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Future Functionality: β-ν Spectra from FISPACT-II inventories.

Greg Bailey, FISPACT-II Workshop, online, November/December 2020

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Overview

1. Motivation, Fusion and β-ν spectra
2. Characteristics of nuclide β-ν decay spectra.
3. Currently available models and data.
4. The methodology of finding such spectra from complex inventories.
5. Initial findings and results.

Motivation: β-v spectra and Fusion

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- Fusion reactors are expected to produce radioactive material. Require knowledge of expected:
  - Activities
  - Dose rates
  - Decay heating
- Current decay data has limited detail in range of emitted β energies.
- Almost no information on the associated v, but they should be determinable from the β data **if it is complete.**

- Currently photon spectra output from simulations and used for dose rate calculations
  - ✓ Information of expected dose rates from β emitters is desired.
- Decay data includes 'light particle' energies for heating calculations.
  - ✓ The contribution to decay heating from specifically β decay can provide uncertainties.
- Require that nothing has been "missed" from simulations for regulatory purposes.
  - ✓ Complete decay spectra should be known

Motivation: Beyond Fusion

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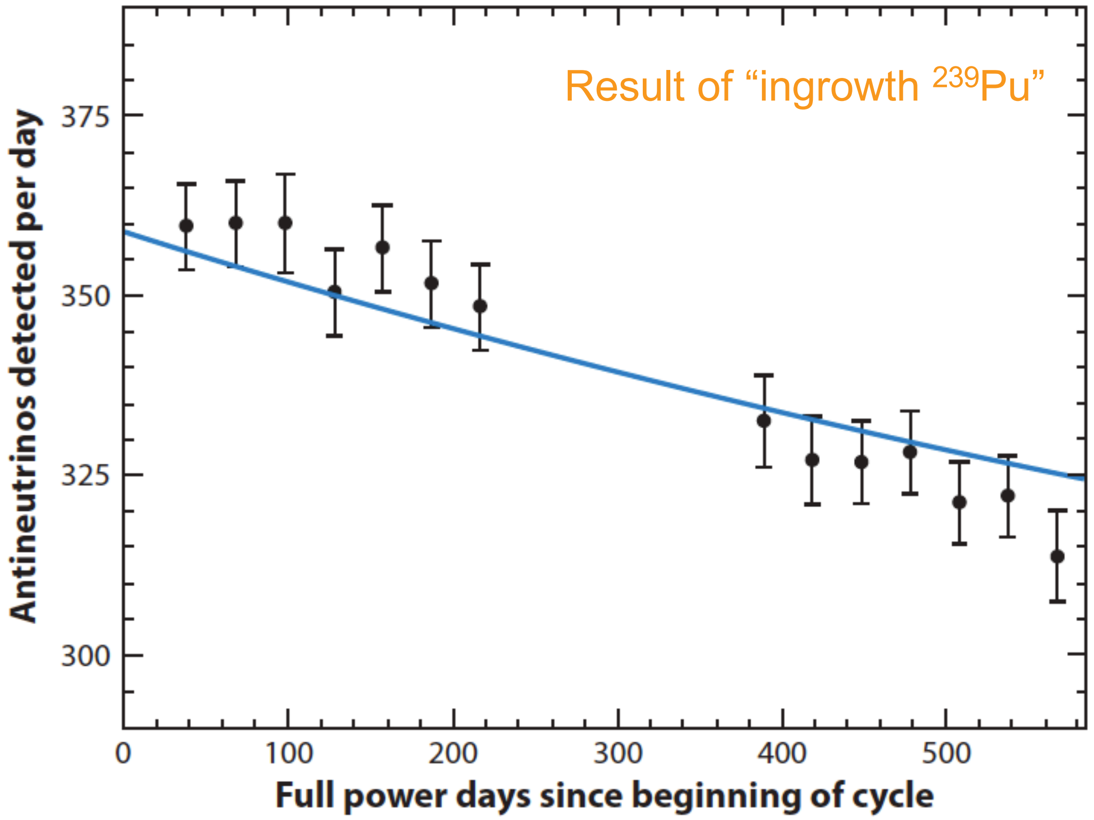
- Antineutrino's have been used to study operating fission reactors as part of neutrino oscillation experiments
- Trend seen arises due to changes in fuel composition. Modelling of Antineutrino spectra is an nontrivial process.

➢ More complete knowledge of β-v spectra would aid studies such of these.

➢ Could introduce ability for β and/or v diagnostics in other fields.

Figure taken from A Hayes and P Vogel, Annu. Rev. Nucl. Part. Sci. 2016. 66:219–44



➢ Develop methods for calculating β spectra from complex inventories and add this functionality to FISPACT-II.

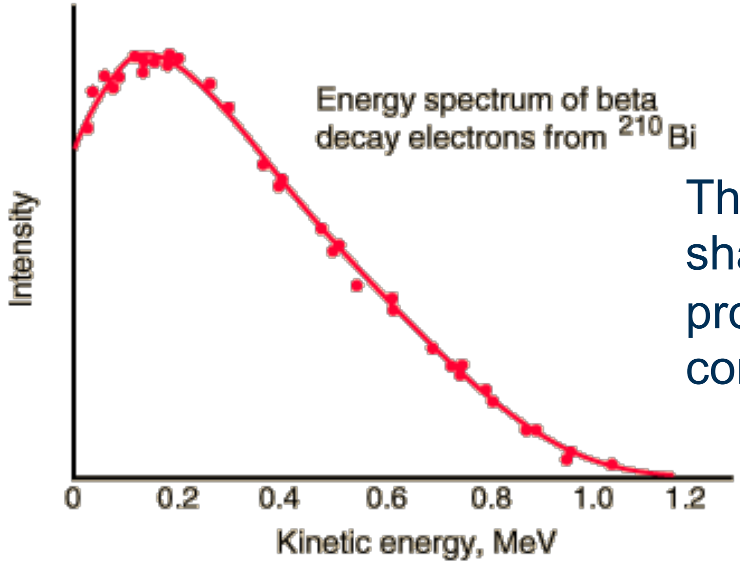
What are β spectra?

