Present and future of neutrinoless double beta decay experiments

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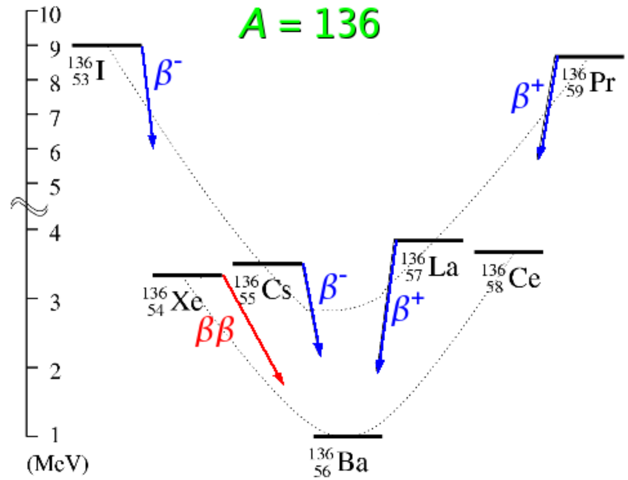
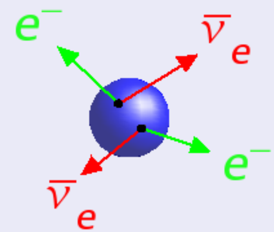
Introduction: double beta decay

second order weak decay
of **even-even nuclei**
in *A* even multiplets



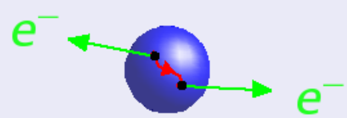
$\beta\beta$-2ν: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

- allowed in Standard Model
- observed with $\tau_{1/2} > 10^{19}$ years

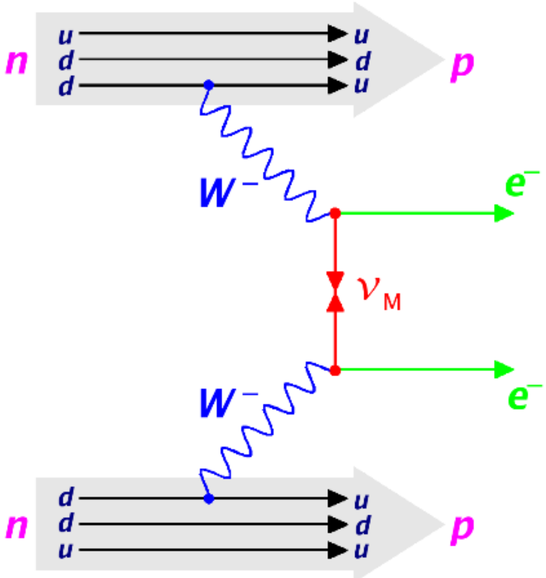


$\beta\beta$-0ν: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

- not allowed in Standard Model (ΔL=2)
- expected $\tau_{1/2} > 10^{25}$ years
- only one *criticized* evidence to date



$\beta\beta$-0ν and neutrino properties



- a virtual neutrino is exchanged
  - neutrino must have **mass** to allow helicity non conservation $\Rightarrow \Delta H=2$
  - neutrino must be a **Majorana particle** to allow lepton number non conservation $\Rightarrow \Delta L=2$

$$\beta\beta\text{-}0\nu \Leftrightarrow \begin{array}{c} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{array}$$

▲ these conditions hold even if other mechanisms are possible and may dominate

light Majorana ν mediated $\beta\beta$-0ν decay rate $\frac{1}{\tau^{0\nu}_{1/2}} = \frac{\langle m_\nu \rangle^2}{m_e^2} \cdot F_N$

nuclear structure factor

$$F_N \equiv G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2$$

phase space — matrix element

effective neutrino Majorana mass

$$\langle m_\nu \rangle = \left| \sum_k m_{\nu_k} \eta_k |U_{ek}|^2 \right|$$

CP phases* — neutrino mixing matrix

* CP conservation $\Rightarrow \eta_k = \pm 1$

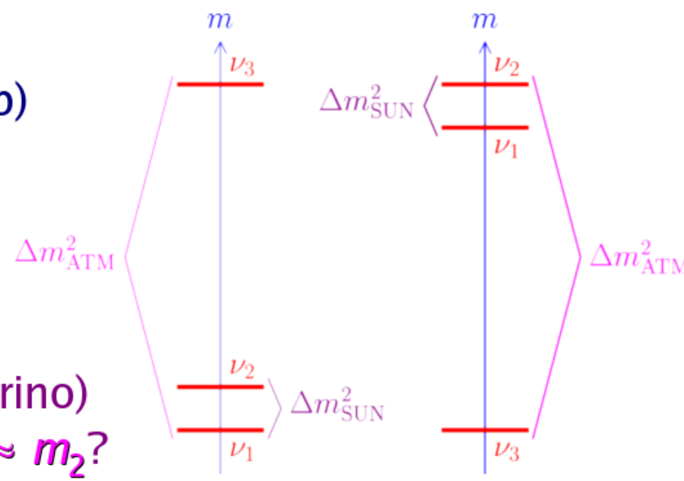
Present knowledge about neutrino properties

neutrino mixing matrix | neutrino mass eigenstate

$$|\nu_l\rangle = \sum_k U_{lk} |\nu_k\rangle$$

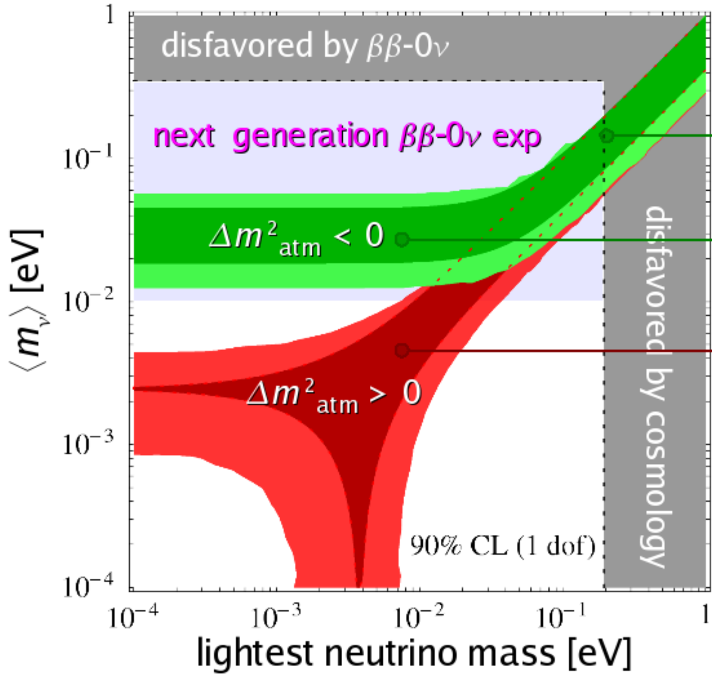
neutrino *l* flavor weak eigenstate

- **neutrino flavor oscillation**
  - neutrinos mix and have mass
  - oscillation experiments measure
    $\Delta m_{ik}^2 = |m_i^2 - m_k^2|$ and $\sin^2 2\vartheta_{ik} = f(|U_{lk}|^2)$
    - *atmospheric* neutrinos $\nu_\mu \rightarrow \nu_\tau$ (SK, K2K)
      - $\Delta m^2_{atm} \equiv \Delta m^2_{23} = 2.1 \times 10^{-3}$ eV^2 ; $\sin^2\vartheta_{atm} \equiv \sin^2\vartheta_{23} = 1.0$ (best fit)
    - *solar* neutrinos $\nu_e \rightarrow \nu_\tau, \nu_\mu$ (Homestake, GNO, SAGE, K/SK, SNO, KamLAND)
      - $\Delta m^2_{sol} \equiv \Delta m^2_{21} = 8.3 \times 10^{-5}$ eV^2 ; $\sin^2\vartheta_{sol} \equiv \sin^2\vartheta_{12} = 0.4$ Low LMA (best fit)
    - from global analysis (CHOOZ and atmospheric)
      - $\sin^2\vartheta_{13} < 0.5$ (at 99.73%)
- **direct neutrino mass measurements** (^{3}H exp)
  - $m_{\nu e} < 2.2$ eV 95% CL
- **cosmology** (WMAP+2dFGRS+...)
  - $\sum m_\nu < \approx 1.0$ eV (but model dependent...)
- **still missing:**
  - mass scale (i.e. mass of the lightest neutrino)
  - hierarchy: $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$?
  - Dirac or Majorana particle?



Role of $\beta\beta$-0ν in future neutrino physics

- next generation experiments aim at $\langle m_\nu \rangle \approx 10$ meV



degeneration: $m_1 \approx m_2 \approx m_3$

inverse hierarchy: $m_3 \ll m_1 \approx m_2$

normal hierarchy: $m_1 < m_2 \ll m_3$

$\langle m_\nu \rangle = f(m_k, \vartheta_{1k}, \eta_k)$

$\vartheta_{1k} \Leftrightarrow U_{ek}$, η_k CP phases

spread due to CP phases

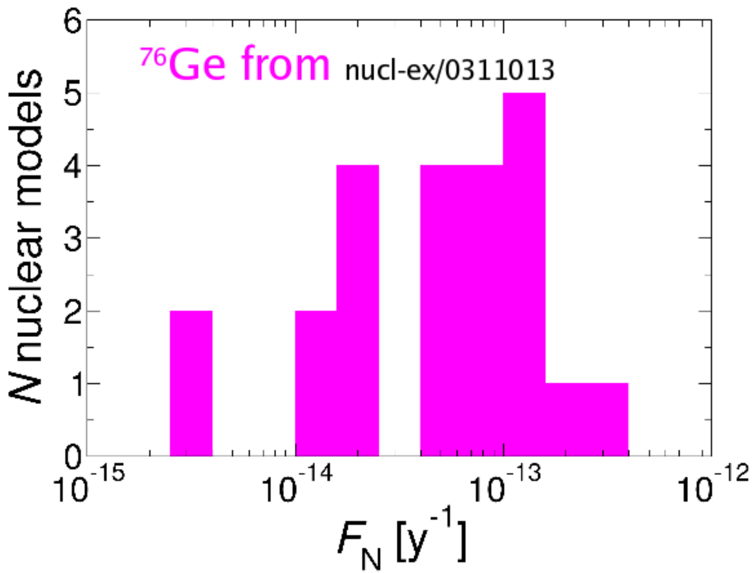
spread due to oscillation parameters uncertainties

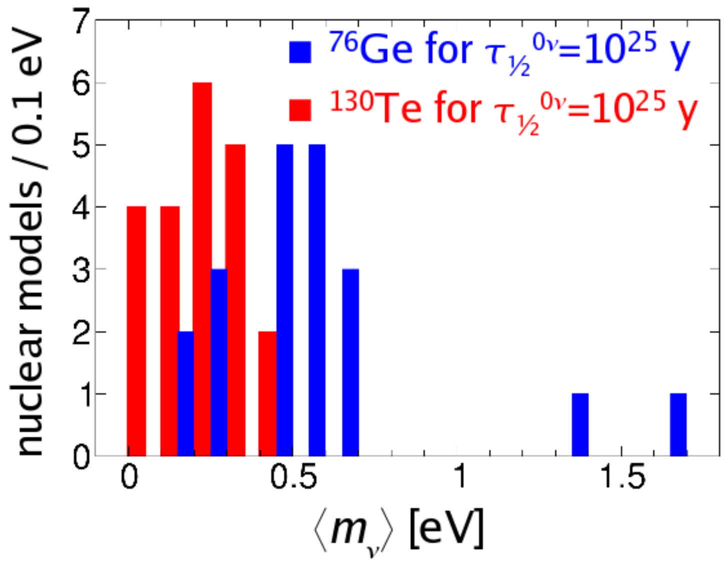
- discovery with $\langle m_\nu \rangle \geqslant 10$ meV
  - the neutrino is a **Majorana particle**
  - **inverse hierarchy** or **degeneration**
  - **absolute ν mass scale** fixed in case of degeneration
- upper limit with $\langle m_\nu \rangle < 10$ meV
  - normal hierarchy (only with Majorana neutrinos)

