Search for Dark Matter Candidates with CUPID-0

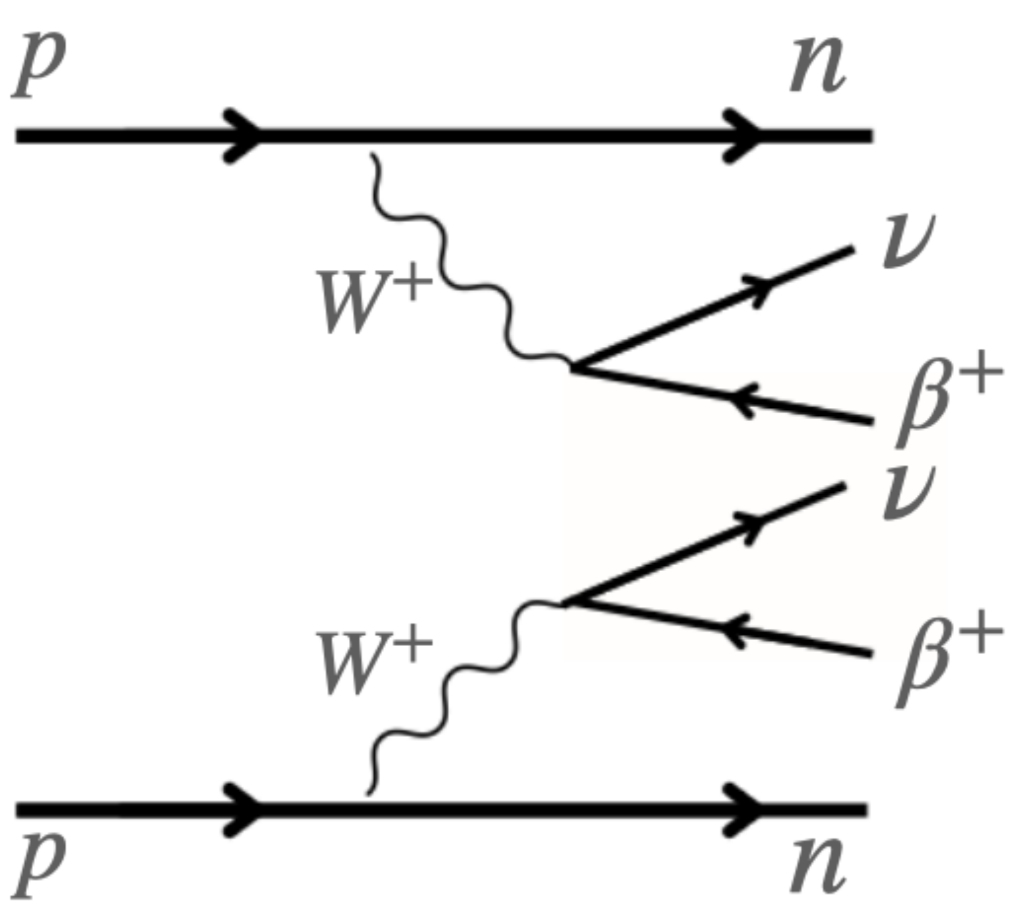
Identification of Dark Matter 2026

Sylvie Pietrarota, Livia Petrillo
Sapienza University of Rome, INFN Roma

The CUPID-0 experiment

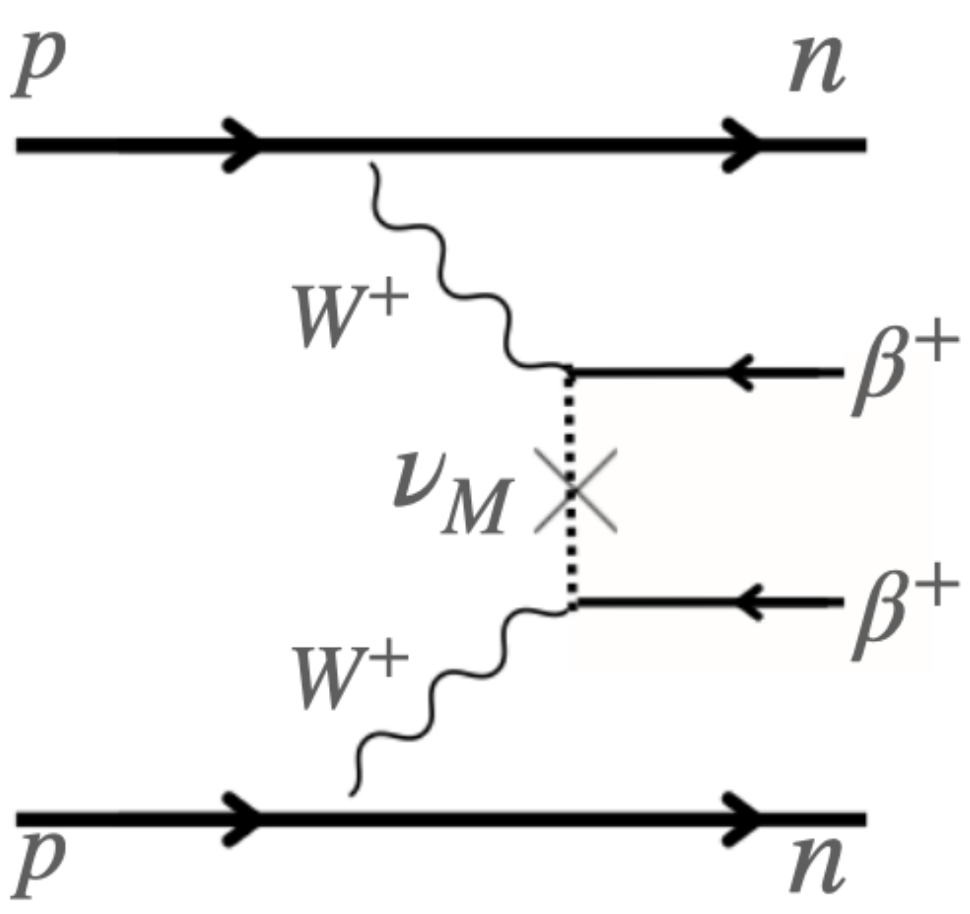
CUPID-0 is the **first demonstrator** of the **CUPID** project, which aims to search for the neutrinoless double β decay (0νββ)

- **Majorana** nature of neutrino
- Violation of the **B-L** symmetry
- **Matter-Antimatter** asymmetry
- Neutrinos **mass hierarchy**



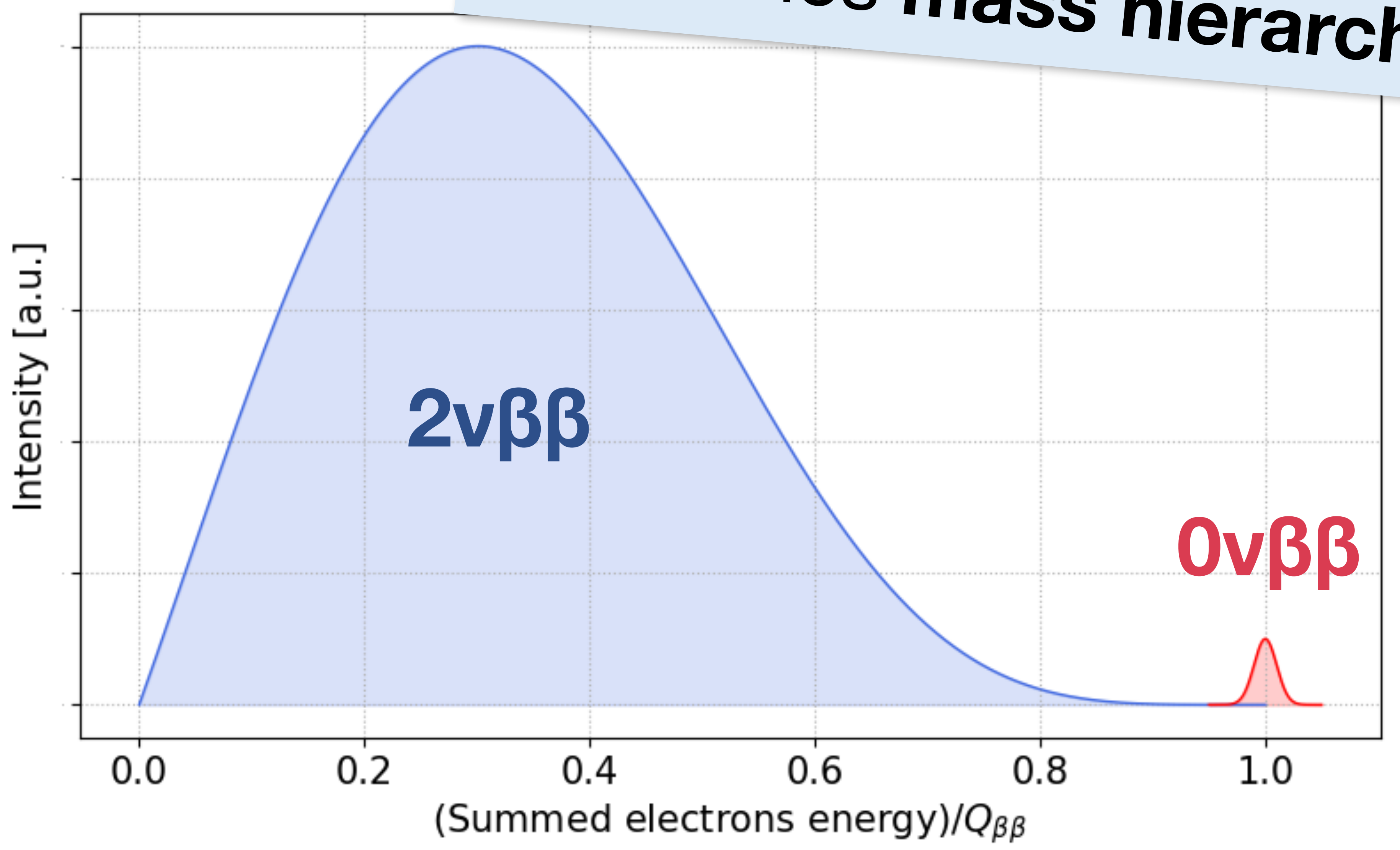
Standard Model allowed double β decay (**2νββ**)

$T_{1/2} \sim 10^{20}$ years



Neutrinoless double β decay (**0νββ**)

