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# LUCIFER:
## an Experimental Breakthrough in the Search for Neutrinoless Double Beta Decay

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***Italy***

# LUCIFER

**L**ow-background **U**nderground **C**ryogenics **I**nstallation **F**or **E**lusive **R**ates

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Co-Investigator : Andrea Giuliani

ERC-2009-AdG 247115


Double Beta Decay pilot project based on scintillating bolometers

# Outline

- Double Beta Decay
- Experimental challenge and role of the background
- Silver and golden isotopes
- The bolometric technique and the golden isotopes
- The LUCIFER way
- Prospects and conclusions

# Decay modes for Double Beta Decay

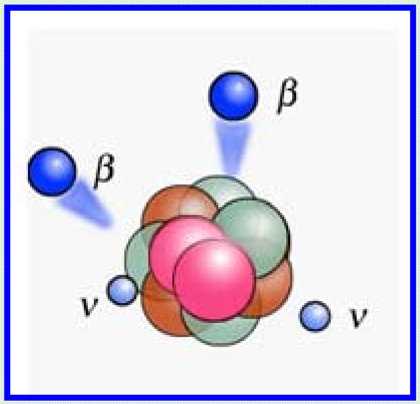
$2\nu\beta\beta$

**Two decay modes** are usually discussed:

$0\nu\beta\beta$

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$$

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-}$$



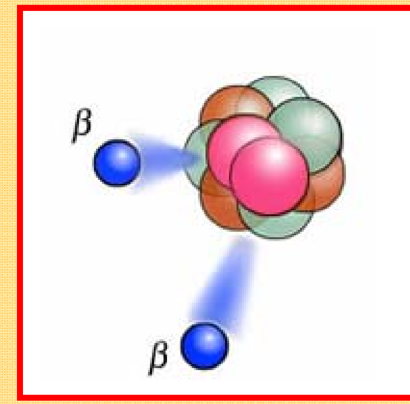

2ν Double Beta Decay allowed by the Standard Model already observed

$\tau \sim 10^{19} - 10^{21}$ **y**

Neutrinoless Double Beta Decay

$^{76}Ge$ claim

$\tau \geq 10^{25}$ **y**




**Neutrinoless process** would imply new physics beyond the Standard Model

violation of lepton number conservation

It is a very sensitive test to new physics since the phase space term is much larger than for the standard process

If observed:

$$m_\nu \neq 0$$
$$\nu \equiv \bar{\nu}$$

# $0\nu$-DBD and neutrino masses

how **$0\nu$-DBD** is connected to neutrino mixing matrix and masses
in case of process induced by **mass mechanism**

neutrinoless
Double Beta Decay
**rate**

Phase
space

Nuclear
matrix elements

Effective
**Majorana mass**

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

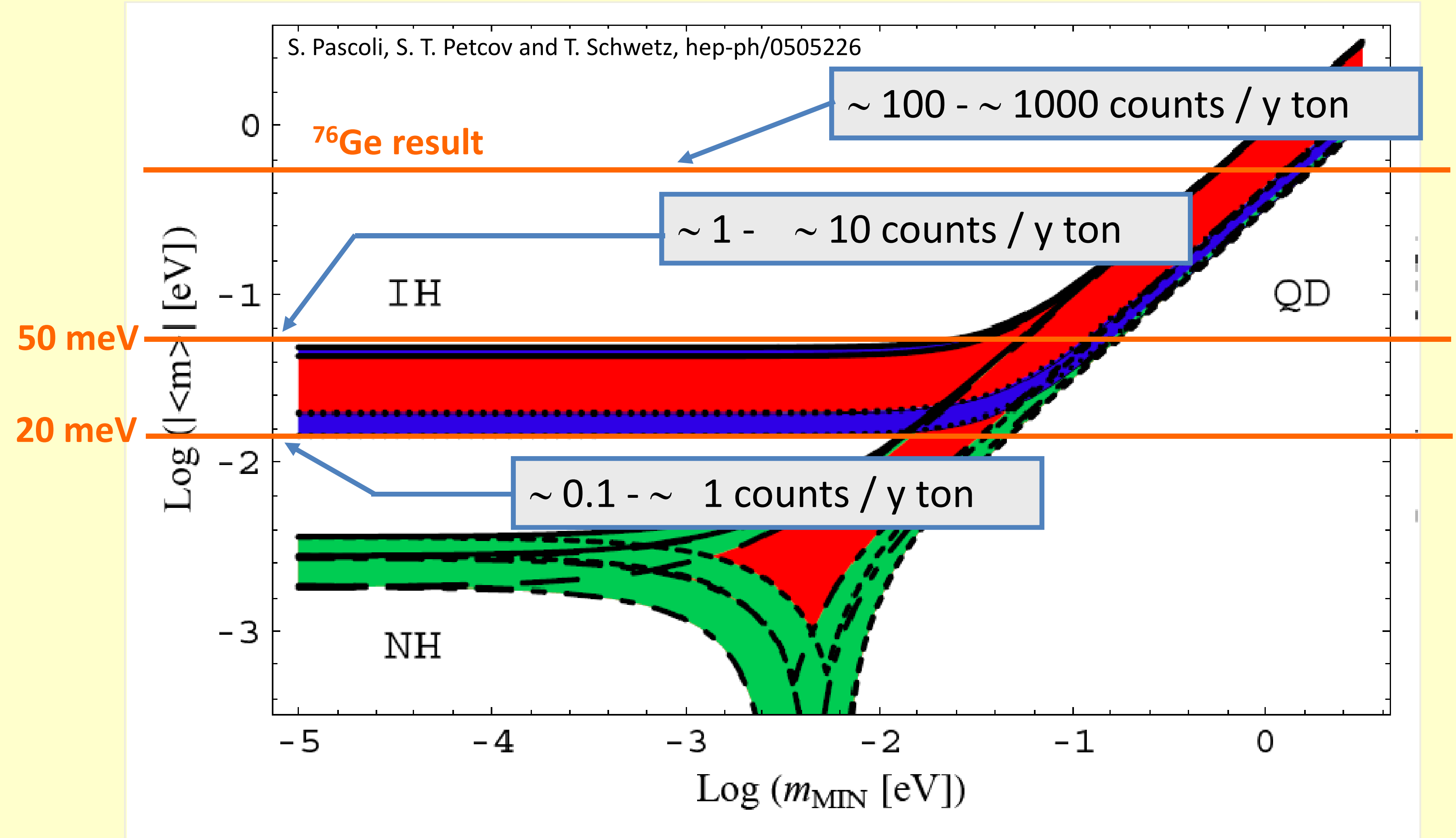
what the **experimentalists**
try to measure

what the **nuclear theorists**
try to calculate

parameter containing
the **physics**

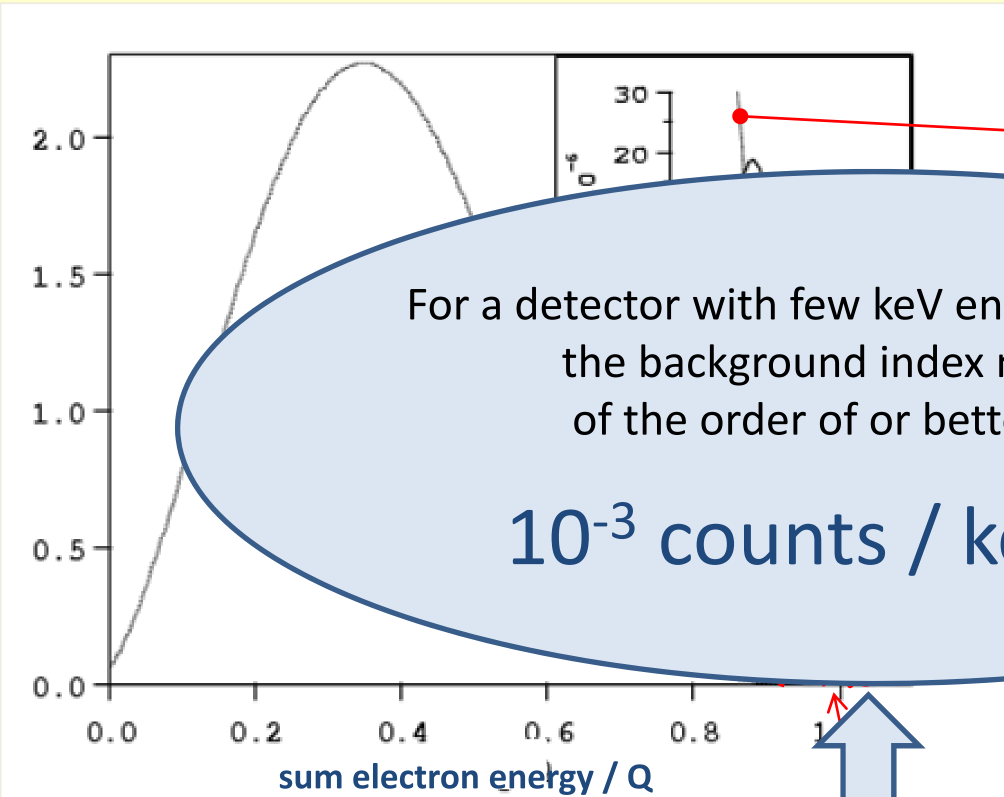
$$\langle M_{\beta\beta}\rangle = \left|\ |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \right|$$

