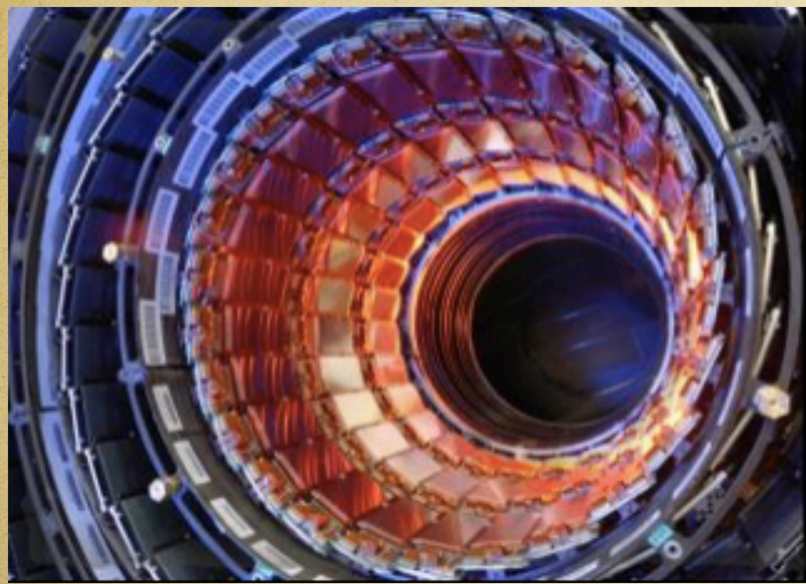
Status of 0νββ research



XXVII GIORNATE DI STUDIO SUI RIVELATORI
Scuola F. Bonaudi

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Villaggio dei Minatori - Cogne (AO)

INFN

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Outline

- The mysterious neutrino
- Dirac or Majorana
- Neutrino-less Double Beta Decay
- Experimental status
- Description of the bolometric approach
- What next ?

a number of questions with us since long ago

- How much does a neutrino weigh ?
- What is the mass ordering (hierarchy)
- Is neutrino a Majorana or Dirac particle
- Do more (sterile) neutrinos exist ?
- Do neutrinos violate CP ?
- Can we observe the CNB (a picture of a universe 1 second old)

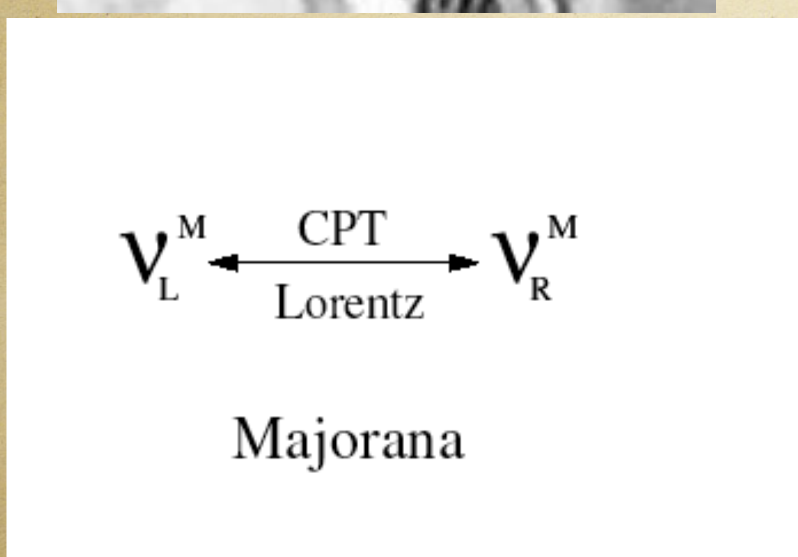
Majorana conjecture

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

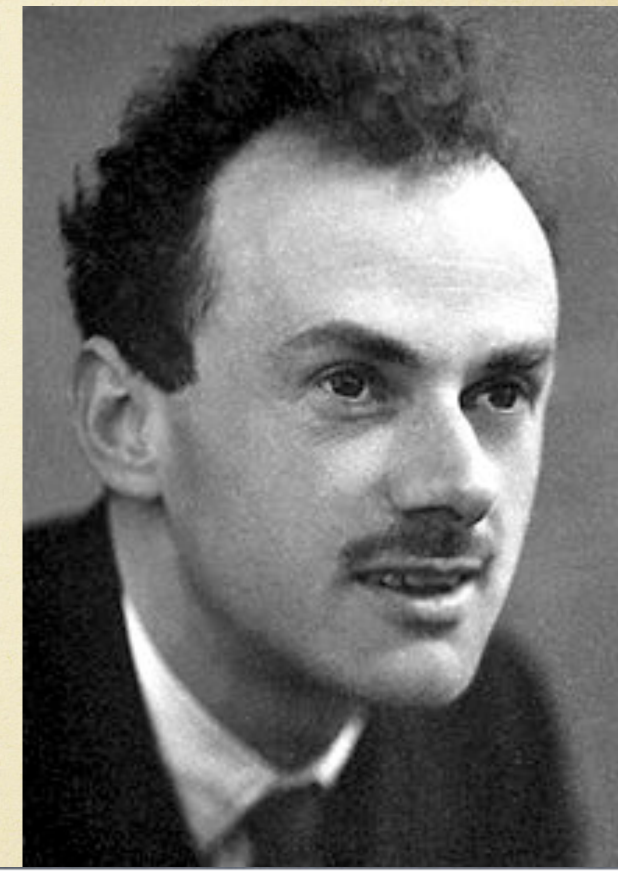
Main consequence :

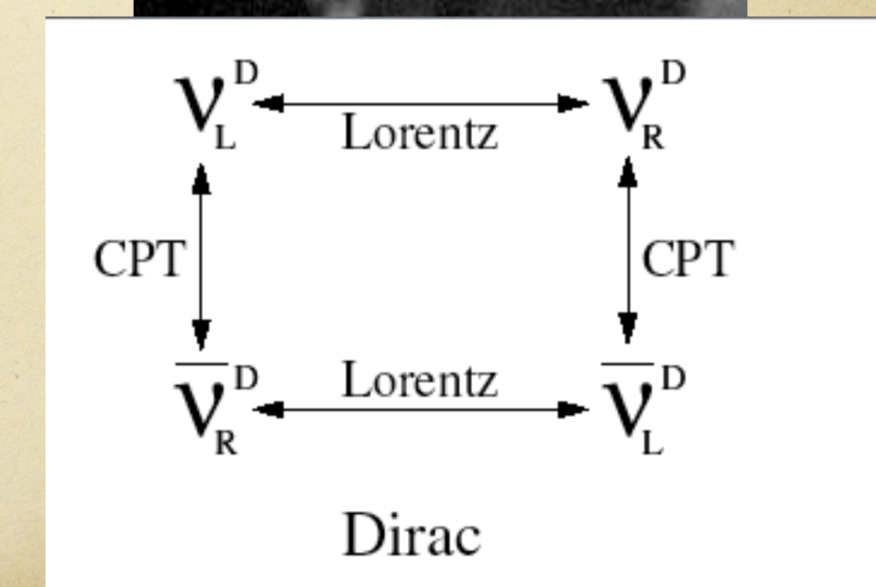
Lepton Number Violation

Majorana vs. Dirac



Majorana





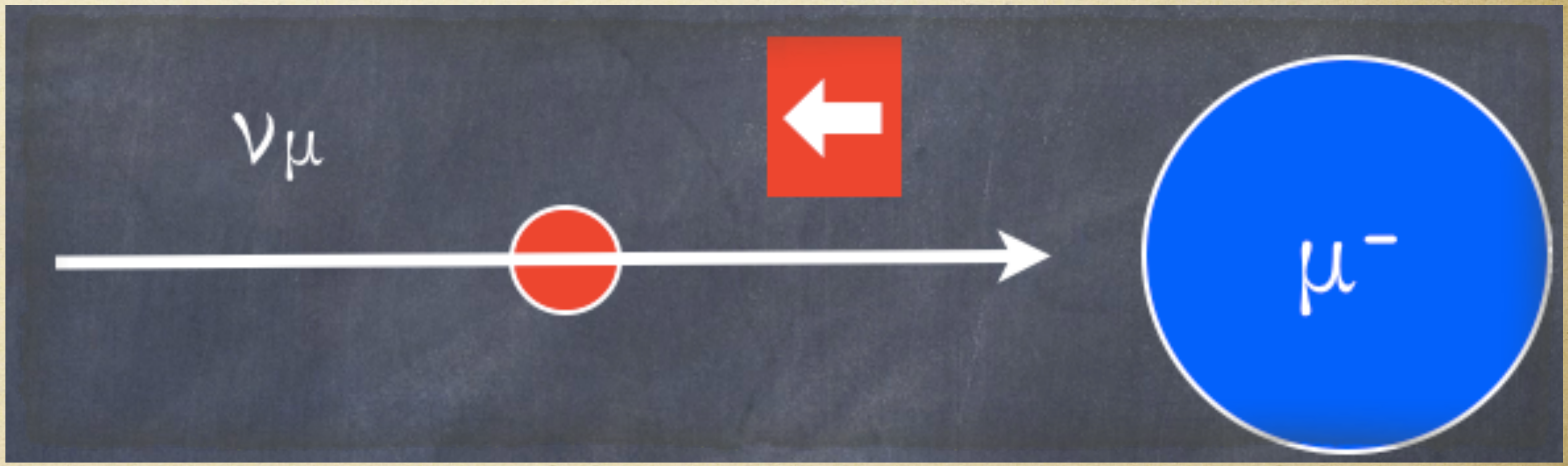
Dirac

Majorana neutrinos

- in the SM, neutrinos (antineutrinos) are strictly produced as left-handed (right-handed) particles. Since neutrino masses are non-zero, this cannot be exactly true.
- the hypothesis of Majorana can be formulated as follows: in the rest frame, neutrinos and antineutrinos are just the same particle and are distinguished only by the spin.
- Majorana neutrinos are the only fermions to be matter and antimatter at the same time. The difference between neutrinos and antineutrinos is not a Lorentz invariant concept, and L must be violated at the order m_ν/p_ν.
- since in usual conditions neutrinos are ultra-relativistic, so that $m_\nu \ll p_\nu$, the deviation from this limit is not observable in most cases.

How to solve ?

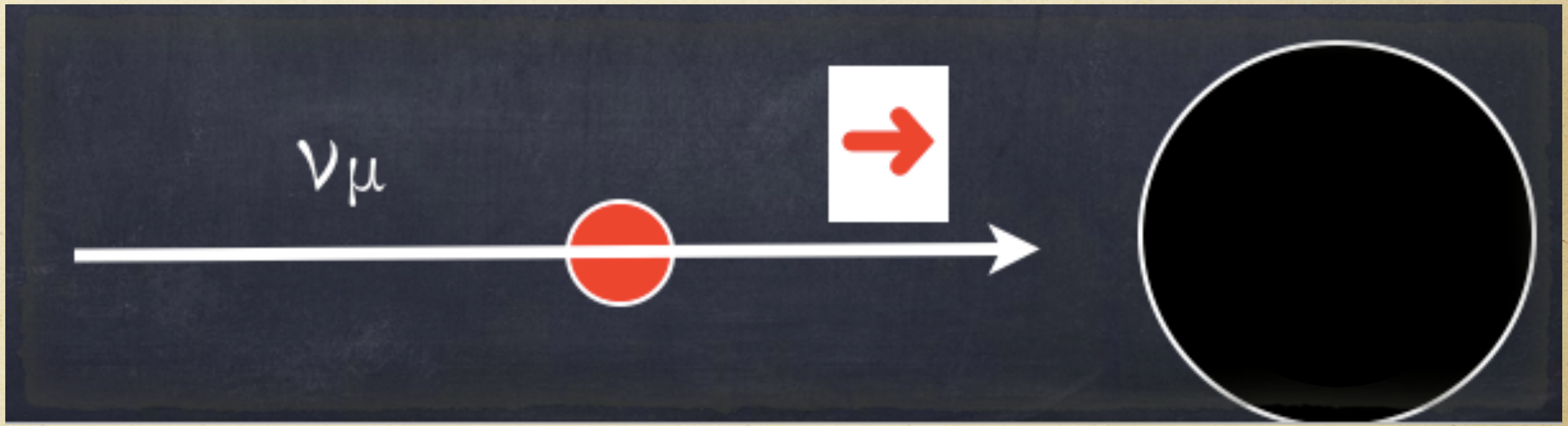
- in principle it is easy
- you take a neutrino beam. It does interact with a target and makes negative muons. If some of the neutrinos flip helicity in the final state you observe antineutrinos produced positive muons



Wait, there is a problem !!!!

Massive neutrinos required

- in case of Dirac $\nu \neq \bar{\nu}$ and ν has L=-1 (as the μ^-)
- if you have a massless ν (lepton) right handed (helicity flip) the result would be



- weak interaction is V-A

No problem: neutrinos are massive

The Nobel Prize in Physics 2015

Photo: A. Mahmoud

Takaaki Kajita

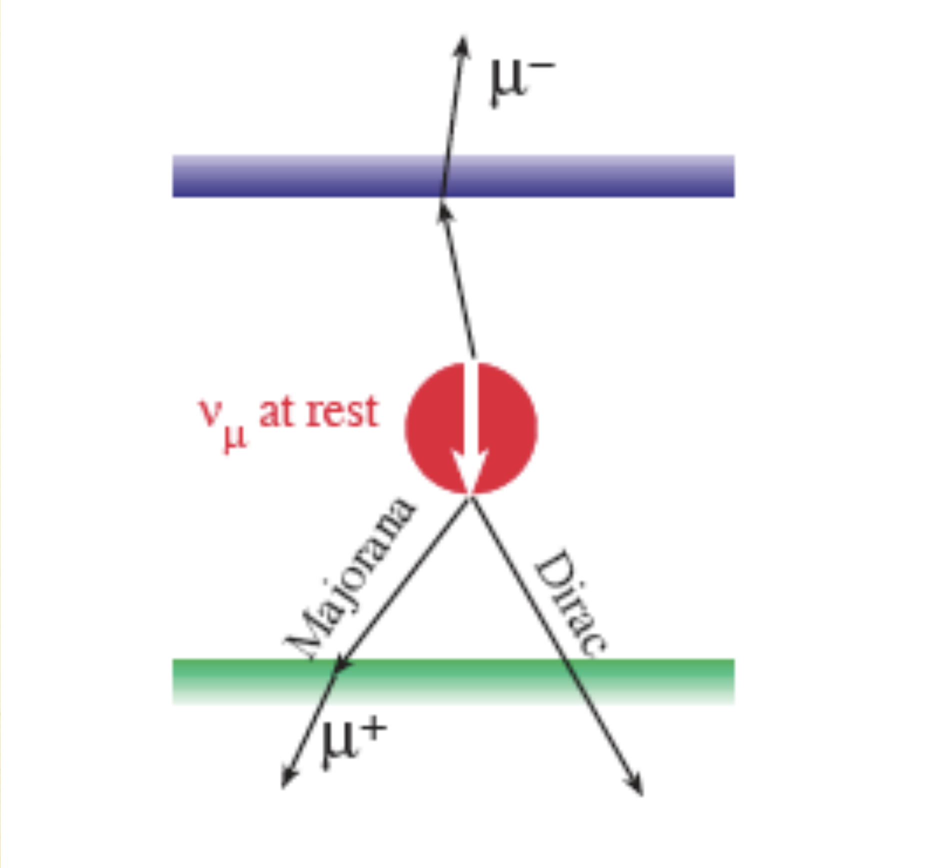
Prize share: 1/2

Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

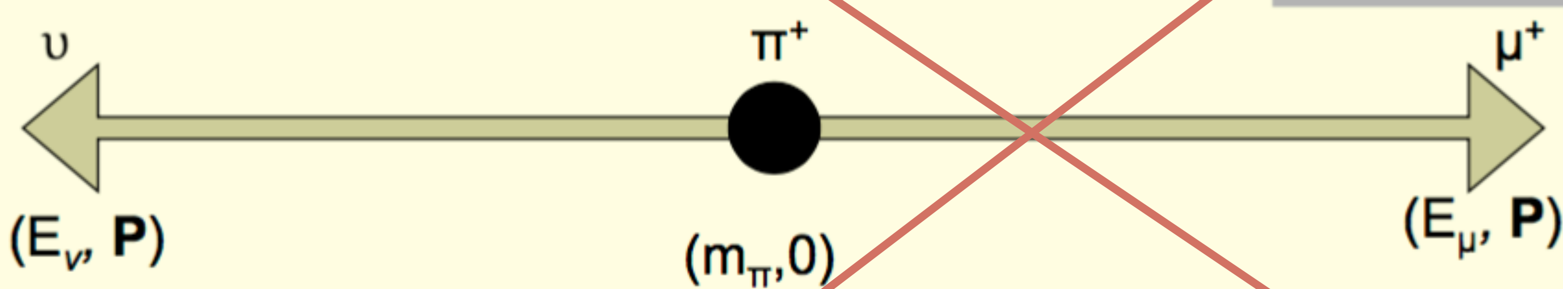
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



Yes , but…

How to produce a right handed neutrino

Pion Decay



CM Frame

$$E_\upsilon + E_\mu = E_\pi$$

$$\sqrt{m_\upsilon{}^2 + P^2} + \sqrt{m_\mu{}^2 + P^2} = m_\pi$$

Lab Frame

$$\gamma = \frac{E_\upsilon}{m_\upsilon} \qquad E_\pi = \gamma m_\pi$$

$$E_\pi = \frac{m_\pi{}^2 - m_\mu{}^2}{2m_\upsilon}$$

This will produce a neutrino at rest in the lab frame.

to make the story short:

for 50meV of ν mass

pion need to have E=80000 TeV

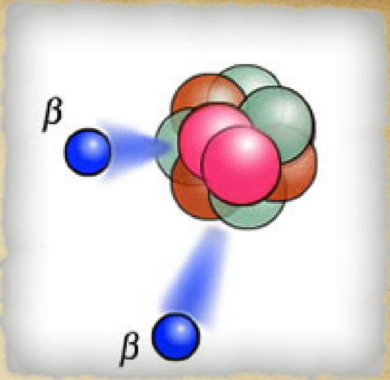
therefore back to 30's

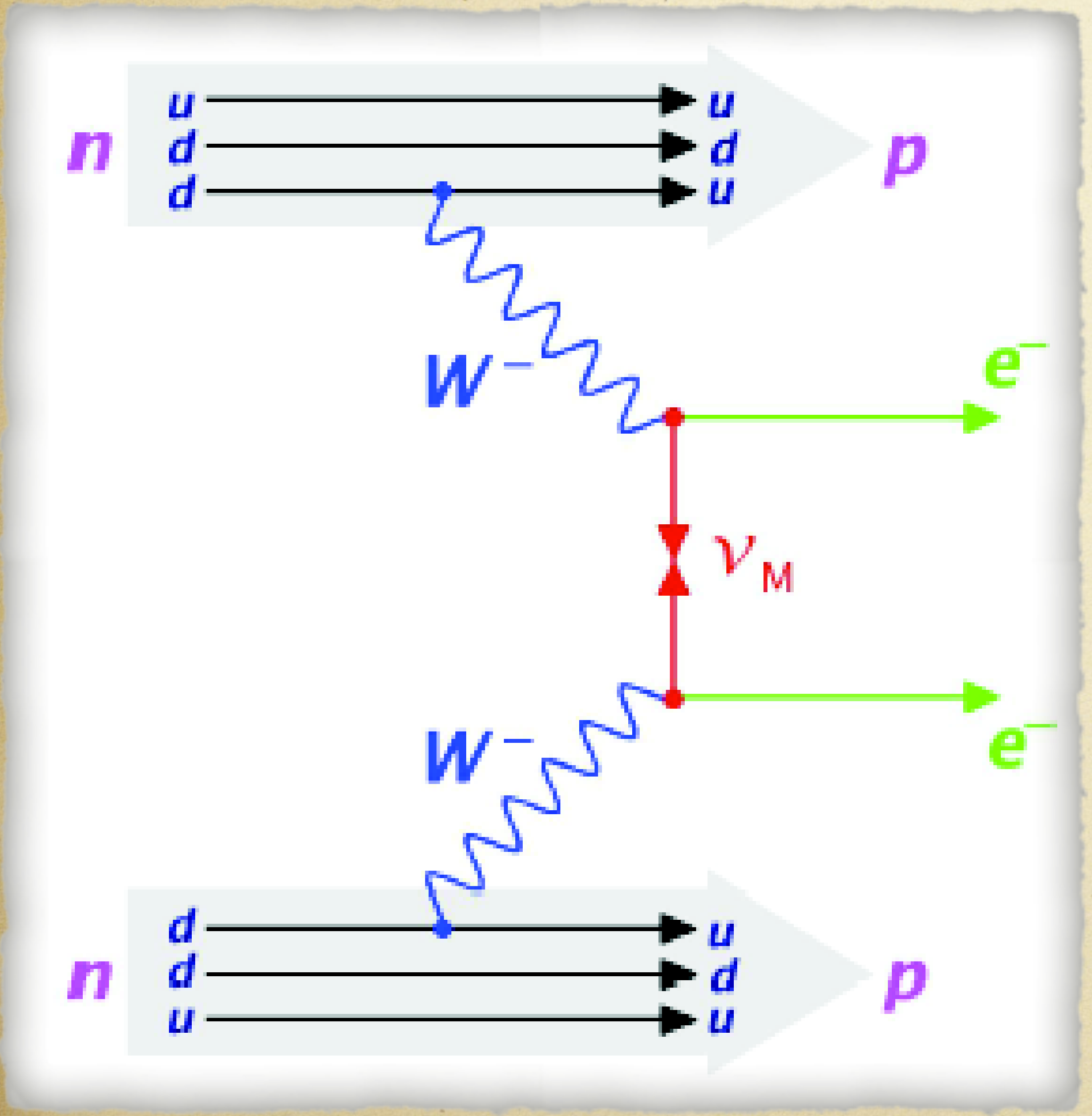
Indeed nobody payed much attention to the Furry hypothesis (1939) that a Majorana neutrino could induce Neutrino-less DBD via helicity flip

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 ($0\nu\beta\beta$)





Only if:

Majorana Neutrinos

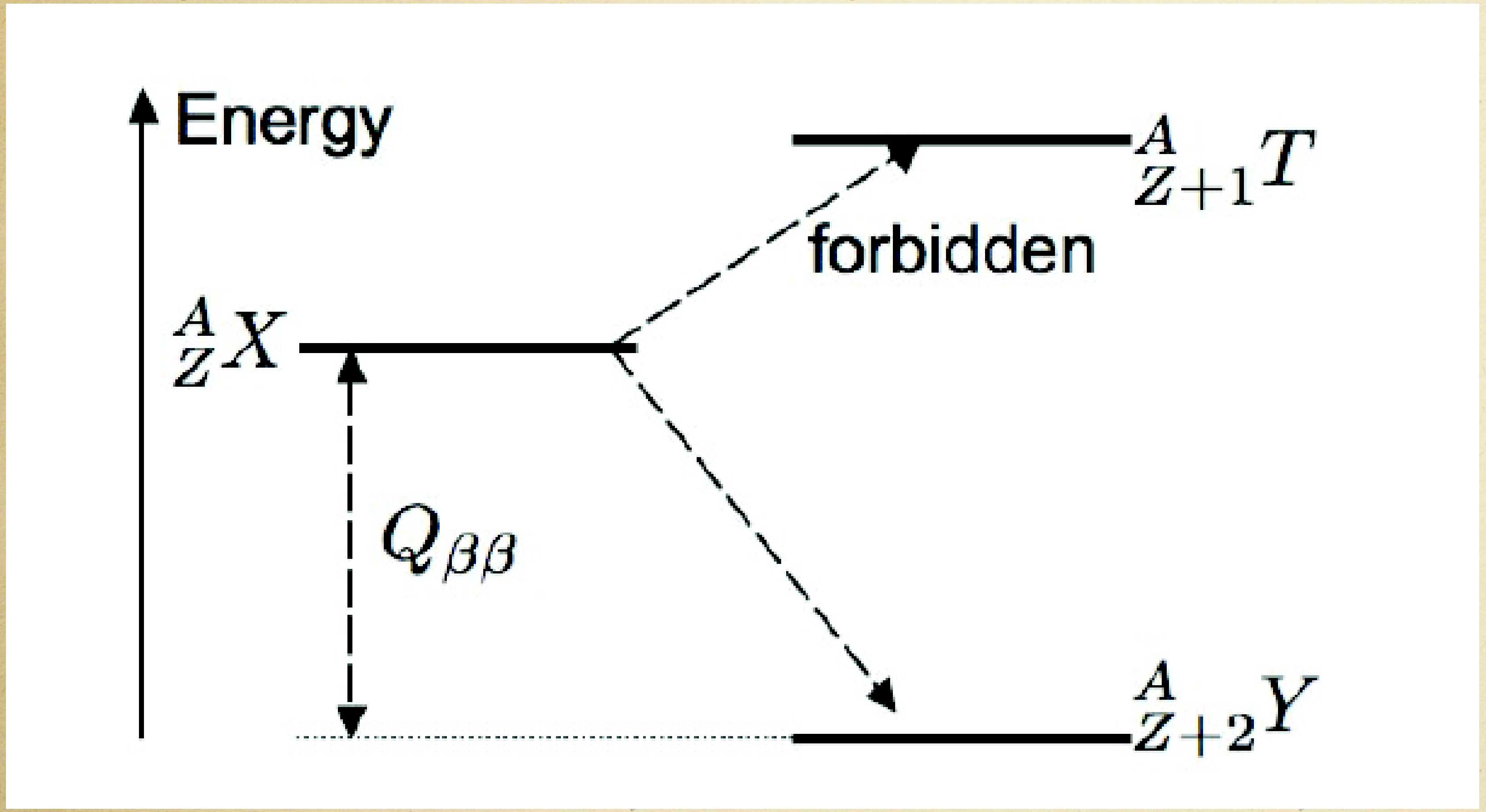
If observed:

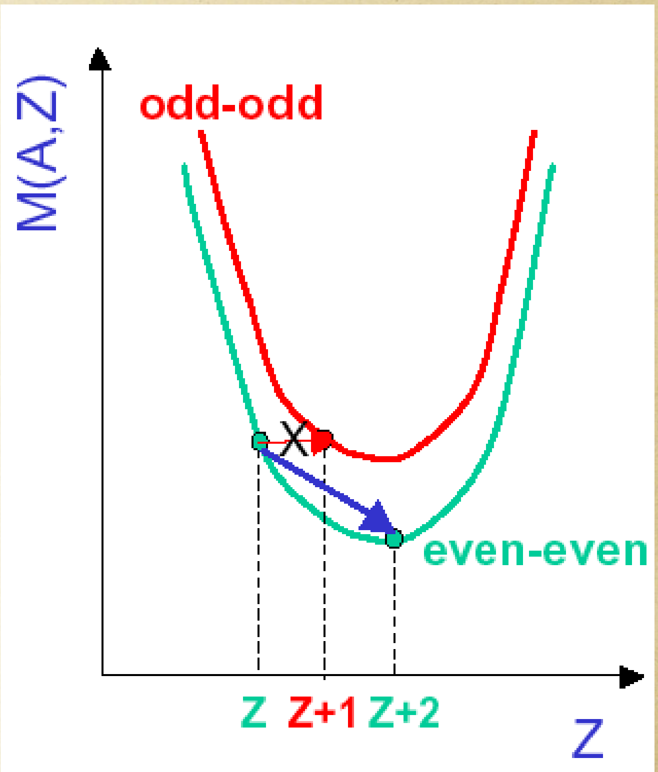
Proof of the Majorana nature of Neutrino

just at first glance…

- it looks unlikely to happen frequently
- two neutrons that beta-decay at the ‘same’ time in the ‘same’ place
- well…let’s see first how a ‘normal’ double beta decay (with emission of two neutrinos) happens and how often it happens

again from the 30’s



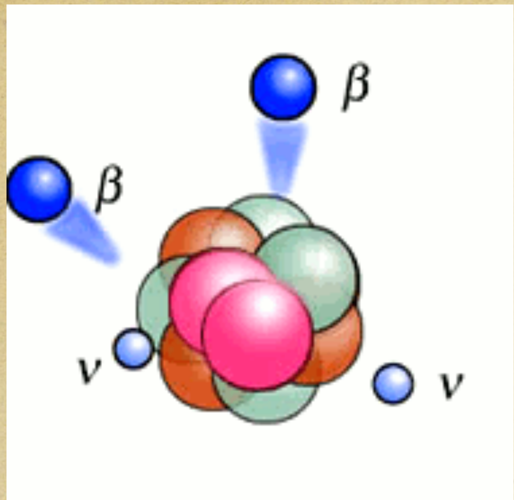


1935

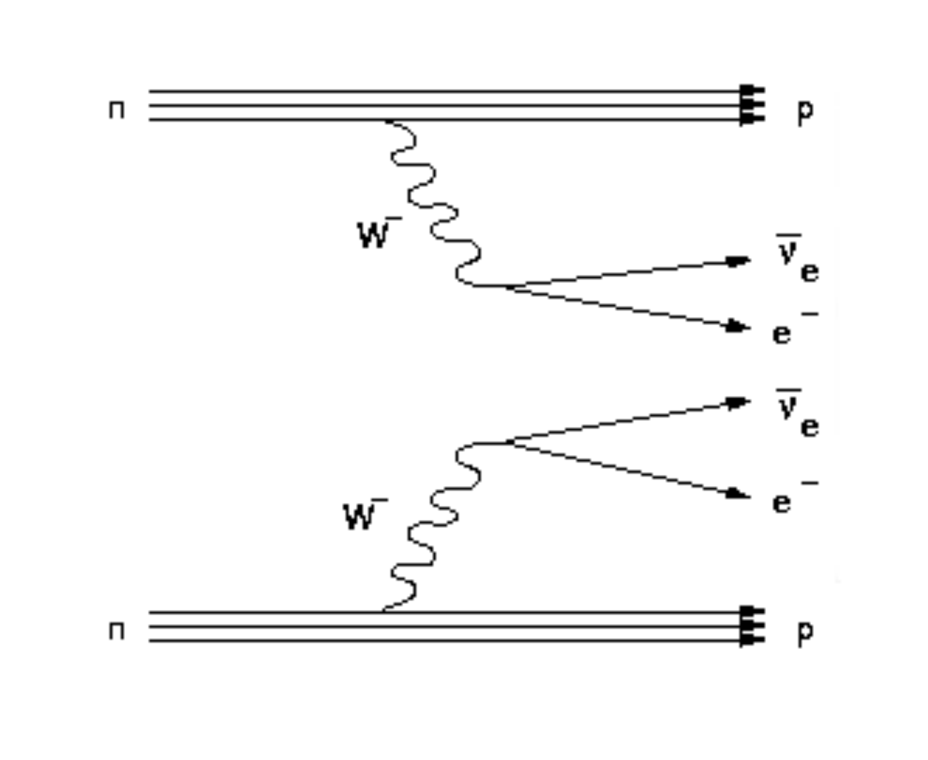
1963

only few nuclei can do it

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



the ‘normal’ one



Nuclide	Half-life, 10^{21} years
^{48}Ca	$0.044^{+0.005}_{-0.004} \pm 0.004$
^{76}Ge	$1.84\ ^{+0.09}_{-0.08}\ ^{+0.11}_{-0.06}$
^{82}Se	$0.096 \pm 0.003 \pm 0.010$
^{96}Zr	$0.0235 \pm 0.0014 \pm 0.0016$
^{100}Mo	$0.00711 \pm 0.00002 \pm 0.00054$
	$0.69^{+0.10}_{-0.08} \pm 0.07$
^{116}Cd	$0.028 \pm 0.001 \pm 0.003$
^{128}Te	7200 ± 400
^{130}Te	$0.7 \pm 0.09 \pm 0.11$
^{136}Xe	$2.165 \pm 0.016 \pm 0.059$
^{150}Nd	$0.00911^{+0.00025}_{-0.00022} \pm 0.00063$
^{238}U	2.0 ± 0.6

overall….. 10^{20} - 10^{21} years

the ‘special’ one !
how long should we wait ?

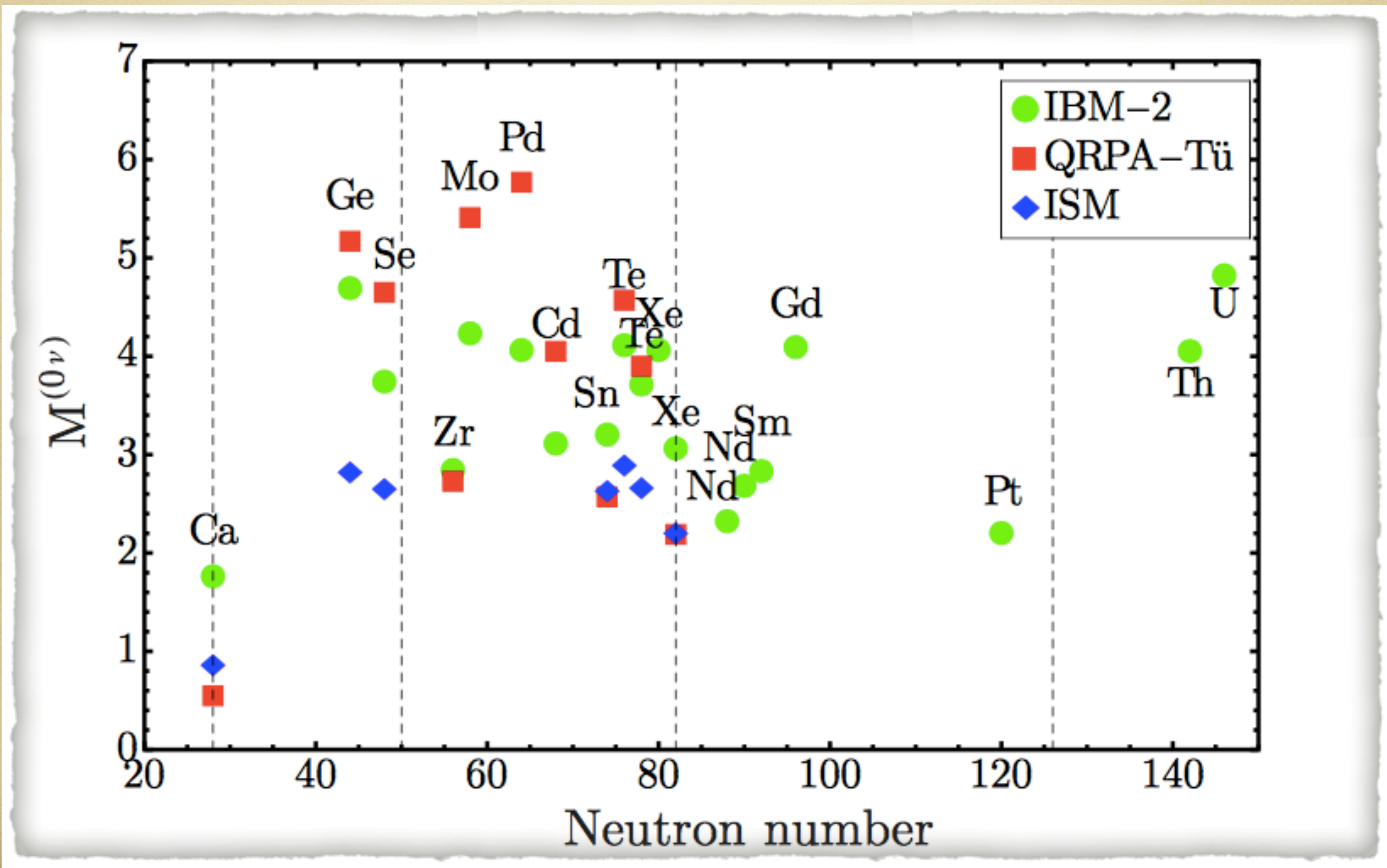
parameter containing the **physics**

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

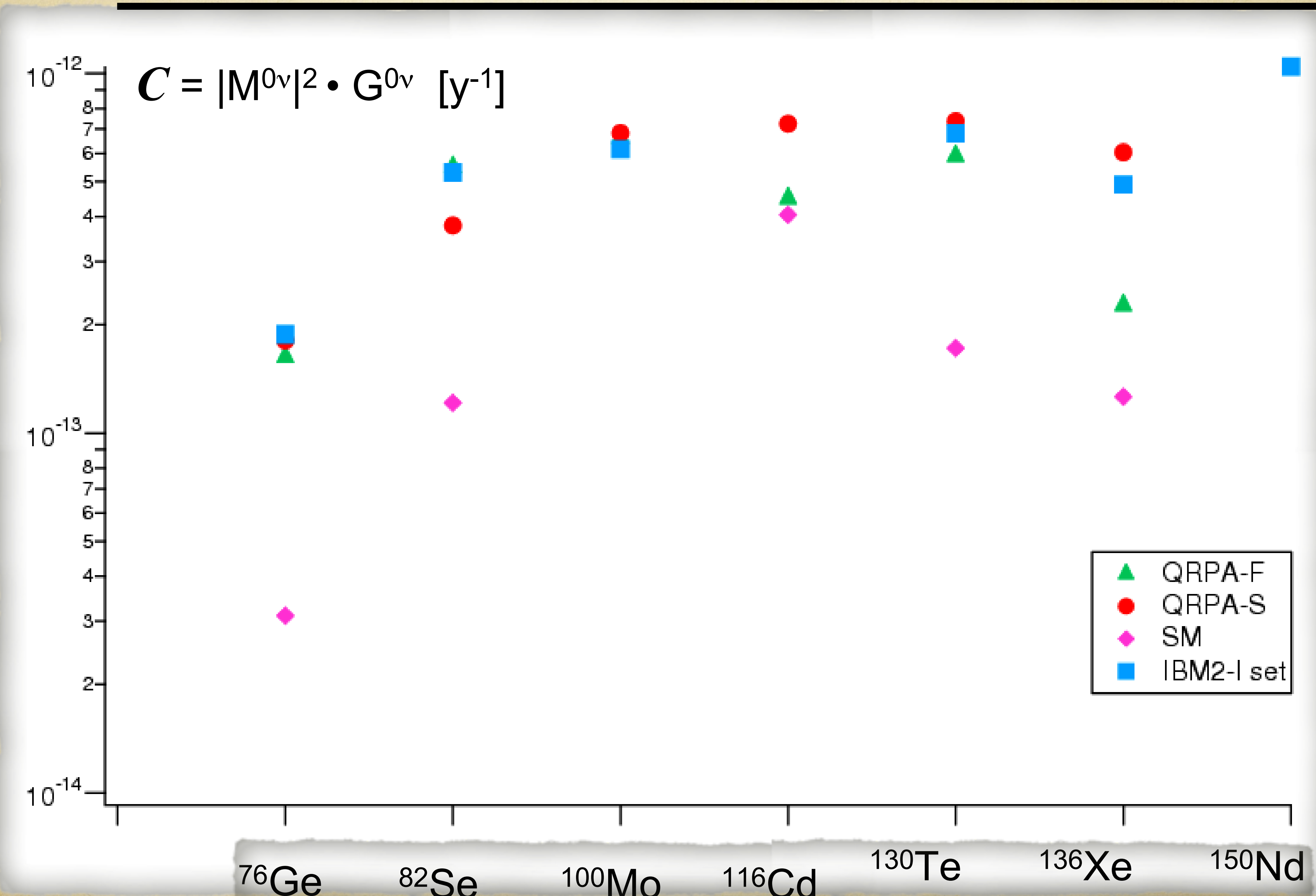
what the **experimentalists** try to measure

what the **nuclear theorists** try to calculate

NME
Different models, some discrepancy



M*(Phase Space)



just on the back of the envelope

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

$C \sim 10^{-12}\ y^{-1}$, $m_e \sim 500$ keV, $m_{\beta\beta} \sim 50$ meV

$\tau_{1/2}^{0\nu} > 10^{24}$ y

[universe life $15\ 10^9$ y , Avogadro number $6\ 10^{23}$]

something more worrisome

$$\mathcal{M} \equiv g_A^2\, \mathcal{M}_{0\nu} = g_A^2 \left(M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)} \right)$$

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

$$g_A = \begin{cases} g_{\text{nucleon}} & = 1.269 \\ g_{\text{quark}} & = 1 \\ g_{\text{phen.}} & = g_{\text{nucleon}} \cdot A^{-0.18} \end{cases}$$

who knows ?

