

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 !)

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

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

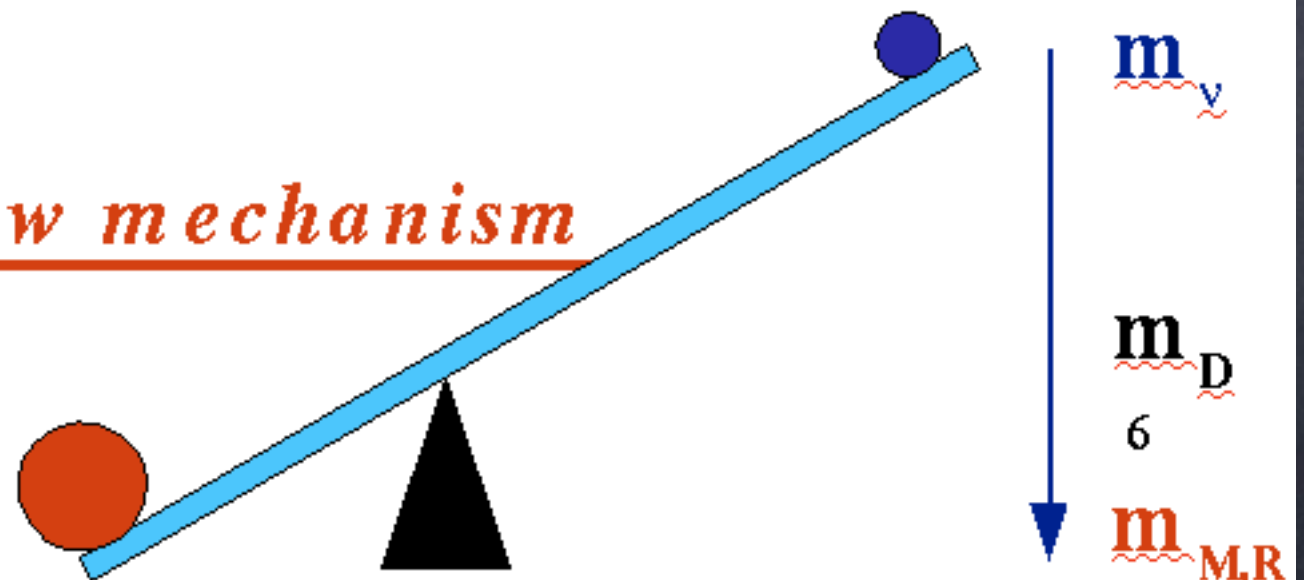
$M_D \sim M_{EW} \sim 100 \text{ GeV}$

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

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

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

See-saw mechanism



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: $M_2 \approx M_{GUT} \approx 10^{14-15}$ GeV.

M_{GUT}

the Majorana conjecture

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

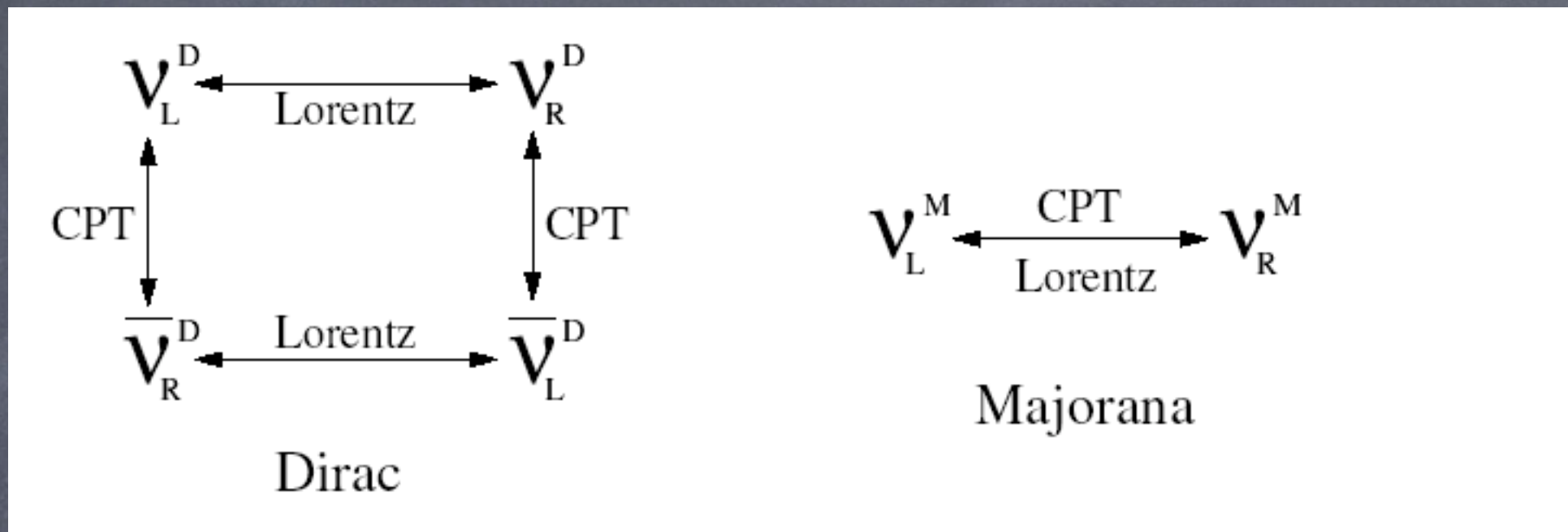
Practical consequence :

Lepton Number Violation

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

Indeed nobody paid 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 ($0\nu\beta\beta$)

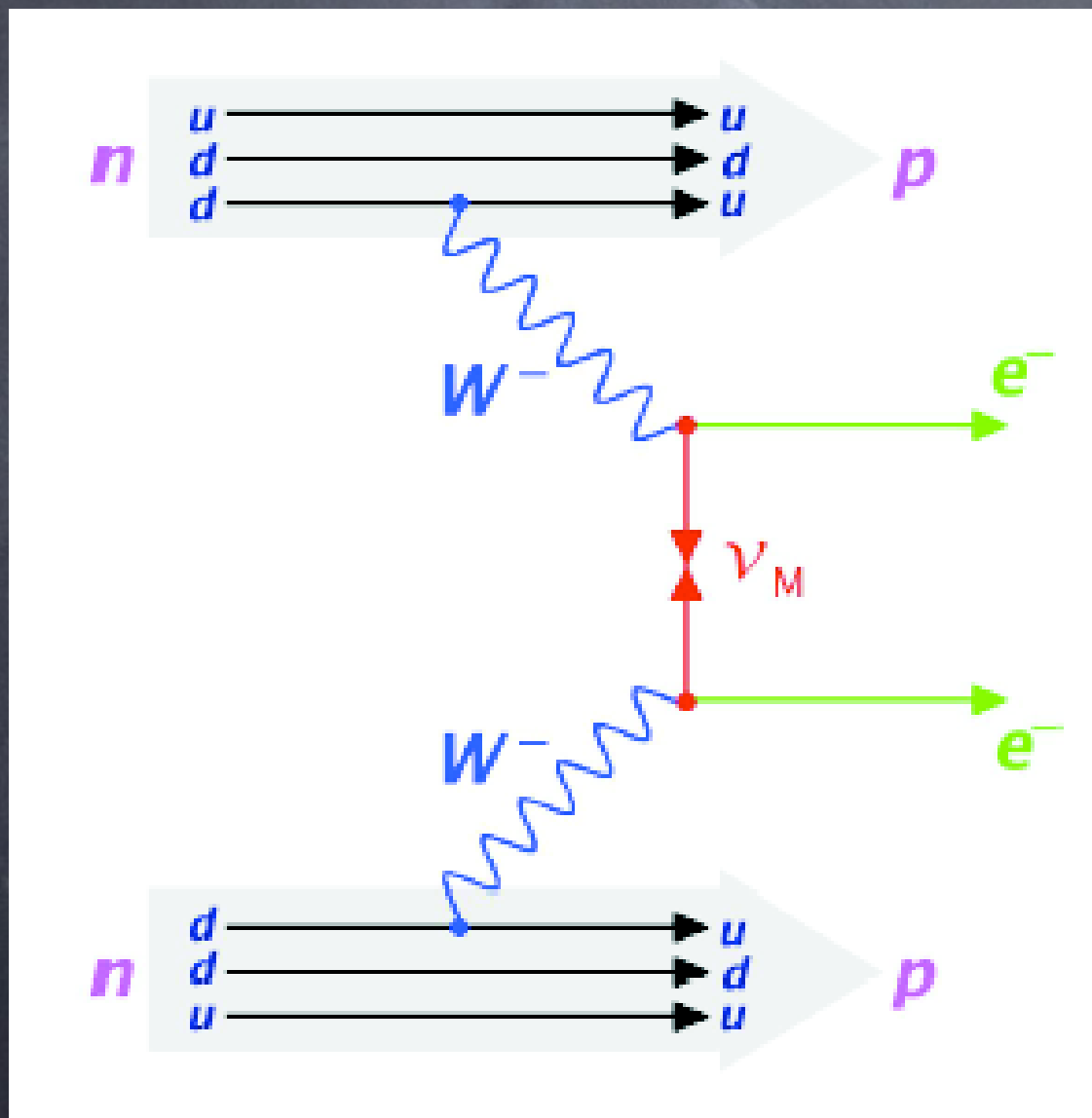
Only if:

Majorana Neutrinos

Massive Neutrinos

If observed:

Proof of the Majorana nature of Neutrino



Does it also measure the mass ?

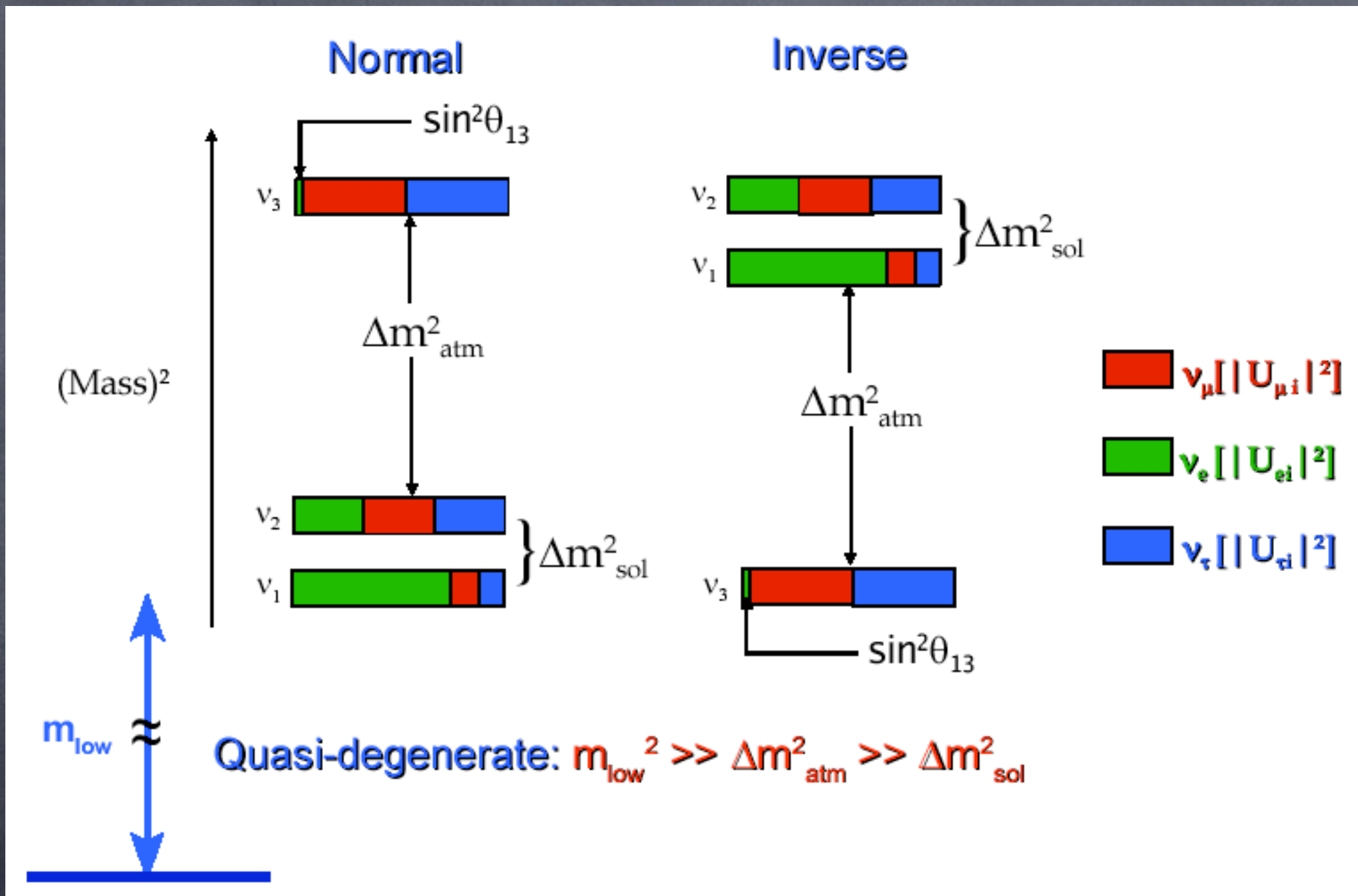
$$m_{\beta\beta} = \sum m_{\nu_k} U_{ek}^2 = \cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13}$$

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

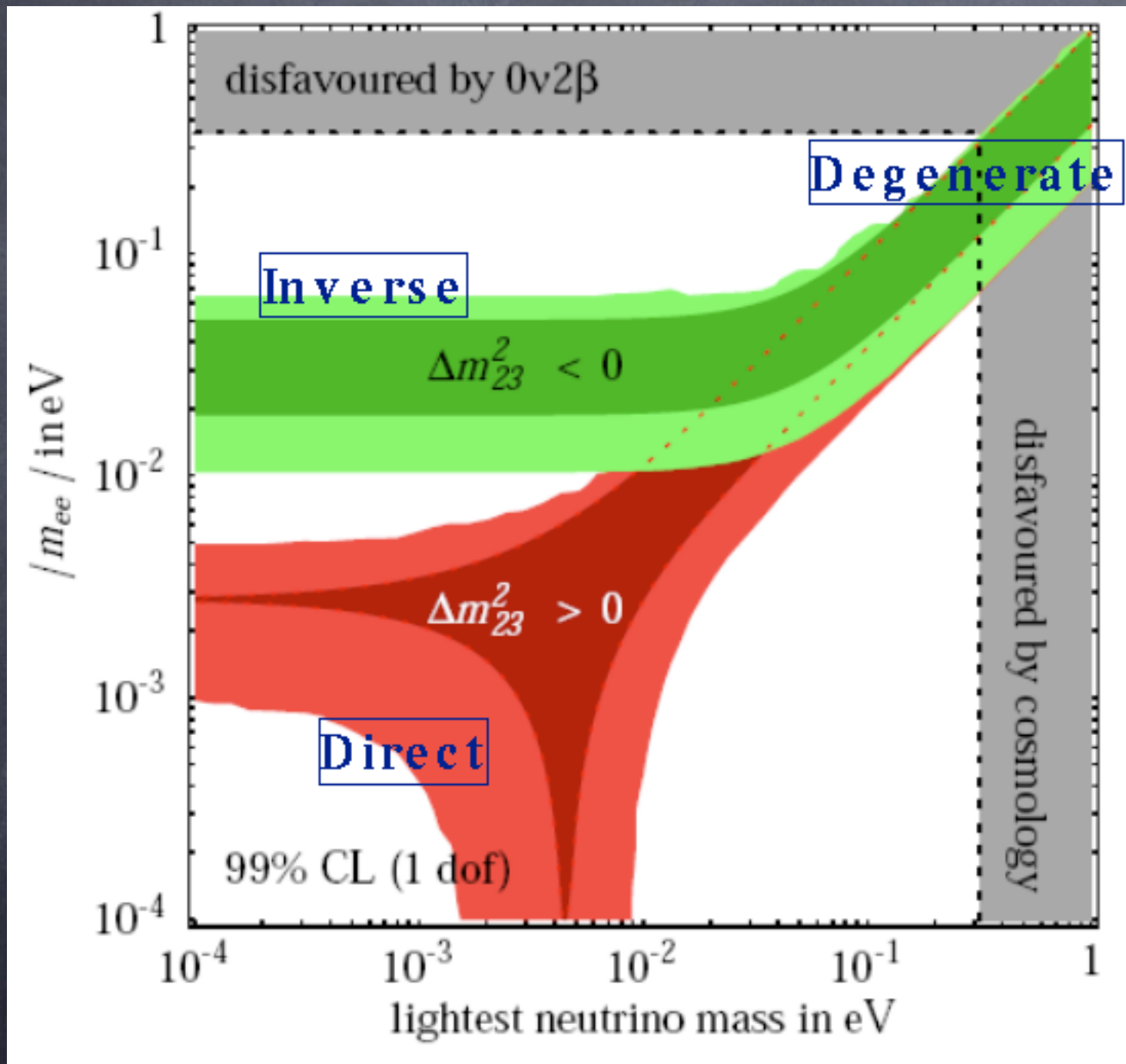
Exercise: parameterize as a function of the known parameters:

$$m_{\beta\beta} = f(U_{ek}, m_{\text{lightest}}, \delta m_{\text{sol}}, \Delta m_{\text{atm}})$$

