Exploring new fitting strategies for the CUORE experiment

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CUORE

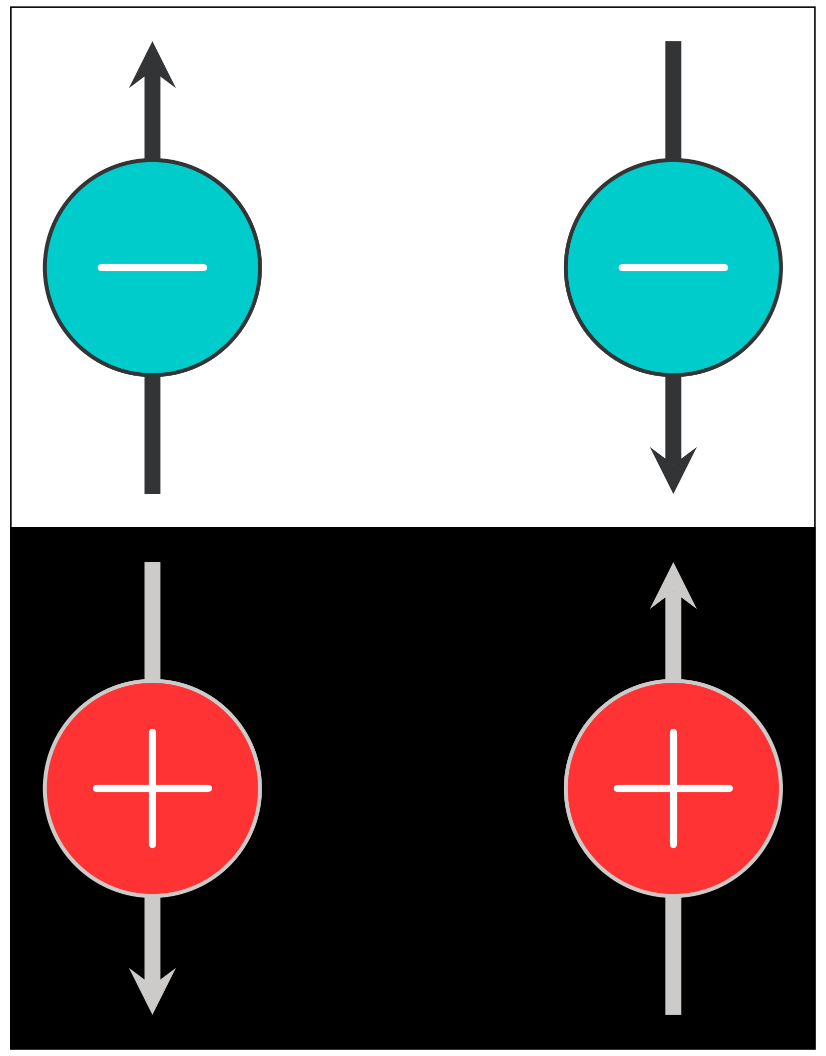
Neutrino

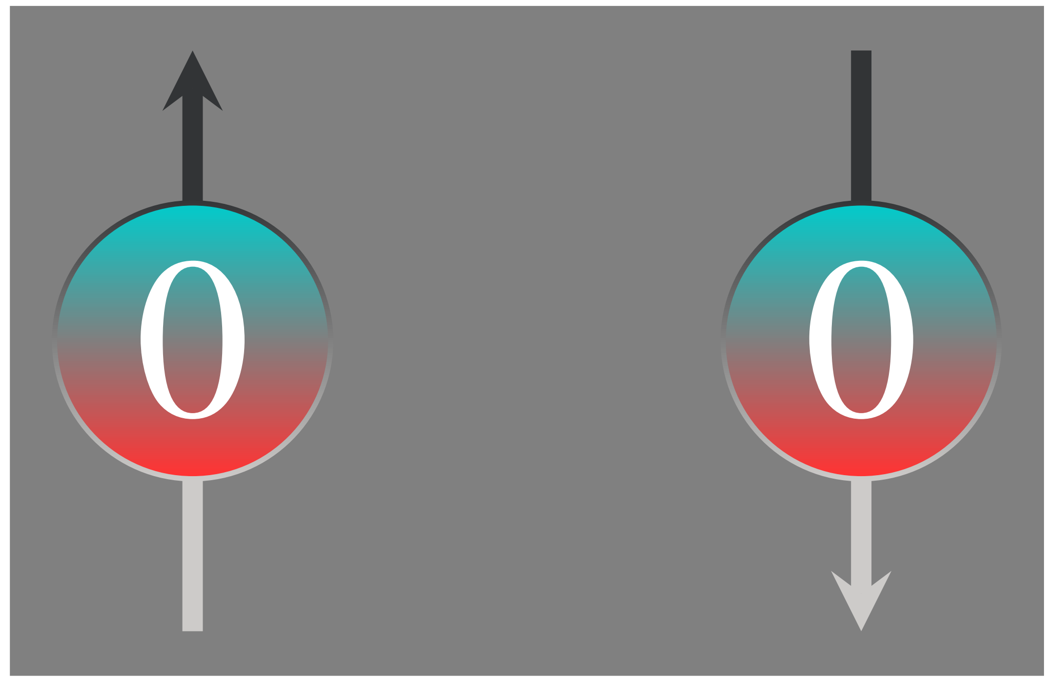
The neutrino is the most elusive particle of the Standard Model.

- It is neutral,
- It interacts only through the weak interaction,
- It has three flavours: e,μ,τ,
- In the ultrarelativistic limit, it has negative helicity

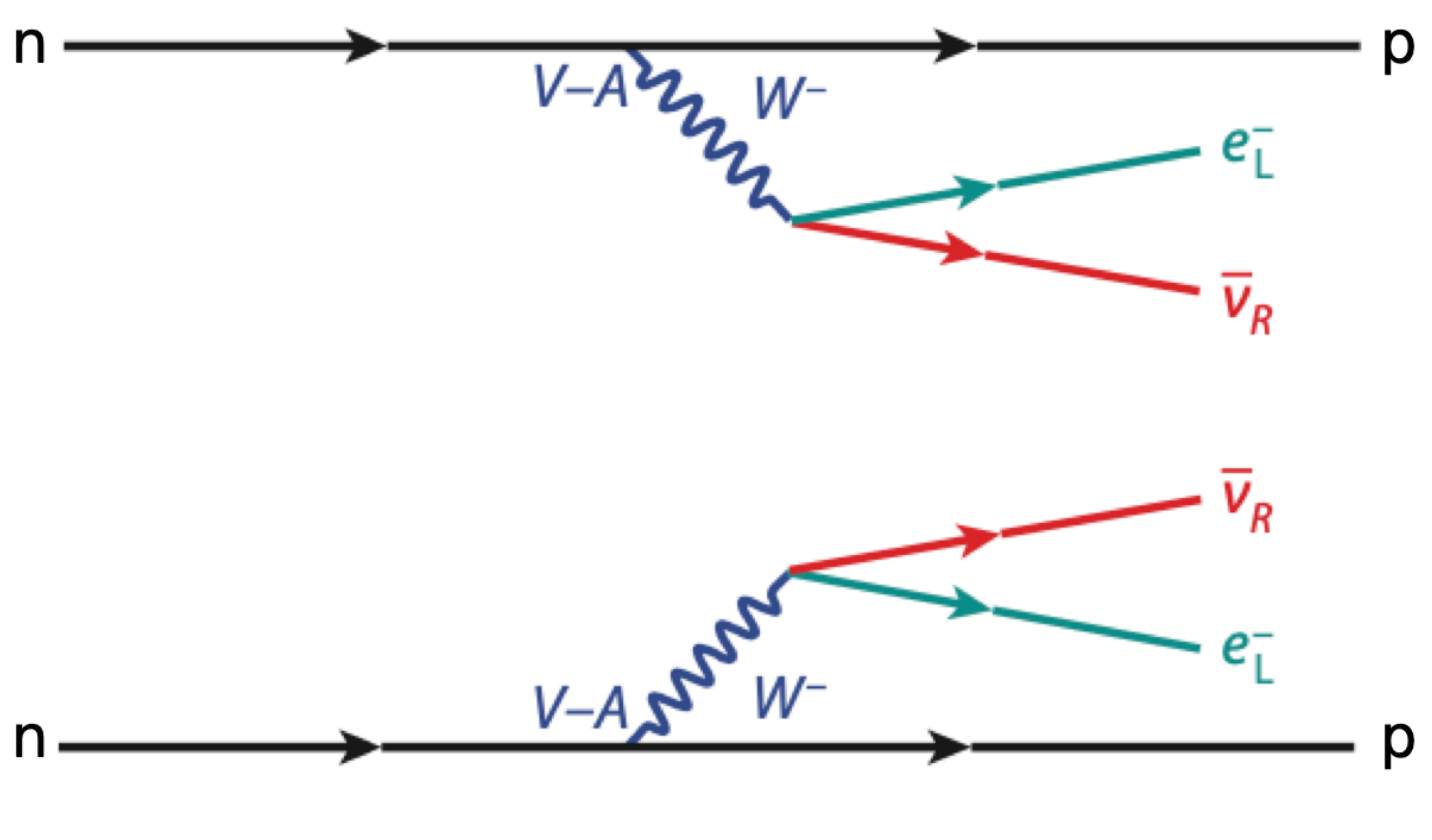
Two hypothesis on its nature can be made:

- Dirac neutrino
- Majorana neutrino: particle and antiparticle are identical



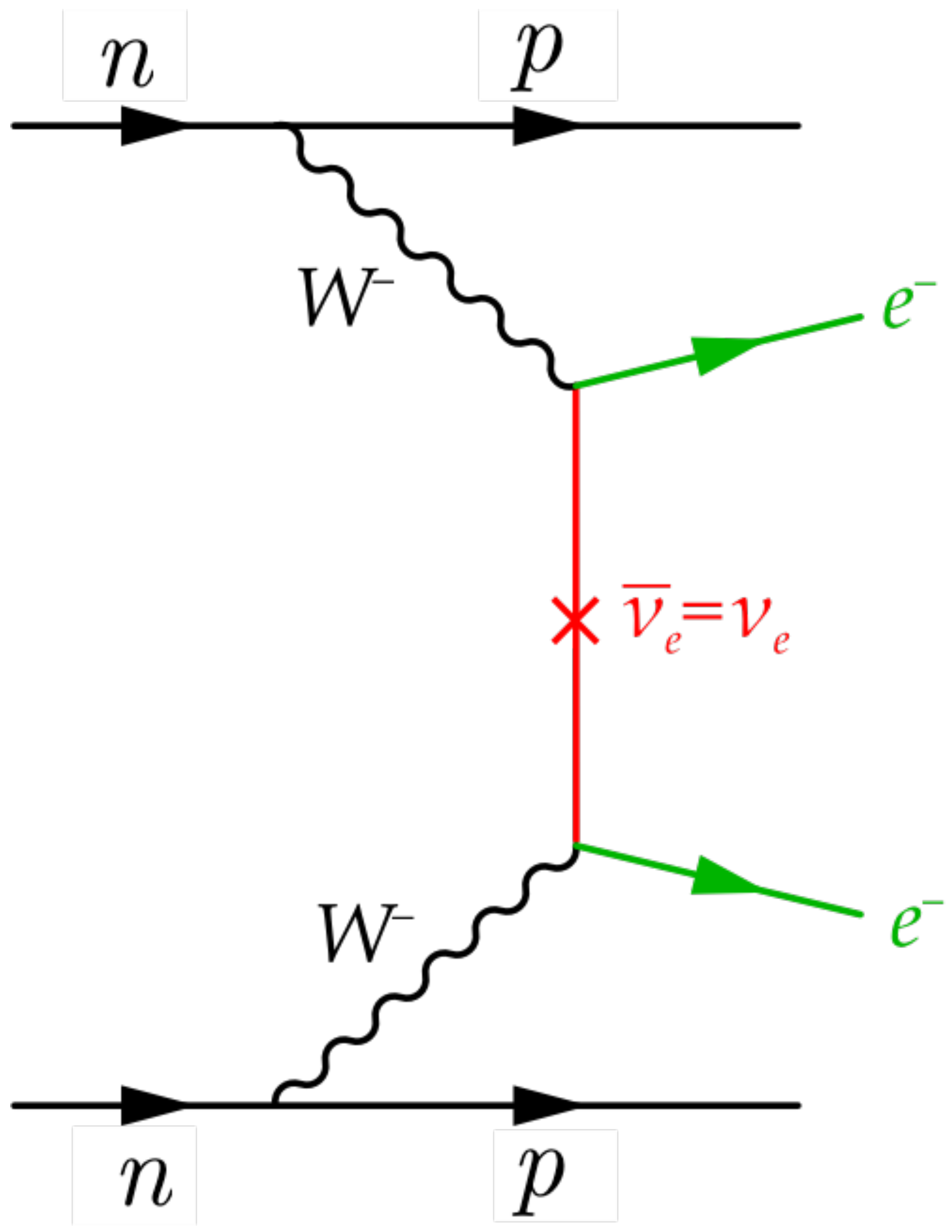


Double beta decay



$$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$$

Double beta decay has already been observed with lifetimes of $10^{19\text{-}21}$ years.

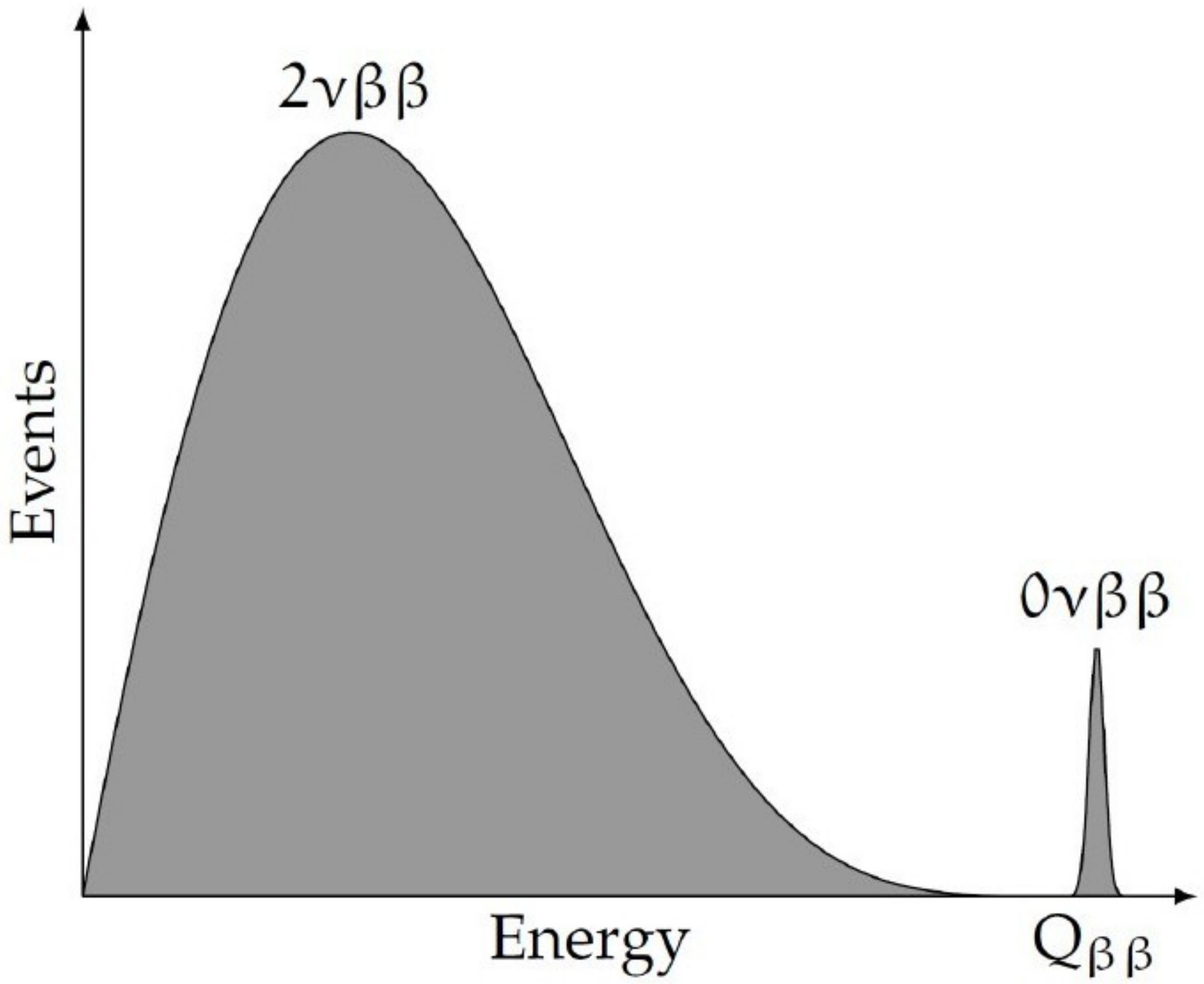


Neutrinoless double beta decay ($0\nu\beta\beta$) can happen if the neutrino:

- Is a Majorana fermion
- Has a non-zero mass.

