NUCLEAR DATA EVALUATIONS OF ACTINIDES: LESSONS FOR THE NEXT DECADE

Roberto Capote
Suncoast Data Evaluation

P(ND)^2-3, Perspectives on nuclear data for the next decade
Campus des Cordeliers, Paris 6ème arrondissement, 09-13 March 2026

INDEN: International Nuclear Data Evaluation Network

Coordinators: RC, P. Dimitriou, G. Schnabel https://nds.iaea.org/INDEN

Special thanks to: A. Trkov, M.W.Herman, M. Sin, B.V.Carlson, G. Nobre, D. Brown, V. Zerkin (EMPIRE) G. Noguere, M. Pigni, D. Bernard, Y. Danon, D. Neudecker, P. Romain, G. Schnabel, STD comm.

Status of major actinide evaluations in US

- IAEA CIELO evaluations of **n+ ^{235,238}U** adopted for ENDF/B-VIII.0 including IAEA evaluated thermal PFNS for ^{235}U(n,f), LANL/LLNL Chi-nu PFNS
- INDEN **n+ ^{235,238}U** evaluations (largely based on CIELO) adopted for ENDF/B-VIII.1
- INDEN **n+ ^{239}Pu** evaluation partially adopted for ENDF/B-VIII.1 - (n,2n) & (n,γ) including IAEA evaluated thermal PFNS for ^{239}Pu(n,f), LANL/LLNL/CEA PFNS/nubar

- New INDEN **n+ ^{239}Pu** evaluation (p44) developed and distributed at NDST2025 including IAEA evaluated thermal PFNS for ^{239}Pu(n,f), LANL/LLNL/CEA PFNS/nubar

What have we learned? What is foreseen for the next decade?

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Definition of (ND) Evaluation

A properly weighted combination of selected experimental data (and nuclear reaction modelling results if needed).

properly weighted = Bayesian approaches

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Goal of (ND) evaluation

To produce the most reliable mean values with uncertainties

(if we have data, improving the models is a bonus but not the goal)

"It doesn't matter how beautiful your theory is,
it doesn't matter how smart you are.
If it doesn't agree with experiment, it's wrong."

Richard Philips Feynman,

Nobel Prize in Physics 1965

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Differential experimental data for major actinides (2014+)

alpha≡(n,γ)/(n,f)

- Wallner et al 2014, AMS ^{238}U/^{235}U and ^{238}U/^{197}Au capture ratio @25 keV,426 keV
- Mosby et al 2018, ^{239}Pu alpha up to 1.4 MeV, LANL
- Kim et al 2016, ^{238}U(n,g), JRC Geel
- Danon et al 2017, ^{235}U alpha and ^{235}U(n,f) below 5 keV, RPI
- Caballero et al, 2026 ^{239}Pu alpha from thermal up to 10 MeV, n_TOF
- Dongwi et al 2025, Snyder et al 2021 TPC ^{239}Pu(n,f) /^{235}U(n,f) (TO BE USED AS SHAPE DATA)
- Silano et al 2025, ^{239}Pu(n,f) /^{235}U(n,f), TUNL
- Michalopoulos 2023 (n_TOF), Ren 2023 (CSNS), Vorobyev et al 2023 (PNPI) ^{238}U(n,f) /^{235}U(n,f)
- Lisowski et al, total XS, several actinides, LANL
- Kerveno et al, ^{238}U(n,n'g), 2021, JRC Geel

- Meot et al 2021, ^{239}Pu(n,2n), CEA/BRC
- Krishichayan et al 2017, ^{238}U(n,2n), TUNL/LLNL
- Chi-Nu 2015-2026, LANL/CEA/LLNL, PFNS for En>0.5 MeV, M. Devlin, K. Kelly, J. Taieb et al
- Marini et al 2022 - ^{239}Pu(n,f) nubar, VENDETA …

Key experimental data drive better evaluations and uncertainty reduction !!

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Example 1: (n,γ) uncertainty in ENDF/B-VIII.1 (INDEN)

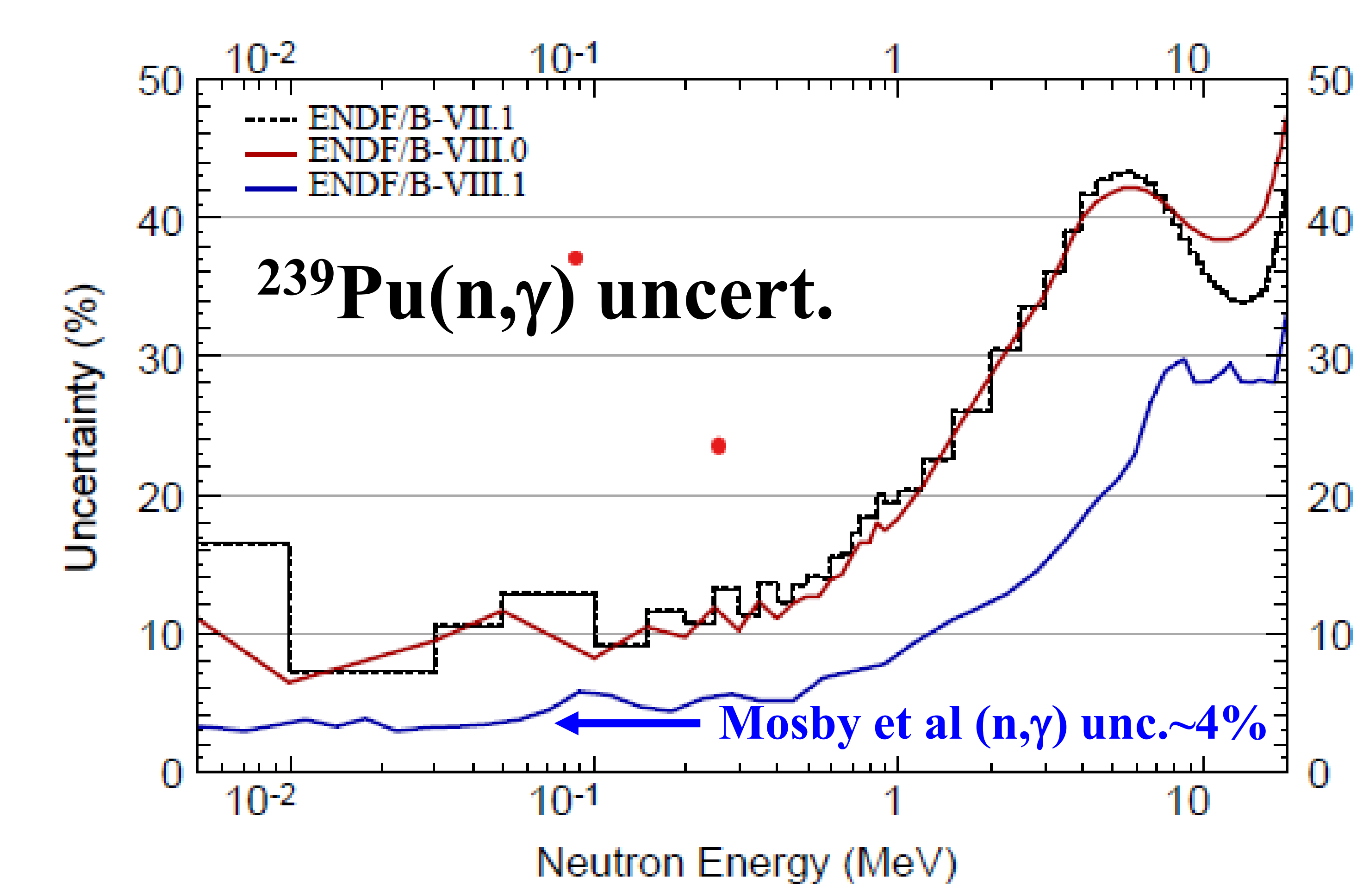
TABLE VI. Selection of absorption (alpha ratio ≡ capture/fission) cross-section measurements of ^{239}Pu for incident neutron energy above 5 keV from the EXFOR database [31]. Experiments selected for fitting are marked by a "+" sign in the first column.

	Author	Year	EXFOR No.
+	Bolotskii *et al.* [76]	(1977)	40548002
+	Ryabov [77, 78]	(1976)	40312003
+	Gwin *et al.* [79]	(1976)	10267029
+	Kononov *et al.* [80]	(1975)	40412005
	Kononov data discarded for E_n > 60 KeV:		
+	Bandl *et al.* [81]	(1972)	20158003
+	Kurov *et al.* [82]	(1972)	40024003
+	Weston *et al.* [83]	(1972)	10301003
-	Farrell *et al.* [84]	(1970)	10326002
+	Belyaev *et al.* [72]	(1970)	40087008
+	Schomberg *et al.* [85]	(1970)	20476005
+	de Saussure *et al.* [86]	(1966)	12409004
+	de Saussure *et al.* [86]	(1966)	12409005
+	Hopkins *et al.* [73]	(1962)	12331007
-	Andreev [74]	(1958)	40385008
-	Spivak *et al.* [75]	(1956)	40350016

Systematic uncertainties:
3% for each EXFOR set
3% common to all measurements

+ LANL Mosby data alpha ratio

Important to use alpha data and update for latest standard (n,f)values



G. Nobre, RC, et al, ENDF/B-VIII.1 paper
https://doi.org/10.48550/arXiv.2511.03564

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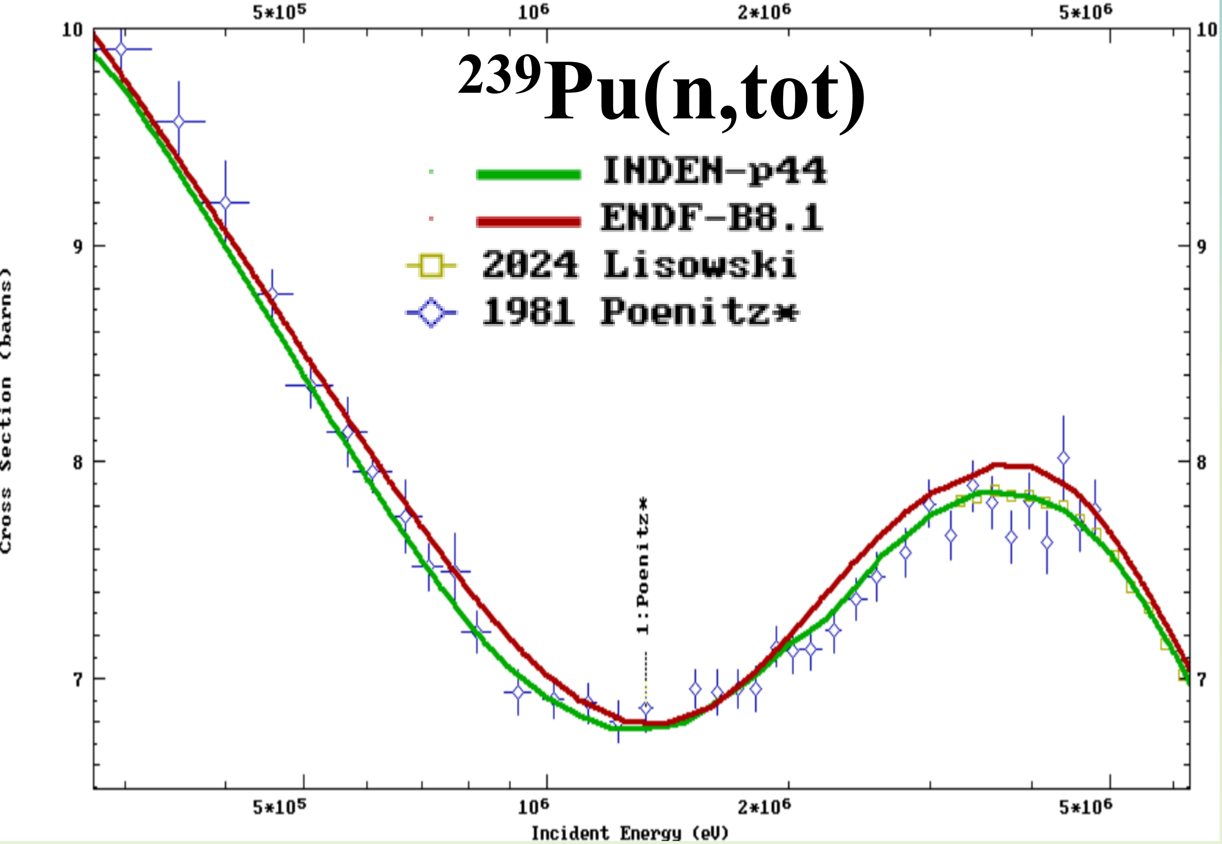
Example 2: Total cross section n + ^{239}Pu (INDEN p44, Jun.25)