Three possibilities:

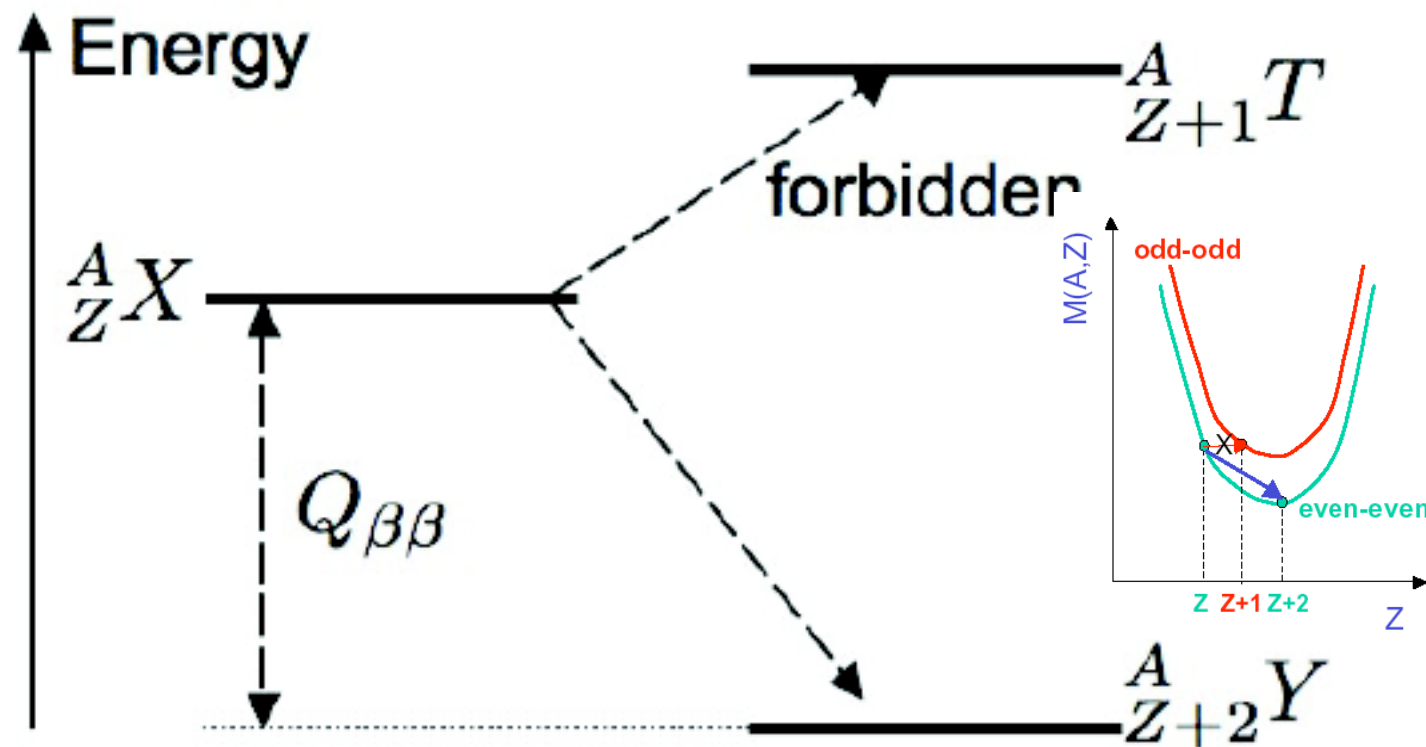


that translates into a nice plot



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

Double Beta Decay



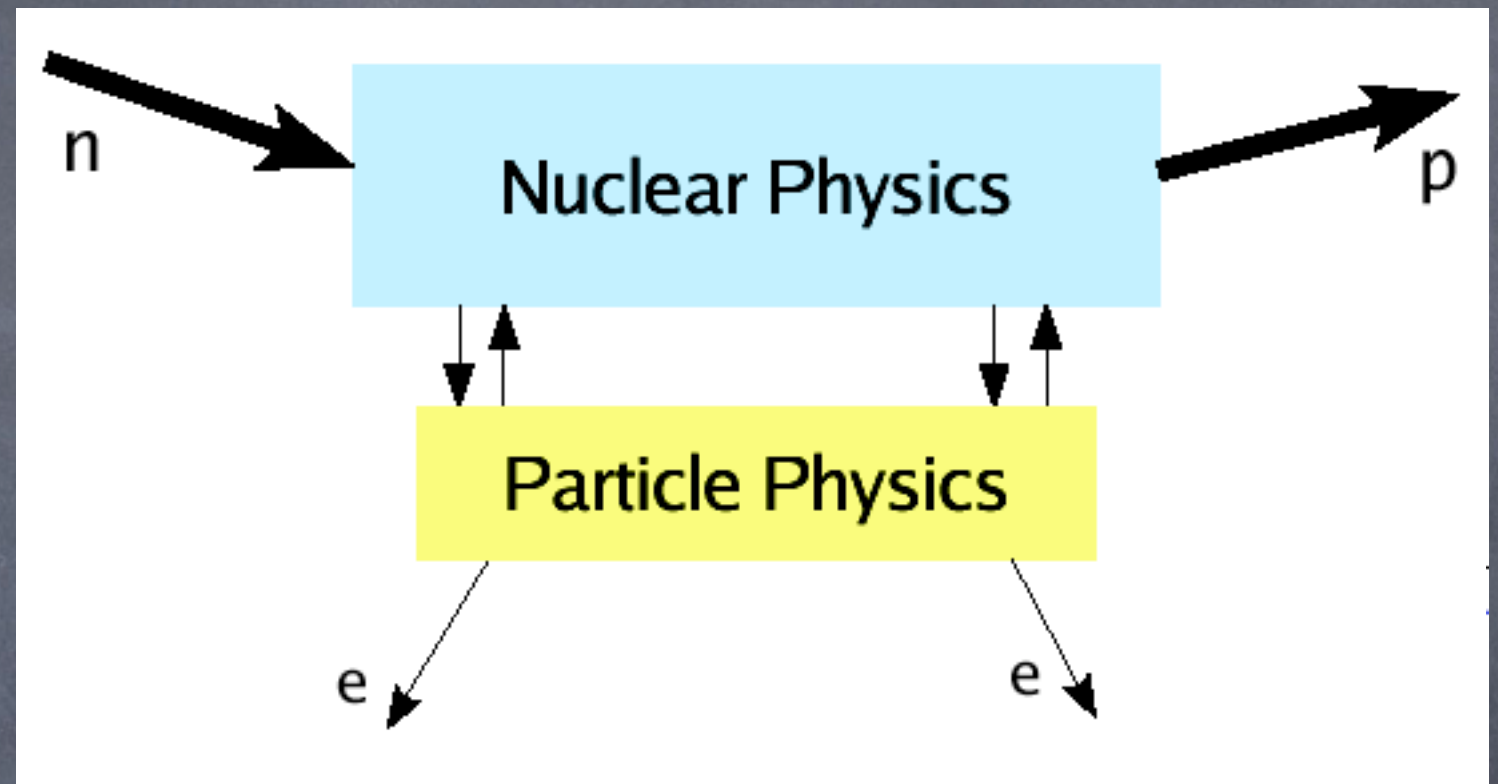
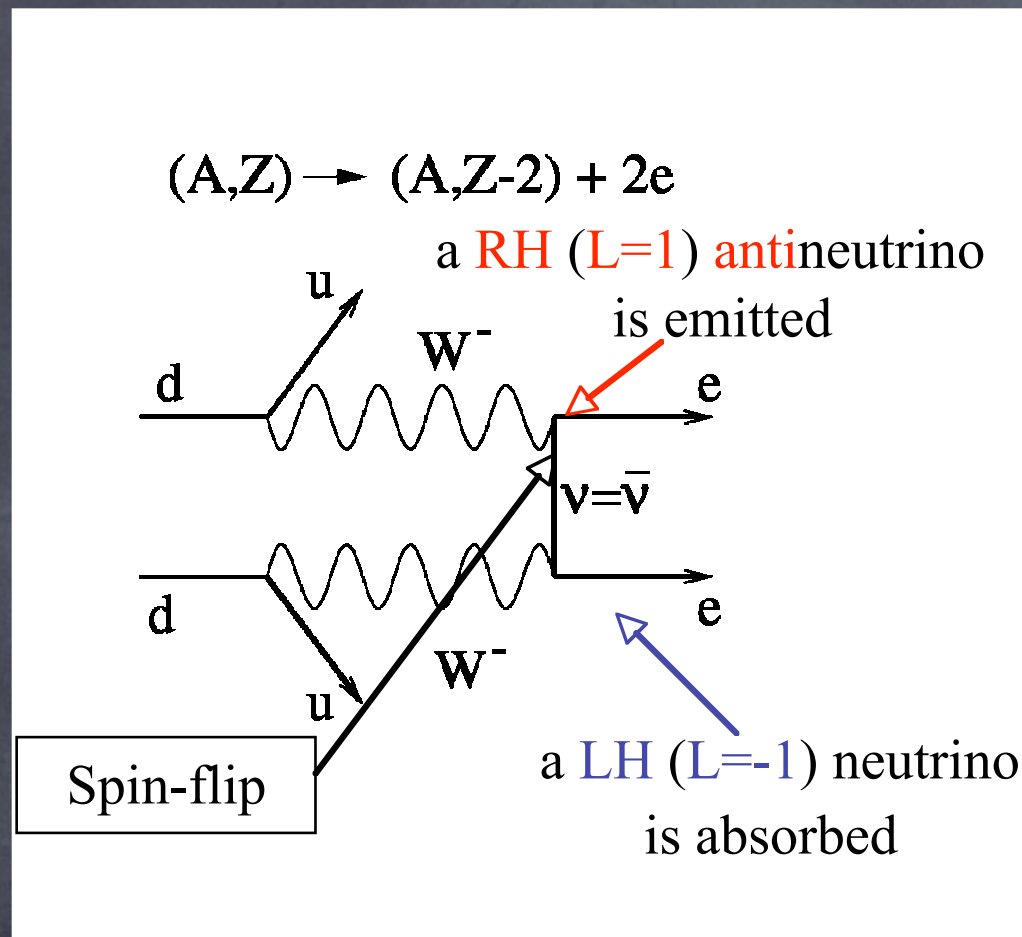
Predicted by Maria Goeppert-Mayer in 1935

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

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

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

The elements of the game



$0\nu\text{-DBD}$ rate
 Phase space $\propto Q^5$
 Nuclear matrix element
 Effective neutrino mass

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

The name of the game: sensitivity

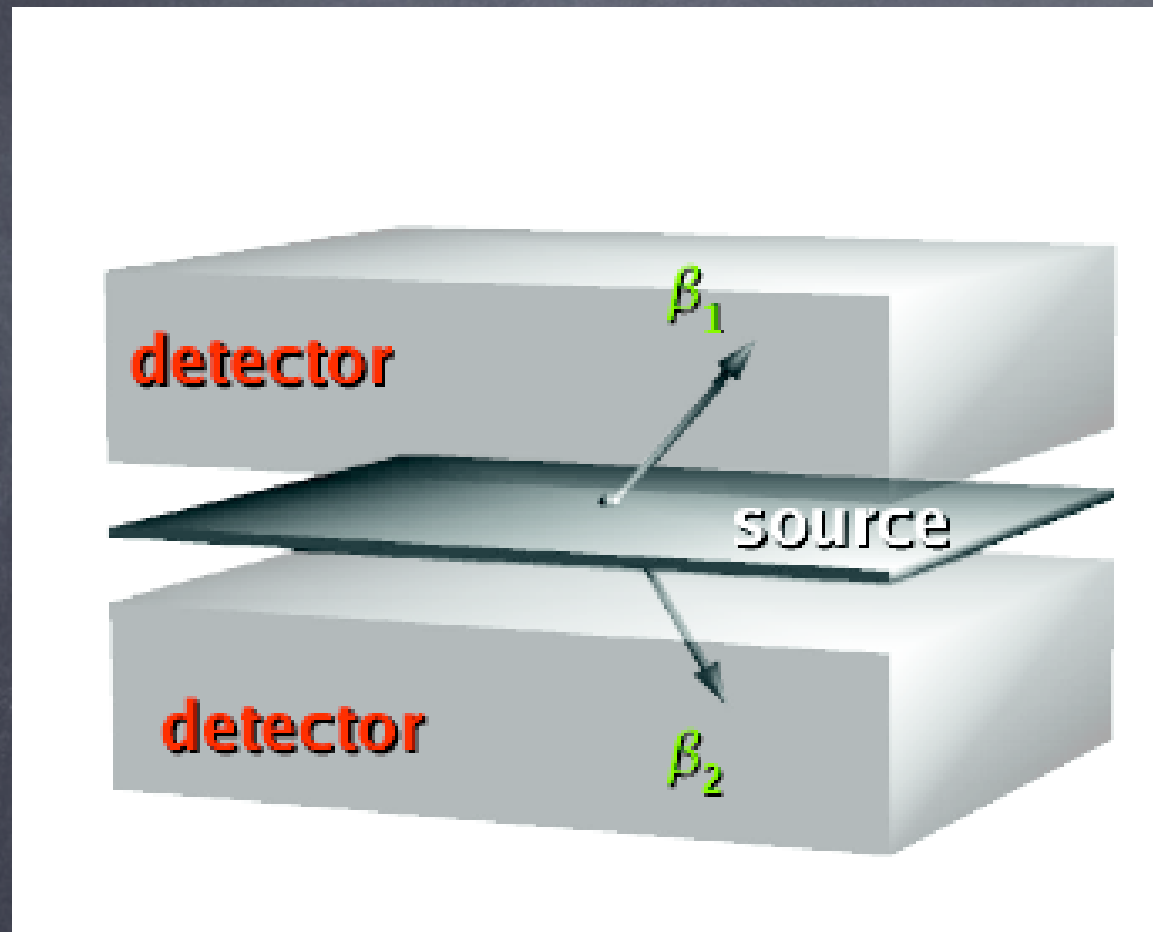
$$S_{n\sigma}^{0\nu} \propto \frac{a}{A} \left[\frac{M T}{b \Delta E} \right]^{1/2} \times \epsilon$$

Isotopic abundance $\rightarrow a$
 Mass(Kg) $\rightarrow M$
 Time (y) $\rightarrow T$
 efficiency $\rightarrow \epsilon$
 Atomic Mass $\rightarrow A$
 background (counts/keV/Kg/y) $\rightarrow b$
 Energy Resolution (KeV) $\rightarrow \Delta E$

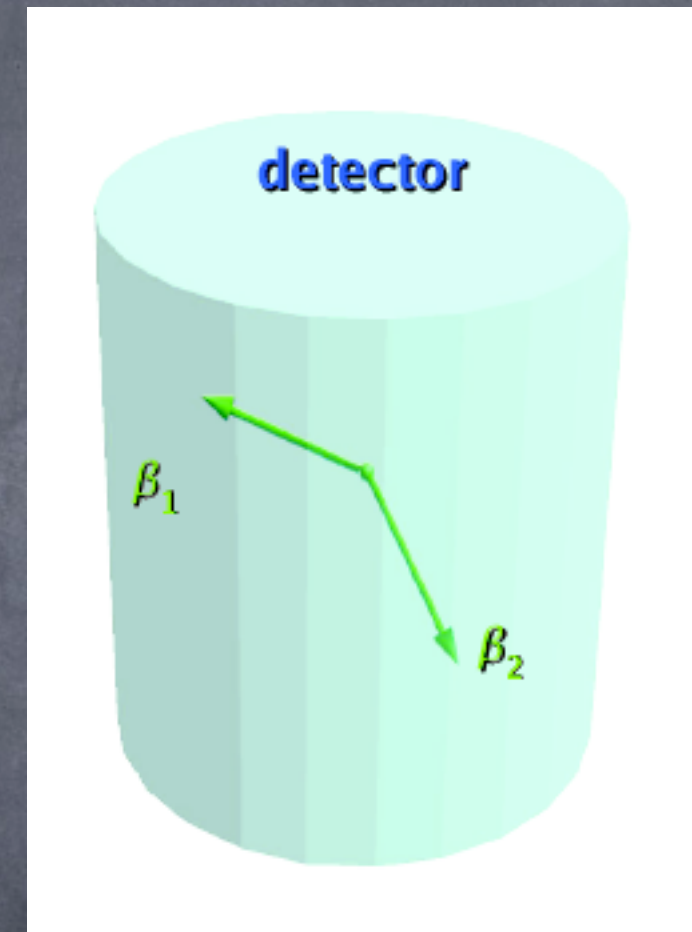
Sensitivity: half life corresponding to the minimal number of detectable events above background, for a given C.L

Two techniques (and a few variations)

