CONFLUX

A Standard Framework for Reactor Neutrino Flux Calculation

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On behalf of the CONFLUX project

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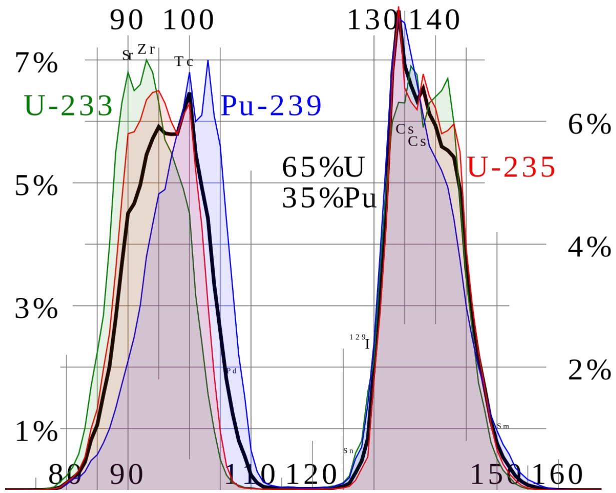
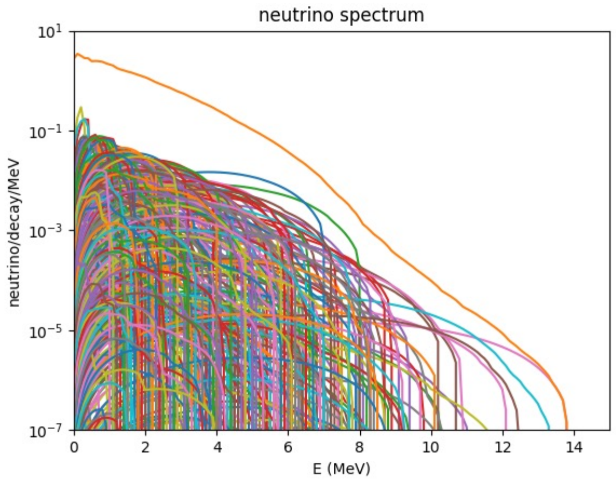
Challenges in Reactor Neutrino Predictions

- Challenges
  - Antineutrinos come from thousands of beta decaying branches produced from reactors
  - Predicting neutrinos involves summarizing beta branches with unknown factors
- Problems:
  - Reactor neutrino spectra directly measured are different from the predictions
  - Reactor neutrino predictions are essential to model dependent neutrino studies and applications neutrino detection



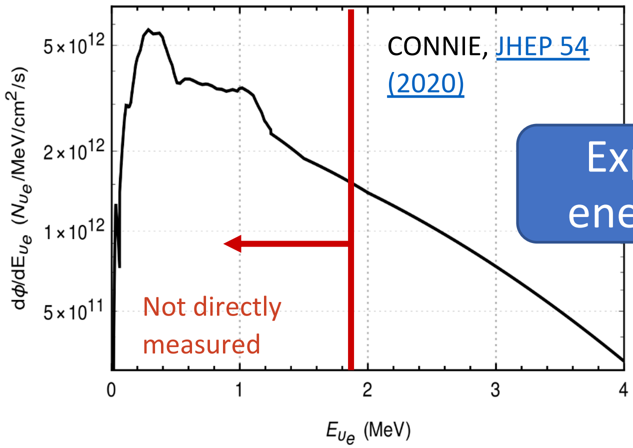
Fission products



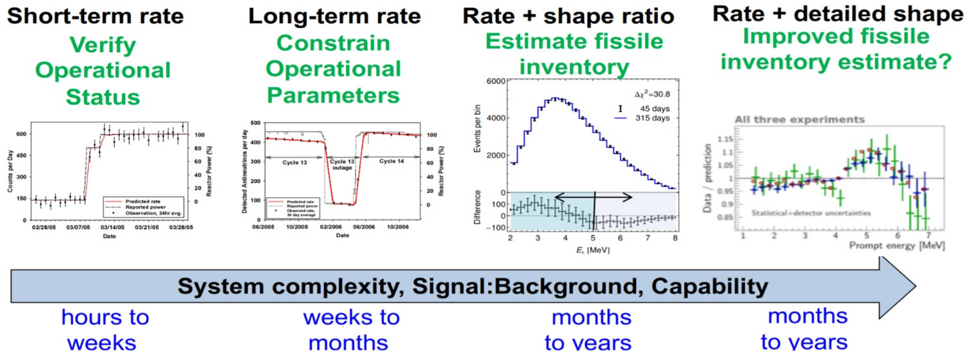
Neutrinos yielded from fission products for different isotopes

Goals

- **Scientific and Application needs:**
  - Reactor neutrino flux prediction for neutrino physics (CEvNS, model dependent BSM studies)
  - References for reactor monitoring, e.g. advanced reactors
- **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
  - Lower the 'barrier to entry' for the neutrino physicists to generate and compare predictions



Expand the energy range



Bowden (2019)

