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JENDL-4.0 Based Cross-section Adjustment by Adding New Experiments on the Basis of the SG33 Benchmark

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Integral Experiments of SG33 Benchmark

- JEZEBEL Pu-239:
  - KEFF, F28/F25, F49/F25, F37/F25
- JEZEBEL Pu-240:
  - KEFF
- FLATTOP-Pu:
  - KEFF, F28/F25, F37/F25
- ZPR6-7:
  - KEFF, F28/F25, F49/F25, C28/F25
- ZRR6-7 high Pu-240 content:
  - KEFF
- ZPPR9:
  - KEFF, F28/F25, F49/F25, C28/F25, SVR(central void), SVR(leakage-dominant)
- JOYO:
  - KEFF

→ Total 20 integral experiments

Additional New Integral Experiments

- PROTEUS proposed by PSI
  - HCLWR-PROTEUS
    - Core 7: moderated by water (Vm/Vf=0.48)
      - KINF
    - Core 8: not moderated
      - KINF
  - Code & Library
    - MCNP6.11 & JEFF-3.1.1
- SNEAK proposed by JSI
  - MOX fuel reflected by metallic depleted uranium
    - 7A: PuO2-UO2, graphite
      - KEFF
    - 7B: PuO2-UO2, ^{nat}UO2
      - KEFF
  - Code & Library
    - THREEDANT & ENDF-B/VII.1

→ + 4 integral experiments

HCLWR-PROTEUS

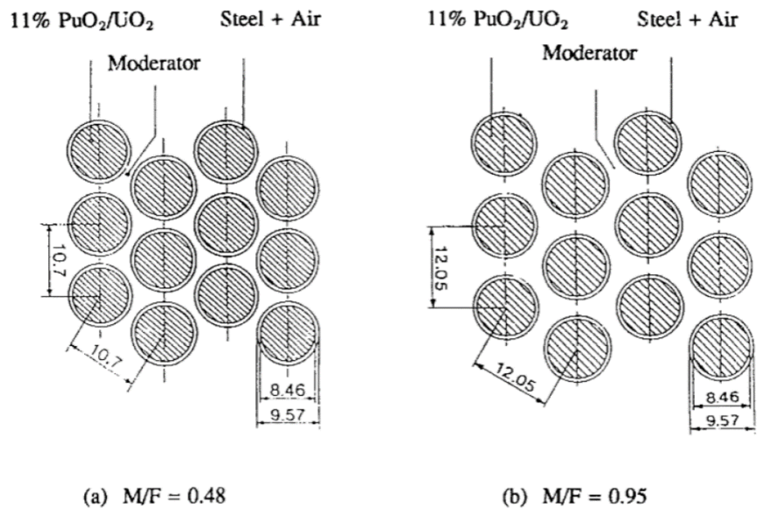


Fig.: Lattice description of the a) tight- and b) wide-pitch configuration*

Table: Nominal Pu vector of the reference date (01.01.1986)*

Isotope	Ratio
Pu-238	1%
Pu-239	64%
Pu-240	23%
Pu-241	8%
Pu-242	4%

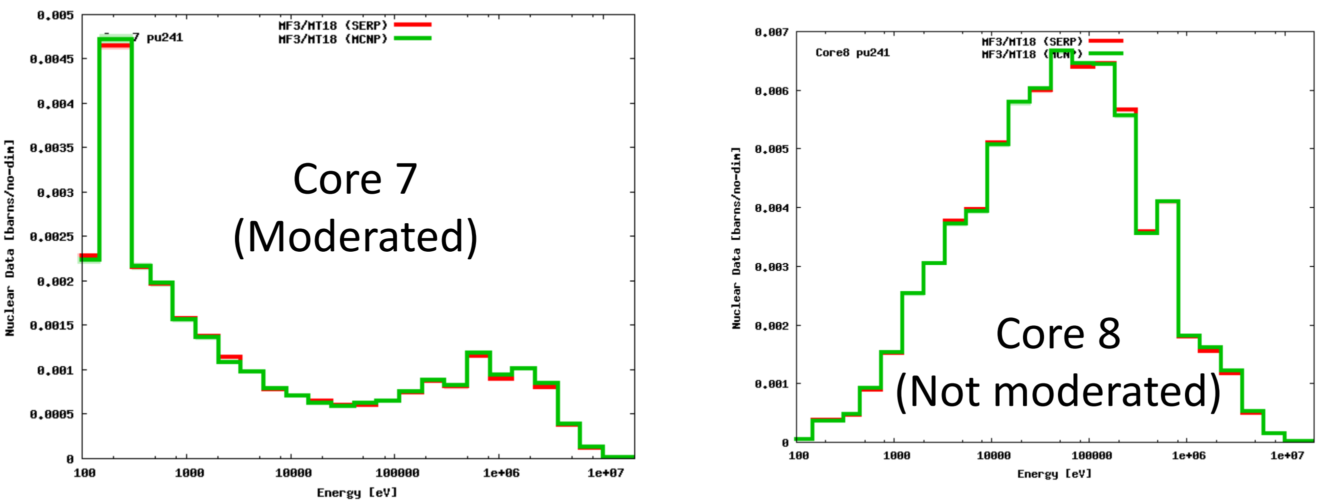


Fig.: Differential sensitivity of Pu-241 fission*

*: M. Hursin, et al., "Description of the Data provided to the SG39 with respect to the HCLWR experiments at Proteus," AN-41-15-05 V.1, PSI (2015)

Atomic Densities of PROTEUS 7 and 8

Table 2: Fuel Composition for Core 7 and Core 8

Isotope	Core7	Core8	Isotope	Core 7	Core 8
U-234	1.8496E-06	1.9480E-06	O-16	4.5841E-02	4.5841E-02
U-235	1.5996E-04	1.5996E-04	Fe-54	1.7857E-06	1.7857E-06
U-236	2.9158E-07	2.9158E-07	Fe-56	2.8239E-05	2.8239E-05
U-238	2.0492E-02	2.0492E-02	Fe-57	6.7734E-07	6.7734E-07
			Fe-58	8.6206E-08	8.6206E-08
Pu-238	2.3974E-05	2.3876E-05	Ca-40	9.3421E-06	9.3421E-06
Pu-239	1.5364E-03	1.5364E-03	Ca-42	6.2351E-08	6.2351E-08
Pu-240	5.5930E-04	5.5930E-04	Ca-43	1.3010E-08	1.3010E-08
Pu-241	1.7580E-04	1.7142E-04	Ca-44	2.0103E-07	2.0103E-07
Pu-242	8.4588E-05	8.4588E-05	Ca-46	3.8548E-10	3.8548E-10
Am-241	3.3298E-05	3.7678E-05	Ca-48	1.8021E-08	1.8021E-08

M. Hursin, et al., “Description of the Data provided to the SG39 with respect to the HCLWR experiments at Proteus,” AN-41-15-05 V.1, PSI (2015)

SNEAK-7A/7B

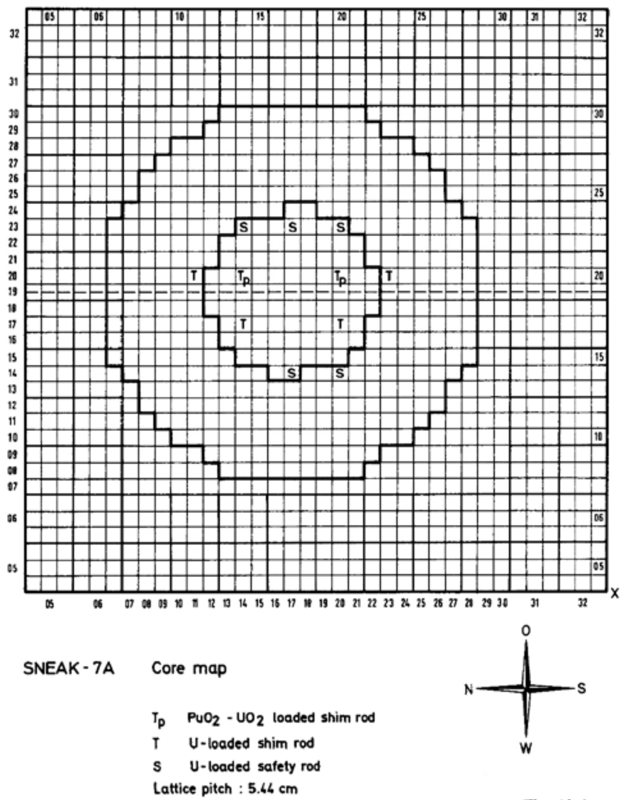


Fig.: SNEAK-7A Core Map*

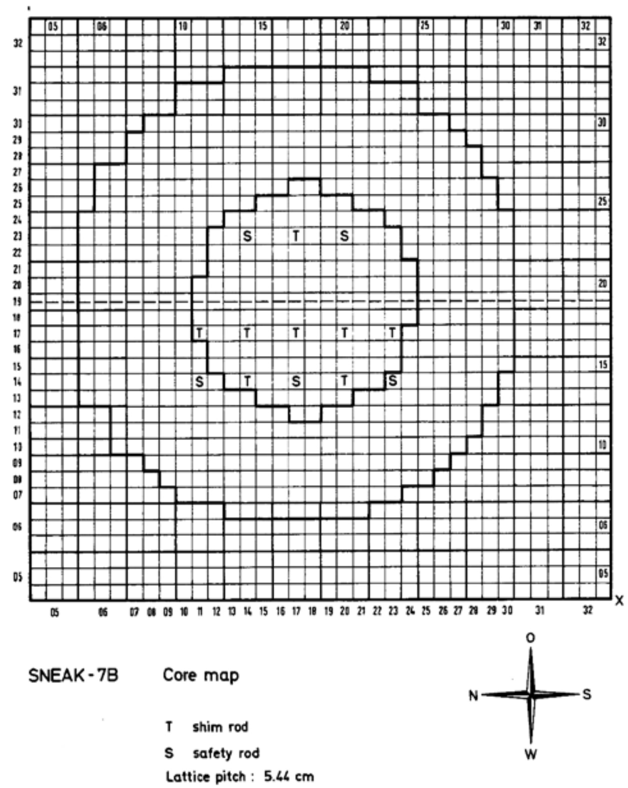


Fig.: SNEAK-7B Core Map*

*: E. Ivanov, et al., "SNEAK 7A and 7B Pu-fueled fast critical assemblies in the Karlsruhe fast critical facility," International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhE), NEA/NSC/DOC(2006)1, March 2015 Edition

Table: Summary of Feature of SNEAK-7A and -7B*

Assembly	Year	Features	Core Components	Blanket
7A	1970/71	1-zone core	PuO2-UO2, graphite	Metallic depleted U
7B	1971		PuO2-Uo2, ^{nat}UO2	

Atomic Densities of SNEAK-7A and -7B

Table 1.7. Atomic Densities for SNEAK-7A R-Z Model, 10^{24} cm^{-3} (Reference 1, p. 69).