Decay spectra inform as to the energies of the products of radioactive decay

β decay:

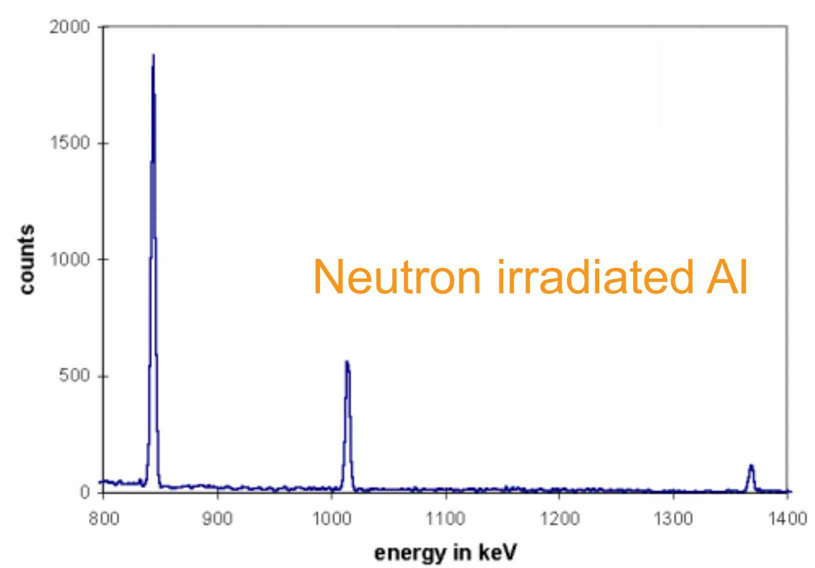
$$\beta^- \text{ decay}: {}^A_Z X_N \rightarrow {}^A_{Z+1} Y_{N-1} + e^- + \bar{\nu}_e,$$

$$\beta^+ \text{ decay}: {}^A_Z X_N \rightarrow \underbrace{{}^A_{Z-1} Y_{N+1} + e^+ + \nu_e}_{\text{3 body system}}.$$



The decay energy is shared between decay products, so an energy continuum is produced

γ decay: $X^* \rightarrow X^{(gs)} + \gamma$ Single decay product

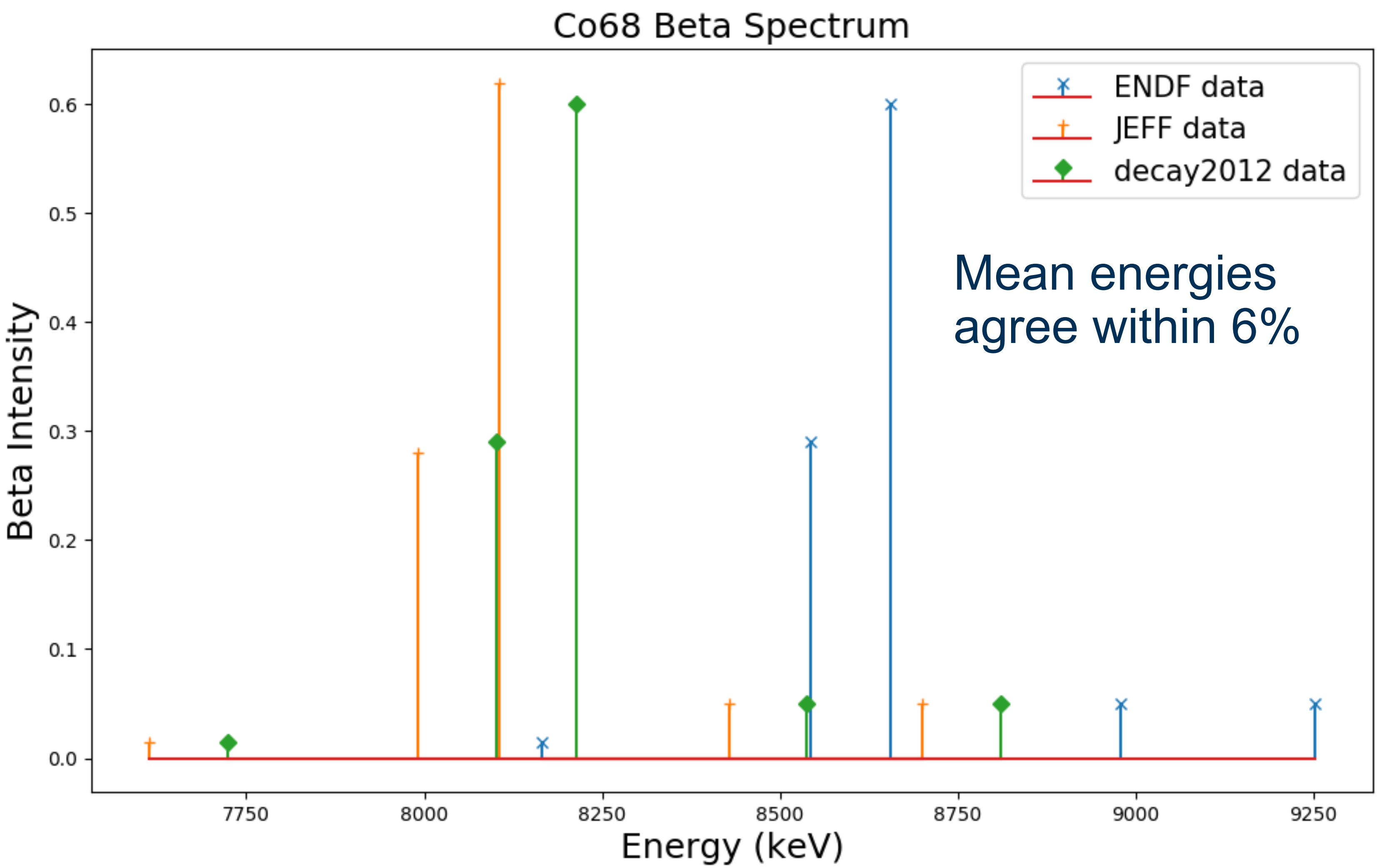


The decay energy is carried by a single decay product so discrete peaks produced

- FISPACT-II calculates and outputs γ spectra. This is possible as the nuclide γ lines are often included in nuclear data libraries.
- No information on the range of expected β energies is currently found by FISPACT-II.

Beta Spectra data in current nuclear data

- Most modern decay data contains discrete beta spectra.
- These are the transition probabilities and daughter level energies.
- Spectrum mean energies are often included.
- Little or no information on neutrino energies/spectra.
- Some continuum spectra are given for some beta delayed neutron decays relevant to fission.



Mean energies agree within 6%

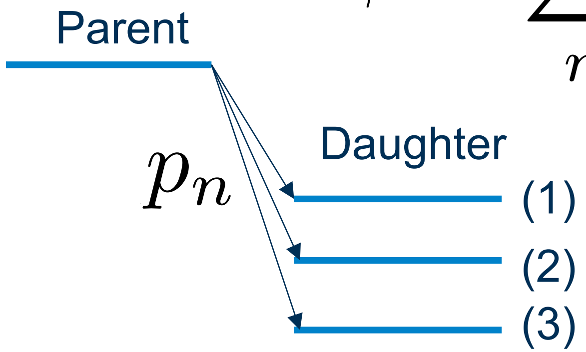
➢ Need to develop a library of beta-neutrino spectra to compliment decay data