Reactor model for non-proliferation

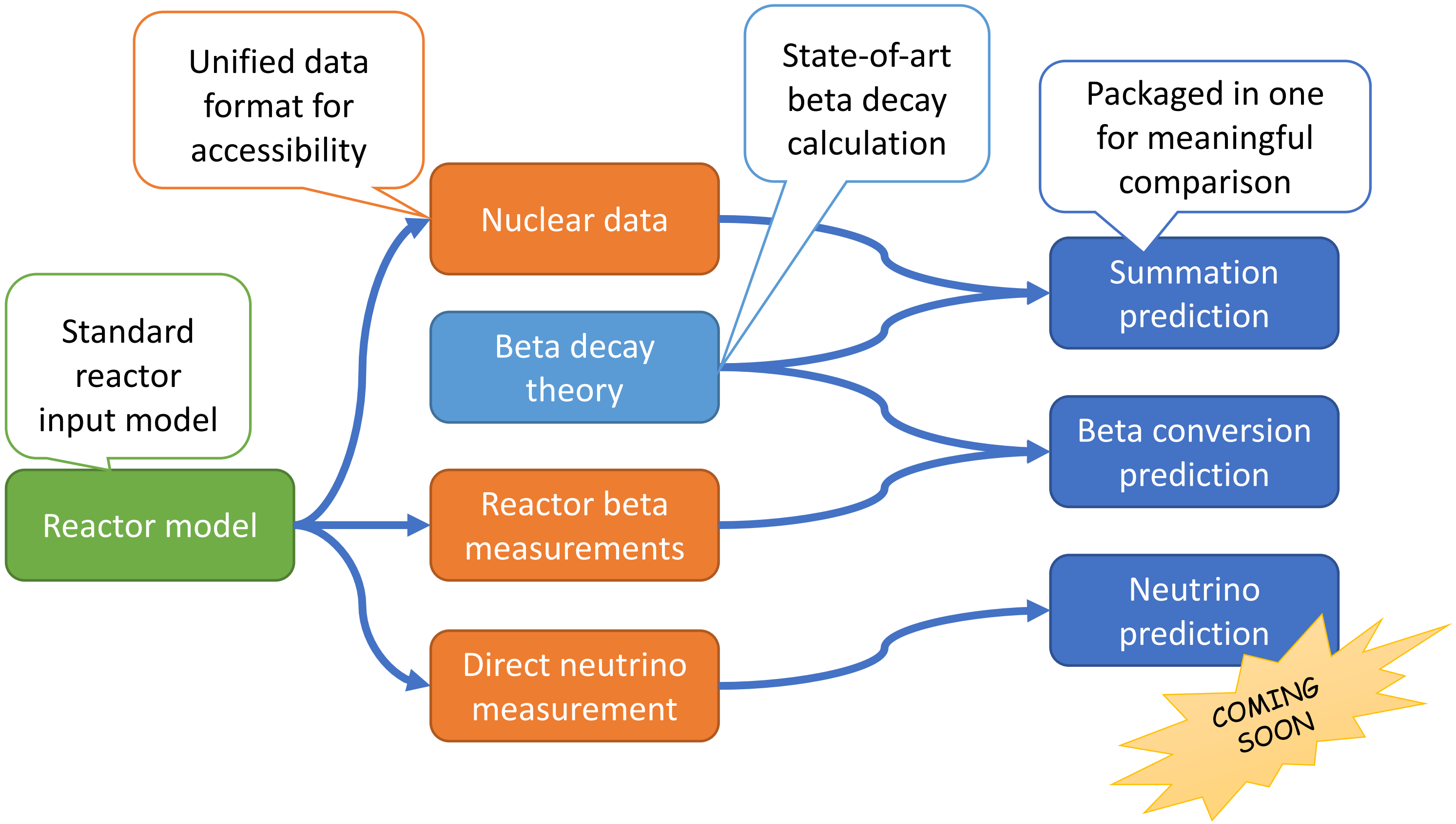
Nuclear Data to Reduce Uncertainties in Reactor Antineutrino Measurements

Summary Report of the Workshop on Nuclear Data for Reactor Antineutrino Measurements (WoNDRAM)

The development of an open software framework enabling uncertainty quantification for and standardized comparisons between direct neutrino measurements and conversion and summation calculations would greatly facilitate progress and reduce hurdles of participation for use case communities. The following recommendations would benefit all three discussed end user communities: nuclear data, reactor monitoring, and particle physics. *That broadened access and utility can be delivered to both the predictions and direct measurement communities by these tools further strengthens the recommendation for their development (recommendation 5).*