Isotope	Inner Core	Outer Core	Blanket
Al	0.0000080	0.0011906 [a]	-
C	0.0260987	0.0255387	0.0000135
Cr	0.0022423	0.0022390	0.0011080
Fe	0.0079713	0.0079824	0.0039549
H	-	-	-
Mg	-	-	-
Mn	0.0001109	0.0001178	0.0000875
Mo	0.0000165	0.0000145	0.0000100
Nb	0.0000089	0.0000077	0.0000085
Ni	0.0011664	0.0011818	0.0009845
O	0.0218462	0.0211909	-
^{239}Pu	0.0026374	0.0023434	-
^{240}Pu	0.0002369	0.0002105	-
^{241}Pu	0.0000215	0.0000191	-
^{242}Pu	0.0000011	0.0000010	-
Si	0.0000933	0.0000932	0.0000453
^{235}U	0.0000586	0.0002958 [b]	0.0001624
^{238}U	0.0079604	0.0080456	0.0399401

(a) This value is 7.2% higher than the value calculated from stretched-platelet atom densities (Table 1.9).
(b) Note that this value is 5.9% higher than the value calculated using the described method for obtaining outer-core atom densities.

Table 1.8. Atomic Densities for SNEAK-7B R-Z Model, 10^{24} cm^{-3} (Reference 1, p. 71).

Isotope	Core	Blanket
Al	0.0012112	-
C	0.0000631	0.0000135
Cr	0.0027560	0.0011080
Fe	0.0098021	0.0039549
H	0.0000071	-
Mg	0.0000095	-
Mn	0.0000646 [a]	0.0000875
Mo	0.0000184	0.0000010 [b]
Nb	0.0000084	0.0000085
Ni	0.0014594	0.0009845
O	0.0331936	-
^{239}Pu	0.0018312	-
^{240}Pu	0.0001645	-
^{241}Pu	0.0000149	-
^{242}Pu	0.0000007	-
Si	0.0001174	0.0000453
^{235}U	0.0002663	0.0001624
^{238}U	0.0145794	0.0399401

(a) The calculated value for Mn using the method described in the previous paragraph is 94% larger than this value.
(b) This value was given as 0.0000100 for SNEAK 7A. All other blanket values are the same for both cores.

*: E. Ivanov, et al., "SNEAK 7A and 7B Pu-fueled fast critical assemblies in the Karlsruhe fast critical facility," International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhE), NEA/NSC/DOC(2006)1, March 2015 Edition

Missing Sensitivity Coefficients

Adjusted nuclides and reactions		Sensitivity coefficients	
		PROTEUS 7 & 8	SNEAK 7A & 7B
U-235	capture	●	●
	fission	●	●
	nu	●	●
	elastic_scattering	●	●
	inelastic_scattering	●	●
	mu_average		
	fission_spectrum		●
U-238	capture	●	●
	fission	●	●
	nu	●	●
	elastic_scattering	●	●
	inelastic_scattering	●	●
	mu_average		●
Pu-239	capture	●	●
	fission	●	●
	nu	●	●
	elastic_scattering	●	●
	inelastic_scattering	●	●
	mu_average		●
	fission_spectrum		●
Pu-240	capture	●	●
	fission	●	●
	nu	●	●
	elastic_scattering	●	●
	inelastic_scattering	●	●
	mu_average		
Pu-241	capture	●	●
	fission	●	●
	nu	●	●
	elastic_scattering	●	●
	inelastic_scattering	●	●
	mu_average		

Adjusted nuclides and reactions		Sensitivity coefficients	
		PROTEUS 7 & 8	SNEAK 7A & 7B
B-10	capture	●	
	elastic_scattering	●	
	inelastic_scattering	●	
	mu_average		
O-16	capture	●	
	elastic_scattering	●	
	inelastic_scattering	●	
	mu_average		
Na-23	capture	●	
	elastic_scattering	●	
	inelastic_scattering	●	
	mu_average		
Cr-52	capture	●	
	elastic_scattering	●	
	inelastic_scattering	●	
	mu_average		
Fe-56	capture	●	●
	elastic_scattering	●	●
	inelastic_scattering	●	●
	mu_average		●
Ni-58	capture	●	
	elastic_scattering	●	
	inelastic_scattering	●	
	mu_average		

- For PROTEUS, sensitivity coefficients of fission spectrum and mu-average are missing
- For SNEAK, sensitivity coefficients of C-12, O-16, Cr-52 and Ni-58 are missing

Input Data for Additional Integral Experiments

- C/E values
  - Calculated values with a nuclear data library, x, are converted into those with JENDL-4.0 by using sensitivity coefficients:

$$C_{JENDL-4.0} = C_x \times S_x \frac{\sigma_{JENDL-4.0} - \sigma_x}{\sigma_x}$$

- Sensitivity coefficients
  - Given 33-group sensitivity coefficients are used without any modifications because the sensitivity coefficients are little sensitive to the nuclear data libraries
- Uncertainty and correlation
  - Experimental uncertainty :
    - Given data are used as they are
  - Analytical model uncertainty :
    - Ignored (set to zero)
  - Correlation factor:
    - Correlation factors between the other experiments are ignored (set to zero)

HCLWR-PROTEUS

Table: C/E and experimental uncertainty on kinf for PROTEUS Core7 and 8

Core #	Calculations	Experiments		C/E	
		Cell method	Buckling method	Cell method	Buckling method
7	1.12136	1.115±0.006	1.121±0.005	1.006±0.006	1.000±0.005
8	1.13465	1.178±0.004	1.185±0.012	0.963±0.004	0.958±0.012

M. Hursin, et al., "Description of the Data provided to the SG39 with respect to the HCLWR experiments at Proteus," AN-41-15-05 V.1, PSI (2015)

- Conversion of C/E value (JEFF-3.1.1 → JENDL-4.0)
  - Core 7: +0.372% (C/E = 1.006 →1.0097)
  - Core 8: +0.439% (C/E = 0.963 → 0.9672)

SNEAK-7A/7B

Table: C/E and experimental uncertainty on keff for SNEAK-7A and 7B

	Calculation	Experiment	C/E
SNEAK-7A KEFF	1.006497	1.0010 +- 0.0029	1.00549 +- 0.0029
SNEAK-7B KEFF	1.005863	1.0016 +- 0.0035	1.00426 +- 0.0035

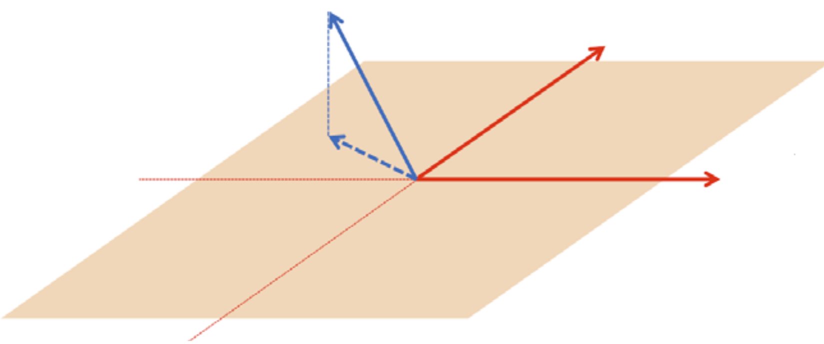
I. Kodeli, “Sensitivities profiles: Flattop-Pu, SNEAK-7A, SNEAK-7B, ASPIS-FE88,” WPEC/SG39 website, https://www.oecd-nea.org/science/wpec/sg39/

- Conversion of C/E value (ENDF/B-VII.1 → JENDL-4.0)
  - Core 7: +0.398% (C/E = 1.00549 → 1.00949)
  - Core 8: +0.479% (C/E = 1.00426 → 1.00906)

Trial Application of Sub-space Method

Sub-space decomposition nuclear data space *

If a unit nuclear data vector is NOT on this plane, this nuclear data cannot be reconstructed by a set of sensitivity vectors; the norm of the projected vector on this sub-space corresponds to usefulness of the integral data set to validate this nuclear data.



SVD to sensitivity matrix *

$$\mathbf{S} = \mathbf{U}\mathbf{D}\mathbf{V}^T$$

Sensitivity matrix

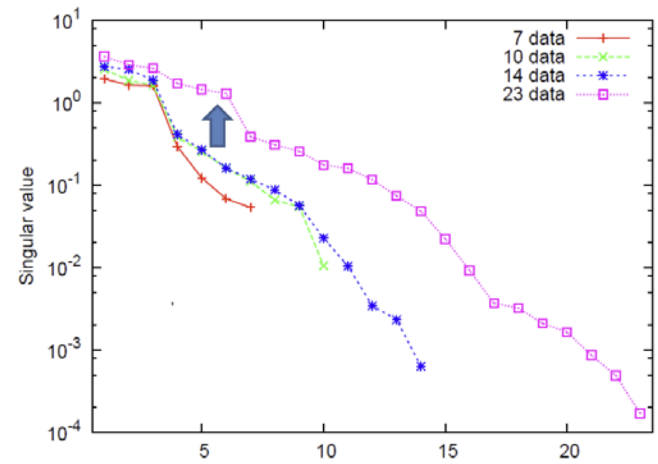
$$\mathbf{D} = \mathrm{diag}(\sigma_1, \sigma_2, \dots)$$

$$\mathbf{U} = (\mathbf{u}_1, \mathbf{u}_2, \dots)$$

Left-hand singular vectors

A orthonormal set of vectors $S = \{\mathbf{u}_1, \mathbf{u}_2, \dots\}$ spans a sensitivity sub-space.

