LUCIFER

a new Technique for Double Beta Decay

(and an unusual funding source)

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Outline

- Neutrino-less Double Beta Decay
- The experimental (standing) problem
- Toward 0 background : LUCIFER

Majorana conjecture

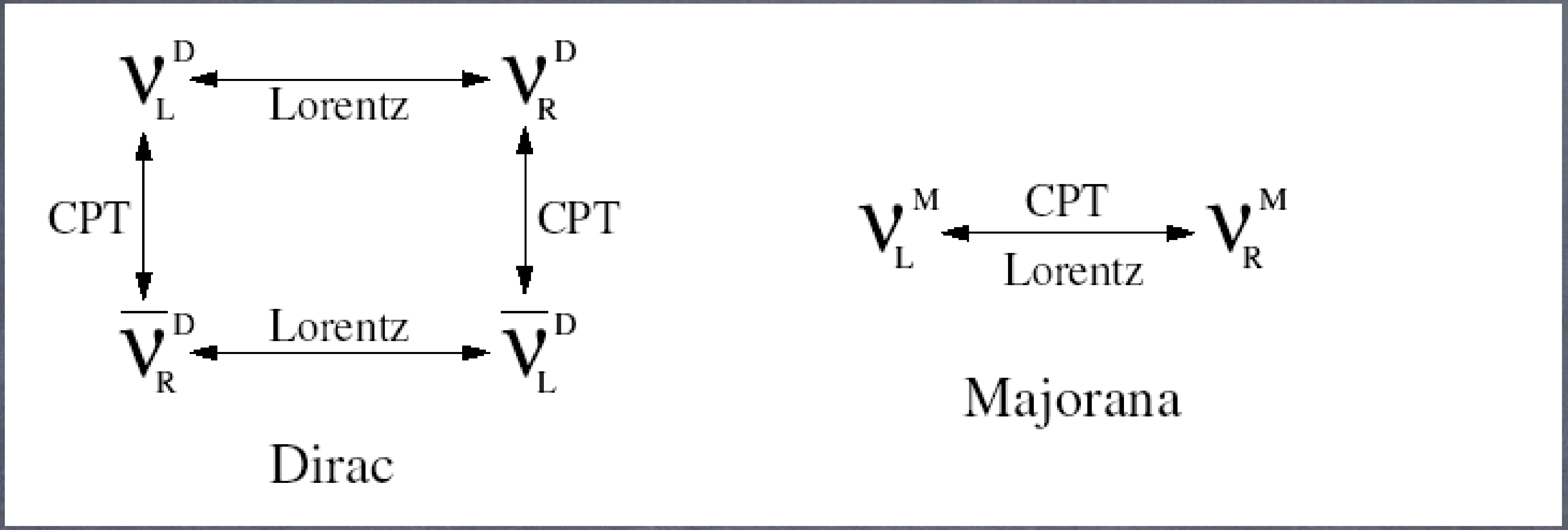
$$\nu = \bar{\nu}$$

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

one elegant explanation (beyond the SM)

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

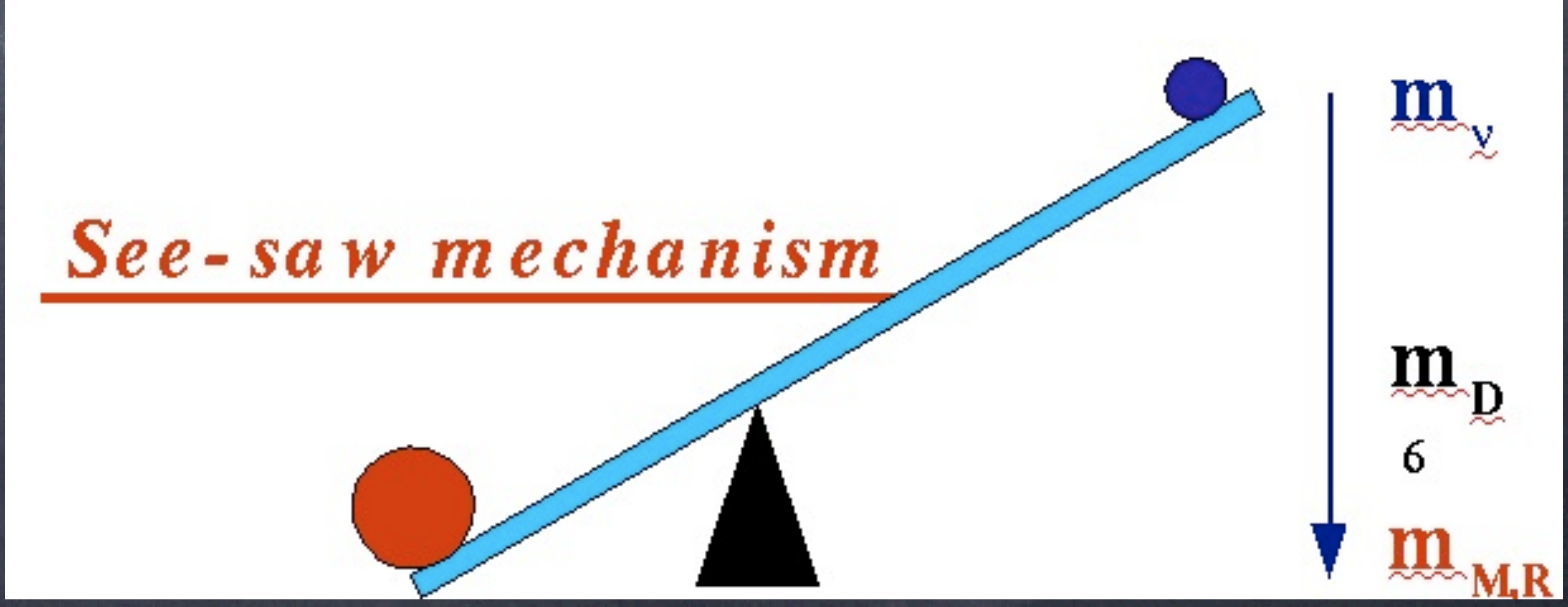
where $M_{M,L} \sim 0$

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

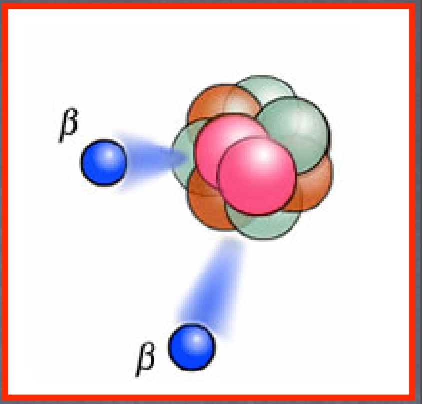
$M_{M,R} \sim$ Gauge singlet unprotected $\sim M_{GUT}$

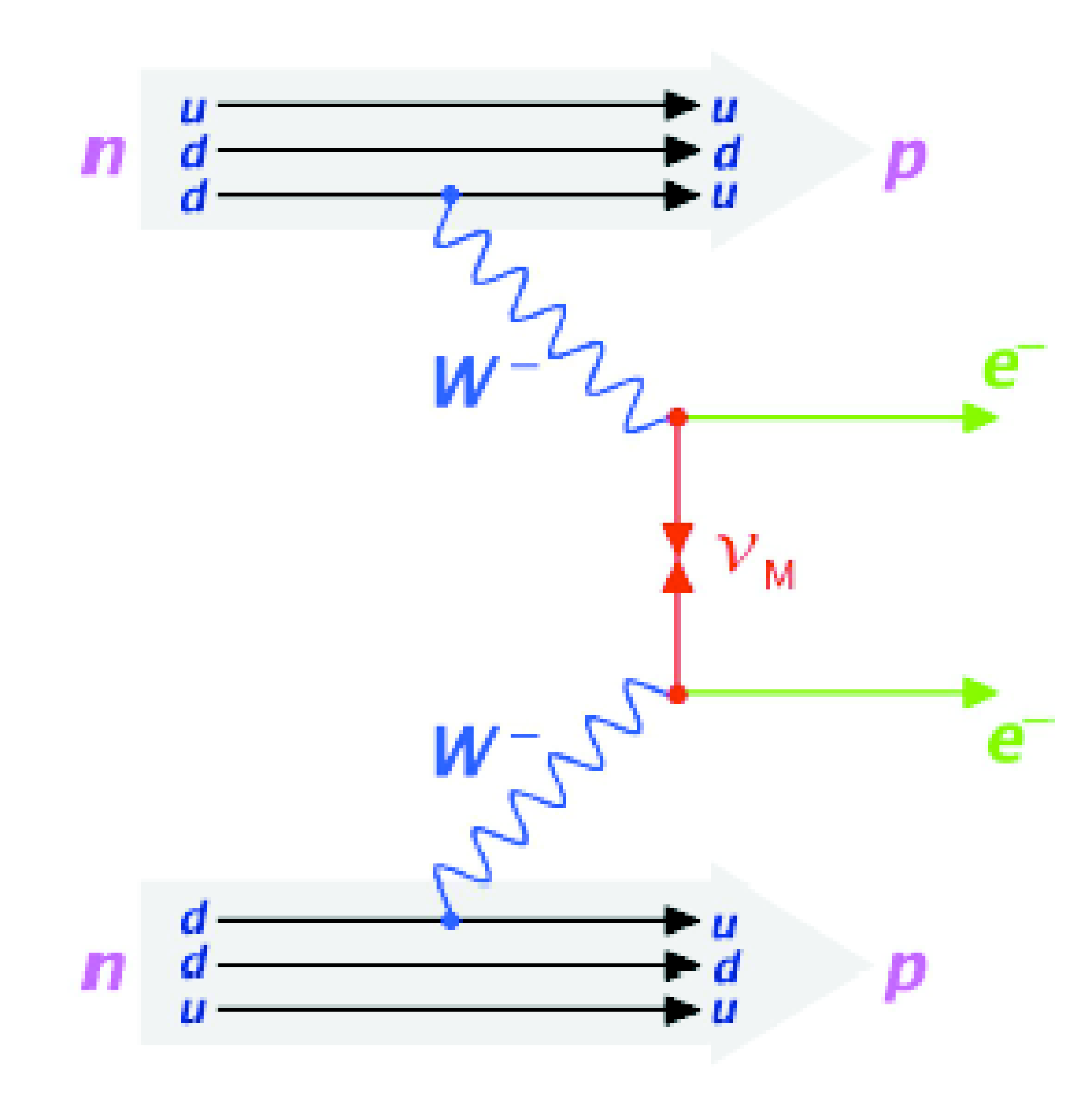
$$m_N \simeq M_{M,R}$$

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



Neutrino-less DBD ($0\nu\beta\beta$)





Only if:

Majorana Neutrinos

Massive Neutrinos

If observed:

Proof of the Majorana nature of Netrino

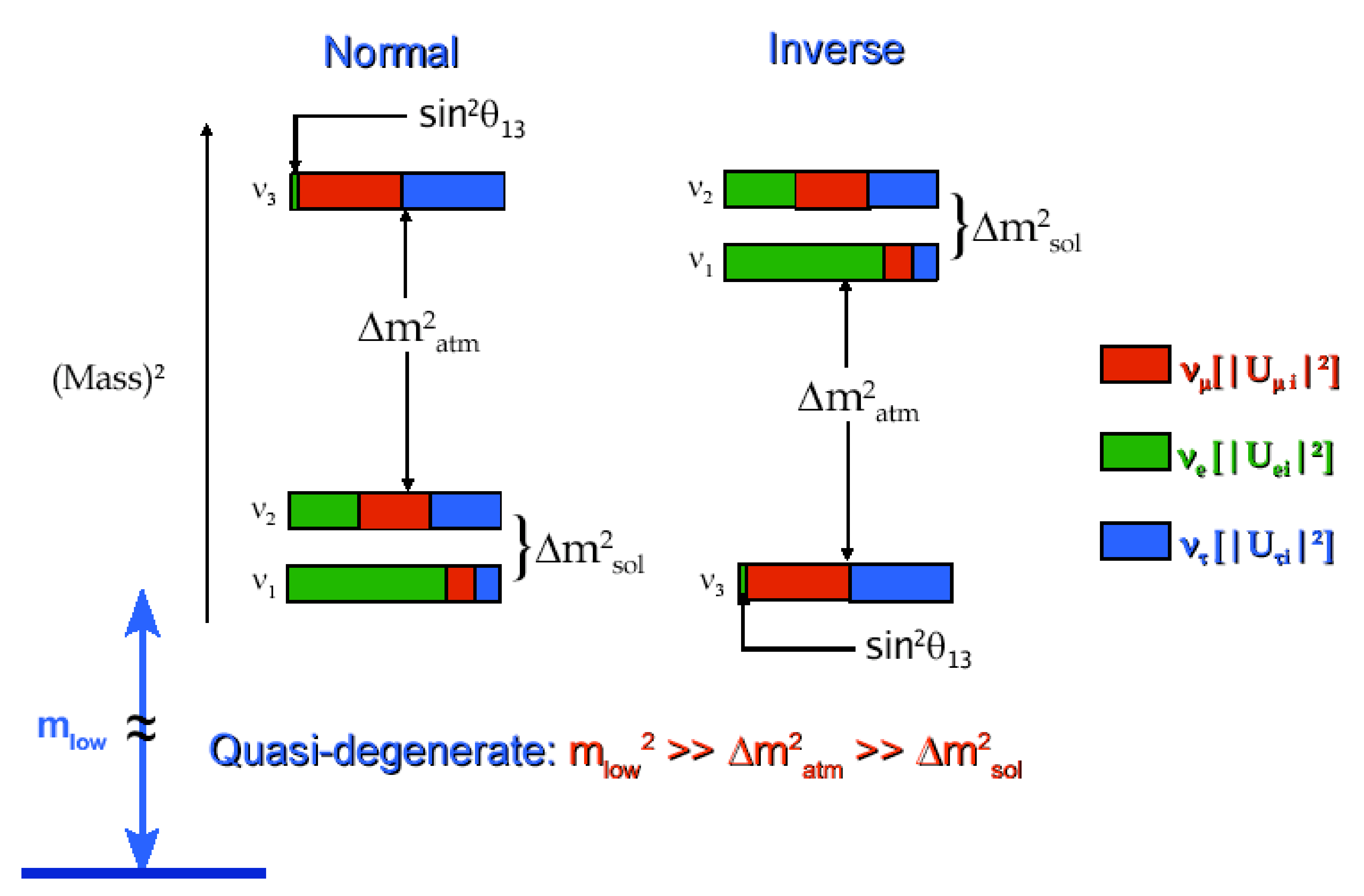
Does it also measure the mass ?