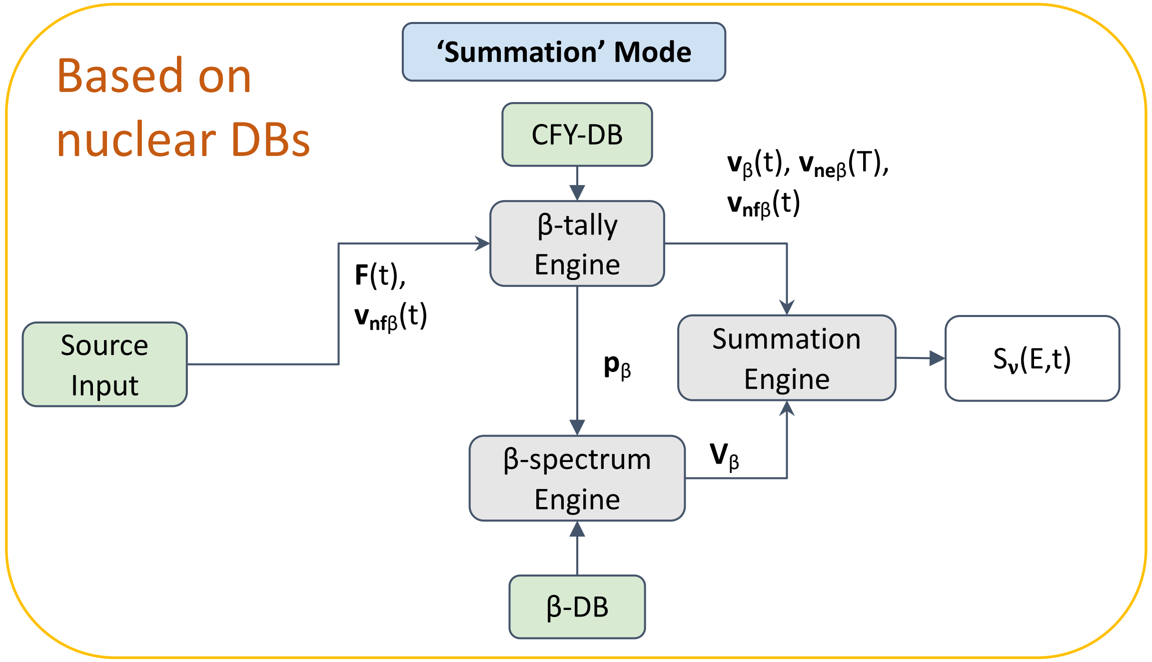
Calculation Of Neutrino FLUX

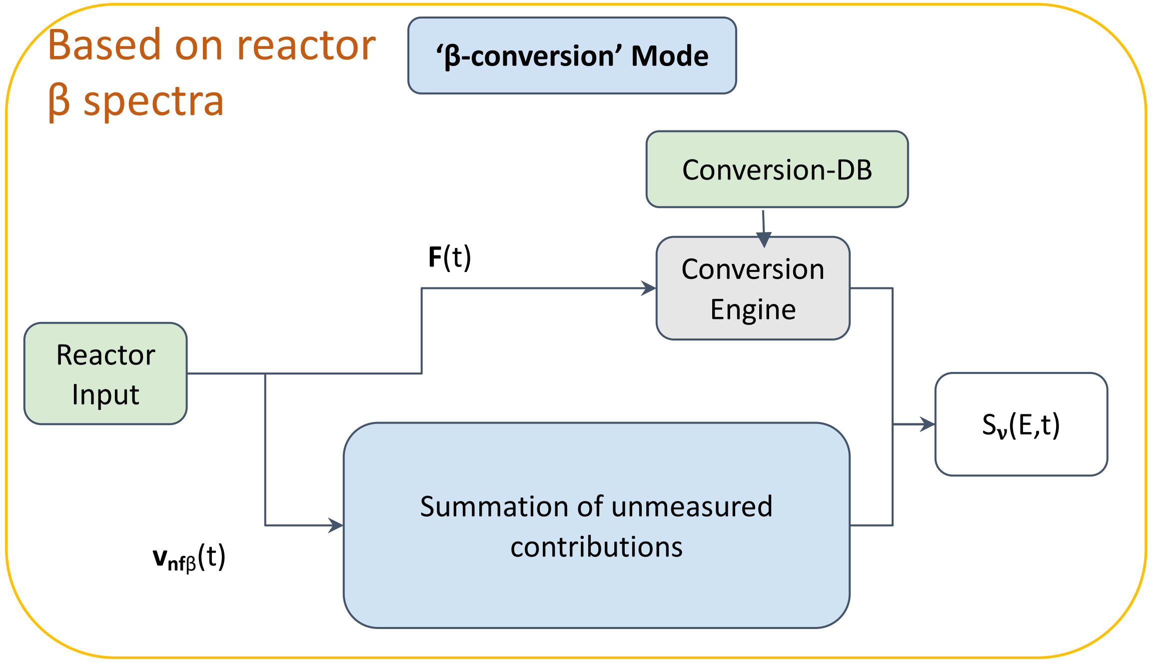
- Predictions are based on
  - Summation β spectra, or
  - Conversions of reactor β measurements
  - Direct reactor neutrino measurements
- Modular data and theory in software
  - Easy to update
  - Cross-mode comparison
  - Customizable modules



The Software Structure

- Prediction with three different modes (two functional, one in development)
- Flexible time dependent reactor model inputs
- Coded in Python3, can be installed and imported in analyzers own calculations





Flexible Inputs of Different Modes

- User input: Time dependent fission fragments or composition of a reactor
- **Summation:**
  - The β branch info parsed from databases such as ENSDF, ENDF, JEFF
  - Nuclear DBs are parsed into xml formats for accessibility
  - Updated β decay measurement with TAGS
- **Conversion:**
  - β spectrum measurements of fission isotopes
  - Converted neutrino flux from beta spectra