Source $\neq$ Detector



Source $\subseteq$ Detector



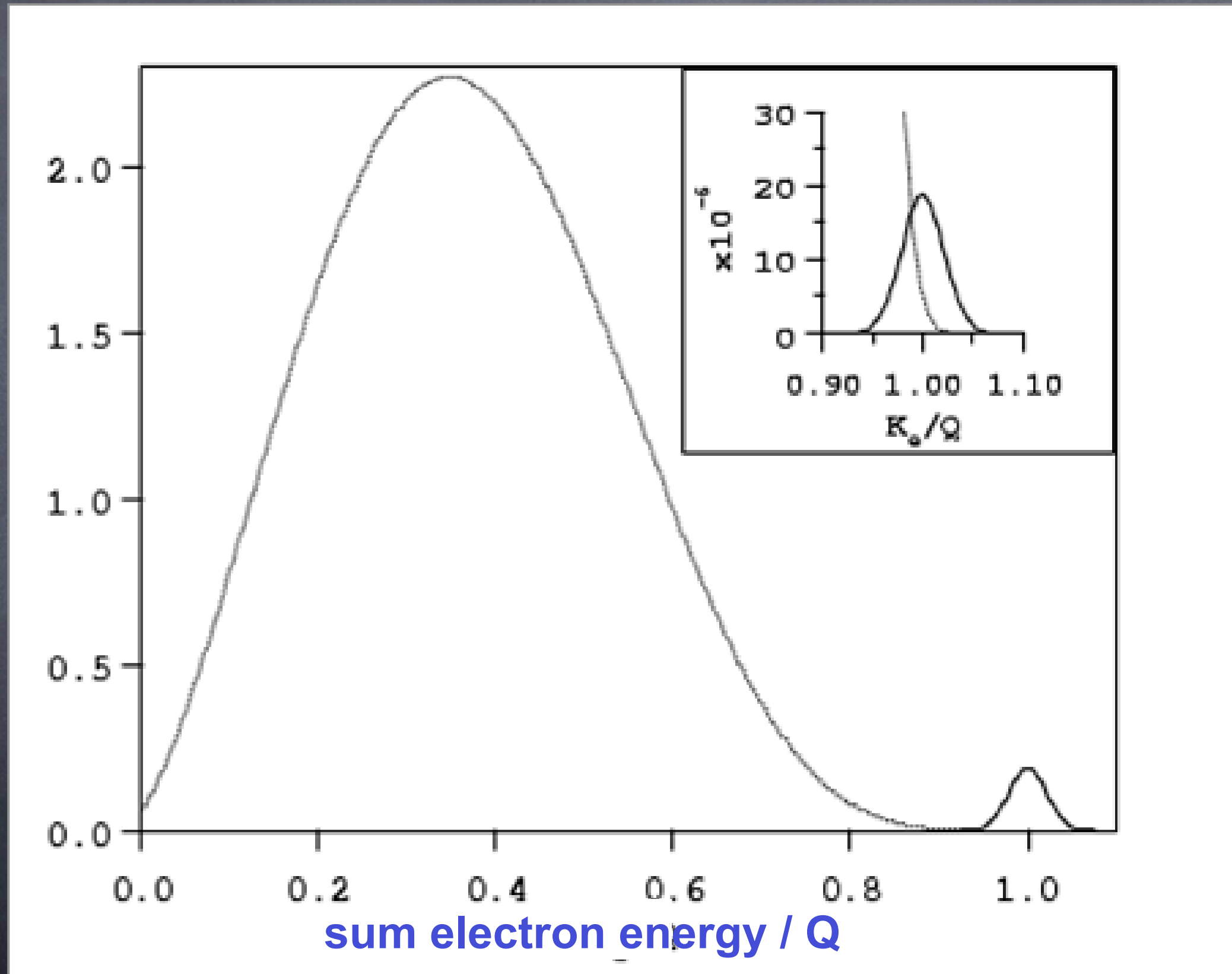
+++ Topology, Background

--- $M, \Delta E, \epsilon$

+++ $M, \Delta E, \epsilon$

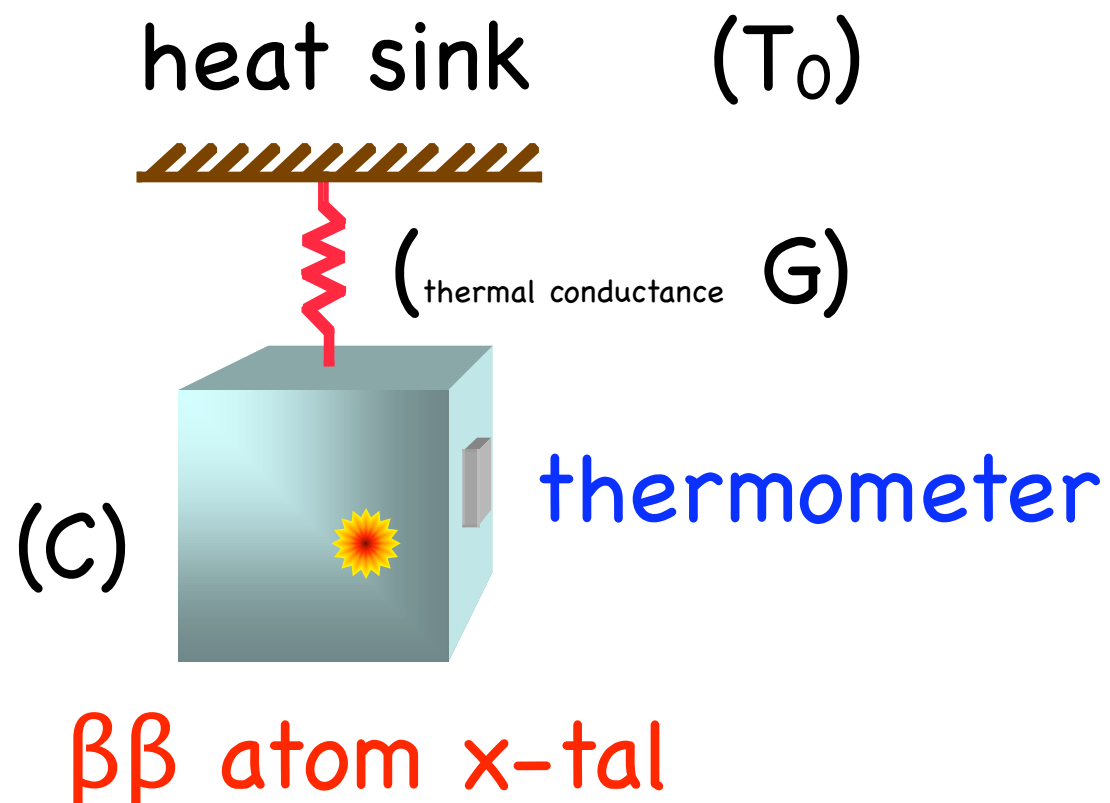
--- Topology, Background

The role of energy resolution



(very) Low Temperature Calorimeter

A True Calorimeter



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

Implication: Low $C \Rightarrow$ Low T

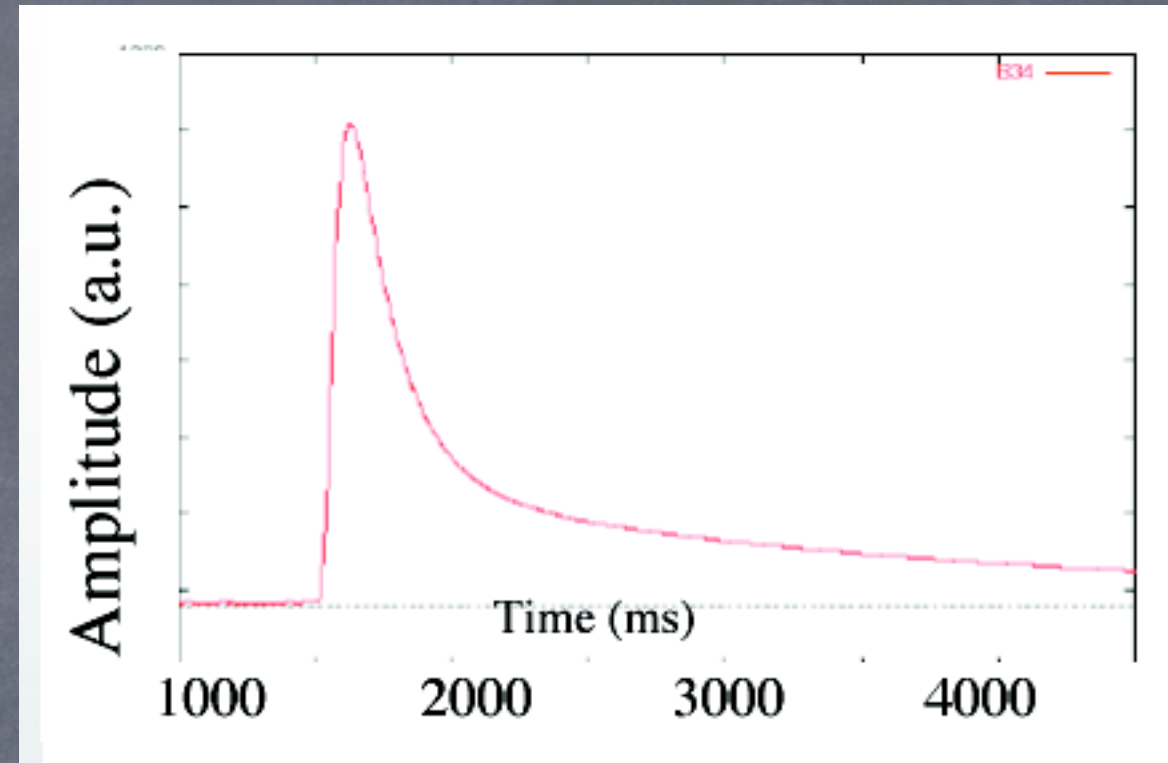
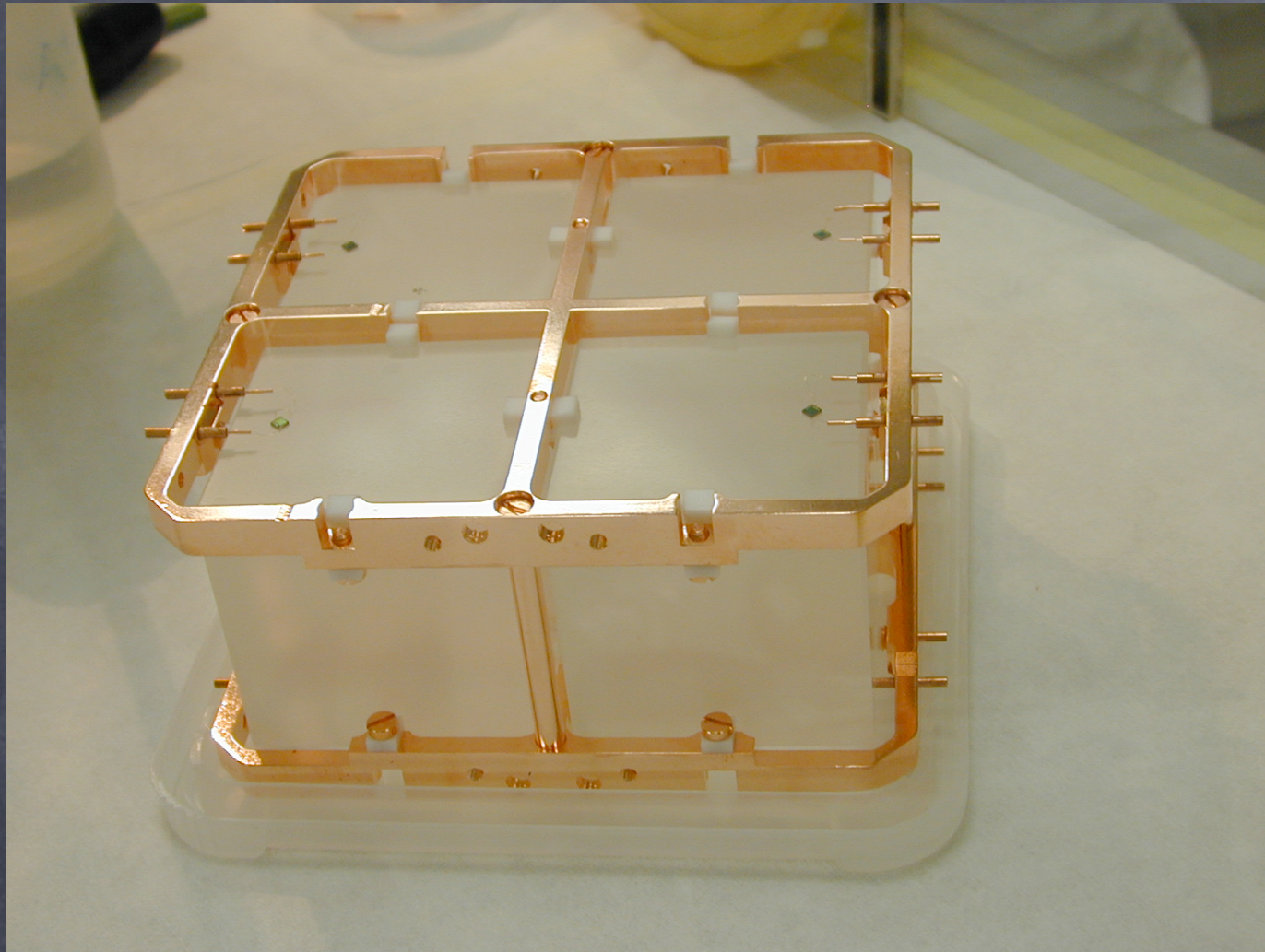
Bonus: (almost) No limit to ΔE ($k_B T^2 C$)

