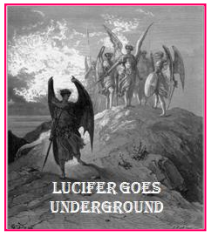


LUCIFER

TAUP 2011 – Munich

A Scintillating Bolometer Array for the Search of Neutrinoless Double Beta Decay

Laura Cardani

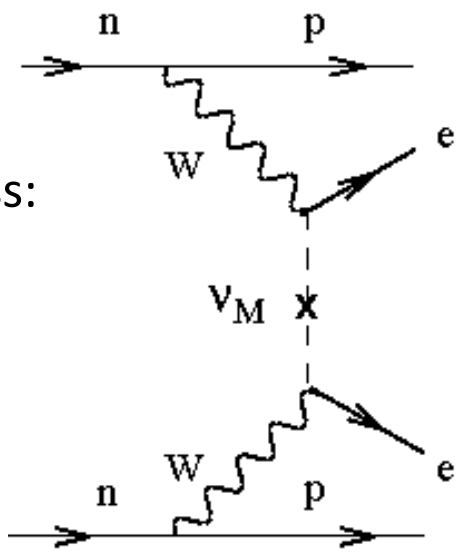
La Sapienza, University of Roma

(0ν)DBD

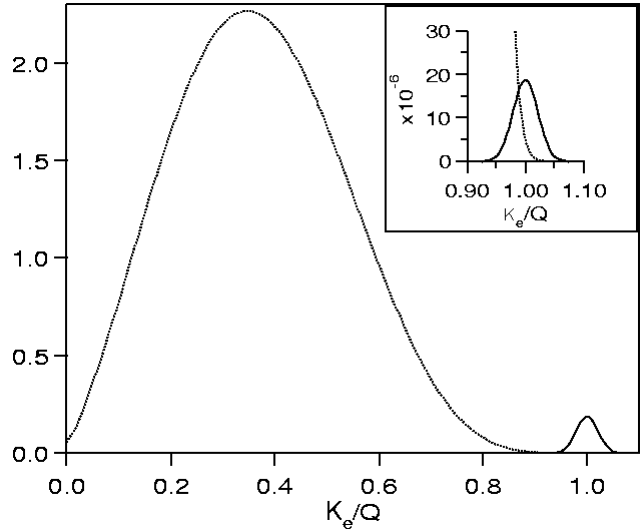
Importance of the process:
- it can happen only if ν is a Majorana particle;
- its observation could lead to a measure of the effective mass:

$$m_{\beta\beta} = \left| \sum_{j=1}^{3} U_{ej}^{2} m_j \right| = \left| \sum_{j=1}^{3} \left| U_{ej} \right|^{2} e^{i\phi_j} m_j \right|$$

$$\left[T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} \left| M_{0\nu} \right|^{2} \left\langle m_{\beta\beta} \right\rangle^{2}$$



What are we looking for?



This process is very rare so:

→ Low background

→ Large source mass

→ Good energy resolution

Bolometer Search for (0ν)DBD

The Sensitivity $S^{0\nu}$ of an experiment is defined as the half-life corresponding to the minimum number of signal events observable above background at a given statistical significance.

$$S^{0\nu} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{M\ t}{b\ \Delta E}}$$

Where:

ε = efficiency

i.a. = isotopic abundance

A = atomic mass number

M = detector mass [kg]

t = live time of the experiment [y]

ΔE = energy resolution

b = background [counts/keV/kg/y]

Bolometer Search for (0ν)DBD

The Sensitivity $S^{0\nu}$ of an experiment is defined as the half-life corresponding to the minimum number of signal events observable above background at a given statistical significance.

$$S^{0\nu} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{M\ t}{b\ \Delta E}}$$

What can we improve?

ε = efficiency → ≈100% for bolometers

i.a. = isotopic abundance → enrichment feasibility? → $$$ / Contaminations

A = atomic mass number

M = detector mass [kg] → For the next generation is already ≈1 ton

t = live time of the experiment [y] → For the next generation is already ≈ 5 y

ΔE = energy resolution → ≈5 keV for bolometers

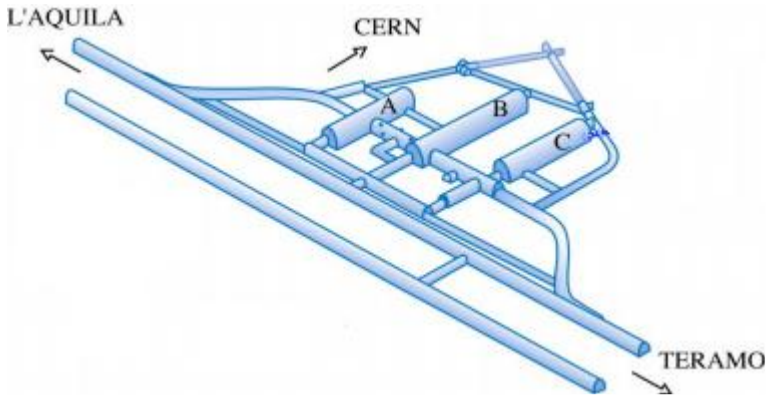
b = background [counts/keV/kg/y] main challenge!

Background Reduction

How can we suppress the background in the energy region of interest?

Underground laboratories.

Ex: the detectors we will present have been studied in LNGS (Italy) → 3650 m.w.e.



muon flux: $(2.58\pm0.3)\times10^{-8}$ μ/(s cm^2)

Mei and Hime, Phys. Rev. D 73, 053004, 2006 [astro-ph 0512125]

neutron flux [<10MeV] : $\approx4\times10^{-6}$ n/(s cm^2)

F. Arneodo et al., Il Nuovo Cim. 112A, 819, 1999

gamma flux: ≈ 0.73 γ/(s cm^2)

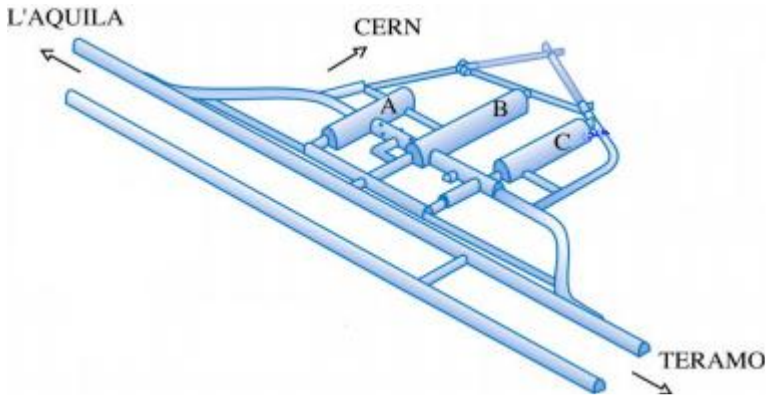
C. Bucci et al., Eur. Phys. J. A, 41, 155-168, 2009

Background Reduction

How can we suppress the background in the energy region of interest?

Underground laboratories.

Ex: the detectors we will present have been studied in LNGS (Italy) → 3650 m.w.e.



muon flux: $(2.58\pm0.3)\times10^{-8}$ μ/(s cm^2)

Mei and Hime, Phys. Rev. D 73, 053004, 2006 [astro-ph 0512125]

neutron flux [<10MeV] : $\approx4\times10^{-6}$ n/(s cm^2)

F. Arneodo et al., Il Nuovo Cim. 112A, 819, 1999

gamma flux: ≈ 0.73 γ/(s cm^2)

C. Bucci et al., Eur. Phys. J. A, 41, 155-168, 2009

Proper shieldings or vetoes.

→ "External" contributions to the background suppressed

→ Ultimate limit given by contaminations of the detector itself (and materials in the nearby)

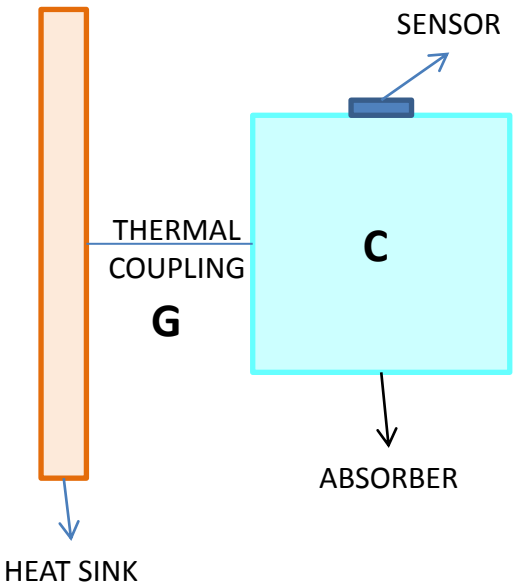
Bolometers background dominated by surface α contaminations of the materials: contributions ≈ 10^{-2} counts/keV/kg/y

Scintillating Bolometers

Scintillating bolometers can overcome this problem by tagging the events!

Working principle: BOLOMETERS

E. Fiorini and T. Niinikoski, Nucl. Instrum. Methods 83 (1984) 224



A bolometer can be sketched as:

Absorber

If the interaction releases an energy E, we have a temperature increase:

$$\Delta T = \frac{E}{C} \quad \Rightarrow \quad \Delta T(t) = \frac{E}{C}\exp(-\frac{t}{\tau}) \qquad \tau = C/G$$

→ dielectric and diamagnetic crystals ($C \div T^3$) operated at low temperatures (0.01 K).

Sensor

That converts ΔT into a readable voltage signal.

Proved technique

See S. Di Domizio's and P. Gorla's talks

Scintillating Bolometers

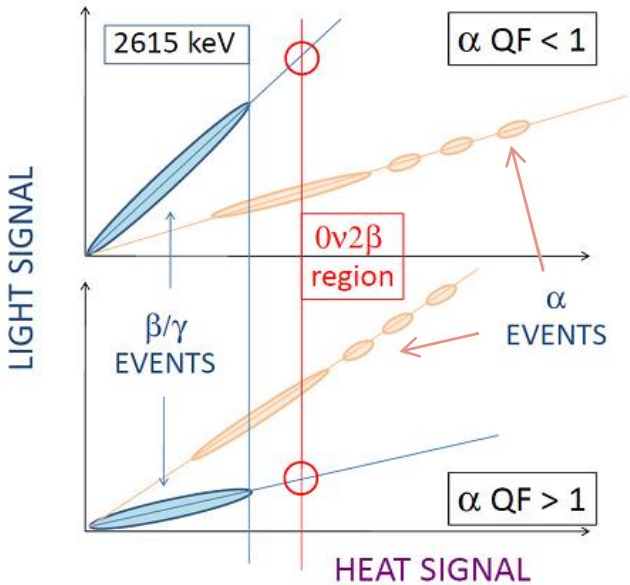
Advantages of this technique

- Different isotopes can be tested
- Very high efficiency
- Excellent energy resolution (‰)
- Possibility of growing radio—pure crystals.

