The NEνFAR project:
New Evaluation of ν Fluxes At Reactors

DE LA RECHERCHE À L'INDUSTRIE

JRJC 2019

Modeling of reactor antineutrino spectra

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1. Introduction

- Reactor antineutrino
- Experimental context
- NEνFAR project

2. Tools for modeling reactor ν

- Fission fragment distribution
- β decay model

3. Preliminary results

- Fission spectra

4. Conclusion

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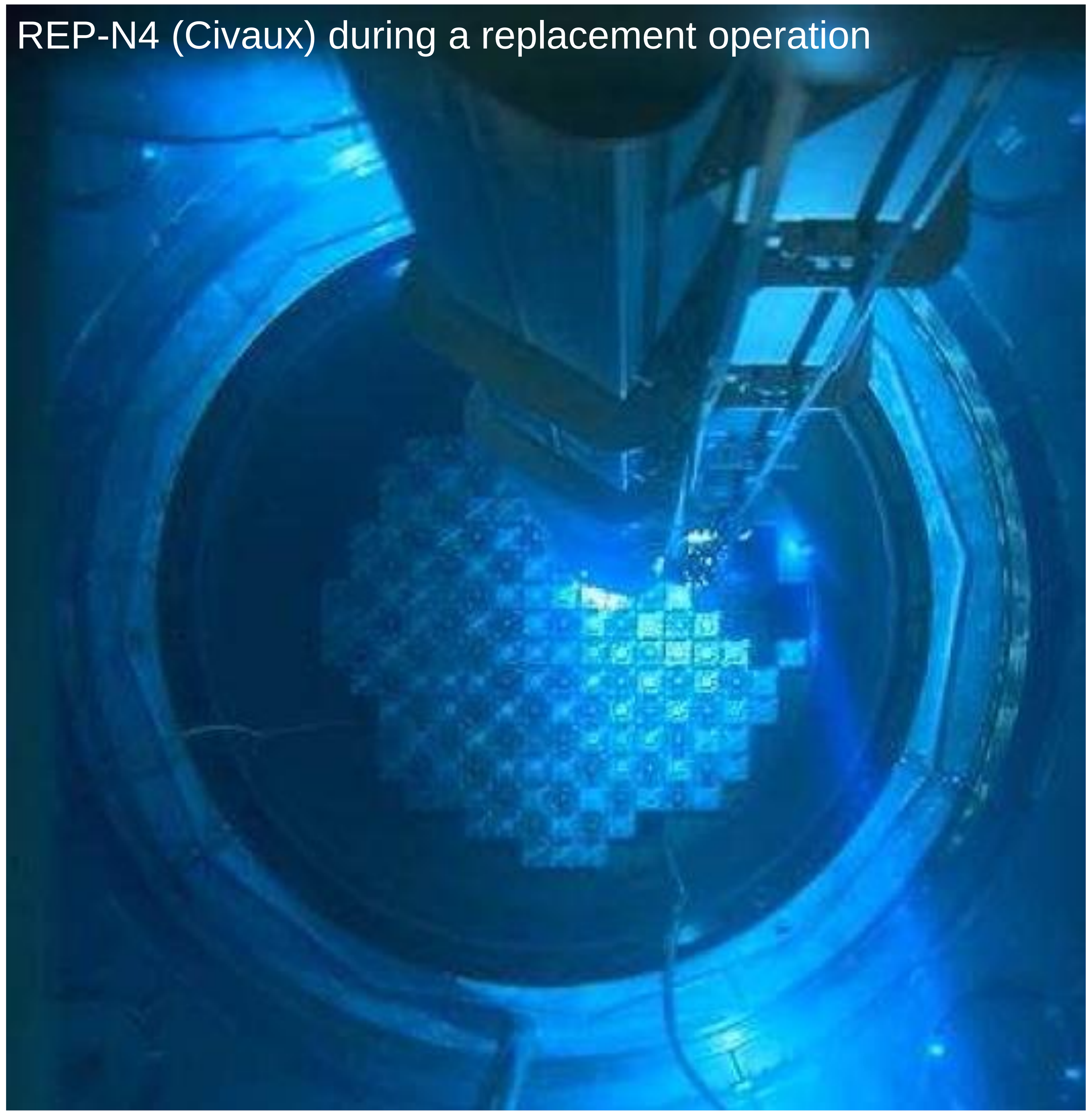
Reactor antineutrino

Commercial nuclear reactor

- Pressurized water reactor (PWR)

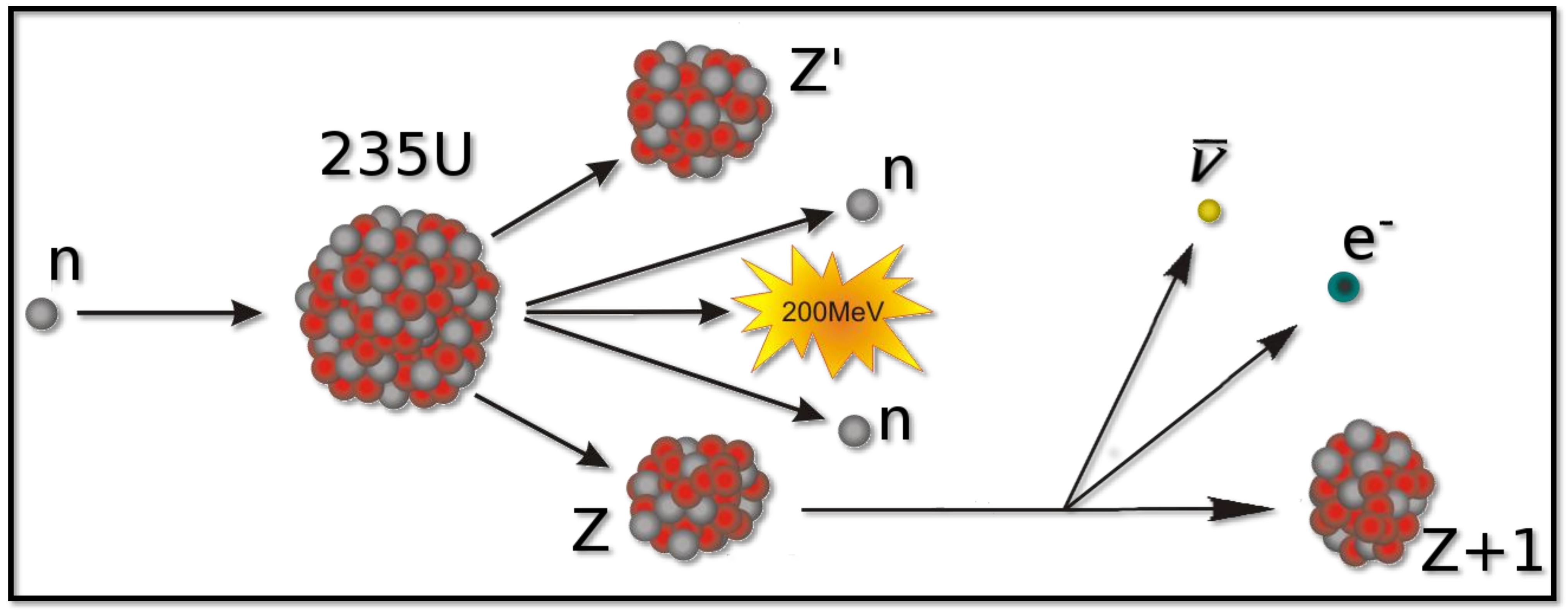

REP-N4 (Civaux) during a replacement operation

Commercial nuclear reactor

- Pressurized water reactor (PWR)

- Fuel = UO_2 (^{238}U + few ^{235}U %)
  - ↗ Pu isotopes by neutron capture on ^{238}U
  - **Burnup process**
  - Thermal power: **^{235}U (54%), ^{239}Pu (32%), ^{238}U (8%), ^{241}Pu (6%)**

- $\bar{\nu}_e$ **originate from neutron-induced fissions** of $^{235,\,238}$U and $^{239,\,241}$Pu isotopes in the reactor core
  - A few $\bar{\nu}_e$ originate from **neutron capture** on ^{238}U



^{235}U fission and fission fragment decay scheme

Reactor antineutrino

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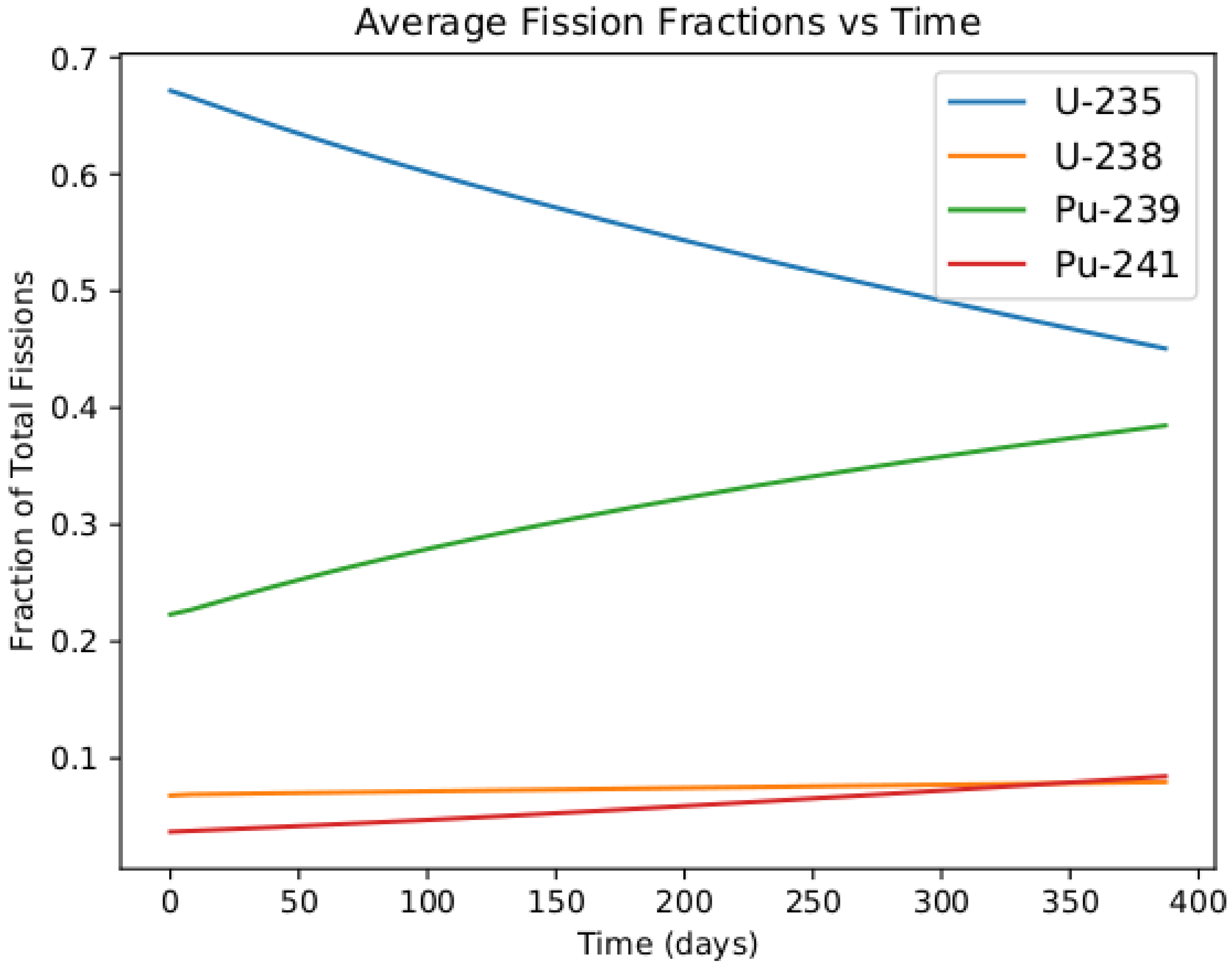

Reactor core fuel evolution due to burnup

Reactor antineutrino

Commercial nuclear reactor

- Pressurized water reactor (PWR)

- Fuel = UO_2 (^{238}U + few ^{235}U %)
  - ↗ Pu isotopes by neutron capture on ^{238}U
  - **Burnup process**
  - Thermal power: **^{235}U > ^{239}Pu > ^{238}U > ^{241}Pu**

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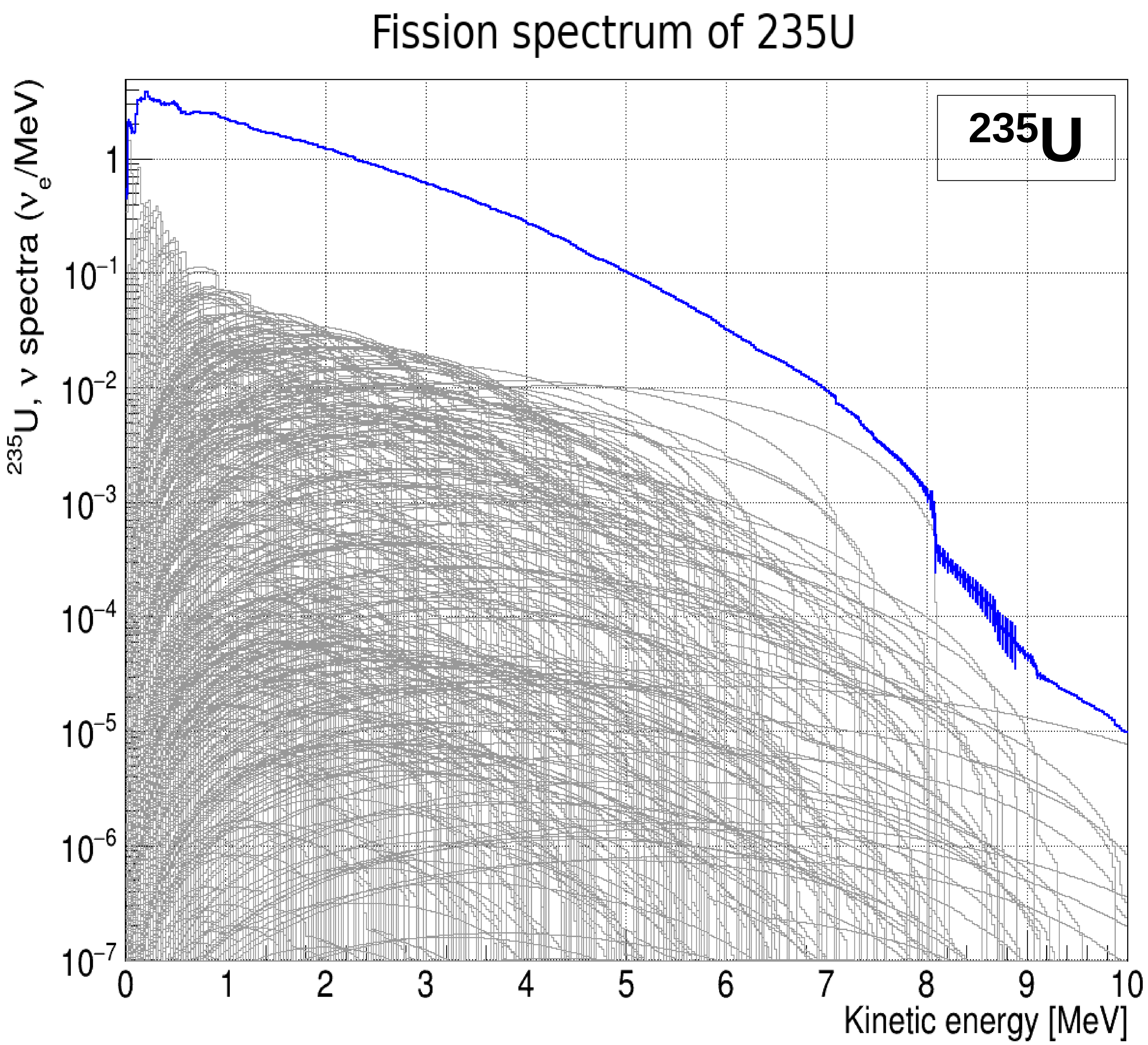