$2\nu\beta\beta$

$g_A \to g_A \cdot (1-\delta)$ $\qquad$ $S \cdot (1-\delta)^4$

For instance, if we have a decrease by δ = 10 (20)% of the axial coupling, lifetime would increase by a factor of $1/(1-\delta)^4 = 1.5\ (2.5)$

for ^{82}Se
$\delta = 0.55$
the 'factor' would be 11 !!!!!!

what are we looking at ?

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

The observable comes as a combination of the three neutrino masses, the mixing angles and the Majorana phases.

Let's parameterize as a function of the known parameters

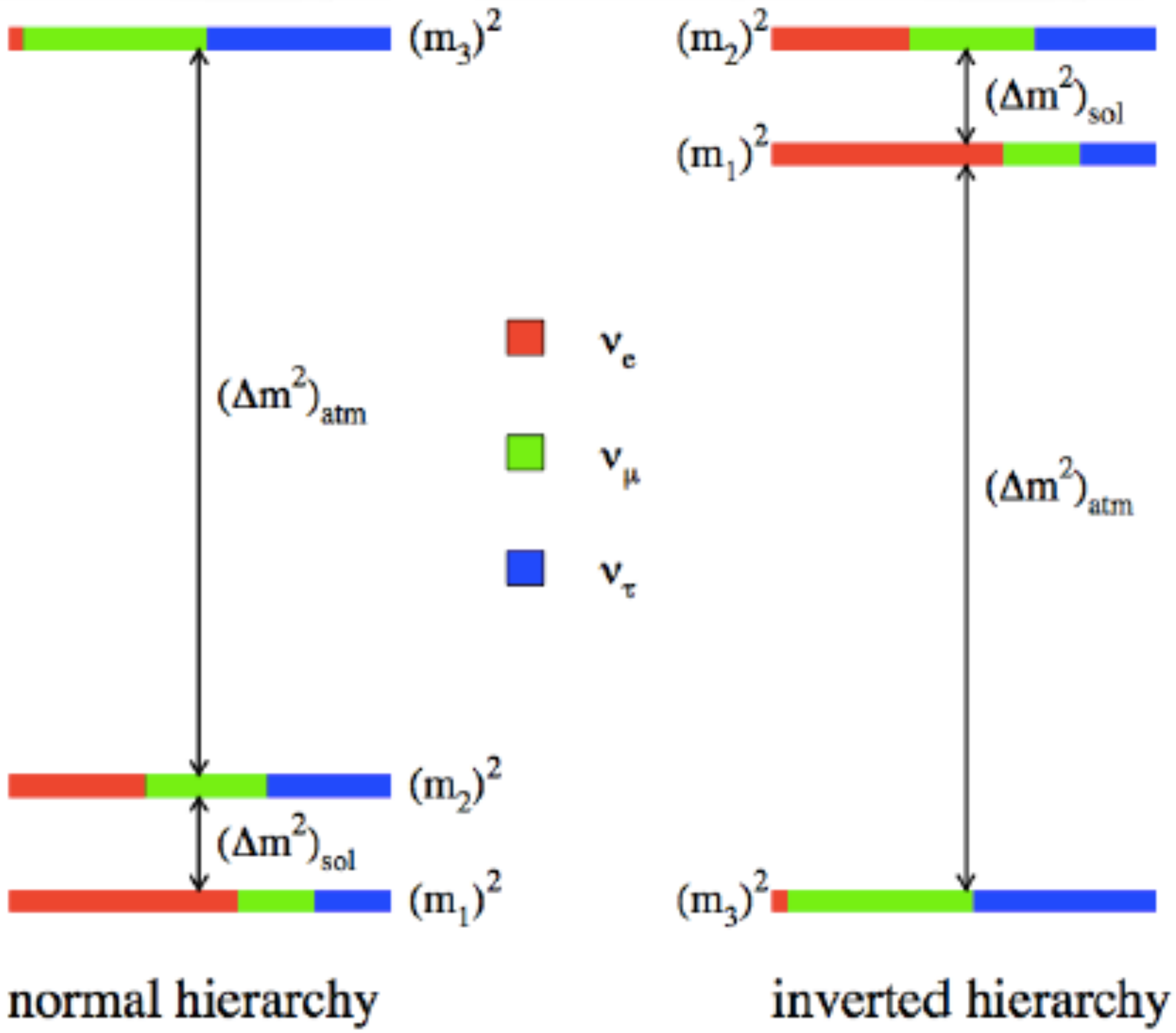
$$m_{\beta\beta} = f(U_{ek}, m_{lightest}, \delta m_{sol}, \Delta m_{atm})$$

Here what we know

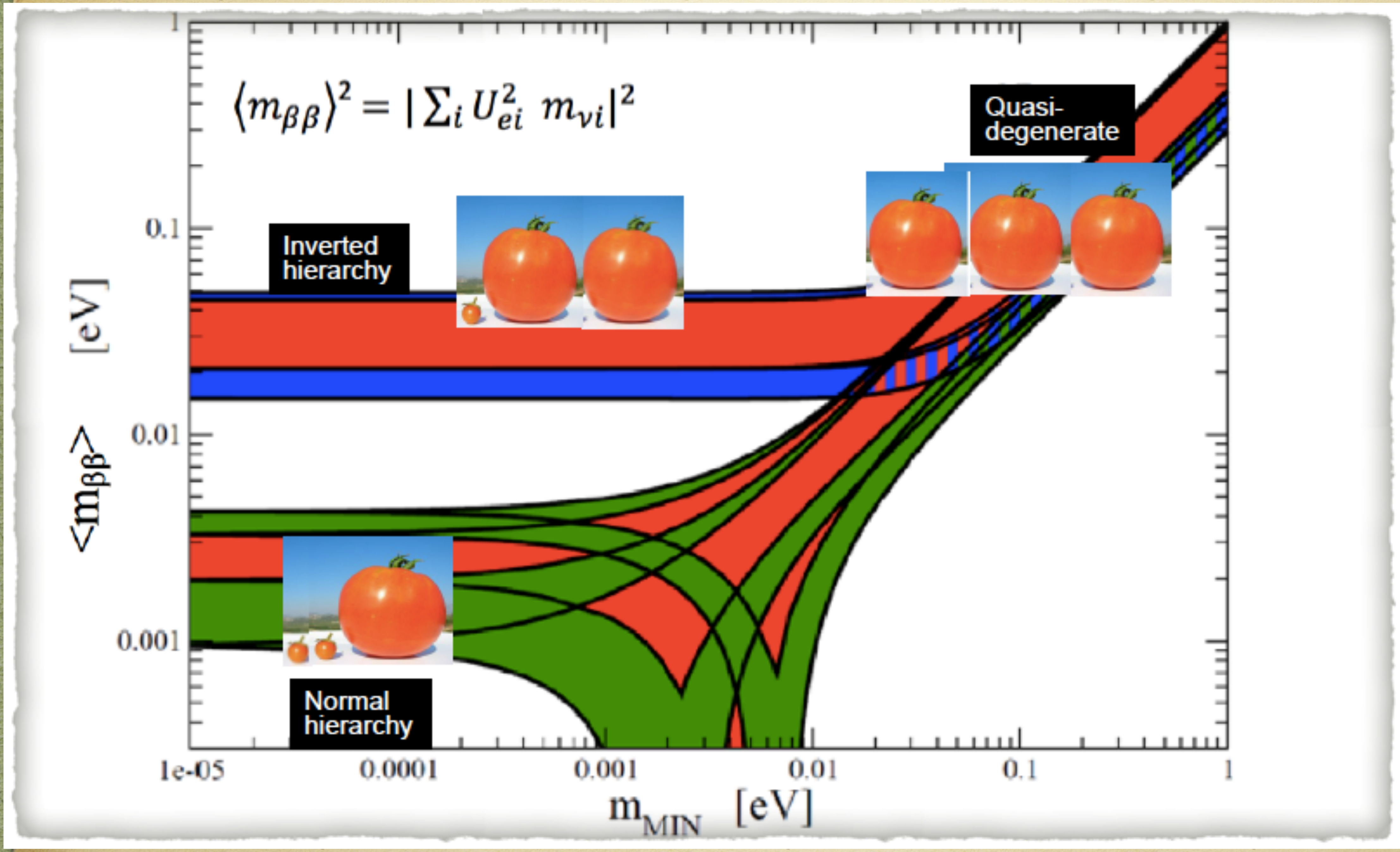
parameter	best fit ± 1σ
Δm^2_{21} [10^{-5}eV^2]	7.56±0.19
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NH)	2.55±0.04
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IH)	2.49±0.04
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$
$\sin^2\theta_{23}/10^{-1}$ (NH)	$4.30^{+0.20}_{-0.18}$ [a]
$\sin^2\theta_{23}/10^{-1}$ (IH)	$5.96^{+0.17}_{-0.18}$ [b]
$\sin^2\theta_{13}/10^{-2}$ (NH)	$2.155^{+0.090}_{-0.075}$
$\sin^2\theta_{13}/10^{-2}$ (IH)	$2.140^{+0.082}_{-0.085}$
δ/π (NH)	$1.40^{+0.31}_{-0.20}$
δ/π (IH)	$1.44^{+0.26}_{-0.23}$

sign of Δm^2 unknown (ordering of masses)

Two possibilities:



the final result is :



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

.

set a goal of exploring IH. Get down to 10-20 meV

The name of the game

expected number of ββ0ν events

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

detector mass

isotopic abundance

live time

efficiency

molecular mass

ββ0ν half-life

mean number of background counts around the Q-value

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

background rate in counts/keV/kg/y

energy resolution (detector FWHM)

detector mass

live time

how many events ?

Number of events = (Number of moles* Avogadro number*data collection time)/lifetime

$N_A = 6 * 10^{23}$

$N_y = 1$

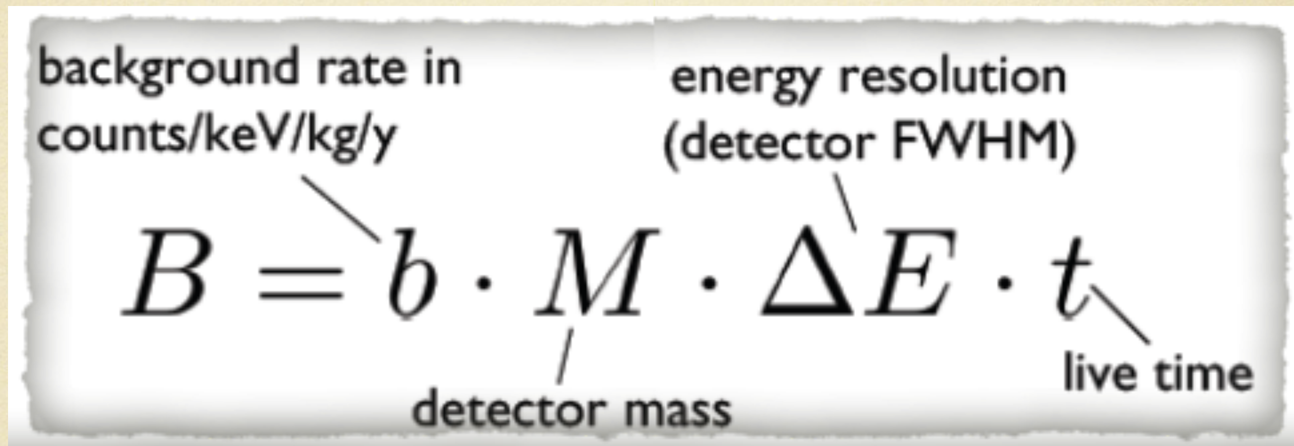
$\tau = 10^{26}$

$N_{eventi} = 10$

1600 moles

that for ^{130}Te makes 200 Kg

and how little background?



1 count of background with a detector of 200 kg of (good)* mass and and an energy resolution of 10 keV requires 0.001 counts/keV/kg/y (if you want to be more impressed is 1 count per ton) !

* *if the good isotope is not 100%, the mass that generates background is the total one !

Sensitivity is S/√B

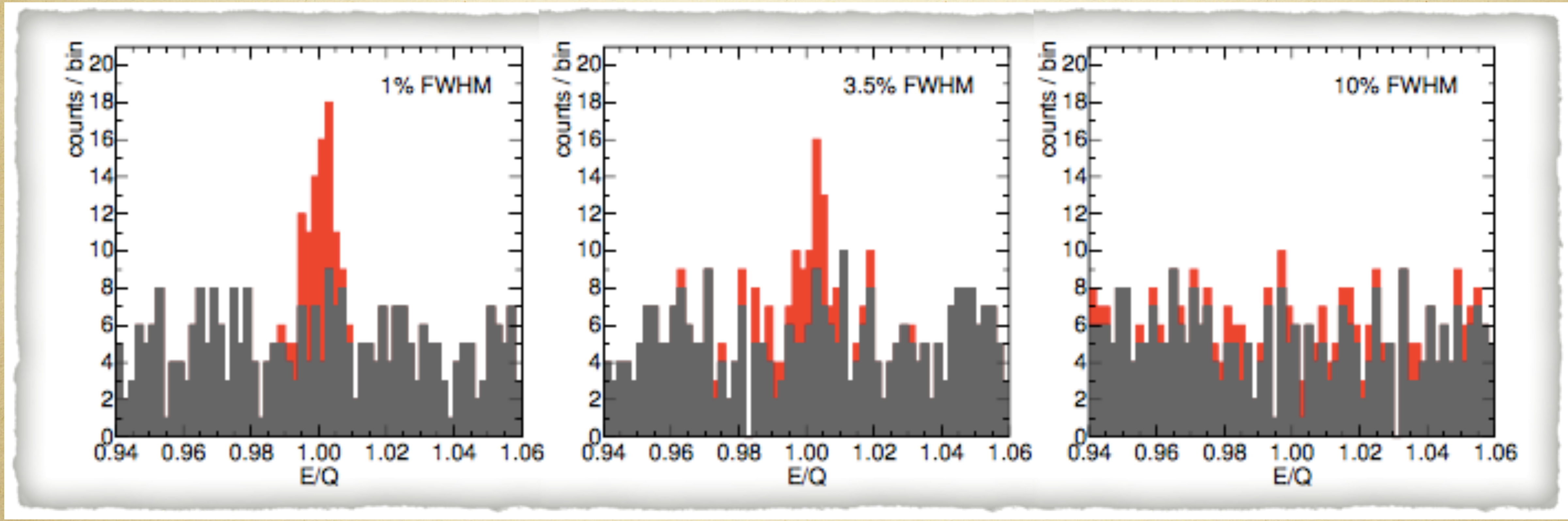
Sensitivity $\propto K \sqrt{\dfrac{M \cdot t}{B \cdot \Delta E}}$ (i.a. • ε)

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

which way ?

- increase abundance of the right isotope (linear)
- increase M a lot (square root)
- decrease B (ideally get to mythical zero background and get rid of the square root)
- get an extraordinary good energy resolution (remember we are talking of a signal of a few MeV but still gaining only by a square root)

effect of energy resolution



S= 50 events

B= 1 count/keV

brutal consideration

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

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

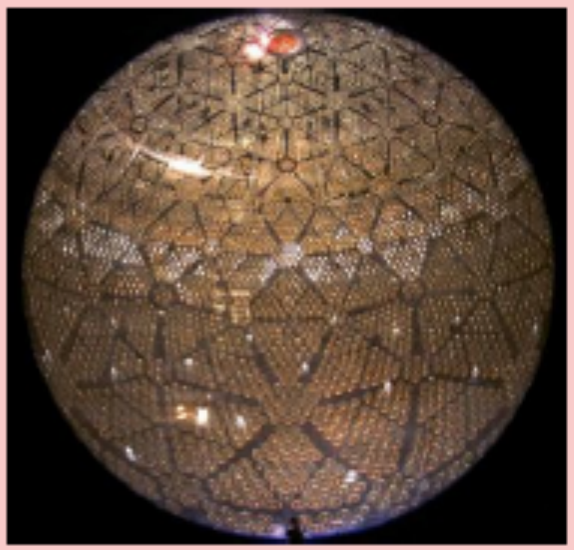
To get a factor 10 in $m_{\beta\beta}$ you have a choice :

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

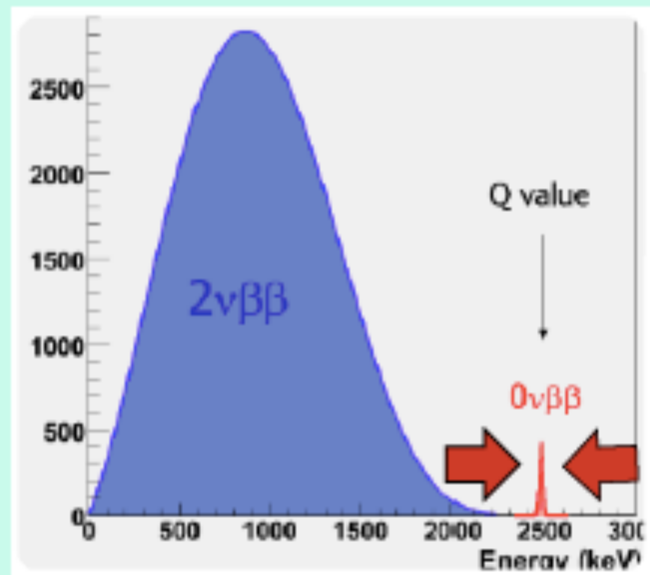
meaning :

The "Brute Force" Approach



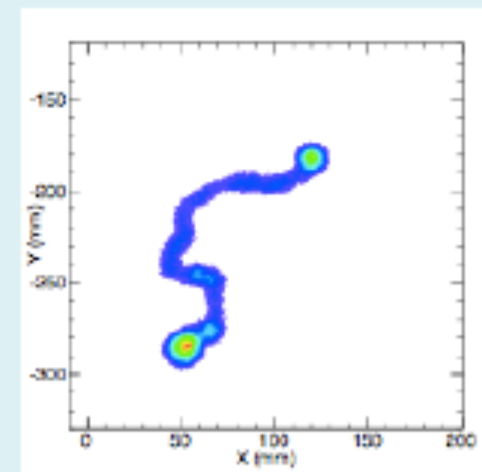
focus on the numerator with **a huge amount of material**
(often sacrificing resolution)

The "Peak-Squeezer" Approach



focus on the denominator by **squeezing down ΔE**
(various technologies)

The "Final-State Judgement" Approach

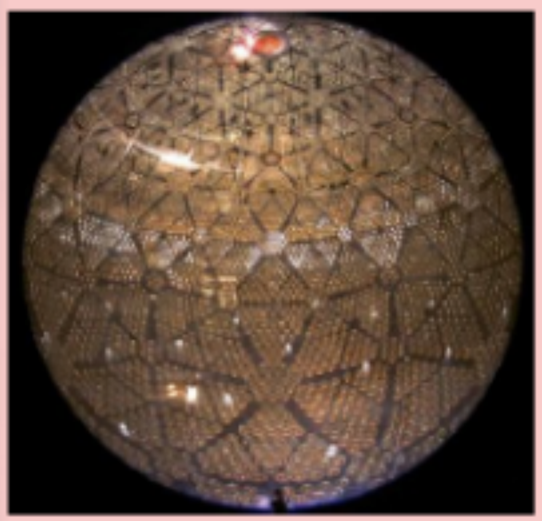


try to make the background zero by **tracking or tagging**

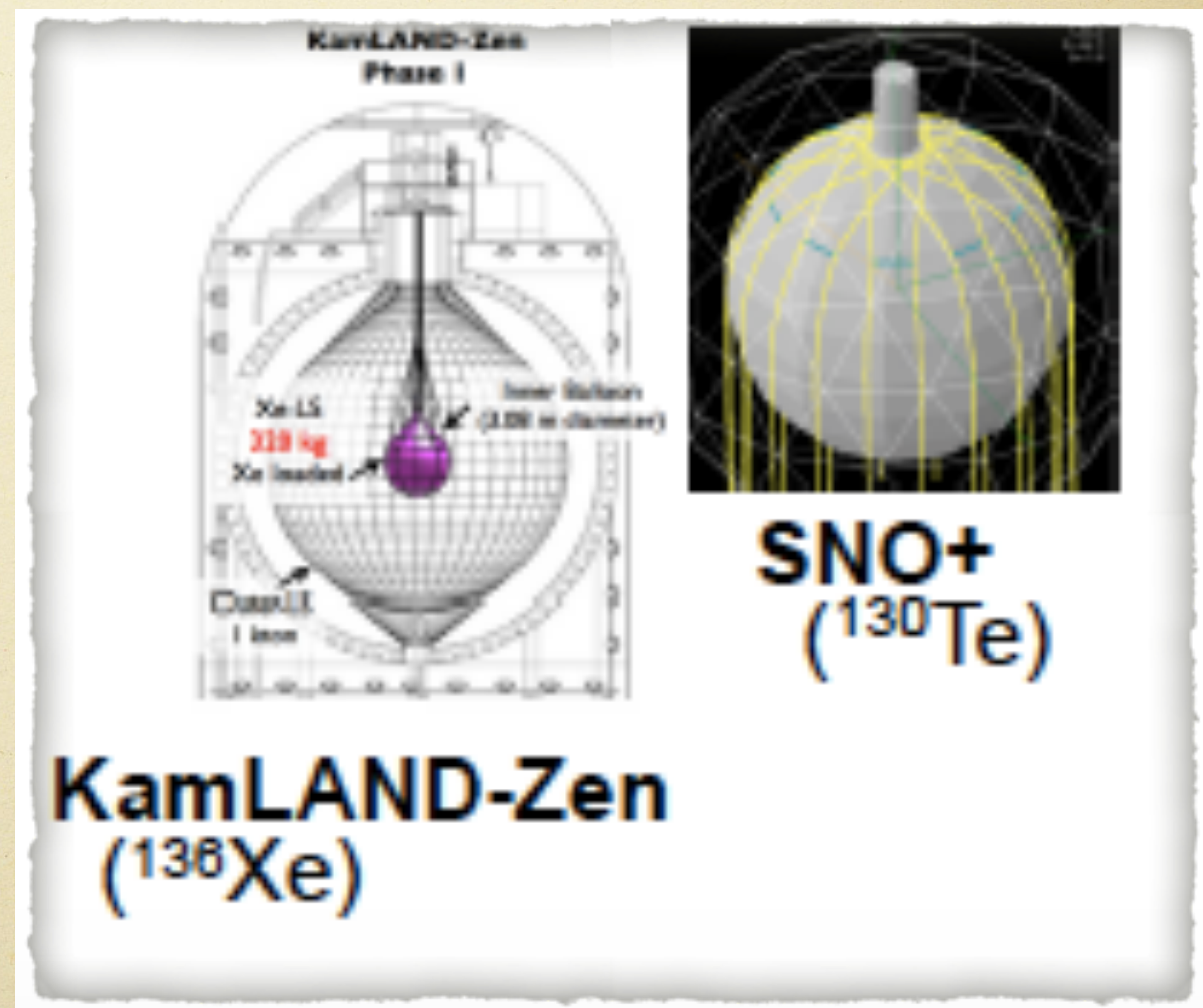
or better make the right cocktail of all of the above

the state of the art: brute force

The "Brute Force" Approach



focus on the numerator with **a huge amount of material**
(often sacrificing resolution)

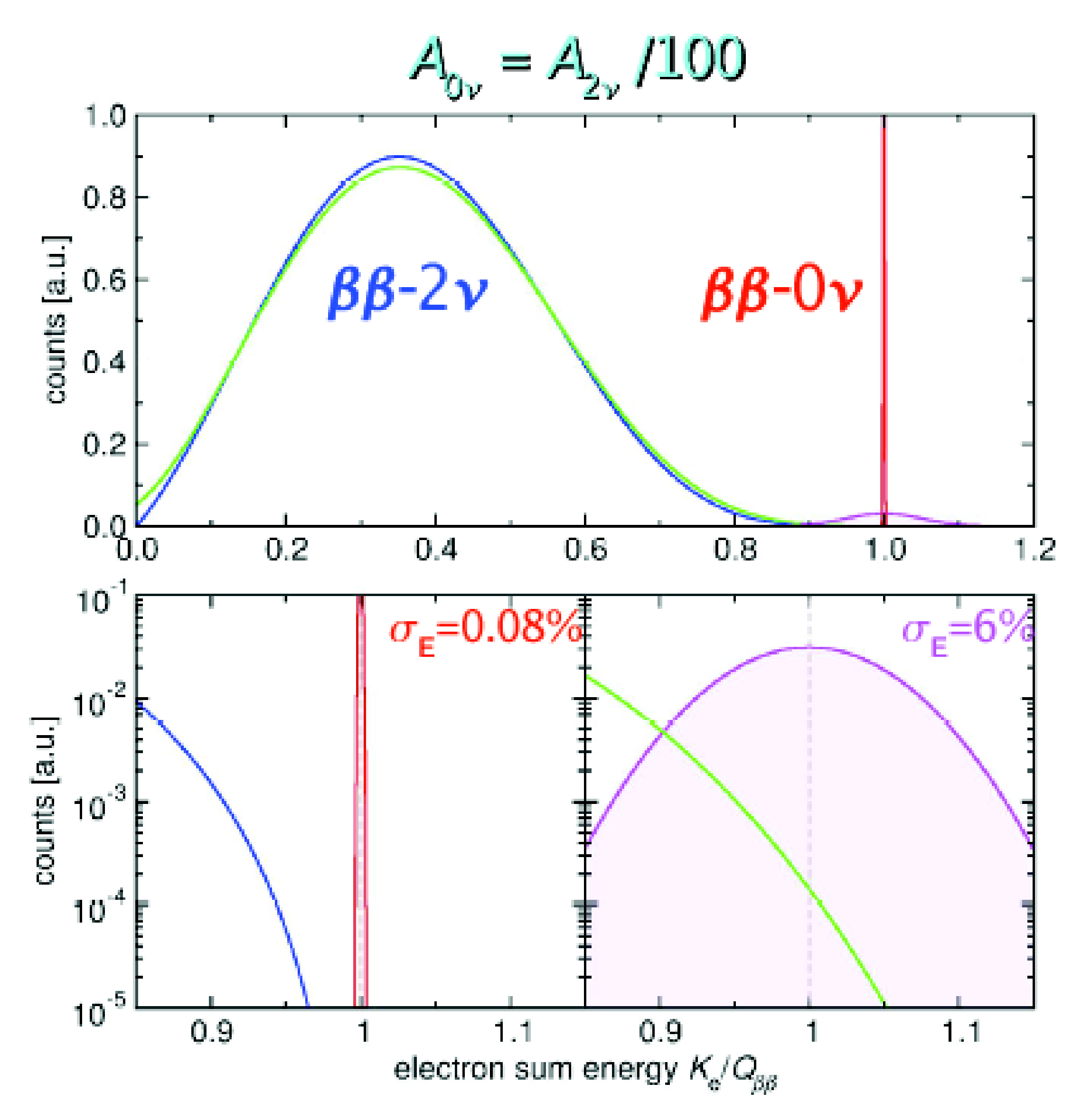


a caveat on energy resolution

irreducible physics background

$$\delta = \frac{\Delta E^{FWHM}}{Q_{\beta\beta}}$$

$$\frac{S}{B} \approx \frac{m_e}{7 Q_{\beta\beta} \delta^6} \frac{T^{2\nu}_{1/2}}{T^{0\nu}_{1/2}}$$



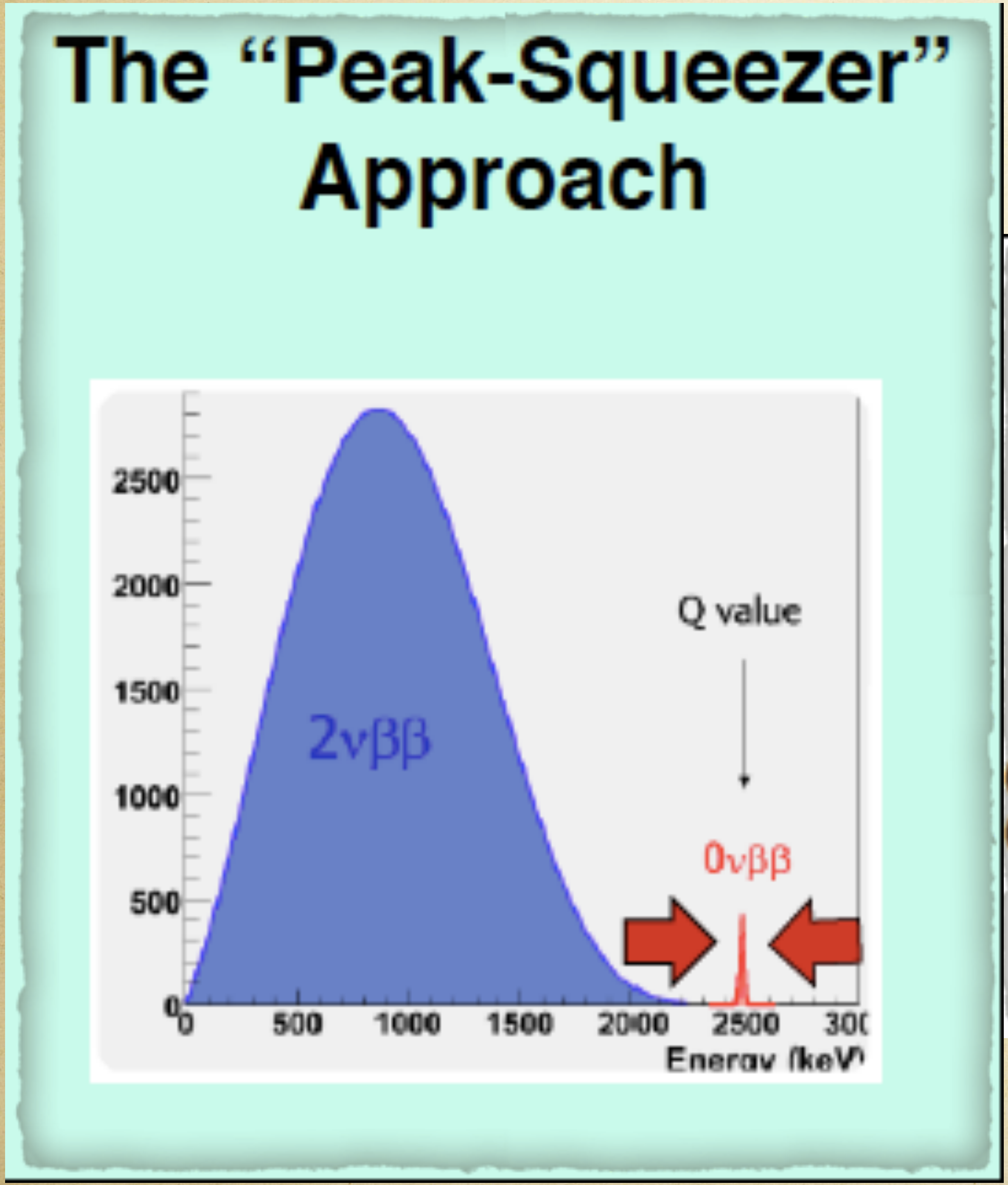
Please note δ^6

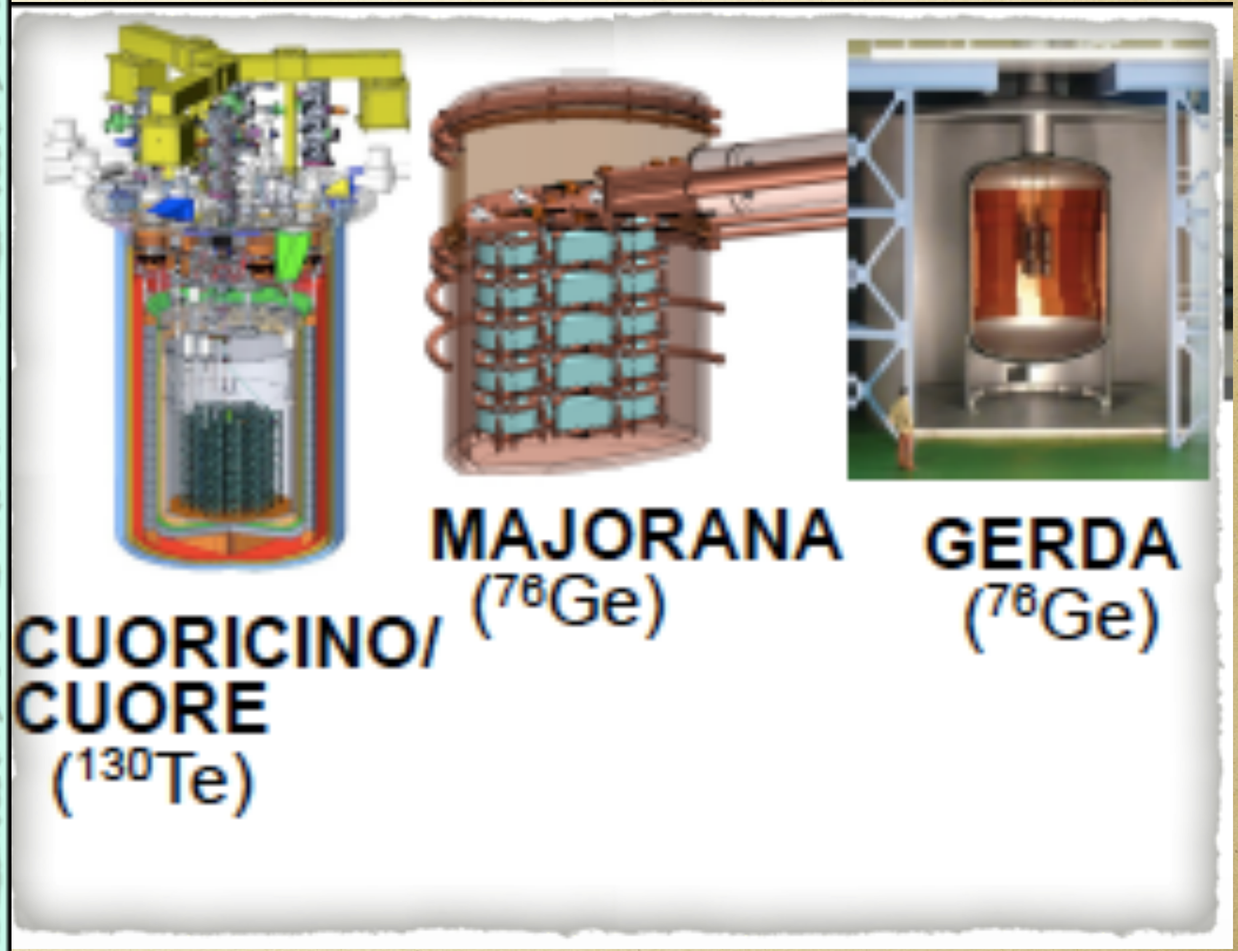
$T^{0\nu} \simeq \mathbf{10^{28}} y$ S/B = 1

