Neutrino self-coupling limits using cryogenic quantum sensors

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Majoron searches with the BeEST experiment

GdR InF

I. Neutrino self-interactions with scalar particle emission

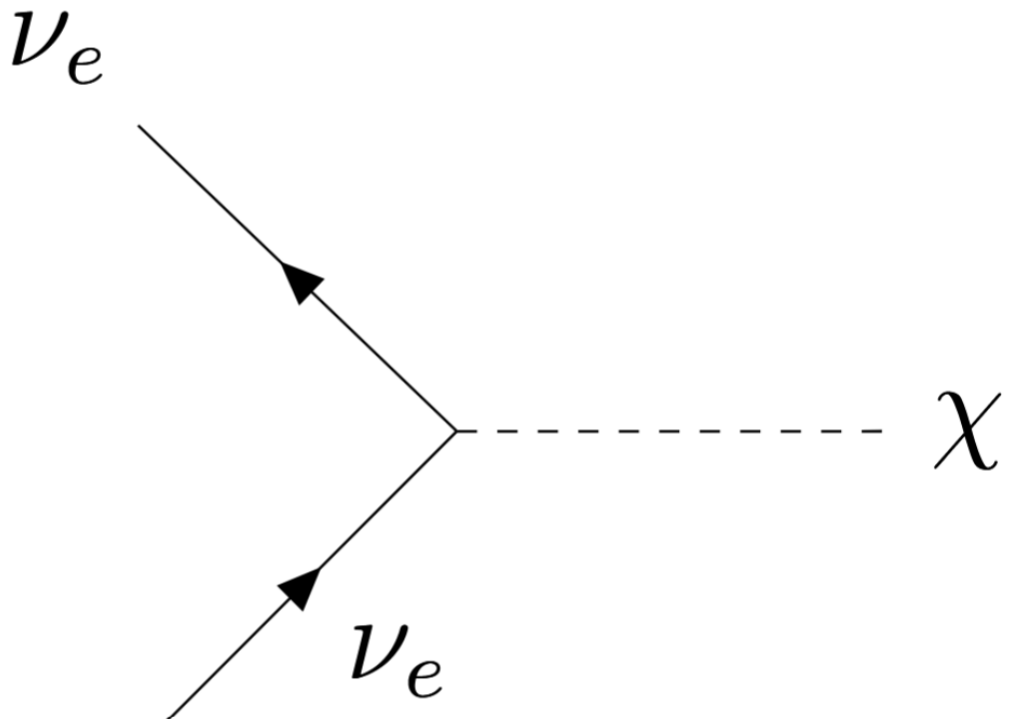
Neutrino self-coupling

- Introduce a new scalar particle :
  The Majoron

- Interesting framework for explaining baryogenesis, dark matter…

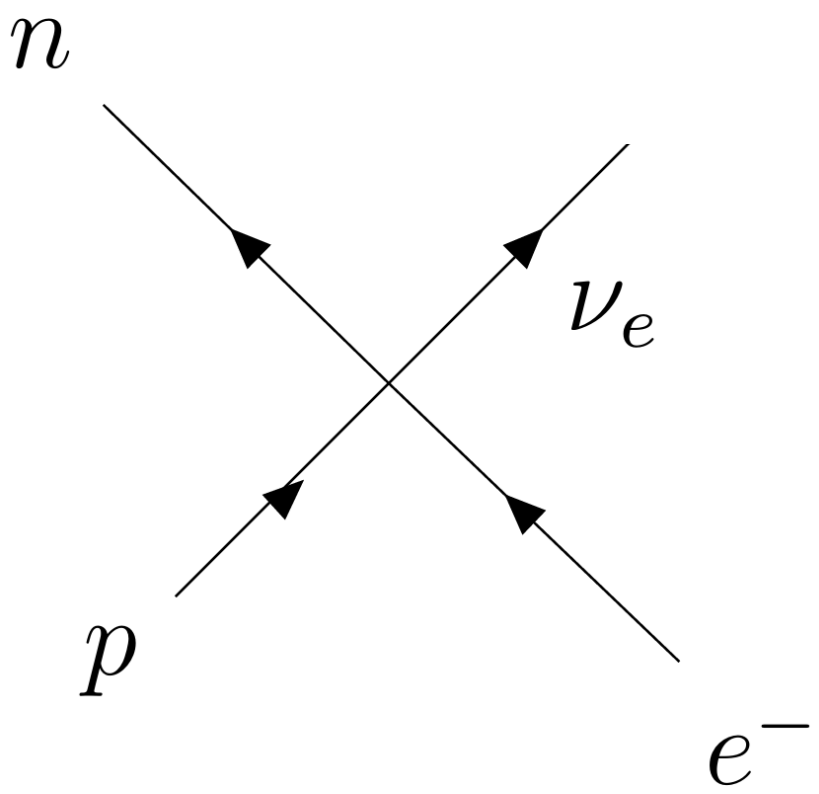
Neutrino self-coupling

- Introduce a new scalar particle : The Majoron
- Interesting framework for explaining baryogenesis, dark matter…
- **Consider a generic vertex with a scalar field**



Majoron three-body decay

- Use electron capture as a means to study the vertex



Majoron three-body decay

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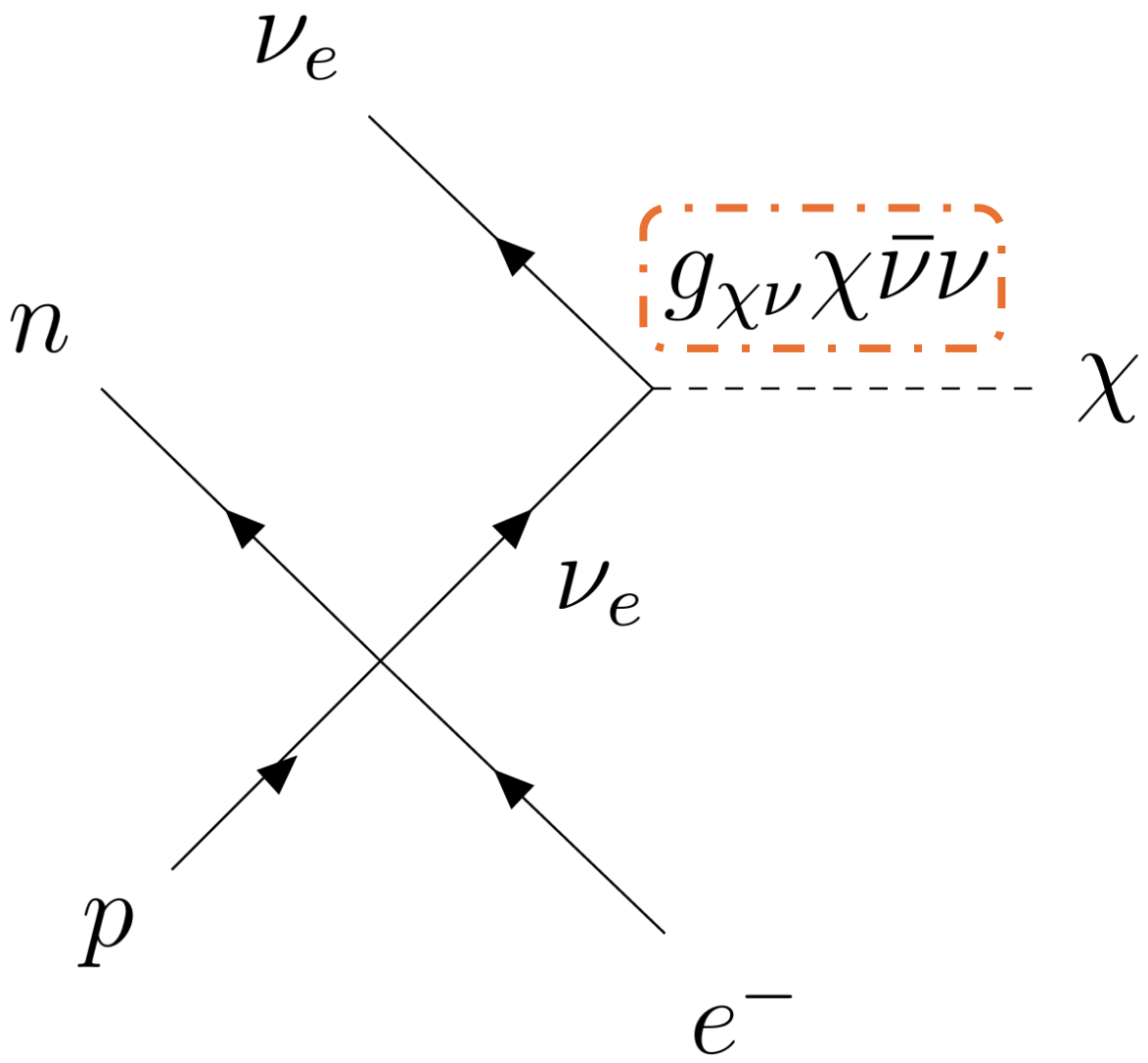
- **Put constraints on g and Majoron mass**



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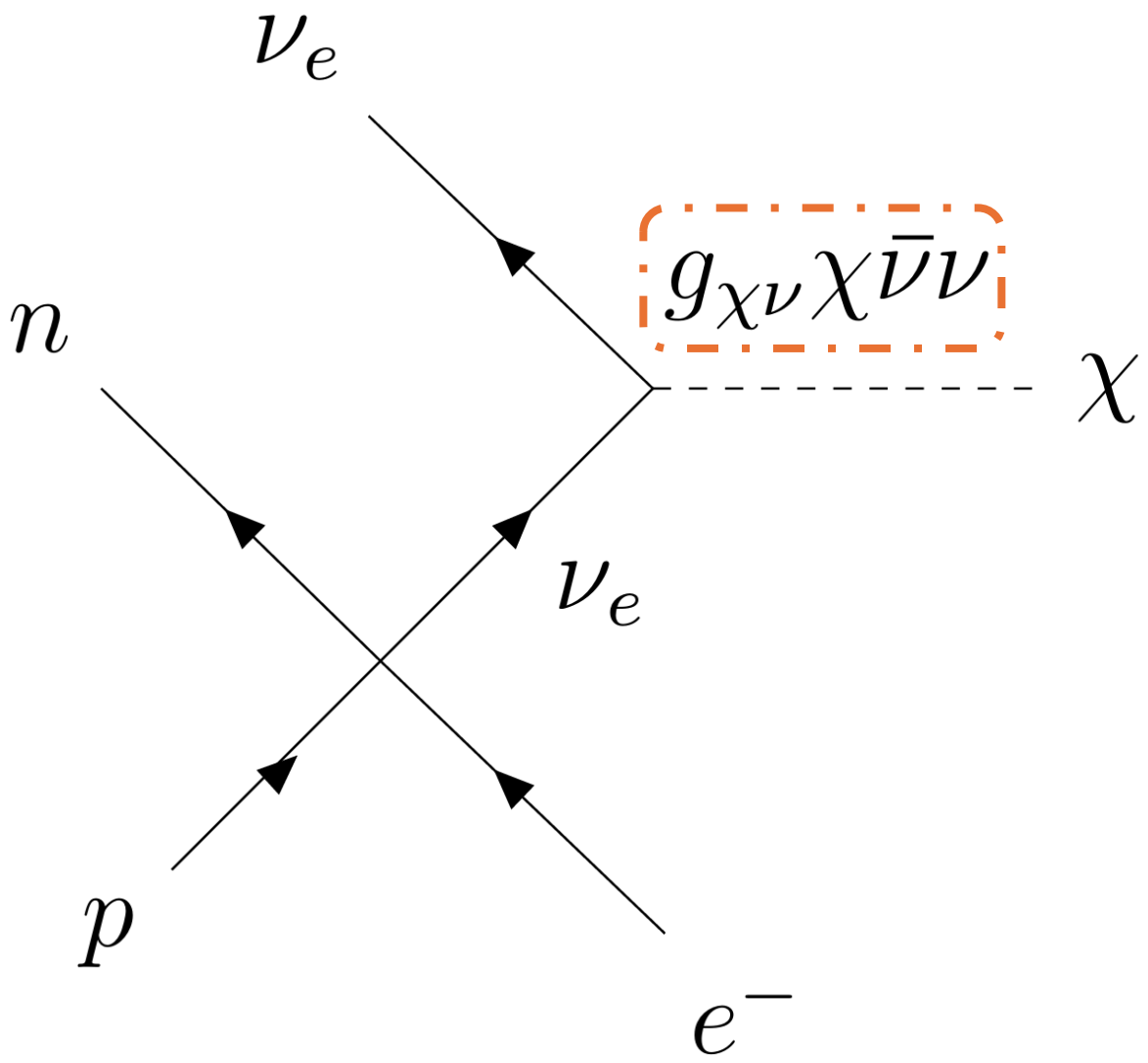
- **Three Body decay : continuous spectrum (discrete in EC)**



Majoron three-body decay

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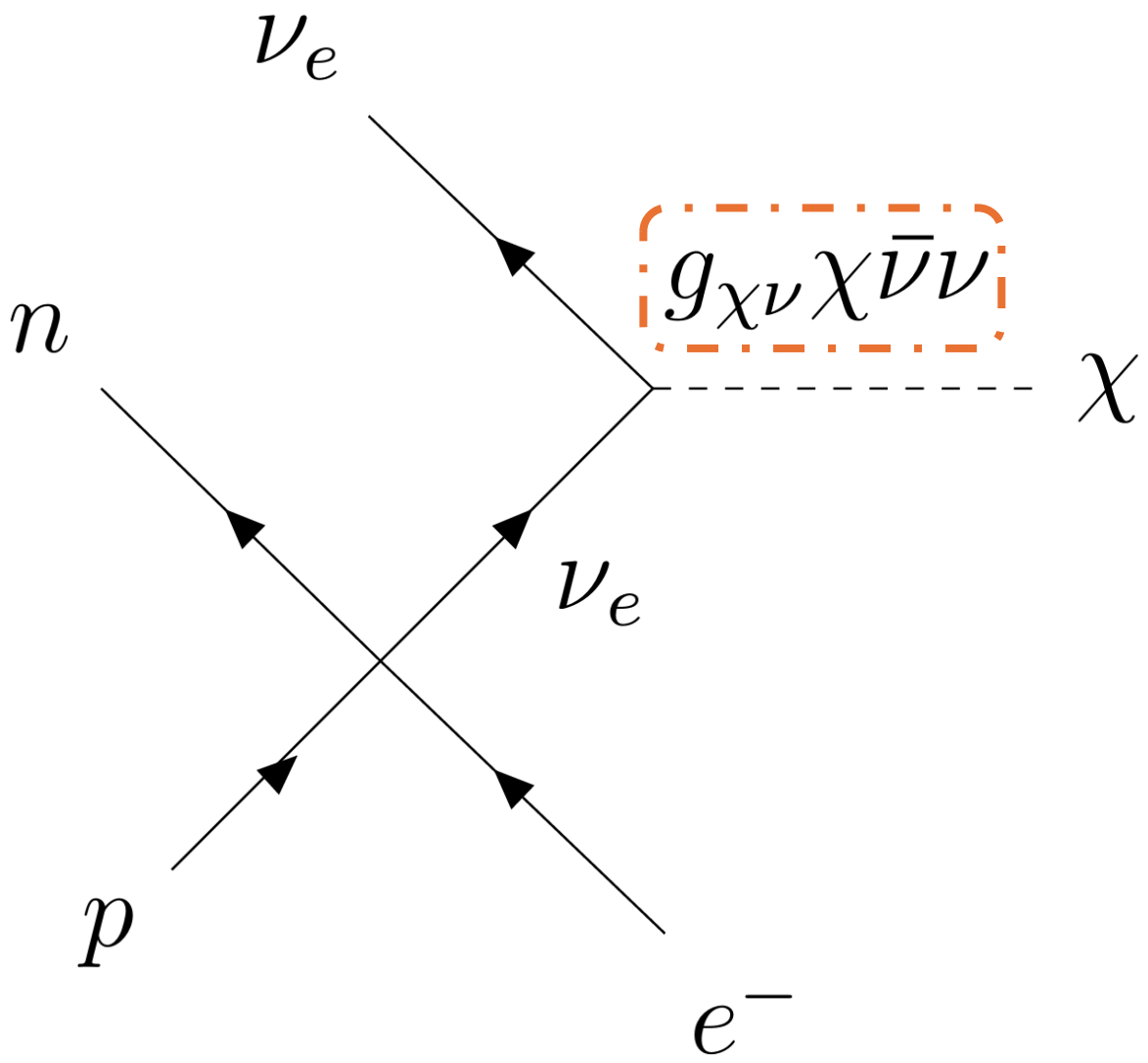
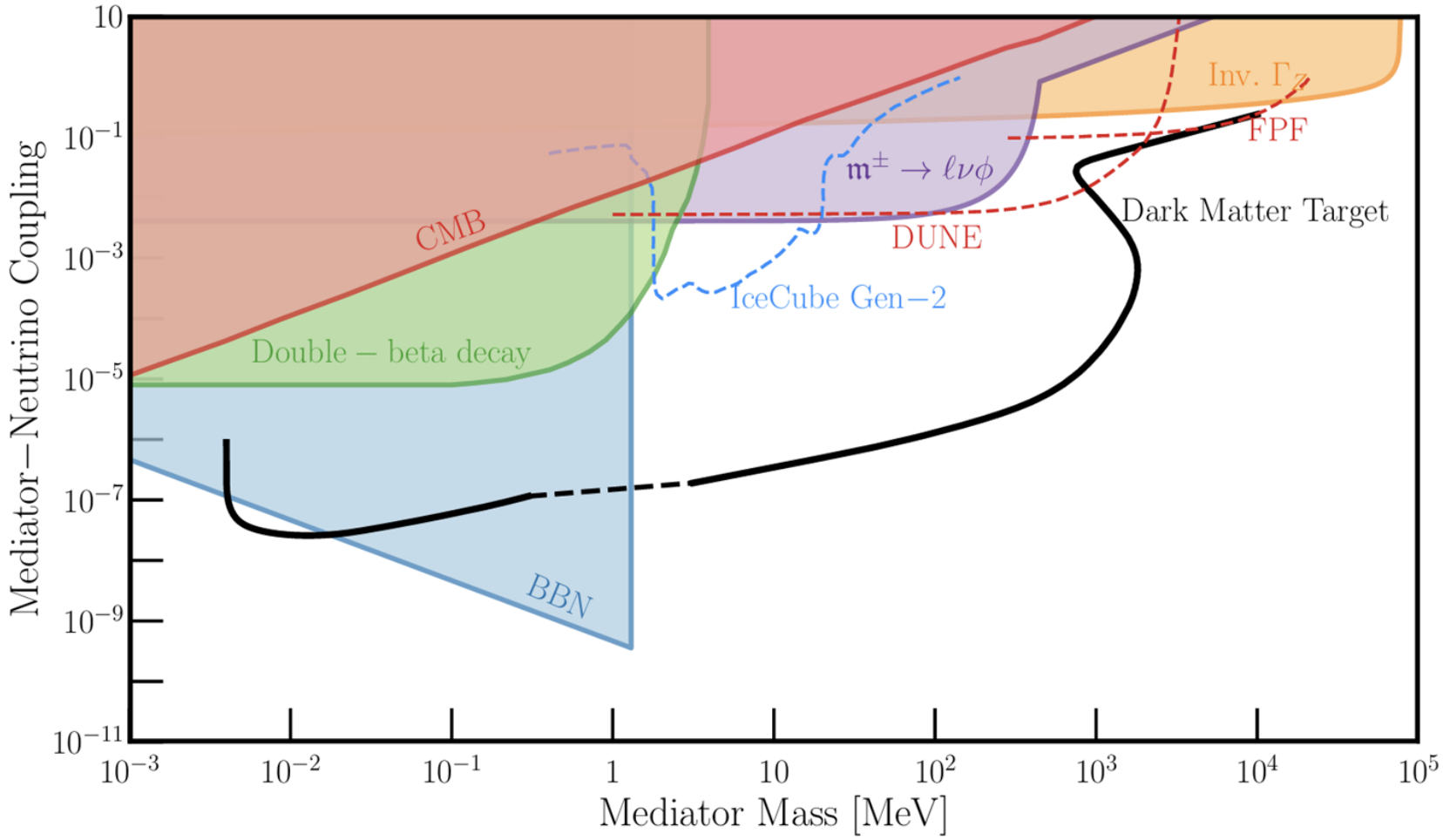
- **Put constraints on g and Majoron mass**
- **Three Body decay : continuous spectrum (discrete in EC)**
- Phenomenological derivations carried out by Dave McKEEN at TRIUMF



Constraints on the Majoron mass and couplings

Neutrino self-interactions constraints : a lot of room



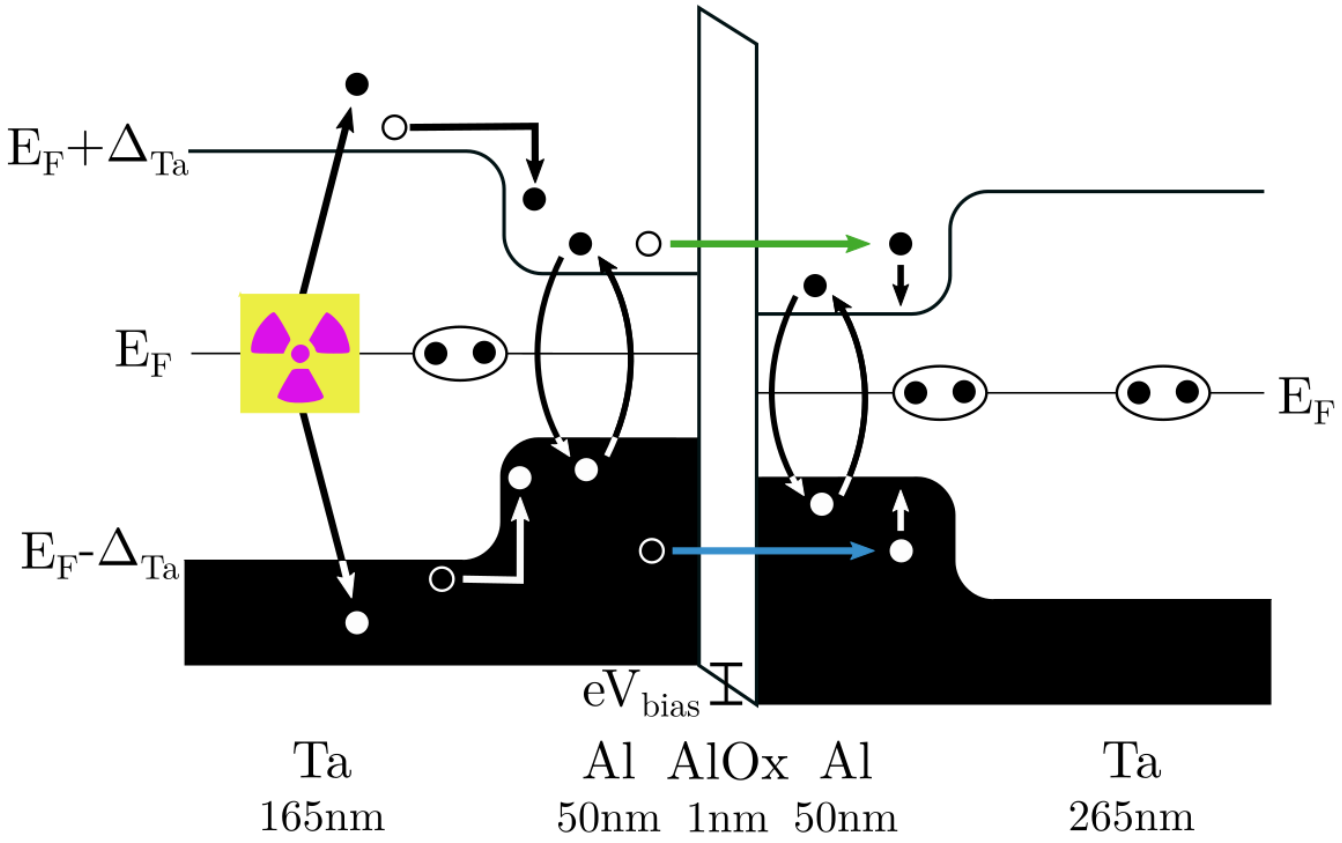
II. Exclusion constraints with Phase II BeEST data

The BeEST experiment

- **Majoron study : prospective work on potential constraints using BeEST data**
- BeEST objective search for heavy neutrinos at the keV-scale
- Recoil measurements of ^{7}Be Electron Capture
- **Nuclei kinetic energies at the eV scale : STJ detectors**