How to observe $0\nu\beta\beta$ decay

CUORE



The experimental signature of double beta decay is a peak at the Q-value of the decay:

$$Q = M_i - M_f - 2m_e = T_{e1} + T_{e2}$$

To maximize the sensitivity, the experiment must satisfy the following requirements:

- High Q-value to prevent γ background
- High number of emitting nuclei
- Good energy resolution

The CUORE experiment

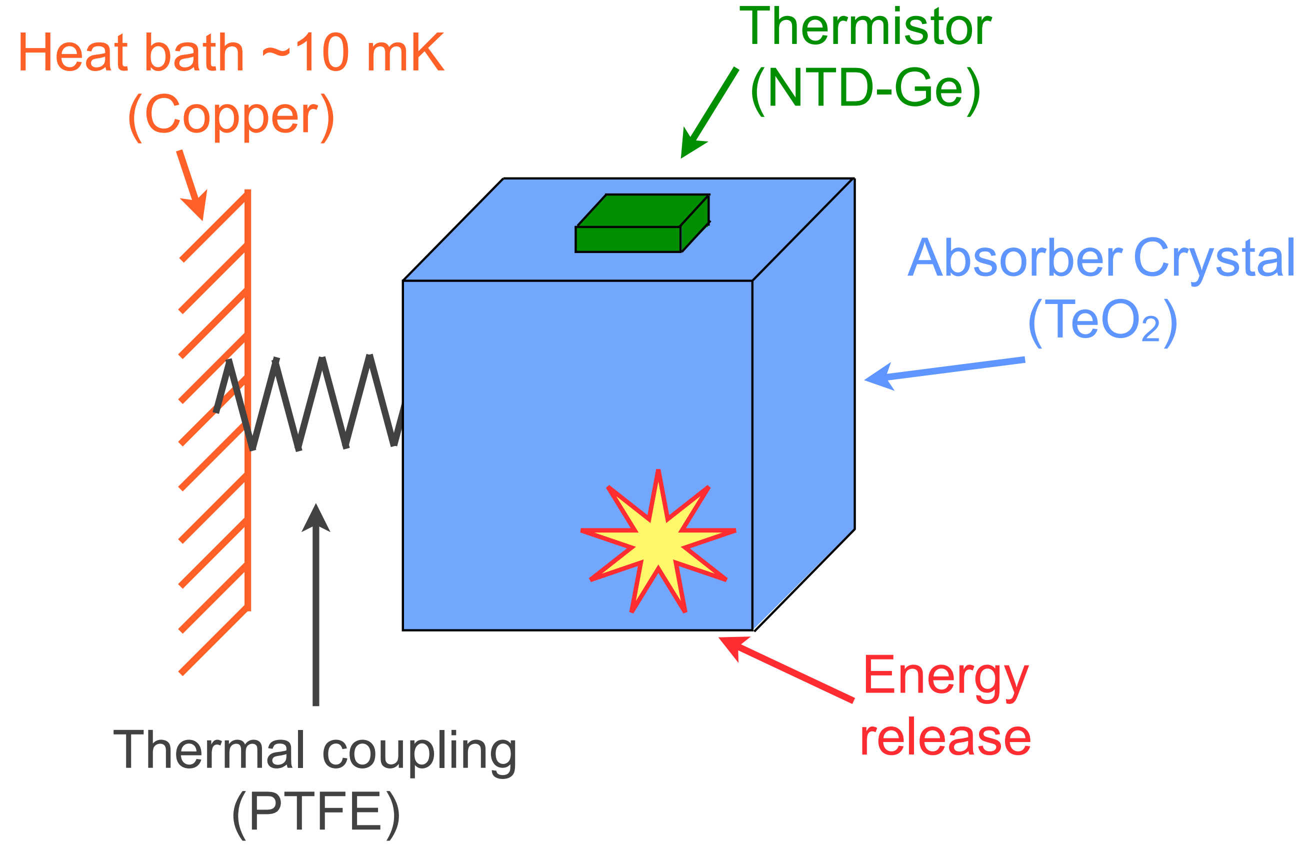
CUORE (Cryogenic Underground Observatory of Rare Events) is located at LNGS.

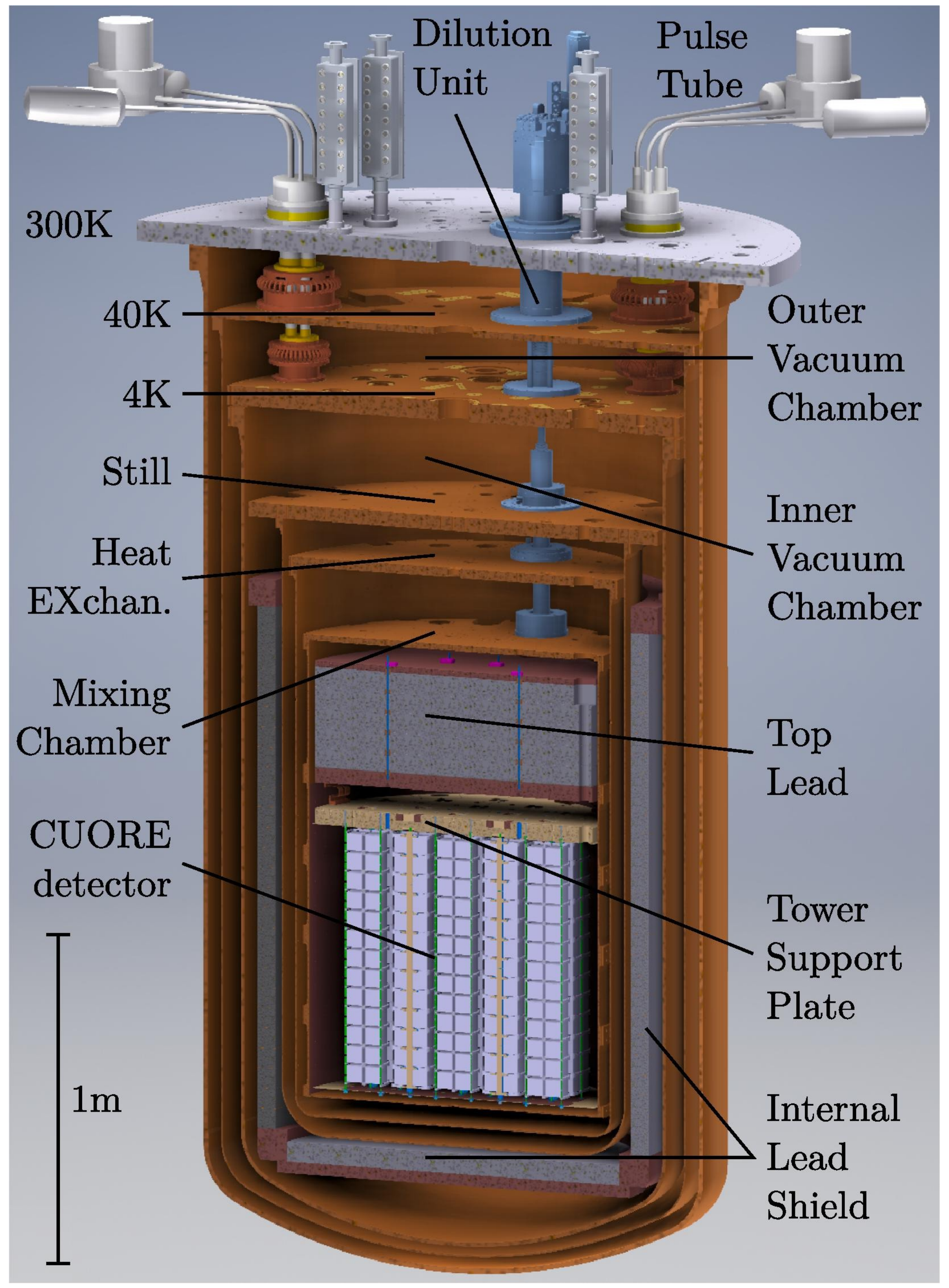
The aim is the observation of neutrinoless double beta decay in the ^{130}Te contained in TeO_2 crystals with cryogenic calorimeters (bolometers).

The energy release is converted in phonons:

$$\Delta T = \frac{E}{C} \sim 100\,\mu\mathrm{K/MeV} \text{ at } T \simeq 10\,\mathrm{mK}$$

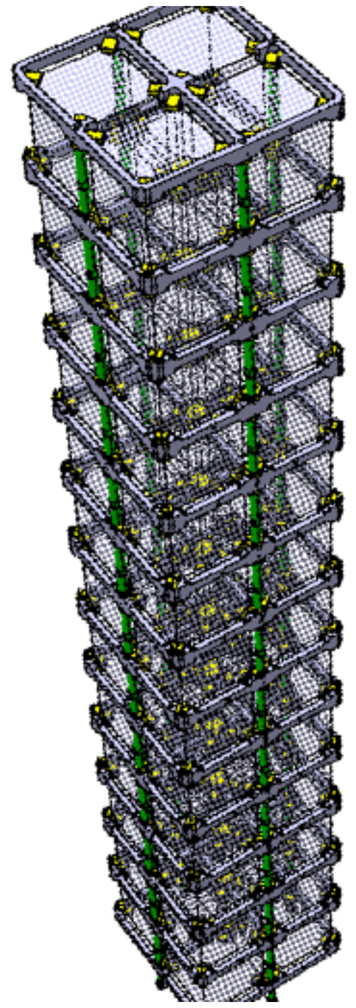
The temperature variation is observed with thermistors.

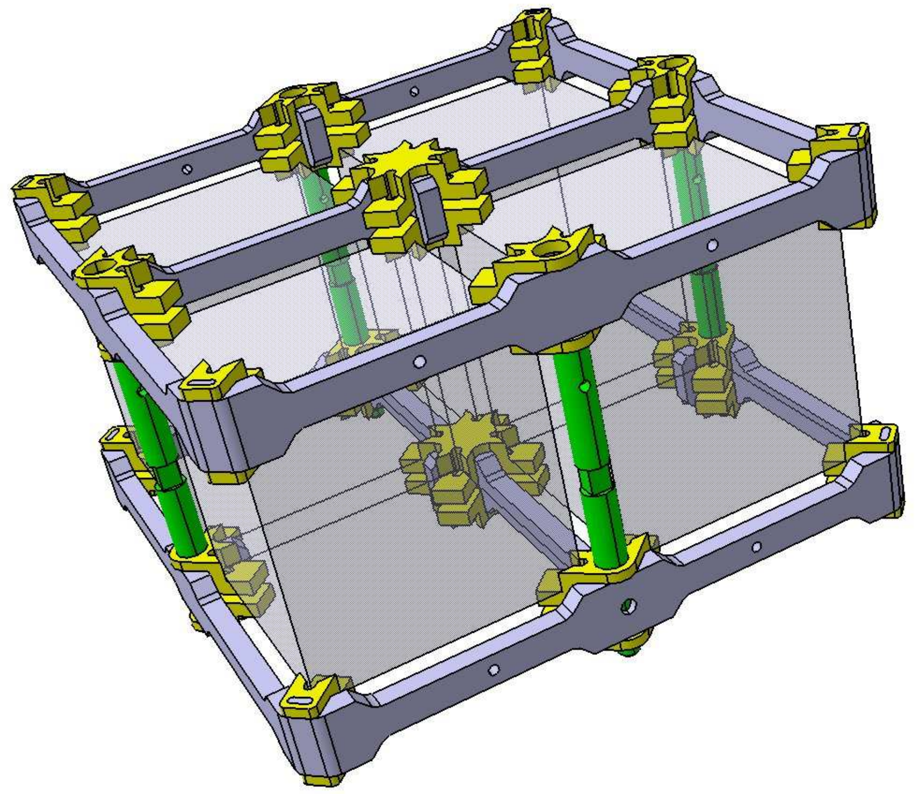


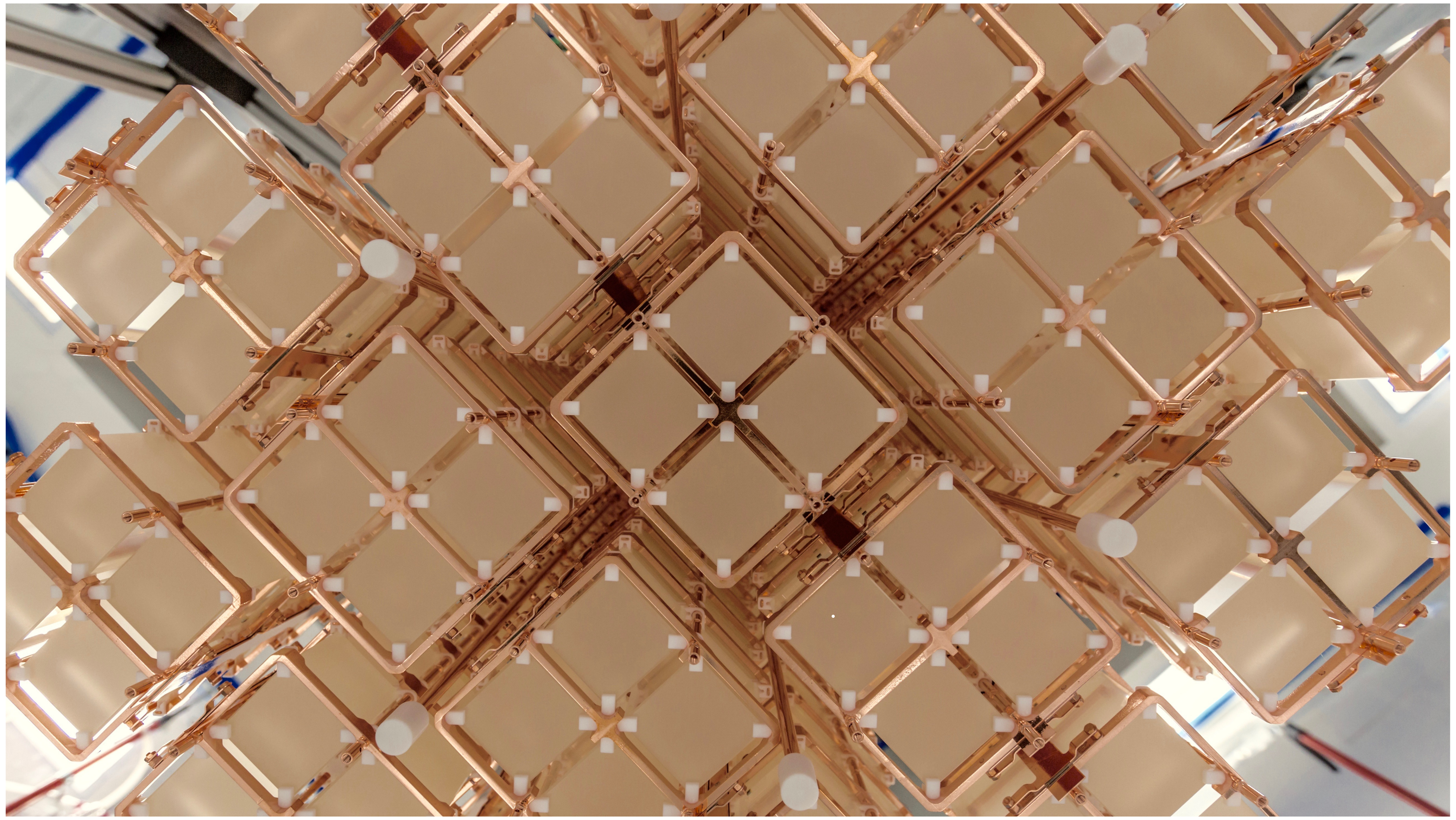


The CUORE experiment

CUORE is a modular detector, made of 988 crystals divided in 19 towers. Each tower is made of 13 floors, containing 4 crystals each.





