_{\nu_e} \rangle = \mathcal{O}(1\,eV)$, $\Rightarrow$ low noise techniques

- Deep underground experiments
- Very efficient active and passive radiation shields.

Experimental techniques

Geochemical Experiments Look for an abnormal abundance of the nucleus (A,Z+2) produced in geological times by the $\beta\beta$ decay of the nucleus (A,Z).

GOOD $\Rightarrow$Very long integrated decay time and large samples

BAD $\rightarrow$No way to separate neutrinoless and two neutrino decays. Heavy assumptions on the geological history of the sample. Evidence of $\beta\beta$ decays in ^{82}Se, ^{96}Zr, ^{128}Te, ^{130}Te.

Radiochemical Experiments Store a $\beta\beta$ candidate material. After a while, count the nuclei produced by $\beta\beta$ decays. Again, impossible to separate neutrinoless $\beta\beta$ from 2 neutrino $\beta\beta$. Successfully used to measured 2 neutrino $\beta\beta$ decays in ^{238}U in ^{238}Pu.

Direct measurements The only way to identify neutrinoless double beta decays. Two possible experimental techniques:

Spectrometers (source $\neq$ detector), a passive source of $\beta\beta$ emitters is embedded within an electron tracker. All the candidate nuclei can be tested but limited experimental resolution.

Calorimeters :source = detector. Limited choice of materials but excellent experimental resolution and reduction of backgrounds.

Dependence from the parent nuclei

Big systematic errors in the computation of the nuclear matrix elements $\Rightarrow$ search the process in different nuclei.

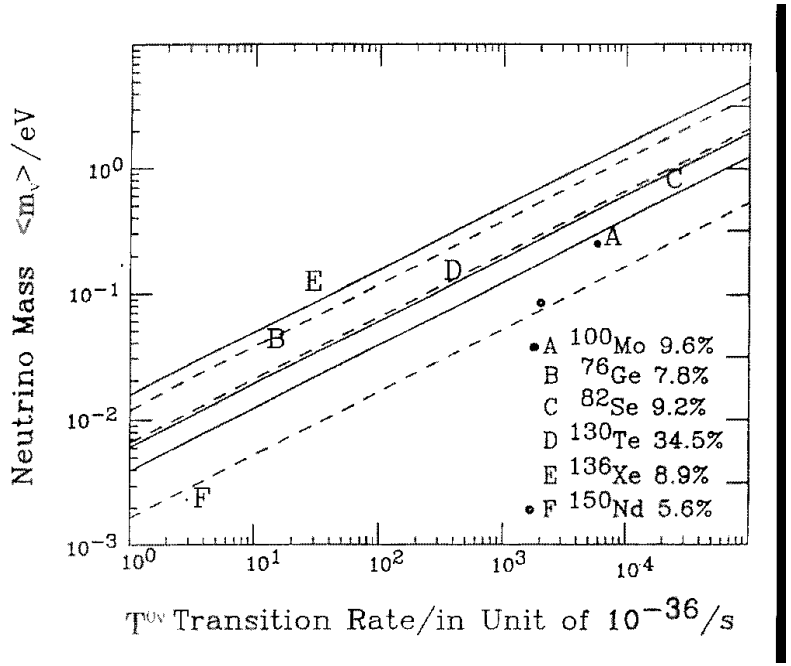
Double beta decays with 2 neutrinos signals are used as a control sample to check the estimations of the nuclei matrices (the process involved has however a completely different set of intermediate states).

$$T^{0\nu} = S^{0\nu}[\langle m_\nu \rangle^2]$$

$S^{0\nu}$: Nuclear sensitivity $= G^{0\nu}|M^{0\nu}|^2$

$G^{0\nu}$: Phase space volume $\propto Q^5_{\beta\beta} \Rightarrow$ High z nuclei

$M^{0\nu}$: Nuclear matrix element

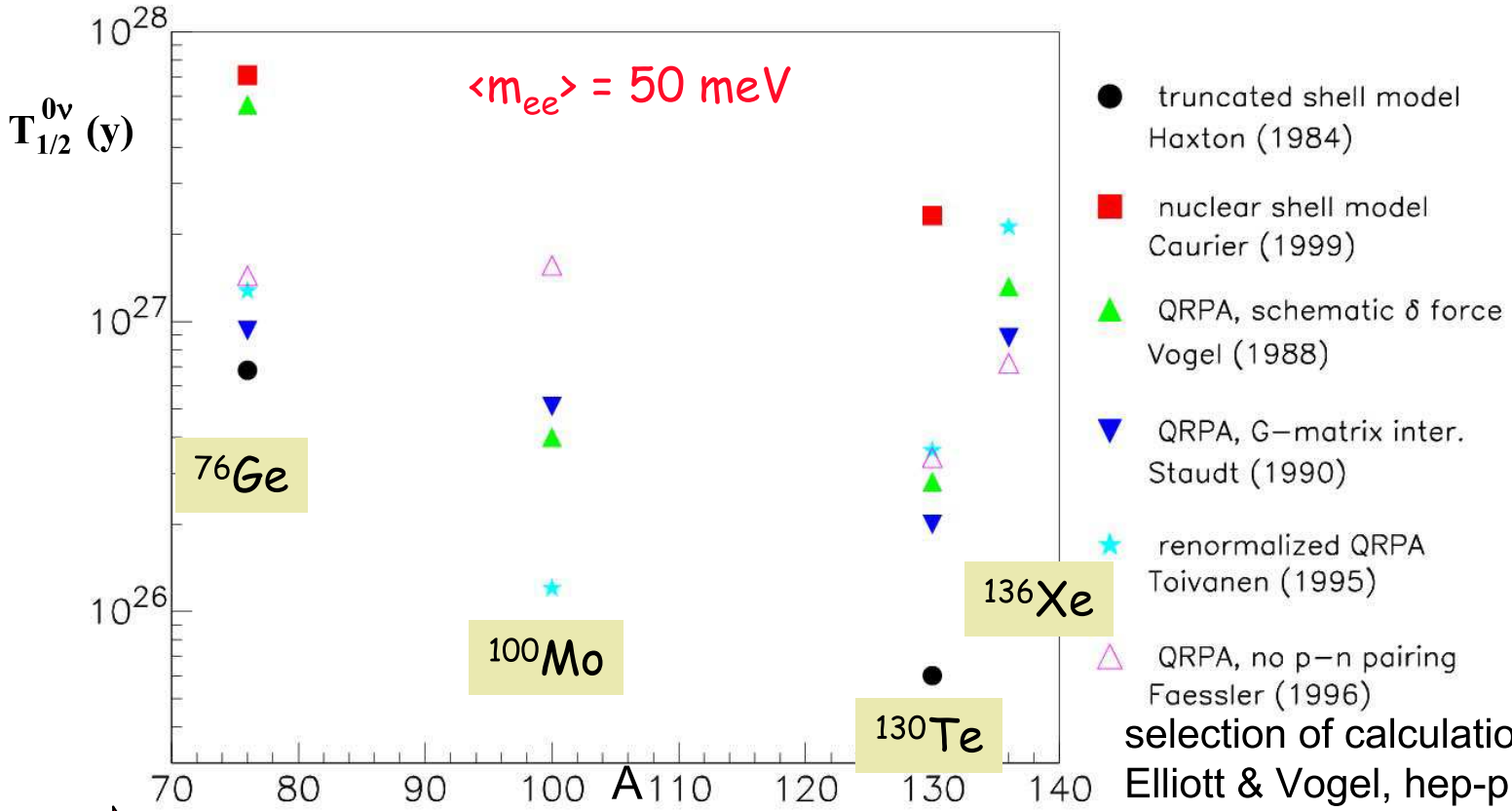


Nuclear Matrix Element Calculations

$$T_{1/2}^{0\nu} = \frac{1}{\Gamma(Q_{\beta\beta}^5)\ M^2\ \langle m_{ee}\rangle^2}$$

$^{76}Ge \rightarrow {}^{76}Se$	$Q_{\beta\beta}$ = 2039 keV	nat. abund. = 7.4%
$^{100}Mo \rightarrow {}^{100}Ru$	$Q_{\beta\beta}$ = 3034 keV	nat. abund.= 9.6%
$^{130}Te \rightarrow {}^{130}Xe$	$Q_{\beta\beta}$ = 2529 keV	nat. abund.= 34%
$^{136}Xe \rightarrow {}^{136}Ba$	$Q_{\beta\beta}$ = 2479 keV	nat. abund.= 8.9%

$T_{1/2}$ for nuclear matrix element calculations



selection of calculations from Elliott & Vogel, hep-ph/0202264

need more than one isotope to get information about $\langle m_{ee}\rangle$

Heidelberg - Moscow (LNGS) experiment, Eur. Phys. J. A12, 147 (2001)