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

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

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

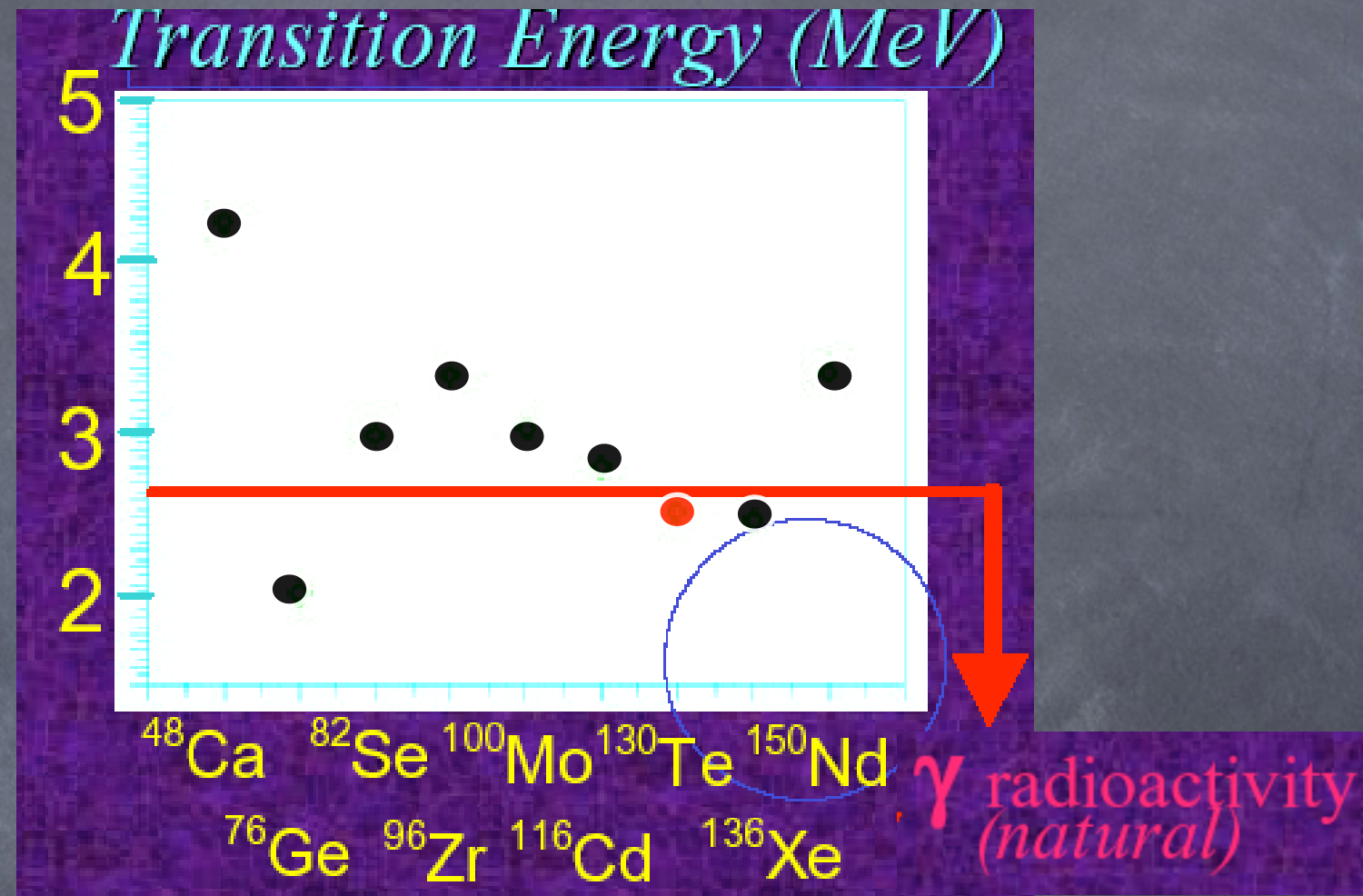
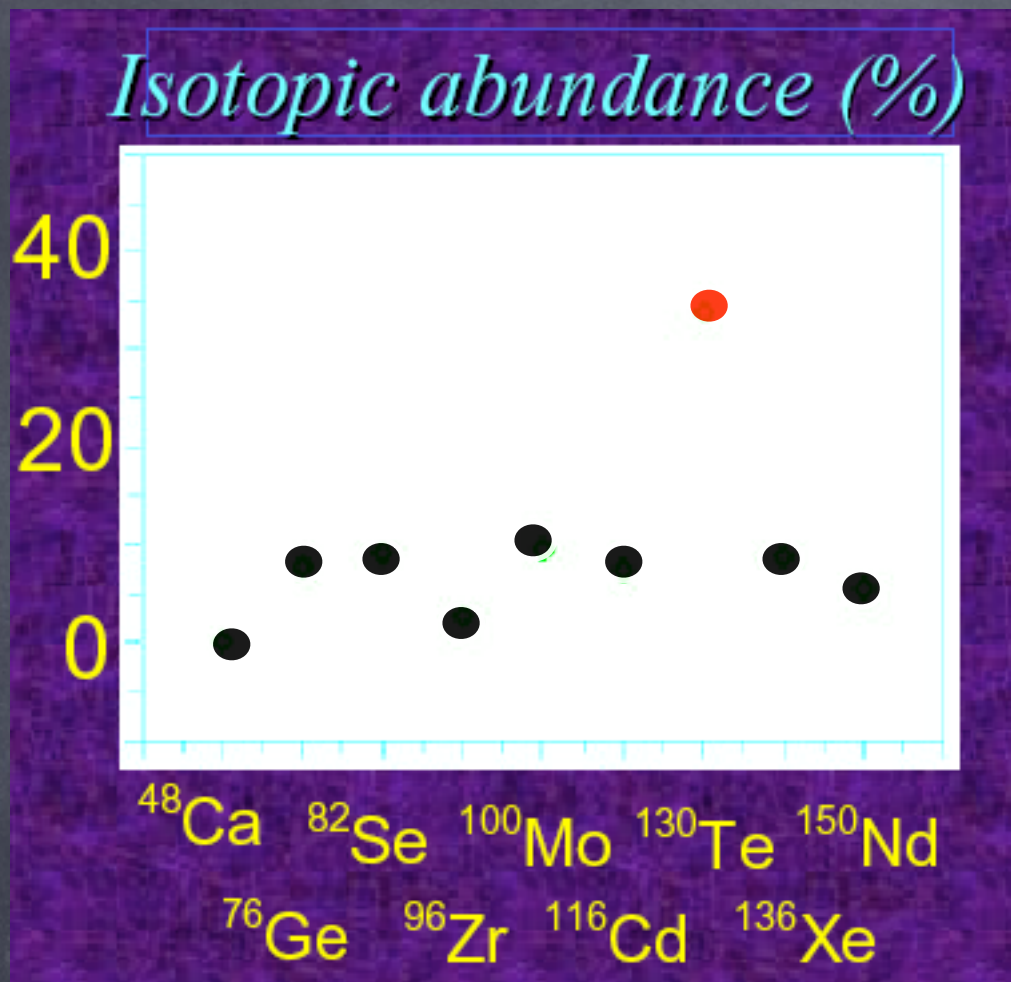
TeO_2 : a viable (show)case



$T_0 \sim 10 \text{ mK}$ **Numerology:**
 $C \sim 2 \text{ nJ/K} \sim 1 \text{ MeV}/0.1 \text{ mK}$
 $G \sim 4 \text{ pW/mK}$

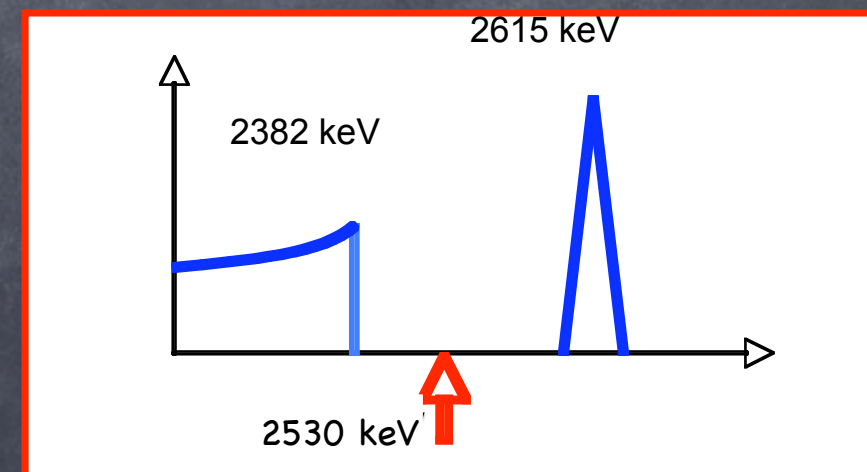
Need to be able to
detect temperature jumps
of a fraction of μK (per
mil resolution on MeV
signals)

Te: why ?



TeO₂ crystals

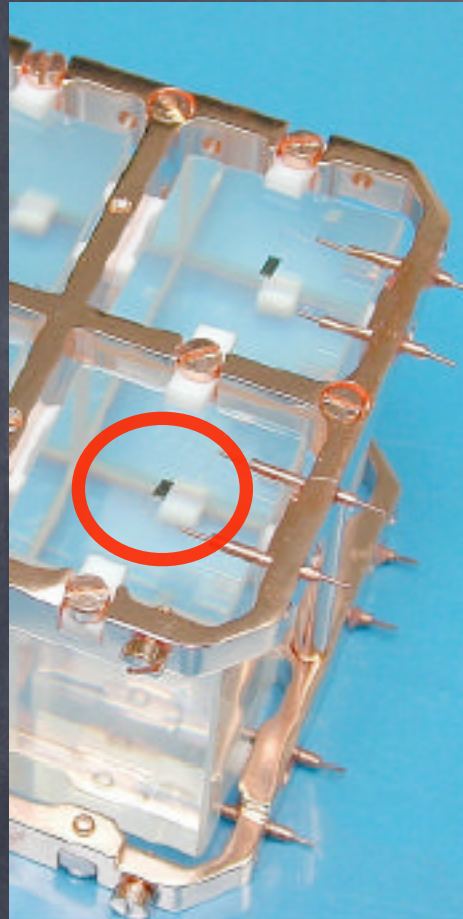
- low heat capacity
- large crystals available
- radio-pure crystals



to read the temperature you need a thermometer

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

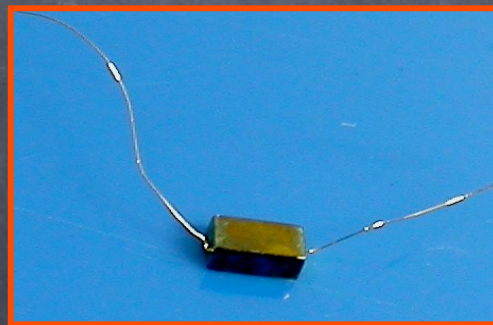
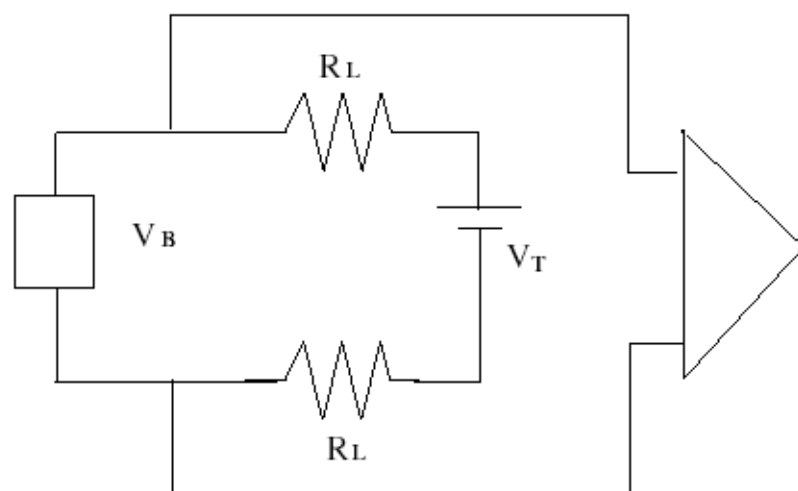
Neutron Transmutation
Doped (NTD) Germanium
Thermistor



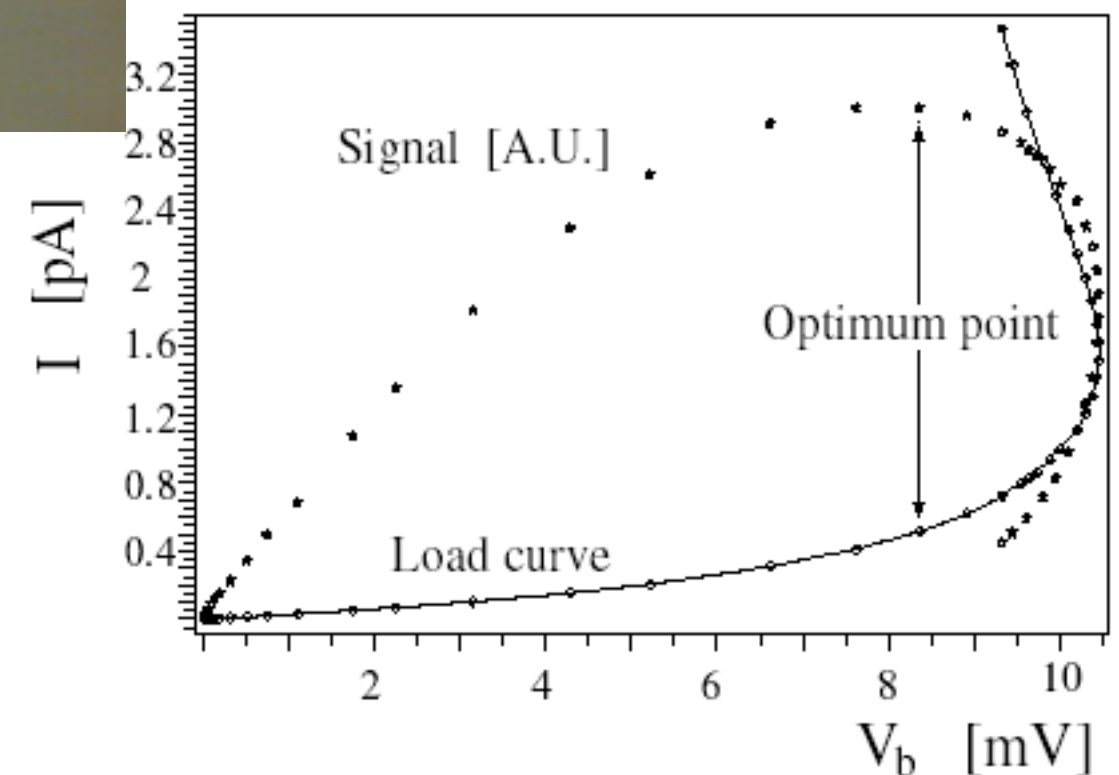
$I \sim 50 \text{ pA}$

$dR/dE \sim 20 \text{ k}\Omega/\text{KeV}$

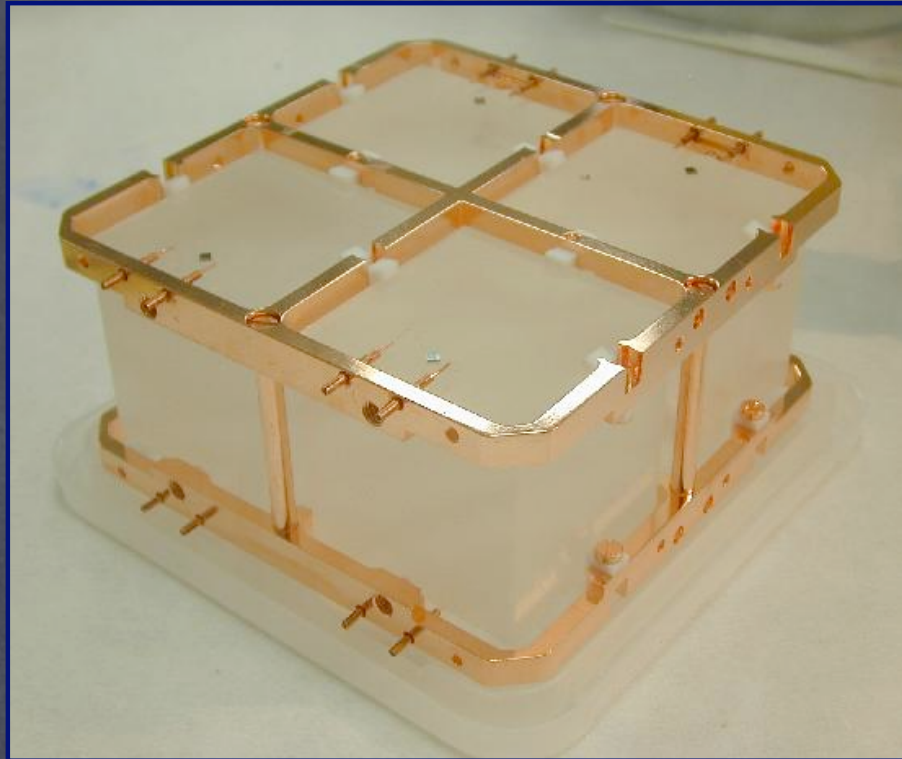
0.2mV/MeV



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



Cuoricino: the demonstrator



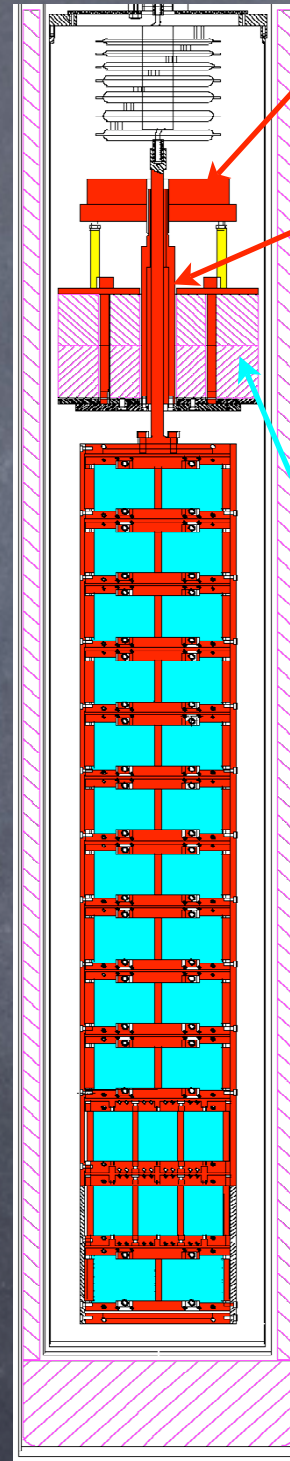
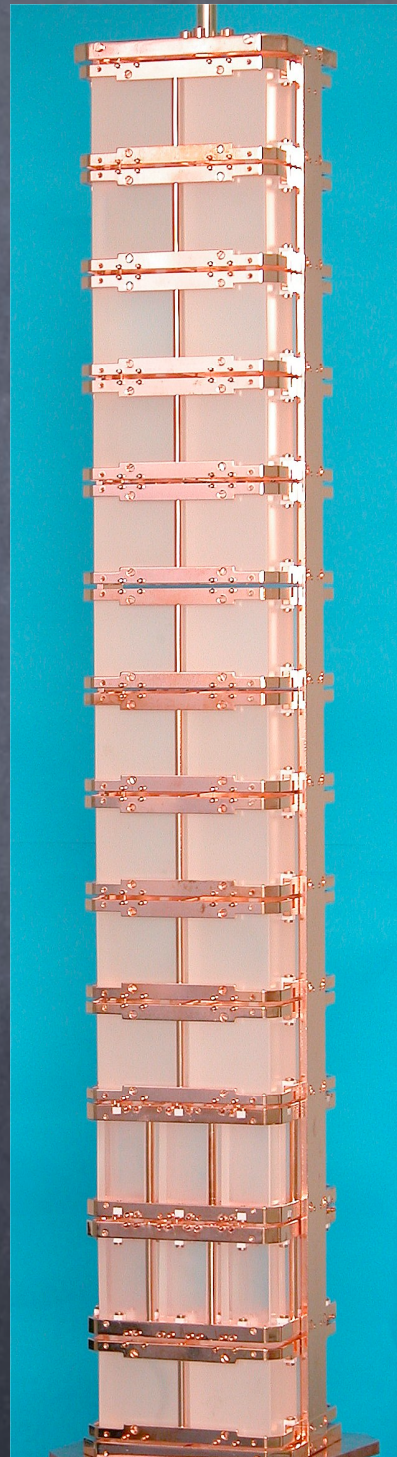
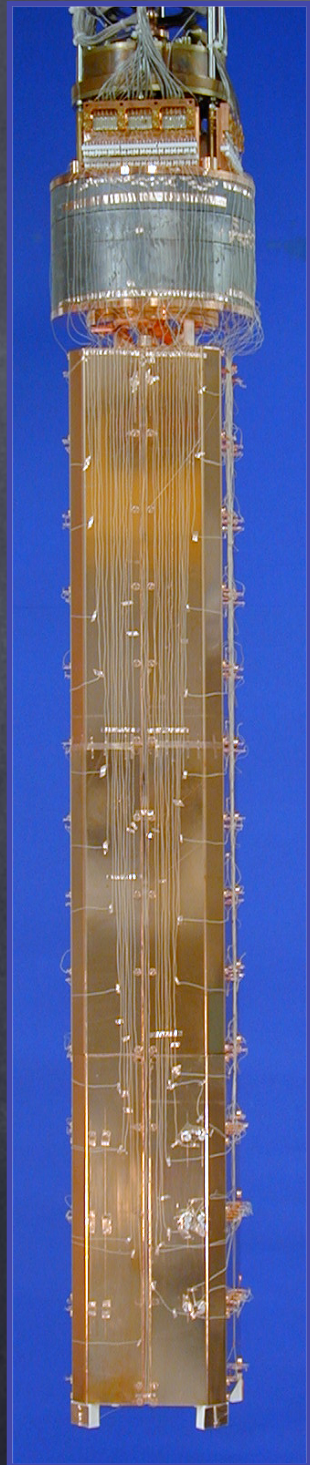
The bulk of Cuoricino calorimeter is made by 44 TeO_2 crystals of $5 \times 5 \times 5 \text{ cm}^3$ (790 gr of weight). There are 18 additional crystals of $3 \times 3 \times 6 \text{ cm}^3$ (330 gr)



