Nuclear Data Activities on Fission Yields at LBNL

Eric F. Matthews
UC Berkeley

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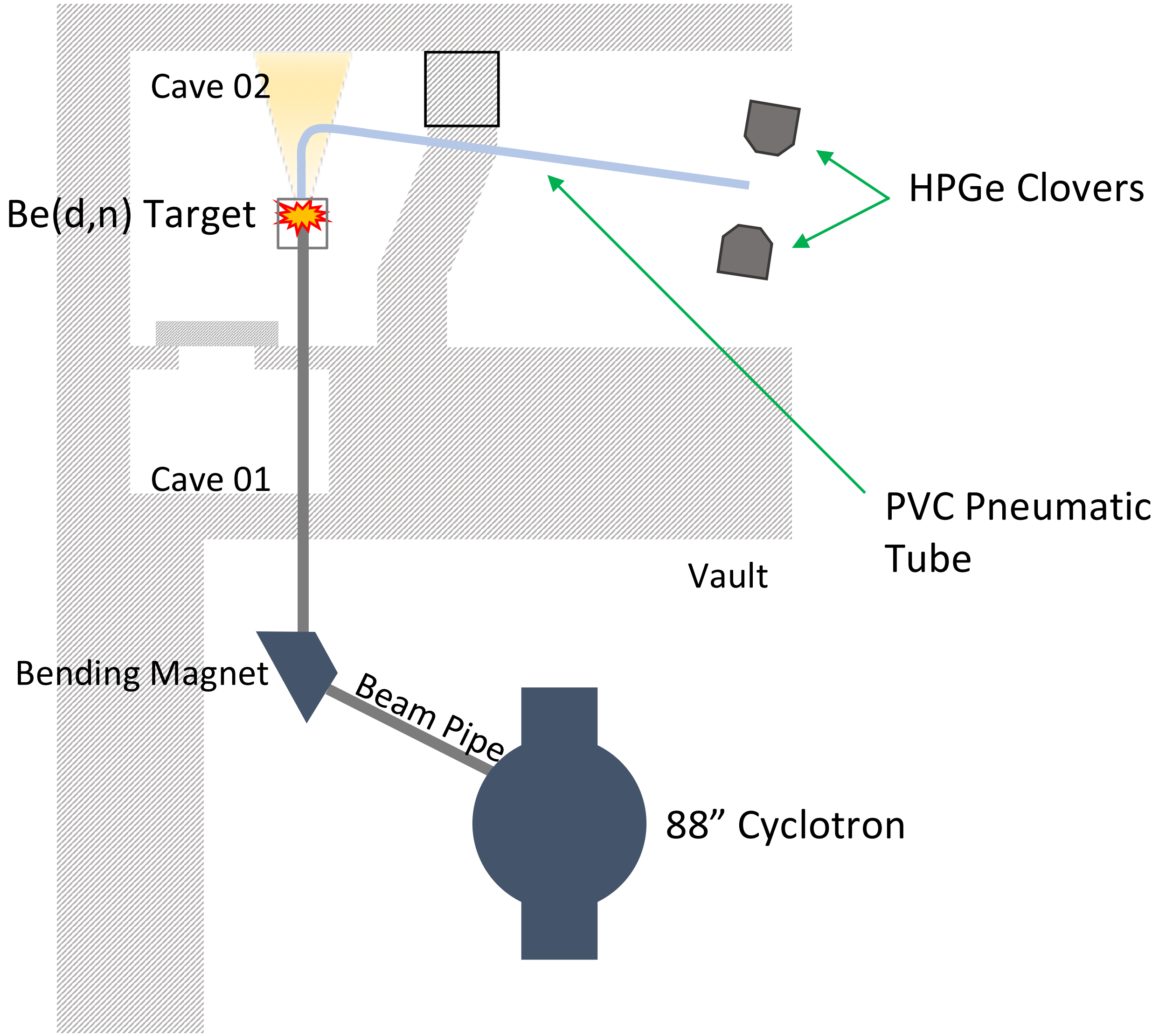
Fission Yield Measurements at the Fast Loading User Facility for Fission Yields (FLUFFY)

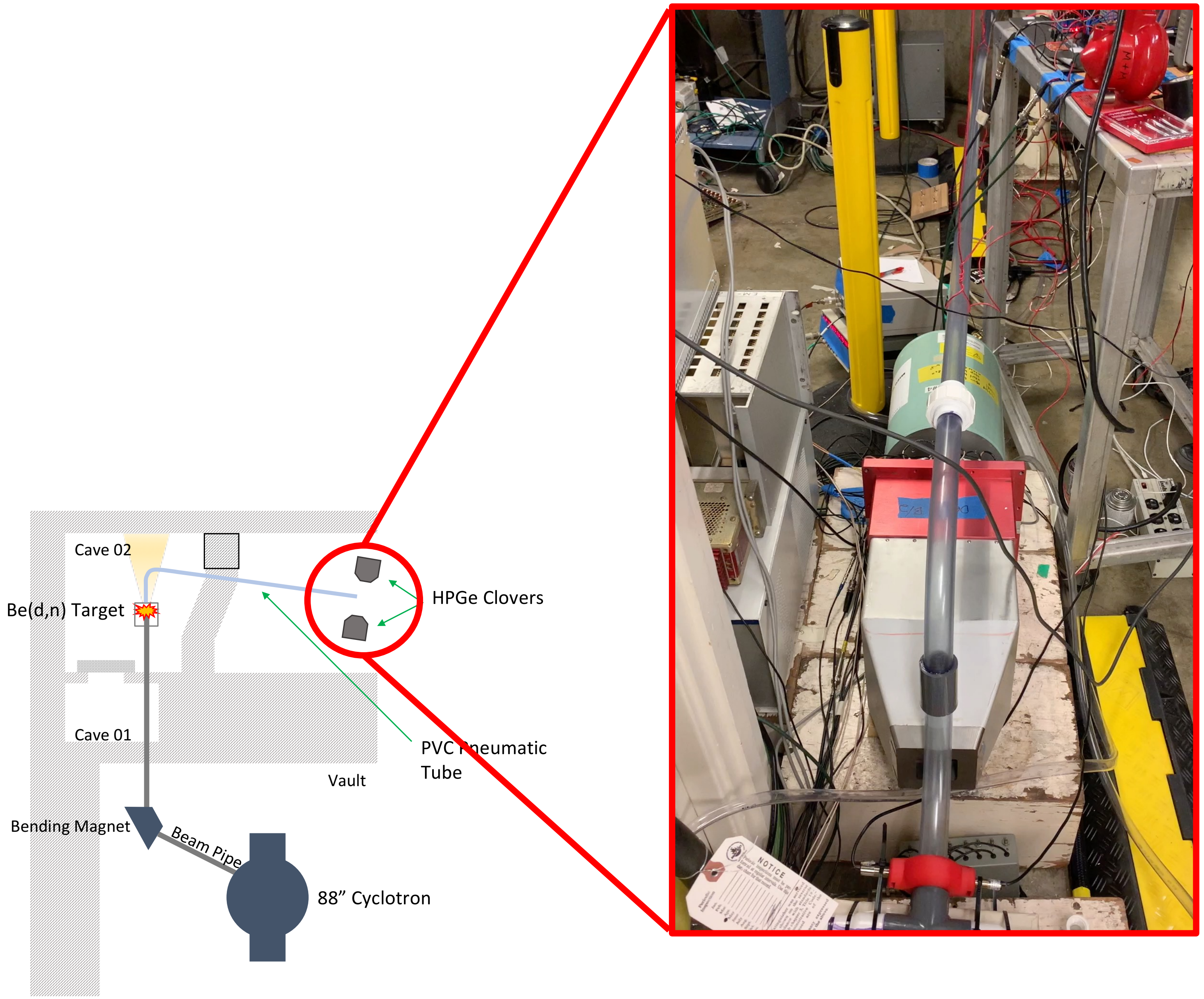
FLUFFY

- The Fast Loading User Facility for Fission Yields (FLUFFY) was developed at LBNL to rapidly shuttle actinide samples between a neutron source and counting array.
- Transport times of <1 second allow observation of short-lived fission products.



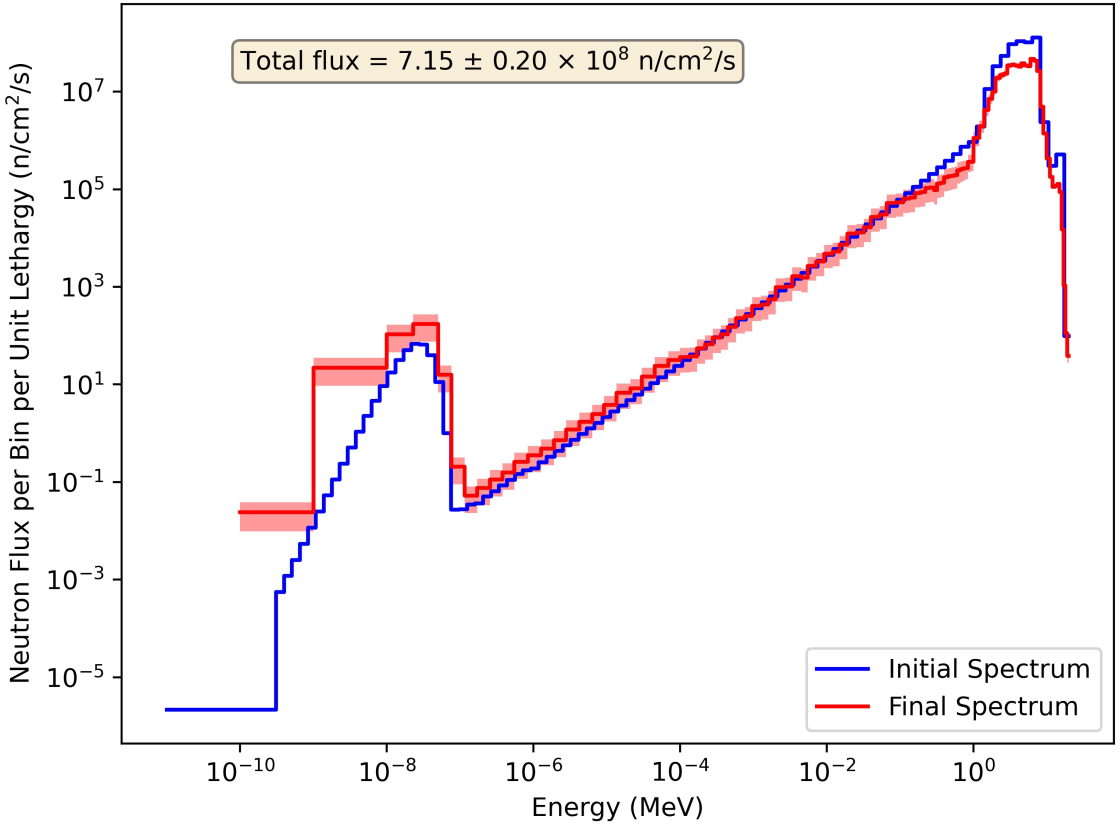
FLUFFY

- Flux: **7.2 x 10^8 n/cm^2/s**
- This high flux along with the rapid transport time allows for the observation of 80+% of the yield in peak mass chains.



