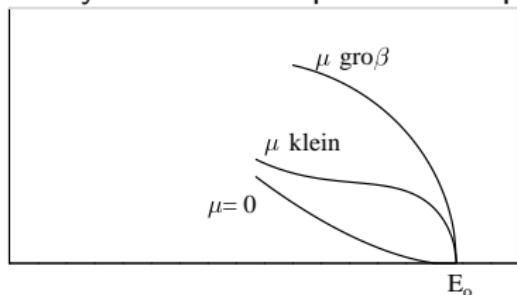


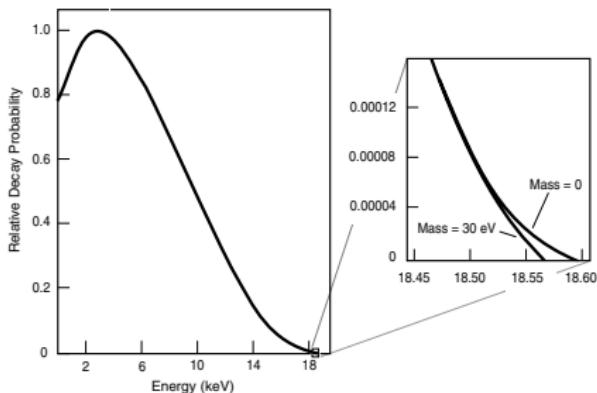
# Direct measurements of neutrino masses

$\beta$  decays: neutrino mass modify the electron spectrum shape close to the endpoint  $E_0$ .



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

A very tiny effect



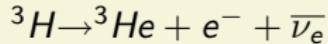
Electron spectrum:

$$\frac{dN}{dE} = G_F^2 \frac{m_e^5 c^4}{2\pi^3 h^7} \cos^2(\theta_C) |M|^2 F(Z, E) p E (E_0 - E) [(E_0 - E)^2 - m_\nu^2]^{1/2}$$

- max electron energy:  $E_e^{Max} = E_0 - m_\nu = M_s - M_e - m_\nu$
- $M_s, M_e$ : atomic mass (start, end of the process)
- $F(Z, E)$ : Coulomb correction
- Neutrino mass effects visible only close to  $E_0$ .
- Decay rate in a region  $\Delta E$  close to  $E_0$  depends from  $Q = E_0 - m_e$  and  $\propto (\Delta E/Q)^3$ .

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

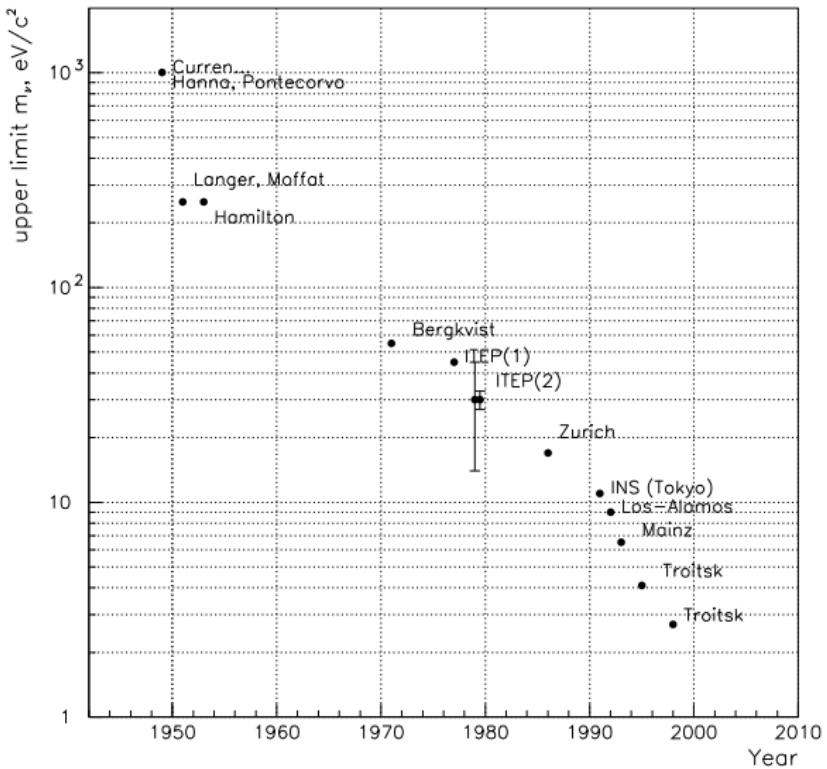
Best candidate: Tritium :



$$E_0 \simeq 18.6 \text{ KeV}$$

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:

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

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

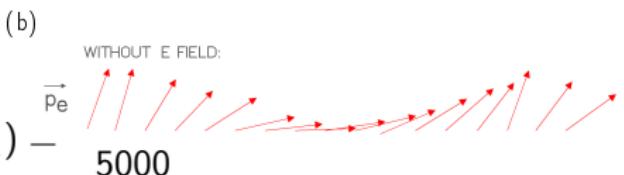
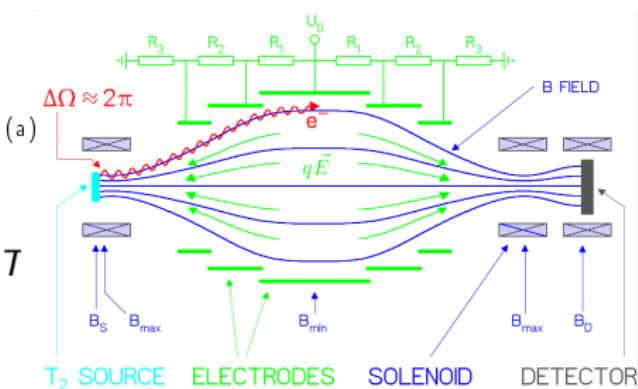
$$T_{\perp} = \frac{1}{2}mv_{\perp}^2 = \frac{1}{2}mv_{\perp}r\omega \propto B$$

$$B_1 = \frac{B_0}{5000} (\simeq 1.7 \times 10^{-3} T) \Rightarrow T_{\perp}(B_1) -$$

$\Rightarrow$  In the smallest  $B_T$  region the trajectory is almost longitudinal

$\Rightarrow$  Applying an electrostatic potential  $-U_0$ : electrons transit if

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



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

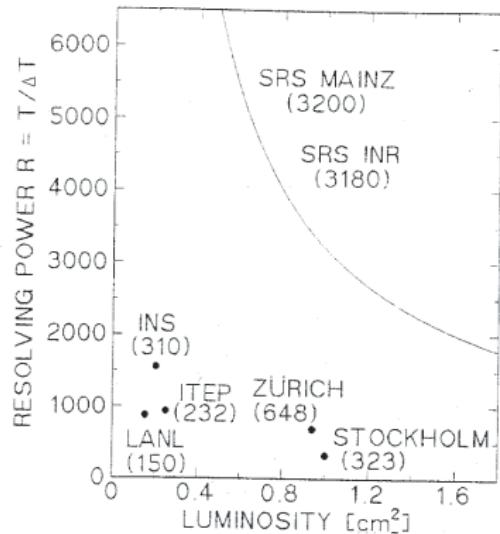
⇒ Energy interval transmitted to the detector:

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

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

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

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

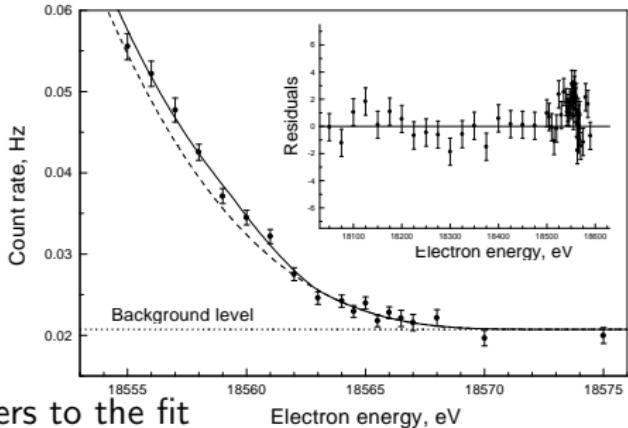


## The negative mass square problem

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  $m_\nu^2$ .**

To solve the problem:

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



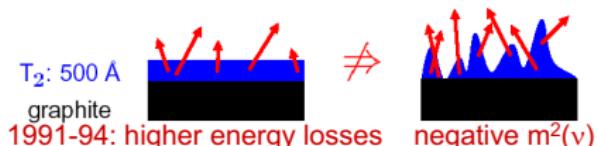
*Particle Data Book 1998: "...Unexpected effects have resulted in significantly negative  $m_\nu$ , in the new, precise tritium beta decay experiments. It is felt that a real neutrino mass as large as 10-15 eV would cause observable spectral distortions even in the presence of the end-point count excess."*

# Mainz: (final) neutrino mass results 1998-2001

## detailed investigations of systematic effects

### roughening transition of $T_2$ film

avoided by keeping film  $T < 2\text{K}$



1991-94:

higher energy losses \_ negative  $m^2(v)$

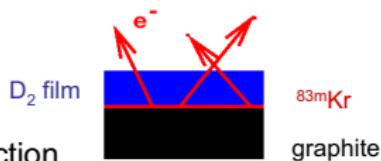
L. Fleischmann et al., J. Low Temp. Phys. **119** (2000) 615