# The size of the challenge



# Electron sum energy spectra in DBD

The shape of the two electron sum energy spectrum enables to distinguish among the two different decay modes




two neutrino DBD
um with maximum at ~1/3 Q

on

For a detector with few keV energy resolution,
the background index must be
of the order of or better than

$10^{-3}$ counts / keV kg y

Q ~ 2-3 MeV for the most promising candidates

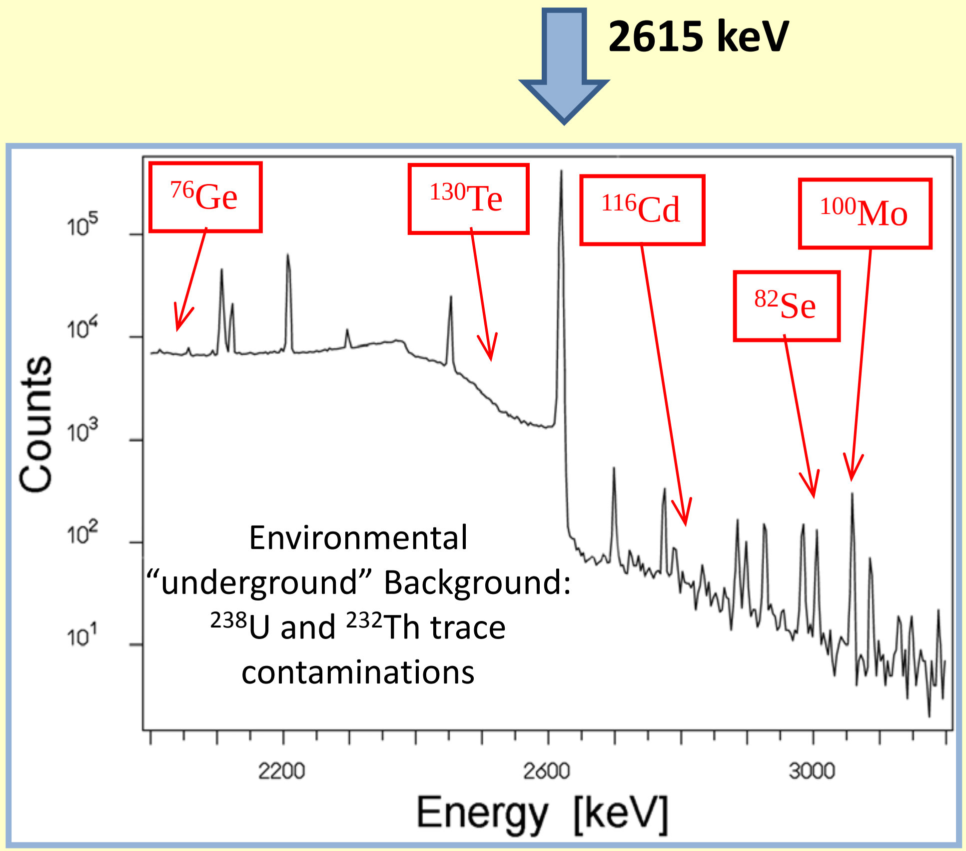
The order of magnitude of the target bakground is ~ **few counts / y ton**

# The importance of a high Q-value

A **high Q-value** is important for two reasons:

- High phase space for the decay: $\propto$ **$Q^5$**
- If **Q > 2615 keV**, the signal is out of the bulk of the natural $\gamma$ radioactivity

Position of the Q-values for some interesting candidates superimposed to a $\gamma$ spectrum taken underground without any form of passive shielding



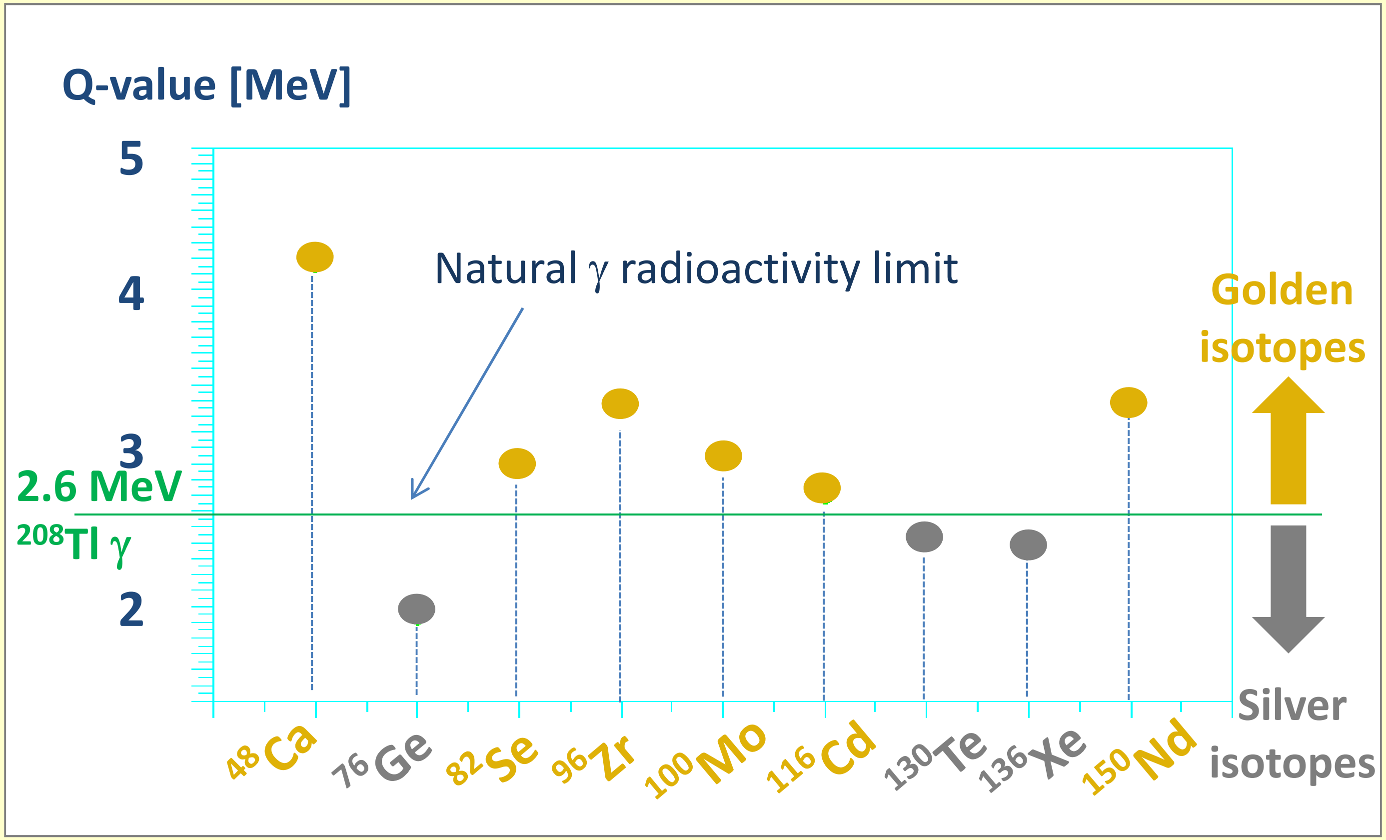
# Silver and golden isotopes

Only **a few isotopes** are really in the game for the search for neutrinoless Double Beta Decay

From the point of view of the **Q-value**, they can be divided into:

Golden isotopes: **$^{48}$Ca – $^{82}$Se – $^{96}$Zr – $^{100}$Mo – $^{116}$Cd – $^{150}$Nd**

Silver isotopes: **$^{76}$Ge – $^{130}$Te – $^{136}$Xe**




Other factors favour certain isotopes with respect to others:

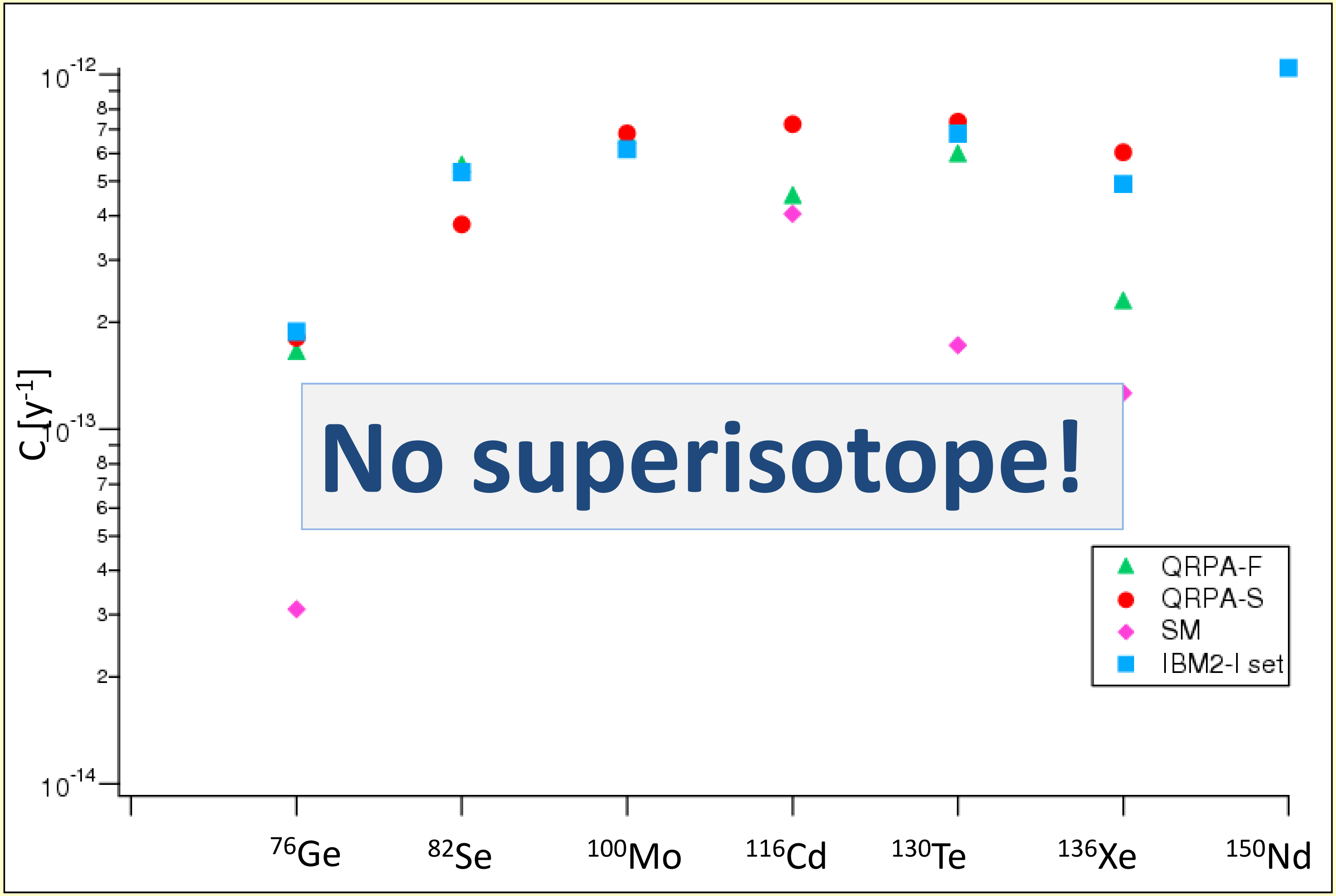
- Easy association to an **experimental technique**
- High **isotopic abundance** and/or easy **enrichment**
- Achievable **radiopurity**

# The role of nuclear matrix elements in isotope choice

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

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

the real figure of merit: the higher the better



# Which technique can study one or more golden isotopes?

① **Tracko-calo approach**: the source is a thin foil inserted in a nuclear detector with tracking and calorimetric capability → ~5 kg source in each module
NEMO – SuperNEMO experiments → $^{100}$Mo , $^{82}$Se or $^{150}$Nd

② **Bolomteric approach**: the source is embedded in a crystal which is cooled down at ~10 mK and work as a bolometer → only energy is measured but with high resolution → ~0.5 kg source in each crystal
Cuoricino – CUORE experiments → $^{\mathbf{130}}$**Te**, but potentially **most of golden isotopes**

*Silvia Capelli , Thursday*

The nuclear **energy** is measured as a **temperature increase** of a single crystal

$$\boxed{\Delta T = E/C}$$

In order to get low heat capacities, the temperature must be very low (**5 – 10 mK**)

Thanks to a proper thermometer, $\boxed{\Delta T \Rightarrow \Delta V}$

Typical signal sizes: **0.1 mK / MeV**, converted to about **1 mV / MeV**

# Silver and golden isotopes with the bolometric technique

| Nucleus | I. A. [%] | Q-value [keV] | Materials successfully tested as bolometers in crystalline form |
|---|---|---|---|
| $^{76}$Ge | **7.8** | **2039** | **Ge** |
| $^{136}$Xe | **8.9** | **2479** | **NONE** |
| $^{130}$Te | **33.8** | **2527** | $TeO_2$ |
| $^{116}$Cd | **7.5** | **2802** | $CdWO_4$, $CdMoO_4$ |
| $^{82}$Se | **9.2** | **2995** | **ZnSe** |
| $^{100}$Mo | **9.6** | **3034** | $PbMoO_4$, $CaMoO_4$, $SrMoO_4$, $CdMoO_4$, $SrMoO_4$, $ZnMoO_4$, $Li_2MoO_4$, $MgMoO_4$ |
| $^{96}$Zr | **2.8** | **3350** | $ZrO_2$ |
| $^{150}$Nd | **5.6** | **3367** | **NONE → many attempts** |
| $^{48}$Ca | **0.187** | **4270** | $CaF_2$, $CaMoO_4$ |

**Seven excellent candidates** can studied with high energy resolution and with the bolometric approach

# Is a pure bolometer the best device to study a golden isotope ?

Following the previous arguments, an obvious way to get low background and to perform **multi-isotope search** with high sensitivity would be:

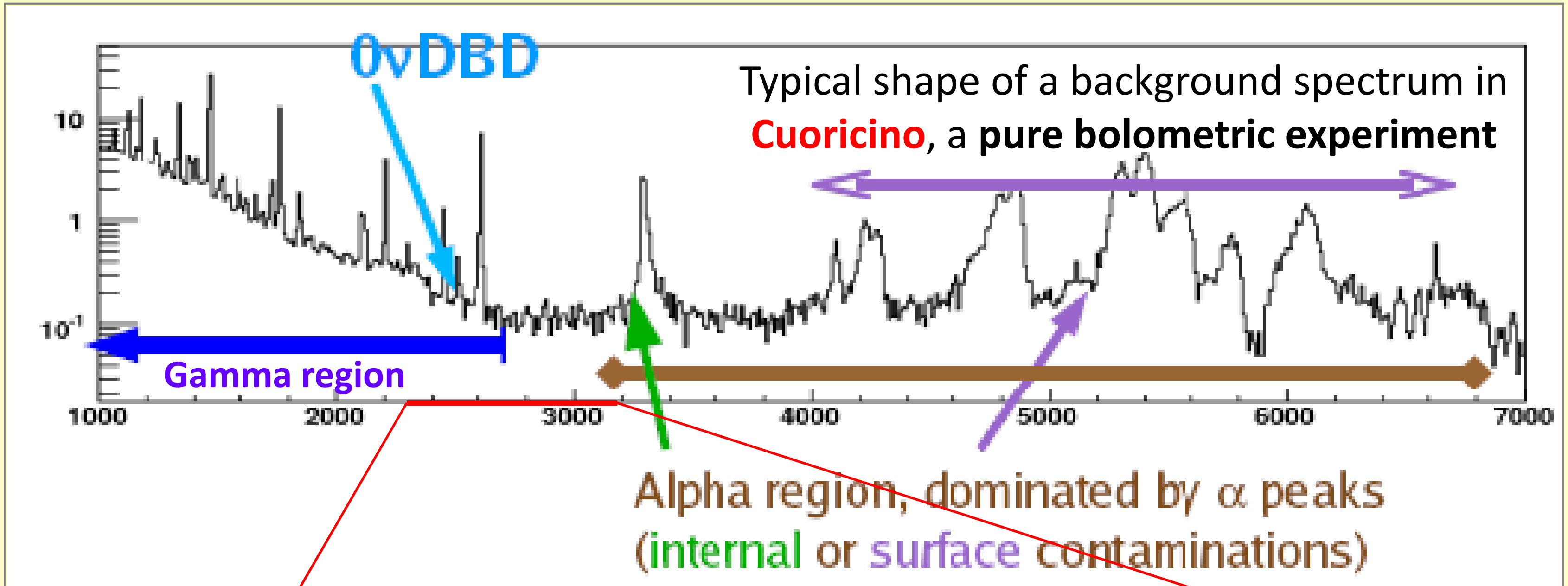
- Invest money in **enrichment**
- Invest money in **crystal growth** with radio-clean procedures
- Exploit the **existing facilities** for large mass bolometric experiments (Cuoricino, CUORE at LNGS)