July 2020 Experiment

- On July 21-26, 2020, ^{238}U and ^{235}U samples were irradiated at the Fast Loading User Facility for Fission Yields (FLUFFY) at LBNL's 88-inch cyclotron.
  - 24 hours of 1 s-25 s ^{238}U data (455.3 mg)
  - 24 hours of 5 s-125 s ^{238}U data (455.3 mg)
  - ~16 hours of 1 s-25 s ^{235}U data (~20 mg)
  - Neutron energy spectrum data for 14 MeV deuteron breakup on graphite
    - 8 hour foil pack irradiation
    - Single nTOF irradiation

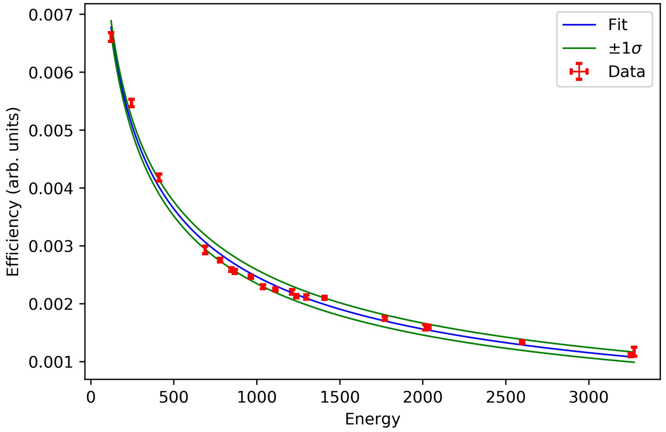


Measured energy spectrum for 14 MeV deuteron breakup on graphite.

The Experimental Data

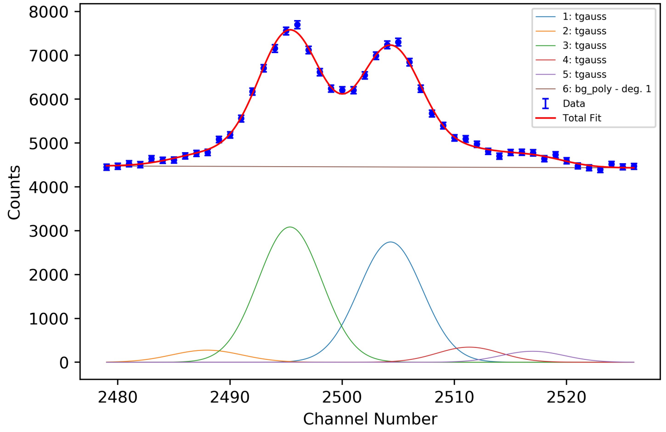
- The experimental data produced by FLUFFY is γ emissions as a function of time since irradiation start, time since capsule arrival at counting station, and as a function of the emitting product isotope:

$$\boldsymbol{N_{\gamma}(Z, A, I, t_0, t_1, n_{cycles})}$$



γ Efficiency

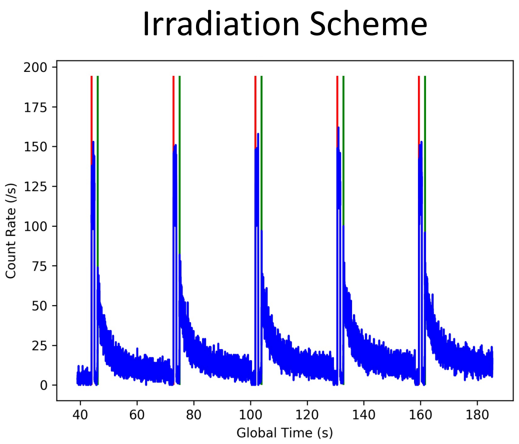
+



γ Counts

The FIER Model

- The Fission Induced Electromagnetic Response (FIER) code offers a model that produces analogous FPY γ emission data.



FIER

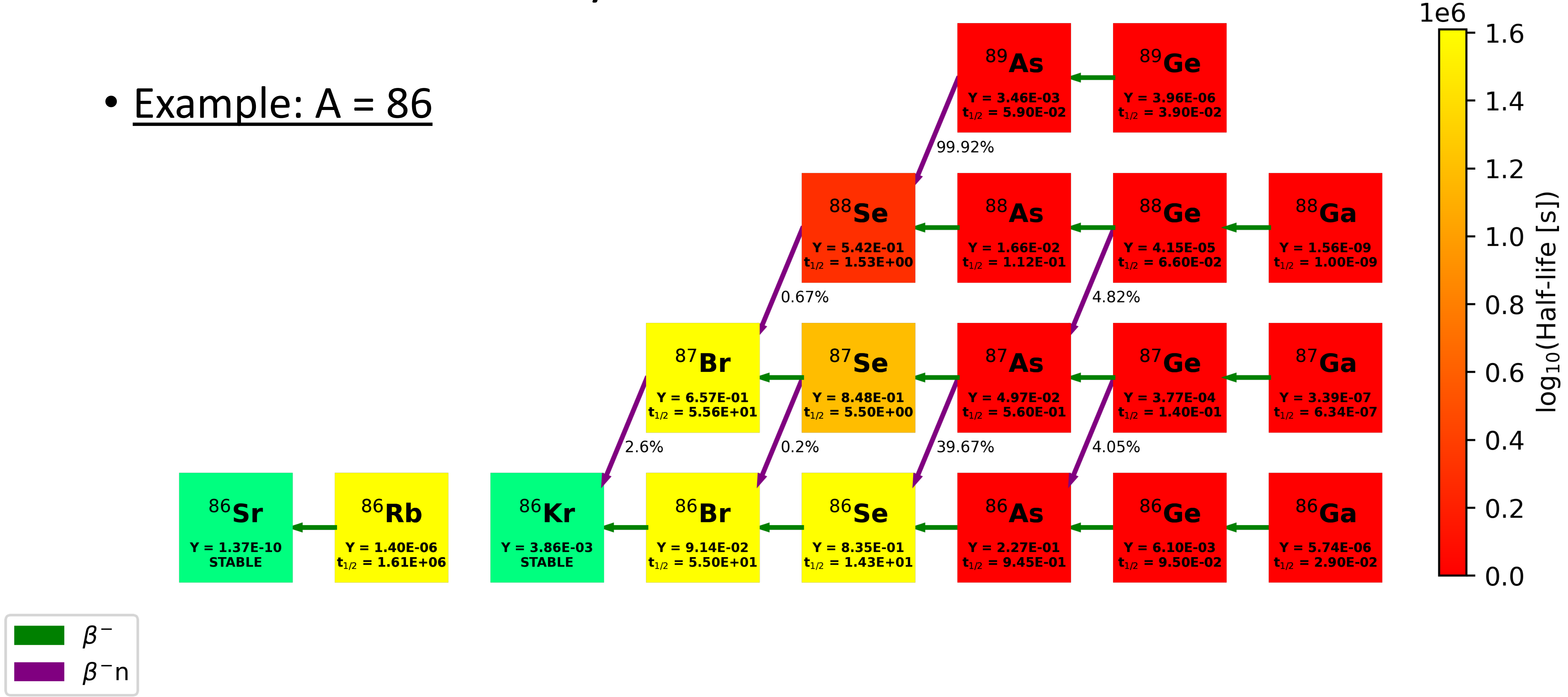
$$\boldsymbol{N_{\gamma}(Z, A, I, t_0, t_1, n_{cycles})}$$

- Chi-squared minimization between FIER and experimental data is used to determine fission yields and correct decay data:

$$\chi^2 = \frac{\left[N_\gamma(Z, A, I, t_0, t_1, n_{cycles}) - FIER(Z, A, I, t_0, t_1, n_{cycles})\right]^2}{\sigma_{N_\gamma}^2}$$

Mass Chain Analysis

- Example: A = 86



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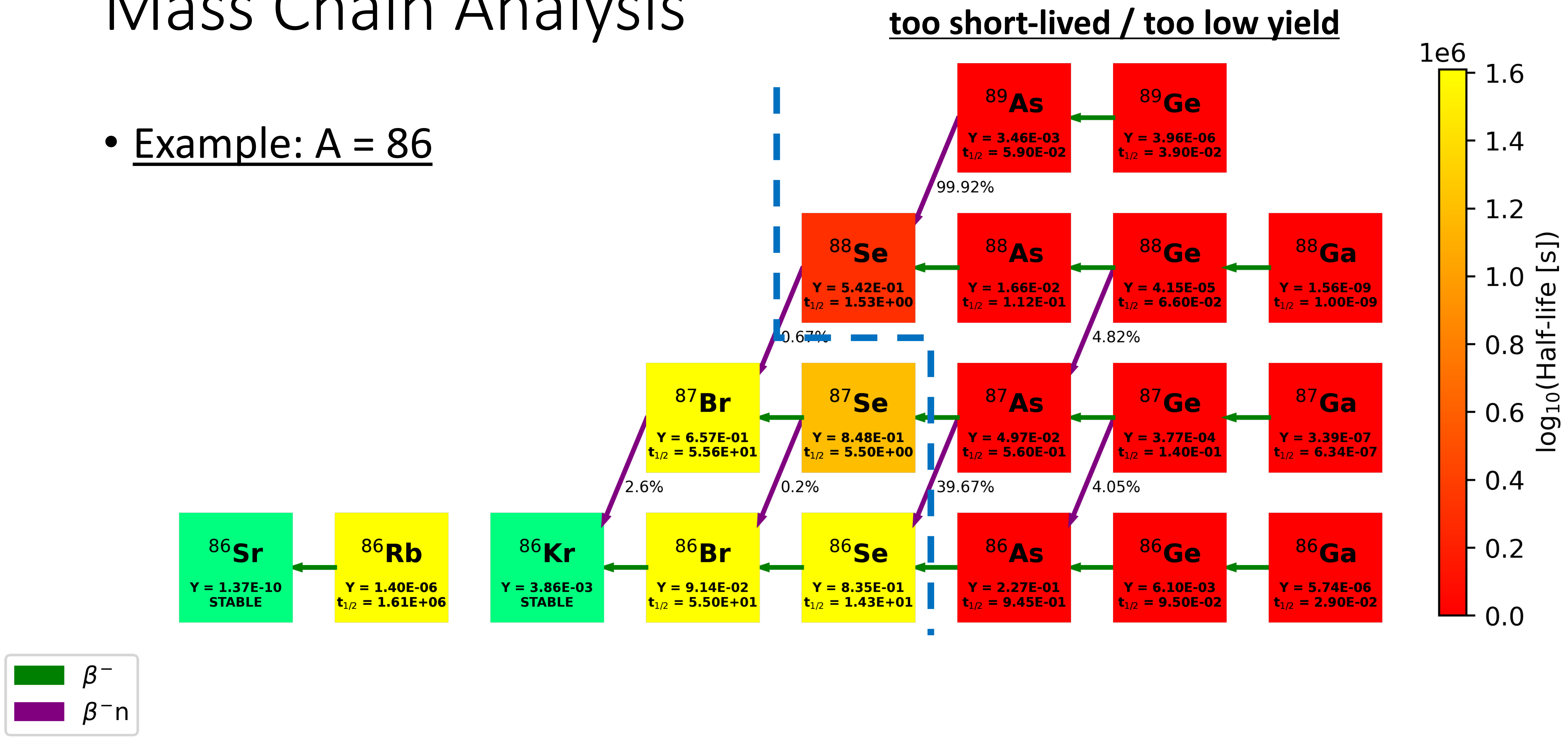

