

Misura della massa assoluta dei neutrini



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- ◆ Stato dell'arte dei neutrini massivi
- ◆ La determinazione della scala di massa
- ◆ Il ruolo delle misure cinematiche
 - ↳ Attuali risultati sperimentali e prospettive future
- ◆ Il ruolo del doppio decadimento beta
 - ↳ Attuali risultati sperimentali e prospettive future

Proprietà dei neutrini con massa

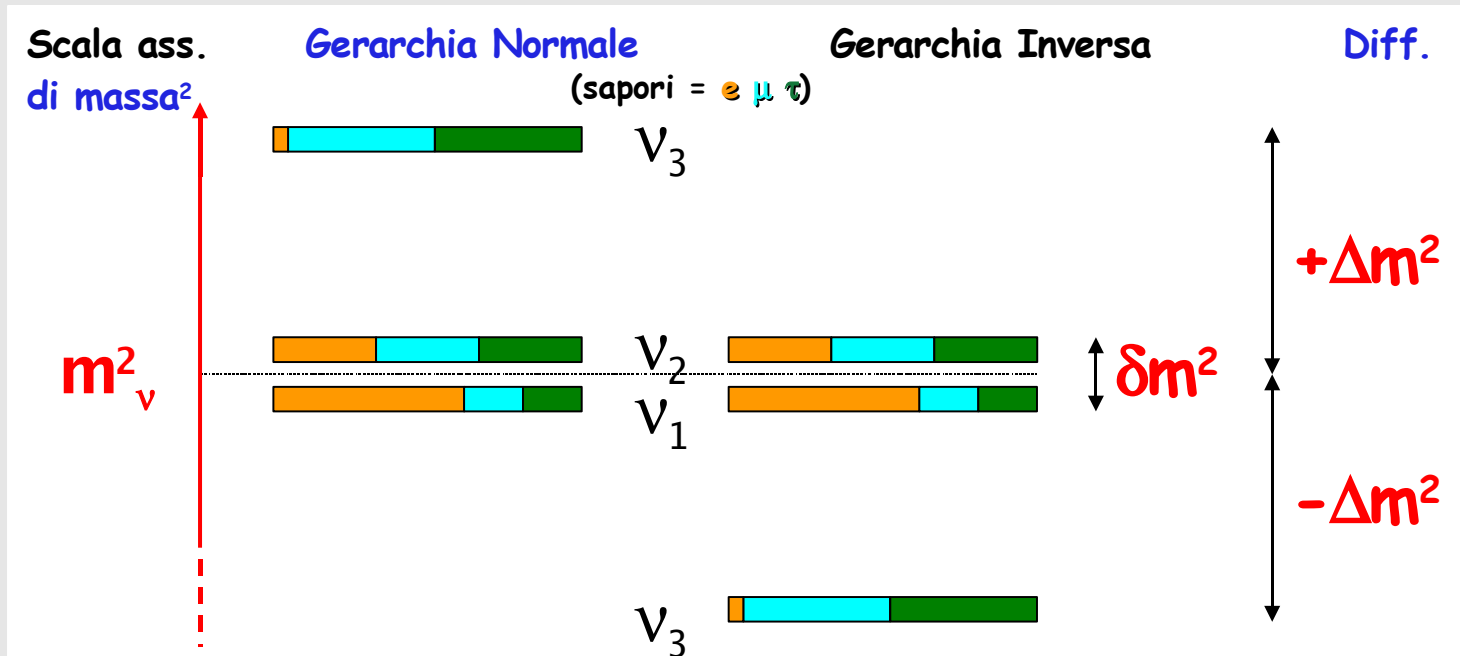
❖ i neutrini oscillano:

$$(\nu_e, \nu_\mu, \nu_\tau)^T = U (\nu_1, \nu_2, \nu_3)^T$$

❖ dagli esperimenti sulle oscillazioni:

$$\begin{aligned} \delta m^2 &\sim 8 \times 10^{-5} \text{ eV}^2 & \sin^2 \theta_{12} &\sim 0.3 \\ \Delta m^2 &\sim 3 \times 10^{-3} \text{ eV}^2 & \sin^2 \theta_{23} &\sim 0.5 \\ m_\nu &< O(1) \text{ eV} & \sin^2 \theta_{13} &< \text{few}\% \\ \text{sign}(\pm \Delta m^2) &\text{unknown} & \delta \text{ (CP)} &\text{unknown} \end{aligned}$$

- Scala di massa?
- Dirac o Majorana?
- Gerarchia?
- Contenuto ν_e in ν_3 ?



La misura della scala di massa

β -decay: m_β

model independent

status: $m_\beta < 2.3$ eV

potential: $m_\beta < 200$ meV

Exp.: KATRIN, MARE(?)

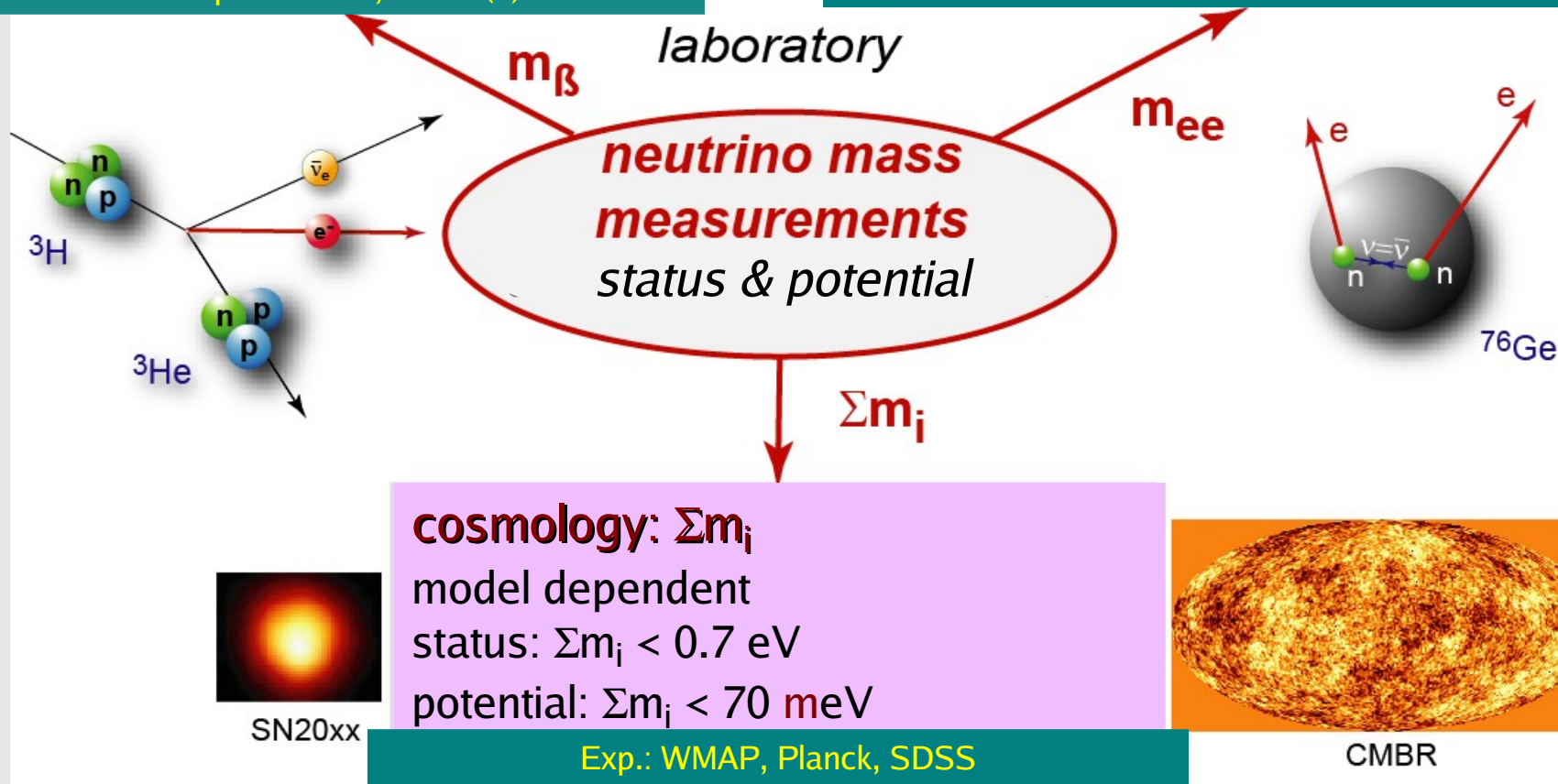
$0\nu\beta\beta$ -decay: m_{ee}

model dependent, ν -nature (CP)

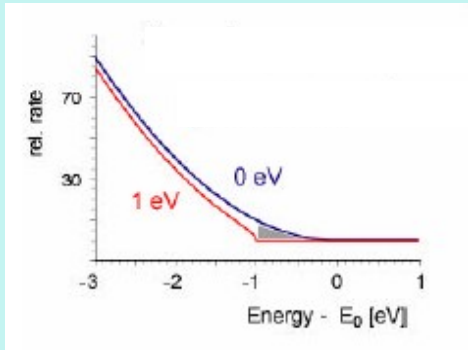
status: $m_{ee} < 0.5$ eV

potential: $m_{ee} < 20$ -50 meV

Exp.: Majorana, GERDA, CUORE, SUPERNEMO, ...



Decadimenti beta singolo e doppio beta a confronto



β decay

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

Il decadimento ha luogo per neutrini sia di Dirac che di Majorana

Con buona approssimazione, la parte finale dello spettro è sensibile ad una combinazione di masse al quadrato (pesate dal contenuto di “sapore elettronico”) detta “**massa effettiva del neutrino elettronico**” m_{β} :

$$m_{\beta} = [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{\frac{1}{2}}$$

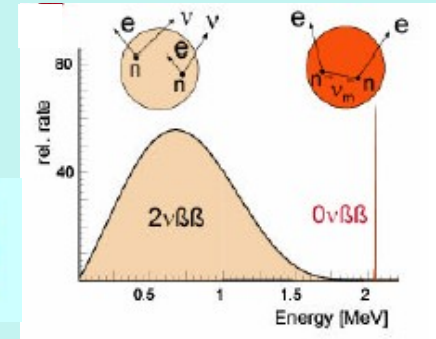
no interferenza distruttiva

Limite attuale: $m_{\beta} < \sim 2 \text{ eV}$

Sensibilità futura: $m_{\beta} < \sim 0.2 \text{ eV}$

$0\nu\beta\beta$ decay

$$m_{ee} = \left| \sum U_{ei}^2 m_i \right|$$



Il decadimento ha luogo solo se il neutrino è di Majorana

Il decadimento è sensibile alla cosiddetta “**massa effettiva di Majorana**” m_{ee} (e fasi relative) che, assumendo tre neutrini, è una combinazione lineare di tre canali neutrinici con ampiezze complesse:

$$m_{ee} = |c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

possibile interferenza distruttiva

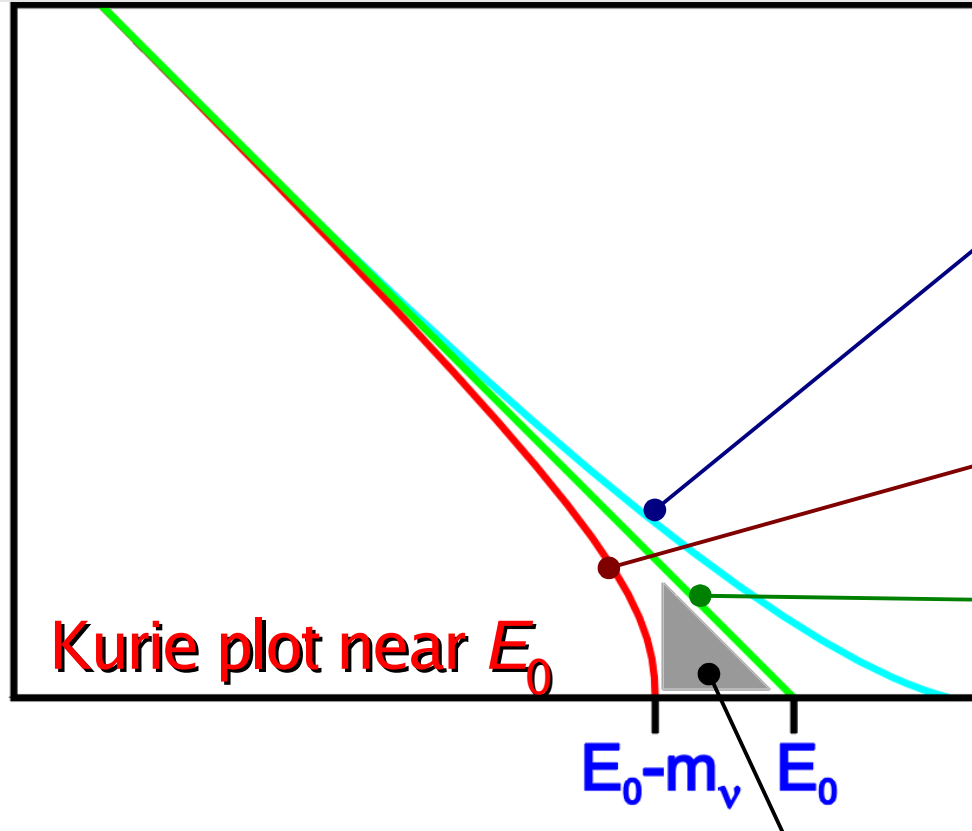
Limite attuale: $m_{ee} < \sim 0.5 \text{ eV}$

