Juno EU AM meeting

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Antineutrinos from reactors

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Introduction

- Development of an analysis tool to generate and study the spectrum of antineutrinos from reactors

Features

- Based on available nuclear data (**ab initio** calculation)
- Flexible and easy to use
- Can be coupled with reactor **burnup** simulations

↓

Provides the **unoscillated** $\bar{\nu}_e$ spectrum with **infinite energy resolution**

↔

Known limitations

Uncertainties from nuclear data

↓

To be used for **benchmark** analysis with experimental data (**TAO**, JUNO, …)

Input data

- We want transparent and easy to be updated/modified input data

Live Chart of Nuclides

- Developed and maintained by the IAEA Nuclear Data Section (link)
- The **LiveChart API** (Application Programming Interface) allows the direct download of data
- The Livechart API works very effectively with **Python** data analysis libraries

We load the **nuclear data** we need for the ab initio calculation (fission yields, half-lives, beta decay Q-values, …)

BetaShape

- The BetaShape program has been developed by the LNHB (Laboratoire National Henri Becquerel)
- Can be downloaded for free and run on most OS
- Its output was recently added to the Live Chart of Nuclides

We produce a data library with all the **spectra of antineutrinos** emitted in beta decays

First step: equilibrium spectrum

- Generate the $\bar{\nu}_e$ spectra from the main fissile (^{235}U, ^{239}Pu, ^{241}Pu) and fissionable (^{238}U) isotopes at the **equilibrium** condition
- Most fission products have relatively short half-lives and reach equilibrium (**production rate = decay rate**) in a negligible timescale

SUMMATION SPECTRUM AT EQUILIBRIUM

$$S_\nu(E) = \sum_i f_i \, S_{\nu,i}(E) = \sum_i f_i \sum_j y_{i,j} \, S_{\nu,j}(E)$$

Fission fraction (f_i)

Fission yields ($y_{i,j}$)

$\bar{\nu}_e$ spectrum of j-th isotope ($S_{\nu,j}(E)$)

$i = {}^{235}\mathrm{U}, {}^{238}\mathrm{U}, {}^{239}\mathrm{Pu}, {}^{241}\mathrm{Pu}$

Beta spectra included / missing

- There are $\sim$ **700 fission products** with $Q_{\beta^-} > 1.8$ MeV
- Currently, our database generated with **BetaShape includes** $\sim$ **400** fission product spectra with $Q_{\beta^-} > 1.8$ MeV
- The fraction of included data in terms of fission yields is in the range **90 – 94%**

  …however, their contribution to the total spectrum does not scale as fission yields: it also depends on Q_{β^-} and branching ratios

	^{235}U	^{239}Pu	^{241}Pu	^{238}U
Fission Products (Q>1.8 MeV)	655	696	703	677
Fission Products included	397	426	426	404
% FY included	93.9%	92.8%	91.7%	90.2%

By adding the beta spectra of **only 15 isotopes** we would reach >99% for ^{235}U and ^{239}Pu

Multiplication by IBD cross section

- Since TAO/JUNO will detect $\bar{\nu}_e$ through the IBD reaction, we multiply all $S_{\nu,j}(E)$ spectra by the IBD cross section:

