$0\nu\beta\beta$: Present (Cuoricino) and Future

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Moriond ElectroWeak at La Thuile, March 12th, 2009

once upon a time

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

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

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

(when Science could still be described in Italian !)

courtesy of Luciano Maiani

the Majorana conjecture

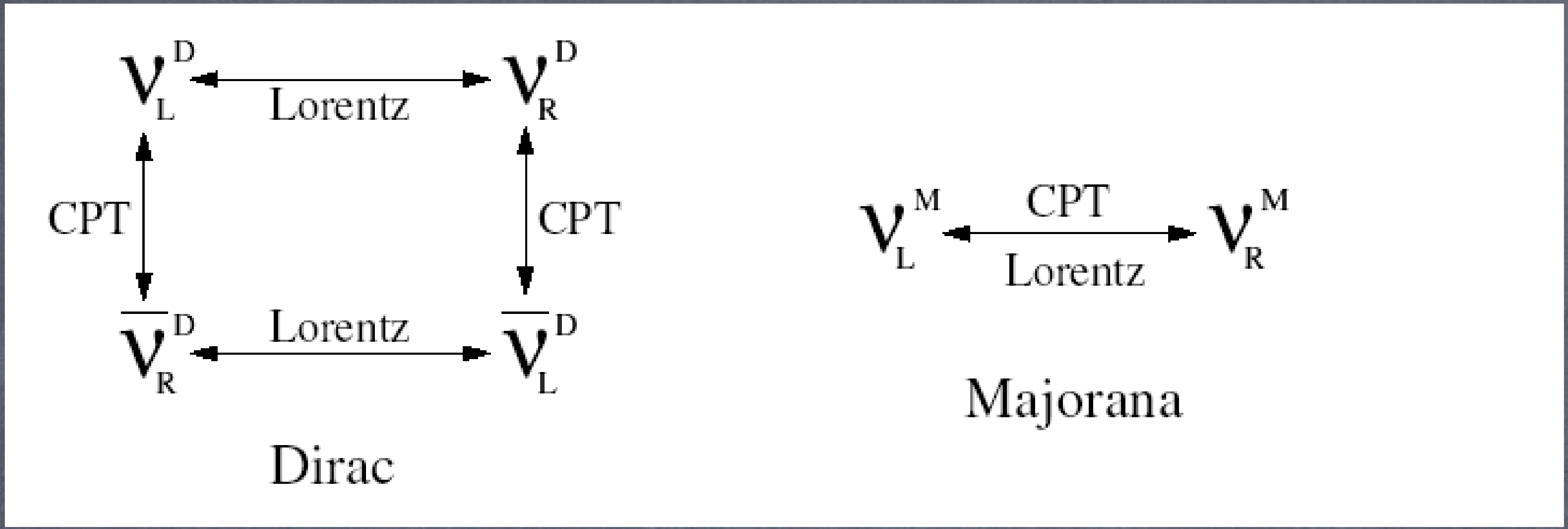
$$\nu = \bar{\nu}$$

Practical consequence :
Lepton Number Violation

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

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

Massive neutrinos makes the story much more attractive



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

one elegant explanation (beyond the SM)

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

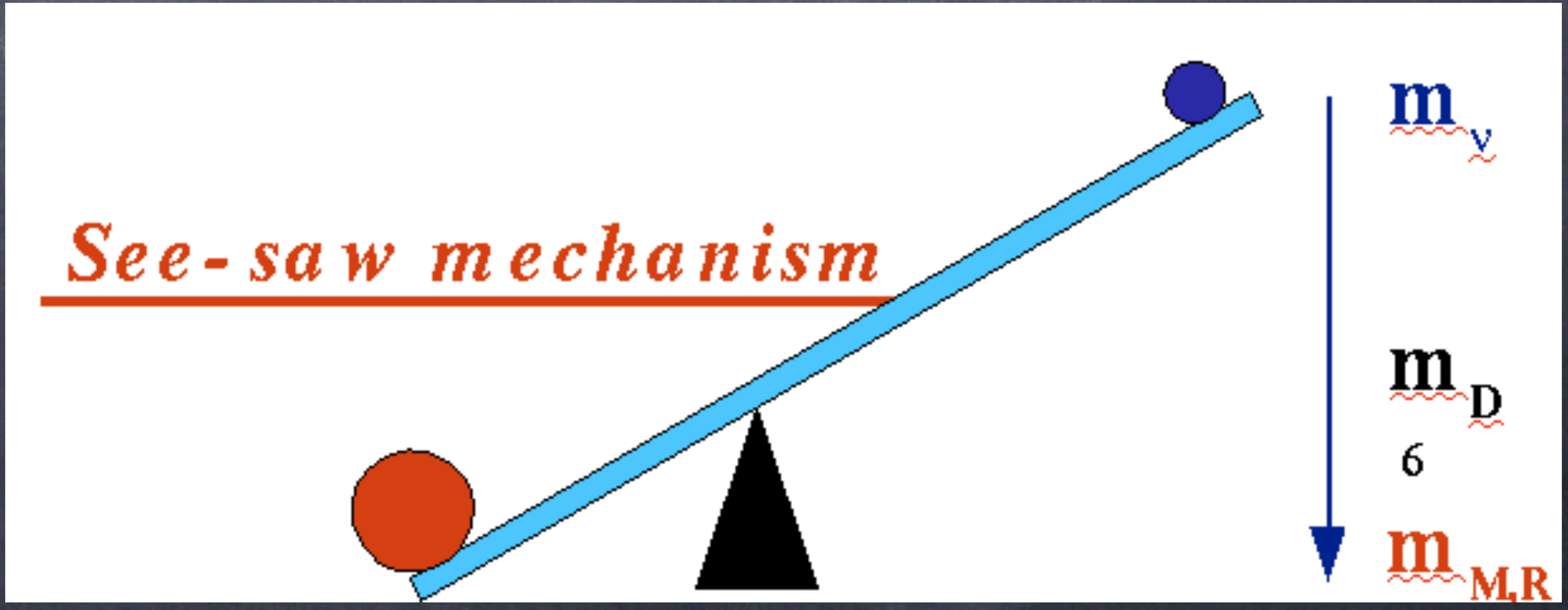
where $M_{M,L} \sim 0$

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

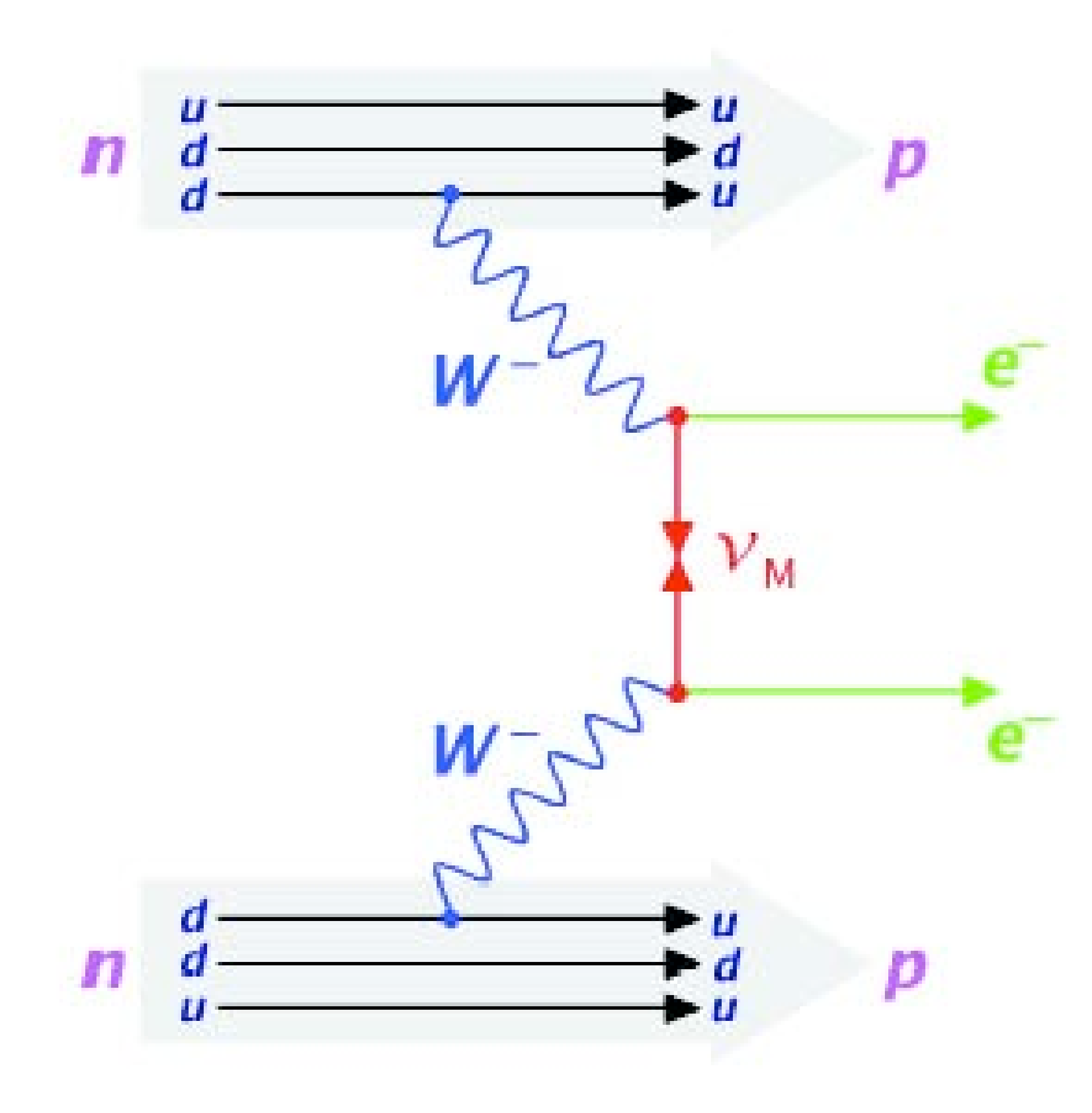
$M_{M,R} \sim$ Gauge singlet unprotected $\sim M_{GUT}$

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

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



Neutrino-less DBD (0νββ)



Only if:

Majorana Neutrinos

Massive Neutrinos

If observed:

Proof of the Majorana nature of Netrino

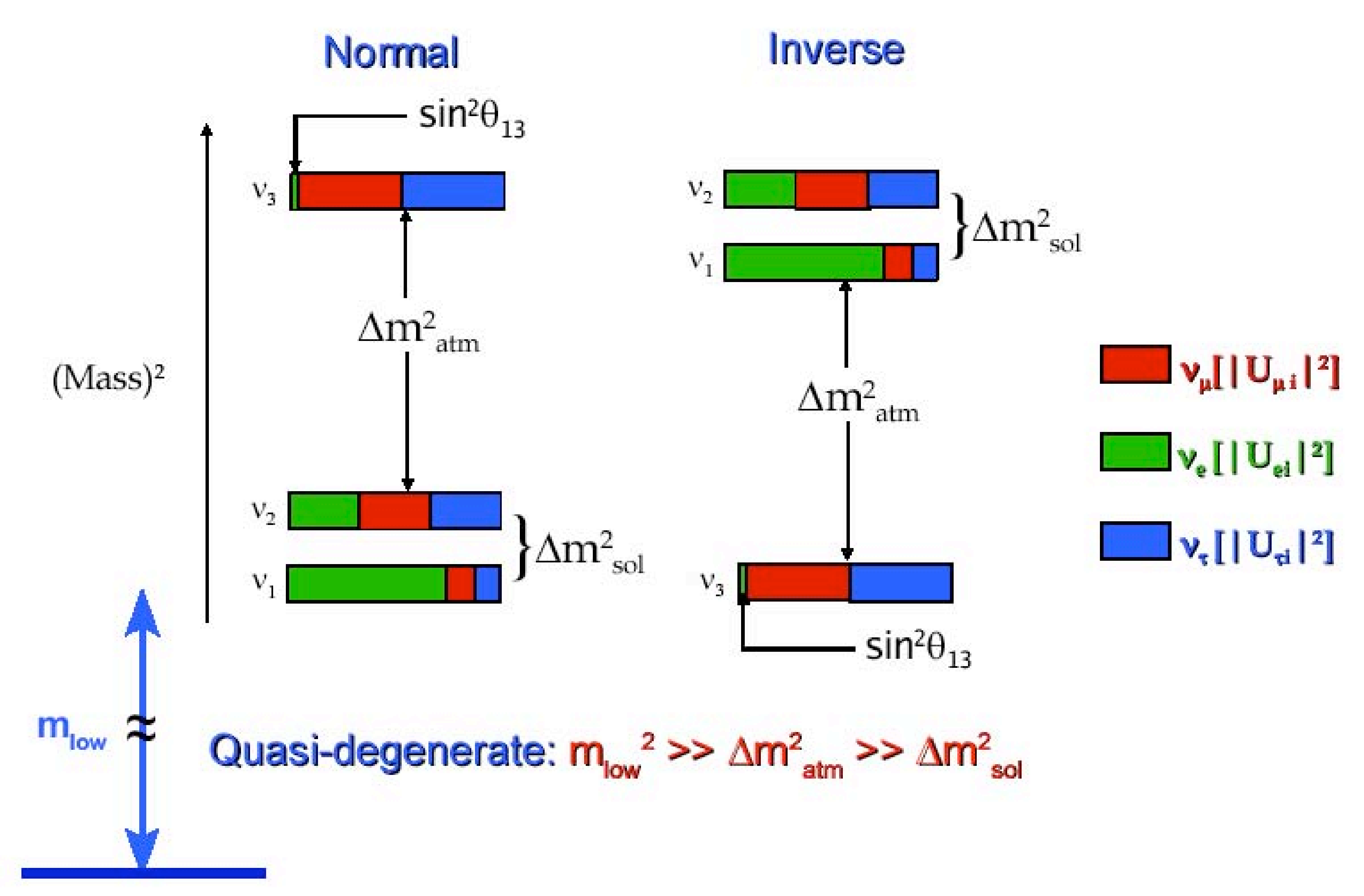
Does it also measure the mass ?

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

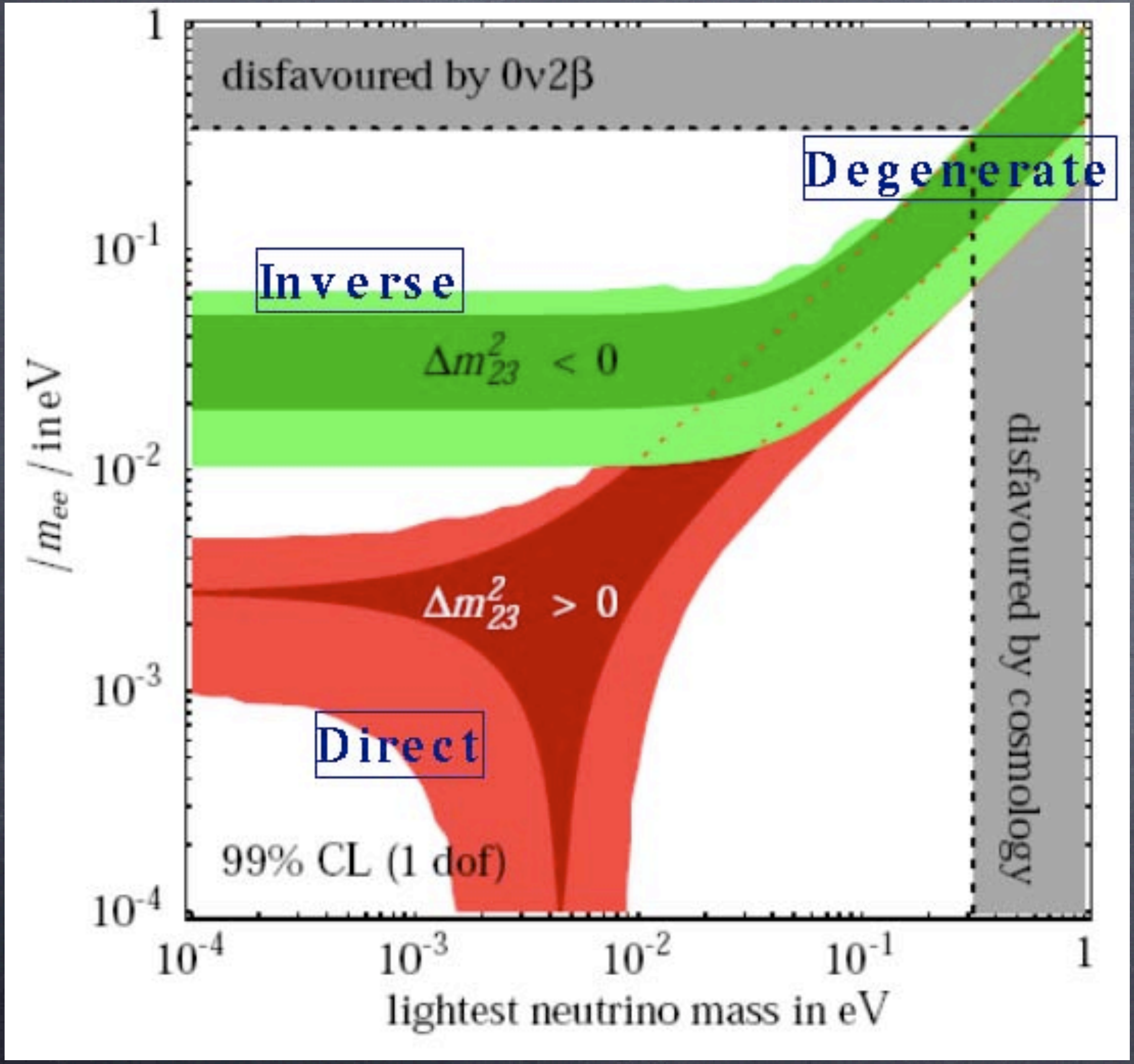
well...not so straight. It comes as a combination of the three neutrino masses, the mixing angles and the Majorana phases.

