WHICH FUTURE FOR NEUTRINOLESS DBD ?

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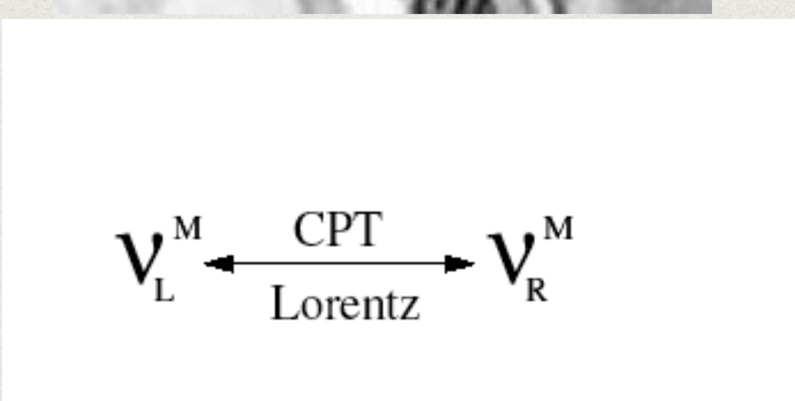
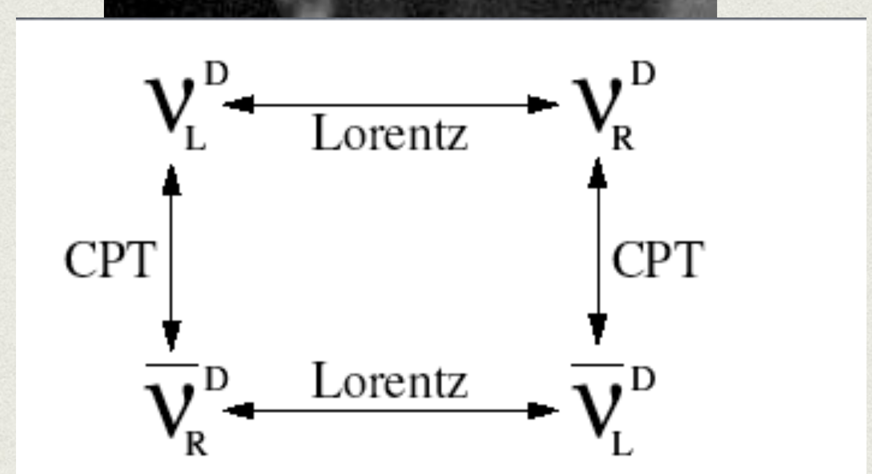
AN ENDLESS RESEARCH FIELD

- 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 VS. DIRAC

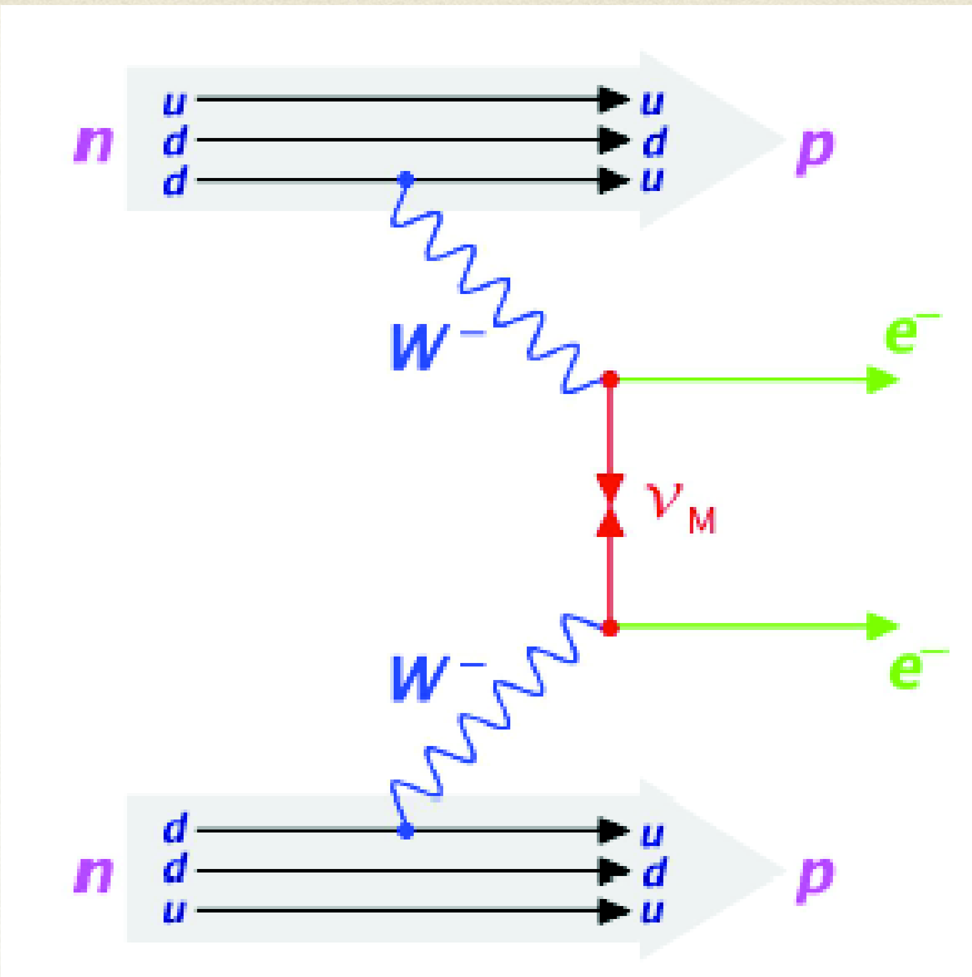


Majorana



Dirac

NEUTRINOLESS DOUBLE BETA DECAY



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

Phase Space Factor

Nuclear Matrix Element

Only if:

Majorana Neutrinos

Massive Neutrinos

If observed:

Proof of the Majorana nature of Neutrino

Indication of mass scale

how long should we wait to see it (if any) ?

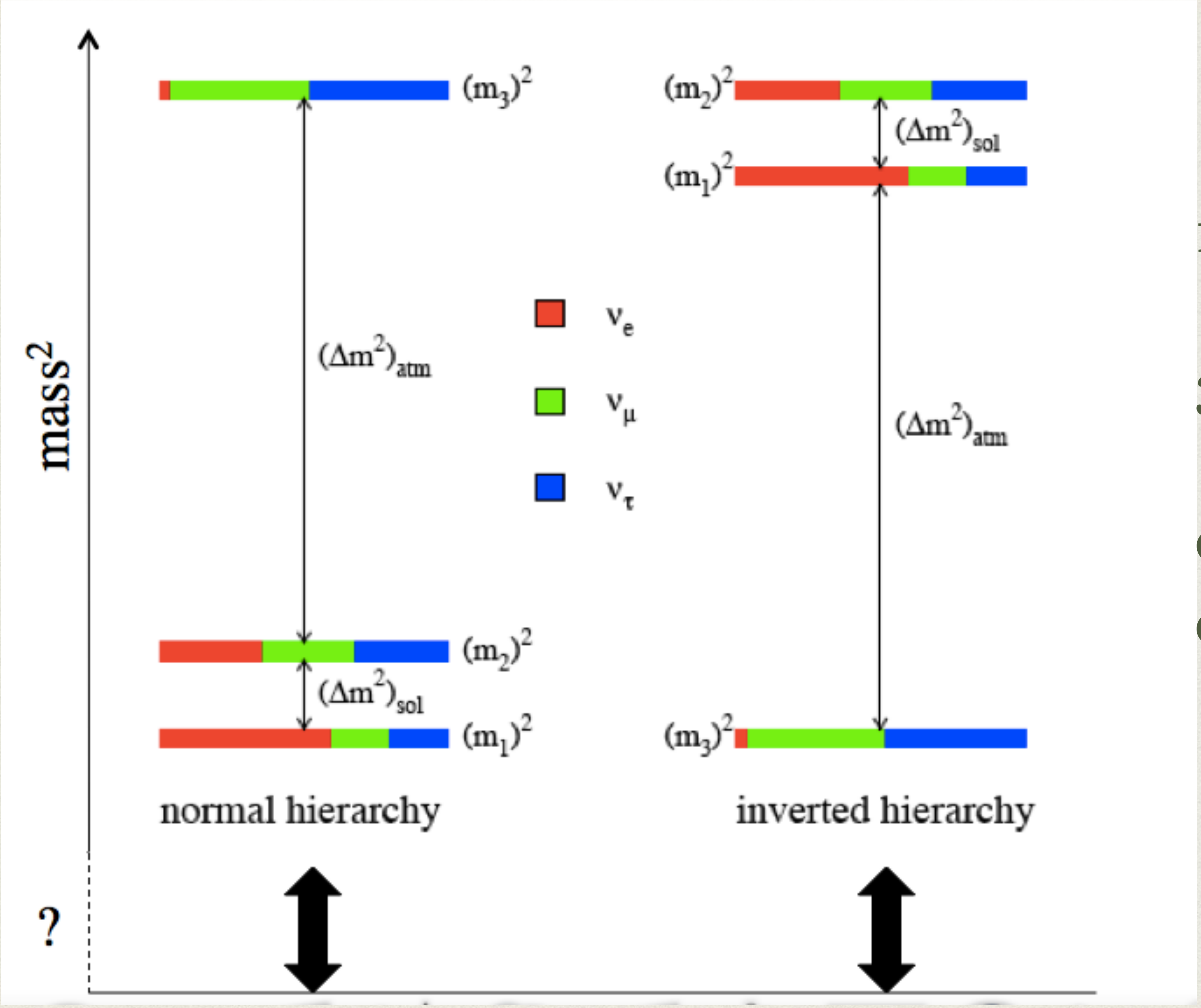
parameter containing the **physics**

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

what the **experimentalists** try to measure

what the **nuclear theorists** try to calculate

MASS HIERACHY

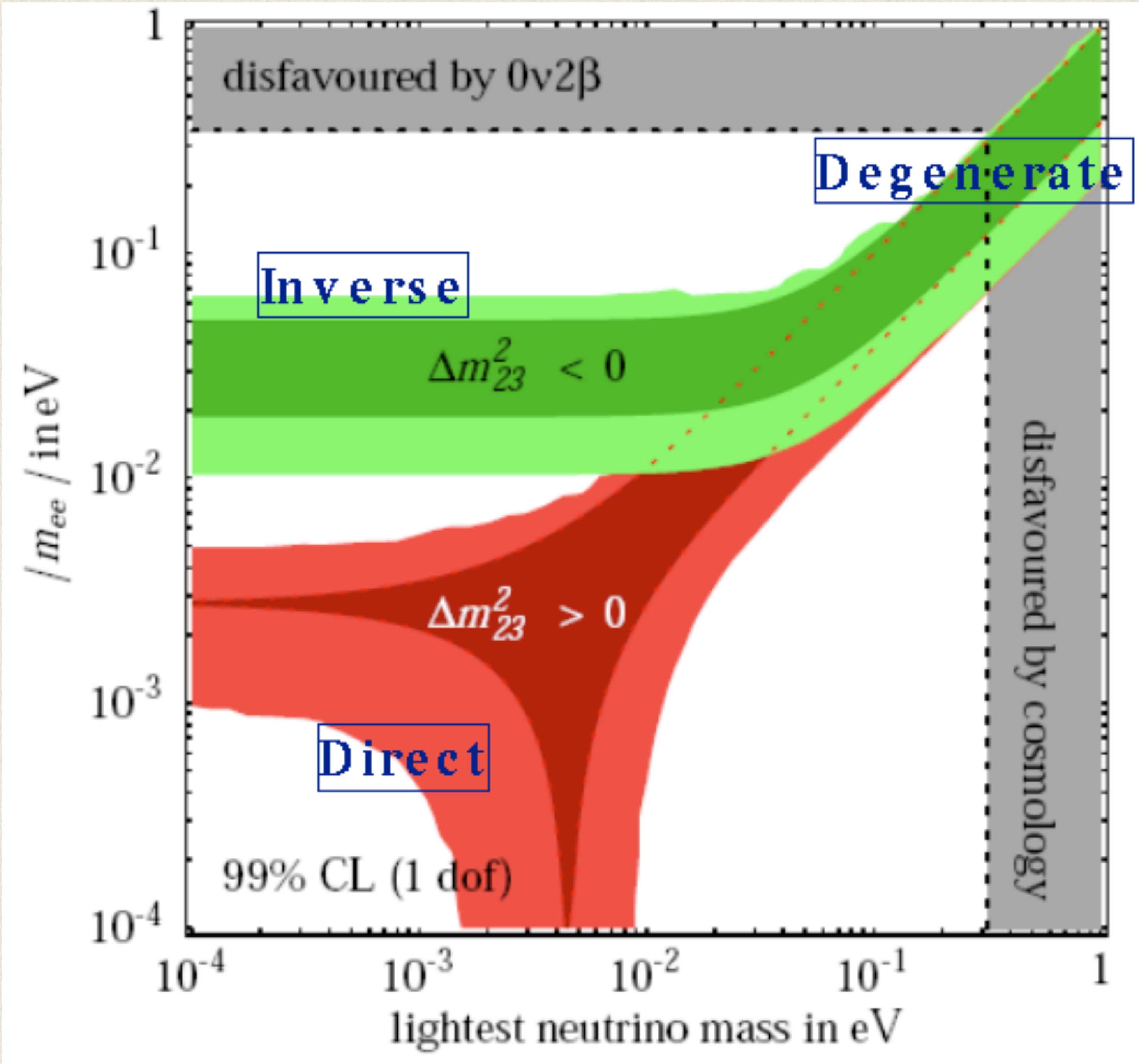


1-2 ordered by matter

3 is free

degeneracy belong to an other type of experiments

NEUTRINOLESS DBD INVERTED OR DIRECT ?