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



$^{83m}\text{Kr}$

graphite

### self charging of $T_2$ film

determination of critical field

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



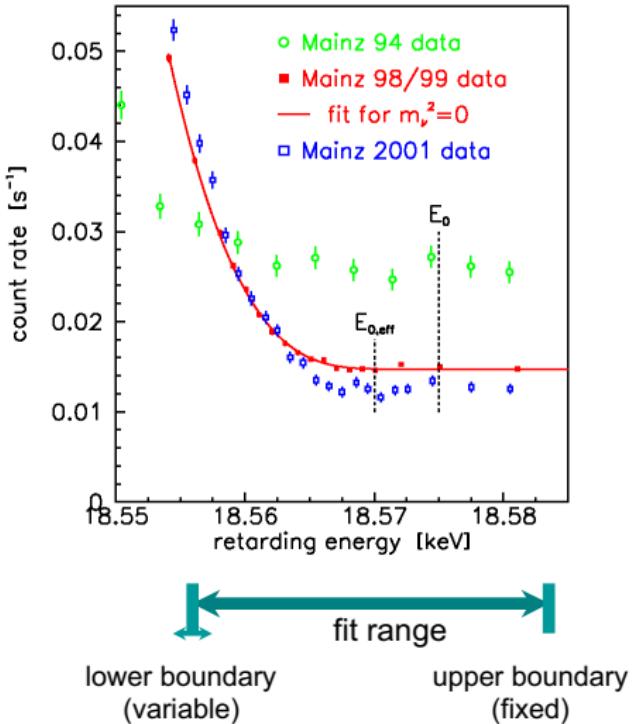
$^{83m}\text{Kr}$

graphite

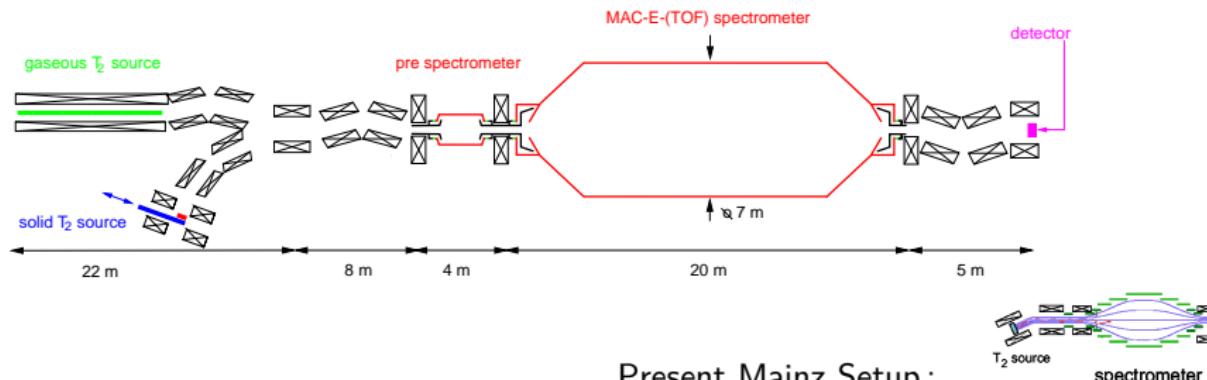
### new: neighbour excitation amplitude fitted with data

agrees with calculations

## Mainz: neutrino mass limits



# Katrin Experiment ( Karlsruhe, start in 2008)

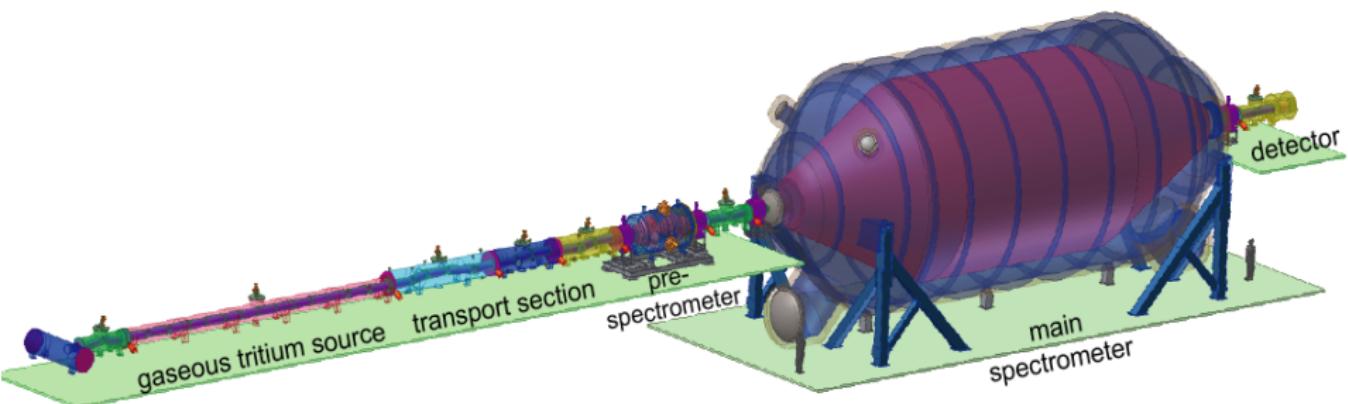


Improve  $m_\nu$  sensitivity by one order of magnitude ( $2 \text{ eV} \rightarrow 0.2 \text{ eV}$ )  $\Rightarrow$  two orders of magnitude on  $m_\nu^2$  ( $4 \text{ eV}^2 \rightarrow 0.04 \text{ eV}^2$ )

PROBLEM: endpoint count rate falls very rapidly ( $\propto \delta E^3$ )

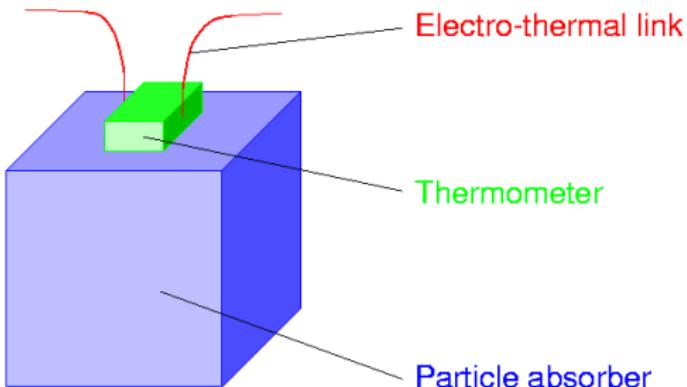
- Improve statistics: more powerful tritium source ( $\times 80$ ) and longer running time (100 days  $\rightarrow$  1000 days)
- Improve energy resolution: Large electrostatic spectrometer with  $\delta E = 1 \text{ eV}$  ( $\times 4$ )
- Better control of systematics: two independent tritium sources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

# The KArlsruhe TRItium Neutrino Experiment



# A different approach: microbolometers

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



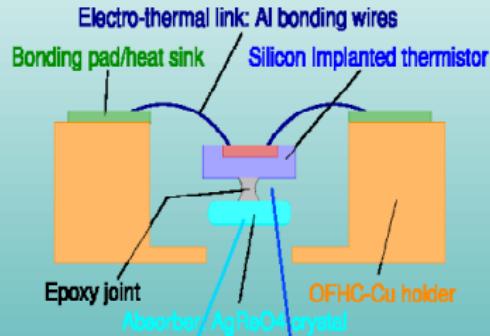
**Good:** No problem with nuclei final states: the whole energy is measured  
Completely different systematic effects (no backscattering, energy losses in the source, solid state excitations . . .)  
Only limit on detector mass: how many microbolometers can be assembled

**Bad:** Slow detectors sensitive to all the decays  $\Rightarrow$  pile-up problems  
Energy dependent backgrounds  
Worse resolution  
Calibration and stability of all the detectors

# Milano $\mu$ -calorimeters for $^{187}\text{Re}$ $\beta$ decay study

Neutrino mass measurement with arrays  
of 10  $\text{AgReO}_4$   $\mu$ -calorimeters.

