Improved ^{235}U, ^{238}U, ^{239}Pu, and ^{240}Pu Photofission Cross Sections Across the GDR

Nuclear Photonics 2025

Oct 6-10, 2025

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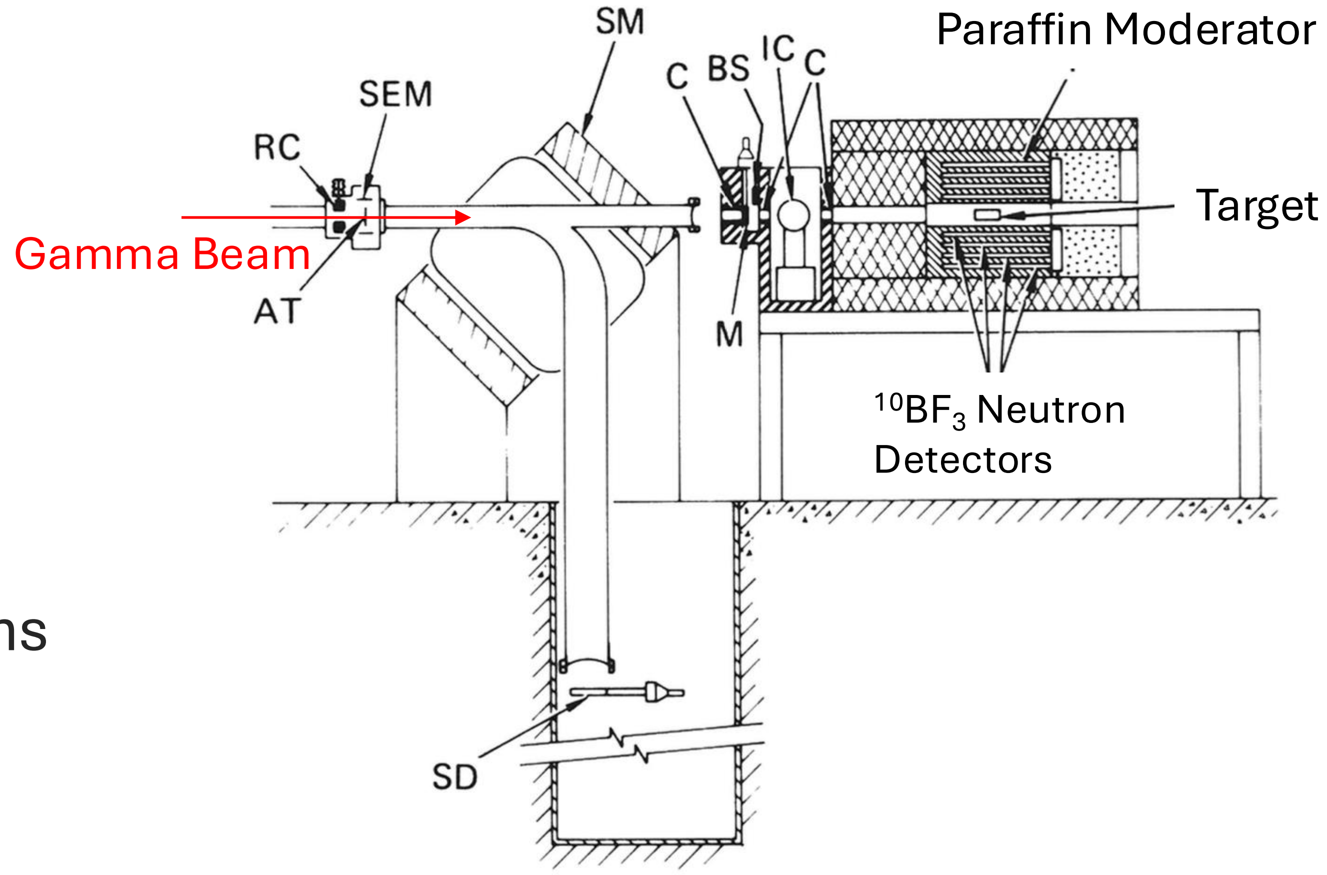
Prepared by LLNL under Contract DE-AC52-07NA27344.

Outline

- History of photofission cross section data
  - Livermore and Saclay
- Measurements at HIGS
  - ^{235}U(γ,f), ^{238}U(γ,f), ^{239}Pu(γ,f), ^{240}Pu(γ,f)
  - ^{238}U(γ,n) activation
- Results

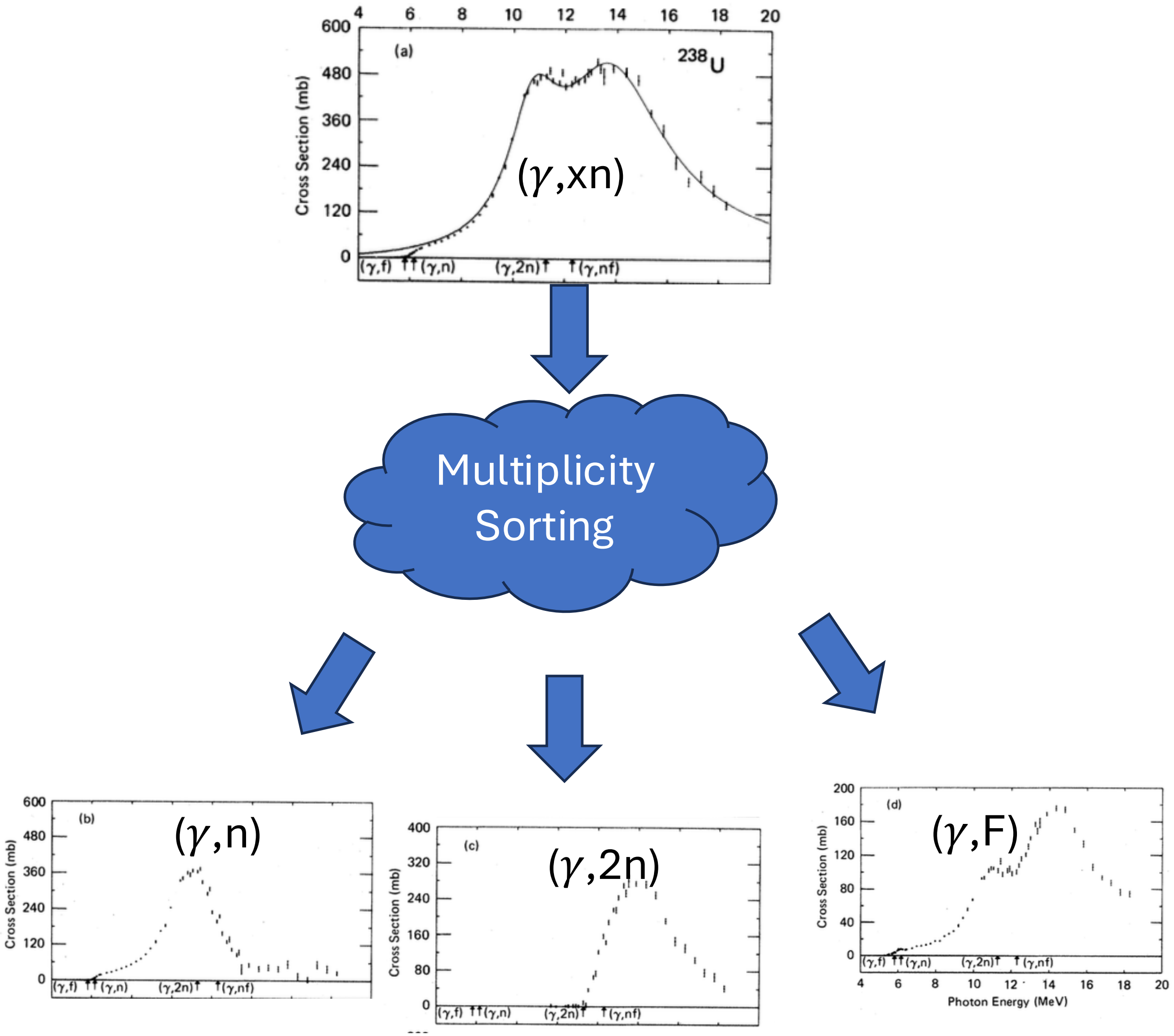
Historical Photofission Cross-Section Measurements

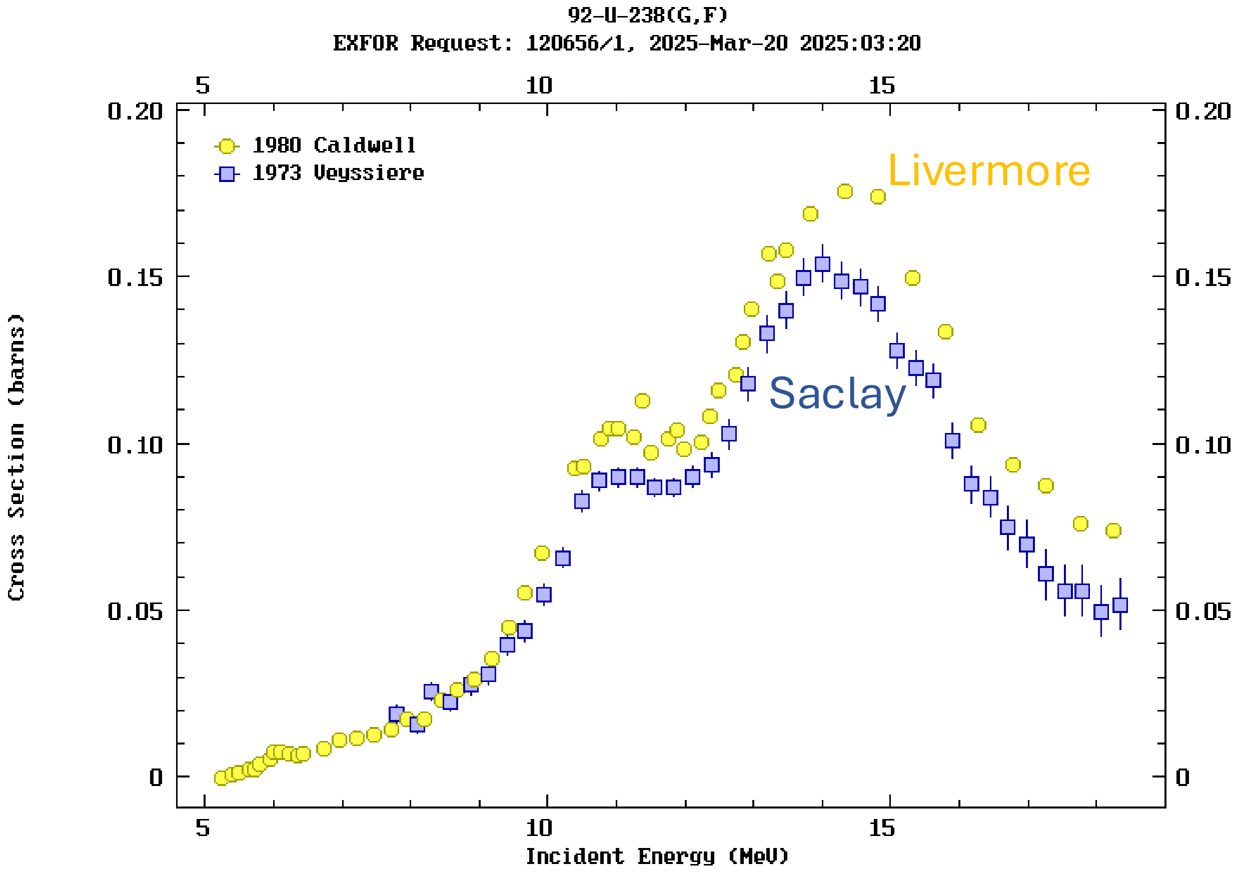
- Systematic photoneutron measurements for most nuclei performed at two labs:
  - Saclay (France)
  - Livermore (USA)
- Similar approach:
  - Quasi-monoenergetic γ-ray beams
  - Detect neutrons with rings of moderated thermal neutron detectors