Nuclide β and ν Spectra

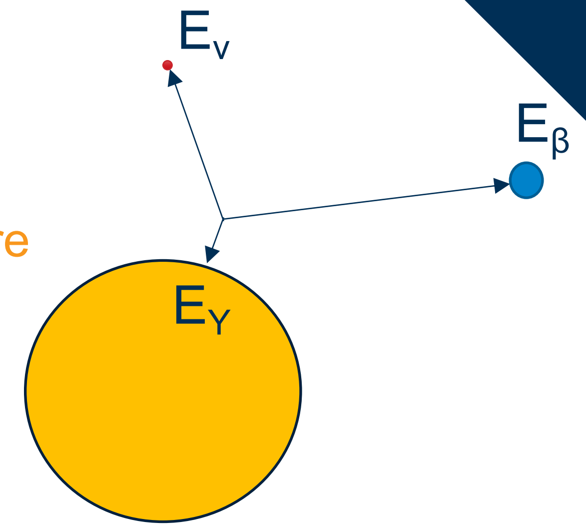
- Existing models and theories can be used construct a prototype library to test methodologies.
  - Development of new models can be pursued in future where needed.
- If a nucleus has multiple possible β decay transitions a complete nuclide spectrum will include weighted contribution from each transition's spectra

$$N_\beta = \sum_n p_n N_n$$

Transition probability



As the beta and neutrino share energy, the spectra are the inverse of one another

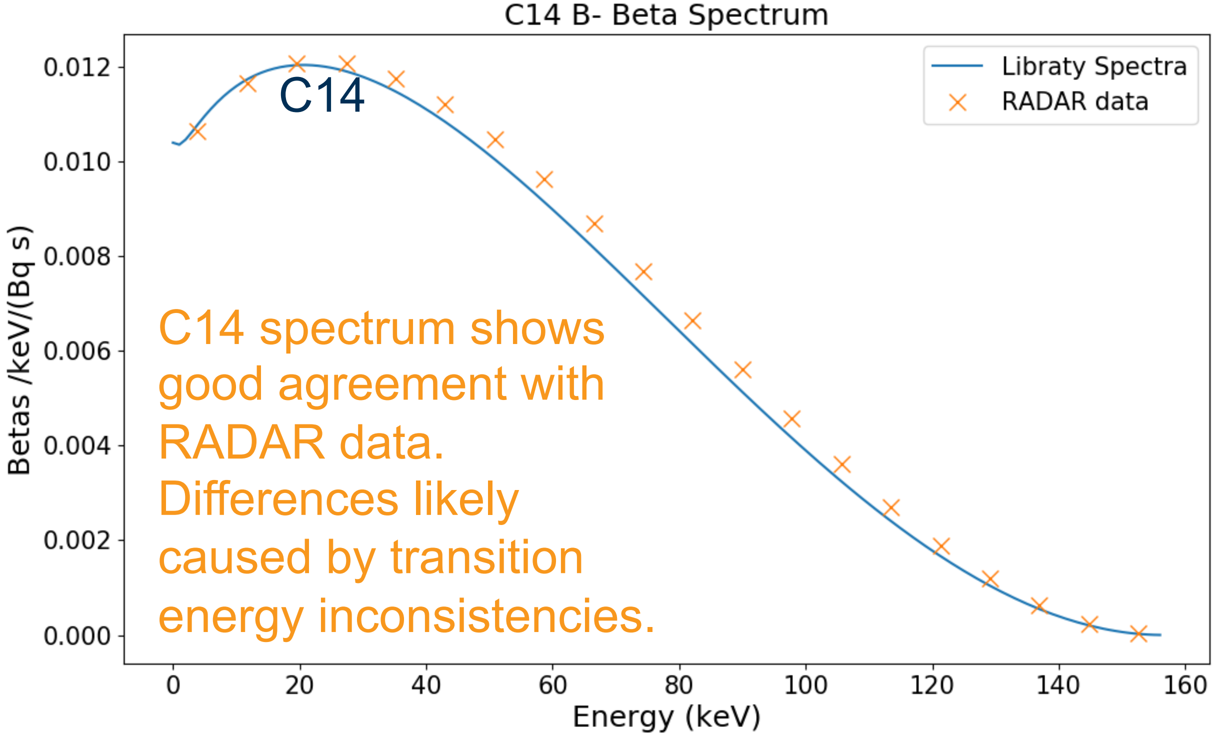


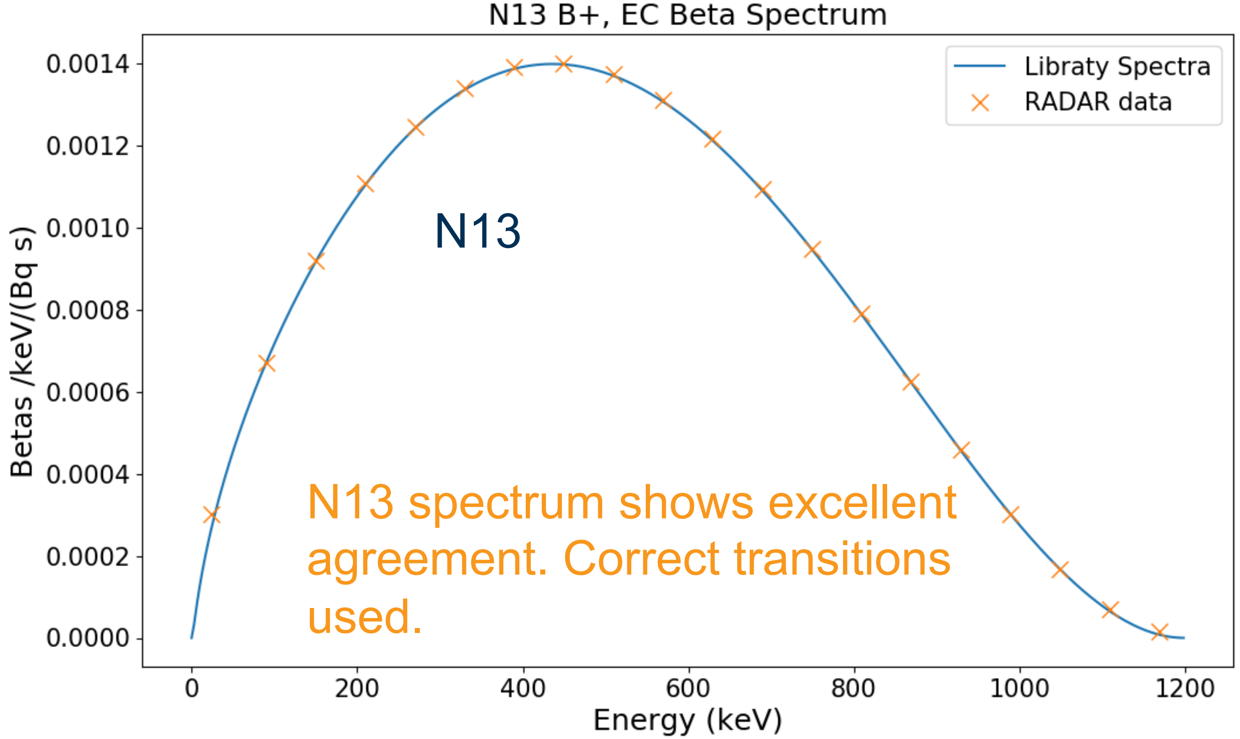
$$N_\beta \propto F(Z, E_\beta) S^{L_{\beta\nu}}(E_\nu, E_\beta) M_{fi}^{L_{\beta\nu}}$$

- After investigating the available options the code **BetaShape** has been chosen to construct the prototype library.
- **BetaShape** has some capacity to account for higher order or forbidden β transitions, so it should provide the most complete results.
- Current prototype library contains spectra for 1567 nuclides.