Three region

1) Degenerate : few 100meV

2) Inverse: few 10meV

3) Direct: few meV

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, $m_{\beta\beta} \sim 20$ meV

$\tau_{1/2}^{0\nu} > 10^{25}$ y

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

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

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
- M: detector mass
- ΔE: energy resolution (detector FWHM)
- t: live time

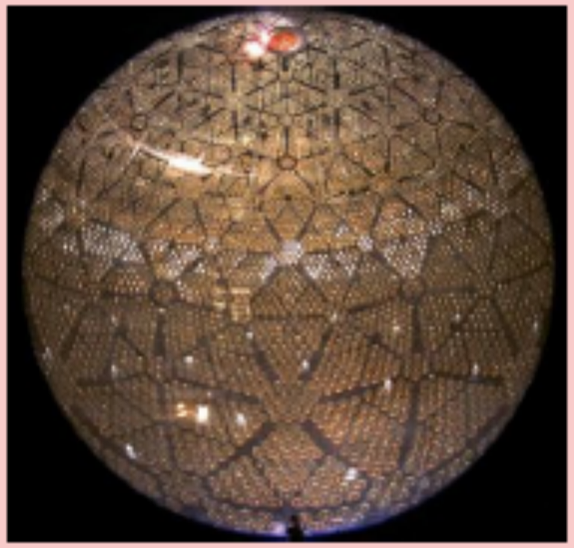
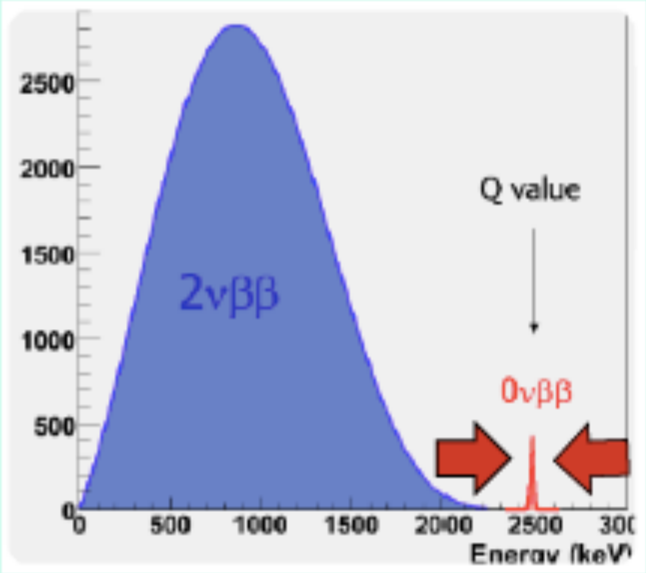
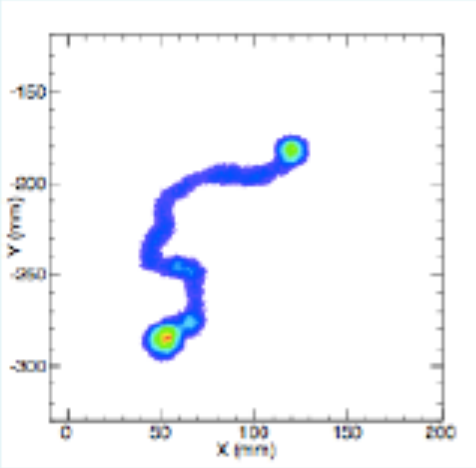
Sensitivity is S/√B

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

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

To gain a factor 10 you need 10000 !

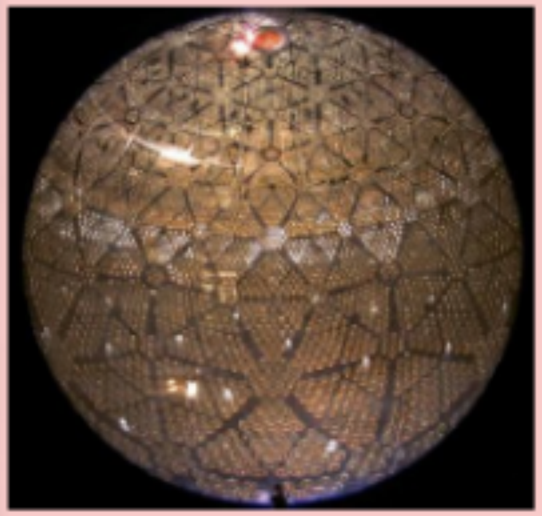
meaning :

The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
	 	
focus on the numerator with **a huge amount of material** (often sacrificing resolution)	focus on the denominator by **squeezing down ΔE** (various technologies)	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



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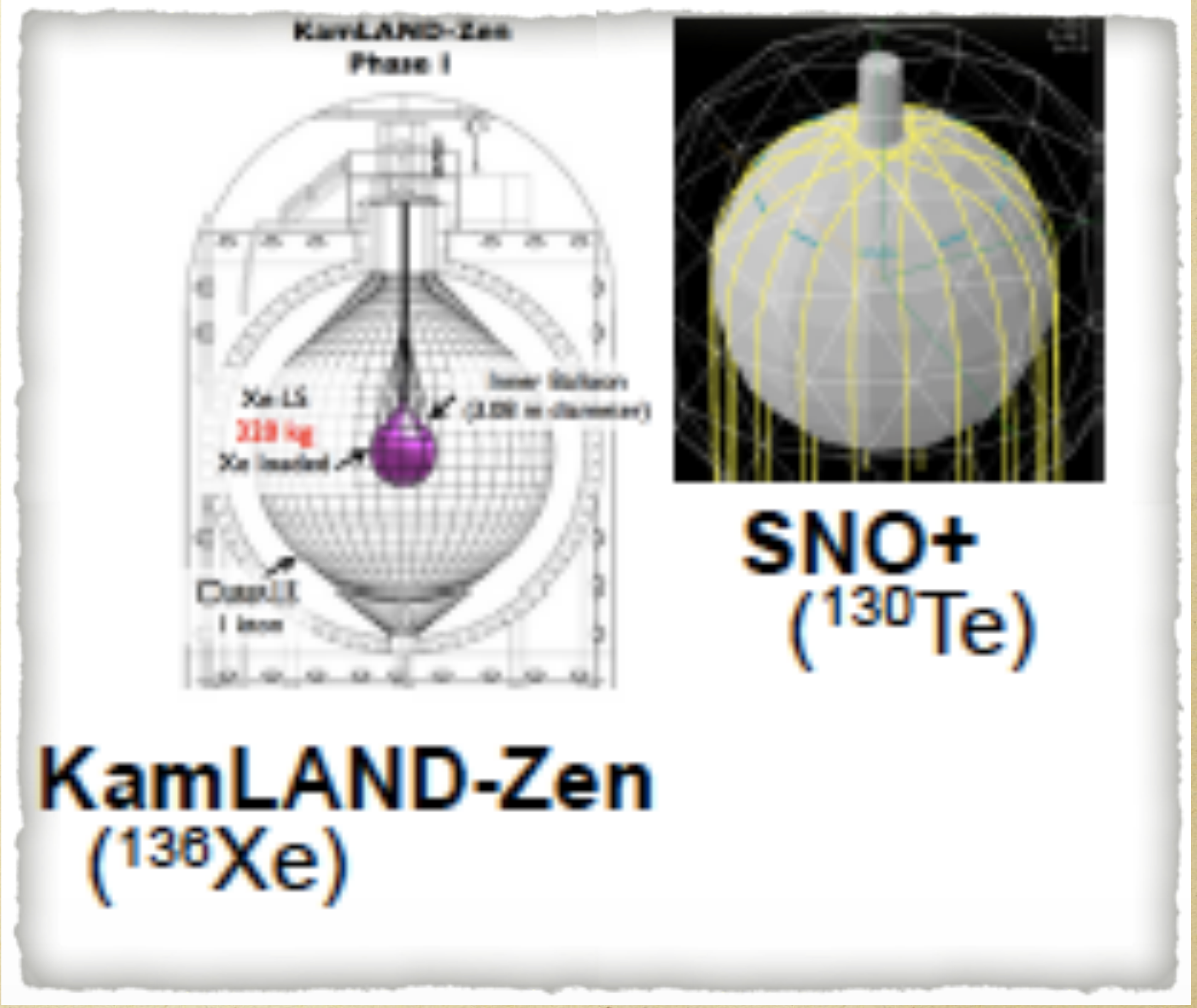


Kamland-Zen

Search for Majorana Neutrinos near the Inverted Mass Hierarchy Region with KamLAND-Zen

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

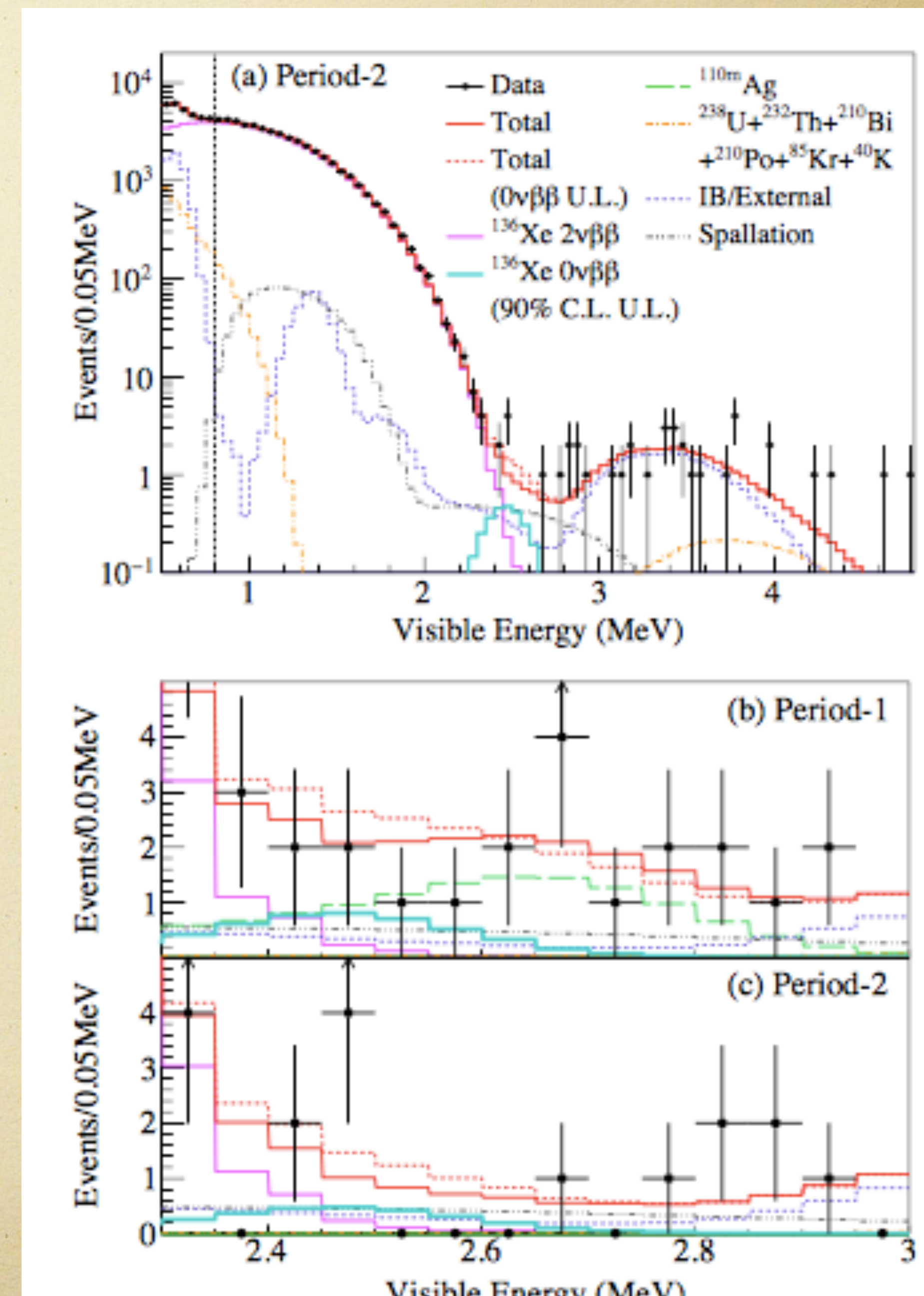
535 days livetime

3700 mole*year

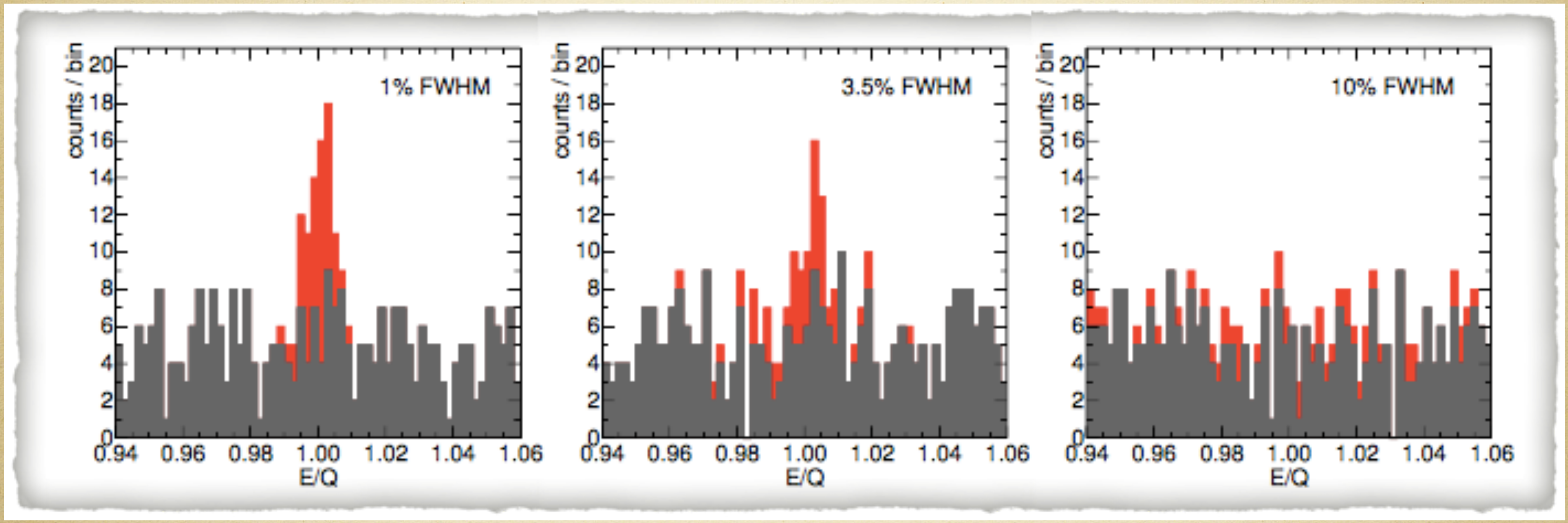
504 kg*year

From the limit on the ^{136}Xe decay half-life, we obtain a 90% C.L. upper limit of m < (61 – 165) meV assuming the axial coupling constant $g_A \simeq 1.27$