$T_{1/2} > 10^{24-26}$ years

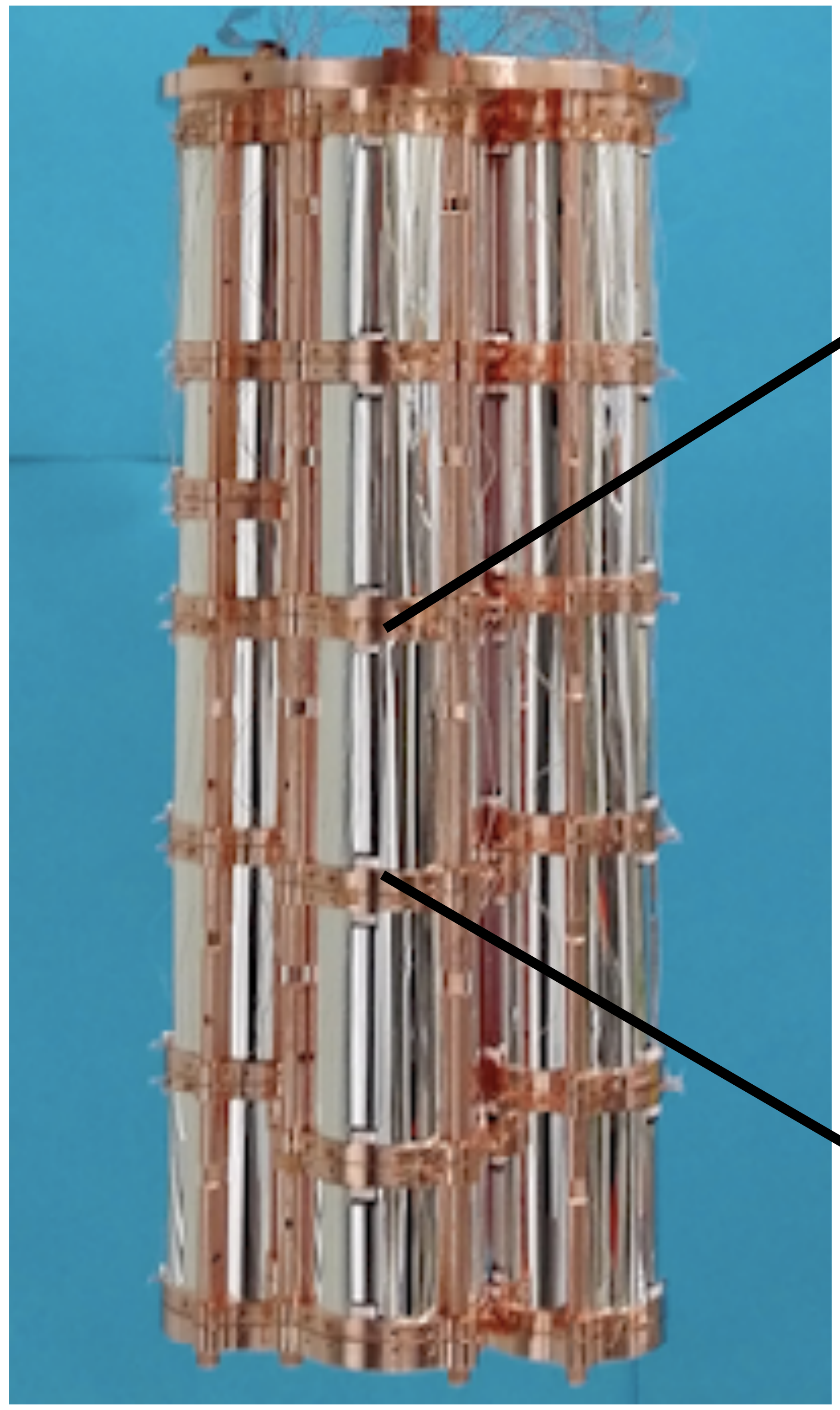


Monochromatic peak at the Q-value

The CUPID-0 experiment

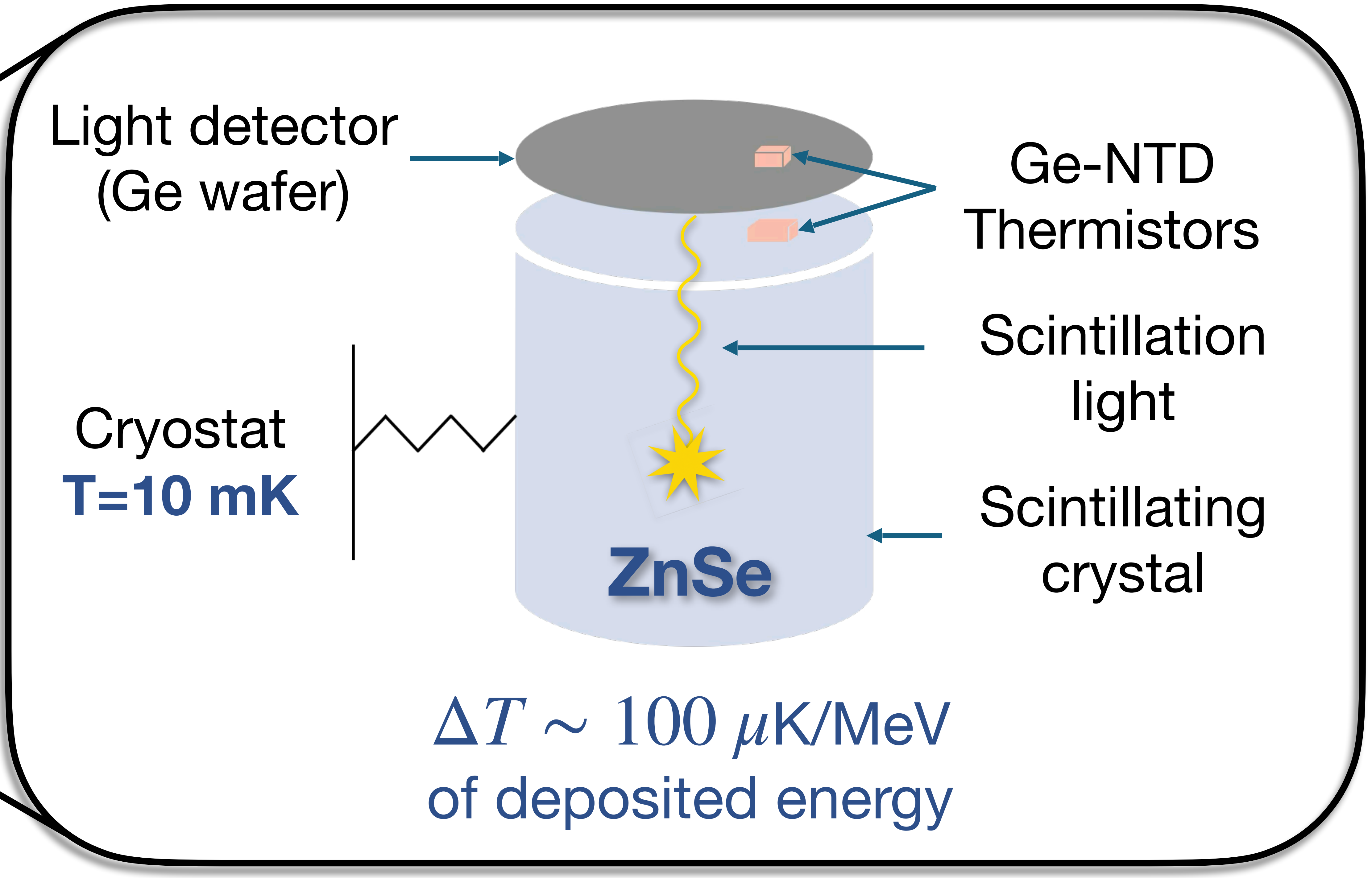
The detector: cryogenic scintillating calorimeters

Array of 26 crystals



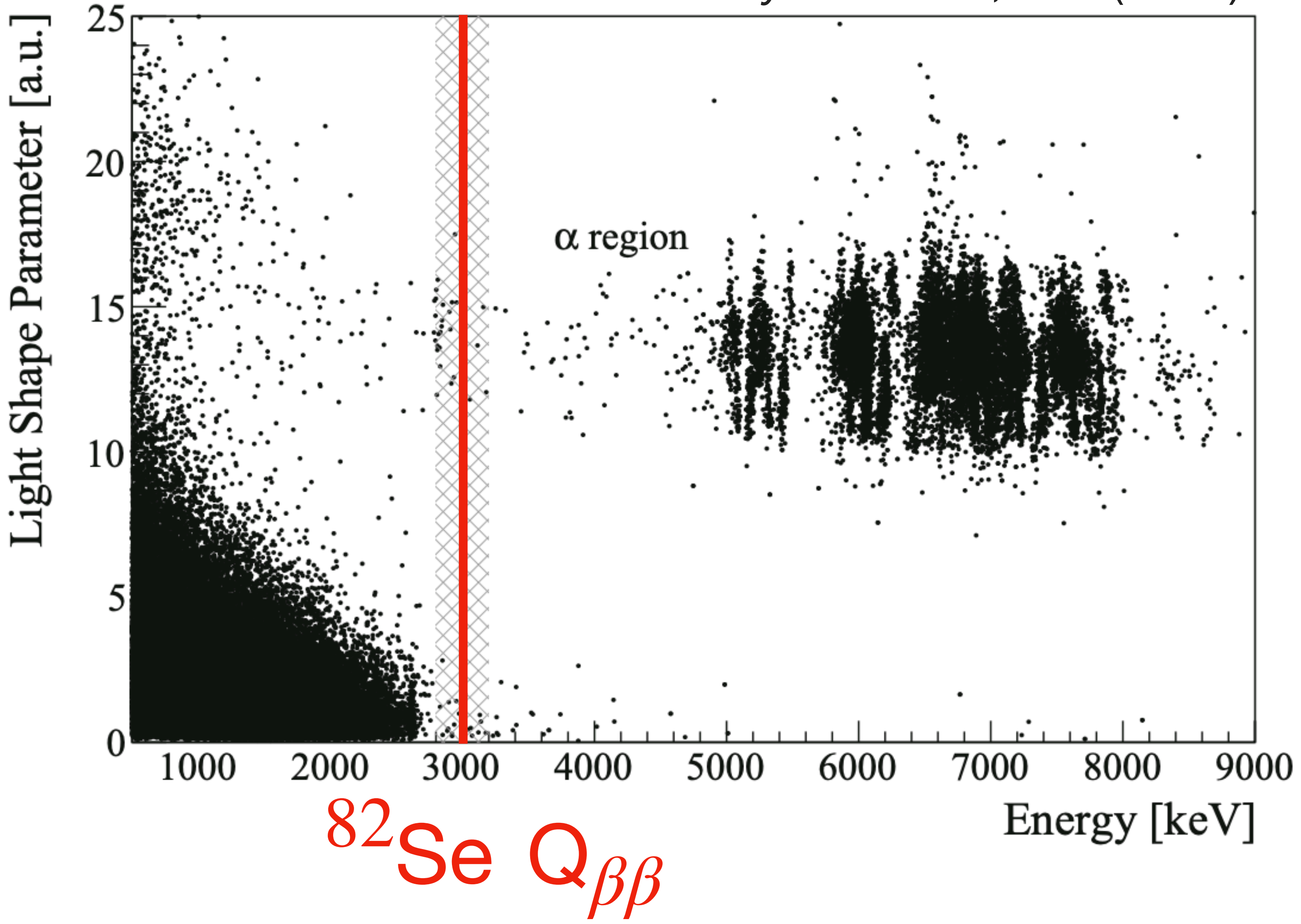
Eur. Phys. J. C **78**, 428 (2018)

$$^{82}\mathrm{Se} \rightarrow {}^{82}\mathrm{Kr} + 2e^{-} + \cancel{2\bar{\nu}_e}$$



The simultaneous measurement of **heat** and **scintillation light** allows to discriminate β/γ events from α particles events

Eur. Phys. J. C **78**, 734 (2018)



The CUPID-0 experiment

Results

CUPID-0 operated from 2017 to 2020 at the Gran Sasso Underground Laboratory (Italy)