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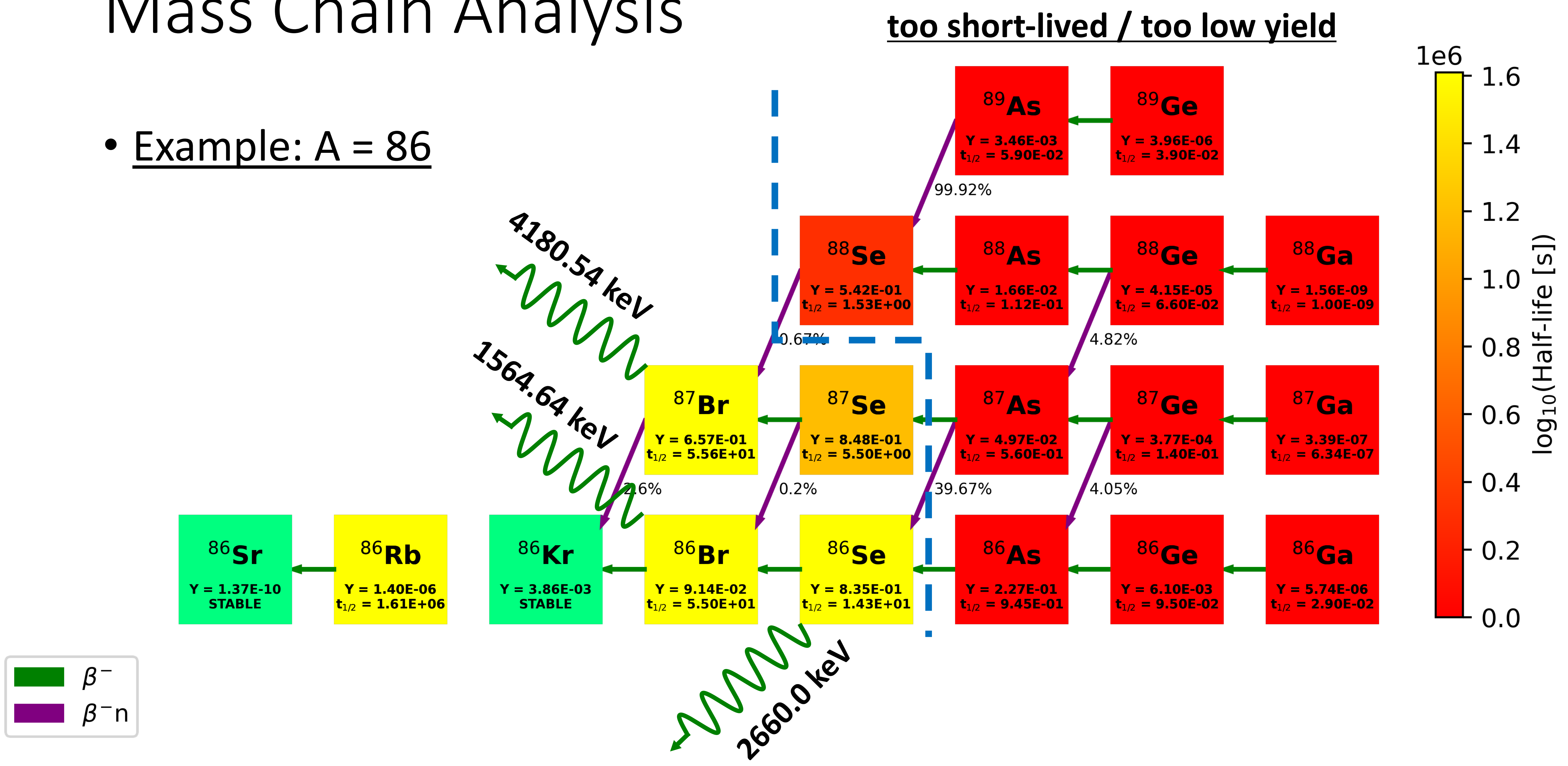
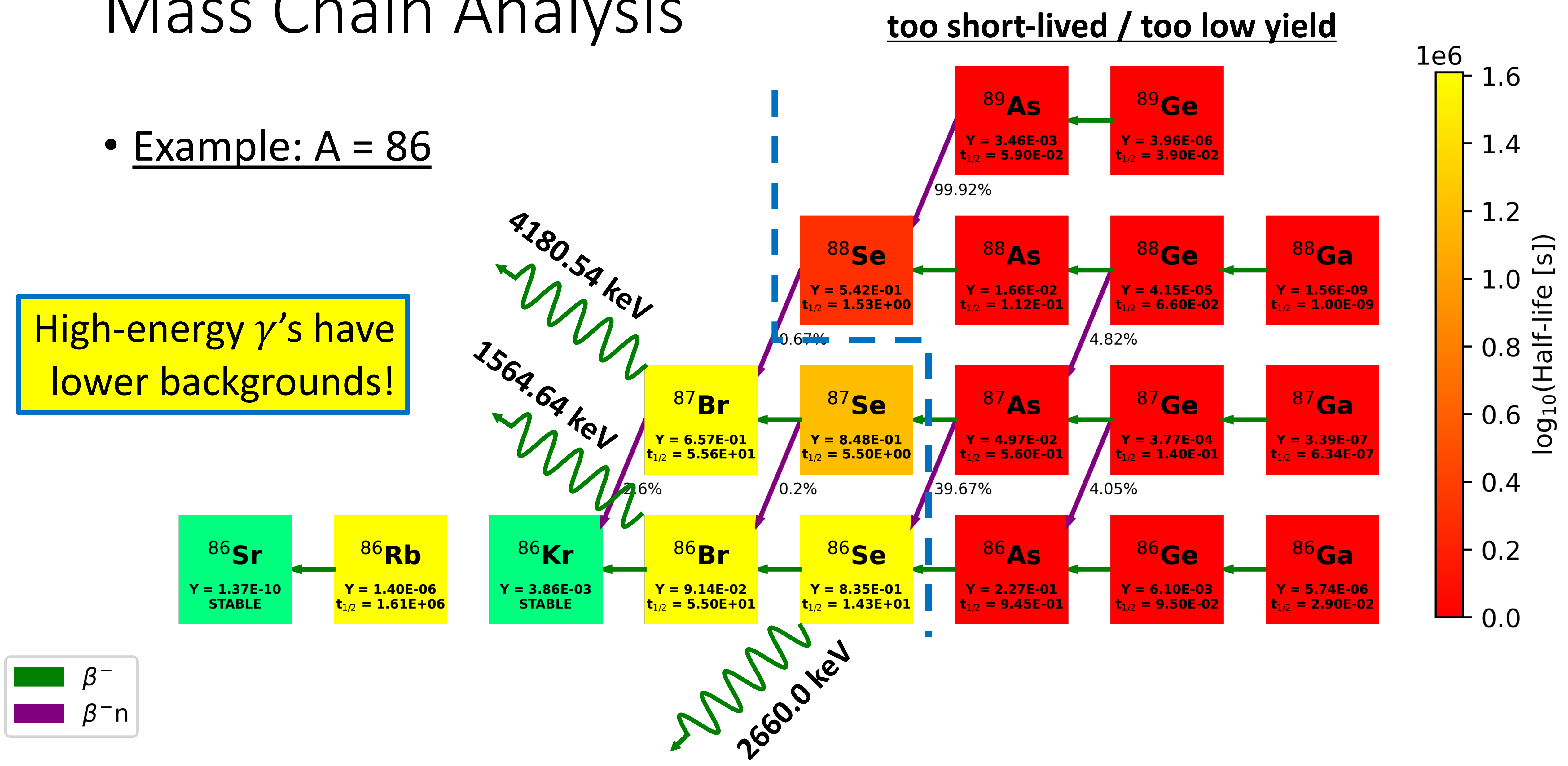


Mass Chain Analysis

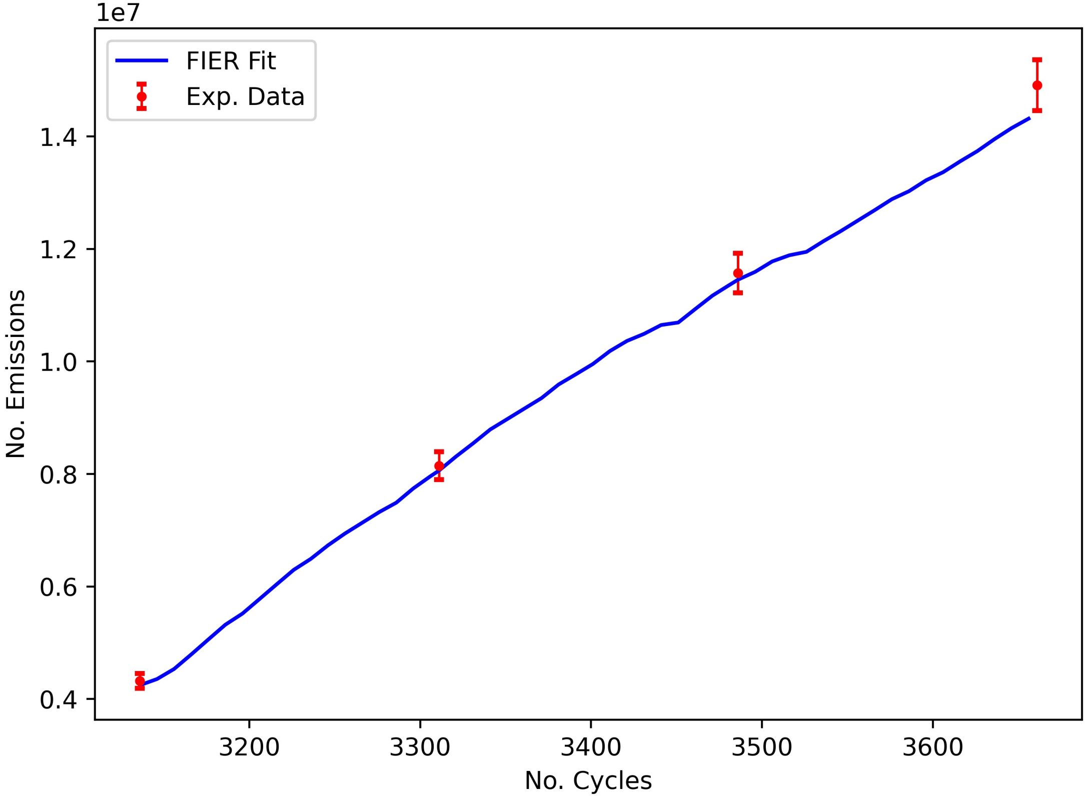
- Example: A = 86

High-energy γ's have lower backgrounds!