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.56	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4

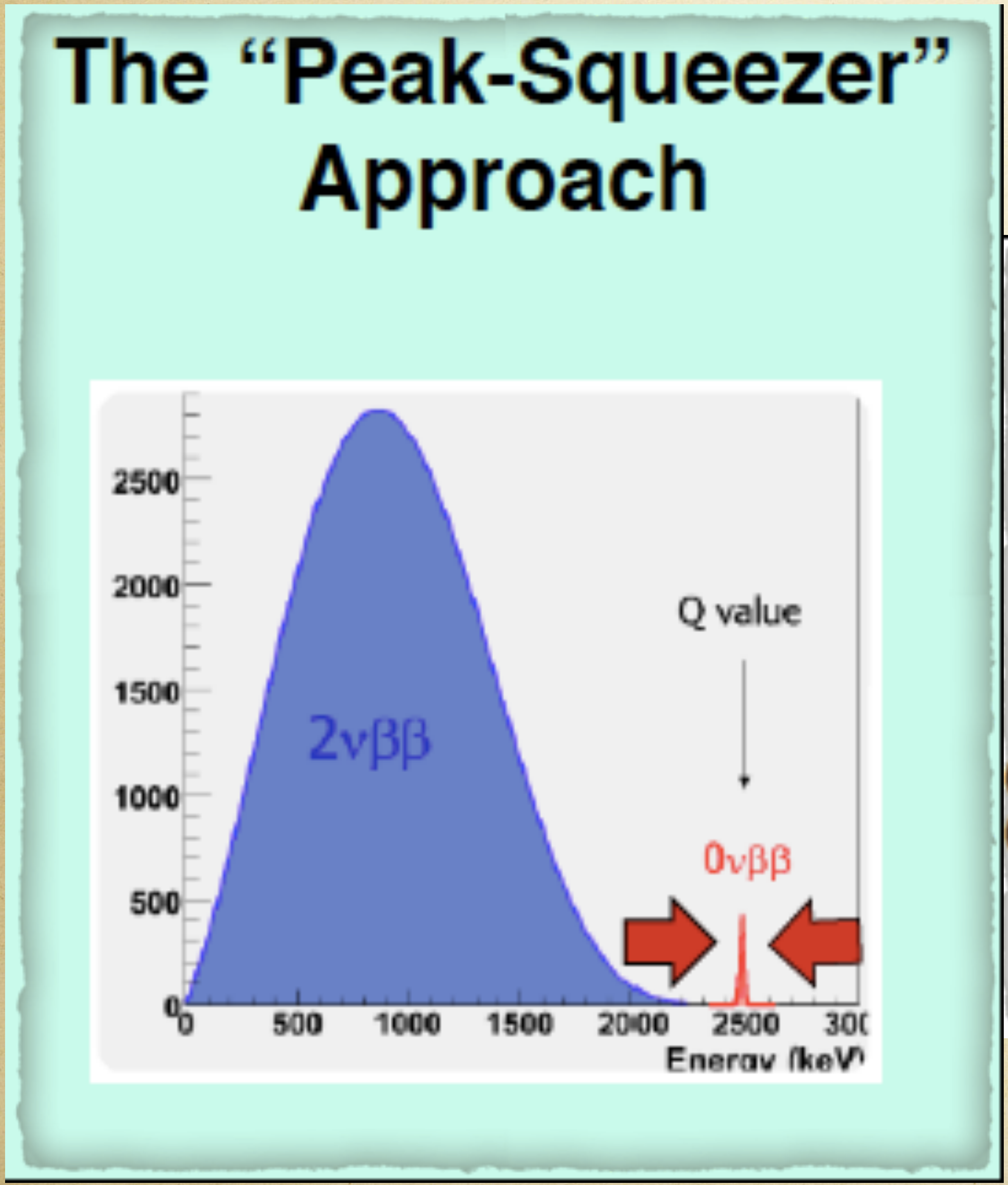


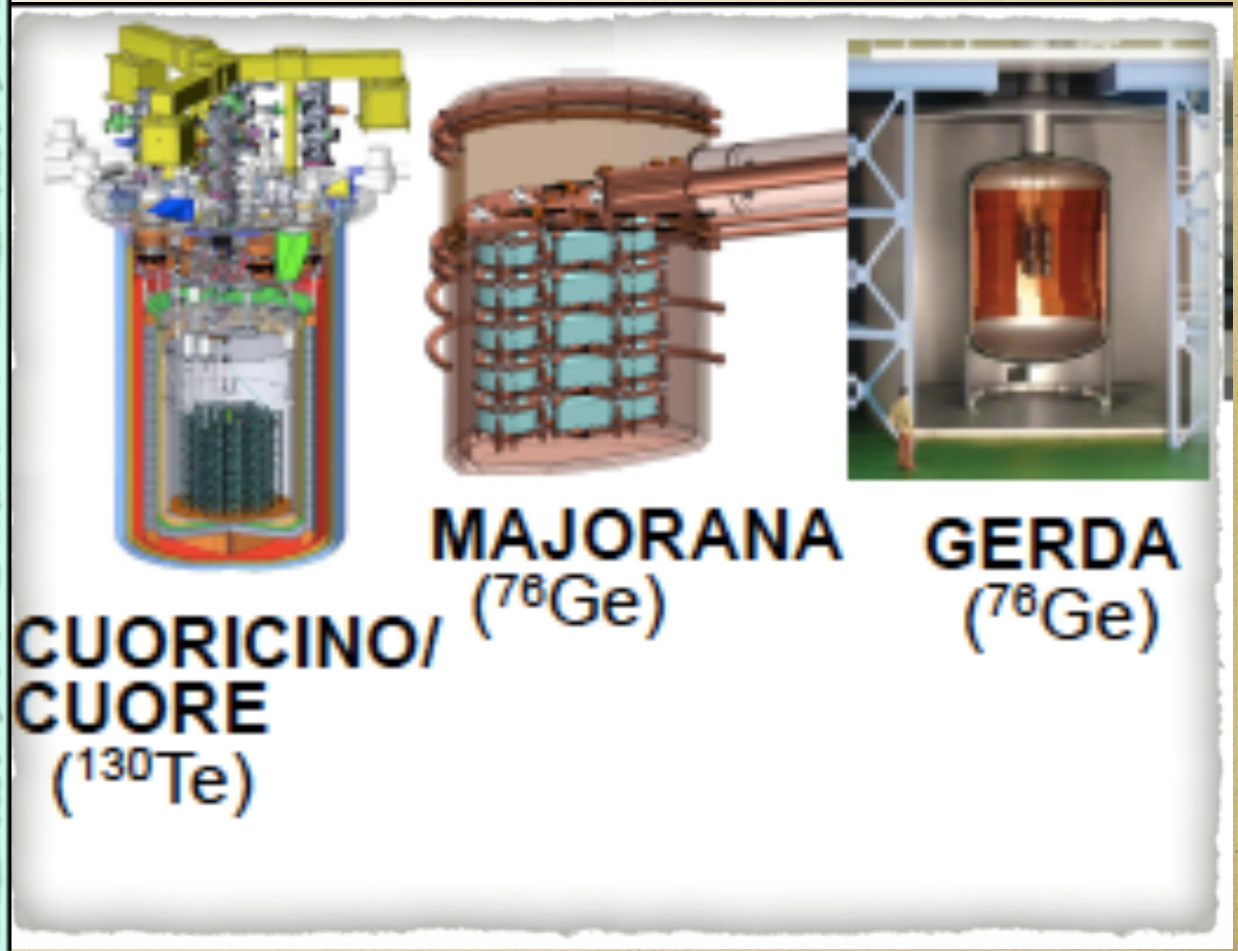
effect of energy resolution



S= 50 events
B= 1 count/keV

the state of the art: peak squeezer

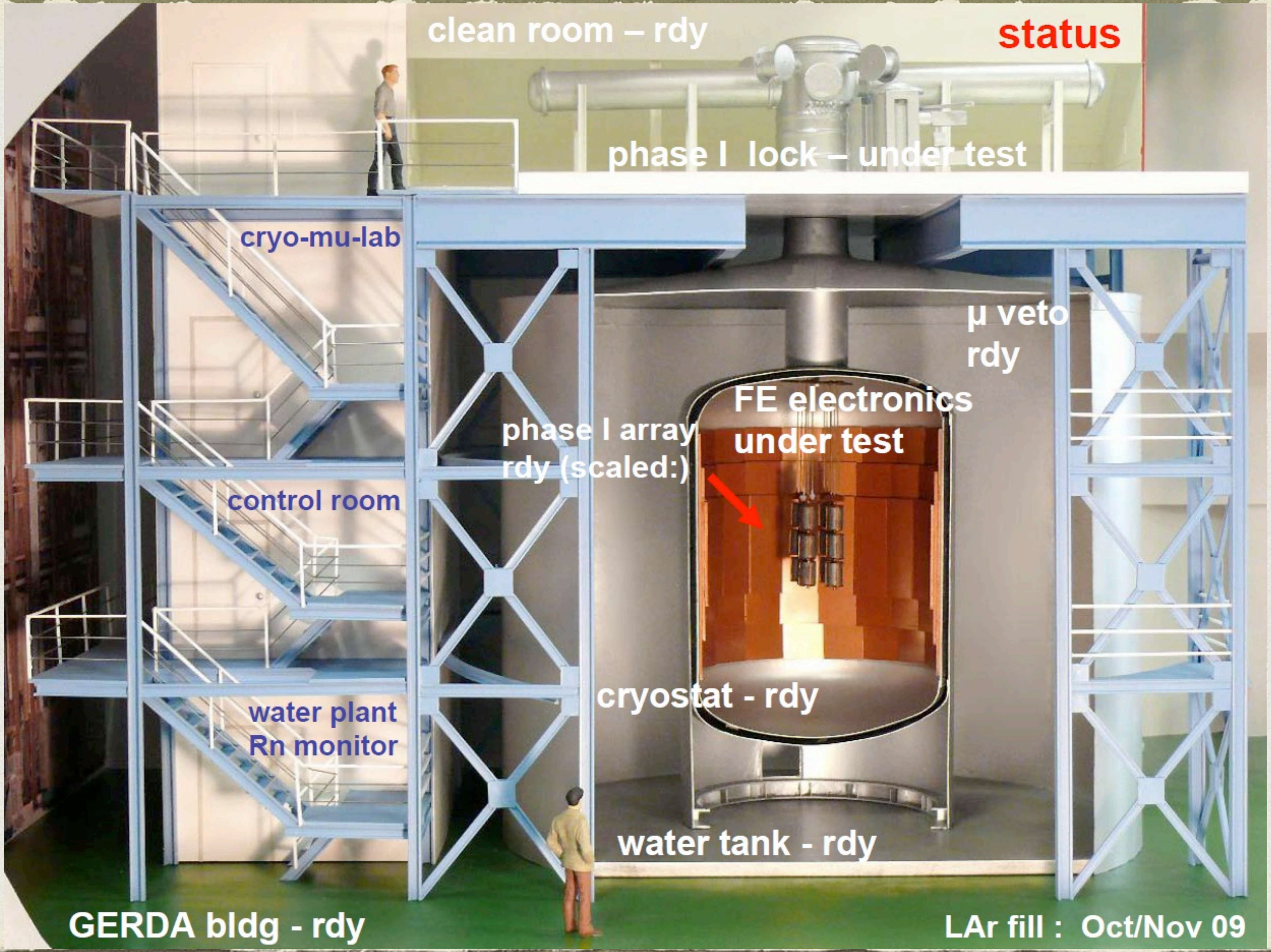




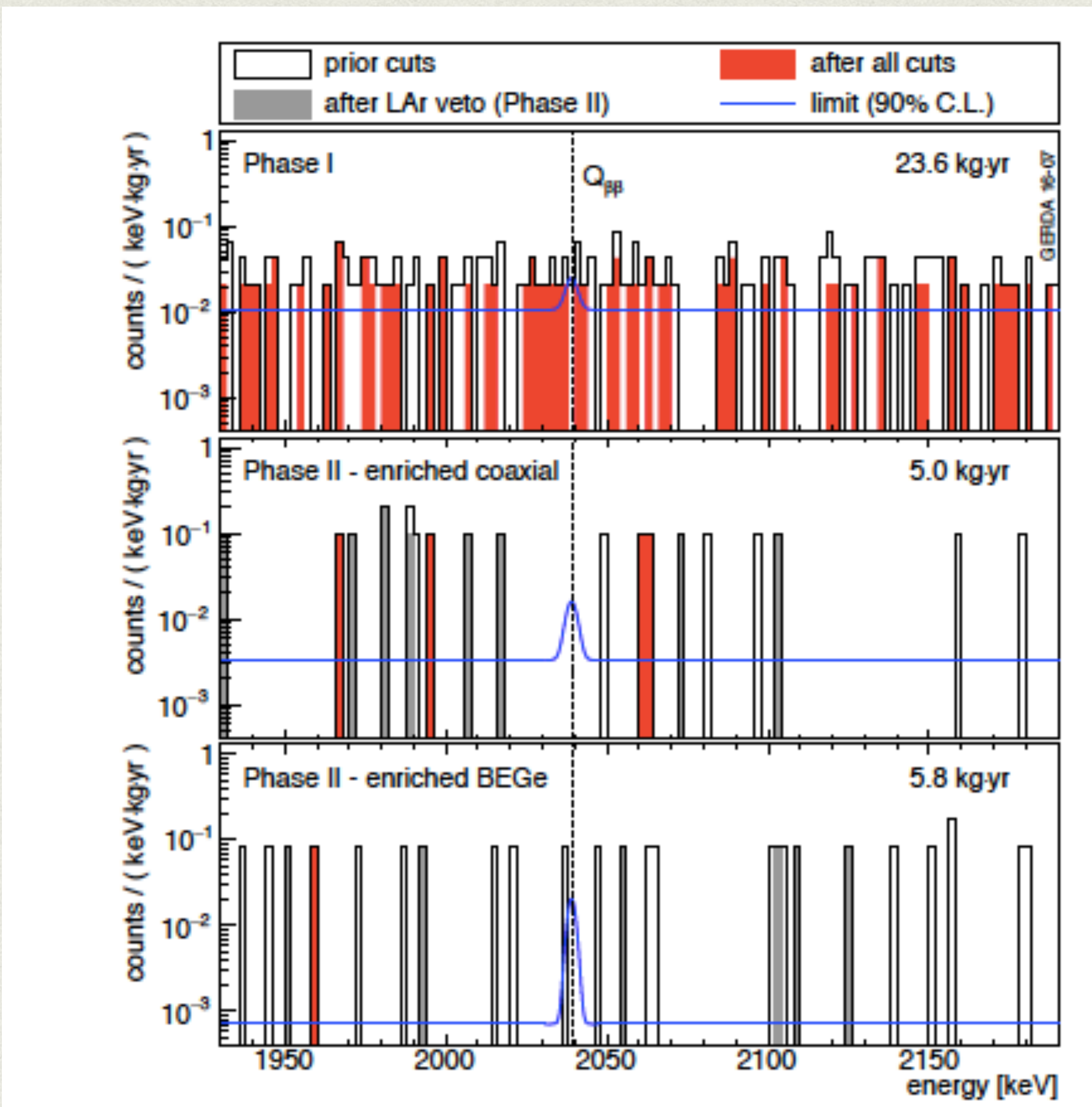
LNGS LEADS THE HUNT

- GERDA with a spectacular limit
- CUORE taking data
- CUPID paving the way for a new generation aiming at B=0

GERDA


clean room – rdy
status
phase I lock – under test
cryo-mu-lab
μ veto
rdy
FE electronics
under test
phase I array
rdy (scaled:)
control room
cryostat - rdy
water plant
Rn monitor
water tank - rdy
GERDA bldg - rdy
LAr fill : Oct/Nov 09

THE BEST RESULT IN TOWN



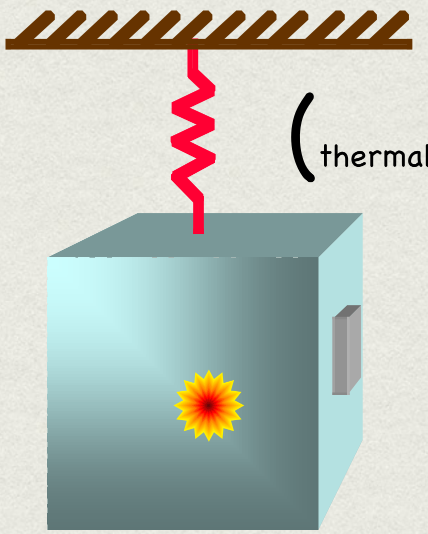