~6 $\bar{\nu}_e$ emitted per fission

Reactor $\bar{\nu}_e$ flux: $\sim 2 \times 10^{20}\ \bar{\nu}_e \cdot s^{-1} \cdot GW_{th}{}^{-1}$

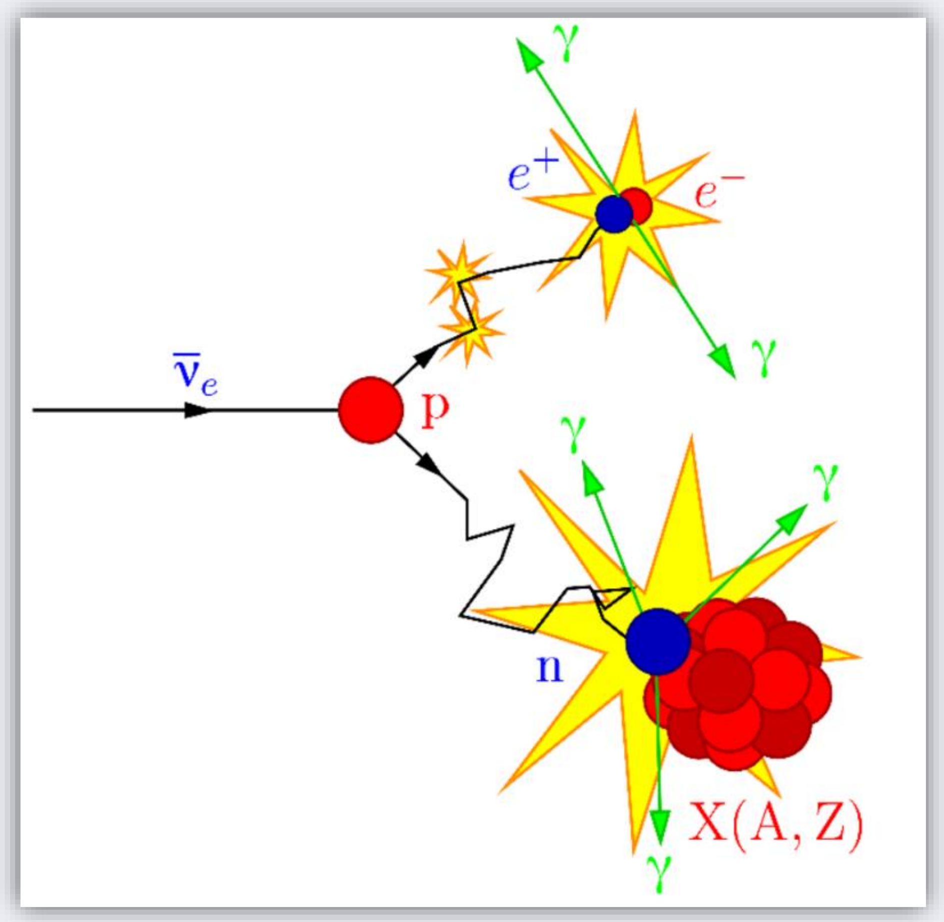
Core fuel evolution ⇒ reactor $\bar{\nu}_e$ spectrum change

Experimental context

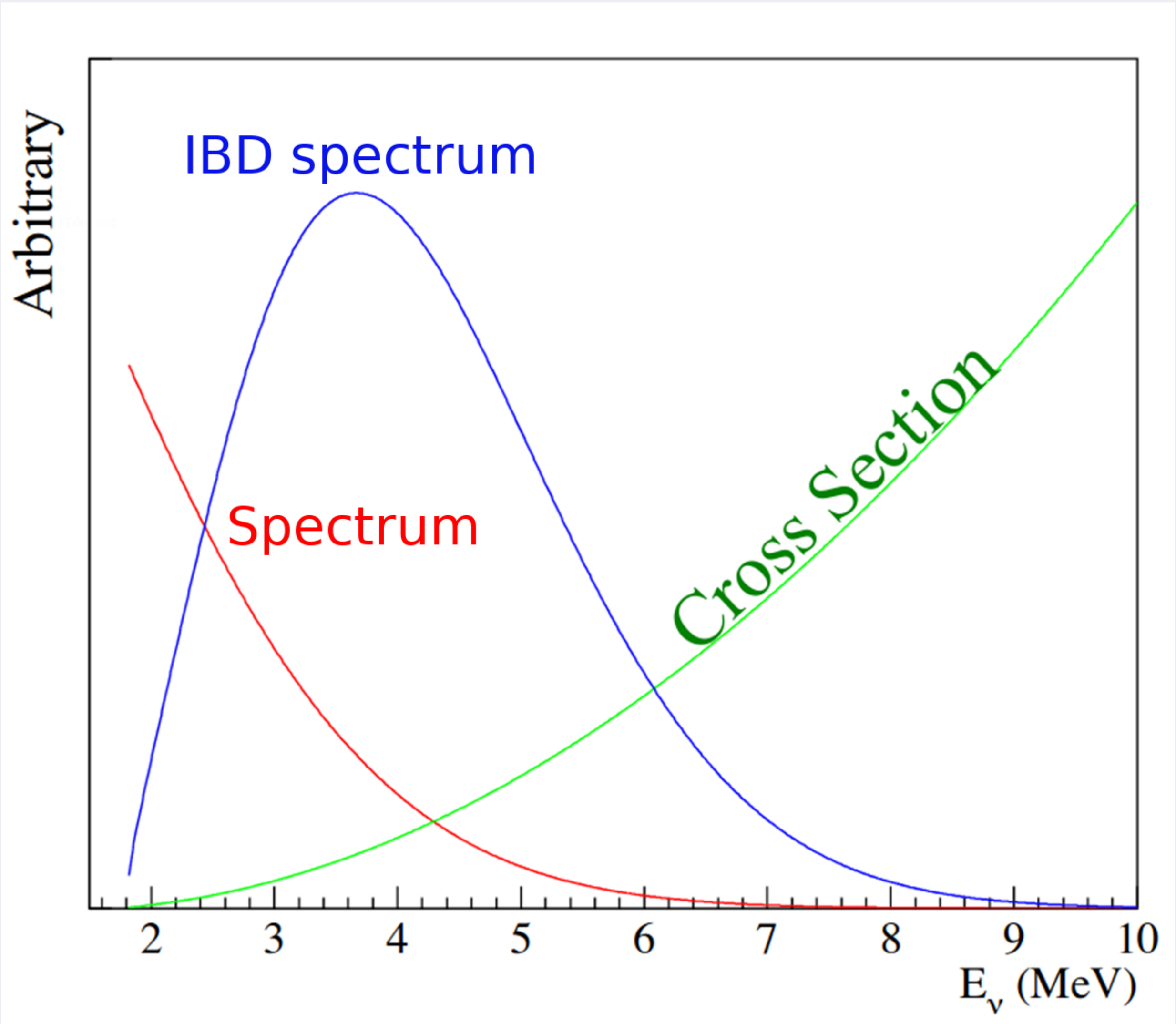
Inverse Beta Decay (IBD)

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

- Pioneered by Reines & Cowan in 1956
- Time/space **correlation** of **prompt positron** and **delayed neutron** signals
- **Kinematic threshold: 1.8 MeV**
- **σ_{IBD}~10^{-43} cm^2**



IBD process



Expected IBD spectrum at reactor

- 2 methods for reactor spectrum modeling
  - Inversion, Schreckenbach (80's)
  - **Summation**, King & Perkins (1958)

- 2011 : **2 model reviews** of reactor $\bar{\nu}_e$ calculation
  ⇒ New comparison with past experiments

2011 model review (**Mueller-Huber**)
+ IBD cross-section revision:

- Reactor antineutrino anomaly

Recent experiment **question validity** of state-of-the-art model due to… :

- Spectral shape anomaly
- Isotopic fuel evolution

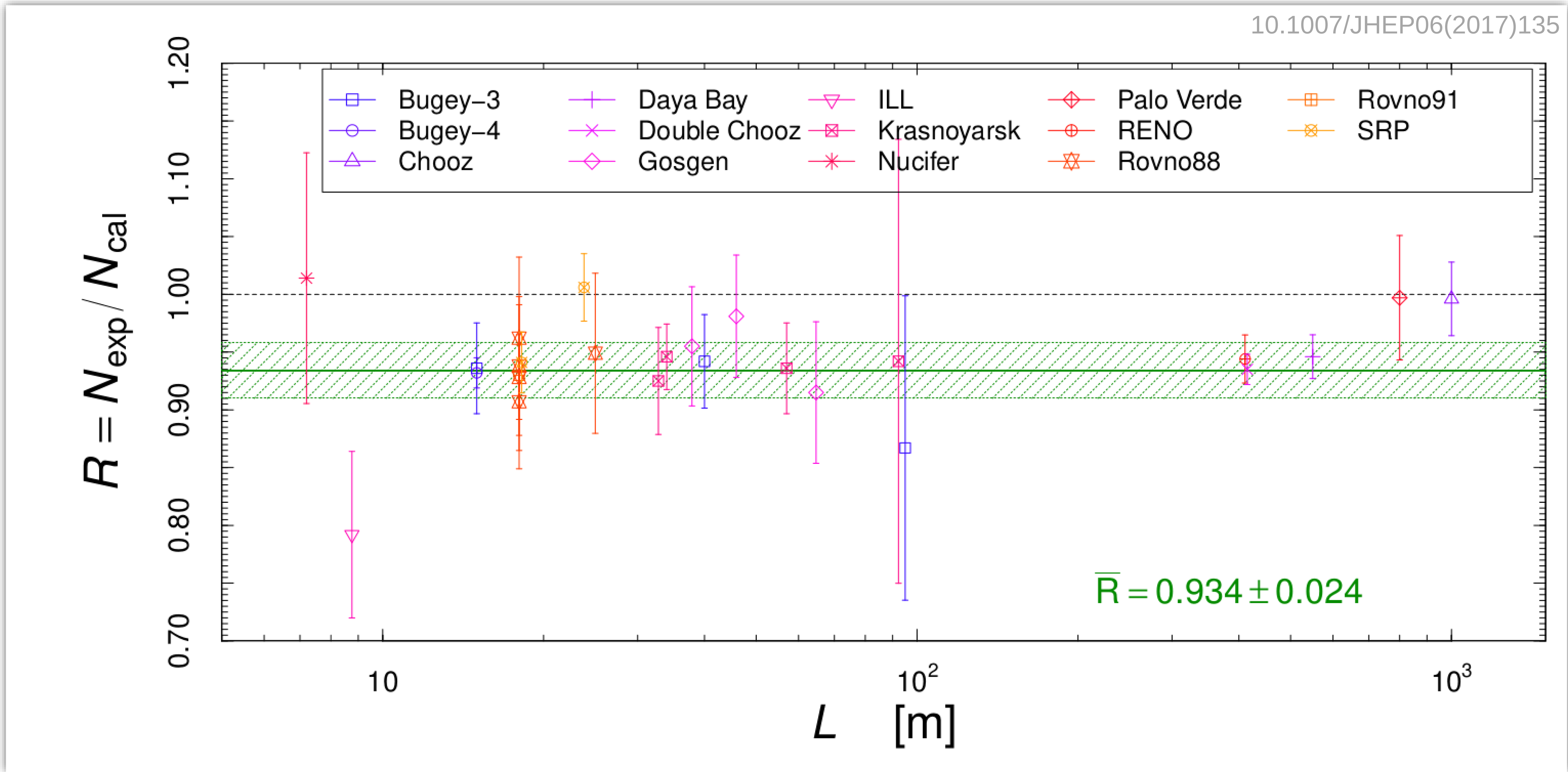
Experimental context

Reactor Antineutrino Anomaly (RAA)

- **Systematic deficit** of measured $\bar{\nu}_e$ flux compared to predictions in >20 experiments
- Confirmed in recent experiments
- Ratio flux meas/pred: **0.934±0.024 (2.7 σ)**

- Is it due to…
  … experimental bias ?
  … new physics (sterile ν) ?
  … model default ?