Sensibilità futura: $m_{ee} < \sim 0.05 \text{ eV}$

COMPLEMENTARY MEASUREMENTS

Misura cinematica

$$\sqrt{\frac{N(E)}{pEF(E)S(E)}}$$



effect of:

- detector energy resolution
- background counts
- β decays to excited states

effect of $m_\nu \neq 0$

$$N(E_\beta, m_{\bar{\nu}_e} = 0)$$

fraction F of decays below the end-point

$$F(\delta E) = \int_{E_0 - \delta E}^{E_0} N(E_\beta, m_{\bar{\nu}_e} = 0) dE$$

$$\approx 2 \left(\frac{\delta E}{E_0} \right)^3$$

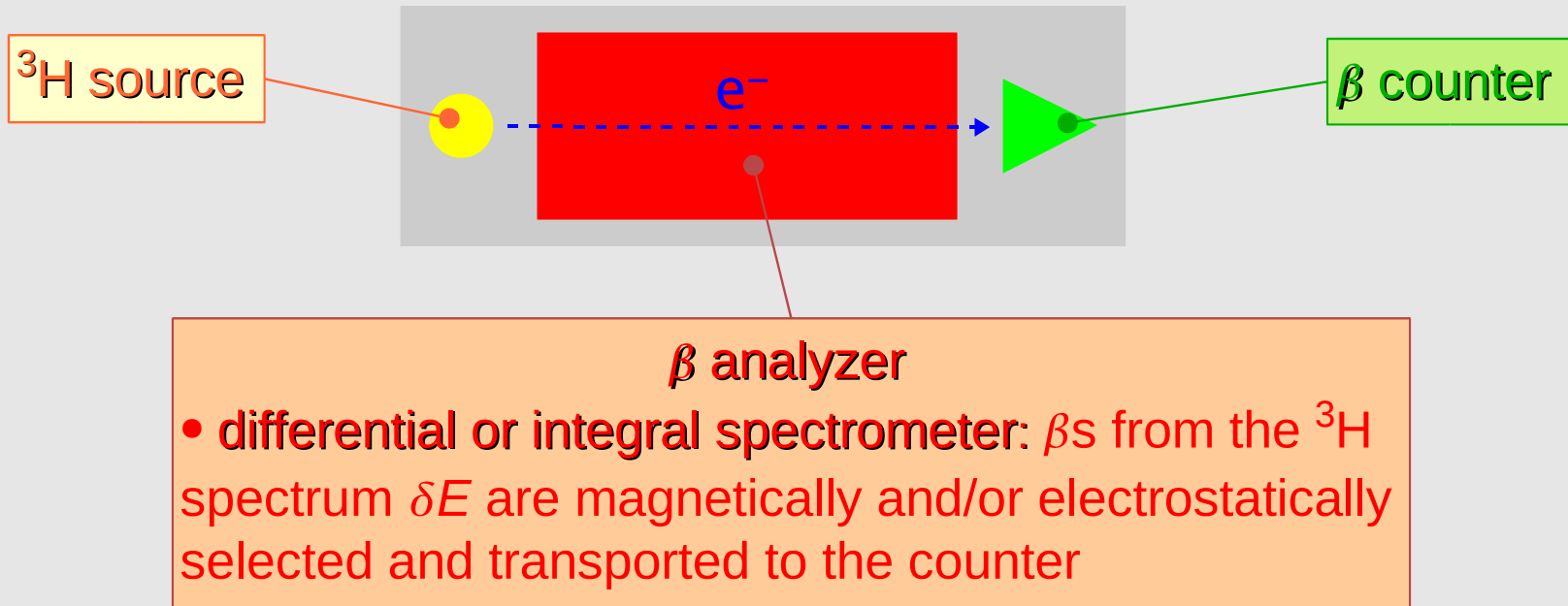
for ${}^3\text{H}$ β decay $F(10 \text{ eV}) \approx 3 \times 10^{-10}$

General experimental requirements

- ◆ high statistics at the β spectrum end-point
- ◆ high energy resolution ΔE
- ◆ high signal-to-background ratio at the end-point
- ◆ small systematic effects

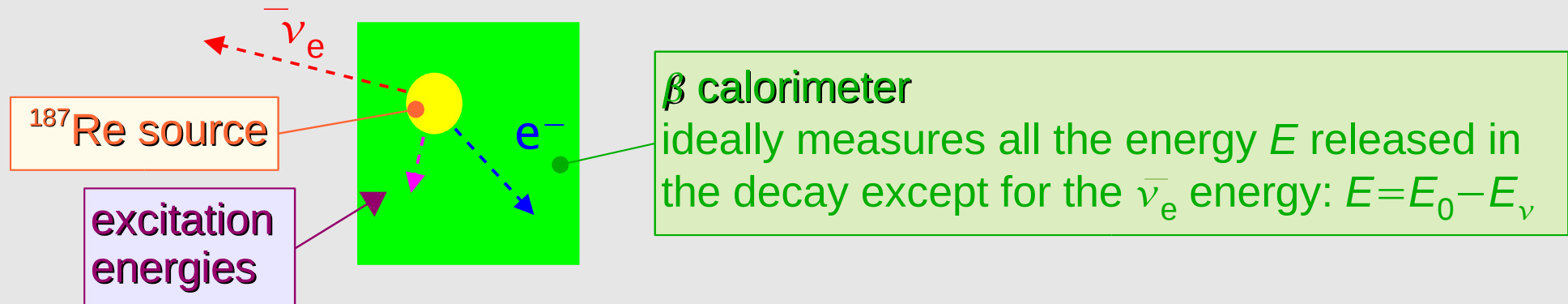
Approcci sperimentali alla misura diretta

- **Spectrometers: source $\neq$ detector**



Present best limit on m_ν : Mainz-Troitsk $\Rightarrow 2.2$ eV (95% C.L.)

- **Calorimeters: source $\subseteq$ detector**



Present best limit on m_ν : Mibeta $\Rightarrow 15$ eV (90% C.L.)

Spettrometria di sorgenti beta

Risultati dallo studio del decadimento beta del Trizio negli ultimi 20 anni

ITEP

T_2 in complex molecule
magn. spectrometer (Tret'yakov)

m_ν

17-40 eV

Los Alamos

gaseous T_2 - source
magn. spectrometer (Tret'yakov)

< 9.3 eV

Tokio

T - source
magn. spectrometer (Tret'yakov)

< 13.1 eV

Livermore

gaseous T_2 - source
magn. spectrometer (Tret'yakov)

< 7.0 eV

Zürich

T_2 - source impl. on carrier
magn. spectrometer (Tret'yakov)

< 11.7 eV

Troitsk (1994-today)

gaseous T_2 - source
electrostat. spectrometer

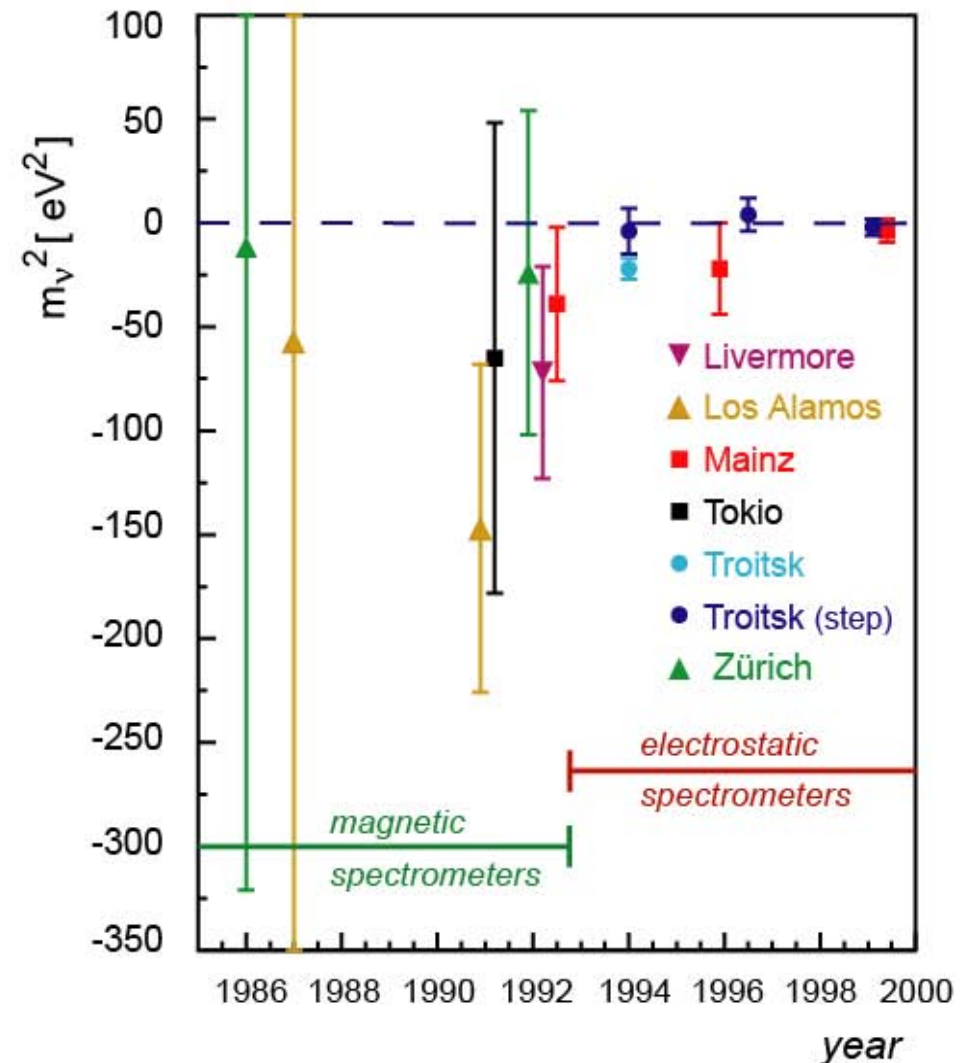
< 2.05 eV

Mainz (1994-today)

frozen T_2 - source
electrostat. spectrometer

< 2.3 eV

experimental results



Filtro elettrostatico con collimazione magnetica adiabatica

MAC-technique

adiabatic guiding of β -particles along the magnetic field lines

inhomogen. B-Feld:
stray field of 2 super-
conducting magnets

$B_{\max} = 3 - 6 \text{ T}$

$B_{\min} < 1 \text{ mT}$

very large solid angle !