$\beta\beta$-0ν and nuclear physics

$$\langle m_\nu \rangle^2 = \frac{1}{F_N} \cdot \frac{m_e^2}{\tau_{1/2}^{0\nu}} \qquad F_N \equiv G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2$$

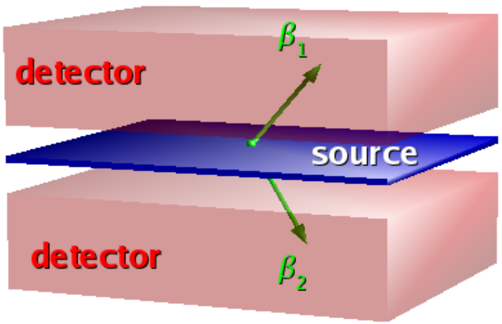
- phase space $G^{0\nu}(Q_{\beta\beta},Z) \propto Q_{\beta\beta}^{\ 5}$ can be precisely evaluated
- matrix element $|M^{0\nu}|$ contains details of **nuclear physics** source of uncertainties
  - also $\langle \boldsymbol{m_\nu} \rangle$ is affected by large uncertainties





- accurate measurements of $\boldsymbol{\tau_{½}^{2\nu}}$ can help reducing spread in nuclear model predictions (QRPA) V.A. Rodin et al., nucl-th/0305005
- search for as **many different isotopes** as possible

Experimental approaches for $\beta\beta$-0ν

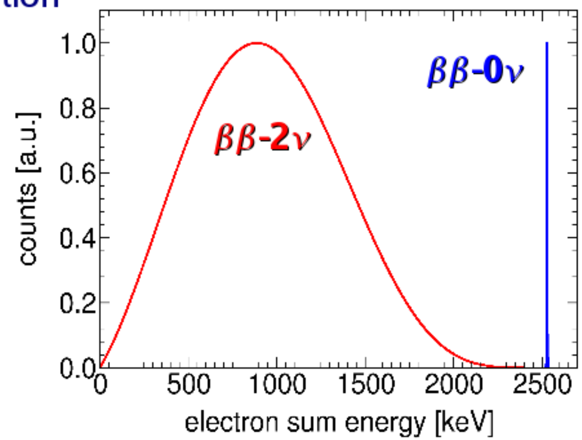


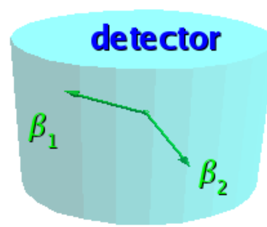
Source ≠ detector

- source in foils
- electrons analyzed by TPCs, scintillators, drift chambers,...
  - ▲ background rejection by event topology
  - ▲ angular correlation gives signature of mass mechanism
  - ▲ any isotopes with solid form possible
  - ▼ small amount of material
  - ▼ poor efficiency
  - ▼ poor energy resolution

Source ⊆ detector (calorimetry)

- detector measures sum energy $E = E_{\beta_1} + E_{\beta_2}$
  - ▶ $\beta\beta$-0ν signature: a peak at $Q_{\beta\beta}$
- scintillators, bolometers, semiconductor diodes, gas chambers
  - ▲ large masses
  - ▲ high efficiency
  - ▲ many isotopes possible
- depending on technique
  - high energy resolution (bolometers, semiconductors)
  - moderate topology recognition (Xe TPC, semiconductors)





Other approaches (geochemical, milking)

- do not separate $\beta\beta$-0ν and $\beta\beta$-2ν

Experimental sensitivity for $\beta\beta$-0ν

$$m_\nu \propto \sqrt{1/\tau^{0\nu}_{1/2}}$$

Experimental $\beta\beta$-0ν rate

- with $N_{\beta\beta}$ decays observed

$$\tau^{0\nu}_{1/2} = \ln 2 \frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

- number of active nuclei $N_{nuclei} = i.a.\, \mathcal{N}_A M / A$
- measuring time [y]
- detector mass [kg]
- detector efficiency

Experimental sensitivity to $\tau_{½}^{0\nu}$

- with **no** decay observed
  - $N_{\beta\beta} \leqslant (bkg \cdot \Delta E \cdot M \cdot t_{meas})^{½}$ at 1σ

$$\sum(\tau^{0\nu}_{1/2}) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

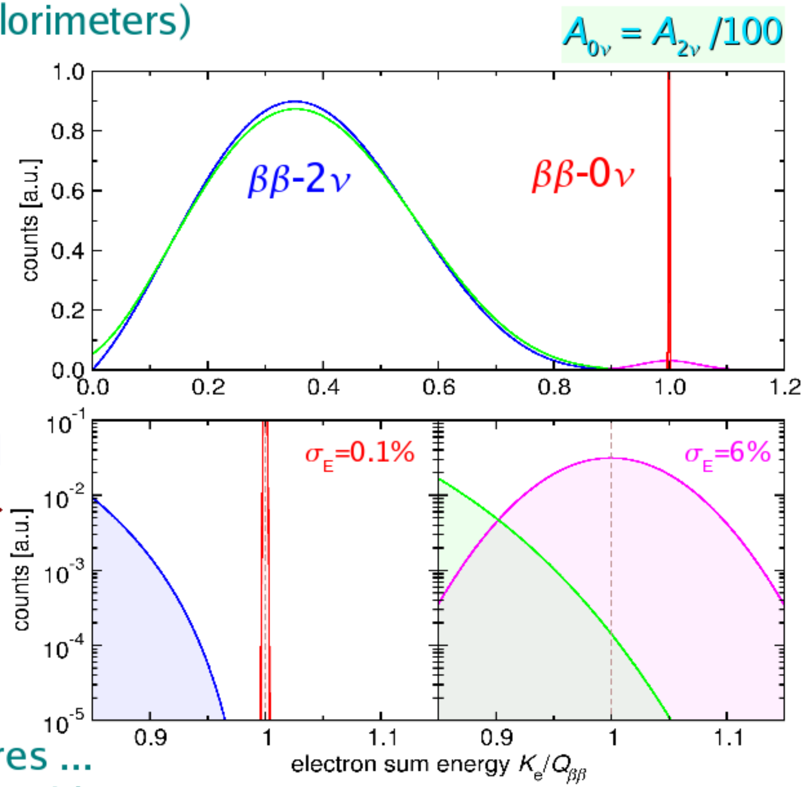
- isotopic abundance
- atomic number
- energy resolution [keV]
- specific background [c/keV/kg/y]

- for $bkg = 0 \Rightarrow N_{\beta\beta} \leqslant 3$ at 2σ

$$\sum(\tau^{0\nu}_{1/2}) \propto \frac{\epsilon\, i.a.}{A} M\, t_{meas}$$

Background in $\beta\beta$-0ν experiments

- **depends on technique**
  - internal to source (and detector for calorimeters)
    - primordials (^{238}U, ^{232}Th, ^{40}K, ...), artificial
    - cosmogenic activation
  - external
    - primordials and artificial in close materials
    - neutrons
    - cosmic rays
  - specific to techniques
    - quenched αs for scintillators
    - primordials on surface for bolometers



- $\beta\beta$-2ν **tail** is an unavoidable background
  - importance of energy resolution
- **solutions also depend on technique**
  - heavy shielding and underground
  - material selection and purification
  - short exposure to cosmic rays
  - PSD, tracking, segmentation, signatures ...
  - choose isotope with $Q_{\beta\beta}$ as high as possible
  - profit of Borex, SNO and SK experience and/or clean environment (⇒ ***immersion***)
- **background estimate and reduction is becoming hard (few counts per year)**
  - **intermediate size experiments are often required**

Present experimental situation

- best result per isotope to date
- exposure: exp = $M \times t_{meas}$
  - positive result
  - running experiments

$$\sum \left(\tau_{1/2}^{0\nu}\right) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

isotope	experiment	latest result	$Q_{\beta\beta}$ [keV]	i.a. [%]	enrich [%]	exp [kg×y]	tech	material	$\tau_{1/2}^{0\nu}$ [10^{23} y]	$\langle m_\nu \rangle$ [eV] min	$\langle m_\nu \rangle$ [eV] max	$\tau_{1/2}^{0\nu}\vert_{10meV}$ [10^{28} y] max
^{48}Ca	Elegant VI	2004	4271	0.19	-	4.2	s	CaF_2	0.14	7.20	44.70	8.8
^{76}Ge	Heidelberg/Moscow	2001	2039	7.8	87	71.7	i	Ge	120.0	*0.44*		17.7
^{82}Se	NEMO-3	2004	2995	9.2	97	0.55	t	Se	1.9	1.30	3.60	5.6
^{100}Mo	NEMO-3	2004	3034	9.6	95-99	4.1	t	Mo	3.5	0.70	1.20	3.9
^{116}Cd	Solotvina	2003	3034	7.5	83	0.5	s	$CdWO_4$	1.7	*1.70*		4.7
^{130}Te	Cuoricino	2004	2533	34.5	-	3.8	b	TeO_2	7.5	0.30	1.68	5.8
^{136}Xe	DAMA	2002	2476	8.9	69	6.4	s	Xe	12.0	1.10	2.90	12.1
^{150}Nd	Irvine TPC	1997	3367	5.6	91	0.01	t	Nd_2O_3	0.012	*3.00*		0.1
^{160}Gd	Solotvina	2001	1791	21.8	-	1.0	s	Gd_2SiO_5	0.013	*26.00*		0.9

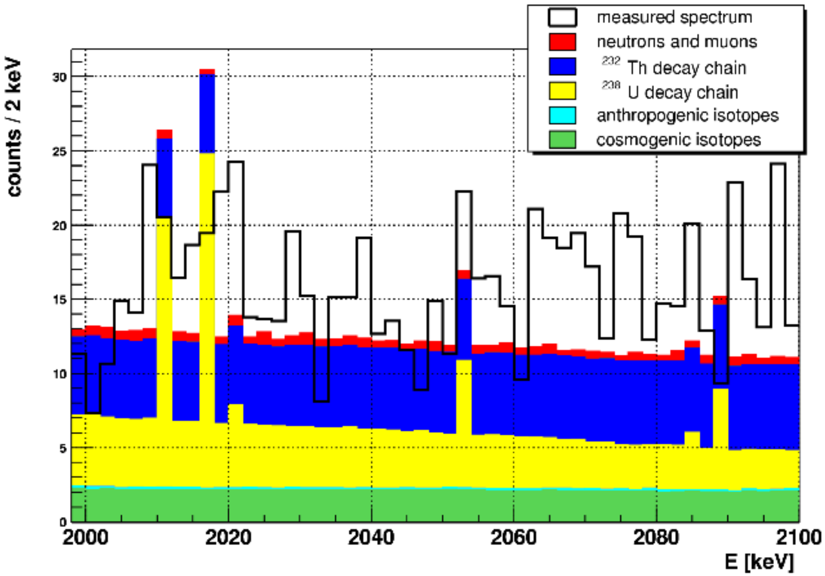
s scintillation
i ionization
t tracking
b bolometric

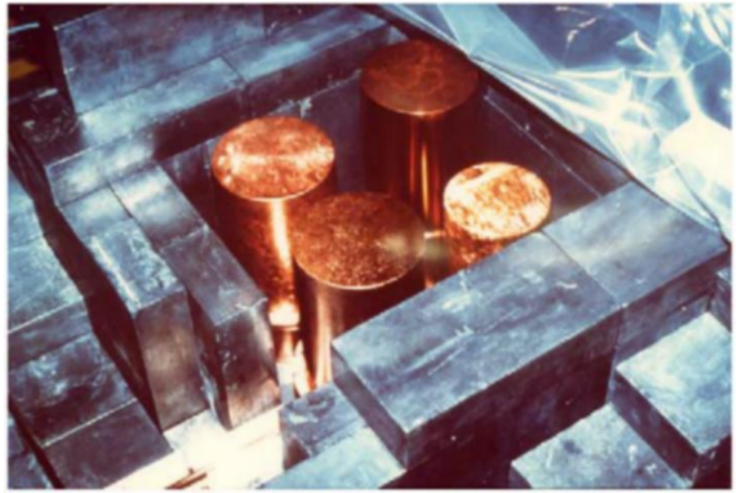
spread due to uncertainties in F_N

half-life expected for $\langle m_\nu \rangle$ = 10 meV and the less favorable F_N

