



D. Rochman

# The TENDL nuclear data library: Standing on the shoulders of giants

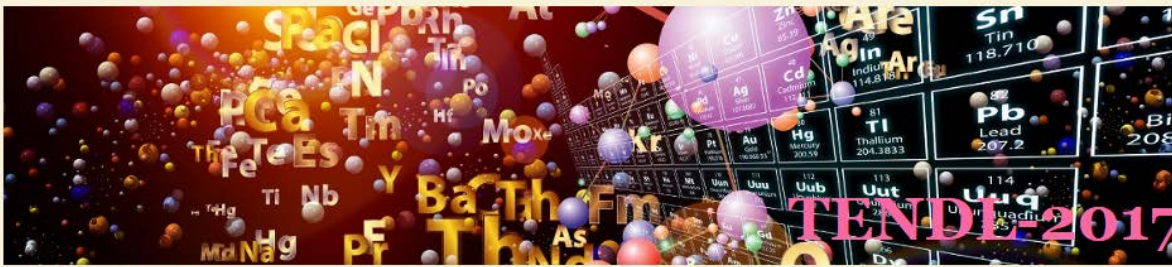
ImPACT International Symposium on “*New Horizons of Partitioning and Transmutation Technologies with Accelerator System*”, 2-3 December 2018, University of Tokyo, Japan

# Summary

- TENDL: a short history and modern approach
- Examples for current research:
  - solving THE equation
  - Include integral observation in a library evaluation ?
  - Uncertainty propagation for Spent Nuclear Fuel

**TALYS-based evaluated nuclear data library**

Home Reference & us Citations



**TENDL-2017**

“ We believe that our great goal can be achieved with systematism and reproducibility. We are so outside the box, that the box is a point”

How to reference

Sub-library files

1. neutron
2. Proton
3. Deuteron
4. Triton
5. He3
6. Alpha
7. Gamma

tar & Ace files

**TENDL-2017: (release date: December 30, 2017)**

Last update: 29 December 2017

TENDL is a nuclear data library which provides the output of the TALYS nuclear model code system for direct use in both basic physics and applications. The 9<sup>th</sup> version is **TENDL-2017**, which is based on both default and adjusted TALYS calculations and data from other sources (previous releases can be found here: [2008](#), [2009](#), [2010](#), [2011](#), [2012](#), [2013](#), [2014](#), and [2015](#)).

Up to 2014, TENDL was produced at NRG Petten. Since 2015, TENDL is mainly developed at PSI and the IAEA (Nuclear Data Section). Still, many people contributes to TENDL with the testing and processing of the files.

- All slides are available here: [https://tendl.web.psi.ch/bib\\_rochman/presentation.html](https://tendl.web.psi.ch/bib_rochman/presentation.html)

# What is the TENDL project ?

- TENDL: TALYS evaluated nuclear data library,
- Goal: improve simulations for TENDL and/or other libraries, or solving

$$0 \leq \chi^2 \leq 1$$

$$\chi^2 = \frac{1}{n} \sum_{i=1}^n \left( \frac{C_i - E_i}{\Delta E_i} \right)^2$$

