
# Simulation of Correlated Fission Data

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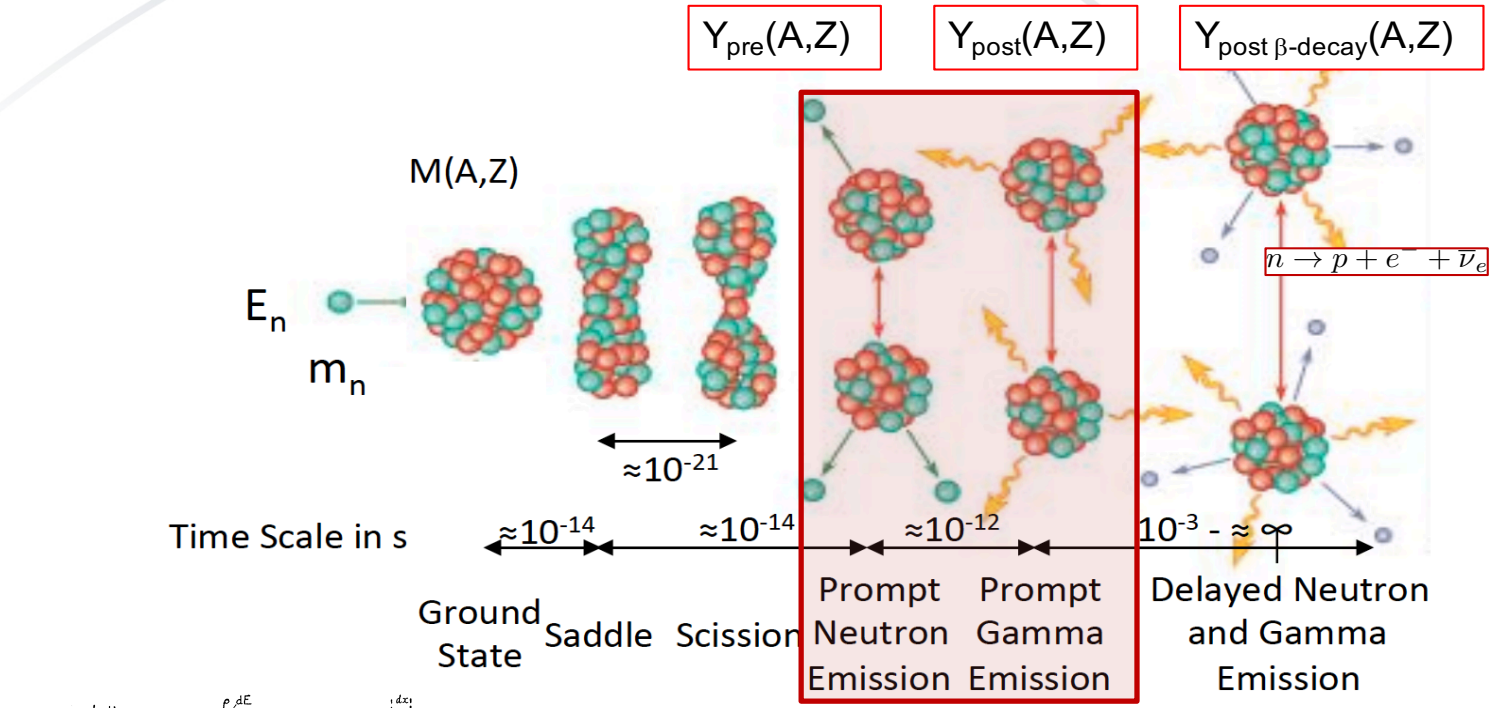
# The nuclear fission process is complex and rich



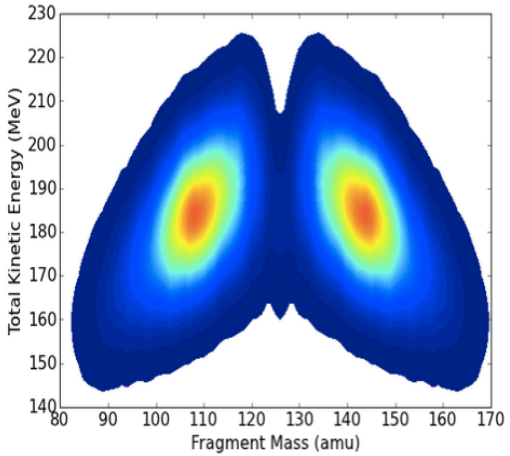

Fission Yields, prompt fission neutrons (PFN) and γ rays (PFG) are all **correlated**.