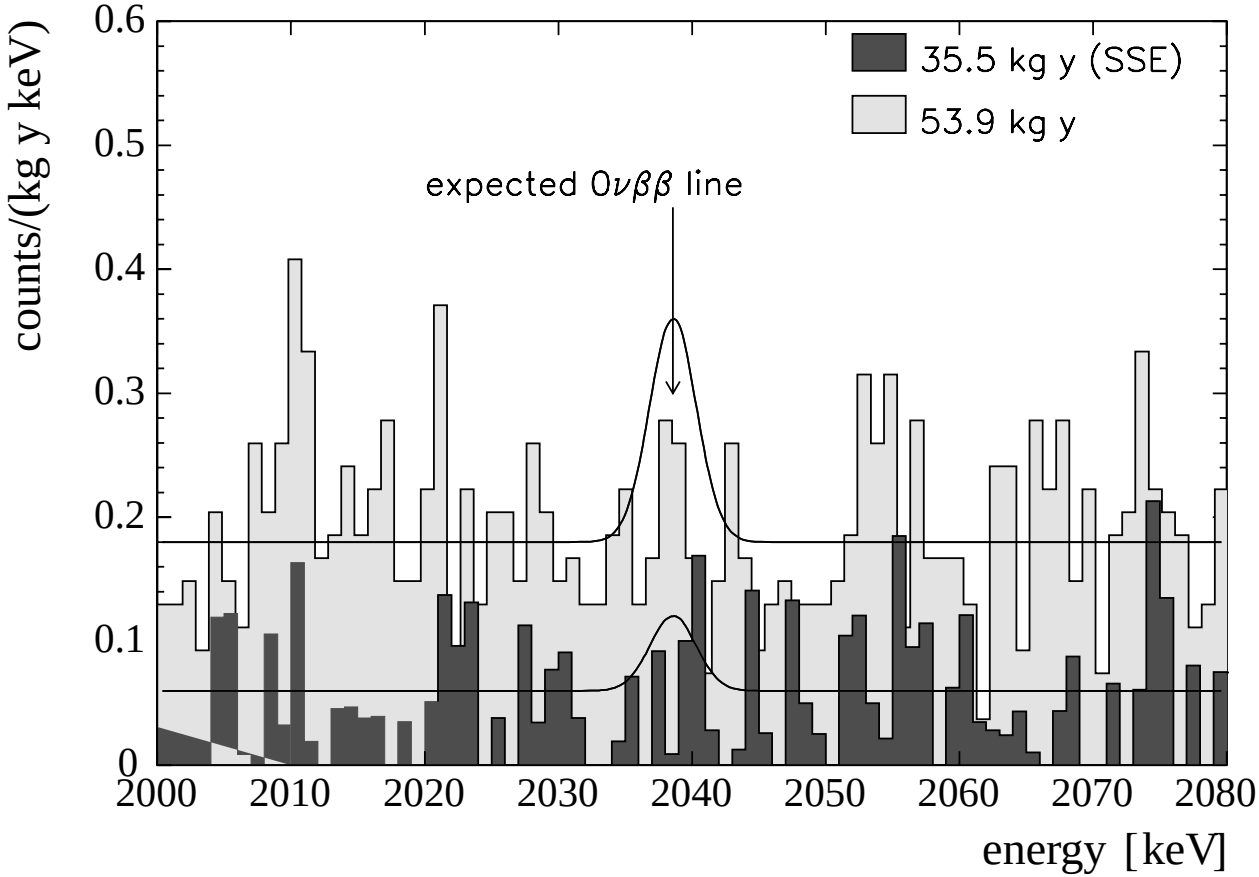
- 11 kG of enriched (86%) ^{76}Ge, in 5 crystals.
- Germanium is both the emitter and the detector.

Background rate: 0.11 counts/KeV/kg/yr

Signal efficiency: $\sim 100\%$

Energy resolution: ~ 3.5 keV

Duty cycle: $\sim 80\%$

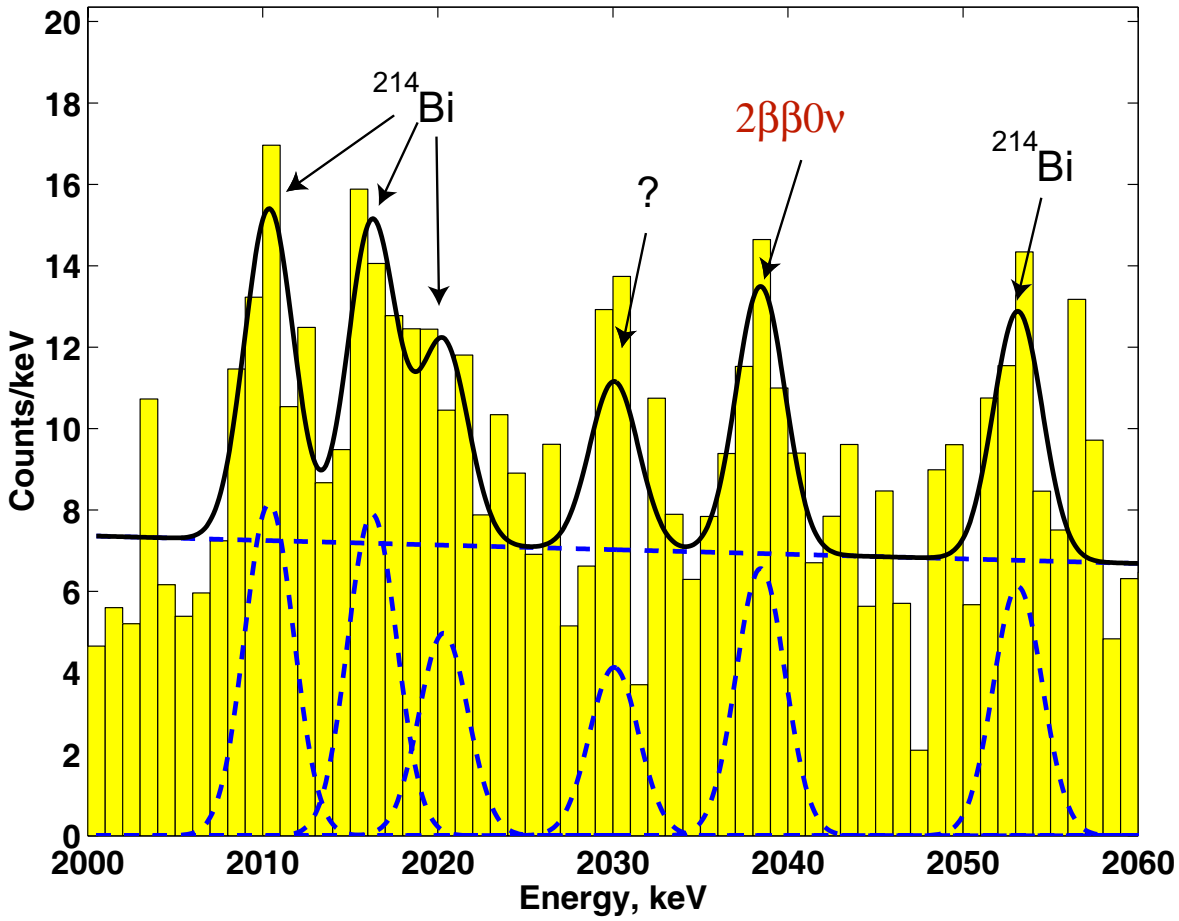


$$T^{0\nu}_{1/2} > 1.3 \cdot 10^{25} \text{ years } (90\% CL) \Rightarrow \langle m_\nu \rangle \leq 0.35(0.42)\, eV$$

$$T^{2\nu}_{1/2} \simeq 1.55 \cdot 10^{21} \text{ years}$$

Evidence of neutrinoless double beta decays

(published as "Results of . . . " Phys.Lett. B586:198-212, 2004)



71.7 Kg yr

$T^{0\nu}_{1/2} = (0.69 - 4.18) \times 10^{25}$ **years**

$m_\nu = 0.44(0.24 - 0.58) \quad eV$

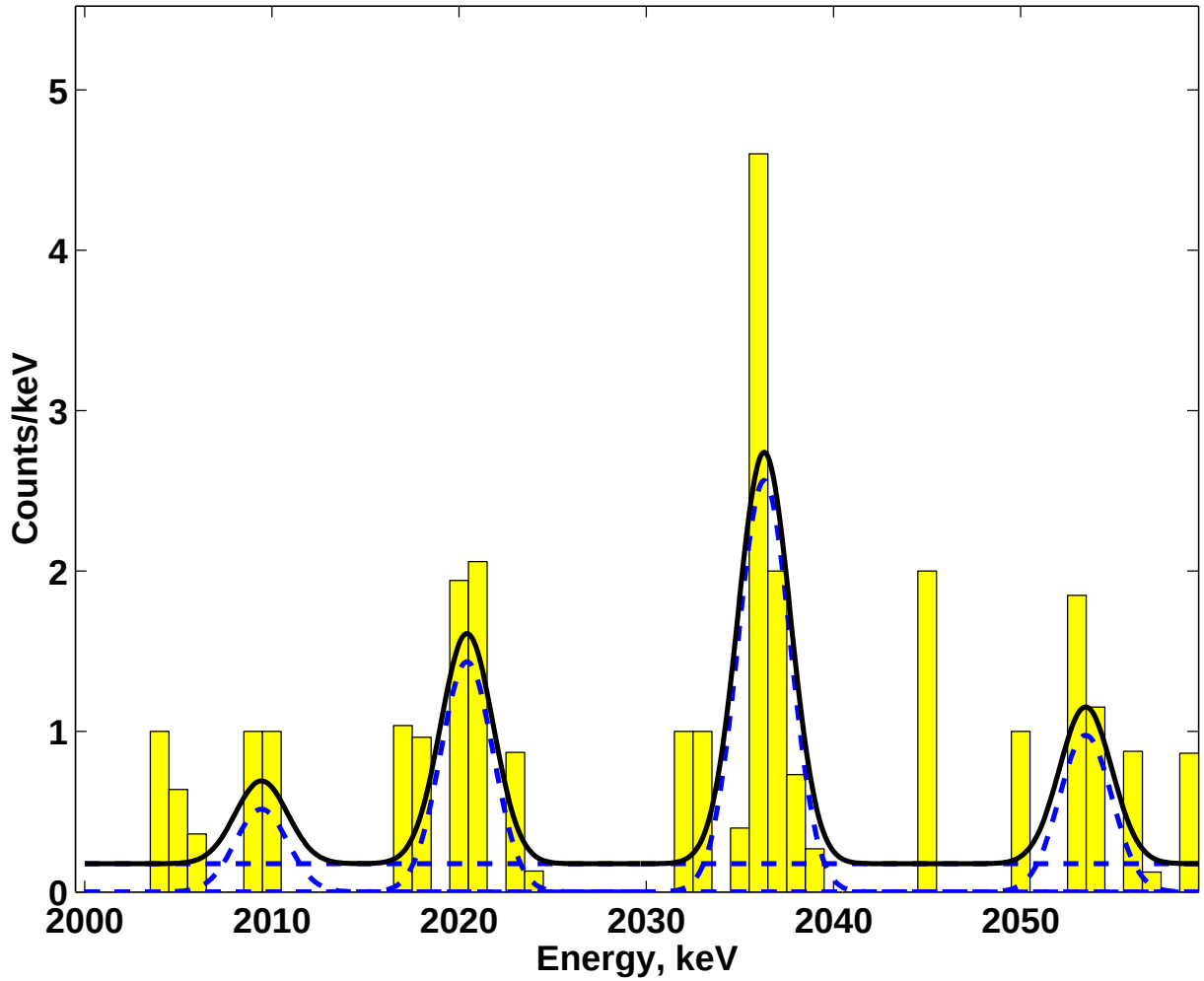
Significance: 4.2σ

Events in the $\beta\beta$ **peak: 29**

Cross Check

Pulse shape analysis of events confined in just one crystal.