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

Three possibilities:

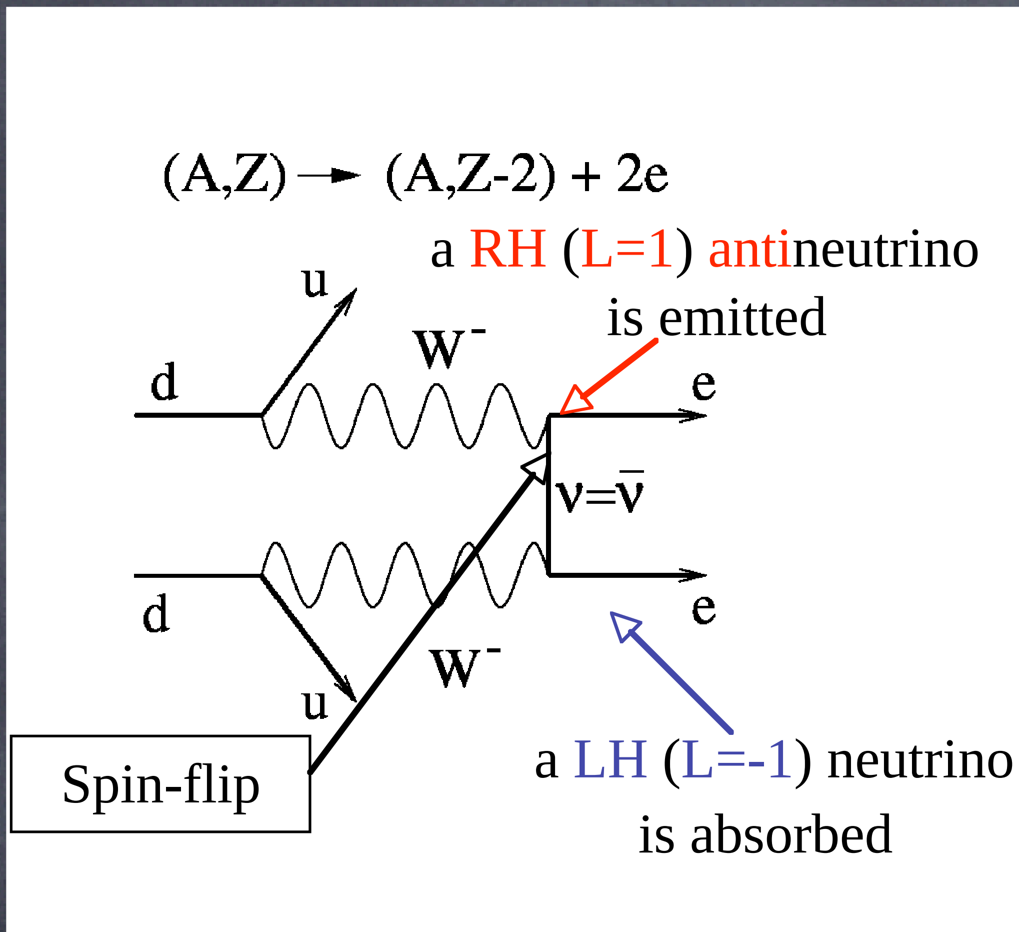


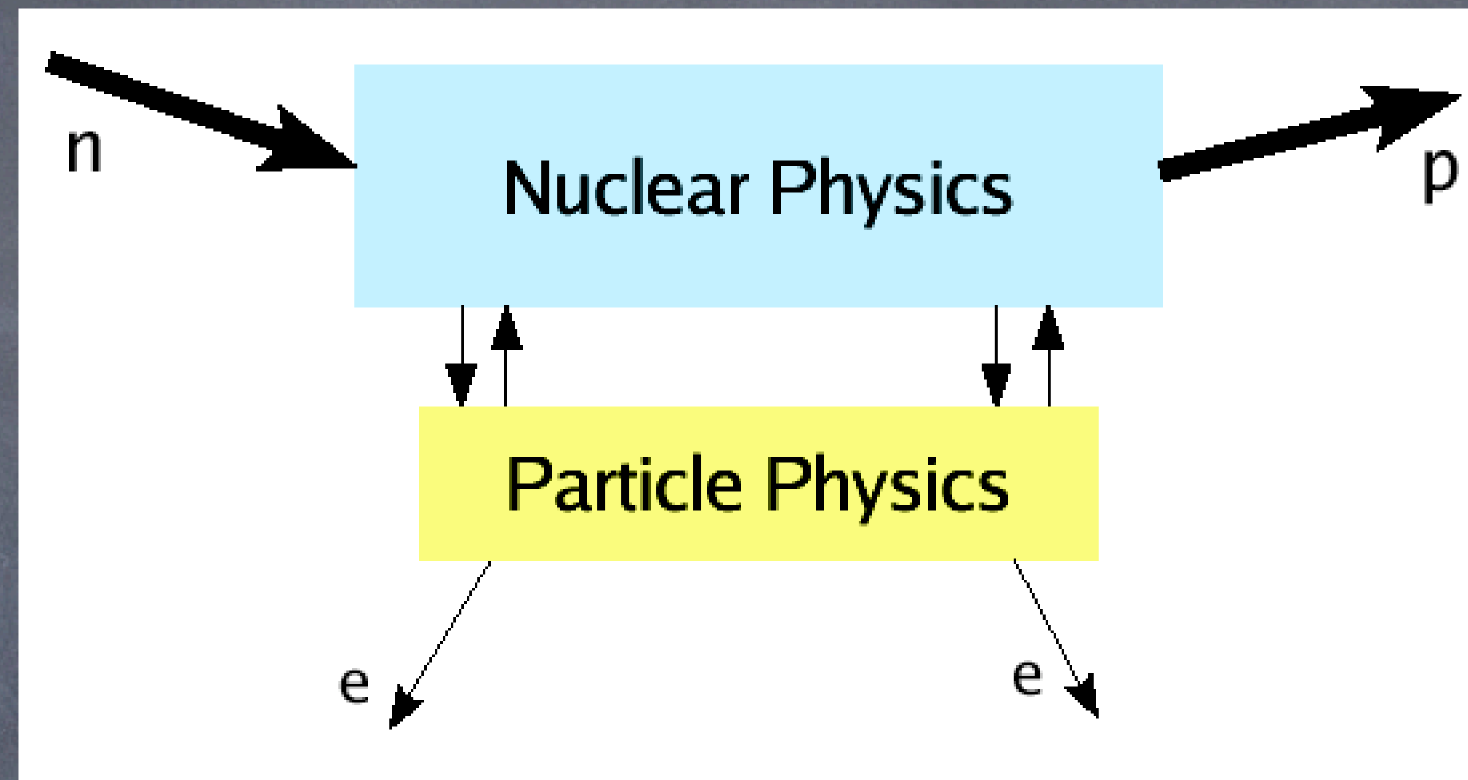
that translates into a nice plot



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

The elements of the game





0ν-DBD rate

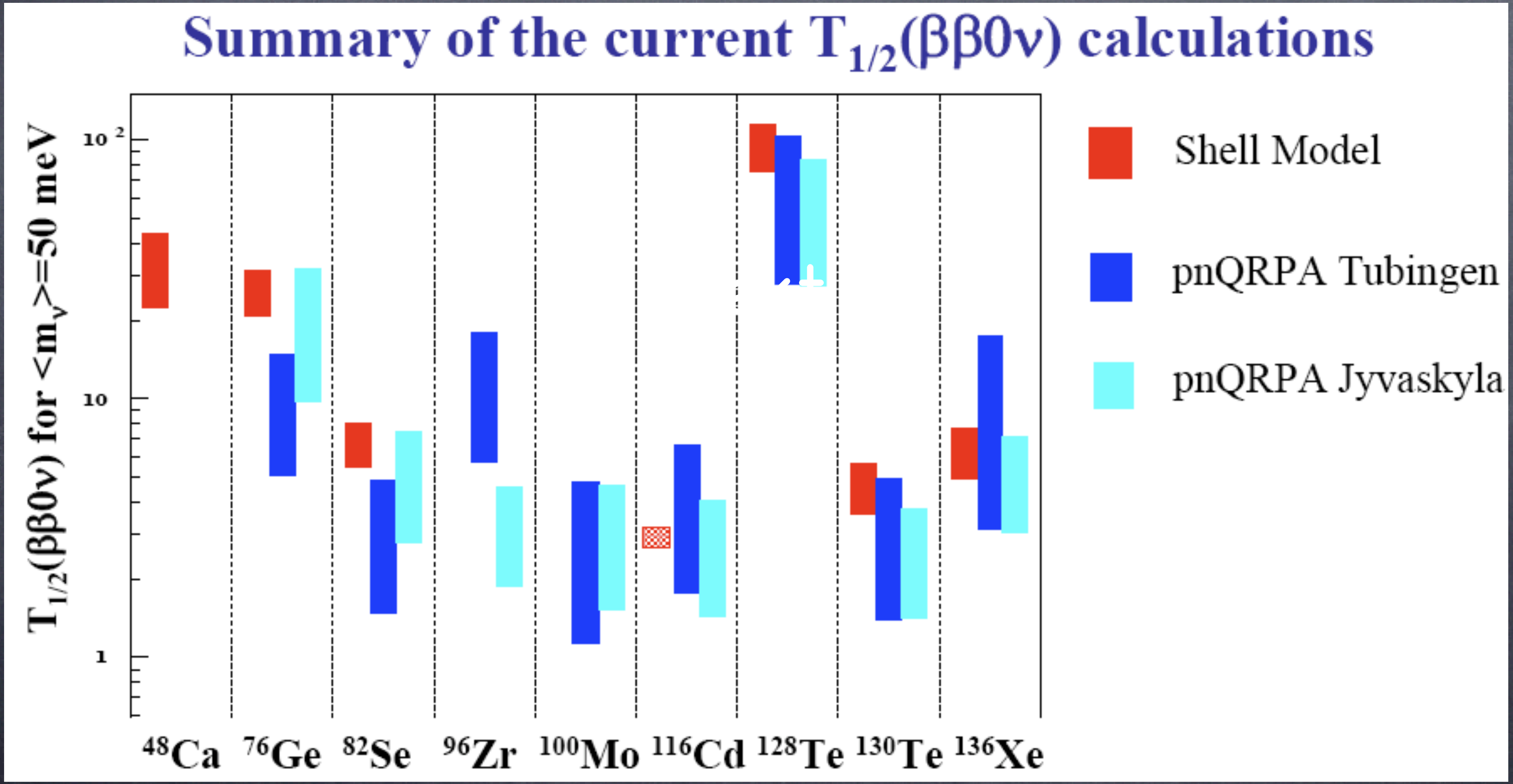
Phase space $\propto Q^5$

Nuclear matrix element

Effective neutrino mass

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

The NME struggle



although differences are now reduced, rate depends on the square and going to m_{ee} there is another square

The name of the game: sensitivity

Isotopic abundance

Mass(Kg)

Time (y)

efficiency

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

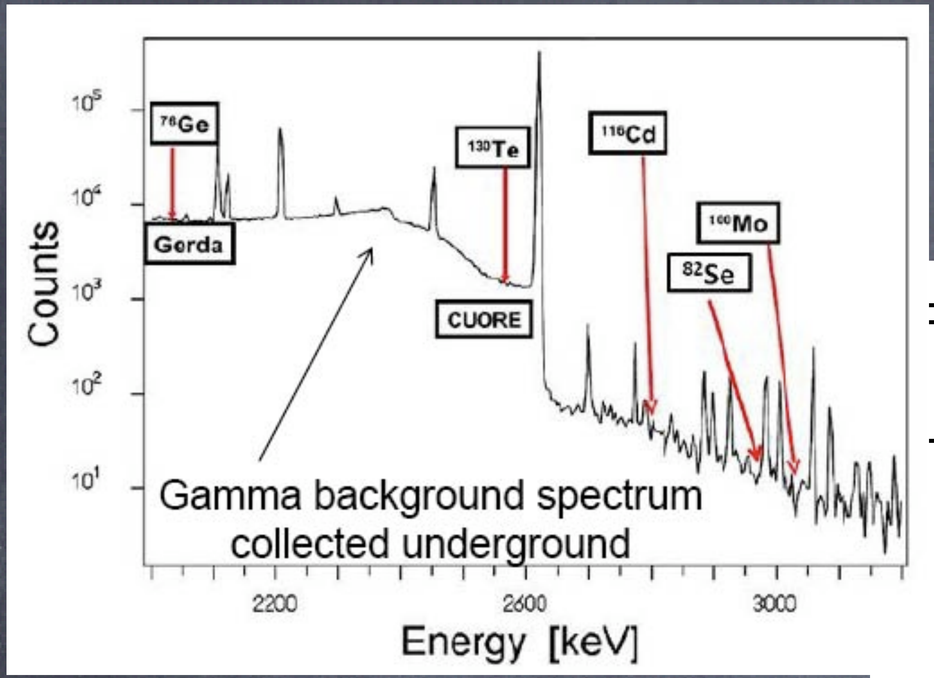
Atomic Mass

background
(counts/keV/Kg/y)

Energy
Resolution
(KeV)

