Challenging the ν mass with CUORE

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once upon a time

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

Il Nuovo Cimento, **14** (1937) 171

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* Dirac *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

(when Science could still be described in Italian !)

courtesy of Luciano Maiani

Surprise

- Majorana made an unexpected discovery
- The minimal description of spin 1/2 particles involves only two degrees of freedom (spin up and down) and not four as in Dirac's
- such a particle is absolutely neutral (i.e. it coincides with its antiparticle as is in the case for the photons)

one elegant explanation (beyond the SM)

Mass Term $\frac{1}{2}\left[\nu_L \quad (\nu_R)^C\right] C \begin{pmatrix} M_{M,L} & m_D \\ m_D & M_{M,R} \end{pmatrix} \begin{bmatrix} \nu_L \\ (\nu_R)^C \end{bmatrix} + h.c.$

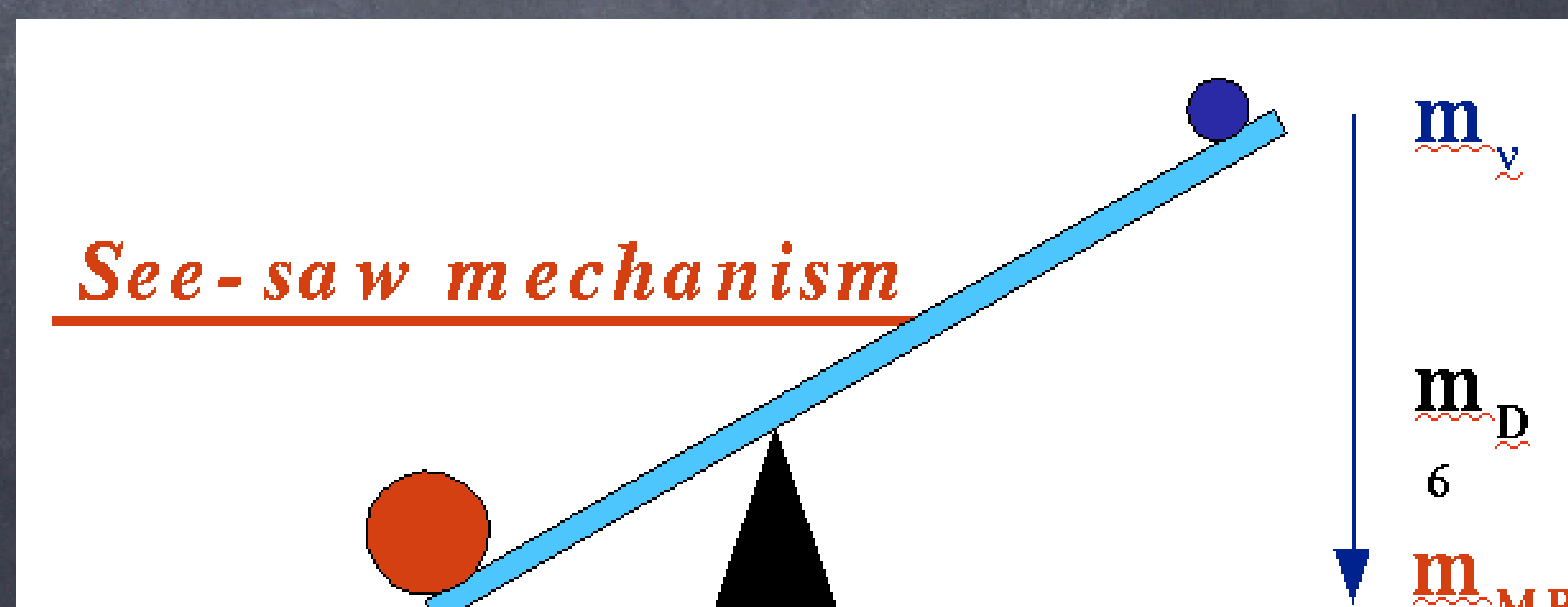
where $M_{M,L} \sim 0$

$M_D \sim M_{EW} \sim 100$ GeV

$M_{M,R} \sim$ Gauge singlet unprotected $\sim M_{GUT}$

$$m_N \simeq M_{M,R}$$

$$m_\nu \simeq \frac{m_D^2}{M_{M,R}}$$



the mass terms

$$\psi_1 = \nu_L + (\nu_L)^\dagger; \quad \frac{1}{2} M_1 \psi_1 \gamma^0 \psi_1 = \frac{1}{2} M_1 [\nu_L \gamma^0 \nu_L + h.c.]$$

- this term has weak isospin=1, it cannot be produced by I=1/2 Higgs doublet: we expect $M_1 \approx 0$, or very small;

0

$$\frac{1}{2} M_D \psi_2 \gamma^0 \psi_1 = \frac{1}{2} M_D [(\nu_R)^\dagger \gamma^0 \nu_L + h.c.]$$

- this term has I=1/2, so $M_D \approx$ normal lepton and quark masses;

M_{EW}

$$\frac{1}{2} M_2 \psi_2 \gamma^0 \psi_2 = \frac{1}{2} M_2 [(\nu_R)^\dagger \gamma^0 (\nu_R)^\dagger + h.c.]$$

- this term has I=0, does not violate the gauge symmetry and M_2 can be anything; most naturally: $M_2 \approx M_{GUT} \approx 10^{14\text{-}15}$ GeV.

M_{GUT}

the Majorana conjecture

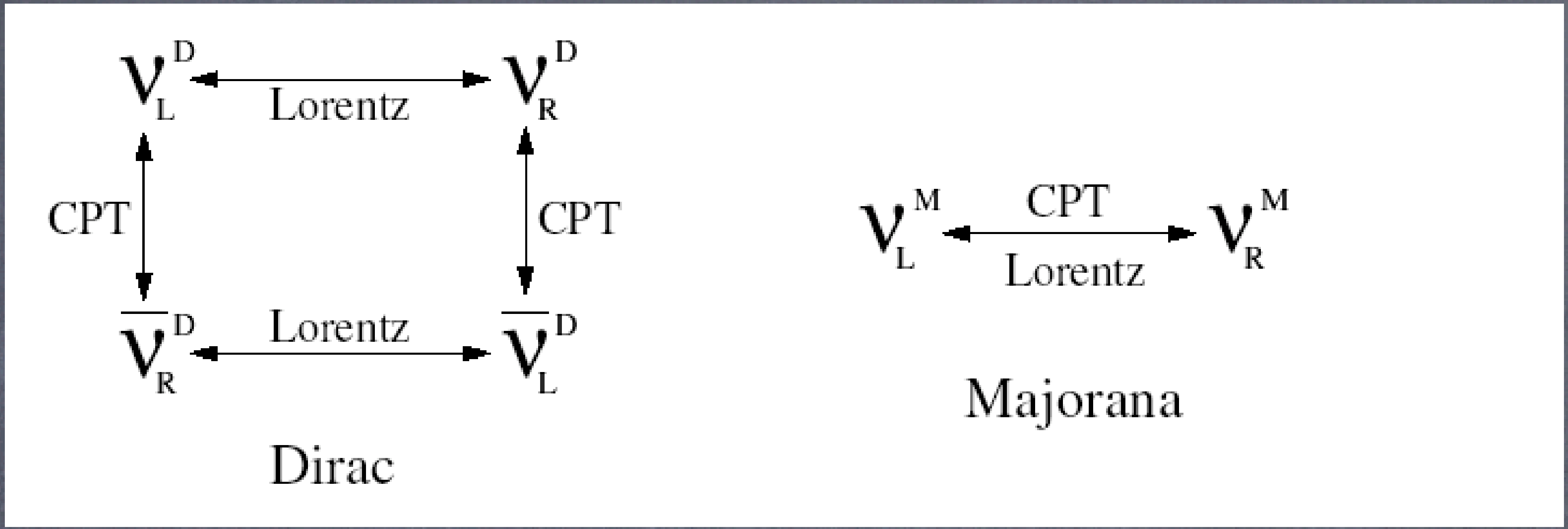
$$\nu = \bar{\nu}$$

Practical consequence :
Lepton Number Violation

Caveat: massless neutrinos do not allow testing of the Majorana nature

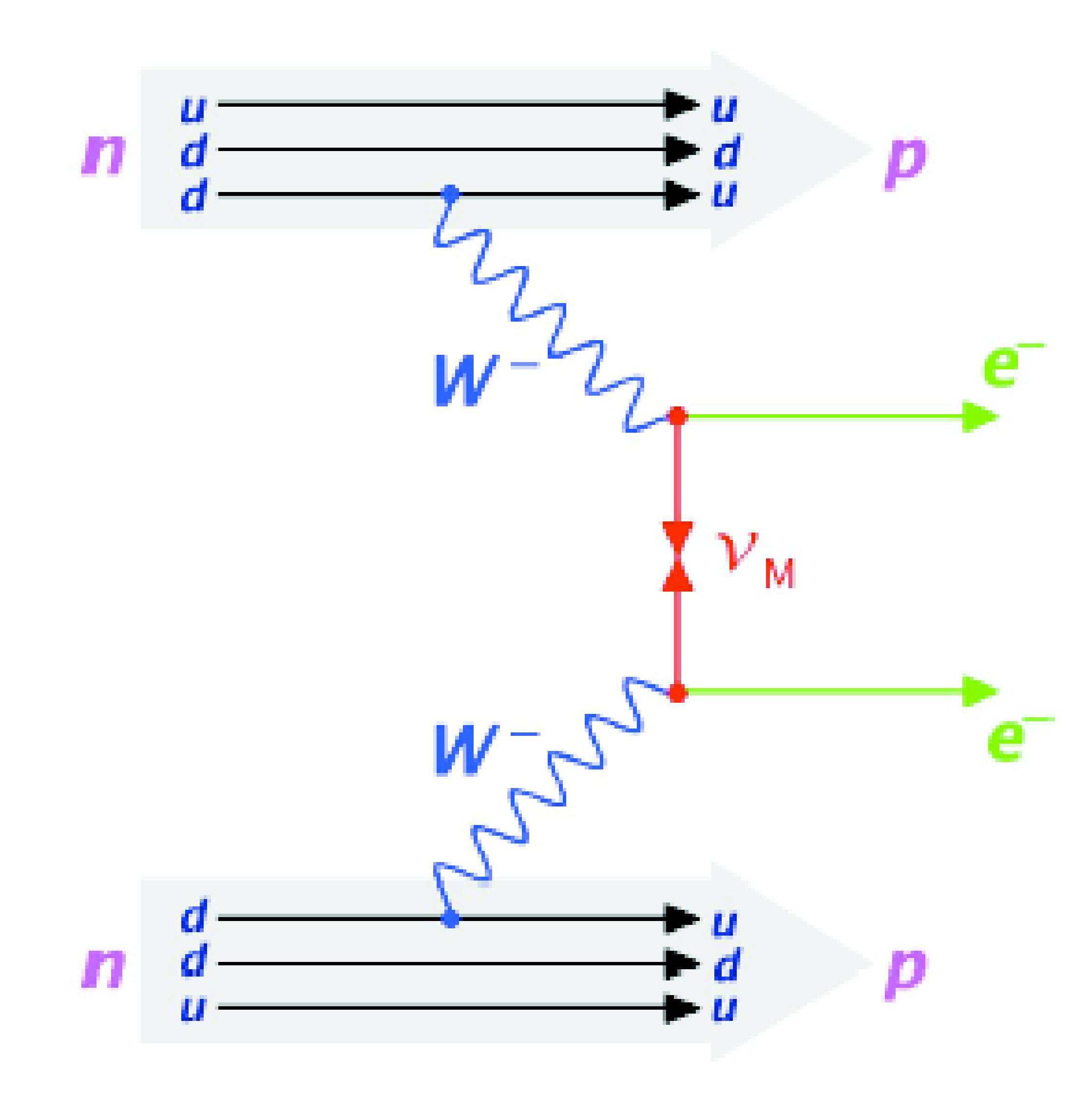
Indeed nobody payed much attention to the Furry hypothesis (1939) that a Majorana neutrino could induce Neutrino-less DBD via helicity flip

Massive neutrinos makes the story much more attractive



Now helicity flip can happen in both Dirac and Majorana cases. However Dirac forbids the absorption of an anti-neutrino right that was emitted as a neutrino left because the Lepton Number Conservation

Neutrino-less DBD (0νββ)



Only if:

Majorana Neutrinos

Massive Neutrinos

If observed:

Proof of the Majorana nature of Netrino

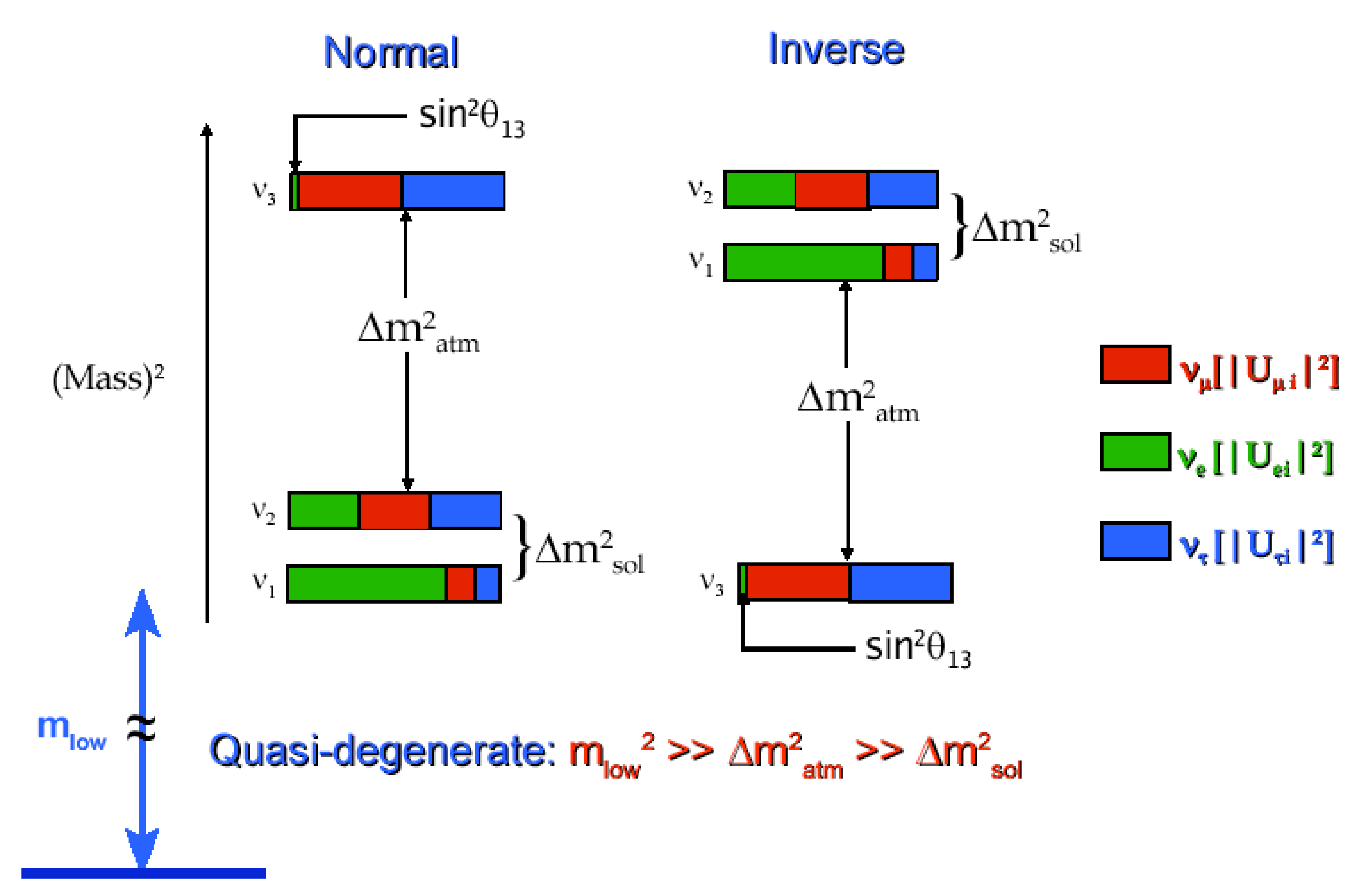
Does it also measure the mass ?

$$m_{\beta\beta} = \sum m_{\nu_k} U_{ek}^2 = \cos^2\theta_{13}(m_1 \cos^2\theta_{12} + m_2 e^{2i\alpha} \sin^2\theta_{12}) + m_3 e^{2i\beta} \sin^2\theta_{13}$$