Lisowski et al, NSE 198 (2024) 1901

https://doi.org/10.1080/00295639.2023.2284432



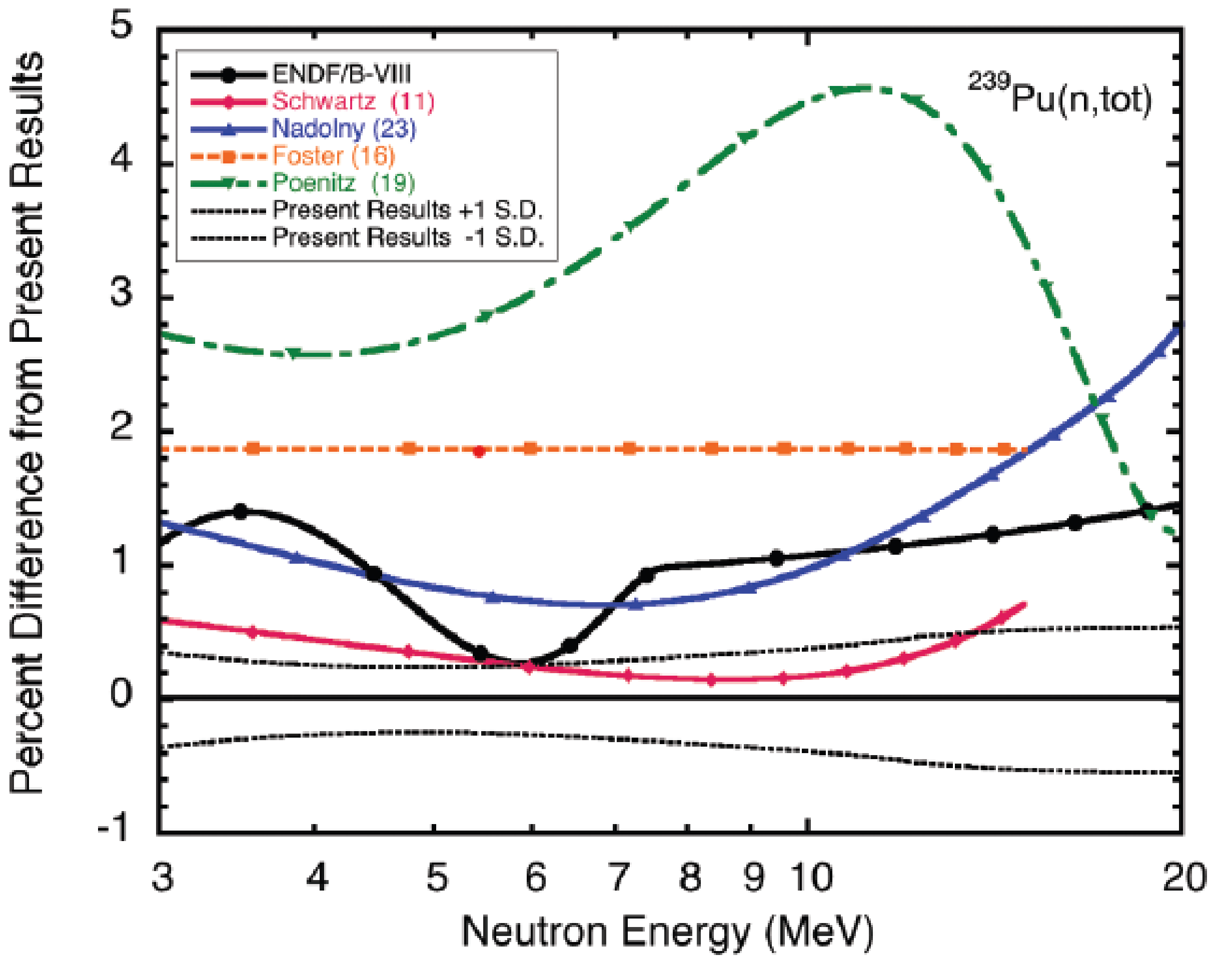


Fig. 10. Percentage difference between the present results for ^{239}Pu and selected measurements. The dotted

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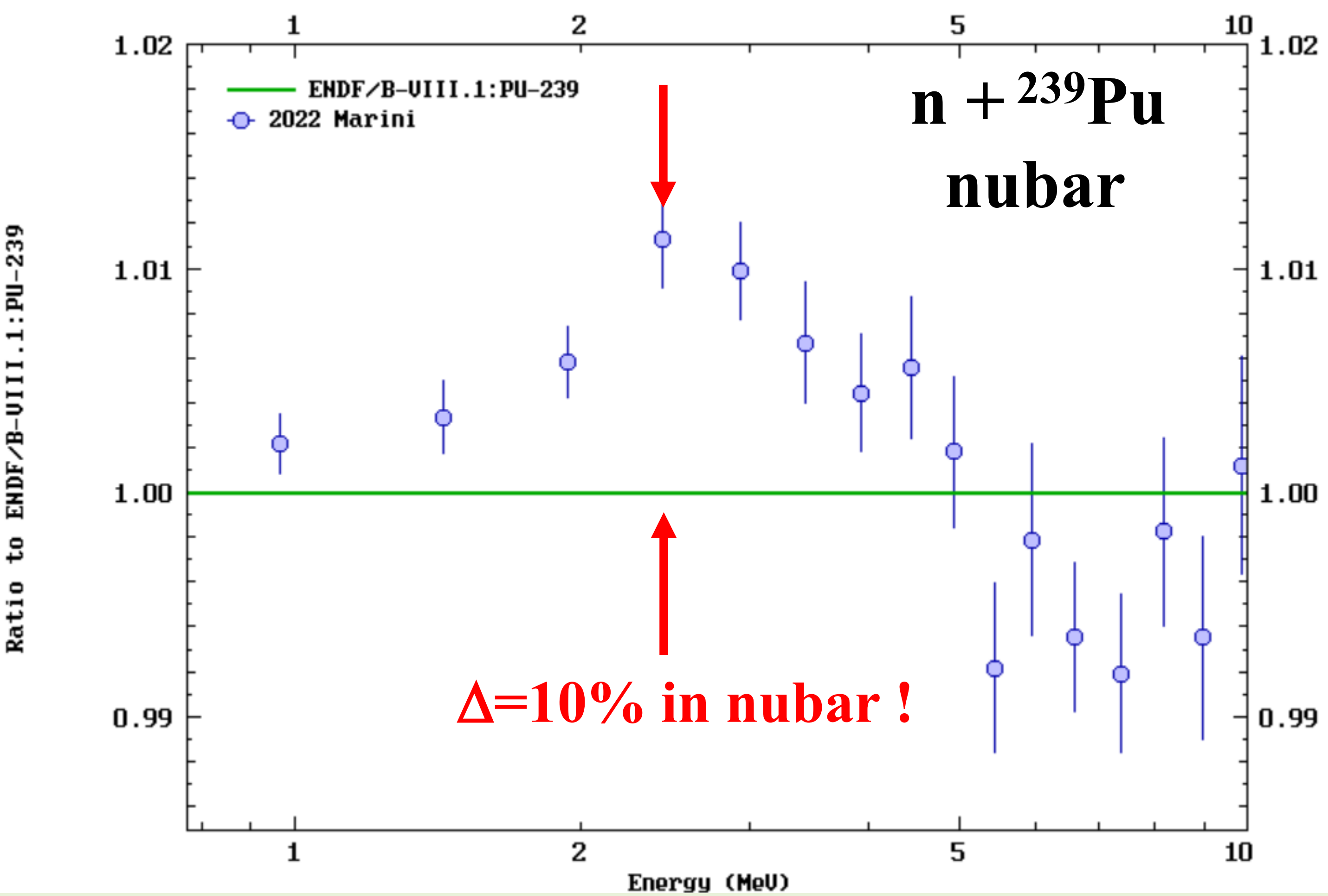
Example 3: nubar vs CEA-LANSCE data

Marini et al, Phys. Lett.B835 (2022)



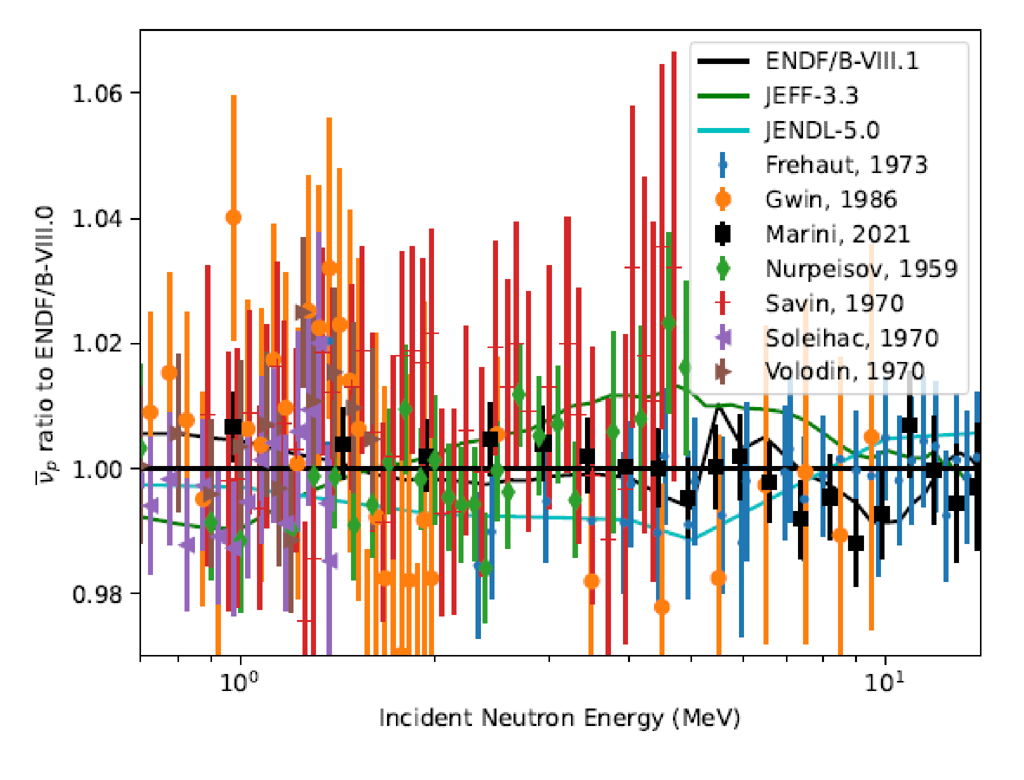


FIG. 5. Evaluated ^{239}Pu $\overline{\nu}$ ratio to ENDF/B-VIII.0 for selected experimental data from EXFOR [31] and for JENDL-5 [16], JEFF-3.3 [32], and the new ENDF/B-VIII.1 evaluations.