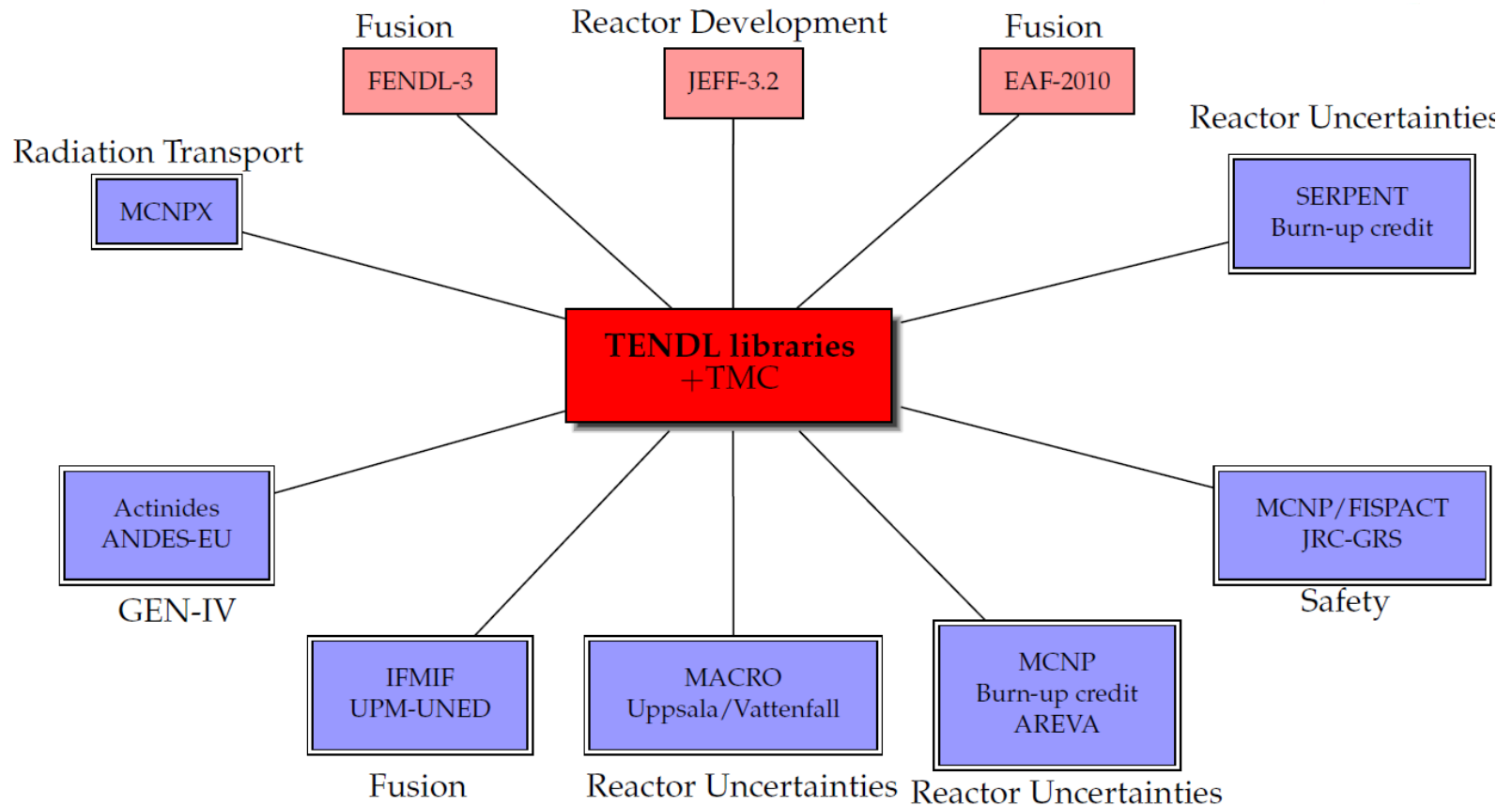
- Available at <https://tendl.web.psi.ch/home.html>
- Comes from T6 (software package)
- T6 leads to TENDL, TMC, BMC, HFR...
- See for instance [NDS 113 \(2012\) 2841](#), [ANE 51 \(2013\) 60](#), [NDS 139 \(2017\) 1](#)

# What is the TENDL project ?

- TENDL is in fact a by-product of a series of codes,
- This is one fundamental difference with other libraries (no manual work),
- It allows to perform „TMC“ for Total Monte Carlo (uncertainty propagation)
- Methods: reproducibility & completeness, development of a portable system, and making use of the knowledge included in other libraries (JEFF, ENDF/B, JENDL),
- Background: theoretical calculations (TALYS) with experimental inputs, with original resonance evaluations,
- Impact:
  - TENDL-2008 to 2017 (2800 isotopes),
  - Neutrons, protons, deuterons, tritons, He3, alpha and gamma induced,
  - all isotopes, all cross sections with covariances, 0-200 MeV,
  - more than 300 isotopes in the NEA JEFF-3.3 library,
  - more than 50 isotopes in the US ENDF/B-VIII.0 library,
  - more than 450 publications using TENDL