- lower pile-up
- higher statistics



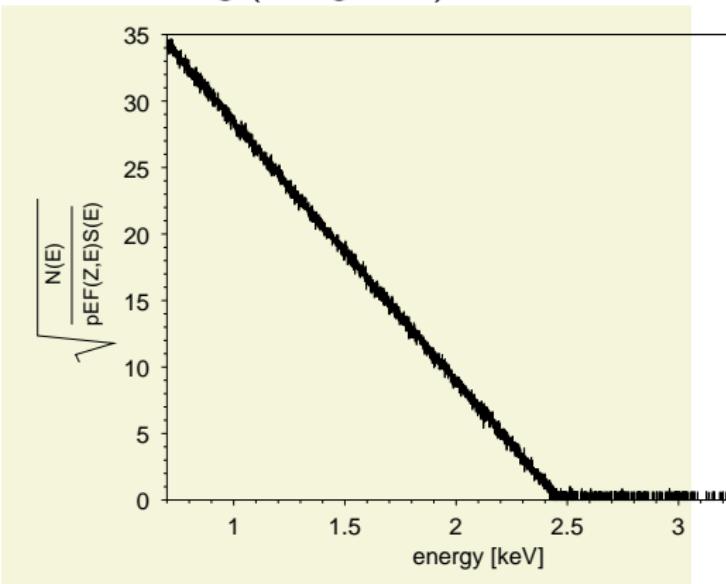
## Absorbers

$\text{AgReO}_4$  single crystals  
 $^{187}\text{Re}$  fraction  $\sim 0.32$   
 $A_\beta \approx 5.4 \times 10^{-4} \text{ Hz}/\mu\text{g}$   
Mass  $250 \sim 300 \mu\text{g}$



# MiBeta results

$6.2 \cdot 10^6$   $^{187}\text{Re}$  decays above 700 eV  
8751 hours mg (of AgReO<sub>4</sub>)



Fit with the following free parameters:

- ①  $\beta$  end - point.
- ②  $m_\nu^2$
- ③ spectrum normalization
- ④ pile-up normalization
- ⑤ background rate

## RESULTS

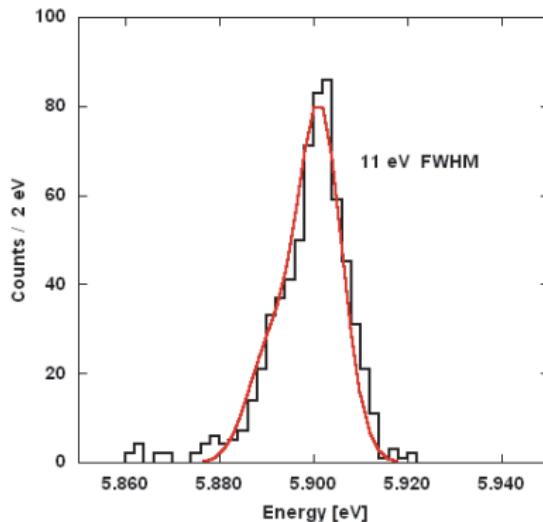
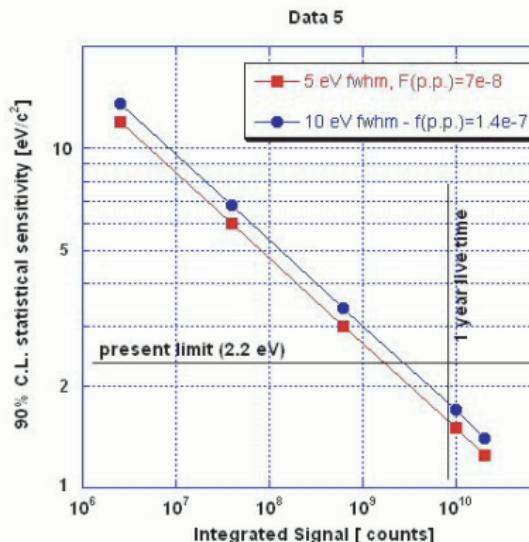
$$Q = 2465.3 \pm 0.5_{\text{stat}} \pm 1.6_{\text{sys}} \text{ eV}$$

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

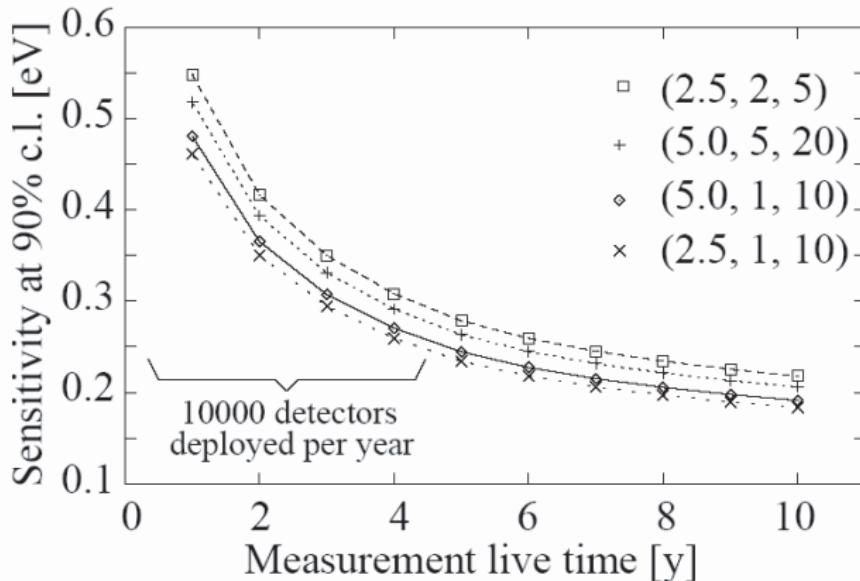
$$m_\nu^2 = -112 \pm 207_{\text{stat}} \pm 90_{\text{sys}} \text{ eV}^2$$

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

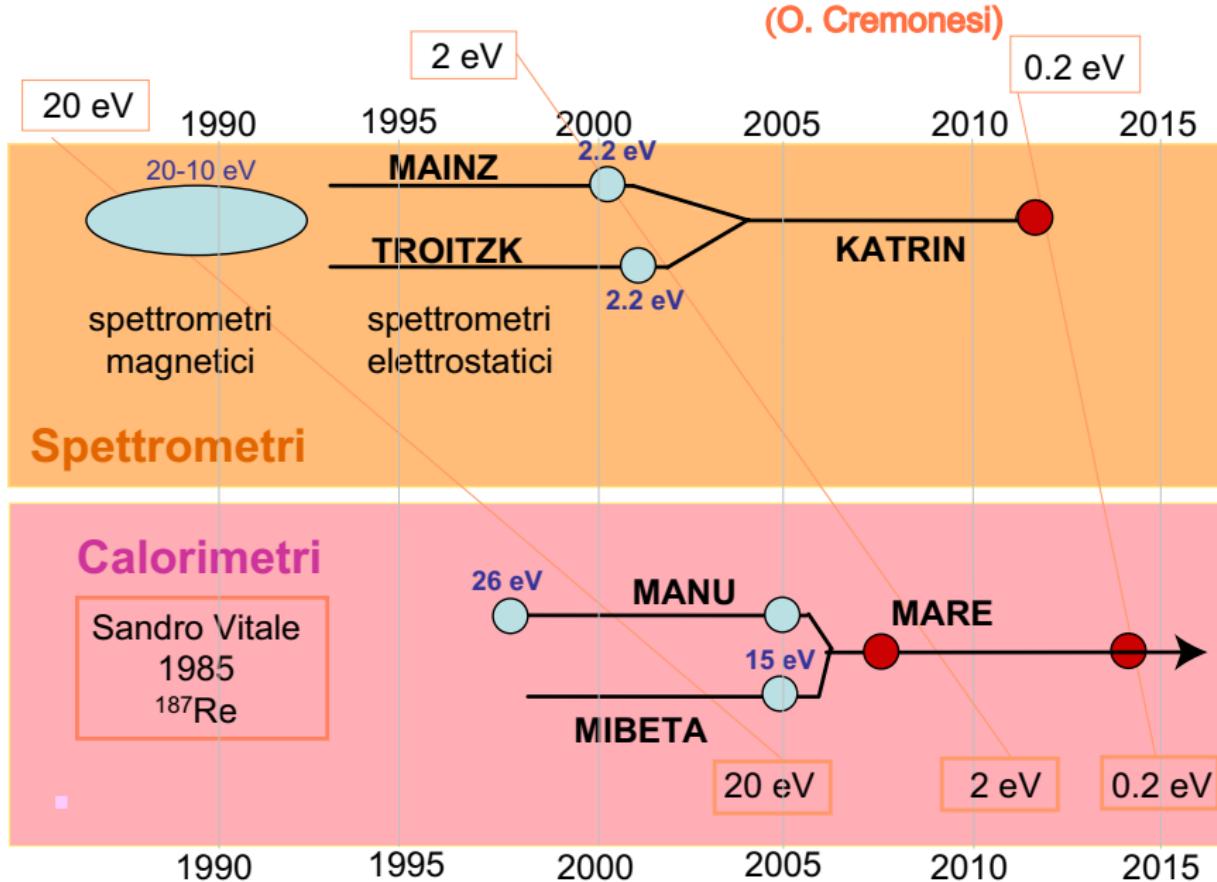
# MANU-2: sensitivity



## Proposal MARE, down to 0.2 eV

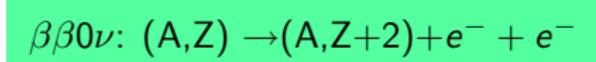
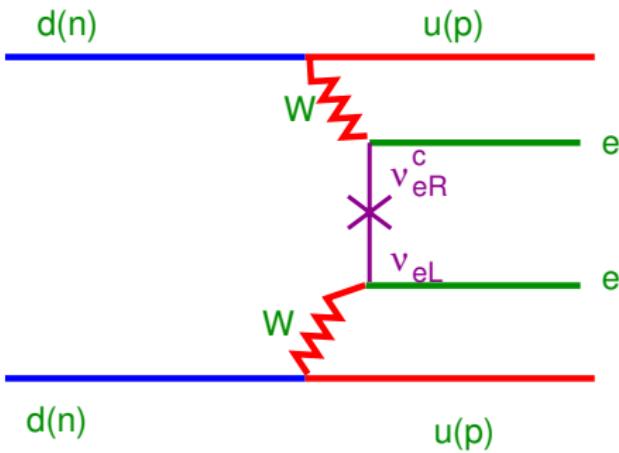