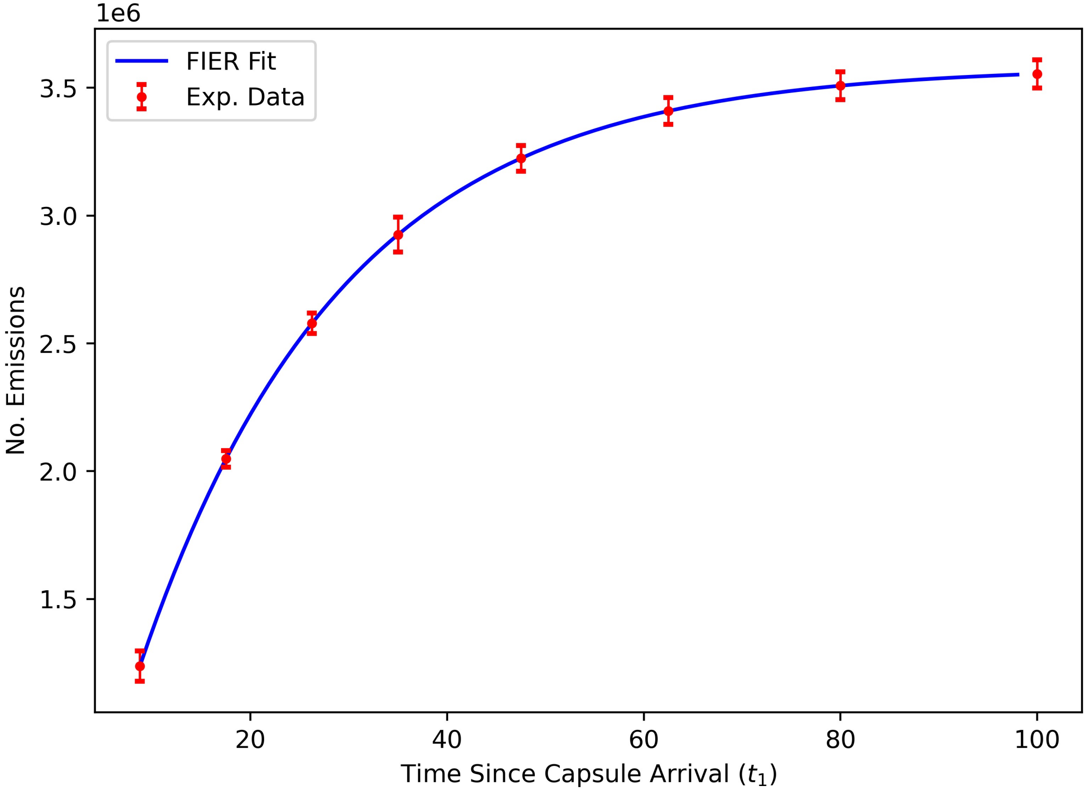


Results

- An example of results from the A = 86 mass chain



Emissions of 1564.0 keV γ's from ^{86}Br as a function of time since capsule arrival fit with FIER. ^{238}U(n,f) data.



Emissions of 2660.0 keV γ's from ^{86}Se as a function of time since capsule arrival fit with FIER. ^{238}U(n,f) data.

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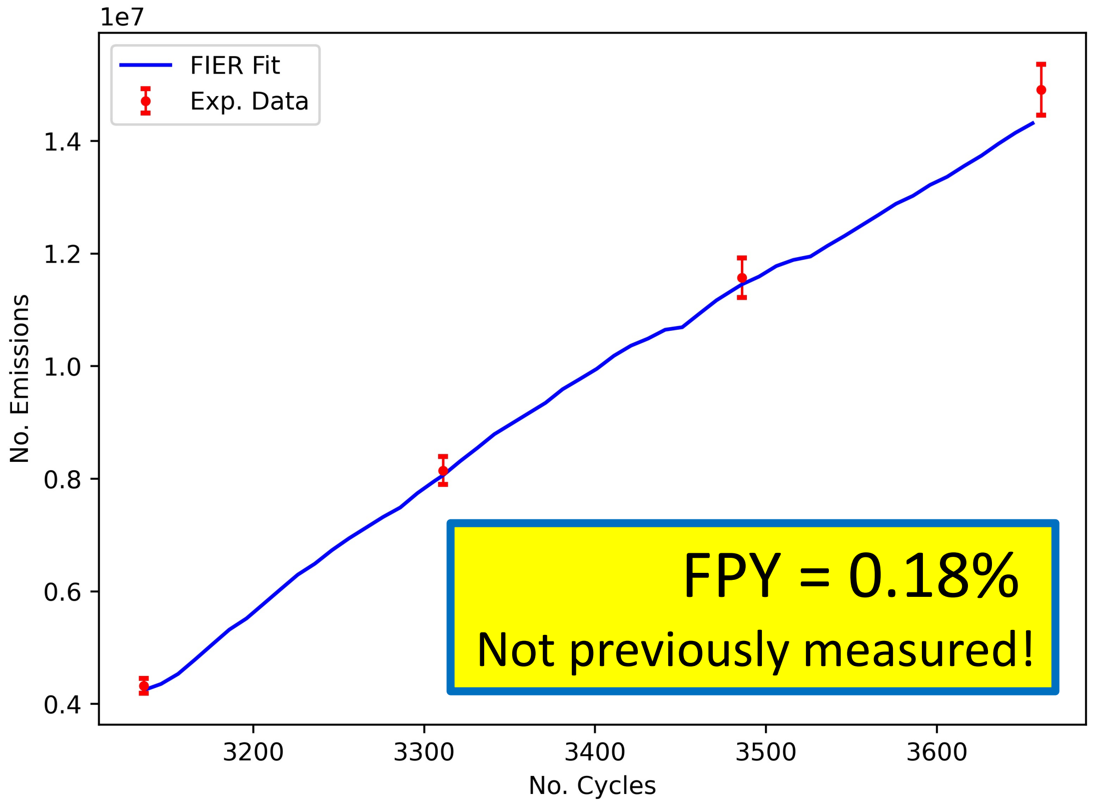

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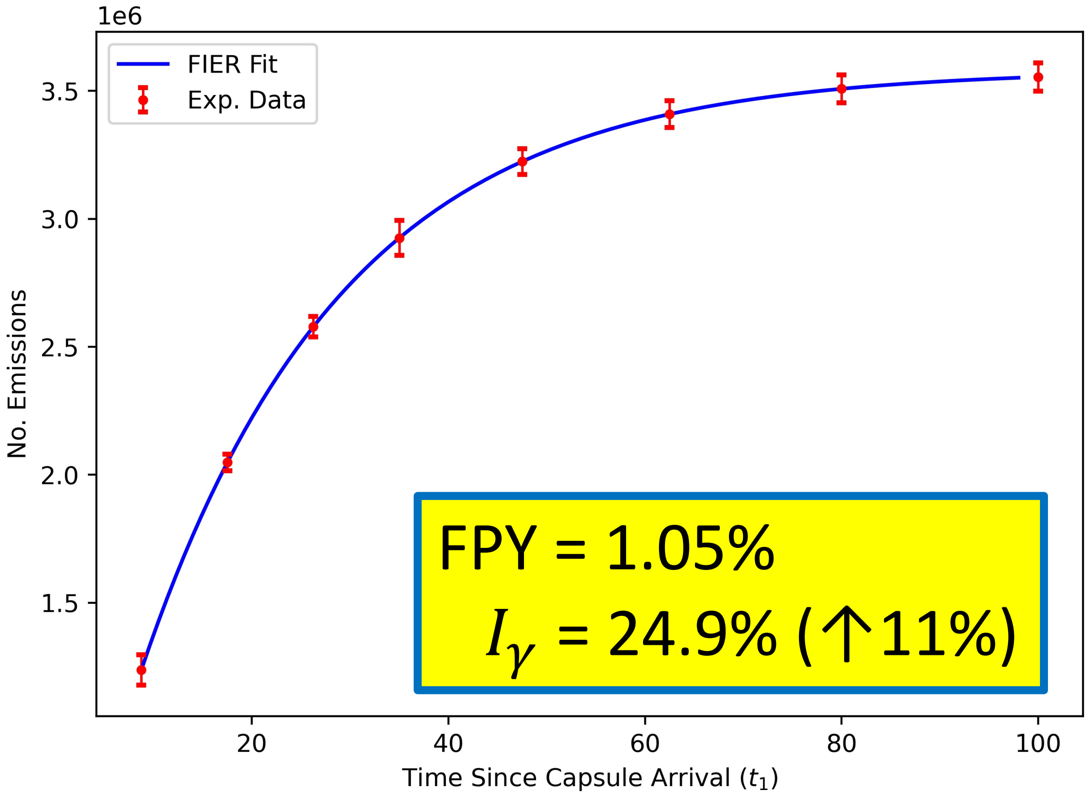
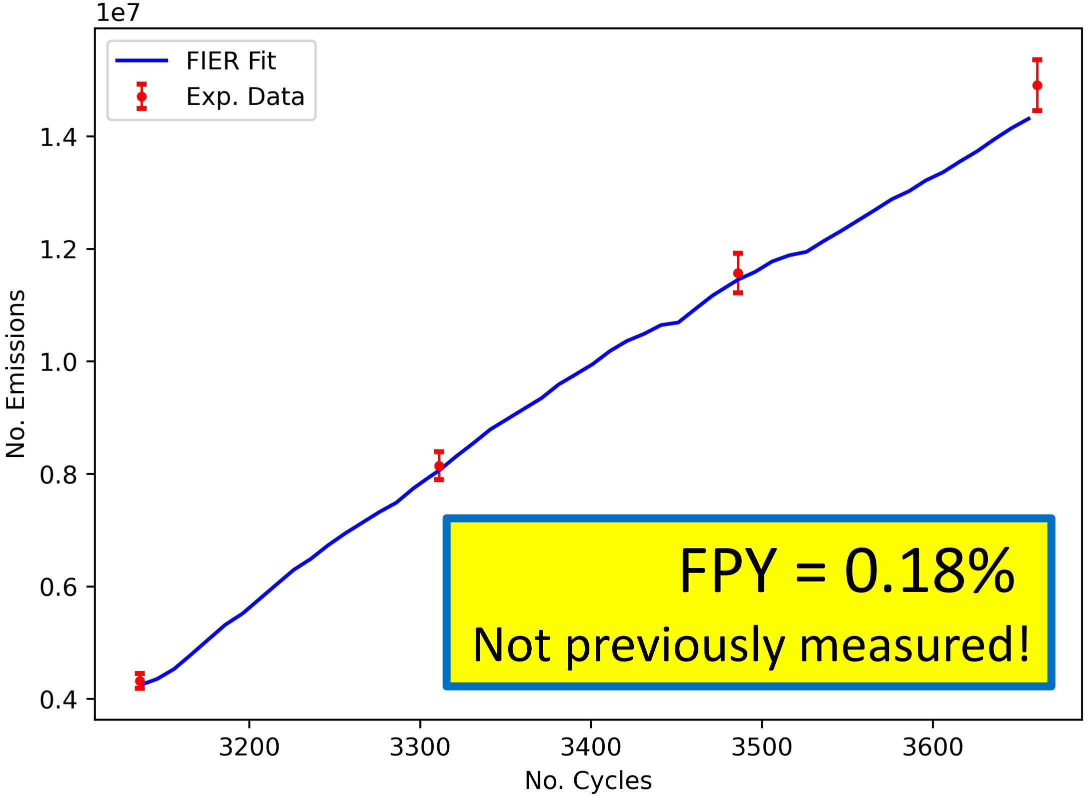


Emissions of 2660.0 keV γ's from ^{86}Se as a function of time since capsule arrival fit with FIER. ^{238}U(n,f) data.