$$S_{\nu,j}^{IBD}(E) = \sigma_{IBD}(E)\, S_{\nu,j}(E)$$

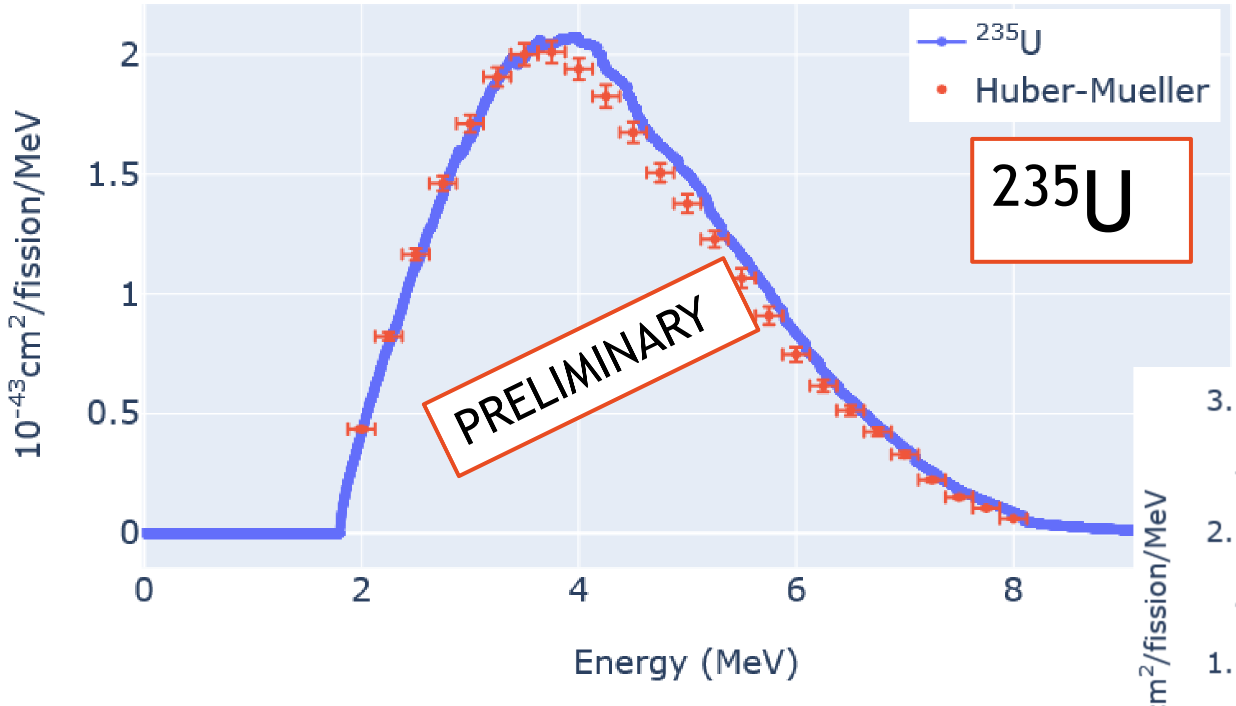
- We take $\sigma_{IBD}(E)$ from Eq. 25 in "A. Strumia, F. Vissani, arXiv:astro-ph/0302055"
- We produced a collection of $S_{\nu,j}^{IBD}(E)$ spectra for all β^- decaying fission products

In this way:

- we reduce the number of $\bar{\nu}_e$ spectra to be summed (1.8 MeV threshold)
- we can analyze the relative contribution of each fission product to the *"IBD detectable"* spectrum

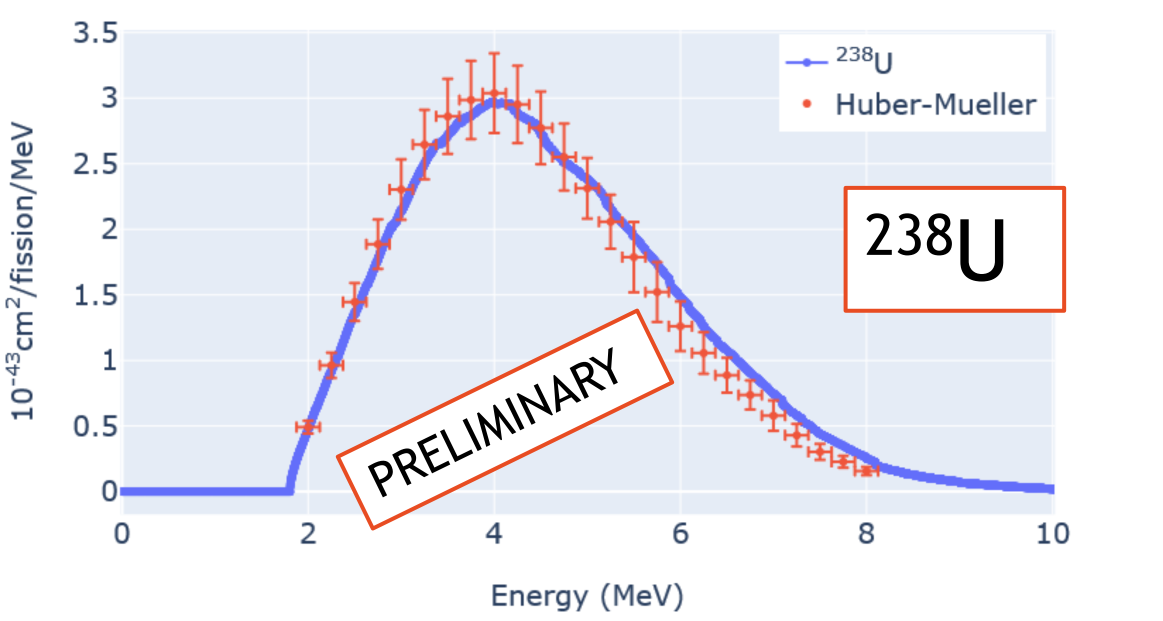
^{235}U and ^{238}U IBD-weighted $\bar{\nu}_e$ spectra