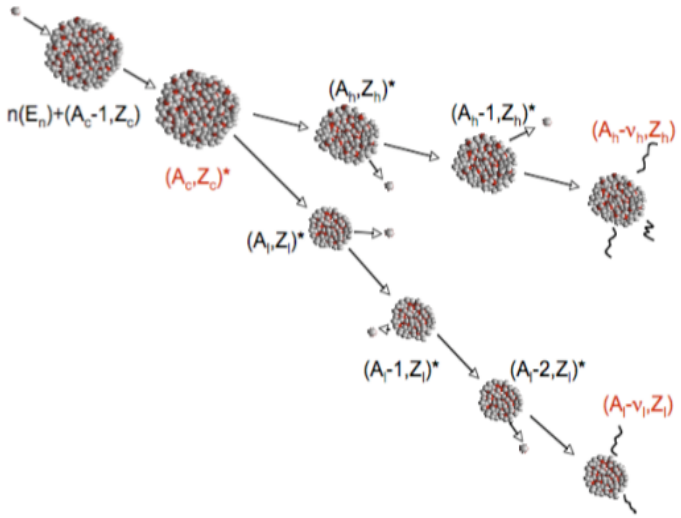
# Event-by-Event Monte Carlo Simulations of the Decay of Fission Fragments

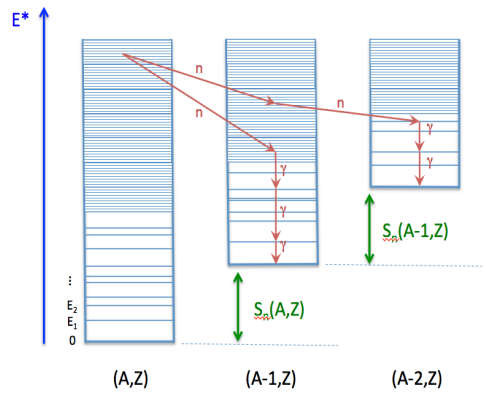
Fragment Yields
Y(A,TKE) in Cf-252 (sf)

Prompt emissions of n and γ (~$10^{-14}$ sec)
+ "late" isomeric γ emissions up to ~μsec

Follow decay of each
excited fission fragment



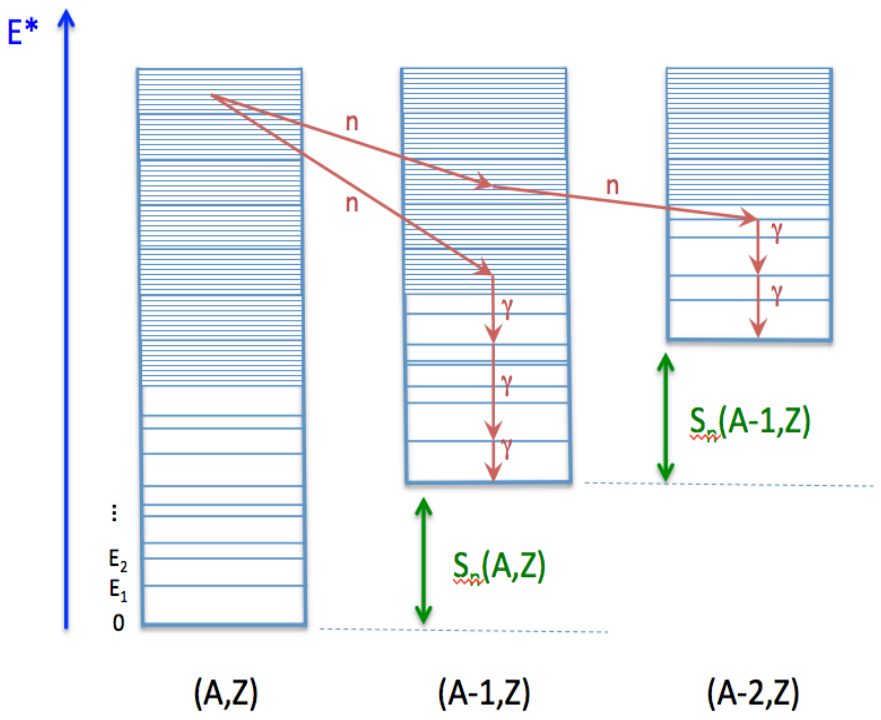

The **CGMF** code follows the sequential emissions of prompt neutrons and γ rays from the excited primary fission fragments, event-by-event. Similar codes (FREYA, FIFRELIN, GEF) are being developed as well.

***Review paper & Integration into MCNP-6.2***: Talou, Vogt, Randrup, Rising, Pozzi *et al*, EPJ A **54**, 9 (2018)

*(LANL, LLNL, LBNL, LANL, UM, et al)*

# **Complete reconstruction of** (post-scission) **fission events**

- **Hauser-Feshbach** statistical theory of nuclear reactions
  - Neutron and γ-ray emission probabilities calculated and sampled at each stage of the decay
  - Weisskopf-Ewing approximation
    → no n-γ competition
    → no (J,π) conservation




- CGMF: Monte Carlo implementation of Hauser-Feshbach deexcitation in FF
- Full kinematic reconstruction of fission fragments, neutrons and gammas emitted

