Calorimetry at 10mK

(and to make it simpler, radiopure)

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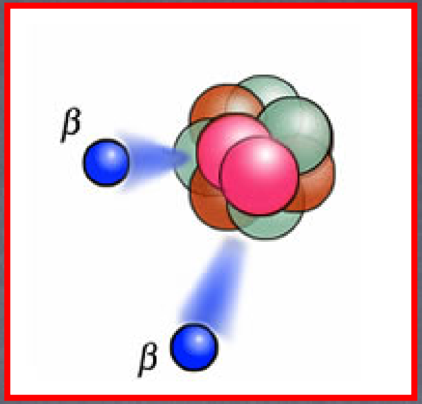
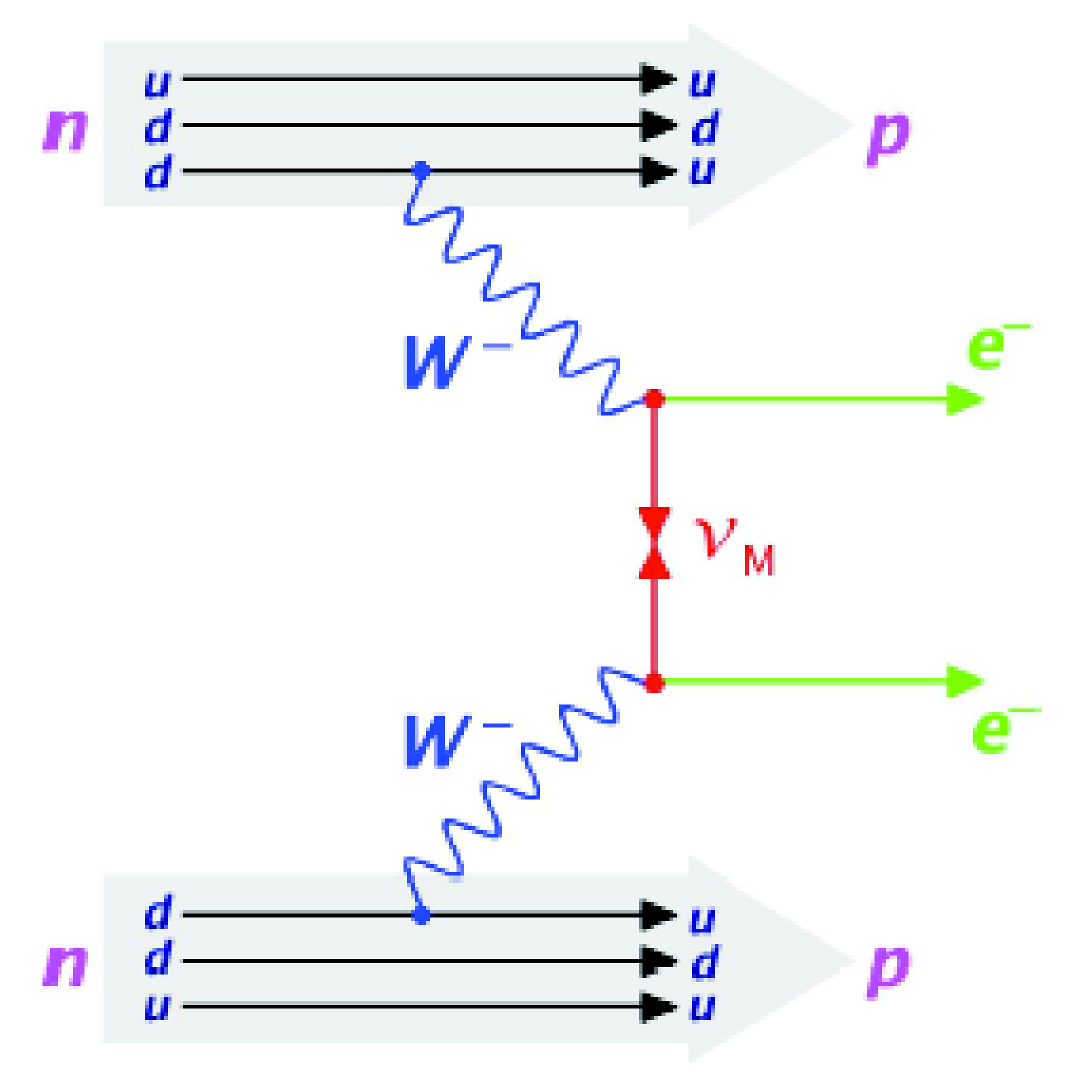
Outline

- Neutrinoless Double Beta Decay search
- Large Mass Bolometers
- TeO2: a showcase
- A step further: Heat + Light

Neutrino-less DBD (0νββ)





Only if:

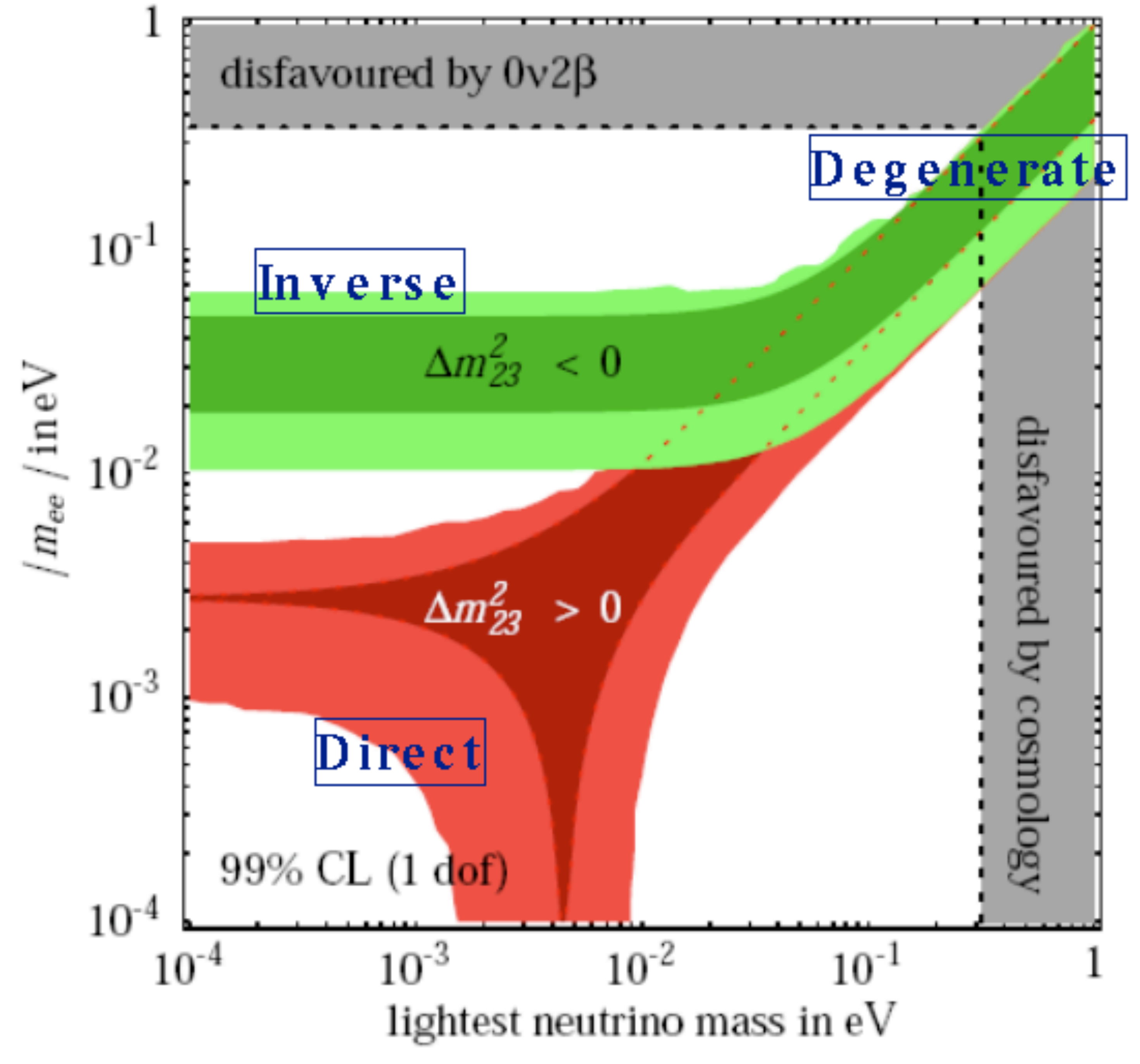
Majorana Neutrinos

Massive Neutrinos

If observed:

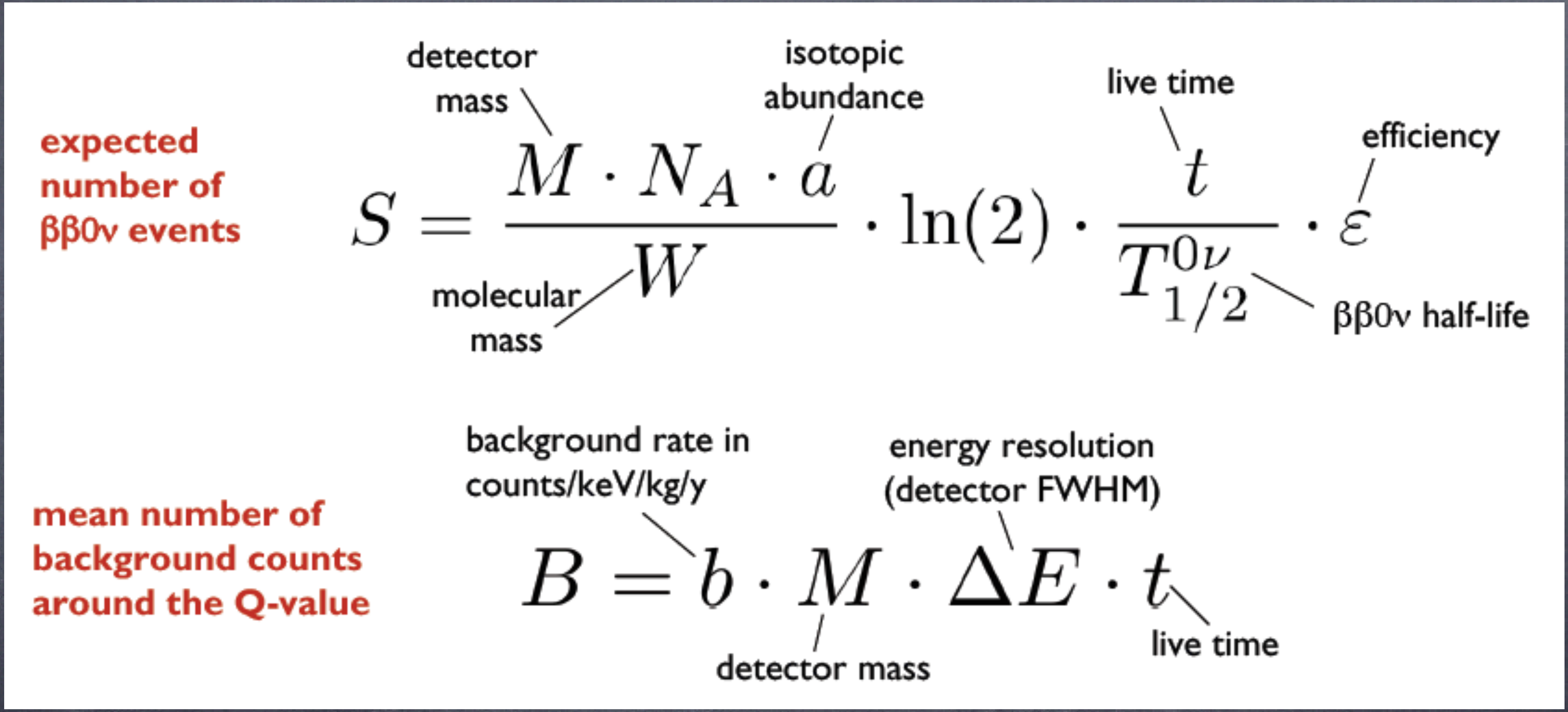
Proof of the Majorana nature of Neutrino and a scale for the mass

that translates into a nice plot



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

The name of the game



expected number of ββ0ν events

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

mean number of background counts around the Q-value

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

The Problem

TeO_2 case

(CUORE)

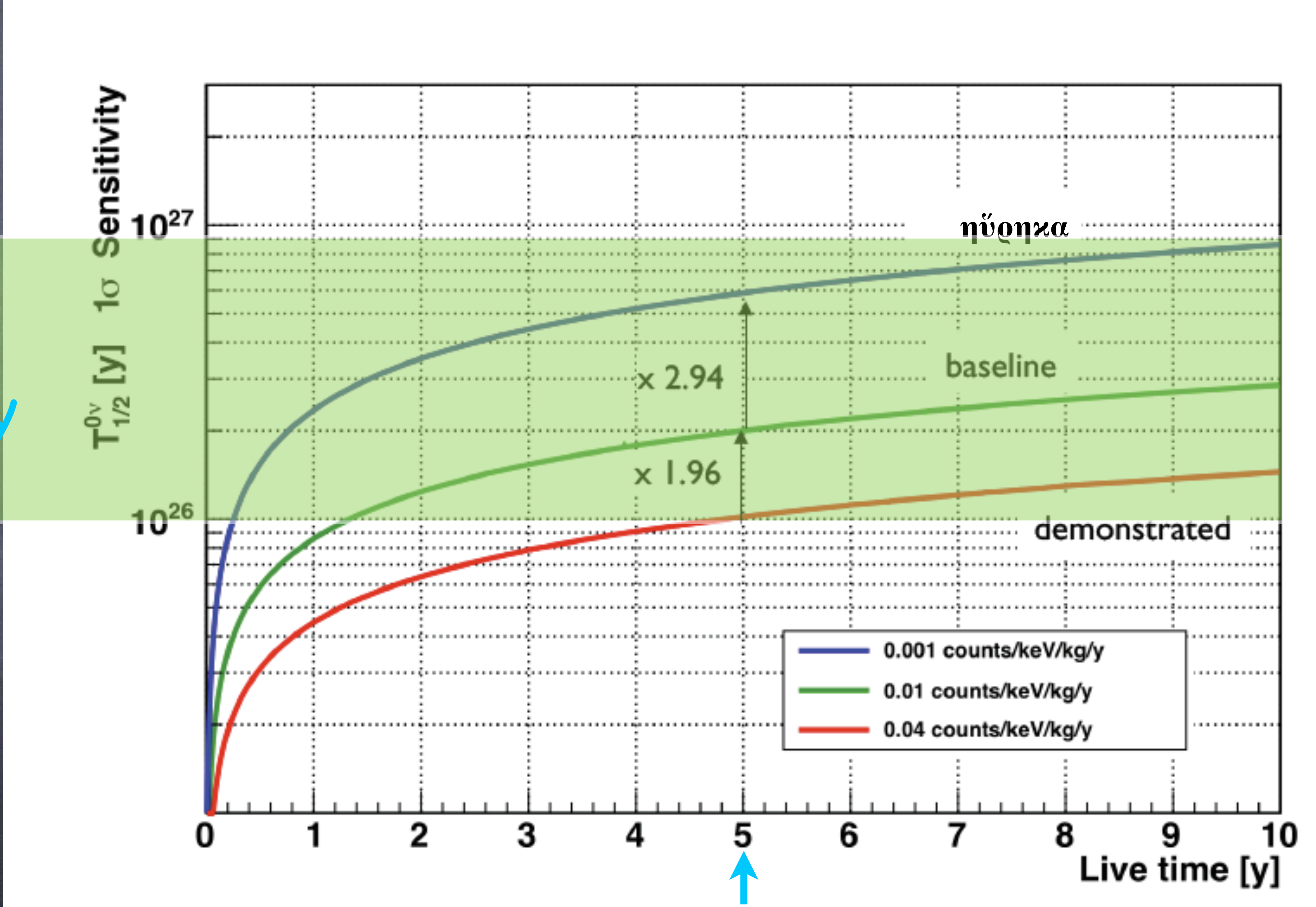
Inverted hyerarchy

740 Kg

of which

200 Kg

of ^{130}Te



1 ton•y

Sensitivity and background

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

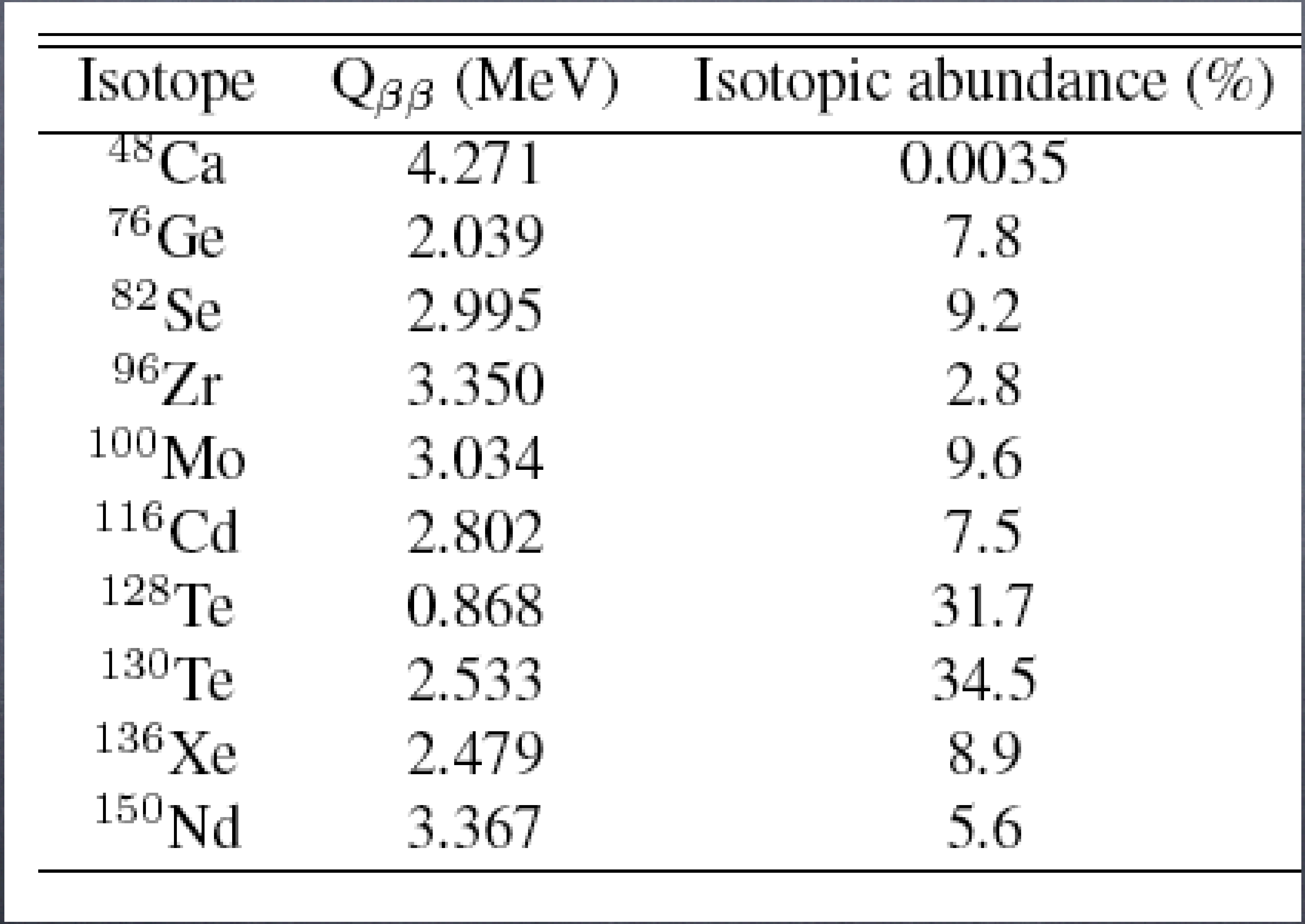
$m_{\beta\beta} \propto \sqrt{}\ (1/\tau)$