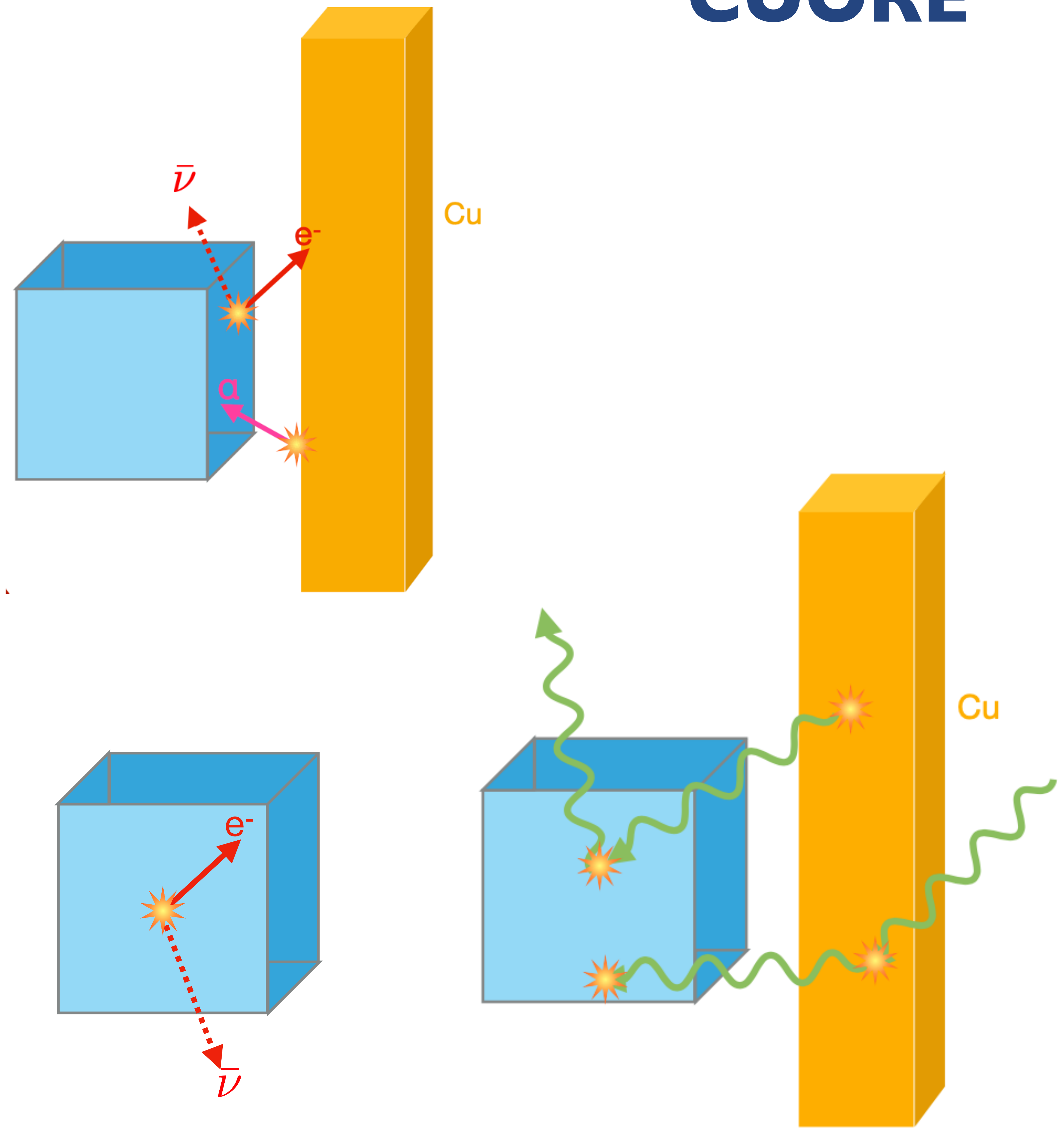


Composition of the background

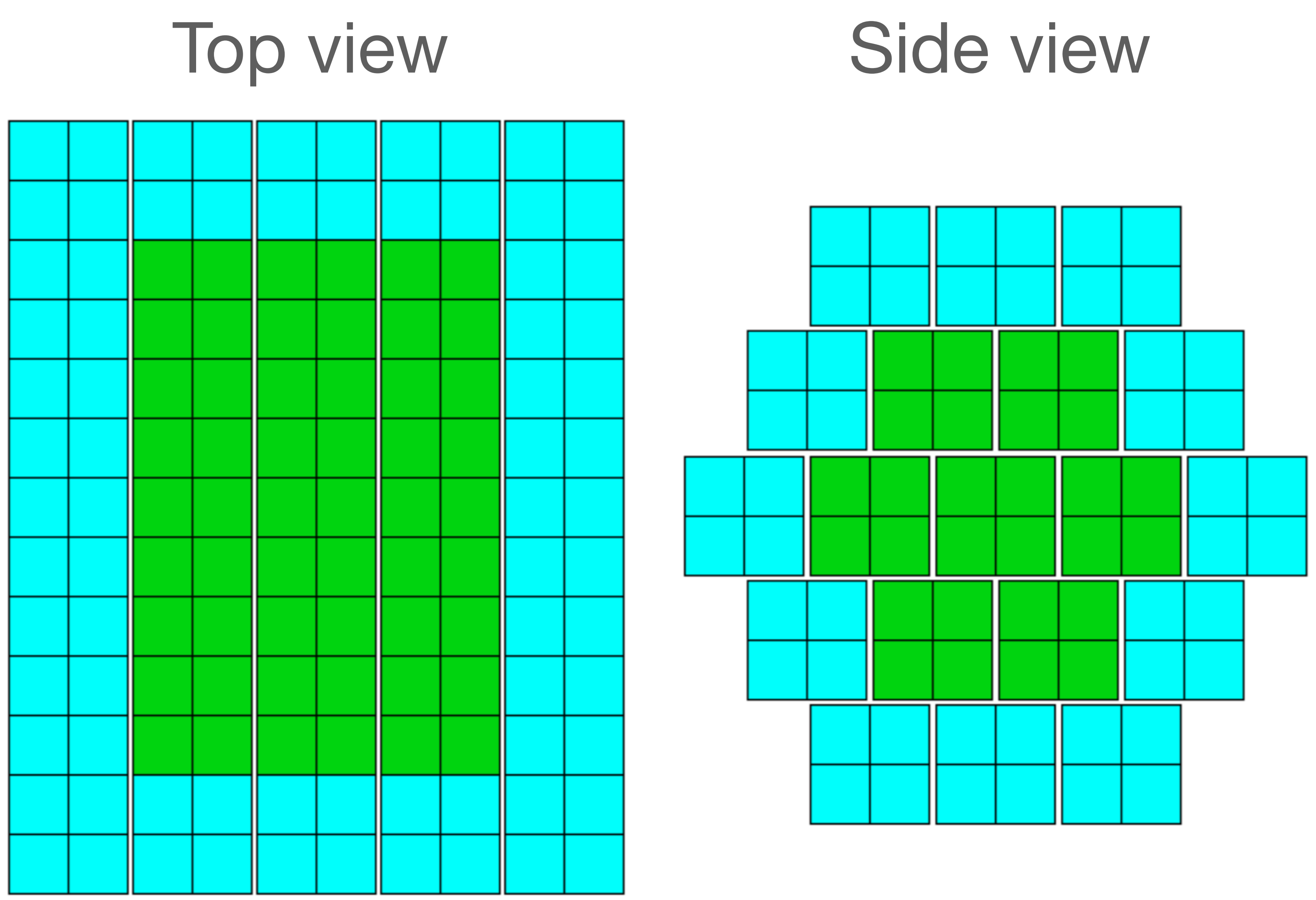
The background is divided in two components:

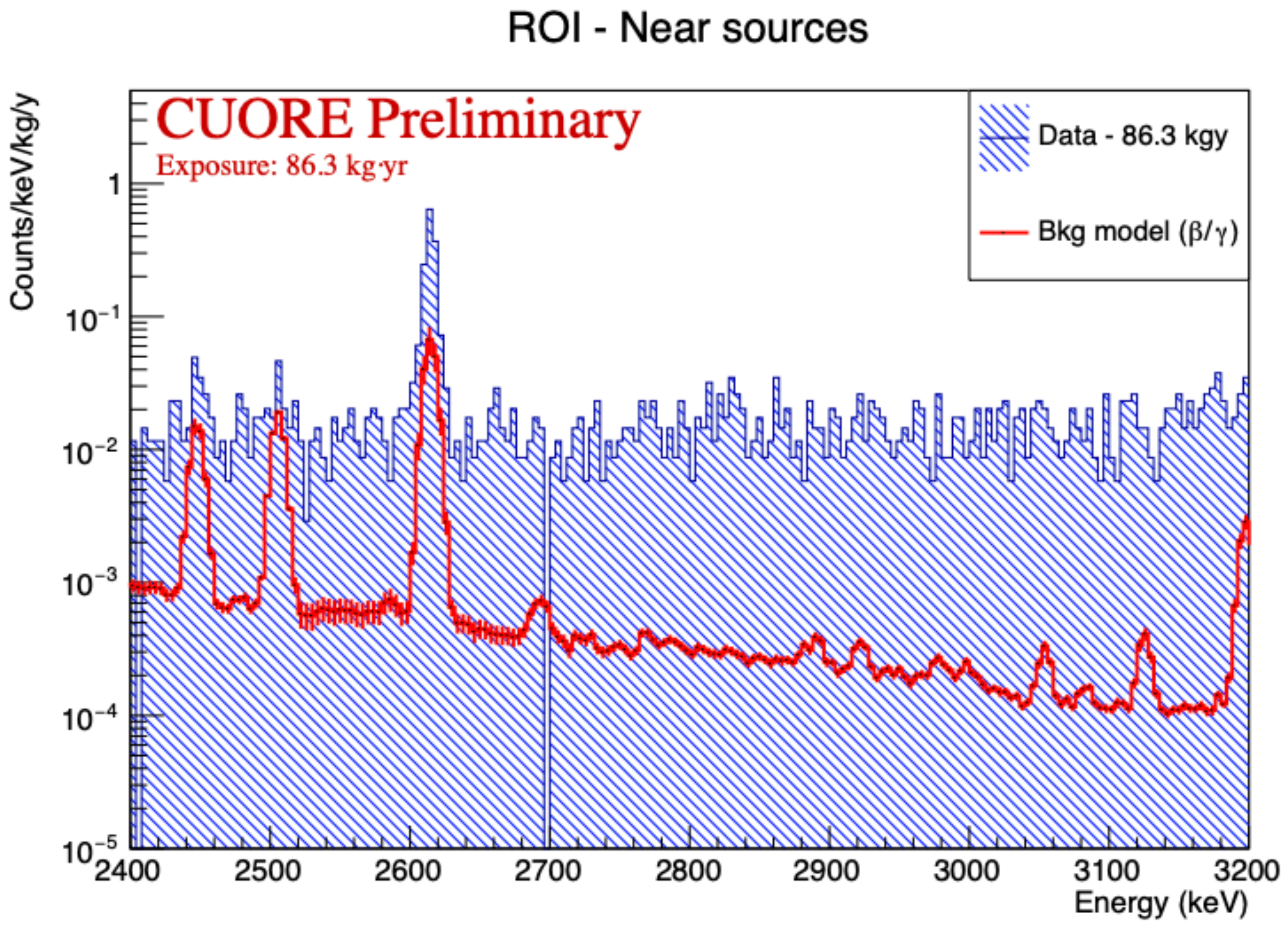
- α background: because of their short range (microns), they are important only in the bulk contamination of crystals.
- β/γ background: they contribute also through external sources because of their longer range.

Thanks to data collected with 1 t yr exposure, it is now possible to describe the geometric distribution of the background.



Background geometric distribution





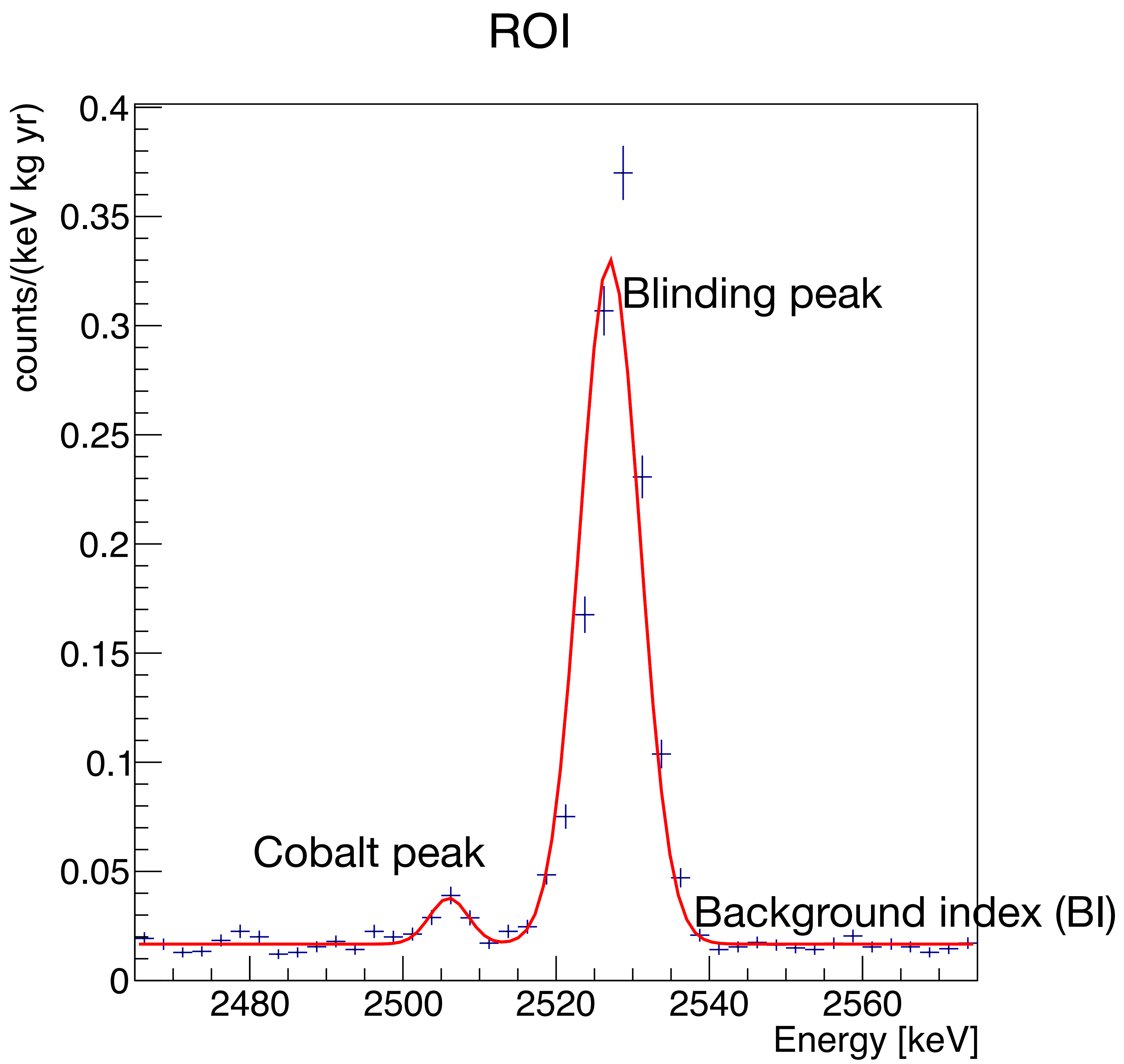
Differences in background distribution can be exploited, due to shielding effects.

