Détection de Rayonnement à Très Basse Température

Perspectives des détecteurs cryogéniques

Détection des événements rares

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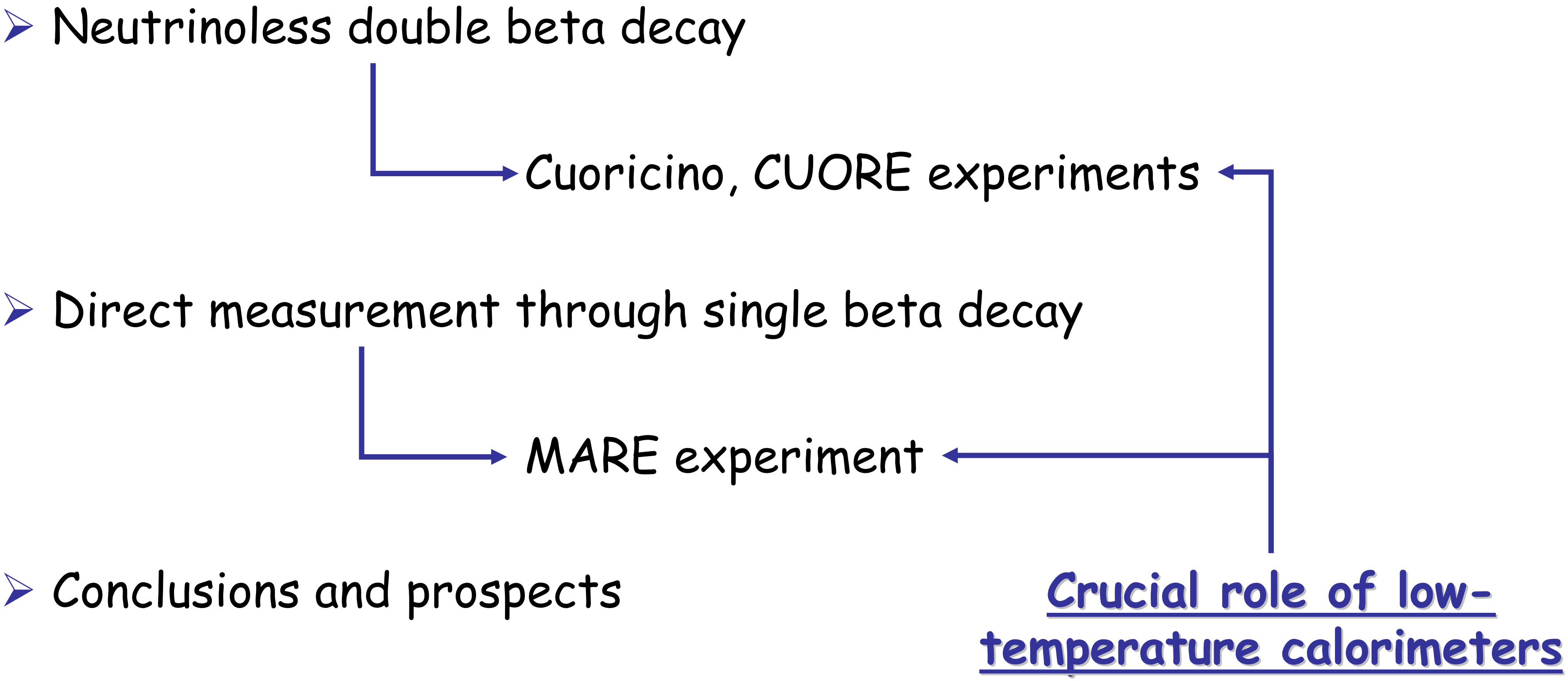
Outline



- The quest of neutrino mass and nature
- Neutrinoless double beta decay
  - Cuoricino, CUORE experiments
- Direct measurement through single beta decay
  - MARE experiment
- Conclusions and prospects

Crucial role of low-temperature calorimeters

General overview: main pieces of the puzzle

Oscillation experiments

↓

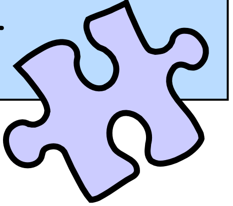
Neutrinos have non-zero mass

ν mass scale is crucial over 2 fronts:
elementary particles physics & cosmology / astrophysics

Cosmology

$\Sigma m_{\nu i} < 0.7 - 1 \text{ eV}/c^2$

- very sensitive
- spread in recent results
- model dependent



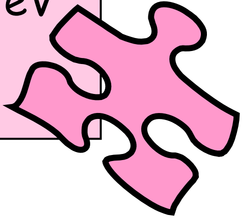
WE NEED TO KNOW:

- absolute ν mass scale
- nature of ν mass

Direct search through β decay

Potential sensitivity
$m(\nu_e) < 2.2 \text{ eV}/c^2$

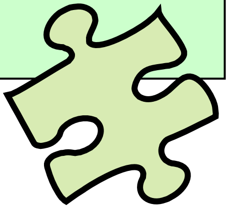
- completely model free
- future sensitivity: 0.2 eV
- in the game if m_ν quasidegenerate



0νββ decay

$\langle m_\nu \rangle < 0.5 \text{ eV}/c^2$

- future sensitivity 0.05 eV
- controversial claim: 0.4 eV
- works only if neutrino is a Majorana particle



Neutrino flavor oscillations and mass scale

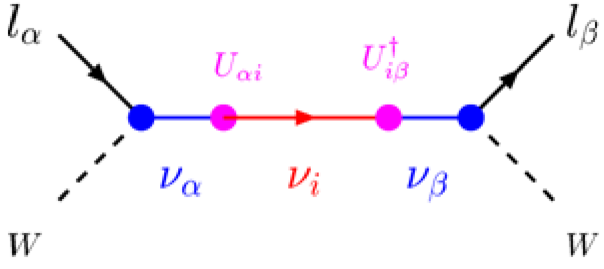
what **we presently know** from **neutrino flavor oscillations**

oscillations do occur → neutrinos are massive

Mass eigenstates (ν_1, ν_2, ν_3)

are different from

Flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$



$$\nu_\alpha = \sum_j U_{\alpha j}\, \nu_j$$

given the three ν mass eigenvalues M_1, M_2, M_3 we have approximate measurements of two ΔM_{ij}^2 $(\Delta M_{ij}^2 \equiv M_i^2 - M_j^2)$

$\Delta M_{12}^2 \sim (9\ \mathrm{meV})^2$ **Solar**

$|\Delta M_{23}^2| \sim (50\ \mathrm{meV})^2$ **Atmospheric**

Neutrino mixing

we have also approximate measurements and/or constraints on U_{lj} → elements of the ν mixing matrix

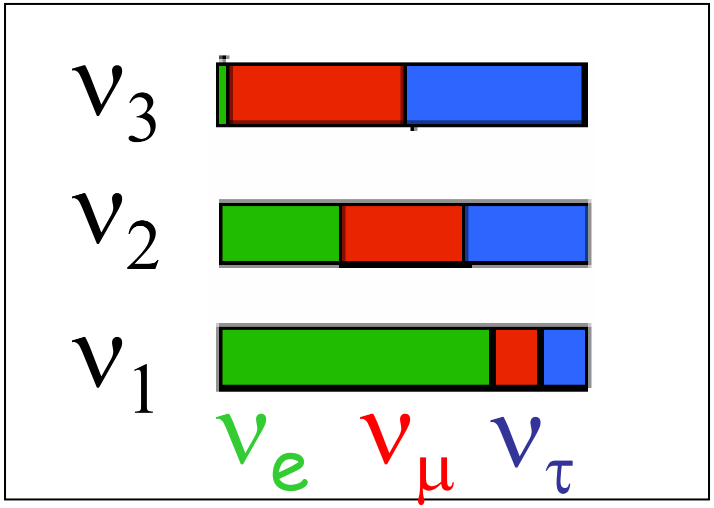
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

parametrized with three angles and three phases

$c_{ij} \equiv \cos\Theta_{ij}$

$s_{ij} \equiv \sin\Theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}\,\nu_1 \\ e^{i\alpha_2/2}\,\nu_2 \\ \nu_3 \end{pmatrix}$$

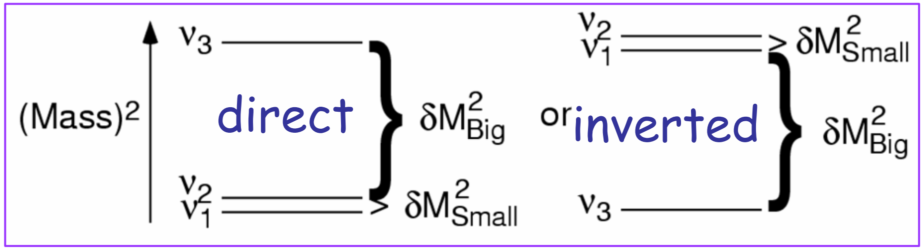


The present knowledge of the values for $U_{\alpha i}$ fixes the composition of the mass eigenstates in terms of flavor eigenstates and vice-versa.

Neutrino flavor oscillations and mass scale

what **we do not know** from neutrino flavor oscillations:

① neutrino mass hierarchy →



② absolute neutrino mass scale → degeneracy ? ($M_1 \sim M_2 \sim M_3$)

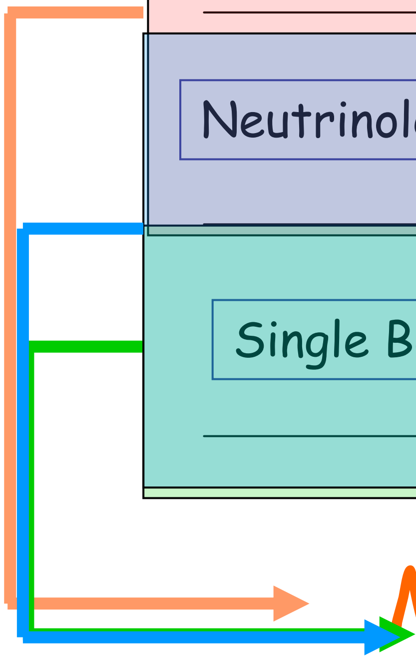
③ DIRAC or MAJORANA nature of neutrinos

Like electrons, neutrinos and antineutrinos are distinct particles. Lepton number plays the role of the electric charge.

Neutrinos and antineutrinos are the same particle. Their behavior is ruled by helicity.

