Beyond 2010, Cape Town, 2nd February 2010

LUCIFER:

an Experimental Breakthrough in the Search for Neutrinoless Double Beta Decay

Andrea Giuliani

University of Insubria (Como)
and INFN Milano-Bicocca

Italy

LUCIFER

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

Principal Investigator: Fernando Ferroni
Co-Investigator : Andrea Giuliani

ERC-2009-AdG 247115

European Research Council erc

Double Beta Decay pilot project based on scintillating bolometers

Outline

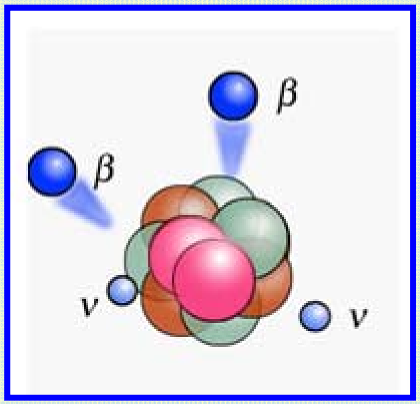
- Double Beta Decay
- Experimental challenge and role of the background
- Silver and golden isotopes
- The bolometric technique and the golden isotopes
- The LUCIFER way
- Prospects and conclusions

Decay modes for Double Beta Decay

Two decay modes are usually discussed:

2νββ

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



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

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

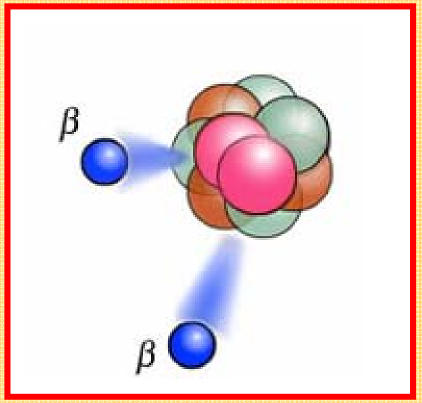
0νββ

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

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: ⇨

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

0ν-DBD and neutrino masses

how **0ν-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**

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

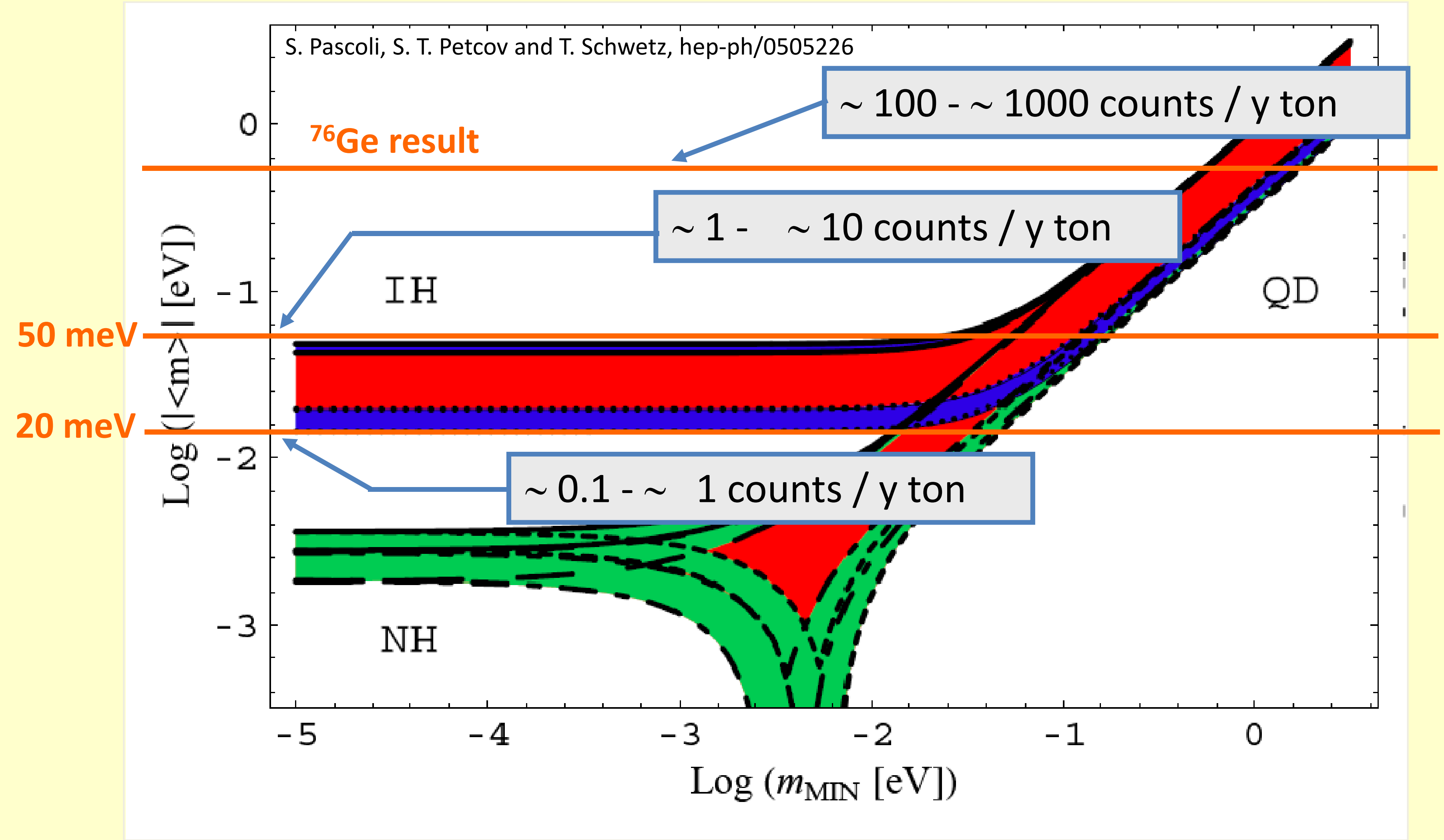
what the **experimentalists** try to measure

what the **nuclear theorists** try to calculate

parameter containing the **physics**

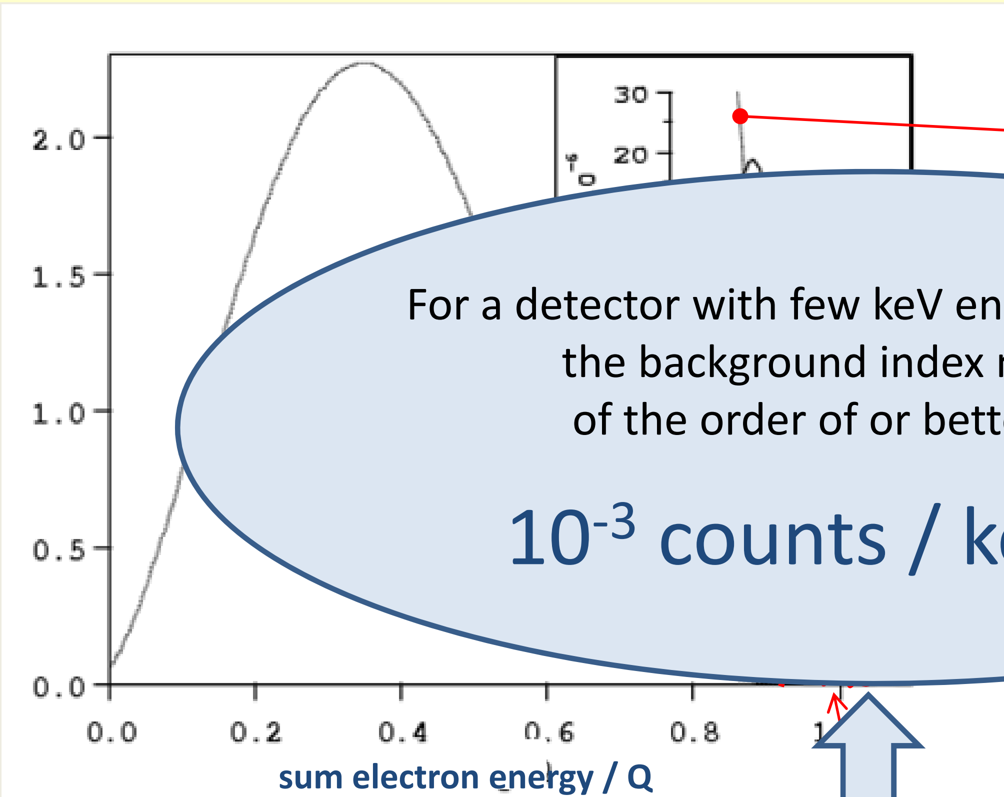
$$\langle M_{\beta\beta}\rangle = \left|\ |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \right|$$