$$\Delta\Omega \sim 2\pi$$

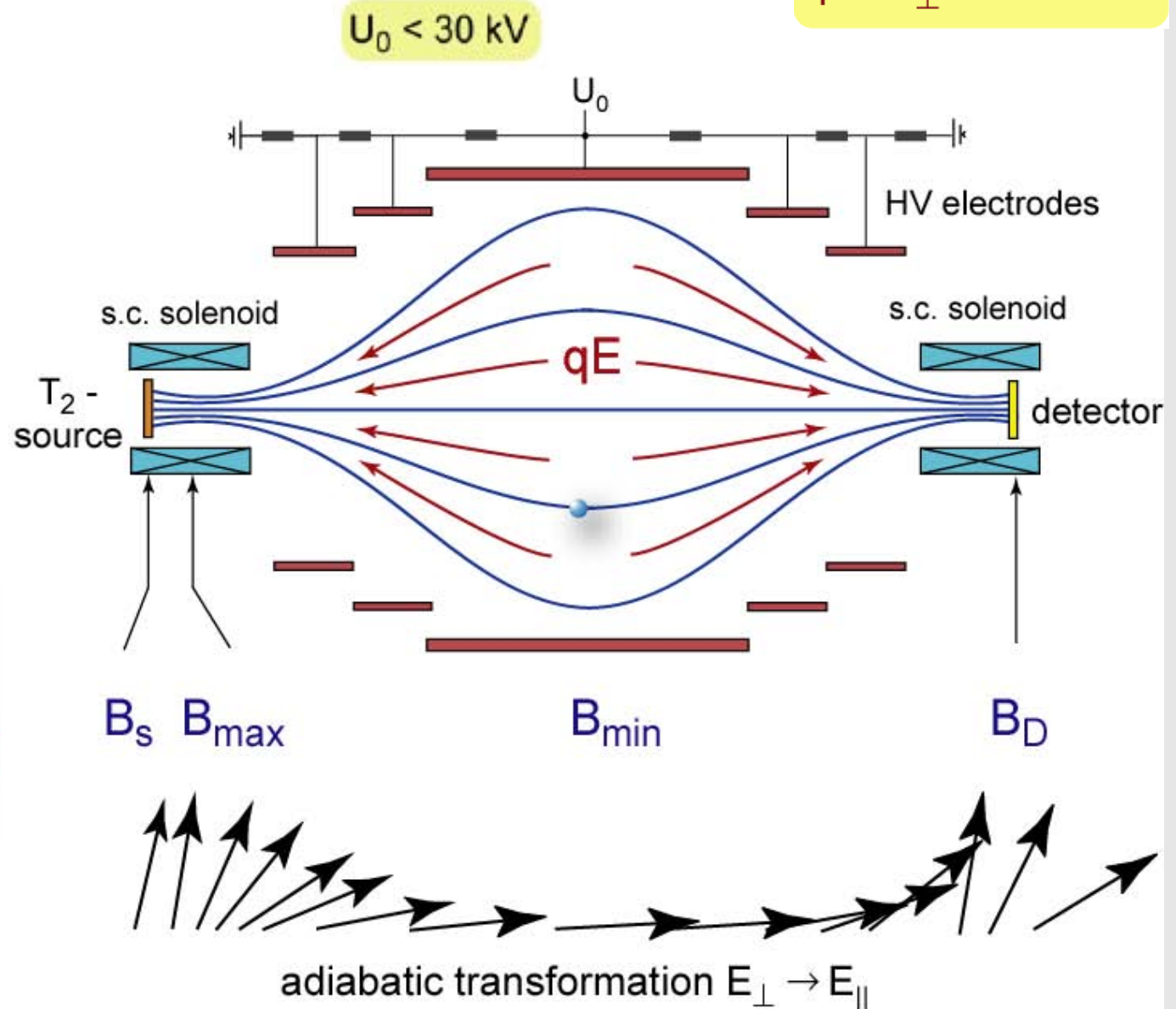
E-technique

energy analysis by
electro static retarding
field (electrodes)

integral particle
transmission $E > U_0$

high pass filter !

$$\vec{F} = (\vec{\mu} \cdot \vec{\nabla}) \vec{B} + q \vec{E}$$
$$\mu = E_{\perp} / B = \text{const}$$



Gli spettrometri più sensibili: Mainz & Troitzsk

Mainz & Troitsk have reached their intrinsic limit of sensitivity



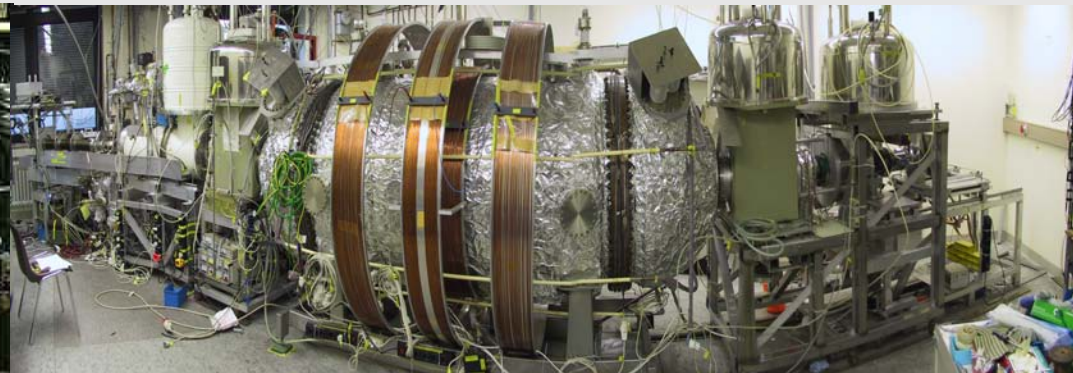
Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

$$m_{\nu}^2 = -2.3 \pm 2.5 \pm 2.0 \text{ eV}^2$$

$$m_{\nu} \leq 2.2 \text{ eV (95\% CL.)}$$



Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

$$m_{\nu}^2 = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2$$

$$m_{\nu} \leq 2.2 \text{ eV (95\% CL.)}$$

both experiments now used for systematic investigations

Calorimetria di sorgenti beta

Calorimeters measure the entire spectrum at once

➤ use low E_0 β decaying isotopes to achieve enough statistics close to E_0

➤ best choice ^{187}Re :



($5/2^+ \rightarrow 1/2^-$ first-forbidden unique)

$E_0 = 2.47 \text{ keV} \Rightarrow$

$$F(\delta E = 10 \text{ eV}) \sim 1.3 \times 10^{-7}$$

natural isotopic abundance: **63%**

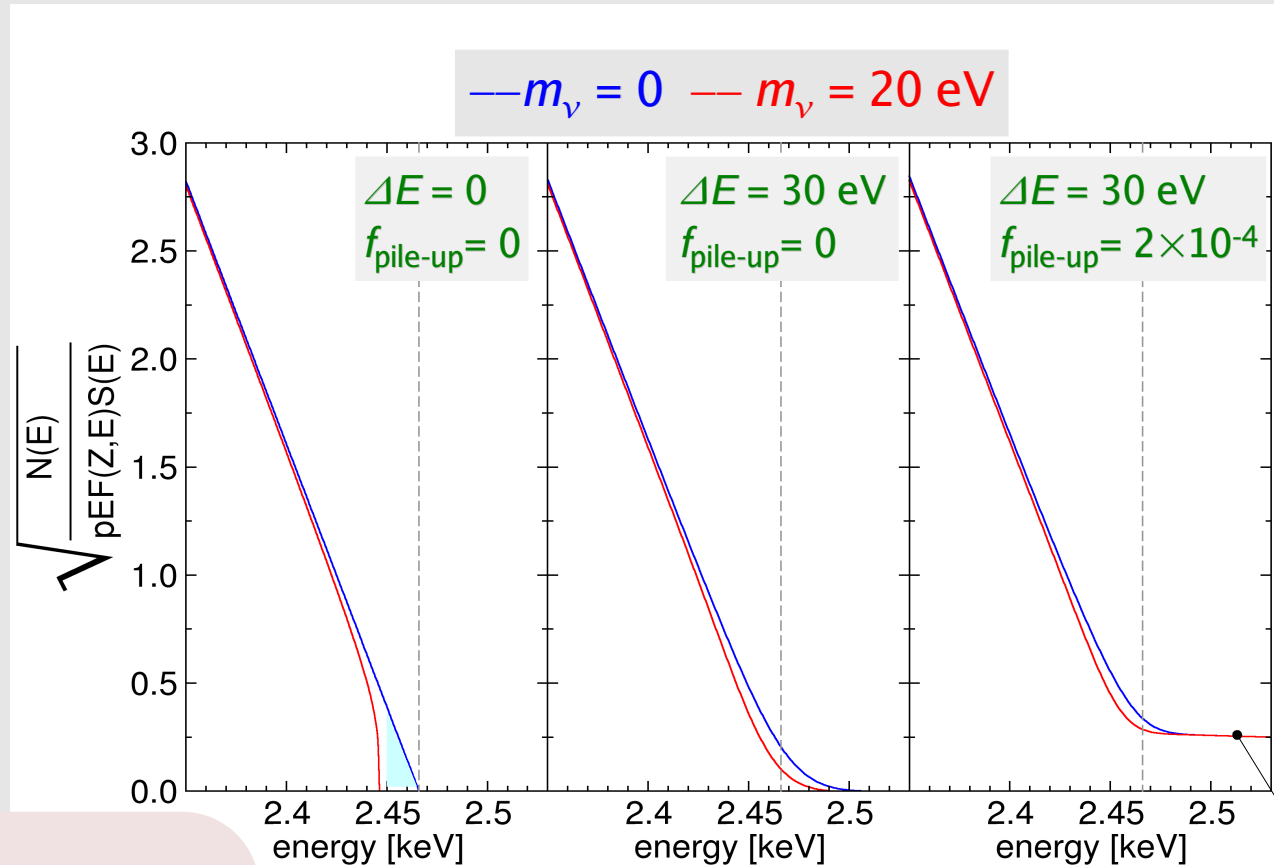
half-life time $\tau_{1/2} = 43.2 \text{ Gy}$

Pile-up

- ◆ time unresolved superposition of β decays
- ◆ for a source activity A_β , a time resolution τ_R and an energy resolution function $R(E_\beta)$

$$N^{\text{exp}}(E_\beta) \approx (N(E_\beta) + \tau_R A_\beta \cdot N(E_\beta) \otimes N(E_\beta)) \otimes R(E_\beta)$$

$\Rightarrow$ generates “background” at the end-point



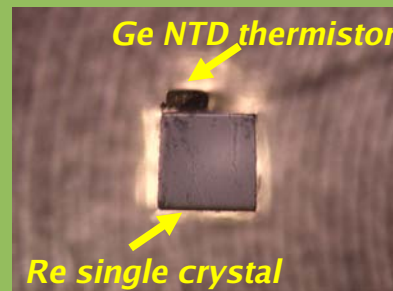
$$\text{pile-up fraction: } f_{\text{pile-up}} = \tau_R A_\beta$$

Stato dell'arte delle misure calorimetriche

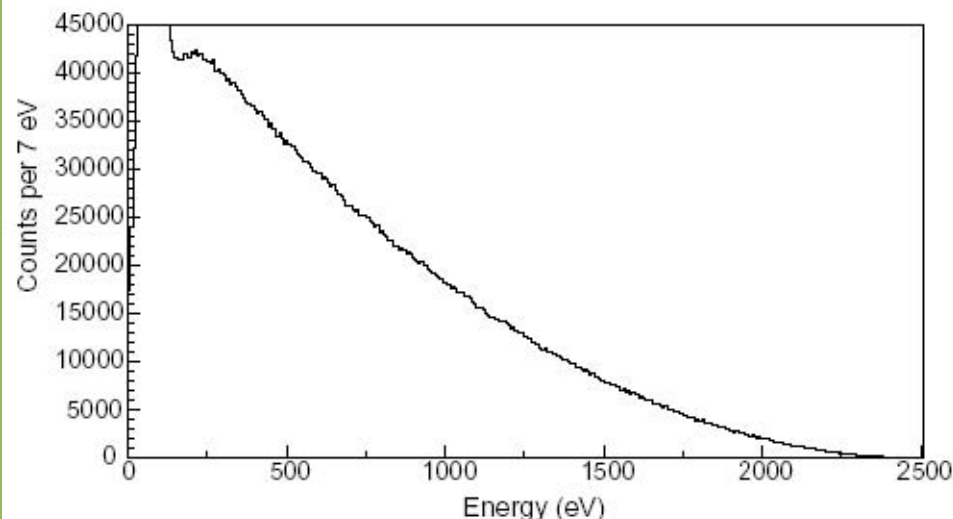
MANU (1999)

Genova

- 1 crystal of metallic Re: 1.6 mg
- ^{187}Re activity ≈ 1.6 Hz
- Ge-NTD thermistor
- $\Delta E = 96$ eV FWHM
- 0.5 years live-time
- $m_\nu^2 = -462^{+579}_{-679} \text{ eV}^2$
- $m_\nu < 19 \text{ eV}$ (90 % C.L.)



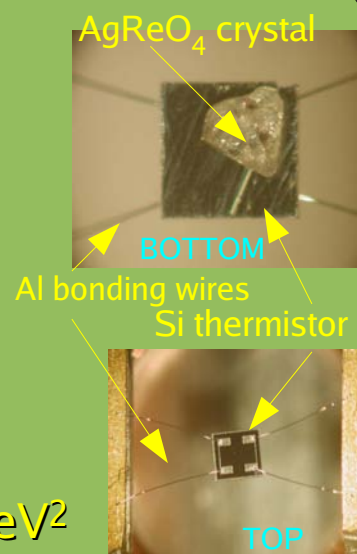
6.0×10^6 ^{187}Re decays above 420 eV



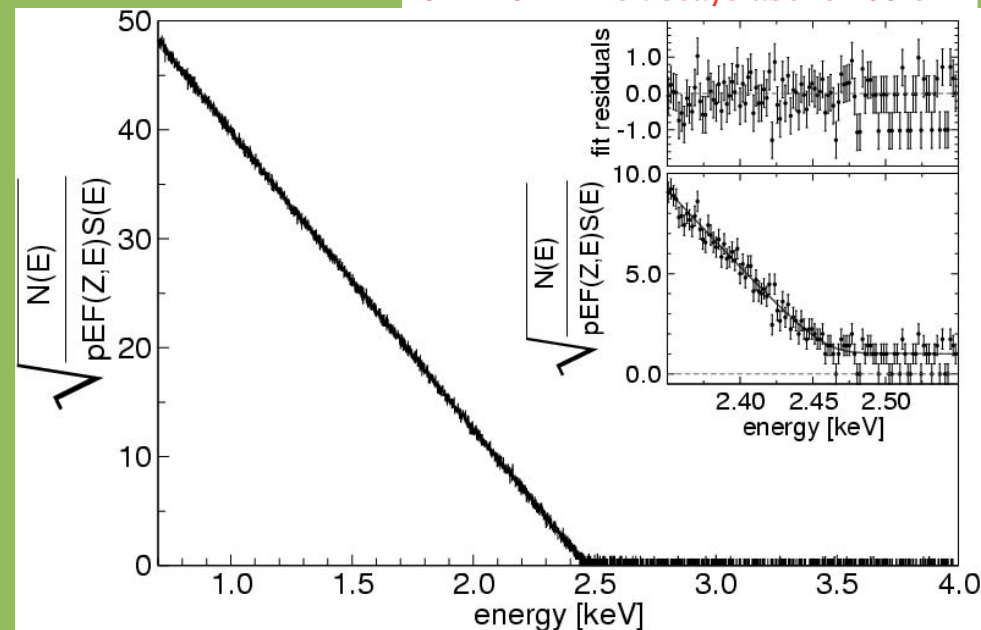
MIBETA (2002-2003)

Milano, Como, Trento

- 10 AgReO_4 crystals: 2.71 mg
- ^{187}Re activity = 0.54 Hz/mg
- Si thermistors (ITC-irst)
- $\Delta E = 28.5$ eV FWHM
- 0.6 years live time
- $m_\nu^2 = -112 \pm 207_{\text{stat}} \pm 90_{\text{sys}} \text{ eV}^2$
- $m_\nu < 15 \text{ eV}$ (90 % C.L.)