But…no possibility to tag the event
poor background rejection (α events)

Scintillating Bolometers

Advantages of this technique



- Different isotopes can be tested
- Very high efficiency
- Excellent energy resolution (‰)
- Possibility of growing radio—pure crystals.

But…no possibility to tag the event
poor background rejection (α events)

Solution: Scintillating Bolometers!

Based on double read-out: HEAT + LIGHT

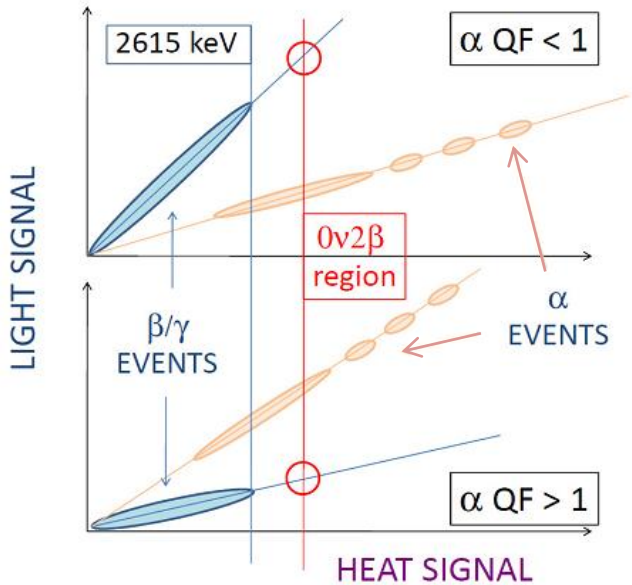
e^- and α of the same energy:
- Release the same heat in the bolometer
- Produce a different amount of light → discrimination

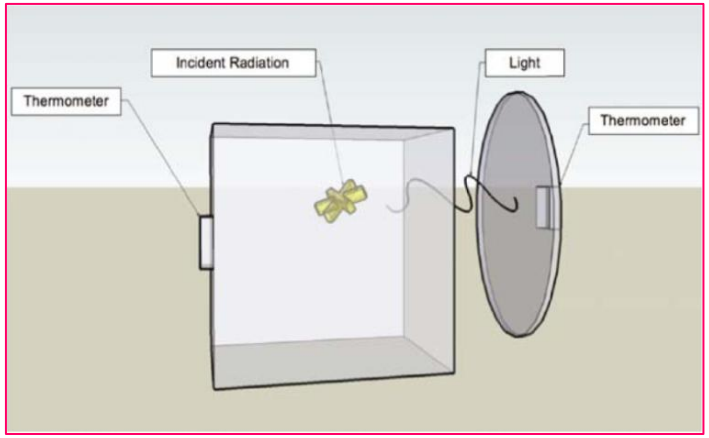
A. Alessandrello et al.,Nuclear Physics B 28 (1992) 233-235

Scintillating Bolometers

Advantages of this technique

- Different isotopes can be tested
- Very high efficiency
- Excellent energy resolution (‰)
- Possibility of growing radio—pure crystals.





Solution: Scintillating Bolometers!

Based on double read-out: HEAT + LIGHT

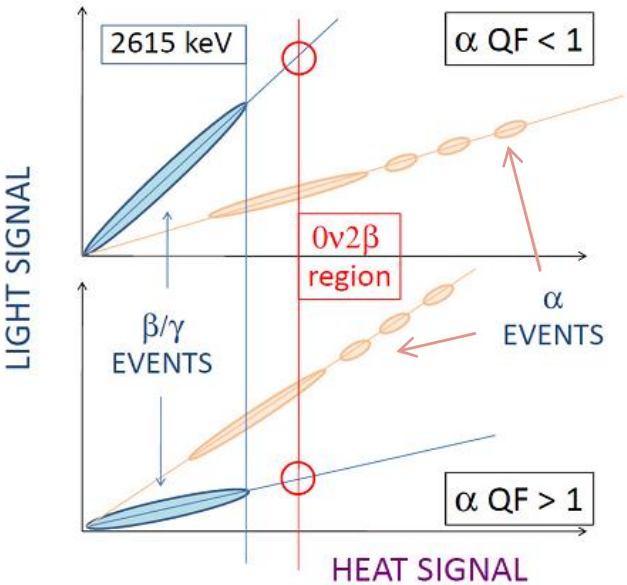
e^- and α of the same energy:
- Release the same heat in the bolometer
- Produce a different amount of light → discrimination

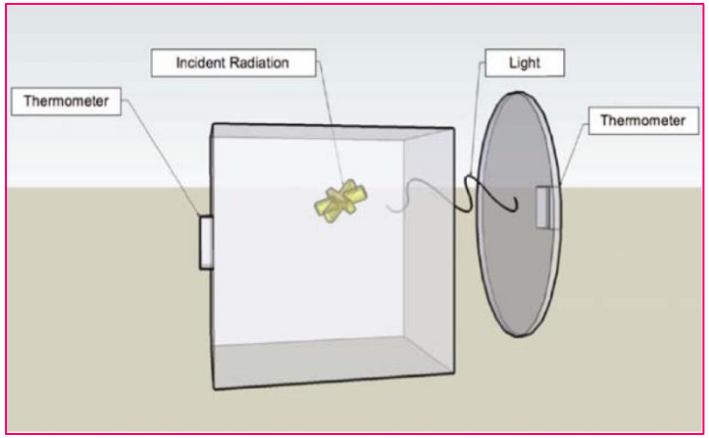
The light can be detected by means of a second bolometer (usually Ge or Si disk)

A. Alessandrello et al.,Nuclear Physics B 28 (1992) 233-235

Scintillating Bolometers

Advantages of this technique





- Different isotopes can be tested
- Very high efficiency
- Excellent energy resolution (‰)
- Possibility of growing radio—pure crystals.

But…no ~~possibility to tag the event~~
~~poor background rejection~~ (α events)

Excellent background rejection

Solution: Scintillating Bolometers!

Based on double read-out: HEAT + LIGHT

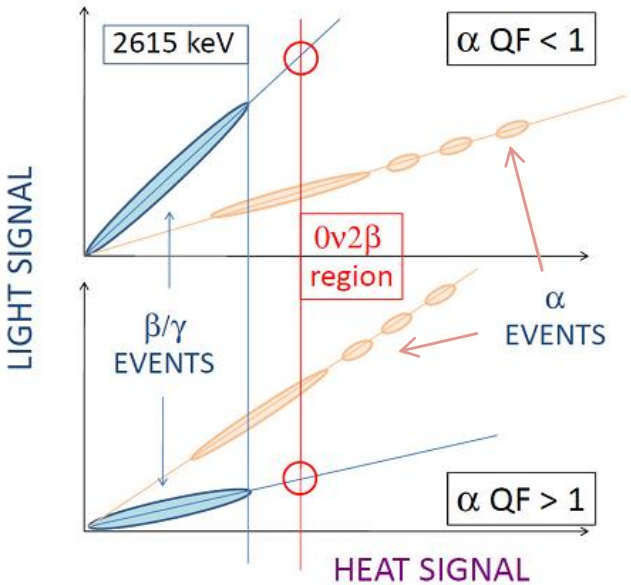
e^- and α of the same energy:
- Release the same heat in the bolometer
- Produce a different amount of light → discrimination

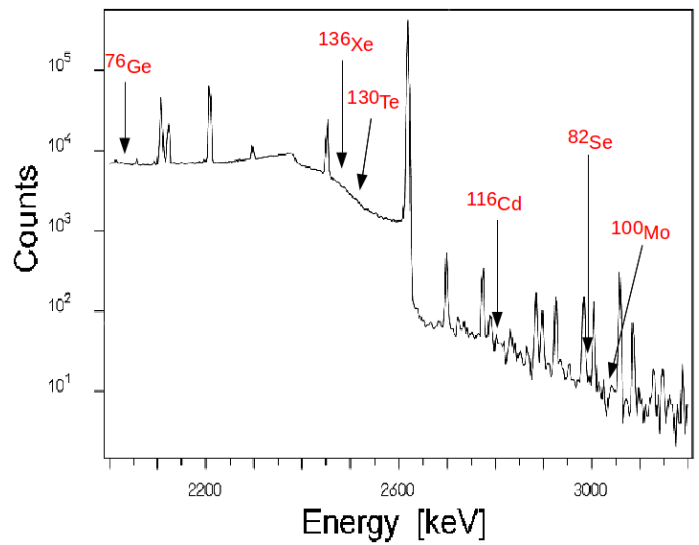
The light can be detected by means of a second bolometer (usually Ge or Si disk)

A. Alessandrello et al.,Nuclear Physics B 28 (1992) 233-235

Scintillating Bolometers

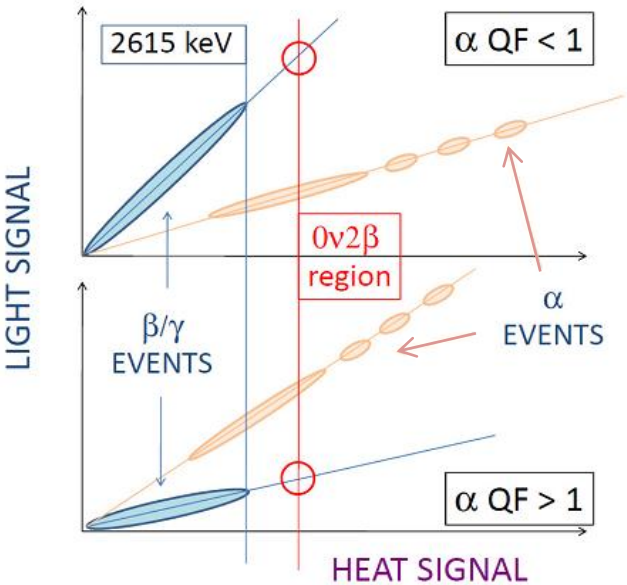
α background eliminated →the main problem is given by the γ contaminations

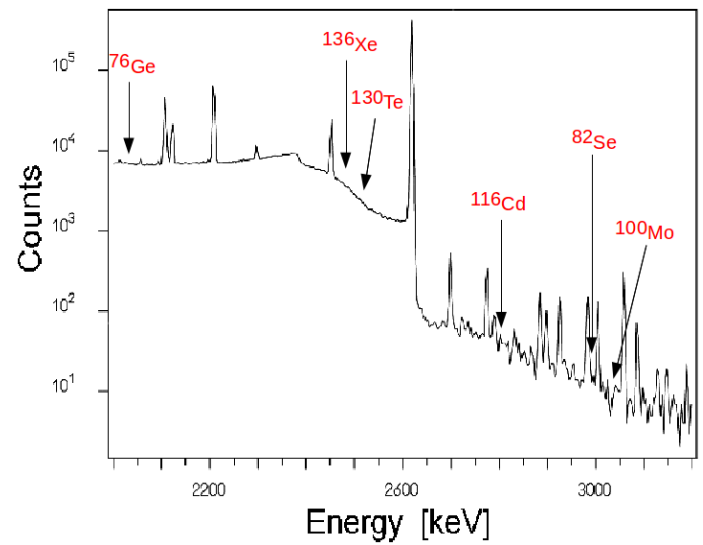


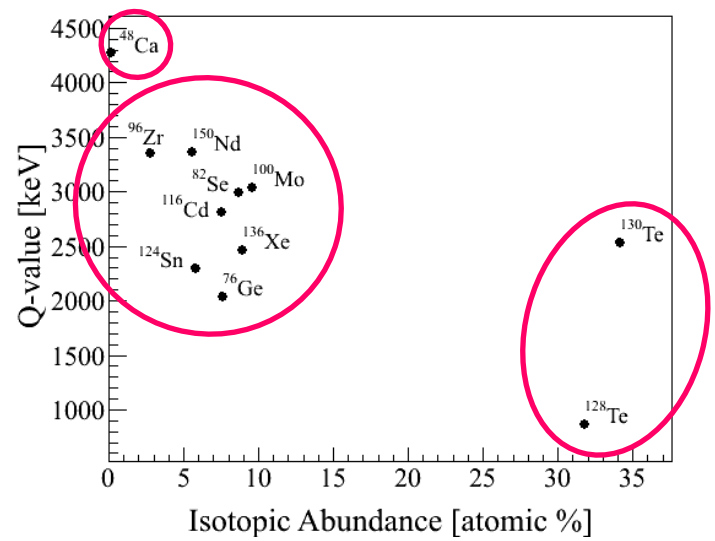


Scintillating Bolometers

α background eliminated →the main problem is given by the γ contaminations







→Which isotope?