# mv in the future



# Neutrinoless Double Beta Decays

Another way to measure neutrino mass:



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

To happen it needs:

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

# Similar processes are allowed:

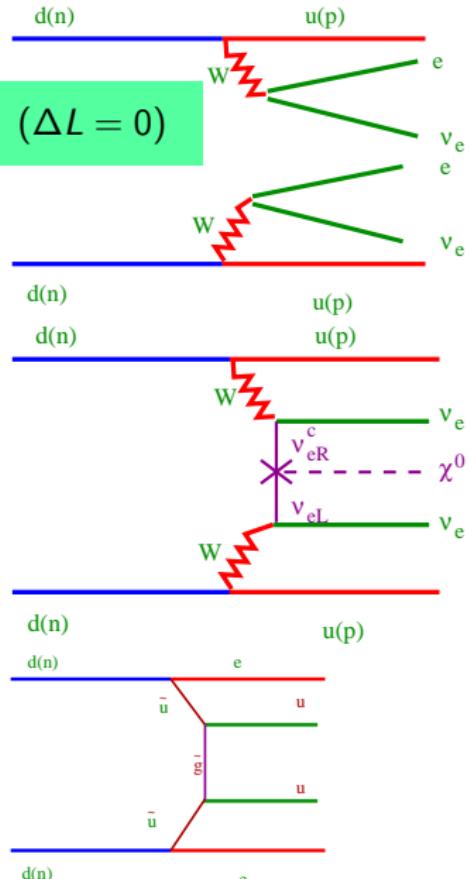
$\beta\beta 2\nu: (A, Z) \rightarrow (A, Z+2) + e^- + e^- + \nu_e^c + \bar{\nu}_e^c \quad (\Delta L = 0)$

$$\left( T_{1/2}^{2\nu} \right) = G^{2\nu}(E_0, Z) |M_{GT}^{2\nu}|^2$$

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

$$\left( T_{1/2}^{\chi^\circ} \right) = G^{\chi^\circ}(E_0, Z) |M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu}|^2 < g_{eff}^2$$

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

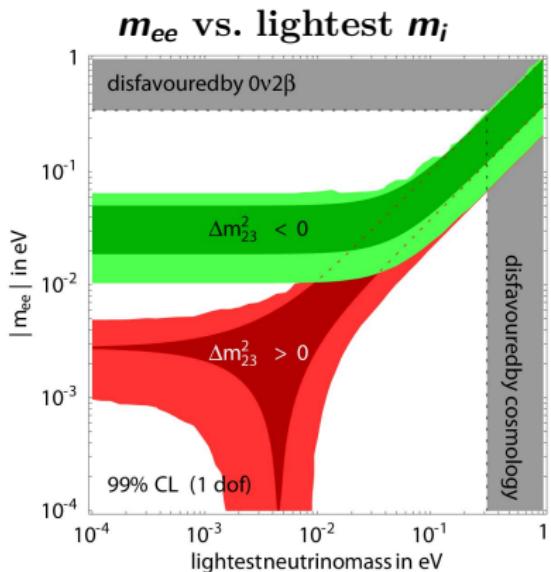
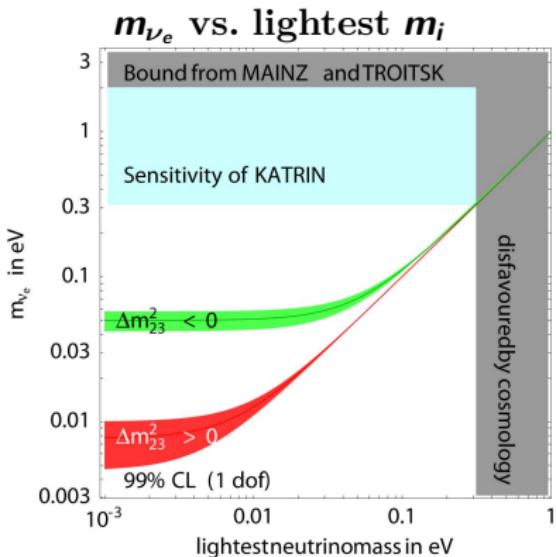


# Beta and Double Beta mass measurement interplay

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

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

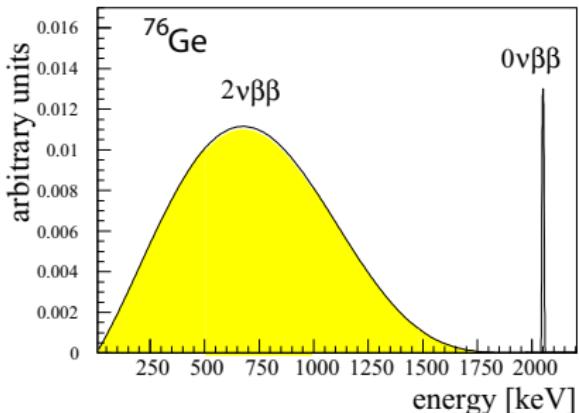
$$|m_{ee}| = \left| \sum_i V_{ei}^2 m_i \right| = \left| \cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13} \right|. \quad (2)$$



$0\nu$  and  $2\nu$   $\beta\beta$  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

:

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

a: isotopic abundance

A: atomic mass

M: mass

t: running time

B: background rate

$\epsilon$ : efficiency

$\Delta E$ : energy resolution

Extremely rare process:  $T_{1/2}^{0\nu} > 10^{24}$  years for  $\langle m_{\nu_e} \rangle = \mathcal{O}(1 \text{ eV})$ ,  $\Rightarrow$  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  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{128}\text{Te}$ ,  $^{130}\text{Te}$ .

**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  $^{238}\text{U}$  in  $^{238}\text{Pu}$ .

**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.

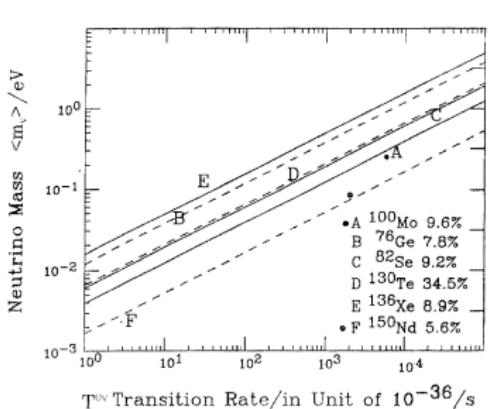
Double beta decays with 2 neutrinos signals are used as a control sample to check the estimations of the nuclei matrices (the process involved has however a completely different set of intermediate states).