^{76}Ge Heidelberg-Moscow experiment / 1

- **calorimetric** experiment with Ge semiconductor detectors
- 5 HP-Ge crystals, enriched to 87% in ^{76}Ge
  - total active mass of 10.96 kg ⇒ 125.5 moles of ^{76}Ge
- run from 1990 to 2003 in Gran Sasso Underground Laboratory
- total exposure 71.7 kg×y
  - 820 moles×y
- main background from U/Th in the set-up
  - $b \approx 0.11$ c/keV/kg/y at $Q_{\beta\beta}$

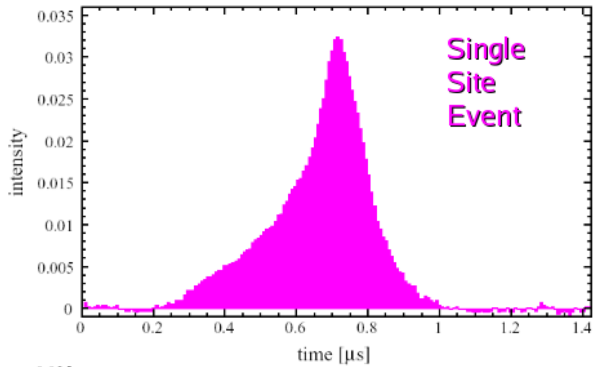


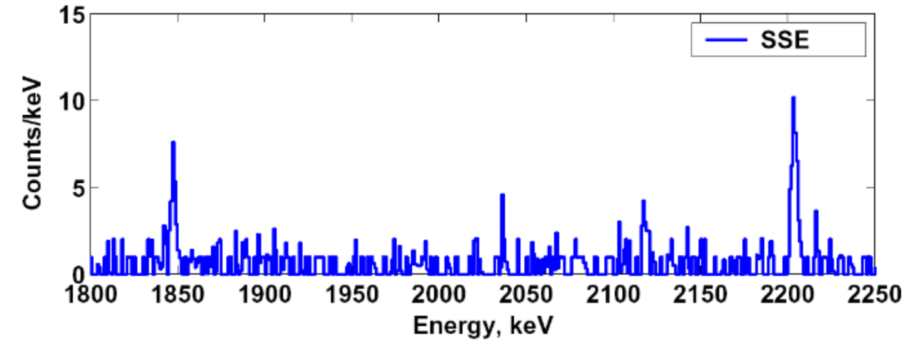


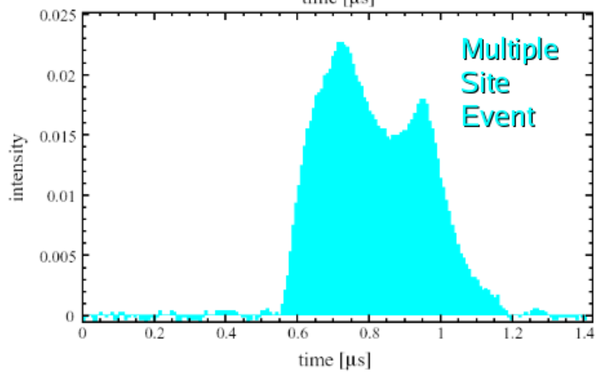
H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B 586 (2004) 198

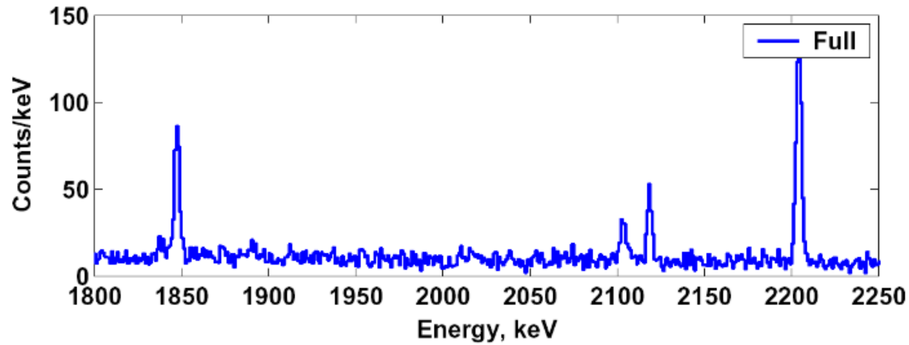
^{76}Ge Heidelberg-Moscow experiment / 2

- PSD since end of 1995 for 4 detectors (51.4 kg×y, i.e. 72% of full data set)
  - **$\beta\beta$ decays** and double escape γ peaks are **Single Site Events**
  - γ interactions are usually Multiple Site Events
  - also internal βs are SSE





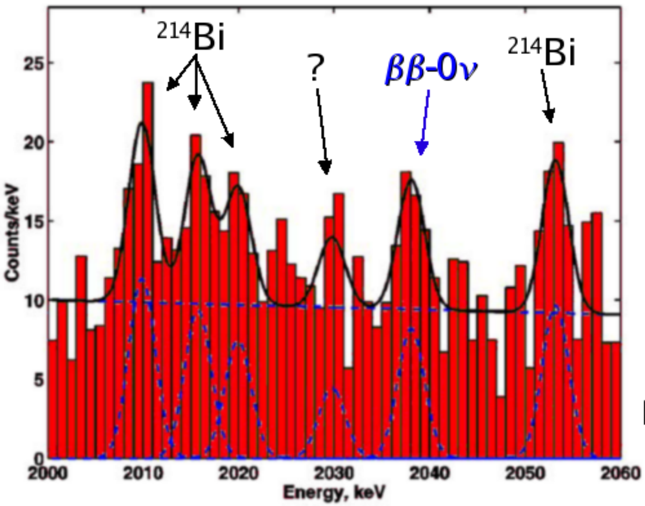




H.V. Klapdor-Kleingrothaus *et al.*, NIM A 522 (2004) 371

Heidelberg-Moscow exp.: evidence for $\beta\beta$-0ν of ^{76}Ge

- best exploitation of the Ge detector technique proposed by E. Fiorini in 1960
  - longest running experiment (13 years) with largest exposure (71.7 kg$\times$y)
  - Status-of-the-art for low background techniques and for enriched Ge detectors
  - reference for all last generation $\beta\beta$-0ν experiments



1990 – 2003 data, all 5 detectors

exposure = 71.7 kg$\times$y

$\tau_{½}^{0\nu}$ = 1.2$\times$10^{25} years

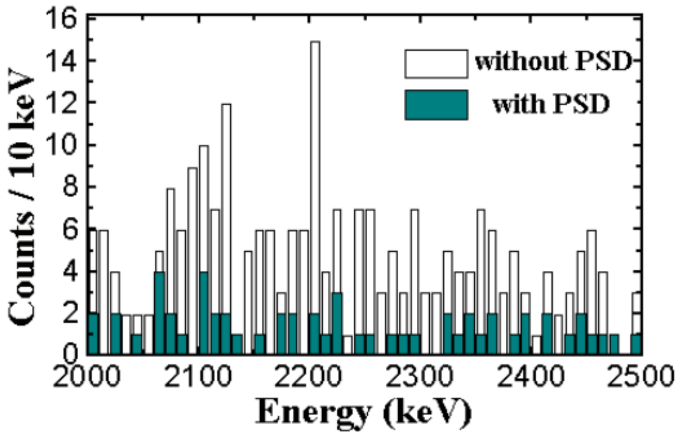
$\langle m_\nu \rangle$ = 0.44 eV

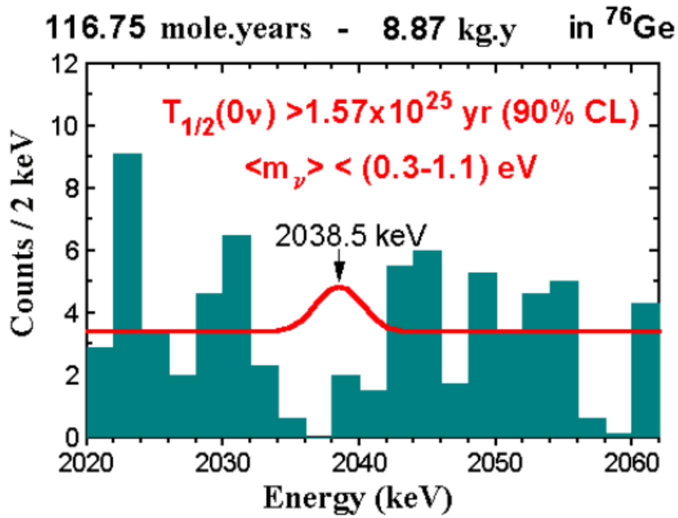
H.V.Klapdor-Kleingrothaus *et al.*, Phys. Lett. B 586 (2004) 198

- still, scientific community **does not fully accept the result**, because:
  - signal is indeed **too faint** (4 σ) to be *blindly* accepted: people still find some weak points in the published analysis H.V.Klapdor-Kleingrothaus *et al.*, NIM A 522 (2004) 371
  - presence of **not understood peaks** around the signal and with *similar* significance
  - impossibility to check an **energy window larger** than the published one
- **nevertheless any future $\beta\beta$-0ν experiment will have to cope with this result**

^{76}Ge IGEX experiment

- Ge semiconductor detectors
- 6 HP-Ge crystals, enriched to 86% in ^{76}Ge
  - total active mass of 8.4 kg
- operated in Homestake, Canfranc and Baksan (1991-2000)
- total exposure 8.87 kg×y
  - 116.75 moles×y
- PSD applied only to a subset (~45%)
- main background from cosmogenics in Ge
  - $b \approx 0.17$ c/keV/kg/y at $Q_{\beta\beta}$



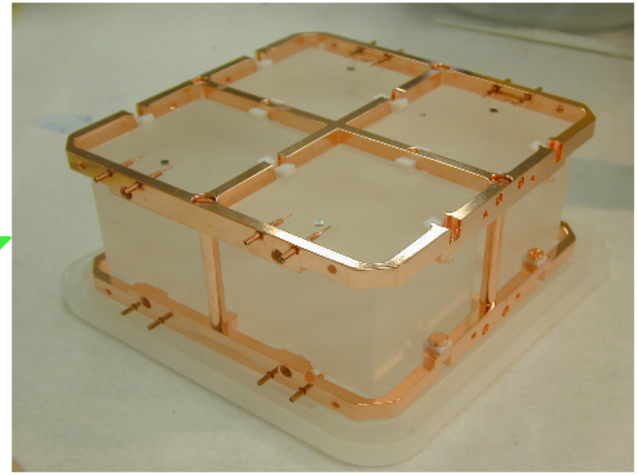


C.E. Aalseth *et al.*, Phys. Rev. D 65 (2002) 092007

^{130}Te CUORICINO experiment / 1

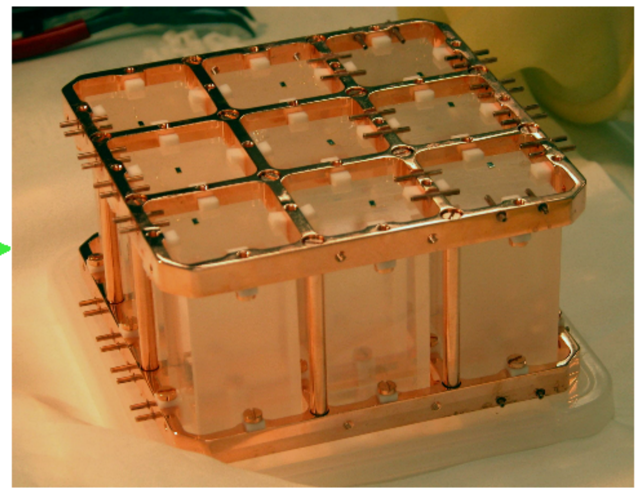
TeO_2 thermal calorimeters

- **Active isotope ^{130}Te**
  - natural abundance: a.i. = 33.9%
  - transition energy: $Q_{\beta\beta}$ = 2529 keV
  - "short" predicted half life
    $\langle m_\nu \rangle \approx 0.3$ eV $\Leftrightarrow$ $\tau_{1/2}^{0\nu} \approx 10^{25}$ years
- **Absorber material TeO_2**
  - low heat capacity
  - large crystals available
  - radiopure