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

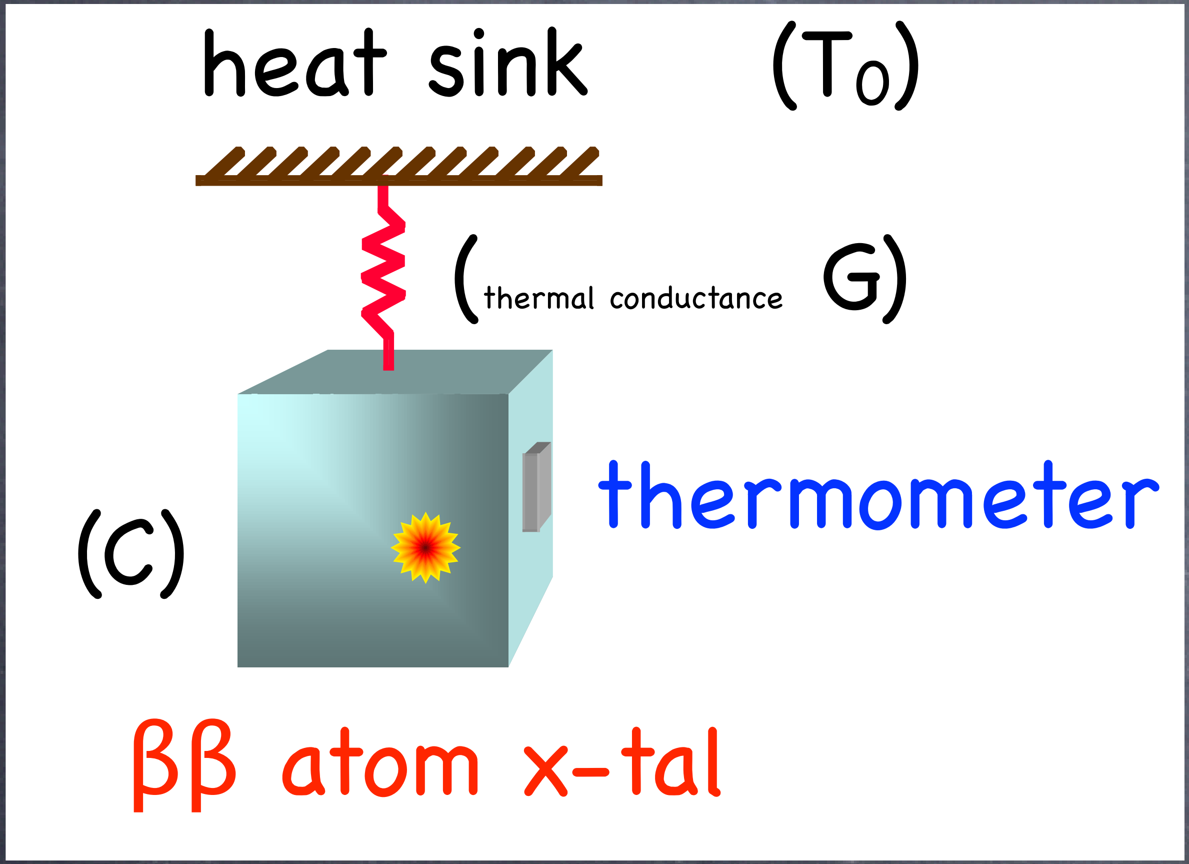
The (limited) material choice



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

(very) Low Temperature Calorimeter

A True Calorimeter



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

(Energy release/ Thermal capacity)

Implication: Low C ⇒ Low T

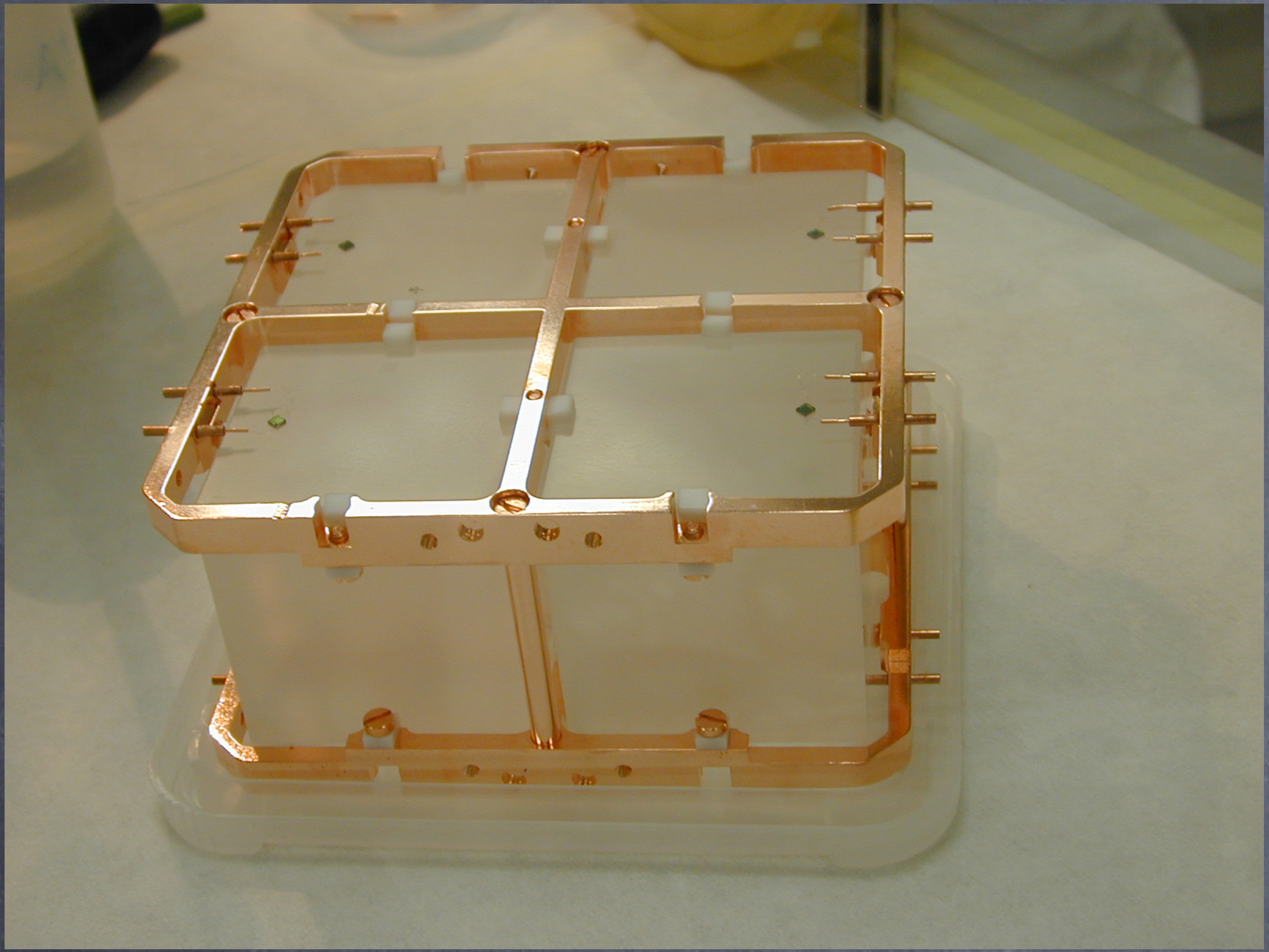
Bonus: (almost) No limit to ΔE ($k_B T^2 C$)

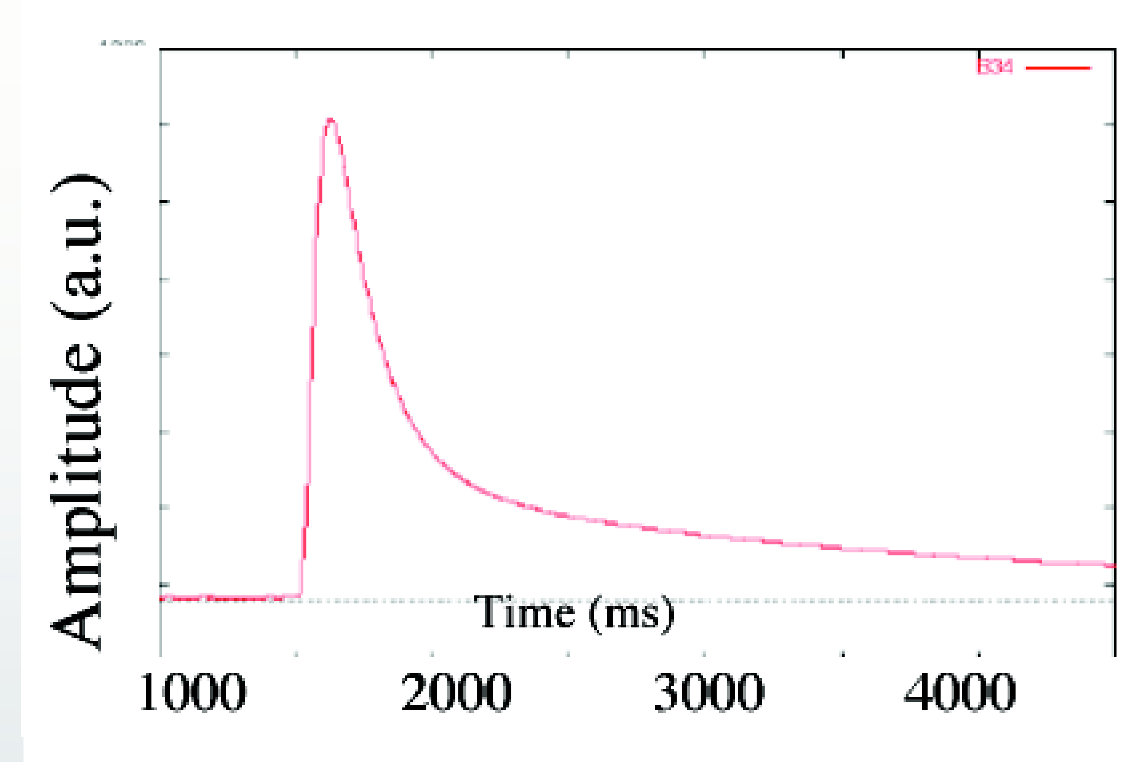
Not for all : $\tau = C/G \sim 1\text{s}$

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

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

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:

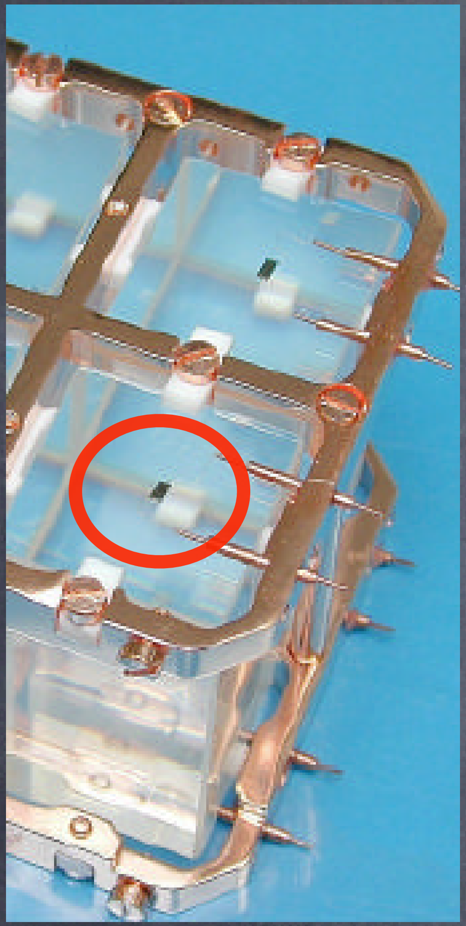
$T_0 \sim 10$ mK

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

$G \sim 4$ pW/mK

to read the temperature you need a thermometer

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

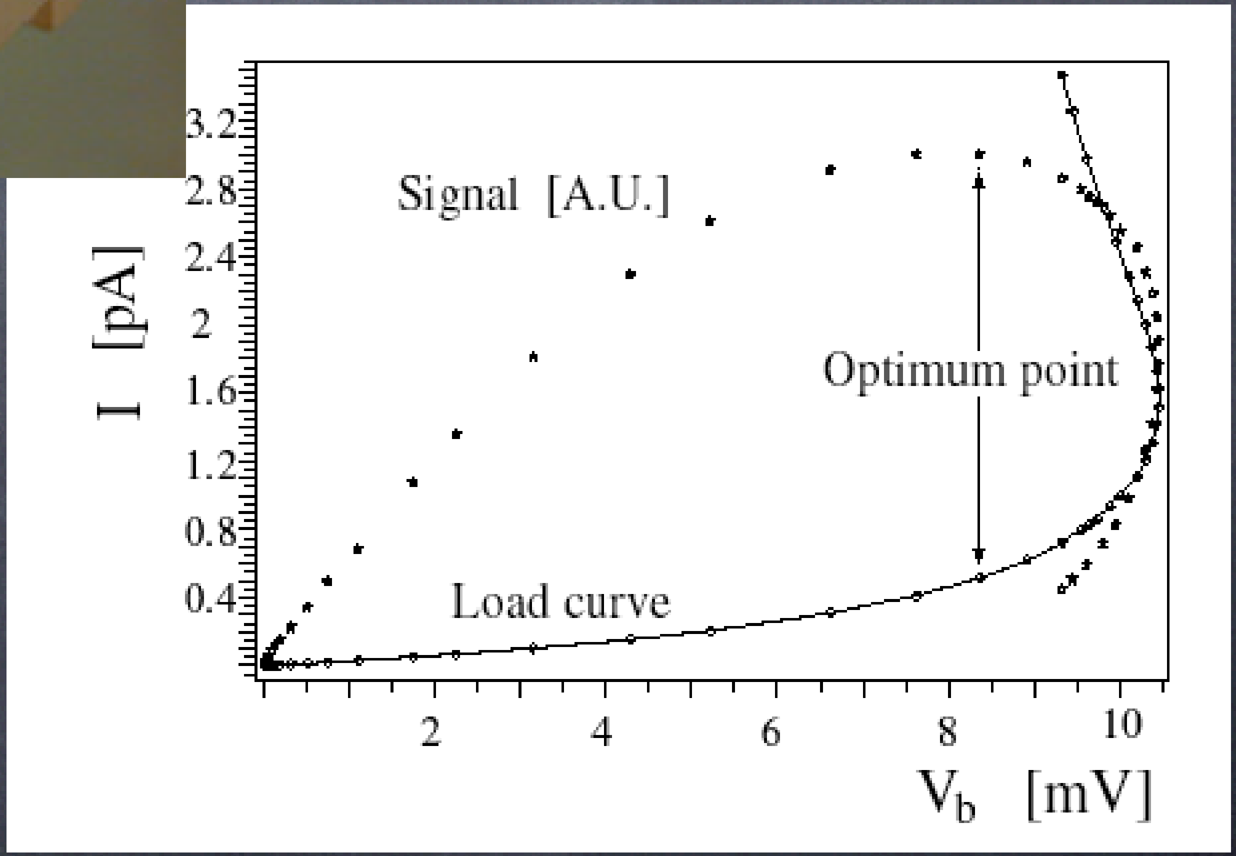


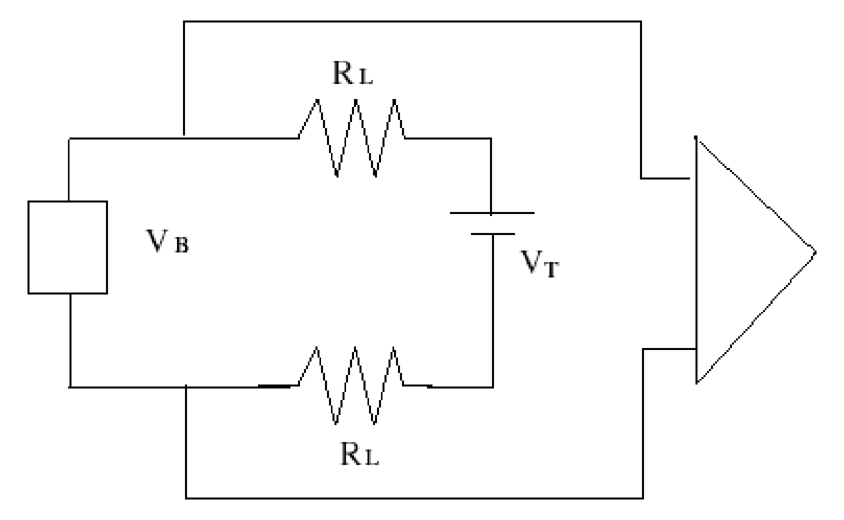
Neutron Transmutation Doped (NTD) Germanium Thermistor