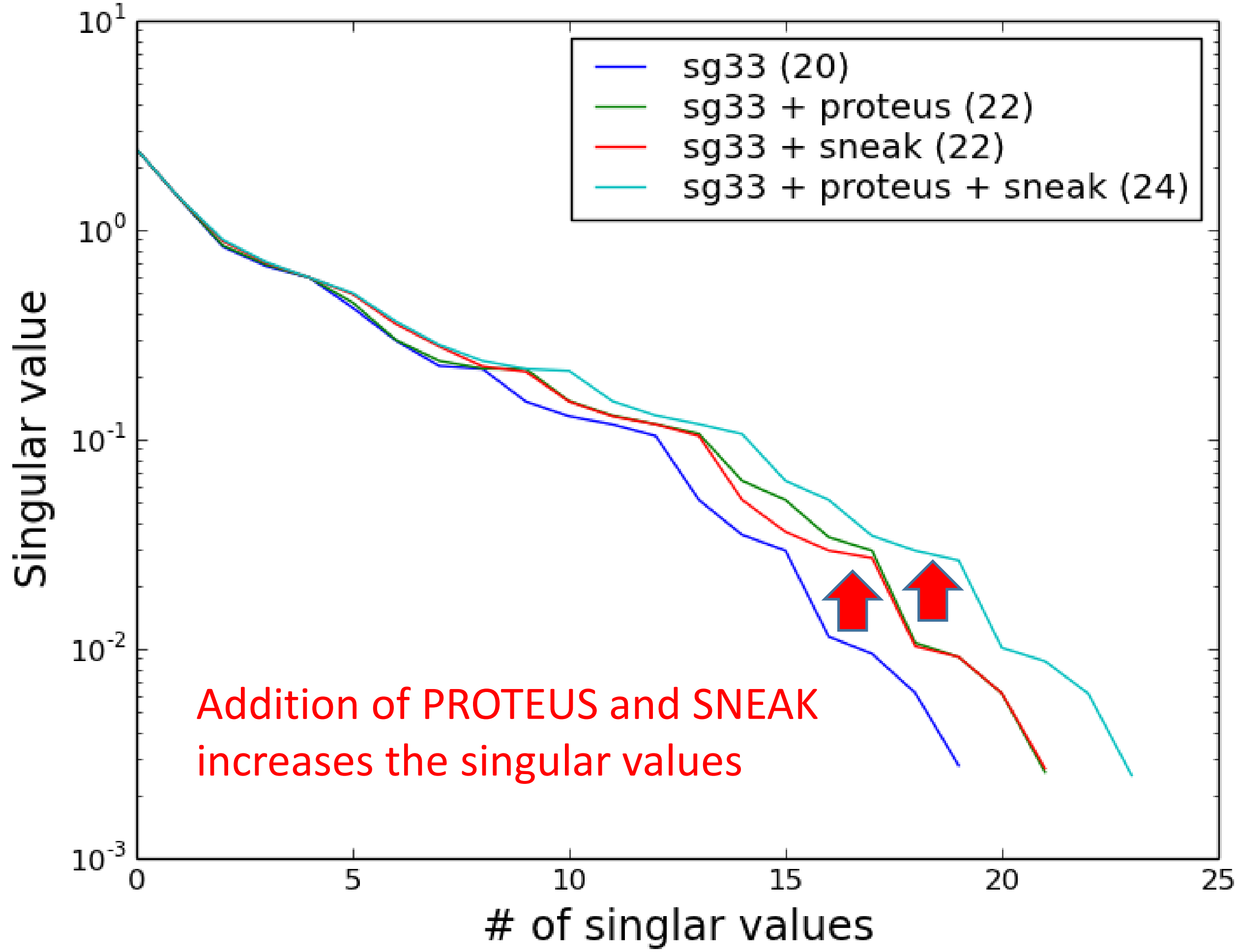
Singular values *



Consideration of the RRR data contributes to increase dimensions of the sensitivity sub-space.

*: G. Chiba, “Application of sub-space method for nuclear data validation,” Consultants’ Meeting on “Compensating Effects due to Nuclear Reaction and Material Cross Correlations in Integral Benchmarks,” IAEA Headquarters, Vienna (2015)

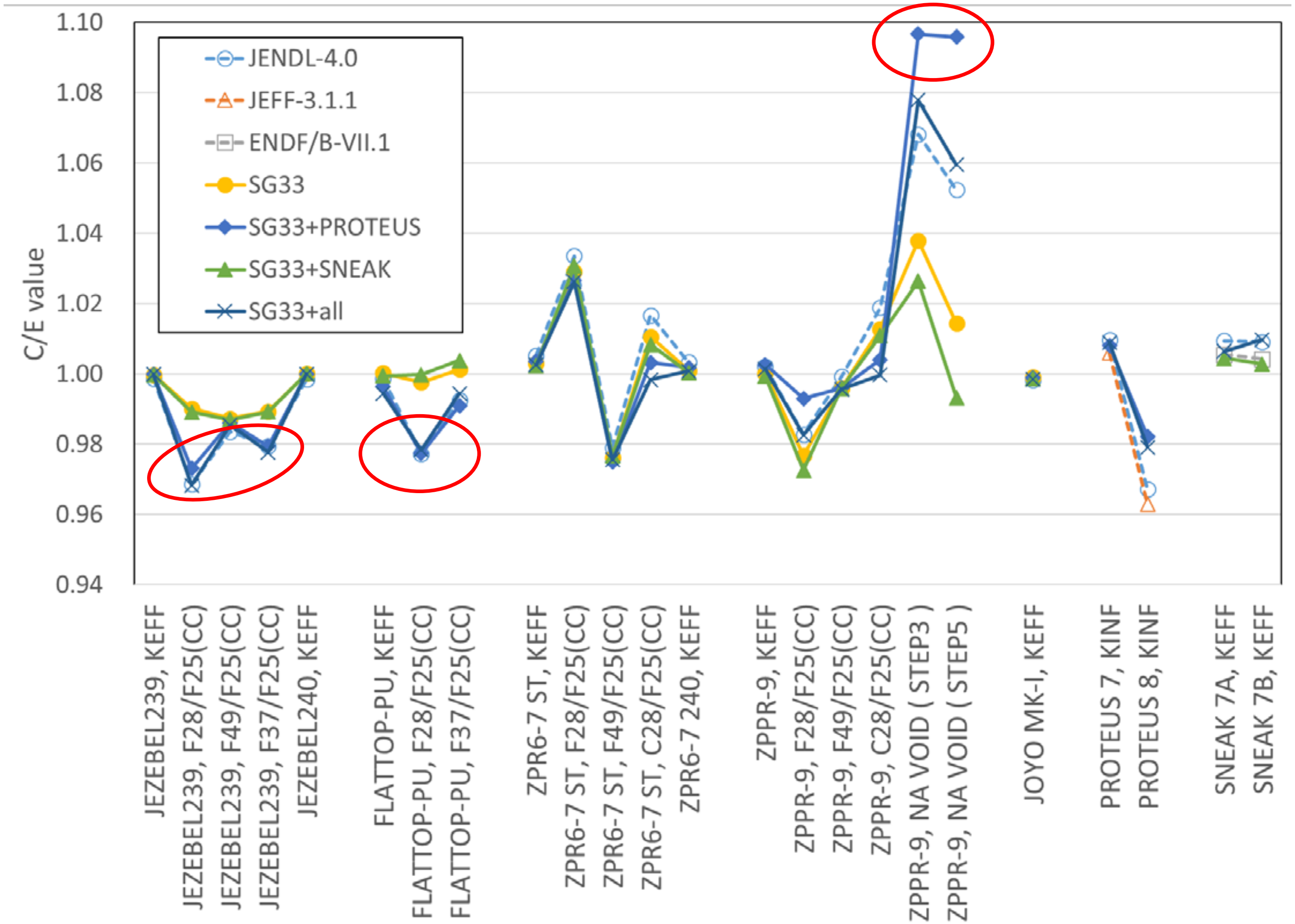
Singular Values of Sensitivity Matrix



- Consideration of PROTEUS and SNEAK data contributes to an increase in dimensions of the sensitivity sub-space*

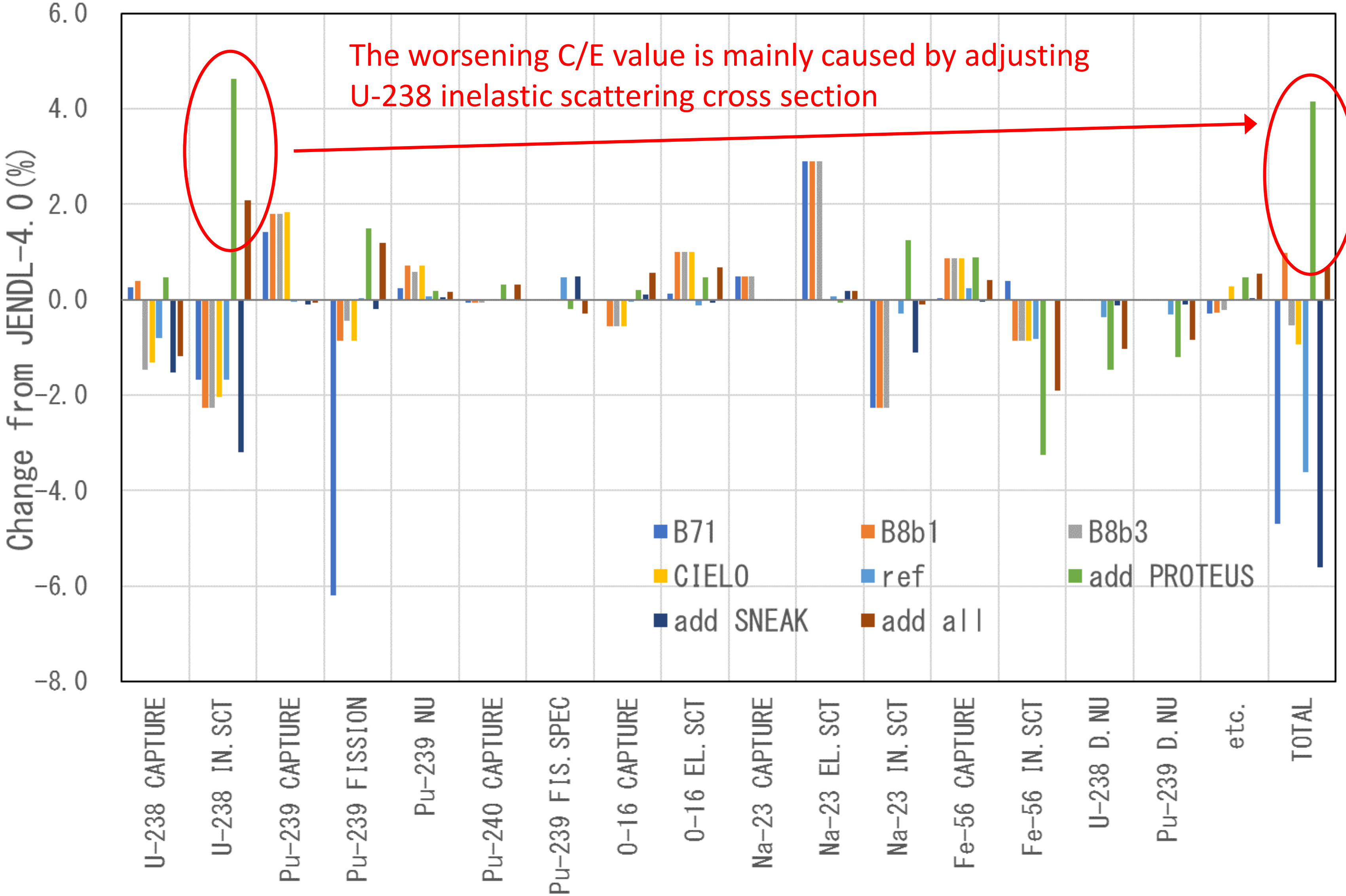
→ This result means that they have additional information