Total mass = 40.7 Kg
 $^{130}\text{Te} \sim 11.2 \text{ Kg}$

Cuoricino

Cuoricino is currently the largest
operating
bolometer in the world

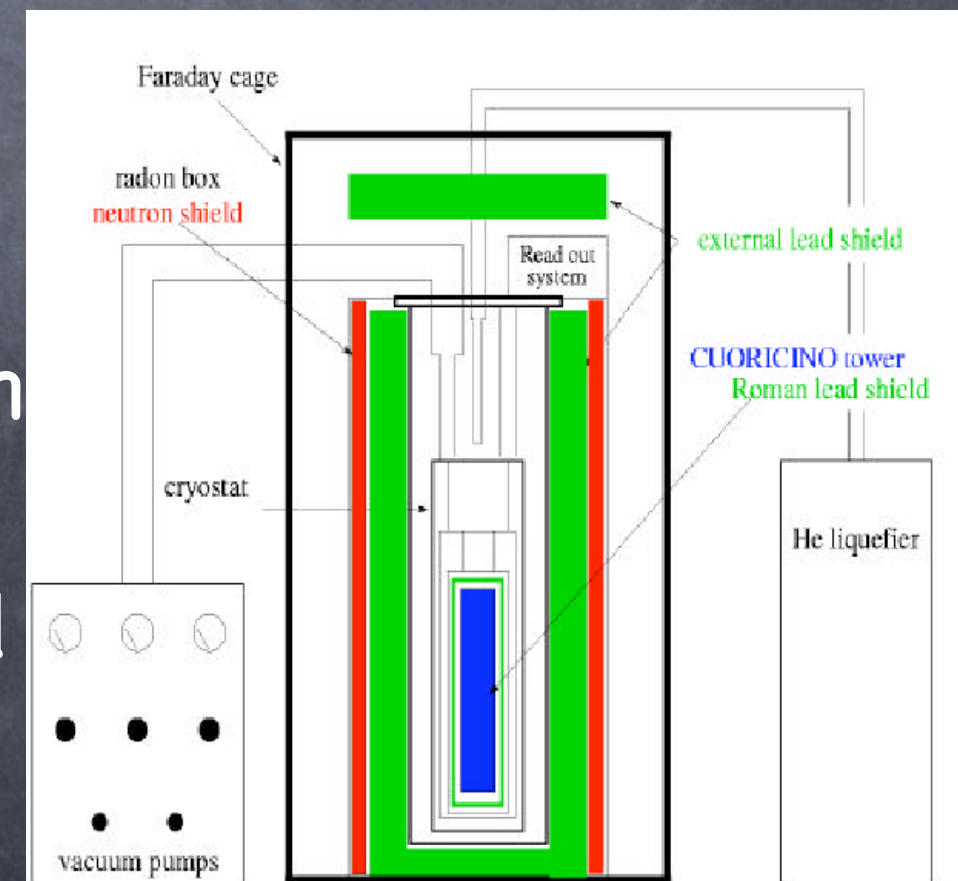


Mixing chamber

Cold finger

10 mK

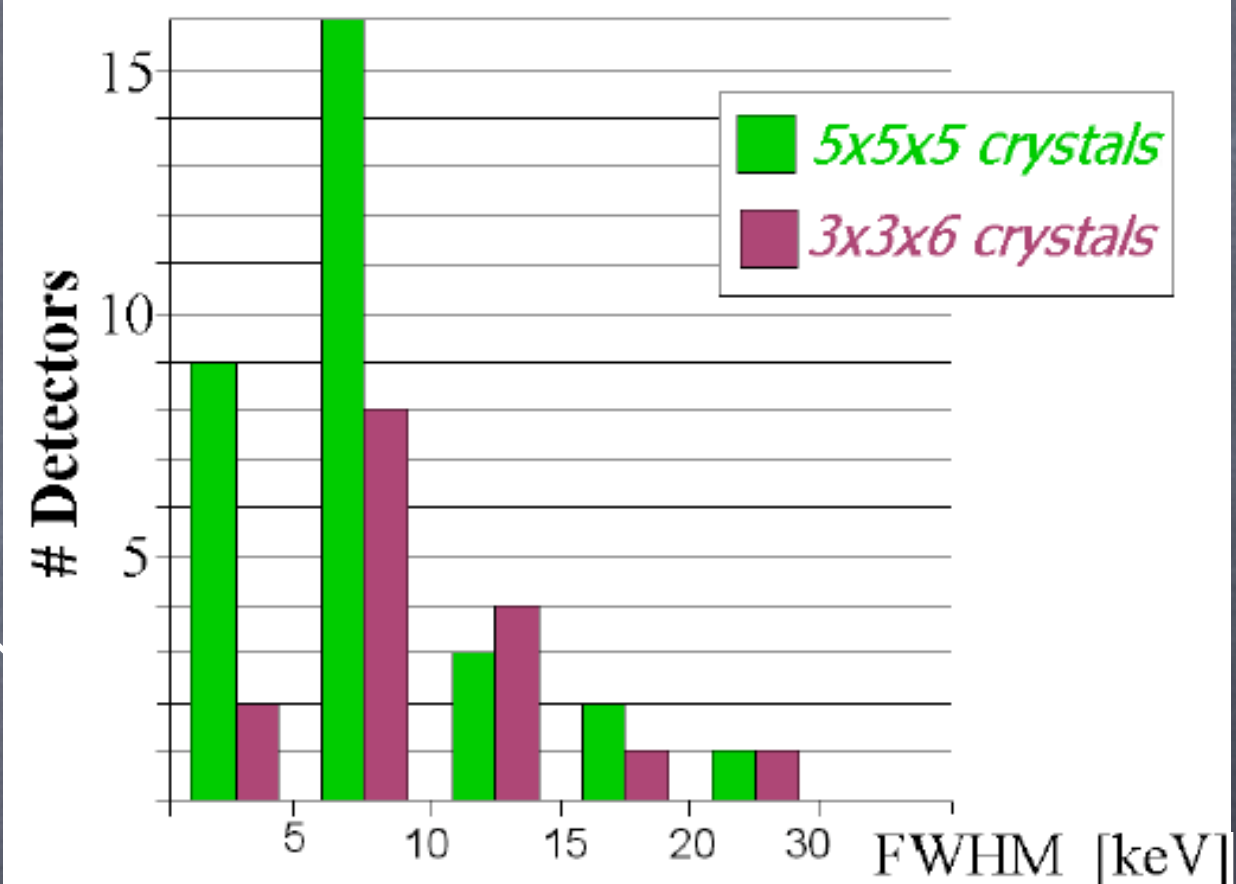
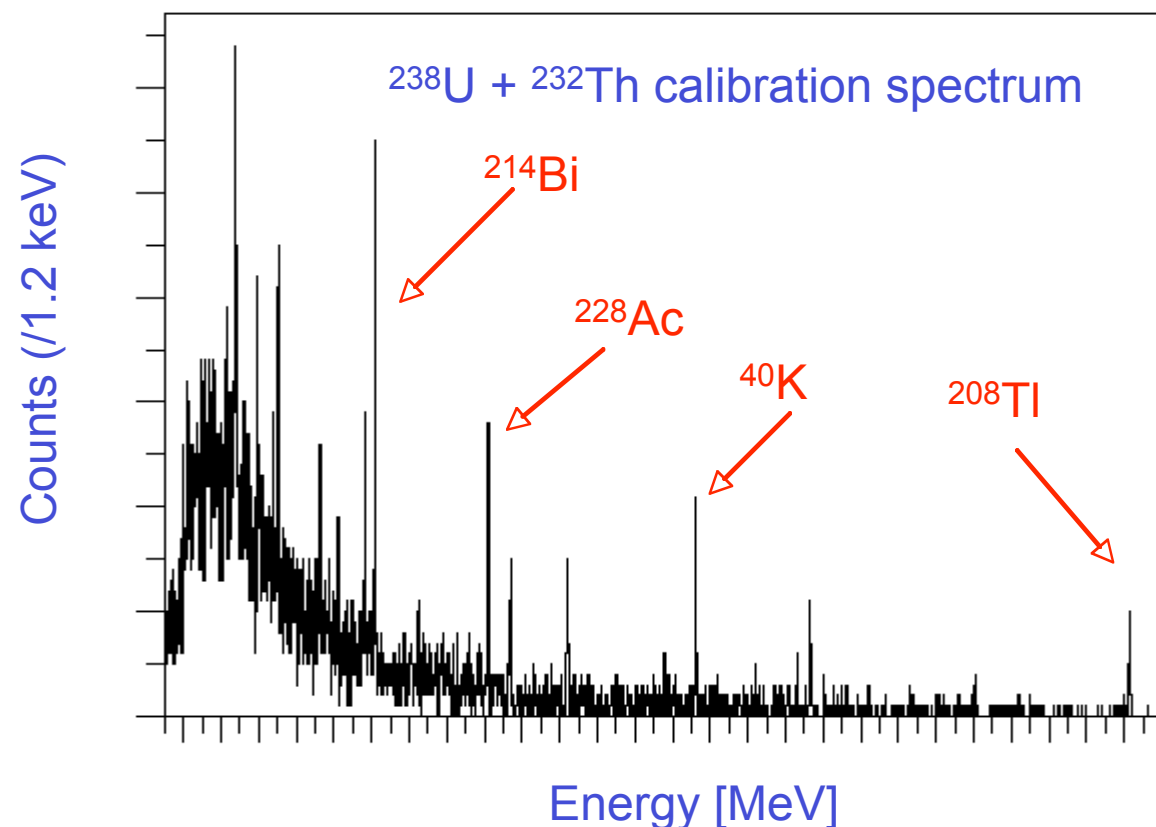
Roman
Lead
Shield



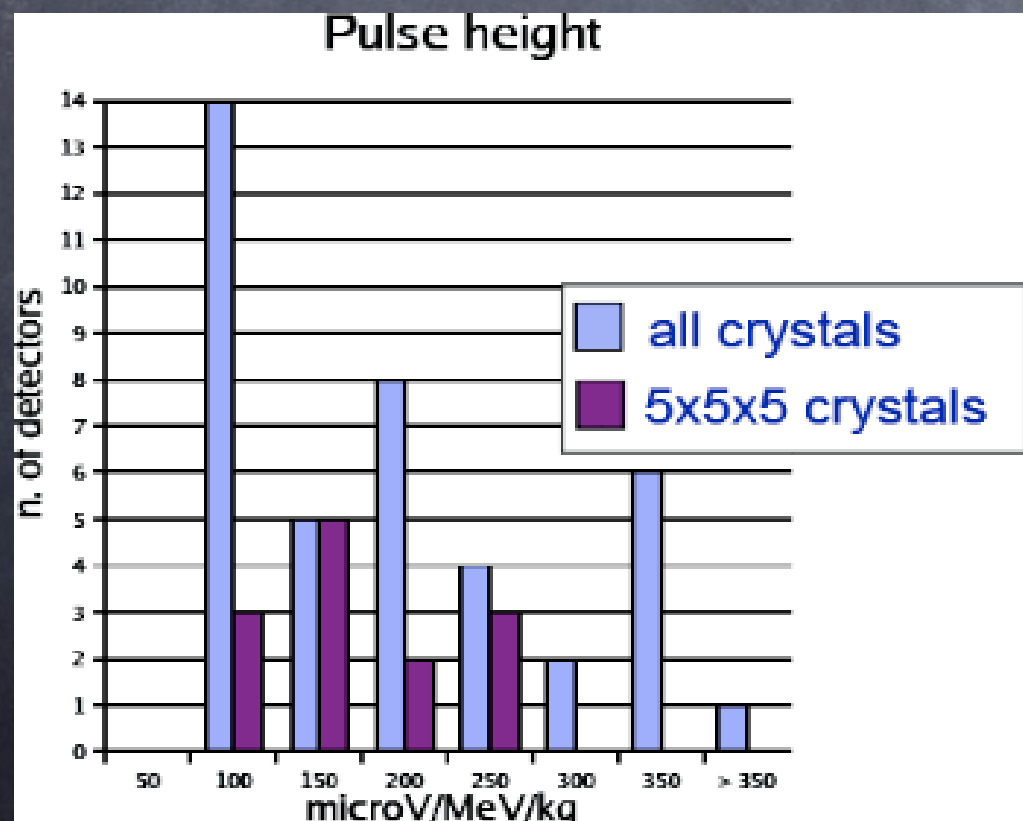
Energy resolution

Sum all over the crystals

(calibration with ^{232}Th source)

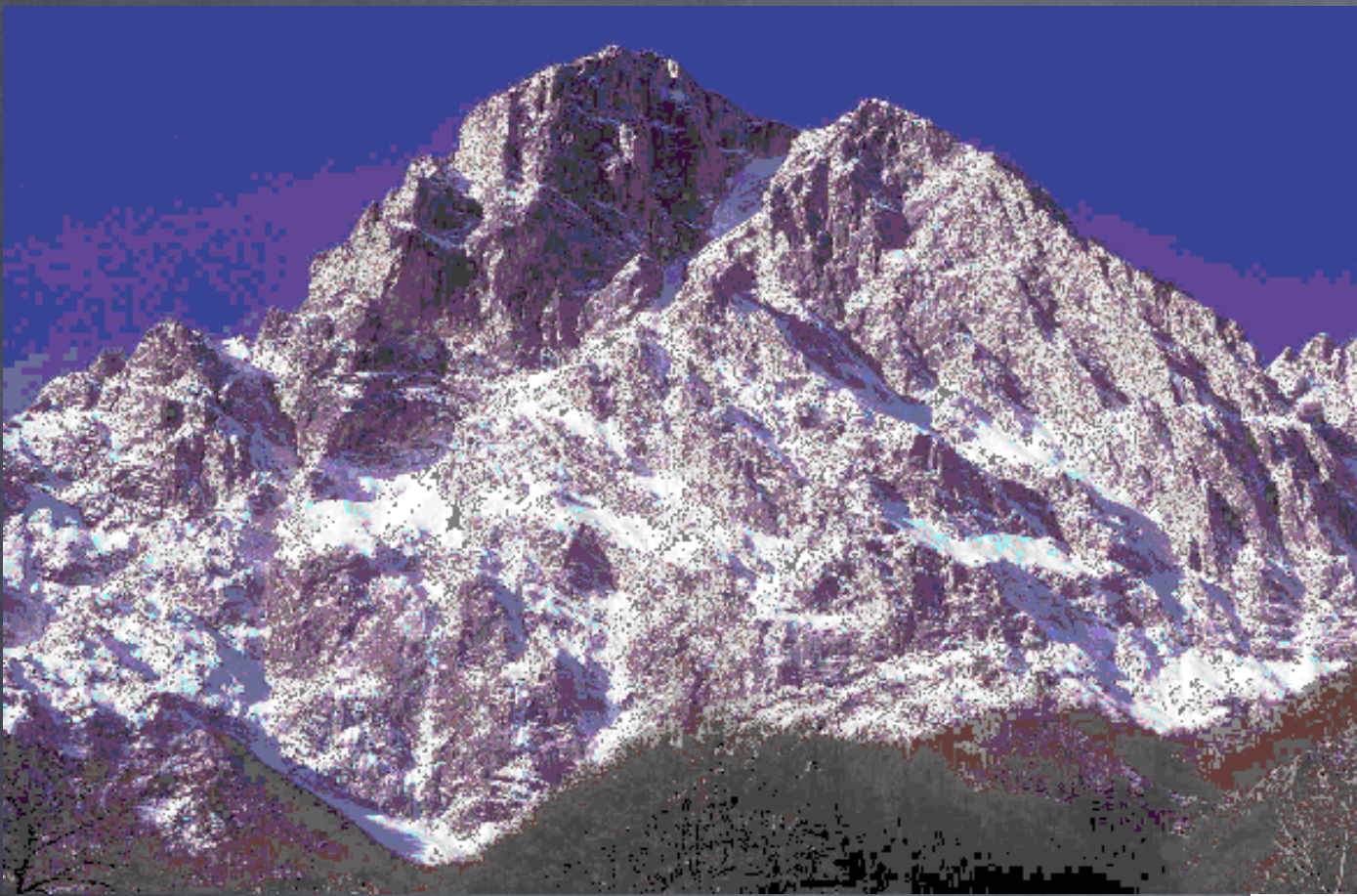


Average resolution 5x5x5 : 7.5 keV
 Average resolution 3x3x6 : 9.6 keV
 Best of all : 3.9 keV