- ☑ Collected 16.59 kg year exposure of ZnSe
- ☑ Validated the dual-readout technique
- ☑ Demonstrated **background** levels ∼$\mathbf{10^{-3}}$ **ckky**
- ☑ Achieved the **best 0νββ half-life limit on $\mathbf{^{82}Se}$**

  Phys. Rev. Lett. **129**, 111801

High energy resolution

Background rejection

High detection efficiency

CUPID-0 is suitable for rare events searches of various kinds

Dark Matter Candidates:
Sterile Neutrinos and Axions

Search for sterile neutrinos

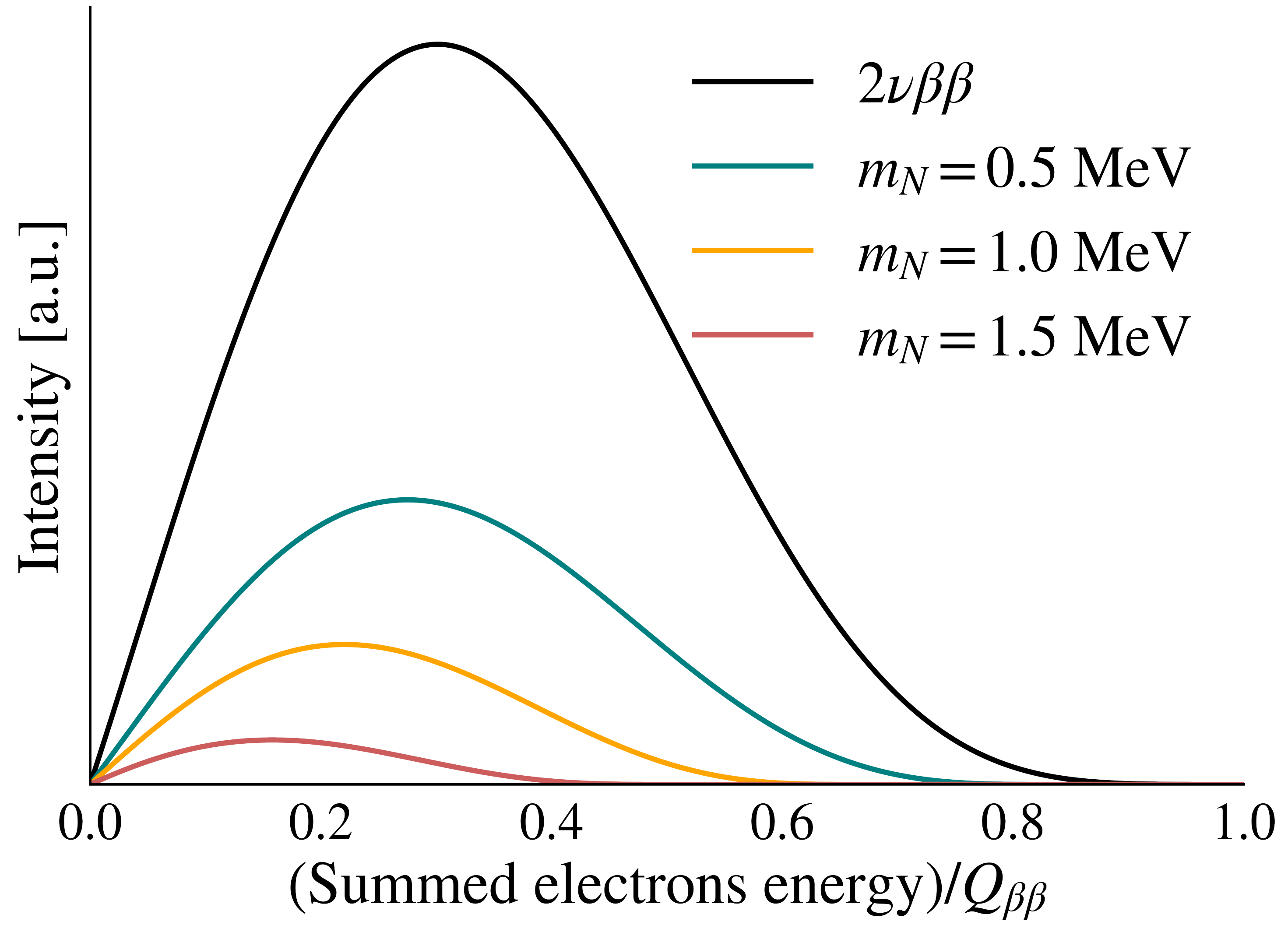
The physics case

Sterile neutrinos are hypothetical **massive non-interacting** neutrinos, that could **mix** with SM neutrinos → A sterile neutrino N could be emitted in double β decay: $^{82}\mathrm{Se} \rightarrow ^{82}\mathrm{Kr} + 2e^- + \bar{\nu}_e + \mathrm{N}$

The rate Γ of this process depends on

- The probability that an electron anti-neutrino oscillates into a sterile one: $\sin^2\theta$
- The sterile neutrino mass: m_N

Spectral shape distortion *induced by the presence of a massive sterile neutrino*



Goal: evaluate the Nvββ decay rate for different m_N values and convert it into a limit on the mixing parameter $\sin^2\theta$

$$\sin^2\theta(m_N) = \frac{G_{2\nu\beta\beta}}{2G_{N\nu\beta\beta}(m_N)} \cdot \frac{\Gamma_{N\nu\beta\beta}(m_N)}{\Gamma_{2\nu\beta\beta}}$$

G = phase space factor

Computed for the first time for ^{82}Se

Search for sterile neutrinos

Analysis method

1. Produce the MC simulation of the Nνββ decay in the CUPID-0 detector for a given m_N value

2. Model the data spectrum as the linear combination of background + signal templates

3. Extract the posterior p.d.f.s of the linear coefficients, proportional to the rates Γ of the corresponding processes, through a **Bayesian fit**

4. Derive the posterior p.d.f. of $\sin^2\theta(m_N)$ and extract the 90% C.I. upper limit

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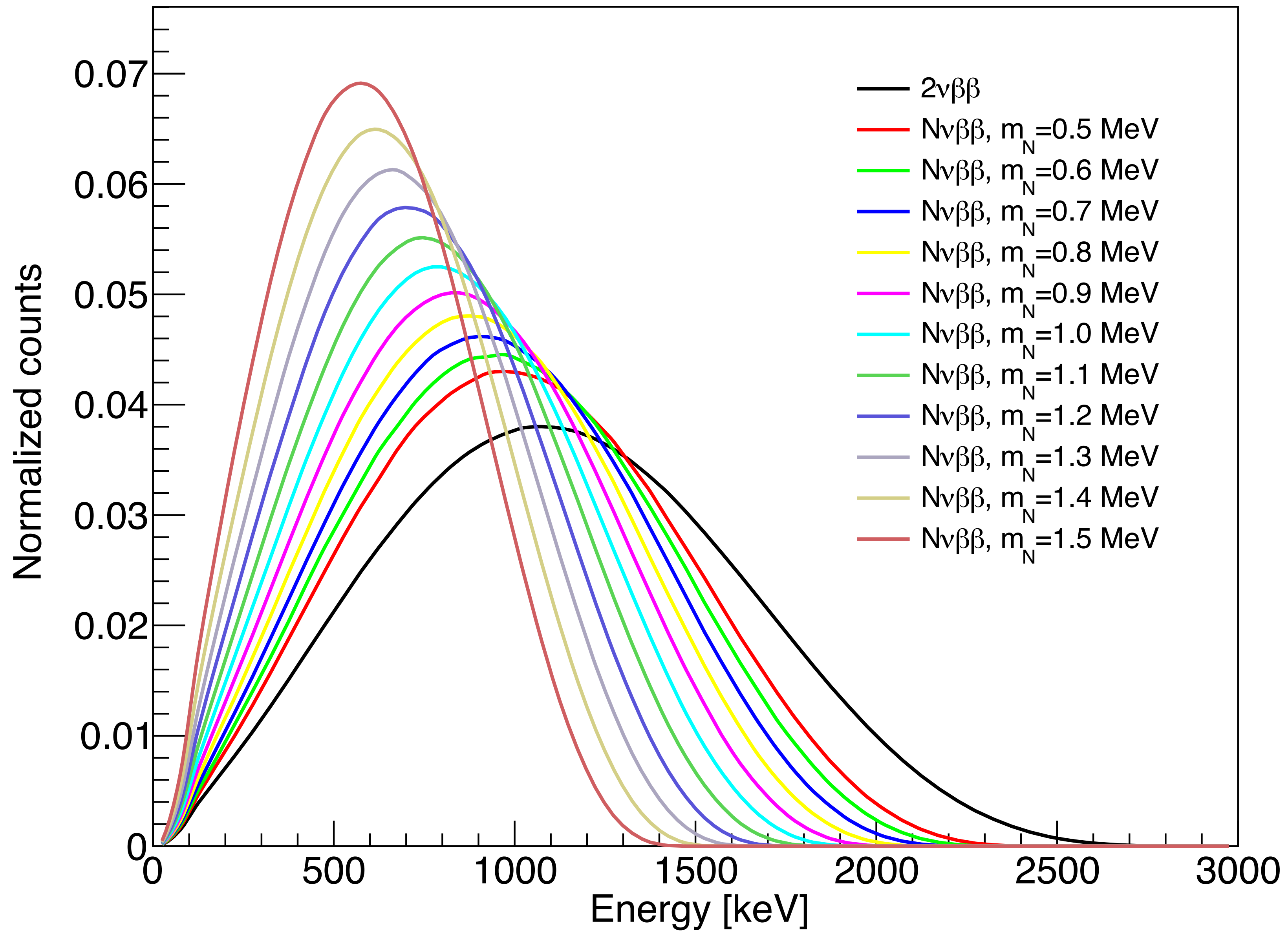
Explored mass range:
$m_N \in [0.5,1.5]$ MeV