$T^{2\nu} \simeq \mathbf{10^{20}} y$ $Q \simeq \mathbf{3}$MeV

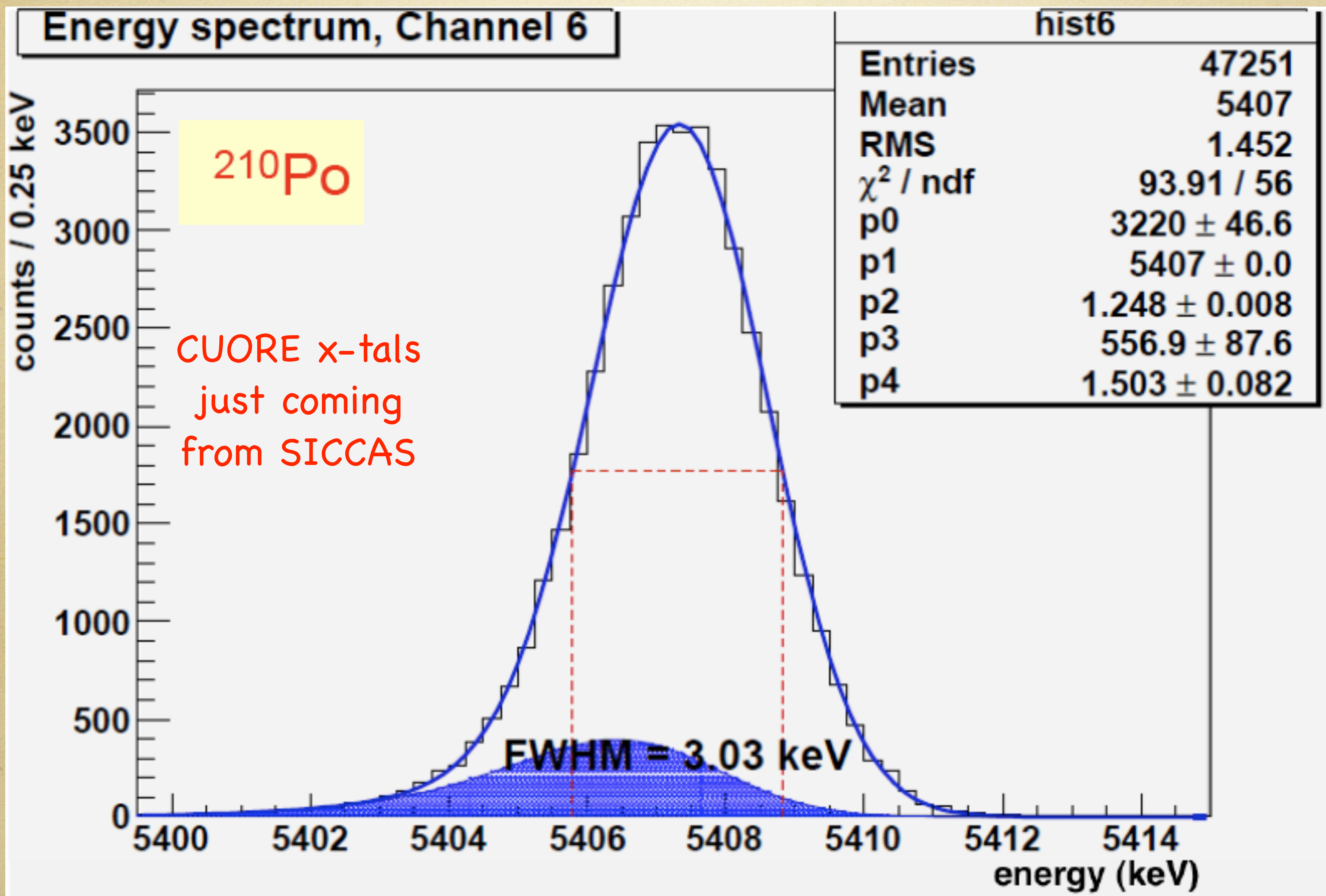
$\longrightarrow$ $\delta = \Delta E^{FWHM}/Q \simeq 2.5\%$

the state of the art: peak squeezer



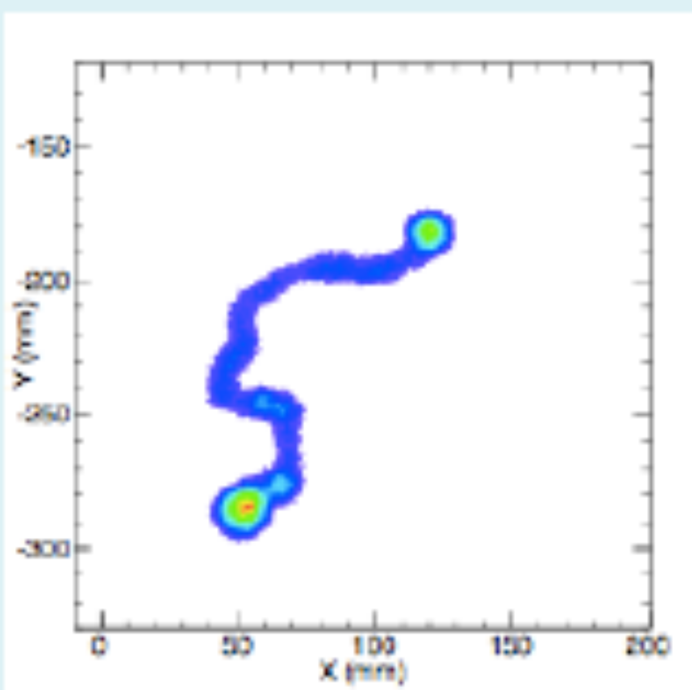


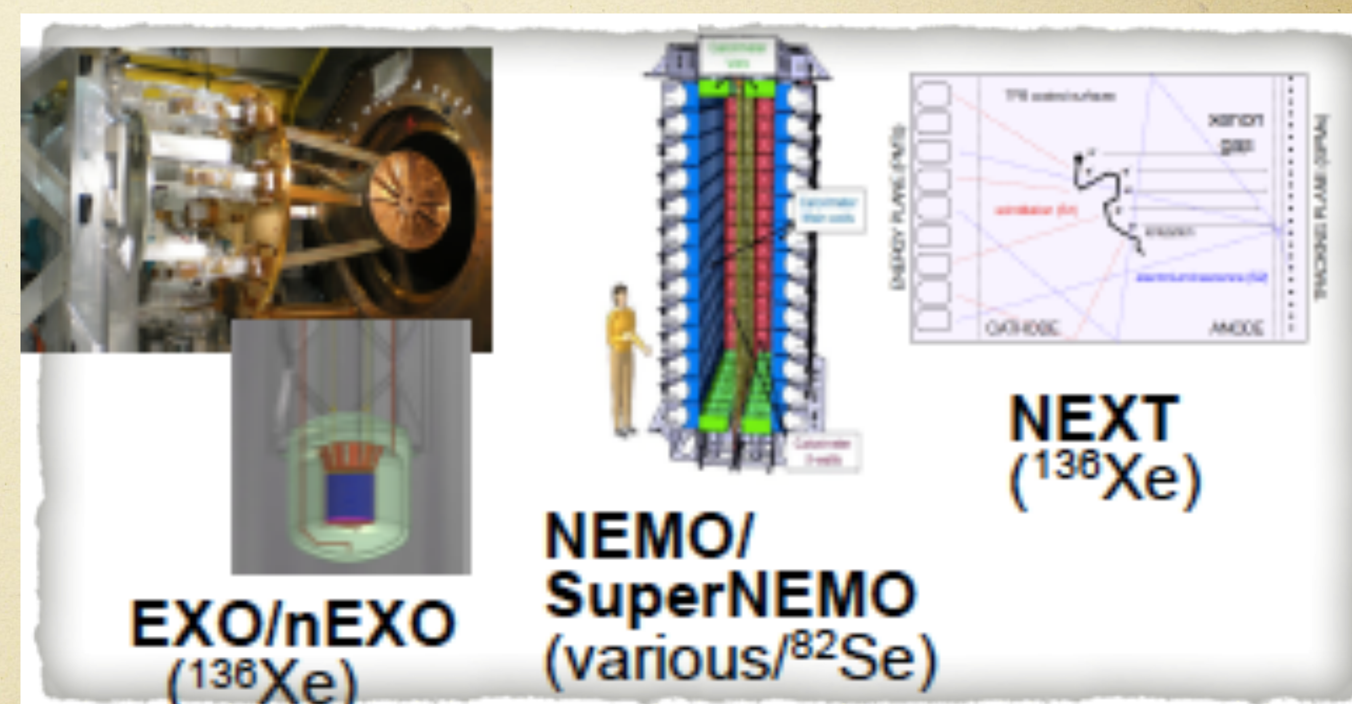
how much can you squeeze ?



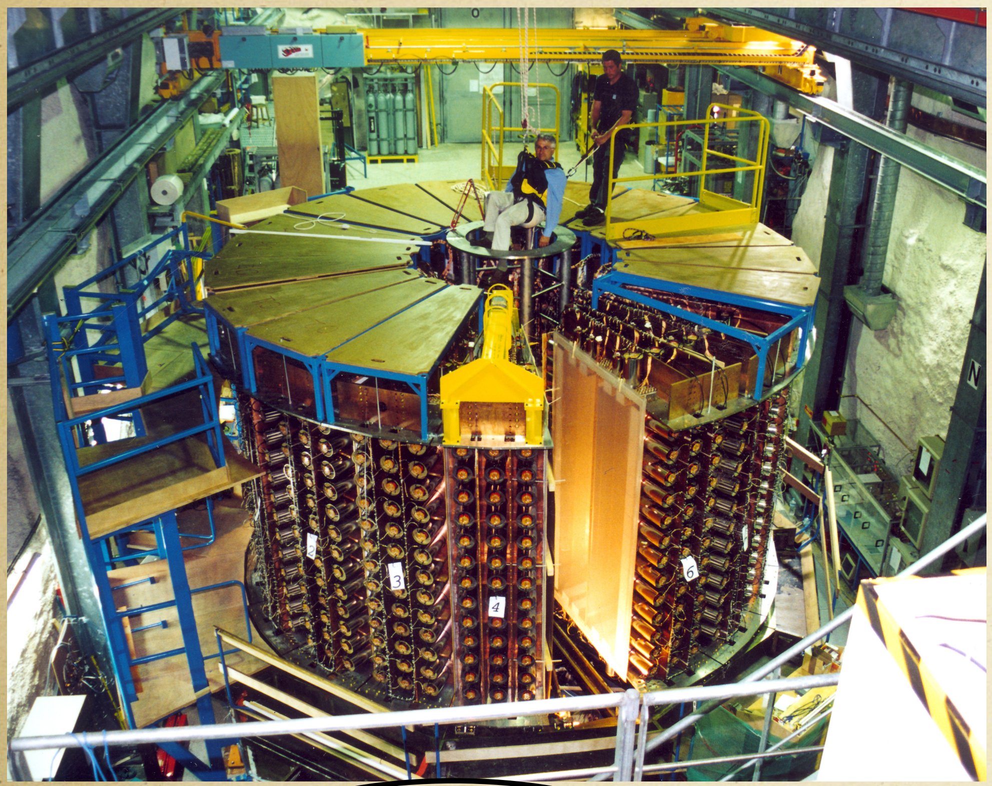
the state of the art: tracking

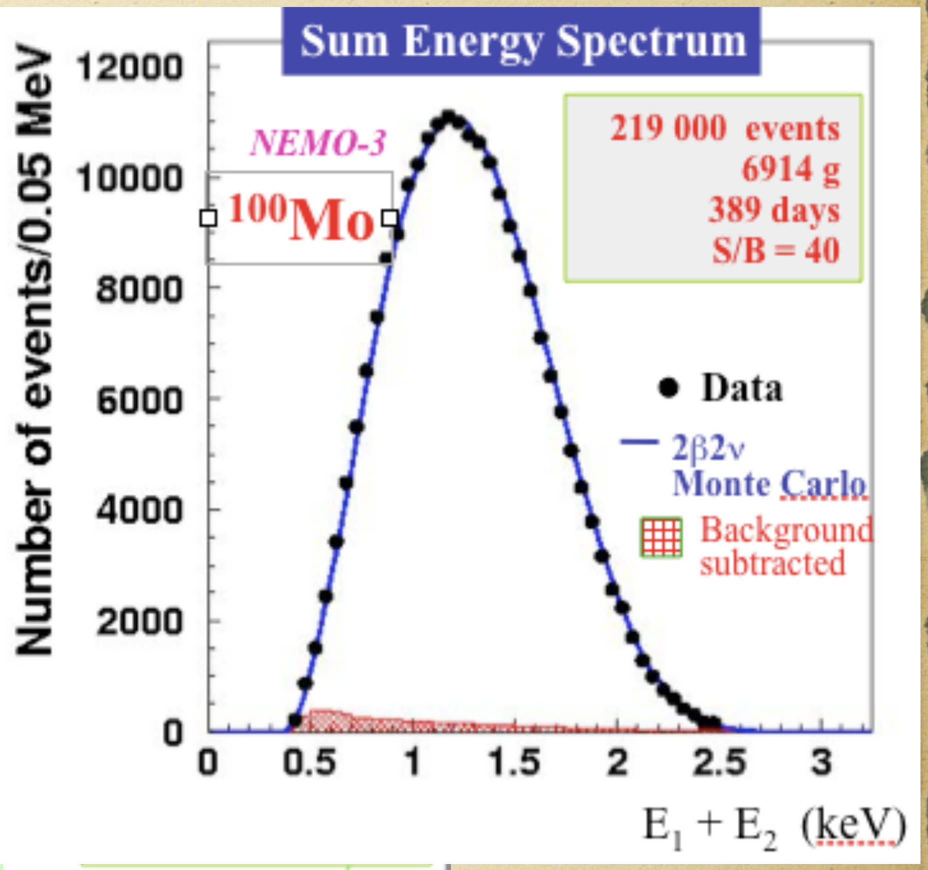
The "Final-State Judgement" Approach





nicely working but...

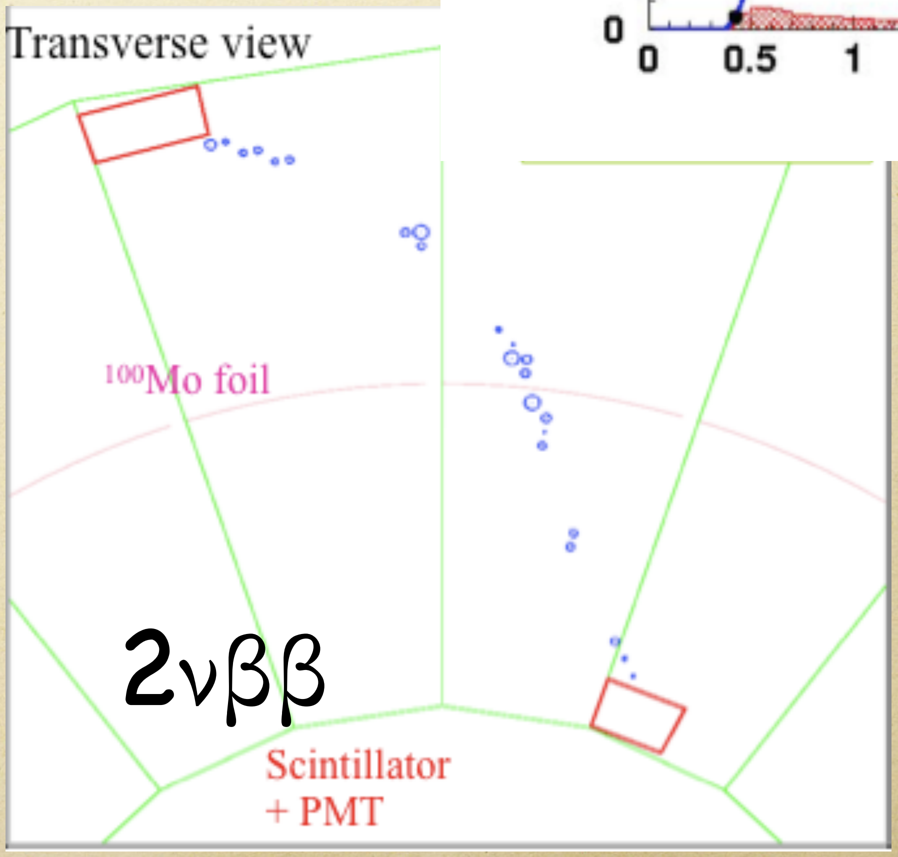




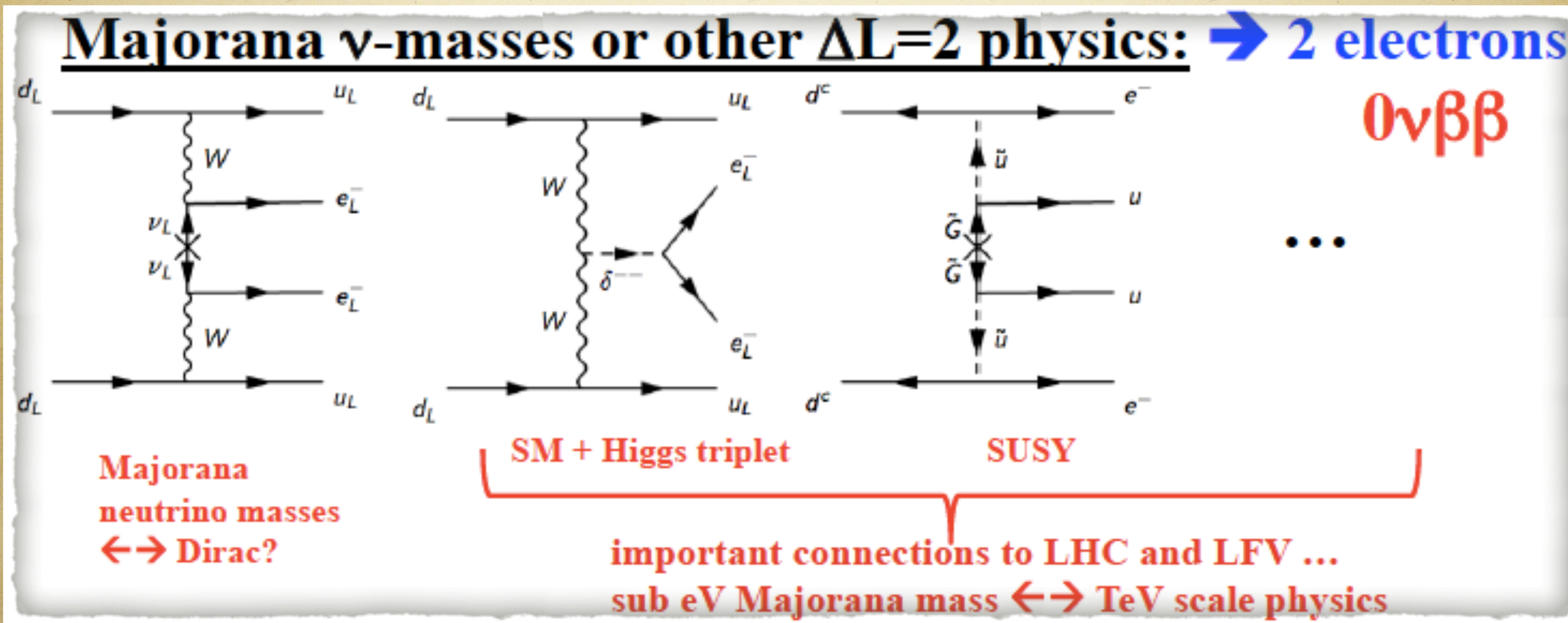
Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², e ~ 60 mg/cm²

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs



back to physics
do not forget ‘New Physics’

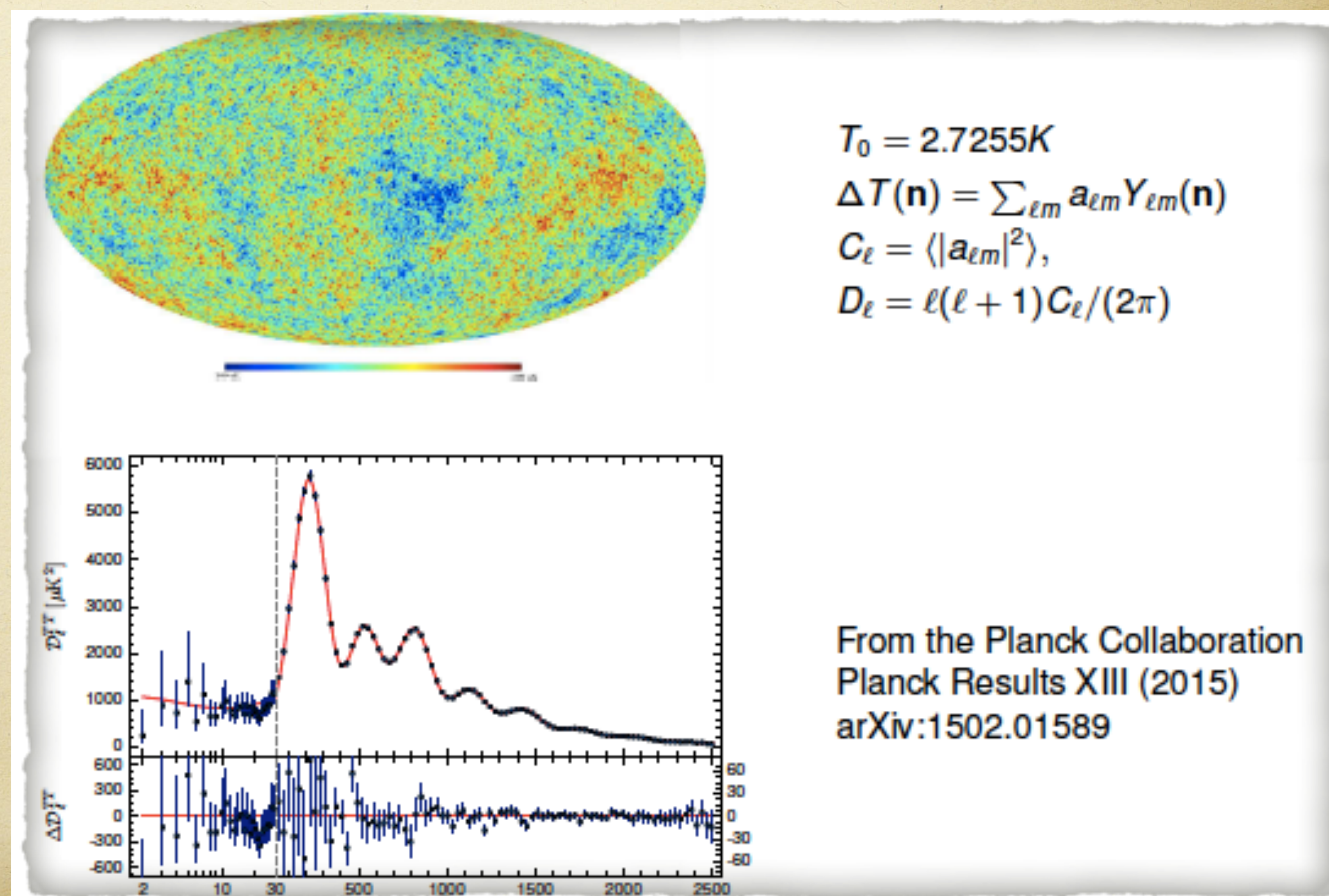


although we go after 0νββ induced by Majorana’s thoughts we might find something else !

do we have any solid limit ?

what do we know about neutrino mass or at least on their sum ?

CMB fit

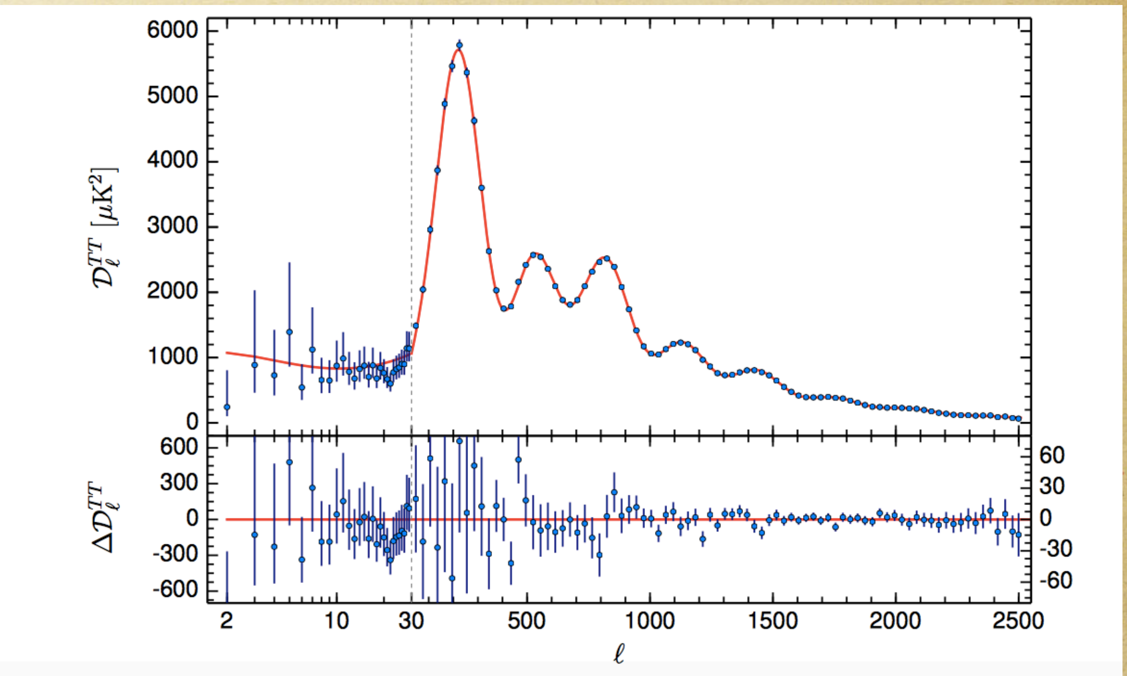


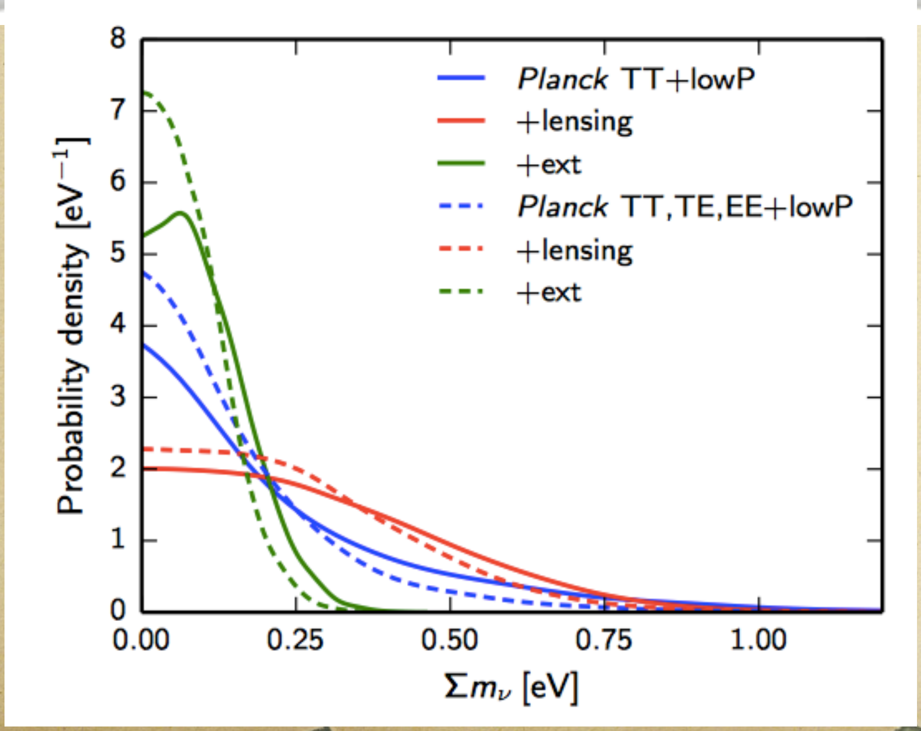
The CMB fit

- Curvature $K = 0$
- No tensor perturbations, $r = 0$
- Three species of thermal neutrinos, $N_{\mathrm{eff}} = 3.046$ with temperature $T_\nu = (4/11)^{1/3}\, T_0$
- 2 neutrino species are massless and the third has $m_3 = 0.06$eV such that $\sum_i m_i = 0.06$eV.
- Helium fraction $Y_p = 4n_{\mathrm{He}}/n_b$ is calculated from N_{eff} and ω_b.

Parameters

- Amplitude uf curvature perturbations, A_s
- Scalar spectral index, n_s
- Baryon density $\omega_b = \Omega_b h^2$
- Cold dark matter density $\omega_c = \Omega_c h^2$
- Present value of Hubble parameter $H_0 = 100h$km/sec/Mpc $(\Omega_\Lambda = 1 - (\omega_b + \omega_c)/h^2)$.





Info from Planck: Neutrino # and mass

$\Sigma m_\nu < 0.23$ eV (95% CL)

$N_{\mathrm{eff}} = 3.15 \pm 0.23$

Planck + Lyman alpha

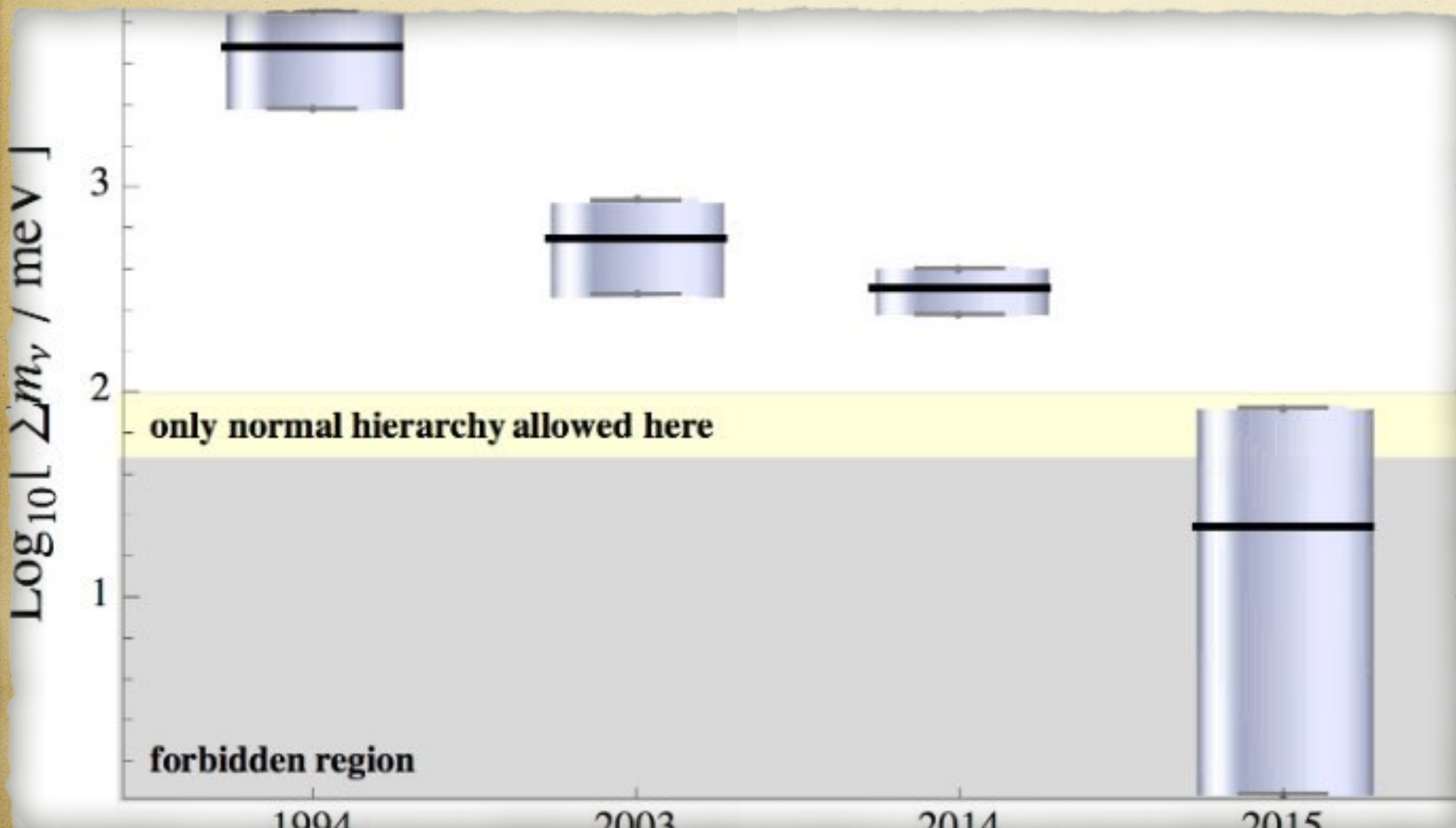
$\Sigma m_\nu < 0.14$ eV (C.L)

Prospects for PLANCK + EUCLID

$\Delta m_\nu \sim 0.03$ eV & $\Delta N_\nu \sim 0.08$

should we believe it ?