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

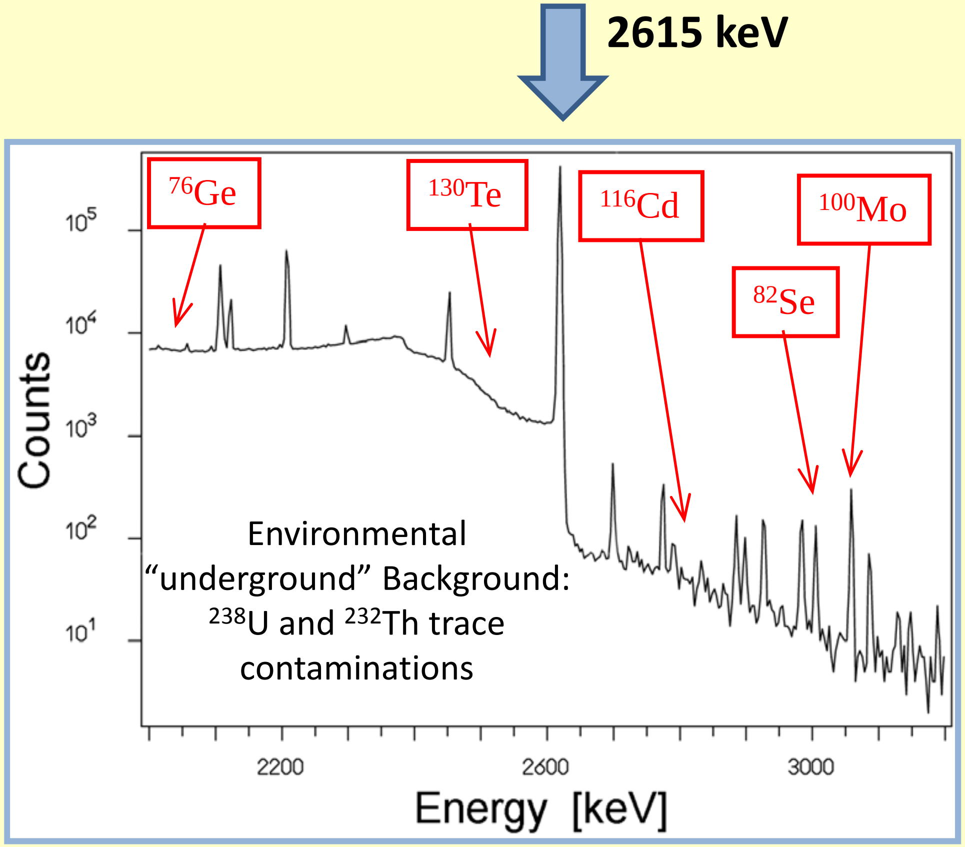
The order of magnitude of the target bakground is **~ few counts / y ton**

The importance of a high Q-value

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

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

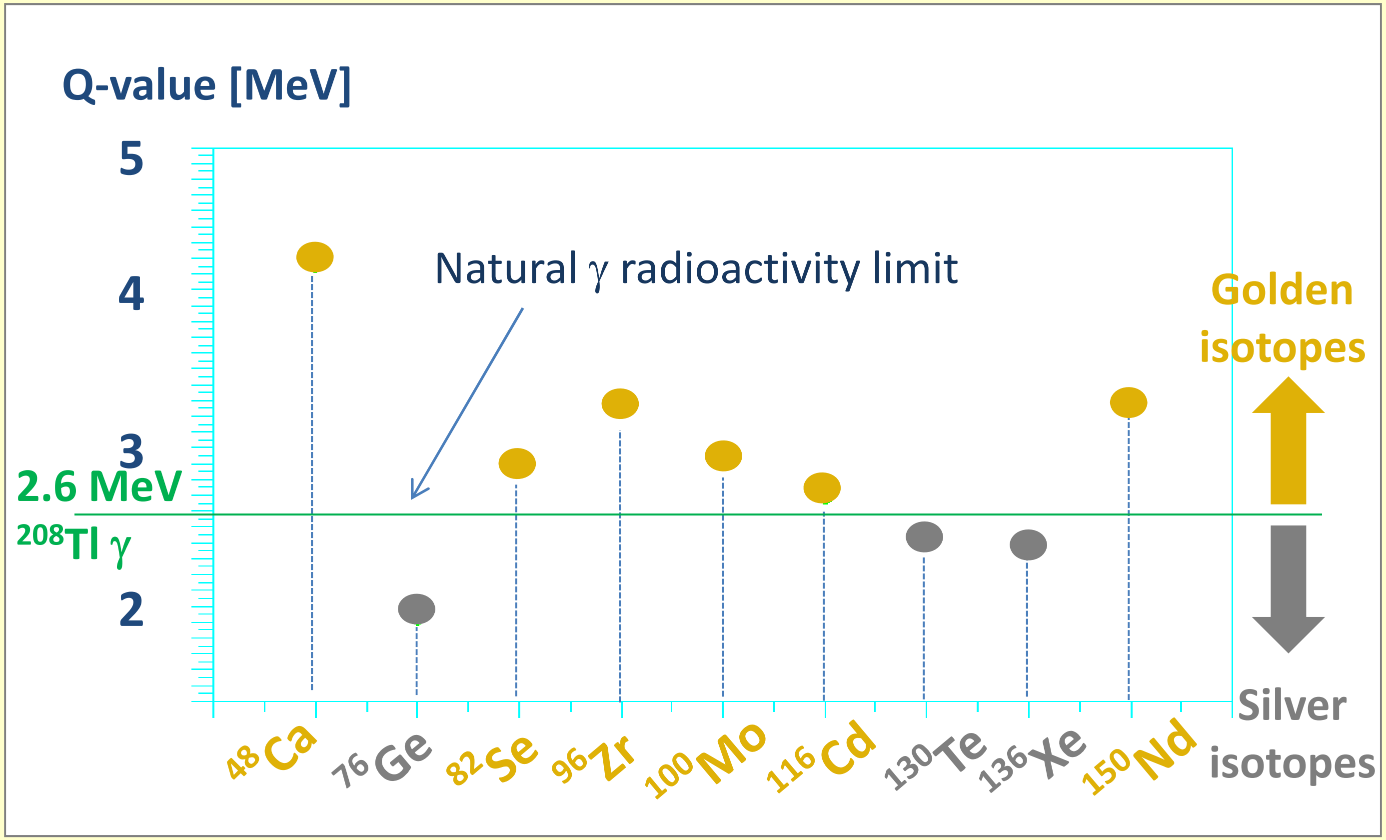
Position of the Q-values for some interesting candidates superimposed to a γ spectrum taken underground without any form of passive shielding



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:

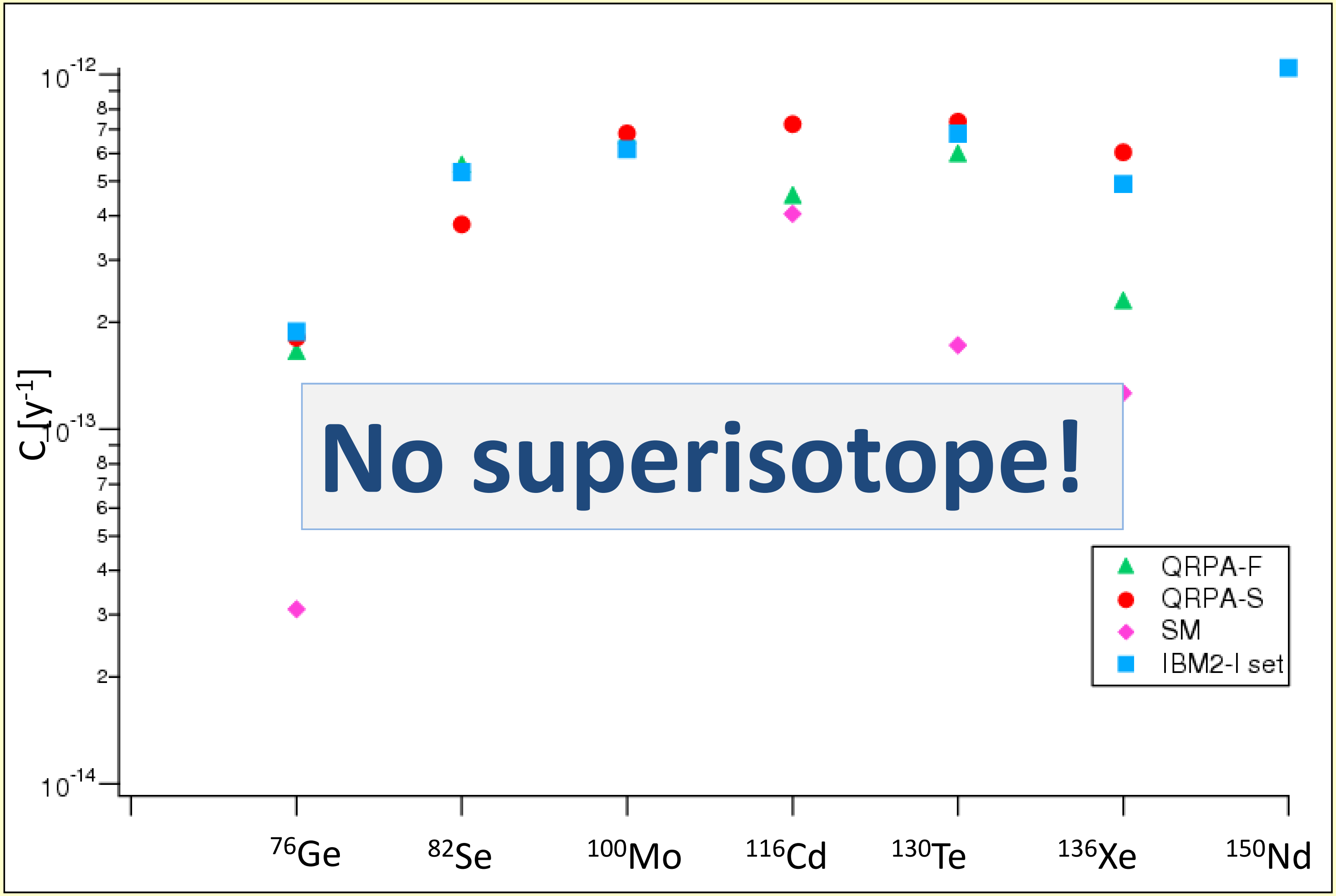
- Easy association to an **experimental technique**
- High **isotopic abundance** and/or easy **enrichment**
- Achievable **radiopurity**

The role of nuclear matrix elements in isotope choice

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

$C = |M^{0\nu}|^2 \bullet G^{0\nu}$ [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 → **^{130}Te**, but potentially **most of golden isotopes**

Silvia Capelli , Thursday

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

$$\Delta T = E/C$$

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

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

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:

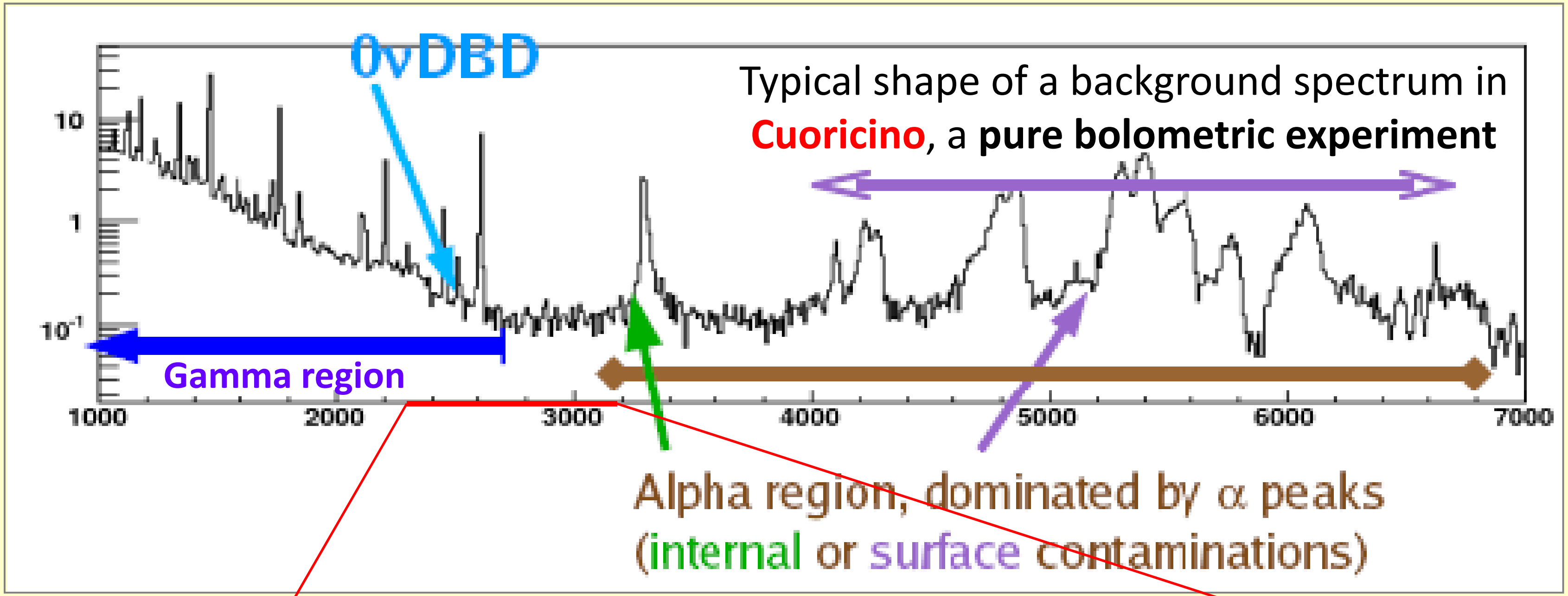
- Invest money in **enrichment**
- Invest money in **crystal growth** with radio-clean procedures
- Exploit the **existing facilities** for large mass bolometric experiments (Cuoricino, CUORE at LNGS)