Energy spectrum of β/γ events contained in a single crystal

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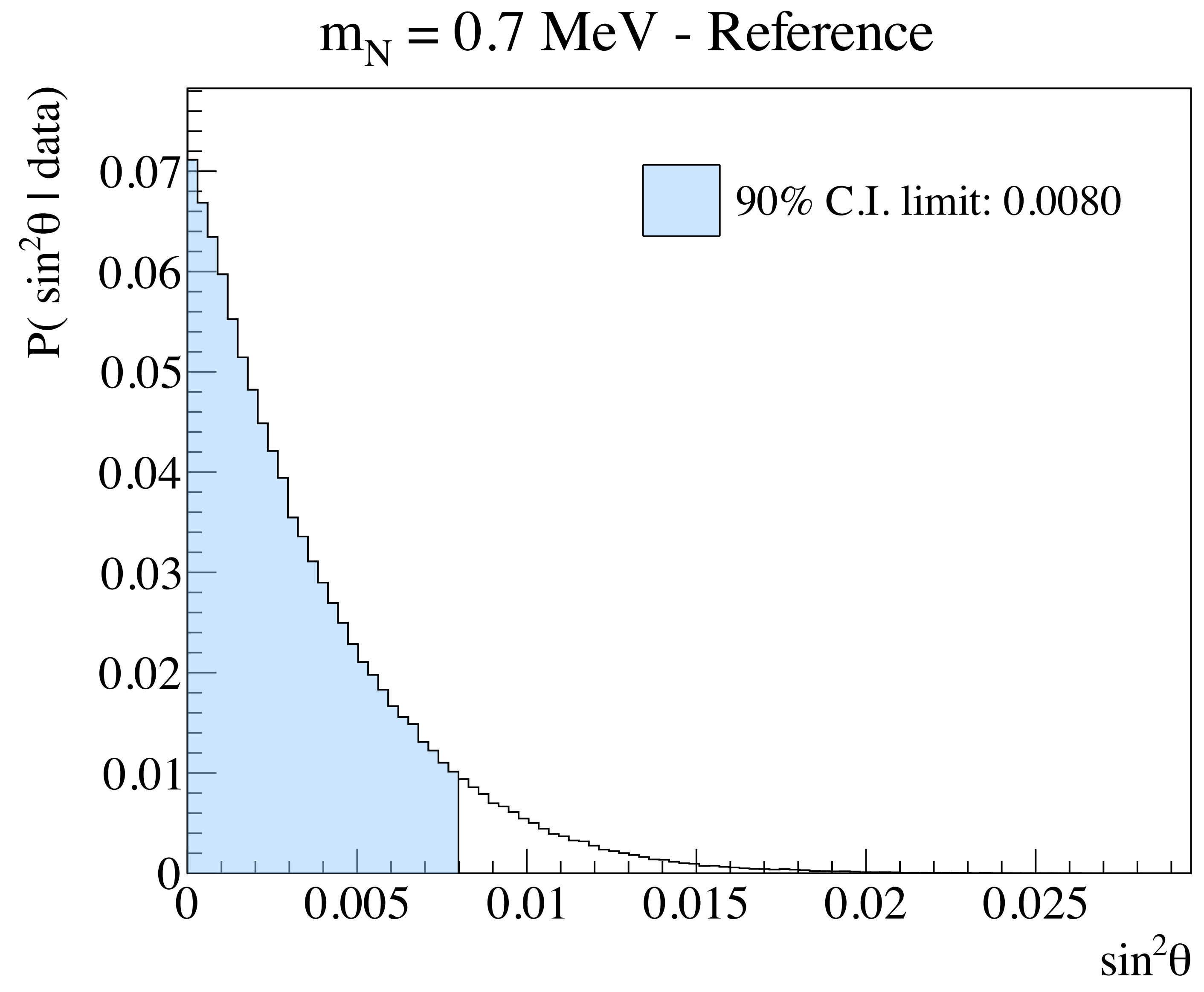
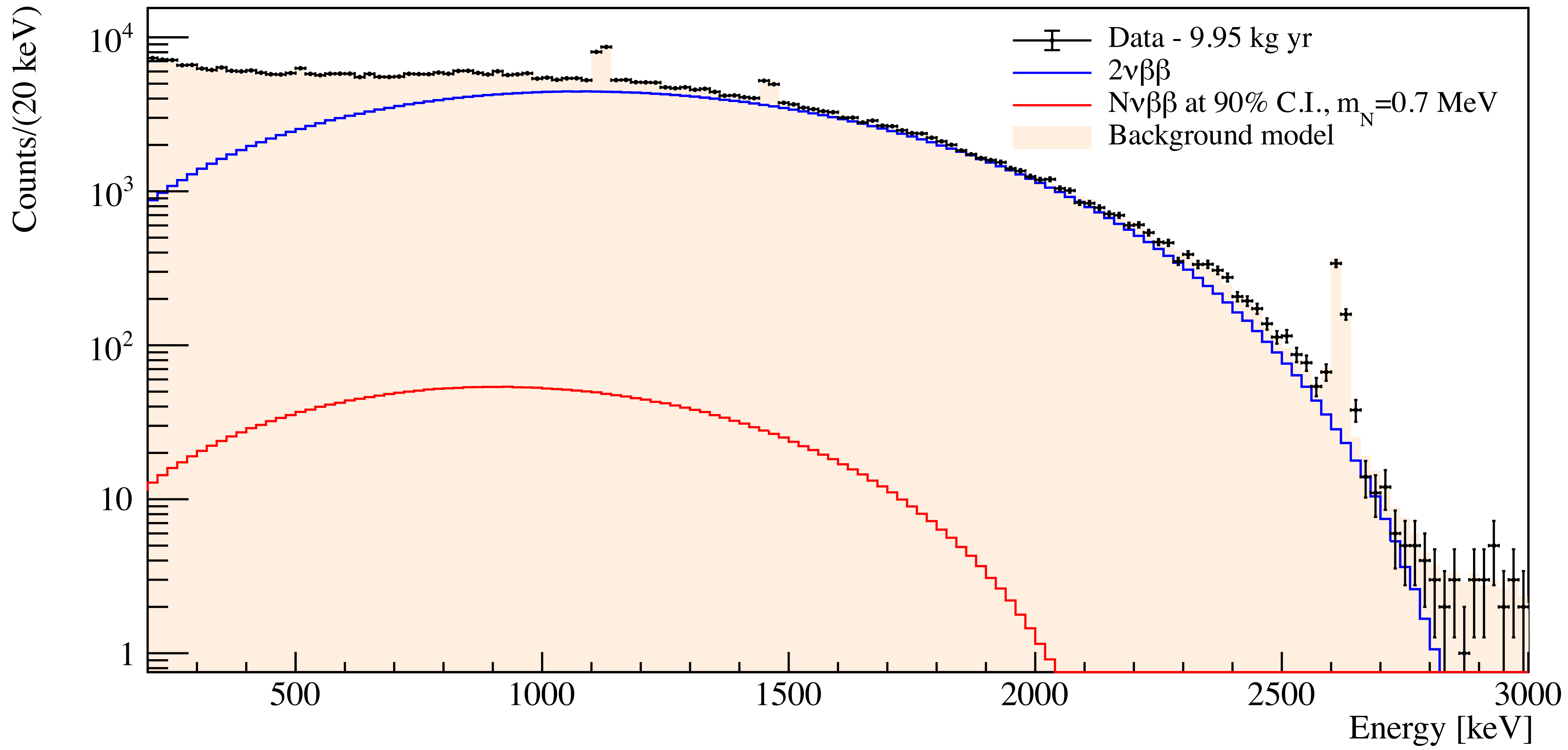
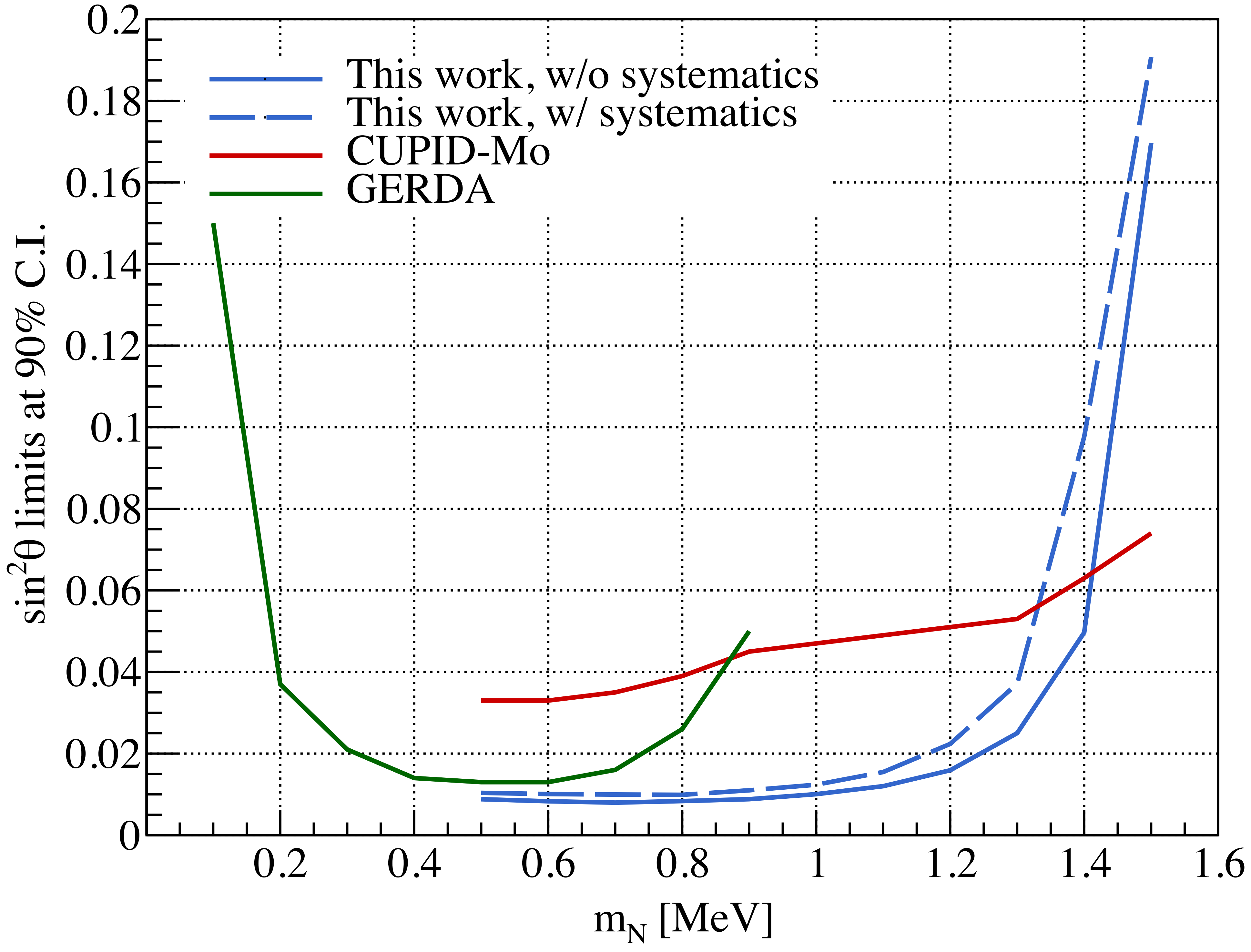




Search for sterile neutrinos

Results

Exclusion plot



Systematics: we explored variations in the fit and combined the posterior p.d.f.s obtained for each modification according to the law of total probability

- ☑ First search of sterile neutrinos in the double β decay of ^{82}Se
- ☑ Direct approach based on kinematic variables
- ☑ Competitive results with other experiments dedicated to the search of $0\nu\beta\beta$ employing different isotopes

arXiv:2603.17602

Accepted by JCAP!