Select events compatible with the $\beta\beta$ shape.



CUORICINO

Source = detector
Bolometric technique:
young (born in ~ 1985) but now firmly established

The bolometric technique for the study of DBD was proposed by **E. Fiorini** and **T.O. Niinikoski** in **1983**

Nuclide under study: ^{130}Te

- 0ν DBD is a factor 5-10 faster than in ^{76}Ge
- A.I.: 34% $\Rightarrow$ enrichment not necessary

experiments can be expanded at low cost

CUORICINO source

6.4×10^{25} ^{130}Te nuclei

Bolometric technique: the nuclear energy is measured as a temperature increase of a single crystal

$\Delta T = E/C$

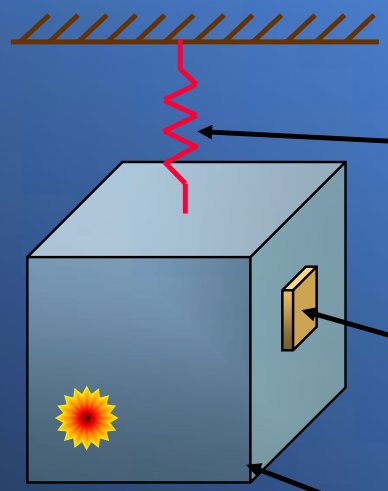
thanks to a proper thermometer, $\Delta T \Rightarrow \Delta V$

In order to get low specific heat, the temperature must be very low (5 - 10 mK)

Typical signal sizes: 0.1 mK / MeV, converted to about 1 mV / MeV

E.Fiorini - NOVE 2006

Cryogenic Detectors

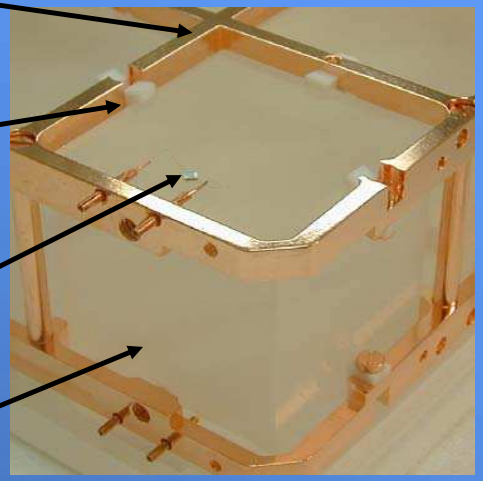


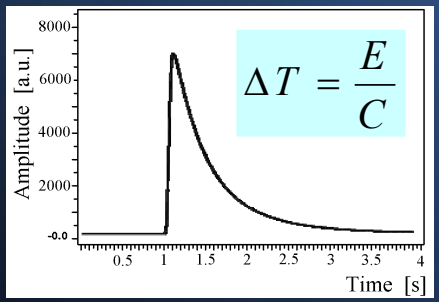
Heat bath (~8 mK)

Weak thermal coupling
(G~4 pW/mK)

Thermometer
(NTD Ge , R~100 MΩ)

Adsorber crystal
(TeO_2, C~10^{-9} J/K)





Cryodet features

- ▲ wide choice of detector materials
- ▲ good energy resolution
- ▲ true calorimeters
- ▼ velocity

Carlo Bucci

TAUP 2005, 10-14 September 2005

CUORICINO bolometers

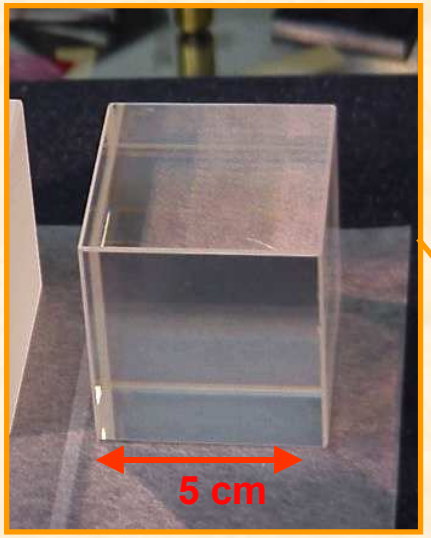
Absorber crystal

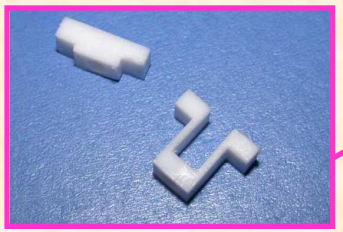
The absorber is a **5x5x5 cm^3** crystal of **TeO_2** which contains the neutrinoless DBD candidate **^{130}Te**

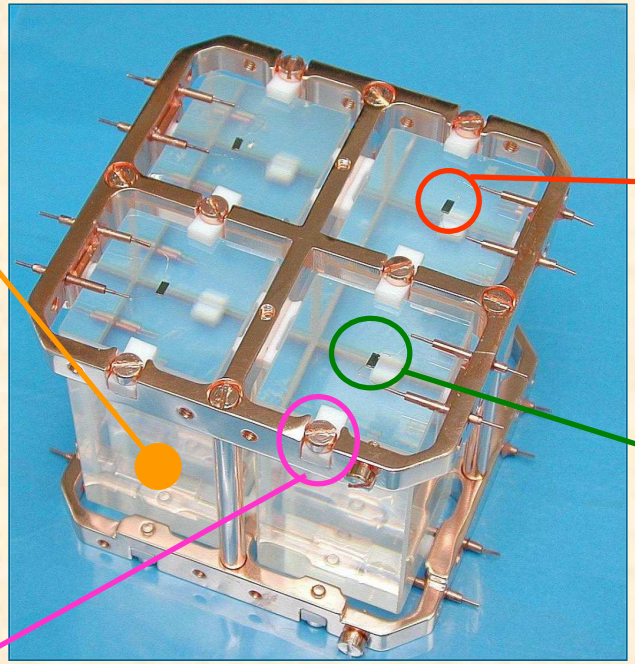
Temperature sensor

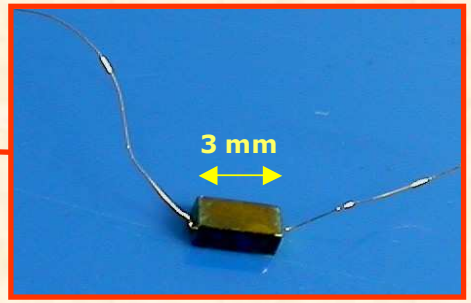
The thermal signal is measured by means of an **NTD Ge Thermistor**

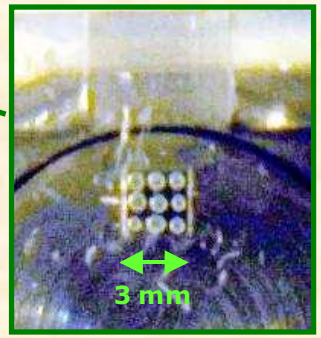
$$R(T) = R_0 \exp \sqrt{\frac{T_0}{T}}$$