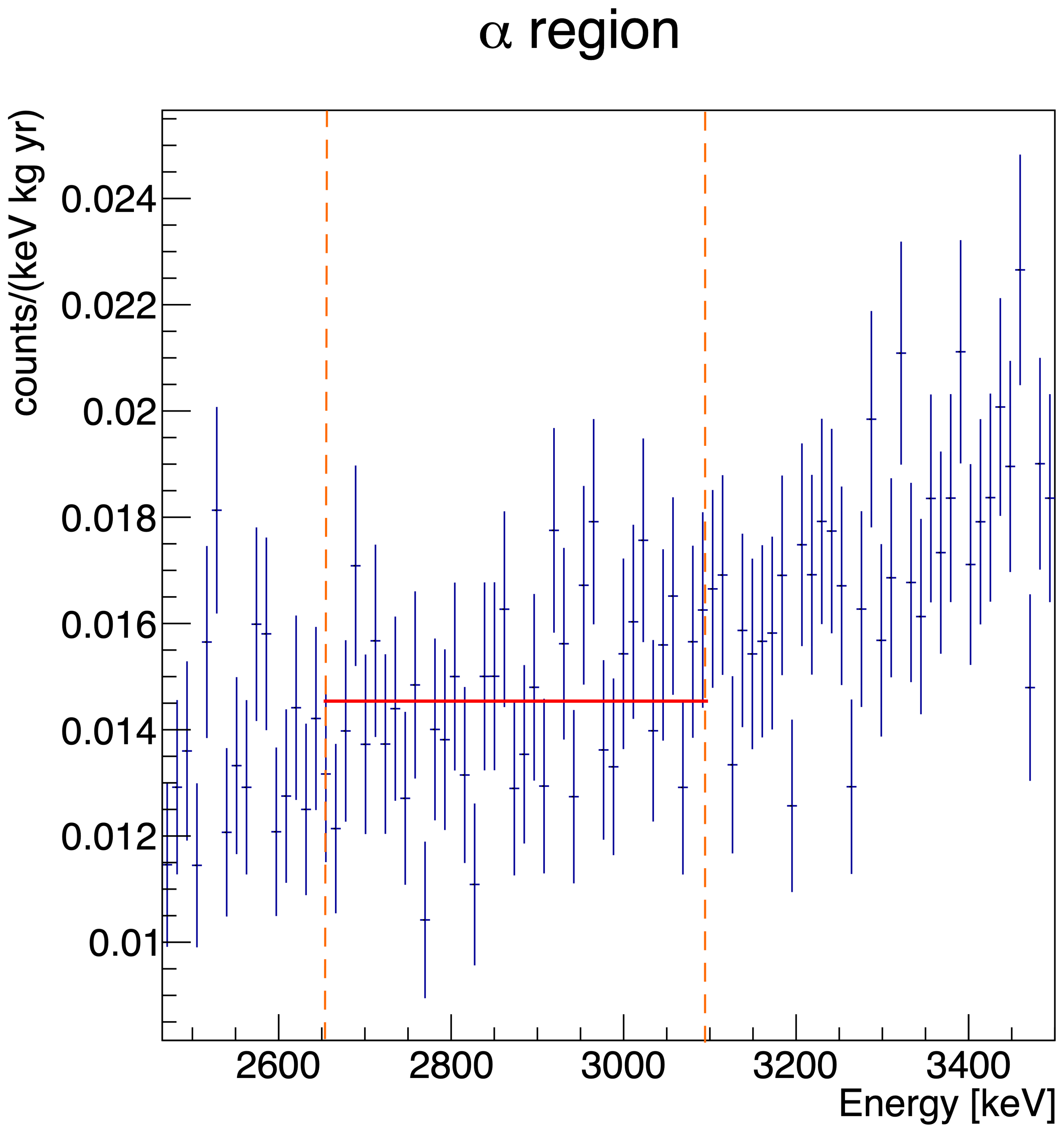
The background should be higher in outer crystals.

β/γ particles are absorbed by outer crystals, but they are only 10% of the background (in red in the picture).

The first step is to study the background distribution.

Background energy distribution

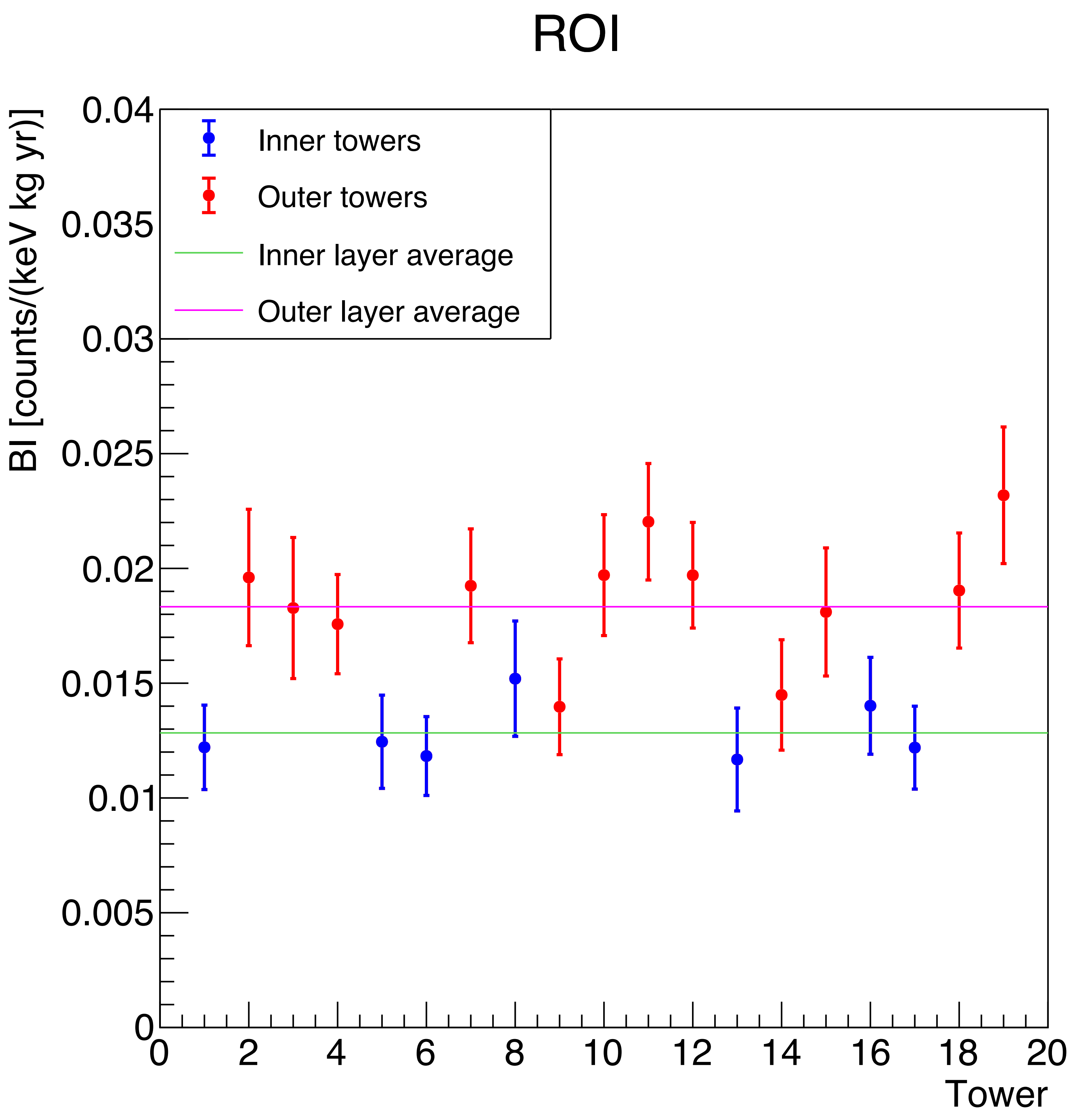


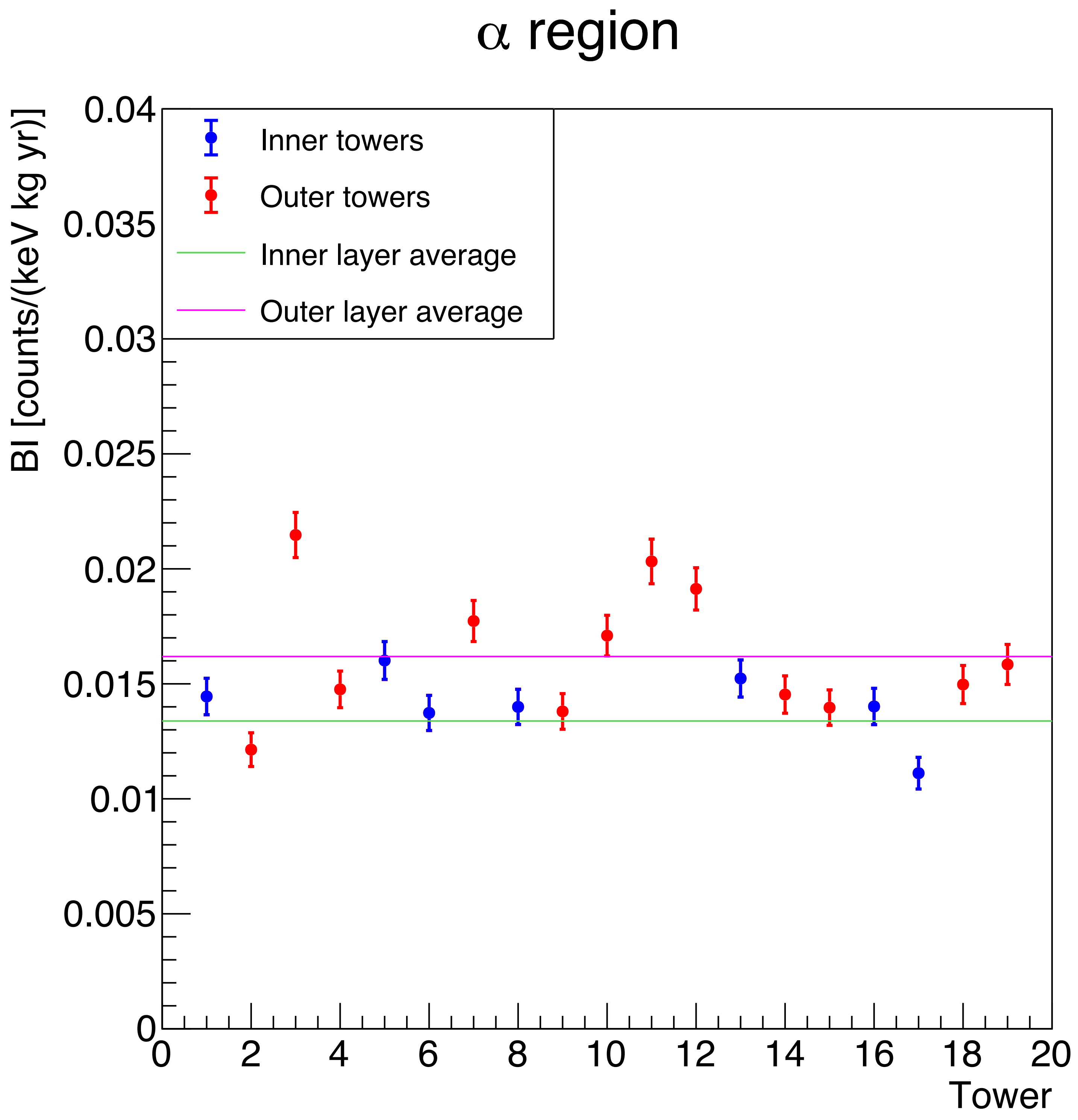


The blinding peak is necessary to avoid bias in the analysis in the ROI.

In the α region the γ background is absent, because it ends at 2615 keV with the thallium line.

Background distribution: towers



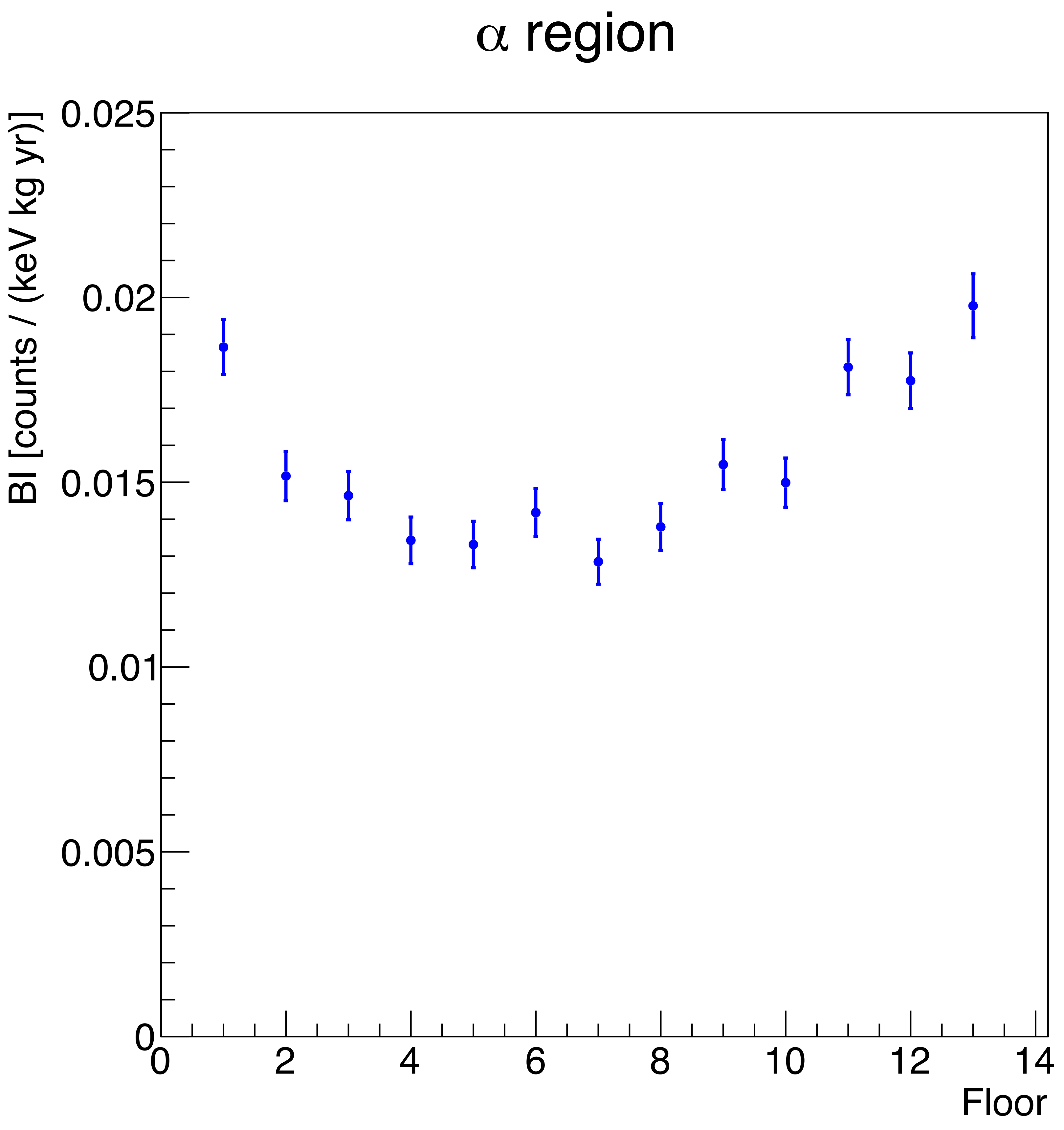


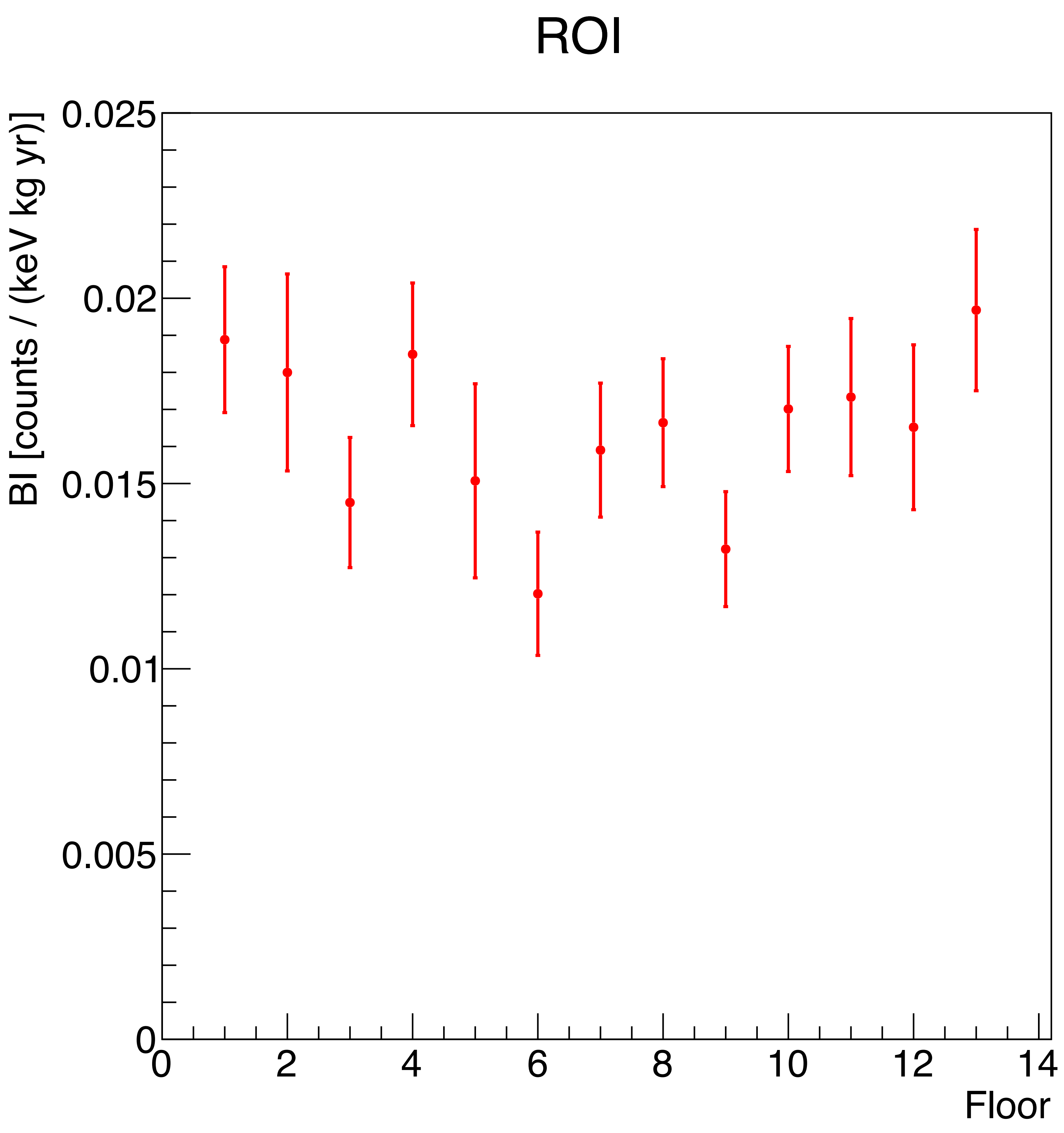
	Exposure	BI (10^{-2} events/(keV kg yr))
Inner layer	26%	1.34
Outer layer	74%	1.62

