Misura della massa assoluta dei neutrini

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INCONTRI DI FISICA
DELLE ALTE ENERGIE

VI
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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

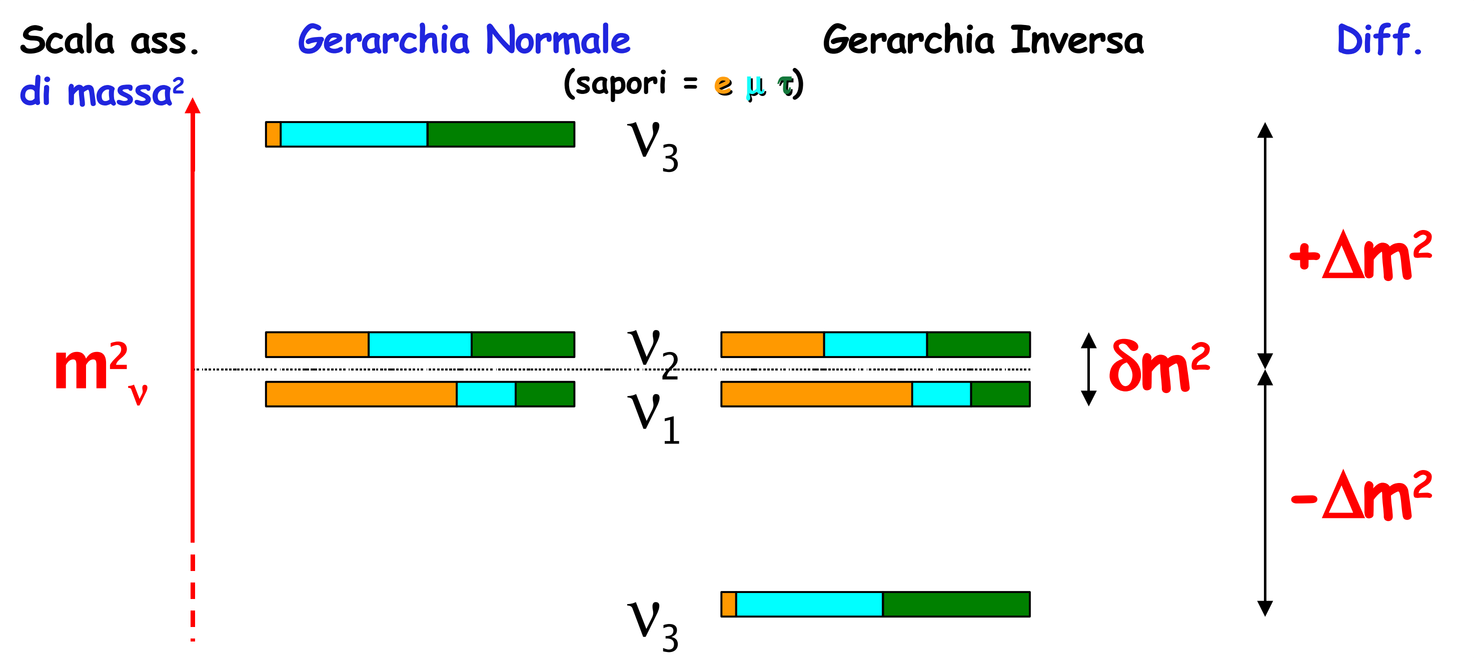
- i neutrini oscillano:

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

- dagli esperimenti sulle oscillazioni:

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

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



... o “quasi degeneri”

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(?)

0νββ-decay: m_{ee}

model dependent, ν-nature (CP)

status: $m_{ee} < 0.5$ eV

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

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

laboratory

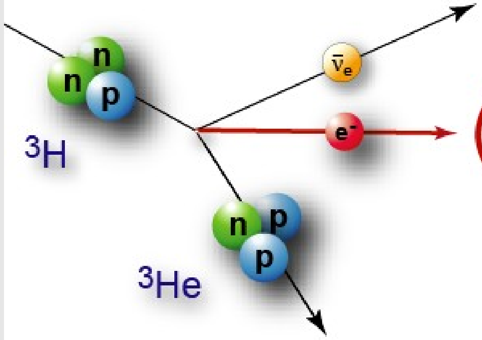
m_β

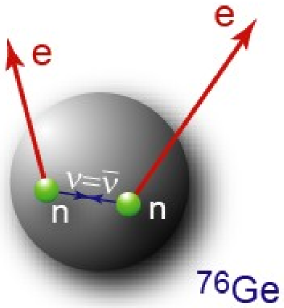
m_{ee}

neutrino mass measurements

status & potential

Σm_i





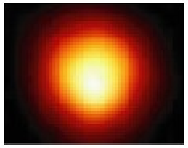
cosmology: Σm_i

model dependent

status: $\Sigma m_i < 0.7$ eV

potential: $\Sigma m_i < 70$ meV

Exp.: WMAP, Planck, SDSS



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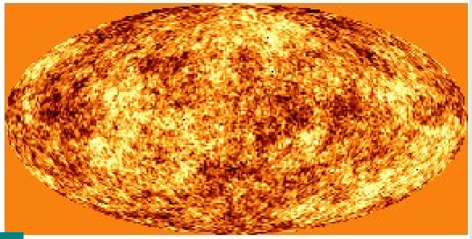
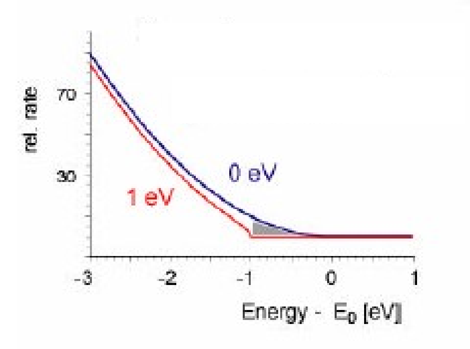


CMBR

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**:

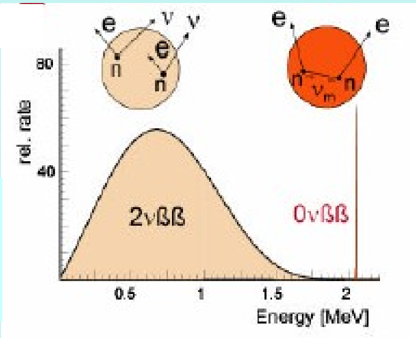
$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

no interferenza distruttiva

Limite attuale: m_β < ~ 2 eV

Sensibilità futura: m_β < ~ 0.2 eV

0νββ 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:

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

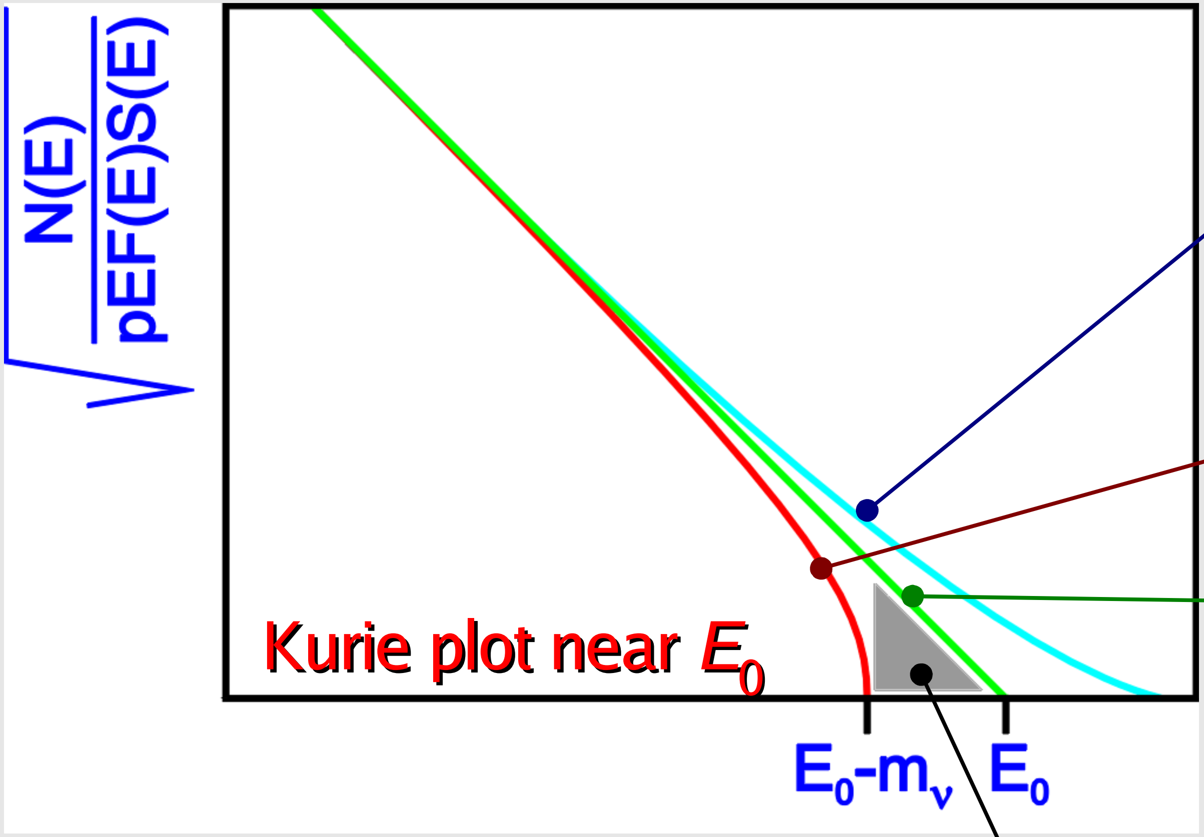
possibile interferenza distruttiva

Limite attuale: m_{ee} < ~ 0.5 eV

Sensibilità futura: m_{ee} < ~ 0.05 eV

COMPLEMENTARY MEASUREMENTS

Misura cinematica



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

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

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

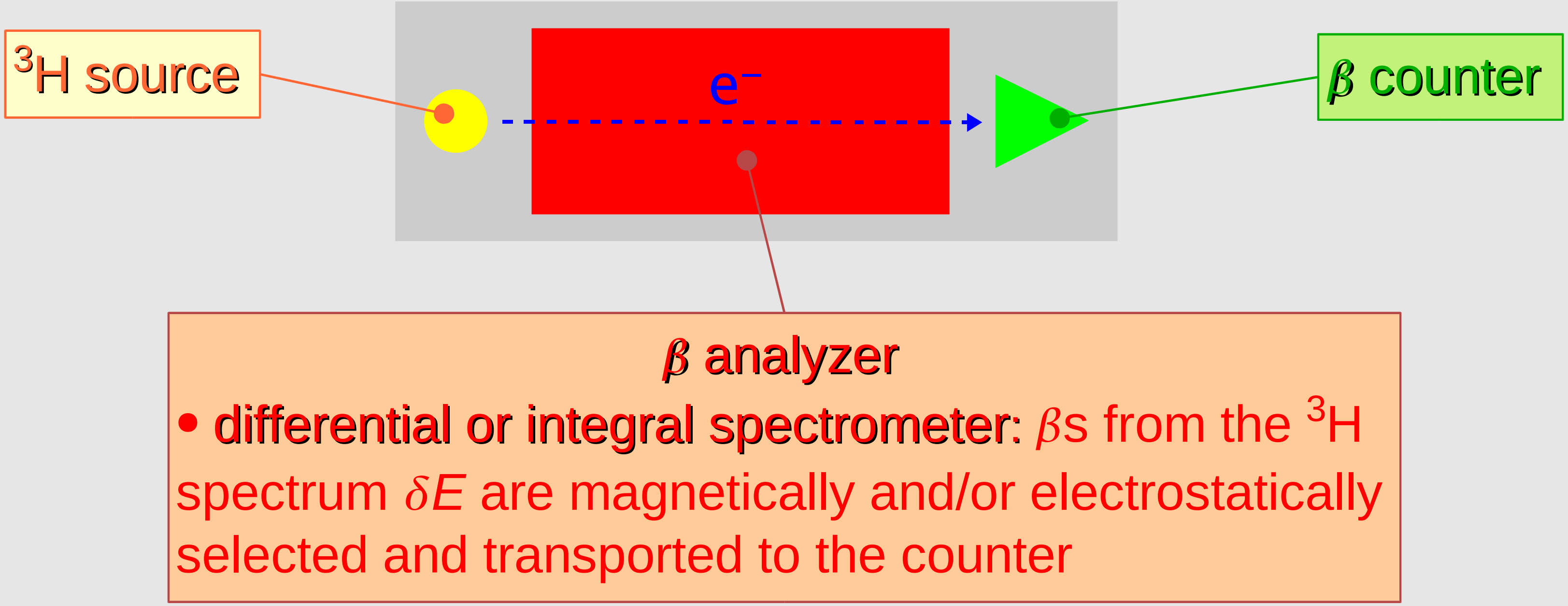
for ^{3}H β decay F(10 eV) ≈ 3×10^{-10}

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 ≠ detector**

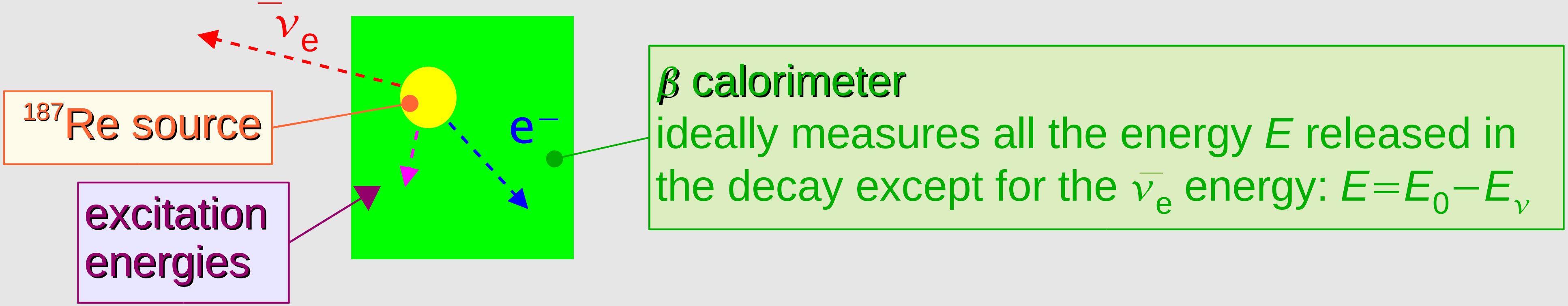


β analyzer

- **differential or integral spectrometer:** βs from the ^{3}H spectrum δE are magnetically and/or electrostatically selected and transported to the counter

Present best limit on m_ν: Mainz-Troitzk ⇒ 2.2 eV (95% C.L.)

- **Calorimeters: source ⊆ detector**



β calorimeter

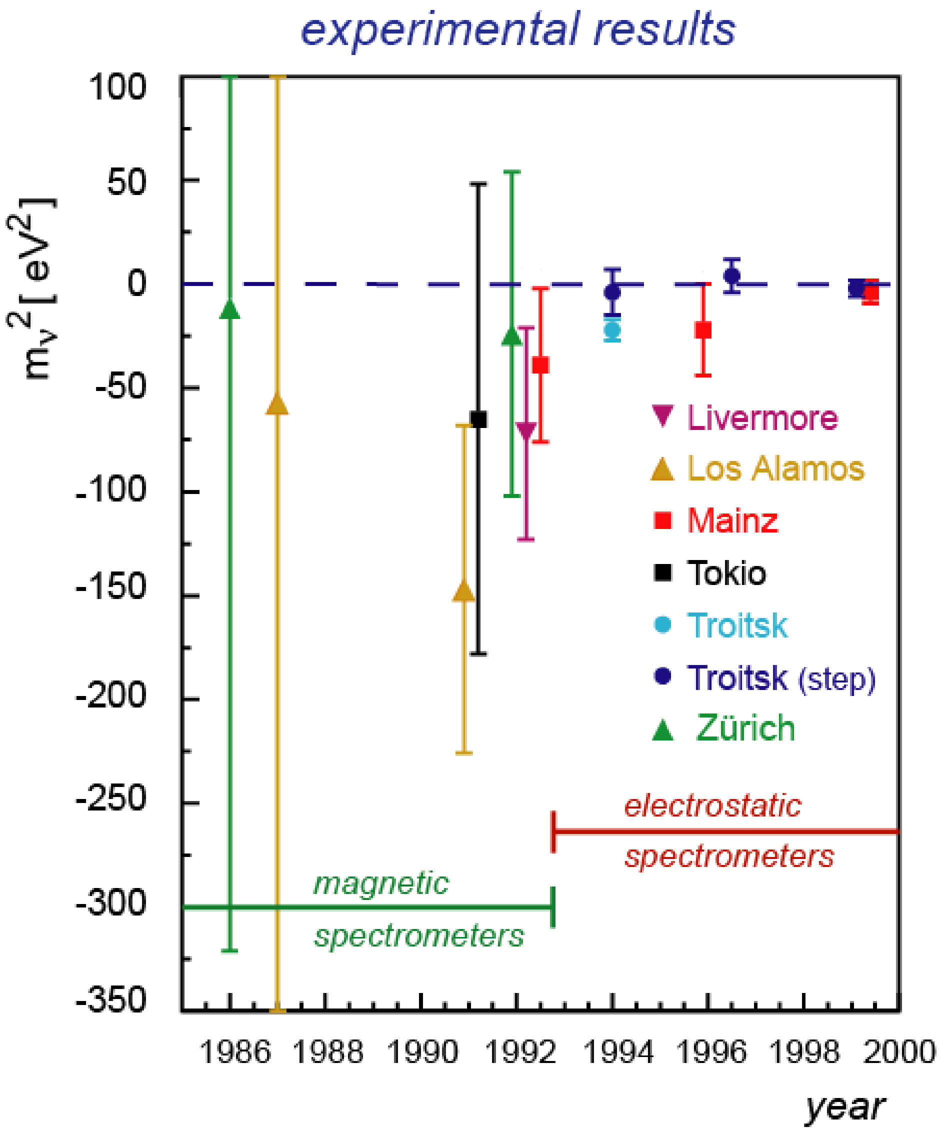
ideally measures all the energy E released in the decay except for the $\bar{\nu}_e$ energy: $E=E_0-E_\nu$

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

Spettrometria di sorgenti beta

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

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



Filtro elettrostatico con collimazione magnetica adiabatica

MAC-technique

adiabatic guiding of ß-particles along the magnetic field lines

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

$B_{max} = 3 - 6$ T

$B_{min} < 1$ mT

very large solid angle !

$\Delta\Omega \sim 2\pi$

E-technique

energy analysis by electro static retarding field (electrodes)

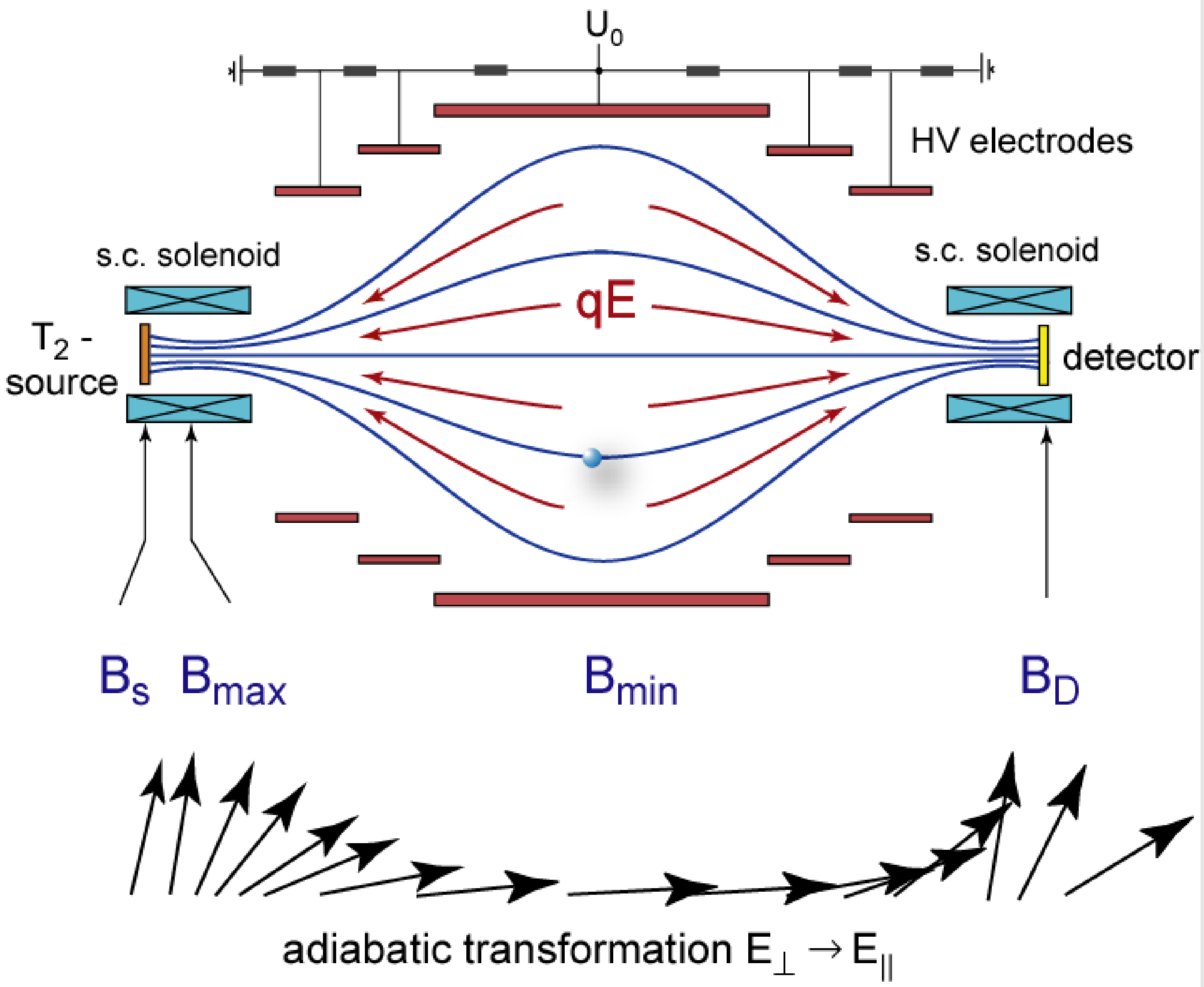
integral particle transmission $E>U_0$

high pass filter !