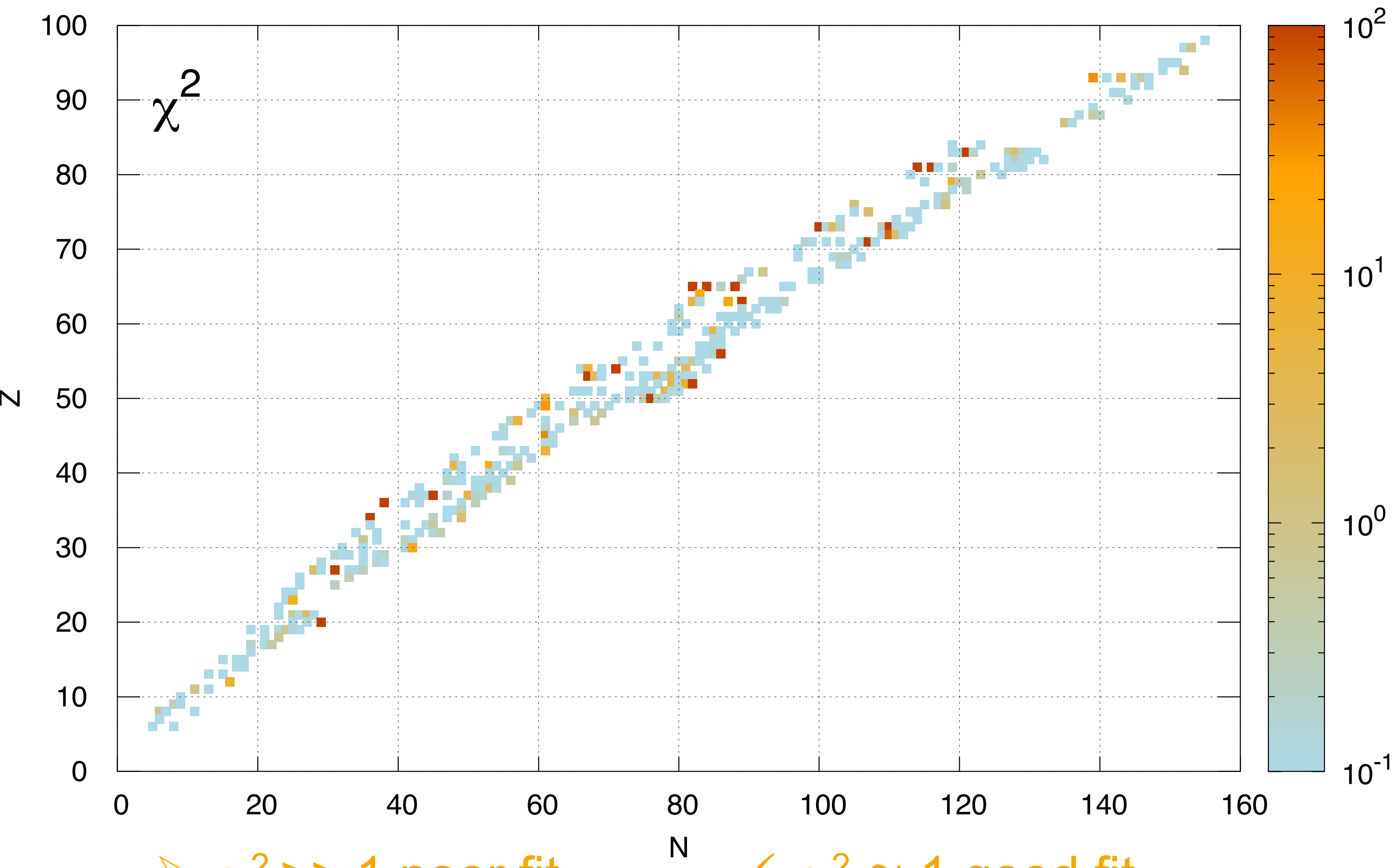
Example spectra and comparisons to RADAR

- RAdiation Dose Assessment Resource (RADAR) collates dosimetry relevant decay data, collected from the Brookhaven National Laboratory's National Nuclear Data Center. This set includes 448 continuum beta spectra.
- Comparisons with the prototype library are generally good. While most spectra show good agreement between the to sets, some do not. The differences are most likely from differing assumed transitions





Early Validation efforts with RADAR data



➢ $\chi^2 >> 1$ poor fit

✓ $\chi^2 \cong 1$ good fit

- 220 nuclides $\chi^2 < 1.5$
- 76 nuclides $\chi^2 > 10$

- In general the BetaShape generated Library and the RADAR spectra show fair agreement.
- The agreement is not perfect, but different models are being used.
- Some nuclide spectra show very poor fits, which model is incorrect need to be investigated.

Comparison of mean spectra energy

While continuum spectra are not common in current decay data mean spectrum energies are, so comparisons can be made.

