CONFLUX – A framework to calculate reactor antineutrino flux

IAEA TM at Seoul, 2025

Xianyi Zhang
On behalf of the CONFLUX project

LLNL-PRES-870927
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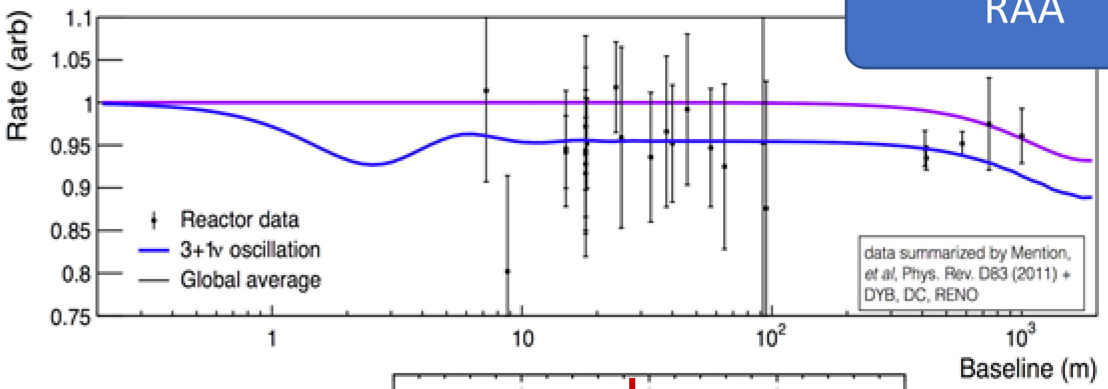
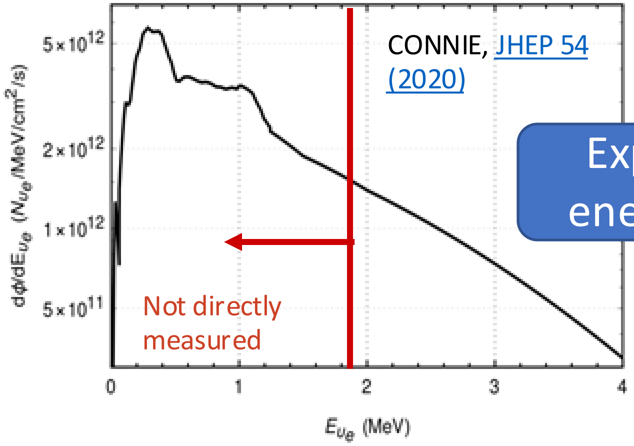
Goals

- **Scientific and Application needs:**
  - Reactor neutrino flux prediction for neutrino physics (CEvNS, model dependent BSM studies)
  - Reference models for reactor monitoring, e.g. advanced reactors
  - Beta decay spectrum with non-zero neutrino mass
- **Structural motivations:**
  - Standardize the neutrino flux prediction
  - A publicly available tool – with modularity and completeness
  - Easy-to-use software with full documentation
  - Create a format for human-readable input data, e.g. reactor evolution & nuclear data

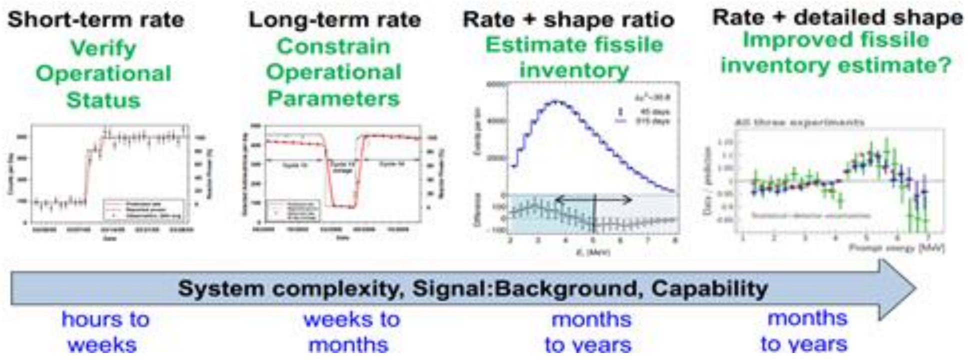
RAA





CONNIE, JHEP 54 (2020)

Expand the energy range

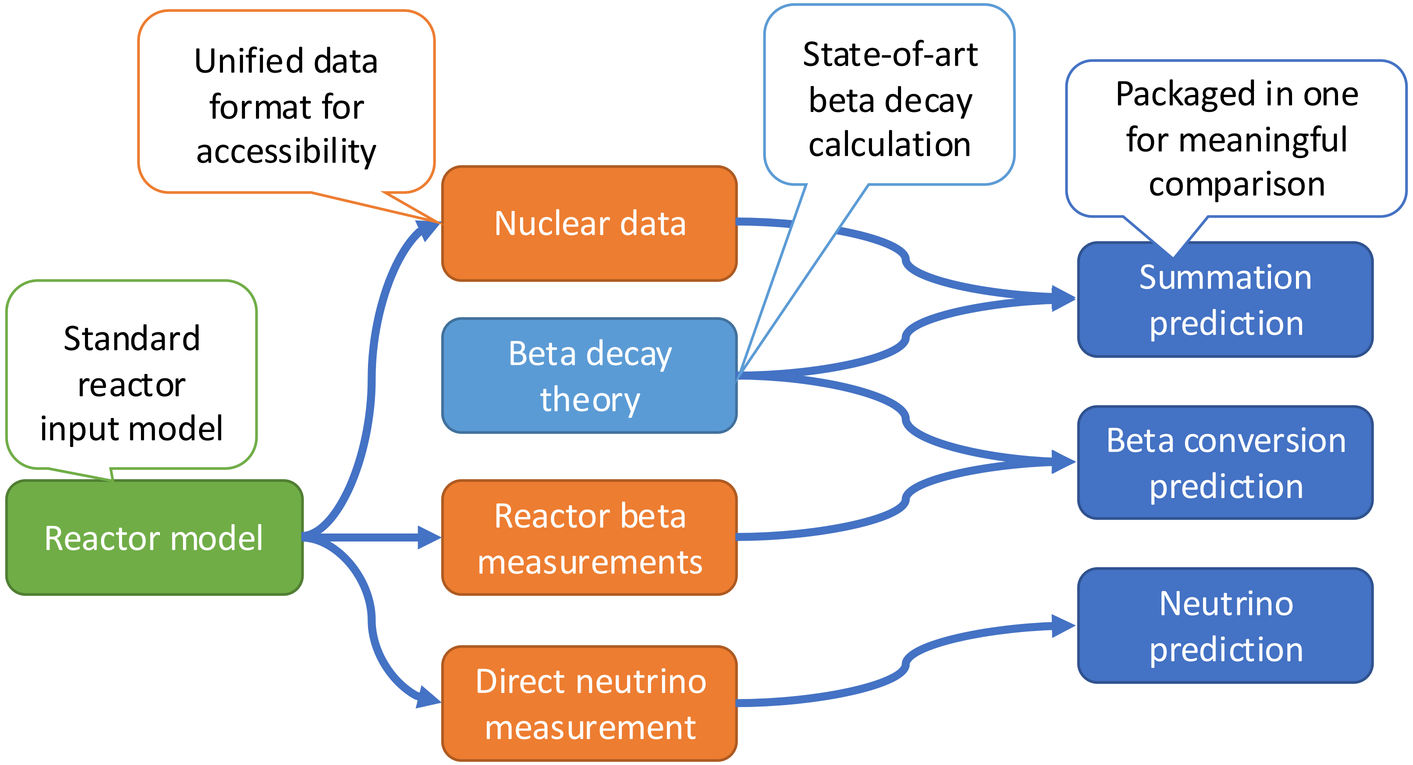


Bowden (2019)