6.2×10^6 ^{187}Re decays above 700 eV



Spettrometri e calorimetri a confronto

Spectrometers

◆ Choice of β -emitter: ^3H

- $E_0 = 18.6 \text{ keV}$
- $\tau_{1/2} = 12.3 \text{ y}$

◆ Advantages

- ▲ high statistics
- ▲ high energy resolution

◆ Drawbacks

- ▼ systematics due to source effects
- ▼ systematics due to decays to excited states
- ▼ background

Calorimeters

◆ Choice of β -emitter: ^{187}Re

- $E_0 = 2.5 \text{ keV}$
- $\tau_{1/2} = 43.2 \text{ Gy}$

◆ Advantages

- ▲ measure neutrino energy
- ▲ no backscattering/self-absorption
- ▲ no excited final state effects
- ▲ no solid state excitation

◆ Drawbacks

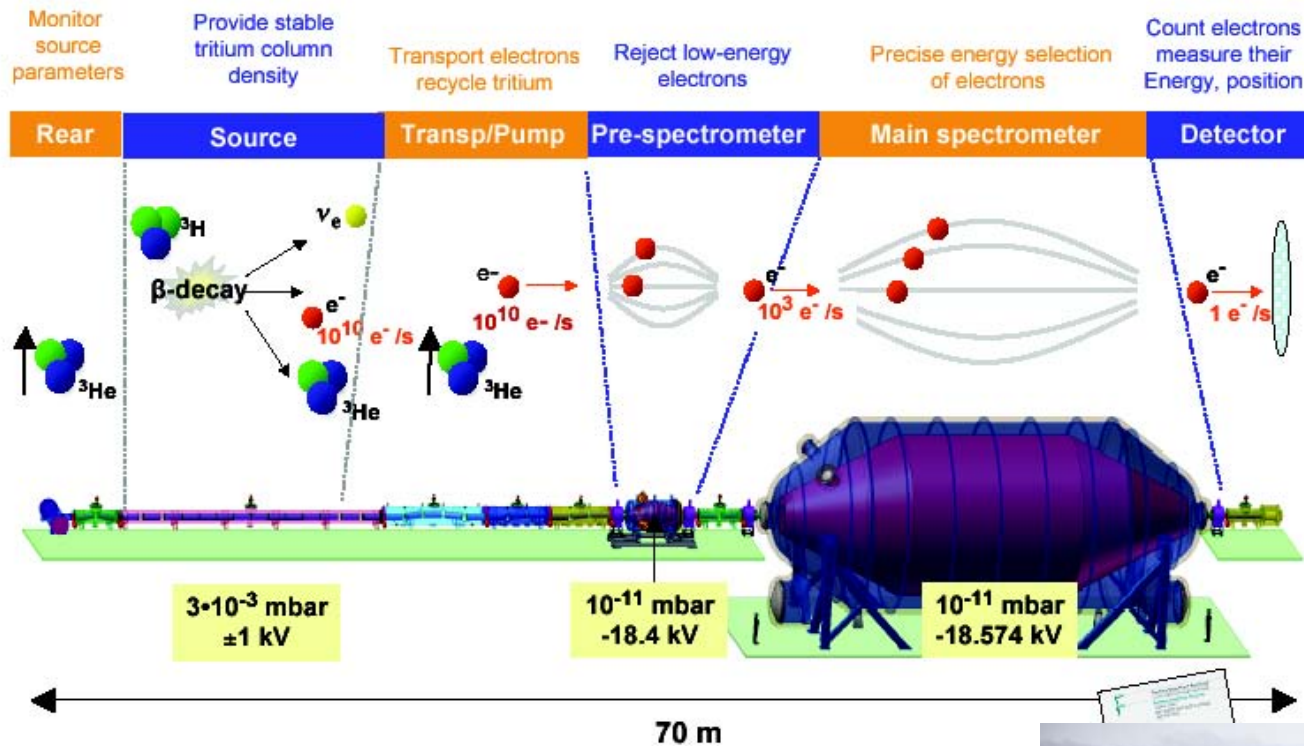
- ▼ limited statistics
- ▼ systematics due to pile-up
- ▼ energy dependent background

*Future planned sensitivity:
KATRIN $\rightarrow 0.2 \text{ eV}$*

*Future planned sensitivity:
MARE $\rightarrow 0.2 \text{ eV}$*

Complementary techniques – Different systematics

Il futuro delle misure con spettrometri: KATRIN



Karlsruhe Tritium Neutrino Experiment



Physics goal:
one order of magnitude
improvement in m_ν

Limit m_ν 2.2 eV $\rightarrow$ 0.2 eV

Start of data taking in 2010 ...

Main components and function $\rightarrow$ Design report 2005, FZK Report 7
<http://www-ik.fzk.de/%7Ekatrin/>

Improve Statistics

- stronger source (factor ~ 80)
- longer measuring period (factor ~ 10)

Improve energy resolution

- $\Delta E \approx 0.93 \text{ eV}$ (factor of 4 improvement)
- Requires larger spectrometer

Reduce systematic errors

- better control of systematics
- energy losses (factor ~ 10)



Il futuro delle misure con calorimetri: MARE

Microcalorimeter Arrays for a Rhenium Experiment

Goal: a sub-eV direct neutrino mass measurement complementary to KATRIN

MARE is divided in two phases:

MARE-1

(2006-2009)

new experiments with large arrays using available technology and ready to start immediately (2007)

2÷4 eV m_ν sensitivity
before KATRIN

MARE-2

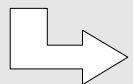
(2010-2015?)

very large experiment with a m_ν statistical sensitivity close to KATRIN but still improvable: 5 years from now for further detector R&D

0.2 eV m_ν sensitivity

phase I is needed:

- because it's the only possible one with present technology
- to investigate systematics in thermal calorimeters



very important to cross-check spectrometer results

Le collaborazioni

KATRIN

FZK (GER)
Universität Mainz (GER)
INR Troitzk (RUS)
University of Washington (USA)
MIT (USA)
University of Wales (UK)
CCLRC Daresbury (UK)
University College London (UK)
NPI (CZK)
Fachhochschule Fulda (GER)
Universität Karlsruhe (GER)
Universität Münster (GER)
Universität Bonn (GER)
JINR (RUS)

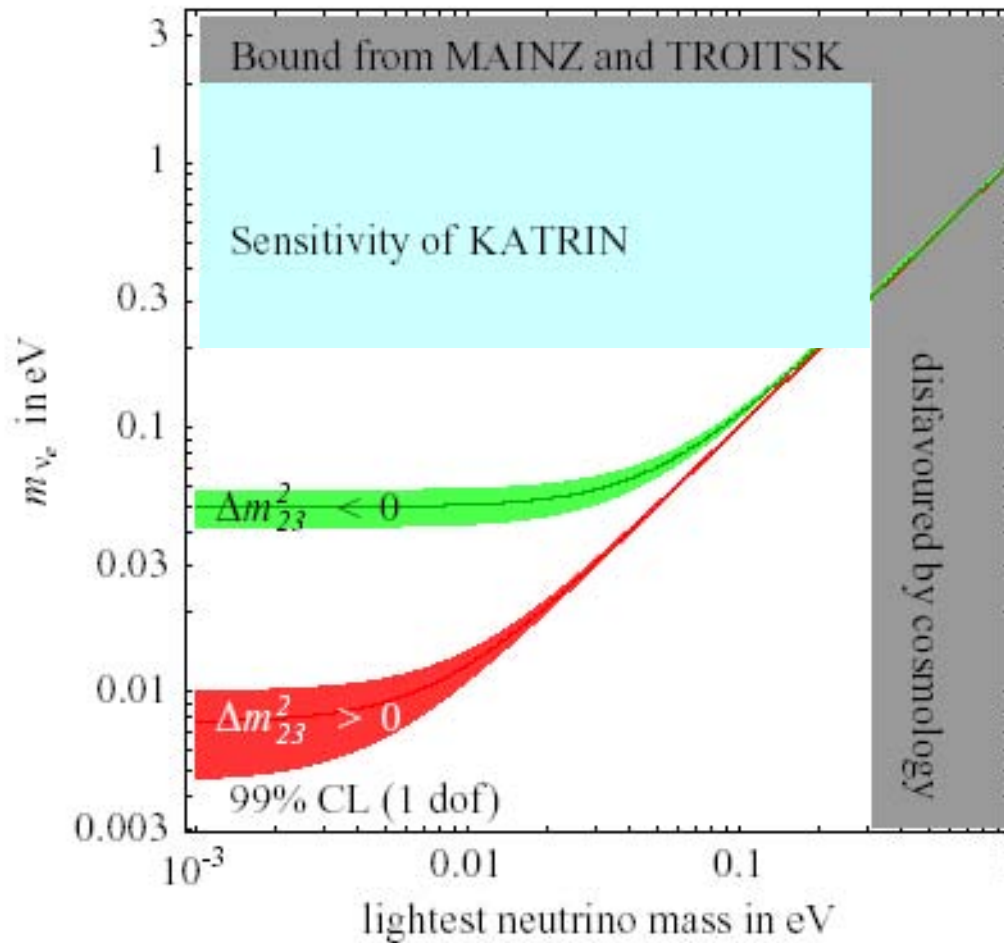


MARE

Università and INFN Genova (IT)
Goddard Space Flight Center (USA)
Universität Heidelberg (GER)
Università dell'Insubria (IT)
Università and INFN Milano-Bicocca (IT)
NIST (USA)
ITC-irst, Trento, and INFN-Padova (IT)
Phys.-Tech. Bundesanstalt (GER)
University of Miami (USA)
Università "La Sapienza" and INFN-Roma1 (IT)
SISSA, Trieste (IT)
University of Wisconsin (USA)



Sensibilità di KATRIN



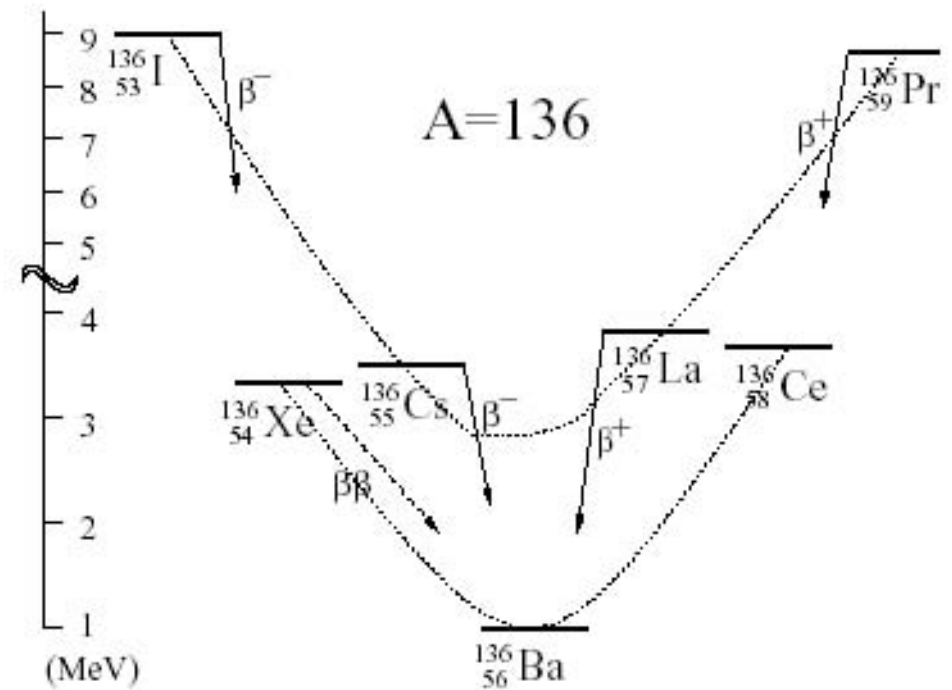
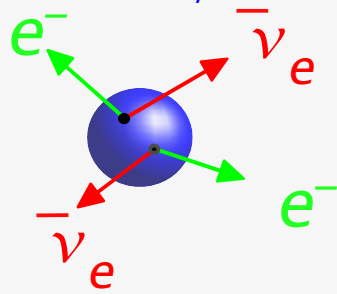
Strumia A. and Vissani F. - hep-ph/0503246