J. T. Caldwell *et al.* Nuclear Science and Engineering, 73(2), 153–163 (1980).

Reaction Channels Extracted From Photoneutrons

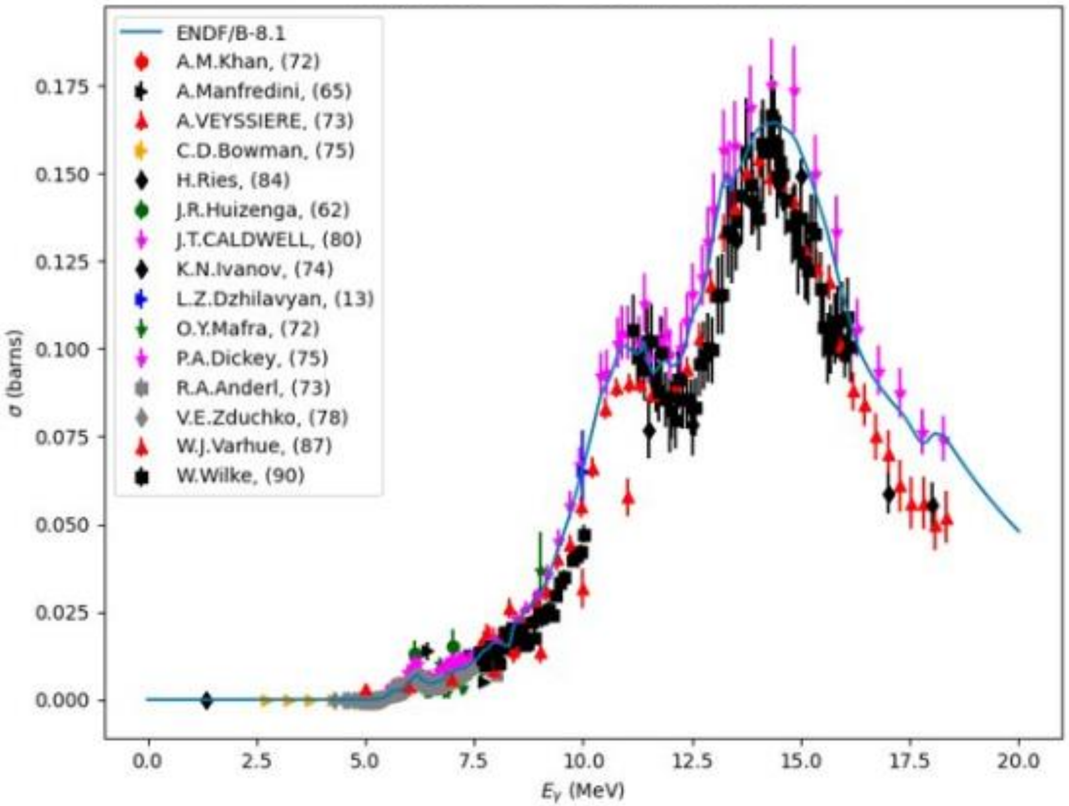




Result: systematic discrepancies between Livermore and Saclay across the nuclear chart

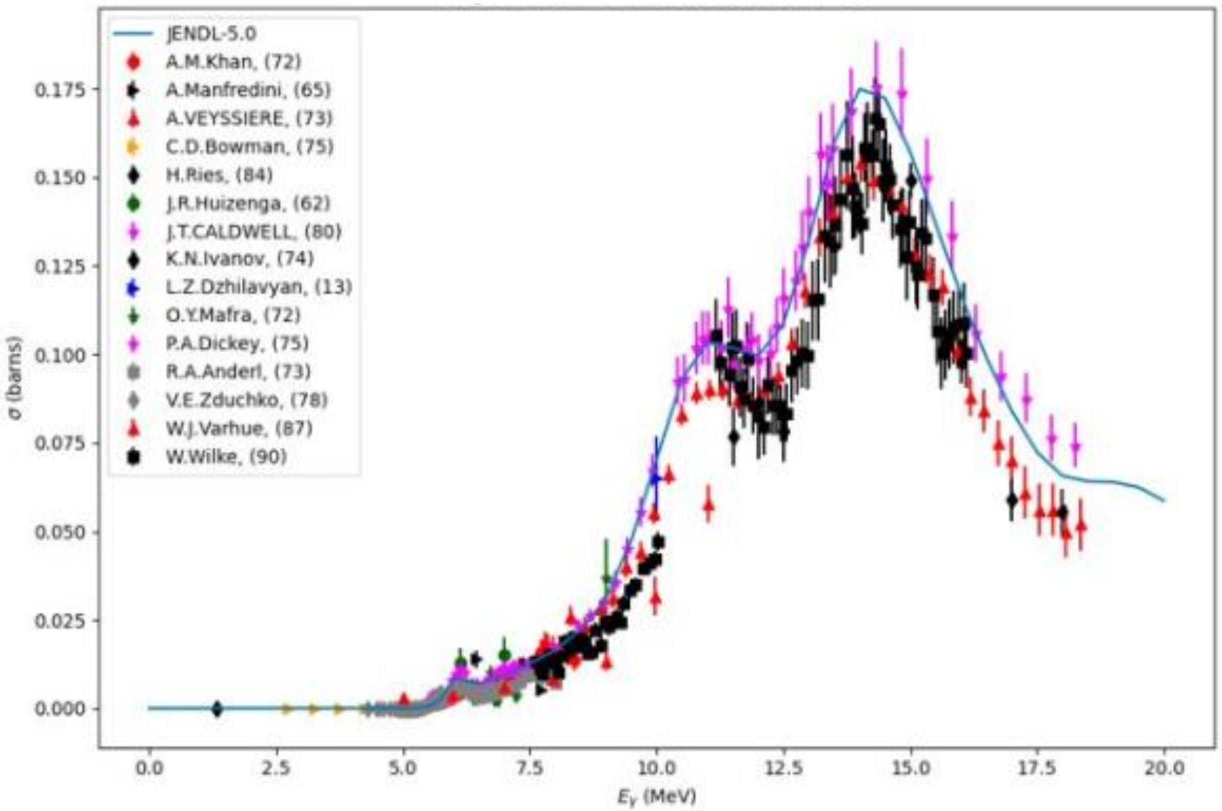
$^{238}U(\gamma,F)$: Evaluators Must Choose Between Discrepant Data

ENDF/B-8.1



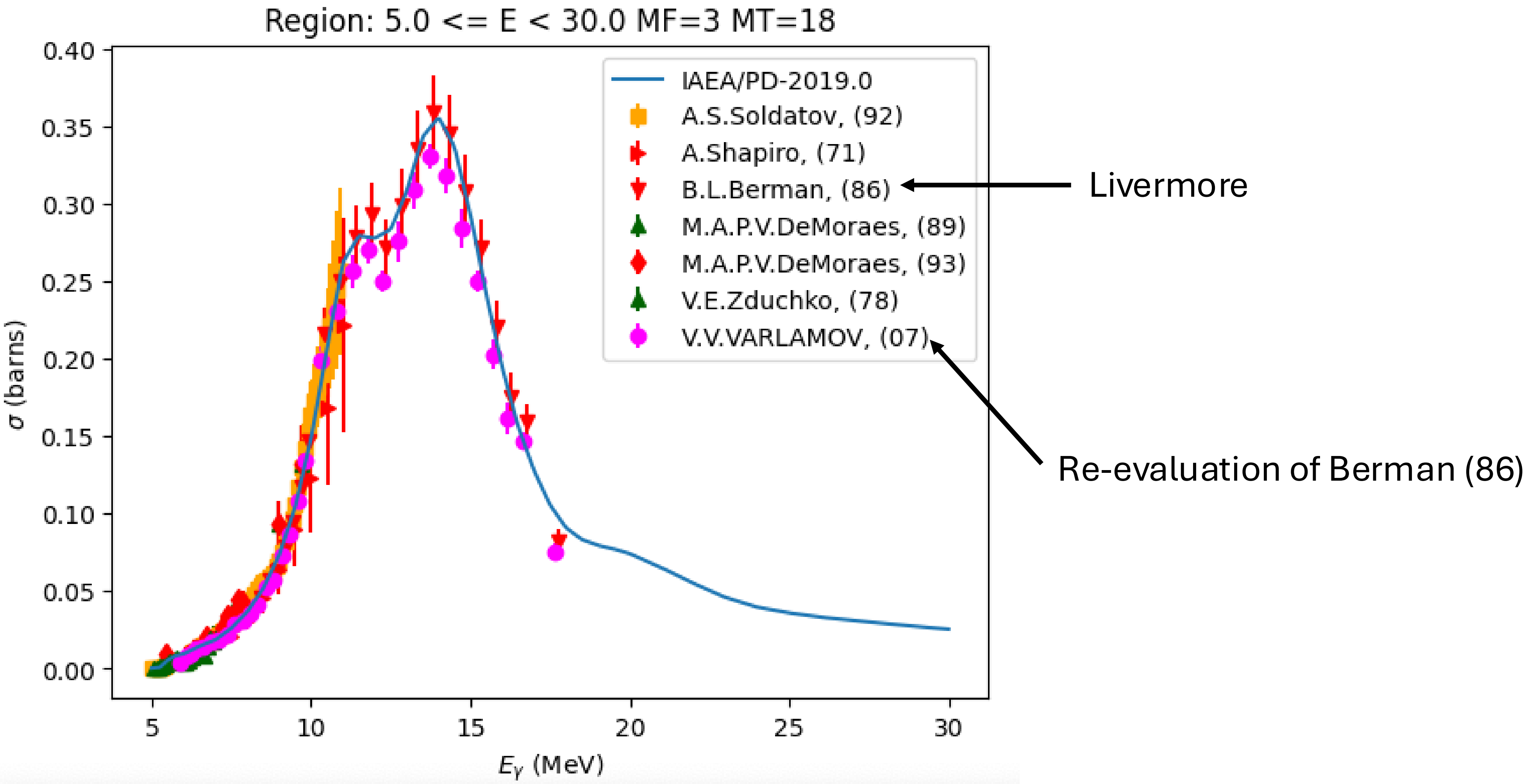
ENDF follows Livermore [Caldwell (80)] at high energies

