$0\nu\beta\beta$
Una sfida estrema

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Il fondo, solo il fondo, niente altro che il fondo

- E' una specialita' romana
- DBD , il segnale si sa calcolare, ma non si sa se il processo esiste
- VIRGO, il processo esiste ma non si sa calcolare
- LHC, l'Higgs si sa calcolare, dovrebbe esistere, se ne produce uno ogni 100 miliardi di interazioni (e poi bisogna osservarlo !)

Indice

- Majorana
- Massa del neutrino
- Doppio Beta
- Richieste sperimentali
- Fondo
- Esperimenti
- Prospettive

Majorana

once upon a time

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

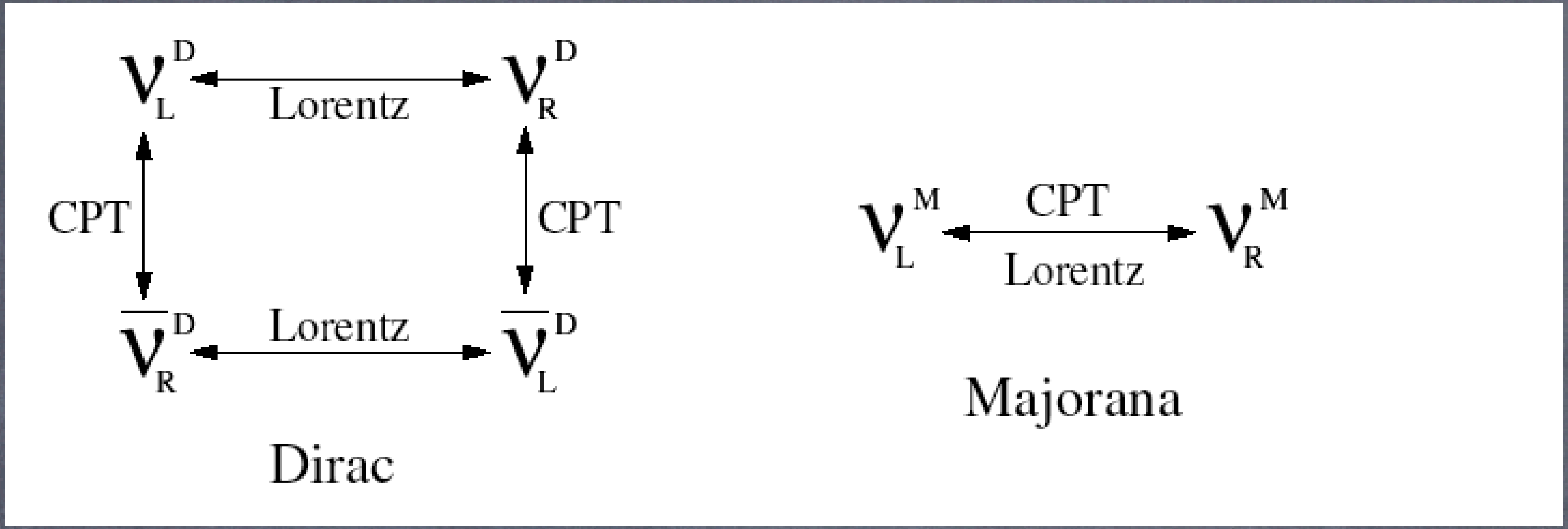
Nota di ETTORE MAJORANA

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 !)

Il neutrino massivo rende l'ipotesi molto attrente



L'elicita' puo' girare sia per un neutrino di Dirac che per uno di Majorana. Tuttavia nel caso di Dirac il processo e' vietato dalla conservazione del numero leptonico.

se Majorana avesse avuto ragione

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

in pratica :

Violazione del Numero Leptonico

col caveat: i neutrini di massa nulla non permettevano di verificare l'ipotesi

Infatti nessuno fece caso a Furry (1939) che suggeri' il DBD senza emissione di neutrini come test del neutrino di Majorana.

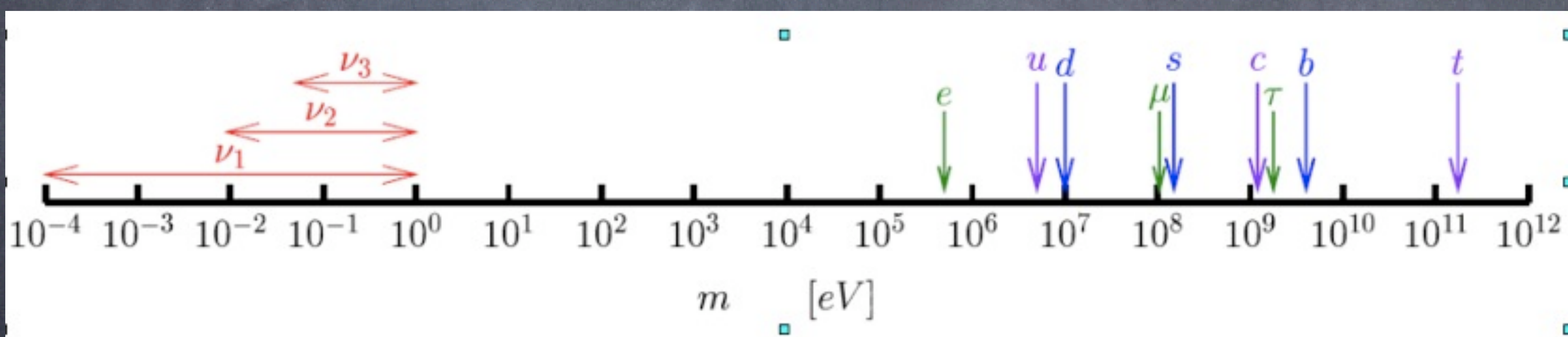
Massa Neutrino

I neutrini pero' oscillano

Atmospheric — Cross-Mixing — Solar

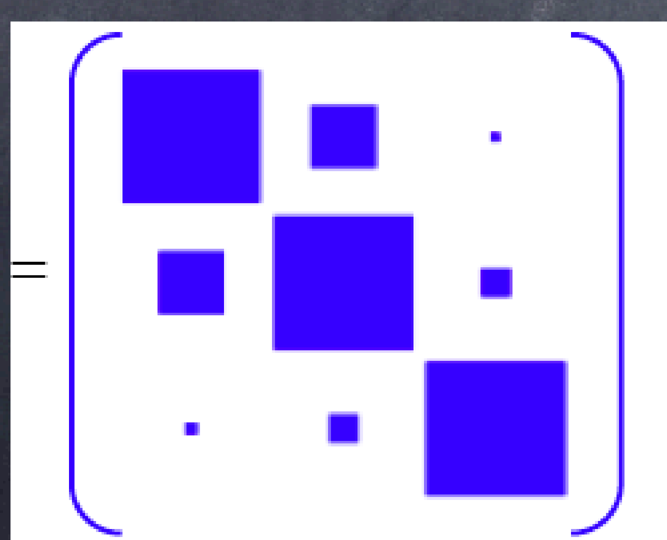
$$U=\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}$$

e quindi hanno massa



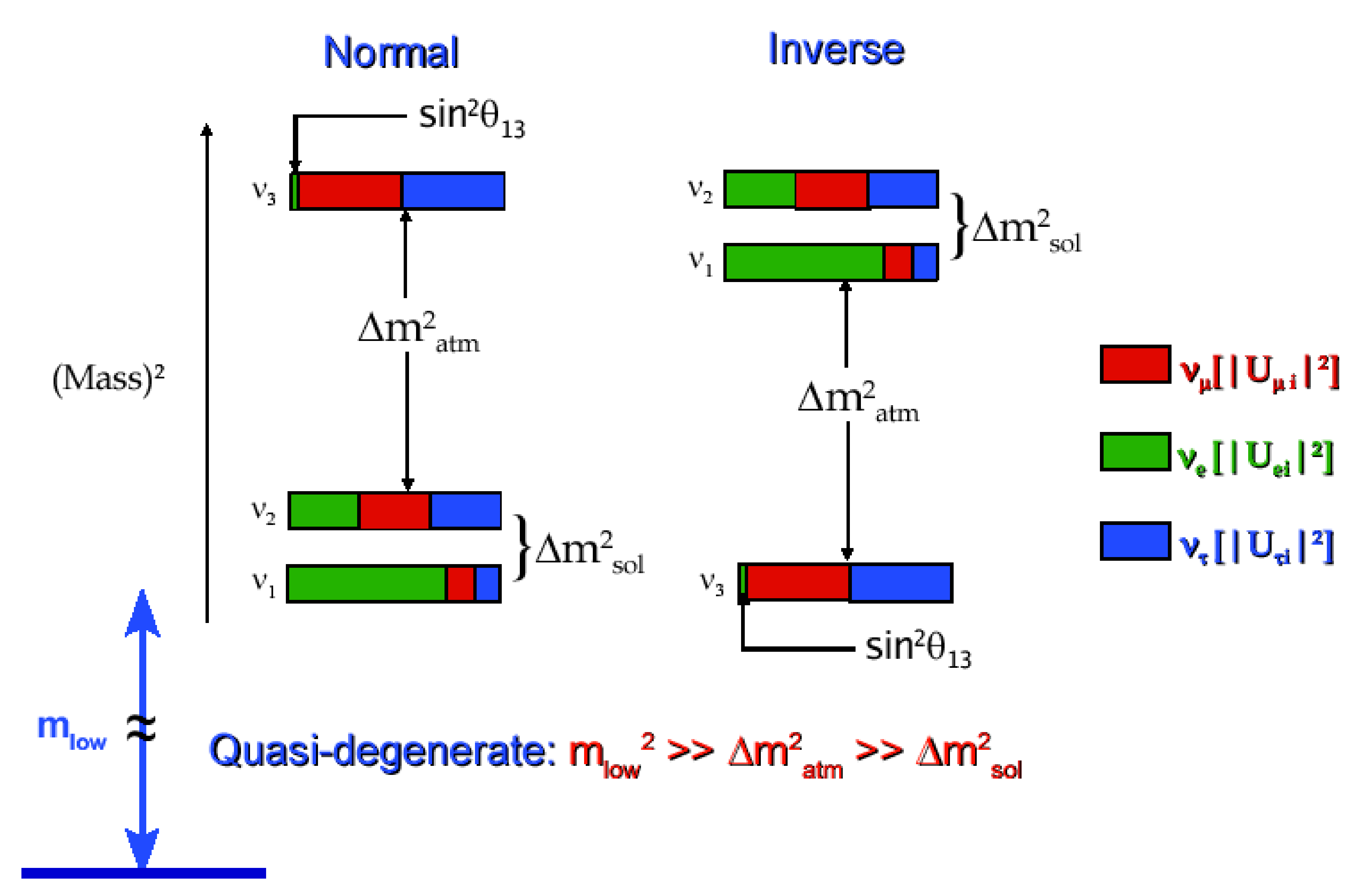
e

V_{CKM} =



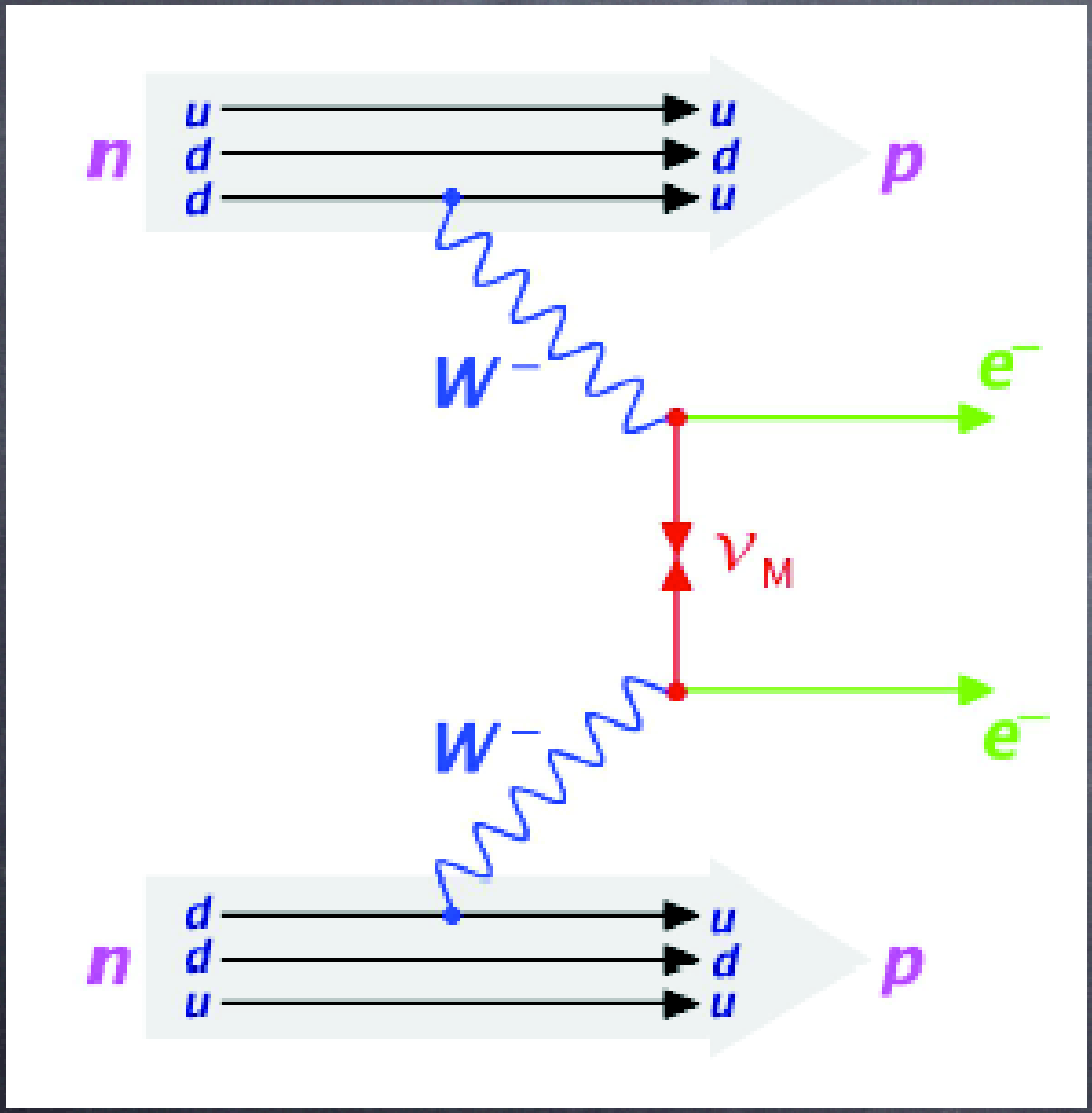
V_{PMNS}

Tre casi:


Normal
Inverse
$\sin^2\theta_{13}$
ν_3
ν_2
ν_1
Δm^2_{atm}
Δm^2_{sol}
(Mass)²
$\nu_\mu[|U_{\mu i}|^2]$
$\nu_e[|U_{ei}|^2]$
$\nu_\tau[|U_{\tau i}|^2]$
m_{low} ≈
Quasi-degenerate: $m_{low}^2 >> \Delta m^2_{atm} >> \Delta m^2_{sol}$

Doppio Beta

Neutrino-less DBD (0νββ)



Solo se:

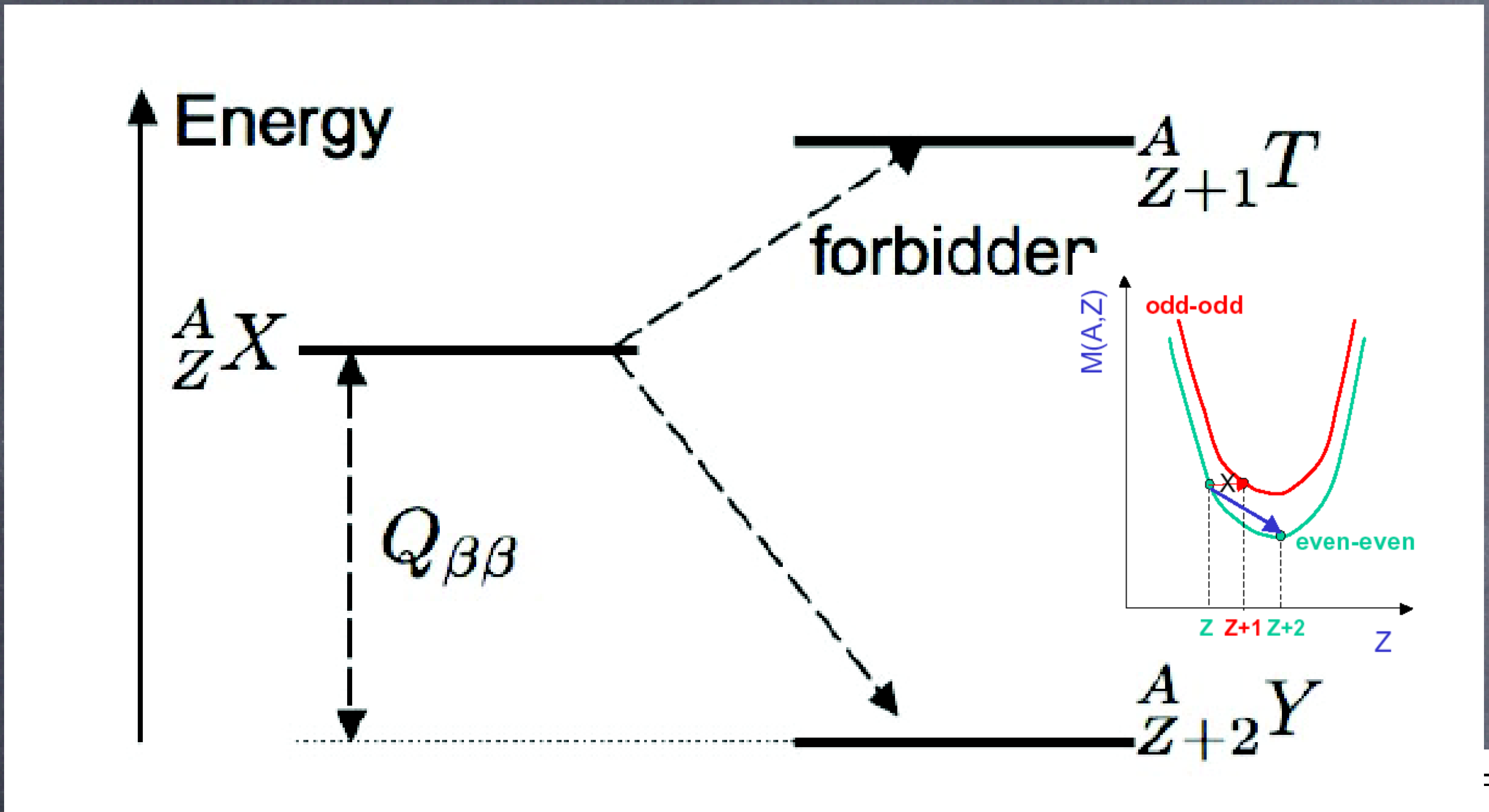
Majorana Neutrinos

Massive Neutrinos

Se osservato:

Prova che il neutrino e' una particella di Majorana

Double Beta Decay



Predetto da Maria Goeppert-Mayer nel 1935

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	2.530	33.9
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

