LUCIFER: Neutrinoless Double Beta Decay search with scintillating bolometers

International Conference on
Technology and Instrumentation in Particle Physics

Gabriele Piperno

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Neutrino open questions

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- Neutrino nature

Dirac

$$\begin{tikzcd} \varepsilon_l \arrow[r, leftrightarrow, "\text{Lorentz}"] \arrow[d, leftrightarrow, "\text{CPT}"'] & \varepsilon_r \arrow[d, leftrightarrow, "\text{CPT}"] \\ \bar{\varepsilon}_r \arrow[r, leftrightarrow, "\text{Lorentz}"] & \bar{\varepsilon}_l \end{tikzcd}$$

$$\varepsilon_l \xleftrightarrow[\text{CPT}]{\text{Lorentz}} \varepsilon_r$$

Majorana

$$\nu \equiv \bar{\nu}$$

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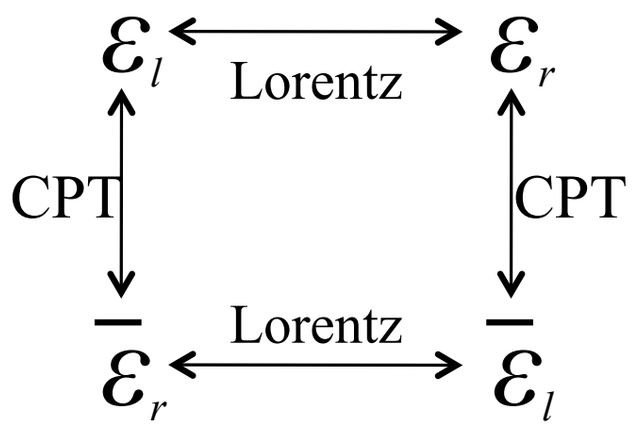

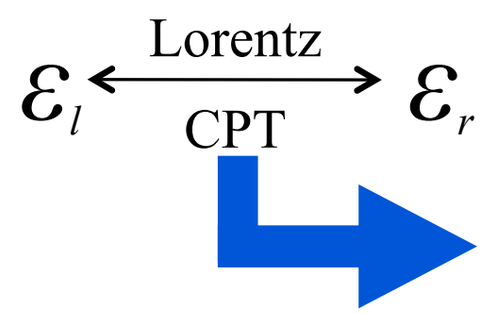

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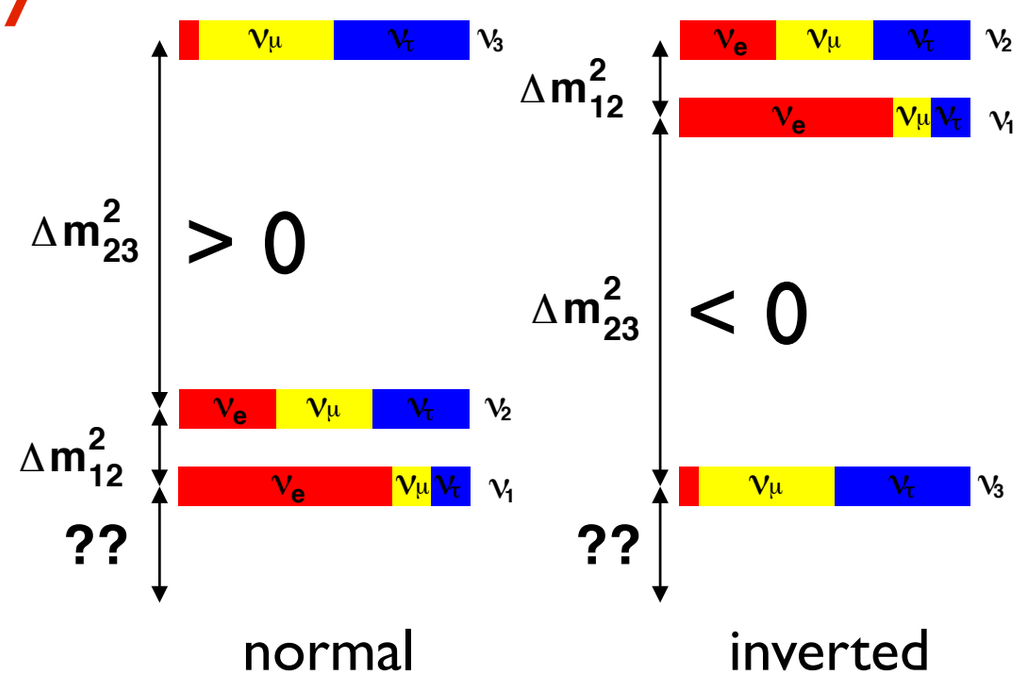
Mass hierarchy



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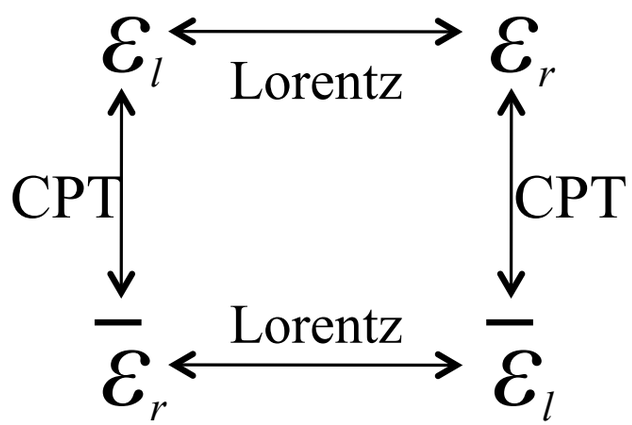

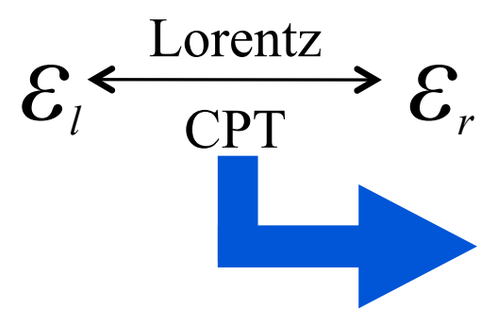

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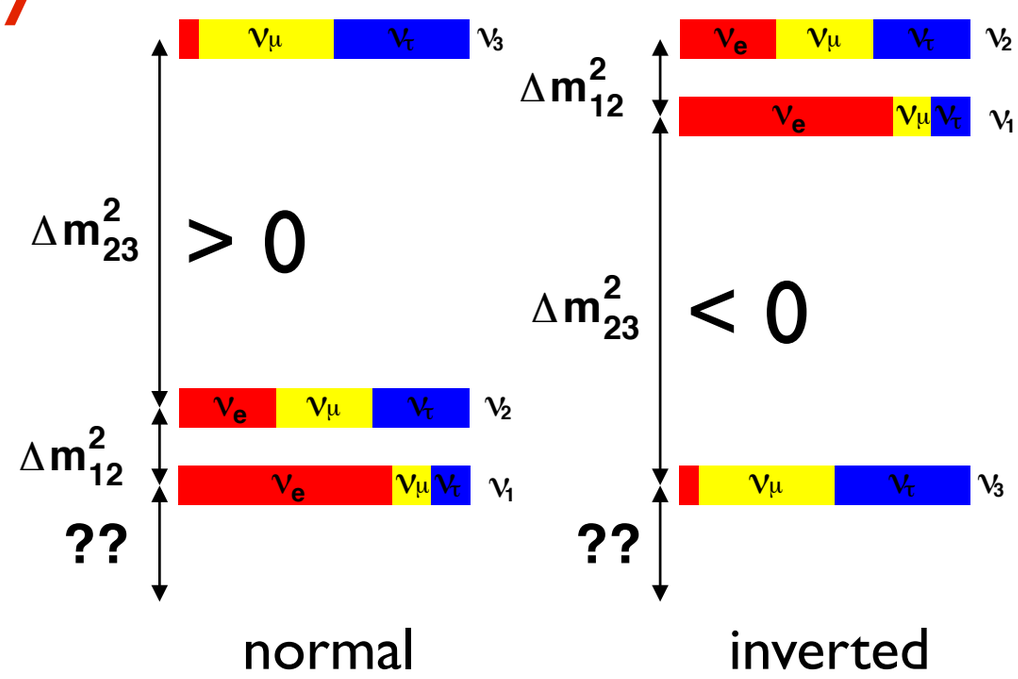

Absolute mass scale

(Neutrinoless) Double Beta Decay

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

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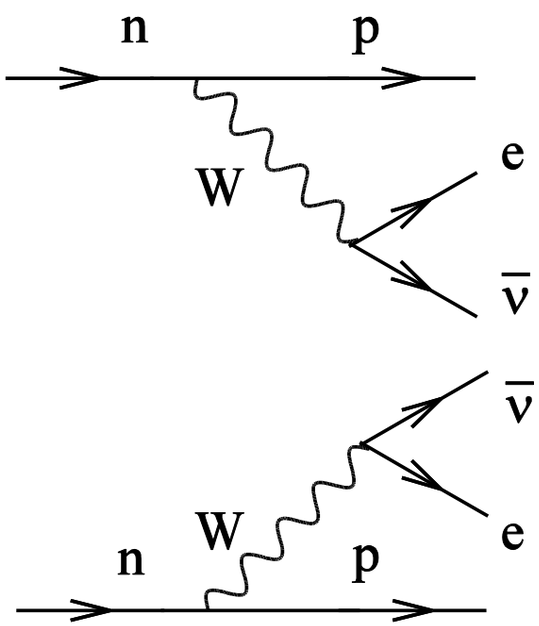

- with neutrino emission (2νββ)
  - Standard Model allowed
  - observed
  - $T_{1/2} \sim [10^{18}, 10^{22}]$ y

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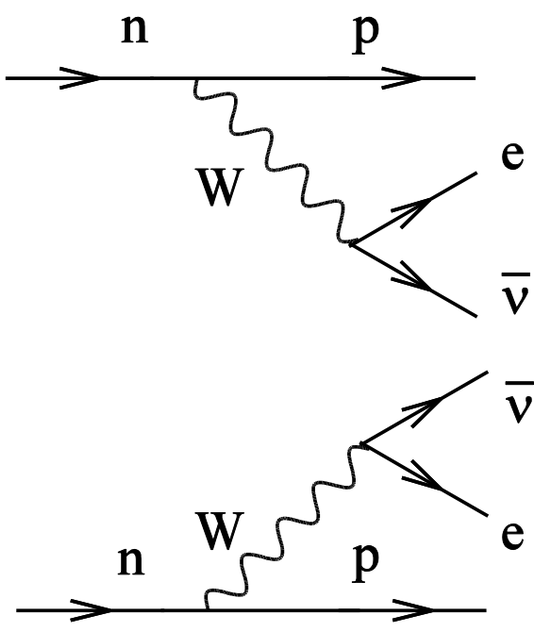

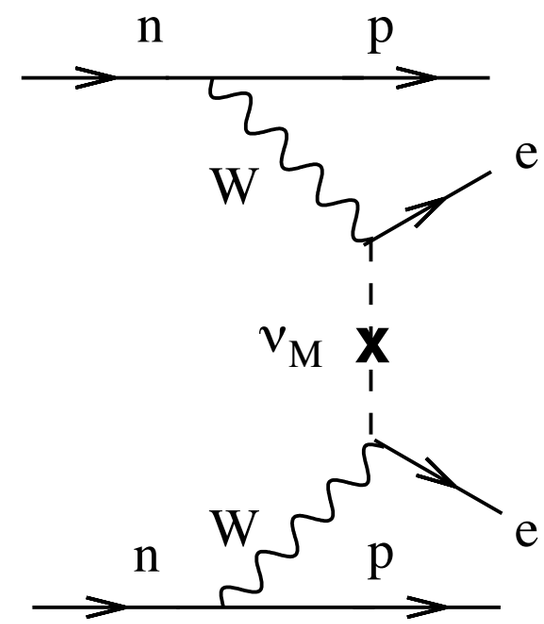

- with neutrino emission ($2\nu\beta\beta$)
  - Standard Model allowed
  - observed
  - $T_{1/2} \sim [10^{18}, 10^{22}]$ y
- no neutrino emission ($0\nu\beta\beta$)
  - Standard Model forbidden
  - lepton number violation ($\Delta L=2$)
  - never observed
  - $T_{1/2} > 10^{25}$ y
  - depends on neutrino mass
  - possible only if neutrino is a Majorana particle

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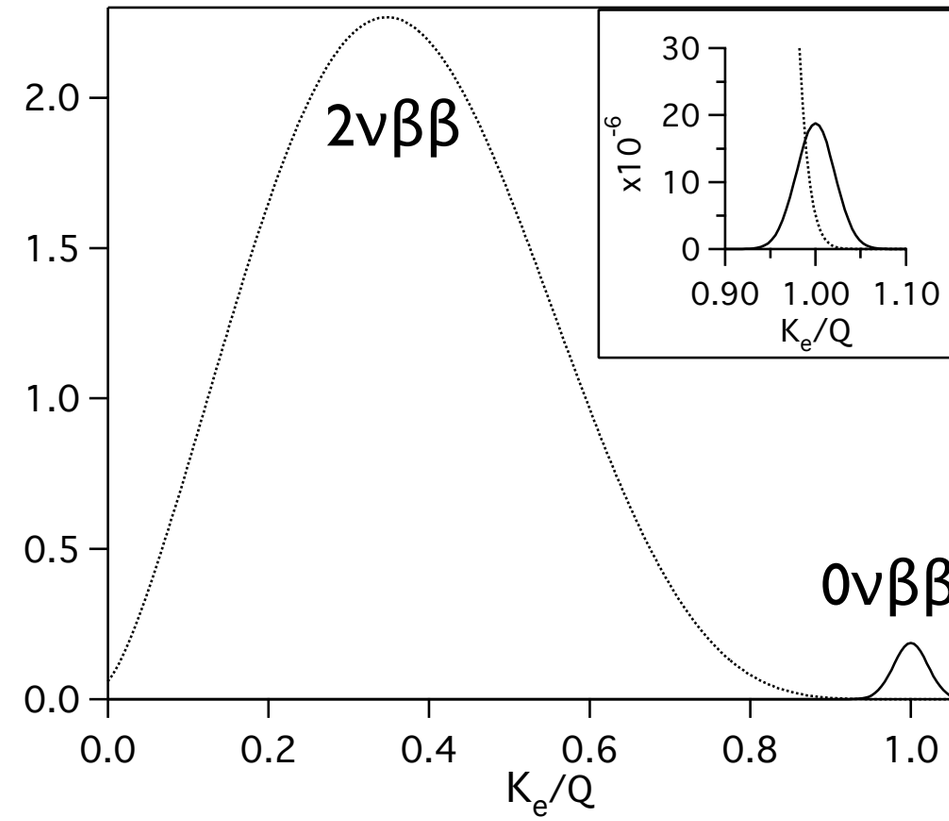
2νββ: continuos spectrum

0νββ: peak at Q-value $Q_{\beta\beta}$



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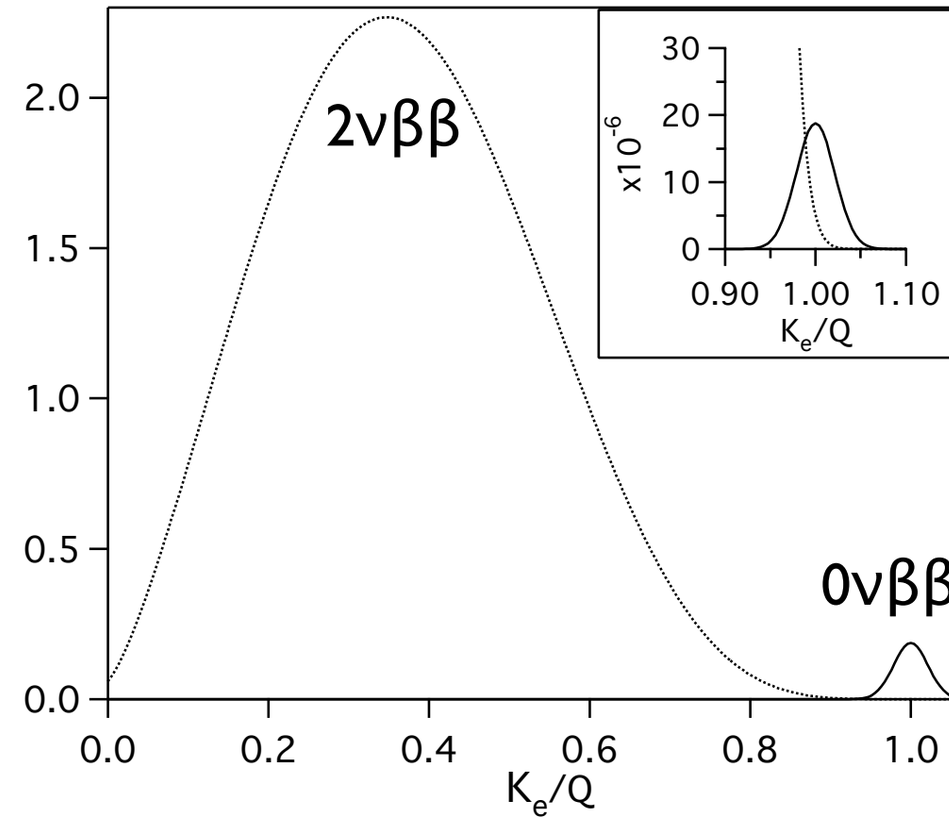
$$Q_{\beta\beta} = M_m - M_d - 2m_e$$

Mother nucleus mass

Daughter nucleus mass

Electron mass



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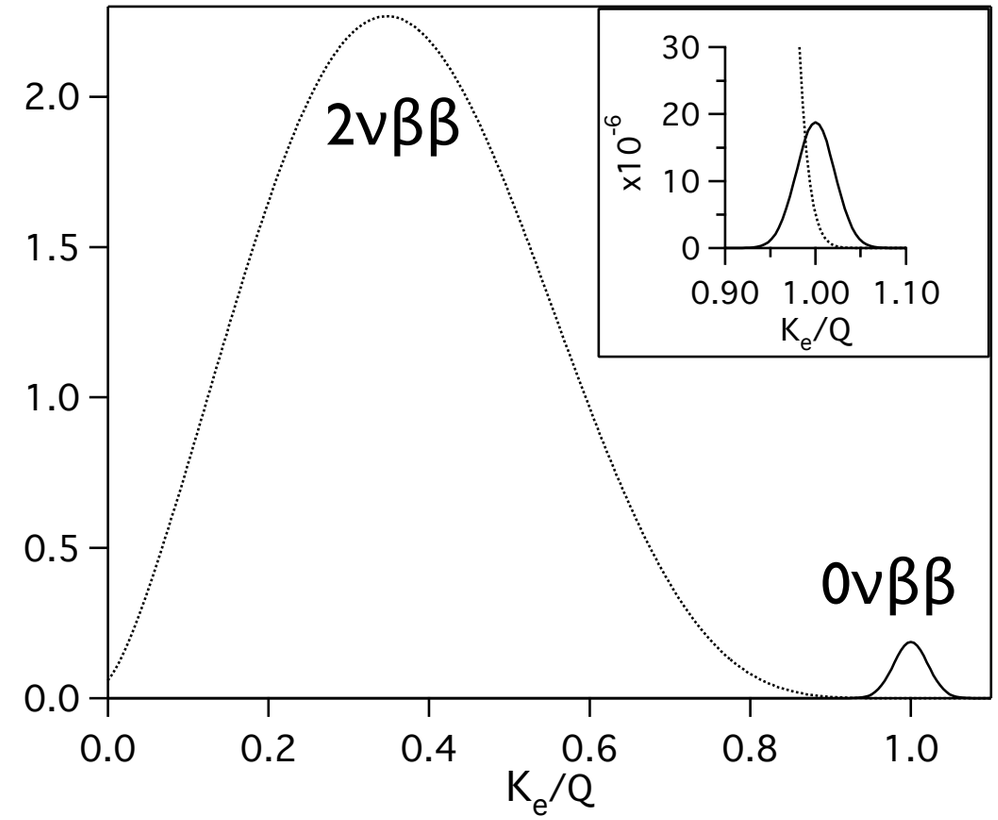

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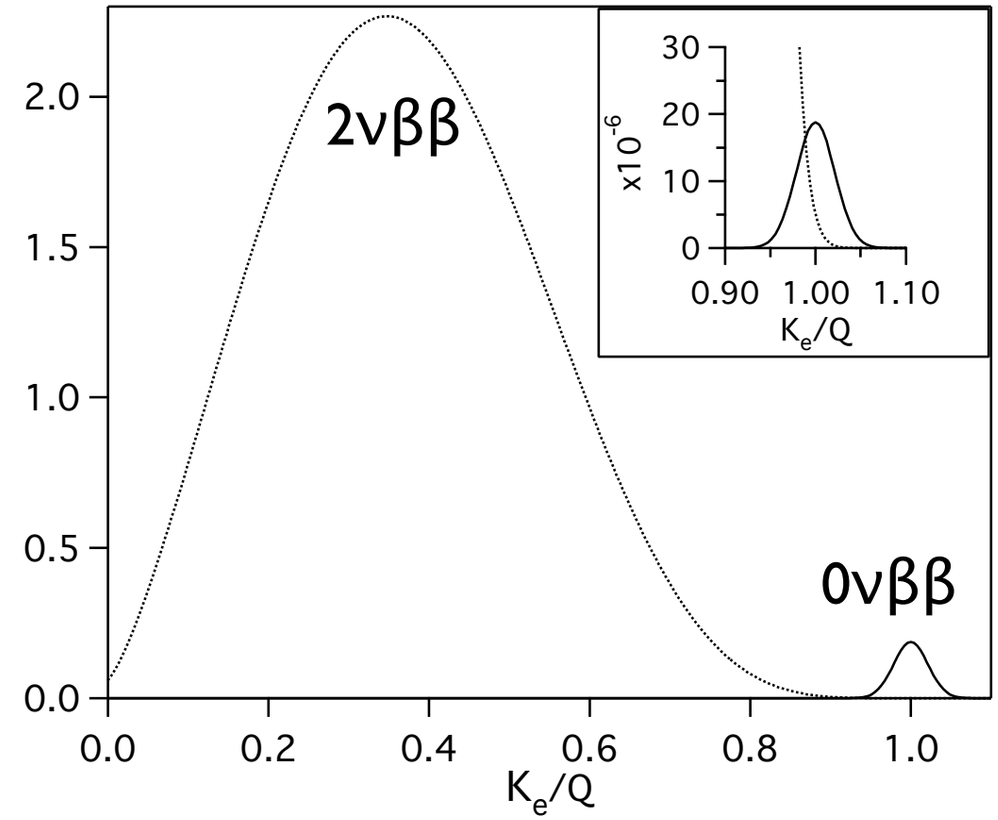

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  ➡ large mass ([100,1000] kg), low background @ $Q_{\beta\beta}$