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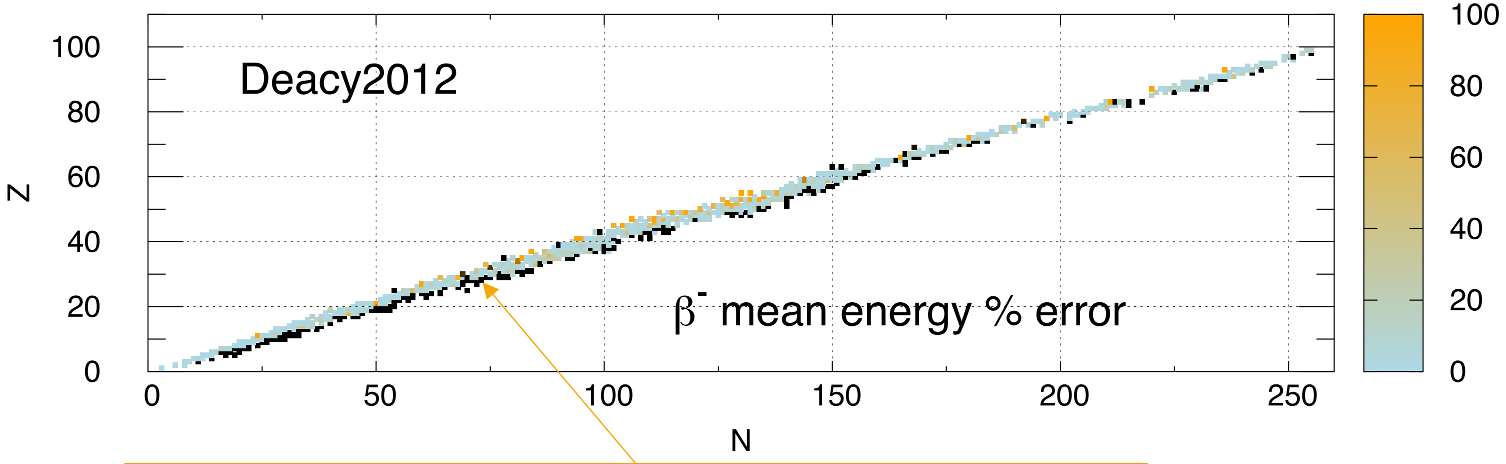
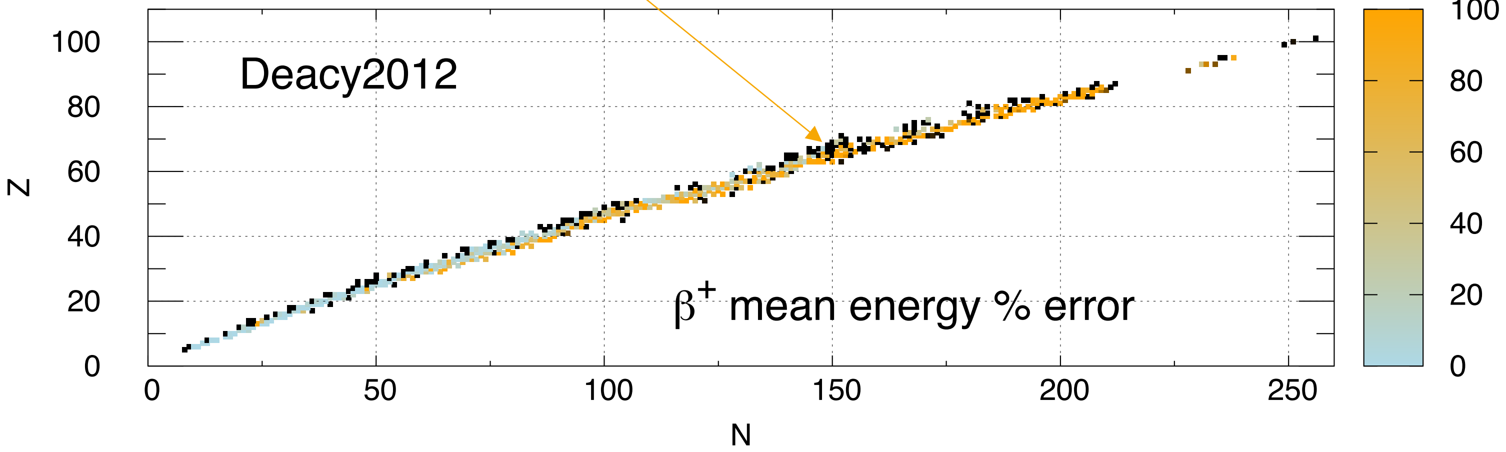


= Mean energies not in decay2012, can be determined.



$$\bar{E} = \frac{\int_0^\infty E N_\beta(E) dE}{\int_0^\infty N_\beta(E) dE}$$

Nuclide β continuum spectra

- % difference between mean spectra energies in decay2012 and continuum spectra
- Fairly good agreement across the nuclide chart for β- spectra.
- Agreement worsens as mass number increases for the β+ spectra.
- Number of nuclides from decay2012 do not have mean energies (black). These can be determined from the continuum spectra

Calculating an inventory β spectrum

A beta or neutrino spectrum, at a given time step, from a complex inventory will be dependant on the sum of the nuclide spectra. This sum needs to be weighted according to each nuclides contribution.