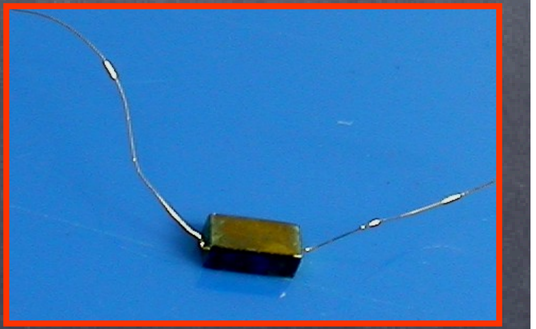
I ~ 50 pA

dR/dE ~ 20kΩ/KeV

0.2mV/MeV

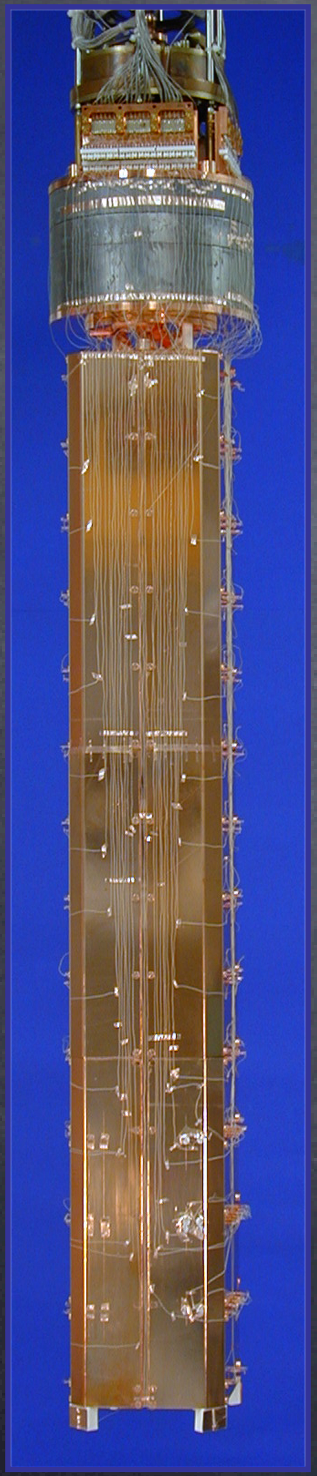


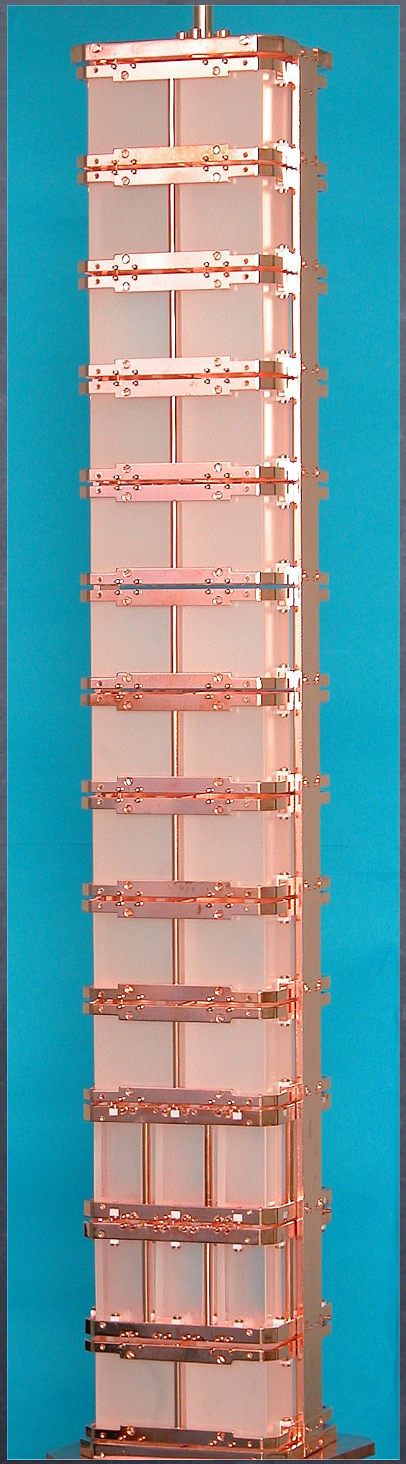


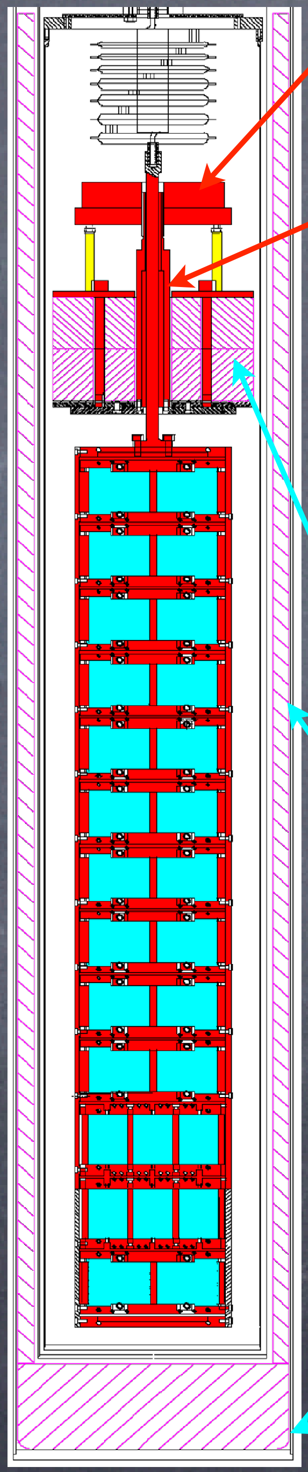


$$T_b = T_0 + \frac{P}{G}$$

Cuoricino





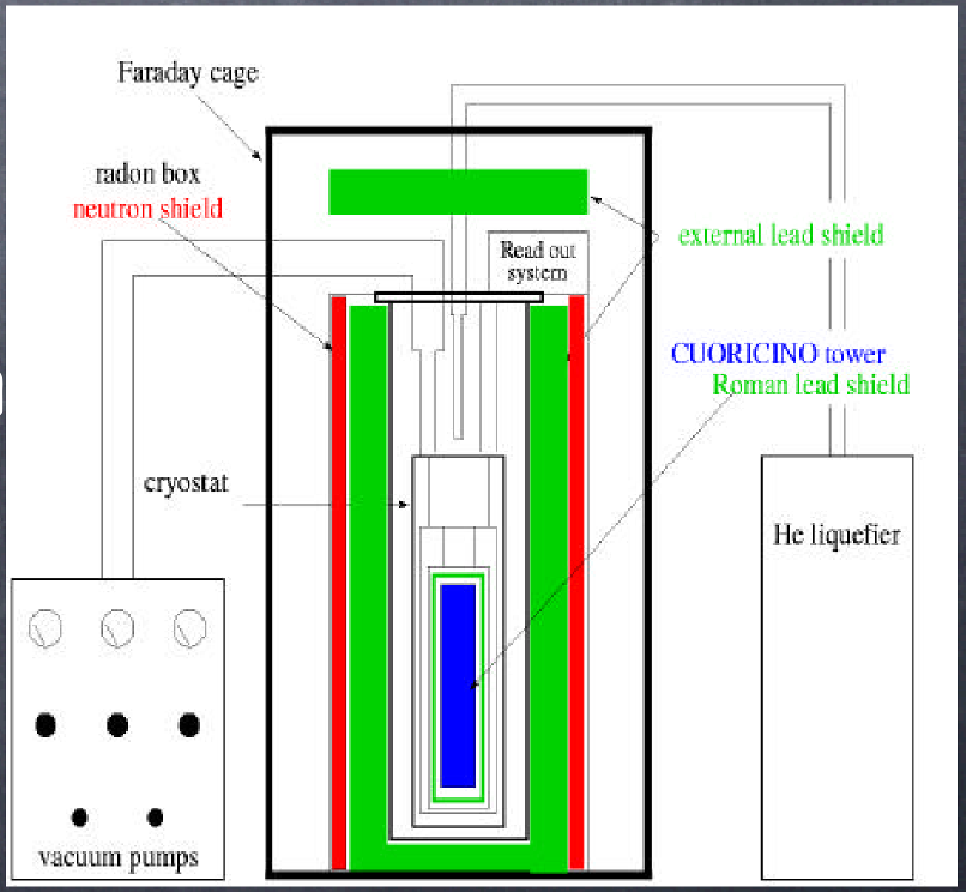


Mixing chamber

Cold finger

10 mK

Roman Lead Shield



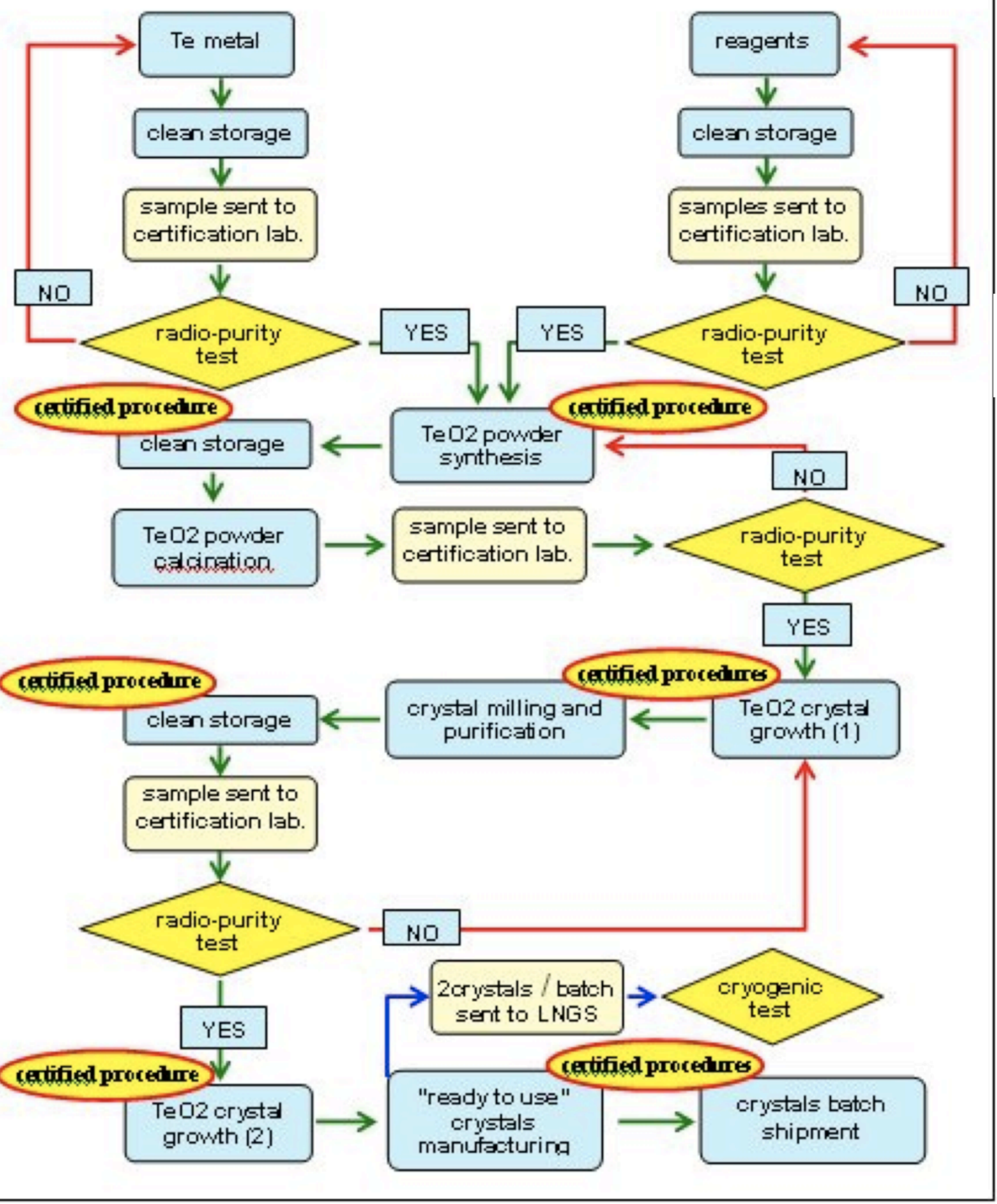
The production challenge

- In a normal case, you ask a producer to make your crystals (BGO, CsI, $PbWO_4$, LYSO...) after having specified the protocol in a dedicated R&D
- You can test the delivered units, one by one, fastly for possible main defects (transmission, absorption, LY..) and reasonably soon for high level checks (resolution, radiation resistance)
- You are therefore able to intervene during production almost in real time

for 10mK calorimetry

- once you have defined protocol and production parameter it is almost impossible to follow up delivery with tests
- Basic checks: Pulse Height (mV/ μK) and Po contamination requires cooling them after the transport (by sea and not air !)....say 1-2 months
- High level checks: Bulk U,Th contamination, surface α emission takes months (remember that counting rate is hopefully < 0.1 counts/Kg/KeV/year)

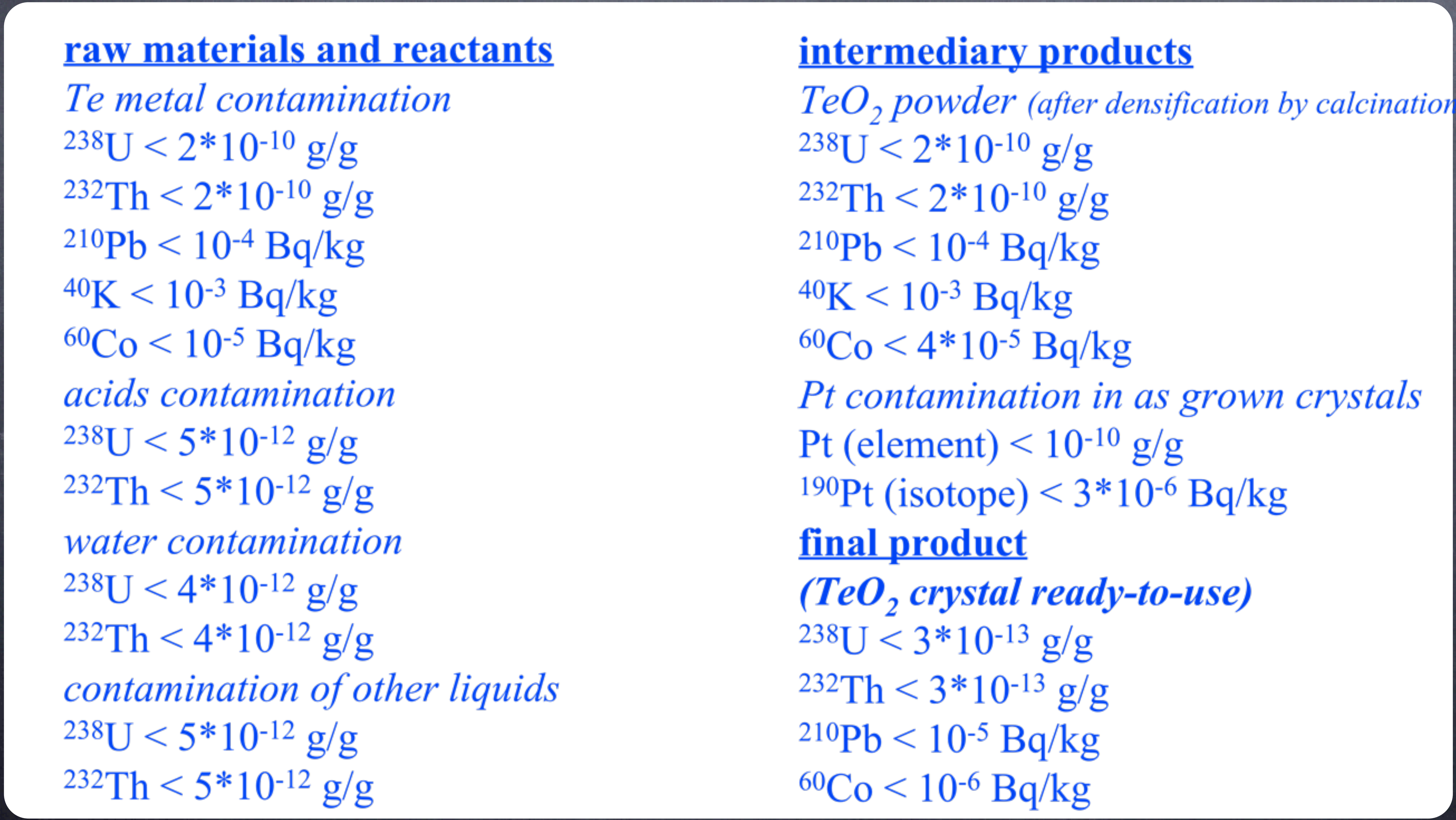
Production management



TeO_2 crystals produced at SICCAS (China) have bolometric and radio-purity characteristics within tolerance limits imposed by CUORE collaboration

a list of requests

close to or below detection limit of most sensitive techniques used for quantitative elemental analysis (NAA, ICP-MS)



raw materials and reactants

Te metal contamination

^{238}U < $2*10^{-10}$ g/g

^{232}Th < $2*10^{-10}$ g/g

^{210}Pb < 10^{-4} Bq/kg

^{40}K < 10^{-3} Bq/kg

^{60}Co < 10^{-5} Bq/kg

acids contamination

^{238}U < $5*10^{-12}$ g/g

^{232}Th < $5*10^{-12}$ g/g

water contamination

^{238}U < $4*10^{-12}$ g/g

^{232}Th < $4*10^{-12}$ g/g

contamination of other liquids

^{238}U < $5*10^{-12}$ g/g

^{232}Th < $5*10^{-12}$ g/g

intermediary products

TeO_2 powder (after densification by calcination)

^{238}U < $2*10^{-10}$ g/g

^{232}Th < $2*10^{-10}$ g/g

^{210}Pb < 10^{-4} Bq/kg

^{40}K < 10^{-3} Bq/kg

^{60}Co < $4*10^{-5}$ Bq/kg

Pt contamination in as grown crystals

Pt (element) < 10^{-10} g/g

^{190}Pt (isotope) < $3*10^{-6}$ Bq/kg

final product

(TeO_2 crystal ready-to-use)

