# Fragment-by-Fragment and Event-by-Event Multiplicity Correlations in Fission

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# Introduction and Motivation

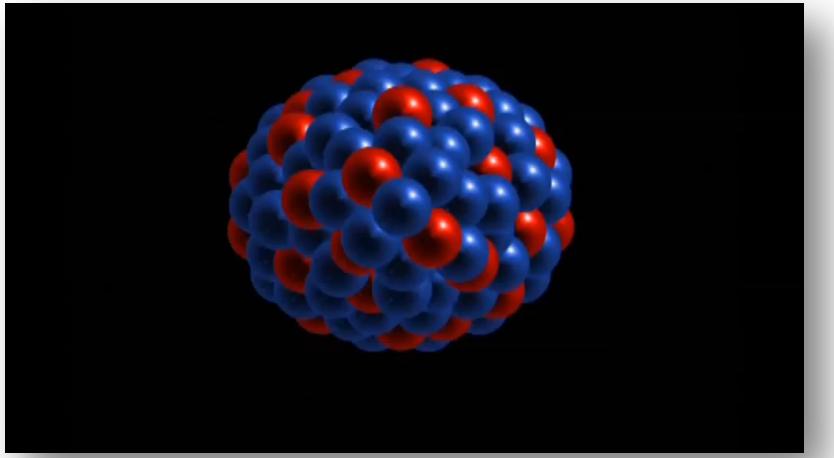
Special nuclear material undergoes spontaneous and induced nuclear fission.

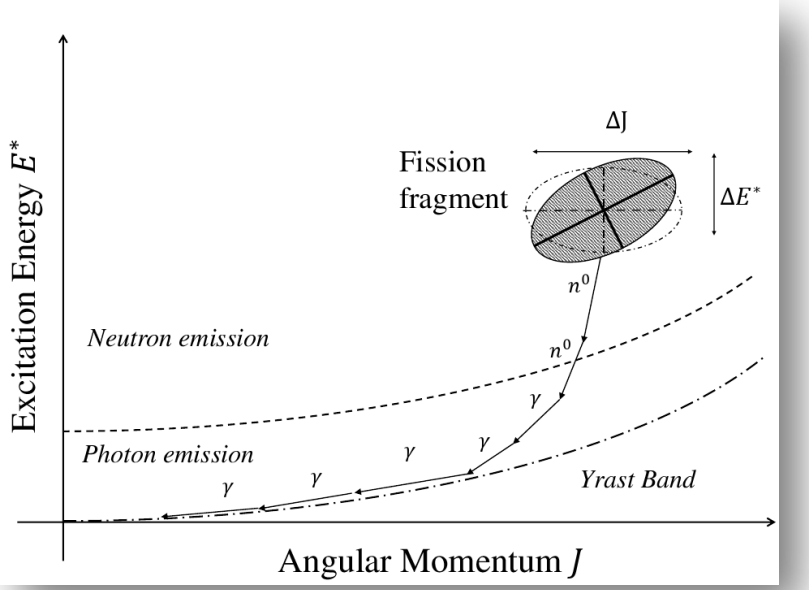
Following fission, neutrons and photons are released by the fission fragments.

The properties of the neutrons and the photons emitted by the fragments are characteristic of the fission process.

Therefore, the study of the correlated neutron-photon signature helps us idenitify and characterize special nuclear material.

We focus on **neutron-photon multiplicity correlations in $^{252}$Cf(sf).**





# Mission Relevance

In nonproliferation applications, the correlated signatures of neutron and photon emission are *leveraged to characterize sources.*

To develop new measurement techniques we rely on *Monte-Carlo simulations* and evaluated nuclear data.

Due to the complexity of the fission process, the properties of neutrons and photons are *highly correlated* to each other.

We rely on *physics-based fission event generators* to describe the correlated emission, such as LLNL developed FREYA, and LANL developed CGMF. The predictions of these models are then used in Monte Carlo simulations.