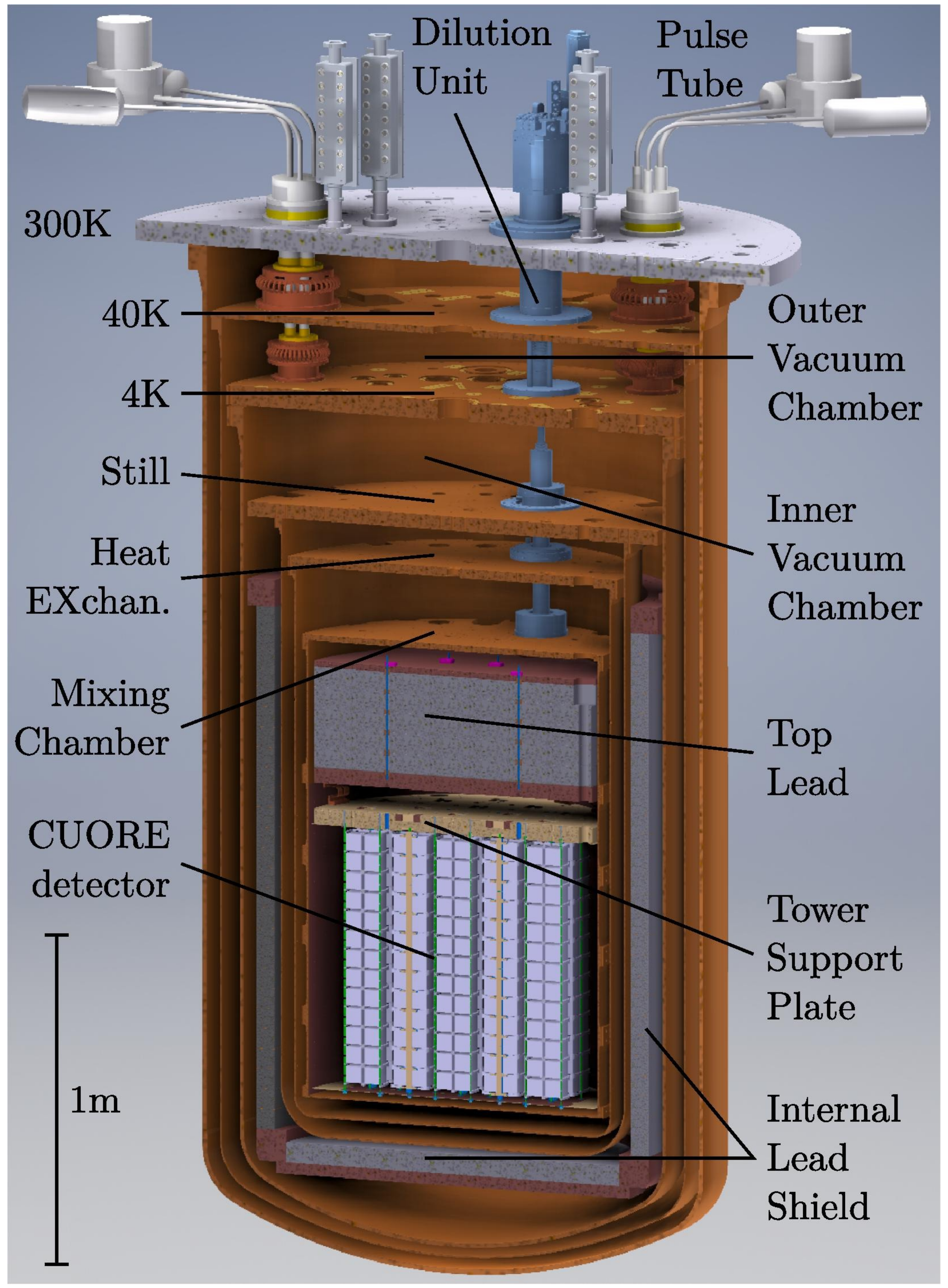
- The background is lower for the inner towers
- The background in the inner layer is 1.5 times lower than the outer layer

Background distribution: floors

- The background in the intermediate floors is lower
- The floor at the top is the most affected by particles coming from the support structure







How to improve the sensitivity?

The CUORE fit is made with bayesian inference. Instead of using an average background for the full detector, the detector can be divided in two parts and the number of signal events may be used as a shared parameter.

Two approaches are possible:

- Obtaining an analytic formula
- Toy-MC experiments with Bayesian inference

First of all, a simplified formula can be obtained.

The sensitivity is proportional to

$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M\,t}{\mathrm{BI}}} \qquad \mathrm{BI} = \frac{N_b}{M t\,\mathrm{ROI}}$$

- I define two variables:

$$\xi = \frac{(Mt)_{\mathrm{low}}}{Mt} \qquad f = \frac{\mathrm{BI}_{\mathrm{low}}}{\mathrm{BI}}$$

- Recombining the $S/\sqrt{B}$ ratios of the two parts in the gaussian approximation, the gain is

$$G(\xi, f) = \sqrt{\frac{\xi}{f} + \frac{(1-\xi)^2}{1-\xi f}}$$

Toy-MC experiments

CUORE

- I generated the histogram in the ROI with flat background
- I fitted with the hypothesis of signal + background
- I found the limit on the signal events
- I computed the half-life of the decay

From N experiments the median half-life sensitivity is determined.

This procedure is replicated in the case of combined fit, with the number of signal events as a shared parameter.

$$f_1(E,\vec{\theta}) = \xi\ [b_1 + N_{\beta\beta}\,\mathcal{G}(E, Q_{\beta\beta}, \mathrm{FWHM})]$$

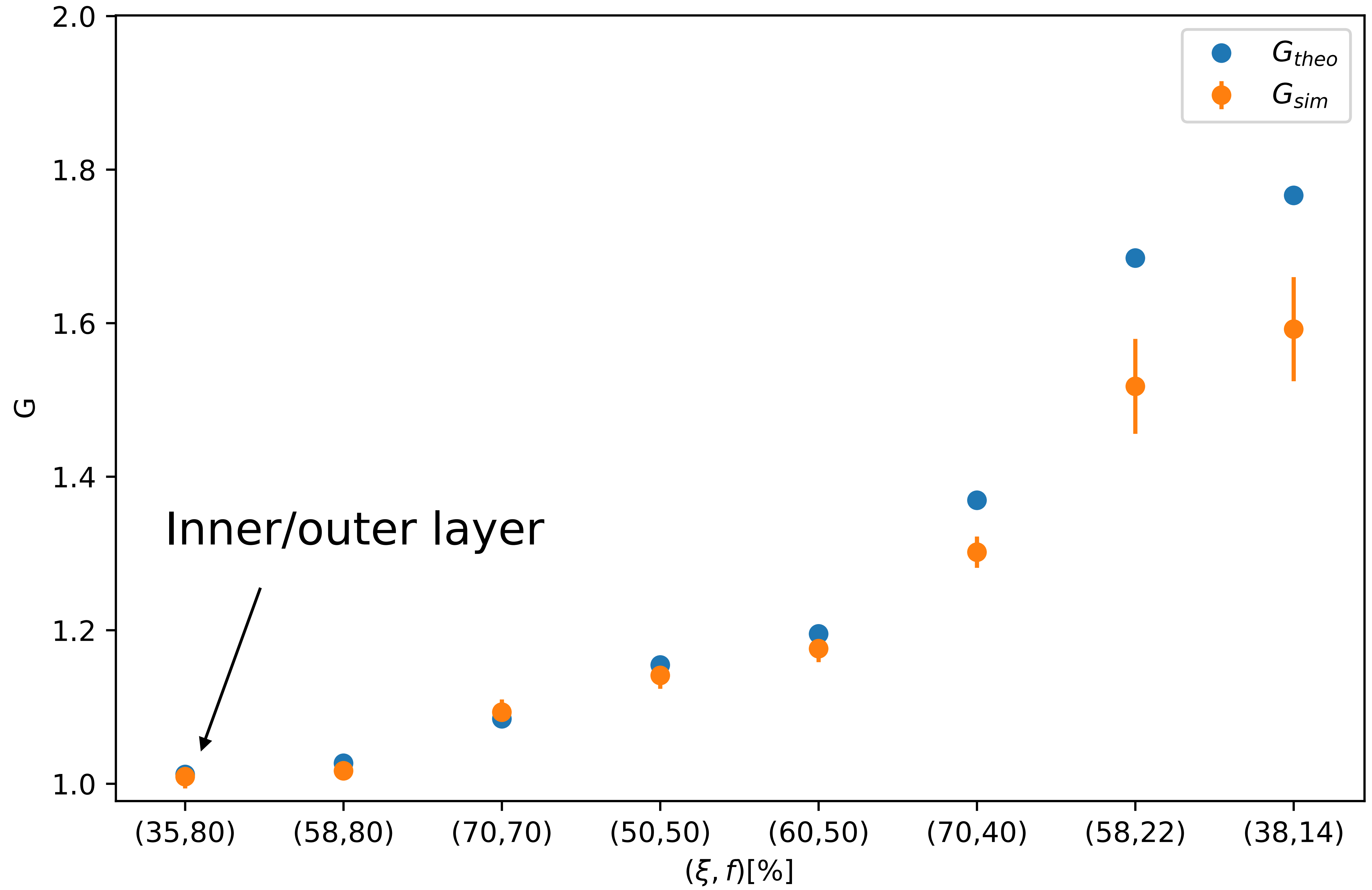
$$f_2(E,\vec{\theta}) = (1-\xi)\ [b_2 + N_{\beta\beta}\,\mathcal{G}(E, Q_{\beta\beta}, \mathrm{FWHM})]$$

The likelihood is poissonian for each bin:

$$\mathcal{L}(\vec{\theta}) = \mathcal{L}_1(\vec{\theta})\mathcal{L}_2(\vec{\theta}) =$$

$$= \prod_i \mathrm{Pois}(n_i|f_1(E_i,\vec{\theta})) \cdot \prod_j \mathrm{Pois}(n_j|f_2(E_j,\vec{\theta}))$$

Toy-MC experiments



- The formula is accurate in the region with low gain: the gaussian approximation is valid
- The gain is so low (2%) for two reasons:
  - Low exposure of the inner layer
  - Dominance of the α background and of bulk contamination with respect to external sources

Conclusions

- I reached two goals:
  - The background has been analysed with the highest granularity to date
  - These results may be useful to better constrain the surface α contamination in the background model
- CUORE will take data until an exposure of 3 t yr will be reached
- Thanks to the higher exposure, this analysis can be improved thanks to the possibility of achieving higher granularity.

Backup slides

Neutrino oscillations and PMNS matrix

CUORE

- For mass eigenstates,

$$i\frac{\partial}{\partial t}\left|\nu_i\right\rangle = E_i\left|\nu_i\right\rangle$$

- In flavour space,

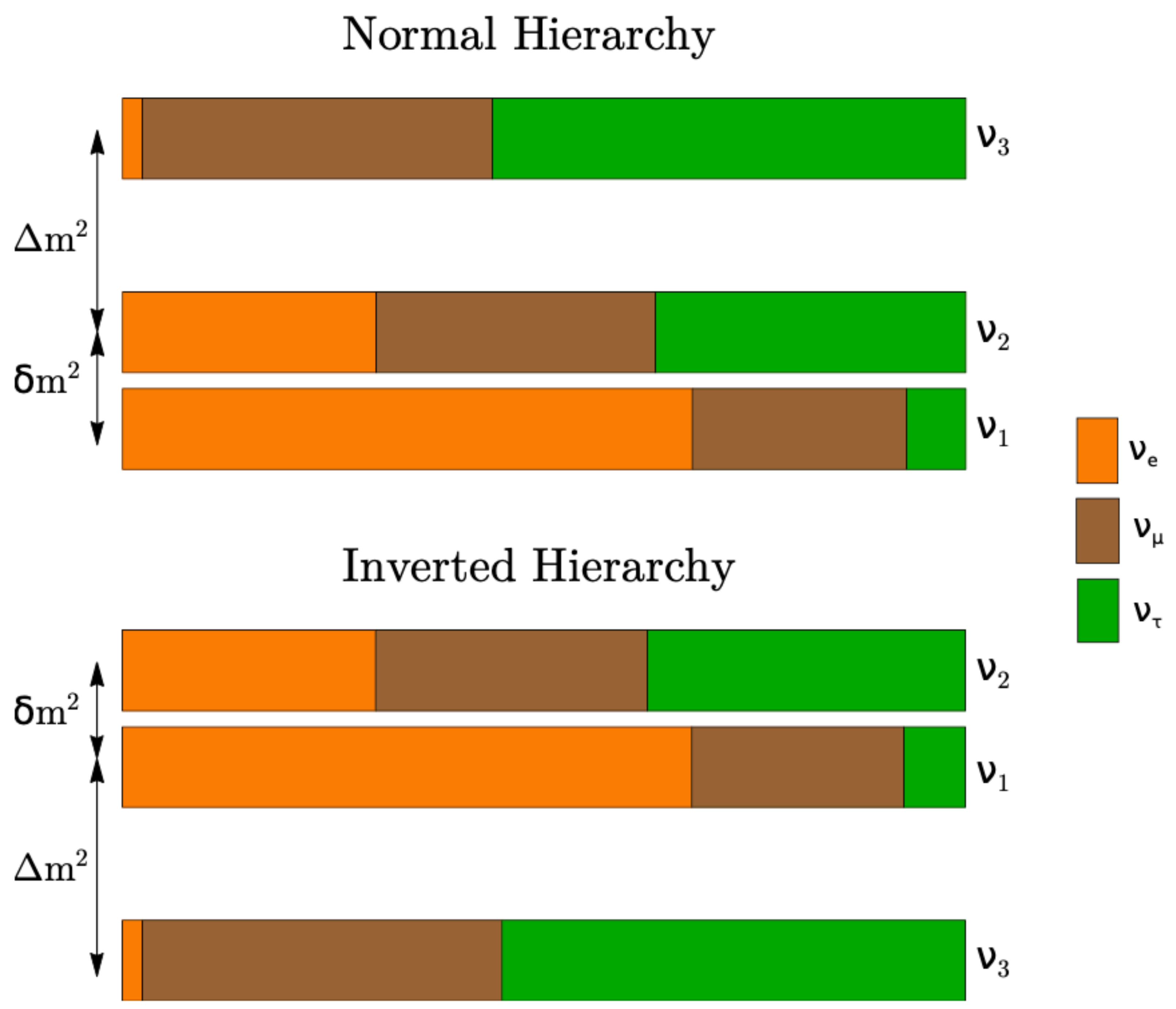
$$i\frac{\partial}{\partial t}\left|\nu_f\right\rangle = \sum_{f'}(U\Lambda U^\dagger)_{ff'}\left|\nu_{f'}\right\rangle \qquad \Lambda = E_i\delta_{ij}$$

- Then the transition amplitude will be

$$\mathcal{A}_{ff'}(t) \equiv \langle\nu_{f'},0|\nu_f,t\rangle = \langle\nu_f,0|\sum_{f''}\left(\sum_{j=1}^{n}U^*_{fj}\,e^{-iE_jt}\,U_{fj}\right)|\nu_{f''},0\rangle$$

$$\mathcal{P}_{\nu_f\to\nu_f} = \mathcal{A}_{ff'}\mathcal{A}^*_{ff'} = 1-4\sum_{i>j}\left|U^2_{fi}U^2_{fj}\right|\sin^2\phi_{ij}$$

$$\phi_{ij} = \frac{E_i-E_j}{2}t = \frac{m_i^2-m_j^2}{4Et}.$$



$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Neutrinoless double beta decay