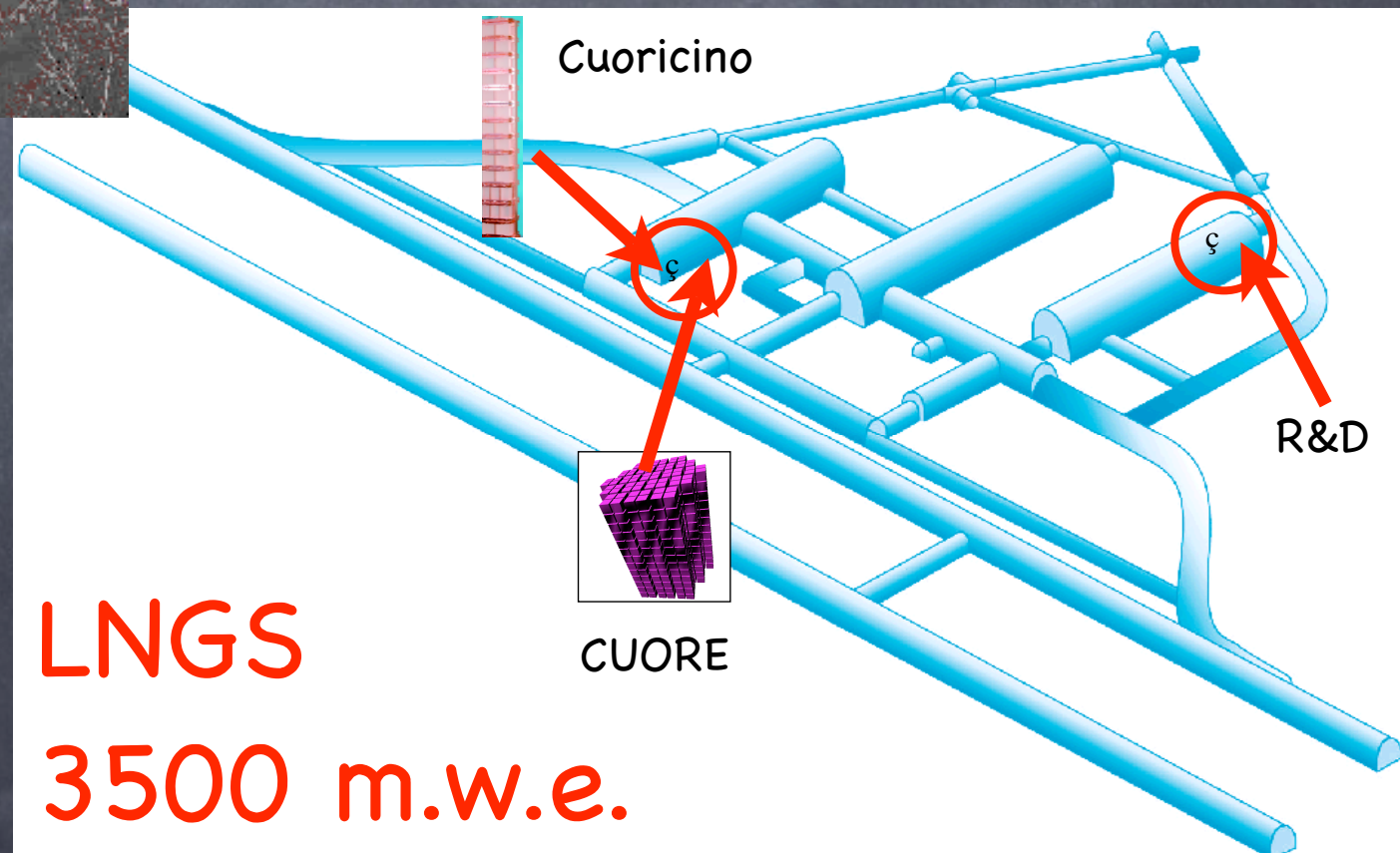
- Resolution limited by
- Thermal/Phononic ($\Delta \sim \text{eV}$)
 - Electronic noise ($\Delta \leq 1 \text{ keV}$)
 - Microphonics $\Delta \sim 3\text{--}5 \text{ keV}$
 - Detector responses $\Delta \sim \text{keV}$

Cuoricino, where ?

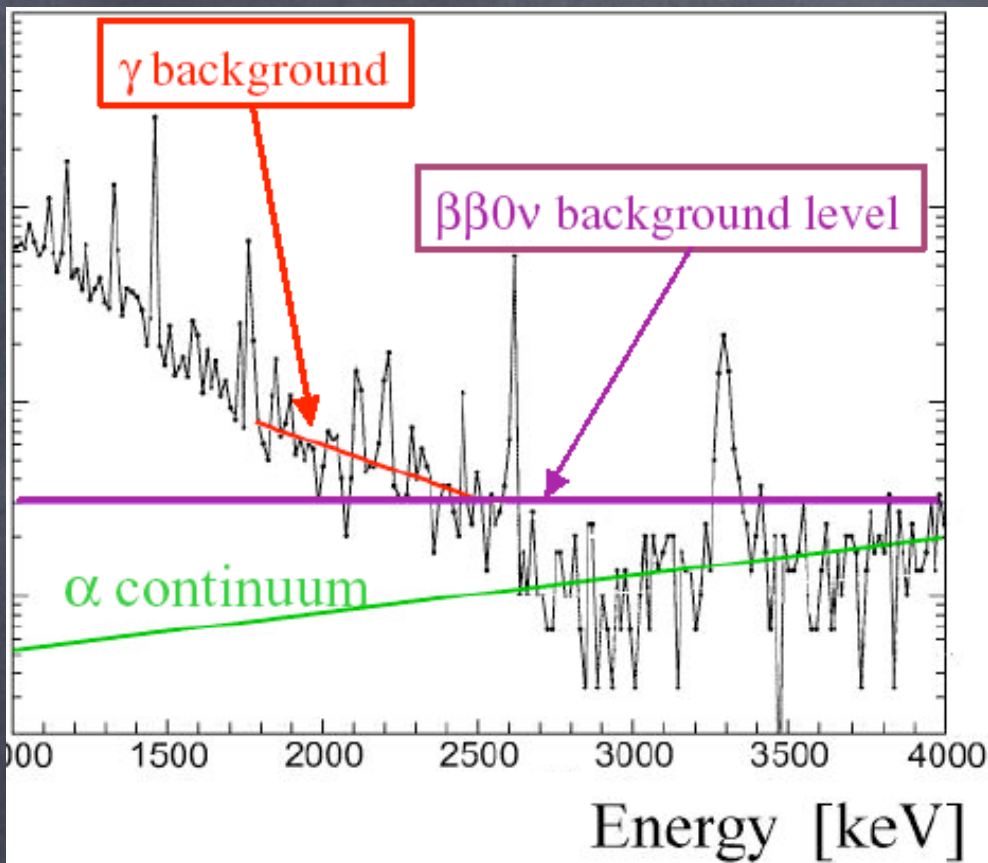


The Shield
Corno Grande 2916 m

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

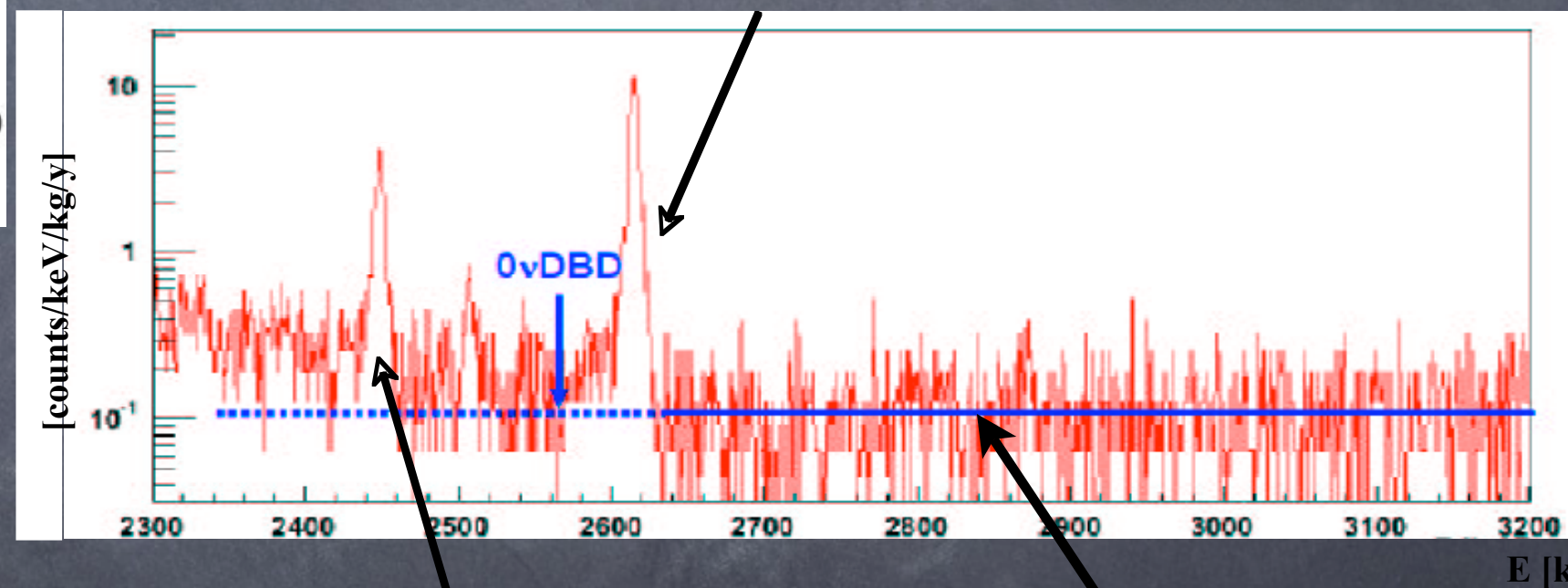


Cuoricino: Background



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

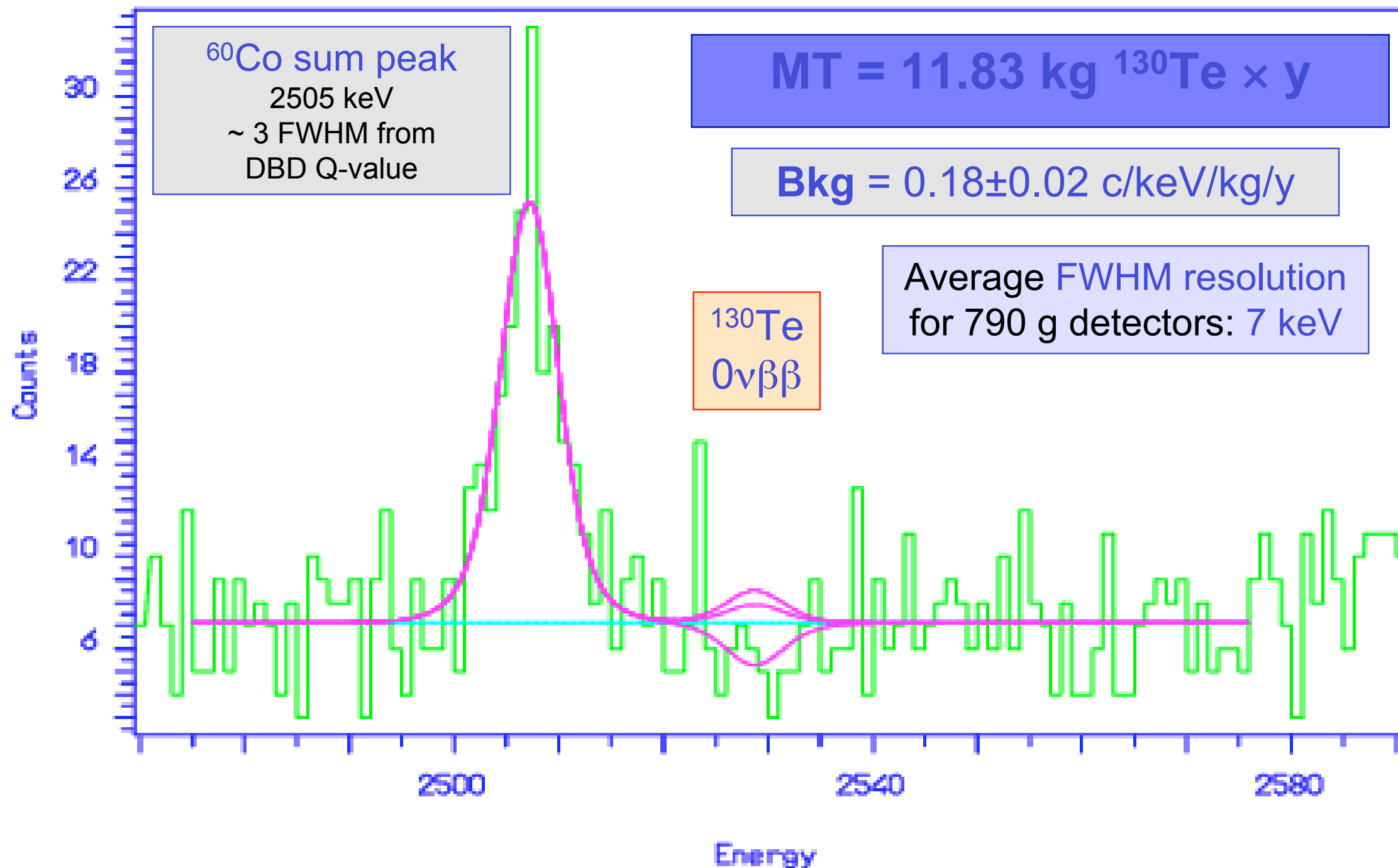
Flat background in the energy region above the ^{208}Tl 2615 line