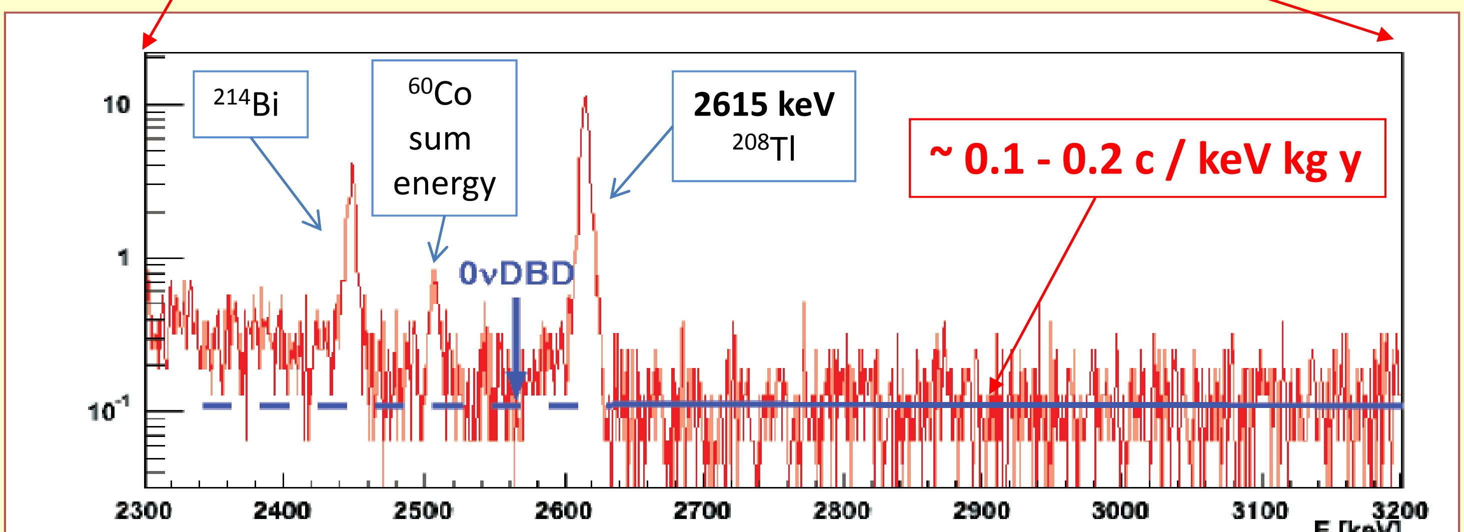
~~**In parallel to $^{130}$Te**, study the potentially much better candidates **$^{82}$Se, $^{116}$Cd, $^{100}$Mo, $^{48}$Ca** and others~~

Unfortunately, the Cuoricino / CUORE R&D experience tells us that the improvement with respect to $^{130}$Te study would be minor or negligible

**WHY ?**

# The Cuoricino background and the surface radioactivity

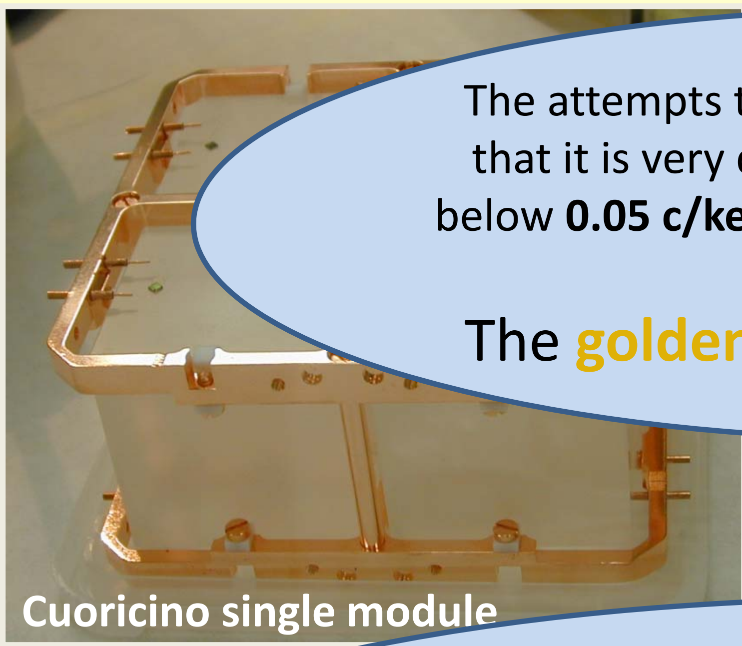


# The origin of the continuum above ~2.5 MeV

Bolometers are fully sensitive, up to the detector surface → **no dead layer**

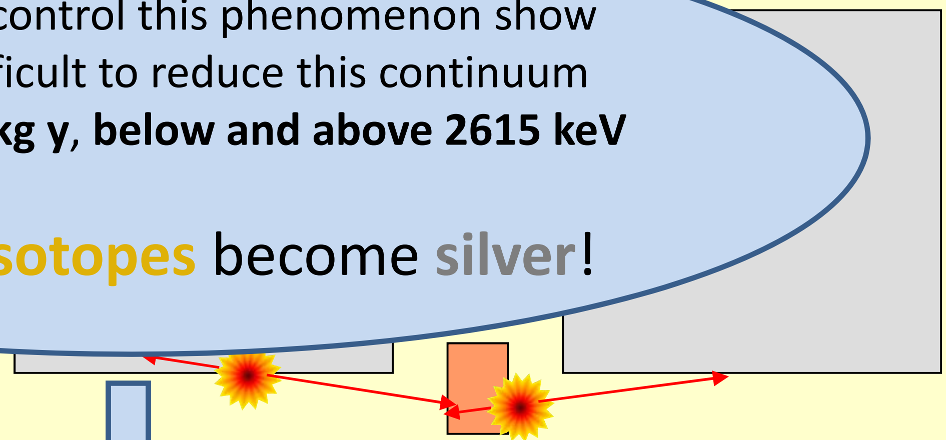
Shallow (up to **10 μm deep**) surface contamination (for example **$^{210}$Pb**) of the bolometers themselves or of the materials surrounding them emit **alpha particles**



Cuoricino single module

The attempts to control this phenomenon show that it is very difficult to reduce this continuum below **0.05 c/keV kg y**, **below and above 2615 keV**

The golden isotopes become silver!




The dual mission is:

**(1) Investigate golden isotopes + (2) Kill alpha particles**

↓

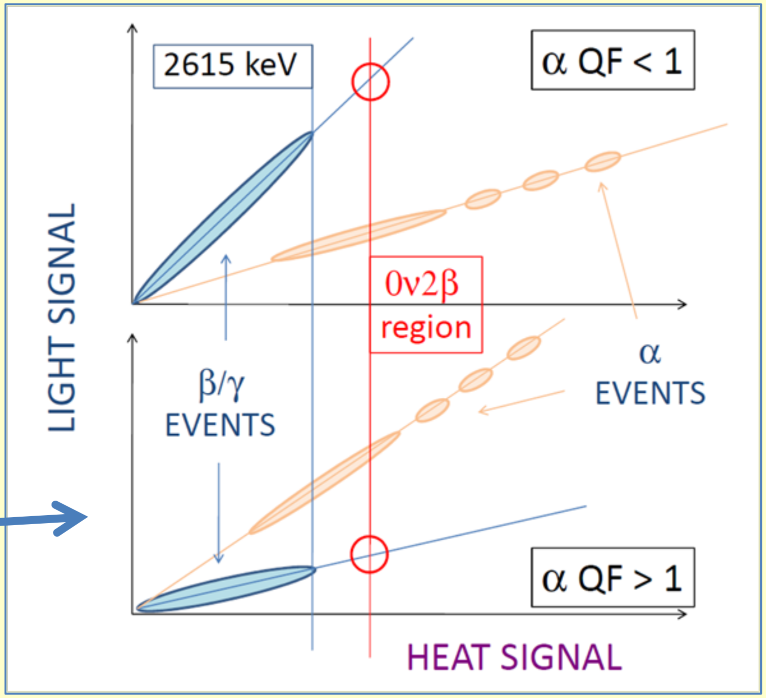
# The LUCIFER way

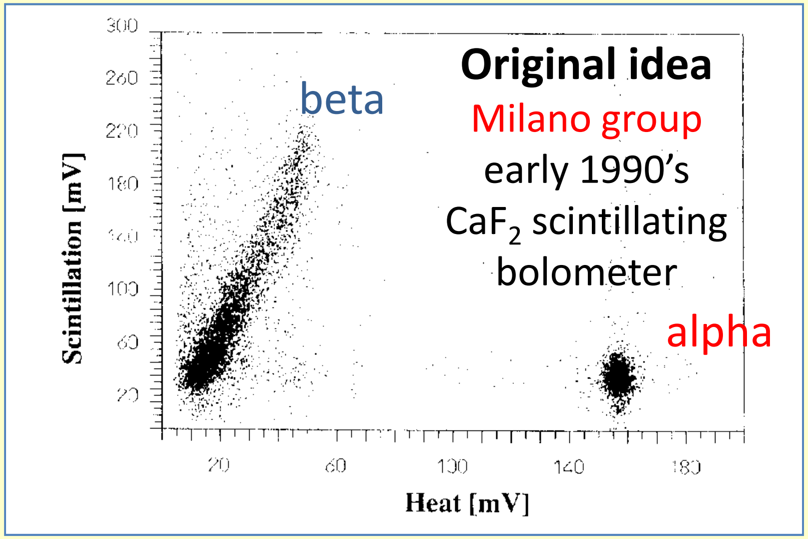
# The fundamental idea and the LUCIFER precursors

A device able to measure simultaneously the **phonon (heat)** excitations and the **photon (scintillation)** excitations generated in a crystal by the same nuclear event can efficiently discriminate **alphas from betas / gammas**.