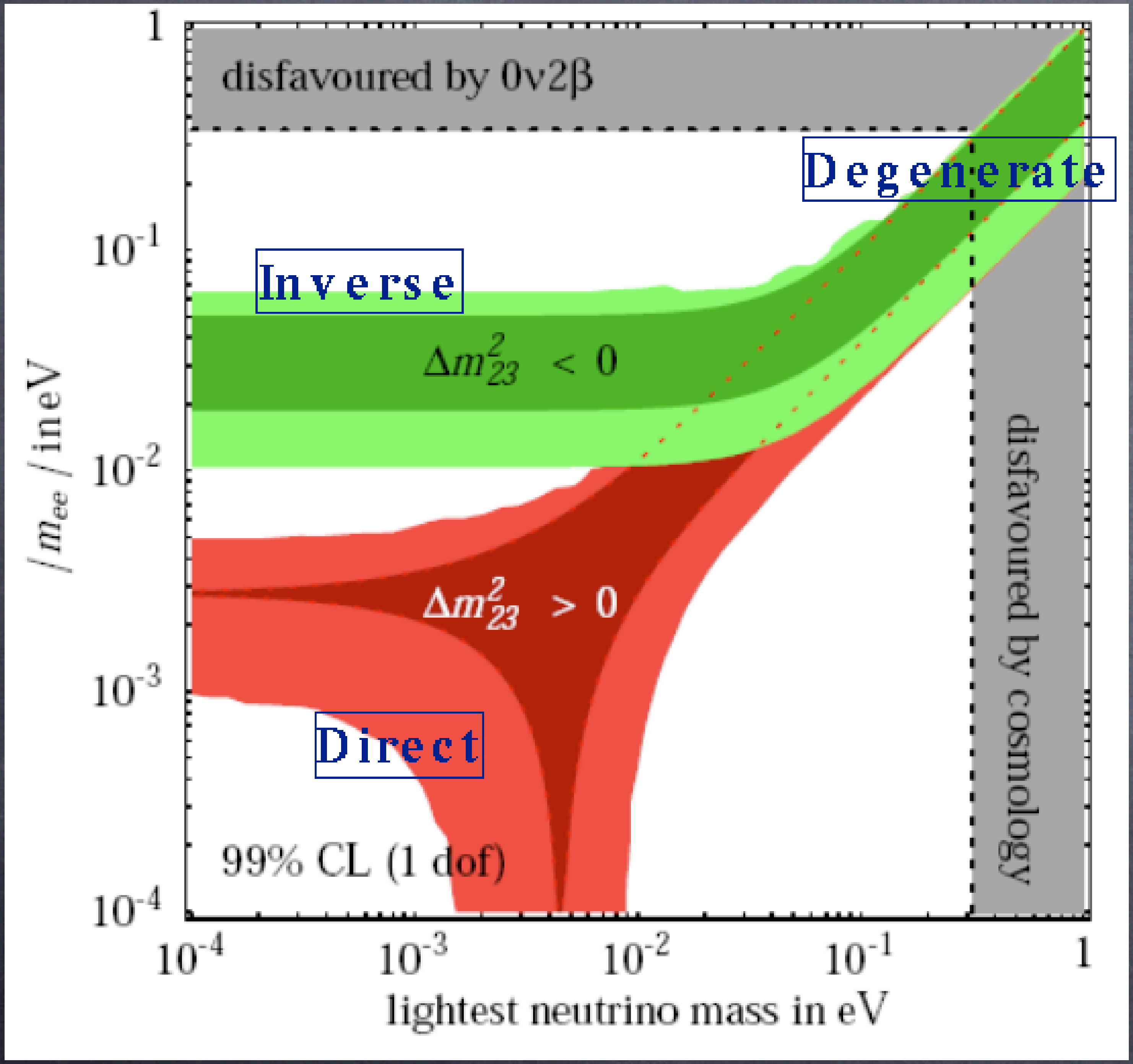
well...not so straight. It comes as a combination of the three neutrino masses, the mixing angles and the Majorana phases.

Exercise: parameterize as a function of the known parameters: $m_{\beta\beta} = f(U_{ek}, m_{lightest}, \delta m_{sol}, \Delta m_{atm})$

Three possibilities:

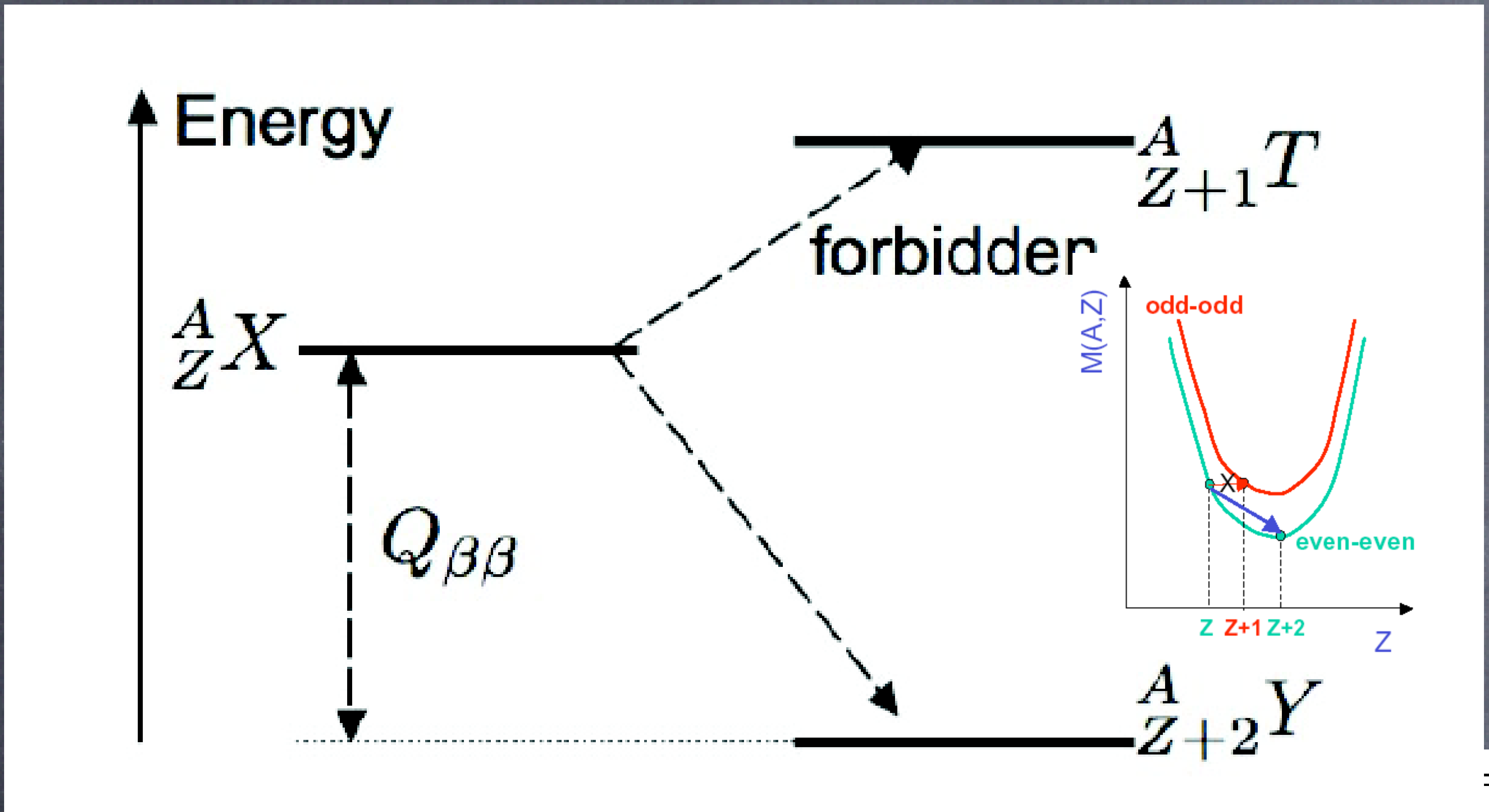


that translates into a nice plot



The question is which, if any, part of this phase space can be attained by a realistic experiment.

Double Beta Decay



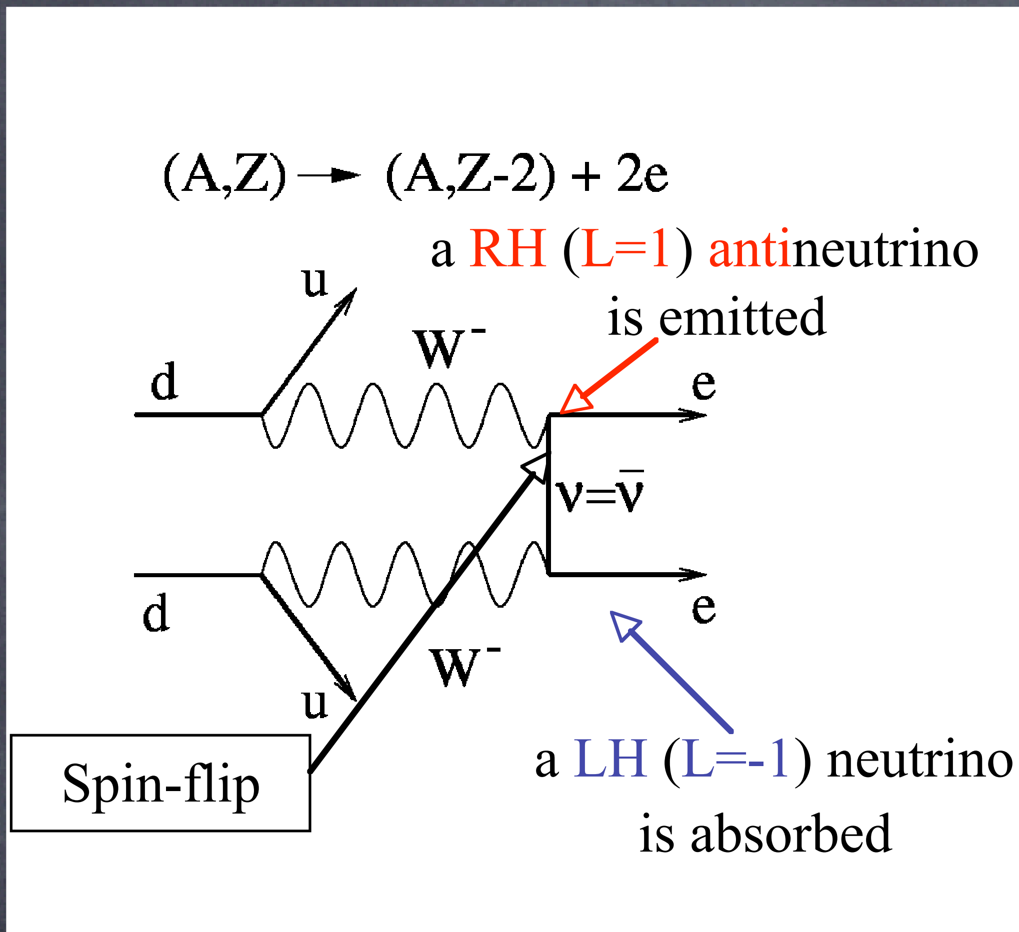
Predicted by Maria Goeppert-Mayer in 1935

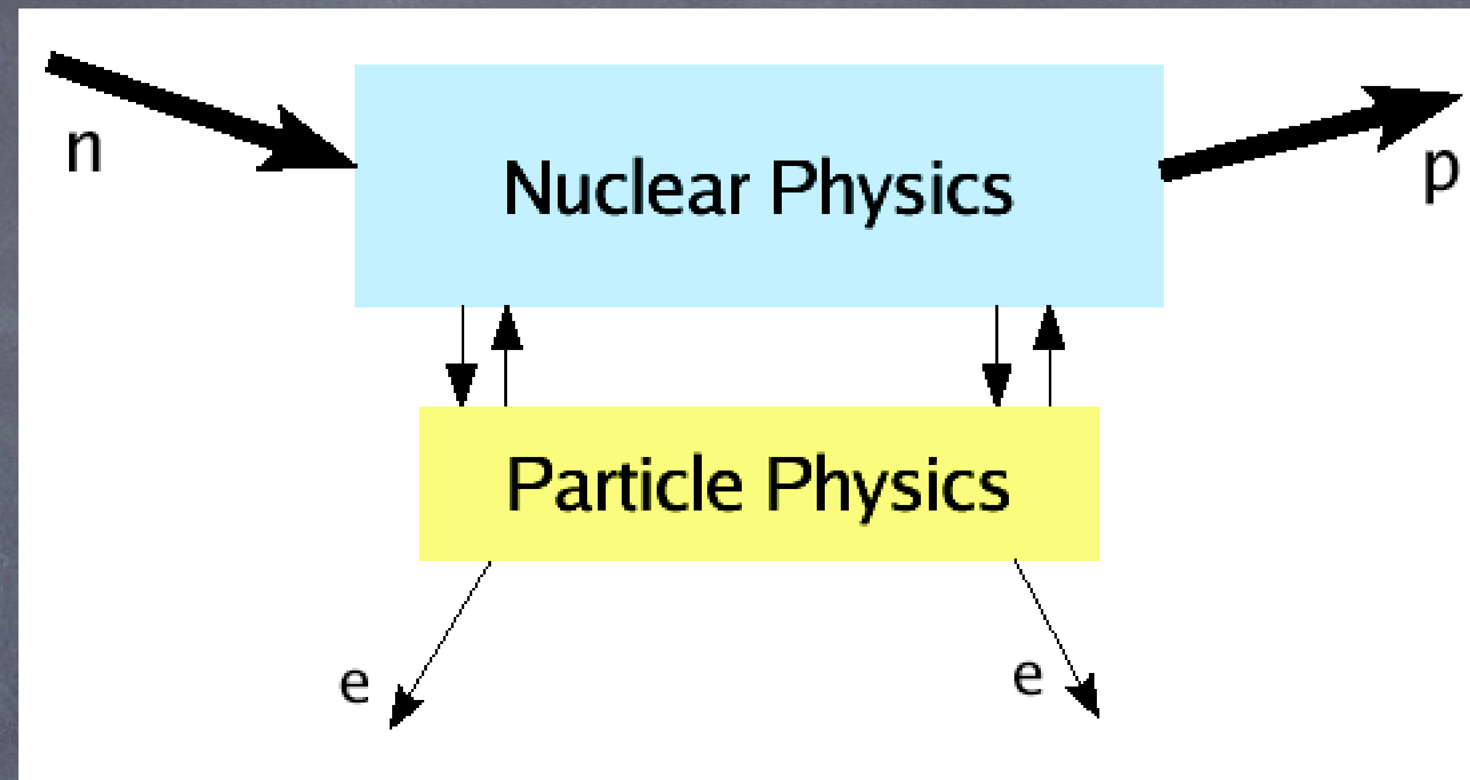
Geochemical evidence followed by direct observation of DBD in ^{82}Se (S. Elliot & M. Moe 1986)

$T_{1/2} \sim 10^{20}$ years !!