Experiment to prediction $\bar{\nu}_e$ flux ratio



Experimental context

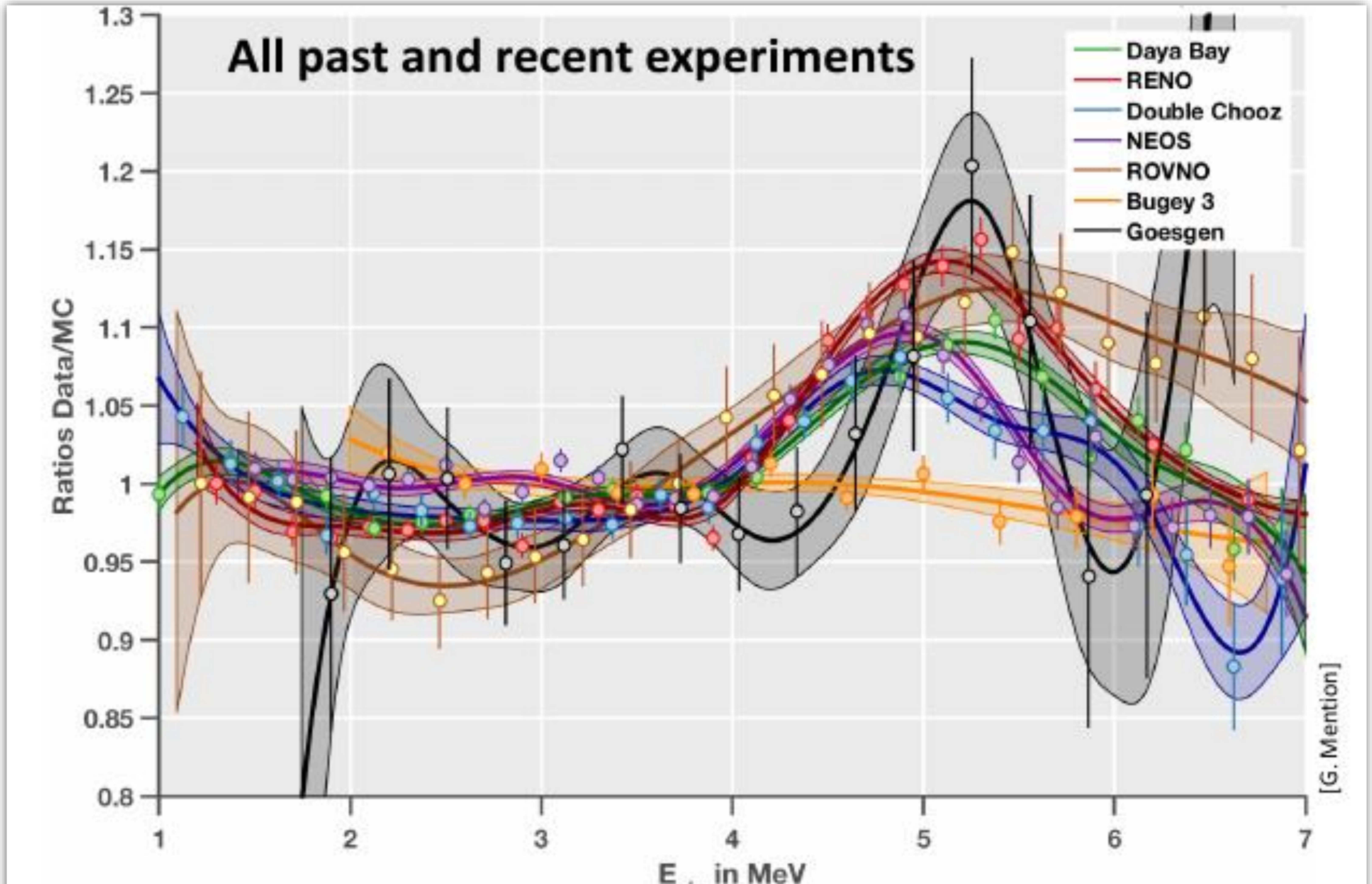
Spectral shape anomaly

- Observed **spectrum distorded** w.r.t. predictions

- Tension among different experiments distorsions
  - Some do not see a distorsion

- Is it due to…
  … detector effect ?
  … model default ?

Shape only (normalized) ratio



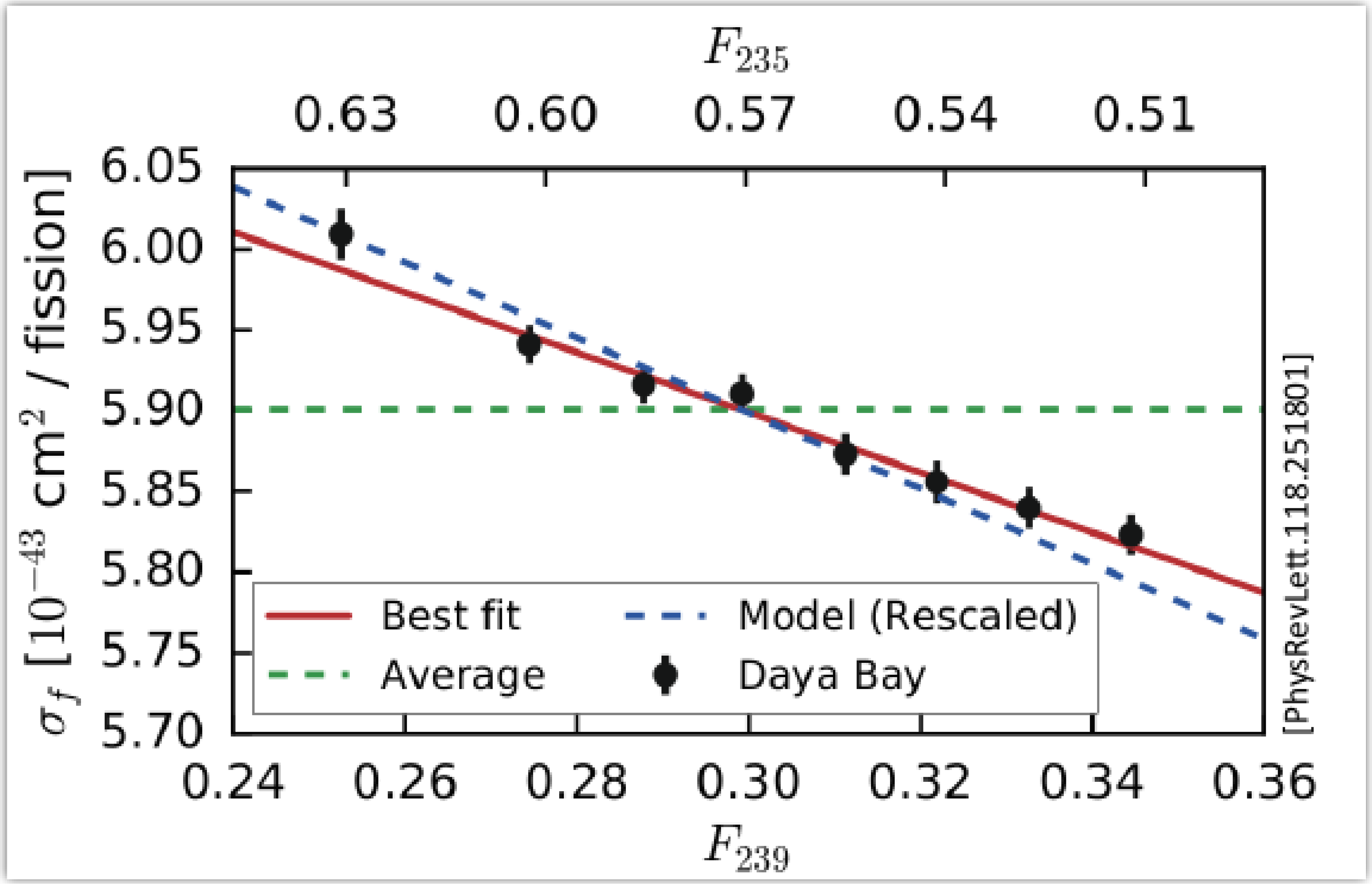
10.1016/j.physletb.2017.08.035, updated plots

Experimental context

Isotopic fuel evolution

- Unclear status of the $\bar{\nu}_e$ flux evolution w.r.t. fuel composition (^{235,238}U, ^{239,241}Pu)
  - ➢ Daya Bay: predicted slope **uncompatible** measur. at 3.1σ (within uncertainty)
  - ➢ RENO: predicted slope **compatible** measur. (within uncertainty)
- Tension could be explained by …
  … reactor physics at stake ?
  … bias in experimental uncertainties ?
  … model default ?

Detected number of $\bar{\nu}_e$ w.r.t. fuel evolution at Daya Bay



NEνFAR project

(New Evaluation of ν Flux At Reactor)

- **Possible misprediction from the model**
  - ➢ lift approximations in the models
  - ➢ refine β decay models

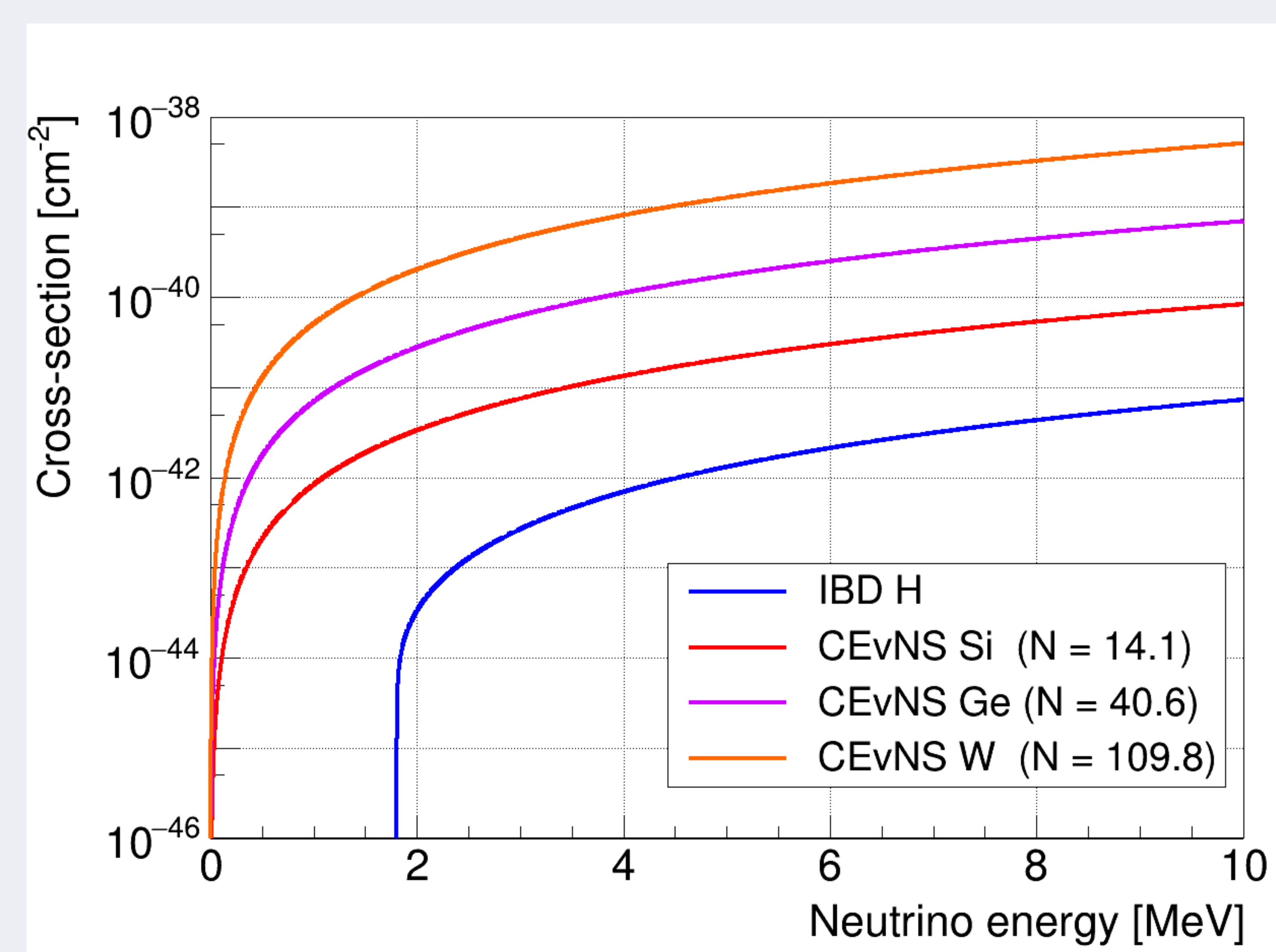
- Go back on **uncertainty budget**
  - ➢ Experimental and model uncertainties

- Evaluate the impact of **uncompleteness** and **quality** of nuclear databases
  - ➢ Provide updated nuclear decay database

- Provide model below 1.8 MeV
  - ➢ relevant to **coherent elastic neutrino-nucleus scattering** (CEνNS) experiments

CEνNS

- $\sigma_{CE\nu NS} \sim 100 \times \sigma_{IBD}$
- No threshold



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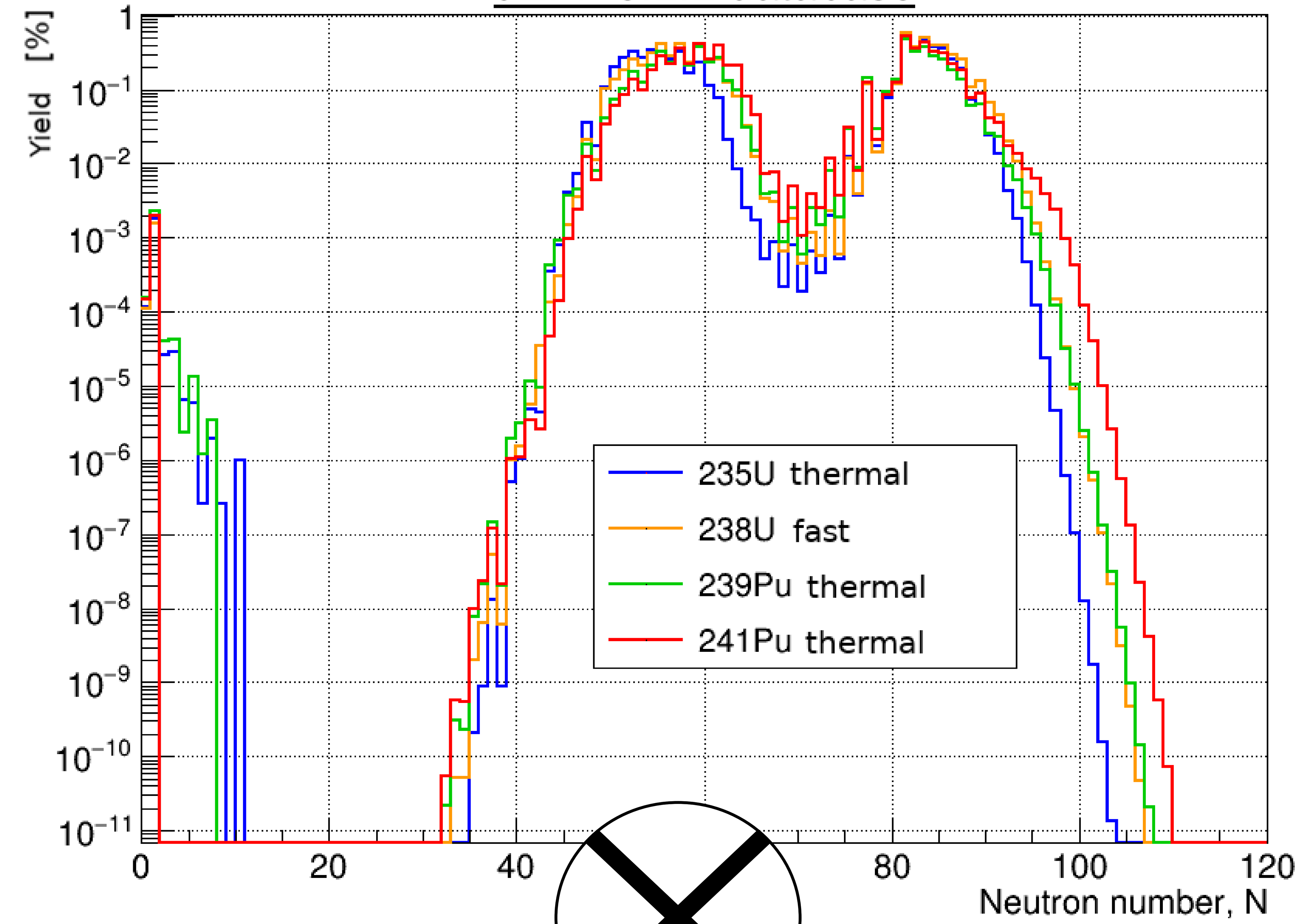
Fission fragment distribution