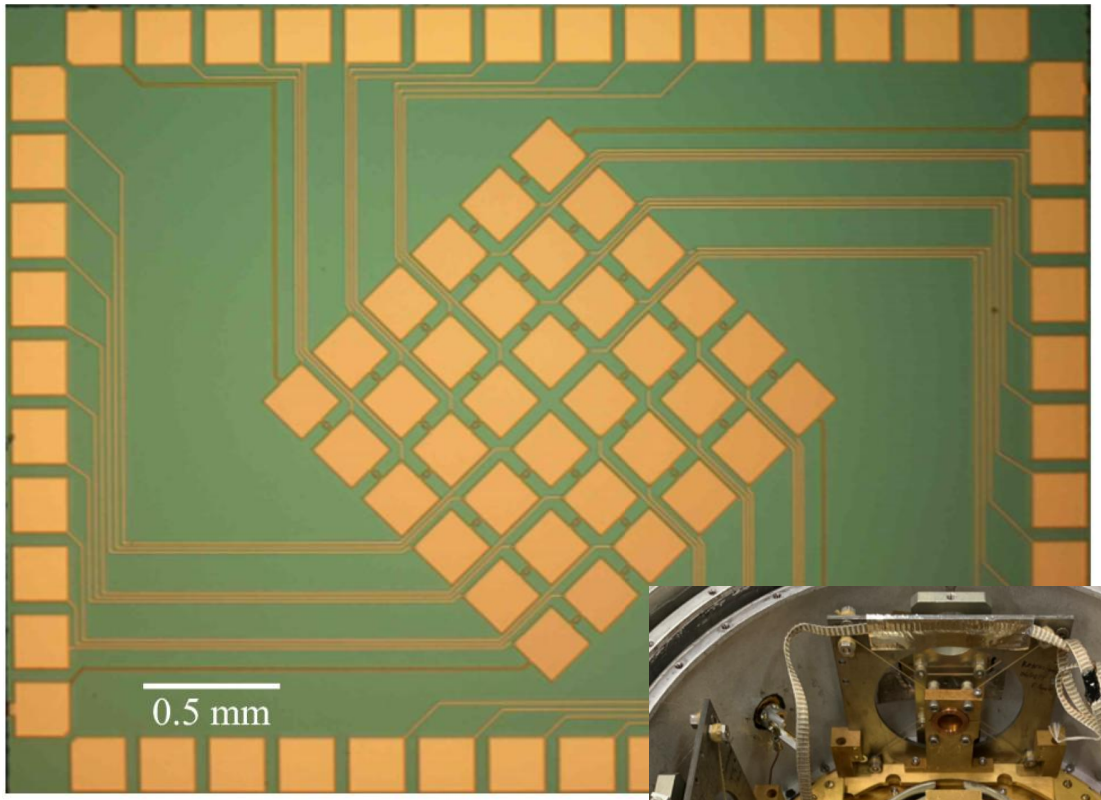
Superconducting Tunnel Junctions

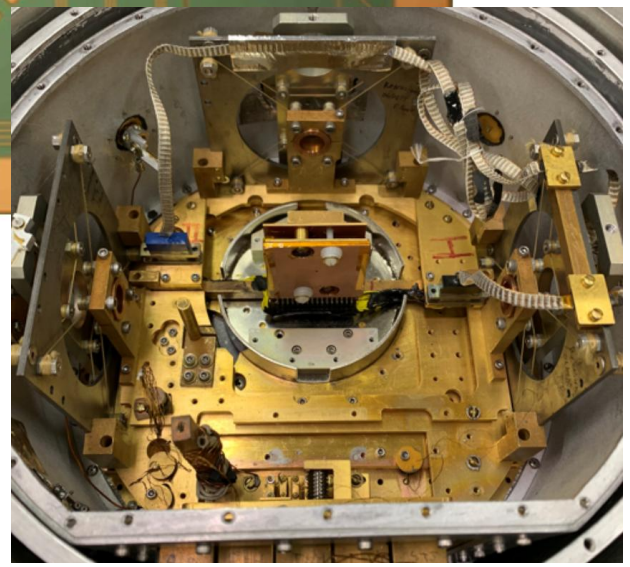
- Five layers detector : absorber, trapping layer, biased isolant, trapping layer and final layer
- Onset of superconductivity : formation of cooper pairs
- Recoil breaks copper pairs and create a quasiparticle
- Quasiparticles scatter down into the trapping layers
- Breaks other pairs in the process
- **Measuring the tunneling current to recompose the momentum of the nucleus**



Superconducting Tunnel Junctions

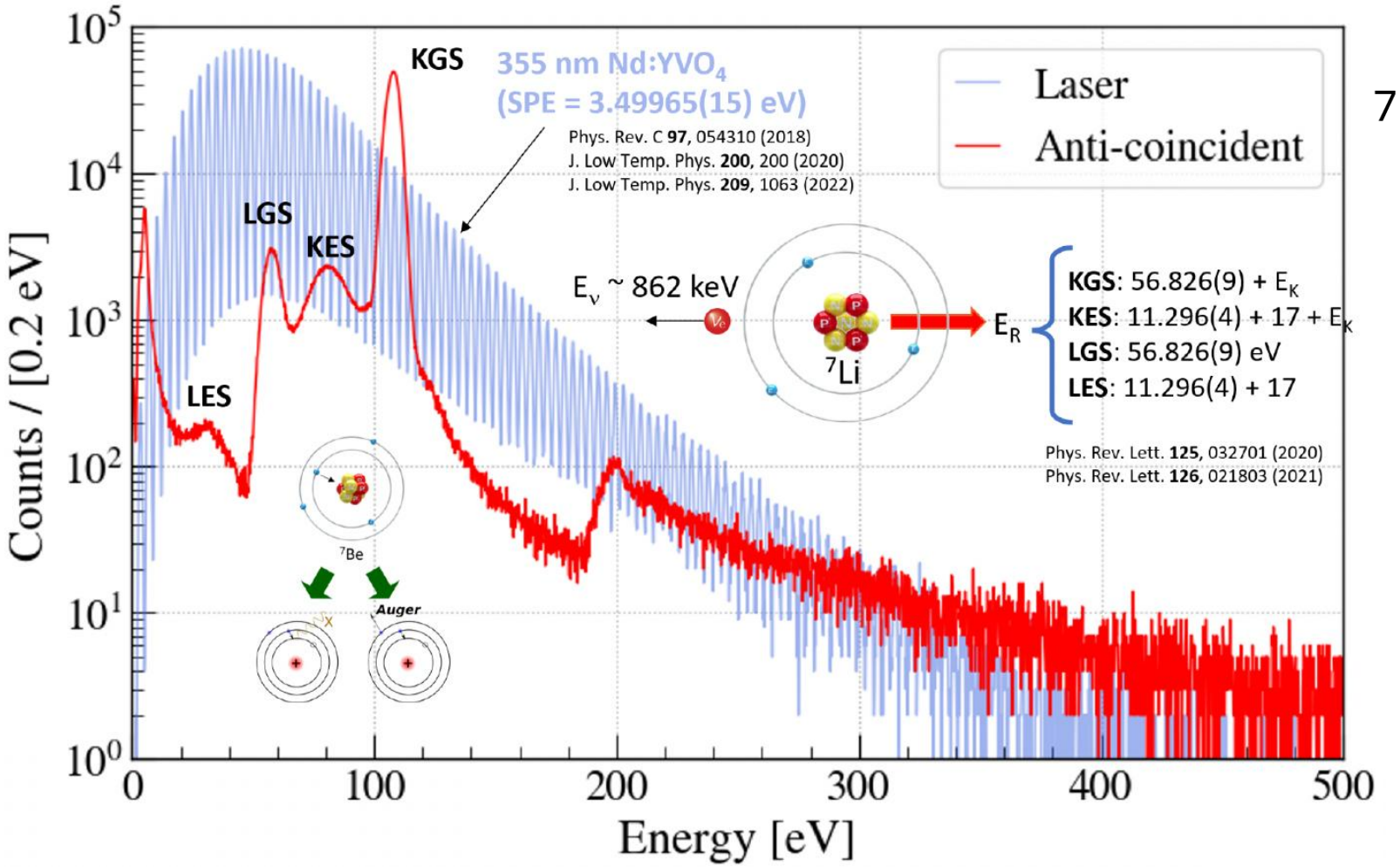
- Superconducting gap of meV
- **Few eV resolution**
- **10^3 counts/s per pixel**
- Low threshold
- ^{7}Be implanted in 36-pixel array for BeEST phase III

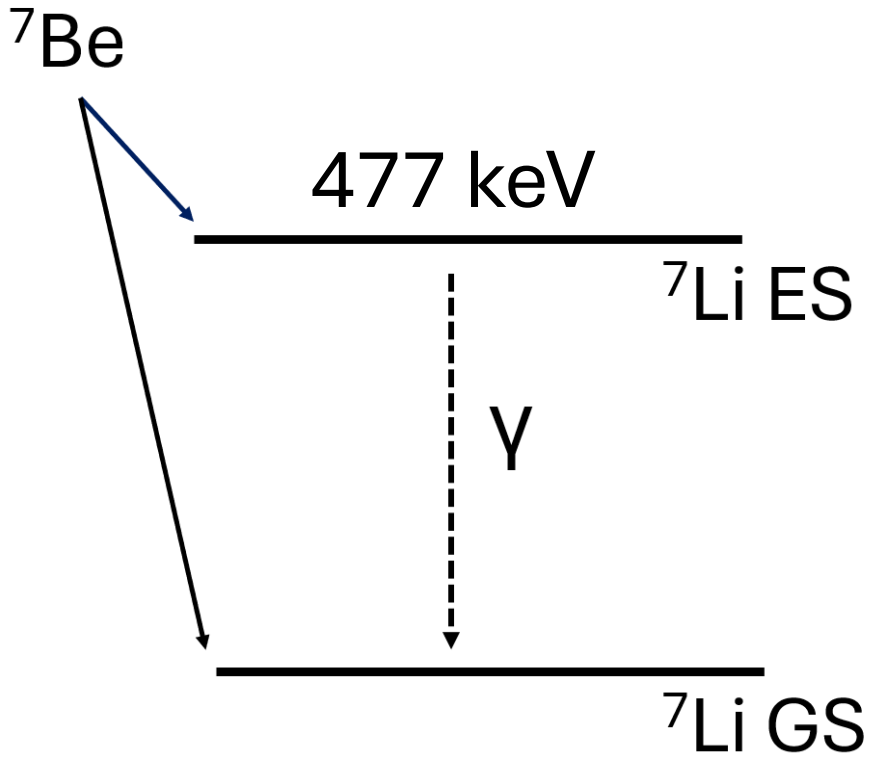




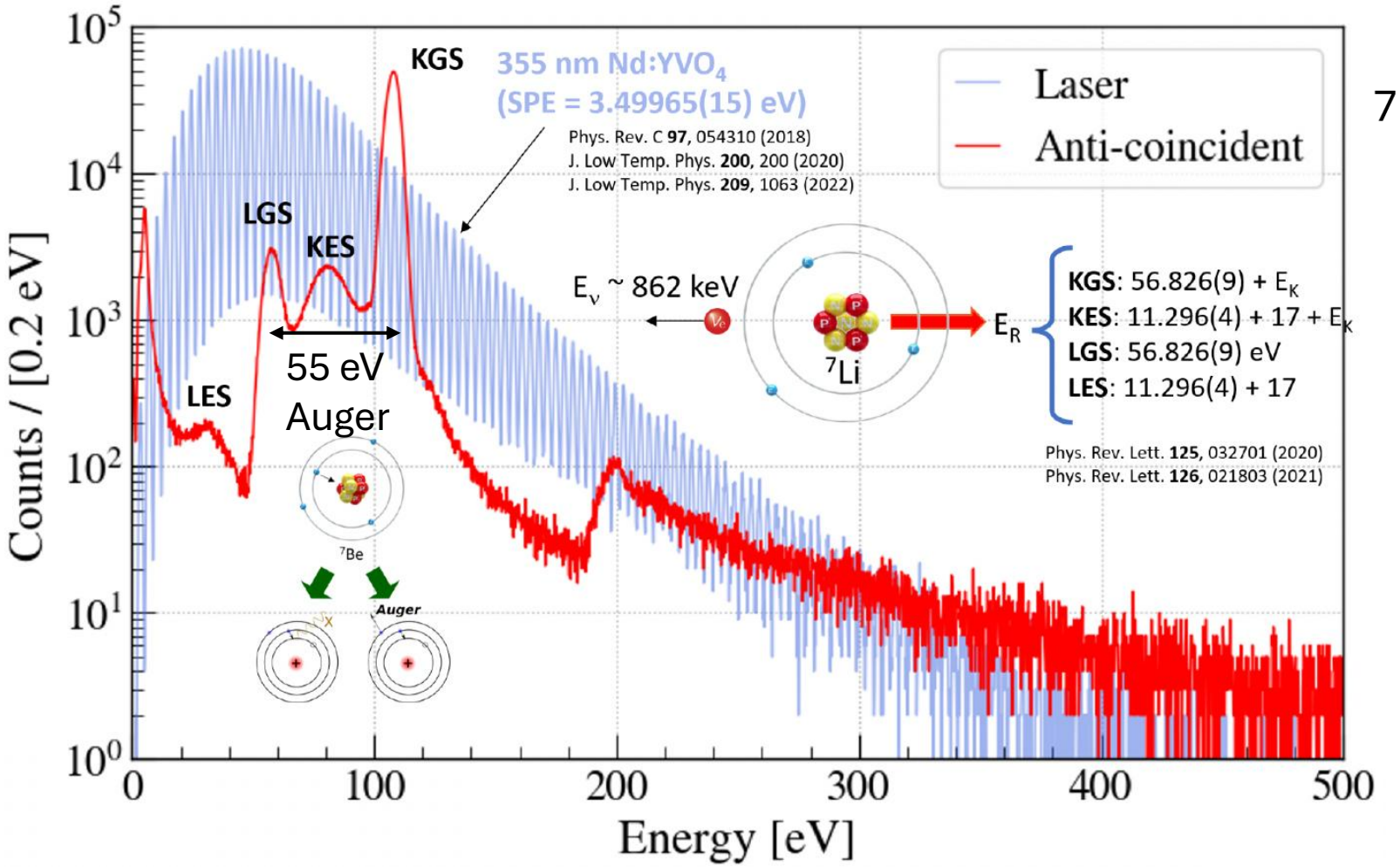
Cooled to 100 mK (ADR)

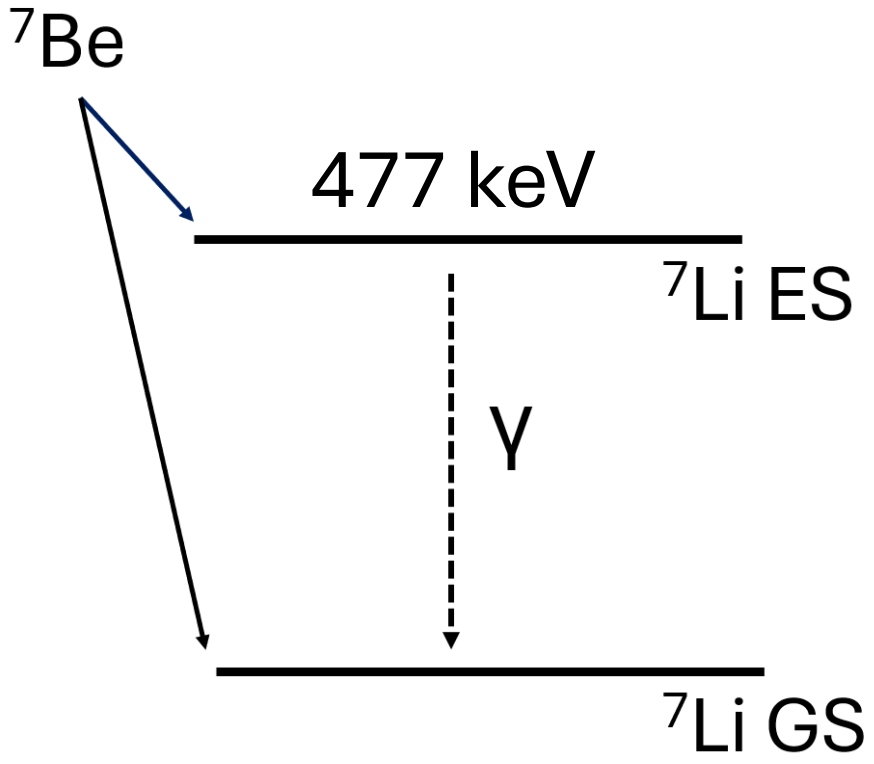
BeEST Electron Capture Spectrum



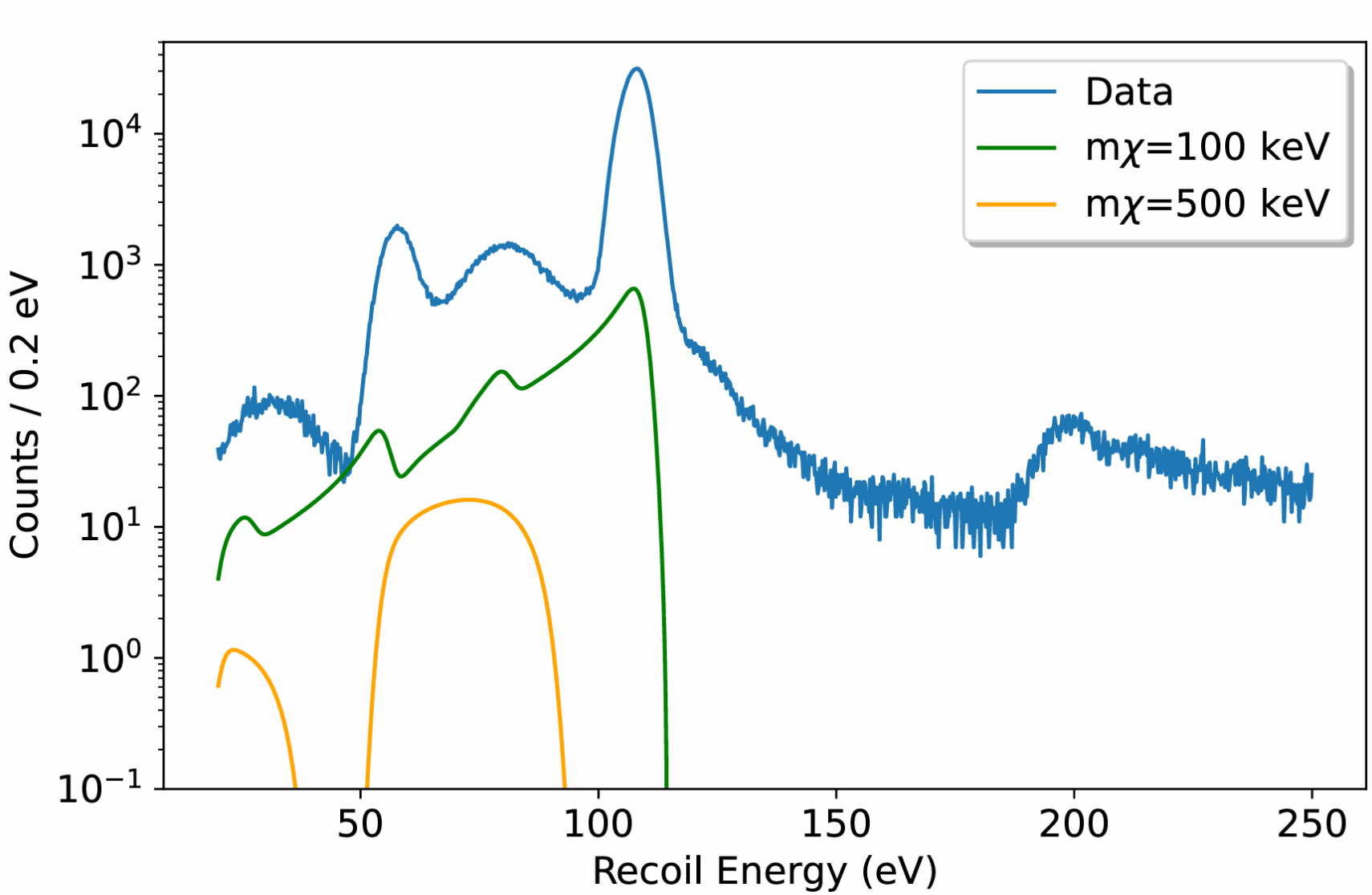


BeEST Electron Capture Spectrum





Majoron Signal shape for g=1



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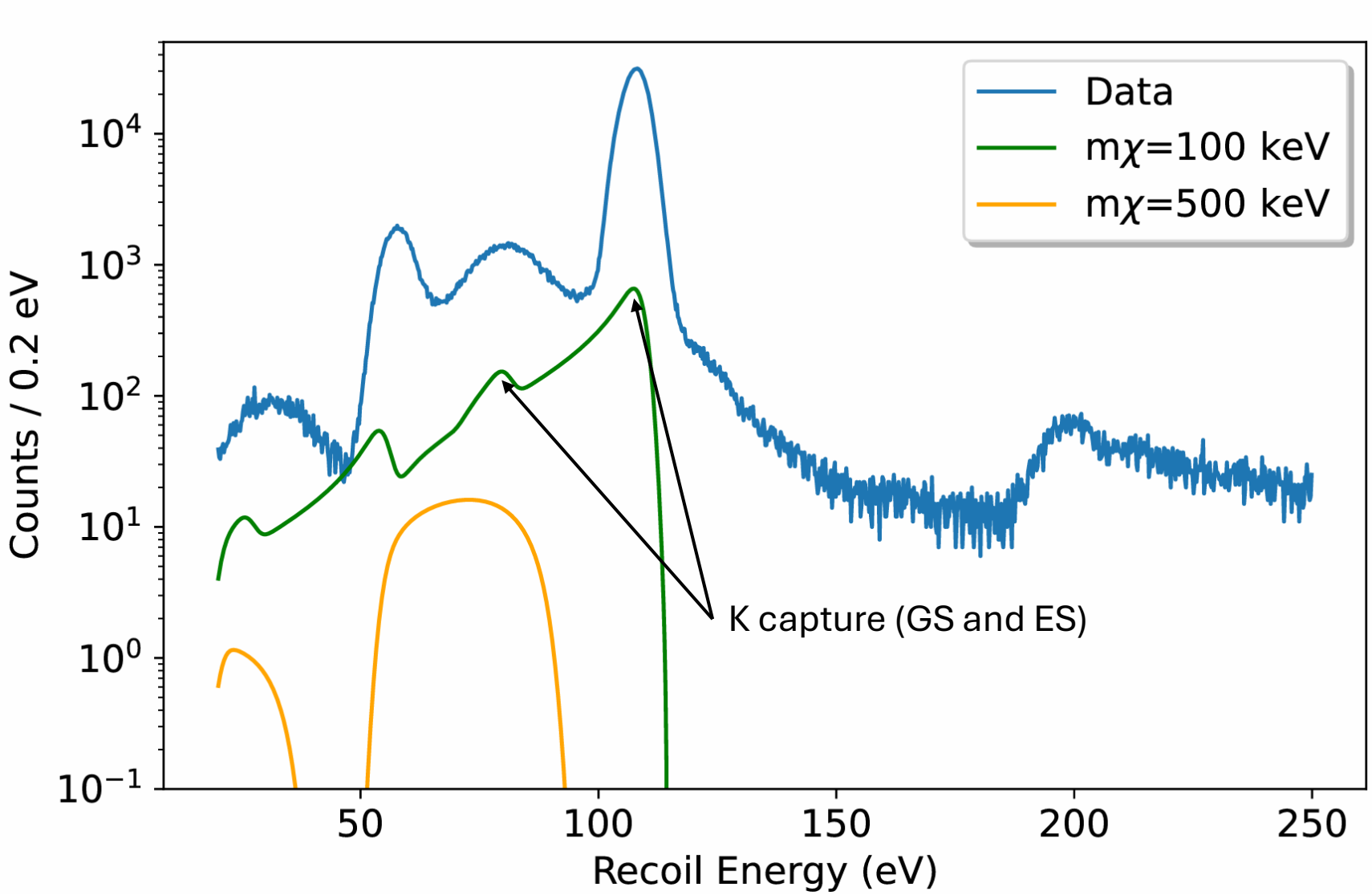