G. Nobre, RC, et al, ENDF/B-VIII.1 paper
https://doi.org/10.48550/arXiv.2511.03564

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Example 4: ^{238}U(n,inl) - impact of deformation (EW)

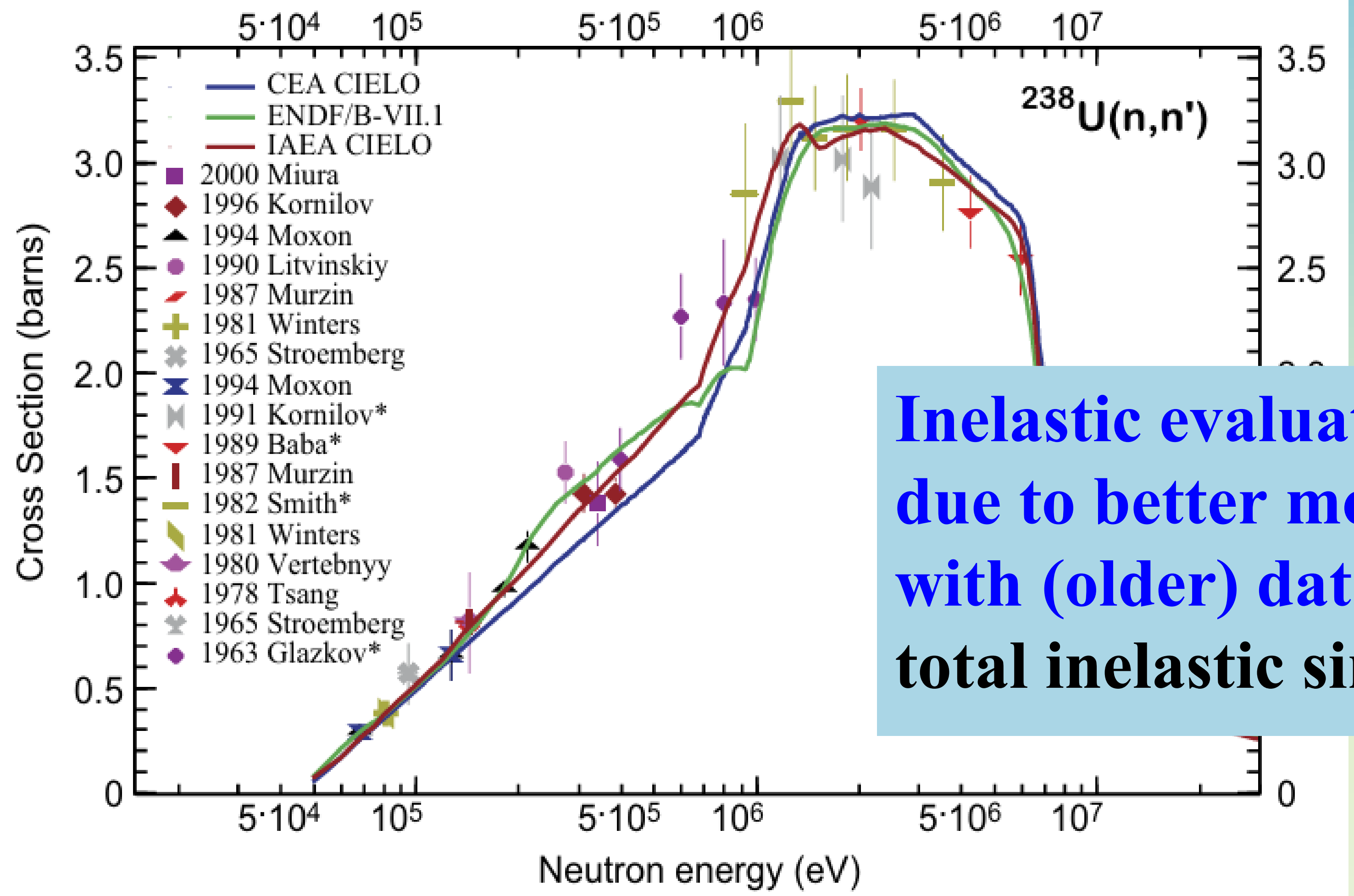

FIG. 14. (Color online) ^{238}U(n,n') cross sections in the IAEA CIELO-1 and CEA CIELO-2 evaluations.

Capote et al, NDS **118** (2014) 26
Capote et al, EPJ WoC **69** (2014)0008
Kawano et al, PRC **94** (2016) 014612
Capote et al, NDS **148** (2018) 254
Brown et al, NDS **148** (2018) 1

Inelastic evaluation improved due to better modeling in agreement with (older) data. No new data of total inelastic since 2000.

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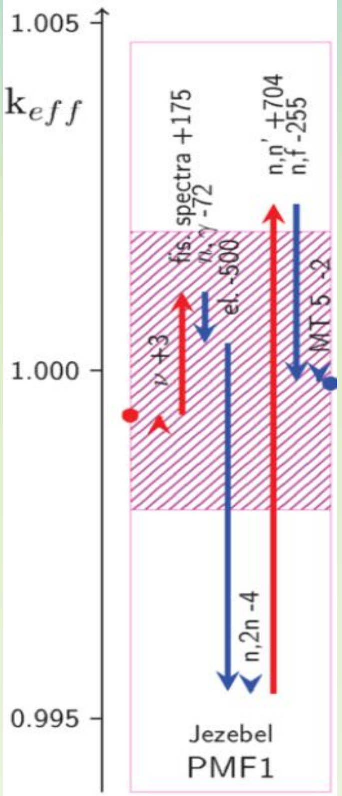
Inconsistencies of evaluated inelastic cross sections: Can we get additional information from integral experiments?

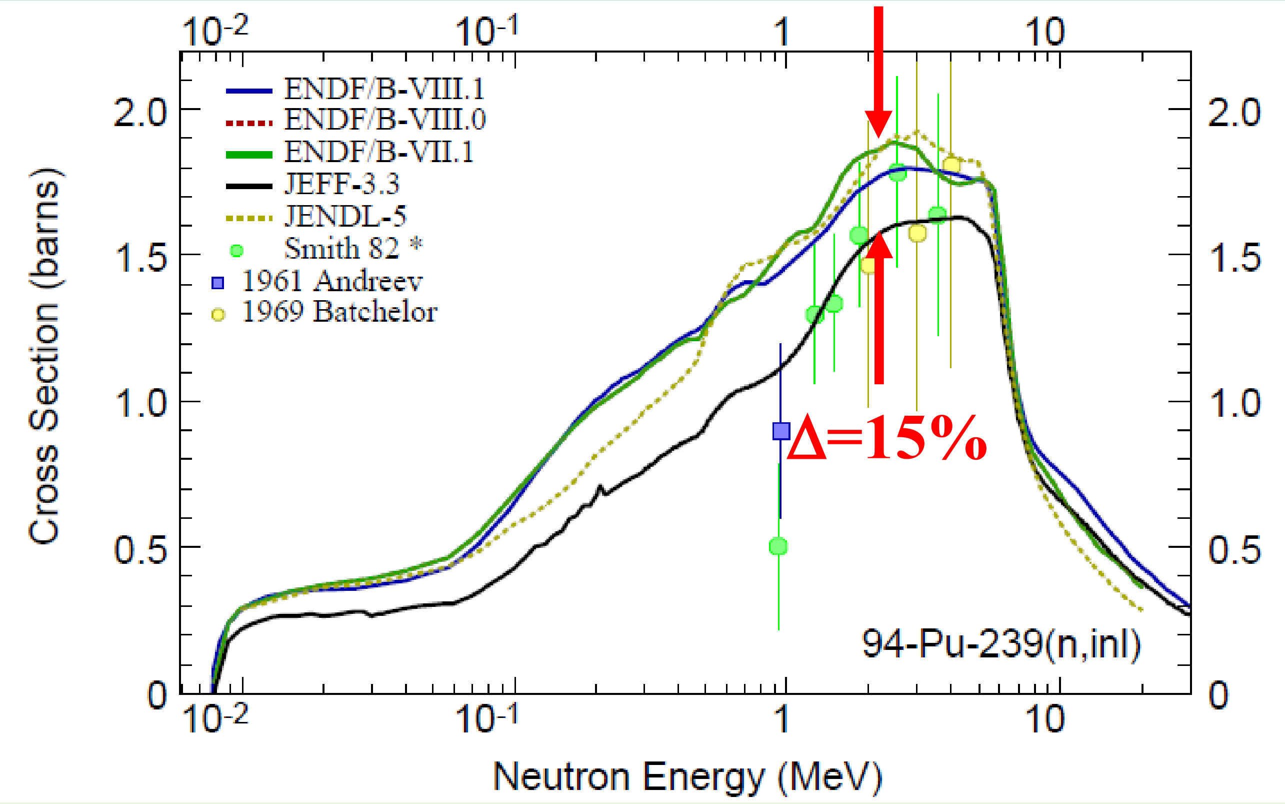
IAEA CM 22-23 June 2015, Inelastic scattering of major actinides
https://nds.iaea.org/publications/indc/indc-nds-0692/

MB Chadwick et al, NDS148(2018)189

Pu-239 CEA CIELO to Pu-239 IAEA CIELO



G. Nobre, RC, et al, ENDF/B-VIII.1 paper
https://doi.org/10.48550/arXiv.2511.03564



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Key experimental data for major actinides since 2014
INTEGRAL experiments

- RPI quasi-differential neutron production experiments (^{235,238}U,^{239}Pu)
  impacted IAEA CIELO ^{238}U evaluation adopted for ENDF/B-VIII.0
- EUCLID criticality experiments: two new crits (~cube 3x2 and slab 8x1) to be combined with Jezebel (spherical crit)

  impacted the post-B81 INDEN ^{239}Pu evaluation (p44), June 2025, see below

Key experimental data drive evaluation and uncertainty reduction !!

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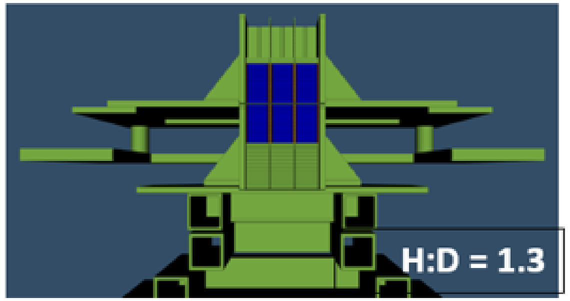
EUCLID design: 3x2, 8x1 (+Jezebel – pmf001)

J. Hutchison et al, *EPJ Web of Conf.* **284** (2023) 15006; *Nucl. Sc. & Eng.* **199** (2025) 42-60

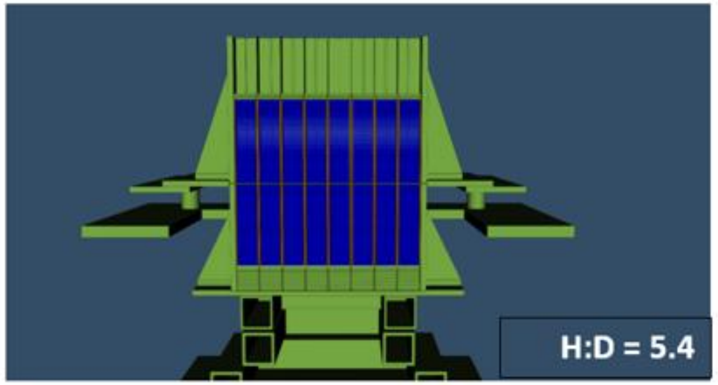
CUBE
3x2

3 X 2 (Low Mass/Cube)
Critical with 384 ZPPR plates (41 kg Pu)



SLAB
8x1

8 X 1 (High Mass/Slab reactor)
Critical with 1033 ZPPR plates (109 kg Pu)



LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT — NCSP NUCLEAR CRITICALITY SAFETY PROGRAM — NCERC NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER — MCNP6

