quark - lepton
Prague, Czech Rep., July 6-9, 2005

Review of Neutrino Mass Measurements

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- Indirect and direct determinations of the neutrino mass scale
- Laboratory bounds: double and single β decay
- Status and prospects for single β decay
- Status and prospects for double β decay
- Conclusions

Neutrino flavor oscillations and mass scale

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

① oscillations do occur → neutrinos are massive

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

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

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

③ 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

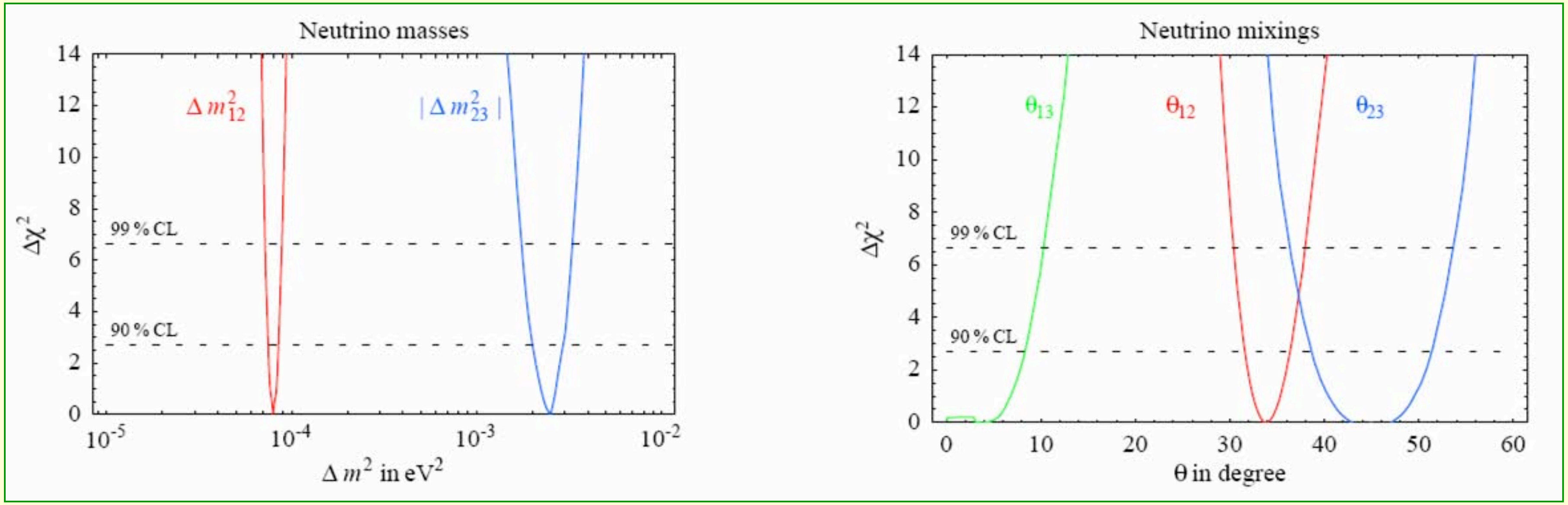
$c_{ij} \equiv \cos\Theta_{ij}$

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

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

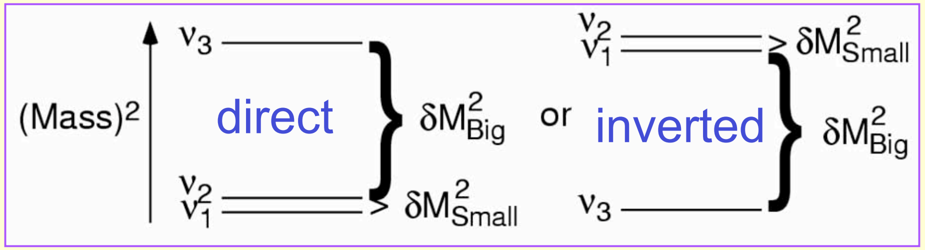
Neutrino flavor oscillations and mass scale

The present knowledge can be summarized in this plot *(Strumia-Vissani hep-ph/0503246)*



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

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

Model dependent tools

Neutrinoless Double Beta Decay

- it works only if neutrino is a Majorana particle ($\nu \equiv \nu^c$)
- uncertainties from nuclear physics
- other mechanisms (not only massive neutrinos) can mediate the process

Cosmology (Cosmic Microwave Background + Large Scale Structure)

very sensitive, but considerable spread in recently published results

Aalseth et al, hep-ph/0412300

author	WMAP	CMB_{hi-l}	SDSS	2dF	other data	Σm_ν [eV]
Bar'03 [93]	x	x	x	x	h (HST)	< 0.75
Teg'03 [94]	x	x	x		SNIa	<1.7
ASB'03 [95]	x	x		x	XLF	$= 0.36$-1.03
WMAP [32]	x	x		x	$Ly\alpha$, h (HST)	< 0.7
Bla'03 [96]	x			x	$\Omega_m = 1$	$= 2.4$
Han'03 [97]	x	x		x	h (HST), SNIa	< 1.01
Han'03 [97]	x	x		x		< 1.2
Han'03 [97]	x			x		< 2.12

- parameter degeneracy
- dependence on priors on cosmological parameters
- sensitivity to even small changes of input data

necessity of **direct measurement** and **cross checks** at this scale

Model independent tool: the kinematics of β decay

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

→ processes involving neutrinos in the final state

Single Beta Decay

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

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

$$\frac{dN}{dE} \propto G_F^2\, |M_{if}|^2\, (E_e + m_e c^2)\, (Q - E_e)^2\, F(Z,E_e)\, S(E_e)\, [1 + \delta_R(Z,E_e)]$$

electron kinetic energy distribution

finite neutrino mass

$$(Q - E_e)^2 \Rightarrow (Q - E_e)\sqrt{(Q - E_e)^2 - M_\nu^2 c^4}$$

→ only a small spectral region very close to Q is affected

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

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

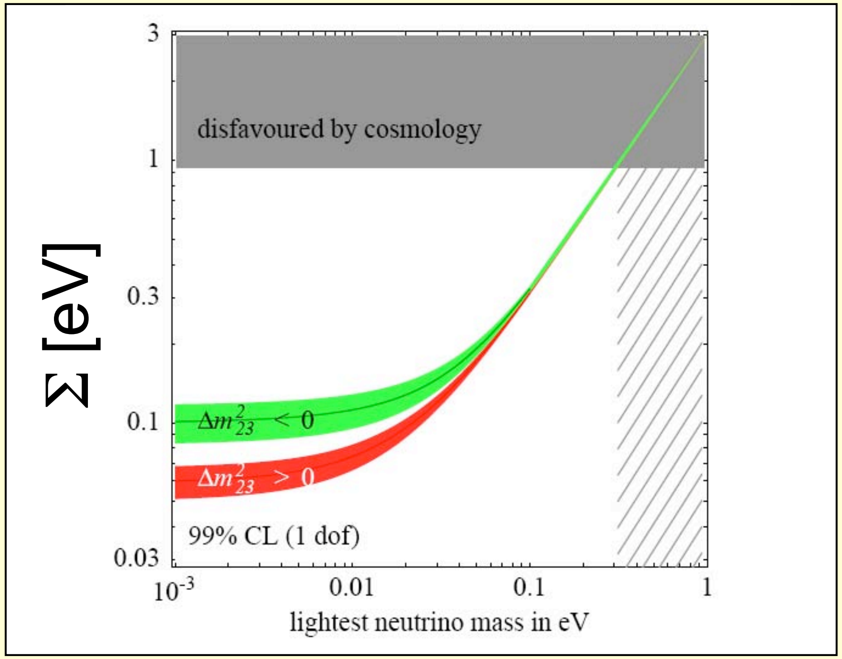
double beta decay
coherent sum
virtual neutrino
Majorana phases

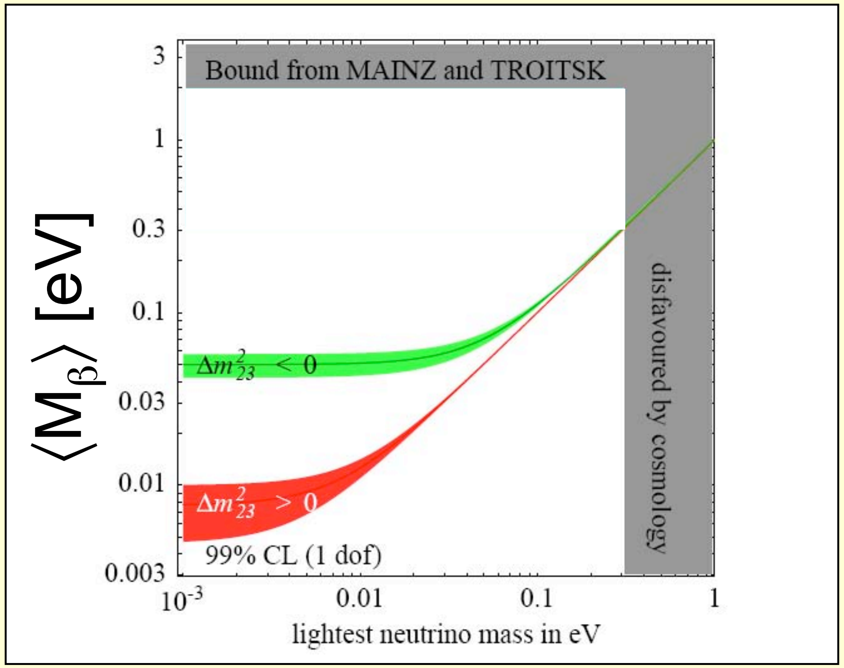
Present bounds

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

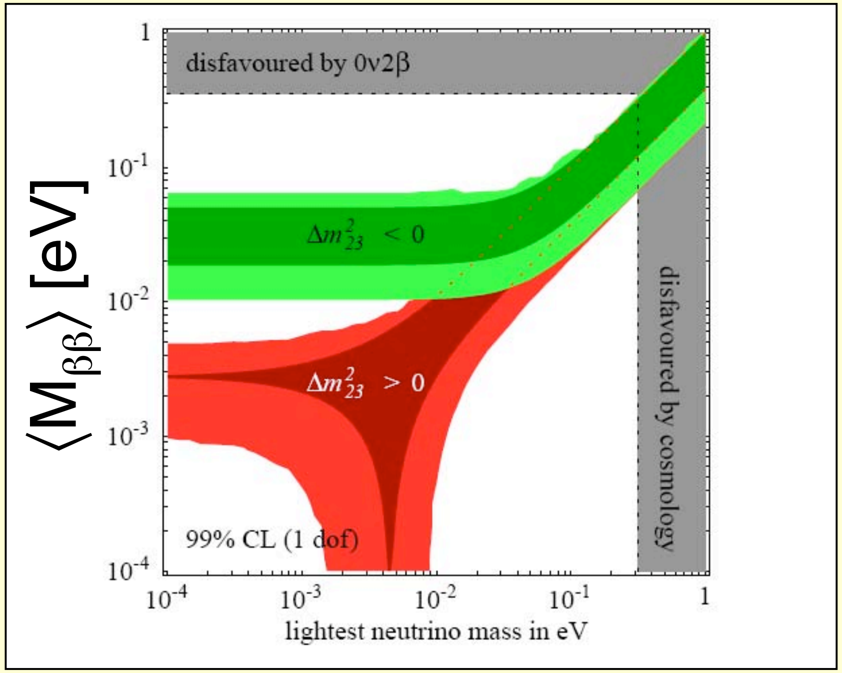
Two bands appear in each plot, corresponding to inverted and direct hierarchy