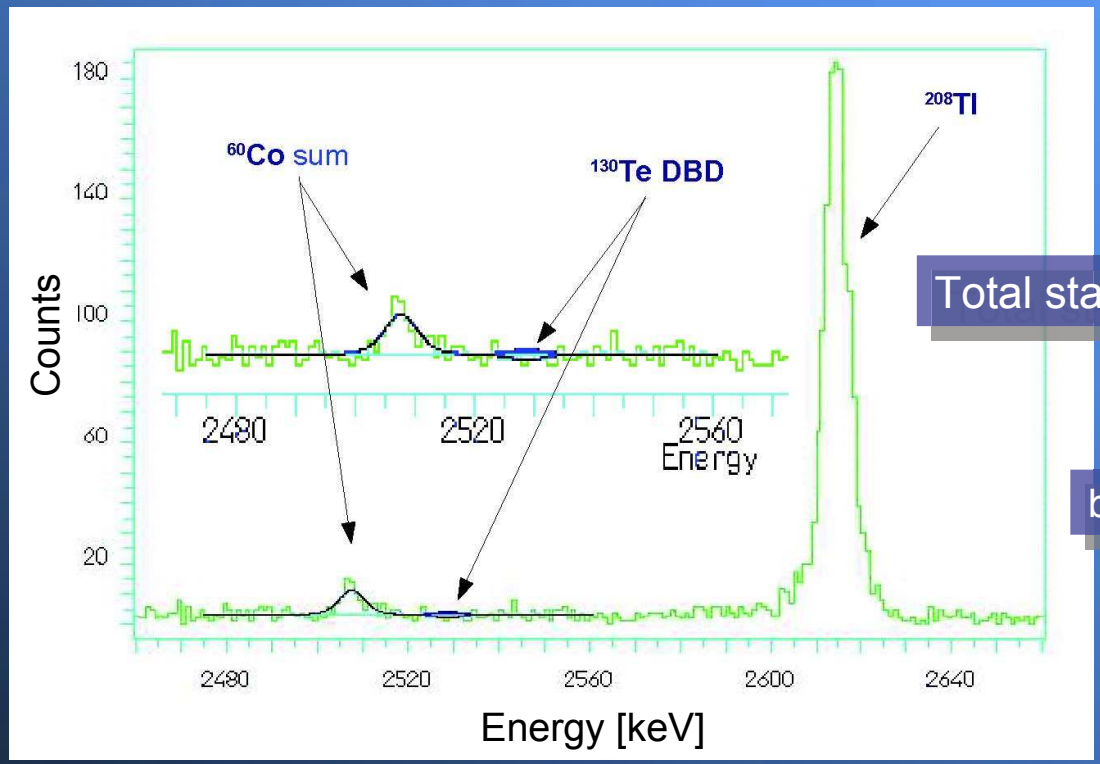








Cuoricino result on ^{130}Te ββ–0υ decay



Total statistic ~ 5.36 kg (^{130}Te) × y

b = 0.18 ± 0.02 c/keV/kg/y

Maximum Likelihood
flat background + fit of 2505 peak

Anticoincidence background spectrum of the 5x5x5 cm^3 crystals around the ii-0υ region

$$\tau_{1/2}^{0\nu} \geq 1.86 \cdot 10^{24}\, y \left(90\%\, CL\right) \Rightarrow \left\langle m_\nu \right\rangle \leq 0.20 - 1.05\, eV^* \quad \left(90\%\ CL\right)$$

* Dependent on the value for the nuclear matrix elements

Carlo Bucci

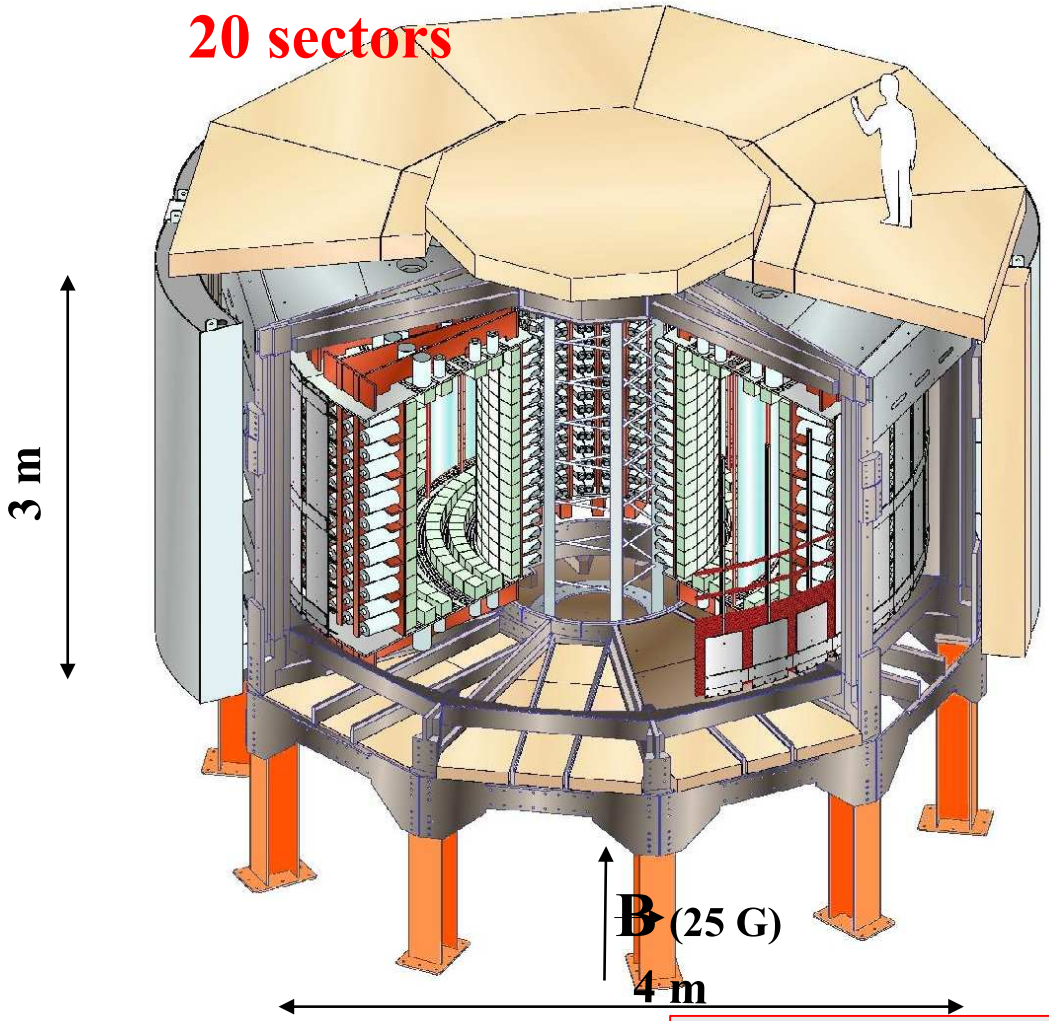
TAUP 2005, 10-14 September 2005

Cuoricino vs Heidelberg Moscow

	He-Mo	Cuoricino
$Q_{\beta\beta}$ (keV)	2039	2529
Detector mass (kg)	11	40.7
Active mass (kg)	9.5	11
Duty cycle	80%	64%.
Energy resolution (keV)	3.5	8
Efficiency	100%	85%
Background rate (counts/kg/keV/yr)	0.11	0.19
Merit factor	1	0.96

The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², e ~ 60 mg/cm²

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

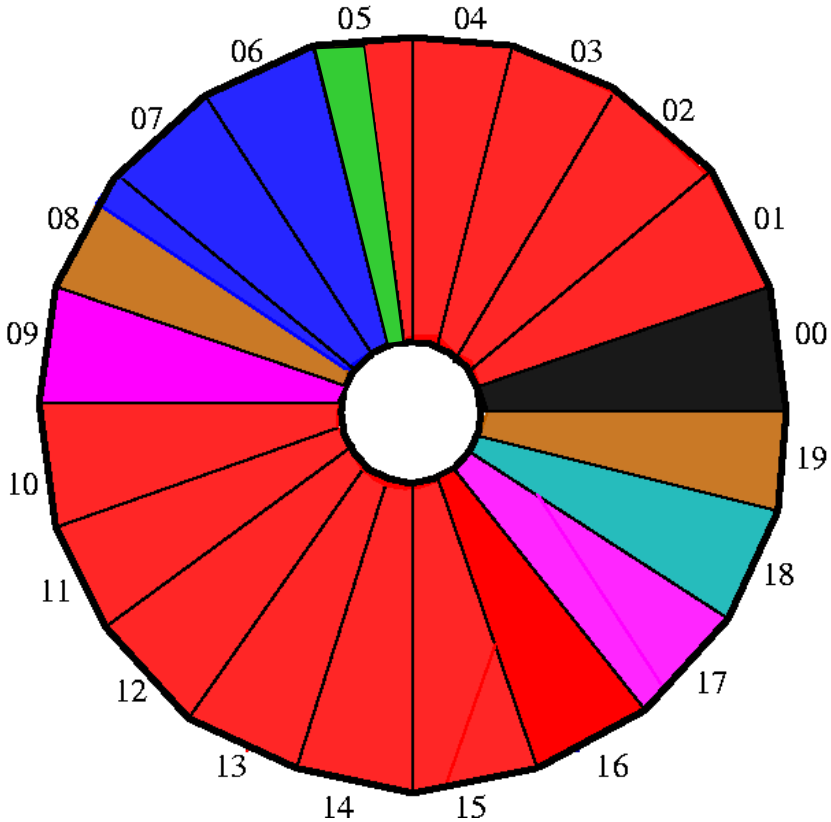
Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

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

Able to identify e^+, e^-, and γ

Xavier Sarazin for the NEMO-3 Collaboration *Neutrino 2004 Paris 14-19 June 2004*