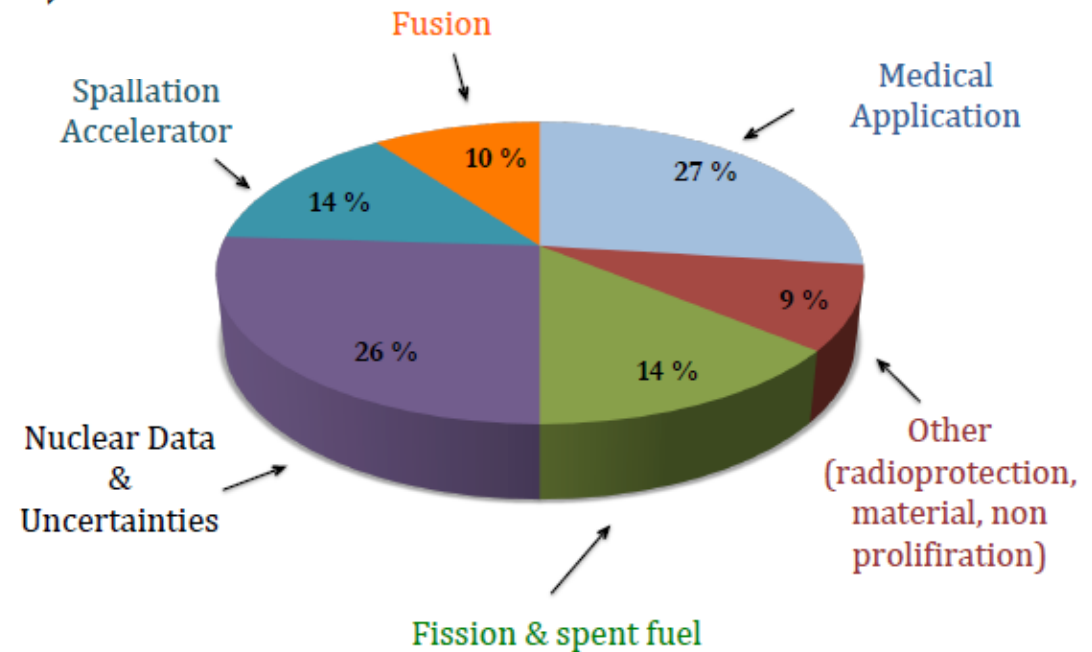
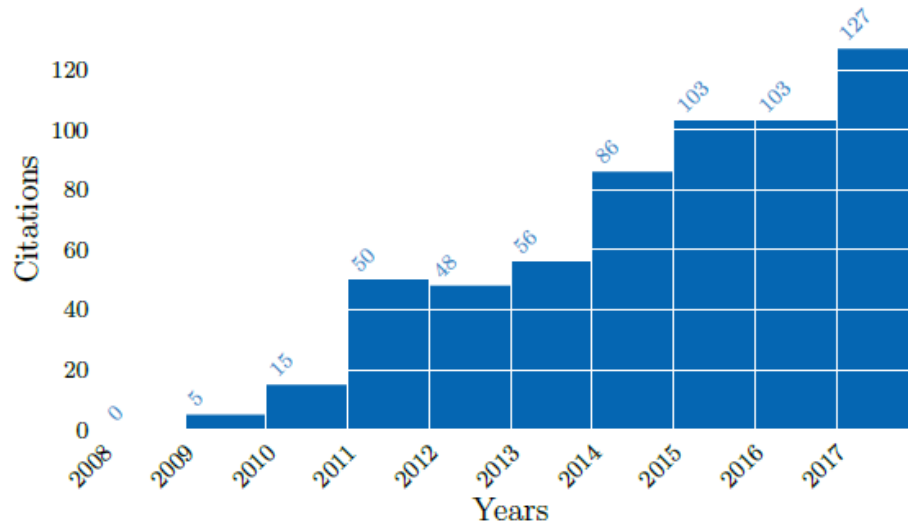
# What is the TENDL project ?

- Fully implemented in FISPACT-II, part of GEANT, CASMO...,
- Used in fission, fusion applications, medical isotope productions



# What is the TENDL project ?

TENDL citations





# TENDL: from MF-1 to MF-40, 200 MeV

- ➡ **MF-1:** Description + fission parameters
- ➡ **MF-2:** Resonance parameters (Reich-Moore or Multi-level Breit Wigner)
- ➡ **MF-3:** Cross sections (n,tot), (n,el), (n,non), (n,inl<sub>i</sub>), ..., (n,γ), (n,p<sub>i</sub>), (n,α<sub>i</sub>)
- ➡ **MF-4:** Elastic angular distribution (Legendre Polynomials)
- ➡ **MF-5:** Fission neutron spectrum
- ➡ **MF-6:** Double differential distributions and spectra for (n,2n), ..., (n,α<sub>i</sub>)
- ➡ **MF- 8-10:** Isomeric cross sections
- ➡ **MF- 12-15:** Gamma yields, angular distributions and spectra
- ➡ **MF- 31-32-33-34-35, 40:** nubar, Resonance parameter, cross section, angular distribution and fission neutron spectrum, radionuclide production.



Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

**SciVerse ScienceDirect**

Nuclear Data Sheets 113 (2012) 2841–2934

**Nuclear Data  
Sheets**

[www.elsevier.com/locate/nds](http://www.elsevier.com/locate/nds)

Modern Nuclear Data Evaluation with the TALYS Code System

A.J. Koning\* and D. Rochman

**TENDL: Complete Nuclear Data Library for innovative Nuclear Science and Technology**

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<sup>4</sup>NRG, Westerdinweg 3, 1755 LE Petten, Netherlands