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

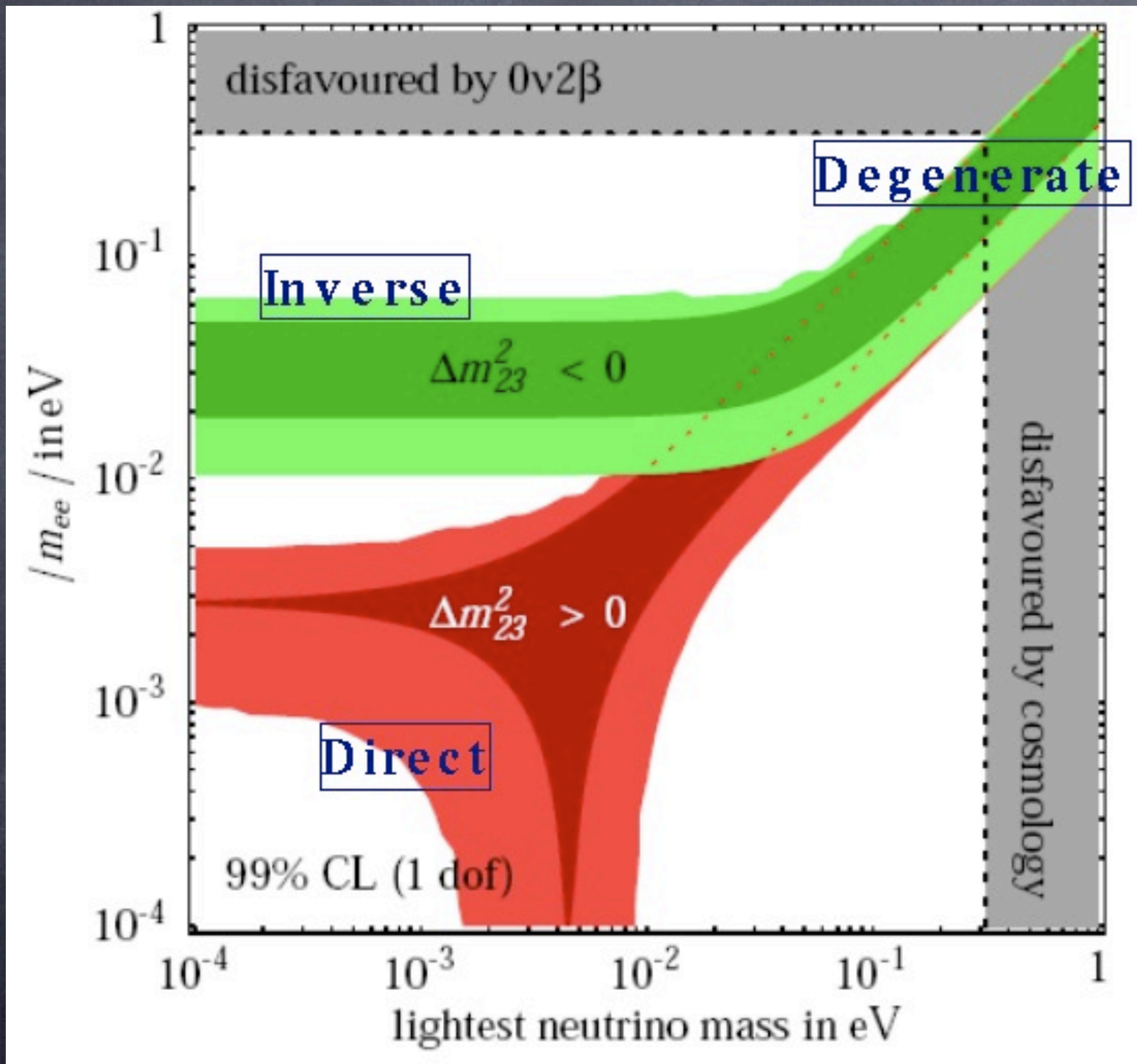
well...not so straight. It comes as a combination of the three neutrino masses, the mixing angles and the Majorana phases.

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.

The name of the game

expected number of ββ0ν events

$$S = \frac{M \cdot N_A \cdot a}{W} \cdot \ln(2) \cdot \frac{t}{T^{0\nu}_{1/2}} \cdot \varepsilon$$

- M: detector mass
- a: isotopic abundance
- t: live time
- ε: efficiency
- W: molecular mass
- $T^{0\nu}_{1/2}$: ββ0ν half-life

mean number of background counts around the Q-value

$$B = b \cdot M \cdot \Delta E \cdot t$$

- b: background rate in counts/keV/kg/y
- ΔE: energy resolution (detector FWHM)
- M: detector mass
- t: live time

Sensitivity and background

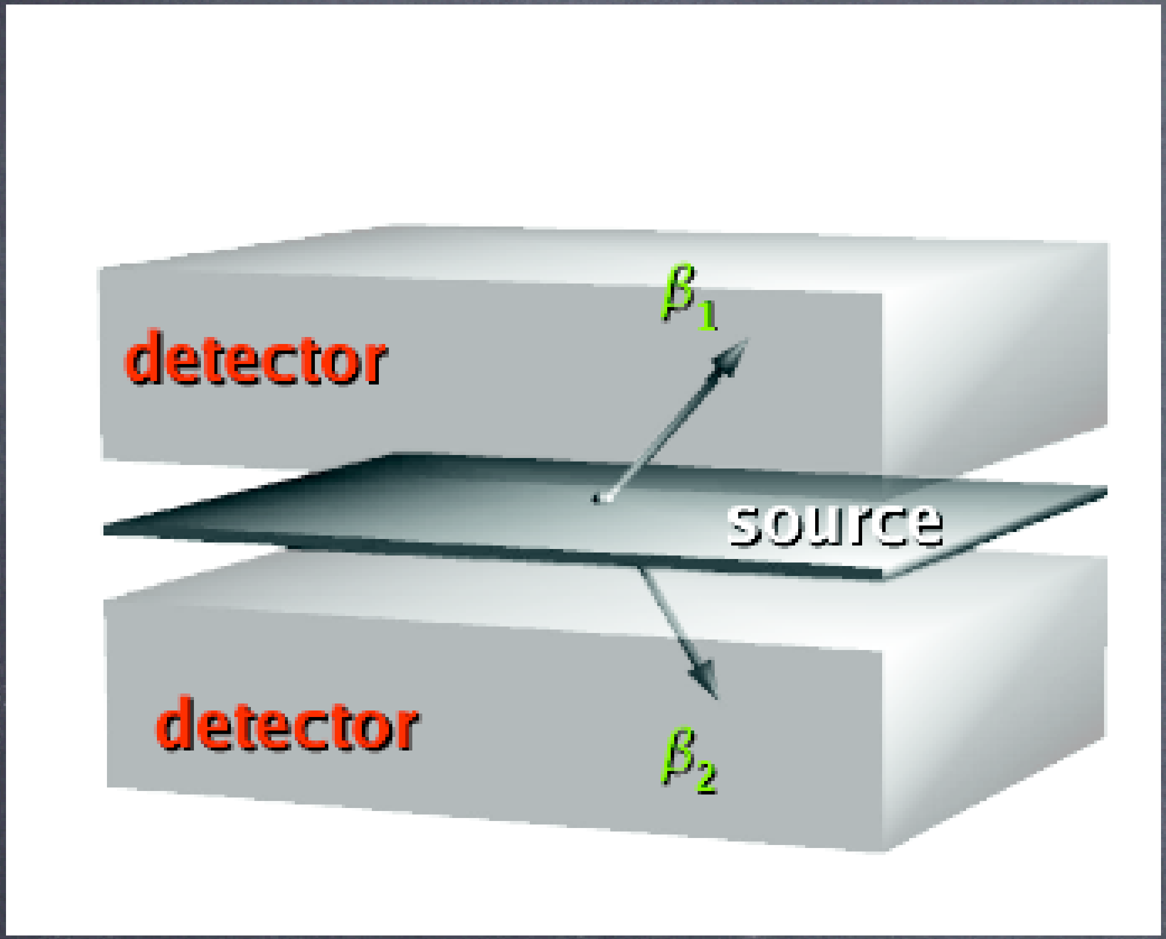
$$\text{Sensitivity} \propto K\sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \qquad (\text{i.a.} \bullet \varepsilon)$$

The (limited) isotope choice

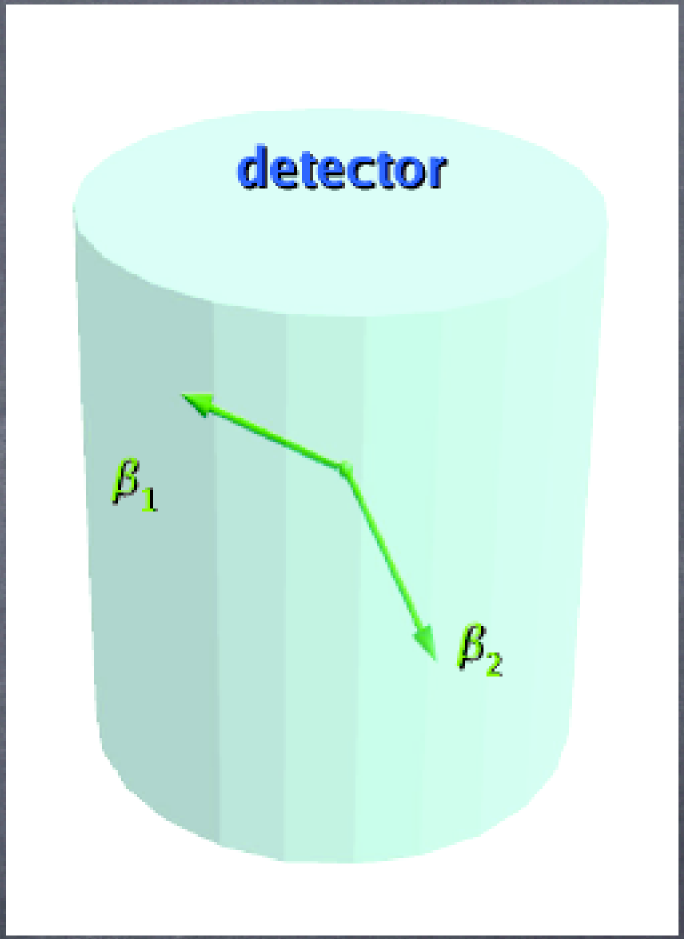
Isotope	$Q_{\beta\beta}$ (MeV)	Isotopic abundance (%)
^{48}Ca	4.271	0.0035
^{76}Ge	2.039	7.8
^{82}Se	2.995	9.2
^{96}Zr	3.350	2.8
^{100}Mo	3.034	9.6
^{116}Cd	2.802	7.5
^{128}Te	0.868	31.7
^{130}Te	2.533	34.5
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

Two techniques (and a few variations)