ML designed with D-optimality analysis

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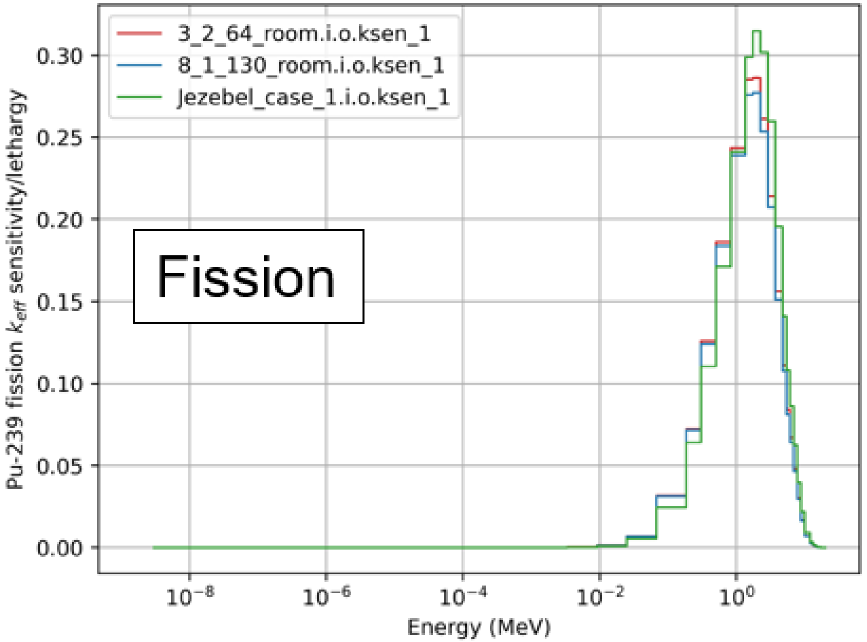
EUCLID sensitivities: Jezebel, 3x2, 8x1

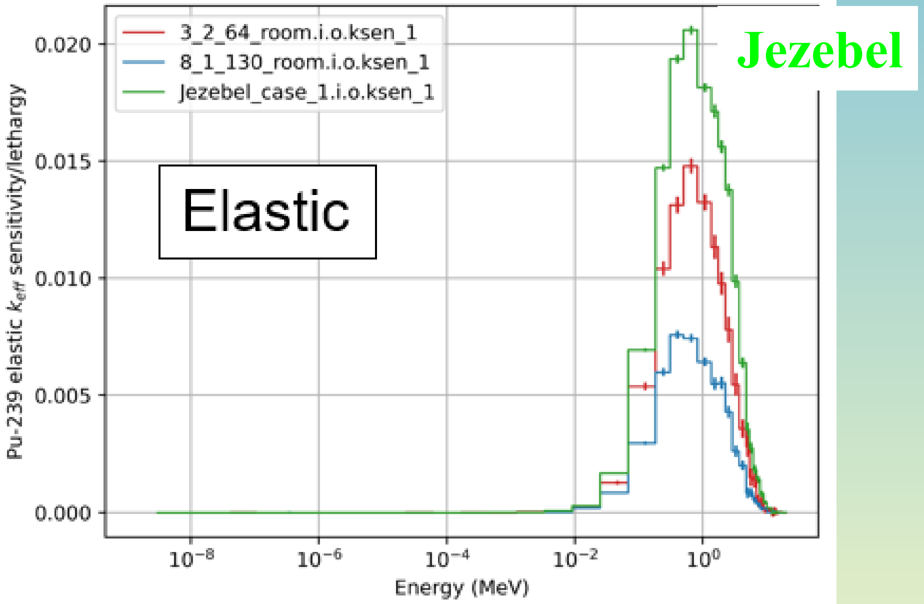
k_{eff} sensitivities are similar to Jezebel for fission but different for scattering

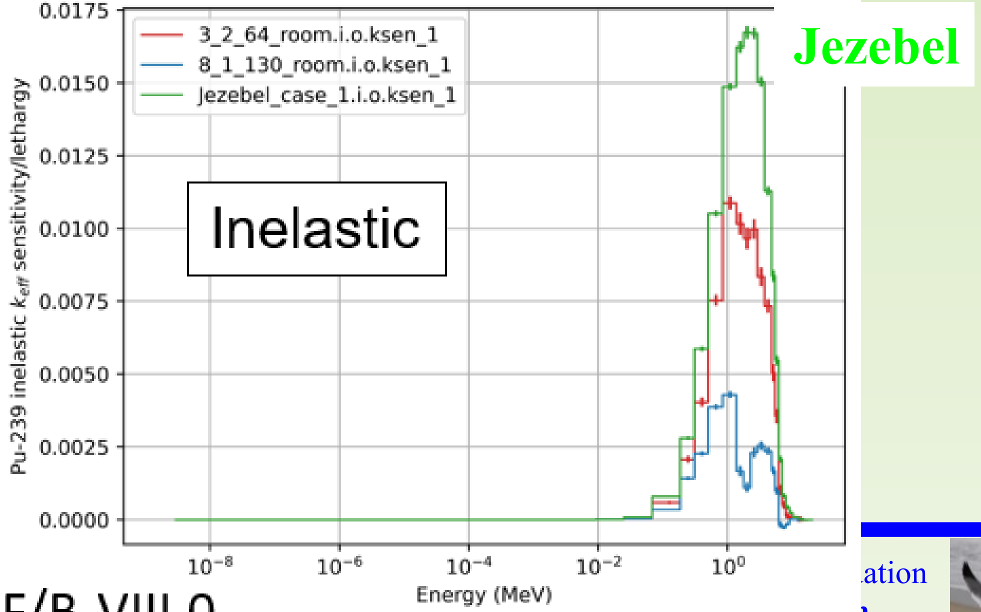
- Jezebel – detailed benchmark, case 1
- 3 X 2 X 64
- 8 X 1 X 130



Scattering sensitivities differ in magnitude and shape for **8x1** vs. **3x2**

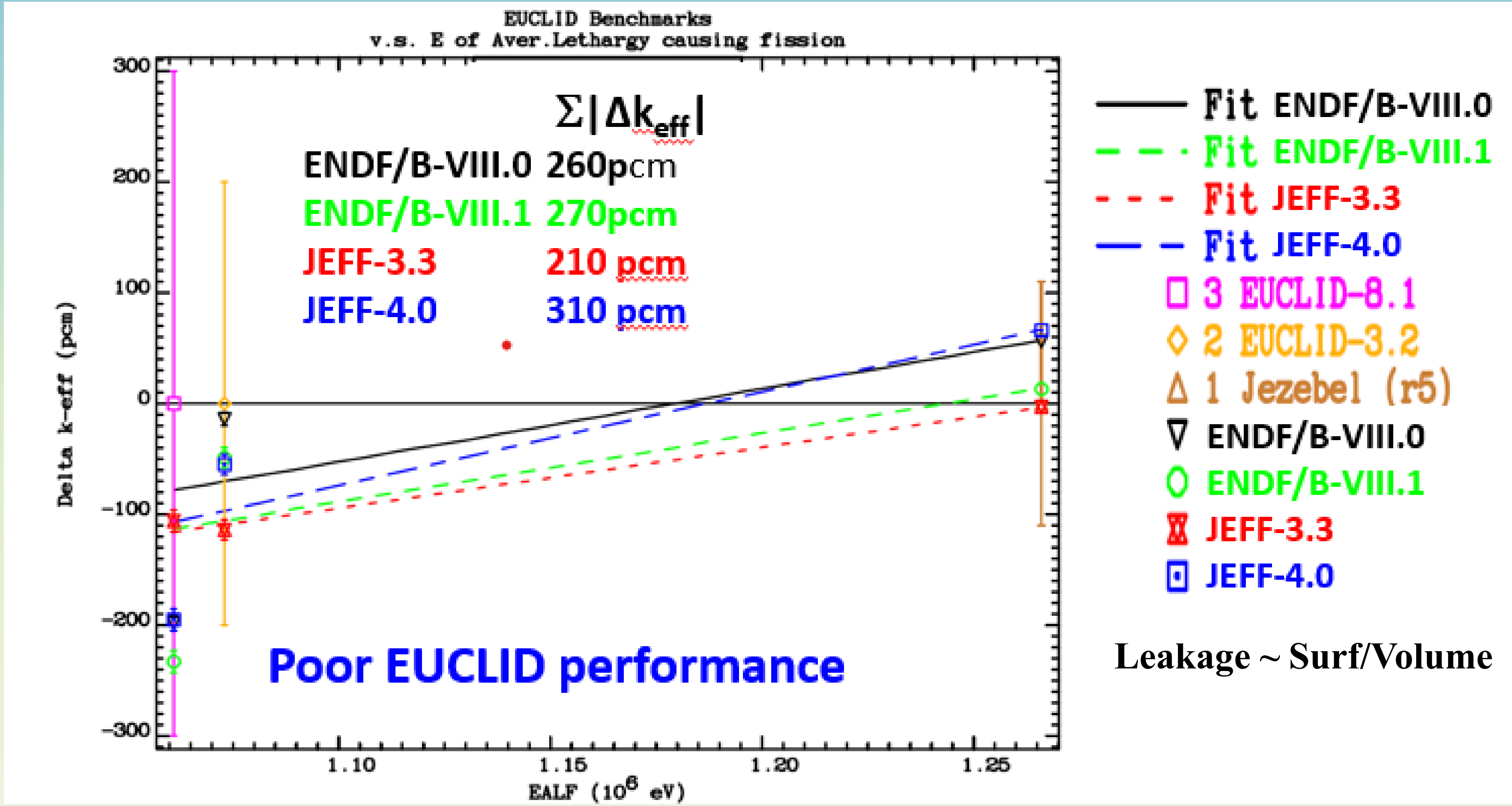
vs. Jezebel



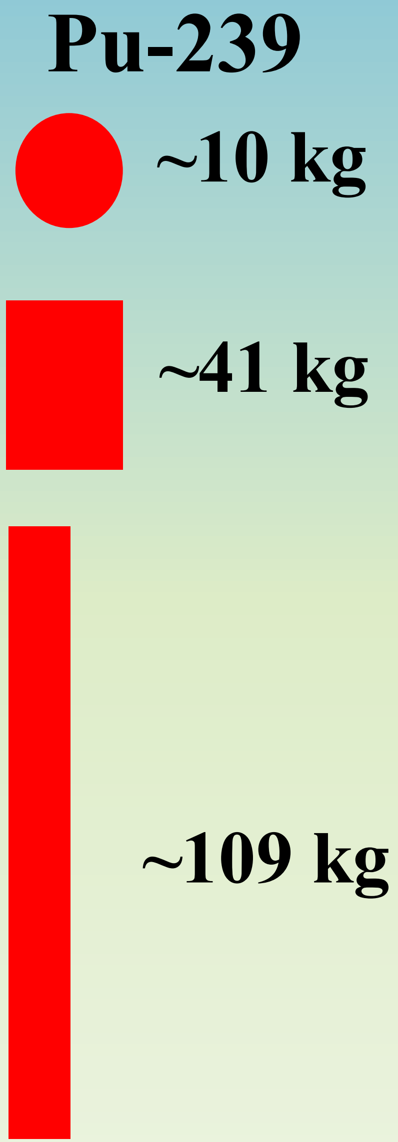


MCNP calculations using ENDF/B-VIII.0

EUCLID 3x2, 8x1 and Jezebel data vs existing evaluations



Leakage ~ Surf/Volume



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NEW DEVELOPMENTS FOR THE NEXT DECADE
(I) DCC OMP using Soft Rotator Model (SRM)