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





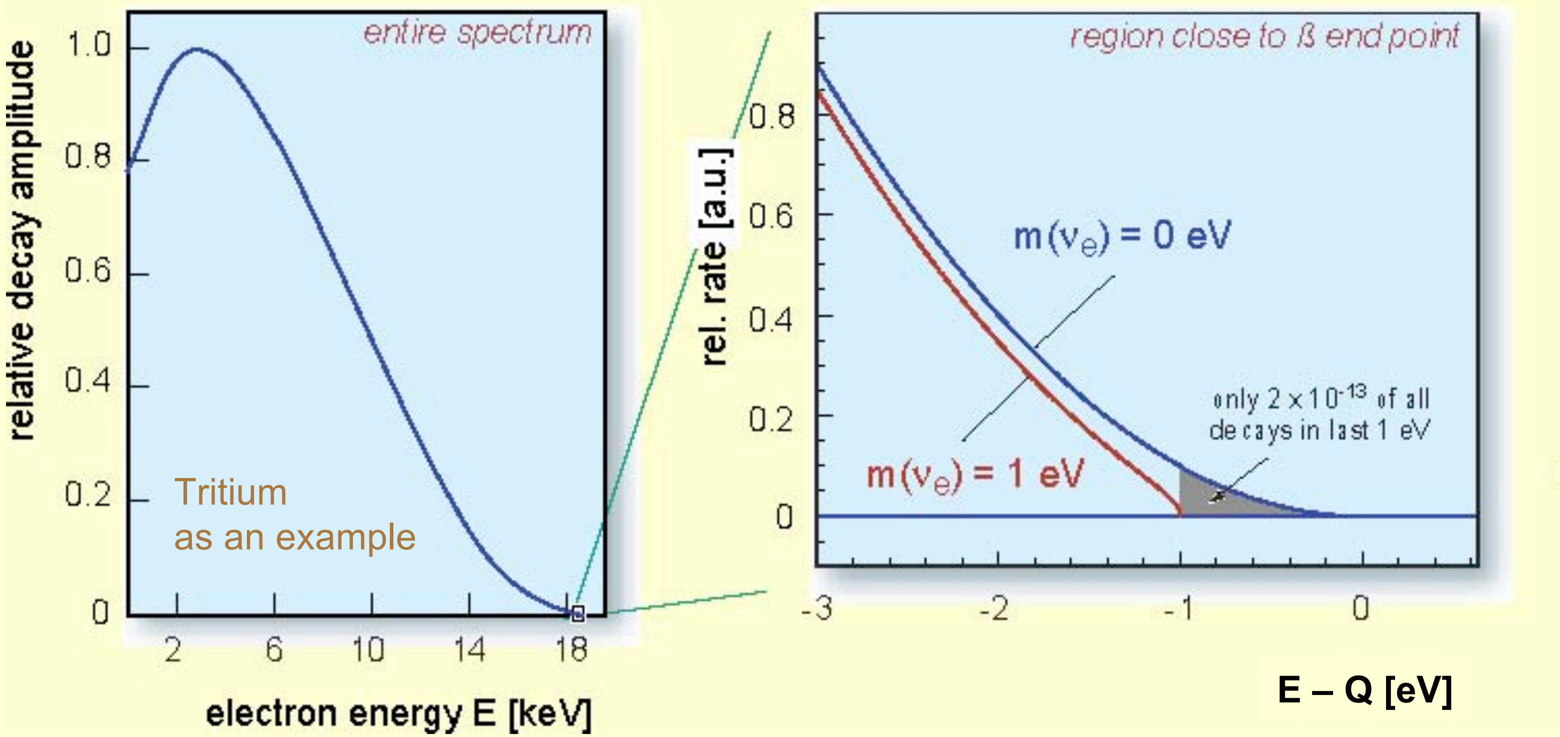
Strumia-Vissani hep-ph/0503246



SINGLE BETA DECAY

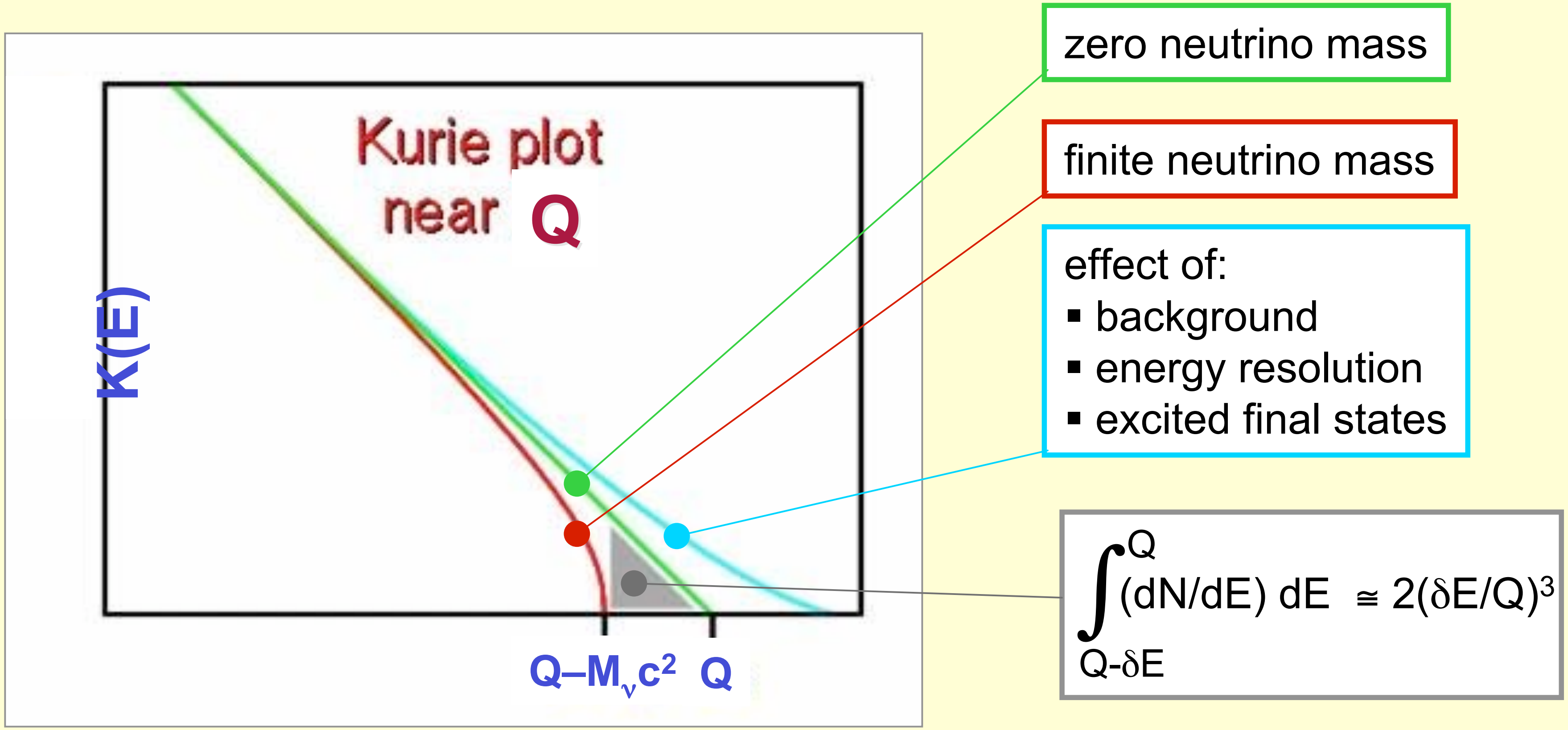
Effects of a finite neutrino mass on the beta decay

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



Effects of a finite neutrino mass on the Kurie plot

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



Mass hierarchy

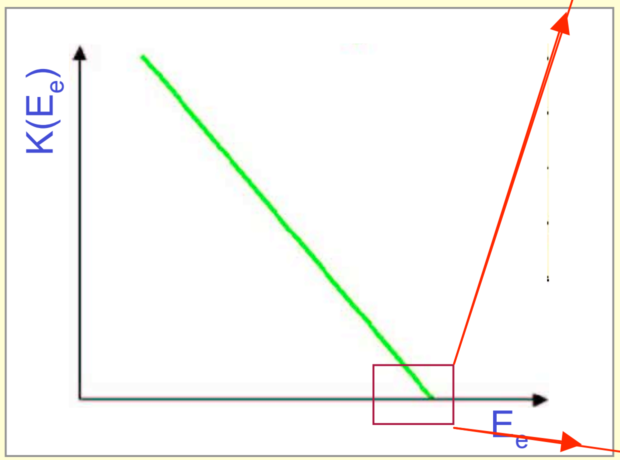
In case of mass hierarchy:

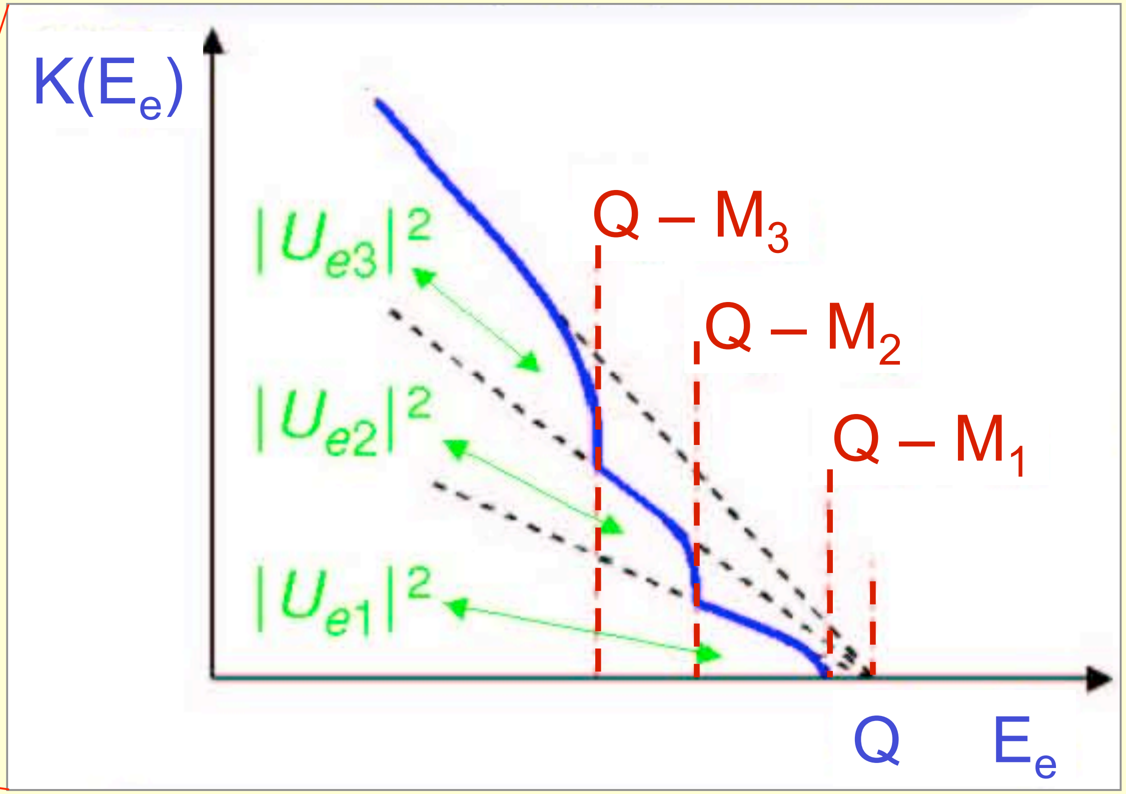
- the Kurie plot ≡ superposition of three different sub - Kurie plots
- each sub - Kurie plot corresponds to one of the three different mass eigenvalues

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)

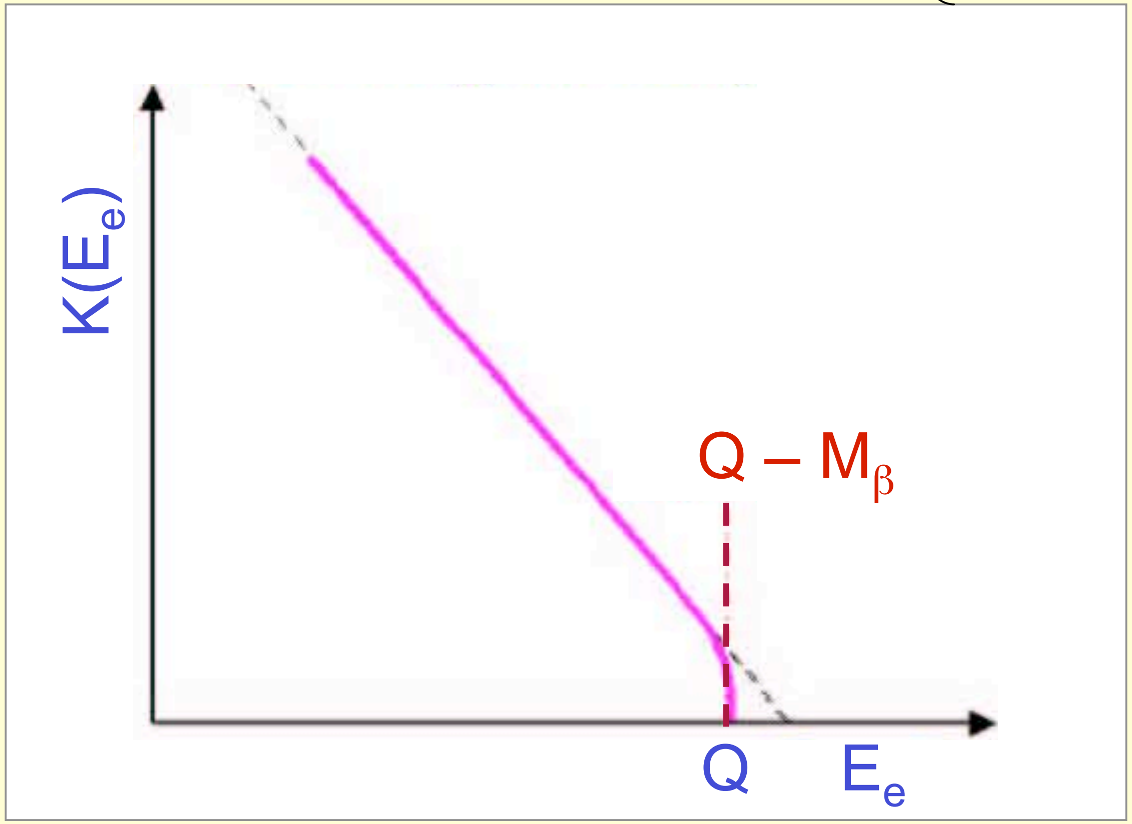




Mass degeneracy

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

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



Two complementary experimental approaches

① 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
- future planned sensitivity: ~ 0.2 eV

② 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 energy
- cryogenic microcalorimeters
- present achieved sensitivity: ~ 10 eV
- future planned sensitivity: under study

→ completely different systematic uncertainties

Electrostatic spectrometers with Magnetic Adiabatic Collimation (MAC-E-filter)

These instruments enabled a major step forward in sensitivity after 1993

They are the basic devices for next generation experiments aiming at the sub-eV range

High magnetic field B_{max} at source and detector. Low field B_{min} at center.

All electrons emitted in the forward hemisphere spiral from source to detector

In the adiabatic limit
$E_{k\perp} / B = \text{constant}$

$$E_{k\perp}(\text{center}) = E_{k\perp}(\text{source}) \; (B_{min}/B_{max})$$

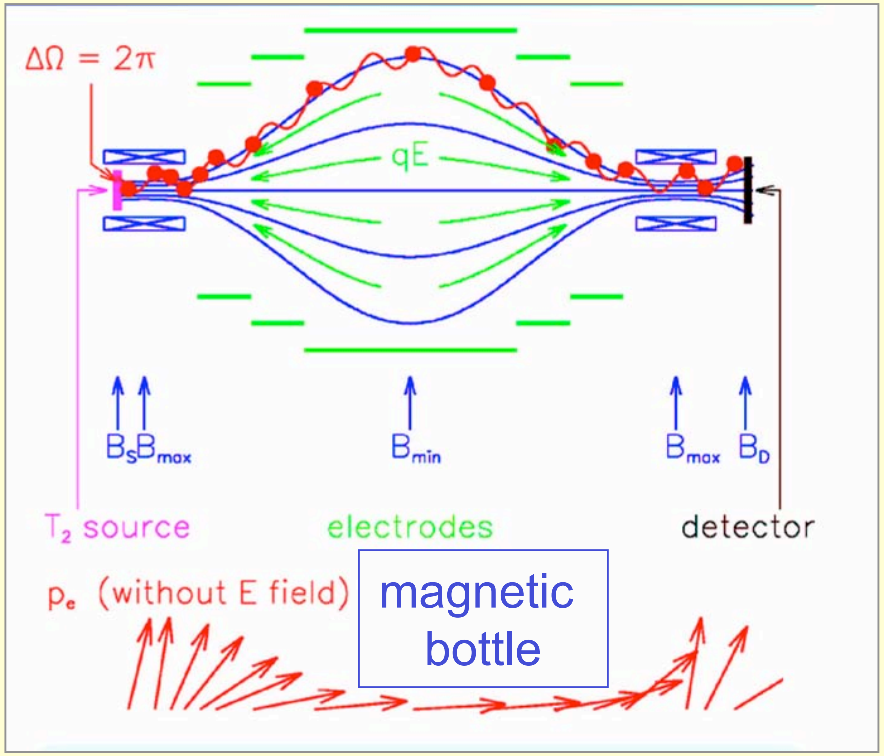
Since $E_e = E_{k\perp} + E_{k\parallel} = \text{constant}$

efficient collimation effect in the center

The retarding electric field at the center has maximum potential U_0 and admits electrons with

$$E_{k\parallel} > eU_0$$

Integral spectrometer



Resolving power: $\Delta E / E = B_{min} / B_{max} \cong 2 \times 10^{-4}$ → $\Delta E \cong 4$ eV at $E \cong 18$ keV

Experiments with MAC electrostatic spectrometers

In the 90's two experiments based on the same principle improved limit on neutrino mass down to about 2 eV at 95% c.l.