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

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

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

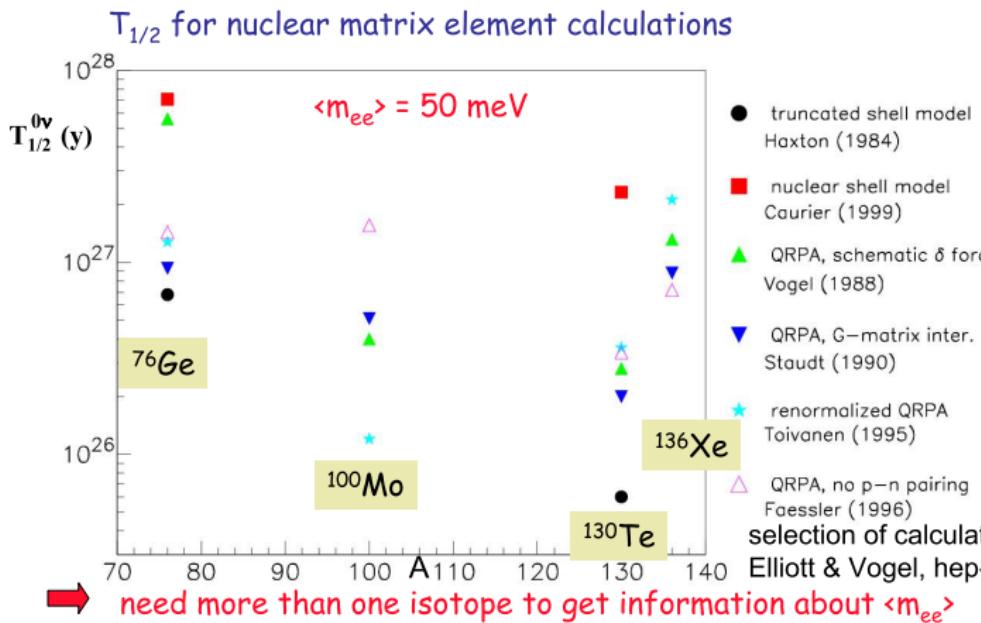
$M^{0\nu}$ : Nuclear matrix element



# Nuclear Matrix Element Calculations

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

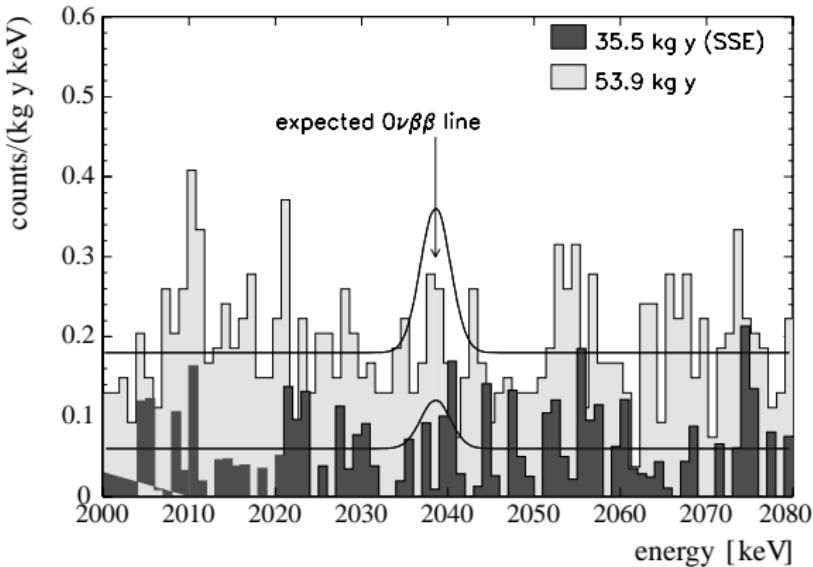
${}^{76}\text{Ge} \rightarrow {}^{76}\text{Se}$	$Q_{\beta\beta} = 2039 \text{ keV}$	nat. abund. = 7.4%
${}^{100}\text{Mo} \rightarrow {}^{100}\text{Ru}$	$Q_{\beta\beta} = 3034 \text{ keV}$	nat. abund. = 9.6%
${}^{130}\text{Te} \rightarrow {}^{130}\text{Xe}$	$Q_{\beta\beta} = 2529 \text{ keV}$	nat. abund.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



# Heidelberg - Moscow (LNGS) experiment

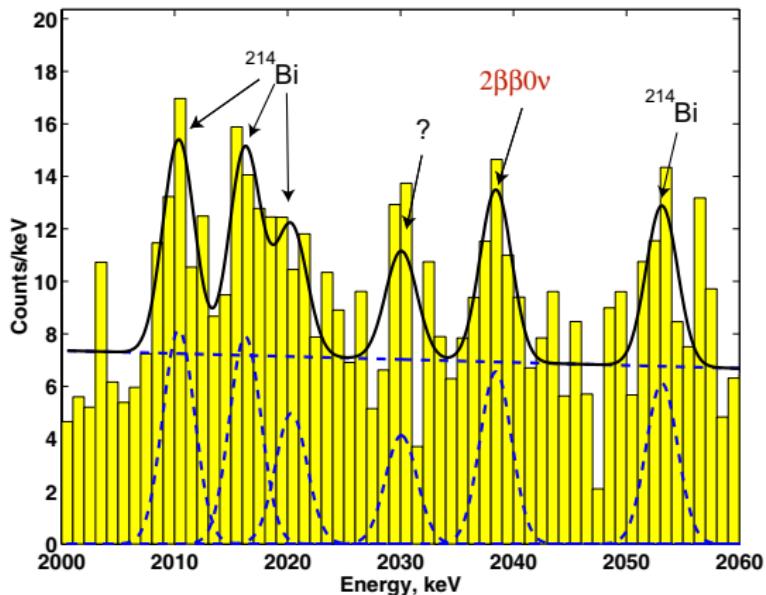
Eur. Phys. J. A12, 147 (2001)

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



# Evidence of neutrinoless double beta decays

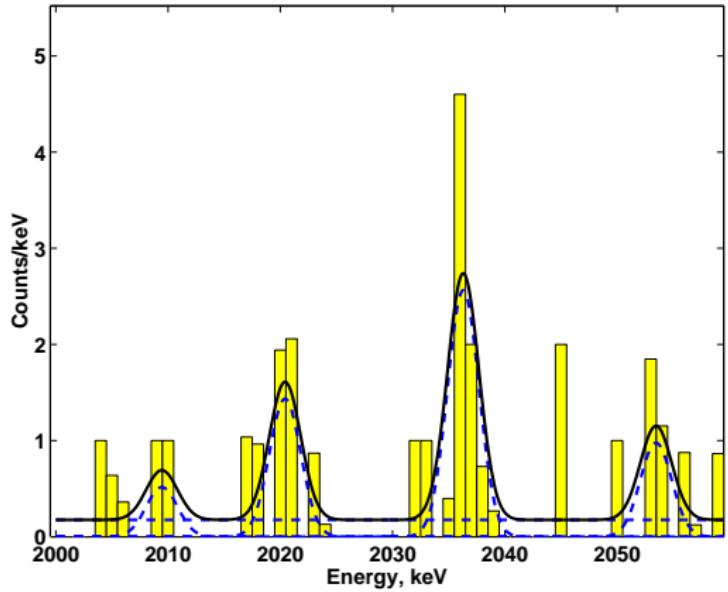
(published as "Results of . . ." Phys.Lett. B586:198-212, 2004)



71.7 Kg yr  
 $T_{1/2}^{0\nu} = (0.69 - 4.18) \times 10^{25}$   
years  
 $m_\nu$  =  
 $0.44(0.24 - 0.58)$  eV  
Significance:  $4.2\sigma$   
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:  $^{130}\text{Te}$

CUORICINO source

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



$6.4 \times 10^{25} {}^{130}\text{Te}$  nuclei

experiments can be expanded at low cost

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

$$\Delta T = E/C$$

thanks to a proper thermometer,

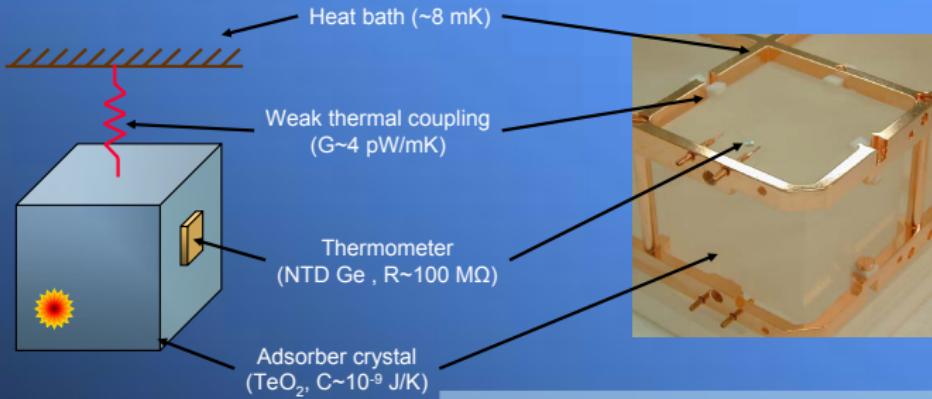
$$\Delta T \Rightarrow \Delta V$$

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

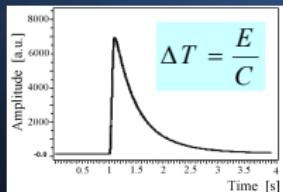
E.Fiorini - NOVE 2006

# Cryogenic Detectors



## Cryodet features

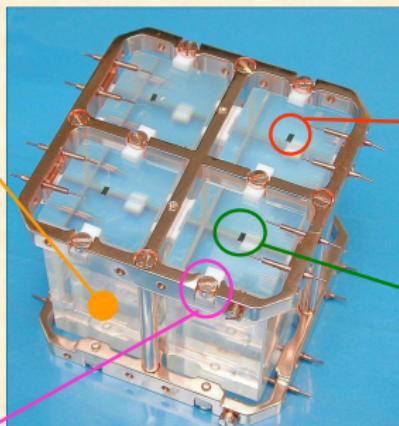
- ▲ wide choice of detector materials
- ▲ good energy resolution
- ▲ true calorimeters
- ▼ velocity



# CUORICINO bolometers

## Absorber crystal

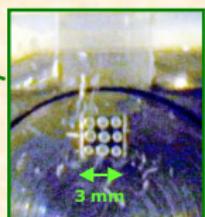
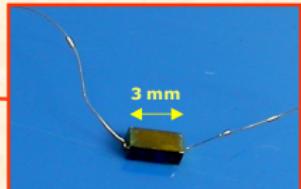
The absorber is a **5x5x5 cm<sup>3</sup>** crystal of **TeO<sub>2</sub>** which contains the neutrinoless DBD candidate **<sup>130</sup>Te**



## Temperature sensor

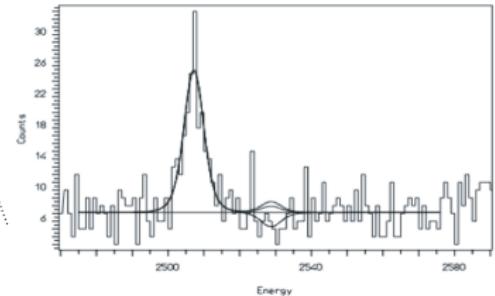
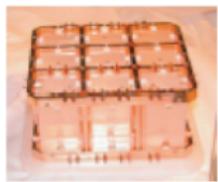
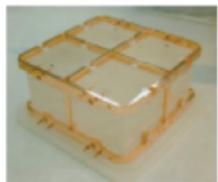
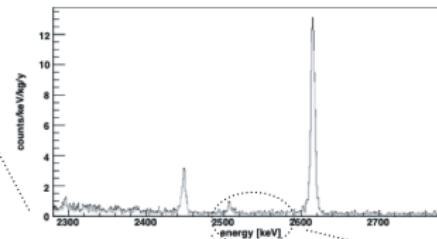
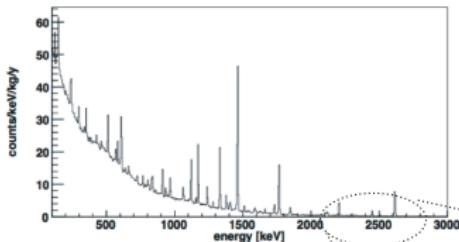
The thermal signal is measured by means of an **NTD Ge Thermistor**