JENDL



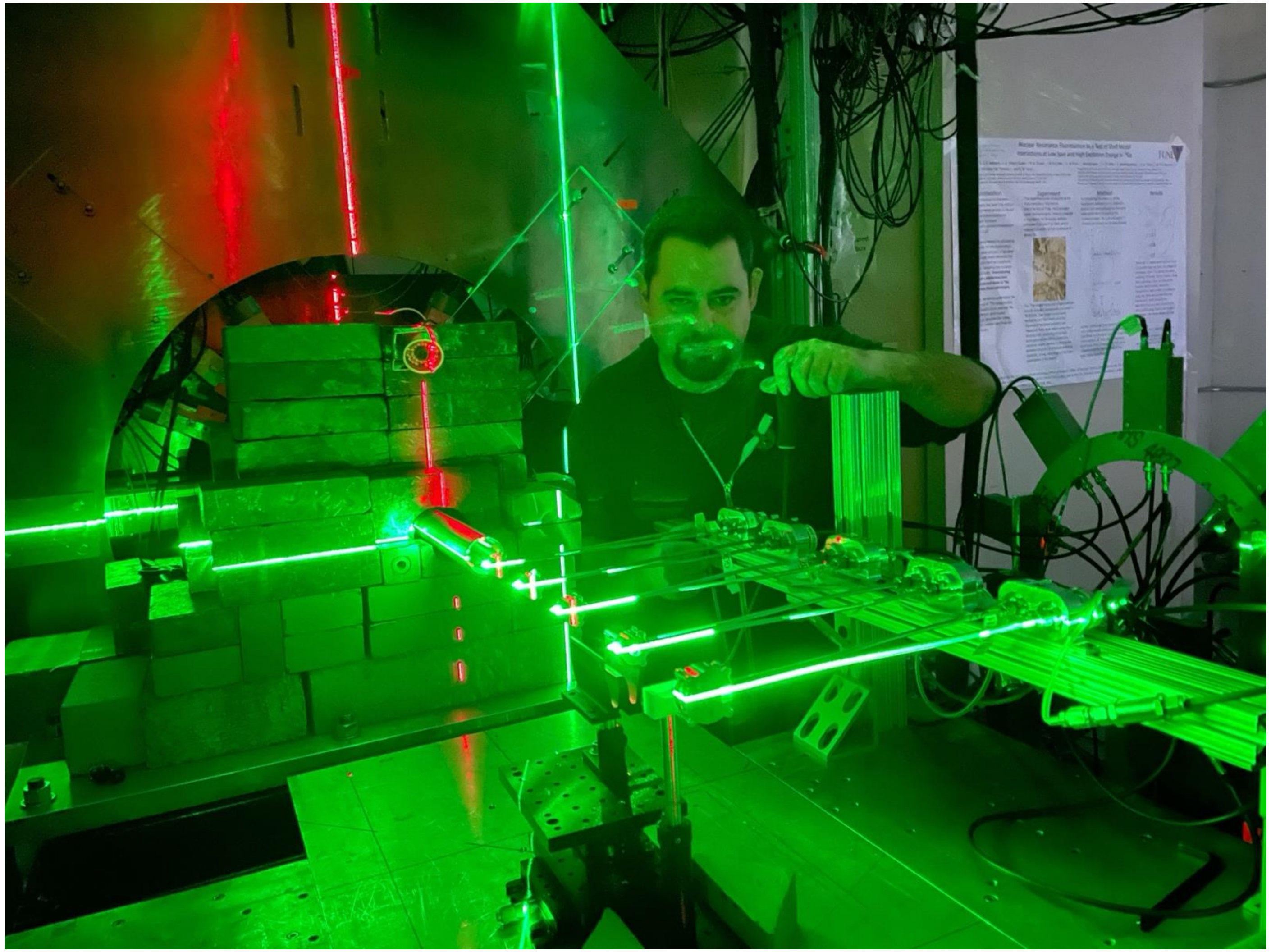
JENDL is between Livermore and Saclay [Veyssiere (73)] at high energies

^{239}Pu(γ,F): Single Monoenergetic Measurement Above 12 MeV



No Saclay data for this nucleus, evaluations have a single measurement to rely on.

Modern Photofission Cross-Section Measurements at HIGS



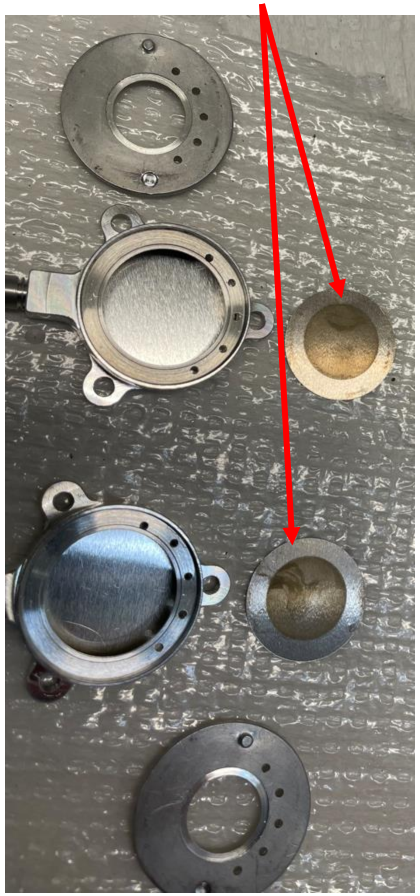
New Approach: Fission Detection Without Neutrons

- Neutron detection is hard
- Disentangling photofission neutrons from (γ,n), (γ,2n) and (γ,3n) is harder
- Detect fission fragments with ionization chambers instead
  - >97.5% fission detection efficiency

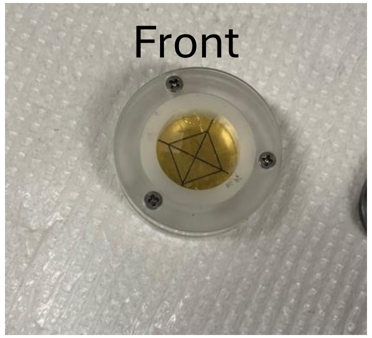
C. Bhatia *et al.* NIM A 757, 7-19 (2014).

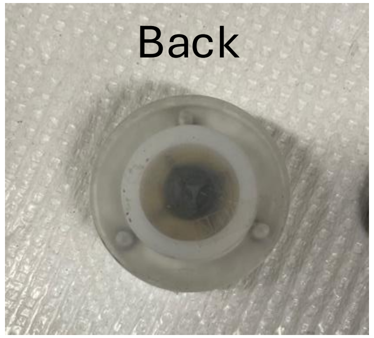
^{238}U deposits

~100 µg/cm^2



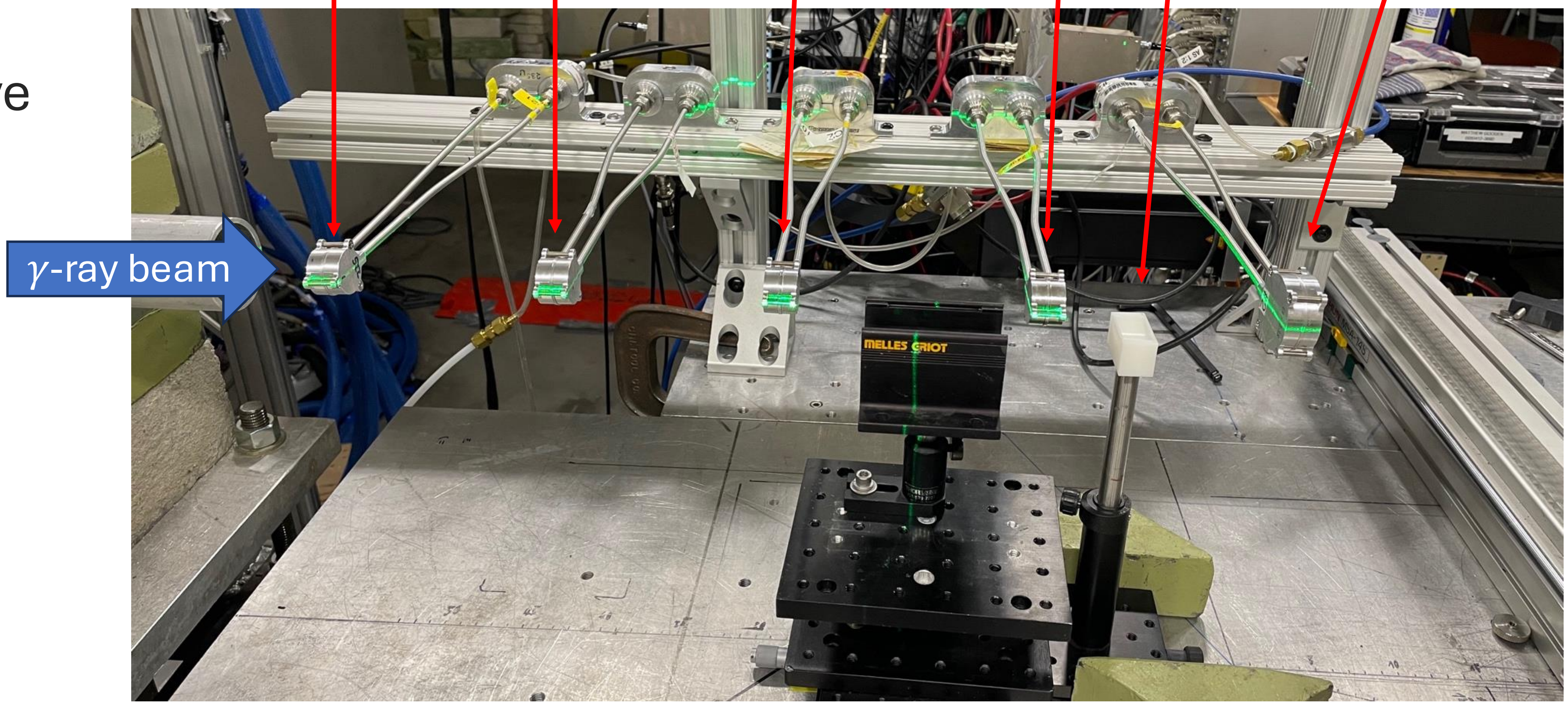
- Activation measurements at select energies
  - Foil package with ^{197}Au, ^{238}U
- ^{238}U(γ,n)
  - ^{237}U has 6.7 day half life, 208 keV γ ray
- ^{197}Au(γ,n)
  - ^{196}Au has 6.2 day half life, 355 keV γ ray