Contribution to the counting rate in the $0\nu\text{DBD}$ region: **~ 60%**

Degraded alpha particles

Cuoricino
 $b=0.18 \pm 0.02$
c/keV/kg/y

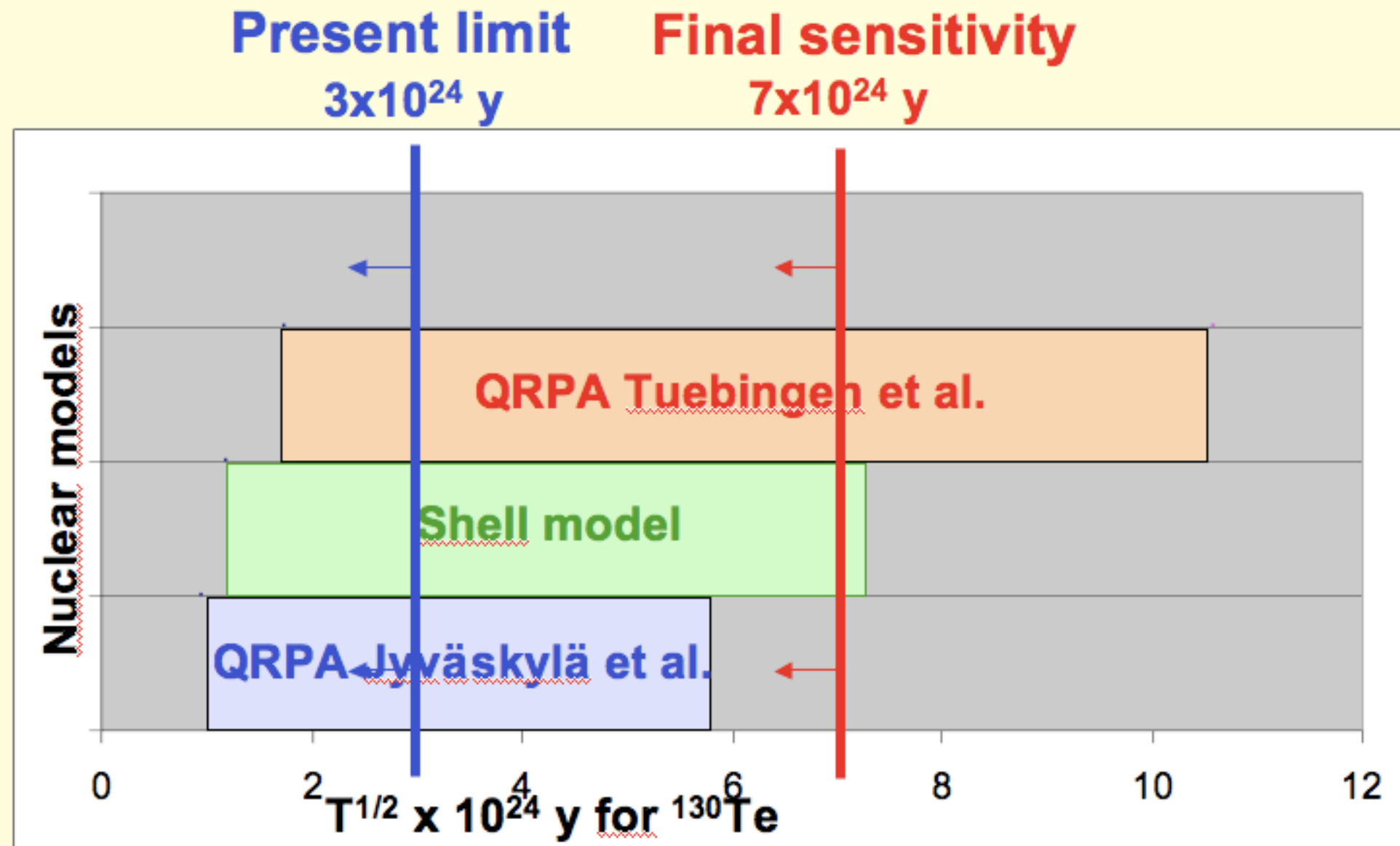
Cuoricino: result



$$\tau_{1/2}^{0\nu} (y) > 3.0 \times 10^{24} y \quad (90\% \text{ c.l.})$$

$$\langle M_{\beta\beta} \rangle < 0.20 - 0.98 \text{ eV}$$

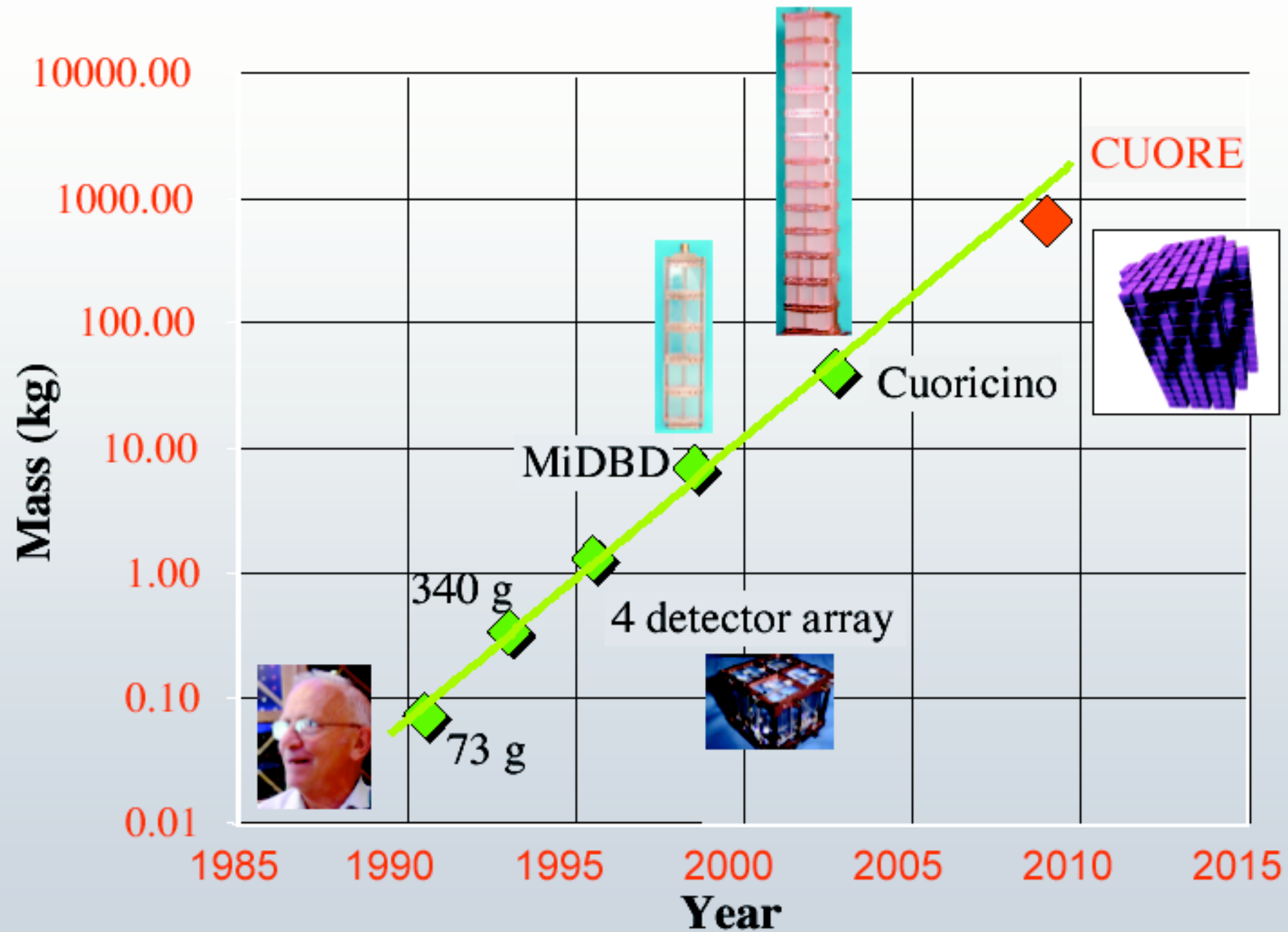
in the parameter space



Cuoricino might discover DBD
but cannot disprove 'Klapdor'

$$T_{1/2}^{0\nu}(^{130}\text{Te}) = \frac{T_{1/2}^{0\nu}(\text{Klapdor})}{\frac{G_{^{130}\text{Te}}^{0\nu}}{G_{^{76}\text{Ge}}^{0\nu}} \cdot \left| \frac{M_{^{130}\text{Te}}^{0\nu}}{M_{^{76}\text{Ge}}^{0\nu}} \right|^2}$$

The Moore's Law of Bolometry



CUORE : who ?

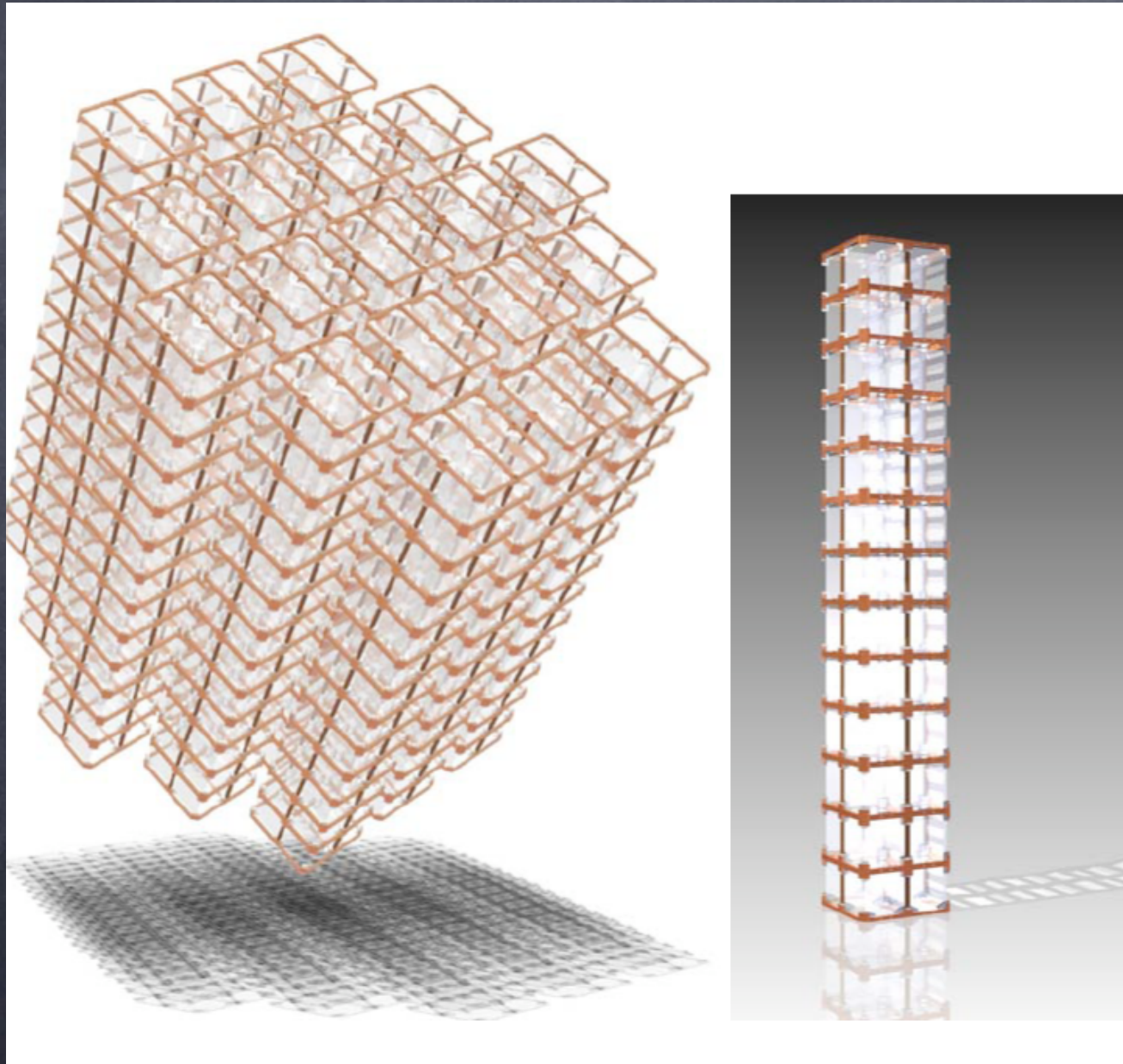


and since very recently



CUORE design

Cuoricino times 19



988 TeO_2 Crystals

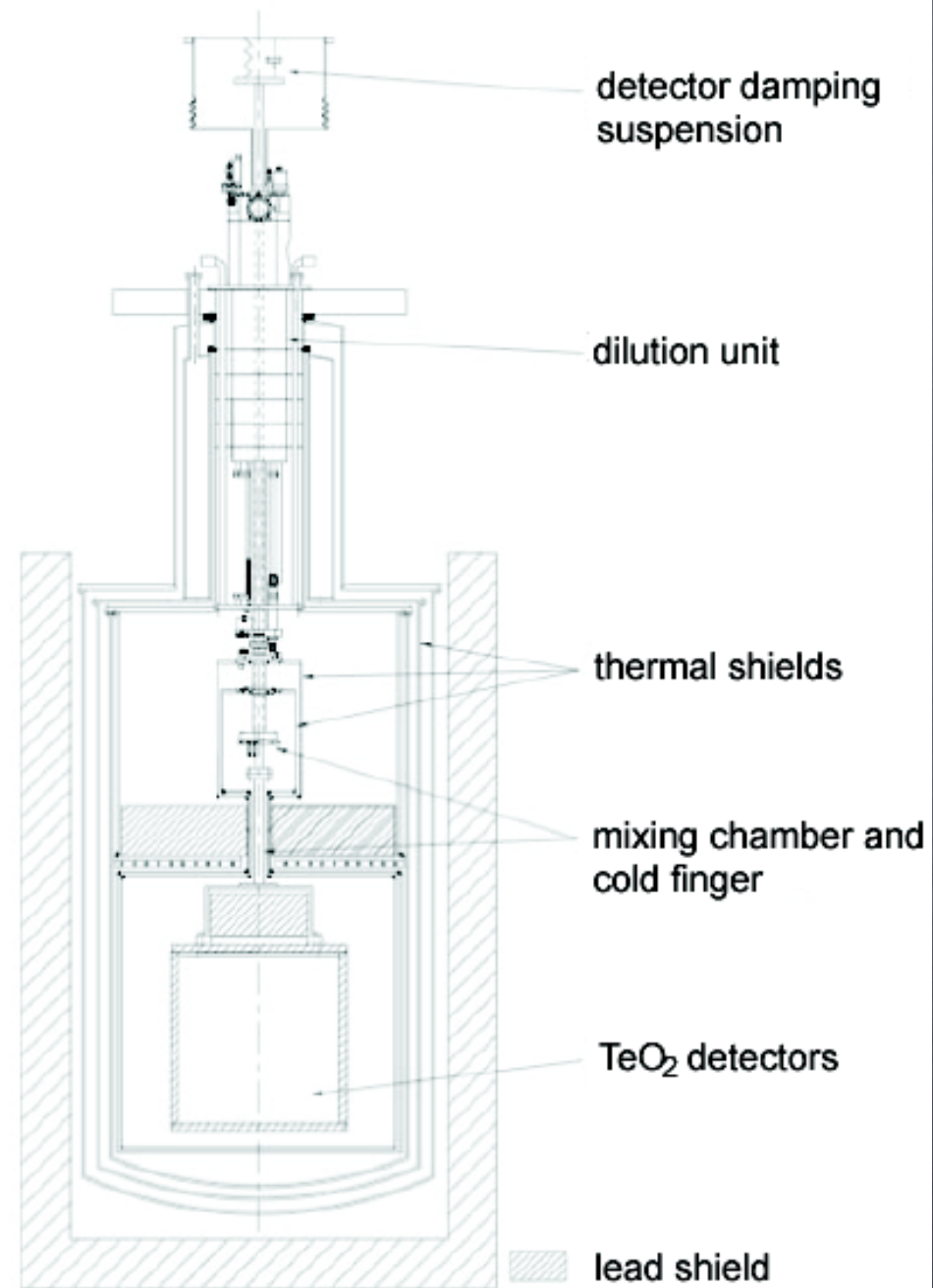
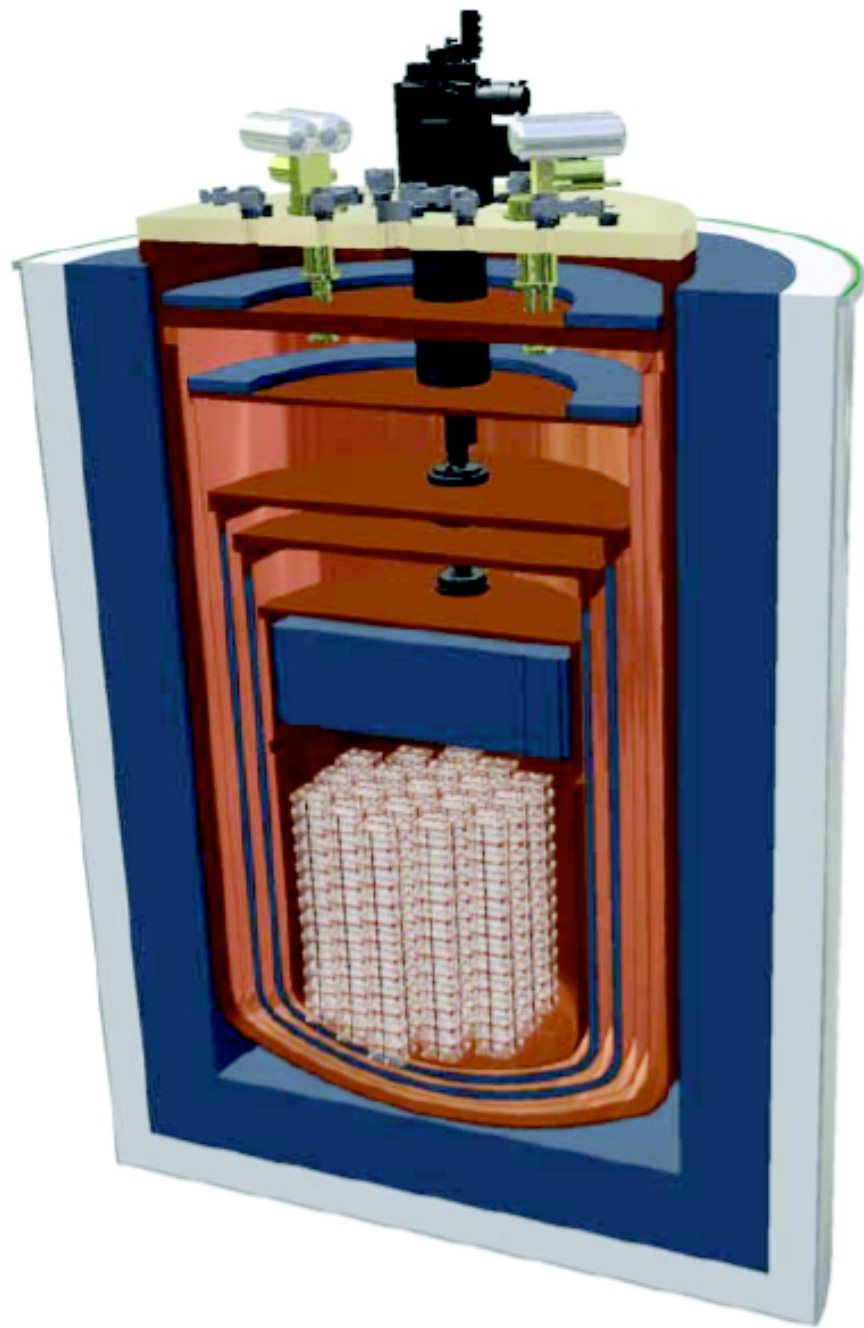
19 Towers of 52 crystals each