Isotope	$Q_{\beta\beta}$ (MeV)	Isotopic abundance (%)
^{48}Ca	4.271	0.0035
^{76}Ge	2.039	7.8
^{82}Se	2.995	9.2
^{96}Zr	3.350	2.8
^{100}Mo	3.034	9.6
^{116}Cd	2.802	7.5
^{128}Te	0.868	31.7
^{130}Te	2.530	33.9
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

The elements of the game





0ν-DBD rate

Phase space ∝ Q^5

Nuclear matrix element

Effective neutrino mass

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

The name of the game: sensitivity

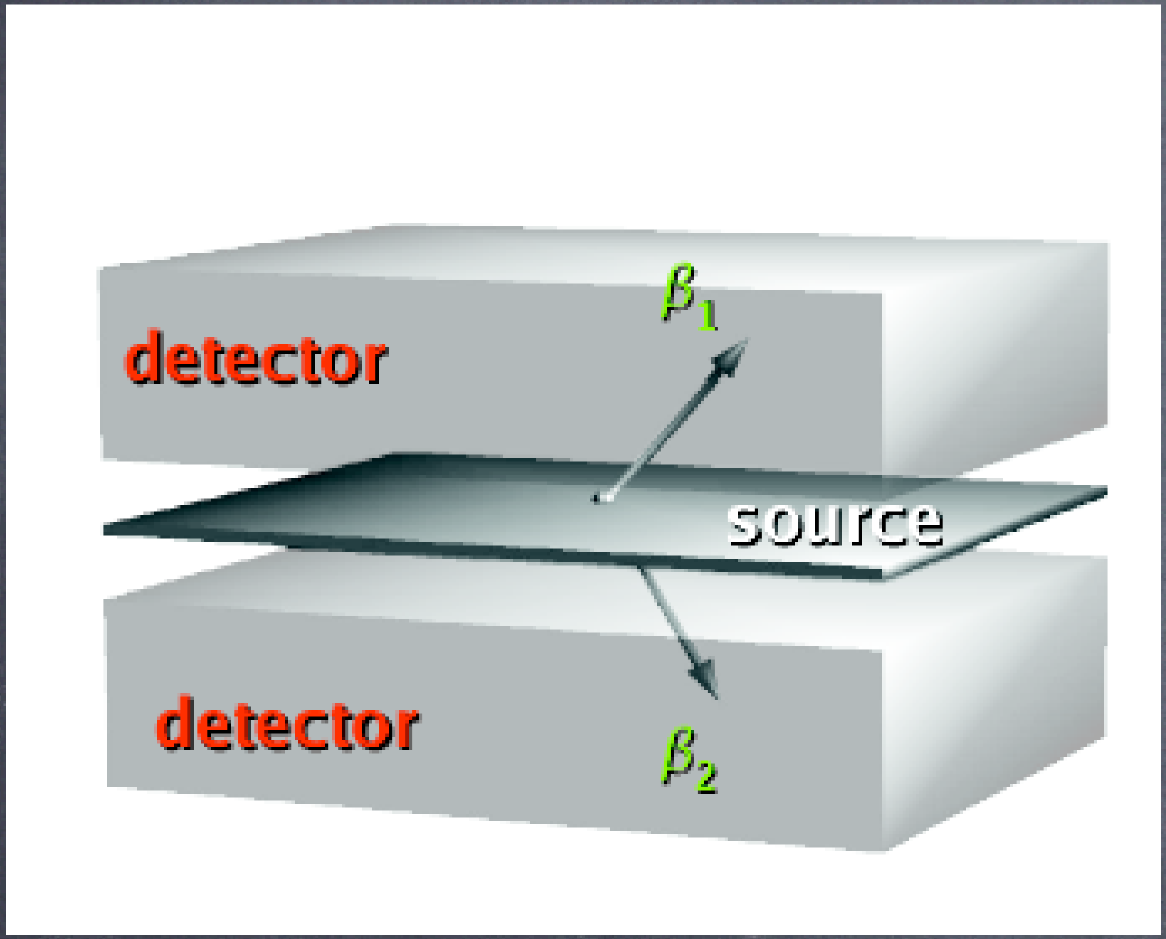
$$S^{0\nu}_{n\sigma} \propto \frac{a}{A}\left(\frac{M\,T}{b\,\Delta E}\right)^{1/2} \times \varepsilon$$

- Isotopic abundance (a)
- Mass(Kg) (M)
- Time (y) (T)
- efficiency (ε)
- Atomic Mass (A)
- background (counts/keV/Kg/y) (b)
- Energy Resolution (KeV) (ΔE)

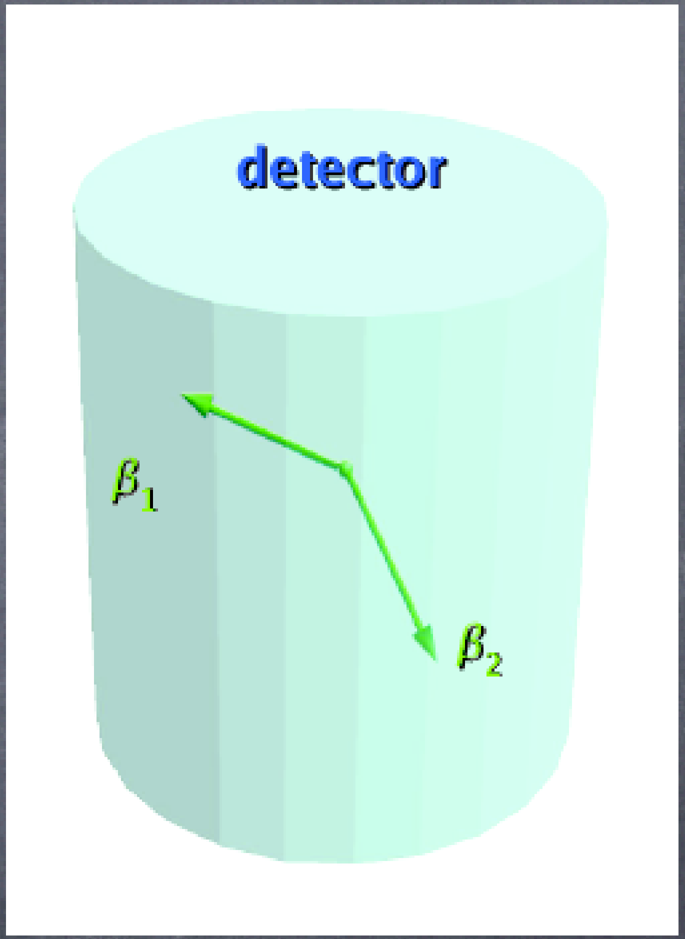
Sensitivity: half life corresponding to the minimal number of detectable events above background, for a given C.L

Two techniques (and a few variations)

Source ≠ Detector



Source ⊆ Detector

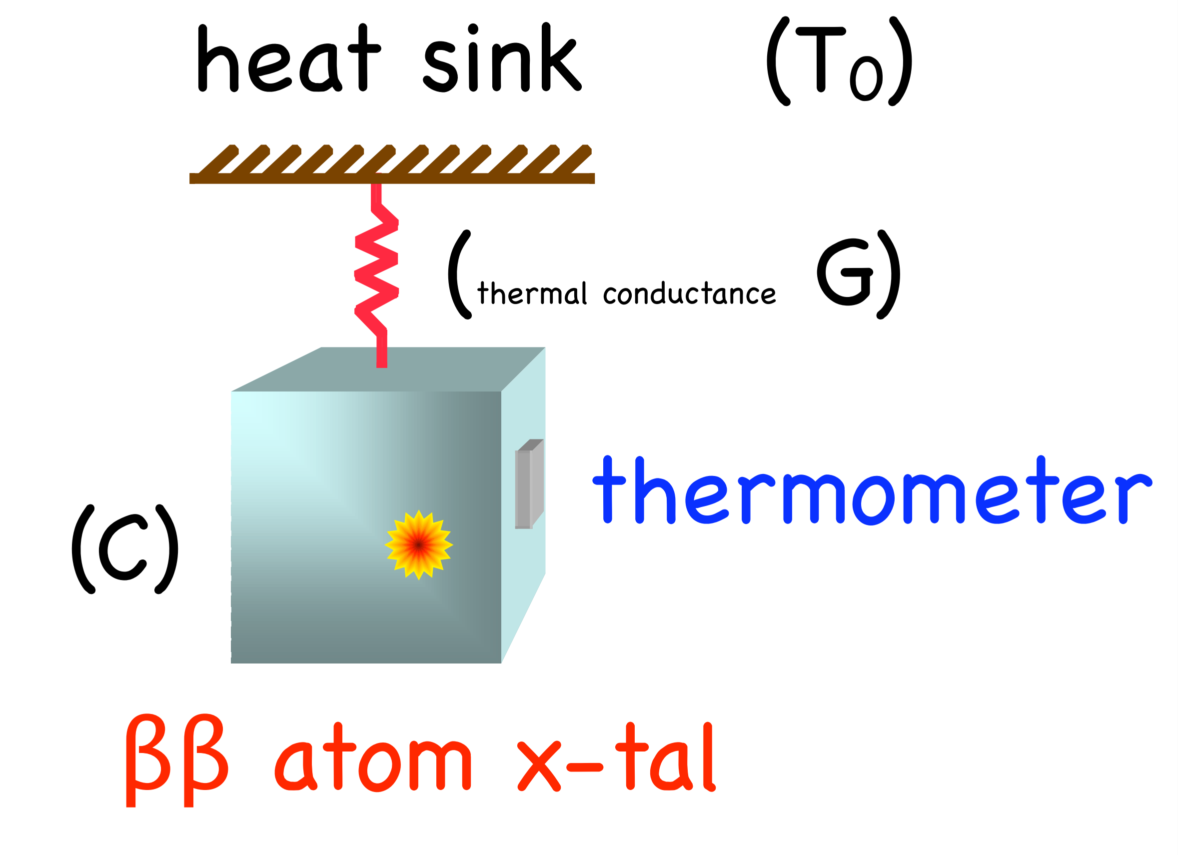


+++ Topology, Background
--- M, ΔE, ϵ

+++ M, ΔE, ϵ
--- Topology, Background

(very) Low Temperature Calorimeter

A True Calorimeter



Basic Physics: $\Delta T = E/C$
(Energy release/ Thermal capacity)

Implication: Low C ⇒ Low T

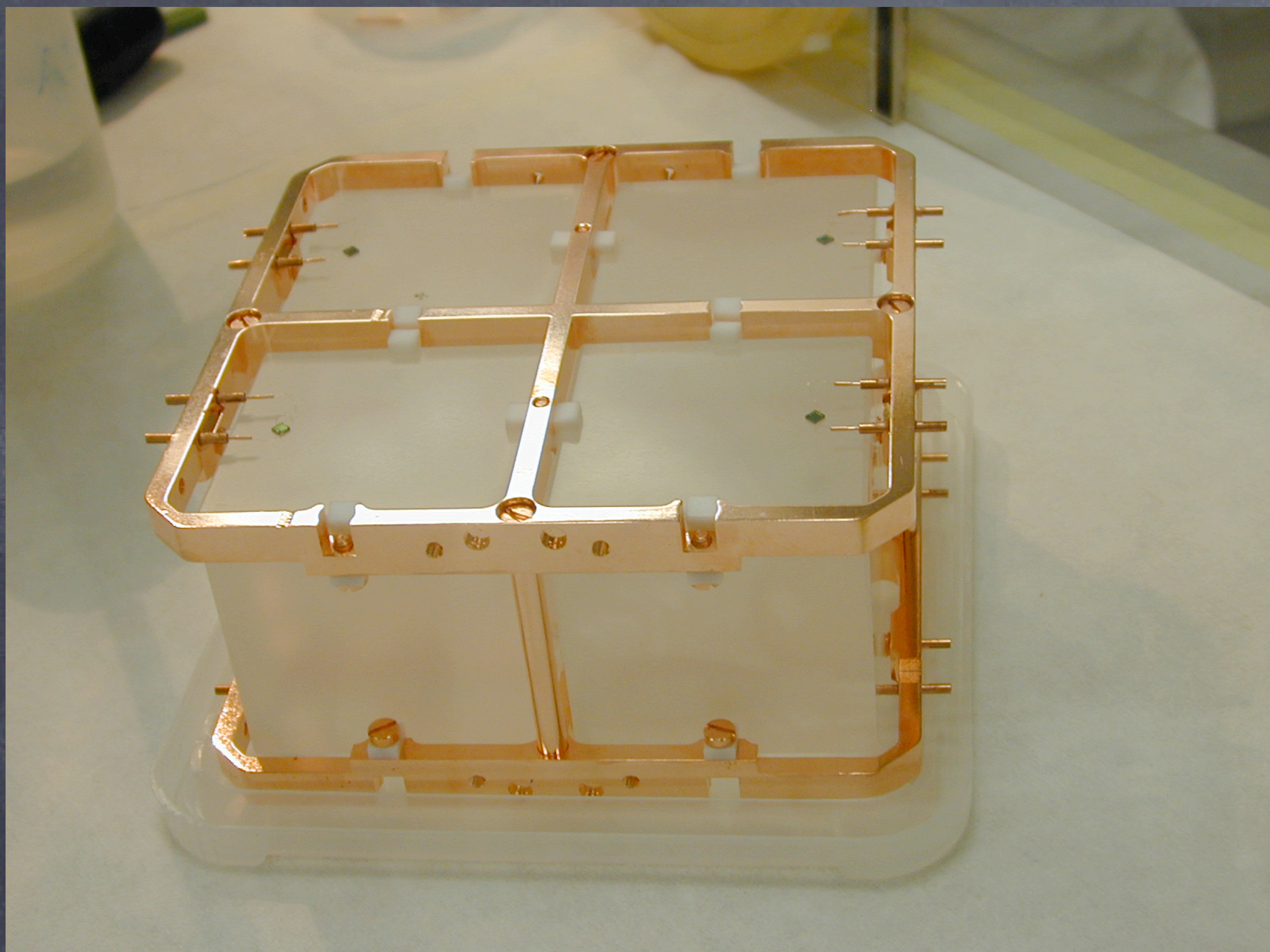
Bonus: (almost) No limit to ΔE ($k_B T^2 C$)

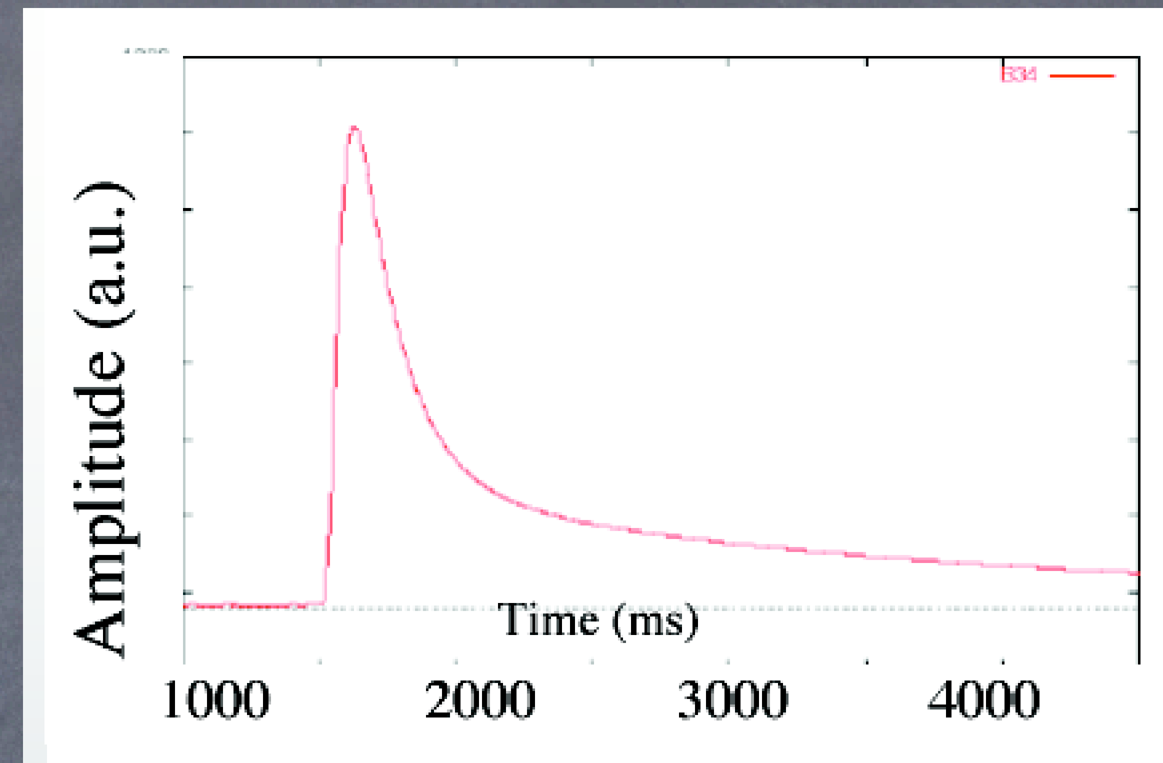
Not for all : $\tau = C/G \sim 1s$

$$C(T) = \beta \frac{m}{M} \left(\frac{T}{\Theta_D} \right)^3$$

$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau} \right)$$

TeO_2 : a viable (show)case





$T_0 \sim 10$ mK

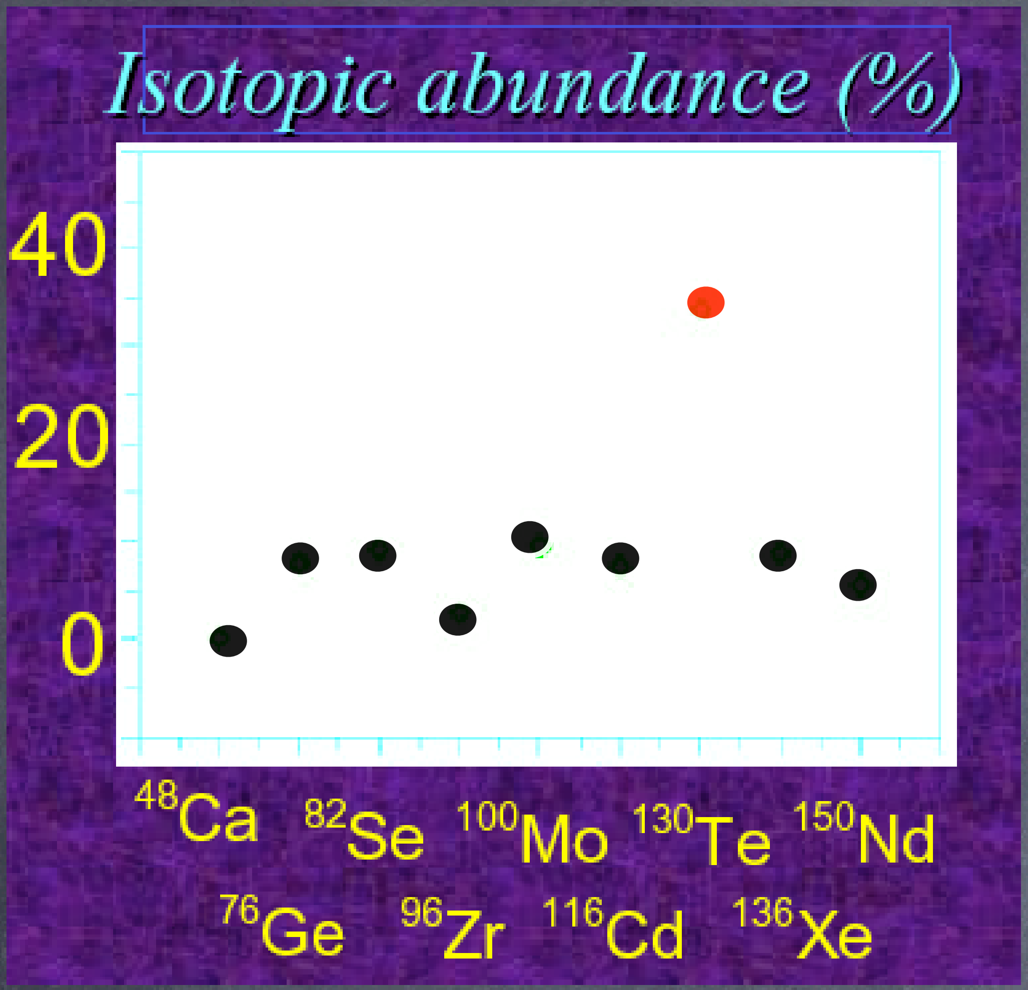
Numerology:

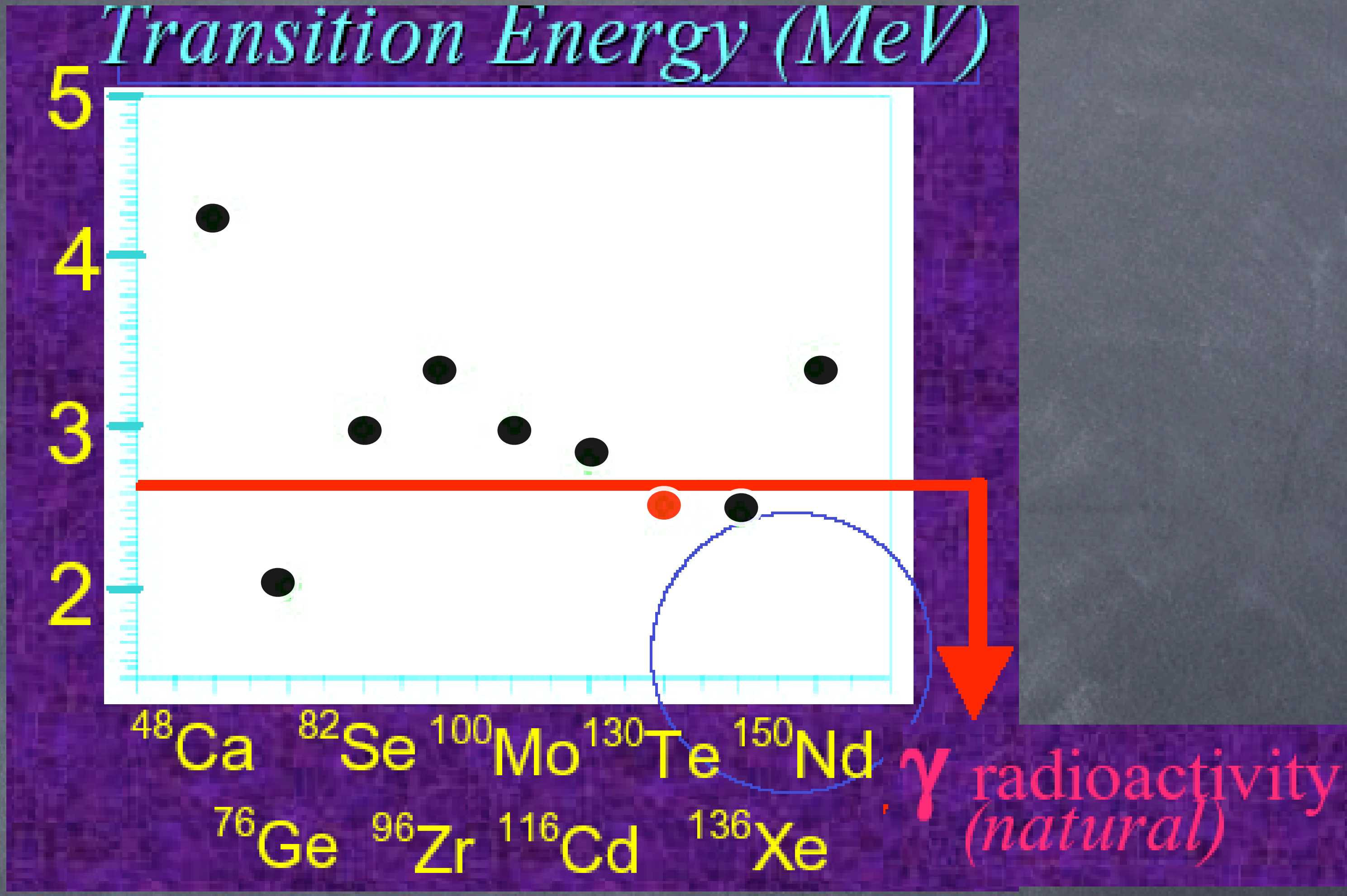
$C \sim 2$ nJ/K ~ 1 MeV/0.1 mK

$G \sim 4$ pW/mK

Need to be able to detect temperature jumps of a fraction of μK (per mil resolution on MeV signals)

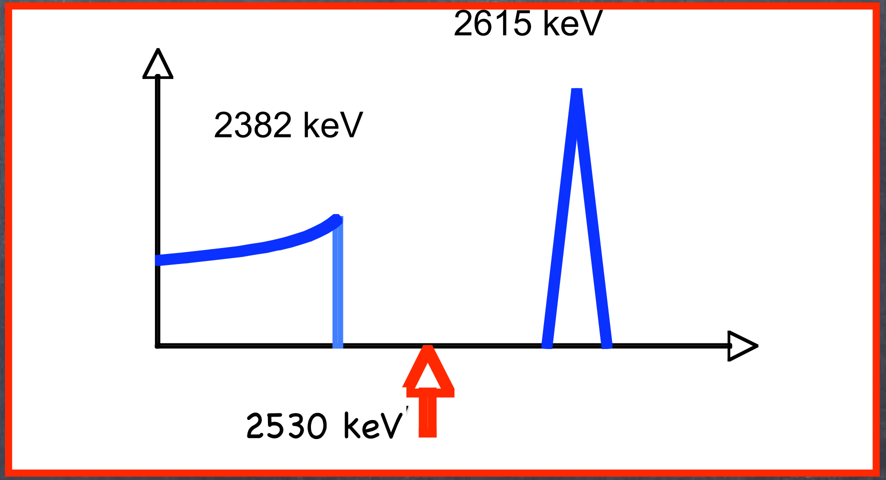
Te: why ?





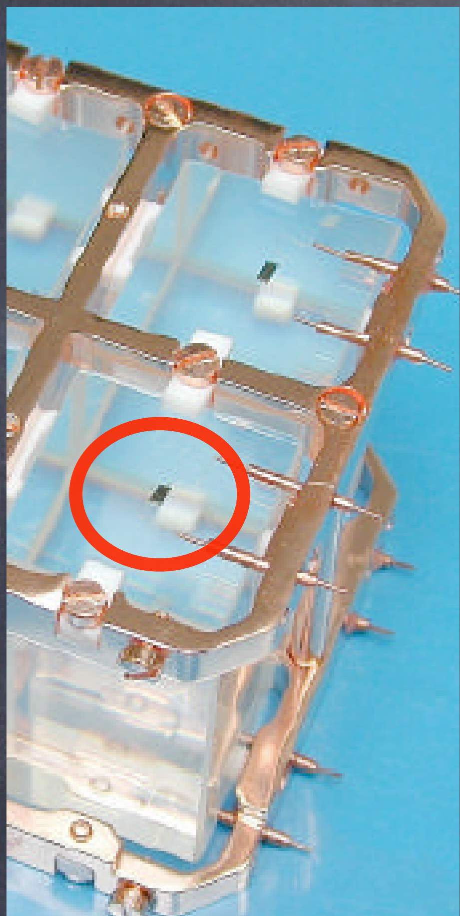
TeO$_2$ crystals

- low heat capacity
- large crystals available
- radio-pure crystals



to read the temperature you need a thermometer

$$A(T) = \left| \frac{d \ln R}{d \ln T} \right|$$

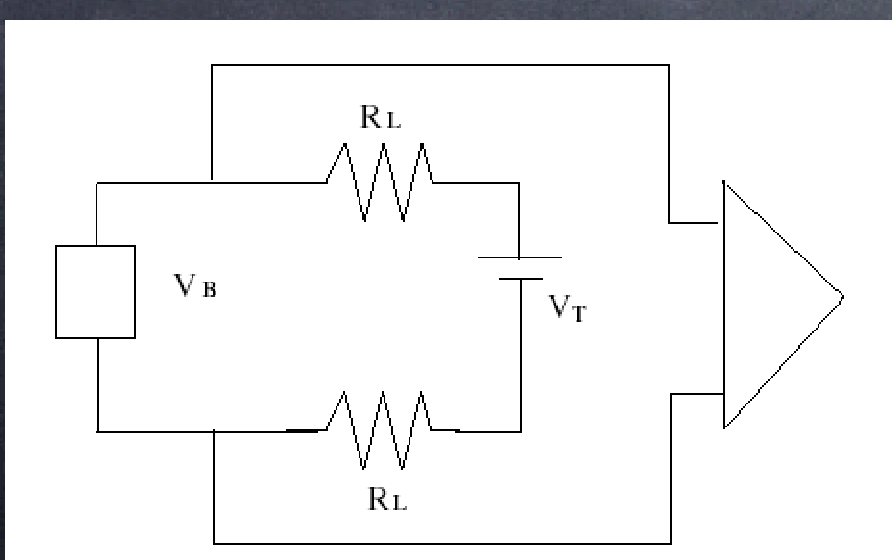


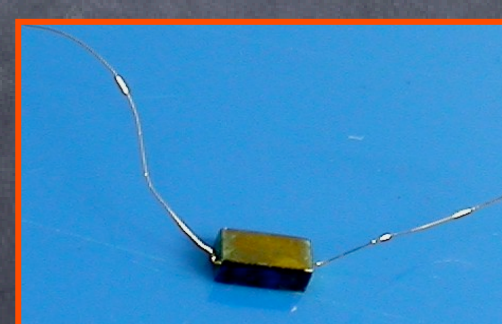
Neutron Transmutation Doped (NTD) Germanium Thermistor

