

Esperimenti sul decadimento doppio beta

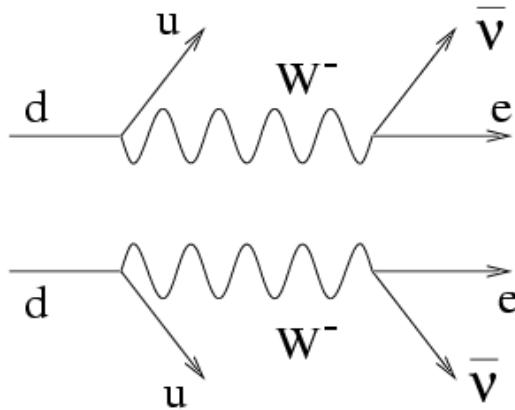
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- ◆ doppio decadimento beta e proprietà del neutrino
- ◆ approcci sperimentali
- ◆ risultati attuali
- ◆ esperimenti in presa dati
- ◆ il futuro

Il doppio decadimento beta 2 neutrini: $2\nu 2\beta$



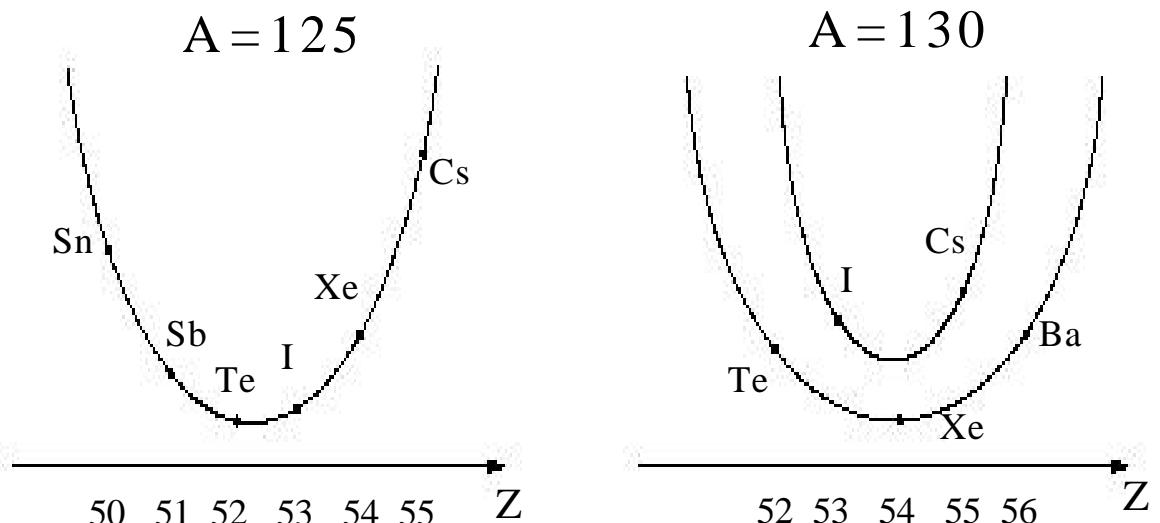
$$(A, Z) \Rightarrow (A, Z+2) + 2 e^- + 2 \nu_e$$



osservato: $\tau \geq 10^{19}$ y

- ~ 70 anni fa (Teoria di Fermi): canale a due neutrini 1935 M. Goeppert-Meyer
- ~ 15 anni fa ($m_\nu = 0$ E.W. Standard Model) è un decadimento permesso

esiste un insieme di nuclei (pari-pari) per cui il decadimento beta singolo è proibito e che decadono sull'isomero di massa minore tramite $2\nu 2\beta$

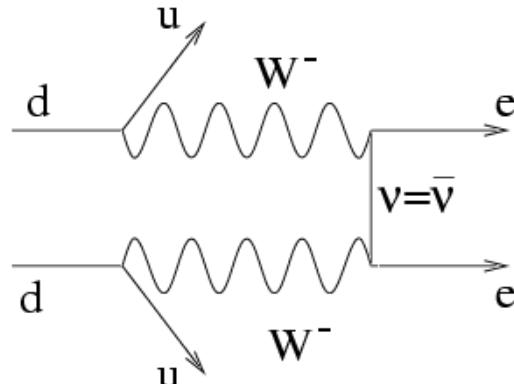
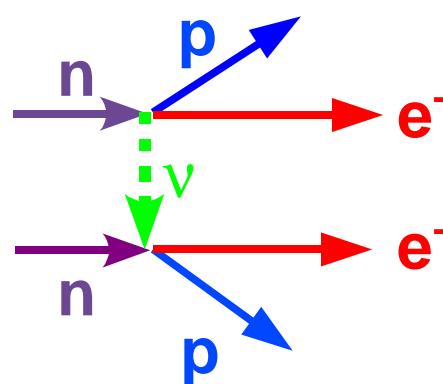


Il doppio decadimento beta 2 neutrini: $2\nu 2\beta$

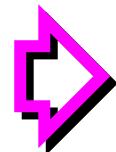
Il processo non ha particolare rilevanza per lo studio dell'interazione debole, la sua peculiarità sta nella vita estremamente lunga degli isotopi e l'interesse per la misura sperimentale di tale vita è legato alla verifica delle previsioni teoriche: TEST DEI MODELLI NUCLEARI !!

Isotope	$t_{1/2}^{2\nu 2\beta}(y)$ [measured]	$t_{1/2}^{2\nu 2\beta}(y)$ [calculated]
^{48}Ca	$(4.2^{+2.1}_{-1.0}) \times 10^{19}$	$6 \times 10^{18} - 5 \times 10^{20}$
^{76}Ge	$(1.42^{+0.09}_{-0.07}) \times 10^{21}$	$7 \times 10^{19} - 6 \times 10^{22}$
^{82}Se	$(0.9 \pm 0.1) \times 10^{20}$	$3 \times 10^{18} - 6 \times 10^{21}$
^{96}Zr	$(2.1^{+0.8}_{-0.4}) \times 10^{19}$	$3 \times 10^{17} - 6 \times 10^{20}$
^{100}Mo	$(8.0 \pm 0.7) \times 10^{18}$	$1 \times 10^{17} - 2 \times 10^{22}$
$^{100}\text{Mo}(0^{+*})$	$(6.8 \pm 1.2) \times 10^{20}$	$5 \times 10^{19} - 2 \times 10^{21}$
^{116}Cd	$(3.3^{+0.4}_{-0.3}) \times 10^{19}$	$3 \times 10^{18} - 2 \times 10^{21}$
^{128}Te	$(2.5 \pm 0.4) \times 10^{24}$	$9 \times 10^{22} - 3 \times 10^{25}$
^{130}Te	$(0.9 \pm 0.15) \times 10^{21}$	$2 \times 10^{19} - 7 \times 10^{20}$
^{150}Nd	$(7.0 \pm 1.7) \times 10^{18}$	$6 \times 10^{16} - 4 \times 10^{20}$
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$	$\times 1.2 \quad 10^{10} \times 10^9 \quad 3$

Il doppio decadimento beta 0 neutrini ... IERI



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



? osservato: $\tau \geq 10^{25} \text{ y}$

~ 70 anni fa (Teoria di Fermi): canale 0 neutrini 1939 W. Furry
suggerito come potente test per verificare se il ν è identico alla sua antiparticella

~ 15 anni fa ($m_\nu = 0$ E.W. Standard Model)

è un decadimento PROIBITO dallo S.M. (in cui ν è una particella di Dirac a massa 0)

- richiede un meccanismo di cambio di elicità che è pensabile solo se il neutrino ha massa
- comporta una violazione del numero leptonico che è possibile solo se i neutrini sono particelle di Majorana

un “simpatico” esercizio per un teorico

un item sperimentale per “amatori” (cercato da più di 60 anni !)

new physics beyond
the Standard Model ?

Il doppio decadimento beta 0 neutrini OGGI ...

... il panorama è completamente cambiato

- SOLAR NEUTRINOS DATA ([Sage](#), [Gallex](#), [SKamiokande](#), [SNO](#))
- ATMOSPHERIC NEUTRINOS DATA ([Macro](#), [SKamiokande](#))
- REACTOR DATA ([Kamland](#))

provano che

**neutrinos oscillations are a reality
the Standard Model is not adequate
new physics beyond the Standard Model exists**

OGGI sappiamo che ...