→ Monte Carlo histories of fission events:

$$A, Z, KE, U_i, J_i, \pi_i, \nu_n, \nu_\gamma$$
$$\vec{p}_F(\text{pre}), \vec{p}_F(\text{post}) \text{ in LAB frame}$$
$$\{\vec{v}_{n_i}, E_{n_i}\}_{i=1,\nu_n}, \{\vec{v}_{\gamma_j}, E_{\gamma_j}\}_{j=1,\nu_\gamma}$$

# Prompt Fission Neutrons & γ Rays

- Until recently, models were limited to average observables only
- **We can now model prompt neutrons and γ rays on an event-by-event basis and infer**:

  - Multiplicity Distributions: $P(\nu)$, $P(N_\gamma)$
  - Angular Distributions: $\Theta_{n\text{-}n}$, $\Theta_{n\text{-}FF}$
  - Exclusive data: $\phi(\varepsilon_n|\nu=3)$, $\phi(\varepsilon_\gamma|\gamma\text{–}\gamma\text{–}\gamma)$, …
  - Correlations: n-n, n-γ, γ–γ, n-γ-FF
  - Time-dependent emissions: $N_\gamma(t)$
  - Correlations with emitting fission fragments (A,Z,KE,J)
  - …

# Many important physics input needed for neutron-rich fission fragments

- Global optical model calculations
- $\gamma$-ray strength functions for E1, M1 and E2 transitions
- Nuclear structure of neutron-rich nuclei
- Level densities

# And intriguing fission physics questions

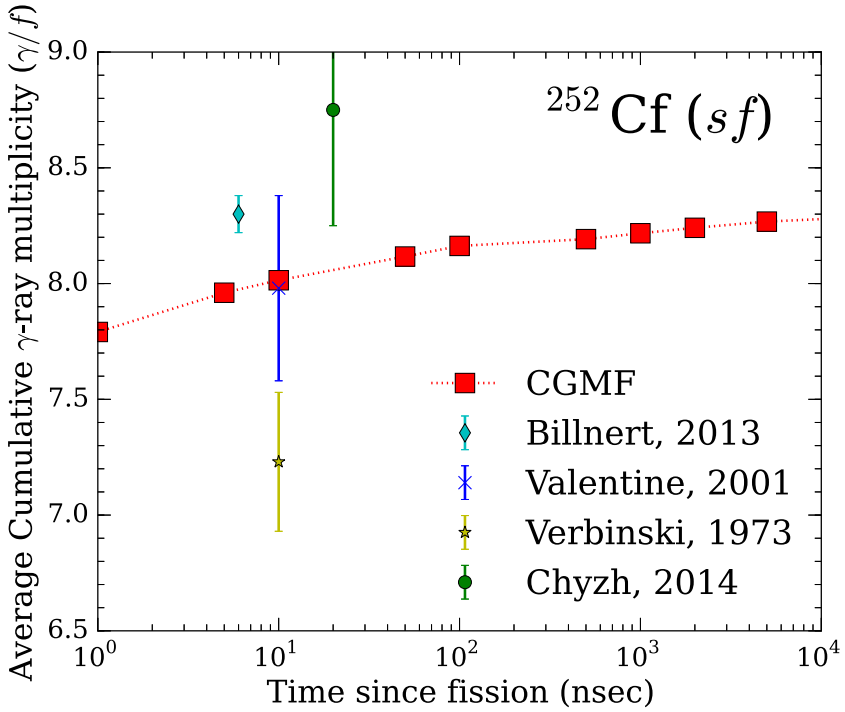
- Excitation energy sorting at scission? → $P(\nu|A,TKE;E_{inc})$
- Pre-fission neutron emission? “scission neutrons”, pre-scission neutrons, multi-chance fission, pre-equilibrium neutrons
- Relations between fission cross sections, fission fragment angular distributions and prompt fission data? → fission paths/channels/barriers