Results

γ emission rates from the daughter FP simultaneously constrain the FPY and I_γ of the parent.

- An example of results from the A = 86 mass chain



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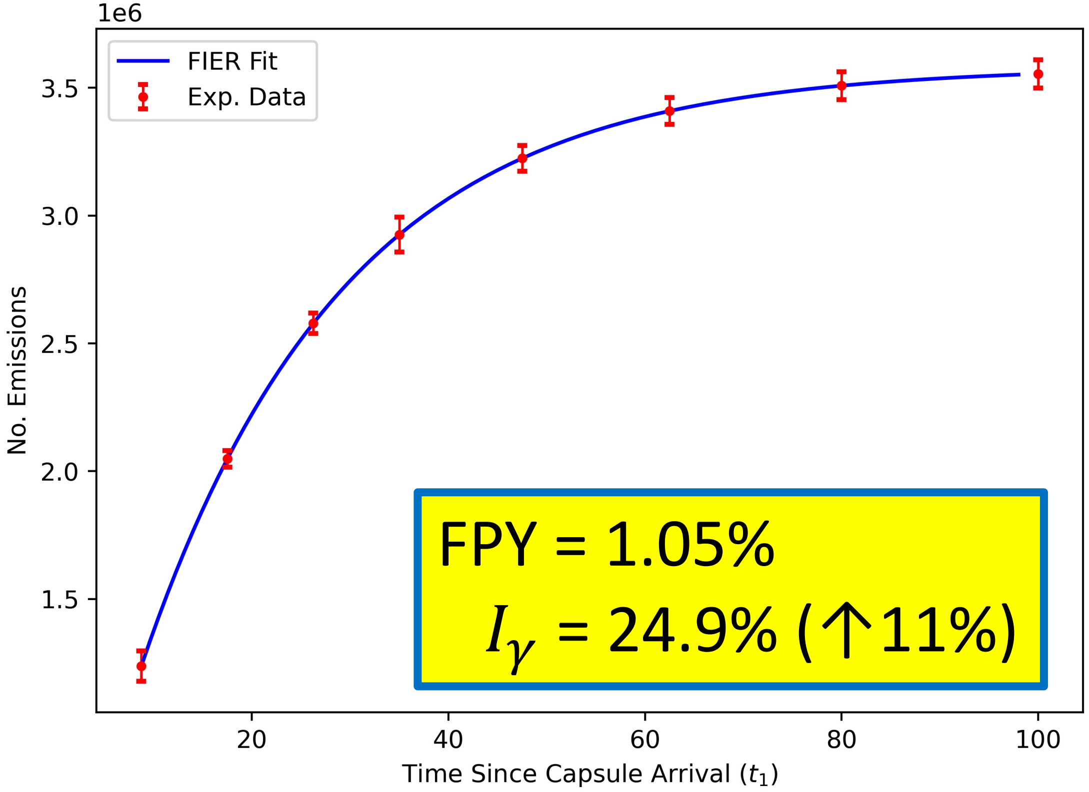

Emissions of 2660.0 keV γ's from ^{86}Se as a function of time since capsule arrival fit with FIER. ^{238}U(n,f) data.

Contributors

BERKELEY LAB

Lee Bernstein

Jon Morrell

Josh Brown

Bethany Goldblum

Thibault Laplace

Donald Nordwick

Aysia Demby

Jon Batchelder

Lawrence Livermore National Laboratory

Darren Bleuel

Chris Brand

Anton Tonchev

Jack Silano

Pacific Northwest NATIONAL LABORATORY

Bruce Pierson

Los Alamos NATIONAL LABORATORY EST. 1943

Matt Gooden

Fission Yield Correlation/Covariance Matrices

Motivation

- Neither the ENDF/B-VIII.0 or JEFF-3.1 fission yield evaluations include information on covariances between fission yields. [1,2]
- Covariances between fission yields affect several important applications:
  - Forensics and safeguards calculations
  - Reactor antineutrino rates
  - Reactor inventory, decay heat, and poisoning

[1] – Evaluation and Compilation of Fission Product Yields – T.R. England and B.F. Rider (1994)

[2] – R. W. Mills, Fission product yield evaluation, Ph.D. thesis, University of Birmingham (1995)

Previous Work

- Pigni et al. – 2013
  - Variance estimation with Wahl systematics
- Schmidt – 2013
  - Parameter perturbation in the GEF code
- Leray et al. – 2017
  - Parameter perturbation in the GEF code
- Kawano and Chadwick – 2013
  - Bayesian method for ^{239}Pu FPY

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- Work by Pigni, Schmidt, and Leray relies on an underlying model of fission and parameter uncertainties.
- Results of these work are not readily accessible due in part to ENDF format limitations.

Motivation

- The goal of this work is to generate a set of covariance matrices for the fissioning systems of a given fission yield evaluation **with as little fission model bias/uncertainty as possible.**
- This method seeks to use simple conservation rules in order to constrain a sample space for Monte-Carlo estimation.
- The resulting covariance matrix will predominantly reflect the evaluated uncertainties in the independent fission yields.
- **Public availability of the covariance matrices is a high priority.**

Conserved Relationships

- In order to obtain correlation, conserved quantities can be enforced upon a set of resampled fission yields [1]:

Total Yield:

$$\sum_i Y_i = 2$$

[1] - Generation of Fission Yield Covariances to Correct Discrepancies in the JEFF Fission Yield Library – L. Fiorito et al. (2015) - https://www.oecd-nea.org/science/wpec/sg37/Meetings/2015_May/SG37_8_LF.pdf

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Charge Parity:

$$\sum_i Y_i(Z_1, A_i) = \sum_i Y_i(Z_{CN} - Z_1, A_i)$$

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Mass Symmetry:

$$\sum_{A_i > \frac{A_{CN} - \bar{\nu}}{2}} Y_i(A_i) = 1$$

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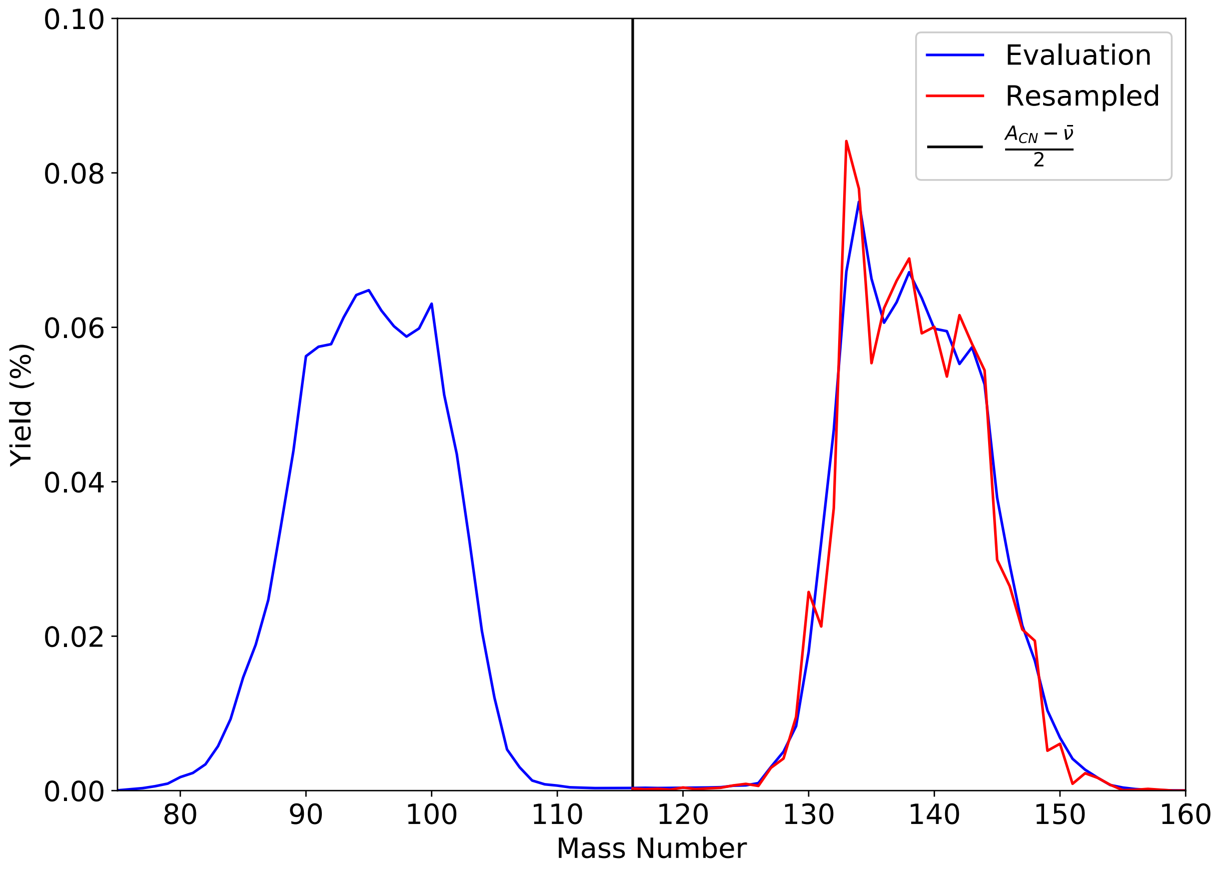
FY Covariance Matrix Generation

- The way in which a set of fission yields are resampled can be structured to conserve these relationships:
- **1)** Randomly selected the “light” or “heavy” side of the fission product spectrum to resample.
- **2)** Randomly select (weighted by uncertainty) a product in each A chain, resample its yield about its evaluated uncertainty.
- **3)** Scale all other yields in that A chain by the same percent change.



