INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Focus week : Neutrino Mass

Mar 17 to 20, 2008

Neutrinoless Double Beta Decay
Experimental status

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Italy

Outline of the talk

- Neutrino mass and Double Beta Decay
- Experimental challenge and strategies
- Present situation
- Overview of the future projects
- Some very promising experimental approaches
- Prospects and conclusions

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Neutrino flavor oscillations

Premise

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

Flavor eigenstates $\neq$ Mass eigenstates

$$\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Weak interaction

Propagation

Neutrino flavor oscillations

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

① oscillations do occur → neutrinos are massive

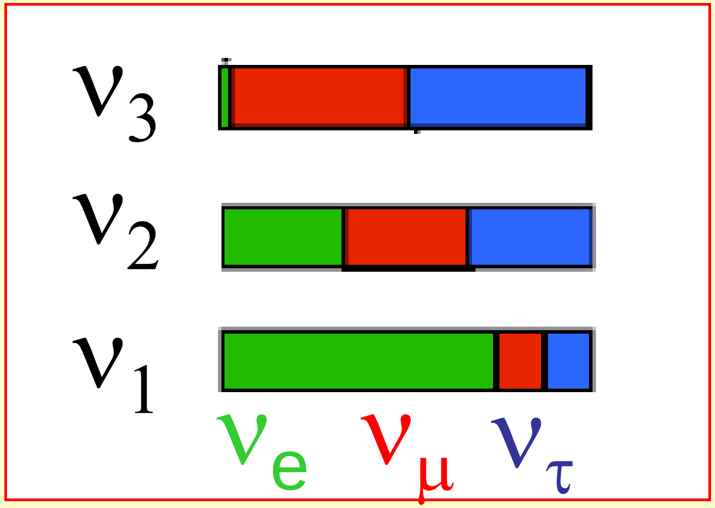
Neutrino mixing and masses

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

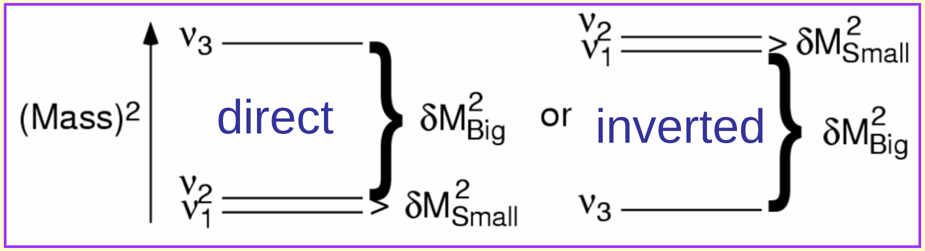


$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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

$$\nu \neq \bar{\nu}$$

$$\nu \equiv \bar{\nu}$$

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

Direct determination

Model dependent

Laboratory measurements

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

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

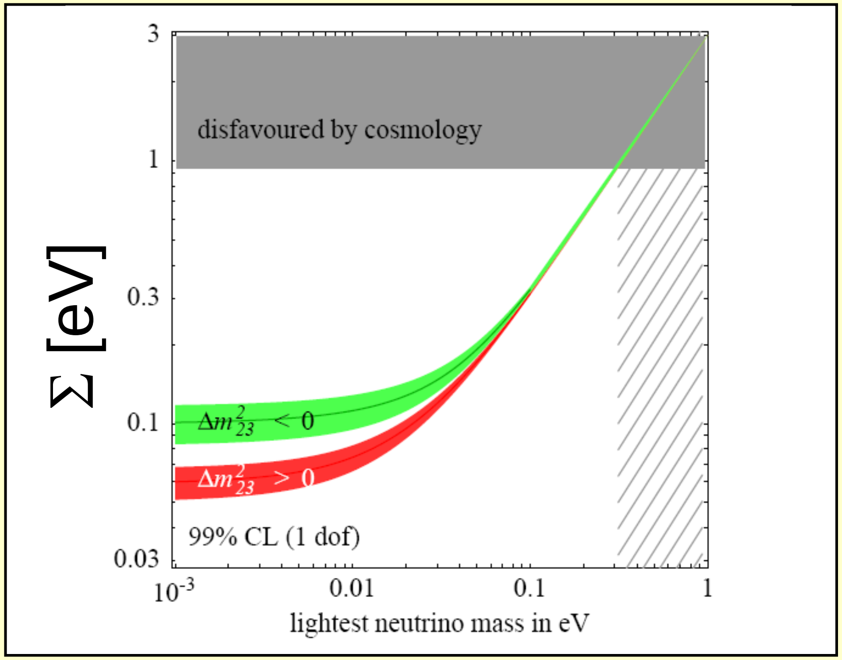
double beta decay
coherent sum
virtual neutrino
Majorana phases

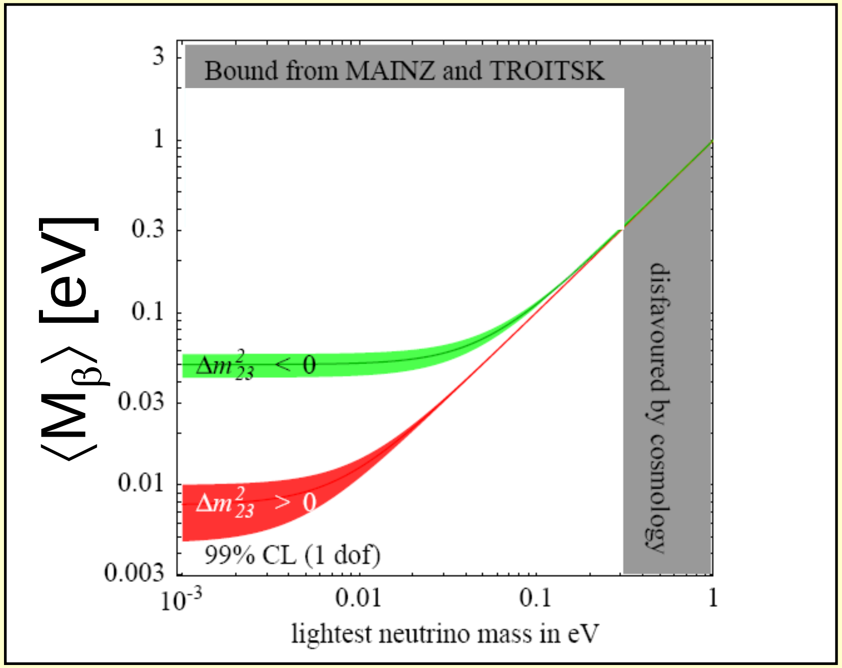
Present bounds

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

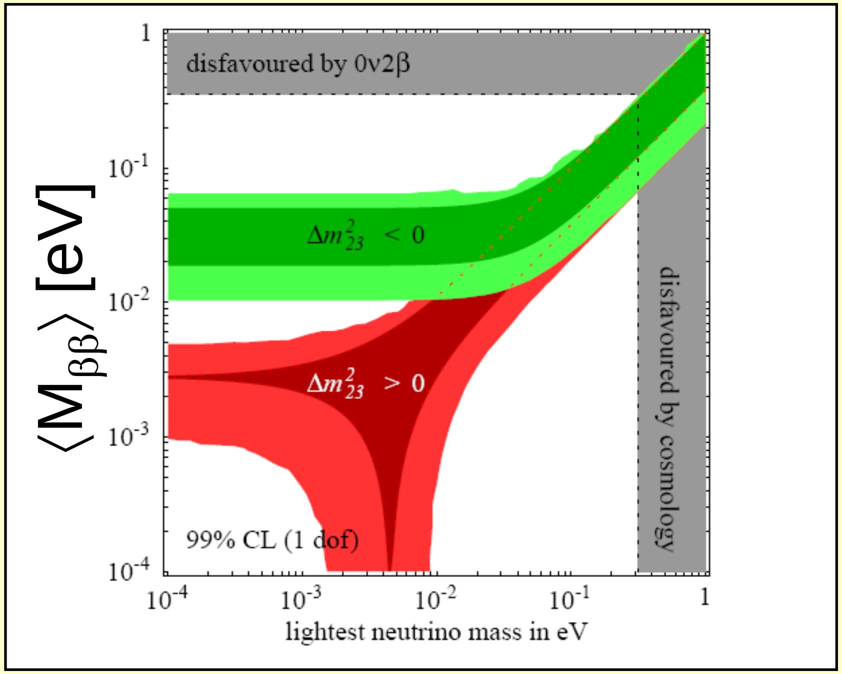
Two bands appear in each plot, corresponding to inverted and direct hierarchy

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





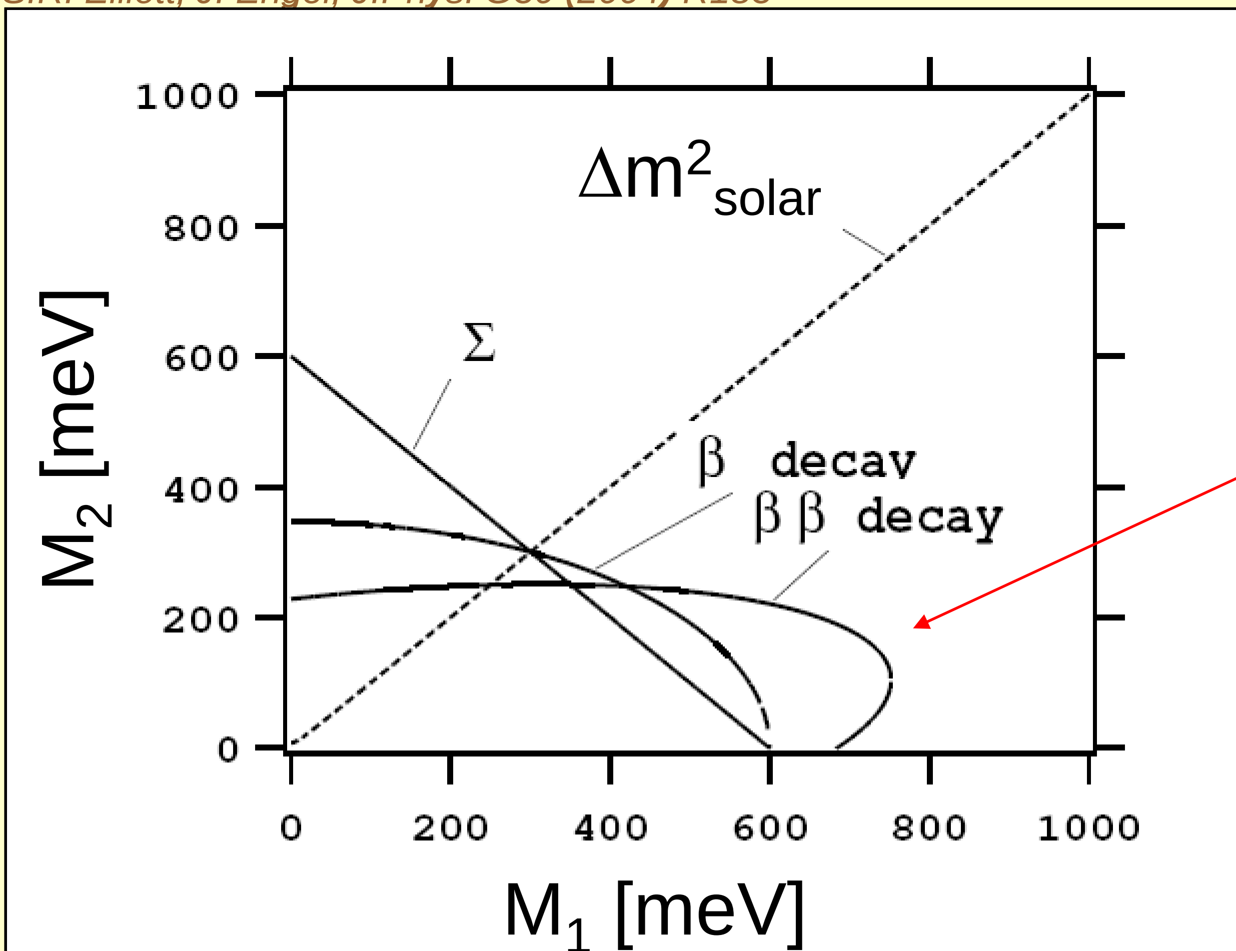
Strumia-Vissani hep-ph/0503246



Combined information

For simplicity, a two neutrino scenario with degenerate masses
The two masses are over-constrained $\Rightarrow$ Majorana phases

S.R. Elliott, J. Engel, J.Phys. G30 (2004) R183

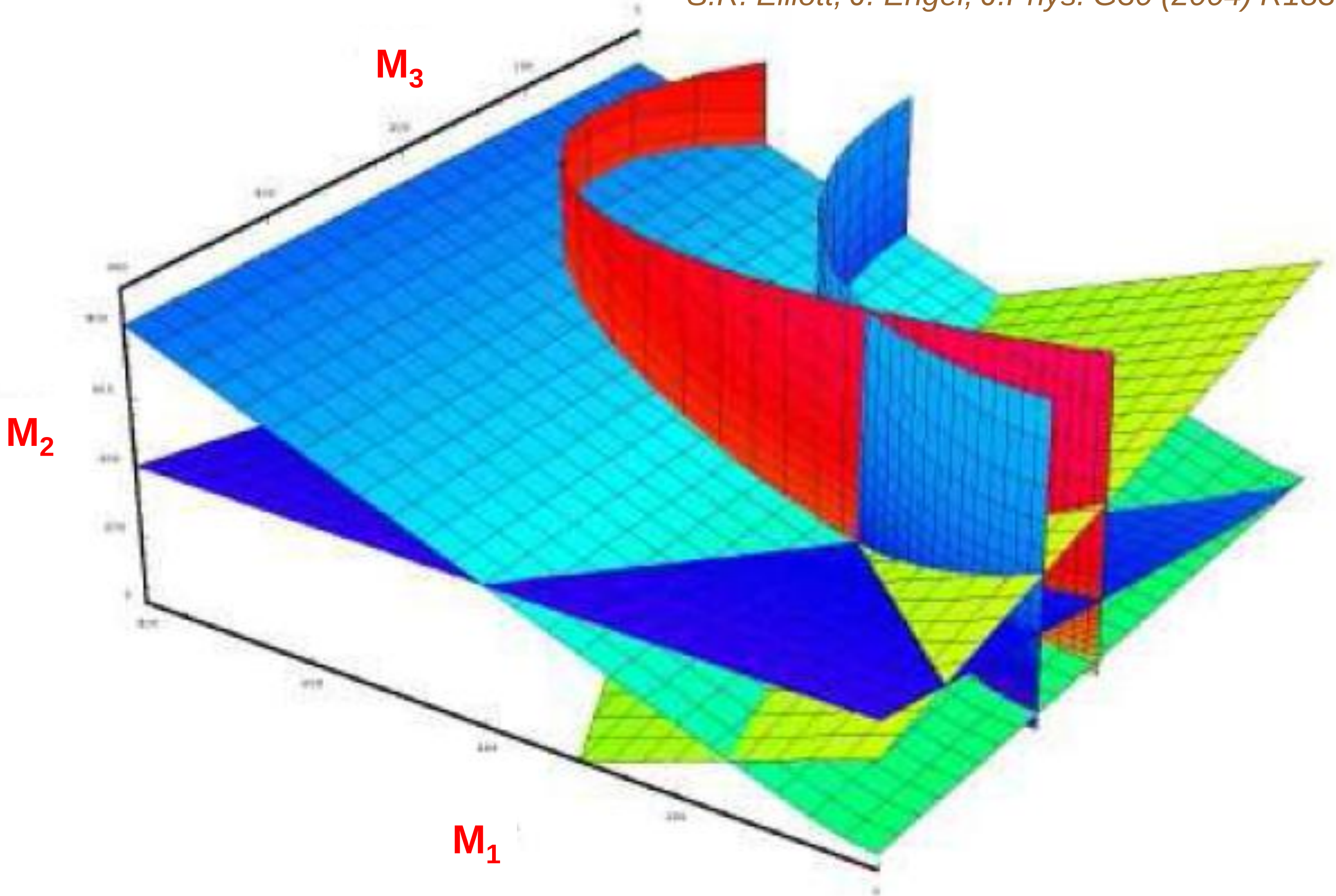


wrong value
of the Majorana
phase

right value
of the Majorana
phase

Combined information: three neutrinos

S.R. Elliott, J. Engel, J.Phys. G30 (2004) R183



Decay modes for Double Beta Decay

Three 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

③ $(A,Z) \rightarrow (A,Z+2) + 2e^- + \chi$ ← Double Beta Decay
with Majoron (light neutral boson)
never observed – $\tau > 10^{22}$ y

Processes ② and ③ would imply new physics beyond the Standard Model

violation of lepton number conservation

They are very sensitive tests to new physics since the phase space term is much larger for them than for the standard process (in particular for ②)

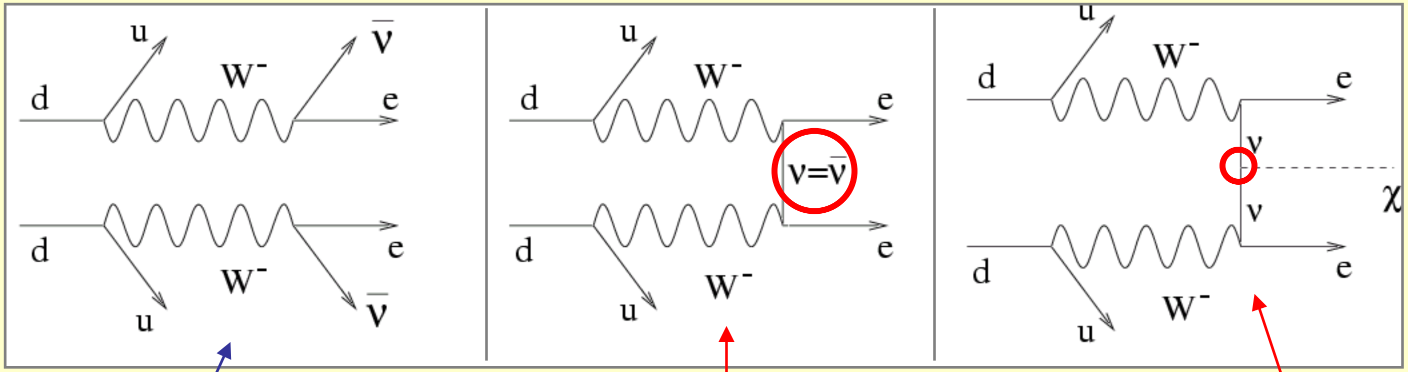
interest for 0ν-DBD lasts for 70 years !