Alphas emit a different amount of light with respect to beta/gamma of the same energy (normally lower → α **QF < 1, but not in all cases**).

A **scatter plot light vs. heat** separates alphas from betas / gammas.



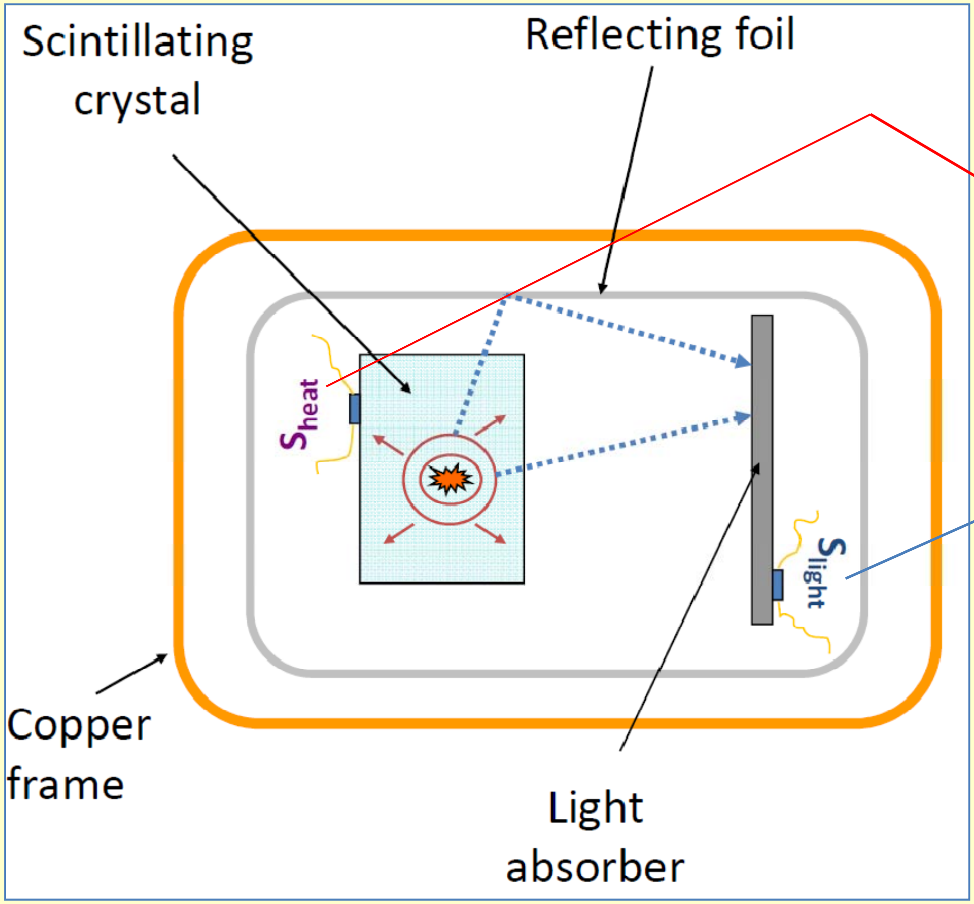

The **experimental basis** for **LUCIFER** is the R&D activity performed by **Stefano Pirro** at LNGS ,
in the framework of the programs:

- **BOLUX**, funded by **INFN** – CSN5
- **ILIAS-IDEA** funded by the **European Commission** (WP2-P2)

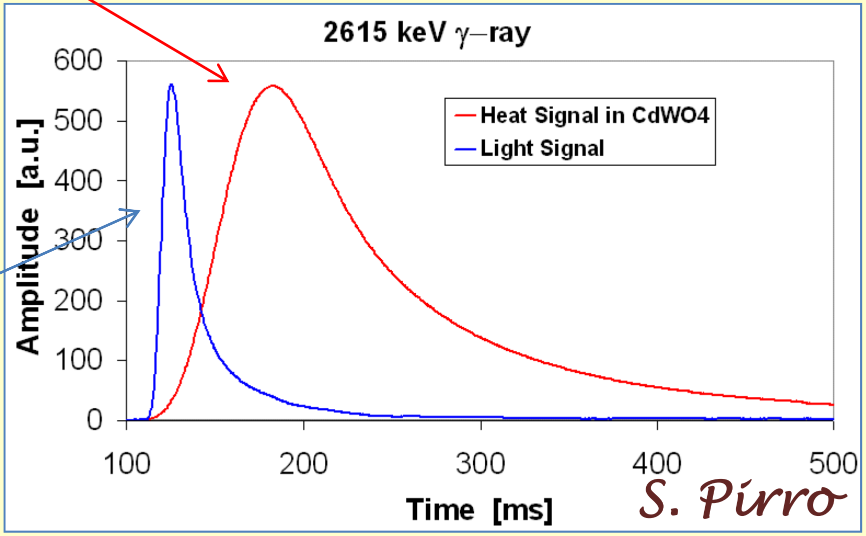
# Double bolometer for heat and light

The most convenient method to realize a light detector at low temperatures is the development of an **auxiliary bolometer**, made with a thin absorber opaque to the light emitted by the **main bolometer**, and facing one polished side of it.

## Scintillating bolometer




Real light and heat signals acquired with **a $CdWO_4$** scintillating bolometer



# Silver and golden isotopes in scintillating bolometers

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| $^{96}Zr$ | 2.8 | 3350 | $ZrO_2$ |
| $^{150}Nd$ | 5.6 | 3367 | NONE → many attempts |
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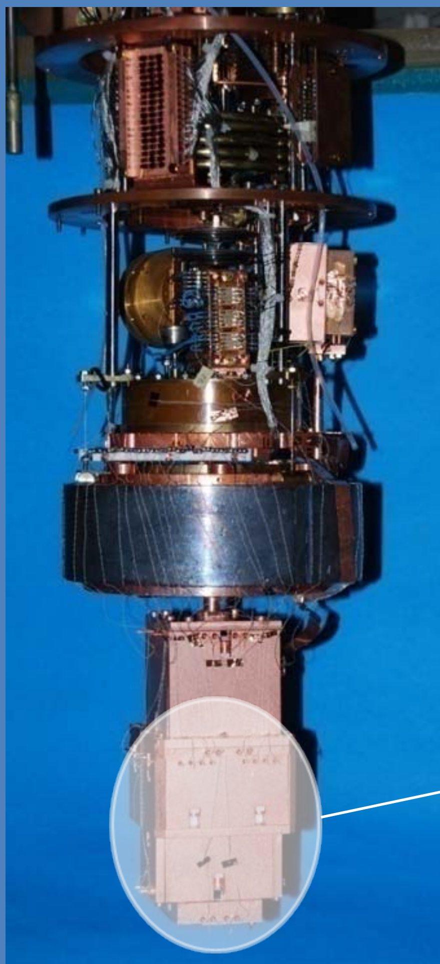
Underlined compounds are **good scintillators**

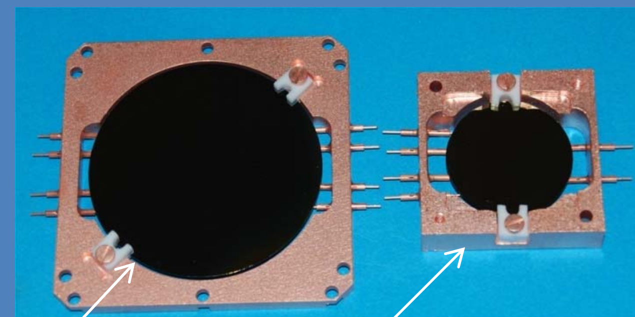
*S. Pirro*

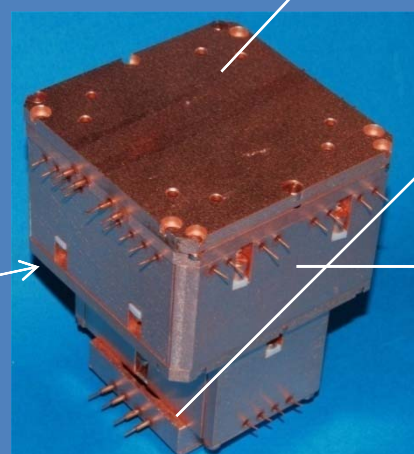
**Four golden candidates ($^{116}$Cd – $^{100}$Mo – $^{82}$Se – $^{48}$Ca)**
can studied as scintillating bolometers