<sup>5</sup>Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

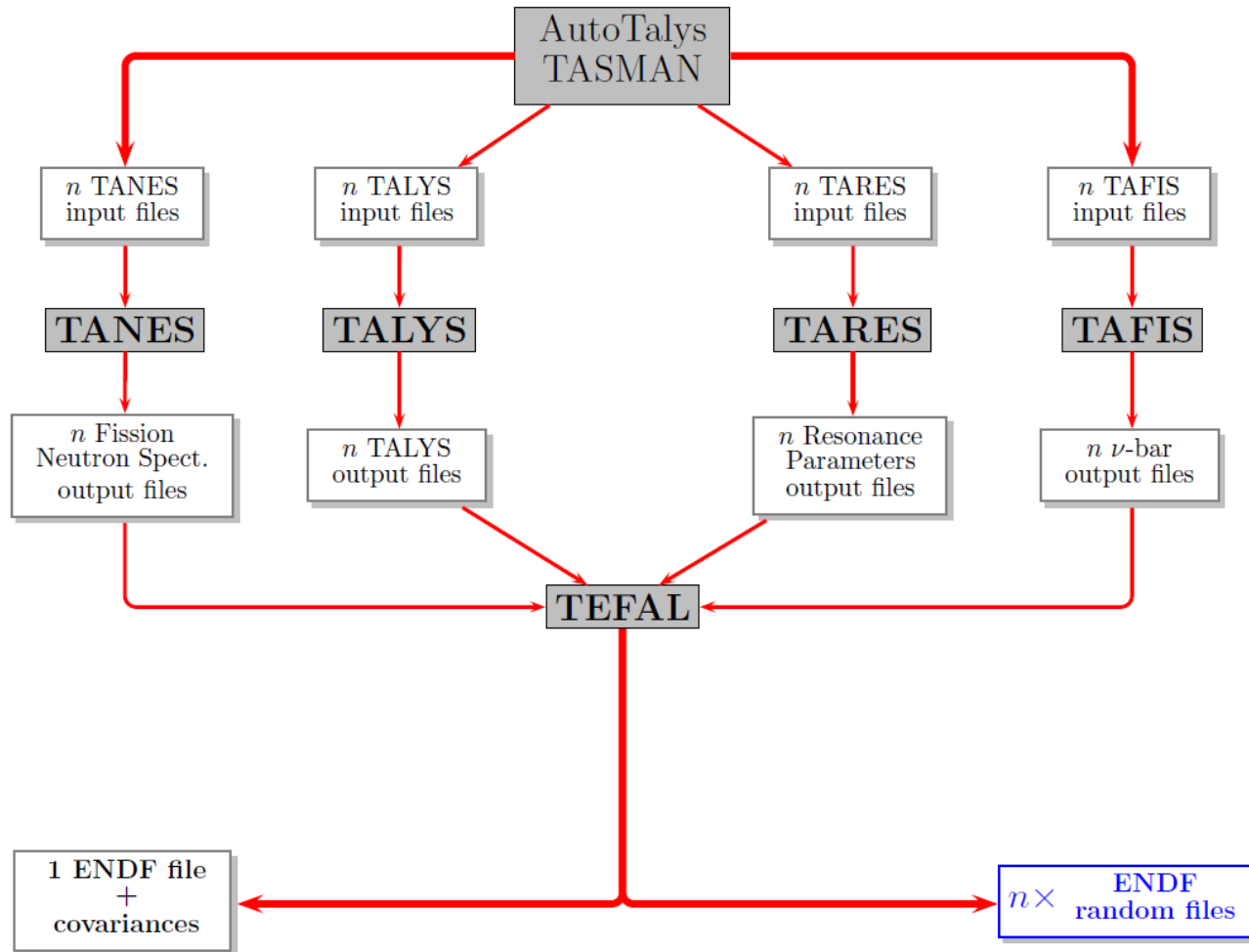
<sup>6</sup>Nuclear Energy Agency, OECD, 92100 Boulogne-Billancourt, France

<sup>7</sup>United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon OX14 3DB, United Kingdom

(Dated: November 7, 2018; Received xx July 2018; revised received xx September 2018; accepted xx October 2018)