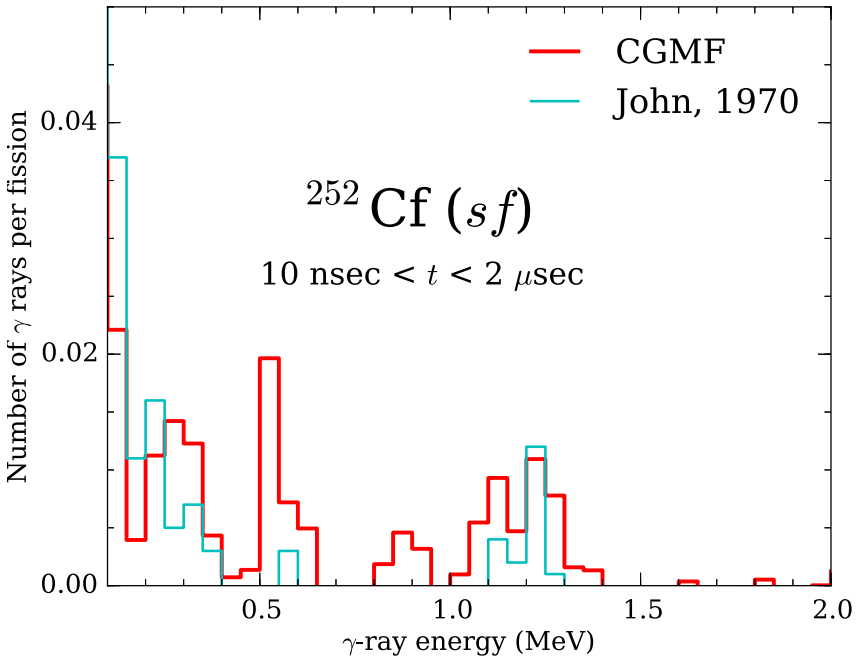
# Specific Studies

1. Role of fission fragment isomers
2. Influence of the entrance channel on $\gamma$-ray observables
3. Theoretical calculations of primary fission fragments for predicting prompt fission data
4. From $\gamma$-ray intensities to Independent Fission Yields (IFY)
5. Sensitivity & Optimization Studies (with FREYA team)
6. Integration into transport simulations with MCNP6.2
7. A consistent model for post-scission observables (see Okumura's talk)

# 1 – Fission Fragment Isomers

Populating *ns* to *sec* isomers in fission fragments delays the emission of prompt $\gamma$ rays.

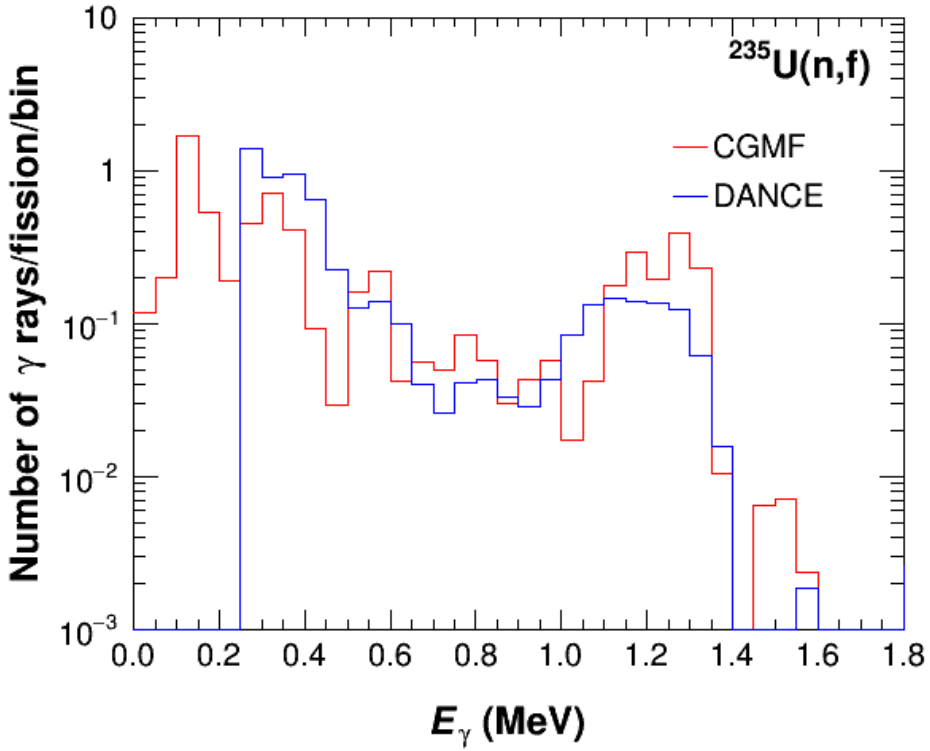


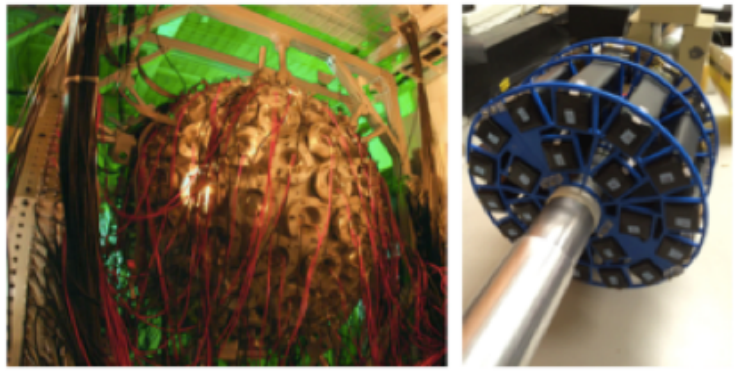




Talou et al, PRC **94**, 064613 (2016)