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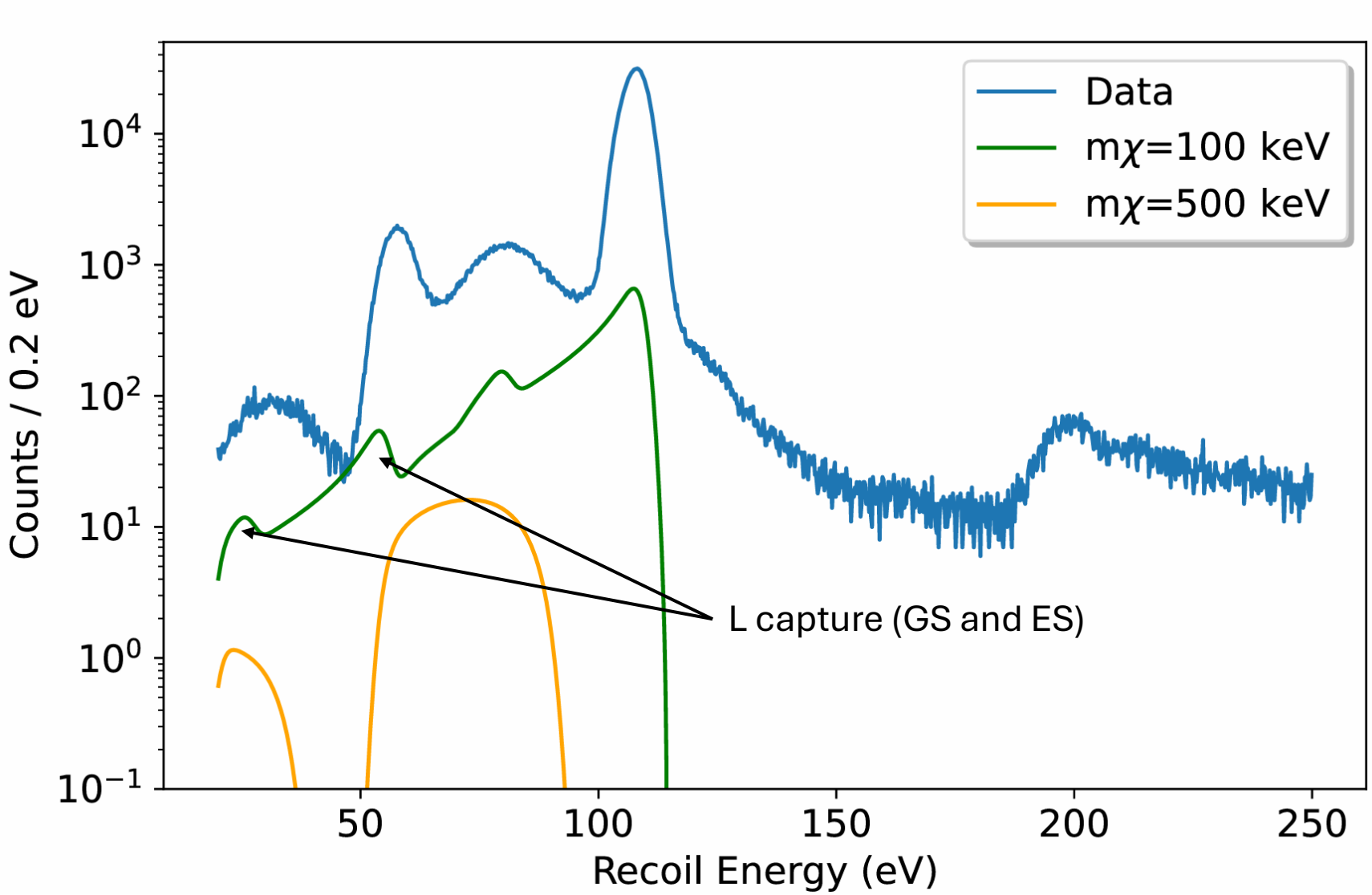

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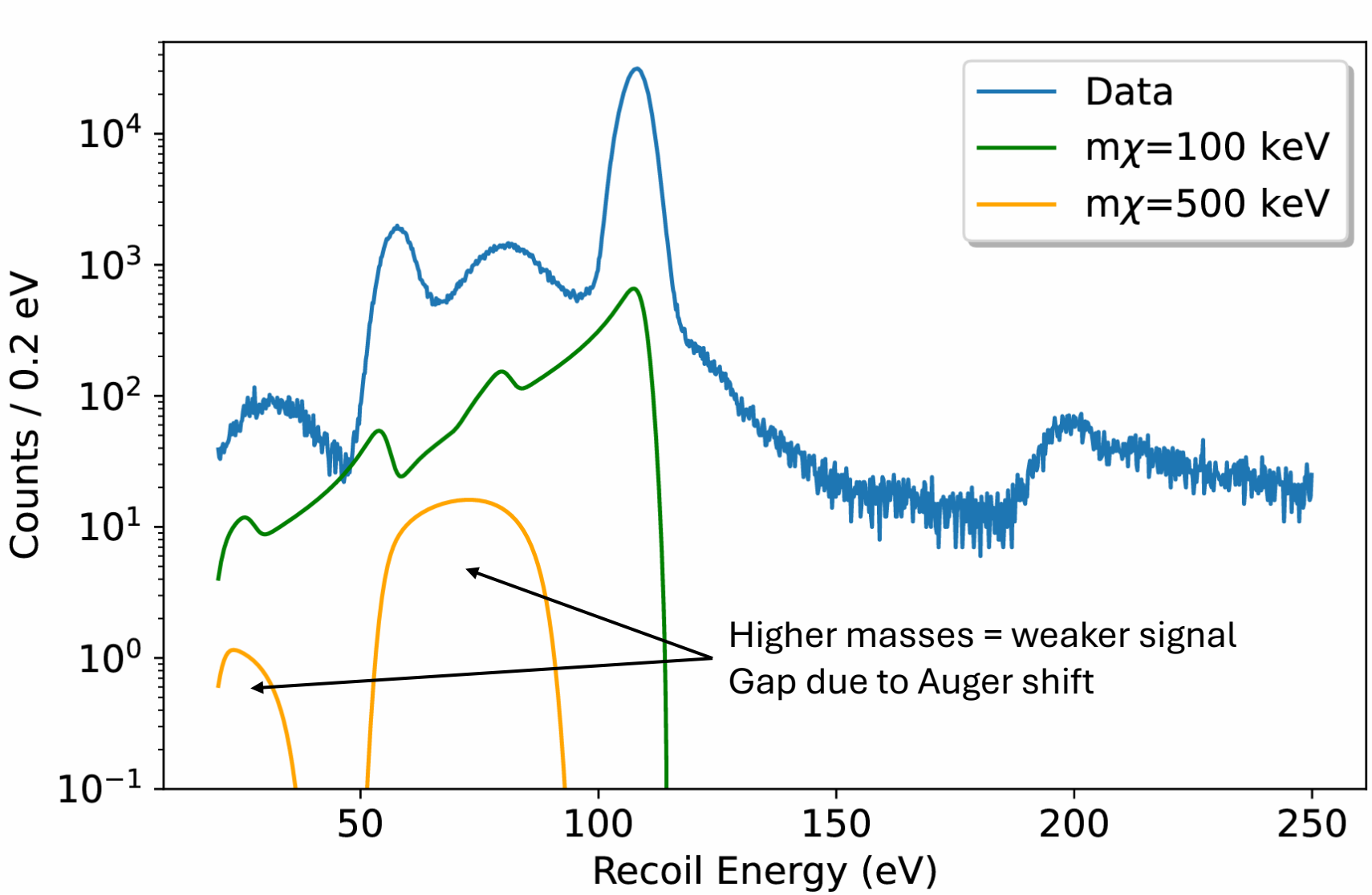

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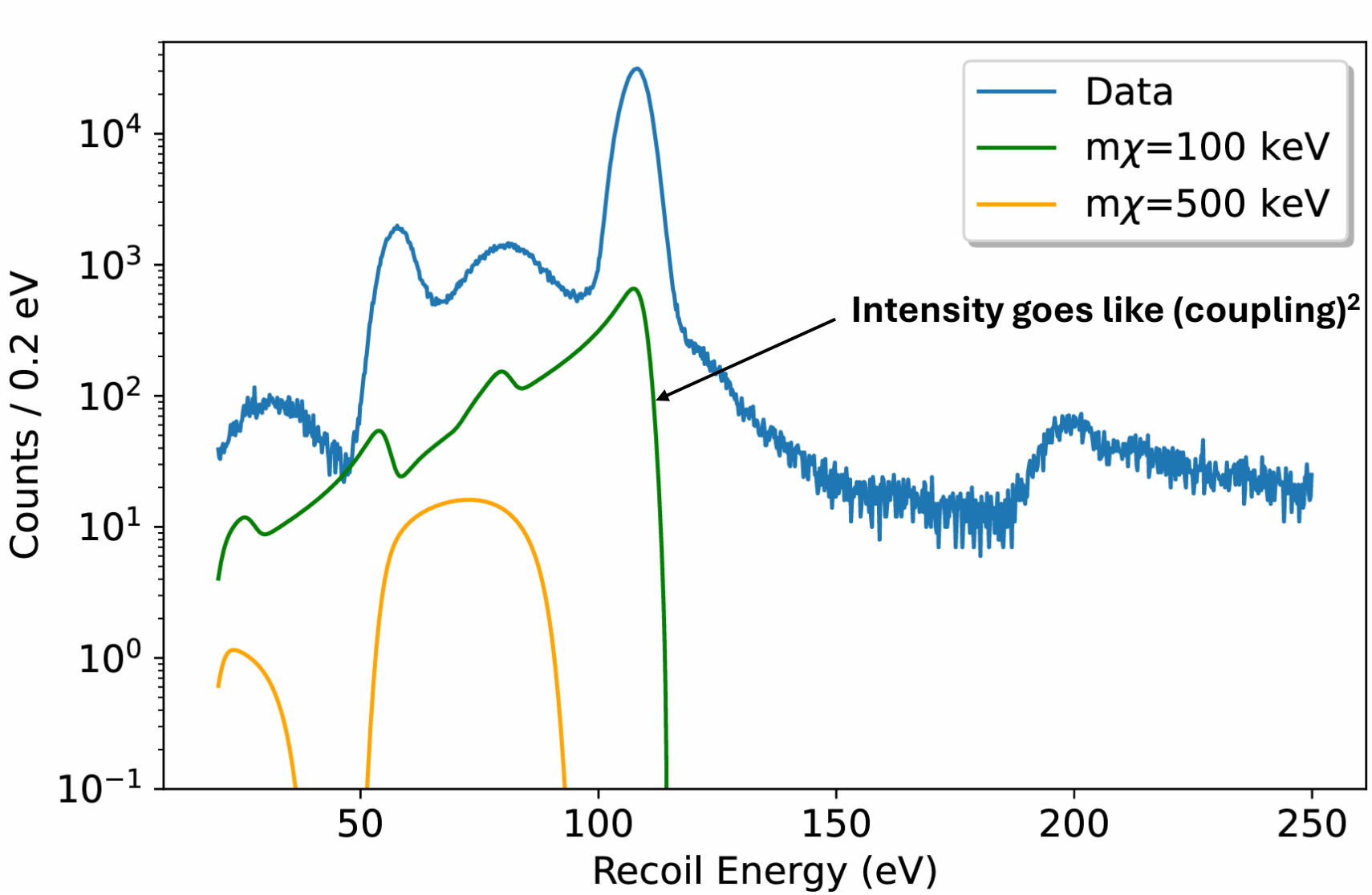
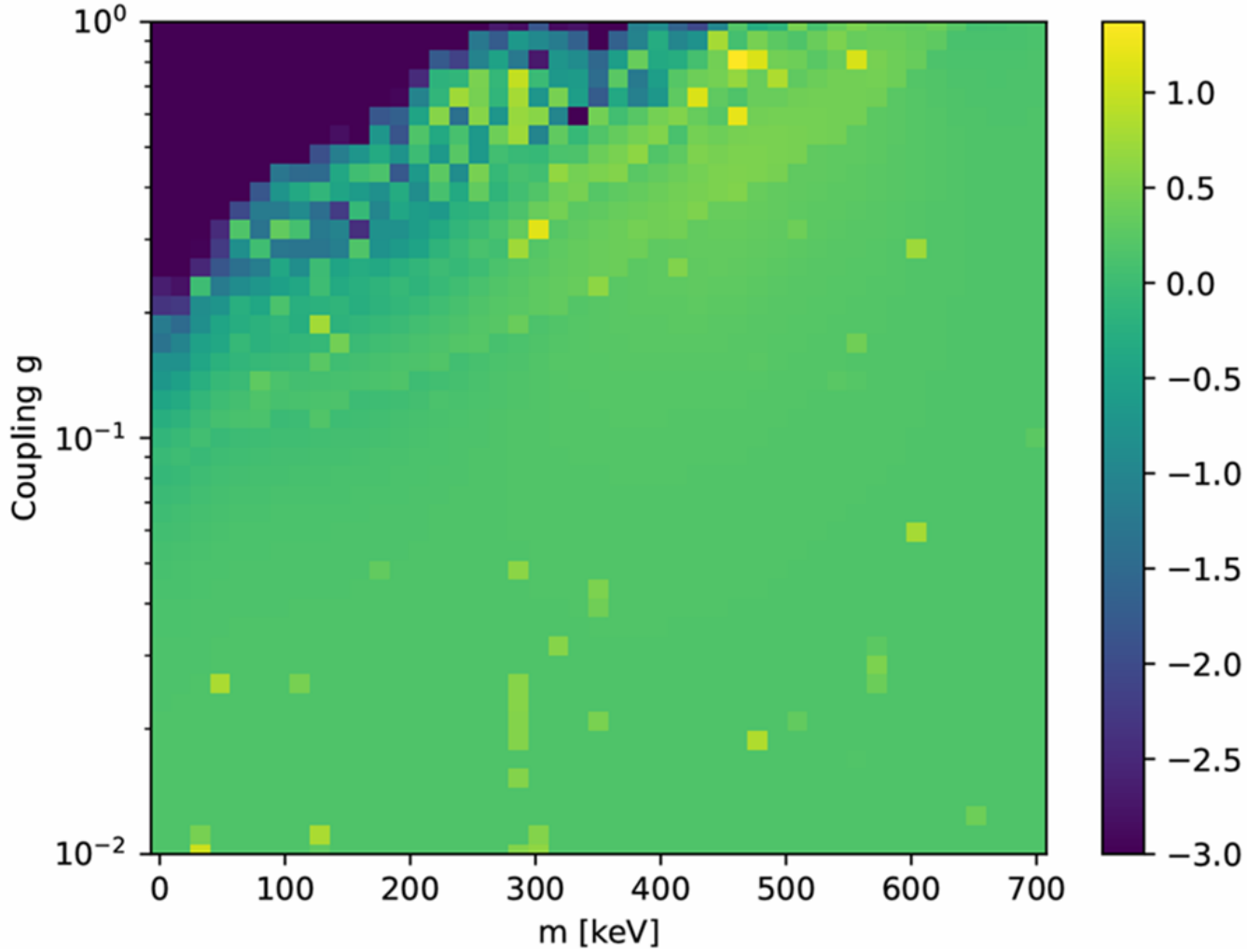


Exclusion plot of coupling and mass

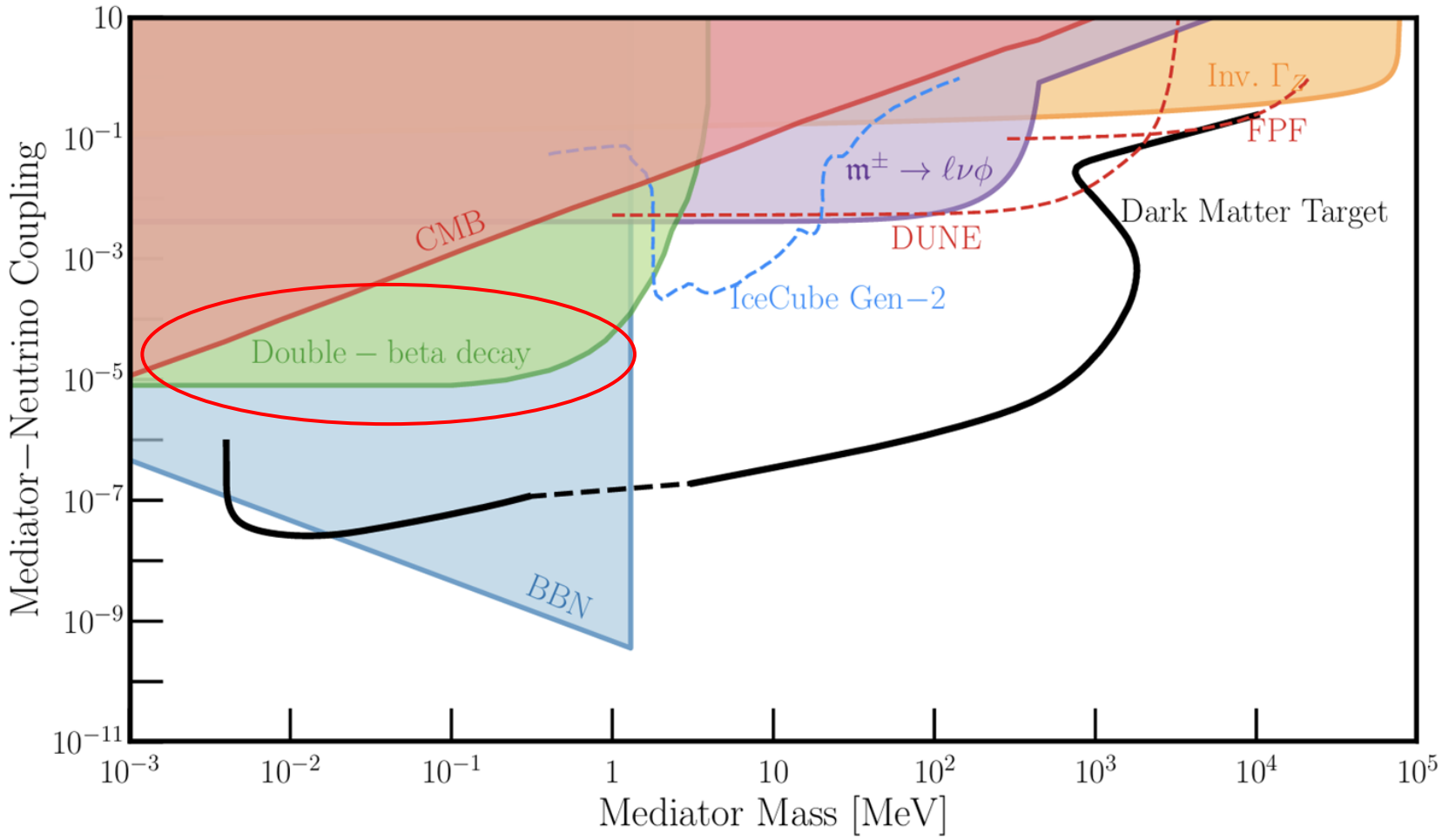
Sensitivity study with **simulated data** from the BeEST fitting function (33 parameters) :

- Same number of generated events as the real set of data
- Use the profile likelihood by adding the Majoron Signal
- **Purple zone is the excluded zone (Wilk's theorem)**
- **Lower limits evolving as $N^{-1/4}$ (g^2)**

Not competitive constraints, even with tremendous statistics, especially for higher masses.



Constraints on the Majoron mass and couplings

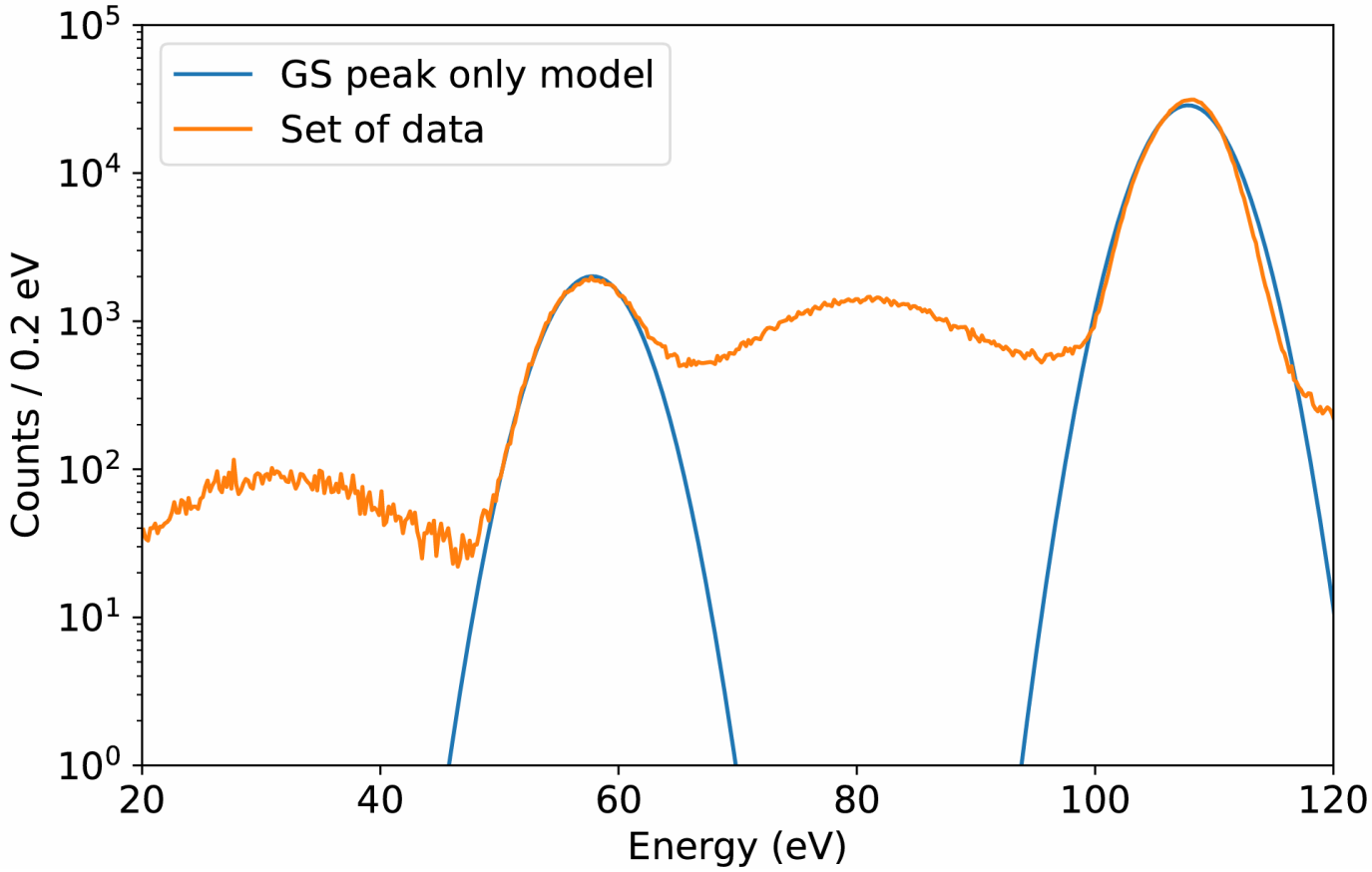


III. Prevision for constraints in future BeEST phase

Gamma suppresion

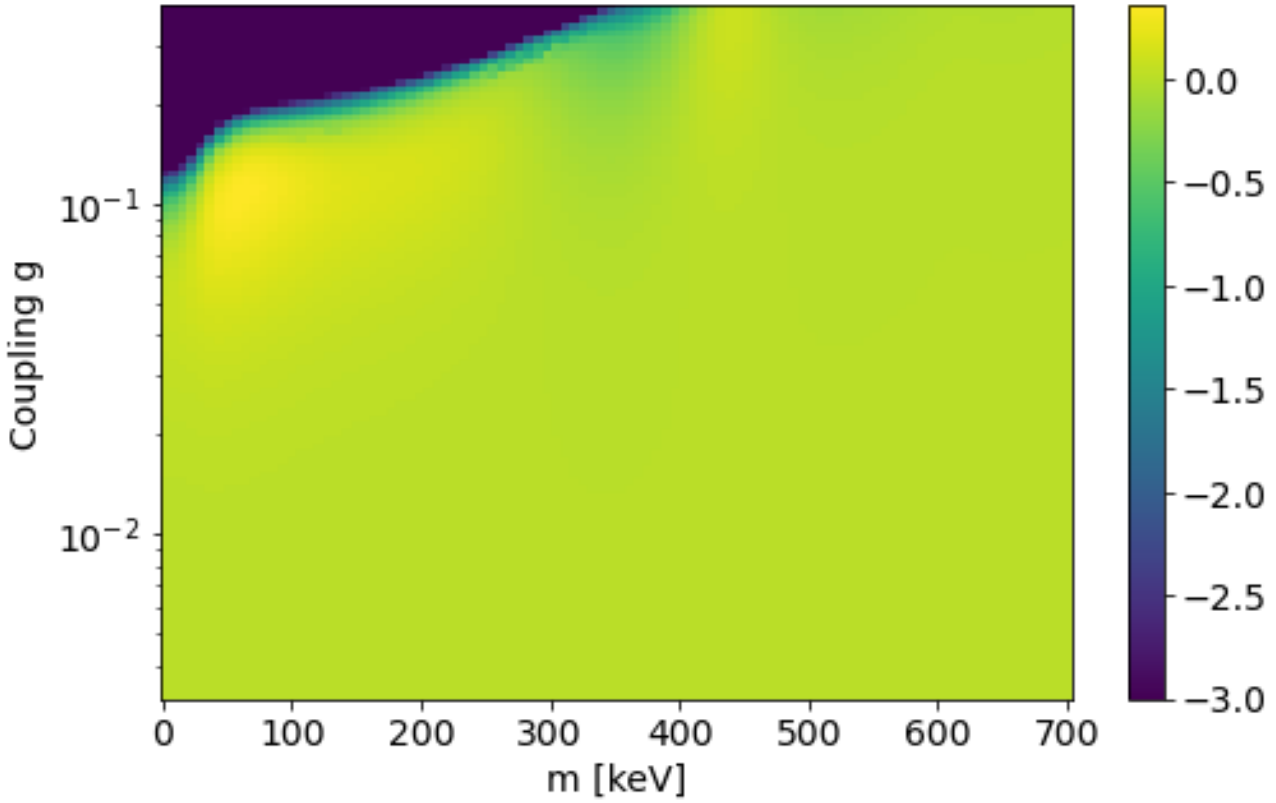
In future phase IV of BeEST, ES peaks can be removed by gamma coincidence :