Reactor model for non-proliferation

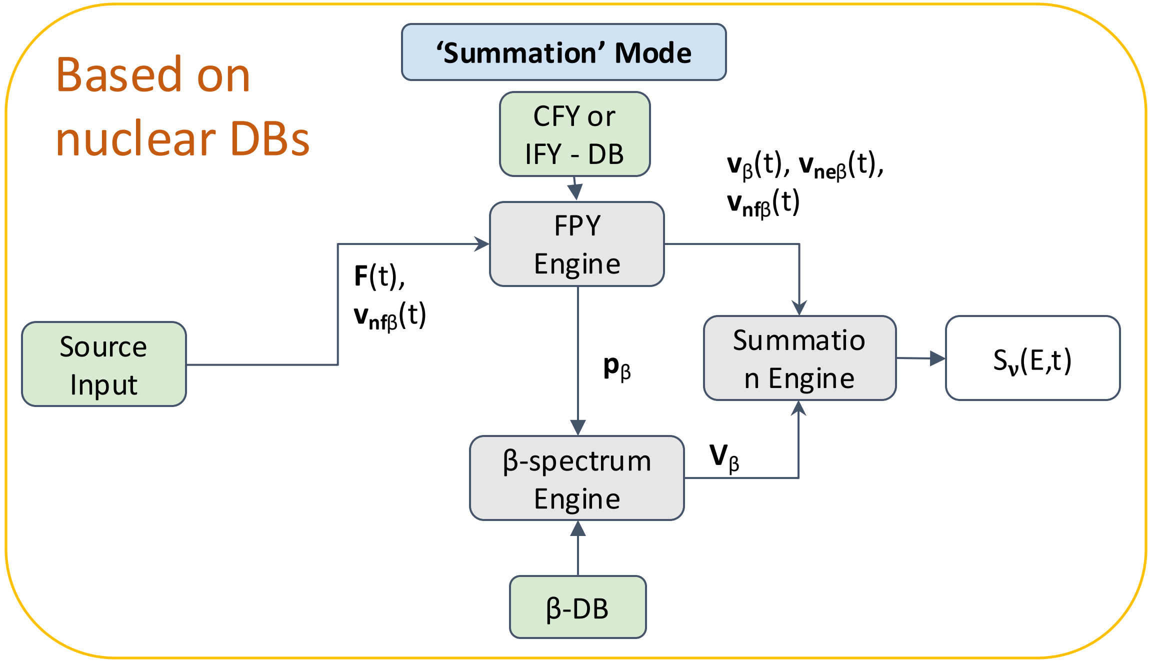
Calculation Of Neutrino FLUX

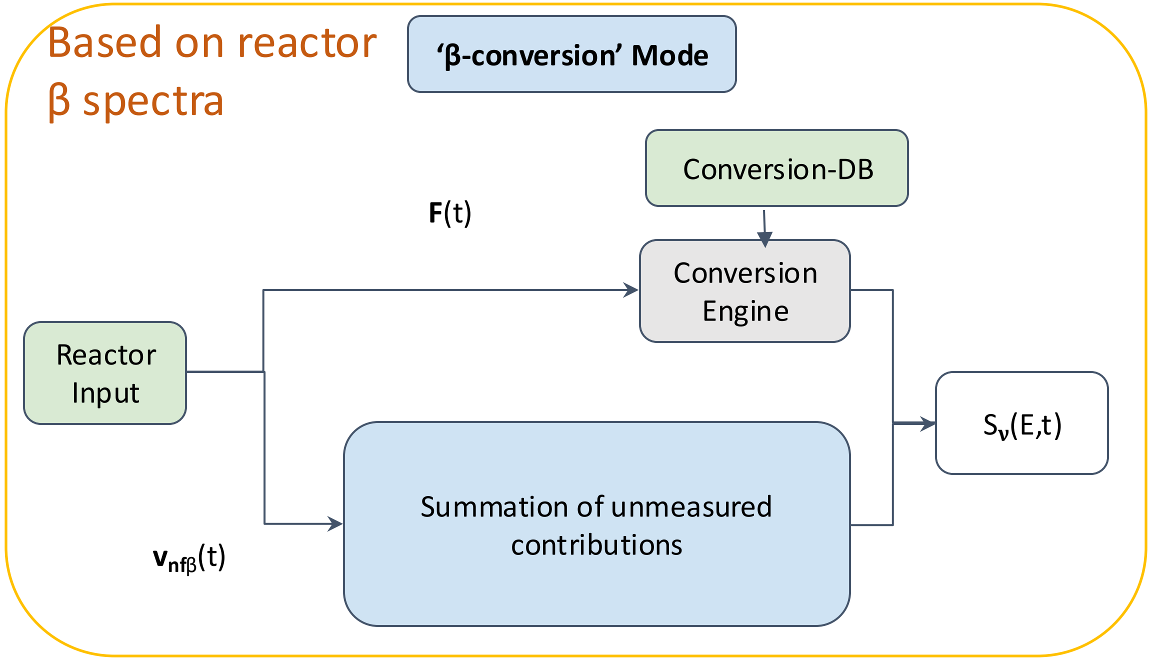
- Reactor neutrino flux prediction - a key ingredient in neutrino research
- Predictions has been based on
  - Summation of β spectra, or
  - Conversions of reactor β measurements
- Existing predictions were done with
  - Various input data
  - Independent teams
  - Different corrections in β spectra
- **Aim to let people quickly calculate reactor neutrino flux and test their theories**



The CONFLUX Framework

- Prediction with three different modes
- Flexible user inputs (from complicated reactor model with many ingredients to just fissile isotopes)
- Nuclear DBs (fission products from JEFF, ENDF, beta decay data from ENSDF) are parsed into xml formats for accessibility
- Coded in Python3, can be installed and imported as headers file in customized calculation





Flexible Inputs of Different Modes

- **User input:**
  - Time dependent reactor or beta decay, or combined model
- **Summation:**
  - The β branch info parsed from databases such as ENSDF, ENDF, JEFF, JENDL
  - Updated β decay measurement with TAGS
  - Covariance in fission products
- **Conversion:**
  - β spectrum measurements of fission isotopes
  - Converted neutrino flux from beta spectra
- **Neutrino:**
  - Isotopic neutrino spectrum data from existing measurements

Beta spectrum DB


```xml
<?xml version="1.0" ?>
<betaDB>
  <isotope HL="2.49 S     " Q="6.94" isotope="521370">
    <branch end_point_E="6.79" forbideness="-6" fraction="1" sigma_E0="0.3" sigma_frac="0"/>
  </isotope>
  <isotope HL="24.5 S     " Q="5.88" isotope="531370">
    <branch end_point_E="5.88" forbideness="7" fraction="0.452" sigma_E0="0.03" sigma_frac="0.005"/>
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    <branch end_point_E="4.8938" forbideness="4" fraction="0.0005" sigma_E0="0.0301" sigma_frac="0"/>
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    <branch end_point_E="4.11383" forbideness="5,6.0,7.0" fraction="0.0086" sigma_E0="0.0301" sigma_frac="0"/>
    <branch end_point_E="4.08392" forbideness="0" fraction="0.01" sigma_E0="0.03015" sigma_frac="0"/>
    <branch end_point_E="4.07125" forbideness="0" fraction="0.0045" sigma_E0="0.0301" sigma_frac="0"/>
```