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

The isotope choice

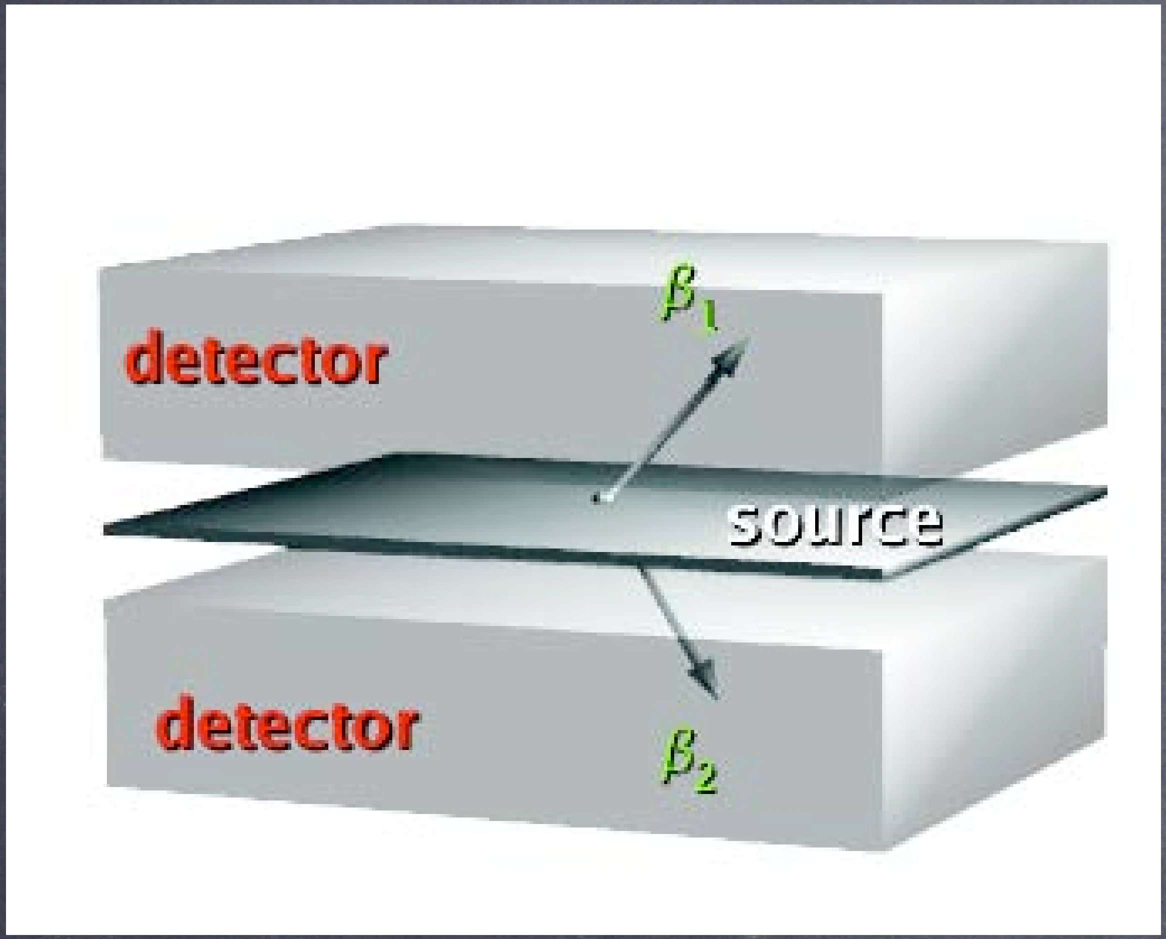


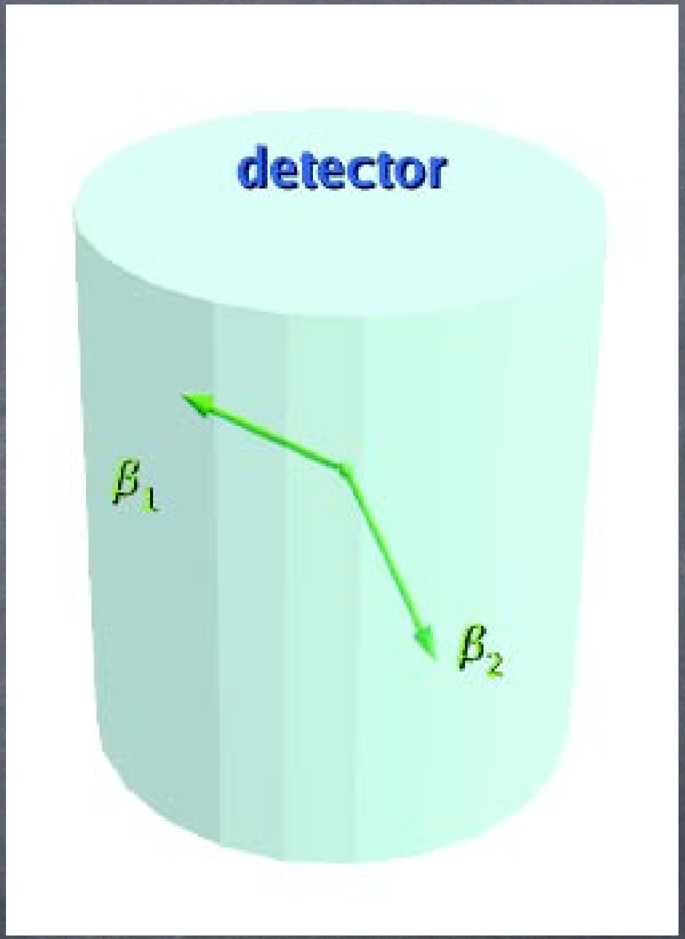
Isotope	$Q_{\beta\beta}$ (MeV)	Isotopic abundance (%)
^{48}Ca	4.271	0.0035
^{76}Ge	2.039	7.8
^{82}Se	2.995	9.2
^{96}Zr	3.350	2.8
^{100}Mo	3.034	9.6
^{116}Cd	2.802	7.5
^{128}Te	2.527	34.0
^{130}Te	2.533	34.5
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

Two techniques (and a few variations)

Source ≠ Detector

Source ⊆ Detector



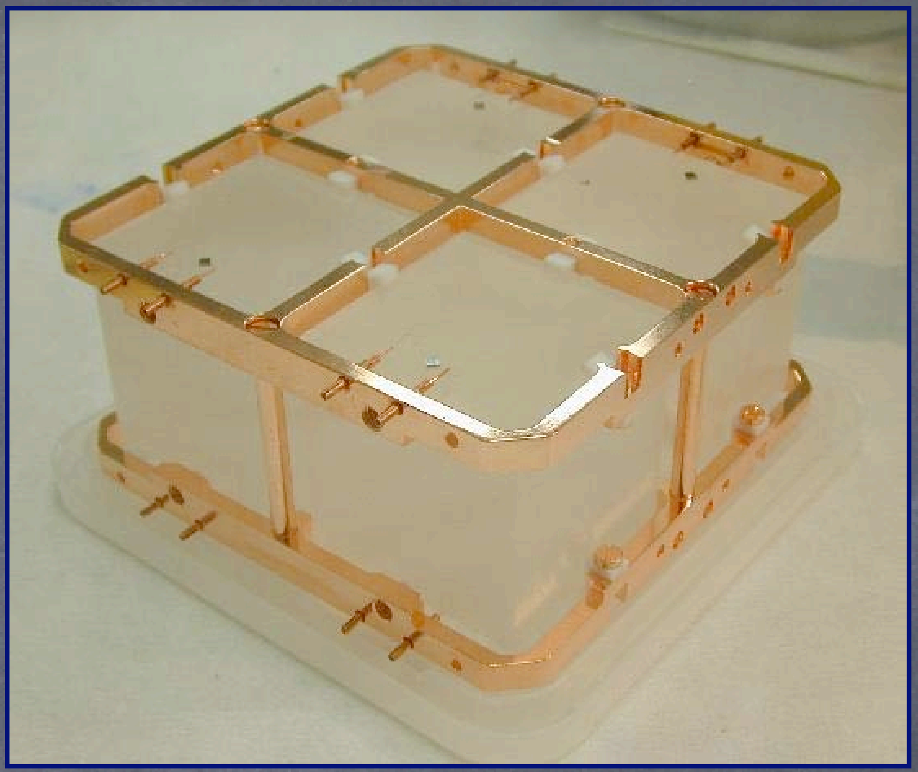


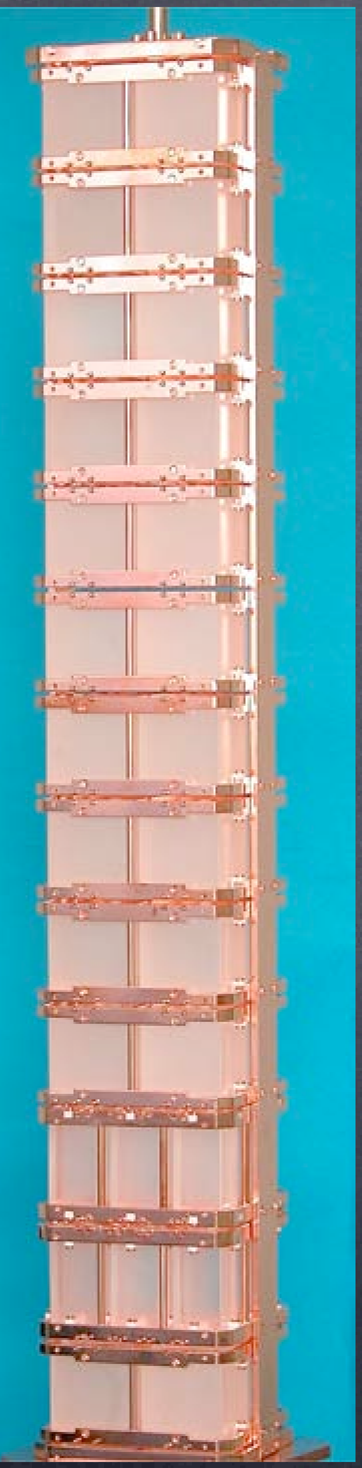
+++ Topology, Background
--- M, ΔE, ε

+++ M, ΔE, ε
--- Topology, Background

Until June 2008

Cuoricino



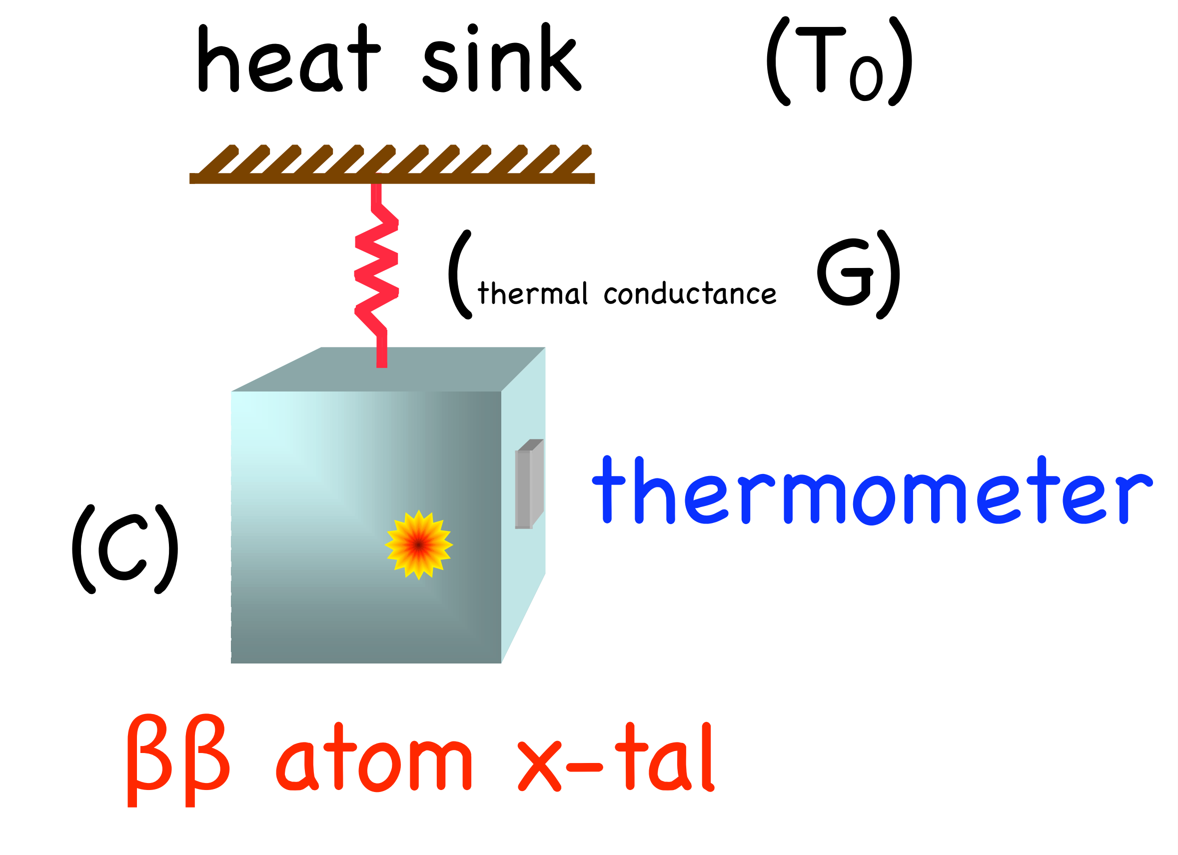


The bulk of Cuoricino calorimeter is made by 44 TeO_2 crystals of 5x5x5 cm^3 (790 gr of weight).
There are 18 additional crystals of 3x3x6 cm^3 (330 gr)

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

(very) Low Temperature Calorimeter

A True Calorimeter



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

(Energy release/ Thermal capacity)

Implication: Low C ⇒ Low T

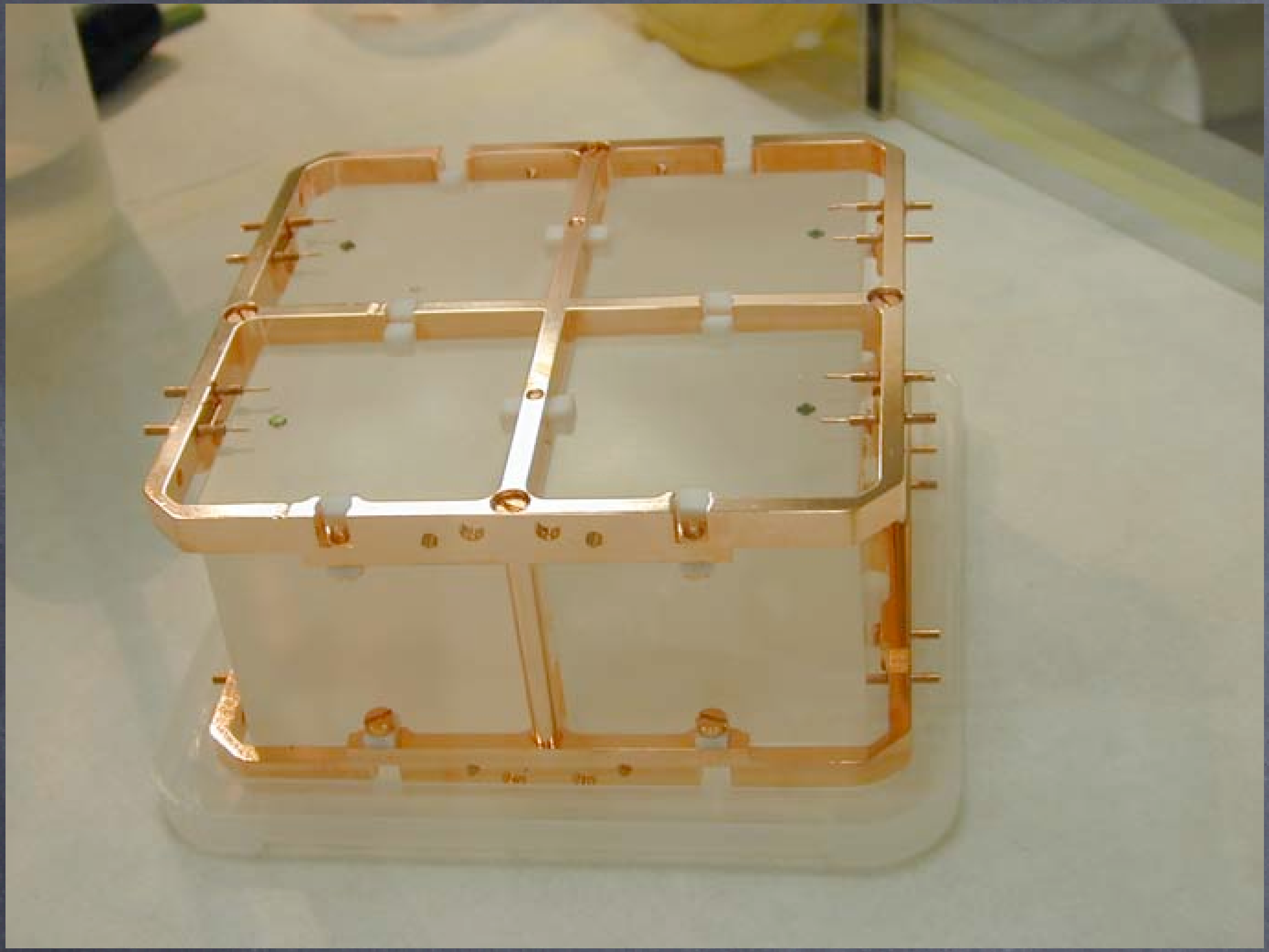
Bonus: (almost) No limit to ΔE ($k_B T^2 C$)

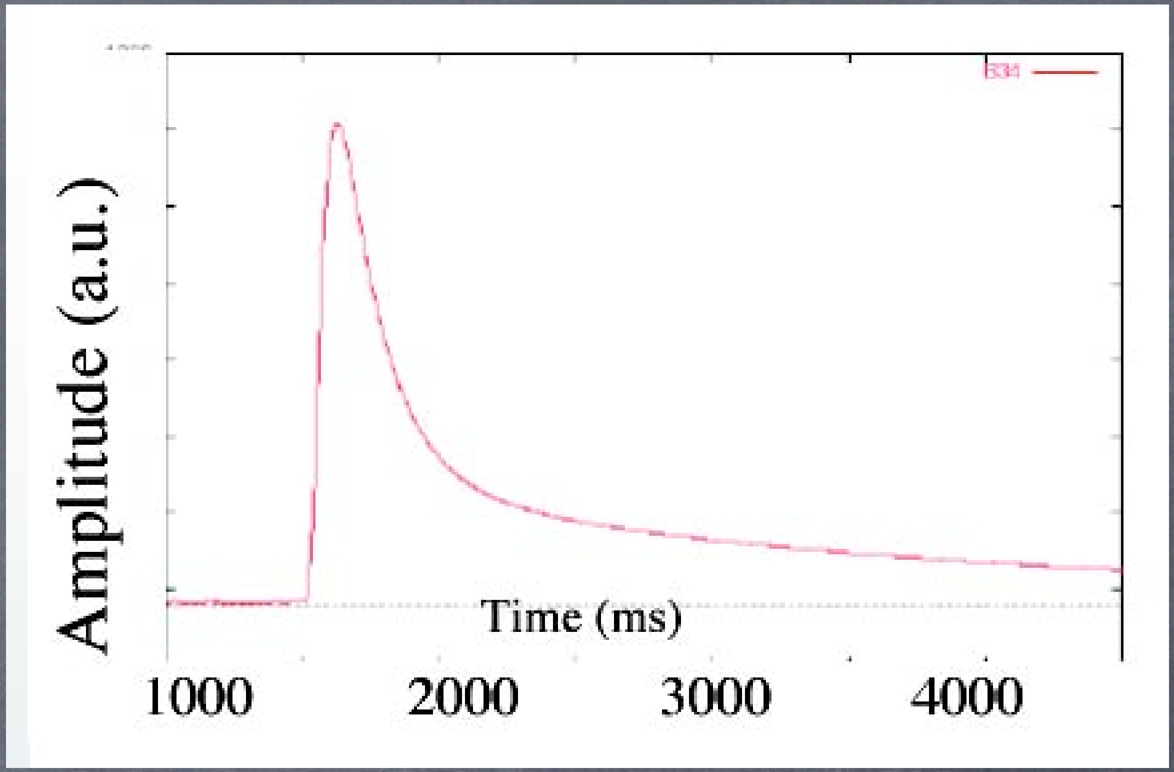
Not for all : $\tau = C/G \sim 1s$

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

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

TeO_2 : a viable (show)case





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

Numerology:

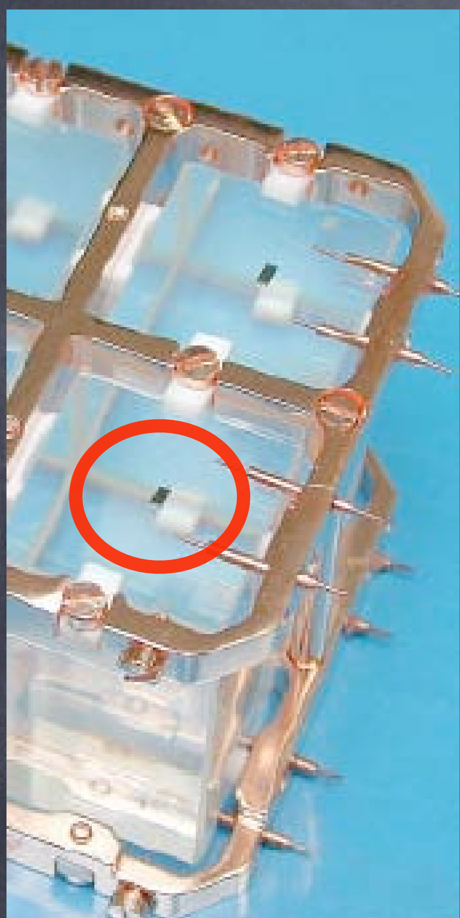
$T_0 \sim 10$ mK

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

$G \sim 4$ pW/mK

to read the temperature you need a thermometer

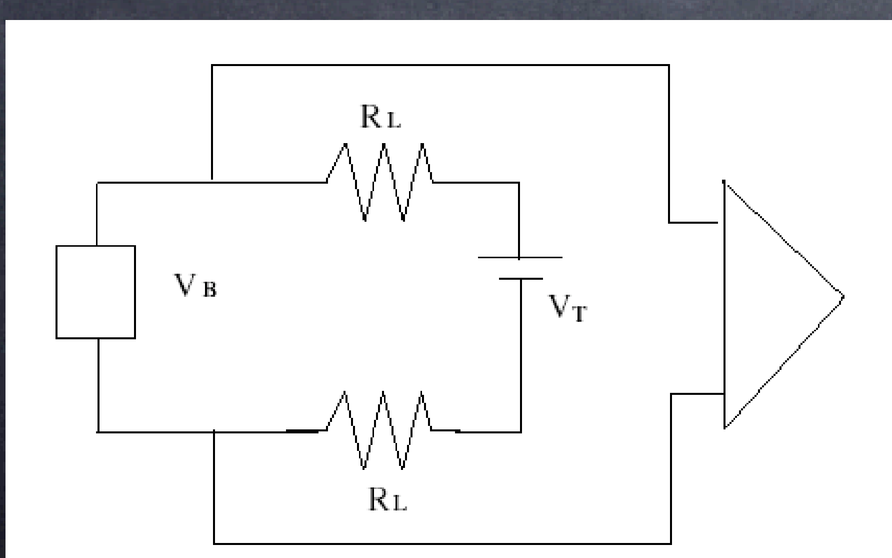
$$A(T) = \left| \frac{d \ln R}{d \ln T} \right|$$