Selenium, Cadmium and Molibdenum

…according to the enrichment feasibility!

Promising Crystals

	Q-value [keV]	Useful material	LY [keV/MeV]	QF	Enrichment [€/g]
$CdWO_4$	2809	32%	17.6	0.19	>150 - 200
$ZnMoO_4$	3034	44%	1.1	0.16	50 - 80
ZnSe	2995	56%	7.4	4.2	50 - 80

An extensive R&D activity was performed in the last years.
arXiv:nucl-ex/0510074v11

Promising Crystals

	Q-value [keV]	Useful material	LY [keV/MeV]	QF	Enrichment [€/g]
$CdWO_4$	2809	32%	17.6	0.19	>150 - 200
$ZnMoO_4$	3034	44%	1.1	0.16	50 - 80
ZnSe	2995	56%	7.4	4.2	50 - 80

A $CdWO_4$ array (mass of the single crystal = 0.51 kg) was successfully tested some years ago.

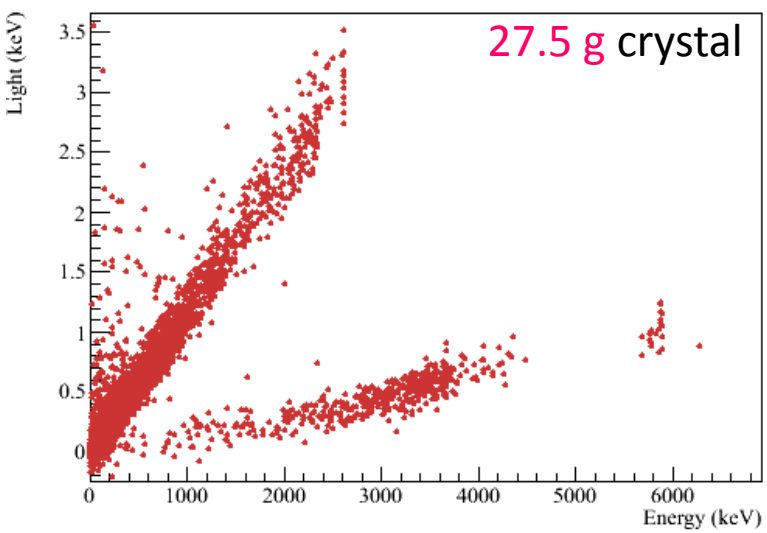
Problems: Presence of ^{113}Cd
Enrichment

Astropart.Phys. 34 (2010) 143-150

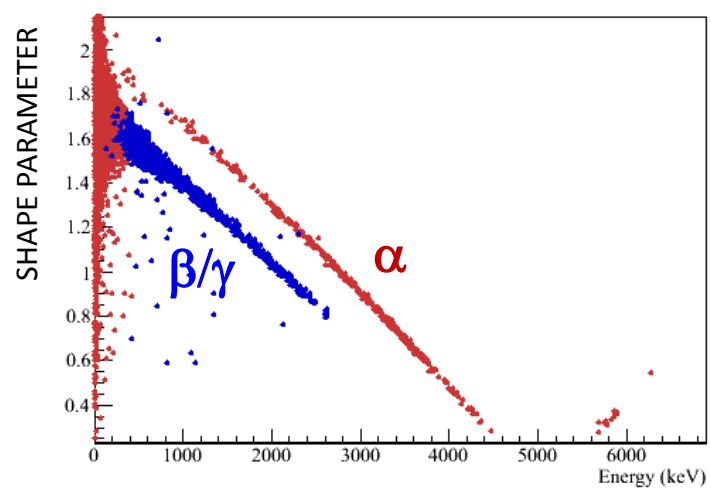
Promising Crystals

	Q-value [keV]	Useful material	LY [keV/MeV]	QF	Enrichment [€/g]
$CdWO_4$	2809	32%	17.6	0.19	>150 - 200
$ZnMoO_4$	3034	44%	1.1	0.16	50 - 80
ZnSe	2995	56%	7.4	4.2	50 - 80

An intense R&D activity on $ZnMoO_4$ on-going[2].



Poor LY but good Pulse Shape Discrimination



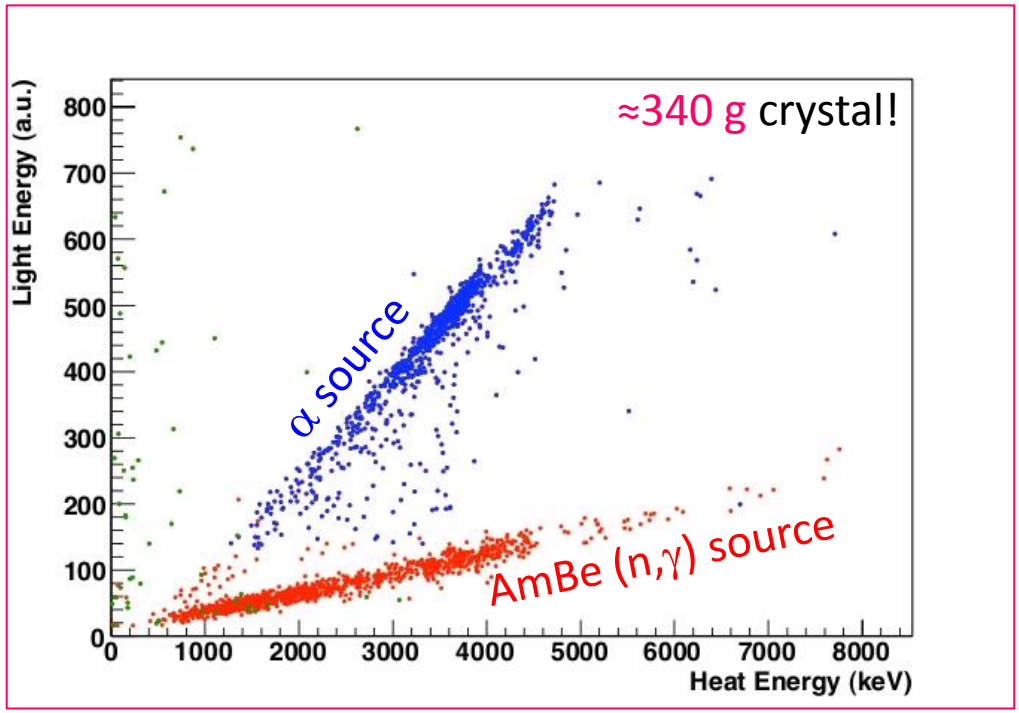
But no large crystals (yet). Radiopurity?

2) JINST 5 (2010) P11007

Promising Crystals

	Q-value [keV]	Useful material	LY [keV/MeV]	QF	Enrichment [€/g]
$CdWO_4$	2809	32%	17.6	0.19	>150 - 200
$ZnMoO_4$	3034	44%	1.1	0.16	50 - 80
ZnSe	2995	56%	7.4	4.2	50 - 80

Several samples of ZnSe have been recently tested[3].



Disadvantages…

QF > 1 → LY(α)>LY(β/γ)

No theoretical model can explain this behavior

We discarded this hypothesis:

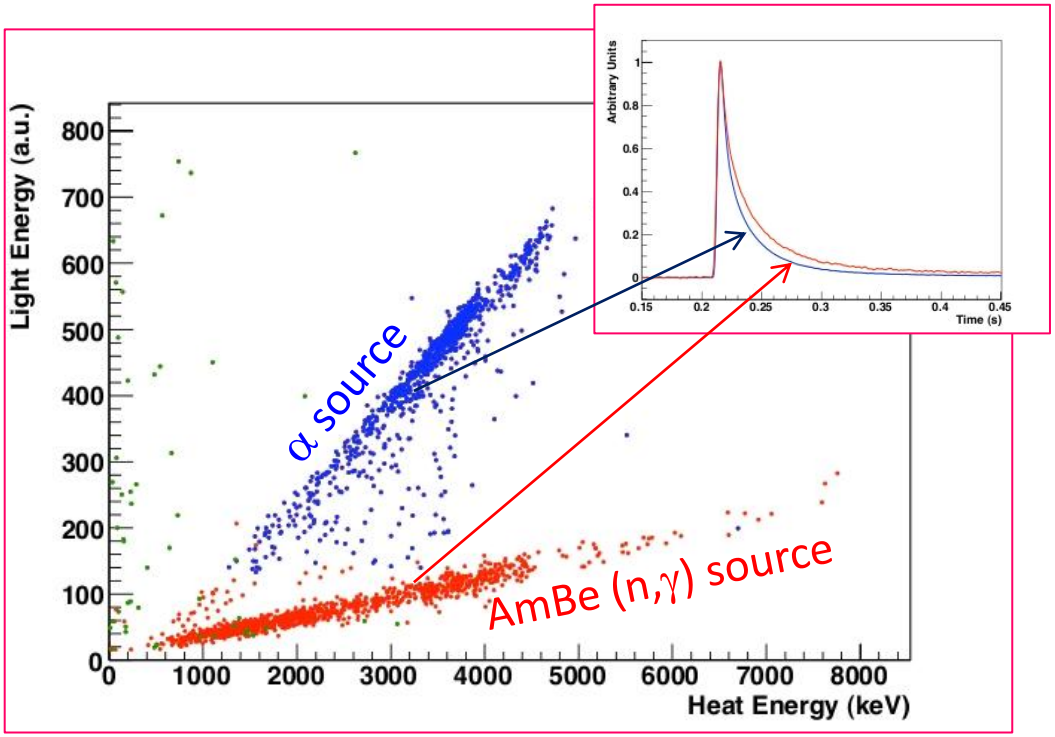
1) ZnSe self—absorption
2) Light collection efficiency
3) Light detector transparent to certain wavelenghts