$$T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}\ \text{yr}.$$

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].

CUORE PRINCIPLE

heat sink (T_0)



(thermal conductance G)

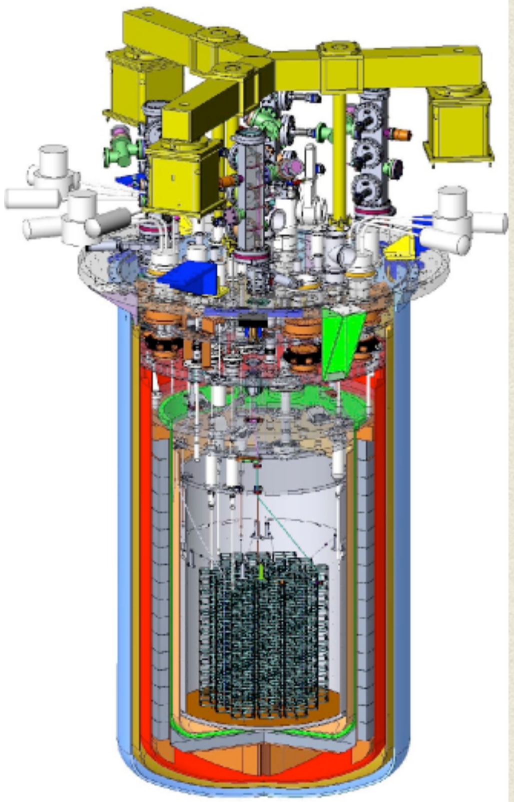
thermometer

ββ atom x-tal

Basic Physics: $\Delta T = E/C$

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

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



$T_0 \sim 10$ mK

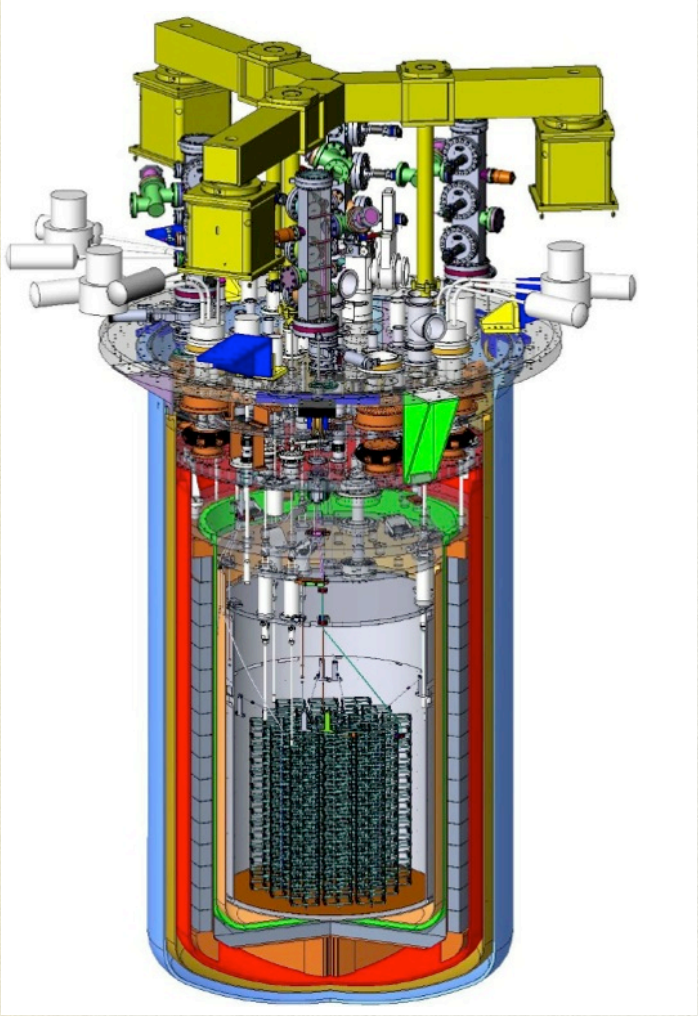
$C \sim 2$ nJ/K ~ 1 MeV/0.1 mK

$G \sim 4$ pW/mK

CUORE

Cryogenic Underground Observatory for Rare Events

Searching for neutrinoless double beta decay of ^{130}Te

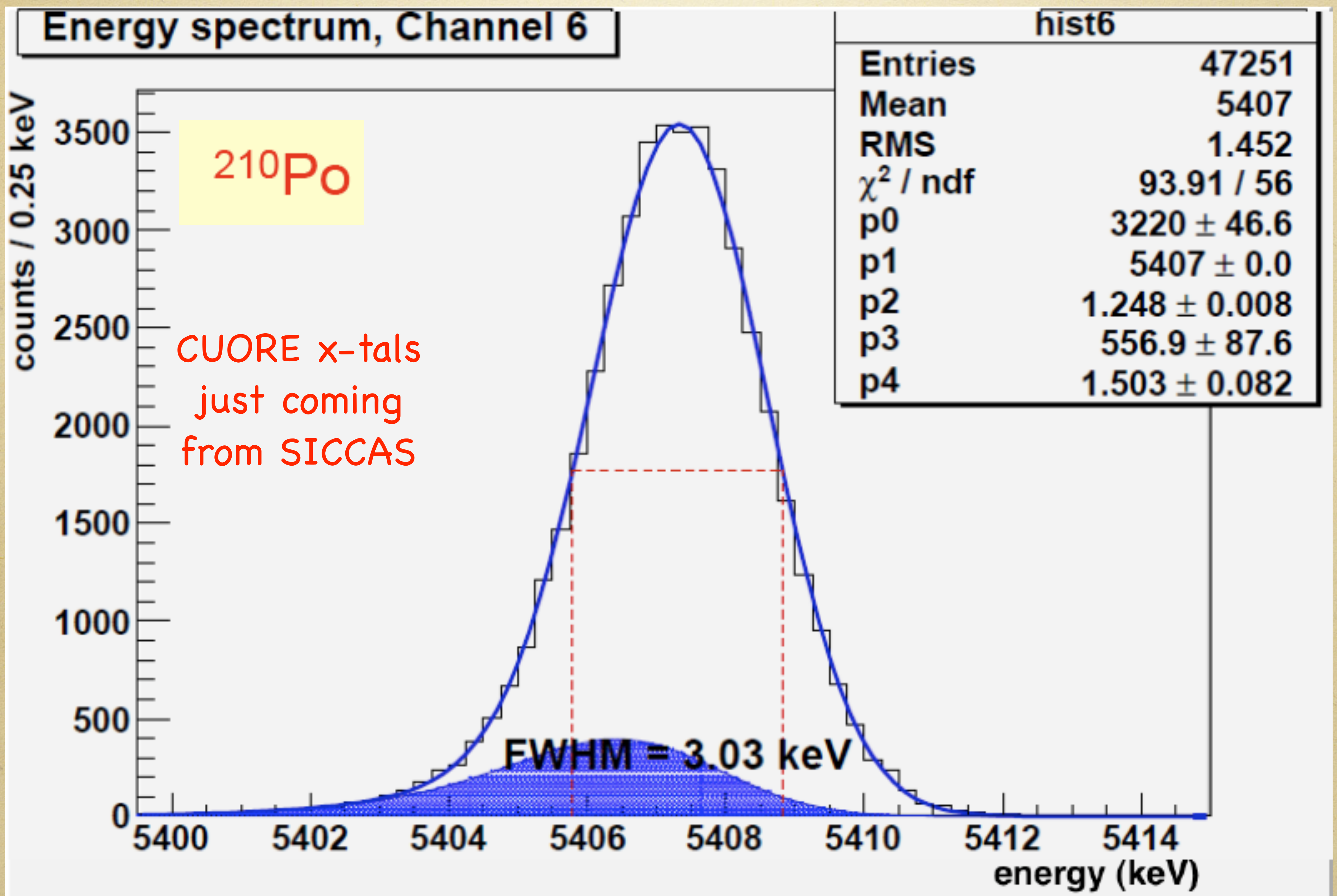


CUORE Hut

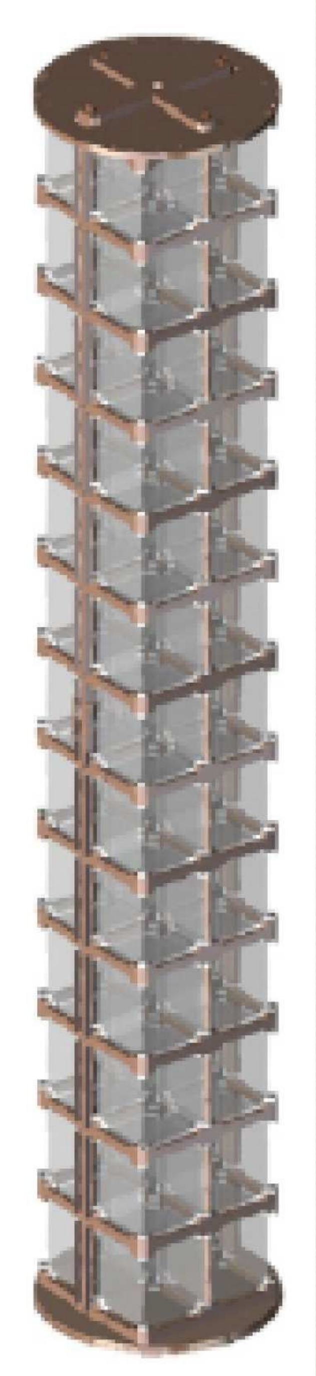
Expected 5 Years sensitivity:
$T_{1/2}$ = 2.1 x 10^{26} y, $m_{\beta\beta}$=41–95 **meV**
background counting rate
10^{-2} c/keV/kg/y