Beta 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"/>
    <branch end_point_E="5.27895" forbideness="5" fraction="0.004" sigma_E0="0.03007" sigma_frac="0"/>
    <branch end_point_E="4.8938" forbideness="4" fraction="0.0005" sigma_E0="0.0301" sigma_frac="0"/>
    <branch end_point_E="4.662" forbideness="0" fraction="0.089" sigma_E0="0.0301" sigma_frac="0"/>
    <branch end_point_E="4.65993" forbideness="8" fraction="0.009" sigma_E0="0.03015" sigma_frac="0"/>
    <branch end_point_E="4.57727" forbideness="6" fraction="0.019" sigma_E0="0.03007" sigma_frac="0"/>
    <branch end_point_E="4.36784" forbideness="0" fraction="0.011" sigma_E0="0.03007" sigma_frac="0"/>
    <branch end_point_E="4.34568" forbideness="6" fraction="0.023" sigma_E0="0.03007" sigma_frac="0"/>
    <branch end_point_E="4.21187" forbideness="3,2.0" fraction="0.005" sigma_E0="0.03015" sigma_frac="0"/>
    <branch end_point_E="4.16445" forbideness="5,6.0,7.0" fraction="0.0052" sigma_E0="0.0301" sigma_frac="0"/>
    <branch end_point_E="4.12744" forbideness="0" fraction="0.0011" sigma_E0="0.03015" sigma_frac="0"/>
    <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"/>
```


FPY 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"/>
      <CONT DY="1.54228e-14" FPS="0.0" Y="2.40981e-14" ZA="24066"/>
      <CONT DY="0.0" FPS="0.0" Y="0.0" ZA="24067"/>
      <CONT DY="0.0" FPS="0.0" Y="0.0" ZA="24068"/>
      <CONT DY="1.34924e-18" FPS="0.0" Y="2.10819e-18" ZA="24069"/>
      <CONT DY="0.0" FPS="0.0" Y="0.0" ZA="24070"/>
      <CONT DY="4.60767e-12" FPS="0.0" Y="7.19949e-12" ZA="25066"/>
      <CONT DY="3.44296e-12" FPS="0.0" Y="5.37962e-12" ZA="25067"/>
      <CONT DY="4.2621e-13" FPS="0.0" Y="6.65953e-13" ZA="25068"/>
      <CONT DY="5.1387e-14" FPS="0.0" Y="8.02922e-14" ZA="25069"/>
```

Beta Spectrum Calculation

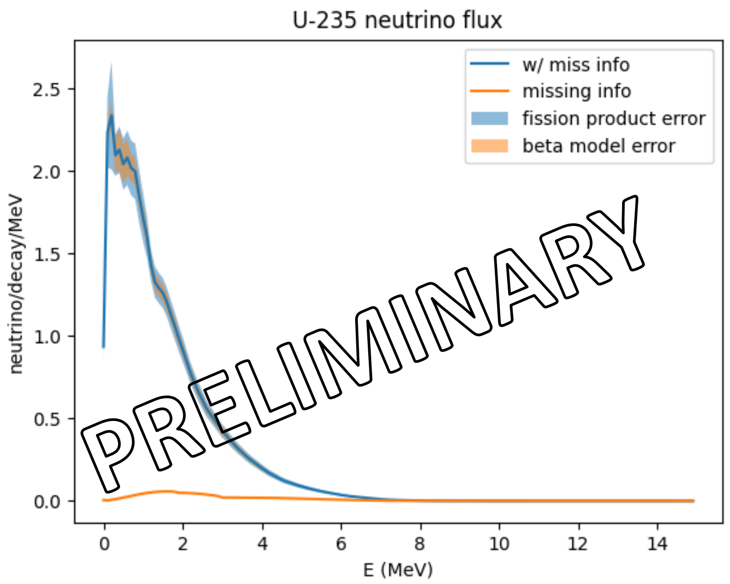
- A common β spectrum generator for the summation and conversion modes.
- Use of state-of-art theoretical calculation with BSG [CPC 240 (2019) 152].
- Some corrections are important for low energy beta spectra.
- Spectrum shape corrections are built to be freed up to test model uncertainties affected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

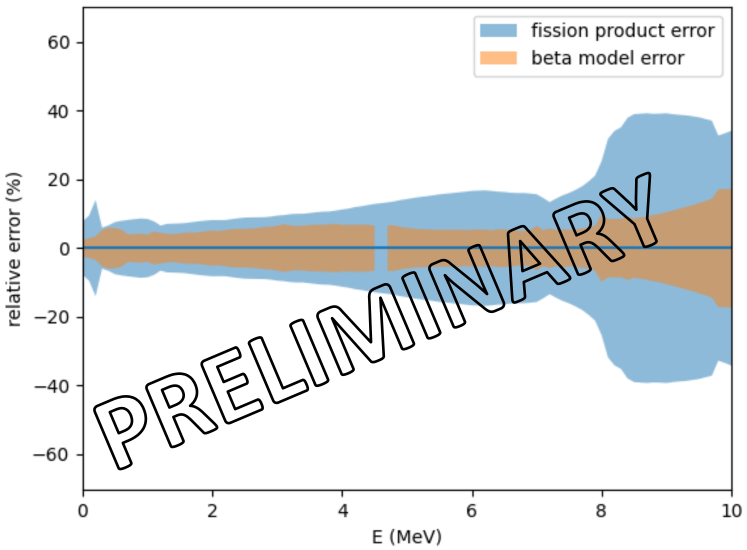
Item	Effect	Formula	Magnitude
1	Phase space factor	$pW(W_0 - W)^2$	Unity or larger
2	Traditional Fermi function	F_0	
3	Finite size of the nucleus	L_0	10^{-1}-10^{-2}
4	Radiative corrections	R	
5	Shape factor	C	
6	Atomic exchange	X	
7	Atomic mismatch	r	
8	Atomic screening	S	10^{-3}-10^{-4}
9	Shake-up	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