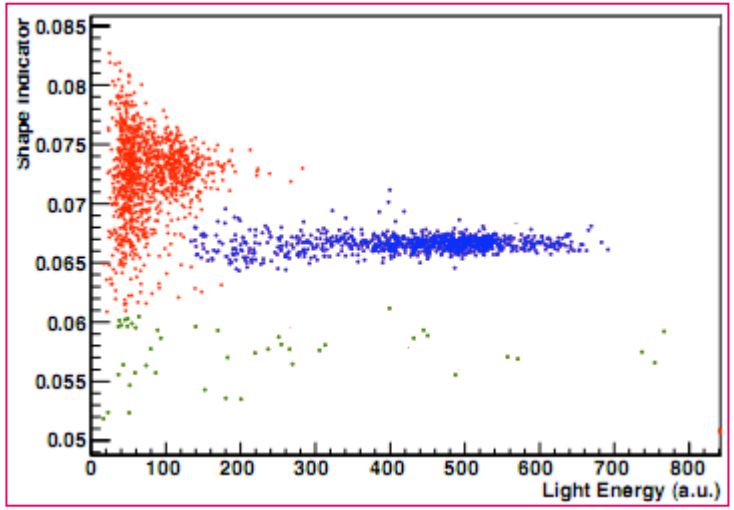
3) Astropart.Phys. 34 (2011) 344-353

Promising Crystals

	Q-value [keV]	Useful material	LY [keV/MeV]	QF	Enrichment [€/g]
$CdWO_4$	2809	32%	17.6	0.19	>150 - 200
$ZnMoO_4$	3034	44%	1.1	0.16	50 - 80
ZnSe	2995	56%	7.4	4.2	50 - 80

Several samples of ZnSe have been recently tested[3].





3) Astropart.Phys. 34 (2011) 344-353

Promising Crystals

	Q-value [keV]	Useful material	LY [keV/MeV]	QF	Enrichment [€/g]
$CdWO_4$	2809	32%	17.6	0.19	>150 - 200
$ZnMoO_4$	3034	44%	1.1	0.16	50 - 80
ZnSe	2995	56%	7.4	4.2	50 - 80

Disadvantages…

QF > 1 → LY(α)>LY(β/γ)

No theoretical model can explain this behavior

Other tests are needed

Promising Crystals

	Q-value [keV]	Useful material	LY [keV/MeV]	QF	Enrichment [€/g]
$CdWO_4$	2809	32%	17.6	0.19	>150 - 200
$ZnMoO_4$	3034	44%	1.1	0.16	50 - 80
ZnSe	2995	56%	7.4	4.2	50 - 80

Disadvantages…

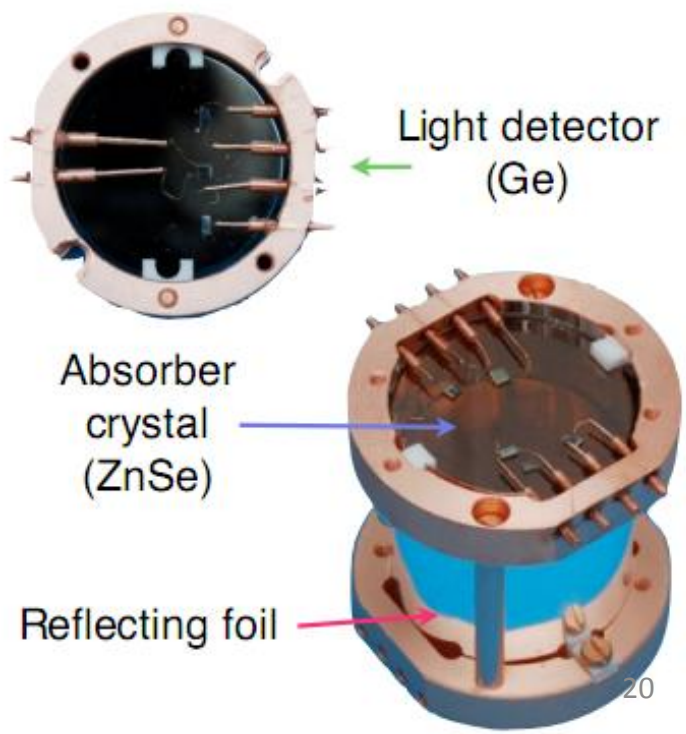
QF > 1 → LY(α)>LY(β/γ)

No theoretical model can explain this behavior

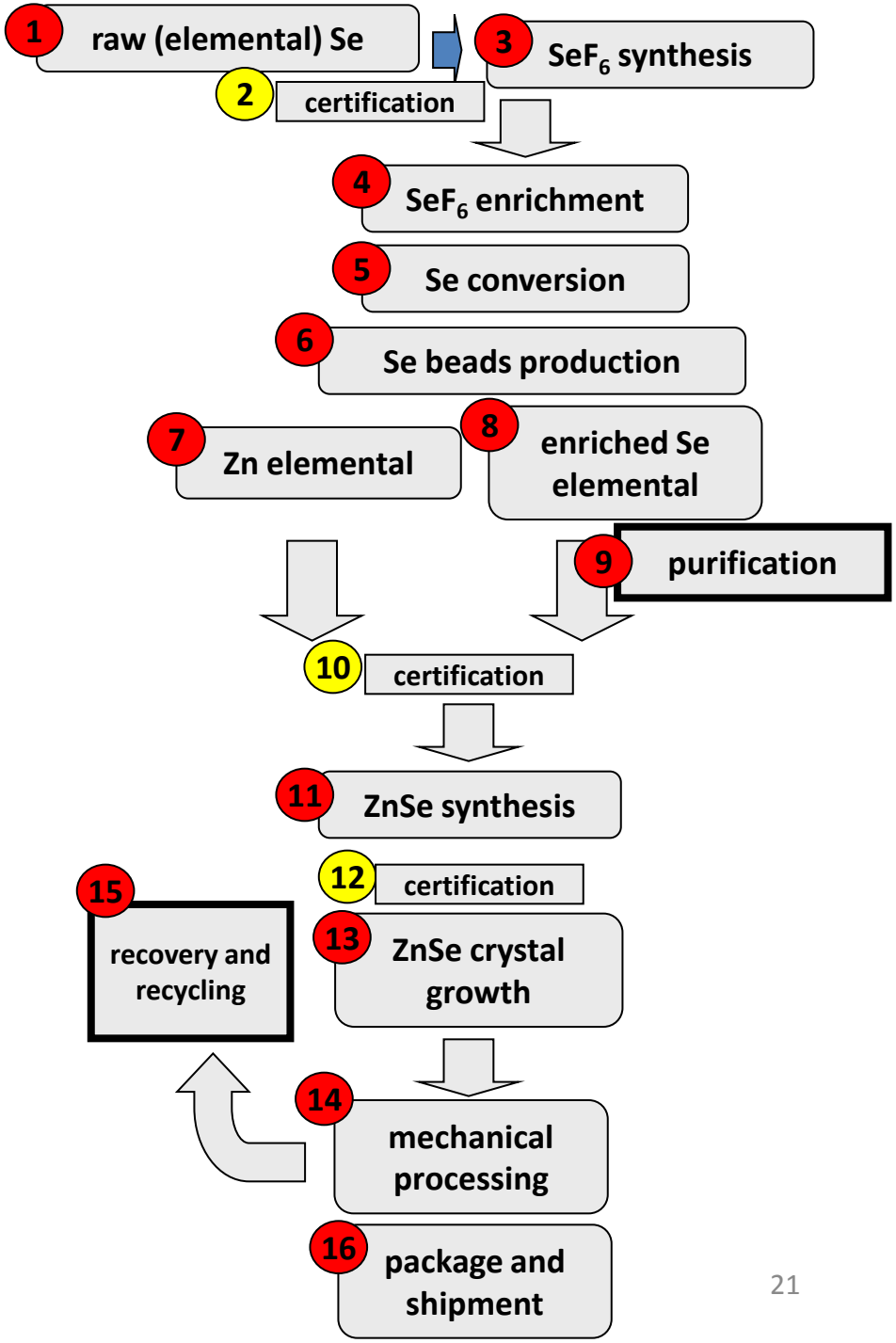
Nevertheless…

- Very radio-pure compounds can be obtained
- Large LY
- Excellent discrimination
- Good energy resolution (≈9 keV @ 2615 keV)

→ Can be the baseline for LUCIFER project.