Search for solar axions

The physics case

- Axions could be **produced** in the Sun in a variation of the PP cycle → monochromatic flux of axions @ 5.5 MeV

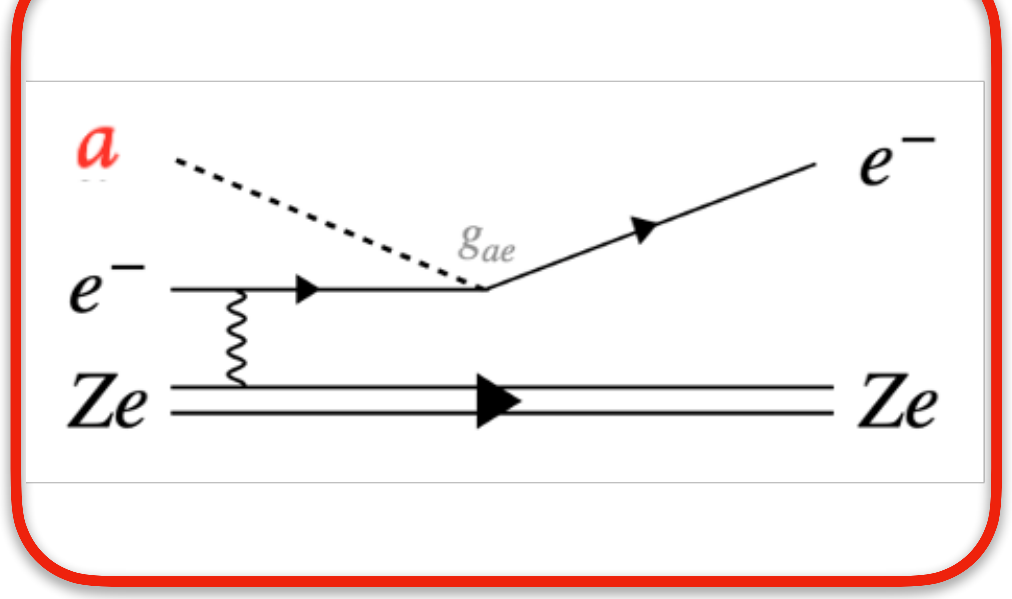
$${}^2_1H + p \rightarrow {}^3_2He + a(5.493\ \text{MeV})$$

The incident flux is proportional to the neutrino PP flux via the axion-nucleon coupling $g_{aN}^{(3)}$ and the axion mass

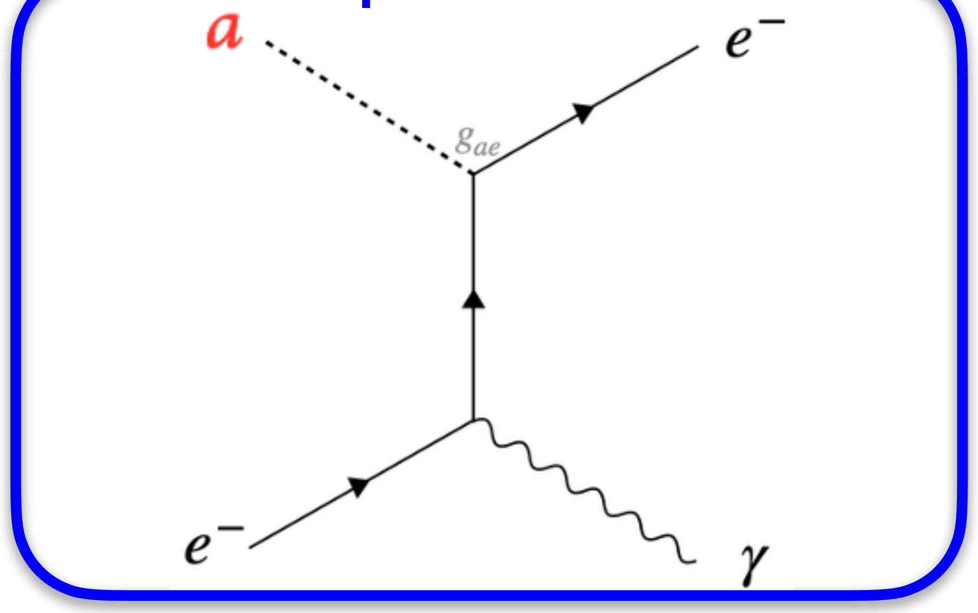
$$\Phi_a \approx 0.54\,(g_{aN}^{(3)})^2\,\beta_a^3\,\Phi_{\nu PP}$$

- They could **interact** with the CUPID-0 detector through 3 processes:

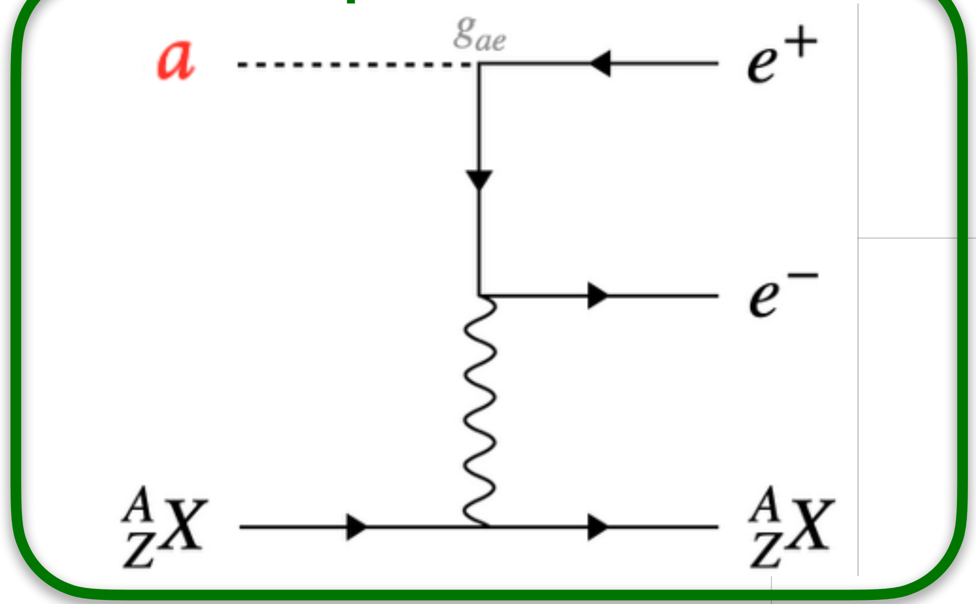
Axio-electric effect



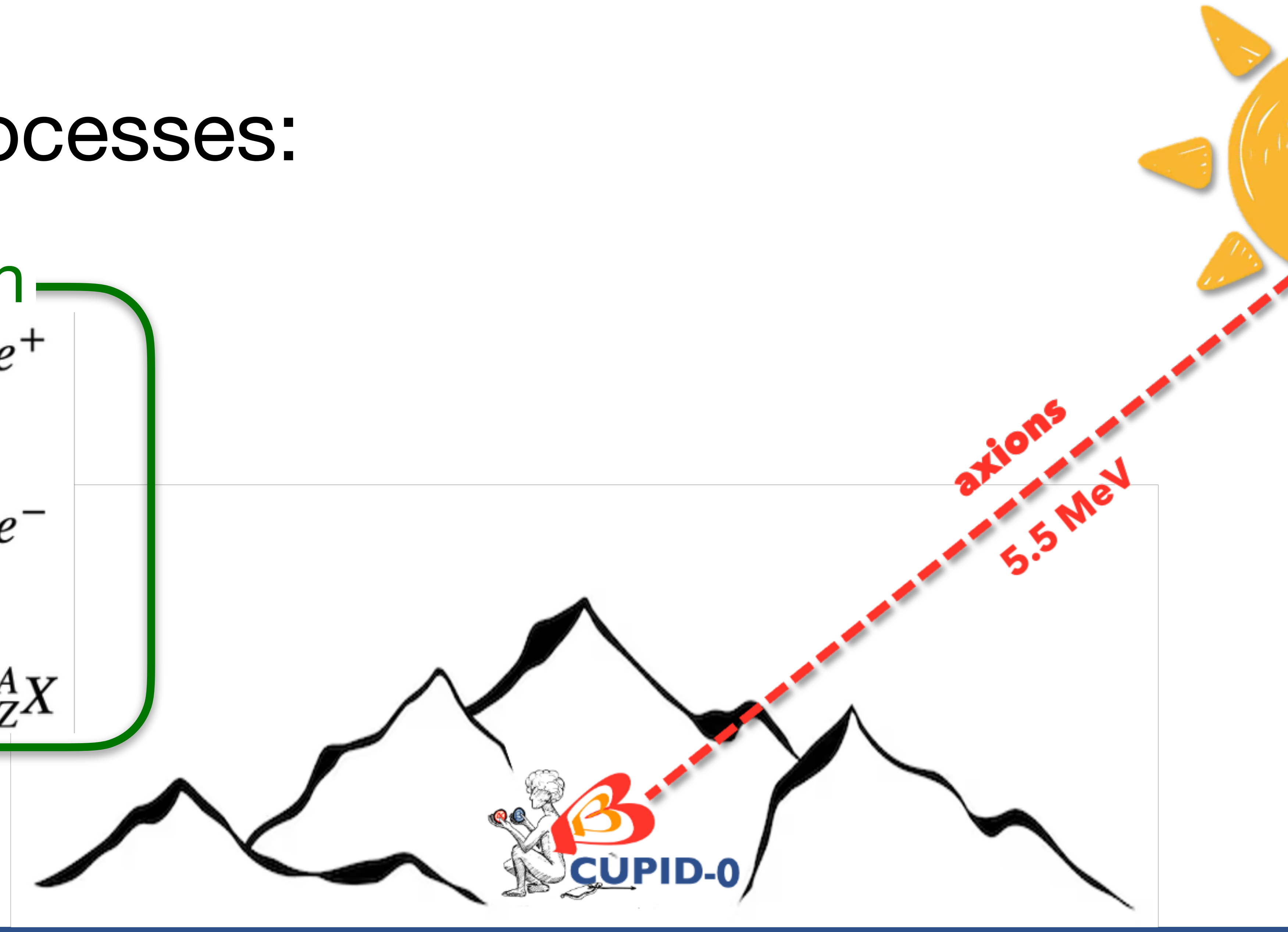
Compton effect



Pair production



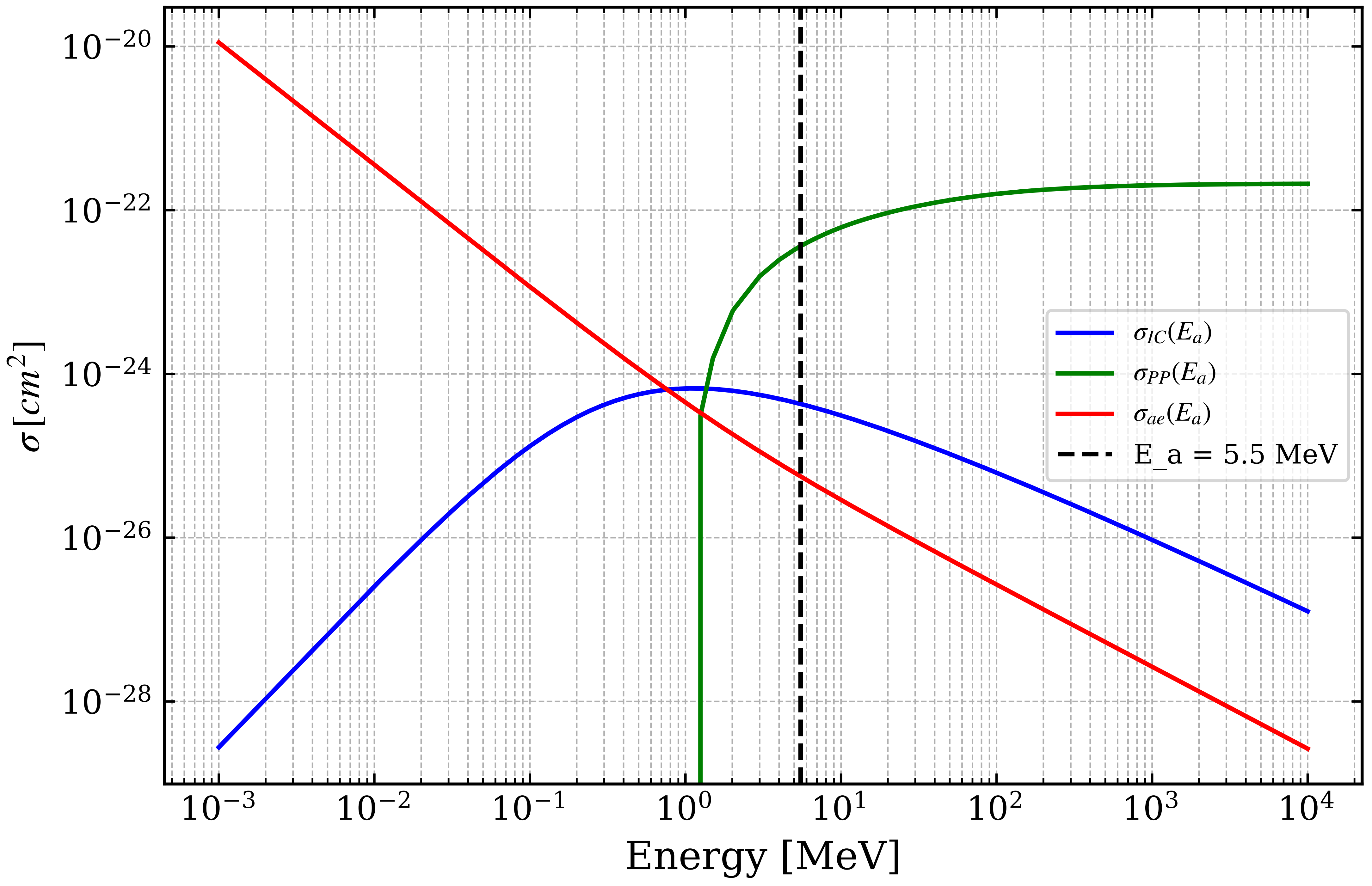
Mediated by the axion-electron coupling g_{ae}