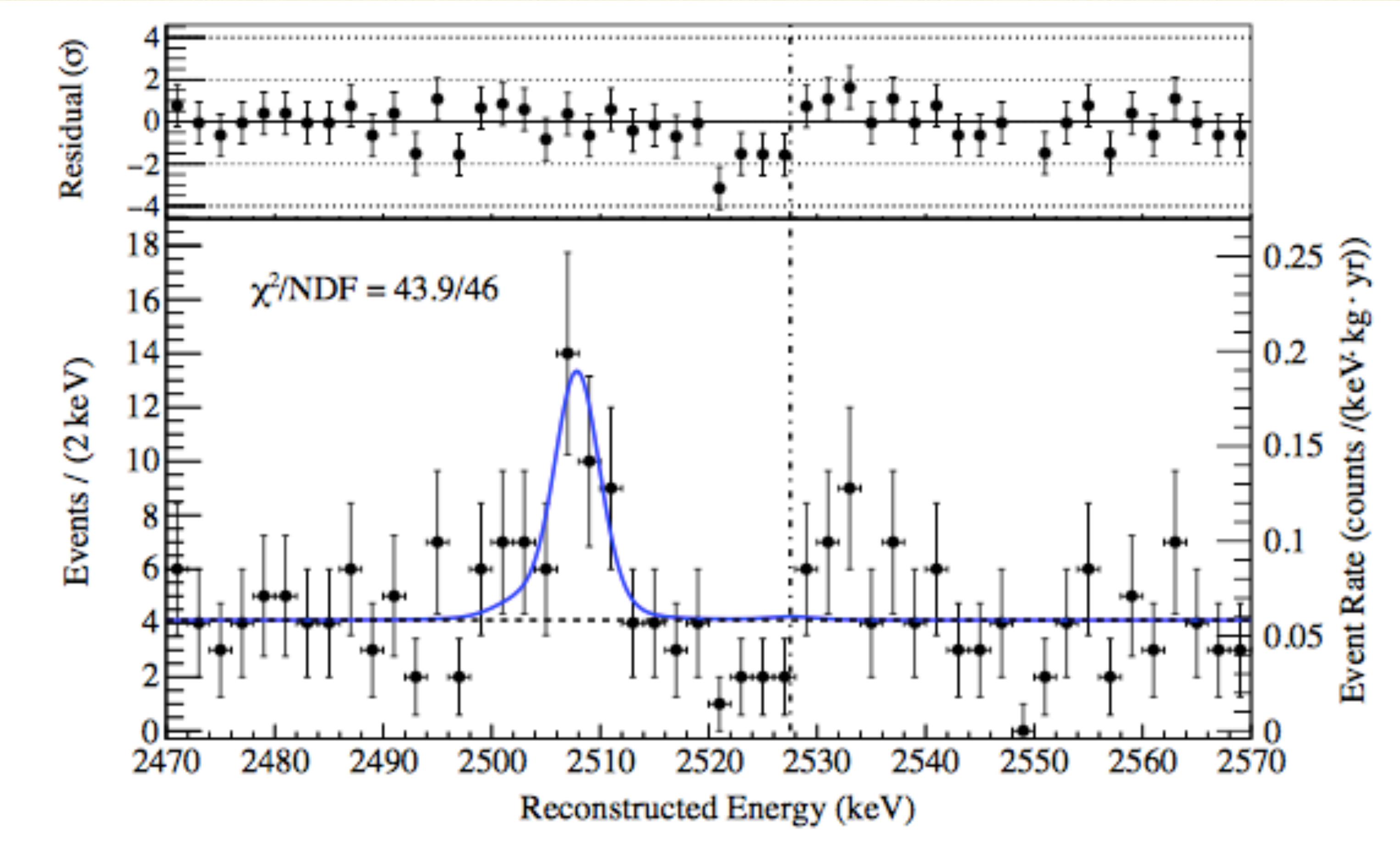
200 Kg
^{130}Te

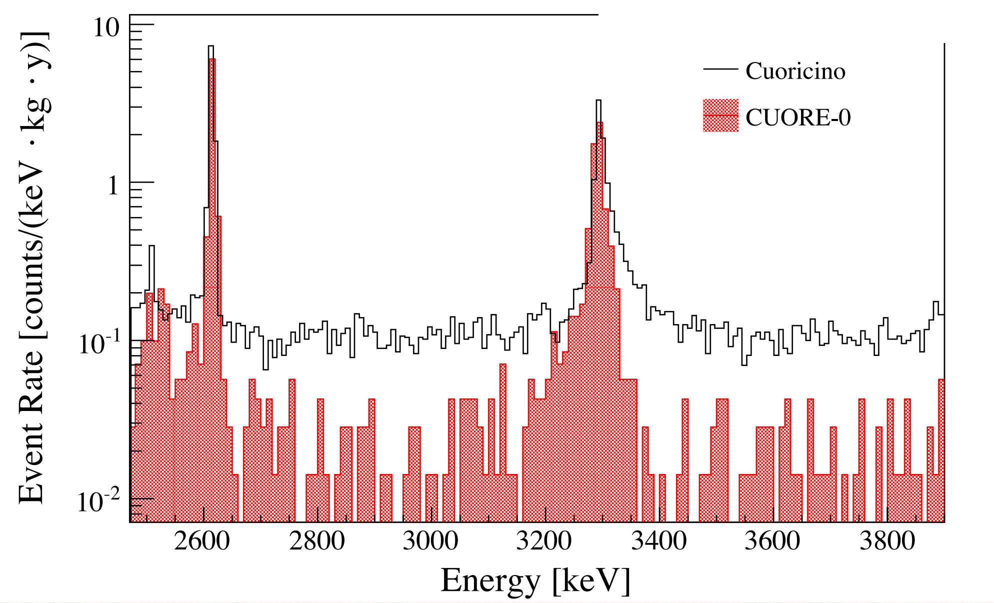
how much can you squeeze ?



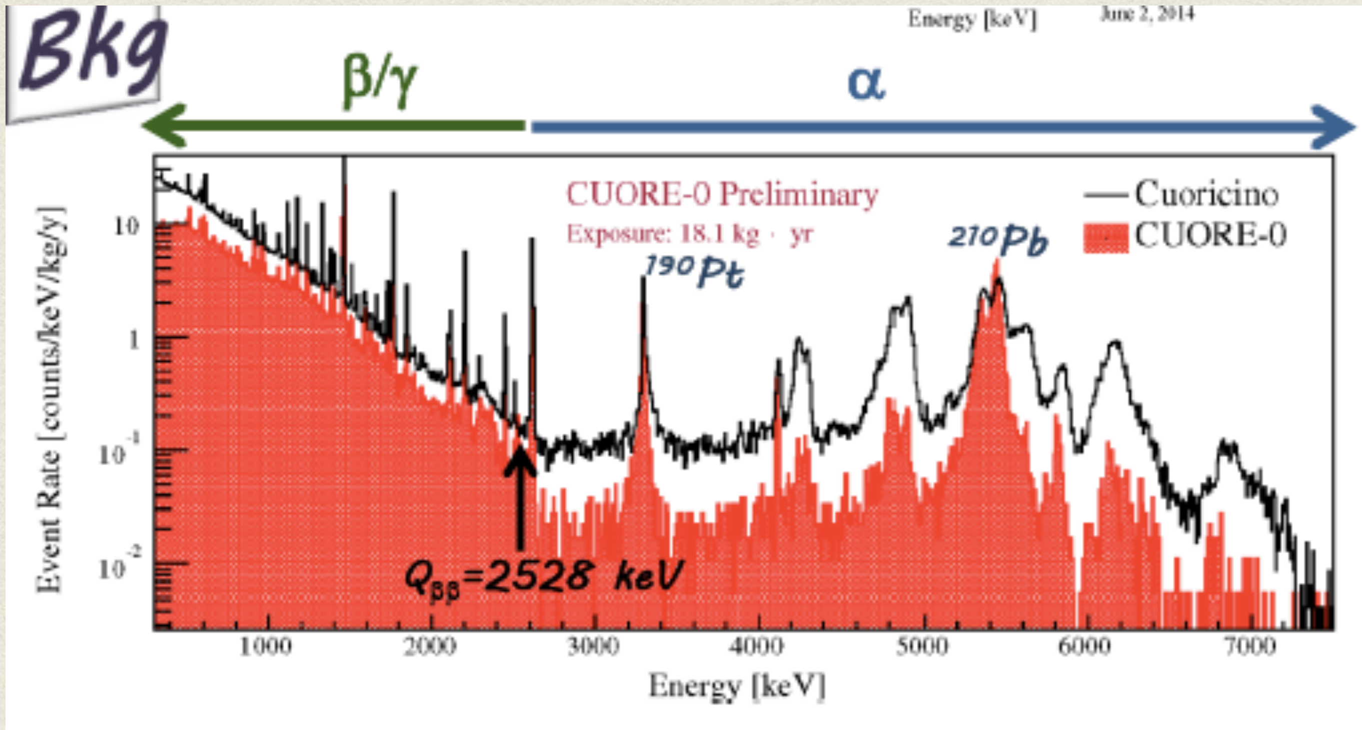
EXPERIENCE FROM CUORE-0







BUT WILL STOP AT



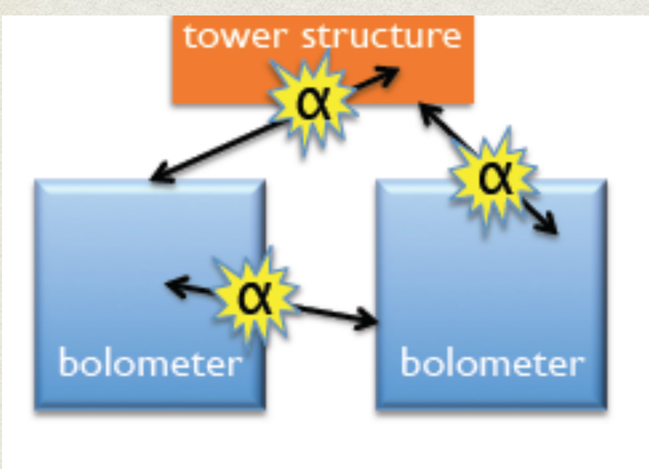
Cuoricino background model confirmed:

- *environmental γ from material bulk contaminations*
  -> mainly from cryostat (same as Cuoricino)
- *surface (α) contaminations of close materials*

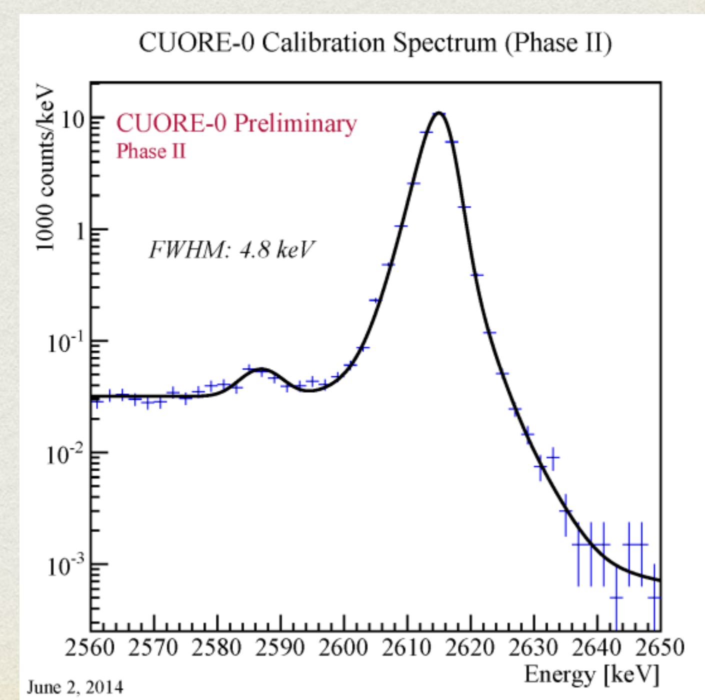
Evident reduction with respect to Cuoricino