C/E Values

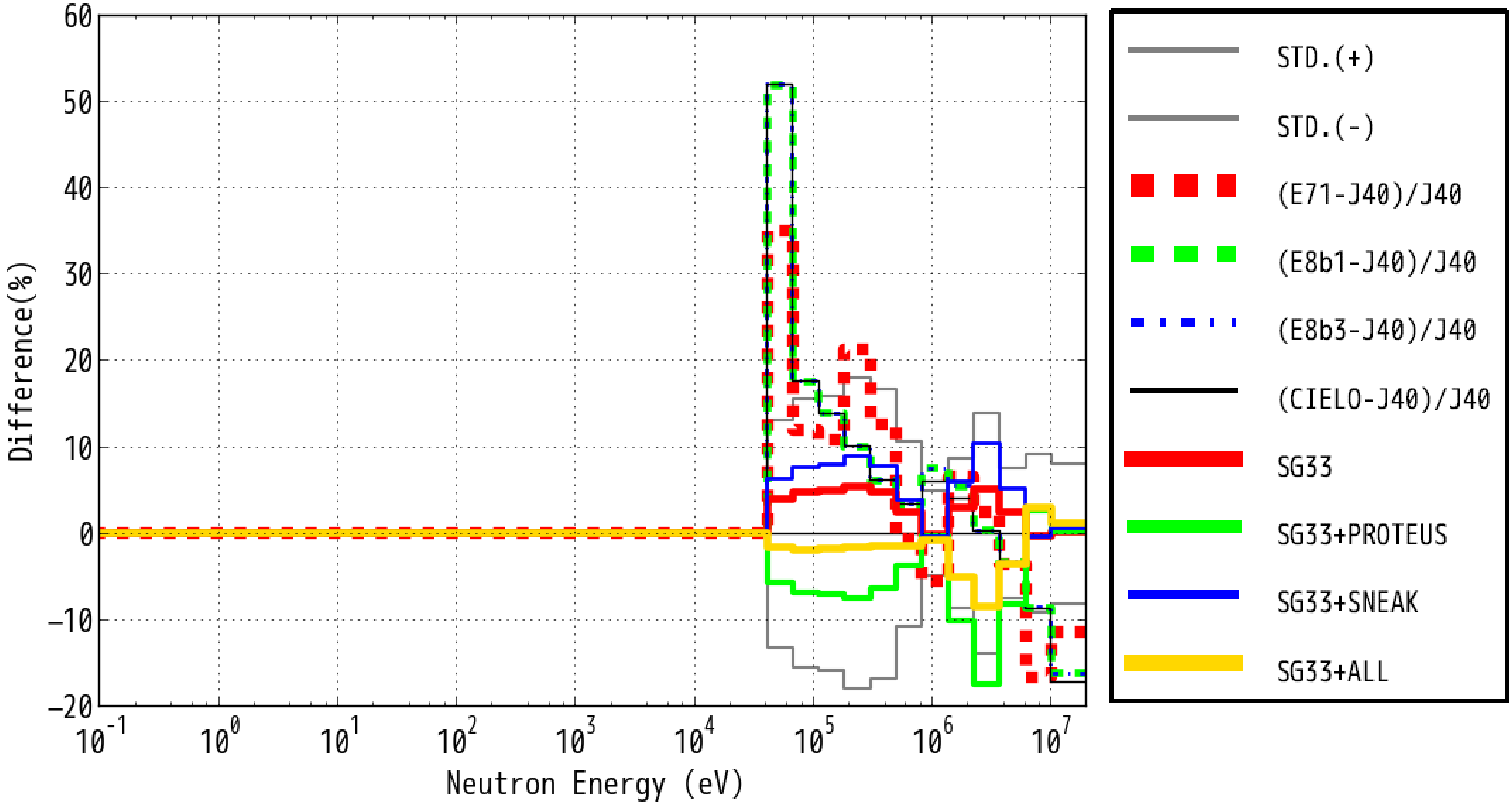


- C/E values of JEZEBEL and FLATTP-PU are not improved when adding PROTEUS
- Addition of PROTEUS worsens the C/E values of ZPPR-9 sodium void worth

ZPPR-9 Sodium Void Reactivity (Step5)

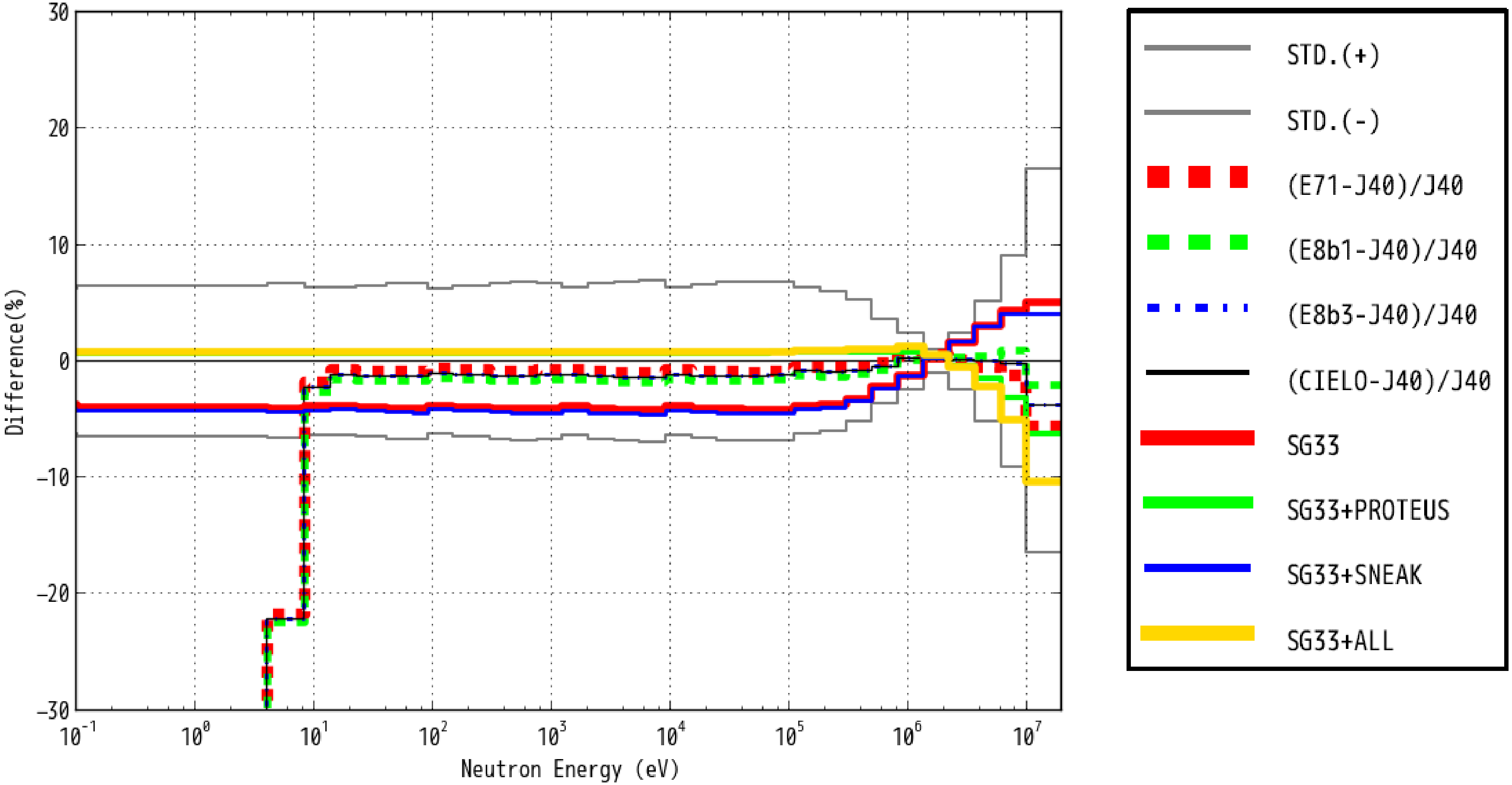


U-238 inelastic scattering cross sections



- SG33 and SNEAK increase U-238 inelastic scattering cross section but PROTEUS reduces it → There is a contradiction

Pu-239 fission spectrum



- Since the sensitivity coefficients of fission spectrum for PROTEUS are not available, this result must include a compensation effect
- According to the adjusted result of U-238 inelastic, PROTEUS prefers harder spectrum → But Pu-239 fission spectrum is adjusted to be softer