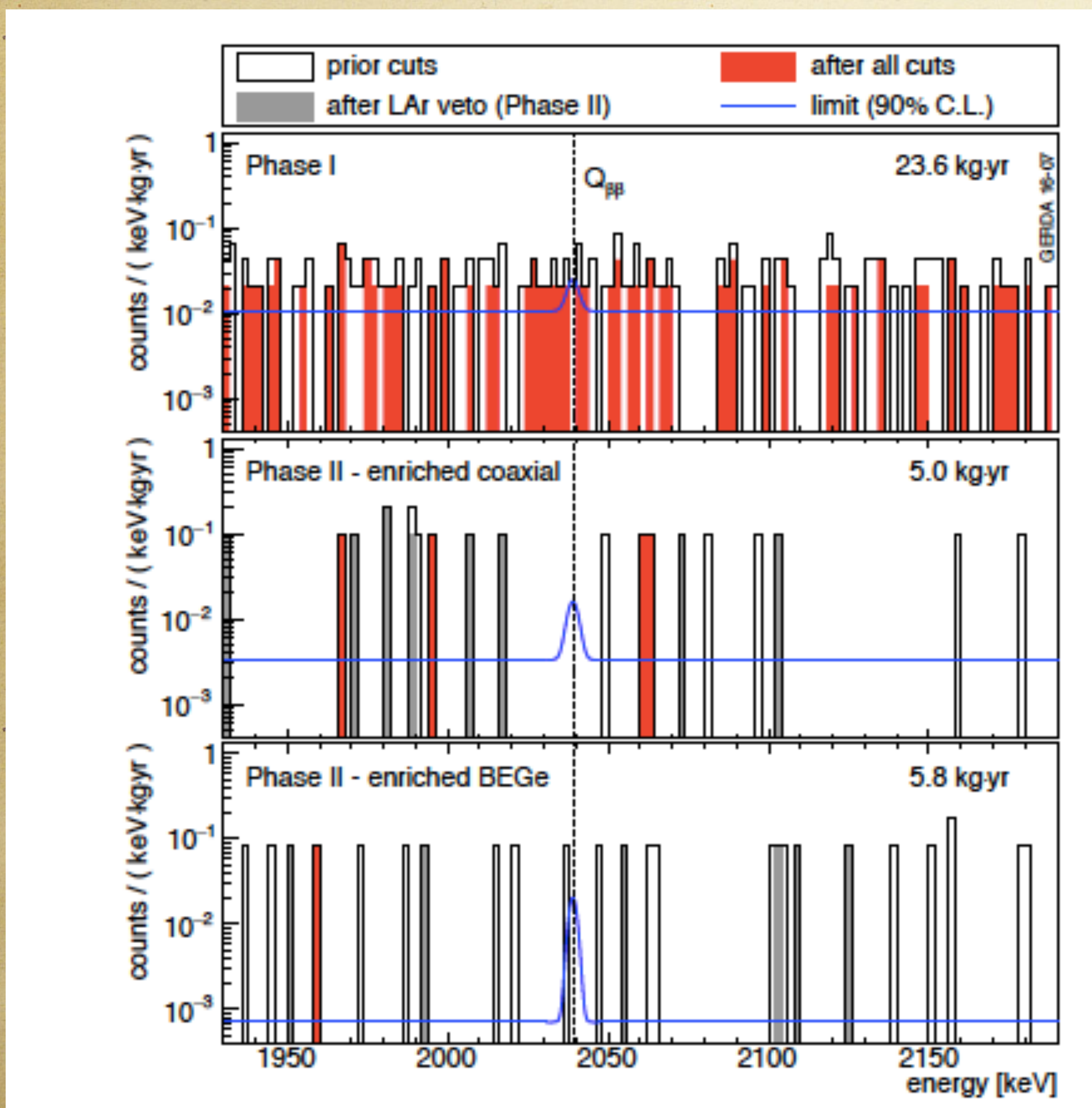
time evolution of CMB prediction on neutrino mass



a better understanding brings more solidity to results

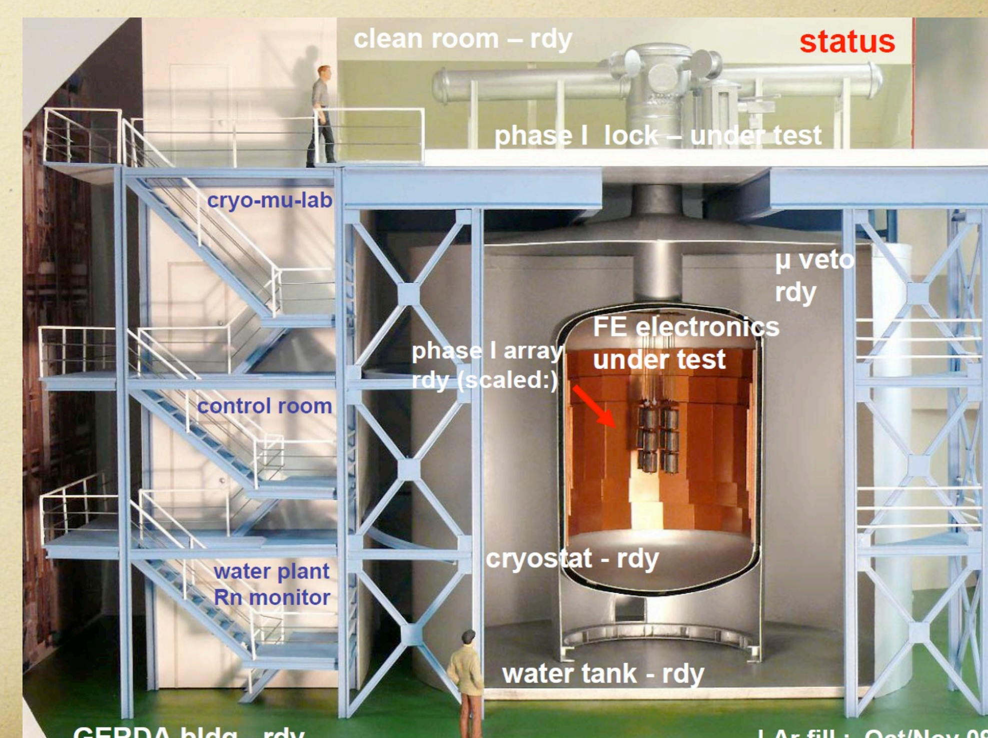
State of the art: GERDA

$$T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}\ \mathrm{yr}.$$

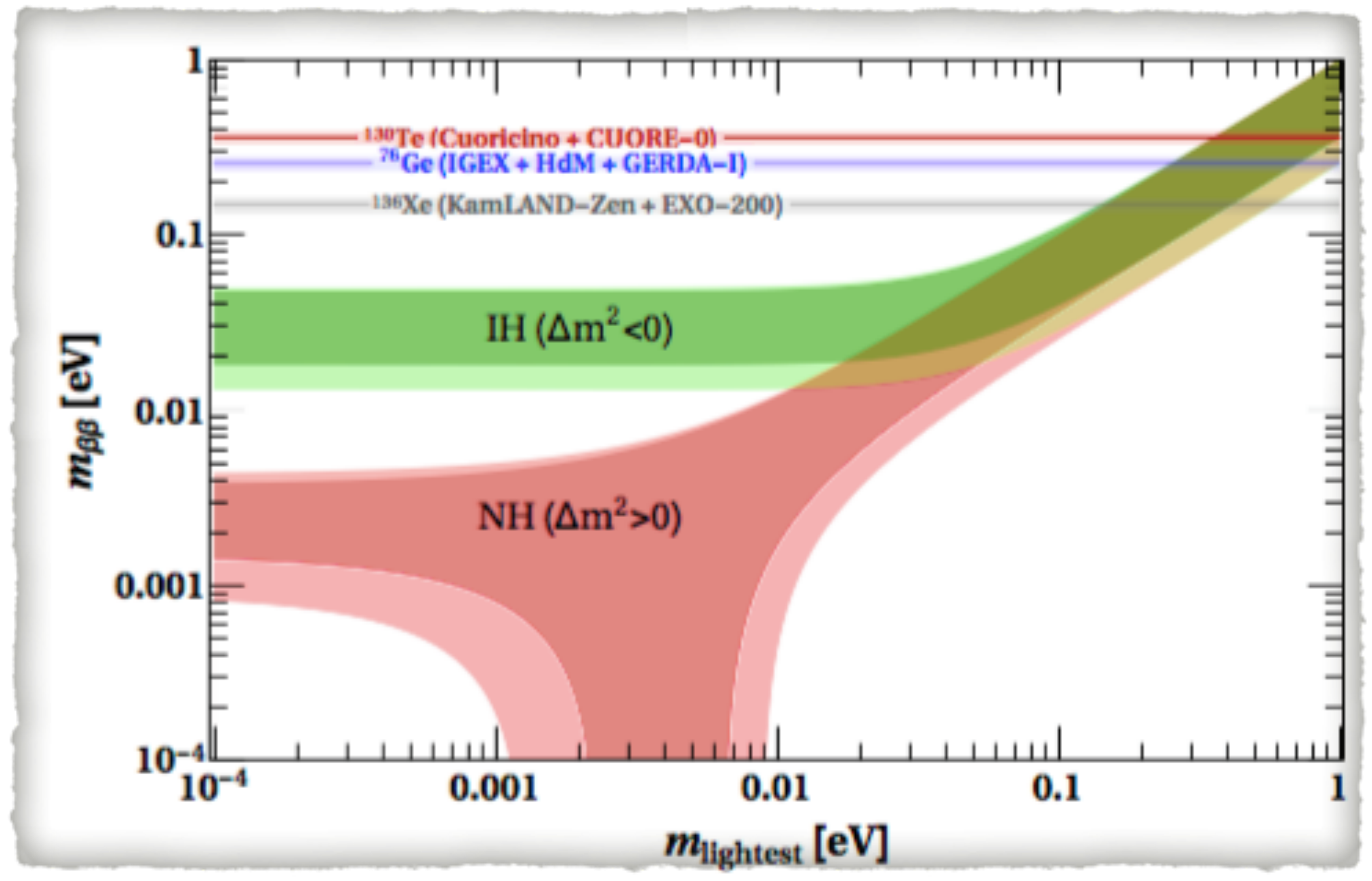


We expect only a fraction of a background event in the energy region of interest (1 FWHM) at design exposure of 100 kg·yr. GERDA is hence the first 'background free' experiment in the field. Our sensitivity grows therefore almost linearly with time instead of by square root like for

the GERDA half-life sensitivity of $4.0 \cdot 10^{25}$ yr for an exposure of 343 mol·yr is similar to the one of Kamland-Zen for ^{136}Xe of $5.6 \cdot 10^{25}$ yr based on a more than 10-fold exposure of 3700 mol·yr [9].

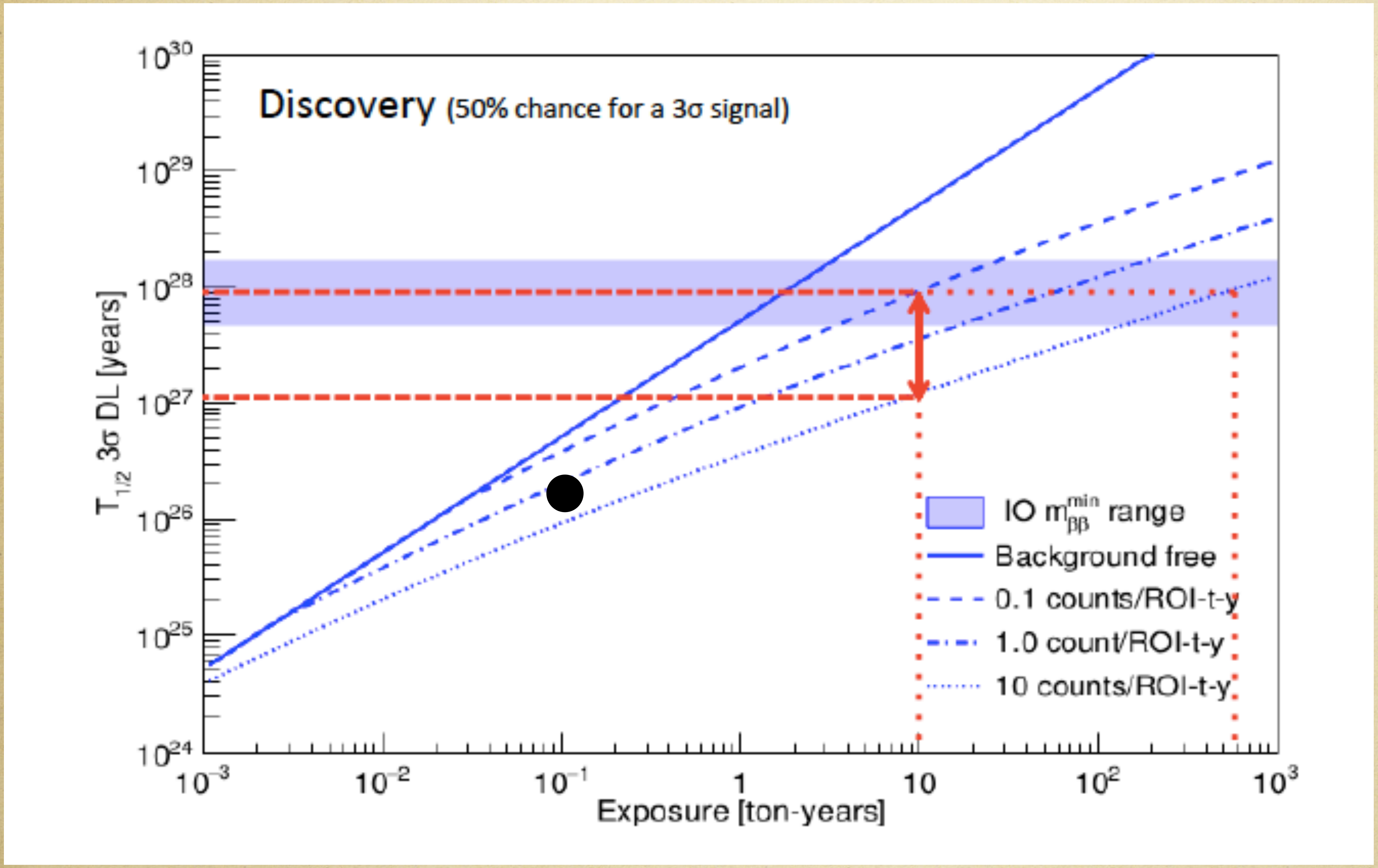


which translate in



assuming no g_A quenching

Tough future

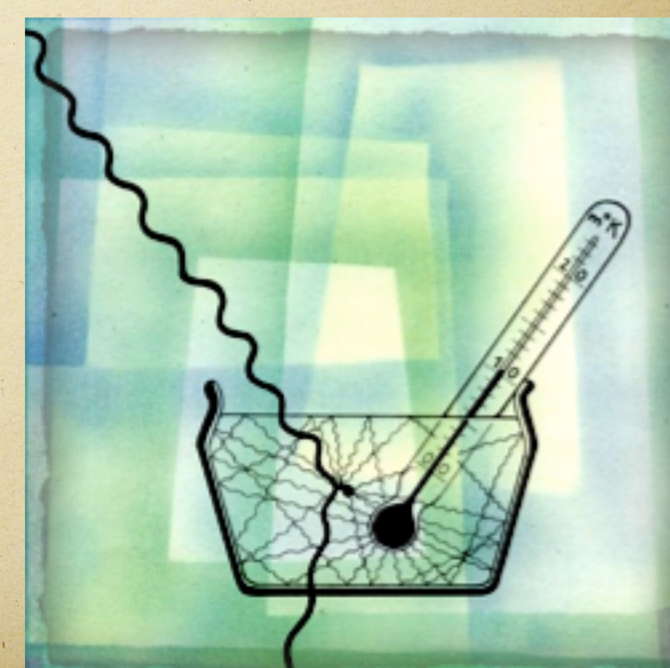


- GERDA discovery potential for 100kg/y with actual level of backg

end of part I

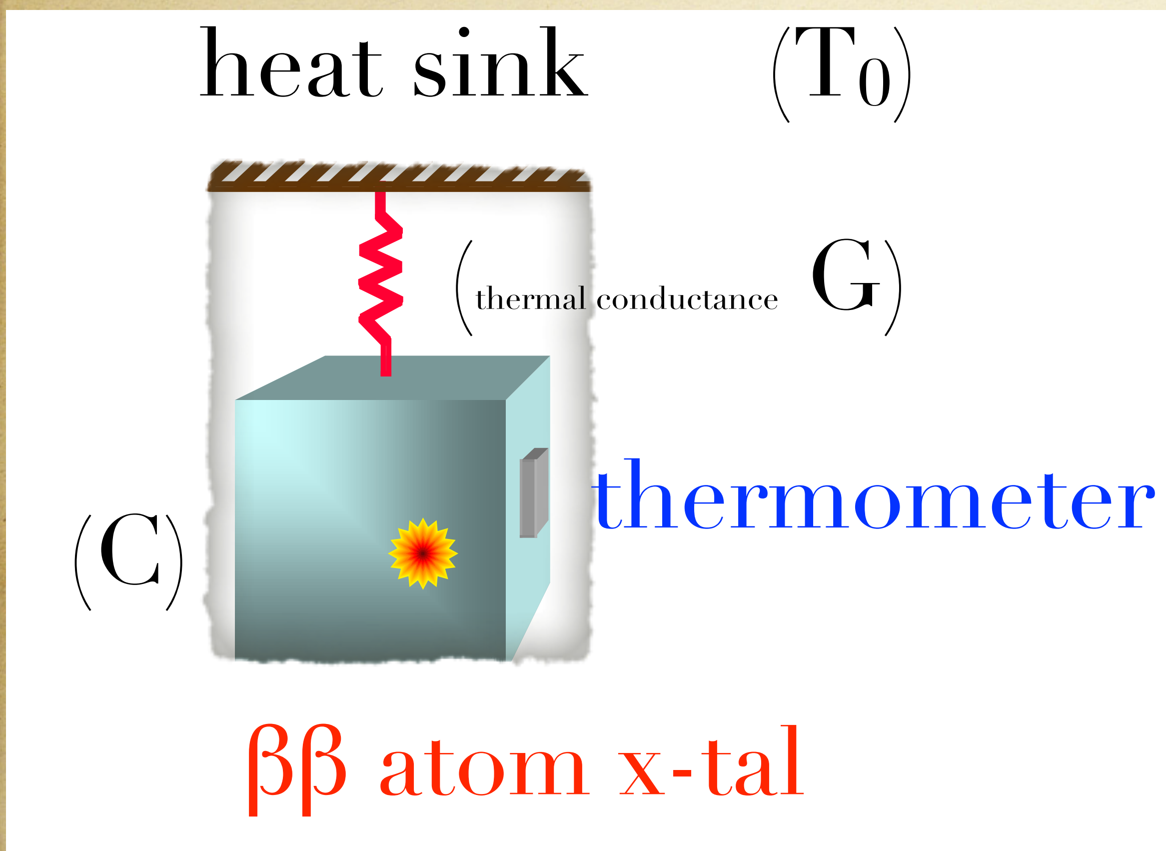
Bolometric technique

- from MiBeta to CUORE via Cuoricino and Cuore0
- Scintillating bolometers as an evolution toward Zero 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 apps : $\tau = C/G \sim 1\,\mathrm{s}$

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

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

Why a bolometer

- M, t, B, ΔE are the parameters of the game
- t is irrelevant
- M is ‘easy’ with a calorimeter
- ΔE is a definite bonus
- B is what this part of the talk is mostly about

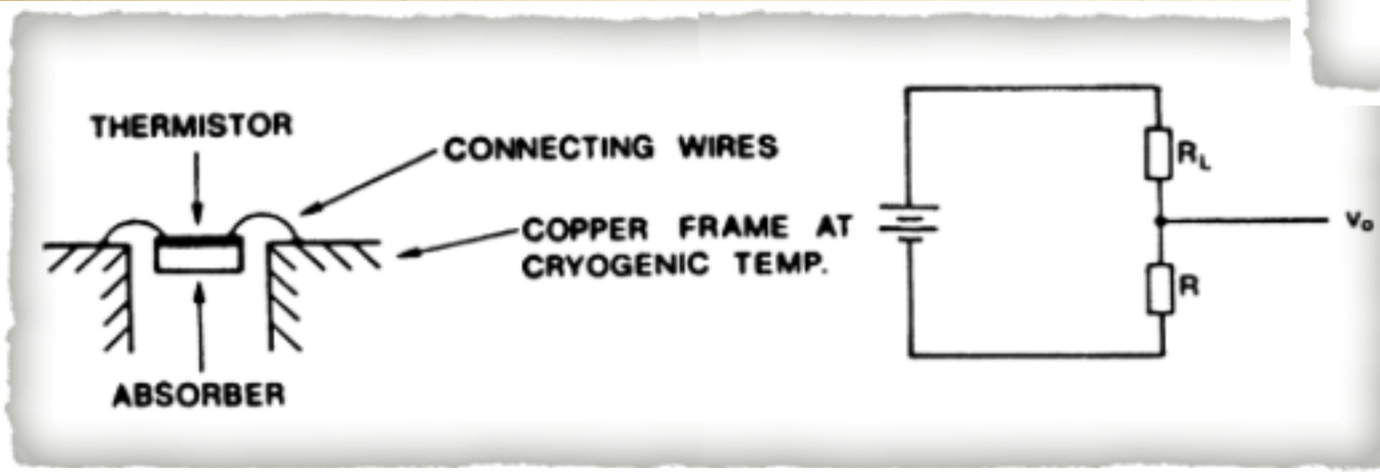
the Dawn !

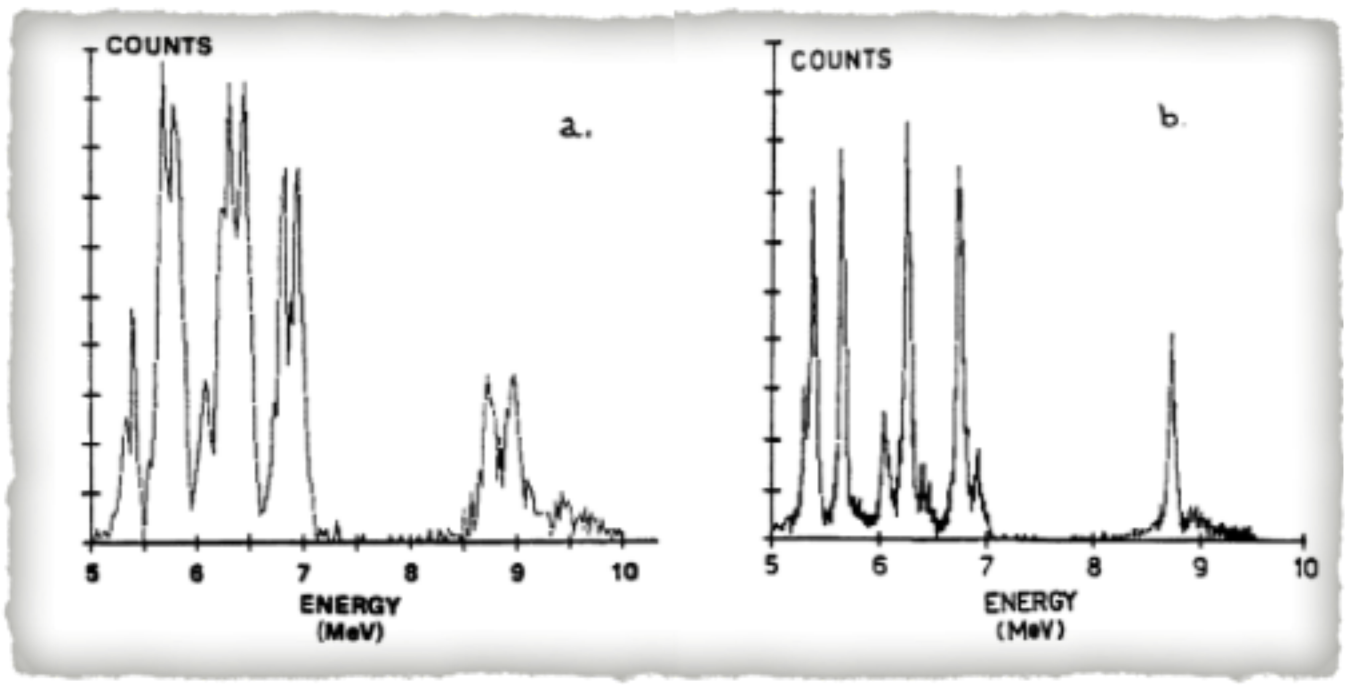
Cryogenic Detectors and Materials Research in Physics and Astrophysics
E. Fiorini

Prehistory and future of thermal detectors

T.O. Niinikoski

CERN, Geneva, Switzerland





Low-temperature calorimetry for rare decays

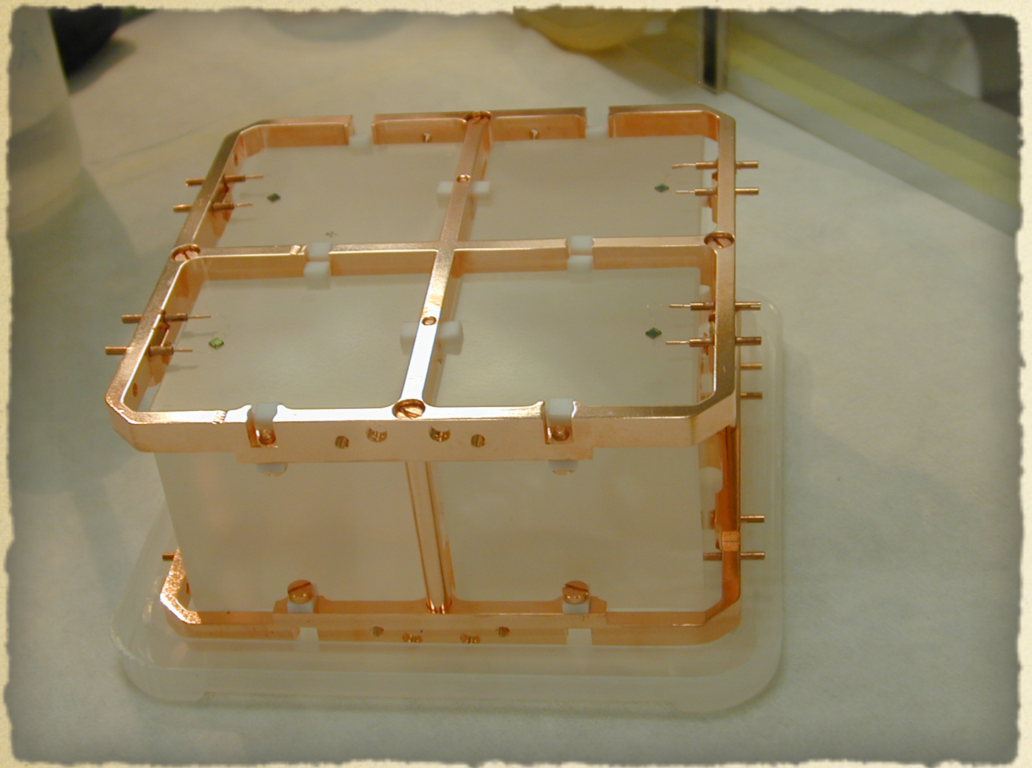
E. Fiorini

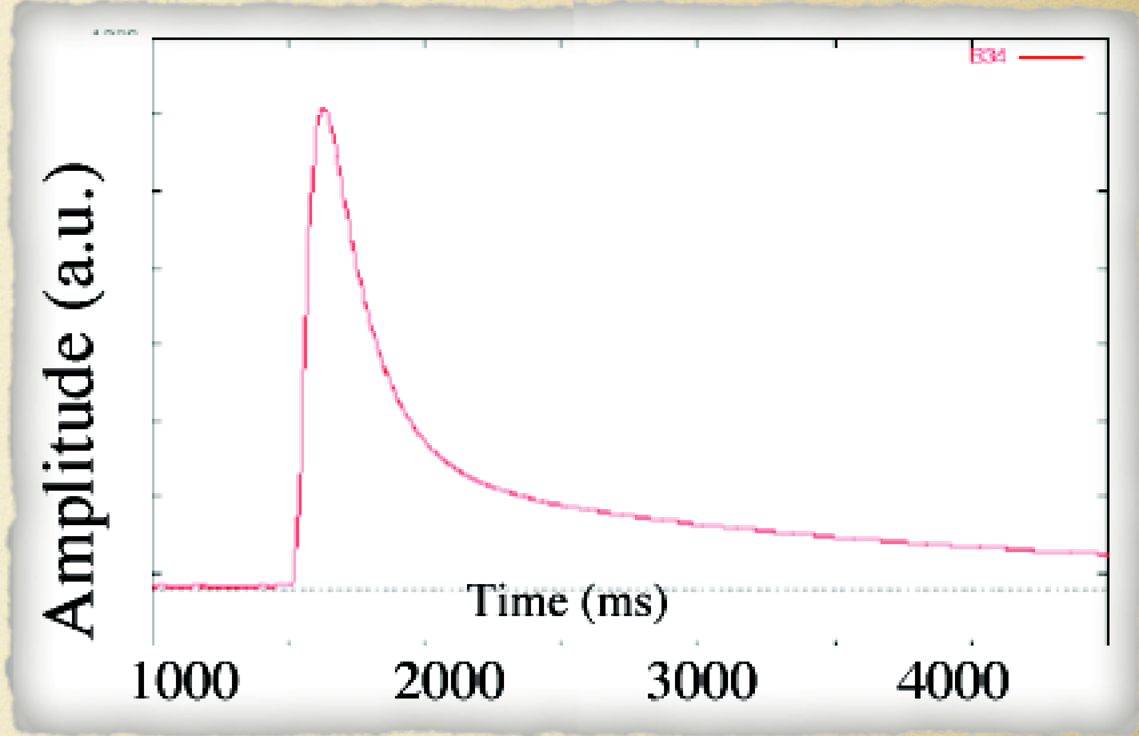
Dipartimento di Fisica dell'Università and INFN, Milano, Italy

T.O. Niinikoski

CERN, Geneva, Switzerland

TeO_2 : a viable (show)case





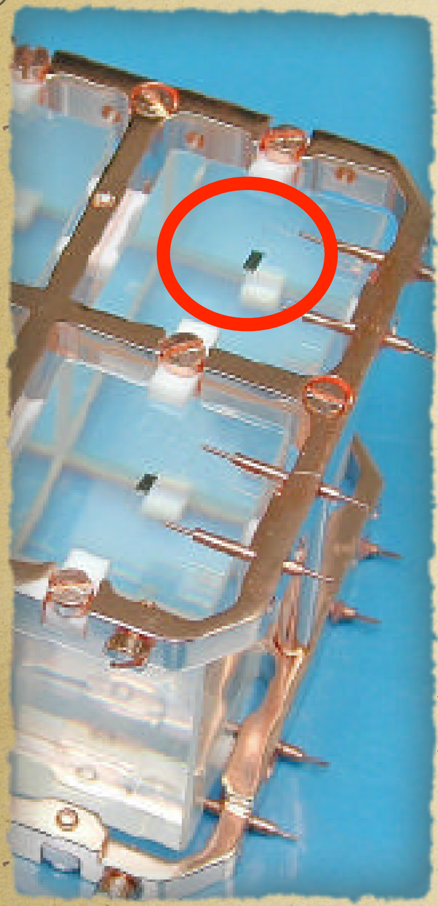
Numerology:

$T_0 \sim 10$ mK
$C \sim 2$ 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)

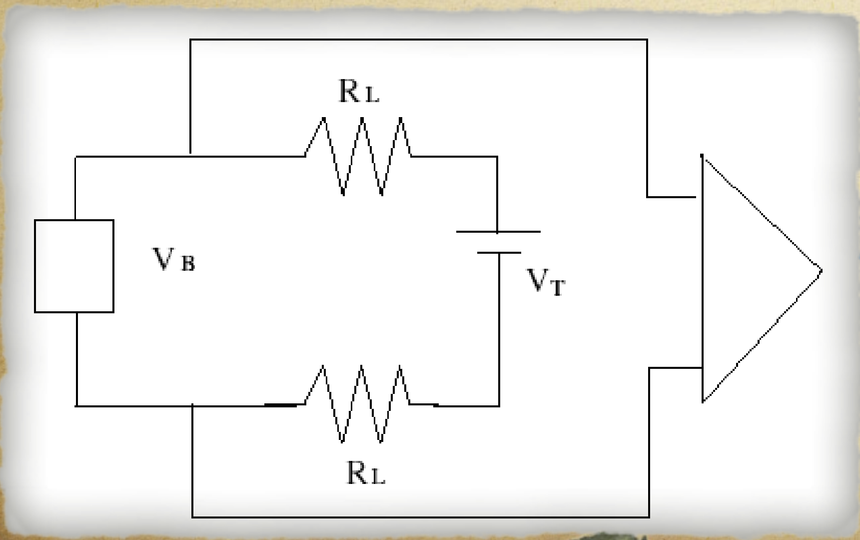
to read the temperature you need a thermometer

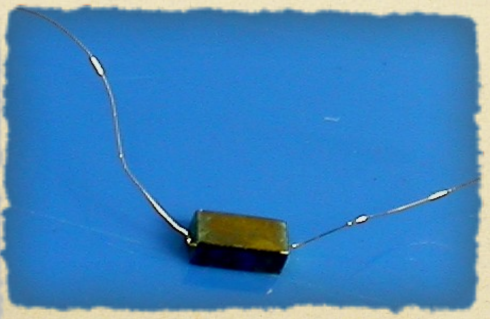
$$A(T) = \left| \frac{d \ln R}{d \ln T} \right|$$



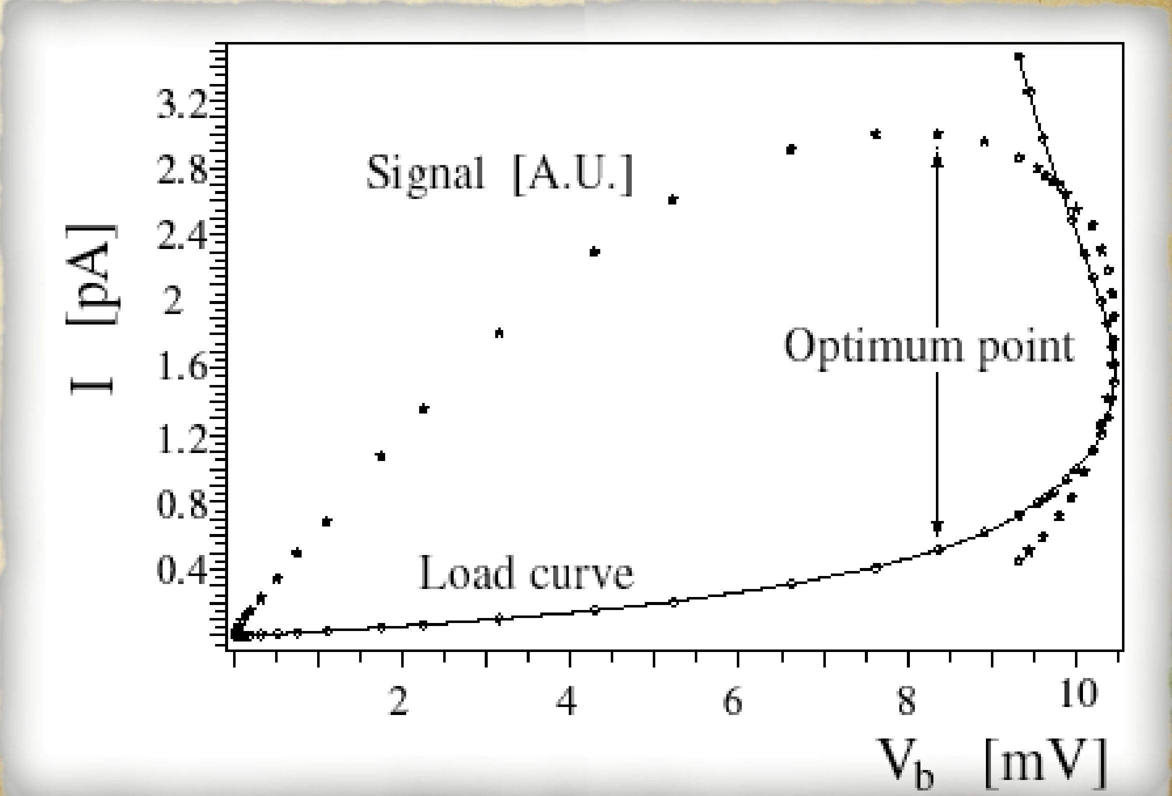
dR/dE ~ 3MΩ/MeV

Neutron Transmutation Doped (NTD) Germanium Thermistor





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



Neutron Transmutation Doping

A pure Ge Crystal is exposed to the thermal neutron flux of a nuclear reactor. Some Ge gets transmuted into dopants.

$$
\begin{aligned}
{}^{70}Ge\,(21\%) + n &\rightarrow {}^{71}Ge\,(\sigma_T = 3.43 \pm 0.17b,\ \sigma_R = 1.5b) \\
{}^{71}Ge &\rightarrow {}^{71}Ga\,(t_{1/2} = 11.4day) \qquad Acceptor \\
\\
{}^{74}Ge\,(36\%) + n &\rightarrow {}^{75}Ge\,(\sigma_T = 0.51 \pm 0.08b,\ \sigma_R = 1.0 \pm 0.2b) \\
{}^{75}Ge &\rightarrow {}^{75}As\,(t_{1/2} = 83min) \qquad Donor \\
\\
{}^{76}Ge\,(7.4\%) + n &\rightarrow {}^{77}Ge\,(\sigma_T = 0.16 \pm 0.014b,\ \sigma_R = 2.0 \pm 0.35b) \\
{}^{77}Ge &\rightarrow {}^{77}Se\,(t_{1/2} = 38.8hr) \qquad Double\ Donor
\end{aligned}
$$

Higly Uniform

Doping level is 10^{17} atoms/cm^3.