- *factor of 6 for surface contaminations*
- *factor ~2.5 in the ROI*

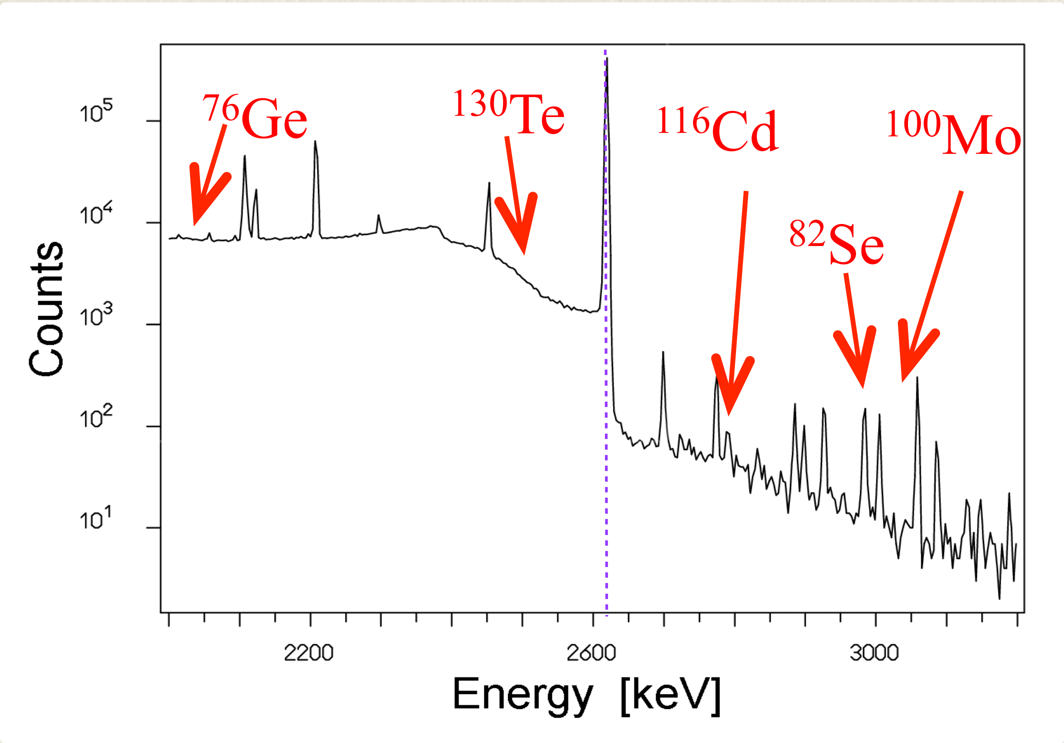
	$0\nu\beta\beta$ ROI c/keV/kg/y	2700-3900 keV c/keV/kg/y	ε(%)
Cuoricino	0.153±0.006	0.110±0.001	83
CUORE-0	0.063±0.006	0.020±0.001	78

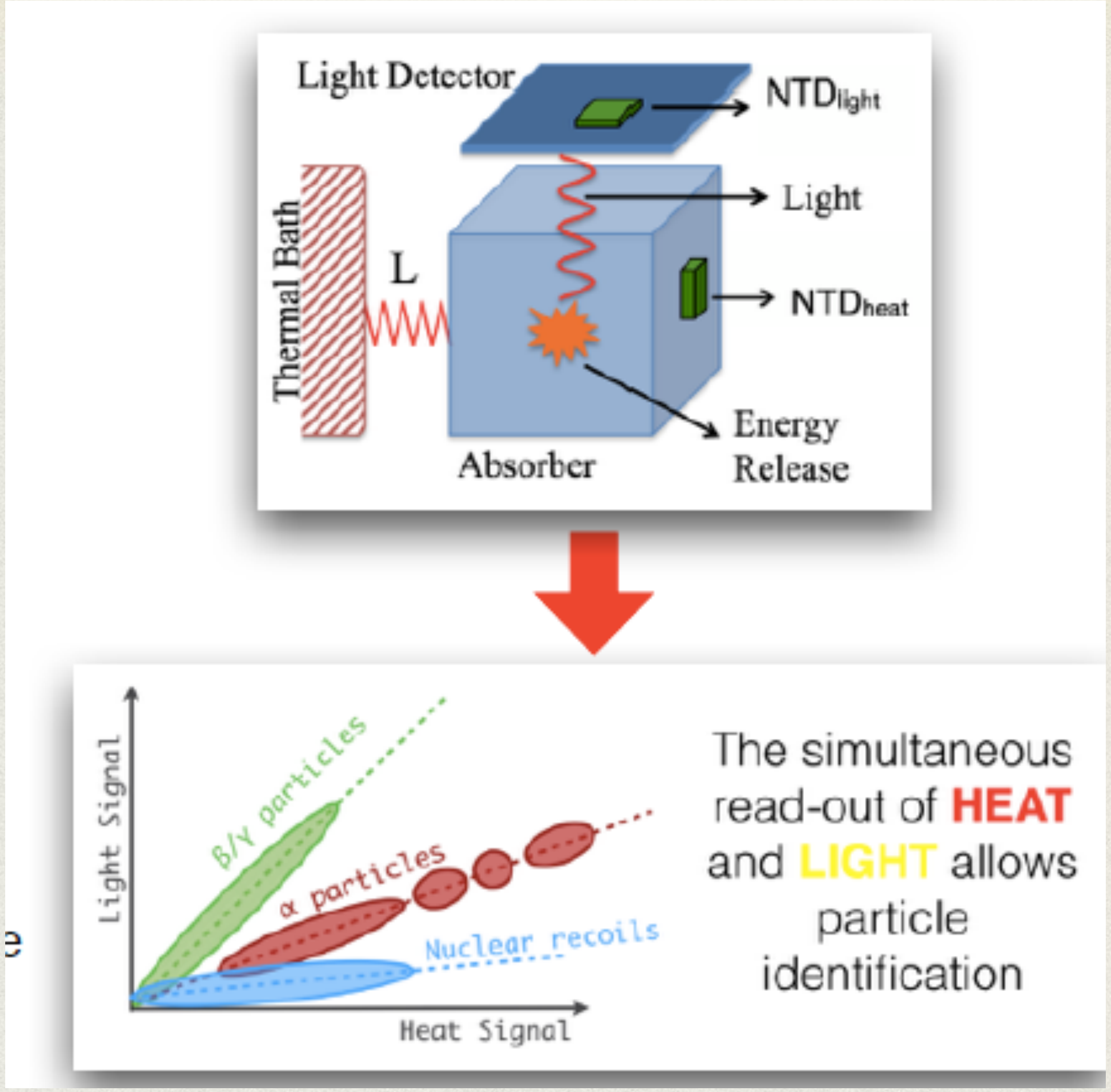


irreducible if you do not tell alphas from gammas in spite of formidable energy resolution



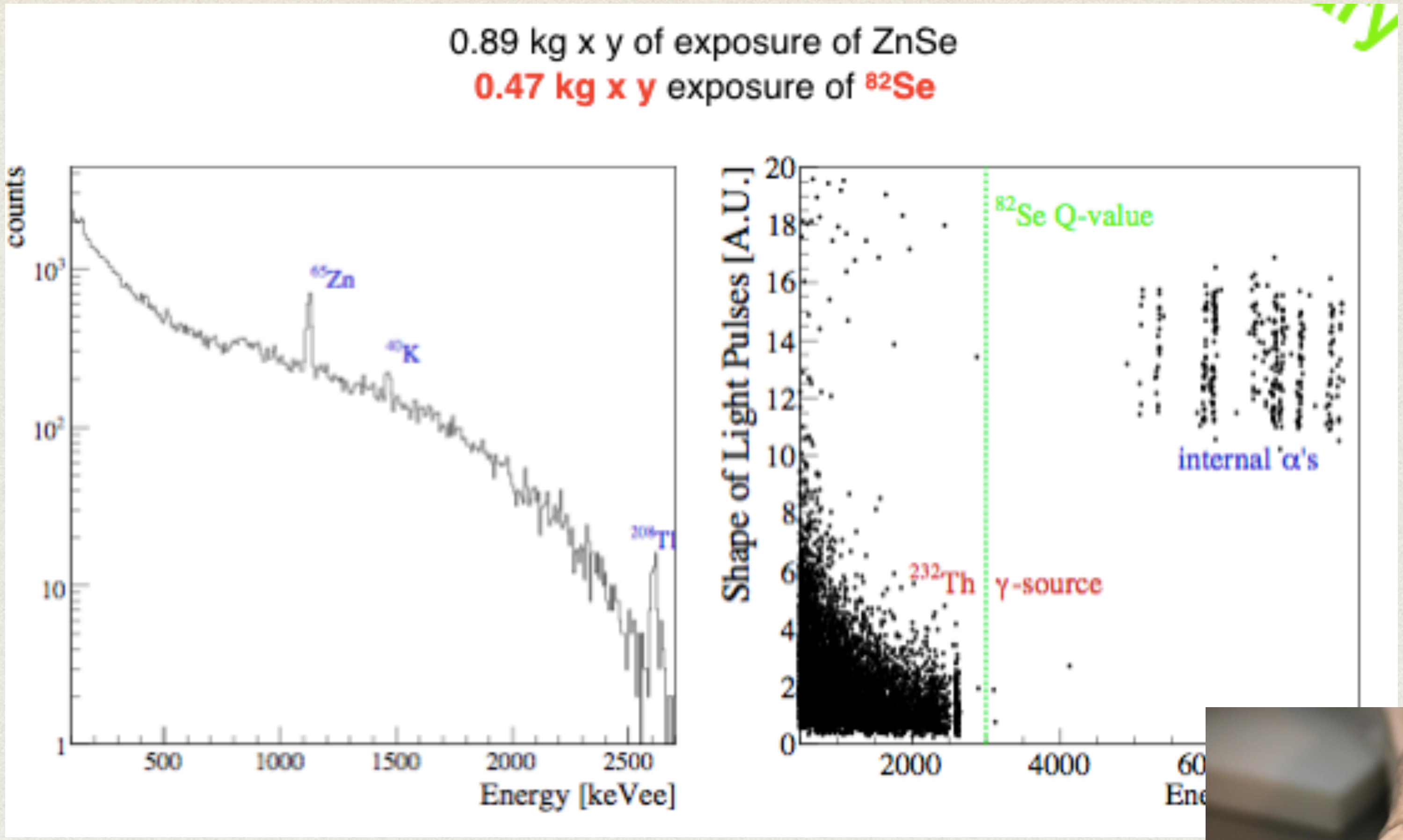
AN OPTION FOR A BRIGHT FUTURE

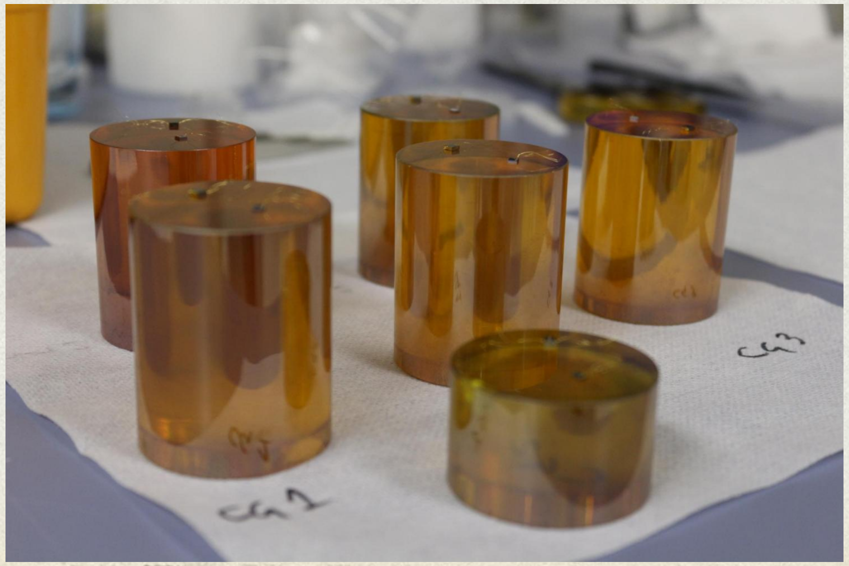


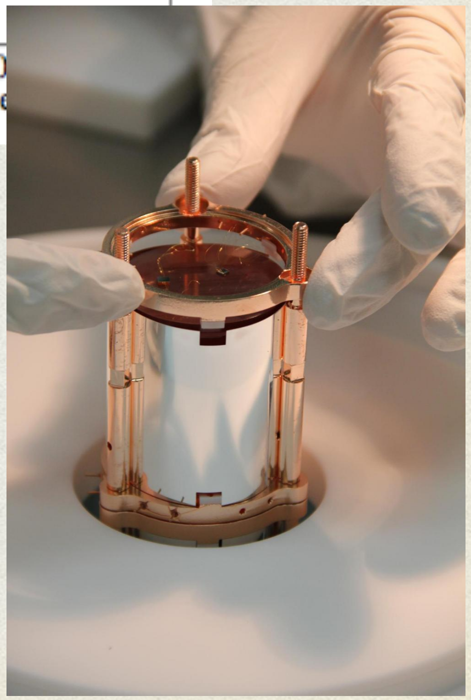


A **background-free experiment** is possible:
α-background: identification and rejection
β-background: ββ isotope with large Q-value