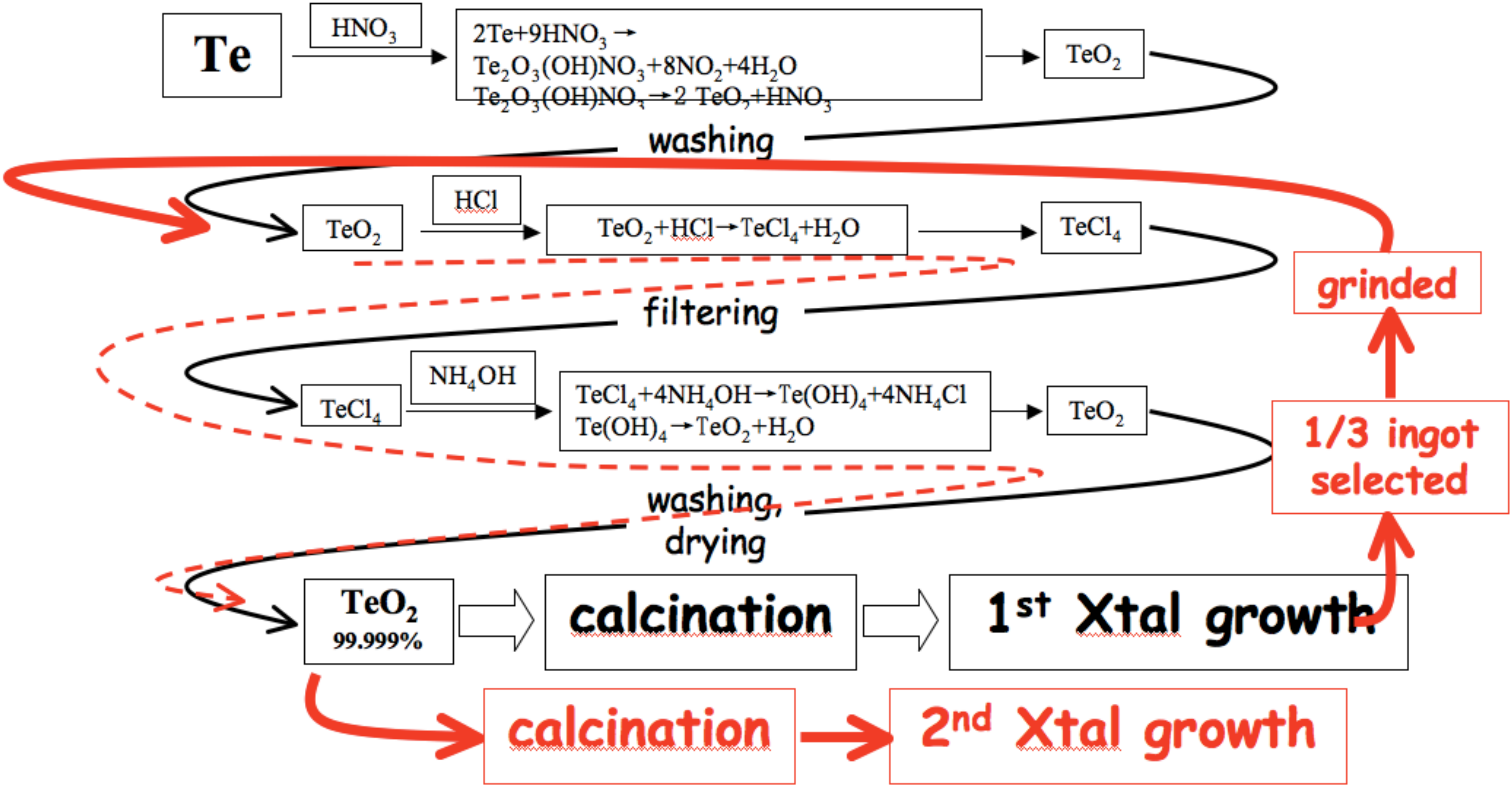
^{238}U < $3*10^{-13}$ g/g

^{232}Th < $3*10^{-13}$ g/g

^{210}Pb < 10^{-5} Bq/kg

^{60}Co < 10^{-6} Bq/kg

made simpler by the complex chemistry of the production !



Te

HNO_3

$2Te+9HNO_3 \rightarrow$
$Te_2O_3(OH)NO_3+8NO_2+4H_2O$
$Te_2O_3(OH)NO_3 \rightarrow 2\ TeO_2+HNO_3$

TeO_2

washing

TeO_2

HCl

$TeO_2+HCl \rightarrow TeCl_4+H_2O$

$TeCl_4$

filtering

$TeCl_4$

NH_4OH

$TeCl_4+4NH_4OH \rightarrow Te(OH)_4+4NH_4Cl$
$Te(OH)_4 \rightarrow TeO_2+H_2O$

TeO_2

washing, drying

TeO_2
99.999%

calcination

1st Xtal growth

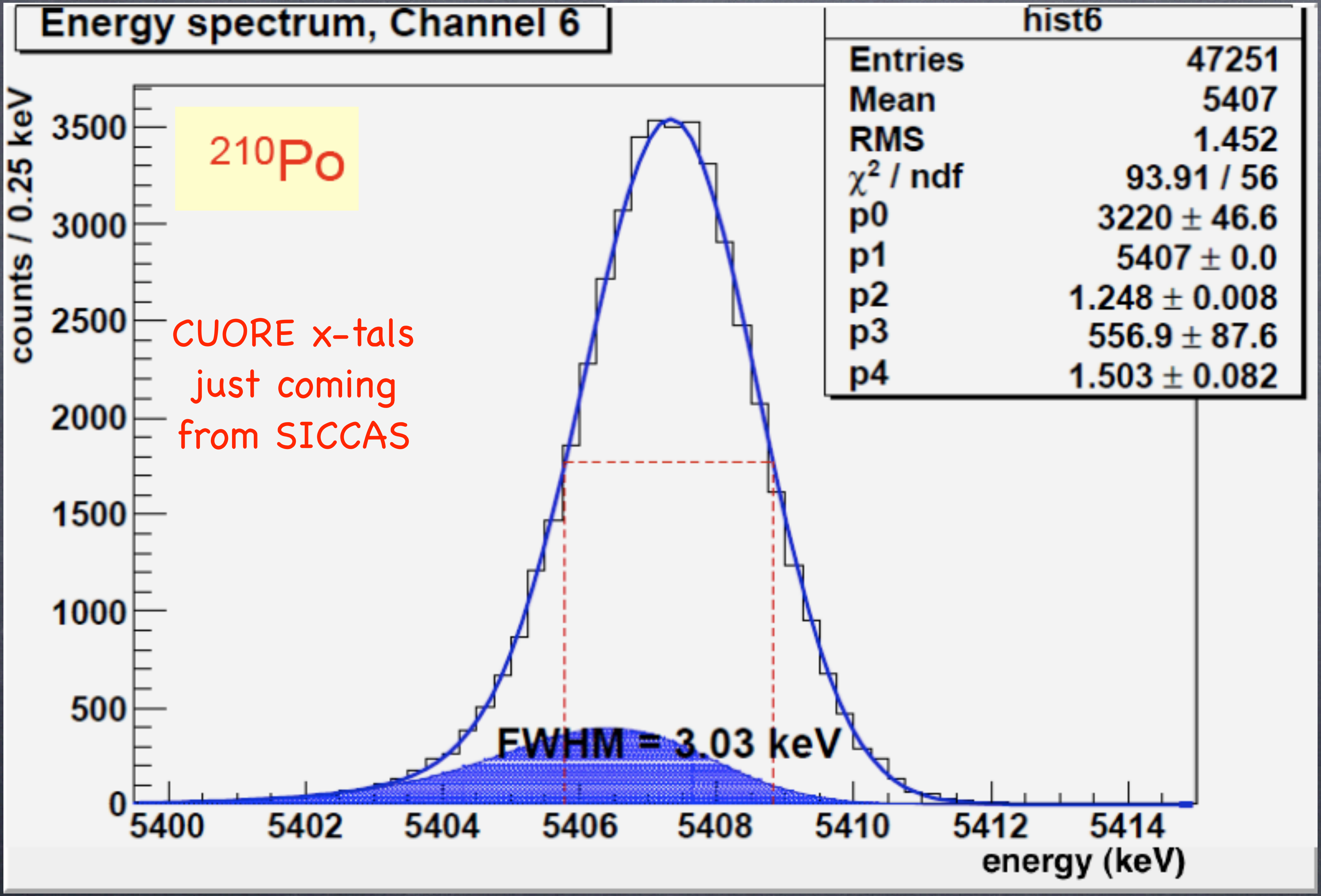
1/3 ingot selected

grinded

calcination

2nd Xtal growth

Energy Resolution



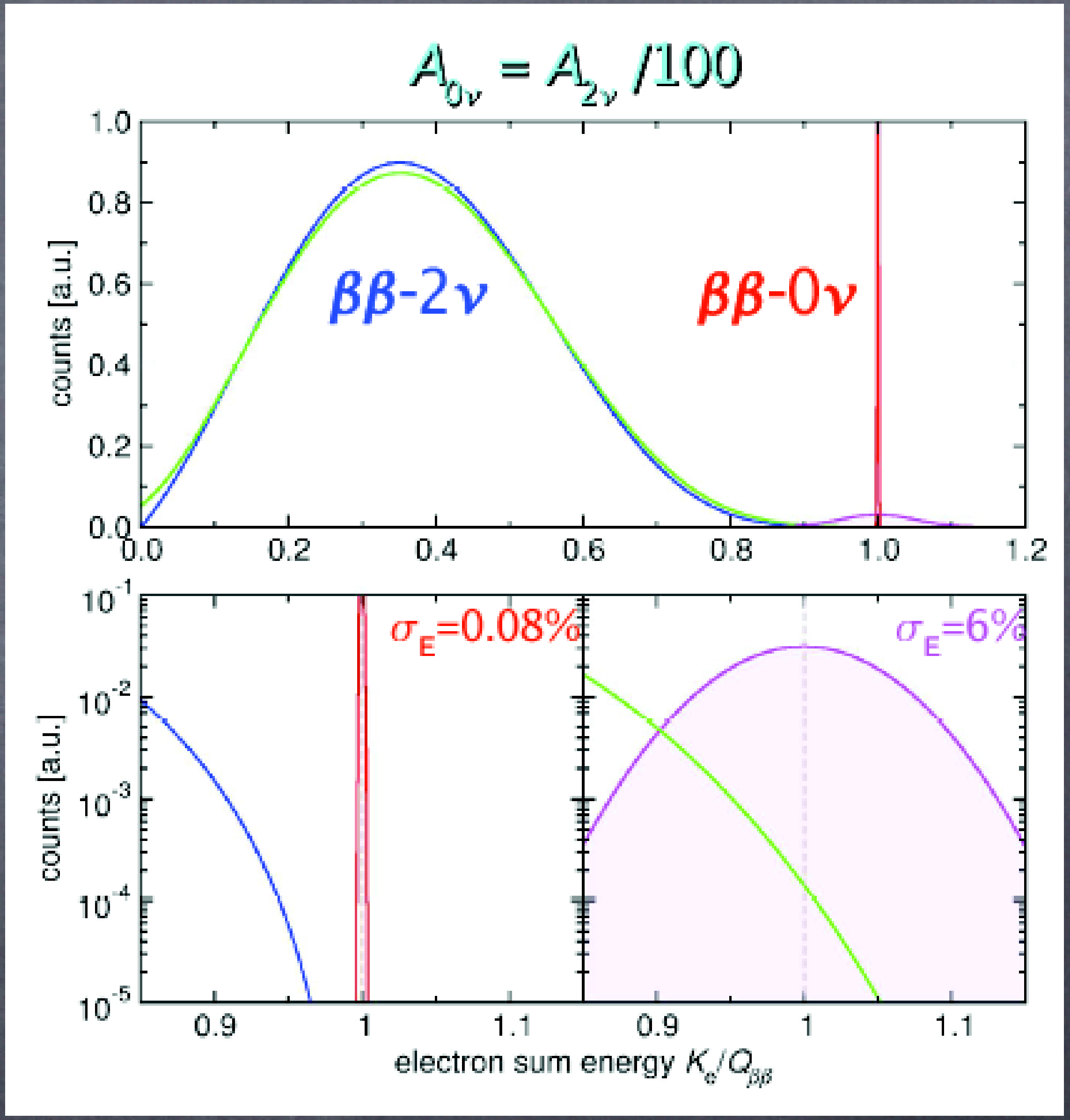
^{210}Po

CUORE x-tals
just coming
from SICCAS

The impact of ΔE ?

- background will accumulate proportionally to the width of the window determined by energy resolution. You can always hope to reduce the background and alleviate the problem

- irreducible backround however cannot be reduced !!
  The 2vDBD tail will always be there



On the back of the envelope

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

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

Please note $\delta^6 \, (Q^{11}/Q^5)$

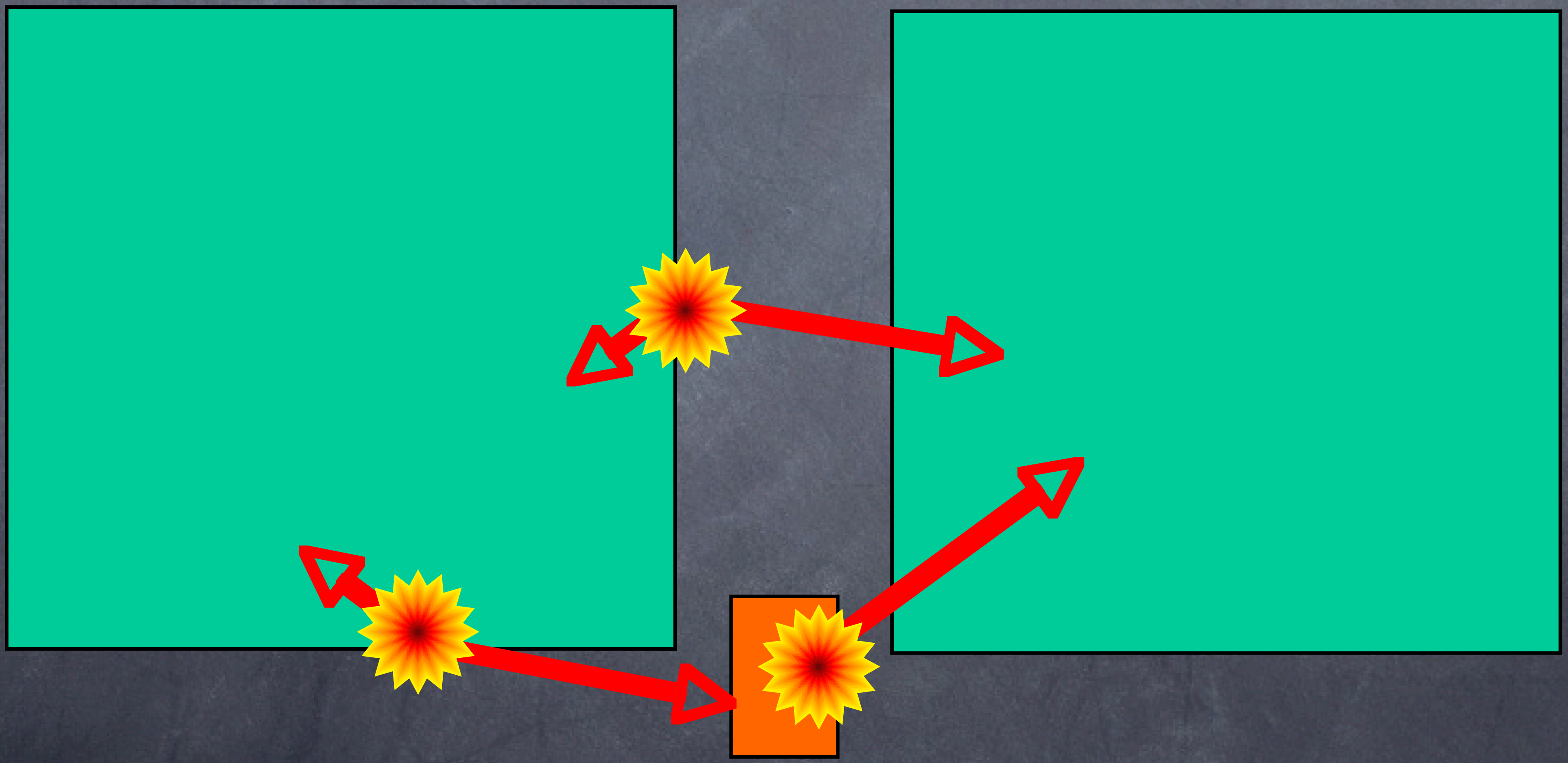
$T^{0\nu} \simeq 10^{28} y$ $\quad$ $S/B = 1$

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

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

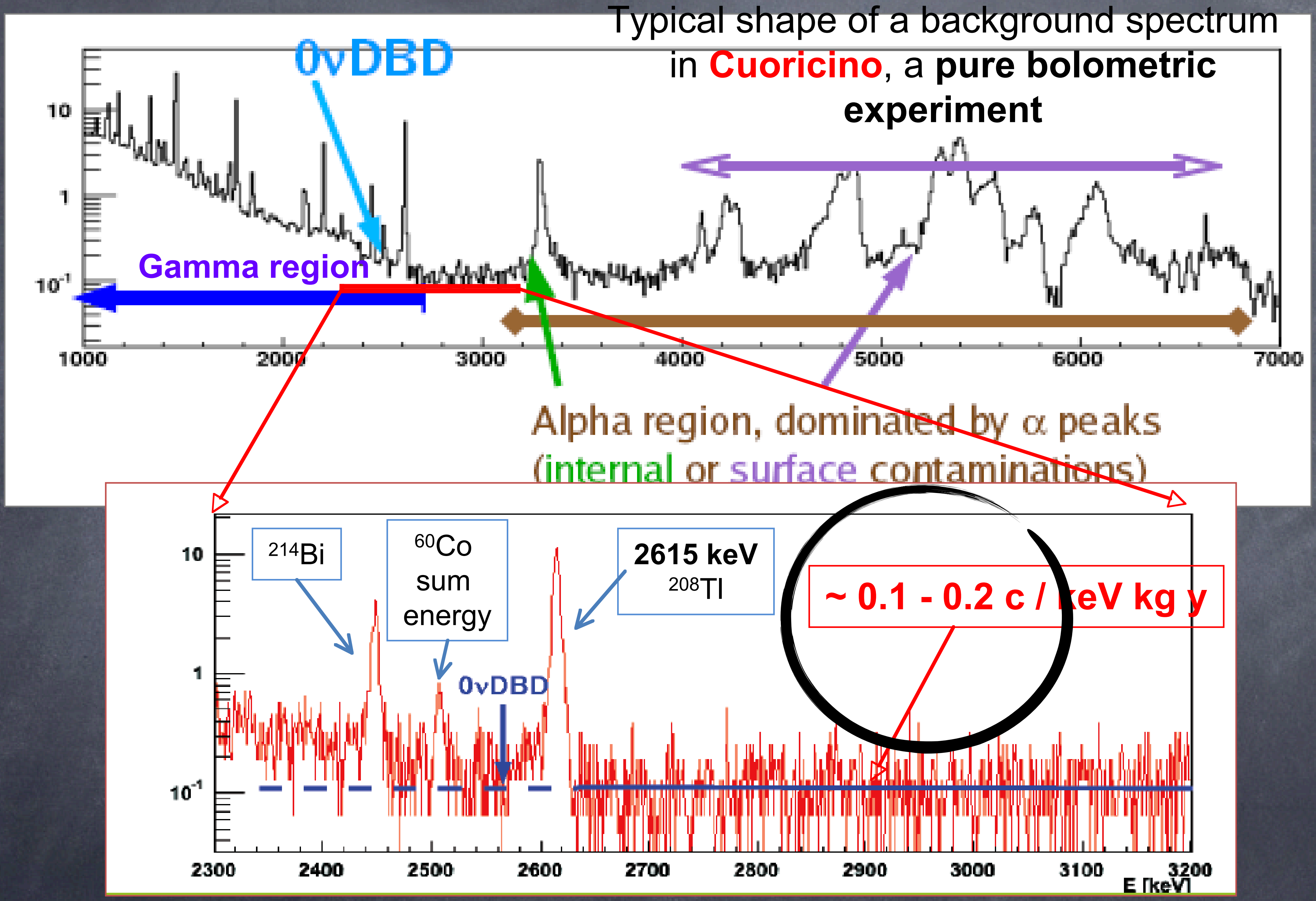
The problem to solve:

α background



Degraded α's

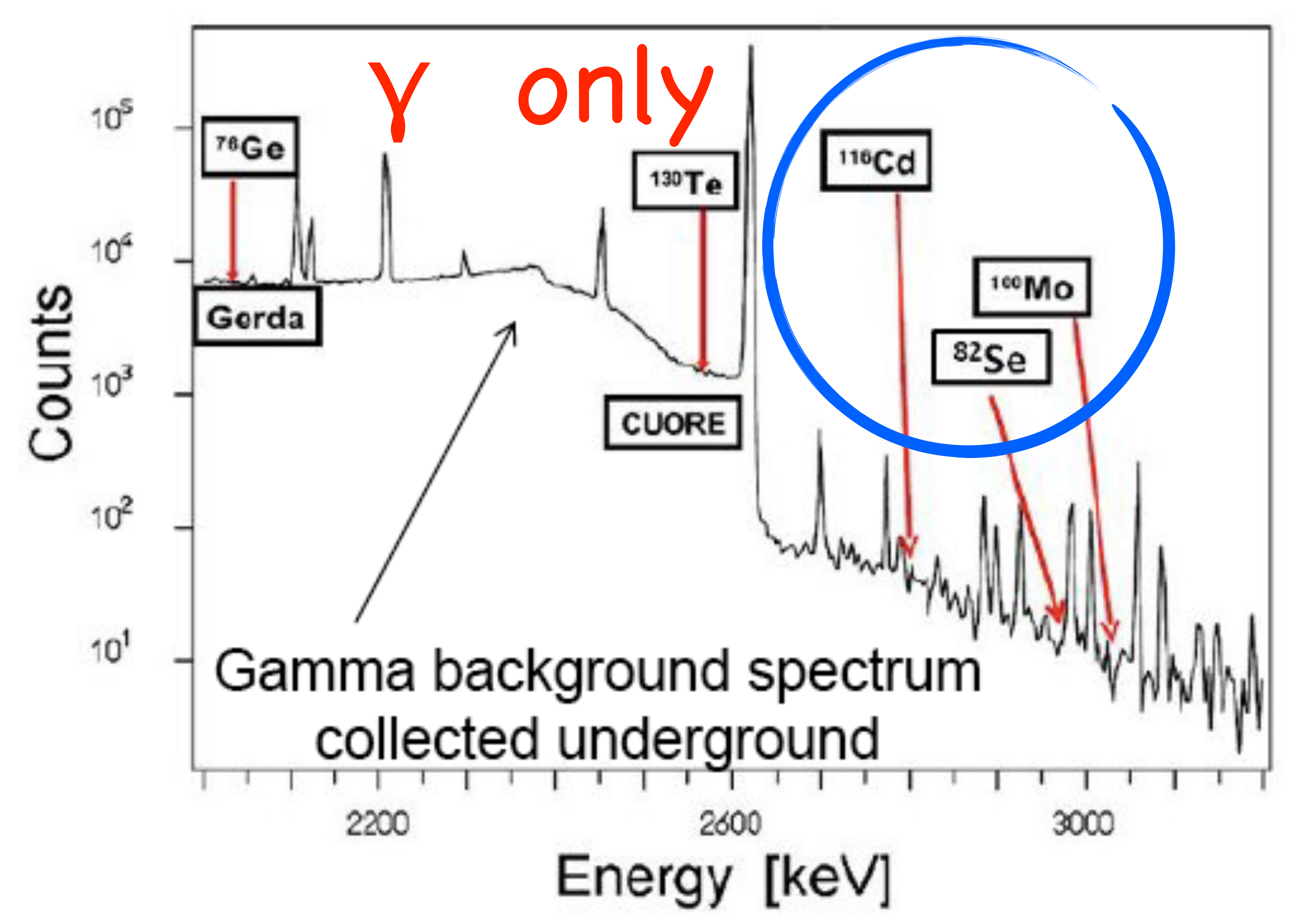
Where we start from



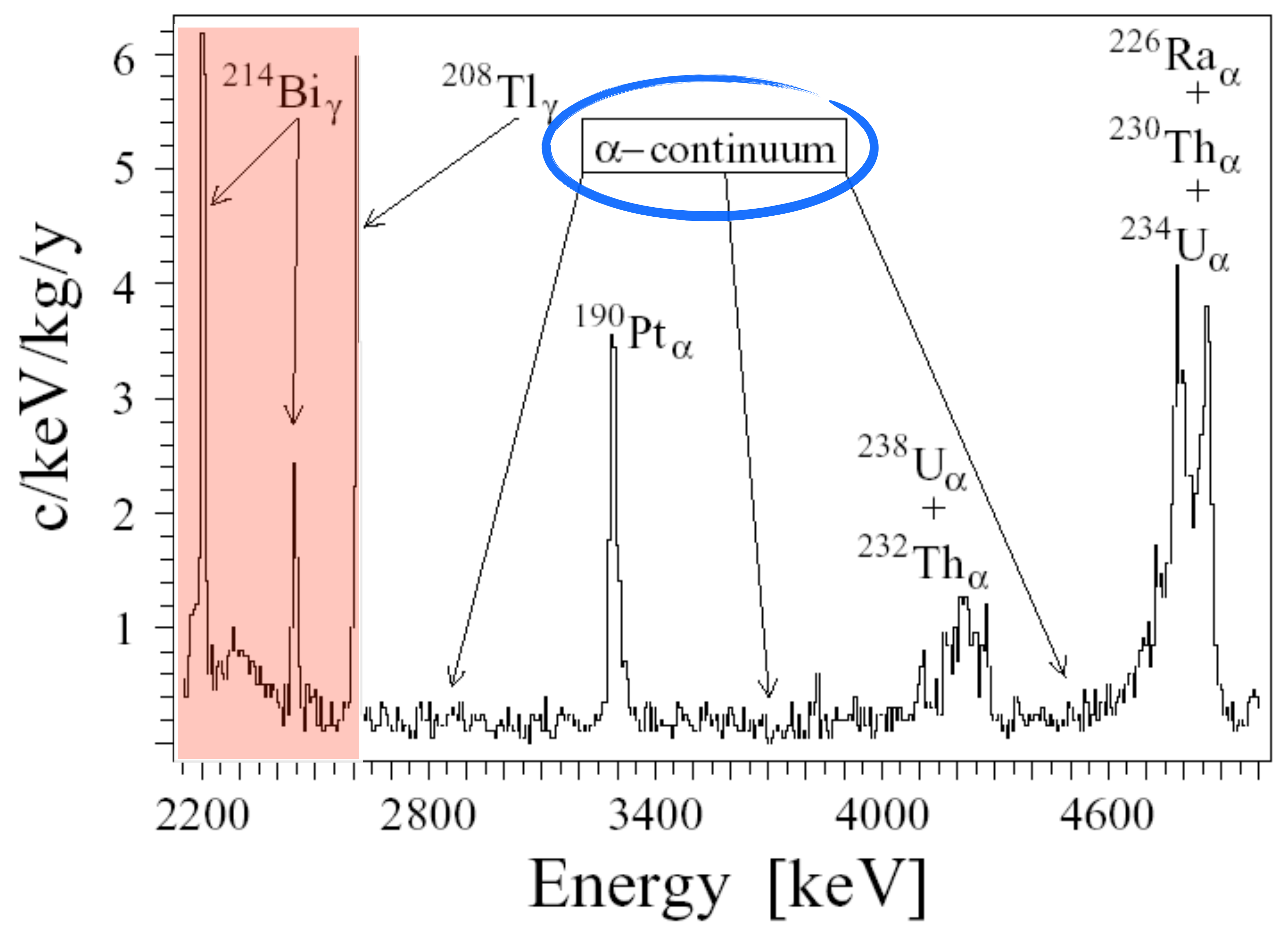
Typical shape of a background spectrum in **Cuoricino**, a **pure bolometric experiment**

Alpha region, dominated by α peaks (internal or surface contaminations)

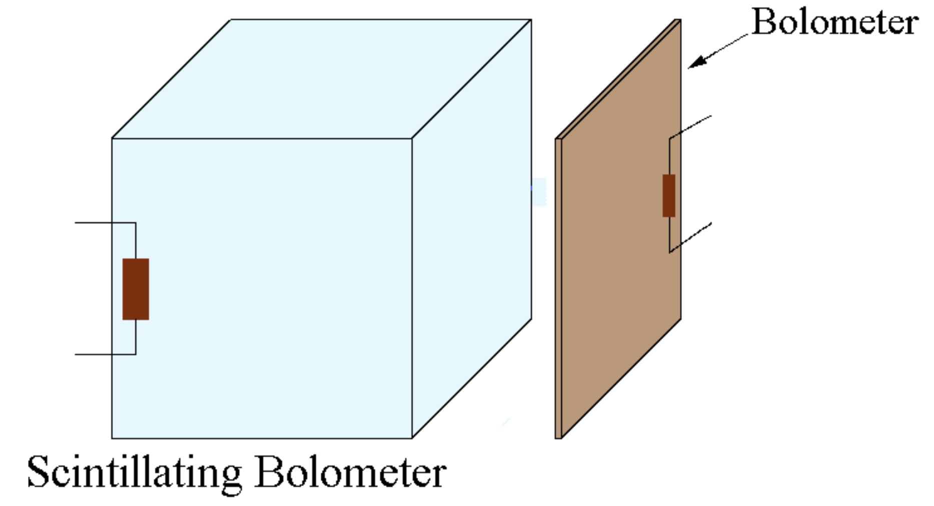
The γ step is 'easy'

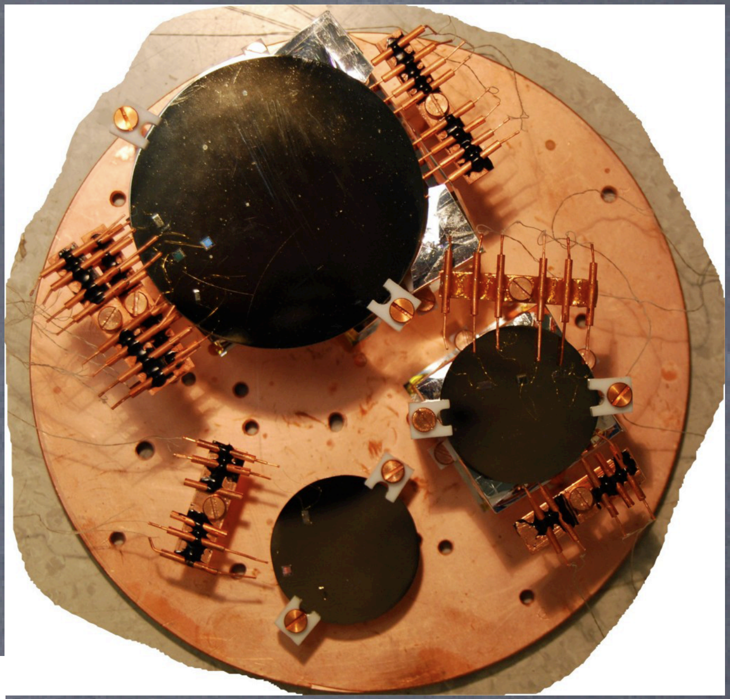


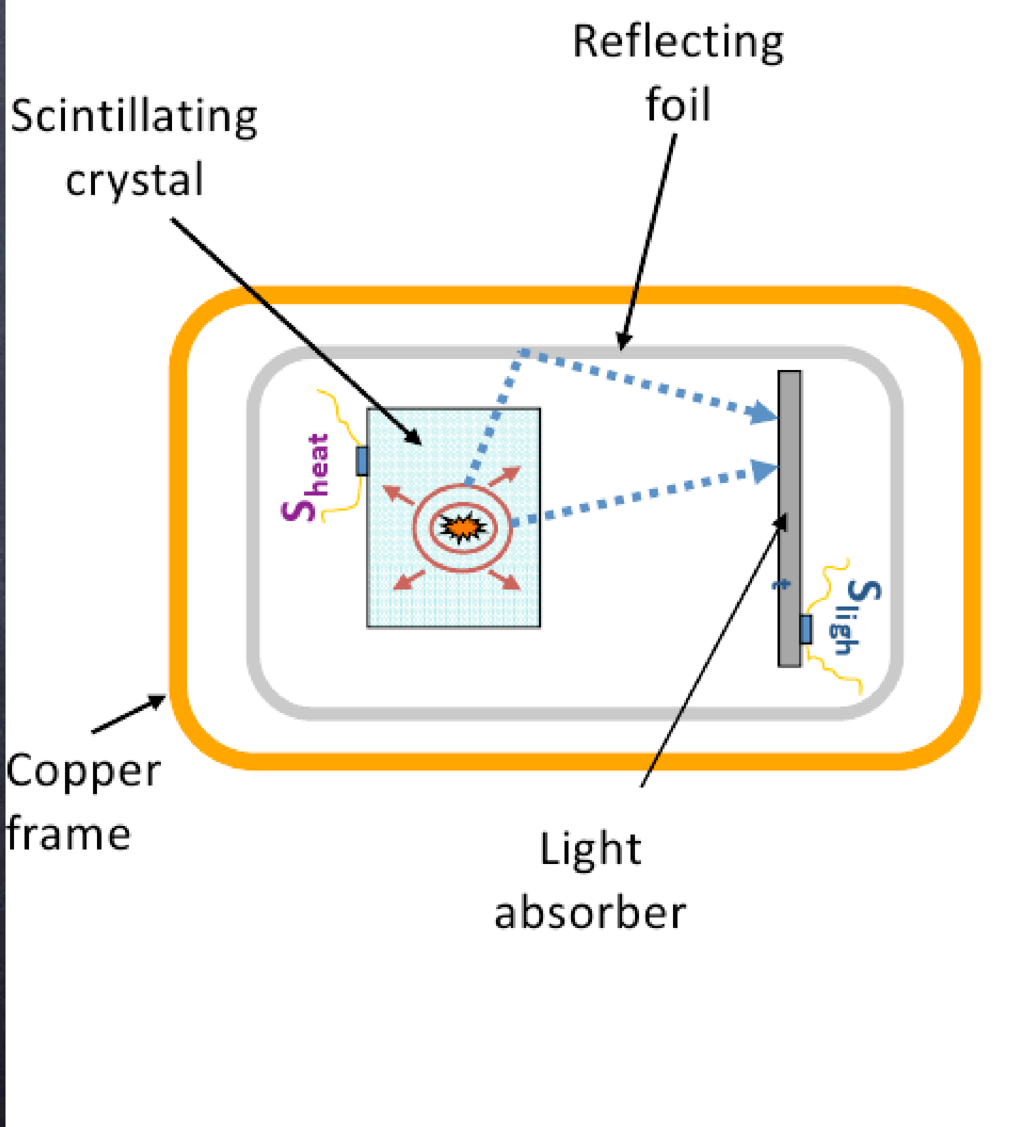
The α step is ‘difficult’