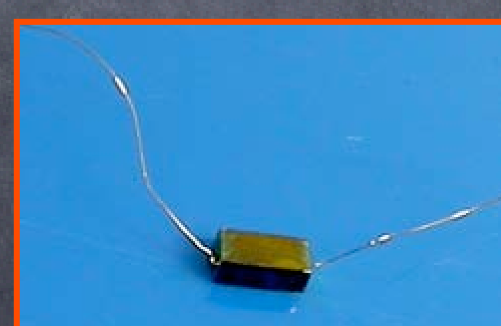


Neutron Transmutation Doped (NTD) Germanium Thermistor

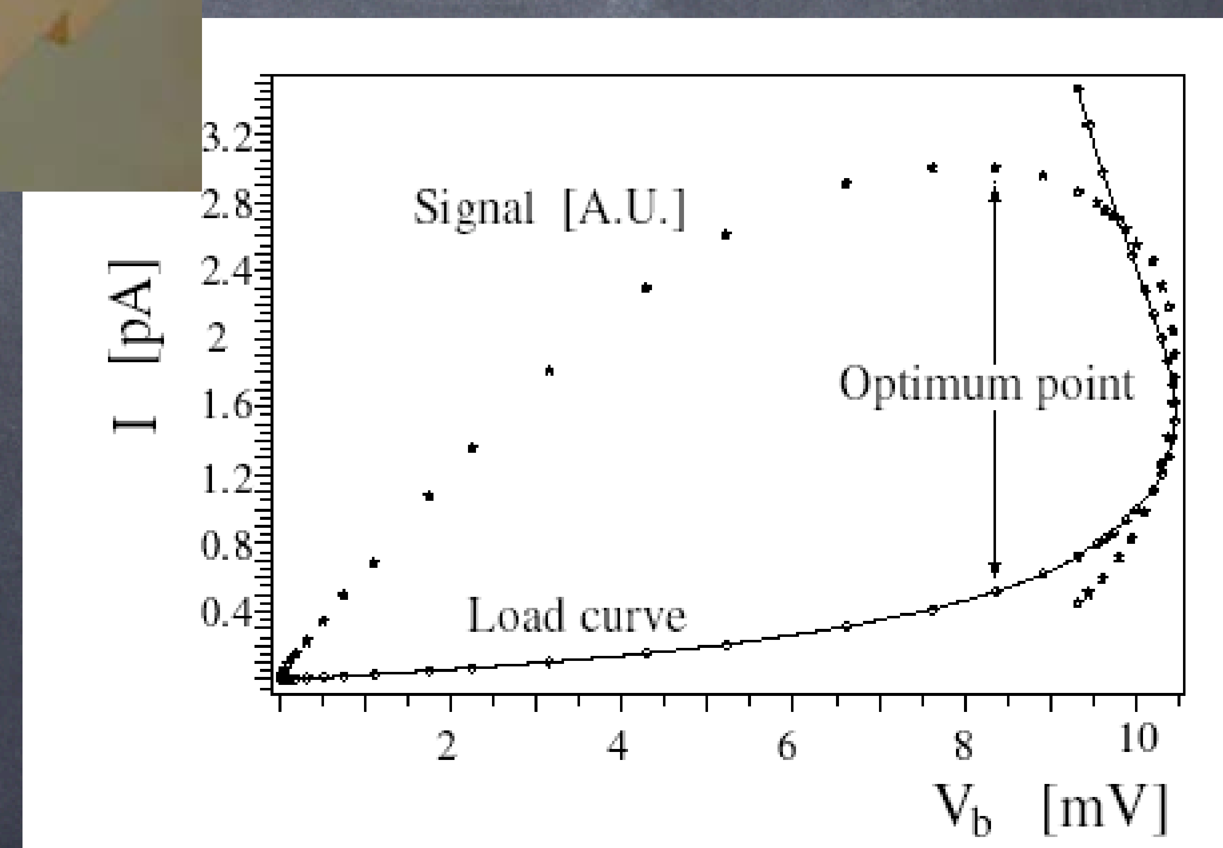
I ~ 50 pA
dR/dE ~ 20kΩ/KeV

0.2mV/MeV

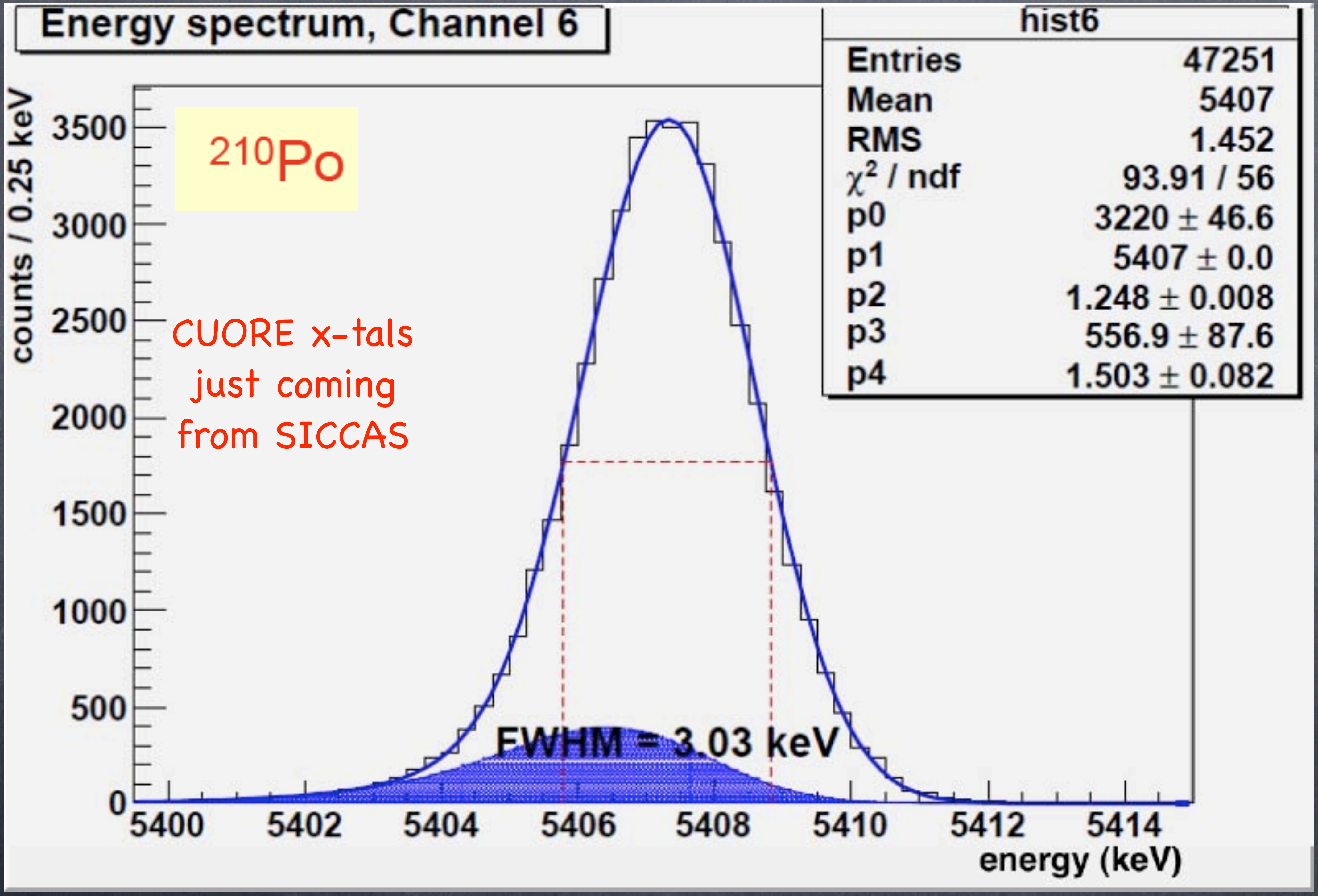




$$T_b = T_0 + \frac{P}{G}$$

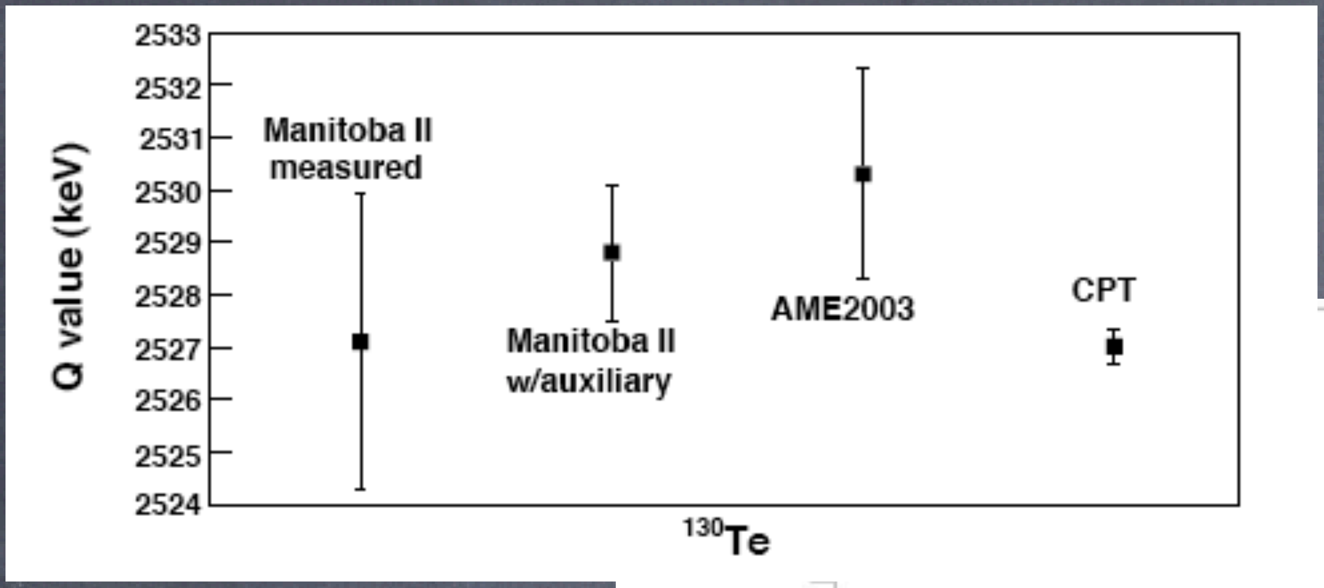


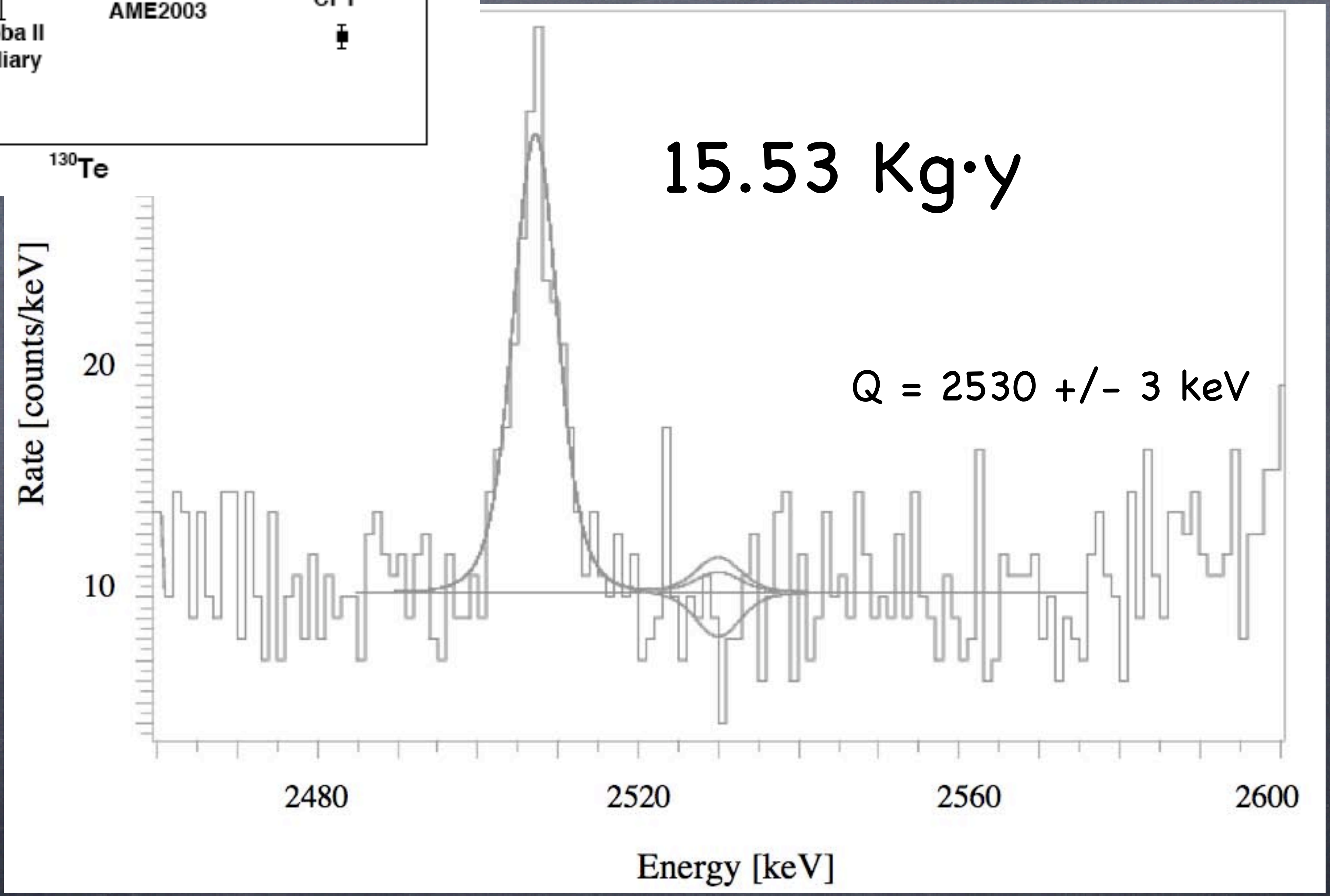
Energy Resolution



Cuoricino: result

up to 1 h ago

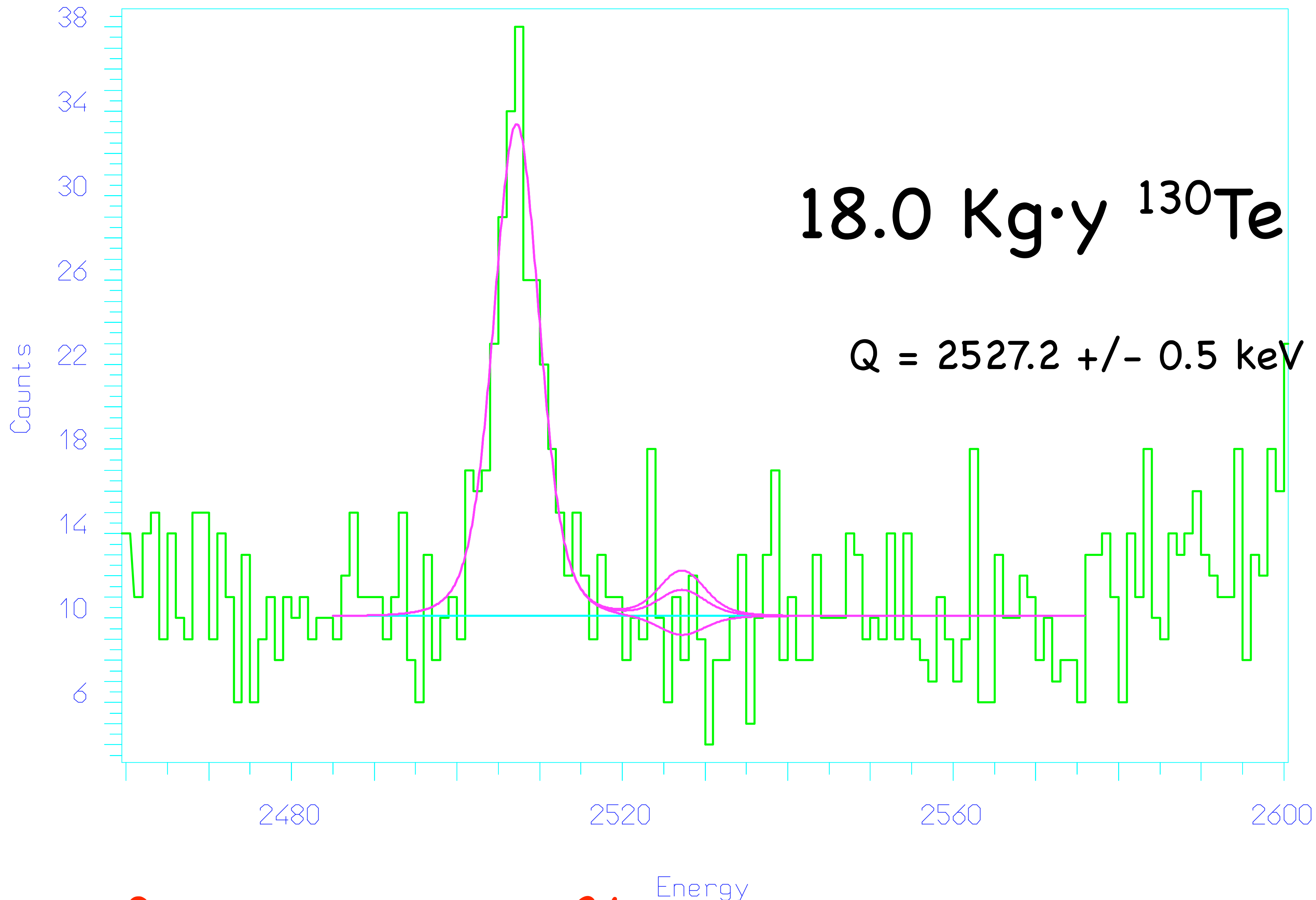




$\tau_{1/2}^{0\nu}$ (y) > 3.0 × 10^{24} y (90% c.l.)

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

and since 16.20 on 12 March 2009
Cuoricino final result



$T_{1/2}^{0\nu} = 2.94 \cdot 10^{24}$ y

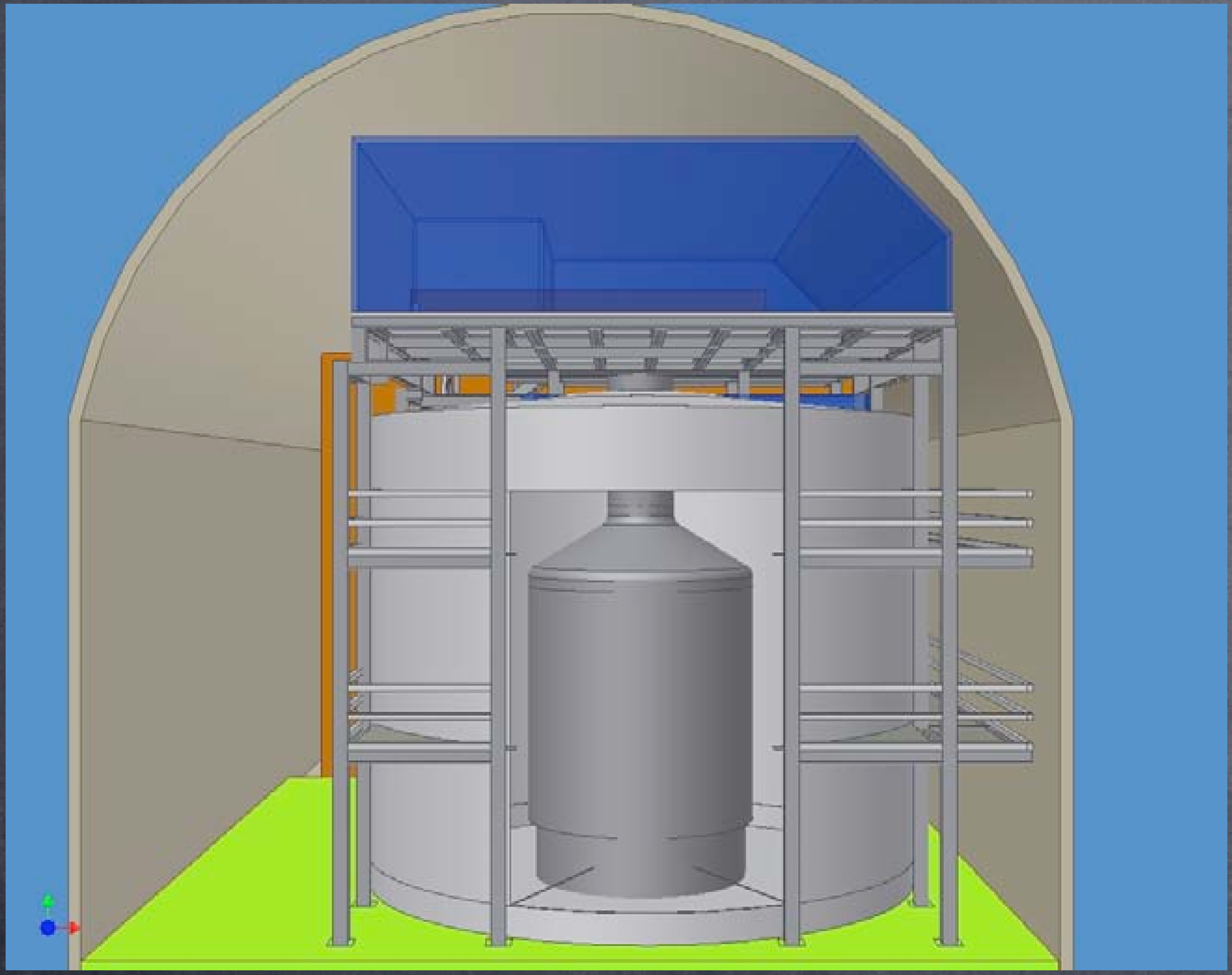
thanks Maura !

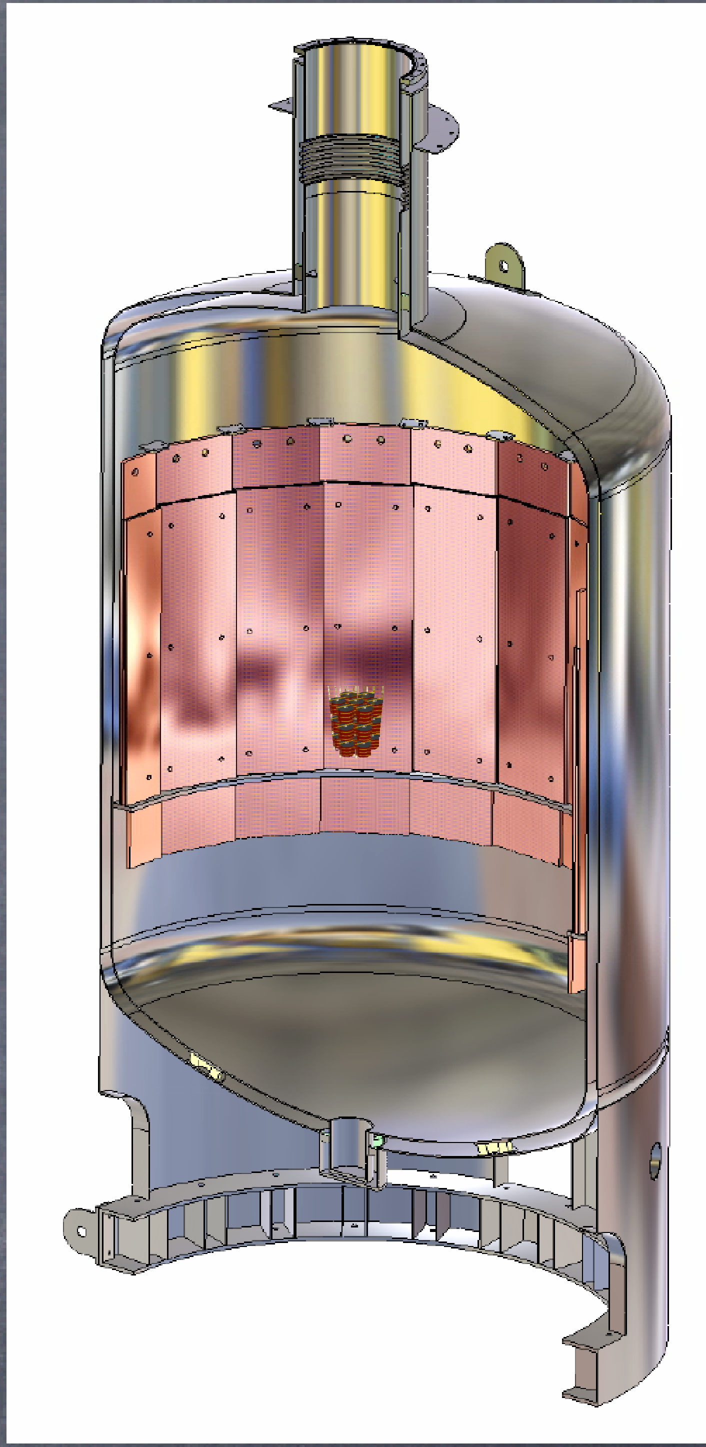
The (near) Future

- GERDA (as an extrapolation of Ge ionization calorimeters)
- SuperNemo (improved tracking detectors)
- EXO (LXe with a super, yet daring, feature)
- CUORE (as a safe extrapolation of Cuoricino)

GERDA at LNGS

^{76}Ge IGEX + HdM diodes at phase I



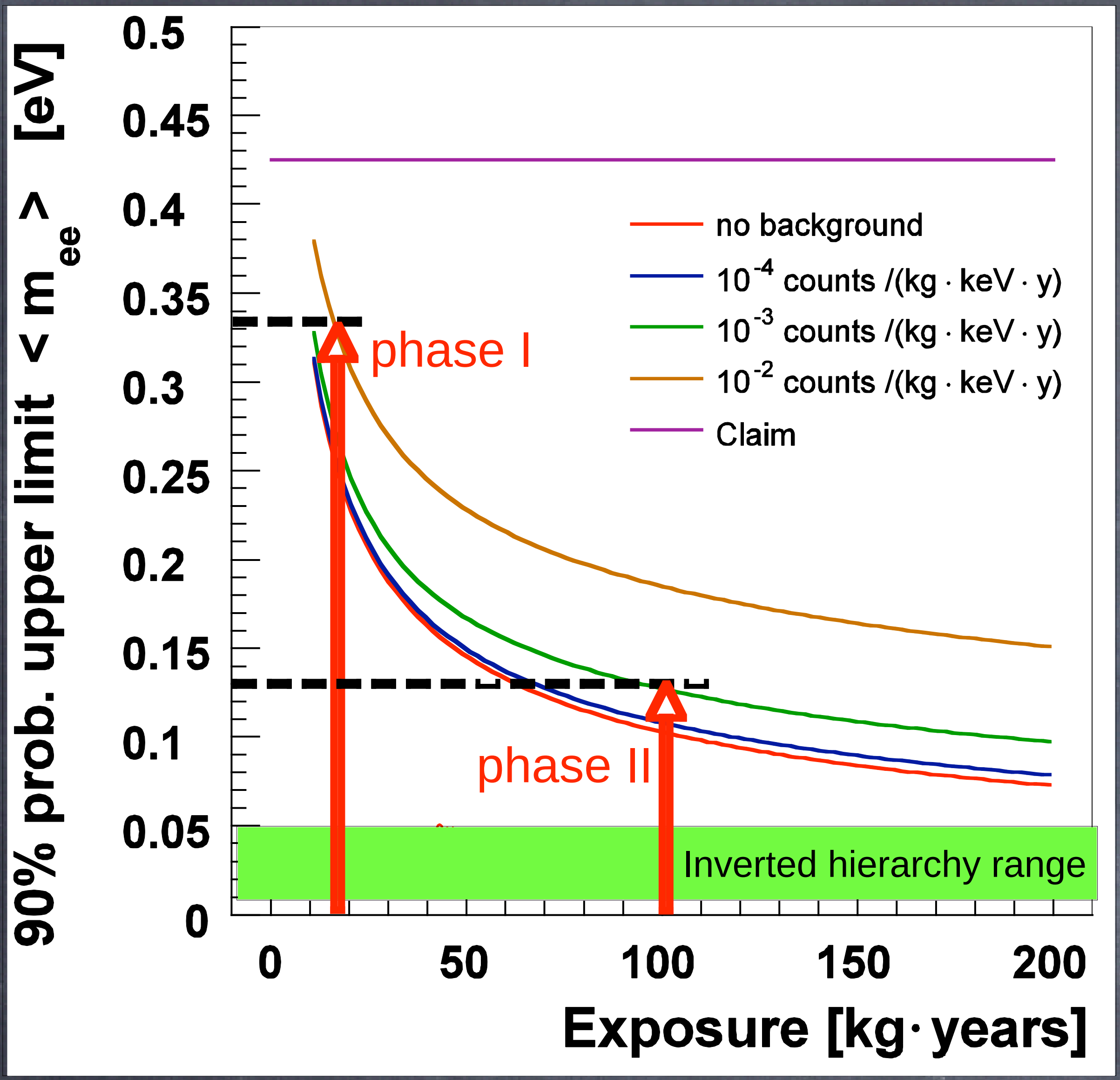


15 kg ^{76}Ge

Water shield
LAr bath , bare crystals

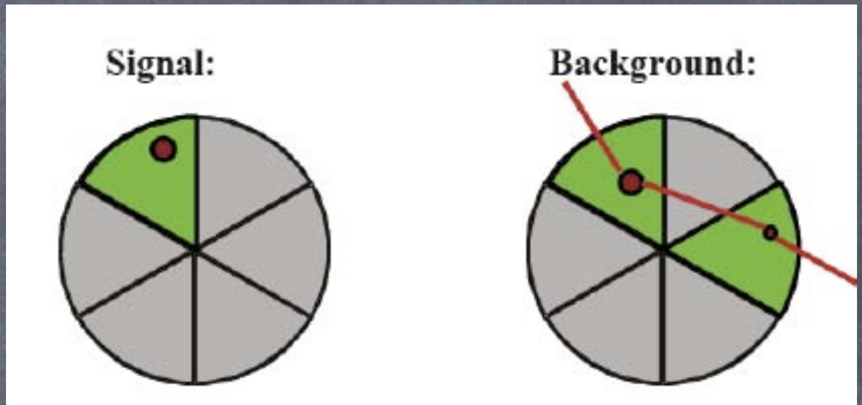
Prove or disprove
KKDC claim in 1 year

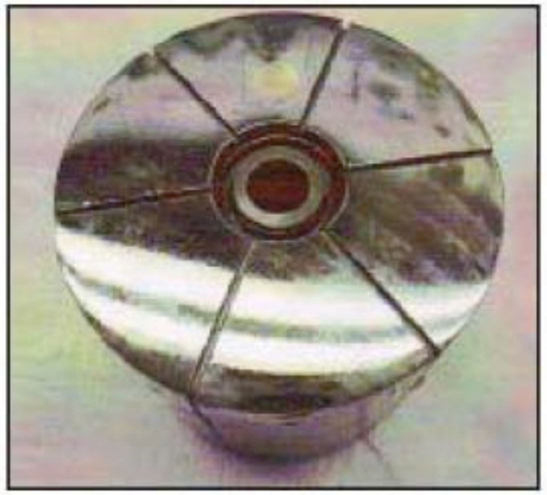
GERDA phases



- Phase 1 : 15 Kg, B < 10^{-2} c/(kg keV y) . Scrutinize KKDC claim.
- Phase 2: 40 Kg enriched, segmented diodes, B < 10^{-3} c/(kg keV y)
- Phase 3: 1 Ton, worldwide