Both experiments have reached their final sensitivity

Troitsk (Russia)

- gaseous T_2 source
- unexplained anomaly close to the end point

Mainz (Germany)

- frozen T_2 source
- complicated systematic in the source solved

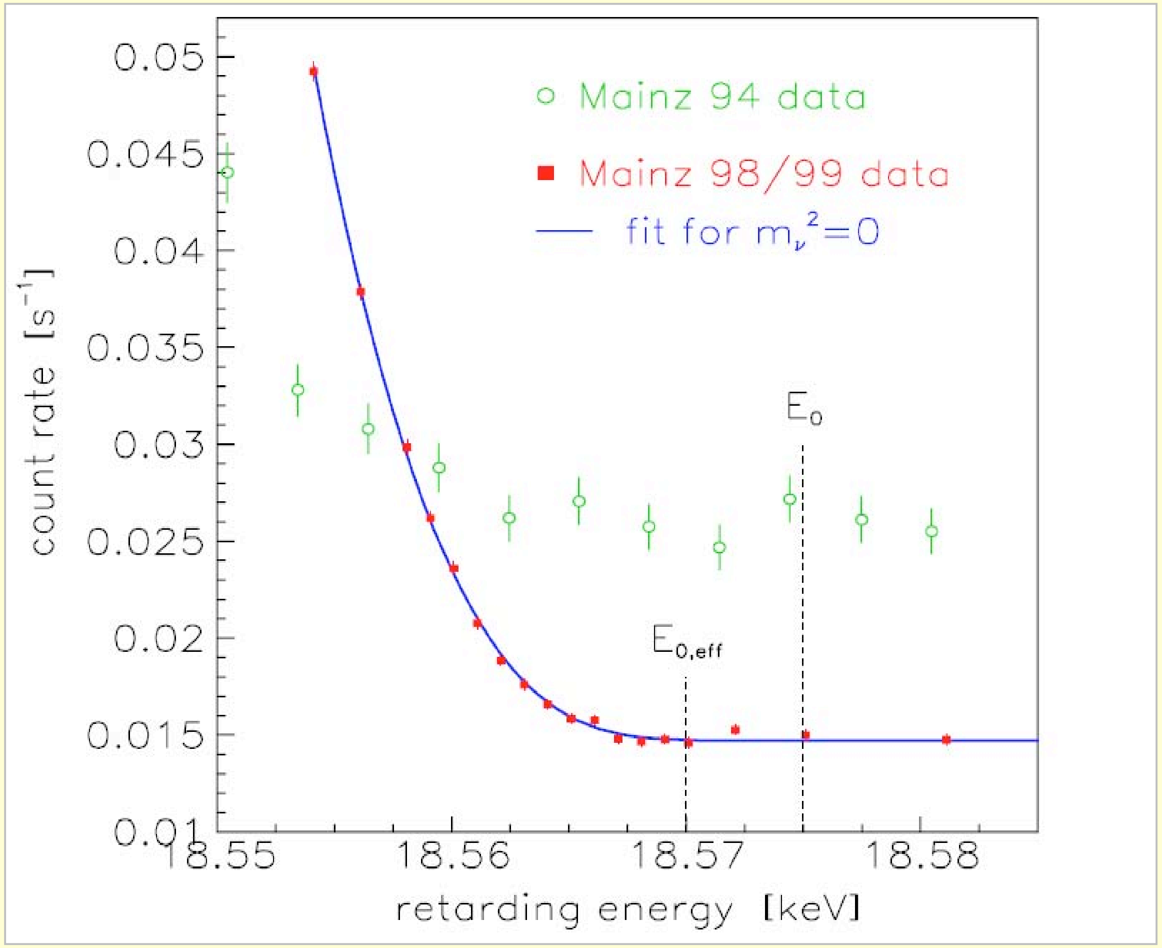
collaborations has joined + other institutions (large international collaboration)

KATRIN

KArlsruhe TRItium Neutrino experiment

new generation experiment aiming at a further factor 10 improvement in sensitivity

Mainz experiment: the results



Clear improvement
in signal-to-background ratio
from 1994 set-up
to 1998-2001 set-up

To reduce systematic
uncertainties,
only the final 70 eV are used

Similar results from Troitzk,
but anomaly at the end-point
(unknown peak of variable
position and intensity)

$\langle M_\beta \rangle^2 = -0.6 \pm 2.2 \pm 2.1\ eV^2$ $\langle M_\beta \rangle < 2.3\ eV$ (95% c.l.)

Final experimental sensitivity reached

results obtained after
a difficult struggle against
subtle systematic effects

Next generation of MAC spectrometer: the KATRIN proposal

letter of intent - 2001
hep-ex/0109033

Goal: to reach sub-eV sensitivity on $\langle M_\beta \rangle$

KATRIN design report
Jan 2005

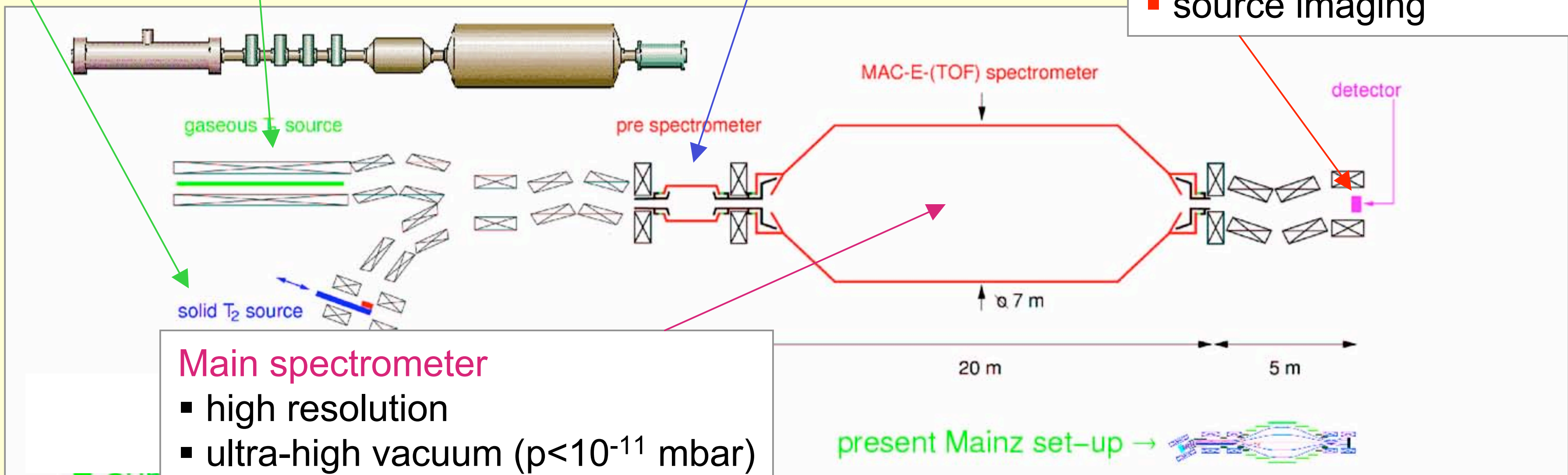
Strategy

- better energy resolution ⇒ ΔE_{FW} ~ 1 eV
- higher statistic ⇒ stronger T_2 source – longer measuring times
- better systematic control ⇒ in particular, improve background rejection

Double source
control of systematic

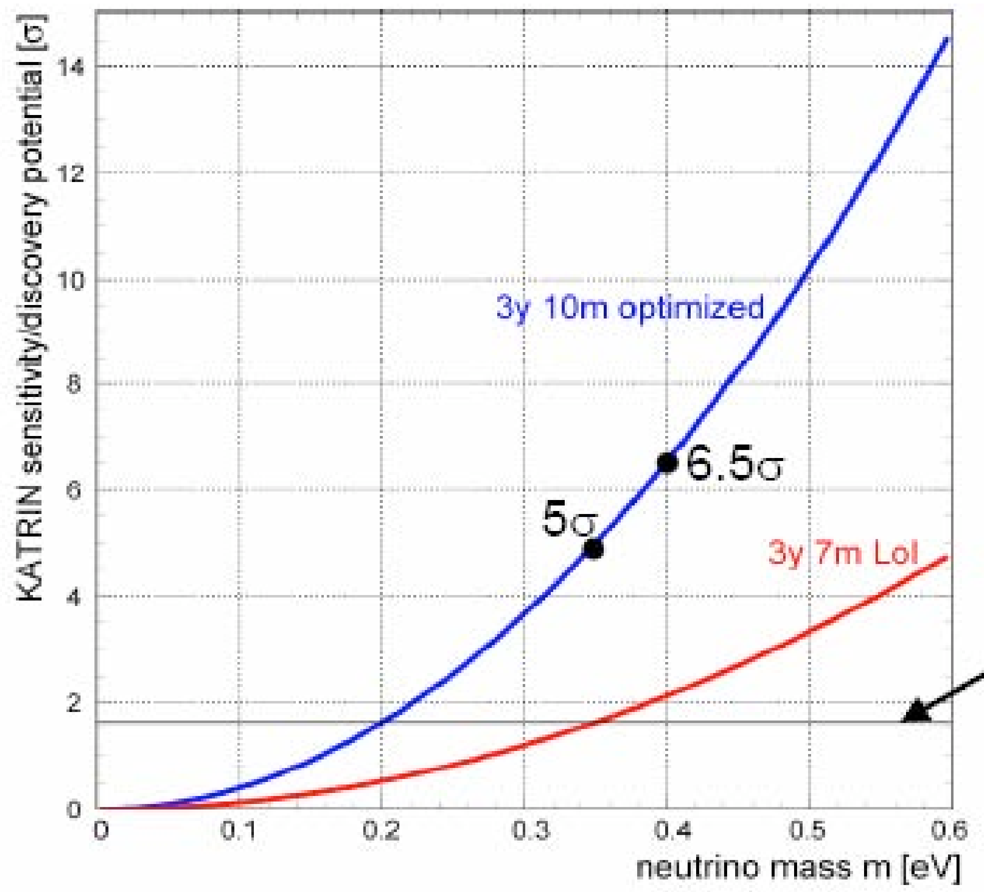
Pre-spectrometer
selects electrons with E>Q-100 eV
(10^{-7} of the total)

Better detectors:
- higher energy resolution
- time resolution (TOF)
- source imaging



Main spectrometer
- high resolution
- ultra-high vacuum (p<10^{-11} mbar)
- high luminosity

KATRIN sensitivity



sensitivity
$\langle M_\beta \rangle$ < 0.2 eV (90%c.l.)

discovery potential
$\langle M_\beta \rangle$ = 0.35 eV @ 5σ

90% c.l. upper limit
for m_ν = 0 eV

**first tritium runs:
mid 2009**

The calorimetric approach to the measurement of the neutrino mass

Calorimeters measure the entire spectrum at once

- use low Q beta decaying isotopes to achieve enough statistic close to Q
- best choice: ^{187}Re – Q = 2.47 keV - 1 mg of natural Re ⇒ ~ 1 Bq

→ event frac. in the last 10 eV: 1.3x10-7 ← vs. 3×10^{-10} for T beta spectrum

Advantages of calorimetry

- no backscattering
- no energy loss in the source
- no excited final state problem
- no solid state excitation

Drawbacks of calorimetry

- systematic induced by pile-up effects
- energy dependent background

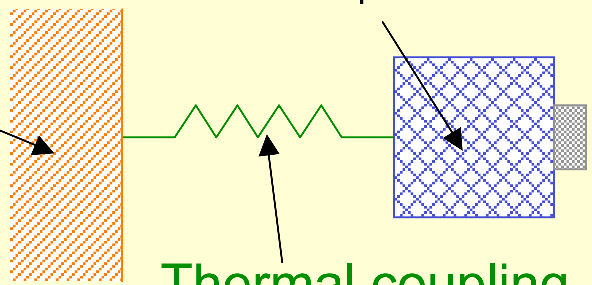
$$(dN/dE)_{exp}=[(dN/dE)_{theo}+ A\tau_r(dN/dE)_{theo}\otimes (dN/dE)_{theo}] \otimes R(E)$$

generates "background" at the end-point

Bolometric detectors of particles: basic concepts

Energy absorber
crystal containing Re
M ~ 0.25 mg
basic parameter: C

Heat sink
T ~ 80 mK
dilution refrigerator



Thermometer
Si-implanted thermistor
basic parameters:
R ≅ 1.5 MΩ
T ≅ 100 mK
dR/dT ≅ 50 kΩ/mK

Thermal coupling
read-out wires
in the future, μ–machined legs
basic parameter: G
G ≅ 0.02 pW / mK

Variable Range Hopping
conduction regime
exponential increase of R
with decreasing T

- Temperature signal: $\Delta T = E/C \cong 1$ mK for $E = 2.5$ keV
- Bias: $I \cong 0.5$ nA ⇒ Joule power ≅ 0.4 pW ⇒Temperature rise ≅ 20 mK
- Voltage signal: $\Delta V = I \times dR/dT \times \Delta T$ ⇒ $\Delta V \cong 30\ \mu V$ for $E = 2.5$ keV
- Signal recovery time: $\tau = C/G \cong 20$ ms
- Noise over signal bandwidth (≅ 1 kHz): $V_{rms} = 0.2\ \mu V$