- **Without ES peaks, to what extent is the exclusion plot improved ?**
- **Assume a perfect removal of ES peaks to study the best case scenario**
- Use a gaussian model with only GS peaks for the sensitivity study



Best case scenario : GS peaks toy model

4 peaks gaussian model



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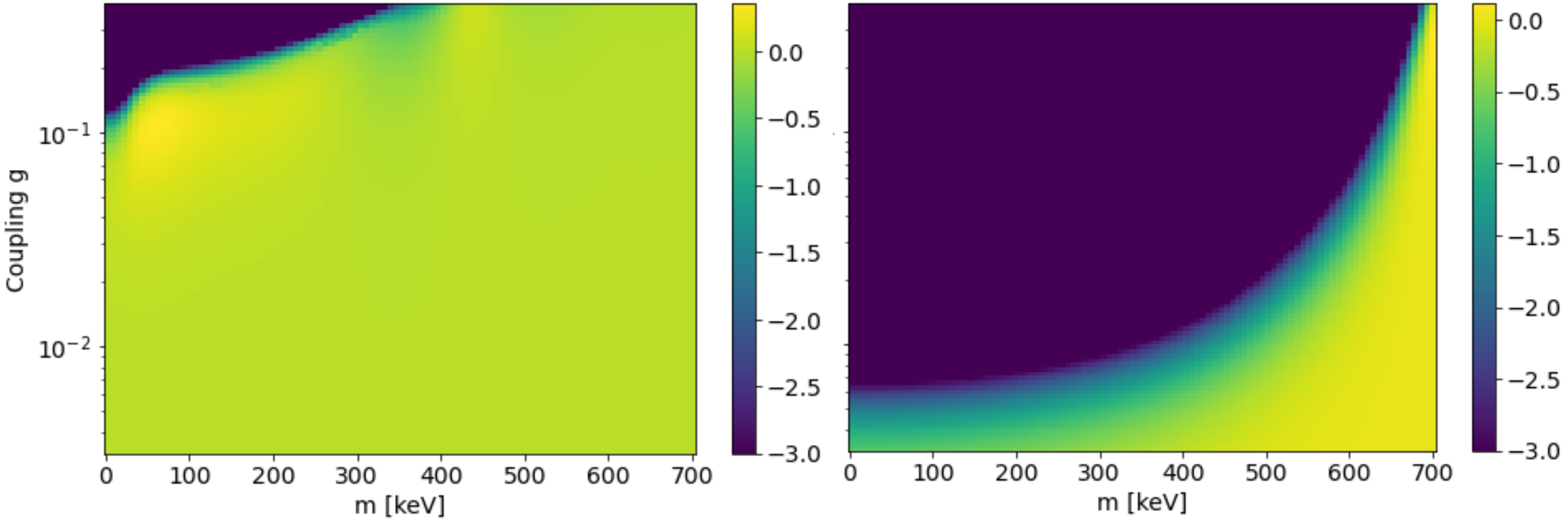
GS peaks only



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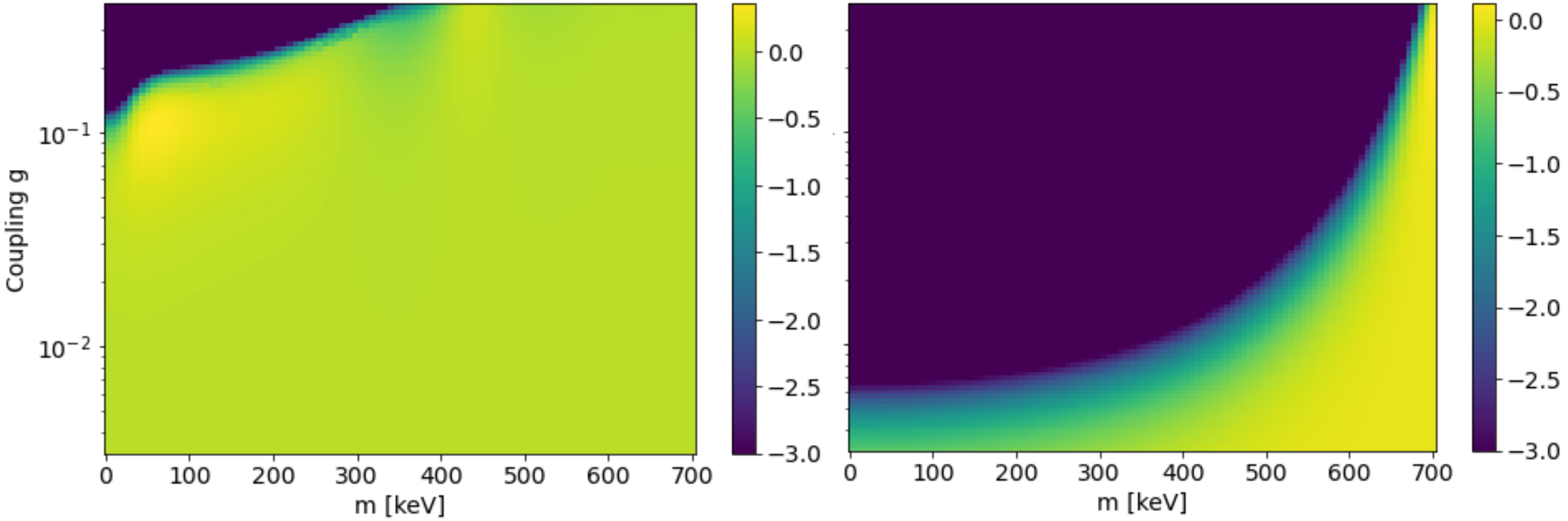

At most a gain of one order of magnitude

Best case scenario : GS peaks toy model

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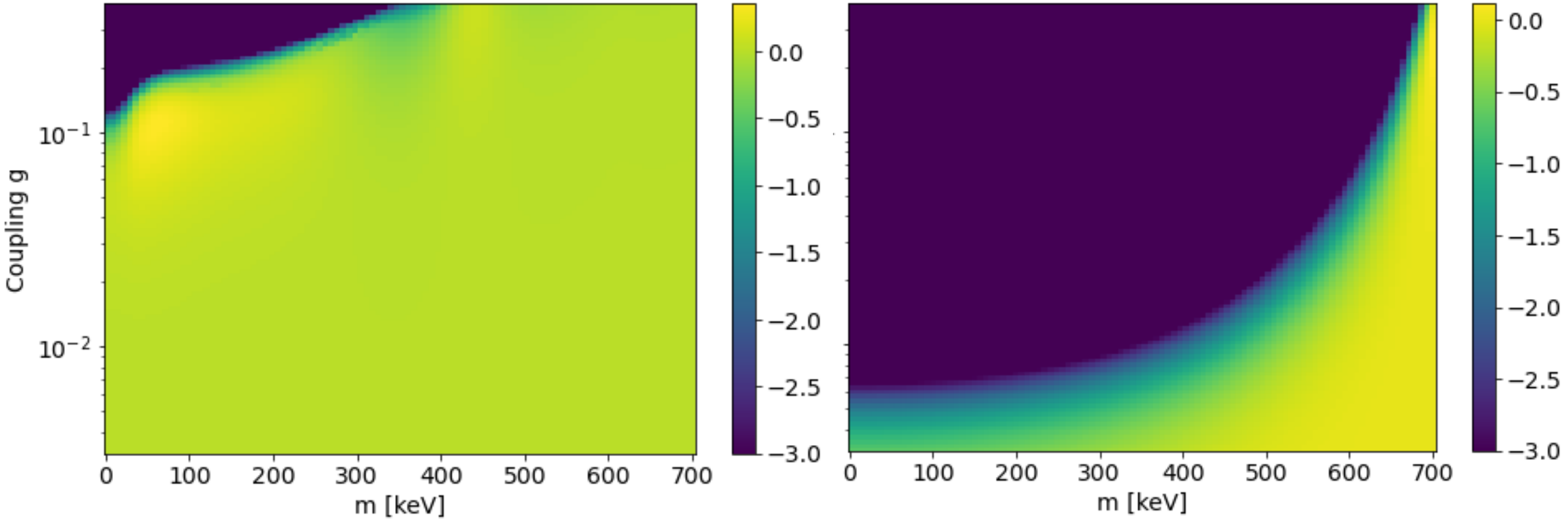
GS peaks only



Cause : presence of continuous Majoron Signal between GS peaks

Best case scenario : GS peaks toy model

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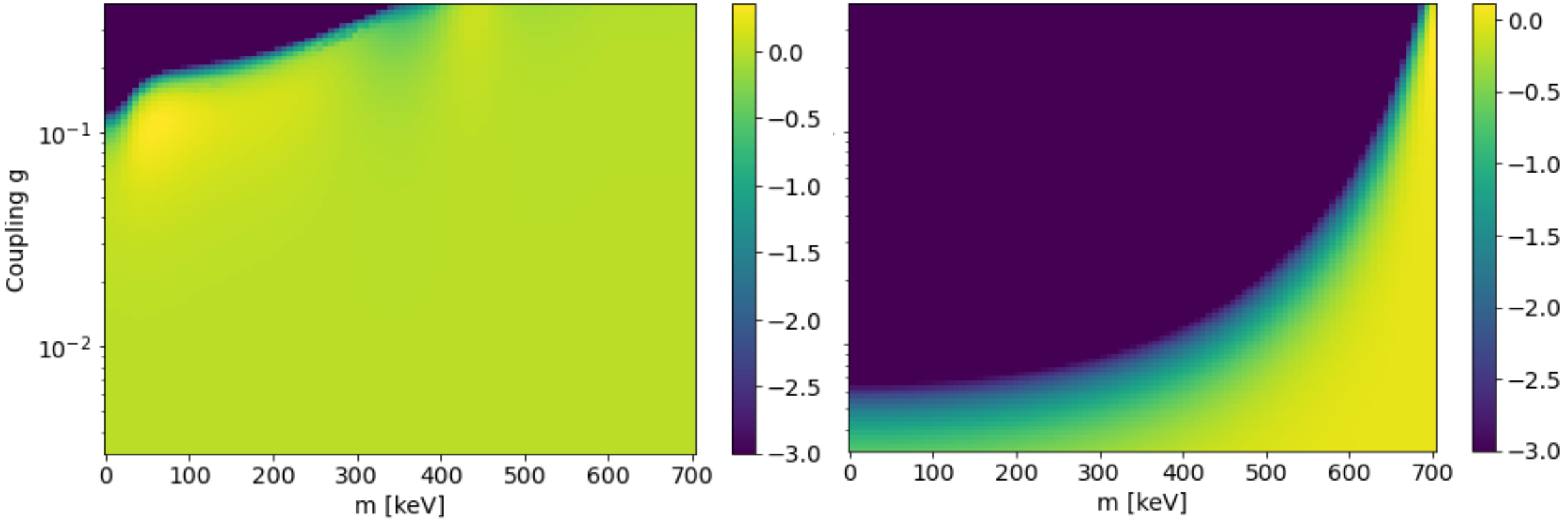
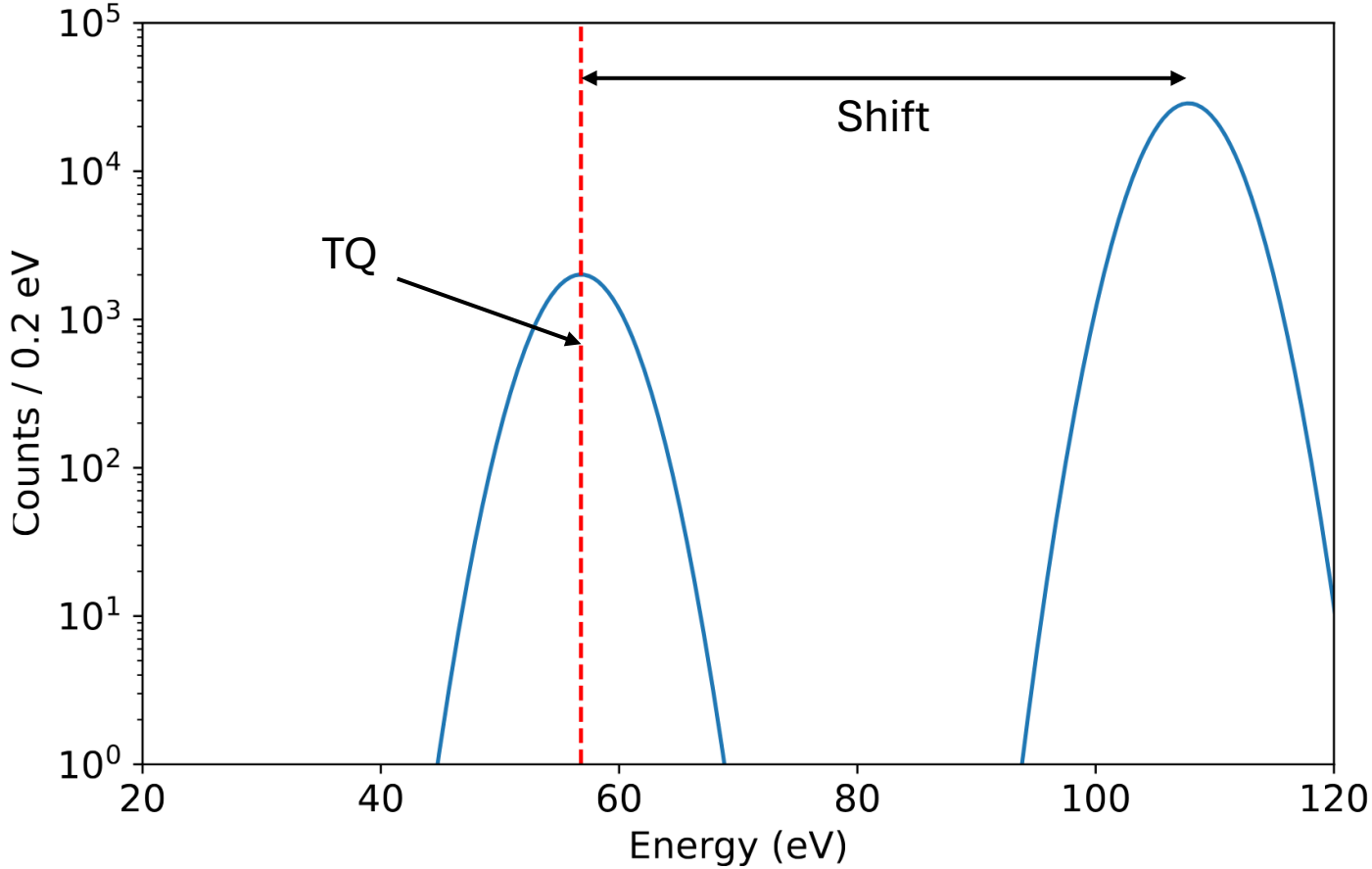


Still not competitive

IV. Is there a more suitable nucleus than ^{7}Be for pure EC ?

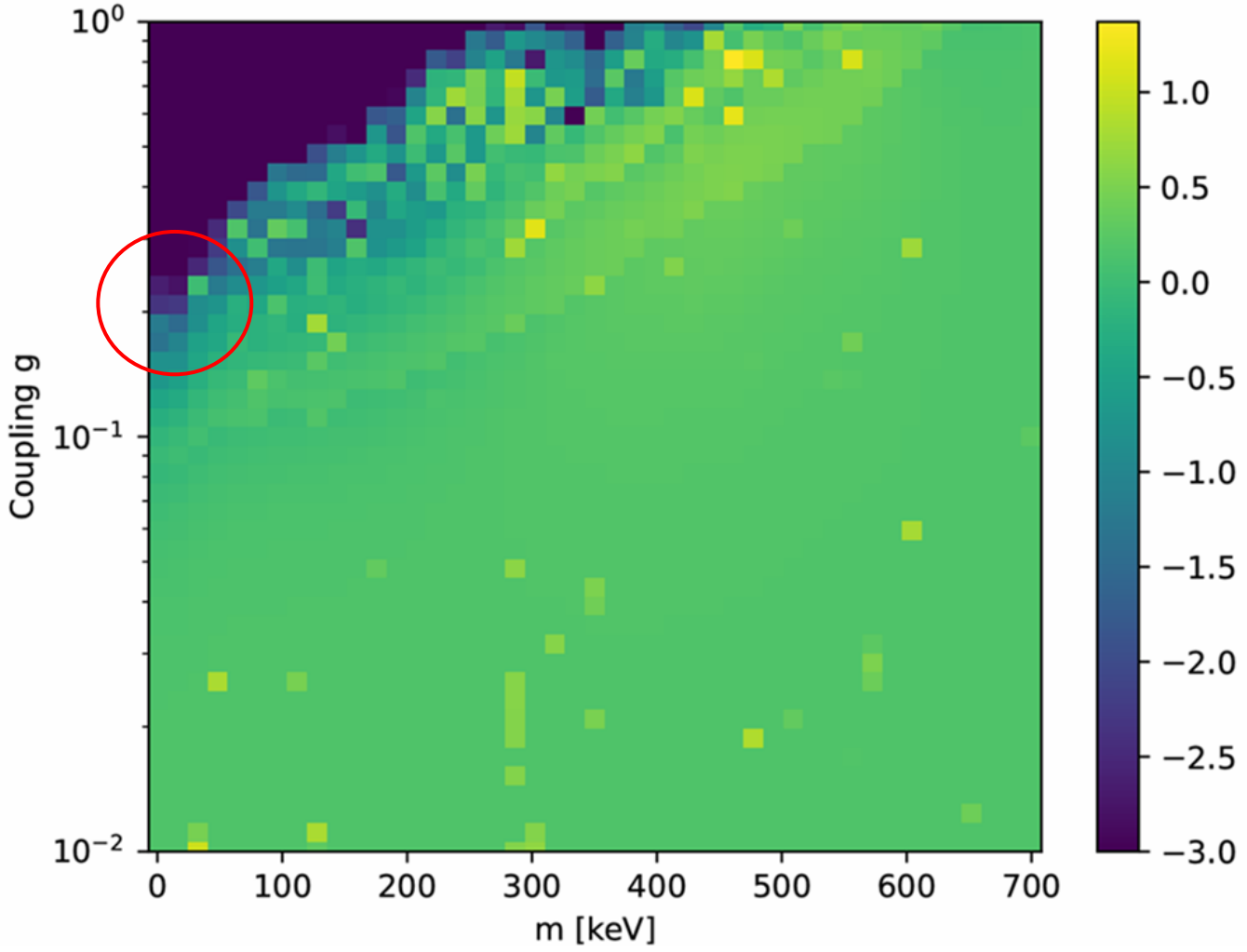
Which nucleus' features matter ?

- Each nucleus corresponds to an electron capture spectrum
- Define an EC spectrum with 3 parameters : **TQ (L-GS peak), L/K and the shift between peaks**
- Fix the L/K ratio for simplicity (not relevant)

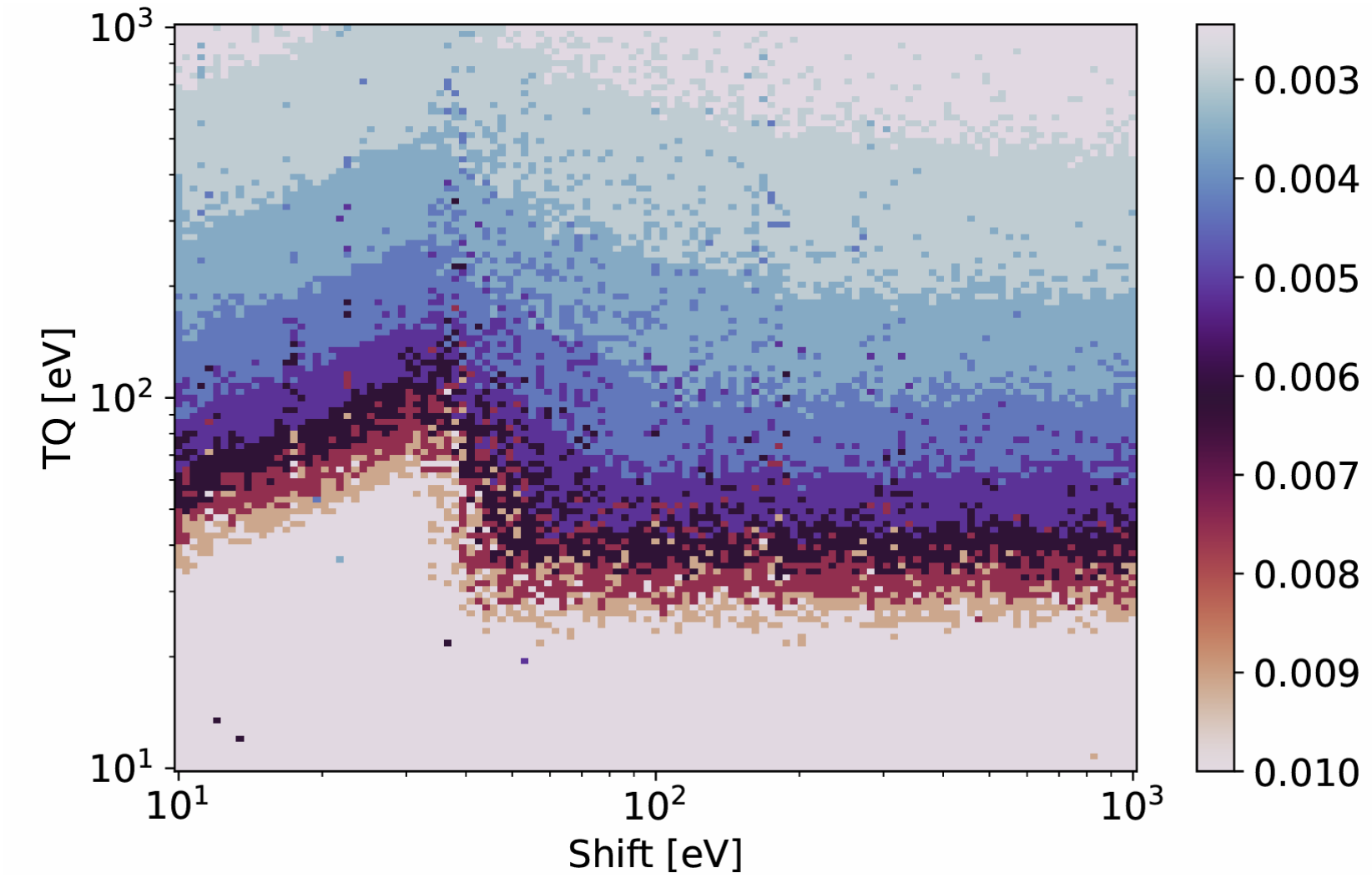


Which nucleus' features matter ?