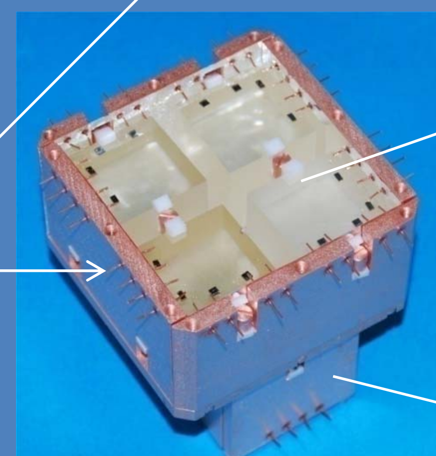
# The best technical results so far: $CdWO_4$



Light Detector





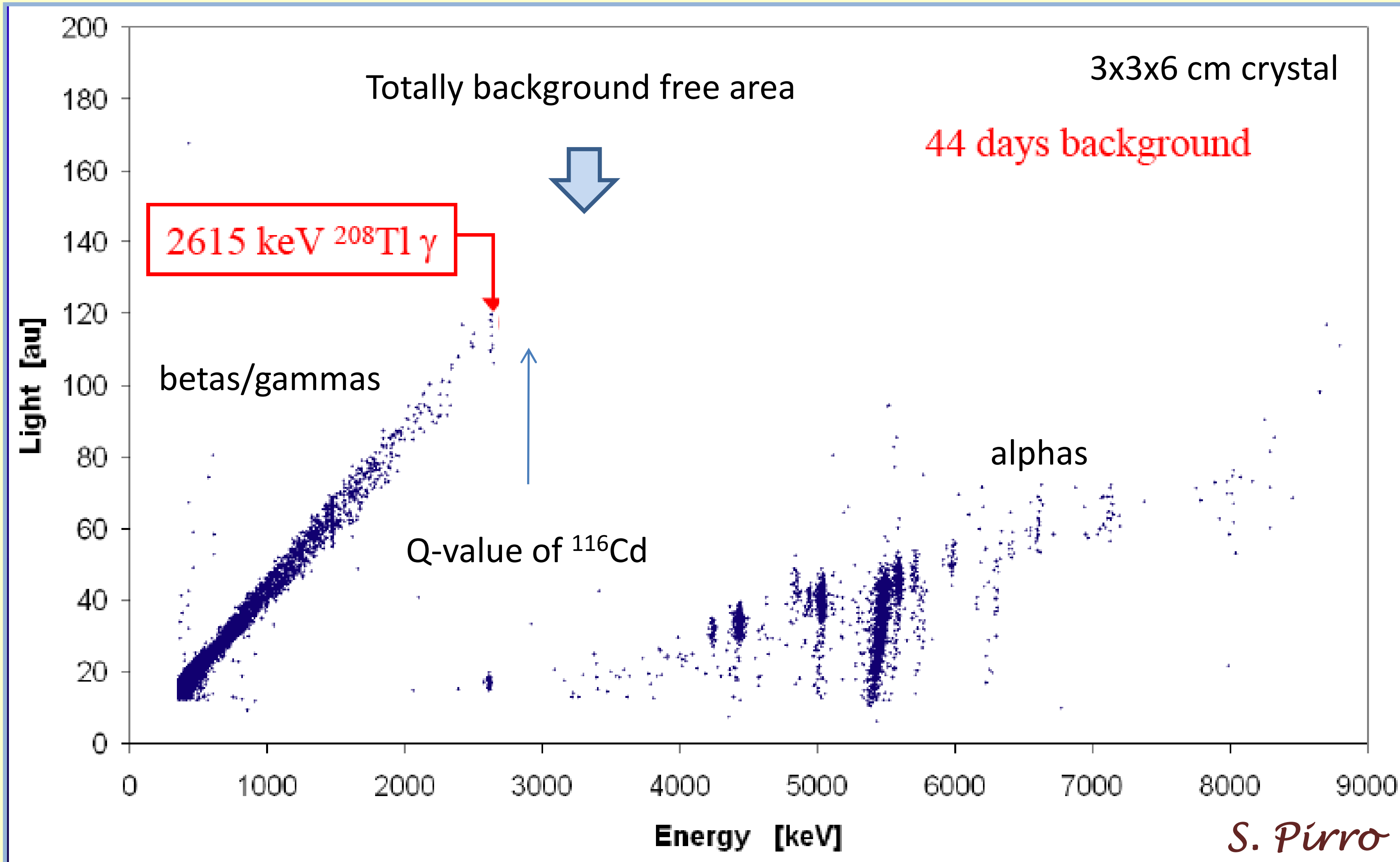


3x3x3 cm $CdWO_4$

3x3x6 cm $CdWO_4$

*S. Pirro*

# Discrimination power in $CdWO_4$



# A good compromise: ZnSe

**$CdWO_4$** is an excellent candidate for a DBD experiment based on scintillating bolometers. However, **three drawbacks**:

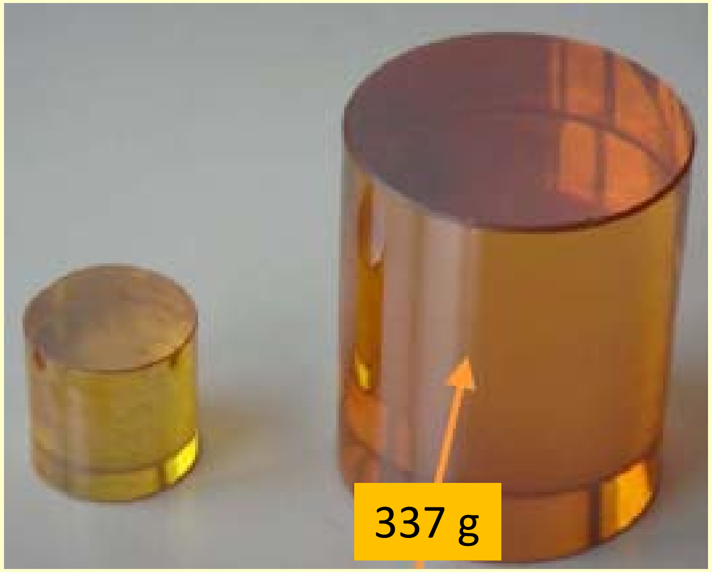
- High atomic mass of W → only **32% useful material** in case of 100% enrichment
- Crystals examined so far exhibit a **huge internal alpha contamination**
- **$^{109}$Cd has a huge neutron** cross section → residual abundance in enriched material

**ZnSe** is another excellent candidate which is not affected by these problems:

- $\langle A \rangle_{Zn} = 64.4$ → **56% useful material**
- Preliminary measurements show that the crystals are reasonably radiopure
- No isotope with particularly high neutron cross sections