Source ≠ Detector



Source ⊆ Detector



+++ Topology, Background

--- M, ΔE, ε

+++ M, ΔE, ε

--- Topology, Background

The Problem

TeO$_2$ case

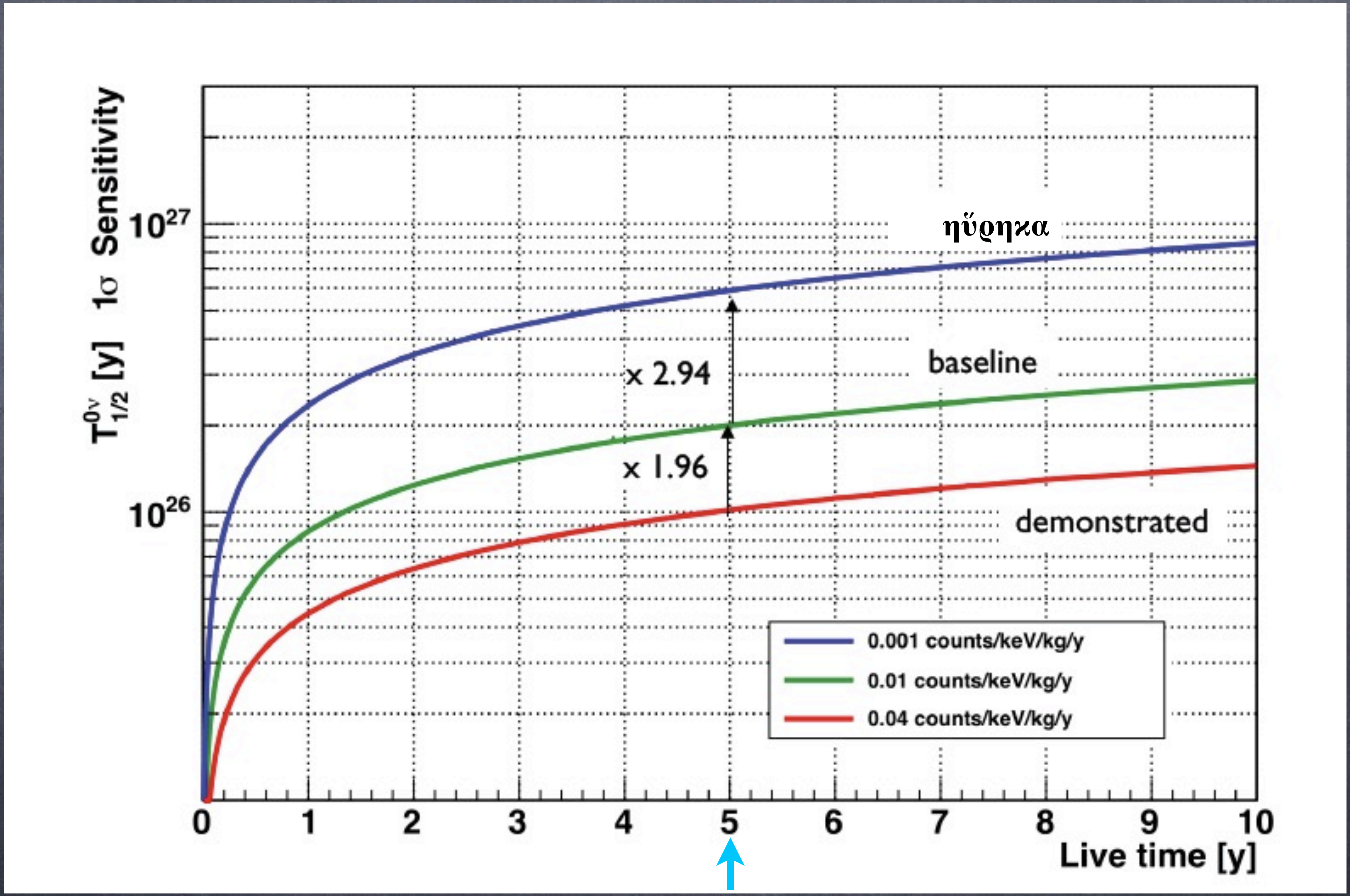
(CUORE)

740 Kg

of which

200 Kg

of ^{130}Te



1 ton•y

Where is the Physics ?

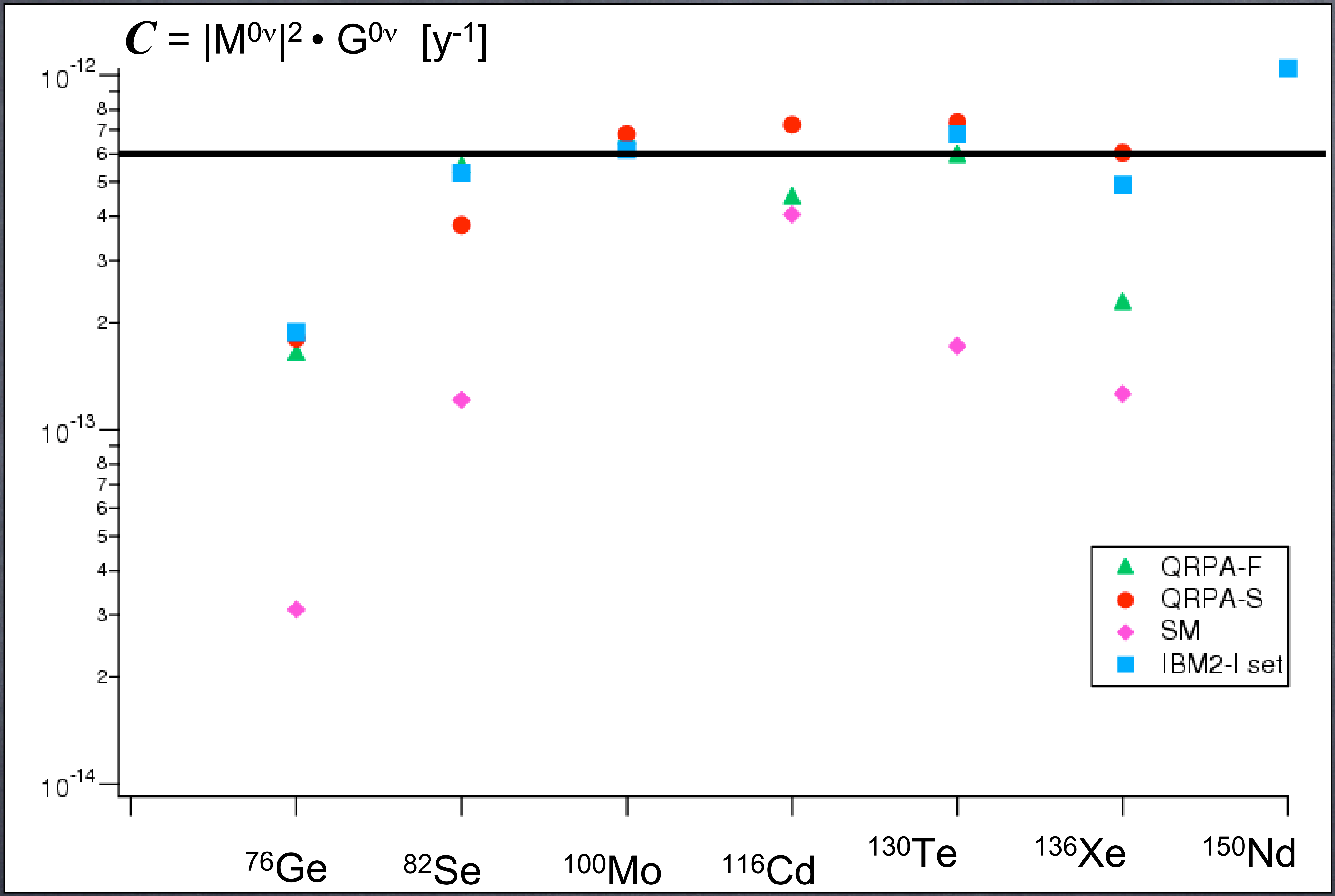
parameter containing the **physics**

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

what the **experimentalists** try to measure

what the **nuclear theorists** try to calculate

The role of NME



Sensitivity and background

Sensitivity $\propto K\sqrt{\dfrac{M\cdot t}{B\cdot\Delta E}}$ (i.a. • ε)

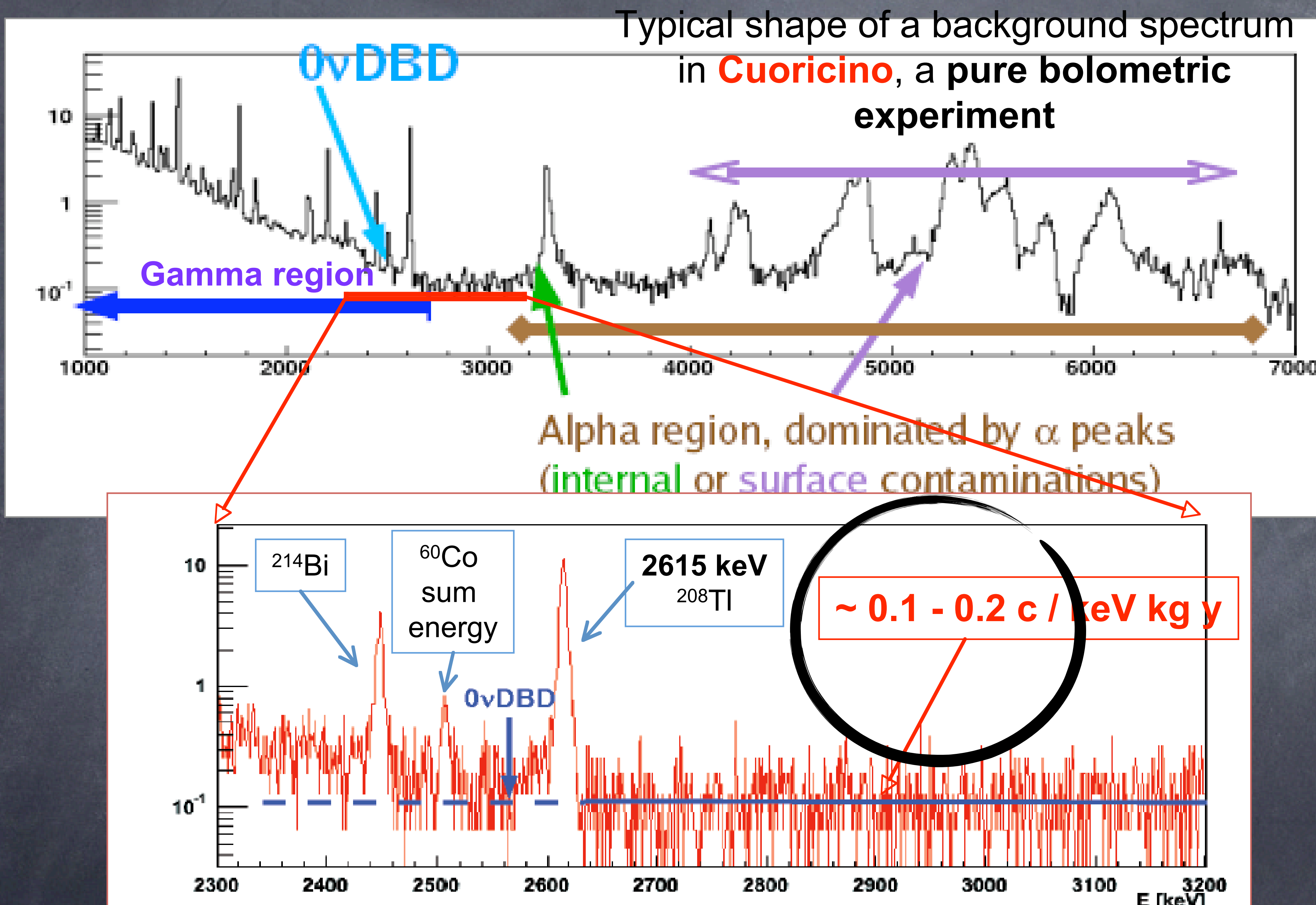
$m_{\beta\beta} \propto \sqrt{(1/\tau)}$

To get a factor 10 in $m_{\beta\beta}$ you have a choice :