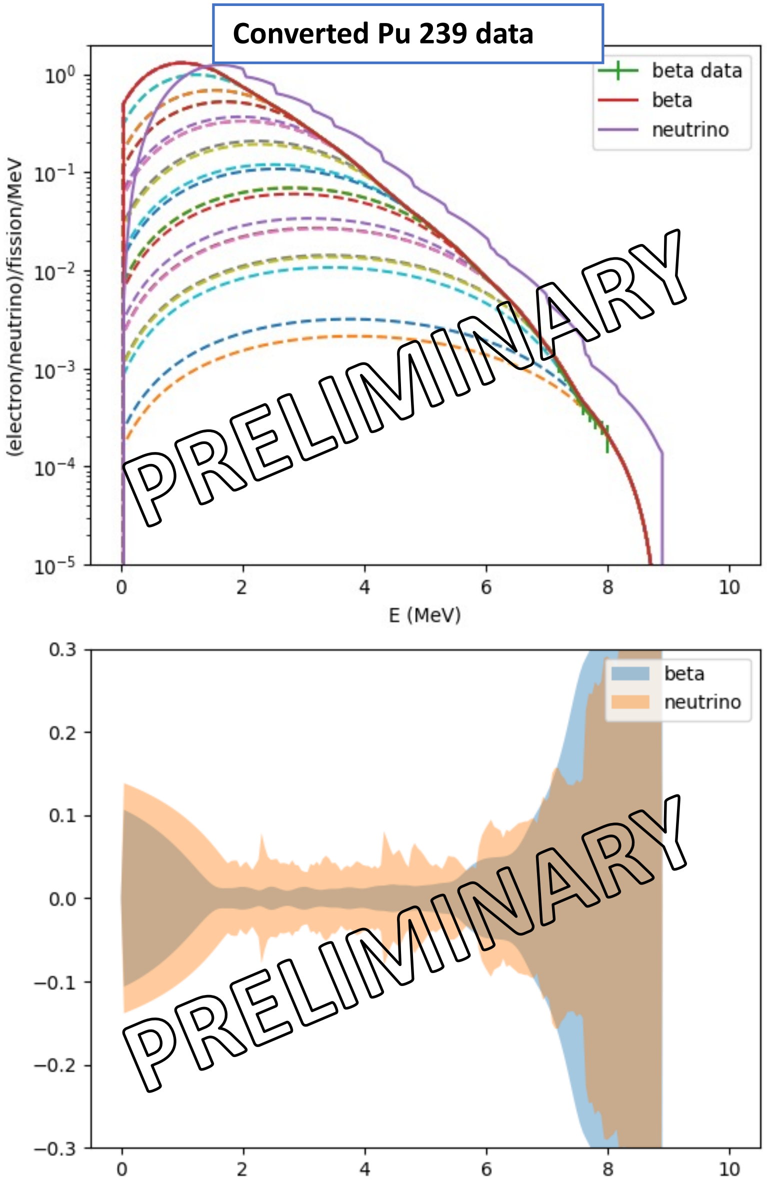
- Fission products counted from
  - ENDF/B-VIII, or JEFF-3.3 on default.
- Uncertainty:
  - Beta model uncertainty
  - Beta branch fraction
  - Fission product yield
  - Fission fragments
- Default assumption:
  - Missing branching assumed as single-branch non-forbidden decay to the ground state
  - Missing information of spin-parity changes are assumed as non-forbidden





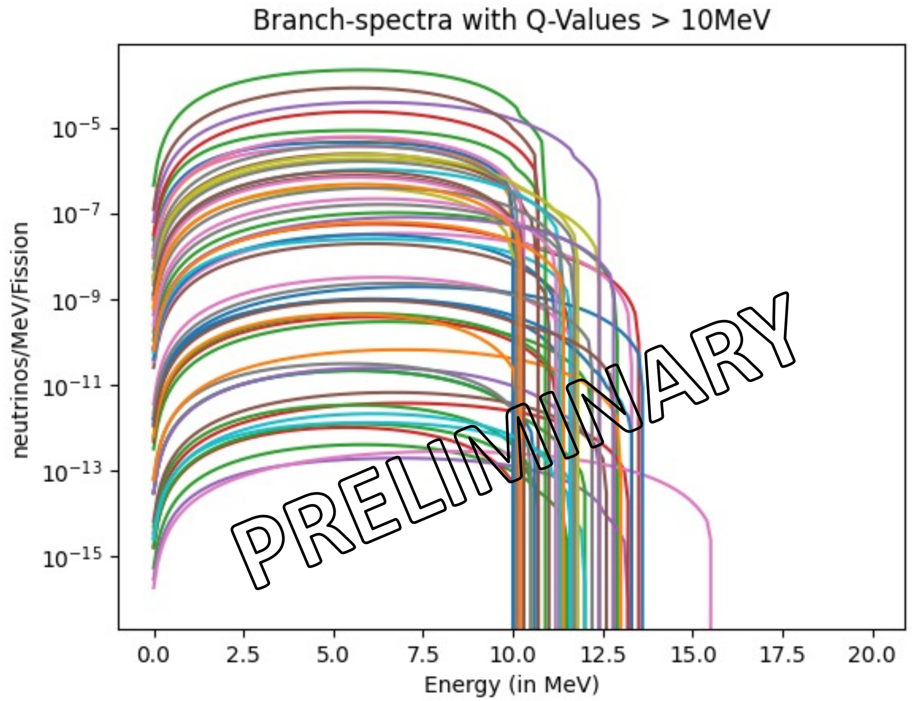
Beta-conversion

- Beta data used is the ILL fission beta spectra of U235, Pu239, and Pu241.
- Beta data are fitted with virtual branches generated by BSG
  - Branch number is of user choice
- Uncertainty:
  - Data uncertainty randomized for MC to calculate the covariance matrix
- Unmeasured contributions are corrected with summation calculations



