Prompt fission neutron spectra and TKE of $^{235}U(n, F)$ and $^{239}Pu(n, F)$

Vladimir Maslov
Joint Institute for Nuclear and Energy Research,
220109, Minsk-Sosny, Belarus

SCOPE

235U+n 239Pu+n Prompt Fission Neutron Spectra

1. Thermal region
2. Fast region
3. Emissive (n,xnf) fission

Collaboration

"^{239}Pu(n, F) & "^{235}U(n,F) PROMPT FISSION NEUTRON SPECTRA"

WAS STARTED BY COLLABORATION OF 2008-2011

V.M. Maslov[1)], V.P.Pronyaev[2)], N.A. Tetereva[1)],A.B. Kagalenko[2)],N.V. Kornilov[2)], T. Granier[3)], F.-J. Hambsch[4)], B. Morillon[3)]

1) Joint Institute of Nuclear and Energy Research, 220109,Minsk-Sosny, Belarus

2) Institute of Physics and Power Engineering, 249033, Obninsk, Russia

3) CEA, Centre DAM-Ile de France, 91927,Arpajon, Cedex, France

4) EU-JRC Institute for Reference Materials and Measurements, Geel, Belgium

PFNS in Major Data Libraries

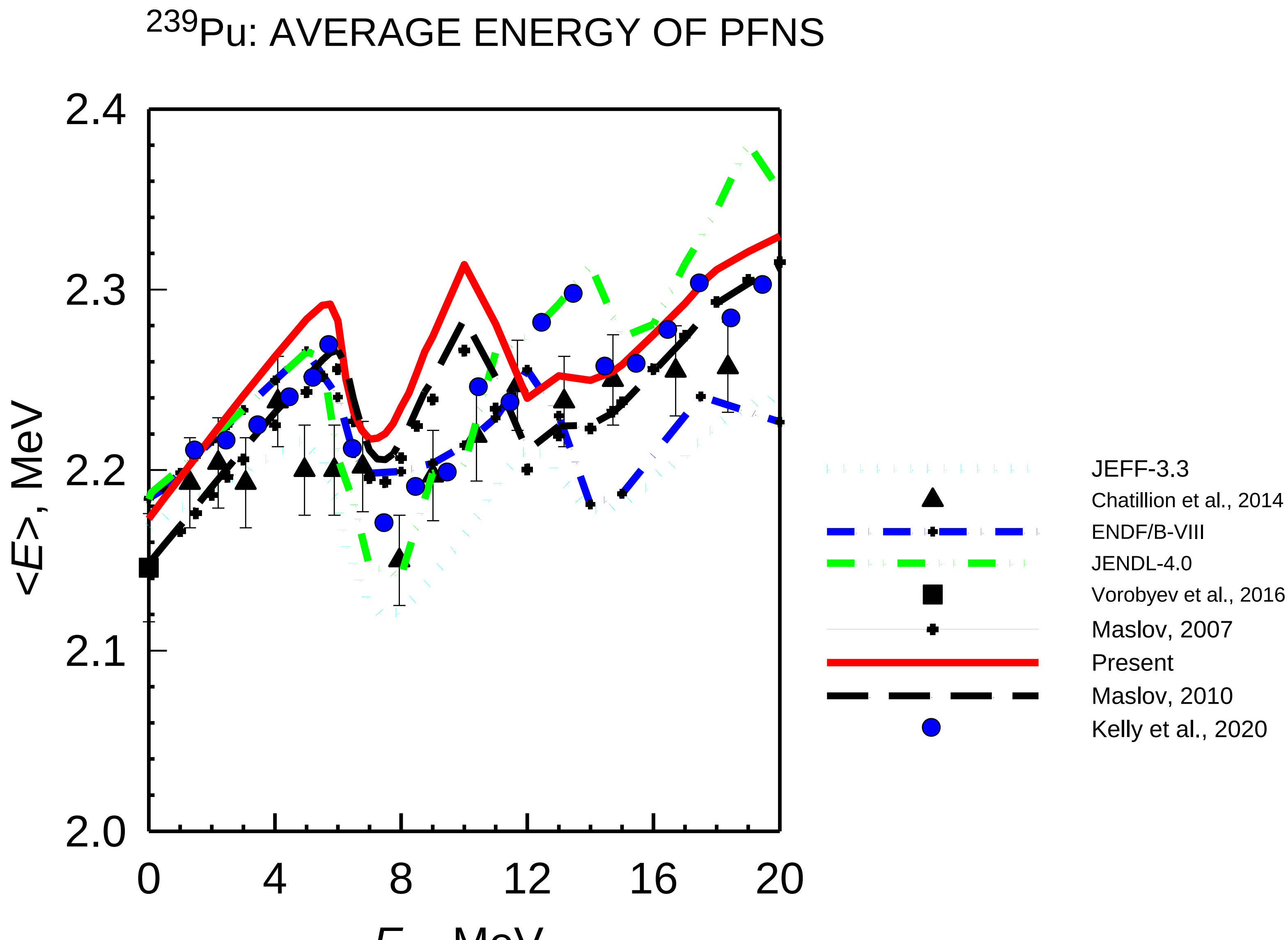
1. PFNS discrepancies in MDL are often quoted as PFNS uncertainty