- esistono le oscillazioni, e quindi autostati di sapore $\nu_e \nu_\mu \nu_\tau$ e di massa $\nu_1 \nu_2 \nu_3$
- la fisica del neutrino è descritta da una matrice di mixing non diagonale :

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

- possiamo misurare il valore di alcuni elementi della matrice di mixing

<i>Reactors (CHOOZ)</i>	<i>Accelerators (JPARC)</i>	<i>Solar + Reactors</i>
<i>Atmospheric + K2K</i>	<i>Accelerators (JPARC)</i>	<i>Solar + Reactors</i>
$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$		
$\theta_{23} \sim 45^\circ$	$\theta_{13} \sim 13^\circ \quad \delta_{CP} = CP \text{ violation}$	$\theta_{12} \sim 30^\circ$
		$\alpha, \beta : Majorana phase$

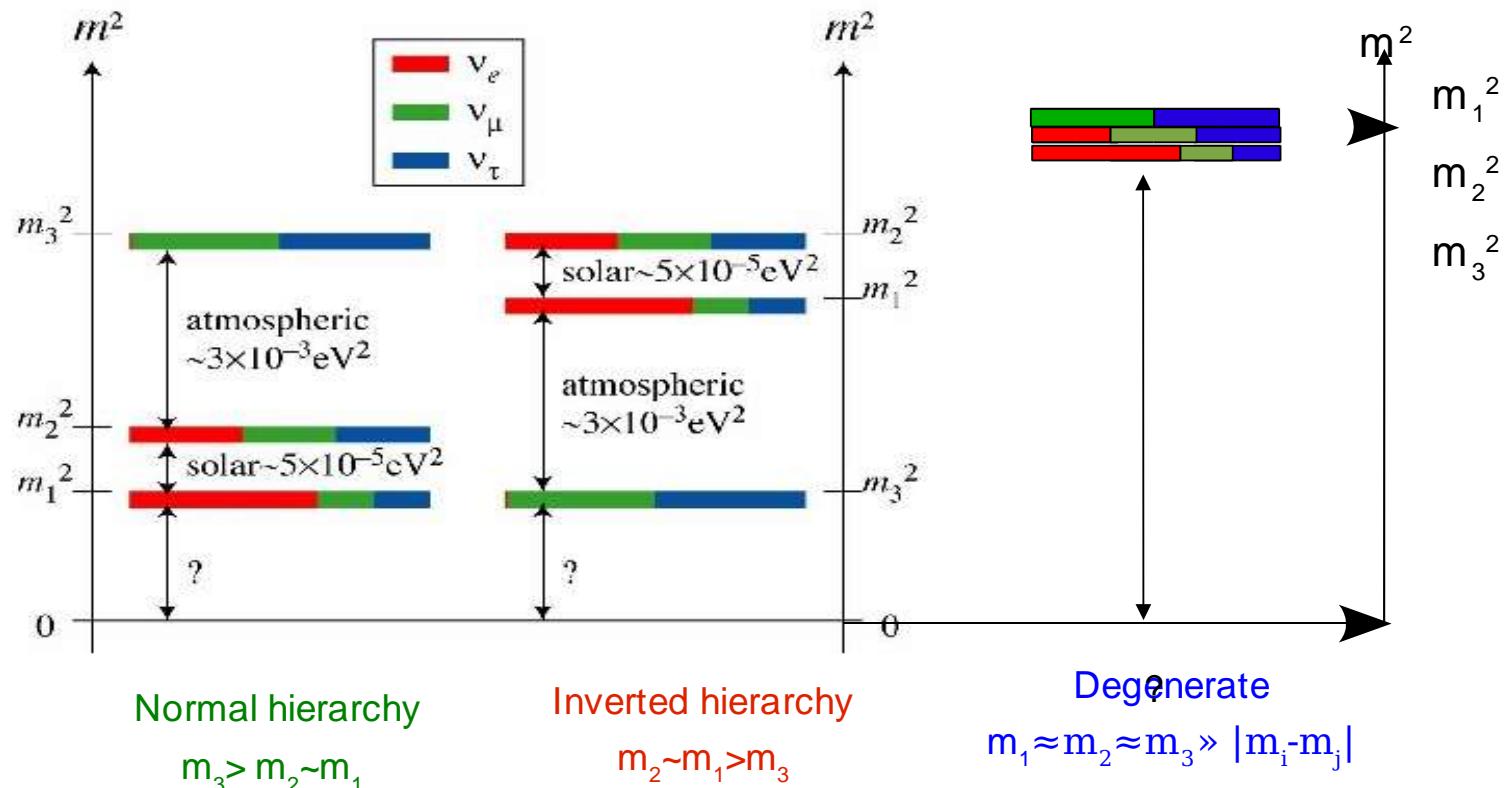
- e i valori di Δm^2
 - $\nu_\mu \rightarrow \nu_\tau \quad \Delta m^2_{23} \sim 2 \cdot 10^{-3} \text{ eV}^2$
 - $\nu_e \rightarrow \nu_\mu \quad \Delta m^2_{12} \sim 5 \cdot 10^{-5} \text{ eV}^2$

ma NON sappiamo ...

- se il neutrino è una particella di Dirac o di Majorana
- quale è il valore assoluto delle masse

Decadimento del trizio $m_{\nu_e} < 2.3 \text{ eV}$
Cosmologia $\sum m_i < \sim 1 \text{ eV}$
 $\beta\beta(0\nu) \quad \langle m_\nu \rangle < 0.3\text{-}0.8 \text{ eV}$

- quale è la gerarchia delle masse



Il doppio decadimento beta 0 neutrini OGGI ...

... è la via più facilmente percorribile per sapere se:

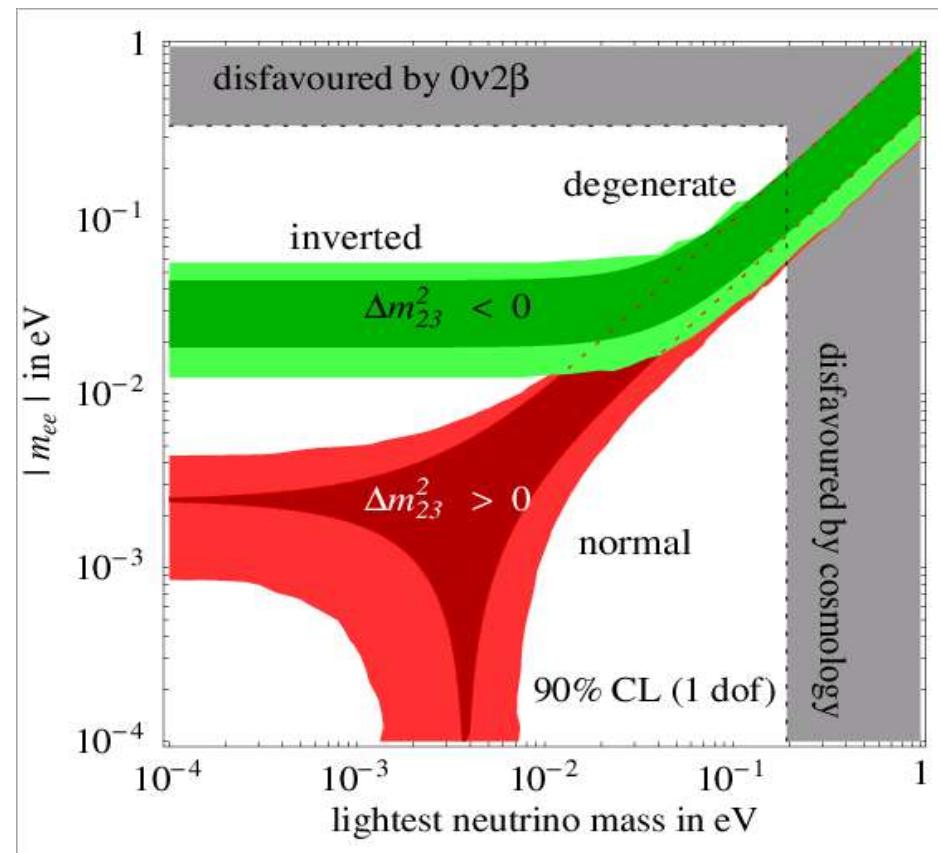
- il neutrino è una particella di Dirac
- quale è la gerarchia delle masse
- quale è la scala delle masse

$m_{ee} = \langle m_\nu \rangle = \text{"massa di Majorana"}$

$$= \left| \sum |U_{ei}|^2 m_i e^{i\alpha_i} \right|$$

m_{ve} = massa neutrino elettronico

$$= \sqrt{\sum |U_{ei}|^2 m_i^2}$$



Search of $\Delta L=2$ process to look for Majorana neutrinos

Matrix mass of Majorana neutrinos

$$\begin{pmatrix} \langle m_{ee} \rangle & \langle m_{e\mu} \rangle & \langle m_{e\tau} \rangle \\ & \langle m_{\mu\mu} \rangle & \langle m_{\mu\tau} \rangle \\ & & \langle m_{\tau\tau} \rangle \end{pmatrix}$$

$\langle m_{ee} \rangle$	Double beta decay	$(A, Z) \longrightarrow (A, Z+2) + 2e^-$
$\langle m_{e\mu} \rangle$	$\mu - e$ conversion	$\mu^- + (A, Z) \longrightarrow e^+ + (A, Z-2)$
$\langle m_{\mu\mu} \rangle$	Tri-muons production	$\nu_\mu N \longrightarrow \mu^- \mu^+ \mu^+ X$
$\langle m_{e\tau} \rangle$ $\langle m_{\mu\tau} \rangle$ $\langle m_{\tau\tau} \rangle$	K rare decay $e^\pm p \longrightarrow \nu_e l^\pm l^\mp X$	$K^+ \longrightarrow \pi^- \mu^+ \mu^+$ with $ll' = (e\tau), (\mu\tau), (\mu\mu), (\tau\tau)$

Limits

$$\begin{pmatrix} 10^{-10} & 1.7 \cdot 10^{-2} & 4.2 \cdot 10^3 \\ & 500 & 4.4 \cdot 10^3 \\ & & 2.0 \cdot 10^4 \end{pmatrix} \text{ GeV}$$

Experimentally, the $\beta\beta(0\nu)$ decay is the most sensitive physical process

to search $\Delta L=2$ and Majorana neutrino

$0\nu2\beta$ e le proprietà del neutrino

$0\nu2\beta$ vita media:

$$\tau_{\frac{1}{2}} = \frac{1}{G(Q, Z) |M_{nucl}|^2 \langle m_n \rangle^2}$$

dove:

- $G(Q, Z)$ = spazio delle fasi
- $\langle m_n \rangle^2$ = massa di Majorana
- $|M_{nucl}|^2$ matrice nucleare
 - theoretically evaluated (shell model, QRPA models ...)
 - different results according to the nuclear model used
 - important to extract from the measured (limit) lifetime the value (limit) of $\langle m_n \rangle$
 - exp. measurement to fix parameters of nuclear models are planned for the future

$0\nu2\beta$ punto di vista sperimentale

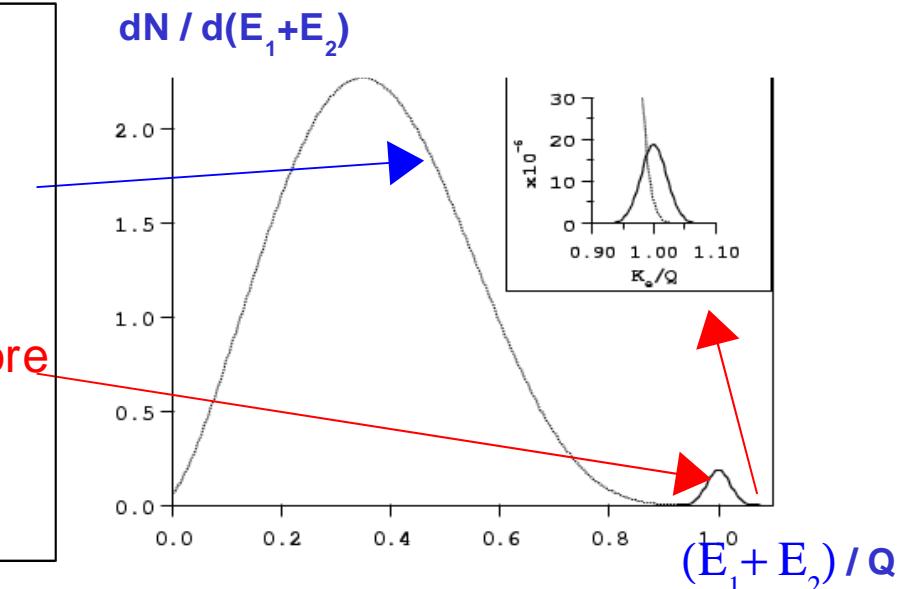
si cercano i due e^- , l'energia somma è:

$2\nu2\beta \Rightarrow (E_1 + E_2) = \text{CONTINUO end point a Q-value}$

$0\nu2\beta \Rightarrow (E_1 + E_2) = \text{PICCO al Q-value}$

allargato dalla risol. en. del rivelatore

(you can also look for the daughter nucleus old approach used in geochemical and radiochemical exp. in '70-'80 but only to search for the inclusive decay)



$S^{0\nu}_{1/2}$ = **On-sensitivity** = vita di dimezzamento corrispondente al minimo numero di eventi rivelabili al di sopra del fondo a un determinato C.L.

$N_{\beta\beta}$ = number of candidate nuclei
(mass and i. a.)

T = running time

ϵ = detection efficiency

Γ = energy resolution

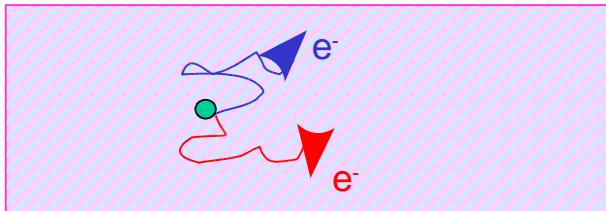
B = background

(a peak has to be revealed over the background)

$$S^{0\nu}_{1/2} = \ln 2 \times N_{\beta\beta} \times \underbrace{\frac{T}{B \Gamma}}_{\epsilon} \times \Gamma^{1/2}$$

$$\langle m_\nu \rangle^2 \sim \frac{1}{G(Q, Z) |M_{\text{nucl}}|^2 S^{0\nu}_{1/2}}$$

$0\nu\beta\beta$ due differenti techniche



Source \equiv Detector

(calorimetric technique)

- + high energy resolution
- no event topology

advantages:

easy to reach a high $N_{\beta\beta}$ (\Rightarrow large masses)

generally with high resolution detectors

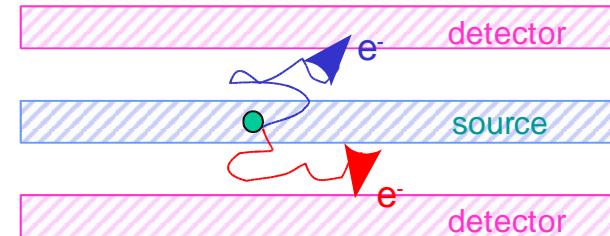
no background from $2\nu 2\beta$ event

good knowledge of background sources

disadvantages:

no or little possibility to reject background

constraints on detector material



Source \neq Detector

+ event shape reconstruction

- low energy resolution

advantages:

wider choice of sources

different sources in the same apparatus

clear reconstruction of event topology

high efficiency in background rejection

good knowledge of background sources

disadvantages:

complicate apparatus

growing in mass ($N_{\beta\beta}$) is not straightforward

poor energy resolution

bkg from $2\nu 2\beta$ event can be a limiting factor

$0\nu\beta\beta$ present experiments

a comparison between the different experiments requires to extract from the lower **limit** for τ an upper **limit** for m_ν

$$\langle m_\nu \rangle^2 = \frac{1}{G(Q, Z) |M_{\text{nucl}}|^2 \tau}$$

this is not straightforward, indeed uncertainties on theoretical evaluations of $|M_{\text{nucl}}|^2$ span one order of magnitude at least

Experiment	Isotope	$\tau_{1/2}^{0\nu}$ [y]	range $\langle m_\nu \rangle$ [eV]
Heidelberg Moscow 2001	^{76}Ge	$1.9 \cdot 10^{25}$	0.3-2.5
IGEX 2002	^{76}Ge	$1.57 \cdot 10^{25}$	0.3-2.5
Cuoricino 2005	^{130}Te	$2 \cdot 10^{24}$	0.3-0.7
NEMO 2005	^{100}Mo	$4.6 \cdot 10^{23}$	0.6-1.0
Bernatowicz et al. 1993	^{128}Te	$7.7 \cdot 10^{24}$	1.0-4.4
Belli et al. 2003	^{136}Xe	$1.2 \cdot 10^{24}$	0.8-2.4
Bizzetti et al. 2003	^{116}Cd	$1.7 \cdot 10^{23}$	1.6-5.5
Ejiri et al. 2001	^{100}Mo	$5.5 \cdot 10^{22}$	1.4-256
Osawa I. et al. 2002	^{48}Ca	$1.8 \cdot 10^{22}$	

claimed evidence
only by a part
of the collaboration

started in 2003

^{76}Ge : the Heidelberg-Moscow experiment

Data sheet

source=detector experiment

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

detector = 5 Ge diodes

source = 10.9 kg diodes

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

Q - value = 2039 keV

Location = Lab. Naz. del Gran Sasso - Italy

Countries = Germania + Russia

statistics= 53.9 kg y, with PSA = 35.5 kg y

performances =

4.2 keV FWHM resolution at DBD Q-value

background in $0\nu 2\beta$ region =

0.19 ± 0.01 c/keV/kg/y

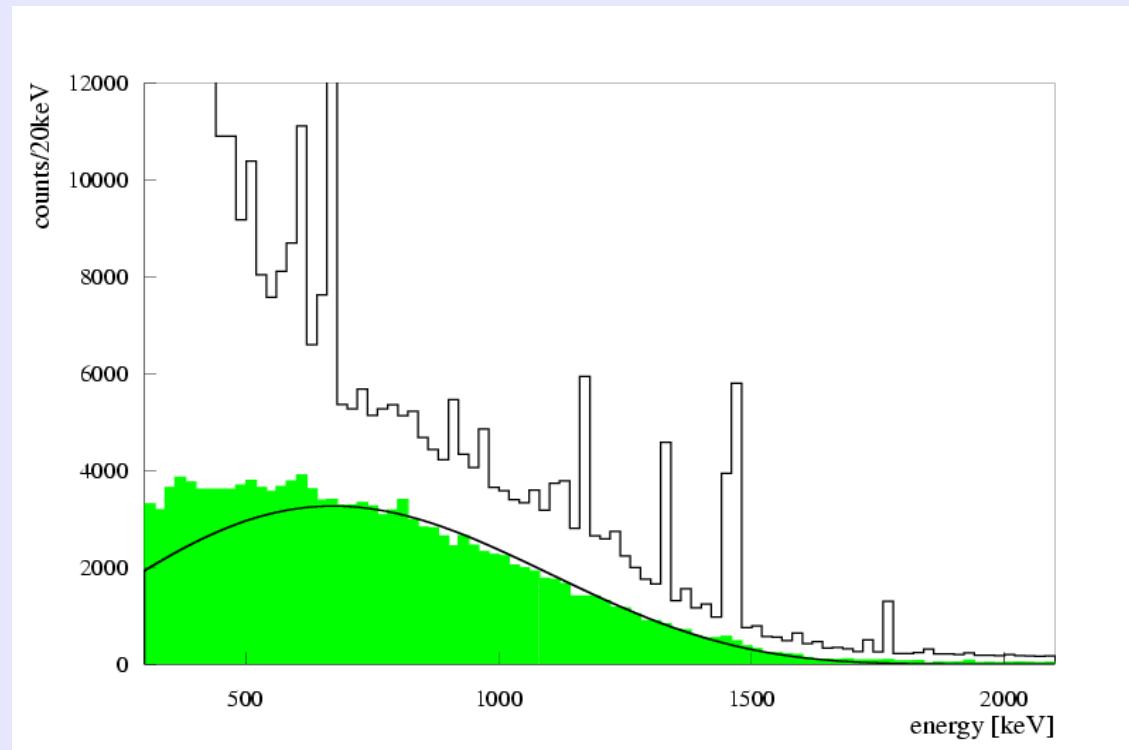
0.06 ± 0.01 c/keV/kg/y with PSA

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

^{76}Ge : the Heidelberg-Moscow experiment

accurate background model based on MC simulations and direct measurements of the contaminations of the different parts of the exp. apparatus, this allow to extract the 2ν half-life

$$T_{1/2}^{2\nu} > (1.55 \pm 0.01(\text{stat})^{+0.19}_{-0.15} (\text{syst})) \times 10^{21}$$