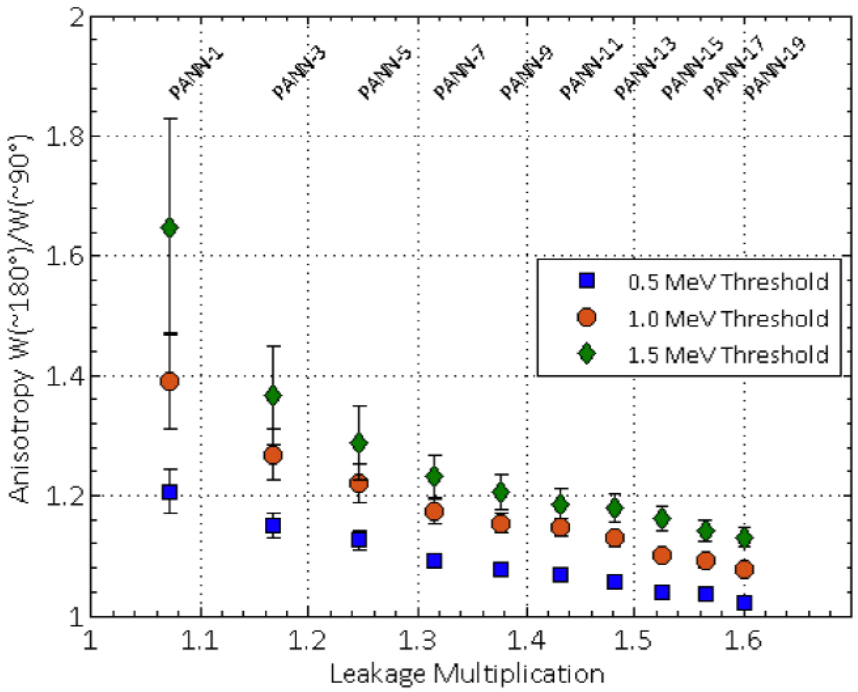



**Fig. 7.** Measured neutron anisotropy as a function of the assembly leakage multiplication showing a monotonically decreasing trend. 2-std. statistical error bars shown.

Shin, T. H. et al. *"Prompt fission neutron anisotropy in low-multiplying subcritical plutoniummetal assemblies"* Nuclear Instruments and Methods A, **915**, 110-115 (2019)

# Background

We investigate multiplicity correlations in two ways:

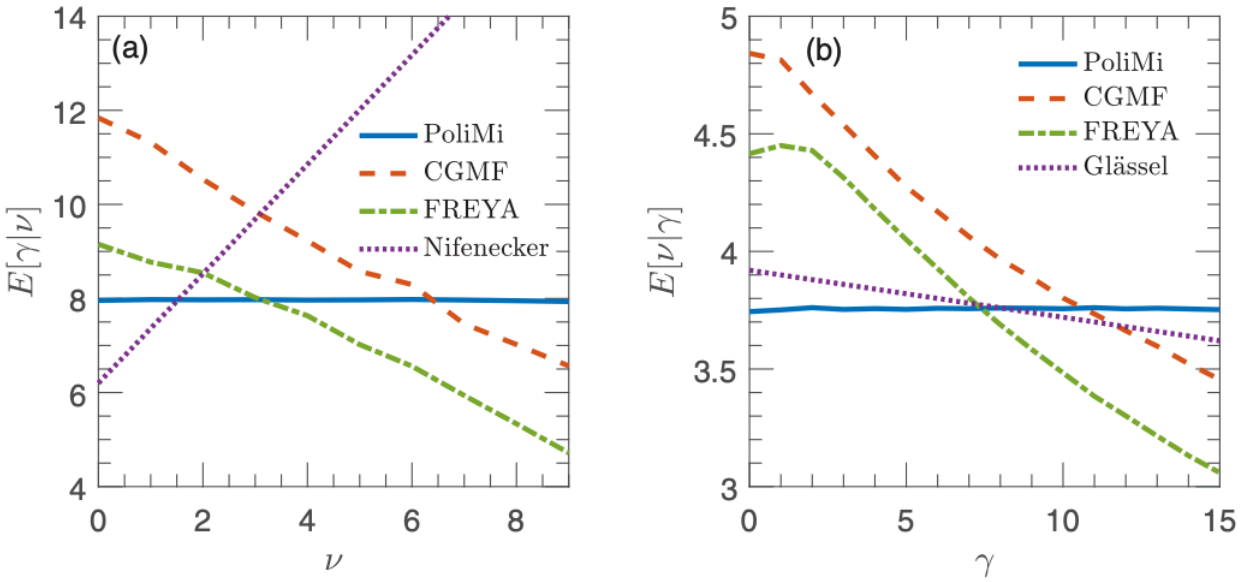
- **Event-by-event**: measure event-by-event neutron and photon multiplicities following each fission event,
- **Fragment-by-fragment**: Determine neutron and photons mean multiplicities over a range of fragment initial conditions (mass, energy, *etc*).