Fission product yields DB


```xml
<?xml version="1.0" ?>
<nfy-092_U_235>
  <HEAD AWR="233.025" FissionZA="92235" LE="3" MT="IFP">
    <LIST Ei="0.0253" Ii="2" NFPi="1247">
      <CONT DY="1.3122e-19" FPS="0.0" Y="2.05032e-19" ZA="23066"/>
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```

Theoretical Beta Spectrum Calculation

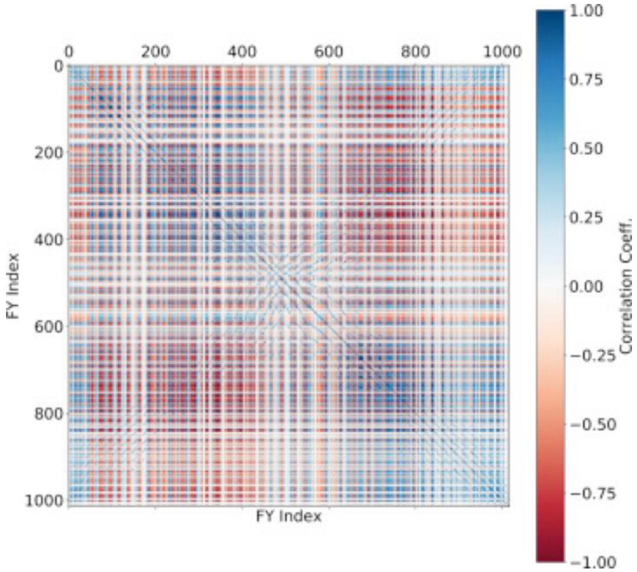
- A common β spectrum generator for the summation and conversion modes.
- Use of state-of-art theoretical calculation with BSG [CPC 240 (2019) 152].
- Spectrum shape corrections are built to be freed up to test model uncertainties affected by specific parameters.
- Some corrections are important for low energy beta spectra. (important for CEvNS prediction)
- Non-zero neutrino mass is optional to calculate neutrino mass and sterile neutrino contributions

Item	Effect	Formula	Magnitude
1	Phase space factor	$pW(W_0 - W)^2$	Unity or larger
2	Traditional Fermi function	F_0	
3	Finite size of the nucleus	L_0	10^{-1}-10^{-2}
4	Radiative corrections	R	
5	Shape factor	C	
6	Atomic exchange	X	
7	Atomic mismatch	r	
8	Atomic screening	S	10^{-3}-10^{-4}
9	Shake-up	See item 7	
10	Shake-off	See item 7	
11	Isovector correction	C_I	
12	Recoil Coulomb correction	Q	
13	Diffuse nuclear surface	U	
14	Nuclear deformation	D_{FS} & D_C	
15	Recoiling nucleus	R_N	
16	Molecular screening	ΔS_{Mol}	
17	Molecular exchange	Case by case	
18	Bound state β decay	Γ_b/Γ_c	Smaller than $1 \cdot 10^{-4}$
19	Neutrino mass	Negligible	

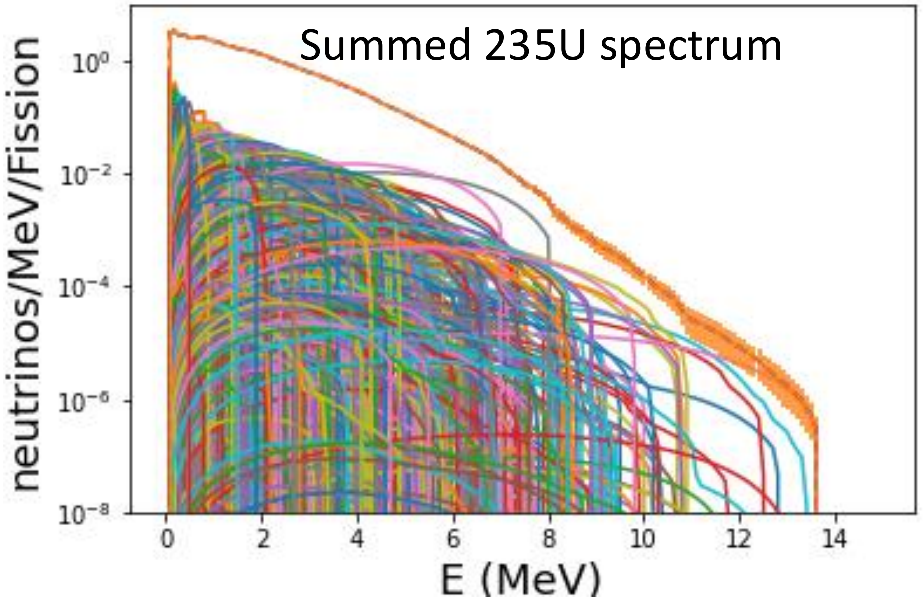
CPC 240 (2019) 152

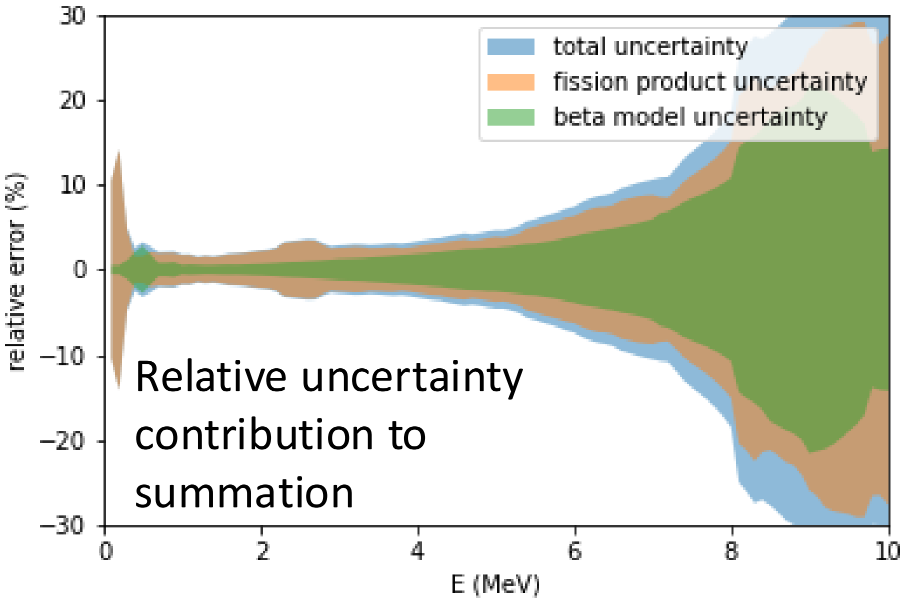
Summation mode

- Reads cumulative or independent fission products from ENDF-6 format (ENDF, JEFF, JENDL)
- Calculates beta spectrum using the BSG engine (been updated since its publication)