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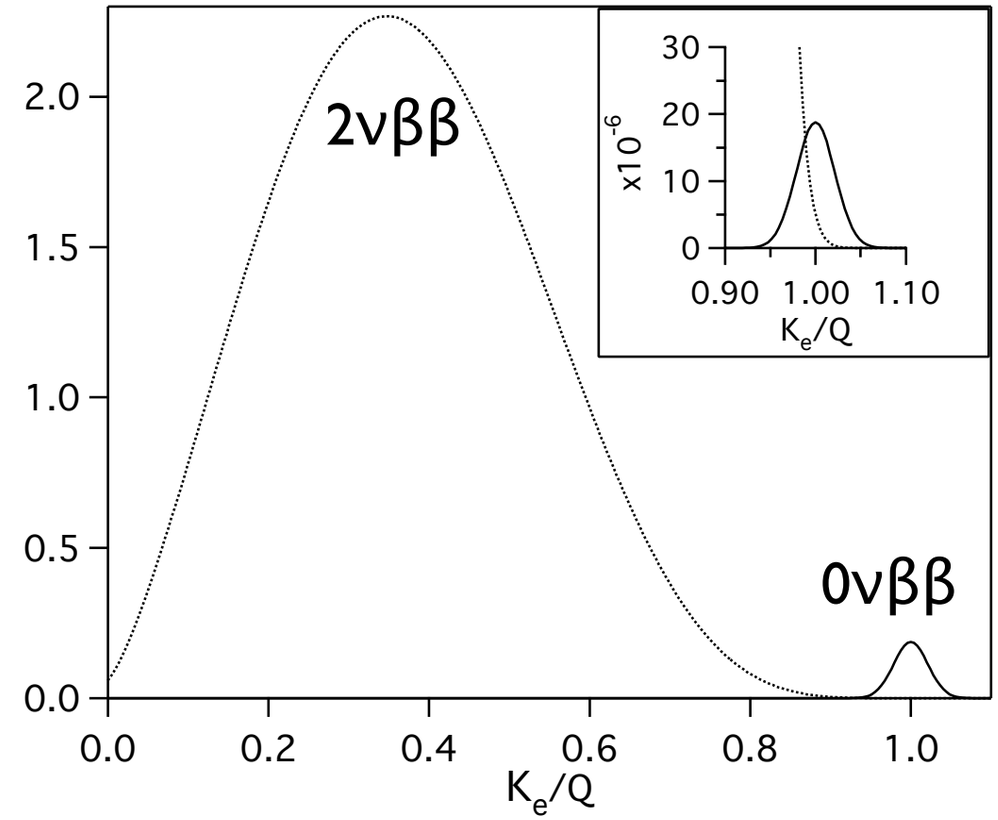

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- few 0νββ counts expected
  - ➡ large mass ([100,1000] kg), low background @ $Q_{\beta\beta}$
- 2νββ right tail = 0νββ background
  - ➡ good energy resolution @ $Q_{\beta\beta}$

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$$S^{bkg} \propto \varepsilon \, \frac{i.a.}{A} \sqrt{\frac{MT}{B\Delta E}} \quad [y]$$

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if $B \approx 0$
zero-background detectors

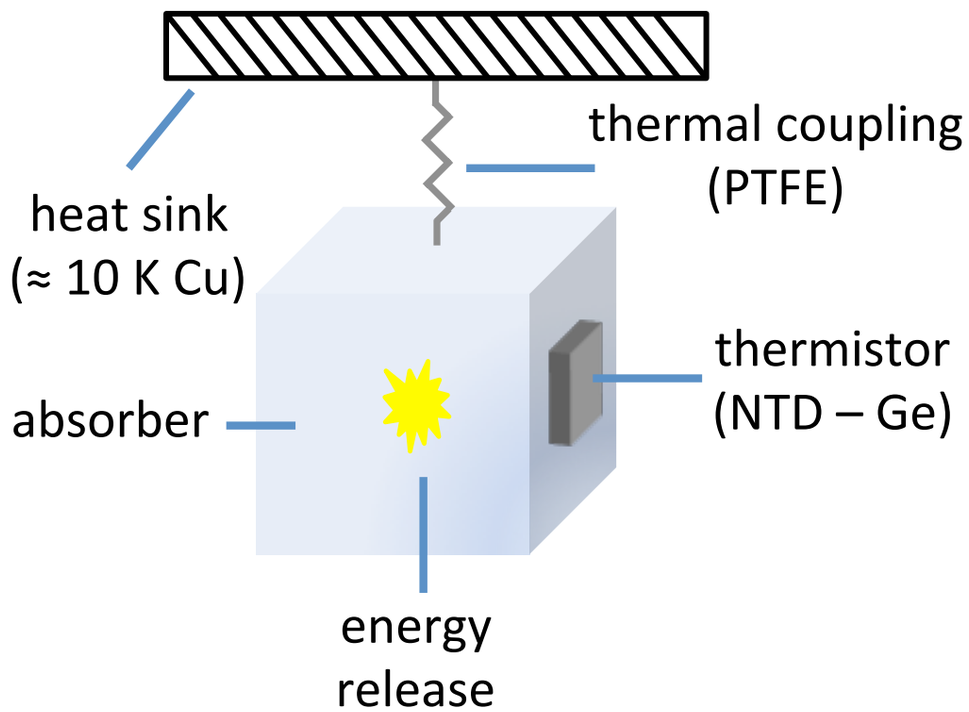
$$S^{0bkg} \propto \varepsilon \, \frac{i.a.}{A} MT \quad [y]$$

Sensitivity increases linearly with M and T

Bolometric technique

Bolometric technique

Bolometer = calorimeter (crystal) working at ~10 mK



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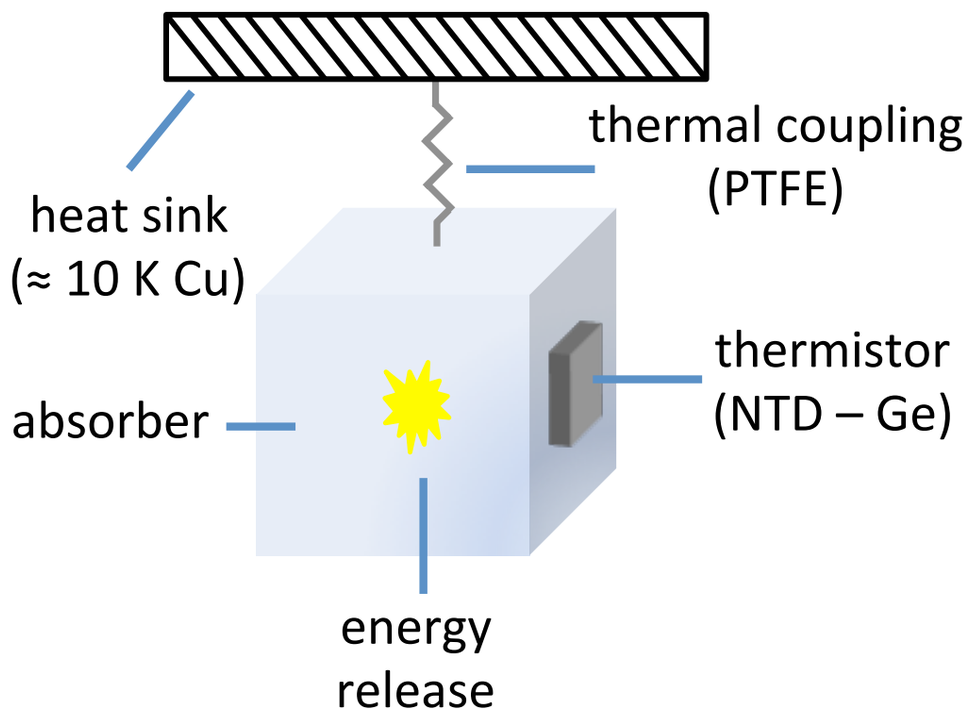

Particle interaction raises the crystal temperature (0.1 mK/MeV)

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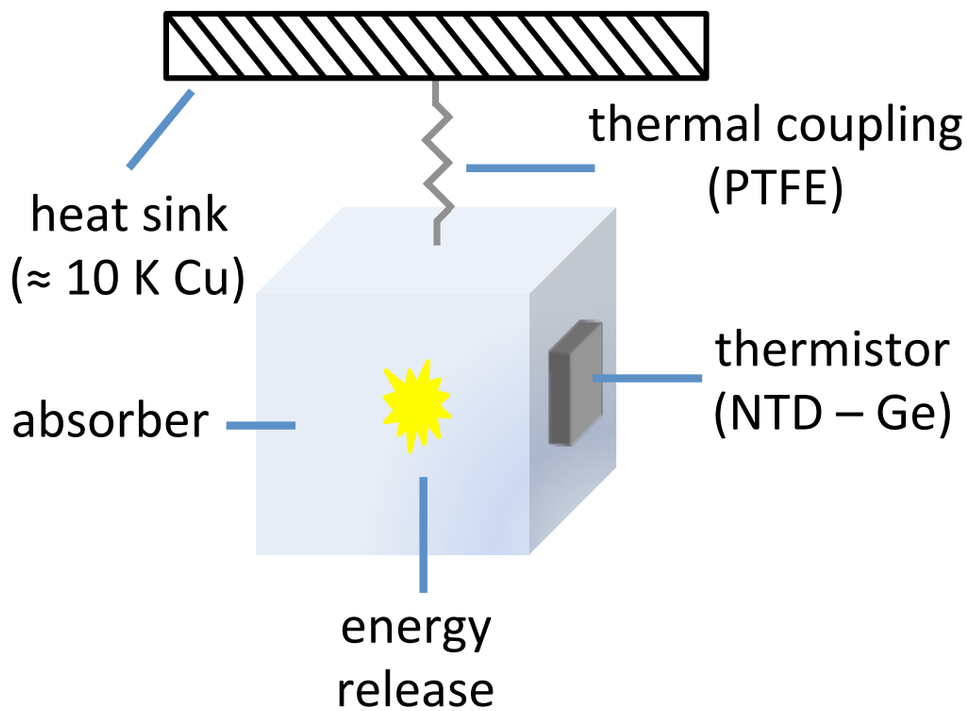

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2 components

Absorber
absorbs the energy release

Sensor
measures the temperature variation

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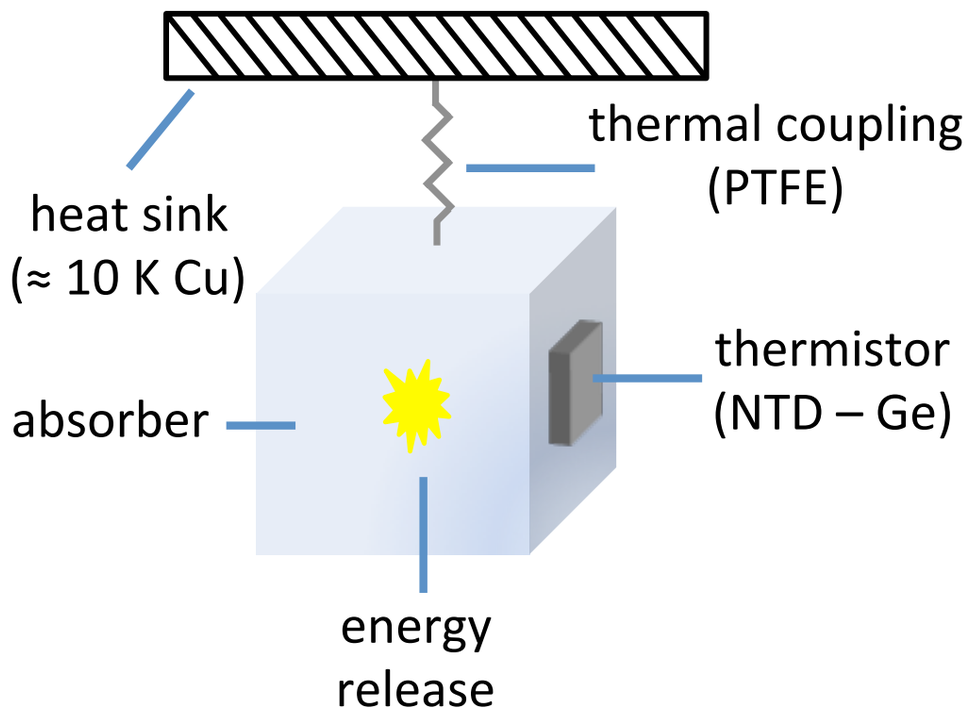

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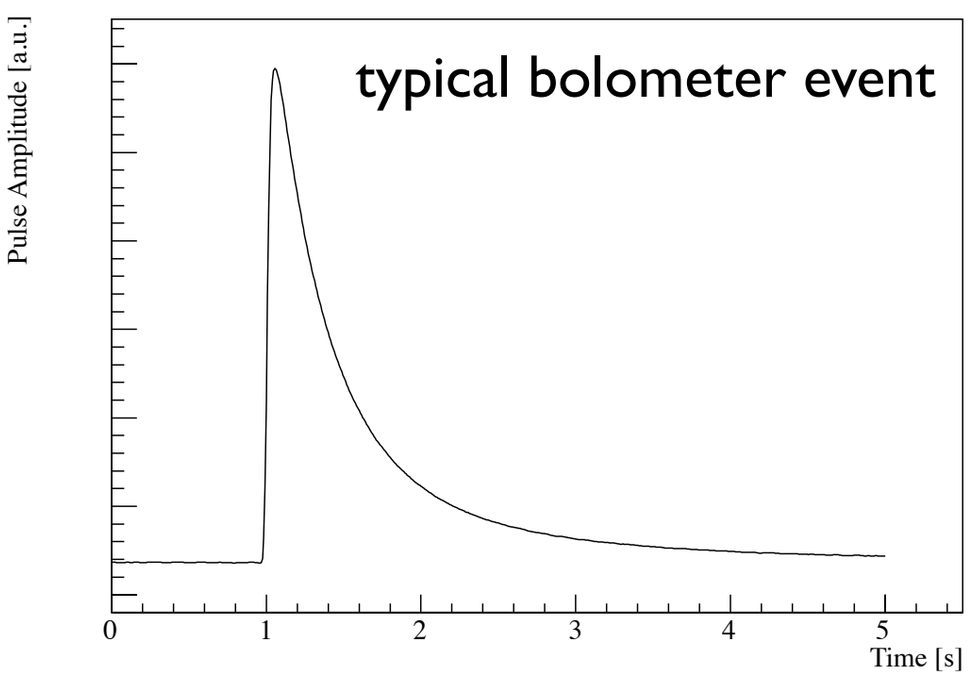

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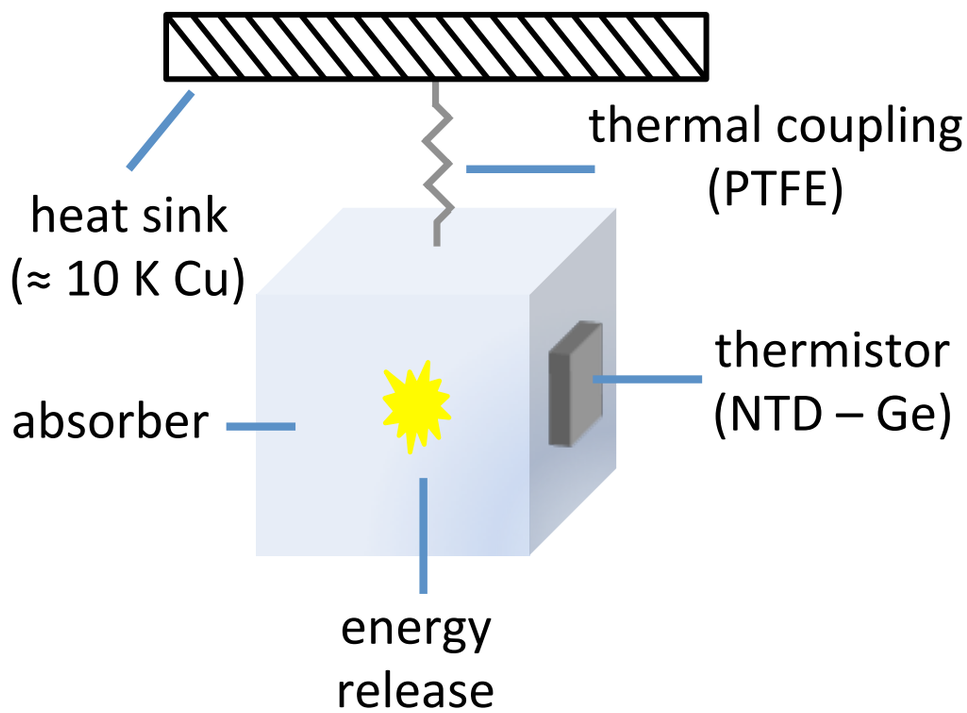

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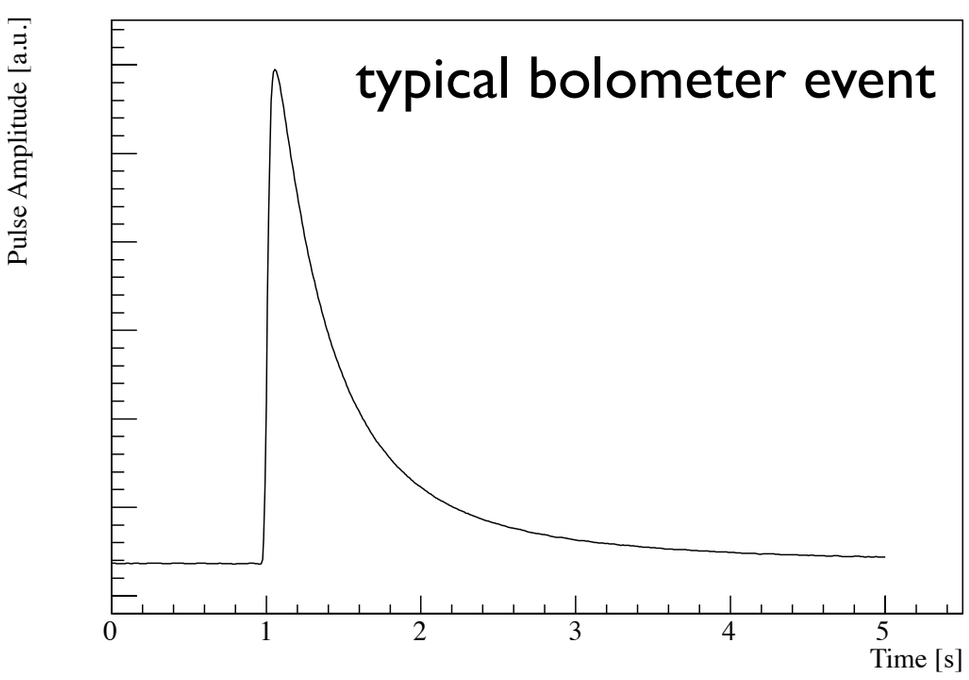

- absorber grown with ββ emitter inside
- high containment efficiency (75÷80%)
- energy resolution ~ ‰
- intrinsic radiopurity
- scalability
- study different compounds

Isotope selection

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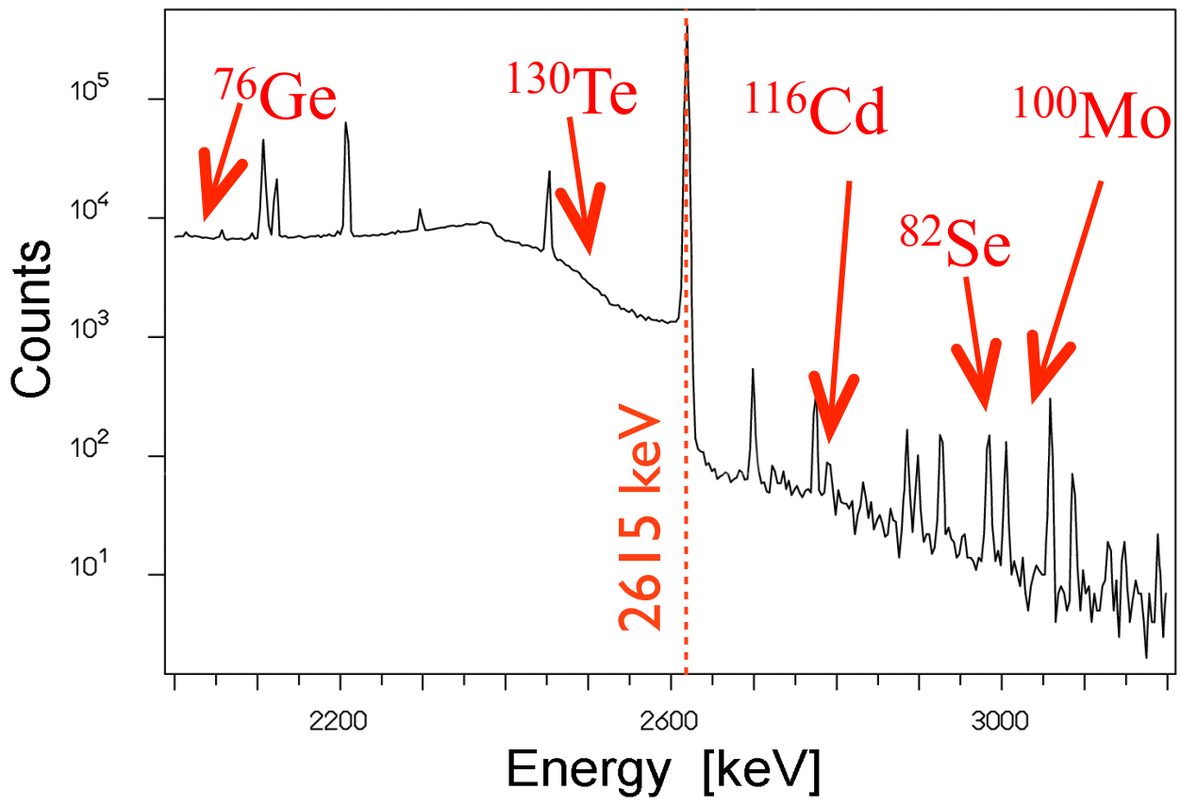

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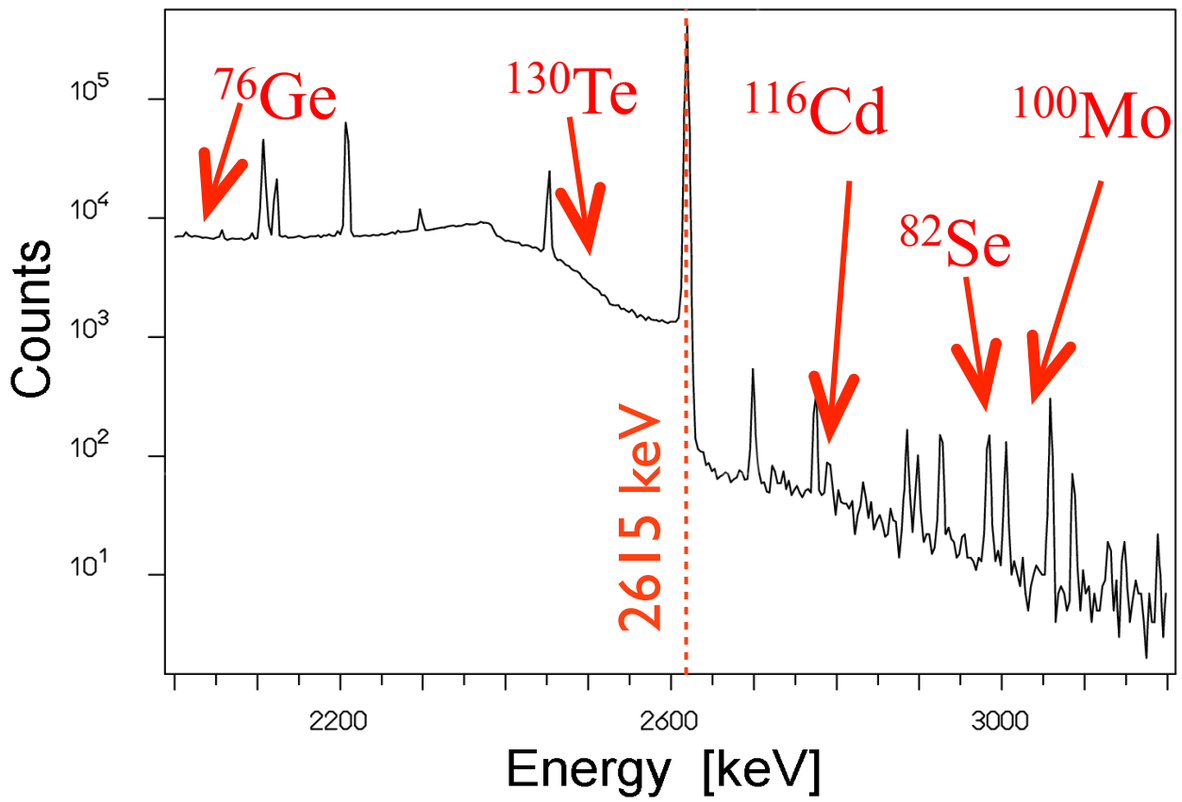