Several ZnSe crystals have been tested, with masses up to **337 g**

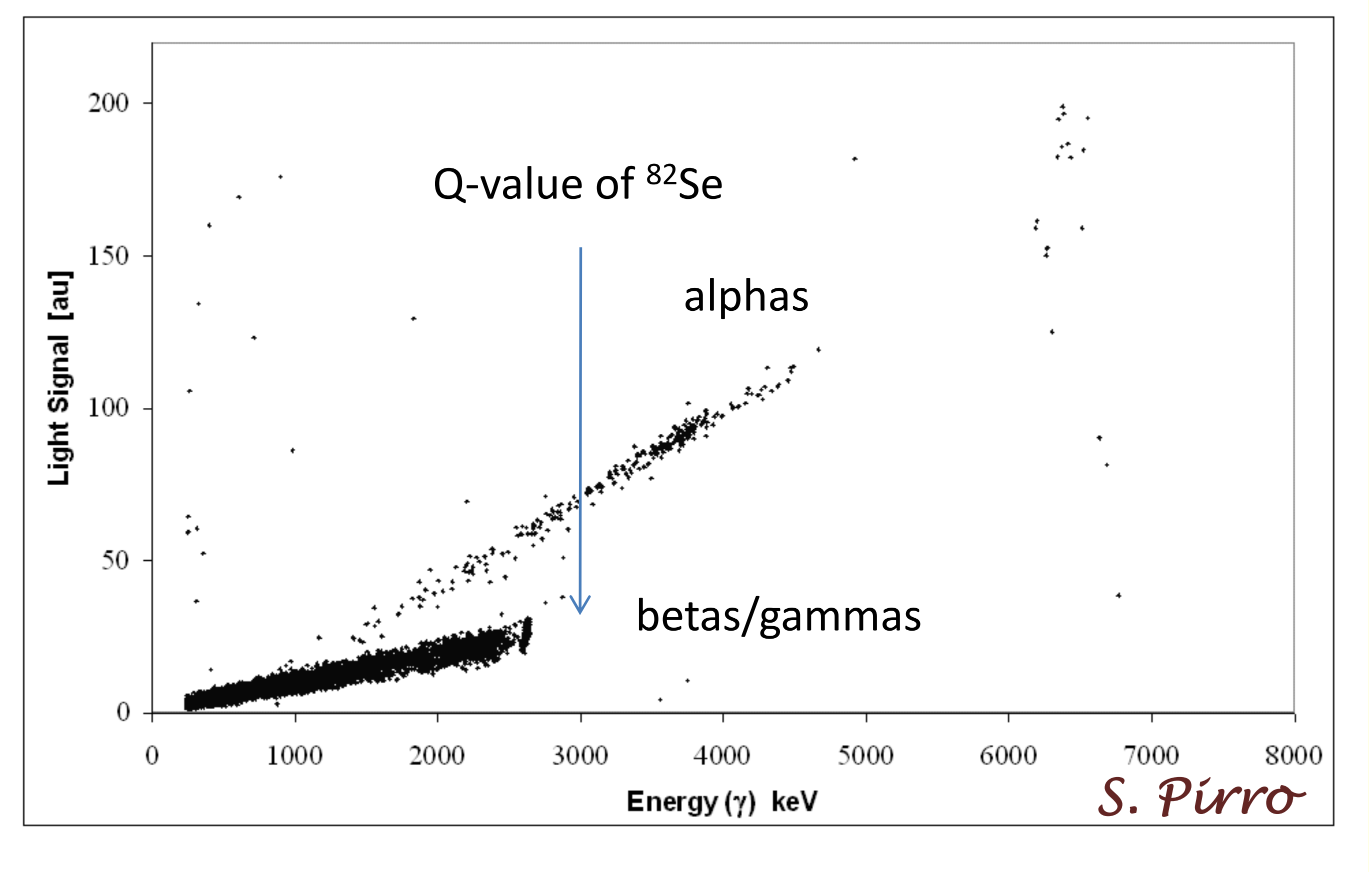
→ excellent bolometric performance, similar to those observed in $TeO_2$ for CUORE



# Two surprises for ZnSe (1)

…**one** is interesting but not really welcome

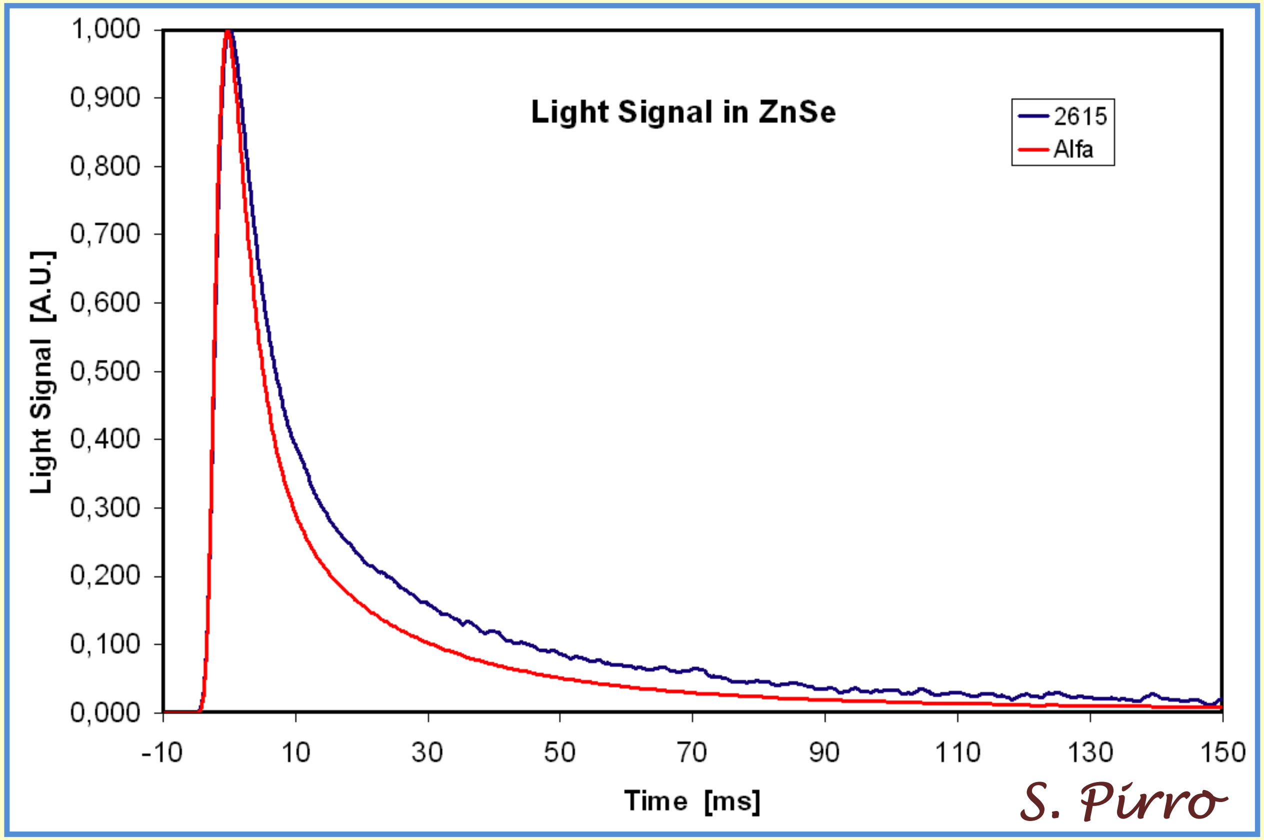
$\alpha$ **QF > 1:** alphas give more light than gammas → risk of leakage in the beta/gamma region?



# Two surprises for ZnSe (2)

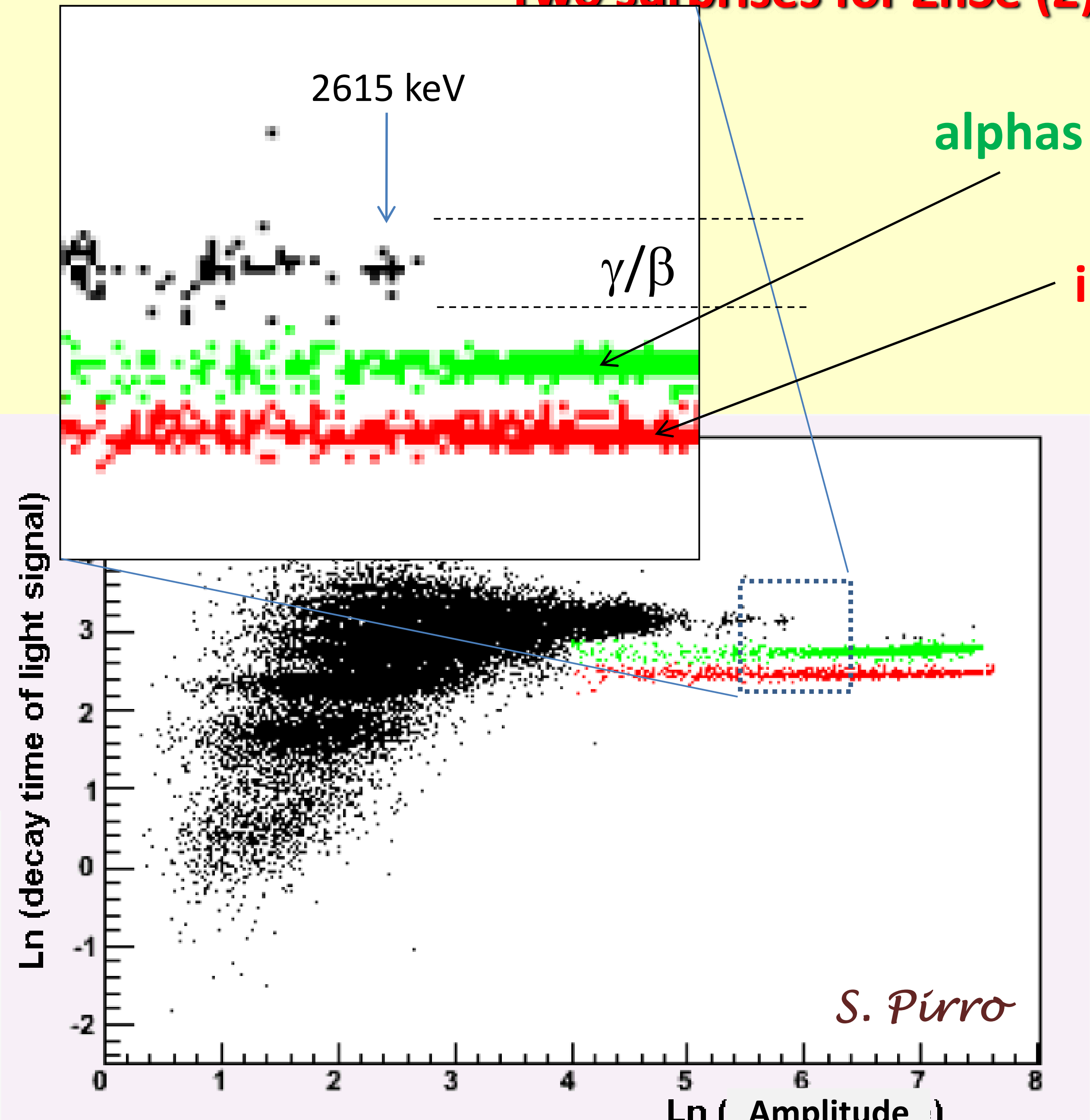
…**the other one** is very exciting → improve dramatically the discrimination power