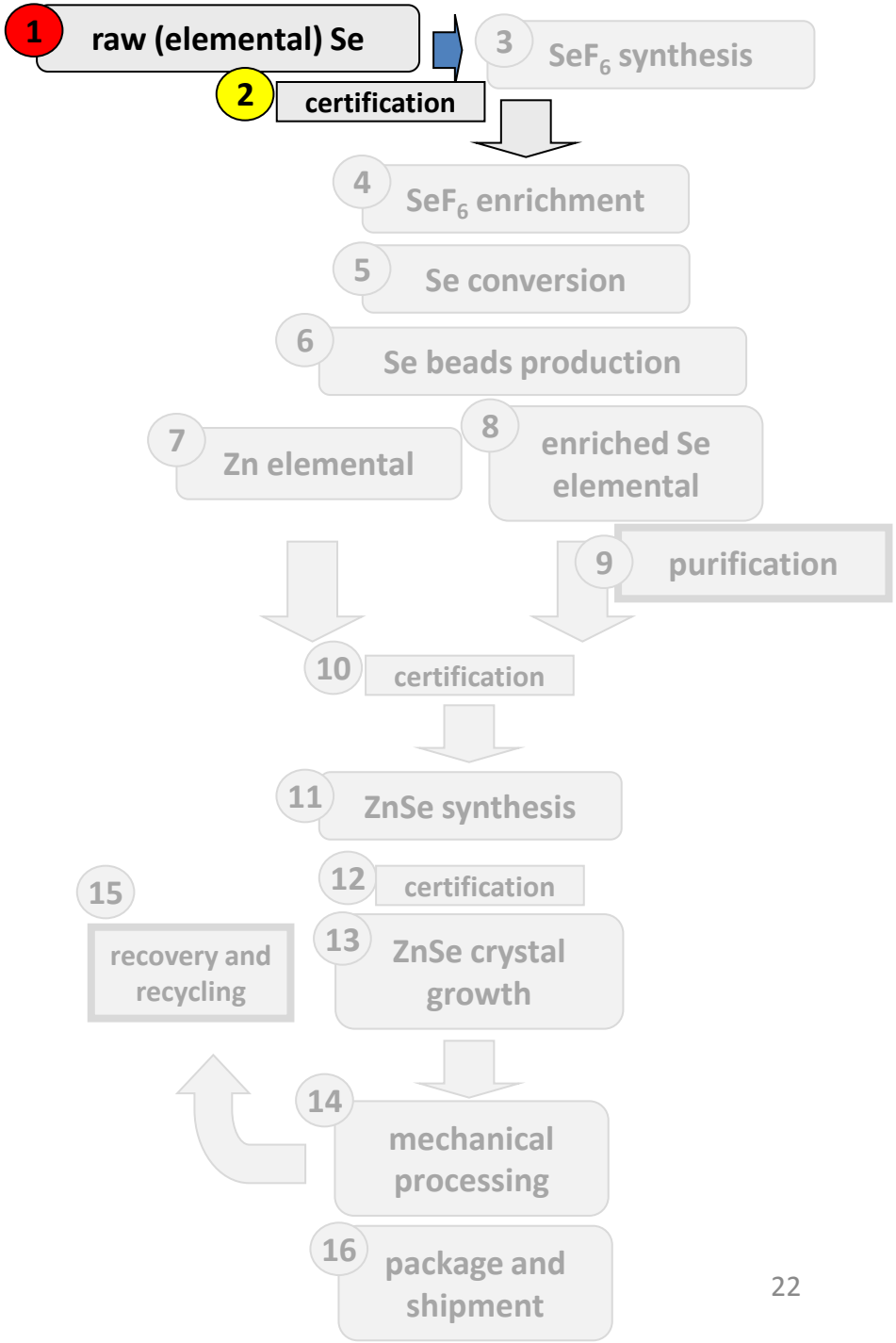


ZnSe: production



ZnSe: production

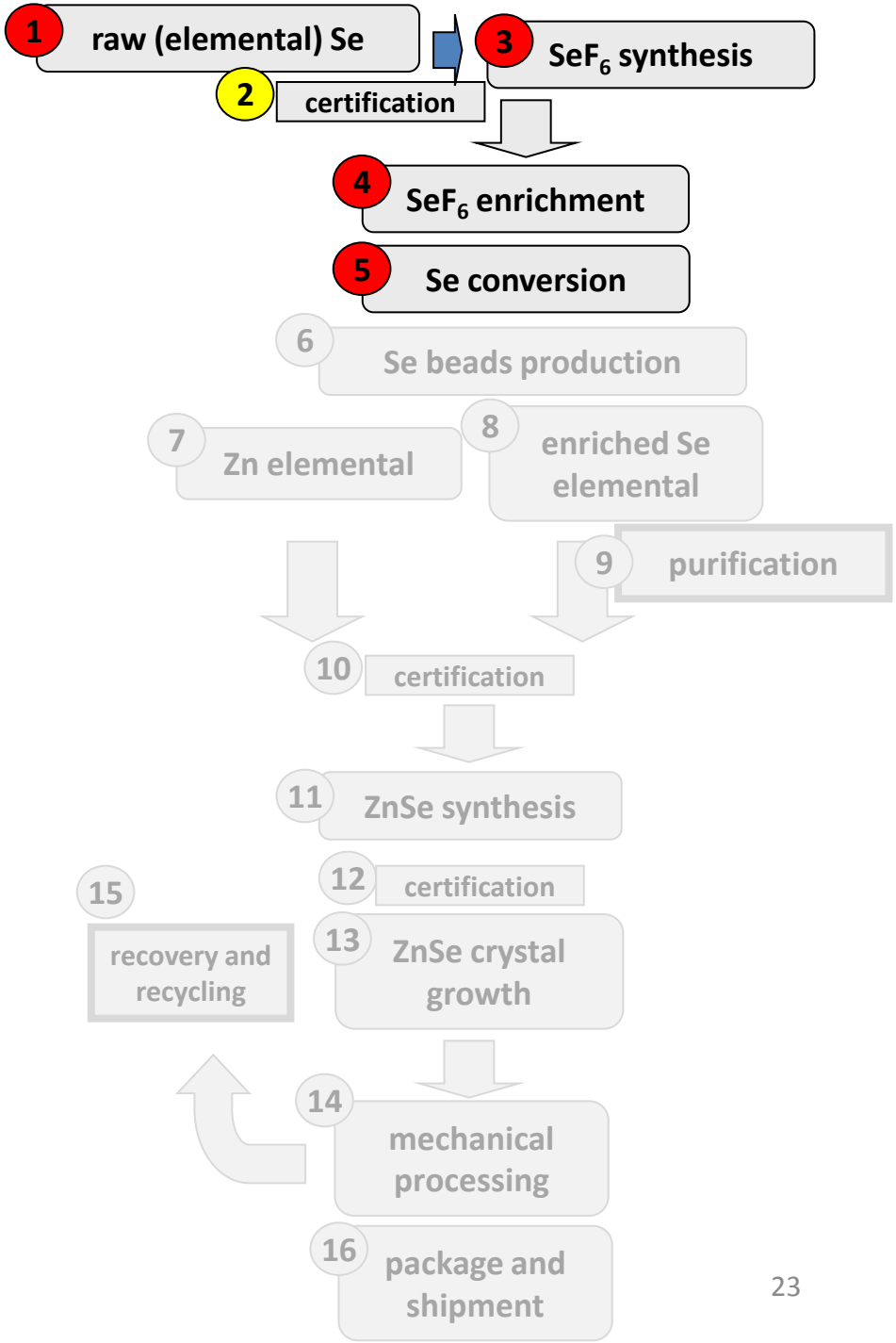
1) Need radio-chemical pure Se
   → measurements with ICP-MS



ZnSe: production

1) Need radio-chemical pure Se
   → measurements with ICP-MS

2) Enrichment (URENCO) > 95%
   The enrichment is feasible
   Chemical problems in Se conversion
   (mainly reagents contaminations!)

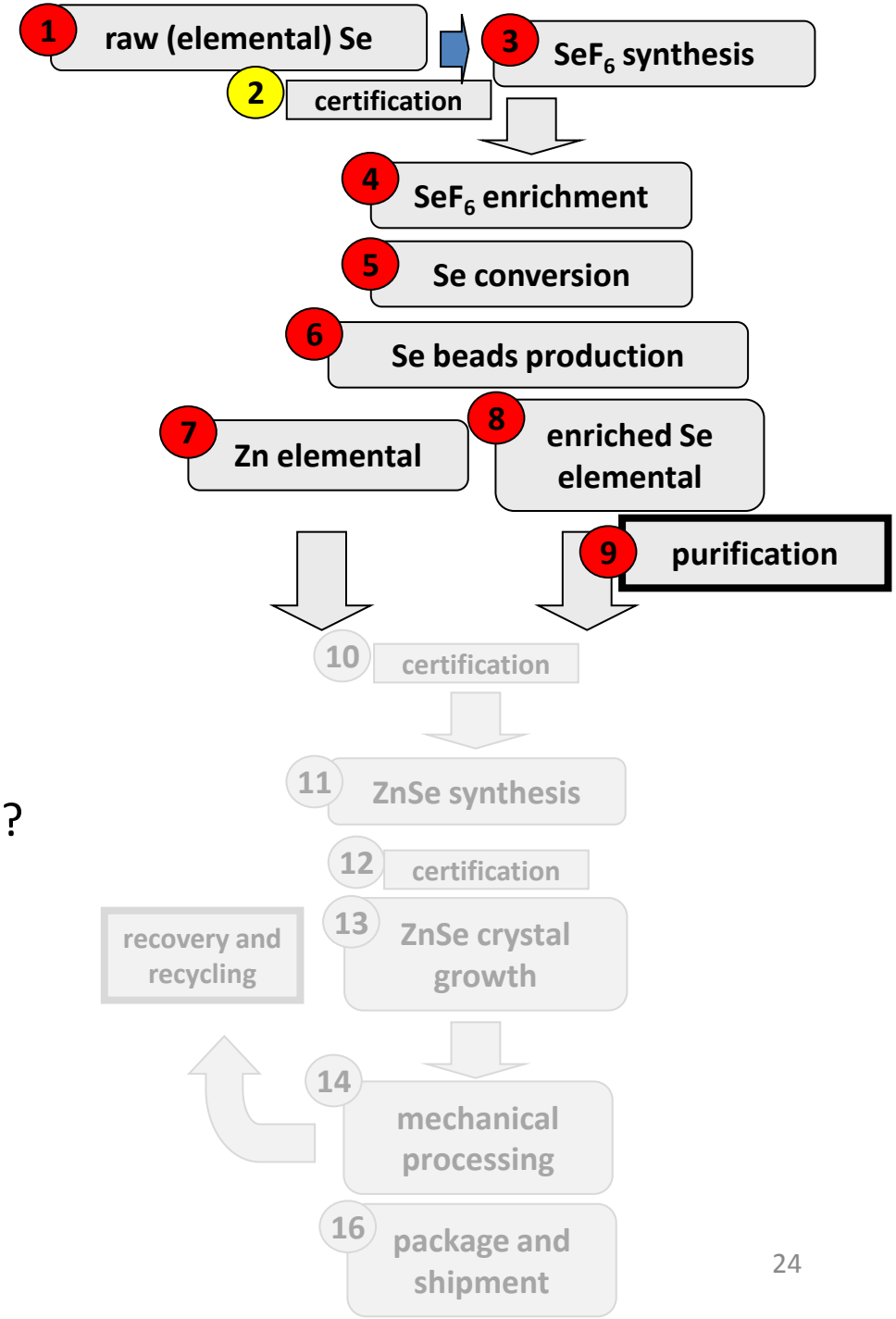


ZnSe: production

1) Need radio-chemical pure Se
   → measurements with ICP-MS

2) Enrichment (URENCO) > 95%
   The enrichment is feasible
   Chemical problems in Se conversion
   (mainly reagents contaminations!)

3) Beads (powder not good for crystals)
   require dedicated instruments.
   HpGe γ spectroscopy
   Purification (99.999%) →zone refining?