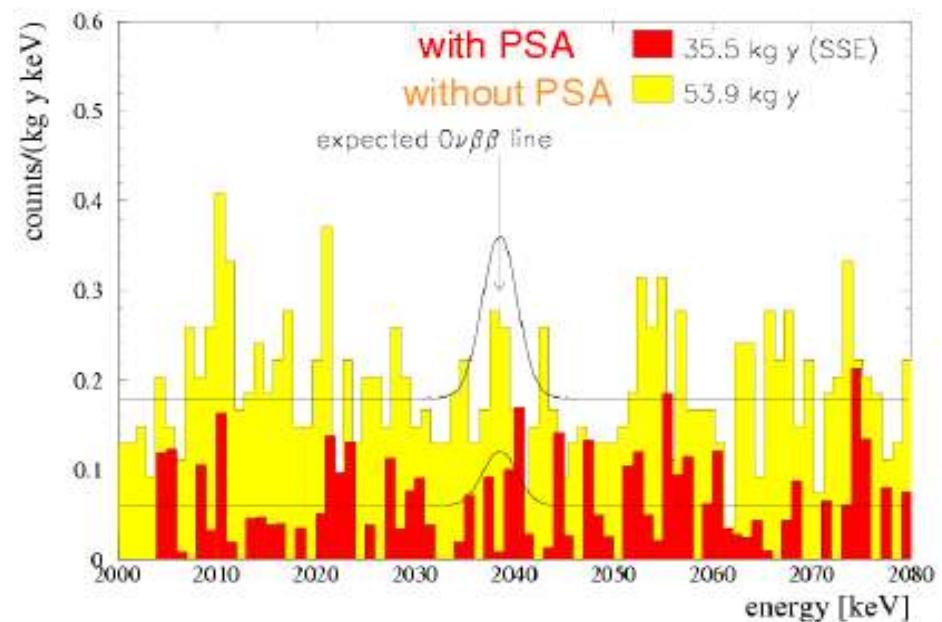
^{76}Ge : the Heidelberg-Moscow experiment

the entire collaboration (14 authors):

Klapdor-Kleingrothaus et al.
Eur. Phys. J. 12 (2001) 147

$$\tau_{1/2}^{0n} > 1.9 \cdot 10^{25} \text{ y at 90\% C.L.}$$
$$\langle m_\nu \rangle < 0.35 \text{ eV}^*$$

* using nuclear calculations of Staudt et al.
Europhys. Lett 13 (1990) 31



later a re-analysis by part of the
collaboration (4 authors):
“Evidence for Neutrinoless DBD”
Klapdor-Kleingrothaus et al.
Mod. Phys. Lett. A 16 (2001) 2049

$$\tau_{1/2}^{0n} = (0.8 - 18.3) \cdot 10^{25} \text{ y at 90\% C.L.}$$
$$\langle m_\nu \rangle = 0.11 - 0.56 \text{ eV}$$

the way in which the re-analysis was done has been hardly criticised

Aalseth et al. *Mod. Phys. Lett. A* 17 (2002) 1475, Feruglio et al. *Nucl. Phys. B* 637 (2002) 345, Zdesenko et al. *Phys. Lett. B* 546 (2002) 206 independent reply by two authors ...

the debate can last for ever ... or until the next generation Ge experiments

^{130}Te : Cuoricino

Data sheet

Location = Lab. Naz. del Gran Sasso - Italy

Countries = Italia + Spagna + Stati Uniti



source=detector experiment

- tech. suggested in 1985 by E. Fiorini and T.O. Niinikoski
- first experiment in 1997
- with Cuoricino international collaboration

detector = array of 62 TeO_2 bolometers

- 44 big (790 g) + 18 small (330 g) crystals

source ~ 40 kg natural TeO_2 (^{130}Te i.a. 33.8 % =>~ 11 kg ^{130}Te)

Q-value ~ 2530 keV

Statistics ~ 6 kg (^{130}Te) y - started April 2003

performances = ~ 8 keV FWHM at DBD Q-value

bkg in $0\nu 2\beta$ region = 0.18 ± 0.01 c/keV/kg/y

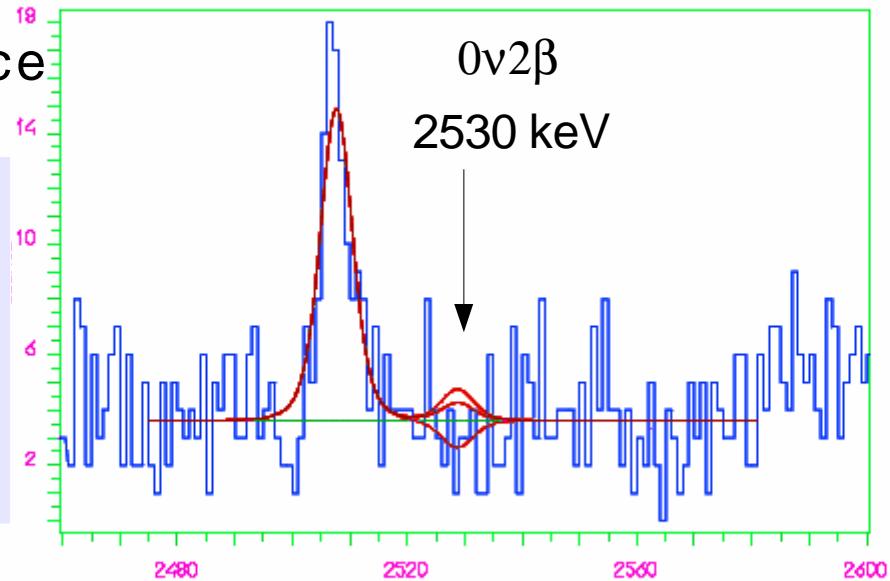


^{130}Te : Cuoricino NOW

started in April 2003

long interruption for maintenance

$\tau_{1/2}^{0\nu} > 2 \times 10^{24} \text{ y at 90\% C.L.}$
 $\langle m_\nu \rangle < 0.3-0.7 \text{ eV}$



Cuoricino within 3 years

- 3 years real time (waiting for CUORE)
- 60% bkg live time
- improve the present statistics from 6 to 25 kg (^{130}Te) y
- the limit improves as the sqrt of the statistics => we gain a factor 2 on the half-life

$S_{1/2}^{0\nu} \sim 4 \times 10^{24} \text{ y at 90\% C.L.}$ $\langle m_\nu \rangle < 0.2-0.5 \text{ eV}$

^{100}Mo , ... : NEMO-3

Data sheet

location = Modane Underground Laboratory
(Frejus) - France

source \neq detector experiment

- 3th generation exp
- study of both $2\nu 2\beta$ and $0\nu 2\beta$

detector = **Tracking detector** He+alcohol+Ar
(6180 drift wire chambers operated in Geiger mode)

Calorimeter
(1940 plastic scintillators + PMTs)