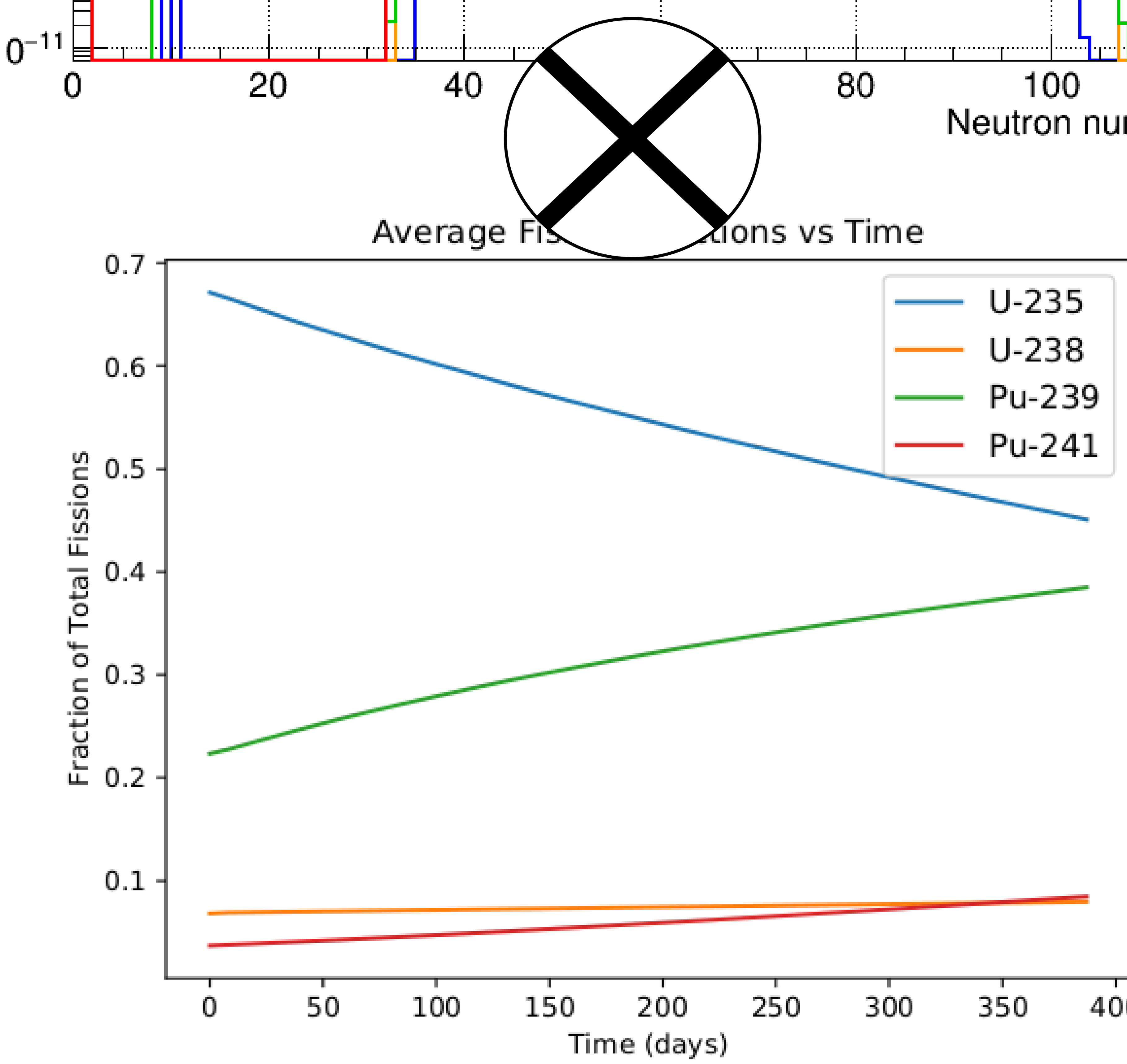
- Neutron-induced fissions of $^{235,\,238}$U and $^{239,\,241}$Pu
  - ➢ Fission fragments = neutron rich nuclei
  - ➢ Fragments undergo **successive β^- decays** to reach a stable element

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + e^- + \bar{\nu}_e$$

Cumulative fission yield distribution from JEFF 3.1.1 database



- Fission ~ **random process**, you do not get the same fission fragments every time a fission occurs
  - ➢ **Fission fragment distribution**
    - ❑ Bi-modal
    - ❑ 1 fission = 2 or 3 fission fragments
  - ➢ Up to 700-800 β decay emitters
  - ➢ Fission fragment distributions slightly depends on the fissioning isotope

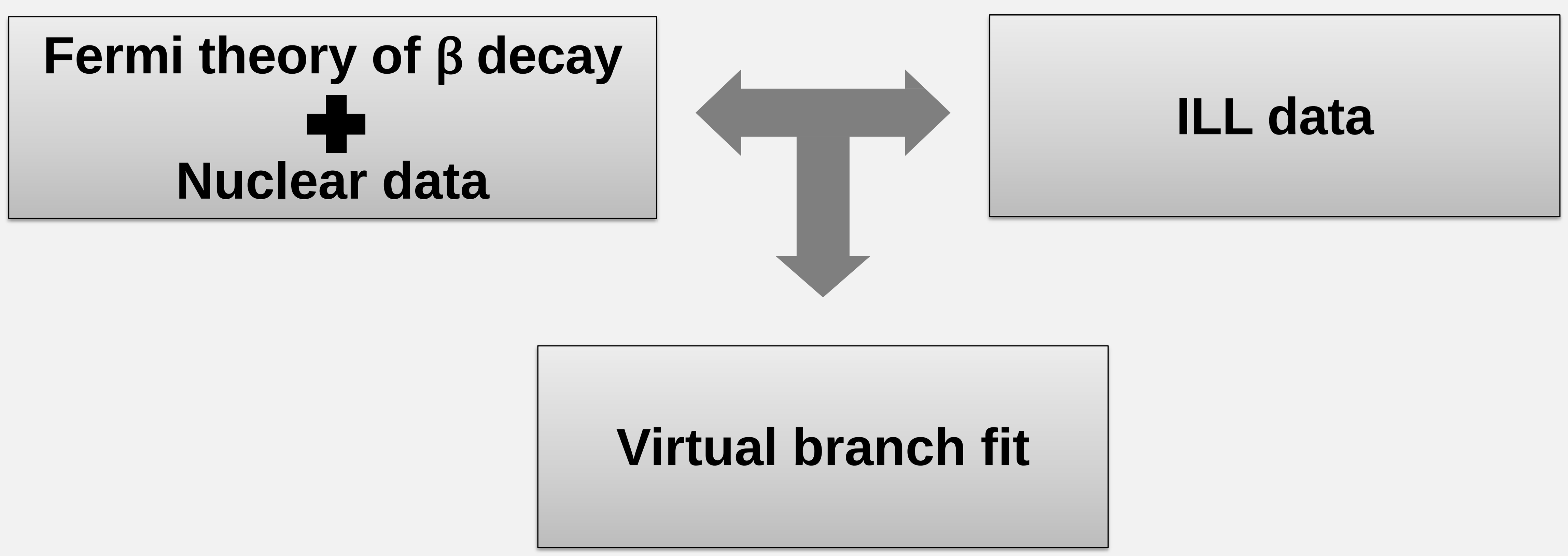


We can compute the **core distribution of β^- emitters** at any time

β decay model

Inversion method

Inverting an experimental electron fission spectrum using energy conservation at the β branch level



Huber model of ^{235}U, $^{239, 241}$Pu

Summation method

Fission spectrum of isotope k = sum of thousands β branches from all known branches listed in nuclear databases

$$S_{\beta,k}(E) = \sum_i FY_i \sum_j BR_{ij}\, S_\beta(Z_i, A_i, Q_{\beta\, ij}, E)$$

Fermi theory of β decay

$$S_\beta(W) = K\, C(Z,W)\, F_0(Z,W)\, pW(W_0 - W)^2$$

Nuclear decay data (ENSDF, …)

Fission yield data (JEFF, ENDF, …)

Mueller model of ^{238}U

β decay model

Inversion method

Inverting an experimental electron fission spectrum using energy conservation at the β branch level

- Make fission $\bar{\nu}_e$ spectrum
- Small uncertainties ~2-3%
- State-of-the-art model

- Limited by exp data
- No low energy model
- **Approximations**

Huber model of ^{235}U, $^{239, 241}$Pu

Summation method

Fission spectrum of isotope k = sum of thousands β branches from all known branches listed in nuclear databases

- Any energy
- Fine modeling
- Detailed spectrum

- Uncomplete database
- Large uncertainties >3%
- **Approximations**

Mueller model of ^{238}U

- **Coulomb function** approximation (*e.g.* Fermi function, λ function = 1, …)

Dirac equation solution (DES)
⬇
DES combinaison = Coulomb amplitude (CA)
⬇
CA combinaison = Coulomb function

- ξ approximation
  - Some transitions require nuclear structure calculus
    - Non-unique forbidden transition
    - Approximated by transition easier to model (unique forbidden or allowed)

β decay model: β and ν spectra

- **1st step**, make an **electron** spectrum ; e.g. ^{131}Sn* (Z=50, A=131), $E_0 = 4.9\ \mathrm{MeV}$, 1st unique forbidden

$$S_\beta(W) = K\, C(Z,W)\, F_0(Z,W)\, pW(W_0 - W)^2$$

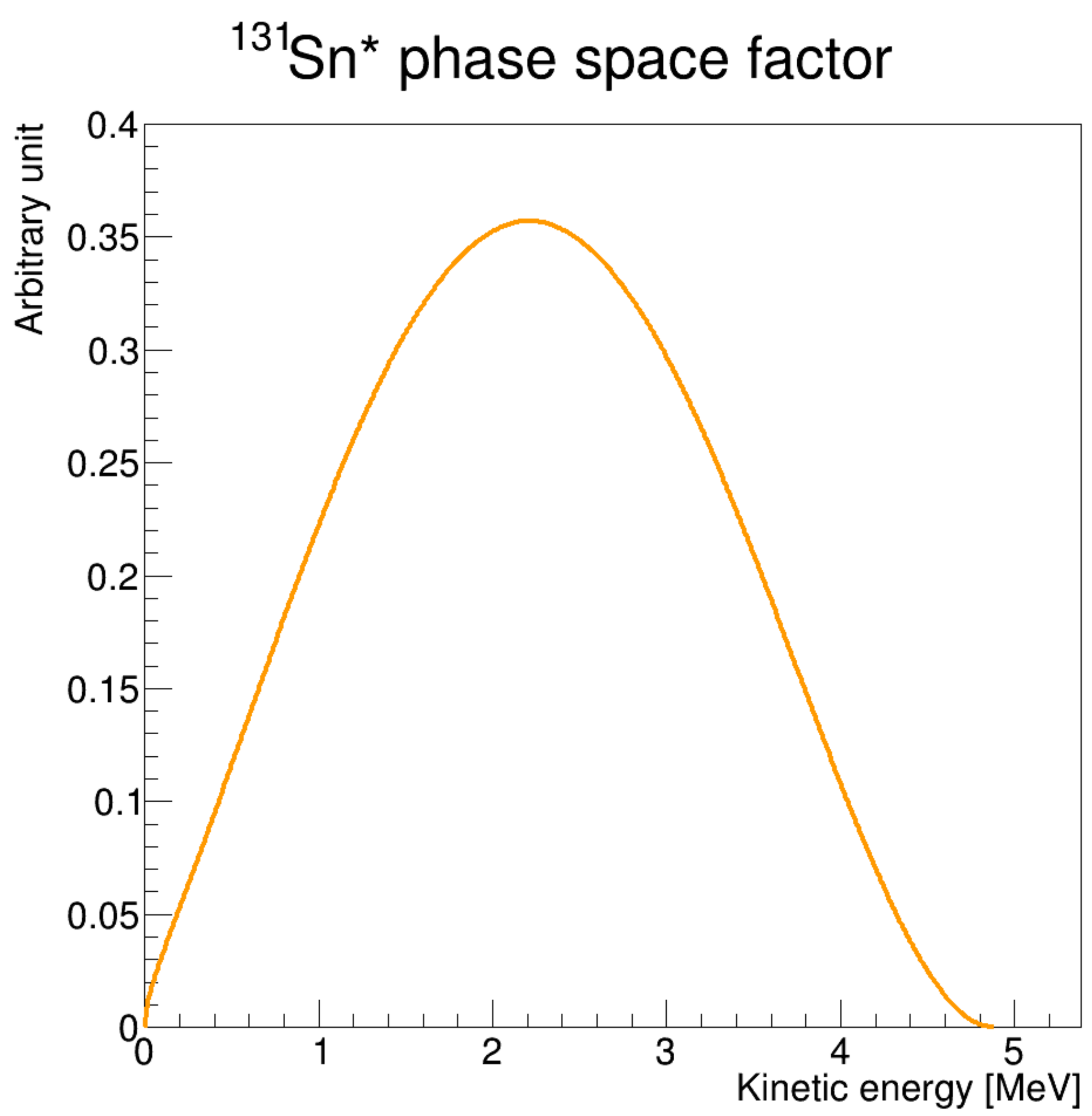
- p: electron momenum
- W: total energy
- W_0: max available energy for the transition
- E_0: max kinetic energy for the transition