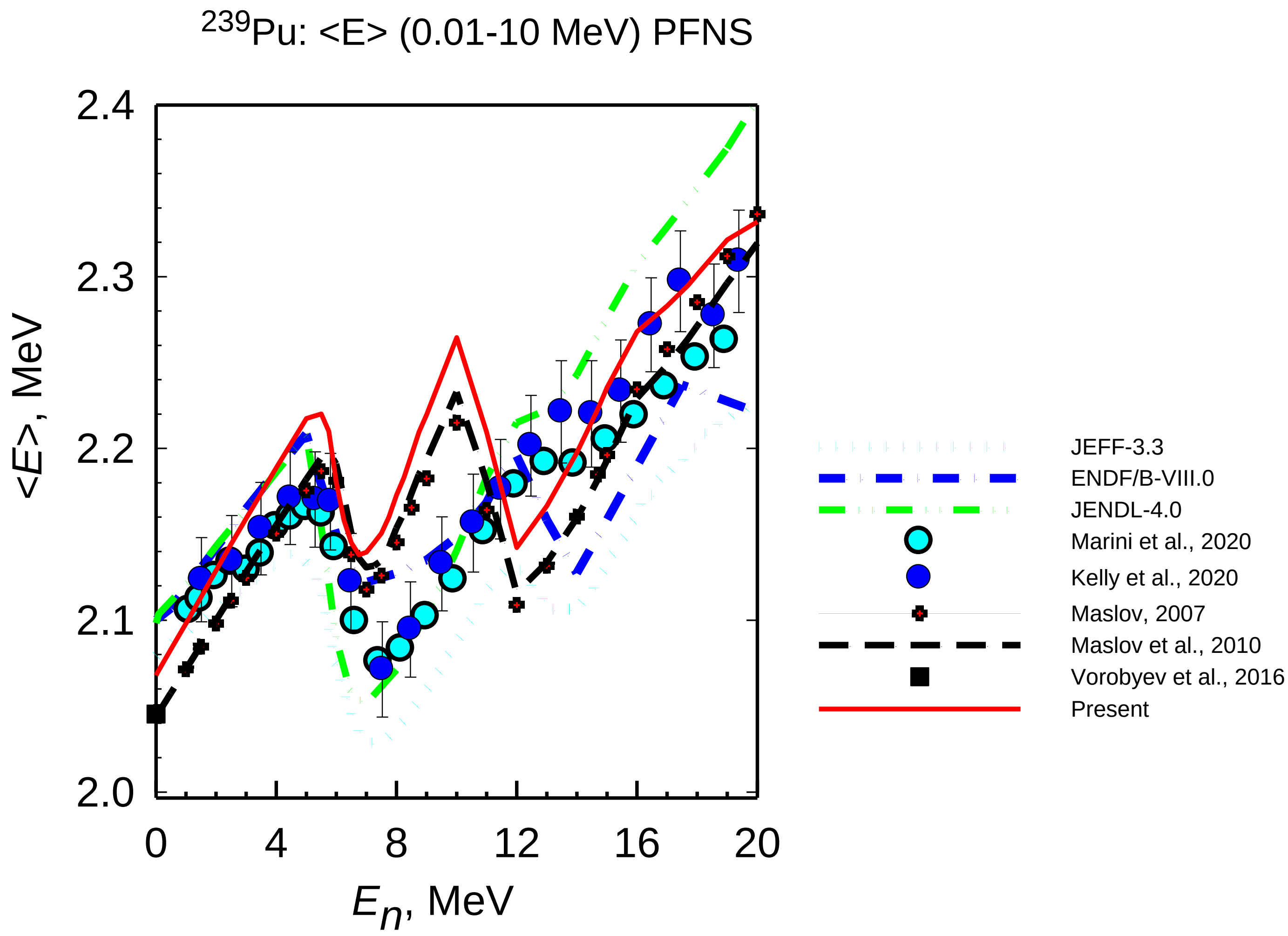
2. $^{235}U(n_{th}, f)$, $^{239}Pu(n_{th}, f)$ PFNS in MDL till recently essentially repeated each other