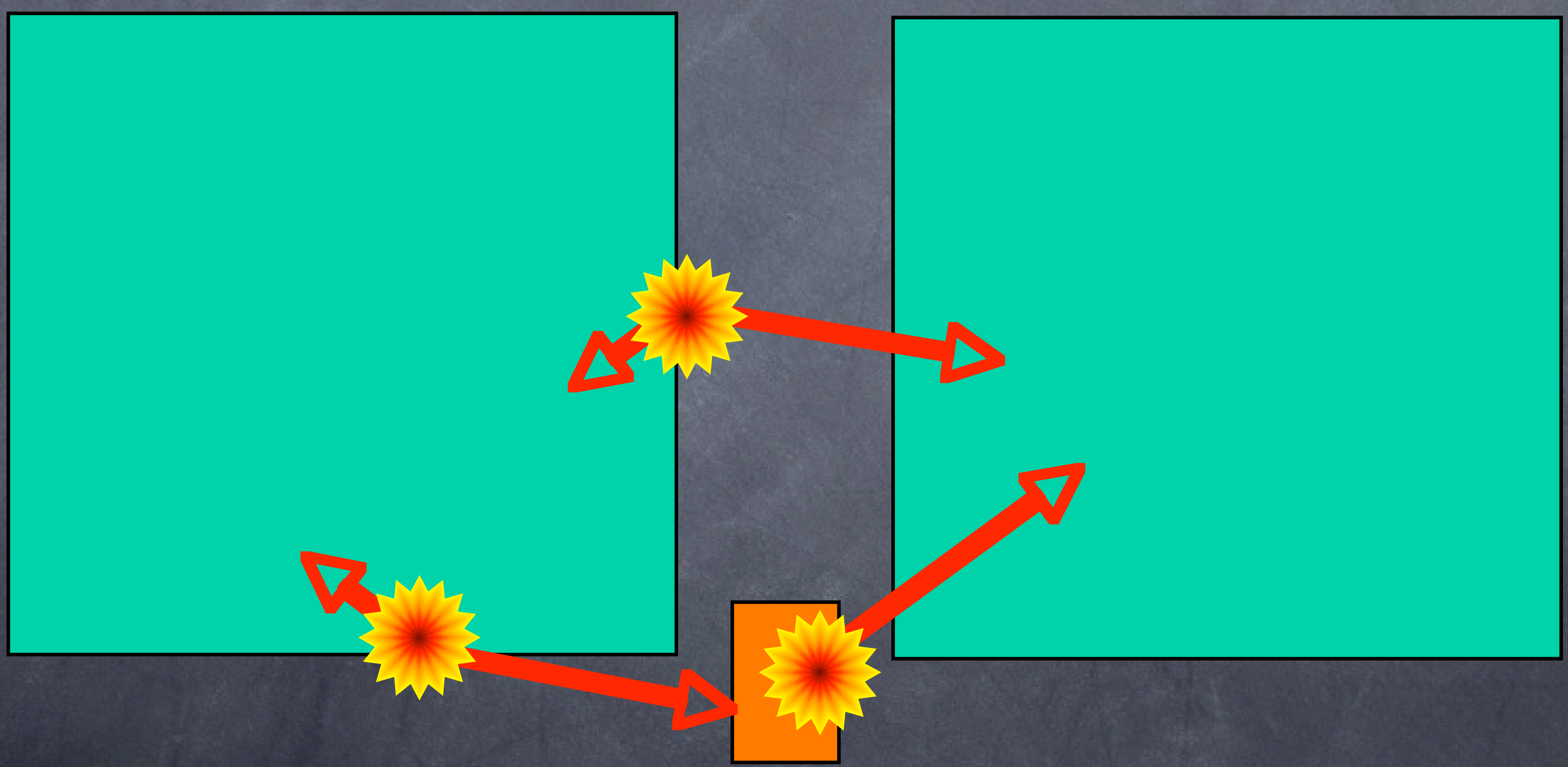
M	100 Ton	instead of 1 Ton
t	500 y	instead of 5 y
ΔE	50 eV	instead of 5 keV

B 0.001 instead of 0.1

Where we start from



The standard interpretation of the background

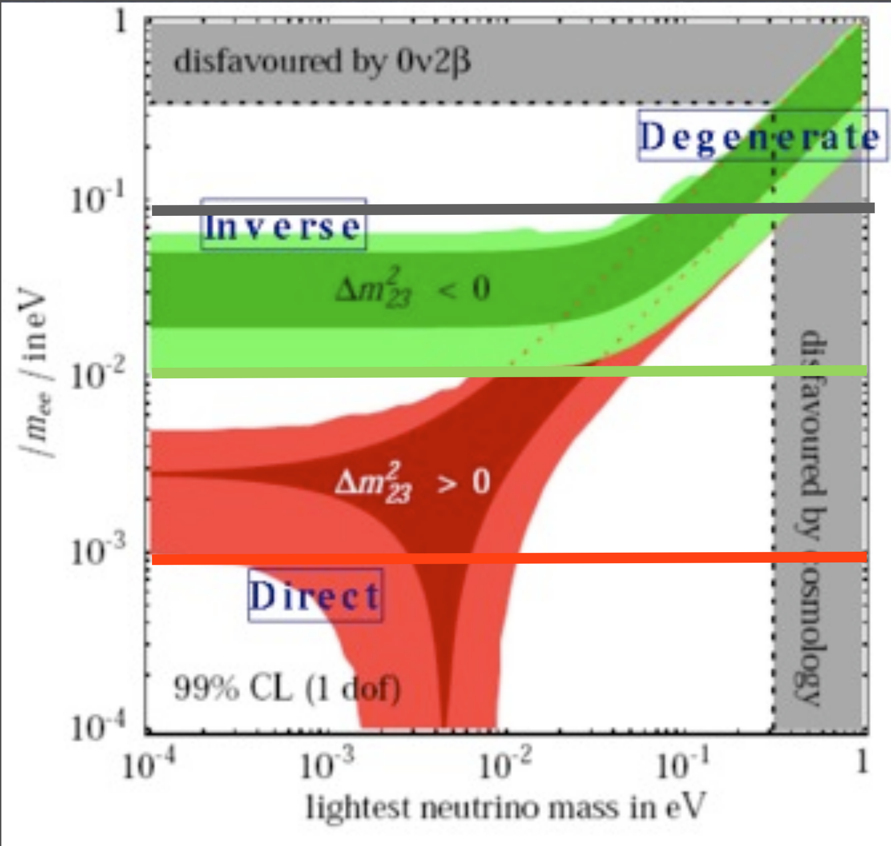


Degraded α's

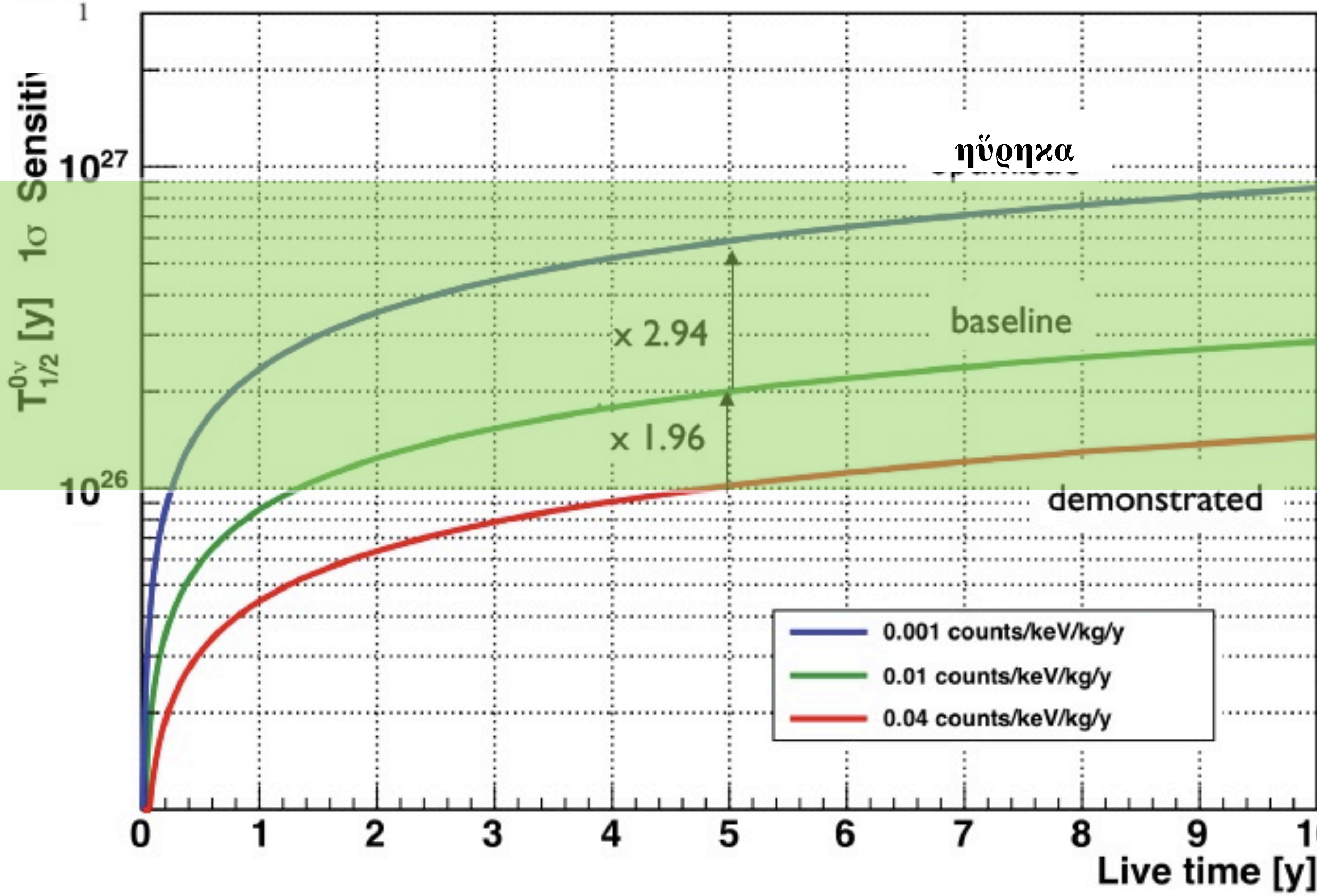
therefore :

$$\left[T^{0\nu}_{1/2}\right]^{-1} = C \cdot \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$$C = |M^{0\nu}|^2 \cdot G^{0\nu} \quad [y^{-1}]$$