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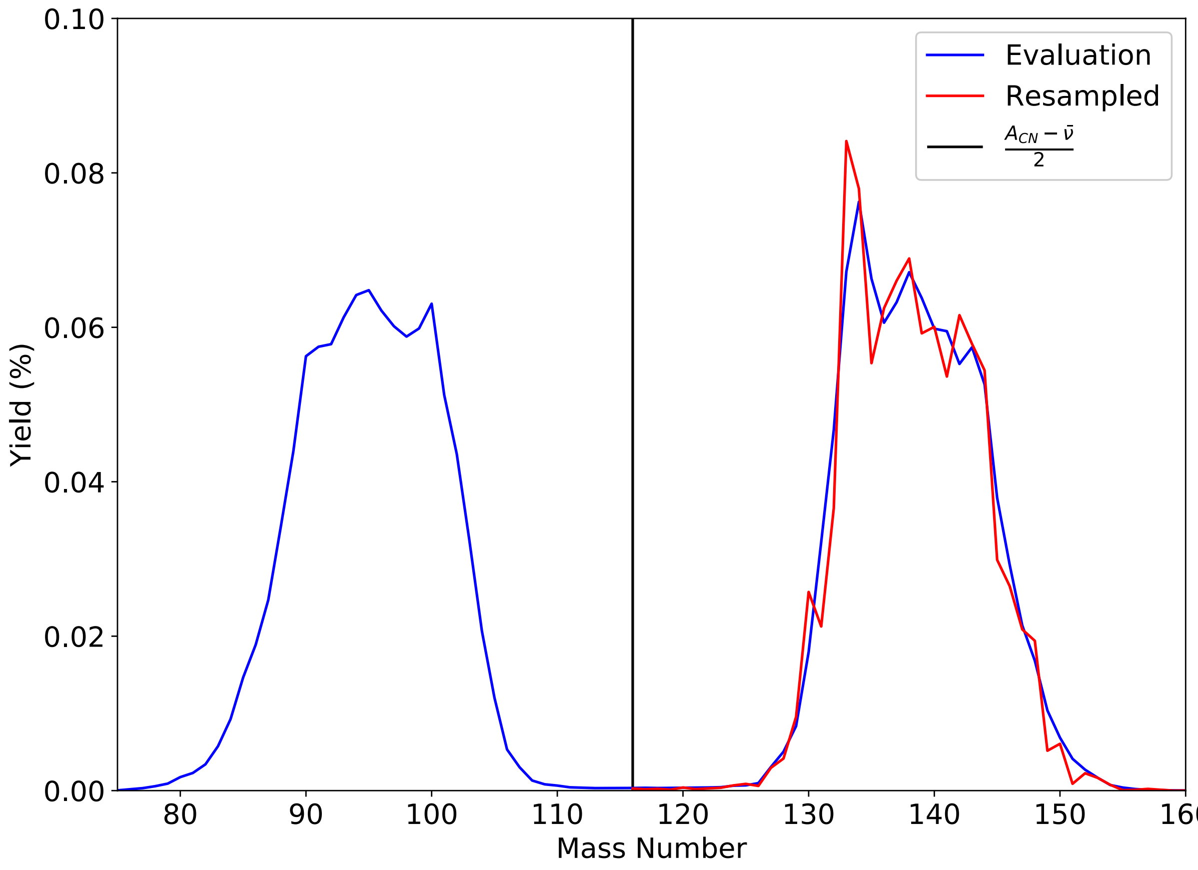


Step 3 is allowed if the Z distribution for a given A is Gaussian, which empirical data and the ENDF/B-VII.0 evaluation supports [1].

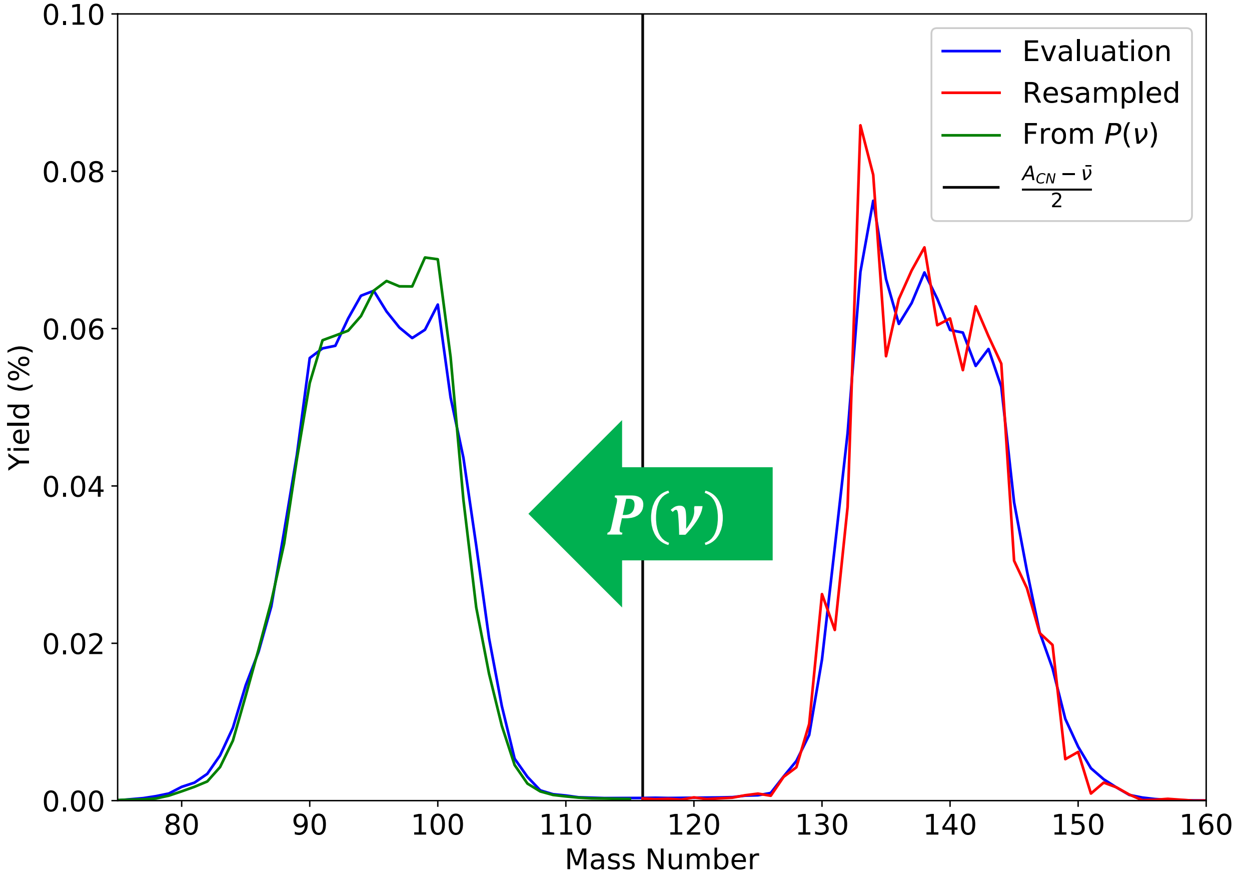
[1] – Evaluation and Compilation of Fission Product Yields – T.R. England and B.F. Rider (1994)

FY Covariance Matrix Generation

- **4)** Normalize the resampled yields such that they sum to 1.
- **5)** Generate the fission yields on the complementary side of the fission product spectrum using the neutron multiplicity of the compound system.

$$Y_{frac}(Z_{CN} - Z, A_{CN} - A - \nu\ ) = P(\nu)\, Y(Z, A)$$

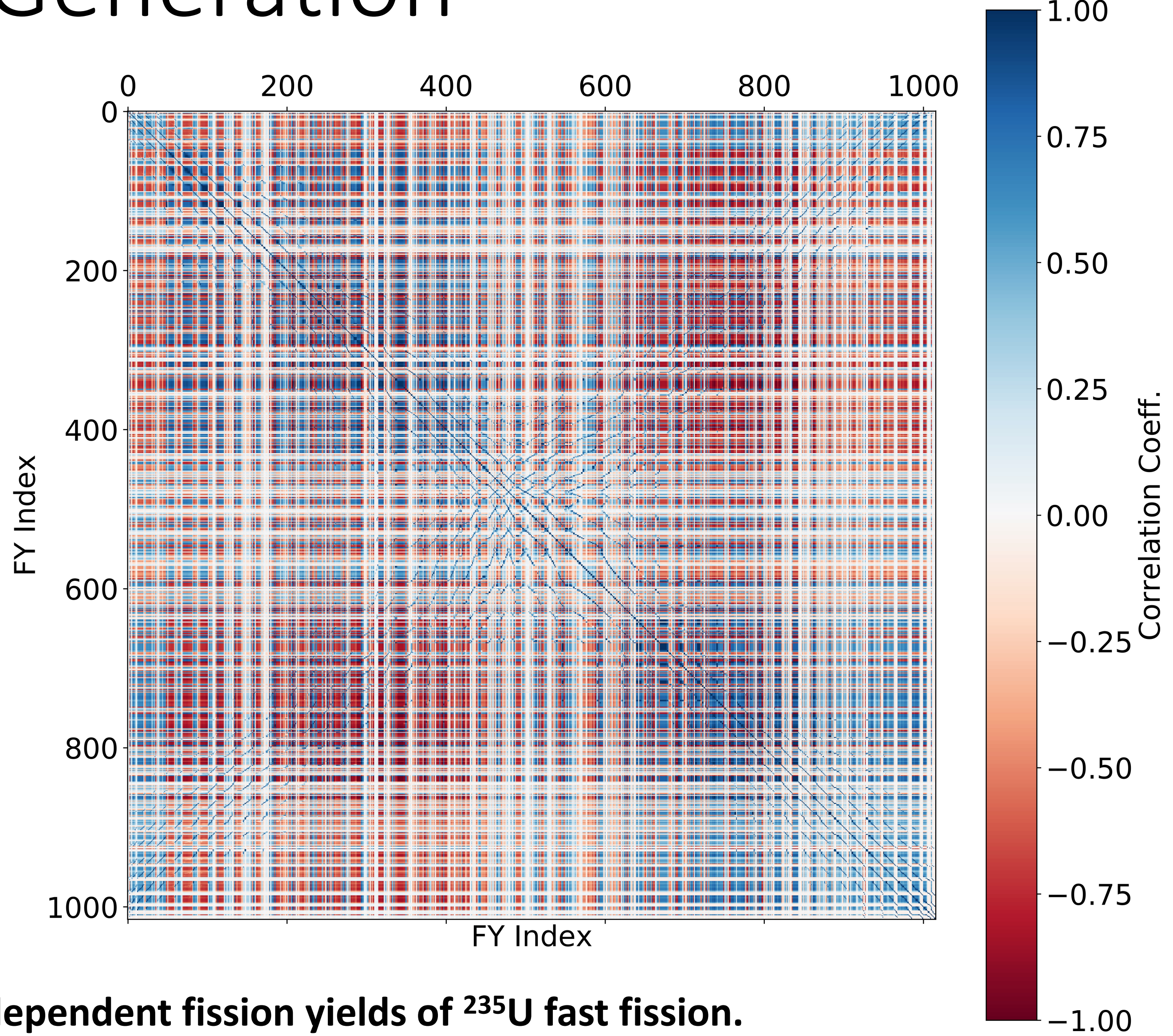
$$Y(Z_{CN} - Z, A_i) = \sum_{\nu} Y_{frac}(Z_{CN} - Z, A_i)$$



By Step 5 we've ensured all of the conservation rules are met.