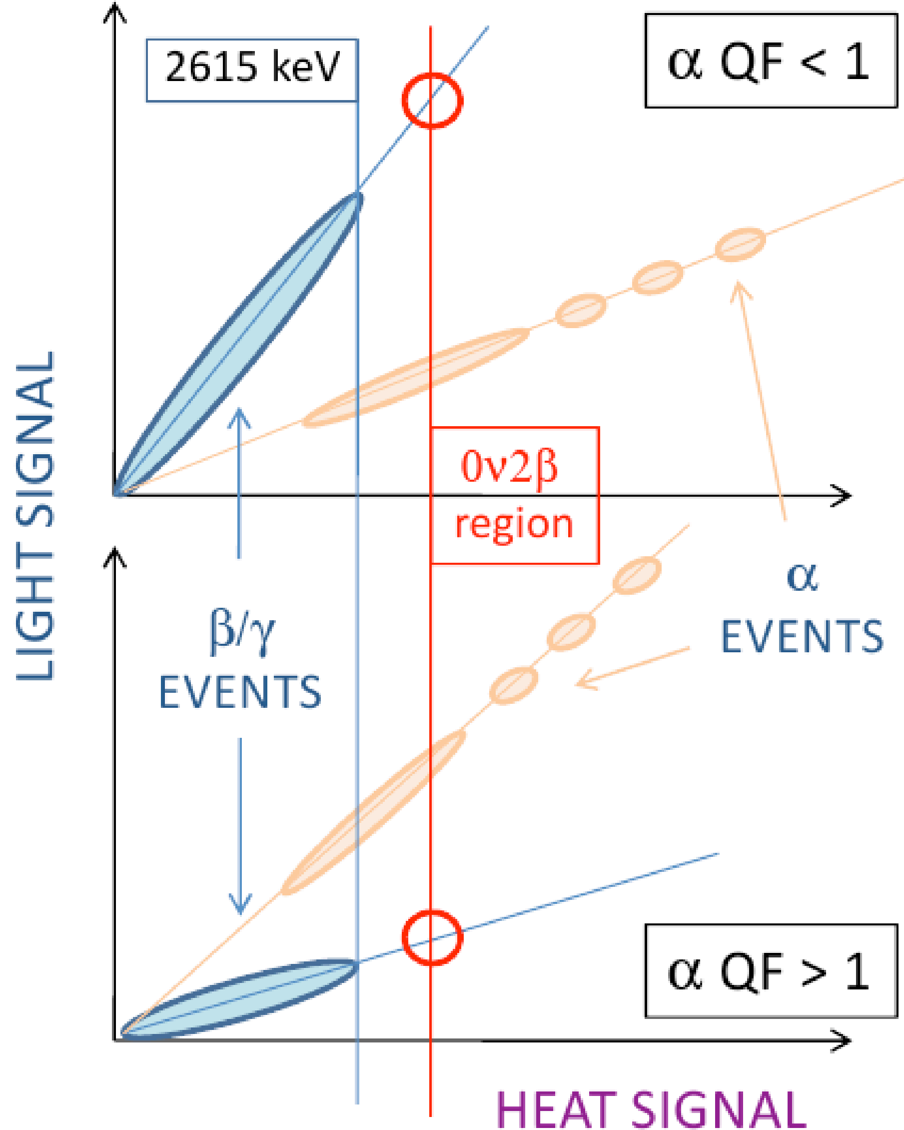


Double read-out









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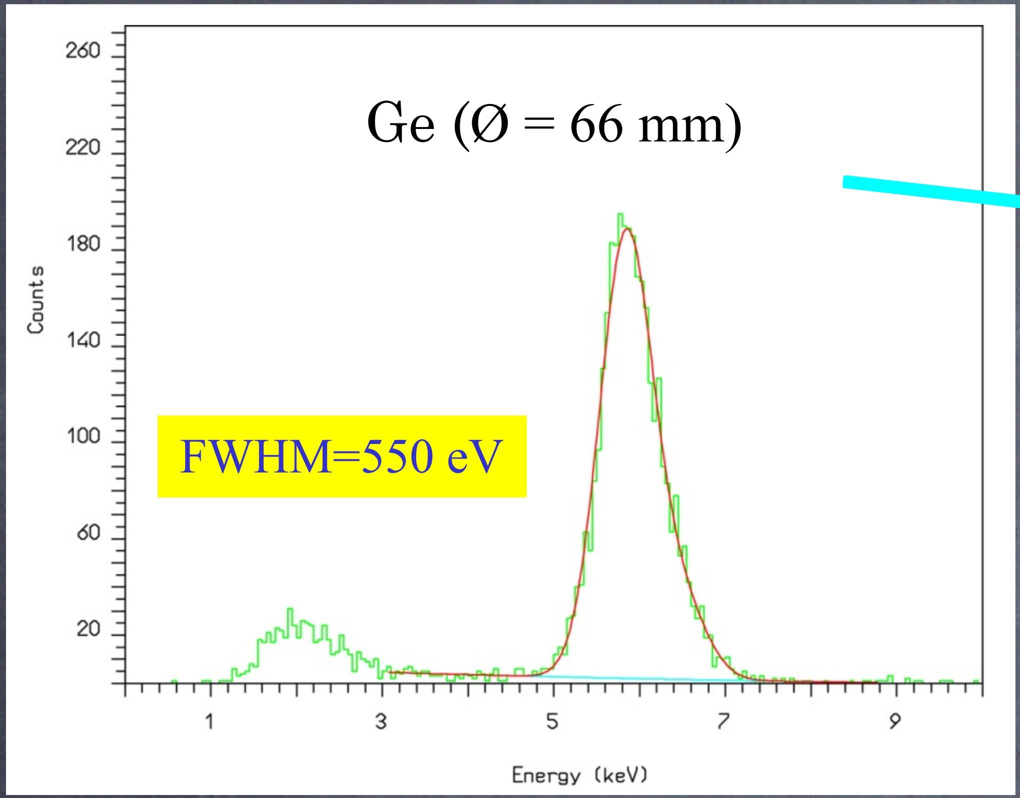
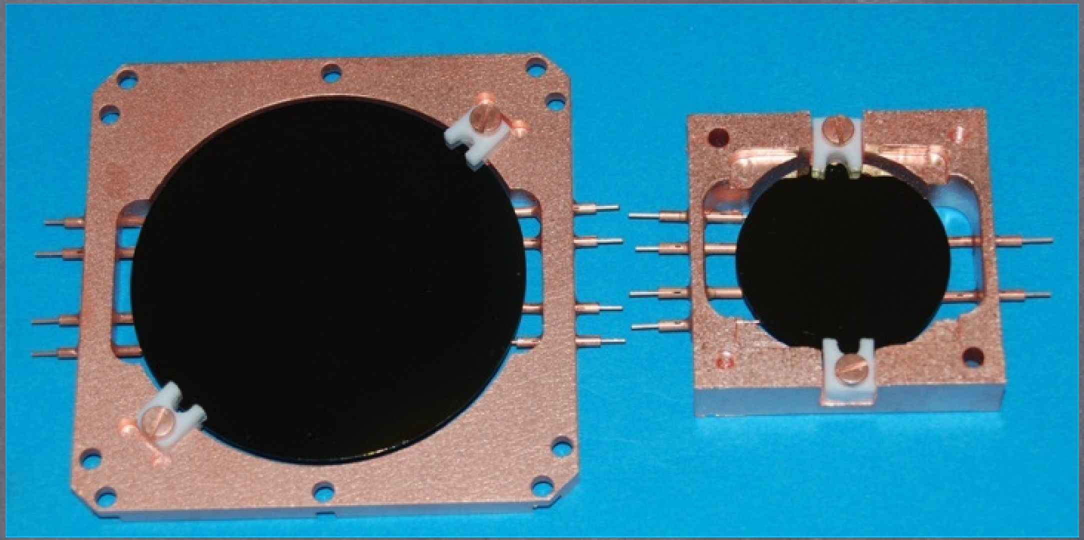
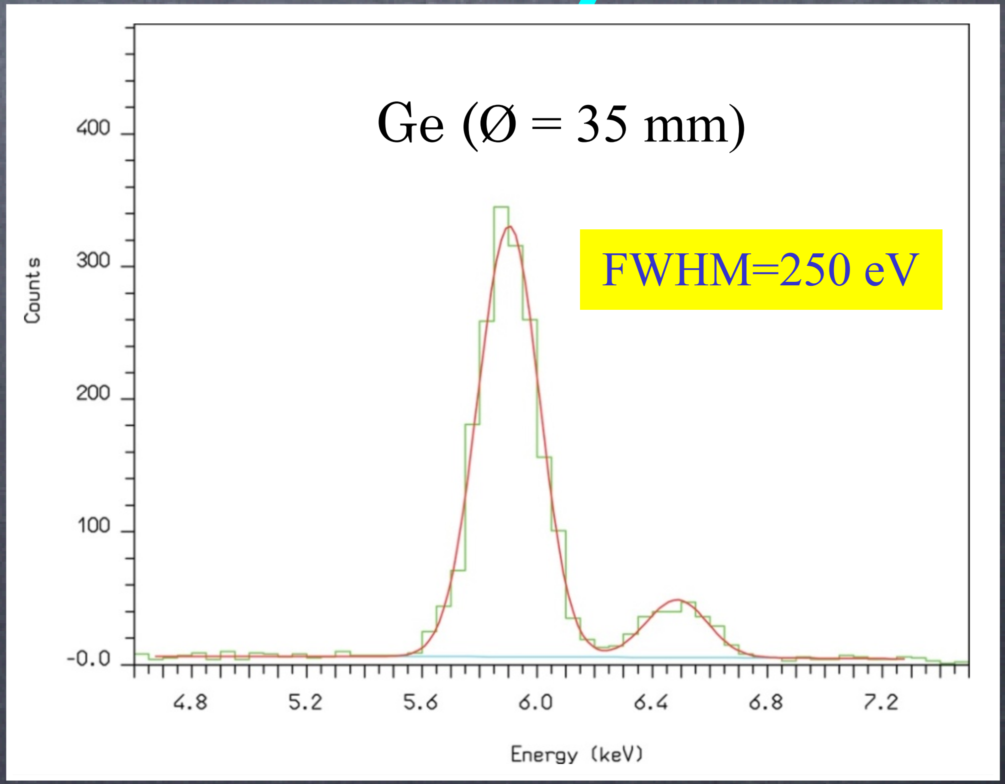
Light detectors

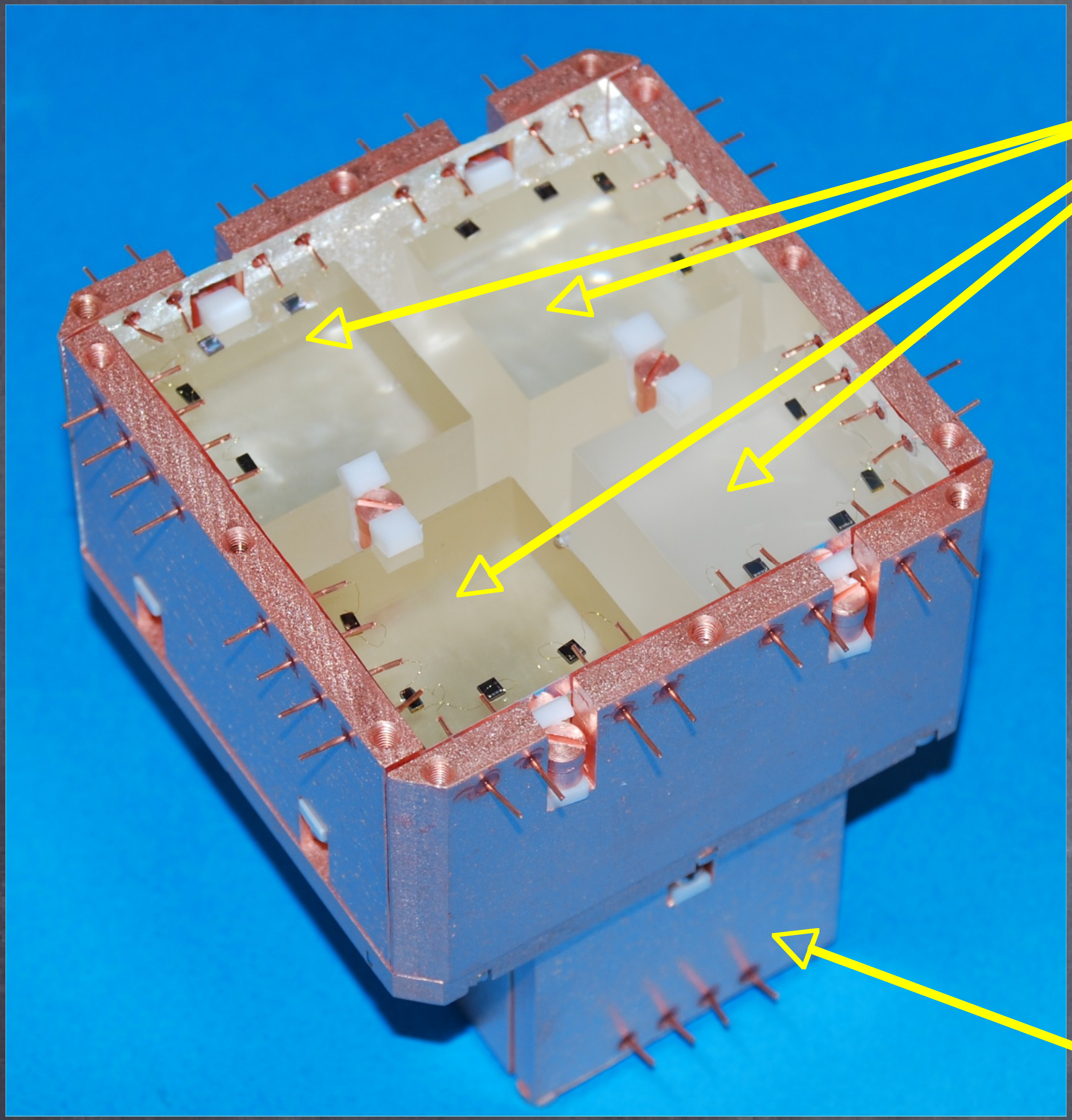






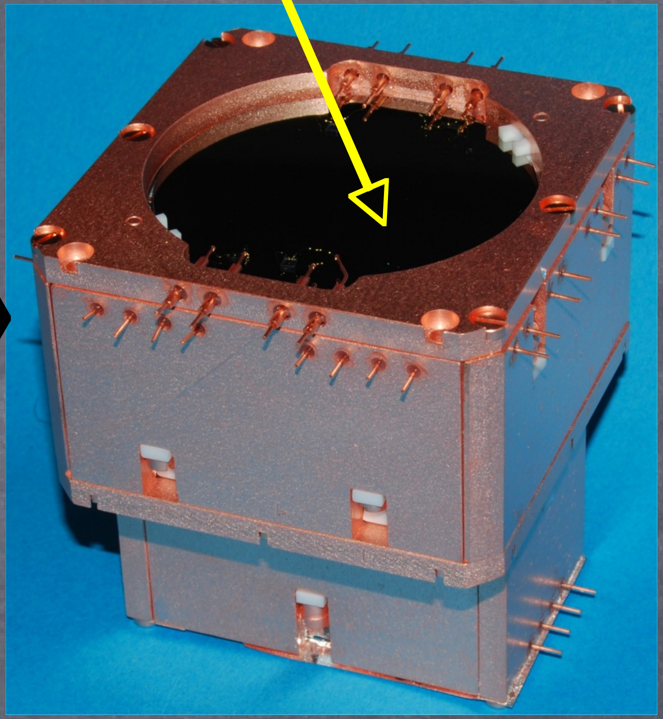
Light detectors are generally Pure Germanium disks (thickness 0.3-1 mm) .
The Performances of a LD are normally evaluated through the Energy resolution on the ^{55}Fe doublet (5.9 & 6.5 keV X-Ray)

The best so-far



4 3x3x3 cm^3 (215 g each) $CdWO_4$

1 common LD facing the 4 crystals



$CdWO_4$ – 3x3x6

Roman
Pb shield

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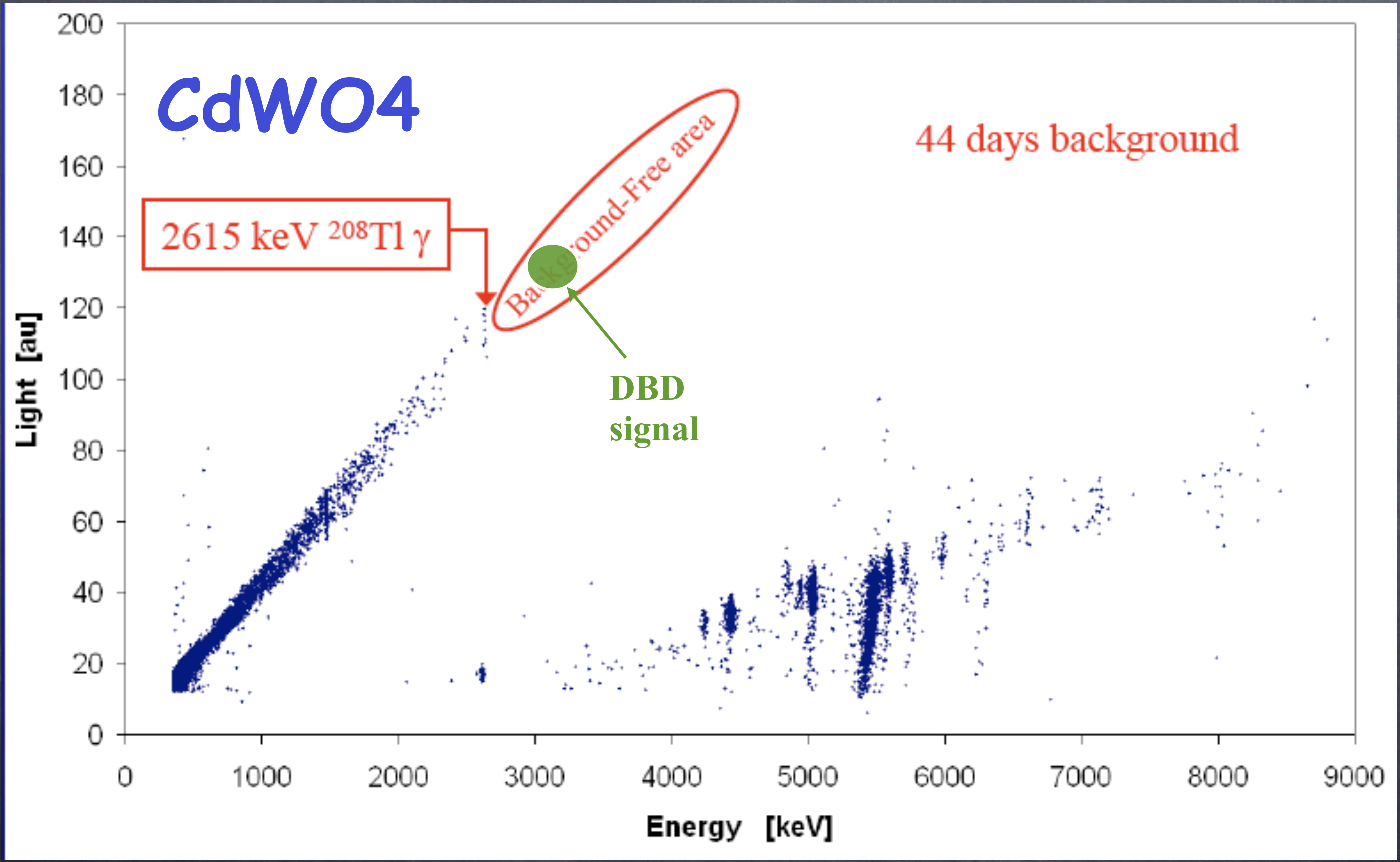
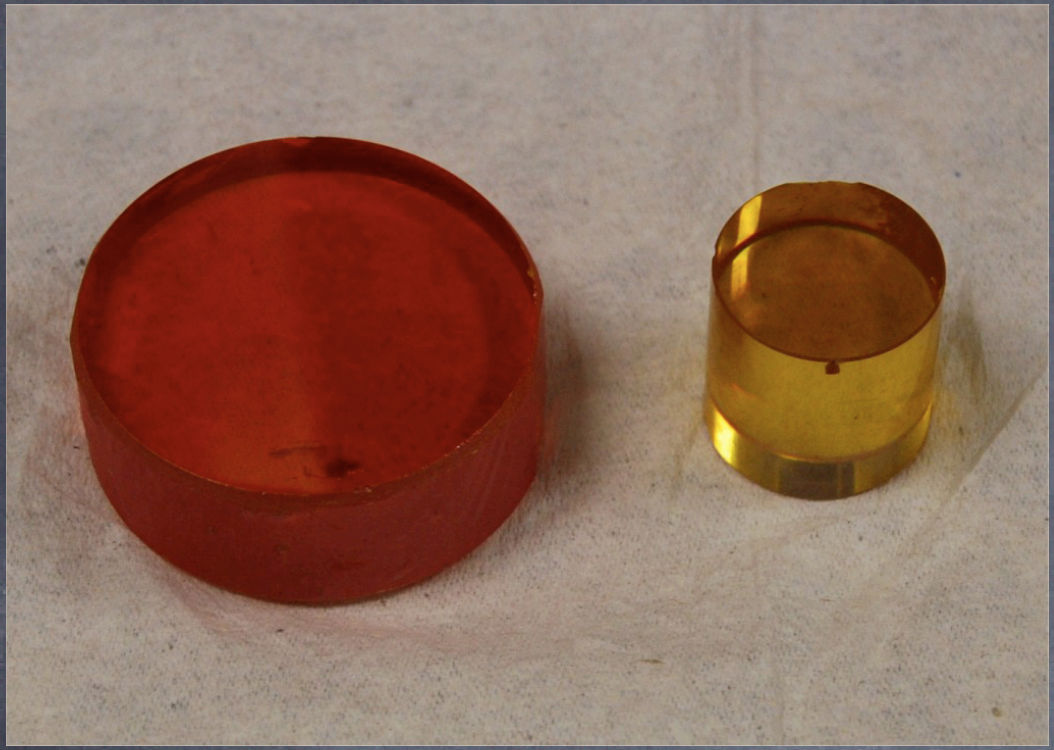
just to make the case clear