Photofission Experimental Layout

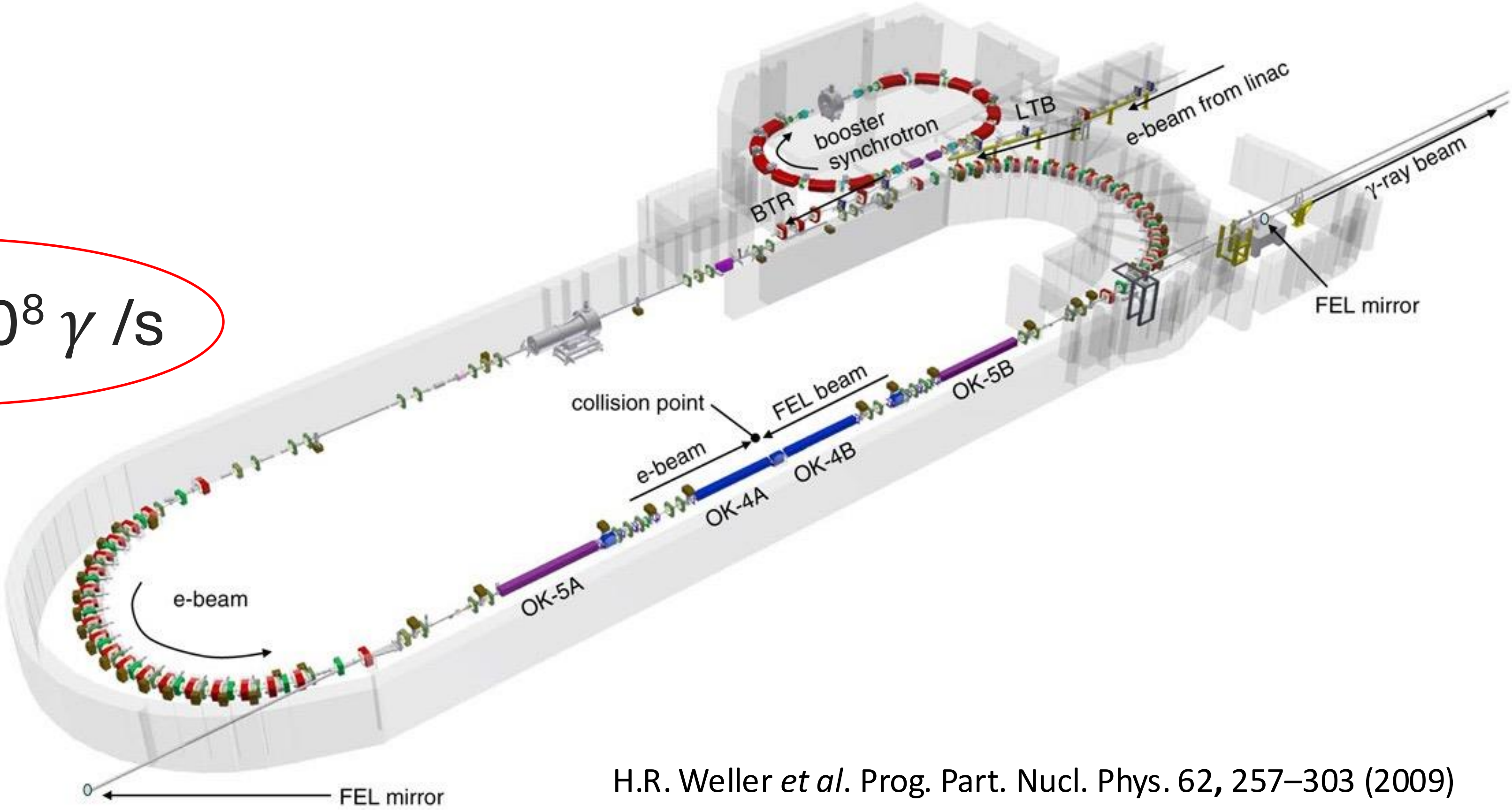
- Four DFCs loaded with a pair of foils with same isotope
  - 0.5” diameter active deposits
- One DFC with ^{235}U+^{238}U pair for beam divergence characterization
  - 1” diameter active deposits



High Intensity Gamma-ray Source (HIGS)

- Beam energies: 7 – 19 MeV
  - 0.25 MeV steps 7 – 17 MeV
  - 0.5 MeV steps 17 – 19 MeV
- Energy spread: 3% FWHM
- Flux on target: $5 \cdot 10^7 - 4 \cdot 10^8\ \gamma$ /s

This is why we can have <100 μg targets and detect fission fragments

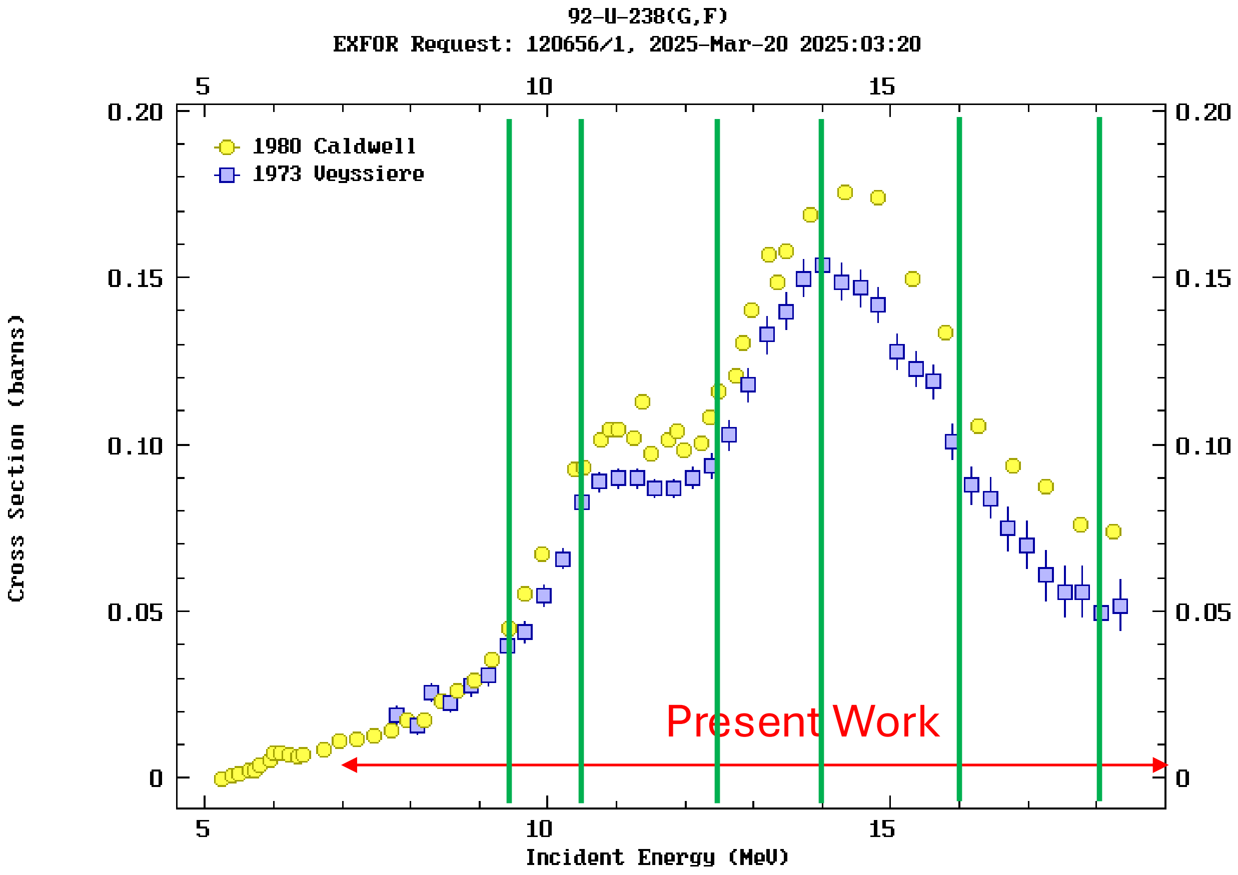


H.R. Weller *et al*. Prog. Part. Nucl. Phys. 62, 257–303 (2009)

HIGS Experiment February 26th – March 7th, 2025

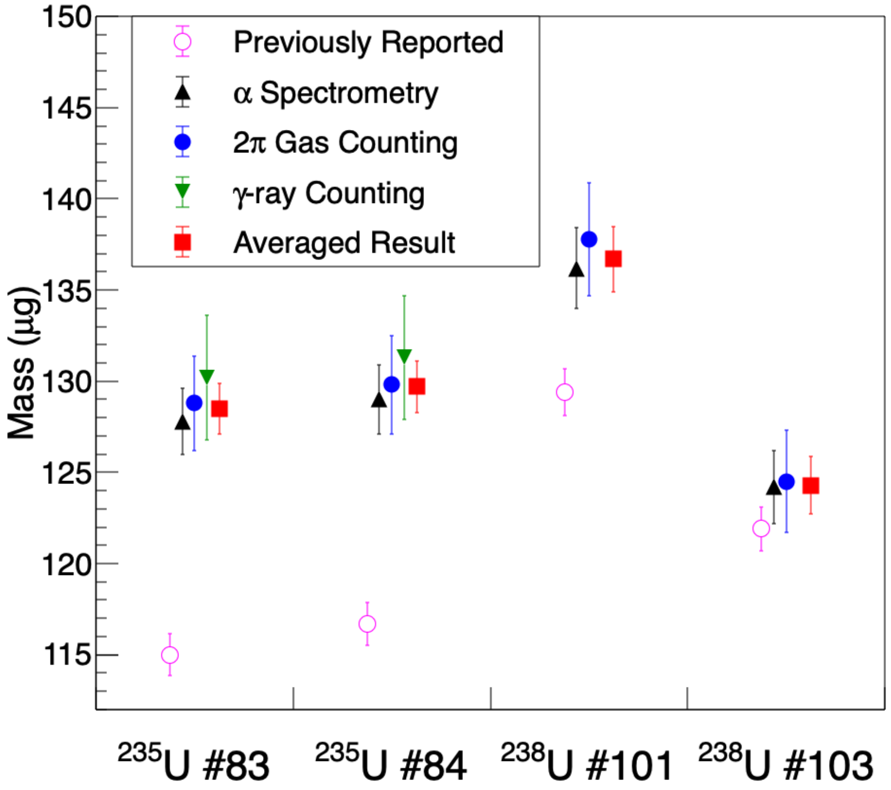
- 74 hours of HIGS PAC beamtime HIGS-P-10-24 (PI Sean Finch)
  - Two FEL wavelengths required to span the full energy range
    - 540 nm: 7-13 MeV
    - 460 nm: 13-19 MeV
  - Mirror change halfway through
- 7 MeV ≤ E_γ ≤ 19 MeV
  - 0.25-MeV steps up to 17 MeV
    - 0.5-MeV steps up to 19 MeV
  - Six $^{238}U(\gamma,n)$ activation measurements