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

La massa del neutrino vista dal Doppio Beta

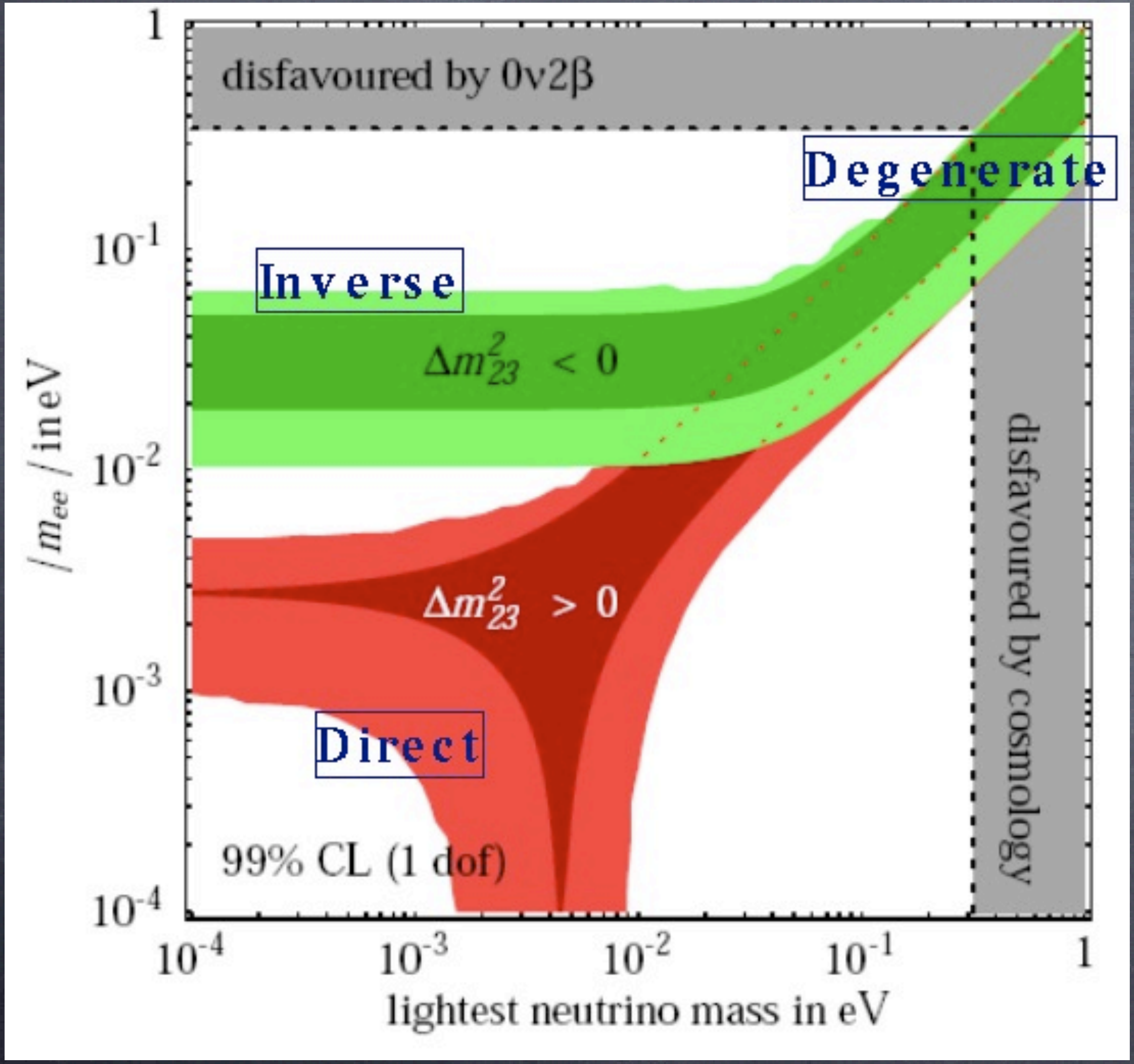
Ci misuriamo la massa ?

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

beh...insomma.... Una combinazione di masse, angoli e fasi

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

Un bel plot a colori



Dove e' la Fisica ?

Un volgare spazio delle fasi

la Fisica !

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

Quello che lo sperimentale **misura**

Un problema per **teorici nucleari**

La dura verita' sperimentale

A che gioco giochiamo

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

Sensibilita'

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

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

Ripeto perche' sia chiaro:
se vuoi fare un fattore 10 meglio sulla massa del neutrino devi fare 100 sul lifetime

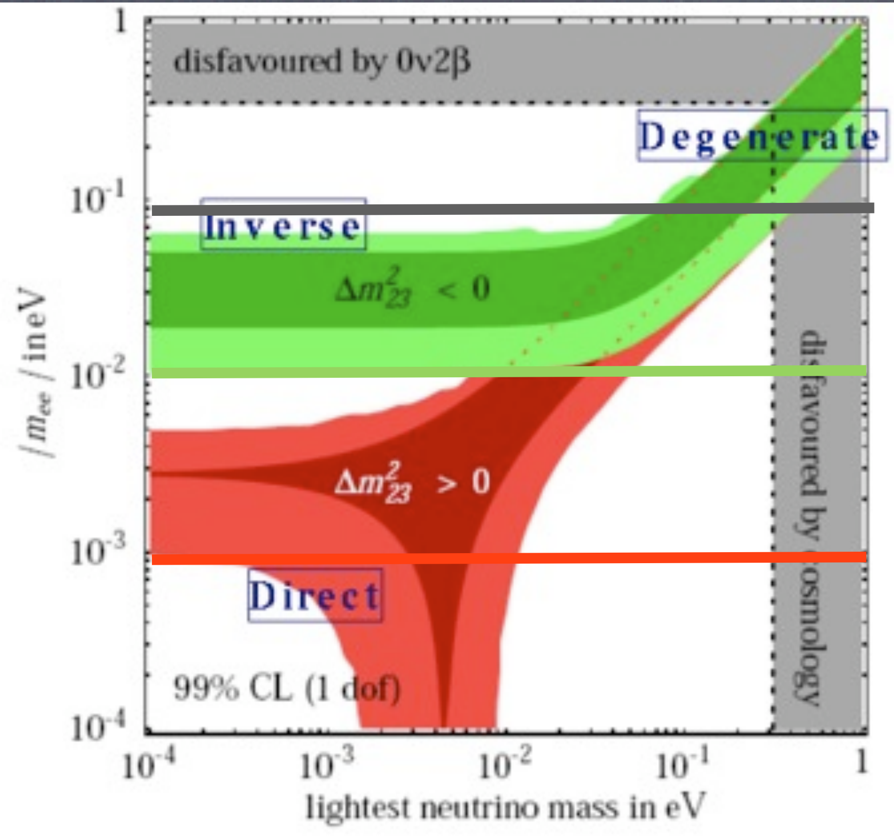
Valori di partenza

- abbondanza isotopica 0.3 (Te, il resto costa caro !)
- efficienza 0.9 (un calorimetro)
- tempo vivo 2 anni (duty cycle !)
- risoluzione di energia 5(keV) al MeV (bolometro)
- massa 50 kg (qualche evento per un tempo di dimezzamento di 10**25 anni)
- fondo 0.2 conteggi/keV/Kg/anno (quello che si e' saputo fare sino a oggi)

il problema di fare meglio

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

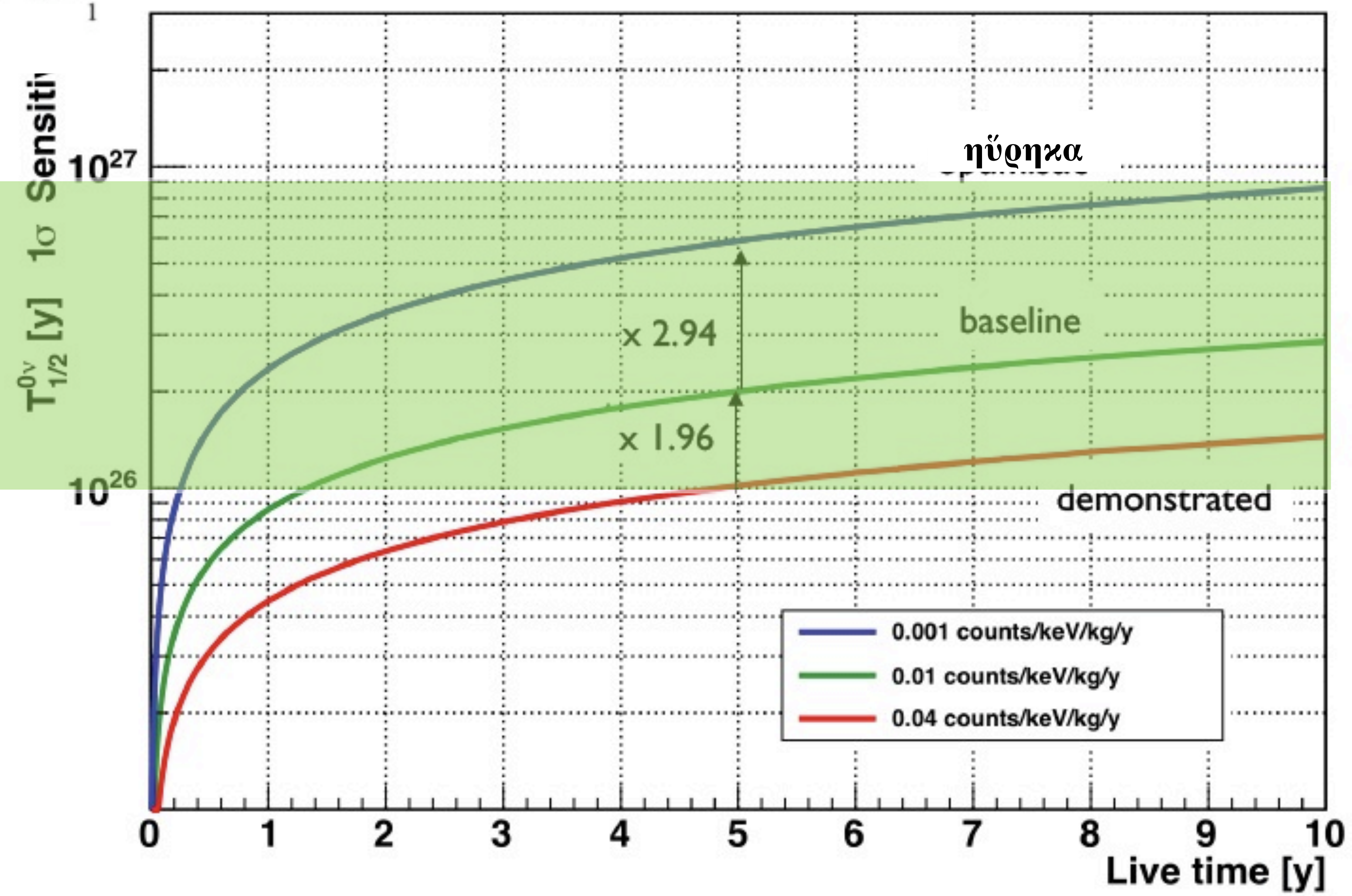
$$C = |M^{0\nu}|^2 \cdot G^{0\nu} \quad [y^{-1}]$$



Inverted hyerarchy

TeO_2 case

(CUORE)



I limiti del ragionevole

Un nuovo esperimento vale la pena se migliora di un fattore 10 $m_{\beta\beta}$, quindi 100 la Sensibilita'

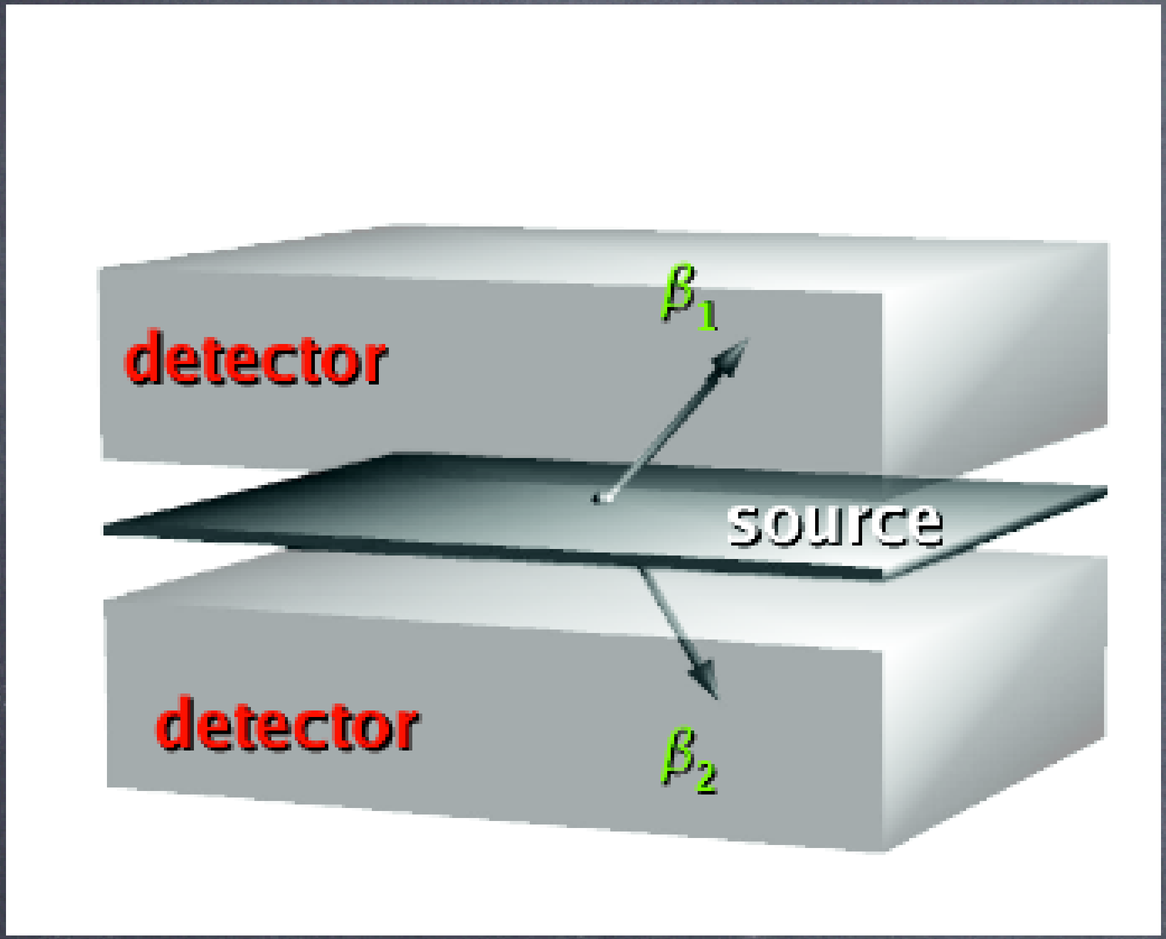
A voi la scelta:

M	5 Ton	invece di 50 Kg
t	500 y	invece di 5 y
ΔE	50 eV	invece di 5 keV

B 0.001 invece di 0.1(2)