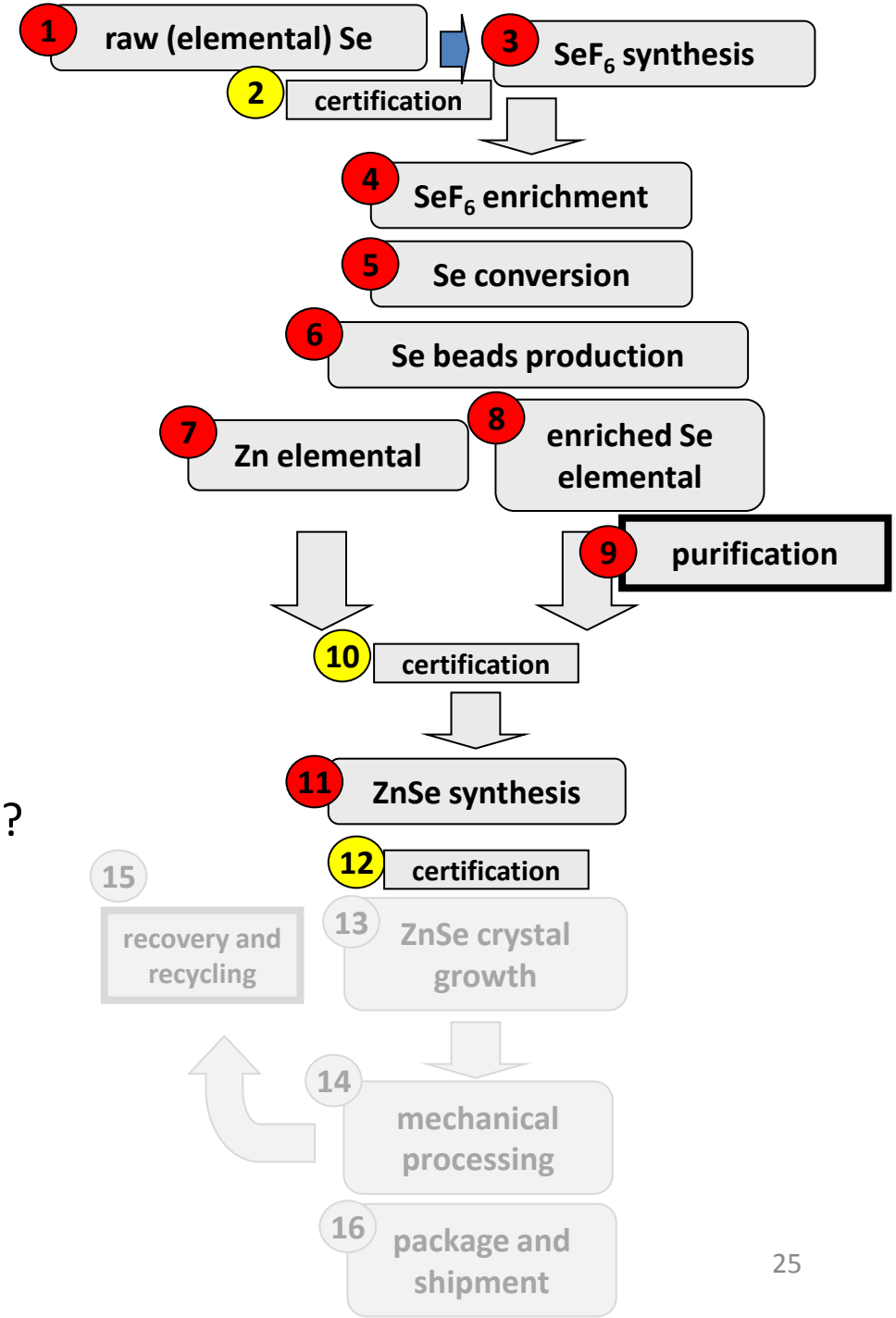
ZnSe: production

1) Need radio-chemical pure Se
   → measurements with ICP-MS

2) Enrichment (URENCO) > 95%
   The enrichment is feasible
   Chemical problems in Se conversion
   (mainly reagents contaminations!)

3) Beads (powder not good for crystals)
   require dedicated instruments.
   HpGe γ spectroscopy
   Purification (99.999%) →zone refining?

4) Synthesis of ZnSe:
   High temperature method or
   Low temperature method (CVD)
   → optimize the yield



ZnSe: production

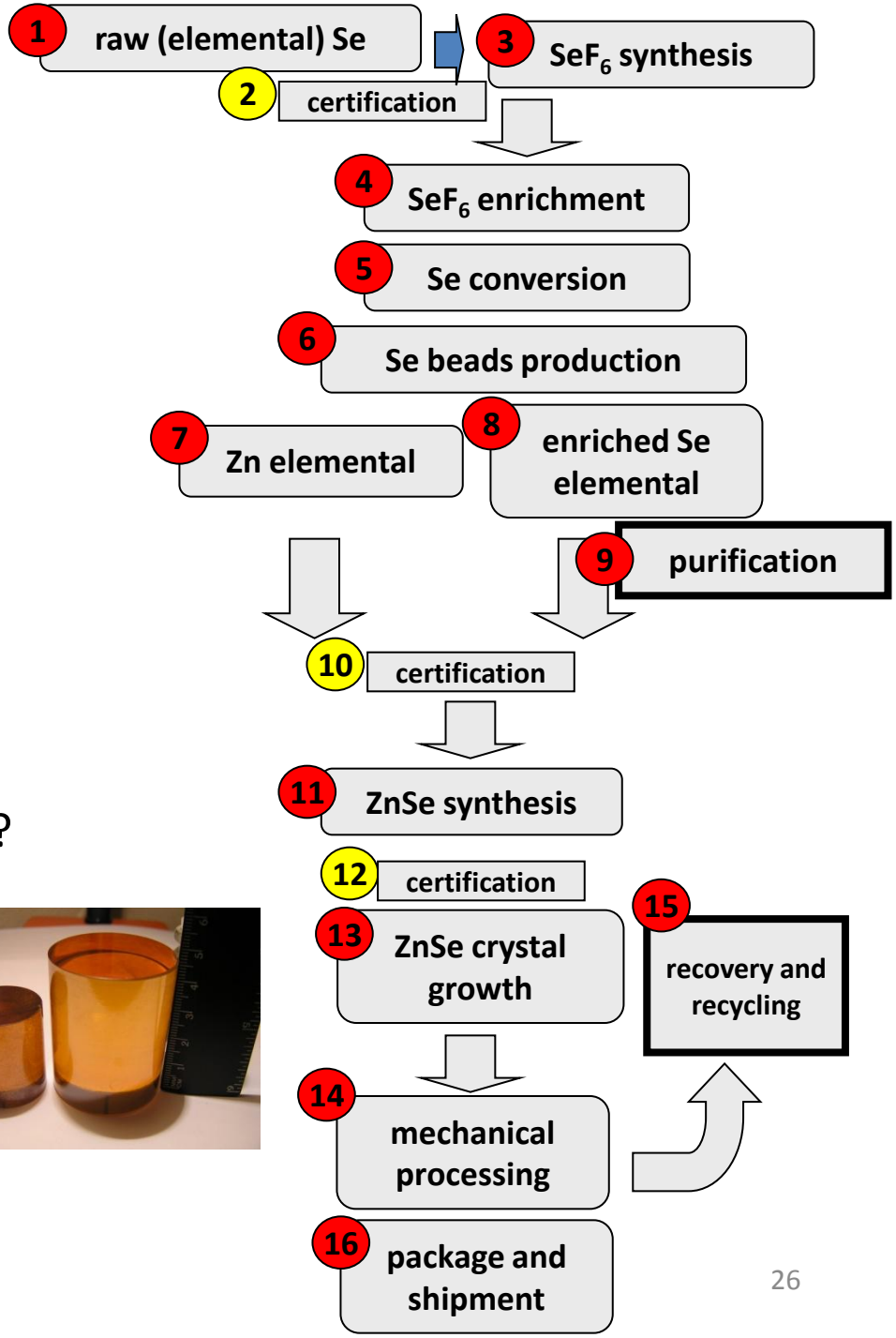
1) Need radio-chemical pure Se
   → measurements with ICP-MS

2) Enrichment (URENCO) > 95%
   The enrichment is feasible
   Chemical problems in Se conversion
   (mainly reagents contaminations!)

3) Beads (powder not good for crystals)
   require dedicated instruments.
   HpGe γ spectroscopy
   Purification (99.999%) →zone refining?

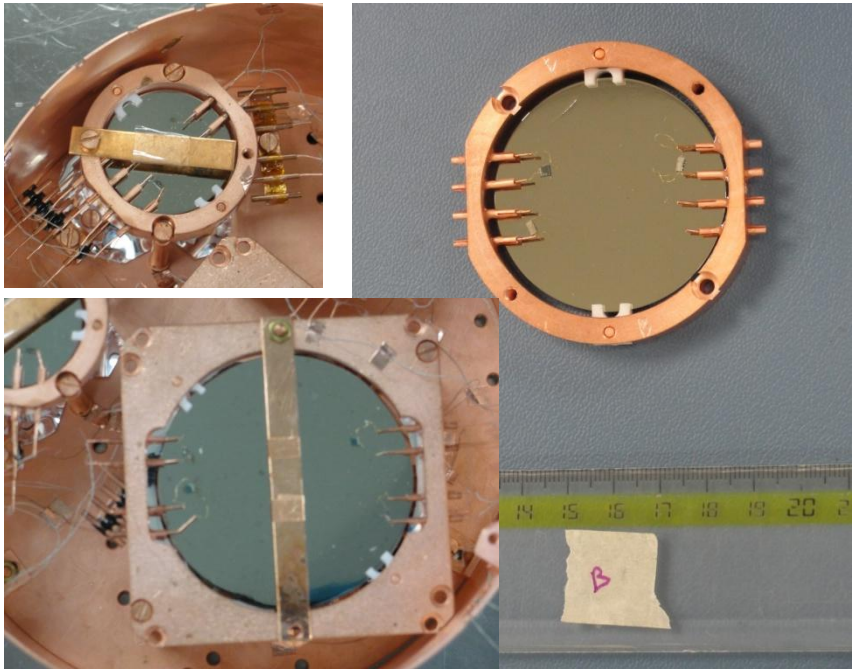
4) Synthesis of ZnSe:
   High temperature method or
   Low temperature method (CVD)
   → optimize the yield

5) Growth of ZnSe crystal:
   Avoiding twining and Reproducibility

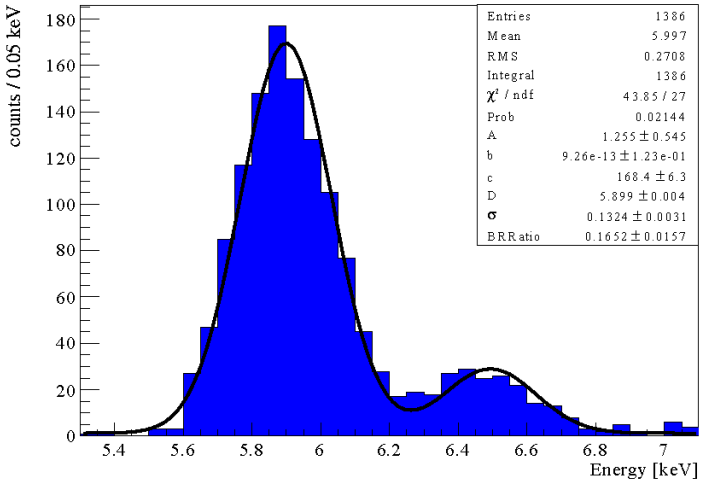


Light Detectors

Optimization of the Light Detectors (Si or Ge bolometers)