We use fragment-by-fragment correlations to test the predictions of fission event generators.

These correlations are used to *validate predictions* of correlated signatures and develop *new signatures of SNM.*

We use event-by-event correlations to consolidate evaluated nuclear data.

These correlations are used to *address systematic biases* and to *characterize SNM.*



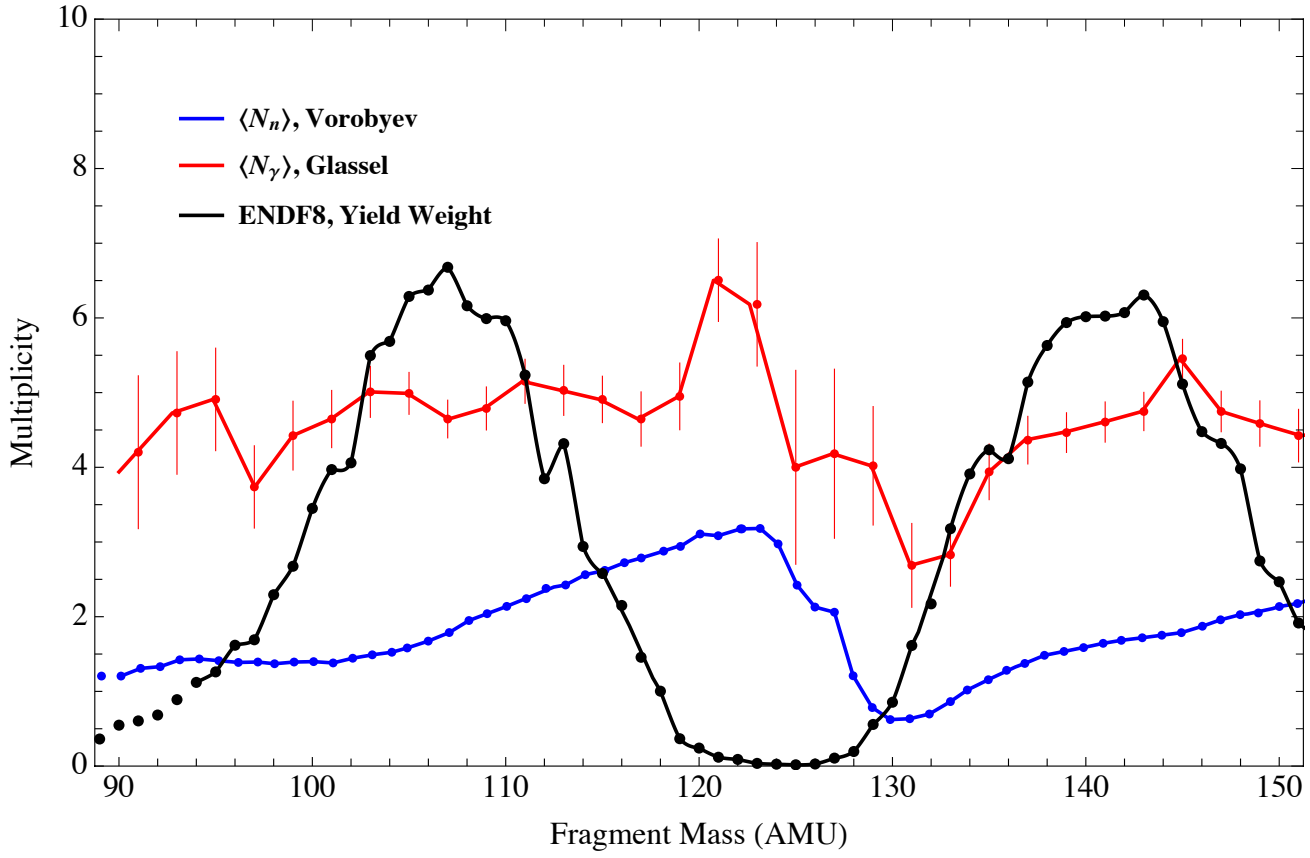

Marcath, M. J. et al. *"Measured and simulated 252Cf(sf) prompt neutron-photon competition"* Physical Review C **97**, 044622 (2018)

# Fragment-by-Fragment Correlations

Fragment-by-fragment correlations arise primarily due to correlations between the rotational and intrinsic energy of the fragments.

Fragment-by-fragment correlations are also dependent on the nuclear structure of each fragment.

Because de-excitation paths to the ground state are averaged out, fragment-by-fragment are used to validate the excitation process of fragments following fission.