Calculation Output with Selected Conditions

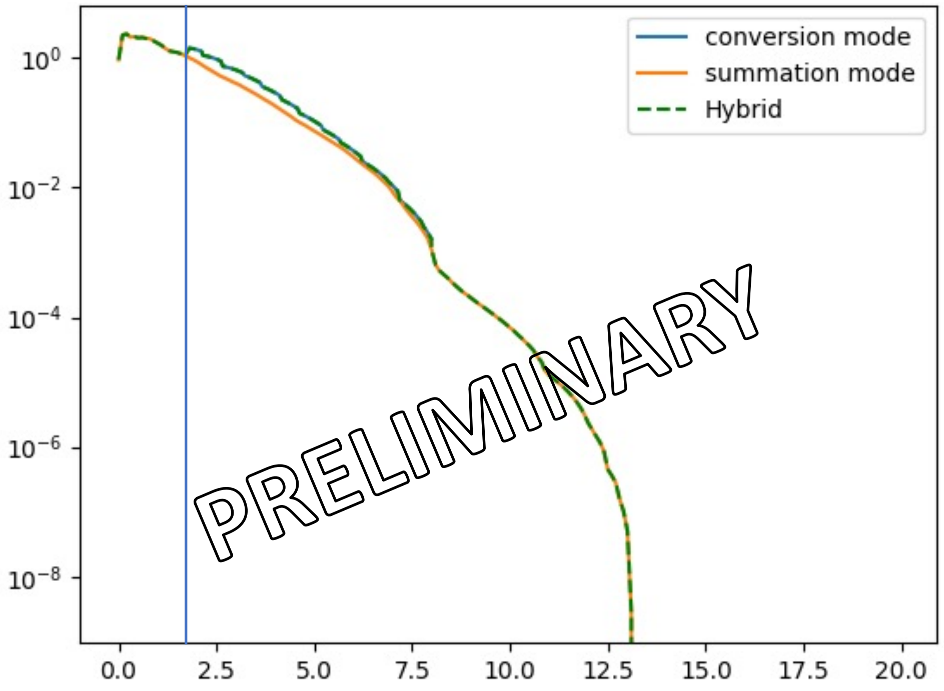
- Beta spectrum calculation for selected isotopes, with respect to atom number, end point energy, contributions to the total neutrino flux, etc.



Isotope	percent-contribution	Q-Value
Br-90	$5.6 * 10^{-3}$	10.959 MeV
As-86	$5.5 * 10^{-3}$	11.541 MeV
Rb-100	$3.5 * 10^{-3}$	13.574 MeV
Rb-96	$2.1 * 10^{-3}$	11.571 MeV
As-84	$1.3 * 10^{-3}$	10.094 MeV
In-130	$9.7 * 10^{-4}$	10.249 MeV
Rb-97	$3.8 * 10^{-4}$	10.432 MeV
Br-92	$2.7 * 10^{-4}$	12.537 MeV
Cd-131	$1.4 * 10^{-4}$	12.87 MeV
Ga-80	$1.2 * 10^{-4}$	10.38 MeV
Ga-84	$1.1 * 10^{-4}$	13.69 MeV
Ga-82	$6.3 * 10^{-5}$	12.484 MeV
In-132	$6.2 * 10^{-5}$	14.14 MeV
Rb-98	$4.0 * 10^{-5}$	12.054 MeV
Br-93	$3.1 * 10^{-5}$	11.09 MeV

Combined/compared prediction with two modes

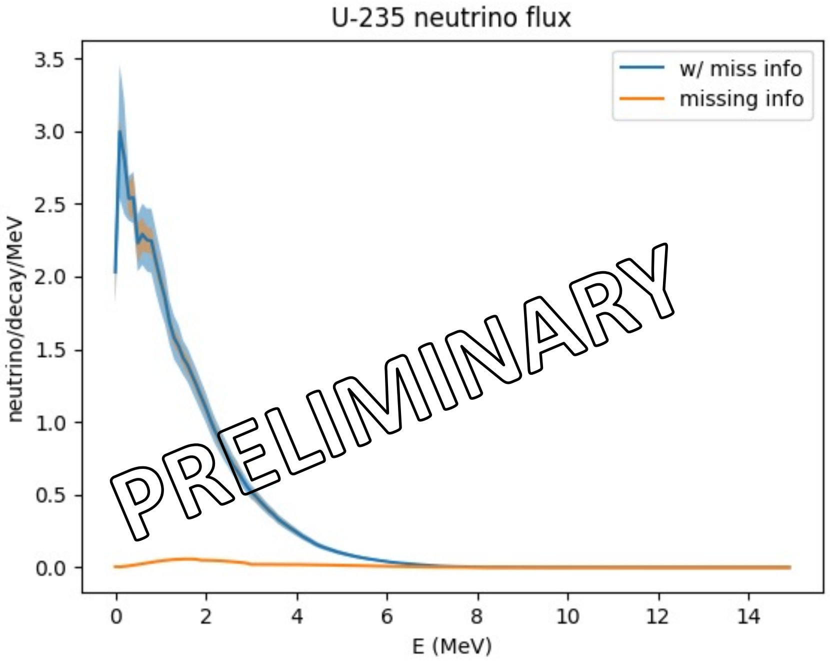
- Results and reference spectra of two modes can be added and modified for combined prediction
- Different modes use common theories and nuclear databases, allow direct cross-mode comparisons