Tools for the investigation of the ν mass scale

Tools	Present sensitivity	Future sensitivity (a few year scale)
Cosmology (CMB + LSS)	0.7 - 1 eV	0.1 eV
Neutrinoless Double Beta Decay	0.5 eV	0.05 eV
Single Beta Decay	2.2 eV	0.2 eV



Model dependent

Direct determination

Laboratory measurements

(LT calorimeters are key instruments)

Complementarity of cosmology, single and double β decay

Cosmology, single and double β decay measure different combinations of the neutrino mass eigenvalues, constraining the neutrino mass scale

In a standard three active neutrino scenario:

$$\Sigma \equiv \sum_{i=1}^{3} M_i$$

cosmology
simple sum
pure kinematical effect

$$\langle M_\beta \rangle \equiv \left(\sum_{i=1}^{3} M_i^2 \, |U_{ei}|^2 \right)^{1/2}$$

beta decay
incoherent sum
real neutrino

$$\langle M_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} M_i \, |U_{ei}|^2 \, e^{i\alpha_i} \right|$$

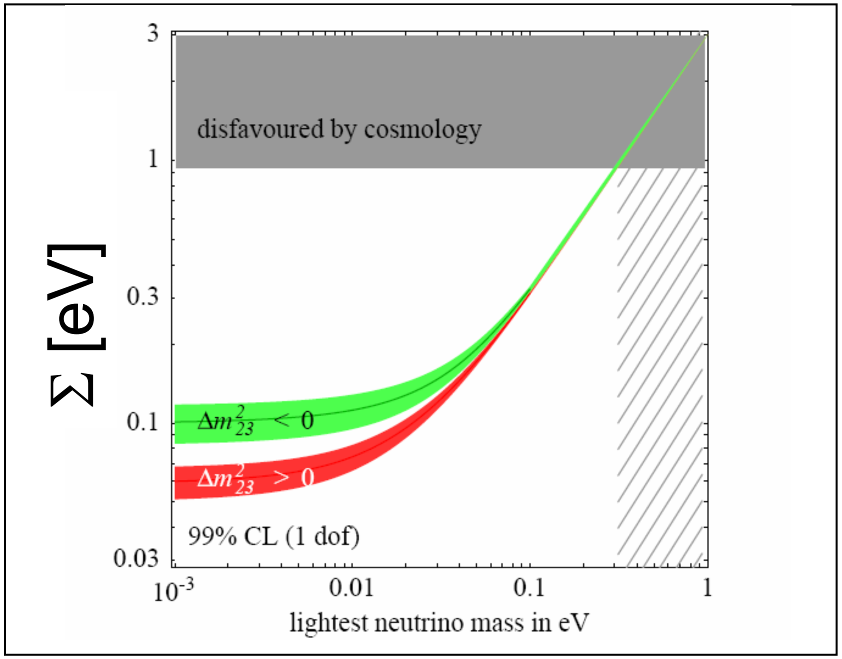
double beta decay
coherent sum
virtual neutrino
Majorana phases

Present bounds

The three constrained parameters can be plotted as a function of the lightest neutrino mass

Two bands appear in each plot, corresponding to inverted and direct hierarchy

The two bands merge in the degenerate case (the only one presently probed)



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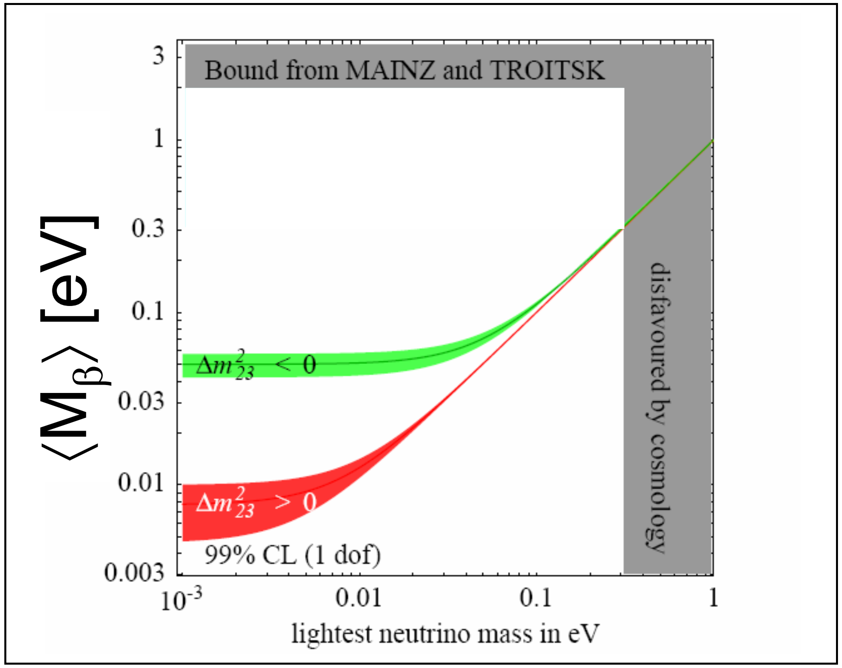
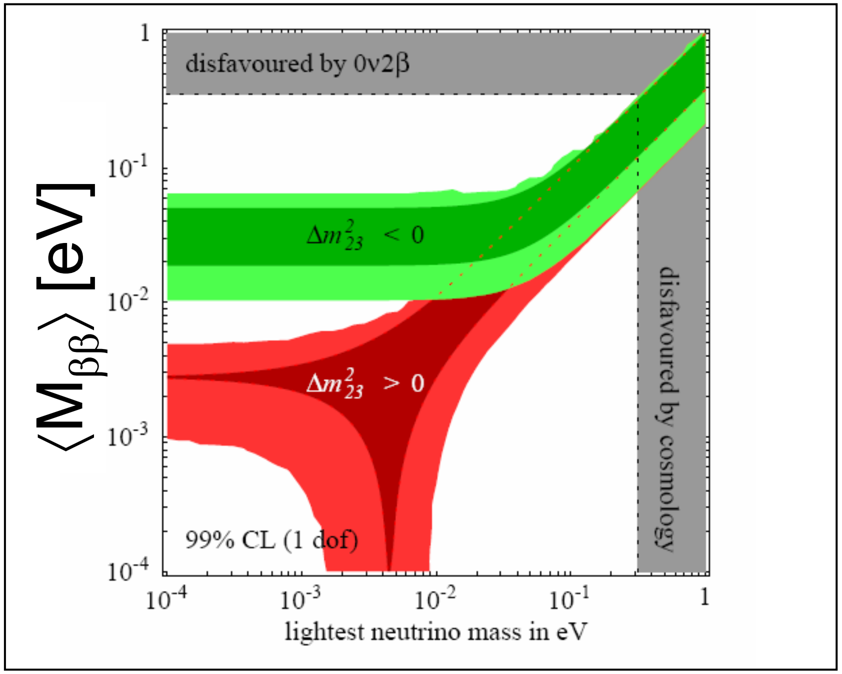




DOUBLE BETA DECAY

Decay modes for Double Beta Decay

Two decay modes are usually discussed:

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ ←

2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{19} - 10^{21}$ y

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

neutrinoless Double Beta Decay (0ν-DBD)
never observed (except a discussed claim)
$\tau > 10^{25}$ y

Process ② would imply new physics beyond the Standard Model

violation of lepton number conservation

It is a very sensitive test to new physics since the phase space term is much larger for the neutrinoless process than for the standard one

interest for 0ν-DBD lasts for ~ 70 years !

Goeppert-Meyer proposed the standard process in 1935
Racah proposed the neutrinoless process in 1937

0ν-DBD, neutrino mass and neutrino flavor oscillations

Observation of **0ν-DBD** → $m_\nu \neq 0$

$\overline{\nu} \equiv \nu$

how **0ν-DBD** is connected to neutrino mixing matrix and masses

neutrinoless Double Beta Decay **rate**

Phase space

Nuclear matrix elements

Effective **Majorana mass**

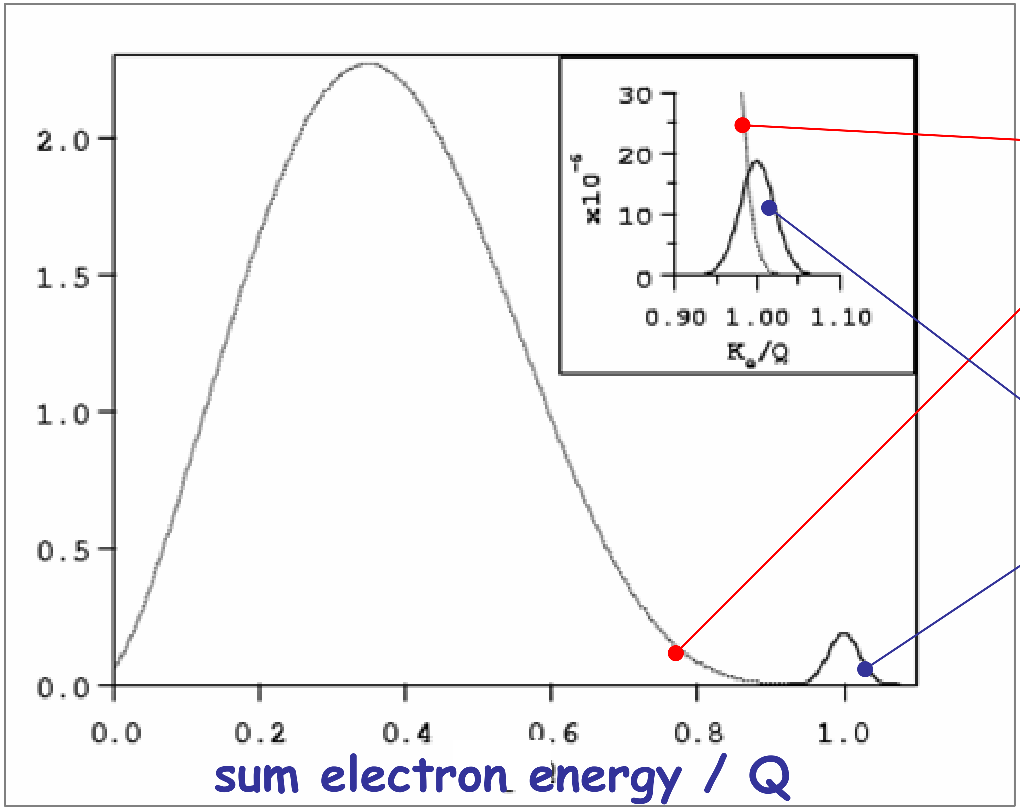
$$1/\tau = G(Q,Z)\,|M_{nucl}|^2 \langle M_{\beta\beta} \rangle^2$$

$$\langle M_{\beta\beta} \rangle = \left| |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \right|$$

can be of the order of ~ 50 meV in case of inverted hierarchy

Electron sum energy spectra in DBD

The shape of the two electron sum energy spectrum enables to distinguish among the two different discussed decay modes



two neutrino DBD

continuum with maximum at ~1/3 Q

neutrinoless DBD

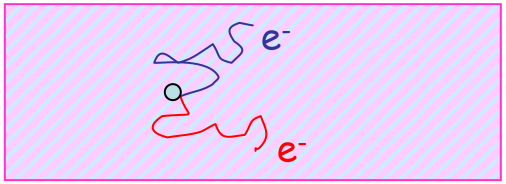
peak enlarged only by
the detector energy resolution
Typical energy for most
interesting candidates: 2 - 3 MeV

Experimental approaches to direct searches

Two approaches for the detection of the two electrons:

Calorimetric

①



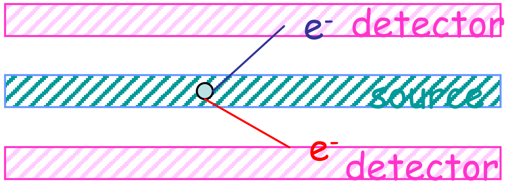
Source ≡ Detector
(calorimetric technique)

- scintillation
- **cryogenic macrocalorimeters (bolometers)**
- solid-state devices
- gaseous detectors

high efficiency and energy resolution

"Tracko-calo"

②



Source ≠ Detector

- scintillation
- gaseous TPC
- gaseous drift chamber
- magnetic field and TOF

event reconstruction,
but low energy resolution

Experimental sensitivity to 0ν-DBD

sensitivity F: lifetime corresponding to the minimum detectable number of events over background at a given confidence level

$b \neq 0$

b: specific background coefficient **[counts/(keV kg y)]**

$b = 0$

live time

source mass

energy resolution

$$F \propto (MT / b\Delta E)^{1/2}$$

$$F \propto MT$$

background level

importance of the nuclide choice

(but large uncertainty due to nuclear physics)

sensitivity to $\langle M_{\beta\beta} \rangle \propto (F/Q\,|M_{nucl}|^2)^{1/2} \propto \dfrac{1}{Q^{1/2}\,|M_{nucl}|}\left(\dfrac{b\Delta E}{MT}\right)^{1/4}$

Present experimental situation in the search for 0ν-DBD

The three presently most sensitive experiments:

- Heidelberg - Moscow (HM) (LNGS) (Source ≡ Detector)

  the most sensitive DBD experiment since 10 years (stopped in May 03)
  classical technique of high resolution Ge diodes
  A subset of the collaboration claims for discovery

- CUORICINO (LNGS) (Source ≡ Detector)

  it is an intermediate generation experiment with a sensitivity to neutrino mass similar to HM (stopped in June 08)
  innovative technique of low-temperature calorimetry

- NEMO3 (LSM) (Source ≠ Detector)

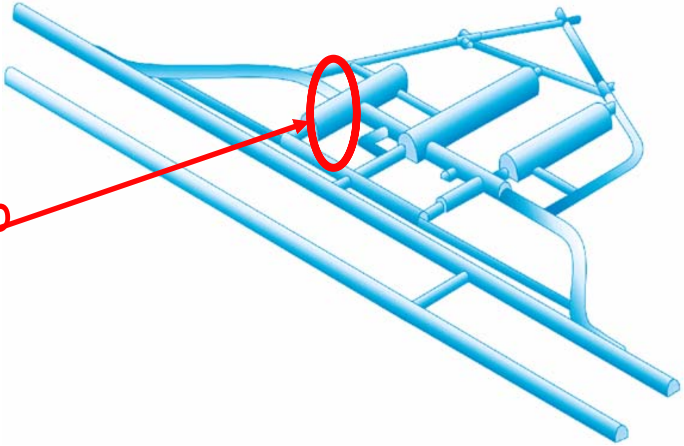
  it is an intermediate generation experiment capable to study different candidate nuclides and to improve the HM results (running)
  more developed example of "tracko-calo" approach

Cuoricino

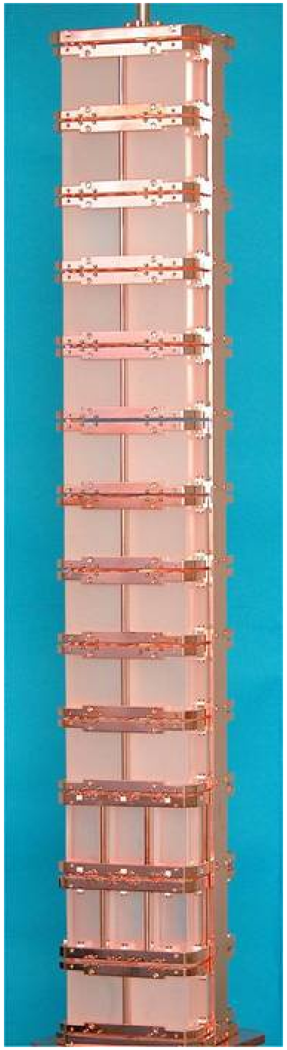
Neutrinoless DBD

Underground National Laboratory of Gran Sasso
located in the highway tunnel
3500 m.w.e.
24μ /m²/d

ITALY



Cuoricino
(hall A)



T= 10 mK

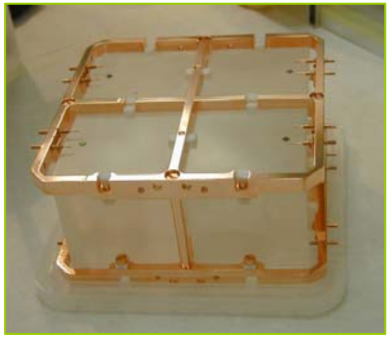
total active mass

- TeO_2 : 40.7 kg
- ^{130}Te : 11.3 kg
- ^{128}Te : 10.5 kg

- 11 modules with 4 *big* detectors
  - 44 TeO_2 crystals
  - $5\times5\times5$ cm^3 ⇒ 790 g
  - **TeO_2 mass ⇒ 34.76 kg**

- 2 modules with 9 *small* detectors
  - 18 TeO_2 crystals
  - $3\times3\times6$ cm^3 ⇒ 330 g
  - **TeO_2 mass ⇒ 5.94 kg**
- 4 crystals are enriched
  - $2\times^{130}TeO_2 + 2\times^{128}TeO_2$

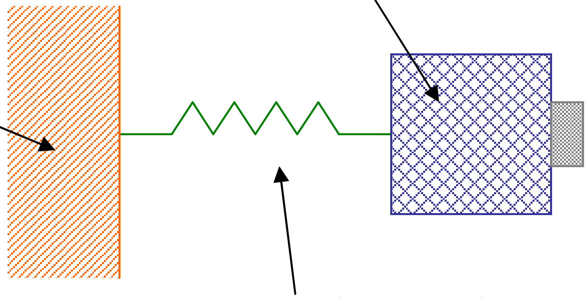
◆ **Heat** @ 10 mK with Ge/NTD thermometer



Scheme of a TeO_2 macrocalorimeter

Te dominates in mass the compound
Excellent mechanical and thermal properties

Energy absorber
TeO_2 crystal
$C \cong 2$ nJ/K $\cong 1$ MeV / 0.1 mK



Heat sink
$T \cong 10$ mK

Thermometer
NTD Ge-thermistor
$R \cong 100$ MW
$dR/dT \cong 100$ kW/mK

Thermal coupling
$G \cong 4$ nW / K = 4 pW / mK

- Temperature signal: $\Delta T = E/C \cong 0.1$ mK for $E = 1$ MeV
- Bias: $I \cong 0.1$ nA ⇒ Joule power $\cong 1$ pW ⇒Temperature rise $\cong 0.25$ mK
- Voltage signal: $\Delta V = I \times dR/dT \times \Delta T \Rightarrow \Delta V = 1$ mV for $E = 1$ MeV
- Signal recovery time: $\tau = C/G \cong 0.5$ s
- Noise over signal bandwidth (a few Hz): $V_{rms} = 0.2$ mV

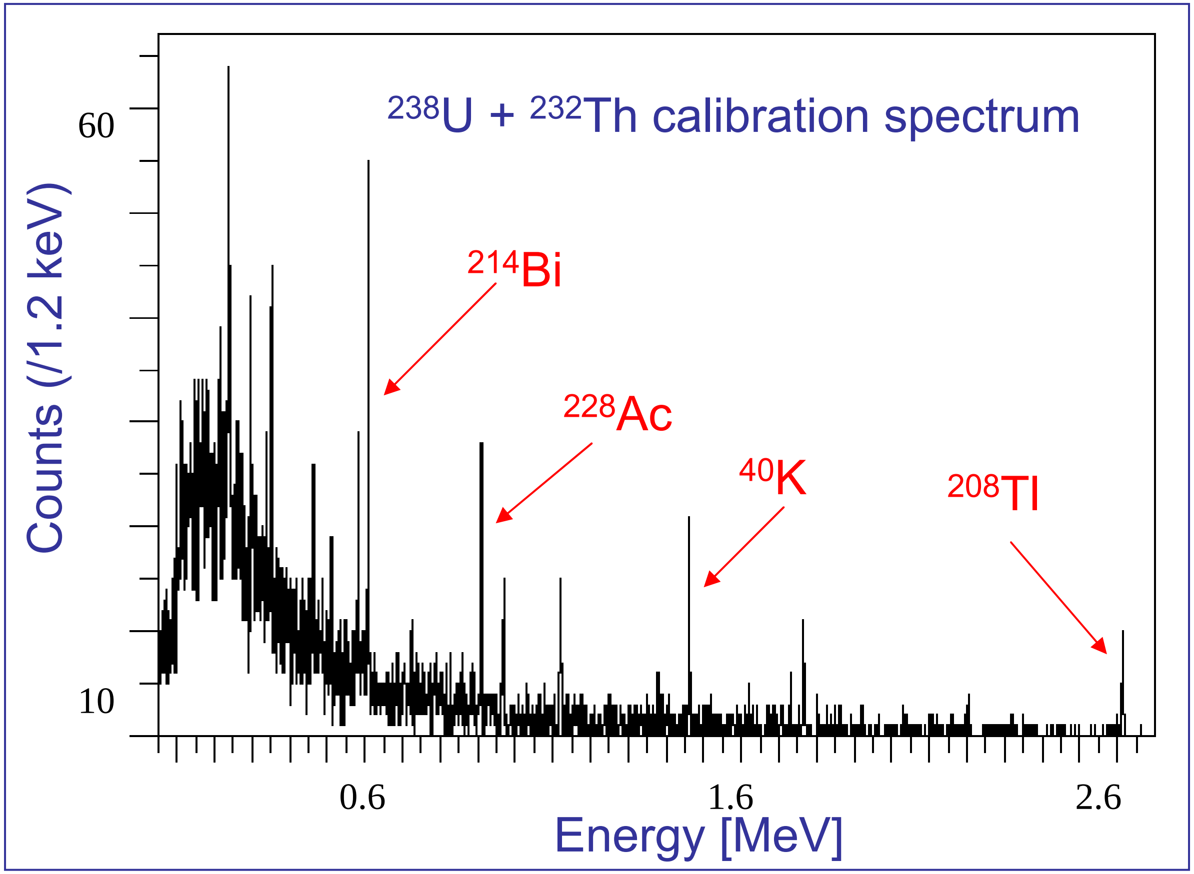
In real life signal about
a factor 2 - 3 smaller