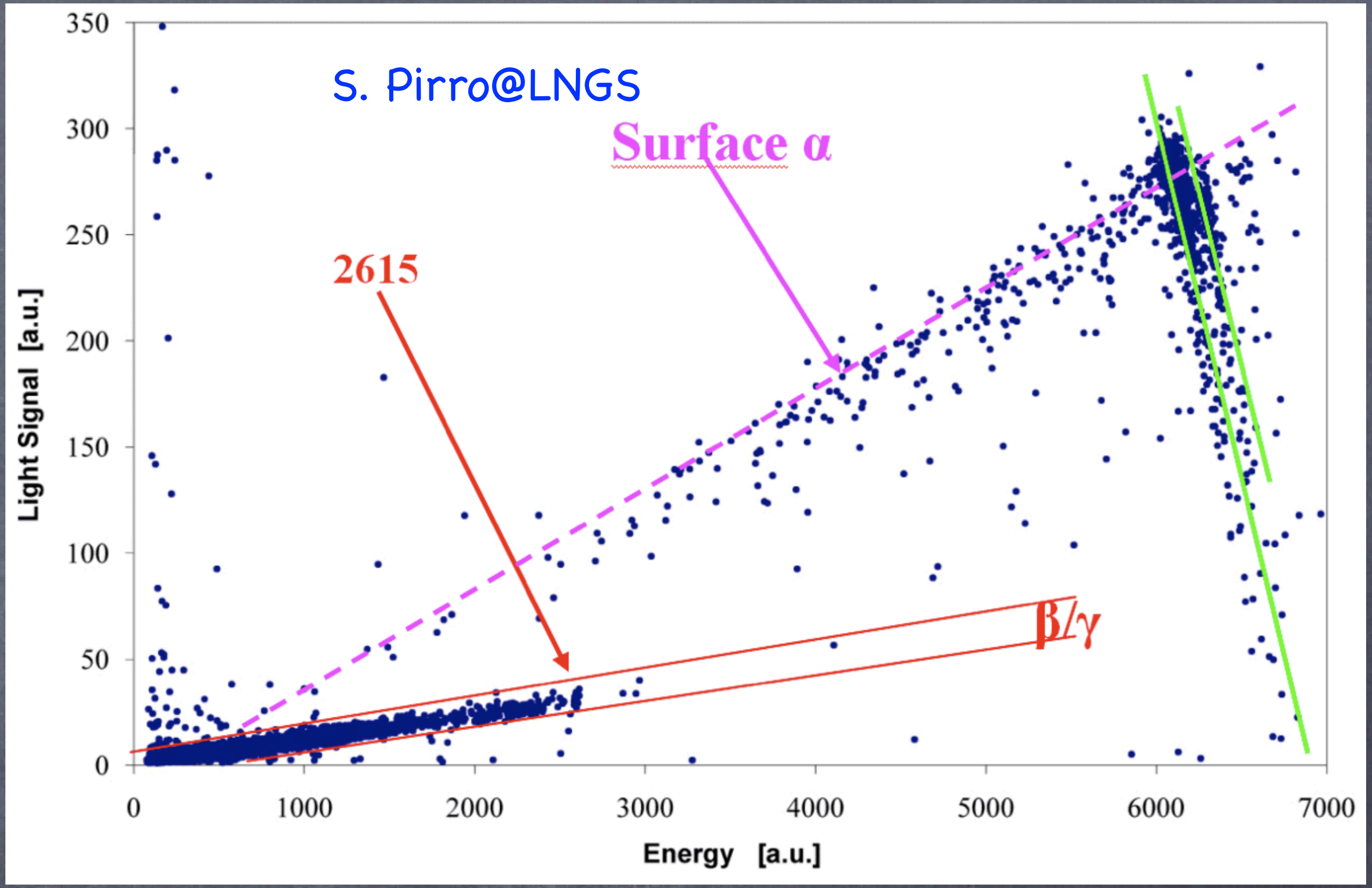
Where should you bet money ?

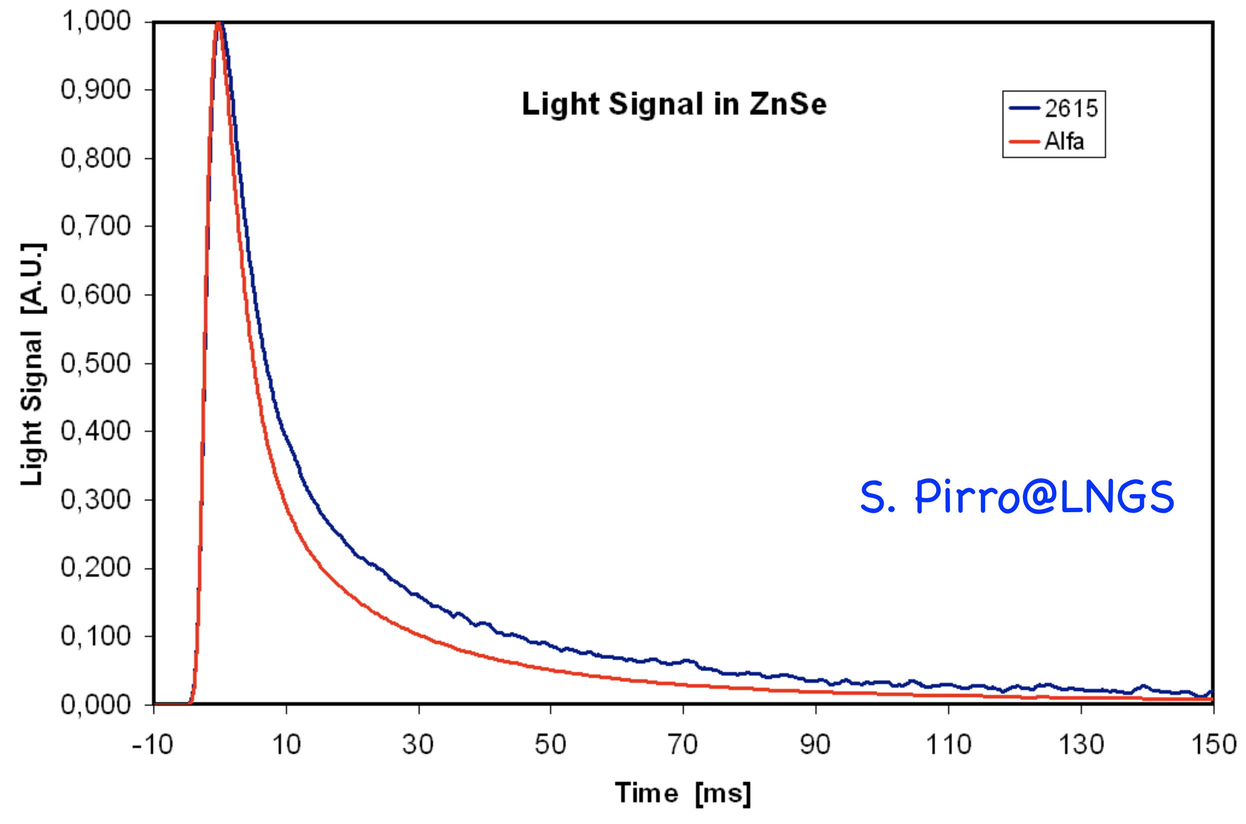
- Cadmium based
  - pro: very good quality crystals, no R&D need
  - cons: goes with W (loss of effective mass, enrichment very costly, 113Cd (n-capture), 109Cd (pile up)
- Molibdenum based
  - pro: very good PSA for alpha-beta discrimination on time constant of main bolometer, enrichment is doable
  - cons: radiopurity un-achievable, the only very good scintillar is CaMoO4: unusable because 48Ca
- Selenium based
  - pro: crystals are radiopure, enrichment is doable, PSA on light slope, time on light and time on crystal, the most mass effective
  - cons: Q inverted, crystal production not yet with solid protocols and reproducibility

The best compromise (possibly)



ZnSe

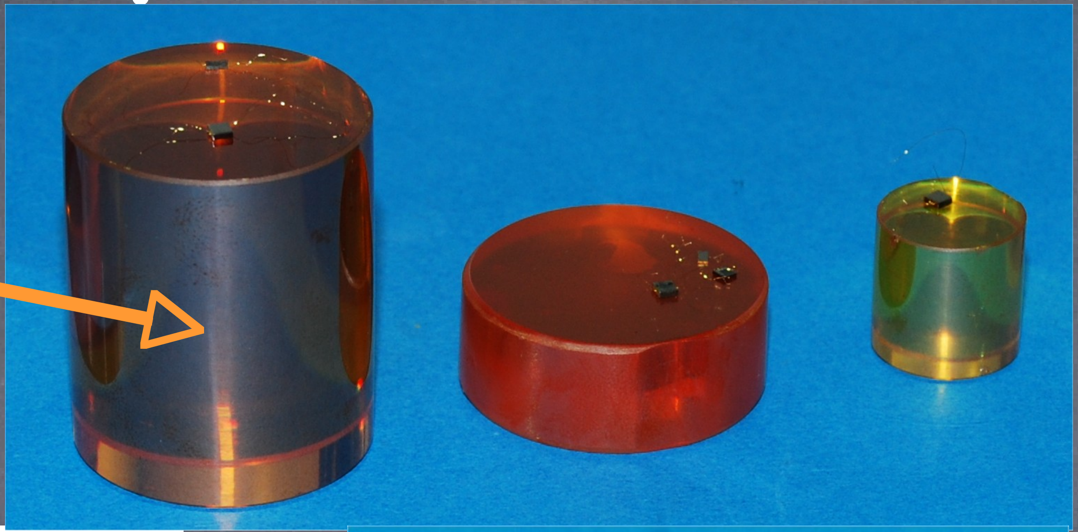


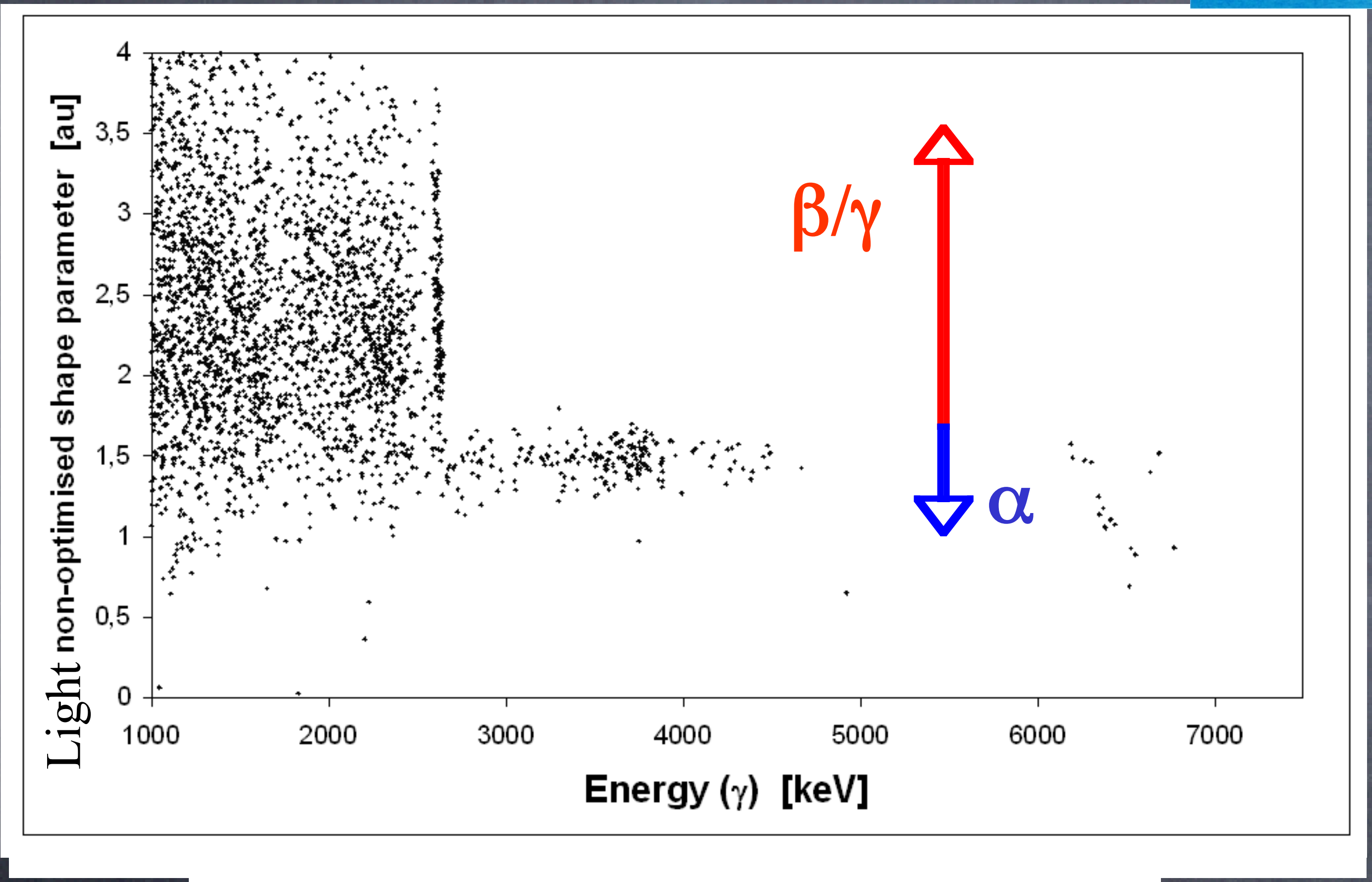


Goal: $b < 0.001$ c/Kg/KeV/y

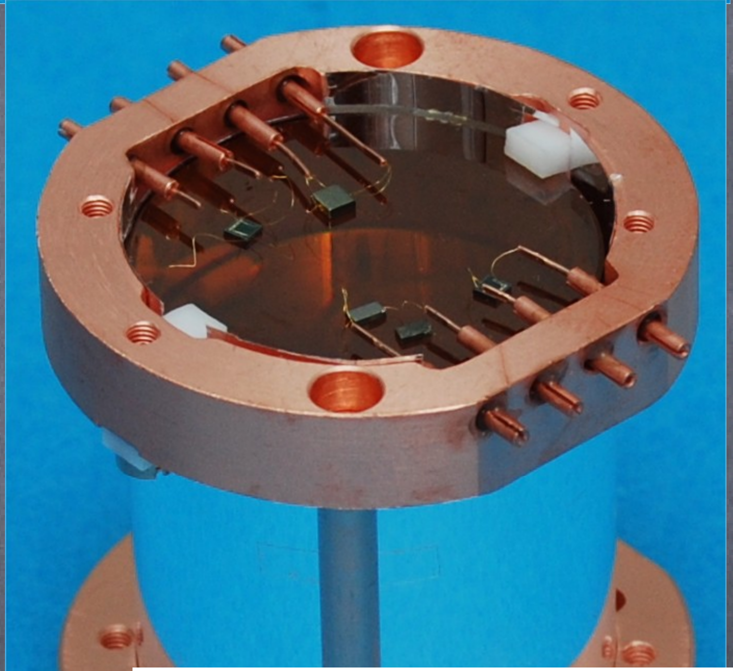
Pulse Shape Analysis

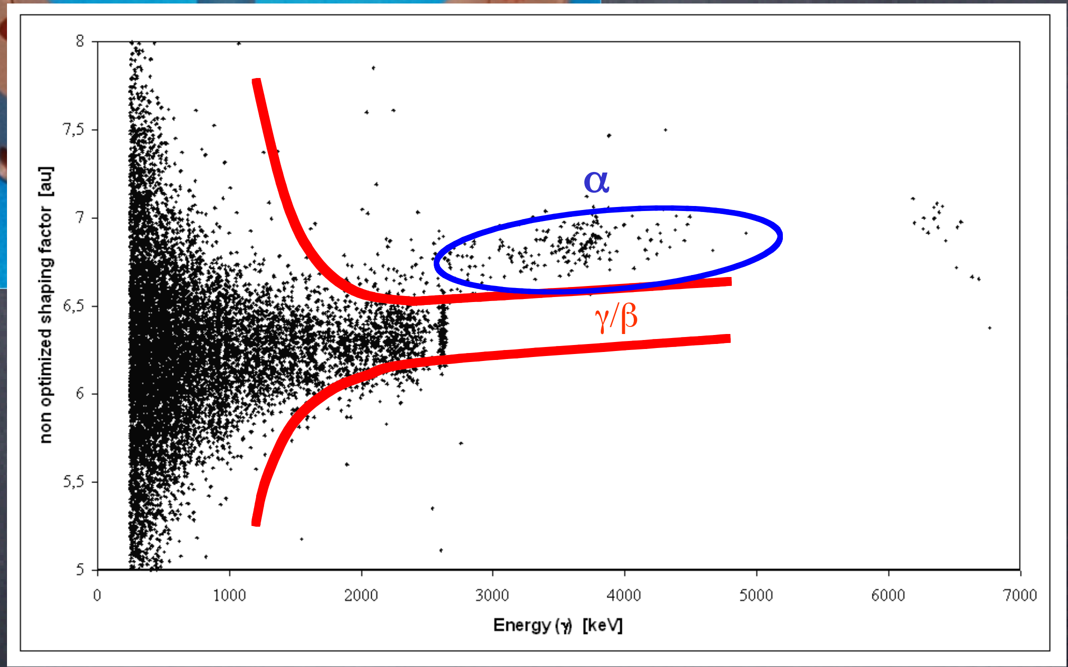
337 g “new” ZnSe Crystal





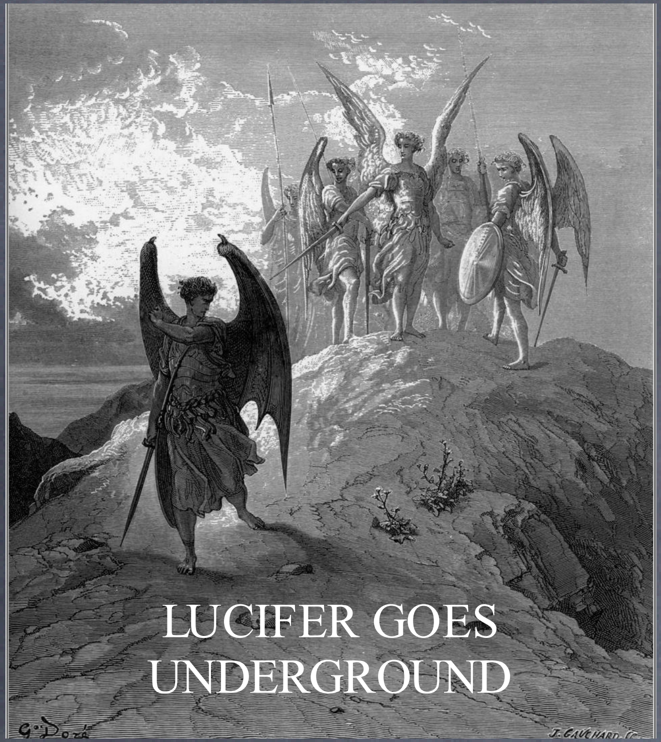
Calibration with ^{232}Th and a smeared α source