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



# Risultati Cuoricino

Phys.Rev.C78:035502,2008



Active mass: 40.7 kg

Exposure: 11.83 kg yr

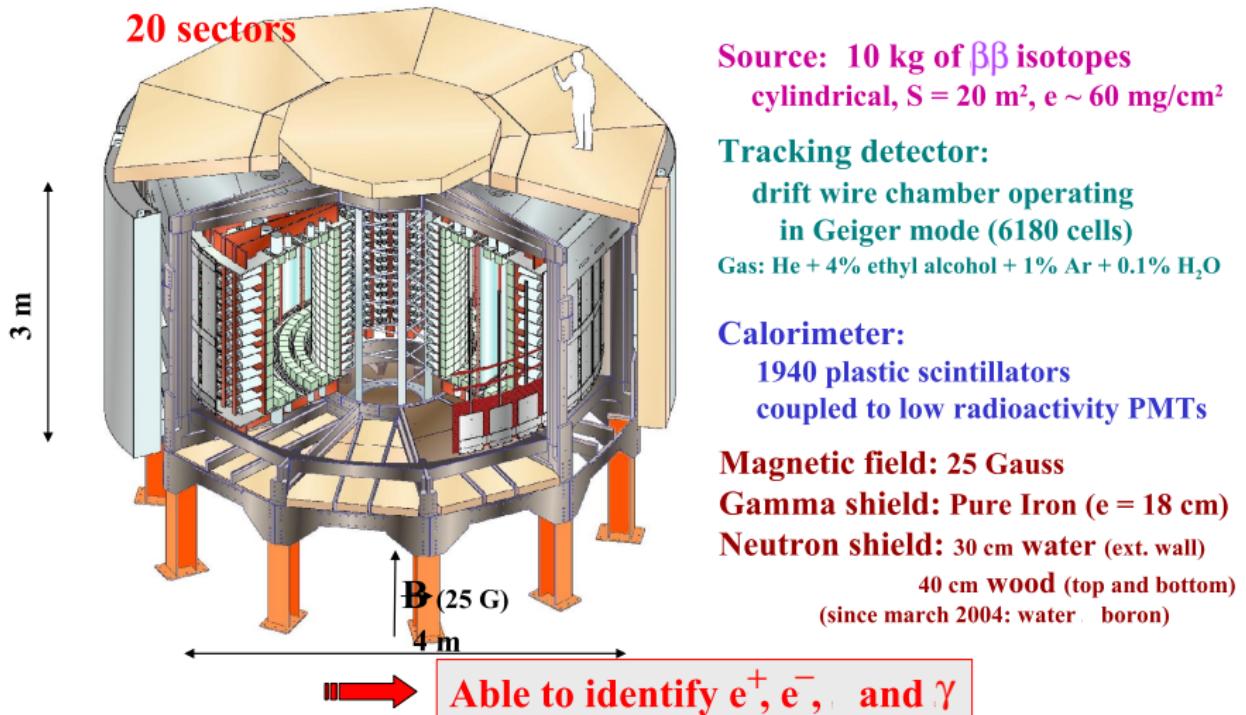
$T_{1/2}^{0\nu}({}^{130}\text{Te}) > 3.0 \times 10^{24}$  yr (90% CL)  
 $\langle m_\nu \rangle < 0.19 - 0.68$  eV

# Cuoricino vs Heidelberg Moscow

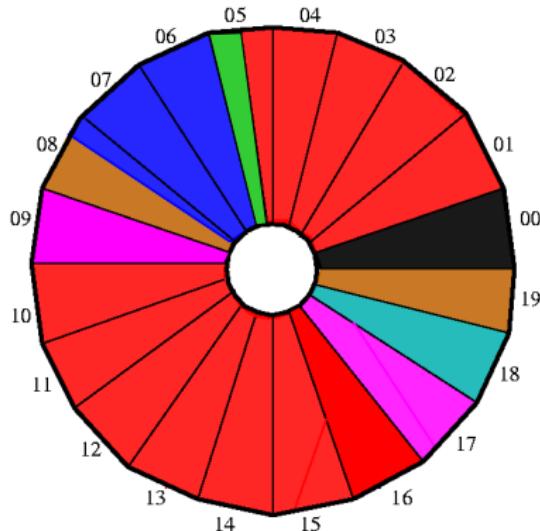
	He-Mo	Cuoricino
$Q_{\beta\beta}$ (keV)	2039	2529
Detector mass (kg)	11	40.7
Active mass (kg)	9.5	11
Duty cycle	80%	64%.
Energy resolution (keV)	3.5	8
Efficiency	100%	85%
Background rate (counts/kg/keV/yr)	0.11	0.19
Merit factor	1	0.96

# The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



## decay isotopes in NEMO-3 detector



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

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

**search**

**measurement**

**$^{116}\text{Cd}$  405 g**

$Q_{\beta\beta} = 2805 \text{ keV}$

**$^{96}\text{Zr}$  9.4 g**

$Q_{\beta\beta} = 3350 \text{ keV}$

**$^{150}\text{Nd}$  37.0 g**

$Q_{\beta\beta} = 3367 \text{ keV}$

**$^{48}\text{Ca}$  7.0 g**

$Q_{\beta\beta} = 4272 \text{ keV}$

**$^{130}\text{Te}$  454 g**

$Q_{\beta\beta} = 2529 \text{ keV}$

**$^{\text{nat}}\text{Te}$  491 g**

**Cu 621 g**

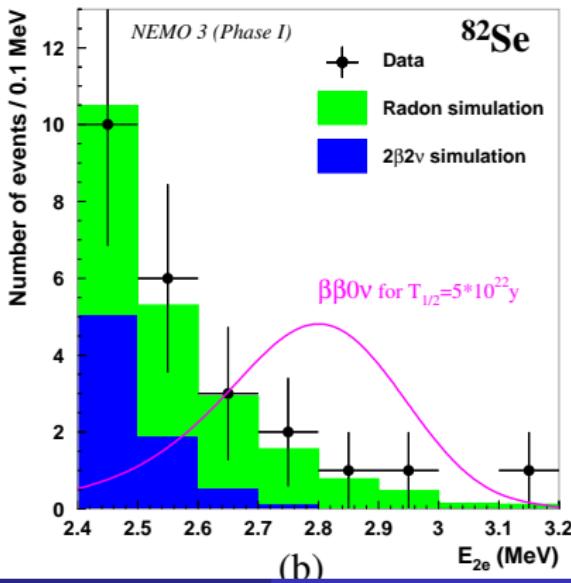
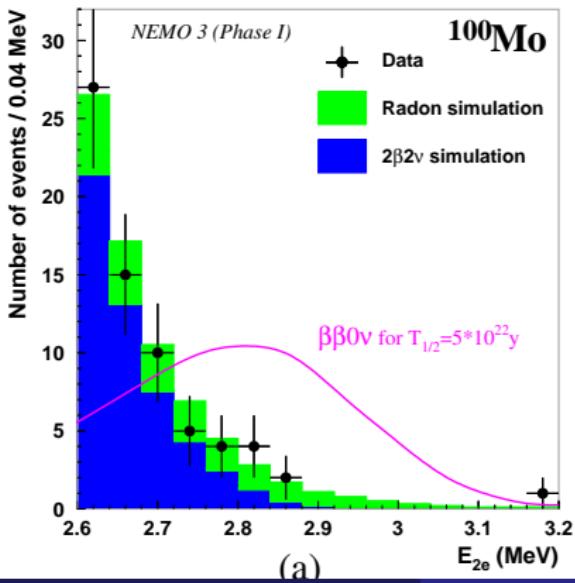
**External bkg measurement**

(All the enriched isotopes produced in Russia)

# Nemo 3 results on neutrinoless double beta decays

Phys.Rev.Lett 95, 182302, 2005

$$T_{1/2}(^{100}\text{Mo}) = 4.6 \cdot 10^{23} \text{ years} \Rightarrow m_{ee} < (0.7 - 2.8) \text{ eV}$$
$$T_{1/2}(^{82}\text{Se}) = 1.0 \cdot 10^{23} \text{ years} \Rightarrow m_{ee} < (1.7 - 4.9) \text{ eV}$$



# Tracking SuperNemo

- concept: scale NEMO setup
- tracking calorimeter
- already tested technology (NEMO)
  - event topology (Detection of the 2 electrons)
  - single and sum energy + angular correlation
  - particle identification
  - Background control
  - source purification
  - background level measurement
  - external background reduction (Rn)
- No strong theoretical criteria for isotope selection:  $^{82}\text{Se}$ 
  - transition energy: 2 995 keV
  - natural i.a.: 8.7%