Energy resolution (FWHM): $\cong 1$ keV

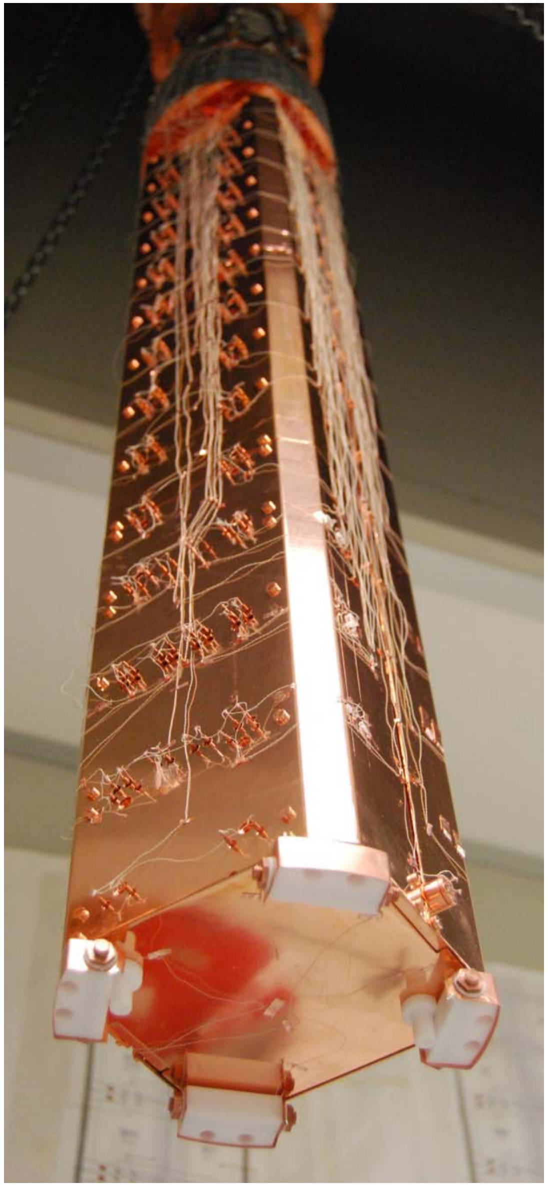
Technical results on detector performances

Performance of CUORICINO-type detectors ($5 \times 5 \times 5\ cm^3$ - 790 g):

- Detector base temperature: ~ 7 mK
- Detector operation temperature: ~ 9 mK
- Detector response: ~ 250 mV/ MeV
- FWHM resolution: ~ 3 keV @ 2.6 MeV



In Cuoricini sempiterna memoria



End of June 2008:
Cuoricino has been shut down

Saturation of sensitivity
Need of experimental space in hallA for further tests

Neutrinoless DBD results

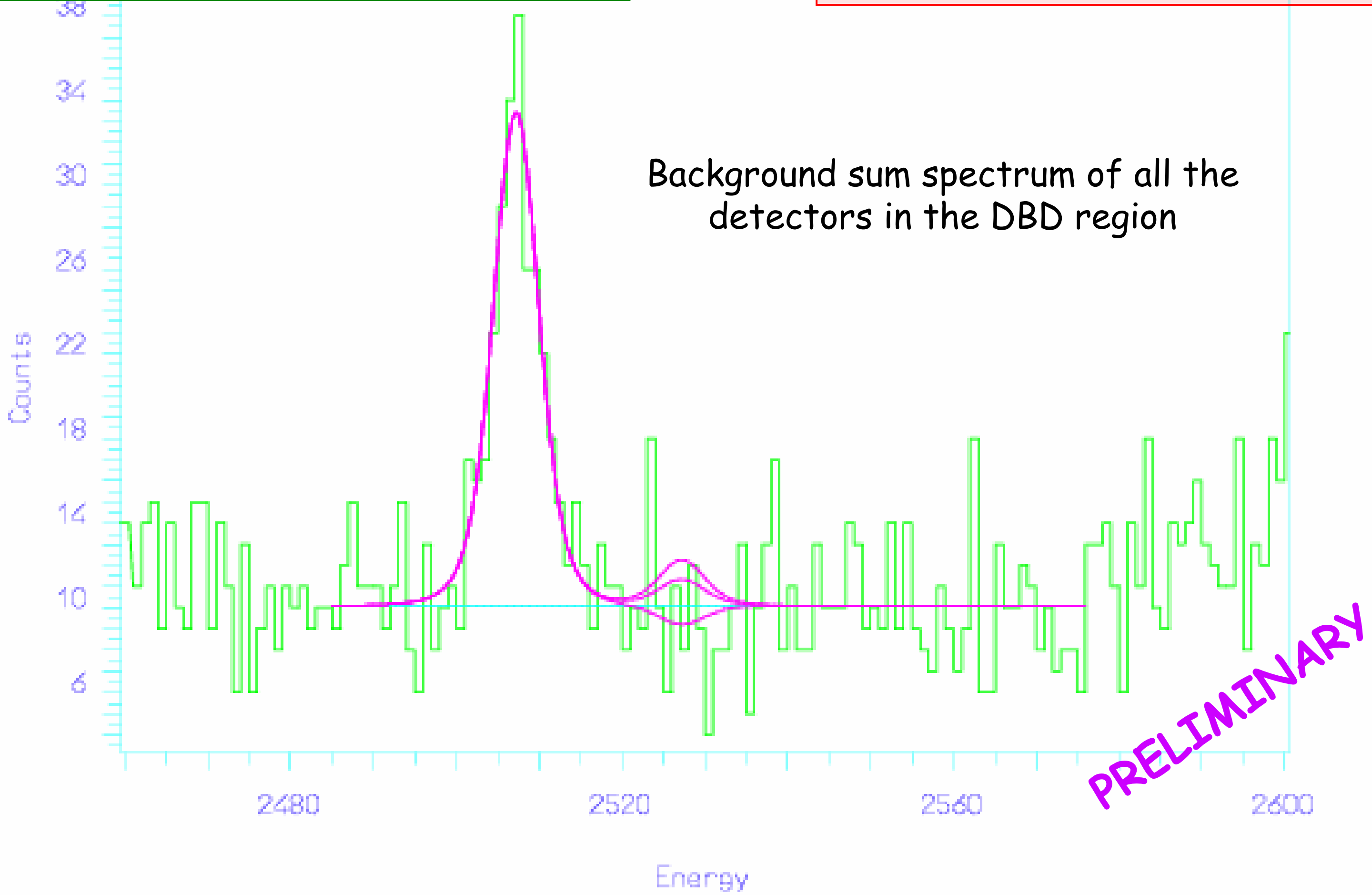
UPDATED RESULTS:

very preliminary

MT = 18 kg ^{130}Te × y

$T_{1/2}^{0\nu}$ (y) > 2.94 × 10^{24} y

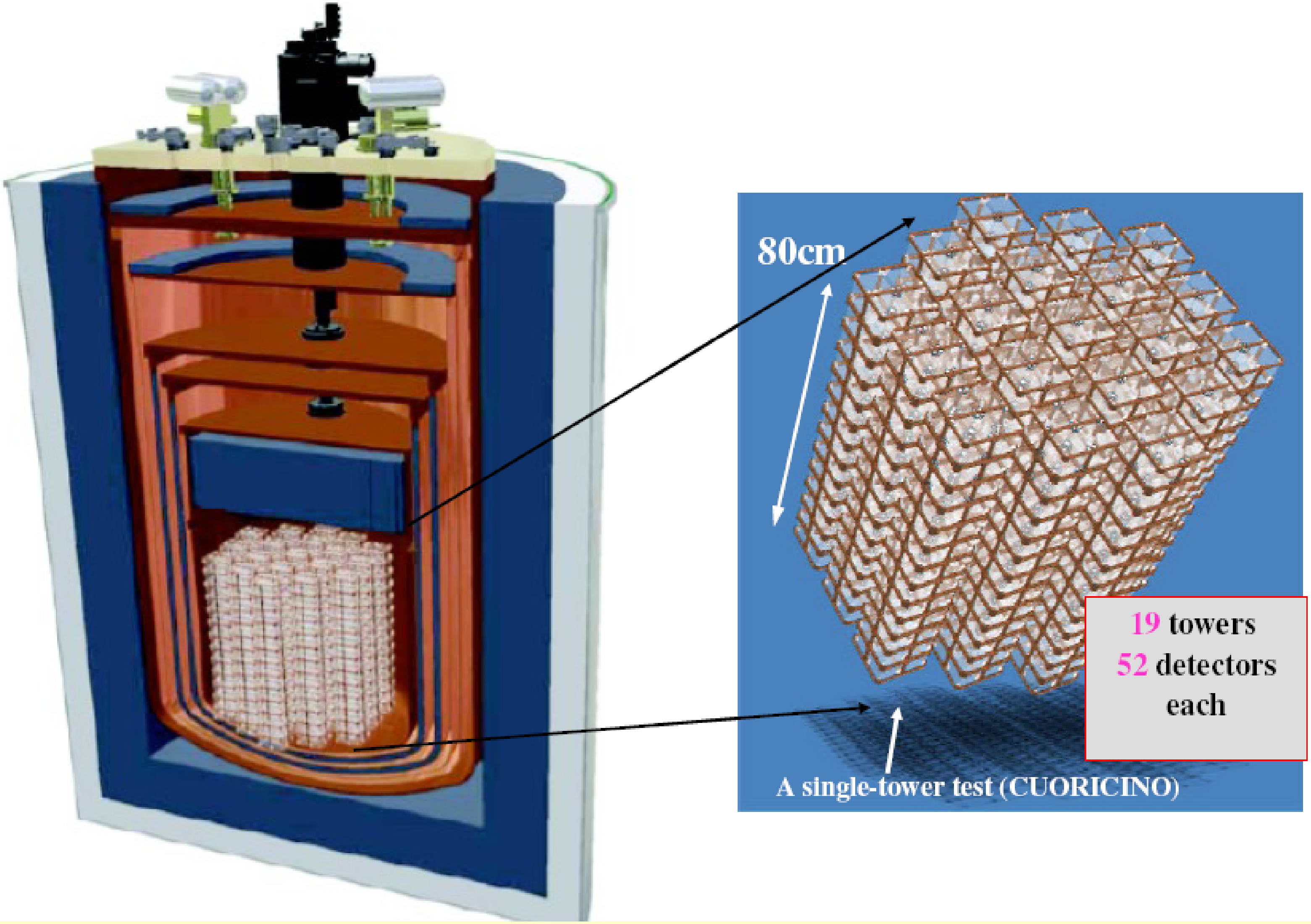
m_{ee} < 0.2 – 0.68 eV



Background sum spectrum of all the detectors in the DBD region

CUORE

Cryogenic Underground Observatory for Rare Events



Closed packed array of 988 TeO_2 5x5x5 cm^3 crystals ⇒741 kg TeO_2 ⇒ 204kg ^{130}Te