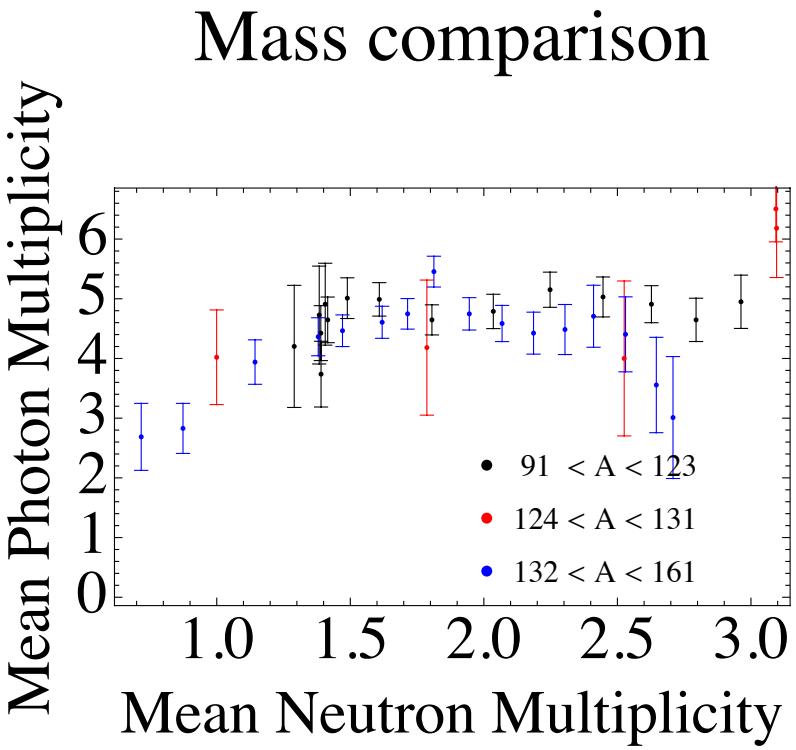


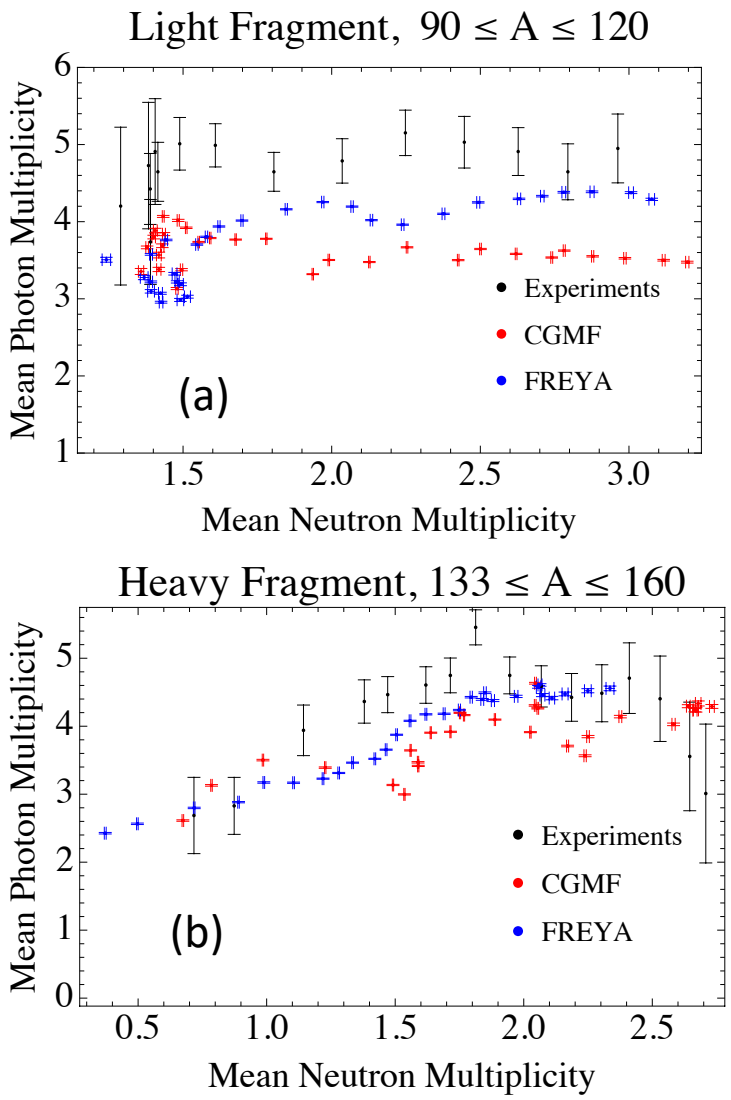
# Results: Fragment-by-Fragment

We have found different multiplicity correlations for the light and heavy fragment.

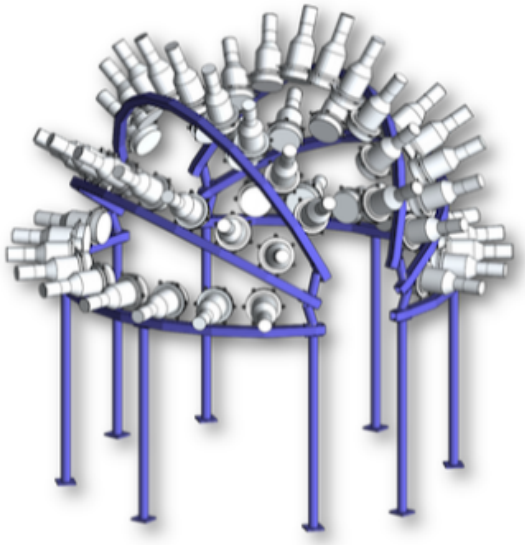
The light fragment shows relatively small correlations compared to heavy fragment. Correlations cannot be described linearly.