$$\vec{F} = (\vec{\mu}\cdot\vec{\nabla})\,\vec{B} + q\,\vec{E}$$

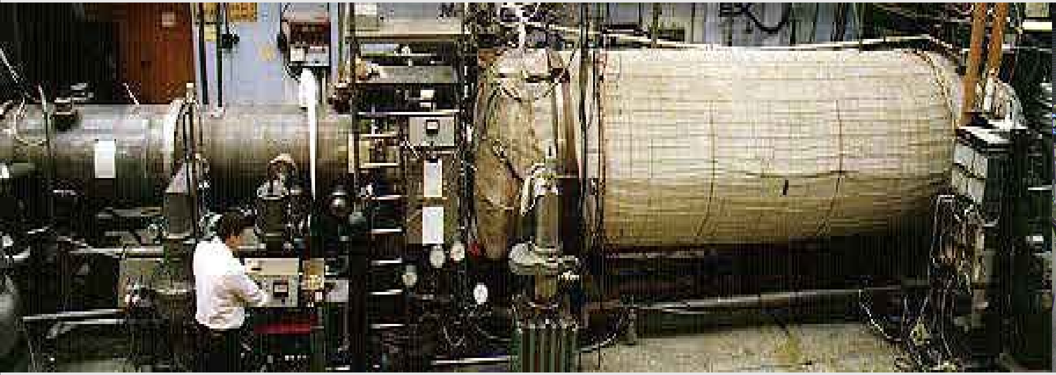
$$\mu = E_\perp / B = \text{const}$$

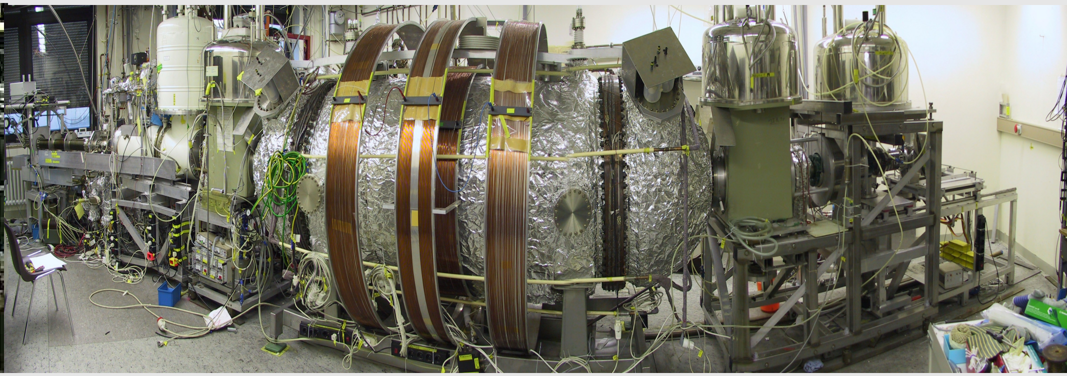
$U_0 < 30$ kV



Gli spettrometri più sensibili: Mainz & Troitsk

Mainz & Troitsk have reached their intrinsic limit of sensitivity





Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

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

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

Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

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

$m_\nu \leq 2.2$ 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:

$$^{187}_{75}\mathrm{Re} \rightarrow {}^{187}_{76}\mathrm{Os} + e^- + \bar{\nu}_e$$

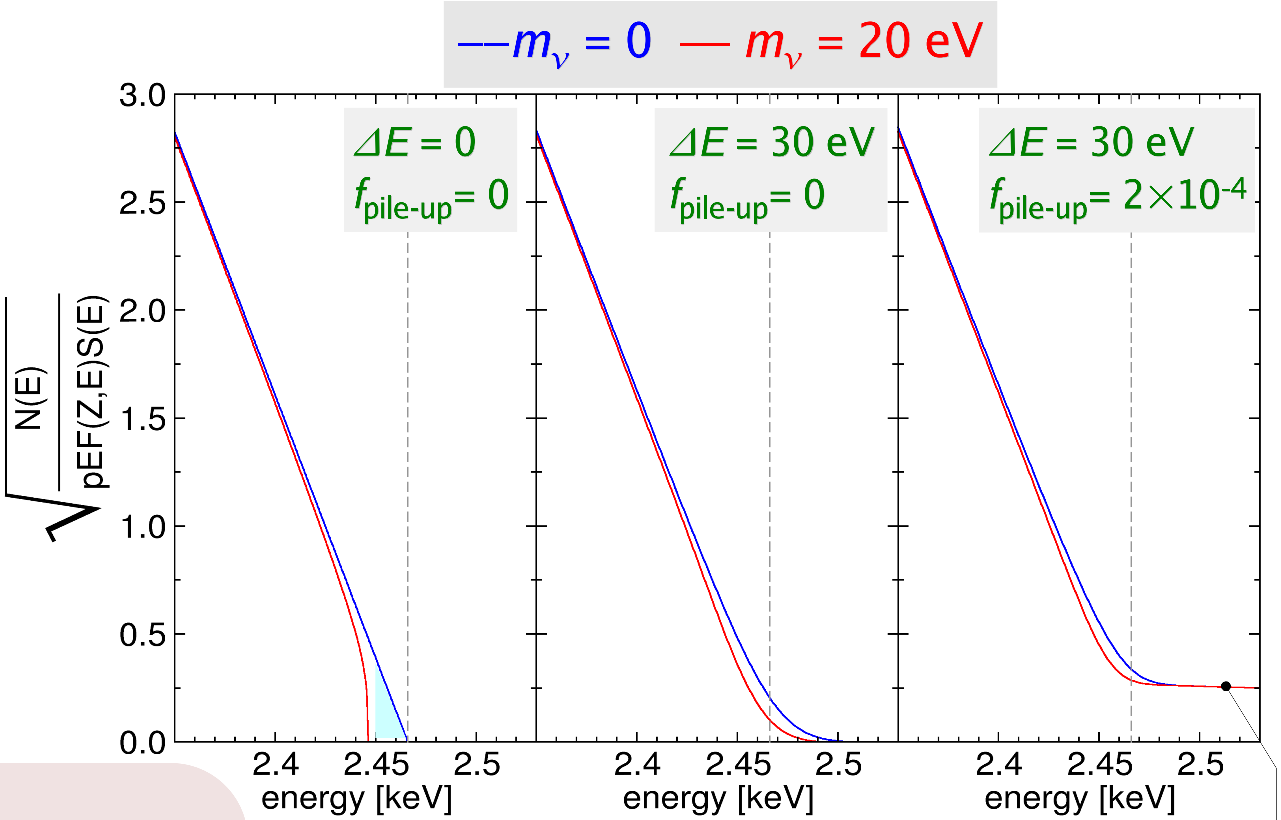
($5/2^+ \rightarrow 1/2^-$ first-forbidden unique)

E_0 = 2.47 keV ⇒

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

natural isotopic abundance: **63%**

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



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

Pile-up

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

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

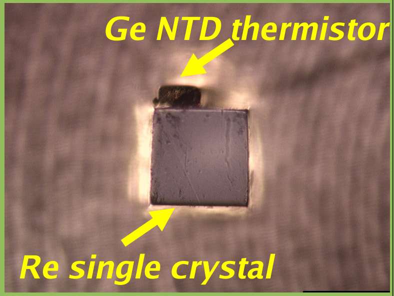
⇨ generates “background” at the end-point

Stato dell'arte delle misure calorimetriche

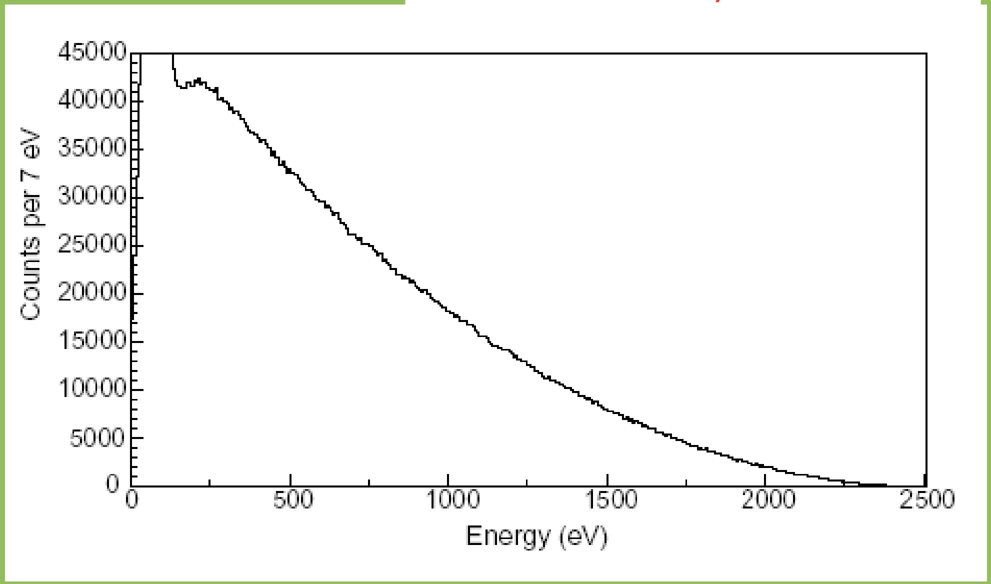
MANU (1999)

Genova

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



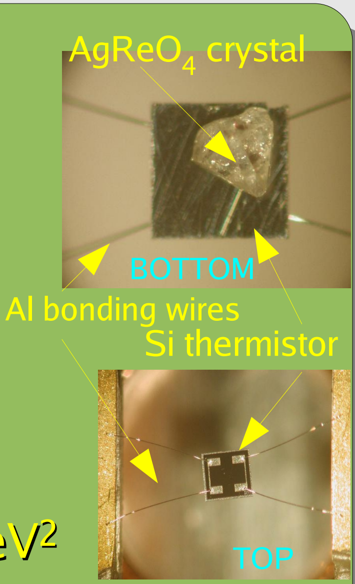
6.0×10^6 ^{187}Re decays above 420 eV



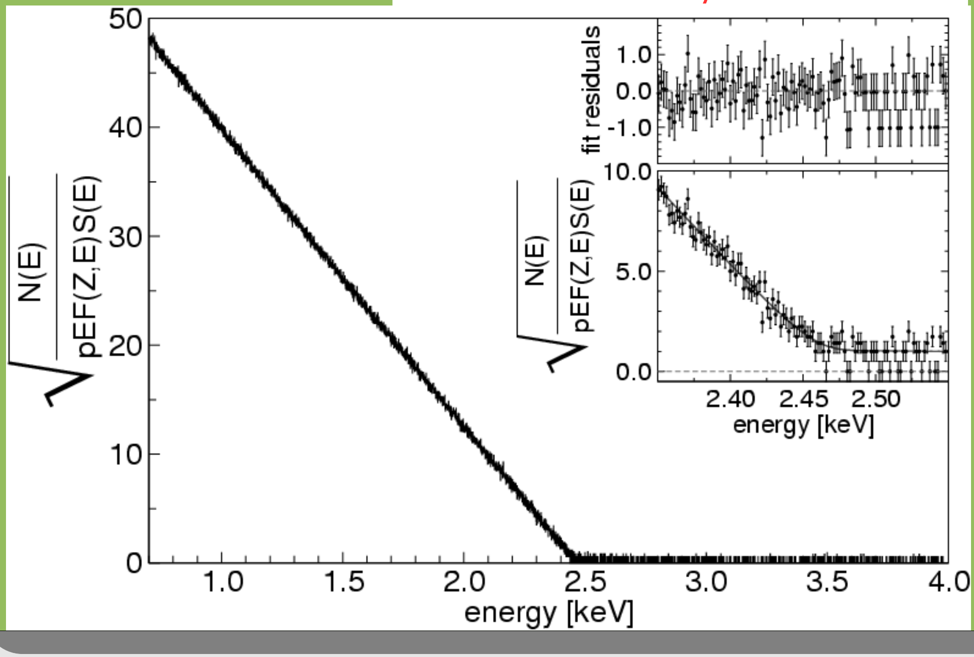
MIBETA (2002-2003)

Milano, Como, Trento

- 10 AgReO$_4$ crystals: 2.71 mg
- ^{187}Re activity = 0.54 Hz/mg
- Si thermistors (ITC-irst)
- ΔE= 28.5 eV FWHM
- 0.6 years live time
- $m_\nu^2 = -112 \pm 207_{stat} \pm 90_{sys}$ eV^2
- **m_ν < 15 eV (90 % C.L.)**



6.2×10^6 ^{187}Re decays above 700 eV



Spettrometri e calorimetri a confronto

Spectrometers

- **Choice of β-emitter: ^{3}H**
  - E_0 = 18.6 keV
  - $\tau_{1/2}$ = 12.3 y
- **Advantages**
  - ▲ high statistics
  - ▲ high energy resolution
- **Drawbacks**
  - ▼ systematics due to source effects
  - ▼ systematics due to decays to excited states
  - ▼ background