# More recent results from DANCE+NEUANCE

G. Rusev, I. Stetcu



DANCE NEUANCE

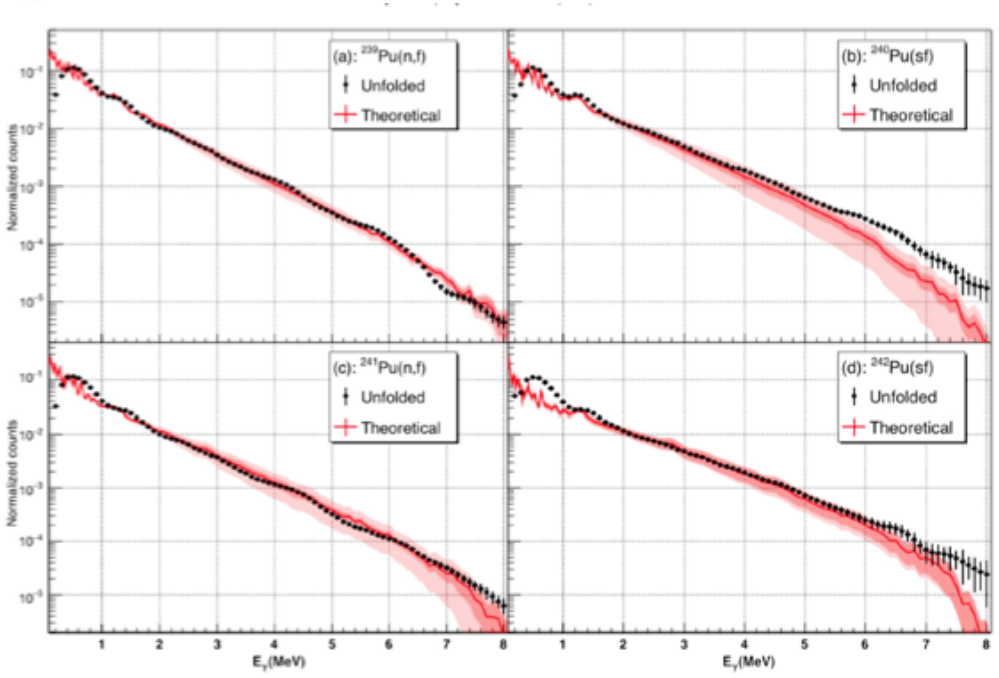
Analysis in progress

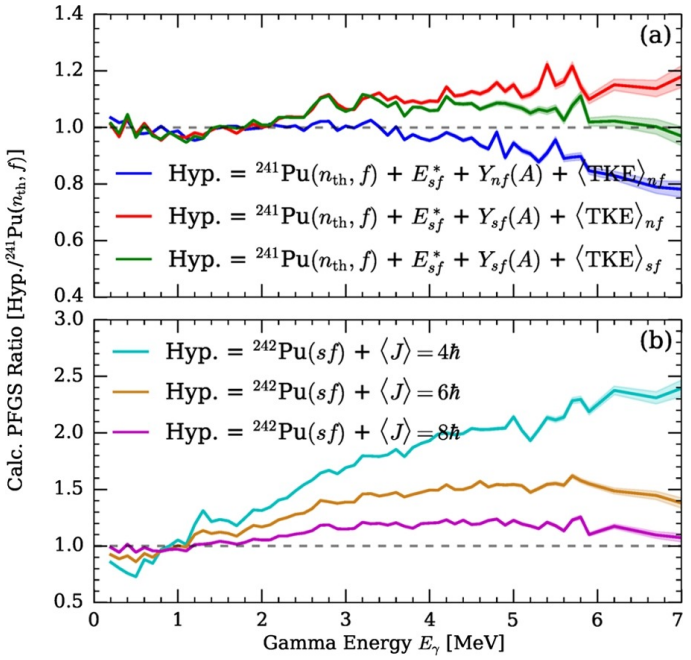
Experimental conditions: $E_n$=0.6 MeV, $\Delta$t=50 ns - 2 $\mu$s

# 2 – Entrance Channel

Chyzh, Jaffke, Wu et al., Phys. Lett. B 782, 652 (2018)

- DANCE measurements of prompt fission γ spectra show differences between spontaneous fission and neutron-induced fission reactions