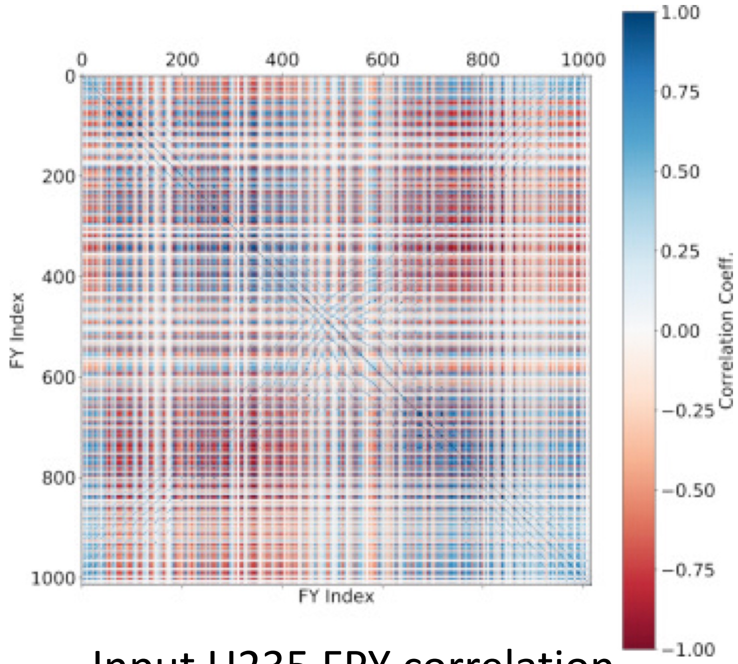


Simple combination between the summation and conversion results

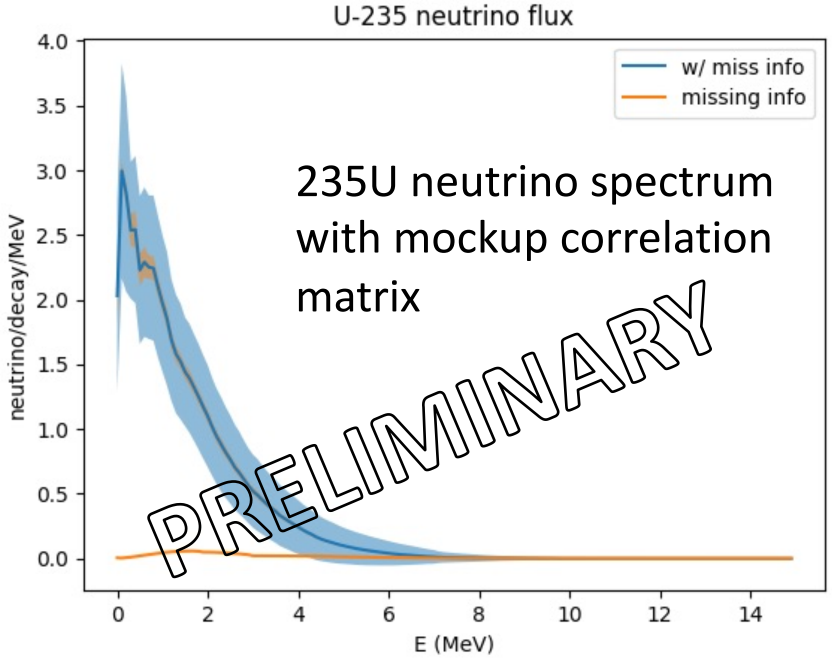
Summation Calculation with Correlated Fission Products

- Correlation/covariance matrices of fission fragments or beta branches can be given as additional input in the summation.





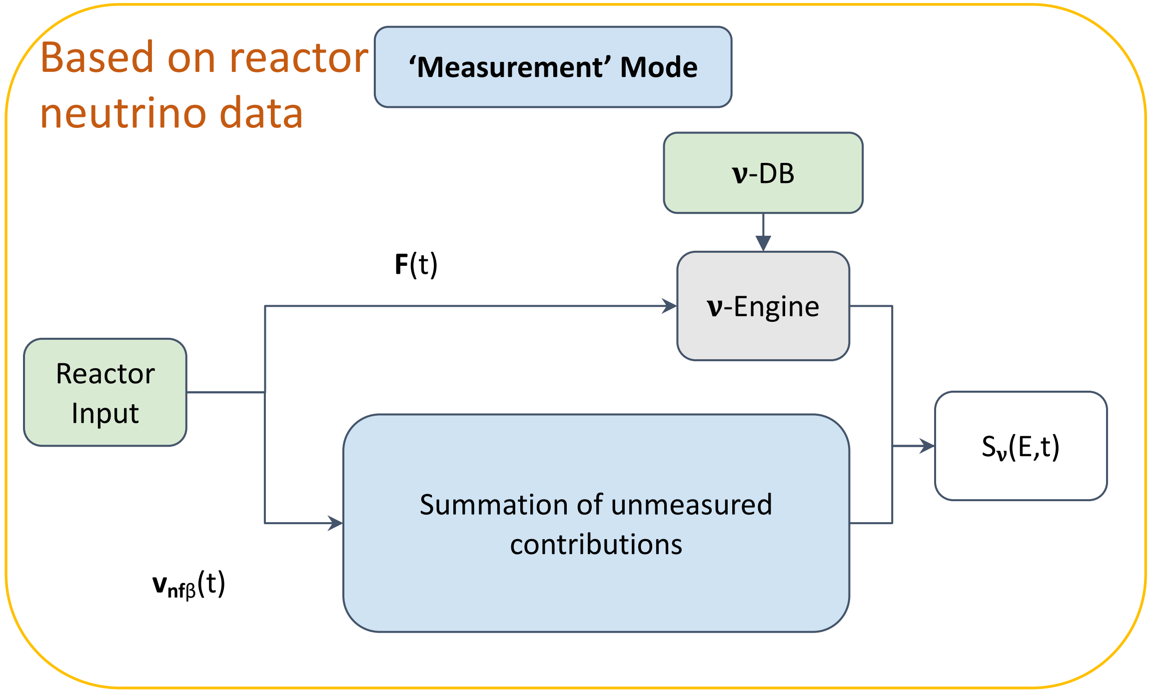
Input U235 FPY correlation
[j.adt.2021.101441](j.adt.2021.101441)