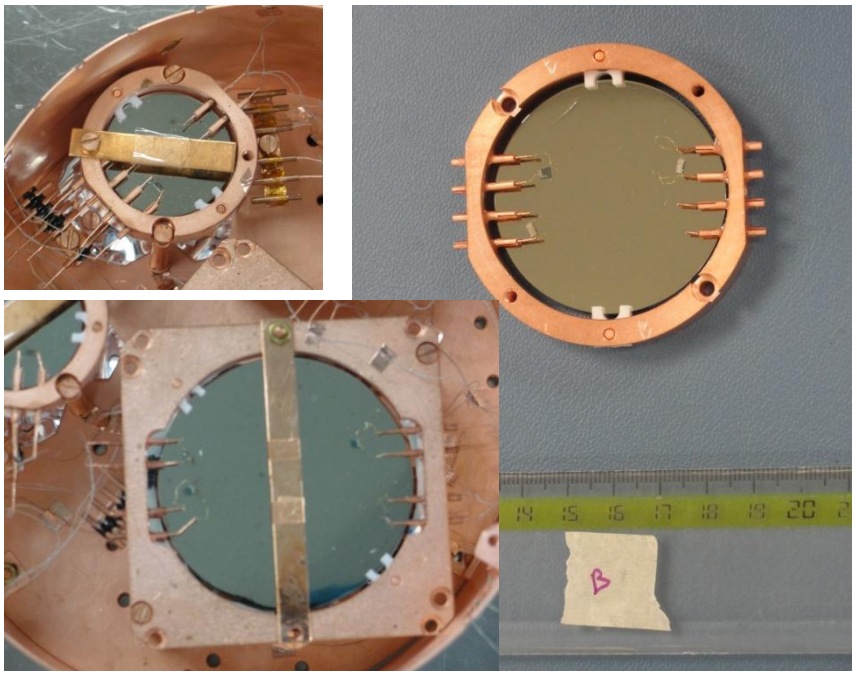


Excellent energy resolution: σ ≈ 140 eV

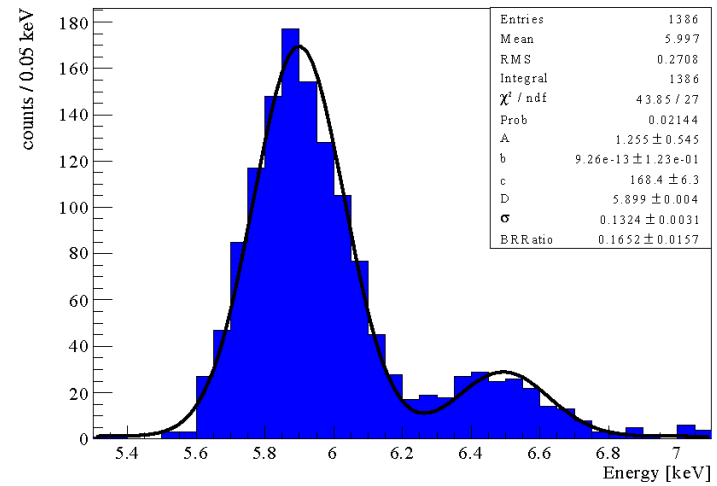


Light Detectors

Optimization of the Light Detectors (Si or Ge bolometers)



Excellent energy resolution: $\sigma \approx$ 140 eV

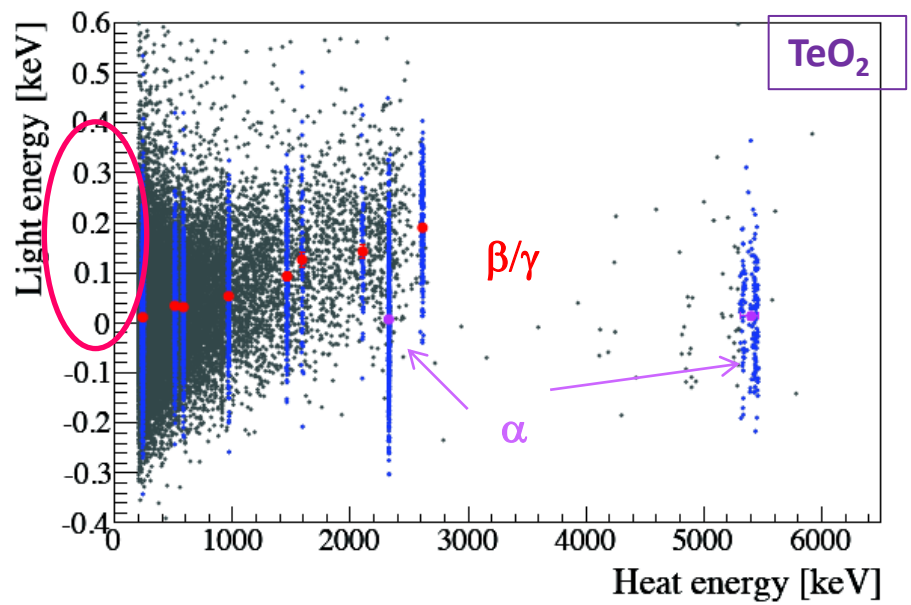


Test on the LD performances:

Measurement of TeO_2 (no scintillation!)

First detection of Cerenkov light!

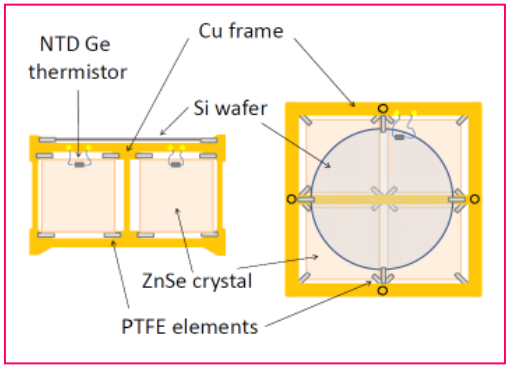
arXiv:1106.6286 and arXiv:1107.5679



Now R&D focused on the LD optimization (dimensions, surface treatments..) and reproducibility.

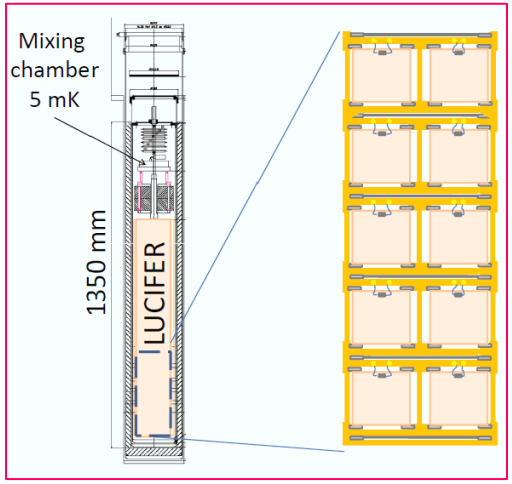
LUCIFER

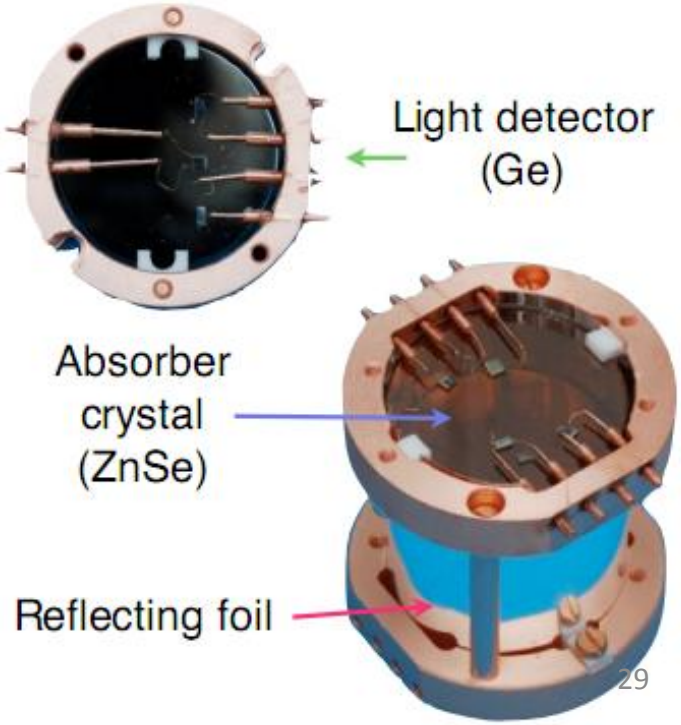
The produced crystals will be arranged in an array and operate deep underground.



This project, financed by an European Grant (ERC) will demonstrate the power of this technique.

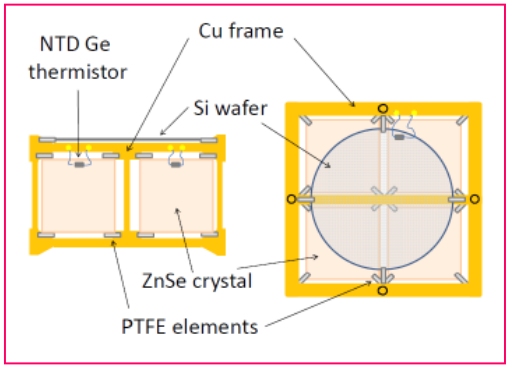
However, a good sensitivity can be reached:





LUCIFER

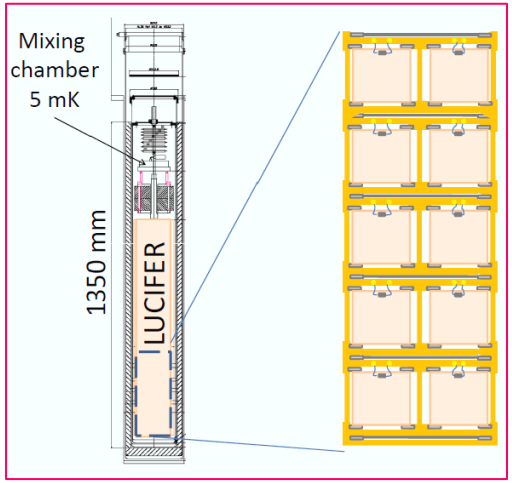
The produced crystals will be arranged in an array and operate deep underground.



This project, financed by an European Grant (ERC) will demonstrate the power of this technique.

However, a good sensitivity can be reached:

Assuming:
- ➢ $b = 10^{-3}$ counts/keV/kg/y
- ➢ $\Delta E = 5$ keV
- ➢ i.a. = 95%
- ➢ Live Time = 5 y

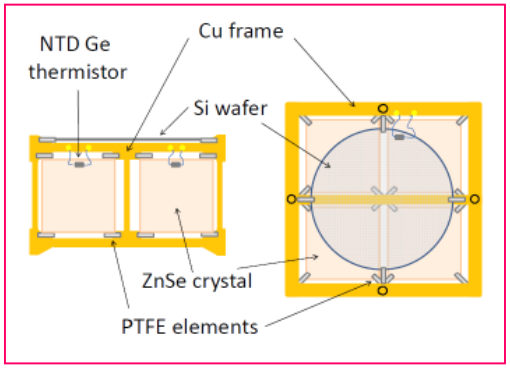


Option	Isotope weight	Half life limit (x 10^{26} y)	Sensitivity to mββ [meV]*
ZnSe baseline	17.6 kg	2.31	52 -65
Improvement 1	20.5 kg	2.59	49 - 61
Improvement 2	27.8 kg	3.20	44 - 55

* J.Mendez et al. arXiv:0801.3760;
* F.Simkovic et al. Phys.Rev. C77 (2008);
* J.Suhonen et al. Int.J.Mod.Phys E17 (2008)

LUCIFER

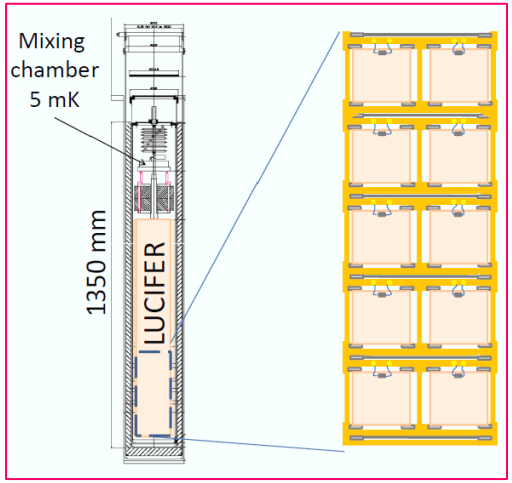
The produced crystals will be arranged in an array and operate deep underground.