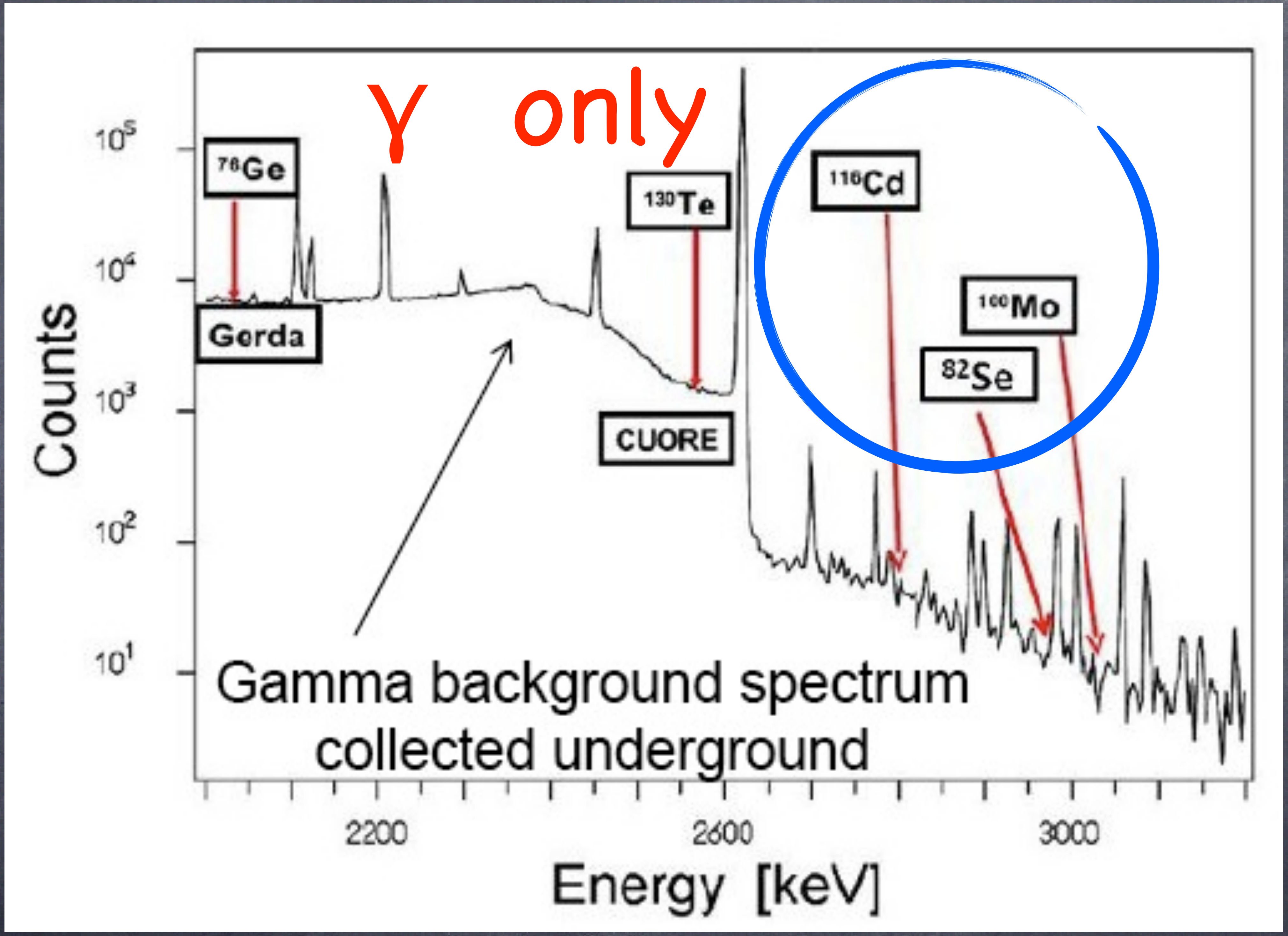
Inverted hyerarchy



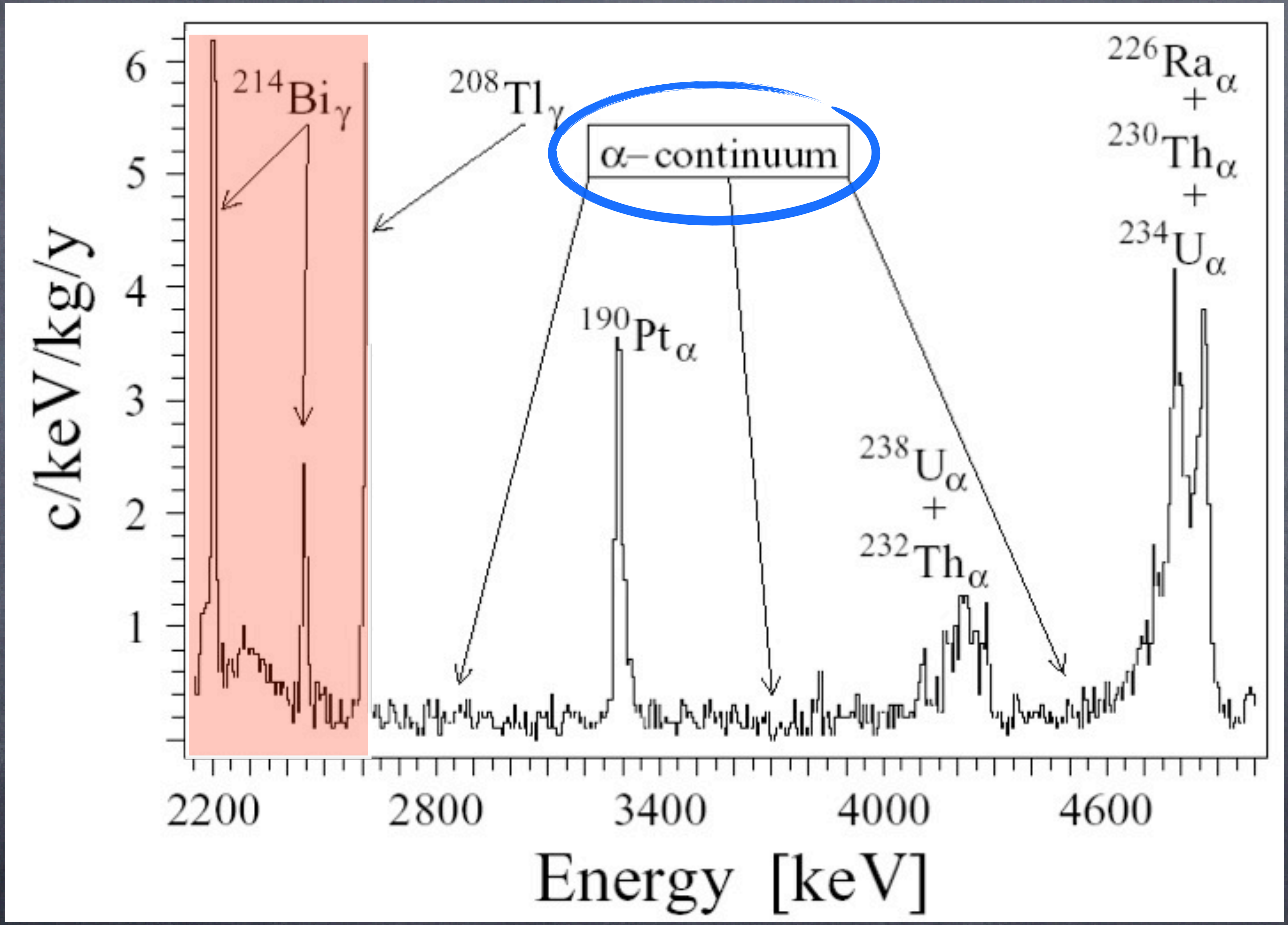
TeO_2 case

(CUORE)

The γ step is 'easy'

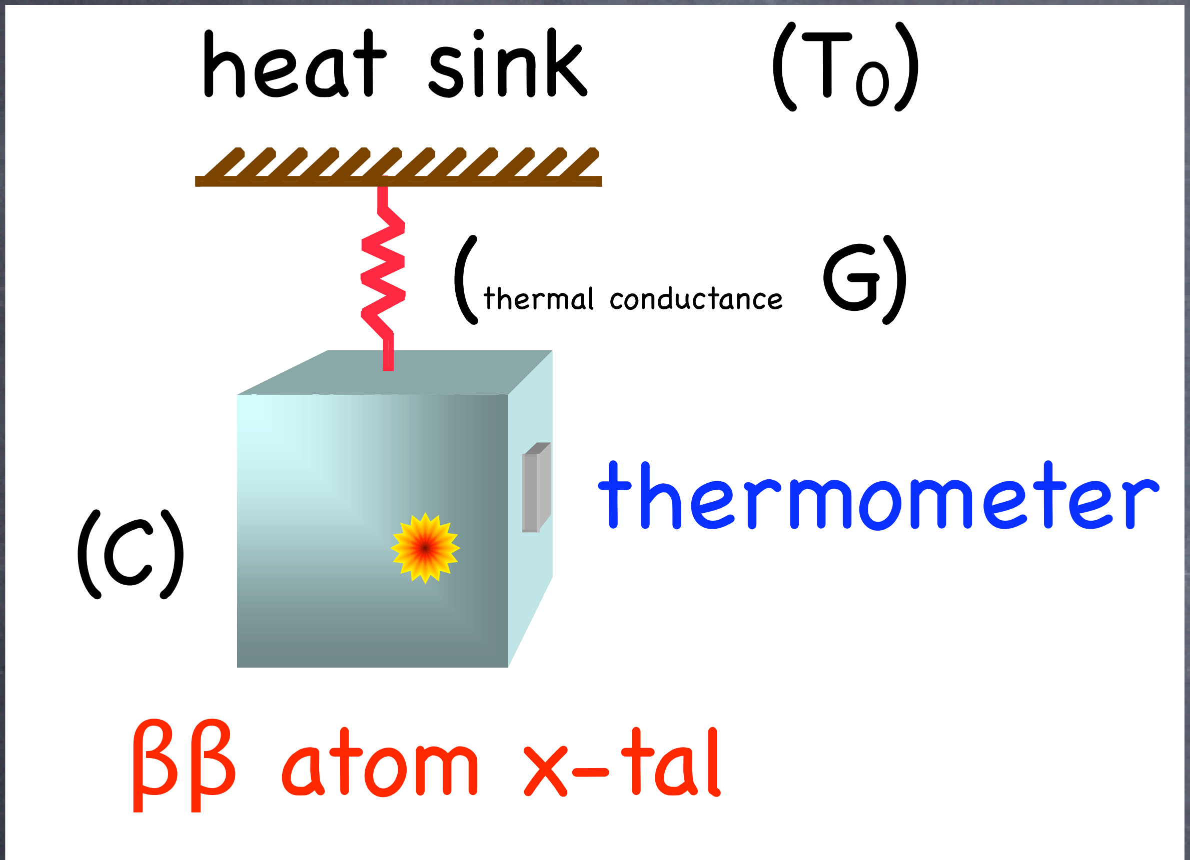


The α step is ‘difficult’



(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 : $\tau = C/G \sim 1s$

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

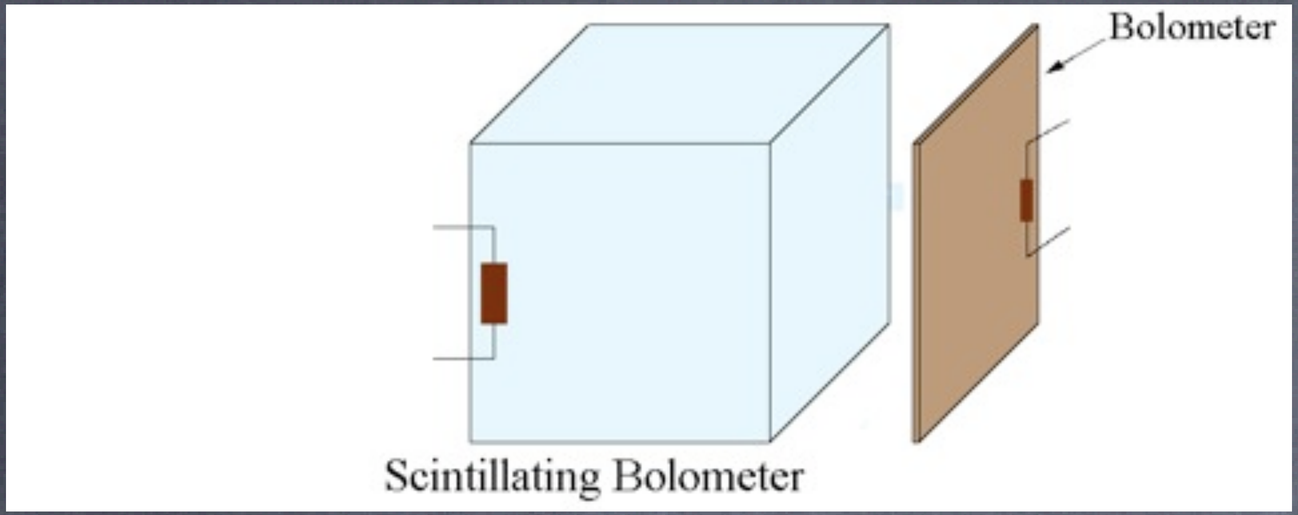
$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau} \right)$$

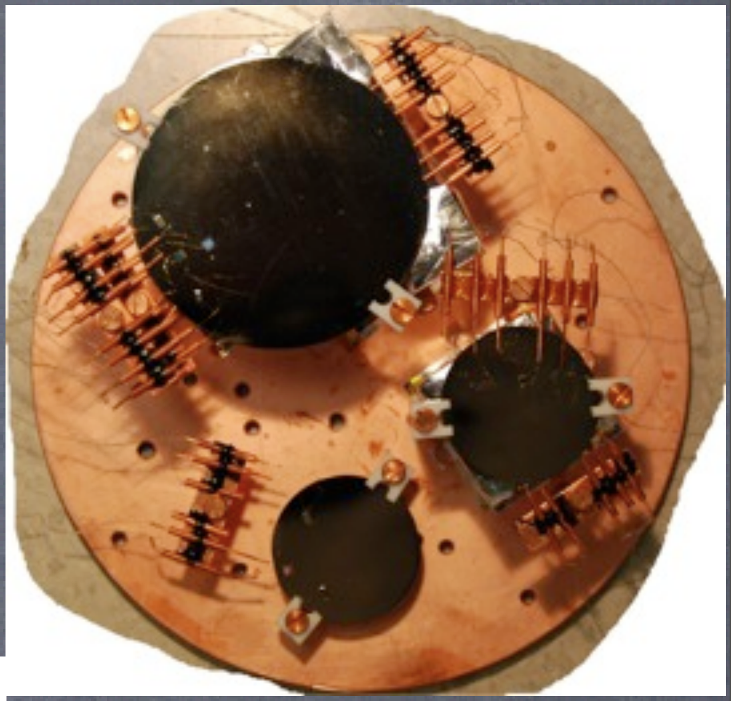
LUCIFER concept

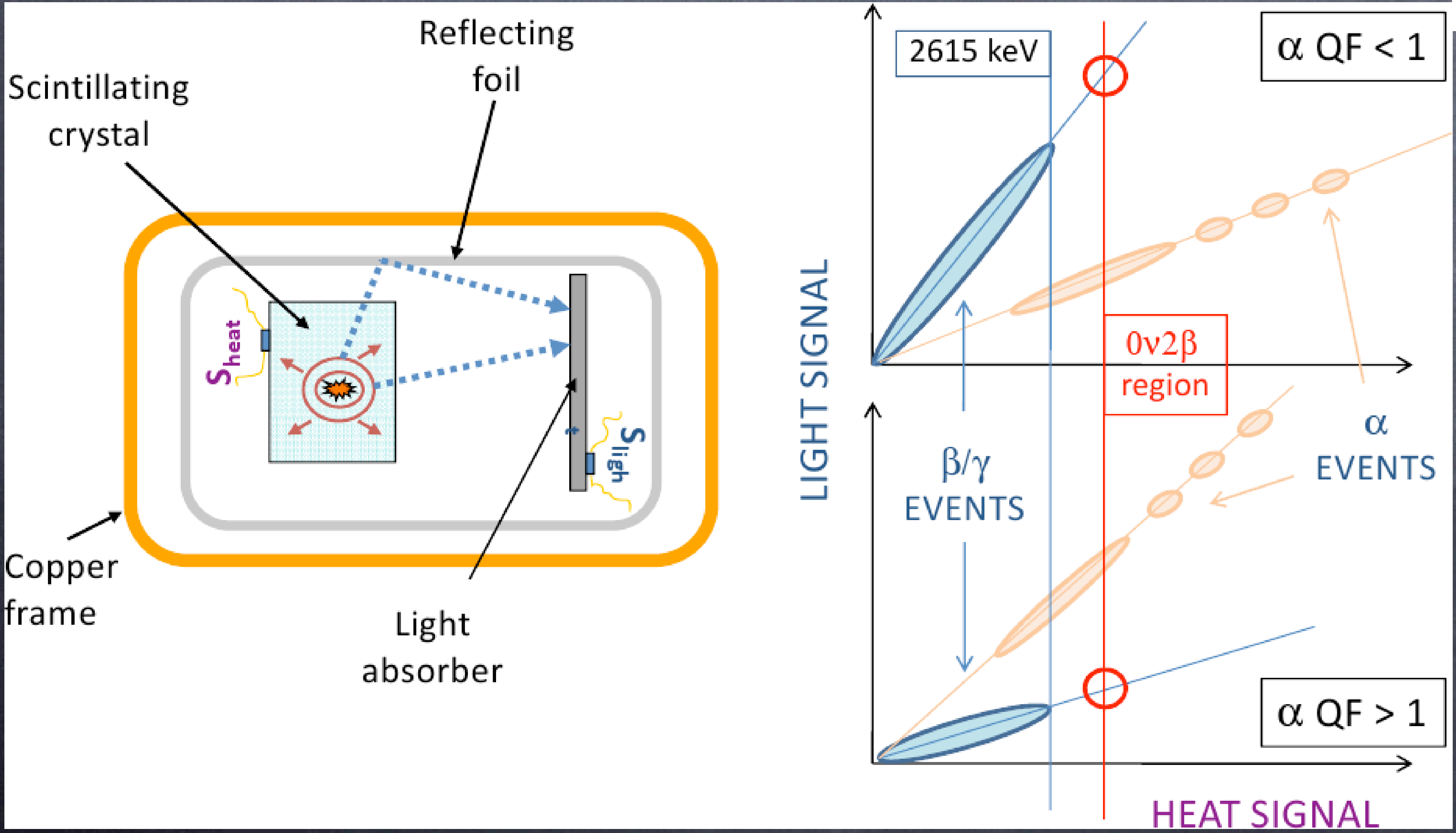
Lucifer is a Latin word (from the words *lucem ferre*), literally meaning "light-bearer", which in that language is used as a name for the dawn appearance of the planet Venus, heralding daylight.