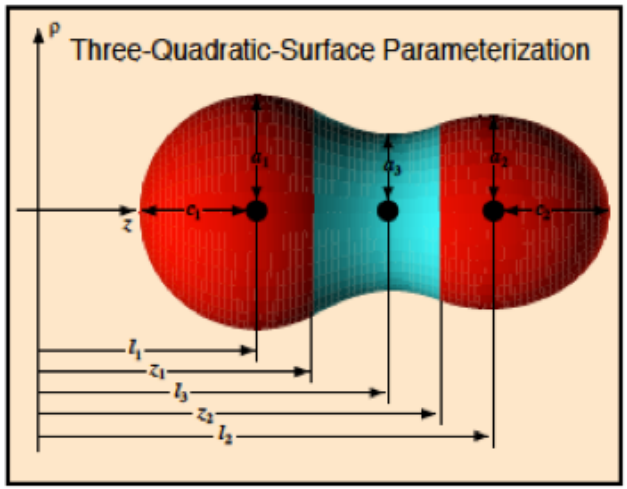


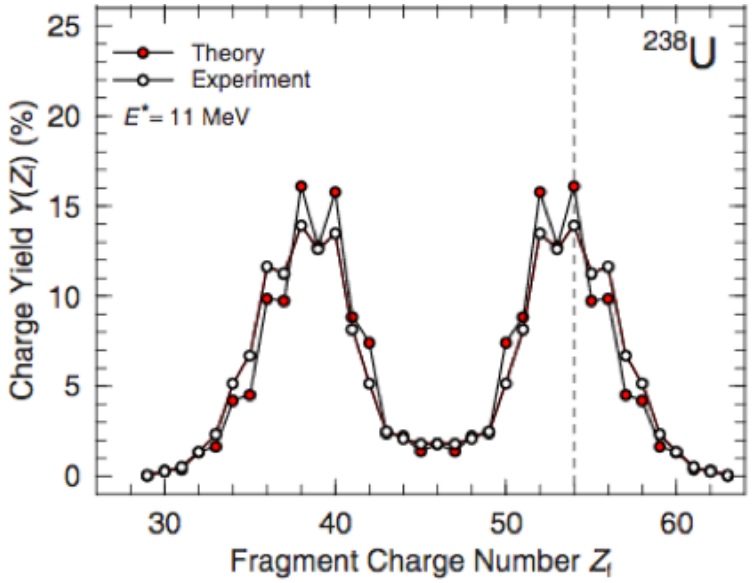




Theory explains this effect (fission yields, angular momentum) only qualitatively

# 3 – Model-calculated FY for CGMF

- Use macroscopic-microscopic description of nuclear shapes
  Möller and Ichikawa, EPJ A **51**, 173 (2015)
- Brownian motion on potential energy surface
  Randrup and Möller, PRL **106**, 132503 (2011)
- Langevin simulations
  Sierk, PRC **96**, 034603 (2017)
  Usang, Ivanyuk, Ishizuka, Chiba, PRC **94**, 044602 (2016)