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

Double Beta Decay and neutrino physics

DBD is a second order weak transition ← very low rates

Diagrams for the three processes discussed above:

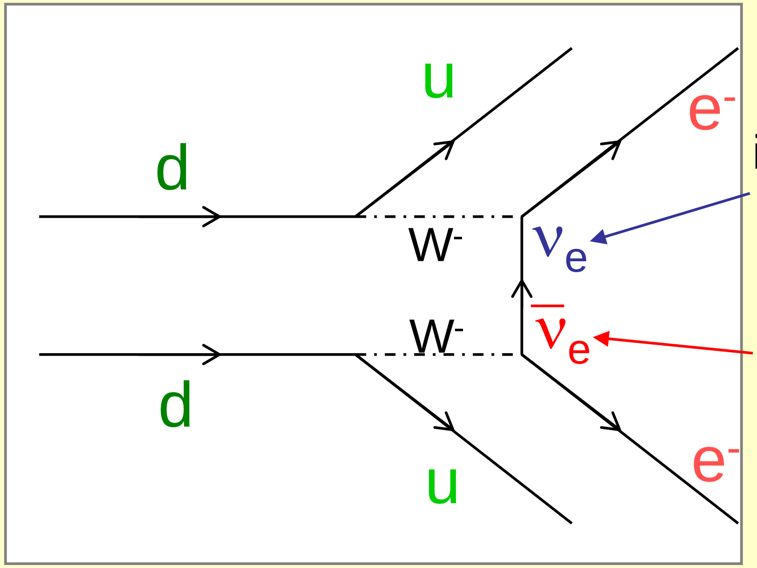


Standard process
two "simultaneous" beta decays

DBD with Majoron emission
A Majoron couples to the exchanged virtual neutrino

0ν-DBD
a virtual neutrino is exchanged between the two electroweak lepton vertices

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** → $m_\nu \neq 0$, $\bar{\nu} \equiv \nu$

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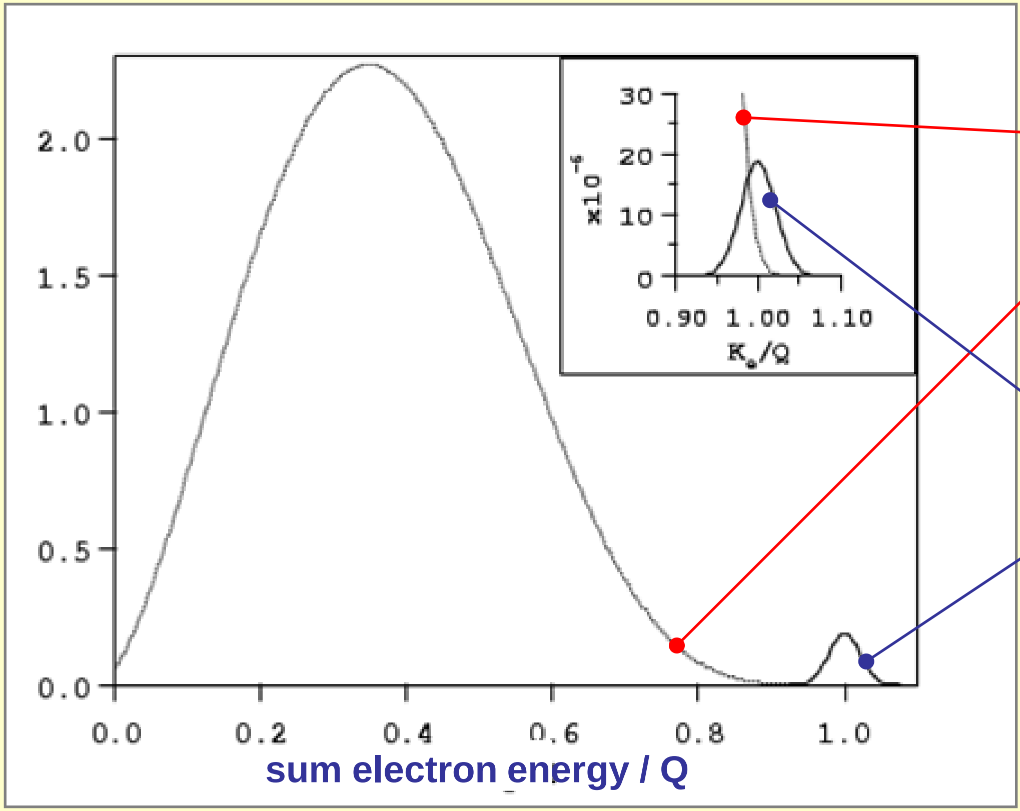
Electron sum energy spectra in DBD

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



two neutrino DBD
continuum with maximum at ~1/3 Q

neutrinoless DBD
peak enlarged only by the detector energy resolution

The Majoron spectrum is a continuum with maximum close to Q
(phase space for a particle decaying to three light objects)

Q ~ 2-3 MeV for the most promising nuclides

additional signatures:

- single electron energy distribution
- angular distribution

0ν-DBD: parameters determining the rate

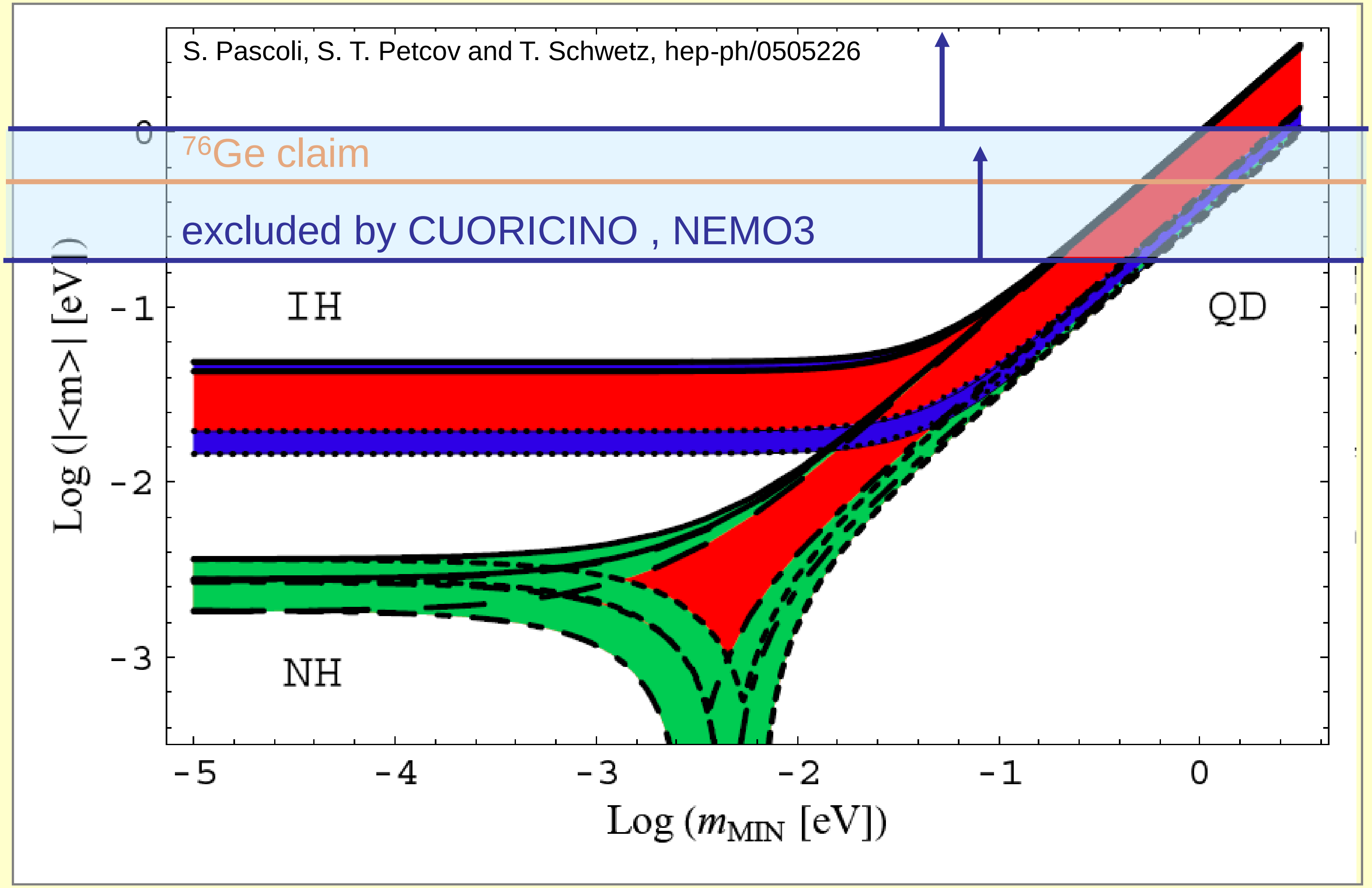
how **0ν-DBD** is connected to neutrino mixing matrix and masses
in case of process induced by mass mechanism

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

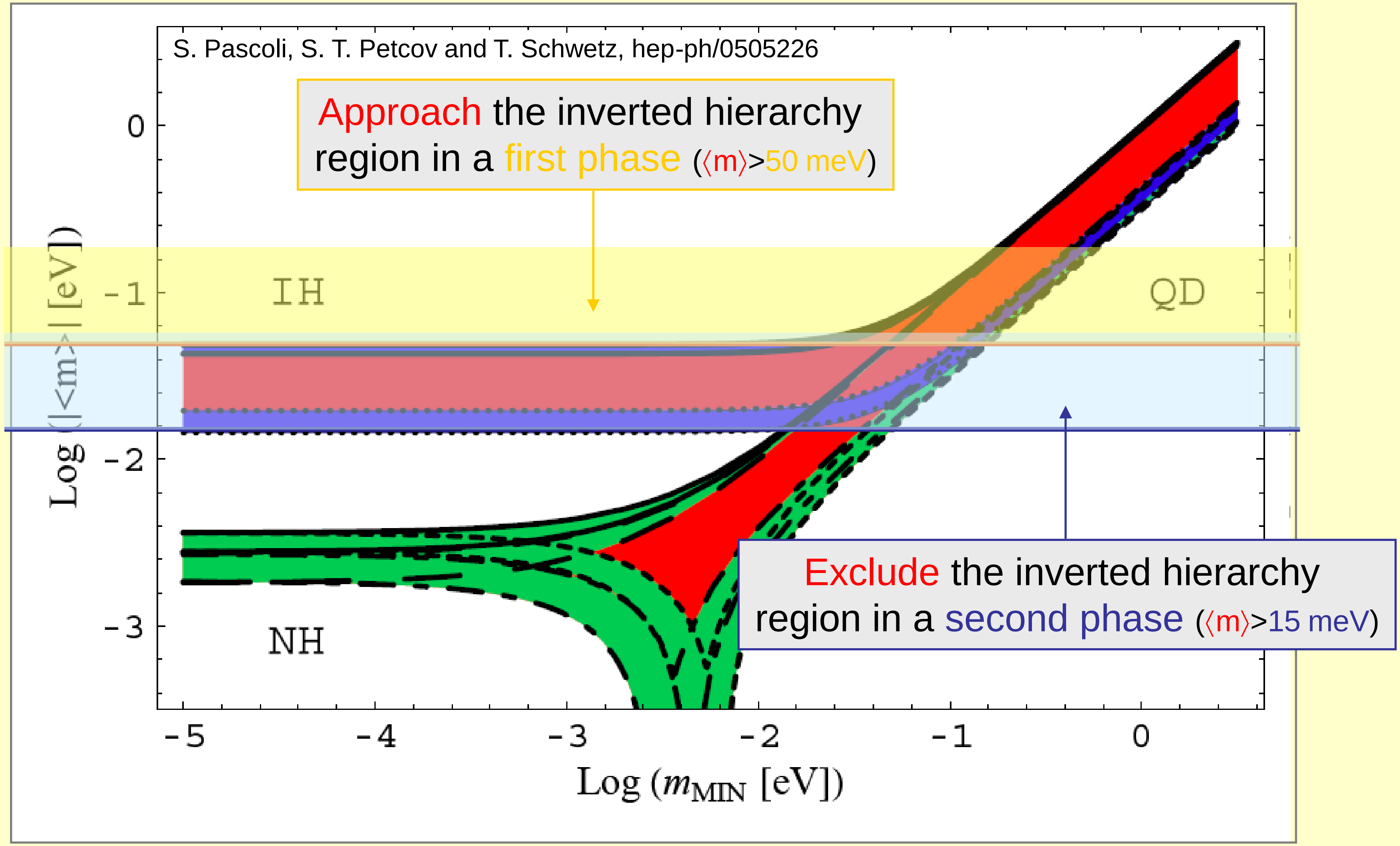
- $1/\tau$ — neutrinoless Double Beta Decay **rate**: what the experimentalists try to measure
- $G(Q,Z)$ — Phase space
- M_{nucl} — Nuclear matrix elements: what the nuclear theorists try to calculate
- $\langle M_{\beta\beta}\rangle$ — Effective **Majorana mass**: parameter containing the physics

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

From where we start…

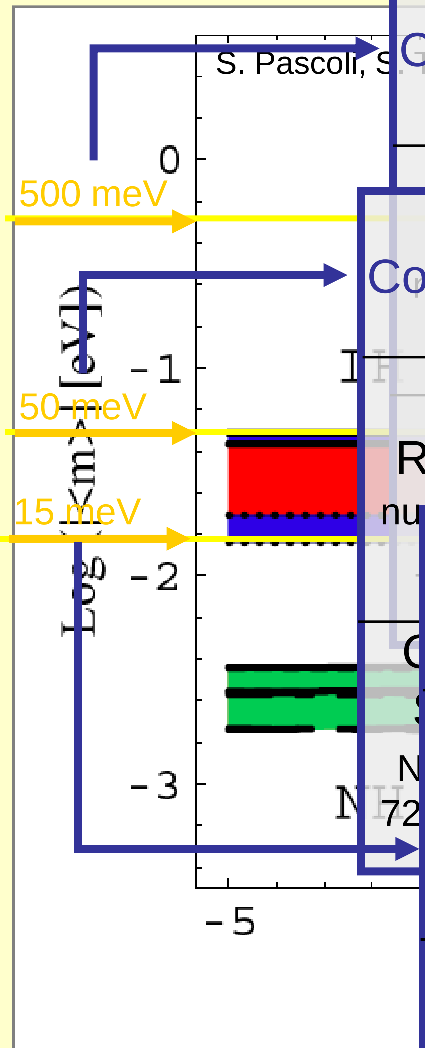


…and where we want to go



There are techniques and experiments in preparation which have the potential to reach these sensitivities

The size of the challenge



Counts / y ton	Ge natural	Ge enriched	TeO_2 natural	TeO_2 enriched
Rodin et al. nucl-th/0503063	17	207	77	204
Civitarese Suhonen Nucl. Phys. A 729, 867 (2003)	37	434	575	1519

Counts / y ton	Ge natural	Ge enriched	TeO_2 natural	TeO_2 enriched
Rodin et al. nucl-th/0503063	0.17	2.1	0.77	2.04
Civitarese Suhonen Nucl. Phys. A 729, 867 (2003)	0.37	4.3	5.7	15

Counts / y ton	Ge natural	Ge enriched	TeO_2 natural	TeO_2 enriched
Rodin et al. nucl-th/0503063	0.016	0.19	0.07	0.18
Civitarese Suhonen Nucl. Phys. A	0.033	0.39	0.52	1.37

Sensitive masses at the 1 ton scale are required

Background requirements

To start to explore the inverted hierarchy region

Sensitivity at the level of 1-10 counts / y ton

To cover the inverted hierarchy region

Sensitivity at the level of 0.1 -1 counts / y ton

The order of magnitude of the target bakground is
~ 1 counts / y ton

- Natural ra
  (source its

- Neutrons

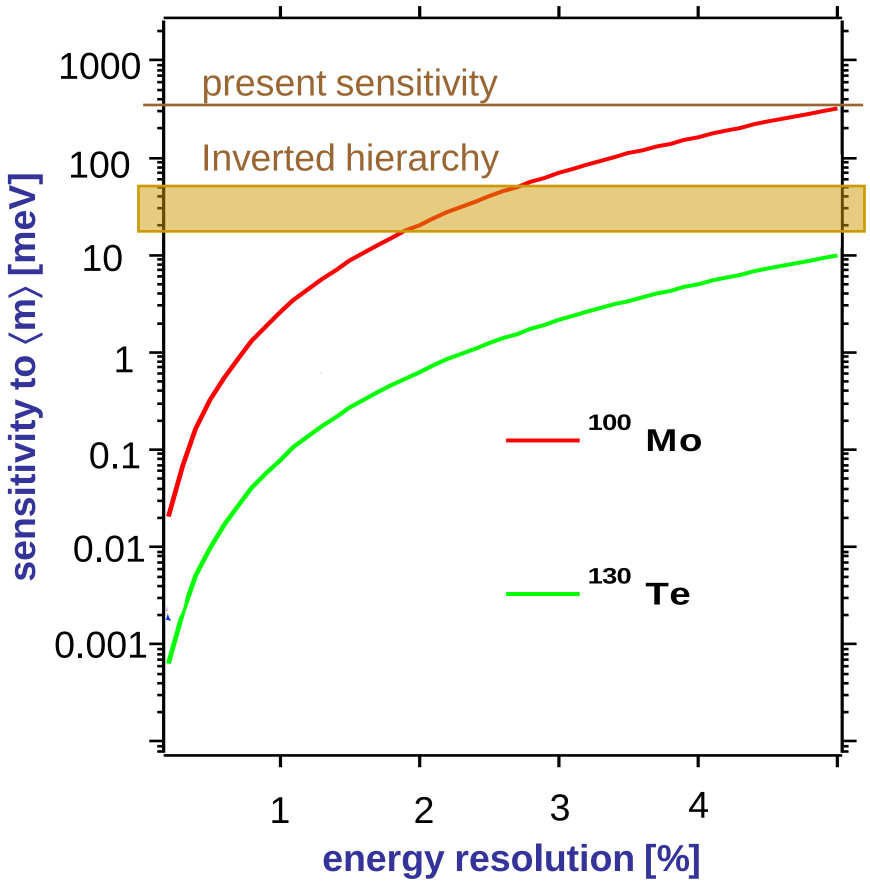
- Cosmoger

- 2 ν Double Beta Decay

seful

n

A challenge for the space-resolving techniques, which normally have low energy resolution (~ 10 %)