CUORE status

- CUORE has a dec … on has started

- The CUORE refr … n ordered

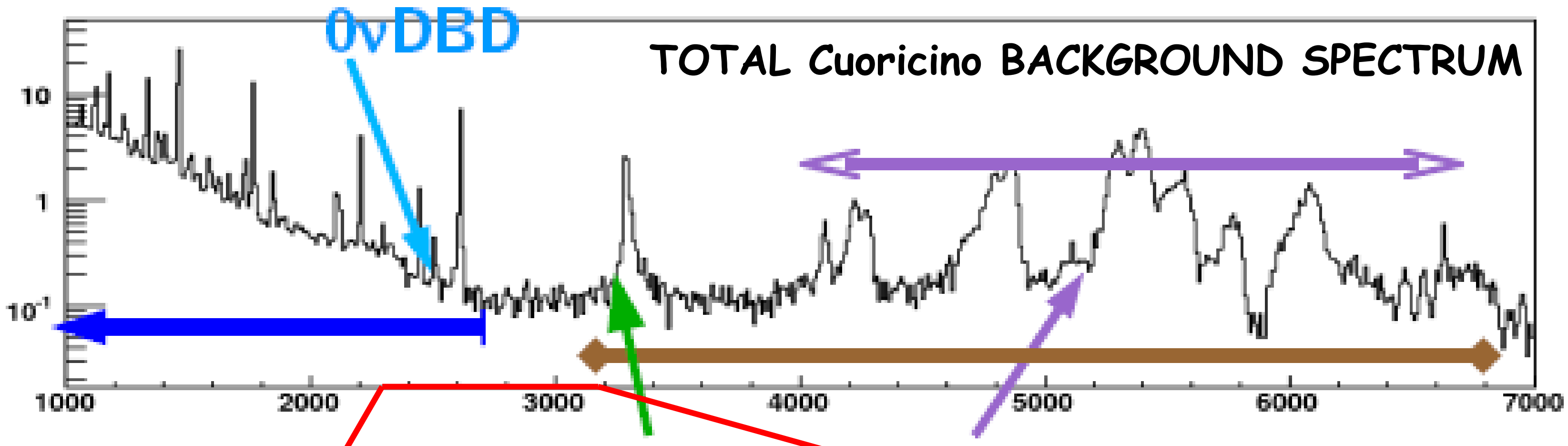
- 1000 crystals are … ch in Nov 2008

- The first CUORE … 9 and operated in 2010

- CUORE sensitivi
  $\langle M_{\beta\beta} \rangle \sim$ 50 meV with … ierarchy region
  a factor 2 better wi … ted hierarchy region

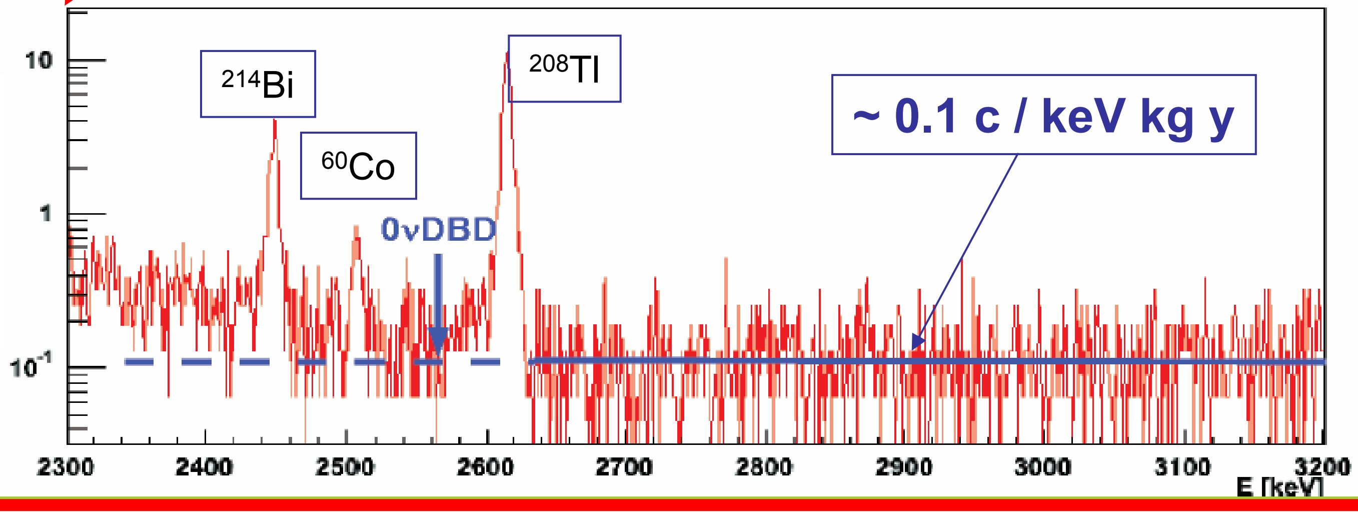
CUC … 2012

Surface background in Cuoricino



Gamma region

Alpha region, dominated by peaks and by their tails due to shallow contamination of the crystal surfaces



~ 0.1 c / keV kg y

Strategies for the control of the surface background from inert materials

(A) Passive methods ⇒ surface cleaning

- Mech

Crucial test in progress
in the former CUORICINO location

- Passivation

(B) Active methods ("reserve weapons" and diagnostic) ⇒events ID

→ ① surface sensitive bolometers

Crucial importance of macrobolometers

→ many interesting high-Q-value candidates
can be studied with very low background

SINGLE BETA DECAY

Model independent tool: the kinematics of β decay

basic idea to measure ν mass: use only kinematics → $E^2 = M^2c^4 + p^2c^2$

→ processes involving neutrinos in the final state

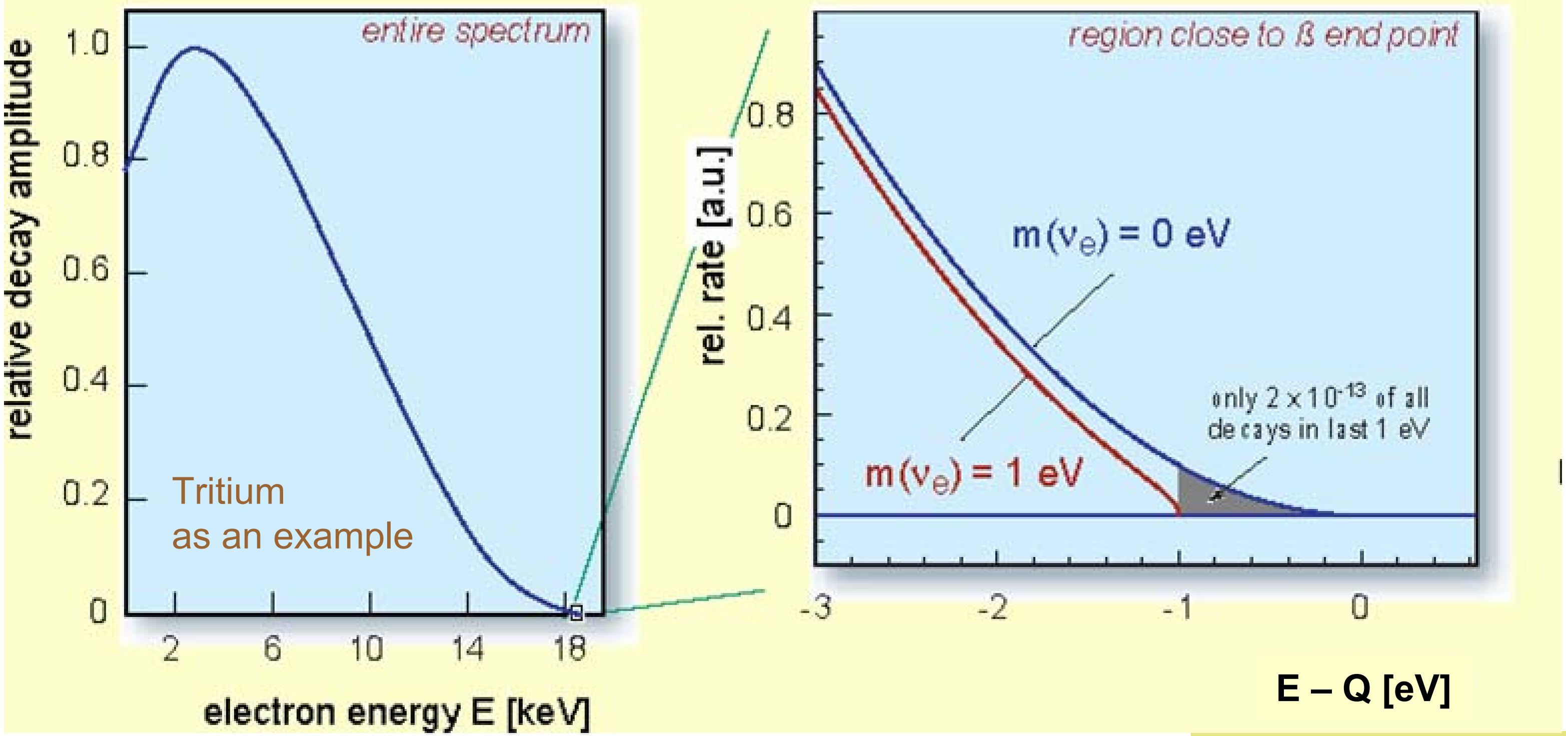
Single β Decay

$(A,Z) \rightarrow (A,Z+1) + e^- + \nu_e$

$Q = M_{at}(A,Z) - M_{at}(A,Z+1) \cong E_e + E_\nu$

The modified part of the beta spectrum is over range of the order of $[Q - M_\nu c^2 , Q]$