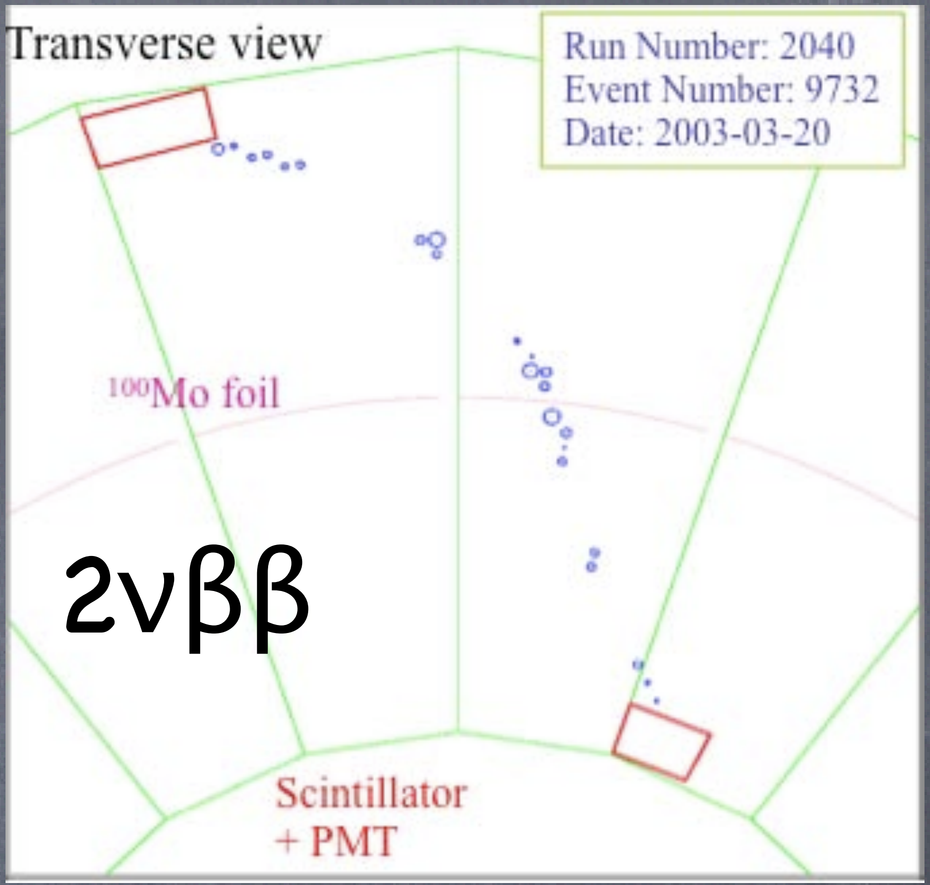
Start in 2009





Challenge: decrease the background from 0.17 (HdM) to 0.01 first and to 0.001 then [c/(kg keV y)]

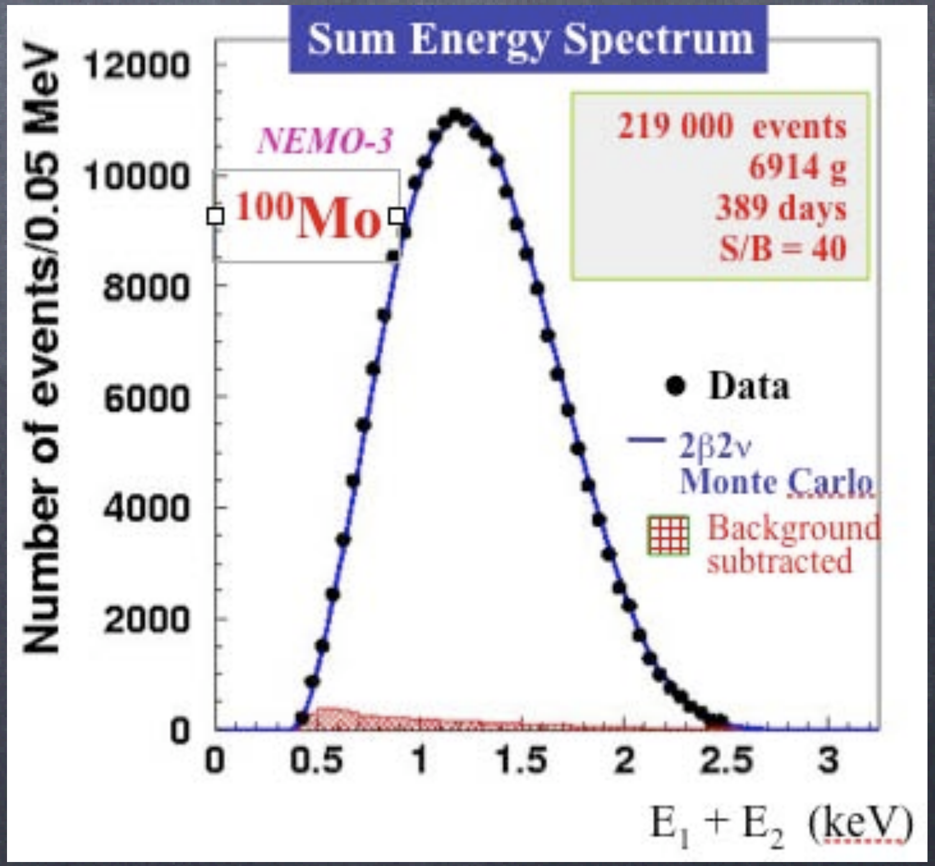
From NEMO at Frejus LSM



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

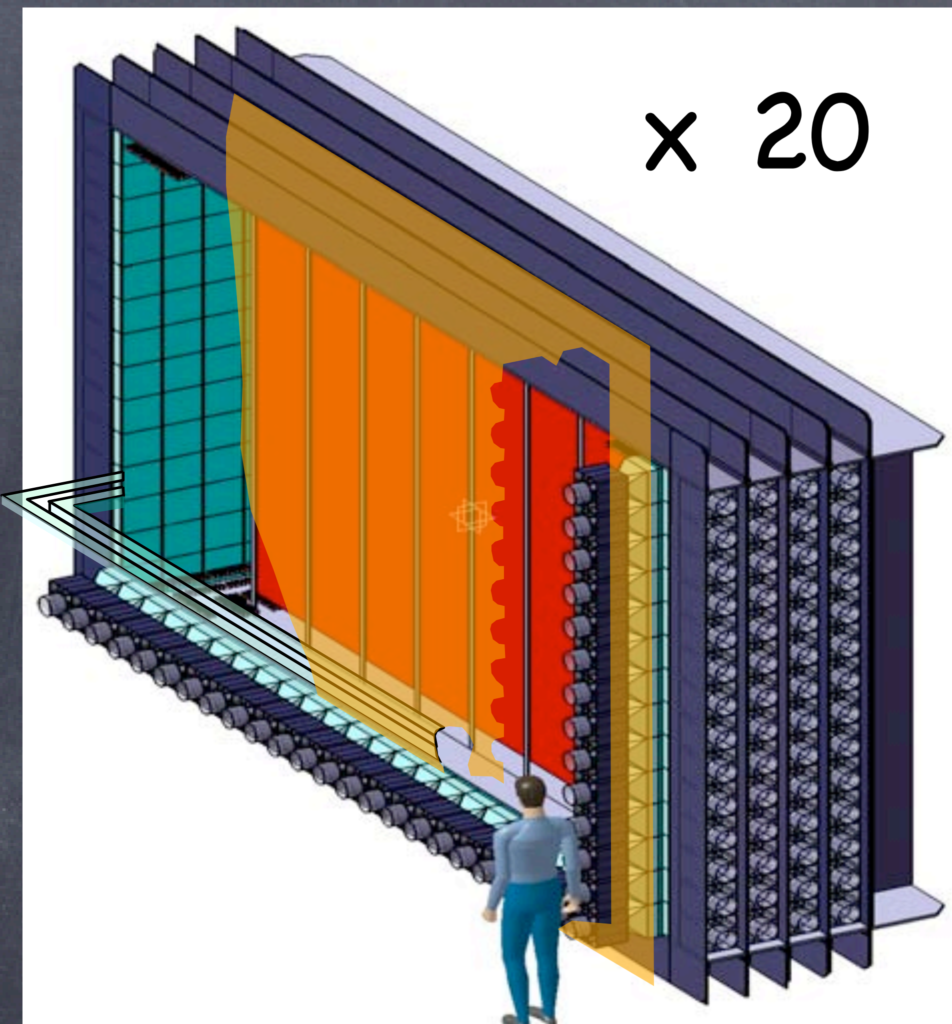
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

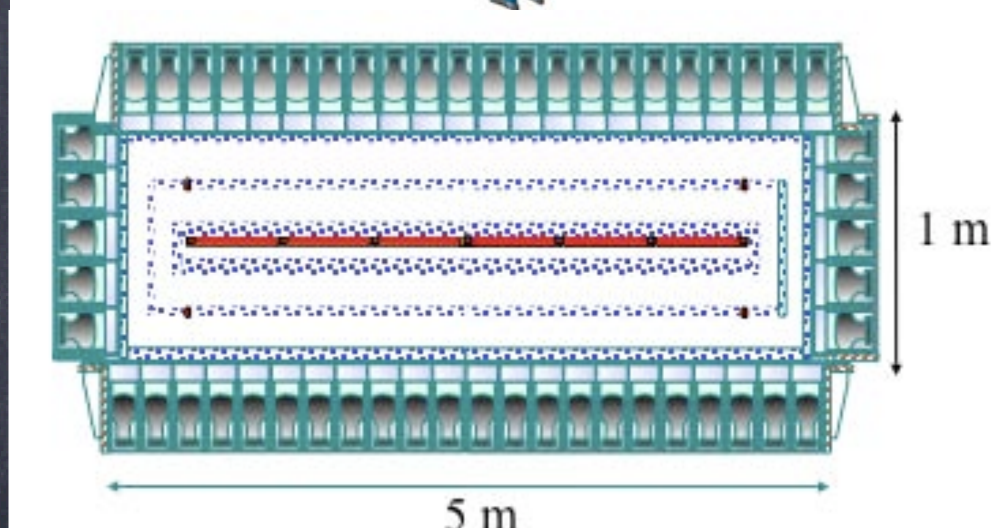


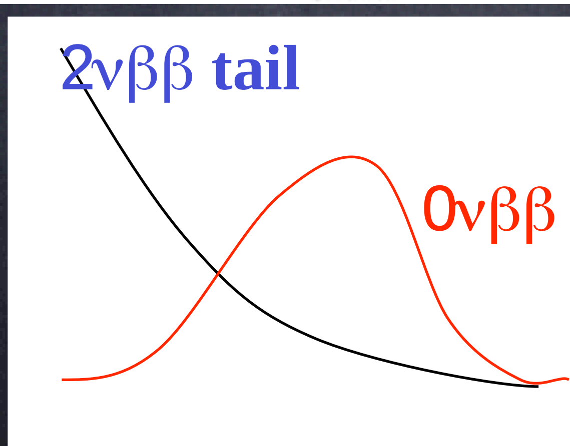
Magnetic field: 25 Gauss
Gamma shield: Pure Iron (e = 18cm)
Neutron shield:
30 cm water (ext. wall)
40 cm wood (top and bottom)
(since march 2004: water + boron)

to SuperNEMO at ?

challenge: a lot of improvement at the same time in a huge detector







NEMO-3		SuperNEMO
^{100}Mo $T_{1/2}(\beta\beta2\nu) = 7.\ 10^{18}$ y	Choice of isotope	^{82}Se (and/or ^{150}Nd) $T_{1/2}(\beta\beta2\nu) = 10^{20}$ y
7 kg	Isotope mass **M**	100 - 200 kg
$\varepsilon(\beta\beta0\nu)$ = 8 %	Efficiency ε	$\varepsilon(\beta\beta0\nu) \sim$ 30 %
^{214}Bi < 300 µBq/kg ^{208}Tl < 20 µBq/kg ^{208}Tl, ^{214}Bi) ~ 1 evt/ 7 kg /y $\beta\beta2\nu$ ~ 2 evts / 7 kg / y	N_{exclu} = f(BKG) *Internal contaminations* ***^{208}Tl and ^{214}Bi** in the $\beta\beta$ foil* $\beta\beta(2\nu)$	^{214}Bi < 10 µBq/kg ^{208}Tl < 2 µBq/kg (^{208}Tl, ^{214}Bi) ~ 1 evt/ 100 kg /y $\beta\beta2\nu$ ~ 1 evt / 100 kg/ y
FWHM(calo)=8% @3MeV	*IF*	FWHM(calo)=4% @3MeV
$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ y $<m_\nu> < 0.3 – 0.7$ eV	SENSITIVITY	$T_{1/2}(\beta\beta0\nu) > 2\ 10^{26}$ y $<m_\nu> < 50$ meV