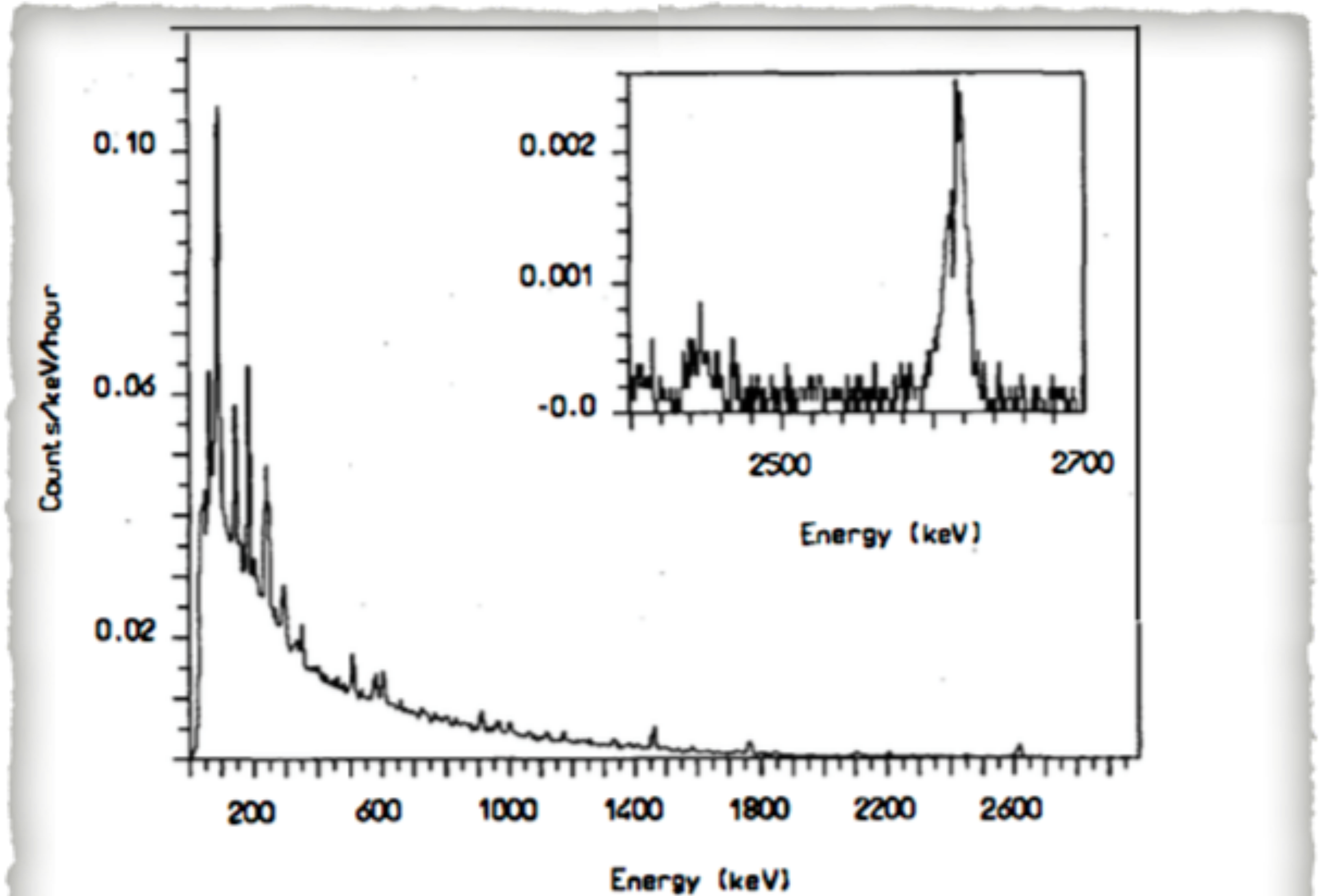
Required fluence is 3.5×10^{18} n/cm^2.

The long saga of the ultra cold ^{130}Te

MILANO ^{130}Te NEUTRINOLESS DOUBLE BETA DECAY SEARCH WITH THERMAL DETECTORS

A.Alessandrello, C.Brofferio, D.V.Camin, P.Caspani, O.Cremonesi, E.Fiorini, A.Foraboschi, A.Giuliani, A.Nucciotti, M.Pavan, G.Pessina, E.Previtali, L.Zanotti
Dipartimento di Fisica dell'Università di Milano, I-20133 Milano, Italy

A 330 g TeO_2 crystal has collected data for about 10500 h live time setting a new lower limit of $2.1 \cdot 10^{22}$ y (90% C.L.) for ^{130}Te neutrinoless double beta decay.



1. 330 g TeO_2 detector final spectrum (10510 h), low energy portion of the spectrum and $\beta\beta_{0\nu}$ region in the insert.

pls. note that the scale quotes counts/hour (!!)

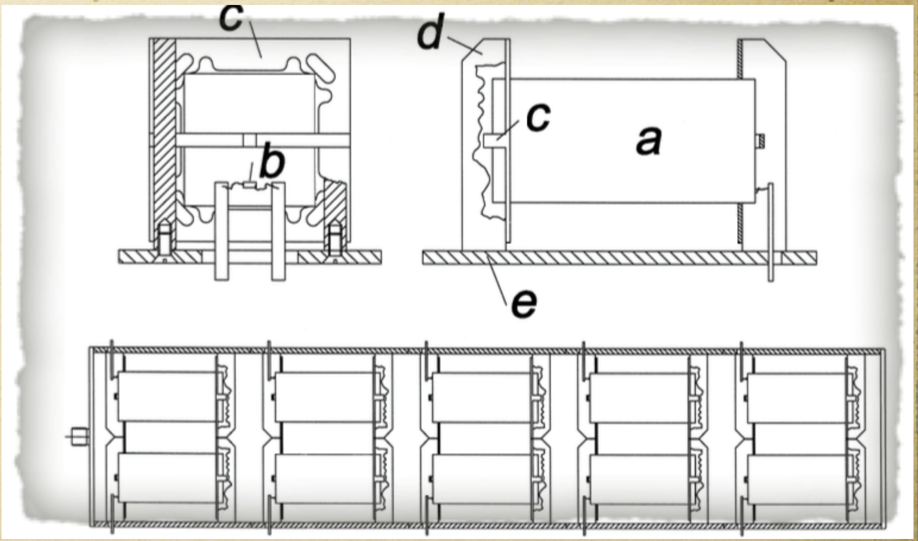
resolution was 17keV

background high

BUT THE WAY WAS OPEN !

step after step

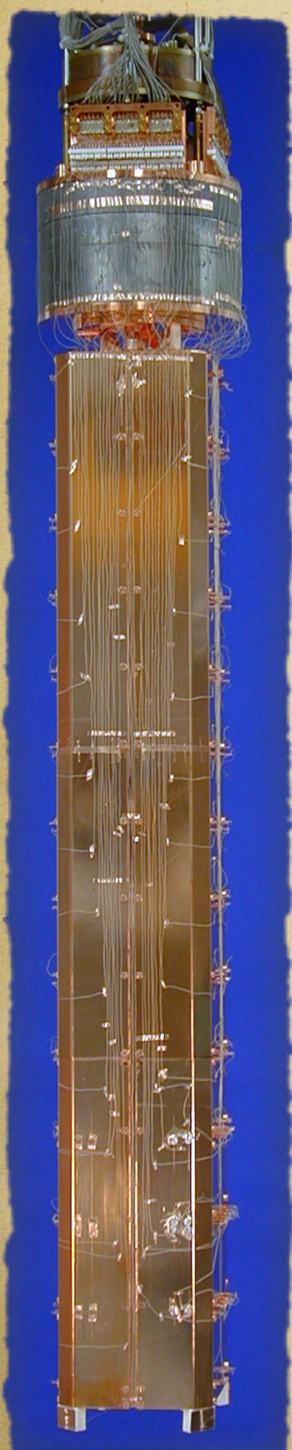
- limit from that single crystal was $2.1\ 10^{22}$ y
- next step, 4 crystals, 1.3 kg
- and then Mi-Beta, 20 crystals, 6.8 kg (natural tellurium, meaning 2.3 ^{130}Te)

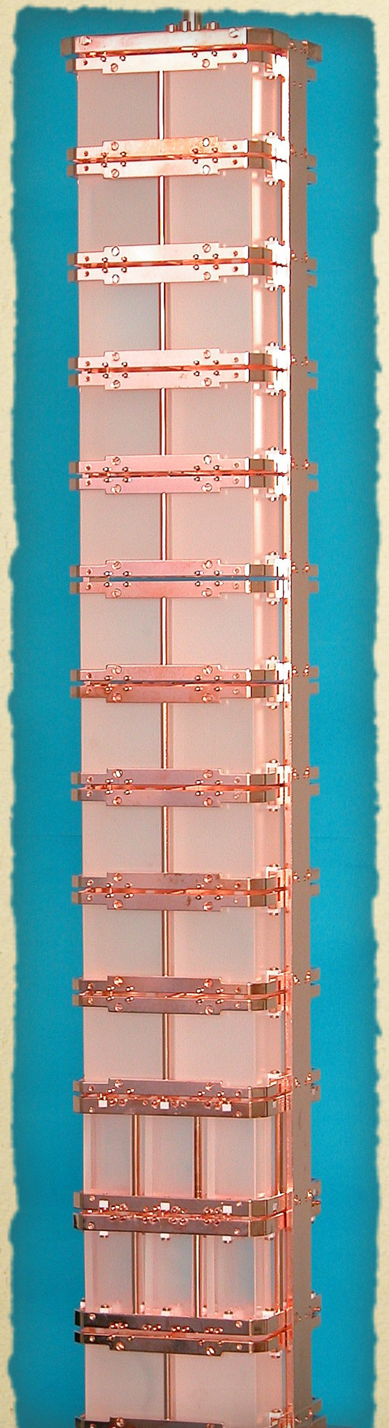


- set a limit of $5.6\ 10^{22}$ y

ready for a tougher game

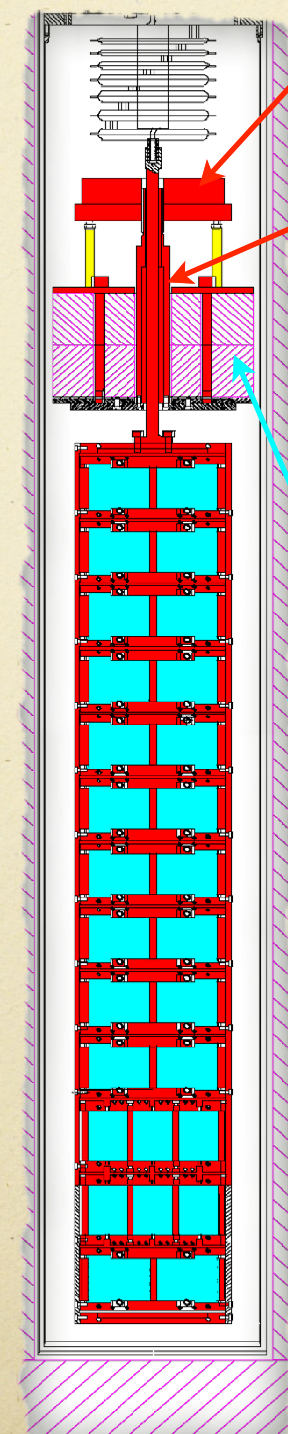
Cuoricino





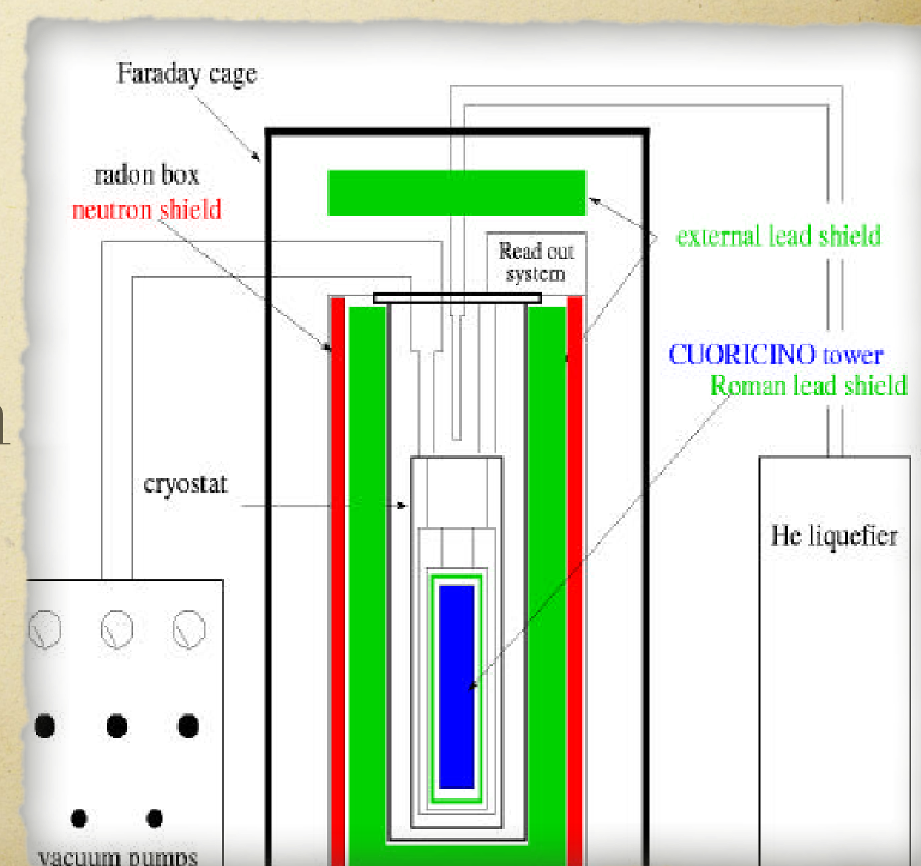
Mixing chamber

Cold finger



Roman Lead Shield

10 mK



a digression on Roman Lead

Lead is a very good shield from external radioactivity

however it has got a problem

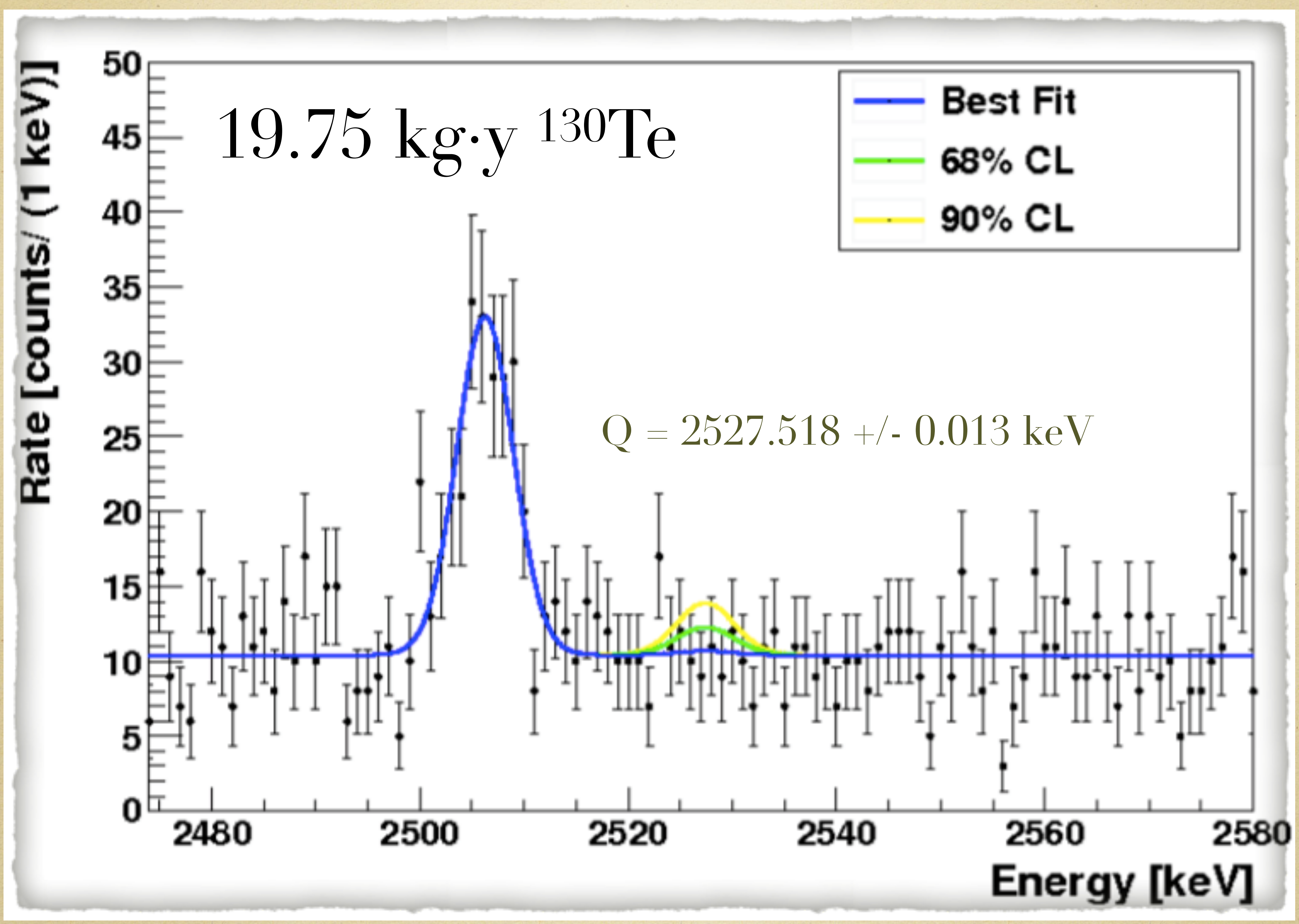
iso	NA	half-life	DM	DE (MeV)	DP
^{204}Pb	1.4%	$>1.4\times10^{17}$ y	Alpha	2.186	^{200}Hg
^{205}Pb	syn	1.53×10^{7} y	Epsilon	0.051	^{205}Tl
^{206}Pb	24.1%	^{206}Pb is stable with 124 neutrons			
^{207}Pb	22.1%	^{207}Pb is stable with 125 neutrons			
^{208}Pb	52.4%	^{208}Pb is stable with 126 neutrons			
^{210}Pb	trace	22.3 y	Alpha	3.792	^{206}Hg
			Beta	0.064	^{210}Bi

the half-life of isotope 210 is 22 years
too long for our patience to let it disappears !
too short for not harming us !

Elegant solution
although with a strong component of luck

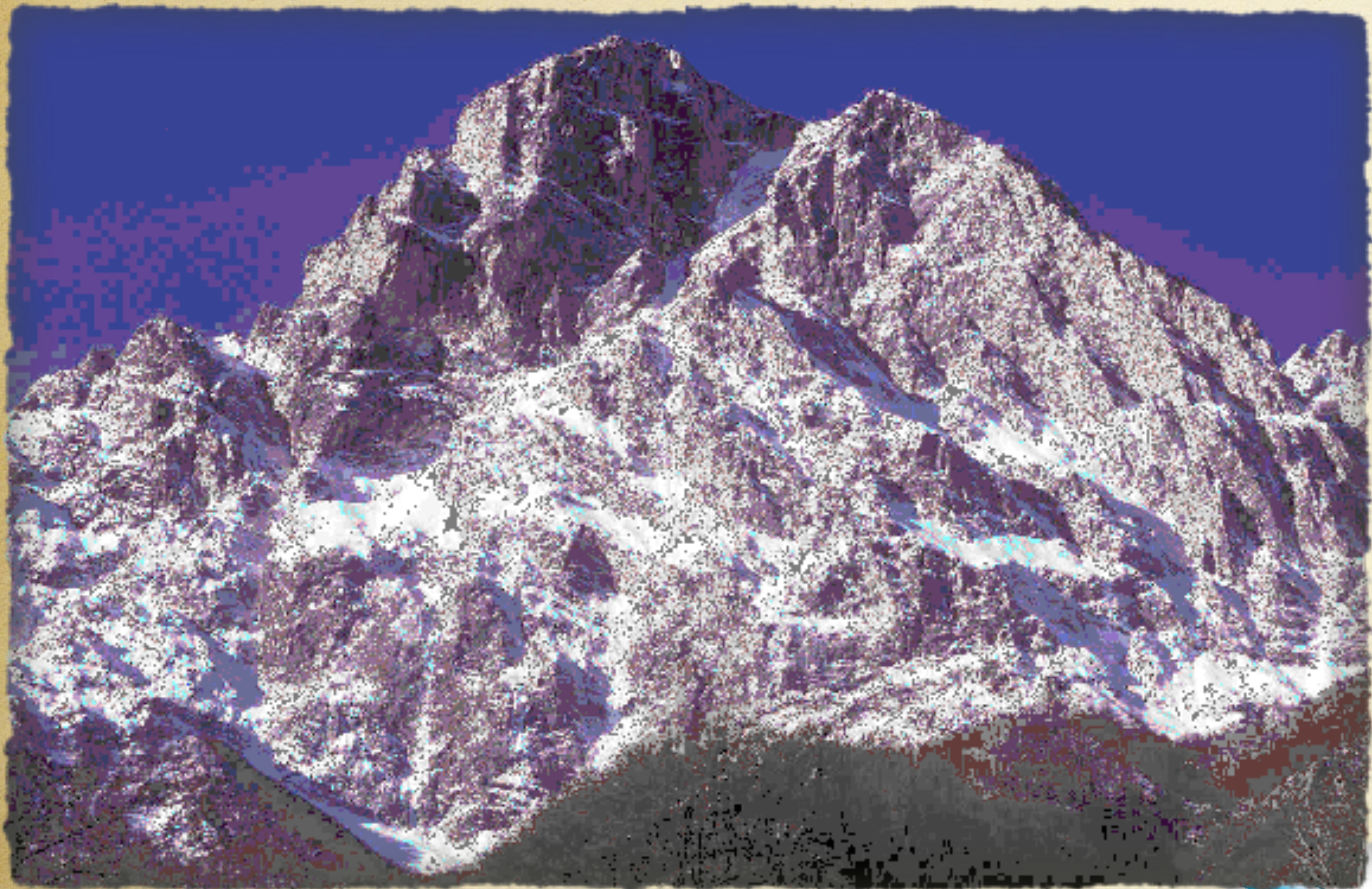
a collaborative effort by INFN and Cultural Heritage Ministry

Cuoricino final result



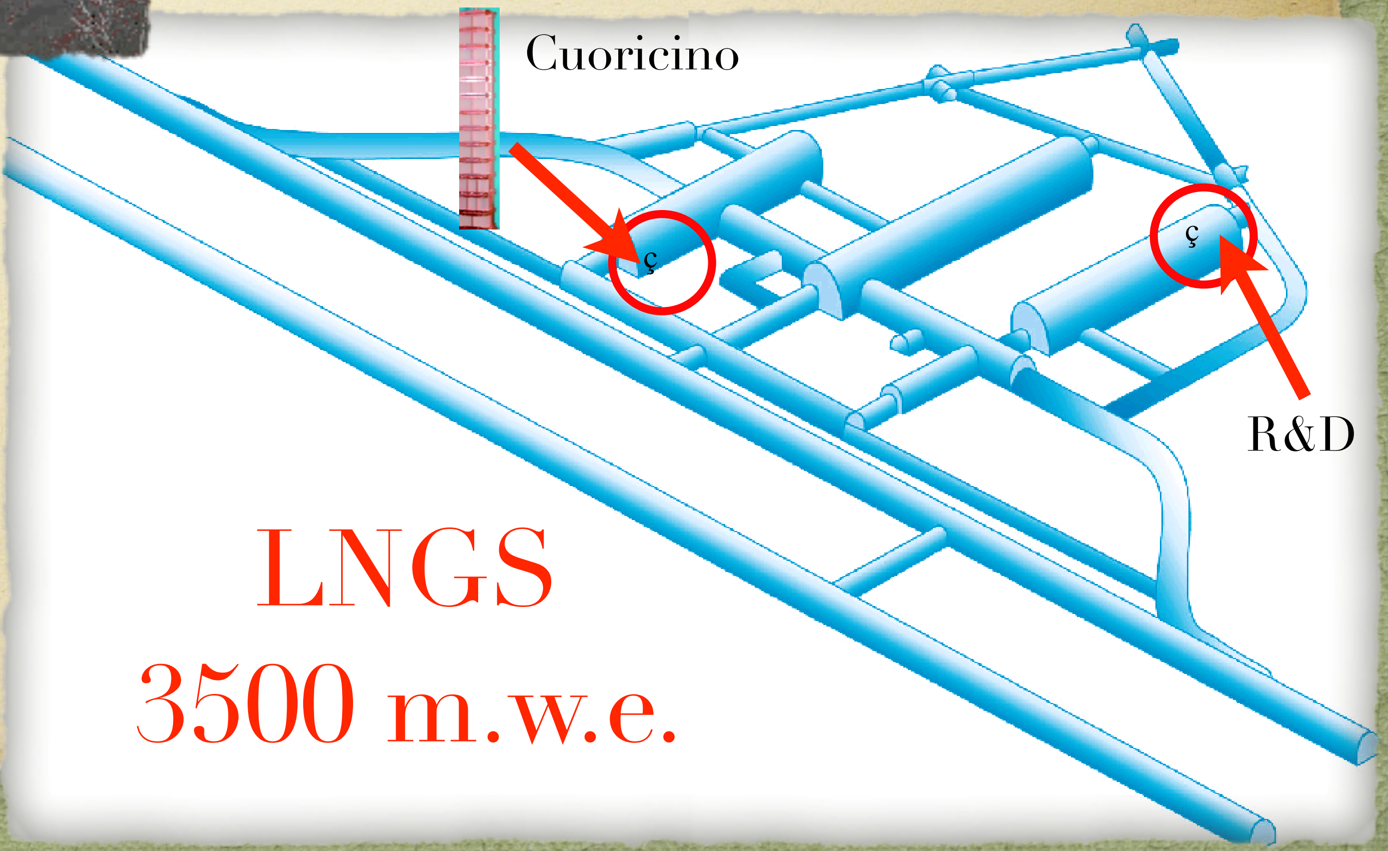
$\tau_{1/2}^{0\nu} = 2.8 \cdot 10^{24}$ y

Cuoricino, where ?



The Shield
Corno Grande 2916 m

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

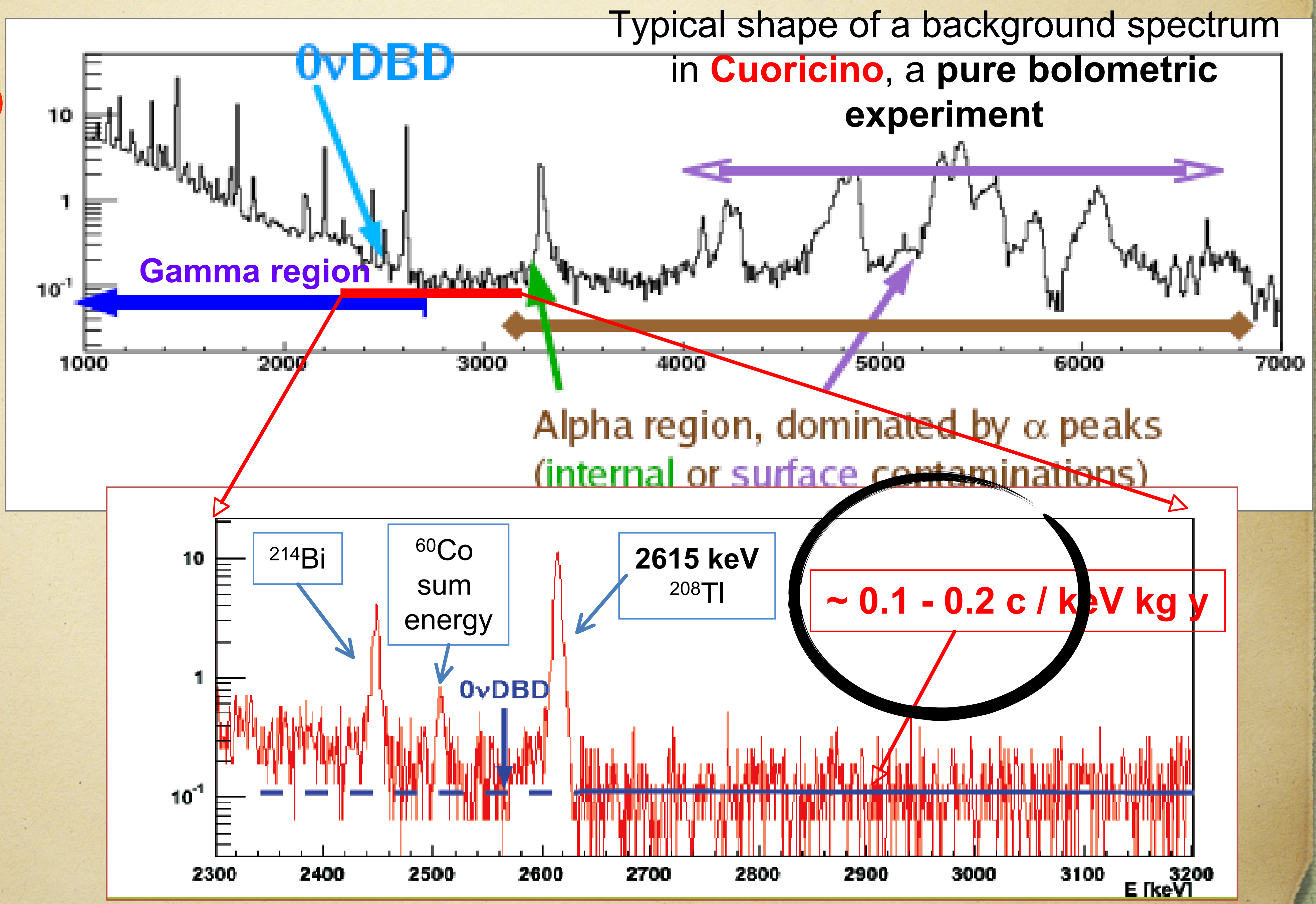


it is time to deal with the enemy: what is the background ?