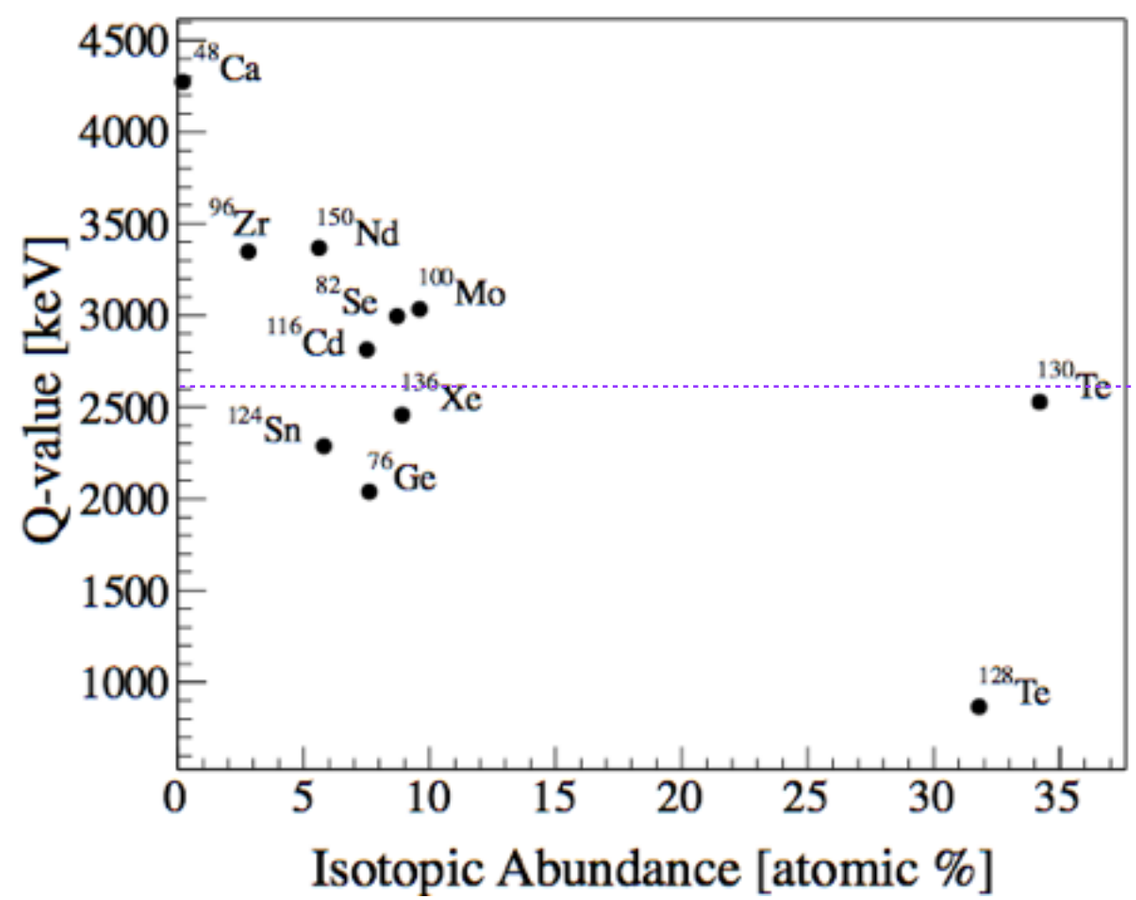

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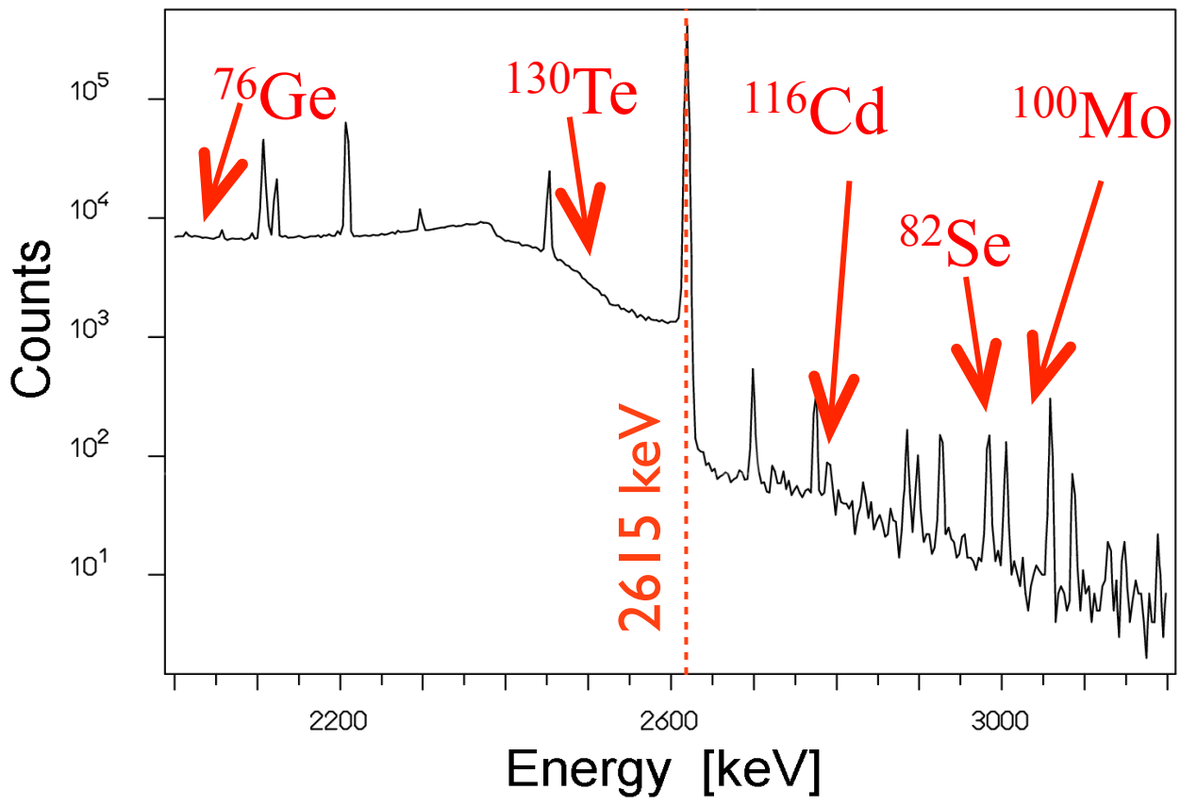
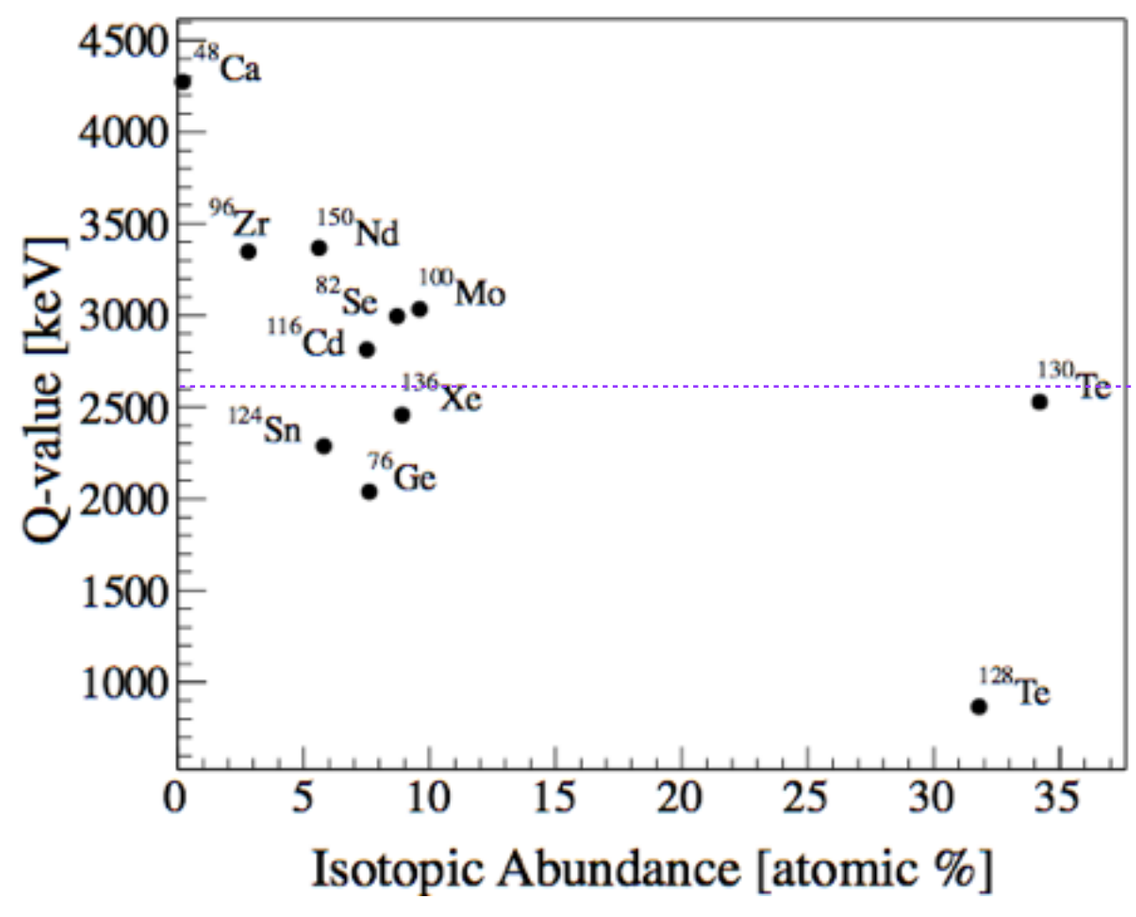


above 2615 keV γ radioactivity extremely reduced



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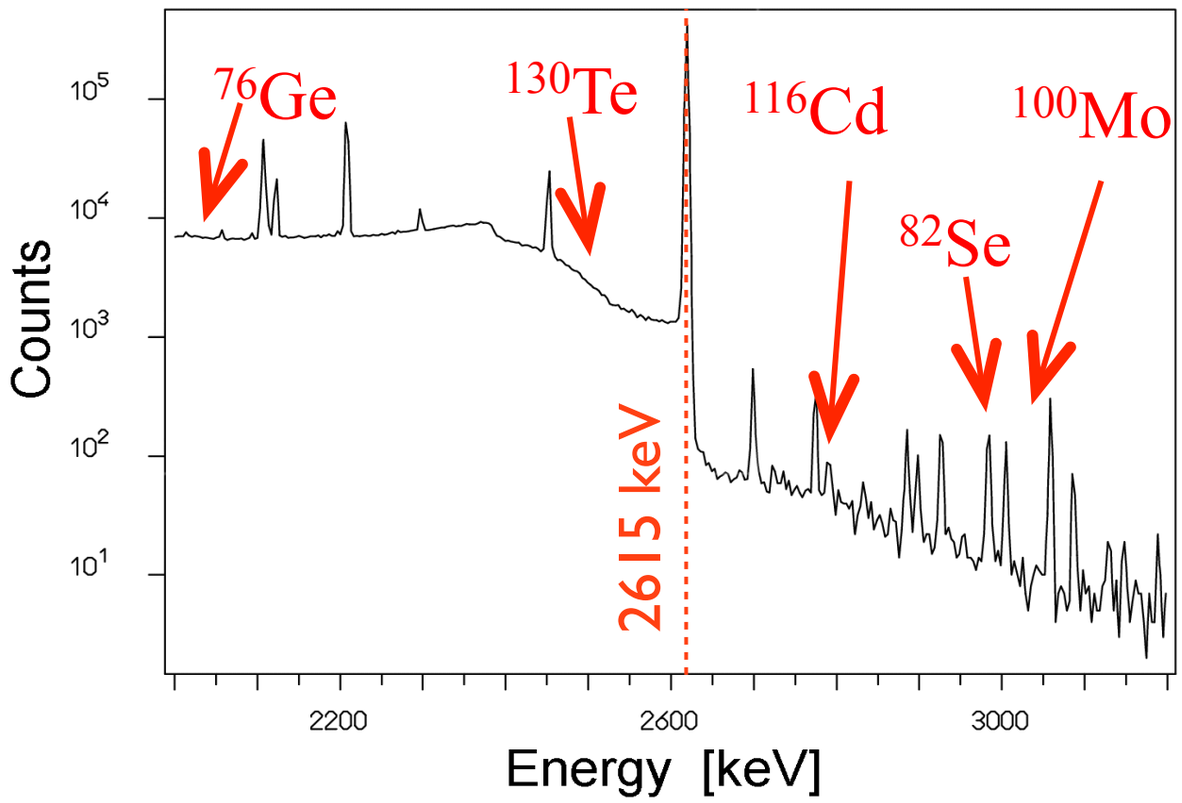

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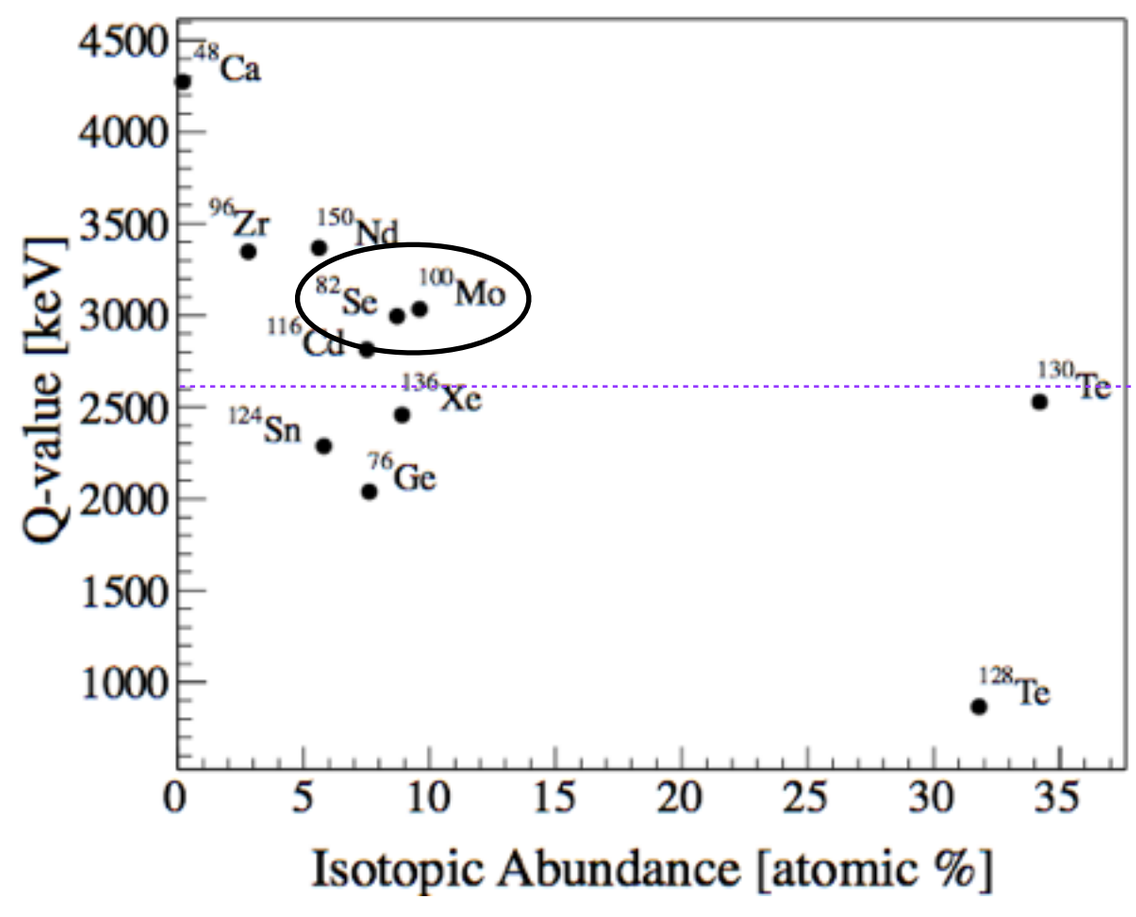

^{82}Se and ^{100}Mo are a good choice:

- $Q_{\beta\beta}$ > 2615 keV
- mass fraction in the crystal
- enrichment feasibility

Bolometers background

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Source:

Reduction technique:

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• cosmic radiation	$\longrightarrow$	underground facility

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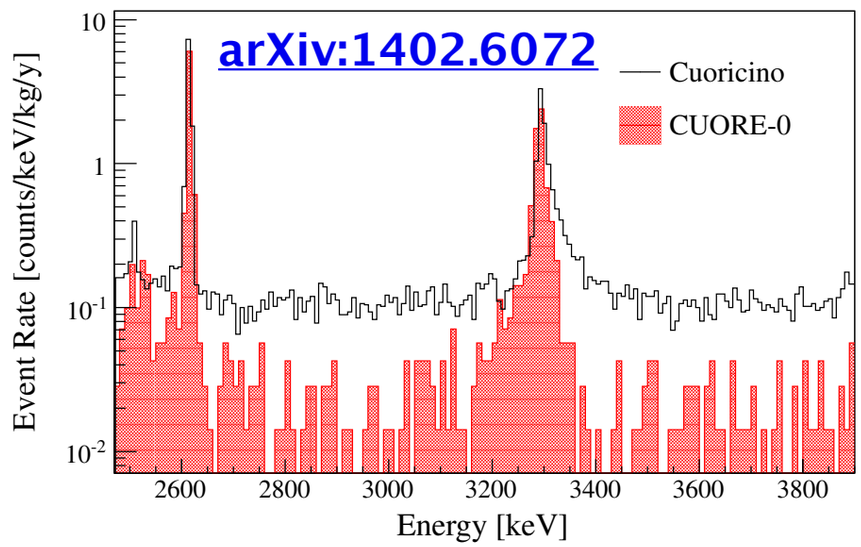

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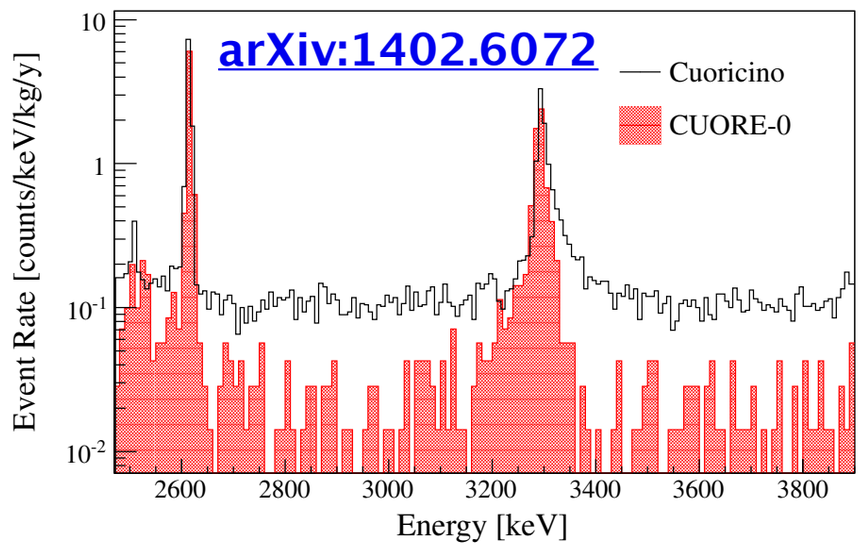

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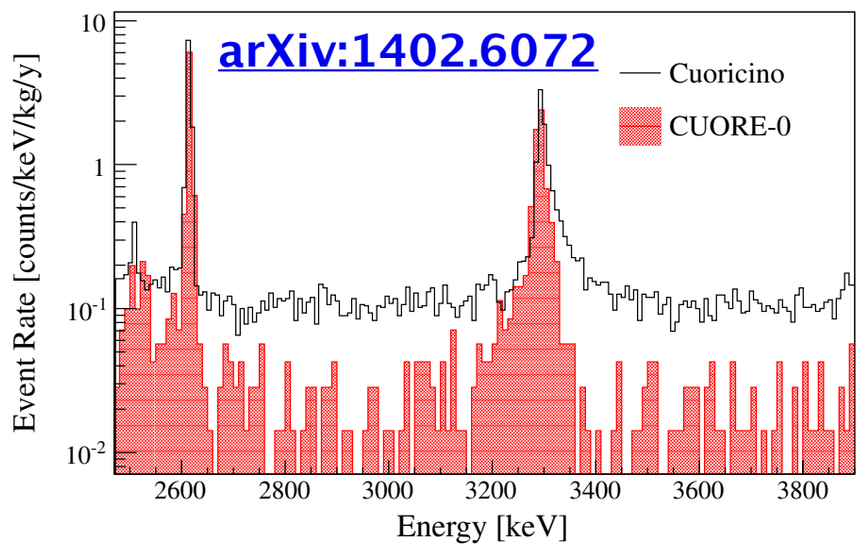

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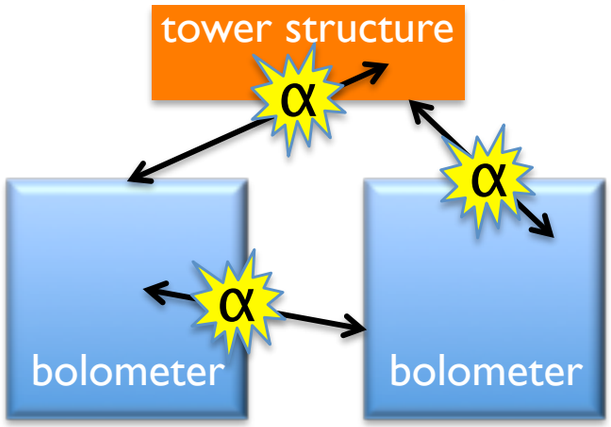
principal source of background: smeared αs from crystal surface/tower structure



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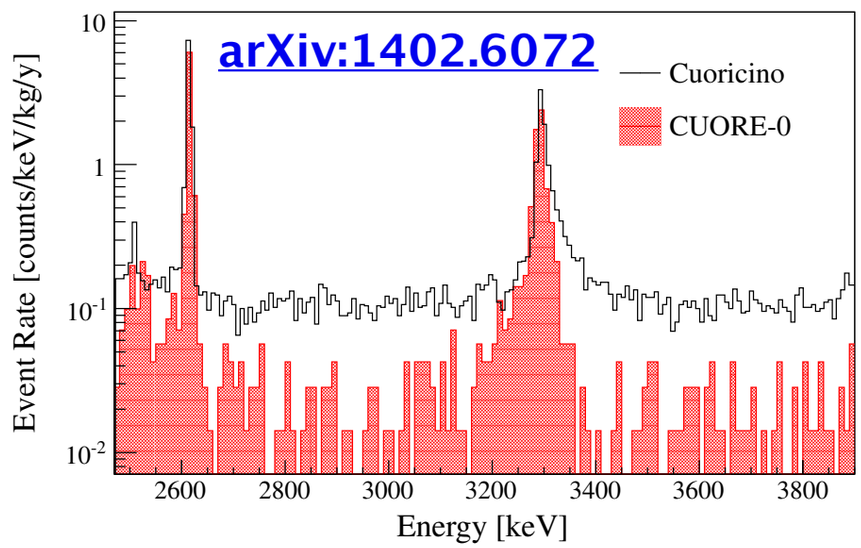