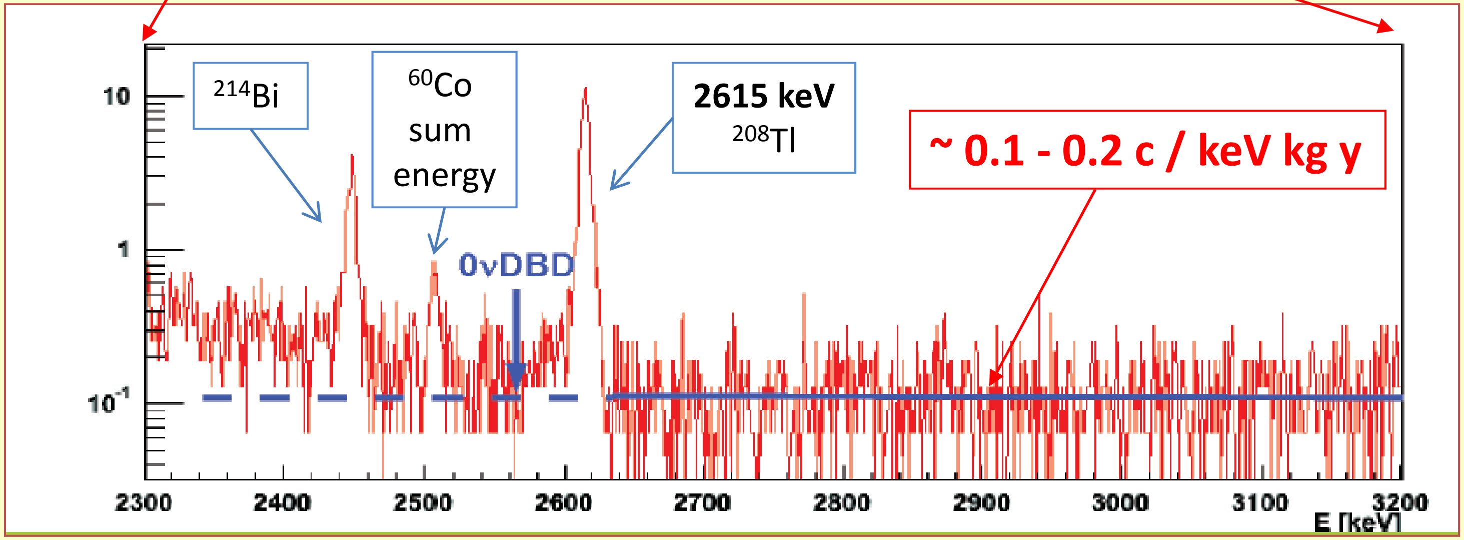
~~**In parallel to ^{130}Te**, study the potentially much better candidates **^{82}Se, ^{116}Cd, ^{100}Mo, ^{48}Ca** and others~~

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

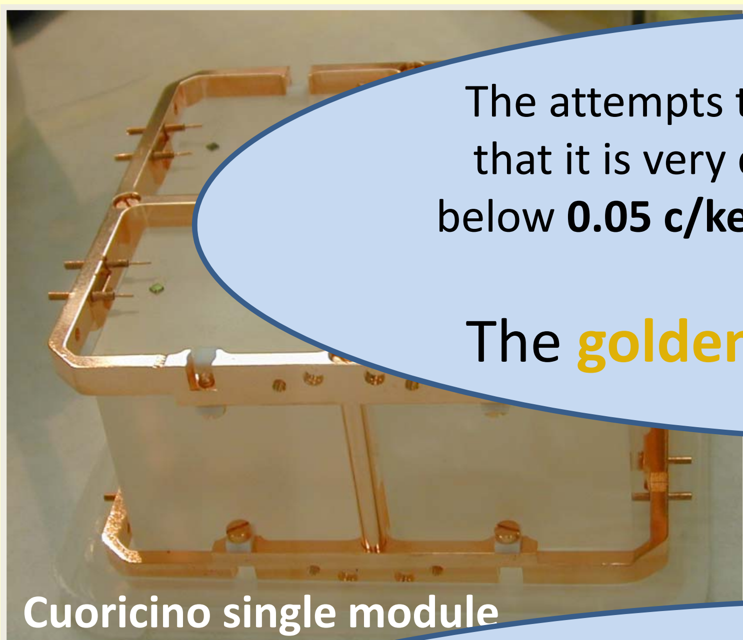


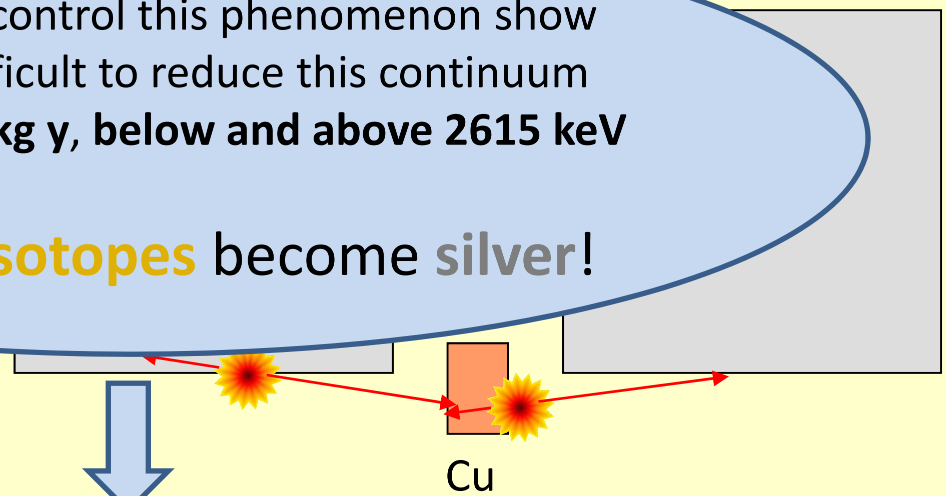


The origin of the continuum above ~2.5 MeV

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**





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

↓

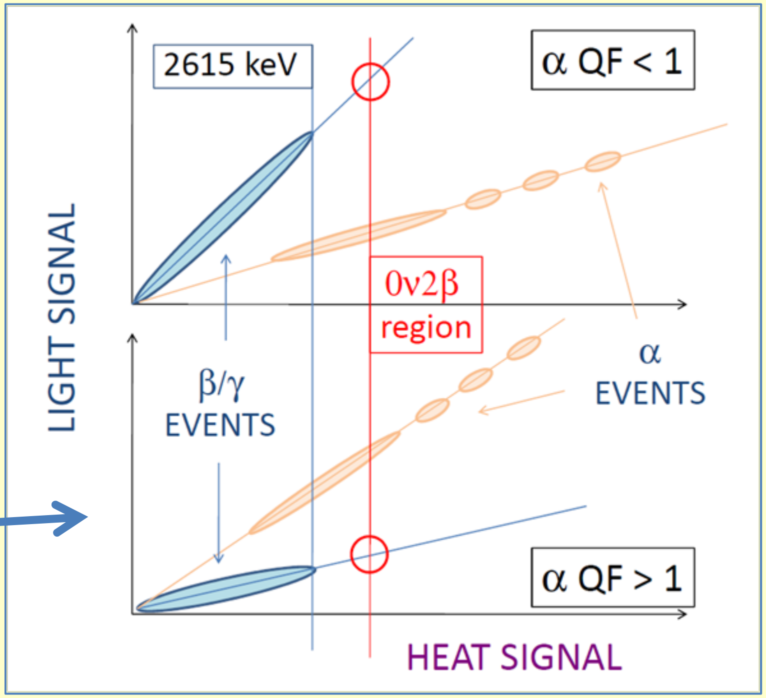
The LUCIFER way

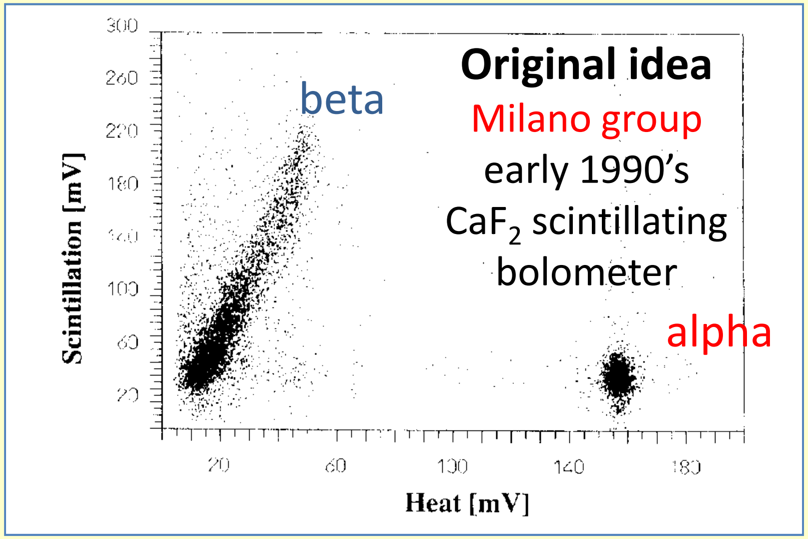
The fundamental idea and the LUCIFER precursors

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.