- This process is important both in the SM and in cosmology because it provides a mechanism for leptogenesis.
- The matrix element is

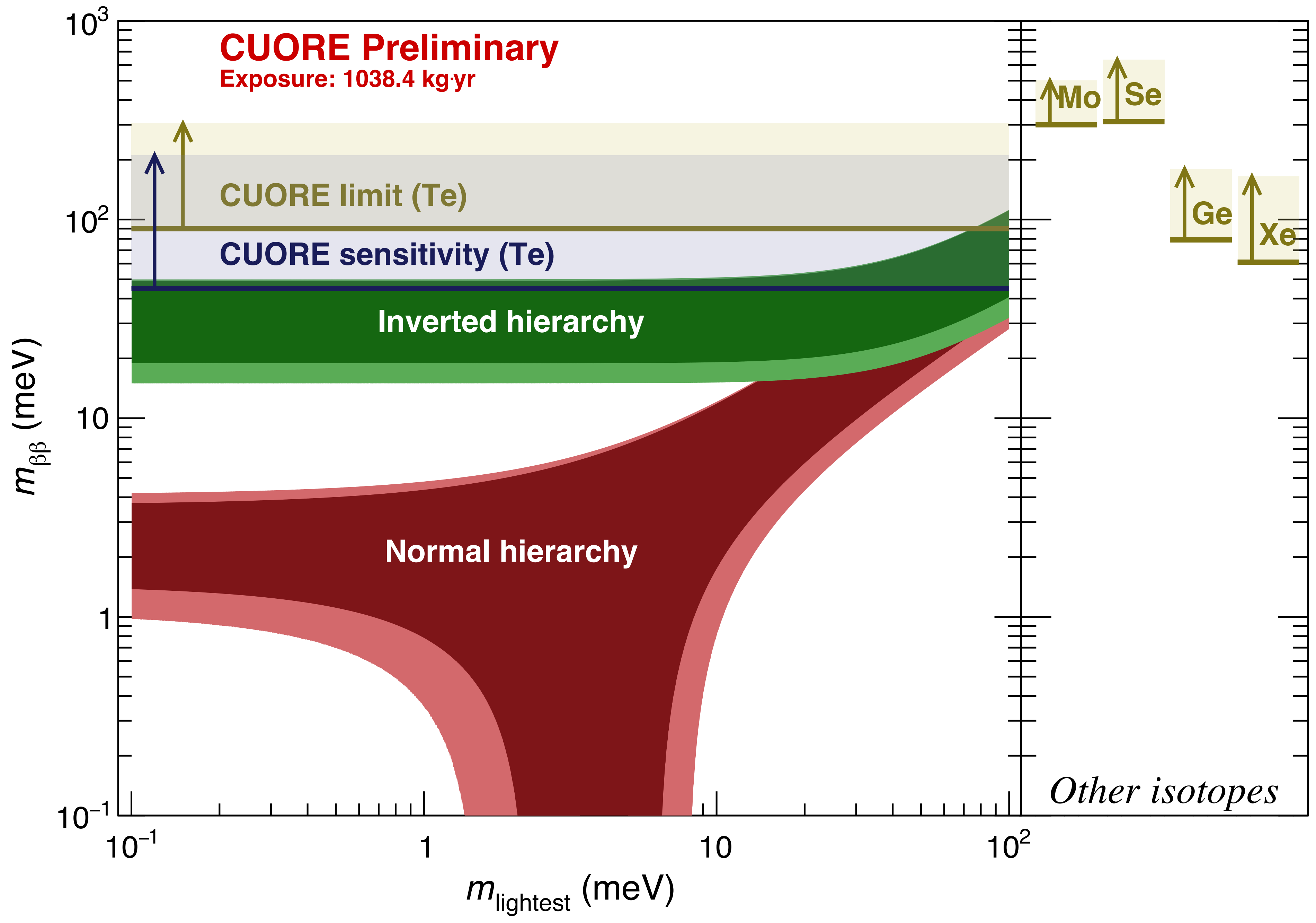
$$L_{\mu\nu} = \sum_i \bar{e}(x)\gamma_\mu(1-\gamma^5)U_{ei}\nu_i(x)\overline{\nu_i^c}(y)U_{ei}\gamma_\nu(1+\gamma^5)e^c(y)$$

- The amplitude is proportional to

$$m_{\beta\beta} = \left|\sum_i e^{i\xi_i}|U_{ei}|^2 m_i\right|$$

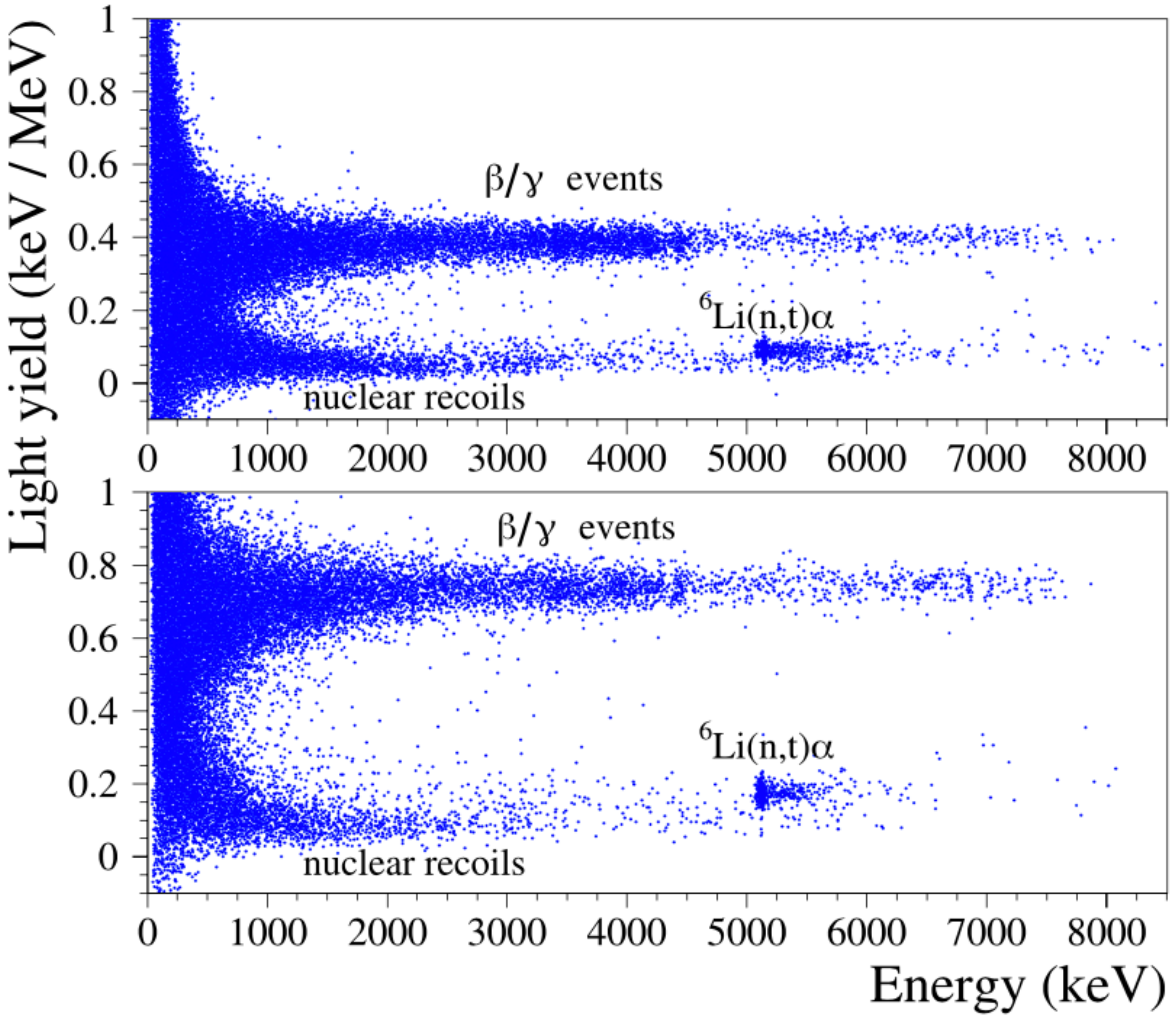
- The half-life can be written as

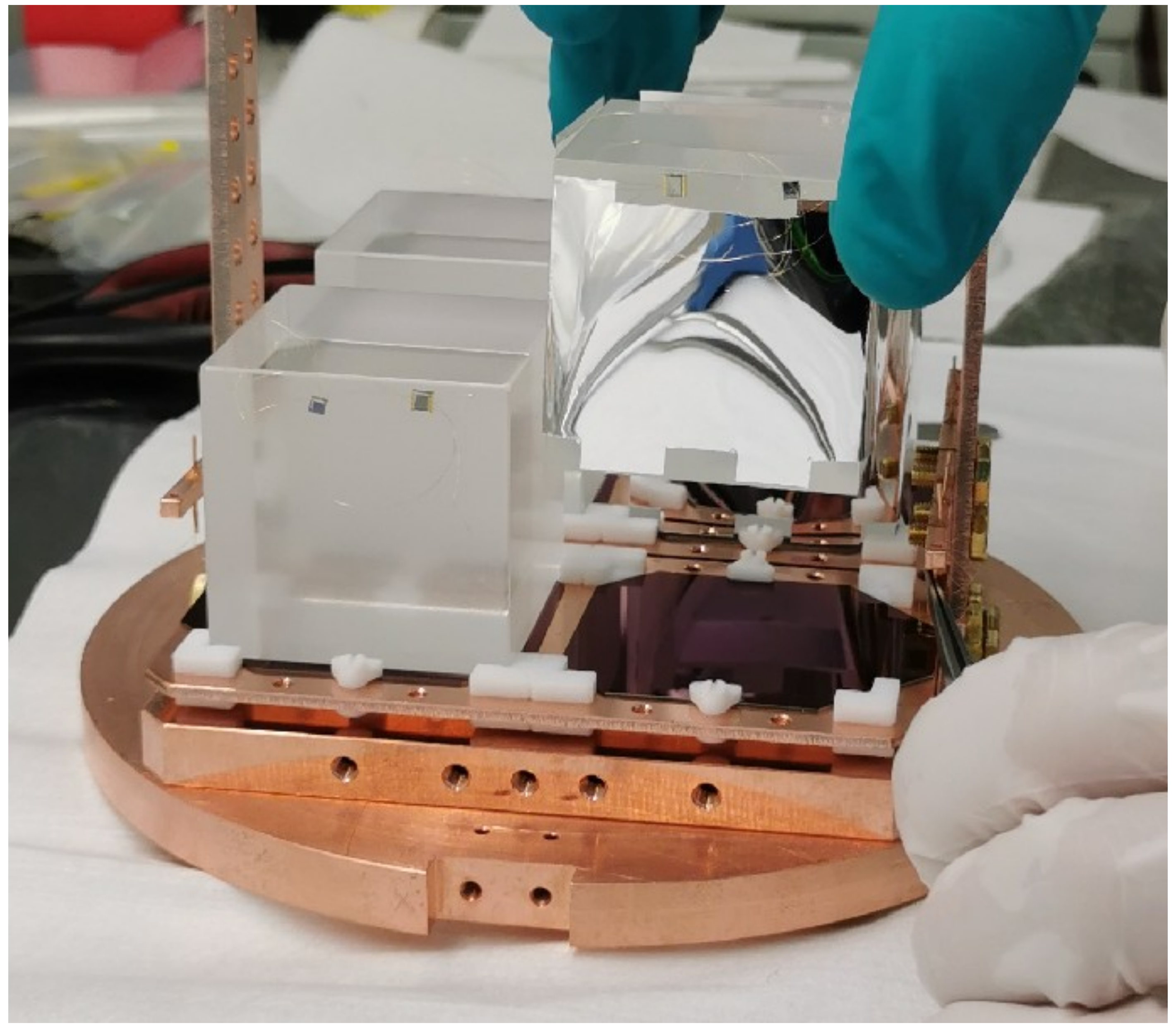
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}|\mathcal{M}|^2\left|\frac{m_{\beta\beta}}{m_e}\right|^2$$



CUPID

- CUPID (CUORE with Particle IDentification) is the successor of CUORE
- It will provide particle discrimination thanks to scintillation light