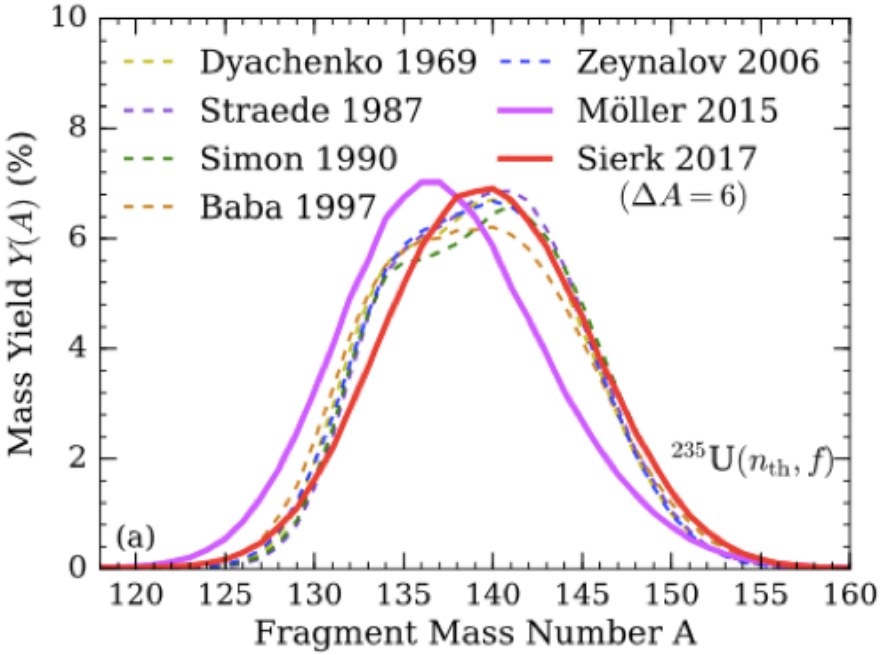




P. Möller, C. Schmitt, EPJ A **53,** 7 (2017)

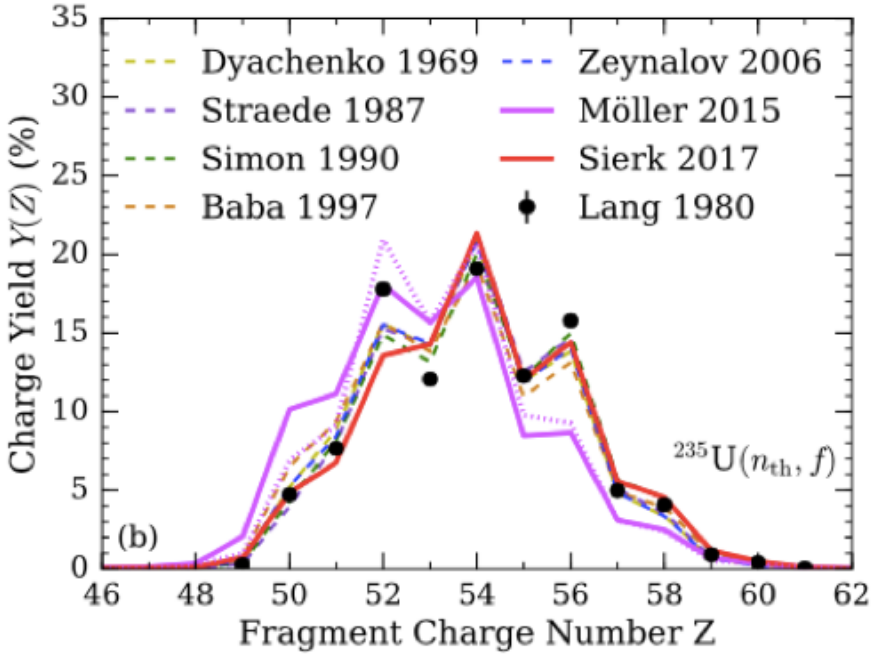
# Calculations for $^{235}$U and $^{239}$Pu thermal neutron-induced fissions

Jaffke, Möller, Talou, Sierk, Phys. Rev. C **97**, 034608 (2018)

Y(A)



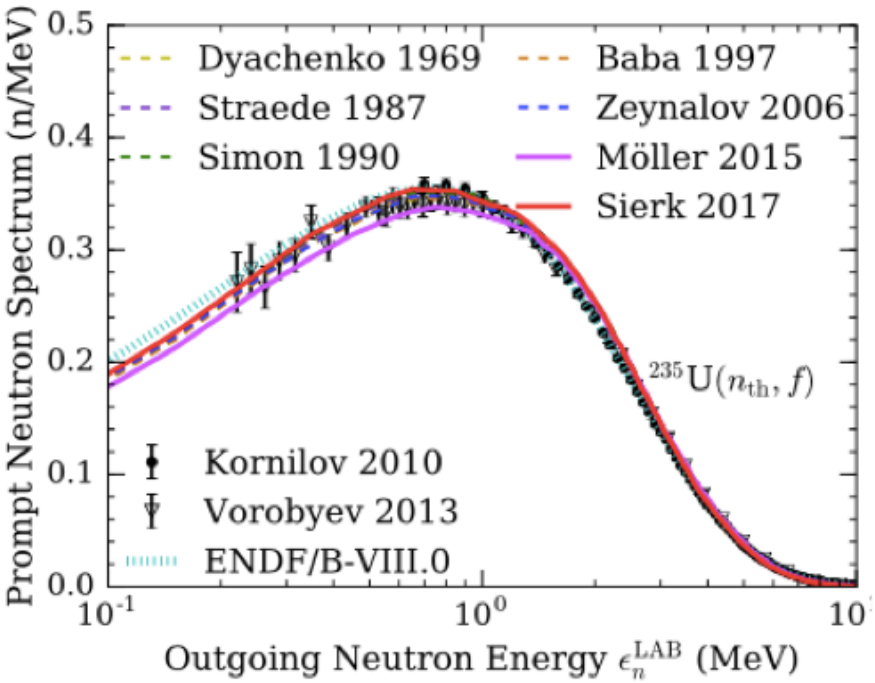

Y(Z)