235U neutrino spectrum with mockup correlation matrix

Coming soon

- Software is under beta testing and documentation
- **Aim to release the software and publish documentations of CONFLUX to the community in 2022**
- Neutrino experiment-based prediction
    - Tabulated neutrino data from fissile isotopes
    - Combined calculation with the summation mode to fit specific reactor



Potential Scientific Output

- **Neutrino spectra and flux prediction on different reactor types:**
  - Reactor CEvNS detection
  - BSM neutrino physics
- **Contribute to the nuclear data community**
  - Cross-database comparisons
  - Search for deviations to prioritize beta decay measurements to be revisited
- **Studies on the reactor simulation for near field reactor survey**

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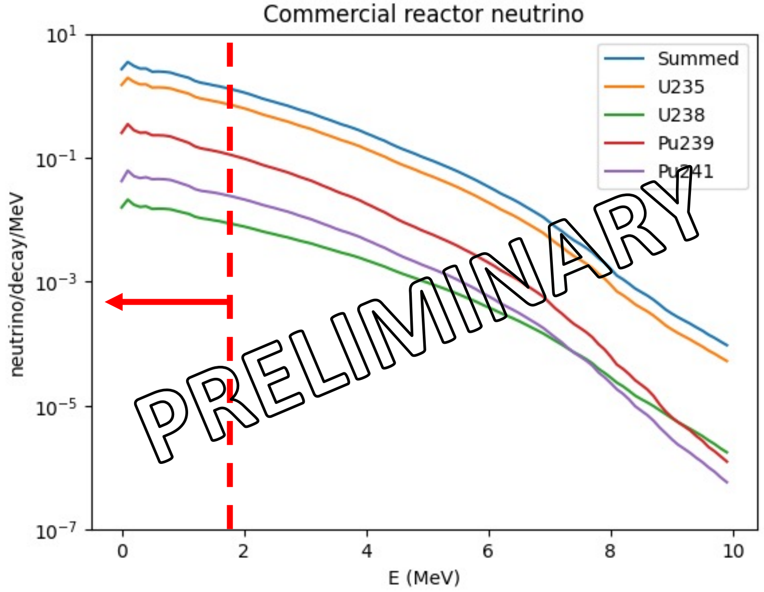
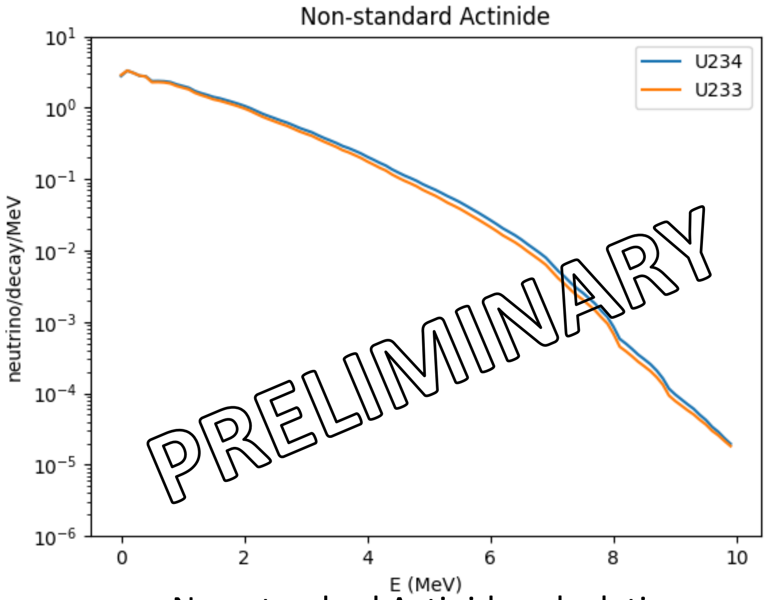


Reactor neutrino flux calculation below IBD



Non-standard Actinide calculation

Summary

- CONFLUX is a framework of reactor neutrino prediction for neutrino physicists.
- The goal is to provide calculation modules with standard, easy-to-access nuclear data and state-of-art theories of beta decays.
- Analyzers can use flexible reactor inputs and corrections.
- The framework is under construction and able to calculate reactor neutrino flux with time dependent reactor inputs.
- CONFLUX is a tool can be utilized to provide a wide range of scientific output for the nuclear and particle physics communities, important contributions to neutrino frontier topics.

Thank you!

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]}, …}}
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