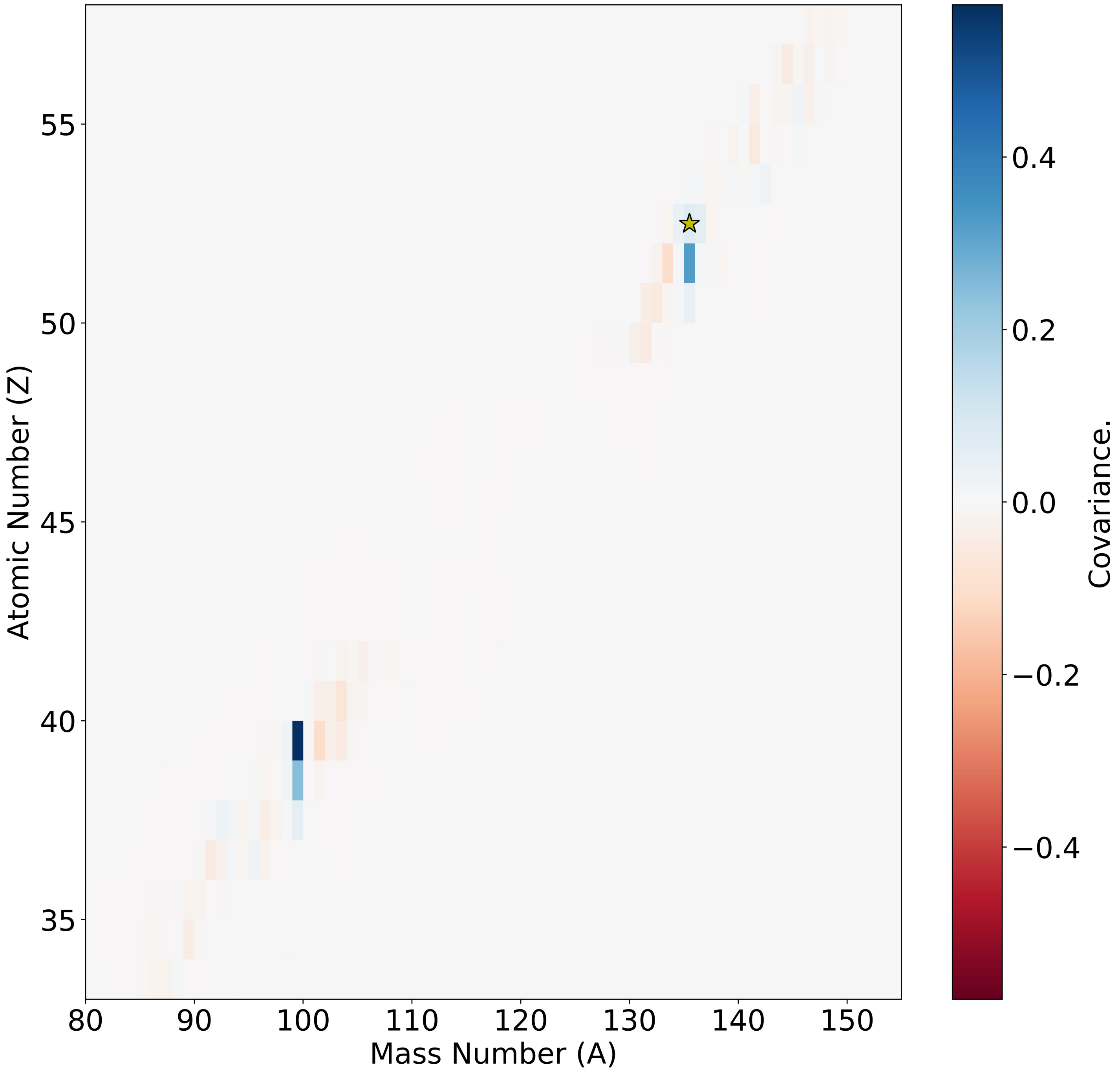
FY Covariance Matrix Generation

- **6)** Repeat steps 1-5) N times. Select N such that statistical noise is minimized.
- **7)** Calculate the resulting correlation matrix from the N trials.

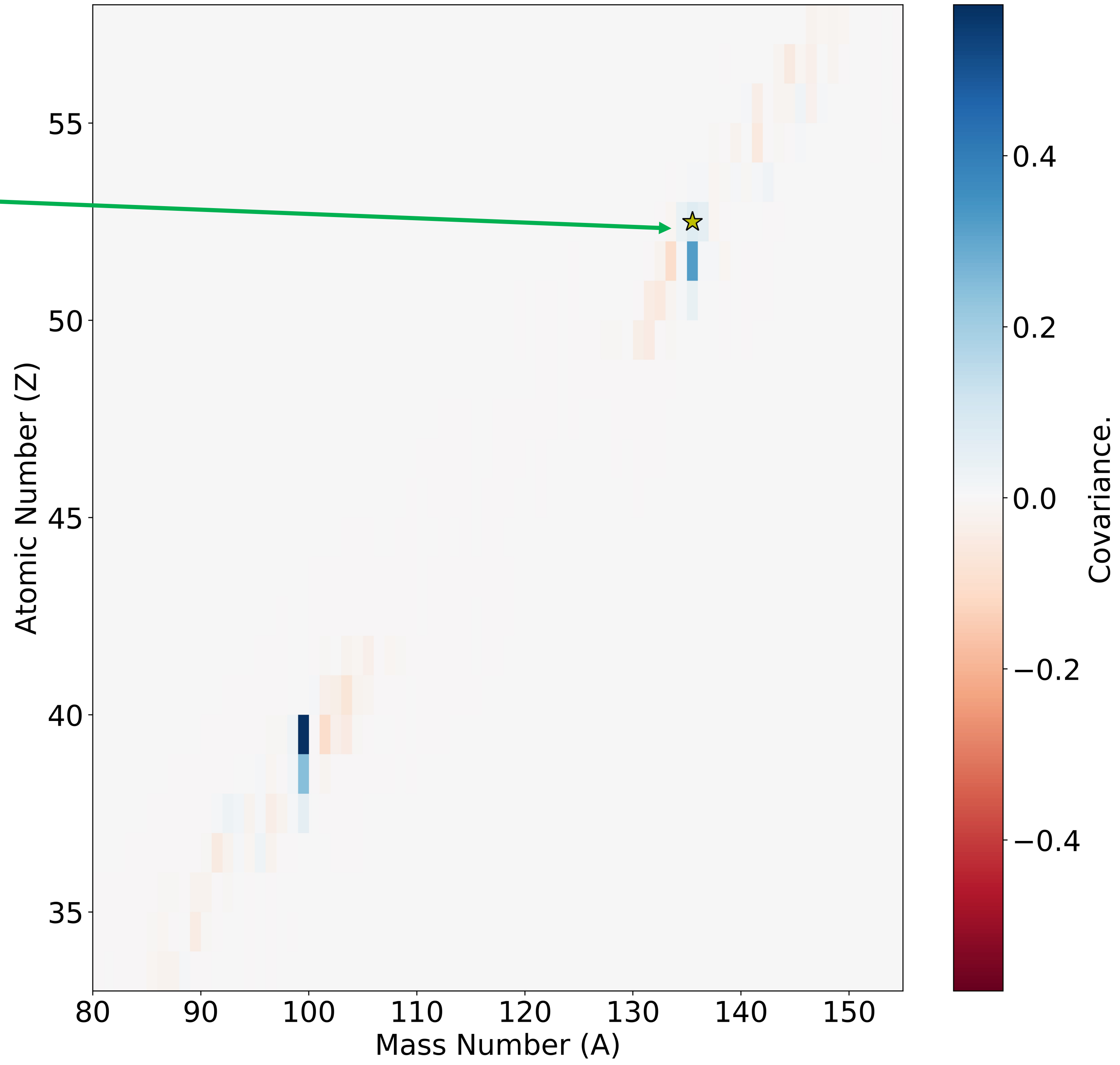


Correlation matrix for independent fission yields of ^{235}U fast fission.