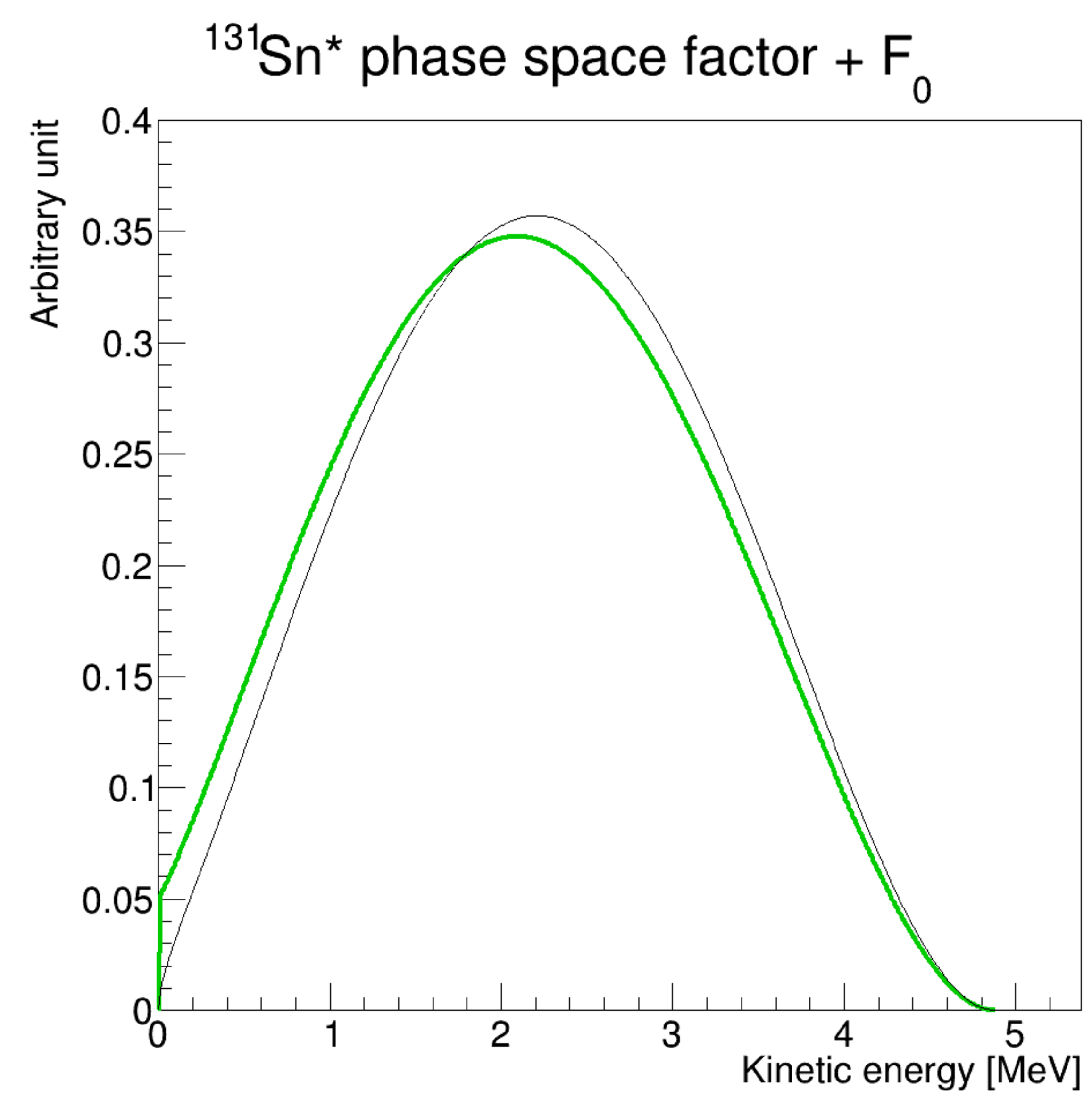
Phase space factor
Counts degenerency of quantum states

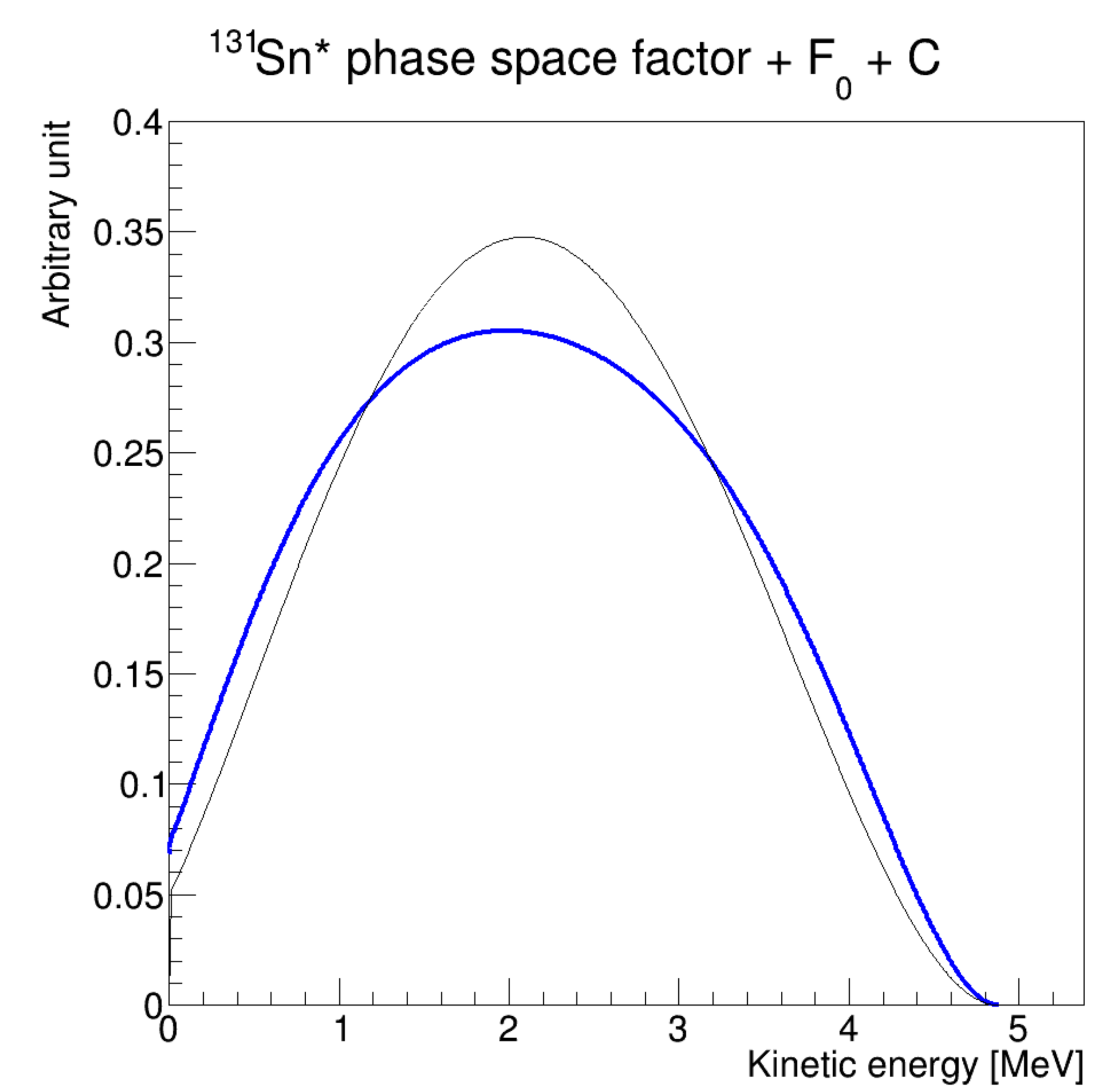
Fermi function
Considers electromagnetic interaction

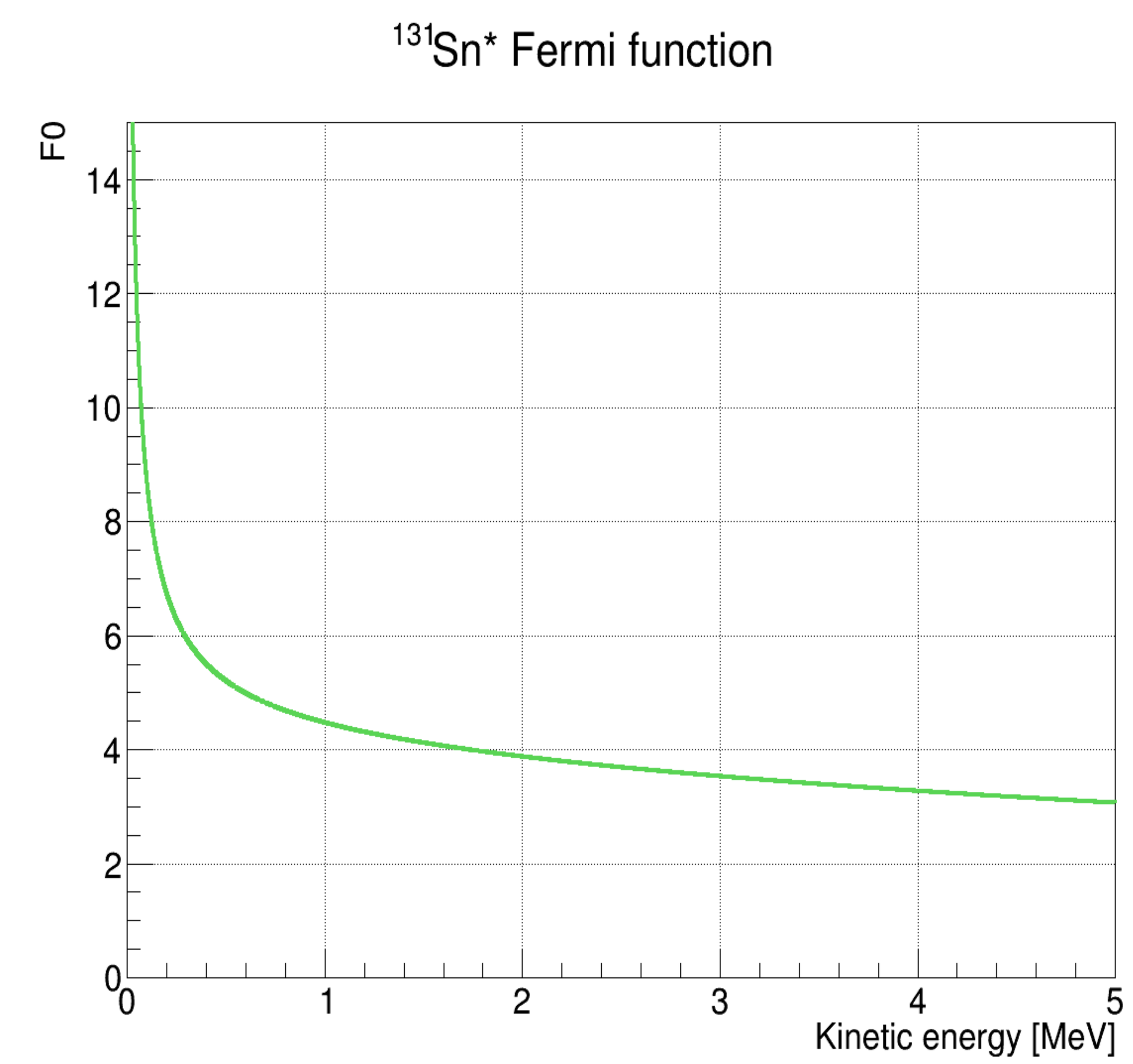
Shape factor
Difference between decay types (allowed, forbidden, …)

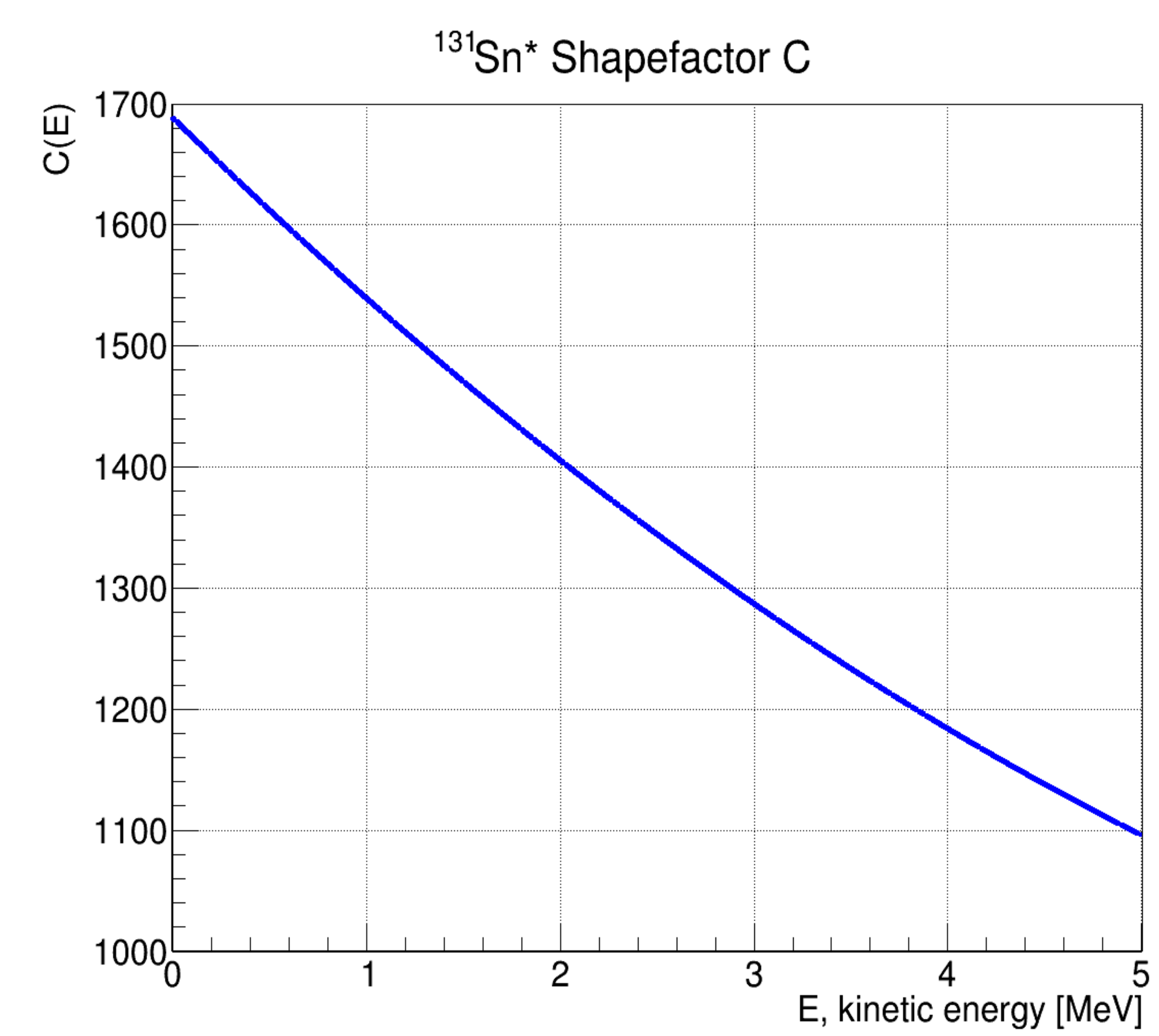
Normalization cste
$\int \mathrm{d}W\, S_\beta = 1$











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Shape factor
Difference between decay types (allowed, forbidden, …)