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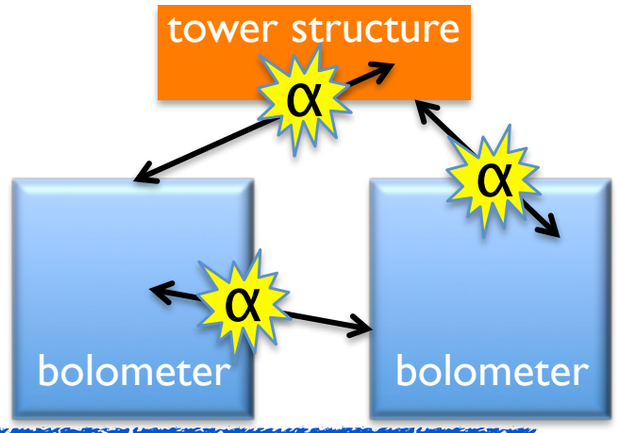

a more effective background reduction is needed

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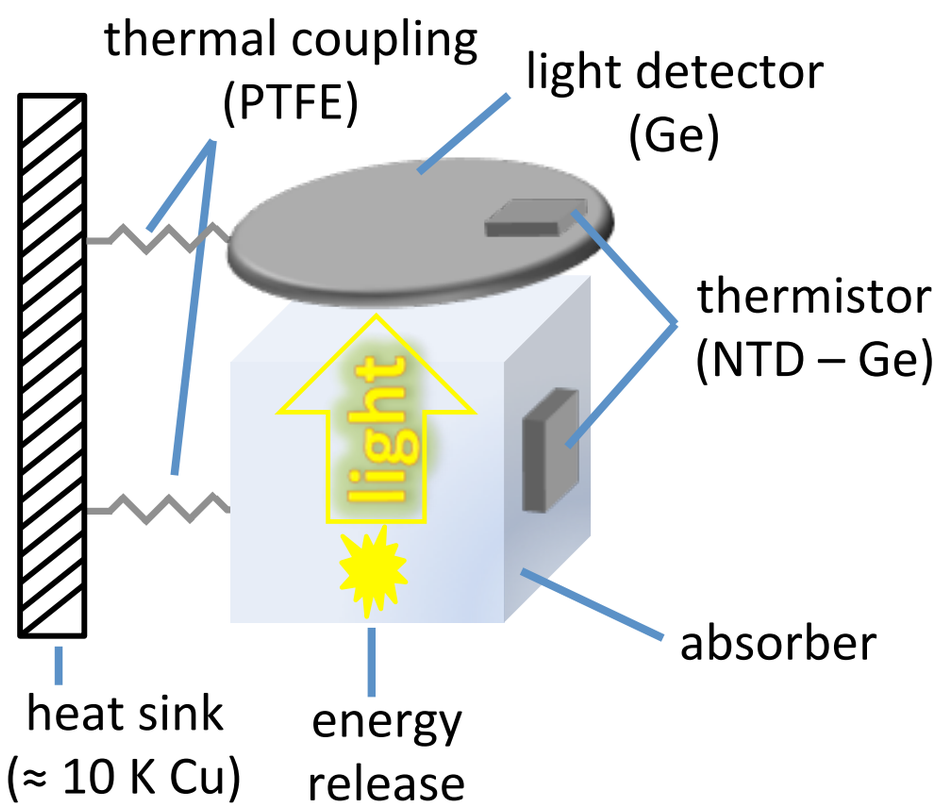

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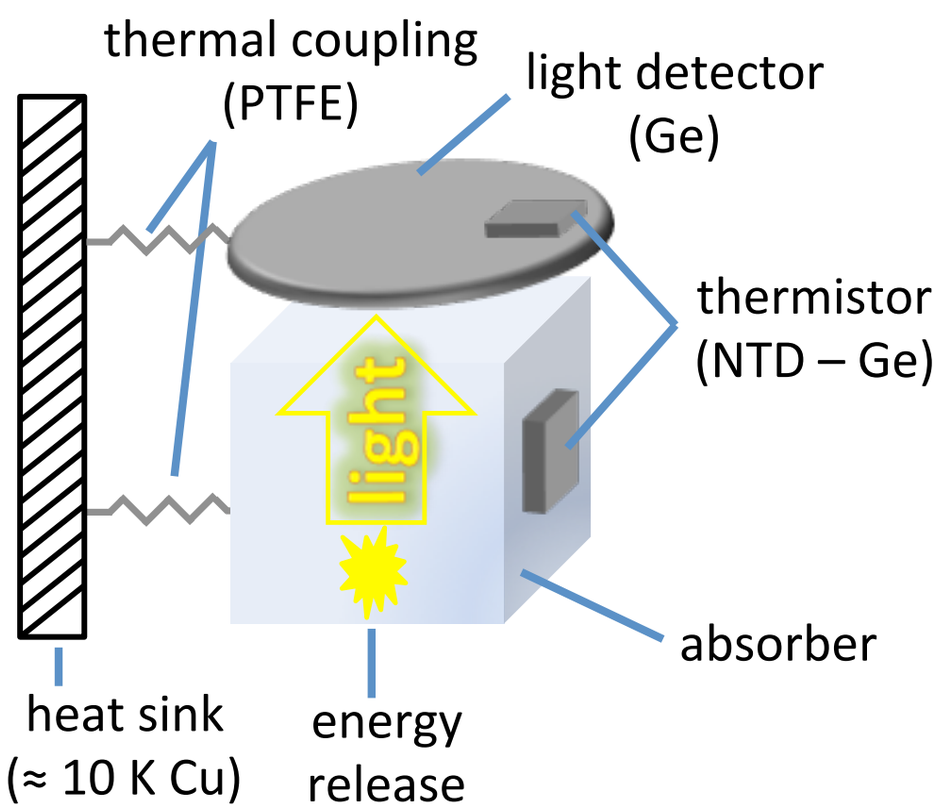

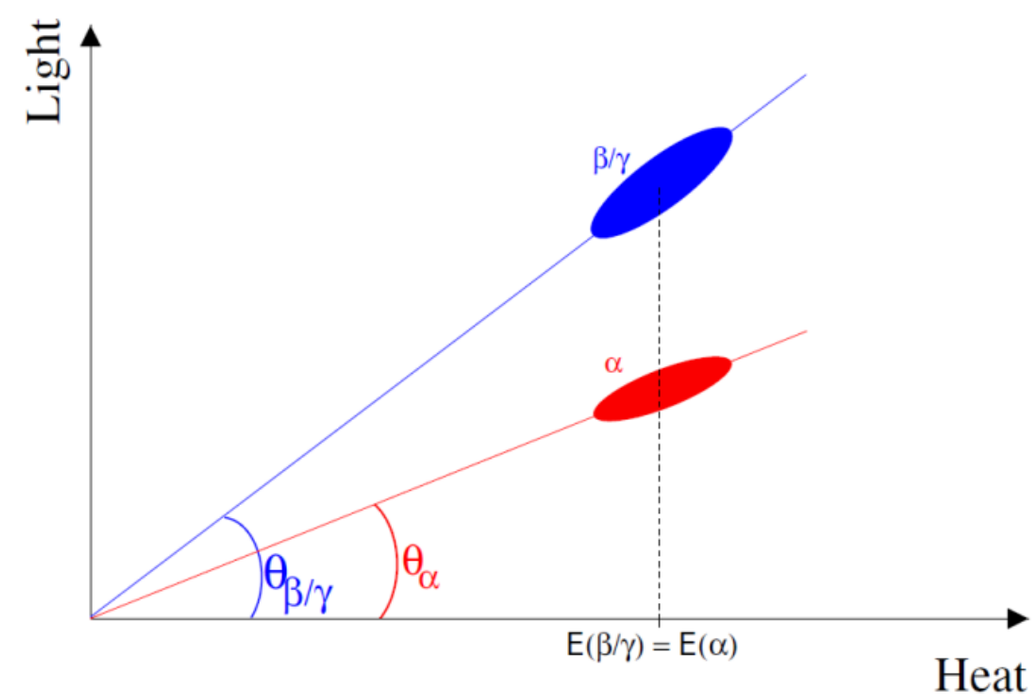

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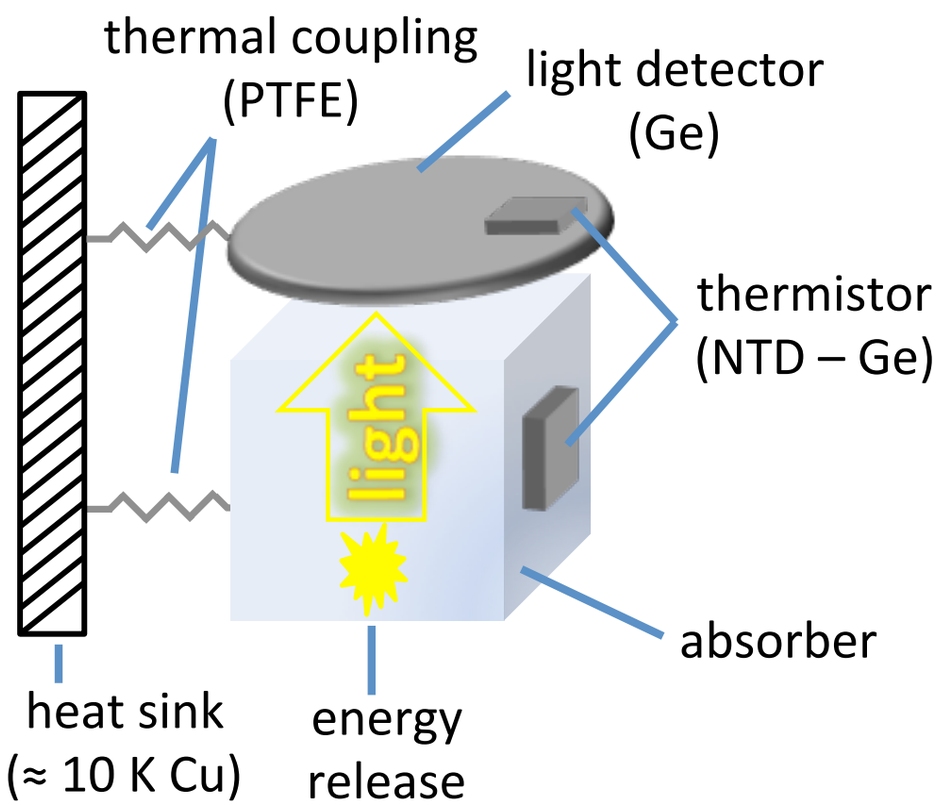

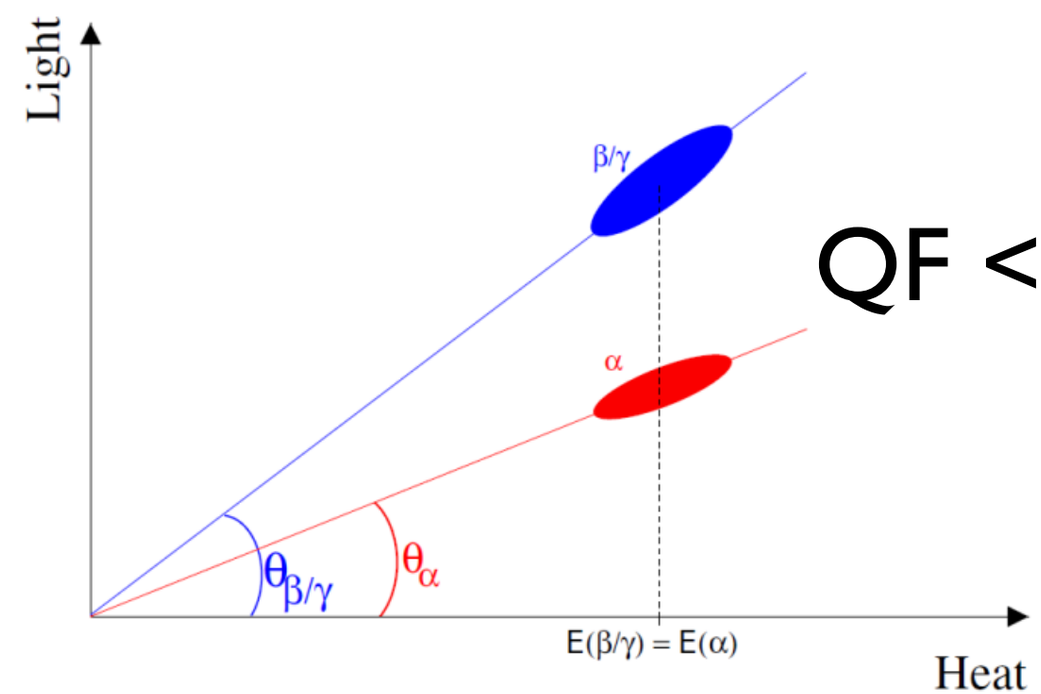

QF < 1

$$\underset{\text{Quenching Factor}}{QF} = \frac{\alpha \text{ light}}{\beta/\gamma \text{ light}}$$

for events of same energy

The LUCIFER experiment

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Low background Underground Cryogenic Installation For Elusive Rates

To study ^{82}Se (and/or ^{100}Mo) $0\nu\beta\beta$ with ZnSe ($ZnMoO_4$) scintillating bolometers

J.W. Beeman *et al.*, *AdHEP* **2013** p. 1-15 (2013)

The LUCIFER experiment

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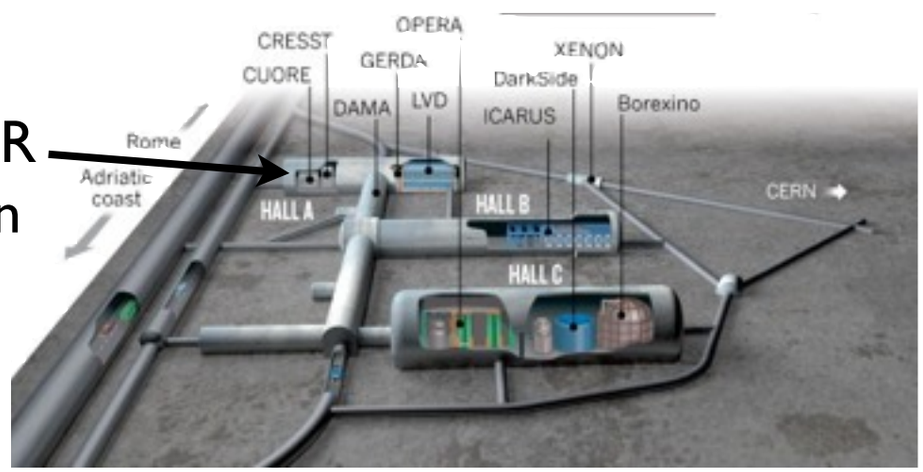

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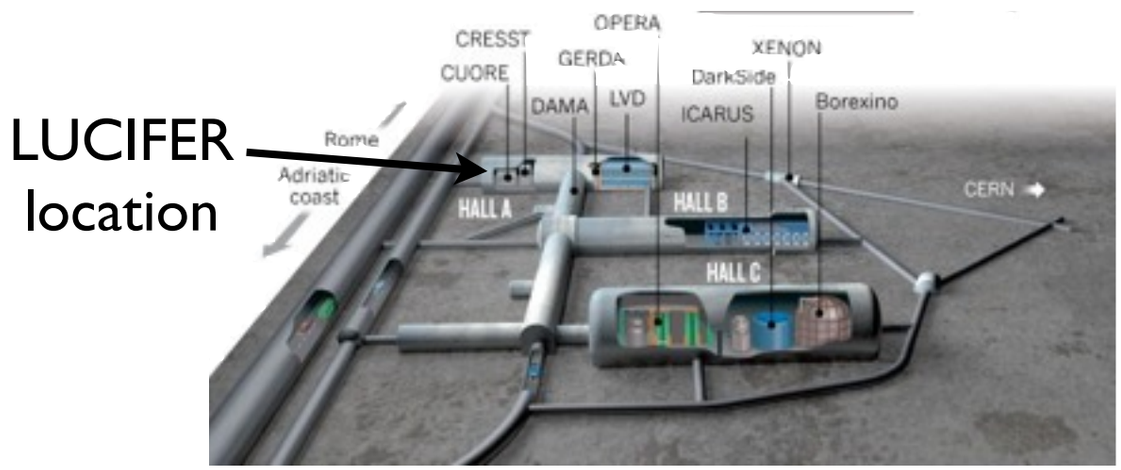

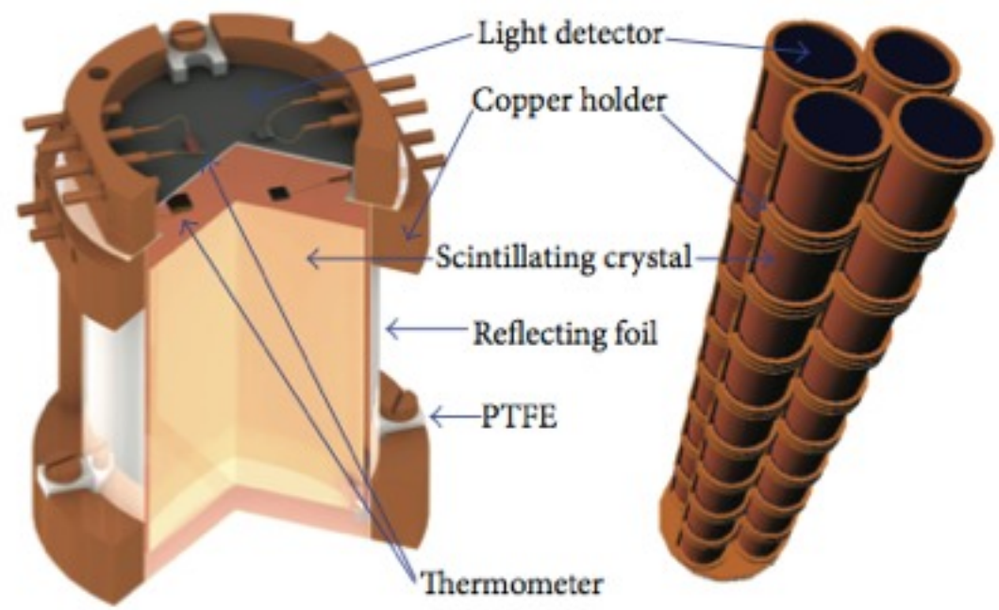

36 crystals enriched at 95%

J.W. Beeman *et al.*, *AdHEP* **2013** p. 1-15 (2013)

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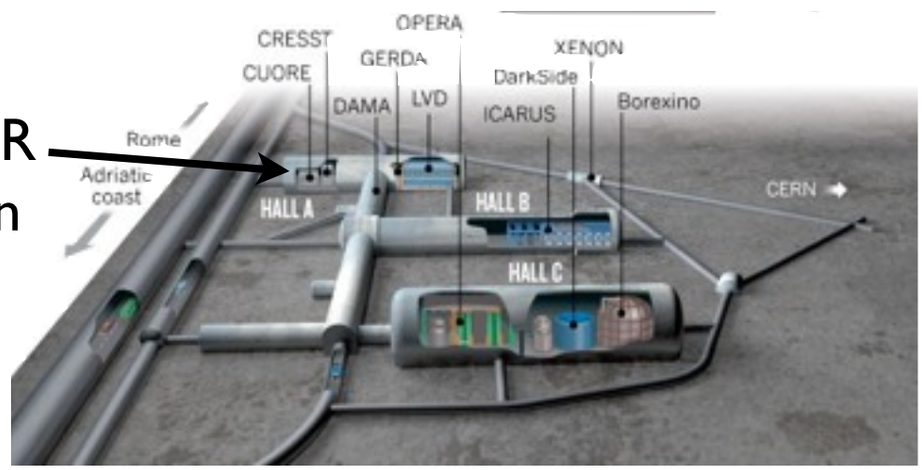

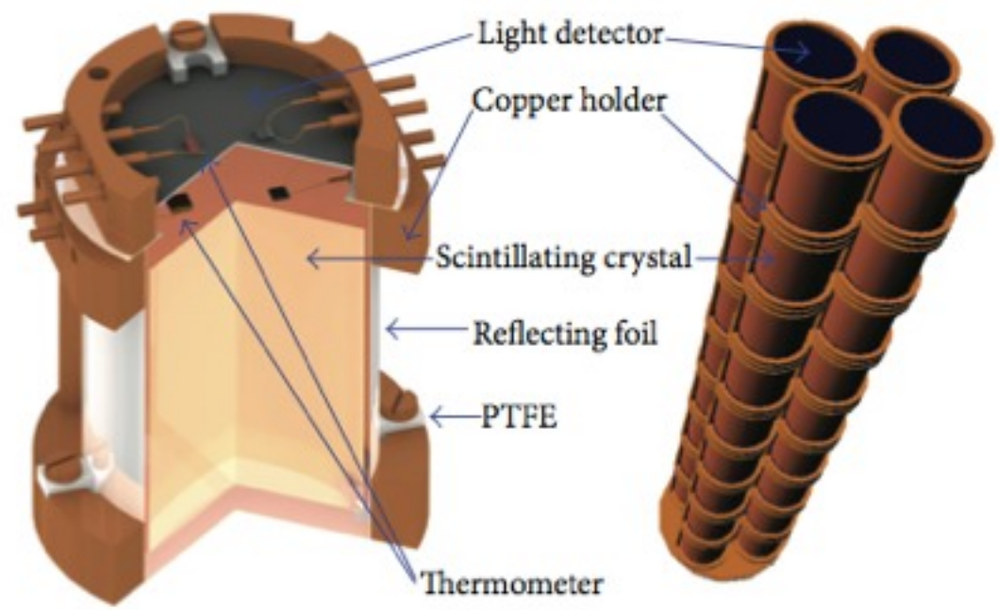

36 crystals enriched at 95%

	ββ emitter	crystal	$Q_{\beta\beta}$ [keV]	ββ emitter mass [kg]	QF
primary choice	^{82}Se	ZnSe	2997	≈ 9.8	4.2
secondary choice	^{100}Mo	$ZnMoO_4$	3034	≈ 6.2	0.14

J.W. Beeman *et al.*, *AdHEP* **2013** p. 1-15 (2013)

ZnSe bolometers

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J.W. Beeman *et al.*, *JINST* **8** P05021 (2013)