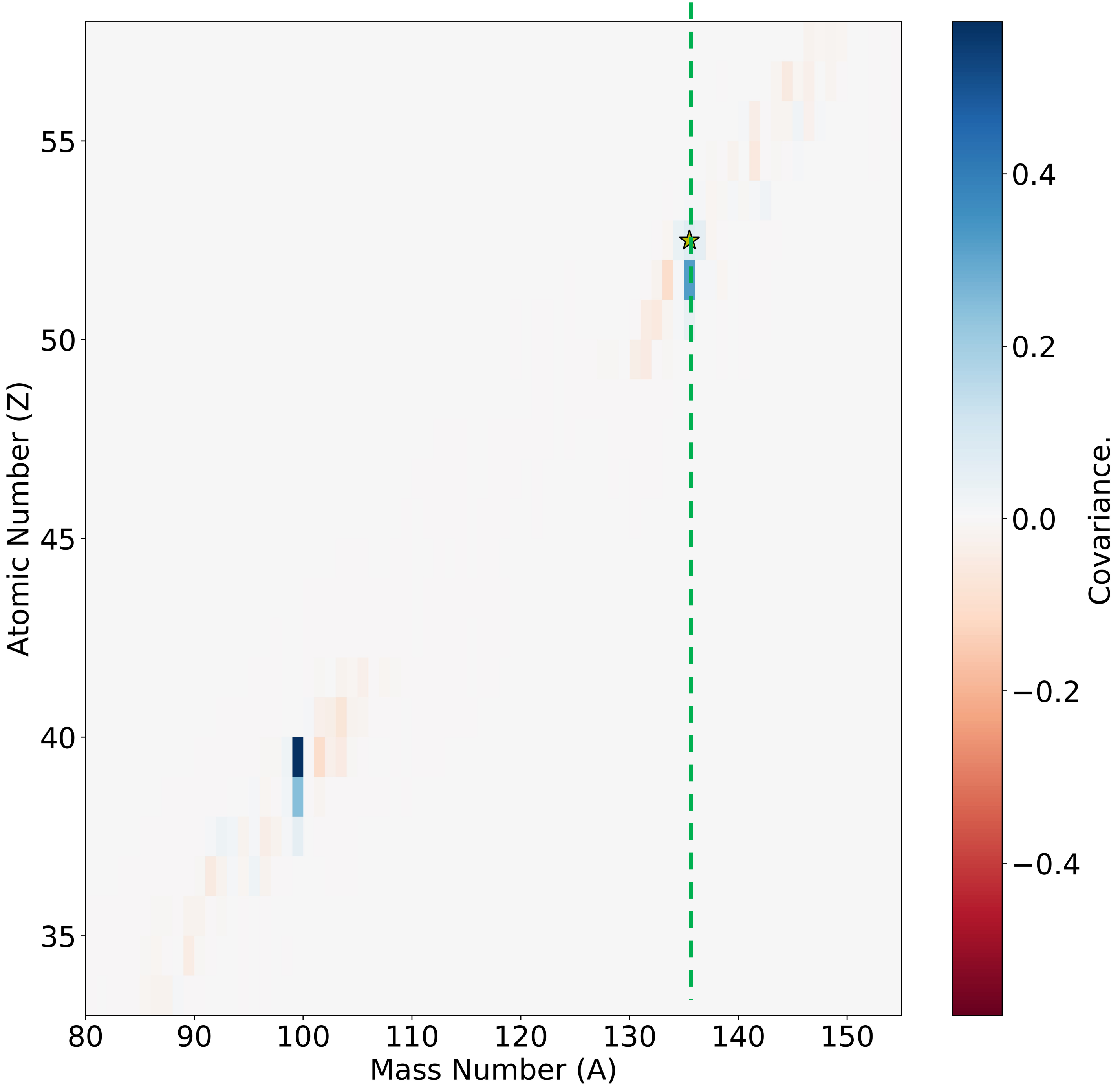
- **Example:** ^{135}Te
- Presented is the covariance between independent yields as function of Z and A and that of ^{135}Te.
- The evaluated yield for ^{135}Te is $2.47 \pm 0.57\%$



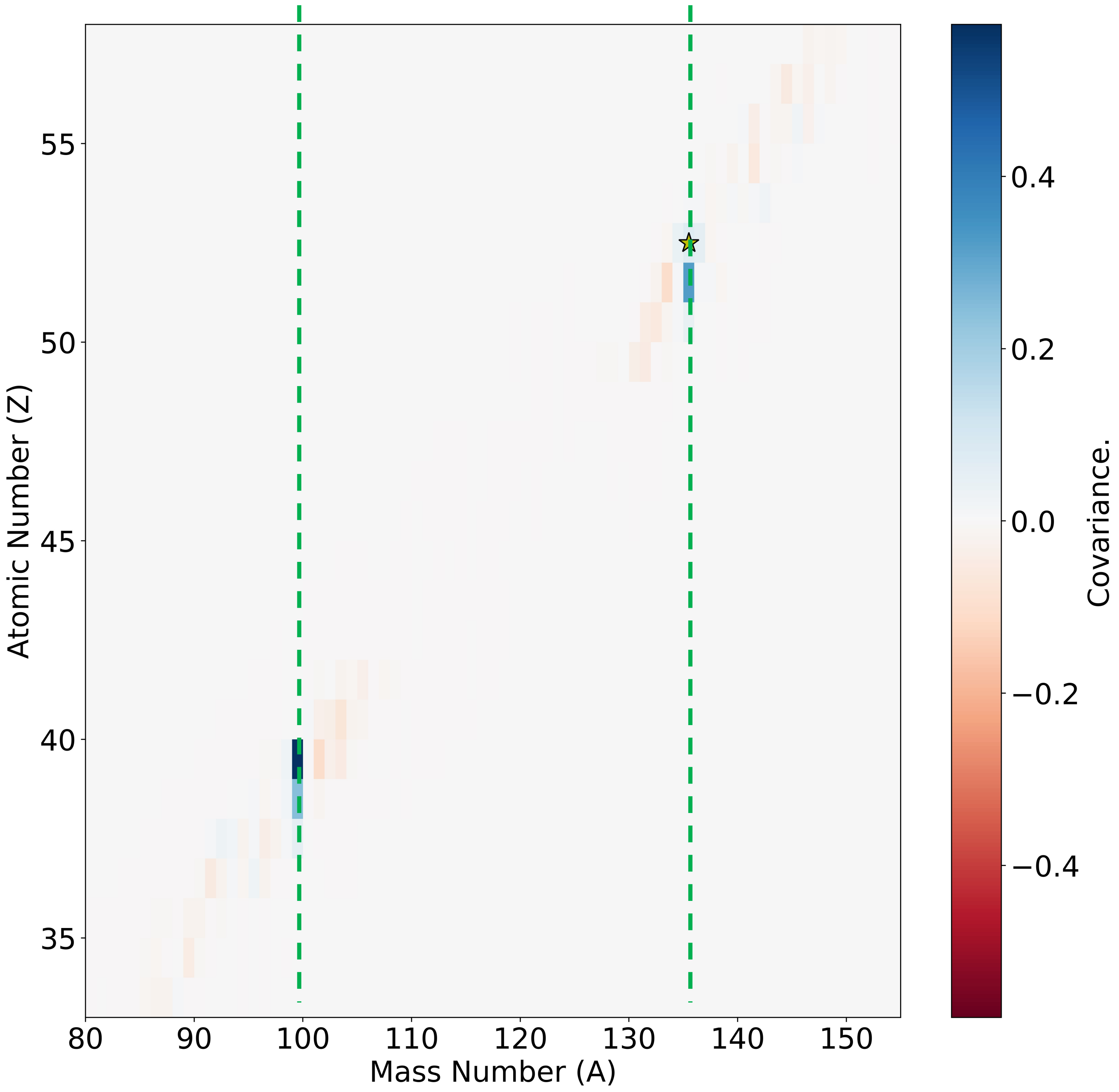
- **<u>Features:</u>**
- ^{135}Te is positively correlated with itself.



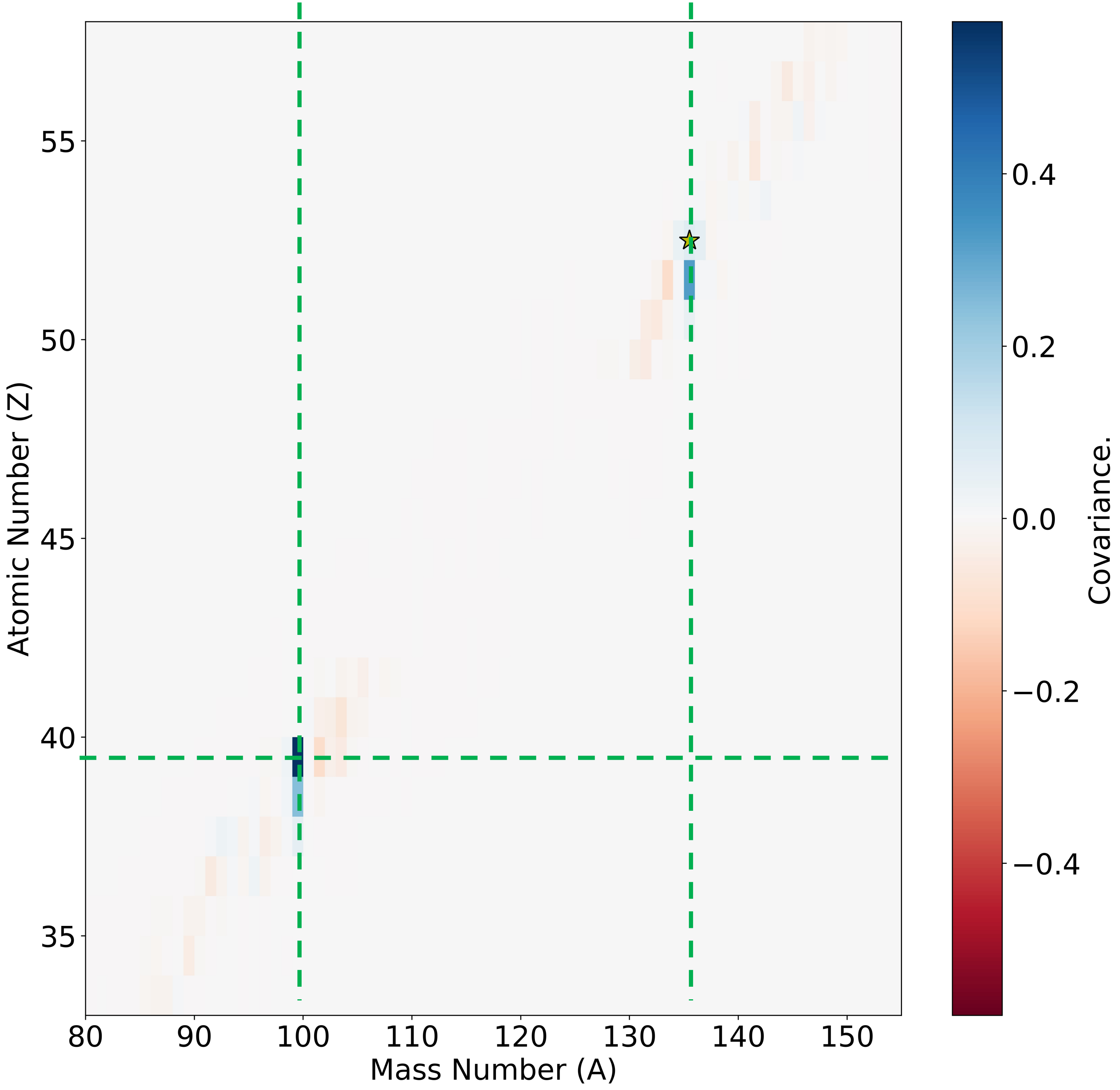
- **Features:**
- ^{135}Te is positively correlated with itself.
- Products along the A chain have positive correlation.



- **Features:**
- ^{135}Te is positively correlated with itself.
- Products along the A chain have positive correlation.
  - This positive correlation is reflected along a complementary $A = 99$ chain.



- **Features:**
- ^{135}Te is positively correlated with itself.
- Products along the A chain have positive correlation.
  - This positive correlation is reflected along a complementary $A = 99$ chain.
- Products along A chains that do not have complementary Z have negative correlation.



Conclusions

- A model-agnostic method for independent fission yield covariance matrix generation is being developed.
- **This method has been successfully applied to all compound systems in the ENDF/B-VIII.0 and JEFF-3.1 evaluations.**
- The results demonstrate expected behavior and trends.
- Final results serve as an interim solution for independent fission yield covariance matrices until a new evaluation is completed.
    - The results are publicly available at nucleardata.berkeley.edu/FYCOM
    - **Publication accepted to Atomic Data and Nuclear Data Tables on April 20, 2021.**

Thank You!

Eric F. Matthews