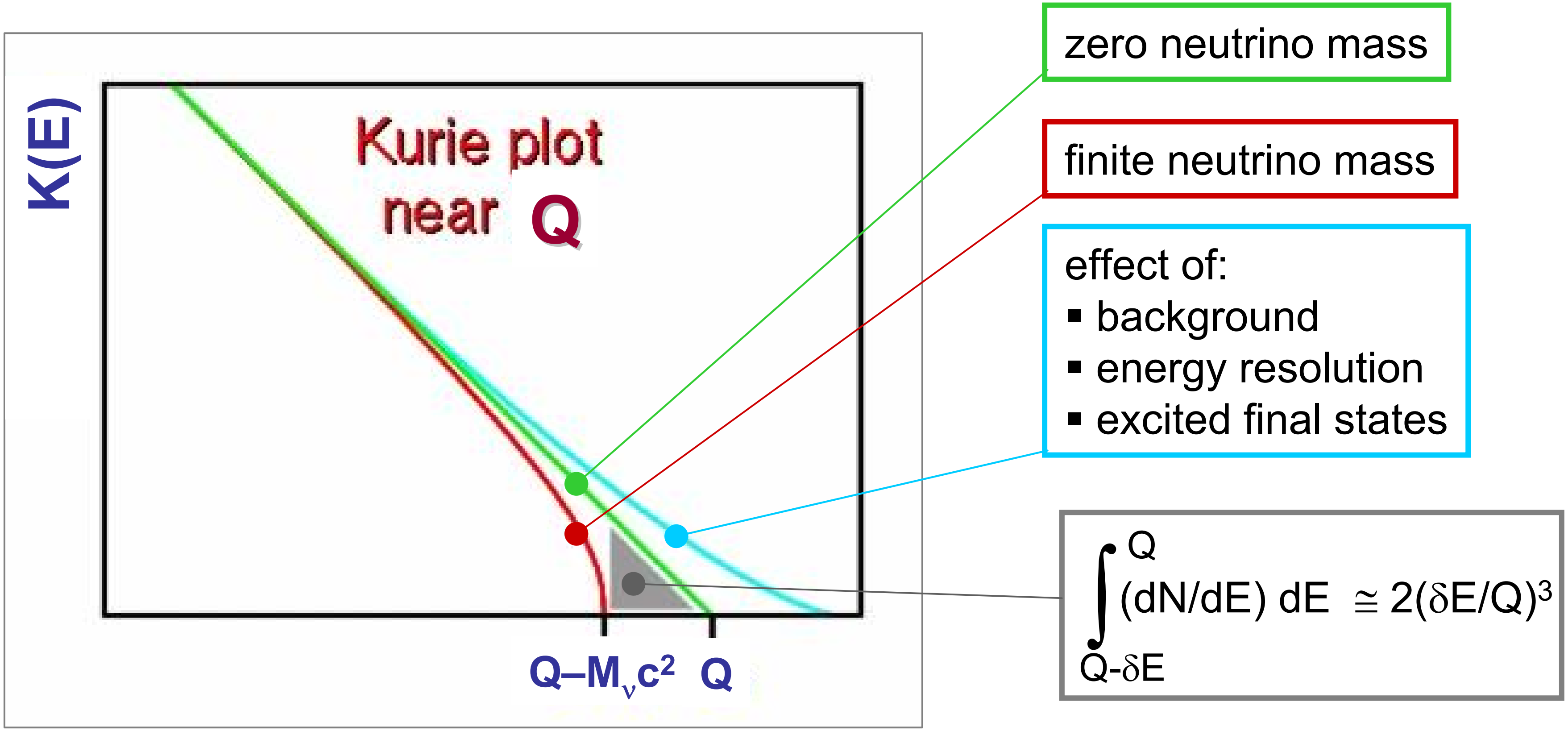
Effects of a finite neutrino mass on the beta decay



The count fraction laying in this range is $\propto (M_\nu/Q)^3$ → **low Q are preferred**

Effects of a finite neutrino mass on the Kurie plot

The Kurie plot $K(E_e)$ is a convenient linearization of the beta spectrum



zero neutrino mass

finite neutrino mass

effect of:
- background
- energy resolution
- excited final states

$$\int_{Q-\delta E}^{Q} (dN/dE)\, dE \cong 2(\delta E/Q)^3$$

Mass hierarchy

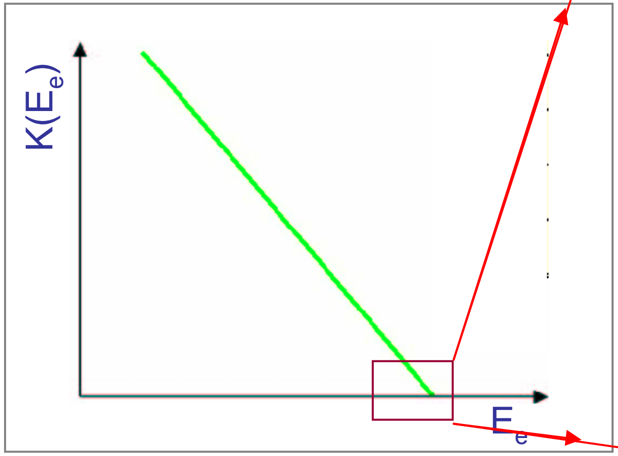
In case of mass hierarchy:

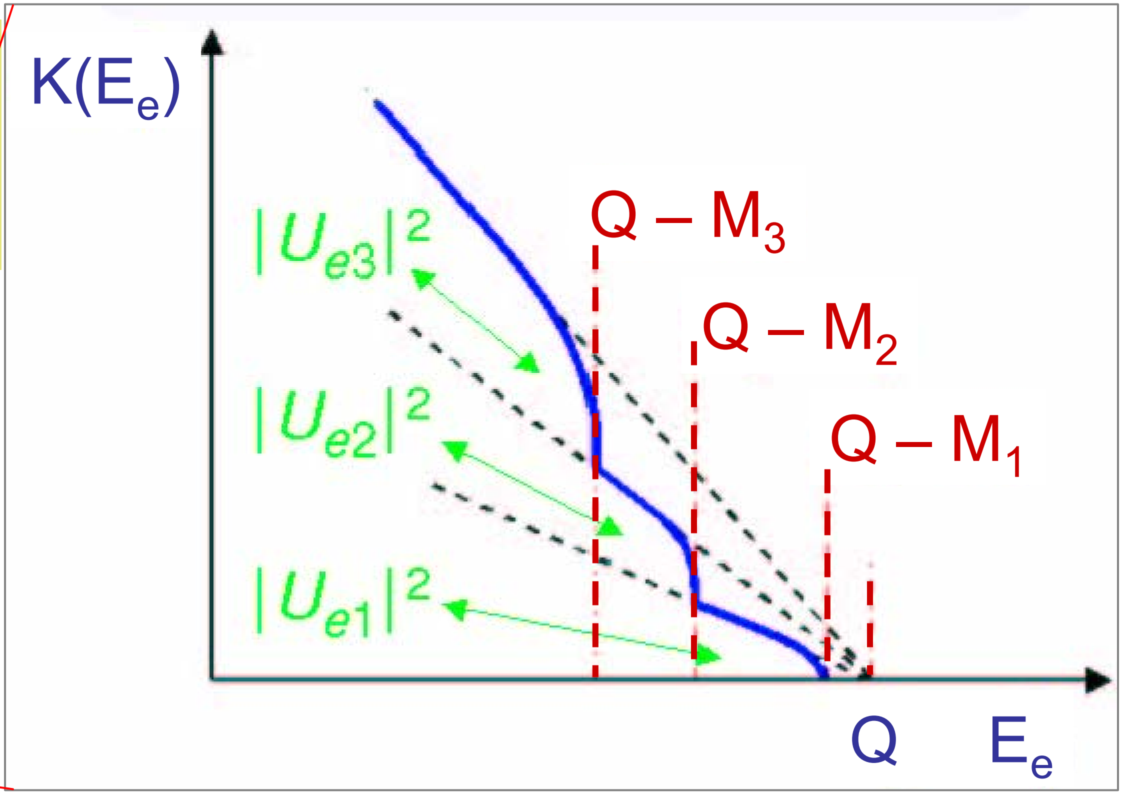
- the Kurie plot ≡ superposition of three different sub - Kurie plots
- each sub - Kurie plot corresponds to one of the three different mass eigenvalues

The weight of each sub – Kurie plot will be given by $|U_{ej}|^2$, where

$$|\nu_e\rangle = \sum_{i=1}^{3} U_{ei} \, |\nu_{Mi}\rangle$$

This detailed structure will not be resolved with present and planned experimental sensitivities (~ 0.2 eV)

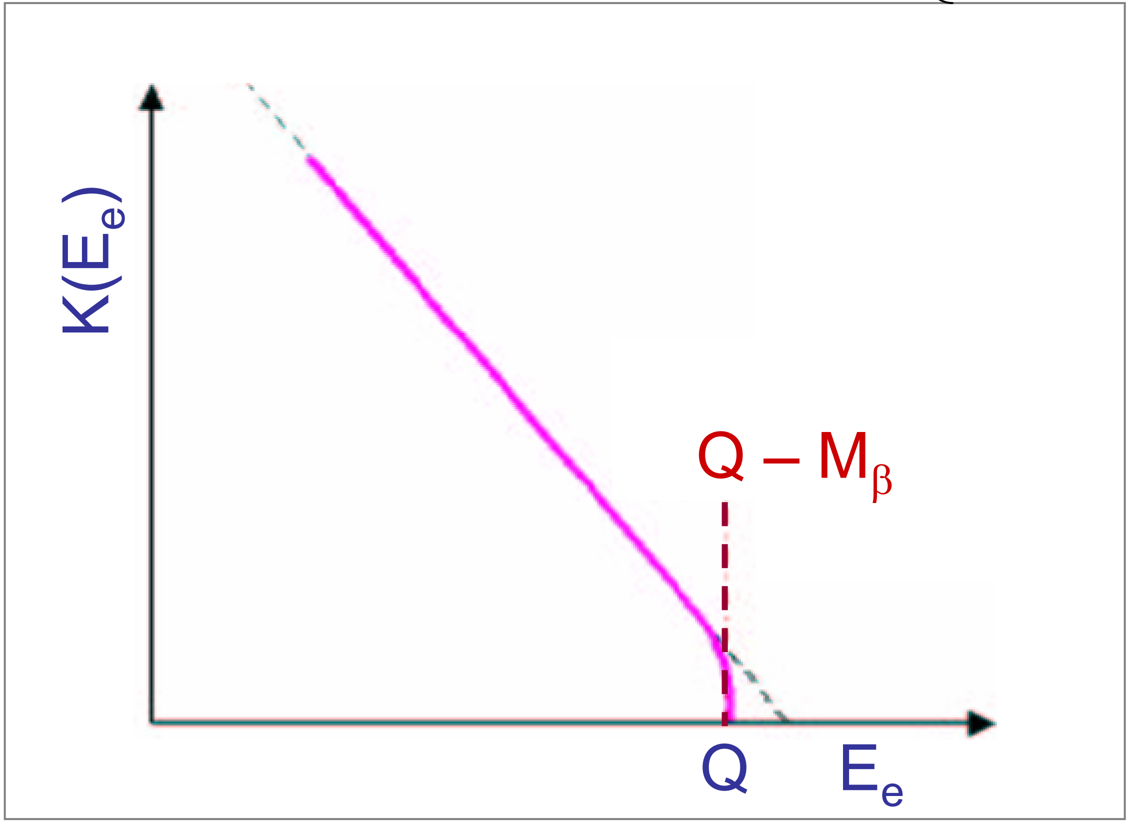




Mass degeneracy

If the 3 mass components cannot be resolved or degeneracy holds: the Kurie-plot can be described in terms of a single mass parameter, a mean value of the three mass eigenstates

$$\langle M_\beta \rangle = \left(\sum M_i^2 \, |U_{ei}|^2 \right)^{1/2}$$



Experimental searches based on nuclear beta decay

Requests:

- high energy resolution ⇒ a tiny spectral distortion must be observed
- high statistics in a very narrow region of the beta spectrum
- well known response of the detector ⇒ spectral output for an energy δ function input
- control of any systematic effect that could distort the spectral shape

Approximate approach to evaluate sensitivity to neutrino mass $\sigma(M_\nu)$:

Require that the deficit of counts close to the end point due to neutrino mass be equal to the Poissonian fluctuation of number of counts in the massless spectrum

$$\sigma(M_\nu) \cong \sqrt[4]{\frac{1.6\, Q^3\, \Delta E}{A\, T_M}}$$

total source activity

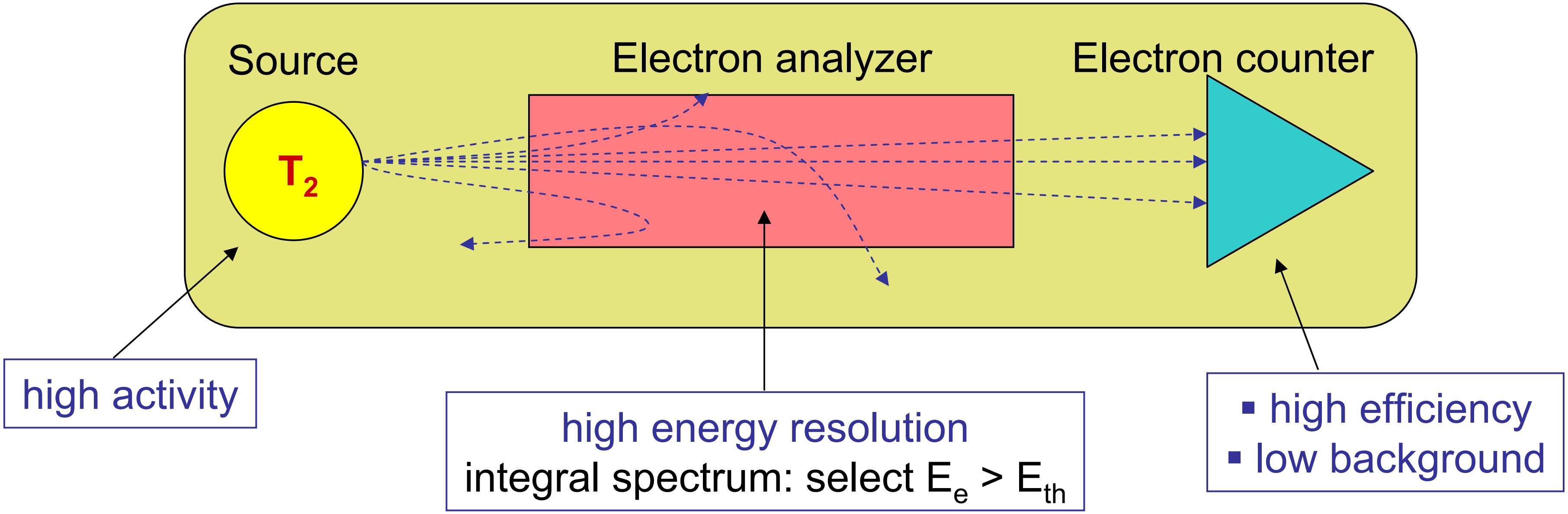
energy resolution

live time

Spectrometers

source separate from detector (the source is T - Q=18.6 keV)

- determine electron energy by means of a selection on the beta electrons operated by proper electric and magnetic fields
- measurement of the electron energy out of the source
- magnetic and electrostatic spectrometers
- present achieved sensitivity: ~ 2 eV (Troitsk/Mainz)
- future planned sensitivity: ~ 0.2 eV (KATRIN)



Source

Electron analyzer

Electron counter

T_2

high activity

high energy resolution

integral spectrum: select $E_e > E_{th}$

- high efficiency
- low background

Microcalorimeters

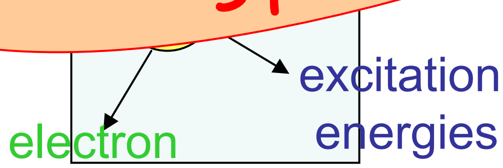
source ≡ detector (calorimetric approach) (the source is ^{187}Re - Q=2.5 keV)

- determine all the "visible" energy of the decay with a high resolution low energy "nuclear" detector
- measurement of the neutrino
- cryogenic microcalori
- present achie
- future

on
dN/dE

presence of decays to
states, the calorimeter
asures both the electron and
the de-excitation energy

Spectrometers and micro-calorimeters have completely different systematic uncertainties



Contra: All the beta electrons are collected
Not-resolved low-energy pulse pile-up
is the main problem
→ it distorts the end-point region

Calorimeter requirements

Requirements for a sensitive calorimetric measurement:

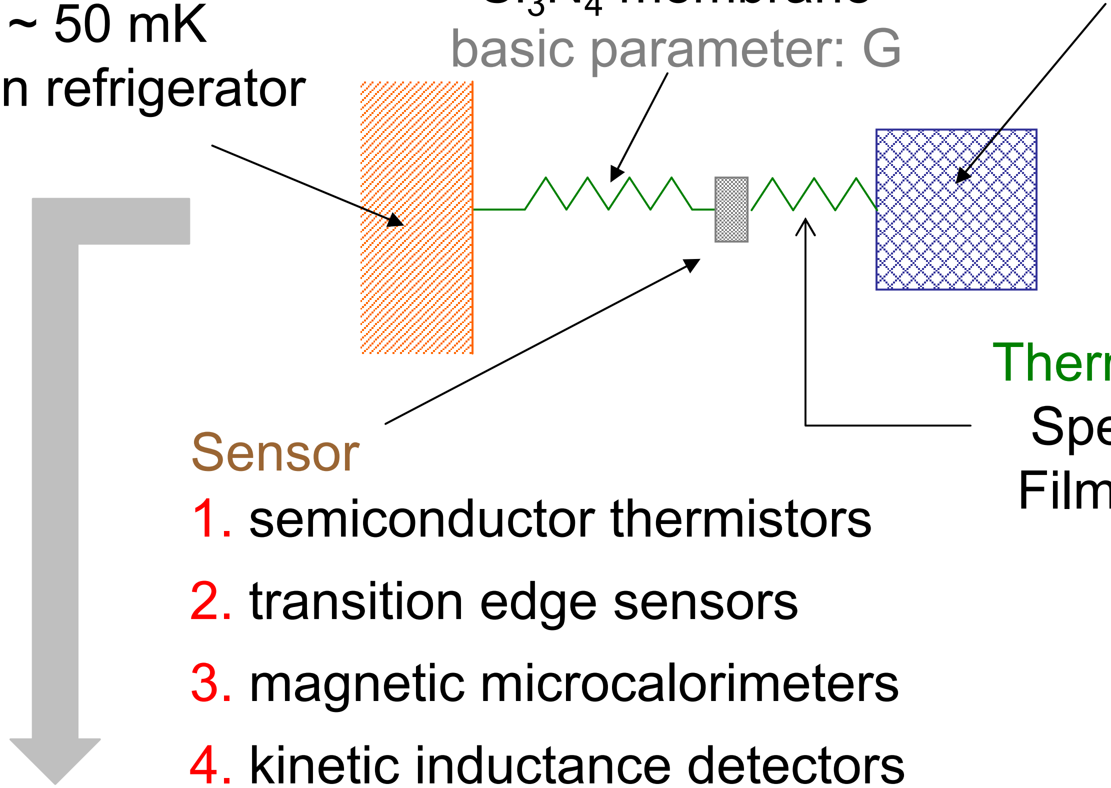
- precise determination of the β energy
- high statistics
- low pile-up fraction

✓ short pulse-pair resolving time
✓ fractionate the whole detector in many independent elements

In terms of detector technology:
development of a single element with these features:

- extremely high energy resolution in the keV range (1‰)
- very fast risetime (present 100 μs → planned 1 μs)
- high reproducibility of the single element
- possibility of multiplexing

Scheme of a ^{187}Re microcalorimeter



Heat sink
T ~ 50 mK
dilution refrigerator

Thermal coupling
read-out wires
μ–machined legs
Si_3N_4 membrane
basic parameter: G

Energy absorber
crystal containing Re
M ~ 0.25 - 1 mg
~1 mg ↔ ~1Bq
basic parameter: C

Sensor
1. semiconductor thermistors
2. transition edge sensors
3. magnetic microcalorimeters
4. kinetic inductance detectors

Thermal coupling
Special epoxy
Film deposition

3 - 4 eV energy resolution with optimized absorbers
10-20 eV energy resolution obtained with Re-based absorber

MIBETA (Milano/Como) experiment: the detectors

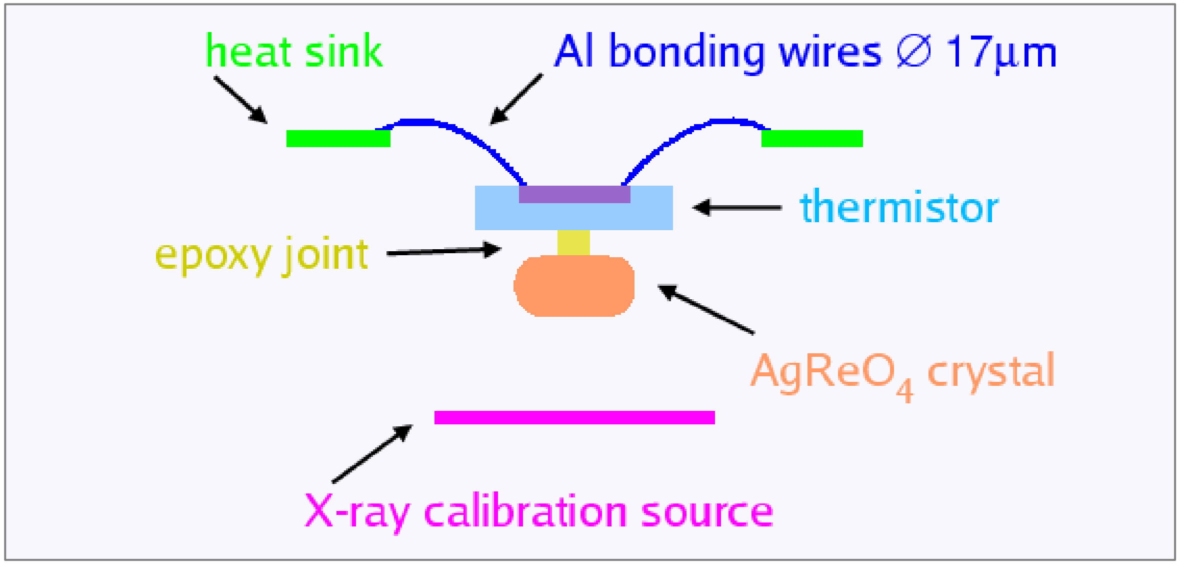
Energy absorbers

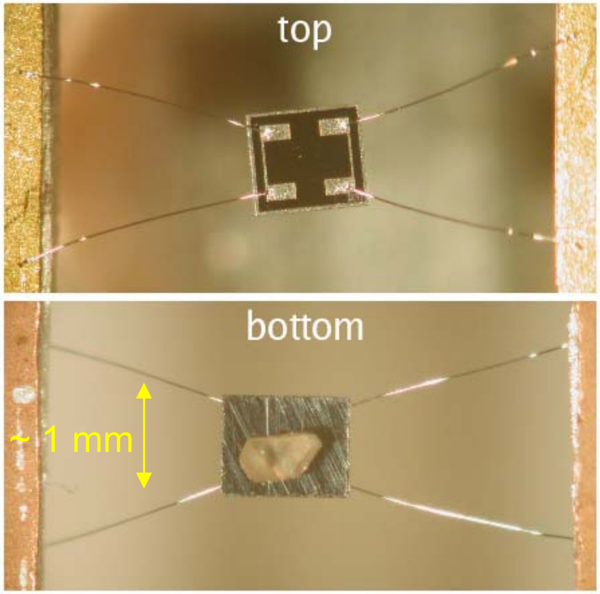
- AgReO$_4$ single crystals
- ^{187}Re activity $\cong$ 0.54 Hz/mg
- M $\cong$ 0.25 mg $\Rightarrow$ A $\cong$ 0.13 Hz