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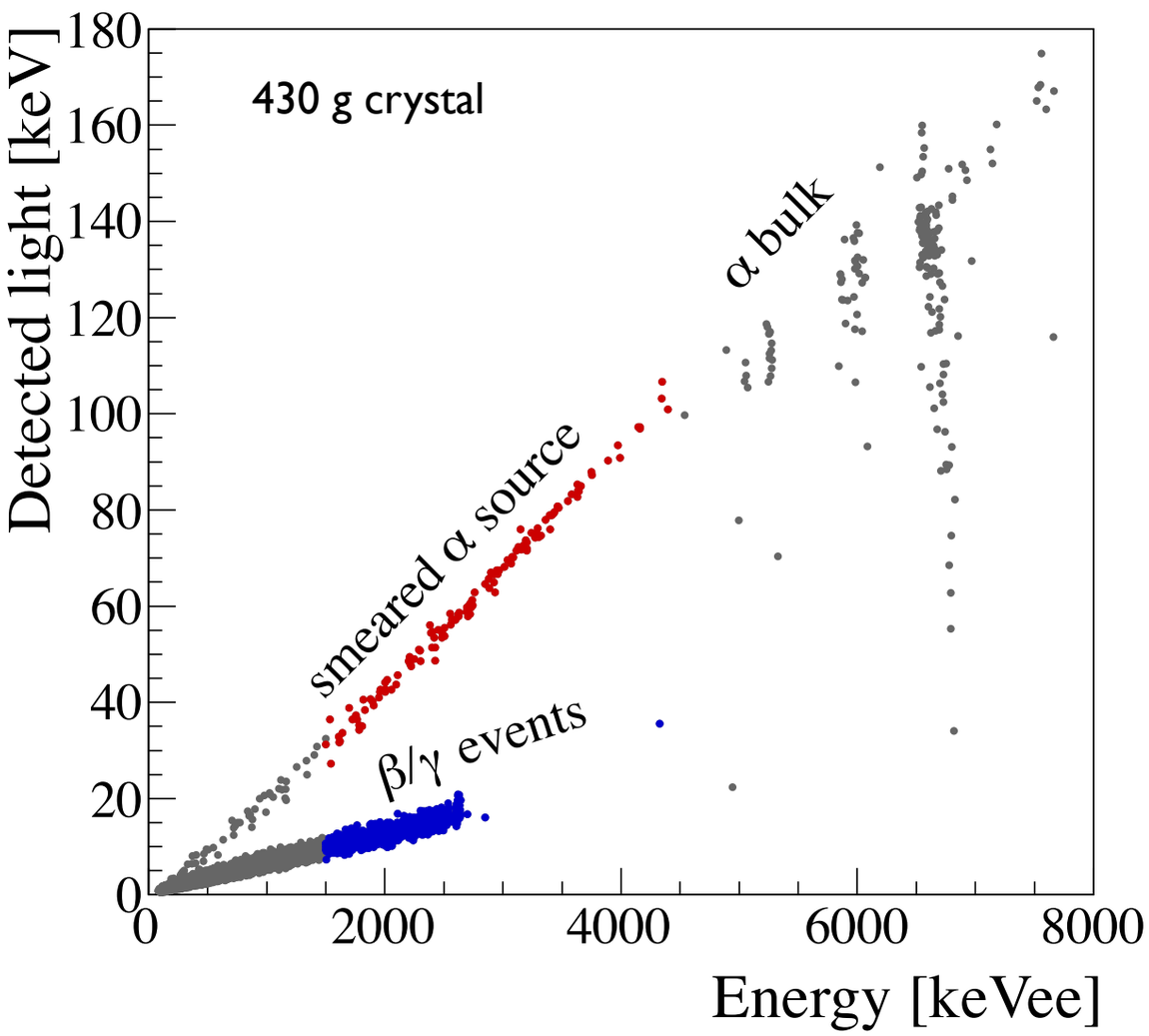

very good particle identification achievable using light detector

J.W. Beeman *et al.*, *JINST* **8** P05021 (2013)

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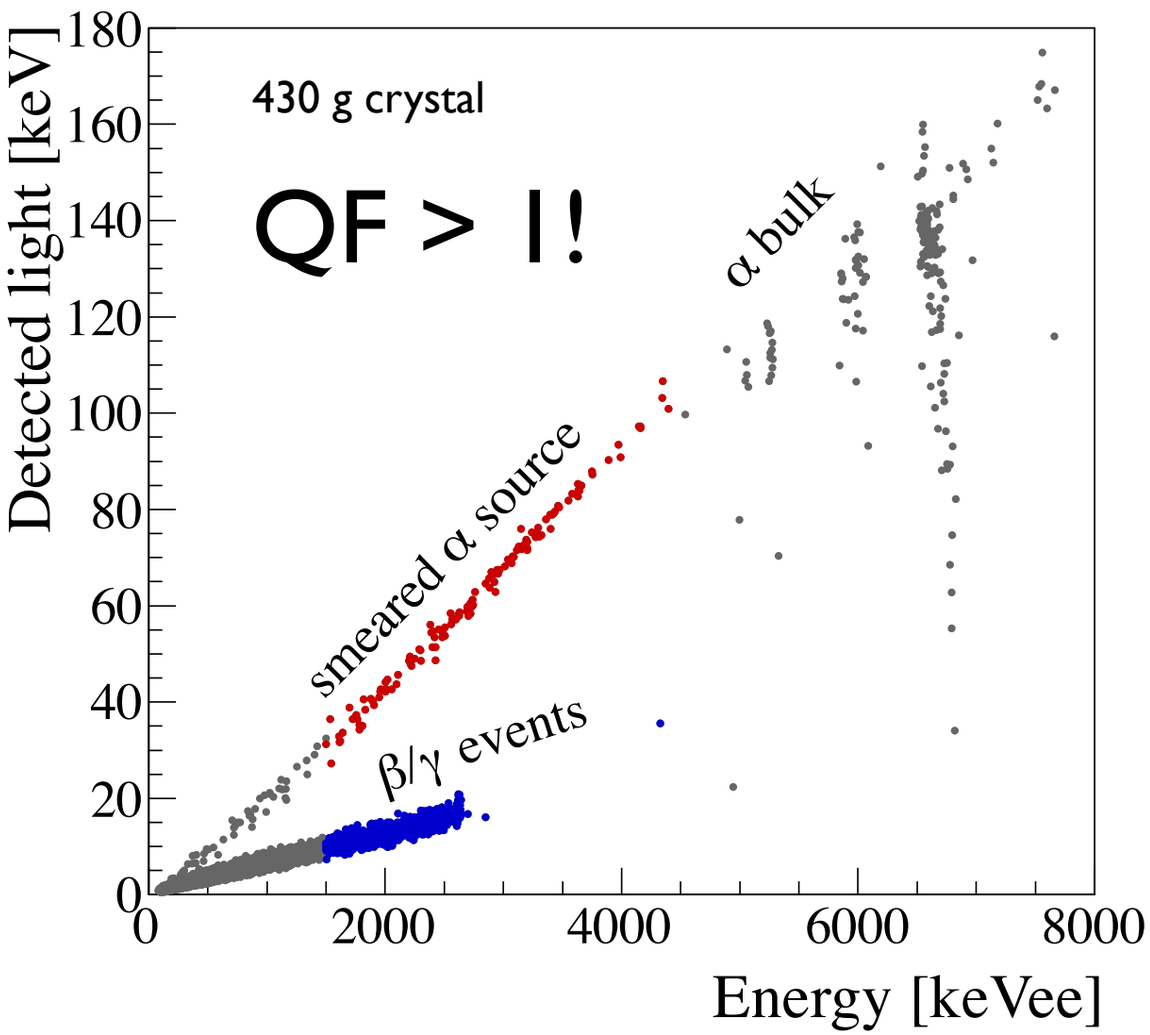

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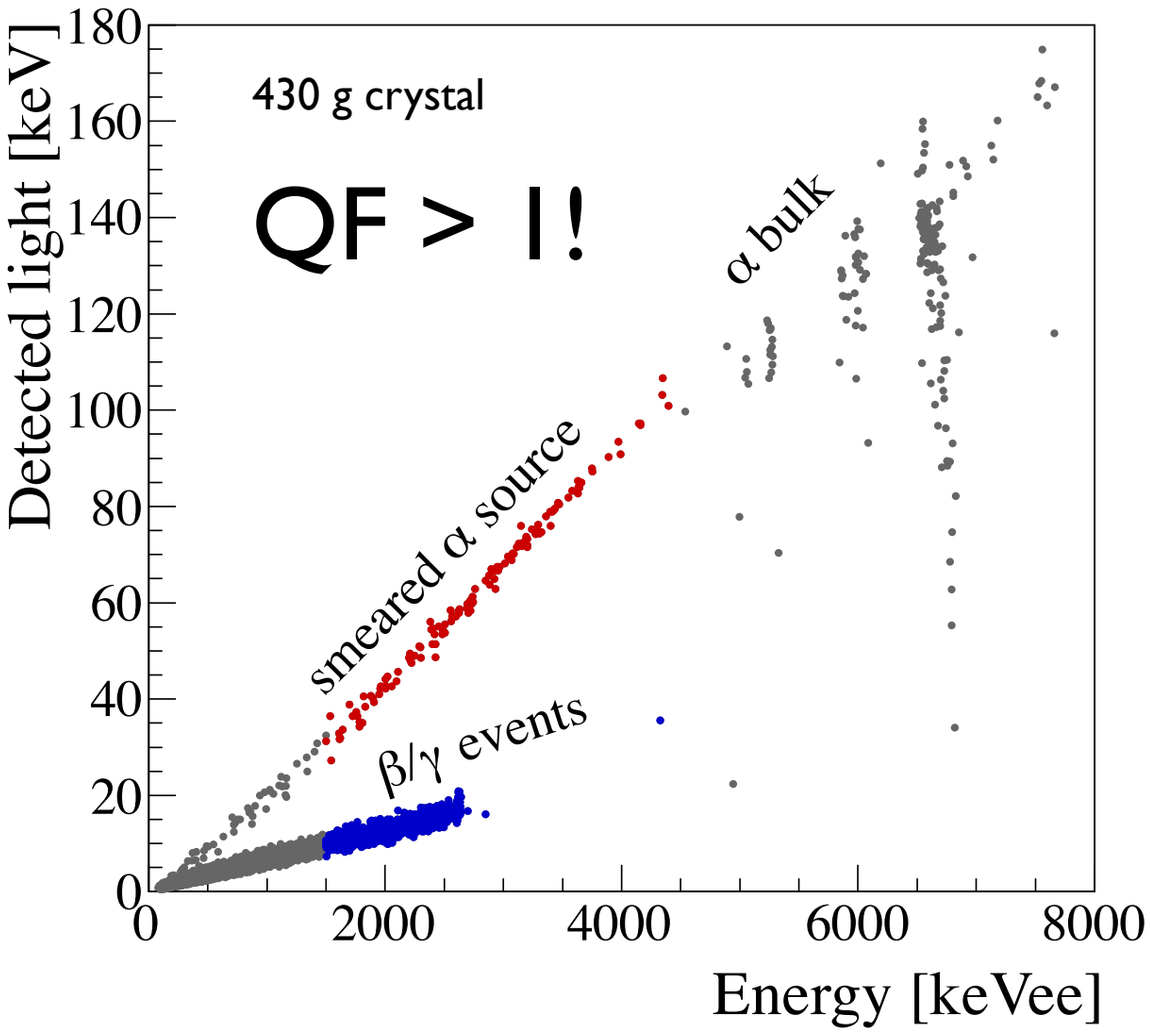

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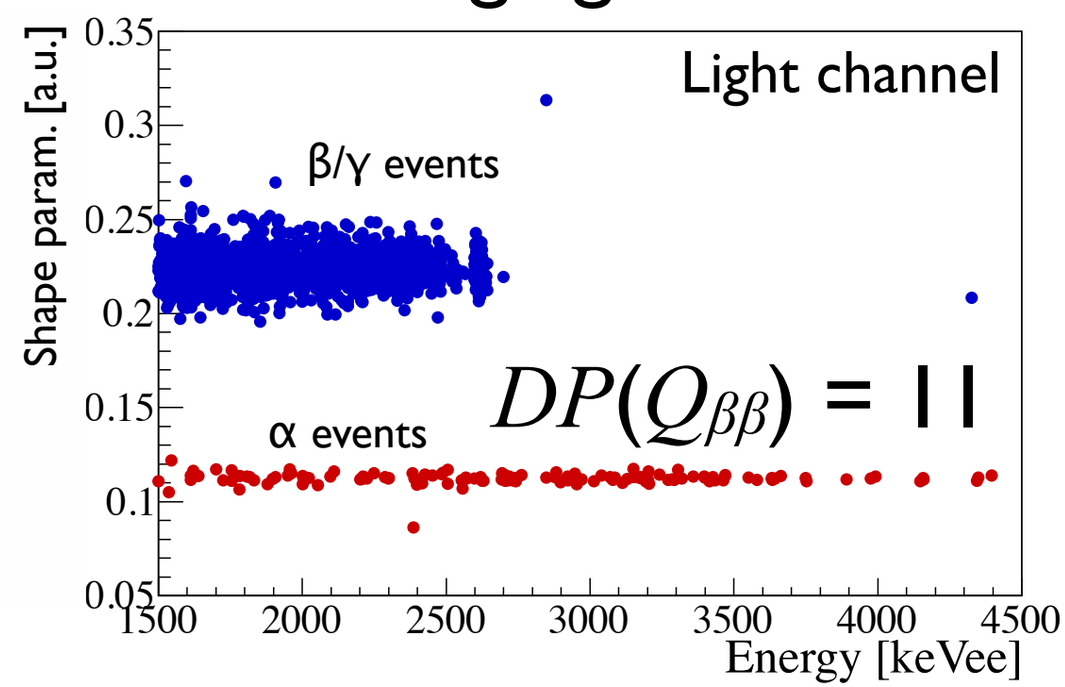

$$DP(E) = \frac{|\mu_{\beta/\gamma}(E) - \mu_{\alpha}(E)|}{\sqrt{\sigma^2_{\beta/\gamma}(E) + \sigma^2_{\alpha}(E)}}$$

J.W. Beeman *et al.*, *JINST* **8** P05021 (2013)

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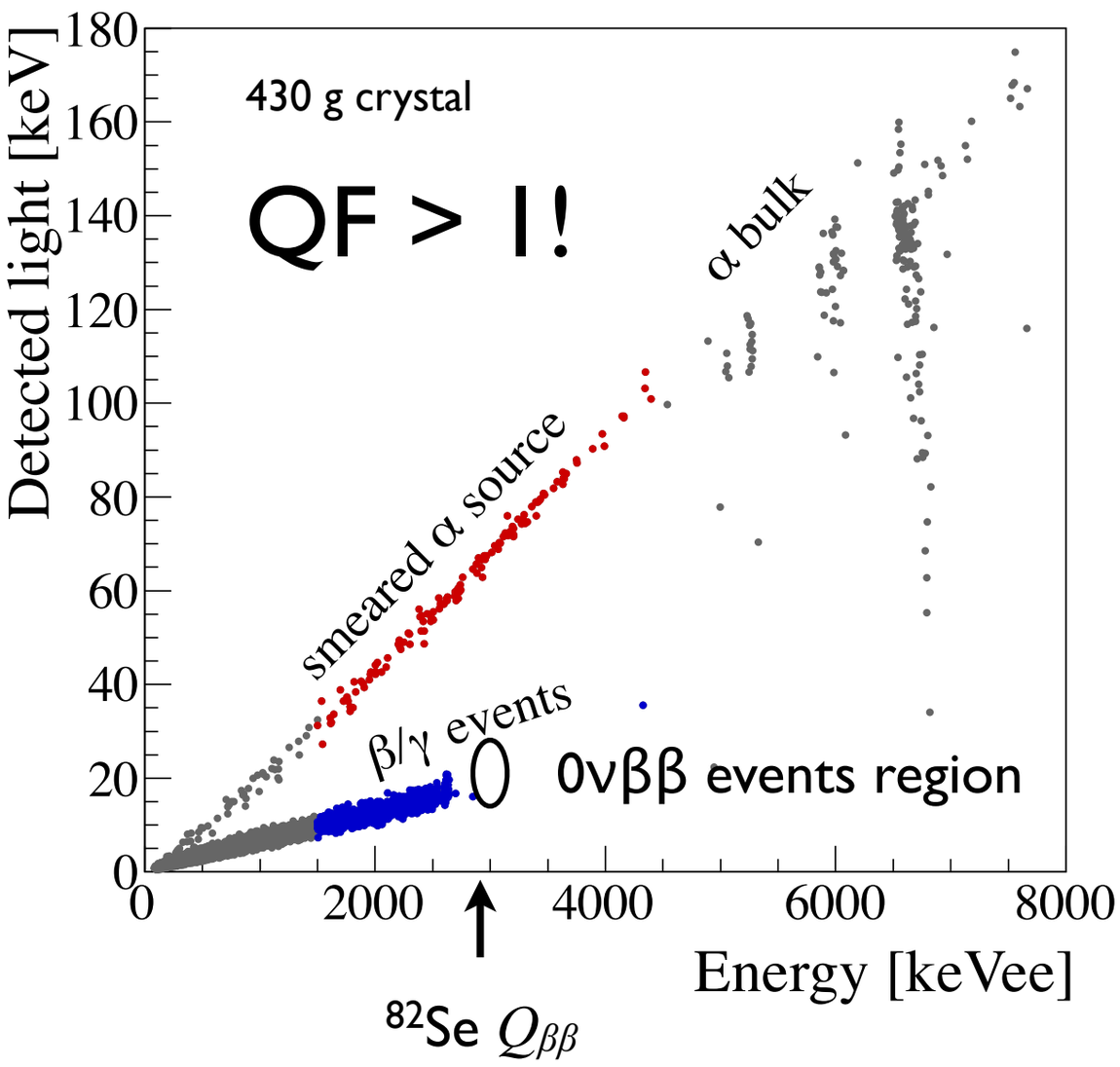

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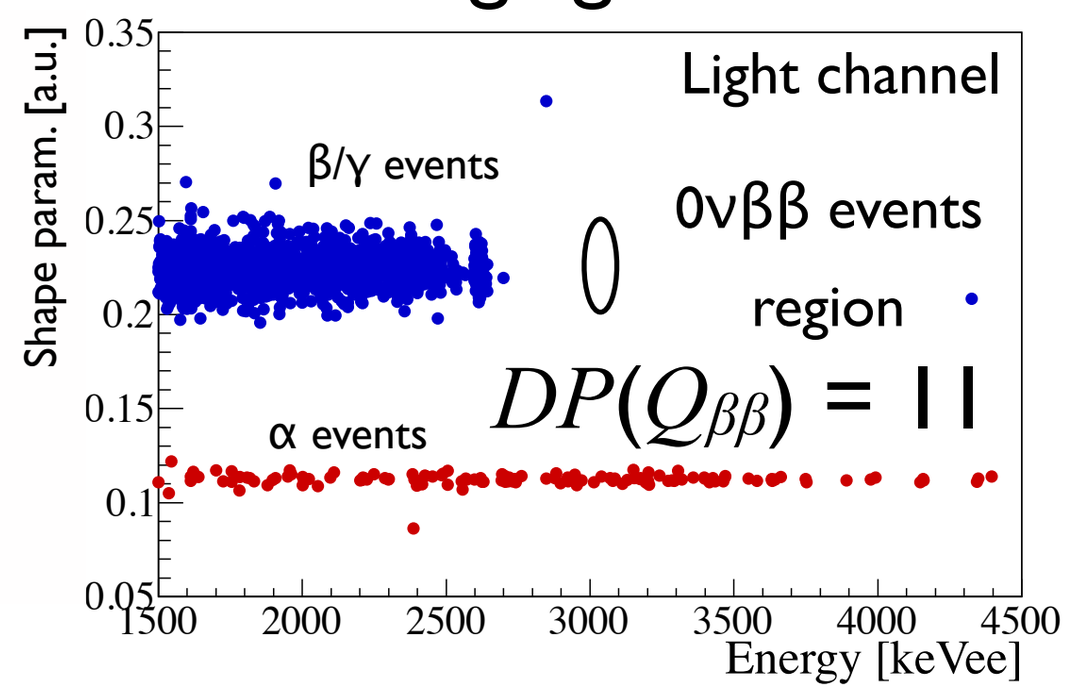

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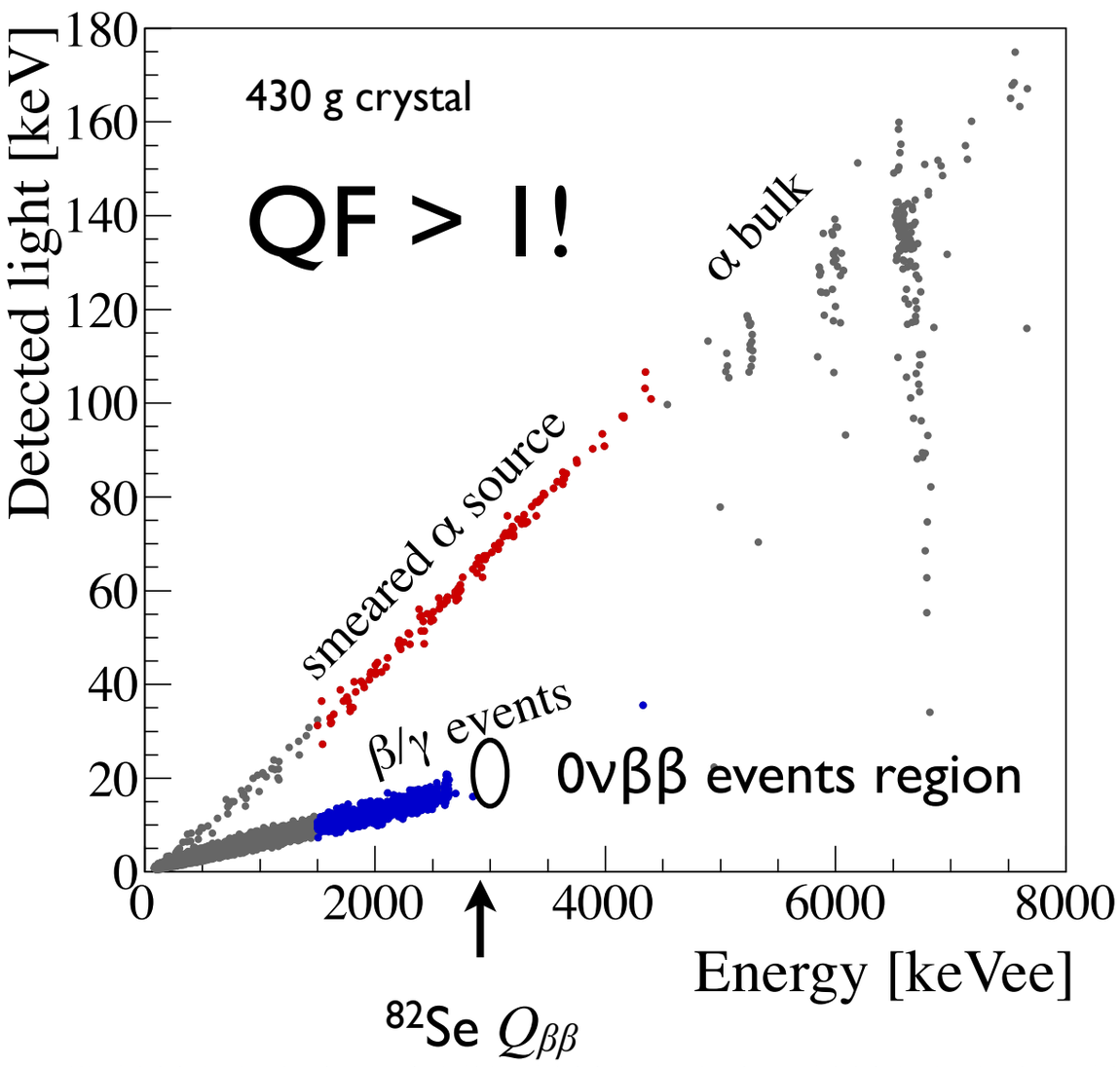