magnetic field $B=25$ G

sources = 20 m^2

total mass ~ 10 kg

Mo^{100} , Se^{82}

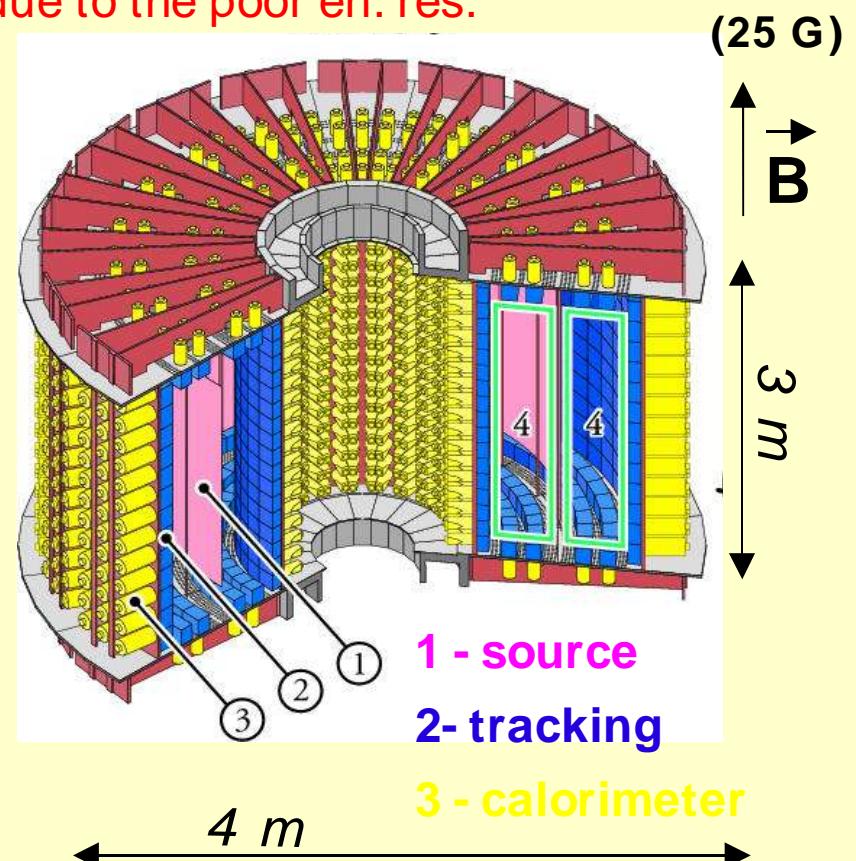
Te^{130} , Cd^{116}

Zr^{96} , Ca^{48} , Nd^{150}

} $0\nu 2\beta$

} $2\nu 2\beta$

performances and background =
track reconstruction
energy resolution $\sigma_E/E \sim 3\%$ at 3 MeV
background in $0\nu 2\beta$ region =
high efficiency in bkg rejection
bkg due to the $2\nu 2\beta$ is a limiting factor
due to the poor en. res.

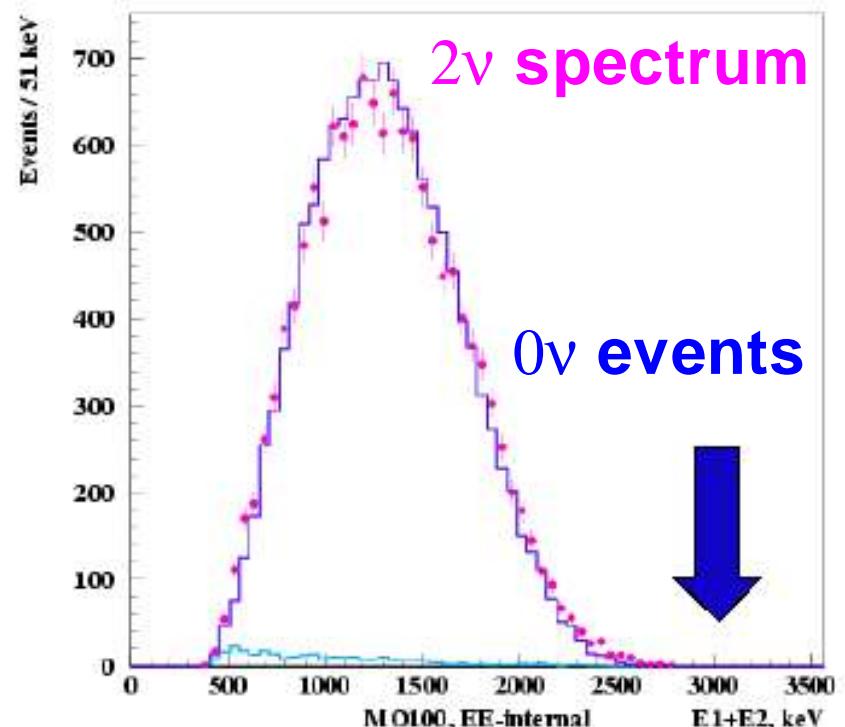
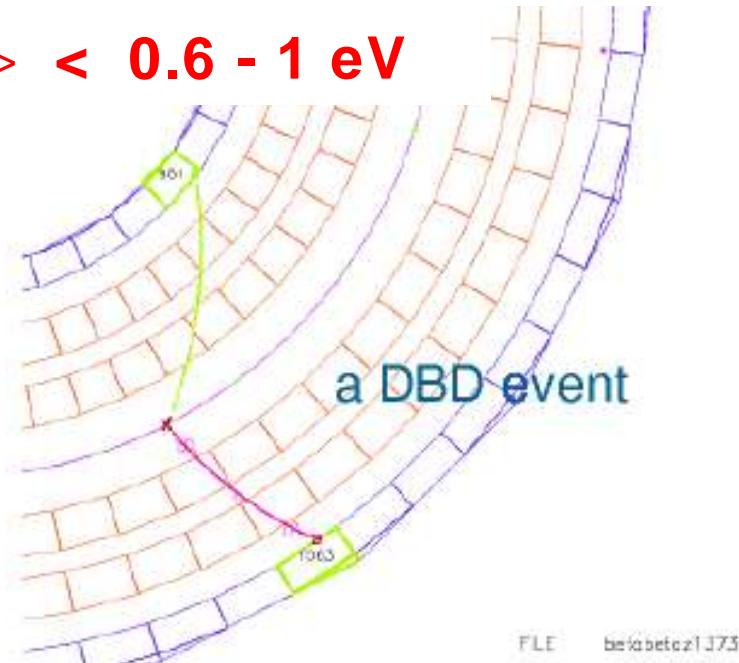


NEMO-3: ^{100}Mo RESULTS

$2\nu 2\beta$: $\tau_{1/2}^{2\nu} = (7.14 \pm 0.02_{\text{stat}} \pm 0.54_{\text{syst}}) 10^{18} \text{ y}$

$0\nu 2\beta$: $\tau_{1/2}^{0\nu} > 4.6 \cdot 10^{23} \text{ y}$ at 90% C.L.

$\langle m_\nu \rangle < 0.6 - 1 \text{ eV}$



NEMO-3: ^{100}Mo and ^{82}Se sensitivity year 2008-2009

^{100}Mo

$T_{1/2}^0 > 4 \cdot 10^{24} \text{ y}$
 $\langle m_\nu \rangle < 0.2 - 0.35 \text{ eV}$
 (90% C.L.)

^{82}Se

$T_{1/2}^0 > 0.8 \cdot 10^{24} \text{ y}$
 $\langle m_\nu \rangle < 0.65 - 1.8 \text{ eV}$
 (90% C.L.)

The Future of Double Beta Decay

Experiment	Author	Isotope	Detector description	$T^{5y}_{1/2}(y)$	$\langle m_\nu \rangle^*$
COBRA	Zuber 2001	^{130}Te	10 kg CdTe semiconductors	1×10^{24}	0.71
CUORE	Arnaboldi et al. 2001	^{130}Te	760 kg of TeO_2 bolometers	7×10^{26}	0.027
EXO	Danevich et al 2000	^{136}Xe	1 t enriched Xe TPC	8×10^{26}	0.052
GEM	Zdesenko et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen + water shield	7×10^{27}	0.018
GENIUS	Kleingrothaus et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen	1×10^{28}	0.015
MAJORANA	Aalseth et al 2002	^{76}Ge	0.5 t enriched Ge segmented diodes	4×10^{27}	0.025
DCBA	Ishihara et al 2000	^{150}Nd	20 kg enriched Nd layers with tracking	2×10^{25}	0.035
CAMEO	Bellini et al 2001	^{116}Cd	1 t CdWO_4 crystals in liquid scintillator	$> 10^{26}$	0.069
CANDLES	Kishimoto et al	^{48}Ca	several tons of CaF_2 crystal in liquid scintillator	1×10^{26}	
GSO	Danevich 2001	^{160}Gd	2 t $\text{Gd}_2\text{SiO}_5:\text{Ce}$ cristal scintillator in liquid scintillator	2×10^{26}	0.065
MOON	Ejiri et al 2000	^{100}Mo	34 t natural Mo sheets between plastic scintillator	1×10^{27}	0.036
Xe	Caccianiga et al 2001	^{136}Xe	1.56 t of enriched Xe in liquid scintillator	5×10^{26}	0.066
XMASS	Moriyama et al 2001	^{136}Xe	10 t of liquid Xe	3×10^{26}	0.086

* using nuclear calculations of Staudt et al. *Europhys. Lett.* 13 (1990) 31

^{76}Ge : GERDA

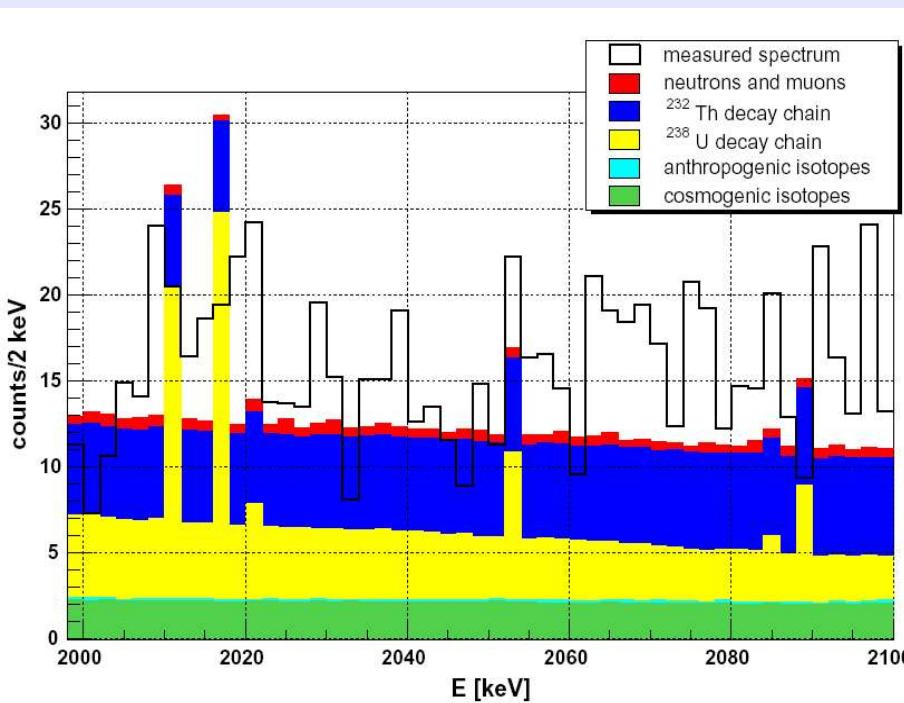
FASE I : test “Klapdor claim”

FASE II : $\langle m_\nu \rangle \sim 10 - 30 \text{ meV}$

Italia-Russia-Germania-Polonia
Laboratori Nazionali del Gran Sasso

Parte dall'esperienza di IGEX e HM con l'idea di ridurre a ~0 il fondo esterno
e controllare molto bene quello intrinseco (^{60}Co e ^{68}Ge).