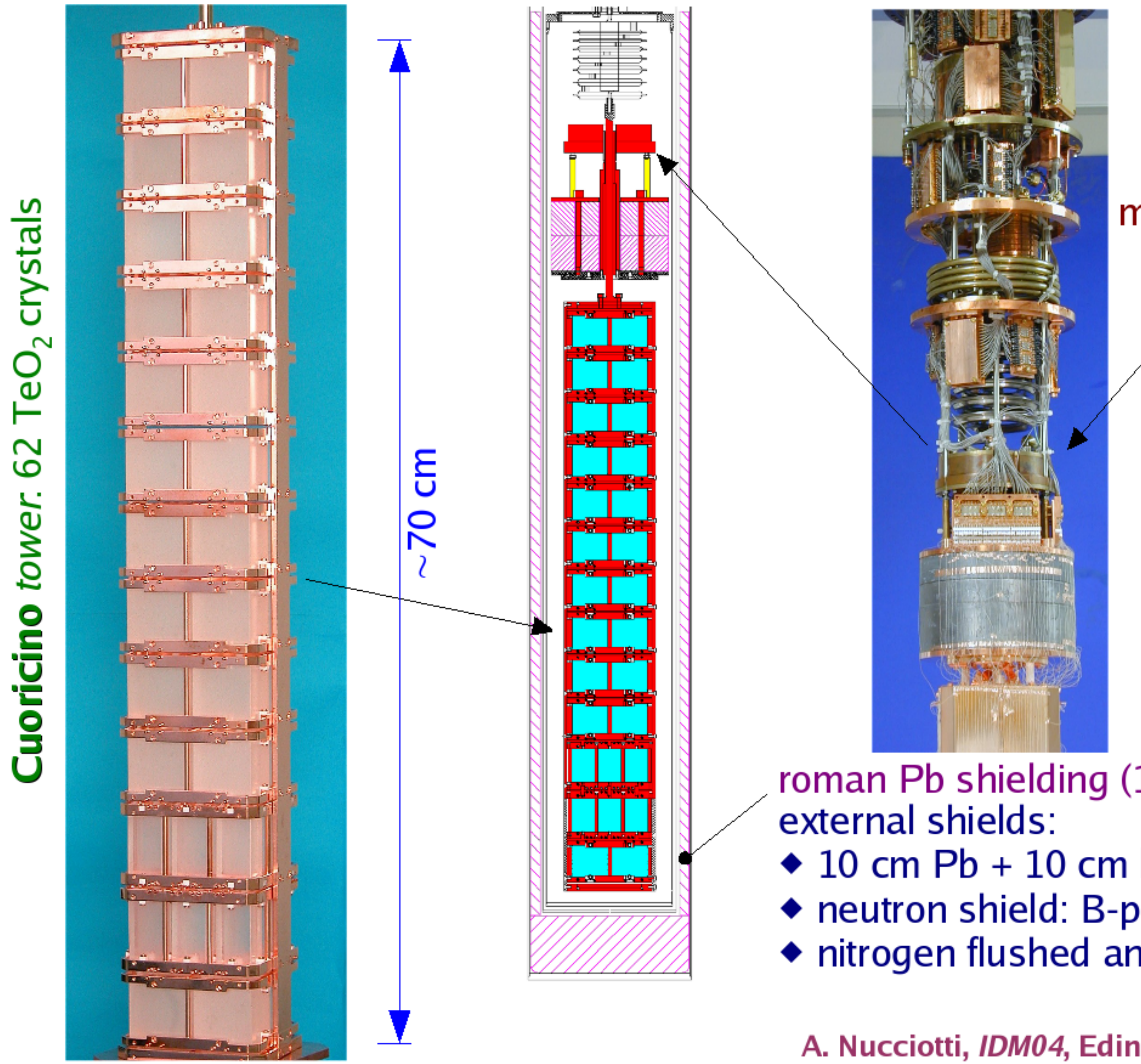


CUORICINO experiment @ LNGS

- 62 TeO_2 detectors in the ***tower*-like structure** foreseen for **CUORE**
- 11 modules with 4 detectors 790 g each
  ▷ 34.76 kg TeO_2 mass
- 2 modules with 9 detectors 330 g each
  ▷ 5.94 kg TeO_2 mass
- **total mass 41 kg**
- ▶ **intermediate size $\beta\beta$ experiment**
- ▶ **test for radioactivity**



^{130}Te CUORICINO experiment / 2



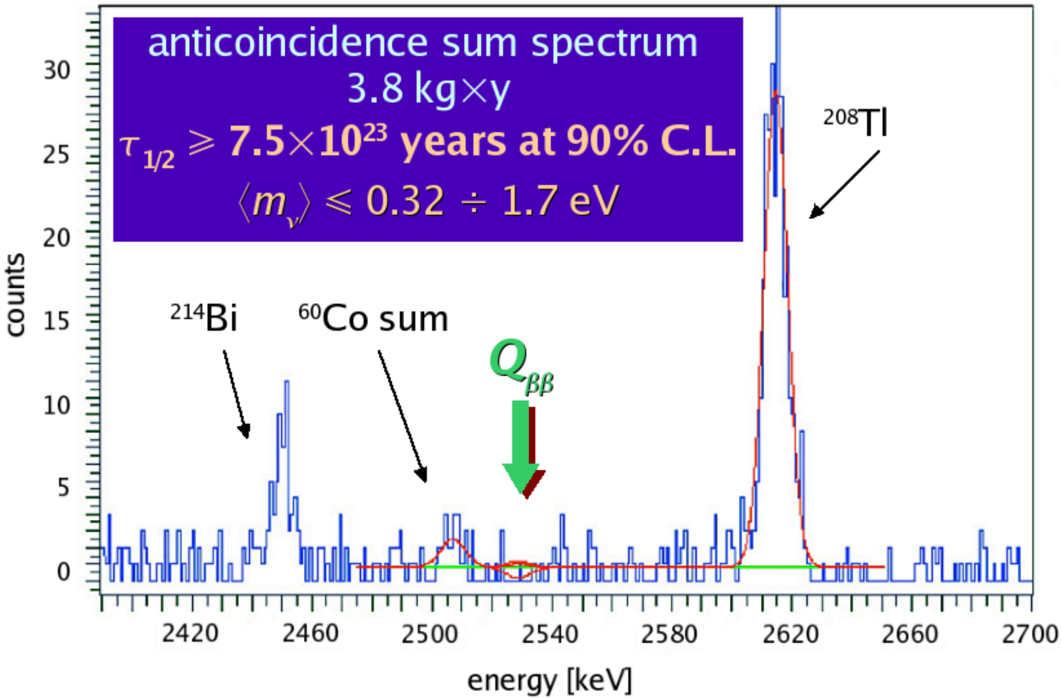
roman Pb shielding (1 cm lateral)

external shields:

- 10 cm Pb + 10 cm low act Pb
- neutron shield: B-polyethylene
- nitrogen flushed anti-radon box

^{130}Te CUORICINO experiment / 3

- total exposure 3.8 kg×y
  - 8.2 moles×y of ^{130}Te
- energy resolution FWHM ΔE = 8 keV at $Q_{\beta\beta}$ (σ_E=1.3‰)
- anticoincidence applied to reduce surface U/Th background and external γs
- background mainly from U/Th on Cu and TeO_2 surfaces (α and β)
  - $b \approx 0.19$ c/keV/kg/y at $Q_{\beta\beta}$

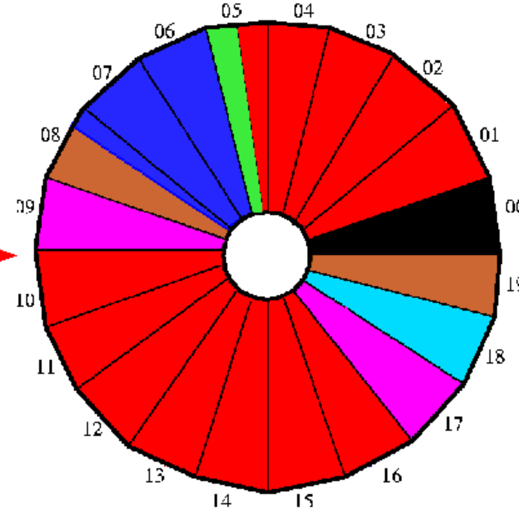


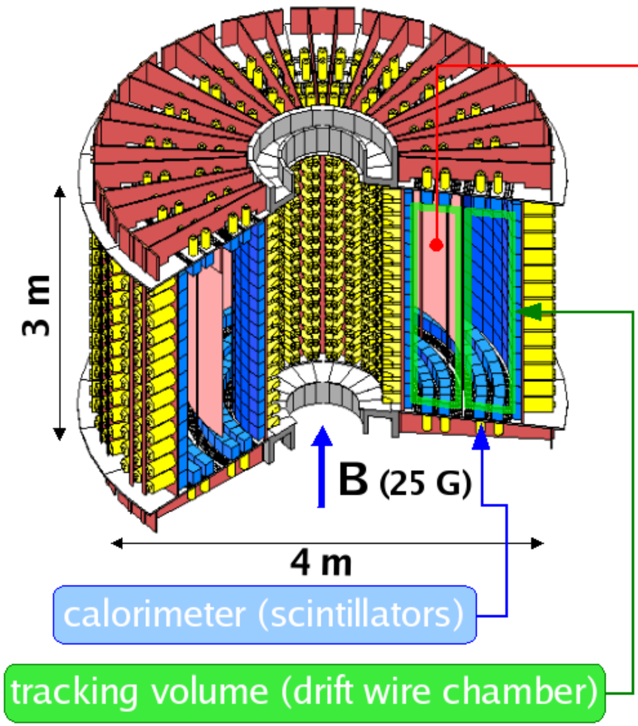
- experiment still running
- in 3 y ⇒ 120 kg×y
  - $\tau_{1/2} \geqslant 6.1\times10^{24}$ y at 1σ
  - $\langle m_\nu \rangle \leqslant 0.1 \div 0.6$ eV

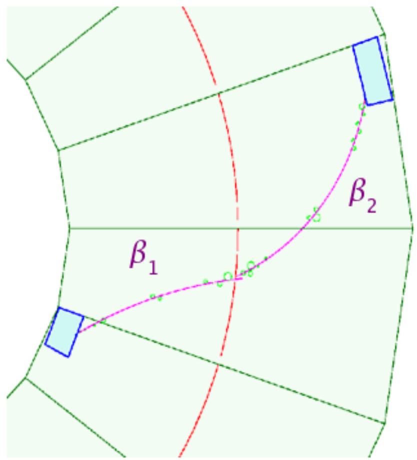
C. Arnaboldi et al., Phys. Lett. B 584 (2004) 260
Latest results presented by E. Fiorini at Neutrino 2004

NEMO-3 experiment on ^{100}Mo and ^{82}Se / 1

- **Tracking detector** for $\beta\beta$-2ν and $\beta\beta$-0ν @ Frejus
  - 10 kg of enriched material in foils
  - 6180 Geiger cells ⇒ drift wire chamber
  - 1940 plastic scintillators + PMTs
- iron (γ) + water with B (n) shielding
- can identify e$^-$, e$^+$, γ and α