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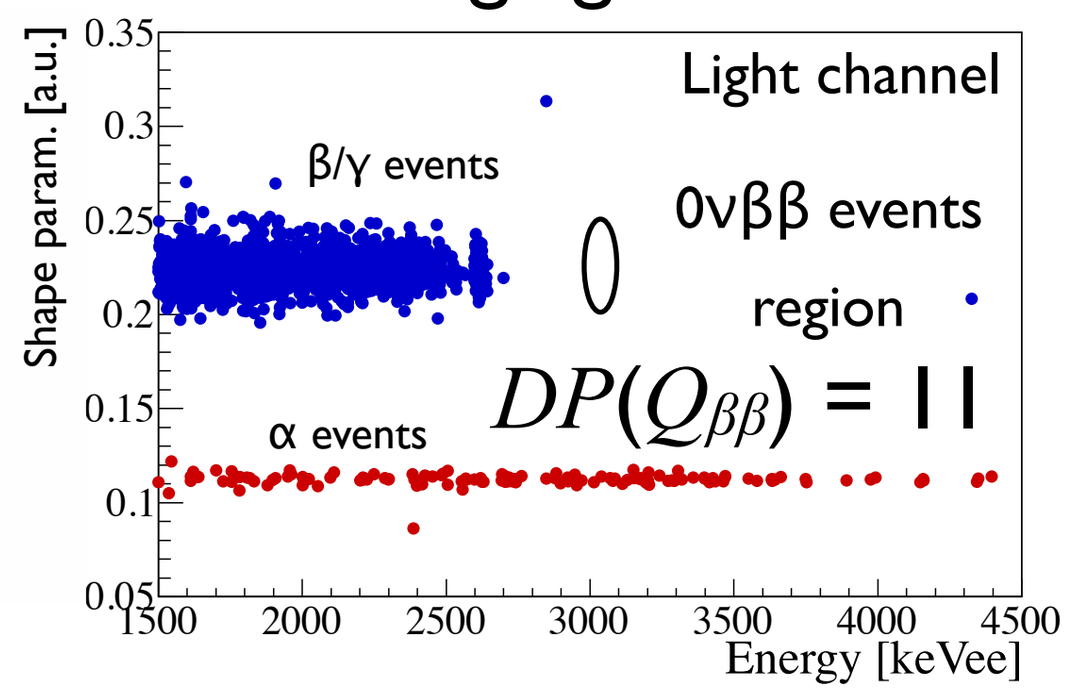

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Rejection of α background and 0 events in 0νββ region

J.W. Beeman *et al.*, *JINST* **8** P05021 (2013)

ZnSe β/γ Spectrum

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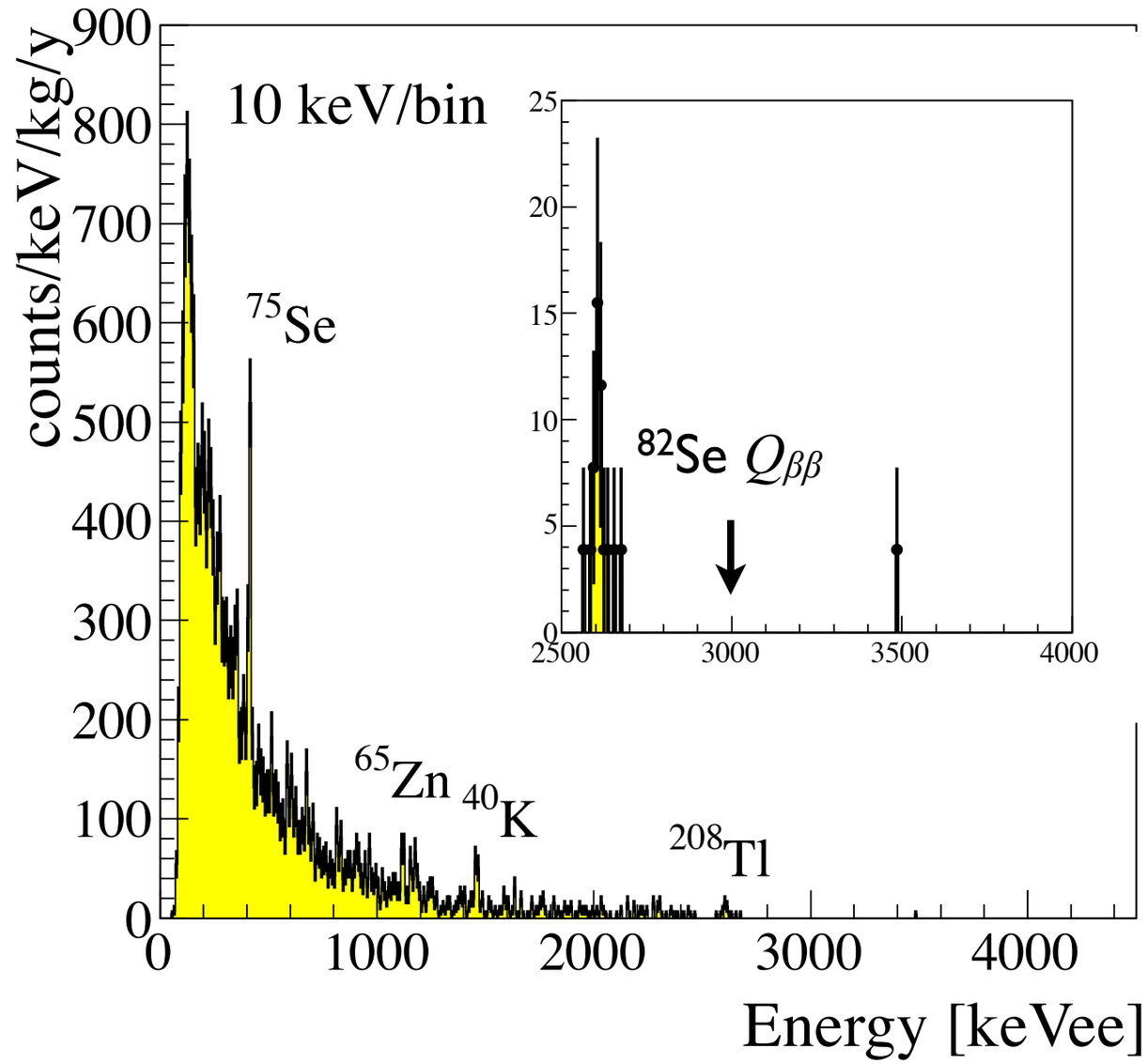
β/γ spectrum in 524 h (rejecting αs with light detector)



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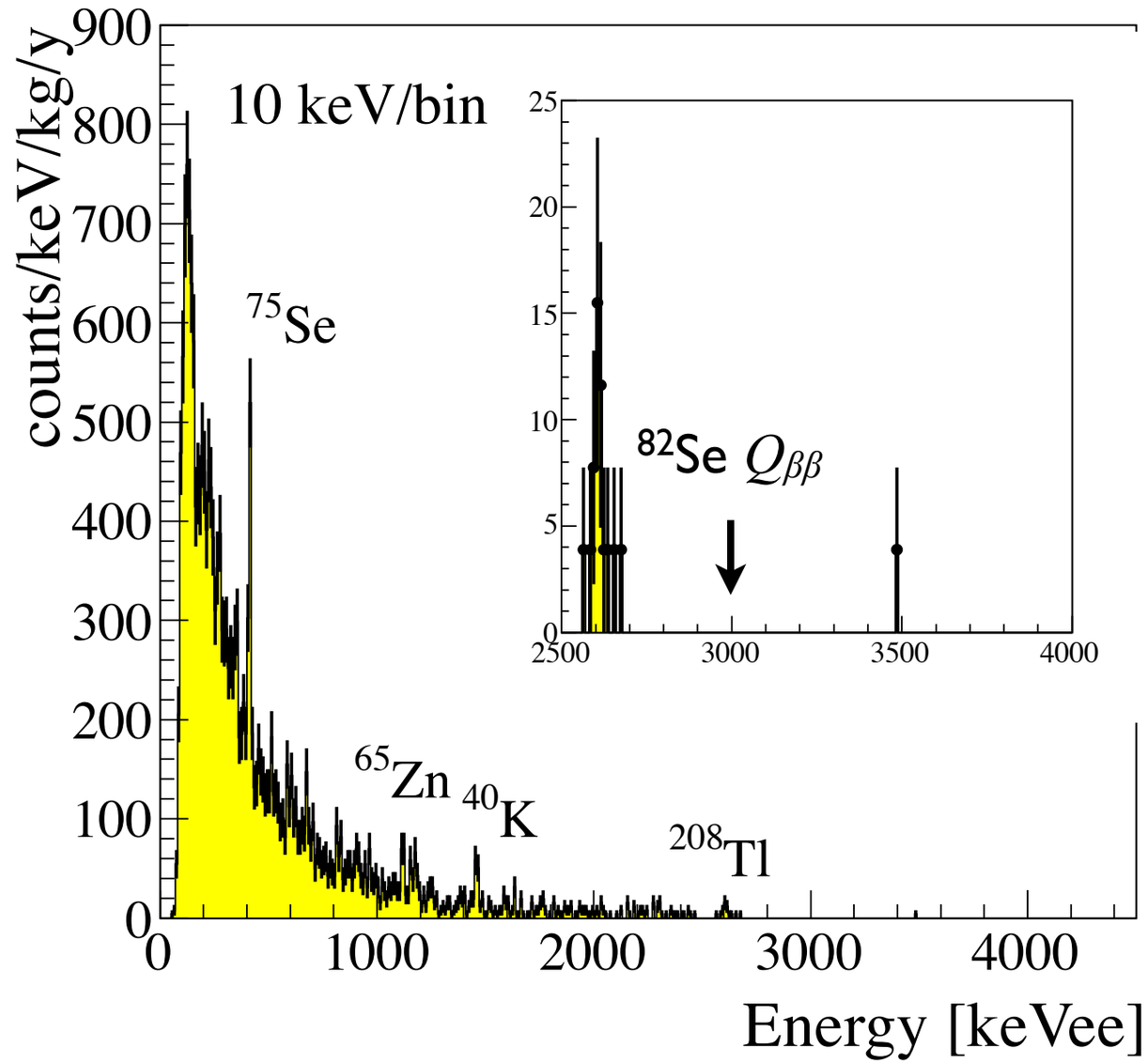
inner contamination:

3×10^{-4} counts/keV/kg/y ^{238}U

3×10^{-3} counts/keV/kg/y ^{232}Th



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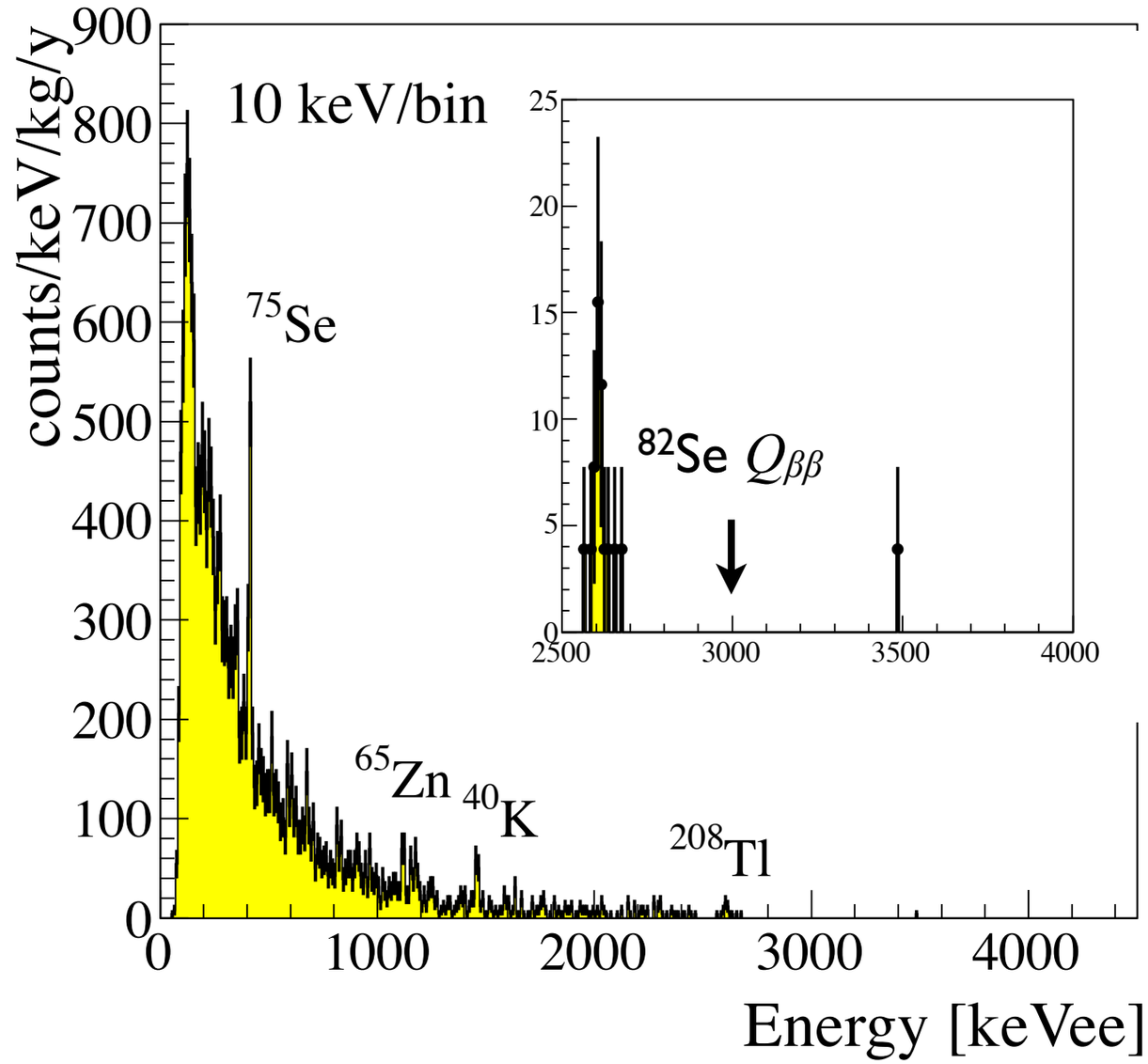

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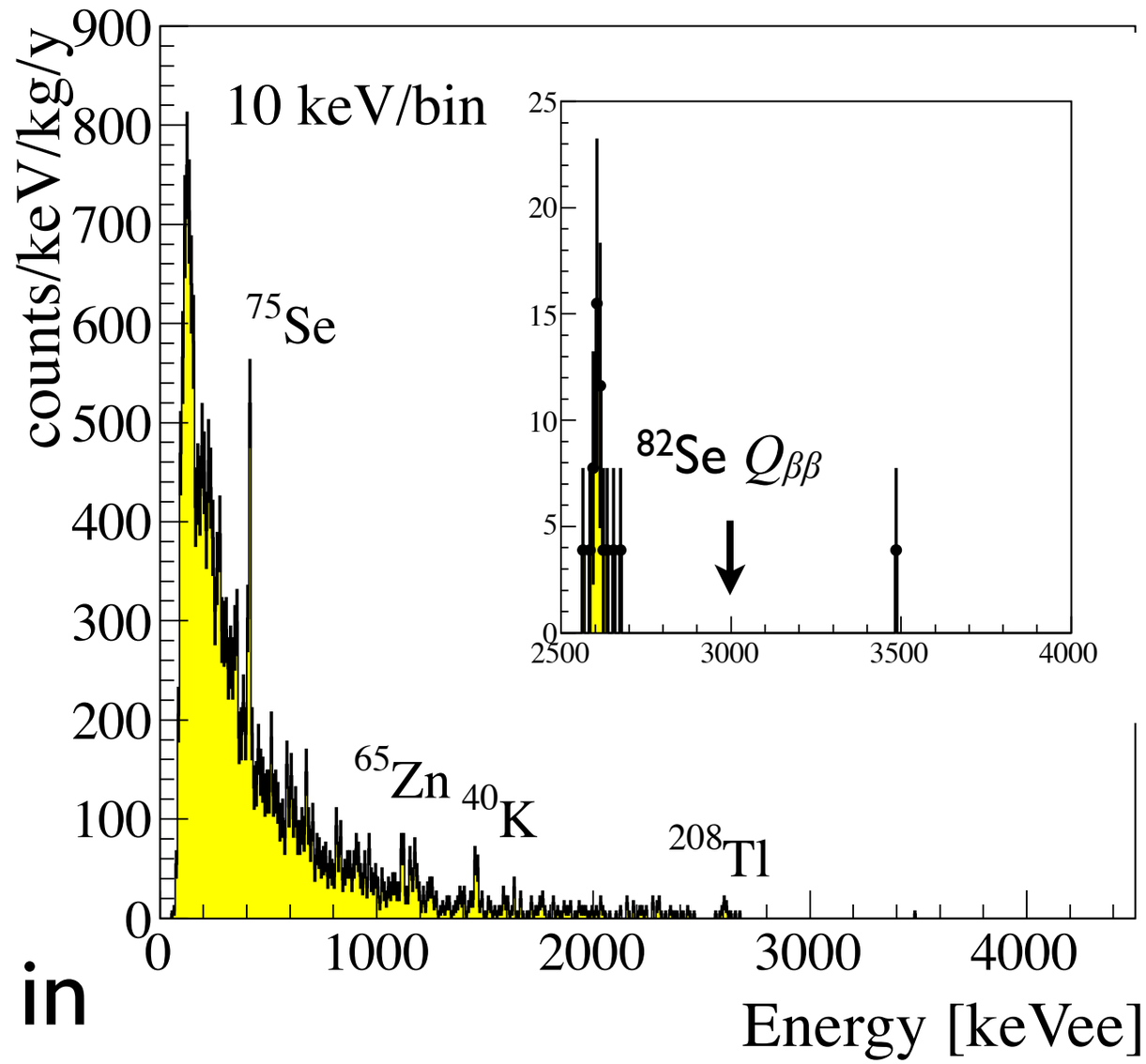

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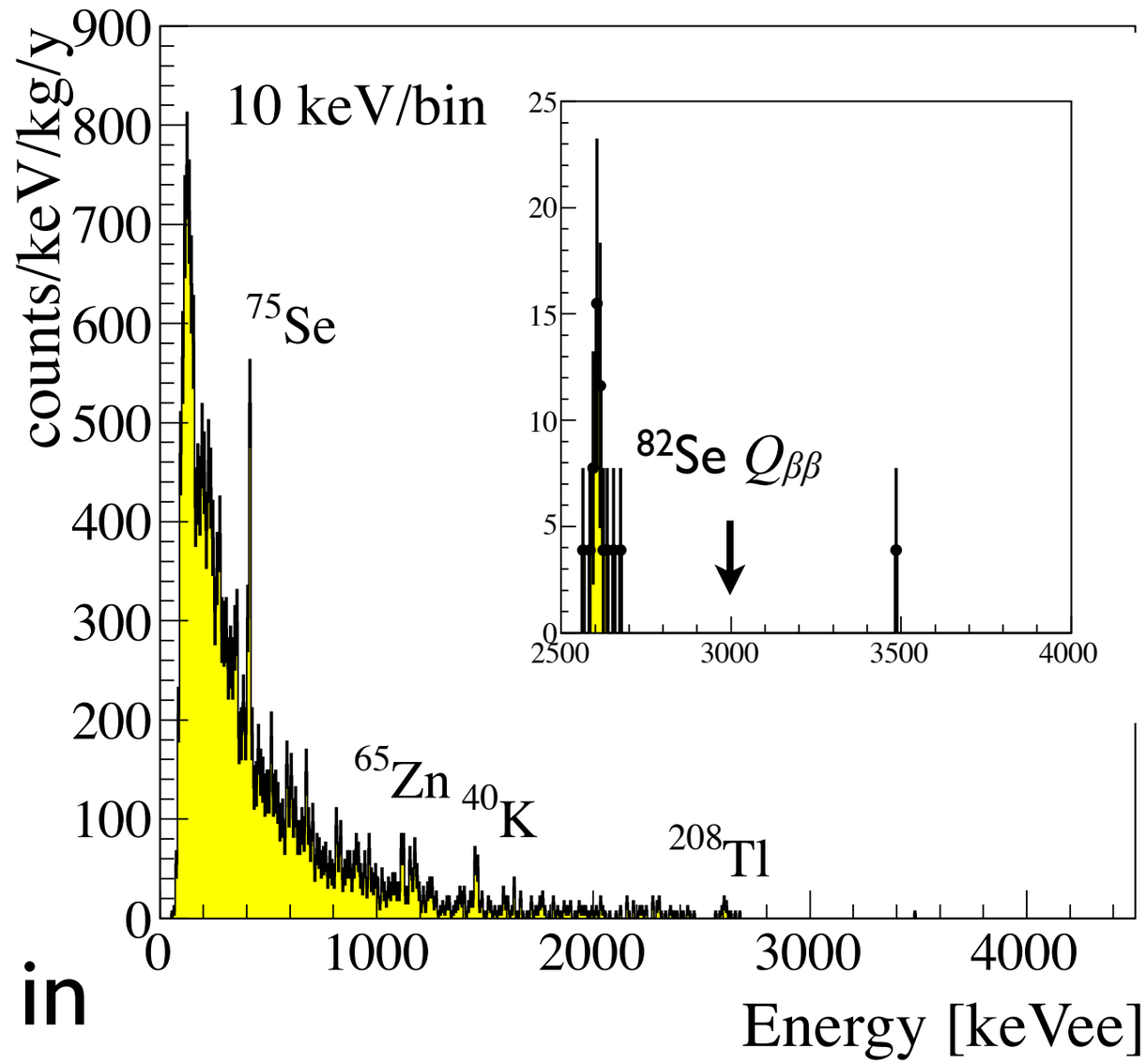

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zero-background is achievable

$ZnMoO_4$ bolometers

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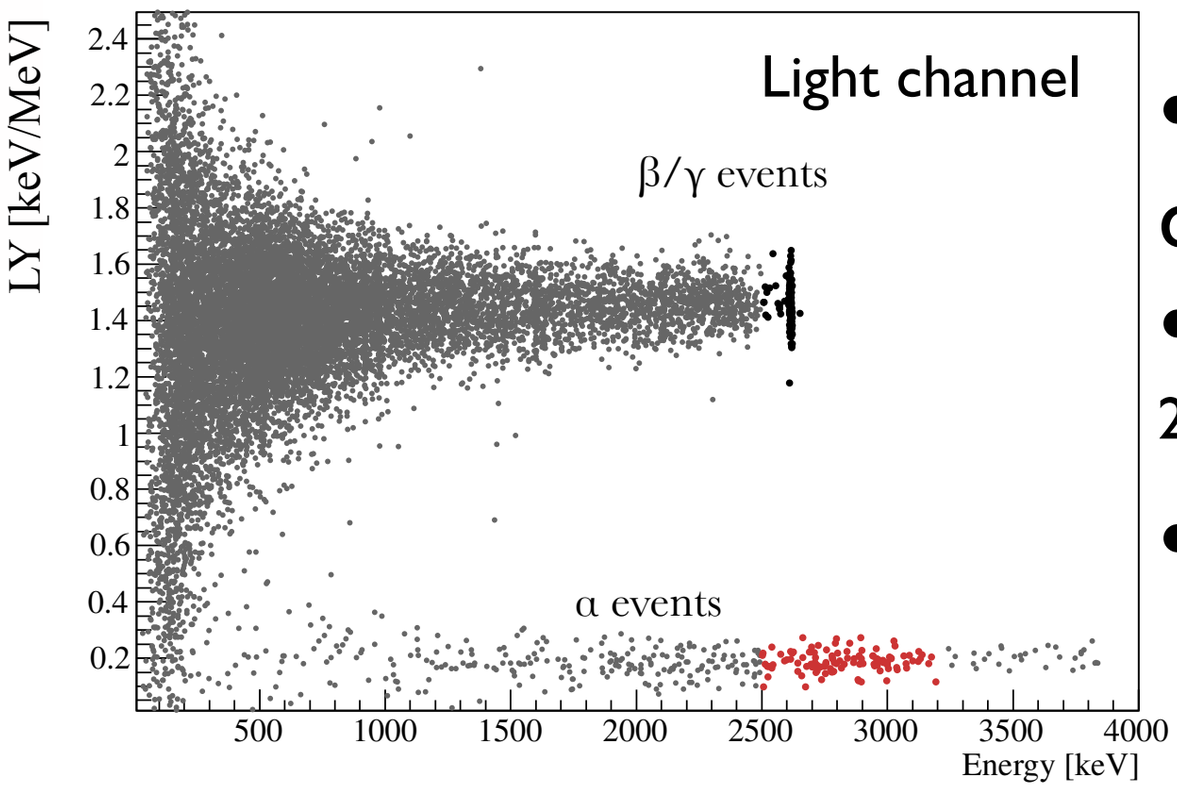