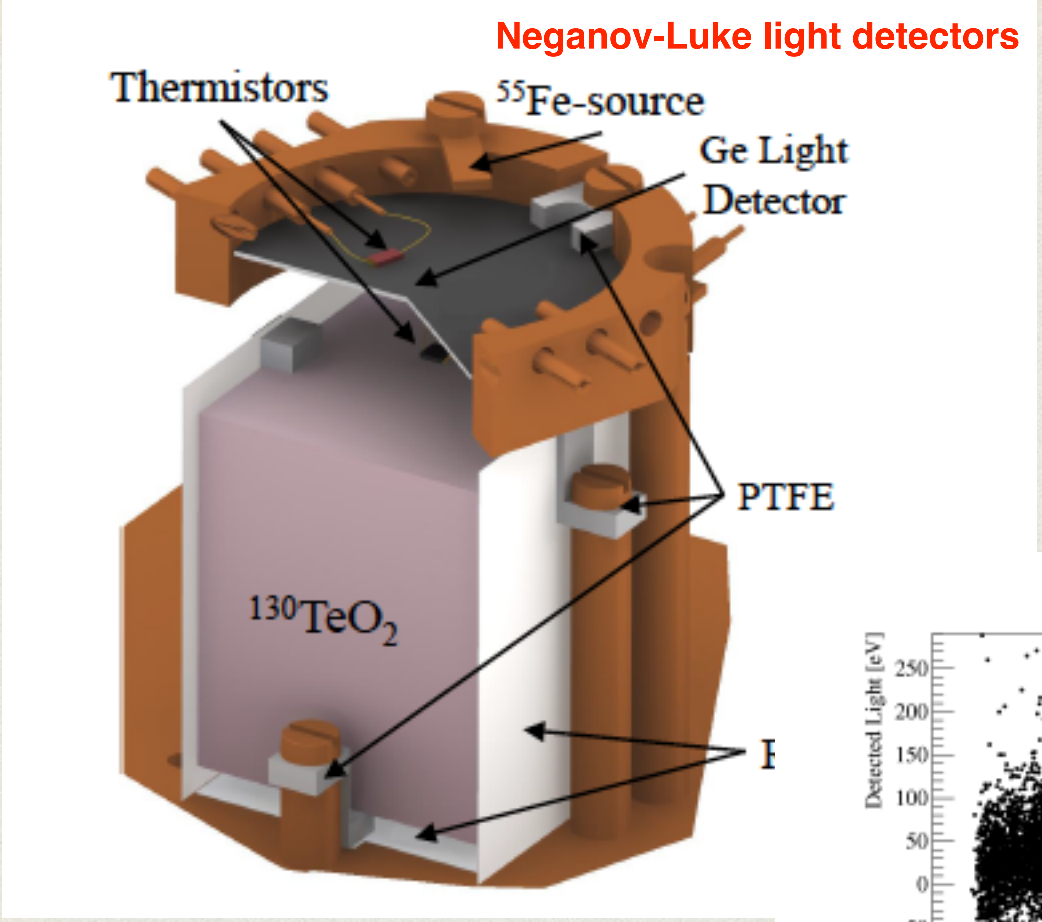
CUPID-0 (LUCIFER)