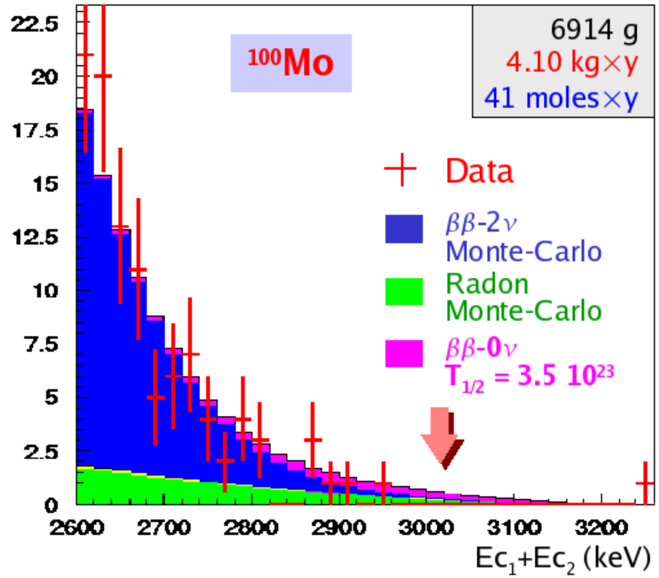


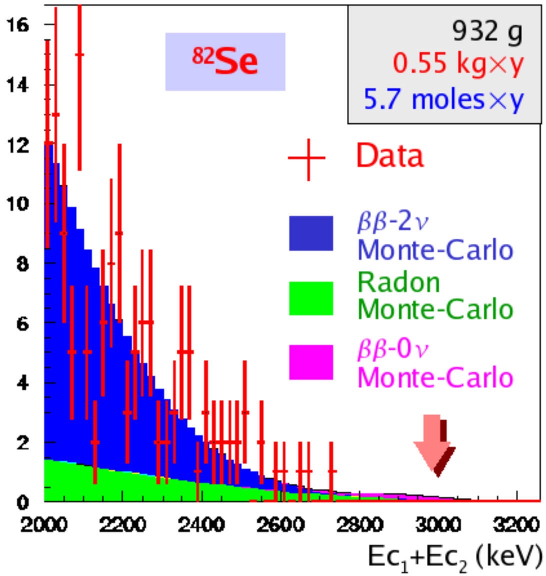




^{100}Mo	(6.9 kg)	⇒ $\beta\beta$-0ν
^{82}Se	(0.9 kg)	
^{130}Te	(0.5 kg)	
^{116}Cd	(0.4 kg)	
^{150}Nd	(37g)	
^{96}Zr	(9.4 g)	
^{48}Ca	(7.0g)	
^{nat}Te	(0.6 kg)	
Cu	(0.6 kg)	

NEMO-3 experiment on ^{100}Mo and ^{82}Se / 3





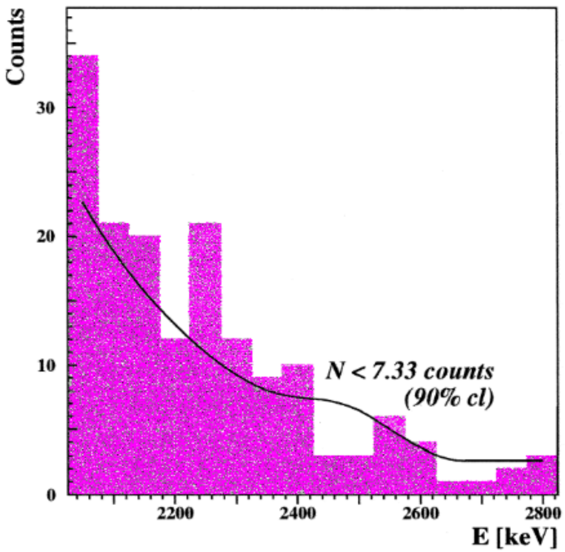
- main background sources (^{100}Mo)
  - **radon** (1 c/keV/kg/y), **ββ-2ν** (0.3 c/keV/kg/y), **^{208}Tl in the foils** (0.1 c/keV/kg/y)
- **likelihood analysis with 3 variables**:
  - $Ec_1 + Ec_2$ (sum of kinetic energies)
  - angle between 2 electron tracks
  - Ec_{min} energy of slower electron
- radon reduction in progress
- expected sensitivity (90% CL) in 5 years:
  - $\tau_{1/2}^{0\nu} > 4\times10^{24}$ (8×10^{23}) y for ^{100}Mo (^{82}Se)
  - $\langle m_\nu \rangle \leqslant 0.2 \div 0.35$ ($0.65 \div 1.8$) eV for ^{100}Mo (^{82}Se)

^{100}Mo: $\tau_{1/2}^{0\nu} > 3.5\times10^{23}$ years (90% CL)
$\langle m_\nu \rangle < 0.7 \div 1.2$ eV

^{82}Se: $\tau_{1/2}^{0\nu} > 1.9\times10^{23}$ years (90% CL)
$\langle m_\nu \rangle < 1.3 \div 3.6$ eV

Latest results presented by X. Sarazin at Neutrino 2004

^{136}Xe: Gotthard and DAMA experiments

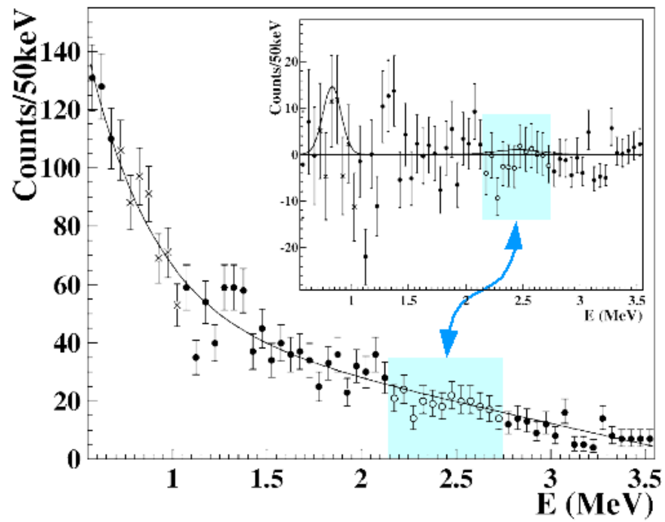


GOTTHARD experiment

- **high pressure Xe TPC** (5 atm) in Gotthard tunnel
  - calorimetric experiment with tracking
- ^{136}Xe enriched at 62.5%
  - ^{136}Xe total mass 3.3 kg (24.2 moles)
- total ^{136}Xe exposure 4.9 kg×y (36 moles×y)
- energy resolution FWHM $\Delta E = 165$ keV
- background $b \approx 0.015$ c/keV/kg/y, largely from $\beta\beta$-2ν
  - $\tau_{1/2} \geqslant 4.4\times10^{23}$ y at 90% CL
  - $\langle m_\nu \rangle \leqslant 1.8 \div 5.2$ eV

DAMA experiment

- **LXe scintillator** in the DAMA set-up at LNGS
  - calorimetric experiment
- ^{136}Xe enriched at 68.8%
  - ^{136}Xe total mass 4.5 kg (32.9 moles)
- total ^{136}Xe exposure 4.5 kg×y (33 moles×y)
- energy resolution FWHM $\Delta E \approx 500$ keV
- background $b \approx 0.08$ c/keV/kg/y
  - $\tau_{1/2} \geqslant 1.2\times10^{24}$ y at 90% CL
  - $\langle m_\nu \rangle \leqslant 1.1 \div 2.9$ eV



Next generation $\beta\beta$-0ν experiments / 1

- next generation experiments must confirm or reject HM ^{76}Ge result
  - **confirmation**: similar $\langle m_\nu \rangle$ must be measured from $\beta\beta$-0ν of other isotopes
  - **rejection**: much lower sensitivities on $\langle m_\nu \rangle$ must be achieved
- in any case with a sensitivity of few 0.01 eV there are good chances to **observe $\beta\beta$-0ν**

- promote as many experiments on different isotopes as possible
- reduce uncertainties in nuclear matrix F_N
- increase sensitivity

increase isotopic abundance by enrichment

$$\sum \left(\tau_{1/2}^{0\nu}\right) \propto \epsilon \cdot \frac{a.i.}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

increase experimental mass and measuring time

reduce background by:
- material selection and proper handling
- choosing proper technique
- using signatures
- improving energy resolution

$bkg = 0 \Rightarrow \sum(\tau_{1/2}^{0\nu}) \propto M\, t_{meas}$

Next generation $\beta\beta$-0ν experiments / 2

- an exercise: other isotopes present vs *required* $\tau_{½}^{0\nu}$ sensitivity to *cover* ^{76}Ge positive result

	$\tau_{½}^{0\nu}$ [10^{25} y] exp	tech	F_N [10^{-13} y^{-1}] min	max	$\langle m_\nu \rangle^{exp}$ [eV] min	max	$\tau_{½}^{0\nu}$ [10^{25} y] min	max	$\tau_{½}^{0\nu}\vert_{10meV}$ [10^{28} y] max	tech
^{48}Ca	0.0014	s	0.30	1.04	13.36	25.11	0.169	6.229	8.8	s, b
^{76}Ge	1.2000	i	0.15	1.54	0.38	1.21	-	-	17.7	i, b
^{82}Se	0.0190	t	0.47	4.54	1.74	5.43	0.039	3.953	5.6	t
^{100}Mo	0.0350	t	0.67	8.70	0.93	3.34	0.020	2.753	3.9	t, s, b
^{116}Cd	0.0170	s	0.56	5.50	1.67	5.26	0.032	3.318	4.7	s, b
^{130}Te	0.0750	b	0.45	17.41	0.45	2.78	0.010	4.094	5.8	b, i
^{136}Xe	0.1200	t	0.22	1.45	1.22	3.18	0.122	8.541	12.1	t, s
^{150}Nd	0.0001	t	52.22	104.45	4.56	6.45	0.002	0.035	0.1	t, b
^{160}Gd	0.0001	s	3.07	3.07	25.57	25.57	0.058	0.600	0.9	s, b

s scintillation
i ionization
t tracking
b bolometric

latest experimental results

nuclear matrix elements F_N selected by Elliott & Vogel *

$\langle m_\nu \rangle$ range with selected F_N elements

experimental $\tau_{½}^{0\nu}$ sensitivity required to *cover* ^{76}Ge $\langle m_\nu \rangle$ range including the spread in selected F_N

longest $\tau_{½}^{0\nu}$ expected for $\langle m_\nu \rangle$ = 10 meV

* S.R. Elliott & P. Vogel, Ann. Rev. Nucl. Part. Sci. 52 (2002) 115

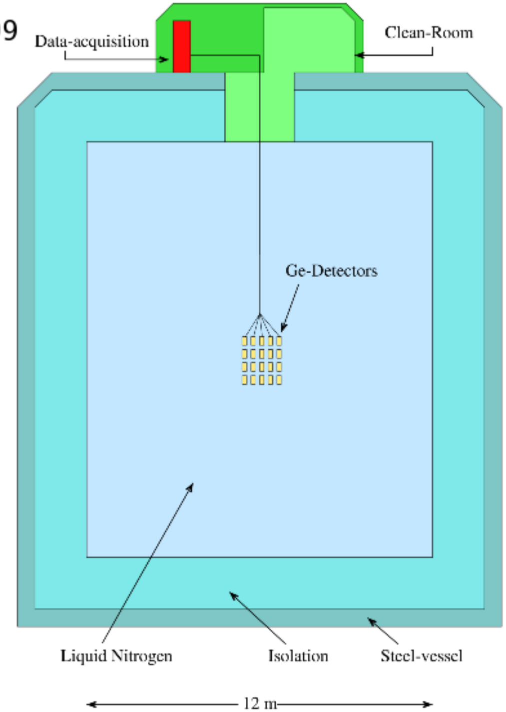
Calorimetric experiment with ionization detectors

- **Germanium diode experiments**
  - ▲ well known technique
  - ▲ high energy resolution
  - ▲ large masses
  - ▲ segmentation and PSD to reduce background
  - ▼ cost of enrichment
  - ▶ standard cooling in ultra low background cryostats
    - **Majorana** experiment
  - ▶ naked crystals in cryogenic liquids (scintillating)
    - **MPI Ge experiment** or **Genius/GEM**
- **CdTe or CdZnTe diode experiments**
  - ▲ many isotopes at once (including $\beta^+\beta^+$)
  - ▲ segmentation (tracking) to reduce background
  - ▼ new technique, still *poor* energy resolution and small masses
    - COBRA K. Zuber, Phys. Lett. B 519 (2001) 1, nucl-ex/0301007