Fermi function
Considers electromagnetic interaction

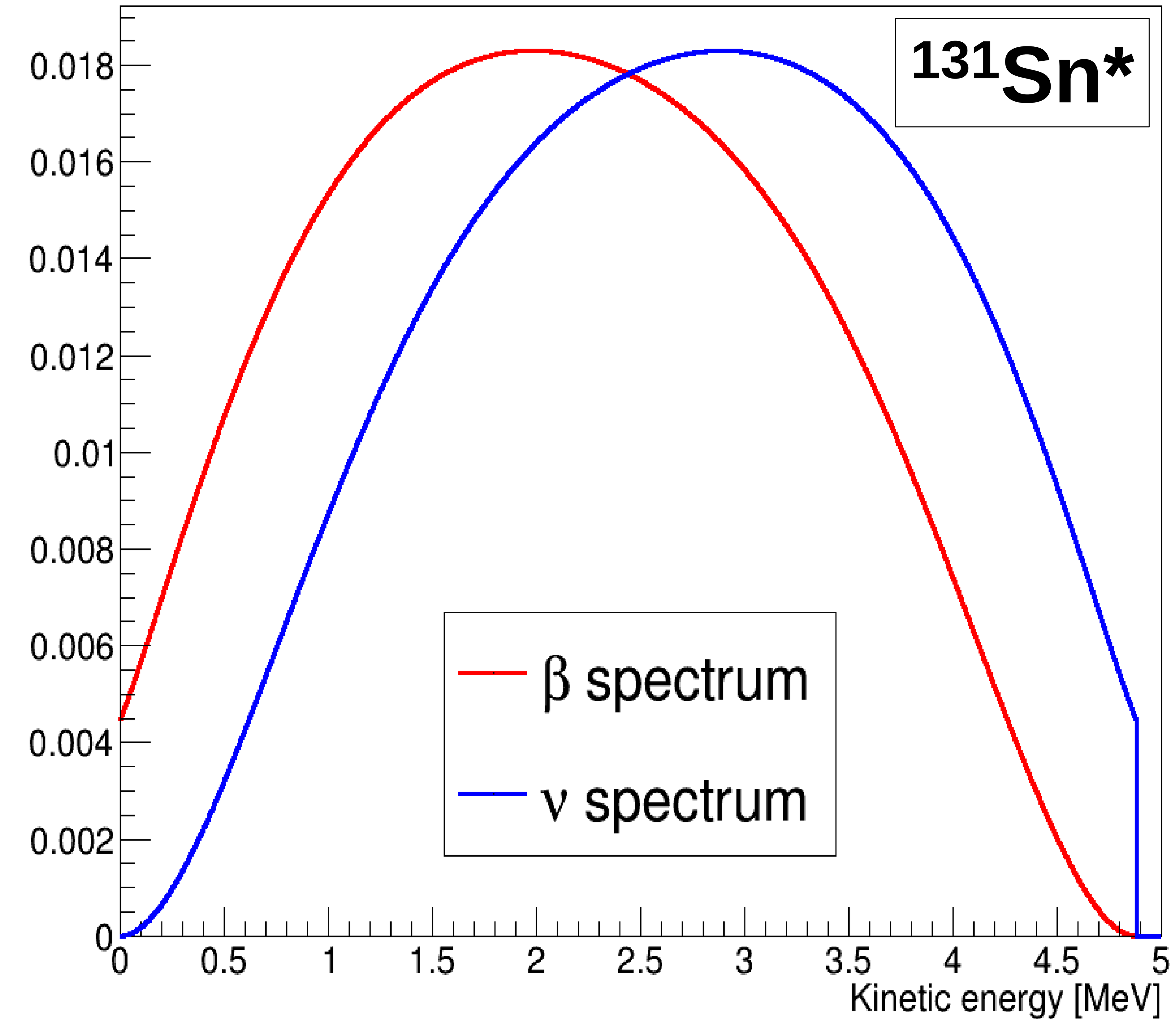
Normalization cste
$\int \mathrm{d}W \, S_\beta = 1$

- **2nd step**, make an **antineutrino** spectrum

↳ Energy conservation at branch level

$$S_\nu(E_\nu) = S_\beta(E_0 - E_\beta)$$

We know how to make β and ν spectra… with **many approximations** and for a potential due to a **point-like nucleus**



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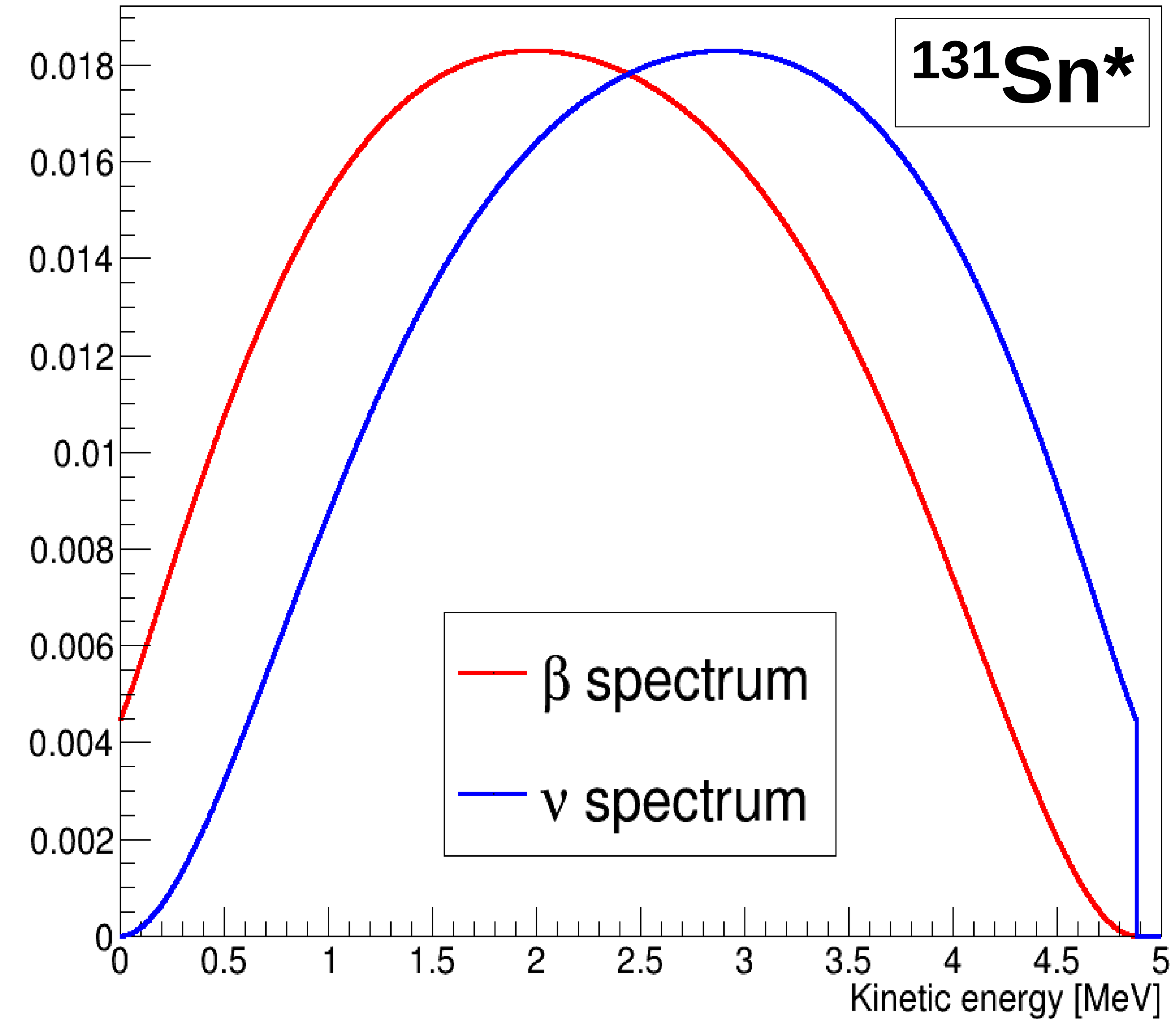
- L_0: Nuclear deformation, correction to F_0
- D_C: Nuclear deformation, correction to C
- L_0 and D_C computed via **Coulomb functions**
- **Home made program DIRAC**

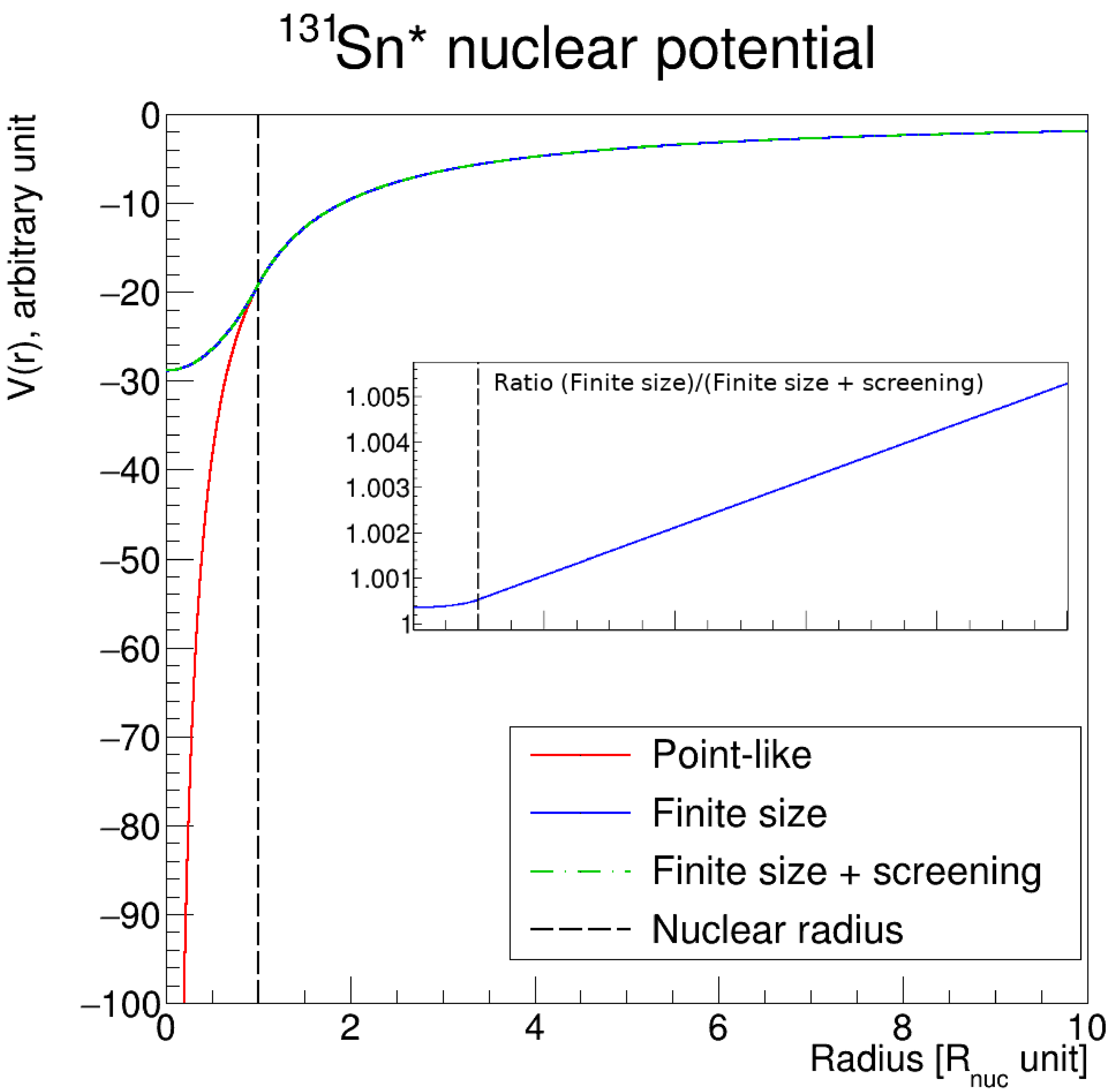
(Directives for an Improved Result of the Amplitude of Coulomb)

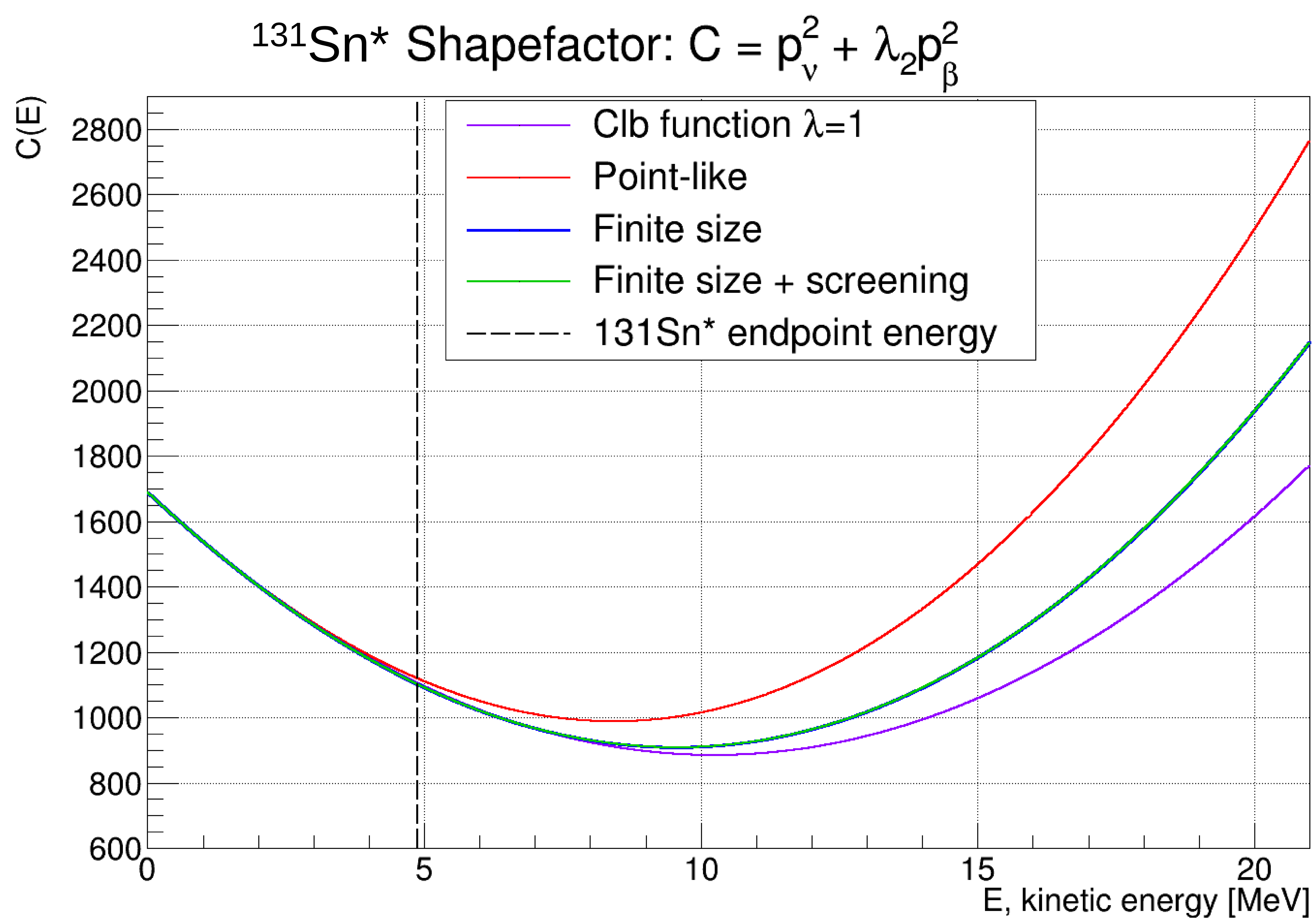


β decay model: Nuclear model impact

- DIRAC program **solves Dirac equation** for any nuclear potential defined on a grid
  - ↳ Some nuclear potential models
    - **Point-like**
    - **Finite spherical size**
    - **Finite size + screening**