Comparison with CGMF and FREYA shows that while overall trends agree, finer behaviors are not completely captured.



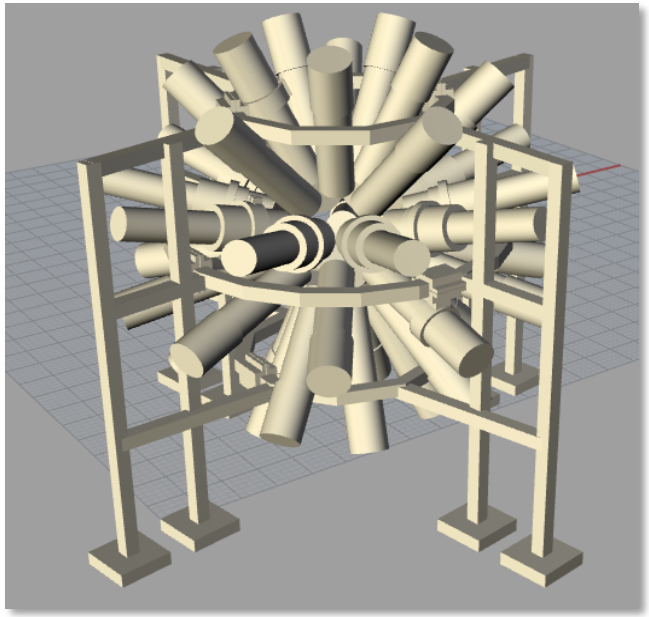
# Event-by-Event Correlations



Event-by-event multiplicity correlations are observable with systems capable of simultaneously measuring neutrons and photons.