There are detectable differences in the light-signal time development between alpha and beta events → **Pulse Shape Discrimination is possible**




The definition and use of proper shape parameters seem to enable **a full separation of beta and alpha** in the region of the DBD Q-value of $^{82}Se$

# Two surprises for ZnSe (2)




**Very preliminary**
More effective shape parameters are under investigation

# Target background

Current background studies show that a **background index < $10^{-3}$ counts/kev kg y** is achievable **above 2.6 MeV IF** one neglects the contribution from surface alphas

The various **techniques of surface cleaning** developed in the CUORE collaboration shows that the contribution coming from surface alphas above 2.6 MeV can be reduced at least down to **$5\times10^{-2}$ counts /keV kg y**

This shows that a rejection efficiency of only **98%** would bring the surface alphas contribution down to **$10^{-3}$ counts/kev kg y**

All but alphas $< 10^{-3}$

alphas $\sim 5\times10^{-2}$

**Reject alphas at 99%**

Target background

$10^{-3}$ counts/keV kg y

The main purpose of LUCIFER is to **show that this background is achievable** with enriched material on a reasonable large scale (**15 – 20 kg of isotope**)

**LUCIFER is a demonstrator…**

# Physics reach

# ...but has a remarkable physics reach by itself

From the LUCIFER proposal:

| *Crystal* | *Isotope weight* | *Useful material* | *Half Life limit ($10^{26}$y)* | *Sensitivity* to $m_{ee}$ (meV)* |
|---|---|---|---|---|
| **$CdWO_4$** | **$^{116}$Cd** 15.1 kg | 32% | 1.15 | 65-80 |
| **$ZnMoO_4$** | **$^{100}$Mo** 11.3 kg | 44% | 1.27 | 67-73 |
| **ZnSe [baseline]** | **$^{82}$Se** 17.6 kg | 56% | 2.31 | 52-65 |
| **ZnSe [option 1]** | **$^{82}$Se** 20.5 kg | 56% | 2.59 | 49-61 |
| **ZnSe [option 2]** | **$^{82}$Se** 27.8 kg | 56% | 3.20 | 44-55 |

** The 1$\sigma$ sensitivity is calculated with the Feldman Cousins approach for 5 y running and a background index $d\Gamma_b/dE = 10^{-3}$ c/keV/Kg/y. The matrix elements come from the two most recent QRPA calculations [ME08]; the energy window is taken as 5 keV, compatible with the resolution achieved in $TeO_2$ macrobolometers and in scintillating-bolometer R&D.*

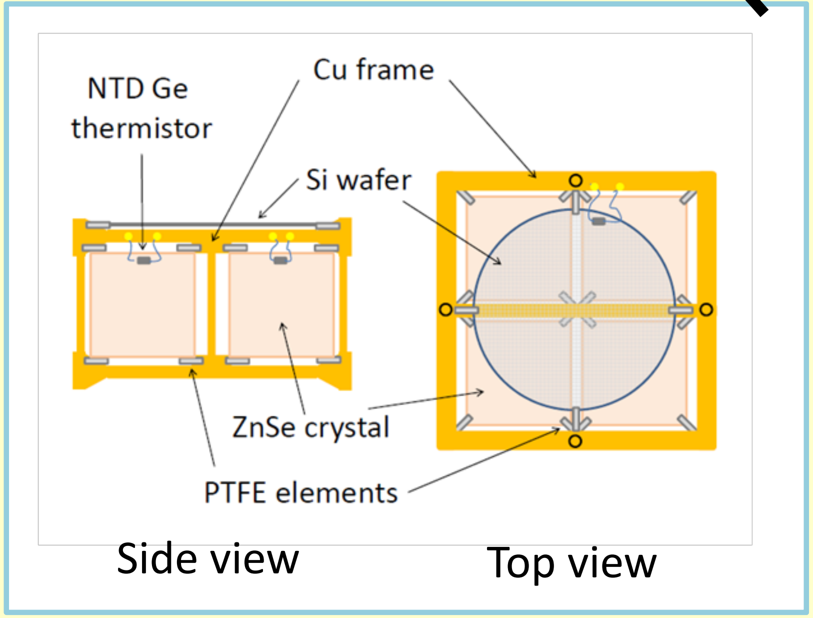
**The most difficult tasks**:

- negotiate a good contract for **enrichment** → Zelenogorsk (Siberia), Russia
- get **radiopure** and **chemically pure** isotope after enrichment
- efficient **crystallization** → Institute for Single Crystals, Kharkov, Ukraina

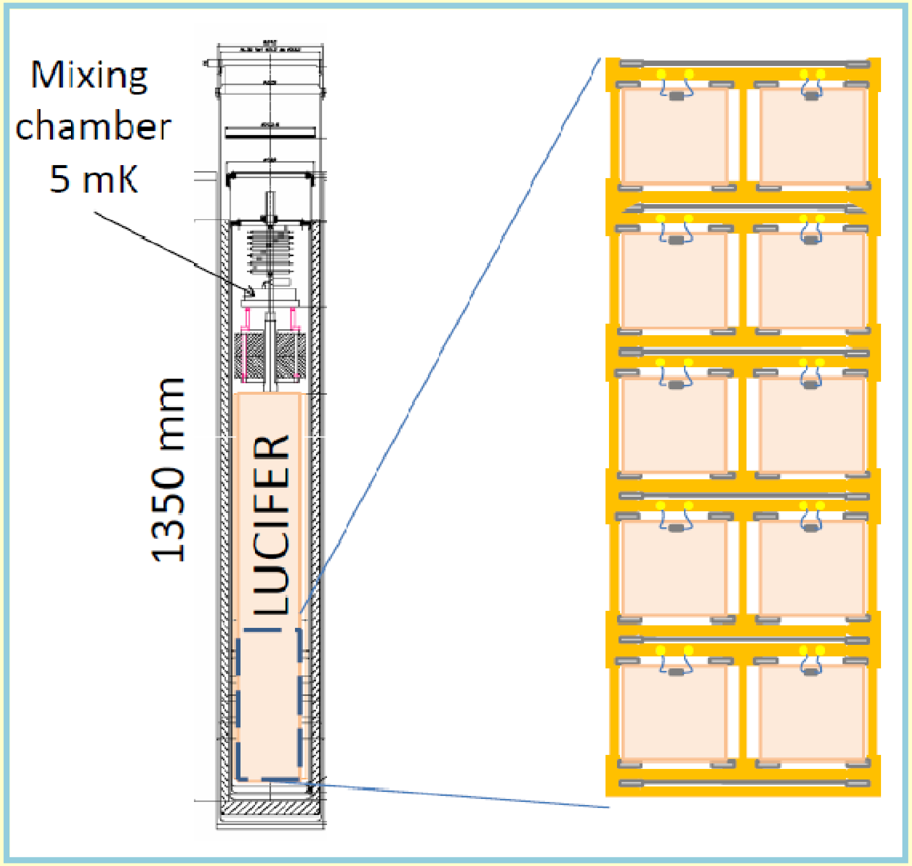
# Structure of the detector

Preliminary

**Single module**:
4 ZnSe crystals
and 1 light detector




**Tower**:
12 single modules



# Prospects and conclusion

- The **bolometric technique** joined with **scintillation** allows to approach zero background in high Q-value isotopes

- **LUCIFER** is a **demonstrator** of this concept

- LUCIFER will study **$^{82}$Se** with **enriched ZnSe crystals** in its baseline version

- Technological problems of **enrichment**, **purification**, **crystallization**

- LUCIFER is a sensitive project by itself (it can **approach the inverted hierarchy region** of the neutrino mass pattern) but it can be seen as a **pilot project** preparing a possible (still to be discussed) **CUORE upgrade** after the $TeO_2$ run (**cover fully the inverted hierarchy region**)