Energy resolution ≅ 10 eV

MIBETA (Milano/Como) experiment: the detectors

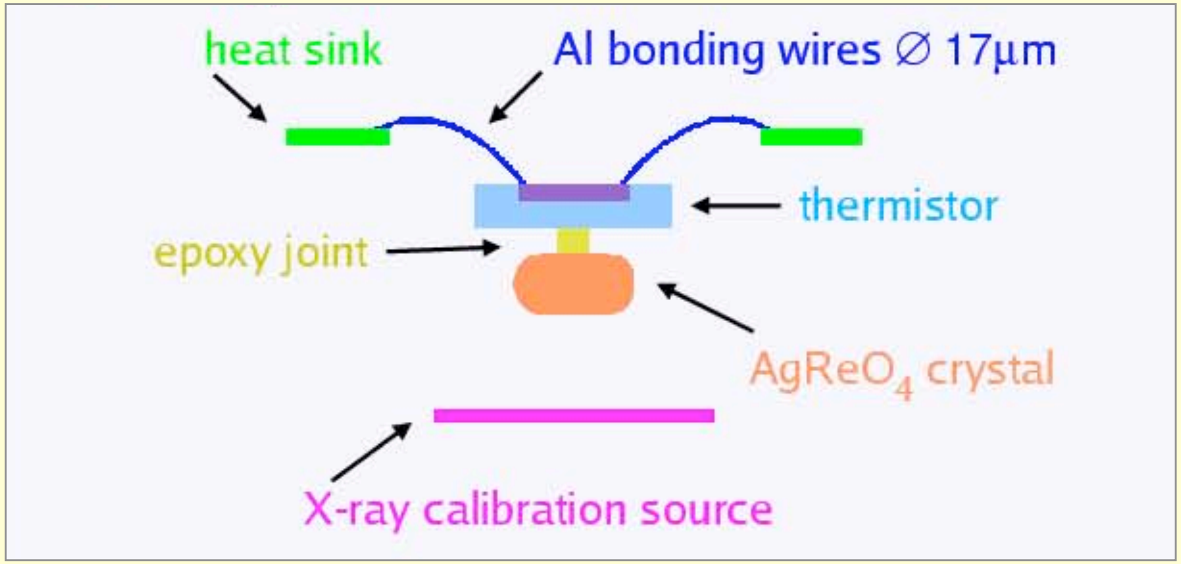
Energy absorbers

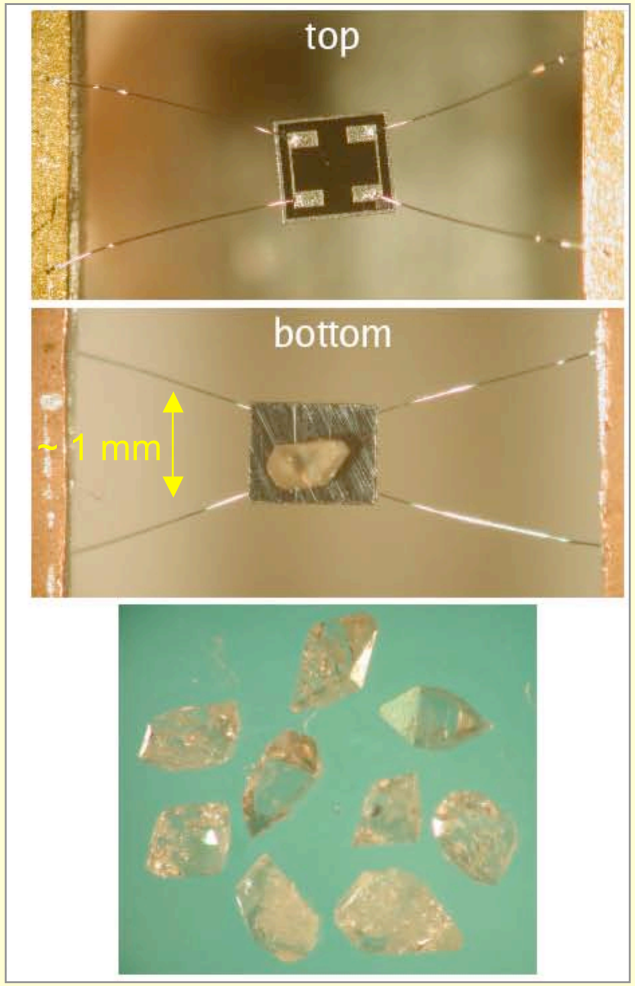
- $AgReO_4$ single crystals
- ^{187}Re activity ≅ 0.54 Hz/mg
- M ≅ 0.25 mg ⇒ A ≅ 0.13 mHz

Thermistors

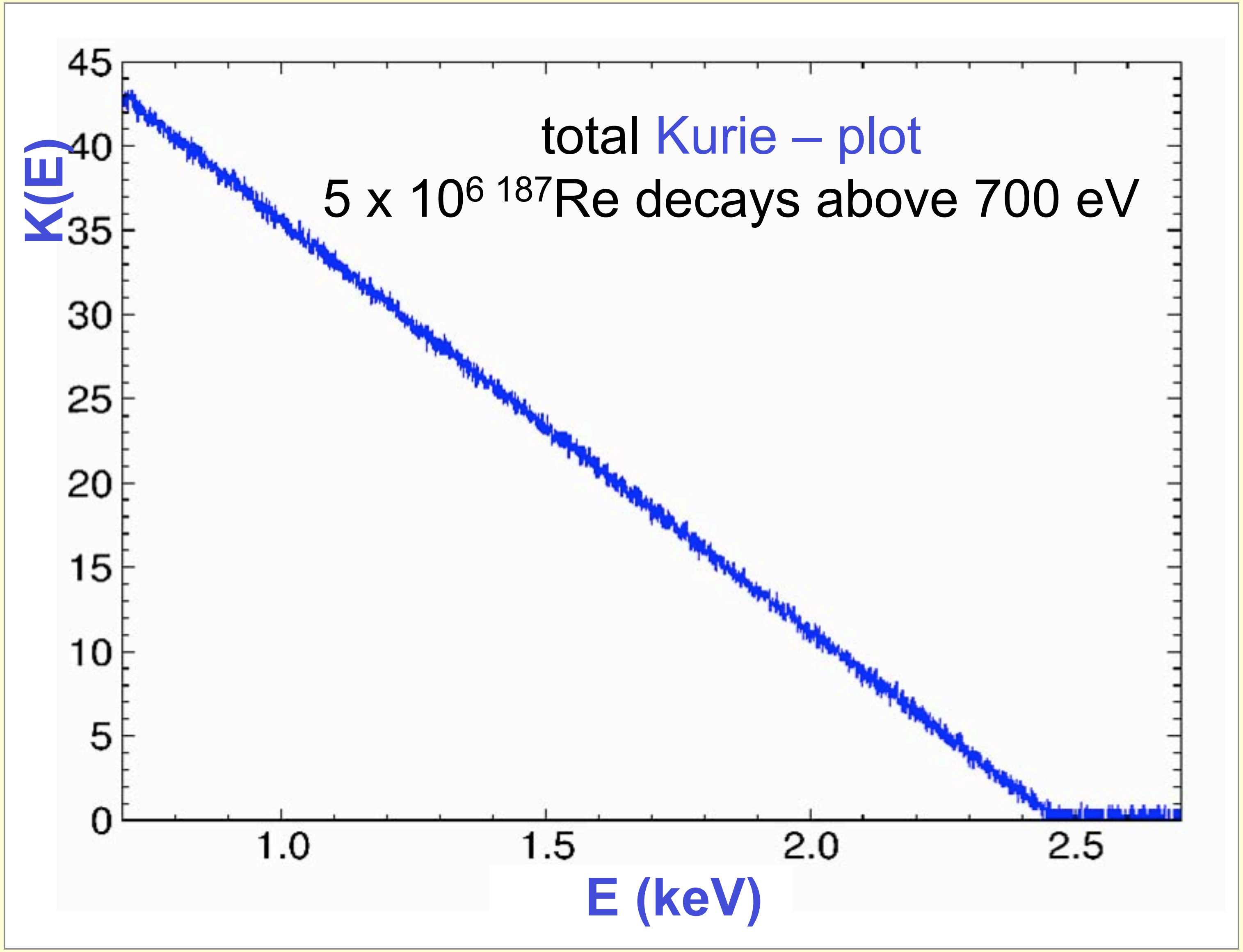
- Si-implanted thermistors
- high sensitivity
- many parameters to play with
- high reproducibility ⇒ array
- possibility of μ-machining

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

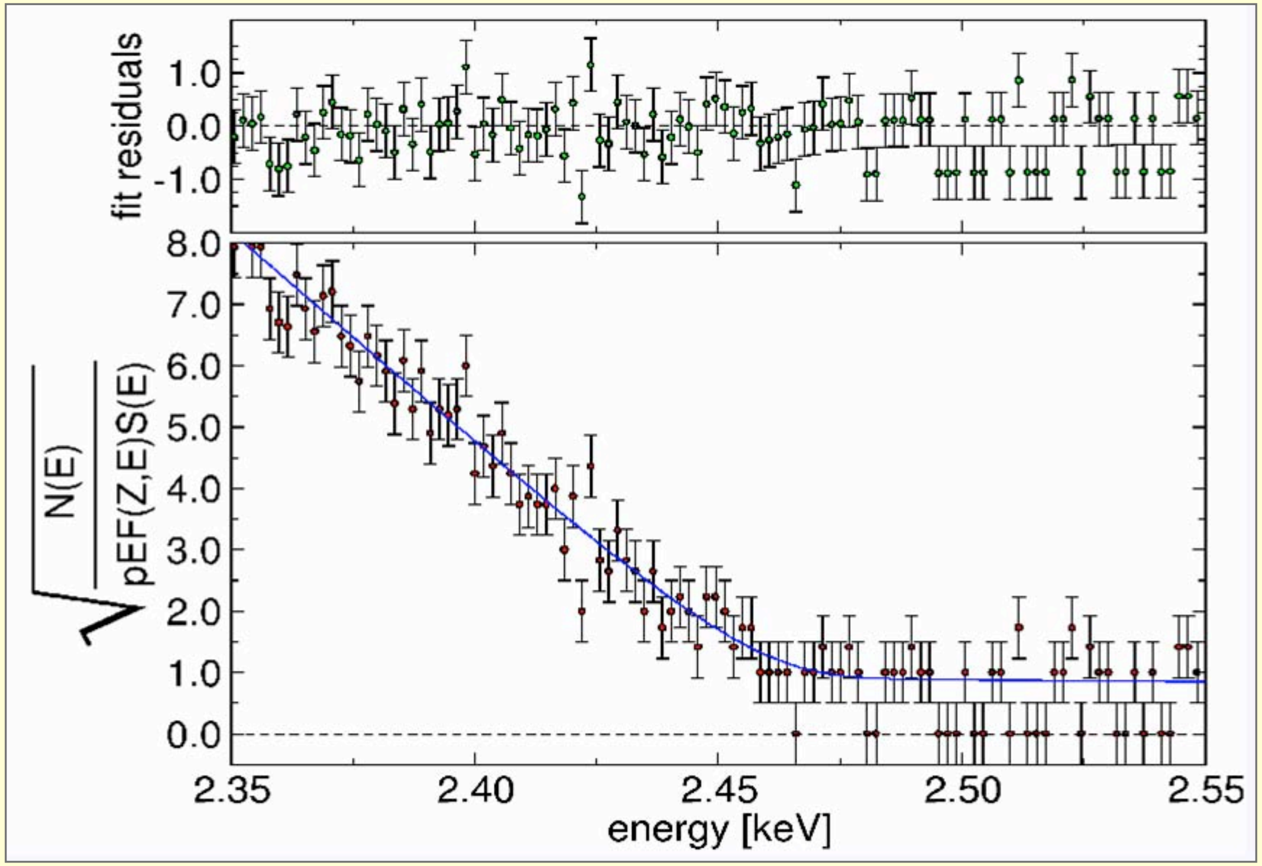




MIBETA experiment: the Kurie - plot



MIBETA experiment: the neutrino mass



Fit parameters

single gaussian:
ΔE_{FWHM} = 27.8 eV

fitting interval:
0.8 – 3.5 keV

free constant background:
6 x 10^{-3} c/keV/h

free pile-up fraction:
1.7 x 10^{-4}

$\langle M_\beta \rangle^2 = -141 \pm 211_{stat} \pm 90_{sys}$ eV^2 (preliminary)

$\langle M_\beta \rangle < 15.6$ eV (90% c.l.)

similar results obtained by the MANU experiment (Genoa)

The future of bolometric experiments

MARE

Microcalorimeter Arrays for a Rhenium Experiment

A next-generation calorimetric determination of the neutrino mass

through the study of the ^{187}Re beta spectrum

INFN, Milano, Italy
University of Milano-Bicocca, Department of Physics, Milano, Italy
University of Insubria, Department of Physics and Mathematics, Como, Italy
University of Genoa, Department of Physics, and INFN, Genoa, Italy
ITC-irst, Trento, Italy
University of Heidelberg, Germany
Goddard Space Flight Center, NASA, Maryland, USA
University of Wisconsin, Madison, WI, USA

proposal in preparation for an expansion of the Re experiment

The future of bolometric experiments: MARE

General strategy: push up bolometric technology in order to:

- multiplicate number of channels
- improve energy resolution
- decrease rise-time

goal:
reach
2 eV sensitivity

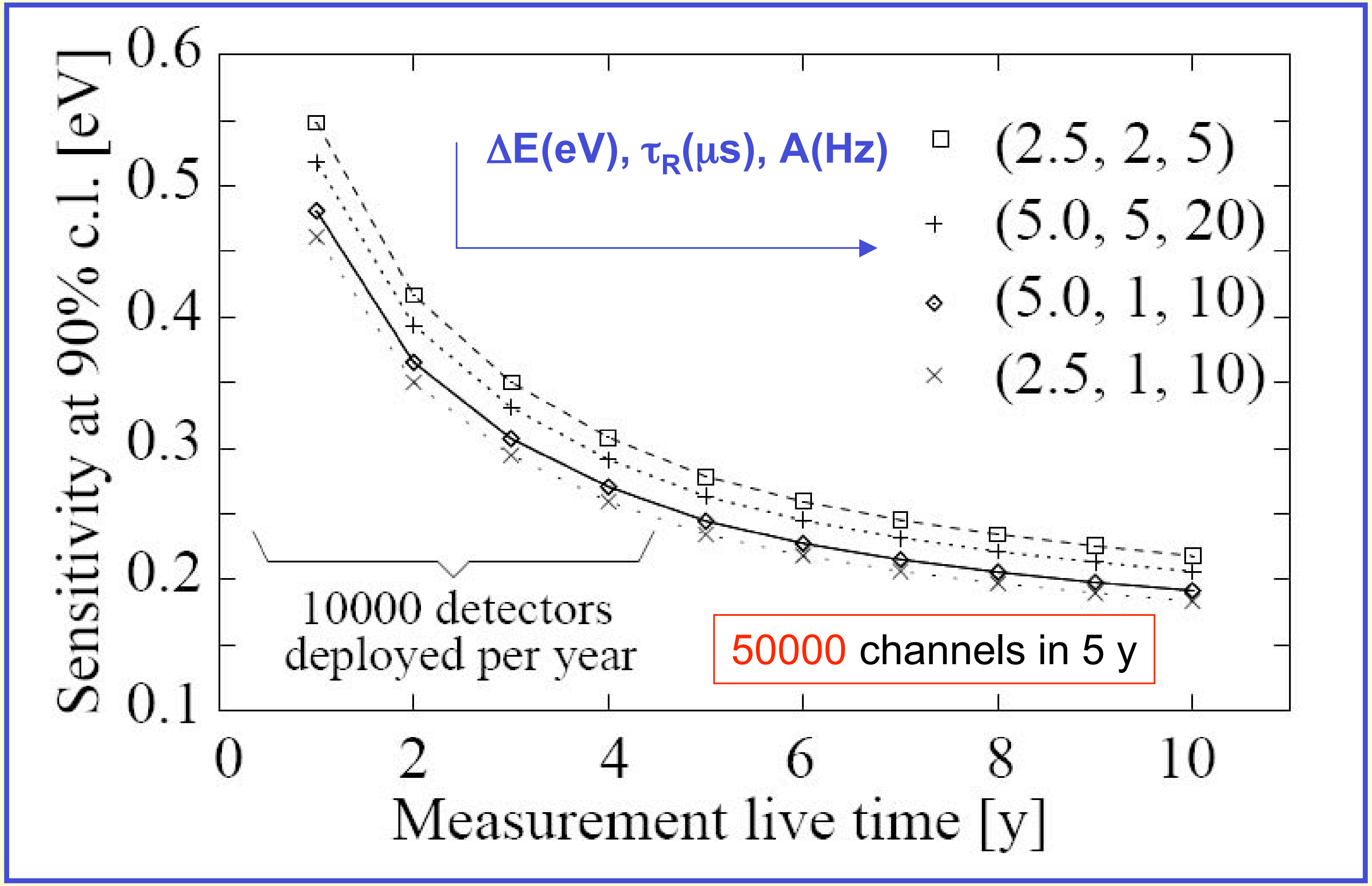
simulations I phase

Montecarlo input parameters			90% CL sensitivity	Possible experimental configurations			
N_{ev} [$\times 10^9$]	$f_{pile\text{-}up}$ [$\times 10^{-5}$]	ΔE [eV]	m_ν [eV]	N_{det}	t_M [y]	$\langle A_\beta \rangle$ [dec/s]	$\langle \Delta t \rangle$ [μs]
1.4	2.0	10	3.5	100	2	0.20	100
3.2	2.5	10	3.0	200	2	0.25	100
4.7	2.5	10	2.5	200	3	0.25	100

The future in bolometric experiments: MARE

simulations II phase

goal:
reach
0.2 eV sensitivity



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 – $\tau \geq 10^{19}$ 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

Processe ② would imply new physics beyond the Standard Model

violation of lepton number conservation

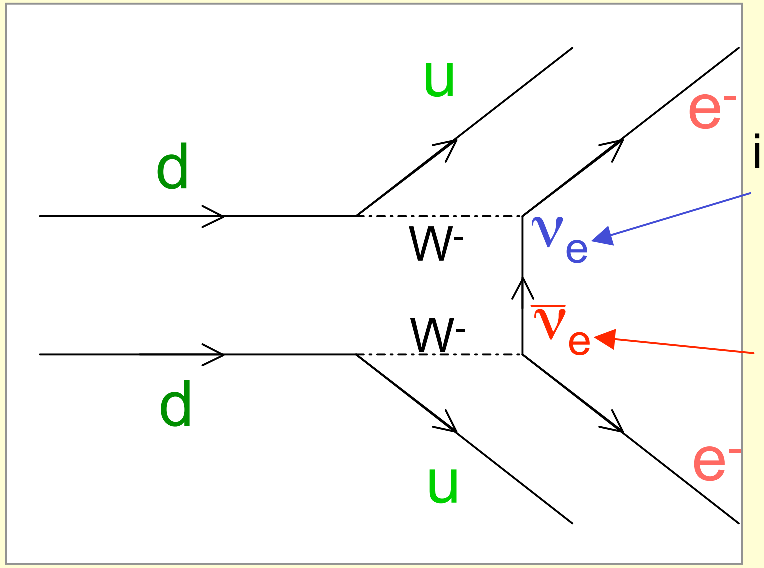
It is a very sensitive test to new physics since the phase space term is much larger for the neutrinoless process than for the standard one

interest for 0ν-DBD lasts for 65 years !

Goeppert-Meyer proposed the standard process in 1935

Racah proposed the neutrinoless process in 1937

Neutrino properties and 0ν-DBD



a LH neutrino (L=-1) is absorbed at this vertex

a RH antineutrino (L=1) is emitted at this vertex

in pre-oscillations standard particle physics (massless neutrinos), the process is forbidden because neutrino has not the correct helicity / lepton number to be absorbed at the second vertex

- IF neutrinos are massive DIRAC particles:
  Helicities can be accommodated thanks to the finite mass, **BUT** Lepton number is rigorously conserved → **0ν-DBD is forbidden**
- IF neutrinos are massive MAJORANA particles:
  Helicities can be accommodated thanks to the finite mass, **AND** Lepton number is not relevant → **0ν-DBD is allowed**

Observation of **0ν-DBD** → $m_\nu \neq 0$, $\overline{\nu} \equiv \nu$

0ν-DBD and neutrino flavor oscillations

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

neutrinoless Double Beta Decay **rate** → $1/\tau$

Phase space → $G(Q,Z)$

Nuclear matrix elements → $|M_{nucl}|^2$

Effective **Majorana mass** → $\langle M_{\beta\beta}\rangle^2$

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

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

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

The problem of nuclear matrix elements

Large systematics introduced by nuclear physics
in the calculation of $|M_{nucl}|^2$

⇓

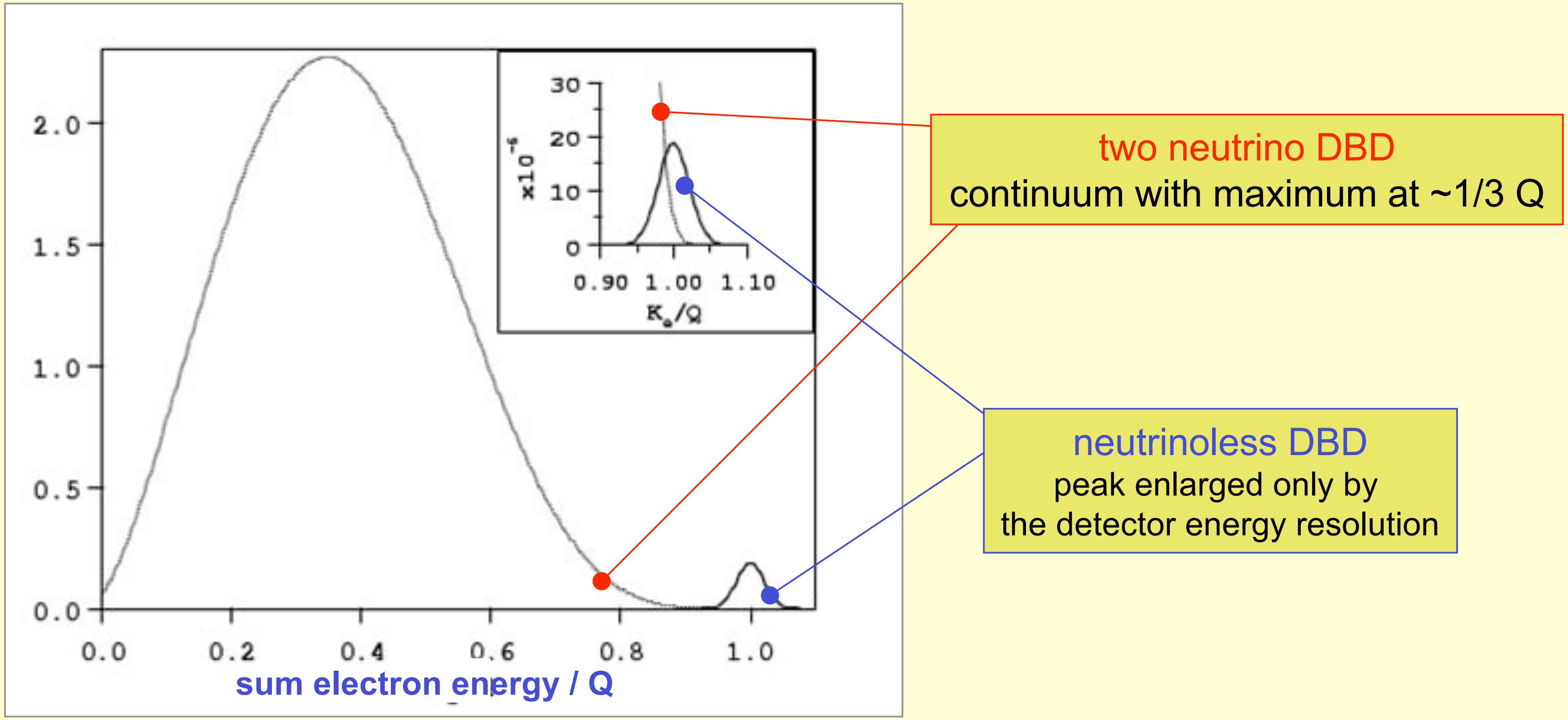
lifetimes foreseen by different nuclear models for $\langle M_{\beta\beta} \rangle$ = 50 meV

Unit: 10^{26} year ⇒ in the best cases, **1 decay / year / 100 moles !**

nuclide	nuclear models					
^{76}Ge	6.8	70.8	56.0	9.3	12.8	14.4
^{130}Te	0.6	23.2	2.8	2.0	3.6	3.4
^{100}Mo			4.0	5.1	1.2	15.6
^{150}Nd				0.1	0.2	

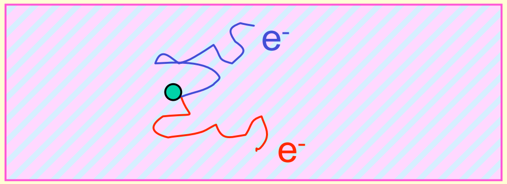
Electron sum energy spectra in DBD

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



Experimental approaches to direct searches

Two approaches for the detection of the two electrons:

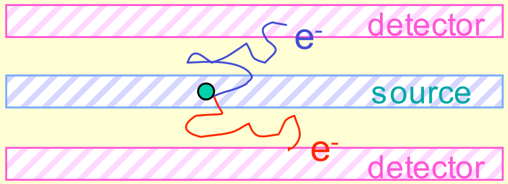
① 

Source ≡ Detector

(calorimetric technique)

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

high energy resolution

② 

Source ≠ Detector

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

event reconstruction

Experimental sensitivity to 0ν-DBD

sensitivity F: lifetime corresponding to the minimum detectable number of events over background at a given (1 σ) confidence level

source mass, live time, energy resolution, background level

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

$$F \propto MT$$

$b \neq 0$

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

$b = 0$

importance of the nuclide choice
(but large uncertainty due to nuclear physics)

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

Present experimental situation in the search for 0ν-DBD

I will give some details about three presently most sensitive experiments:

- Heidelberg – Moscow (HM) (Gran Sasso)

  the most sensitive DBD experiment since 10 years (stopped in May 03)

- NEMO3 (Modane)

  it is an intermediate generation experiment capable to study different candidate nuclides and to improve the HM results (running)

- CUORICINO (Gran Sasso)

  it is an intermediate generation experiment with the potential to improve the HM result (running)

  it is also a prelude to a new generation experiment, CUORE (**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents),

The Heidelberg Moscow experiment

Source = detector
Well established technology of Ge diodes

This technique has been dominating the field for decades and is still one of the most promising for the future
E. Fiorini – 60s

- Five Ge diodes for an overall mass of 10.9 kg isotopically enriched (86%) in ^{76}Ge
- Underground operation in the Gran Sasso laboratory (Italy)
- Lead box and nitrogen flushing of the detectors
- Digital Pulse Shape Analysis (PSA) (factor 5 reduction)

7.6×10^{25} **^{76}Ge** nuclei

identification of Multi-site events (gamma background)

Background in the region of DBD:

b = 0.17 counts/(keV kg y)

$\langle M_{\beta\beta} \rangle < 0.3 – 2.5$ eV

similar results obtained by IGEX experiment

HM: claim of evidence of 0ν-DBD

Suddenly, in December 2001, 4 authors (KDHK) of the HM collaboration announce the discovery of neutrinoless DBD

most probable value of events: 14.8 in 46 kg y exposure

KDHK claim: m_{ee} = 0.11 - 0.56 eV (**0.39 eV** b.v.)
$\tau_{1/2}^{0\nu}$ (y) = (0.8 – 18.3) × 10^{25} y (**1 × 10^{25} y** b.v.)
(95 % c.l.)
H.V. Klapdor-Kleingrothaus et al. Mod. Phys. Lett. A 16 (2001) 2409

later, the authors widen the allowed range for m_{ee} to account for nuclear matrix element uncertainty:

$$\langle M_{\beta\beta} \rangle = 0.05 - 0.84 \text{ eV } (95\% \text{ c.l.})$$

immediate skepticism in DBD community

Aalseth CE et al. , Mod. Phys. Lett. A 17 (2002) 1475
Feruglio F et al. , Nucl. Phys. B 637 (2002) 345
Zdezenko Yu G et al., Phys. Lett. B546(2002)206