- We compare the IBD weighted $\bar{\nu}_e$ spectra with those obtained by Mueller et at (2011)



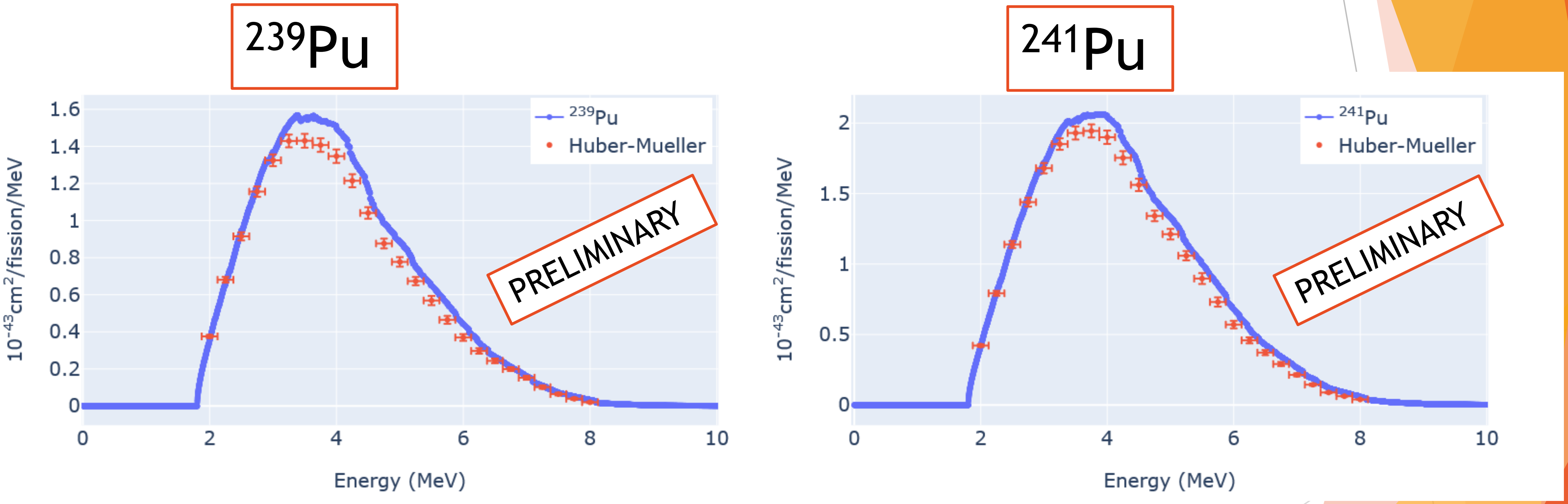
Conversion method from ILL measurements after 12 h irradiation time

^{238}U spectrum:
Built ab initio (450 d irradiation time)