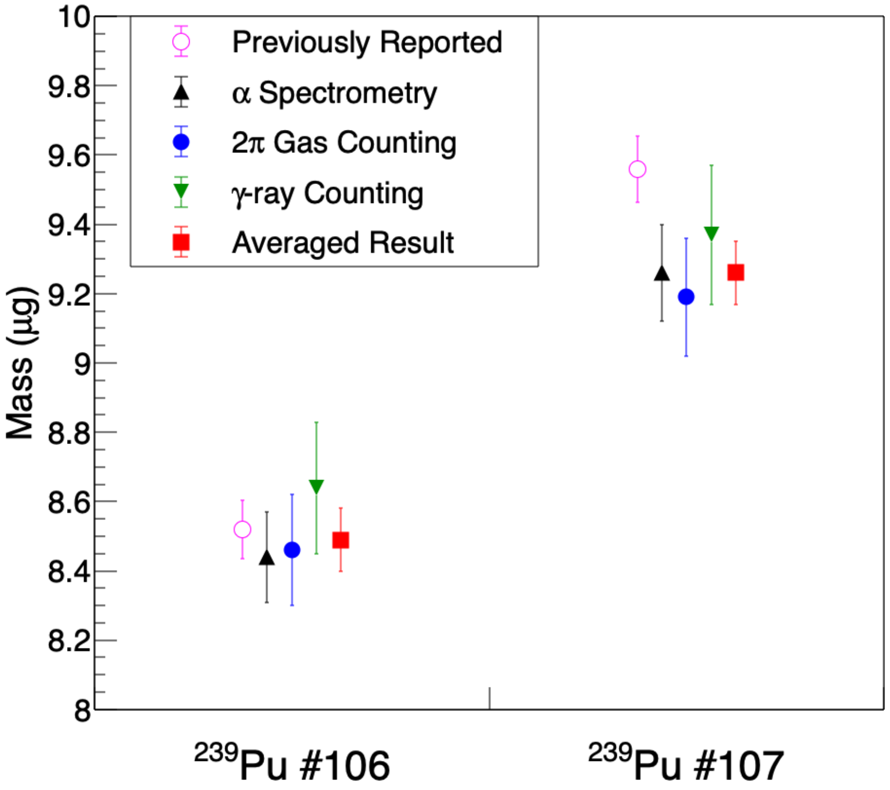
$^{238}U(\gamma,n)$ activation energies



Constraining Uncertainties: Actinide Target Masses

- Three independent methods:
  - Low geometry α spectrometry
  - 2π gas counting
  - γ-ray counting
- Better than 1.3% uncertainty for all targets

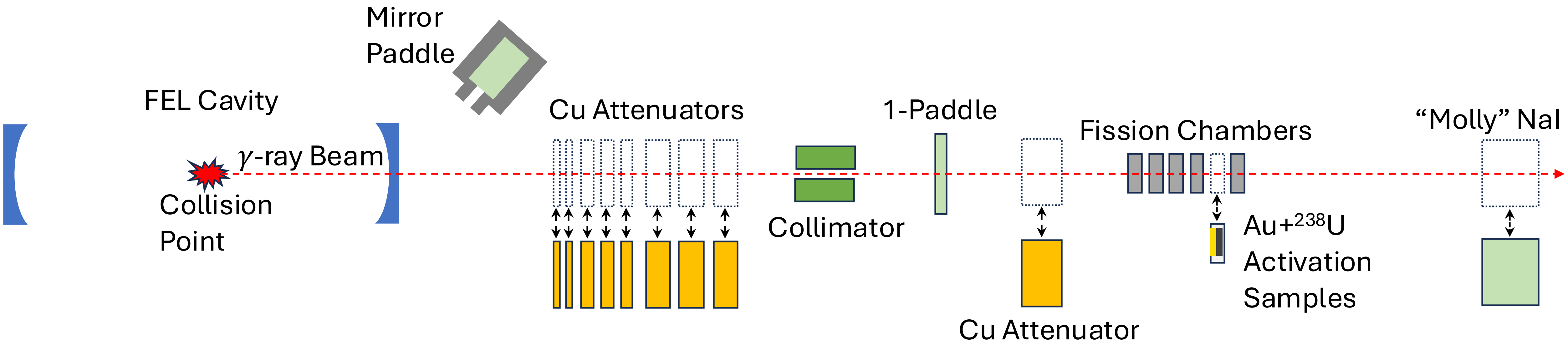




J. A. Silano *et al.*, Nucl. Instrum. Methods in Phys A **1063**, 169234 (2024).

Measuring the HIGS γ-ray Beam Flux

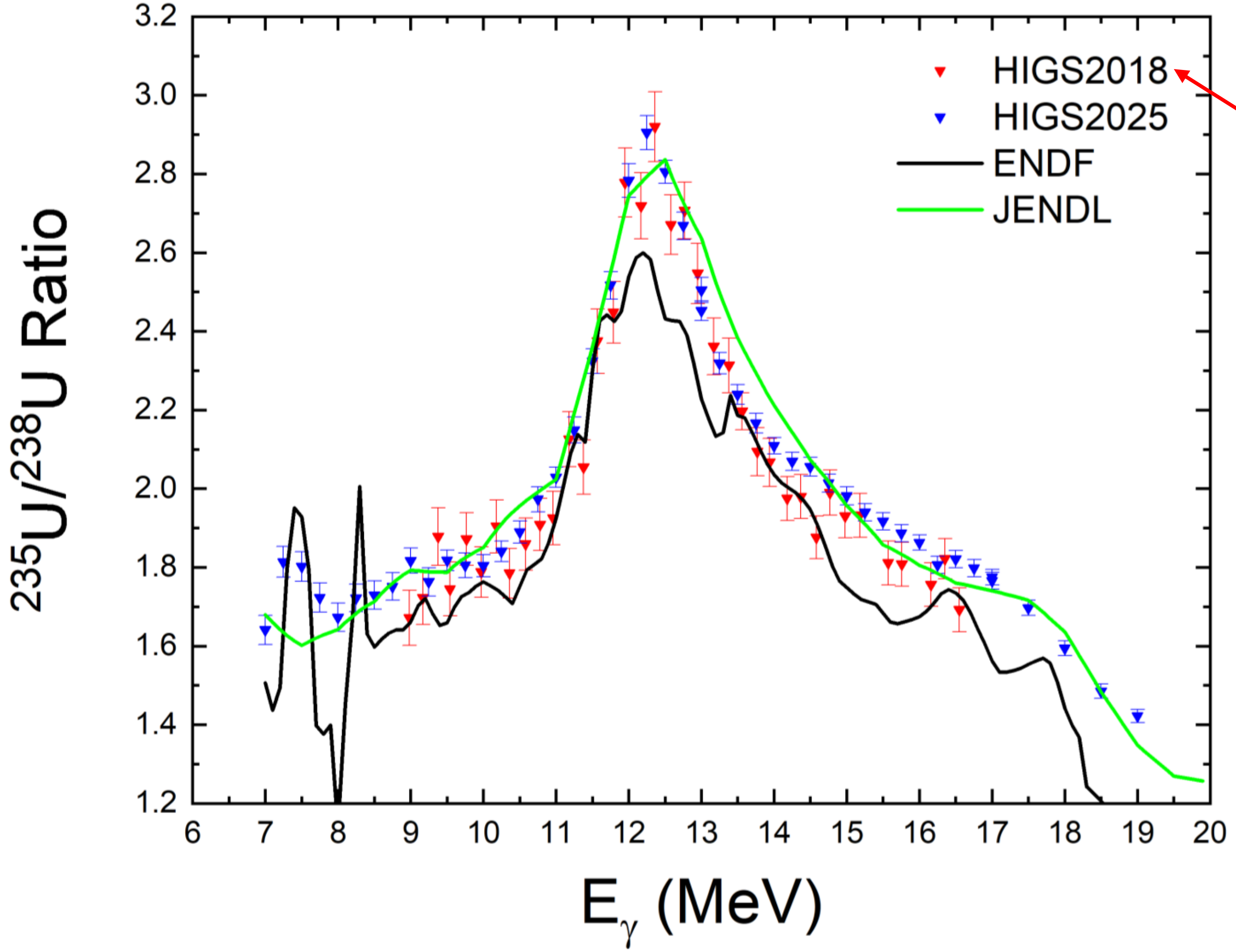
- Mirror Paddle
  - Scintillator observes backscattered radiation from γ-ray beam passing through mirror
- 1 Paddle
  - Thin scintillator directly in beam
- Large NaI detector for calibrating absolute flux
  - ~100% efficiency
- Au activation foils for validation



Results

- Photofission cross-section ratios
  - All targets in the beam simultaneously, flux cancels out
  - Depends only on relative actinide target masses, fission counts, and a few minor corrections
  - Can be measured to higher precision (1.6 – 3.2%) than absolute cross sections
  - Valuable for nuclear data evaluations
- Absolute Photofission Cross Sections
  - The main goal, with 4 – 6% uncertainty
- $^{238}U(\gamma,n)$