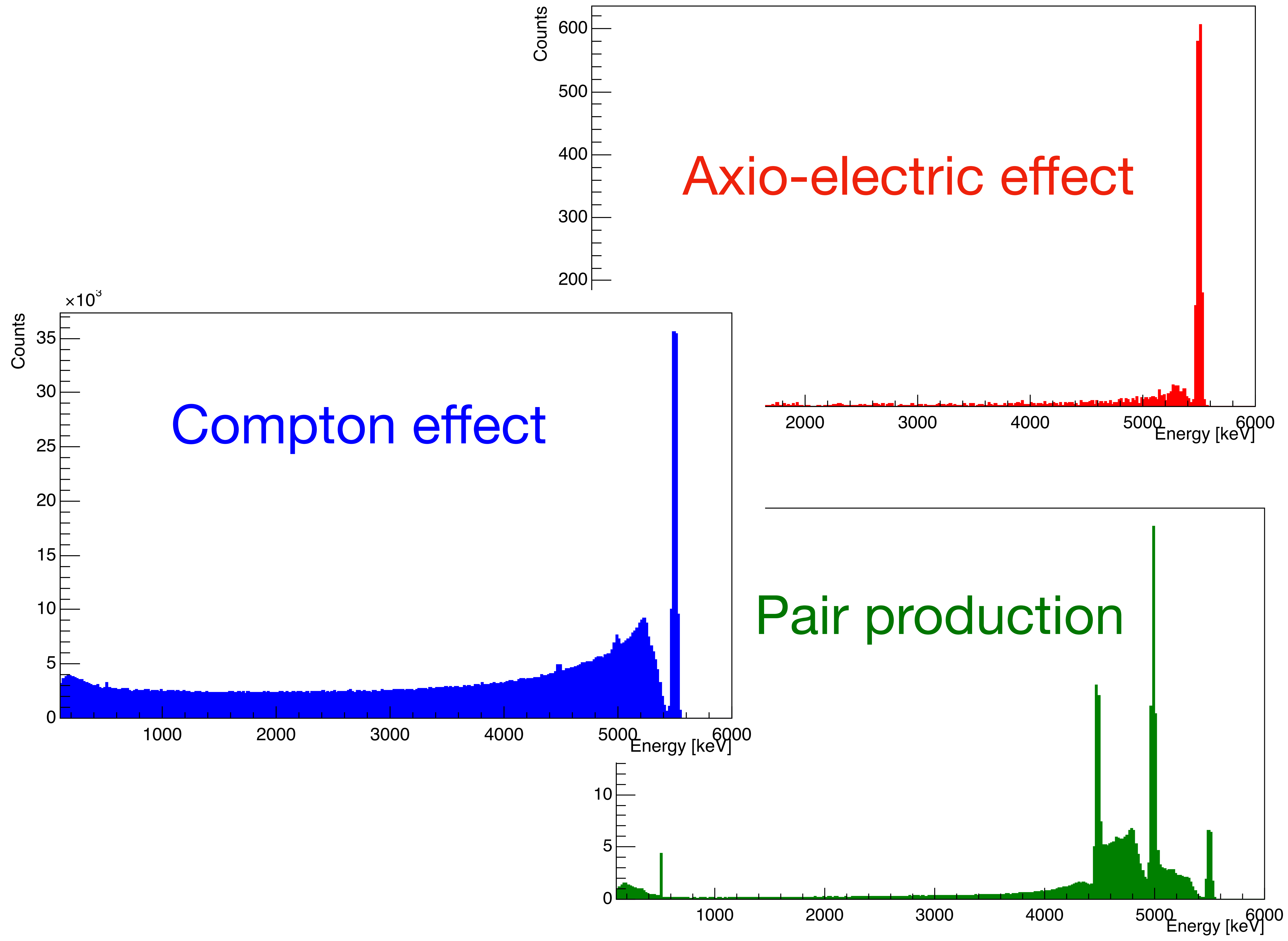


Search for solar axions

The physics case

For an axion of $m_a = 100\ eV$ and $E_a =$ 5.5 MeV, the cross sections are in the ratios **1 : 8 : 650**