Due possibilita' di rivelatore

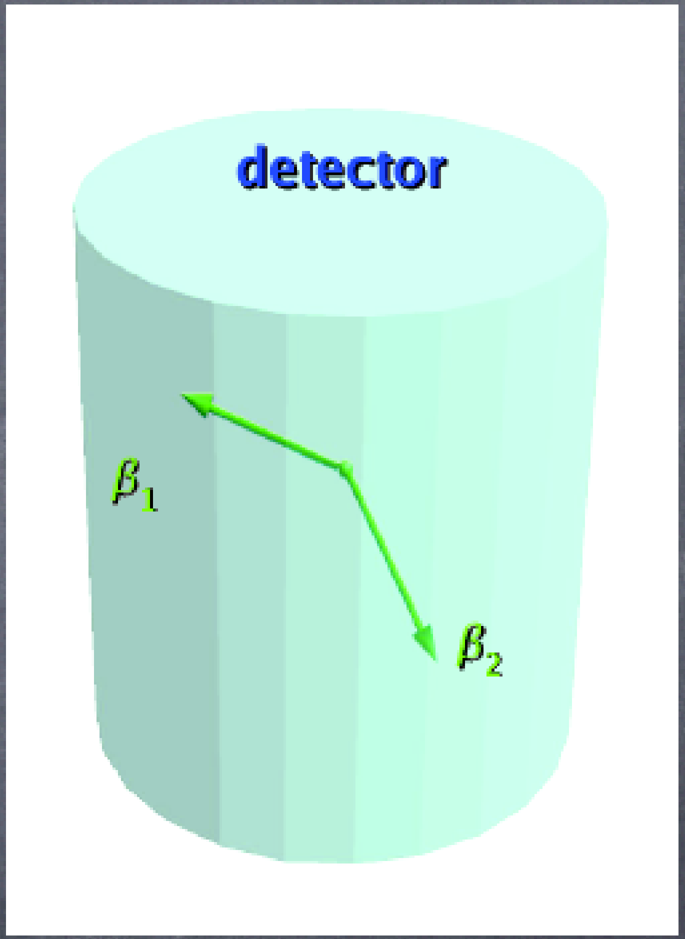
Source ≠ Detector



+++ Topology, Background

--- M, ΔE, ε

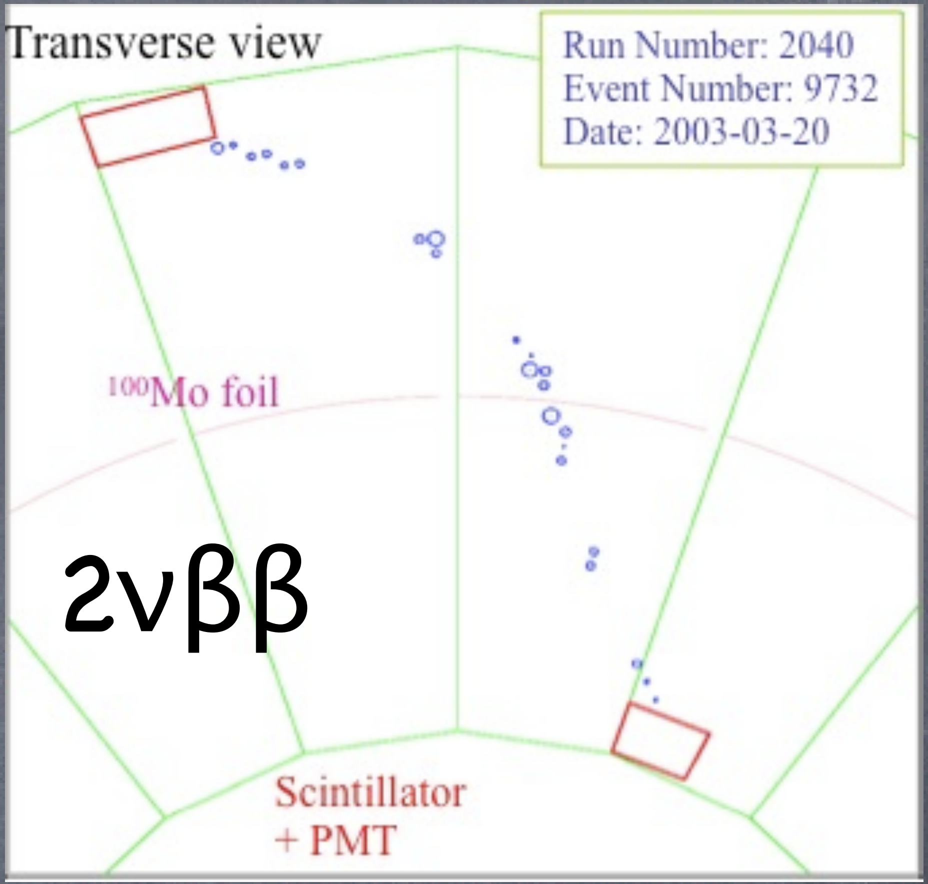
Source ⊆ Detector



+++ M, ΔE, ε

--- Topology, Background

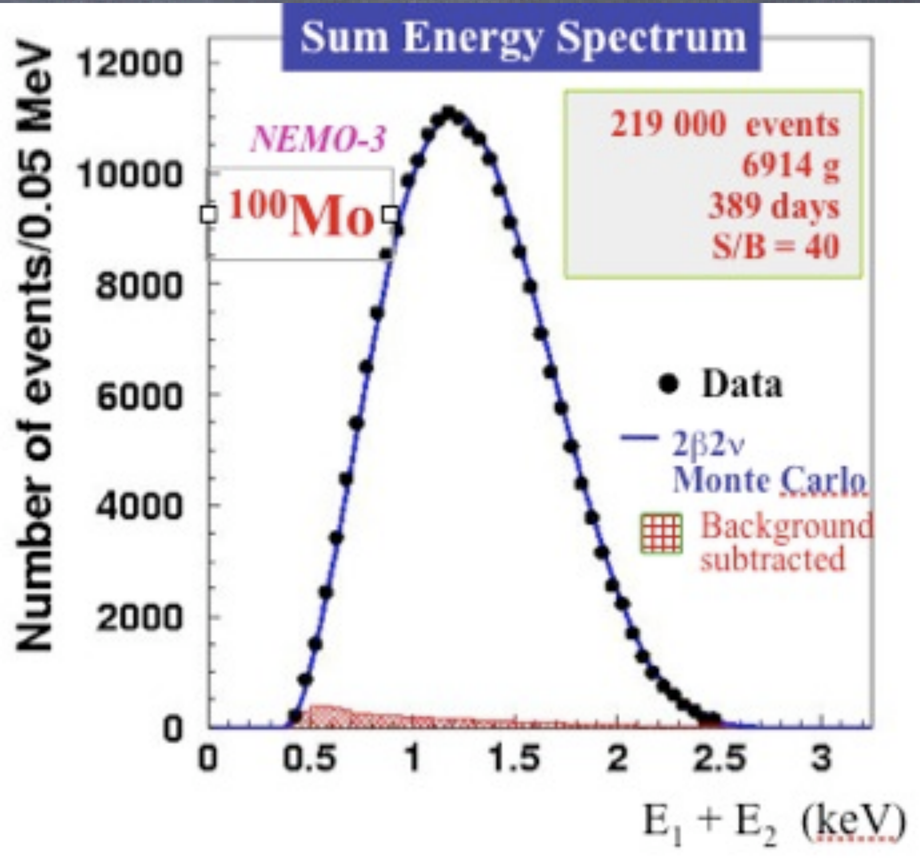
NEMO @ Frejus LSM



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

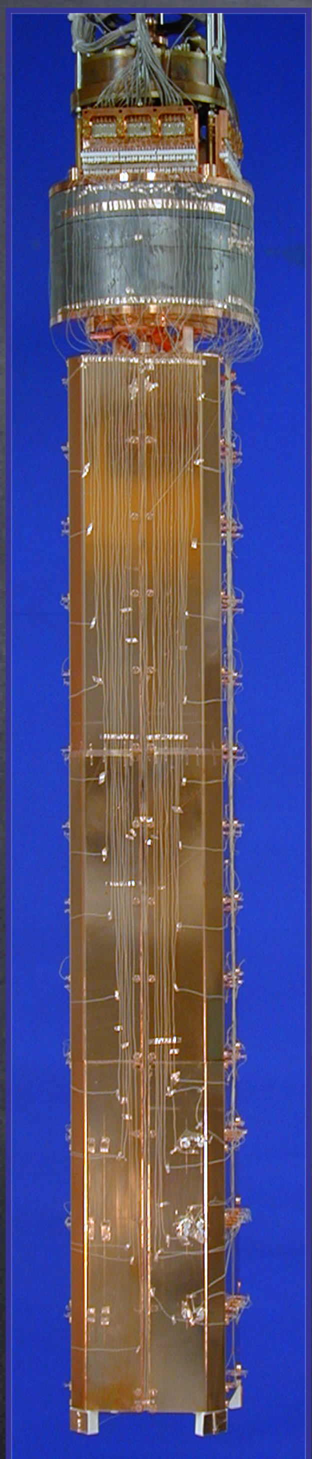
Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

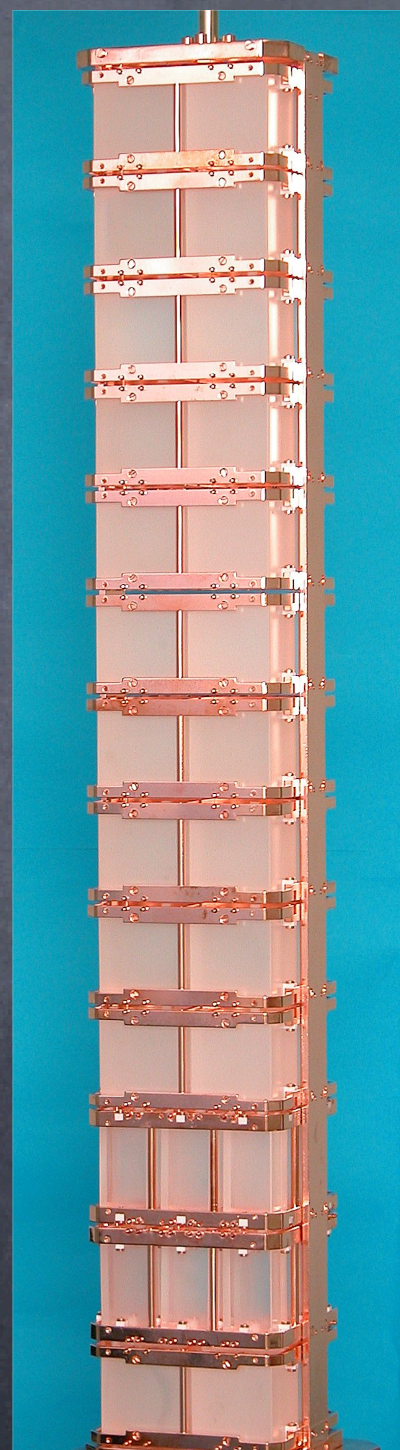
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

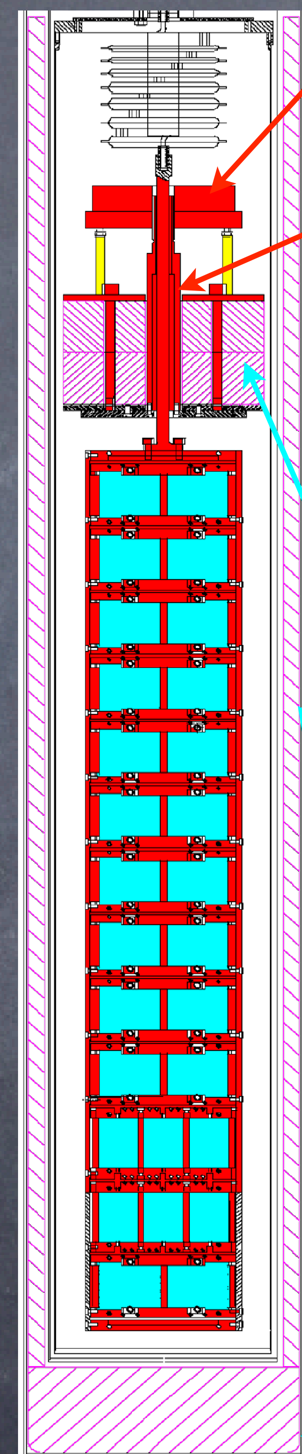


Magnetic field: 25 Gauss
Gamma shield: Pure Iron (e = 18cm)
Neutron shield:
30 cm water (ext. wall)
40 cm wood (top and bottom)
(since march 2004: water + boron)

Cuoricino @ LNGS





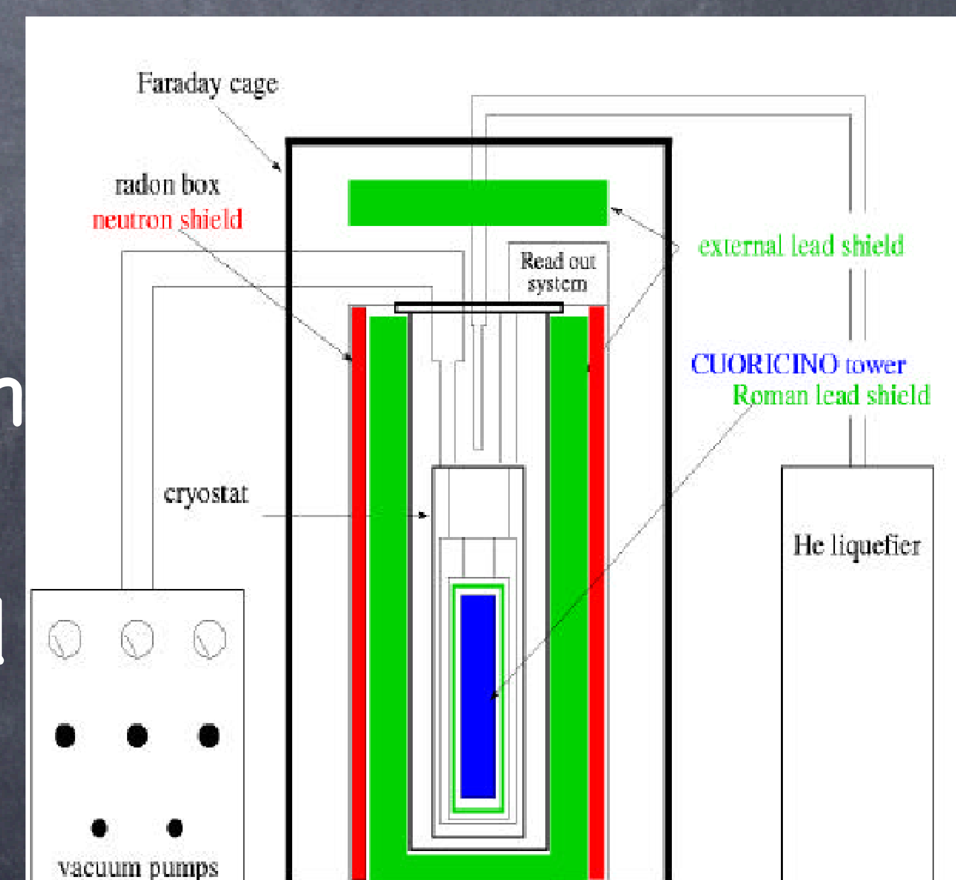


Mixing chamber

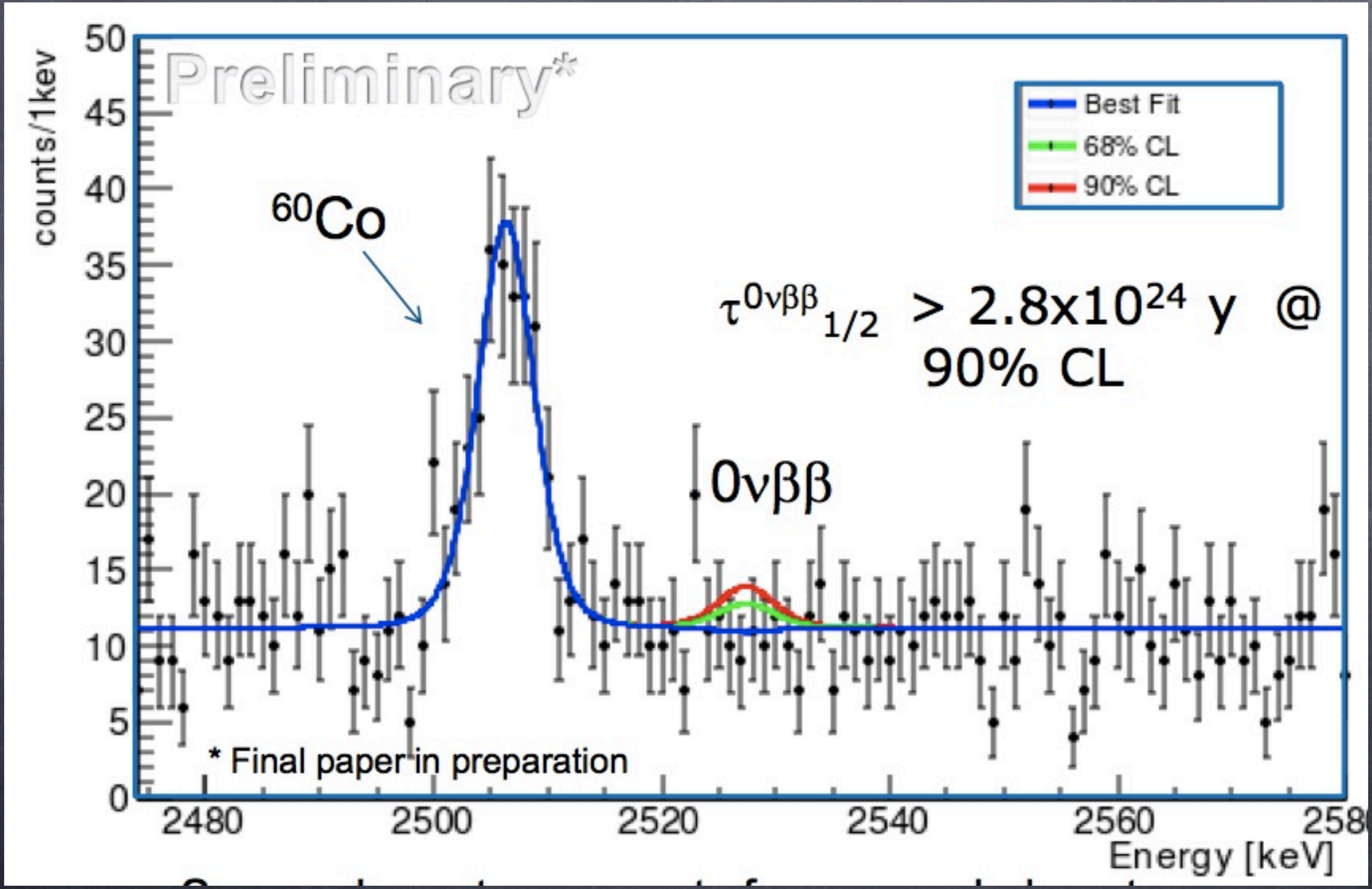
Cold finger

10 mK

Roman Lead Shield

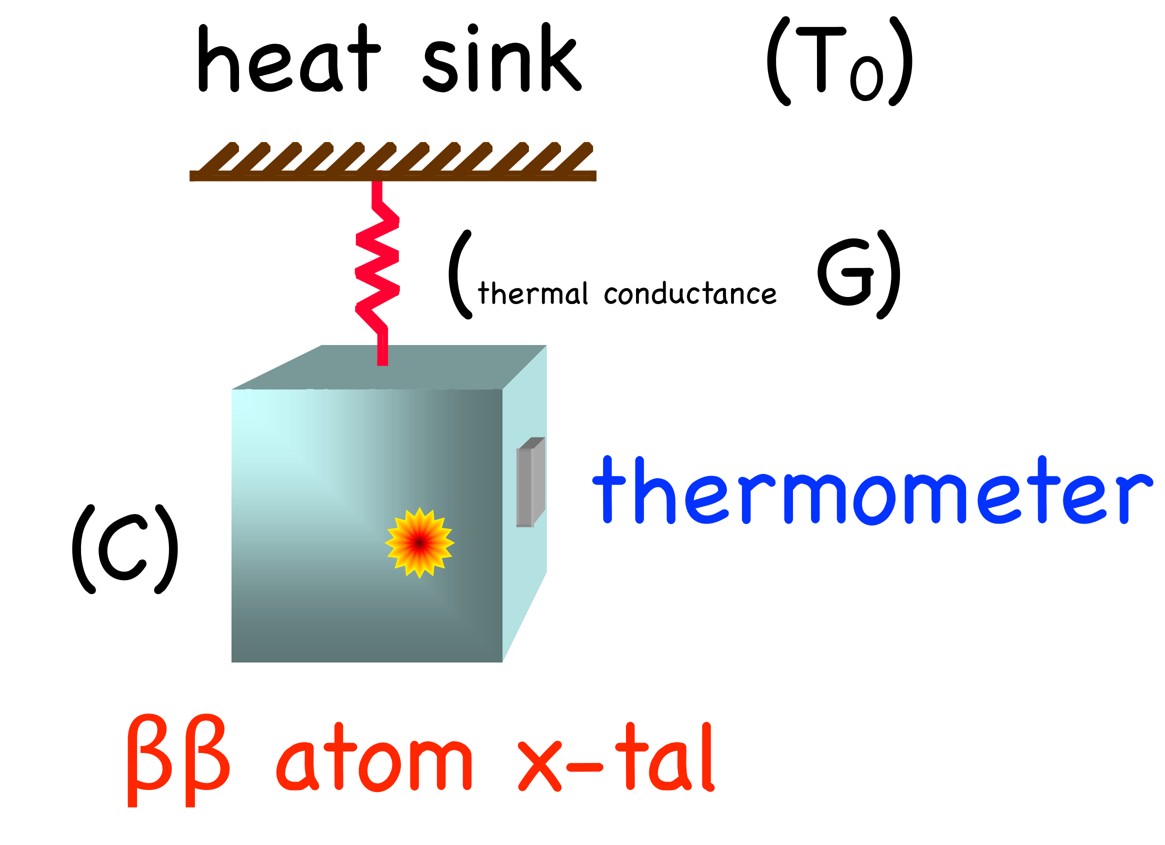


Cuoricino finale



(very) Low Temperature Calorimeter

The True Calorimeter



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

(Energy release/ Thermal capacity)