decay isotopes in NEMO-3 detector



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

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

search

measurement

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

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

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

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

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

^{nat}Te 491 g

Cu 621 g

External bkg measurement

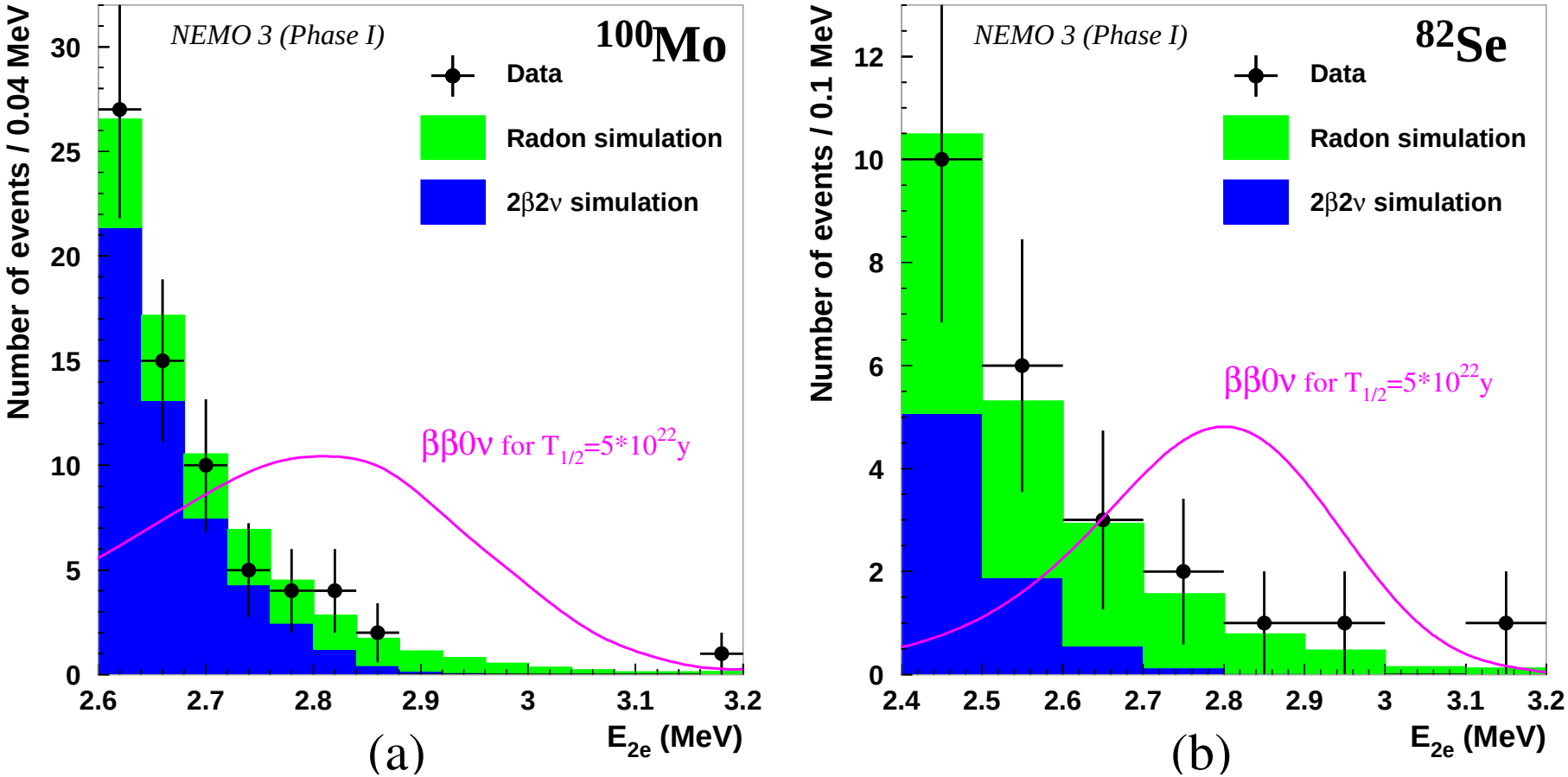
(All the enriched isotopes produced in Russia)

Nemo 3 results on neutrinoless double beta decays

Phys.Rev.Lett 95, 182302, 2005

$$T_{1/2}(^{100}\mathrm{Mo}) = 4.6 \cdot 10^{23} \text{ years} \Rightarrow m_{ee} < (0.7 - 2.8) \text{ eV}$$

$$T_{1/2}(^{82}\mathrm{Se}) = 1.0 \cdot 10^{23} \text{ years} \Rightarrow m_{ee} < (1.7 - 4.9) \text{ eV}$$



Present experimental situation

Nucleus	Experiment	%	Q	Enr	Technique	$_0$ y	<m)
^{48}Ca	Elegant IV	0.19	4271		scintillator	>1.4x10^{22}	7-45
^{76}Ge	Heidelberg-Moscow	7.8	2039	87	ionization	>1.9x10^{25}	.12 - 1
^{76}Ge	IGEX	7.8	2039	87	Ionization	>1.6x10^{25}	.14 – 1.2
^{76}Ge	Klapdor et al	7.8	2039	87	ionization	1.2x10^{25}	.44
^{82}Se	NEMO 3	9.2	2995	97	tracking	>1.x10^{23}	1.8-4.9
^{100}Mo	NEMO 3	9.6	3034	95-99	tracking	>4.6x10^{23}	.7-2.8
^{116}Cd	Solotvina	7.5	3034	83	scintillator	>1.7x10^{23}	1.7 - ?
^{128}Te	Bernatovitz	34	2529		geochem	>7.7 10^{24}	.1-4
^{130}Te	Cuoricino	33.8	2529		bolometric	>2x10^{24}	.2-1.
^{136}Xe	DAMA	8.9	2476	69	scintillator	>1.2x10^{24}	1.1 -2.9
^{150}Nd	Irvine	5.6	3367	91	tracking	>1.2x10^{21}	3 - ?

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How to improve by one order of magnitude the sensitivity on the neutrino mass?

$$m_{ee}^2 \propto T_{1/2}^{0\nu} \propto a\sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

4 orders of magnitude on $\frac{M \cdot t}{B \cdot \Delta E}$ are needed (!!!)

The CUORE way:

- Factor 20 in mass (~ 1 ton) $\Rightarrow$ Money
- Factor 20 in useful running time (10 years) $\Rightarrow$ Longevity
- Factor 20 in background rate $\Rightarrow$ Skill

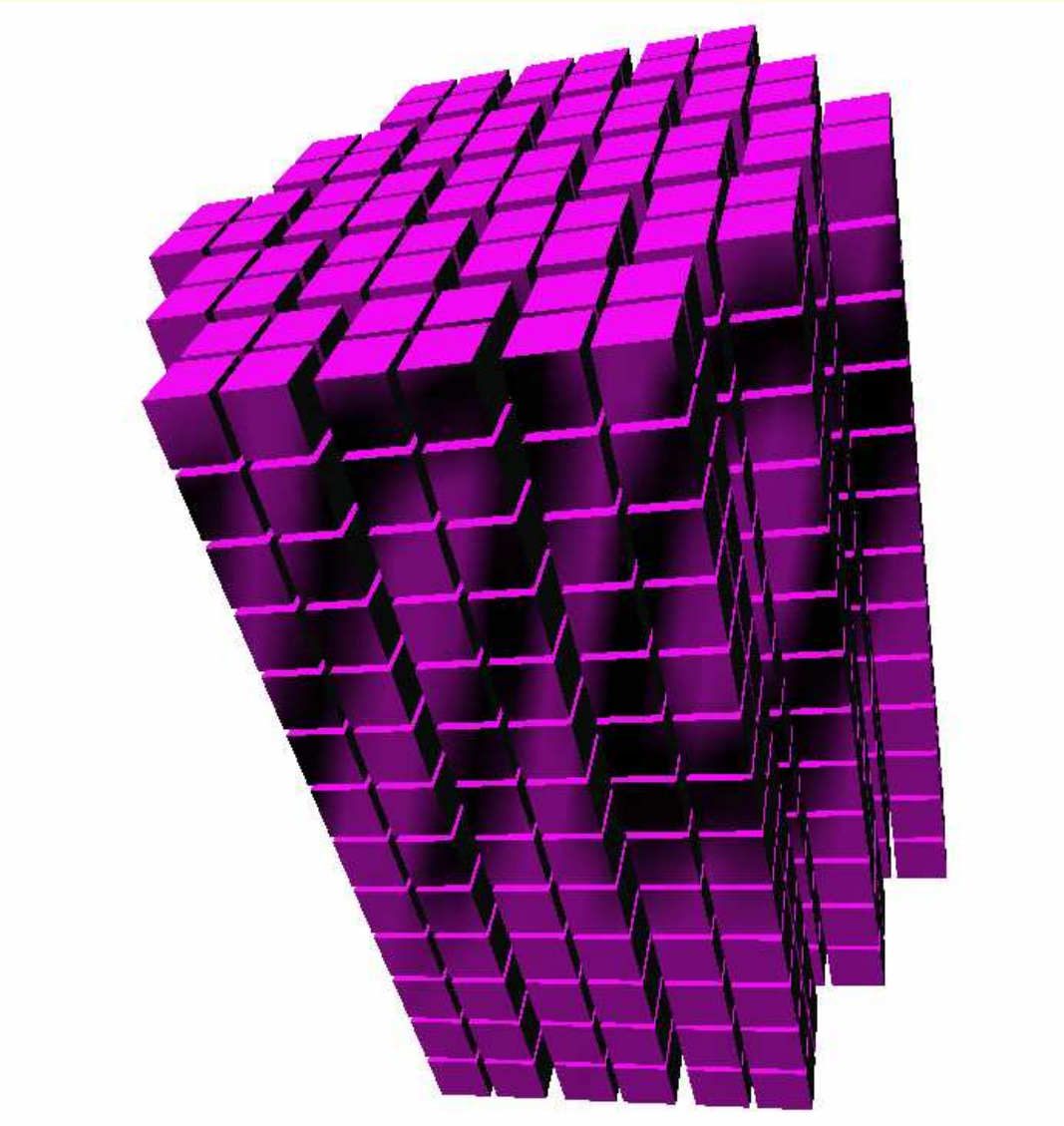
The CUORE project

(approved by the S.C. of Gran Sasso Laboratory and by INFN)

CUORE is an array of **988** bolometers grouped in **19** colums with **13** flours of **4** crystals

750 kg TeO_2 => 600 kg Te
=> **203 kg ^{130}Te**

Crystals are separated by a few mm, only, with little material among them

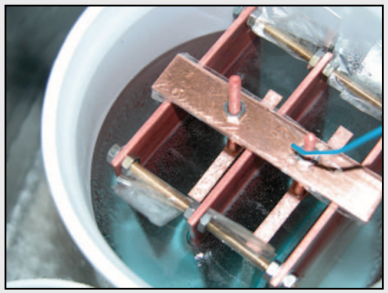


RAD tests

An array of **8 detectors cleaned** with **ultrapure materials** and **procedures**