P(ND)^2 2005 DCC OMP RIPL 2408, rigid rotor, GS rotational band coupled
used in ENDF/B-VIII.0, JENDL-4 evaluations for U-235, B-VIII.1 for Pu-239

P(ND)^2 -2 2014 DCC OMP RIPL 2413, **rigid rotor, multiple-band coupled**
used in U-238 evaluation for IAEA CIELO (ENDF/B-VIII.0)

P(ND)^2 -3 2026 DCC OMP RIPL 2420, **soft rotor, multiple-band coupled** (SRM Hamiltonian)
used in INDEN p44 evaluation for Pu-239

Next decade: To be used in new actinide evaluations: U-233,235; Pu-238,240,241,242

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NEW DEVELOPMENTS FOR THE NEXT DECADE
(I) DCC OMP using Soft Rotator Model (SRM)

Actinides: Big static deformation – <u>expansion around statically deformed shape</u>
E.S. Soukhovitskii, RC et al, PRC **94**(2016)064605, erratum: PRC102(2020)059901
Martyanov et al, EPJ Web of Conferences **146** (2017) 12031 – ND2016 (SRM even-even)
Martyanov et al, EPJ Web of Conferences **239** (2020) 03003 – ND2019 (SRM odd)

- **All existing evaluations based on rigid rotor structure**
- **J(J+1) law breaks above ~500 keV for even-even targets**

- A new optical model formalism based on soft-rotator model SRM developed and applied to both even-even and odd actinides in RIPL-4 CRP
- Better structure information (SRM) may improve transition probabilities (-> n,n’g)
- New SRM DCC OMP results in lower CN cross section below 2-3 MeV

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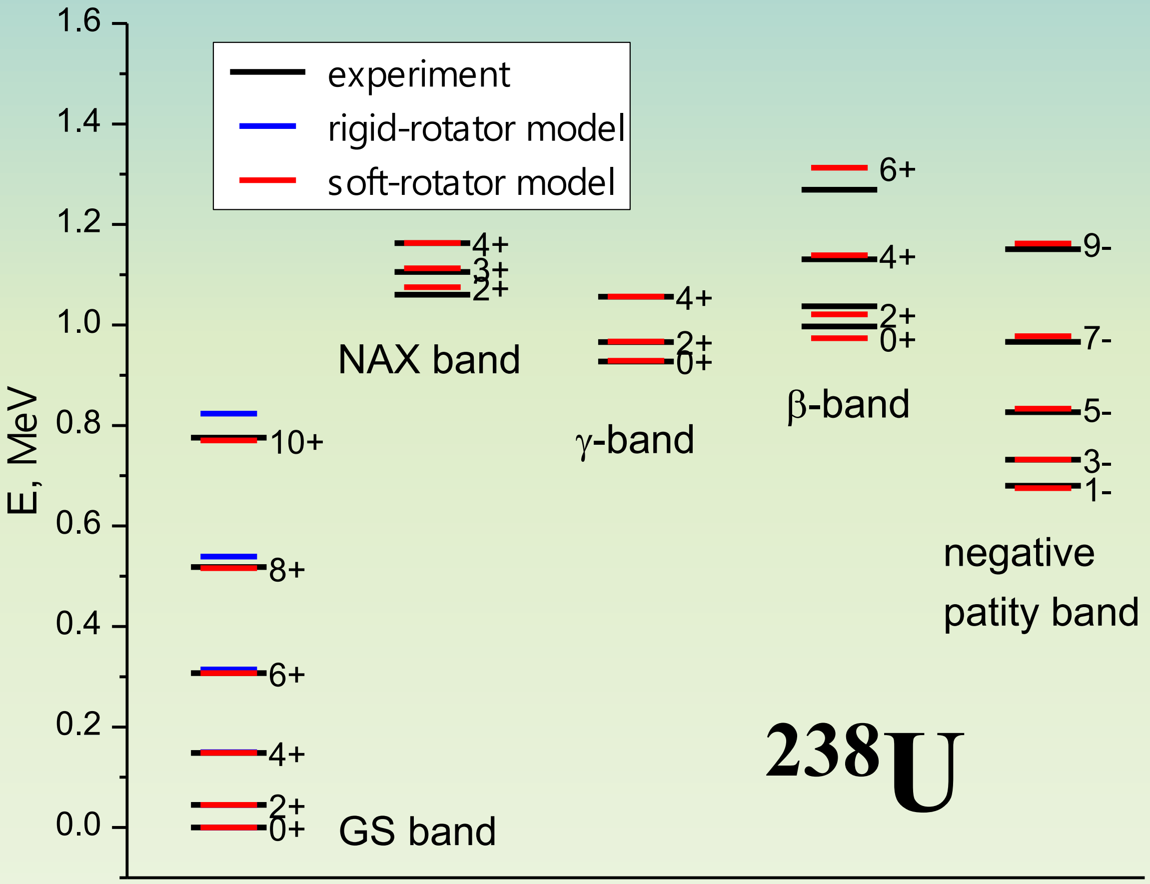
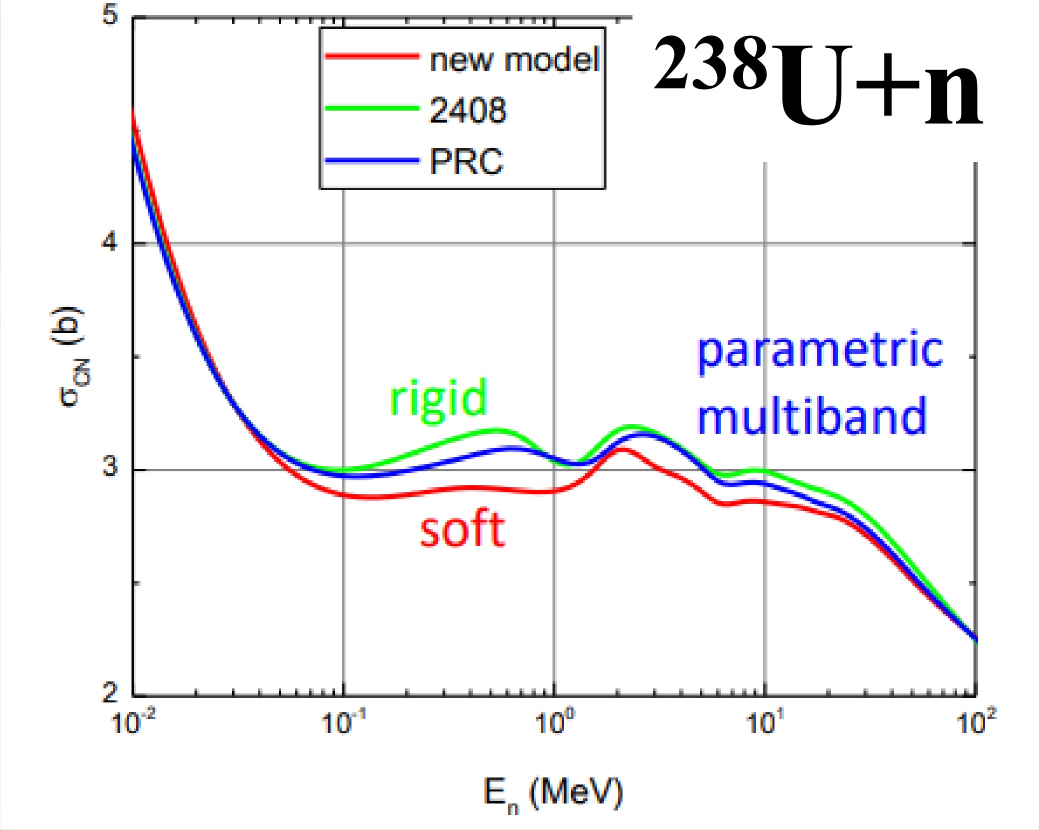
Is softness important?

- GS band levels energies deviate from rigid rotor level sequence for high spins due to nuclear stretching from centrifugal forces.
- Soft-rotor model describes experimental energies very well.
- Gamma-transition probabilities also much improved



Three OMPs (2408 - rigid, new model - soft, parametric multi-band - PRC) fitted to the same scattering data



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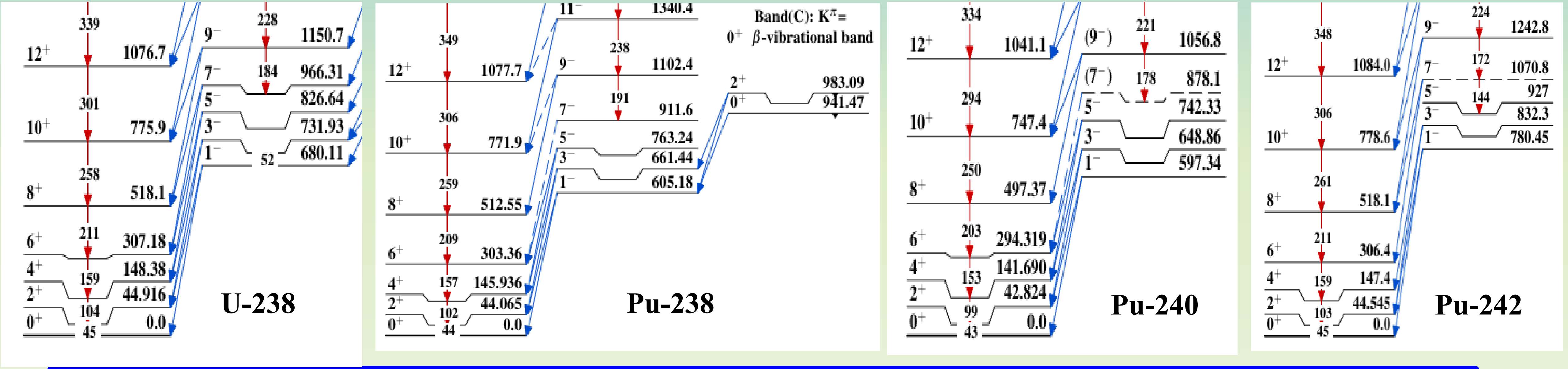
OMP improvements: DCC OMP, soft rotor, 2+ bands

Actinides: Big static deformation – <u>expansion around statically deformed shape</u>
E.S. Soukhovitskii, RC et al, PRC94(2016)064605, erratum: PRC102(2020)059901
Martyanov et al, EPJ Web of Conferences **146**, 12031 (2017) – ND2016
Martyanov et al, EPJ Web of Conferences **239**, 03003 (2020) – ND2019



SRM significantly improves the description of low-lying nuclear structure in DCC OMP

<u>U. Koster (March 10)</u>: **Nuclear structure and reactions living separately …**