- Covariance among **beta branches** and among **fission product yields** are considered in calculate the uncertainties
- For time dependent fission products, half lives of isotopes are also considered



Example correlation matrix [j.adt.2021.101441](j.adt.2021.101441)

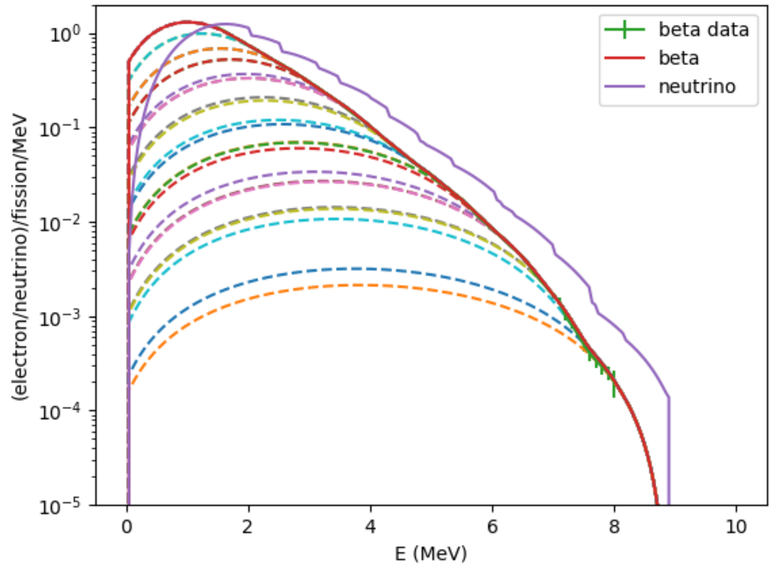




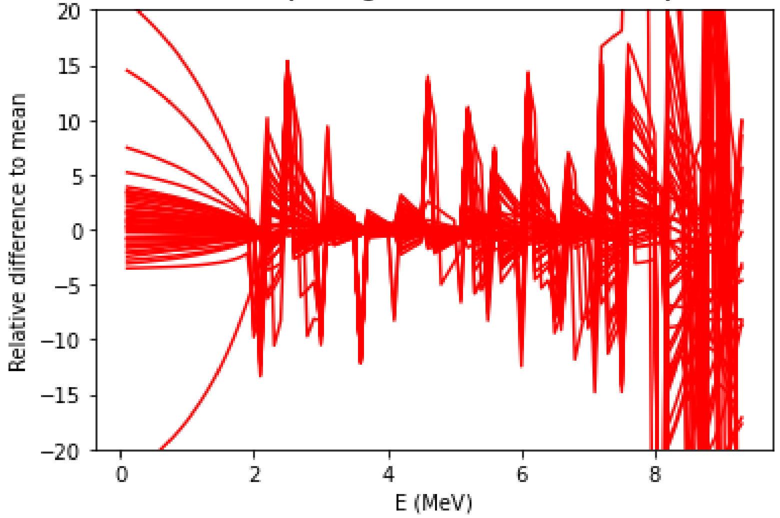
Conversion mode

- Fitting the default ILL legacy data (1980) with virtual beta spectra calculated with default theory engine
- Reference data includes ^{235}U, ^{239}Pu, ^{241}Pu
- Accepts customized beta spectrum data to fit
- Best-fit virtual spectra are converted to neutrino spectrum
- Uncertainties are calculated through MC sampling of reference spectra varied within the uncertainty of data.

Virtual branch fitting and conversion

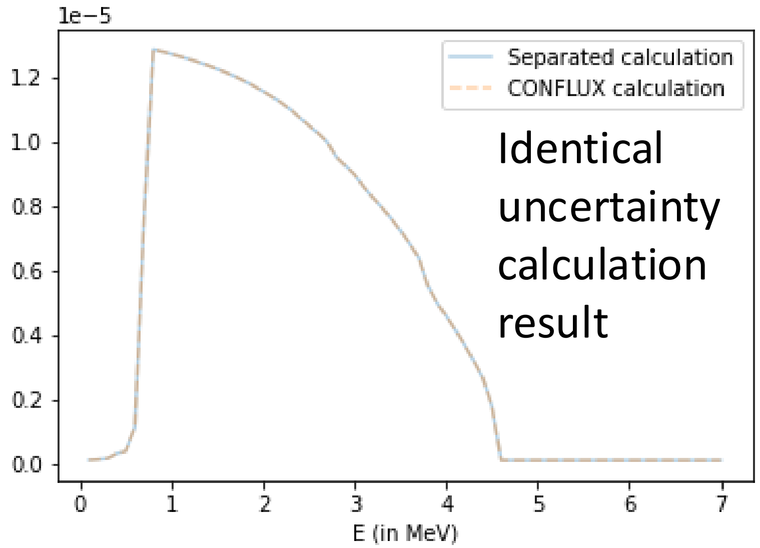


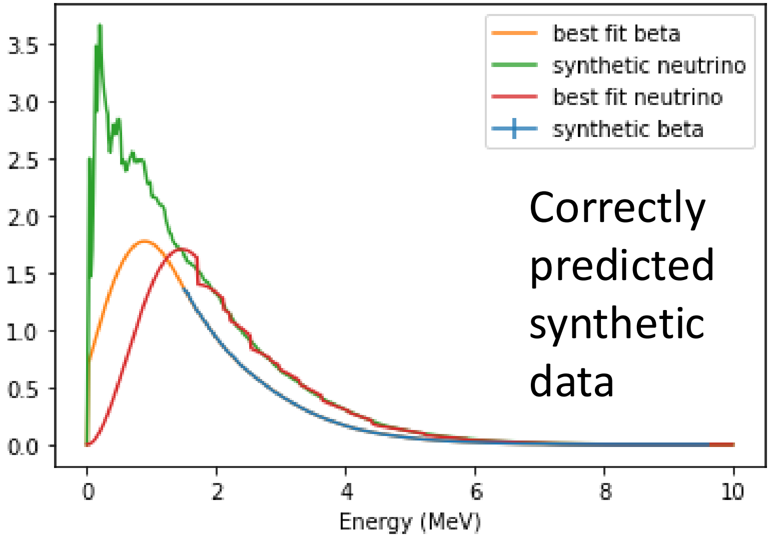
MC sampling for uncertainty

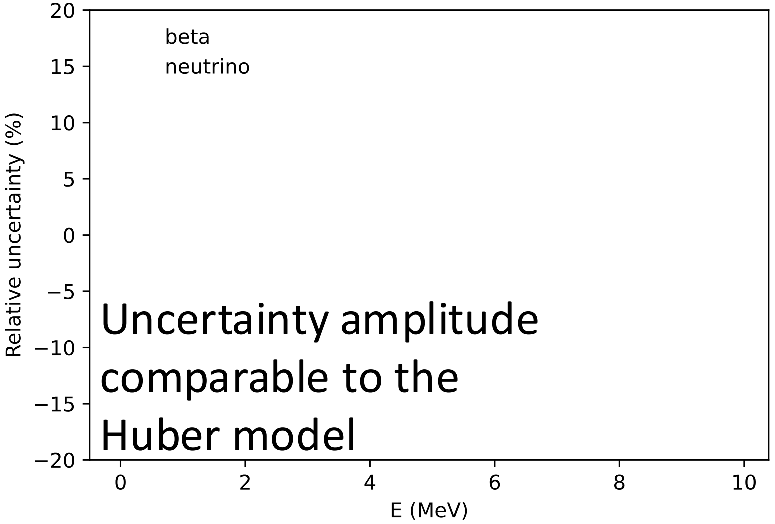


Validate the calculation results

- Uncertainty calculation using covariance matrices:
  - Mathematically verified through independent customized covariance matrix
- Beta-conversion
  - Used synthetic beta and neutrino spectrum, fitting the beta spectrum and correctly predicted the neutrino spectrum through conversion
  - Uncertainty calculation verified by comparing ILL conversion result to the Huber model







Ease of using CONFLUX

- CONFLUX is published open source
  - Can be installed as a python module through pip install
- Simple executable:
  - quickflux is prepackaged to calculate reactor neutrino flux with default setting through JSON macros
  - User no longer required to know programming to run CONFLUX
- Examples of each mode and specific customized reactor neutrino model are provided