# T6: source of TENDL

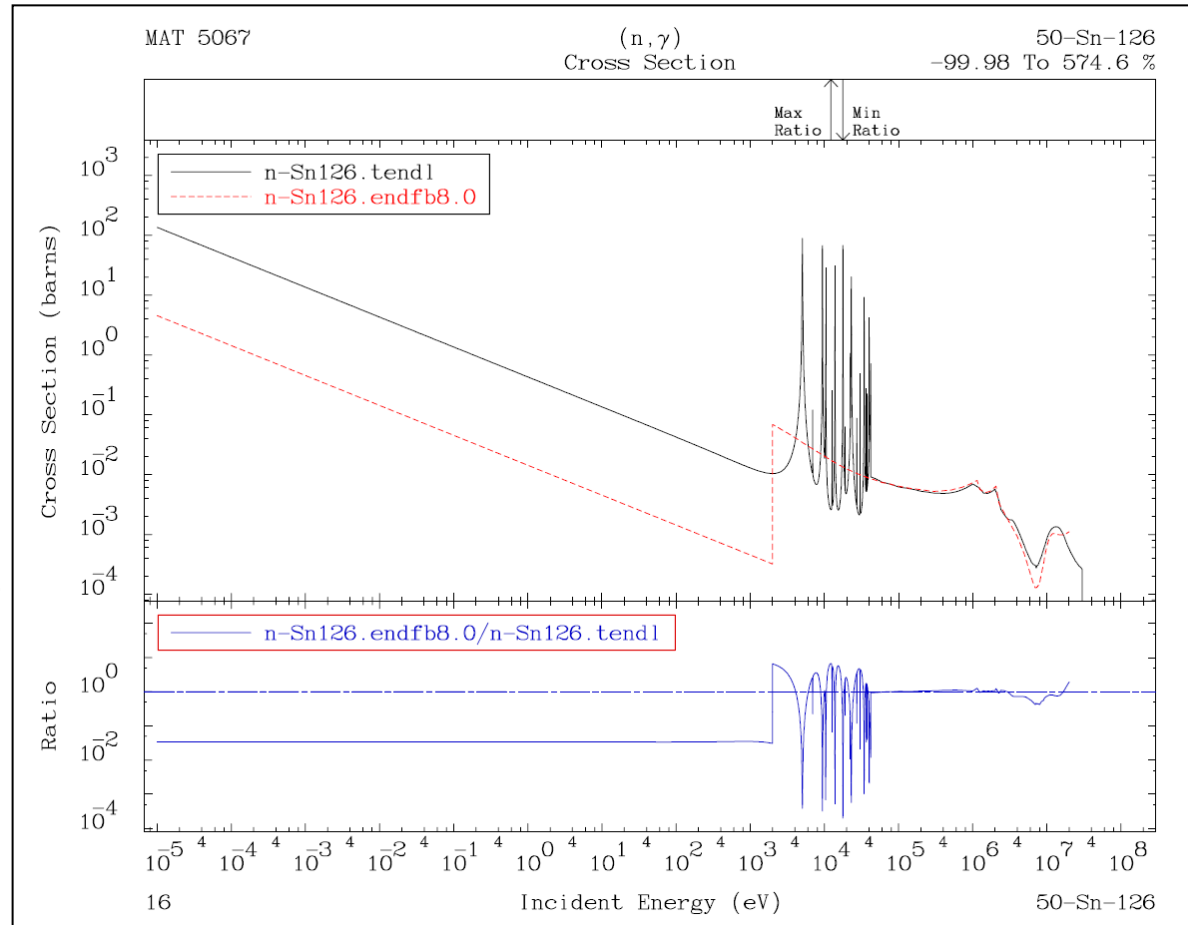
- T6: at the origin of TENDL. Combination of 6 codes plus utilities,
- Available on demand, easy to install,
- Make your own TENDL !





The TENDL way is strongly linked to other methods:

- (fast) TMC: Total Monte Carlo for uncertainty propagation,
- BMC: Bayesian Monte Carlo for model parameter updates and sampling,
- HFR:  
Resonance parameters for all isotopes consistent with the fast neutron range.



# Example 1: Solving THE equation

- The goal of all libraries is to solve this equation:

$$0 \leq \chi^2 \leq 1$$

- $C_i$ : calculated quantities (differential and integral)
- $E_i$ : measured quantities
- $n \rightarrow \infty$

$$\chi^2 = \frac{1}{n} \sum_{i=1}^n \left( \frac{C_i - E_i}{\Delta E_i} \right)^2$$

- Solutions: random search, or GLLS, MOCABA...
- Another solution: iterative search with model parameter weighting + model defects
  1. Select the experimental data
  2. Select a library ( $i=0$ ) and calculate  $\chi^2$
  3. Replace the most sensitive element by  $n$  random evaluations
  4. Calculate  $n \chi^2$
  5. Library  $i = \text{library } (i-1) + \text{best random (smallest } \chi^2)$
  6. Repeat for all elements
- NSE 169 (2011) 68

## Example 2: Using integral data

- Open discussion in the nuclear data community:

*Shall we explicitly use integral data (PIE, reaction rates...) at the evaluation level (when creating a library) ?*

- Motivation 1: integral data are already used during adjustment
- Motivation 2: This should be done at the evaluation level
- Motivation 3: It leads to uncertainty reduction and cross-isotope correlations
- Motivation 4: reduce the bias
- Motivation 5: nothing new: already done with GLLS by SG... at the OECD
- One method: Bayesian Monte Carlo (with or without model defect)