1) $\beta\beta$ source production **2) Energy resolution**

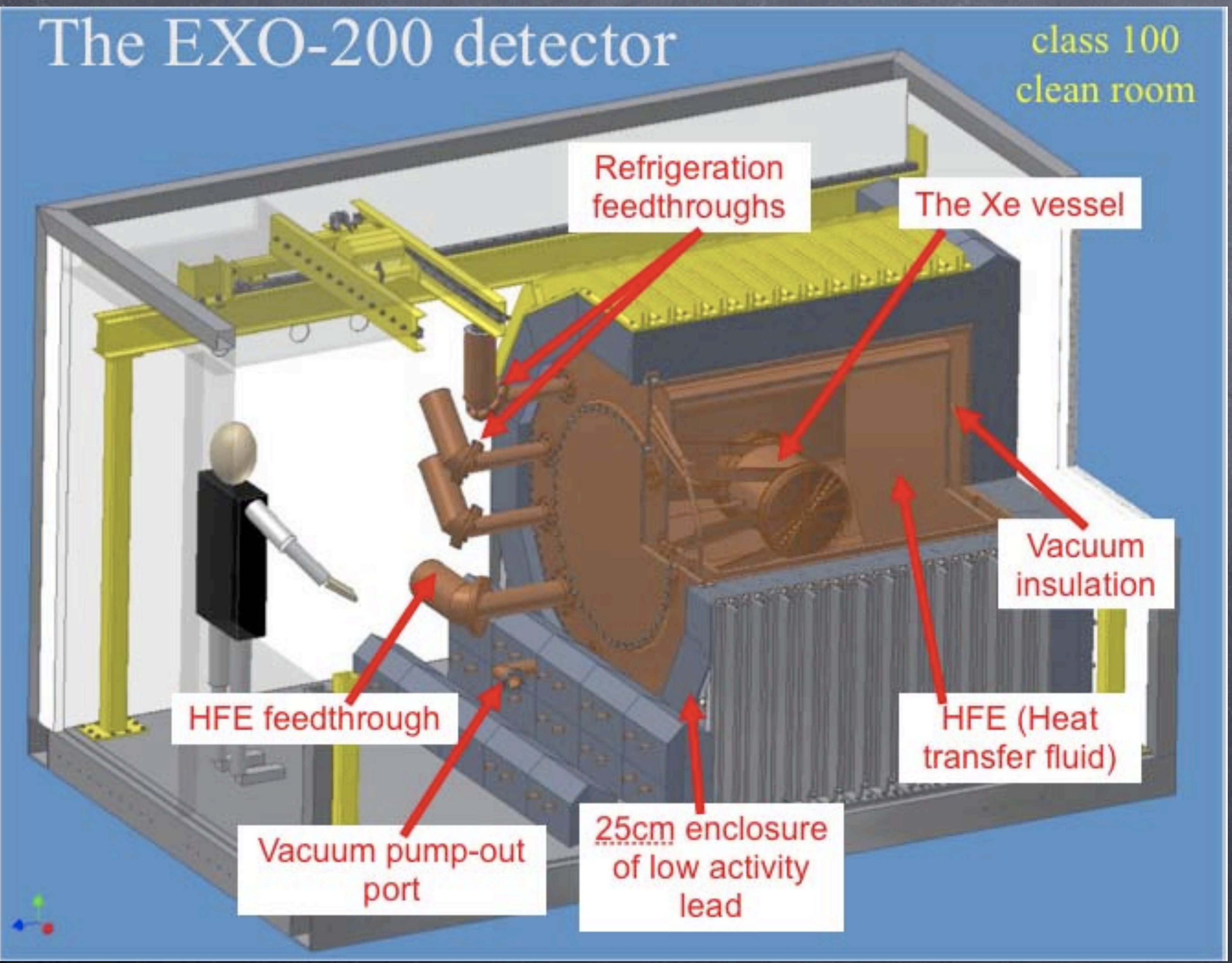
3) Radioprurity **4) Tracking**

EXO at WIMPP

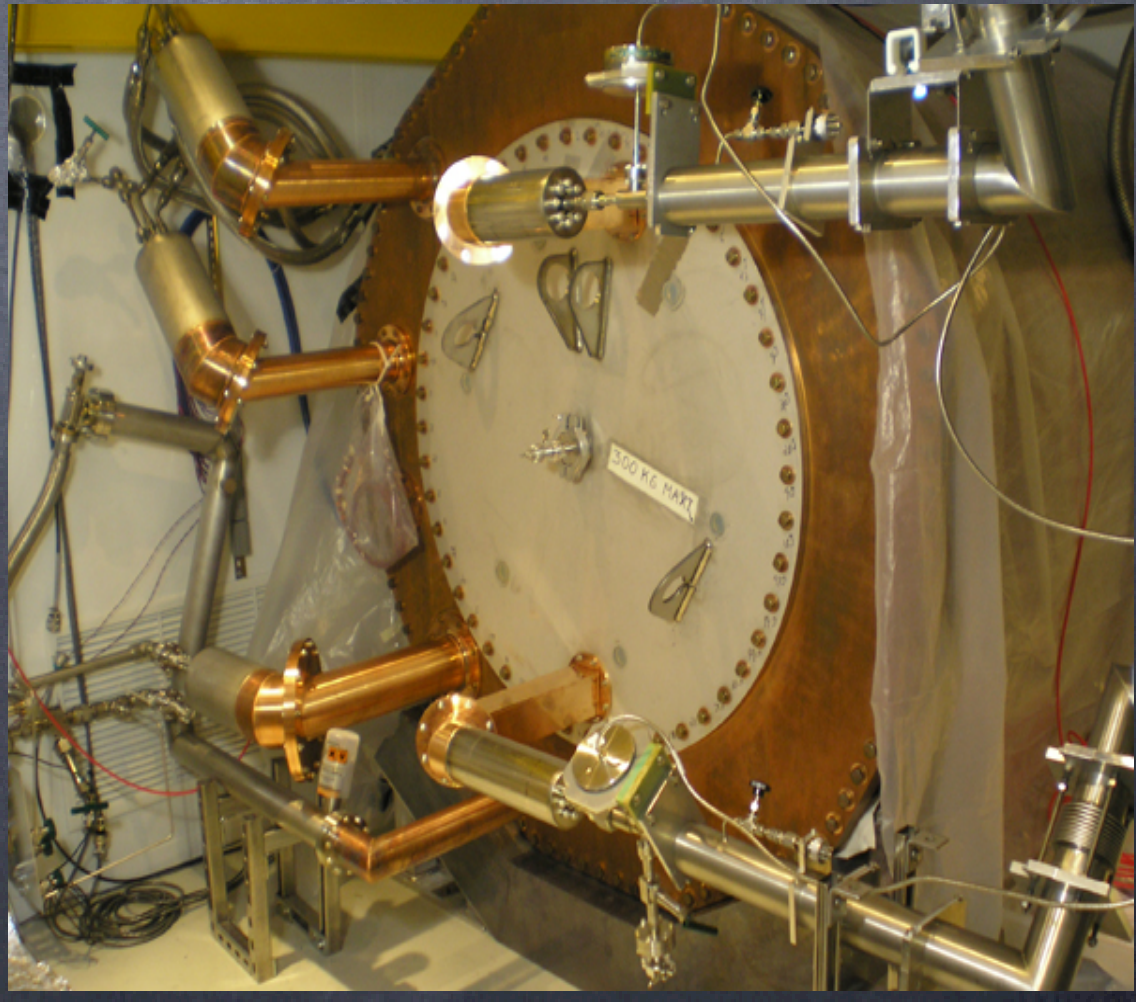
Enriched Xenon Observatory for double beta decay

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-} \ (+ 2\nu_e)$$

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu\beta\beta}$ (yr, 90%CL)	Majorana mass (eV) QRPA	Majorana mass (eV) NSM
EXO-200	0.2	70	2	1.6	40	6.4×10^{25}	$0.27^{\dagger}$	$0.38^{\blacklozenge}$

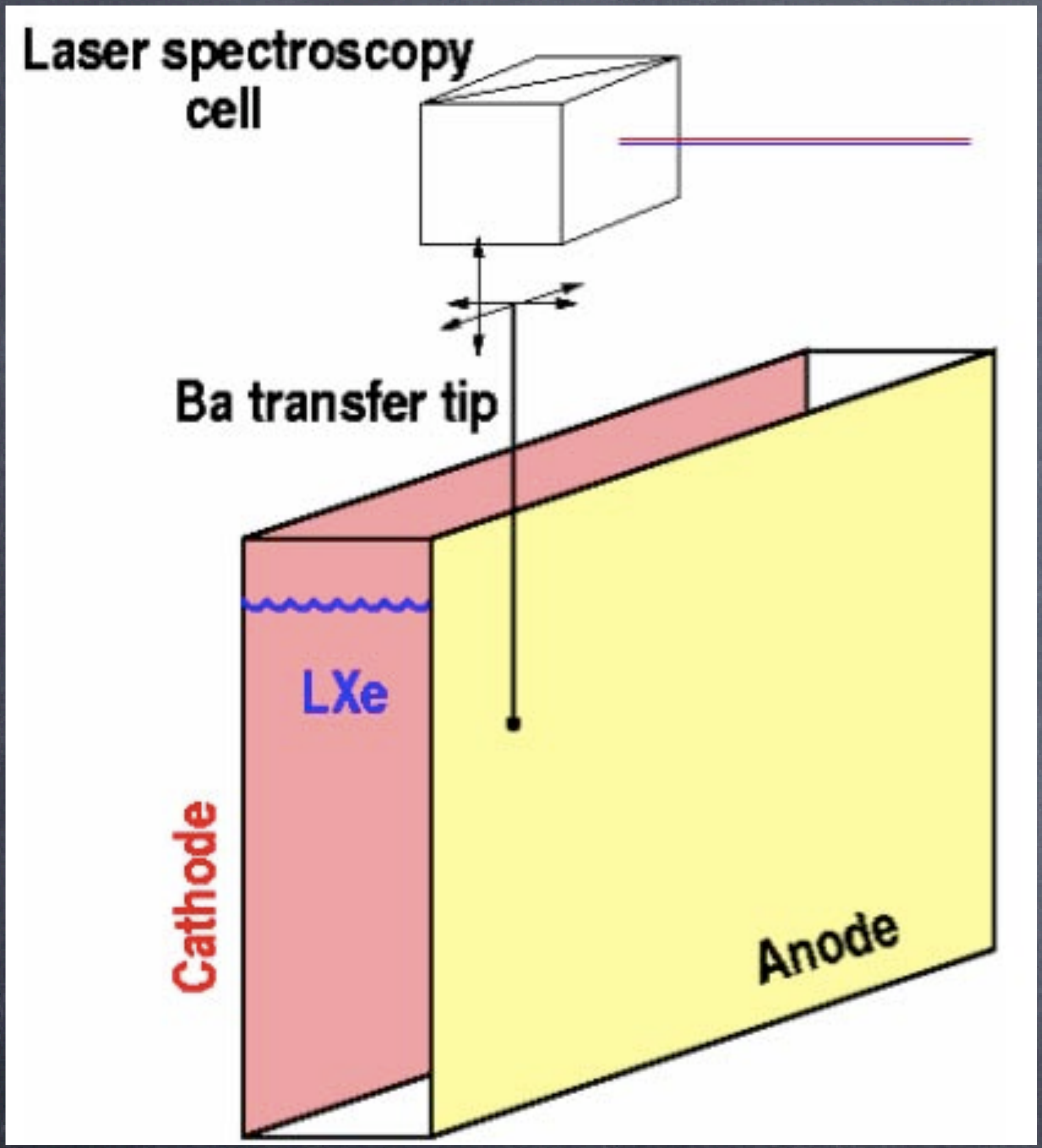


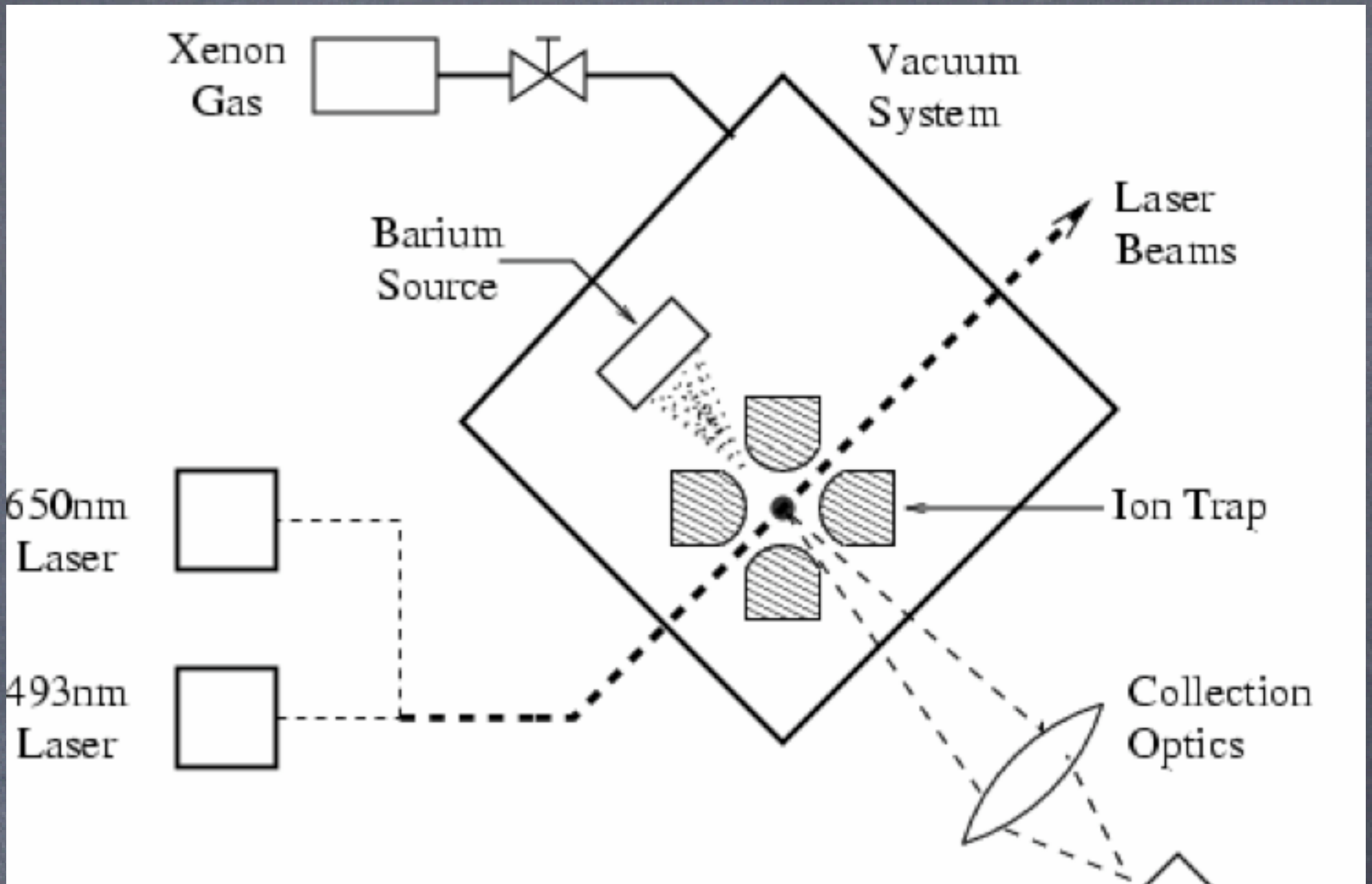
This would be modest



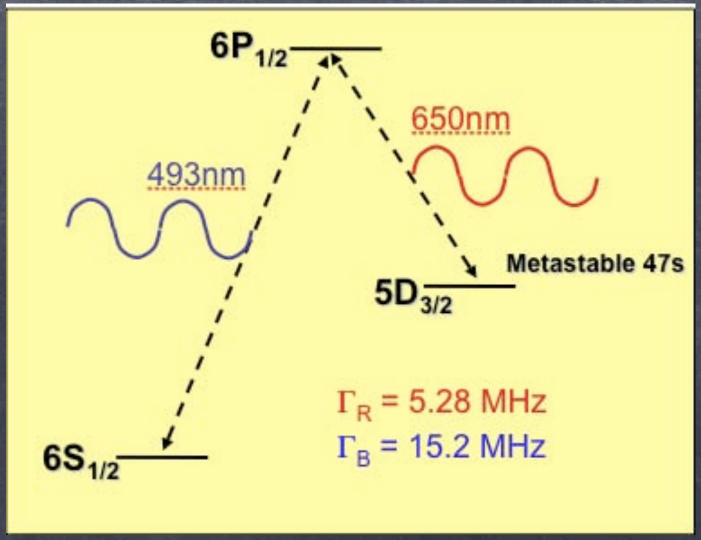
Ba fishing

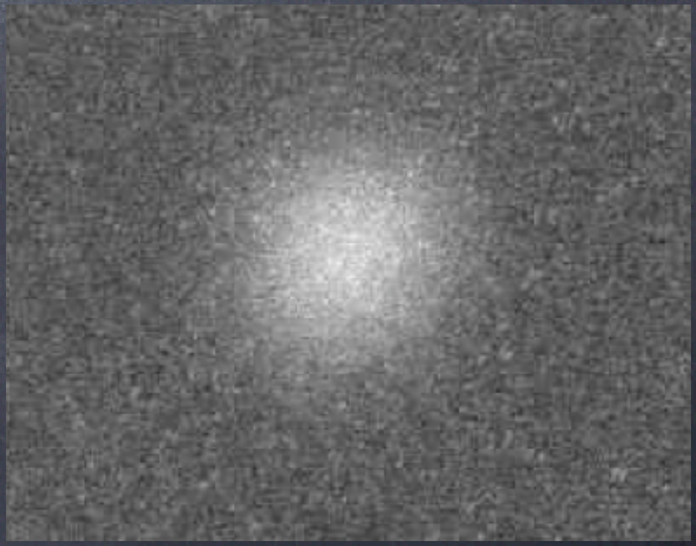
$^{136}Xe \rightarrow\ ^{136}Ba^{++} + 2e^{-}\ (+ 2\nu_e)$