This project, financed by an European Grant (ERC) will demonstrate the power of this technique.

However, a good sensitivity can be reached:

Assuming:
- ➢ $b = 10^{-3}$ counts/keV/kg/y
- ➢ $\Delta E = 5$ keV
- ➢ i.a. = 95%
- ➢ Live Time = 5 y



Option			Sensitivity to [meV]*
ZnS			
Improv			
Improvement 2			44 - 55

Not too optimistic evaluation:
10 kg of ^{82}Se
~100 meV as $<m_{\beta\beta}>$ sensitivity

* J.Mendez et al. arXiv:0801.3760;
* F.Simkovic et al. Phys.Rev. C77 (2008);
* J.Suhonen et al. Int.J.Mod.Phys E17 (2008)

CONCLUSIONS

The main challenge for a next generation experiment on 0νDBD is the background reduction.

Scintillating bolometers allow to suppress the a background
A smart choice of the isotope provides a further reduction
→Very low background in the energy region of interest!

The goal of LUCIFER is to demonstrate the feasibility of a large mass experiment based on this technique

In addition, a good sensitivity on the decay will be achieved.

Data taking is foreseen for 2014!

CONCLUSIONS

The main challenge for a next generation experiment on 0νDBD is the background reduction.

Scintillating bolometers allow to suppress the a background
A smart choice of the isotope provides a further reduction
→Very low background in the energy region of interest!

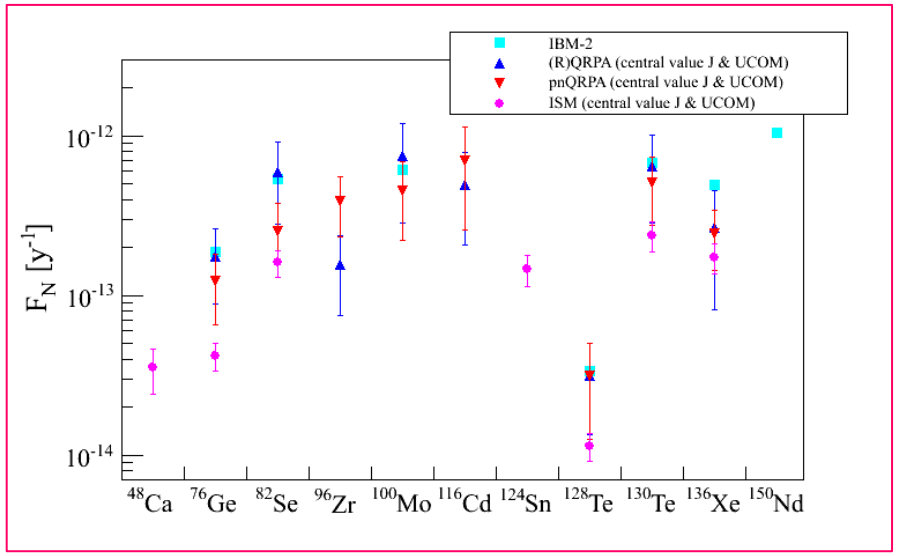
The goal of LUCIFER is to demonstrate the feasibility of a large mass experiment based on this technique

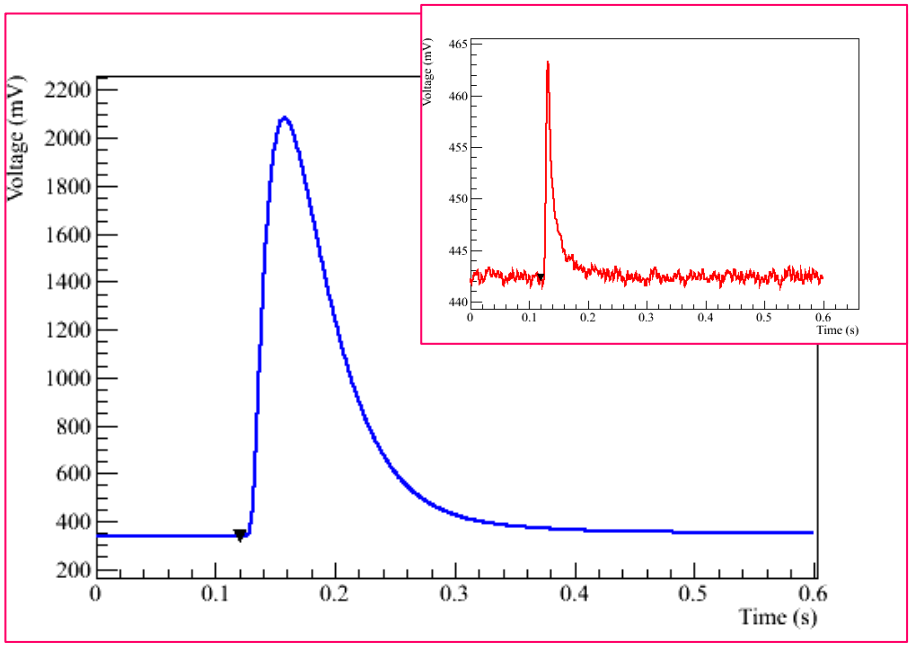
In addition, a good sensitivity on the decay will be achieved.

Data taking is foreseen for 2014!

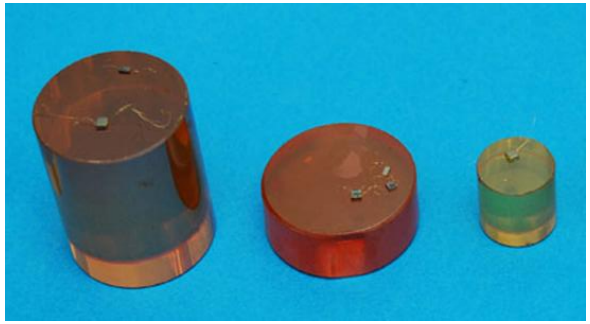
THANK YOU FOR THE ATTENTION

Back Up Slides

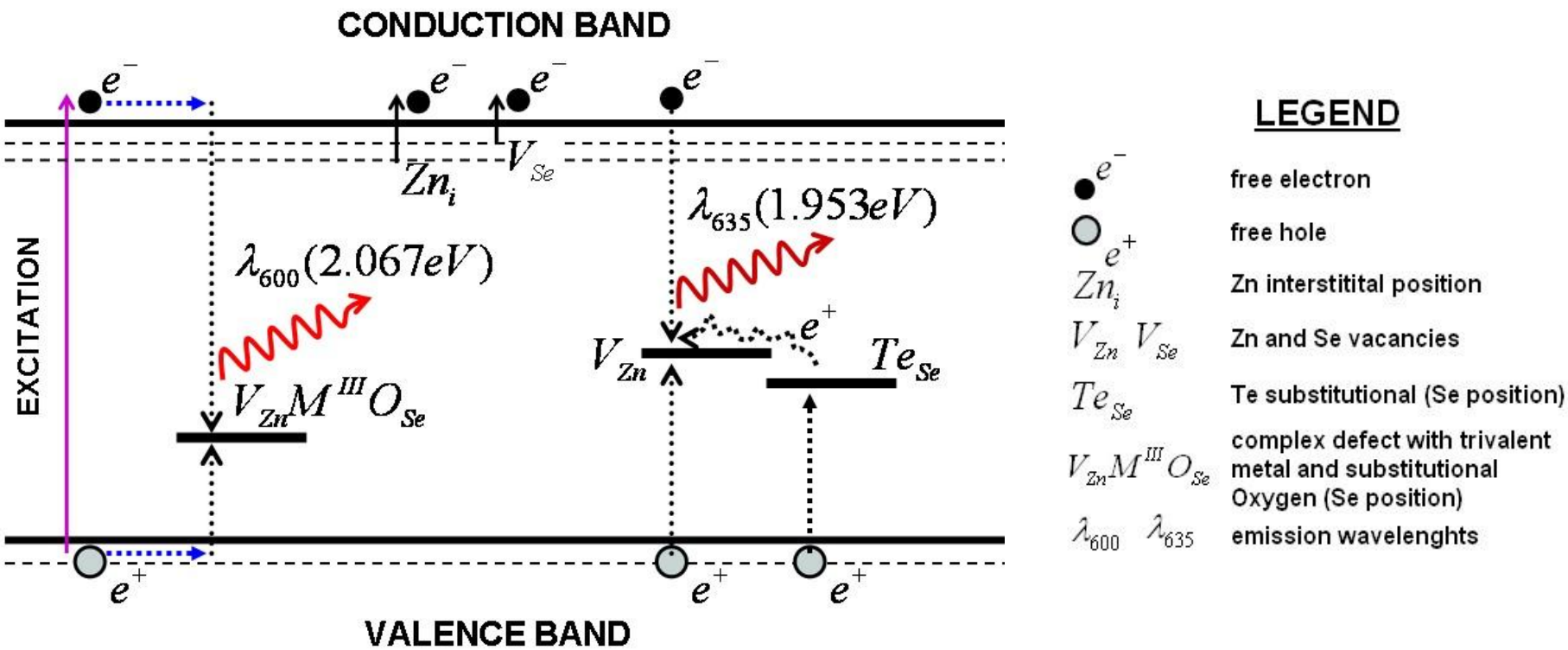




Crystal name	Crystal color	Mass [g]	LY [keV/MeV]	QF_α
Small	Yellow	37.5	1.3	4.4
Large	Red	120	7.5	4.2
Huge	Orange	337	4.6	3



Back Up Slides



N. Starzhinskiy et al, IEEE Trans. Nucl. Science, 55, 1542 (2008)

Back Up Slides

ZnSe features

Molecular formula: ZnSe
Molar mass: 144.35 g/mol
Appearance: light yellow solid
Density: 5.27 g/cm3
Melting point: 1525 °C
Nonhygroscopic, insoluble in water
band gap: 2.70eV (@25°C)
Refractive index: 2.67 (@550 nm), 2.40 (@10.6 µm)

enriched Se specifications (URENCO)
form: beads
size: <4 mm
isotope 82Se concentration: > 95% 82Se
chemical purity: > 99.5% trace metals basis
description: gray
packaging: thick polyethylene (PE) bags inside PE recipient