```
{
  "spectrum": {
    "binlow": 0,
    "binhigh": 20,
    "binwidth": 0.01
  },

  "beta_spec":{
    "neutrino": 1,
    "numass": {
      "value": 0,
      "unit": "eV"
    }
  },

  "rxpower": {
    "value": 20,
    "unit": "MW"
  },

  "sum_model": {
    "qlow": 0,
    "qhigh": 20,
    "missing": 1,
    "time": [0, 0],
    "composition": [
      {
        "name": "U238",
        "Z": 92,
        "A": 238,
        "fissiondb": "JEFF",
        "ei": 0.4,
        "fraction": 0.1
      },
      {
        "name": "U235",
        "Z": 92,
        "A": 235,
        "fissiondb": "JEFF",
        "ei": 0,
        "fraction": 0.9
      }
    ]
  },
```

CONFLUX Published this March

- Software can be downloaded from github.com/CNFLUX/conflux
  - Examples put together to test run various modelling
- Documentation submitted to Comp. Phys. Comm., arxiv.org/abs/2503.18966

CONFLUX: A Standardized Framework to Calculate Reactor Antineutrino Flux

Xianyi Zhang[a,*], Anosh Irani[b], Michael P. Mendenhall[a], Nathan Rybicki[b], Leendert Hayen[c], Nathaniel Bowden[a], Patrick Huber[d], Bryce Littlejohn[b], Sandra Bogetic[e]

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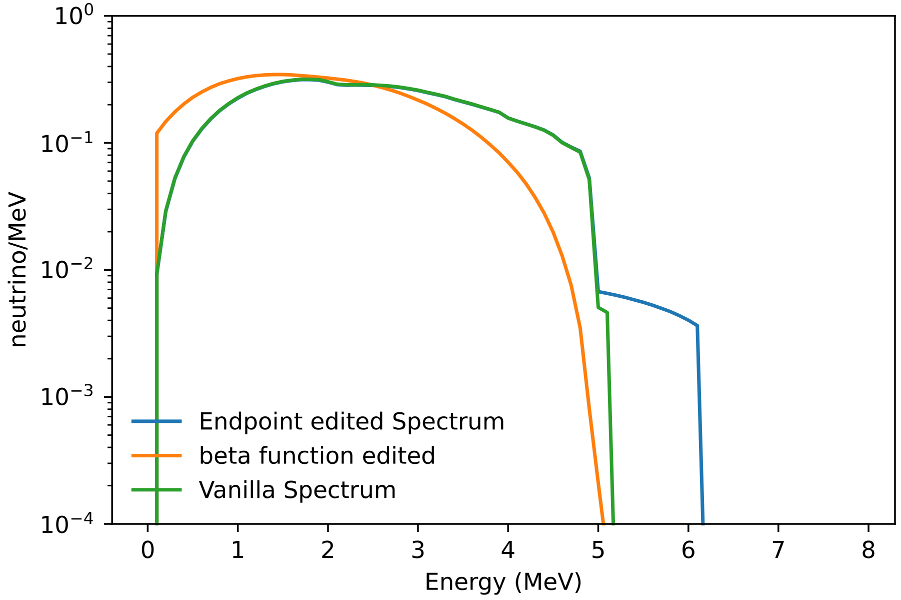
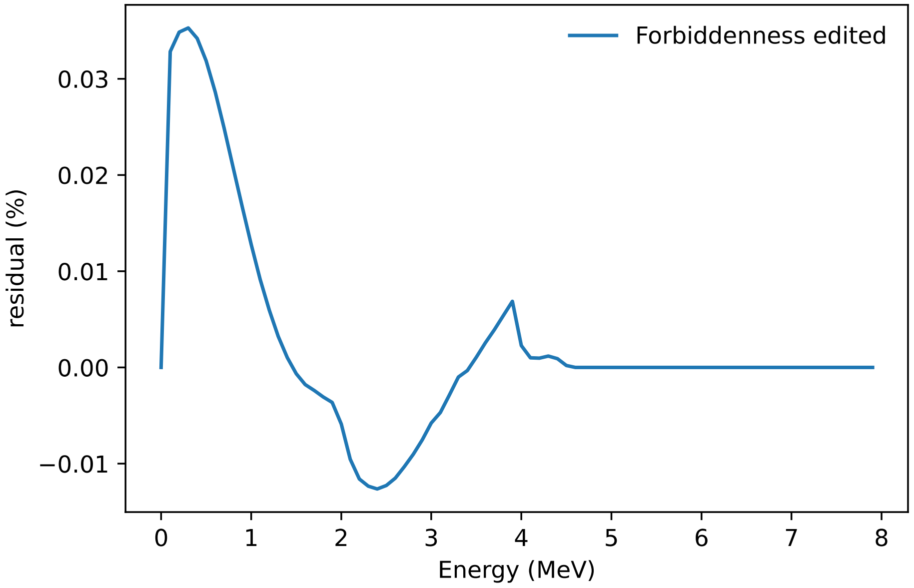
[b] *Illinois Institute of Technology, Chicago, IL, USA*
[c] *The laboratory of corpuscular physics of Caen, Caen, France*
[d] *Virginia Polytechnic Institute and State University, Blacksburg, VA, USA*
[e] *University of Tennessee, Knoxville, TN, USA*

Customizable beta theory engine

- The beta decay calculation engine (BSG by default) allows customized beta theories
- One can swap the beta decay function to for their own study (e.g. test their custom beta decay function's impact to the neutrino spectrum)
- Key parameters, such as the forbidden transitions or Q value, can also be changed for specified isotopes



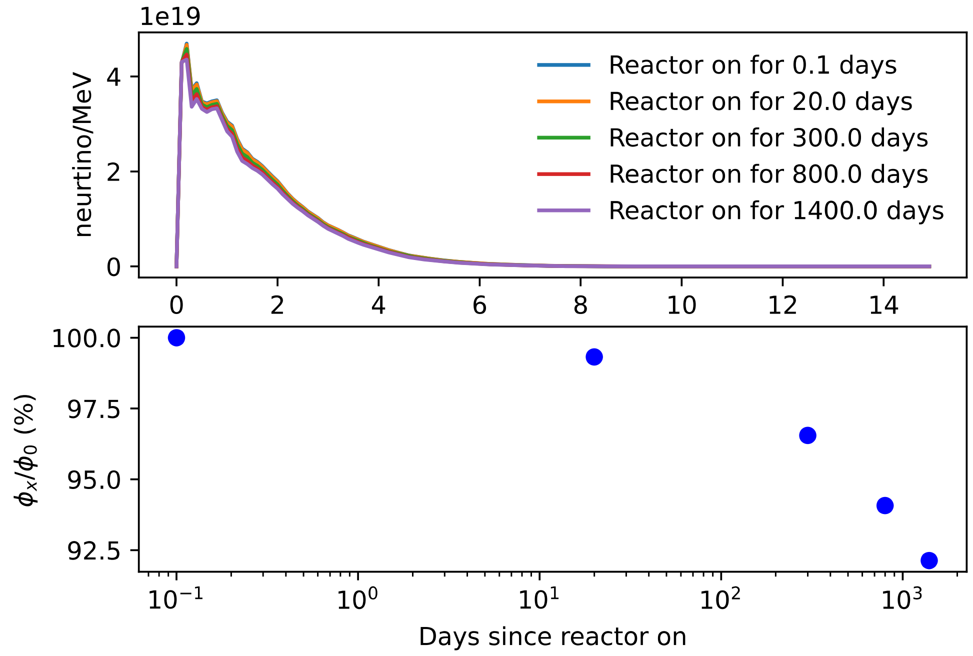
Swapping beta decay theories to basic fermi function, or a different end point energy



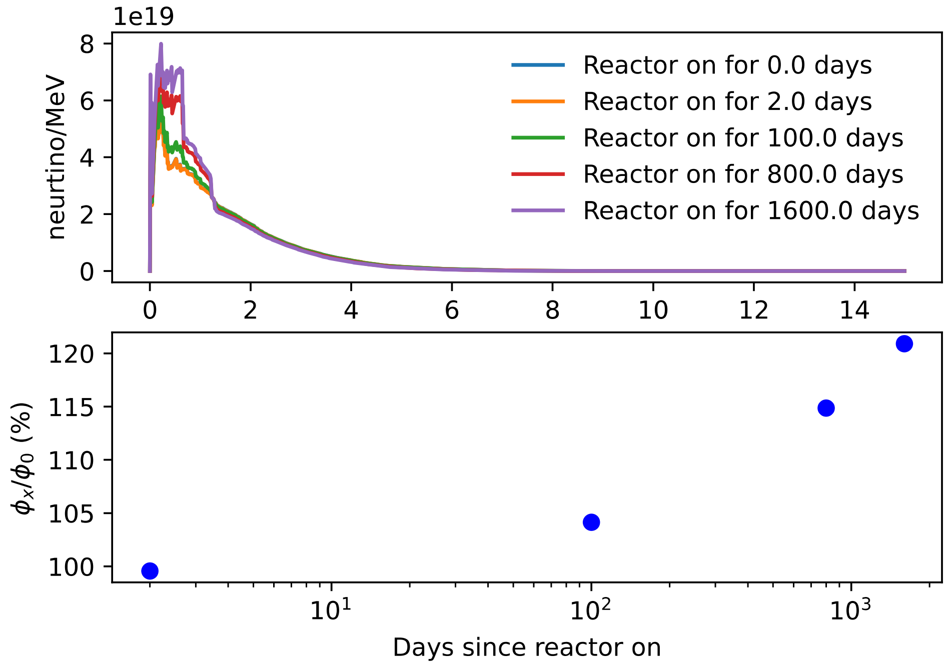
Difference in neutrino spectra after changing forbiddenness

Time dependent reactor modeling