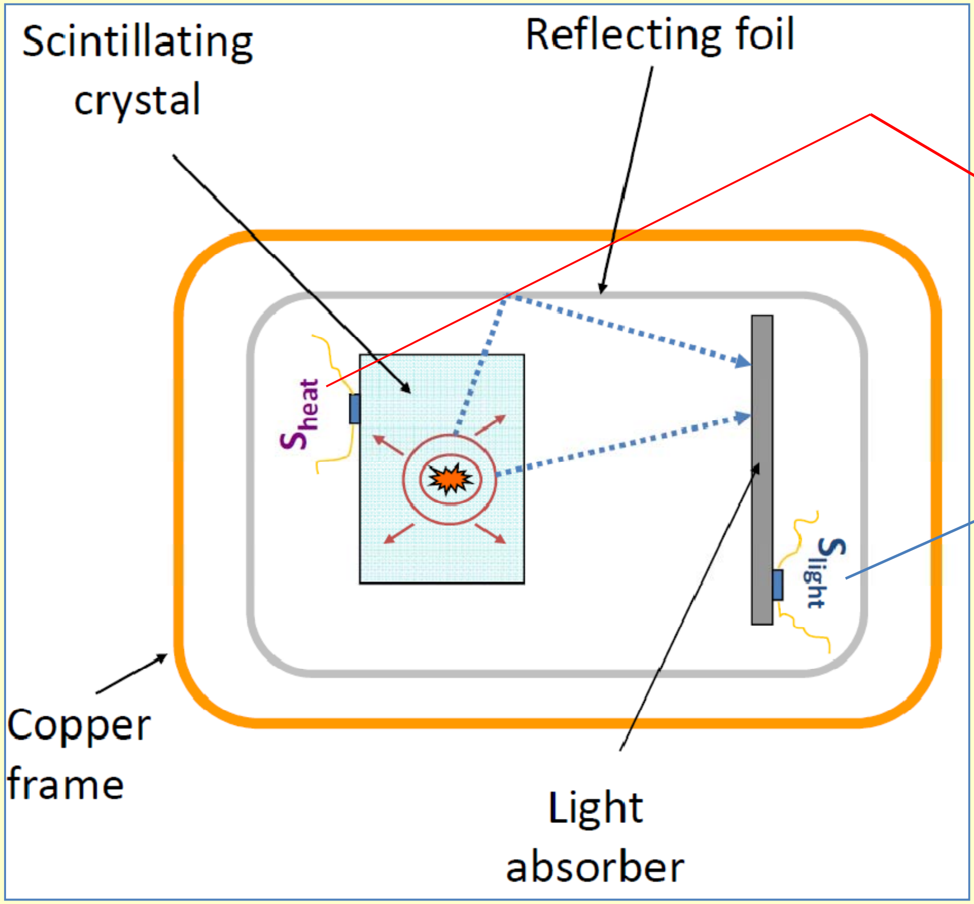
The **experimental basis** for **LUCIFER** is the R&D activity performed by **Stefano Pirro** at LNGS , in the framework of the programs:

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

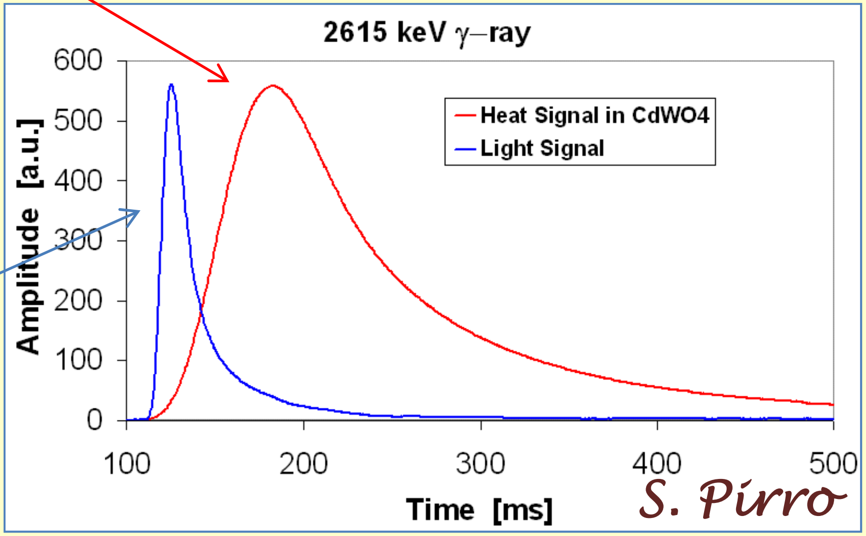
Double bolometer for heat and light

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

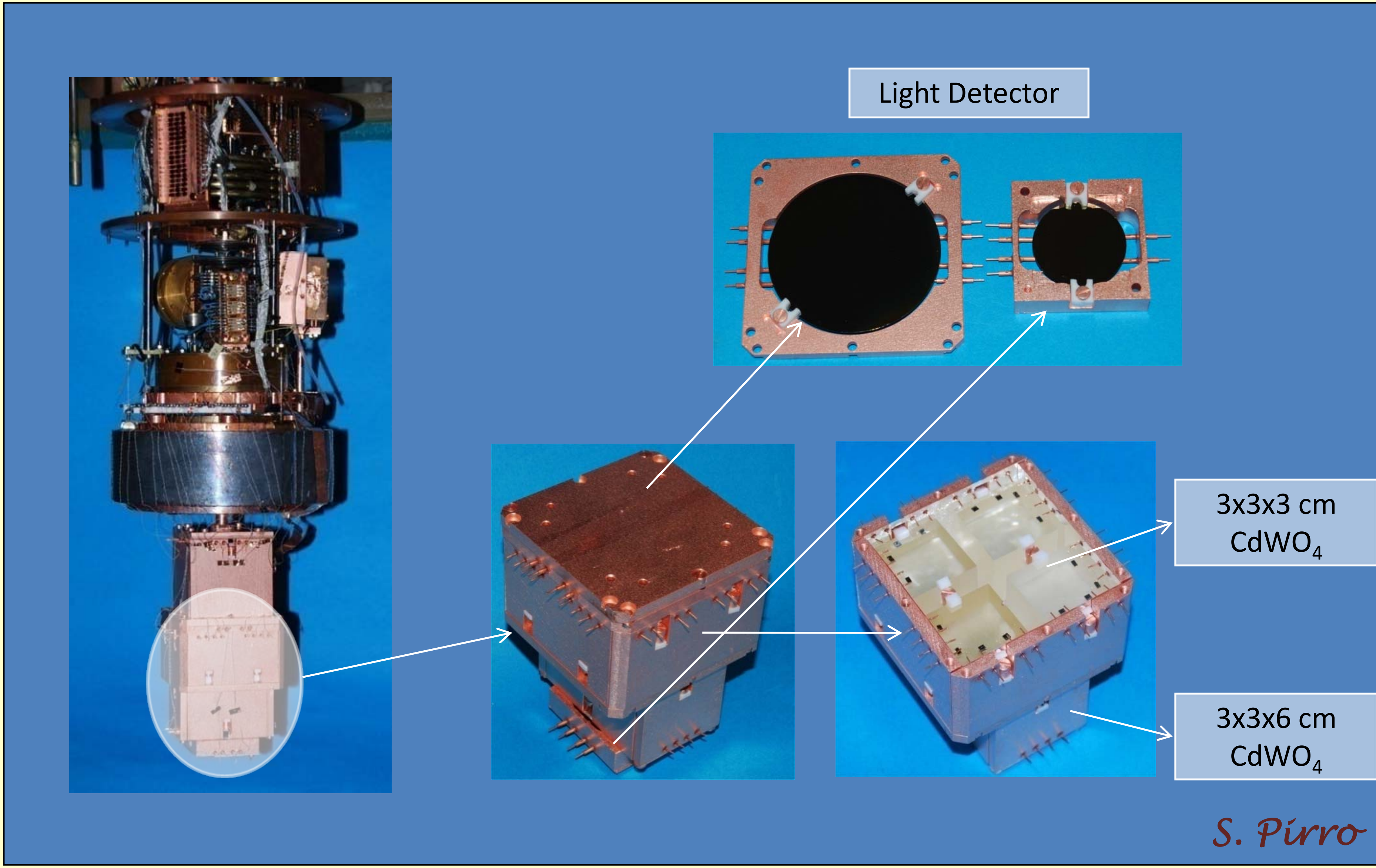
Nucleus	I. A. [%]	Q-value [keV]	Materials successfully tested as bolometers in crystalline form
^{76}Ge	7.8	2039	Ge
^{136}Xe	8.9	2479	NONE
^{130}Te	33.8	2527	TeO_2
^{116}Cd	7.5	2802	$CdWO_4$, $CdMoO_4$
^{82}Se	9.2	2995	ZnSe
^{100}Mo	9.6	3034	$PbMoO_4$, $CaMoO_4$, $SrMoO_4$, $CdMoO_4$, $SrMoO_4$, $ZnMoO_4$, 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, $CaMoO_4$