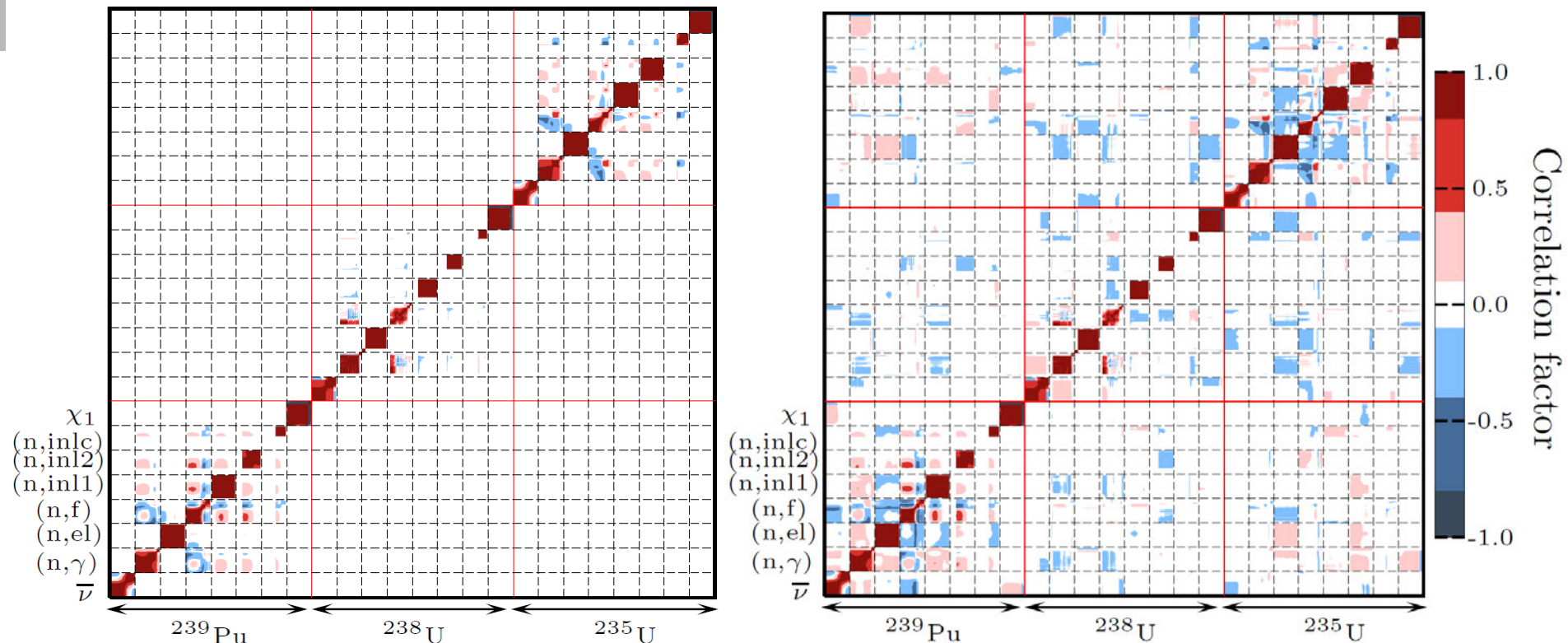
For a random file  $i$  and a set of  $p$  benchmarks:

$$\chi_i = \sum_j^p \left( \frac{k_{\text{eff},i}^{(j)} - k_{\text{exp}}^{(j)}}{\Delta k^{(j)}} \right)^2 \quad (1)$$

$$w_i = \exp\left(-\frac{\chi_i}{2}\right) \quad (2)$$

## Example 2: Using integral data

- Fast range: 14 reactions together ( $k_{\text{eff}}$  and reaction rates) (EPJ/N 4 (2018) 7)