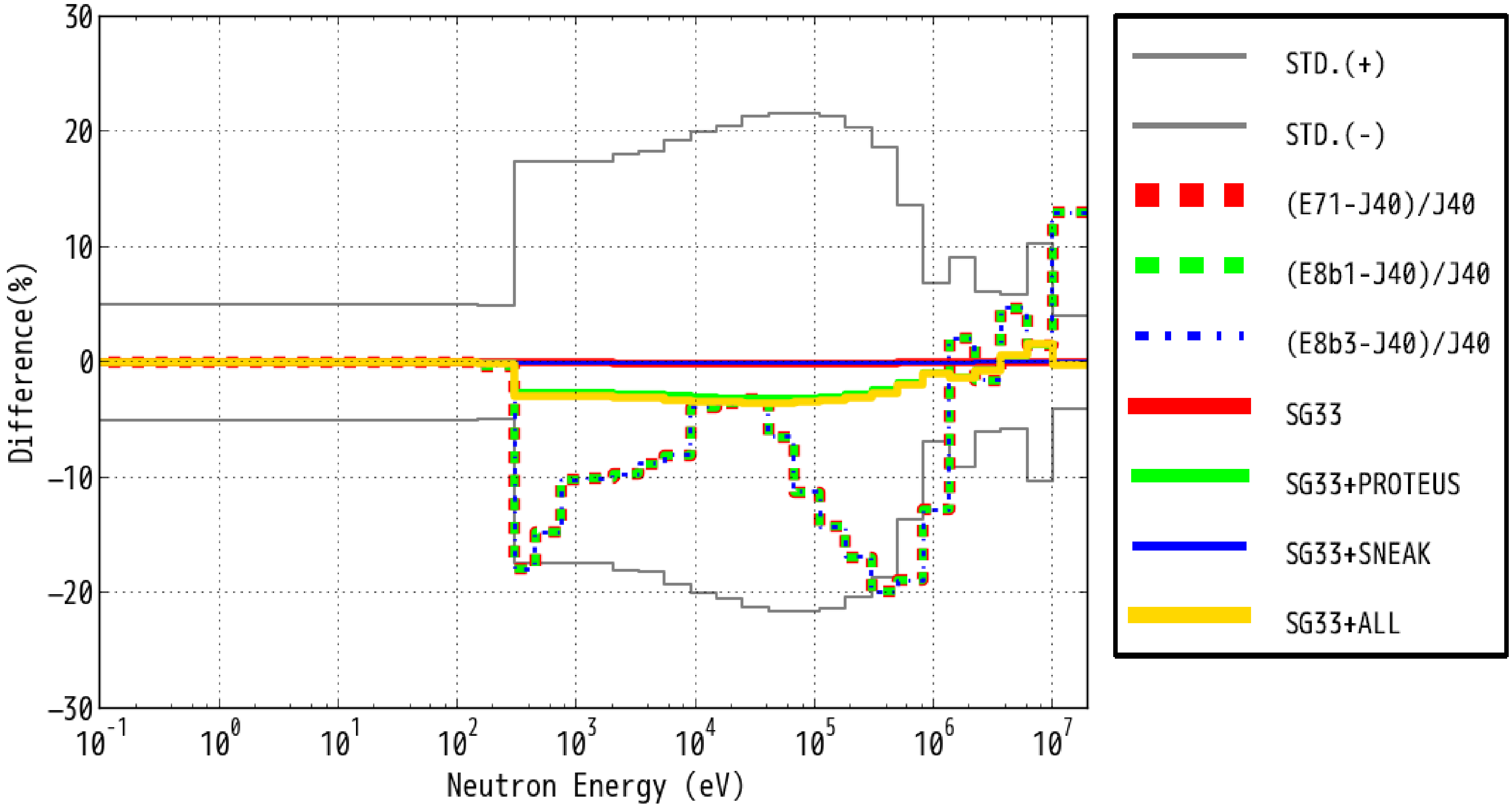
Detailed Versions of CIELO

All the CIELO files were downloaded from

https://www-nds.iaea.org/CIELO/

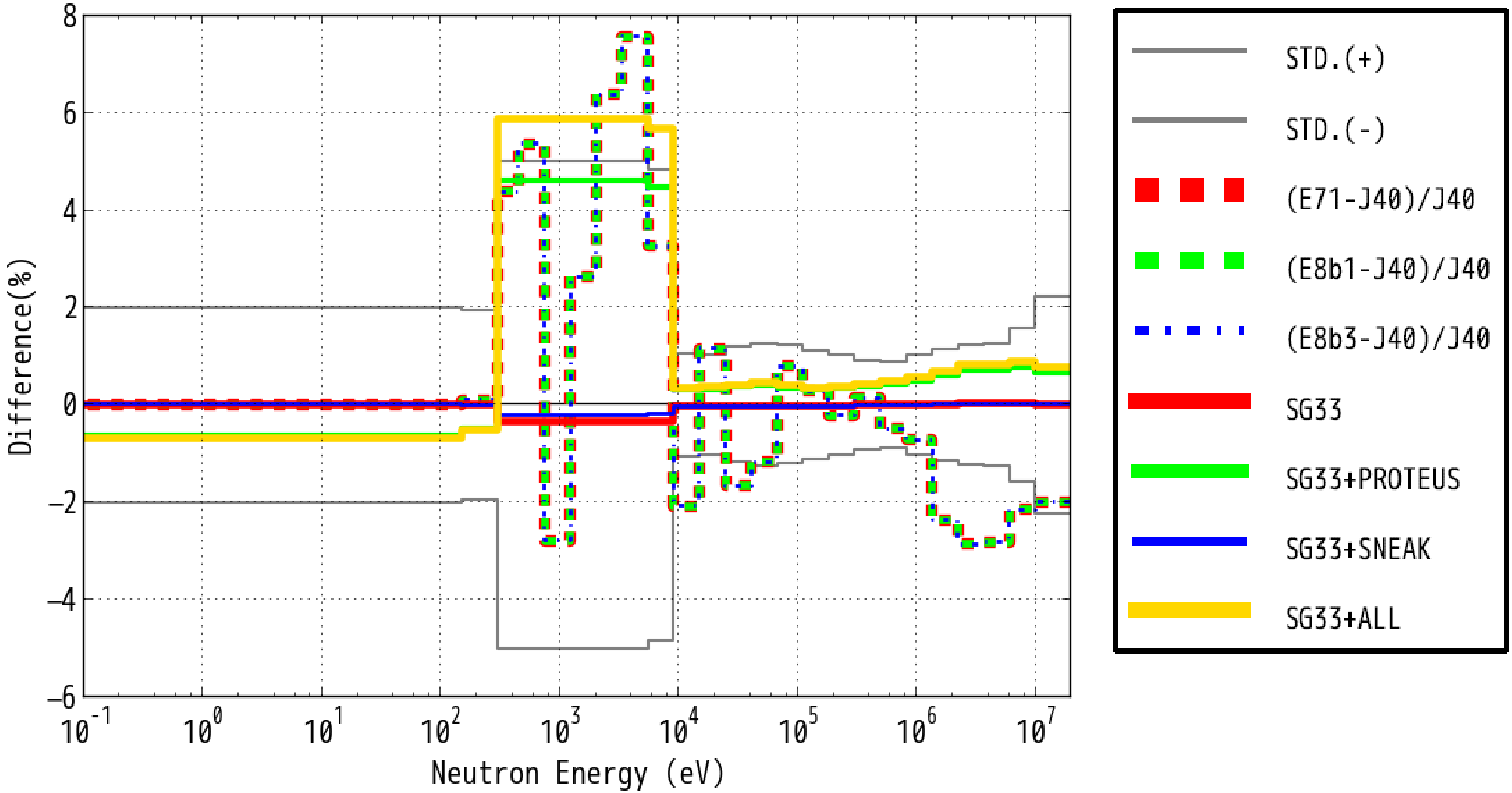
- IAEA-CIELO as of 5 Nov. 2016
  - U-238 Version: u238beta2STD compressed ENDF file (internal IAEA designation u238ib51brlFsST1)
  - U-235 Version: u235beta2STD compressed ENDF file (internal IAEA designation u235ib25o23g6DNcnu5ef4)
- IAEA-CIELO as of 8 Aug. 2016 (+ update 18 Aug. 2016)
  - Pu-239 Version: lanlmbc2v; ENDF/B-VIII beta2 candidate file (mbc2) provided by A.C.(Skip) Kahler
  - O-16 ENDF/B-VIII beta1 candidate file (o16e80b1) downloaded from NNDC
  - Fe-56 Empire "ib15", complex file assembly using JEFF-3.2, JENDL-4.0 and EXFOR (Gforge version 219). Tuned P2 and P4 Legendre coefficients of elastic scattering to improve performance in iron-reflected benchmarks.

Pu-241 elastic scattering cross sections



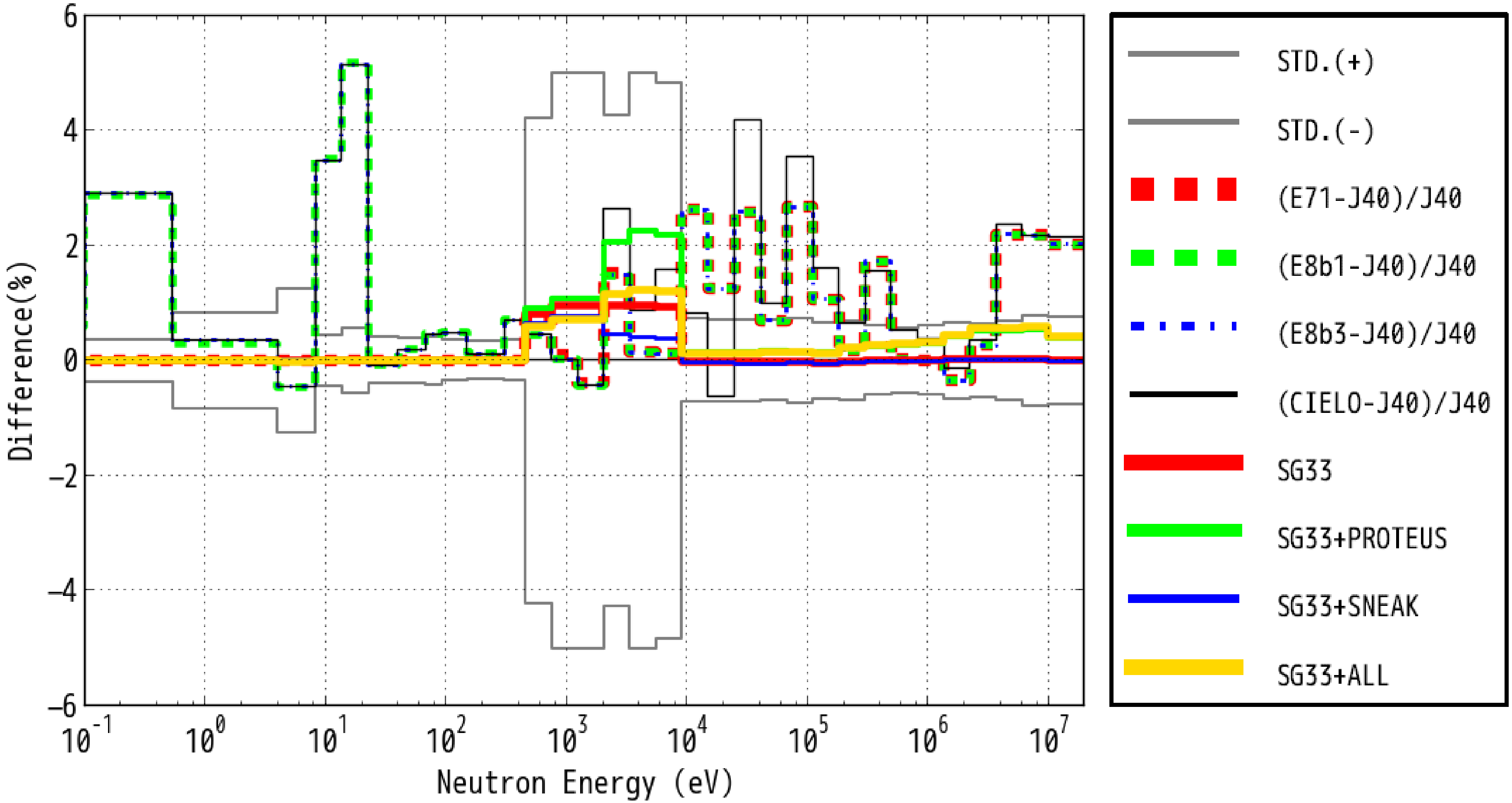
- SG33 and SNEAK give no change on Pu-241 cross section
- Addition of PROTEUS makes changes → new information

Pu-241 fission cross sections



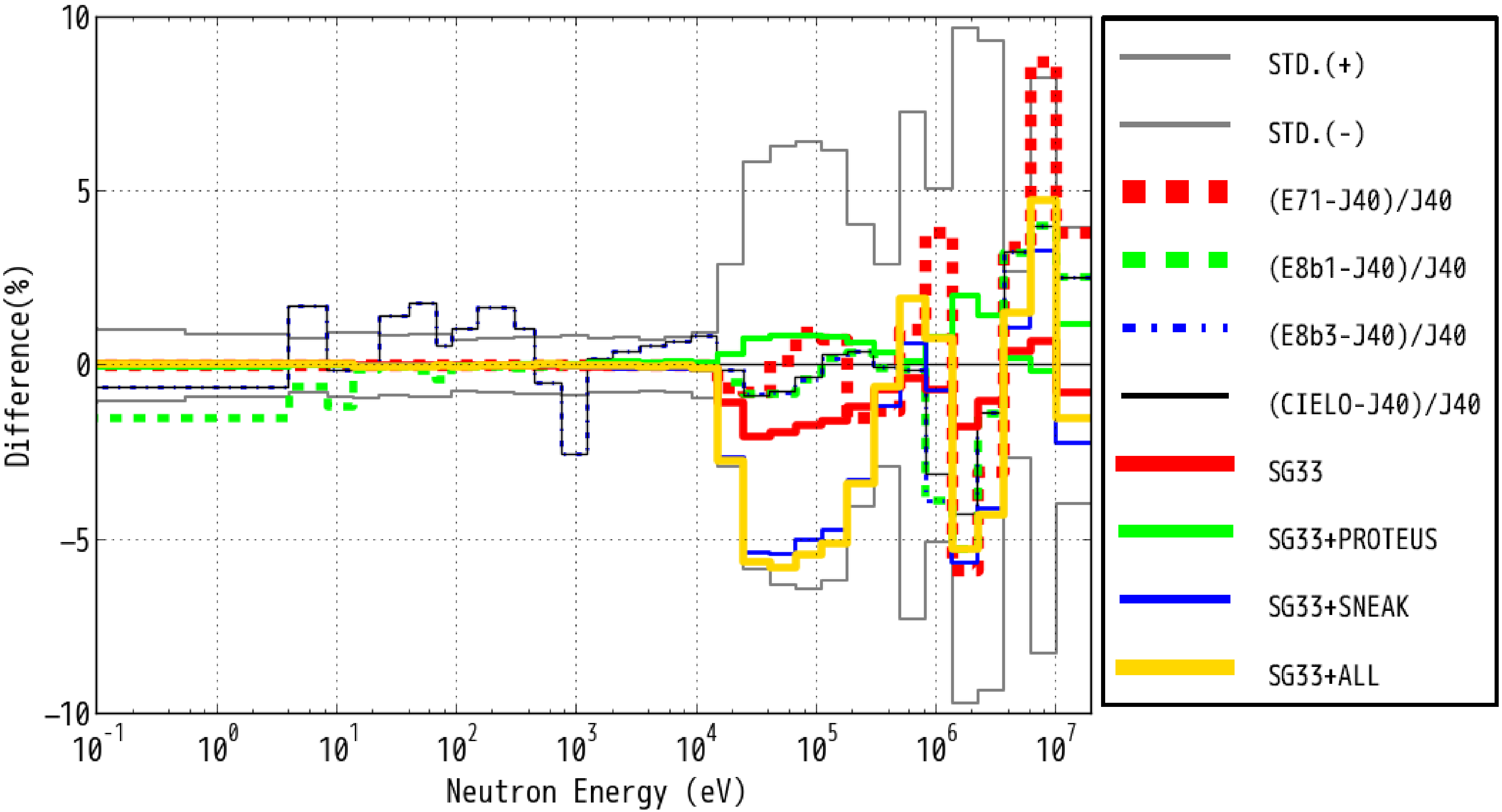
- PROTEUS increases Pu-241 fission cross section in above keV ranges
- PROTEUS supports ENDF-B/VIII.0 beta1 & 3 in keV ranges ?