Bringing light underground

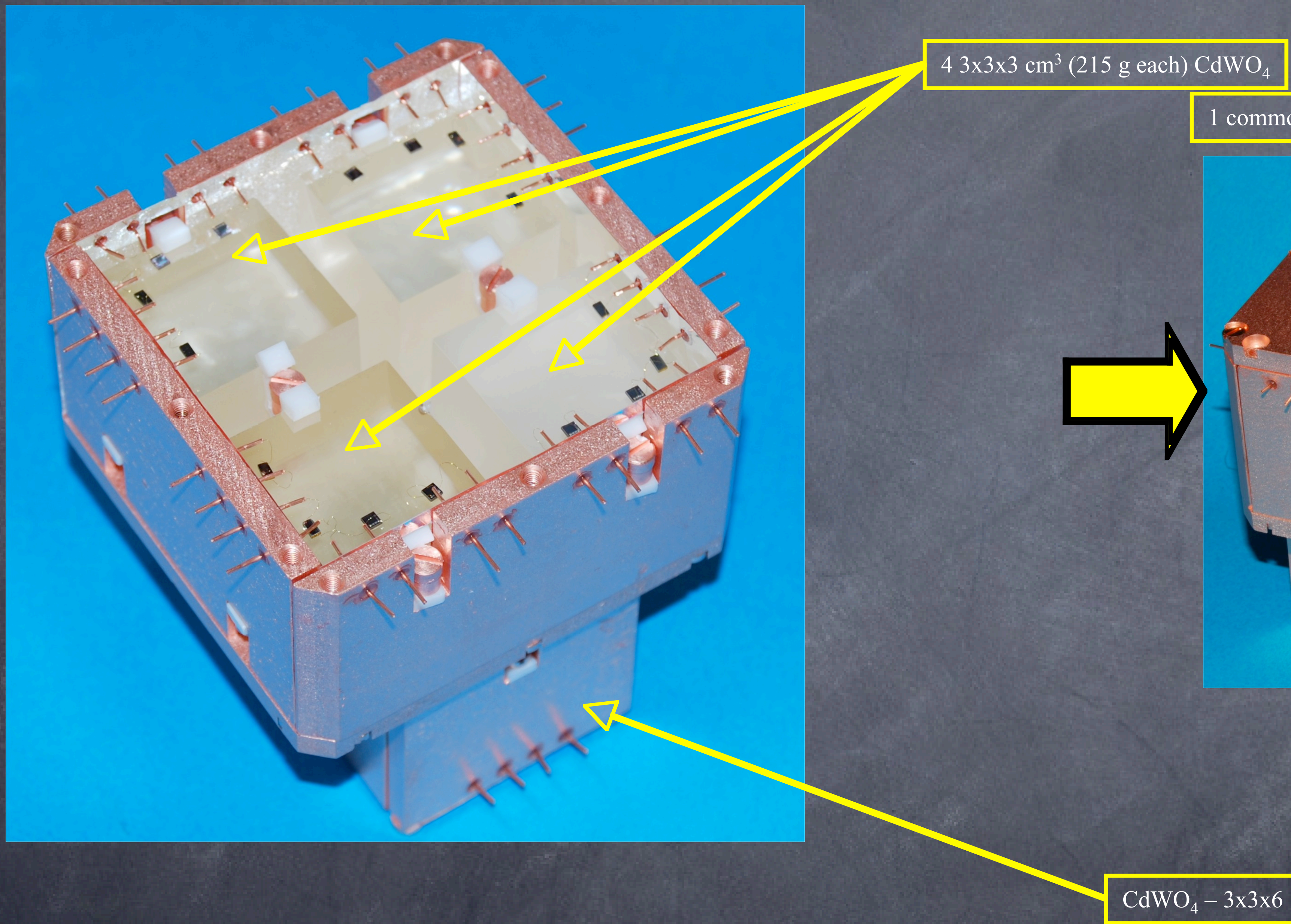
Double read-out

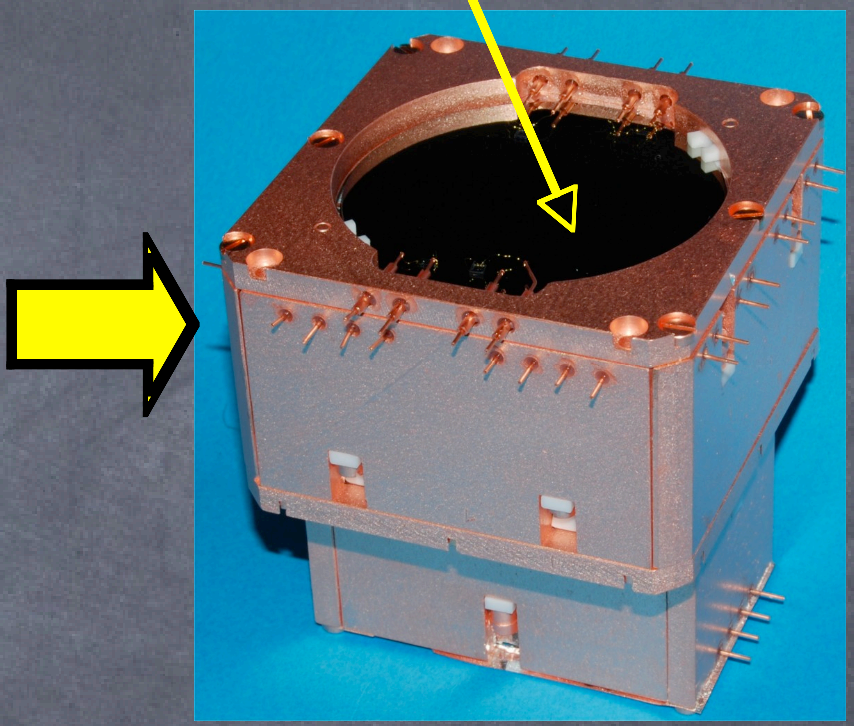






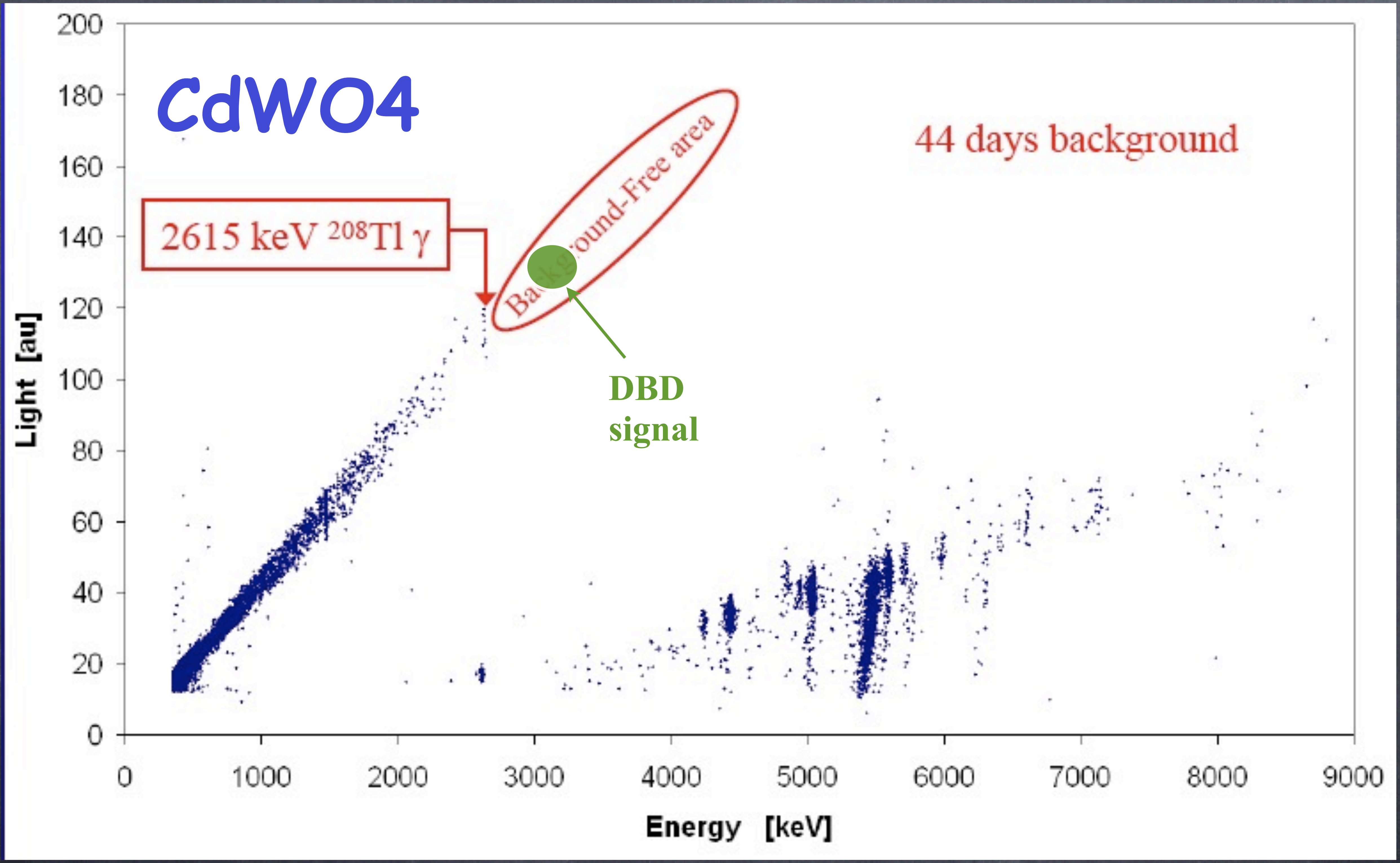
The best so-far