- Time dependent fission fragment
- Neutrinos from Pu breeding in LEU reactor burning cycles
- Inclusion of neutron activated isotope



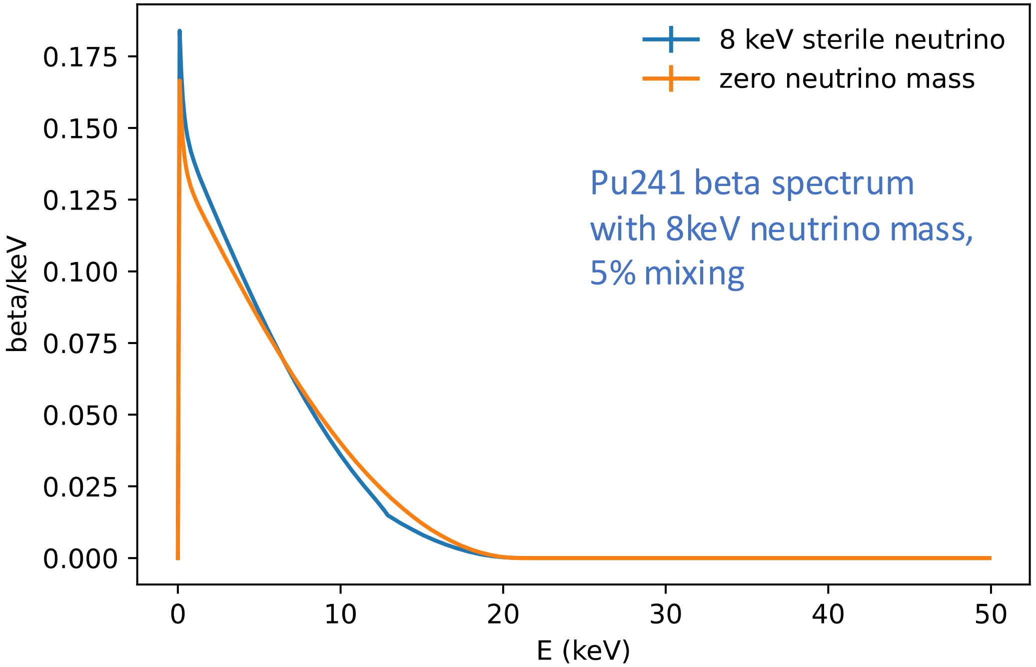
Time dependent neutrino flux



Time dependent neutrino flux, with Pu breeding

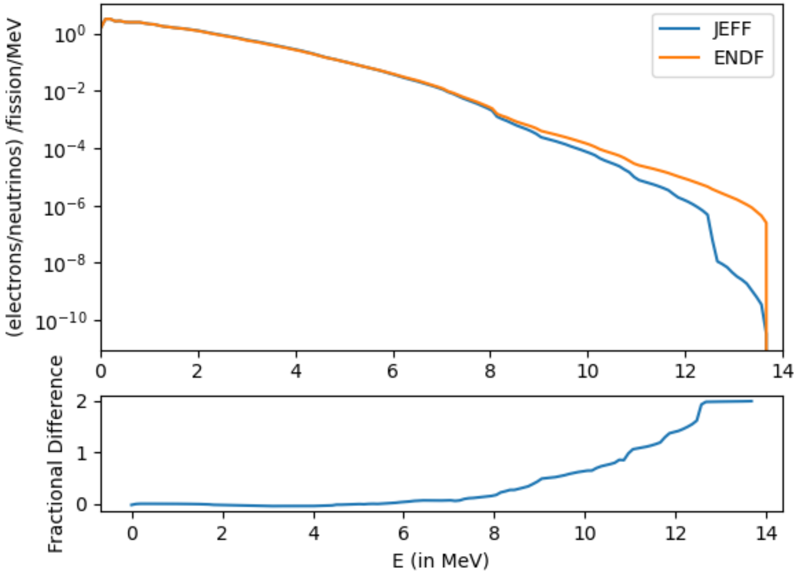
Beta spectrum with non-zero neutrino mass

- Beta and neutrino spectra can be distorted with non zero neutrino mass by
  - Alternating neutrino mass
  - Providing the mixing angle of neutrino oscillation
- Great for sensitivity studies for sterile neutrino and neutrino mass measurement through beta decay

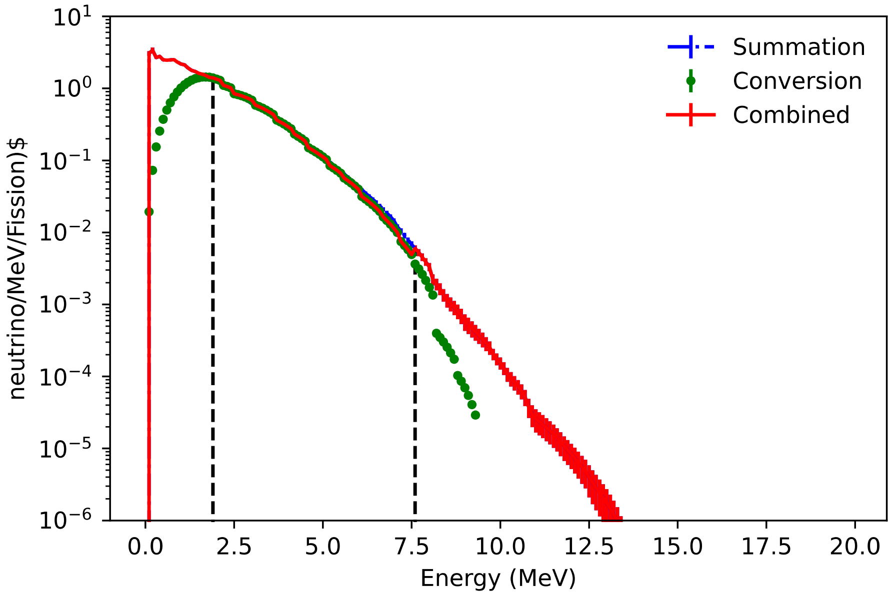


Analyses combining different data

- CONFLUX can be used for controlled comparison between differences in nuclear databases
- Contributions from the summation method and the beta or neutrino measurement can be combined to make complex modelling



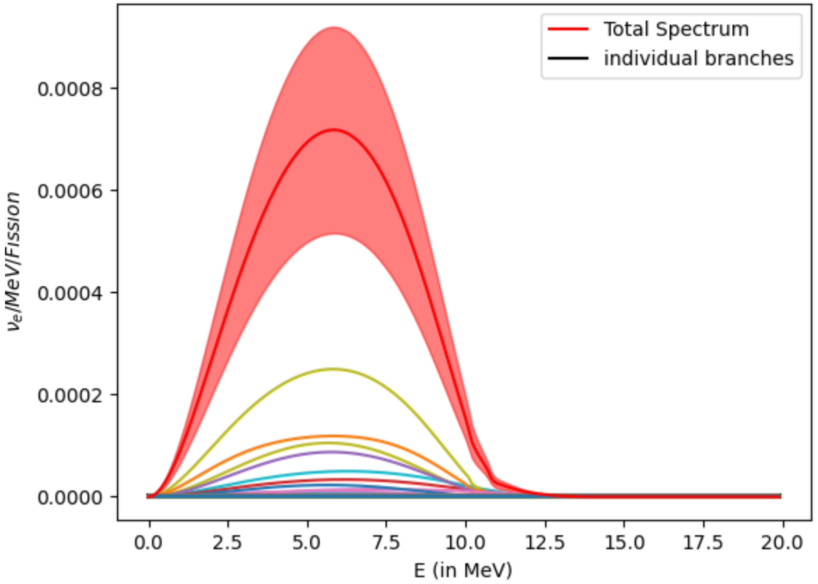
Controlled comparison between JEFF and ENDF



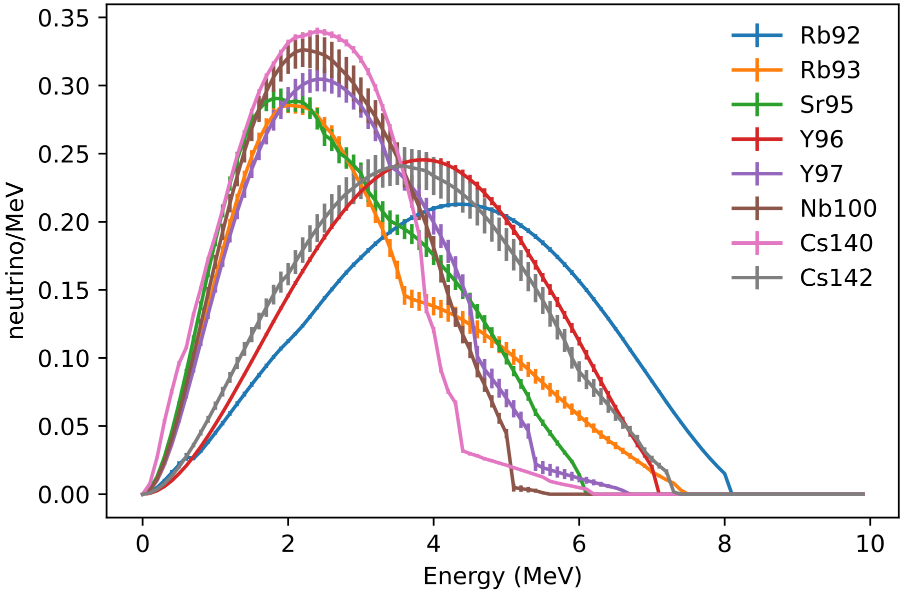
Combining conversion and summation that covers different E range

Selected beta spectrum measurement

- One can choose individual or a list of spectra of isotopes and branches based on their properties
- Important to manage isotopes of specific types (high energy, high uncertainty, complicated branching) to study factors of reactor neutron spectra
- A potential hybrid prediction fitting summation result to measured neutrino spectra



Fission products whose Q value is greater 10 MeV.

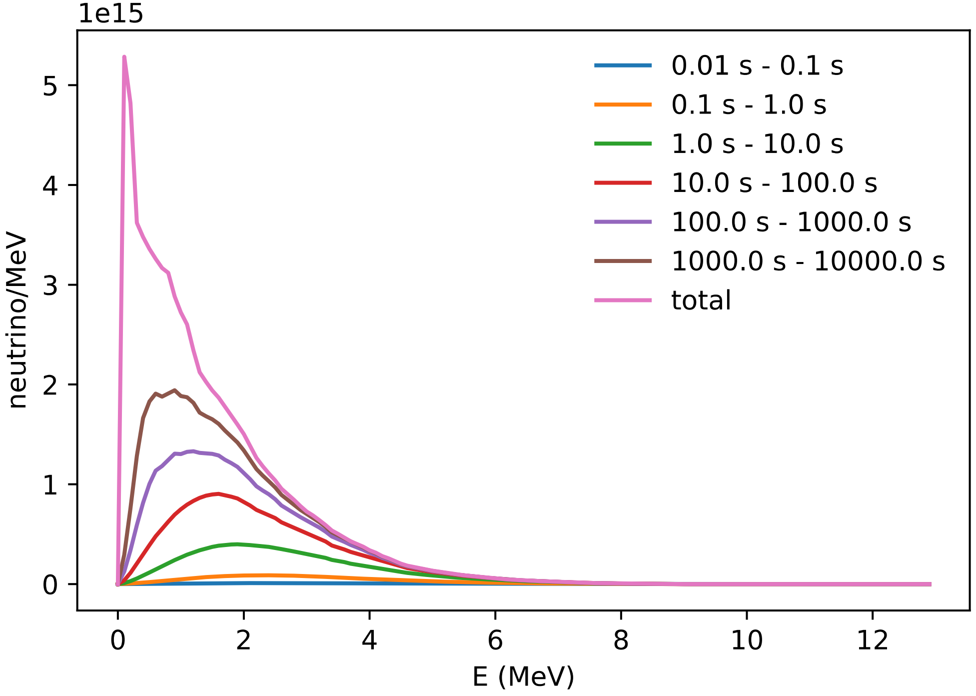


Fission products with high uncertainty or high yield

Burst fission neutrino modeling

Methodology: at each time stamp, we calculate how much percent of each fission product has decayed based to its half-life

CONFLUX's time dependent flux calculation agrees well with more sophisticated model of burst fission



Neutrino flux X seconds after fission using independent fission yields

CONFLUX

239Pu neutrinos/fission in each window

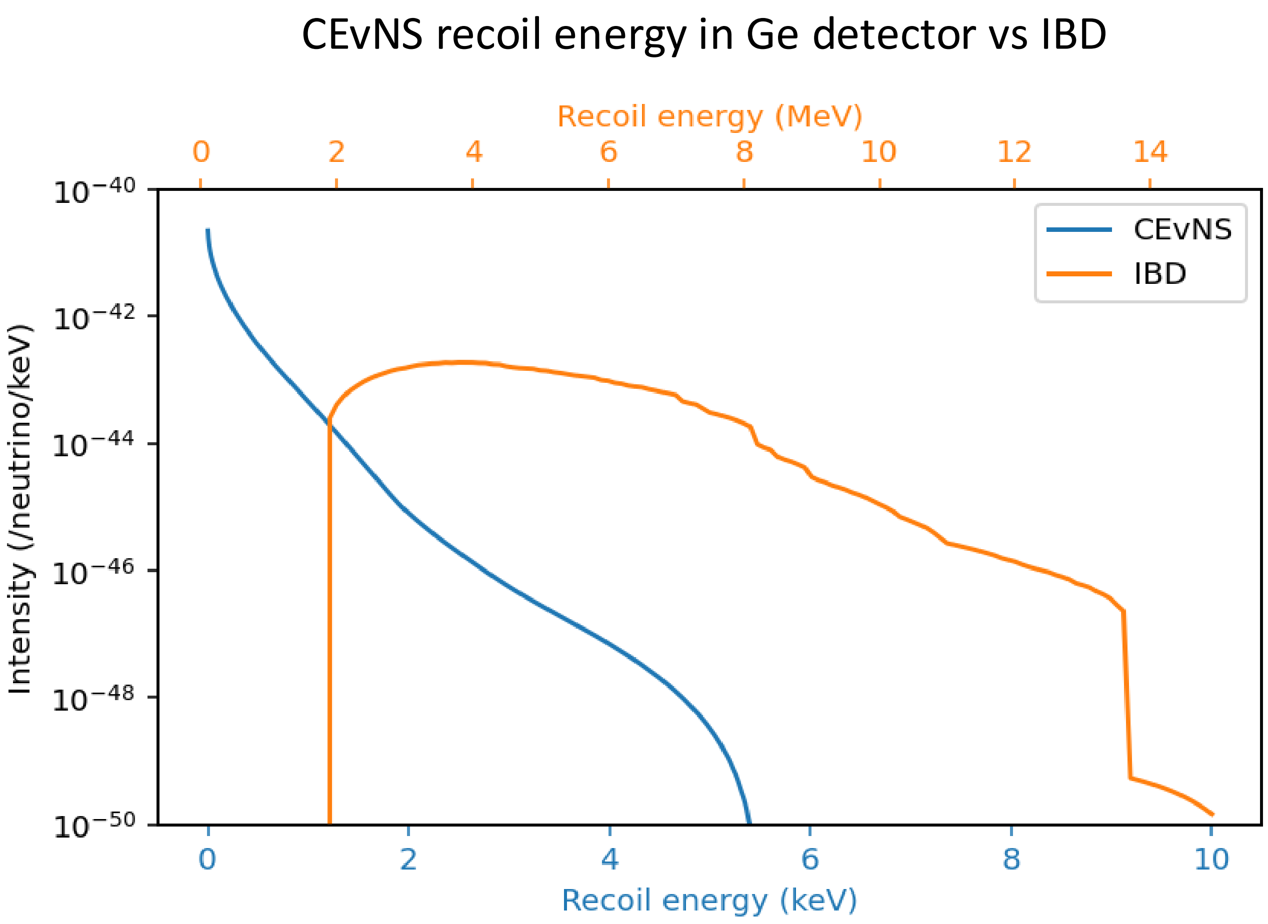
time	0.01 - 0.1 s	0.1 - 1 s	1 - 10 s	10 - 100 s	100 - 1000 s	total
Fast	0.017	0.142	0.567	0.857	0.885	2.469
14 MeV	0.018	0.142	0.519	0.711	0.737	2.126