U-235 fission cross sections



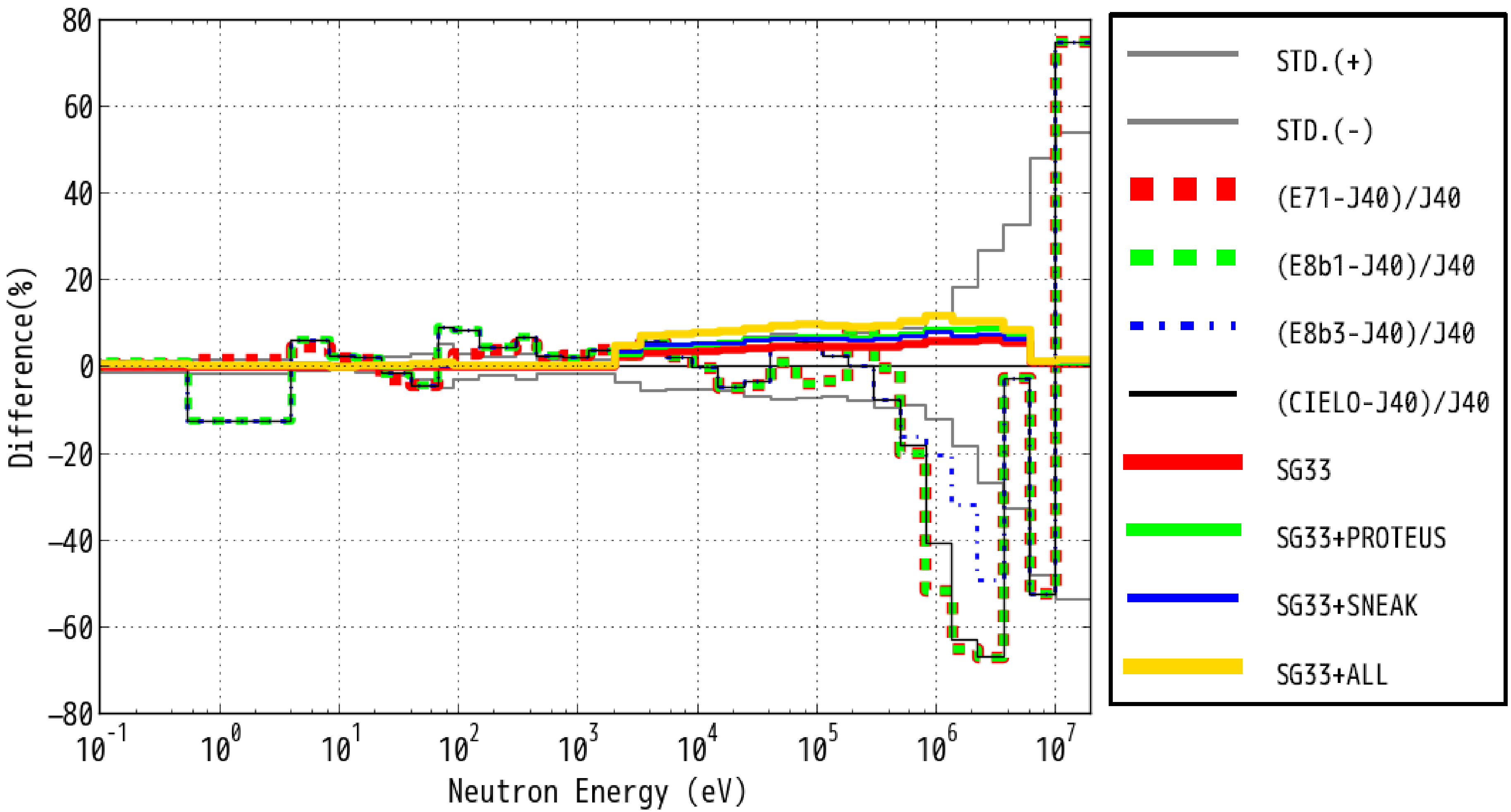
- PROTEUS increases U-235 fission cross section
- SNEAK seems to constrain the increment

U-238 elastic scattering cross sections



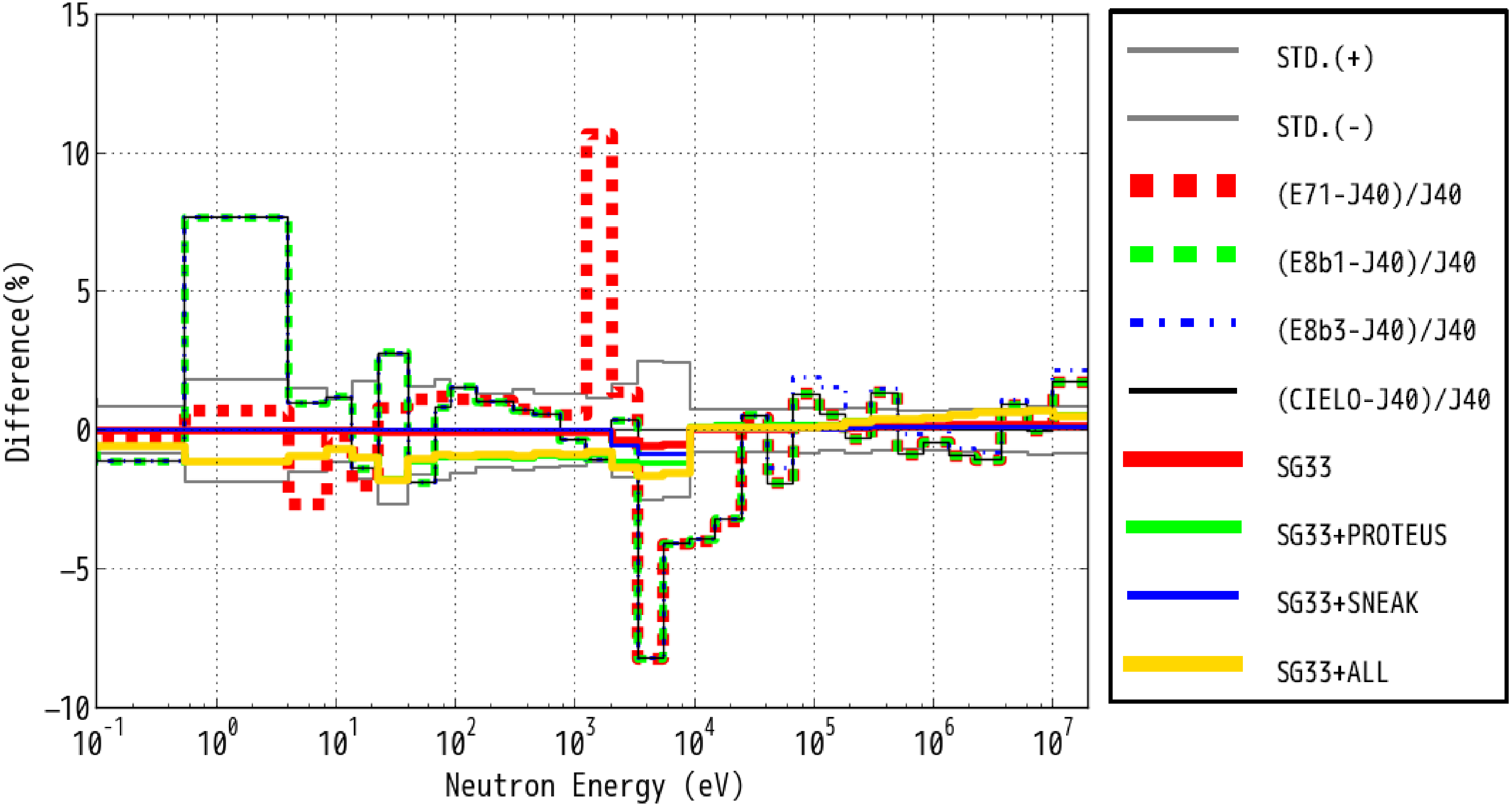
- PROTEUS and SNEAK seem to conflict with each other
- Changes by SNEAK seem to be dominant