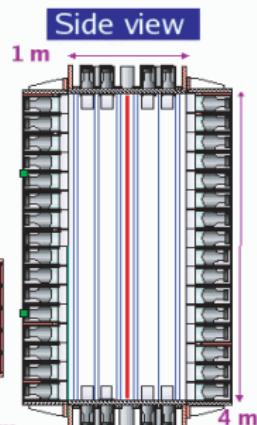
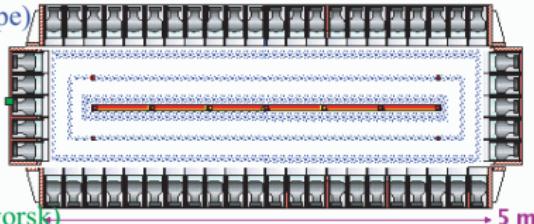
**3 years R&D aiming at a 50 meV <m,>  
sensitivity: accepted by IN2P3 s.c.**

- 5 kg of  $^{82}\text{Se}$  funded by ILIAS (Europe)
- Enrichment:
  - 1 kg of  $^{82}\text{Se}$  in 2005
  - 2 kg of  $^{82}\text{Se}$  in 2006
  - 5 kg of  $^{82}\text{Se}$  in 2007
- Enrichment of 100 kg of  $^{82}\text{Se}$  is possible in 3 years at ECP (Zelenogorsk)

- Planar geometry
  - source ( $40 \text{ mg/cm}^2$ ):  $12\text{m}^2$
  - tracking volume: ~3000 channels
  - calorimeter: ~1000 PMT
- Modular:
  - ~5 kg of enriched isotope/module
  - 100 kg: 20 modules
  - ~ 60 000 channels for drift chamber
  - ~ 20 000 PMT
  - energy resolution = 2.6% @ 3 MeV
  - efficiency: 40%
  - LNGS/LSM

2006-2008: R&D  
2009: first module  
2011: all modules  
2016: final results

Top view



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

## Array of 988 TeO<sub>2</sub> crystals

- 19 Cuoricino-like towers
- 13 levels, 4 crystals per tower
- 5x5x5 cm<sup>3</sup> (750 g each)
- <sup>130</sup>Te: 33.8% isotope abundance
- 741 kg TeO<sub>2</sub>  $\Rightarrow$  200 kg <sup>130</sup>Te

### Goal

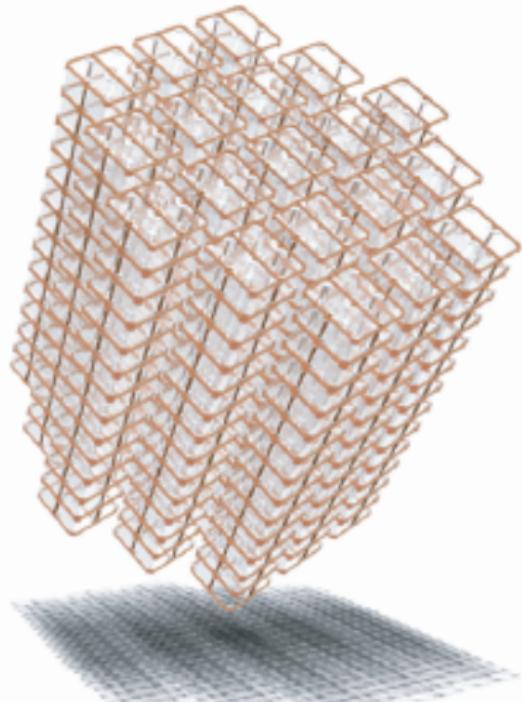
background < 0.01 cnts/keV/kg/y

Resolution = 5 keV

### 5 year sensitivity

$$F^{0\nu} > 2.1 \times 10^{26} \text{ y}$$

$$m_{ee} < \sim 19 - 100 \text{ meV}$$



(approved by INFN and the Science Council of Gran Sasso Laboratory)

# RAD tests

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

## Copper

- Etching
- Electro polishing
- Passivation procedure

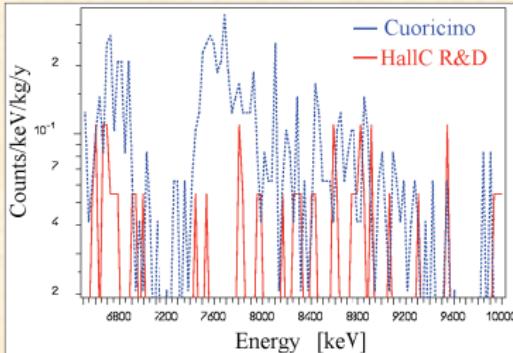
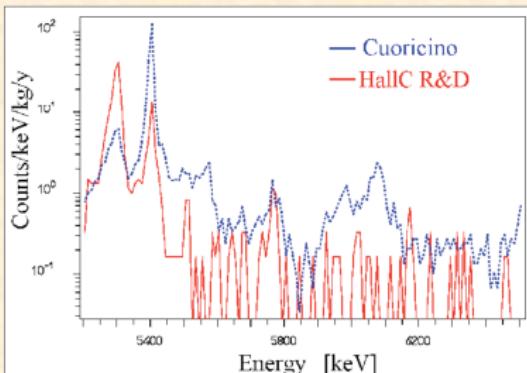
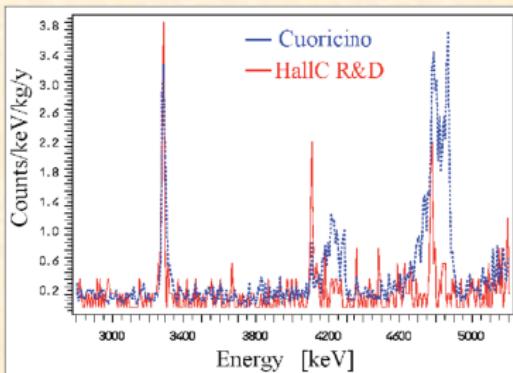


## Crystals

- Crystal etching (Nitric acid)
- Lapping with clean powder ( $2\mu \text{ SiO}_2$ )



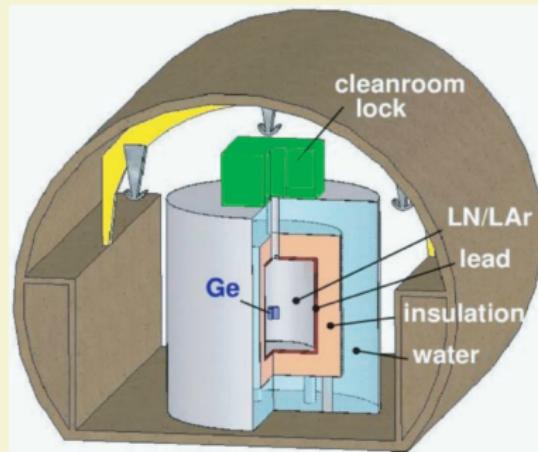
## RAD tests results



- Reduction of a factor  $\sim 4$  on **crystal** surface contaminations
  - Reduction of a factor  $\sim 2$  on **copper** surface contaminations
- » new tests are on going in GranSasso

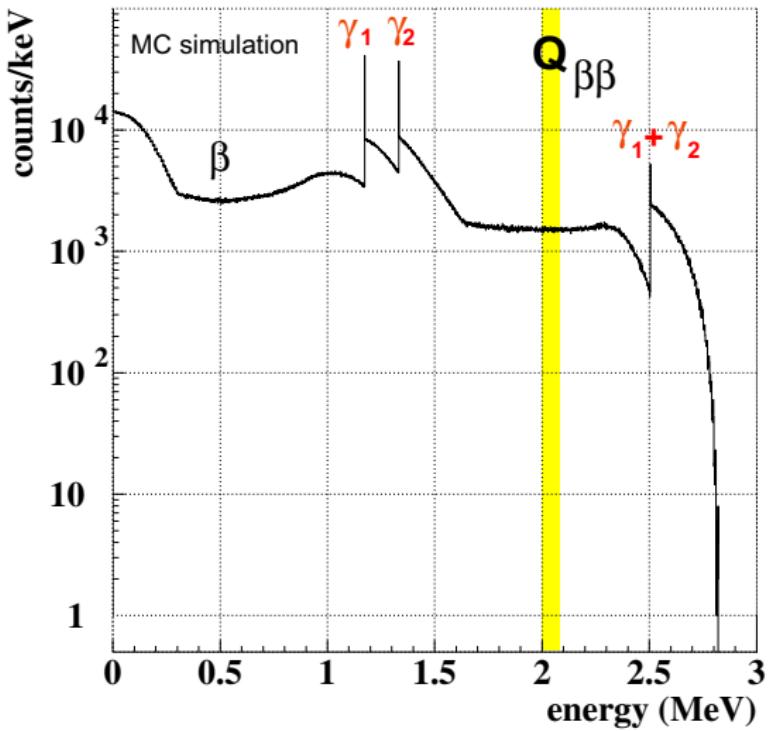
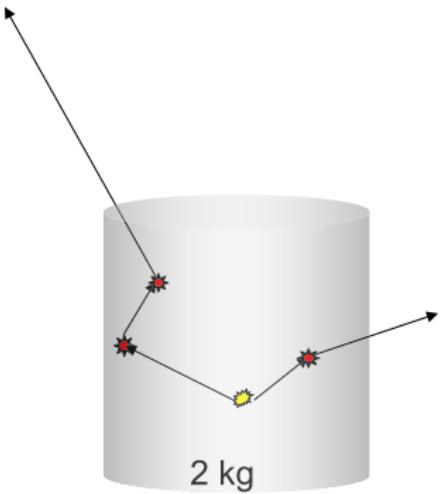
## IONIZATION