Underlined compounds are **good scintillators**

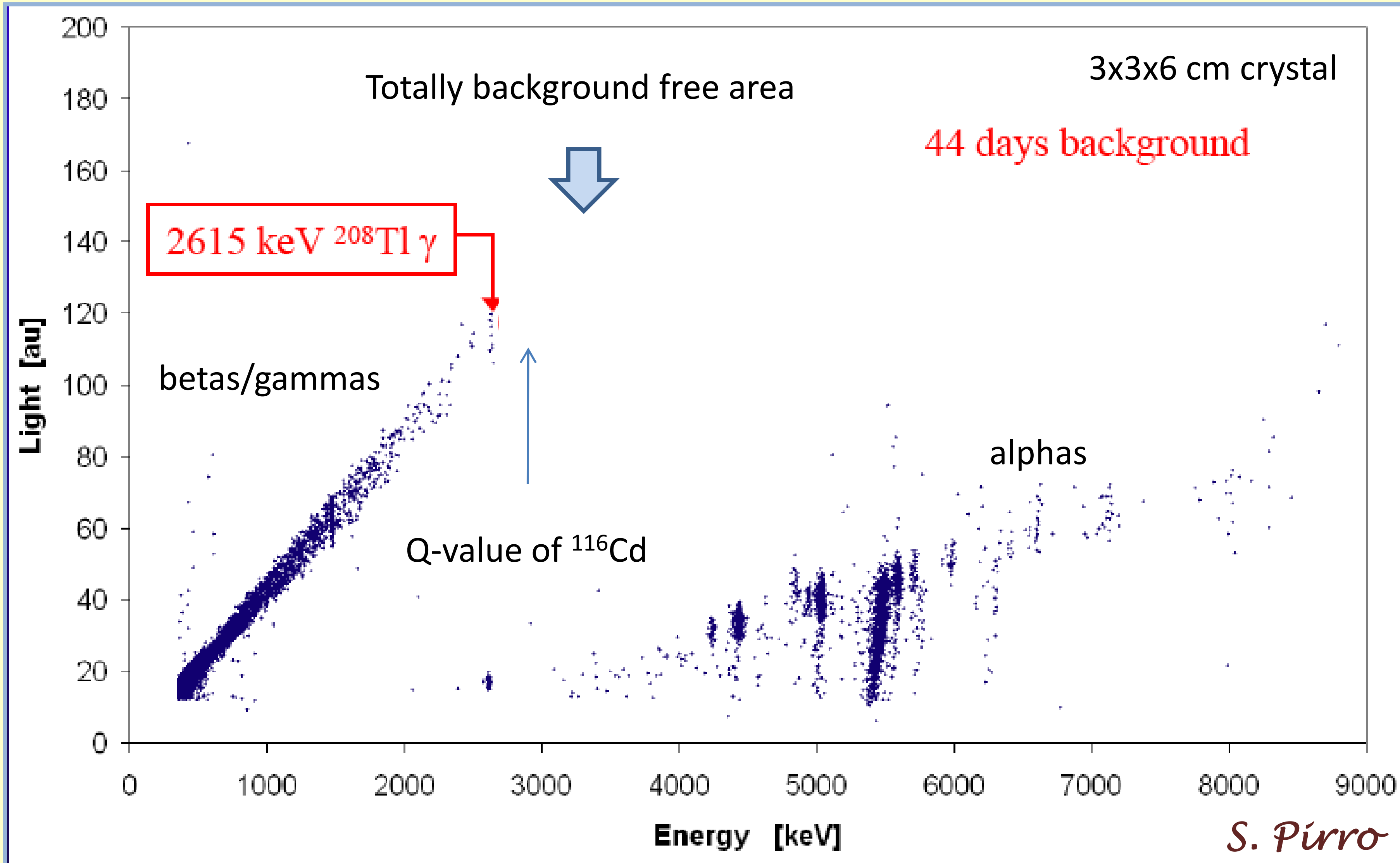
S. Pirro

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

The best technical results so far: $CdWO_4$



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**:

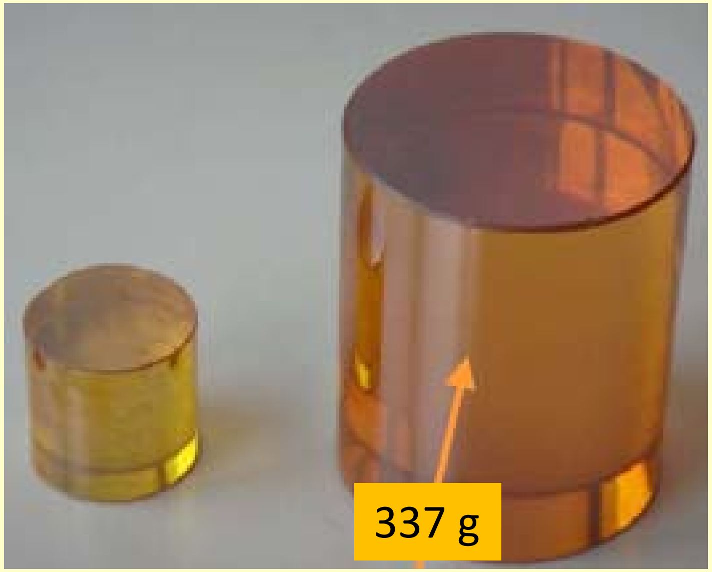
- High atomic mass of W → only **32% useful material** in case of 100% enrichment
- Crystals examined so far exhibit a **huge internal alpha contamination**
- **^{109}Cd has a huge neutron** cross section → residual abundance in enriched material