IL GOAL E' => passare da 0.1 c/(keV kg y) a 0.001 c/(keV kg y) FATTORE 100 !!!



Modello fondo esp. Heidelberg Moscow

contributi esterni:

- **contaminazioni radioattive** dei materiali di costruzione (cemento/roccia ...) e in particolare 2.615 MeV from ^{208}Tl
- **neutroni** da reazioni (alpha,n) & fissione in cemento/roccia e da reazioni indotte dai mu

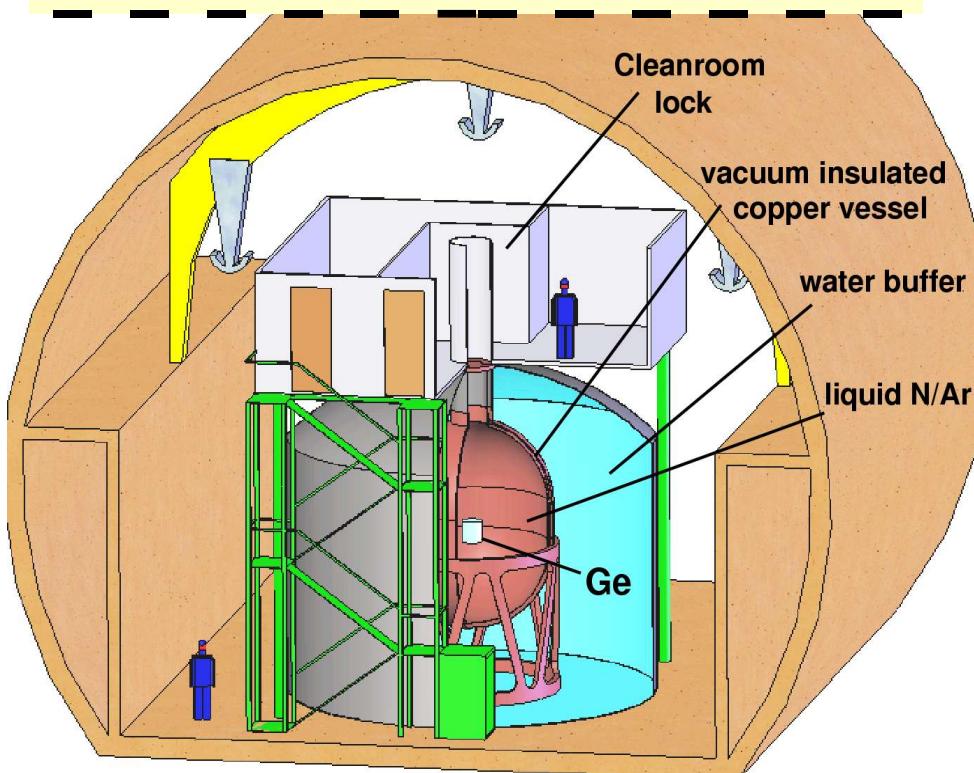
contributi interni (nel Ge)

- **attivazione cosmogenica** a livello del mare, particolarmente rilevante per gli isotopi ^{68}Ge e ^{60}Co con vite media ~ anno(i)

^{76}Ge : GERDA

LNGS - hall A

- array di HPGe immersi in LN/LAr
- il Ge deve essere arricchito !!
- il tutto circondato da acqua



FASE I (start 2007)

15-20 kg existing ^{76}Ge detectors
intrinsic bkg may dominate

assume 0.01 cts/(keV kg y)
assume FWHM resolution = 3.6 keV
 $N_{\text{bkg}} \sim 0.5$ counts for 15 kg y

Klapdor-K.: 28.8 ± 6.9 events in 71.7 kg y

expect 6.0 ± 1.4 cts above bkg of 0.5
for < 1 evt: signal excluded @ 98% CL

FASE II

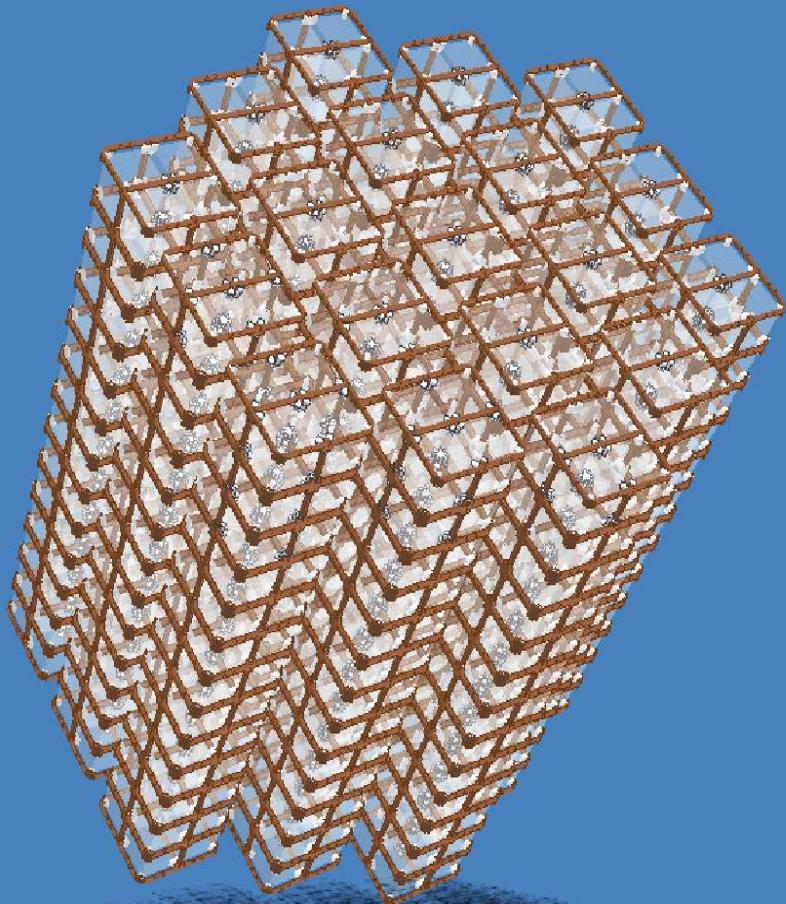
buy 30 kg enriched material
produced 20 kg segmented detectors

verify bkg index 0.001 cts/(keV kg y) (GOAL)
statistics $3y * 35 \text{ kg} \sim 100 \text{ kg y}$

$\langle m_\nu \rangle \sim 10 - 30 \text{ meV}$

¹³⁰ Te: CUORE

GOAL: $\langle m_\nu \rangle \sim 30 \text{ meV}$



**Cryogenic Underground Observatory
for Rare Events**

**Italia-Spagna-Stati Uniti
Laboratori Nazionali del Gran Sasso**



Parte dall'esperienza di MiDBD e Cuoricino.

Il modello del bkg di Cuoricino considera:

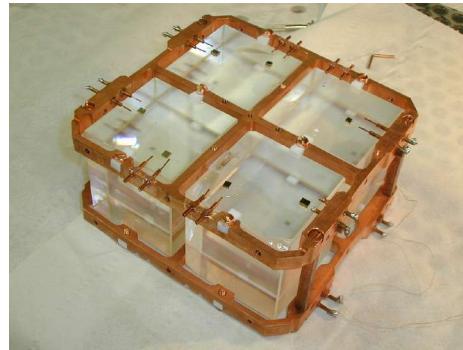
~ 0 il fondo intrinseco di bulk dei rivelatori
dominante il fondo dovuto alle contam. superficiali dei materiali
facilmente controllabile il fondo esterno.