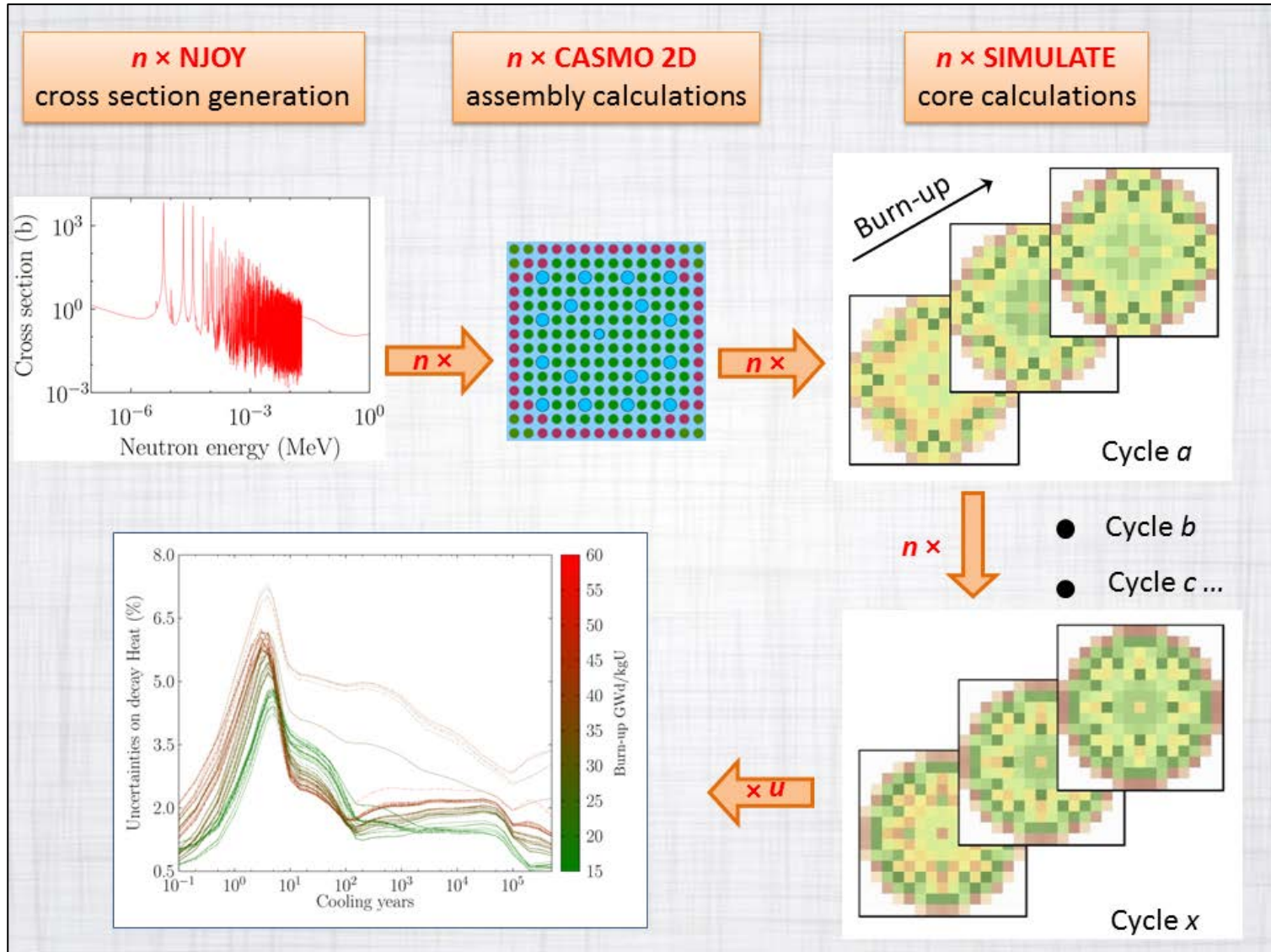
Prior

Posterior

More correlations  $\longrightarrow$  uncertainty reduction

# Example 3: Uncertainty propagation

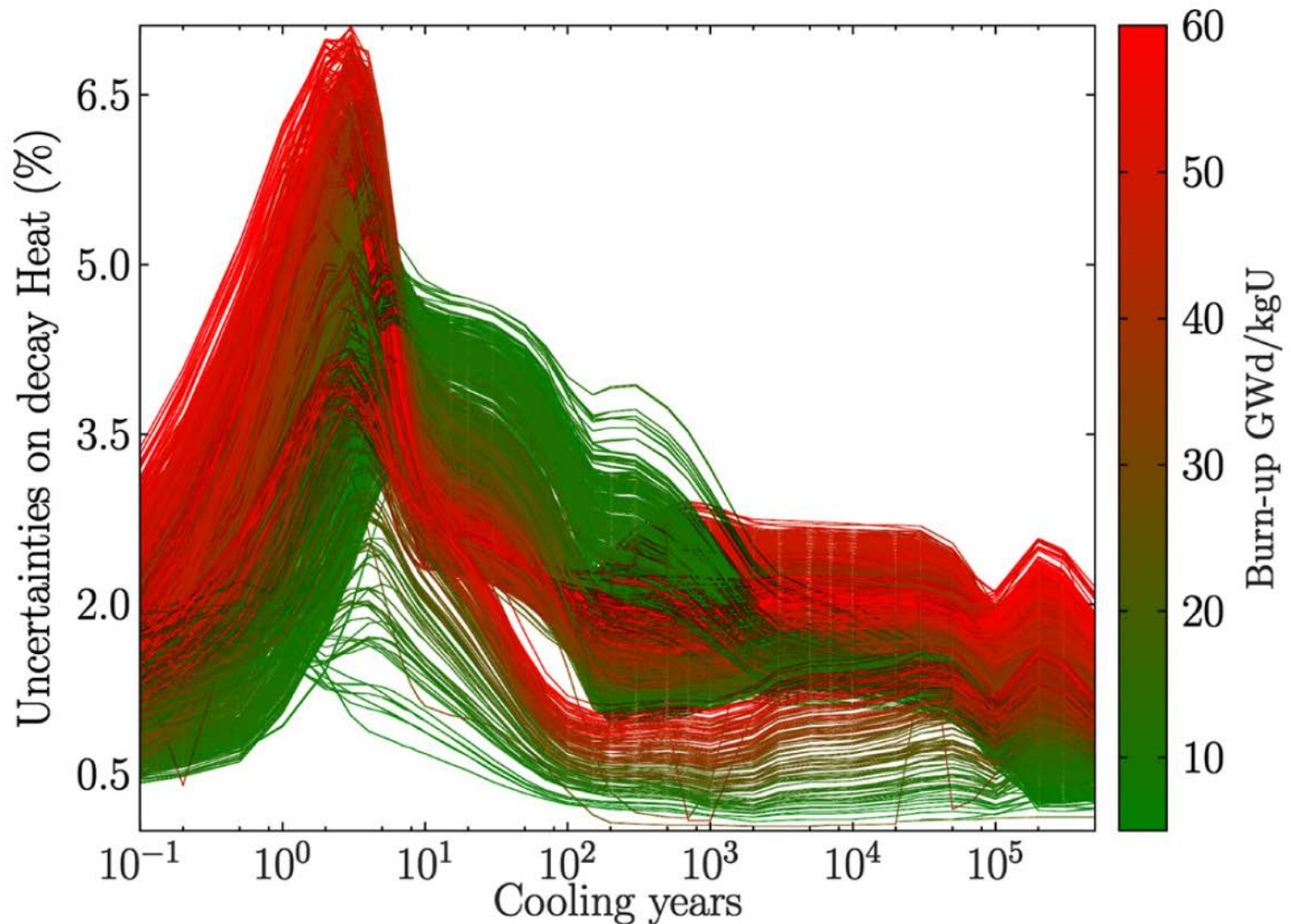
- Nuclear data uncertainties for Spent Nuclear Fuel (EPJ/N 4 (2018) 6)