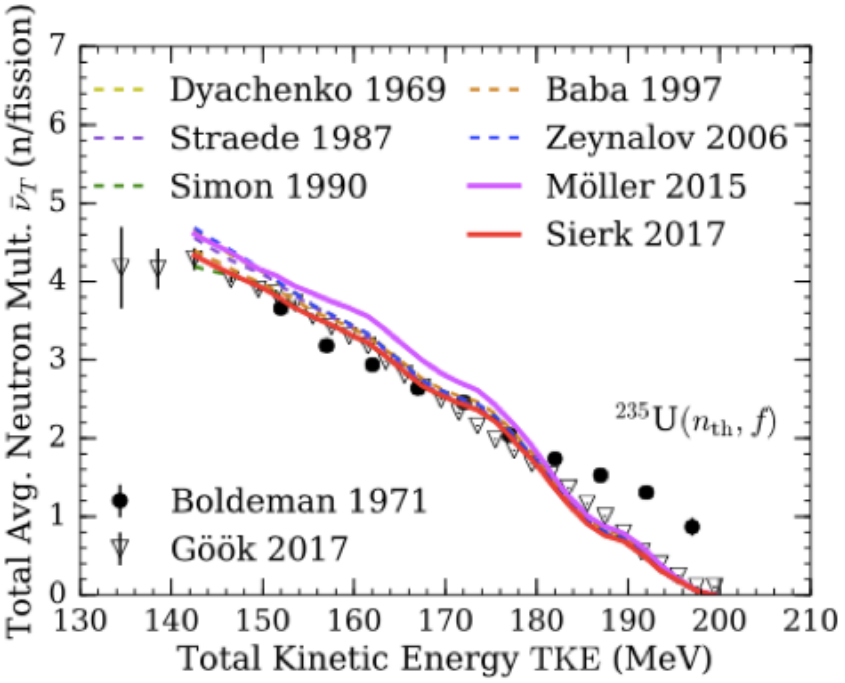

Thermal neutron-induced fission of $^{235}$U

# One can assess the quality of the calculated prompt fission data starting from calculated FY

PFNS

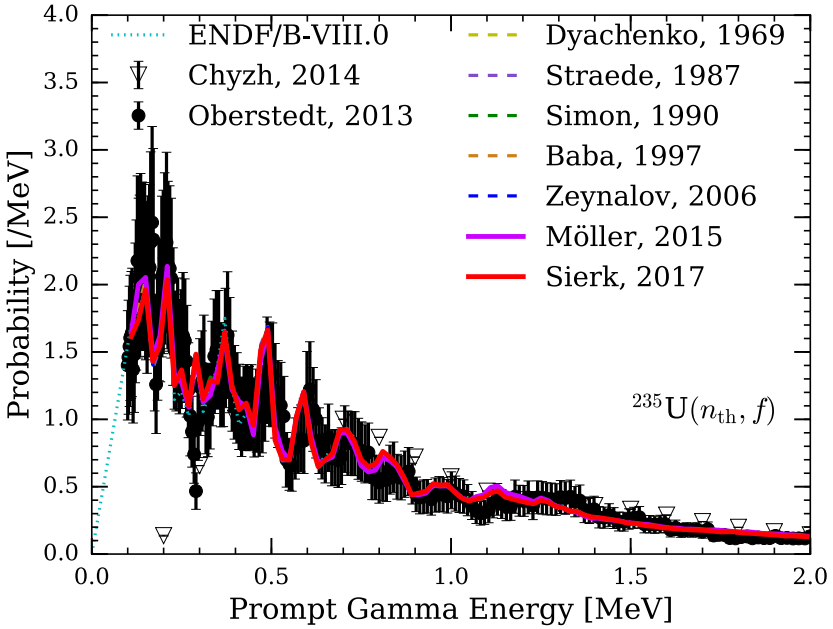


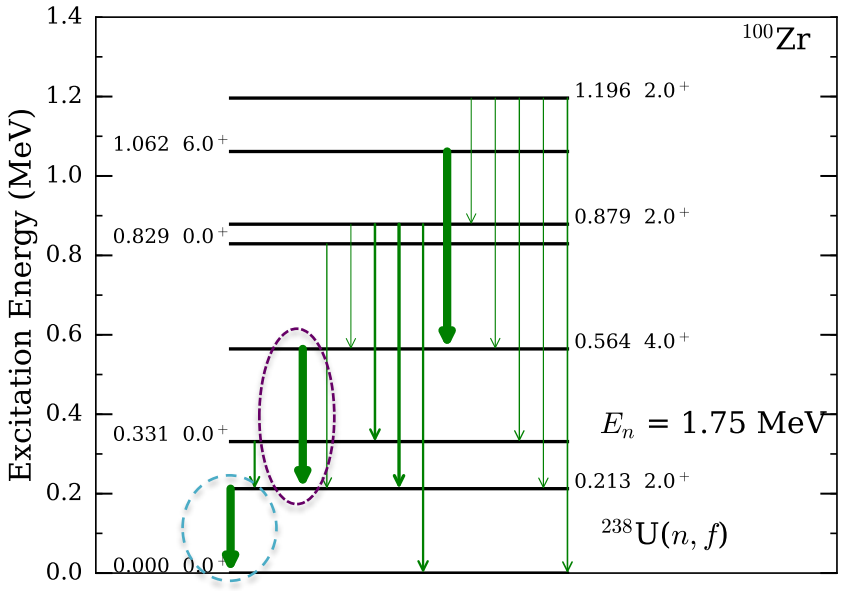

<ν> vs. TKE



# 4 – Using γ spectroscopy to infer FPY

Fotiades, Jaffke *et al.* (submitted to PRC)




- Several assumptions that require simulations
  - How many γ lines are in the energy window considered?
  - How much of the "flux" passes through $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions?
  - Corrections when performing γ–γ or γ–γ–γ coincidences (multiplicity)

# Thank you to my collaborators

- CGMF Developments
  - Stetcu, Jaffke, Kawano, Lovell
- Fission Fragment Isomers
  - Stetcu, Rusev, Lestone, McKigney, Chadwick
- Entrance Channel
  - Chyzh, Wu, Jaffke, et al.
- Macro-micro fission yields
  - Jaffke, Möller, Sierk
- $\gamma$ rays to FPY
  - Fotiades, Devlin, Jaffke