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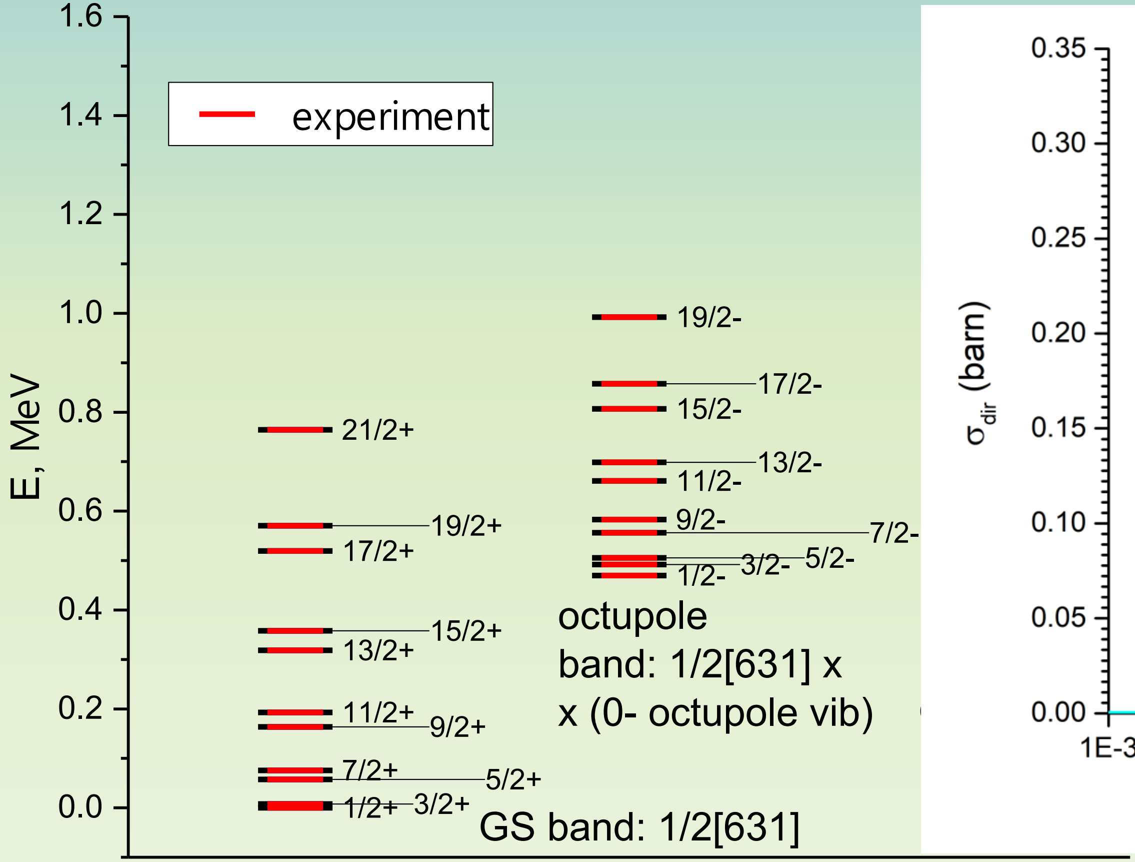
^{239}Pu coupling scheme: New OMP 2420

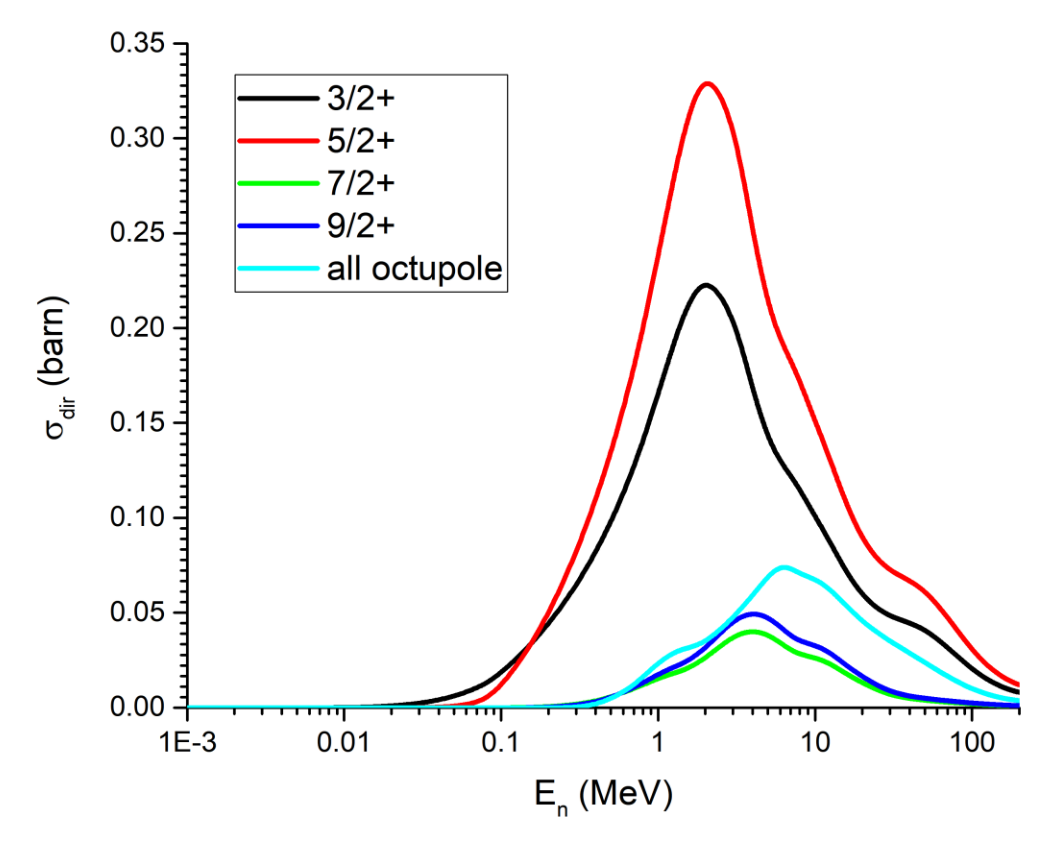
Important octupole band (built on ½$^-$ state)coupled:

½$^-$ ≡ (core exc) $0^- \otimes$ ½$^+$ (single-particle GS)

better physics lead to better nuclear data

U_{exc}(MeV)





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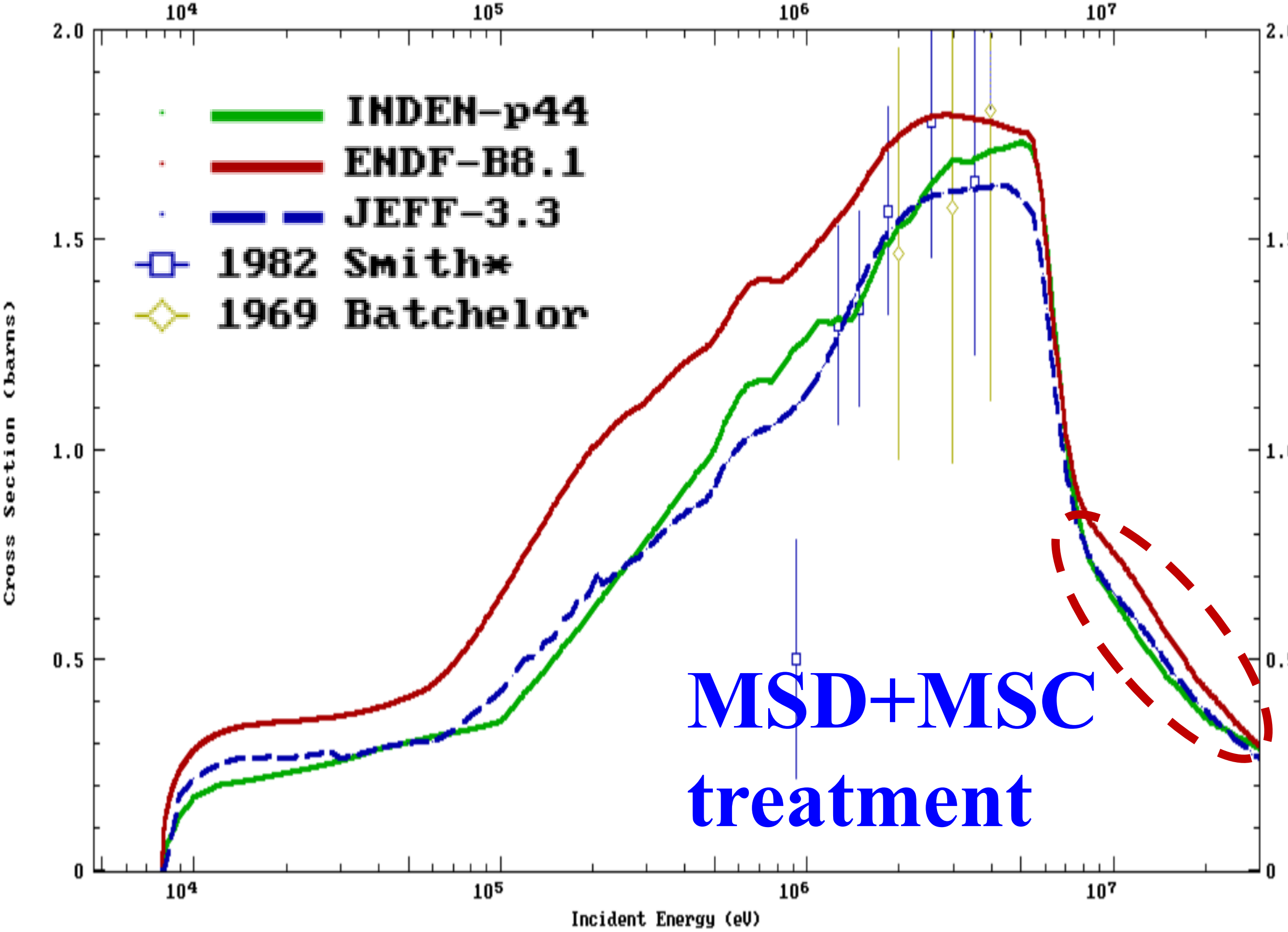
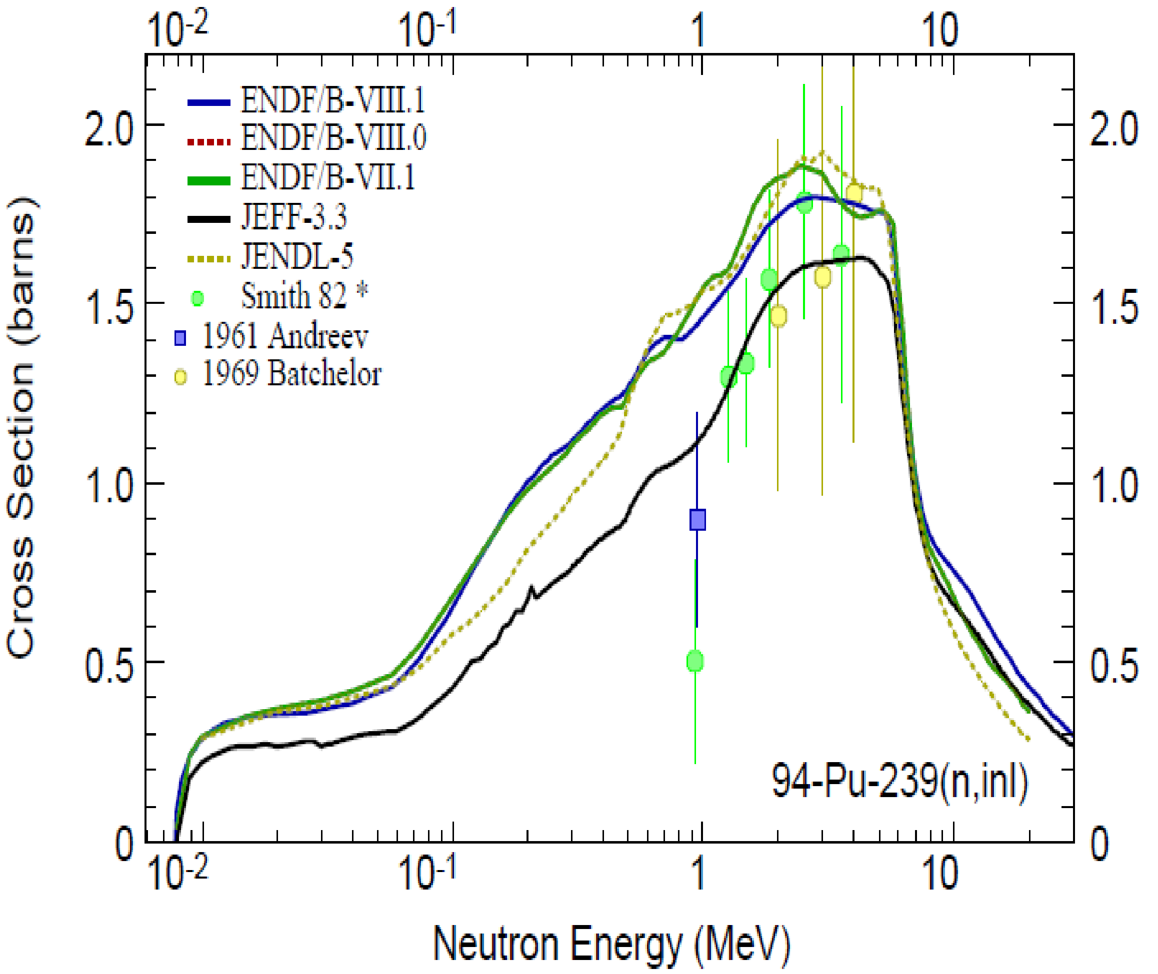
Inelastic cross section n + ^{239}Pu