Pu-239 capture cross sections



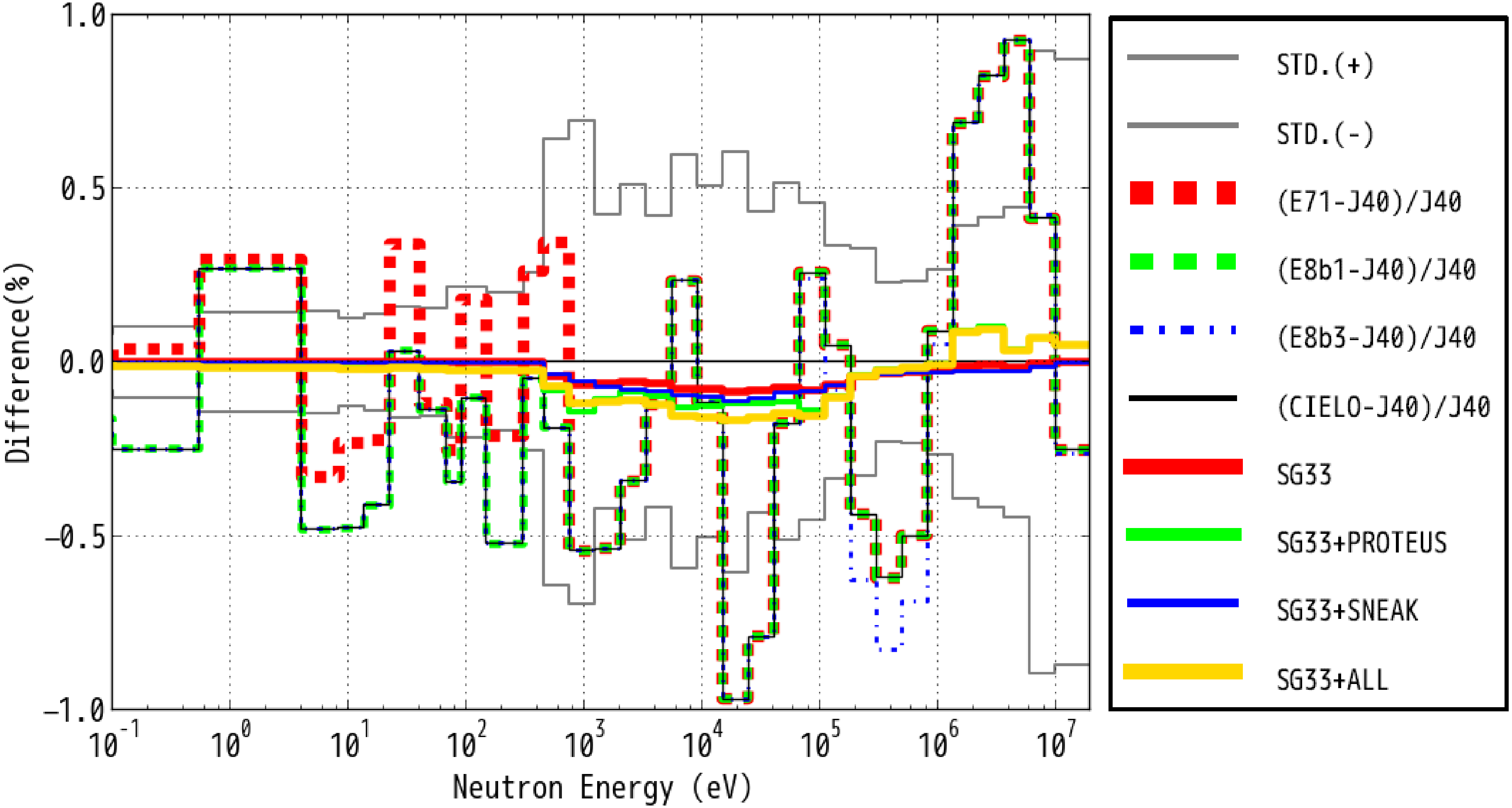
- All integral experiments increase Pu-239 capture cross section → There is no contradiction

Pu-239 fission cross sections



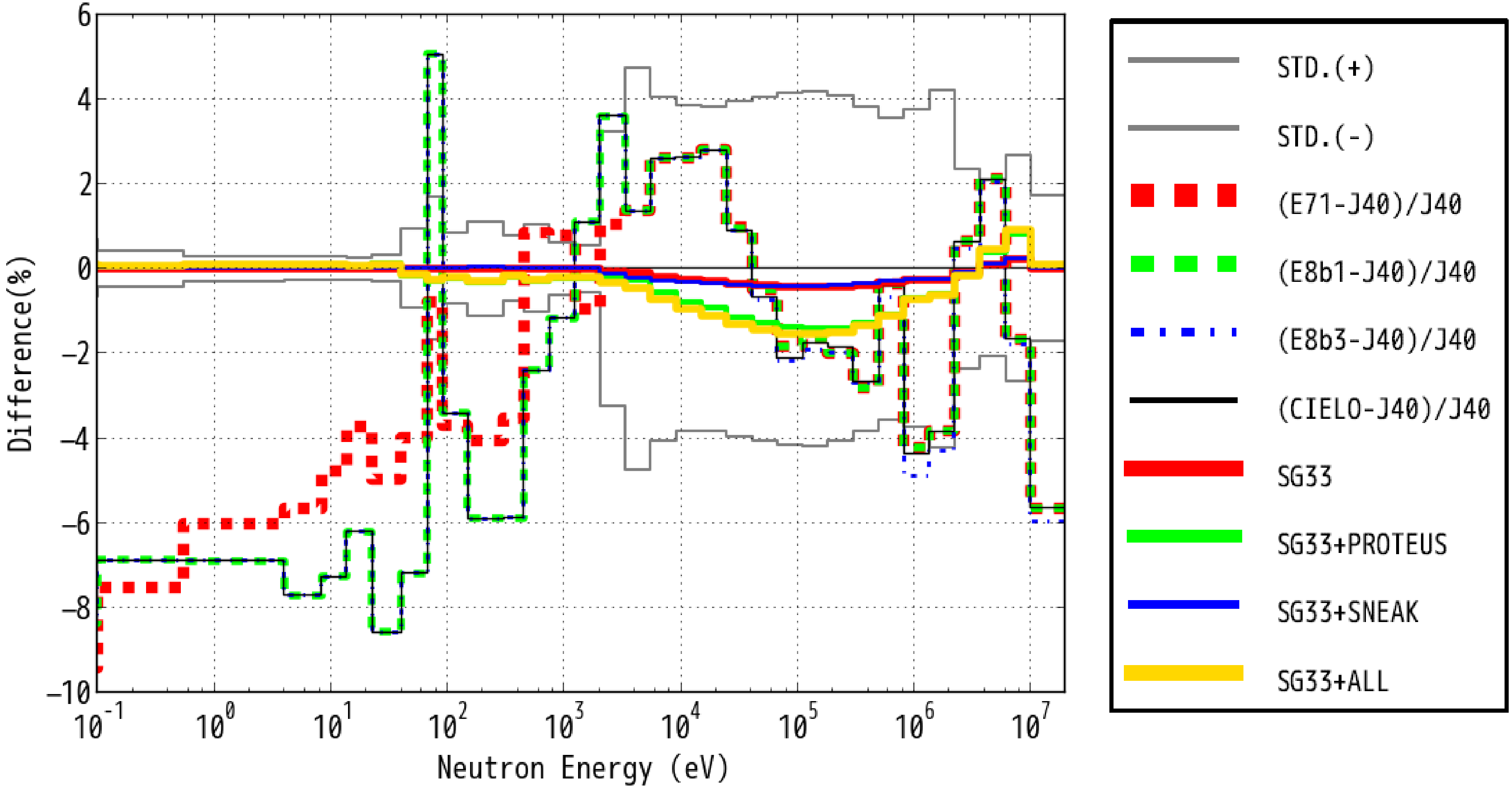
- PROTEUS decreases Pu-239 fission cross section in lower energy ranges

Pu-239 nu-bar



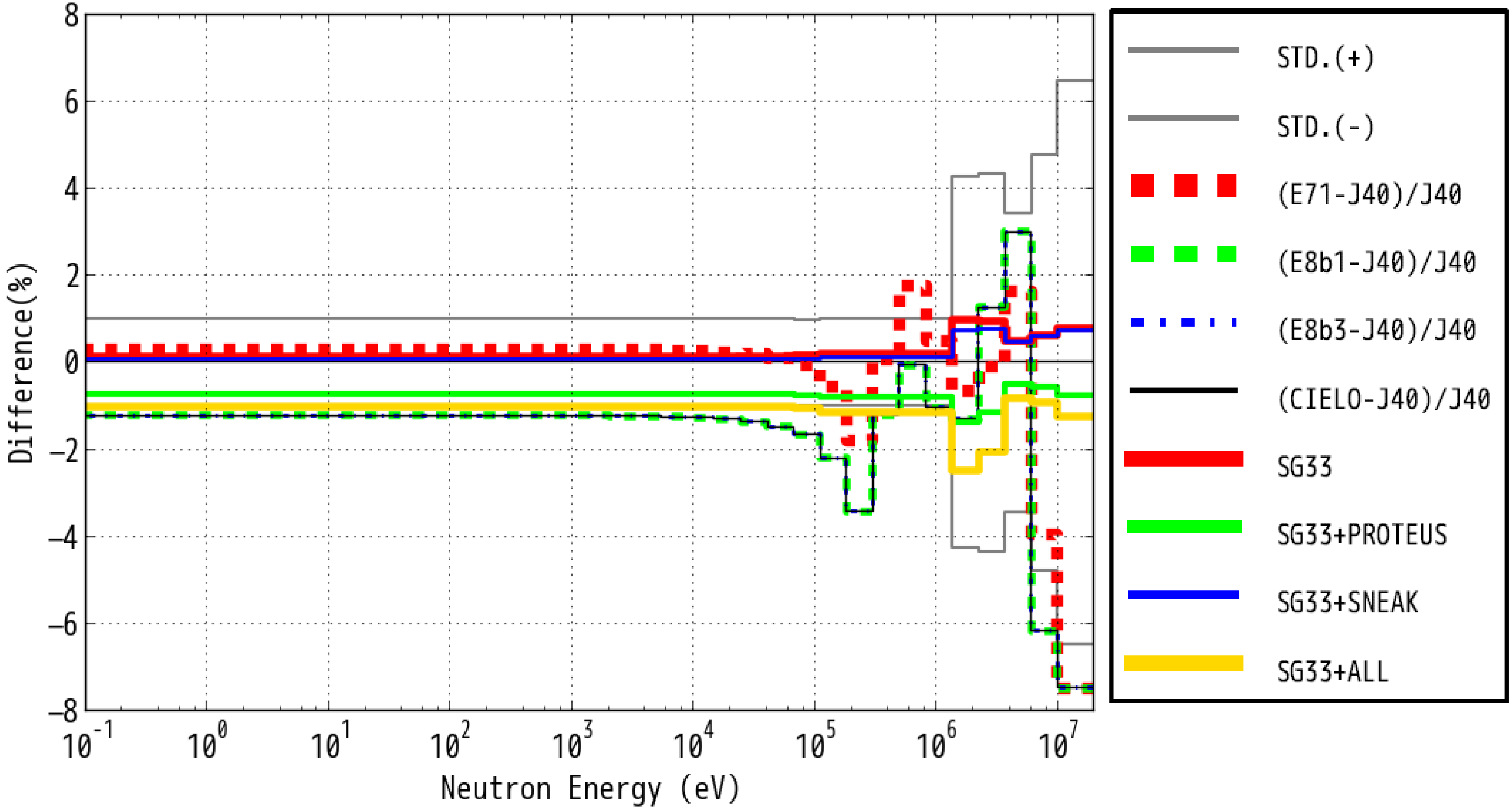
- There is no contradiction among all integral experiments