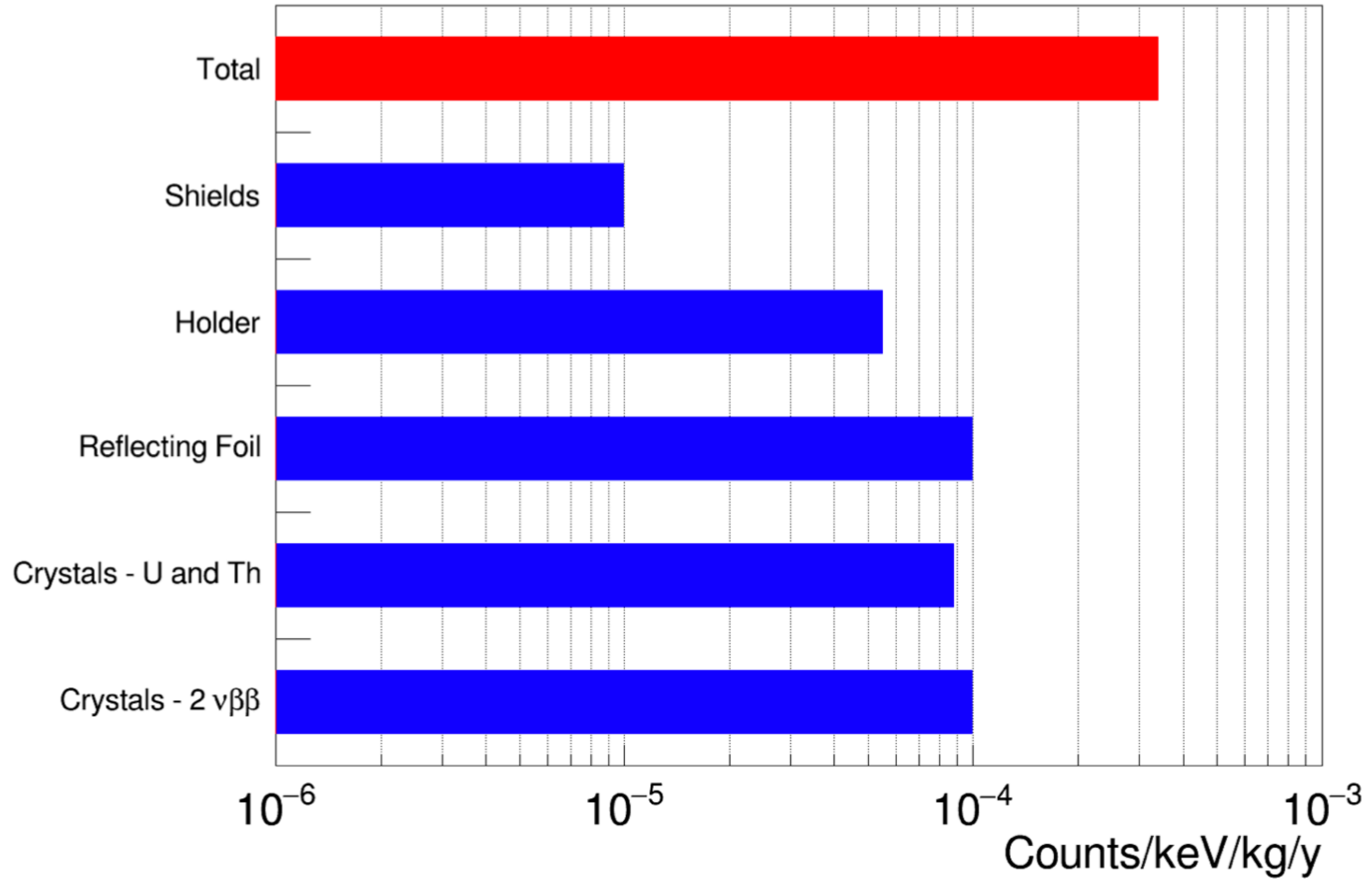


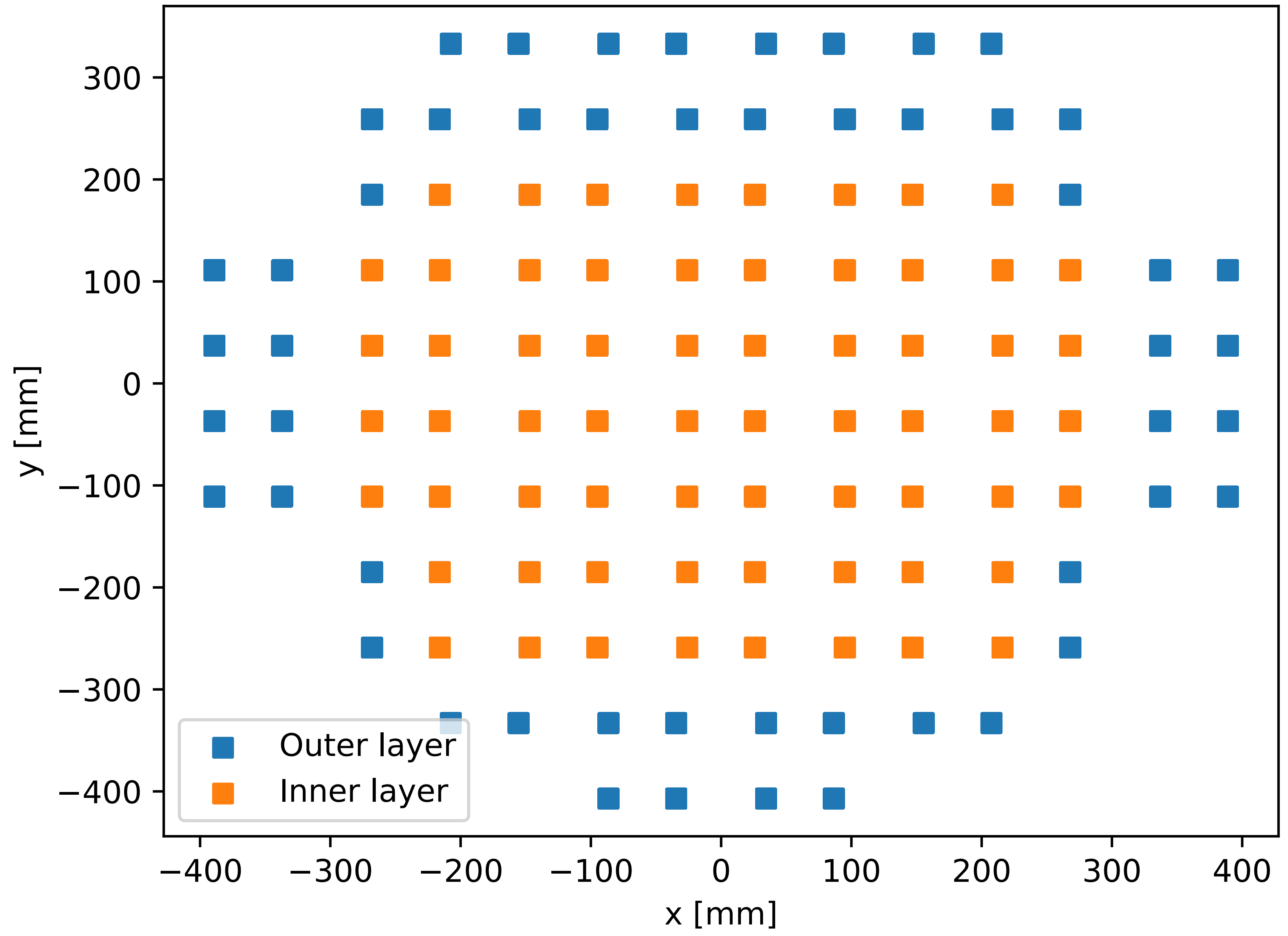


- Cupid will look for double beta decay in ^{100}Mo, at Q=3034 keV
- The background will be around 10^{-4} counts/(keV kg yr)

CUORE

Perspectives for CUPID





- The shielding effect is likely to be of minor importance because the contribution of the shields is around 10%
- In simulations with a division analogous to CUORE, the difference between the layers is small

Region	BI	σ $(10^{-4}\ \text{counts}/(\text{keV kg yr}))$
Inner layer	0.9	0.4
Outer layer	1.2	0.3

See-saw mechanism

CUORE

$$\mathcal{L}_Y = -YH^0\overline{\nu_R}\nu_L + \text{h.c.}$$

Higgs term

$$\mathcal{L}_\text{D} = -Yv\overline{\nu_R}\nu_L + \text{h.c.} = -m_D\overline{\nu}\nu$$

Higgs field acquires VEV (246 GeV)

$$\mathcal{L} = -\frac{m_R}{2}\overline{(\nu_R)^c}\nu_R + \text{h.c.}$$

Majorana term

$$\mathcal{L}_m = -m_D\overline{\nu_R}\nu_L - \frac{m_R}{2}\overline{(\nu_R)^c}\nu_R + \text{h.c.}$$

Mass term

$$\mathcal{L}_m = -\frac{1}{2}\left(\overline{(\nu_L)^c} \quad \overline{\nu_R}\right)\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}\begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix} + \text{h.c.}$$

Matrix form

$$D_\nu \simeq \begin{pmatrix} \frac{m_D^2}{m_R} & 0 \\ 0 & m_R \end{pmatrix}$$

Approximation possible because $m_D \ll m_R$

$$\mathcal{L}_m = -\frac{1}{2}\frac{m_D^2}{m_R}\bar{\nu}\nu - \frac{1}{2}m_R\bar{N}N$$

Using new mass eigenstates

$0\nu\beta\beta$ decay fit (1 ton yr)

CUORE

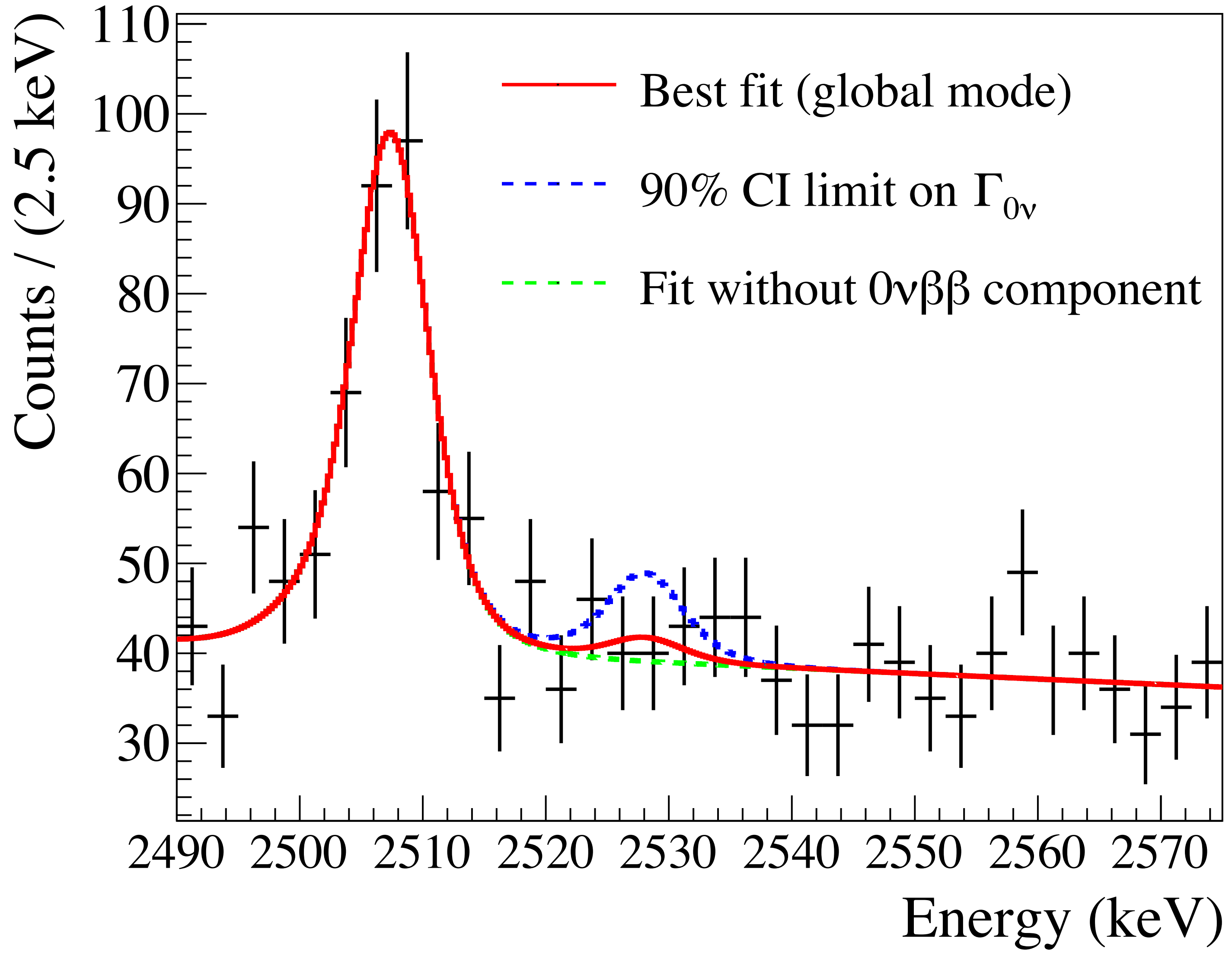
$$\mathcal{L}_{\mathrm{ch,ds}} = \frac{e^{-\lambda}\lambda^n}{n!} \prod_{\mathrm{events}} \left[\frac{s}{\lambda} f(E_i|\vec{\theta}(0\nu)) + \frac{c}{\lambda} f(E_i|\vec{\theta}(^{60}\mathrm{Co})) + \frac{b}{\lambda}\frac{1}{\Delta E} \right]$$

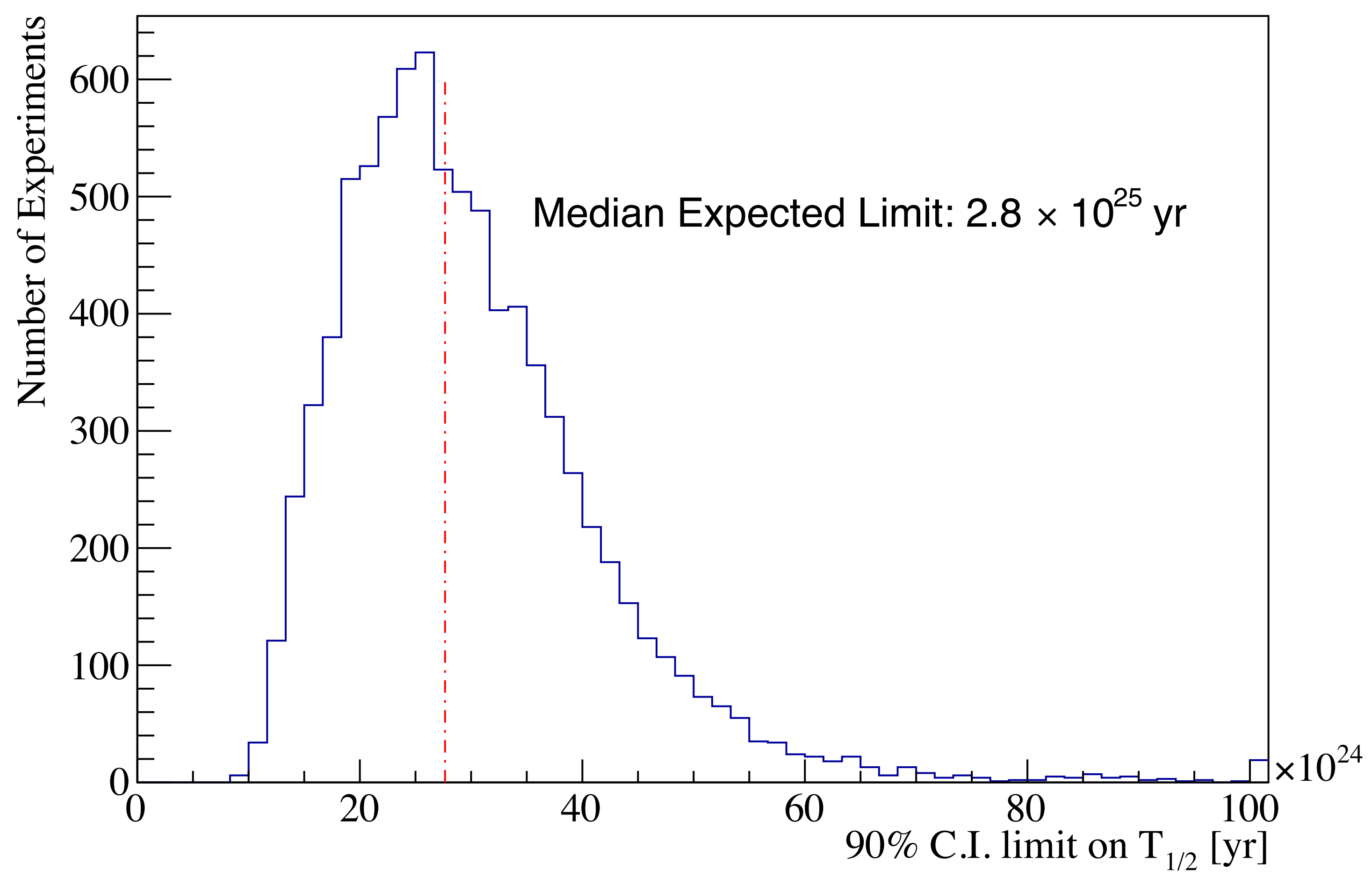
$$\lambda = s + c + b$$

$$s = \frac{N_A\, a}{W} \Gamma_{0\nu} \sum_{\mathrm{ch}} \sum_{\mathrm{ds}} (Mt)_{\mathrm{ch}} \epsilon_{\mathrm{cut_{ch}}} \epsilon_{\mathrm{MC_{ch}}}$$

$$c = \Gamma_{\mathrm{Co}}\, e^{-\frac{t^*}{\tau}}\, \epsilon_{\mathrm{cut_{ch}}}\, (Mt)_{\mathrm{ch}}$$

$$b = \mathrm{BI}\, \Delta E\, (Mt)_{\mathrm{ch}}$$





Possible $0\nu\beta\beta$ emitters

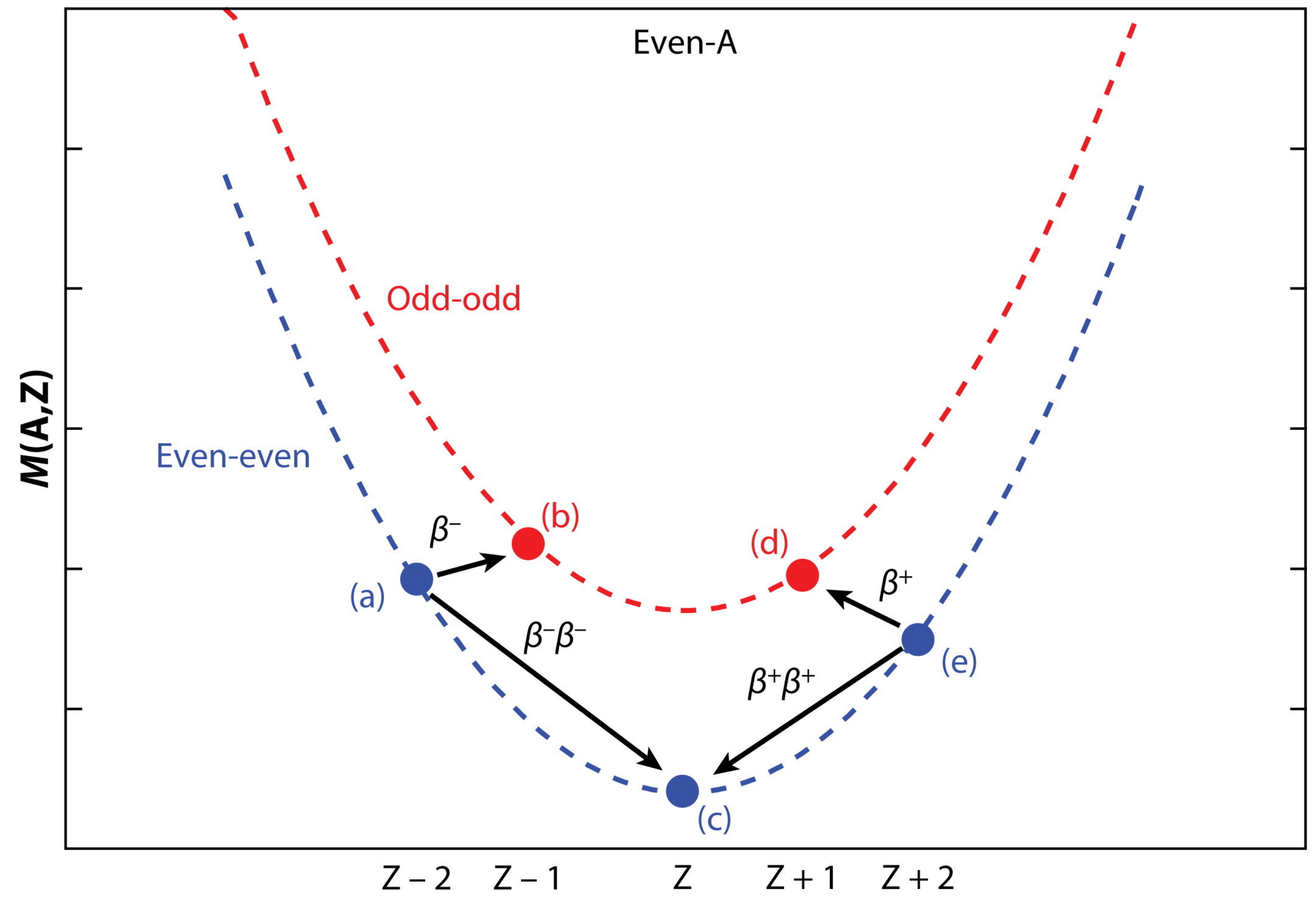
- The Bethe-Weiszacker mass formula is

$$M(A,Z) = Zm_p + (A-Z)m_n - a_V A + a_S a^{2/3} + a_C \frac{Z^2}{A^{1/3}} + \\ + a_A \frac{(N-Z)^2}{A} + \delta(A,Z)$$