**IL GOAL E'
passare da 0.1 c/(keV kg y)
a meno di 0.01 c/(keV kg y)**

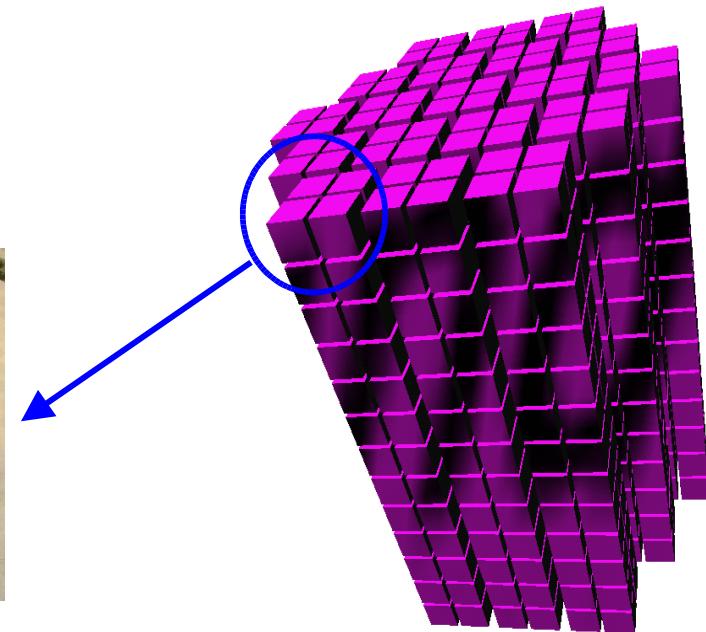
FATTORE > 10 !!!

¹³⁰ Te: CUORE

750 g TeO₂  x 988
0.75 kg x 988 = 741 kg TeO₂
~ 600 kg Te = 200 kg ¹³⁰Te



4 detector/module



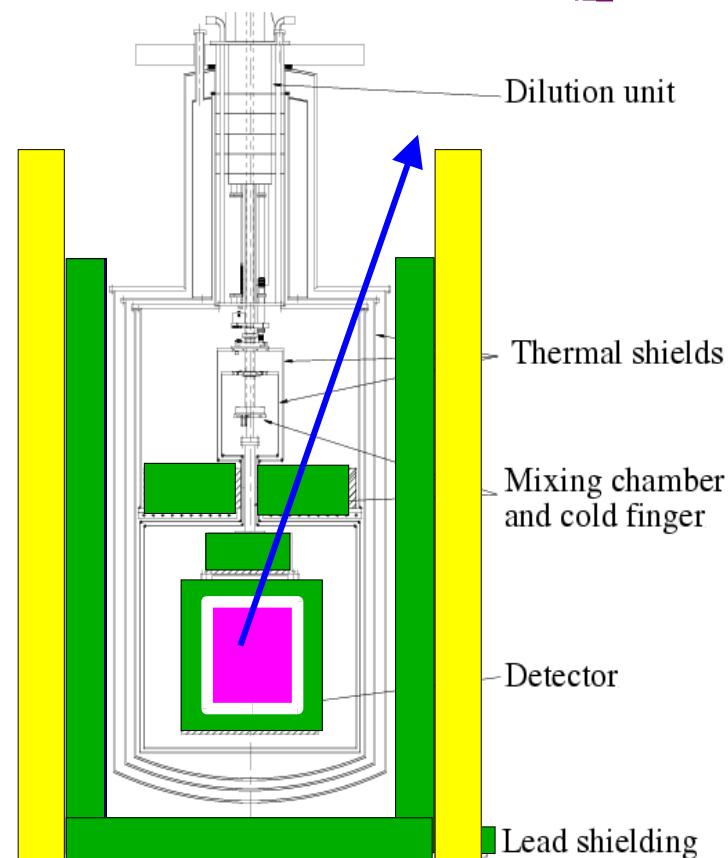
LNGS - hall A

- array di 988 bolometri di TeO₂
- nessuna richiesta di arricchimento
- 19 torri - 13 moduli/torre - 4 rivelatori/modulo
- specially designed cryostat, at 10 mK

massa totale ~ 740 kg TeO₂ = 200 kg ¹³⁰Te

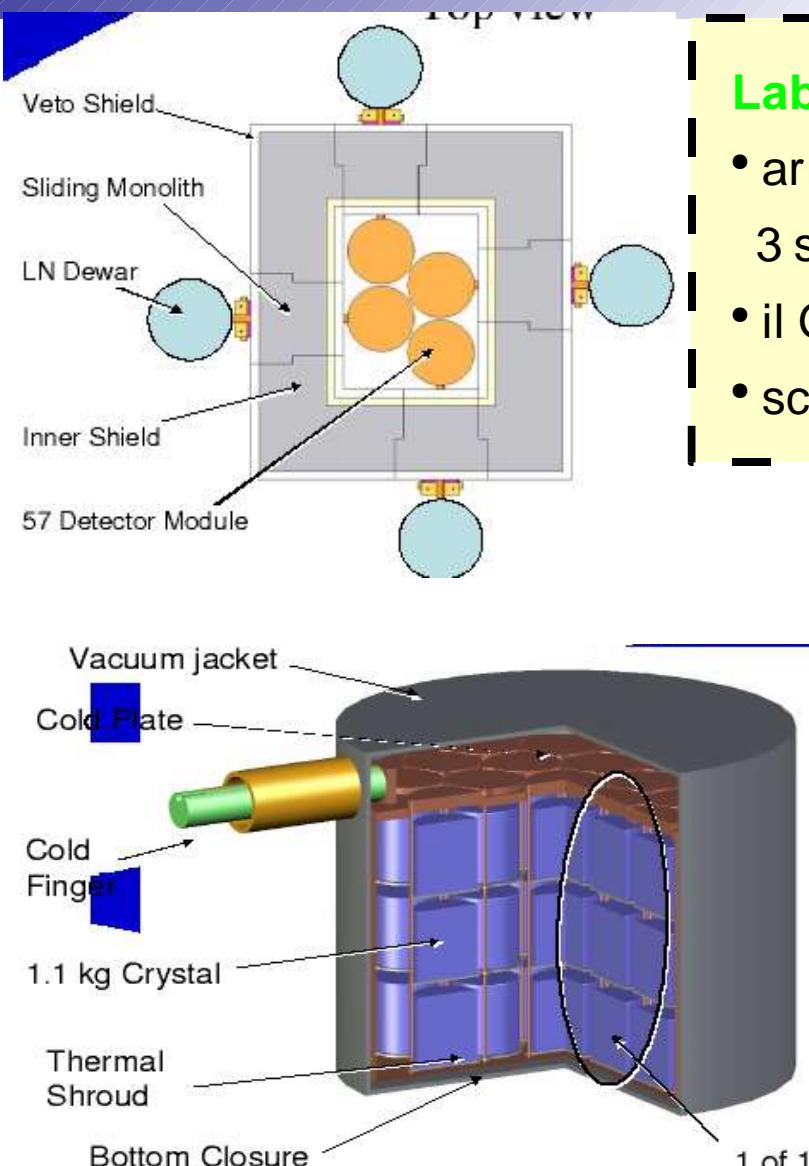
status: partially funded – space assigned