Implication: Low C ⇒ Low T

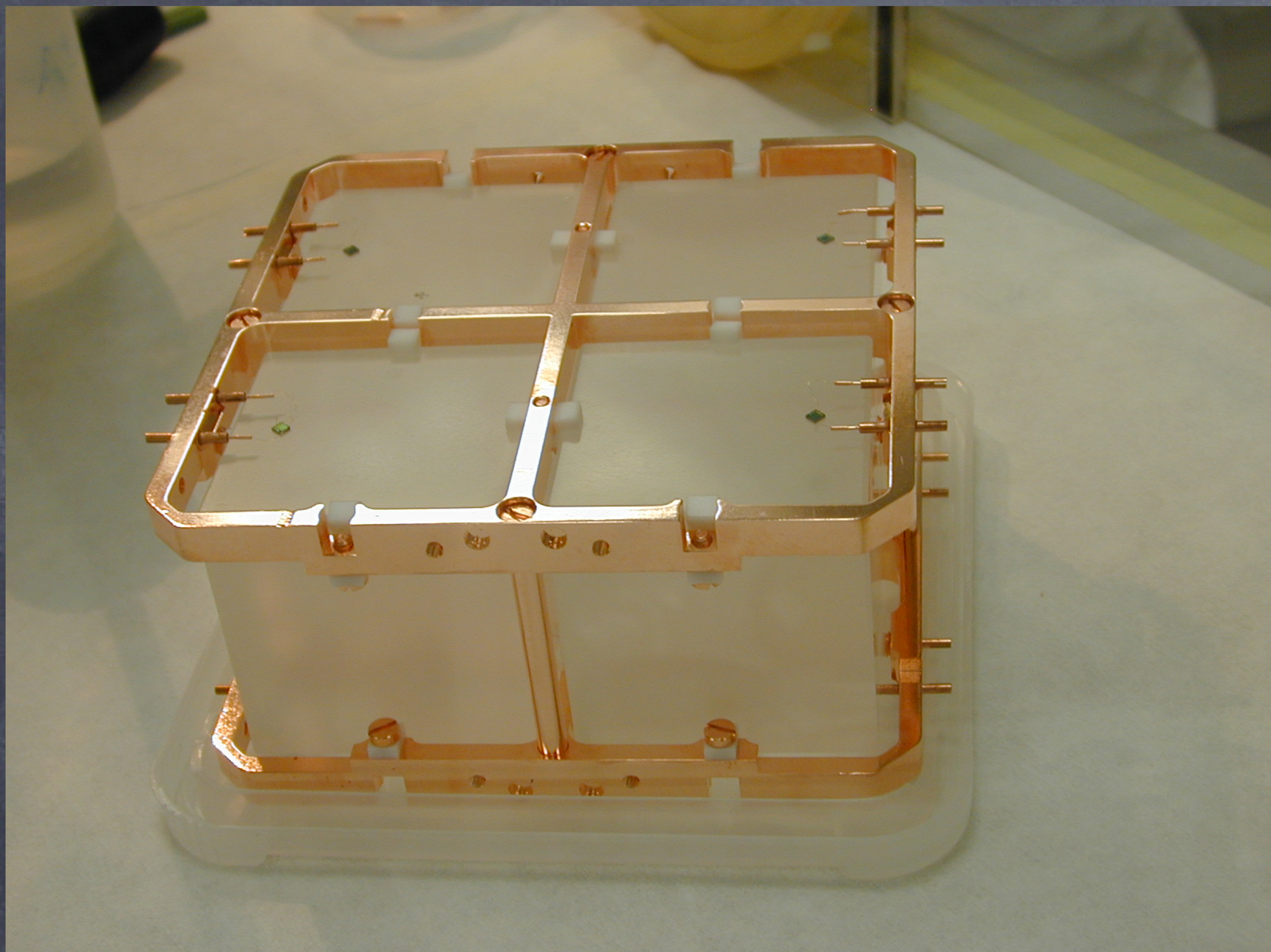
Bonus: (almost) No limit to ΔE ($k_B T^2 C$)

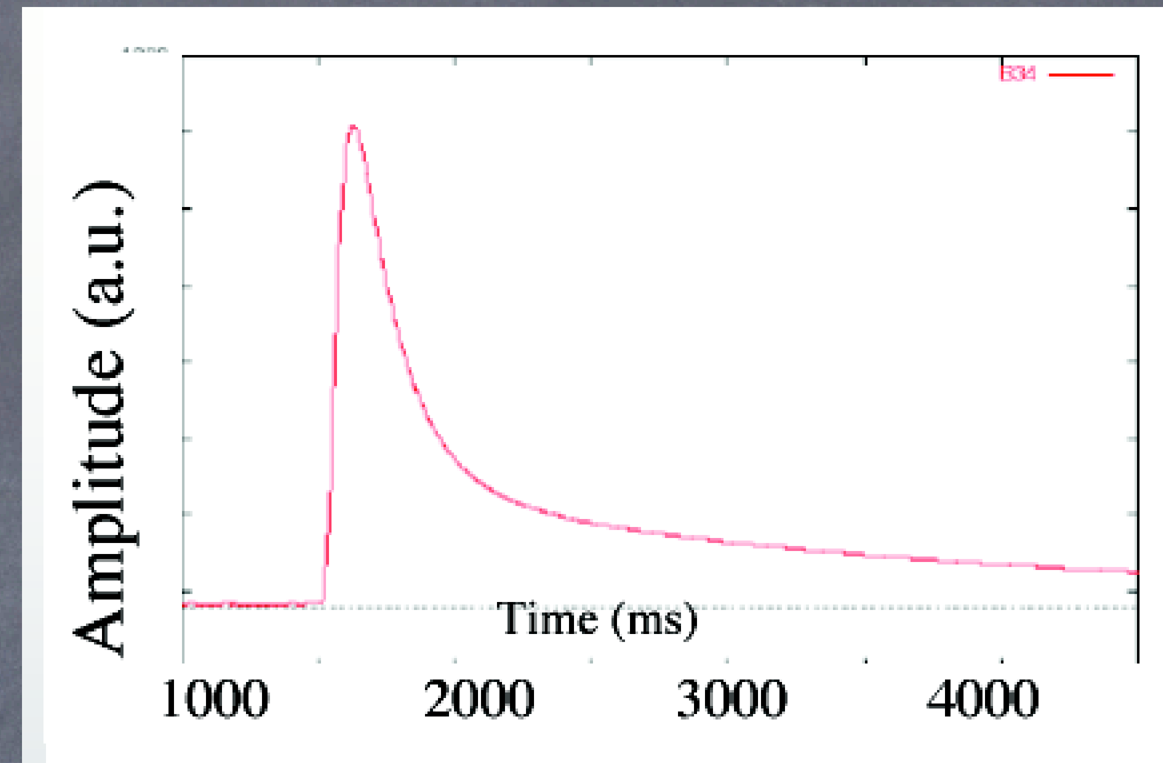
Not for all : $\tau = C/G \sim 1s$

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

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

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)

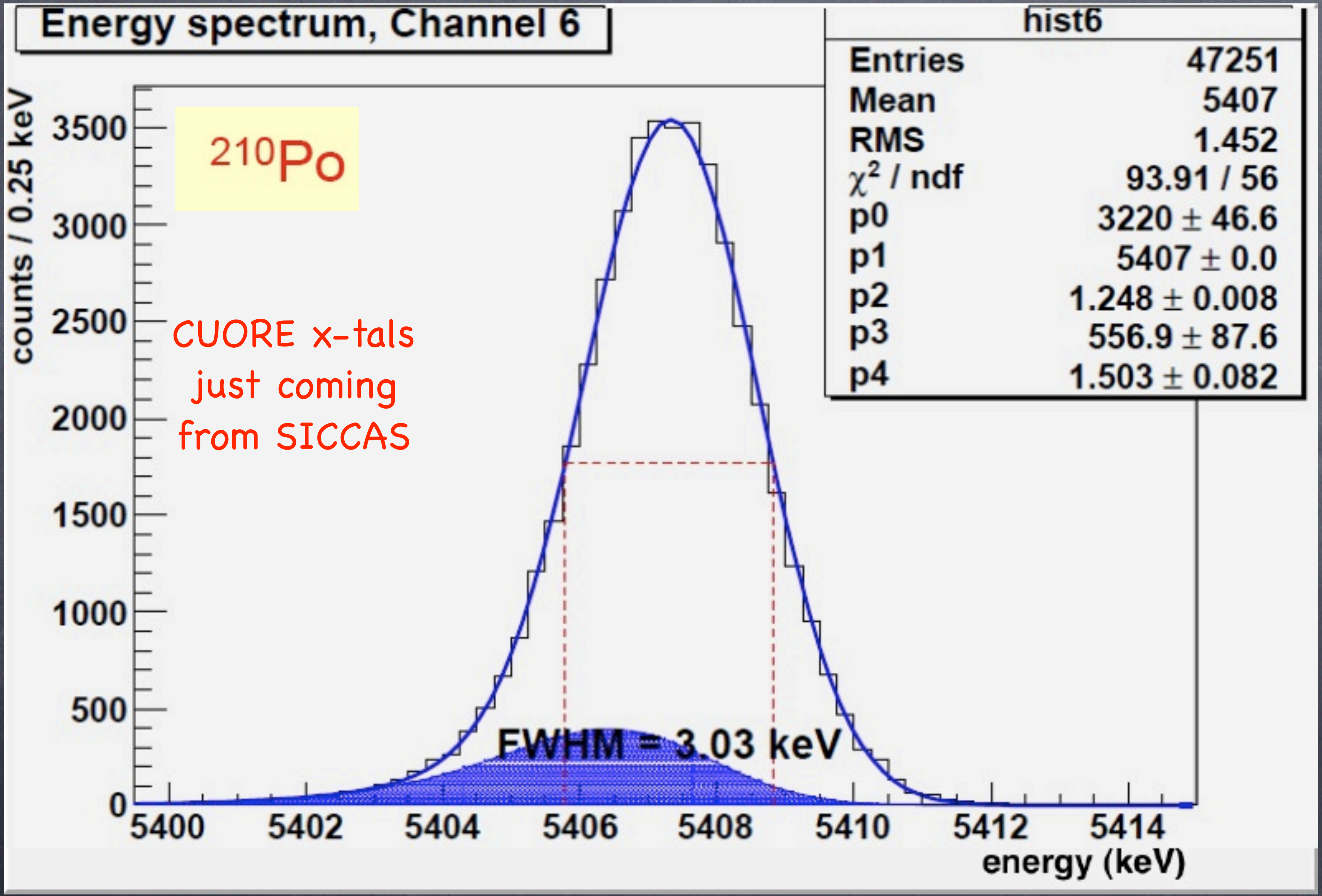
Numerology:

$T_0 \sim 10$ mK

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

$G \sim 4$ pW/mK

Risoluzione di energia



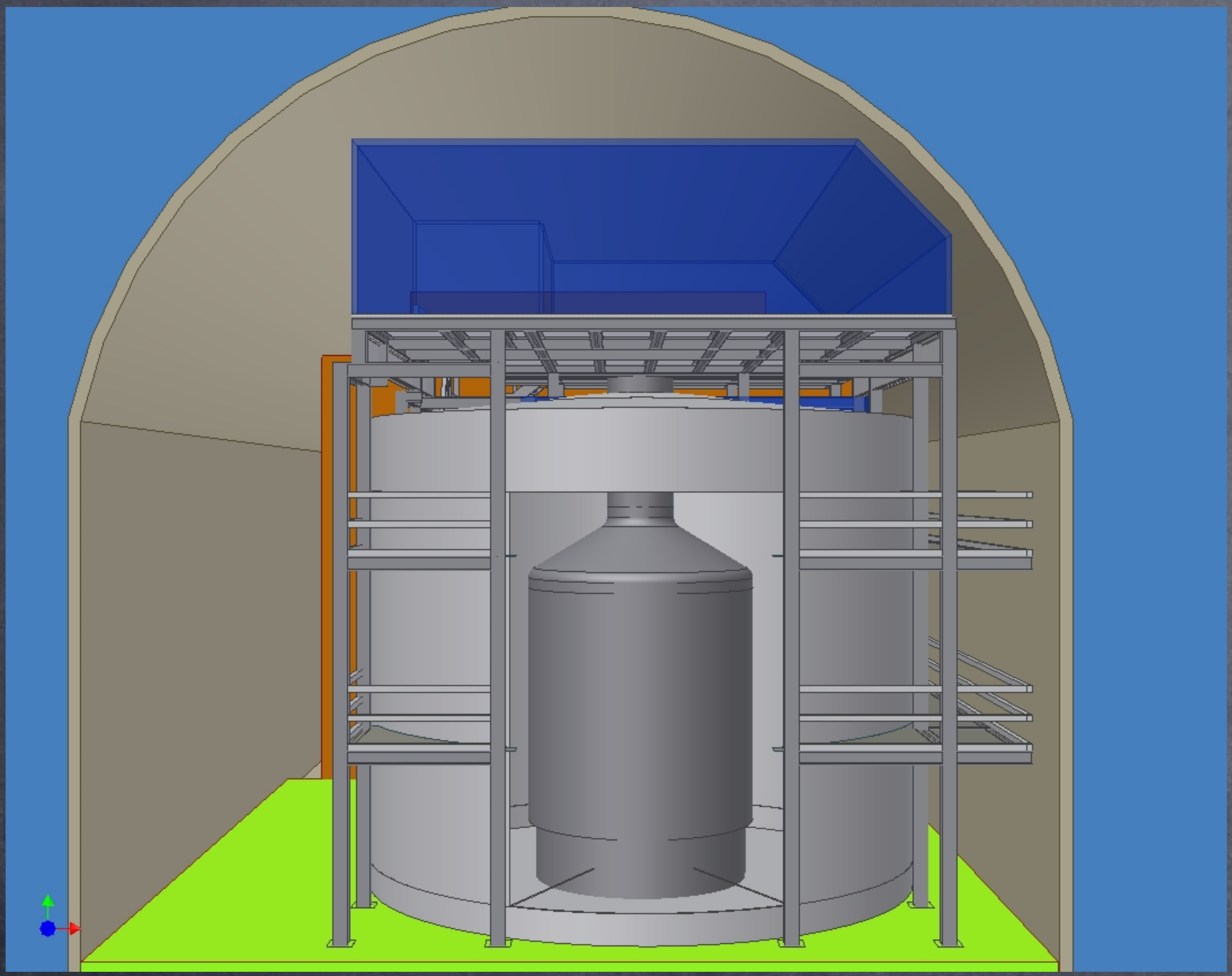
Gli esperimenti

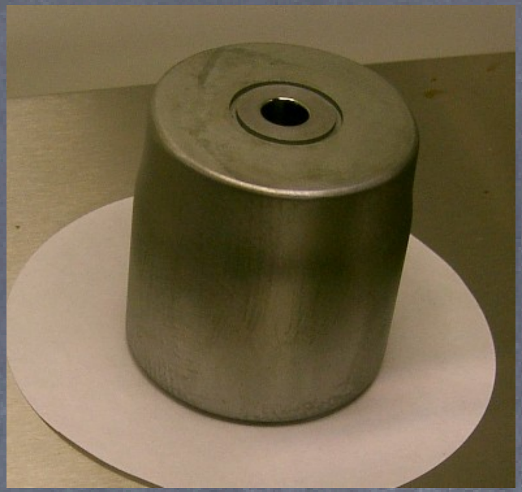
In pista o quasi

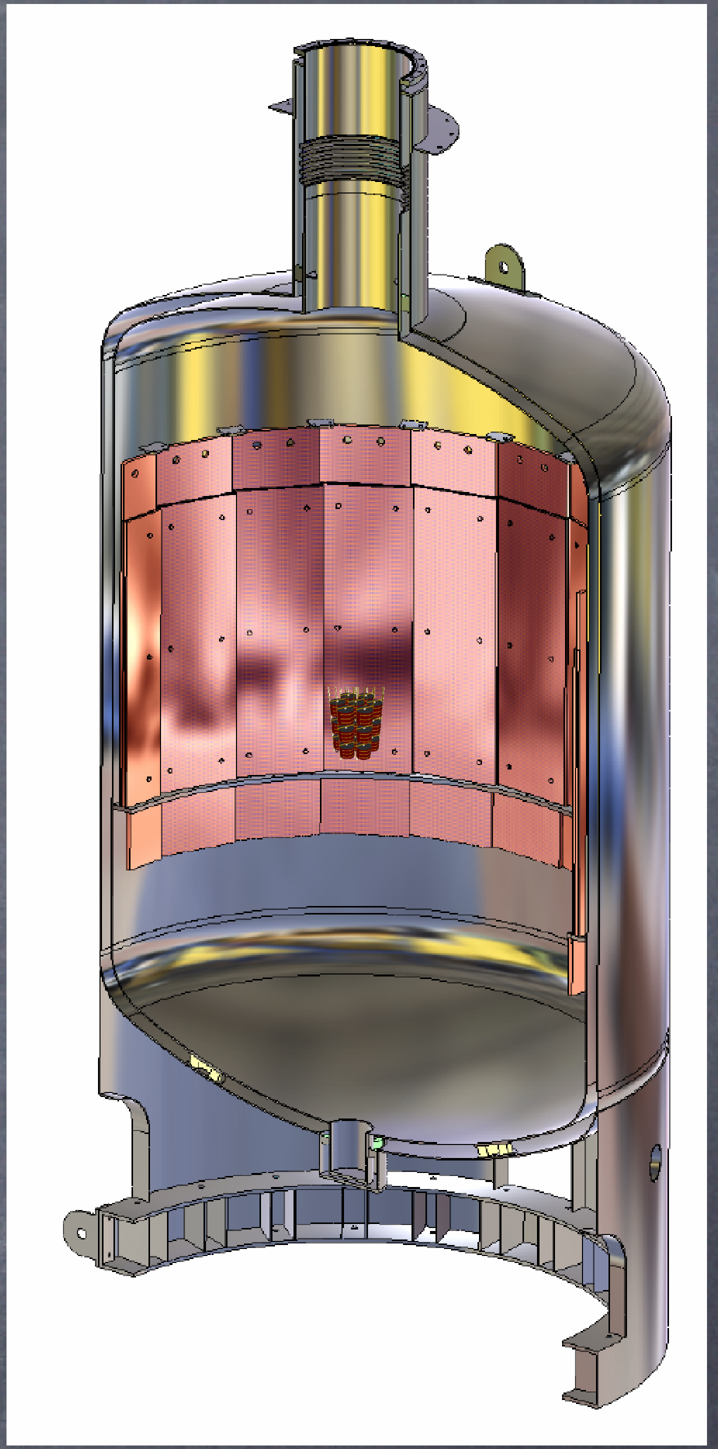
- GERDA (as an extrapolation of Ge ionization calorimeters)
- SuperNemo (improved tracking detectors)
- EXO (LXe with a super, yet daring, feature)
- CUORE (as a safe extrapolation of Cuoricino)
- + a newcomer ....