Experimental strategies

① Detect and identify the daughter nuclei (indirect search)

geochemical experiments
radiochemical experiments

it is not possible to distinguish the decay channel
important in the 70s-80s – no more pursued now

② Detect the two electrons with a proper nuclear detector (direct search)

desirable features

- high energy resolution
- low background
- large source (many nuclides under control)
- event reconstruction method

a peak must be revealed over background (0ν-DBD)

shield cosmic rays (direct interactions and activations)
⇒ underground

very radio-pure materials
^{238}U – ^{232}Th ⇒ $\tau \sim 10^{10}$ y
signal rate ⇒ $\tau > 10^{25}$ y

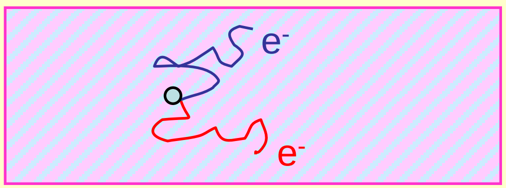
present more sensitive experiments: 10 - 100 kg
future goals: ~ 1000 kg ⇒ 10^{27} – 10^{28} nuclides

- reject background
- study electron energy and angular distributions

Experimental approaches to direct searches

Two approaches:

①



Source ≡ Detector
(calorimetric technique)

- scintillation
- phonon-mediated detection
- solid-state devices
- gaseous detectors

☹ constraints on detector materials

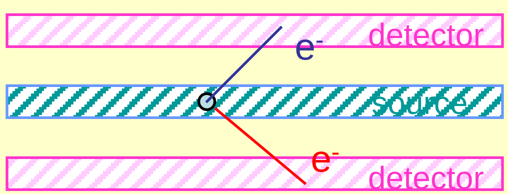
☺ very large masses are possible
demonstrated: up to ~ 50 kg
proposed: up to ~ 1000 kg

☺ with proper choice of the detector, very high energy resolution
Ge-diodes
bolometers

☺ in gaseous/liquid xenon detector, indication of event topology

☹ in contradiction

②



Source ≠ Detector

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

☺ neat reconstruction of event topology

☹ it is difficult to get large source mass

☺ several candidates can be studied with the same detector

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)]** → $b = 0$

source mass, live time, energy resolution

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

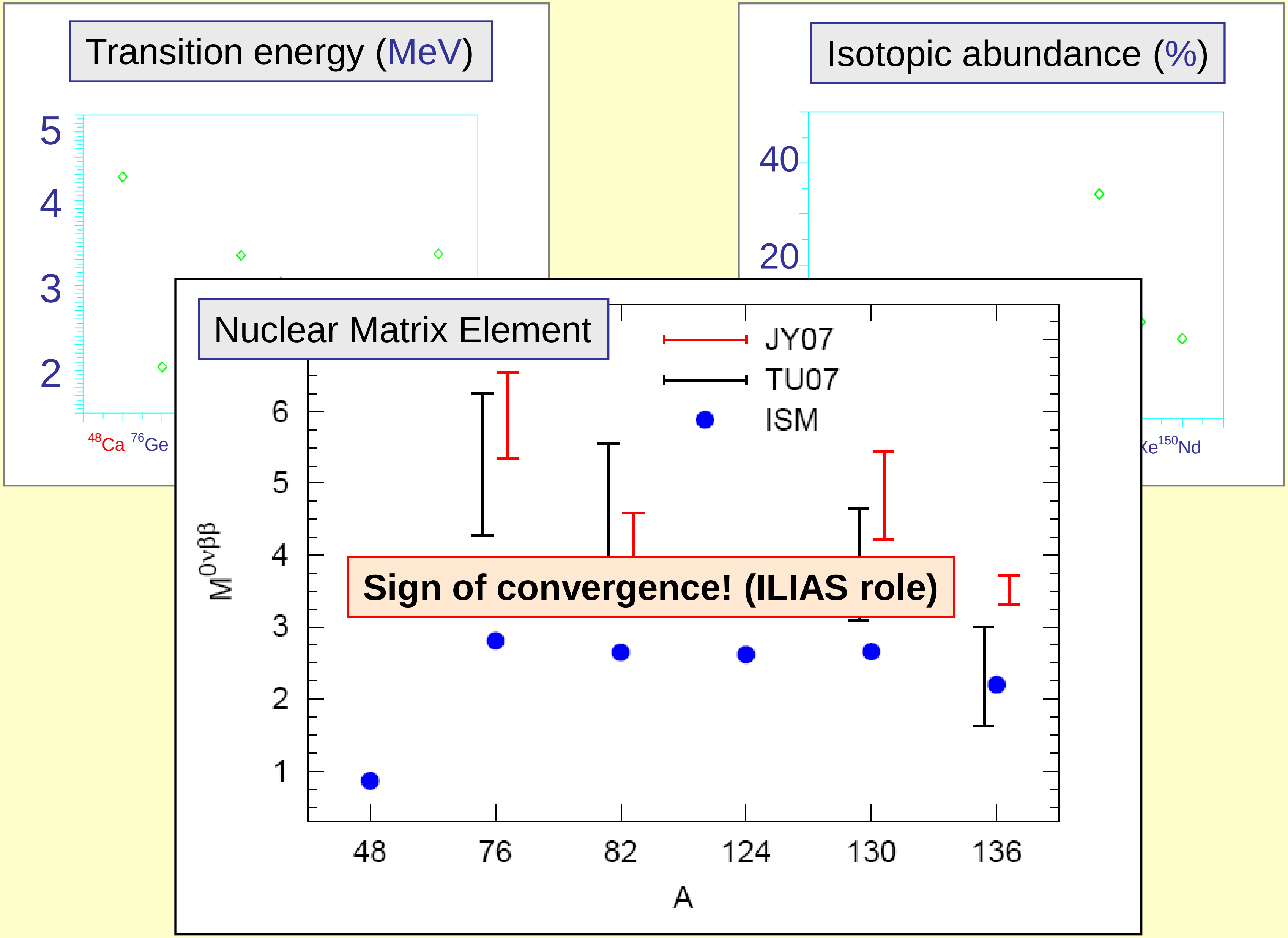
background level

$$F \propto MT$$

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

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

Choice of the nuclide



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Present experimental situation in the search for 0ν-DBD

I will give some details about three crucial experiments:

- Heidelberg – Moscow (HM) (closed)

  dominated DBD scenario over a decade (stopped in May 03)

- NEMO3 (running)

  it is an intermediate generation experiment capable to study different candidate nuclides

- CUORICINO (running)

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

  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) $\times 10^{25}$ y (1 $\times 10^{25}$ 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 eV (95% 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

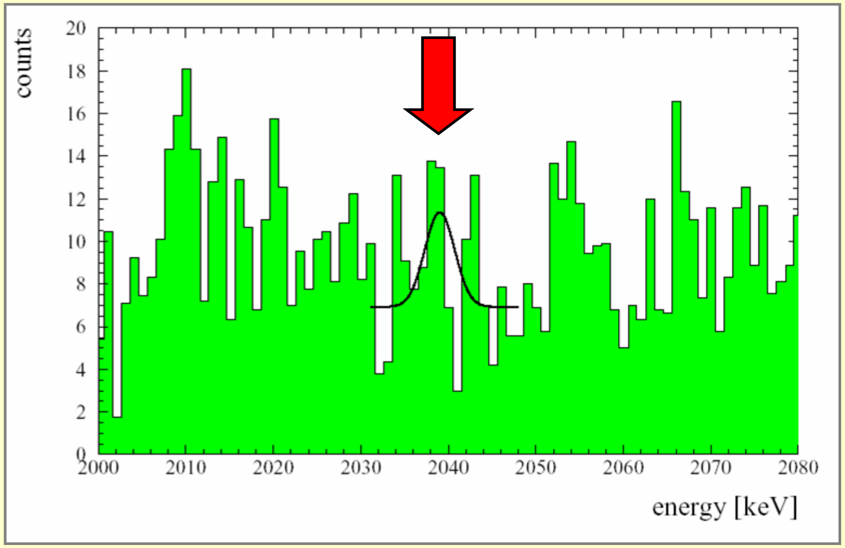
Klapdor-Kleingrothaus HV hep-ph/0205228
H.L. Harney, hep-ph/0205293

} Independent replies to the Comments

Subsequent papers (2004) about claim of evidence

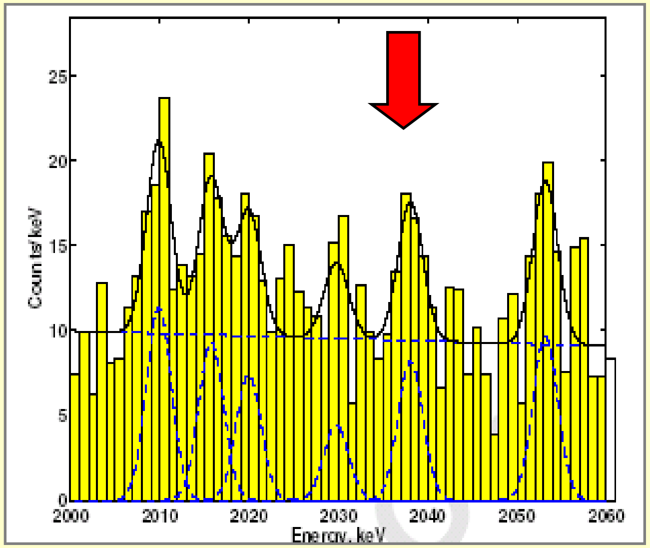
With respect to the 2001 results, now data with higher statistics and with better quality show an increase of the statistical significance of the "peak":

2001



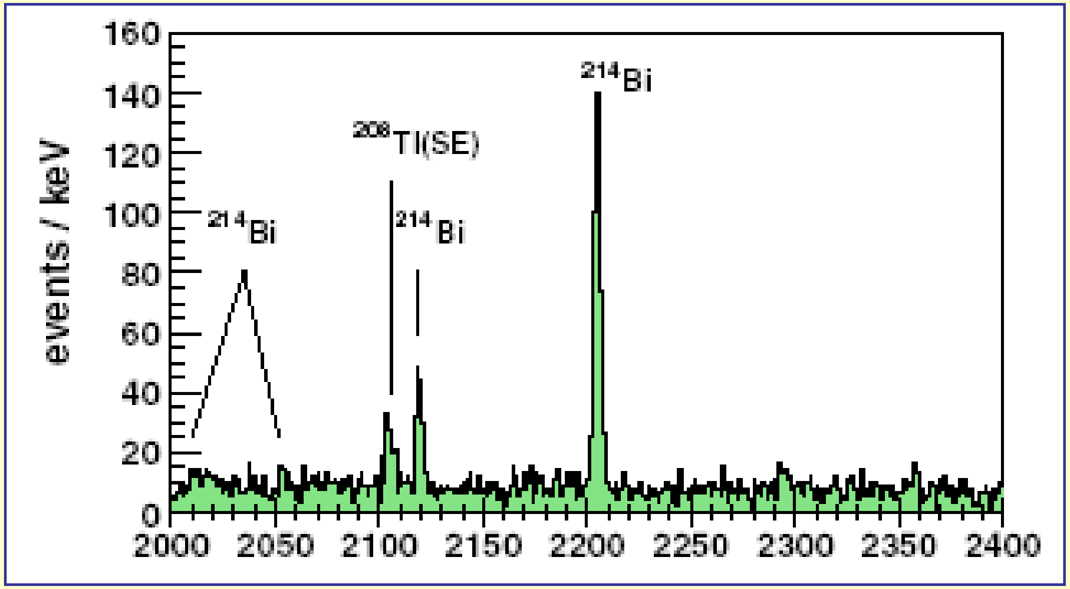
54.98 kg•y 2.2 σ

2004



71.7 kg•y 4 σ

Subsequent papers (2004) about claim of evidence

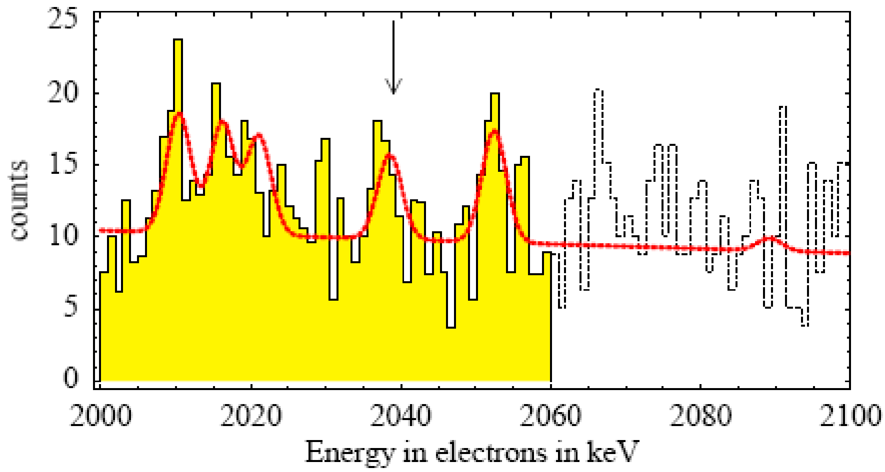


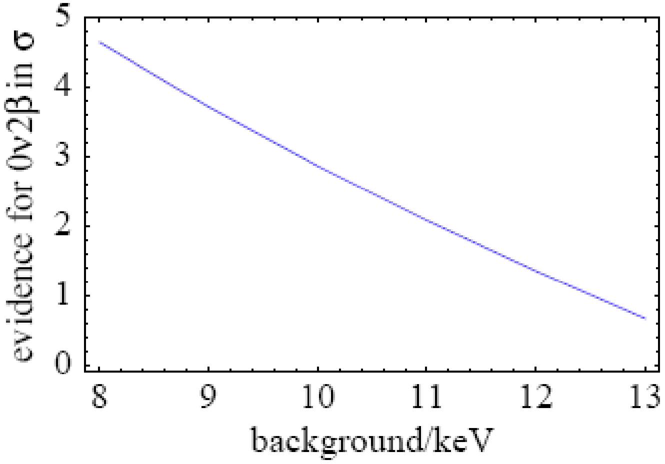
Many background features are still to explain

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: the structure

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

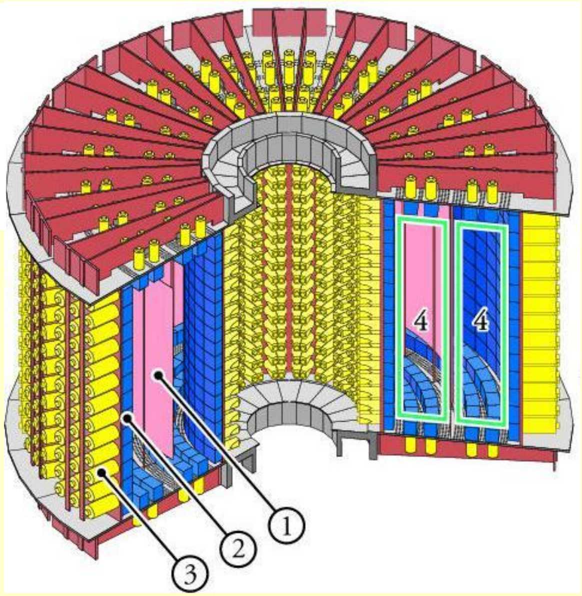
4.1×10^{25} ^{100}Mo nuclei

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

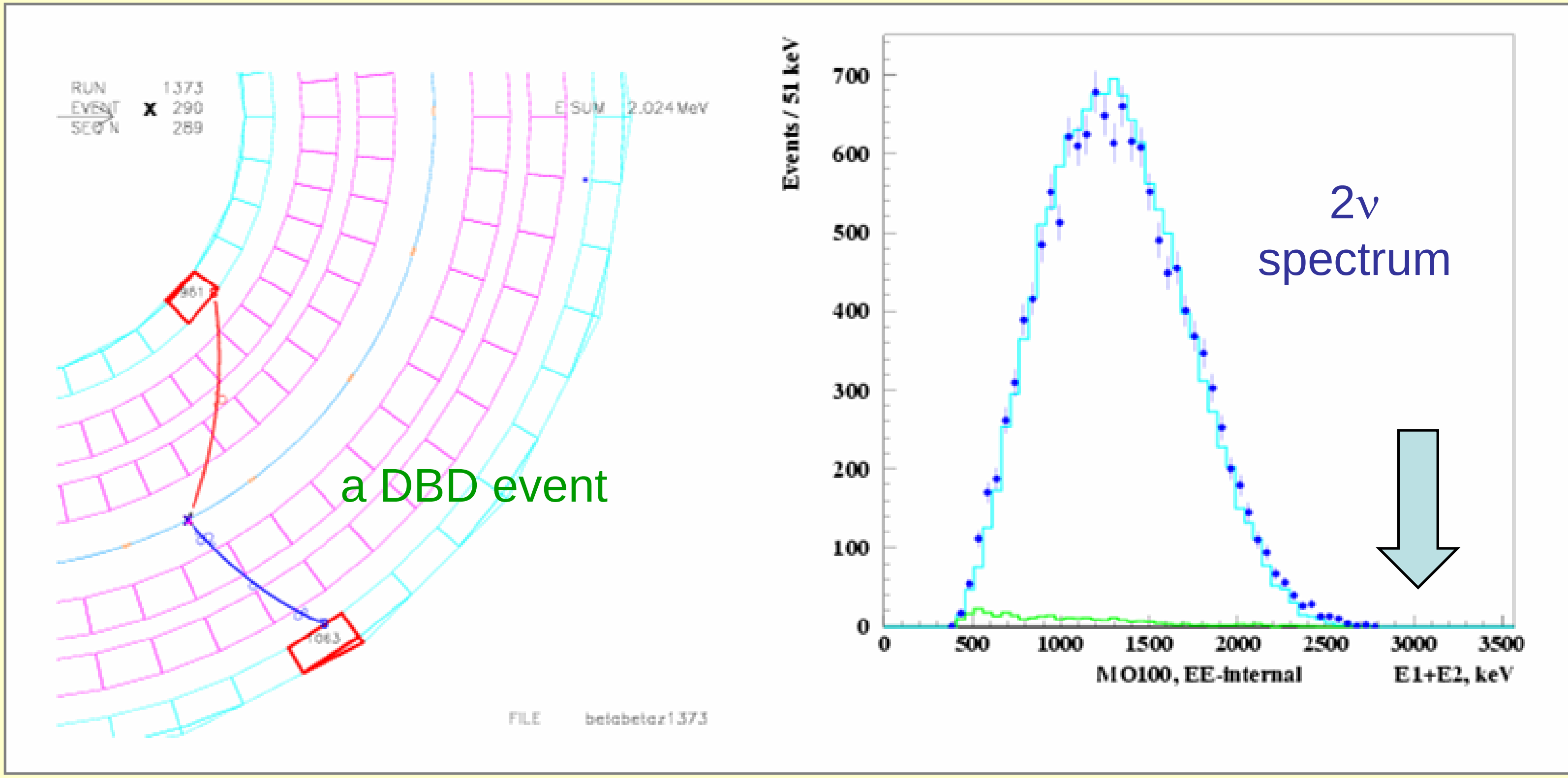
1 SOURCE
2 TRACKING VOLUME
3 CALORIMETER

detector scheme



NEMO3: the results and the sensitivity

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) > 5.8 × 10^{23} y

$\langle M_{\beta\beta} \rangle$ < 0.6 – 1.3 eV

final sensitivity: 0.2 – 0.35 eV

intrinsic limits:

- source strength
- low energy resolution ⇒ 2ν background

NEMO3: 2ν mode, superb nuclear physics

Nuclei	Enriched Source in NEMO 3	$T_{1/2}$, y (NEMO 3) (partially preliminary)
^{48}Ca (4.271 MeV) (0.187%)	7.0 g	$3.9(\pm 0.7 \pm 0.6) \cdot 10^{19}$
^{82}Se (2.995 MeV) (9.2%)	932 g	$9.6(\pm 0.3 \pm 1.0) \cdot 10^{19}$
^{96}Zr (3.350 MeV) (2.8%)	9.4 g	$2.0(\pm 0.3 \pm 0.2) \cdot 10^{19}$
^{100}Mo (3.034 MeV) (9.6%)	6914 g	$7.11(\pm 0.02 \pm 0.54) \cdot 10^{18}$
^{116}Cd (2.802 MeV) (7.5%)	405 g	$2.8(\pm 0.1 \pm 0.3) \cdot 10^{19}$
^{130}Te (2.528 MeV) (33.8%)	454 g	$7.6(\pm 1.5 \pm 0.8) \cdot 10^{20}$
^{150}Nd (3.367 MeV) (5.6%)	37 g	$9.7(\pm 0.7 \pm 1.0) \cdot 10^{18}$

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

↓

6.4×10^{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

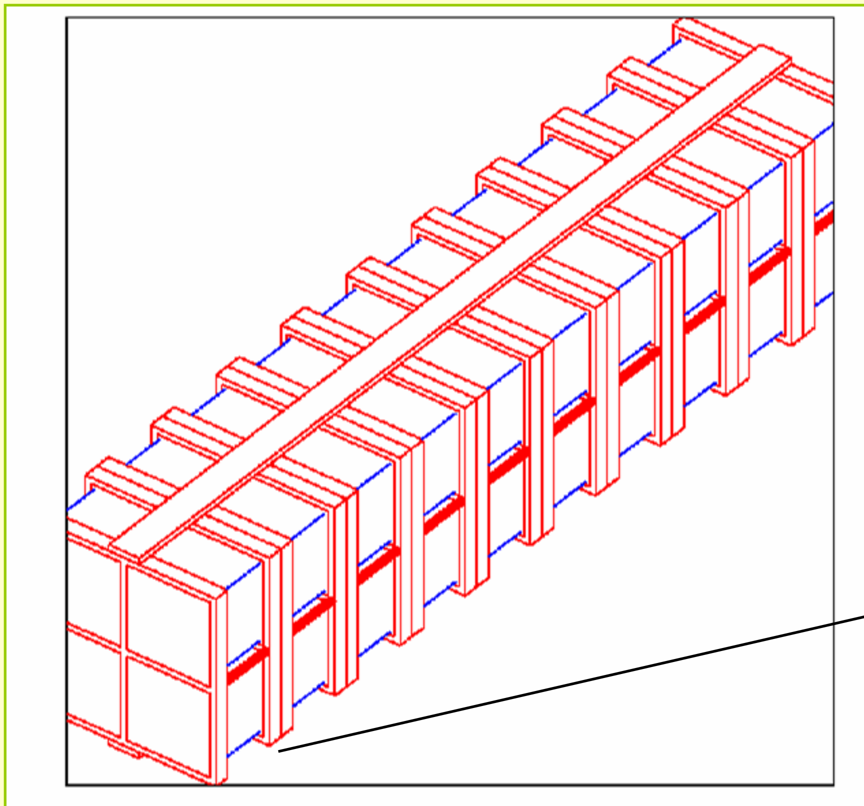
CUORICINO = tower of 13 modules,

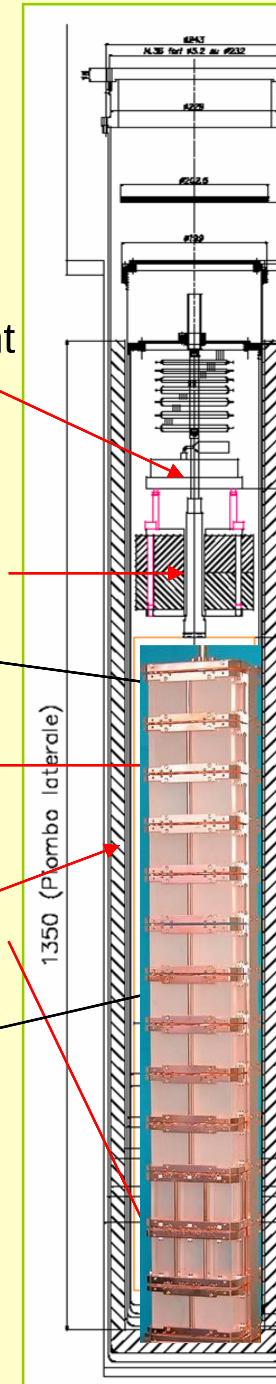
11 modules x 4 detector (790 g) each

2 modules x 9 detector (340 g) each

M = ~ 41 kg

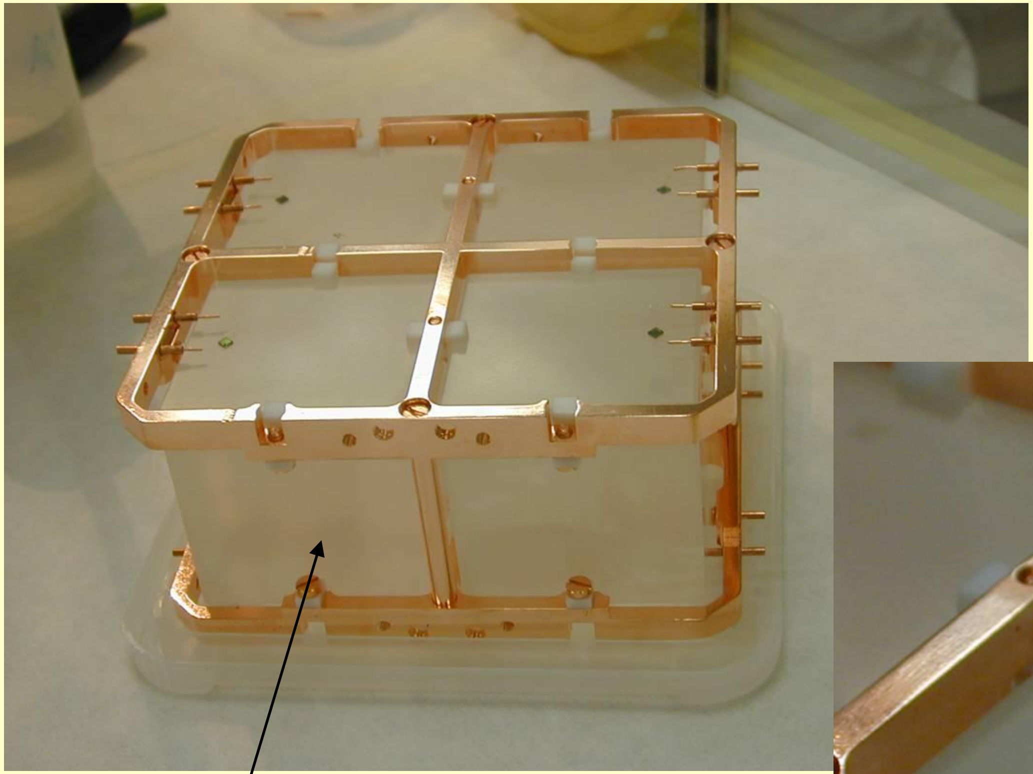
Underground operation in the Gran Sasso laboratory (Italy)

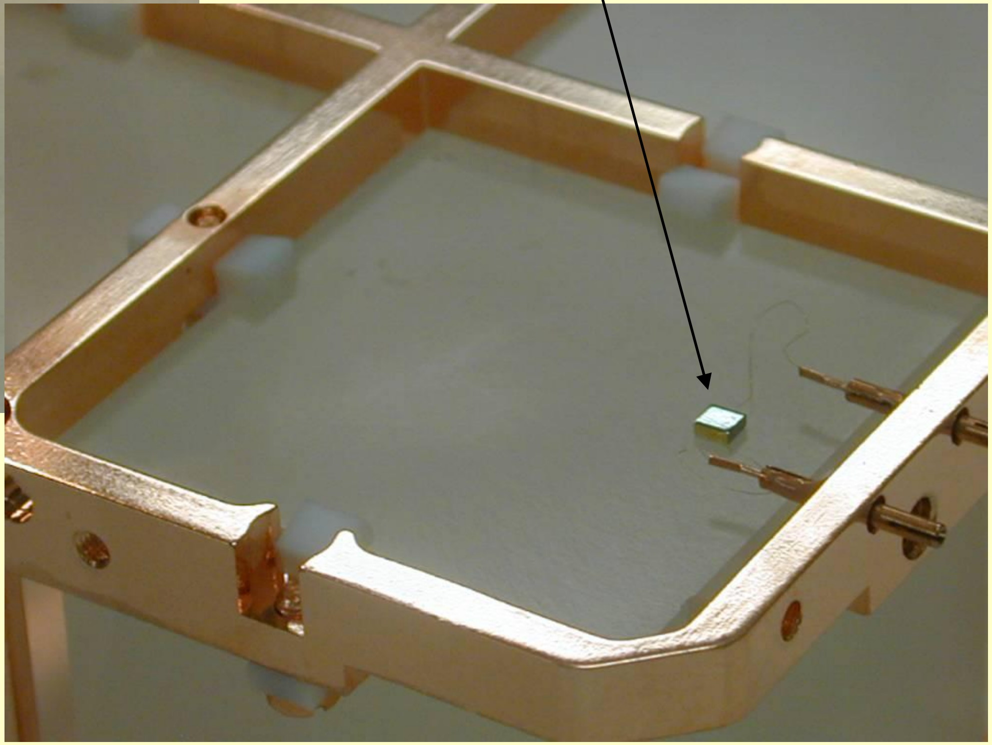




Same cryostat and similar structure as previous pilot experiment

CUORICINO modules





thermometer
(doped Ge chip)

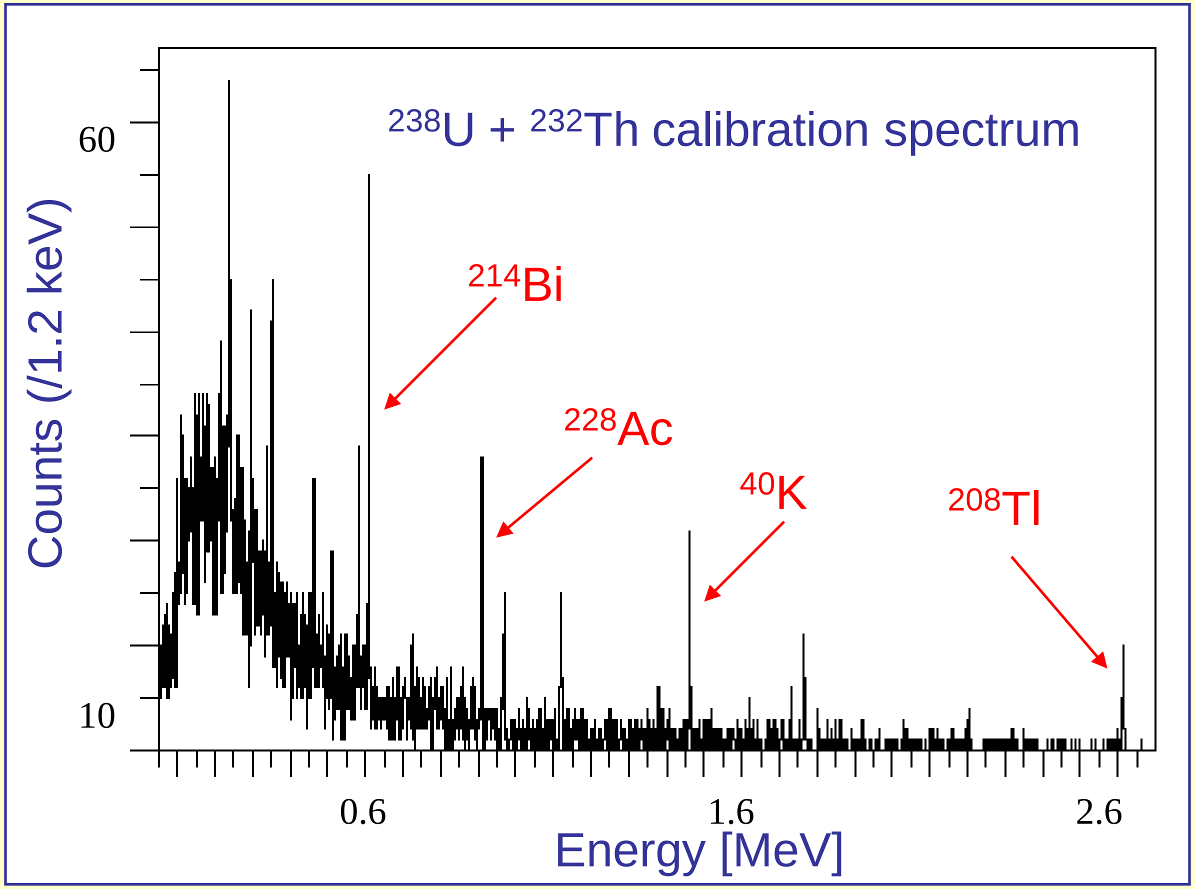
single TeO_2 crystal

- 790 g
- 5 x 5 x 5 cm

Technical results on detector performances

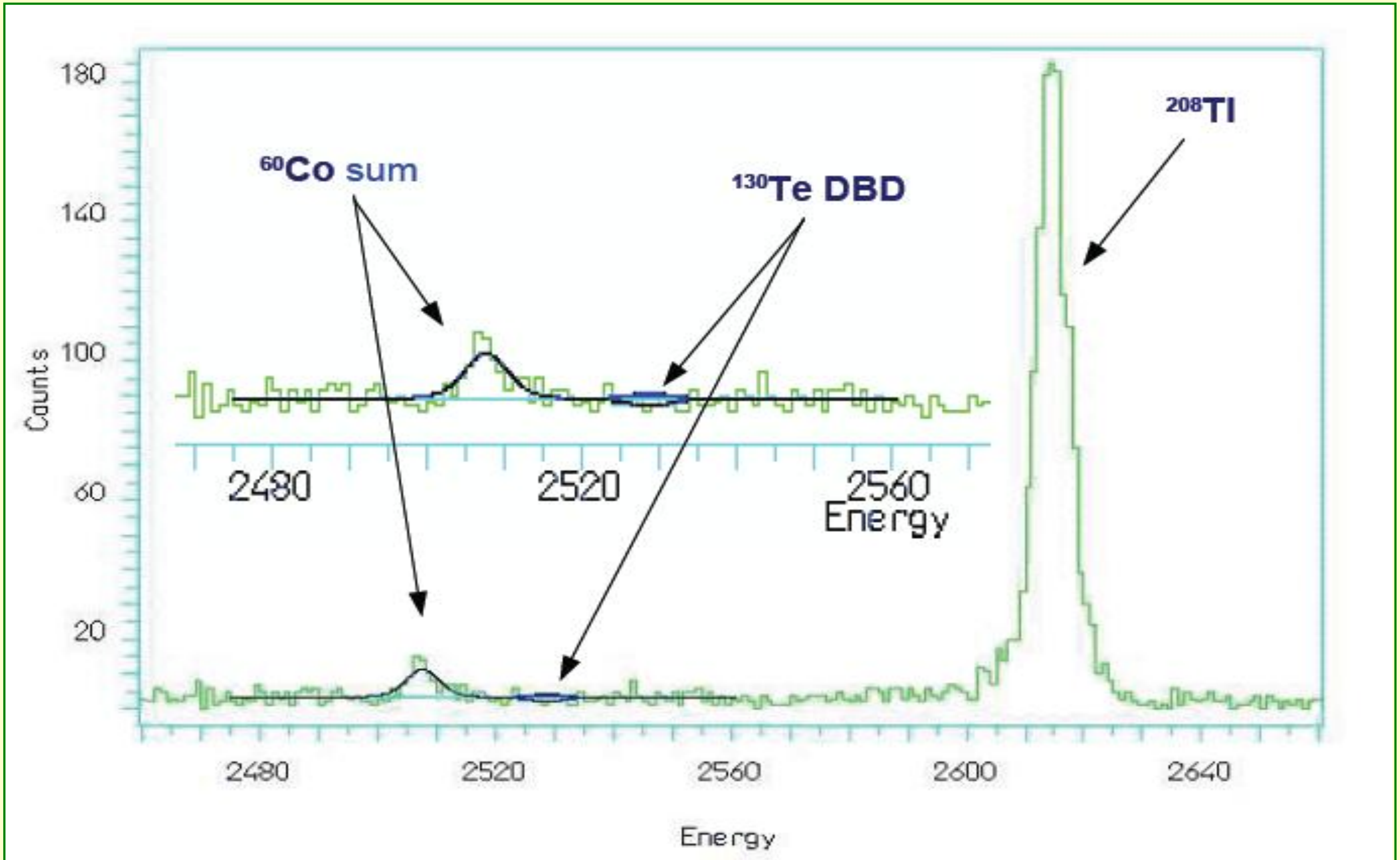
Performance of CUORICINO-type detectors (5×5×5 cm^3 - 760 g):