- Each nucleus corresponds to an electron capture spectrum
- Define an EC spectrum with 3 parameters : **TQ (L-GS peak), L/K and the shift between peaks**
- Fix the L/K ratio for simplicity (not relevant)
- **Calculate the lower exclusion constraint for a massless Majoron**
- Do it for each (TQ,shift)
- **Plot the lower constraints on (TQ,shift)**



Lower constraint plot



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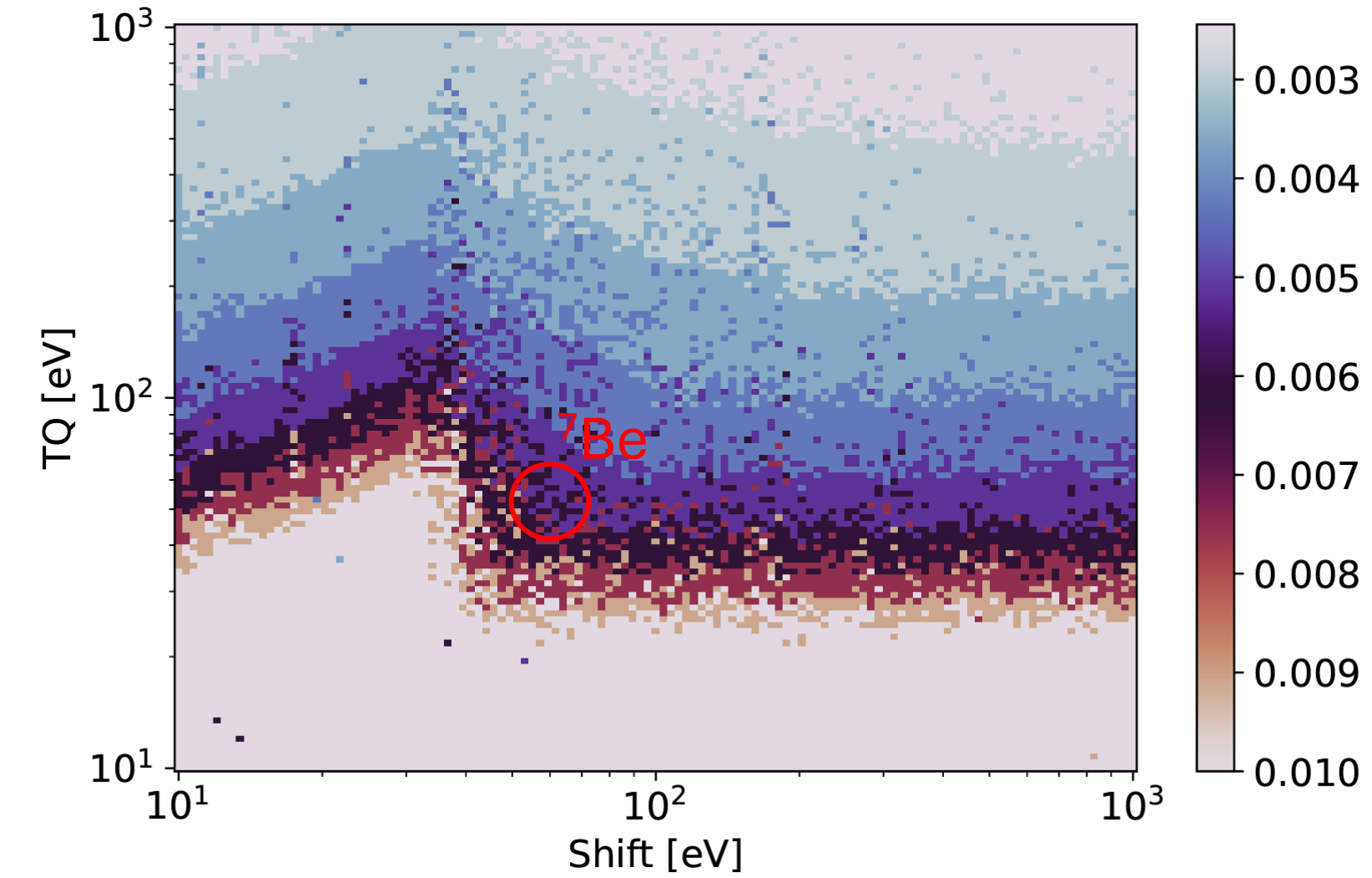

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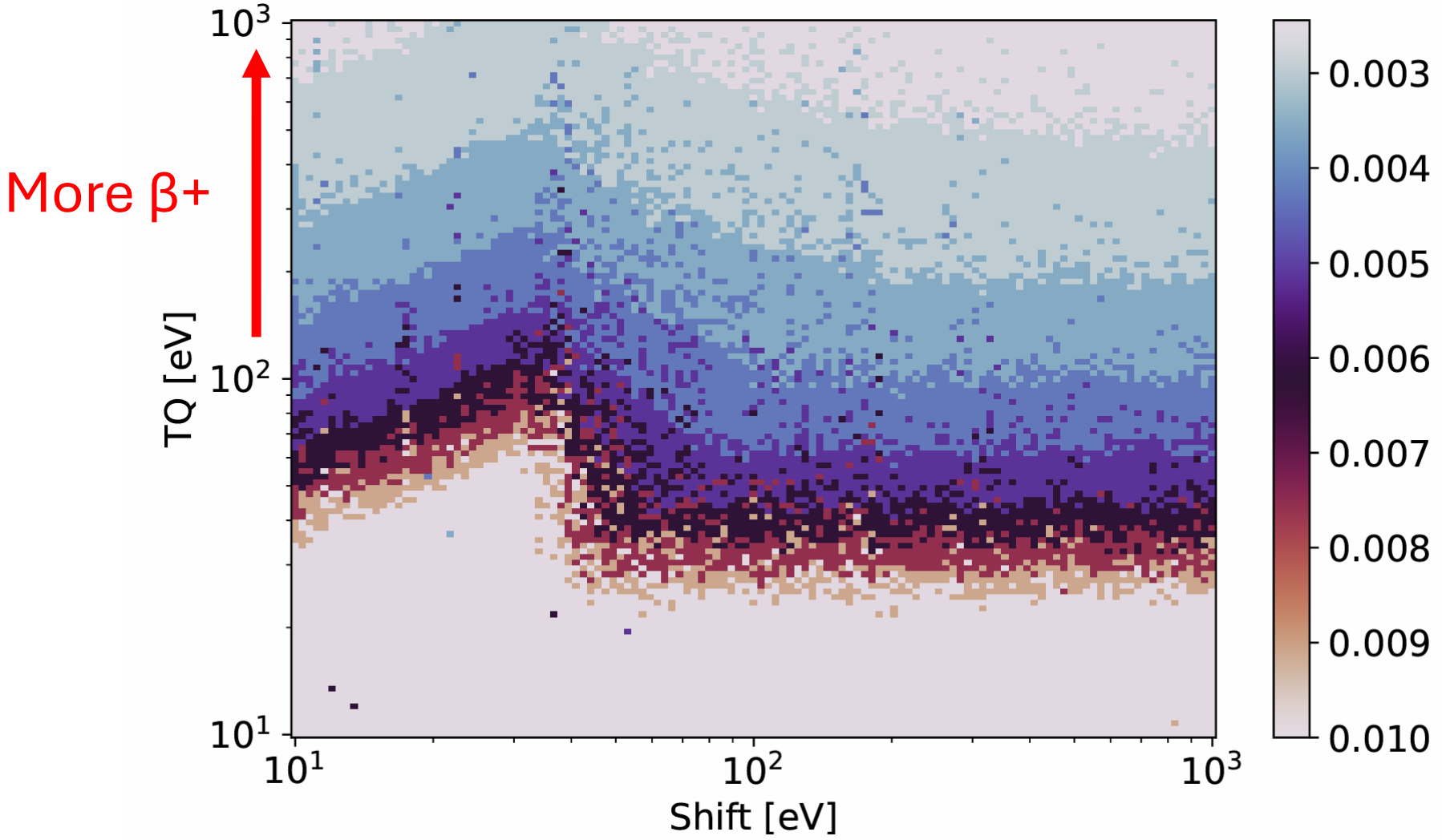

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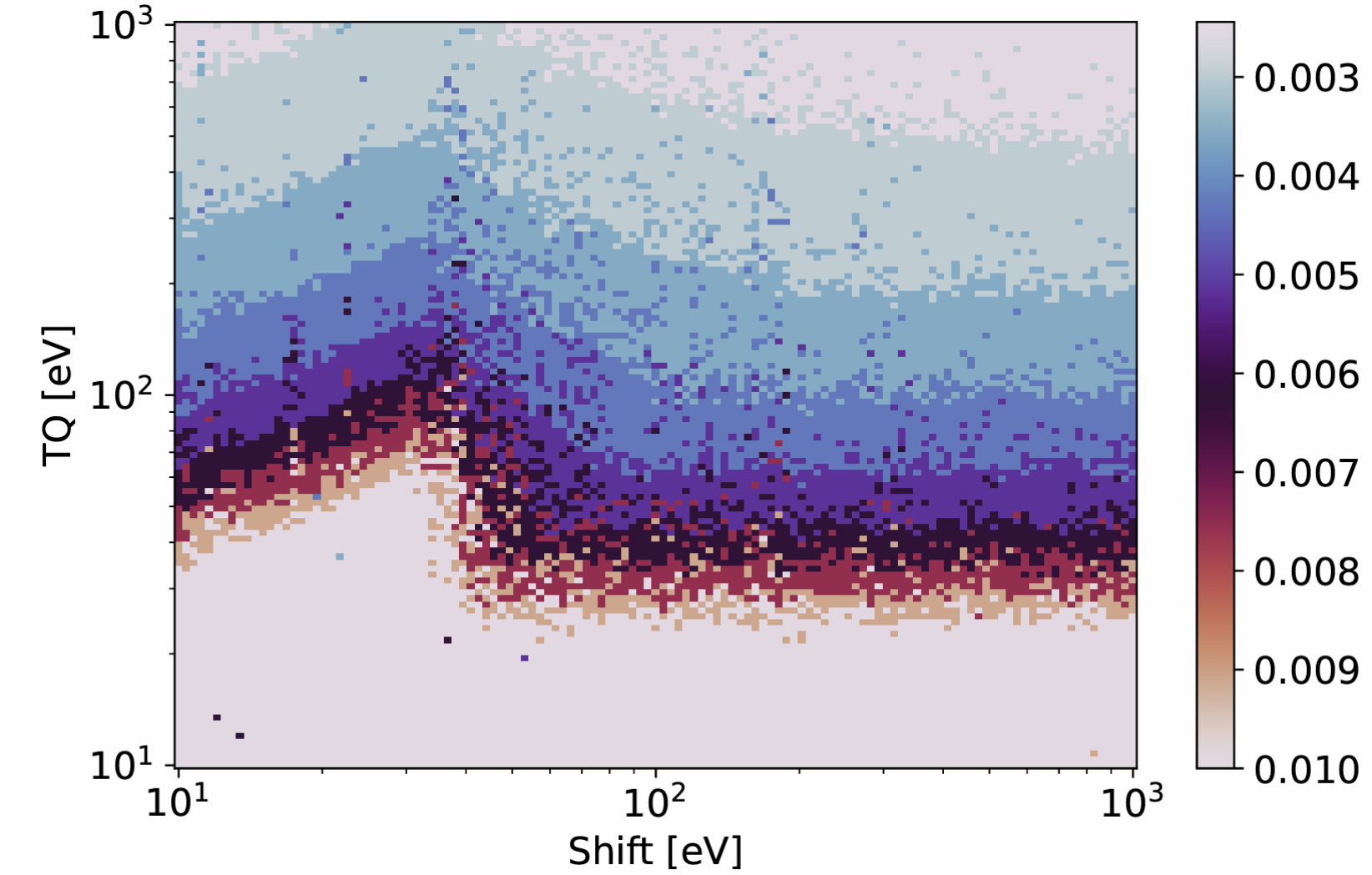

No other possible candidate for pure electron capture

Conclusion

- **With 10^{10} events → probe at most Majoron couplings between 10^{-2} and 10^{-3}**
- Double beta decay experiments → set constraints down to 10^{-5}
- Majoron searches with ^{7}Be not competitive, even with other possible nuclei
- **In conclusion, a « proof of principle » that other three body decay studies could be carried out with STJs in the future**
- **Use the exact same procedure to study other three body decays (maybe other type of mediator ? Vector ?)**

Thanks for listening !

Majoron searches with the BeEST experiment
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NUCLÉAIRE
& PARTICULES

Appendices

Model-building for the Majoron (from [1])

- Introduce a complex scalar field and heavy right-handed neutrinos :

$$\mathcal{L} \supset -y_\nu \bar{\psi}_L \phi N_R - \frac{1}{2} h \xi \overline{N_R^c} N_R + h.c.$$

Model-building (from [1])

- Introduce a complex scalar field and heavy right-handed neutrinos :

$$\mathcal{L} \supset -y_\nu \bar{\psi}_L \phi N_R - \frac{1}{2} h \xi \overline{N_R^c} N_R + h.c.$$

Higgs Mechanism

Scalar field
L=-2

Heavy sterile neutrinos
L=1

The Majoron

- Use ξ potential to spontaneously break the U(1) Lepton symmetry
- Let the Higgs acquires a VEV
- Develop ξ with two scalar fields :

$$\xi = \frac{1}{\sqrt{2}}(\sigma + i\chi)$$

The Goldstone boson

The Majoron

- Use ξ potential to spontaneously break the U(1) Lepton symmetry
- Let the Higgs acquires a VEV
- Develop ξ with two scalar fields : $$\xi = \frac{1}{\sqrt{2}}(\sigma + i\chi)$$
- If candidate for dark matter : U(1) is approximate
- Expand around the expectation value of fields for the mass Lagrangian

Majoron mass

$$V(\phi,\xi) = -\mu_1^2\xi^\dagger\xi + \lambda_1(\xi^\dagger\xi)^2 - \mu_2^2\phi^\dagger\phi + \lambda_2(\phi^\dagger\phi) + 2\lambda_3\phi^\dagger\phi\xi^\dagger\xi$$

$$+$$

$$V_{soft} = -\frac{1}{2}\mu_3^2(\xi^2 + h.c)$$

$$\boxed{m_\chi^2 = 2\mu_3^2}$$

Mass Lagrangian

$$-y_\nu \bar{\nu}_L \phi N_R - \frac{1}{2} Y^M \overline{N_R^c} N_R + h.c.$$

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Lepton Number Breaking term

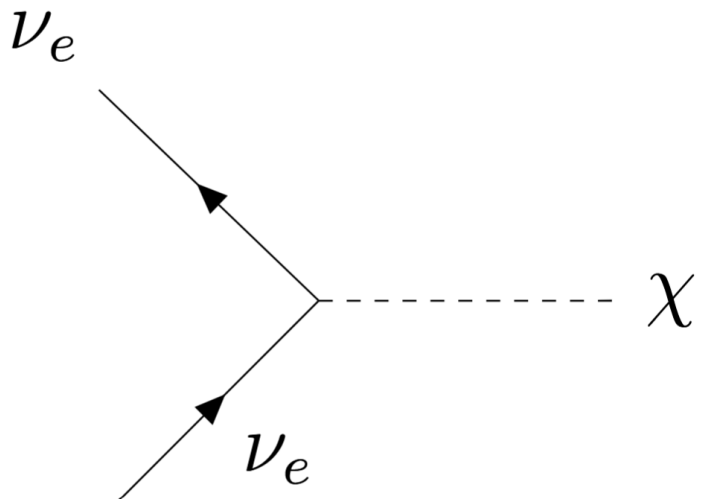
This breaking can be transfered to the baryon number

Leptogenesis → Baryogenesis

Vertex of interest (from [1])

$$\mathcal{L} \supset -\frac{1}{2} h \xi \overline{N_R^c} N_R + h.c.$$

- Integrate out the heavy neutrinos
- Retrieve the following vertex : $g_{\chi\nu}\chi\bar{\nu}\nu$
- Constraints on the couples $(g_{\chi\upsilon}, m_\chi)$



Seesaw mechanism (Type I)

- Consider : $\chi_L \equiv (\nu_L, N_R^c)$

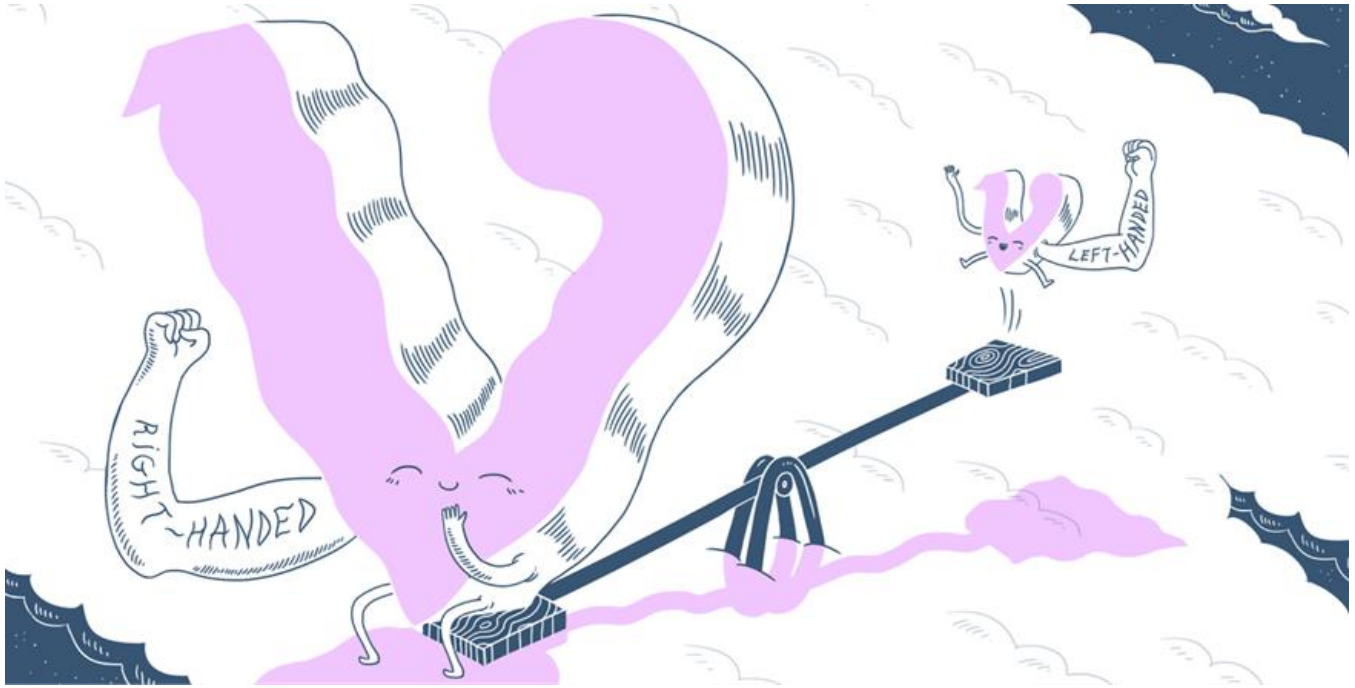
$$\mathcal{L} \supset -\frac{1}{2}\overline{\chi_L}\mathcal{M}_\chi\chi_L \quad \text{with} \quad \mathcal{M}_\chi = \begin{pmatrix} 0 & \tilde{m} \\ \tilde{m} & Y^M \end{pmatrix}$$

- The eigenvectors are the mass vectors and the eigenvalues are the mass states

- The discussion on the Majorana coupling is based on active neutrinos masses and PMNS matrix éléments

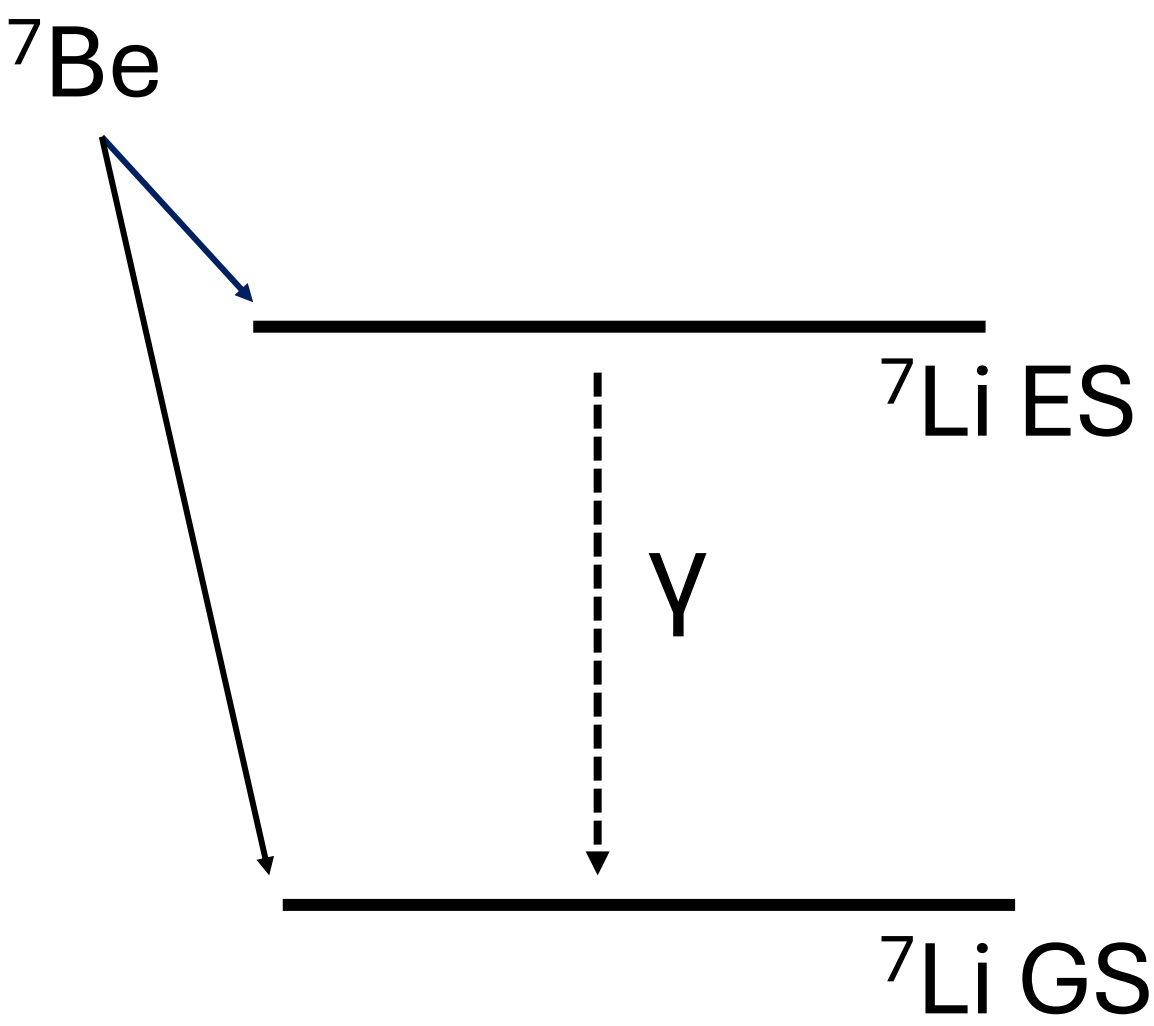
Seesaw-mechanism

$$m_\nu = \tilde{\mathrm{m}} \frac{1}{(Y^M)^2} \tilde{\mathrm{m}}^T$$



^{7}Be Electron Capture

- Capture of a K or L shell electron
- Q-value : 861.963(23) keV [2]
- Excited states : 477 keV
- Initial Recoil : 55 (GS) or 11 eV (ES)
- Auger Electron for GS : 54 eV
- Gamma emission kick (ES) : 17 eV



Three-body decay branching ratio

$$H_{EC} = \frac{G_\beta}{\sqrt{2}} \overline{\psi}_\nu \gamma^\mu (1 - \gamma^5) \psi_e \; \overline{\psi}_n \gamma_\mu (1 - g_A \gamma^5) \psi_p$$