GERDA at LNGS

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





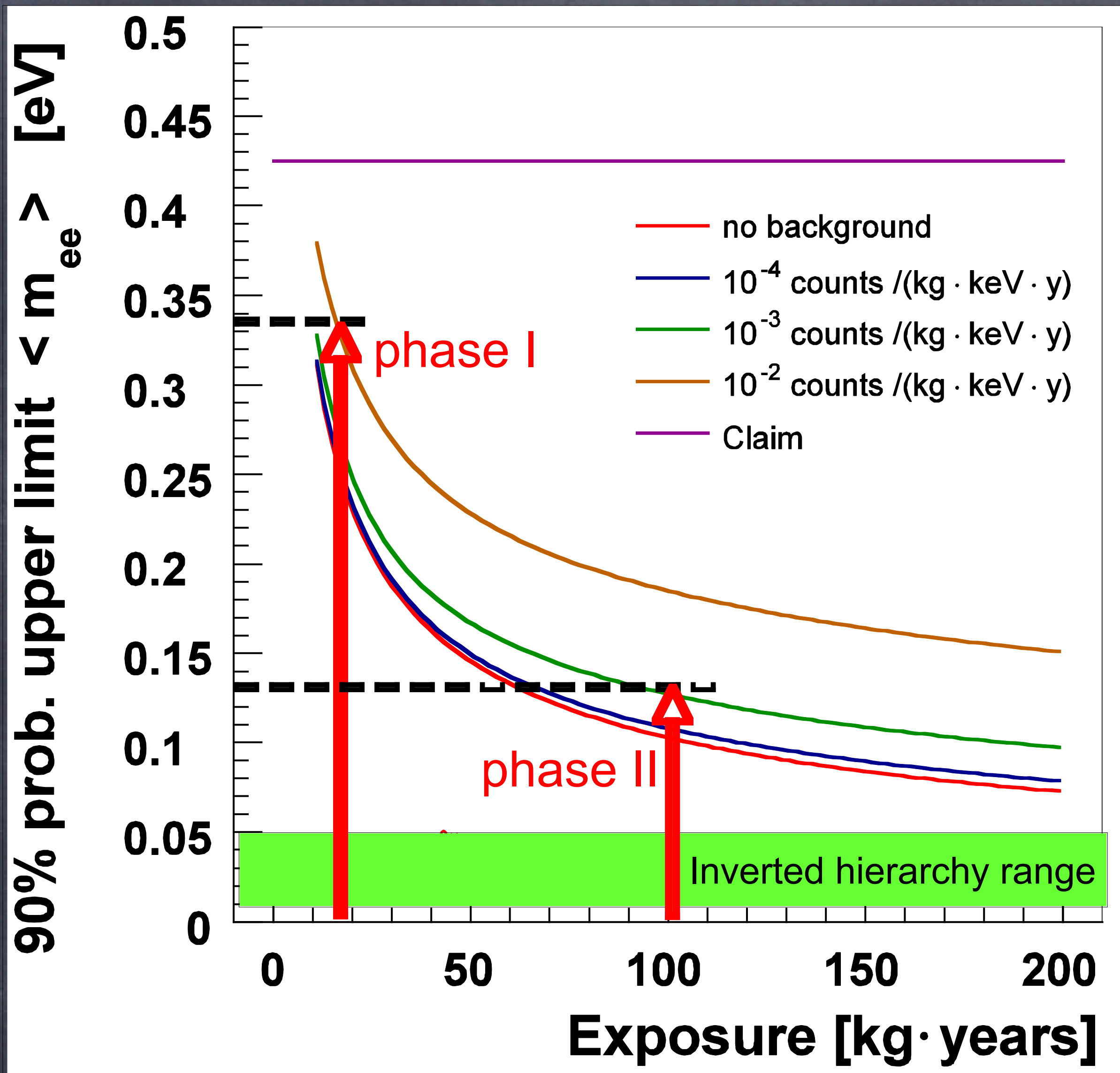


15 kg ^{76}Ge

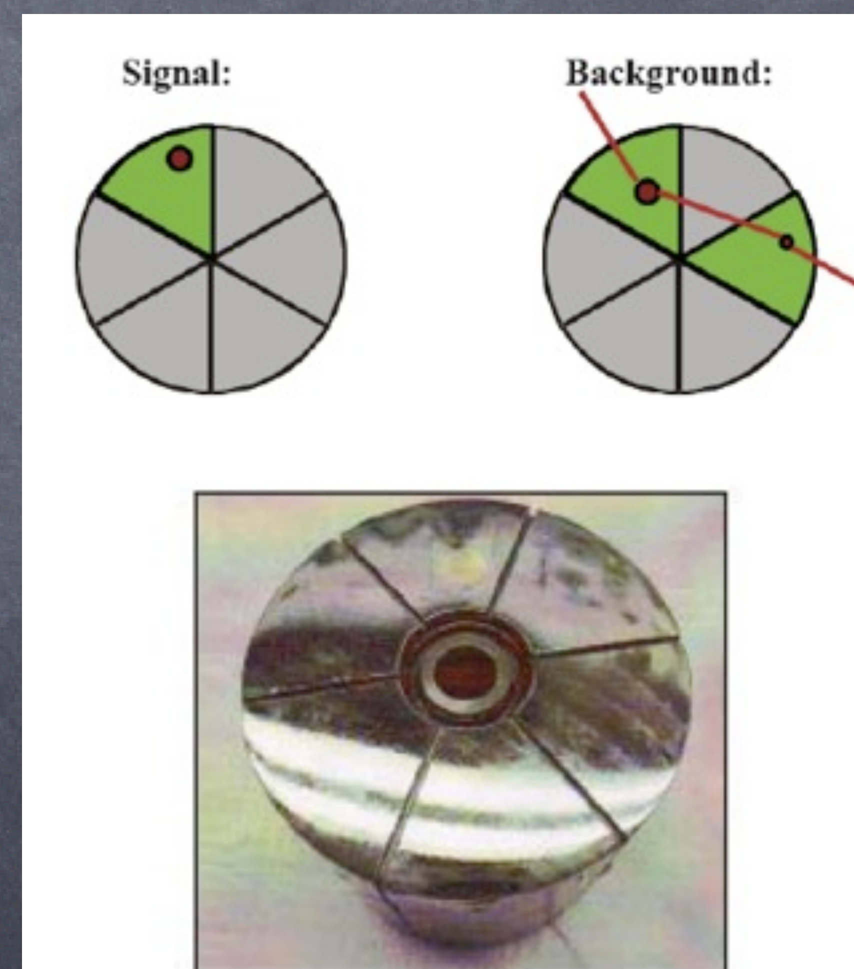
Water shield
LAr bath , bare crystals

Prove or disprove
KKDC claim in 1 year

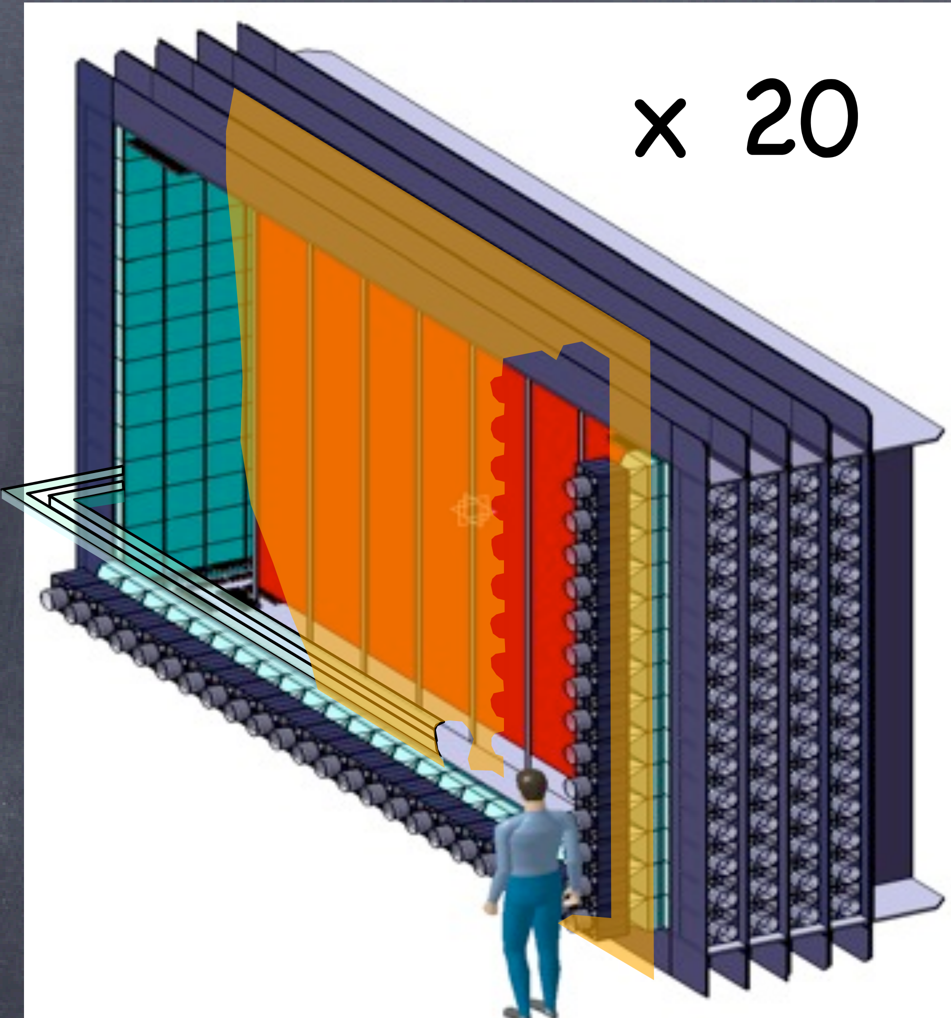
GERDA phases



- 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

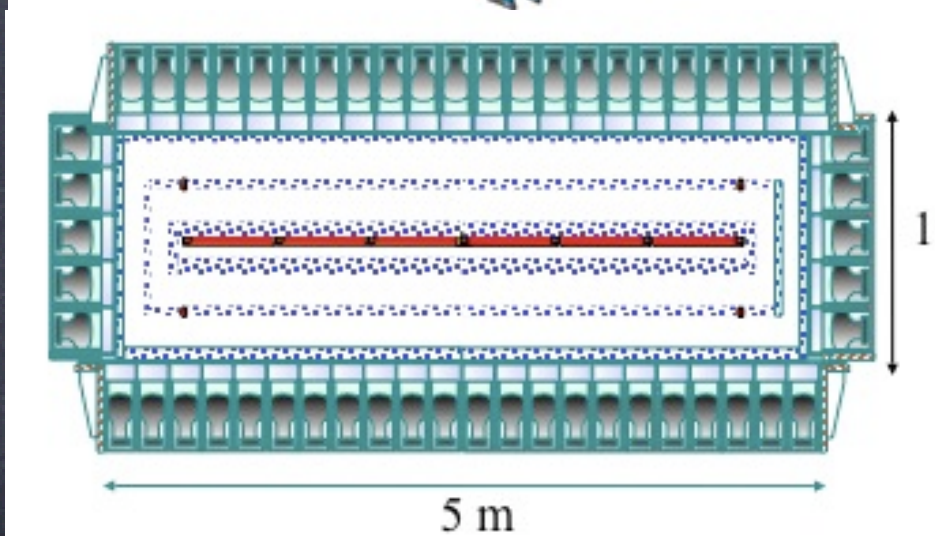


Challenge: decrease the background from 0.17 (HdM) to 0.01 first and to 0.001 then [c/(kg keV y)]

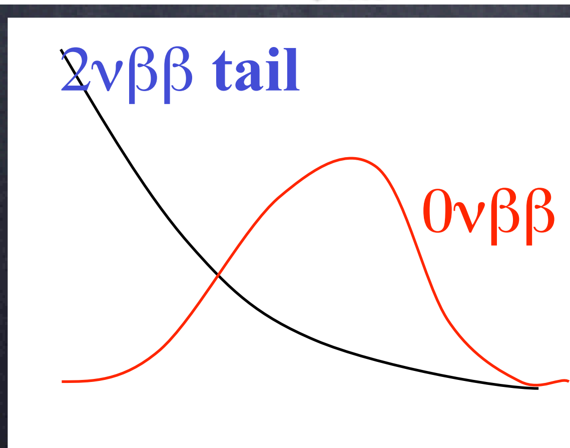


NEMO -> SuperNEMO

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



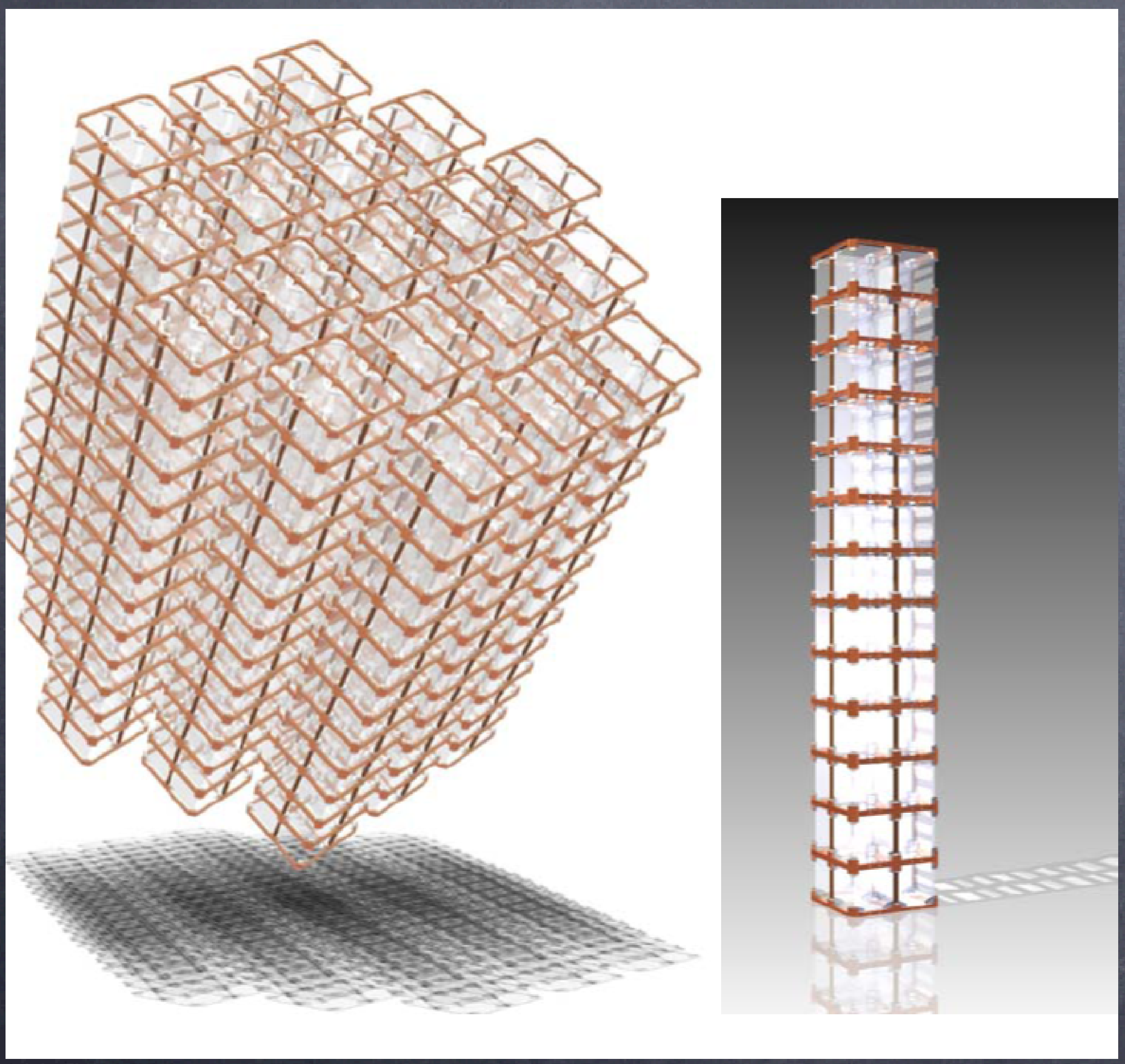
NEMO-3		SuperNEMO
^{100}Mo $T_{1/2}(\beta\beta2\nu) = 7.\ 10^{18}$ y	Choice of isotope	^{82}Se (and/or ^{150}Nd) $T_{1/2}(\beta\beta2\nu) = 10^{20}$ y
7 kg	Isotope mass **M**	**100 - 200** kg
$\varepsilon(\beta\beta0\nu) =$ **8 %**	Efficiency ε	$\varepsilon(\beta\beta0\nu) \sim$ **30 %**
$^{214}Bi <$ **300** µBq/kg $^{208}Tl <$ 20 µBq/kg $^{208}Tl, ^{214}Bi) \sim$ **1** evt/ 7 kg /y	N_{exclu} = f(BKG) *Internal contaminations* ***^{208}Tl and ^{214}Bi*** *in the ββ foil*	$^{214}Bi <$ **10** µBq/kg $^{208}Tl <$ 2 µBq/kg $(^{208}Tl, ^{214}Bi) \sim$ **1** evt/ 100 kg /y
ββ2ν ~ **2** evts / 7 kg / y	ββ(2ν)	ββ2ν ~ **1** evt / 100 kg/ y
FWHM(calo)=**8%** @3MeV	*IF*	FWHM(calo)=**4%** @3MeV
$T_{1/2}(\beta\beta0\nu) >$ **2. 10^{24} y** $\langle m_\nu \rangle <$ **0.3 – 0.7 eV**	**SENSITIVITY**	$T_{1/2}(\beta\beta0\nu) >$ **2 10^{26} y** $\langle m_\nu \rangle <$ **50 meV**



1) ββ source production
2) Energy resolution
3) Radioprurity
4) Tracking

CUORE

Cuoricino X 19



988 cristalli TeO_2

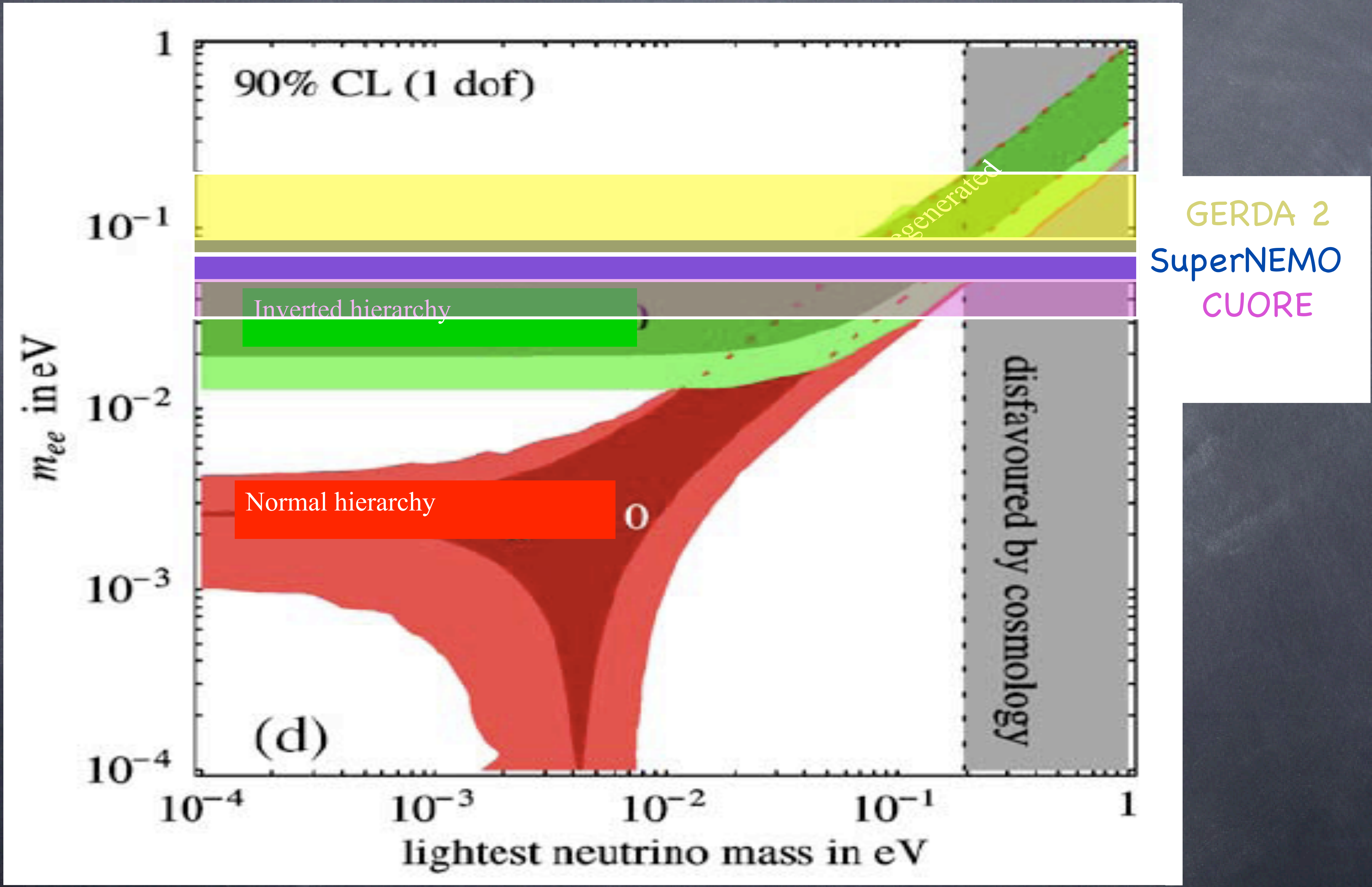
19 Torri di 52 cristalli

741 Kg di TeO_2

^{130}Te ~ 204 Kg

Possibilita' di riuso del criostato con altri cristalli !