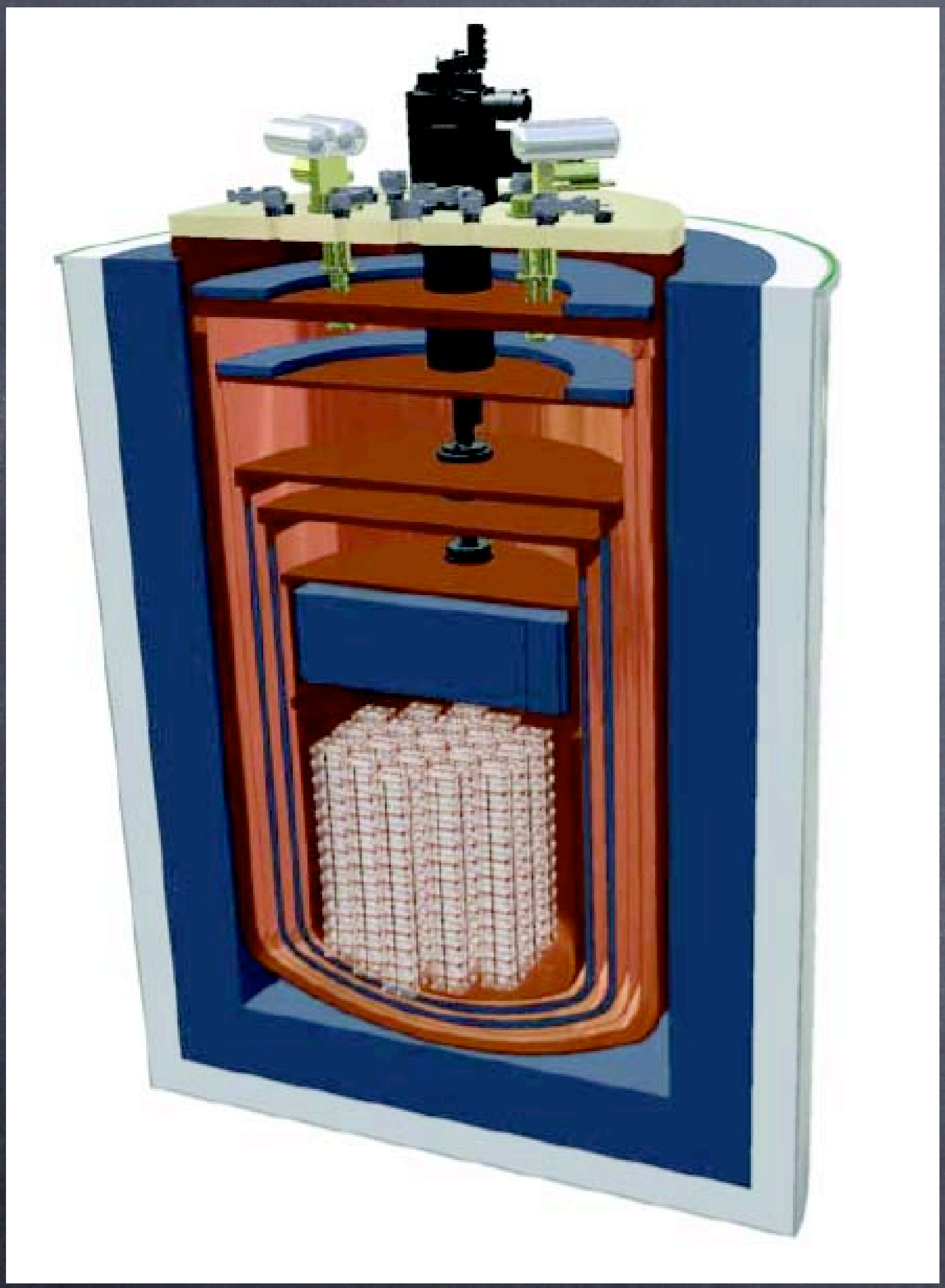
Test set up





Ba⁺ stable : years in ultrapure He

CUORE



Pulse Tube Cooler

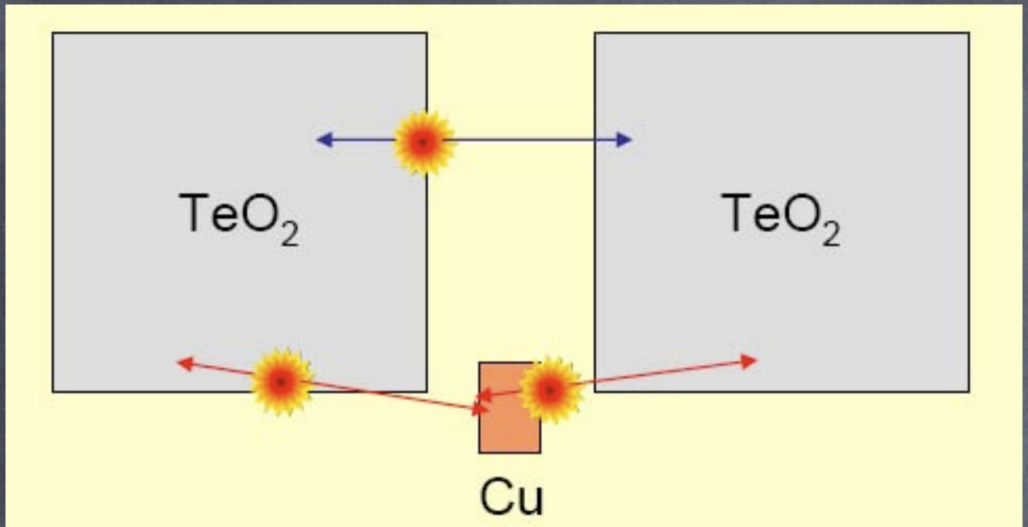
988 TeO_2 Crystals

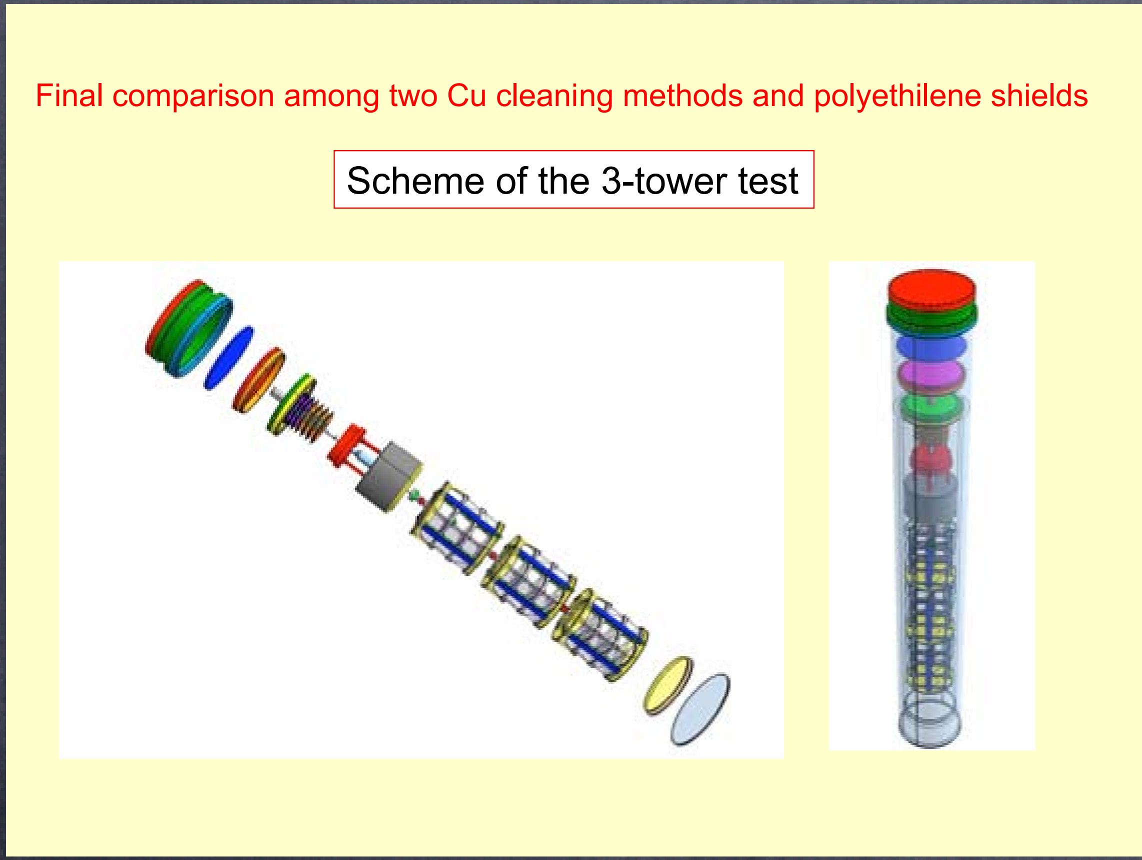
19 Towers of 52 crystals each

741 Kg of TeO_2

Active Mass 204 Kg

the long way to CUORE
or
the immortal Cuoricino





- Plasma cleaning
- Chemistry
- Polyethilene sheets

the chosen 'One' will hold the new CUORE crystals (56) into the Cuoricino cryostat and CUORE-0 will start

Scaling Cuoricino to CUORE

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

$M = m \times 20$

$T = t \times 6$

$b = B / 20$

$\Delta E = \Delta E / 1.5$

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

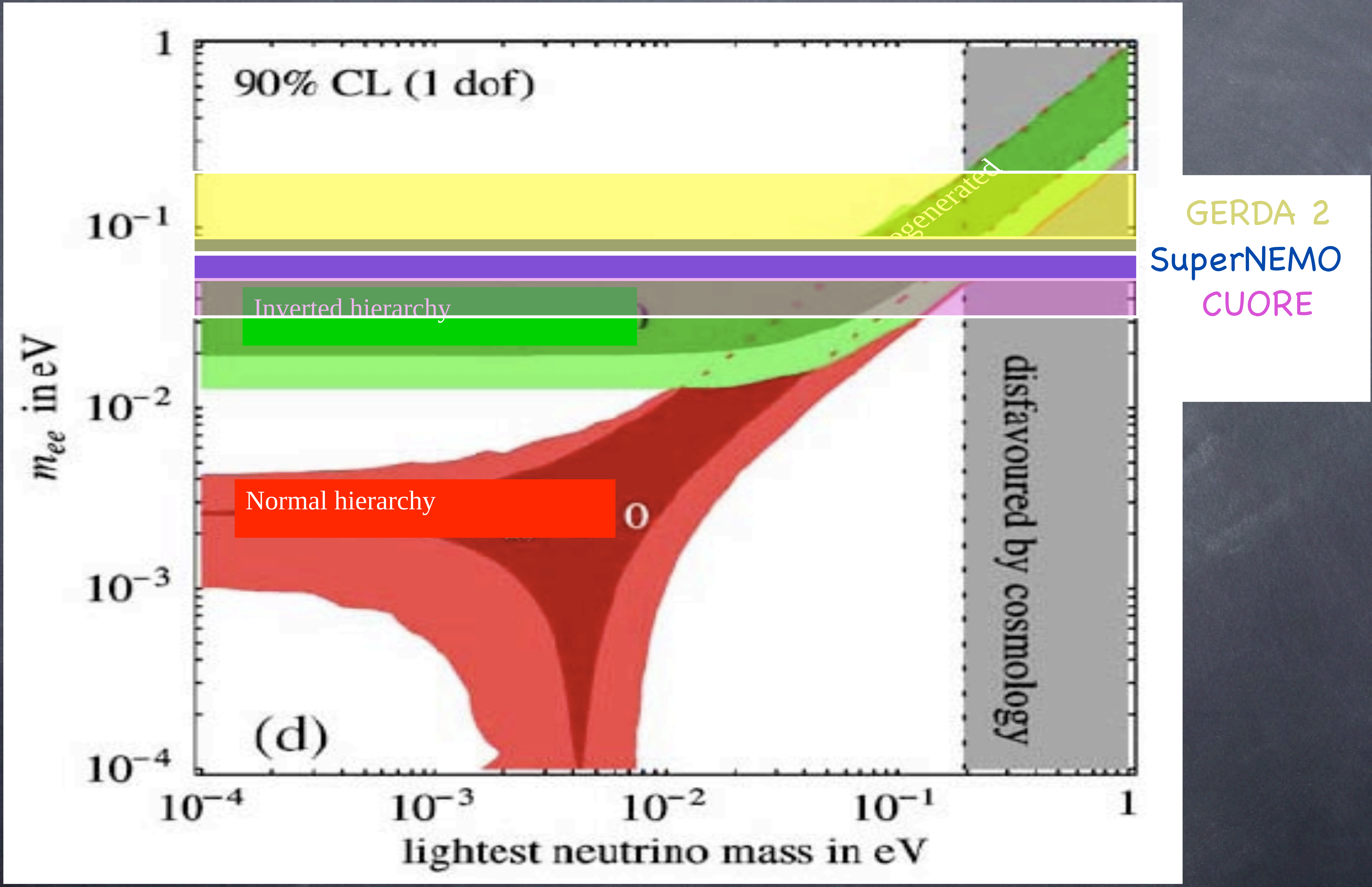
$\tau_{1/2\,(CUORE)} \sim 1.7 \times 10^{26}$

$\langle m_\nu \rangle_{CUORE} \sim \langle m_\nu \rangle_{Cuoricino} / 9 \sim 60$ meV

One step is non trivial. Getting to 0.01 c/Kg/y/KeV

(CUORE is 1 Ton. It means 10 c/y/KeV)

The next generation goal



+ and -

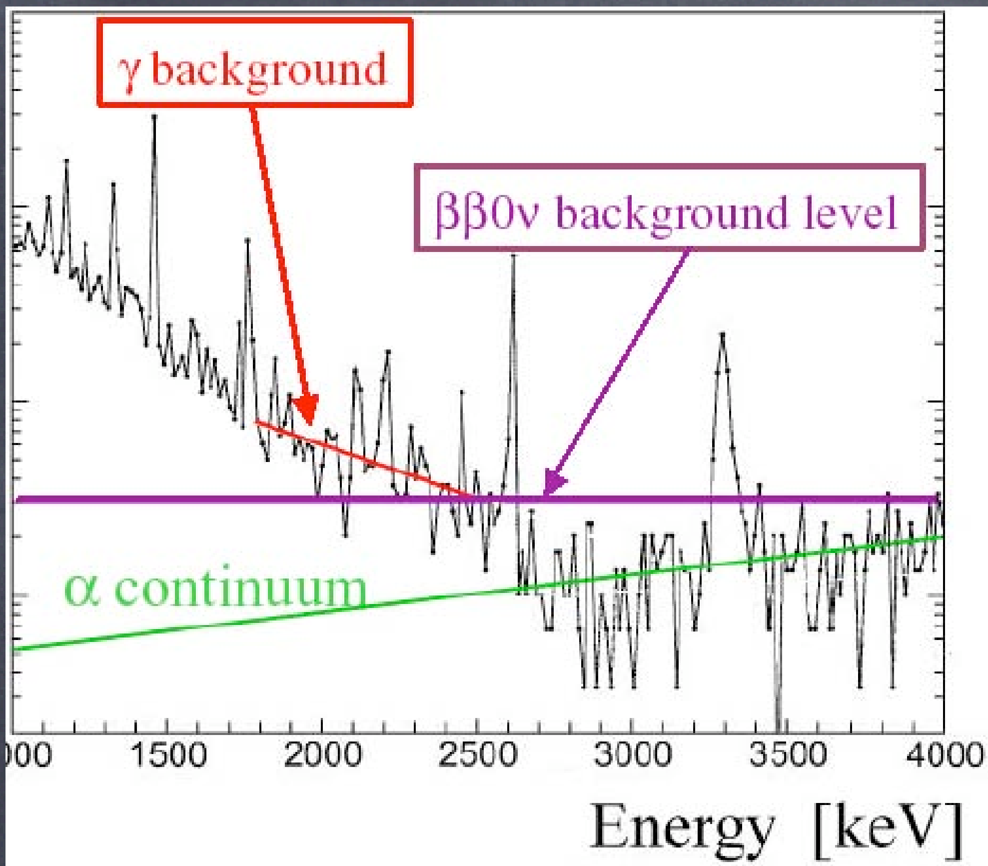
- GERDA : technology + enrichment -
- CUORE: active mass + background -
- SuperNemo: (event)topology + (det) topology -

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 could win or might show the path to victory

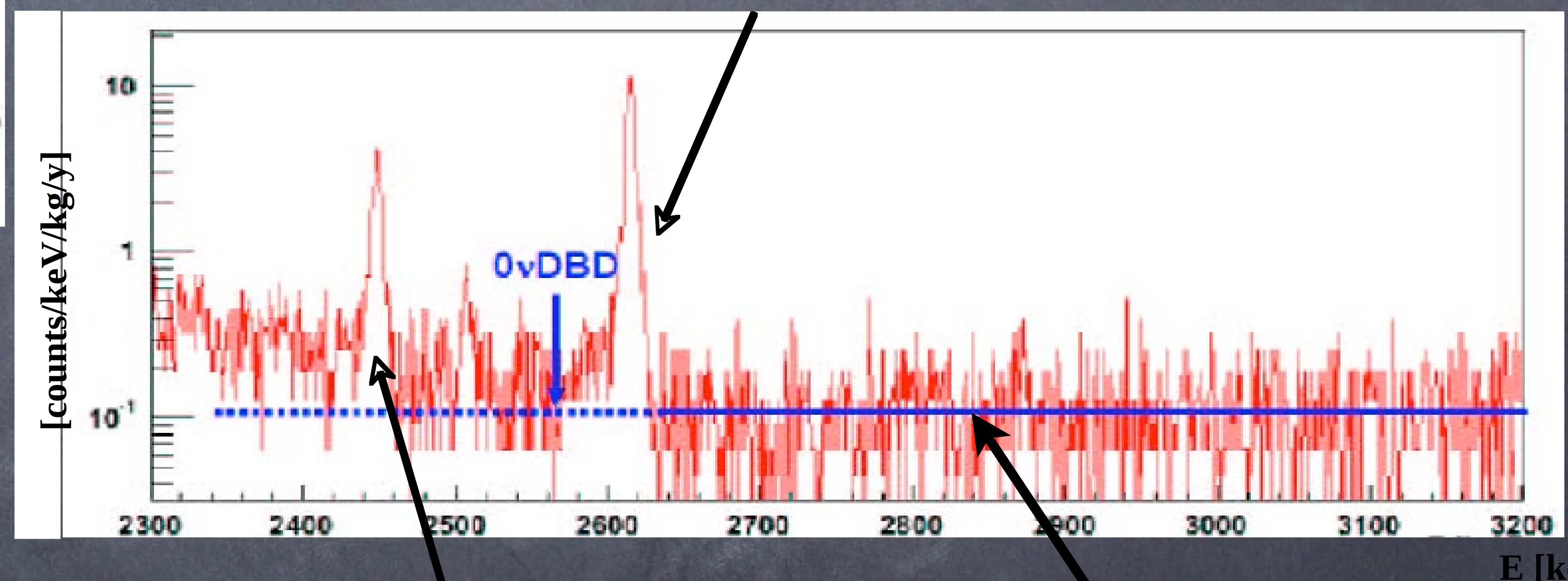
More material

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

Cuoricino

b=0.18 ± 0.02 c/keV/kg/y

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

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

Degraded alpha particles