Leptonic

Hadronic

Three-body decay branching ratio

EC

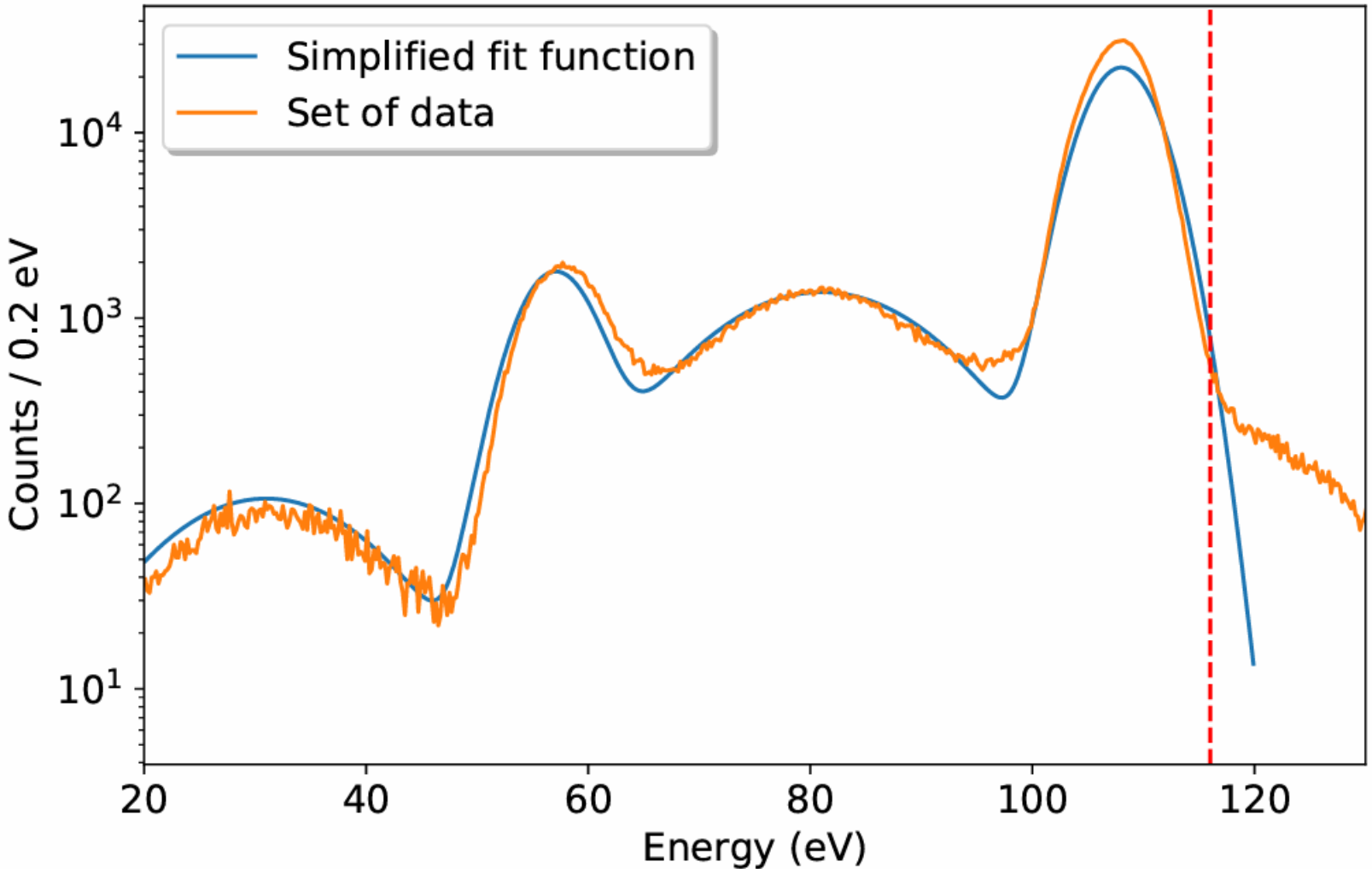
$$\Gamma = \frac{|\psi(0)|^2}{2\pi} G_\beta^2 Q^2 \kappa$$

Majoron

$$\frac{\delta\Gamma}{\delta T'} = \frac{g_{\chi\nu}^2}{32\pi^2} \sqrt{\frac{T'}{T_Q}} \frac{(T'_{max} - T')^2}{(T_Q - T')^3}$$

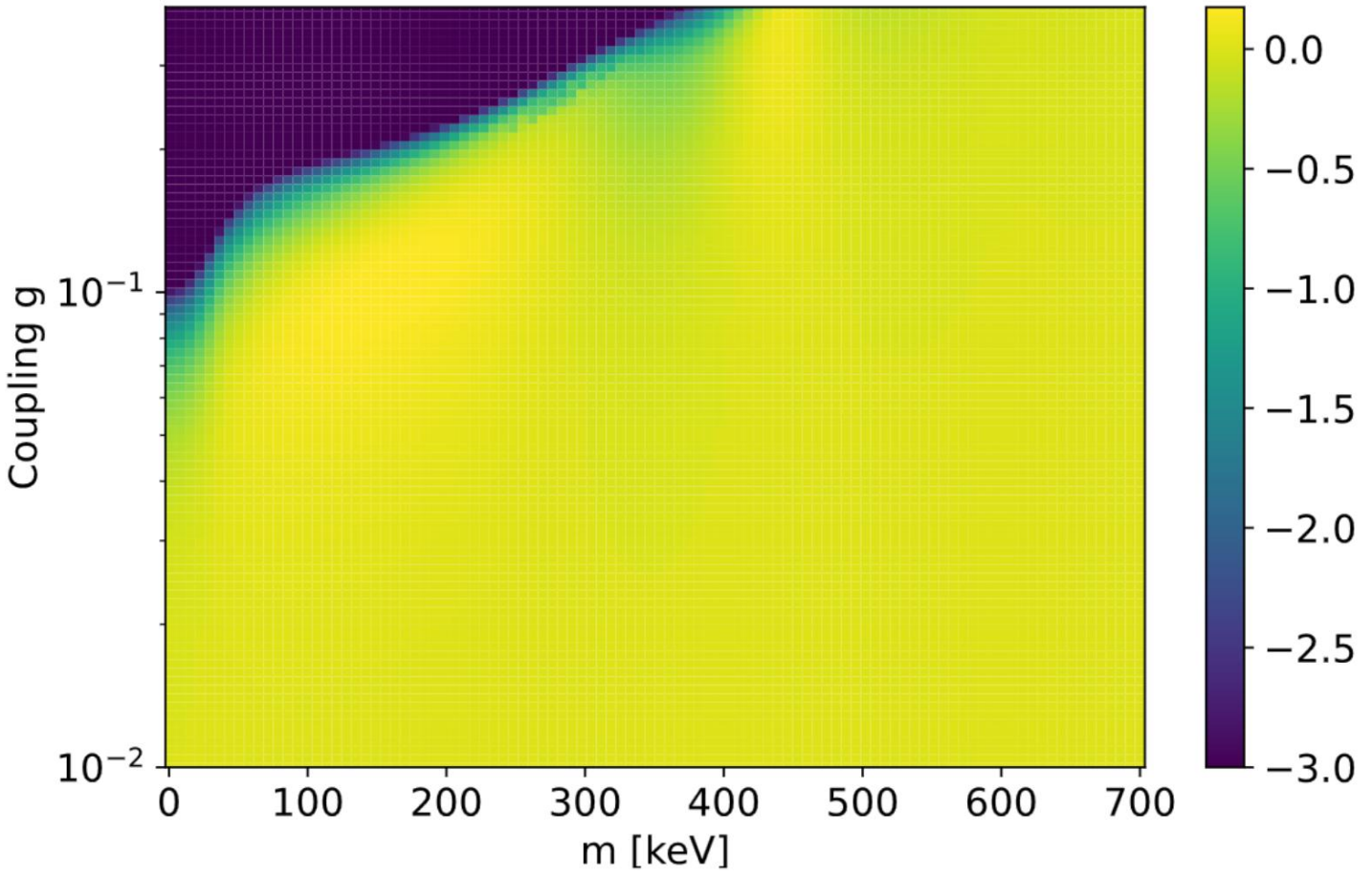
Gaussian toy model

- First sensitivity studies : simplified fit function
- Mimics the four primary peaks shape
- Red line : upper limit for the Majoron Signal

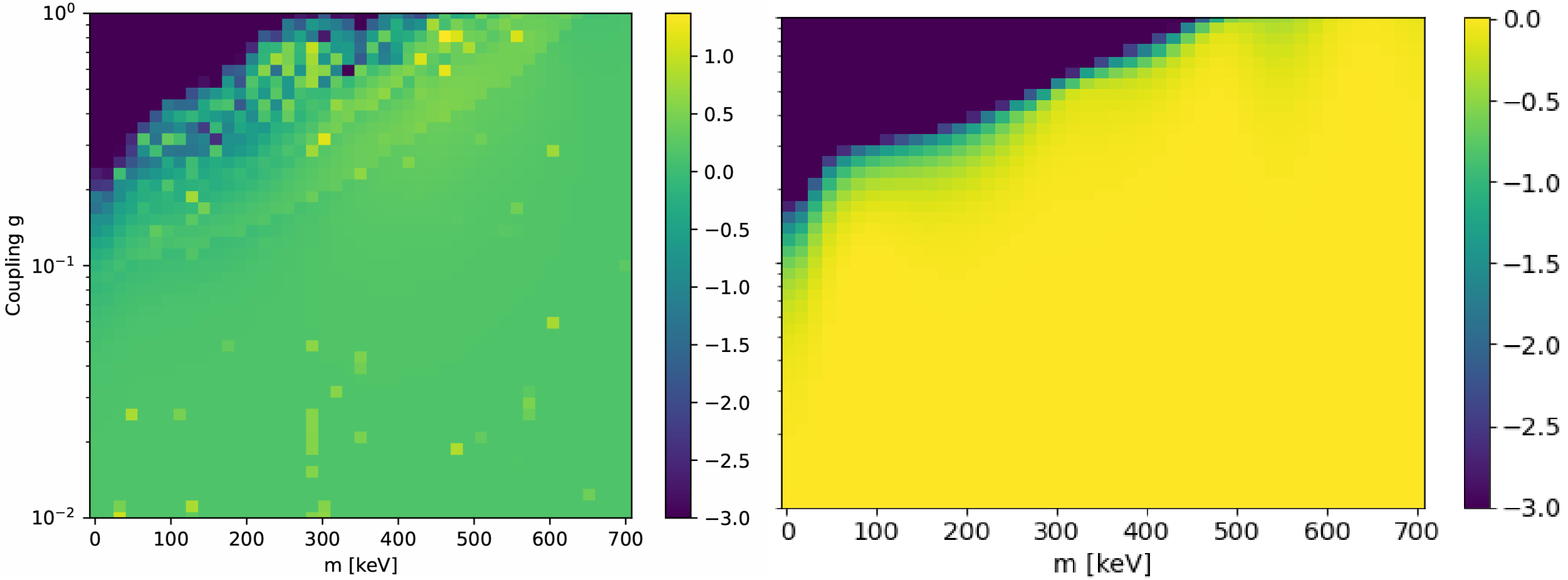


First results with simplified fit function

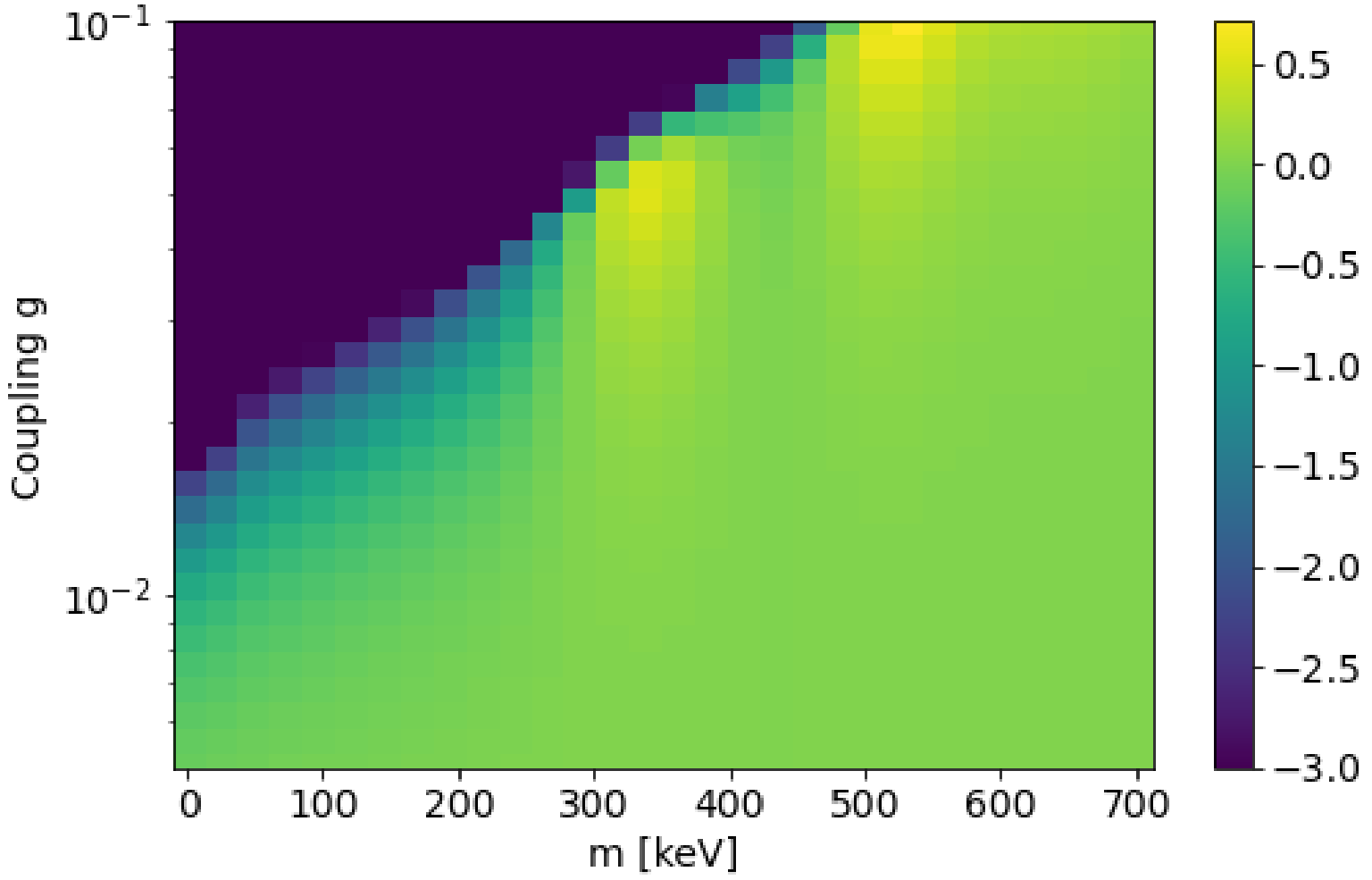
- 1e7 generated simulated events
- Carrying grid search, calculate the likelihood after adding Majoron signal
- Plot the likelihood difference
- Purple zone is the excluded zone (Wilk's theorem)
- Lower limits evolving as $N^{-1/4}$