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**

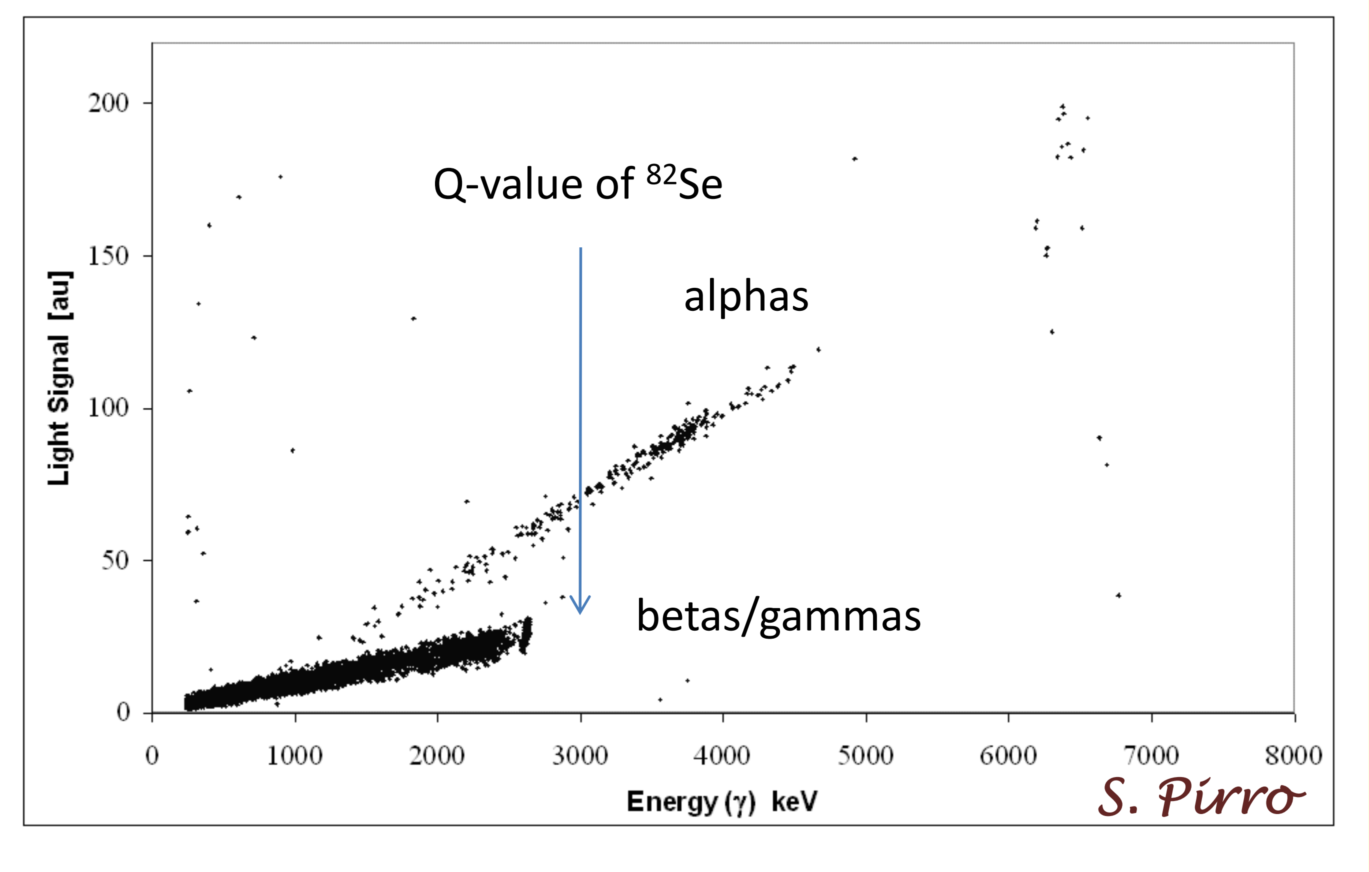
→ excellent bolometric performance, similar to those observed in TeO_2 for CUORE



Two surprises for ZnSe (1)

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

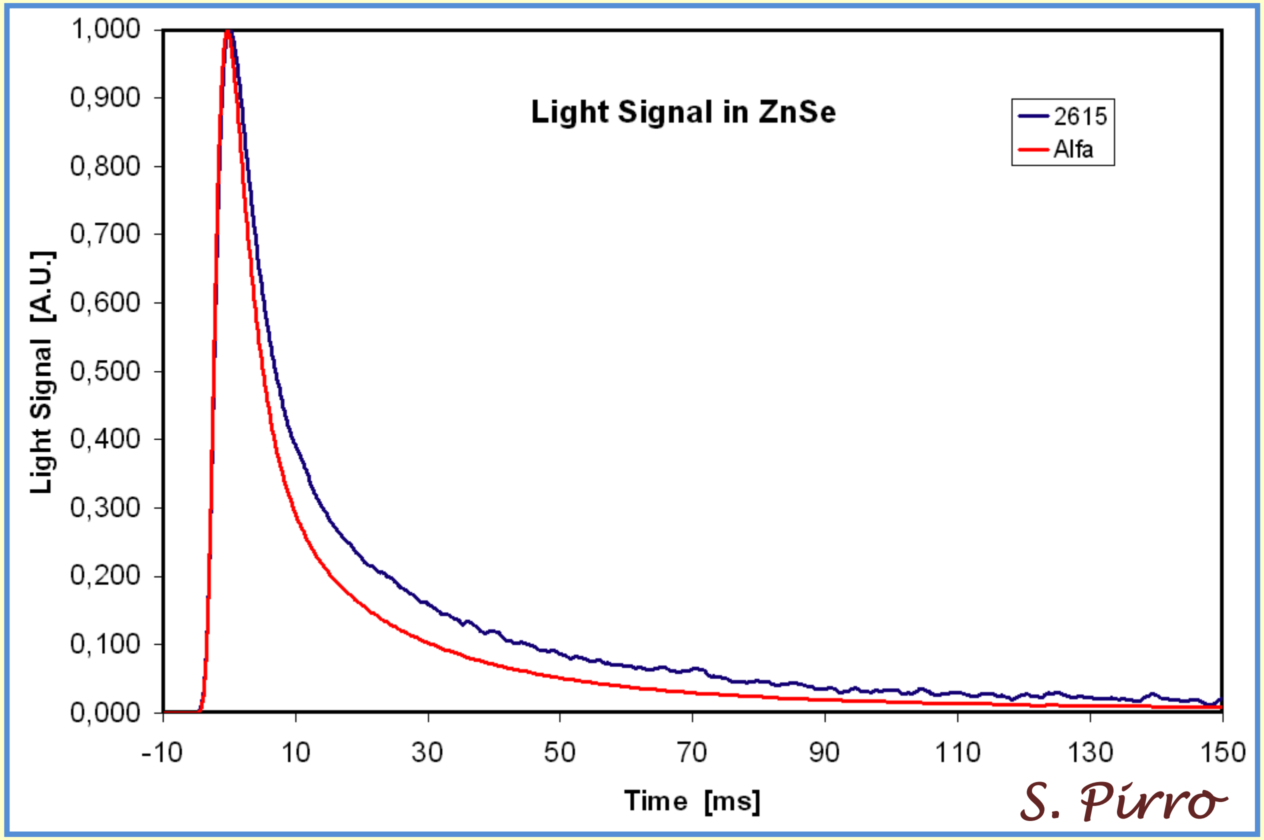
α **QF > 1:** alphas give more light than gammas → risk of leakage in the beta/gamma region?