Work in arXiv:2411.11804

	0.0-0.1 s	0.1-1.0 s	1.0-10.0 s	10.0-100.0 s	100.0-1000.0 s	Total
$N_{\bar{\nu}}$ (Fast)	0.020	0.145	0.572	0.890	0.864	2.491
$N_{\bar{\nu}}$ (14 MeV)	0.018	0.129	0.479	0.697	0.707	2.03

Low energy neutrino spectrum for CEvNS

- Full range neutrino spectrum calculation prepared for CEvNS spectrum study
- Capability of including Pu breeding beta decays
- Also neutrinos from neutron activated beta decays (Al, Li)



Needs from nuclear data

- Decay information of missing branches:
  - Roughly 6% of beta decay branches missing.
  - Unknown impact in the below IBD range.

- Result of pandemonium effect:
  - Biased branching fractions.

- Correlated uncertainty:
  - Correlation among fission yields needs to be accounted.
  - Program needs to calculate correlated uncertainty.

Future update

- Neutrino data mode: use existing neutrino data
  - Needs: standardized reactor neutrino spectra or flux

- Including compatibility with GNDS
  - Formatting input methods so GNDS can be the direct input

- Taking output from MCNP or BEAVR simulation so more detailed reactor models are used for neutrino flux prediction

- Beta+ decays

Summary

- CONFLUX is written to simplify and standardize the reactor neutrino source modelling with existing data
- Spectra, covariance and uncertainty are calculated for nuclear reactors or general beta decays
- Calculation results of CONFLUX have been verified with synthetic data and separated calculations
- CONFLUX can be downloaded from github.com/CNFLUX/conflux
- Executable and examples are available for most simple reactor neutrino predictions

Thank you!

Xianyi Zhang, Nathaniel Bowden, LLNL
Anosh Irani, Bryce Littlejohn, Illinois Tech
Leendert Hayen, LPC Caen
Patrick Huber, VT
Sandra Bogetic, UTK

Potentials for new physics studies

- Quickly providing reactor neutrino flux models for the NuTool applications

- Providing simple sensitivity study toys for BSM physics of CEvNS (neutrino magnetic moment, neutrino decoherence)

Potential Scientific Output

- **Neutrino spectra and flux prediction from different reactor types:**
  - BSM neutrino measurements