^{239}Pu and ^{241}Pu IBD-weighted $\bar{\nu}_e$ spectra

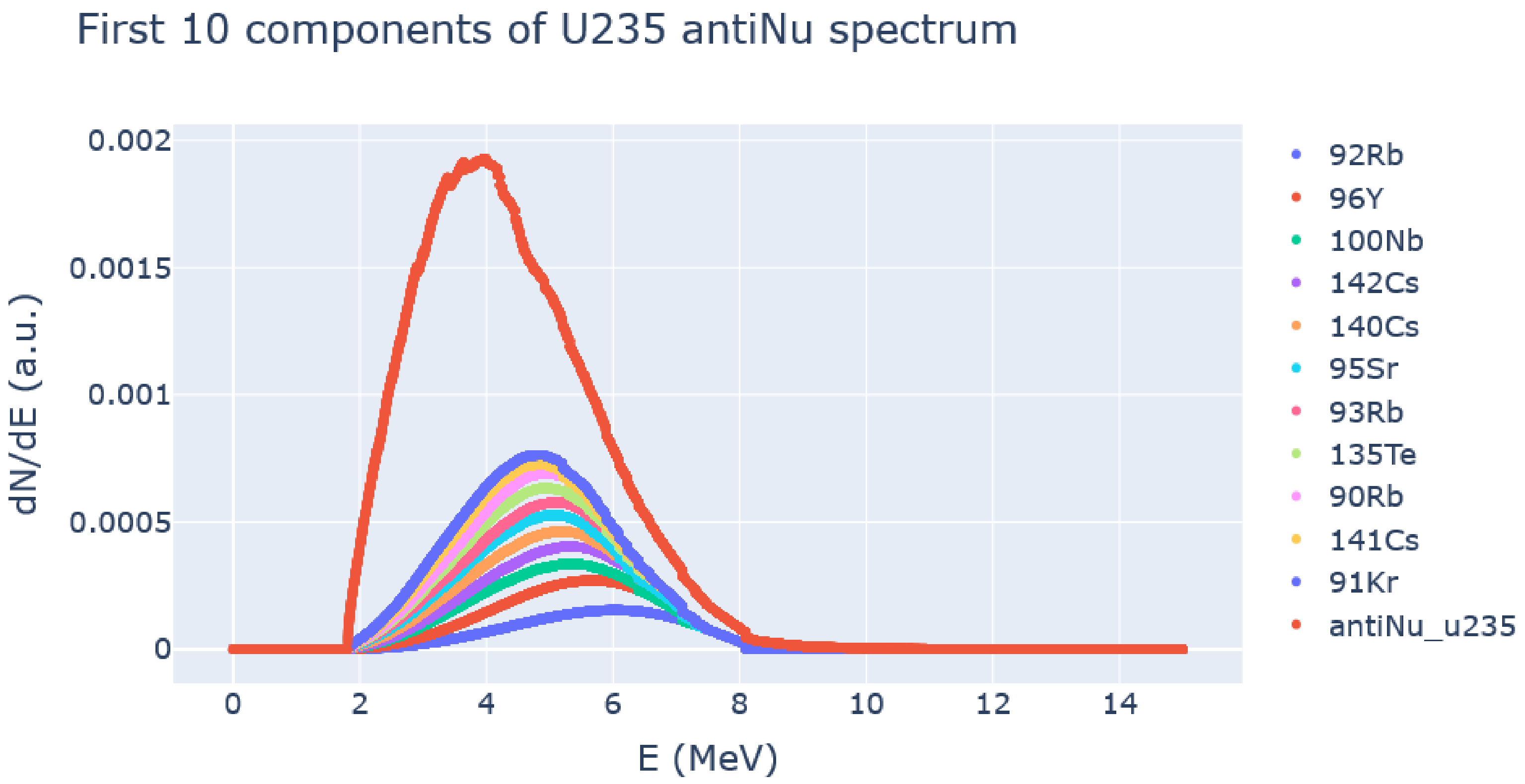
- We compare the IBD weighted $\bar{\nu}_e$ spectra with those obtained by Mueller et at (2011) with the conversion method



- Overestimation at higher energies possibly due to the **PANDEMONIUM EFFECT** → need to investigate which isotopes need for a *pandemonium effect correction* in BetaShape