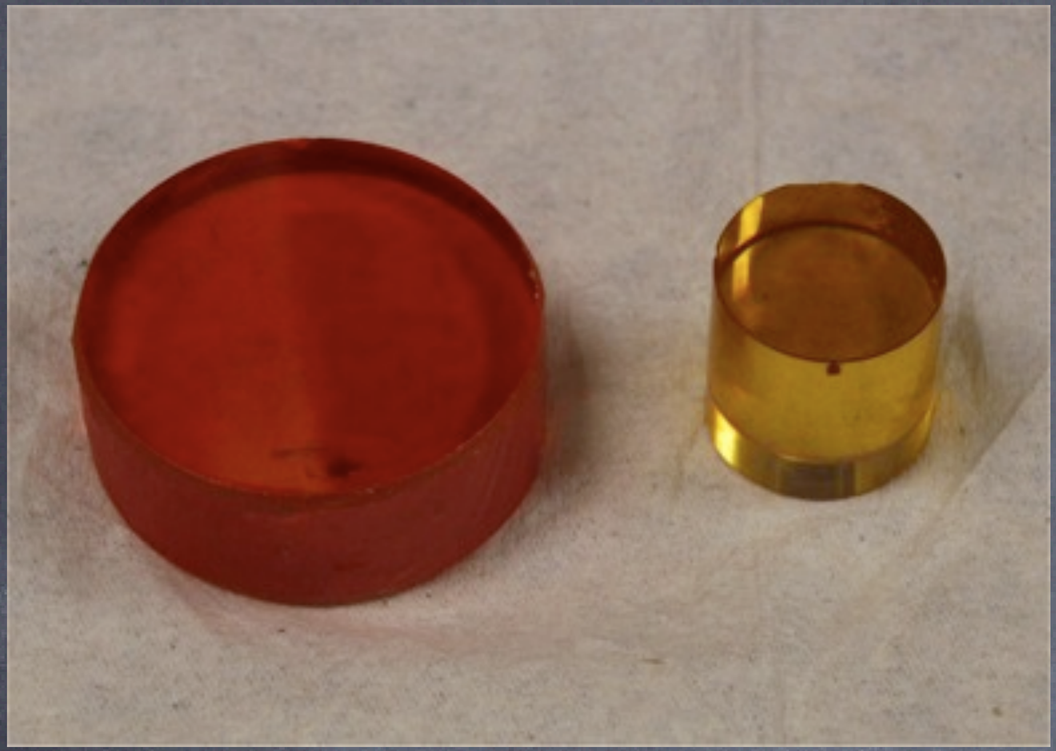


Roman
Pb shield

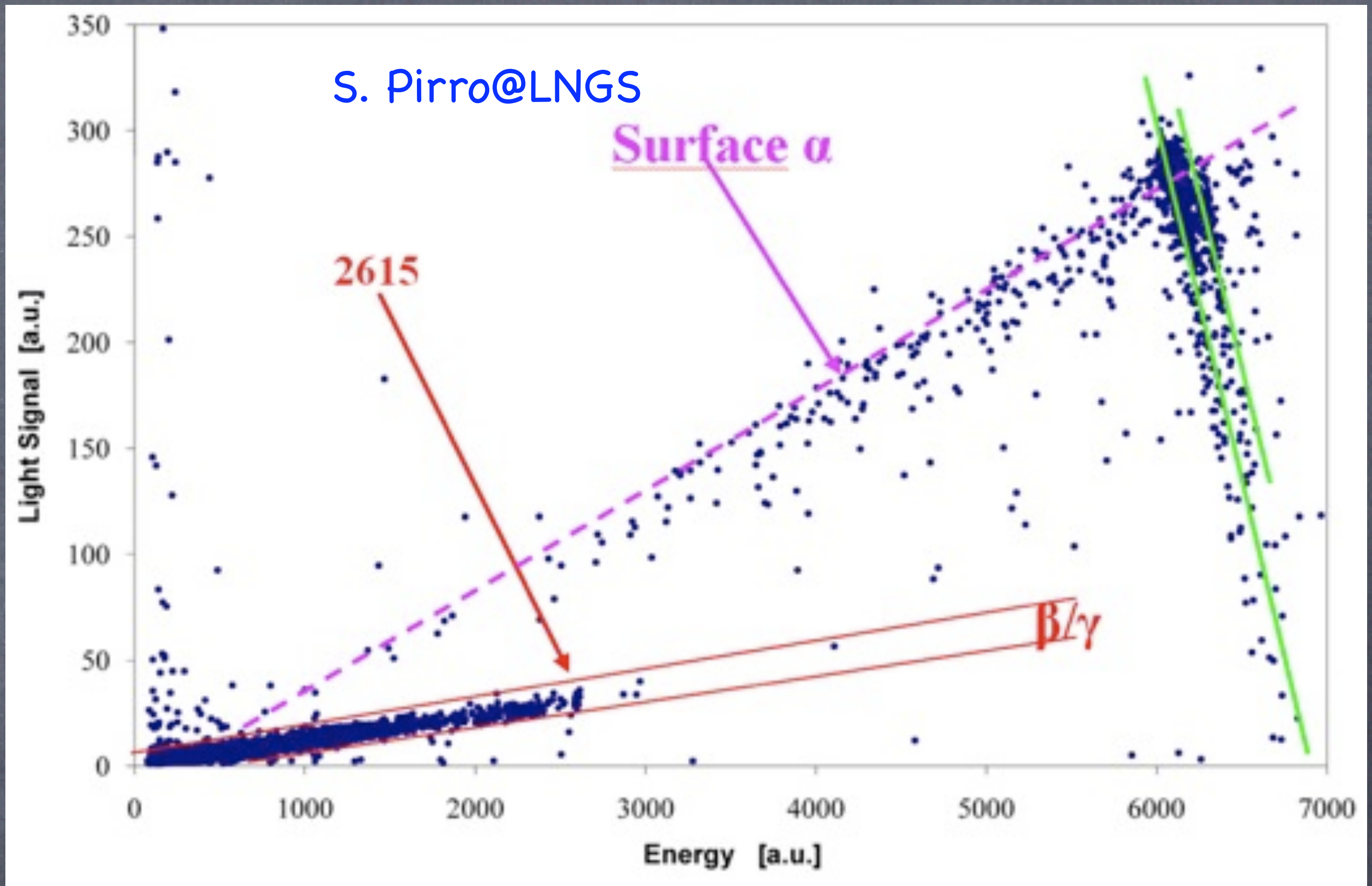
just to make the case clear

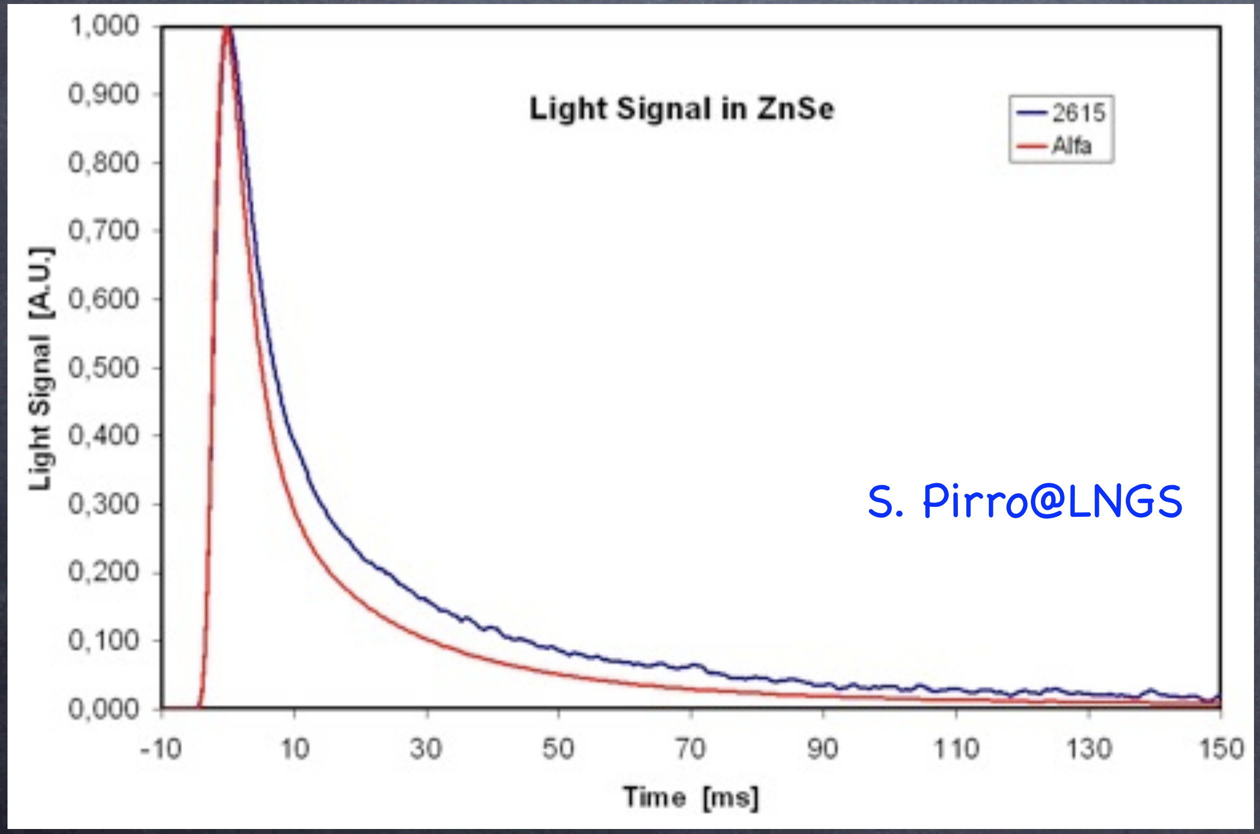


The best compromise (possibly)