- **goal:** analyse HM evidence in a short time using existing  $^{76}\text{Ge}$  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
  - $\approx 20 \text{ kg } ^{76}\text{Ge}$  from HM and Igex
  - expected bkg  $0.01 \text{ c/keV/kg/y}$  (intrinsic)
  - check at 5? HM evidence
  - $15 \text{ kg} \times \text{y } 6 \pm 1 \text{ ?? events on } 0.5 \text{ bkg events}$
- **Phase II:**
  - add new enriched segmented detectors with special care for activation
  - expected background  $\approx 0.001 \text{ c/keV/kg/y}$
  - $2 \times 10^{26} \text{ y}$  with  $100 \text{ kg} \times \text{y}$
  - $\langle m \rangle = 0.09 \pm 0.29 \text{ eV}$
- **Phase III:** =>  $0.01 \text{ eV}$  with 1 ton Ge
  - worldwide collaboration

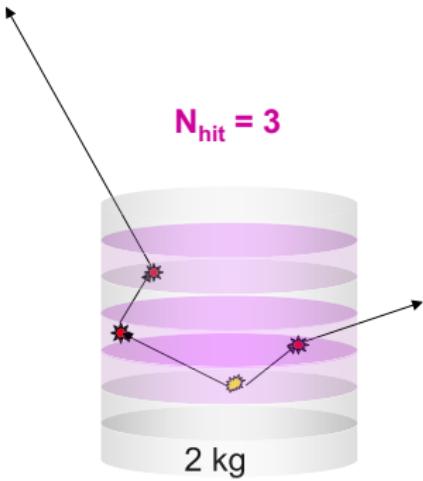


- Approved by LNGS S.C.
- site: Hall A northern wing
- funded 40 kg enriched  $^{76}\text{Ge}$  for phase II
- aggressive time schedule

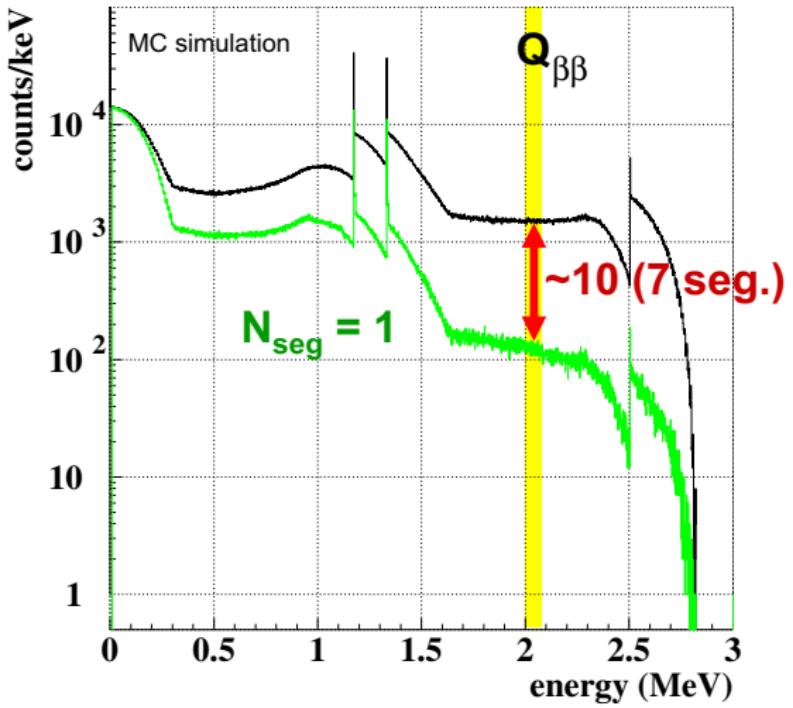
# $^{60}\text{Co}$ background spectrum



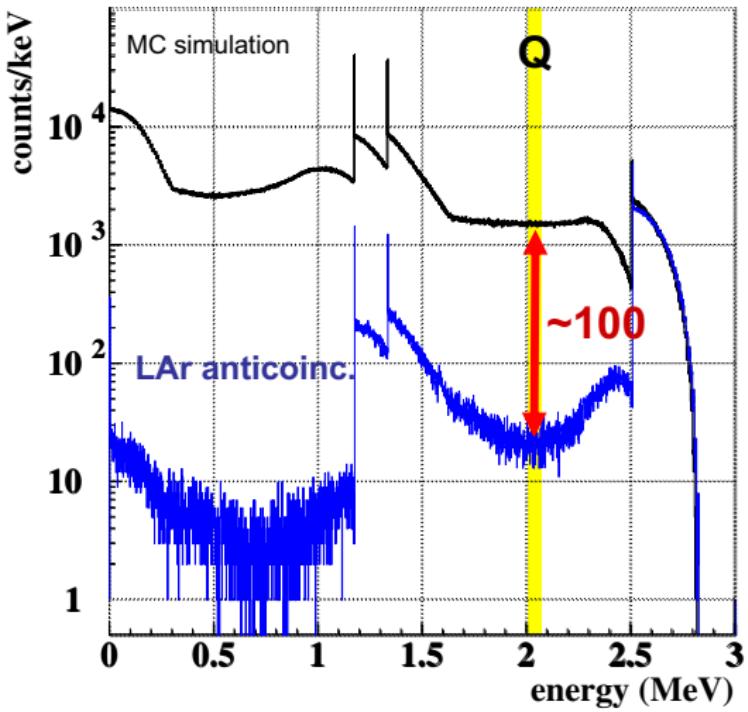
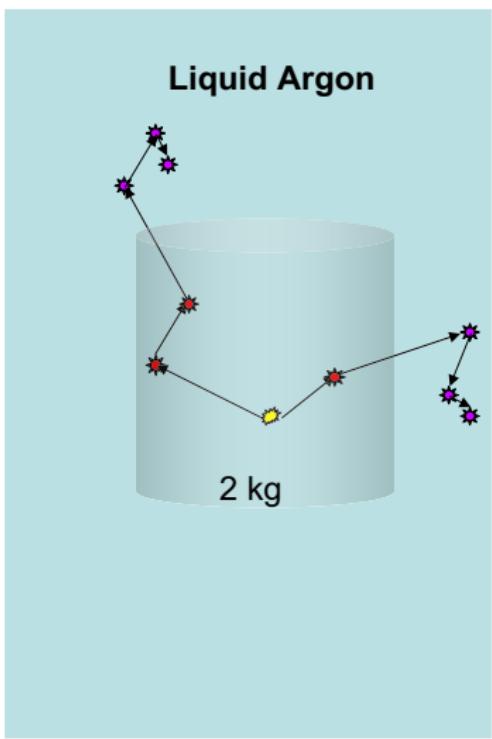
# $^{60}\text{Co}$ : suppression by segmentation



**illustration:**  
**Simple 7-fold segmentation**



# $^{60}\text{Co}$ : suppression by Lar-Ge anticoincidence



## Next generation experiments

Name		%	Q??	% E	B c/y	T (year)	Tech	<m>
CUORE	<sup>130</sup> Te	34	2533	90	3.5	1.8x10 <sup>27</sup>	Bolometric	9-57
GERDA	<sup>76</sup> Ge	7.8	2039	90	3.85	2x10 <sup>27</sup>	Ionization	29-94
Majorana	<sup>76</sup> Ge	7.8	2039	90	.6	4x10 <sup>27</sup>	Ionization	21-67
GENIUS	<sup>76</sup> Ge	7.8	2039	90	.4	1x10 <sup>28</sup>	Ionization	13-42
Supernemo	<sup>82</sup> Se	8.7	2995	90	1	210 <sup>26</sup>	Tracking	54-167
EXO	<sup>136</sup> Xe	8.9	2476	65	.55	1.3x10 <sup>28</sup>	Tracking	12-31
Moon-3	<sup>100</sup> Mo	9.6	3034	85	3.8	1.7x10 <sup>27</sup>	Tracking	13-48
DCBA-2	<sup>150</sup> Nd	5.6	3367	80		1x10 <sup>26</sup>	Tracking	16-22
Candles	<sup>48</sup> Ca	.19	4271	-	.35	3x10 <sup>27</sup>	Scintillation	29-54
CARVEL	<sup>48</sup> Ca	.19	4271	-		3x10 <sup>27</sup>	Scintillation	50-94
GSO	<sup>160</sup> Gd	22	1730	-	200	1x10 <sup>26</sup>	Scintillation	65-?
COBRA	<u><sup>115</sup>Cd</u>	7.5	2805				Ionization	
SNOLAB+	<sup>150</sup> Nd	5.6	3367				Scintillation	