Thermistors

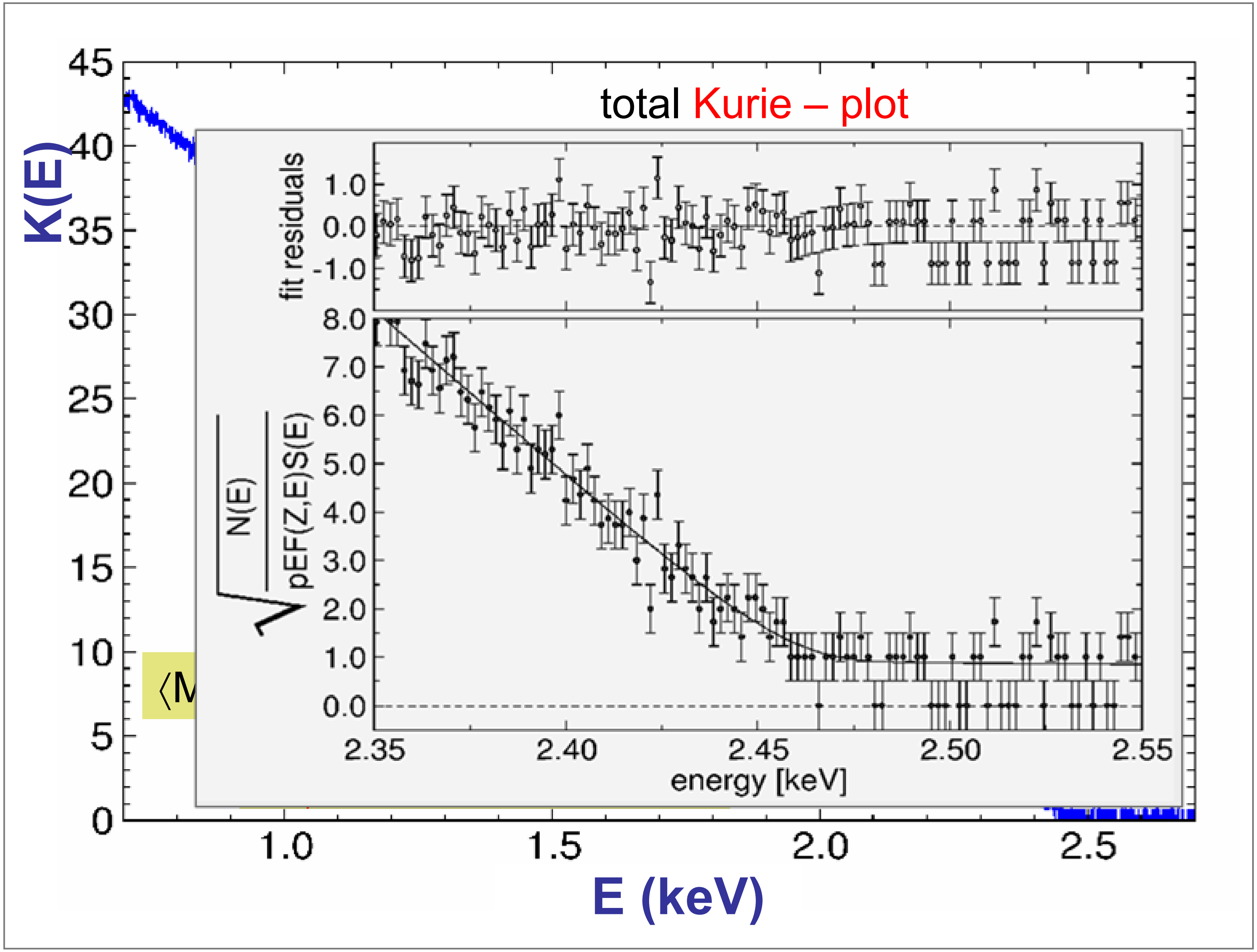
- Si-implanted thermistors
- high sensitivity
- many parameters to play with
- high reproducibility $\Rightarrow$ array
- possibility of μ-machining

typically, array of 10 detectors
lower pile up & higher statistics





MIBETA experiment: the Kurie - plot



The future of bolometric experiments: MARE (Microcalorimeter Arrays for a Rhenium Experiment)

General strategy: push up bolometric technology aiming at:

- multiplication of number of channels
- improvement of energy resolution
- decrease of pulse-pair resolving time

Precursors (MANU, MIBETA)

Semiconductors → Single element / Array of 10 elements / Statistics: N = 10^6 events → $\sigma(\langle M_\beta \rangle) \sim 20$ eV

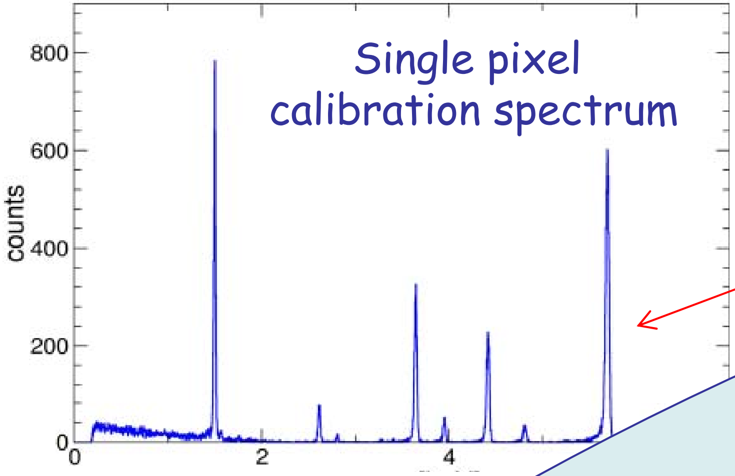
MARE-1 – starting – $\Delta E \sim 10 - 30$ eV – $\tau_R \sim 100\ \mu s$

Transition Edge Sensors / Semiconductors → Arrays of 300 elements / Statistics: N = 10^{10} events → $\sigma(\langle M_\beta \rangle) \sim 2$ eV

MARE-2 – 4 years for R&D – $\Delta E \sim 5 - 10$ eV – $\tau_R \sim 1 - 10\ \mu s$

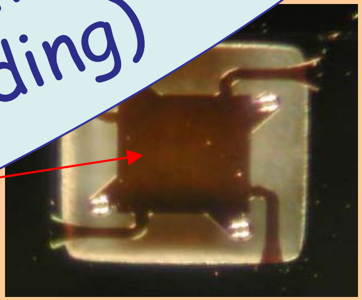
Transition Edge Sensors / Magnetic calorimeters / Kinetic Inductance Det. → Arrays of 50000 elementi / Statistics: N = 10^{13} events / Fast τ_R to control pile-up → $\sigma(\langle M_\beta \rangle) \sim 0.2$ eV

MARE-1 with Si thermistors: imminent data taking

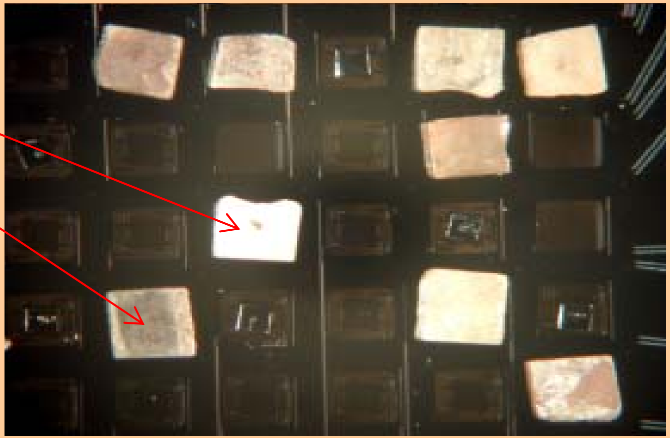


- NASA 6x6 arrays of Si implanted thermistors
- AgReO$_4$ crystals – 0.4 – 0.
- Best operatio
- ΔE ~ 2
-

Set-up with 72 elements completed
Data taking before summer
Expandable to 288 elements
(depends only on funding)



AgReO$_4$ crystals



Conclusions (1)

Why are LT calorimeters so important for neutrino mass and phsyics?

Two basic features of these devices allow experimental approaches impossible or very difficult with other technologies.

① **Wide choice of the detector materials**

→ Inclusion of the relevant isotopes

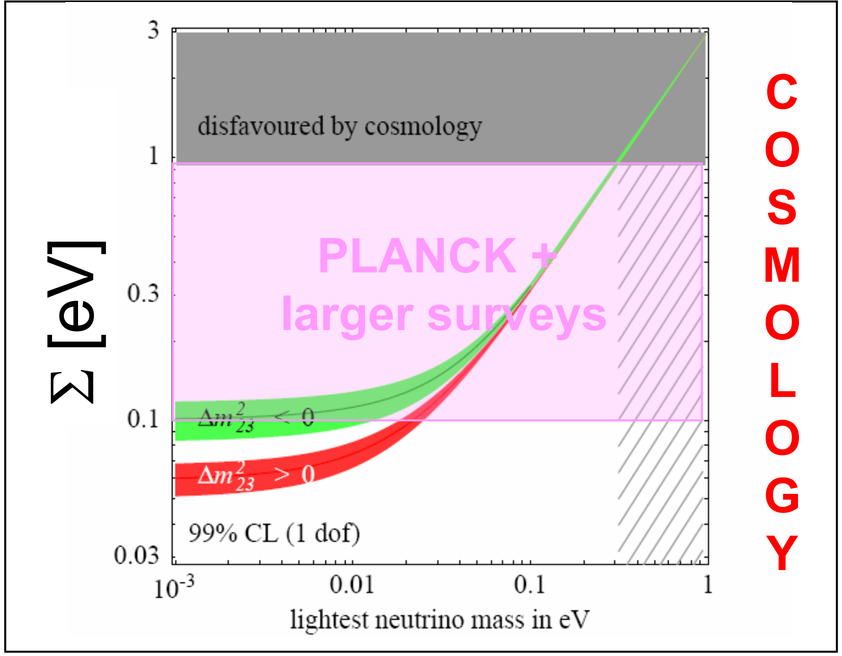
② **Extremely high energy resolution**

→ Identification of characteristic spectral features

Conclusions (2)

Exciting times for neutrino masses:

- degeneracy will be deeply probed
- discovery potential in case of inverted hierarchy



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