Il decadimento doppio beta

processo debole del secondo ordine
per nuclei pari-pari
con numero di massa A pari

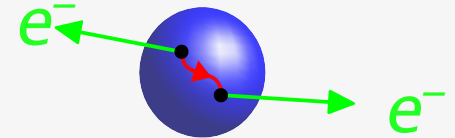
$\beta\beta-2\nu$: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$

- permesso nel Modello Standard
- osservato con $\tau_{1/2} > 10^{19}$ anni

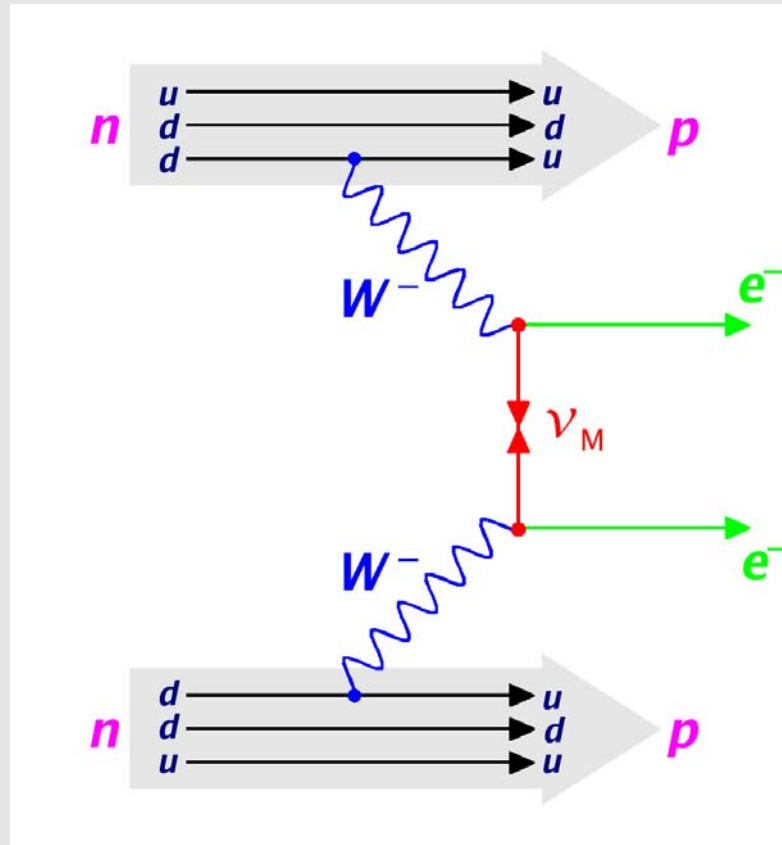


$\beta\beta-0\nu$: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

- non permesso nel Modello Standard ($\Delta L=2$)
- atteso con $\tau_{1/2} > 10^{25}$ anni
- attualmente: una evidenza sperimentale molto criticata



Il decadimento doppio beta 0ν



- 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 $\Rightarrow \Delta L=2$

$$\beta\beta-0\nu \Leftrightarrow \begin{cases} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{cases}$$

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

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

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

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*

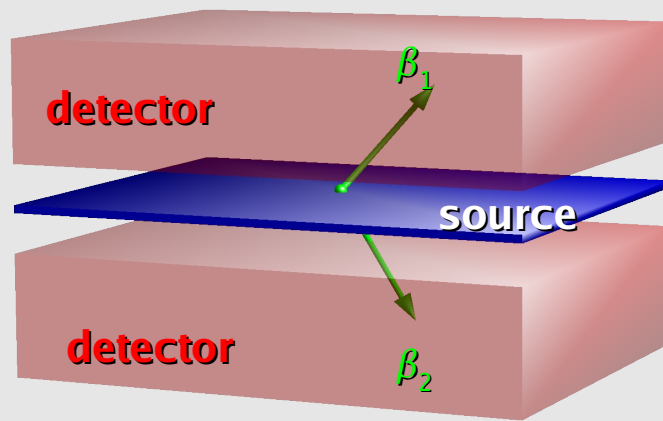
neutrino mixing matrix



- theoretically evaluated (shell model, QRPA models, ...)
- different results according to the nuclear model used
- important to extract from the measured (limit) lifetime the value of $\langle m_\nu \rangle$

↳ great uncertainties in the results!

Approcci sperimentali al $\beta\beta 0\nu$

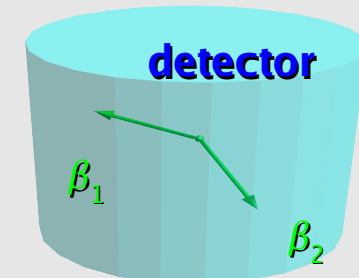
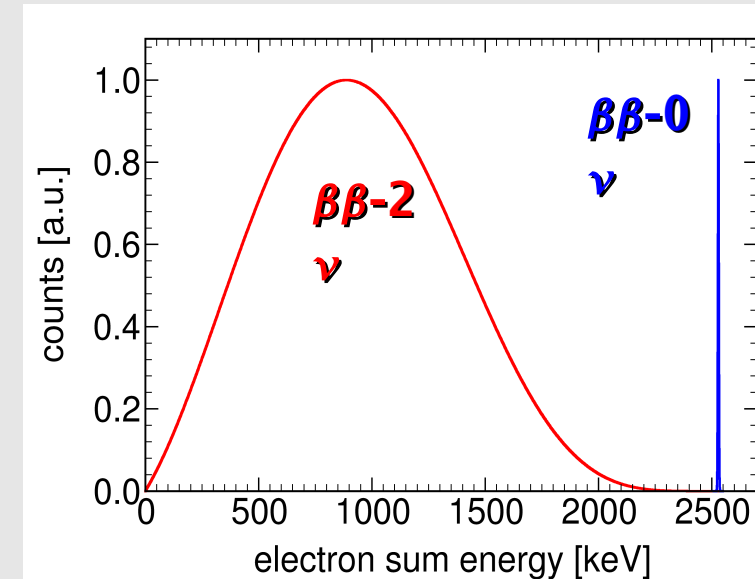


Source $\neq$ detector

- 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 $\subseteq$ detector (calorimetry)

- detector measures sum energy $E = E_{\beta_1} + E_{\beta_2}$
 - $\beta\beta 0\nu$ 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 $\beta\beta 0\nu$ and $\beta\beta 2\nu$

Sensibilità sperimentale

Sensibilità: vita di dimezzamento corrispondente al numero minimo di eventi rivelabili sopra il fondo per un determinato C.L.

Sensibilità su $\tau_{1/2}^{0\nu}$

efficienza del rivelatore

massa del rivelatore [kg]

durata della misura [y]

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

abbondanza isotopica
numero atomico

risoluzione energetica [keV]

fondo radioattivo [c/keV/y/kg]

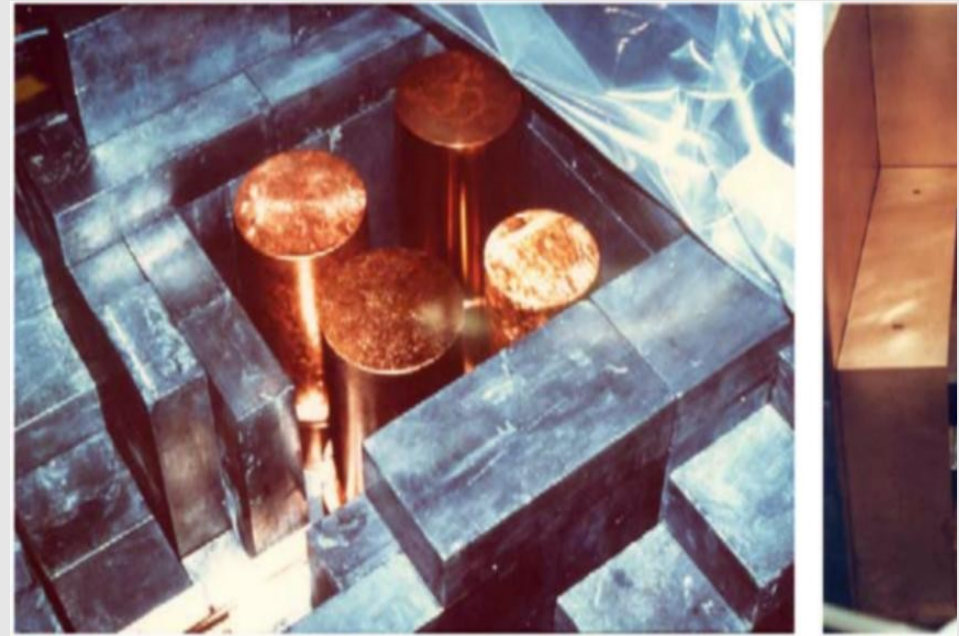
$$m_\nu \propto \sqrt{1/\tau_{1/2}^{0\nu}}$$

Situazione sperimentale attuale

Nucleus	Experiment	i.a.	$Q_{\beta\beta}$	Enr	Technique	$T_{1/20\nu}$ (y	$\langle m_\nu \rangle$ (eV)
^{48}Ca	Elegant IV	0.19	4271		scintillator	$>1.8 \times 10^{22}$	7-45
^{76}Ge	Heidelberg-Moscow	7.8	2039	87	ionization	$>1.9 \times 10^{25}$	0.1 - 0.9
^{76}Ge	IGEX	7.8	2039	87	Ionization	$>1.6 \times 10^{25}$	0.14-1.2
^{76}Ge	Klapdor et al	7.8	2039	87	ionization	1.2×10^{25}	0.44
^{82}Se	NEMO 3	9.2	2995	97	tracking	$>1.2 \times 10^{23}$	1.8-4.9
^{100}Mo	NEMO 3	9.6	3034	95-99	tracking	$>5.8 \times 10^{23}$	.7-2.8
^{116}Cd	Solotvina	7.5	3034	83	scintillator	$>1.7 \times 10^{23}$	1.7 - ?
^{128}Te	Bernatovitz	34	2529		geochem	$>7.7 \times 10^{24}$	1.0 - 4.4
^{130}Te	Cuoricino	33.8	2529		bolometric	$>3 \times 10^{24}$	0.2 - 0.8
^{136}Xe	DAMA	8.9	2476	69	scintillator	$>1.2 \times 10^{24}$	1.1 -2.9
^{150}Nd	Irvine	5.6	3367	91	tracking	$>1.2 \times 10^{21}$	3 - ?

⁷⁶Ge: esperimento Heidelberg-Moscow

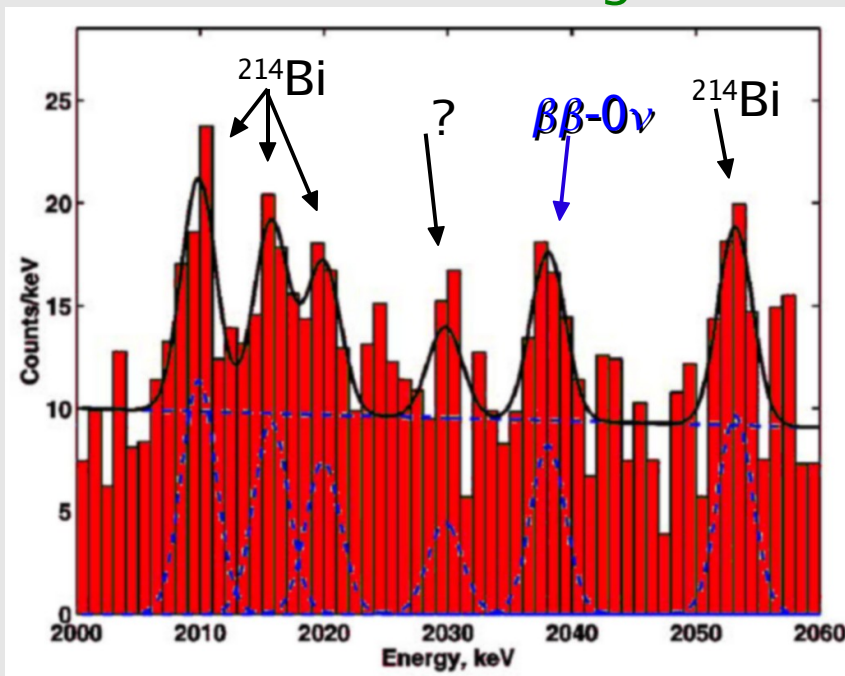
- calorimetric experiment with Ge semiconductor detectors
- 5 HP-Ge crystals, enriched to 87% in ⁷⁶Ge
 - ▶ total active mass of 10.96 kg $\Rightarrow$ 125.5 moles of ⁷⁶Ge
- run from 1990 to 2003 in Gran Sasso Underground Laboratory
- total exposure 71.7 kg $\times$ y
 - ▶ 820 moles $\times$ y
- main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



- PSD since end of 1995 for 4 detectors (51.4 kg $\times$ 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 β s are SSE

^{76}Ge HM: evidenza sperimentale di $\beta\beta 0\nu$

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



1990 – 2003 data, all 5 detectors

exposure = 71.7 kg×y

$$\tau_{1/2}^{0\nu} = 1.2 \times 10^{25} \text{ years}$$

$$\langle m_{\nu} \rangle = 0.44 \text{ eV}$$

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

Risultato controverso:

- Numero di conteggi esiguo
- Sistema automatico di riconoscimento delle righe
- Significatività statistica fortemente dipendente dalla stima del fondo
 - ↳ valutato in una finestra troppo stretta
- Interpretazione: accordo marginale - picchi non completamente spiegati

Tuttavia:

necessità di verifica
da parte degli
esperimenti futuri!