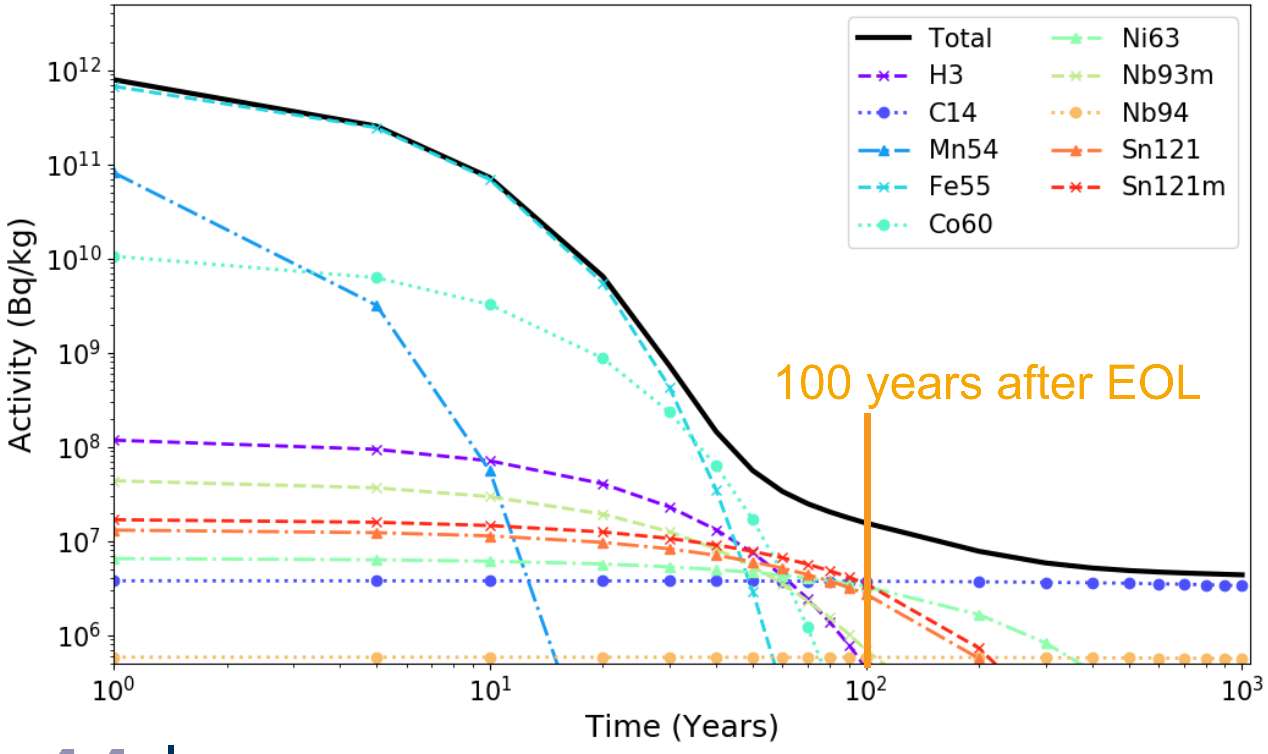
Activity

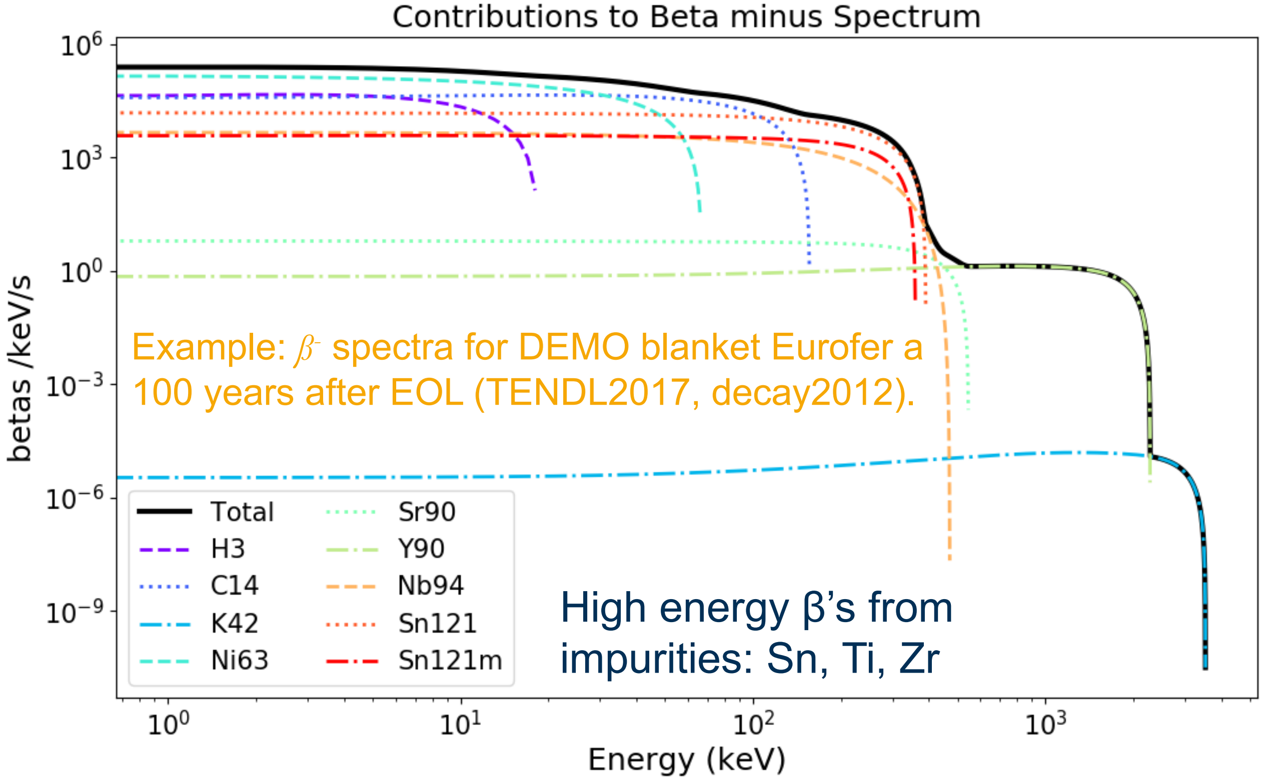
Beta decay branching ratio

$$N_{Ivt}(E) = \sum_i \underbrace{A_i b_i}_{\text{Beta disintegrations for nuclide } i} N_i(E)$$

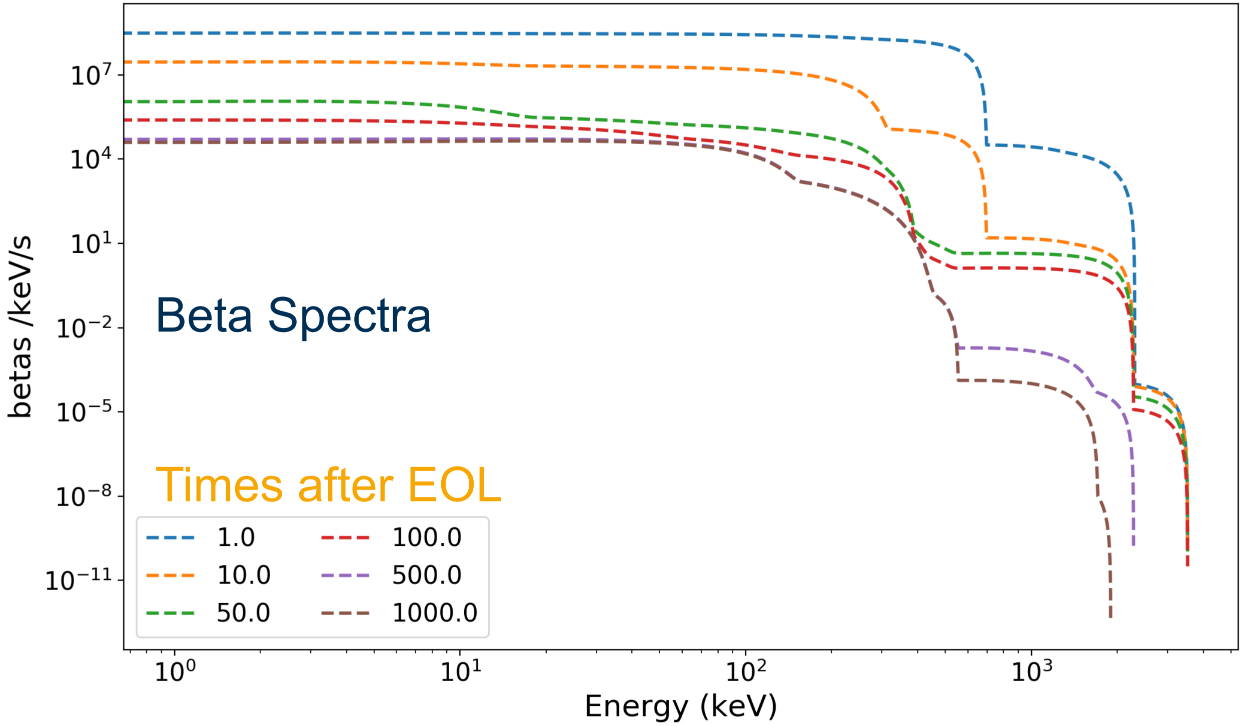
Gives inventory spectra in per unit energy per unit time

- Take the inventory contents and activities from FISPACT-II simulations.
- The branching ratios from current decay data (can be found with **PRINTLIB**).