Genius and GEM

GENIUS hep-ph/99910205, MPI-H-V26-1999

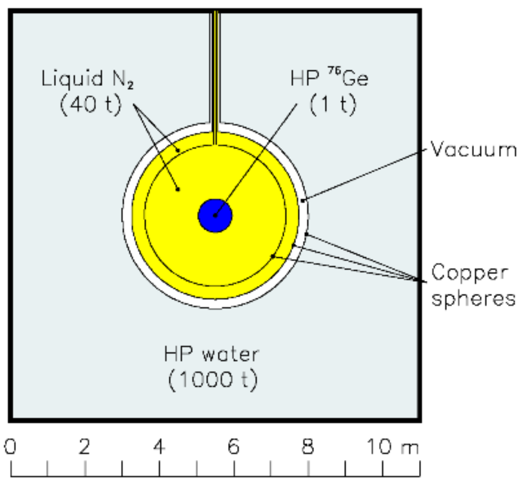
- **idea**: main background sources in HM exp are in **close materials**
  - 1 ton *naked* Ge crystals in LN2
- enriched ^{76}Ge
- 12 m tank to reduce external bkg
- LN2 purity: 10^{-15} g/g U/Th
- expected bkg 0.2 c/keV/t/y
  - $\tau_{1/2} \geqslant 10^{28}$ y in 10 years
  - $\langle m_\nu \rangle \leqslant 0.015 \div 0.05$ eV
- could be used also for solar neutrinos and DM
- authors think may no longer be worth to proceed



PRESENT STATUS

- **Genius-TF** @ LNGS
- 4×2.5 kg naked Ge detectors in LN2

NIM A 511 (2003) 241



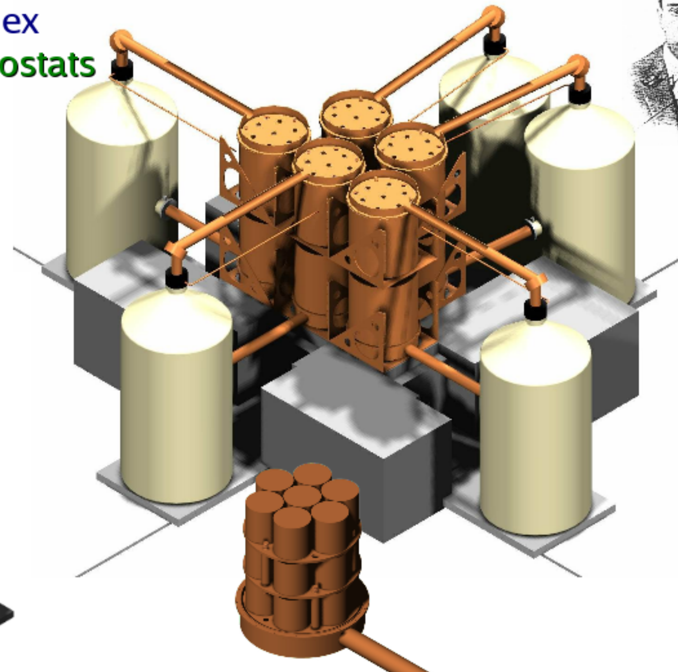
GEM Zdesenko et al., J. Phys. G: Nucl. Part. Phys. 27 (2001) 2129

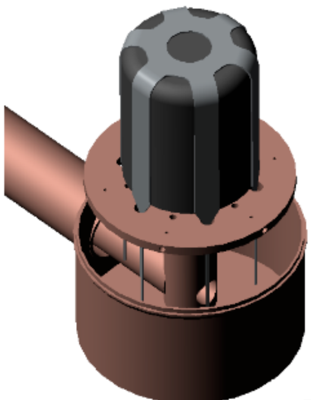
- **very similar to GENIUS, but with less LN2**:
  - 1 ton *naked* Ge crystals in LN2 + water
- expects same bkg as GENIUS: 0.2 c/keV/t/y
  - $\tau_{1/2} \geqslant 10^{28}$ y in 10 years
  - $\langle m_\nu \rangle \leqslant 0.015 \div 0.05$ eV

Majorana

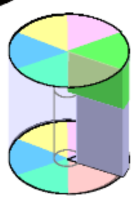
White paper nucl-ex/0311013

- **idea**: **cosmogenics** main background source in Igex
  - 500 kg Ge crystals in ultra low background cryostats
  - segmentation and PSD to reduce bkg
- enriched ^{76}Ge
- 210 crystals in 10 cryostats
- 2 preliminary phases: SEGA and MEGA

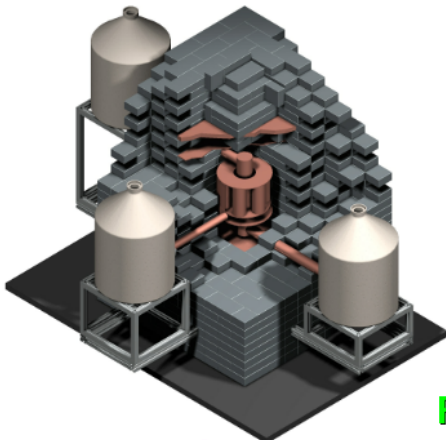




Segmented Enriched Germanium Array



- 1-5 segmented detectors
  - 6 segments: 2×6 ($z\times\phi$)



Multi Element Germanium Assay

- 2+16 detectors
- design test
- material selection

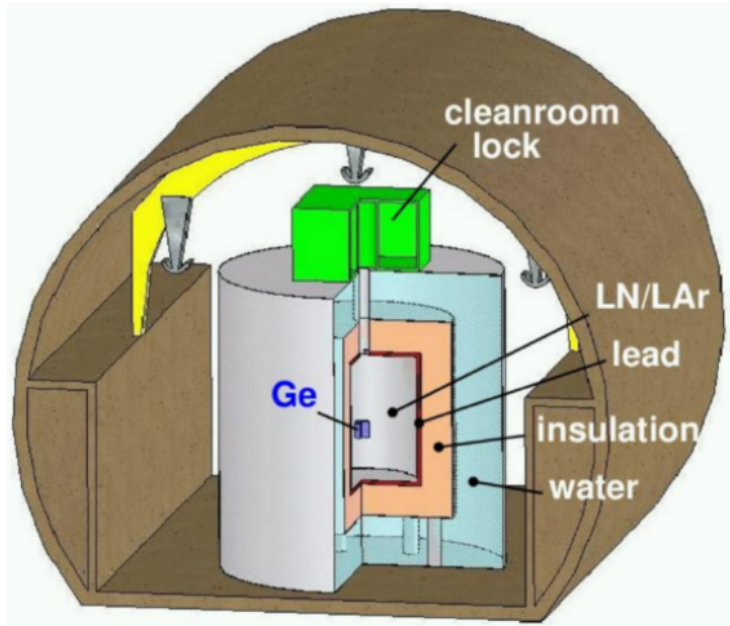
FULL EXPERIMENT (in 9 years from start)

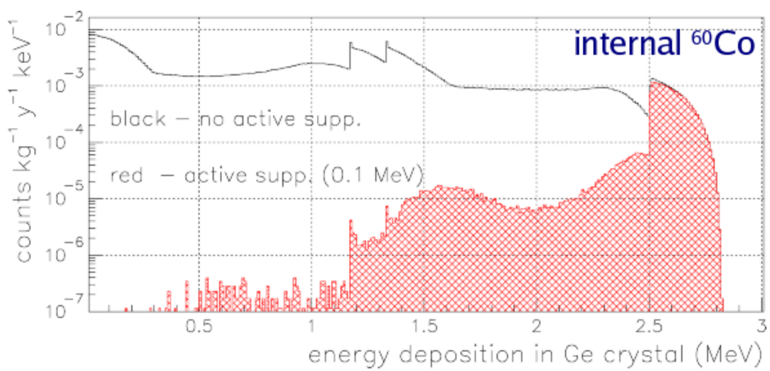
- expected bkg (without cuts) 17 c/keV/t/y
  - mainly from cosmogenics
  - bkg from Cu and close parts eliminated by screening in MEGA
- PSD and segmentation cuts $\Rightarrow$ 0.6 c/keV/t/y
  - $\tau_{1/2} \geqslant 10^{27}$ y in 5 years
  - $\langle m_\nu \rangle \leqslant 0.02 \div 0.07$ eV

New ^{76}Ge Double Beta Decay exp. @ LNGS (aka GERDA)

- **idea**: scrutinize 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
  - $\approx$20 kg ^{76}Ge from HM and Igex
  - expected bkg $\leqslant$0.01 c/keV/kg/y (intrinsic)
  - **check at 5σ HM evidence**
  - 15 kg$\times$y $\Rightarrow$ **6$\pm$1 $\beta\beta$ events on 0.5 bkg events**
- **Phase II:**
  - add **new enriched segmented detectors** with special care for activation
  - expected background $\approx$0.001 c/keV/kg/y
  - $\tau_{1/2} \geqslant 2\times10^{26}$ **y** with 100 kg$\times$y
  - $\langle m_\nu \rangle \leqslant 0.09 \div 0.29$ **eV**
- **Phase III: $\langle m_\nu \rangle \leqslant 0.01$ eV with 1 ton Ge**
  - worldwide collaboration

LoI 16 March 2004, hep-ex/0404039





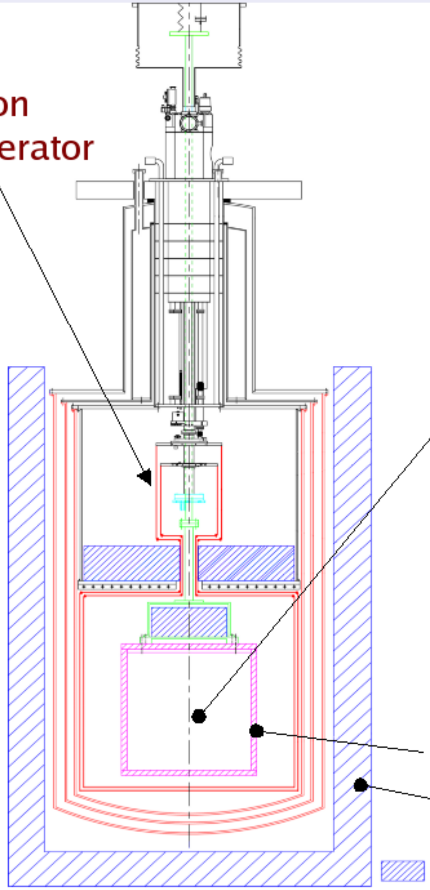
Calorimetric experiments with cryogenic detectors

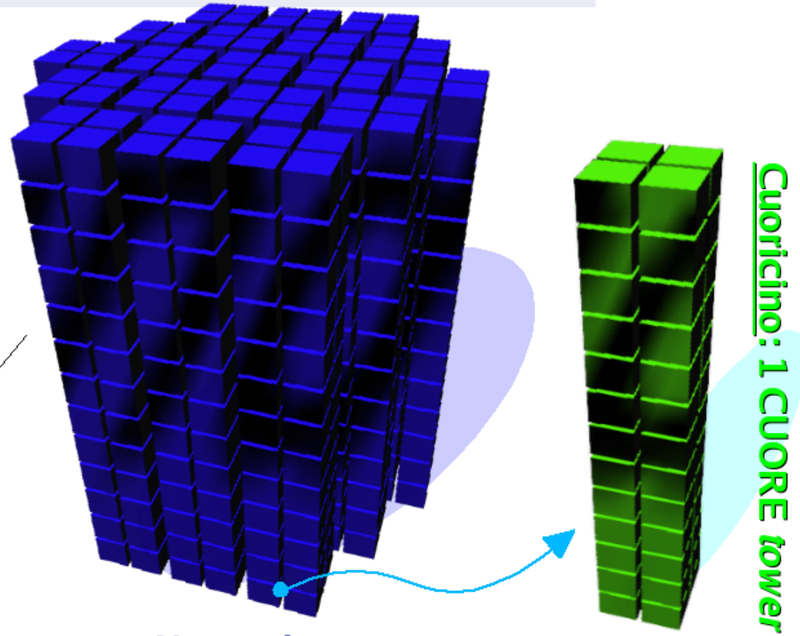
- ▲ true calorimeters
- ▲ wide isotopes choice ^{48}Ca, ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd
- ▲ high energy resolution
- ▲ large masses
- ▲ segmentation to reduce background
- ▼ fully sensitive to surface radioactivity
- ▼ difficult to reduce close materials (holders, wires, cryostats,...)
- ▼ not easy to run stable
- ■ hybrid detectors can do particle identification (i.e. e/γ - α)
  - heat + scintillation detection
  - heat + ionization detection (with PSD + segmentation)
- ▶ **CUORE** (^{130}Te)
- ▶ **Edelweiss** (^{76}Ge) G.Chardin NIM A 520 (2004) 145
- ▶ **MOON** (^{100}Mo)**?**