741 Kg of TeO_2

Active Mass 204 Kg

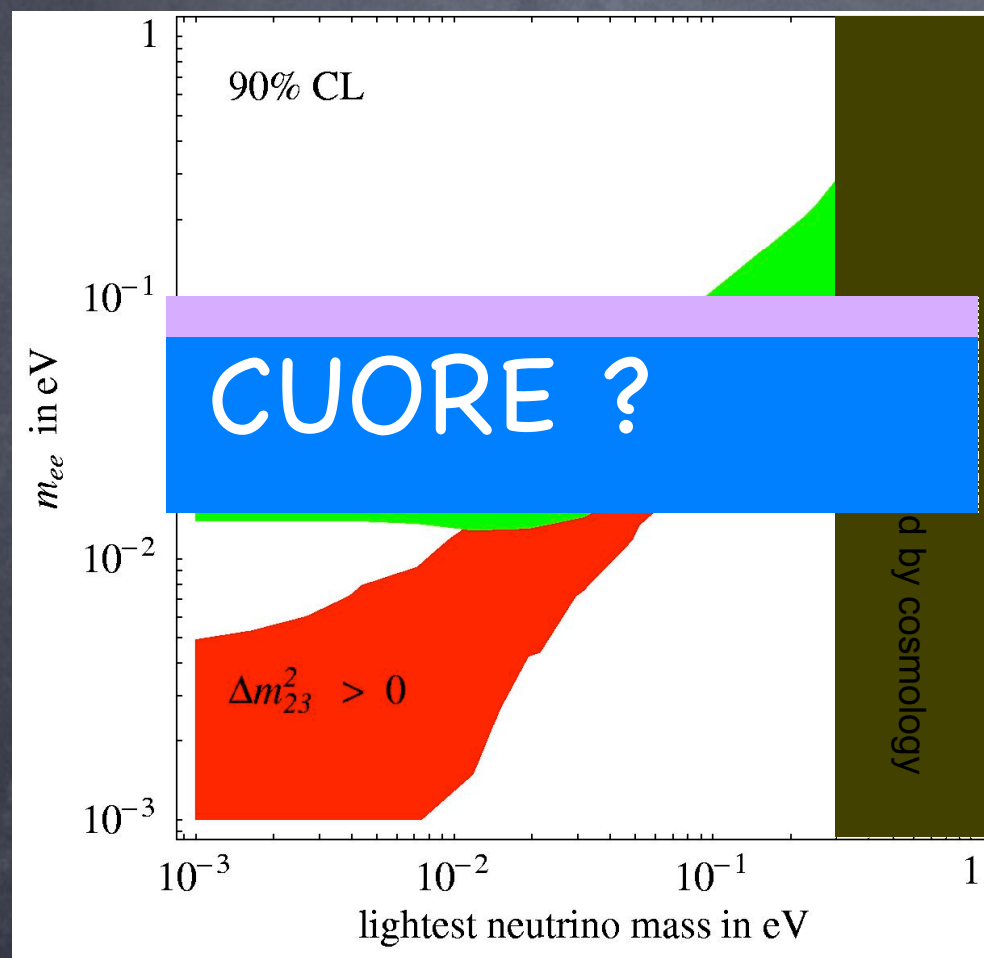
Keep the possibility of replacement with enriched Te Crystals

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

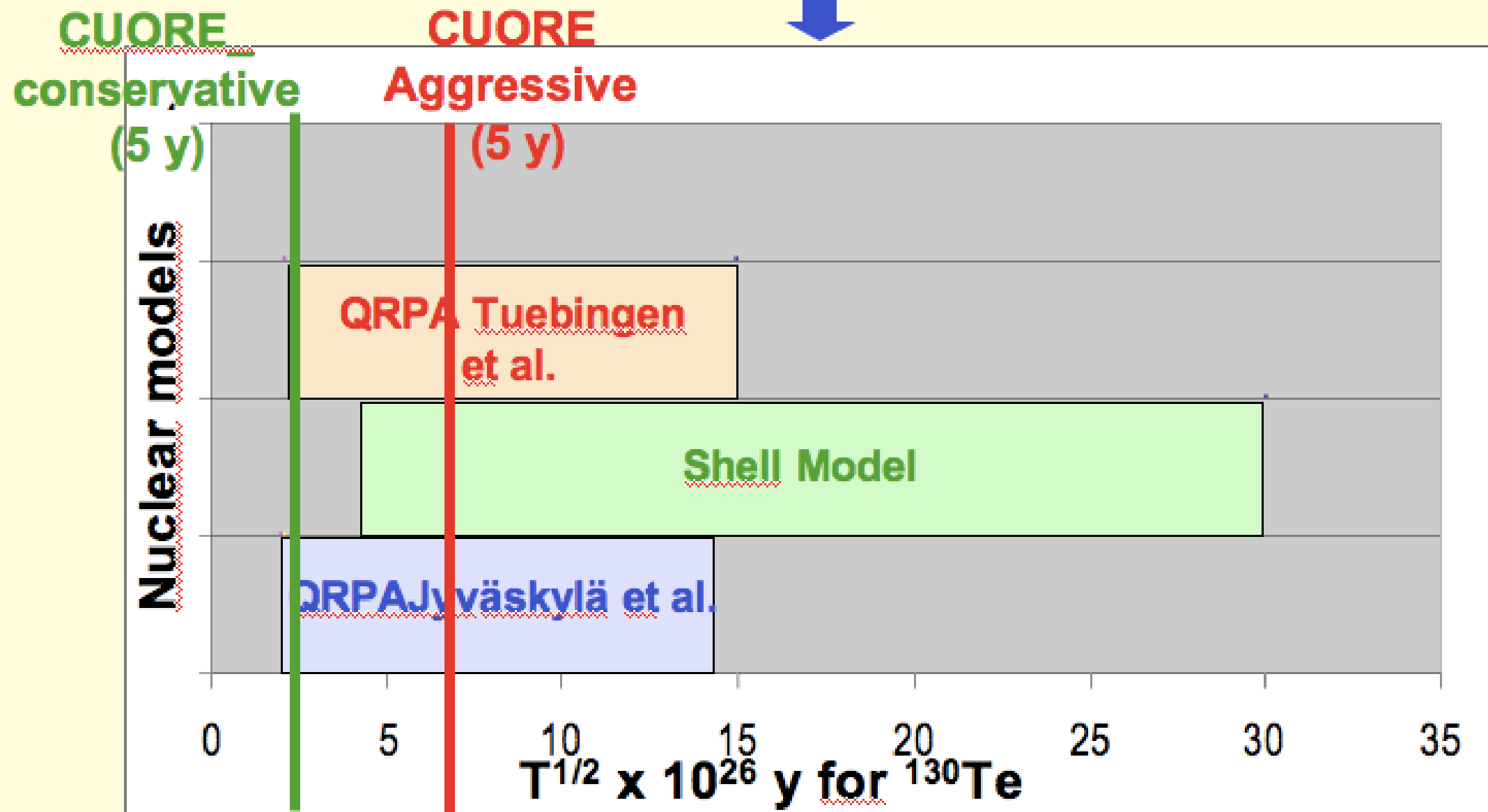
Backgrounds	Sensitivity	Effective Majorana Mass
0.01 counts/keV·kg·yr	$T_{1/2}^{0\nu} = 2.1 \times 10^{26}$ yr	19 – 100 meV
0.001 counts/keV·kg·yr	$T_{1/2}^{0\nu} = 6.5 \times 10^{26}$ yr	11 – 57 meV

CUORE and the inverted hierarchy region

$\langle M_{\beta\beta} \rangle$ band corresponding to the inverted hierarchy

Nuclear models

band of ^{130}Te half lives



Scaling Cuoricino to CUORE

$$\frac{a}{A} \left[\frac{M T}{b \Delta E} \right]^{1/2}$$

$$M = m \times 20$$

$$T = t \times 6$$

$$b = B / 20$$

$$\Delta E = \Delta E / 1.5$$

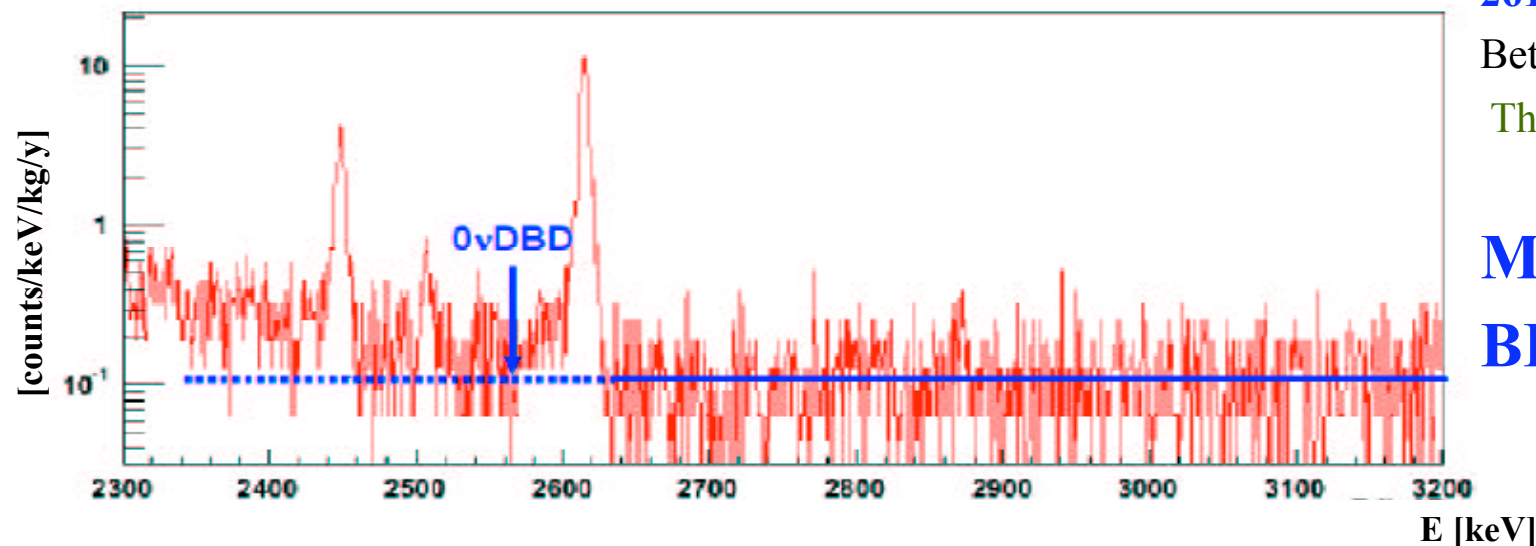
$$S_{\text{CUORE}} = \sqrt{3600} \quad S_{\text{Cuoricino}} \sim 60 S_{\text{Cuoricino}}$$

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

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

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.

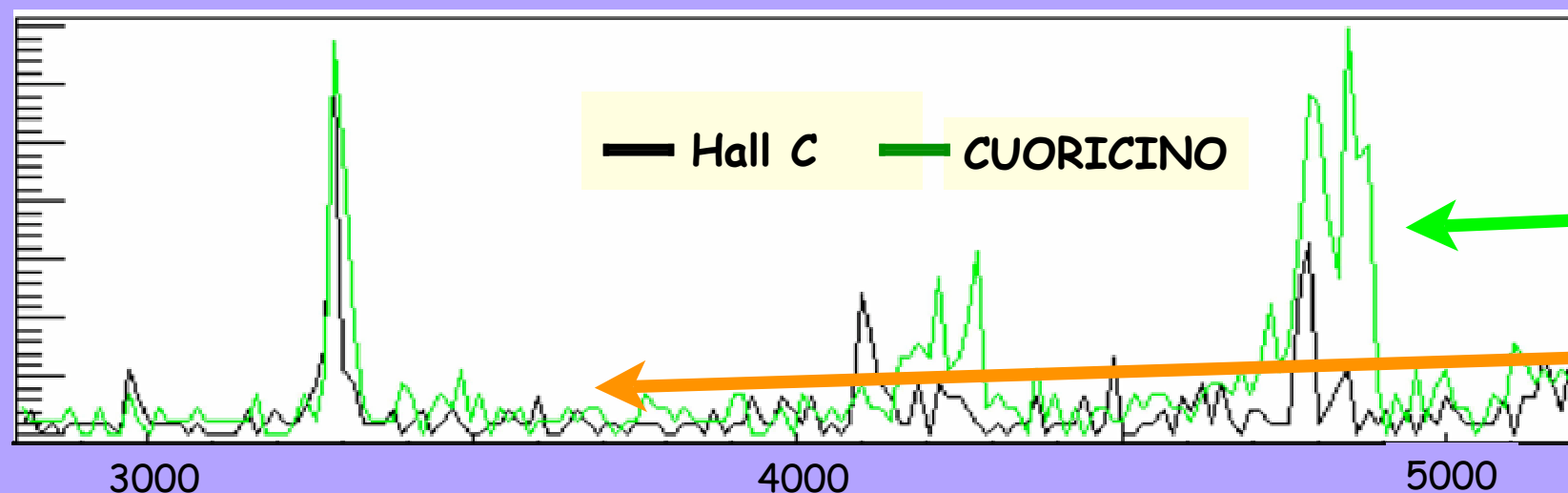
Th (Tl) contribution to DBD background: $\sim 40\%$

**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 0vDBD region: $\sim 60\%$

Origin: **degraded alpha particles** (20 +/- 10) % crystal surface contamination
(80 +/- 10) % "Cu" surface contamination $\sim$

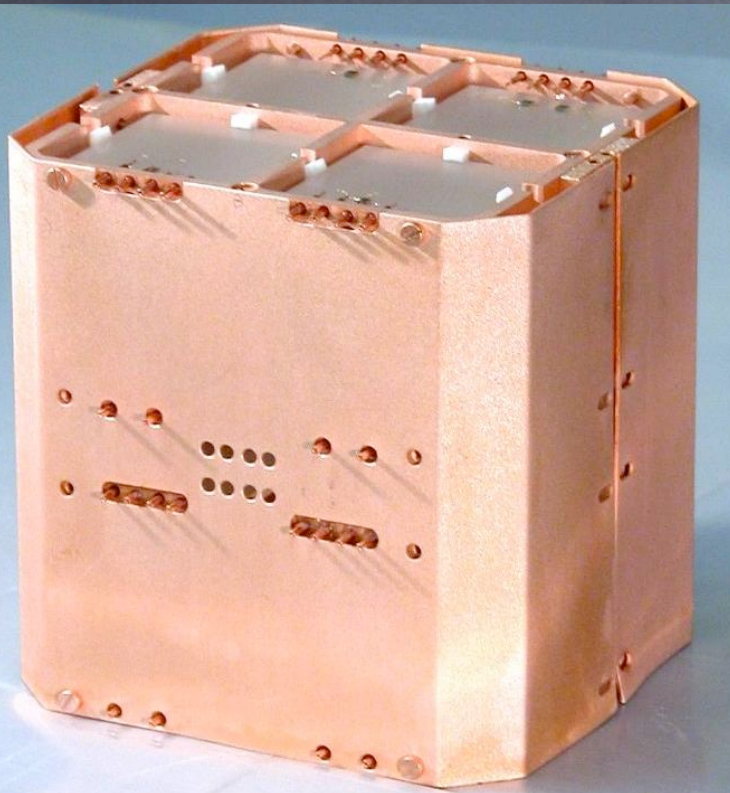


**Reduction of a factor ~ 4
on crystal surface
contaminations.**

**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



Component	Background in DBD region (10^{-3} counts/keV kg y)
Environmental gamma	< 1
Apparatus gamma	< 1
Crystal bulk	< 1
Crystal surfaces	< 1
Close-to-det. material bulk	< 1
Close-to-det. material surface	~ 20 – 40
Neutrons	~ 0.01
Muons	~ 0.01

The only
limiting factor

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