} Comments and reanalysis of HD-M data

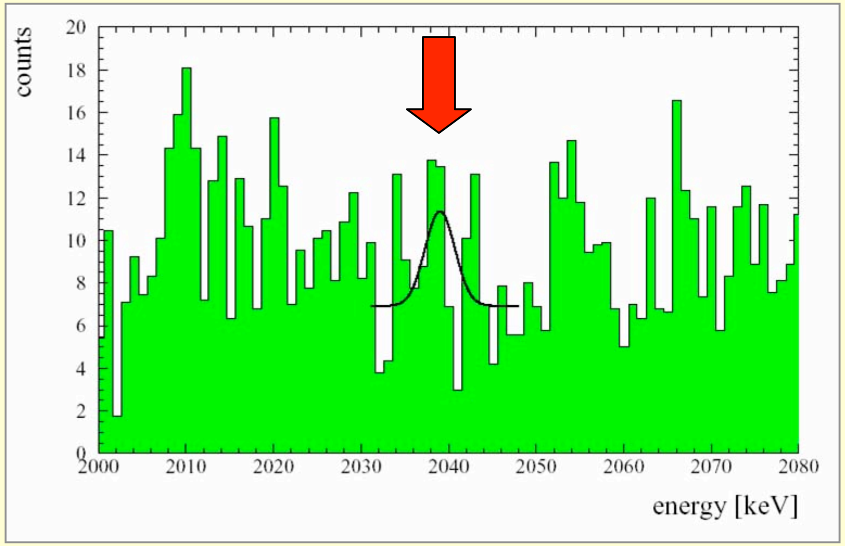
Klapdor-Kleingrothaus HV hep-ph/0205228
H.L. Harney, hep-ph/0205293

} Independent replies to the Comments

Recent new papers about claim of evidence

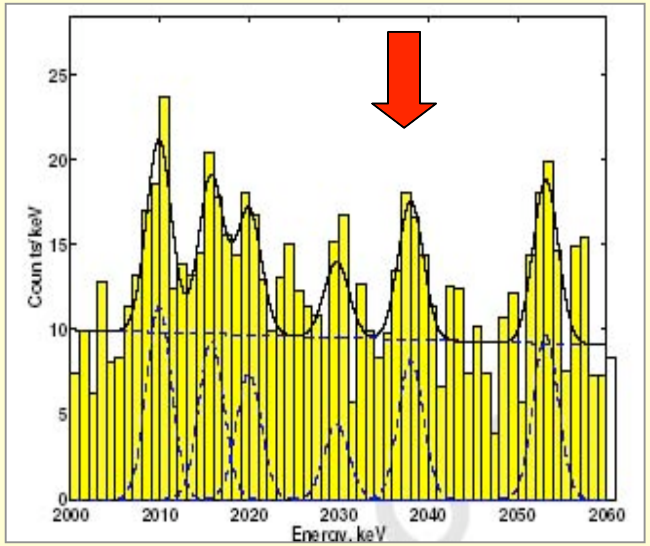
With respect to the 2001 results, now data with higher statistics and with better quality show an increase of the statistical significance of the "peak":

2001



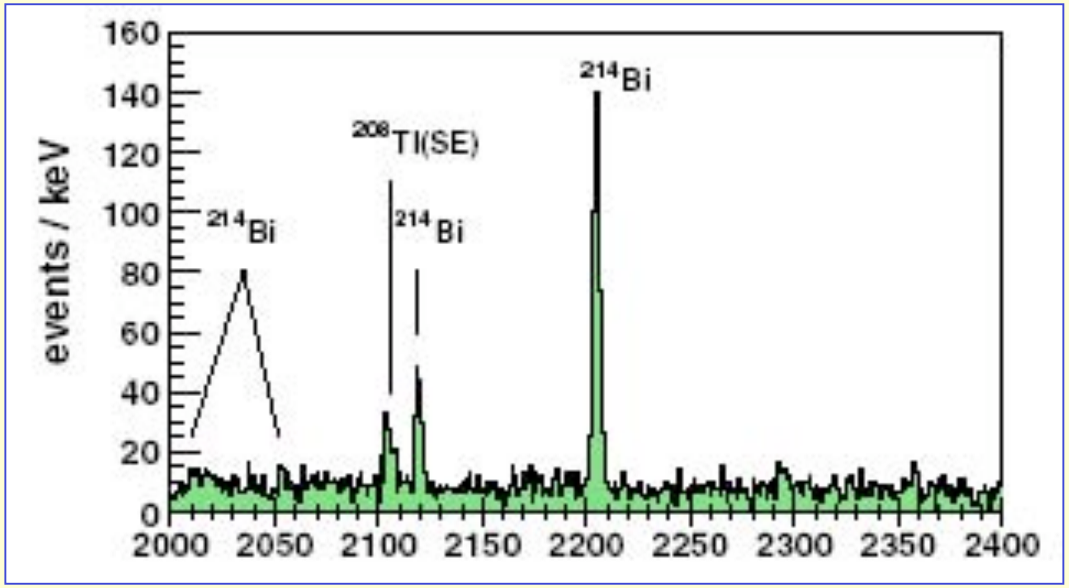
54.98 kg•y 2.2 σ

2004



71.7 kg•y 4.2 σ

Recent new papers about claim of evidence

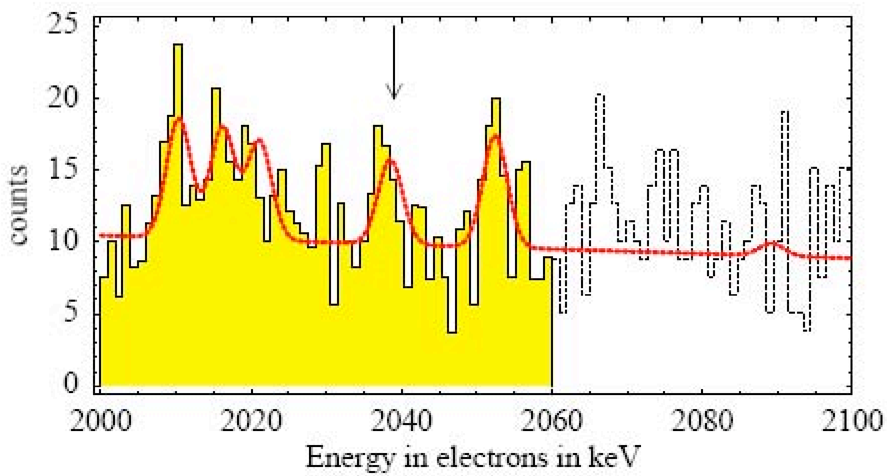


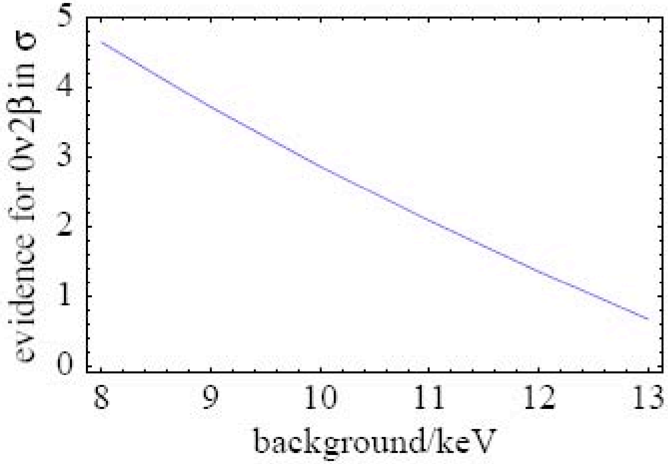
Many background features are still to explain

Looking at a larger range, many structures resemble the DBD "peak" and need to be explained

The statistical significance depends on the flat component of the background

Strumia-Vissani hep-ph/0503246





NEMO3

Source $\neq$ detector
Well established technologies in particle detection:
tracking volume with Geiger cells
plastic scintillators
magnetic field

The most sophisticated
DBD detector with external source

- Different sources in form of foil can be used simultaneously
- Underground operation in the Frejus laboratory (France)
- Water and iron shields

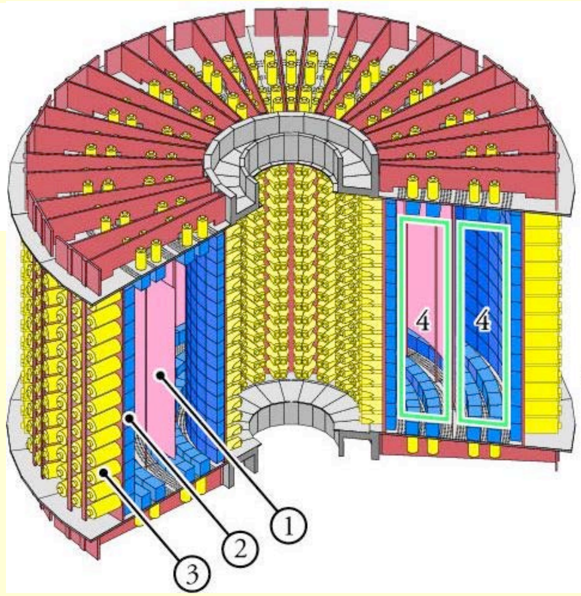
4.1×10^{25} ^{100}Mo nuclei

other sources

Isotope	Study	Mass(g)
^{100}Mo	$\beta\beta0\nu, \beta\beta2\nu$	6914
^{82}Se	$\beta\beta0\nu, \beta\beta2\nu$	932
^{116}Cd	$\beta\beta0\nu, \beta\beta2\nu$	405
^{130}Te	$\beta\beta0\nu, \beta\beta2\nu$	454
^{150}Nd	$\beta\beta2\nu$	36.6
^{96}Zr	$\beta\beta2\nu$	9.4
^{48}Ca	$\beta\beta2\nu$	7.0

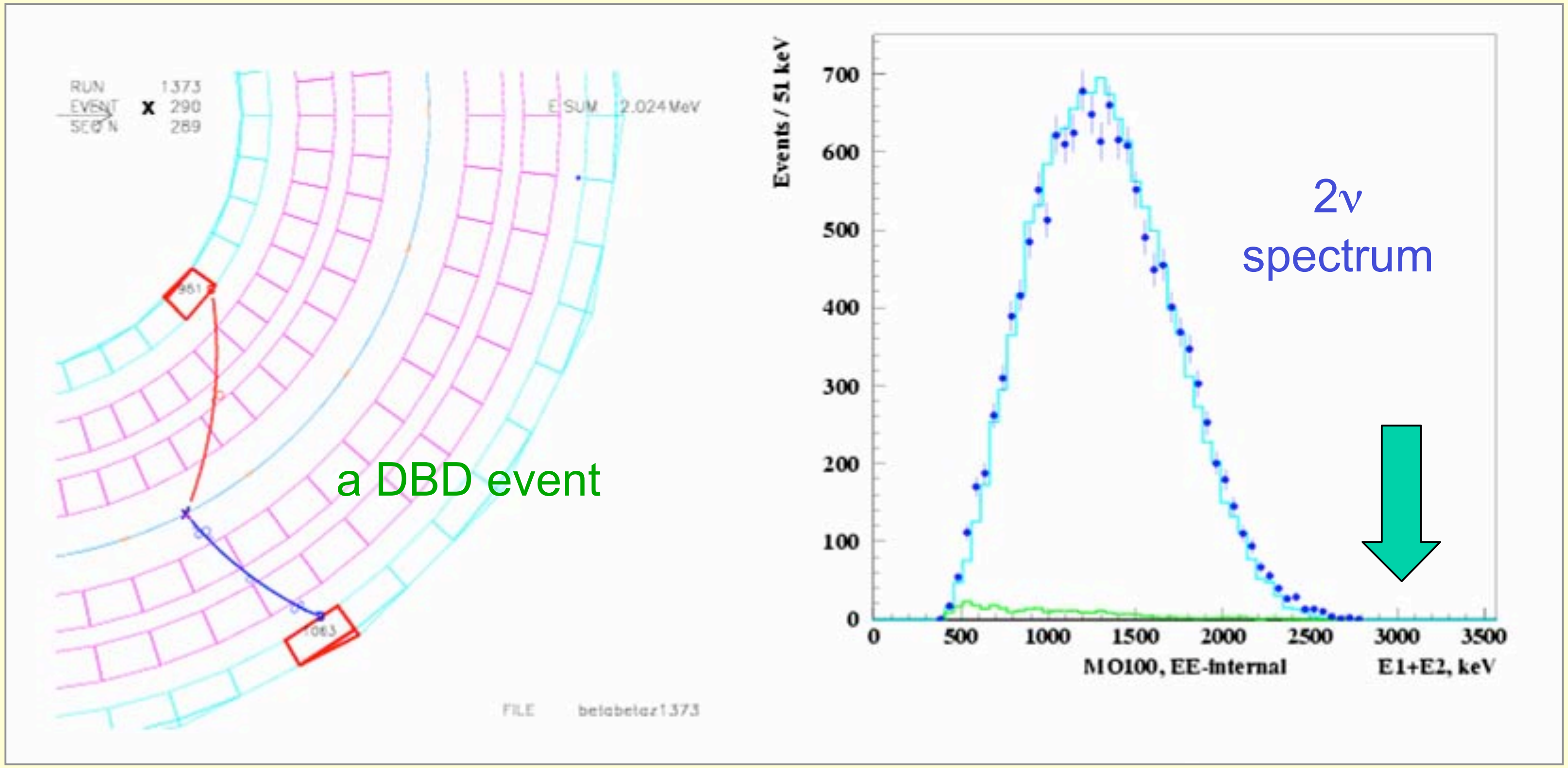
1 SOURCE
2 TRACKING VOLUME
3 CALORIMETER

detector scheme



NEMO3

Beautiful results on ^{100}Mo and on other nuclides



$\tau_{1/2}^{2\nu}$ (y) = 7.8 ± 0.09 $_{stat}$ ± 0.8 $_{syst}$ × 10^{18} y

$\tau_{1/2}^{0\nu}$ (y) > 3.5 × 10^{23} y

$\langle M_{\beta\beta} \rangle$ < 0.7 – 1.2 eV

final sensitivity: 0.2 – 0.35 eV

intrinsic limits:

- source strength
- low energy resolution ⇒ 2ν background

CUORICINO

Source = detector
Bolometric technique:
young (born in ~ 1985) but now firmly established

The bolometric technique for the study of DBD was proposed by **E. Fiorini** and **T.O. Niinikoski** in **1983**

Nuclide under study: ^{130}Te

- 0ν DBD is a factor 5-10 faster than in ^{76}Ge
- A.I.: 34% ⇒ enrichment not necessary

→ experiments can be expanded at low cost

CUORICINO source

5.2×10^{25} ^{130}**Te** nuclei

Bolometric technique: the nuclear energy is measured as a temperature increase of a single crystal

$\Delta T = E/C$ thanks to a proper thermometer, $\Delta T \Rightarrow \Delta V$

In order to get low specific heat, the temperature must be very low (5 – 10 mK)

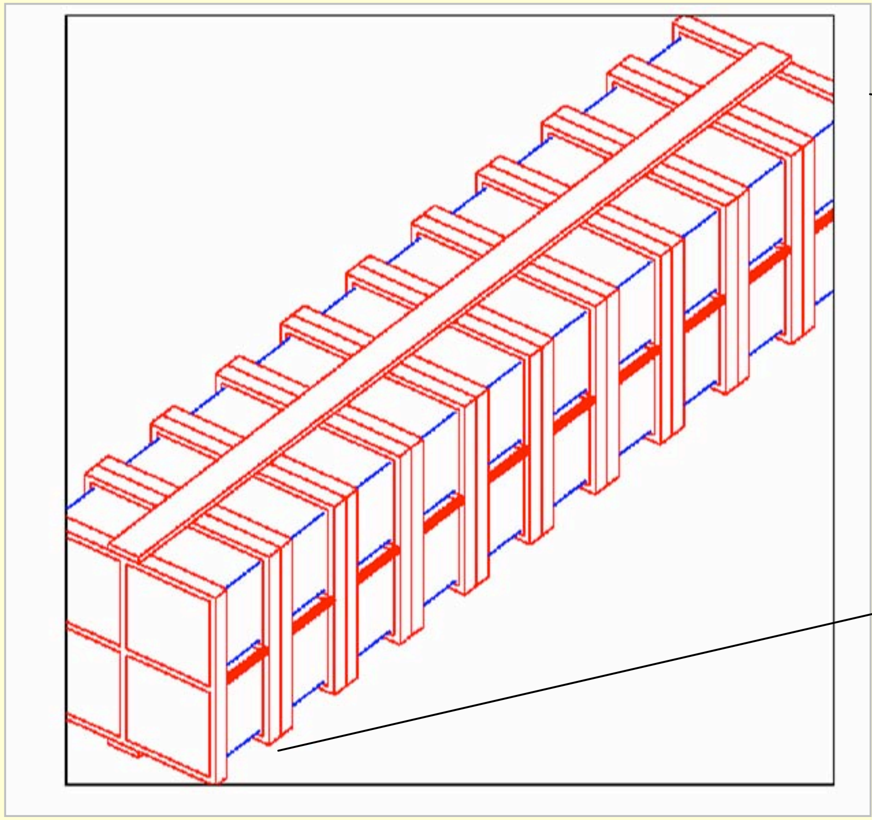
Typical signal sizes: 0.1 mK / MeV, converted to about 1 mV / MeV

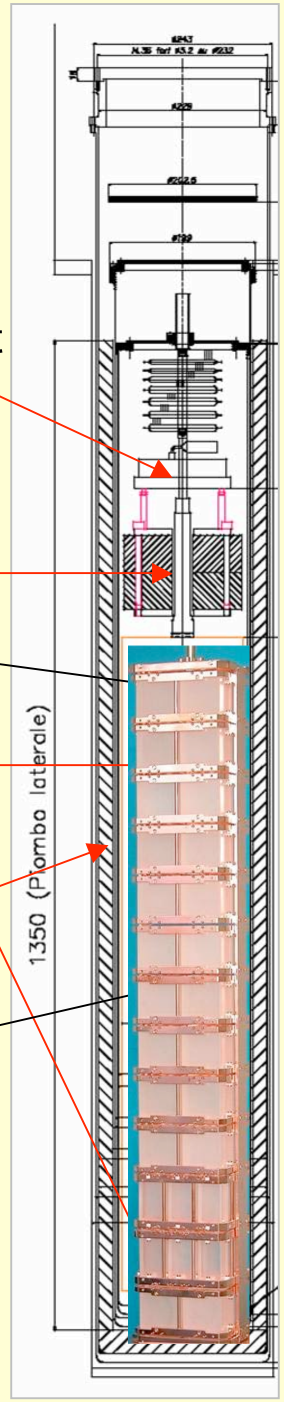
The CUORICINO set-up

CUORICINO = tower of 13 modules,
11 modules x 4 detector (790 g) each
2 modules x 9 detector (340 g) each

M = ~ 41 kg

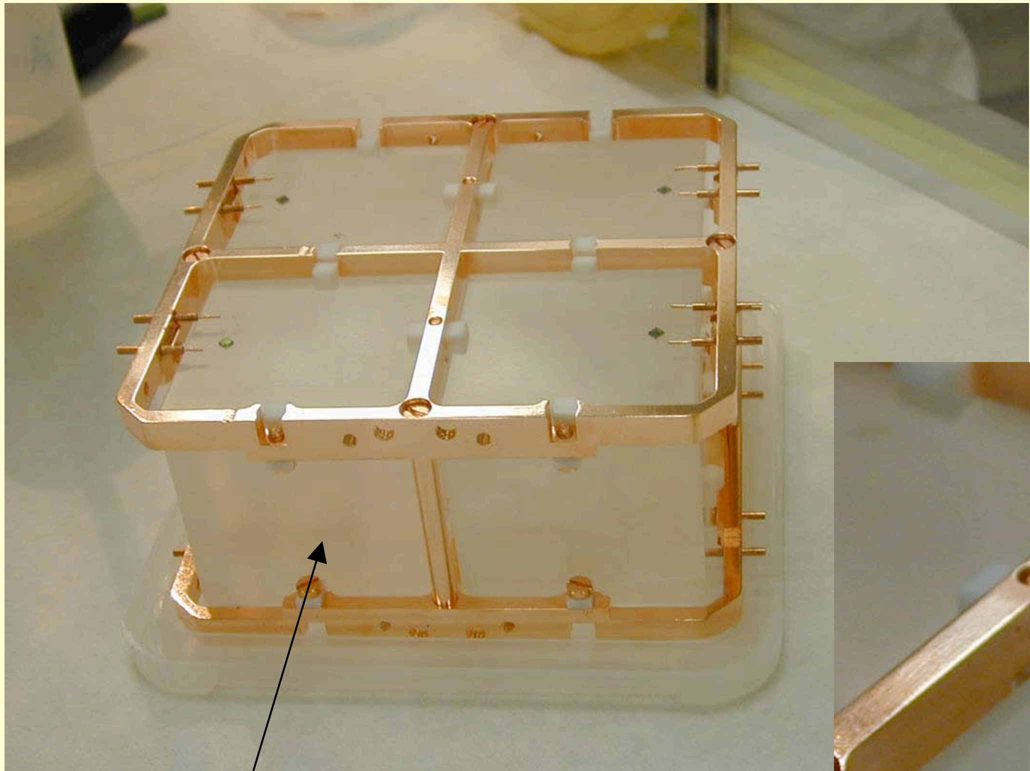
Underground operation in the Gran Sasso laboratory (Italy)



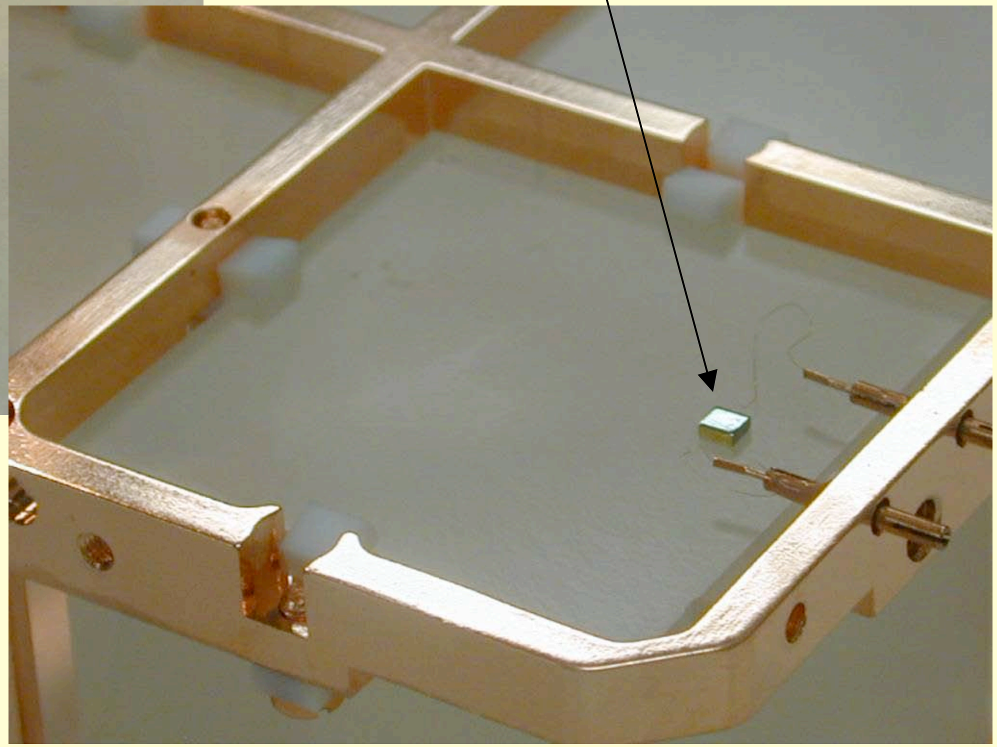


Same cryostat and similar structure as previous pilot experiment

CUORICINO modules

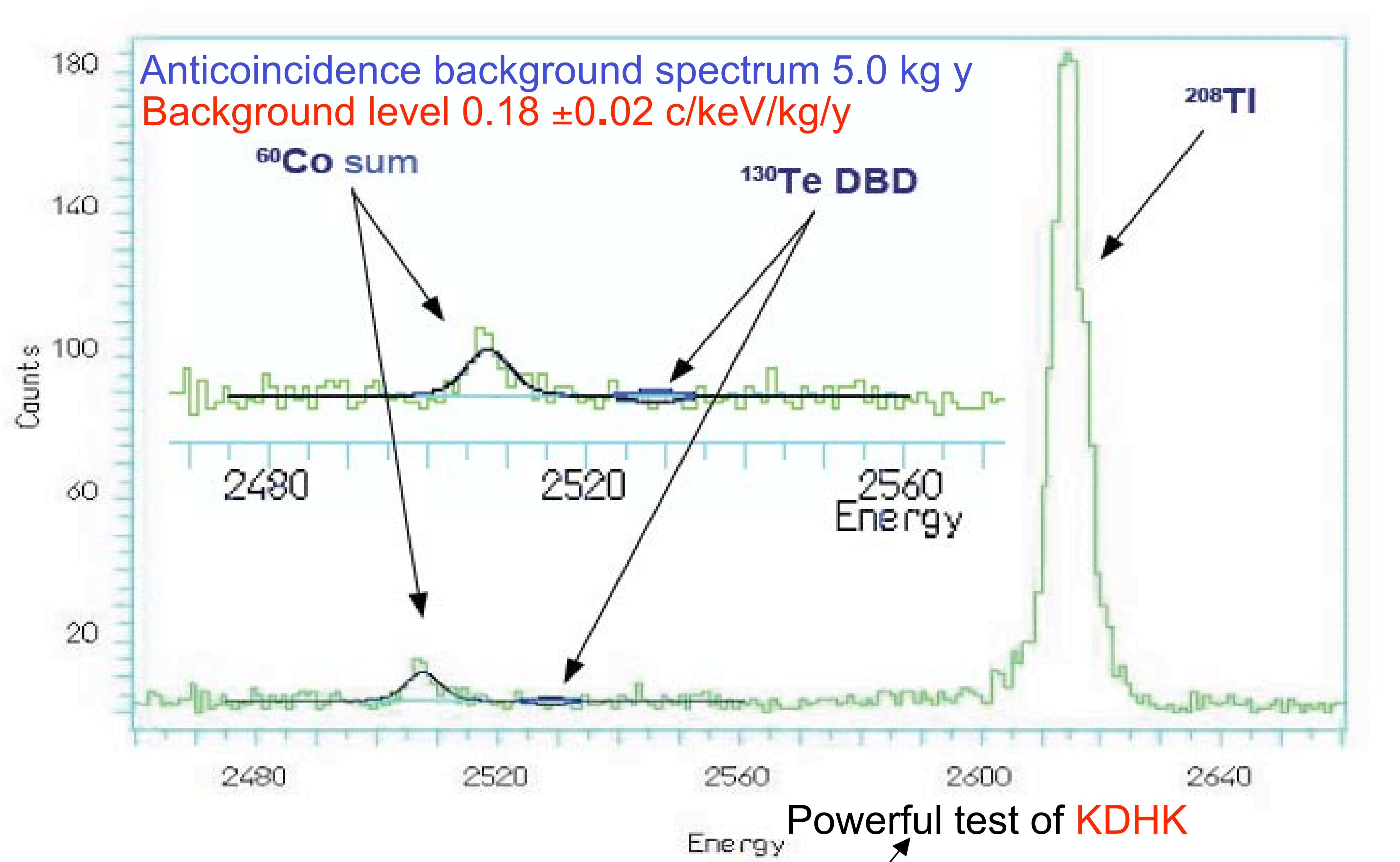


thermometer
(doped Ge chip)



single TeO_2 crystal
- 790 g
- 5 x 5 x 5 cm

CUORICINO results and sensitivity



Powerful test of KDHK

$\tau_{1/2}^{0\nu}$ (y) > 1.8 × 10^{24} y

$\langle M_{\beta\beta} \rangle$ < 0.2 – 1.1 eV (90% c.l.)