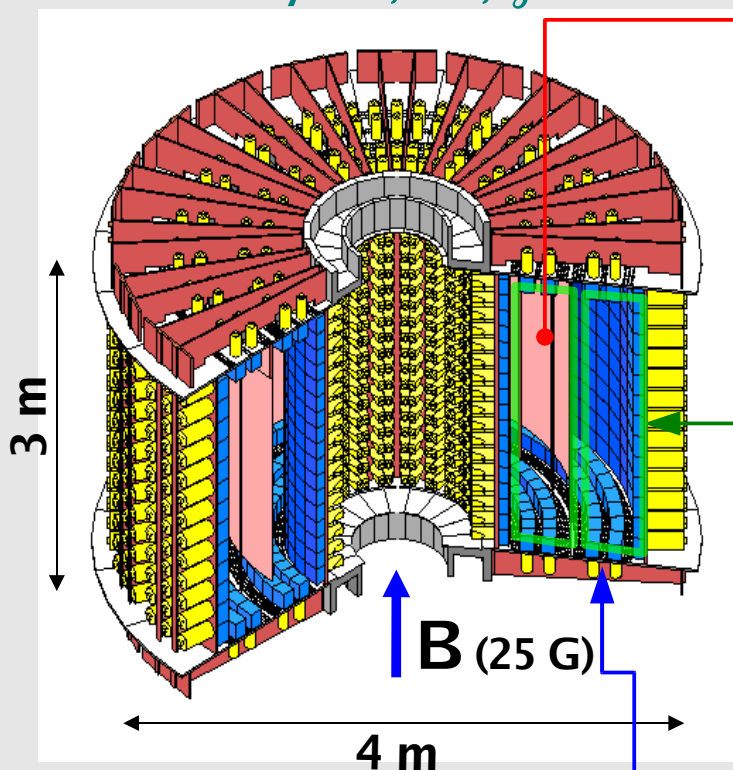
^{100}Mo e ^{82}Se : NEMO-3

■ Tracking detector for $\beta\beta\text{-}2\nu$ and $\beta\beta\text{-}0\nu$ @ Frejus

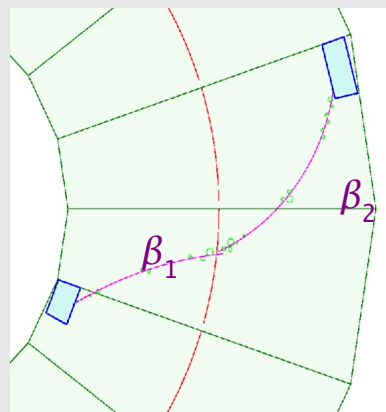
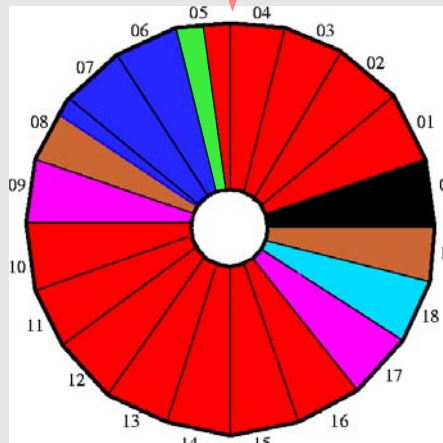
- ▶ 10 kg of enriched material in foils
- ▶ 6180 Geiger cells $\Rightarrow$ drift wire chamber
- ▶ 1940 plastic scintillators + PMTs

■ iron (γ) + water with B (n) shielding

■ can identify e^- , e^+ , γ and α



sources in foils



$\beta\beta\text{0}\nu$ measurement

^{100}Mo 6.914 kg

$Q_{\beta\beta} = 3034$ keV

^{82}Se 0.932 kg

$Q_{\beta\beta} = 2995$ keV

^{100}Mo purified at INL (USA) and ITEP (Russia)

$\beta\beta\text{2}\nu$ measurement

^{116}Cd 405 g

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

^{96}Zr 9.4 g

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

^{150}Nd 37.0 g

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

^{48}Ca 7.0 g

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

^{130}Te 454 g

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

natTe 491 g

Cu 621 g

External bkg measurement

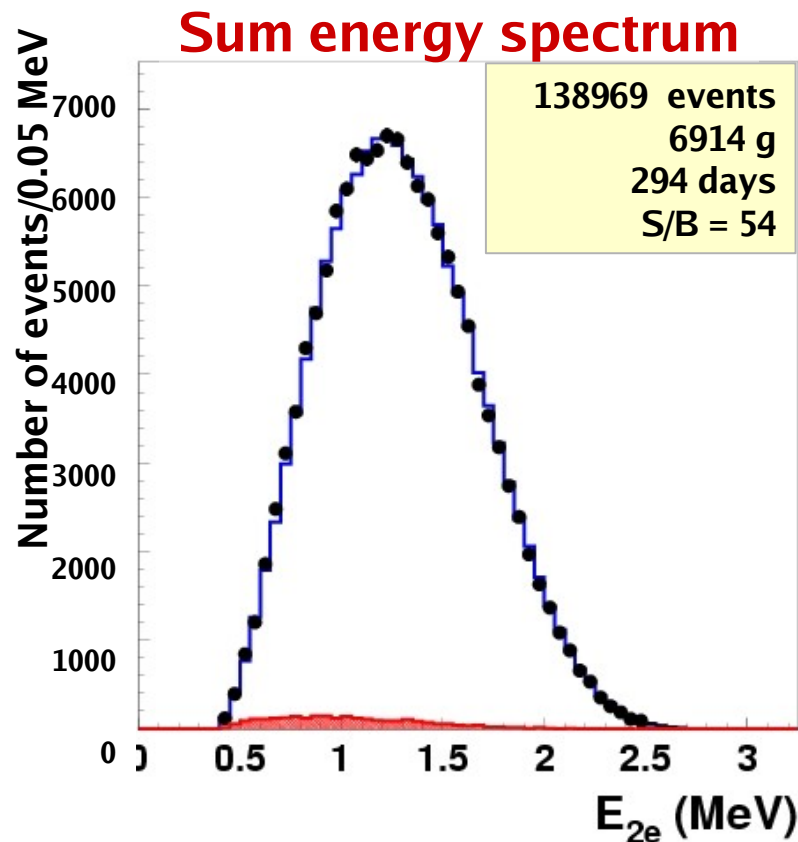
(Enriched isotopes produced in Russia)

calorimeter (scintillators)

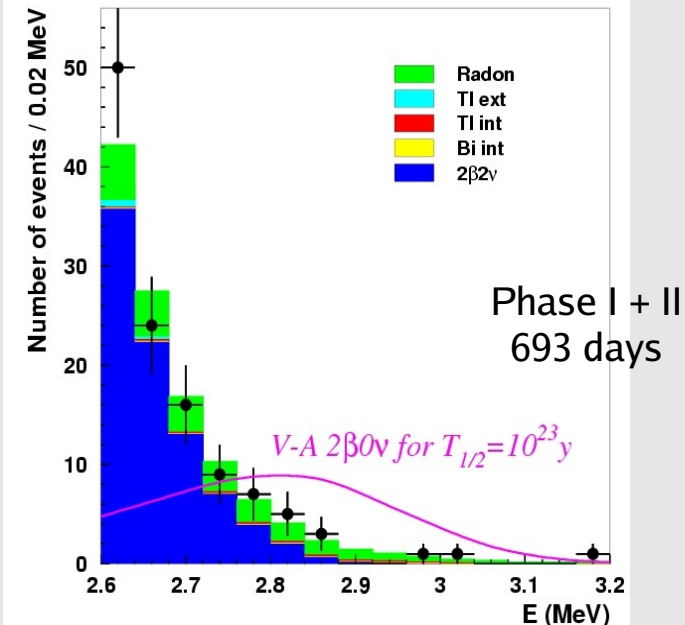
tracking volume (drift wire chamber)

NEMO-3: risultati per ^{100}Mo e ^{82}Se

$$T_{1/2}(\beta\beta 2\nu) = 7.15 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ y}$$

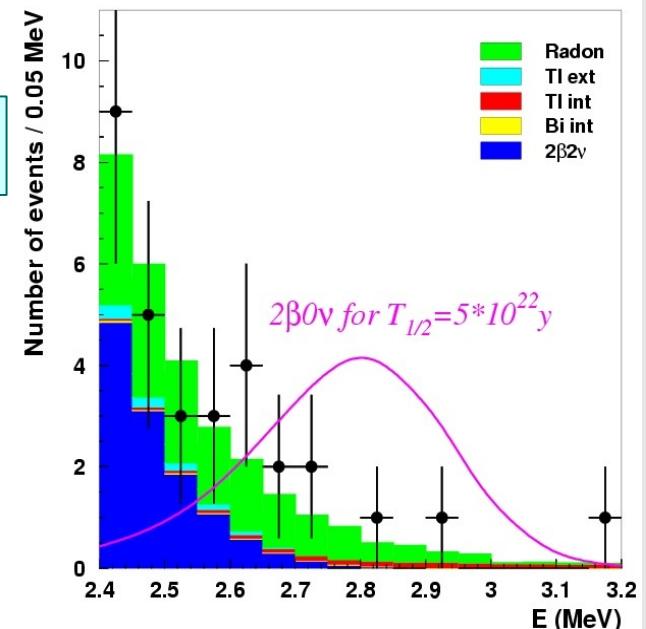


^{100}Mo , 7 kg



$$T_{1/2}(\beta\beta 0\nu) > 5.8 \cdot 10^{23} \text{ y (90 \% C.L.)}$$

^{82}Se , 1 kg



$$T_{1/2}(\beta\beta 0\nu) > 1.2 \cdot 10^{23} \text{ y (90 \% C.L.)}$$

Expected sensitivity End 2009:
 $^{100}\text{Mo } T_{1/2}(\beta\beta 0\nu) > 2 \cdot 10^{24} \text{ y (90\% C.L.)}$
 $^{82}\text{Se } T_{1/2}(\beta\beta 0\nu) > 8 \cdot 10^{23} \text{ y (90\% C.L.)}$

^{130}Te : esperimento Cuoricino

TeO_2 thermal calorimeters

■ Active isotope ^{130}Te

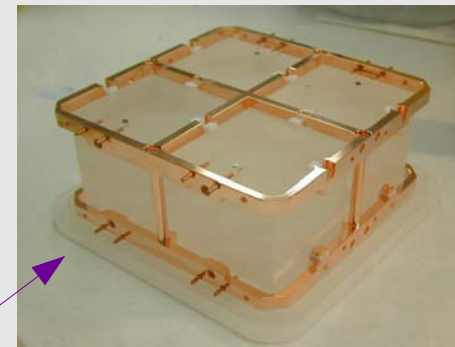
- ▲ natural abundance: a.i. = 33.9%
- ▲ transition energy: $Q_{\beta\beta} = 2529 \text{ keV}$
- ▲ “short” predicted half life
 $\langle m_\nu \rangle \approx 0.3 \text{ eV} \Leftrightarrow \tau_{1/2}^{0\nu} \approx 10^{25} \text{ years}$