These correlations include all the sources of correlation determined on a fragment-by-fragment analysis, with additional contributions from:

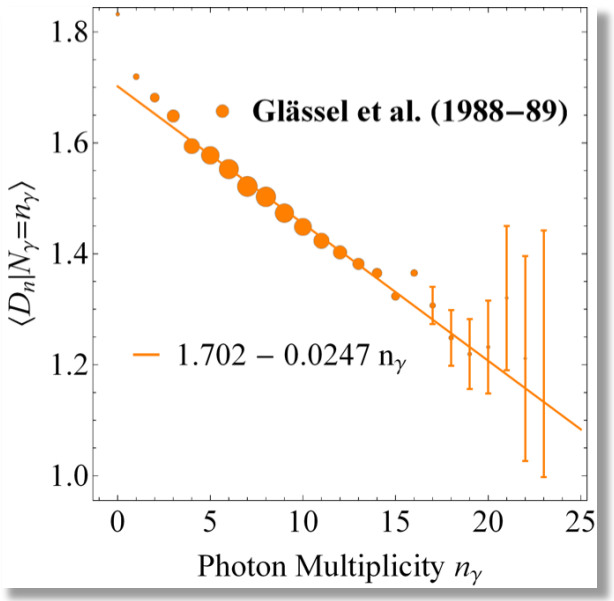
- Neutron-photon decay competition,
- Energy conservation competition.

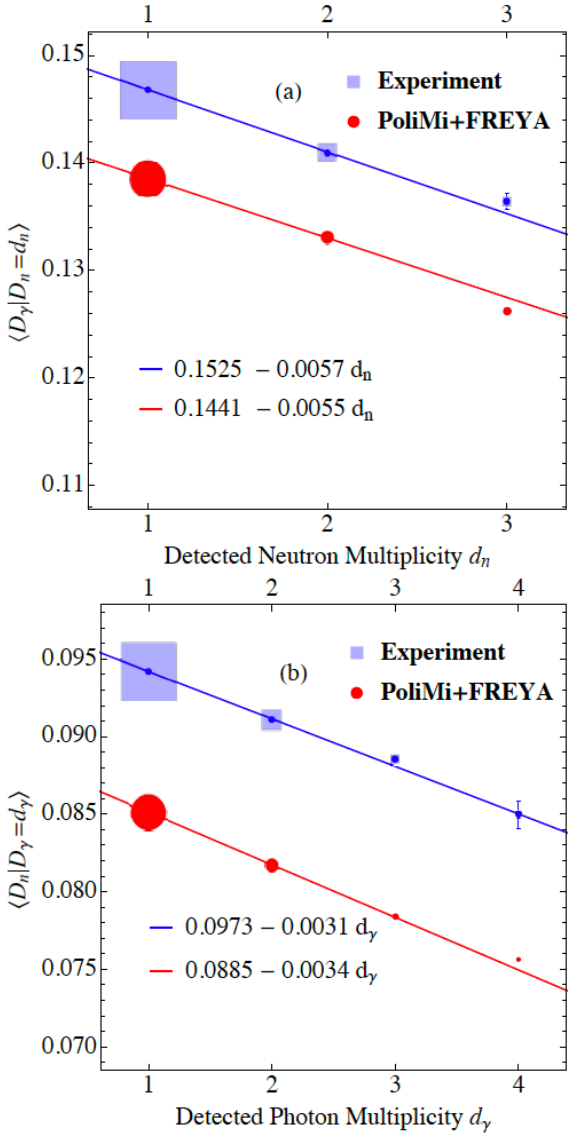


# Results: Event-by-Event

We validate the prediction of fission event generators and past experimental results.