Future planned sensitivity:
KATRIN → 0.2 eV

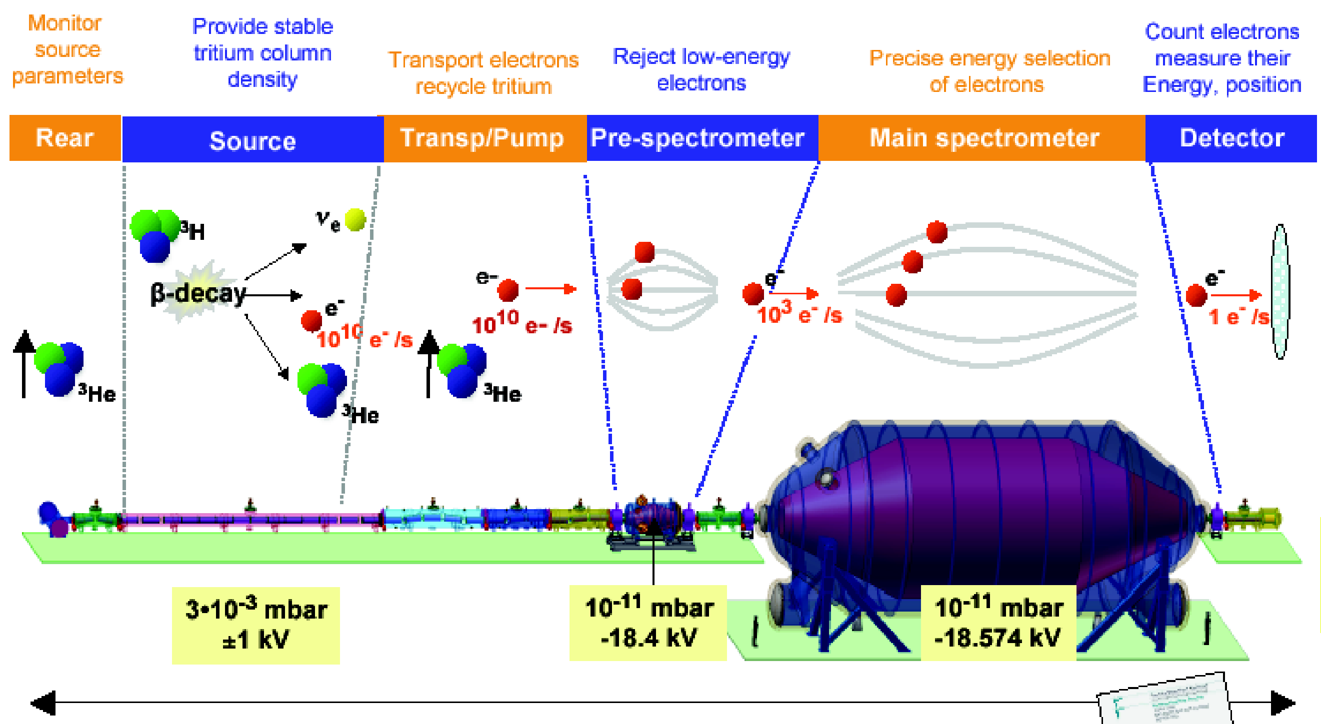
Calorimeters

- **Choice of β-emitter: ^{187}Re**
  - E_0 = 2.5 keV
  - $\tau_{1/2}$ = 43.2 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:
MARE → 0.2 eV

Complementary techniques – Different systematics

Il futuro delle misure con spettrometri: KATRIN



Main components and function→Design report 2005, FZK Report 7

http://www-ik.fzk.de/%7Ekatrin/

Karlsruhe Tritium Neutrino Experiment

Physics goal:
one order of magnitude improvement in m_ν

Limit m_ν 2.2 eV → 0.2 eV

Start of data taking in 2010 ...

Improve Statistics

stronger source (factor ~80)

longer measuring period (factor ~10)

Improve energy resolution

ΔE≅0.93 eV (factor of 4 improvement)

Requires larger spectrometer

Reduce systematic errors

better control of systematics

energy losses (factor~10)

Ottobre 2006

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

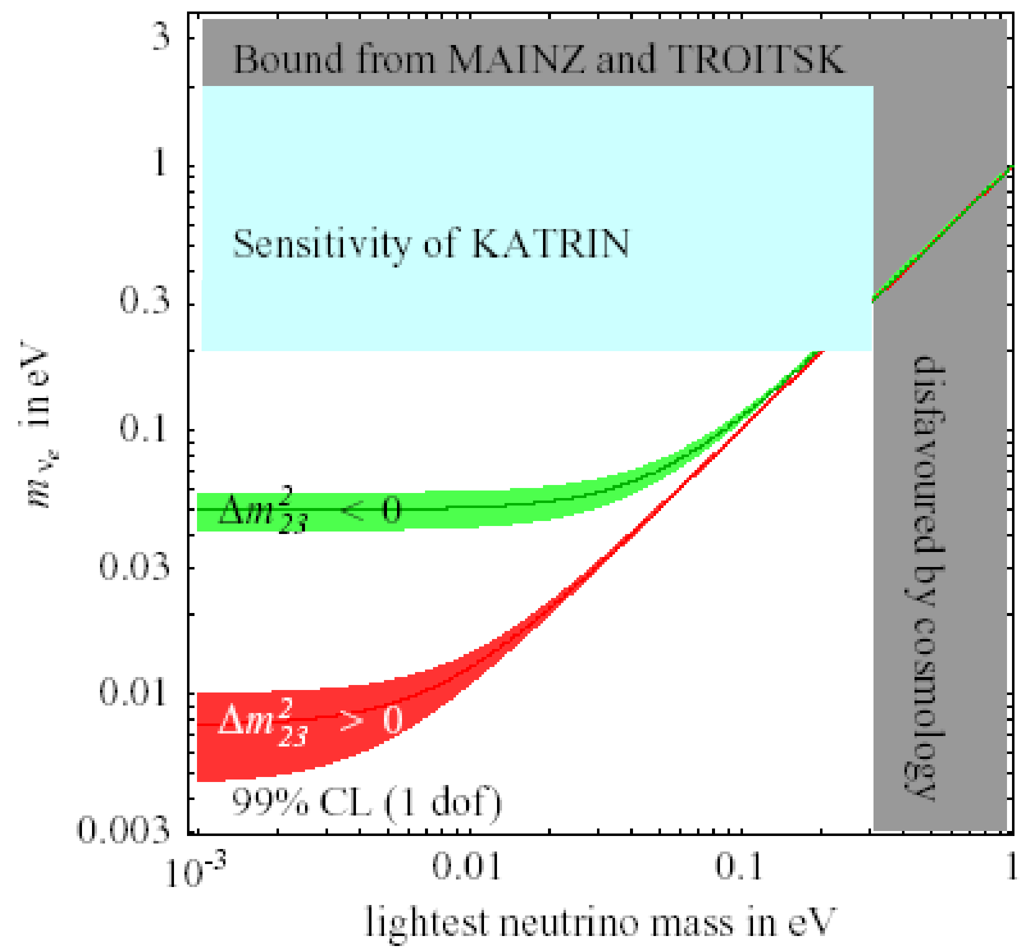
KATRIN

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)

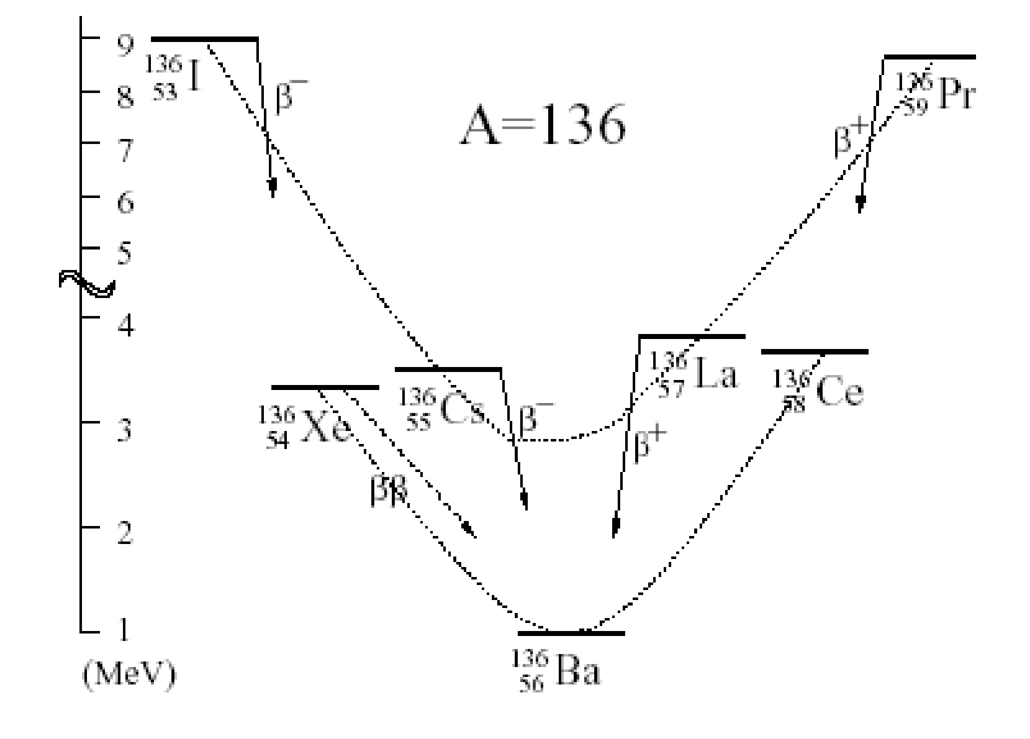
Sensibilità di KATRIN



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

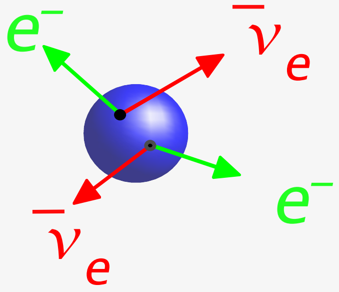
Il decadimento doppio beta

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

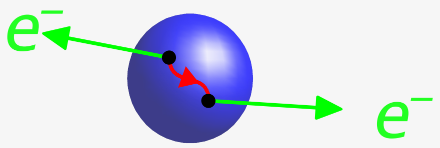


ββ-2ν: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$

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

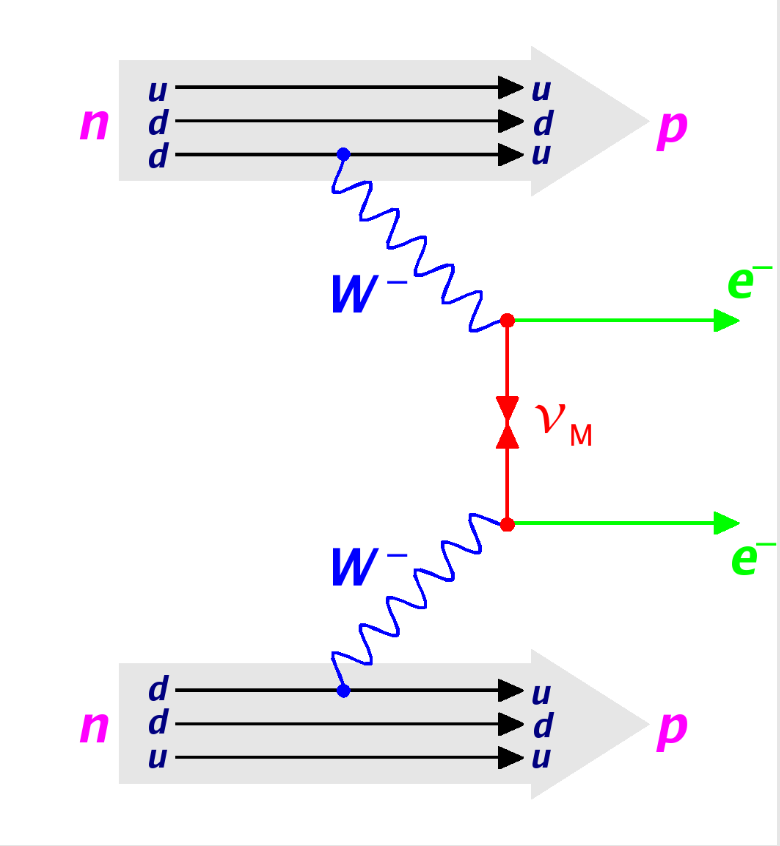


ββ-0ν: $(A, Z) \rightarrow (A, Z+2) + 2e^-$



- **non permesso** nel Modello Standard (ΔL=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 ⇒ **$\Delta H=2$**
  - neutrino must be a **Majorana particle** to allow lepton number non conservation ⇒ **$\Delta L=2$**