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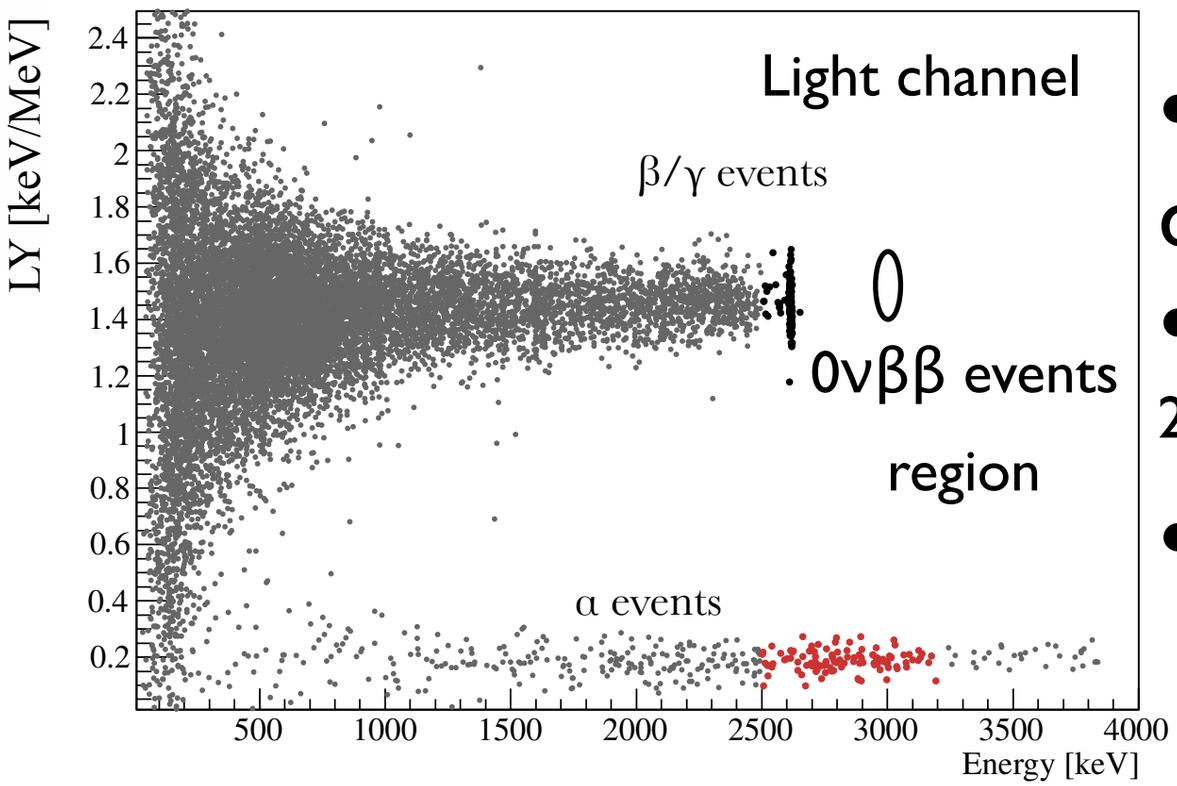

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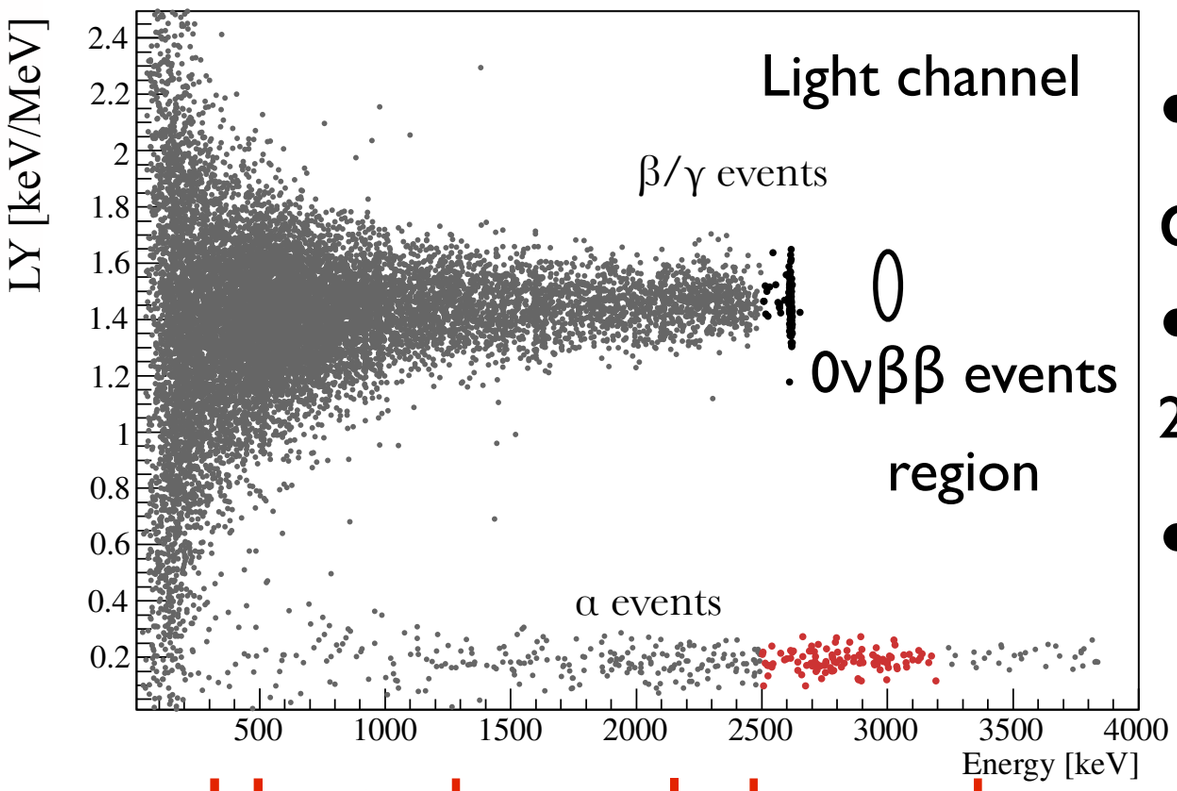

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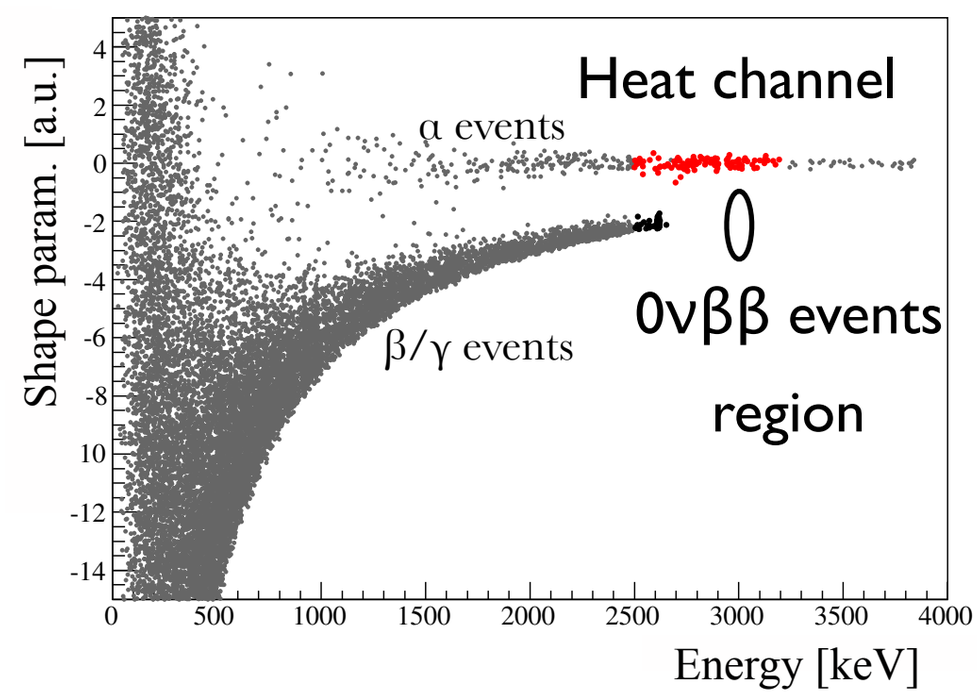

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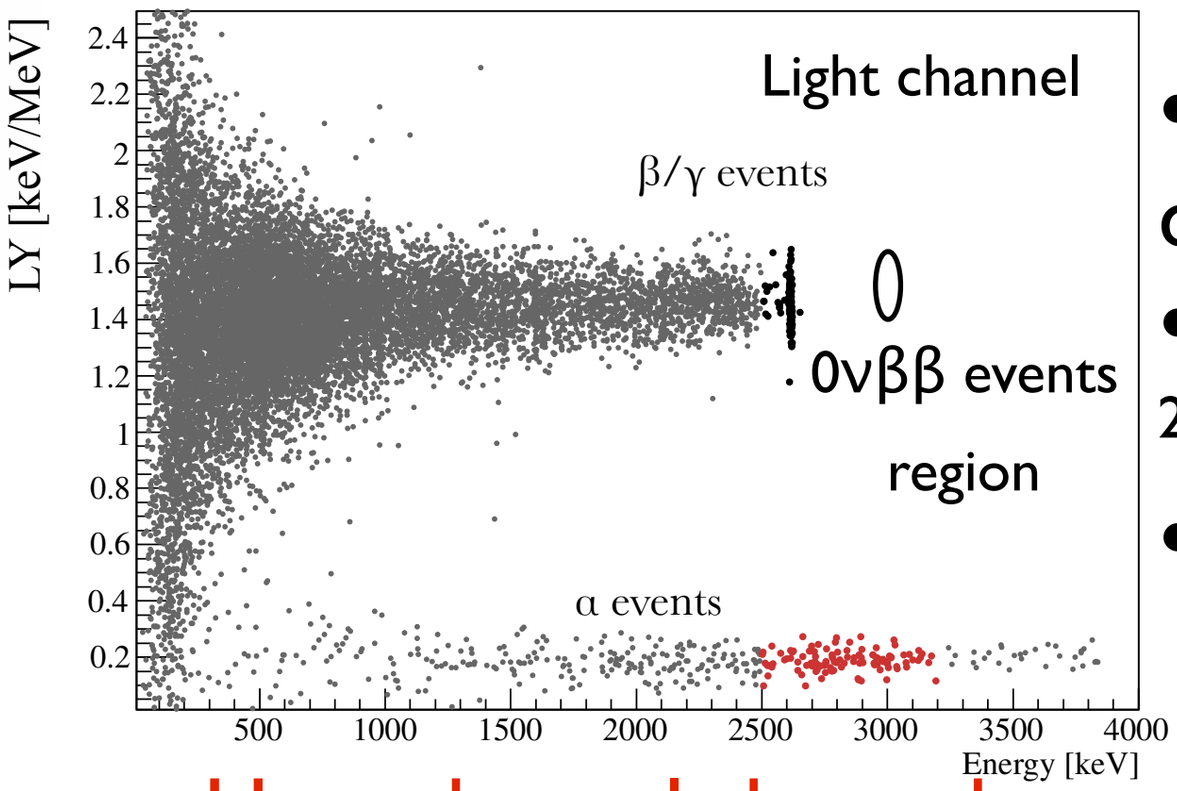

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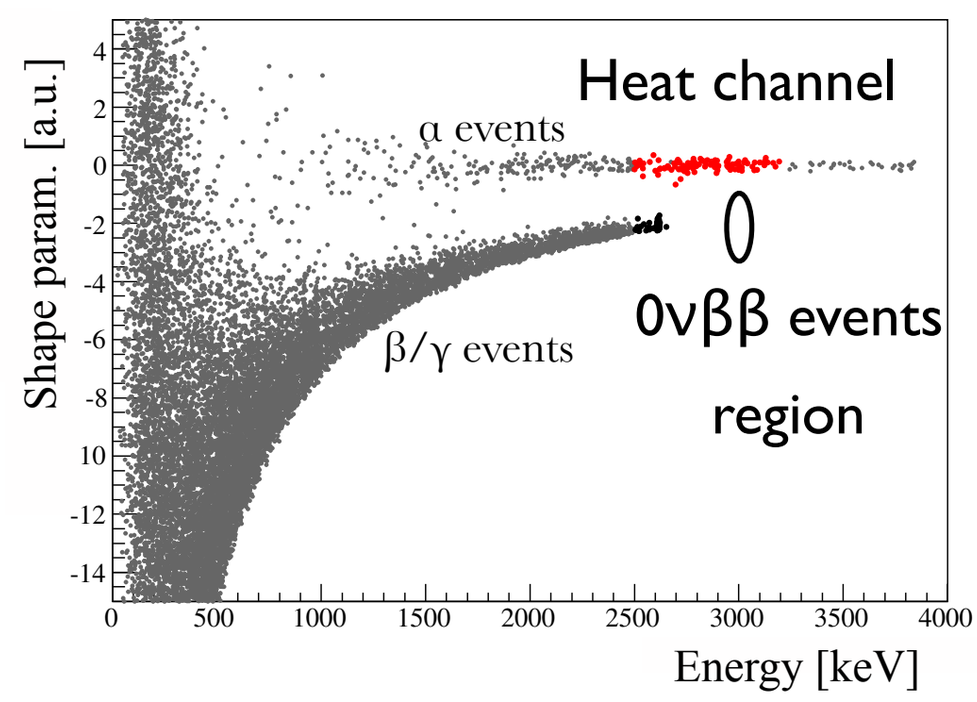

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LUCIFER sensitivity

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crystal	live time [y]	90% CI $T_{1/2}^{0\nu}$ [y]	$\langle m_{\beta\beta} \rangle$ [meV]
ZnSe	5	0.6×10^{26}	65-194
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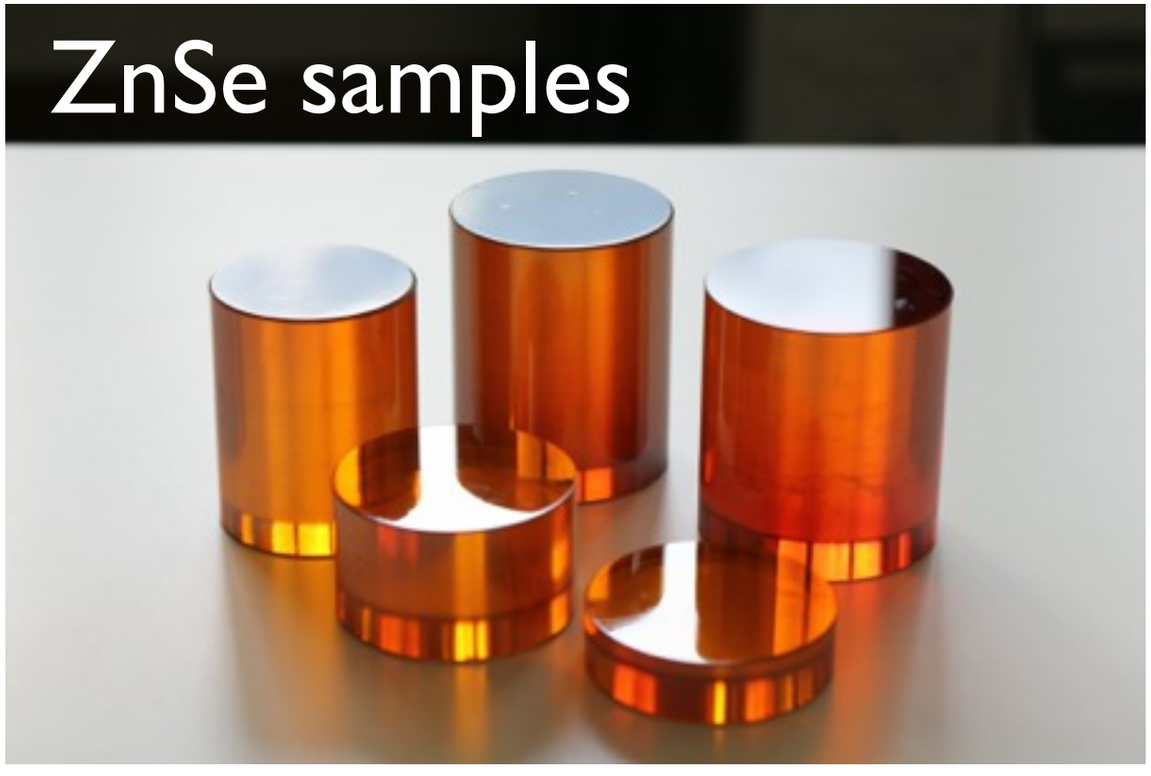

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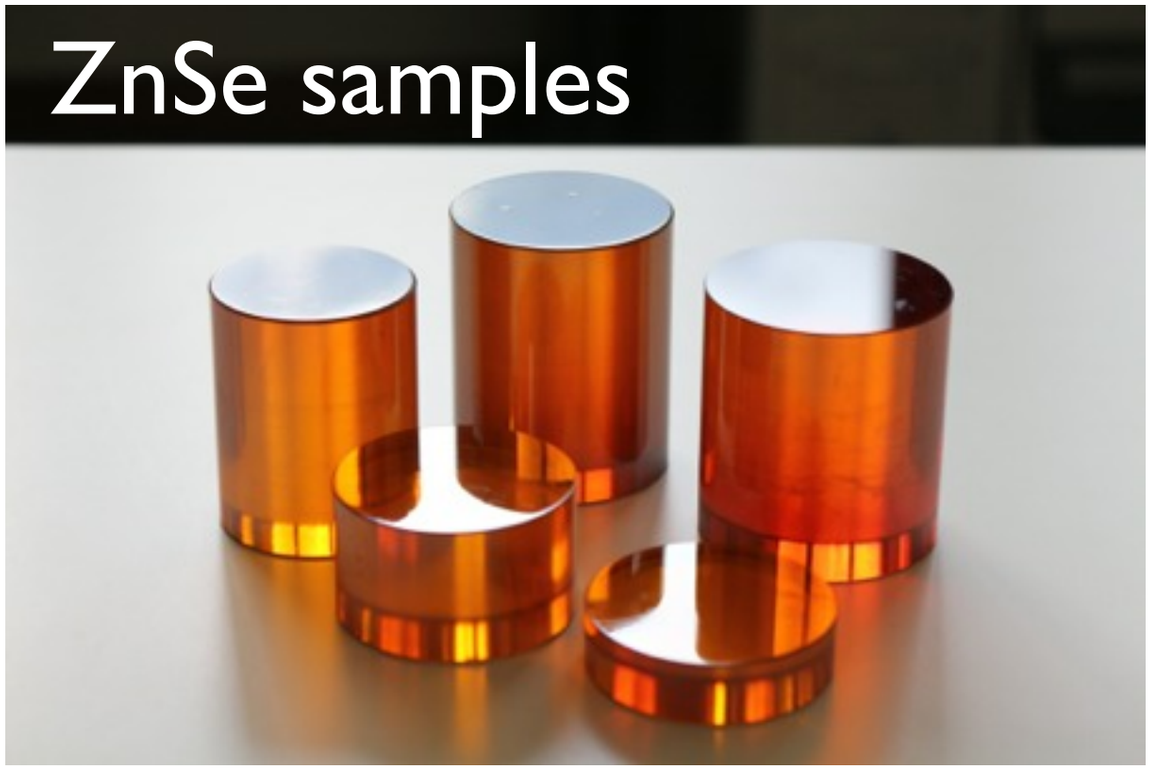

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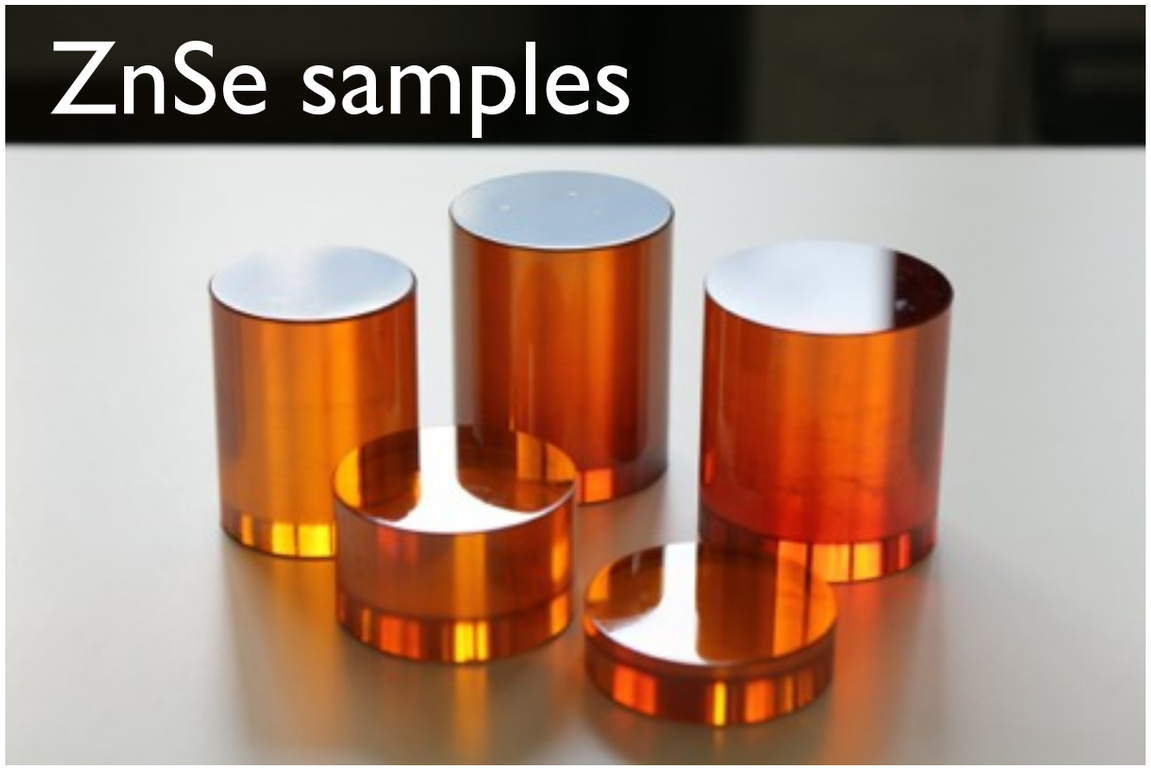

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$T^{0\nu}_{1/2}$ and $\langle m_{\beta\beta} \rangle$ are related by:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z) \left| M^{0\nu} \right|^2 \left(\frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2$$

Phase Space Factor

Nuclear Matrix Element (highly model dependent)