- Detector base temperature: ~ 7 mK
- Detector operation temperature: ~ 9 mK
- Detector response: ~ 250 μV/ MeV
- FWHM resolution: ~ 3.9 keV @ 2.6 MeV

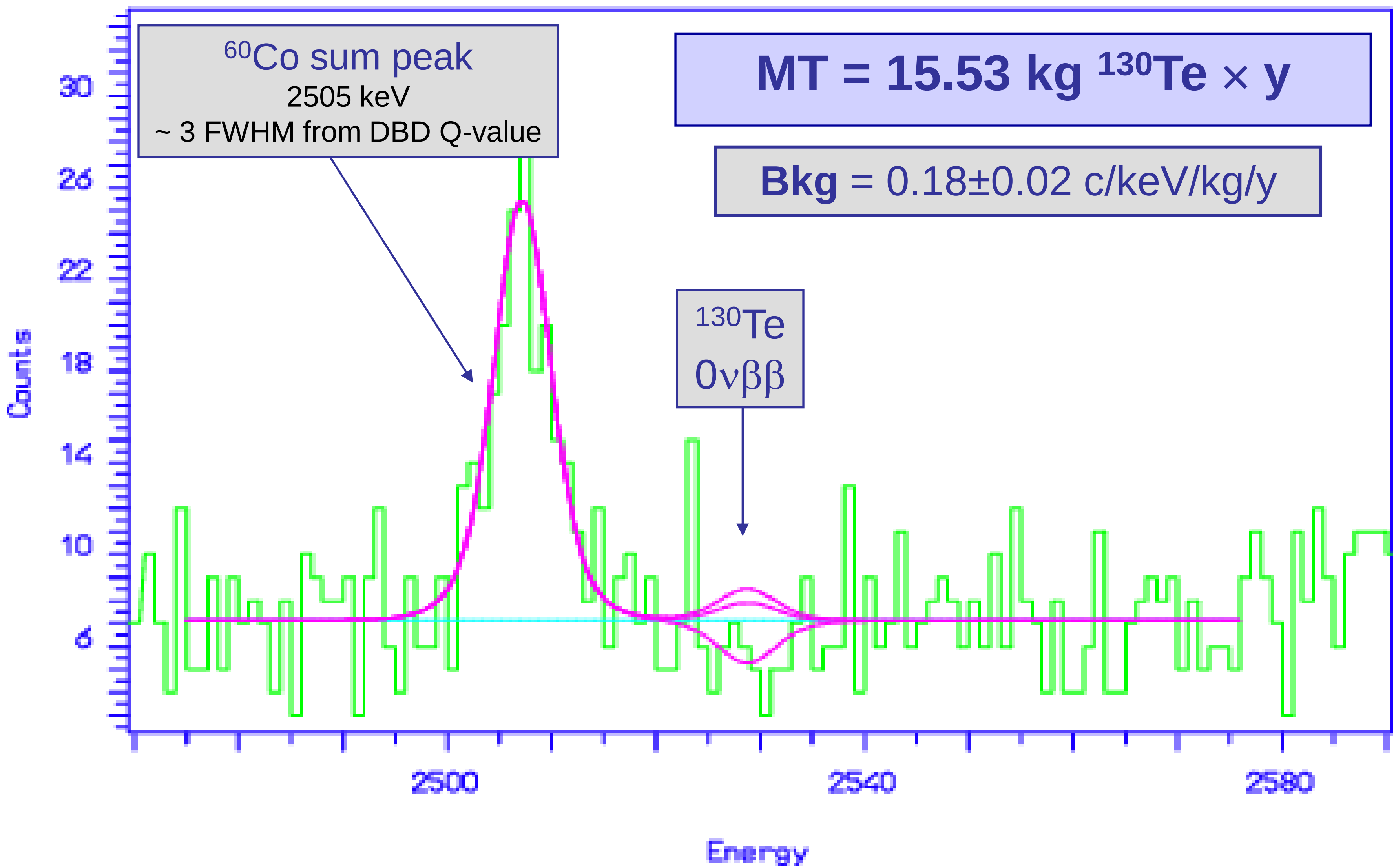


CUORICINO results and sensitivity

How the spectrum looks like in the DBD region



CUORICINO results



$\tau_{1/2}^{0\nu}$ (y) > 3.1×10^{24} y (90% c.l.) → $\langle M_{\beta\beta} \rangle < 0.20 - 0.98$ eV

Is Cuoricino able now to scrutinize the HM claim of evidence?

HM experimental results:

$T_{1/2}^{0\nu}$ (y) = (0.69-4.18) × 10^{25} (3σ range)

Best value: 1.19×10^{25} y

REF. Klapdor et al., Physics Letters B 586 (2004) 198-212

$m_{\beta\beta}$= 0.24 – 0.58 eV (3σ range)

Nuclear matrix element of Muto-Bender-Klapdor

What is done here:

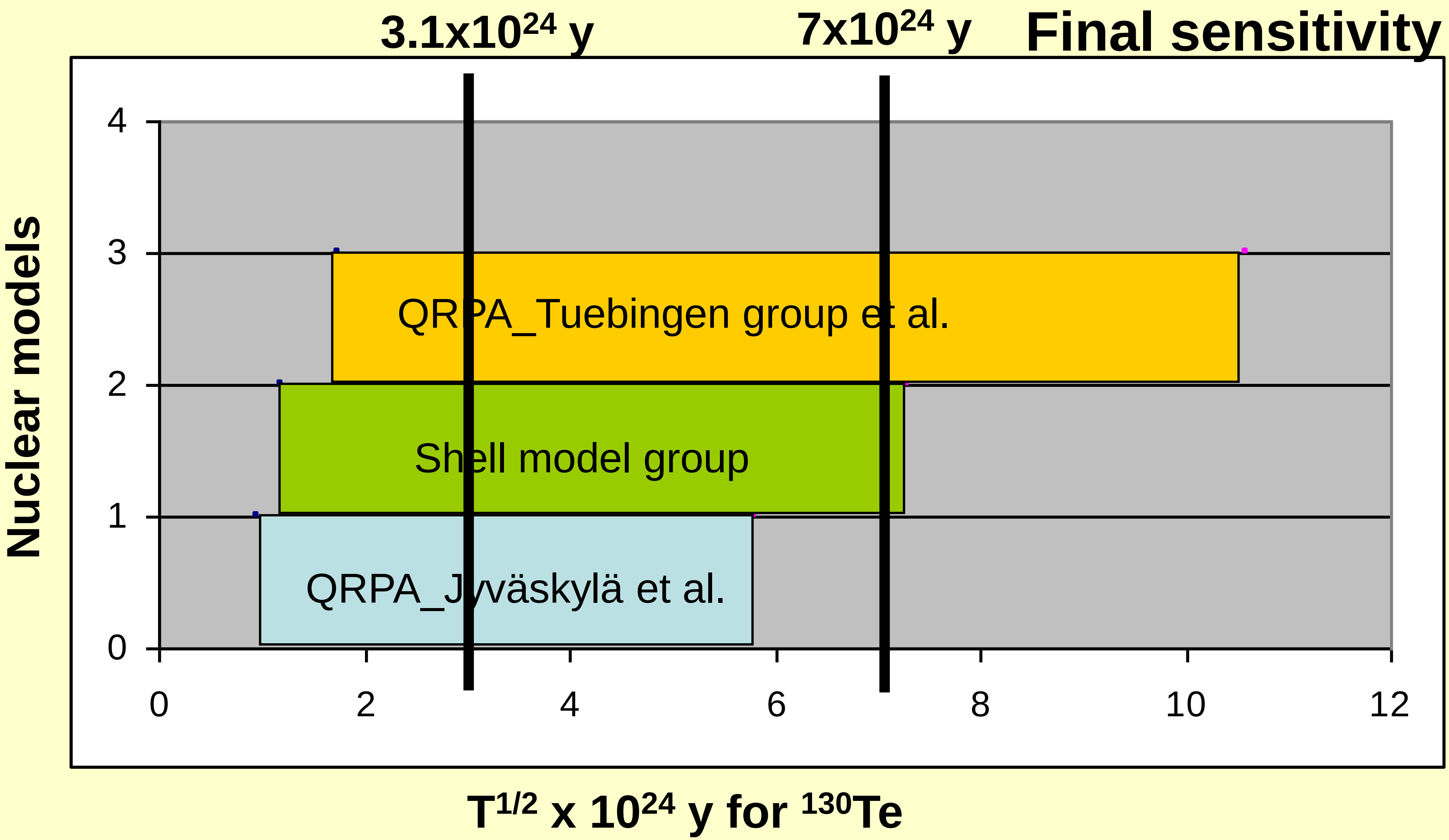
$T_{1/2}^{0\nu}$ (Klapdor) → Choose a nuclear model → $T_{1/2}^{0\nu}$ (^{130}Te)

$$T_{1/2}^{0\nu}(^{130}Te) = \frac{T_{1/2}^{0\nu}(Klapdor)}{\dfrac{G^{0\nu}_{^{130}Te}}{G^{0\nu}_{^{76}Ge}} \cdot \left| \dfrac{M^{0\nu}_{refA(^{130}Te)}}{M^{0\nu}_{refA(^{76}Ge)}} \right|^2}$$

References

- Tuebingen's group: erratum of nucl-th/0503063
- Suhonen's group: nucl-th/0208005
- Shell Model: Poves' talk @ 4th ILIAS Annual Meeting - Chambery

Is Cuoricino able now to scrutinize the HM claim of evidence?



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- Experimental challenge and strategies
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- Overview of the future projects
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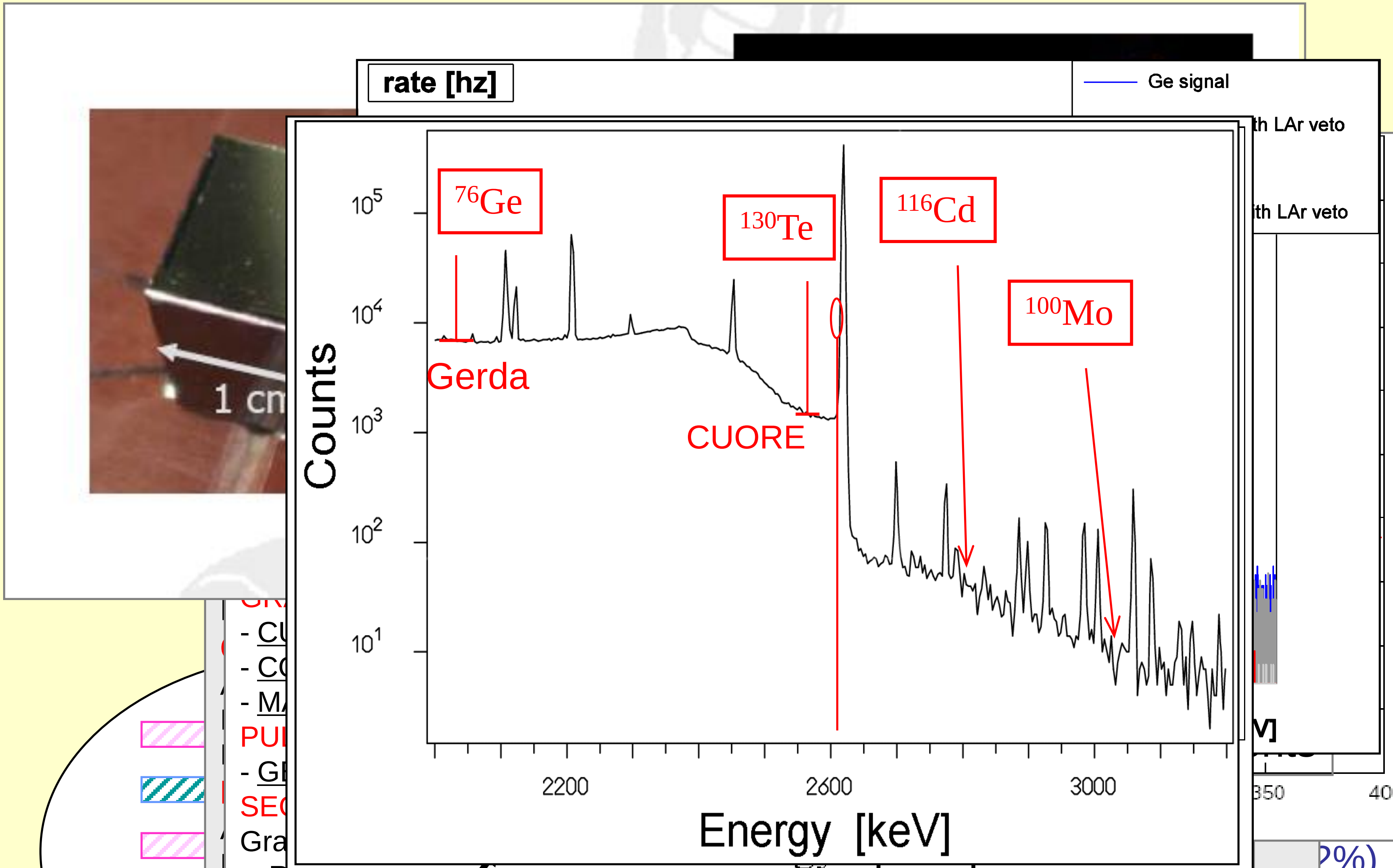


⇒R&D in progress for GERDA/MAJORANA, COBRA

ACTIVE SHIELDING

- GERDA: Ge diodes operated in active LAr

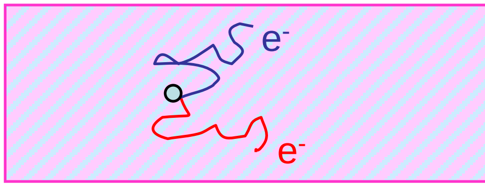
SURFACE SENSITIVITY in bolometers

- R&D in progress in CUORE against energy-degraded α and β background

Simultaneous LIGHT and PHONON detection in bolometers

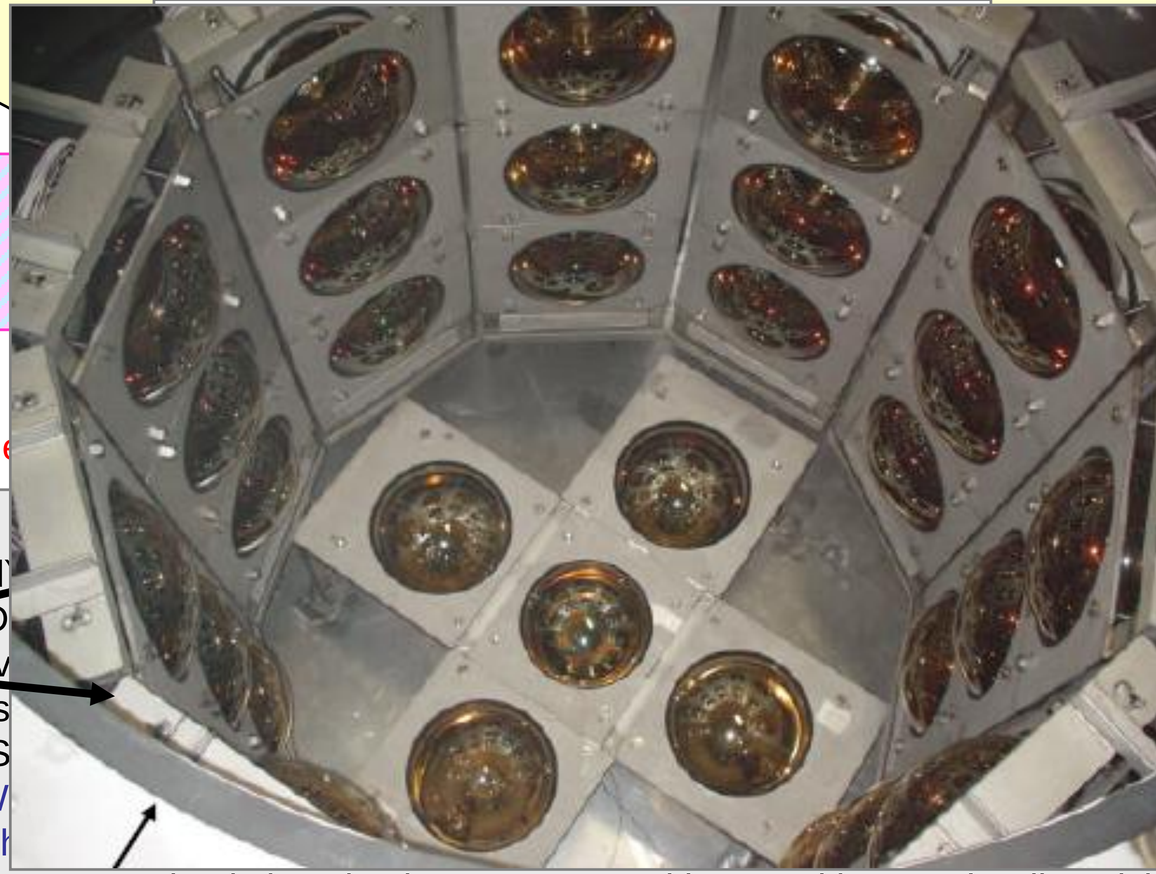
- R&D in progress in CUORE-like detectors for α / γ rejection

Experiments and techniques



Source ≡ Detector

Easy to approach the ton scal



CANDLES – ^{48}Ca

Array of natural pure (not Eu doped)