## Example 3: Uncertainty propagation

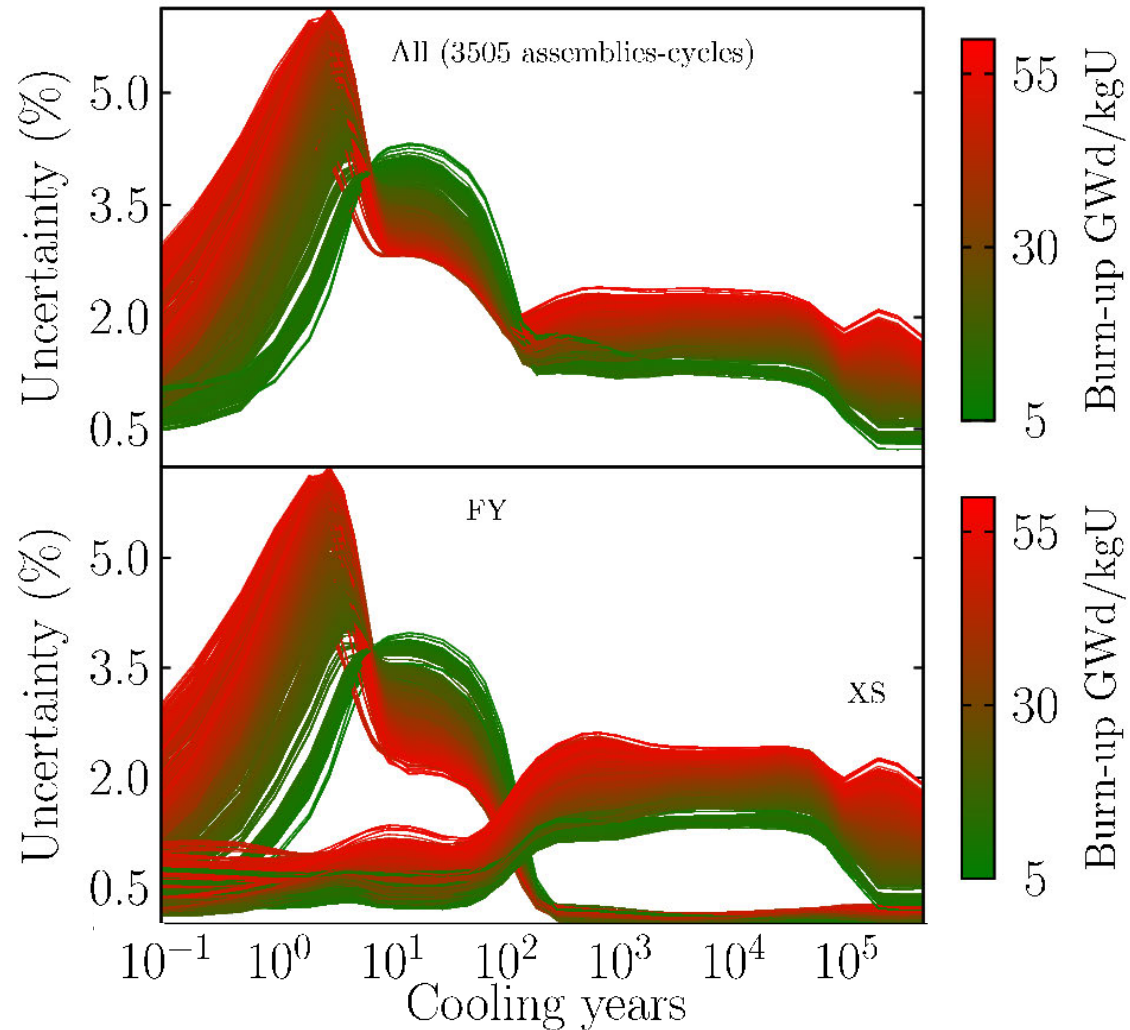
- Nuclear data uncertainties for Spent Nuclear Fuel (one curve = one assembly)
- PWR and BWR assemblies





## Example 3: Uncertainty propagation

- Nuclear data uncertainties for Spent Nuclear Fuel (one curve = one assembly)
- BWR assemblies only



# Conclusion

- Nuclear waste is a major concern in Europe
- The current knowledge of nuclear data have an significant impact for waste estimation and disposal,
- New methods for nuclear data evaluation are still being developed, given the existing computer power,
- Connecting all the dots is an essential part of building a reliable simulation system



photo courtesy of Gerry Hofstetter