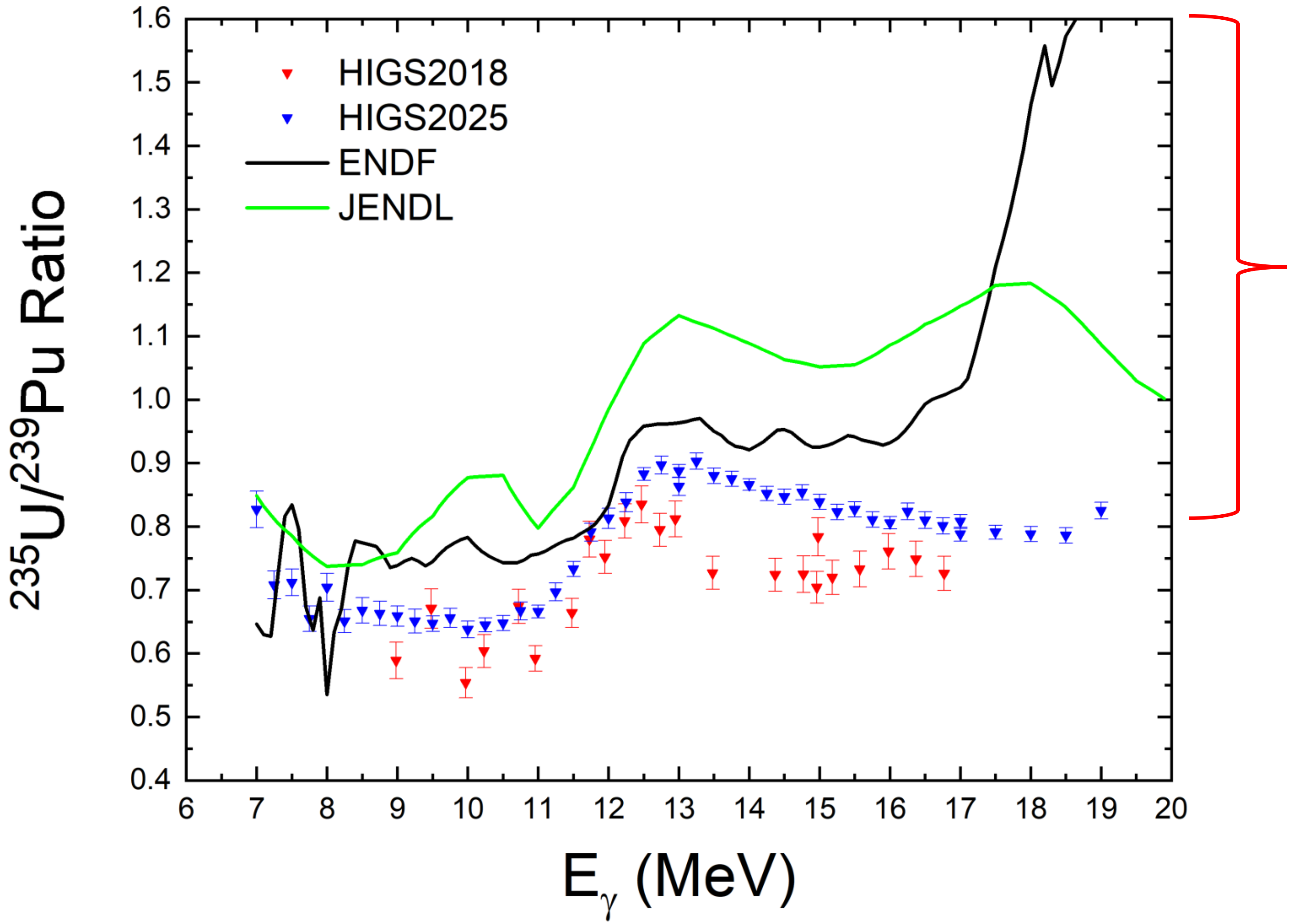
$^{235}U(\gamma,f)/^{238}U(\gamma,f)$ Cross-Section Ratio



Same DFCs,
different configuration,
different targets

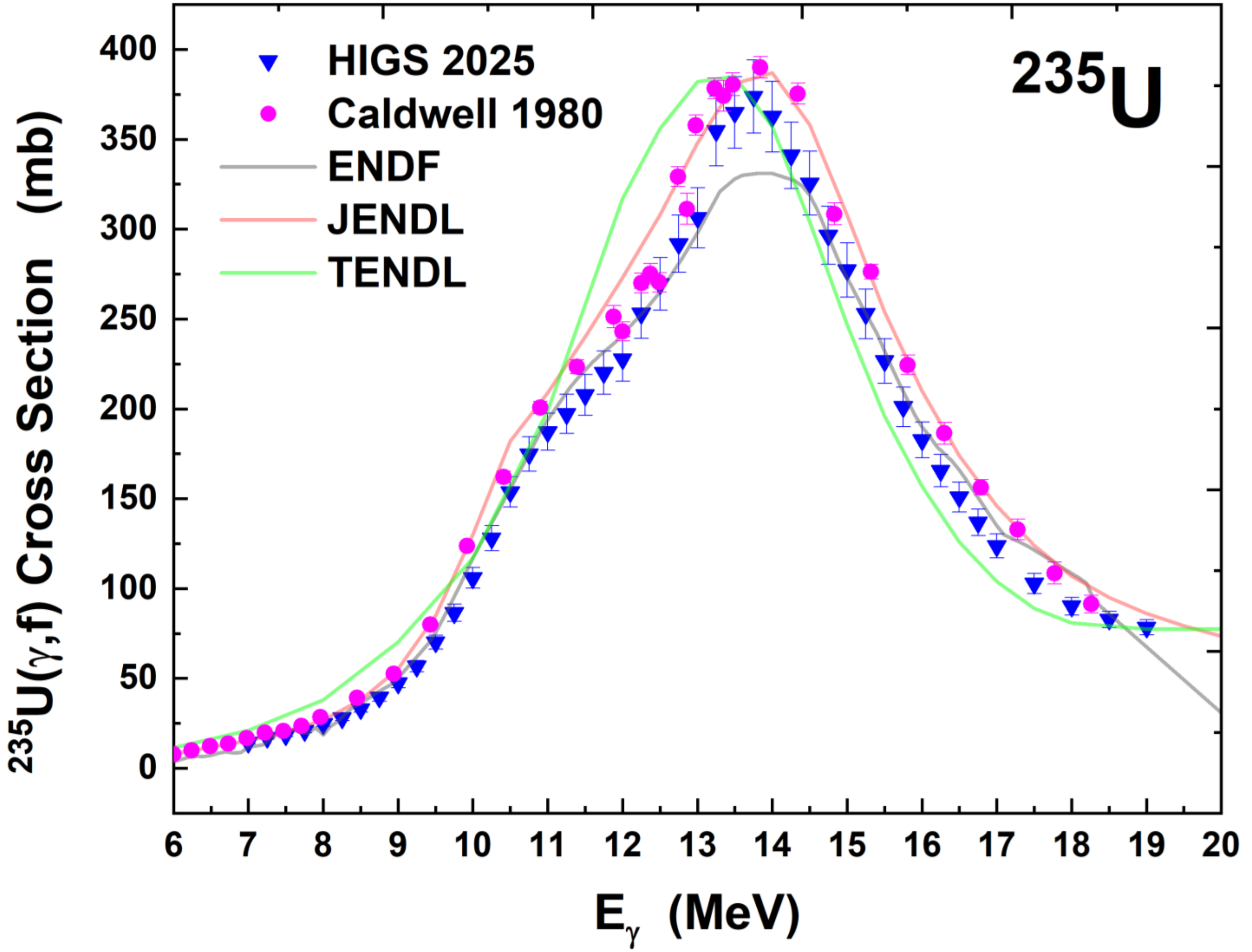
Krishichayan *et al*. Phys. Rev. C **98**, 014608 (2018)
S. Finch *et al*. Phys. Rev. C **107**, 039906 (2023)