Quantifiable impact on Shapefactor and other parameters (*e.g.* Fermi function)

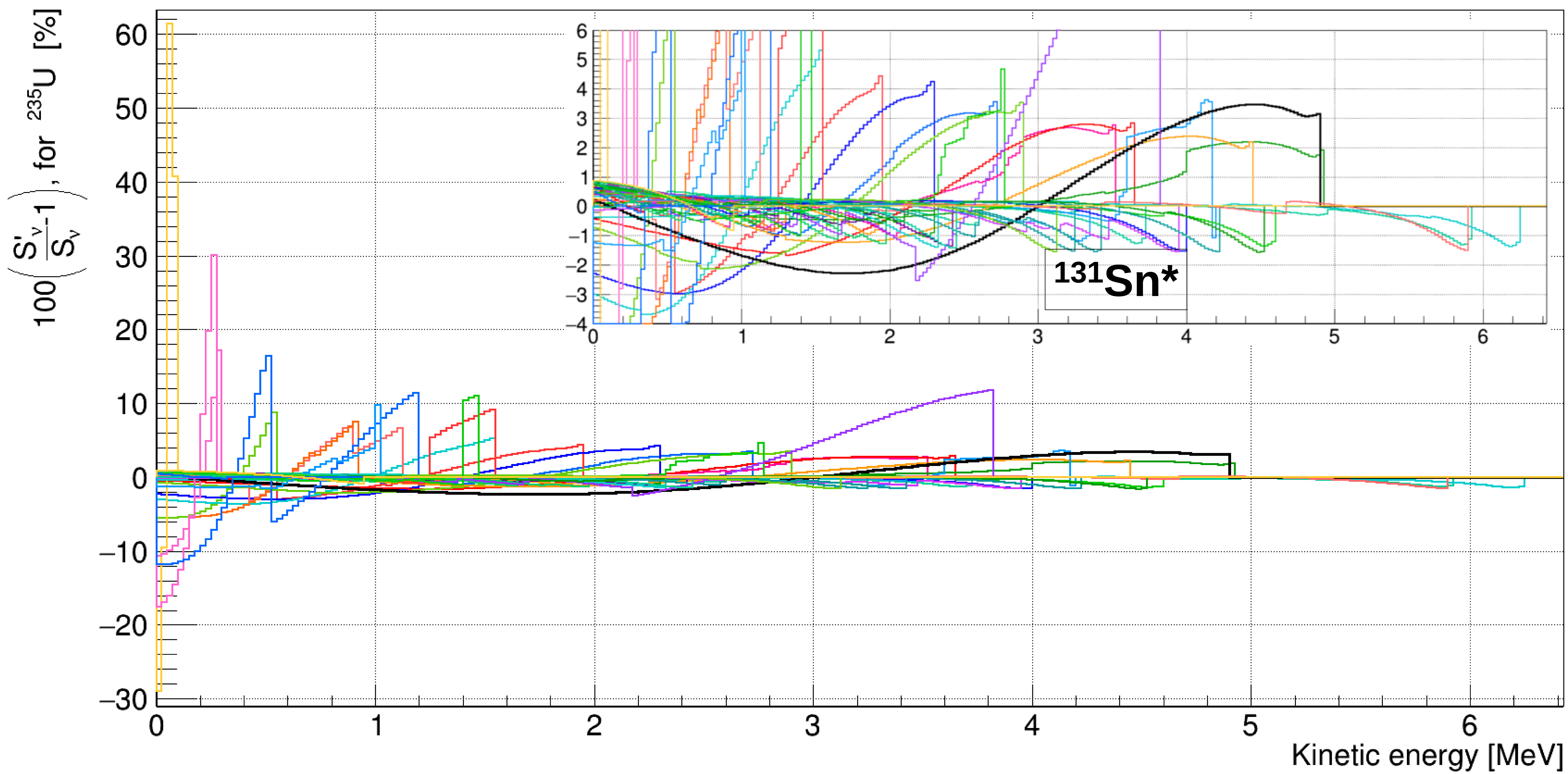




β decay model: isotope ν spectra

- Common to S and S': QED + WM
- Model S: Coulomb function $\lambda = 1$ approximation + linear L_0 approx
- Model S': Exact Coulomb function + spherical screened nucleus model

Neutrino spectrum relative difference S vs S' of 50 important isotopes making ^{235}U fission spectrum



High impact on single isotope $\bar{\nu}_e$ spectra

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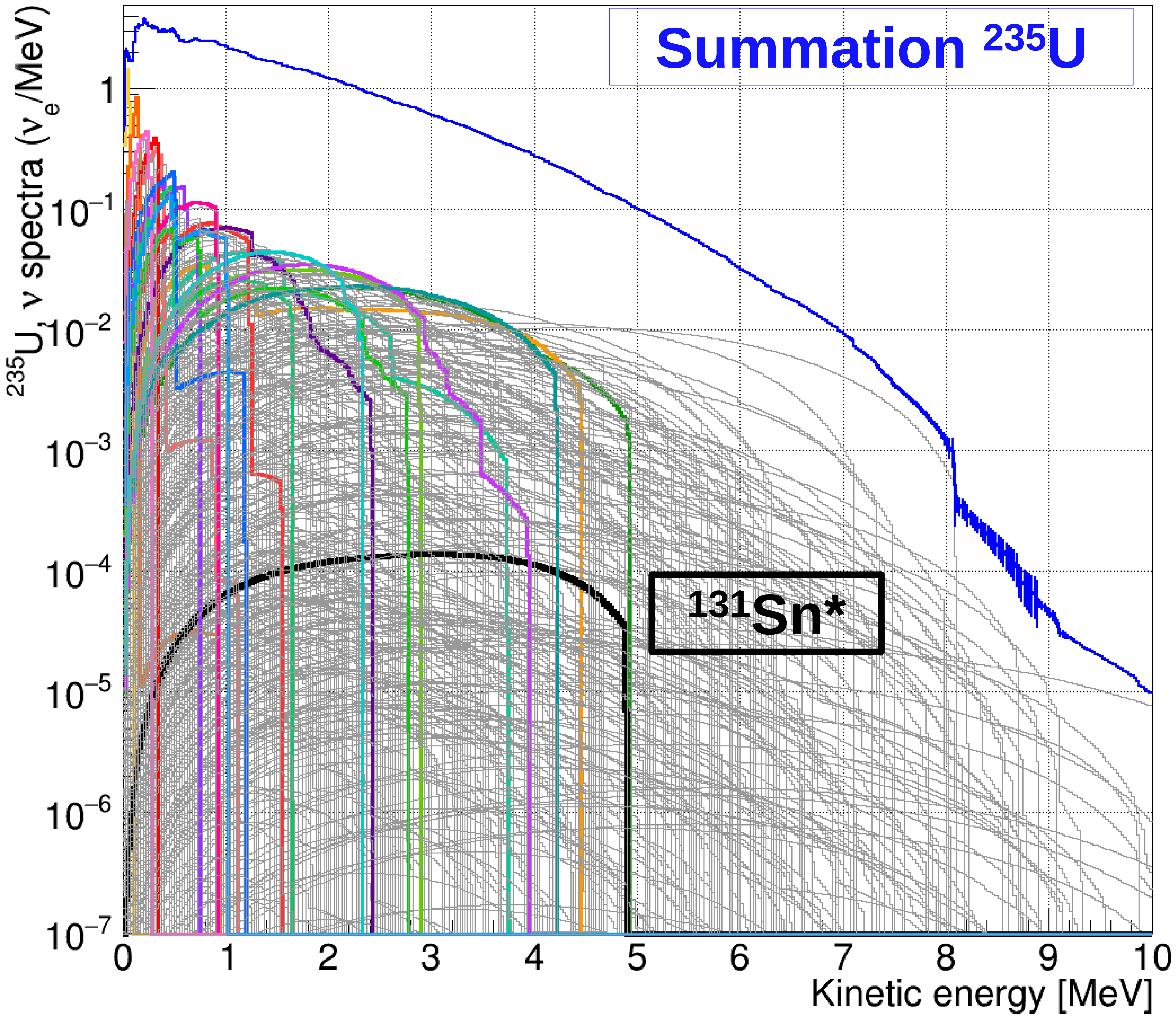
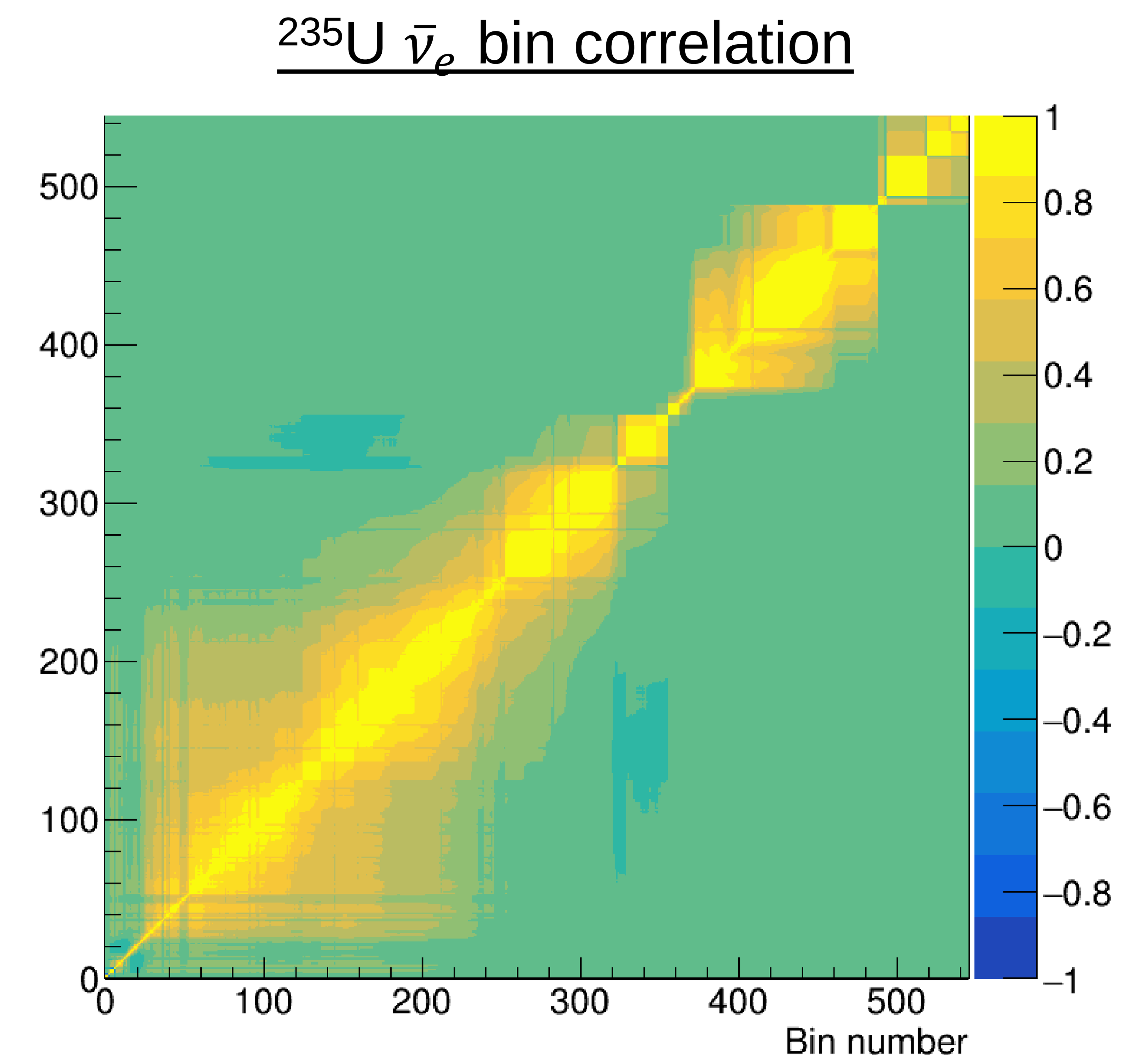
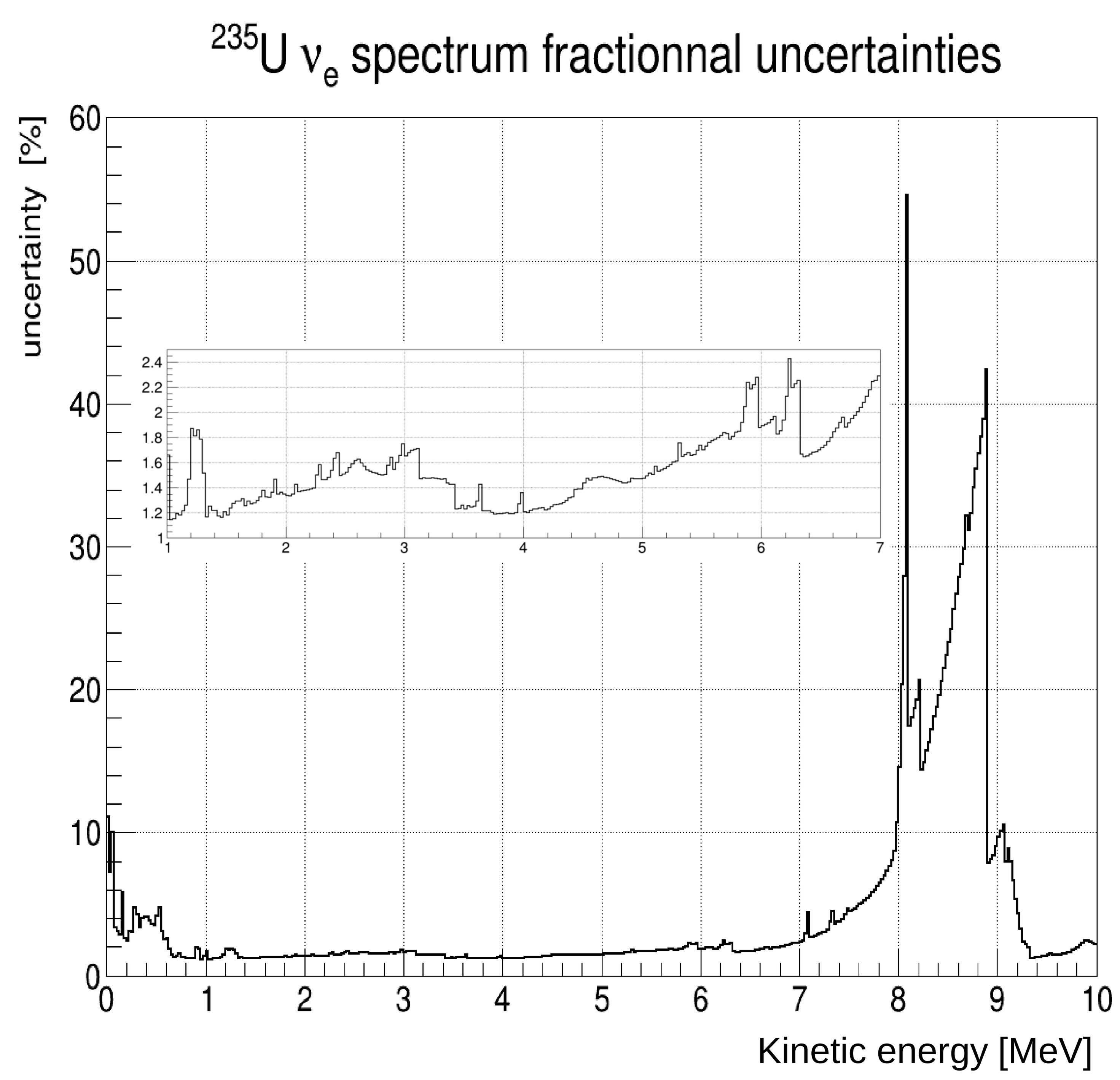
Fission spectrum: Summation spectrum of ^{235}U