We have observed a decrease in the number of photons with increasing neutron multiplicity, in agreement with predictions.

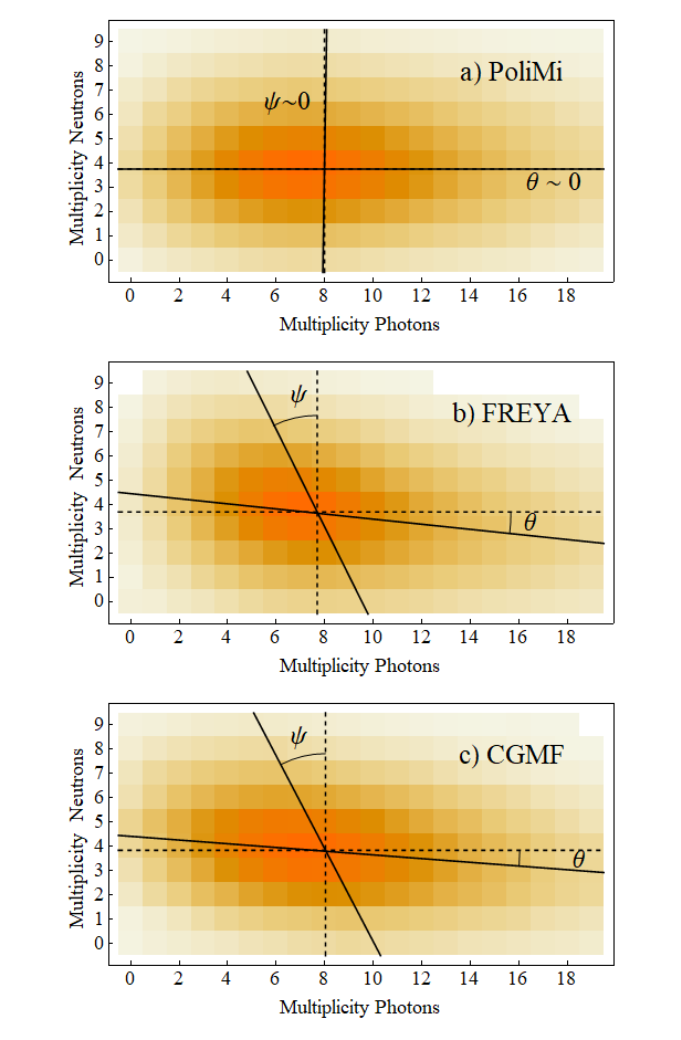


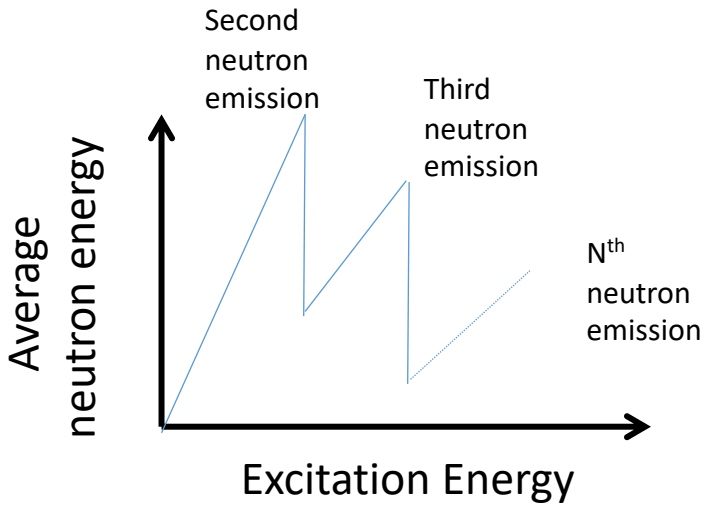



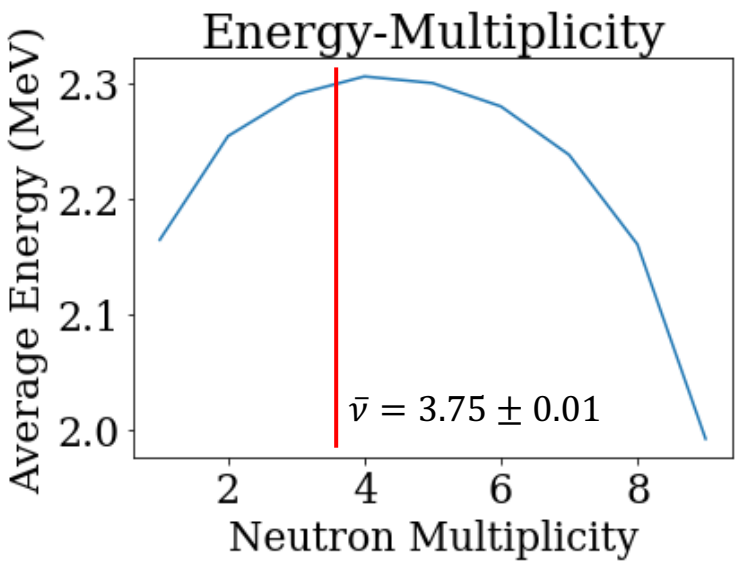
# Expected Impact

Improvement of evaluated nuclear data, reporting correlated multiplicity distributions

Investigation of higher order correlations in fission, e.g., multiplicity energy distributions.



# MTV Impact

To improve the reliability of fission event generators, we measure the *correlated properties of fission*.

We work closely with national labs:

- Collaboration with the developers of CGMF and FREYA
- Collaboration with experimental groups to measure Pu and U isotopes.