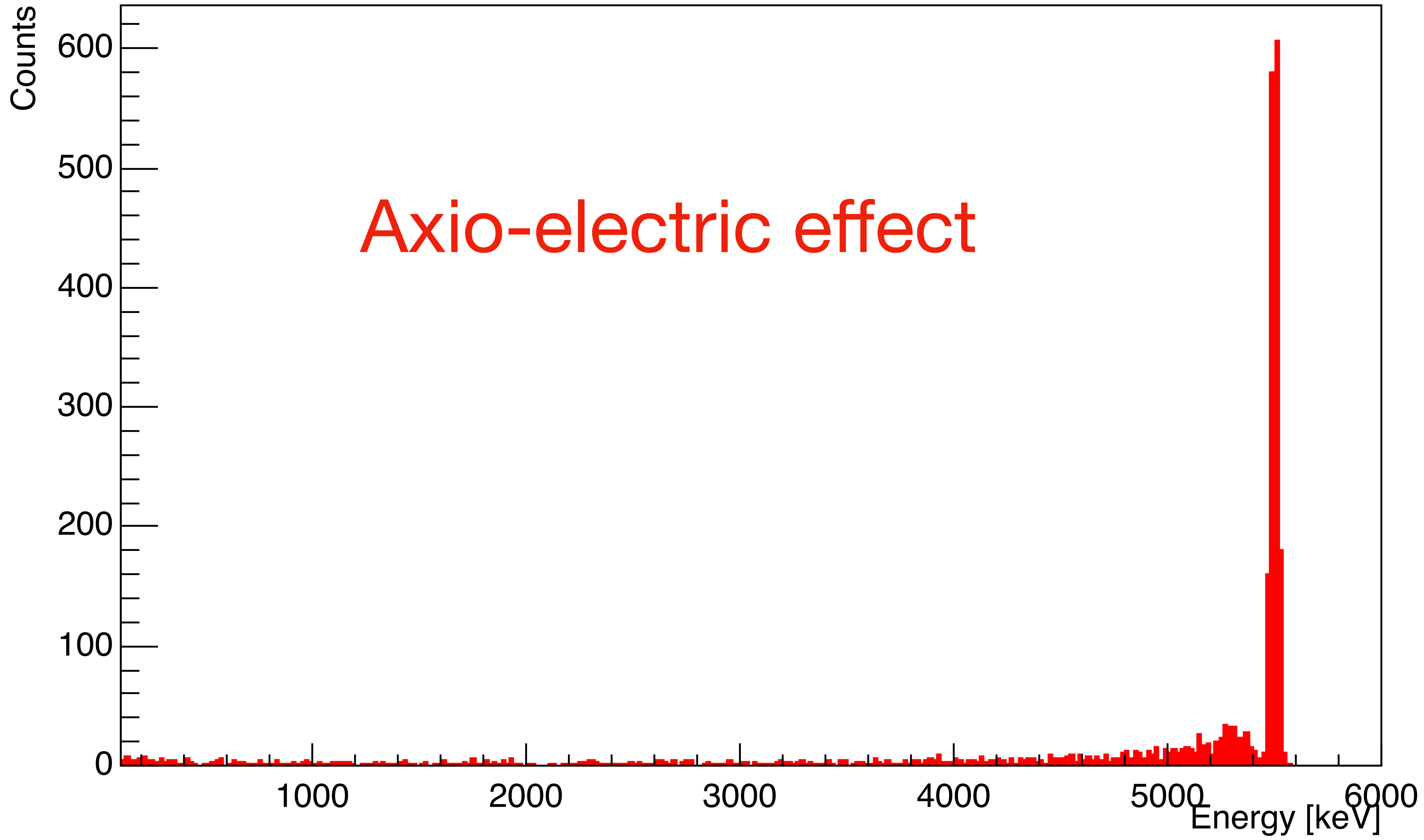


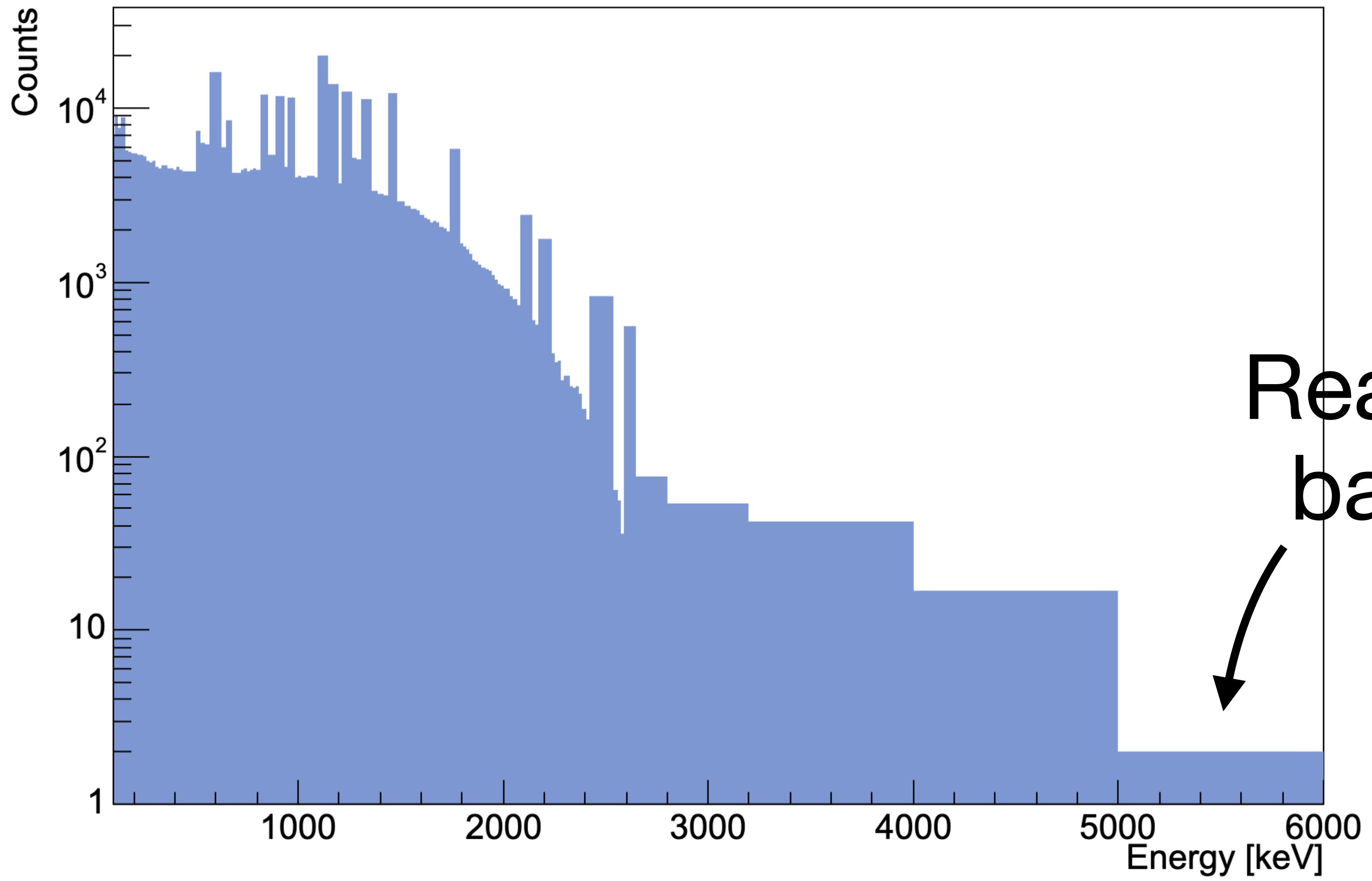
MC simulations of β/γ events contained in a single crystal

Search for solar axions

Analysis method

It features a peak as main signature





Really low β/γ background

Energy spectrum of β/γ events contained in a single crystal

We restrict to the peak region: [5.45, 5.55] MeV

Search for solar axions

Analysis method

Goal: convert the upper bound on the number of axio-electric interactions S into an upper bound on the product $|g_{aN}^{(3)} g_{ae}|$

$$S = \Phi_a \, \sigma_{ae} \underbrace{N_{ZnSe} \, \Delta T}_{\text{Exposure}} \epsilon_{det} \, \epsilon_{sig}$$

Solar axions flux

$$\Phi_a \approx 0.54 \, (g_{aN}^{(3)})^2 \, \beta_a^3 \, \Phi_{\nu PP}$$

Axio-electric effect cross section

$$\sigma_{ae} = 2(Z\alpha m_e)^5 \frac{g_{ae}^2}{m_e^2} \frac{p_e}{p_A} \times \left[\frac{4E_A(E_A^2 + m_A^2)}{(p_A^2 - p_e^2)^4} - \frac{2E_A}{(p_A^2 - p_e^2)^3} \right.$$
$$\left. - \frac{64}{3} p_e^2 p_A^2 m_e \frac{m_A^2}{(p_A^2 - p_e^2)^6} - \frac{16 m_A^2 p_A^4 E_e}{(p_A^2 - p_e^2)^5} - \frac{E_A}{p_e p_A (p_A^2 - p_e^2)^2} \ln \left| \frac{p_e + p_A}{p_e - p_A} \right| \right]$$

Exposure

Data selection efficiency

95.7%

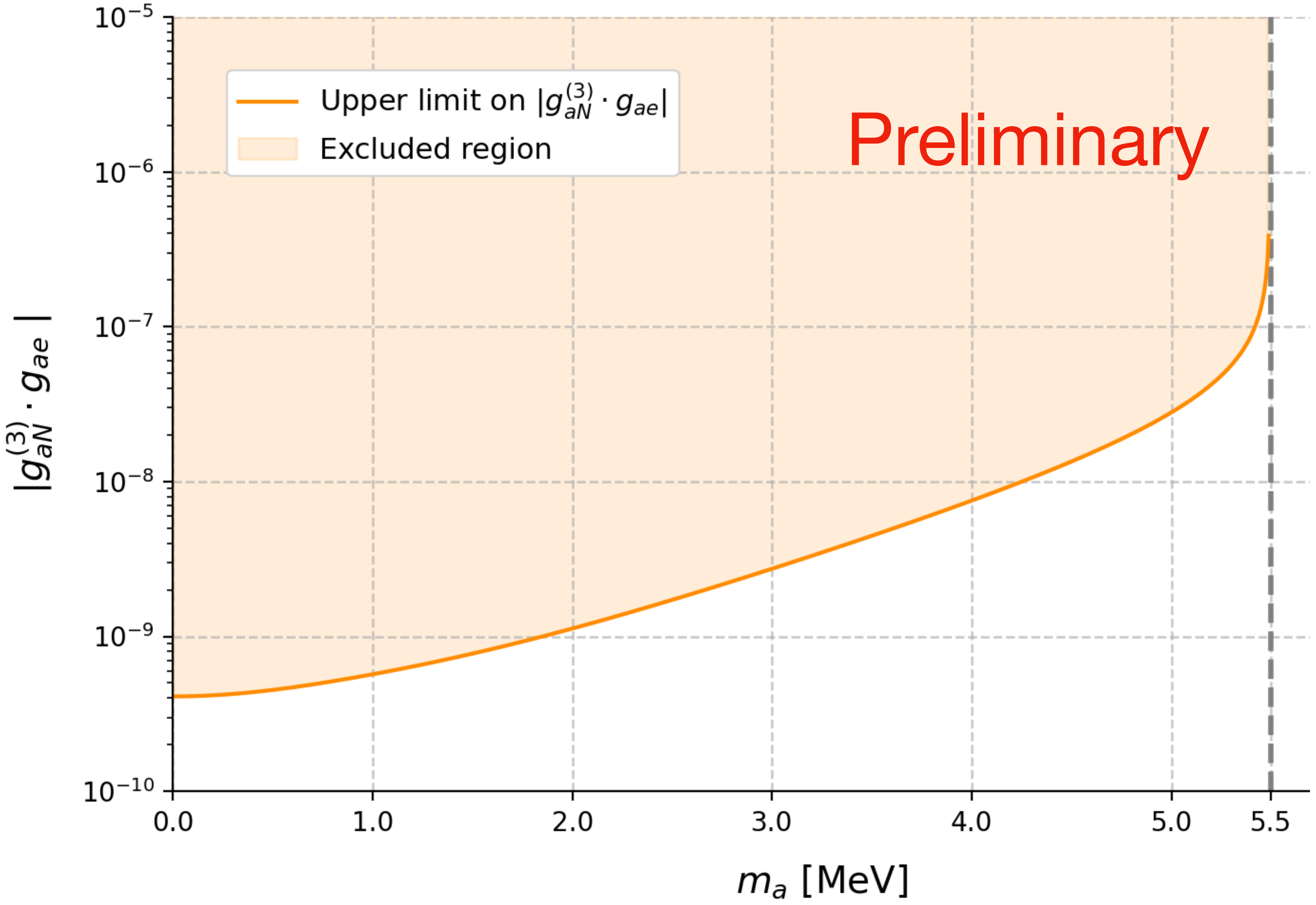
Peak cut efficiency

39%

Search for solar axions

Preliminary results

- No observed events in the peak region → Upper limit from Feldman & Cousins procedure



Preliminary

$$\boxed{|g_{aN}^{(3)} g_{ae}| \leq 4.1 \times 10^{-10} \text{ at 90\% C.L.}}$$

For $m_a = 0$ eV

Outlook

- ✦ Study the other, more probable, processes
- ✦ Include their whole spectral shapes
- ✦ Exploit their fixed cross section ratios

Thanks for the attention!

Zaragoza, 02/06/2026

BACKUP

Search for sterile neutrinos

- Sterile neutrinos are hypothetical **massive non-interacting** neutrinos
- Introduced to address open problems such as DM and the generation of neutrino masses

How to search for sterile neutrinos with CUPID-0?

- They could **mix** with the Standard Model *active* neutrinos → they can contribute to the processes involving neutrinos
- One of these is double β decay

Being one of the main backgrounds, double β decay is measured with high precision in experiments dedicated to the 0νββ, like CUPID-0

Search for sterile neutrinos

Bayesian fit methods

To disentangle the different background sources and the signal, we exploit

- Particle identification capabilities $\rightarrow \alpha$ or β/γ
- Multiplicity information (# crystals involved in an event) $\rightarrow 1$ or 2 crystals

Simultaneous fit of 4 spectra

- β/γ events in 1 crystal
- α events in 1 crystal
- 2 crystals events: single energy
- 2 crystals events: total energy

The posterior p.d.f.s are sampled via MCMC, implemented in BAT.

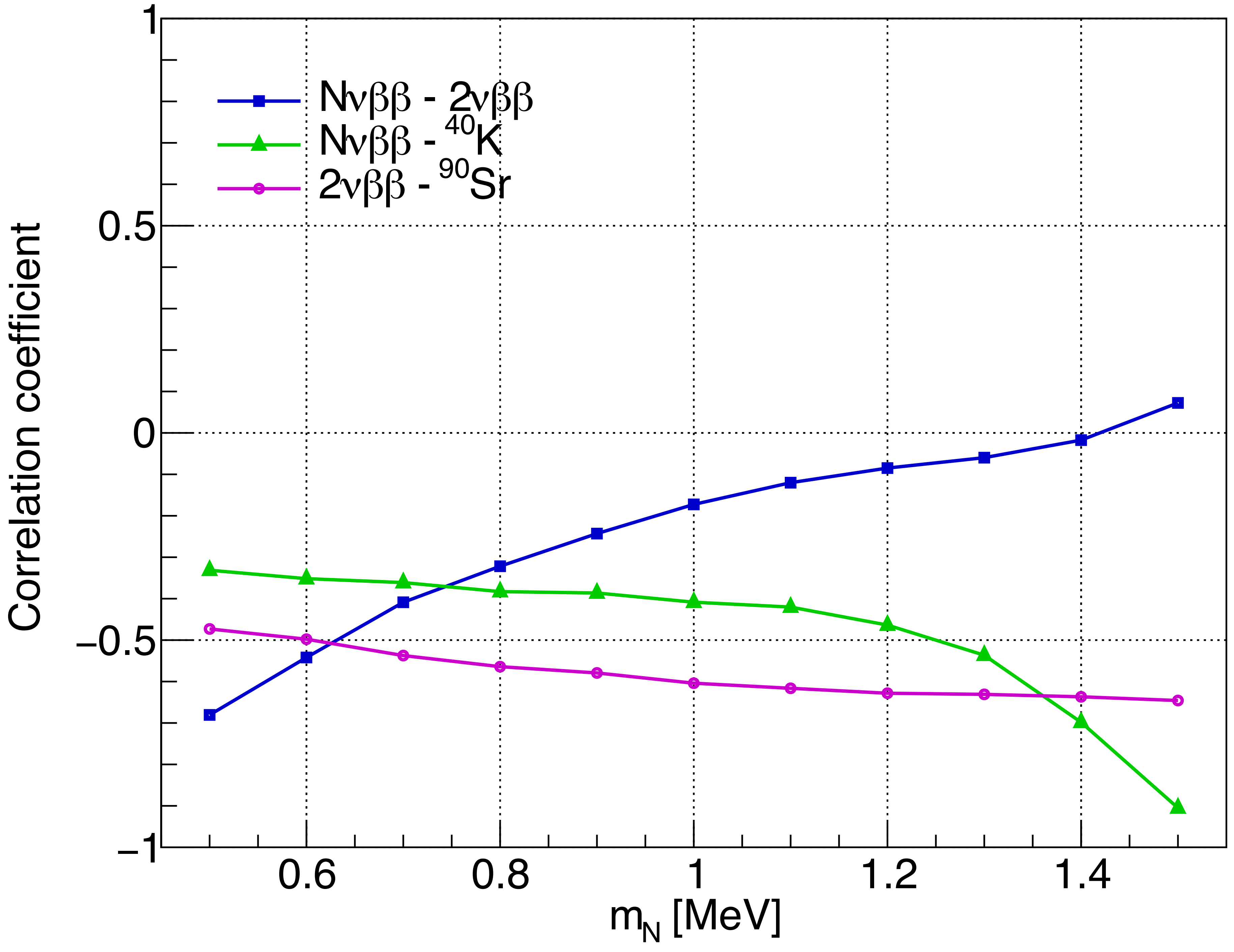
Priors: - gaussian on previously constrained contaminations
- uniform in physically allowed ranges if no previous information
- uniform prior in [0,1] for $\sin^2\theta$