CUORE / 1

Cryogenic Underground Observatory for Rare Events

- array of 988 TeO_2 crystals 5×5×5 cm^3 (750 g) @ LNGS
  - **740 kg TeO_2** granular calorimeter ⇒ **200 kg of ^{130}Te**
- **$\beta\beta$ 0ν, Cold Dark Matter, Axions** searches





CUORE detector
19 *towers* – 52 detectors each

C. Arnaboldi *et al.*, *CUORE: A Cryogenic Underground Observatory for Rare Events*, NIM A 518 (2004) 775; hep-ex/0212053

CUORE / 2

- **compact and granular** ⇒ self shielding detector
- **enrichment** option still open (II phase): only core / full detector
- work in progress to **reduce surface radioactivity** (1/100th of CUORICINO)
  - advanced cleaning techniques
  - new **surface sensitive detectors** for active bkg rejection under test

Present status

- **approved by INFN and LNGS**
- dilution refrigerator design and construction
- underground building design and construction
- material selection and cleaning procedure settling

Full experiment

- **CUORE experiment due to start data taking in 2009 @ LNGS**

◆ for	$b = 1$ count/ton/year/keV
and	$\Delta E_{FWHM} = 10$ keV
in	10 years

- $\tau_{1/2}^{0\nu} \geqslant 6.6 \times 10^{26}$ years at 1σ
- $\langle m_\nu \rangle \leqslant 11 \div 56$ meV

C. Arnaboldi *et al.*, *Physics Potential and Prospects for the Cuoricino and CUORE experiments*, Astropart. Phys. 20 (2003) 91

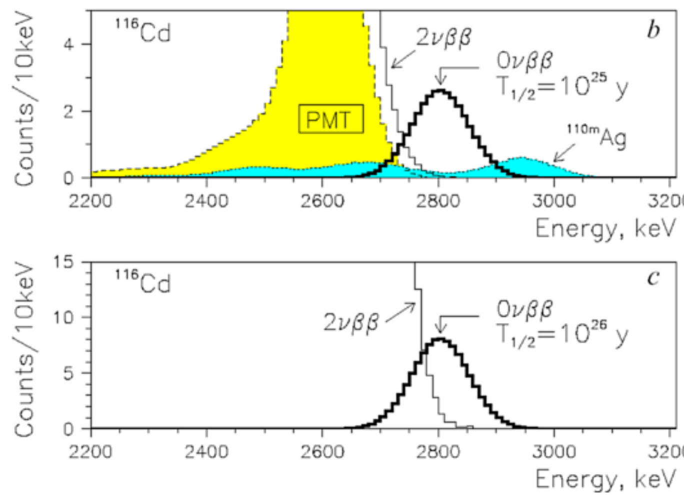
Calorimetric experiments with scintillators

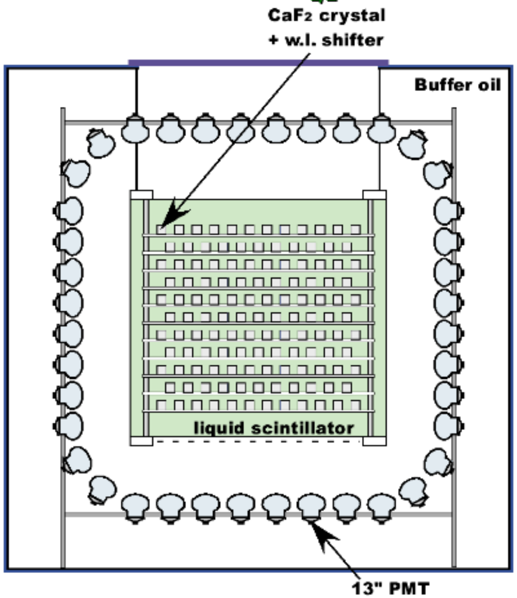
- ▲ large masses (solid or liquid)
- ▲ well known *simple* techniques
- ▲ wide isotopes choice ^{48}Ca, ^{116}Cd, ^{136}Xe, ^{160}Gd
- ▲ *immersion* in clean liquids to reduce background (Borexino, SNO, SK...)
- ▲ PSD to reduce background
- ▼ poor energy resolution
- ▼ in some cases difficult to have radiopure crystals
- ▼ background from PMTs
- ▶ **CAMEO** (^{116}Cd)
- ▶ **CANDLES** (^{48}Ca)
- ▶ **XMASS** (^{136}Xe)
- ▶ **Xenon in Borex** (or SNO) (^{136}Xe) B.Caccianiga Astropart. Phys. 14 (2000) 15
- ▶ *nanocrystals* in SNO (^{48}Ca, ^{82}Se, ^{96}Zr, ^{116}Cd, ^{130}Te, ^{150}Nd)
  A. McDonald at SNOLAB workshop, May 2004

$CdWO_4$ and CaF_2 scintillators

CAMEO nucl-ex/0007012, INFN/BE-00/03 (project frozen because of environmental problems at LNGS)

- **idea**: $CdWO_4$ in CTF or Borex (LNGS), using the Liquid Scintillator as light guide and anticoincidence
- PSD and ΔE = 110 keV (FWHM)
- **CAMEO II**
  - 24×2.7 kg crystals ⇒ **20 kg of ^{116}Cd**
  - $\beta\beta$-2ν, internal and cosmogenic bkg ⇒ 0.6 c/y
  - ▸ $\tau_{1/2} \geqslant 1\times10^{26}$ y in 5÷8 y
- **CAMEO III**
  - 370×2.7 kg crystals enriched to 83% in Borex
  - lower bkg ⇒ $\tau_{1/2} \geqslant 1\times10^{27}$ y; $\langle m_\nu \rangle \leqslant 0.02÷0.07$ eV





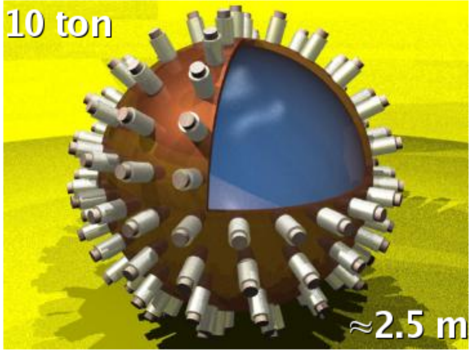
CANDLES

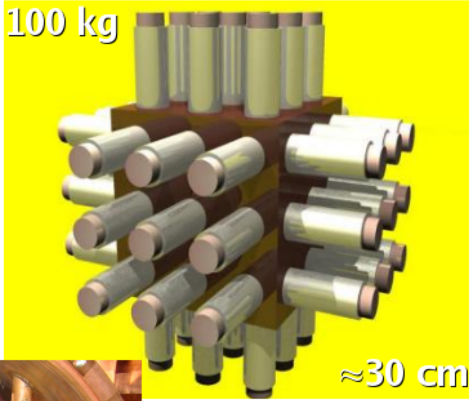
- **idea**: CaF_2 crystals in Liquid Scintillator at Oto Cosm. Obs.
- PSD to reject internal α and
- LS used as active shielding (LS is faster)
- **CANDLES III** (presently under construction)
  - 200 kg crystals ⇒ $\langle m_\nu \rangle \leqslant$ **0.5 eV** in 3 years
- **CANDLES IV**
  - 3.2 tons in 1000 natural crystals ⇒ **77 mol of ^{48}Ca**
  - ΔE = 4% (FWHM) and internal bkg reduced by 1/10
  - ▸ $\langle m_\nu \rangle \leqslant$ **0.15 eV** in 5 years
  - ▸ 2.3% enrichment (940 mol) ⇒ $\langle m_\nu \rangle \leqslant$ **0.03 eV** in 10 years

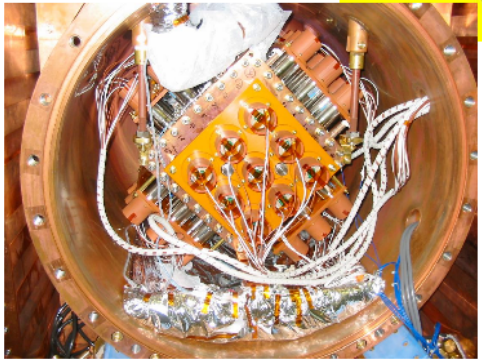
Xe scintillators

XMASS

- **idea**: a self shielding detector for DM and solar ν
- presently running 100 kg prototype
- 10 t natural LXe
  - considering only $\beta\beta$-0ν bkg
    - ▸ $\langle m_\nu \rangle \leqslant$ **0.01 ÷ 0.02 eV** in 5 years
  - but self shielding at 3 MeV is not effective
  - PMT bkg limits $\beta\beta$-0ν sensitivity
- **Detector dedicated to $\beta\beta$-0ν**
- 10 kg ^{136}Xe in 60 acrylic vessels at 50 atm (⇒ LXe)
- inside **SNO** or **SK**
- U/Th in vessel 10^{-12} g/g and σ_E = 57 keV
  - ▸ $\tau_{1/2} \geqslant 1.5\times10^{25}$ y in 1 year ⇒ $\langle m_\nu \rangle \leqslant$ **0.2 ÷ 0.3 eV**
- U/Th in vessel 10^{-16} g/g and more mass
  - ▸ $\langle m_\nu \rangle \leqslant$ **0.02 ÷ 0.03 eV**







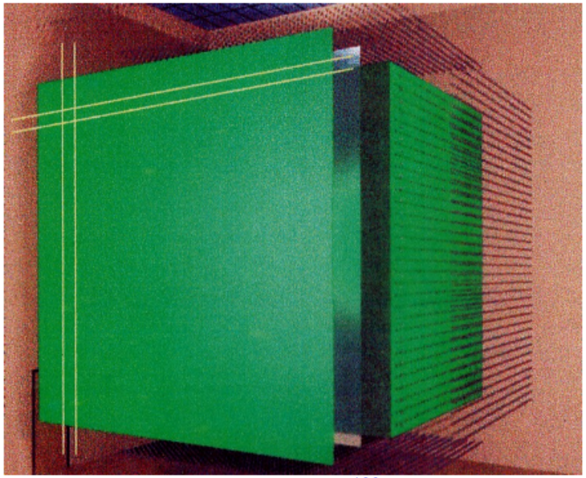
Tracking experiments

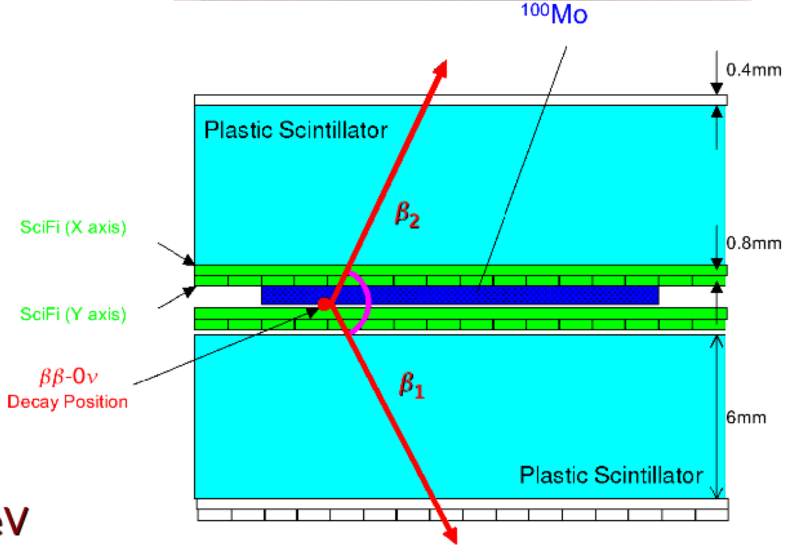
- ▲ background reduction by vertex and track reconstruction
- ▲ mass mechanism demonstration by electron angular correlation
- ▼ poor energy resolution
- ▼ small masses and/or low efficiency ⇒ enrichment necessary
- **MOON** (^{100}Mo)
- **DCBA** (^{82}Se, ^{150}Nd)
- **NEMO-4?** (100 kg of isotopes: ^{82}Se, ^{96}Zr, ^{116}Cd, ^{130}Te, ^{150}Nd, ...)
- **EXO,** a calorimeter with some tracking (^{136}Xe)