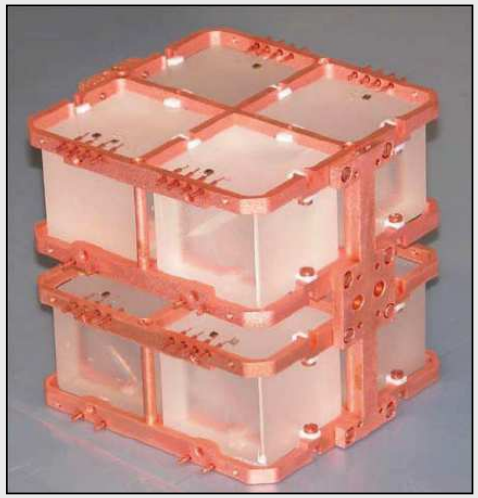
Copper

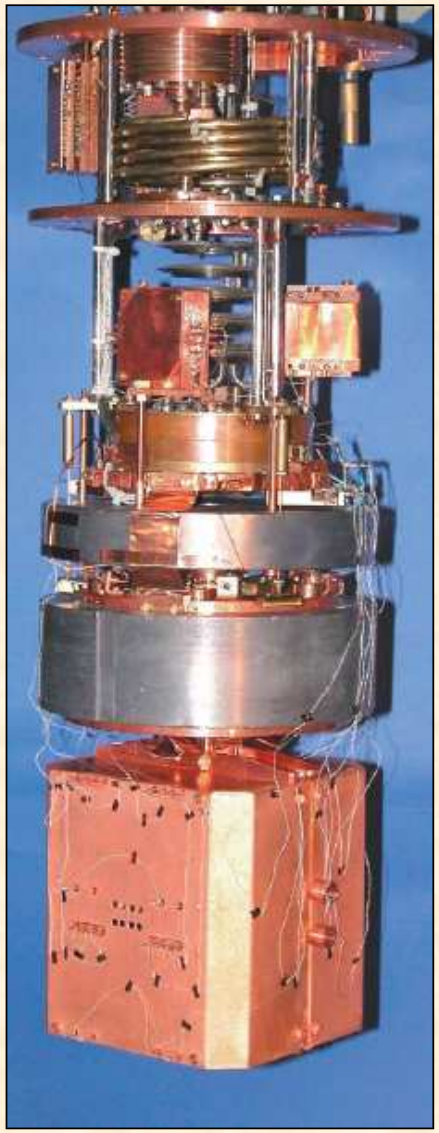
- Etching
- Electro polishing
- Passivation procedure



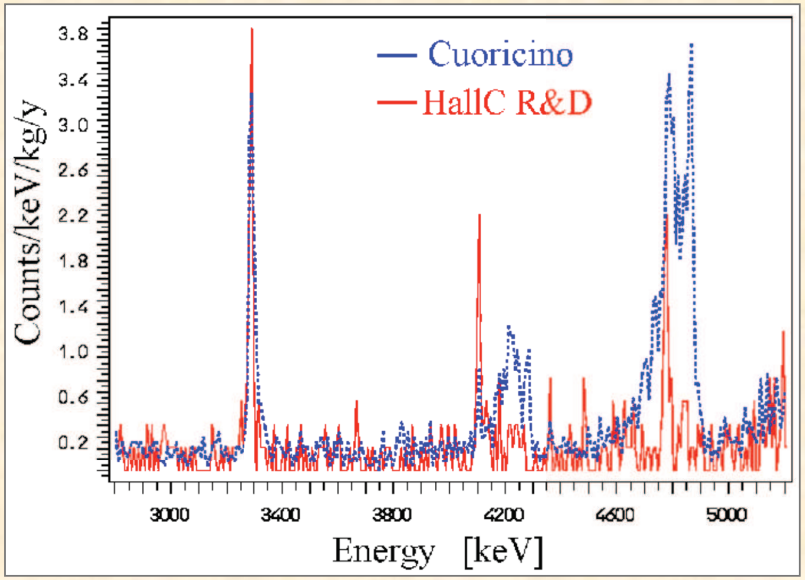
Crystals

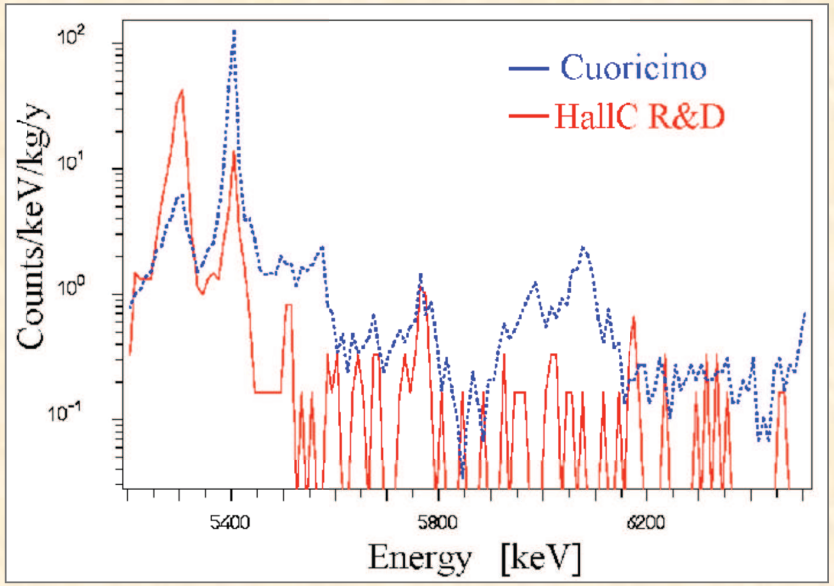
- Crystal etching (Nitric acid)
- Lapping with clean powder (2μ SiO_2)

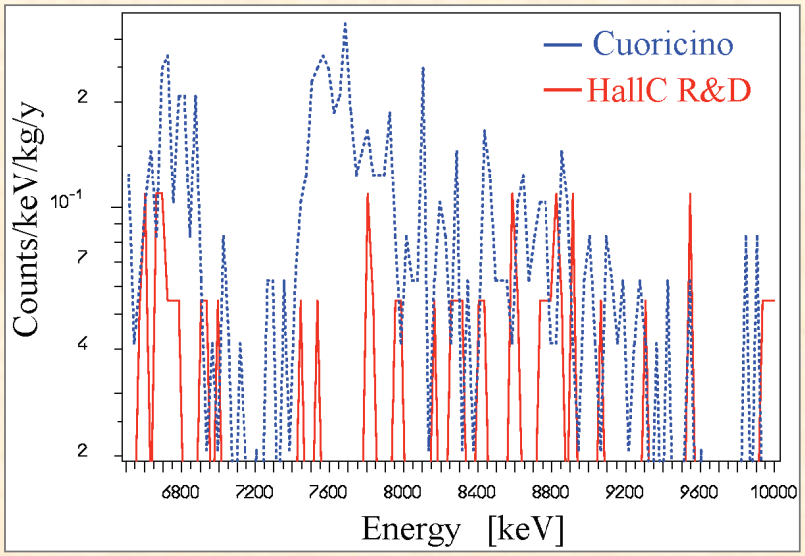




RAD tests results







- Reduction of a factor ~ 4 on **crystal** surface contaminations
- Reduction of a factor ~ 2 on **copper** surface contaminations

» new tests are on going in GranSasso

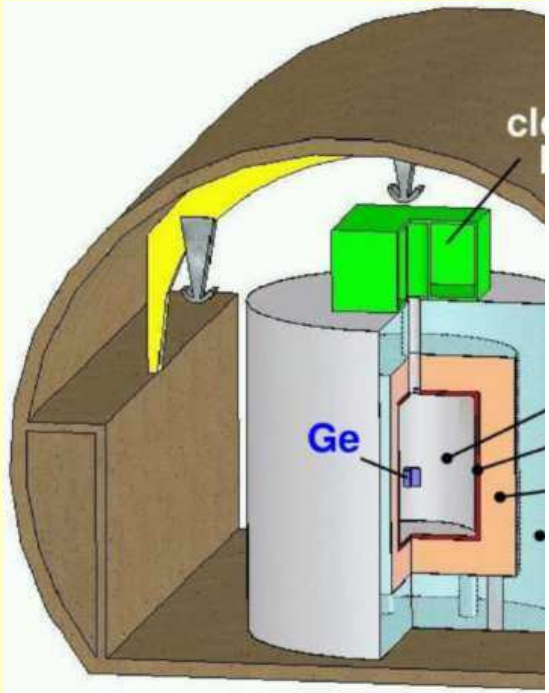
GERDA

IONIZATION

- **goal**: analise HM evidence in a short time using existing ^{76}Ge enriched detectors (HM, Igex)
- approach similar to GENIUS but less LN2
  - **naked Ge crystals in LN2 or LAr**
- more compact than GENIUS
  - 1.5 m LN2(LAr) + 10 cm Pb + 2 m water
  - 2-3 orders of magnitude better bkg than present Status-of-the-Art
  - active shielding with LAr scintillation
- 3 phases experiment
- **Phase I**:
  - radioactivity tests
  - ≈20 kg ^{76}Ge from HM and Igex
  - expected bkg 0.01 c/keV/kg/y (intrinsic)
  - **check at 5σ HM evidence**
  - 15 kg×y **6±1 ββ events on 0.5 bkg events**
- **Phase II**:
  - add **new enriched segmented detectors** with special care for activation
  - expected background ≈0.001 c/keV/kg/y