■ Absorber material TeO_2

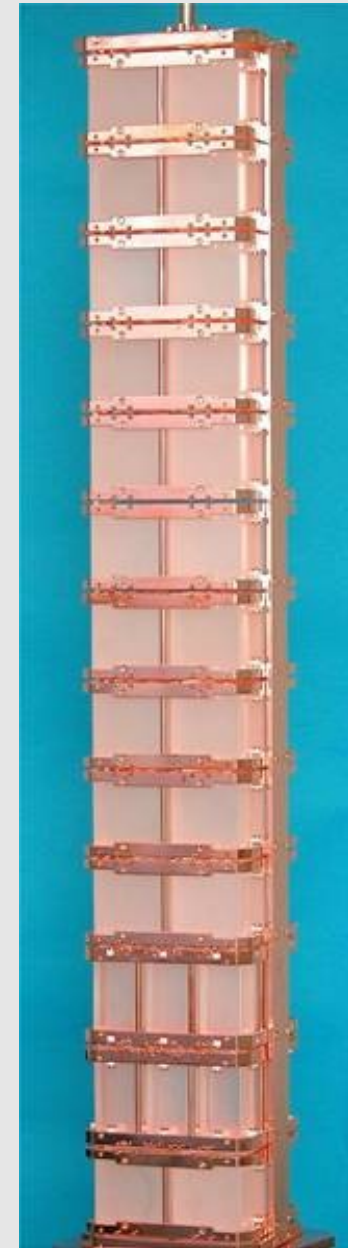
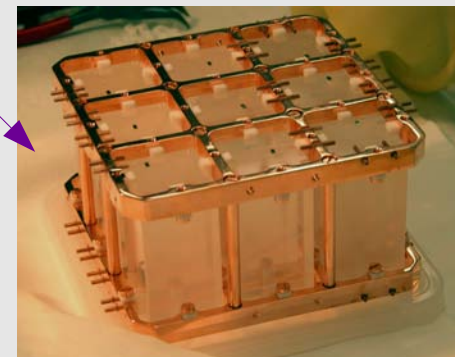
- ▲ low heat capacity
- ▲ large crystals available
- ▲ radiopure

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 40.7 kg
- ▶ intermediate size $\beta\beta$ experiment
- ▶ test for radioactivity

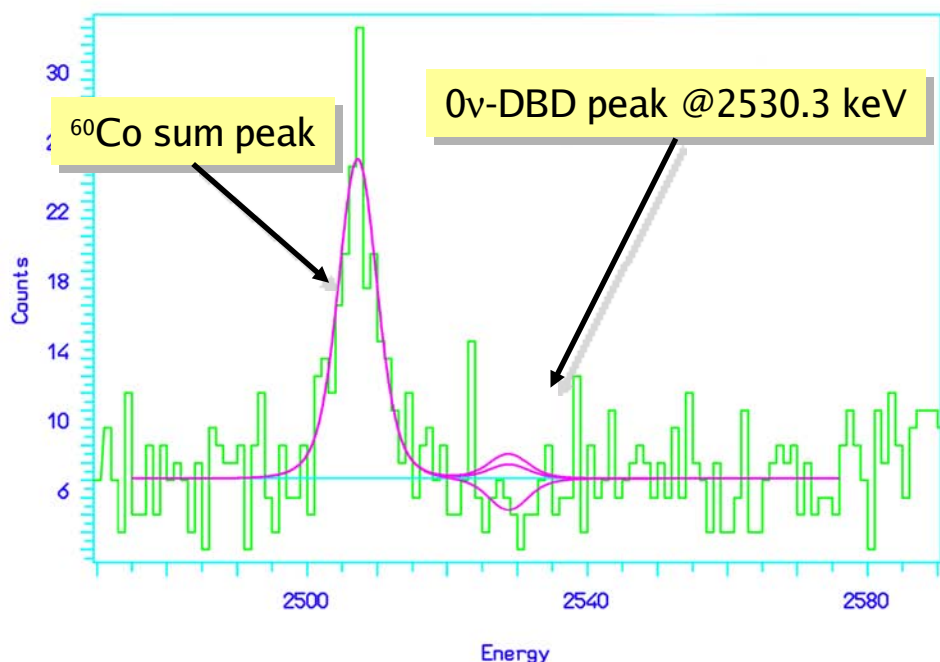


^{130}Te mass:
11 kg



Risultati di Cuoricino su $\beta\beta 0\nu$ del ^{130}Te

Anticoincidence background spectrum the $\beta\beta-0\nu$ region



Started in February 2003
long interruption for maintenance

$$\Delta E_{\text{FWHM}} \sim 8 \text{ keV @ } 2615 \text{ keV}$$

$$\text{Total statistic} \sim 11.8 \text{ kg } (^{130}\text{Te}) \times y$$

$$b = 0.18 \pm 0.01 \text{ c/keV/kg/y}$$

Maximum Likelihood
flat background + fit of 2505 peak

$$\tau_{1/2}^{0\nu} \geq 3.0 \cdot 10^{24} \text{ y (90\% CL)} \quad \Rightarrow \quad \langle m_\nu \rangle \leq 0.16 - 0.84 \text{ eV}^* \quad (90\% \text{ CL})$$

* Depending on the nuclear matrix element values

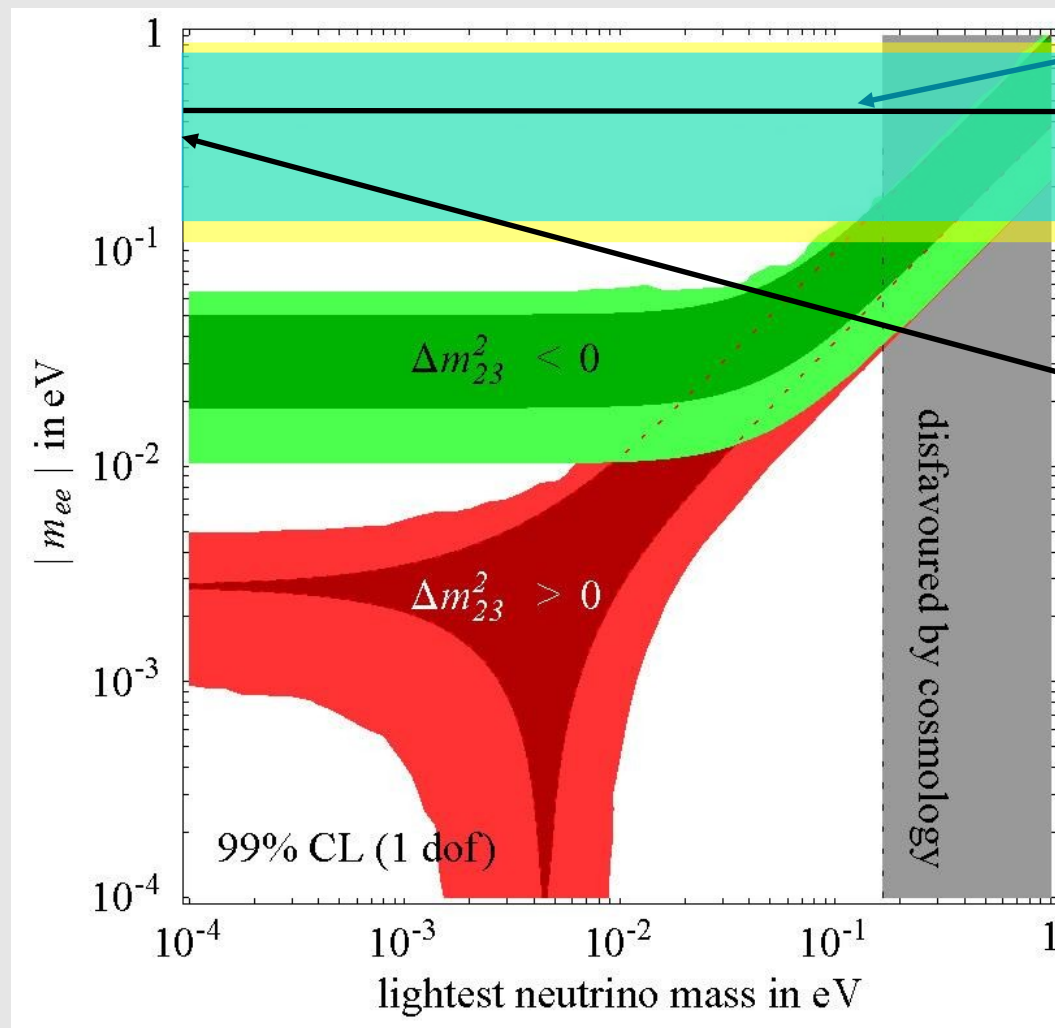
Cuoricino potentiality (on the way to CUORE):

in 3 years running time (60% bkg live time):

$$\tau_{1/2}^{0\nu\beta\beta} \sim 5 \cdot 10^{24} \text{ y @ 90C.L.}$$

$$\langle m_{ee} \rangle < 0.1 - 0.6 \text{ eV}$$

Il decadimento doppio beta e la massa del neutrino



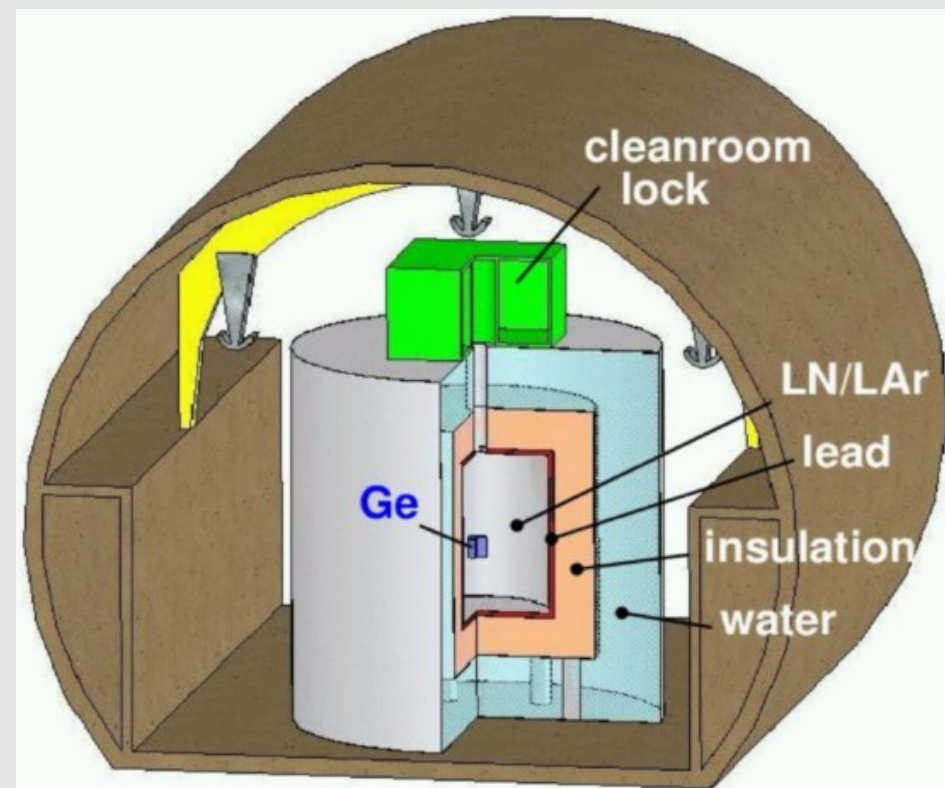
Strumia A. and Vissani F. - hep-ph/0606054

Il futuro del decadimento doppio beta

EXP.		i.a.	$Q_{\beta\beta}$	Enr	Bkg c/y	$T_{1/2\ 0\nu}$ (y)	Tech	$\langle m \rangle$ (meV)
CUORE	^{130}Te	34	2533	-	3.5	7×10^{26}	Bolometric	11-57
GERDA	^{76}Ge	7.8	2039	90	3.85	2×10^{27}	Ionization	29-94
Majorana	^{76}Ge	7.8	2039	90	.6	4×10^{27}	Ionization	21-67
GENIUS	^{76}Ge	7.8	2039	90	.4	1×10^{28}	Ionization	13-42
Supernemo	^{82}Se	8.7	2995	90	1	2×10^{26}	Tracking	54-167
EXO	^{136}Xe	8.9	2476	65	.55	1.3×10^{28}	Tracking	12-31
Moon-3	^{100}Mo	9.6	3034	85	3.8	1.7×10^{27}	Tracking	13-48
DCBA-2	^{150}Nd	5.6	3367	80		1×10^{26}	Tracking	16-22
Candles	^{48}Ca	.19	4271	-	.35	3×10^{27}	Scintillation	29-54
CARVEL	^{48}Ca	.19	4271	-		3×10^{27}	Scintillation	50-94
GSO	^{160}Gd	22	1730	-	200	1×10^{26}	Scintillation	65-?
COBRA	^{116}Cd	7.5	2805				Ionization	
SNOLAB+	^{150}Nd	5.6	3367				Scintillation	