Basinghopping vs gaussian toy model

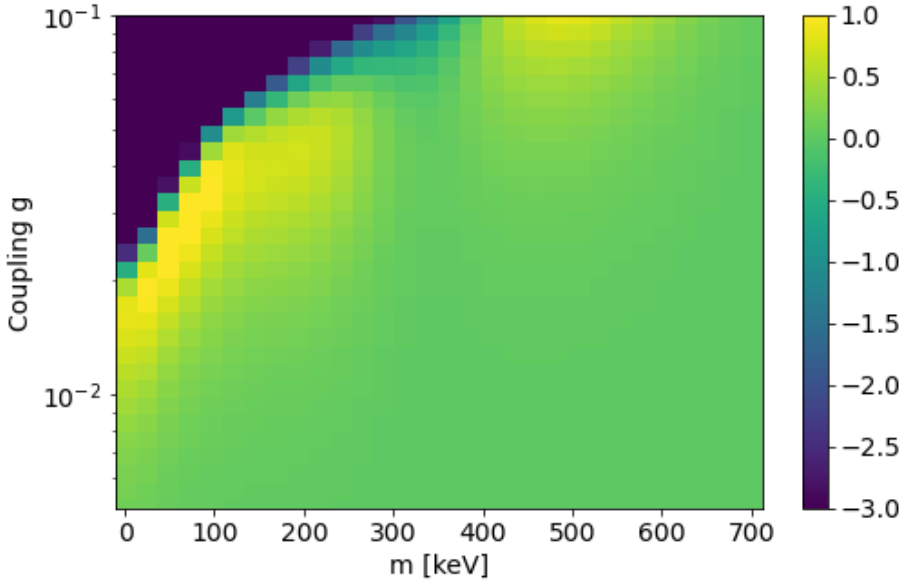


1e10 events without suppresion

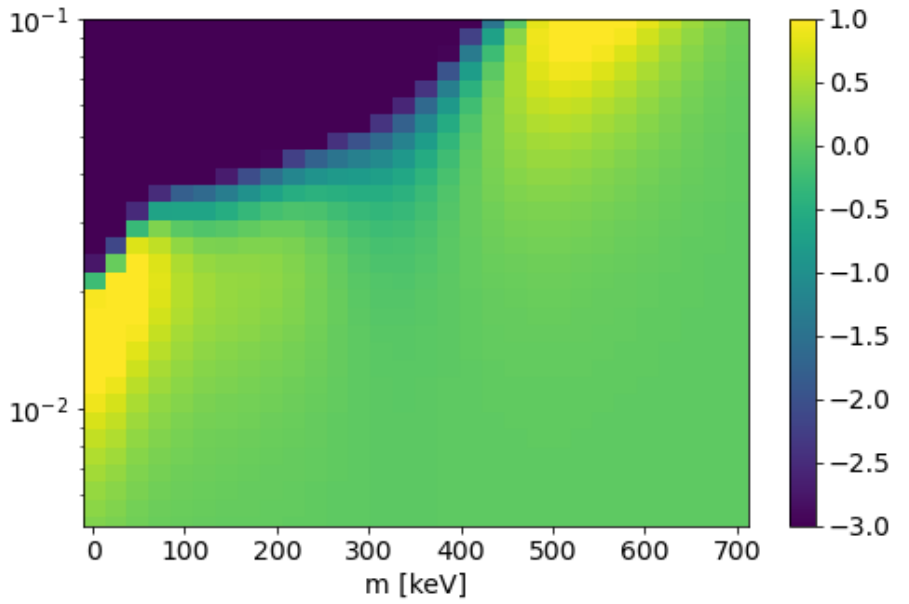


For different gamma detection efficiencies

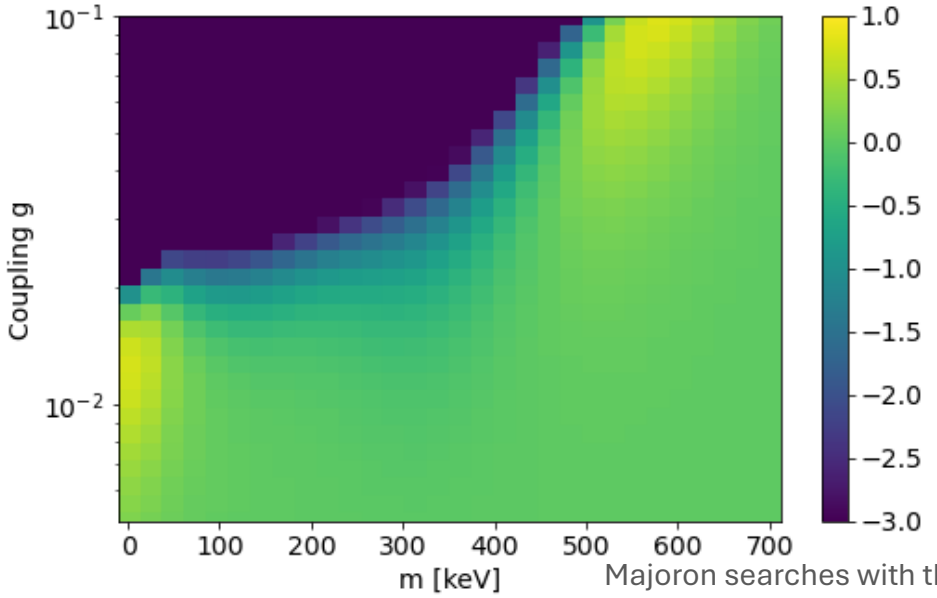
Eff=0.01



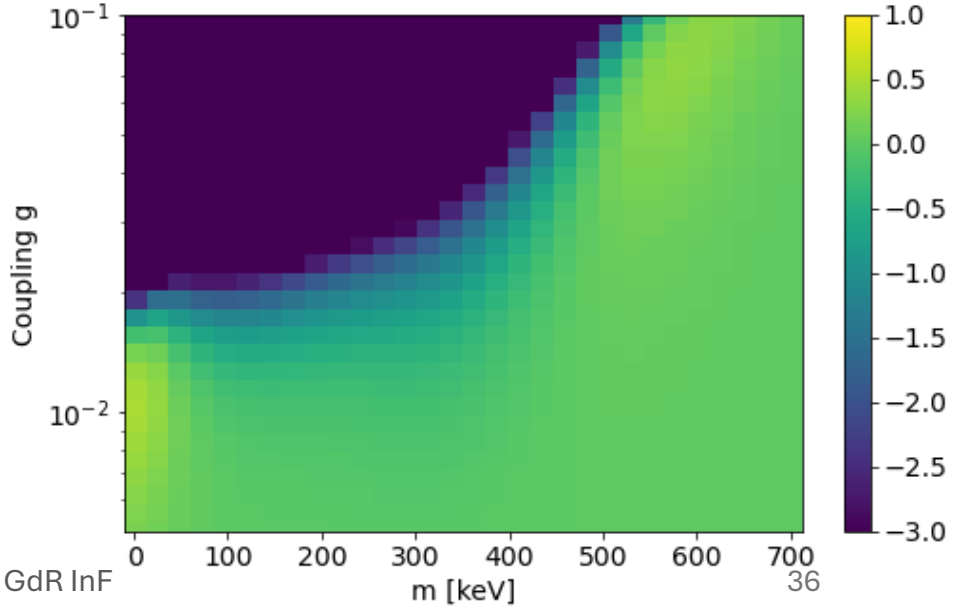
Eff=0.1



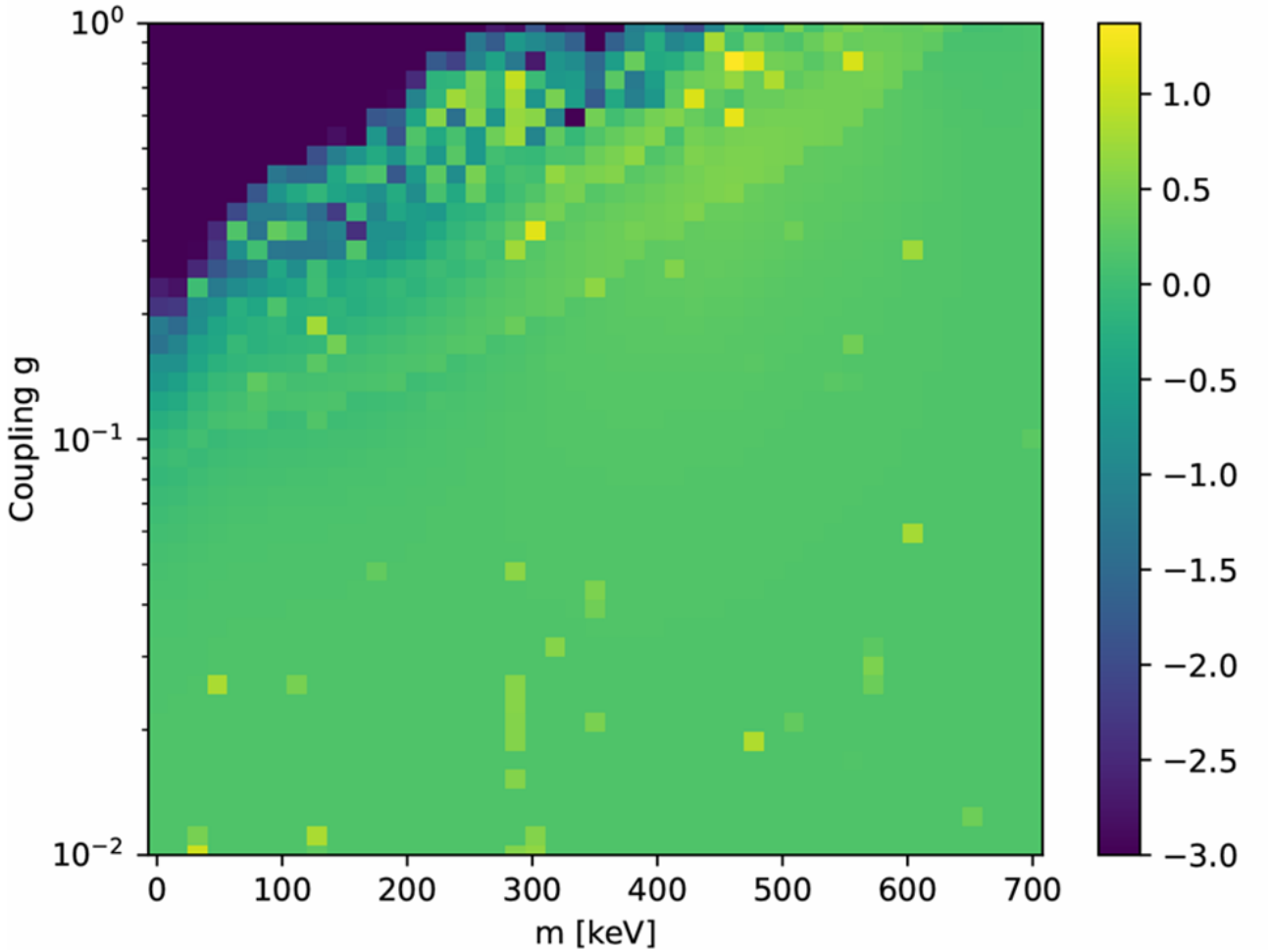
Eff=0.5

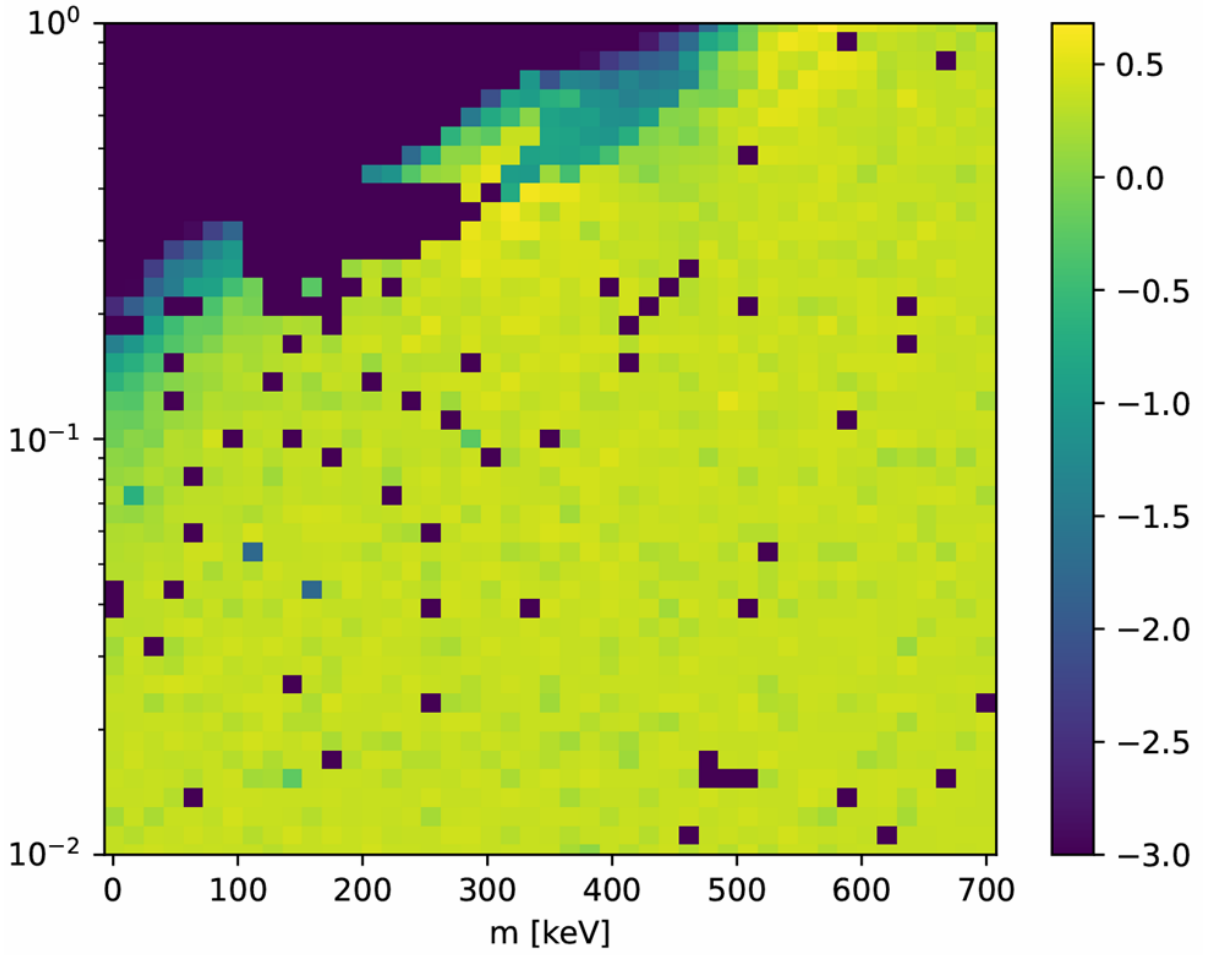


Eff=1

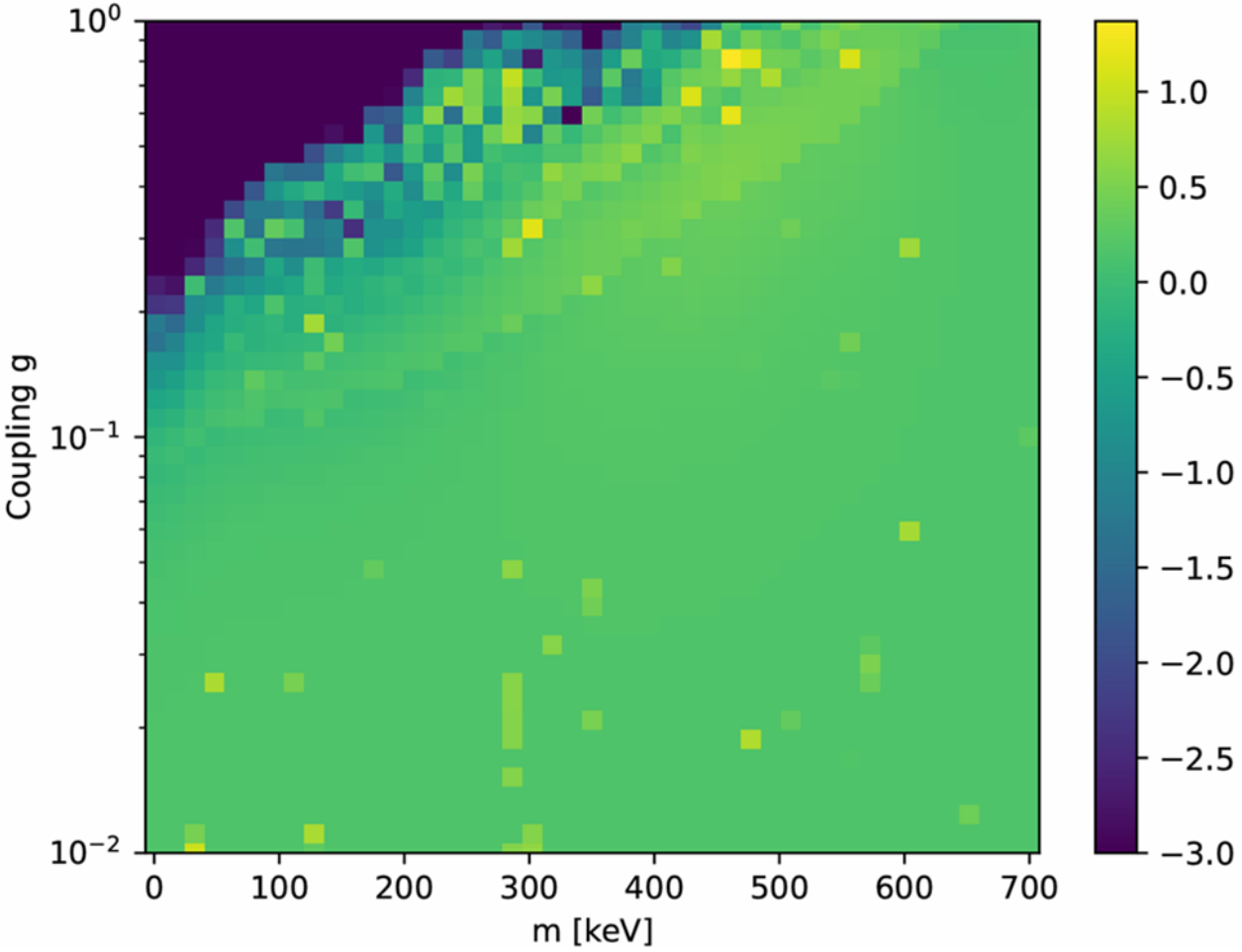


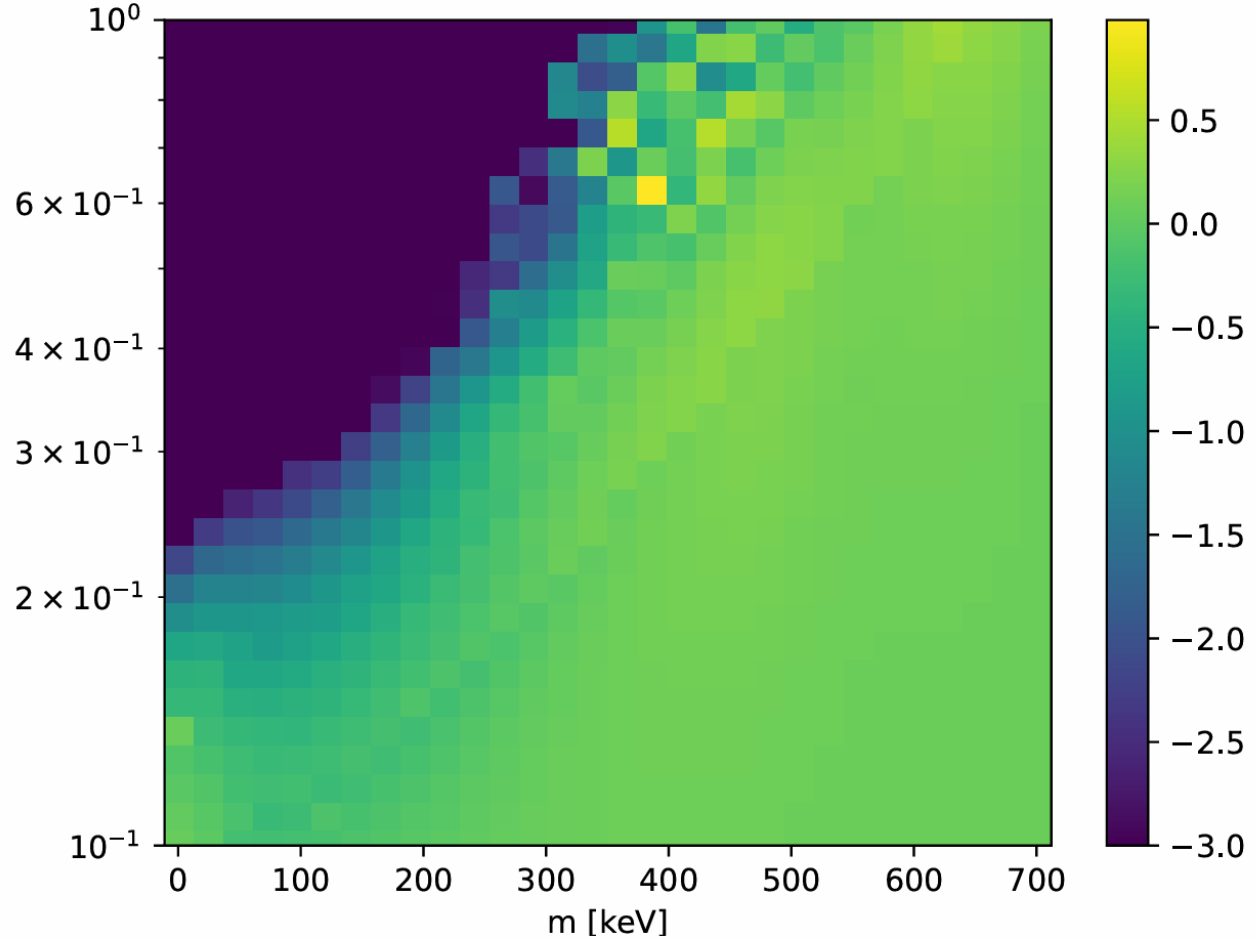
Basinghopping vs simple powell





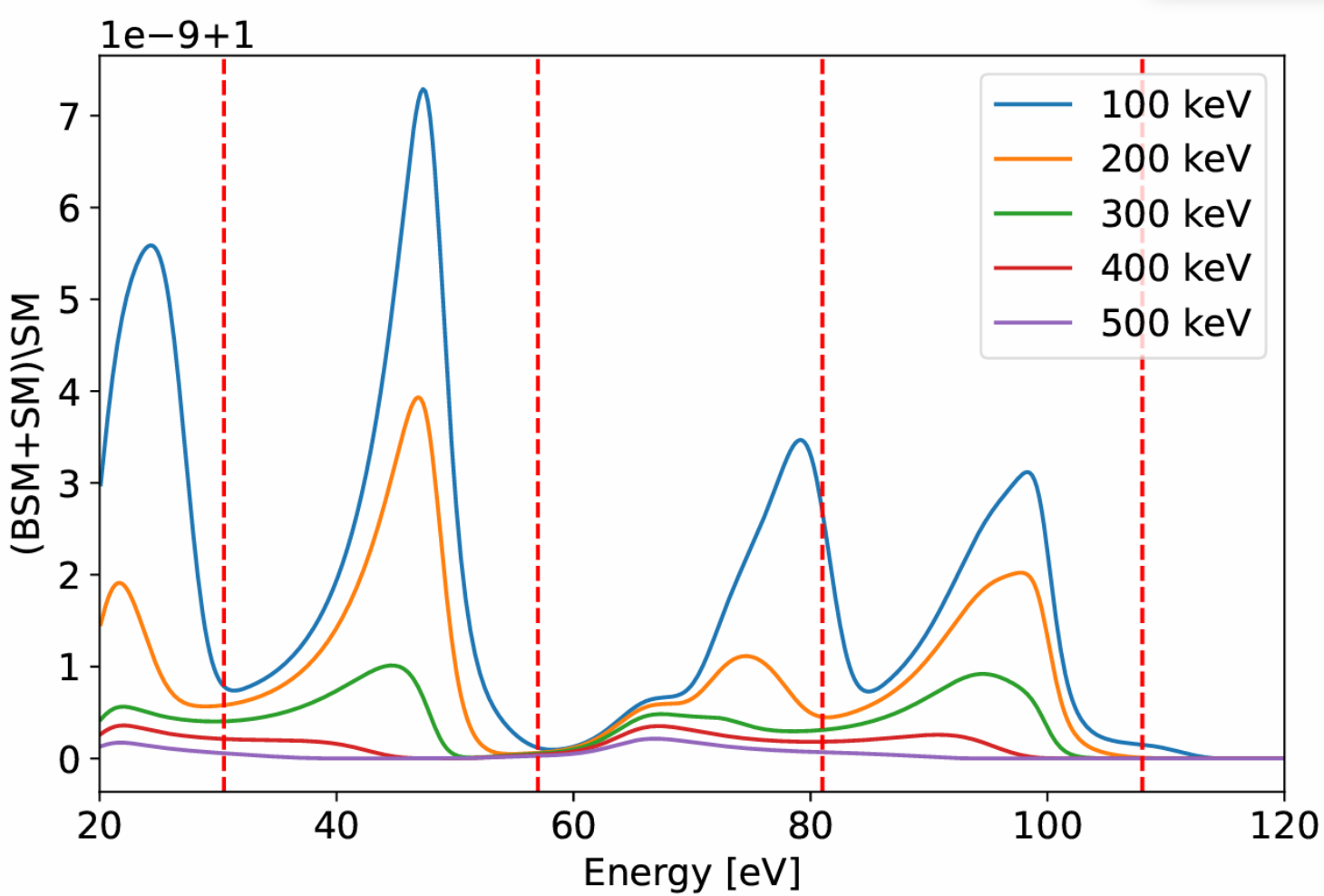
Basinghopping results



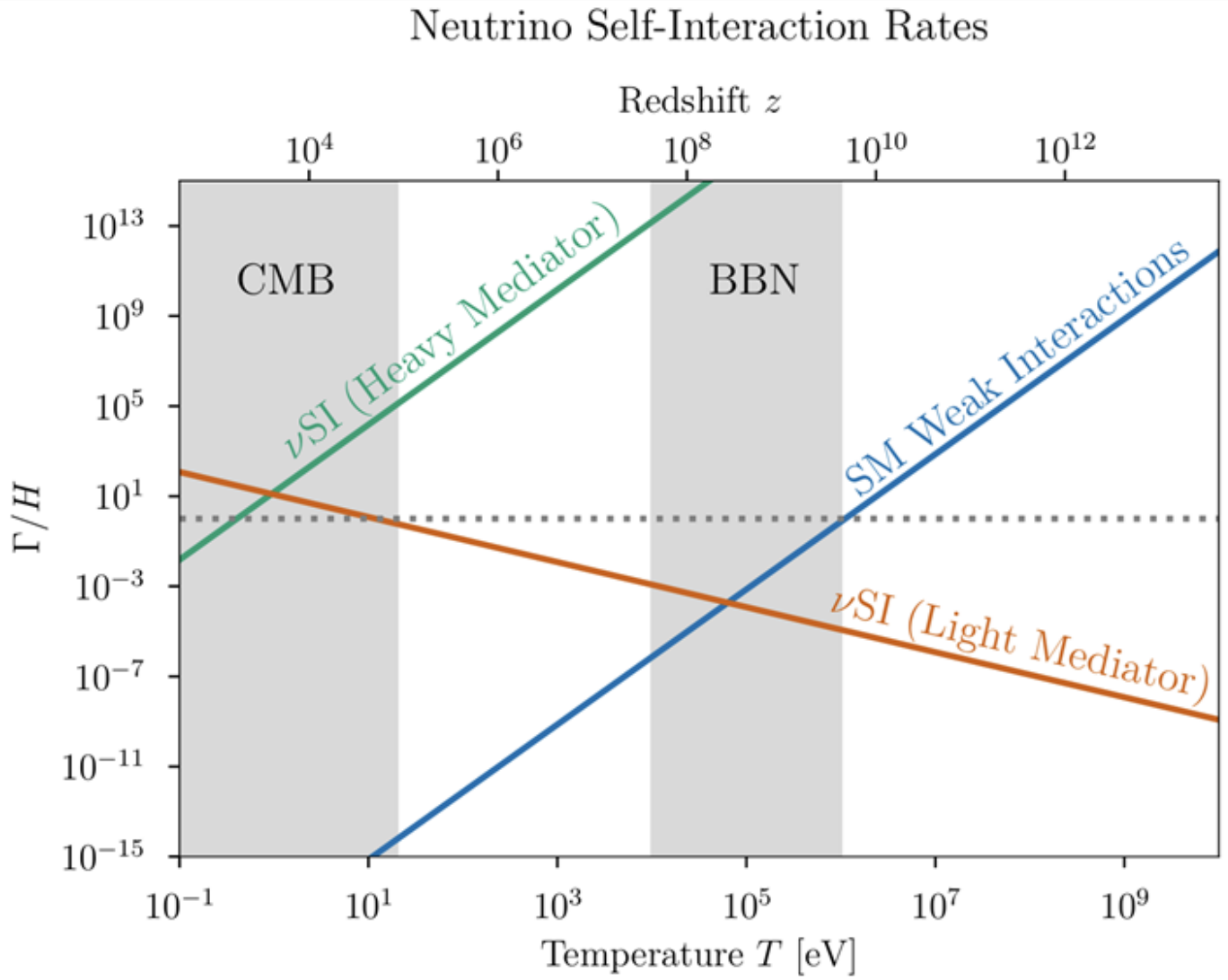


Zones of sensitivity

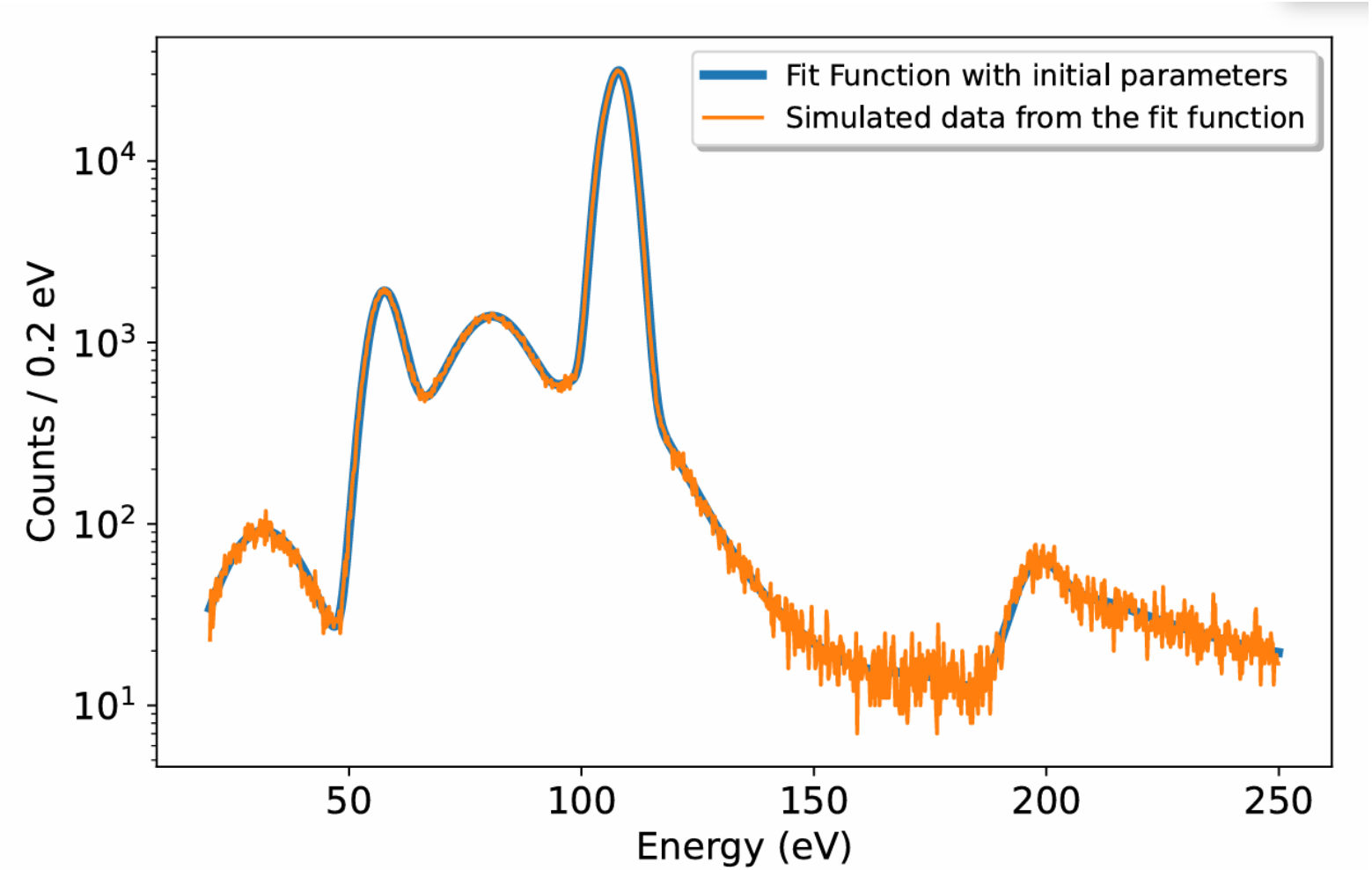
- Several peaks of sensitivity
- Shift with higher masses
- Signal « hidden » by the GS peaks