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

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

ββ0ν e le proprietà del neutrino

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

nuclear structure factor

$$F_N \equiv \underbrace{G^{0\nu}}_{\text{phase space}}(Q_{\beta\beta}, Z)\,|\underbrace{M^{0\nu}}_{\text{matrix element}}|^2$$

effective neutrino Majorana mass

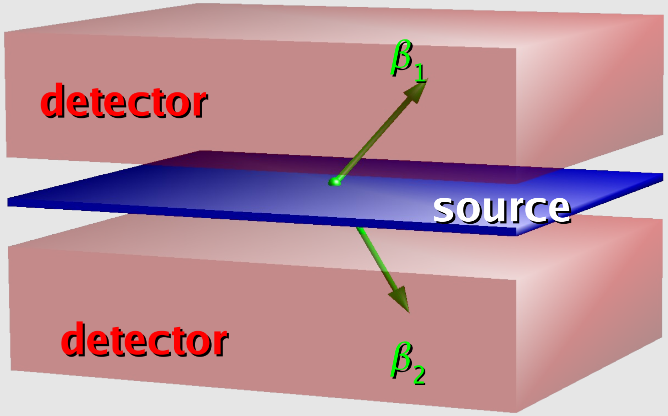
$$\langle m_\nu \rangle = \left| \sum_k m_{\nu_k} \underbrace{\eta_k}_{\text{CP phases*}} |\underbrace{U_{ek}}_{\text{neutrino mixing matrix}}|^2 \right|$$

⬇

- 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 $<m_\nu>$

↳ great uncertainties in the results!

Approcci sperimentali al $\beta\beta0\nu$

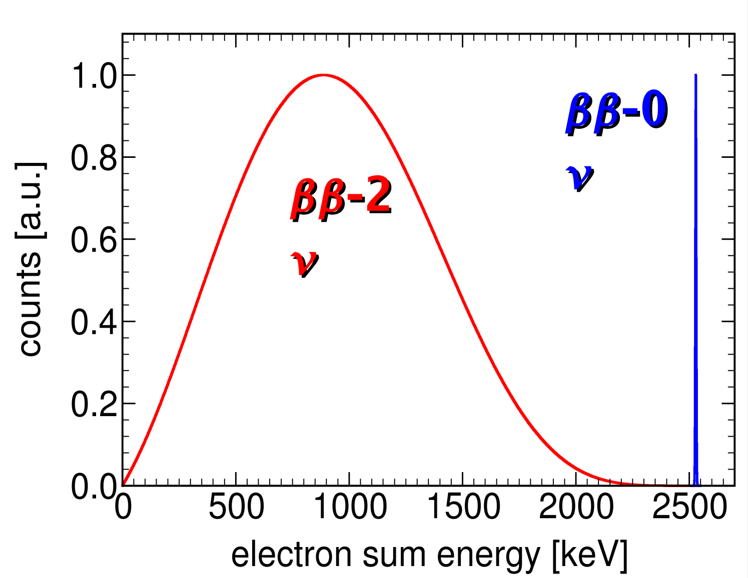


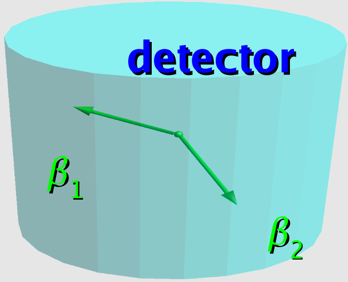
Source ≠ detector

- 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)





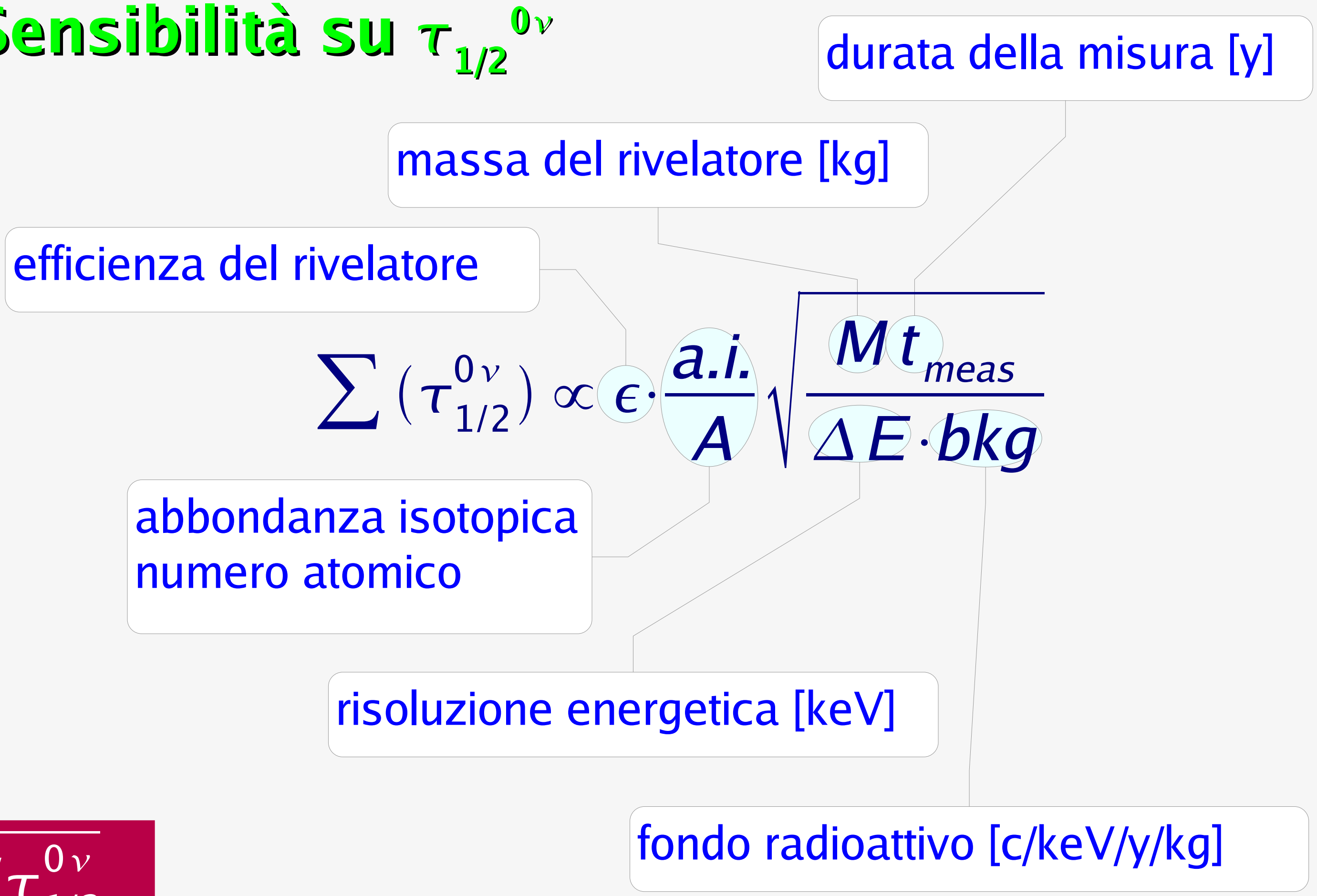
Other approaches (geochemical, milking)

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

Sensibilità sperimentale

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

Sensibilità su $\tau_{1/2}^{0\nu}$



durata della misura [y]

massa del rivelatore [kg]

efficienza del rivelatore

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

abbondanza isotopica
numero atomico

risoluzione energetica [keV]

fondo radioattivo [c/keV/y/kg]

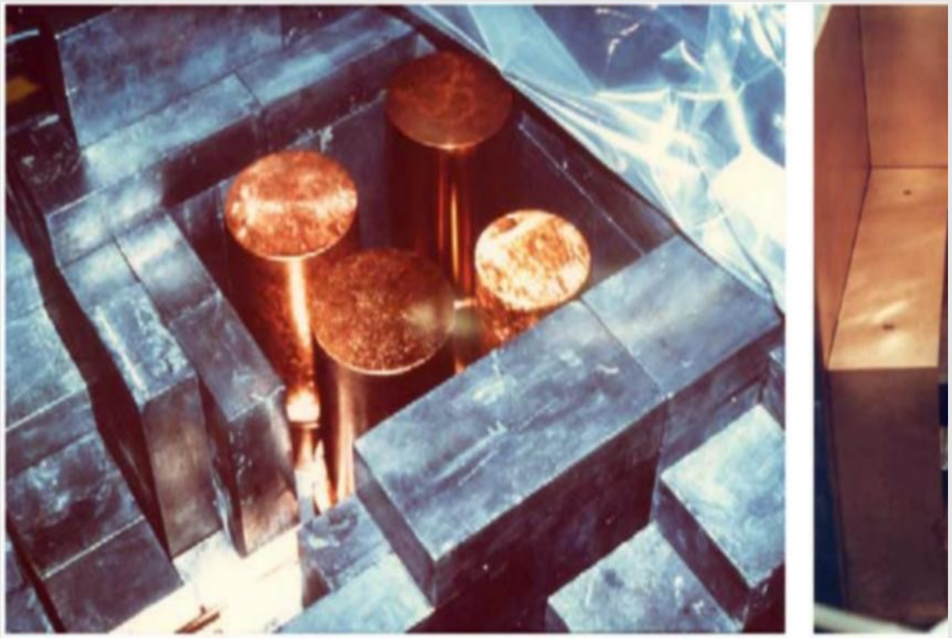
$$m_{\nu} \propto \sqrt{1/\tau_{1/2}^{0\nu}}$$

Situazione sperimentale attuale

Nucleus	Experiment	i.a.	$Q_{\beta\beta}$	Enr	Technique	$T_{½0\nu}$ (y)	$\langle m_\nu \rangle$ (eV)
^{48}Ca	Elegant IV	0.19	4271		scintillator	>1.8x10^{22}	7-45
^{76}Ge	Heidelberg-Moscow	7.8	2039	87	ionization	>1.9x10^{25}	0.1 - 0.9
^{76}Ge	IGEX	7.8	2039	87	Ionization	>1.6x10^{25}	0.14–1.2
^{76}Ge	Klapdor et al	7.8	2039	87	ionization	1.2x10^{25}	0.44
^{82}Se	NEMO 3	9.2	2995	97	tracking	>1.2x10^{23}	1.8-4.9
^{100}Mo	NEMO 3	9.6	3034	95-99	tracking	>5.8x10^{23}	.7-2.8
^{116}Cd	Solotvina	7.5	3034	83	scintillator	>1.7x10^{23}	1.7 - ?
^{128}Te	Bernatovitz	34	2529		geochem	>7.7 ×10^{24}	1.0 - 4.4
^{130}Te	Cuoricino	33.8	2529		bolometric	>3x10^{24}	0.2 - 0.8
^{136}Xe	DAMA	8.9	2476	69	scintillator	>1.2x10^{24}	1.1 -2.9
^{150}Nd	Irvine	5.6	3367	91	tracking	>1.2x10^{21}	3 - ?