^{76}Ge : GERDA

- goal: analyse 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
 - ▶ 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 phase experiment
- Phase I:
 - radioactivity tests
 - ≈ 15 kg ^{76}Ge from HM and Igex
 - expected bkg ≤ 0.01 c/keV/kg/y (intrinsic)
 - check at 5σ HM evidence
 - ▶ 15 kg $\chi \Rightarrow 6 \pm 1$ $\beta\beta$ events on 0.5 bkg events
- Phase II:
 - Add ≈ 20 kg new enriched segmented detectors with special care for activation
 - expected background ≈ 0.001 c/keV/kg/y
 - ▶ $\tau_{1/2} \geq 2 \times 10^{26}$ y with 100 kg χ
 - ▶ $\langle m_{\nu} \rangle \leq 0.09 \div 0.29$ eV
- Phase III: $\langle m_{\nu} \rangle \leq 0.01$ eV with 1 ton Ge
 - ▶ worldwide collaboration



Proposal: hep-ex/0404039

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

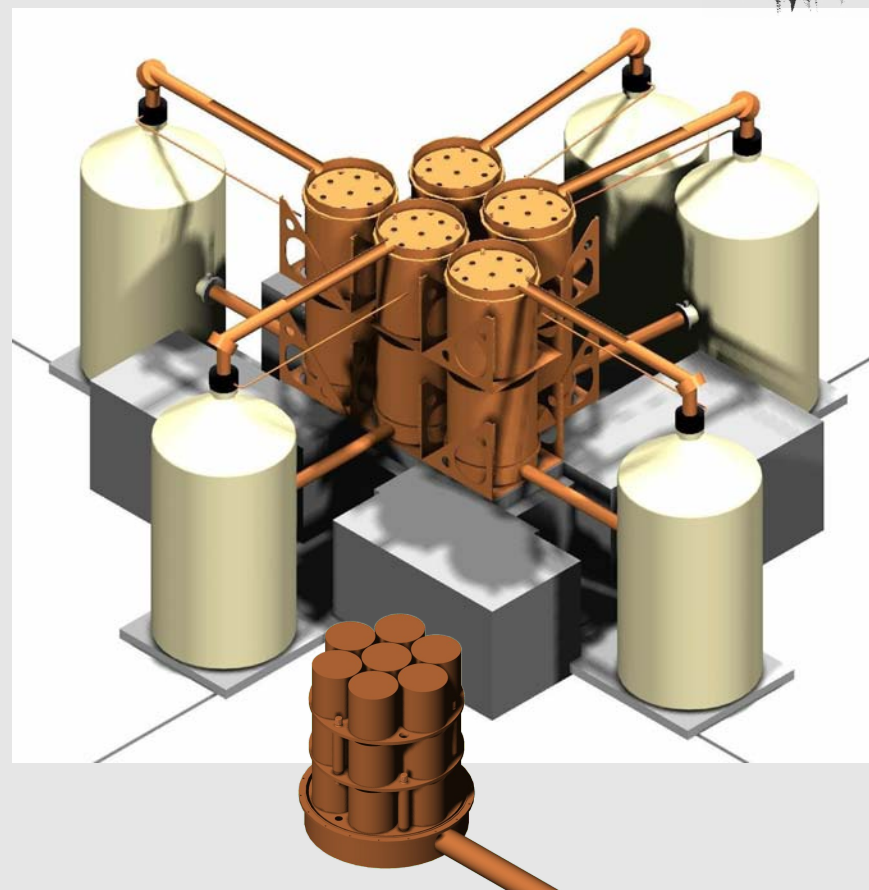
⁷⁶Ge: Majorana

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 ⁷⁶Ge
- 210 crystals in 10 cryostats
- 2 preliminary phases: SEGA and MEGA

FULL EXPERIMENT (in 9 years from start)

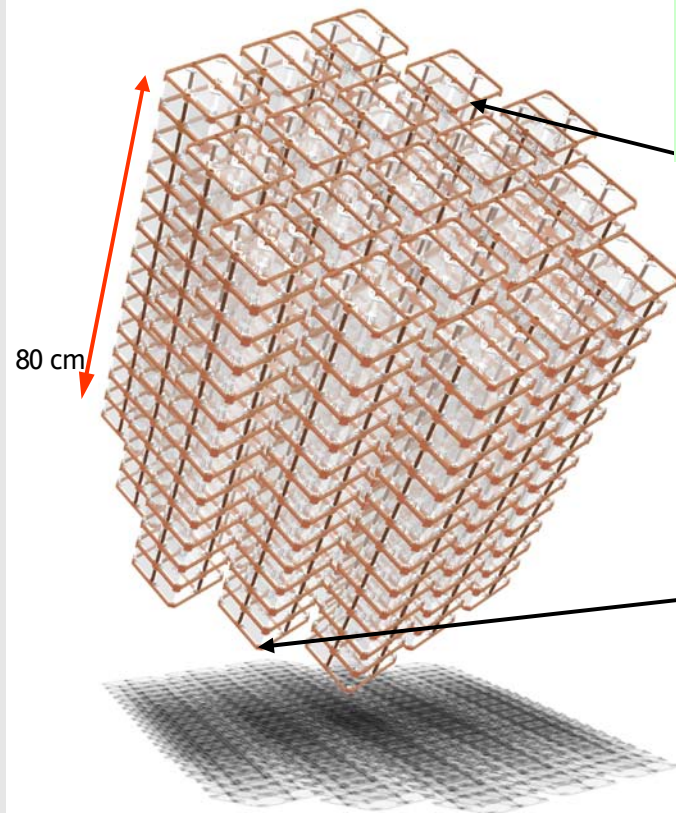
- expected bkg (without cuts) 17 c/keV/t/y
 - ▶ mainly from cosmogenics
 - ▶ bkg from Cu and close parts eliminated by screening in MEGA
- PSD and segmentation cuts $\Rightarrow$ 0.6 c/keV/t/y
 - ▶ $\tau_{1/2} \geq 10^{27}$ y in 5 years
 - ▶ $\langle m_\nu \rangle \leq 0.02 \div 0.07$ eV



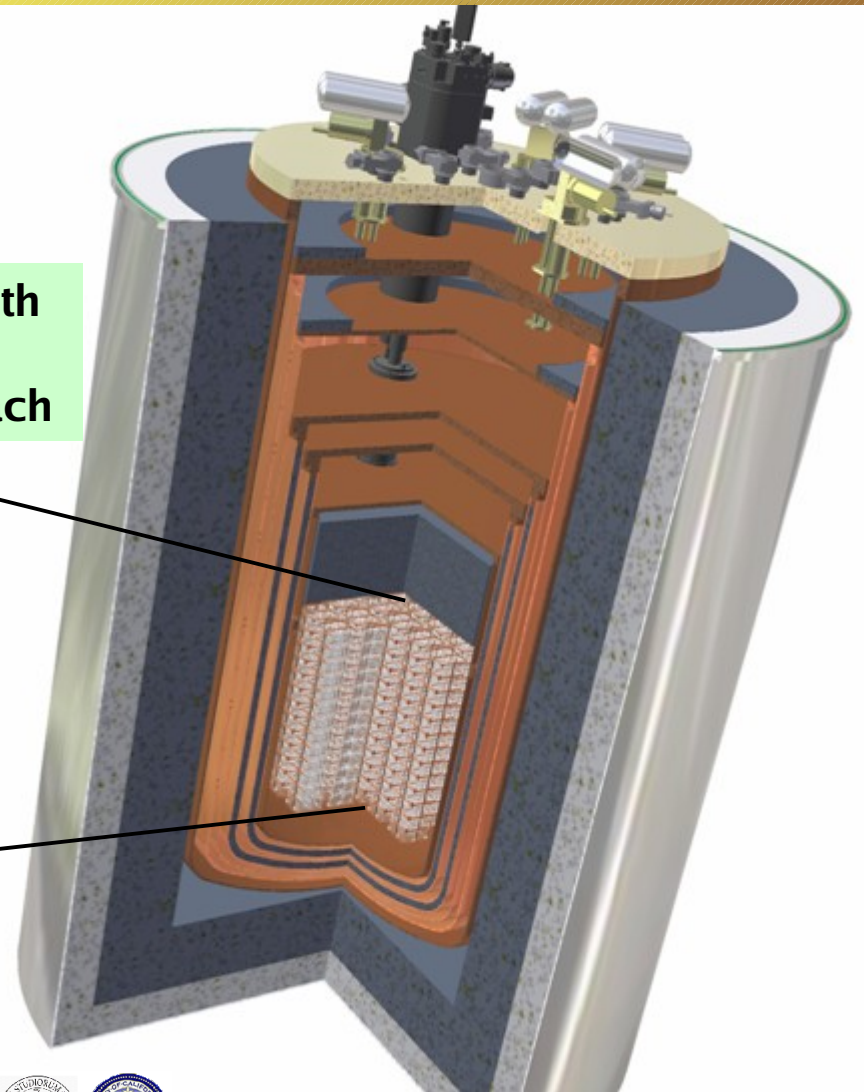
^{130}Te : CUORE - *Cryogenic Underground Observatory for Rare Events*

Array of 988 TeO_2 detectors (750 g each)

$M = 741 \text{ kg}$ of $\text{TeO}_2 = 203 \text{ kg}$ of ^{130}Te



19 towers with
13 planes of
4 crystals each

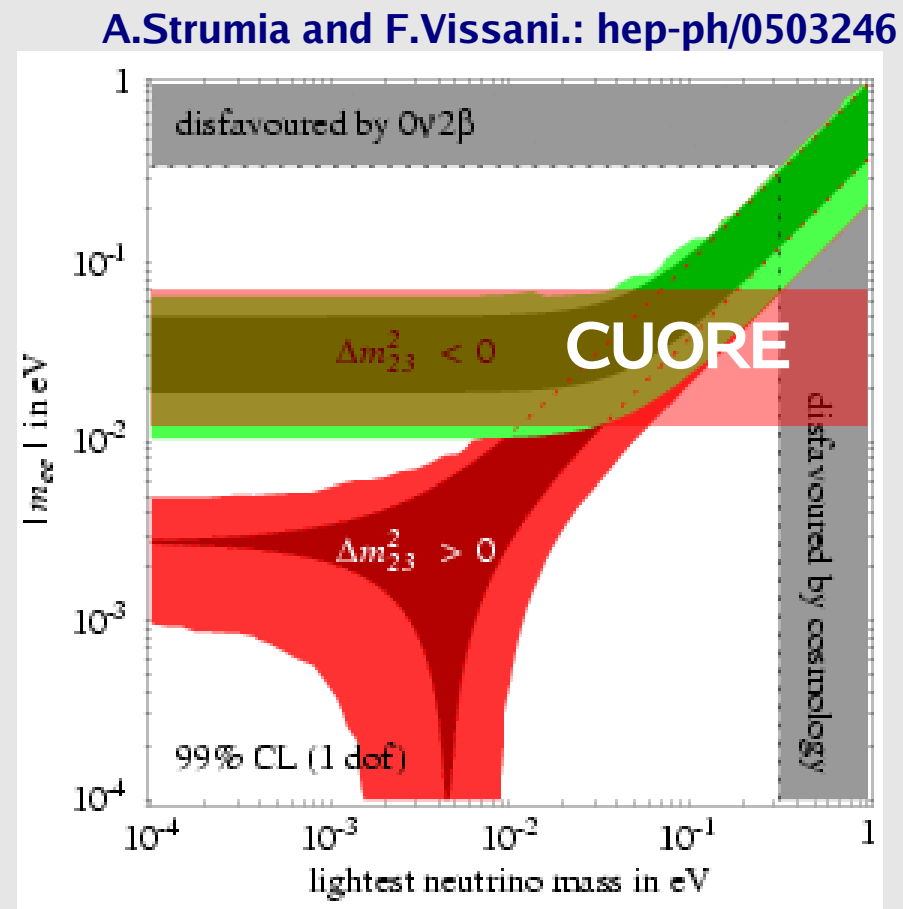


Present Collaboration
39 European Collaborators
28 US Collaborators

CUORE $\beta\beta(0\nu)$ sensitivity will depend strongly on the background level and detector performance.

In five years:

B(counts/keV/kg/y)	Δ (keV)	$T_{1/2}$ (y)	$ \langle m_\nu \rangle $ (meV)
0.01	10	1.5×10^{26}	23–118
0.01	5	2.1×10^{26}	19–100
0.001	10	4.6×10^{26}	13–67
0.001	5	6.5×10^{26}	11–57





- **compact and granular** $\Rightarrow$ self shielding detector
- **enrichment** option still open (II phase): only core / full detector
- work in progress to **reduce surface radioactivity** ($1/100^{\text{th}}$ of Cuoricino)

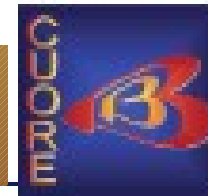
Present status

- **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 2011 @ LNGS**

CUORE site @ LNGS



- La determinazione della massa assoluta dei neutrini è una delle sfide sperimentali più ardue del momento
- Lo studio dello spettro di decadimento beta e la ricerca del decadimento doppio beta senza emissione di neutrini sono misure fra loro complementari (diverse sensibilità, diverse implicazioni teoriche)
- Nel prossimo futuro gli esperimenti di seconda generazione potrebbero darci importanti informazioni!!!