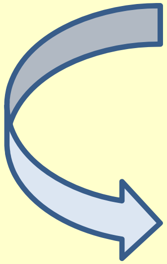


Two surprises for ZnSe (2)

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

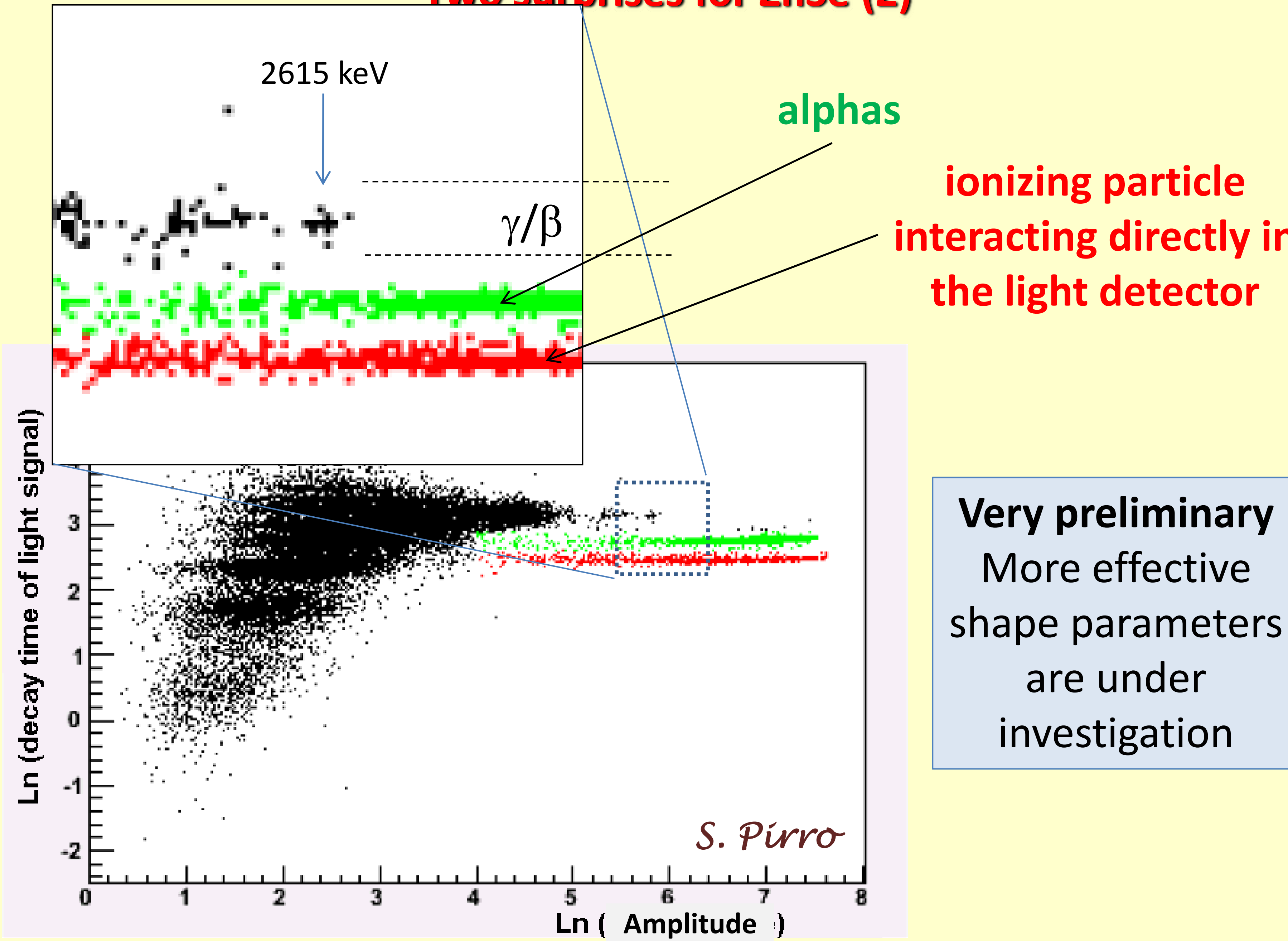
There are detectable differences in the light-signal time development between alpha and beta events → **Pulse Shape Discrimination is possible**





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 **5×10^{-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 $\sim 5 \times 10^{-2}$

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 1σ 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.*

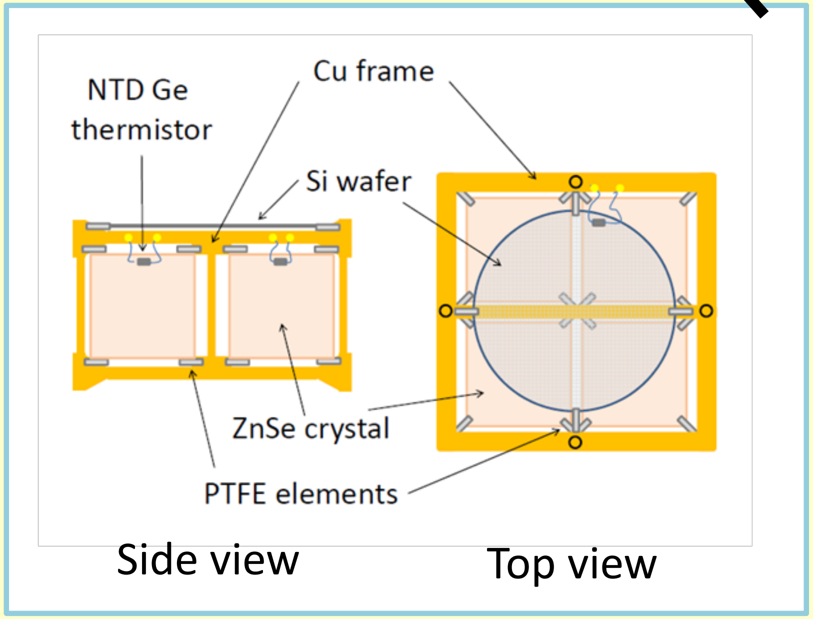
The most difficult tasks:

- 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

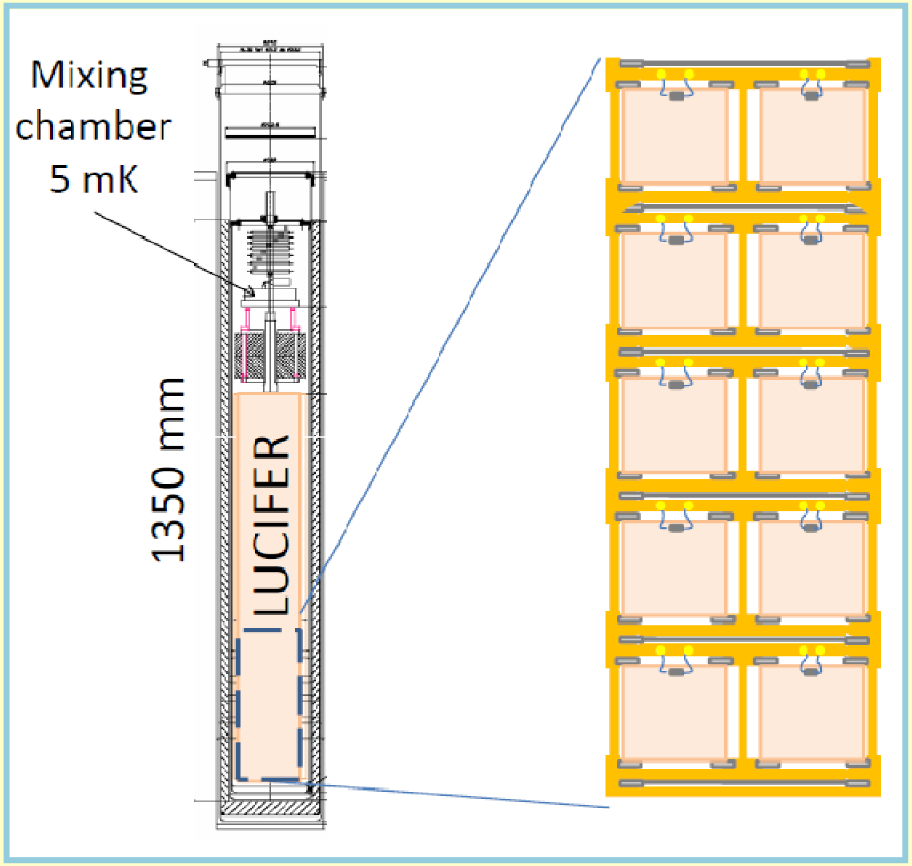
Structure of the detector

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**)