Prove of principle completed (CAND

Next step (CANDLES III): 191 kg div

Further step (CANDLES IV: requires

Final goal (CANDLES V): 100 ton (S

Proved energy resolution: 3.4 % FW

The good point of this search is the h

⇒out of γ (2.6 MeV end point), β (3.3 MeV end point) and α (max 2.5 MeV with quench) natural radioactivity

Other background cuts come from PSD (α/β different timing) and space-time correlation for Bi-Po and Bi-Tl

Source ≠ Detector

Easy to get tracking capability

Low energy resolution (>2%)

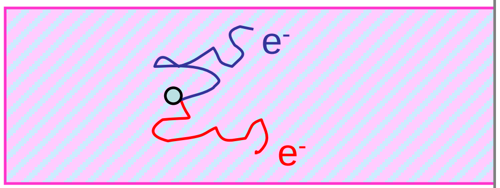
Tracking / topology capability

Easy to approach zero backround

(with the exception of

2ν DBD component)

Experiments and techniques



Source ≡ Detector

Easy to approach the ton scale

EXO – ^{136}Xe

TPC of enriched liquid Xenon

Event position and topology; in prospec

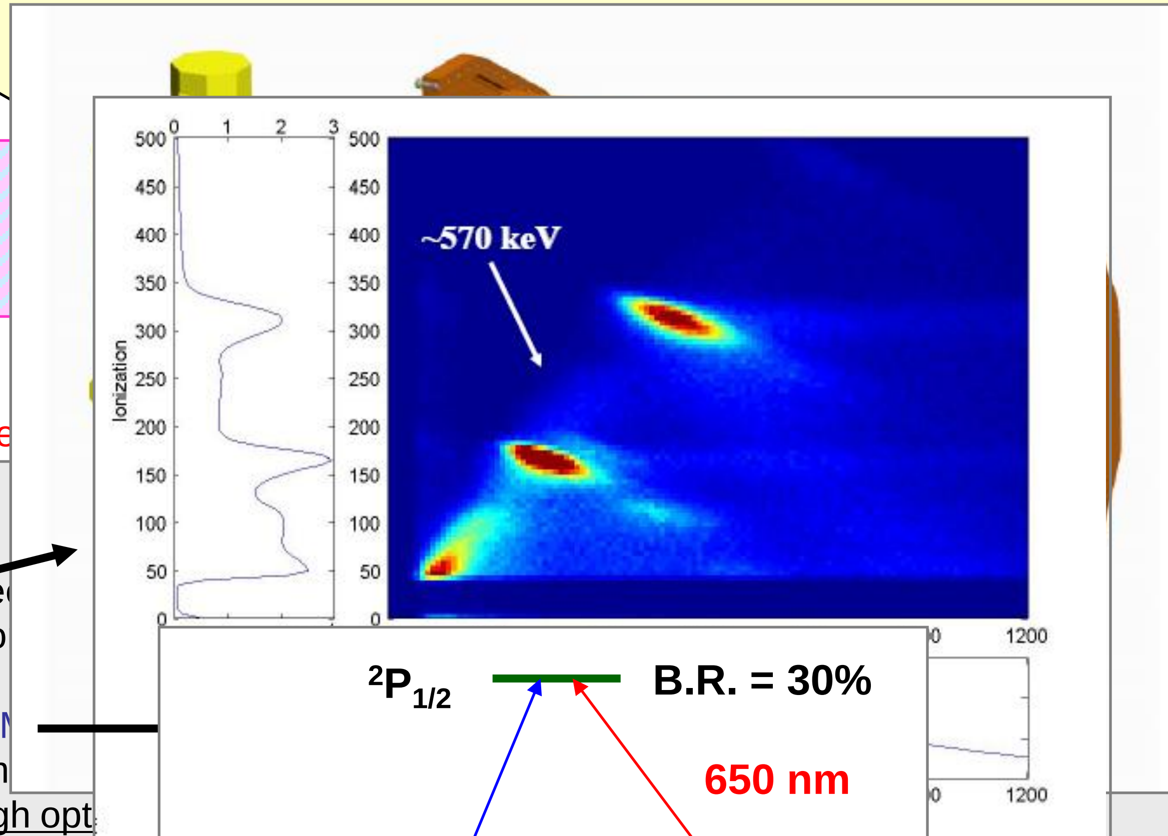
Next step (EXO-200: funded, under co

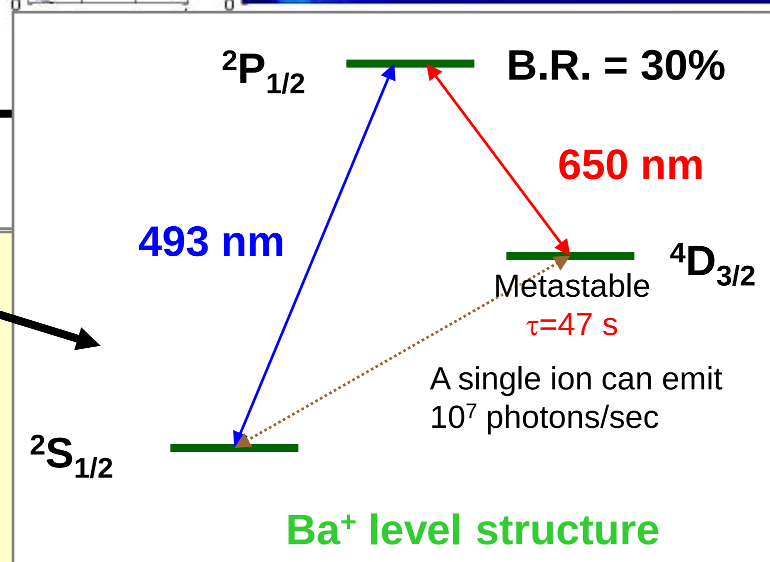
Further steps: 1-10 ton

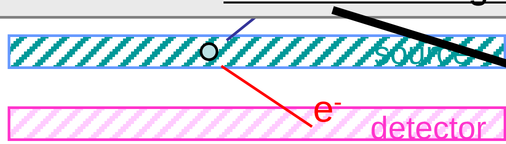
Proved energy resolution: 3.3 % FWHM

In parallel with the EXO-200 developm

Ba^{++} e^- e^- final state is identified through opt







Source ≠ Detector

Easy to get tracking capability

on (>2%)

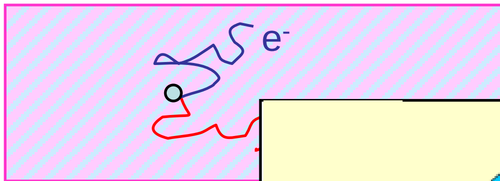
capability

ackround

of

nt)

Experiments and techniques



Source ≡

Easy to approac

XMASS – ^{136}Xe

Multipurpose scintillating

Three development stag

DBD option: low backgro

⇒Special development w

High light yield and colle

Target: to cover inverted

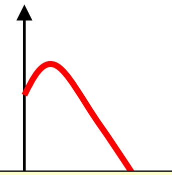
SNO+ – ^{150}Nd

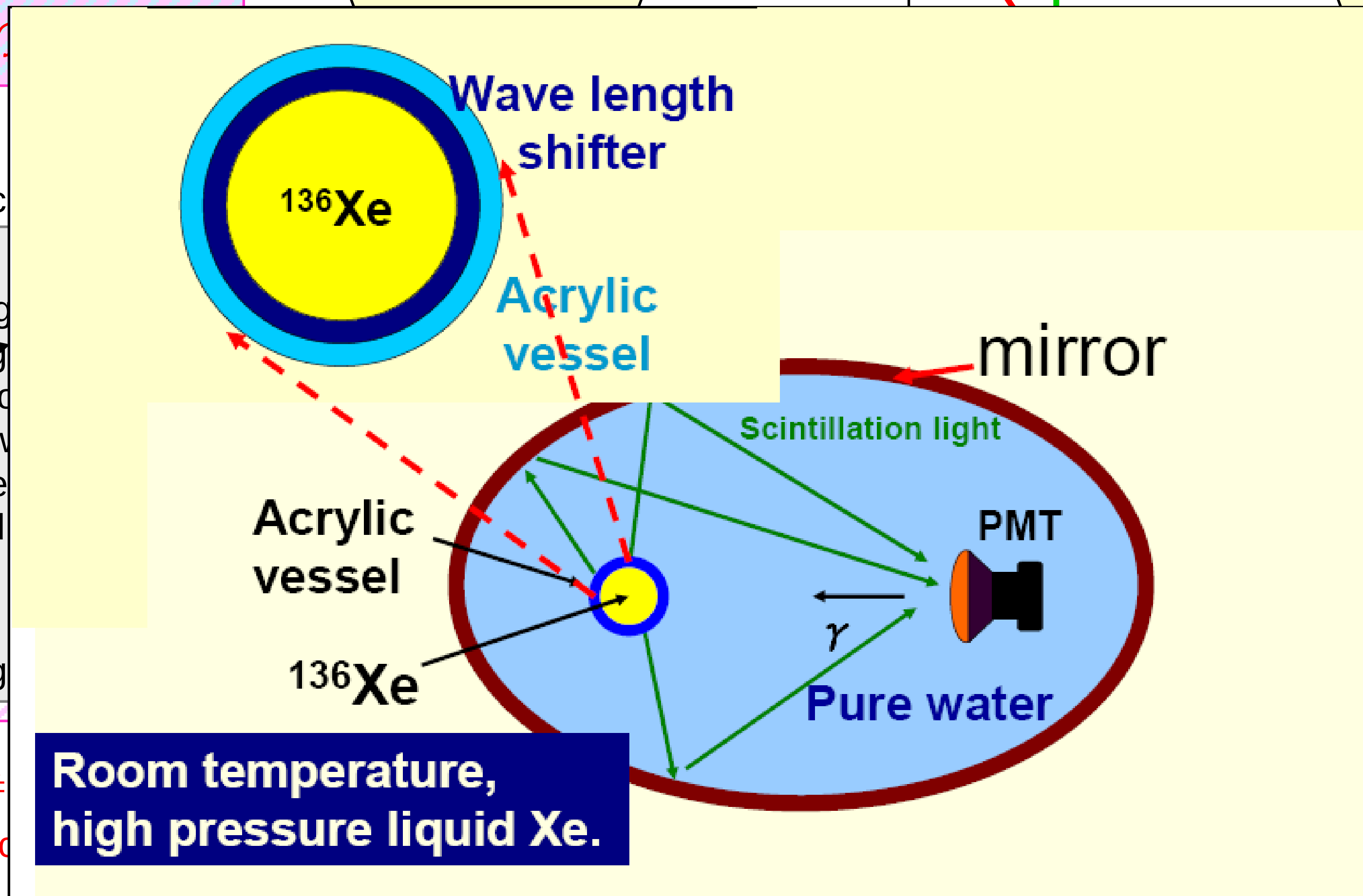
SNO detector filled with

Very interesting and orig

Source ≠

Easy to get trac





s

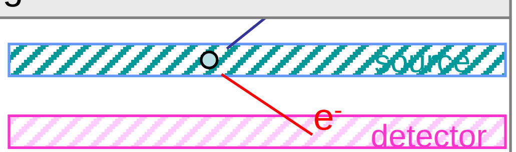
2ν DBD component)

Experiments and techniques

SUPERNEMO - ^{82}Se or ^{150}Nd
Modules with source foils, tracking (drift
Magnetic field for charge sign
Possible configuration: 20 modules with
Energy resolution: 4 % FWHM
Ii can take advantage of NEMO3 experi

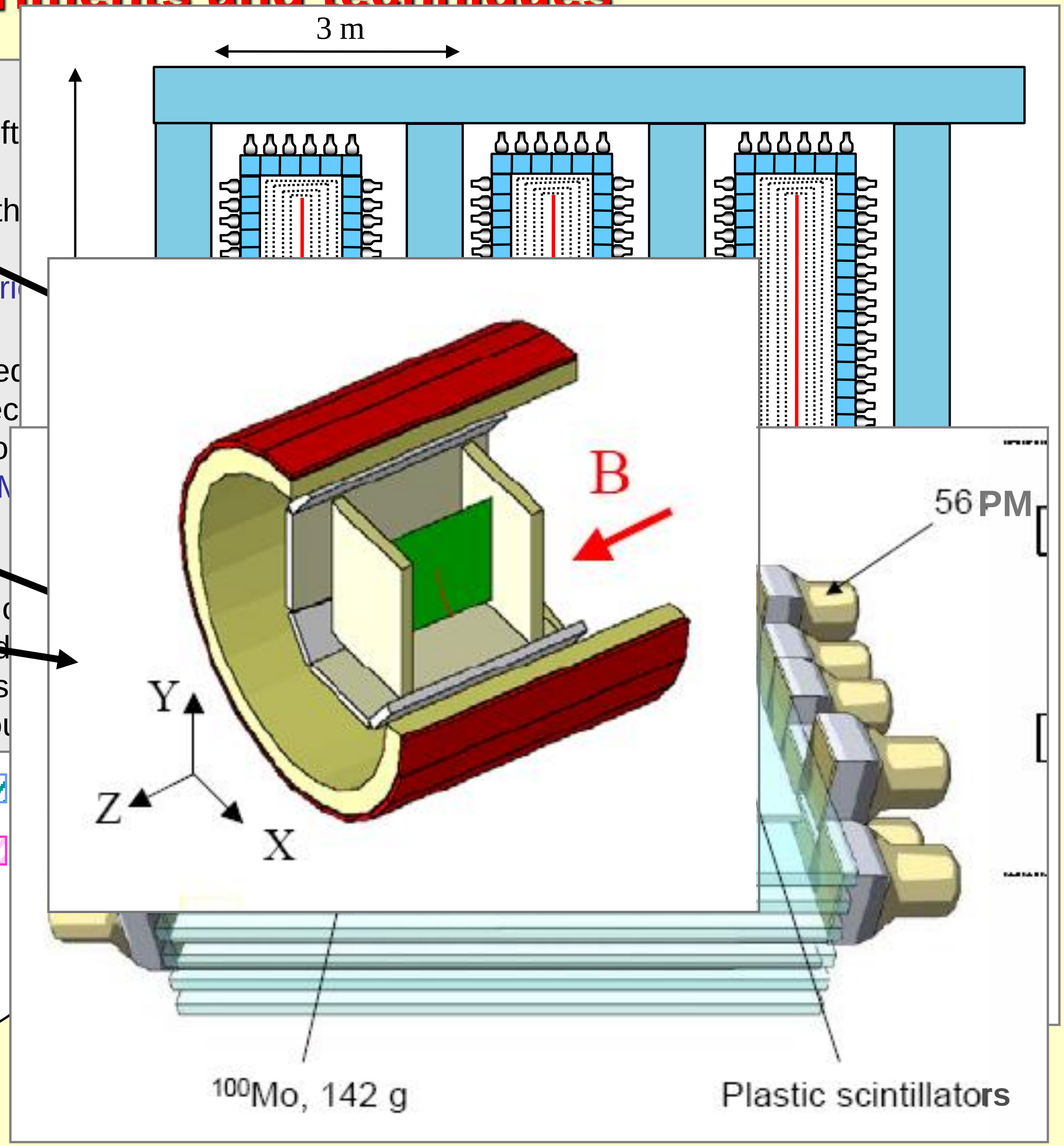
MOON - ^{100}Mo or ^{82}Se or ^{150}Nd
Multilayer plastic scintillators interleaved
MOON-1 prototype without tracking sec
MOON-2 prototype with tracking sectio
Proved energy resolution: 6.8 % FWHM
Final target: collect 5 y x ton

DCBA - ^{82}Se or ^{150}Nd
Momentum analyzer for beta particles c
Prototype: Nd_2O_3 foils ⇒ 1.2 g of ^{150}Nd
Space resolution ~ 0.5 mm; energy res
Final target: 10 modules with 84 m^2 sou



Source ≠ Detector

Easy to get tracking capability



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From CUORICINO to CUORE

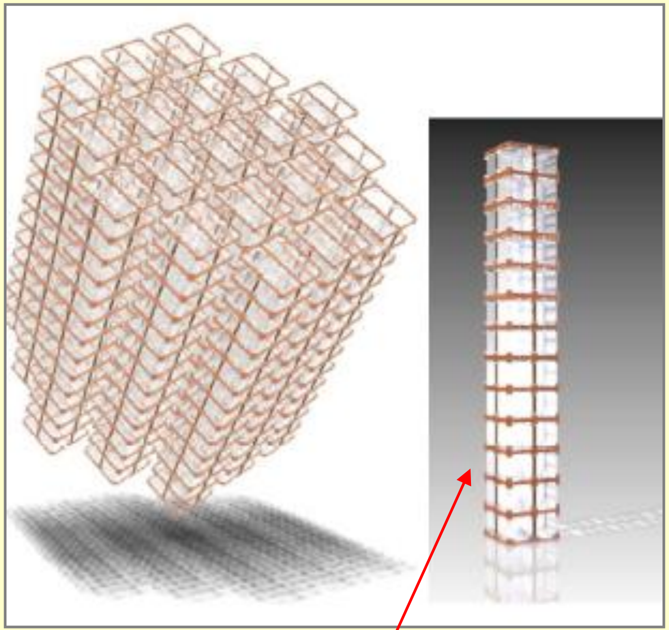
(Cryogenic Underground Observatory for Rare Events)