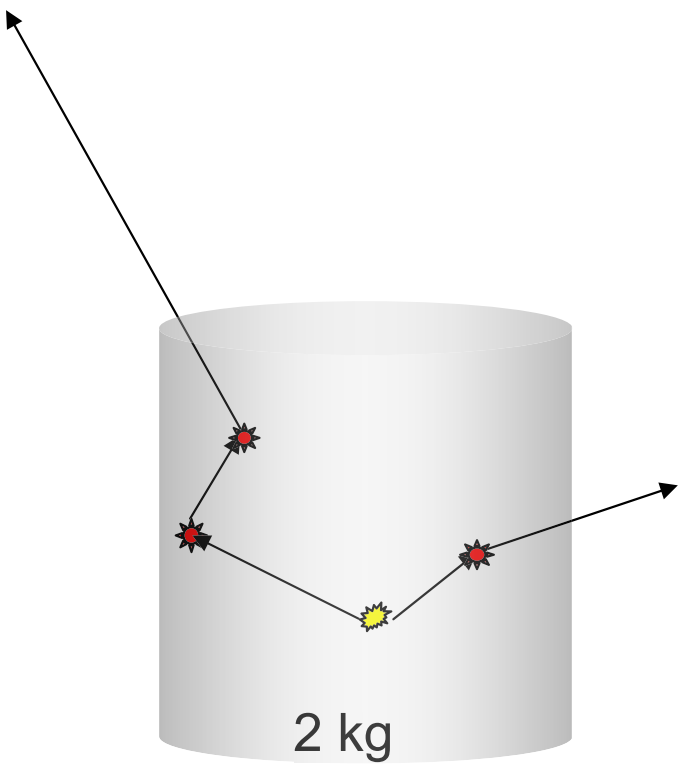
  2×10^{26} y with 100 kg×y

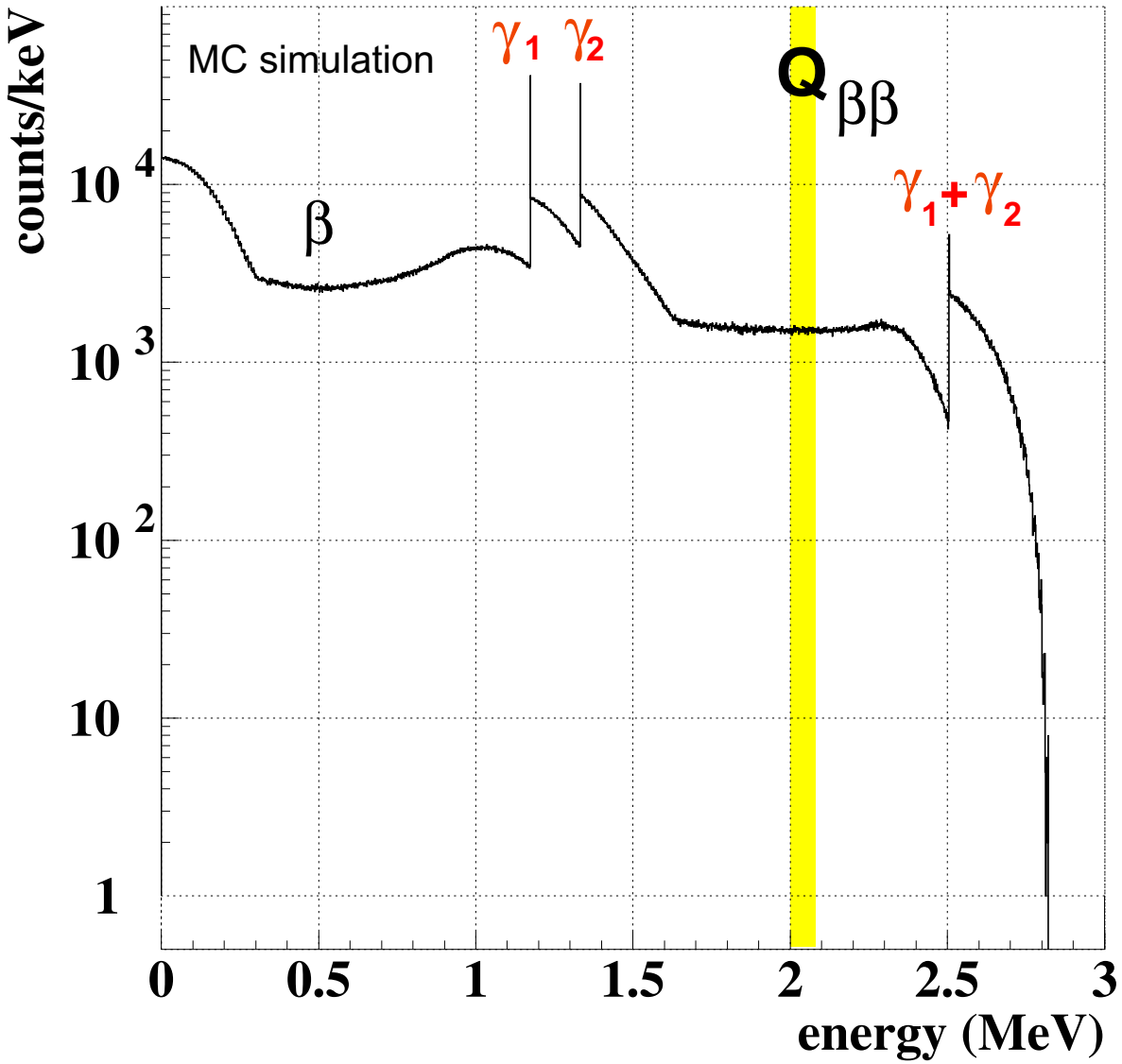
  <m> 0.09 ÷ 0.29 eV
- **Phase III: => 0.01 eV with 1 ton Ge**
  - worldwide collaboration



- Approved by LNGS S.C
  - site: Hall A northern win
- funded 40 kg enriched ^{76} phase II
- aggressive time schedule