3 y sensitivity (with present performance):
1 × 10^{25} y

$\langle M_{\beta\beta} \rangle$ < 0.13 – 0.31 eV

The future: a great number of proposed experiments

COBRA	^{130}Te	10 kg CdTe semiconductors
DCBA	^{150}Nd	20 kg Nd layers between tracking chambers
CAMEO	^{114}Cd	1 t $CdWO_4$ crystals
CANDLES	^{48}Ca	Several tons CaF_2 crystals in liquid scint.
CUORE	^{130}Te	750 kg TeO_2 bolometers
EXO	^{136}Xe	1 ton Xe TPC (gas or liquid)
GEM	^{76}Ge	1 ton Ge diodes in liquid nitrogen
GENIUS	^{76}Ge	1 ton Ge diodes in liquid nitrogen
LNGS-LoI 35/04	^{76}Ge	1 ton Ge diodes in liquid nitrogen/argon
GSO	^{160}Gd	2 t Gd_2SiO_5:Ce crystal scint. in liquid scint.
Majorana	^{76}Ge	500 kg Ge diodes
MOON	^{100}Mo	Mo sheets between plastic scint., or liq. scint.
Xe	^{136}Xe	1.56 t of Xe in liq. Scint.
XMASS	^{136}Xe	10 t of liquid Xe

Potential large-mass (~1 ton) future experiments

More promising projects (attack the 50 meV mass scale):

GERDA
SUPERNEMO } Europe

CUORE } Europe + US

EXO
MAJORANA } US

In Europe, joint effort on common problems

IDEA project – Integrated Double-beta-decay European Activities
funded by the European Commission inside a large astroparticle physics program

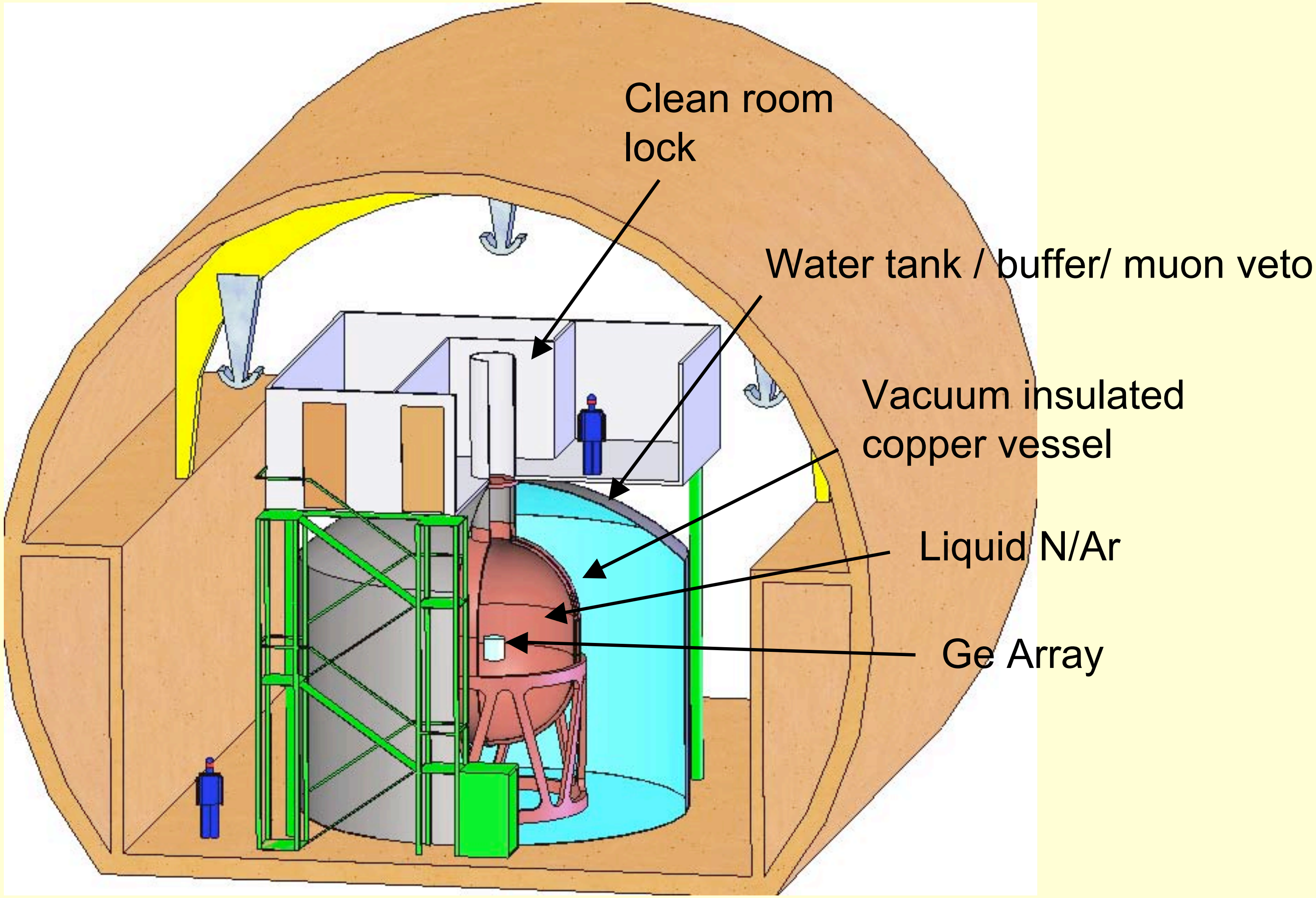
GERDA

New ^{76}Ge experiment. Basic points:

- Collect all the existing ^{76}Ge material (HM+IGEX) ⇒ ~20 kg (+ 30 kg new)
  (collaboration with Kurchatov)
- Operate it in liquid nitrogen, which acts as a coolant and as a passive shielding (+ traditional shielding)
- Replace possibly liquid nitrogen with scintillating liquid argon (active shield)
- Acquire the 20 kg enriched material in a 0 background set-up
  - powerful intermediate experiment
  - test KDHK evidence with the same nuclides (lifetime sensitivity: 3×10^{25} y)
- Procurement of further enriched material ⇒ final ~ 1 ton experiment

$$\langle M_{\beta\beta} \rangle < 20 - 50 \text{ meV}$$

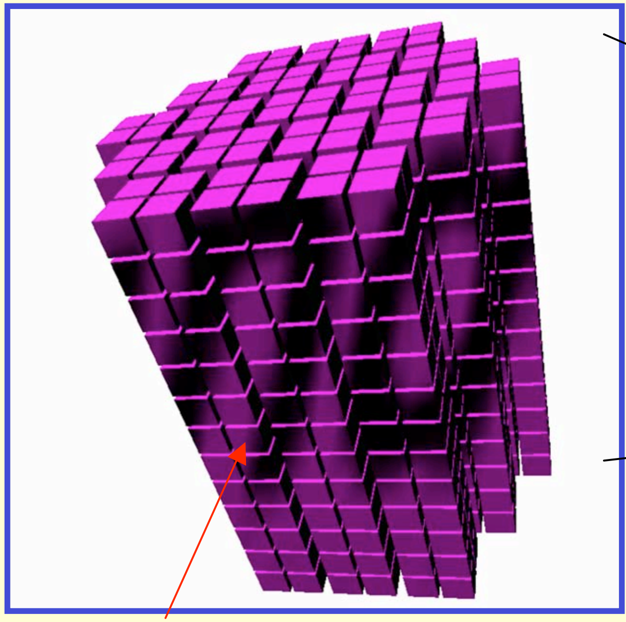
GERDA: Baseline design



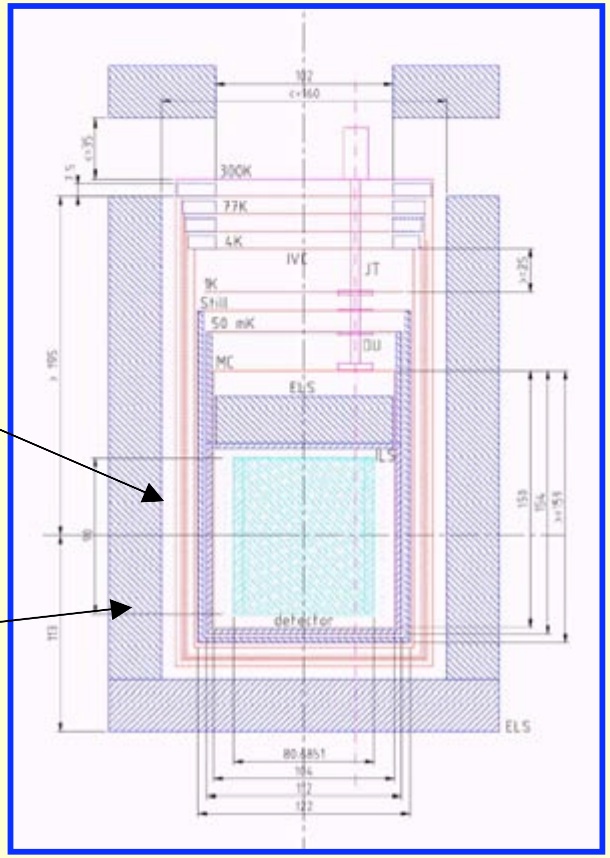
From CUORICINO to CUORE
(Cryogenic Underground Observatory for Rare Events)

CUORE = closely packed array of 988 detectors
19 towers - 13 modules/tower - 4 detectors/module
M ~ 750 kg

Compact structure, ideal for active shielding



Each tower is a CUORICINO-like detector



Special dilution refrigerator

CUORE background and sensitivity

Montecarlo simulations of the background show that

b = 0.001 counts / (keV kg y)

is possible with the present bulk contamination of detector materials

The problem is the surface background (alpha, beta energy-degraded)

→ it must be reduced by a factor 10 – 100

work in progress!

5 y sensitivity with pessimistic background:

b = 0.01 counts/(keV kg y)

$$F^{0\nu} = 9.4 \times 10^{25} \times (T [y])^{1/2}$$

$\langle M_{\beta\beta} \rangle < 20 - 100$ meV

5 y sensitivity with optimistic background:

b = 0.001 counts/(keV kg y)

$$F^{0\nu} = 2.9 \times 10^{26} \times (T [y])^{1/2}$$

$\langle M_{\beta\beta} \rangle < 10 - 50$ meV

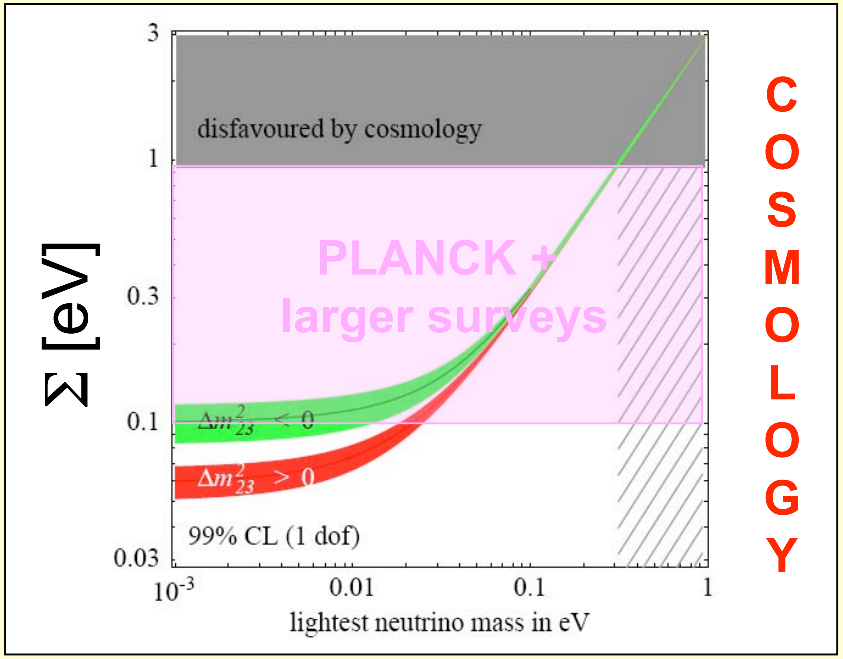
$\langle M_{\beta\beta} \rangle < 7 - 38$ meV

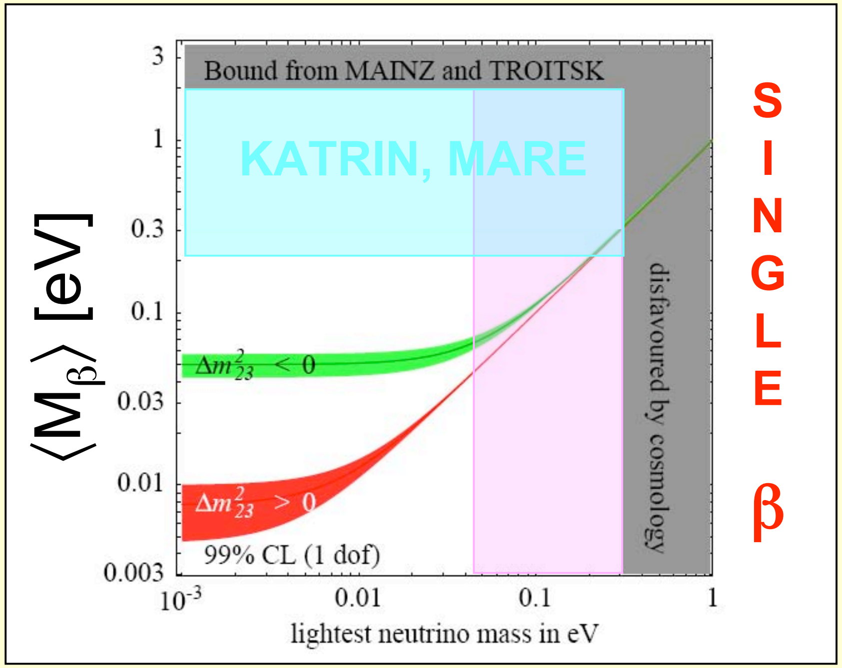
enriched CUORE

Conclusions

Exciting times for neutrino masses:

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





Strumia-Vissani hep-ph/0503246