Search for sterile neutrinos

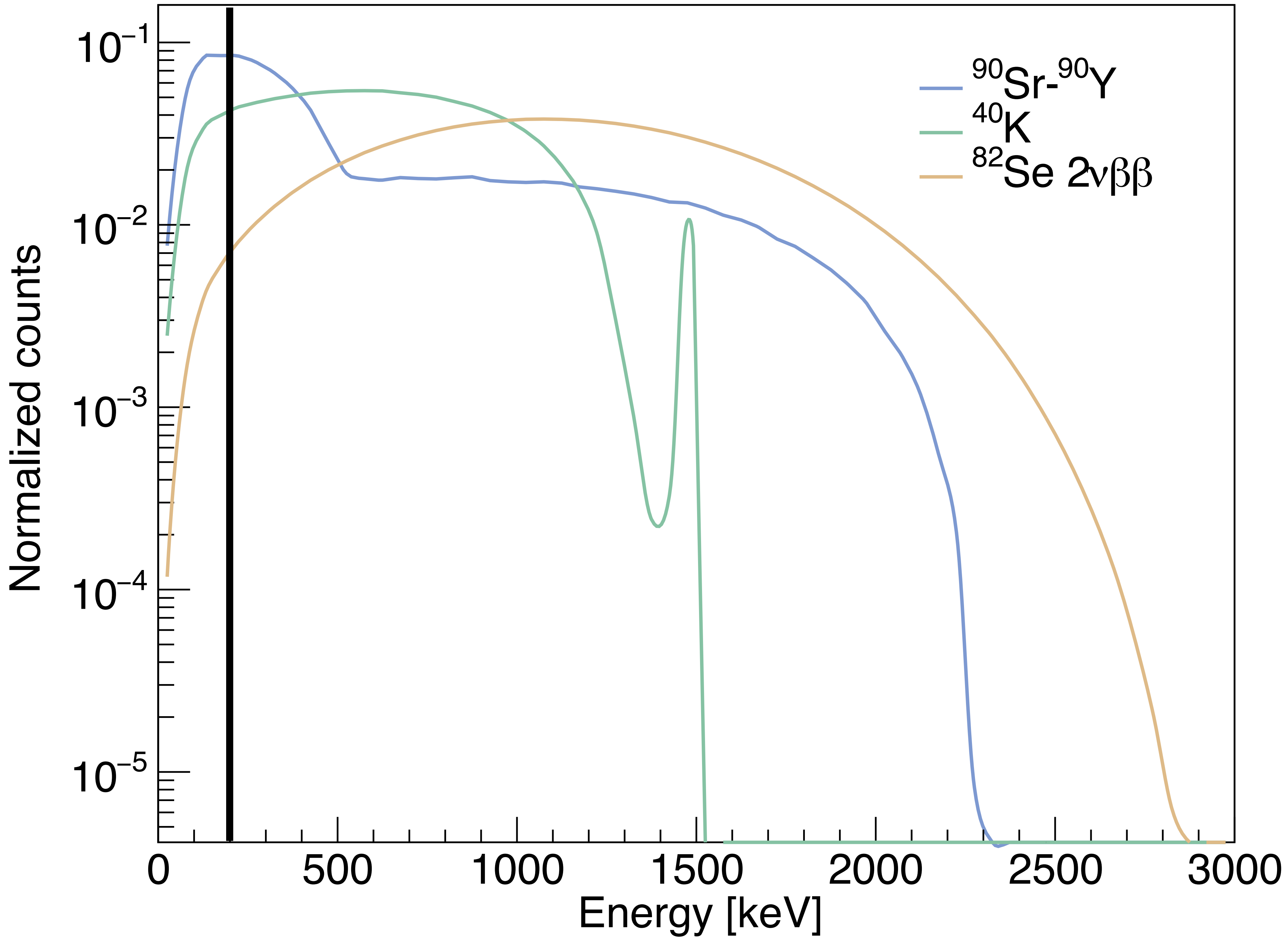
Bayesian fit

Correlations between the signal and background spectra are a source of loss of sensitivity

Main observed correlations



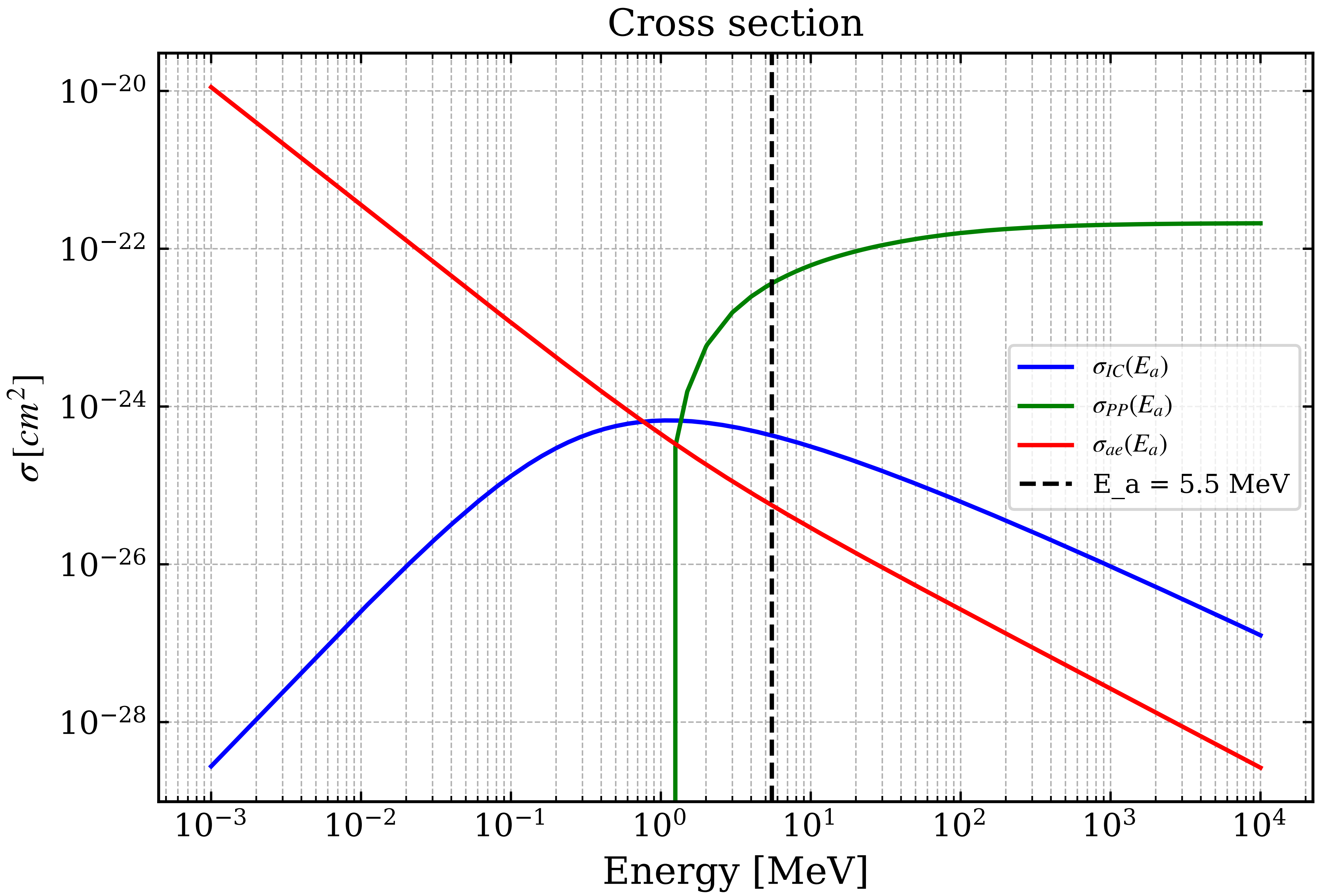
Single crystal, β/γ events



Search for solar axions

Cross sections details

For an axion of $m_a = 100\ eV$, $E_a = 5.5$ MeV, the cross sections are in the ratios **1:8:650**



$$\sigma_{IC} = \frac{g_{ae}^2 \alpha}{8 m_e^2 |\vec{k}_a|}\left[\frac{2m_e^2(m_e+E_a)y}{(m_e^2+y)^2} + \frac{4m_e\left(m_a^4+2m_a^2m_e^2-4m_e^2E_a^2\right)}{y(m_e^2+y)} + \frac{4m_e^2|\vec{k}_a|^2+m_a^4}{|\vec{k}_a|\,y}\ln\left|\frac{m_e+E_a+|\vec{k}_a|}{m_e+E_a-|\vec{k}_a|}\right|\right]$$

$$\sigma_{aee}(E_a) \simeq 2.6\frac{g_{ae}^2}{4\pi\alpha}\sigma_{\gamma ee}(E_a)$$

If $m_a \ll m_e$

$$\sigma_{Ae} = 2(Z\alpha m_e)^5 \frac{g_{Ae}^2}{m_e^2}\frac{p_e}{p_A} \times \left[\frac{4E_A(E_A^2+m_A^2)}{(p_A^2-p_e^2)^4} - \frac{2E_A}{(p_A^2-p_e^2)^3} - \frac{64}{3}p_e^2p_A^2m_e\frac{m_A^2}{(p_A^2-p_e^2)^6} - \frac{16m_A^2p_A^4E_e}{(p_A^2-p_e^2)^5} - \frac{E_A}{p_ep_A(p_A^2-p_e^2)^2}\ln\left|\frac{p_e+p_A}{p_e-p_A}\right|\right]$$