CUORE = closely packed array of 988 detectors

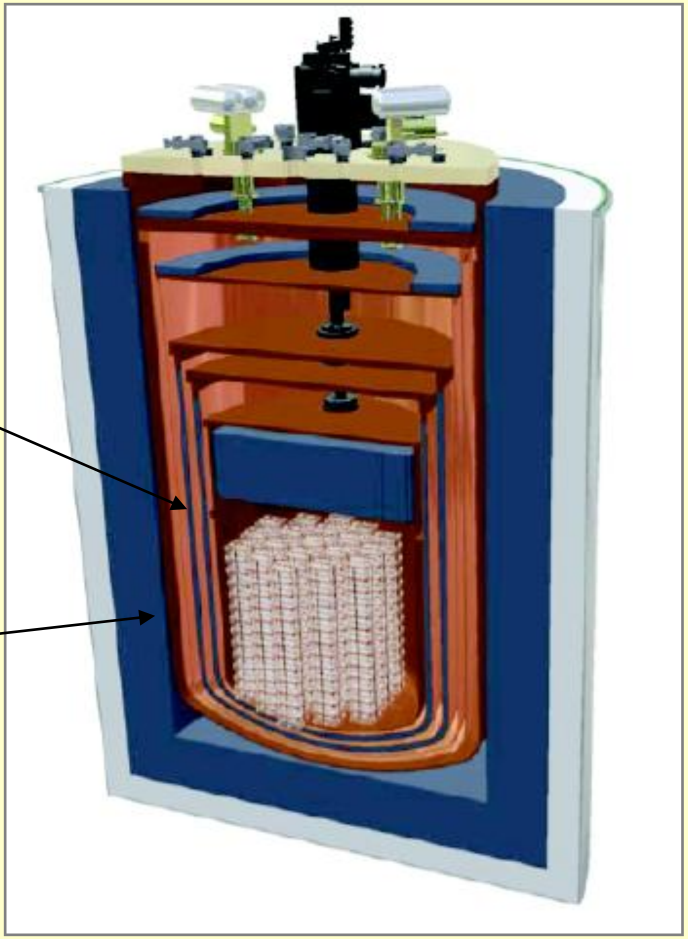
19 towers - 13 modules/tower - 4 detectors/module

M = 741 kg

Compact structure, ideal for active shielding

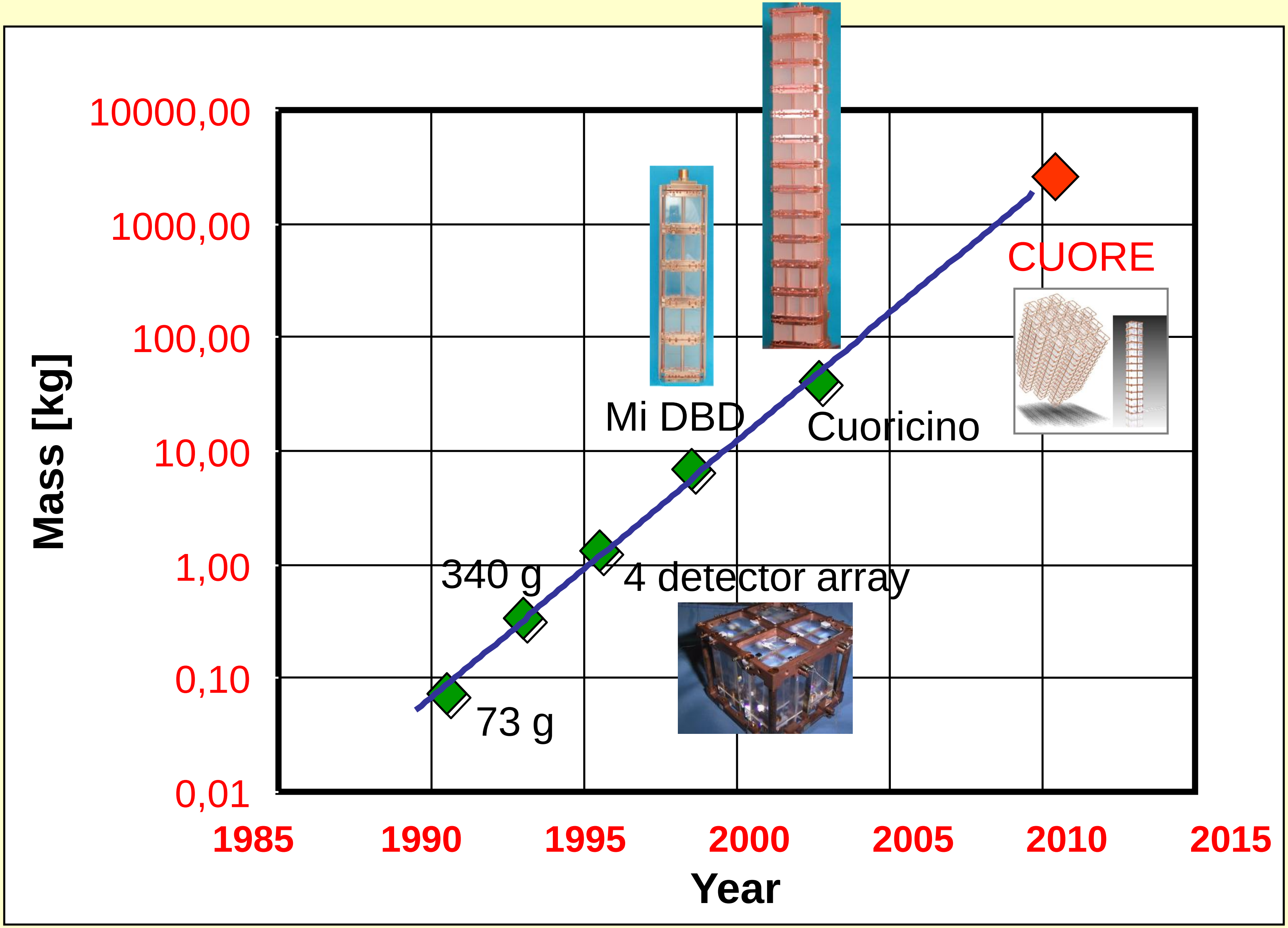


Each tower is a CUORICINO-like detector



Special dilution refrigerator

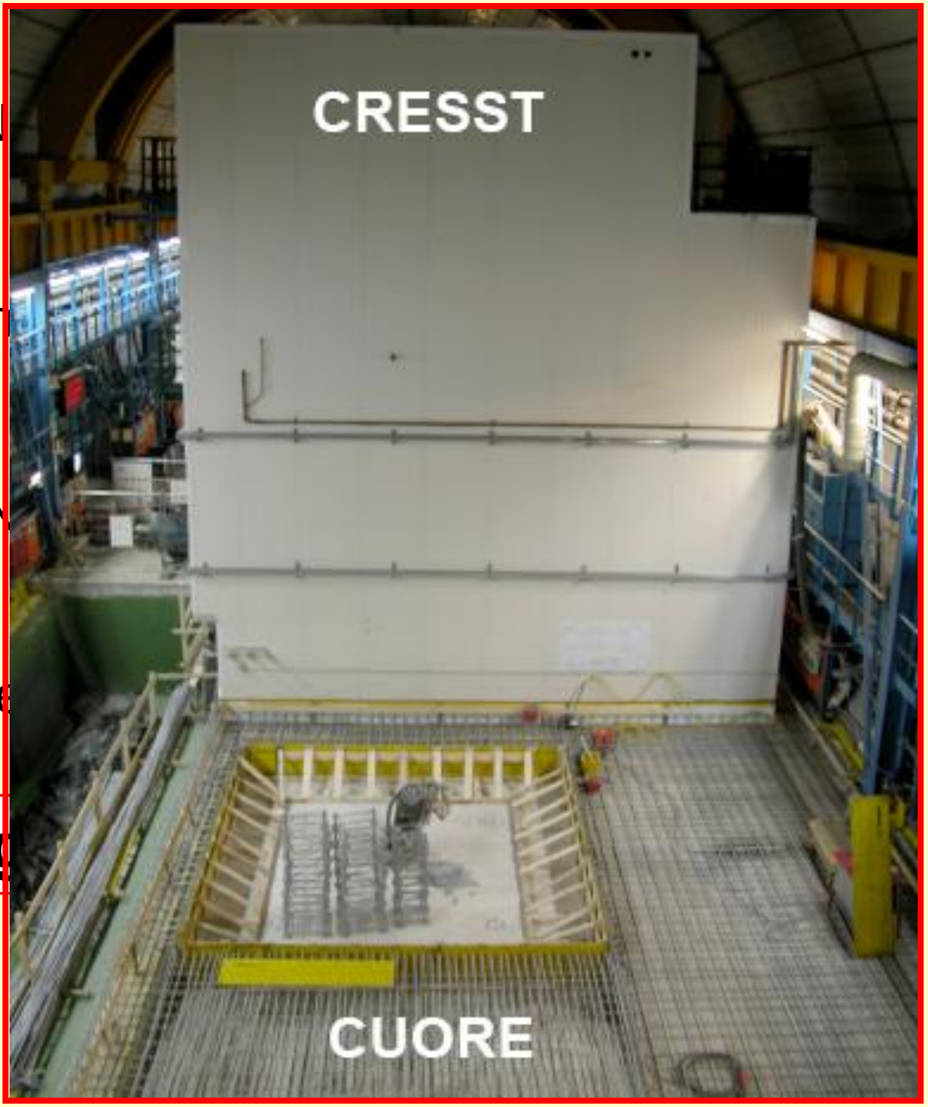
Moore's law for mass increase of TeO_2 detectors



CUORE funding and schedule

- CUORE has a dedicated site in LN
- The CUORE refrigerator is fully fun
- 1000 crystals are fully funded by IN
- The first CUORE tower will be asse

CUORE data takin



CUORE 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 with respect to Cuoricino
work in progress! (only a factor 2 from the conservative assumption)

5 y sensitivity (1 σ) with conservative
Assumption: b = 0.01 counts/(keV kg y)

$$F^{0\nu} = 9.2 \times 10^{25} \times (T [y])^{1/2}$$

$\langle M \rangle$ < 20 – 100 meV

5 y sensitivity (1 σ) with aggressive
assumption: b = 0.001 counts/(keV kg y)

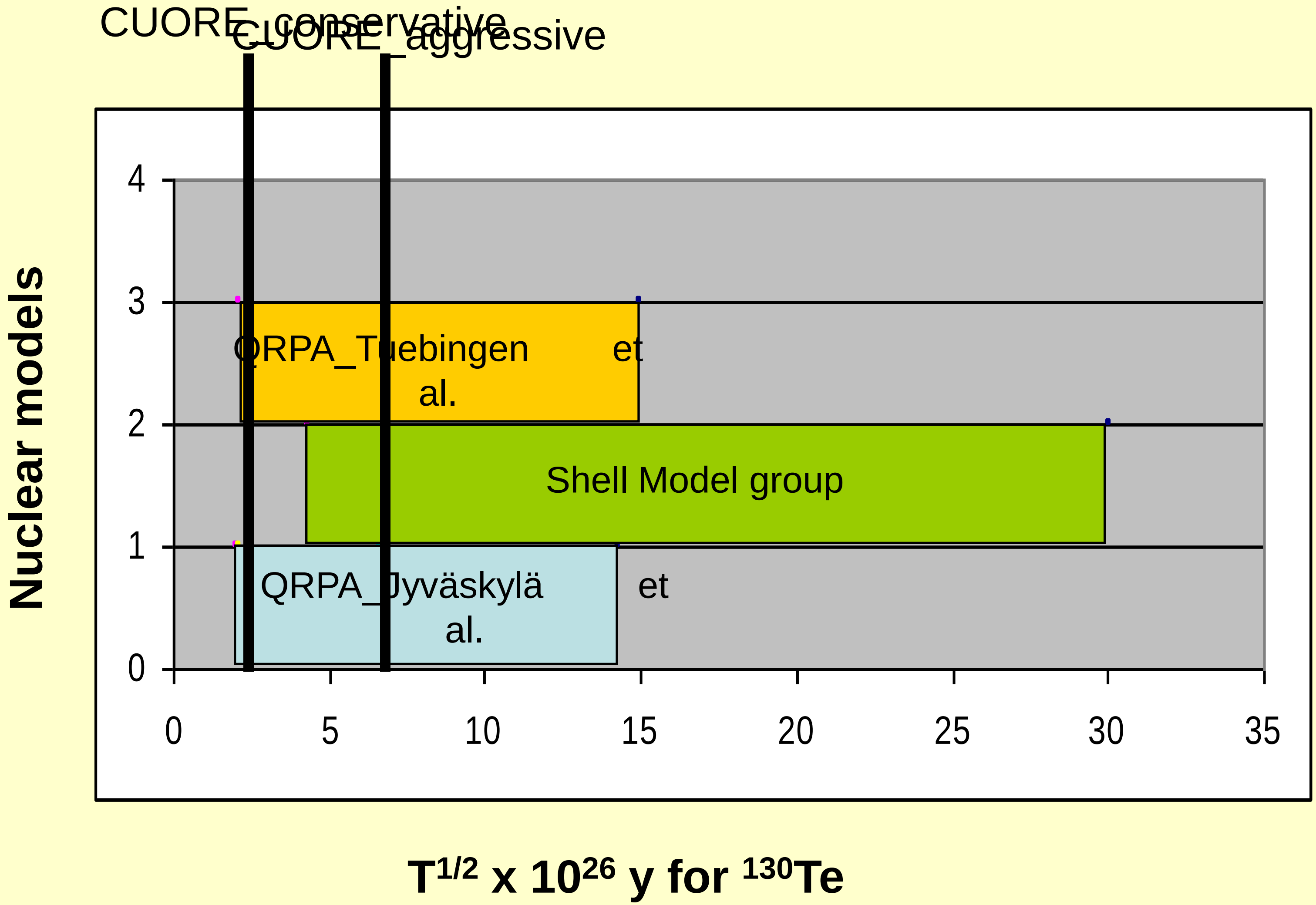
$$F^{0\nu} = 2.9 \times 10^{26} \times (T [y])^{1/2}$$

$\langle M \rangle$ < 11 – 60 meV

$\langle M \rangle$ < 7 – 38 meV

enriched CUORE

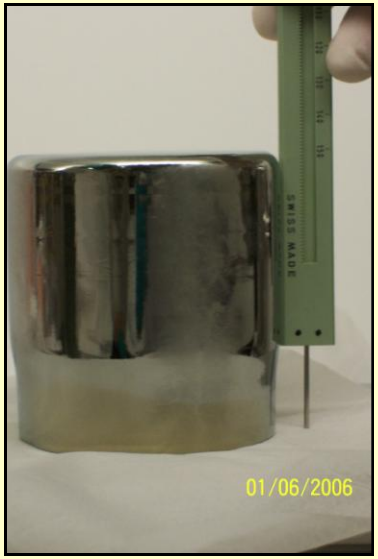
CUORE and the inverted hierarchy region



From HM / IGEX to GERDA
(The GERmanium Detector Array)

- In 2006 3 IGEX diodes and 5 HM diodes were removed from their cryostats
- Dimensions were measured
- Construction of dedicated low-mass holder for each diode

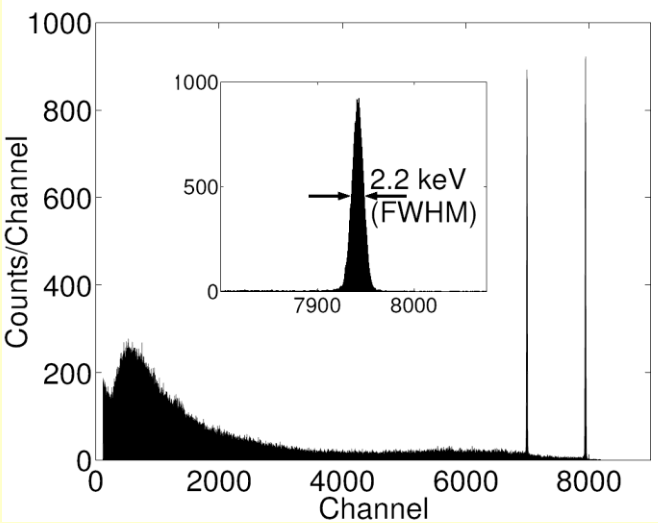




Phase I prototype testing

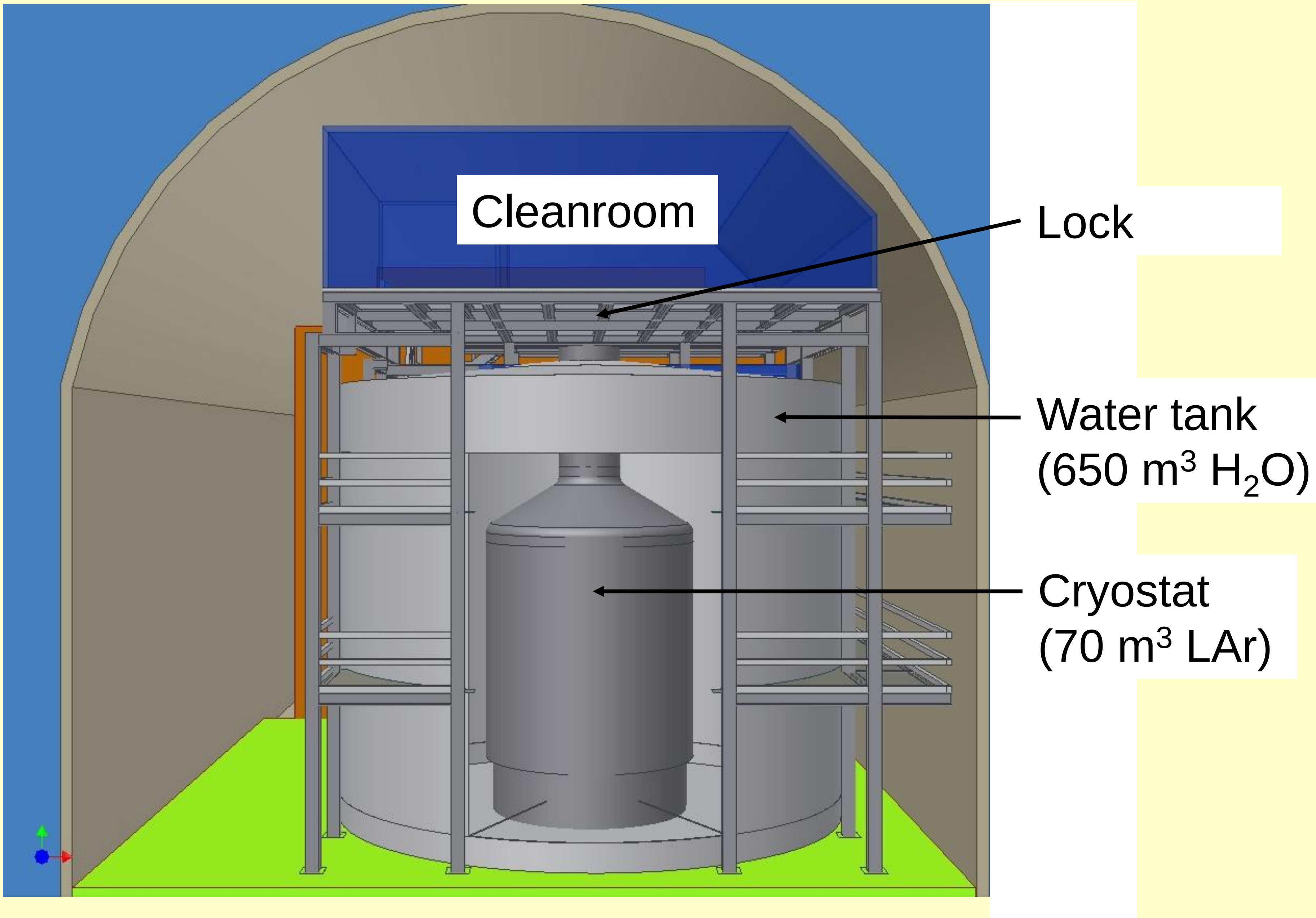
- Low mass detector holder developed and tested
- Definition of detector handling protocol
- Optimization of thermal cyclings