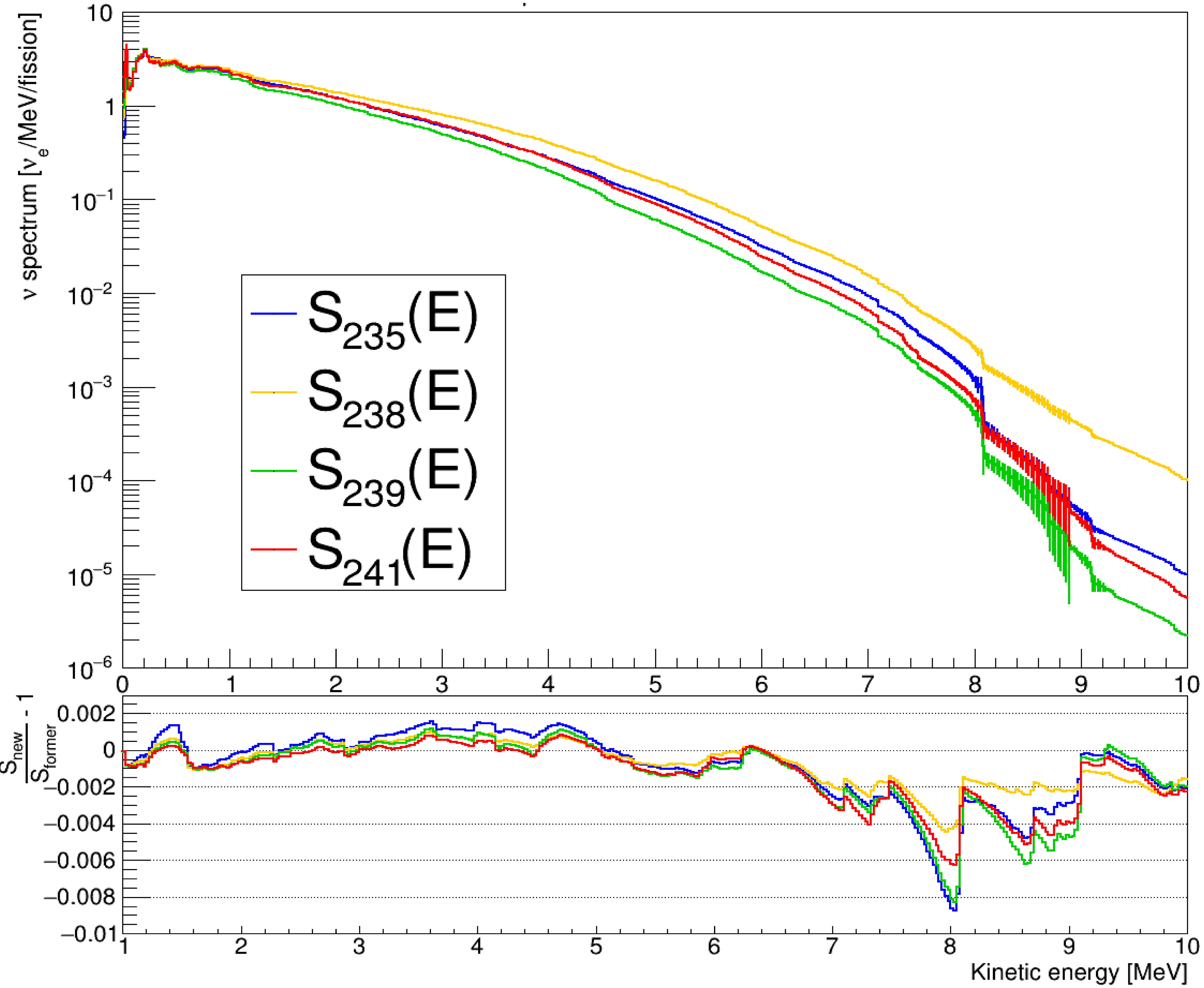


- Uncertainty propagation via Monte-Carlo for each modeled transition
  - Experimental error sources for each isotope
    - ➢ **Endpoint** and **Branching Ratio**
  - Approximated framework for error propagation (*e.g.* no covariance found in evaluated nuclear databases for fission fragments distributions, idem for Branching Ratio, …)
  - **Propagated to total β and ν spectra**

Uncertainty **~2 %**
between 1-7 MeV

Fission spectrum: Summation spectra

Spectrum with L_0, D_C, QED, WM corrections and cumulative fission yield



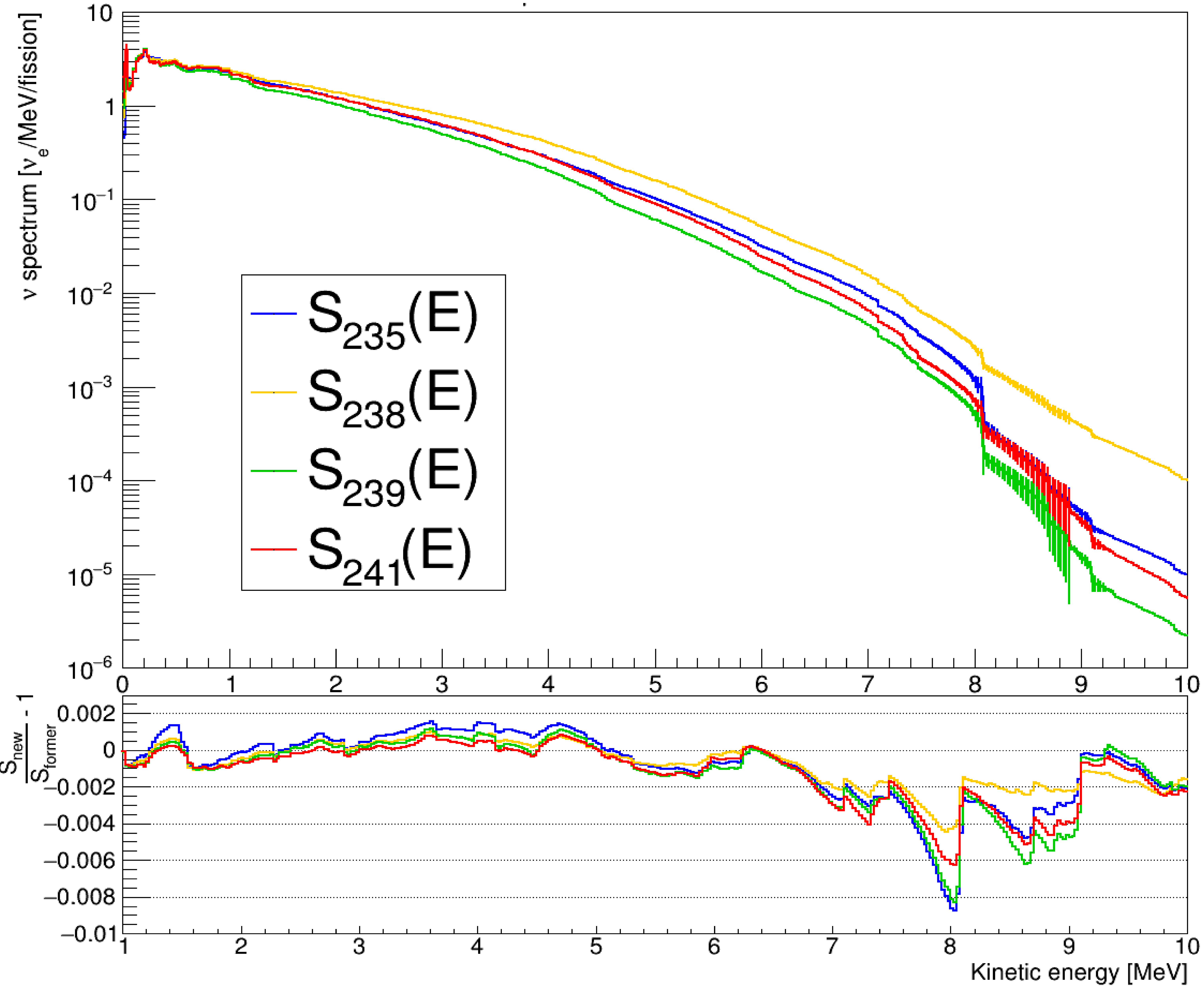
Isotope	$\bar{\nu}_e$/fission
^{235}U	$5.90 \pm 1.0\%$
^{238}U	$6.64 \pm 1.7\%$
^{239}Pu	$5.26 \pm 1.1\%$
^{241}Pu	$5.90 \pm 1.5\%$

Comparable changes for all 4 isotopes in 1-10 MeV

Small impact on summation spectra (~0.8% at 8 MeV, $^1/_{1000}$ otherwise)

Fission spectrum: Summation spectra

Spectrum with L_0, D_C, QED, WM corrections and cumulative fission yield



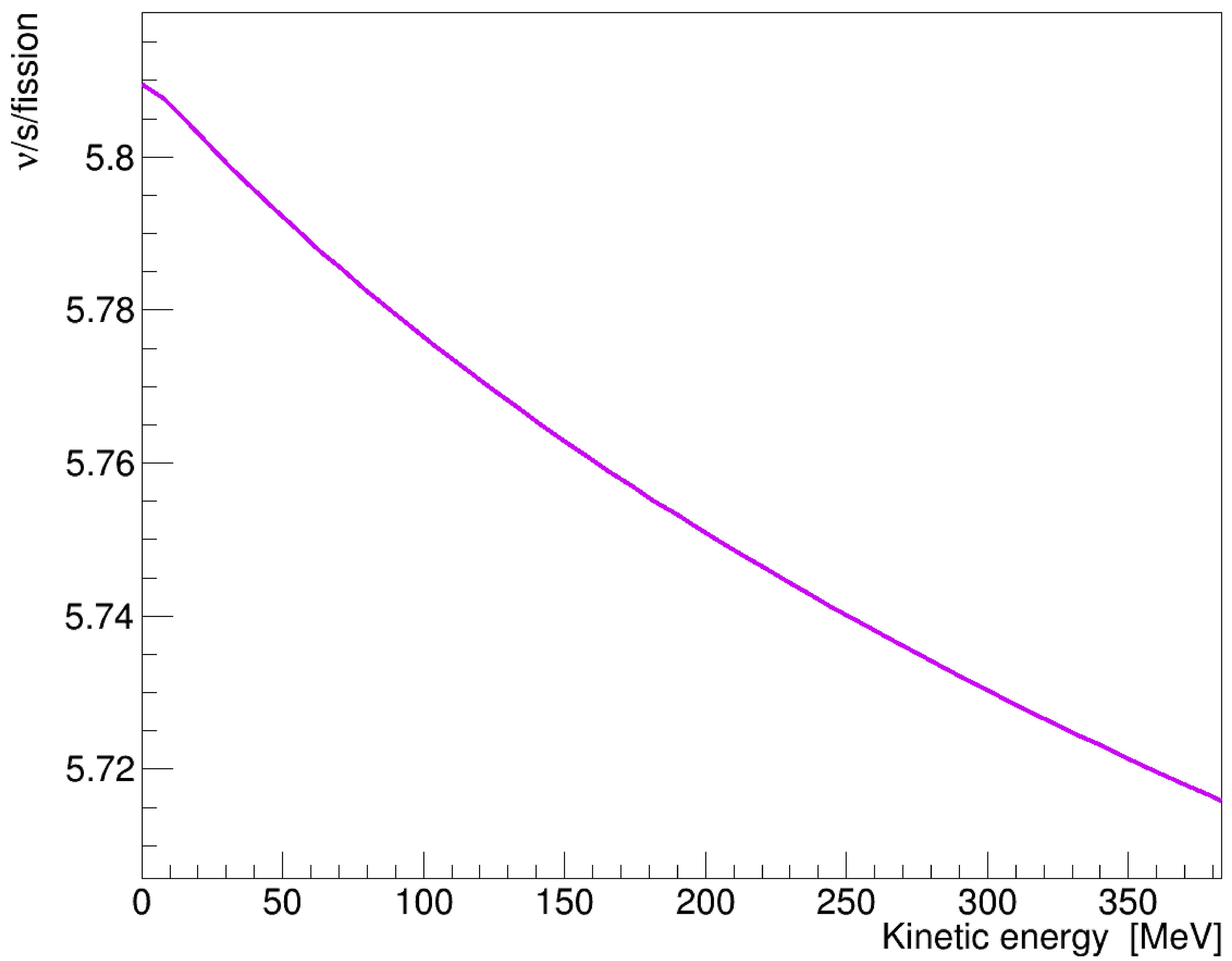
- D_C only impacts forbidden transitions
  - ~9% of all transitions
  - Not the most relevant ones (low fission yield)
- L_0 impacts all transitions
  - Former model has L_0 linear approximation

Comparable changes for all 4 isotopes in 1-10 MeV

Small impact on summation spectra (~1% at 8 MeV, $^{1}/_{1000}$ otherwise)

CONCLUSION

Reactor ν flux w.r.t. time



We have learned…

… about the reason of the NEνFAR project

… how reactor fuel evolves with time

… the fission fragment distributions of fissile isotopes

… how to make β and ν spectra

- about the set of corrections
- how to compute some corrections (DIRAC)
- about the bin covariance matrix

We have improved the summation model…

… by improving nuclear model

- point-like → finite size
- screening of atomic cloud

Few $^{1}/_{1000}$ change w.r.t. energy spectrum

< $^{1}/_{1000}$ change w.r.t. neutrino flux

We can now make a **complete reactor spectrum** with covariance

(but still miss data the fission fragment distribution covariance)

FUTURE WORK

Now we plan to study…

… correlation of Branching Ratio for error propagation

… exchange effect in β branch modeling

… include non-unique decays in the calculation (lift ξ approximation)

… comparison with literature, require identical databases

We will then use the summation model…

… to investigate database completeness

- See how fission spectra evolve through database updates
- Put an estimation on « database uncertainty »

… to check inversion model precision

- Inversion is state-of-the-art
- How precisely can it reproduce a summation spectrum ?


Photo by Christian Veyssière, CEA/Irfu
Double Chooz detector
Thanks for your attention