We are developing a high efficiency multiplicity counting system comprising 40 organic scintillators.

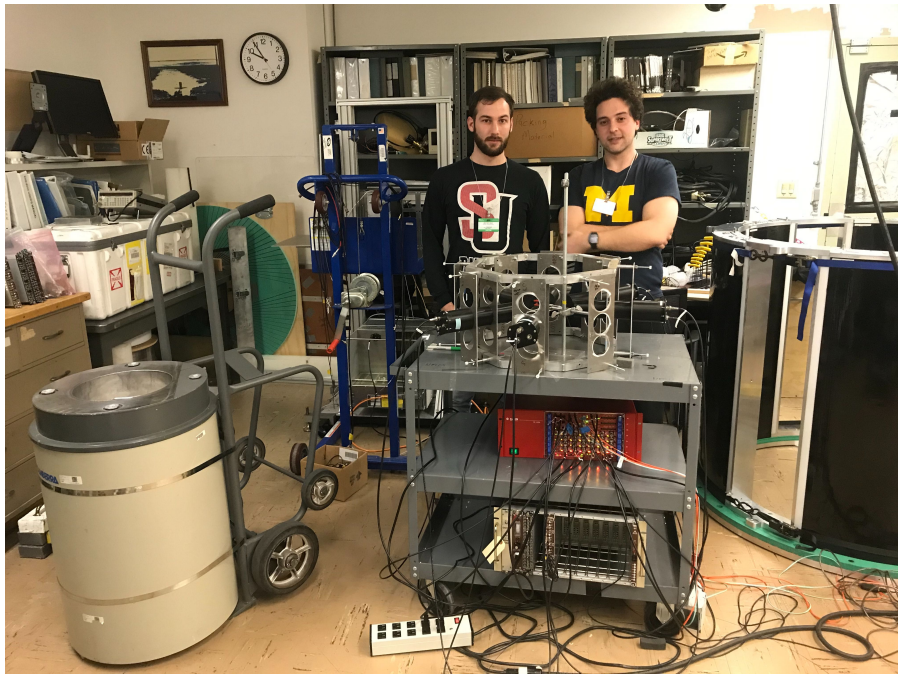
# Conclusion and Next Steps

We have measured the neutron-photon multiplicity correlations in $^{252}$Cf(sf).

Experimental results suggest that the fission event generators determine the correct event-by-event and fragment-by-fragment multiplicity correlations.

We are designing specialized experiment to increase our sensitivity to fission signatures.

We will be investigating the fragment and energy dependence of even-by-event multiplicity correlations.



# Acknowledgements

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