I ~ 50 pA

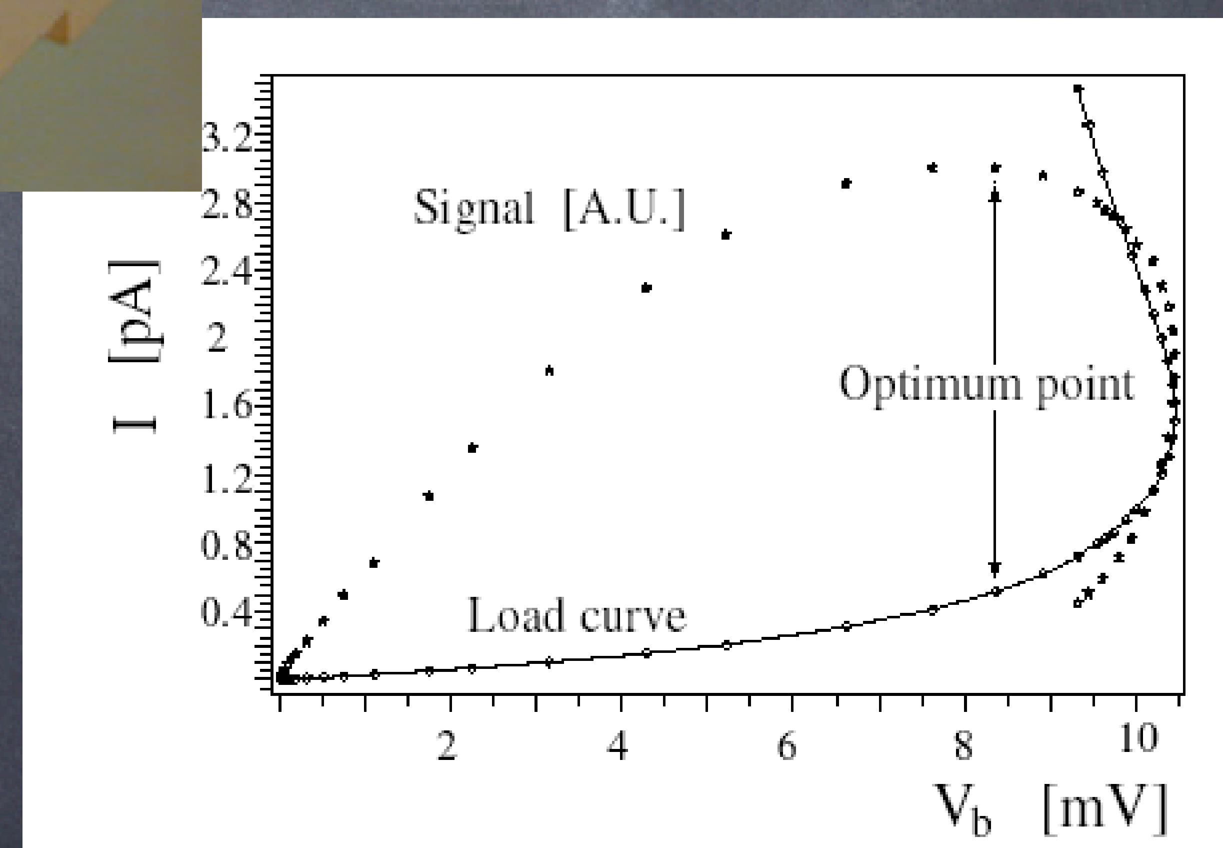
dR/dE ~ 20kΩ/KeV

0.2mV/MeV

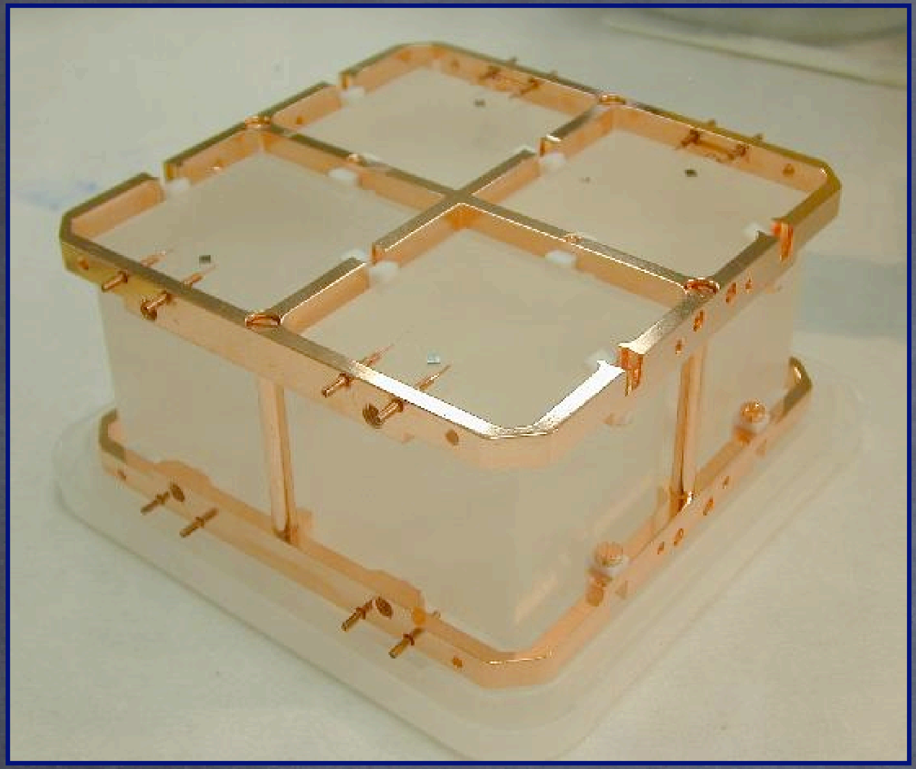




$$T_b = T_0 + \frac{P}{G}$$



Cuoricino: the demonstrator

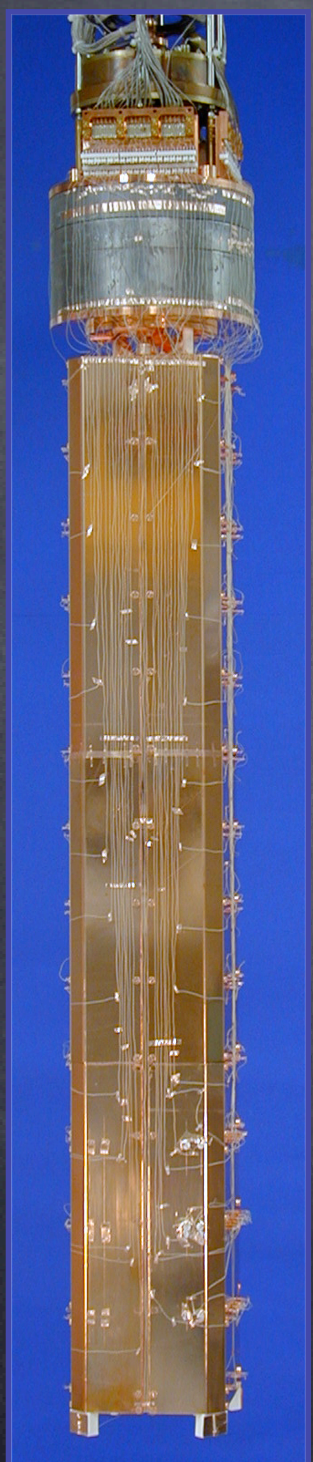


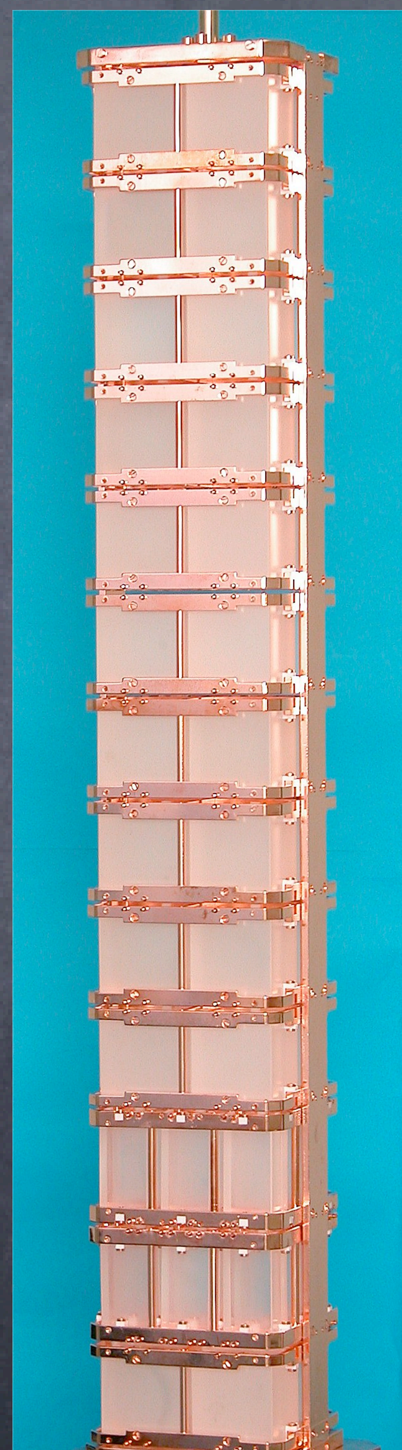
The bulk of Cuoricino calorimeter is made by 44 TeO_2 crystals of 5x5x5 cm^3 (790 gr of weight).
There are 18 additional crystals of 3x3x6 cm^3 (330 gr)

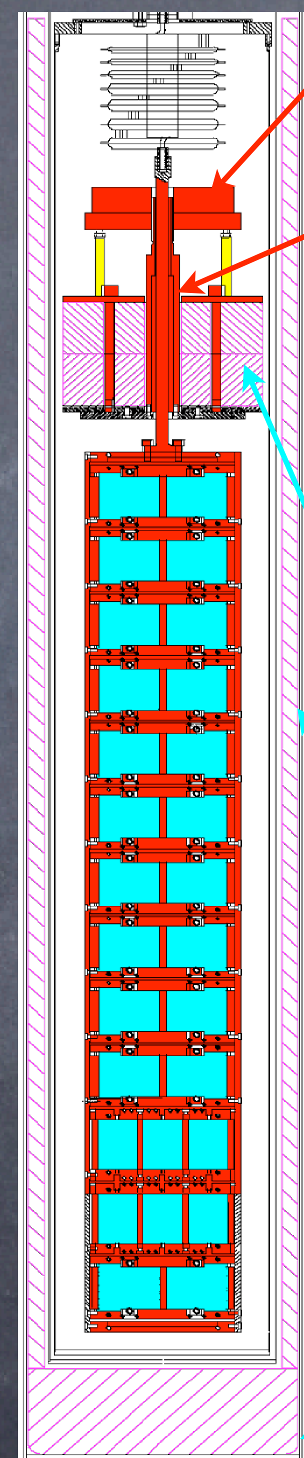
Total mass = 40.7 Kg
^{130}Te ~ 11.2 Kg

Cuoricino

Cuoricino is currently the largest operating
bolometer in the world





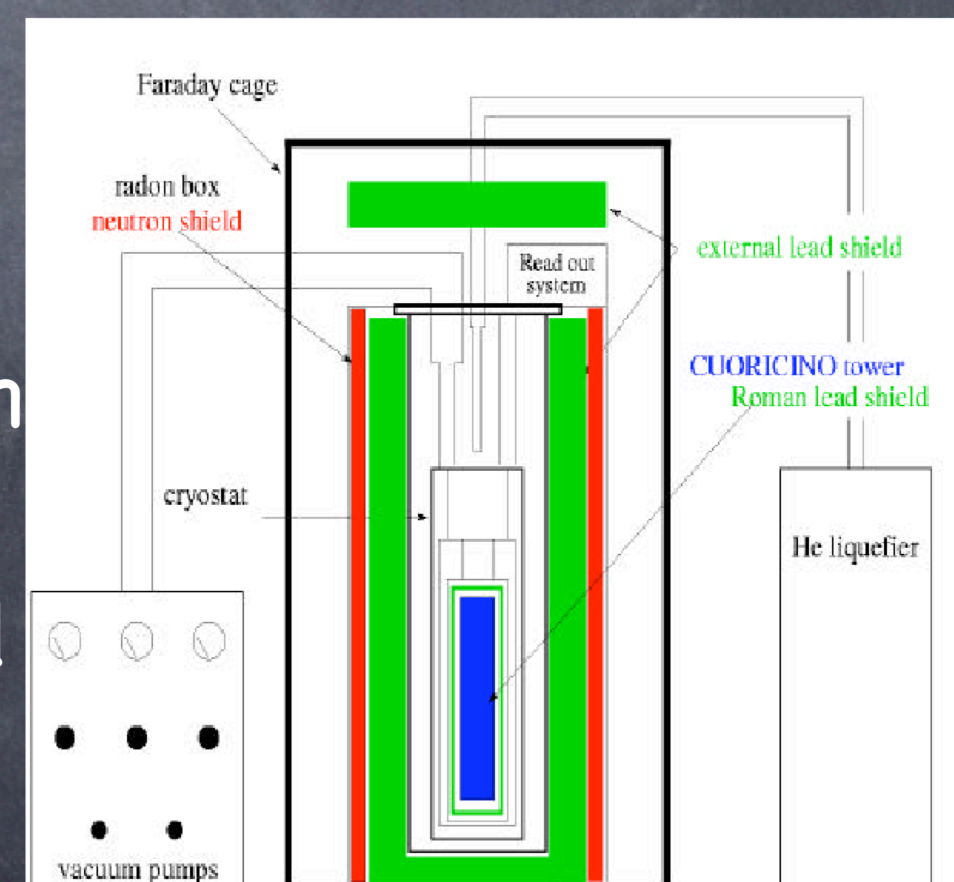


Mixing chamber

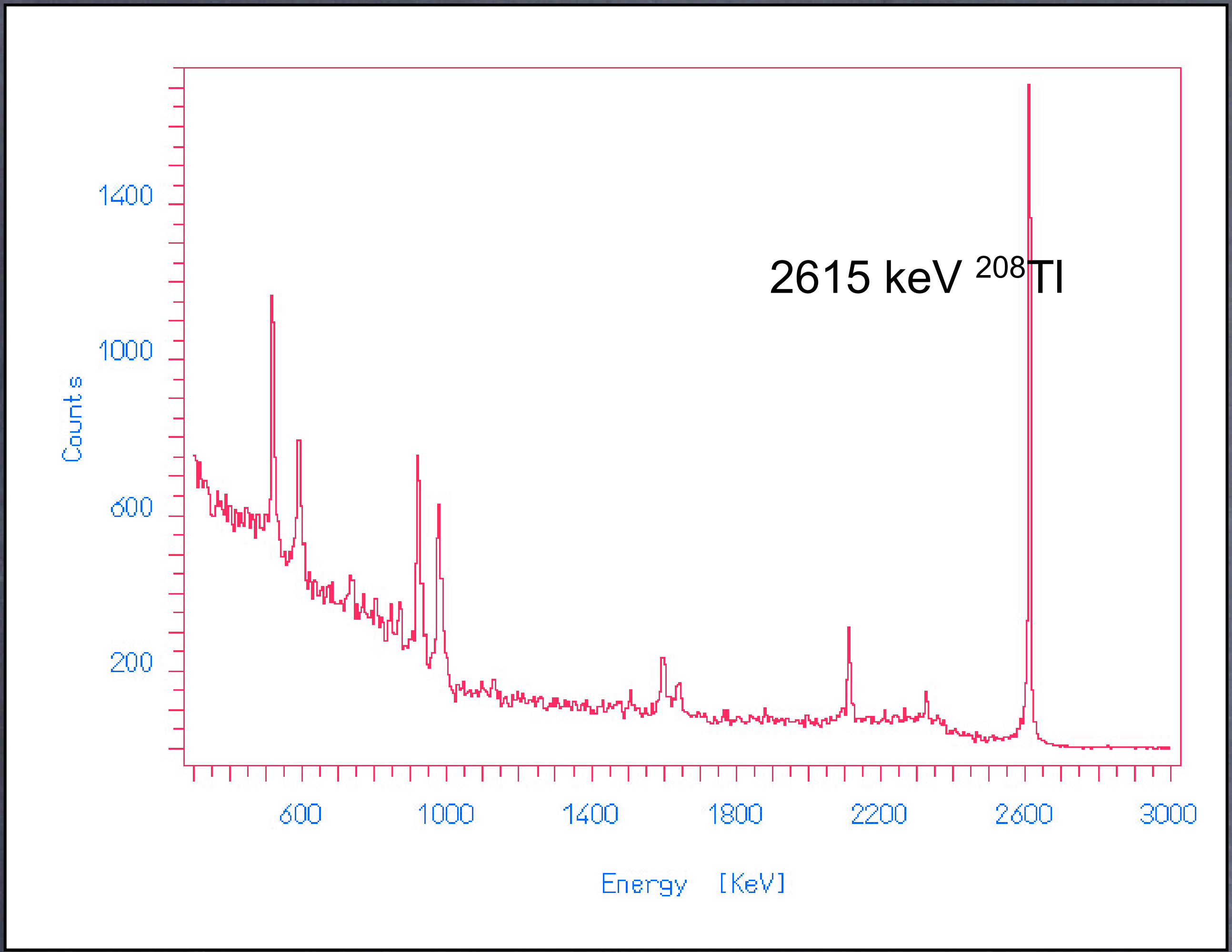
Cold finger

10 mK

Roman
Lead
Shield

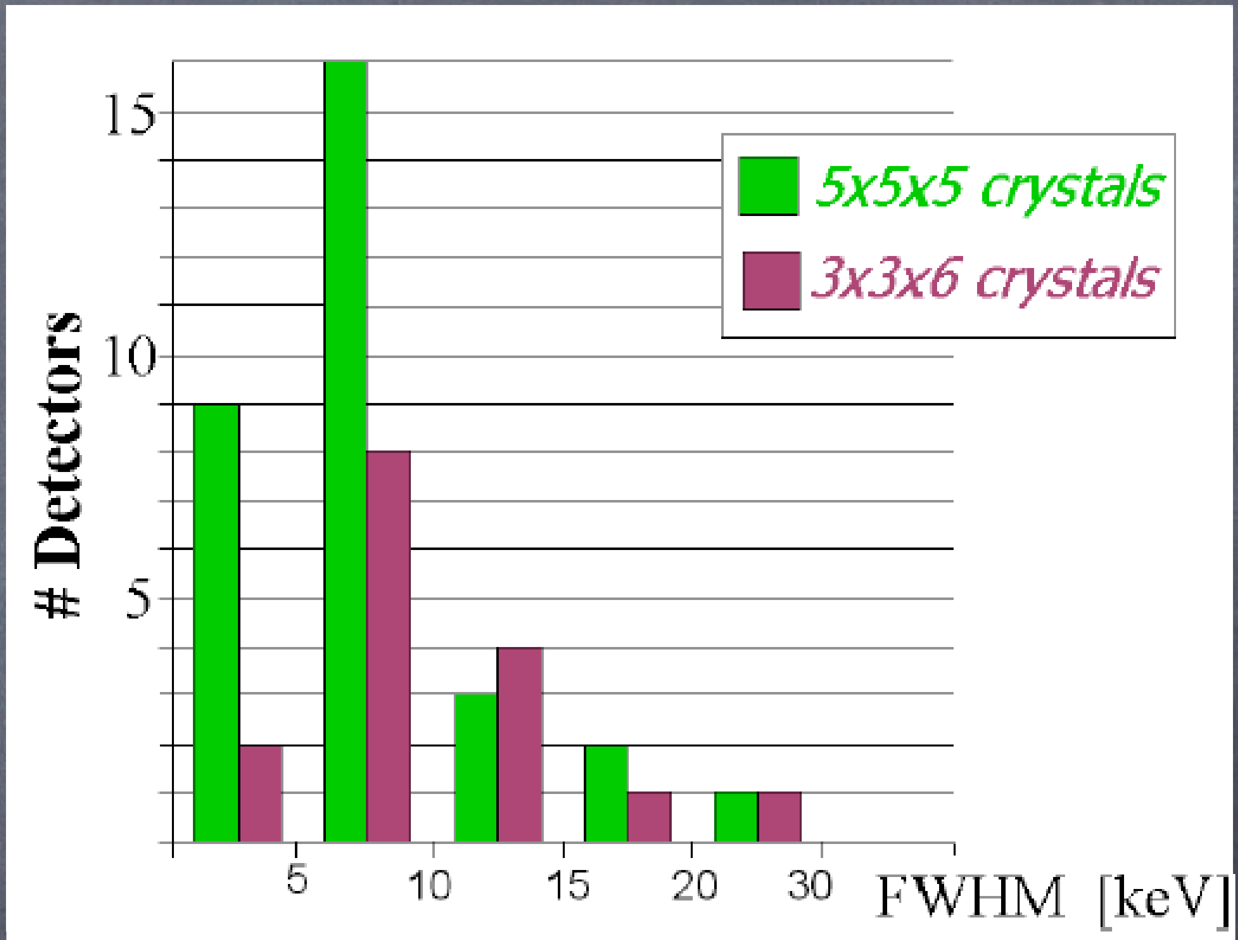


Energy resolution

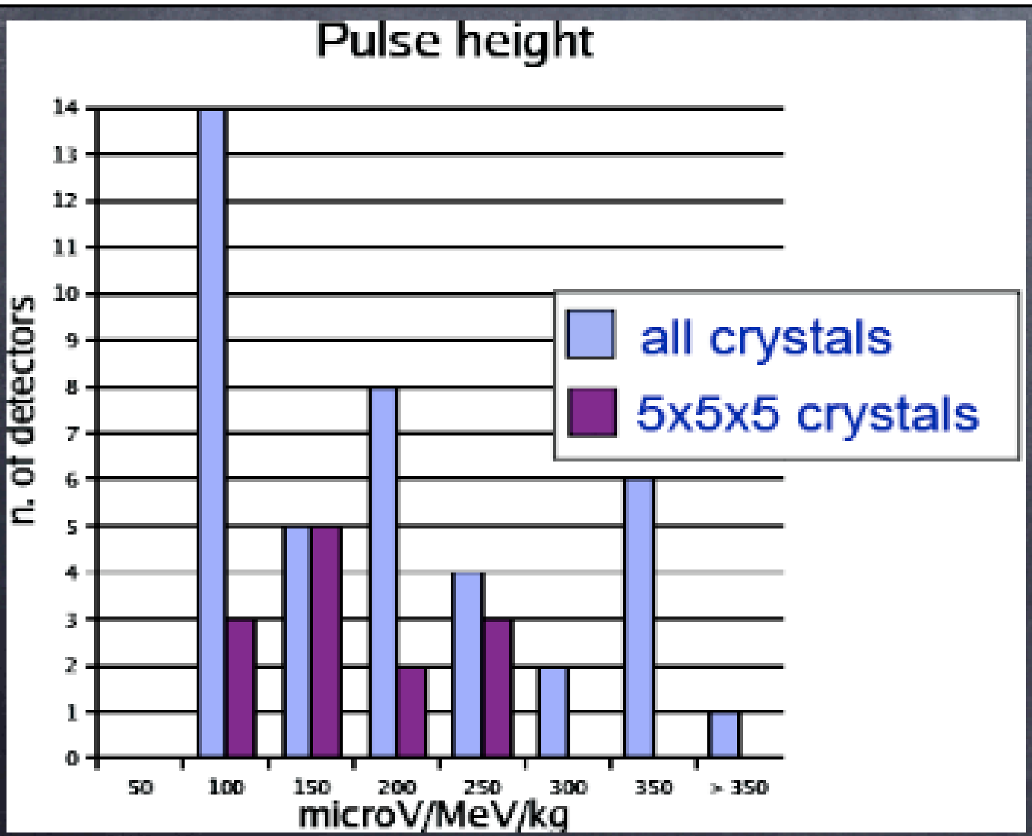


Sum all over the crystals

(calibration with ^{232}Th source)