$^{235}U(\gamma,f)/^{239}Pu(\gamma,f)$ Cross-Section Ratio

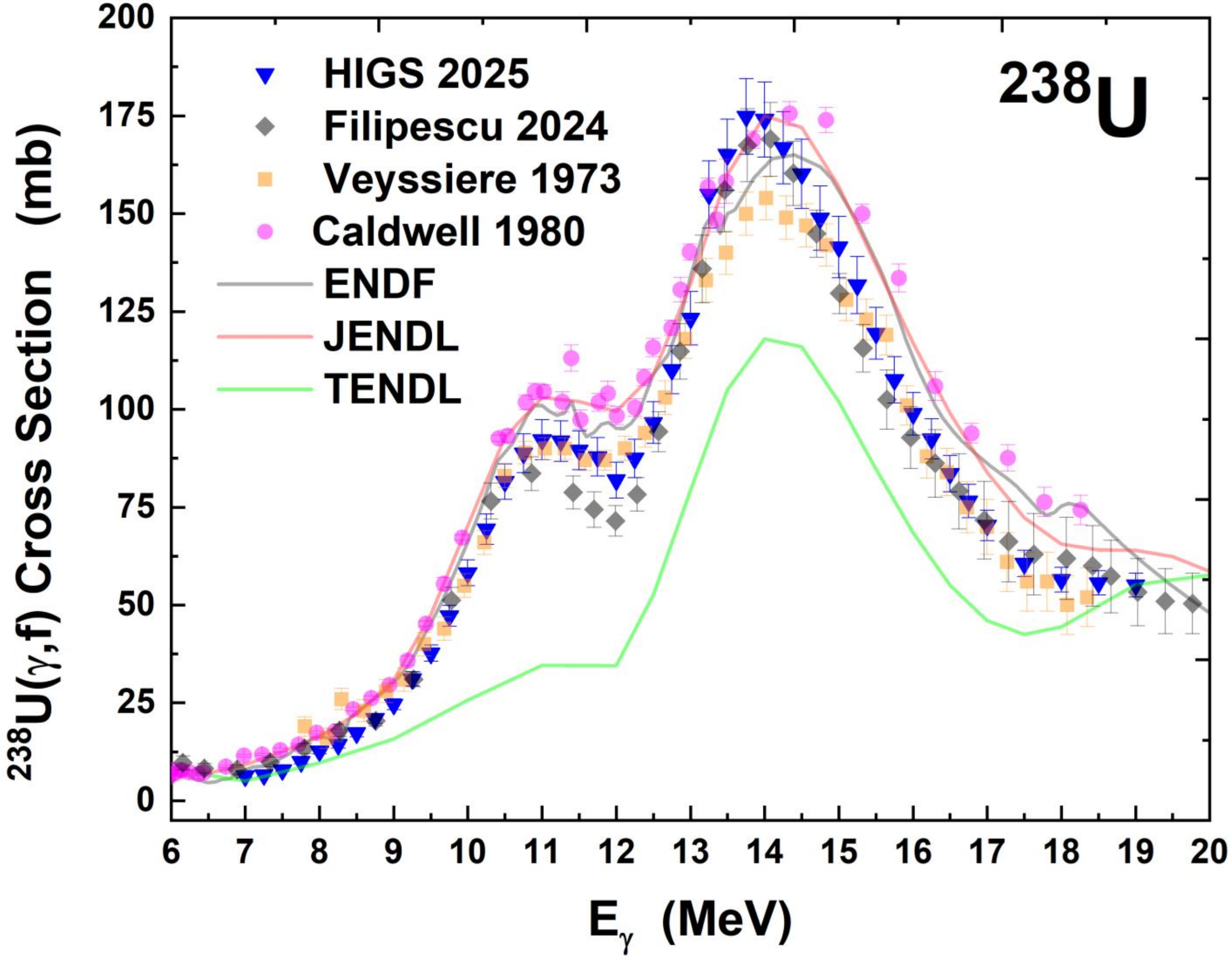


Major discrepancy at high E_γ for any ratio with ^{239}Pu…

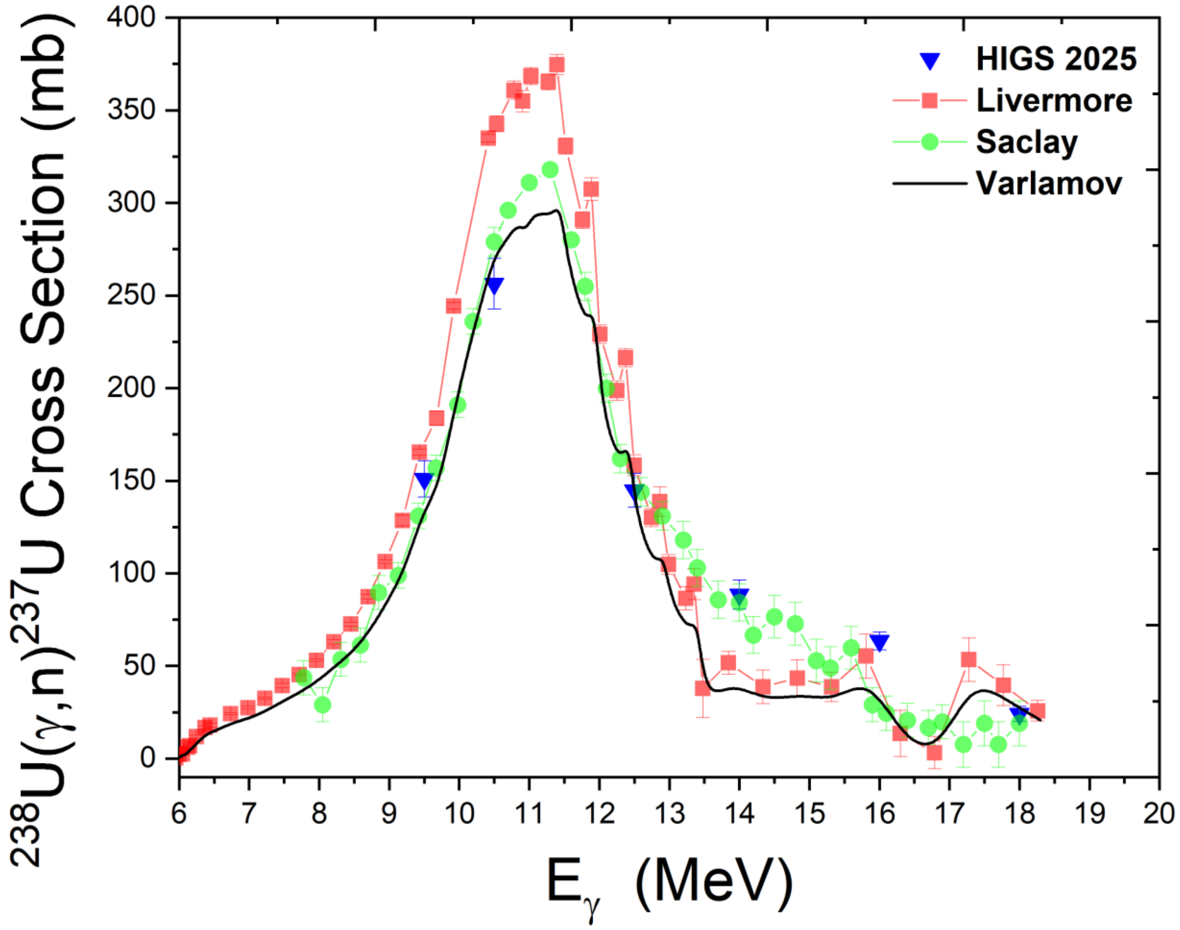
^{235}U Photofission Cross Section



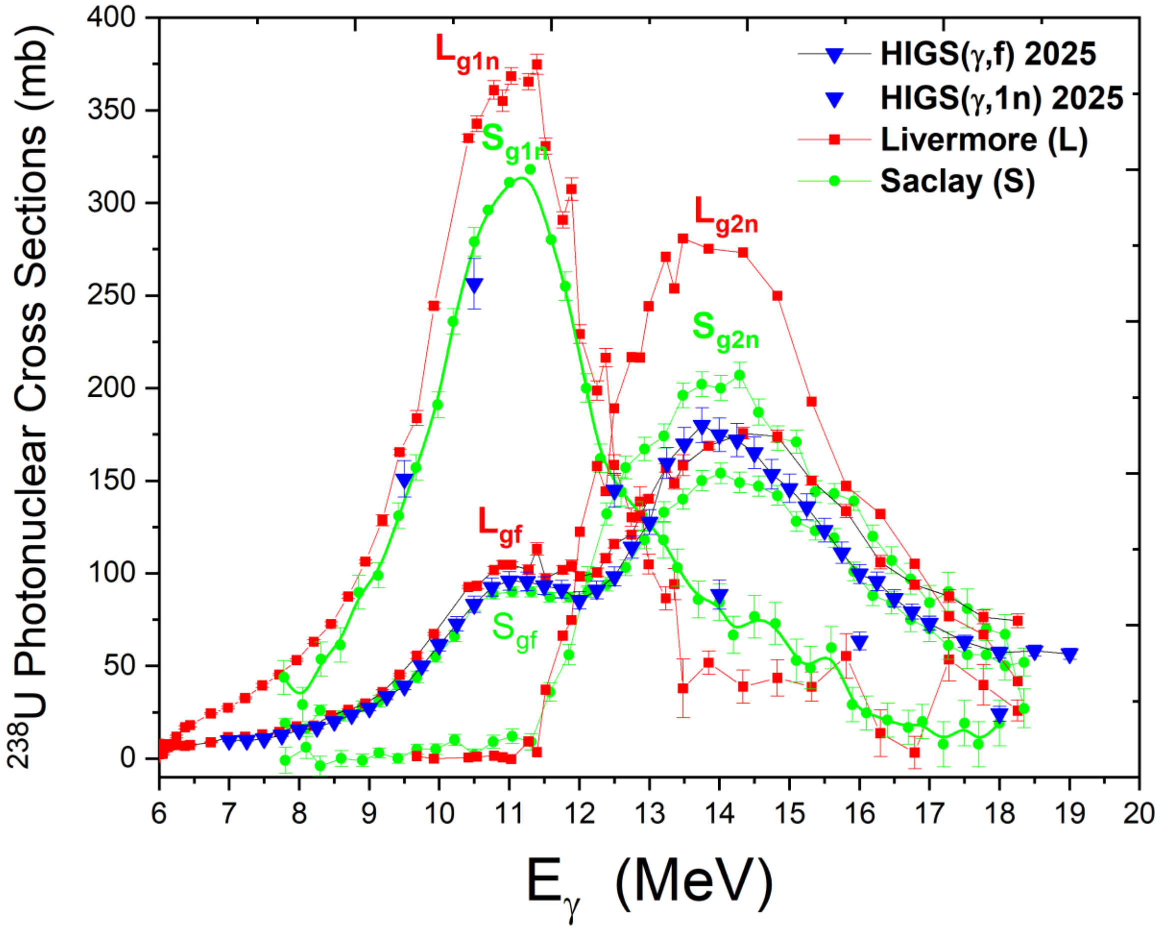
^{238}U Photofission Cross Section



$^{238}U(\gamma,n)$

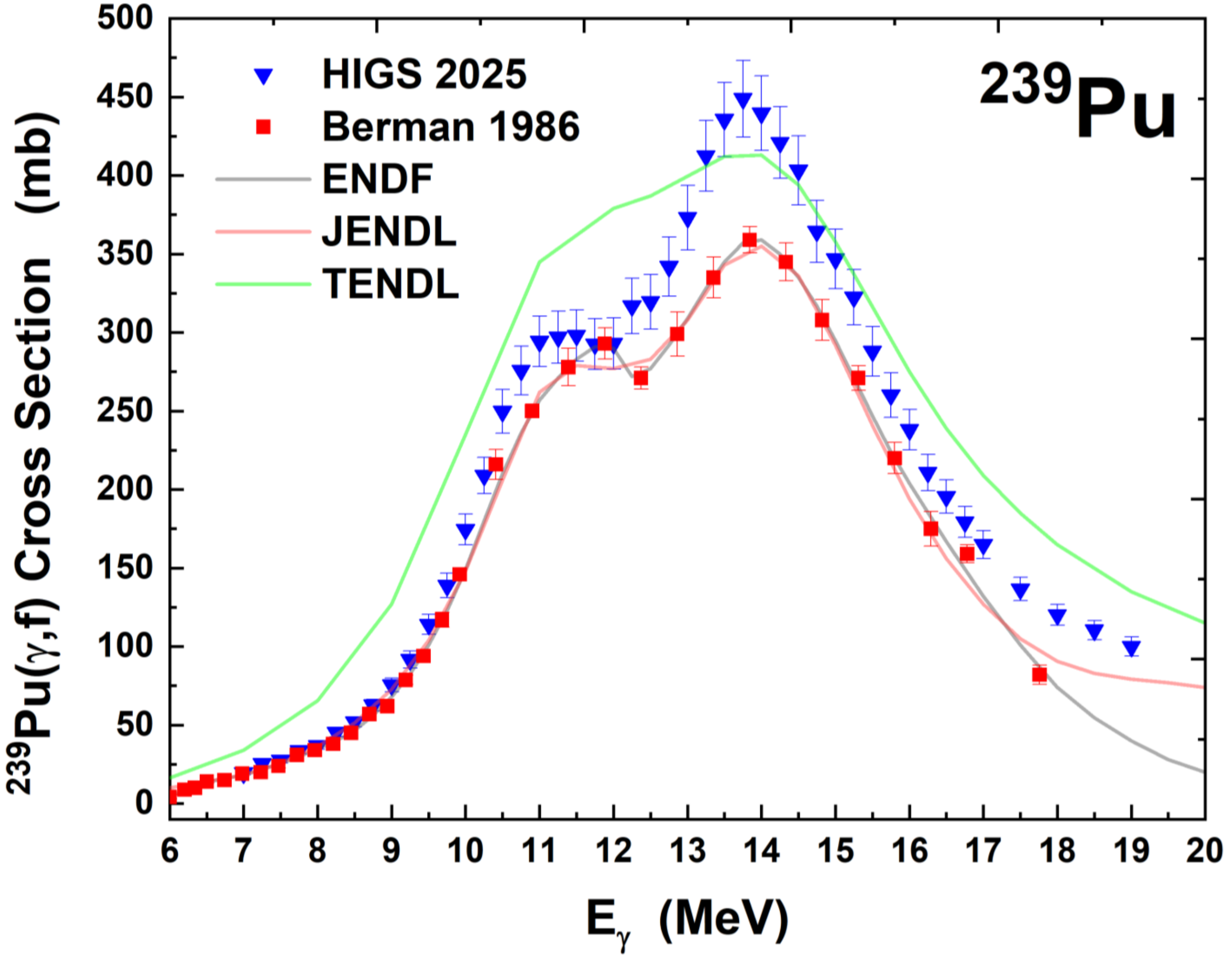


HIGS 2025
Livermore
Saclay
Varlamov
$^{238}U(\gamma,n)^{237}U$ Cross Section (mb)
E_γ (MeV)
0
50
100
150
200
250
300
350
400
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20



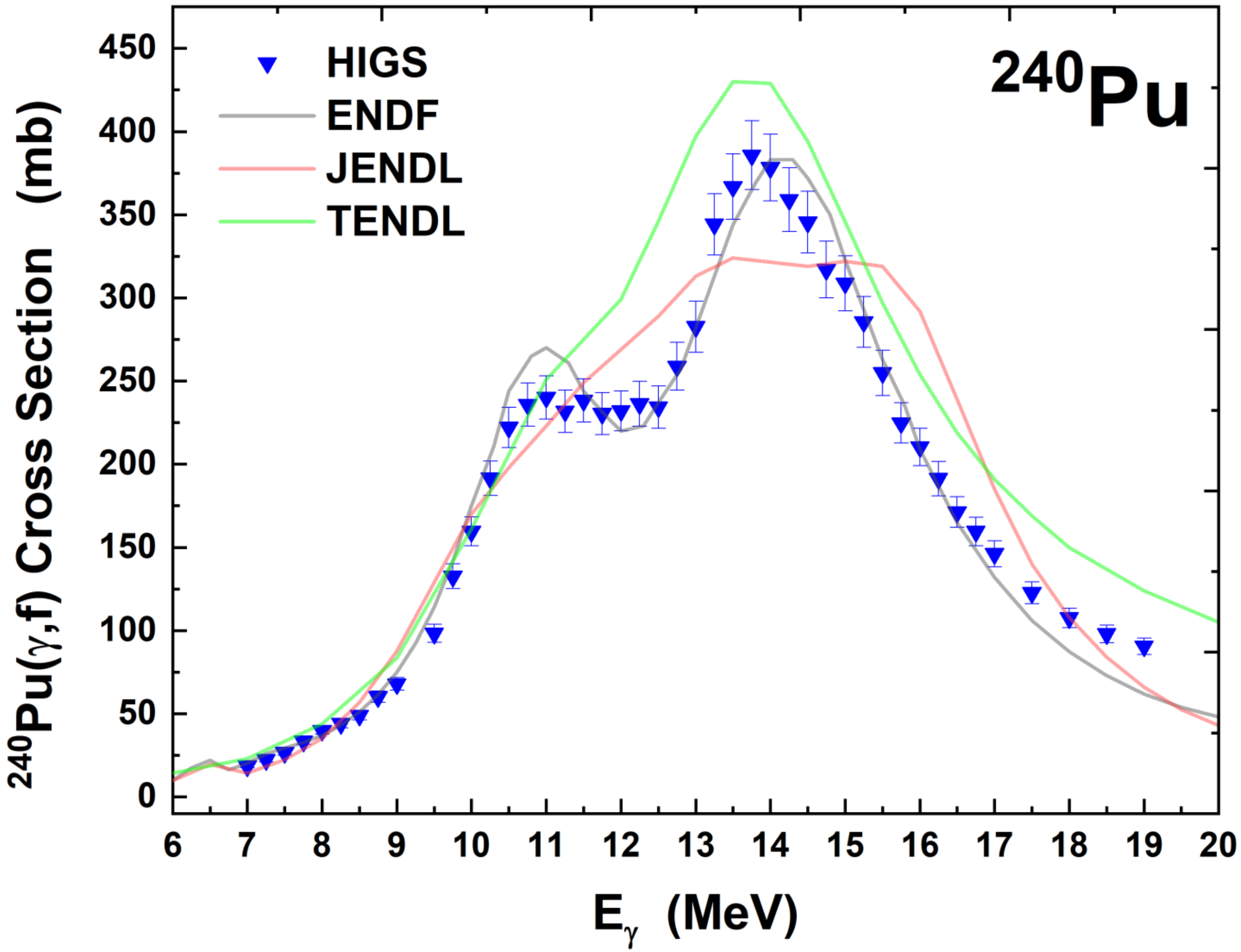
HIGS(γ,f) 2025
HIGS(γ,1n) 2025
Livermore (L)
Saclay (S)
L_{g1n}
S_{g1n}
L_{g2n}
S_{g2n}
L_{gf}
S_{gf}
^{238}U Photonuclear Cross Sections (mb)
E_γ (MeV)
0
50
100
150
200
250
300
350
400
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

^{239}Pu Photofission Cross Section