La prossima generazione e' interlocutoria



Scaling Cuoricino to CUORE

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

$M = m \times 19$

$T = t \times 3$

$b = B / 5$

$\Delta E = \Delta E / 1.5$

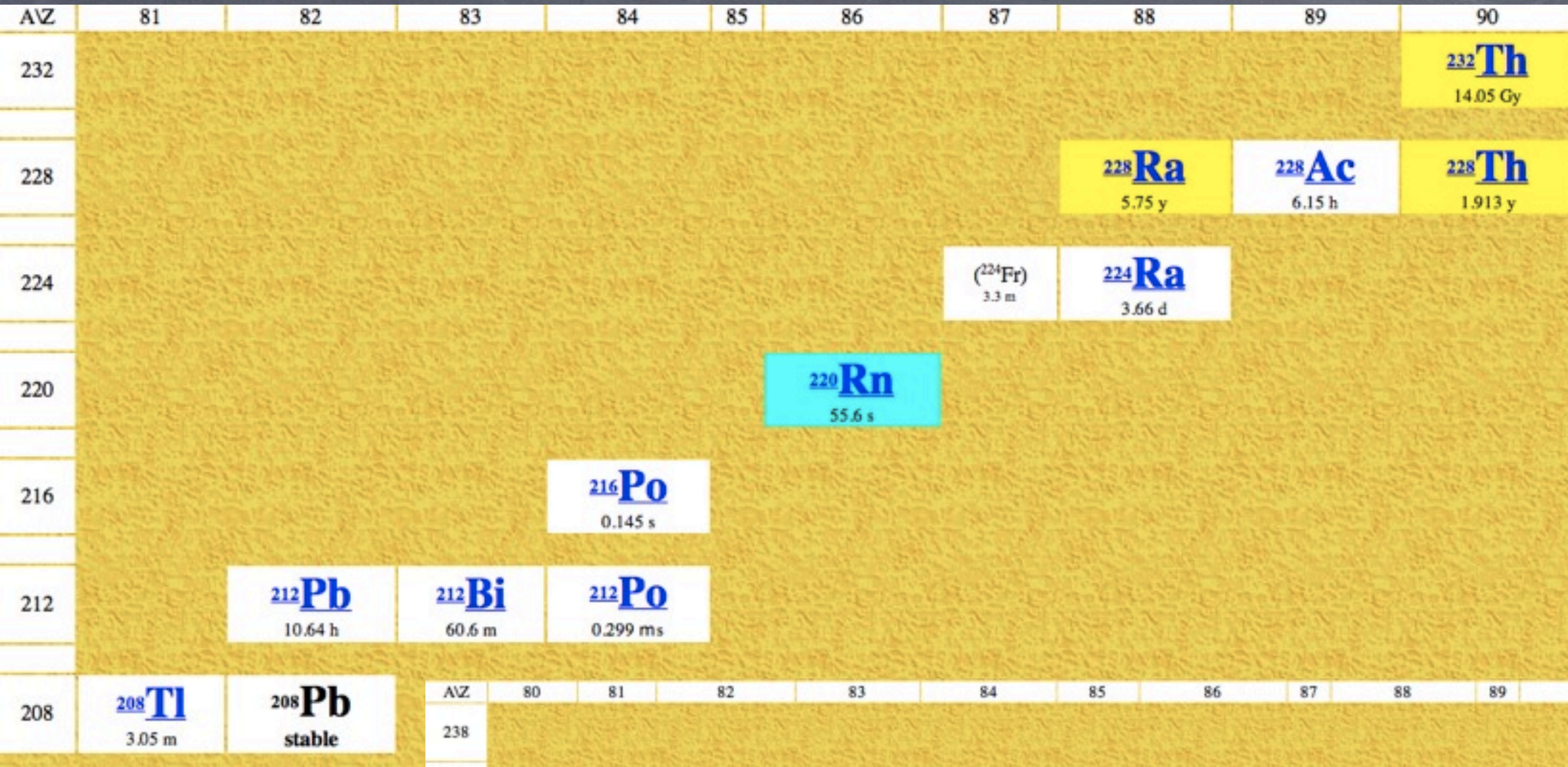
$S_{CUORE} = \sqrt{450}\ S_{Cuoricino} \sim 20\ S_{Cuoricino}$

$T_{1/2}\,(CUORE) \sim 5.6 \times 10^{25}$

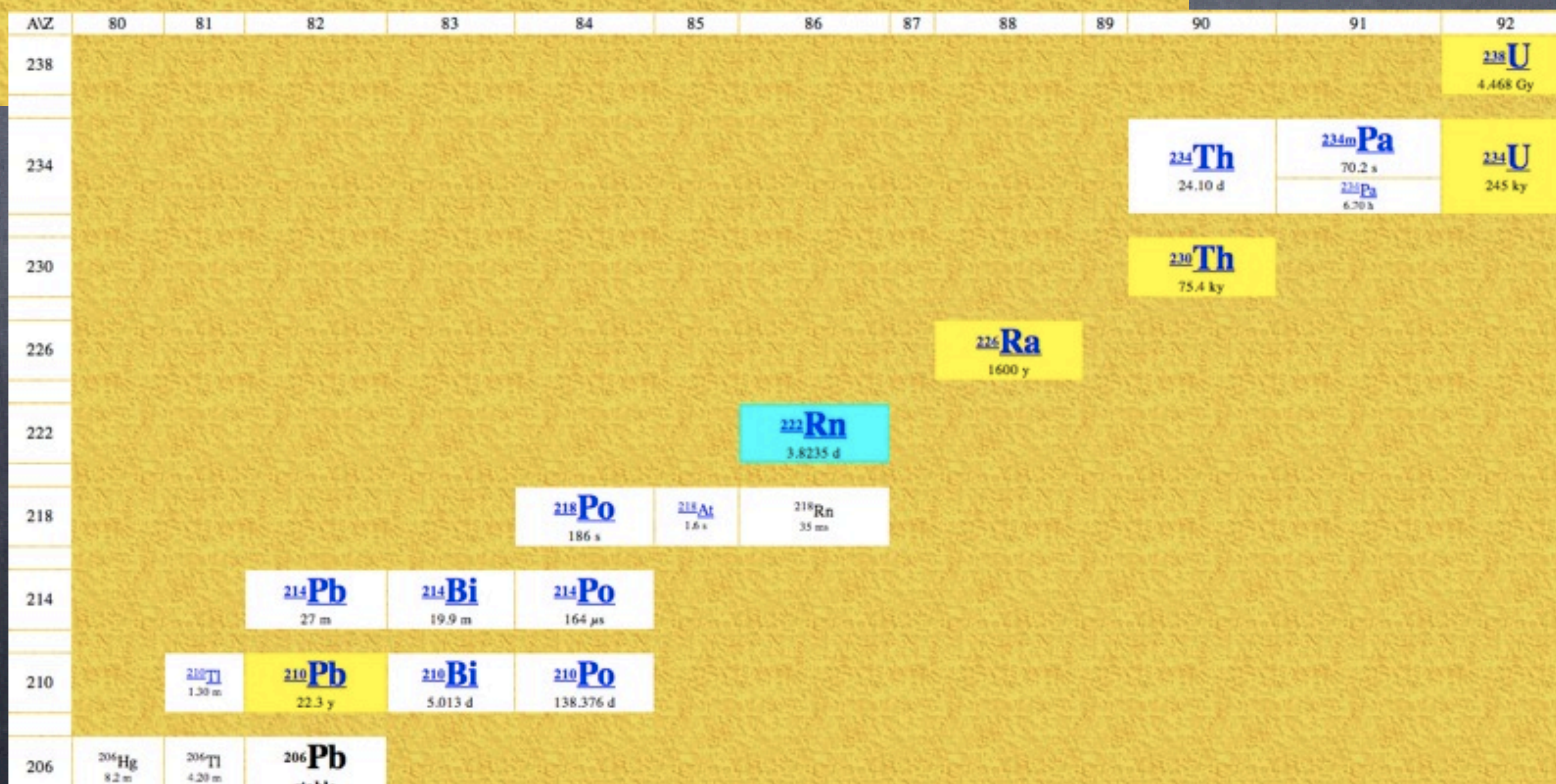
$\langle m_\nu \rangle_{CUORE} \sim \langle m_\nu \rangle_{Cuoricino} / 5 \sim 100$ meV

Fondo

U e Th



A\Z
81
82
83
84
85
86
87
88
89
90
232
228
224
220
216
212
208
232Th
14.05 Gy
228Ra
5.75 y
228Ac
6.15 h
228Th
1.913 y
(224Fr)
3.3 m
224Ra
3.66 d
220Rn
55.6 s
216Po
0.145 s
212Pb
10.64 h
212Bi
60.6 m
212Po
0.299 ms
208Tl
3.05 m
208Pb
stable



A\Z
80
81
82
83
84
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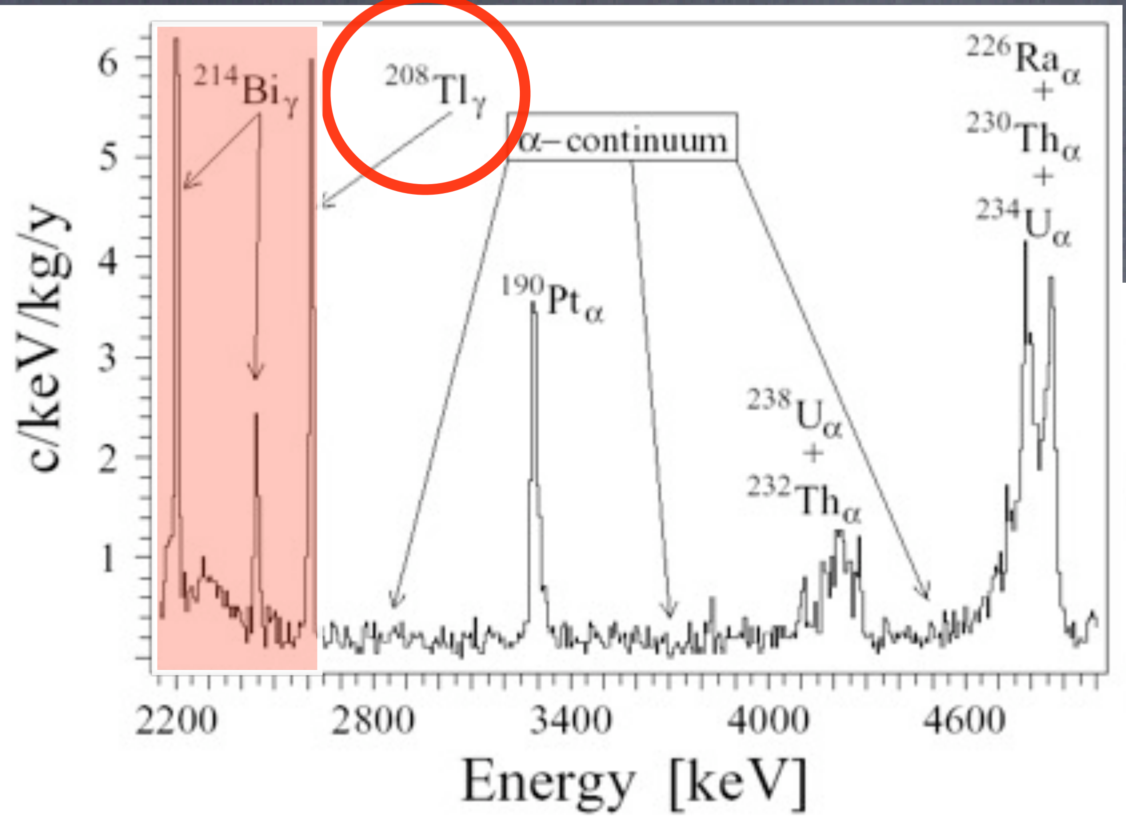
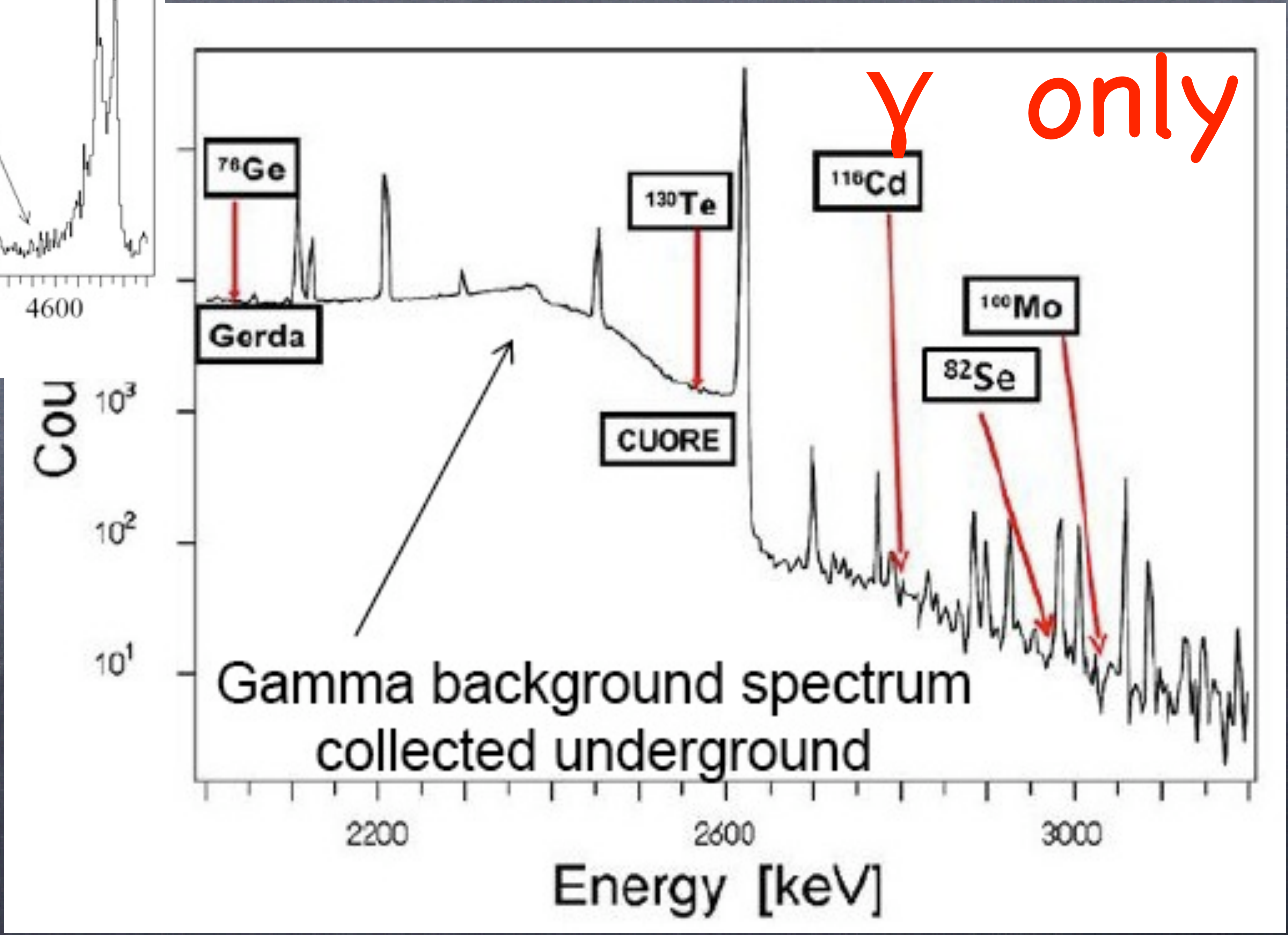
86
87
88
89
90
91
92
238
234
230
226
222
218
214
210
206
238U
4.468 Gy
234Th
24.10 d
234mPa
70.2 s
234Pa
6.70 h
234U
245 ky
230Th
75.4 ky
226Ra
1600 y
222Rn
3.8235 d
218Po
186 s
218At
1.6 s
218Rn
35 ms
214Pb
27 m
214Bi
19.9 m
214Po
164 µs
210Tl
1.30 m
210Pb
22.3 y
210Bi
5.013 d
210Po
138.376 d
206Hg
8.2 m
206Tl
4.20 m
206Pb
stable