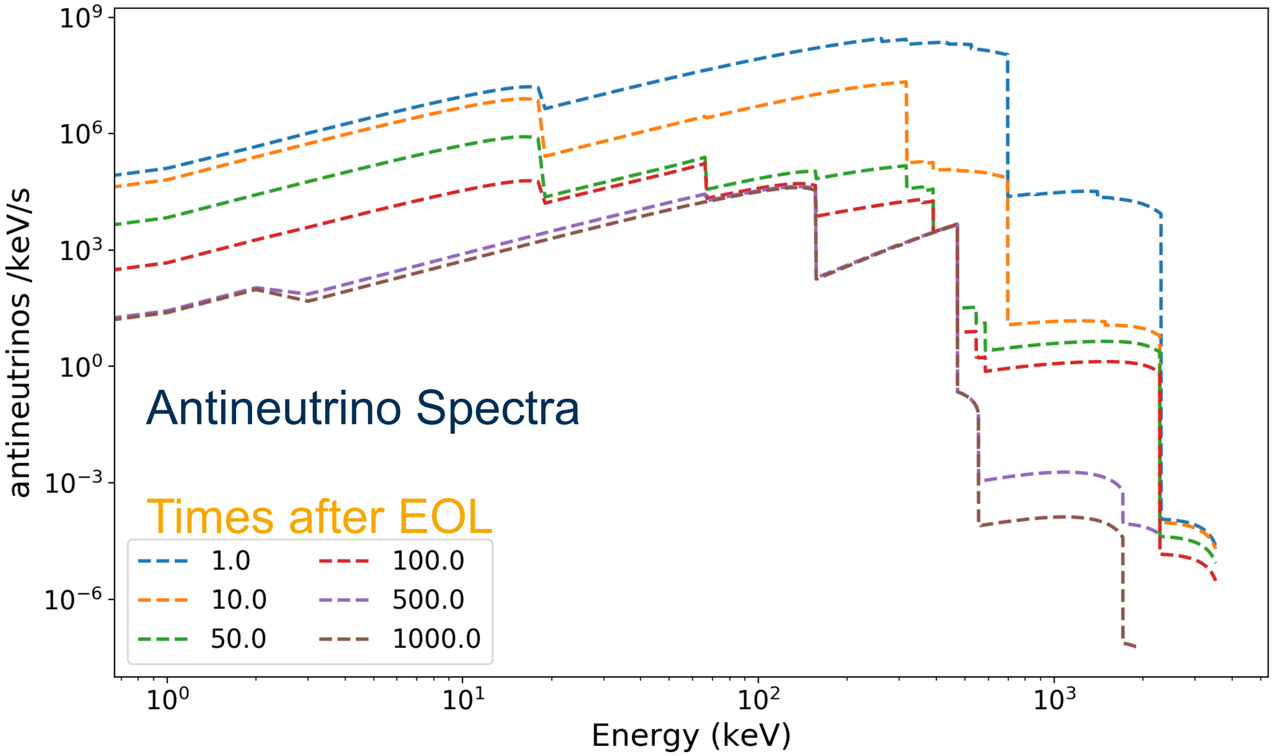
Preliminary Inventory Calculations (1)



$$N_{Ivt}(E) = \sum_i A_i b_i N_i(E)$$

Example: β and ν spectra for DEMO blanket Eurofer for times after End of Life (TENDL2017, decay2012)

➢ End point energies evolve and nuclides decay



- The β and ν share decay energy, so the spectra peak at different energies.
  - ➢ The antineutrino spectra peak a higher energies where the beta spectra are at lower energies.
- Discontinuities in neutrino spectra arise from neutrino maximum energies occurring when beta energy is at minimum.

Preliminary Inventory Calculations (2)

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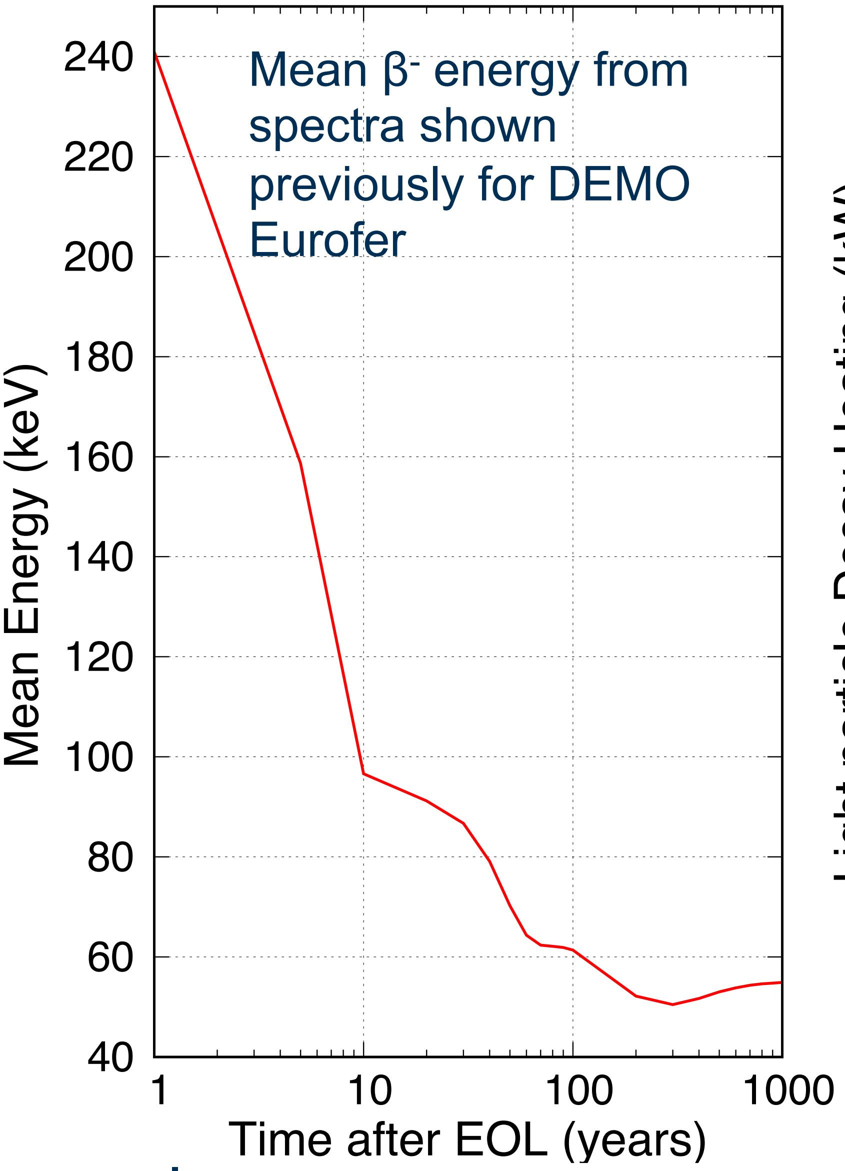
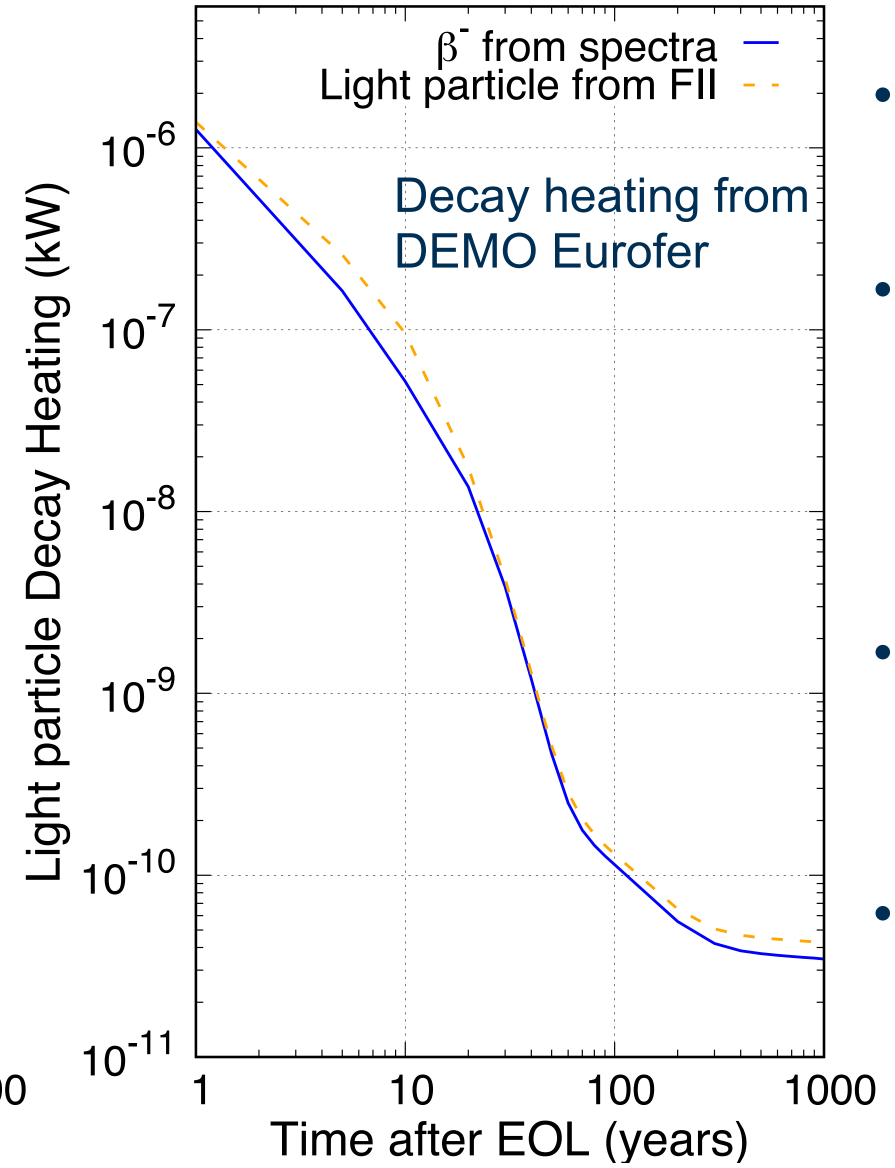