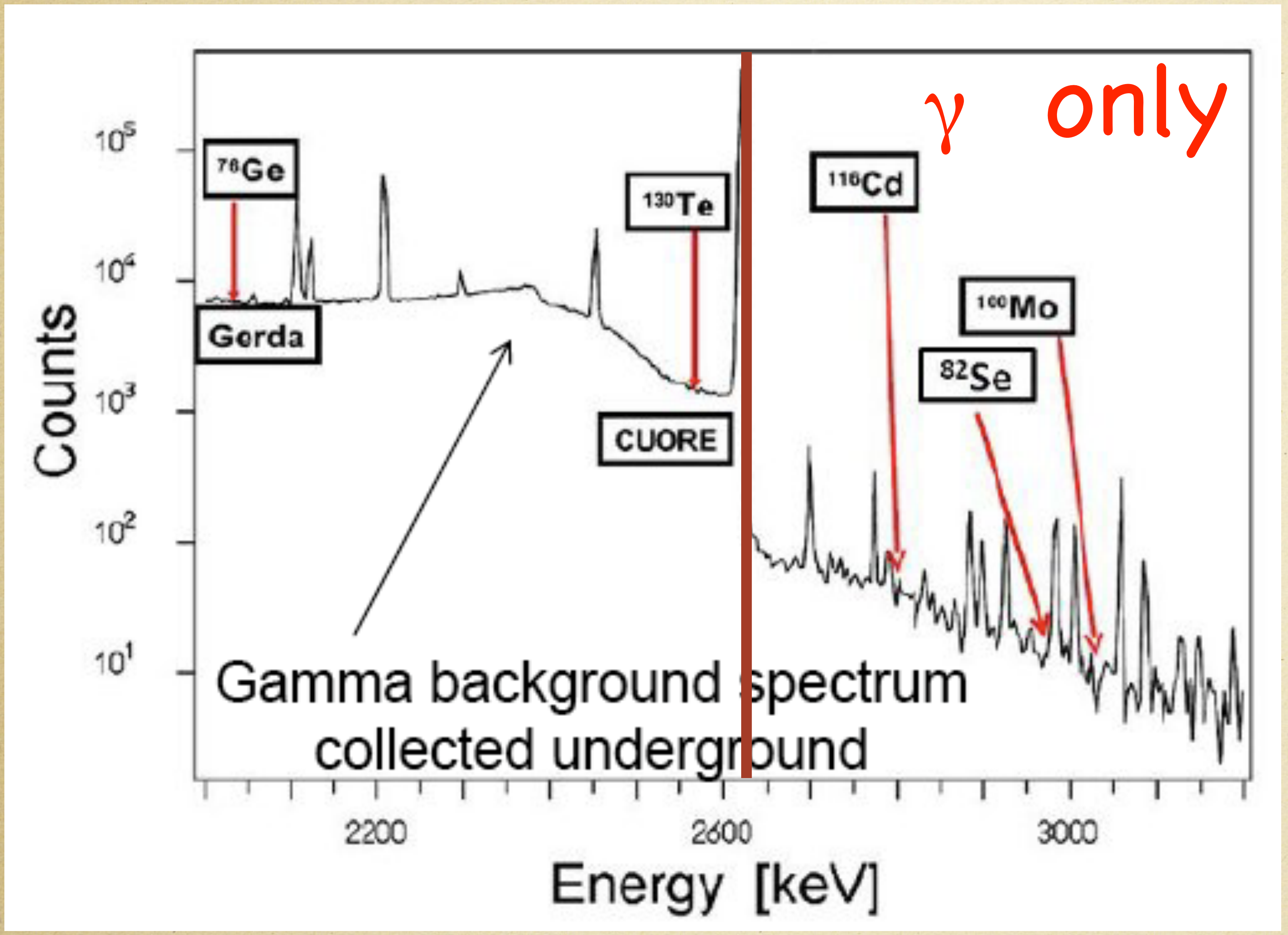
Cuoricino

b=0.18 ± 0.02 c/keV/kg/y

B is experiment dependent. Cuoricino as an example



we have two enemies then

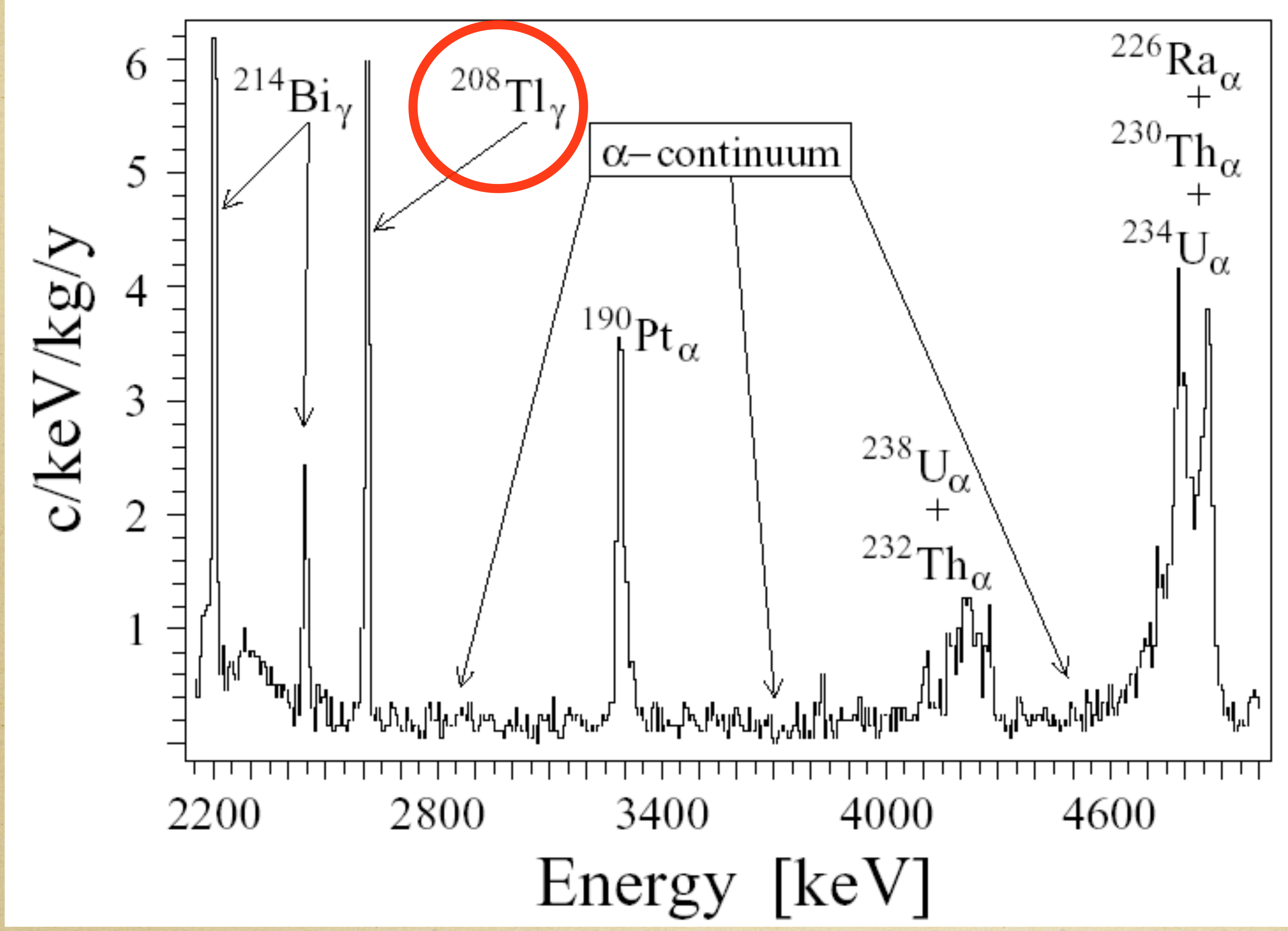


Photons

^{208}Tl is where photons start to disappear

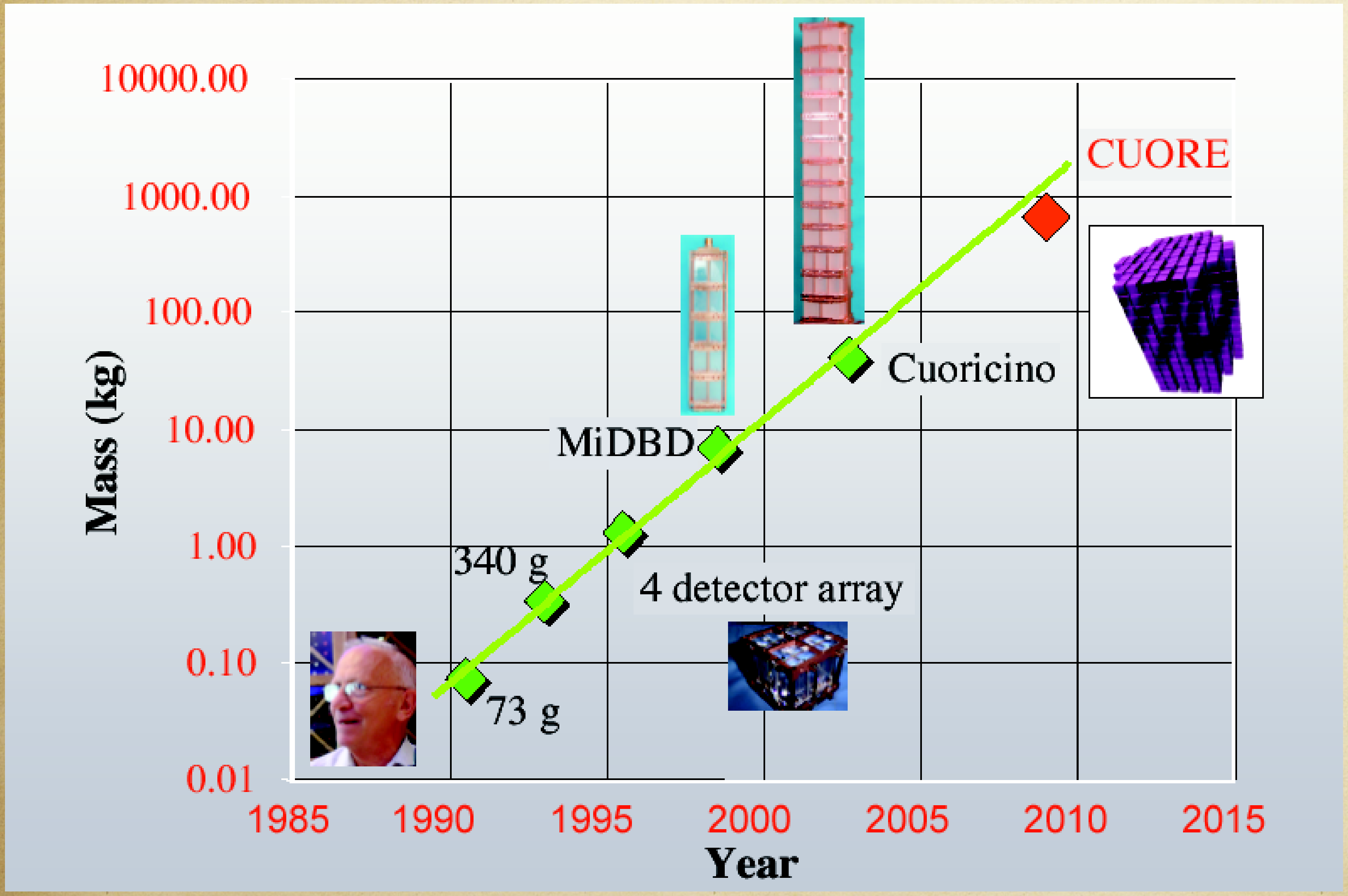
Keep it in mind !

and…



the α land

The last child of the evolution: CUORE



this kind of Moore's law for bolometers is not very precise but it gives the time scale of the generation evolution

CUORE

Pulse Tube Cooler

988 TeO_2 Crystals

19 Towers of 52 crystals each

741 Kg of TeO_2

Active Mass 204 Kg

Scaling Cuoricino to CUORE

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

$$M = m \times 20$$
$$T = t \times 6$$
$$b = B / 20$$
$$\Delta E = \Delta E / 1.5$$

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

$\tau_{1/2\ (CUORE)} \sim 1.2 \times 10^{26}$

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

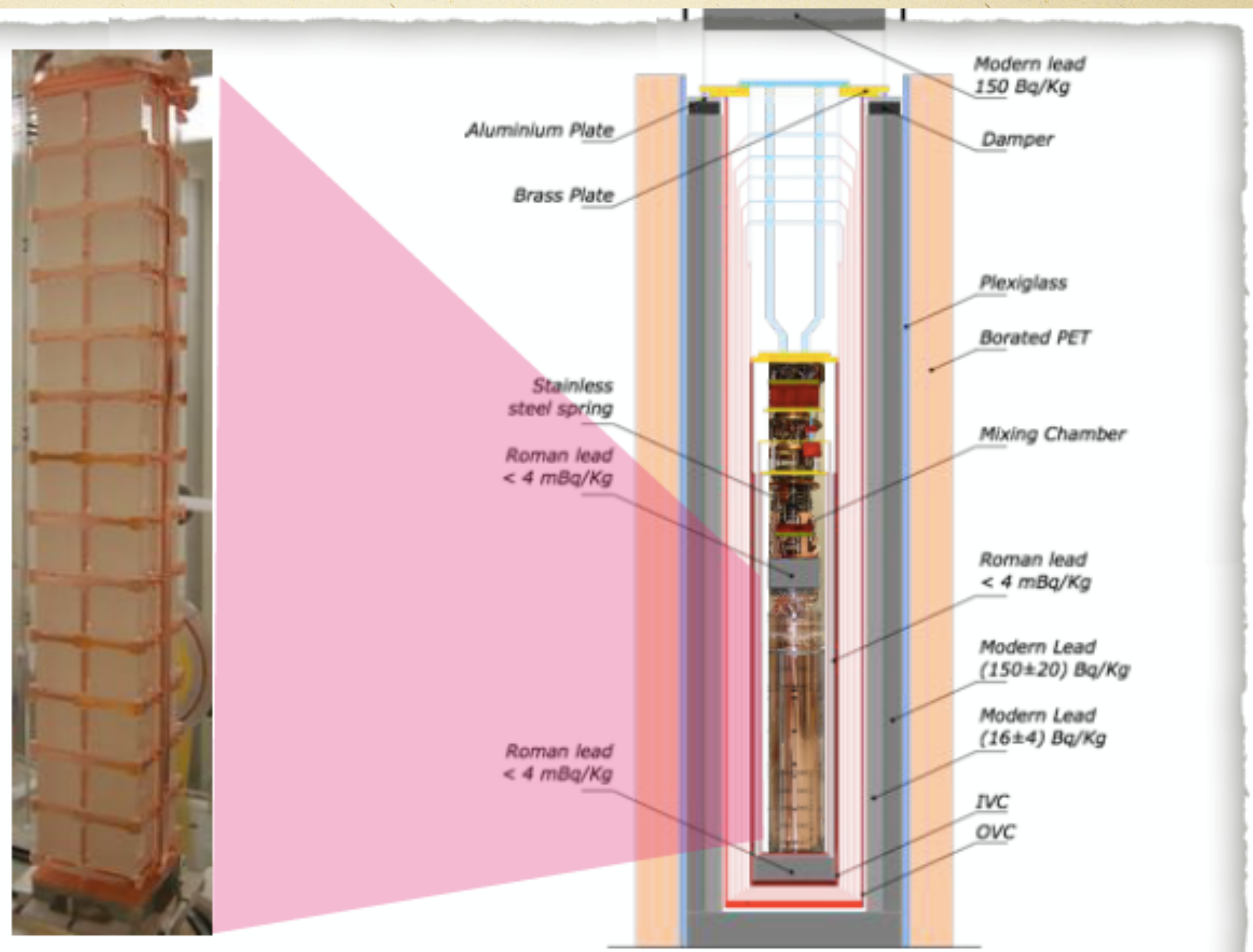
a sanity check: CUORE-0

Size similar to CUORICINO:

- 52x750g crystals
- 13 floor of 4 crystals each

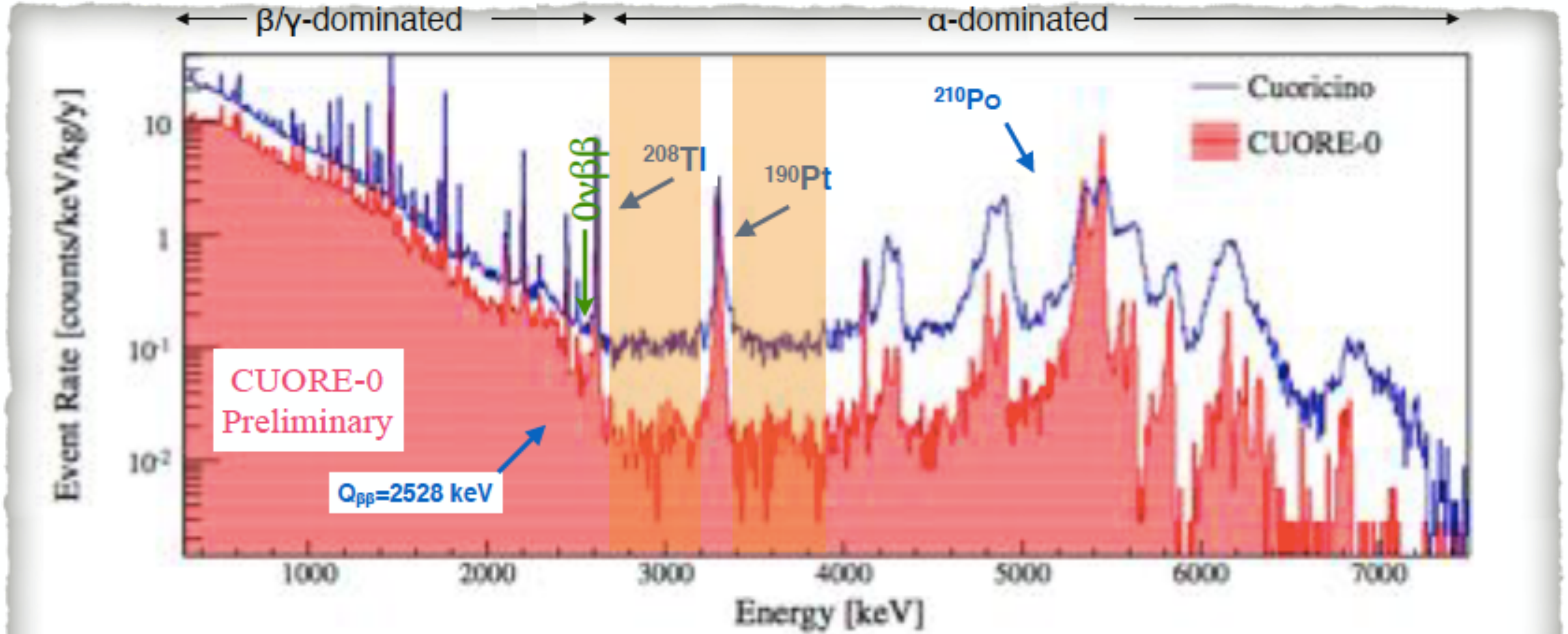
Active mass:

- TeO_2: 39 kg
- ^{130}Te: ~11 kg ($5 \cdot 10^{25}$ nuclei)



Same cryostat as CUORICINO:
γ background (^{232}Th) not expected to change ⇒ test the α background

which says…

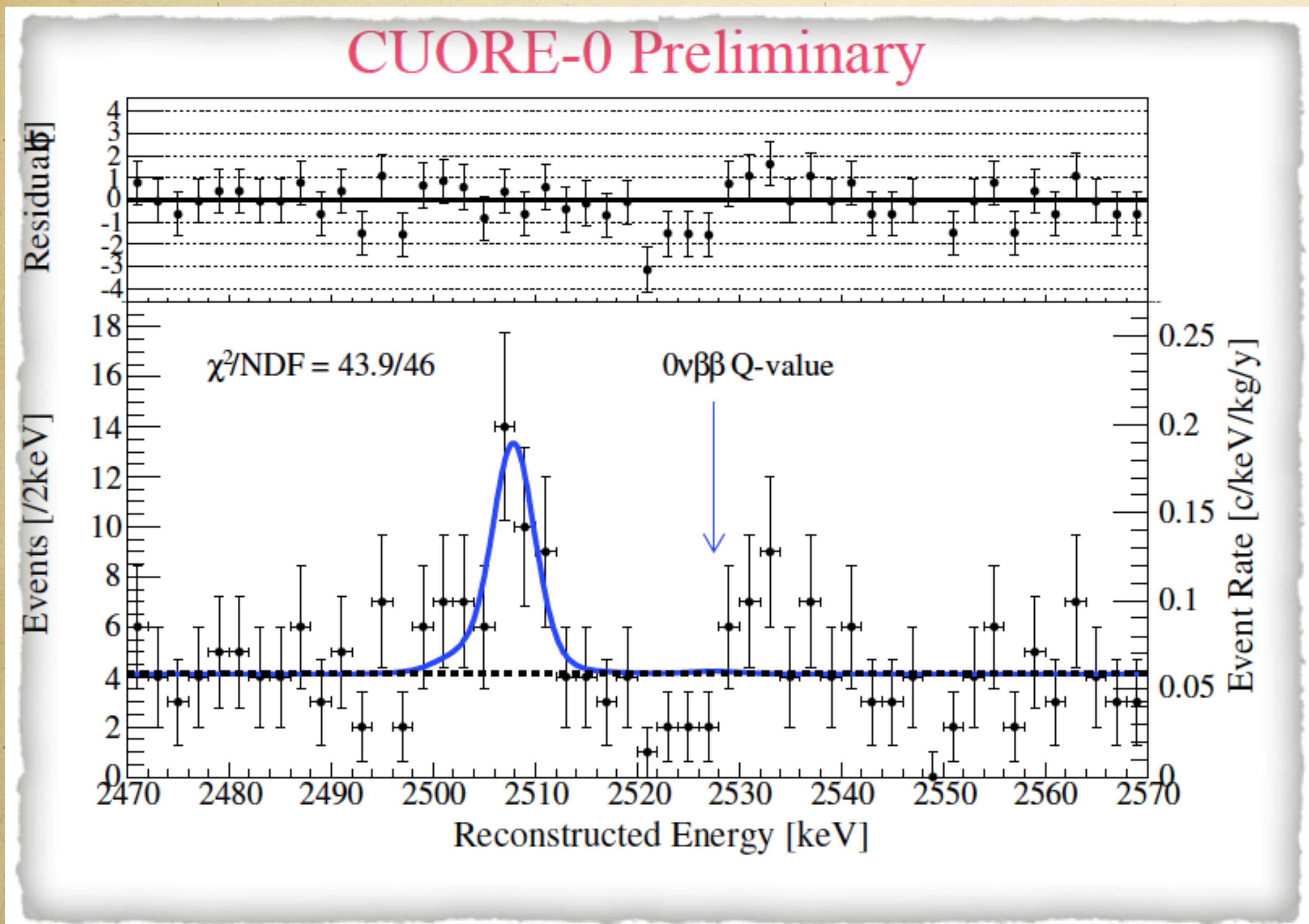


	Avg. flat bkg. [c/(keV · kg · yr)]	
	0νββ region	2700-3900 keV
CUORICINO ε = 83%	0.169 ± 0.006	0.110 ± 0.001
CUORE-0 ε = 81%	0.058 ± 0.04	0.016 ± 0.001

- ^{238}U γ lines reduced by ~2 (better radon control)
- ^{232}Th γ lines not reduced (originate from the cryostat)
- ^{238}U/^{232}Th α lines reduced (detector surface treatment)

now with a MC extrapolation to CUORE
it says that the goal of B=0.01 is reachable

BTW…on the fly



$T^{0\nu}_{1/2} > 2.7 \cdot 10^{24}$ yr

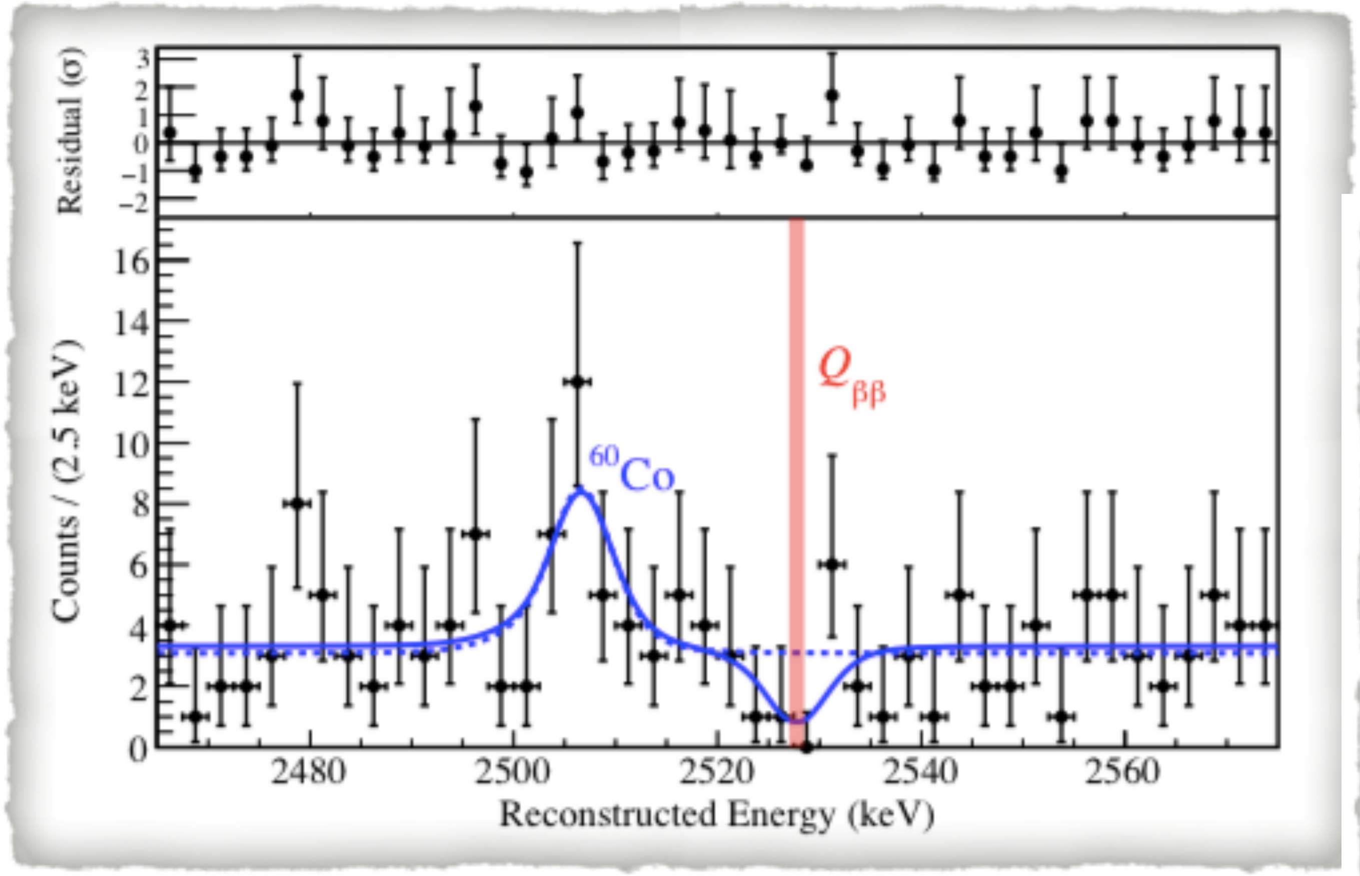
9.8 kg·y ^{130}Te

note the same Cuoricino limit in half time

Combine CUORE-0 and CUORICINO limit

$T^{0\nu}_{1/2} > 4.0 \cdot 10^{24}$ yr @ 90%CL

and CUORE first result



Performance Parameters		
Channels used	876	935
TeO_2 exposure (kg·yr)	37.6	48.7
Effective resolution (keV)	8.3 ± 0.4	7.4 ± 0.7
Background (10^{-2} c/(keV·kg·yr))	1.49 ± 0.18	1.35 ± 0.19

$$T^{0\nu}_{1/2} > 1.5 \times 10^{25} \text{ yr}$$

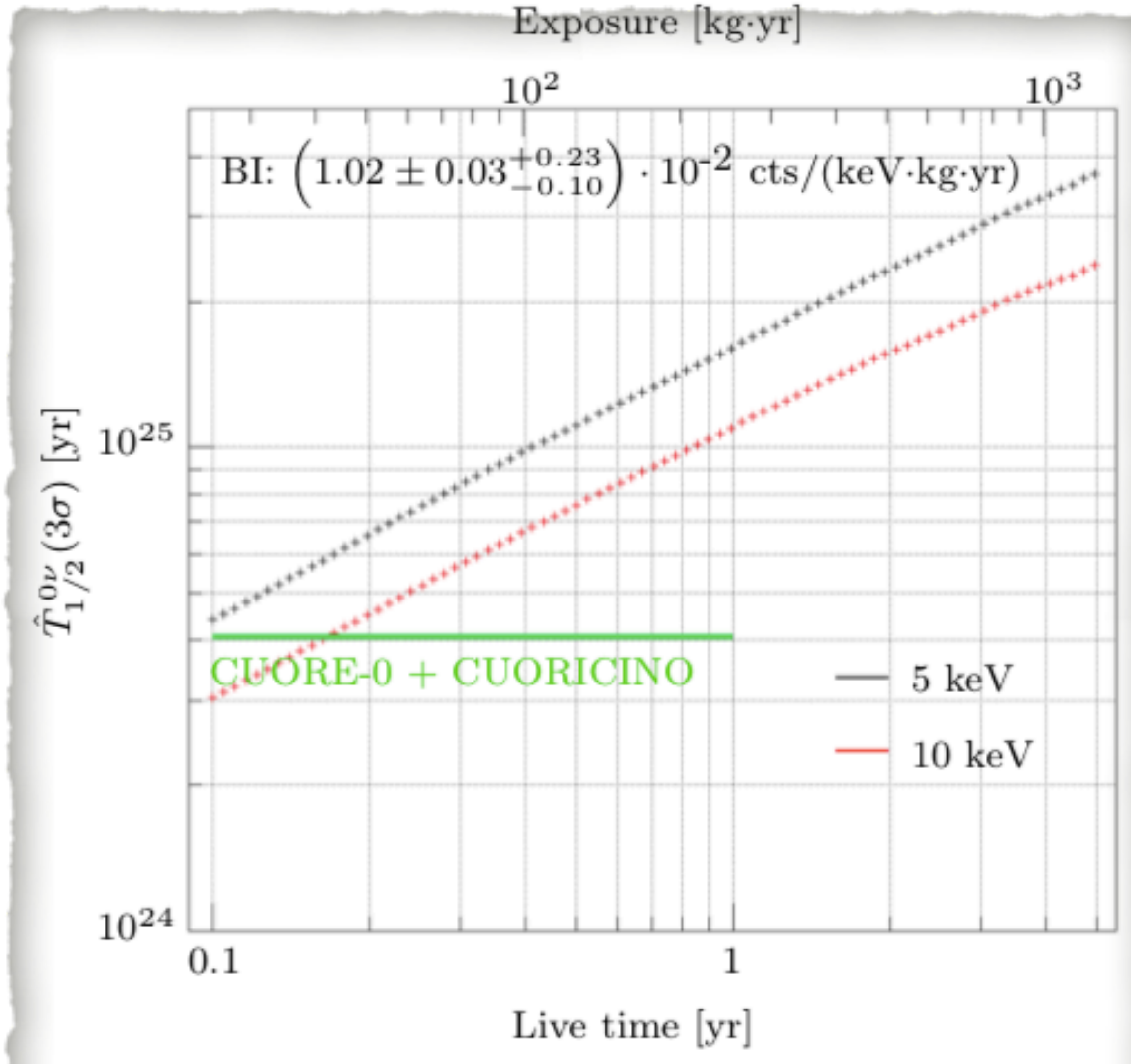
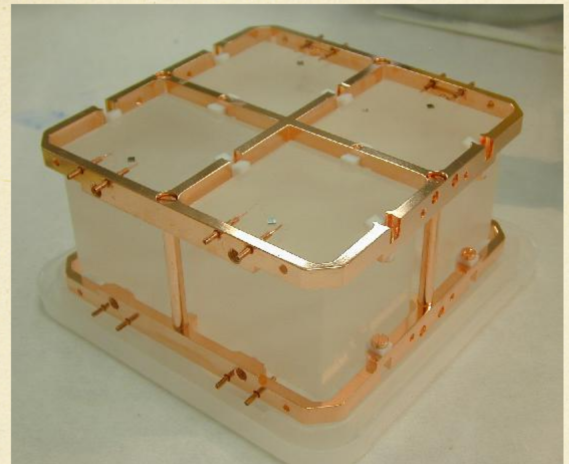
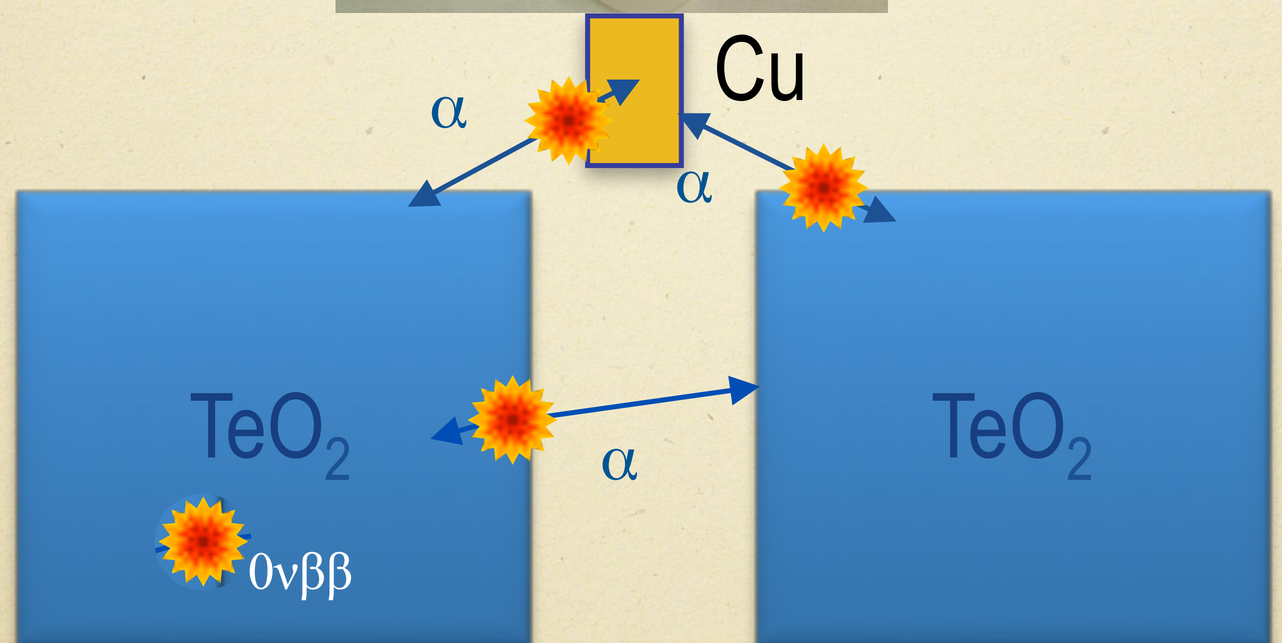


Fig. 3: 3σ discovery sensitivity with a *BI* of $1.02 \cdot 10^{-2}$ cts/(keV·kg·yr) and an FWHM of 5 keV.

the nasty α background





what is measured is part of the α energy
(if it were an internal emission…no problem !)
that induces a flat background

The Problem

TeO2 case

(CUORE)

740 Kg

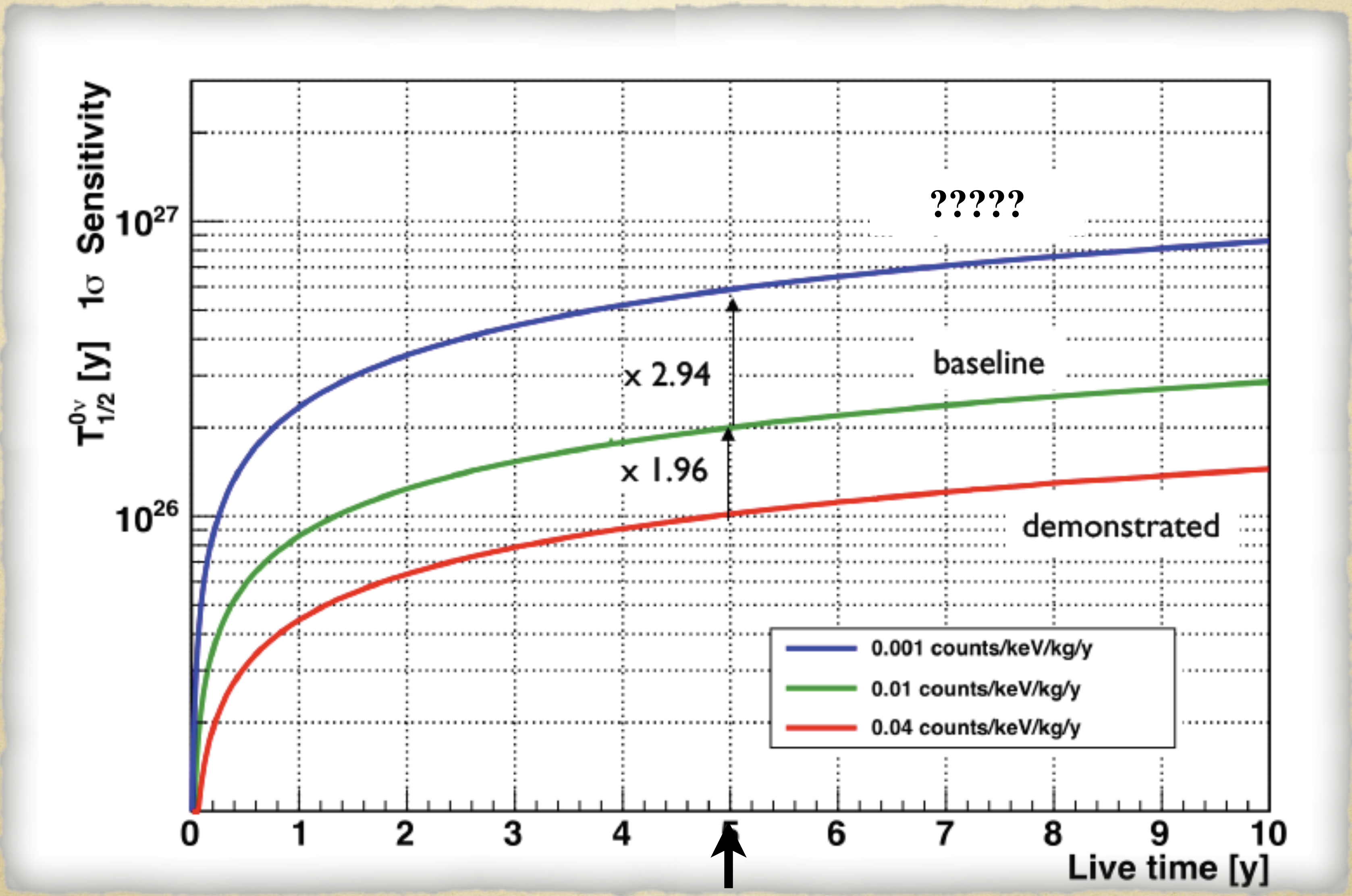
of which

200 Kg

of ^{130}Te

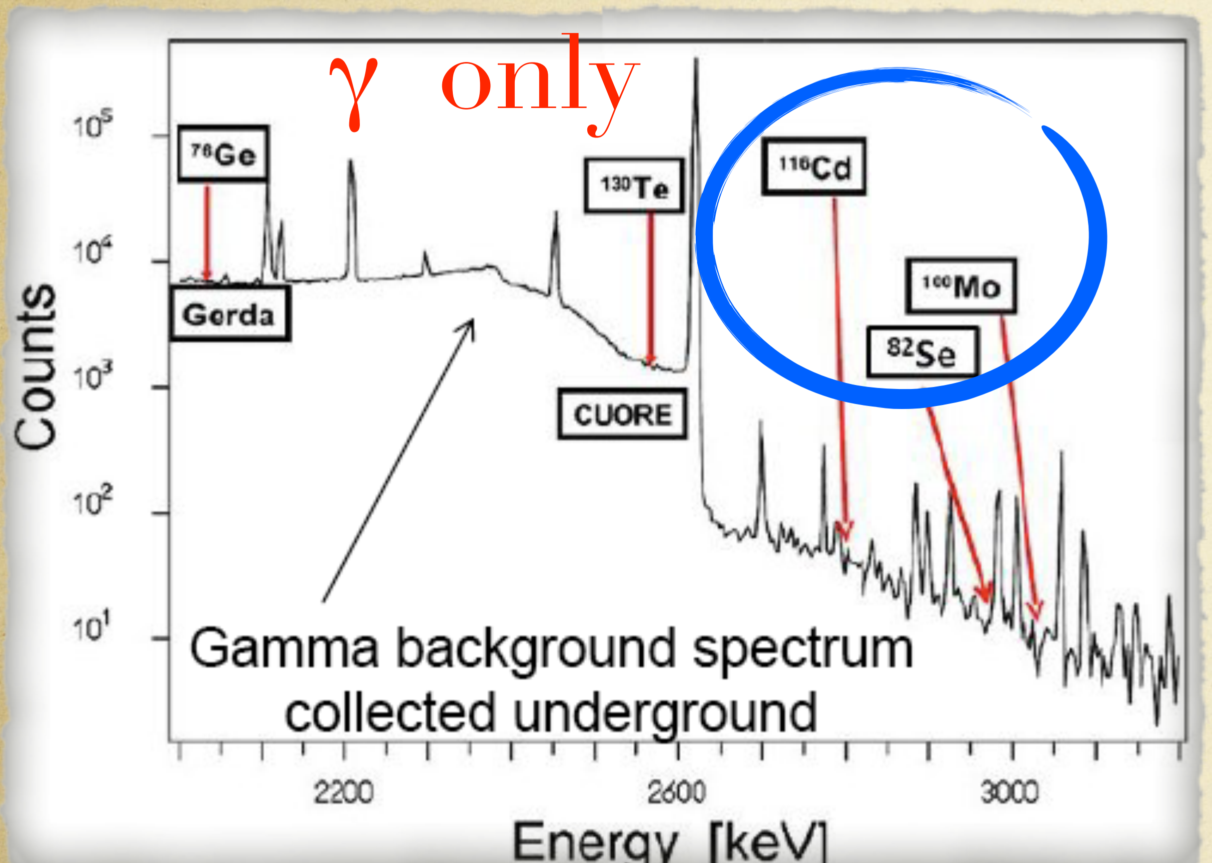
B=0.01 can be achieved

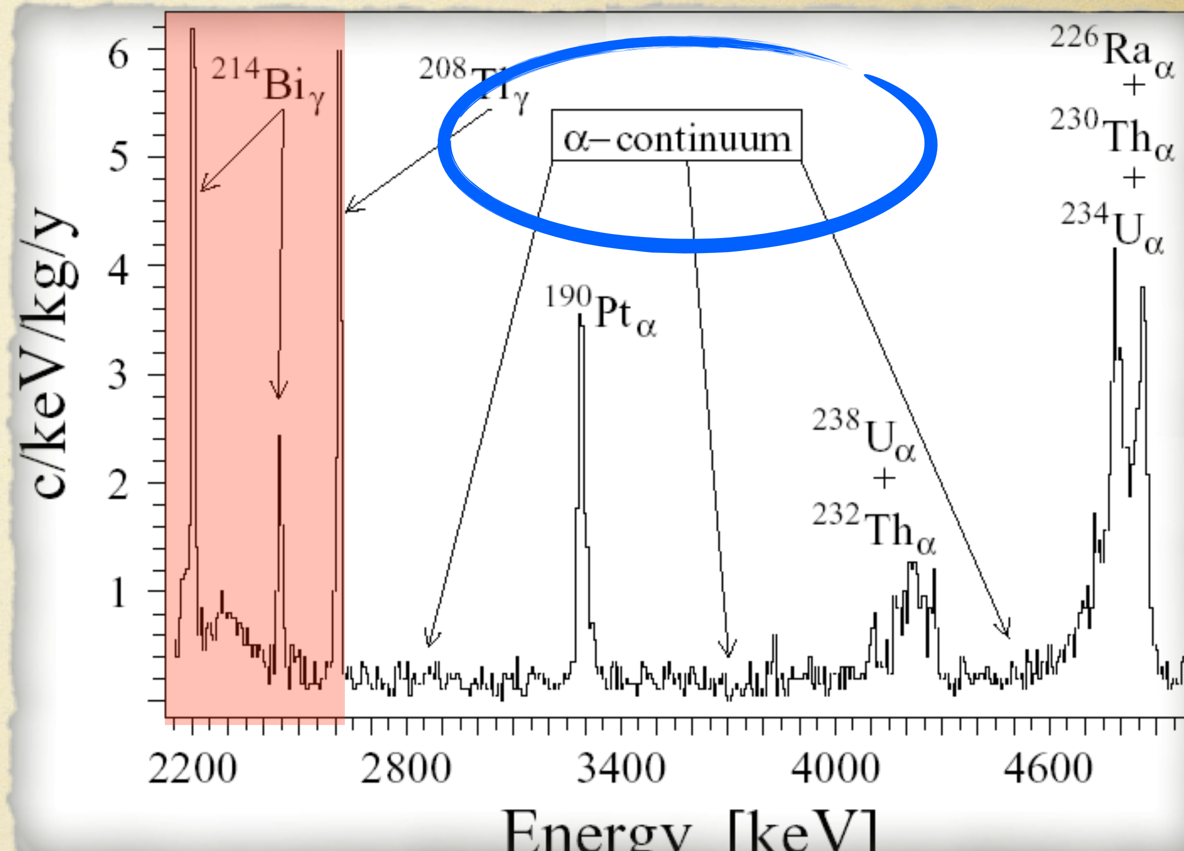
B=0.001 cannot be achieved unless..