Average resolution 5x5x5 : 7.5 keV
Average resolution 3x3x6 : 9.6 keV
Best of all : 3.9 keV



Resolution limited by

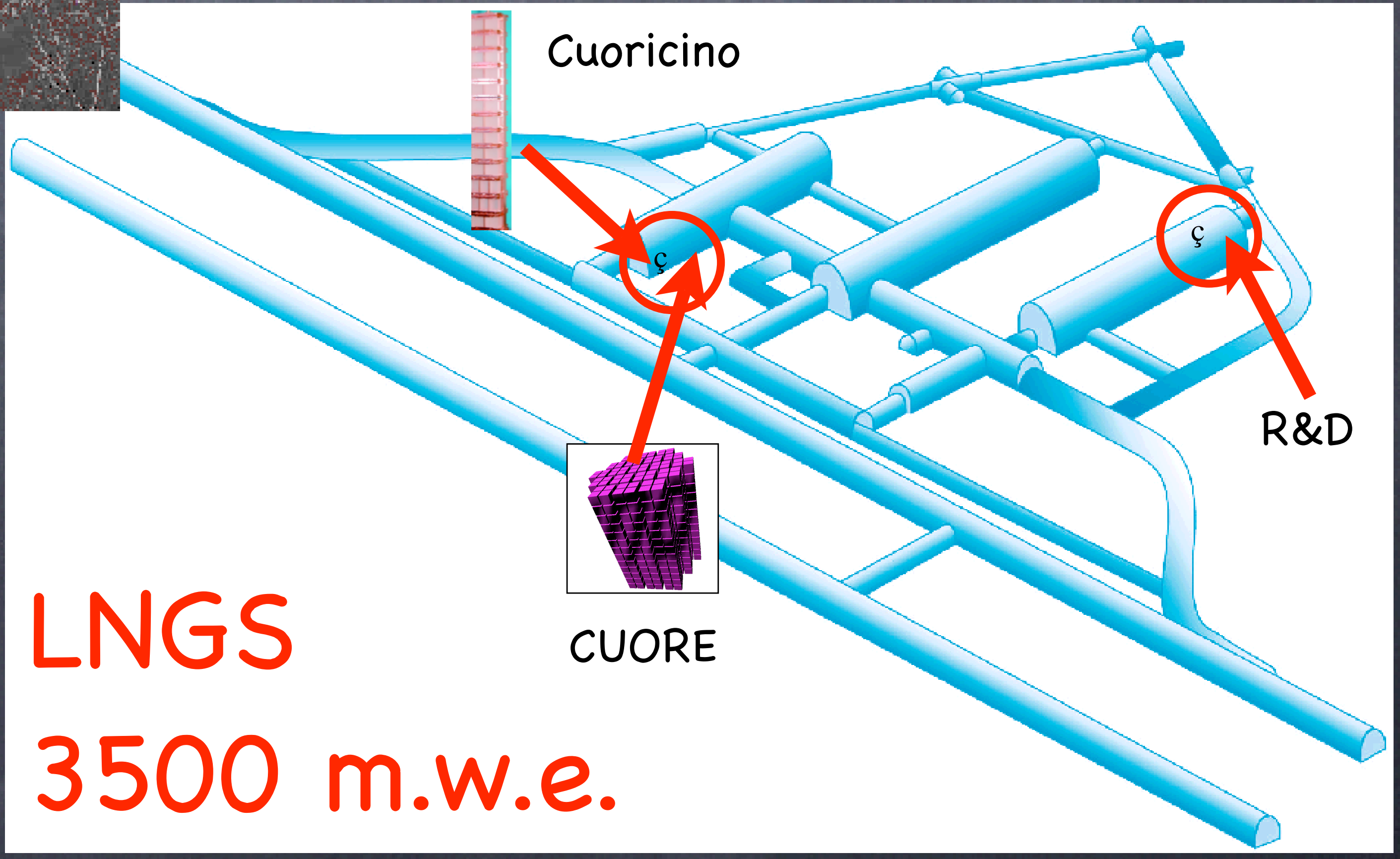
- Thermal/Phononic (Δ ~ eV)
- Electronic noise (Δ ≤ 1 keV)
- Microphonics Δ ~ 3-5 keV
- Detector responses Δ ~ keV

Cuoricino, where ?

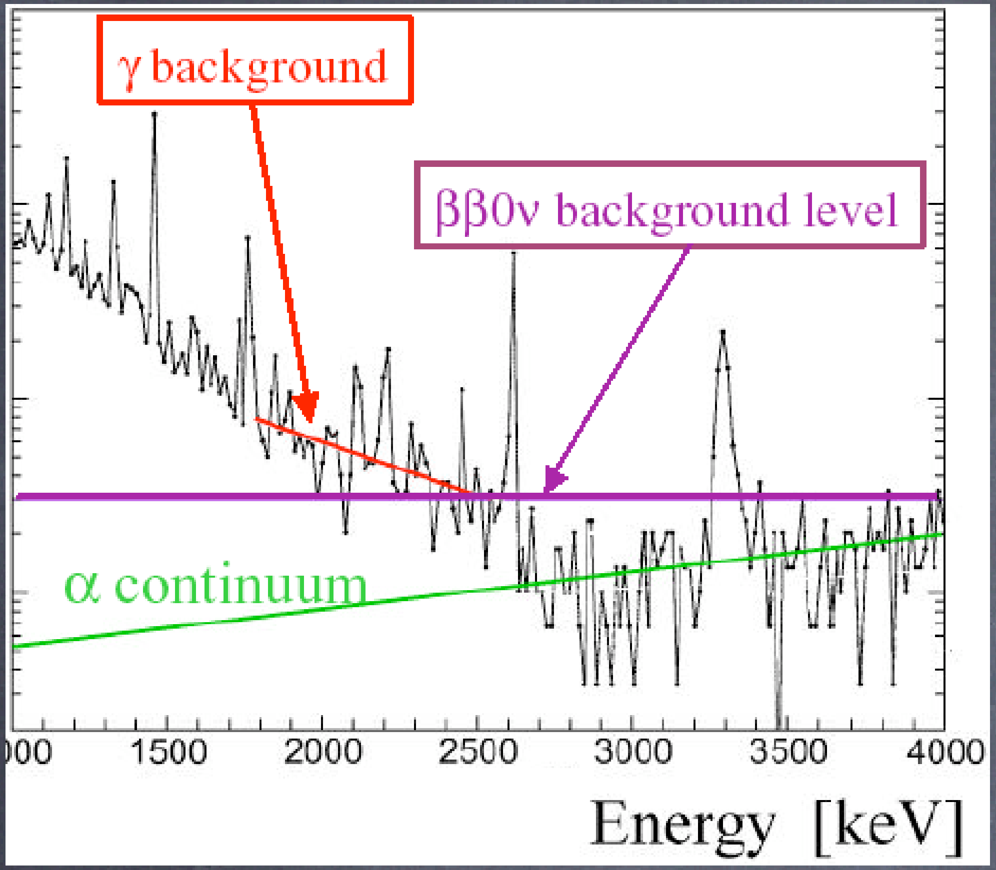
The Shield

Corno Grande 2916 m

A National Park providing great opportunity for walking, trekking, climbing, cross and backcountry skiing

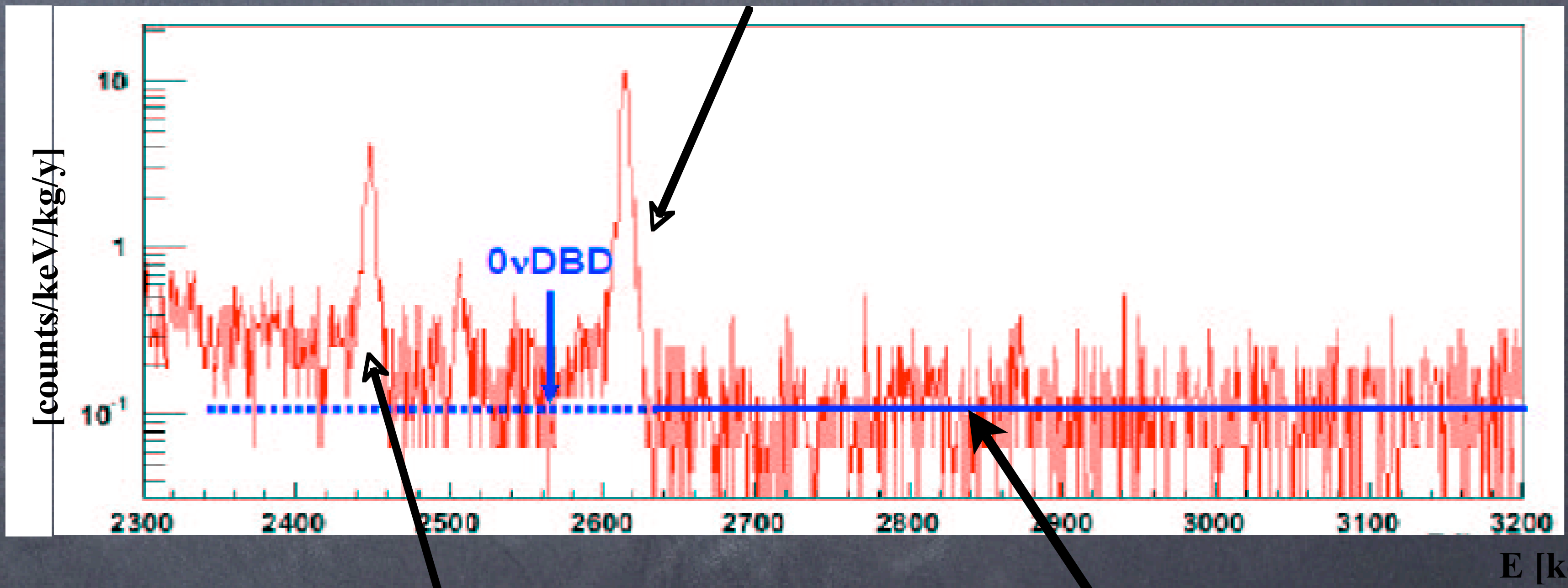


Cuoricino: Background



Cuoricino
b=0.18 ± 0.02 c/keV/kg/y

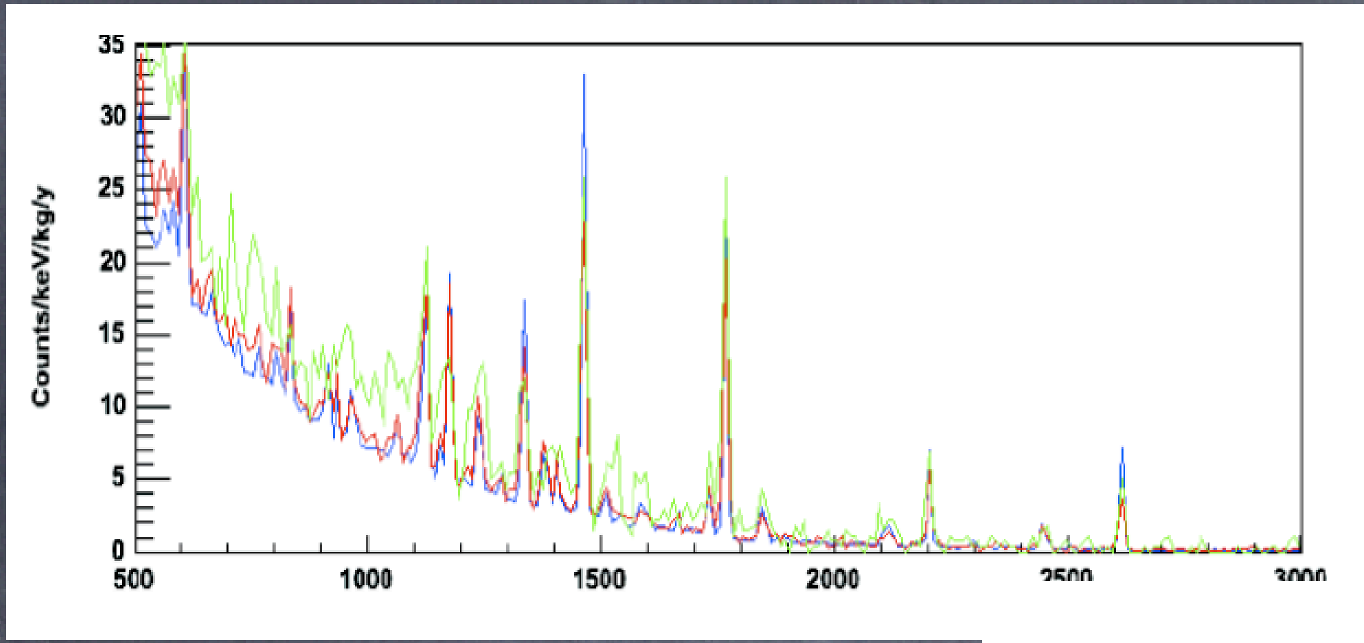
2615 keV Tl line: contribution to the DBD bkg due to a Th contamination (multicompton). .
Th (Tl) contribution to DBD background: **~ 40%**



2505 keV line: sum of the 2 ^{60}Co gammas (1173 and 1332 keV)
Most probable source: neutron activation of the Copper
Contribution to DBD background: negligible

Flat background in the energy region above the ^{208}Tl 2615 line
Contribution to the counting rate in the 0νDBD region: ~ 60%
Degraded alpha particles