one more complication

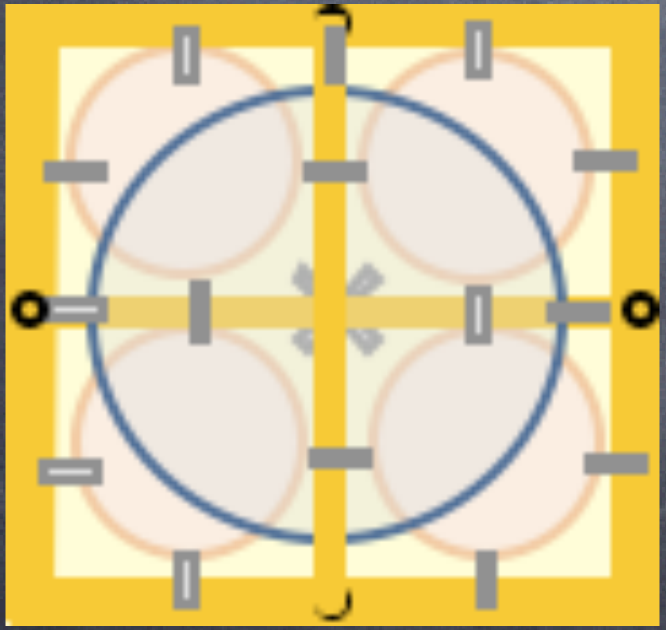
- Te was non enriched (natural i.a. ~ 34%)
- here we need ^{82}Se, a costly item (100 $/gr)
- beside all the requirements illustrated previously here there is one more ‘must’
- DO NOT THROW AWAY PRECIOUS MATERIAL

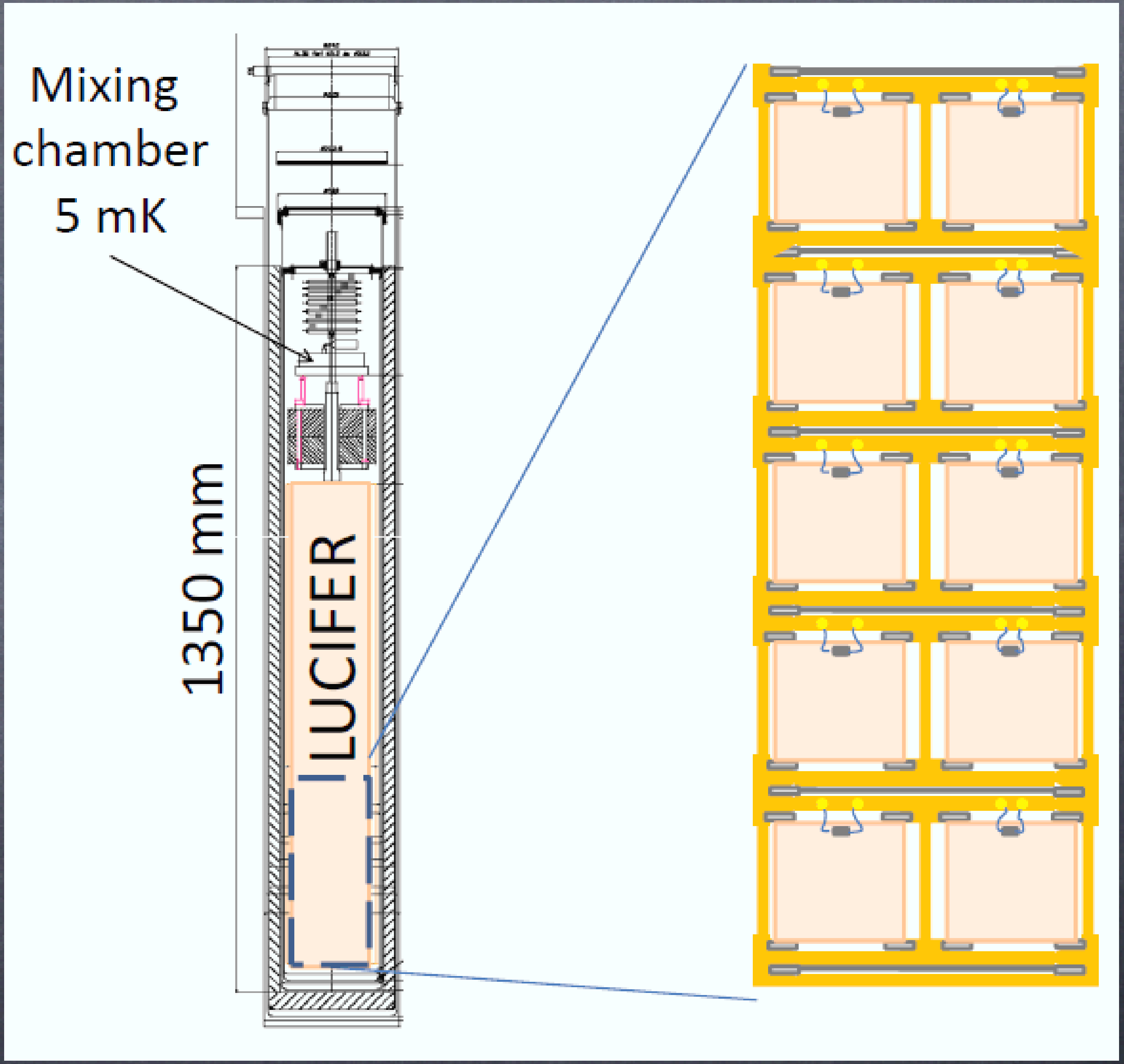

LUCIFER GOES UNDERGROUND

LUCIFER

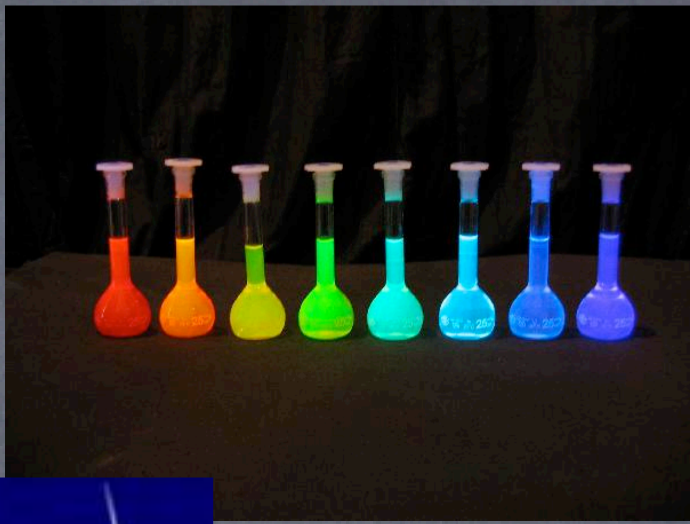
Low-background **U**nderground **C**ryogenic **I**nstallation **F**or **E**lusive **R**ates

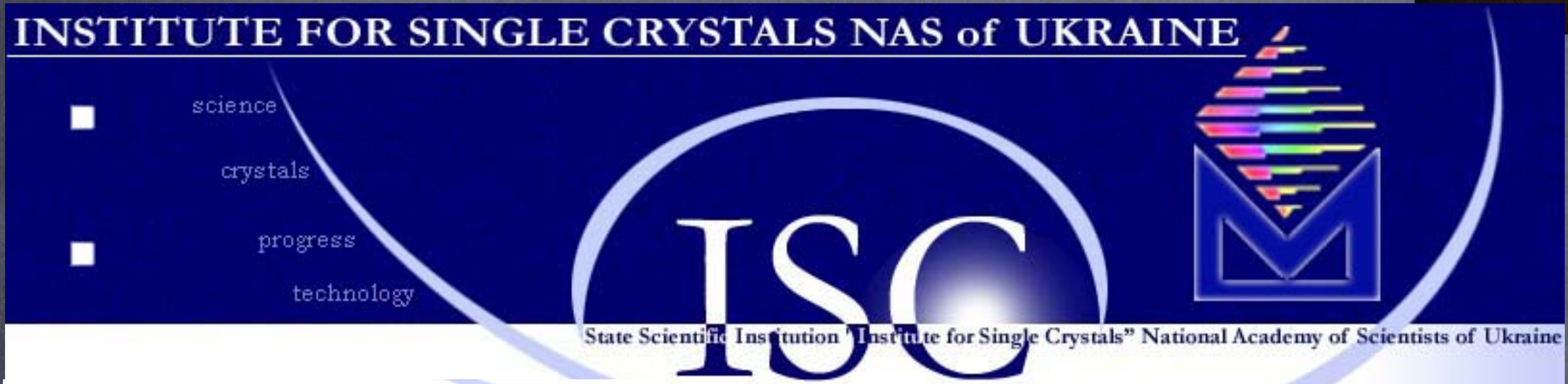
ERC-2009-AdG 247115





ZnSe crystal growing



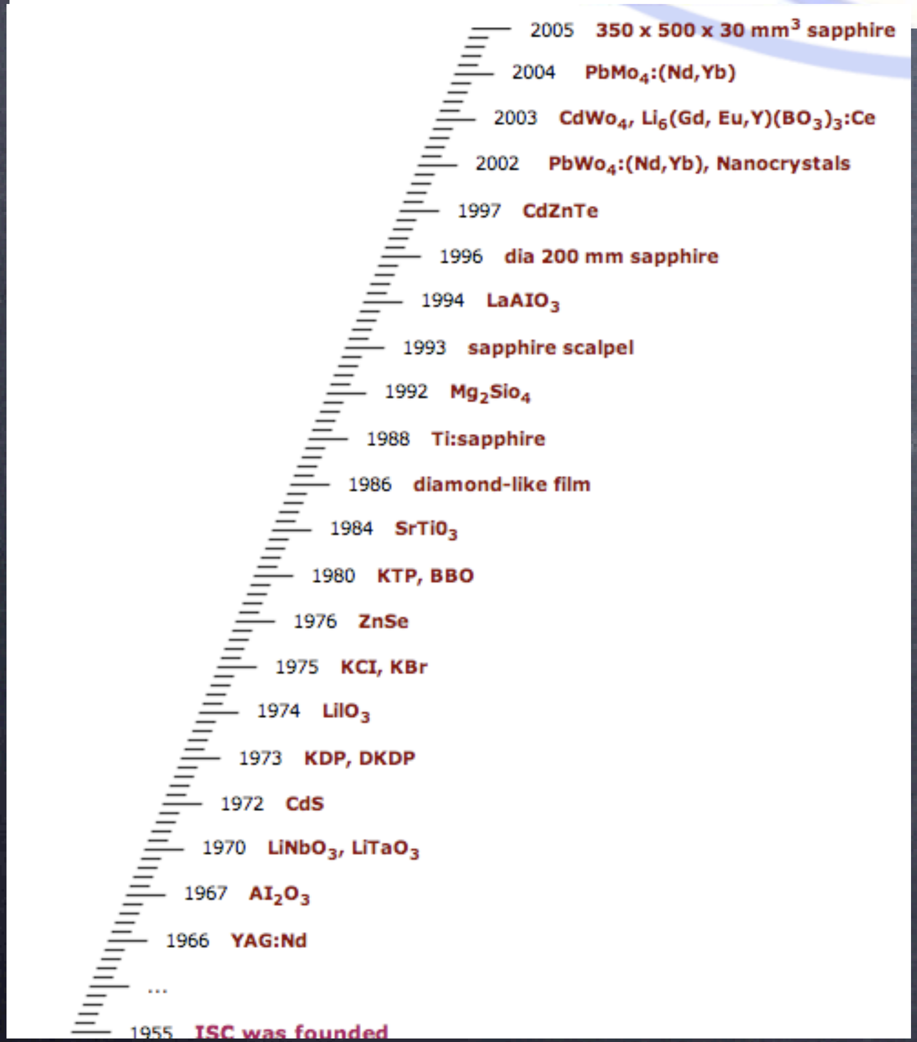


INSTITUTE FOR SINGLE CRYSTALS NAS of UKRAINE

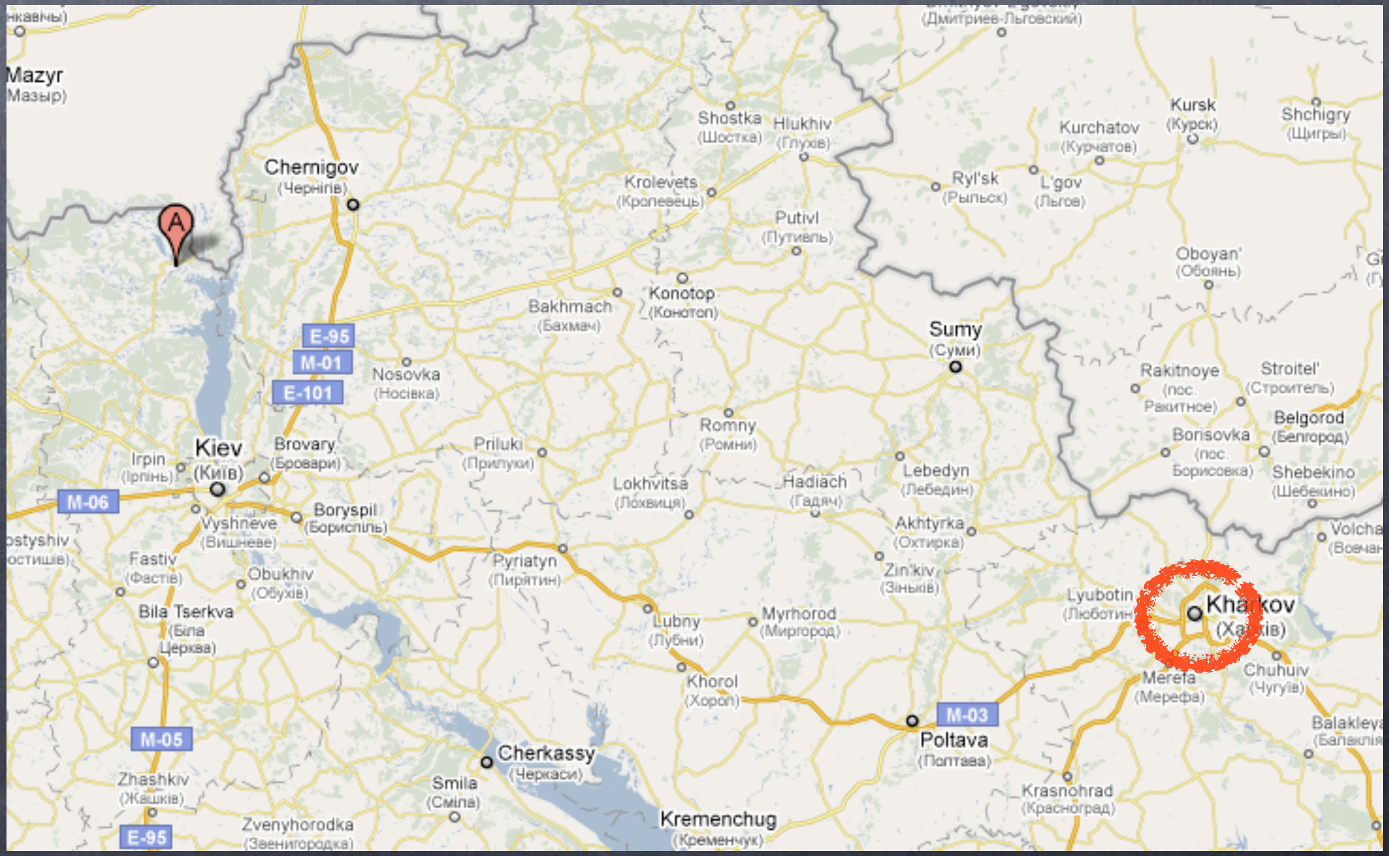
science
crystals
progress
technology

ISC

State Scientific Institution "Institute for Single Crystals" National Academy of Scientists of Ukraine



2005 **350 x 500 x 30 mm^3 sapphire**
2004 **$PbMo_4$:(Nd,Yb)**
2003 **$CdWo_4$, $Li_6(Gd, Eu,Y)(BO_3)_3$:Ce**
2002 **$PbWo_4$:(Nd,Yb), Nanocrystals**
1997 **CdZnTe**
1996 **dia 200 mm sapphire**
1994 **$LaAIO_3$**
1993 **sapphire scalpel**
1992 **Mg_2Sio_4**
1988 **Ti:sapphire**
1986 **diamond-like film**
1984 **$SrTi0_3$**
1980 **KTP, BBO**
1976 **ZnSe**
1975 **KCI, KBr**
1974 **$LiIO_3$**
1973 **KDP, DKDP**
1972 **CdS**
1970 **$LiNbO_3$, $LiTaO_3$**
1967 **AI_2O_3**
1966 **YAG:Nd**
...
1955 **ISC was founded**



Conclusion

- Life is difficult at 10mK
- Protocols for ‘best’ crystal growth fairly well developed
- A big challenge still