  - Reactor CEvNS
- **Contribute to the nuclear data community**
  - Direct cross-database comparisons
  - Search for deviations to prioritize beta decay measurements to be revisited
- **Studies on the reactor simulation for near field reactor survey**
  - **Sensitivity of reactor neutrino survey with different fidelities of reactor simulation**

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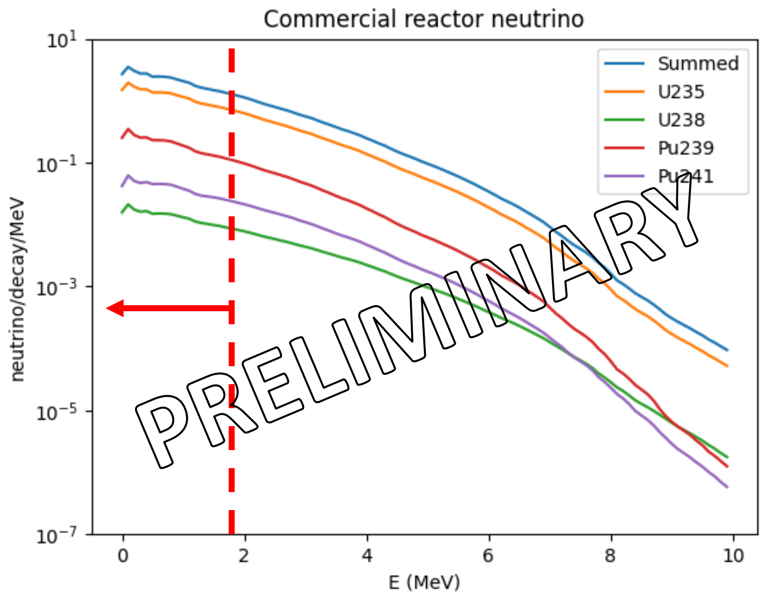
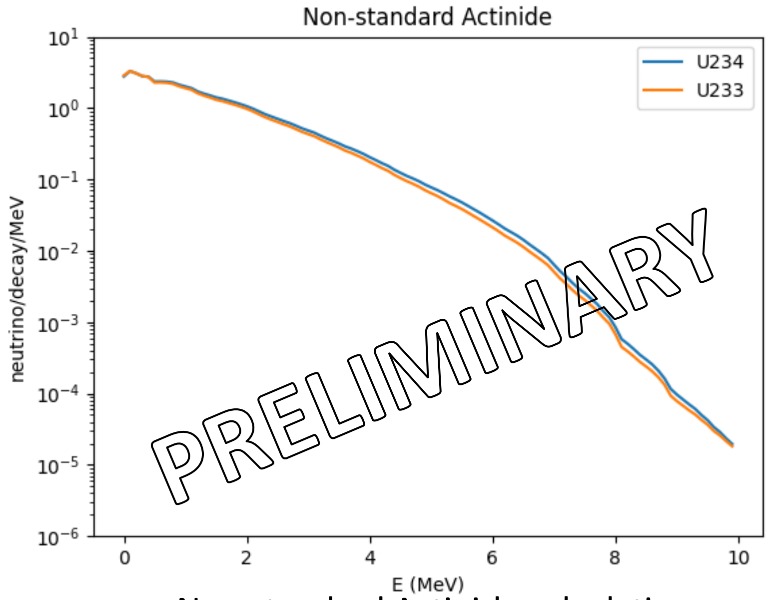


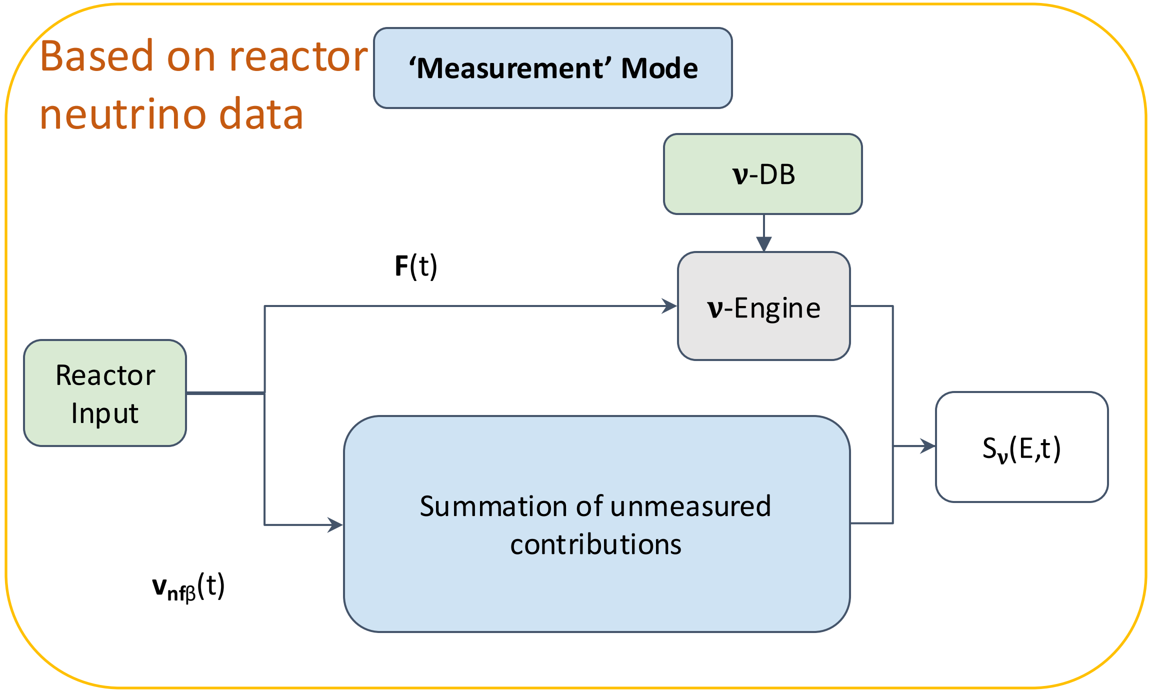
Reactor neutrino flux calculation below IBD



Non-standard Actinide calculation

Backup – Neutrino data mode

- Summarizing existing isotopic reactor neutrino flux/spectrum data
- Let multiple data fit one isotopic neutrino model and search for the best fit model
- Will need
- Ongoing for a future upgraded version



Potential Scientific Output

- **Neutrino spectra and flux prediction on different reactor types:**
  - BSM neutrino measurements
  - Reactor CEvNS
- **Contribute to the nuclear data community**
  - Direct cross-database comparisons
  - Search for deviations to prioritize beta decay measurements to be revisited
- **Reactor neutrino modeling with new neutrino physics (sterile neutrino, mass hierarchy)**
- **Studies on the reactor simulation for near field reactor survey**

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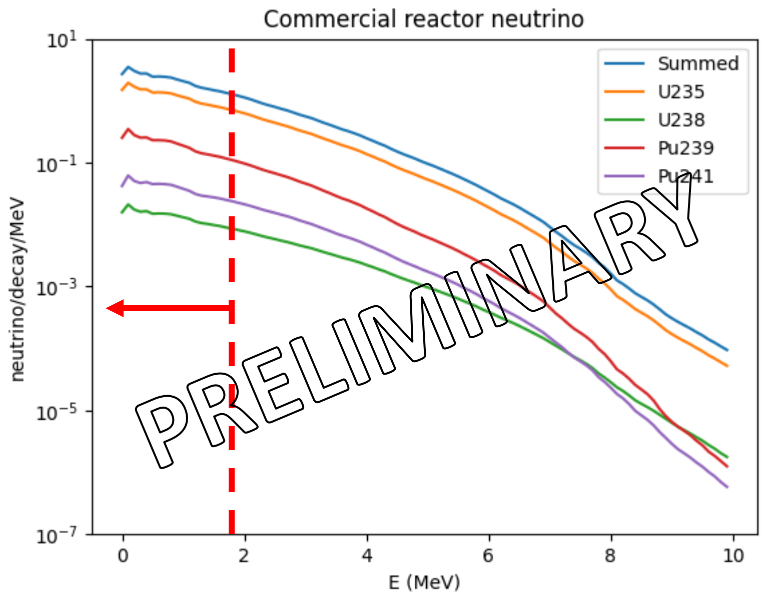
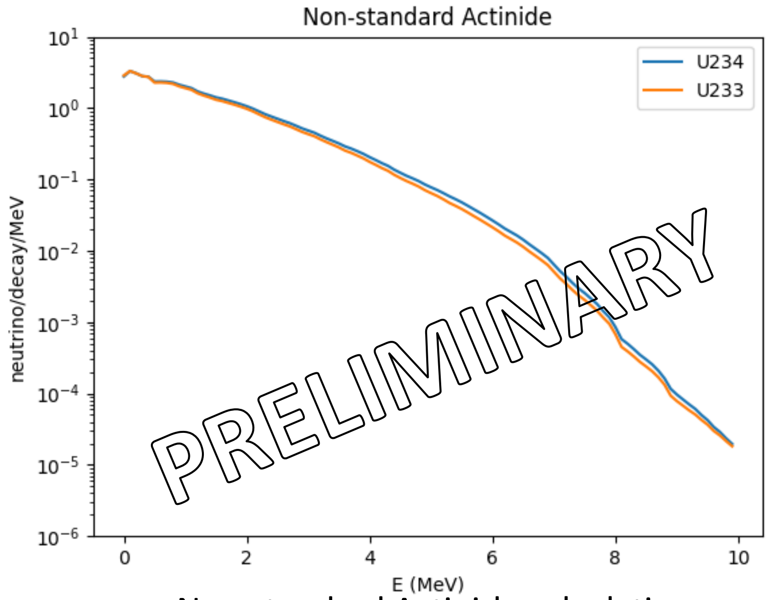


Reactor neutrino flux calculation below IBD



Non-standard Actinide calculation

Backup – examples of inputs

Input:

- Time dependent reactor model with fission fractions (all three modes):

  {{“time_0”, “power_0”, {“235_Thermal”, [frac, d_frac]}, {“238_fast”, [frac, d_frac]}, {...}, ...},

  …

  {“time_n”, “power_n”, {“235_ Thermal”, [frac, d_frac]}, {“238 _fast”, [frac, d_frac]}, {...}, ...}}

- Time dependent radioactive source model with simulated beta branches (summation mode only):

  {{“time_0”, “power_0”, {“beta_branch_0”, [frac, d_frac]}, {“beta_branch_1”, [frac, d_frac]}, …},

  ...

  {“time_n”, “power_n”, {“beta_branch_0”, [frac, d_frac]}, {“beta_branch_1”, [frac, d_frac]}, …}}