^{76}Ge: esperimento Heidelberg-Moscow

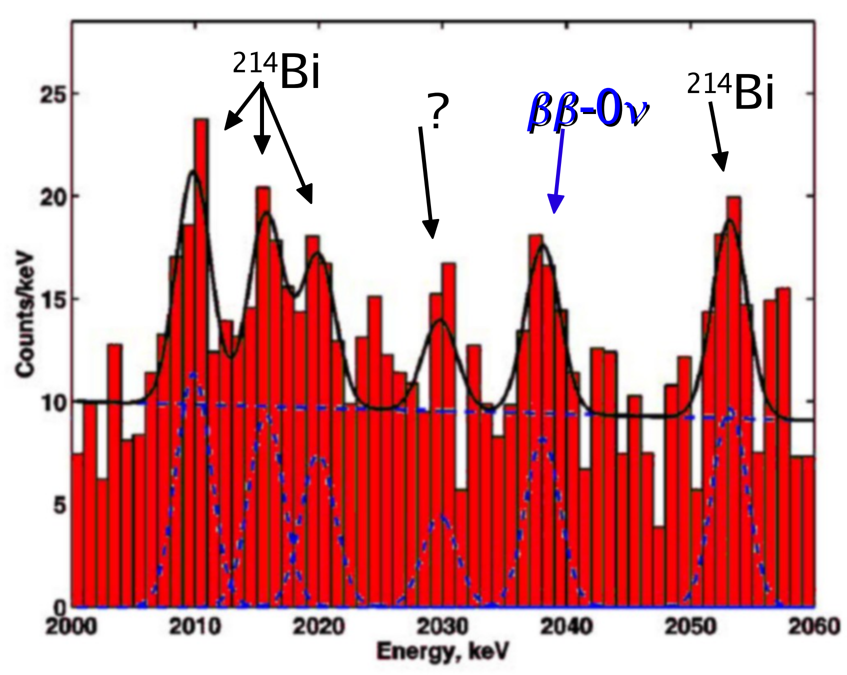
- calorimetric experiment with Ge semiconductor detectors
- 5 HP-Ge crystals, enriched to 87% in ^{76}Ge
  - total active mass of 10.96 kg ⇒ 125.5 moles of ^{76}Ge
- run from 1990 to 2003 in Gran Sasso Underground Laboratory
- total exposure 71.7 kg$\times$y
  - 820 moles$\times$y
- main background from 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 βs are SSE

^{76}Ge HM: evidenza sperimentale di $\beta\beta0\nu$

- 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 $\beta\beta$-0ν experiments



1990 – 2003 data, all 5 detectors

exposure = 71.7 kg×y

$\tau_{½}^{0\nu} = 1.2\times10^{25}$ **years**

$\langle m_\nu \rangle = 0.44$ **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 $\beta\beta$-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

ββ0ν measurement

Isotope	Mass	$Q_{\beta\beta}$
^{100}Mo	6.914 kg	$Q_{\beta\beta}$ = 3034 keV
^{82}Se	0.932 kg	$Q_{\beta\beta}$ = 2995 keV

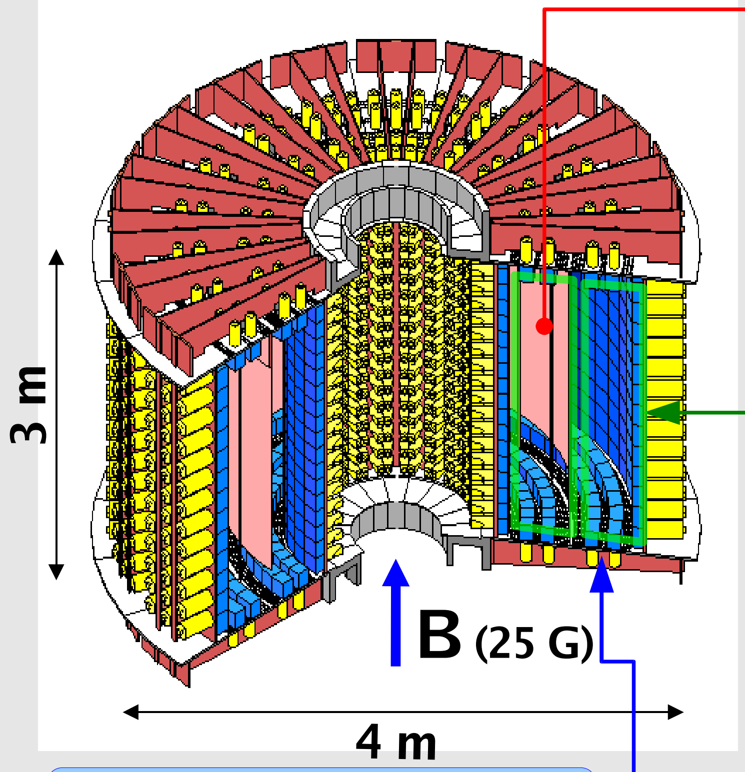
^{100}Mo purified at INL (USA) and ITEP (Russia)

ββ2ν measurement

Isotope	Mass	$Q_{\beta\beta}$
^{116}Cd	405 g	$Q_{\beta\beta}$ = 2805 keV
^{96}Zr	9.4 g	$Q_{\beta\beta}$ = 3350 keV
^{150}Nd	37.0 g	$Q_{\beta\beta}$ = 3367 keV
^{48}Ca	7.0 g	$Q_{\beta\beta}$ = 4272 keV
^{130}Te	454 g	$Q_{\beta\beta}$ = 2529 keV
^{nat}Te	491 g	
Cu	621 g	

External bkg measurement (^{130}Te, ^{nat}Te, Cu)

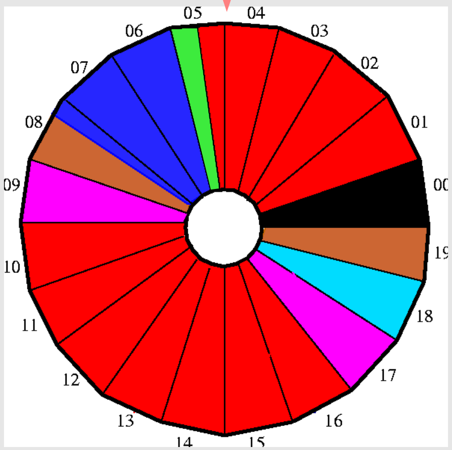
(Enriched isotopes produced in Russia)

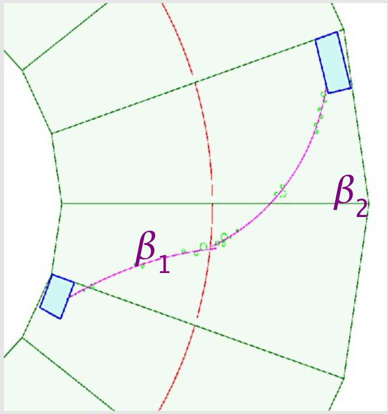


sources in foils

calorimeter (scintillators)

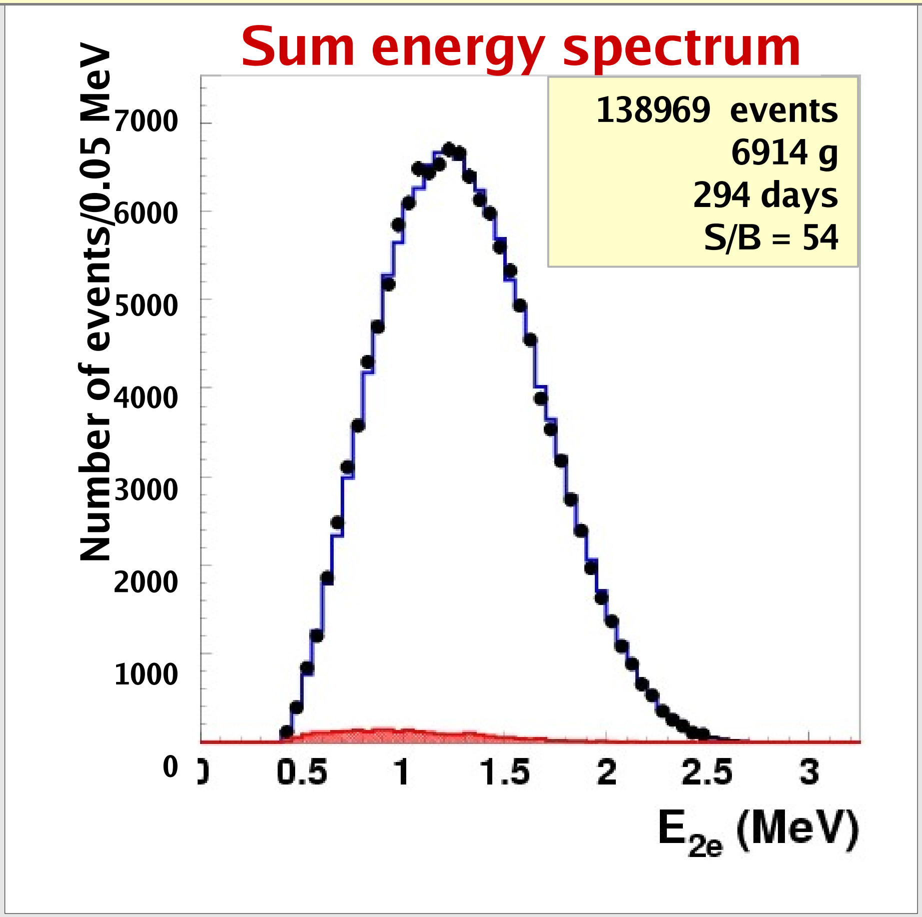
tracking volume (drift wire chamber)



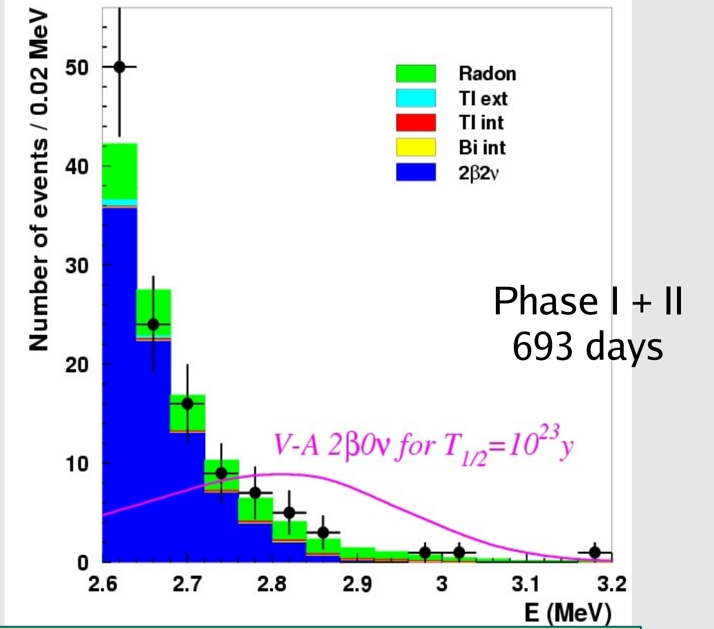


NEMO-3: risultati per ^{100}Mo e ^{82}Se

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

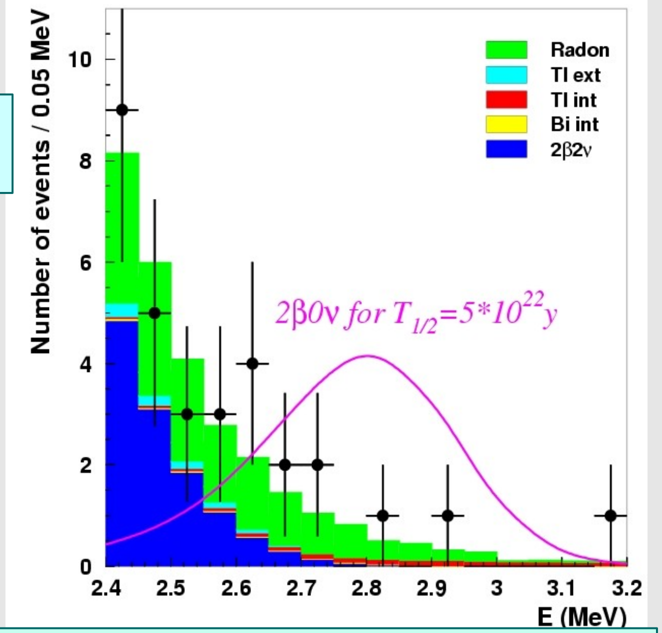


^{100}Mo, 7 kg



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

^{82}Se, 1 kg



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

Expected sensitivity End 2009:

^{100}Mo $T_{1/2}(\beta\beta 0\nu) > 2.\ 10^{24}$ y (90% C.L.)