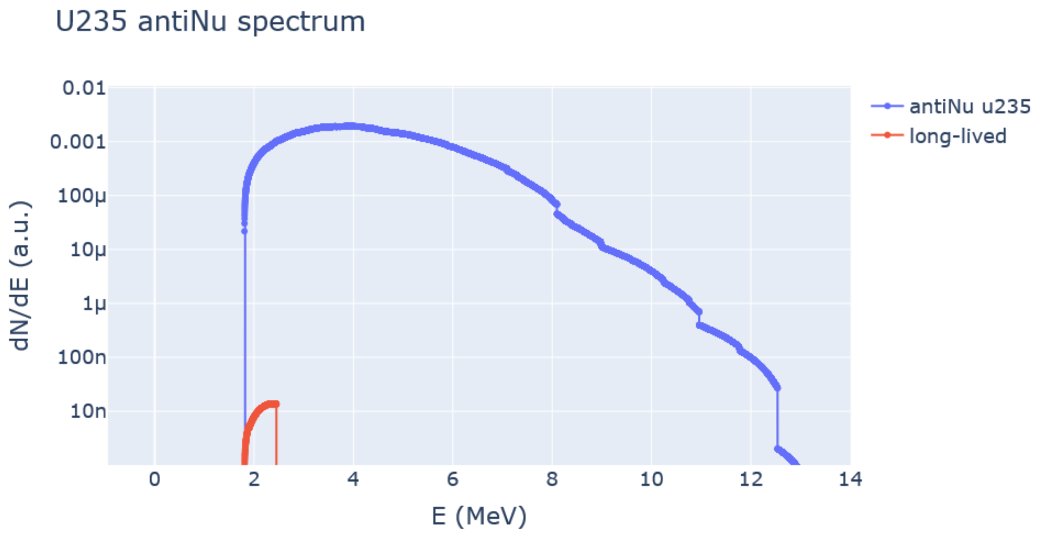
How many spectra to reach 99% ?

- To build up $\geq 99\%$ of our ab initio spectra we use between 130 and 160 spectra out of 400
- The first 10 spectra of ^{235}U spectrum, ordered by integral area, are stacked below



Off-equilibrium long lived isotopes ($T_{1/2} > 10$ d)

- There are only 3 fission products: ^{124}Sb (60.2 d), ^{126}Sb (12.5 d), and ^{156}Eu (15.2 d)
- Their contribution to the $S_{\nu,j}^{IBD}(E)$ spectra is of the order of $10^{-6} - 10^{-5}$ of integral area and limited to the lower energy region



- What about short-lived isotopes which are daughter of long-lived (off equilibrium) ones?
- By searching in the Table of Isotopes there are only few limited cases, that emit neutrinos in the lower energy region below 4 MeV

A	Shielding isotope	t_1/2 (d)	Shielded isotope	Q (MeV)
66	Ni	2.275	Cu	2.63
90	Sr	10504.7	Y	2.28
106	Ru	373.6	Rh	3.54
126	Sn	9.13E+07	Sb	3.67
131	Te131m	1.35	Te131	2.23
132	Te	3.2	I	3.58
140	Ba	12.75	La	3.76
144	Ce	284.6	Pr	2.99
166	Dy	3.4	Ho	1.85

Conclusions and next steps

- A flexible and easy to use tool for generating ***ab initio* antineutrino spectra** is under development.
- A preliminary analysis of equilibrium spectra from ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U fissions has been conducted.
- We must check whether BetaShape already takes into account for the Pandemonium effect or not
- The impact of off-equilibrium long-lived isotopes seems to be negligible…
- The LiveChart API allows also to import **uncertainties** associated to FY data
  - We plan to study the impact of such uncertainties in the next future
  - Through this tool we can focus on the uncertainties of most relevant isotopes
- This tool will be **integrated with PWR reactor simulations** (see Lorenzo Loi's talk tomorrow) to analyze the antineutrino spectrum dependence as a function of burnup (fission fractions)
- This tool is also aimed at analyzing the **fine structures** of the **unoscillated** $\bar{\nu}_e$ spectrum measured by TAO

Juno Italia meeting

May 5 – 6, 2022

Thanks for your attention

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