CUORICINO is one of the 25 towers of CUORE



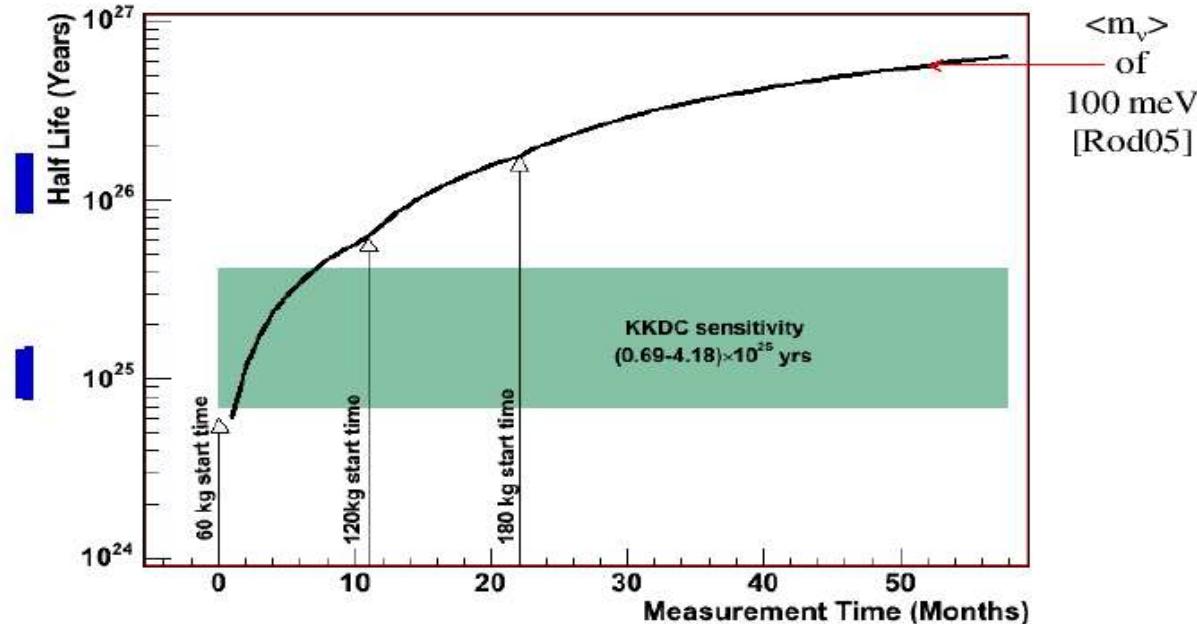


GOAL: $\langle m_\nu \rangle \sim 30 \text{ meV}$



Laboratorio da definirsi

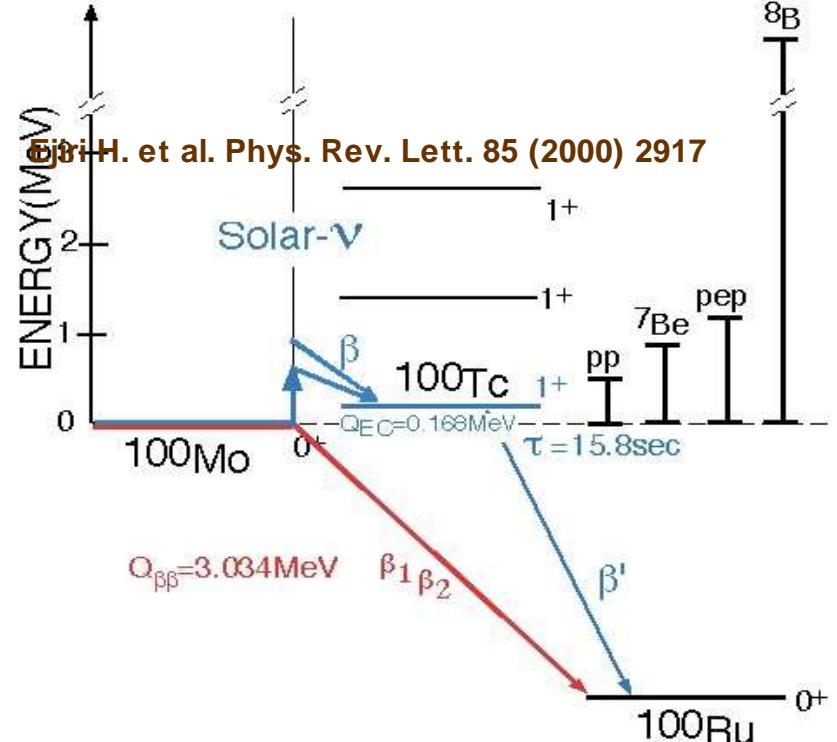
- array di HPGe segmentati, 57 cristalli/modulo,
3 strati da 19 cristalli
- il Ge deve essere arricchito !!
- schermatura “tradizionale” Pb+Cu+n shield and active veto



MOON

GOAL: $\langle m_\nu \rangle \sim 50 \text{ meV}$

^{100}Mo → passive source for $0\nu 2\beta$
 → target for solar neutrinos

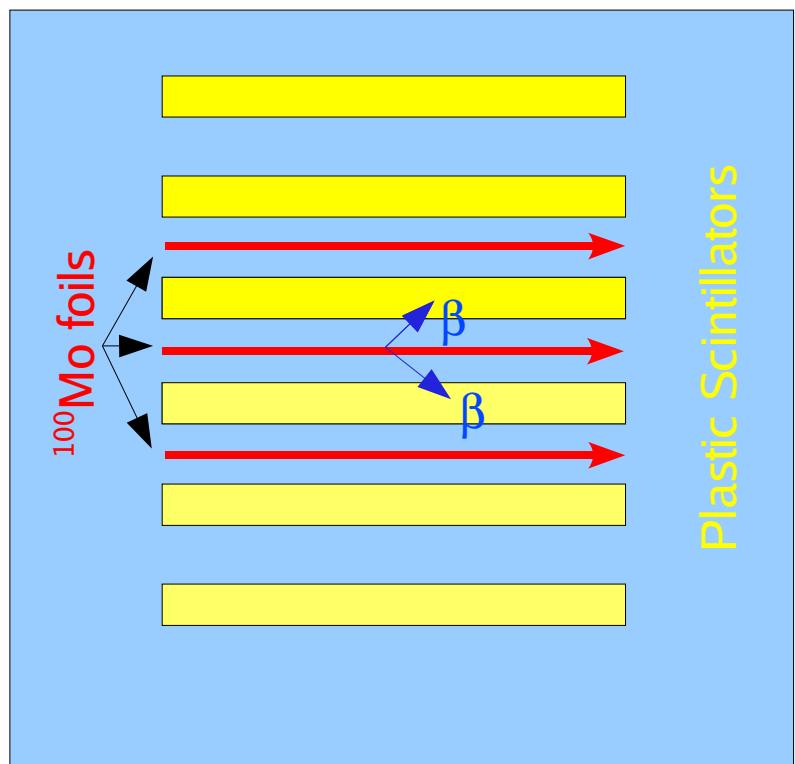


Oto Underground Laboratory - Japan

- sandwich of Plastic Scintillators and Mo foils
- 1 ton ^{100}Mo in the final design
- specially designed cryostat, at 10 mK

Main concerns:

- FWHM: 7%
- Mo radio-purity



SuperNEMO preliminary design

Plane geometry

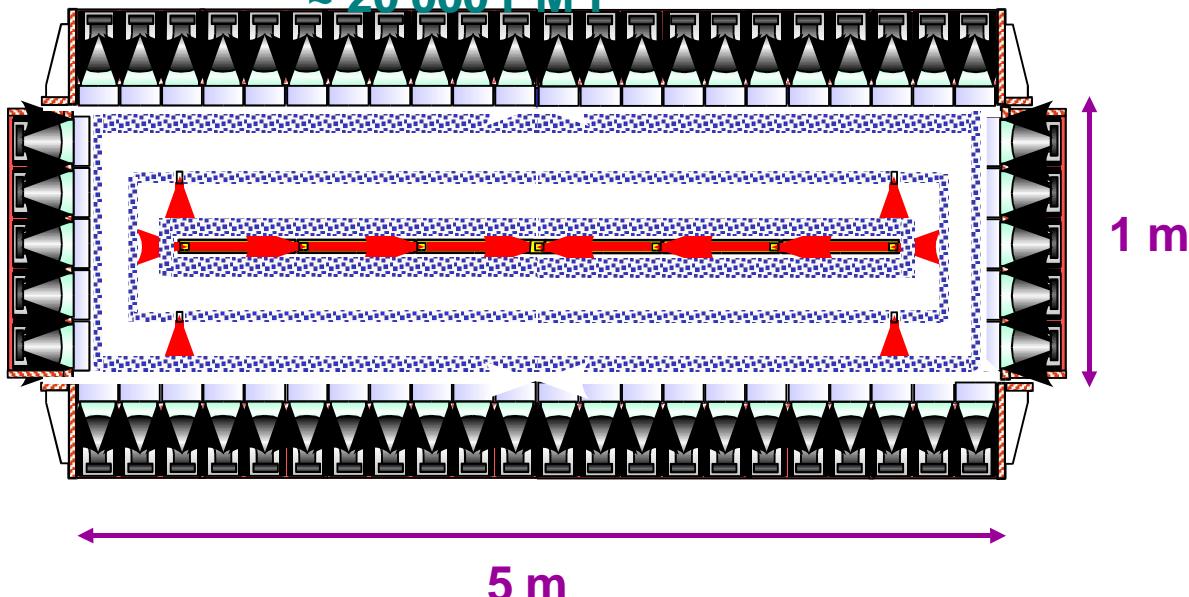
Source (40 mg/cm²) 12m² tracking volume (~3000 channels) calorimeter (~1000 PMT)

Modular (~5 kg of enriched isotope/module)

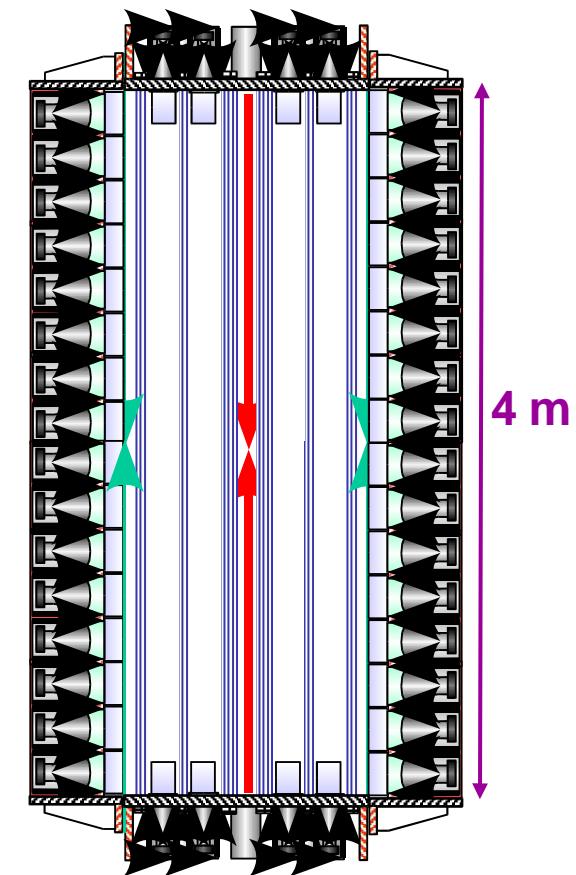
100 kg: 20 modules

~ 60 000 channels for drift chamber

~ 20 000 PMT



Top view



Side view

Conclusioni

- ~ 10/15 anni fa la ricerca del DBD era un “esperimento di nicchia”, non si vedevano forti ragioni per dover credere all'esistenza di neutrini massivi
- **oggi il DBD ha un ruolo centrale nella fisica del neutrino** grazie alla sua possibilità di accedere a informazioni quali la scala delle masse e il carattere di Majorana del neutrino
- prova del ruolo centrale giocato dal DBD è la numerosità degli esperimenti proposti per il futuro
- curiosamente i due esperimenti più avanti in fase di realizzazione saranno in Italia, ai LNGS: sono CUORE e GERDA
(e ancora più curiosamente la tecnica utilizzata da entrambi e' stata suggerita da un italiano)
- è ragionevole pensare che nel giro di ~ 5 anni sapremo se la gerarchia è diretta o inversa !!