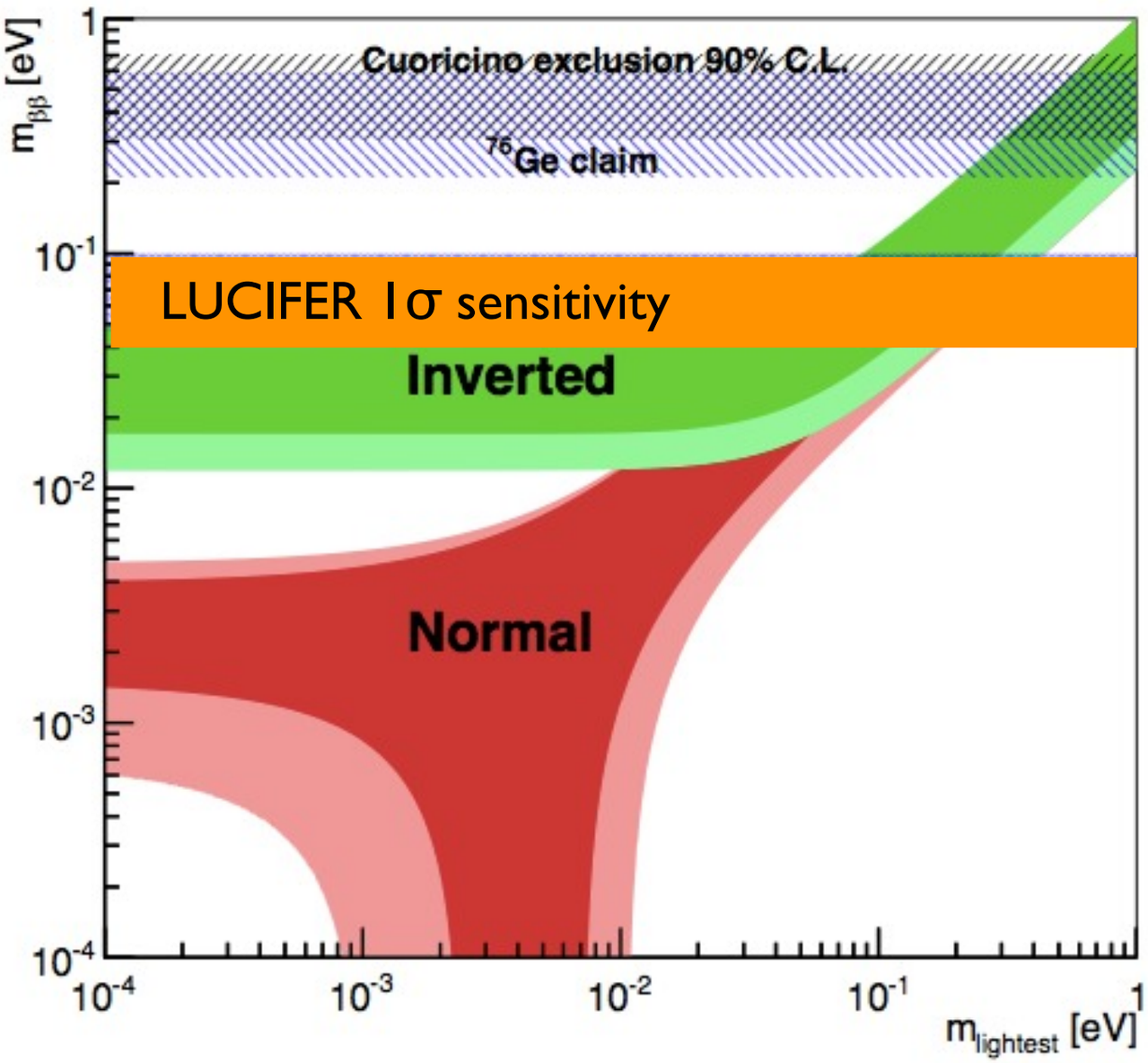
Conclusions

Conclusions

- Neutrinos still pose open questions: nature, mass hierarchy and absolute mass scale
- Neutrinoless Double Beta Decay ($0\nu\beta\beta$), if observed, will provide answer to many of this questions
- Bolometers have proved to be excellent detectors for $0\nu\beta\beta$ search
- It will possible to achieve the goal of a background free detector discriminating α and β/γ events
- LUCIFER ($ZnSe/ZnMoO_4$ scintillating bolometers) is a next generation $0\nu\beta\beta$ experiment demonstrator and will provide a sensitivity $\sim 10^{26}$ y ($m_{\beta\beta} \sim 100$ meV)

BACKUP

Neutrino effective mass



Majorana Neutrino effective mass $m_{\beta\beta}$ is defined as:

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

and is related to $T_{1/2}^{0\nu}$ with:

$$m_{\beta\beta} = \frac{1}{\sqrt{T_{1/2}^{0\nu} G_{0\nu} \left| M_{0\nu} \right|^2}}$$

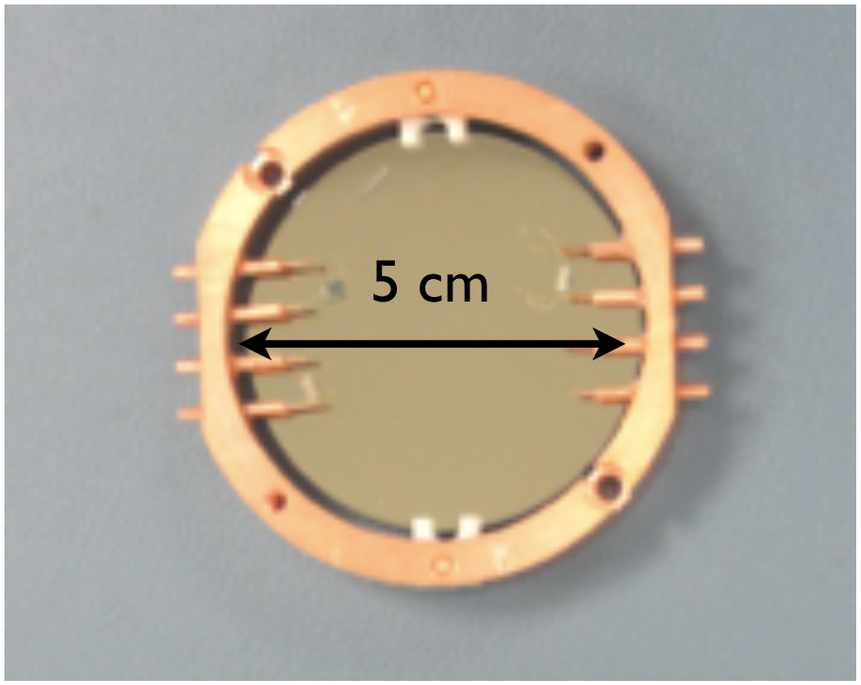
Phase Space Factor

Nuclear Matrix Element (highly model dependent)

Replacing $T_{1/2}^{0\nu}$ with experimental sensitivity you obtain the explorable $m_{\beta\beta}$ values

Light detectors

Germanium slabs operated as bolometers



typical dimensions:

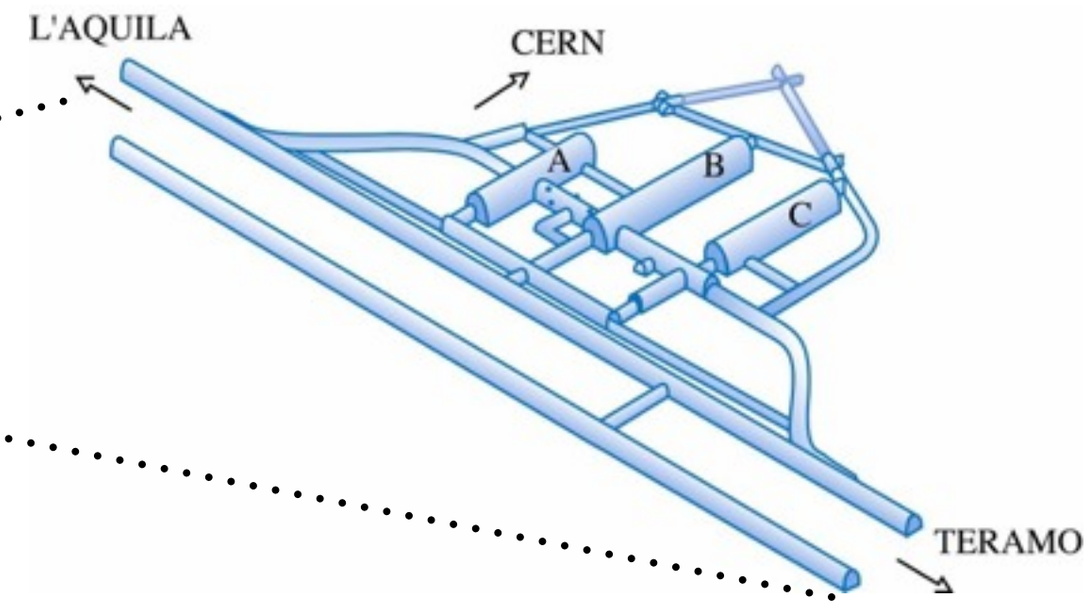
- diameter: 5 cm
- thickness: [0.2, 1] mm

Why bolometers as light detectors?

- sensitive to a wide range of light wavelength
- radio-pure
- high quantum efficiency (≈ photodiodes)
- good energy resolution (FWHM in [80, 250] eV)
- simple to operate at 10 mK

J.W. Beeman *et al.*, *JINST* **8** P07021 (2013)

Laboratori Nazionali del Gran Sasso



1400 m rock shielding = 3650 m water equivalent

muon flux: $(2.58 \pm 0.3) \times 10^{-8}$ μ/(s cm^2)

Mei and Hime, *Phys. Rev. D* **73** 053004 (2006)

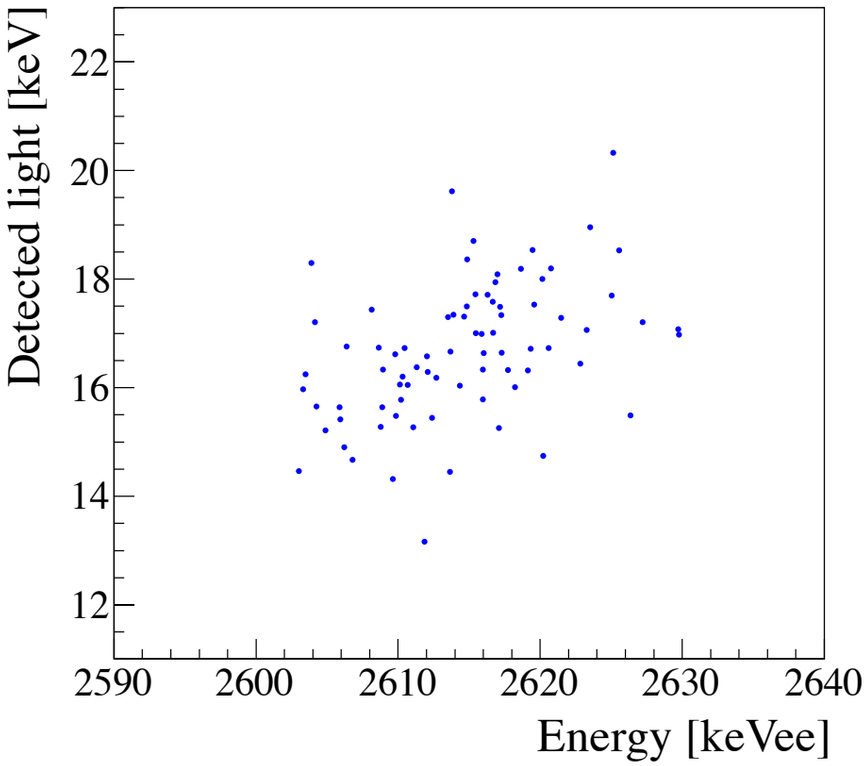
neutron flux [<10MeV] : ≈ 4×10^{-6} n/(s cm^2)

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)

ZnSe energy resolution



Using the heat/light correlation it is possible to improve the energy resolution

Peak	Heat FWHM [keV]	Heat + Light FWHM [keV]
1461 keV	13.4 ±1.0	12.2 ±1.8
2615 keV	16.3 ±1.5	13.4 ±1.3
^{82}Se $Q_{\beta\beta}$	19.4	16.5

Goal: 10 keV FWHM at $Q_{\beta\beta}$

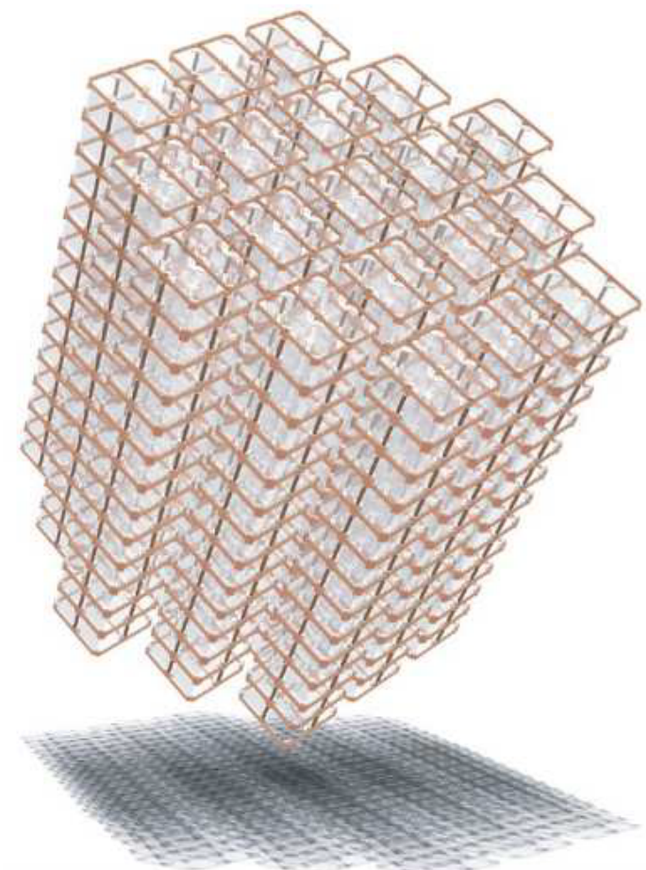
CUORE and CUORE-0

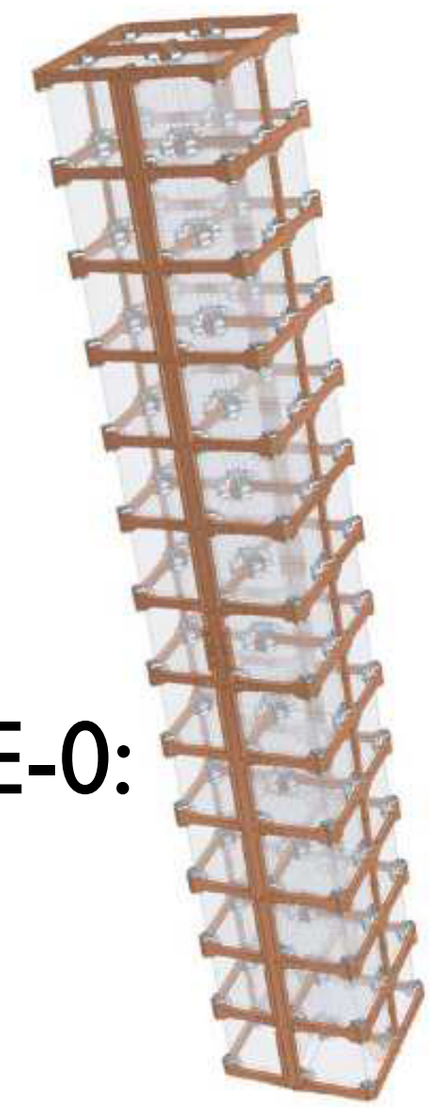
TeO_2 crystals to study ^{130}Te $0\nu\beta\beta$ ($Q_{\beta\beta}$ = 2527 keV)

CUORE:

- 19 towers
- 13 floors per tower
- 4 5×5×5 cm^3 crystals per floor
- 206 kg of ^{130}Te
- under construction

Both hosted at Laboratori Nazionali del Gran Sasso (3650 m.w. e.). CUORE will start data taking in 2015.





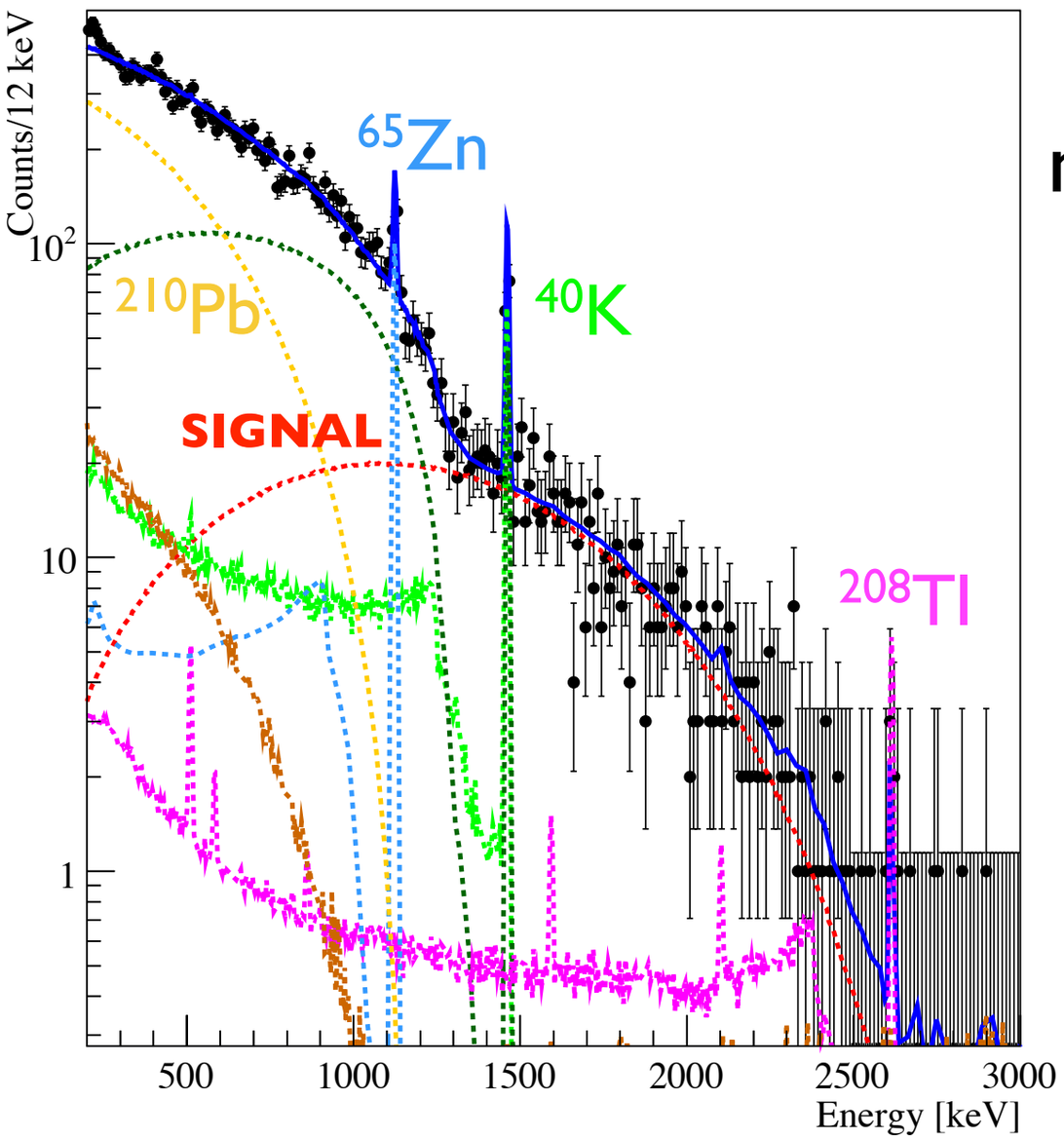
tower prototype, CUORE-0:

- 52 crystals
- 10.84 kg of ^{130}Te
- is taking data

$2\nu\beta\beta$ of ^{100}Mo

Most precise measurement by NEMO:

$T_{1/2} = [7.11 \pm 0.02^{stat} \pm 0.54^{syst}] \times 10^{18}$ y



We operated the 1st bolometric measurement of ^{100}Mo $2\nu\beta\beta$ (2×10^{23} nuclei of ^{100}Mo) with $ZnMoO_4$ crystals:

$T_{1/2} = [7.15 \pm 0.37^{stat} \pm 0.66^{syst}] \times 10^{18}$ y

	Exposure [kg · y]	Statistical Error
NEMO	7.5	~ 0.3%
This measurement	3.5×10^{-3}	~ 5%

This proves that bolometers are very good detectors to search for rare events

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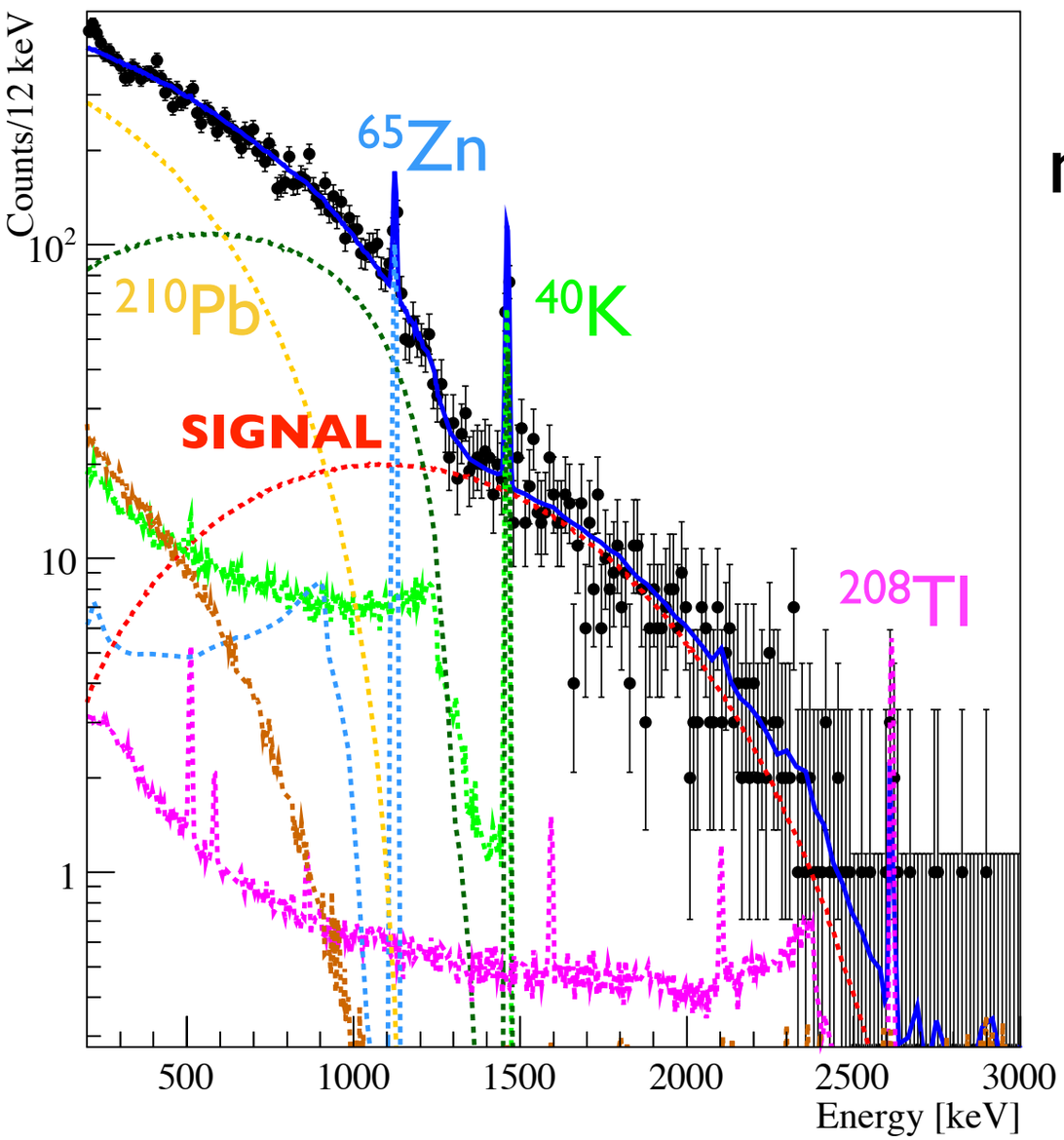

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L. Cardani *et al.*, *J. Phys. G* **12/2013** 41 (2013)