Pu-239 elastic scattering cross sections



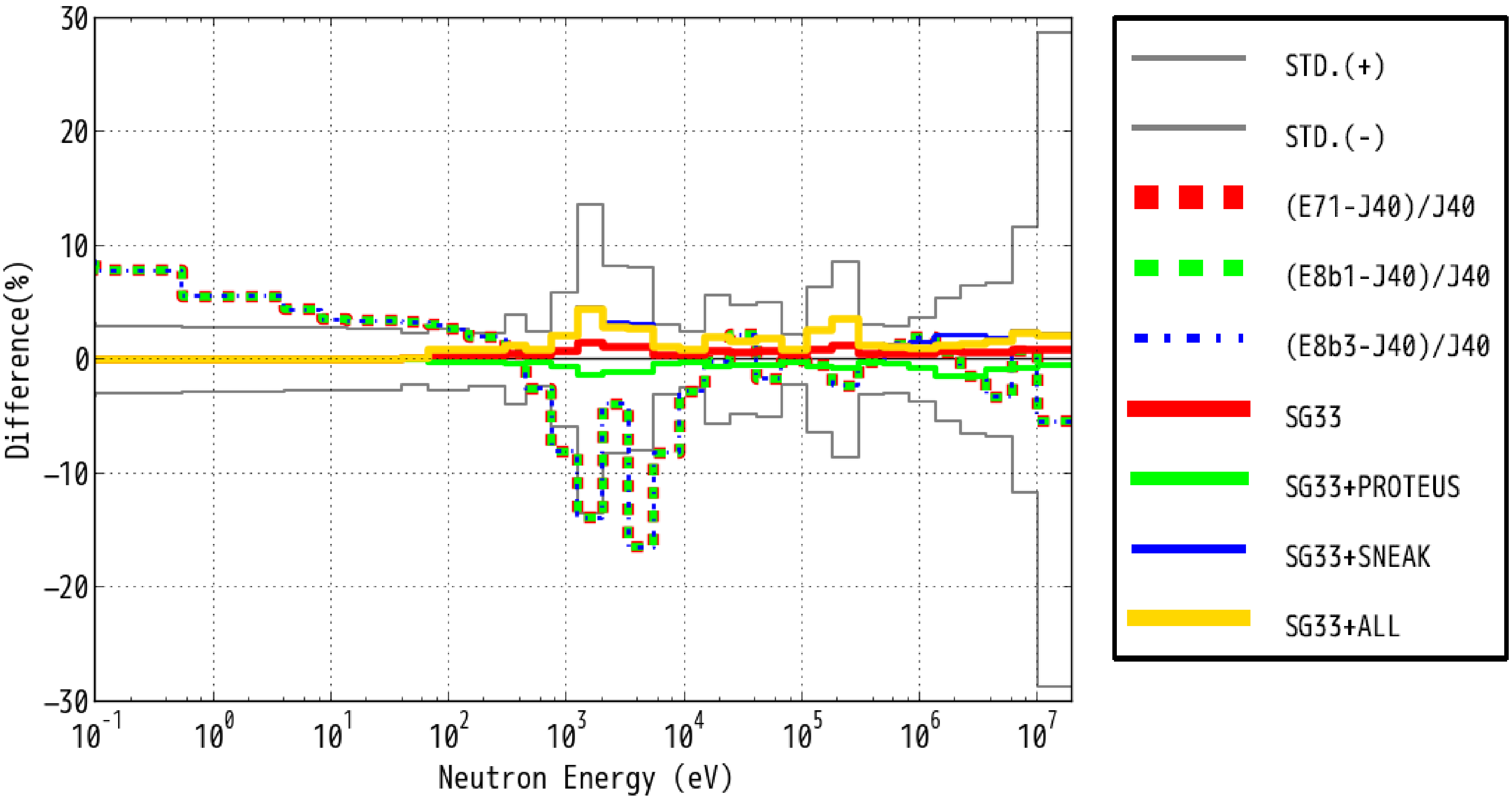
- There is no contradiction among all integral experiments
- PROTEUS makes further reduction of Pu-239 elastic scattering cross section

O-16 elastic scattering cross sections



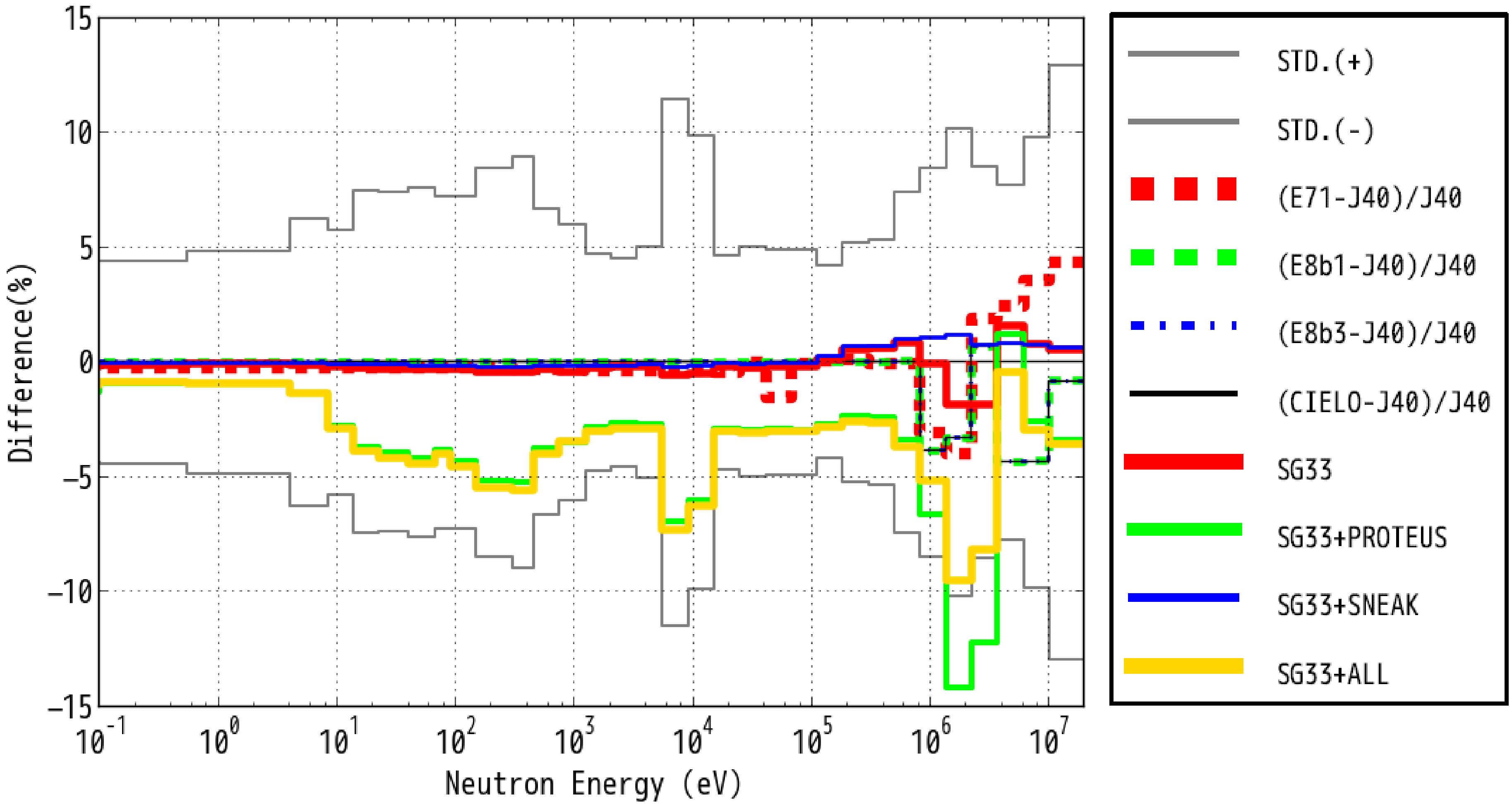
- PROTEUS reduces O-16 elastic scattering cross section
- Can we say that PROTEUS supports CIELO?

Na-23 elastic scattering cross sections



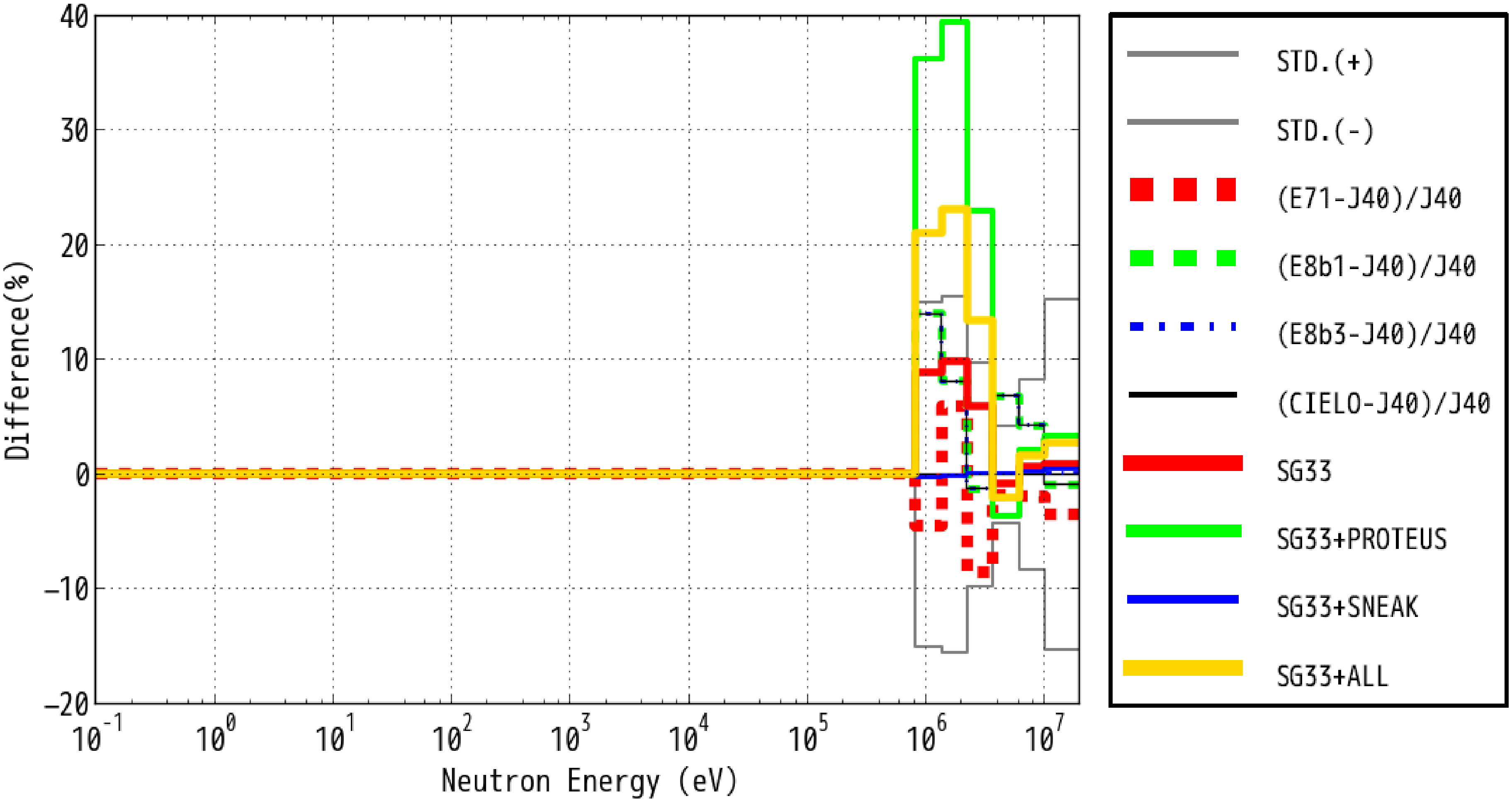
- PROTEUS reduces Na-23 elastic scattering although it does not include sodium
- There must have strong contradiction in the other reactions

Fe-56 elastic scattering cross sections



- PROTEUS reduces Fe-56 elastic cross section

Fe-56 inelastic scattering cross sections



- PROTEUS increases Fe-56 inelastic cross section too much (> 2-sigma) but this reaction only