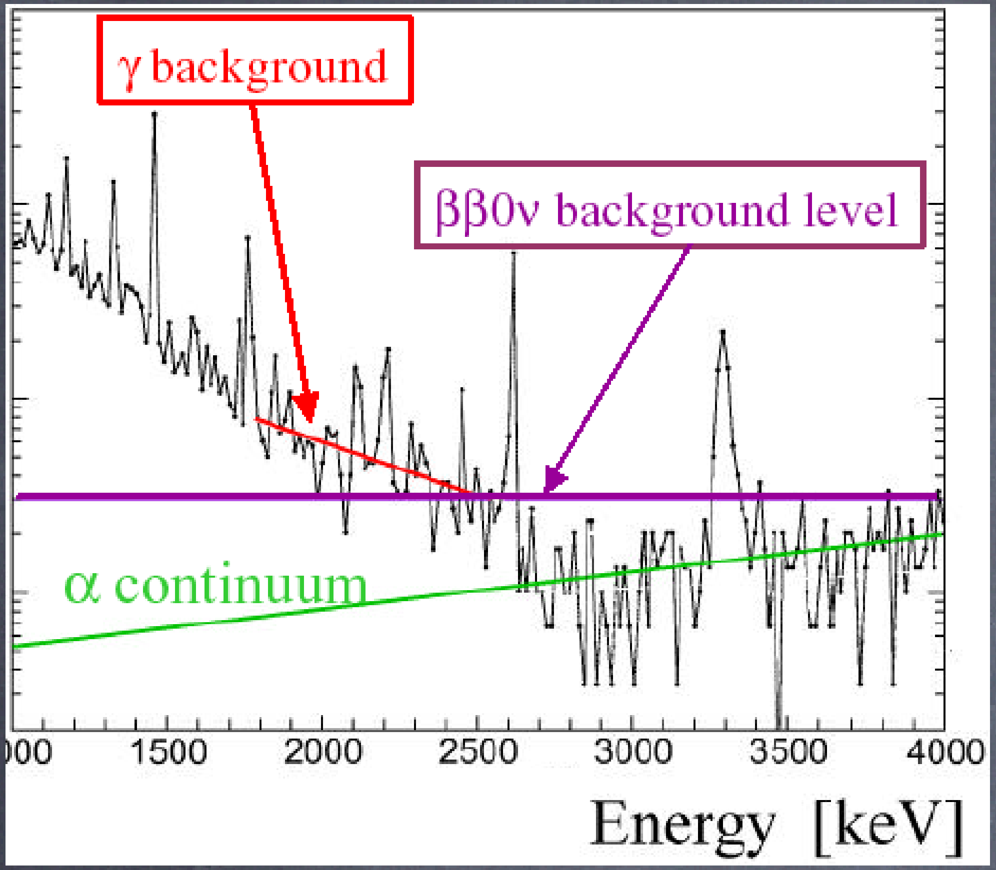
La radioattivita' naturale



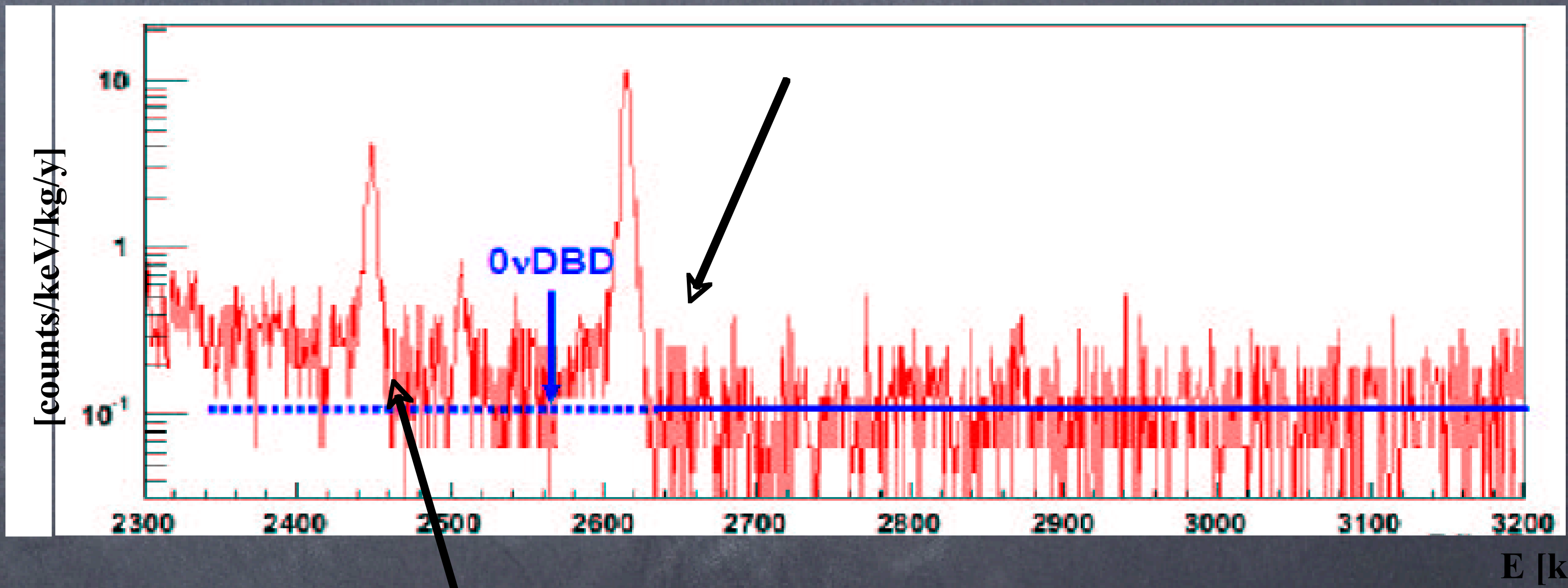


above ^{208}Tl there is the α land

Cuoricino: Background



2615 keV Tl line: contribution to the DBD bkg due to a Th contamination (multicompton). .
Th (Tl) contribution to DBD background: ~ **40%**

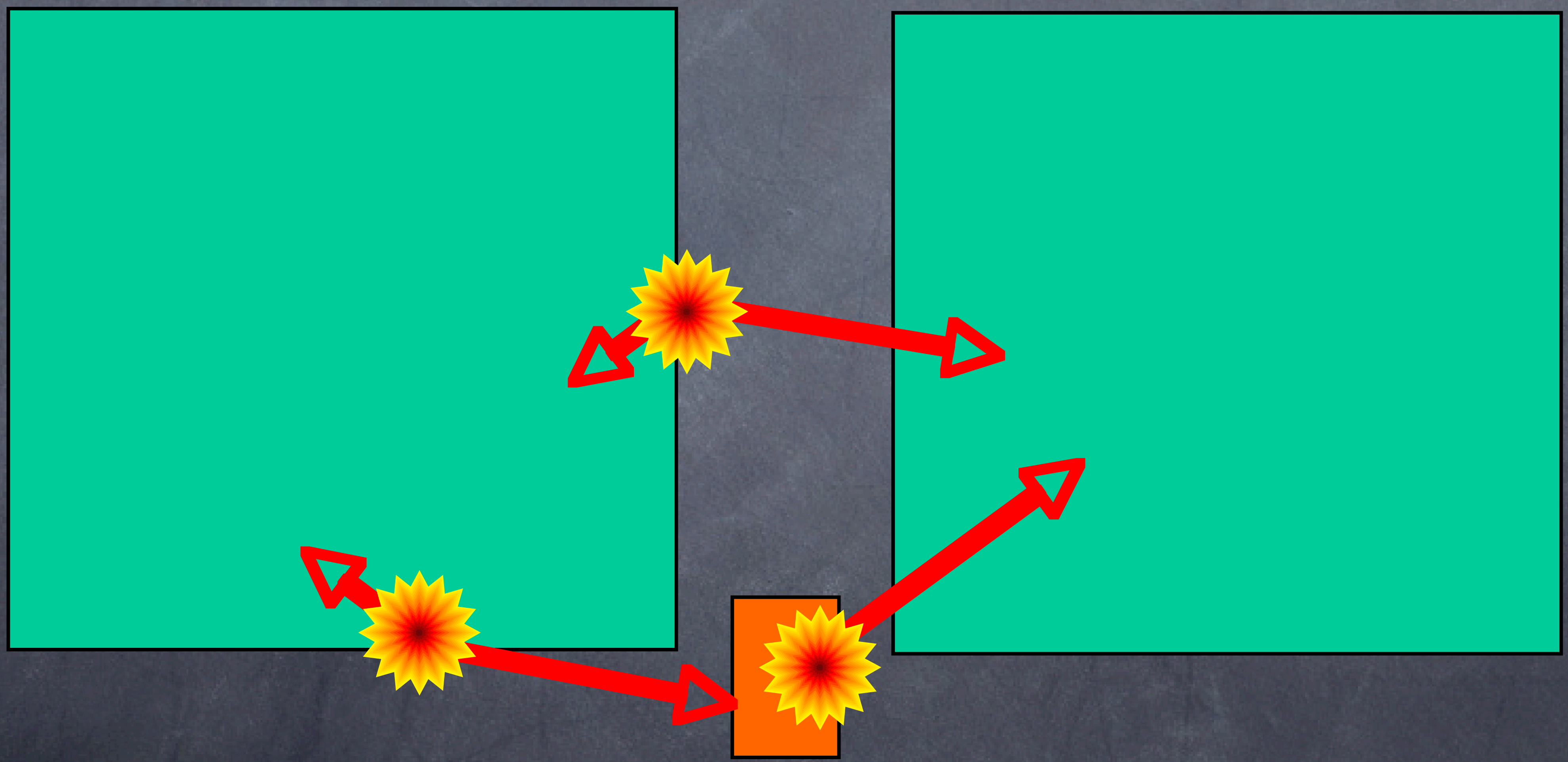


Cuoricino
b=0.18 ± 0.02 c/keV/kg/y

2505 keV line: sum of the 2 ^{60}Co gammas (1173 and 1332 keV)
Most probable source: neutron activation of the Copper
Contribution to DBD background: negligible

Flat background in the energy region above the ^{208}Tl 2615 line
Contribution to the counting rate in the 0νDBD region: ~ 60%
Degraded alpha particles

Il modello standard del fondo



Degraded α's

Quindi c'e' spazio per pensare

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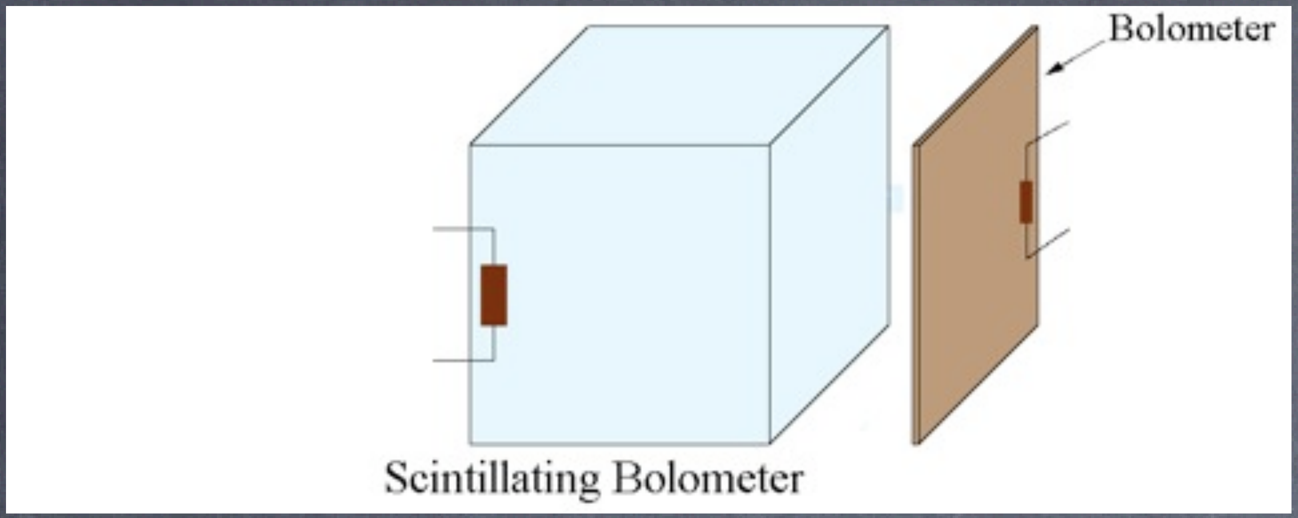
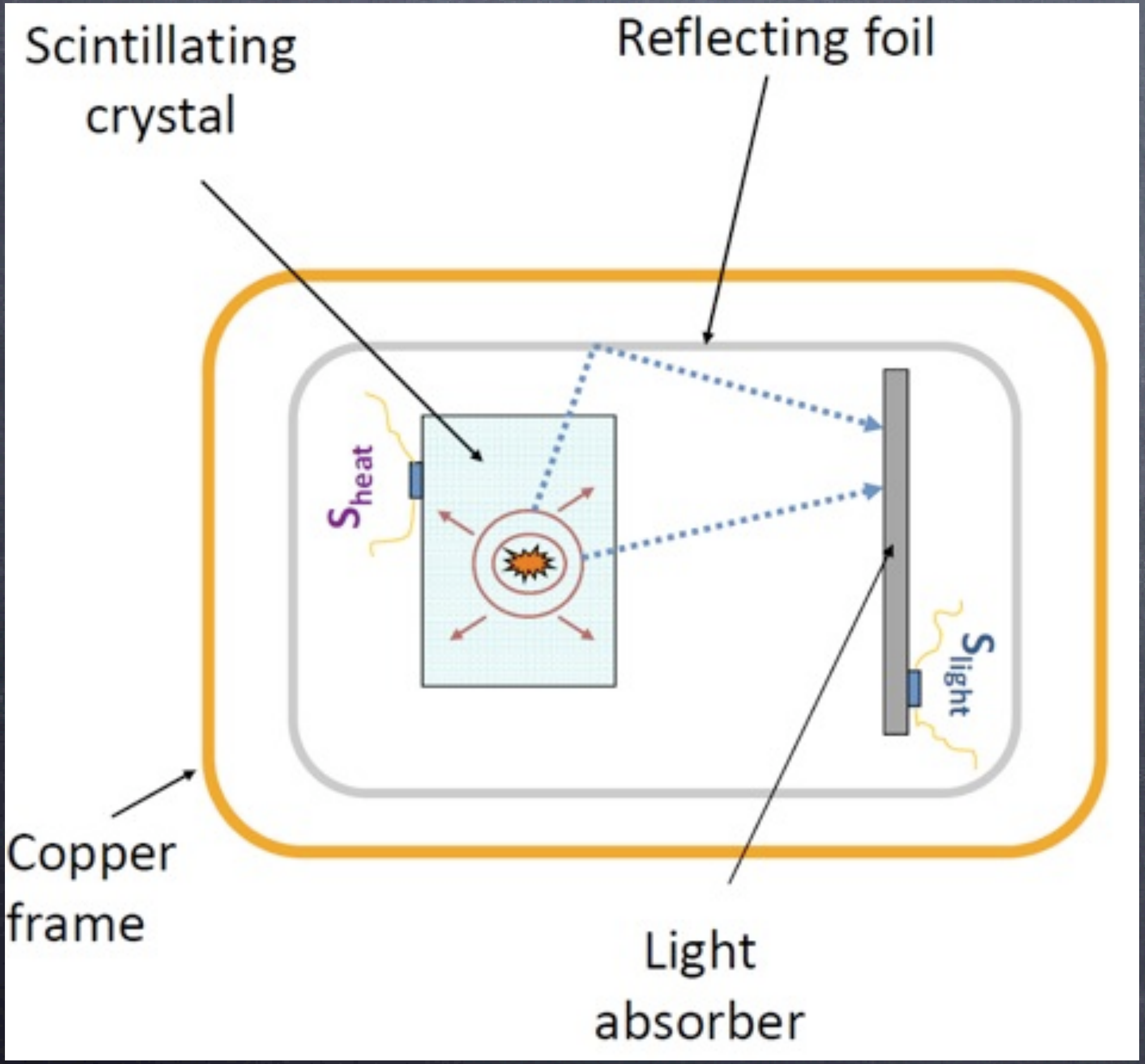
concept