INDEN p44 (SRM,06/25) **Existing evals**

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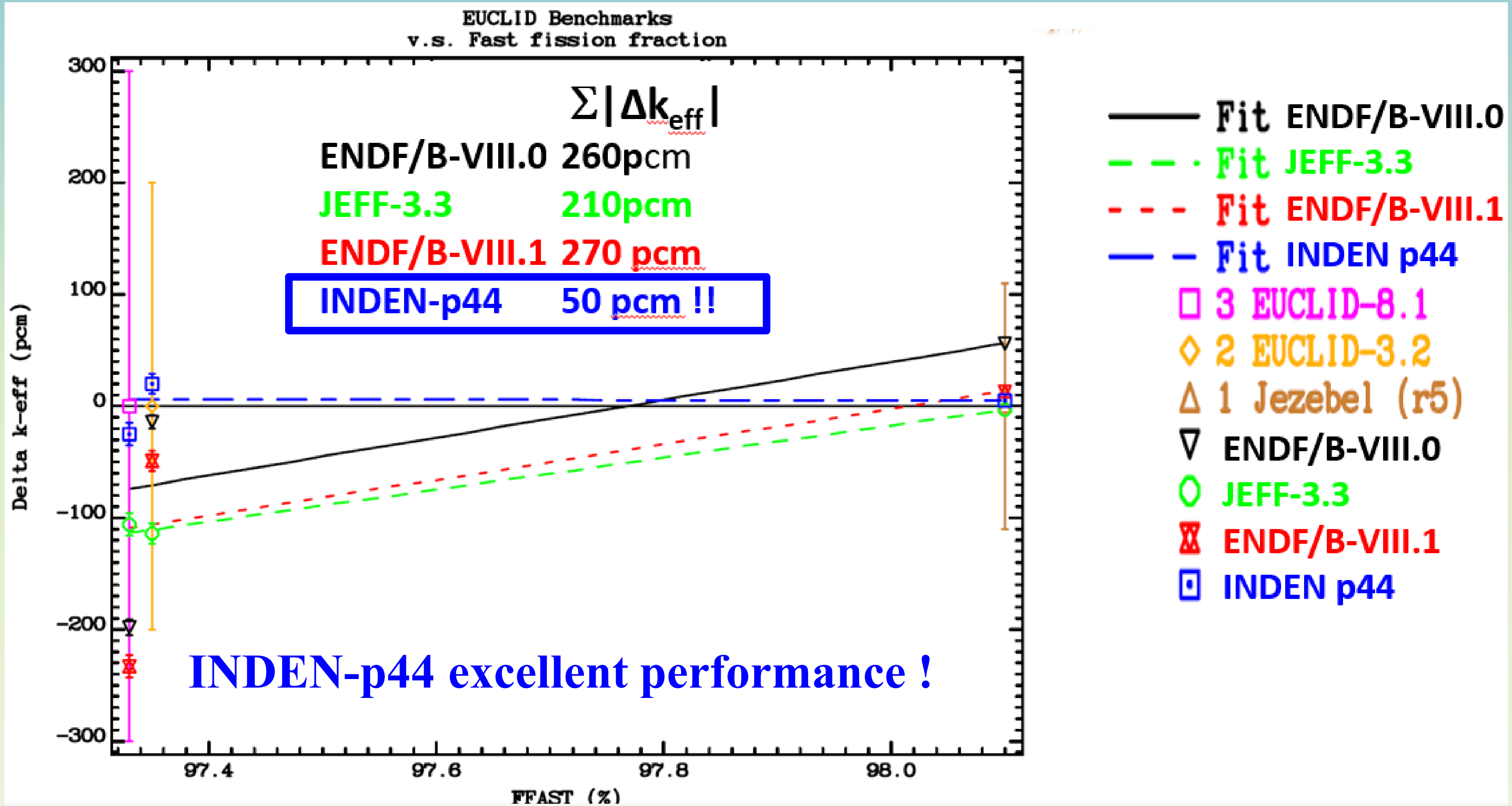
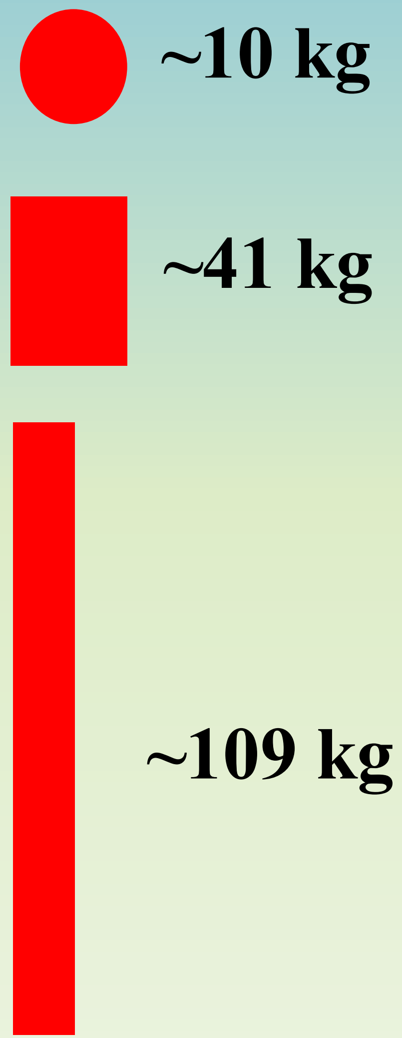
EUCLID design: 3x2, 8x1 (+Jezebel – pmf001)

J. Hutchison et al, *EPJ Web of Conf.* **284** (2023) 15006; *Nucl. Sc. & Eng.* **199** (2025) 42-60

Pu-239





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Similar issue for HEU? k_{eff} depends on leakage

Capote et al, NDS **148** (2018) 254

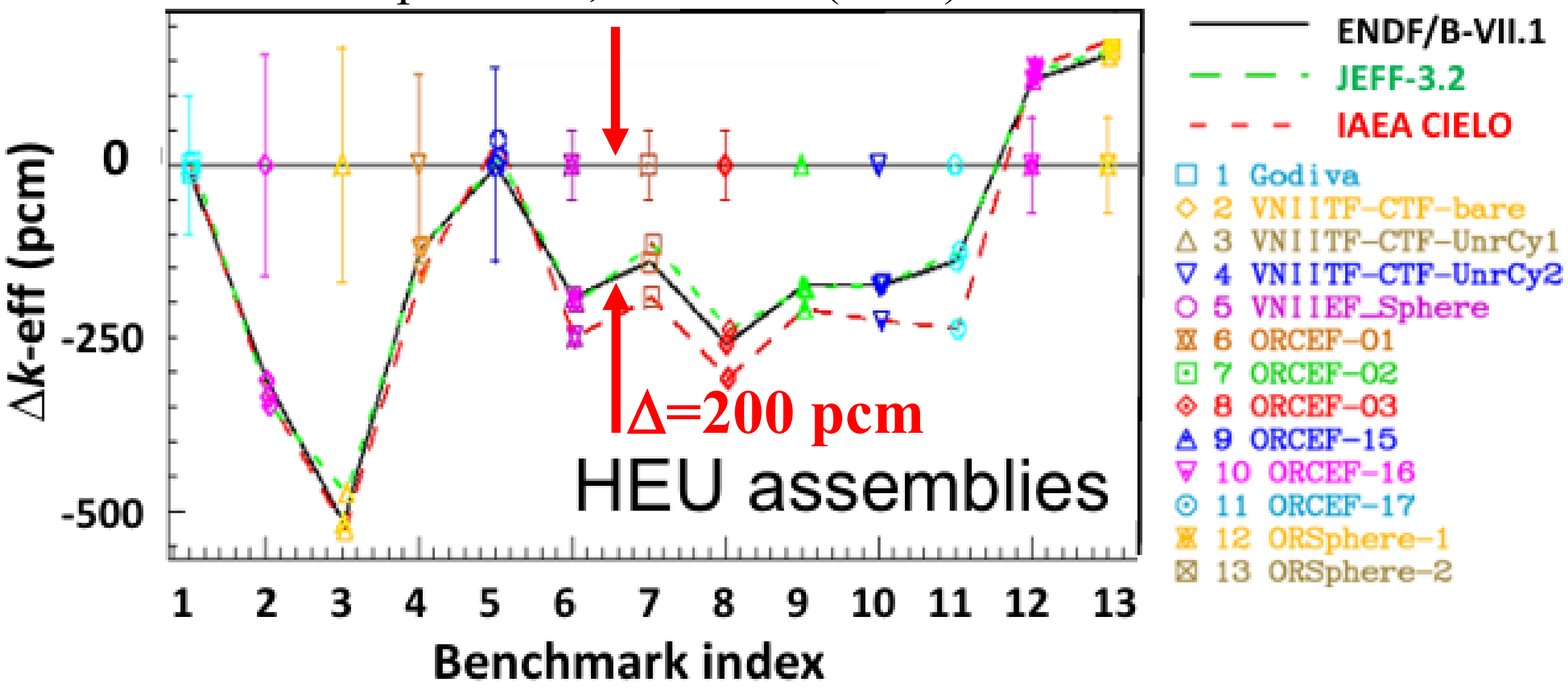

FIG. 35. (Color online) Benchmark results for highly-enriched uranium (HEU) bare assemblies from ICSBEP benchmarks [17]. Symbols linked by lines show the calculated Δk_{eff} values using different libraries.

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NEW DEVELOPMENTS FOR THE NEXT DECADE (II)
Quantum mechanical MSC/MSD PE (n,n' to the continuum)

- All existing actinide evaluations are based on exciton model and/or dummy levels in the continuum treated by DWBA to reproduce the preequilibrium (PE) energy spectrum region.