^{60}Co background spectrum





^{60}Co: suppression by segmentation

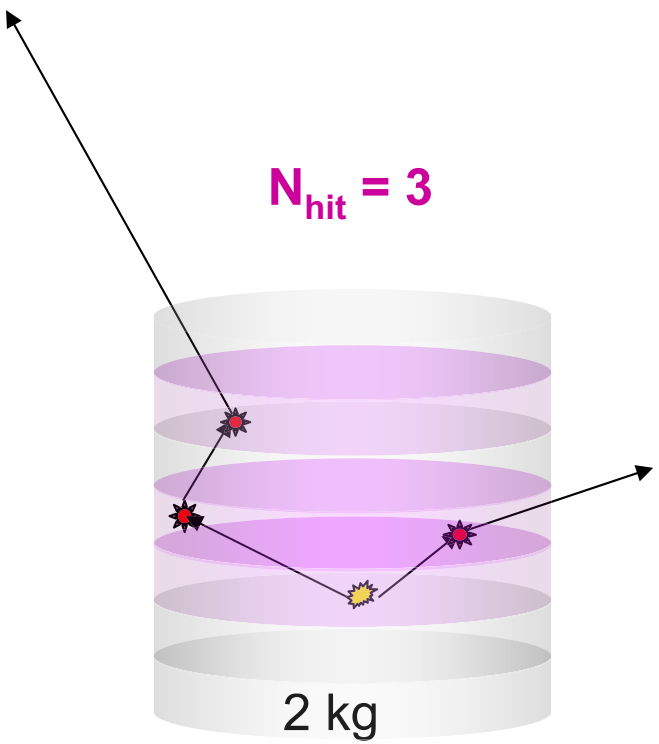
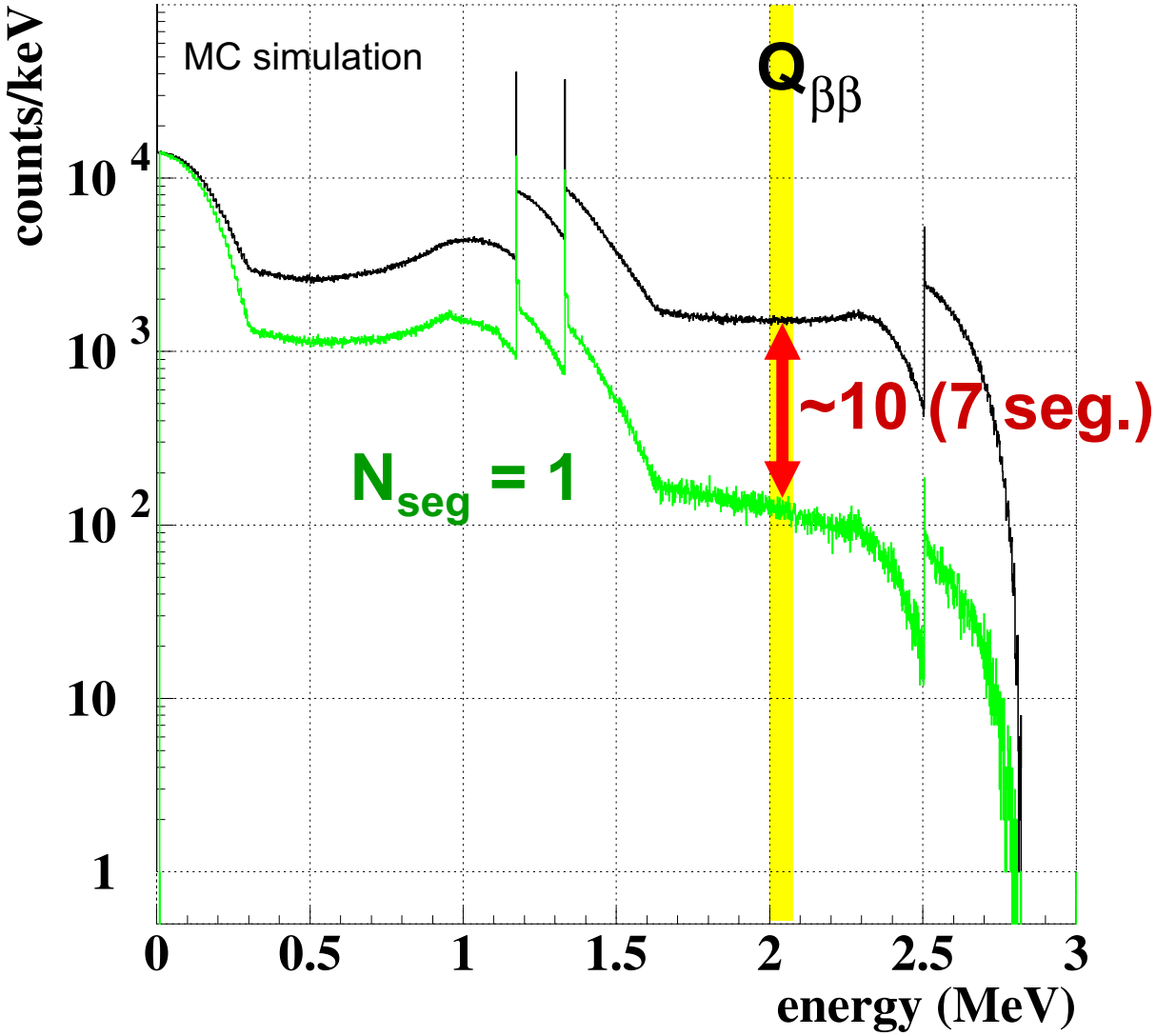
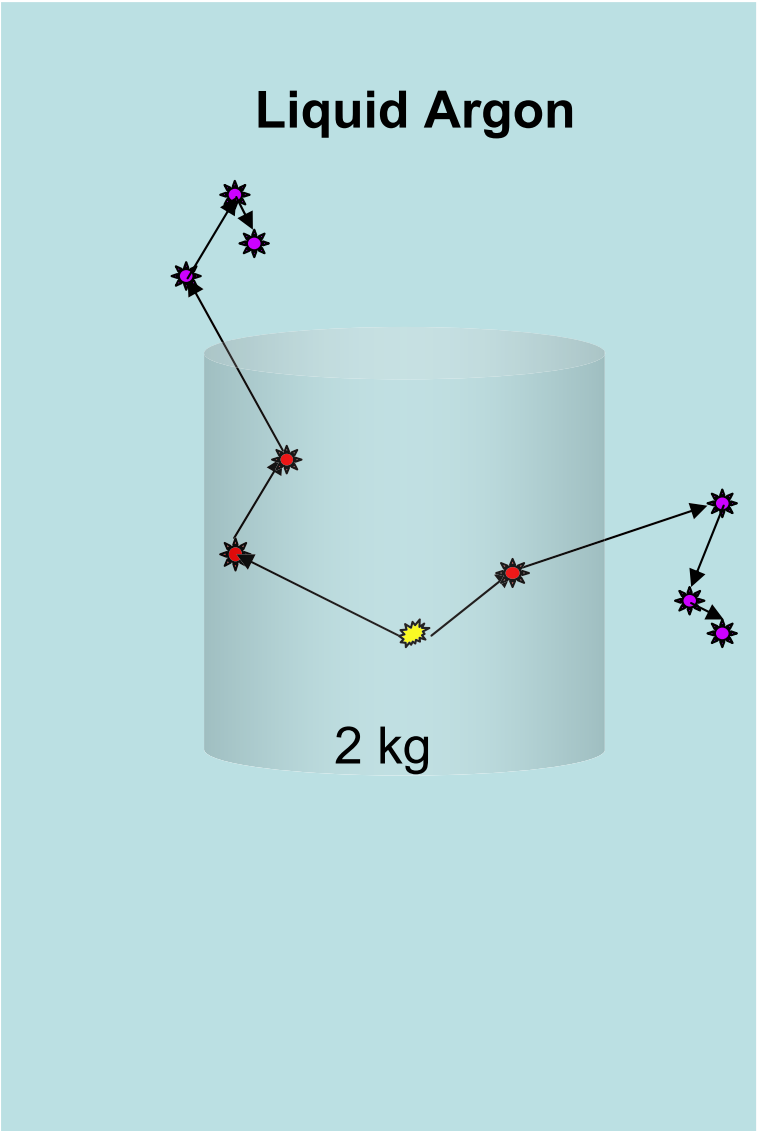
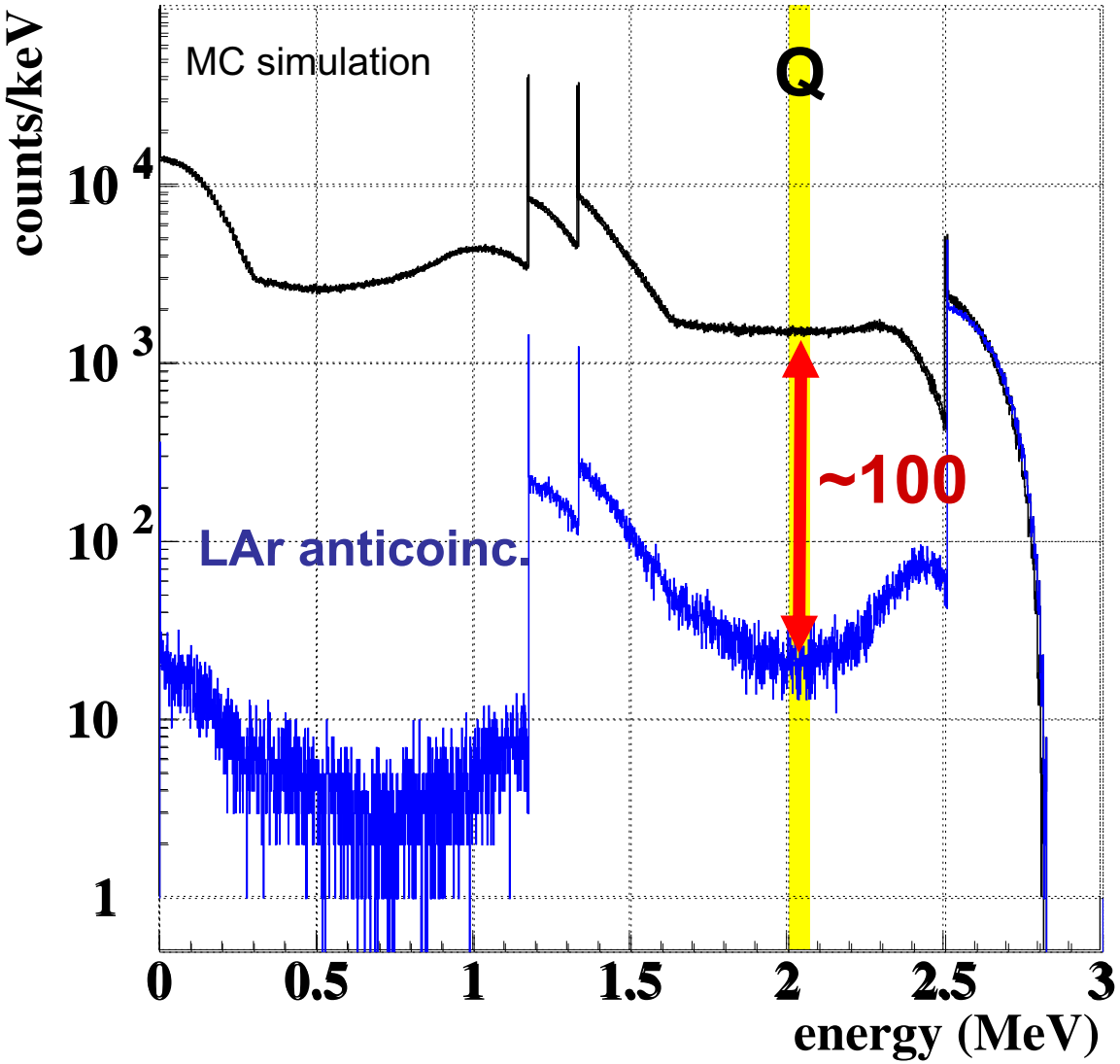


illustration:
Simple 7-fold segmentation



^{60}Co: suppression by Lar-Ge anticoincidence





ANTI-NEUTRINOS- DIRAC OR MAJORAN

Ettore Fiorini, Venice February 10, 2006

Next generation experiments

Name		%	Q	% E	B c/y	T (year)	Tech	<m> meV
CUORE	^{130}Te	34	2533	90	3.5	1.8×10^{27}	Bolometric	9-57
GERDA	^{76}Ge	7.8	2039	90	3.85	2×10^{27}	Ionization	29-94
Majorana	^{76}Ge	7.8	2039	90	.6	4×10^{27}	Ionization	21-67
GENIUS	^{76}Ge	7.8	2039	90	.4	1×10^{28}	Ionization	13-42
Supernemo	^{82}Se	8.7	2995	90	1	210^{26}	Tracking	54-167
EXO	^{136}Xe	8.9	2476	65	.55	1.3×10^{28}	Tracking	12-31
Moon-3	^{100}Mo	9.6	3034	85	3.8	1.7×10^{27}	Tracking	13-48
DCBA-2	^{150}Nd	5.6	3367	80		1×10^{26}	Tracking	16-22
Candles	^{48}Ca	.19	4271	-	.35	3×10^{27}	Scintillation	29-54
CARVEL	^{48}Ca	.19	4271	-		3×10^{27}	Scintillation	50-94
GSO	^{160}Gd	22	1730	-	200	1×10^{26}	Scintillation	65-?
COBRA	^{115}Cd	7.5	2805				Ionization	
SNOLAB+	^{150}Nd	5.6	3367				Scintillation	

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