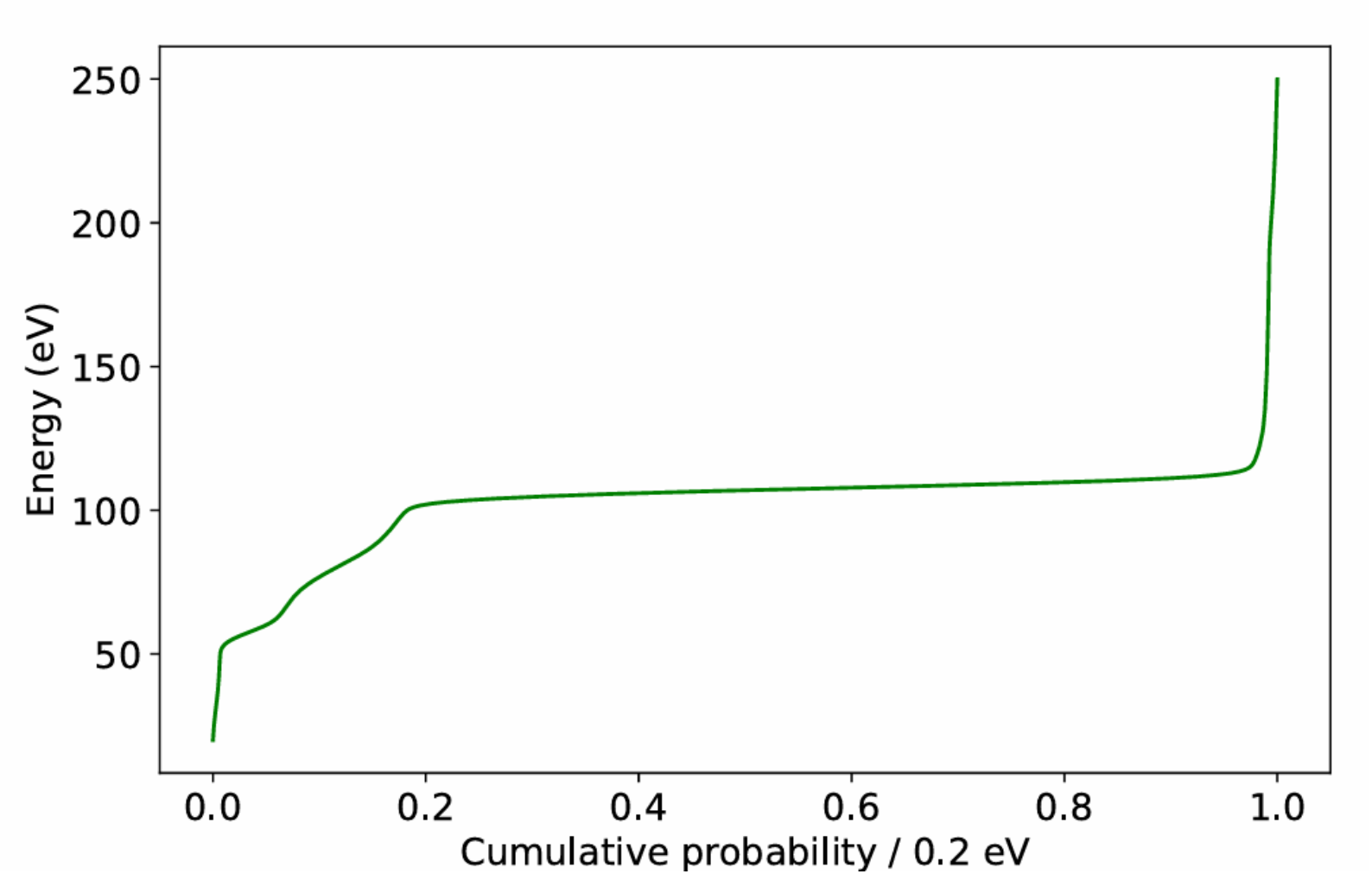
About indirect measurements



Inverse sampling



Inverse sampling



Profile likelihood procedure (from [2])

- Generate simulated data (inverse sampling)
- Refit (important) with basinghopping : the likelihood of reference
- This fit needs to be robust/stable
- Conduct the grid search by adding a BSM signal for each $(g_{\chi\upsilon}, m_{\chi})$
- Which differences should be excluded ?

Wilk's theorem

Let $P(H_0)$ and $P(H_1)$ be respectively the likelihood with and without BSM signature, then :

$$T = -2 \log \frac{P(H_0)}{P(H_{BSM})}$$

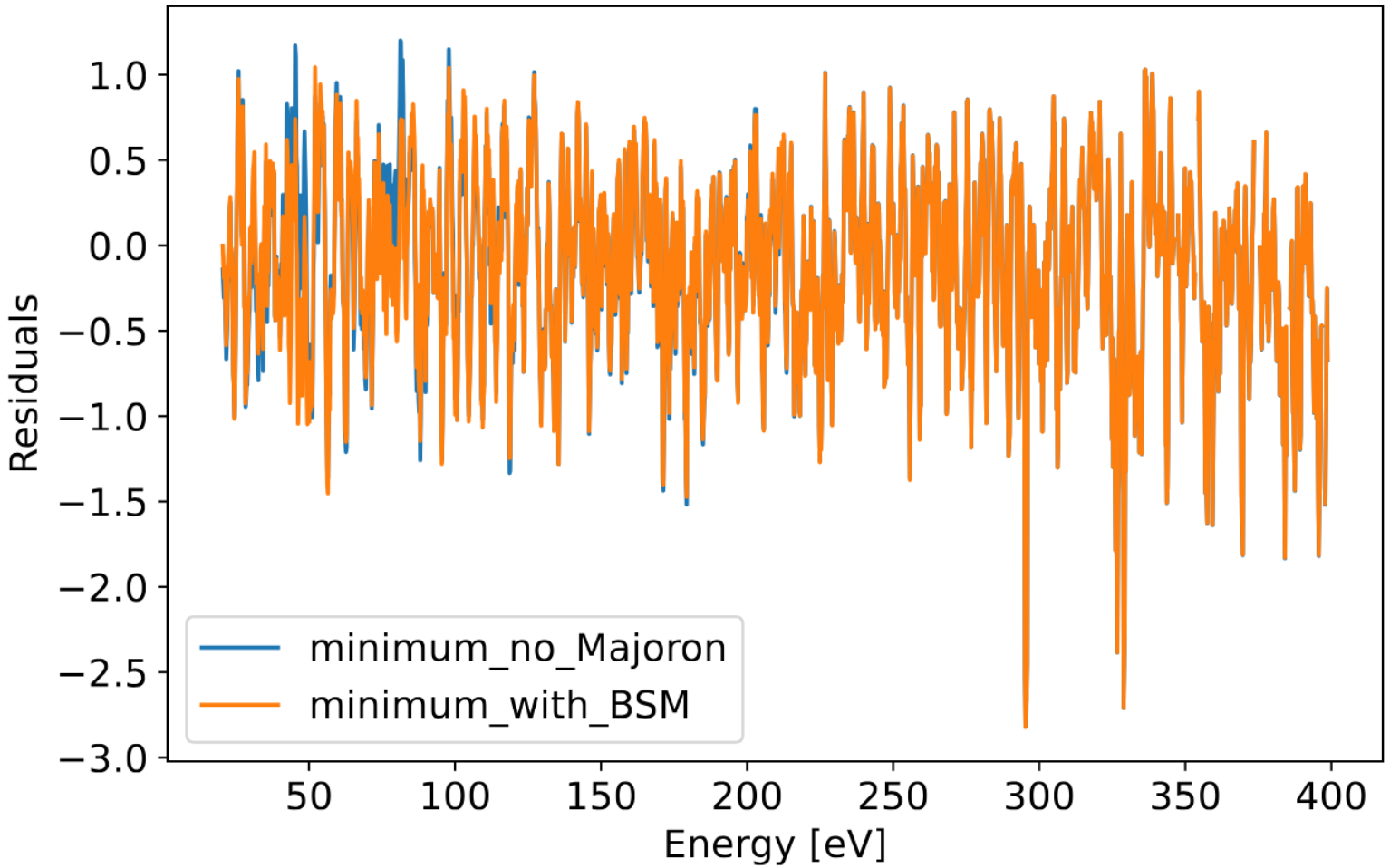
follows χ^2_{Ndf} law with Ndf the number of additionnal parameters in the BSM signal

Ndf = 2 95% limit = -2.995

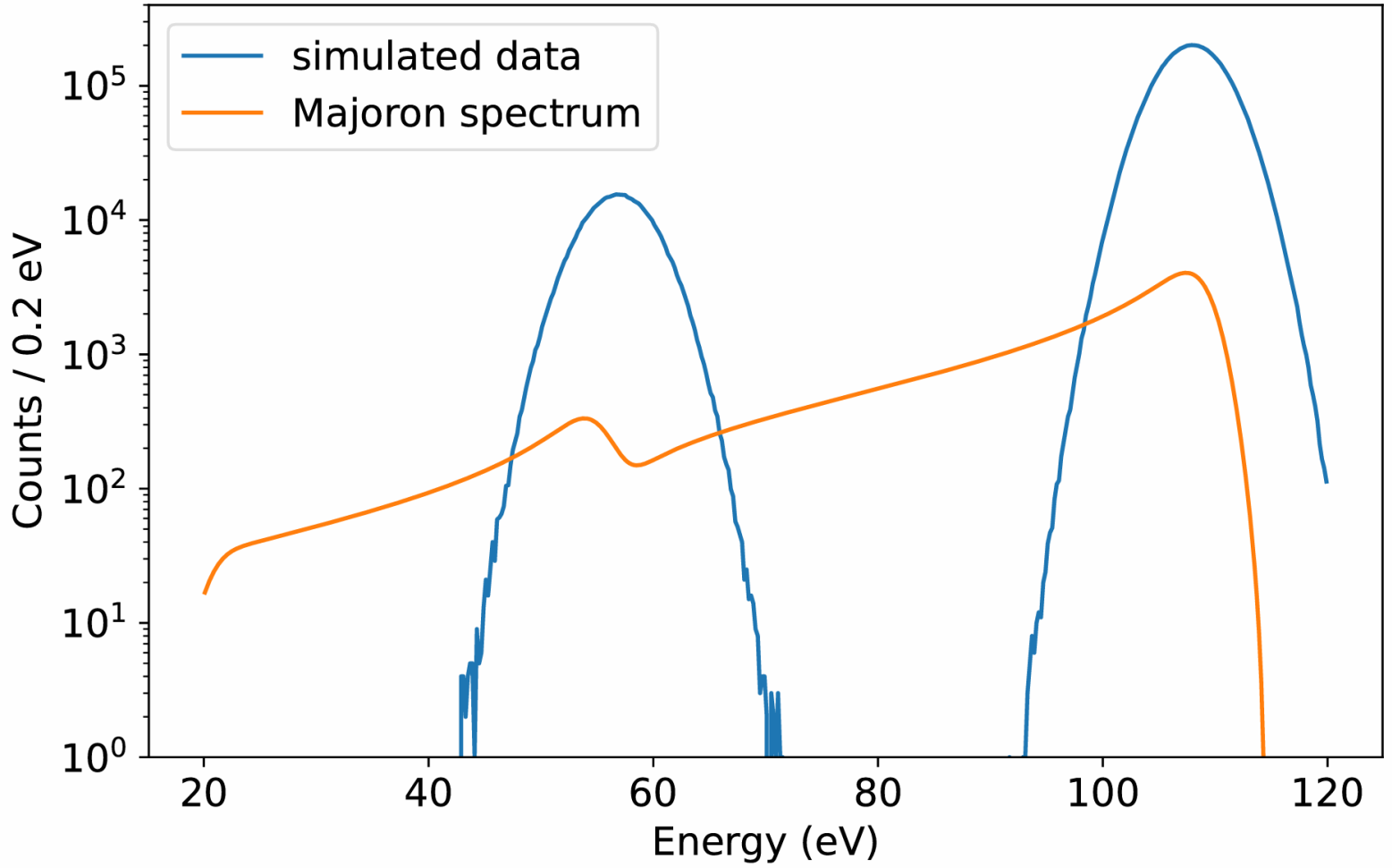
Wilk’s theorem conditions

- ASYMPTOTIC: Sufficient data is observed.
- INTERIOR: Only parameters values which are far from the boundaries of their parameter space are admitted.
- IDENTIFIABLE: Different values of the parameters specify distinct models.
- NESTED: H0 is a limiting case of H1, e.g. with some parameter fixed to a sub-range of the entire parameter space.
- CORRECT: The true model is specified either under H0 or under H1.

Residuals/Better fitting

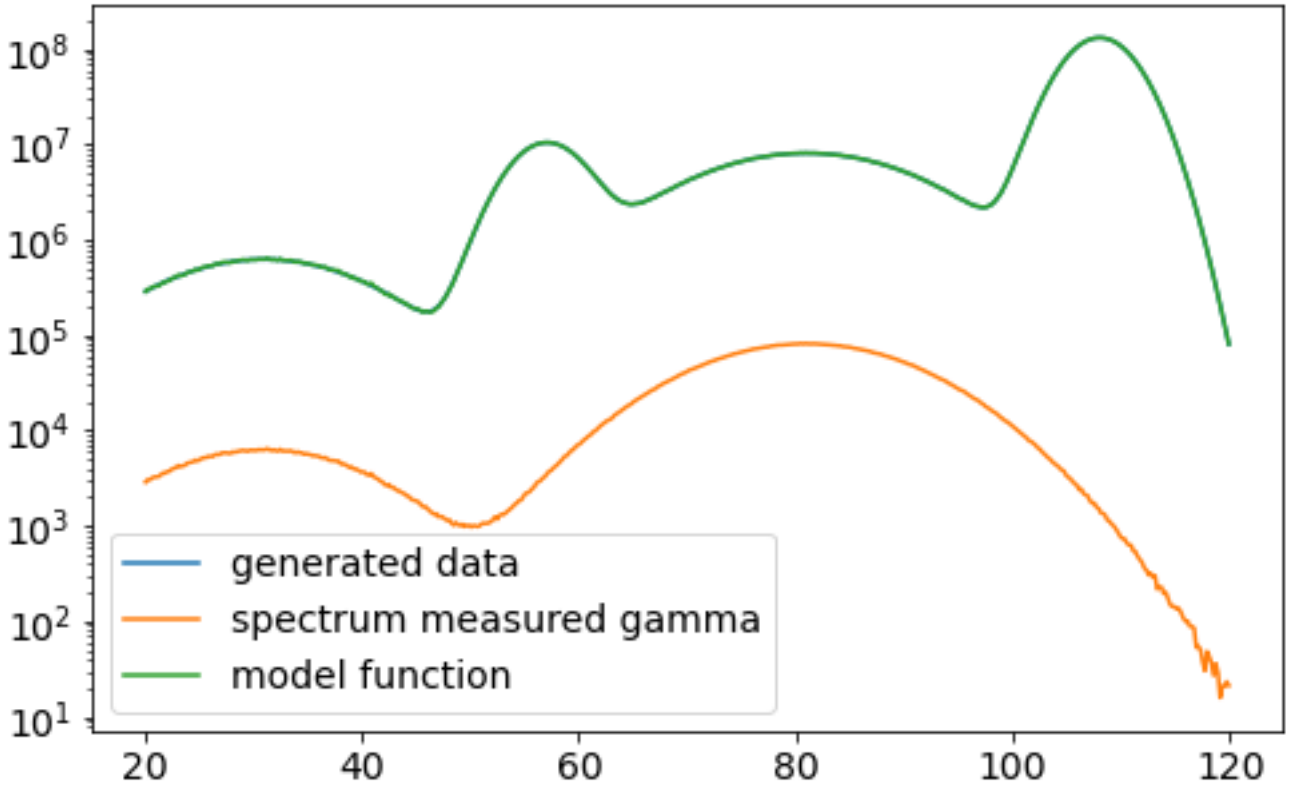


Perfect ES suppression



ES peak suppression

- Generate a simulated gamma spectrum
- With a certain detector efficiency
- Re-scale the spectrum to fix the background in the fit model



Things to do next

- Grid searches with more points
- Grid searches on real data
- Optimization time very long due to ES convolution at each step
- Study the broadening of the three-body spectrum

About BeEST results (extracted from [3])

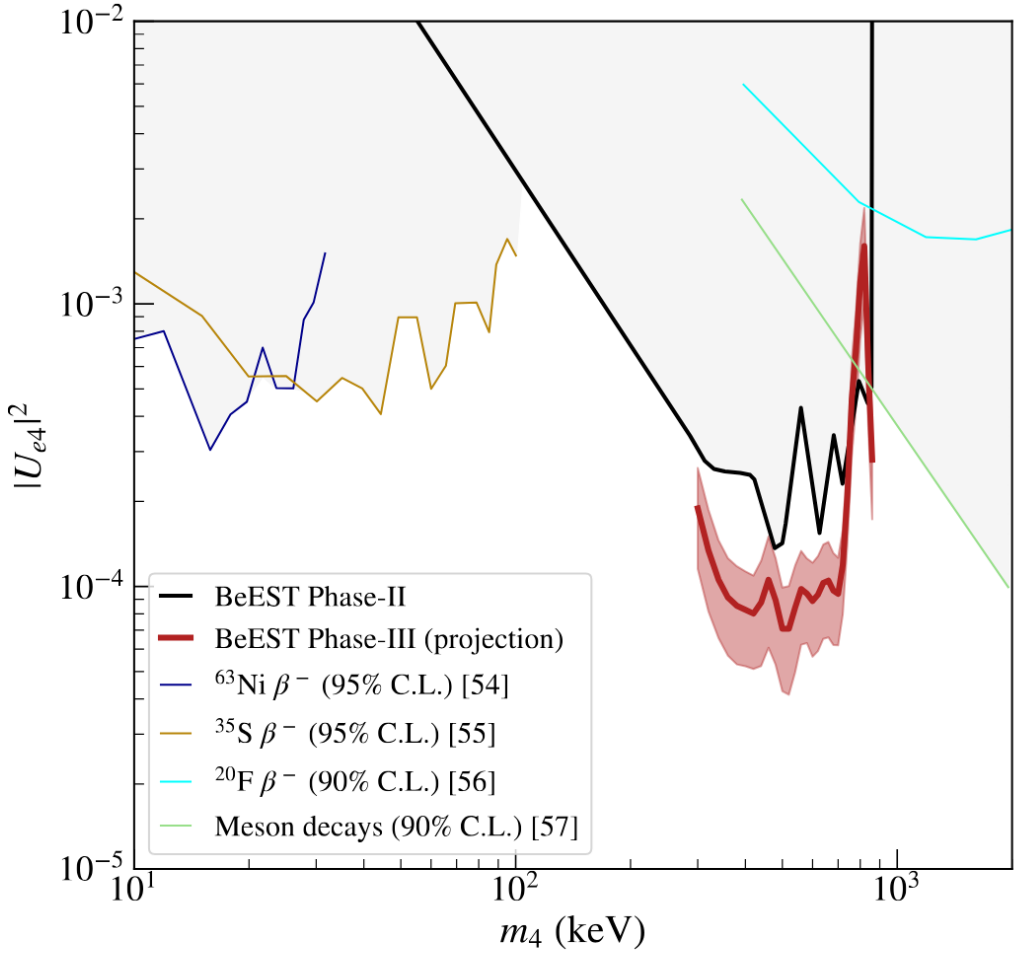
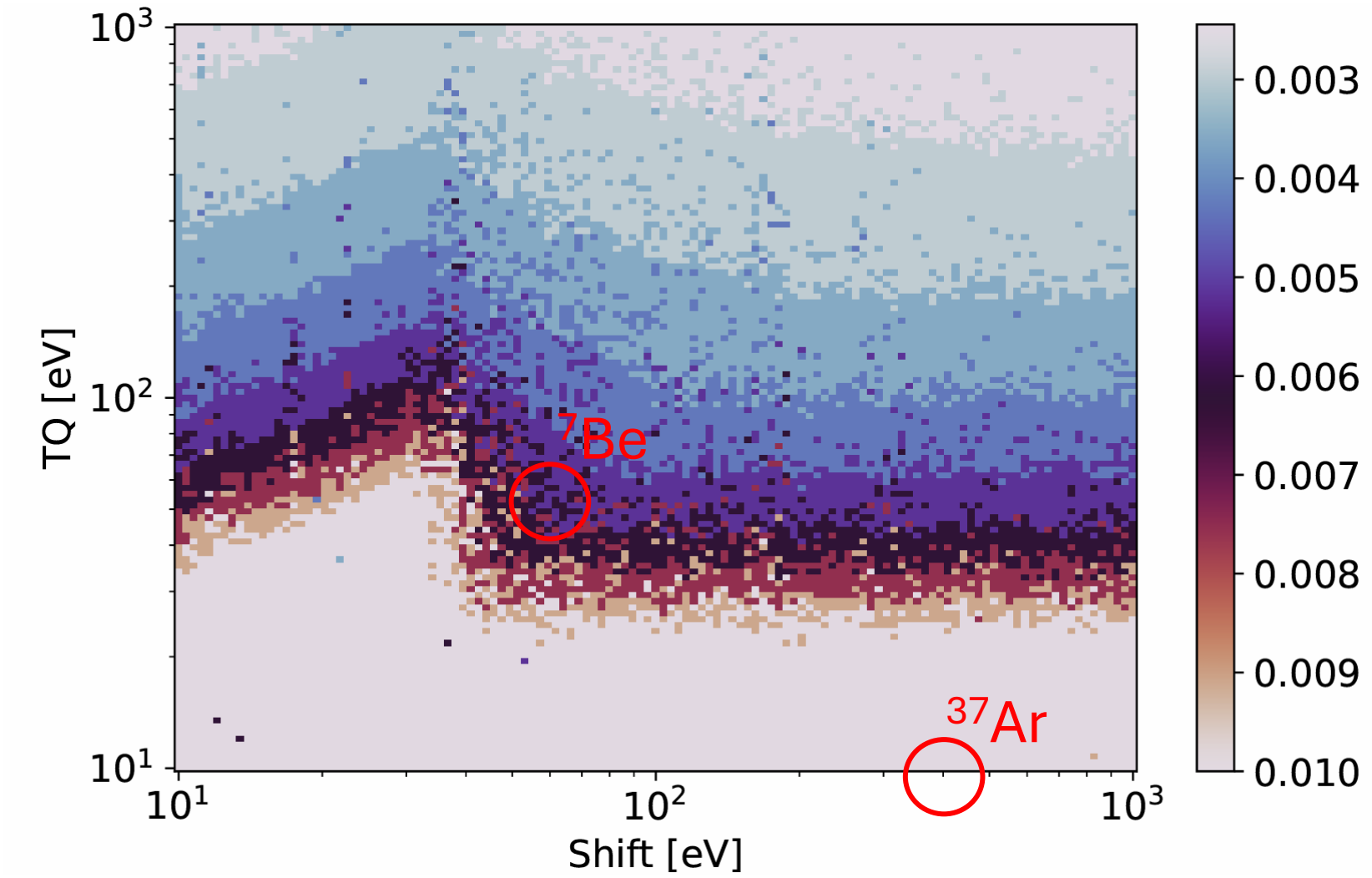


FIG. 25. Projected sensitivity for the BeEST Phase-III with 1σ uncertainty band. Only the statistical considerations were made. Previous limits are shown in gray shaded regions [54–58].

Lower constraint plot with other BeEST candidate



References

[1] Arturo de Giorgi, Luca Merlo, Xavier Ponce Diaz, and Stefano Rigolin. The minimal massive majoron seesaw model. *Journal of High Energy Physics*, 2024(3) : 1–39, 2024.

[2] Sara Algeri, Jelle Aalbers, Knut Dundas Mora, and Jan Conrad. Searching for new physics with profile likelihoods: Wilks and beyond. *arXiv preprint arXiv:1911.10237*, 2019

[3] Inwook Kim, Connor Bray, and al. Signal processing and spectral modeling for the Beest experiment. Phys. Rev. D, 111:052010, Mar 2025.

[4] BERRYMAN, Jeffrey M., BLINOV, Nikita, BRDAR, Vedran, *et al*. Neutrino self-interactions: A white paper. *Physics of the Dark Universe*, 2023, vol. 42, p. 101267.

[5] Rodejohann, Werner. "Neutrino-less double beta decay and particle physics." *International Journal of Modern Physics E* 20.09 (2011): 1833-1930