MOON

- **idea**: Mo foils inside a tracking detector for **solar** ν and **$\beta\beta$-0ν**
- ^{100}Mo 85% enriched
- prove mass mechanism by β angular correlation
- bkg from source and detector
  - Signal Selection by Spatial Correlation
  - Signal Selection by Time Selection
- position by XY scintillating fibers
- energy by 1.8m×1.8m×6mm plastic scintillators
  - energy resolution ΔE_{FWHM}=2% (4.5% with Mo)
  - main background from $\beta\beta$-2ν
- **MOON I (2004 – 2005) prototype**
  - 500 g ^{100}Mo in Elegant V active shield
  - $\tau_{1/2} \geqslant 1\times10^{24}$ y $\Rightarrow \langle m_\nu \rangle \leqslant 1$ eV
- **MOON II (2007)**
  - 100 kg one module (1.8m×1.8m) with 180 layers
  - $\tau_{1/2} \geqslant 4.4\times10^{26}$ y $\Rightarrow \langle m_\nu \rangle \leqslant 0.03$ eV
- **MOON III (?)**
  - 1 ton in 10 modules
  - $\tau_{1/2} \geqslant 1.6\times10^{27}$ y in 10 y $\Rightarrow \langle m_\nu \rangle \leqslant 0.015$ eV

H. Ejiri *et al.*, Phys. Rev. Lett. 89 (2000) 2917





DCBA

- **Drift Chamber Beta ray Analyzer** N. Ishihara et al. NIM A 443 (2000) 101
- $e^+/e^-/\alpha$ identification, insensitive to γ
- use angular correlation between 2 electrons to determine $\beta\beta$-0ν decay mechanism
- ^{82}Se, ^{100}Mo, **^{150}Nd** enriched foil sources with 60% efficiency
- 600 kg in 40 module 15 kg each (not yet settled)
- expected bkg only by $\beta\beta$-2ν
  - resolution on sum energy (FWHM) $\Delta E = 200$ keV
  - $\beta\beta$-2ν bkg reduced by cuts on electron distributions *

Present R&D

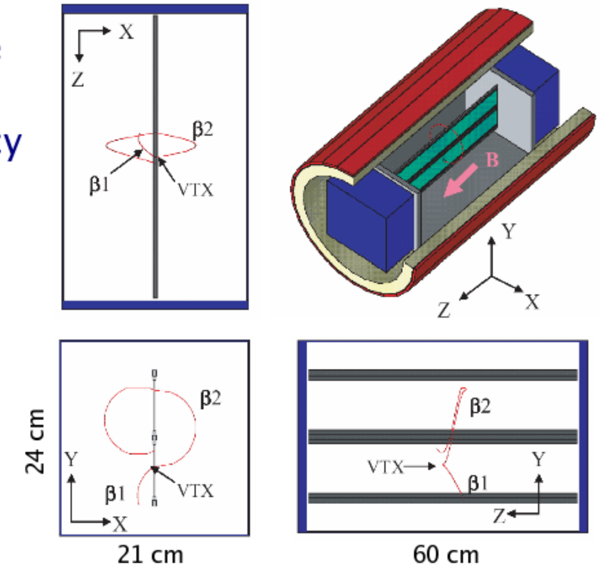
- **DCBA-T** $21\varnothing \times 24 \times 60$ cm^3 with 0.015 mol ^{150}Nd

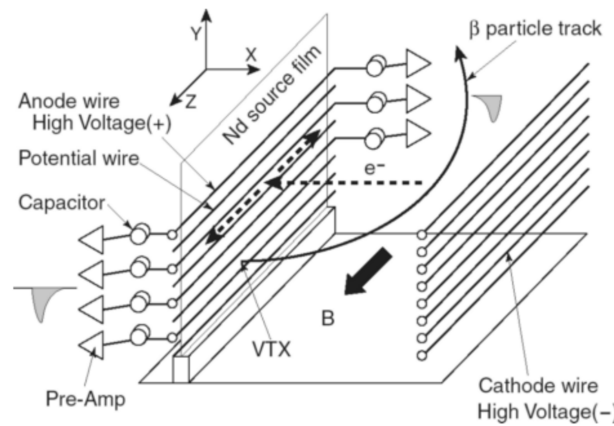
Towards the Final Experiment

- **DCBA-I** one module with 25 m^2 sources
- **DCBA-II** 40 (100) modules
  - 2.7 kmol ^{150}Nd (80% enriched)
  - $\tau_{1/2} \geqslant 10^{26}$ y in 10 years
  - $\langle m_\nu \rangle \leqslant 0.02$ eV
- **DCBA-C** calorimeter to study decay to excited states

* see comment: A.S. Barabash, V.A. Vasilyev, NIM A 473 (2001) 283

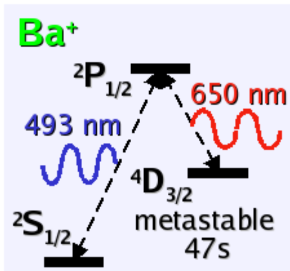
DCBA-T





EXO

- **idea**: scale Gotthard experiment adding **Ba tagging** to suppress background ($^{136}Xe \rightarrow ^{136}Ba^{++} + 2e$)
- single Ba^+ detected by optical spectroscopy
- two options with 63% enriched Xe
  - High pressure Xe TPC
  - LXe TPC + scintillation
- **calorimetry + tracking**
- expected bkg only by $\beta\beta$-2ν
  - energy resolution σ_E = 2%

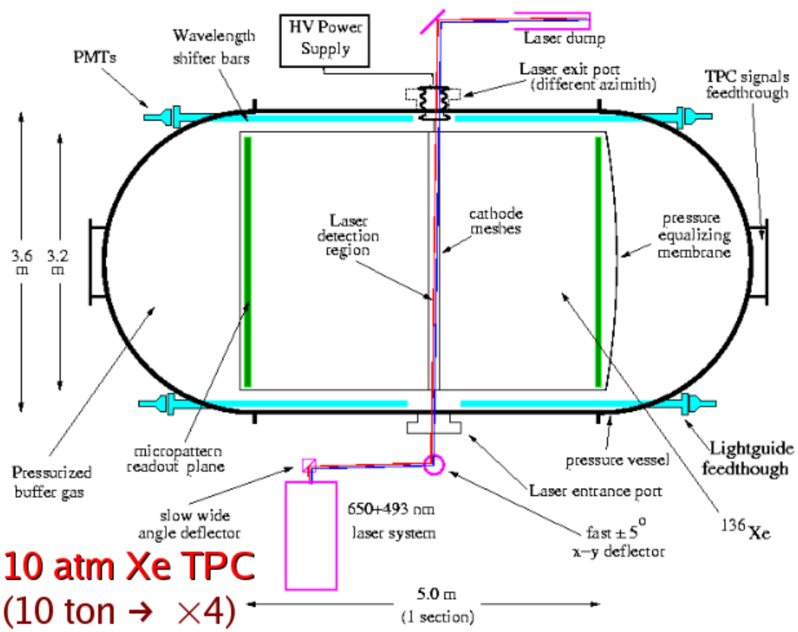


Present R&D

- Ba^+ spectroscopy in HP Xe / Ba^+ extraction
- energy resolution in LXe (ion.+scint.)
- a 200 kg LXe prototype without tagging

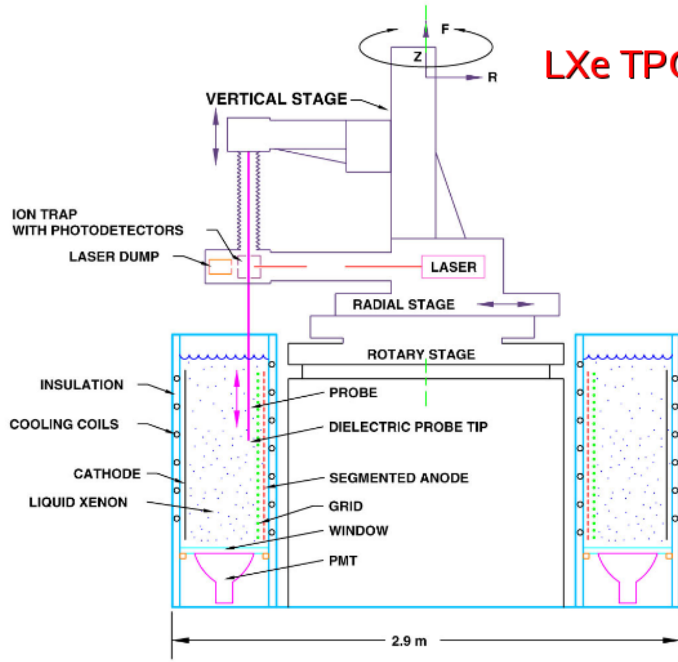
Full scale experiment at WIPP or SNOLAB

- **10 t** (for LXe ⇒ 3 m^3)
  - $b = 4\times10^{-3}$ c/keV/ton/y
  - $\tau_{1/2} \geqslant 1.3\times10^{28}$ **y** in 10 years
  - $\langle m_\nu \rangle \leqslant 0.013 \div 0.037$ eV



10 atm Xe TPC
(10 ton → ×4)

LXe TPC



Summary of future experiments

- **most representative proposals per isotope**
- some proposed experiments are still **too generic** to fit in the table (GERDA, XMASS, COBRA, ...)
- only the **CUORE** experiment is **approved** and is being prepared full size
- $\tau_{1/2}^{0\nu}$ sensitivity **strongly depends** on ***bkg*** estimation
- **cost** is only **very indicative**

	isotope	$Q_{\beta\beta}$ [keV]	technique	i.a. [%] *	*M* [kmol]	t_{meas} [y]	σ_E [keV]	*bkg* [c/y] **	$\tau_{1/2}^{0\nu}$ [10^{28} y]	$\langle m_\nu \rangle$ [meV] min	$\langle m_\nu \rangle$ [meV] max	project status	cost
CANDLES IV+	^{48}Ca	4271	s	2	0.9	5	73	0.35	*0.30*	29	54	R&D (III: 5 mol)	
Majorana	^{76}Ge	2039	i	90	6.6	5	2	1	0.40	21	67	R&D (SEGA)	$$$
GENIUS	^{76}Ge	2039	t	90	13.0	10	2	0.4	1.00	13	42	R&D (CTF: 10kg)	$$$
MOON III	^{100}Mo	3034	t	85	8.5	10	66	*3.8*	0.17	13	48	R&D (I: small)	
CAMEO III	^{116}Cd	3034	s	83	2.7	10	47	4	0.10	22	69	proposed	
CUORE	^{130}Te	2533	b	*35*	1.7	10	4	7.5	0.07	15	91	APPROVED	$
EXO	^{136}Xe	2476	t	65	48.0	10	49	*0.55*	1.30	12	31	R&D (1.5 kmol)	$$
DCBA-II	^{150}Nd	3367	t	80	2.7		85		0.01	16	22	R&D (T: small)	
GSO	^{160}Gd	1730	s	*22*	2.5	10	83	200	0.02	65		proposed	

s scintillation
i ionization
t tracking
b bolometric

* natural isotopic abundance (i.e. no enrichment required)

** only $\beta\beta$-2ν background considered

Conclusions

- neutrinoless double beta decay searches with 10 meV sensitivities can
  - find neutrino nature (Majorana or Dirac particle)
  - fix absolute neutrino mass scale

- HM experiment claims a 4σ evidence for $\langle m_\nu \rangle$ = **440 meV**
- running experiments (Cuoricino and NEMO-3) will reach **100÷300 meV**
  - but they will not be able to fully check HM result

- next generation experiment will reach sensitivities around **10 meV**
  - they will be able to check HM result
  - they will be exploring the physically interesting parameter space
- lot of work is being devoted to
  - theoretical nuclear structure calculations
  - active and passive background reduction
  - isotope enrichment
- many interesting experiments are being proposed for many isotopes
  - only very few can start in a close time (< 5 years)
  - **only CUORE is in the full experiment construction phase**