1 ton•y

unless.....





move above of the ^{208}Tl line

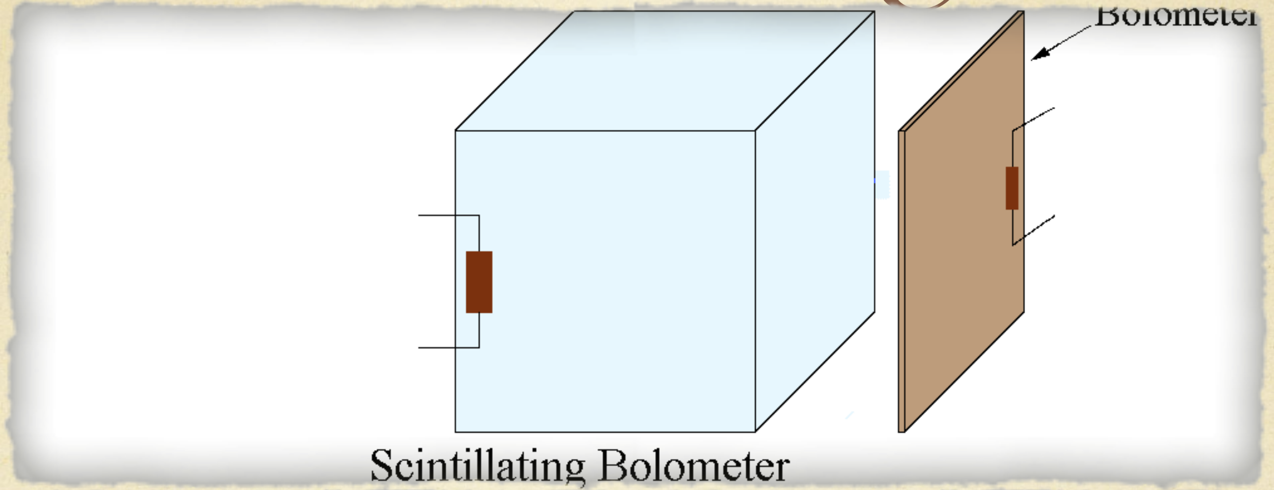
identify the α's event by event

The LUCIFER concept

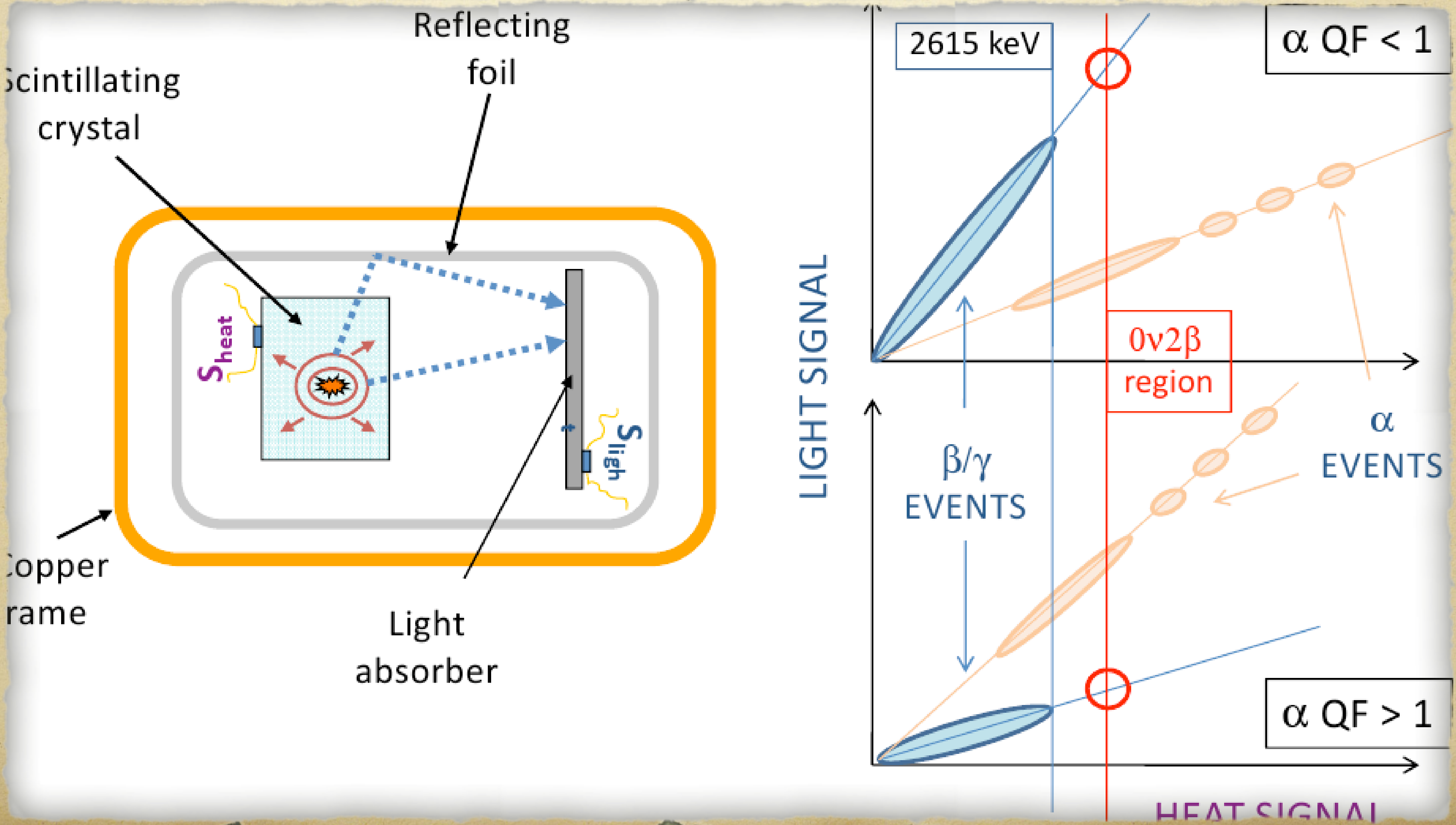
Lucifer is a Latin word (from the words *lucem ferre*), literally meaning "light-bearer", which in that language is used as a name for the dawn appearance of the planet Venus, heralding daylight.

Bringing light underground

Heat & Light

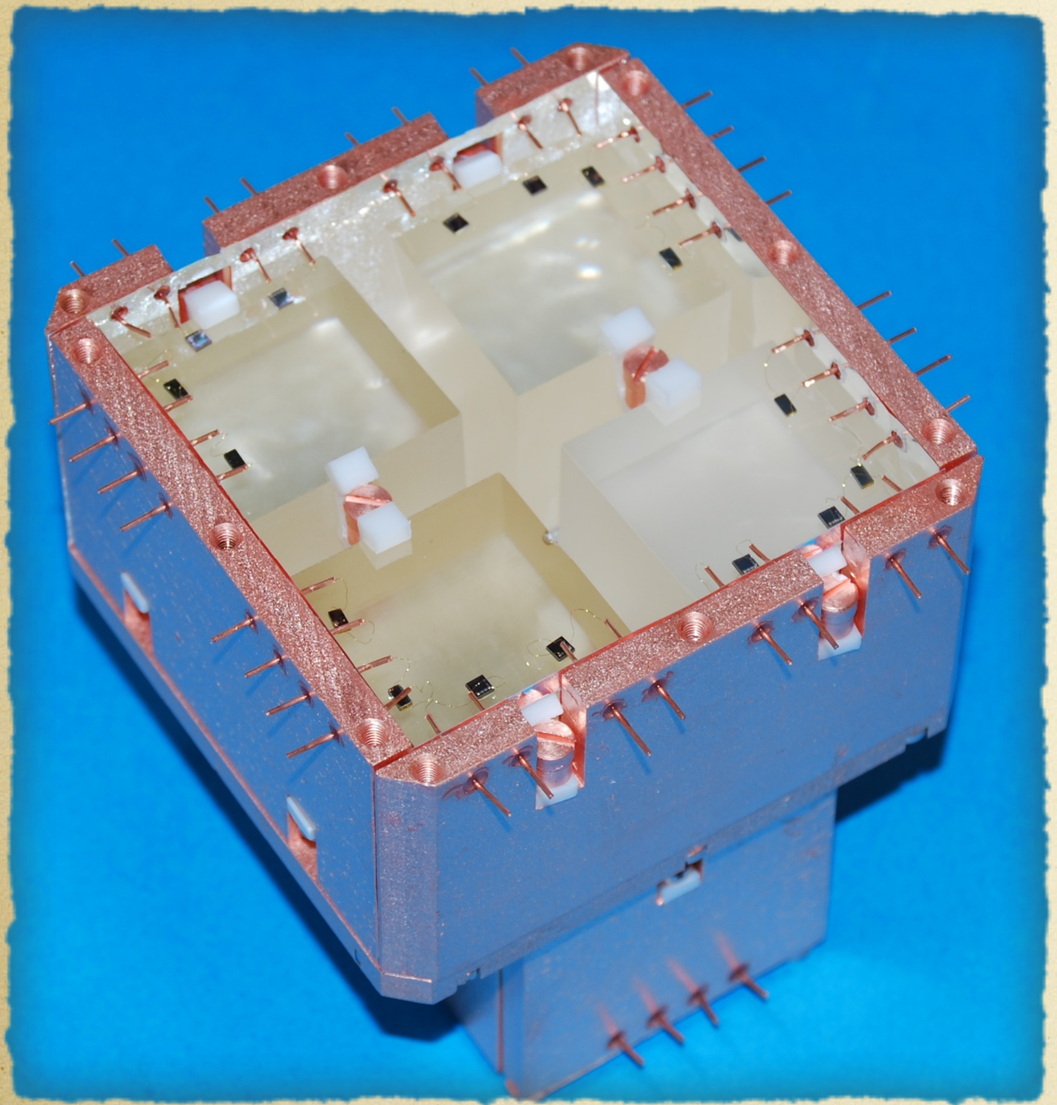


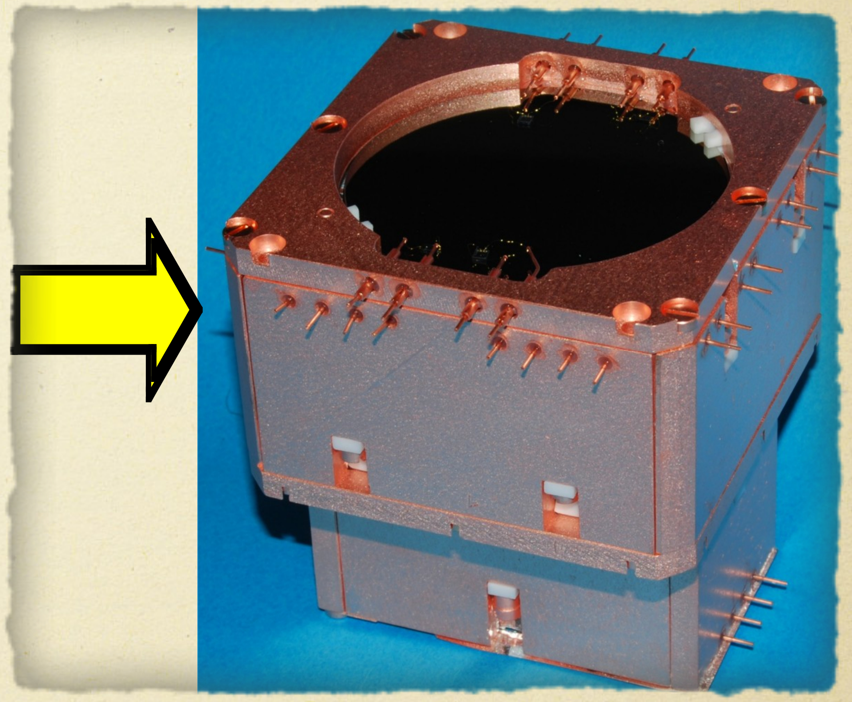
Bolometer
Scintillating Bolometer



Reflecting foil
Scintillating crystal
S heat
S light
Copper frame
Light absorber
2615 keV
α QF < 1
0ν2β region
LIGHT SIGNAL
β/γ EVENTS
α EVENTS
α QF > 1
HEAT SIGNAL

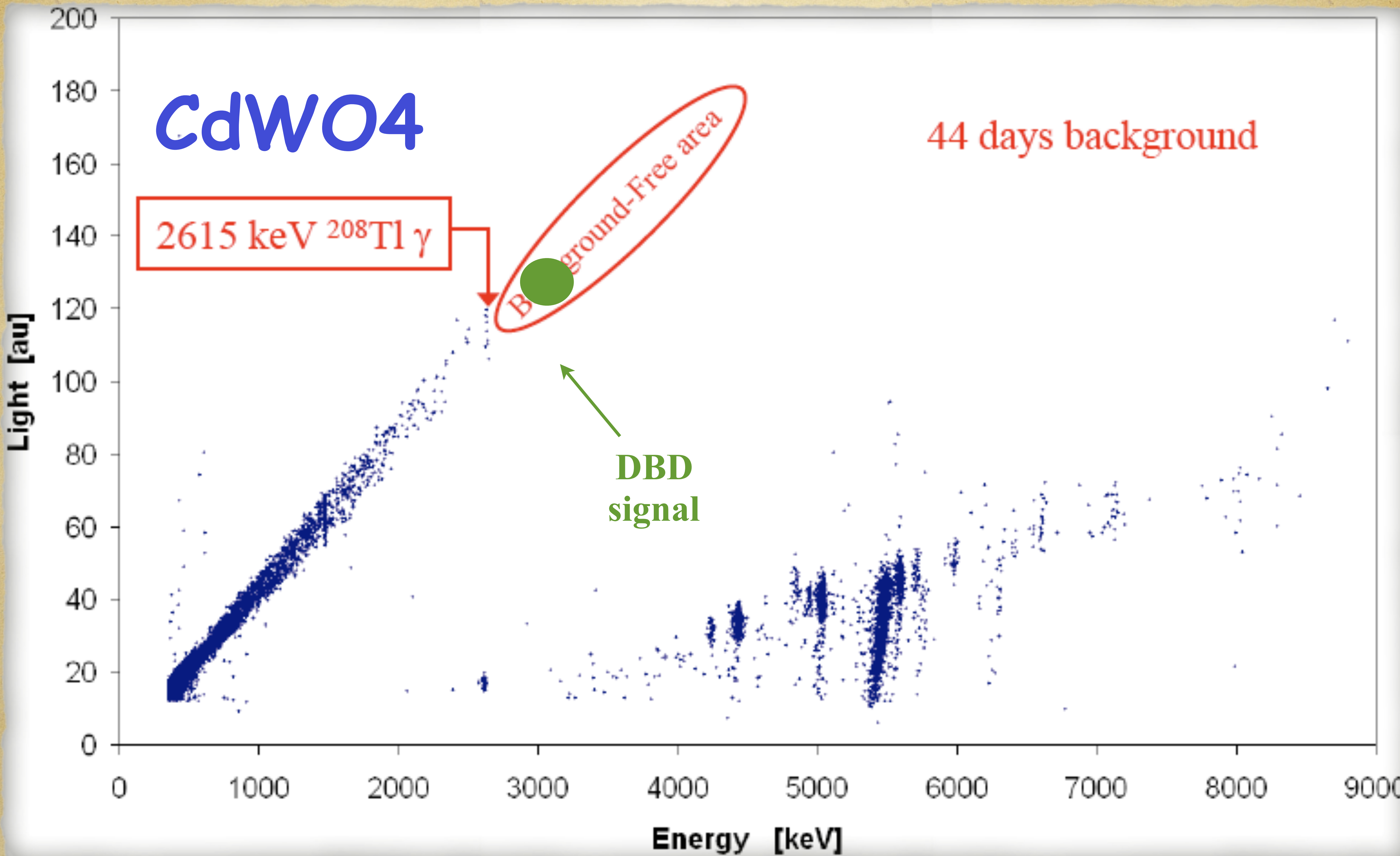
demonstration of the concept





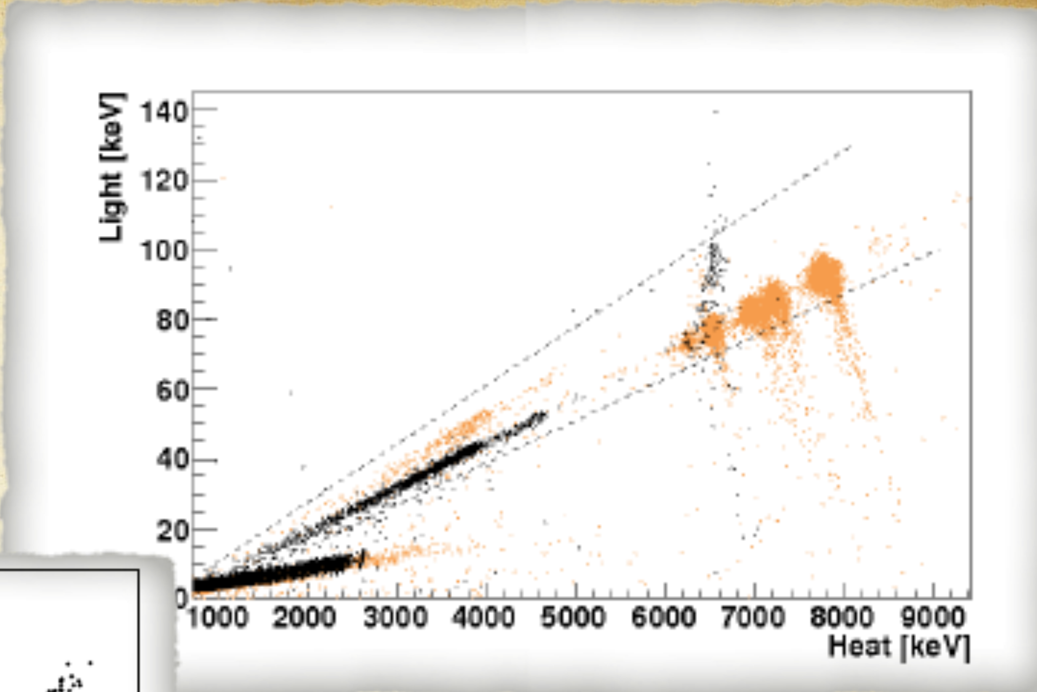
4 $CdWO_4$ bolometers
1 Ge Light detector

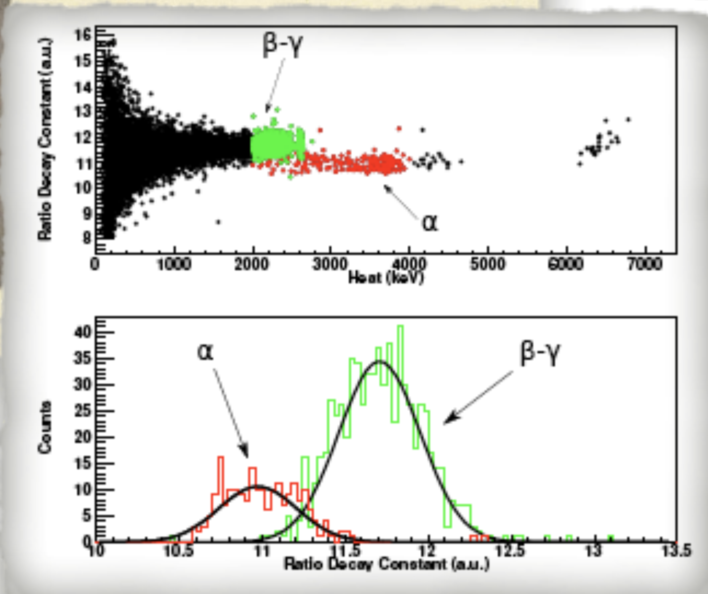
Roman
Pb shield



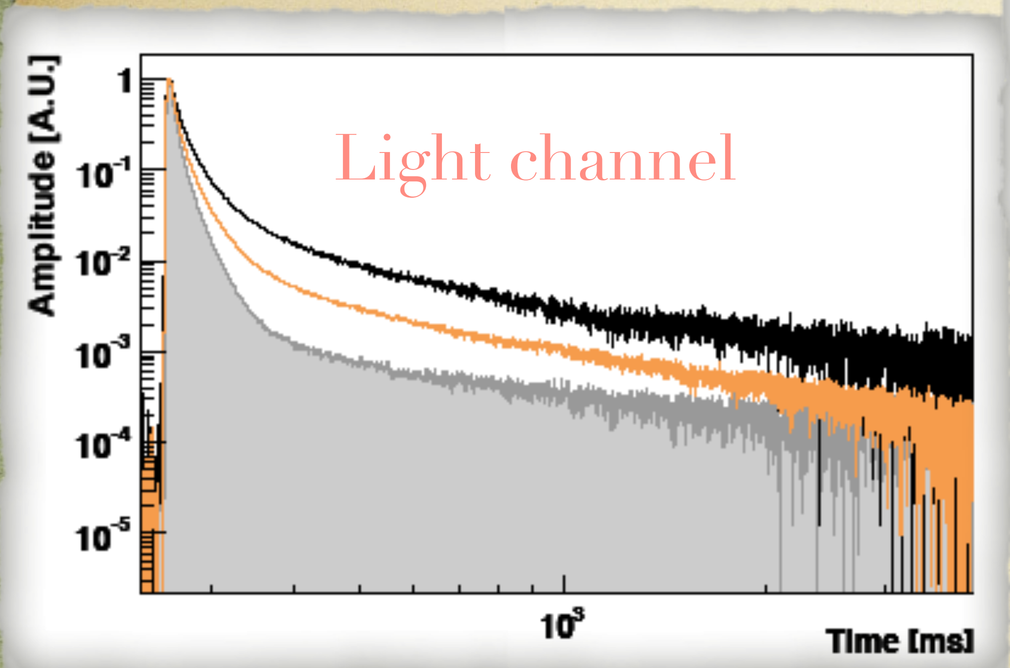
Cadmium makes nice crystals but it is a scary element for an experiment (n x-section)!

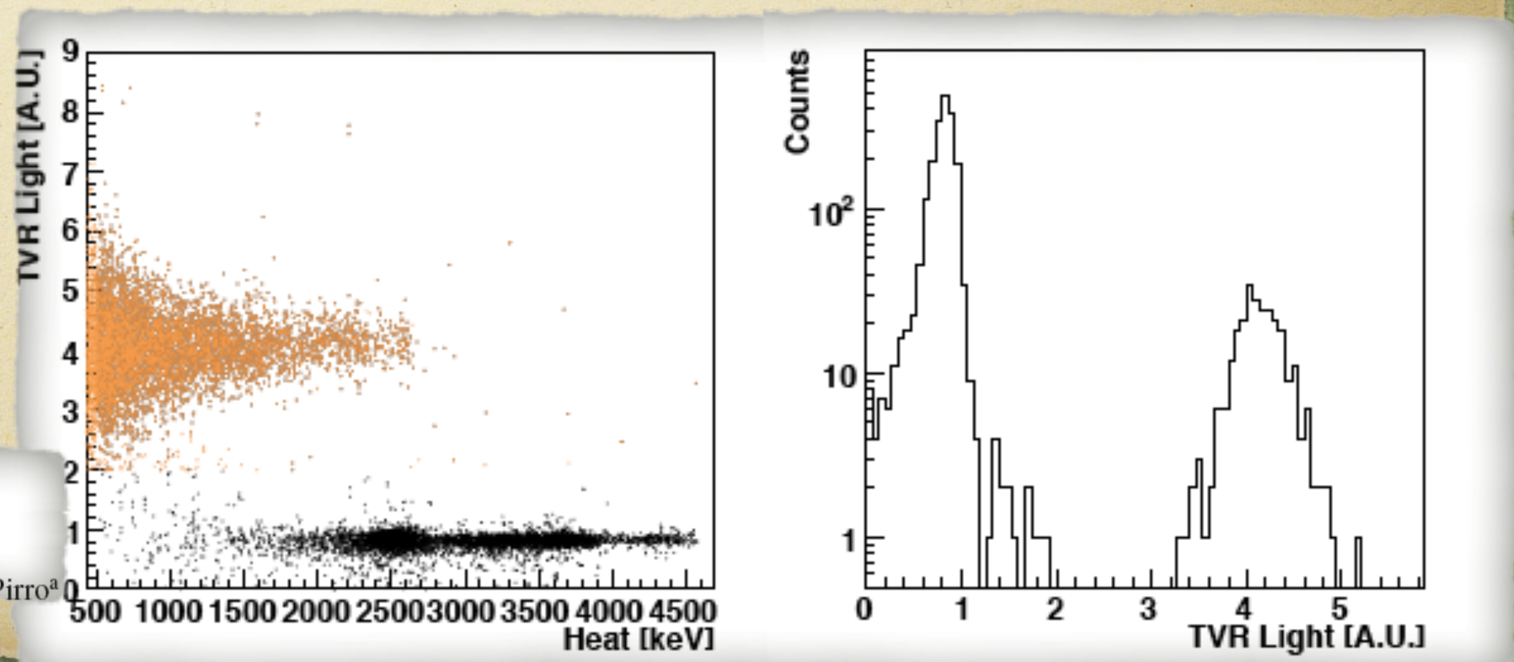
ZnSe





Heat channel





ZnSe scintillating bolometers for Double Beta Decay

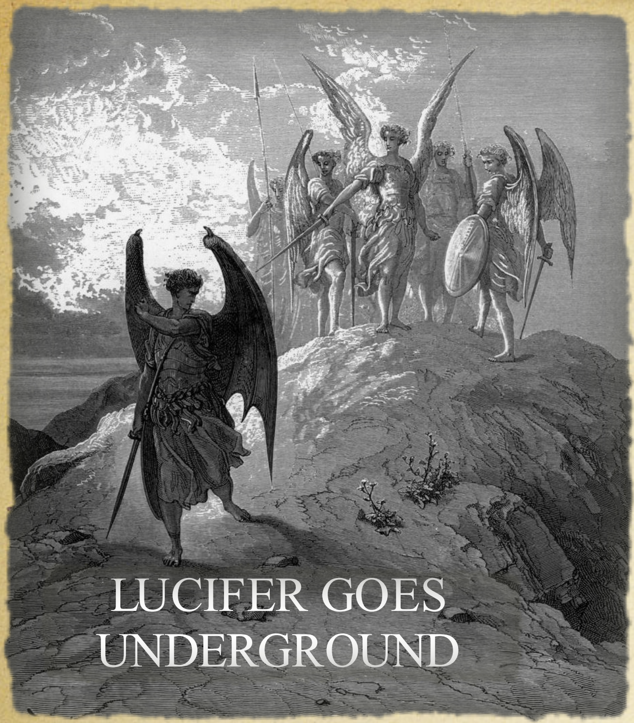
Astropart.Phys. 34 (2011) 344-353

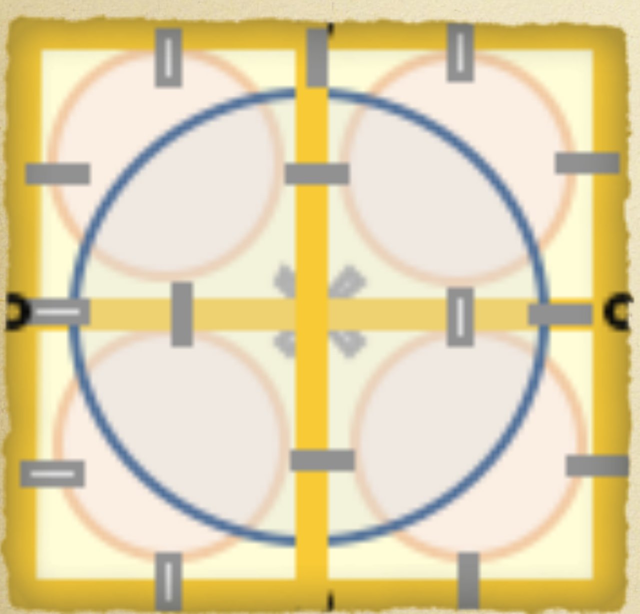
C. Arnaboldi[a], S. Capelli[b,a], O. Cremonesi[a], L. Gironi[b,a], M. Pavan[b,a], G. Pessina[a], S. Pirro[a]

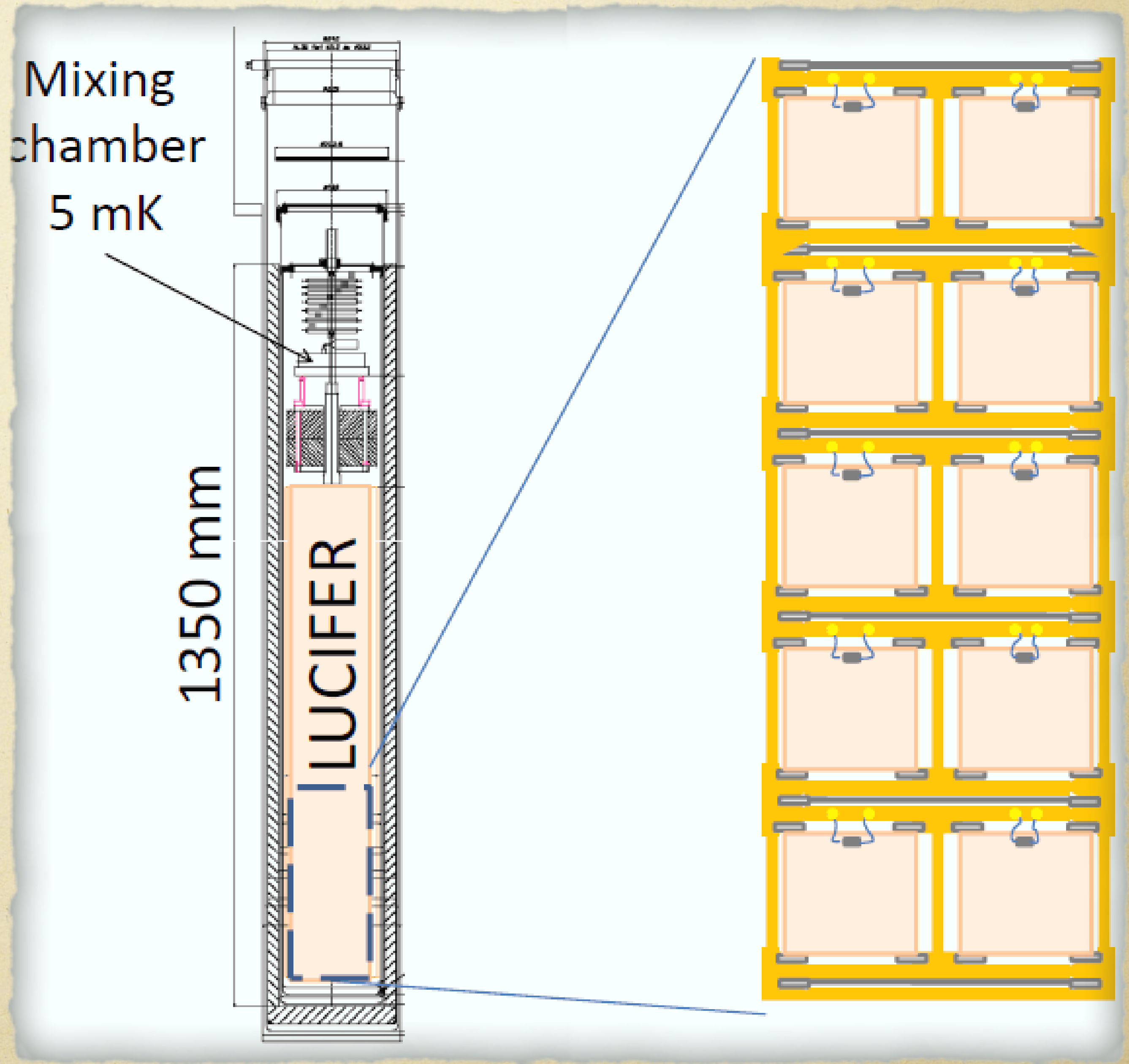
LUCIFER demonstrator

Low-background Underground Cryogenic Installation For Elusive Rates

ERC-2009-AdG 247115







Enrichment, going from Se to ^{82}Se

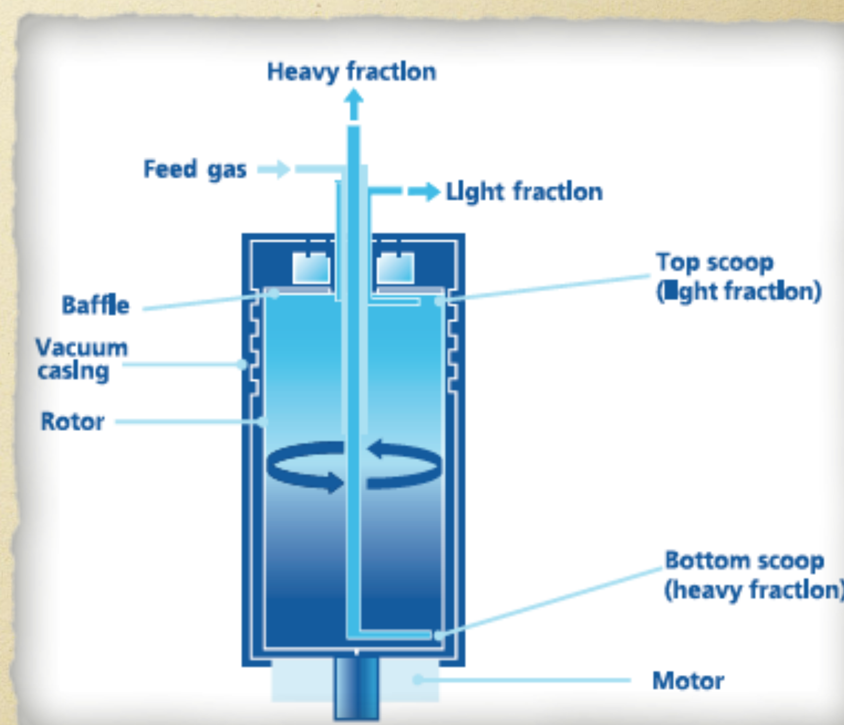
Stable Isotopes

urenco

(Almelo, NL)