Cuoricino: result

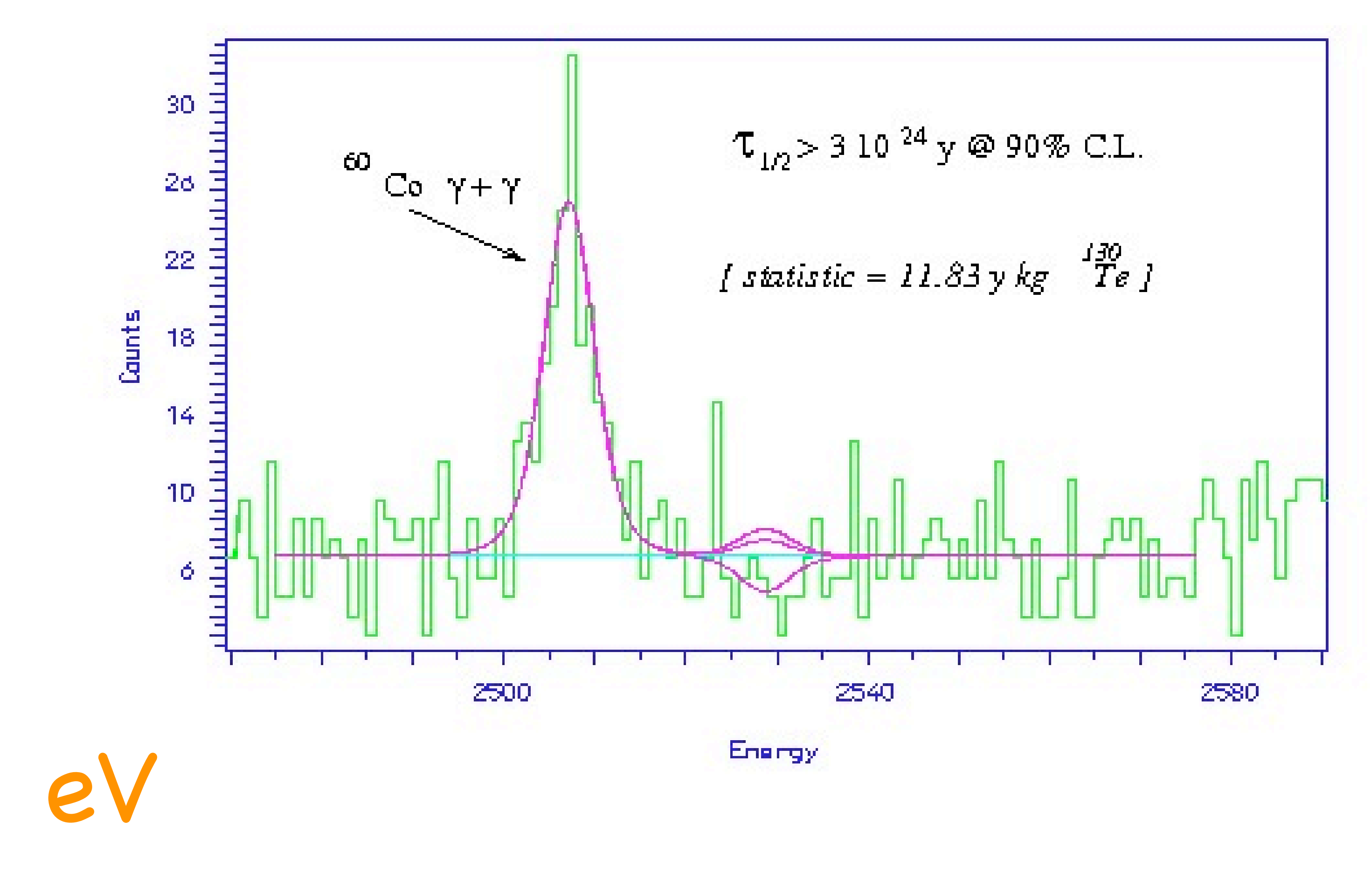


Total statistics

11.83 Kg•y ^{130}Te

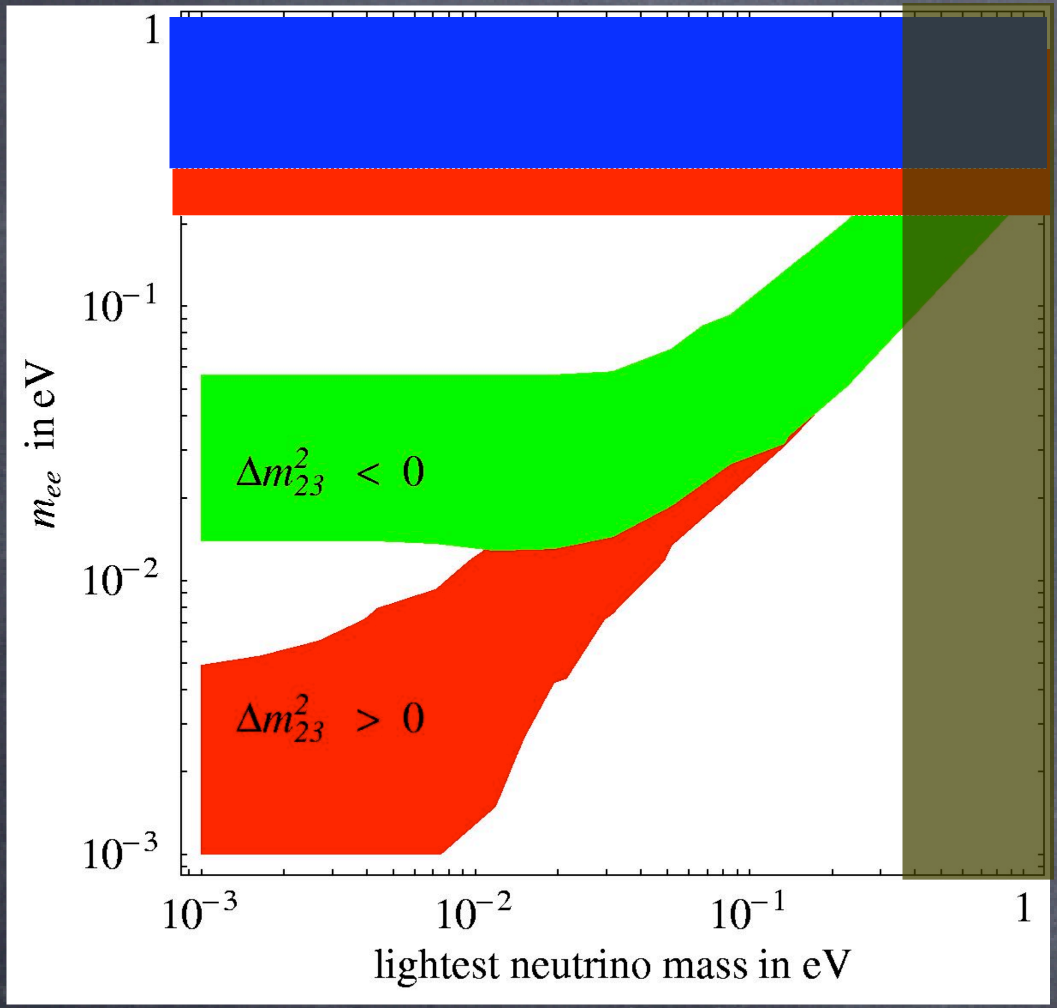
$T_{1/2} \geq 3.0 \bullet 10^{24}$ y

at 90% CL



$\langle m_\nu \rangle \leq 0.15 \div 0.89$ eV

in the parameter space



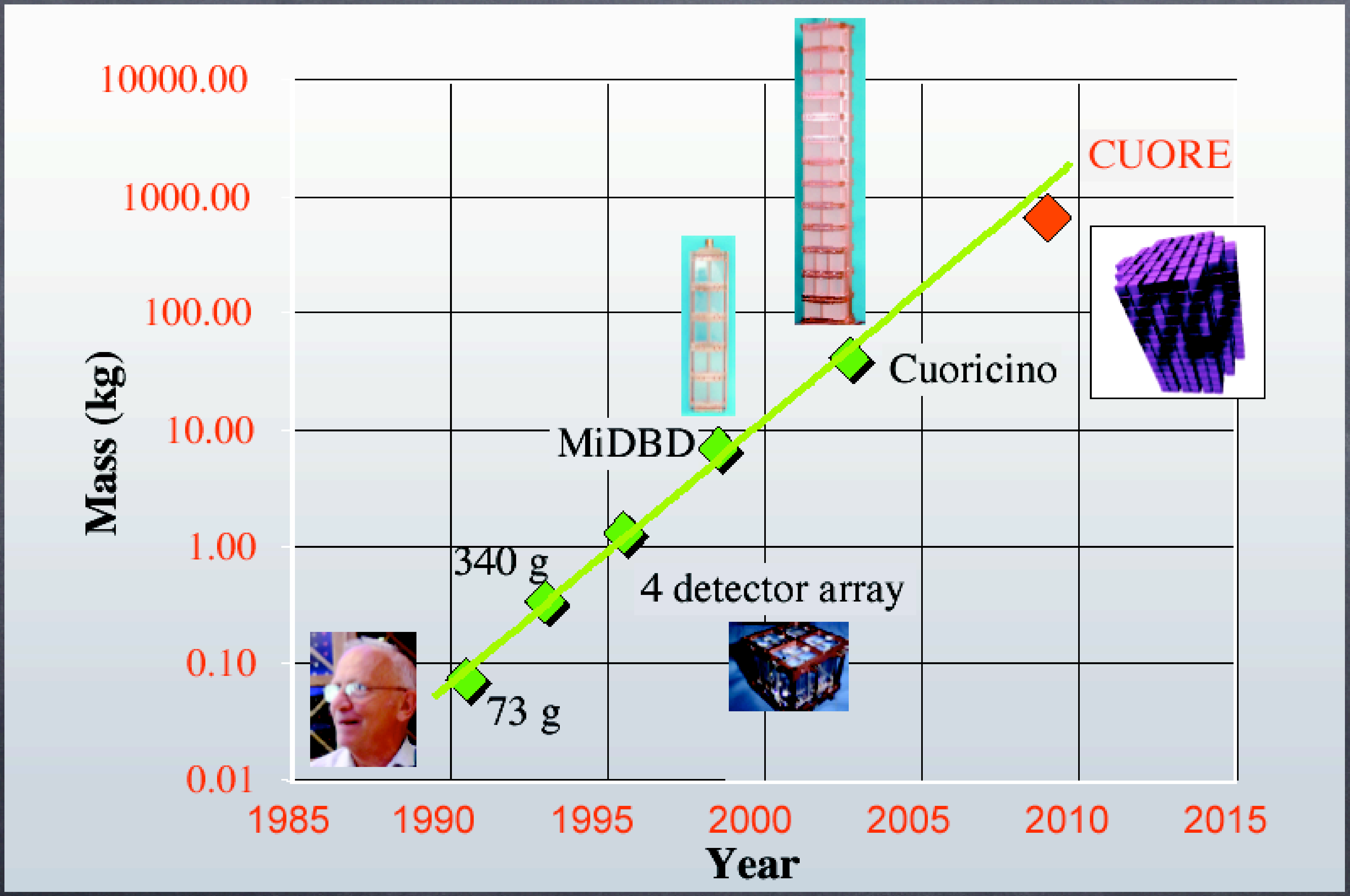
Cuoricino
'Klapdor et al.'
WMAP

Cuoricino sensitivity after 4 y run

$$\tau_{1/2} \geq 6.1 \times 10^{24}\ \text{y}$$
$$\langle m_\nu \rangle \leq 0.1 \div 0.6\ \text{eV}$$

Cuoricino might discover DBD but cannot disprove 'Klapdor'

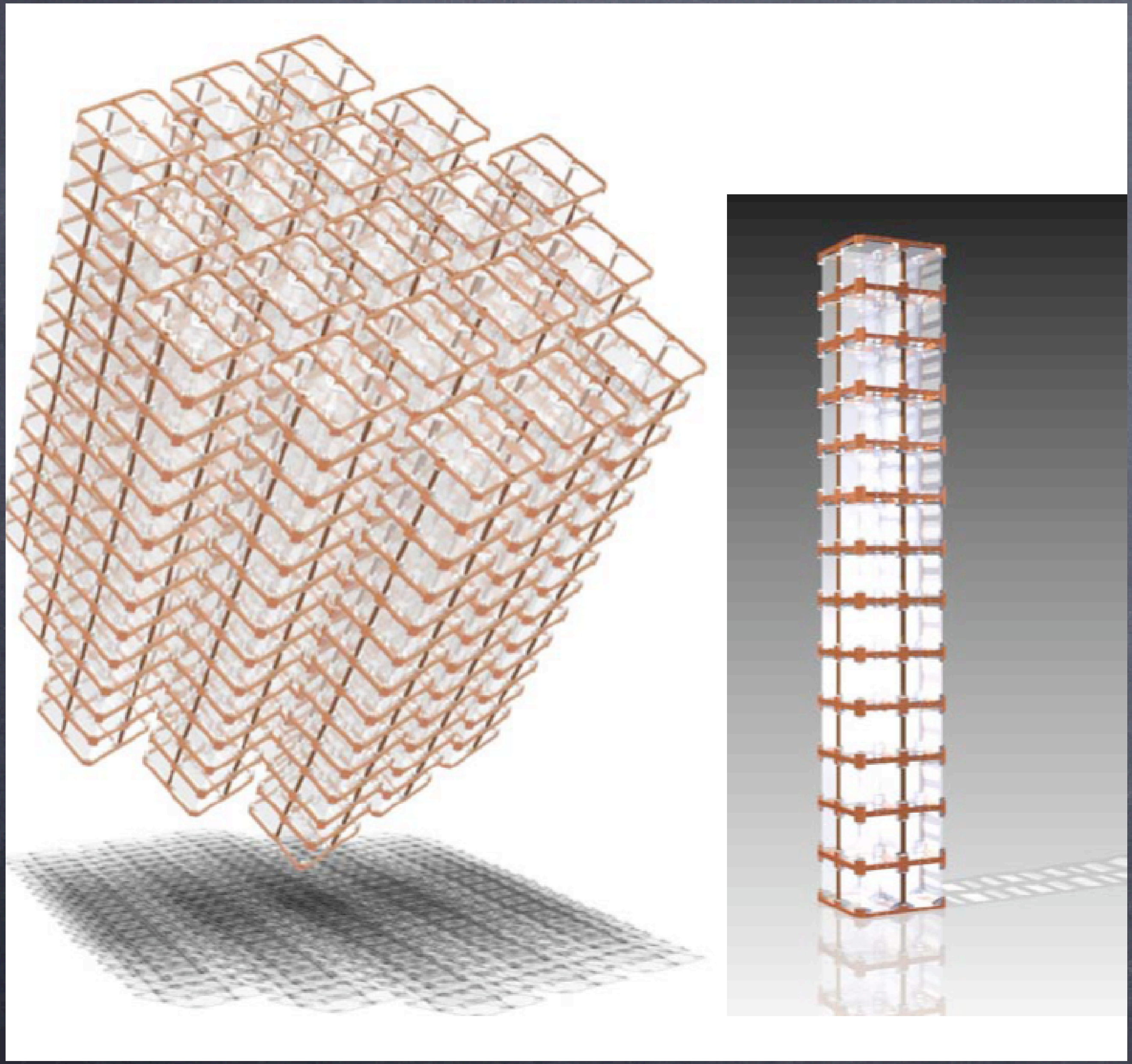
The Moore's Law of Bolometry



CUORE : who ?