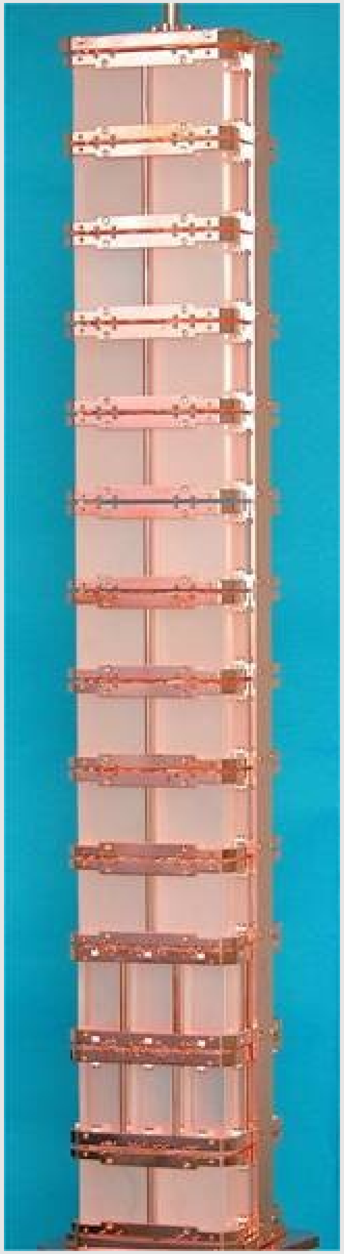
^{82}Se $T_{1/2}(\beta\beta 0\nu) > 8.\ 10^{23}$ y (90% C.L.)

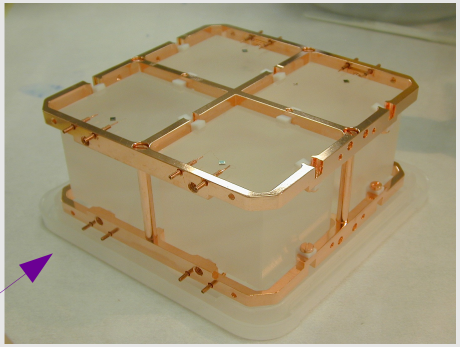
^{130}Te: esperimento Cuoricino

TeO_2 thermal calorimeters

- **Active isotope ^{130}Te**
  - natural abundance: a.i. = 33.9%
  - transition energy: $Q_{\beta\beta}$ = 2529 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

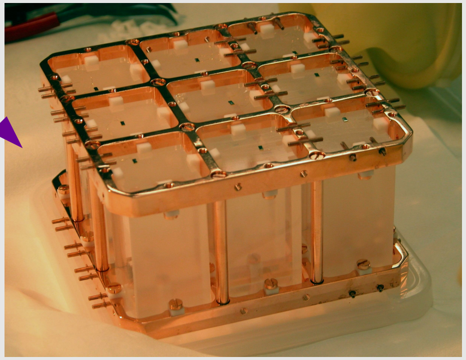




CUORICINO experiment @ LNGS

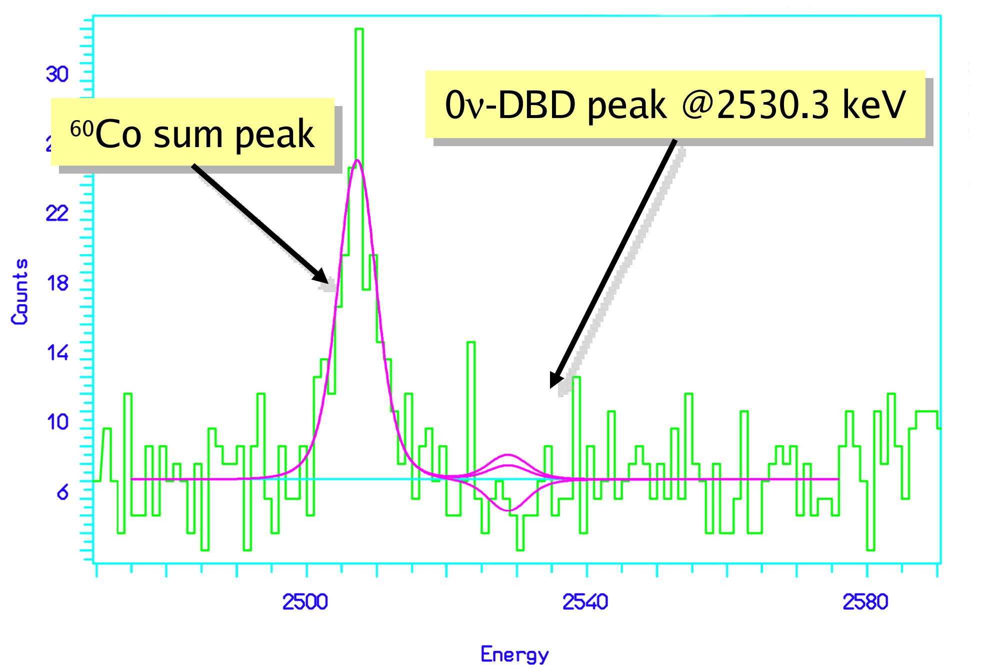
- 62 TeO_2 detectors in the ***tower*-like structure** foreseen for **CUORE**
- 11 modules with **4 detectors 790 g each**
  - ▷ 34.76 kg TeO_2 mass
- 2 modules with **9 detectors 330 g each**
  - ▷ 5.94 kg TeO_2 mass
- **total mass 40.7 kg**
- ▶ **intermediate size $\beta\beta$ experiment**
- ▶ **test for radioactivity**

^{130}Te mass:
11 kg



Risultati di Cuoricino su $\beta\beta0\nu$ del ^{130}Te

Anticoincidence background spectrum the $\beta\beta$–0ν region



^{60}Co sum peak

0ν-DBD peak @2530.3 keV

Started in February 2003
long interruption for maintenance

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

Total statistic ~ 11.8 kg (^{130}Te) × y

b = 0.18 ± 0.01 c/keV/kg/y

Maximum Likelihood
flat background + fit of 2505 peak

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

* Depending on the nuclear matrix element values

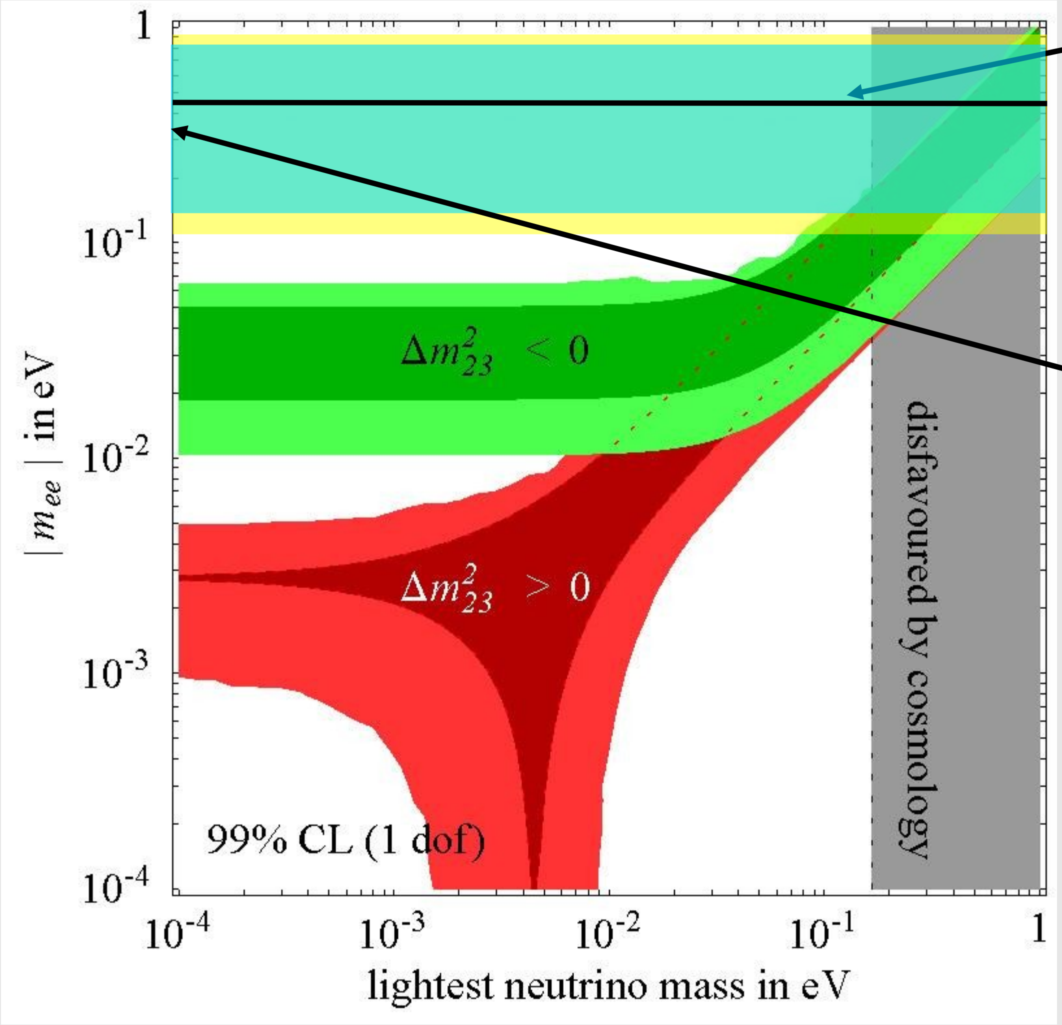
Cuoricino potentiality (on the way to CUORE):

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

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

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

Il decadimento doppio beta e la massa del neutrino



KK-HM evidence (best value 0.44 eV)

Cuoricino limit (with the same NME <0.41 eV)

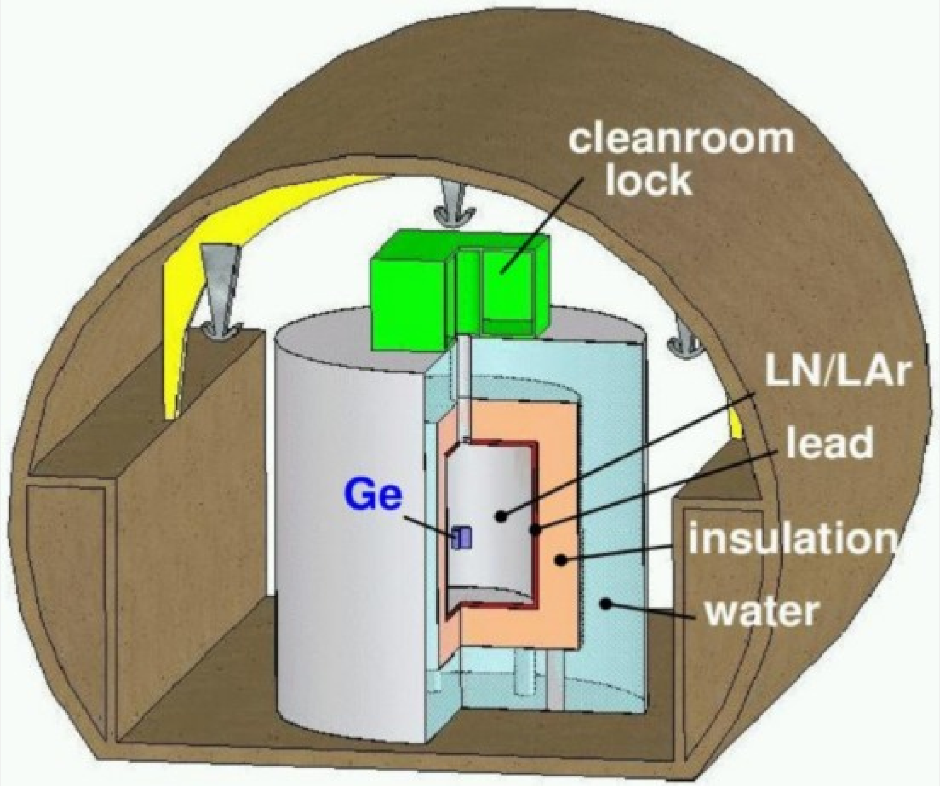
Strumia A. and Vissani F. - hep-ph/0606054