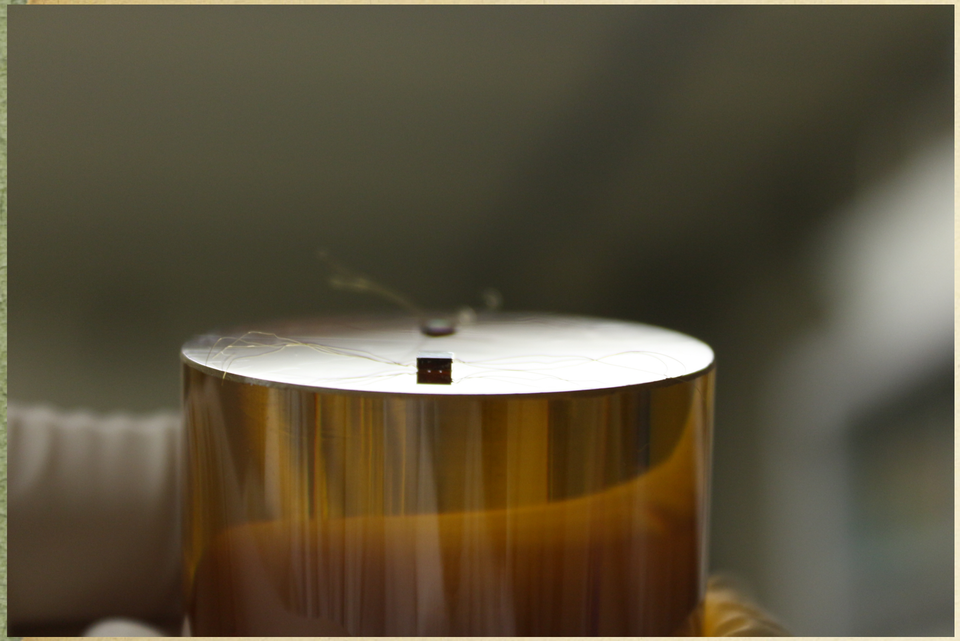
an interesting cooperation

however, it has to be known that the cost is 75Euro/gram



$Zn^{82}Se$ crystals

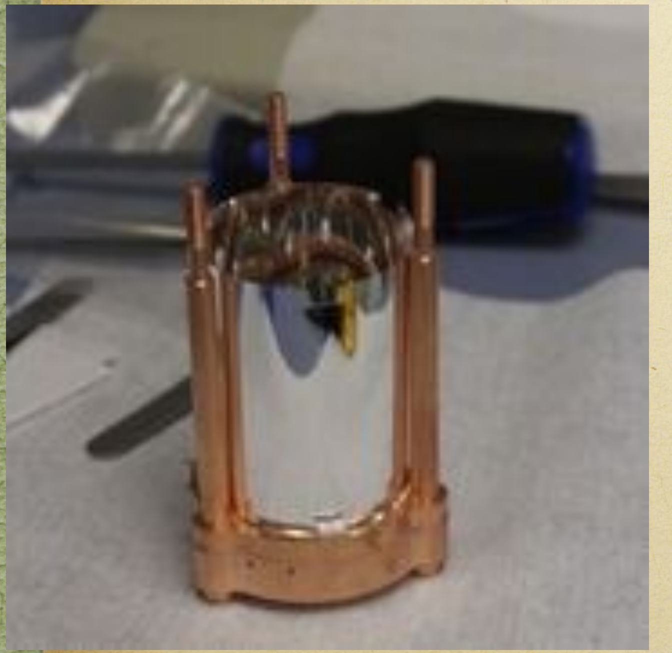
mounting the experiment



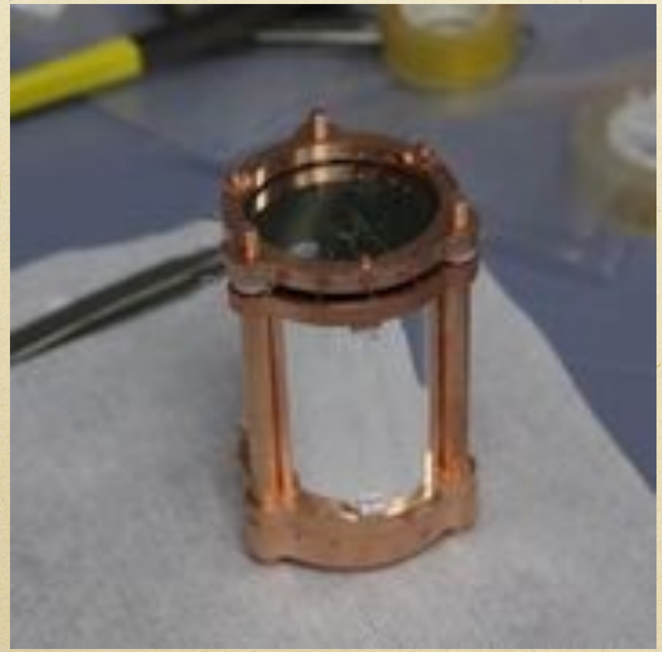
Sensors attached to crystal

ZnSe assembled in copper frames

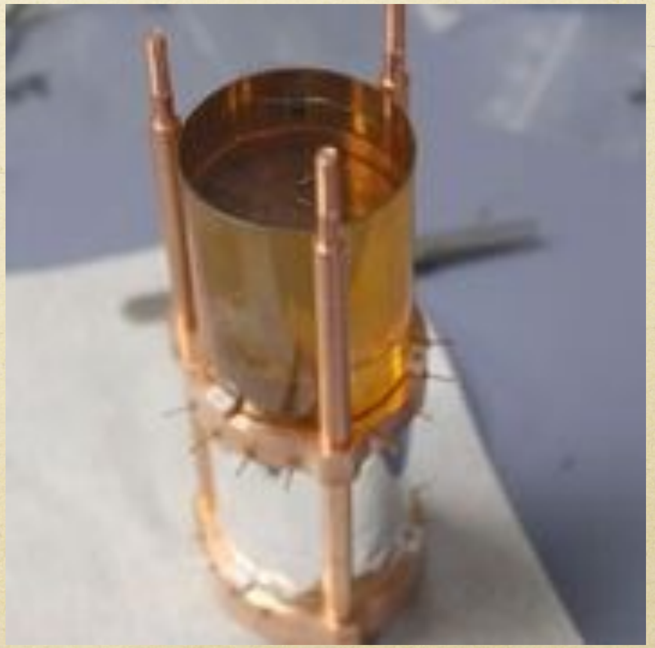
Assembly of light detector



Reflecting foil



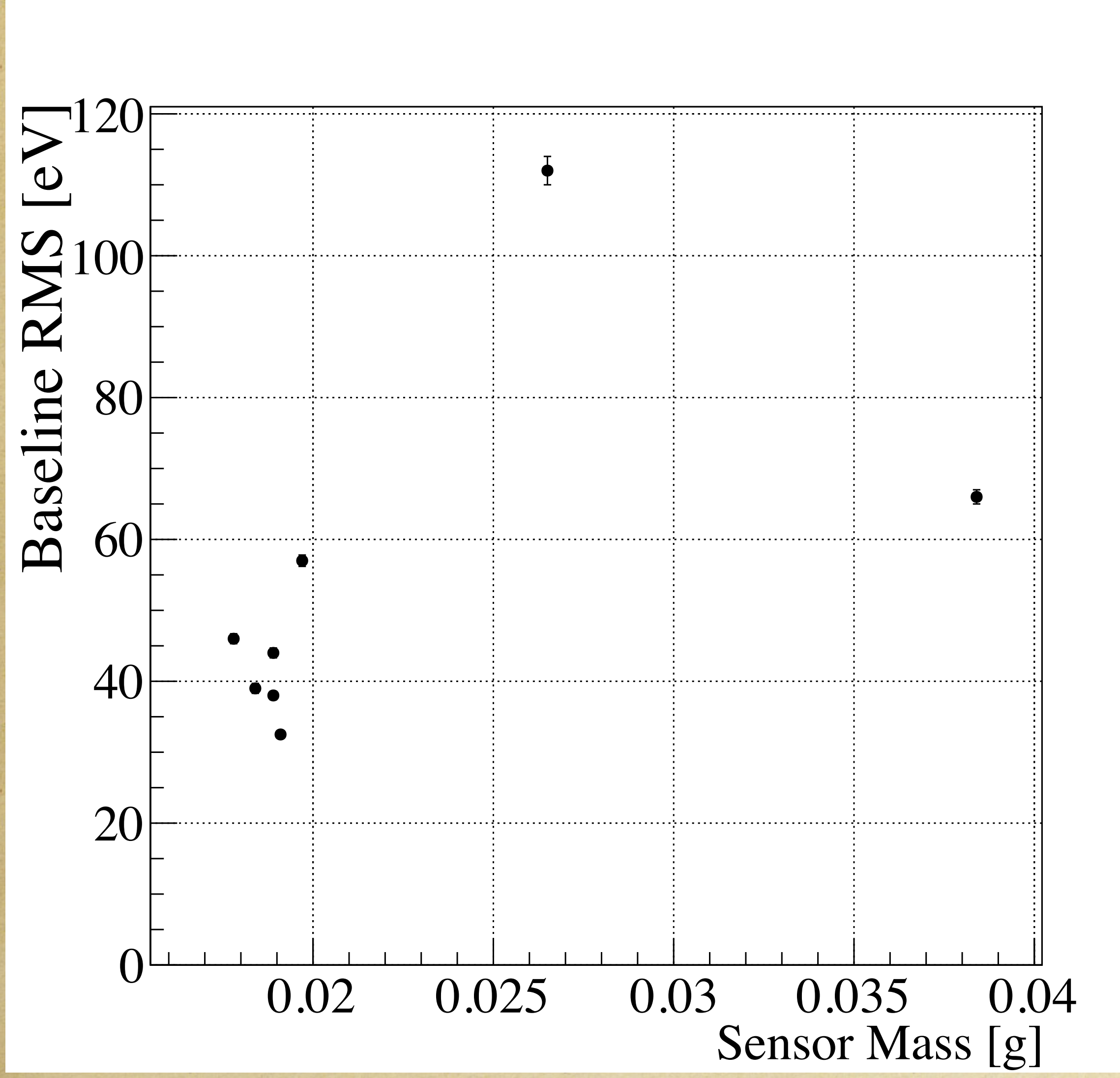
Coupling of light detector

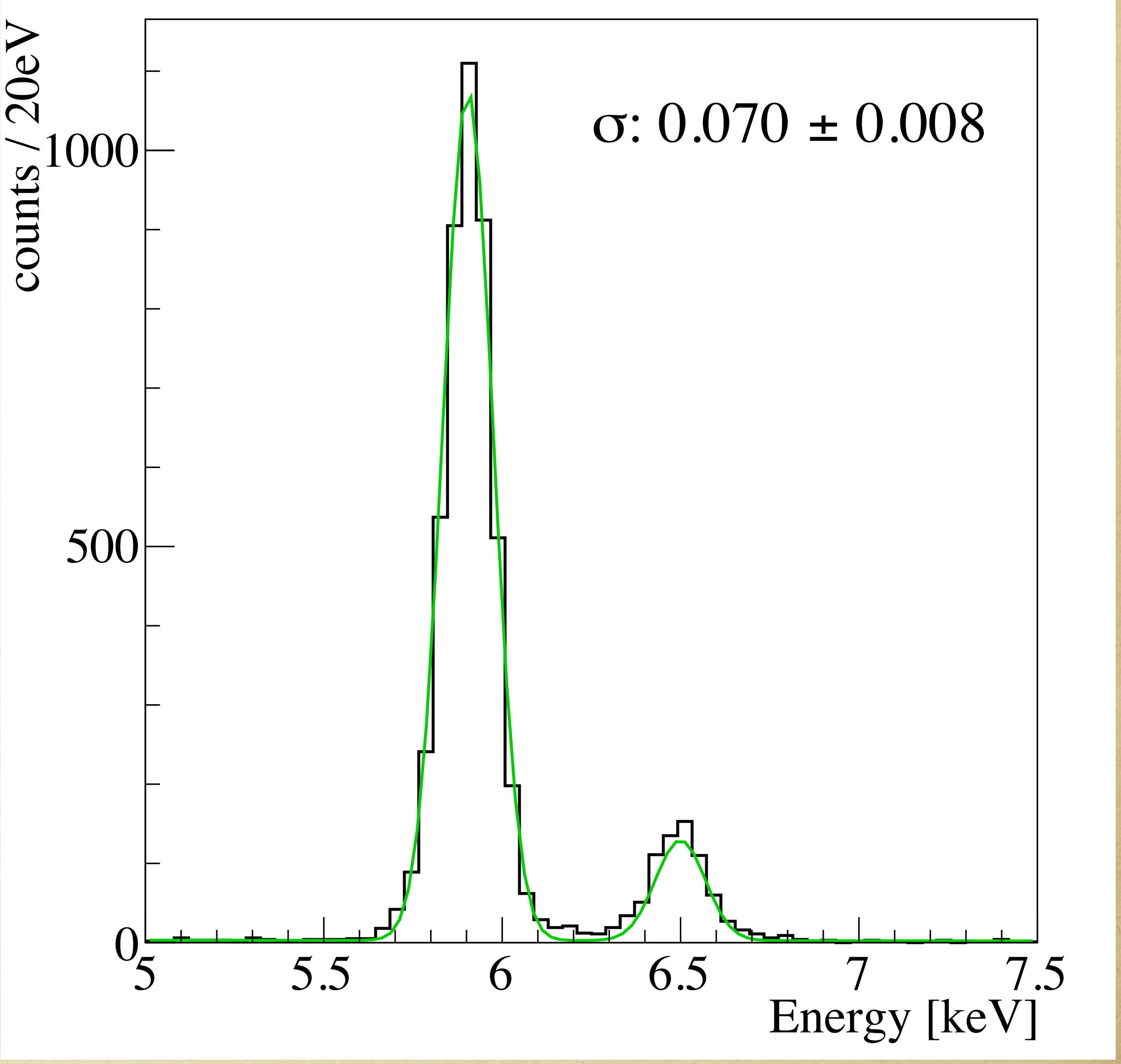


Second ZnSe

Final array

with spectacular L.D.





well behaving

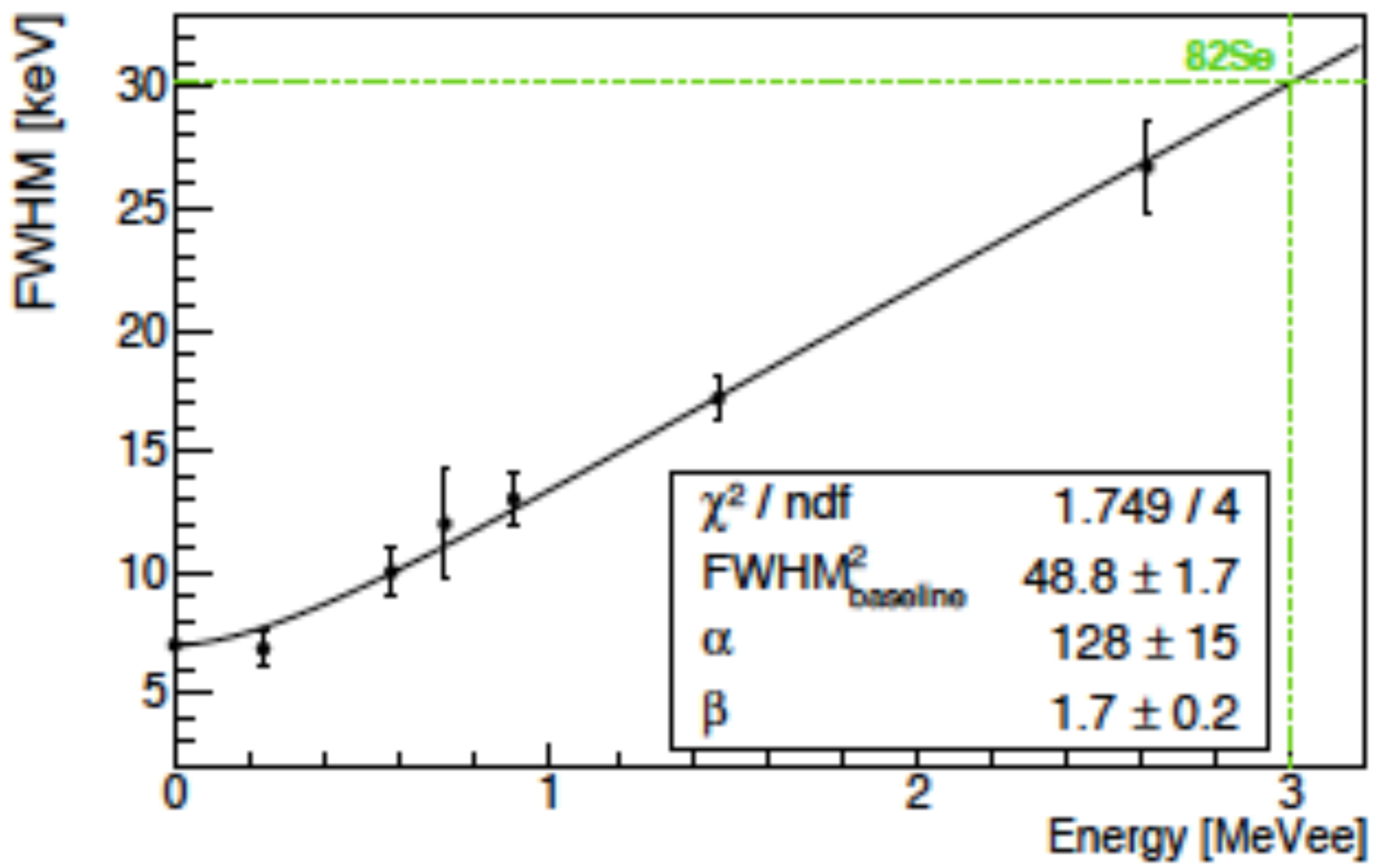
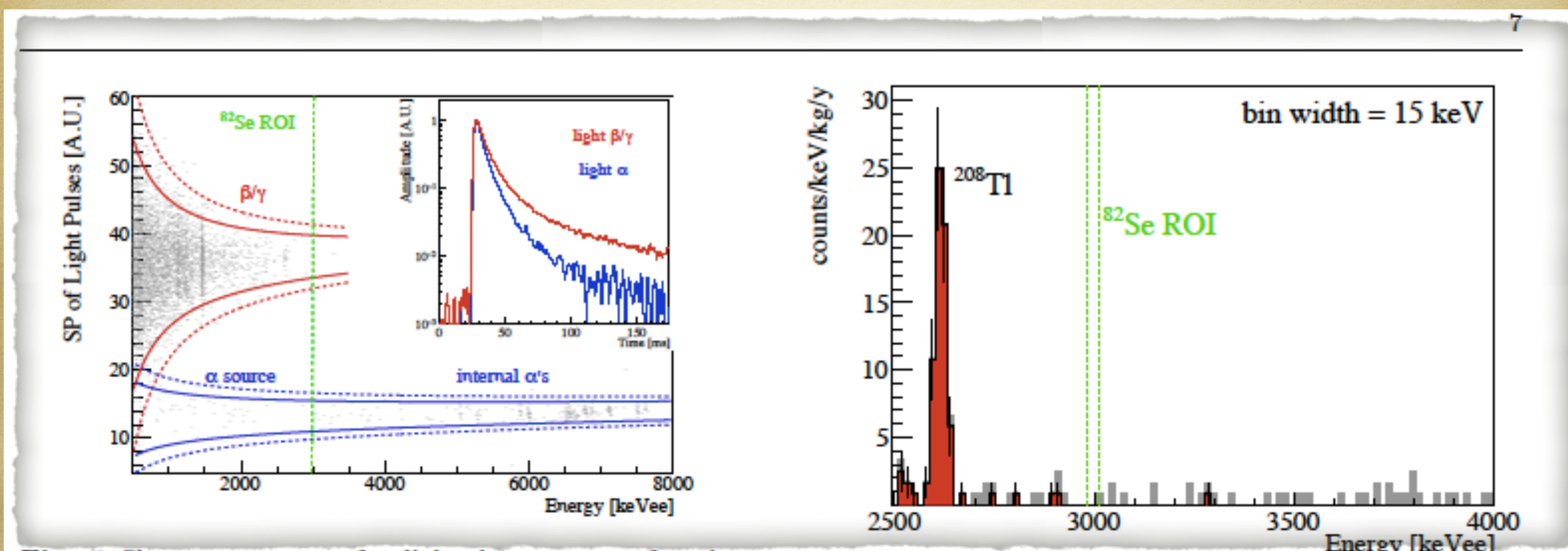


Fig. 4 FWHM energy resolution as a function of the energy ($Zn^{82}Se$-1) for the most intense γ peaks produced by ^{228}Th and ^{40}K sources. The point at zero energy is the baseline energy resolution reported in Table 1. The black line is the fit function: $FWHM^2(E) = FWHM^2_{baseline} + \alpha E^{\beta}$. The green dotted lines indicate the ^{82}Se Q-value.

first look (in unsuited cryostat)



expect B < 0.001 counts/kev/Kg/year in full run (just started in CUORE-0 cryostat)

The future competition

- Xe (EXO, NEXT, Kamland-Zen)
- Ge (Gerda + Legend)
- CUPID (Bolometers with alpha rejection)

the dream

TABLE X. Sensitivity and exposure necessary to discriminate between $\mathcal{NH}$ and $\mathcal{IH}$: the goal is $m_{\beta\beta} = 8\,\text{meV}$. The two cases refer to the unquenched value of $g_A = g_{\text{nucleon}}$ (mega) and $g_A = g_{\text{phen.}}$ (ultimate). The calculations are performed assuming *zero background* experiments with 100% detection efficiency and no fiducial volume cuts. The last column shows the maximum value of the product $B \cdot \Delta$ in order to actually comply with the zero background condition.

Experiment	Isotope	$S^{0\nu}_{0B}$ [yr]	Exposure (estimate)	
			$M \cdot T$ [ton·yr]	$B \cdot \Delta_{\text{(zero bkg)}}$ [counts kg^{-1} yr^{-1}]
mega Ge	^{76}Ge	$3.0 \cdot 10^{28}$	5.5	$1.8 \cdot 10^{-4}$
mega Te	^{130}Te	$8.1 \cdot 10^{27}$	2.5	$4.0 \cdot 10^{-4}$
mega Xe	^{136}Xe	$1.2 \cdot 10^{28}$	3.8	$2.7 \cdot 10^{-4}$
ultimate Ge	^{76}Ge	$6.9 \cdot 10^{29}$	125	$8.0 \cdot 10^{-6}$
ultimate Te	^{130}Te	$2.7 \cdot 10^{29}$	84	$1.2 \cdot 10^{-5}$
ultimate Xe	^{136}Xe	$4.0 \cdot 10^{29}$	130	$7.7 \cdot 10^{-6}$

if you want to know all… pls. read:

arXiv:1601.07512

Neutrinoless double beta decay: 2015 review

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(Dated: April 20, 2016)

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 will not be enough to win.
- We have to prepare for third generation. Toward 0 background.

the best bet today is

Neutrinoless double beta decay: 2015 review

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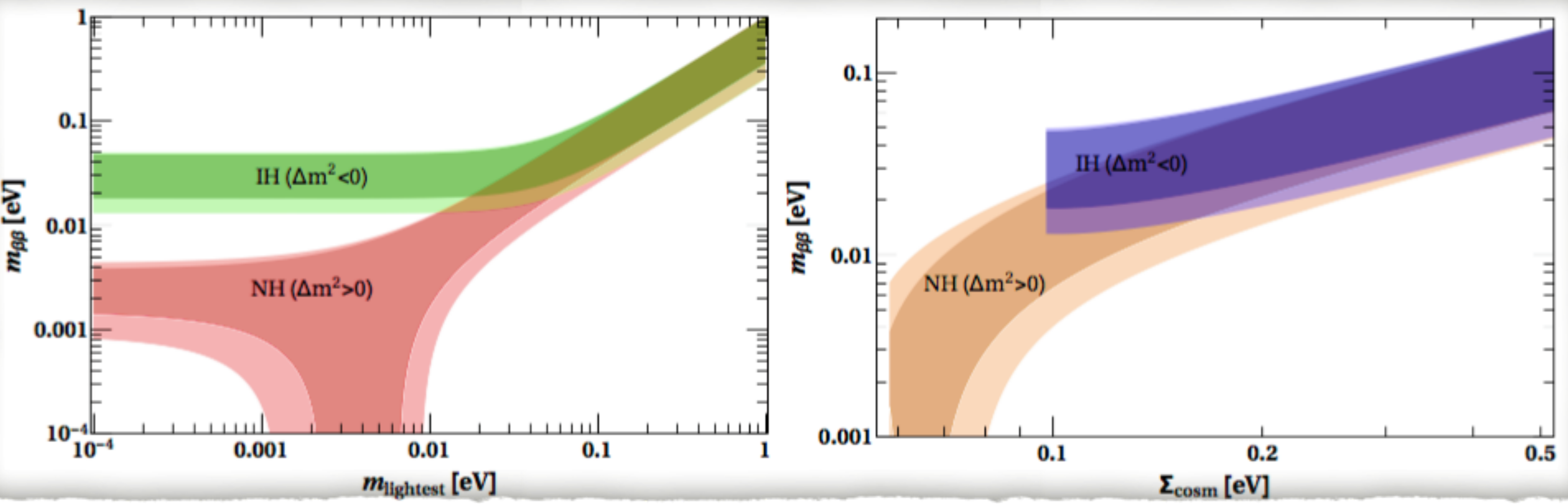
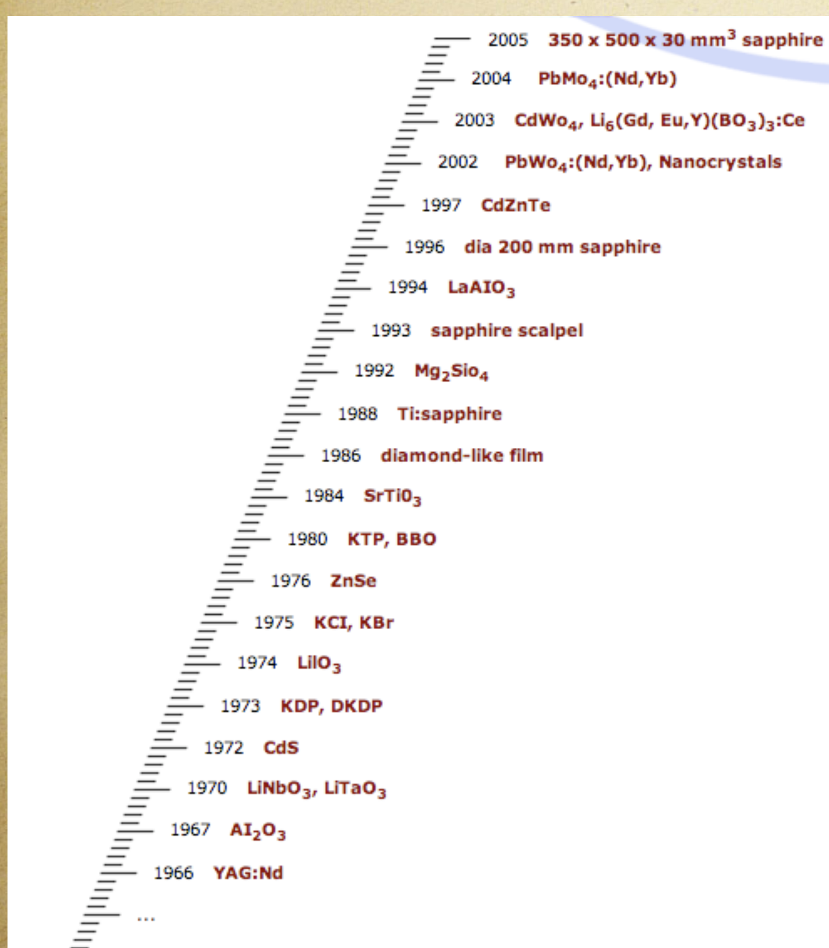
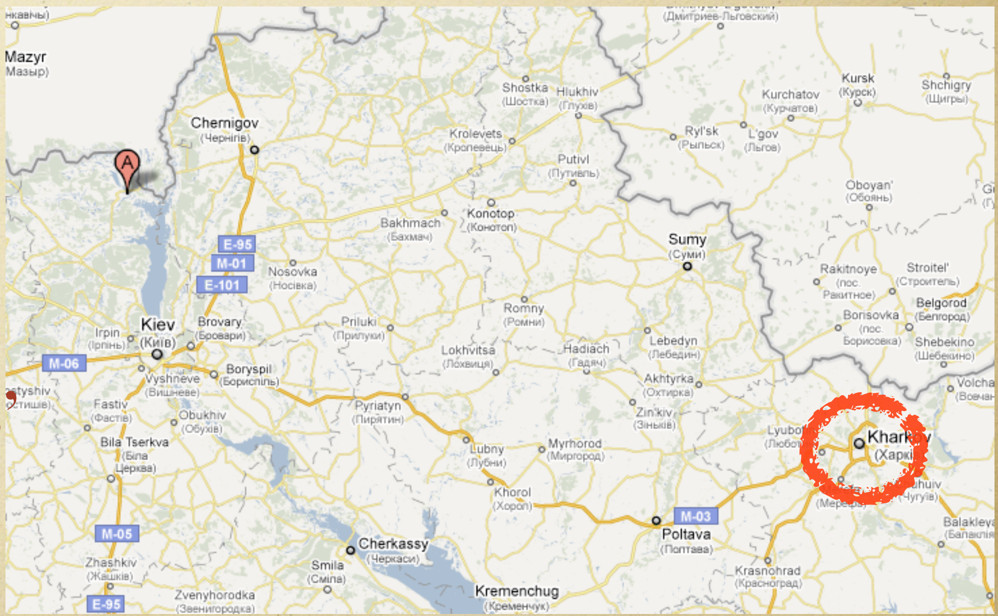


crystals production



possibly the only place

the 'political tensions
made the task
quite tough



the near future

Experiment	Isotope	Techinique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}$ (90% C. L.) [10^{25} yr]
Future							
CUORE, [187]	^{130}Te	bolometers	741 (TeO_2)	1030	5	0.01	9.5
GERDA-II, [172]	^{76}Ge	Ge diodes	37.8 (^{enr}Ge)	100	3	0.001	15
LUCIFER, [188]	^{82}Se	bolometers	17 ($Zn^{82}Se$)	18	10	0.001	1.8
MAJORANA D., [189]	^{76}Ge	Ge diodes	44.8 ($^{enr/nat}$Ge)	100 [a]	4	0.003	12
NEXT, [190, 191]	^{136}Xe	Xe TPC	100 (^{enr}Xe)	300	12.3 – 17.2	$5 \cdot 10^{-4}$	5
AMoRE, [192]	^{100}Mo	bolometers	200 ($Ca^{enr}MoO_4$)	295	9	$1 \cdot 10^{-4}$	5
nEXO, [193]	^{136}Xe	LXe TPC	4780 (^{enr}Xe)	12150 [b]	58	$1.7 \cdot 10^{-5}$ [b]	66
PandaX-III, [194]	^{136}Xe	Xe TPC	1000 (^{enr}Xe)	3000 [c]	12 – 76	0.001	11 [c]
SNO+, [195]	^{130}Te	loaded liquid scintillator	2340 (^{nat}Te)	3980	270	$2 \cdot 10^{-4}$	9
SuperNEMO, [196, 197]	^{82}Se	tracker +	100 (^{82}Se)	500	120	0.01	10

Experiment	Isotope	$S^{0\nu}$ (90% C. L.) [10^{25} yr]	Lower bound for $m_{\beta\beta}$ [eV]		
			g_{nucleon}	g_{quark}	$g_{\text{phen.}}$
CUORE, [187]	^{130}Te	9.5	0.073 ± 0.008	0.14 ± 0.01	0.44 ± 0.04
GERDA-II, [172]	^{76}Ge	15	0.11 ± 0.01	0.18 ± 0.02	0.54 ± 0.05
LUCIFER, [188]	^{82}Se	1.8	0.20 ± 0.02	0.32 ± 0.03	0.97 ± 0.09
MAJORANA D., [189]	^{76}Ge	12	0.13 ± 0.01	0.20 ± 0.02	0.61 ± 0.06
NEXT, [191]	^{136}Xe	5	0.12 ± 0.01	0.20 ± 0.02	0.71 ± 0.08
AMoRE, [192]	^{100}Mo	5	0.084 ± 0.008	0.14 ± 0.01	0.44 ± 0.04
nEXO, [193]	^{136}Xe	66	0.034 ± 0.004	0.054 ± 0.006	0.20 ± 0.02
PandaX-III, [194]	^{136}Xe	11	0.082 ± 0.009	0.13 ± 0.01	0.48 ± 0.05
SNO+, [195]	^{130}Te	9	0.076 ± 0.007	0.12 ± 0.01	0.44 ± 0.04
SuperNEMO, [196]	^{82}Se	10	0.084 ± 0.008	0.14 ± 0.01	0.41 ± 0.04

however...

This transition takes place inside nuclei and the momentum of the virtual nucleon is large, $Q \sim \mathscr{O}(100\,\text{MeV})$ (inverse of the nucleonic size). It is thus much larger than the neutrino mass.

The issue of the quenching/renormalization of g_A should not be considered as a theory. However, if there is a physical cause for this effect, this is likely to depend upon the momentum Q, since at very high Q nucleons can be treated as free particles and free nucleons do not suffer any quenching. And maybe there is only a loose connection between the two processes of double electron emission when two or no neutrinos are emitted: In fact, the transferred momentum is quite different. When Q is larger, as in the case of no neutrino emission in which we are interested, g_A could be closer to the free nucleon value ($\simeq 1.269$), or to that of quark matter ($= 1$) [19, 20].