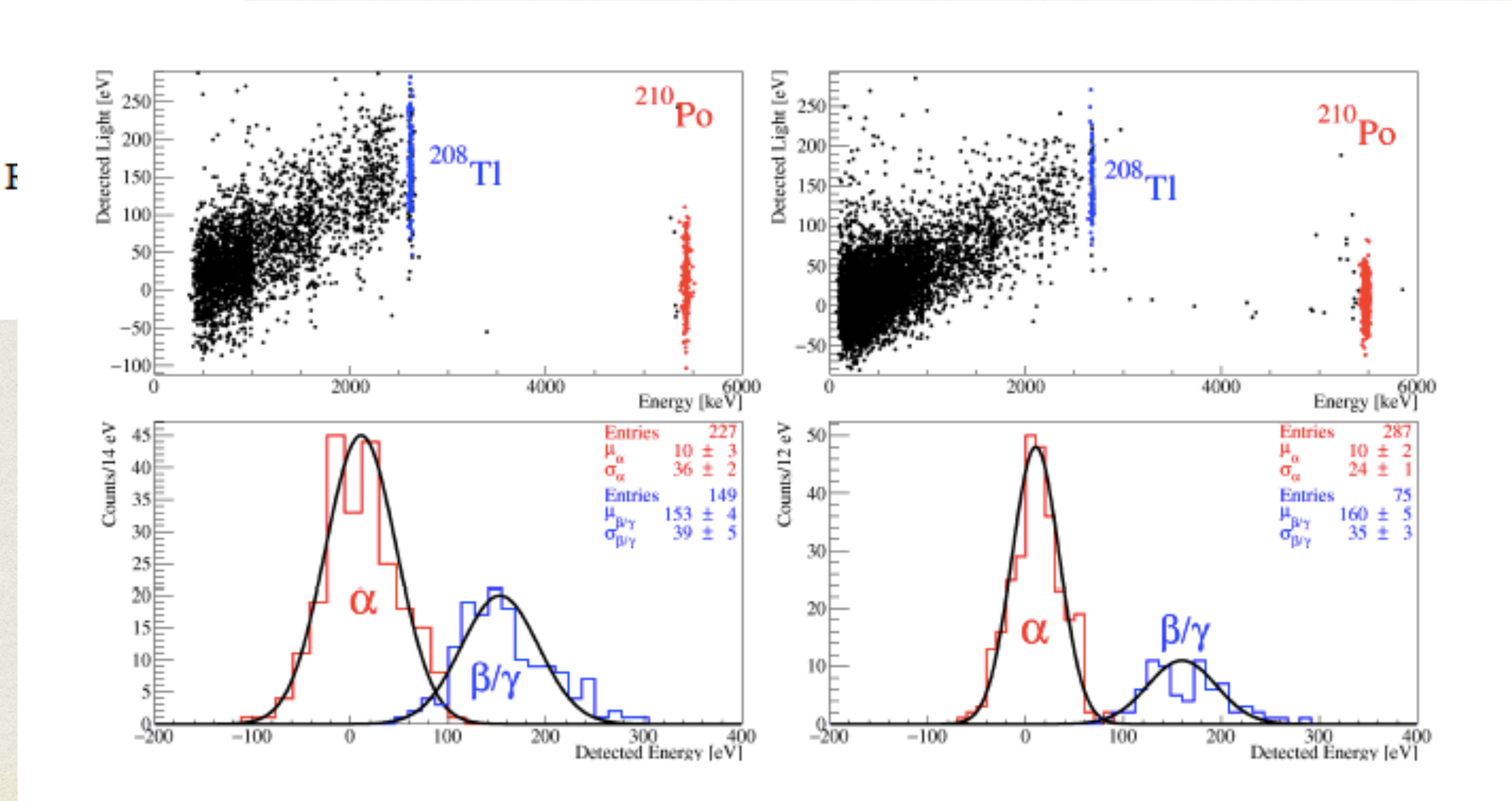


YET ANOTHER OPTION

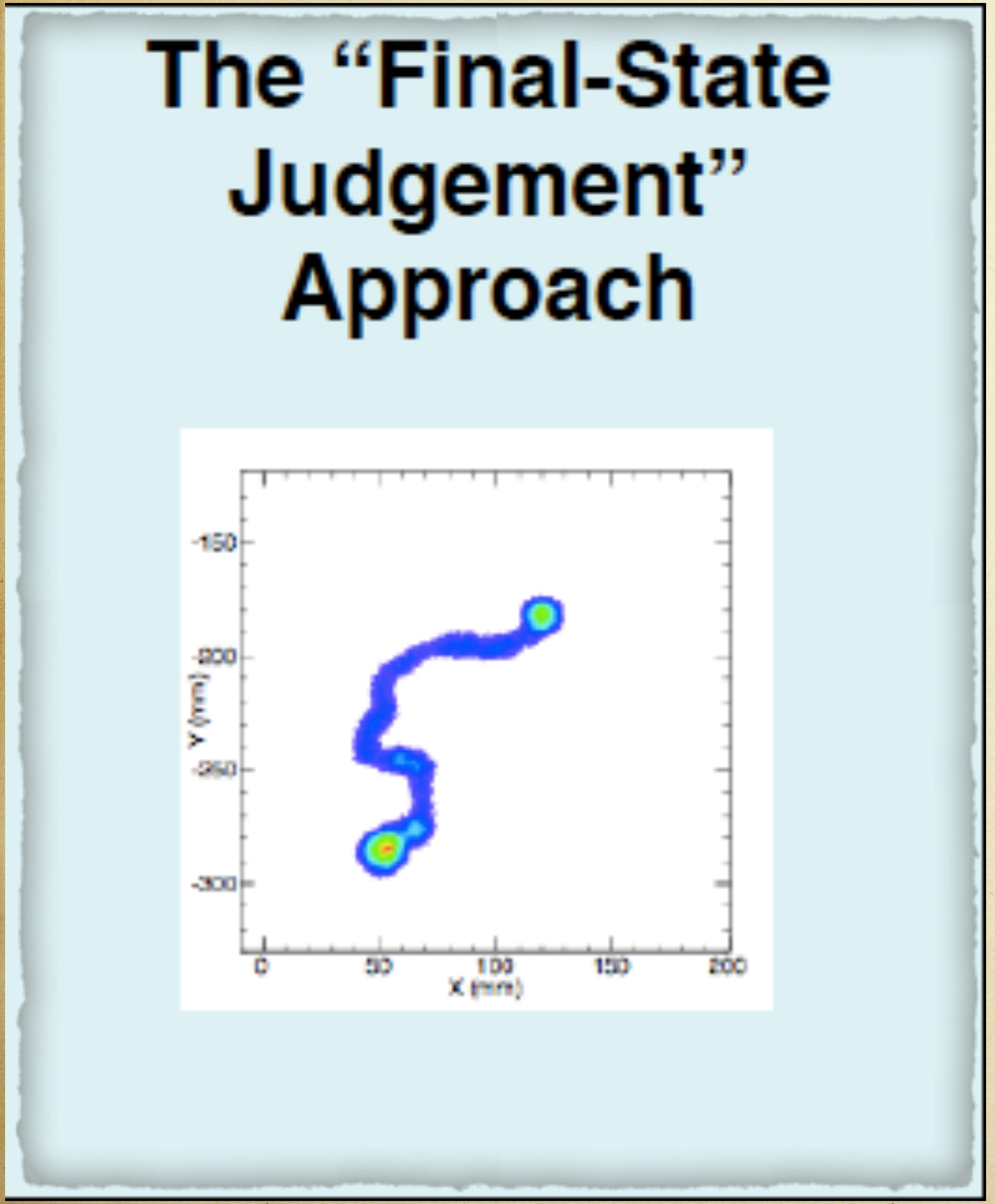


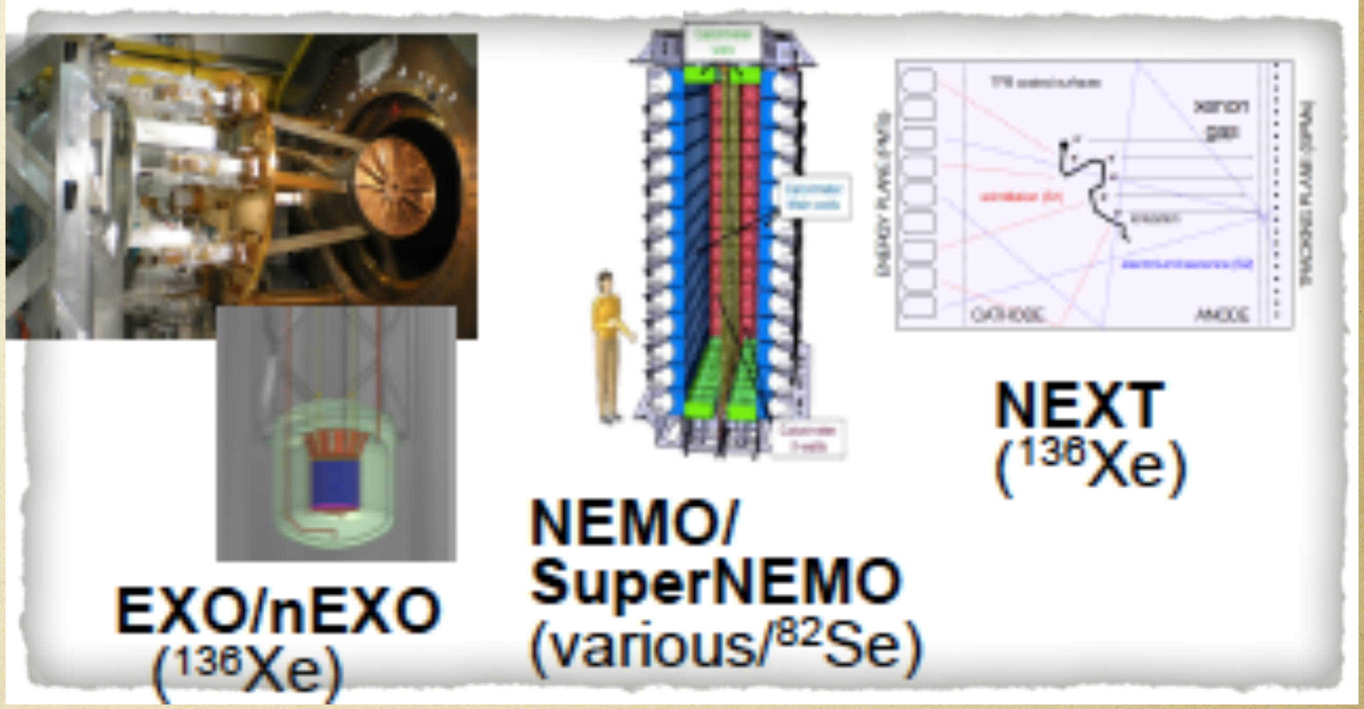
TeO2 does not scintillate

Use Cherenkov effect

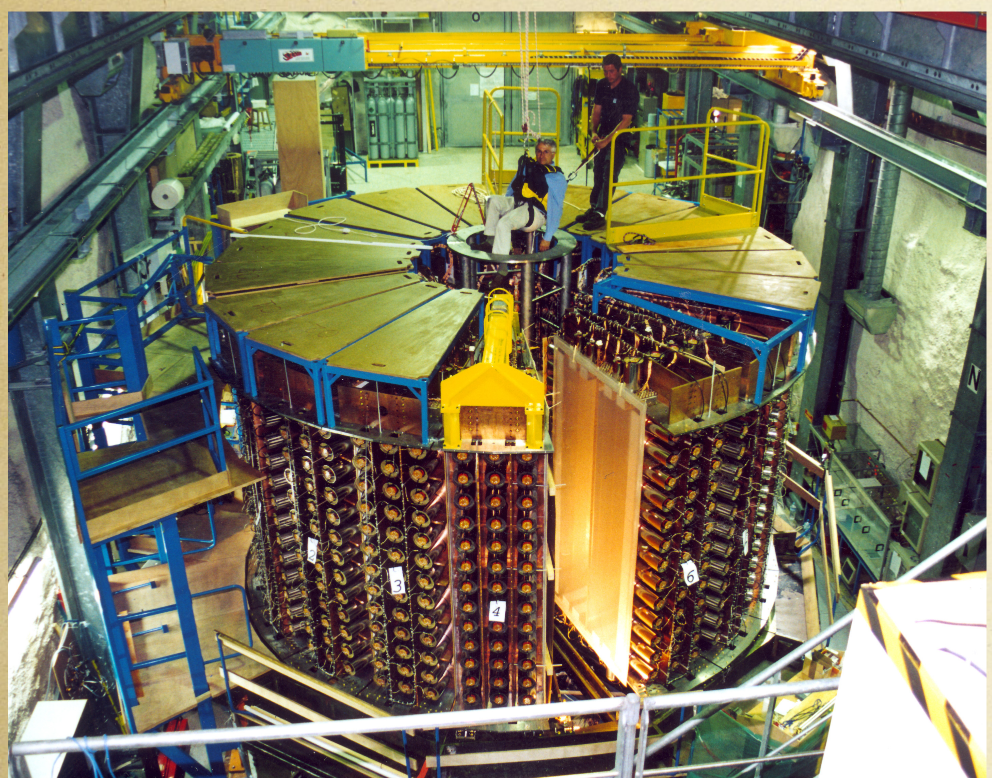


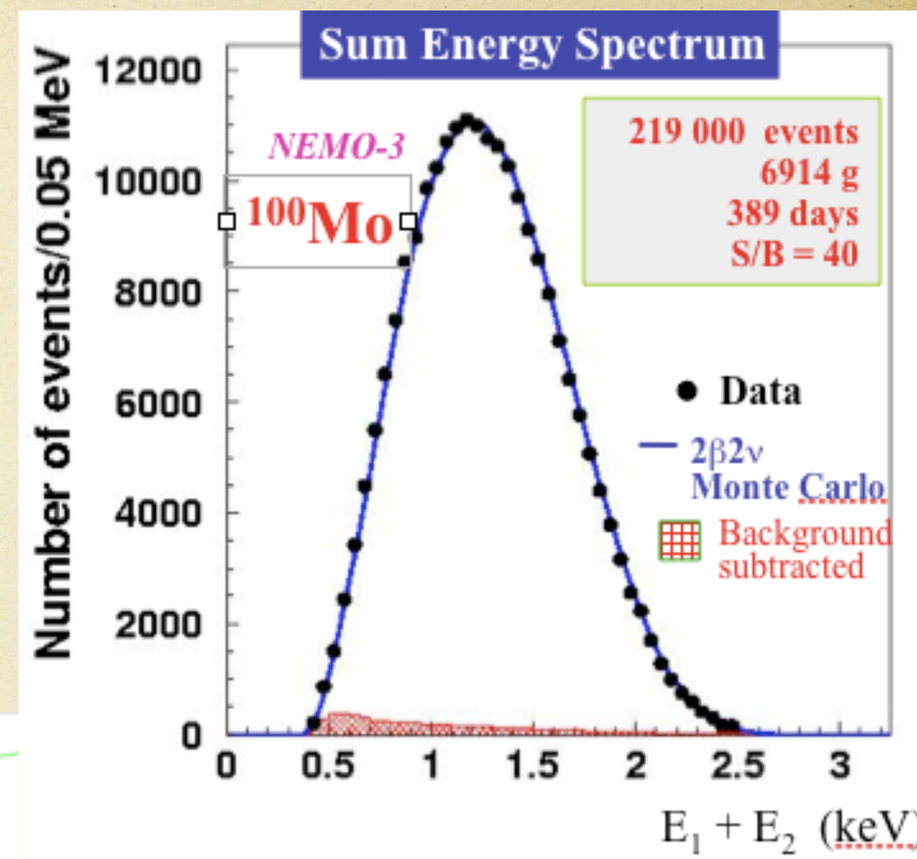
the state of the art: tracking

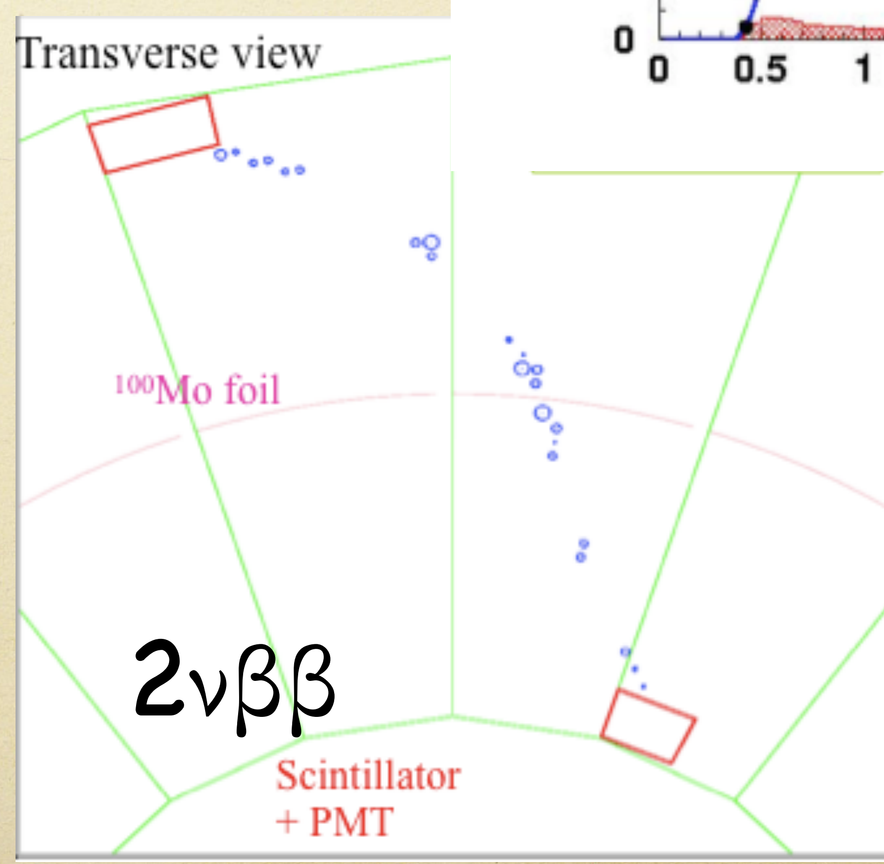




nicely working but…







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

which way ?

- increase isotopic abundance close to 1 (linear though costly)
- increase M a lot (square root, say 1 ton)
- decrease B (get 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)

where do we get if we do so ?

- zero background means you have only to be patient to accumulate the number of event you need

expected number of ββ0ν events

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

detector mass (M), isotopic abundance (a), molecular mass (W), live time (t), ββ0ν half-life ($T_{1/2}^{0\nu}$), efficiency (ε)

stretch isotopic abundance to 100% and assume the same for the efficiency , make the calculation for ^{76}Ge

how patient should you be (to collect 3 say 3 events)

- for a half- life of 10^{28} y approximately 6 years
- being realistic with efficiency and duty cycle say 10 years
- in terms of neutrino masses, let me scale from GERDA result ($5*10^{25}$ y, 0.15-0.33 eV). Gain 200 on half-life means improving on the mass limit as the square root so 10-25 meV at the lower bound of the inverted hierarchy prediction

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$\nu\beta\beta$

$g_A \rightarrow g_A \cdot (1-\delta)$

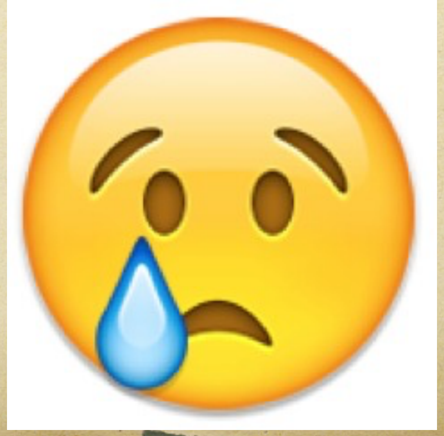
$S \cdot (1-\delta)^4$

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
δ = 0.55
the ‘factor’ would be 11 !!!!!!

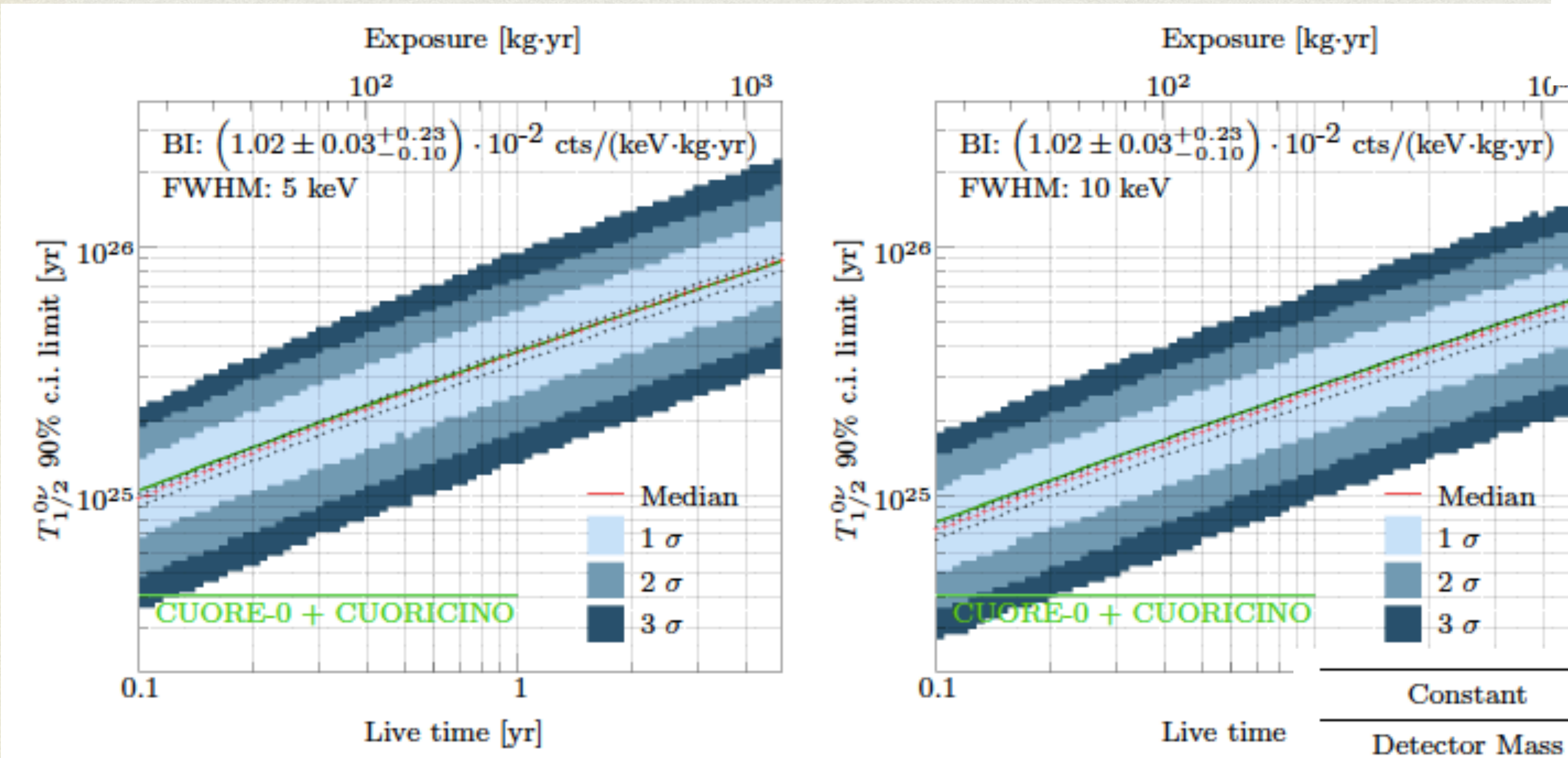
Conclusion

- worth to demonstrate the feasibility of zero background
- by achieving it, 10^{28} y would be a possible goal
- beyond that you only gain by mass increase, knowing however that the next challenge would be the direct ordering of neutrino masses which requires a jump of a factor 100 (100 tons ?)



CUORE SENSITIVITY

BI [cts/(keV·kg·yr)]
$\left(1.02 \pm 0.03(\text{stat})^{+0.23}_{-0.10}(\text{syst})\right) \cdot 10^{-2}$



Constant	Symbol	Value
Detector Mass	m_d	741.67 kg
Avogadro number	N_A	$6.022 \cdot 10^{23}$ mol^{-1}
Molar mass	m_A	159.6 g/mol
Live Time	t_d	0.1–5 yr
Efficiency	ε_{tot}	81.3%
^{130}Te abundance	f_{130}	0.34167
$0\nu\beta\beta$ Q-value	$Q_{\beta\beta}$	2527.518 keV
^{60}Co peak position	μ_{Co}	(2505.692 + 1.9) keV
Energy resolution	FWHM	5, 10 keV