- Quantum mechanical MSD/MSC models have never been used in ND evaluation of actinides

- M Herman used MSC/MSD for the ^{181}Ta evaluation adopted for ENDF/B-VIII.1

EMPIRE implementation available since 2008

Wienke, Capote, Herman, Sin, Phys. Rev. **C78** (2008) 064611

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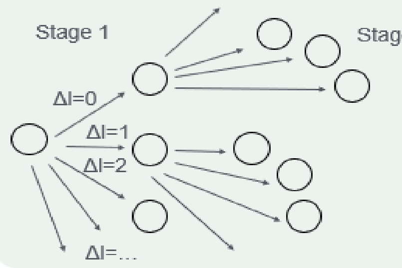
Inelastic to the continuum (PE) MSC + MSD

EMPIRE
Nuclear Reaction Model Code

Multistep approach to pre-equilibrium

MultiStep Direct (TUL)

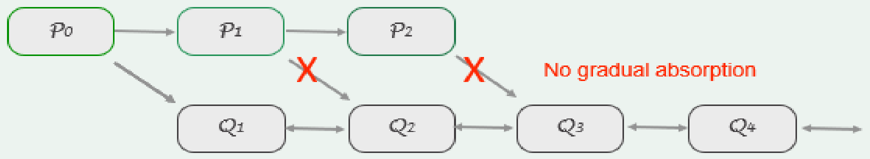
- Fully quantum mechanical follows particle interaction in the P-space
- Uses optical potential and 2-step DWBA calculations for energy losses and l-transfers (0-6) [ORION]
- RPA (Tamm-Dankoff approximation) strength functions unify collective effects with a single-particle picture, replacing p-h level densities.
    - self consistent field parameters or
    - fitted to energies of experimental GMR, GDR, 2^+, 3^-
- Forward-peaked energy-dependent angular distributions
- Caveat: no charge-exchange reactions (exciton model used)



Schematic representation of two-step l-transfer in DWBA calculations. This should be combined with the similar graph for energy losses.

MultiStep Compound (NVWY)

- Strictly derived from GOE (random matrix theory) and statistics
- Similarly to exciton and MSD assumes two-body interaction and evolution through a series of p-h configurations but in Q-space **only**
- Contrary to MSD looses memory of the incident channel => isotropic (in principle symmetric) angular distributions
- In EMPIRE average values of microscopic matrix elements are
    - related to optical model transmission coefficients for $\Gamma^{\uparrow}$
    - imaginary part of the optical potential for a single particle in a potential well in case of $\Gamma_{\downarrow}$ (essentially parameter free!)
- Calculates n, p and γ emission



Tamura, Udagawa, Lenske, Phys. Rev. **C26** (1982) 379
Wienke, Capote, Herman, Sin, Phys. Rev. **C78** (2008) 064611

Nishioka, Verbaarschot, Weidenmueller, Yoshida, Ann. Phys.**172** (1986) 67
Herman, Reffo, Weidenmuller, Nucl. Phys. **A53** (1992) 124

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New INDEN p44 evaluation of Pu-239 (post-B81)

- ❑ **DCC OMP with two band coupling within SRM** developed by Martyanov et al used
- ❑ MSD +MSC used to calculate inelastic to continuum, **perfect agreement with LPS**
- ❑ Compared to the ENDF/B-VIII.1 evaluation the following changes are noted:
  - ✓Inelastic XS decreased significantly and is now compatible with JEFF-3.3 inelastic
  - ✓Elastic XS is a bit lower than JEFF-3.3, much higher than ENDF/B-VIII.1
  - ✓Total cross section is reduced following Lisowski 2024 publication
- ❑ The trend Jezebel-EUCLID is gone, no gradient, 0 bias. A ±25pcm spread remains compared to previous +200 pcm. **Excellent performance achieved**
- ❑ **The new INDEN evaluation uses CEA-LANSCE Marini data from EXFOR.**

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For the next decade

- Undertake new evaluations of actinide nuclei using **DCC OMP with SRM**

Considered nuclei

	Bands/Levels	SF	Total	Angular
238U	5/21	+	+	+
232Th	5/18(21)	+	+	+
240pu	5/18(20)	+	+	+
242pu	3(5)/10(20)	+	+	+
228Th	5/19(20)			
230Th	4(5)/16(20)	+		
232U	5/18(20)	+		
234U	5/18(20)	+		
236U	4(5)/16(20)	+		+
238Pu	5/15(20)	+		
244Pu	2(5)/9(20)	+		
246Cm	5/16(20)	+		
248Cm	4(5)/14(20)	+		
250Cf	5/13(20)			
233U	3/17	+	+	
237Np	1/10	+	+	
235U	1/11	+	+	+
239Pu	2/19	+	+	+

(+ 241Pu)

This OMP is in RIPL-4 (2420 for neutrons)
- requires OPTMAN solver
- OPTMAN output is ECIS compatible

- Use MSD +MSC to calculate PE effects
- Study the criticality leakage impact of the new U-235 evaluation

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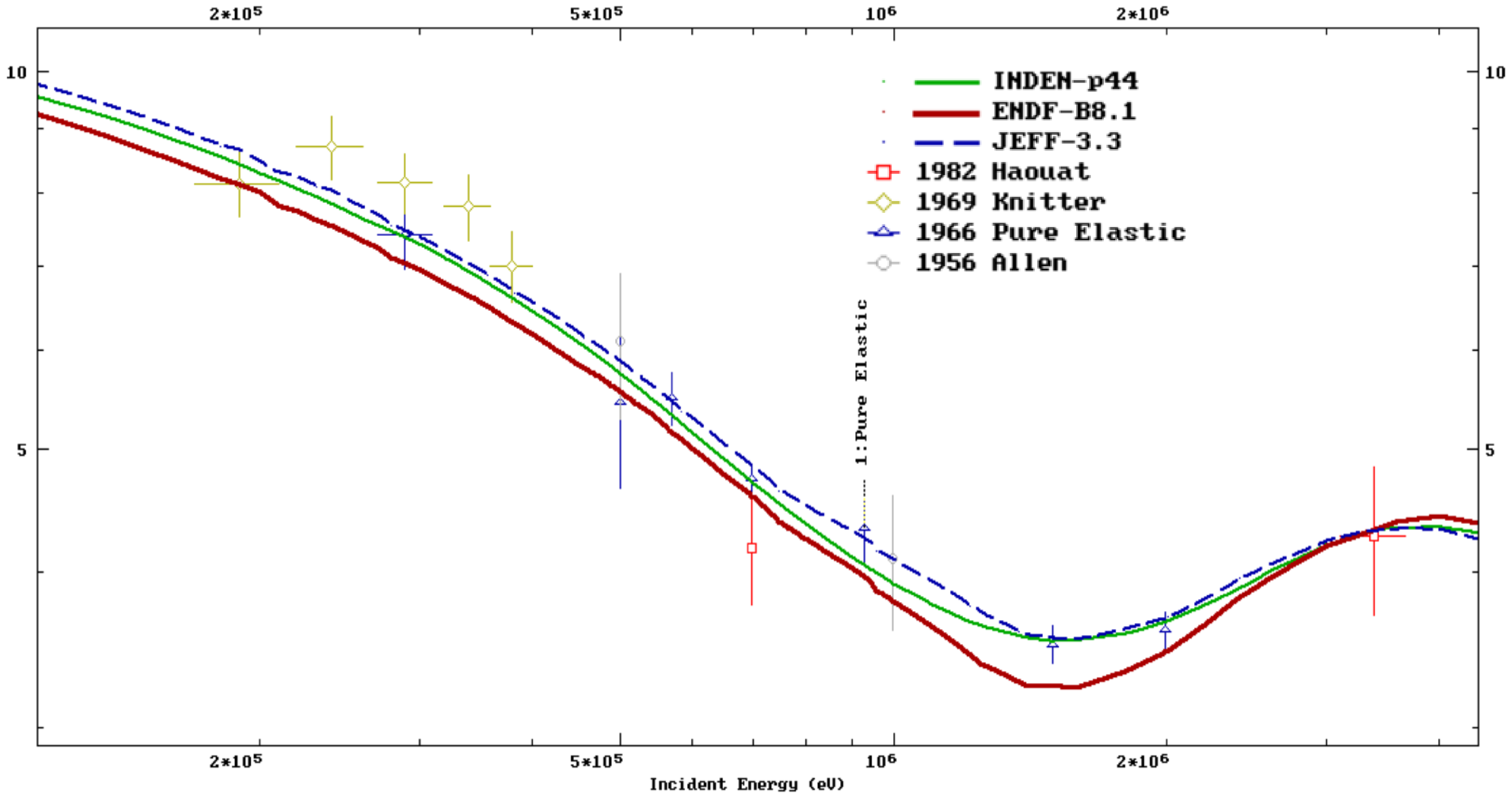
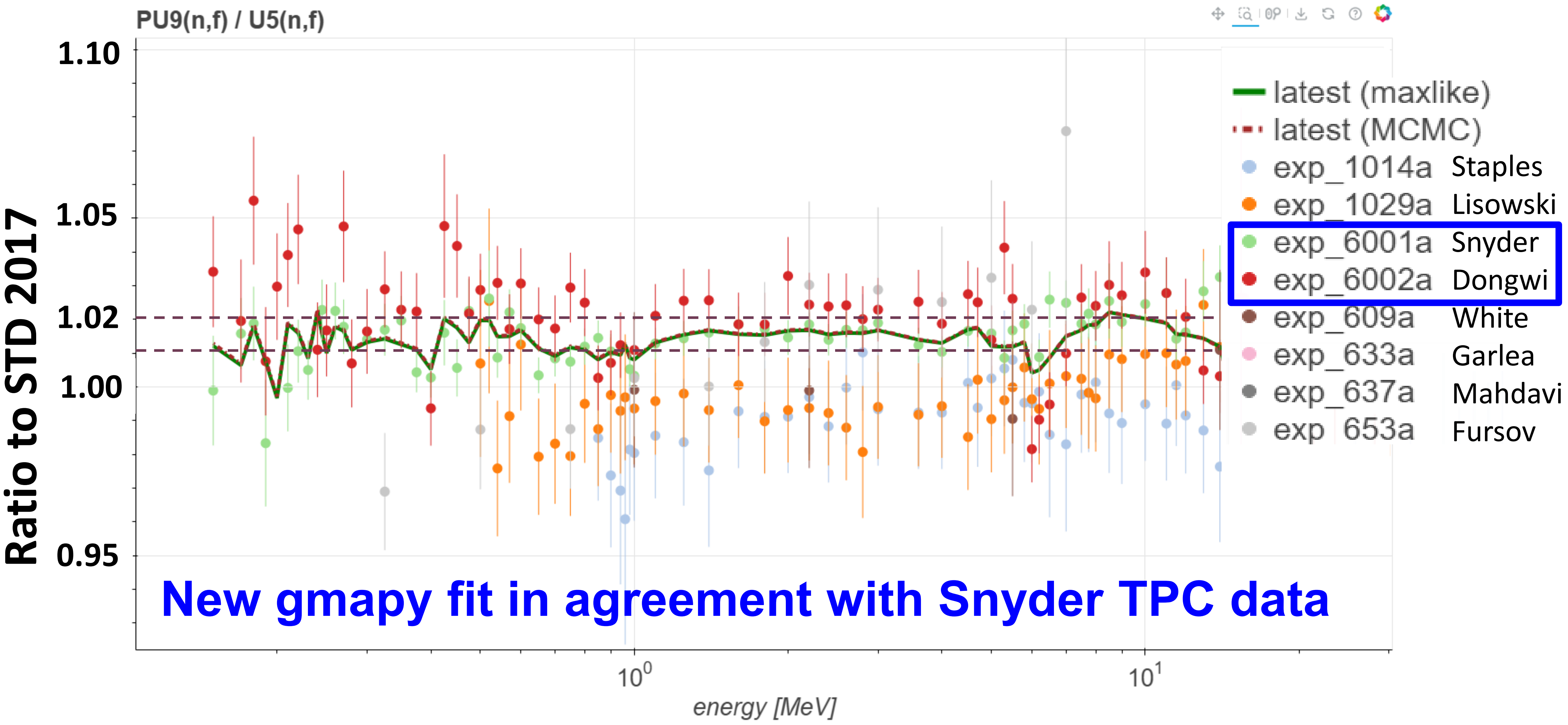
THANKS FOR YOUR ATTENTION !

Elastic cross section n + ^{239}Pu



^{239}Pu(n,f)/^{235}U(n,f) ratio vs data – gmapy (06/2025)



New gmapy fit in agreement with Snyder TPC data

Inconsistencies of evaluated inelastic cross sections