- Large systematic deviation above ~12.5 MeV
- Livermore data issues unfolding the $(\gamma,2n)$ channel?

^{240}Pu Photofission Cross Section



First quasi-monoenergetic γ-ray beam measurement for this nucleus!

Future Plans

- Finalize analysis and publish ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu photofission cross sections for 7 – 19 MeV
- Planned experiment to add ^{242}Pu and increase energy range
  - ^{242}Pu fission chamber foils fabricated at LLNL, currently being characterized
  - Measure $^{242}Pu(\gamma,f)$ in 7 – 19 MeV
  - Measure all targets from 19 – 25 MeV

Acknowledgements

Lawrence Livermore National Laboratory

J. Silano
A. Ramirez
A. Tonchev

JMU JAMES MADISON UNIVERSITY

A. Banu

USNA UNITED STATES NAVAL ACADEMY

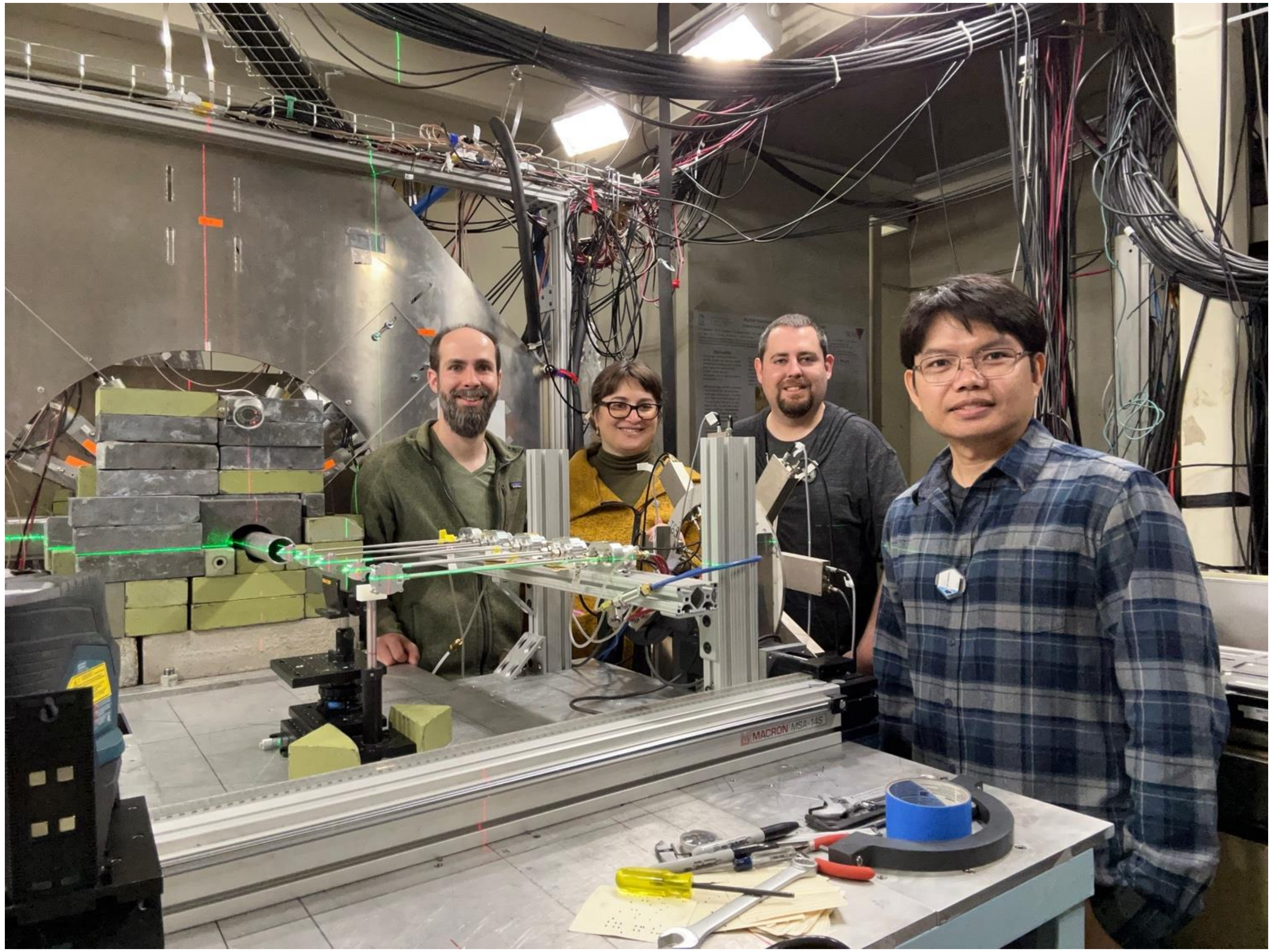
R. Malone

TUNL

S. Finch
F. Friesen

UC Berkeley

D. Brewster



Backup

Fission Chamber Efficiency