- Using the relation shown previously, mean energies can be calculated.
- From the mean energy and the inventory (β^-) activity, heating can be defined:

$$P_{\beta-} = e\bar{E}_{Ivt}A_{Ivt}^{(\beta^-)}$$

Elementary charge

- Difference from missing nuclides and other light particle contributions
  - Auger electrons, β^+, etc
- Results from the complete spectra can provide information of heating contributions

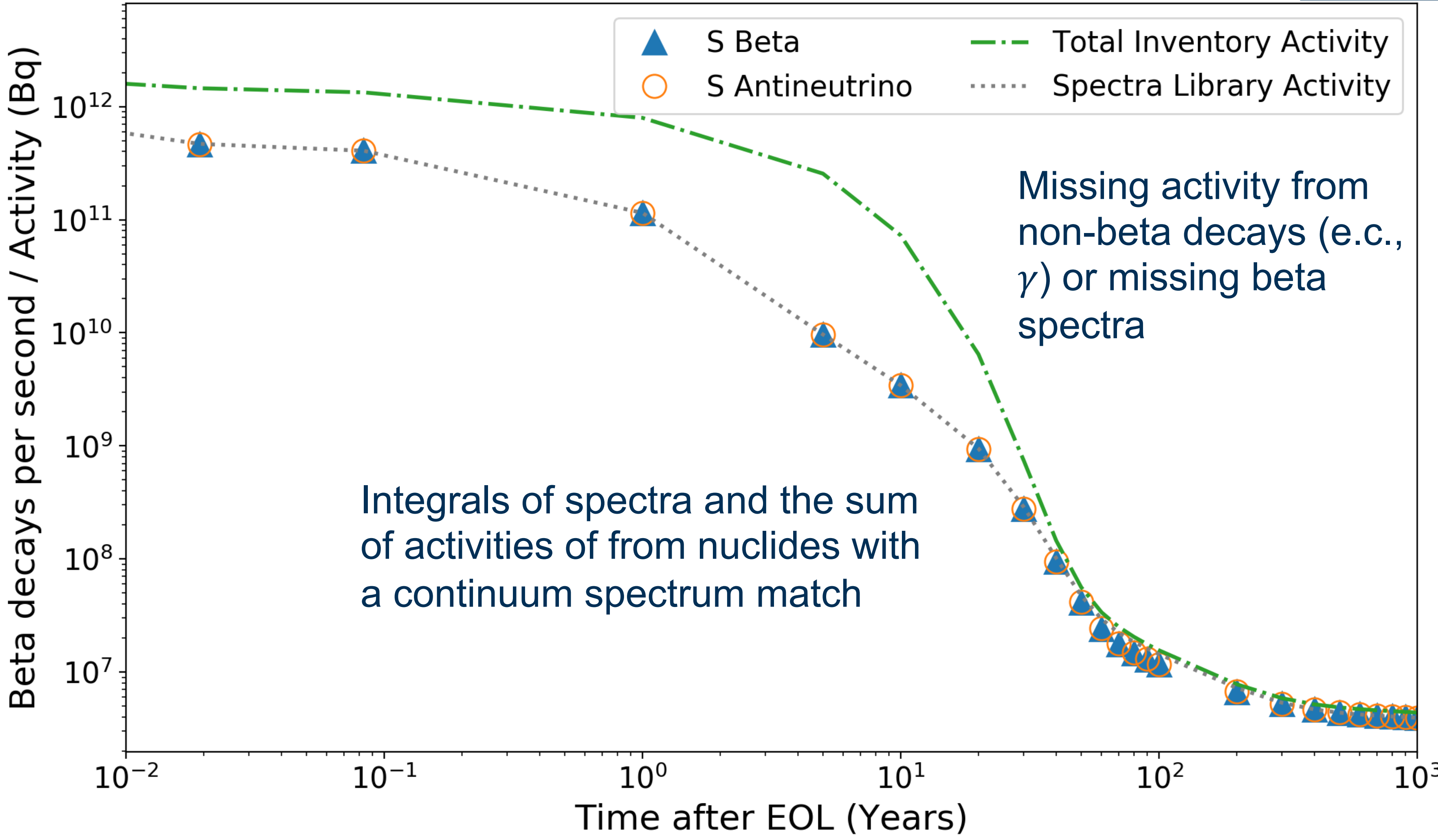
Preliminary Inventory Calculations (3)

- If N_{Ivt} is a measure of beta/neutrinos per unit energy per unit time.
- Then the integral with respect to energy should give an estimate of beta/neutrinos per unit time.

$$S(t) = \int_0^\infty N_{Ivt}(E,t)dE$$

- As the beta and neutrino are emitted from the same decays, these results should be approximately the same

➢ Decays per unit time => A Becquerel => Activity



Conclusions and ongoing work

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- Using existing theory and codes a prototype continuum beta-neutrino library has been developed.
- Methodologies to calculate inventory spectra have been developed and are currently being added to FISPACT-II to be included in a future release.
- Validation efforts have begun, but more work is needed, from more experimental data to quantification of uncertainties.

Possible future work and applications:

- Investigation and development of beta spectra theories and data to expand and improve the prototype library.
- Uncertainty quantification for beta related quantities e.g. decay heating
- Beta dose rates and Bremsstrahlung contributions to photon spectra.

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Thank you

Any Questions?

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