CUORE design

Cuoricino times 19



988 TeO_2 Crystals

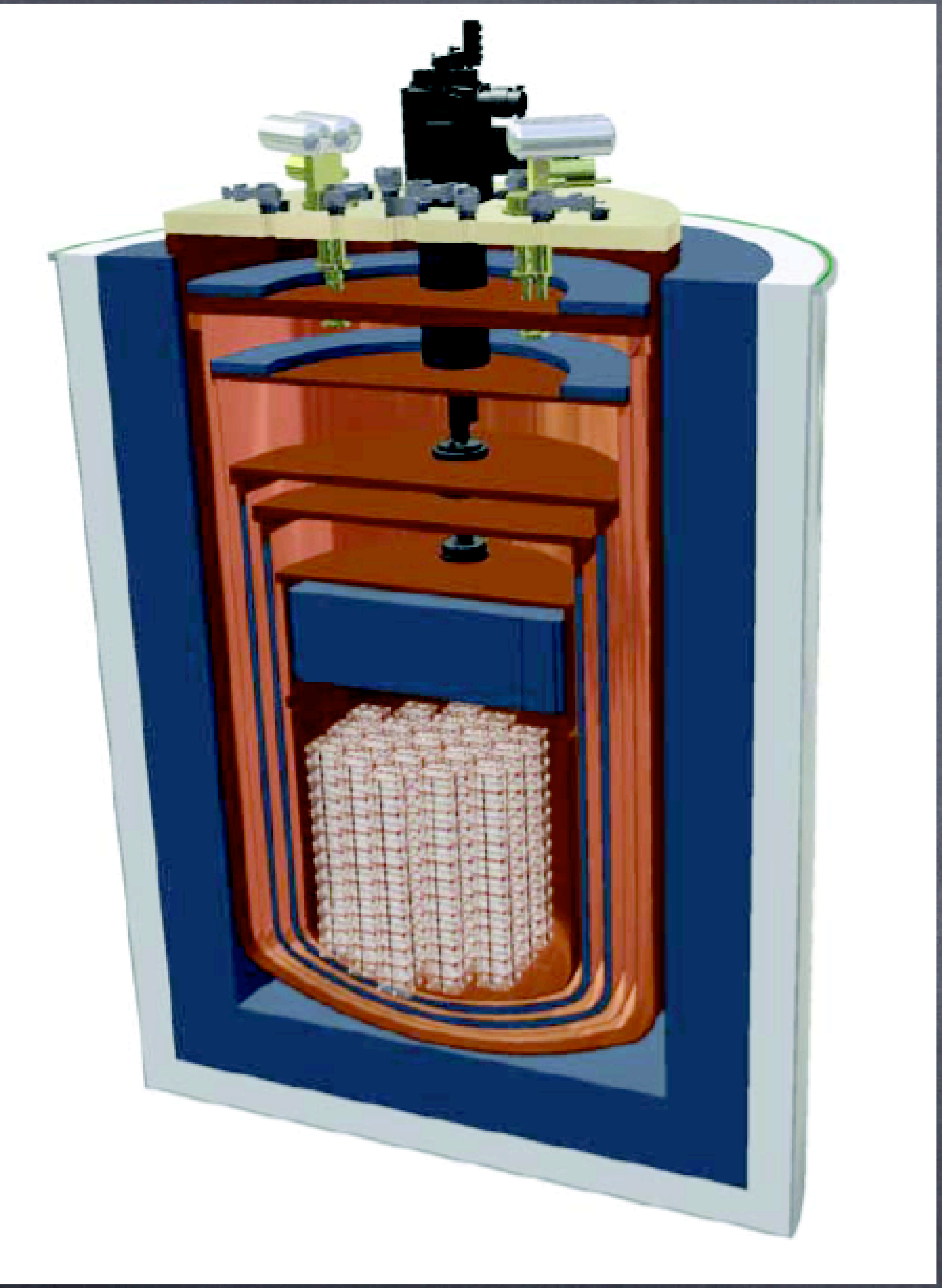
19 Towers of 52 crystals each

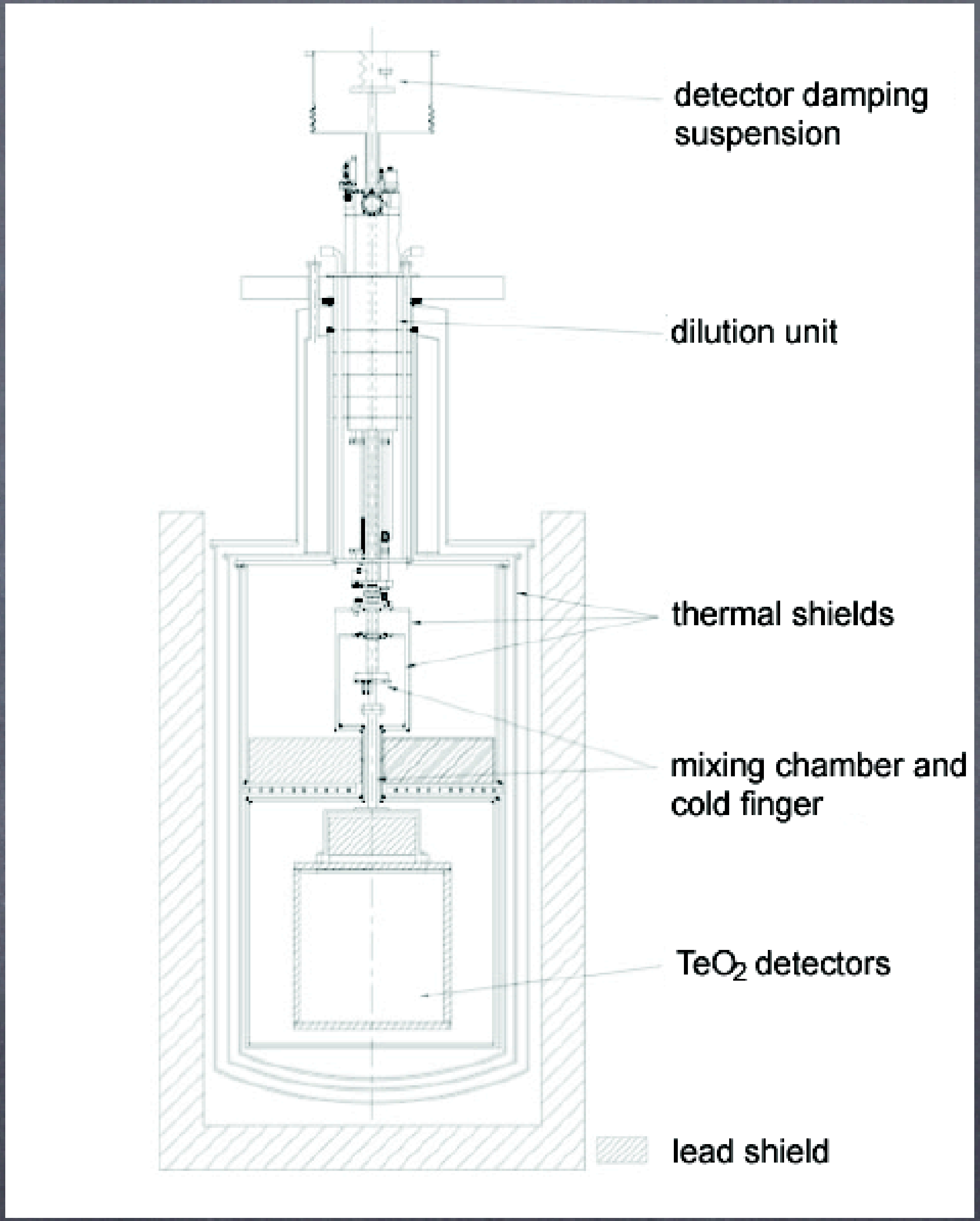
741 Kg of TeO_2

Active Mass 204 Kg

Keep the possibility of replacement with enriched Te Crystals

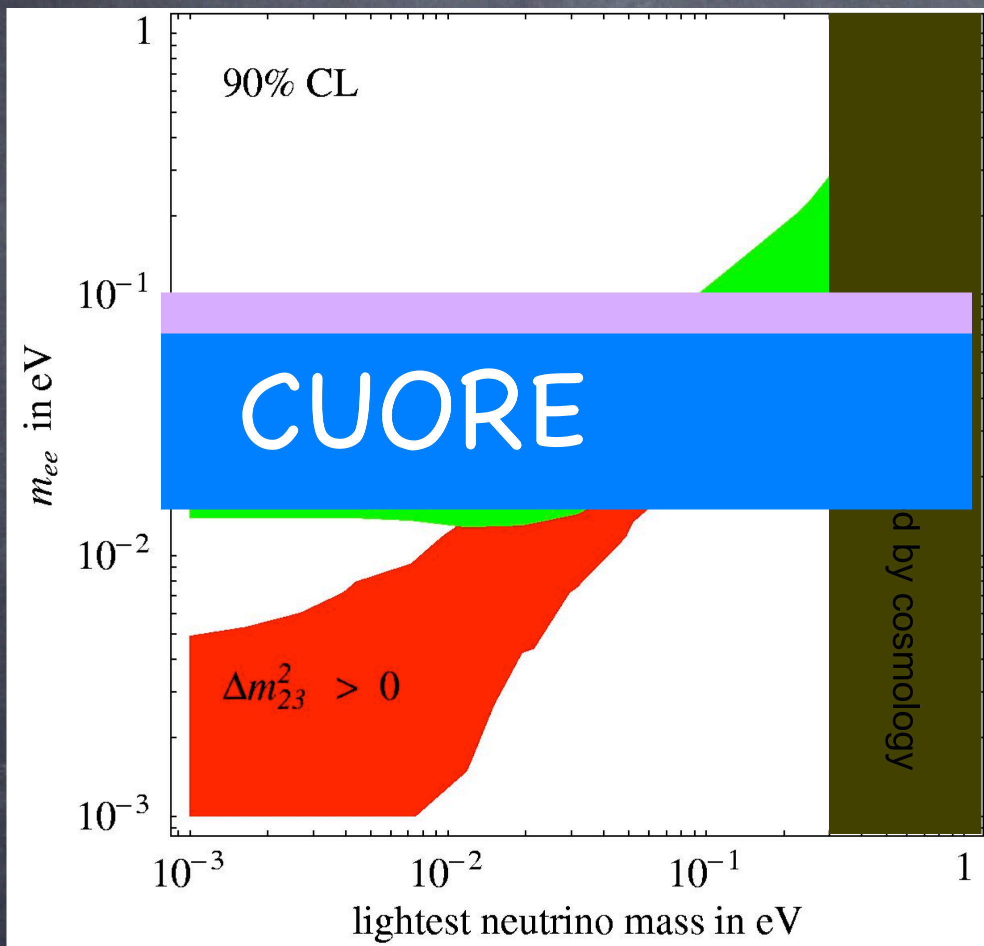
CUORE cryostat





Pulse Tube Cooler

CUORE physics goal (5 years run)



The first generation was mainly devoted to the proof of the technology.

CUORE is a second generation experiment with the possibility of exploring most of the inverted hierarchy

Backgrounds	Sensitivity	Effective Majorana Mass
0.01 counts/keV·kg·yr	$T^{0\nu}_{1/2} = 2.1 \times 10^{26}$ yr	19 – 100 meV
0.001 counts/keV·kg·yr	$T^{0\nu}_{1/2} = 6.5 \times 10^{26}$ yr	11 – 57 meV

Scaling Cuoricino to CUORE

$$\frac{a}{A}\left(\frac{M\,T}{b\,\Delta E}\right)^{1/2}$$

$M = m \times 20$

$T = t \times 6$

$b = B / 20$

$\Delta E = \Delta E / 1.5$

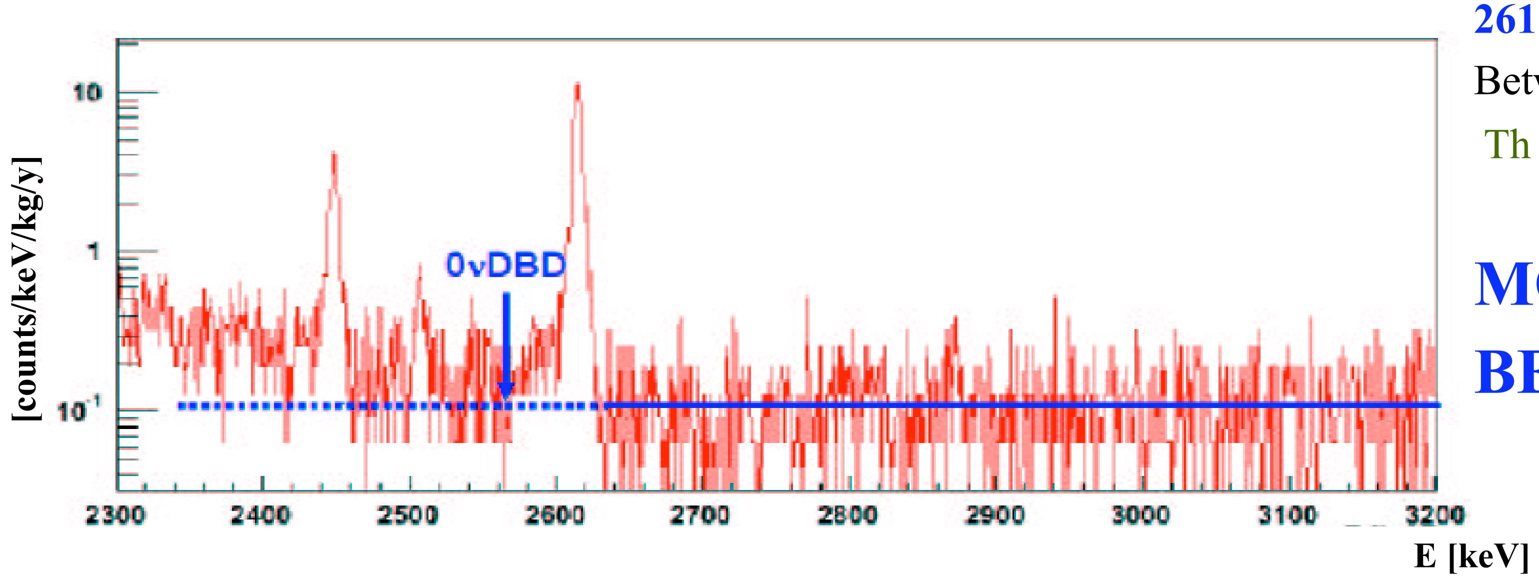
$S_{CUORE} = \sqrt{3600}\; S_{Cuoricino} \sim 60\; S_{Cuoricino}$

$\tau_{1/2\,(CUORE)} \sim 1.7 \times 10^{26}$

$\langle m_\nu \rangle_{CUORE} \sim \langle m_\nu \rangle_{Cuoricino} / 9 \sim 19 \div 100$ meV

One step is non trivial. Getting to 0.01 c/Kg/y/KeV (CUORE is 1 Ton. It means 10 c/y/KeV)

Background reduction



2615 keV Tl line

Between the inner Roman lead shield and the external lead shield.

Th (Tl) contribution to DBD background: **~ 40%**

MORE ROMAN LEAD:

BETTER CRYOSTAT DESIGN

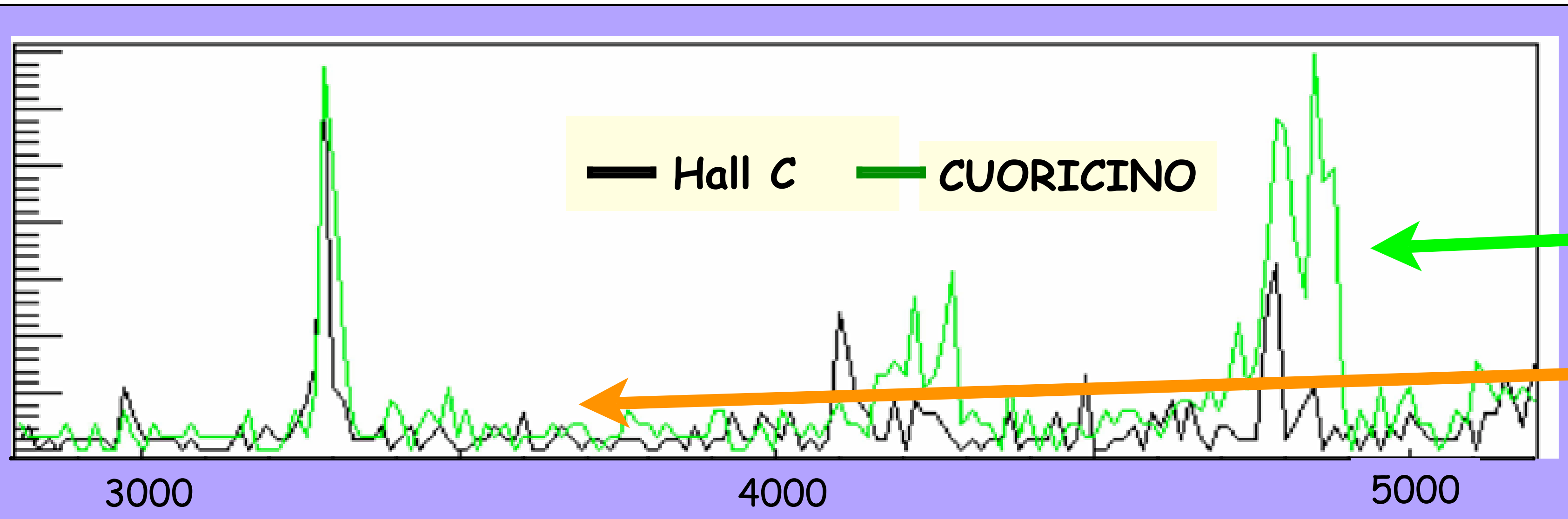
Flat background in the energy region above the ^{208}Tl 2615 line

Contribution to the counting rate in the 0νDBD region: ~ 60%

Origin: degraded alpha particles

(20 +/- 10) % crystal surface contamination

(80 +/- 10) % "Cu" surface contamination

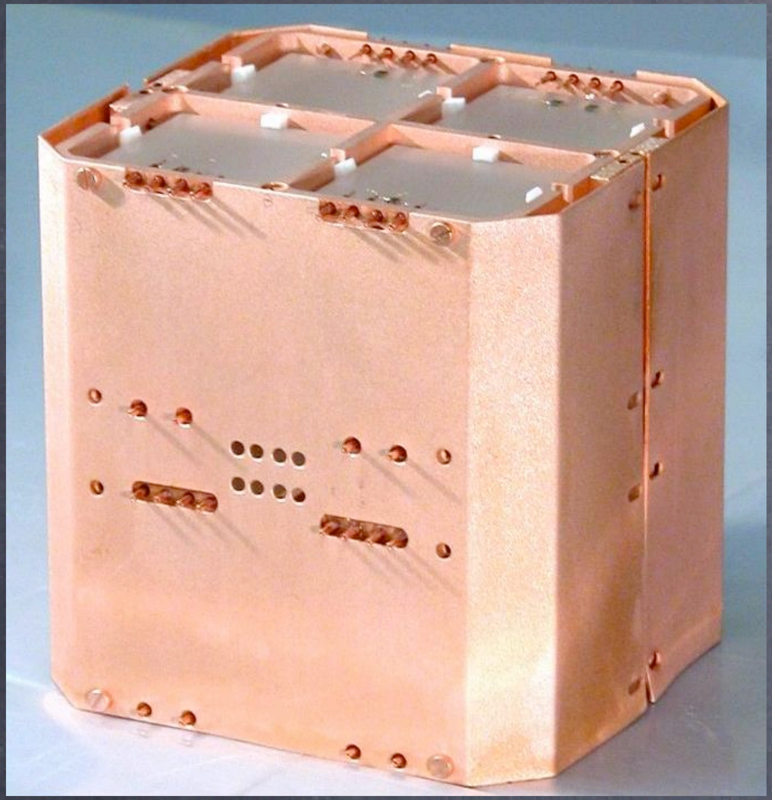


Reduction of a factor ~ 4 on crystal surface contaminations.

Reduction of a factor ~ 2 on Copper surface contaminations.

The fight is not over yet

Array of 8 Detectors: cleaned with ultra-radiopure materials and procedures



Crystal surface contaminations in CUORE	$< 3 \times 10^{-3}$ c/kev/kg/y
Crystal internal contaminations in CUORE	$< 8 \times 10^{-5}$ c/kev/kg/y
Copper surface contaminations in CUORE	$< 5 \times 10^{-2}$ c/kev/kg/y

New structure with reduced Cu amount (MC simul.) $< 2.5 \times 10^{-2}$ c/kev/kg/y

CUORE goal:

0.01 c/kev/kg/y

Still a factor no less than 2.5 to go

Beyond CUORE

- Change Te with 'all ^{130}Te': like a factor 3 in Mass
- Change TeO_2 with 'some scintillating crystal' (enriched -Cadmium or Molybdenum- based): like going to zero background ($S \propto T$)
- adopt a smarter, yet more complex, background rejection system : like going to 0.001 c/Kg/y/KeV, equivalent to a factor 10 in Mass

Conclusions

- Neutrino Physics is one of the leading field in HEP today
- Dirac or Majorana nature of neutrino mass is a fundamental question that needs to be answered at (almost) all cost(s)
- Neutrino-less DBD might possibly be the sole chance to give a measure of neutrino mass
- CUORE is the most promising of the next generation project