Il futuro del decadimento doppio beta

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

^{76}Ge: GERDA

- goal: analise HM evidence in a short time using existing ^{76}Ge enriched detectors (HM, Igex)
- approach similar to GENIUS but less LN2
  - naked Ge crystals in LN2 or LAr
  - 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
  - $\approx$15 kg ^{76}Ge from HM and Igex
  - expected bkg $\leqslant$0.01 c/keV/kg/y (intrinsic)
  - check at 5σ HM evidence
  - 15 kg$\cdot$y $\Rightarrow$ 6$\pm$1 $\beta\beta$ events on 0.5 bkg events
- **Phase II:**
  - Add $\approx$20 kg 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$\cdot$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



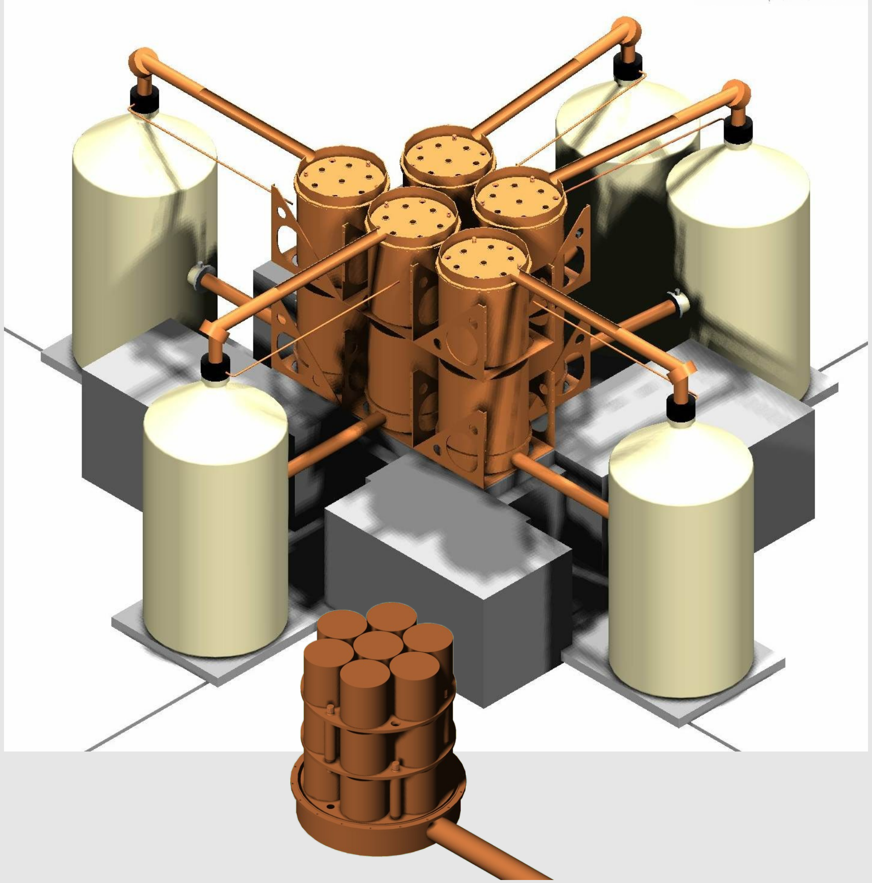
Proposal: hep-ex/0404039

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

^{76}Ge: 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



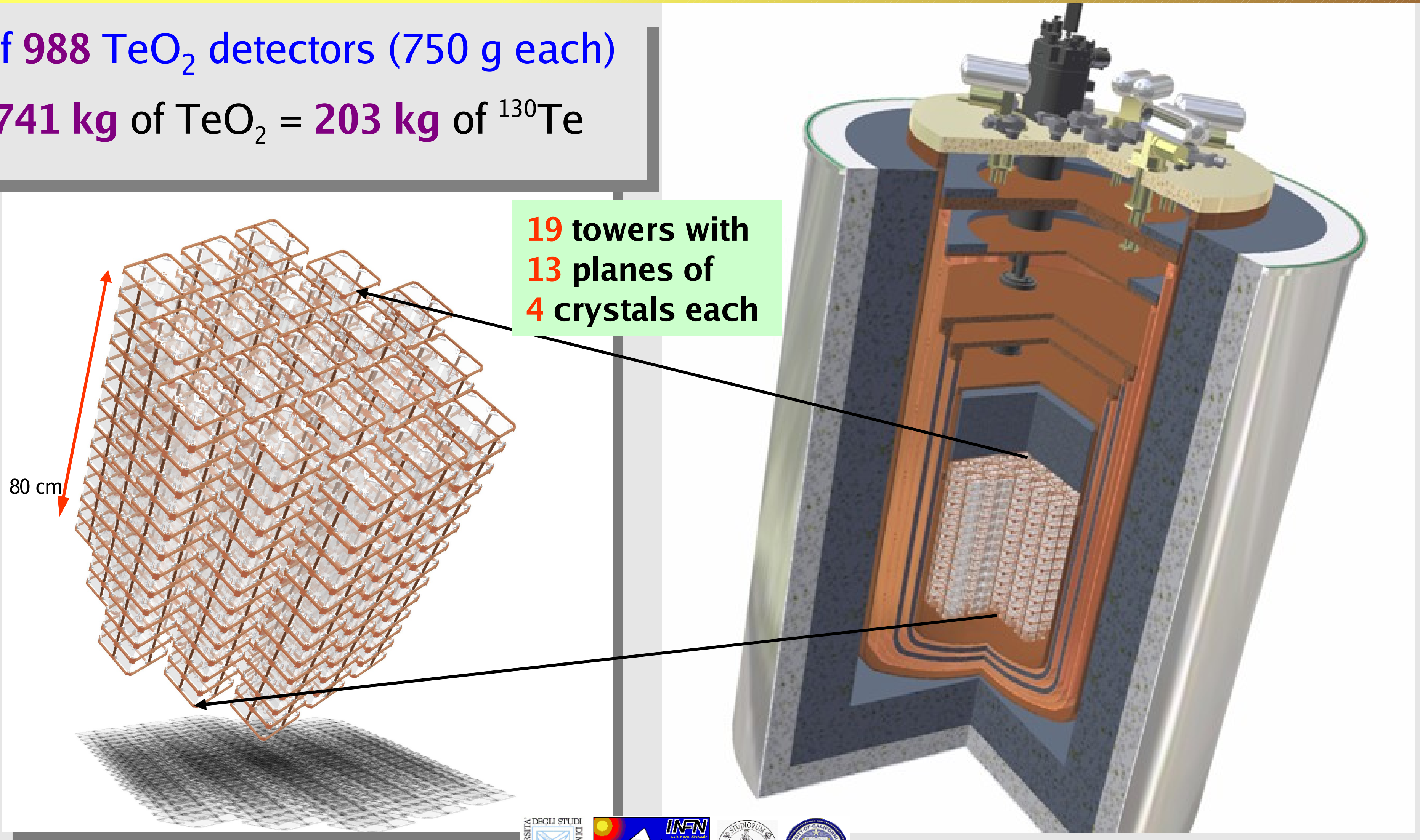
FULL EXPERIMENT (in 9 years from start)

- 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 ⇒ 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 kg** of TeO_2 = **203 kg** of ^{130}Te



19 towers with
13 planes of
4 crystals each

Present Collaboration

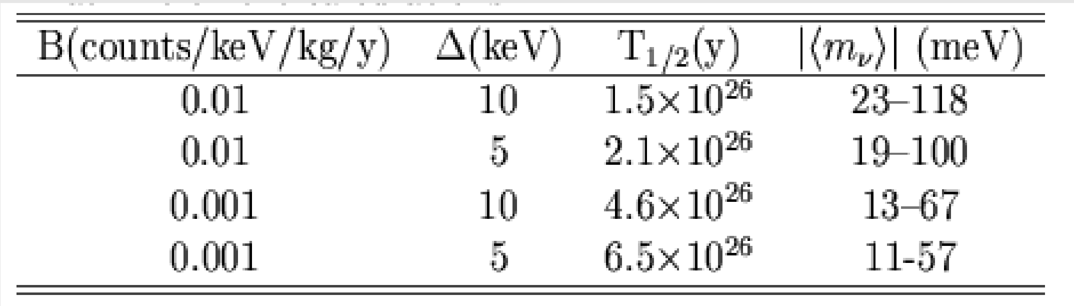
39 European Collaborators

28 US Collaborators

CUORE: la sensibilità attesa

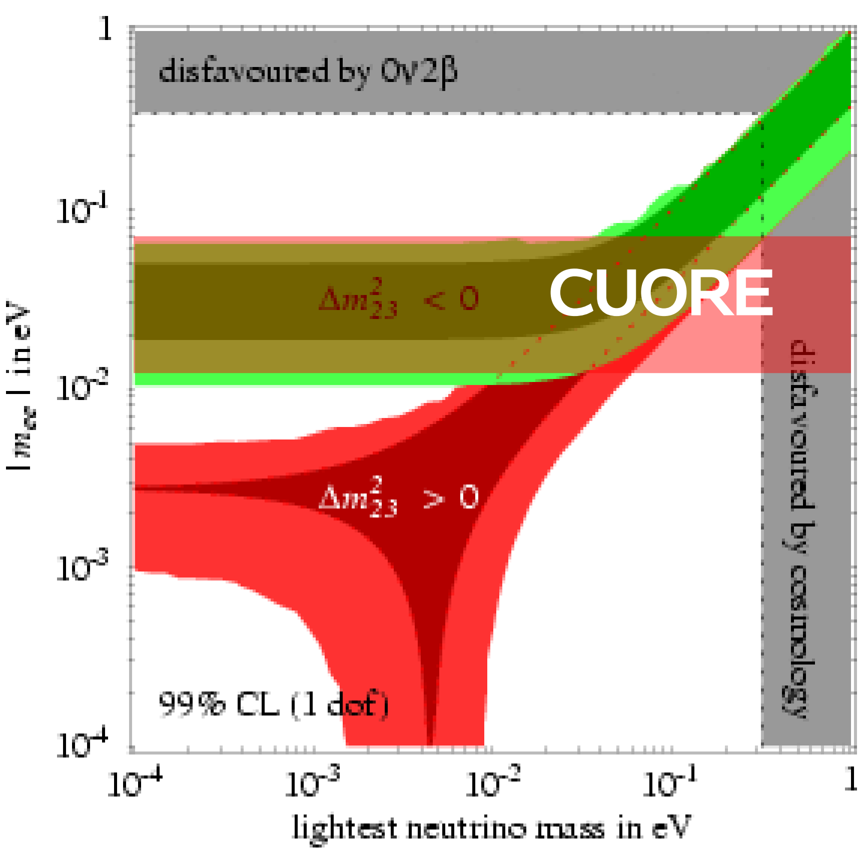
CUORE $\beta\beta(0\nu)$ sensitivity will depend strongly on the background level and detector performance.

In five years:



B(counts/keV/kg/y)	Δ(keV)	$T_{1/2}$(y)	$\lvert\langle m_\nu\rangle\rvert$ (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

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



Spread in $\langle m_\nu\rangle$ from nuclear matrix element uncertainty

CUORE: stato attuale

- **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)

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

Conclusioni

- 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!!!