  >40 warming and cooling cycles carried out



Same performance in LN_2/LAr

GERDA design



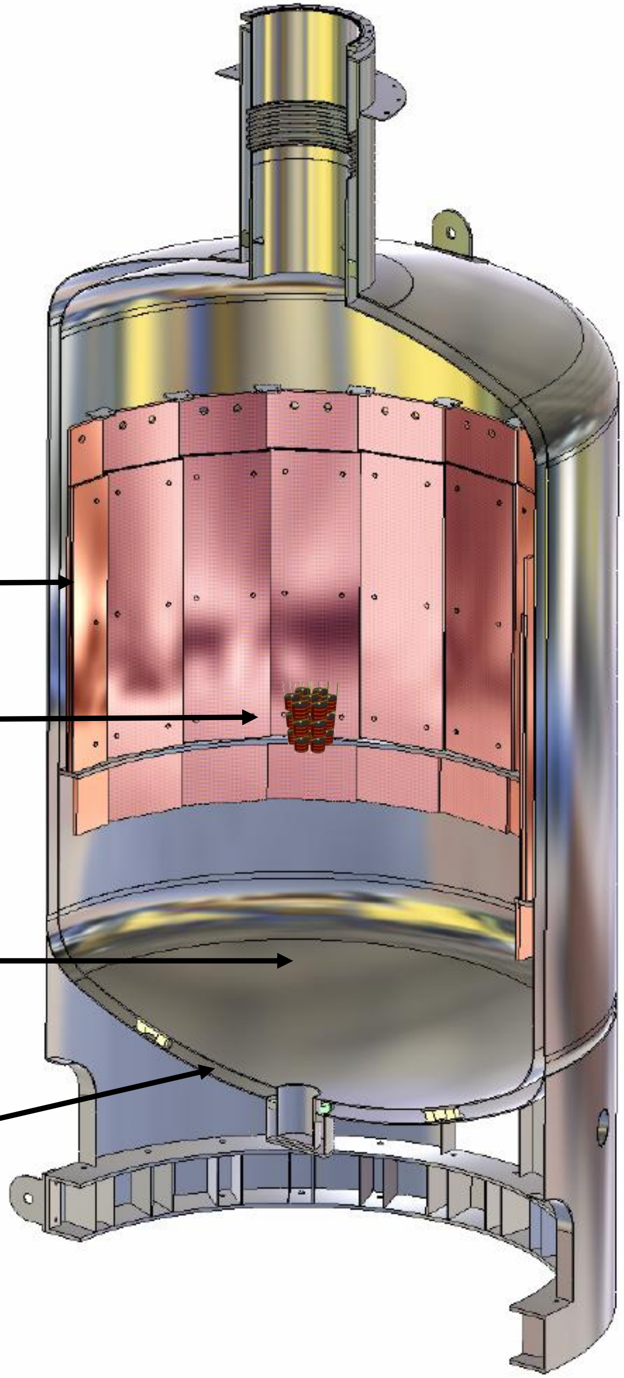
GERDA design

Additional inner copper shield

Germanium-detector array

Liquid argon

Vacuum-insulated double wall stainless steel cryostat



GERDA sensitivity

- Phase I: operate refurbished HM & IGEX enriched detectors (~20 kg)

  Under commissioning
  Background: 0.01 counts/ keV kg y
  Scrutinize ^{76}Ge claim with the same nuclide (exclude 99% c.l. or confirm 5σ)
  Half life sensitivity: 3×10^{25} y
  Start data taking: 2009

- Phase II: additional ~20 kg ^{76}Ge diodes (segmented detectors)

  Background: 0.001 counts / keV kg y
  Sensitivity after 100 kg y (~3 years): 2×10^{26} y

  $\langle M \rangle$ < 90 - 290 meV

- Phase III (depending on physics results of Phase I/II)

  $\Rightarrow$ ~ 1 ton experiment in world wide collaboration with MAJORANA

  $\langle M \rangle$ < 20 - 50 meV

SNO++: a very powerful newcomer

- DBD option in SNO+ is sometimes referred to as SNO++

- it is possible to add ββ isotopes to liquid scintillator, for example
  - dissolve Xe gas
  - organometallic chemistry (Nd, Se, Te)
  - dispersion of nanoparticles (Nd_2O_3, TeO_2)

↓

SNO+ collaboration researched these options and decided that the best isotope and technique is to make a Nd-loaded liquid scintillator

SNO++: concepts

- a liquid scintillator detector has poor energy resolution; but enormous quantities of isotope (high statistics) and low backgrounds help

at 1% loading (natural Nd), there is too much light absorption by Nd

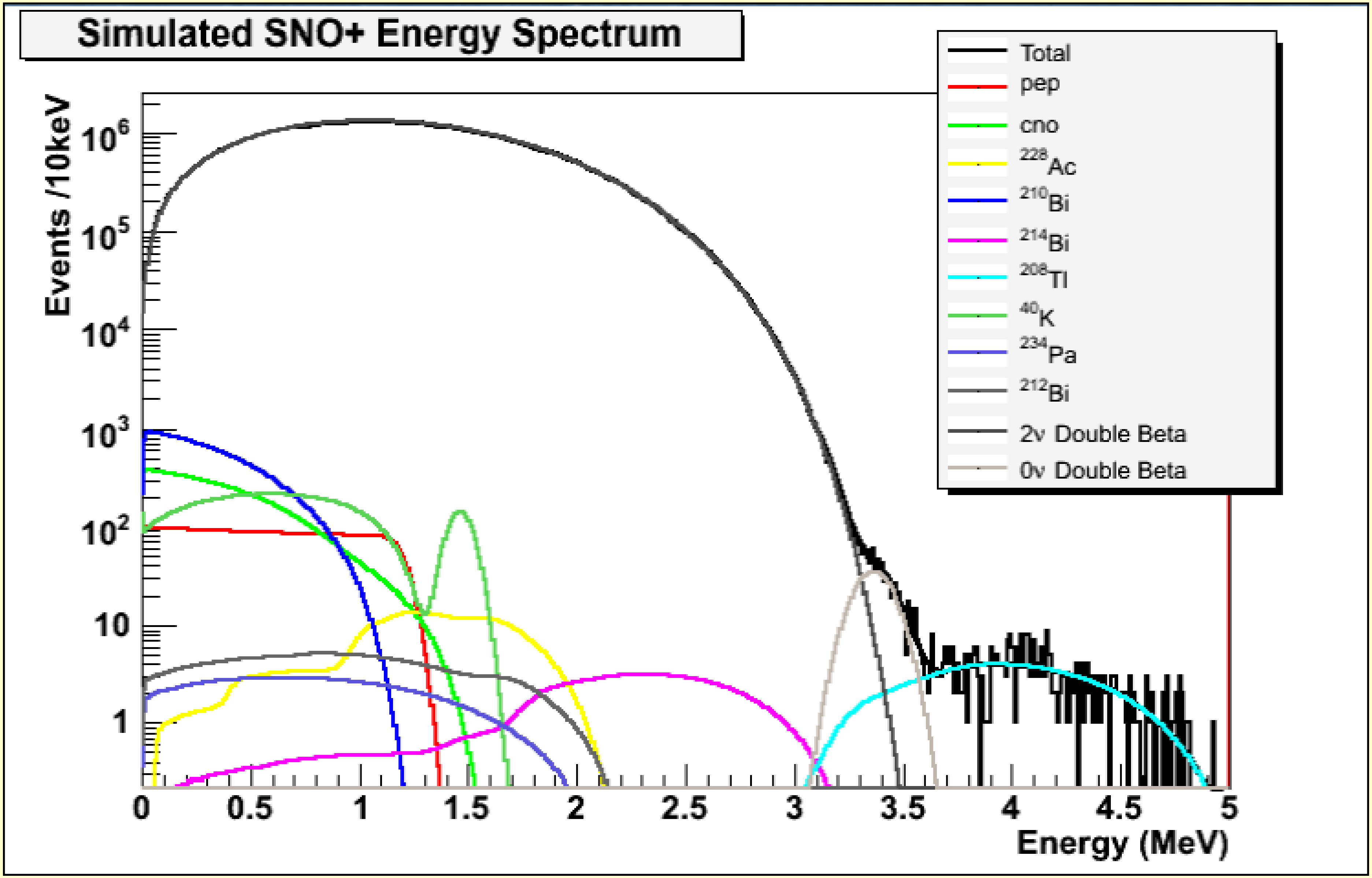
$\Rightarrow$ 47 ± 6 pe/MeV(from Monte Carlo)

at 0.1% loading (isotopically enriched to 56%)

$\Rightarrow$ 400 ± 21 pe/MeV(from Monte Carlo)

good enough to do the experiment

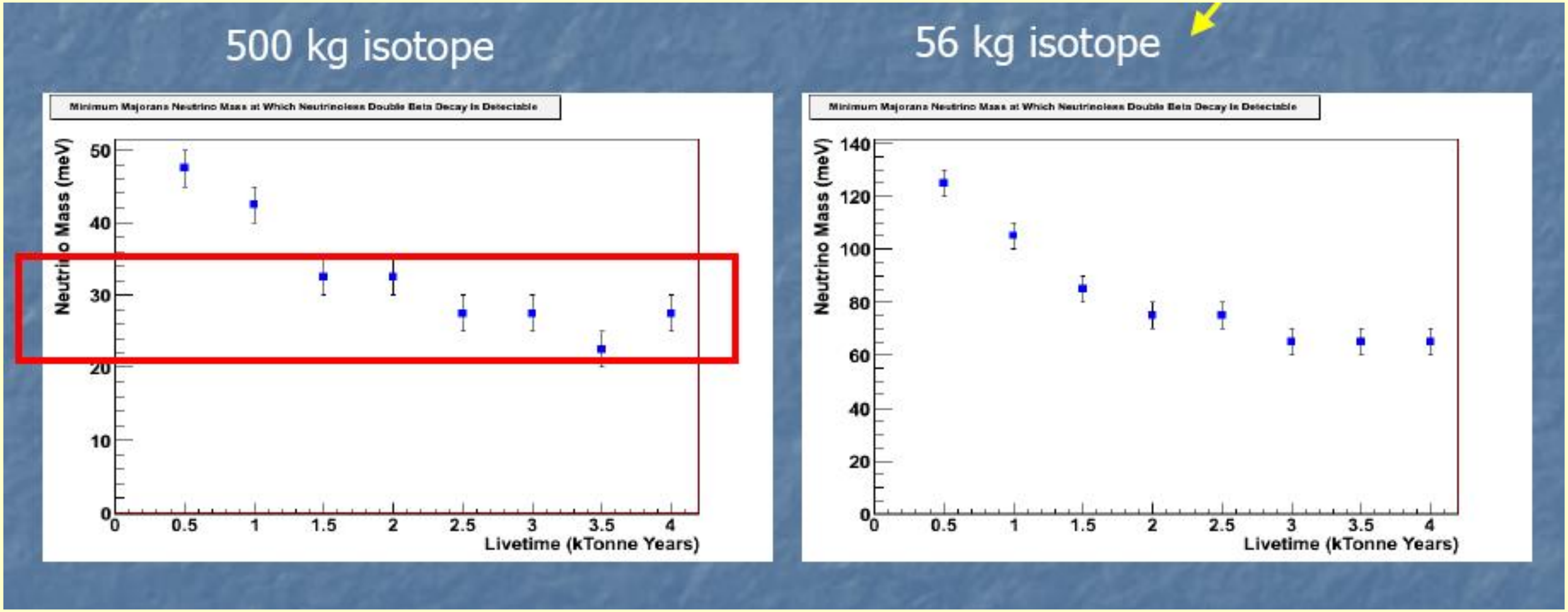
beta decay sensitivity is predicted, but…



1 yr, 500 kg isotope, m_ν = 150 meV

SNO++: sensitivities

enriched natural



Open questions

- Large scale enrichment: laser isotope separation possible in France using a dismissed facility for U $\Rightarrow$ the facility must be re-operated and tuned to ^{150}Nd
- ^{150}Nd nuclear matrix elements

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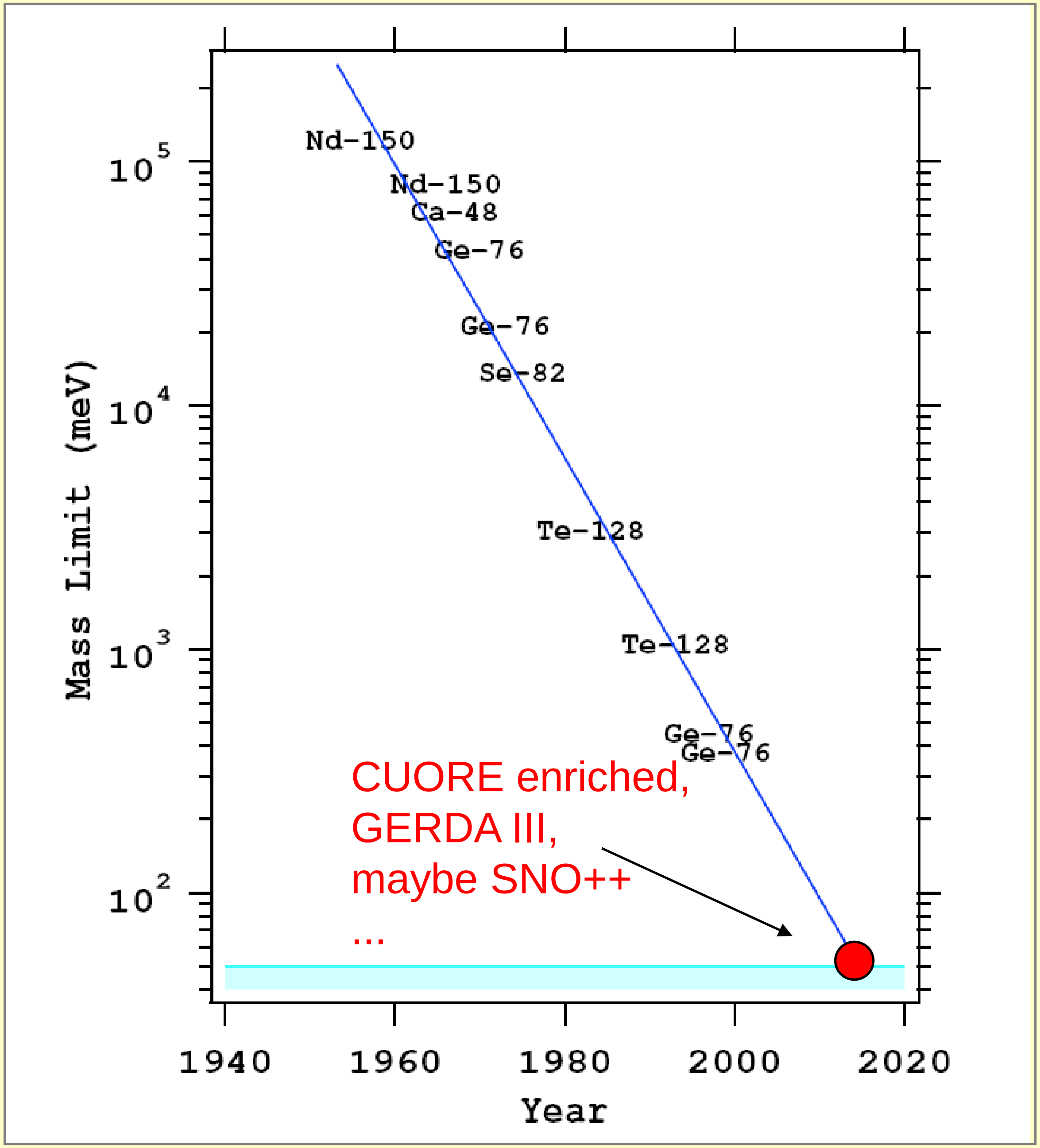
Prediction of the Moore's law for the sensitivity



Future scenarios and branching points in terms of discovery

sensitivity tc

100 - 500

15 - 50 m

2 - 5 me

if this range holds:
- SUPERNEMO could marginally see it in ^{82}Se or ^{150}Nd
- SNO++, if done, could see it in ^{150}Nd
- GERDA phase III could see it in ^{76}Ge
- CUORE could see it in a couple of isotopes in sequence (after ^{130}Te, ^{116}Cd ?)

ssible...)

stimate

EMO

if this range holds:
- new strategies have to be developed
- it is worthwhile to start to elaborate them now
- next generation experiments are precious for the selection of the future approaches
- a large investment in enrichment is mandatory

(^{82}Se or ^{150}Nd)

- CUORE will see it in ^{130}Te and may do multi-isotope searches simultaneously (^{130}Te - ^{116}Cd - ^{100}Mo)

large scale enrichment required

reduction of uncertainties in NME

precision measurement era for 0ν-DBD!

A forum to start to think of a ~5 meV experiment.

$\langle M_{\beta\beta} \rangle$	"average" NME for an "average" nucleus	$T^{0\nu}$
50 meV	⇒	5×10^{26} y
5 meV	⇒	5×10^{28} y

if we require 10 counts in 5 years with 0 background

→ experiment with 10^{29} nuclei and 0 background

for example → **30 ton** of TeO_2 **enriched**
100 ton of TeO_2 **natural**

- selection of the most promising technique
- design of the experiment

only "one bit" information ⇒ direct hierarchy - Majorana nature of neutrino

Conclusions

Exciting times for neutrino masses:

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