ZnSe

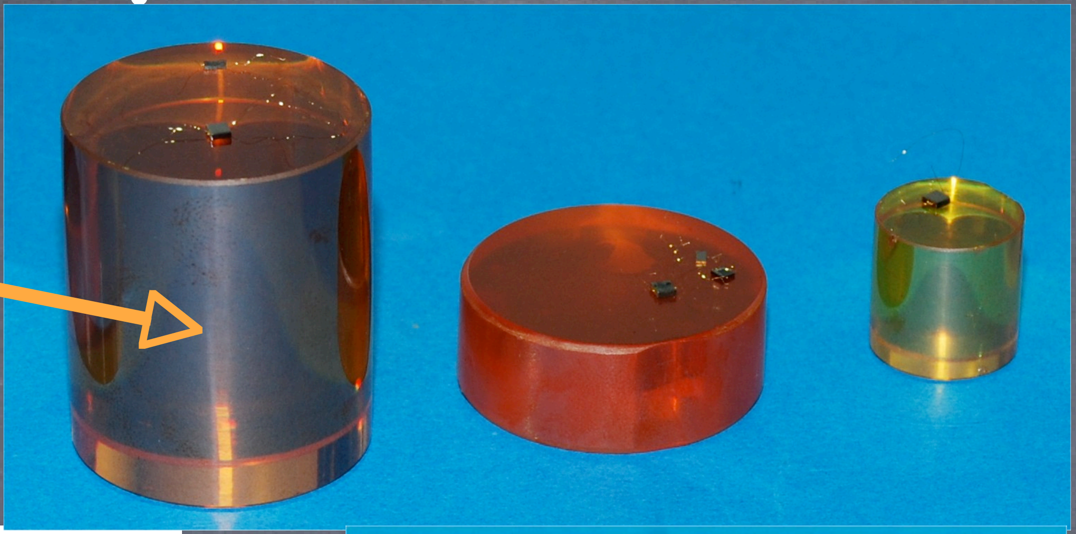


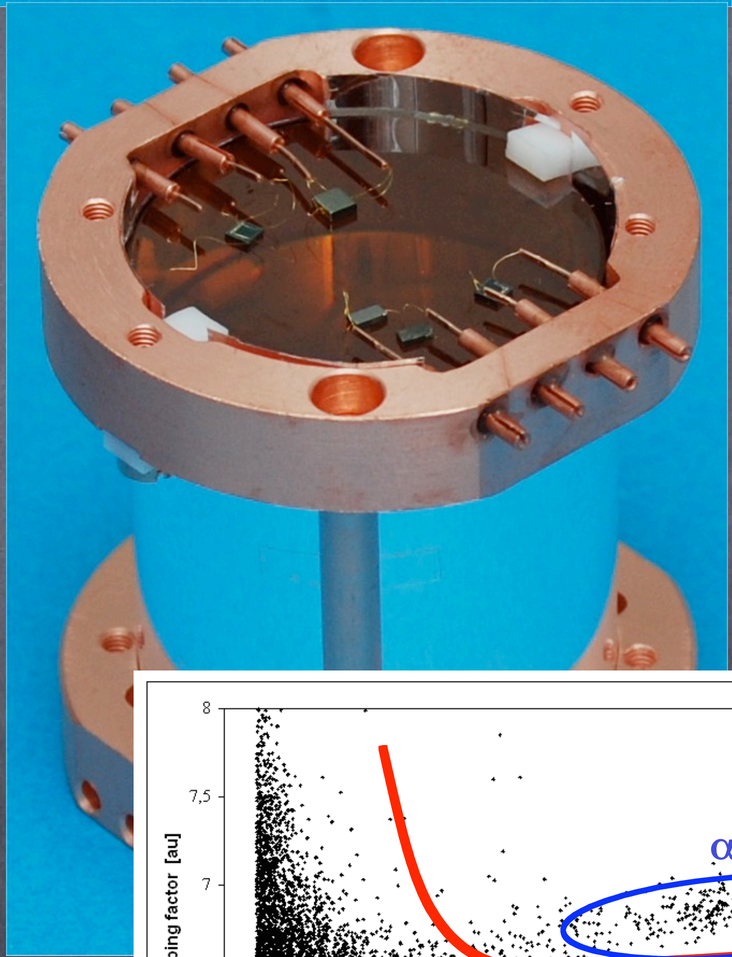


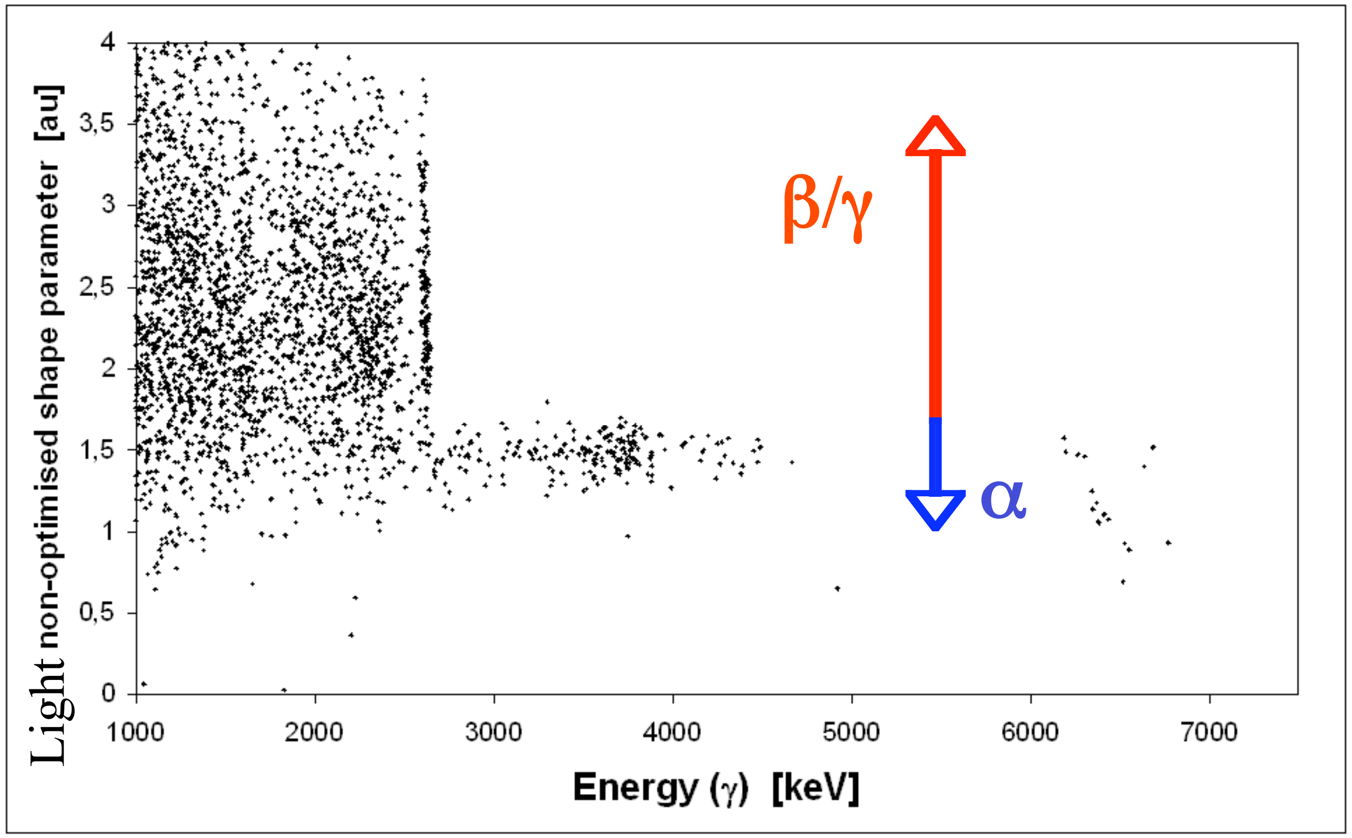
Goal: b < 0.001 c/Kg/KeV/y

Pulse Shape Analysis

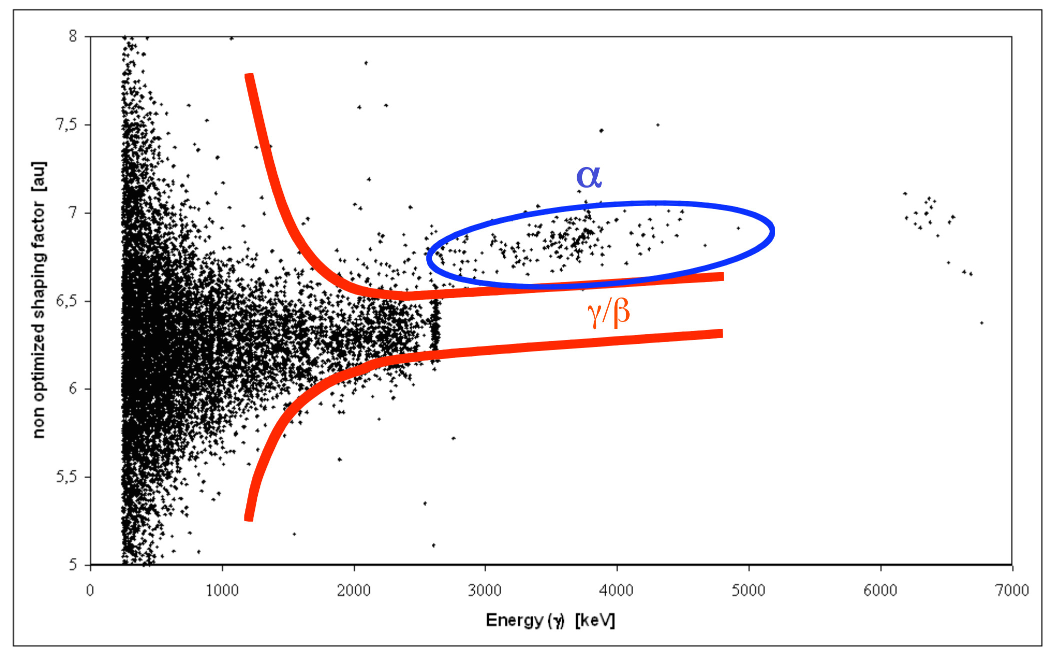
337 g “new” ZnSe Crystal

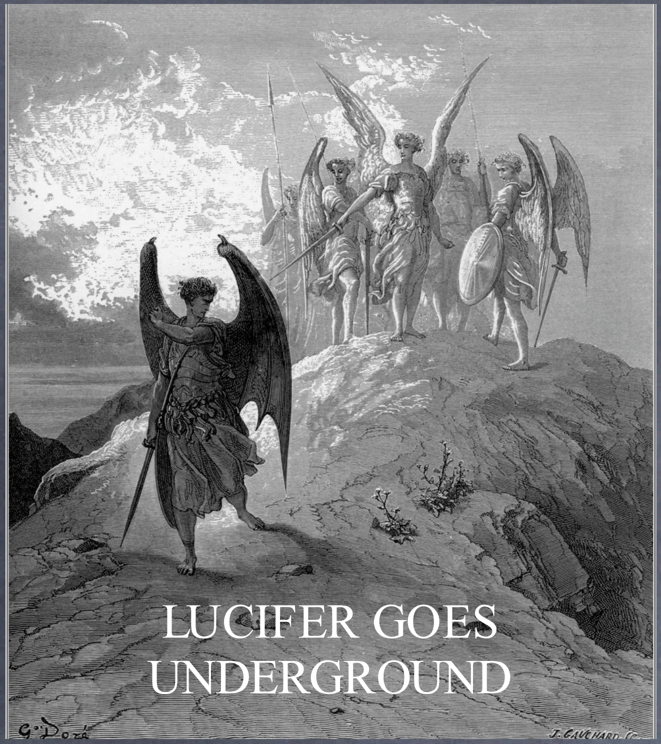






Calibration with ^{232}Th and a smeared α source

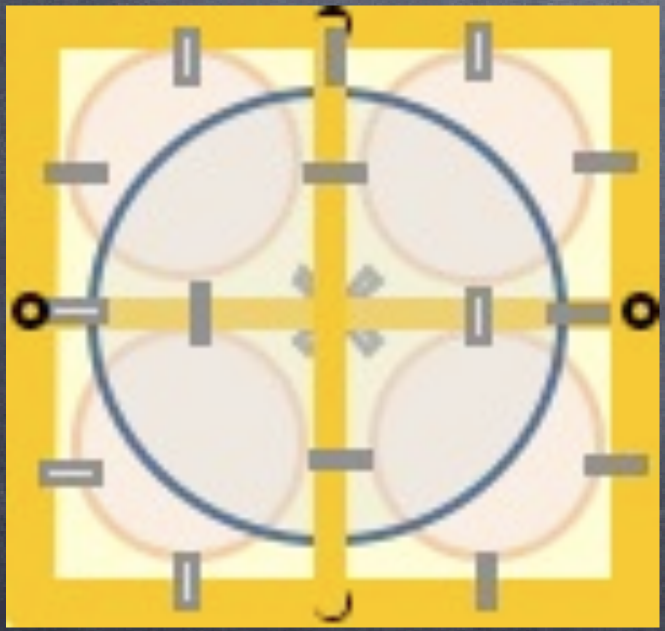


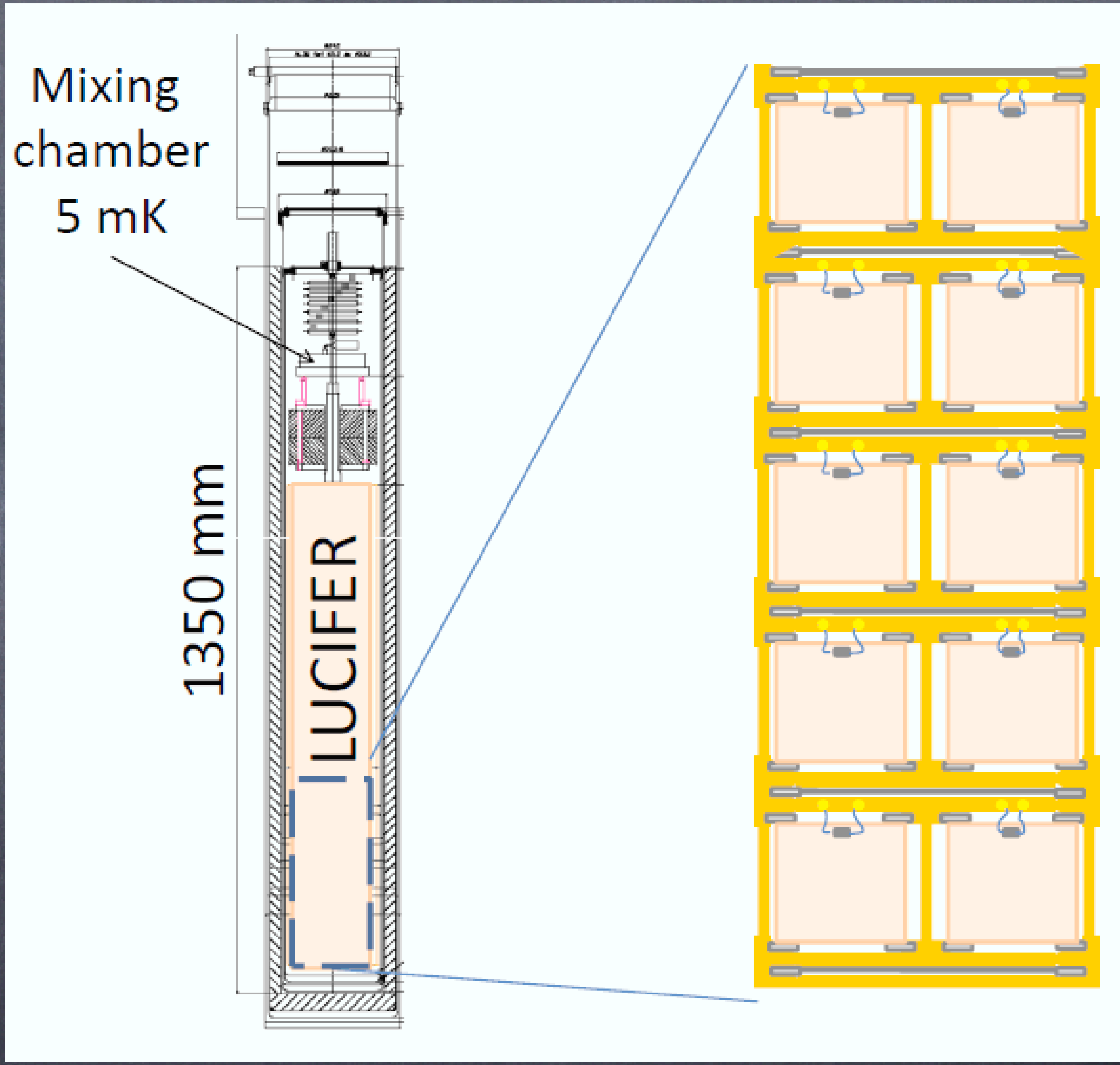


LUCIFER

Low-background **U**nderground **C**ryogenic **I**nstallation **F**or **E**lusive **R**ates

ERC-2009-AdG 247115





The challenge

- negotiate a good contract for ^{82}Se separation
- get chemically pure and radiopure isotope after enrichment
- efficient cristallization

Got Physics ?

- never say never again ! in principle it has twice the nuclei wrt Cuoricino ($T_{1/2}$ > $3*10^{24}$ y) and a factor 200 less in background
- $T_{1/2}$ in excess of 10^{26} y are expected
- the reach depends critically on cost, purification and efficient cristallization (high risk- high reward !)
- It would be great already to open the way to 3rd generation experiment

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
- The second generation experiments might not be enough to win.
- We have to prepare for third generation. Toward 0 background.