- The pairing term constraints the possible nuclei:

$$\delta(A,Z) = \begin{cases} +a_P A^{-1/2} & N \text{ even}, Z \text{ even} \\ 0 & A \text{ odd} \\ -a_P A^{-1/2} & N \text{ odd}, Z \text{ odd} \end{cases}$$

- High Q-value is preferred to reduce γ contamination in the region of interest



Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ (MeV)
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

Bolometric technique in detail

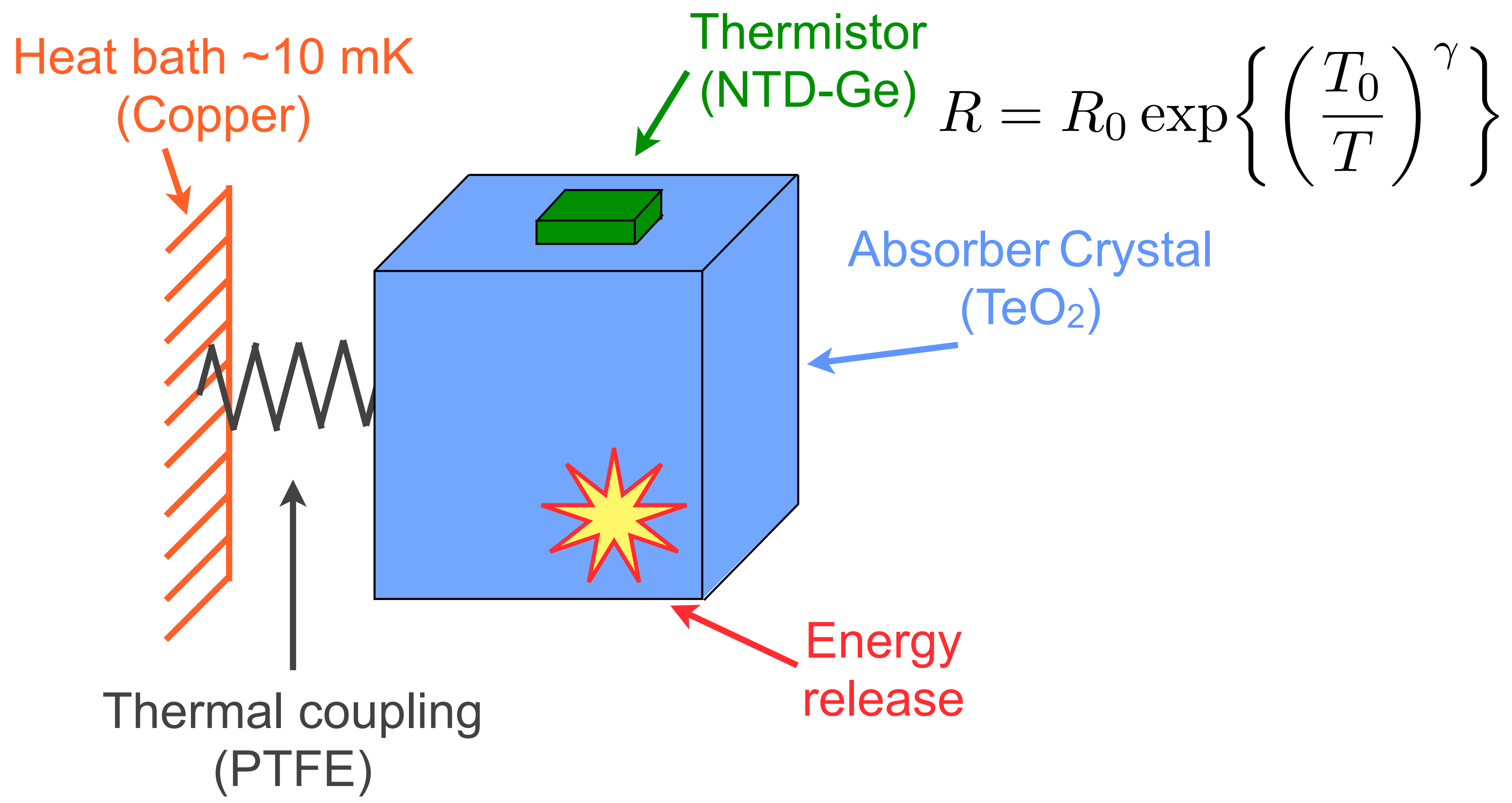
- The bolometer is a calorimeter operating at cryogenic temperatures.

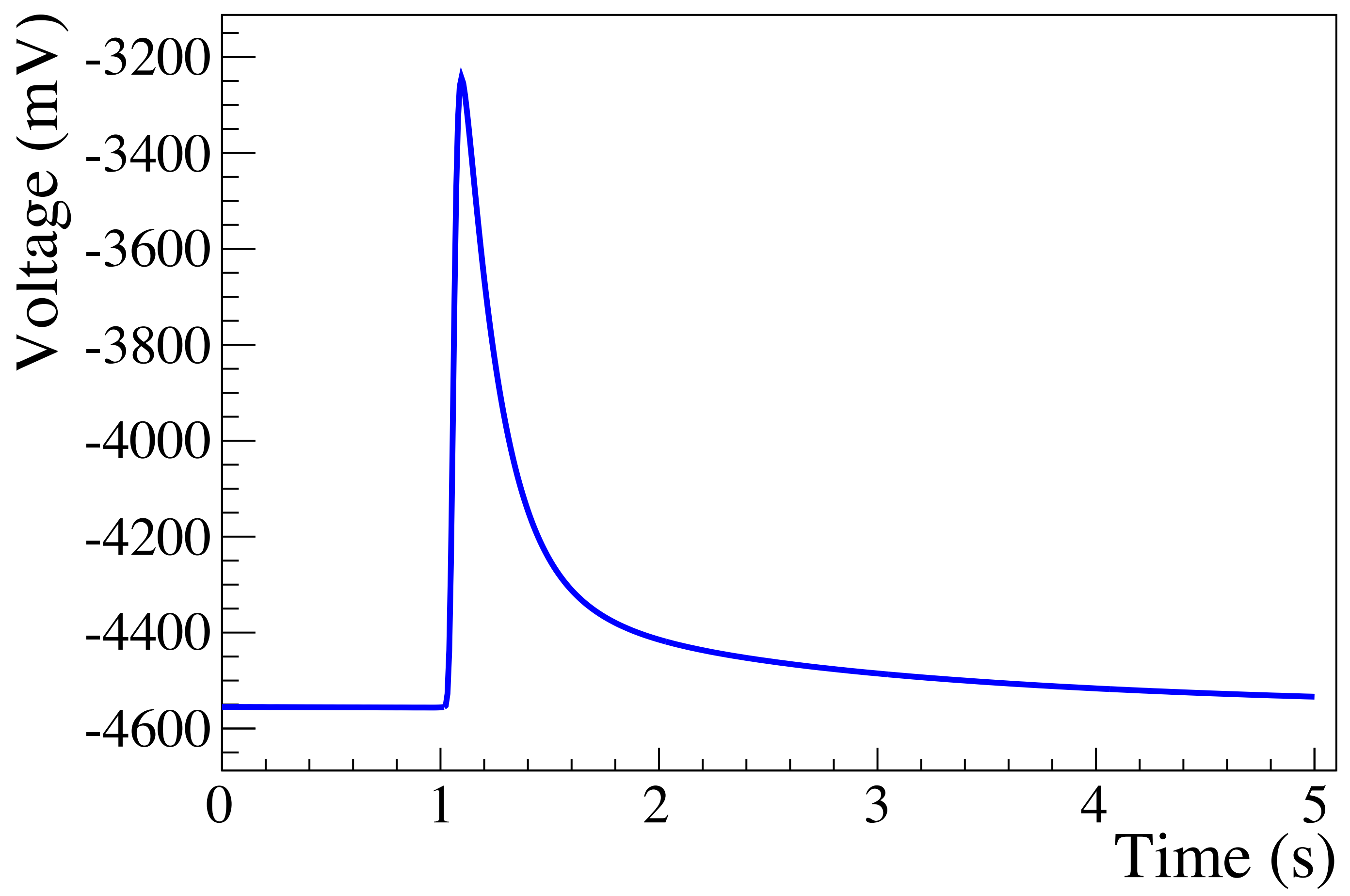
- The thermal characteristics are dictated by the thermal capacity C and the conductance of the thermal bath G:

$$\Delta T = \frac{E}{C} \qquad \tau_t = \frac{L}{c_s}$$

$$T(t) - T_0 = \frac{E}{C} e^{-\frac{t}{\tau}} \qquad \tau = \frac{C}{G}$$

- The capacity depends on the Debye temperature: $C \propto \left(\frac{T}{\Theta_D}\right)^3$





Derivation of the analytic formula

CUORE

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{Mt}{\mathrm{BI}}}$$

$$\xi = \frac{(Mt)_{\mathrm{low}}}{(Mt)_{\mathrm{tot}}} \in [0,1] \qquad f = \frac{\mathrm{BI}_{\mathrm{low}}}{\overline{\mathrm{BI}}} \in (0,1]$$

$$S_{\mathrm{low}} = N_s\,\xi \quad B_{\mathrm{low}} = N_b\,f\,\xi \quad \text{where } N_b = \overline{\mathrm{BI}} M t_{\mathrm{tot}} \Delta E$$

$$S_{\mathrm{high}} = N_s\,(1-\xi) \quad B_{\mathrm{high}} = N_b\,(1-f\,\xi)$$

$$\frac{S}{\sqrt{B}} = \left(\frac{S}{\sqrt{B}}\right)_0 \sqrt{\frac{\xi}{f}}$$

$$\left(\frac{S}{\sqrt{B}}\right)_{\mathrm{low}} = \left(\frac{S}{\sqrt{B}}\right)_0 \sqrt{\frac{\xi}{f}} \quad \left(\frac{S}{\sqrt{B}}\right)_{\mathrm{high}} = \left(\frac{S}{\sqrt{B}}\right)_0 \sqrt{\frac{(1-\xi)^2}{1-\xi f}}$$

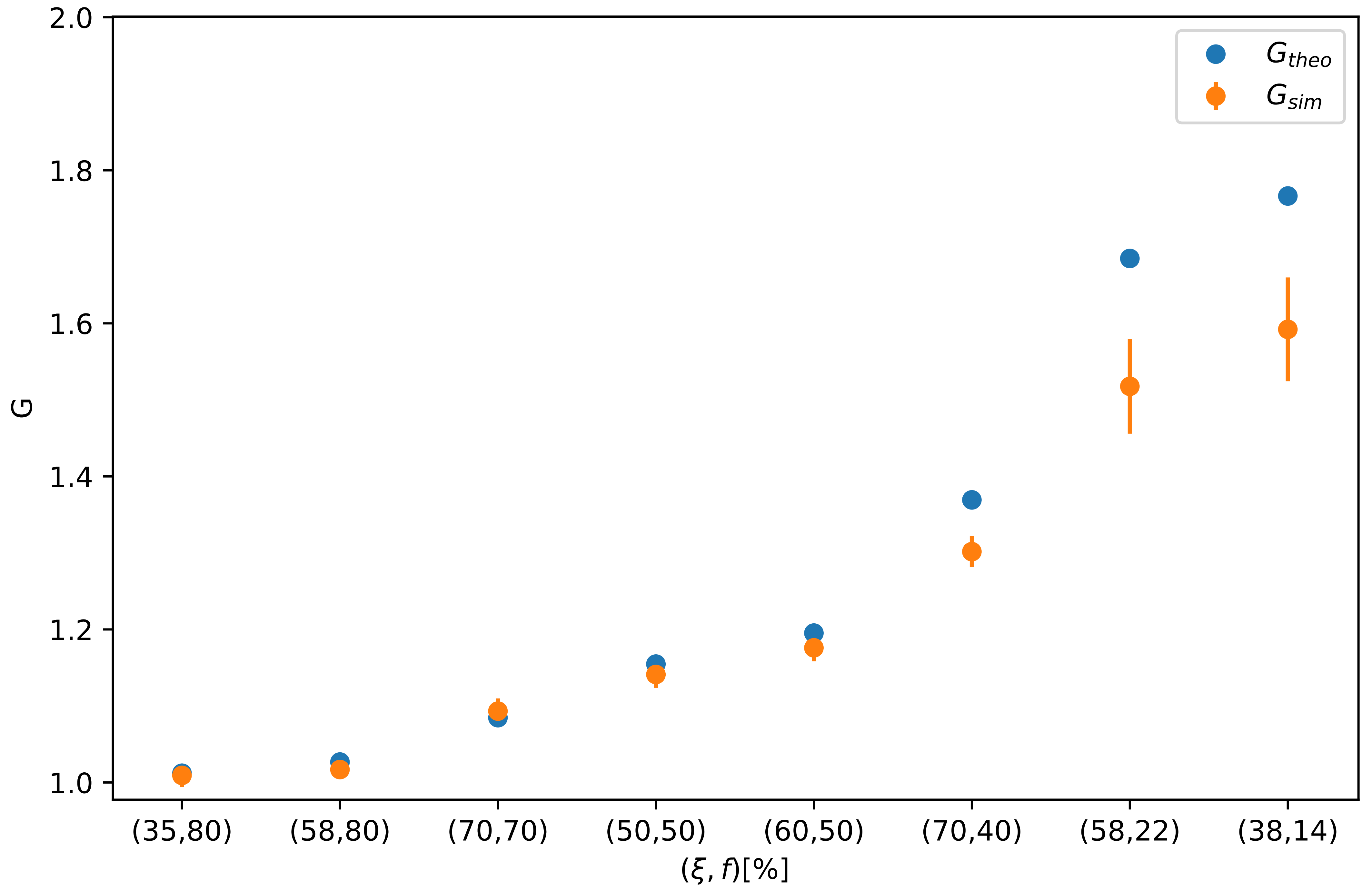
Derivation of the analytic formula

$$\left(\frac{S}{\sqrt{B}}\right)_{\mathrm{low}} = \left(\frac{S}{\sqrt{B}}\right)_0 \sqrt{\frac{\xi}{f}} \quad \left(\frac{S}{\sqrt{B}}\right)_{\mathrm{high}} = \left(\frac{S}{\sqrt{B}}\right)_0 \sqrt{\frac{(1-\xi)^2}{1-\xi f}}$$

$$\frac{1}{\sigma^2} = \sum_i \frac{1}{\sigma_i^2}$$

$$\frac{S}{\sqrt{B}} = \underbrace{\sqrt{\frac{\xi}{f} + \frac{(1-\xi)^2}{1-\xi f}}}_{G} \left(\frac{S}{\sqrt{B}}\right)_0$$

$$G = \sqrt{\sum_{i=1}^{N} \frac{\xi_i}{f_i}}$$



Helicity vs chirality

CUORE

- Helicity is the projection of the spin of the momentum

$$h = \frac{\vec{\sigma} \cdot \vec{p}}{|\sigma||p|}$$

- It is a good quantum number because it commutes with the hamiltonian but it is not a Lorentz invariant

- The left and right handed chirality projectors are

$$P_L = \frac{1 - \gamma_5}{2} \qquad P_R = \frac{1 + \gamma_5}{2}$$

- Chirality is equivalent to helicity if the particle is massless or in the ultrarelativistic limit

- It can be shown that it is a Lorentz invariant and that a left-handed state can transition to a positive helicity with a probability proportional to the ratio m/E