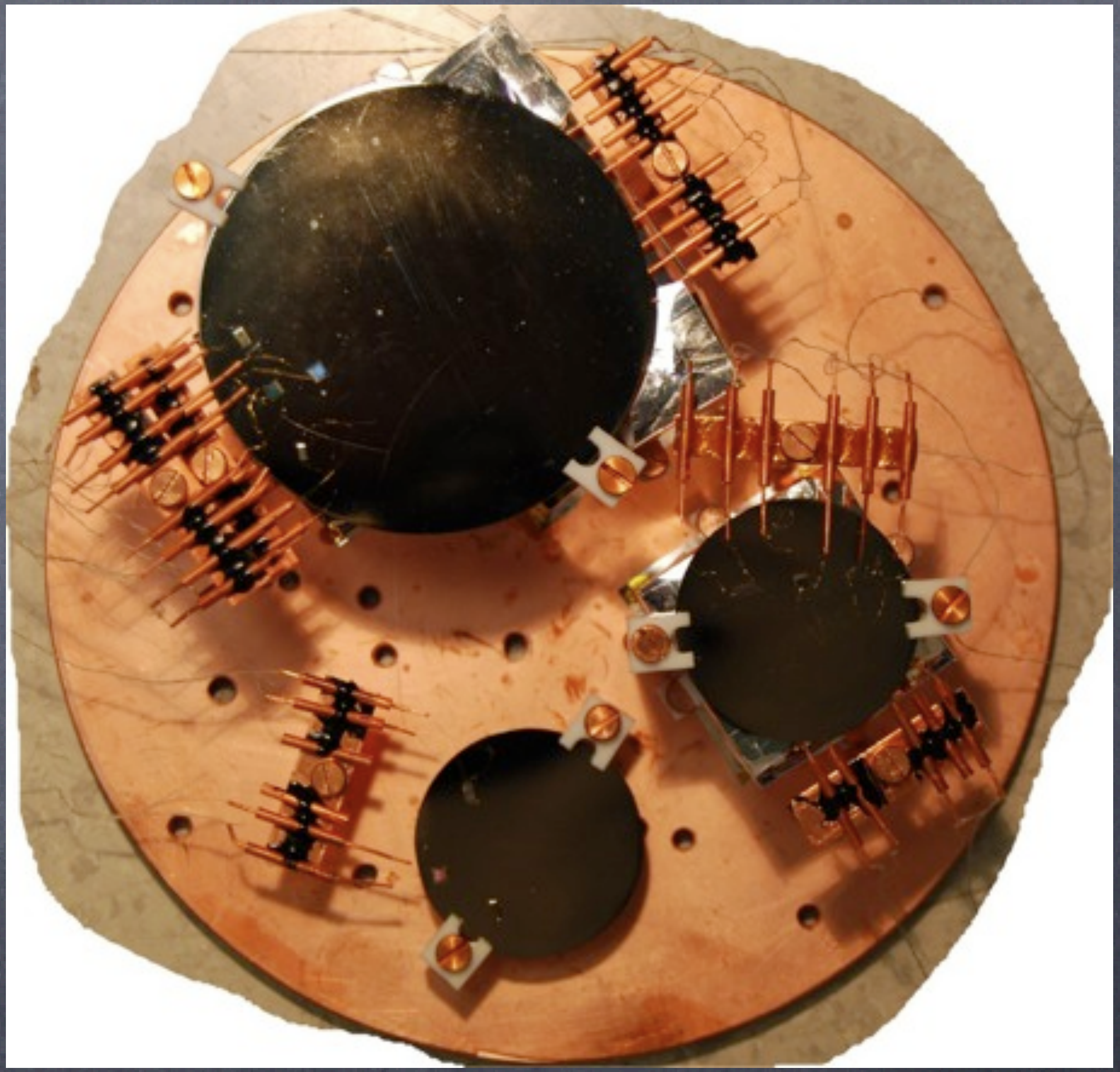
Bringing
light
underground

Double read-out



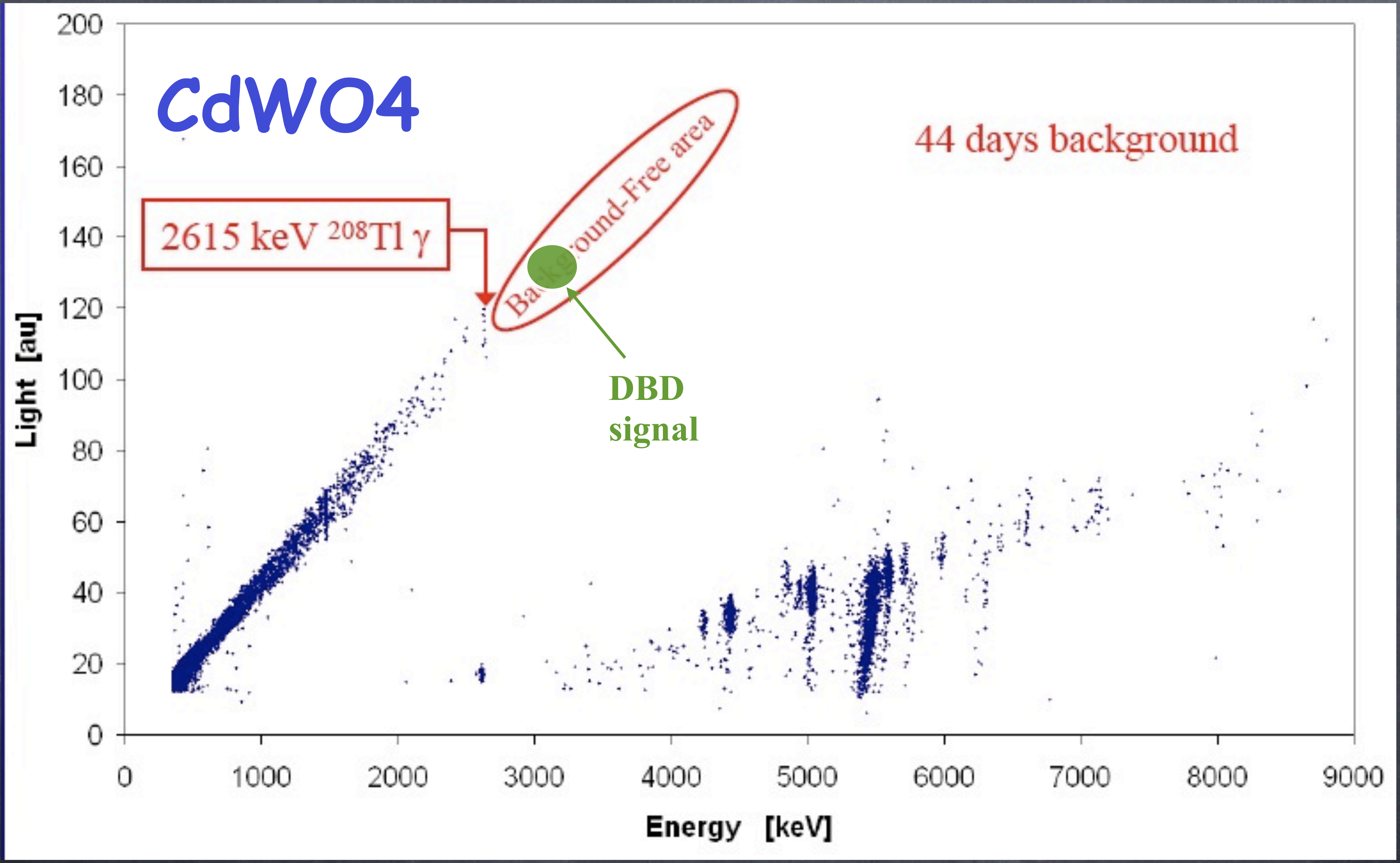


BOLUX@CSN5



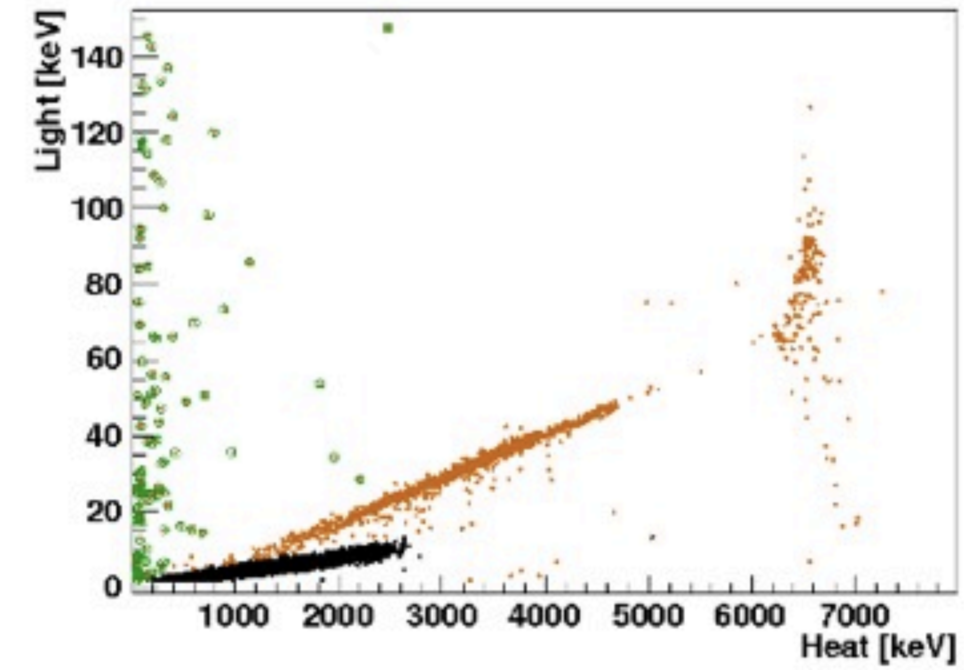
S. Pirro@LNGS

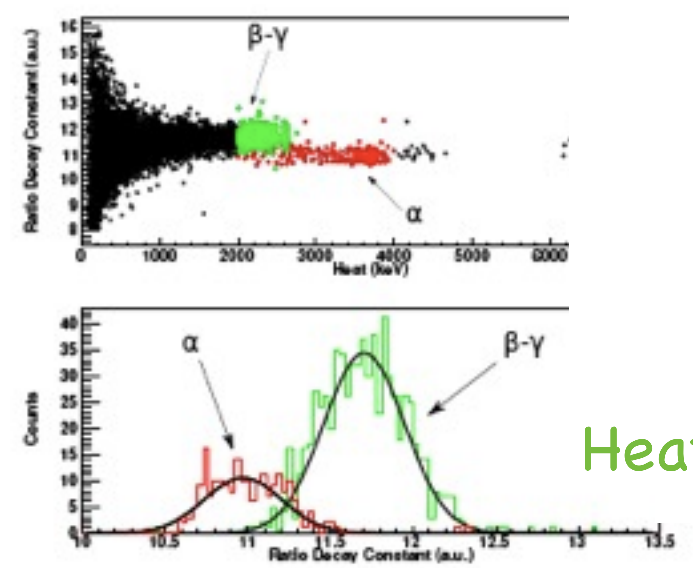
una figura, un programma !



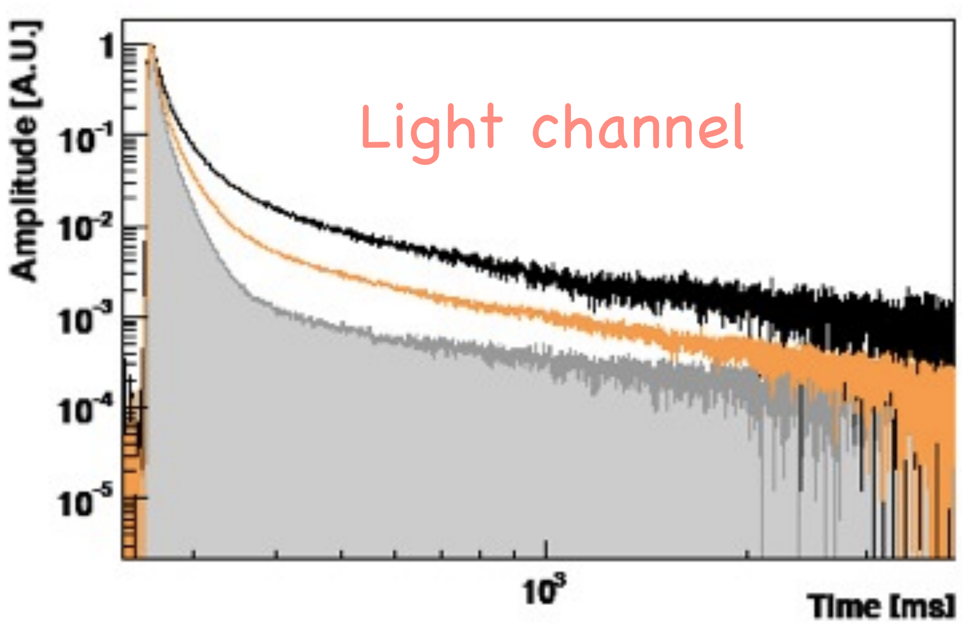
Il cristallo piu' intrigante

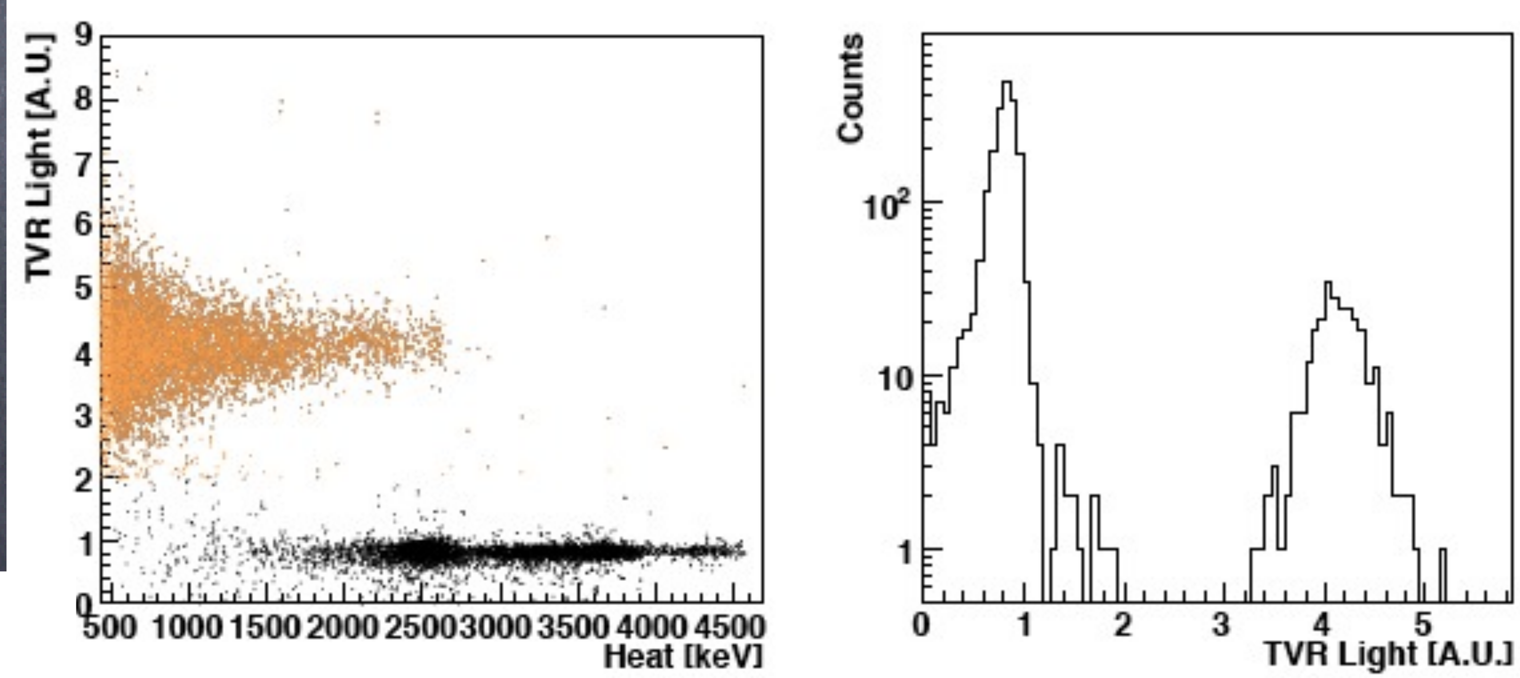
ZnSe





Heat channel





Astropart.Phys. 34 (2011) 344-353

ZnSe scintillating bolometers for Double Beta Decay

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

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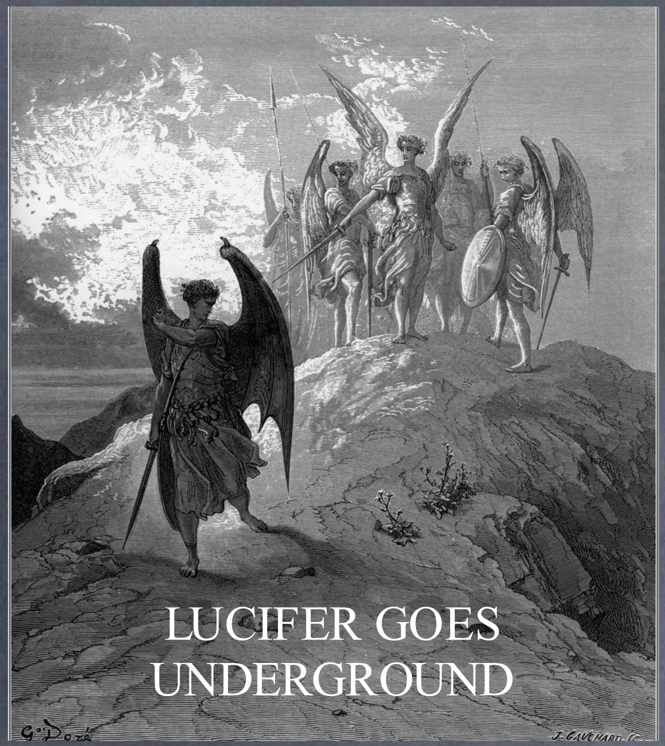
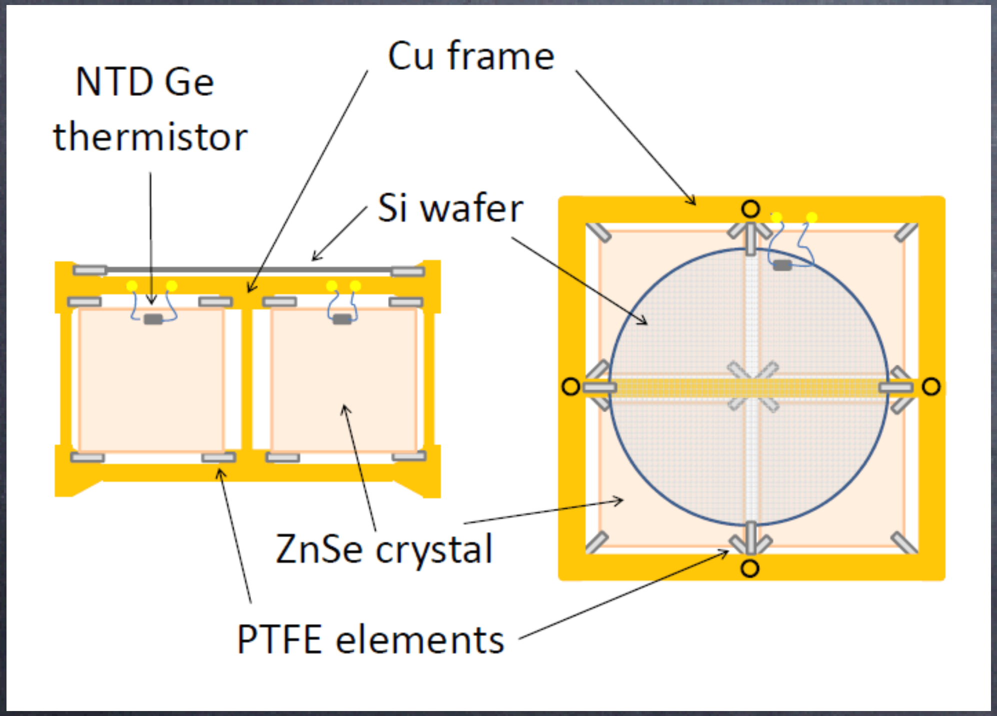
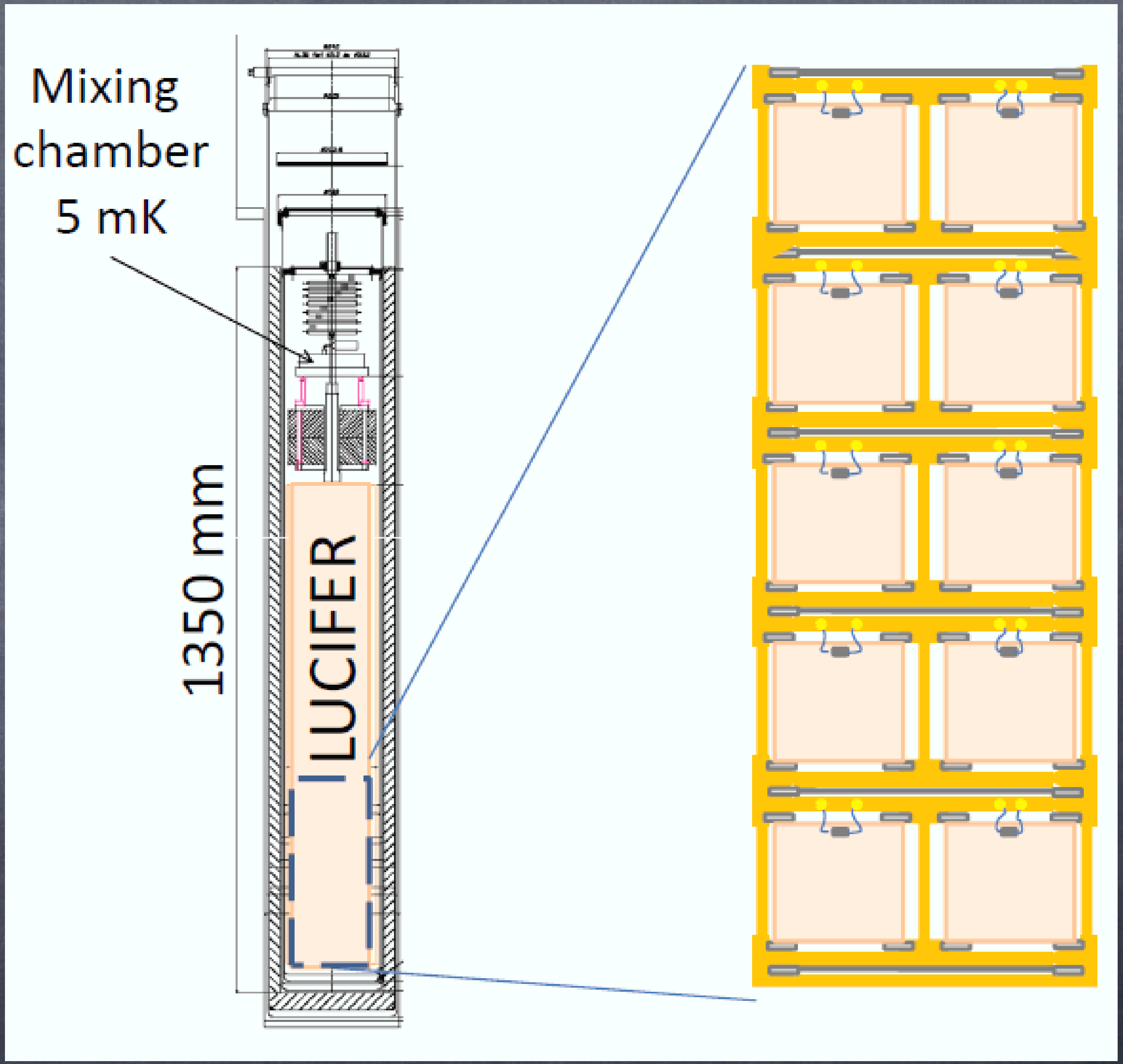
Low-background Underground Cryogenic Installation For Elusive Rates

ERC-2009-AdG 247115







La sensibilita' attesa

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

Cuoricino	1.8	(VERA)
CUORE	21	(ne ottimista ne pessimista)
Gerda(1)	5.2	(ragionevolmente vera)
SuperNemo	25	(tutta da dimostrare)
Lucifer	18	(ottimista) [ma 1 Ton > 100 !]