3. $^{235}U(n_{th}, f)$, $^{239}Pu(n_{th}, f)$ MDL' PFNS are still discrepant with measured PFNS laying well outside the biases of different data sets

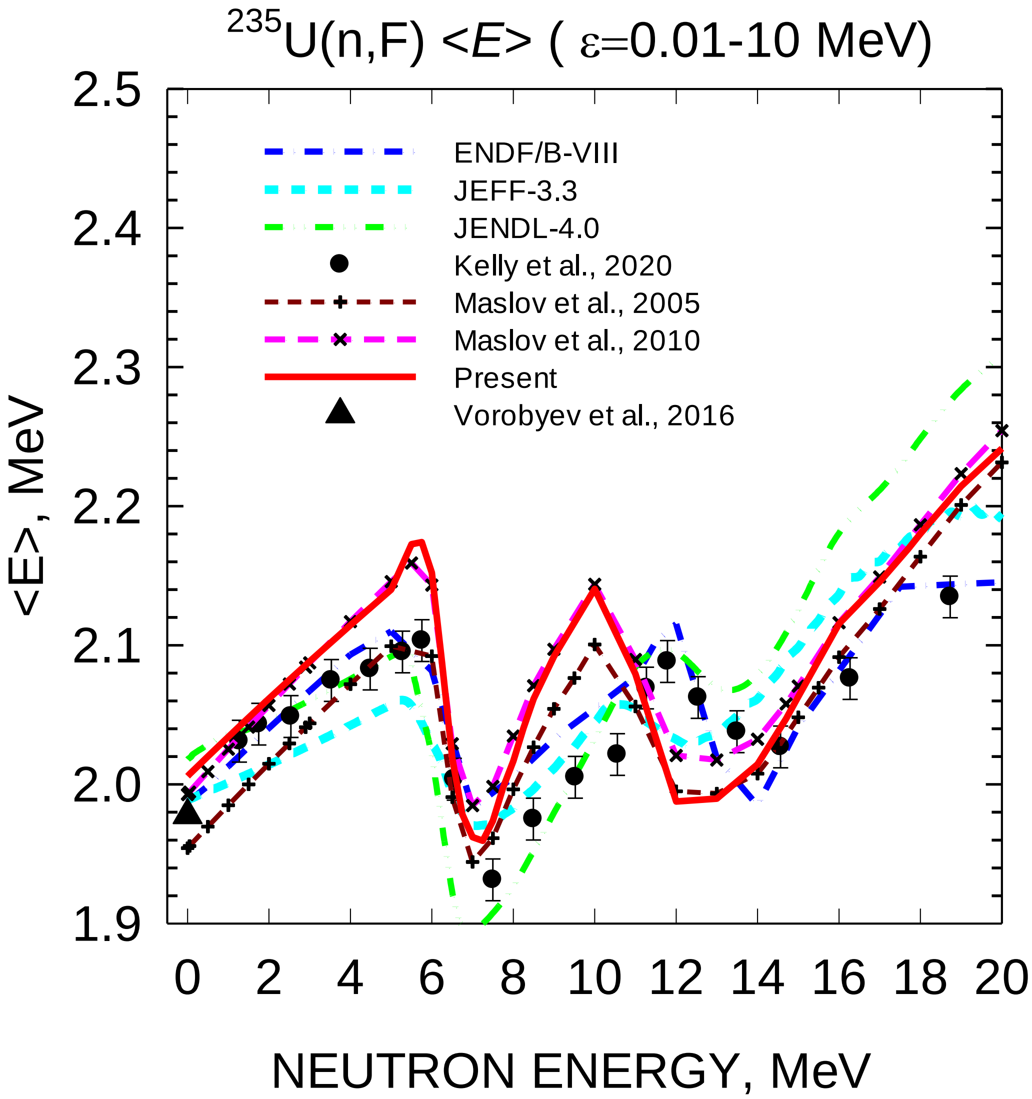
4. That may and still leads to arbitrary tweaking of neutron cross sections, neutron multiplicities to compensate ill-defined shapes of PFNS.

0.4-7 MeV


239Pu: AVERAGE ENERGY OF PFNS
2.4
2.3
2.2
2.1
2.0
<E>, MeV
0
4
8
12
16
20
JEFF-3.3
Chatillion et al., 2014
ENDF/B-VIII
JENDL-4.0
Vorobyev et al., 2016
Maslov, 2007
Present
Maslov, 2010
Kelly et al., 2020

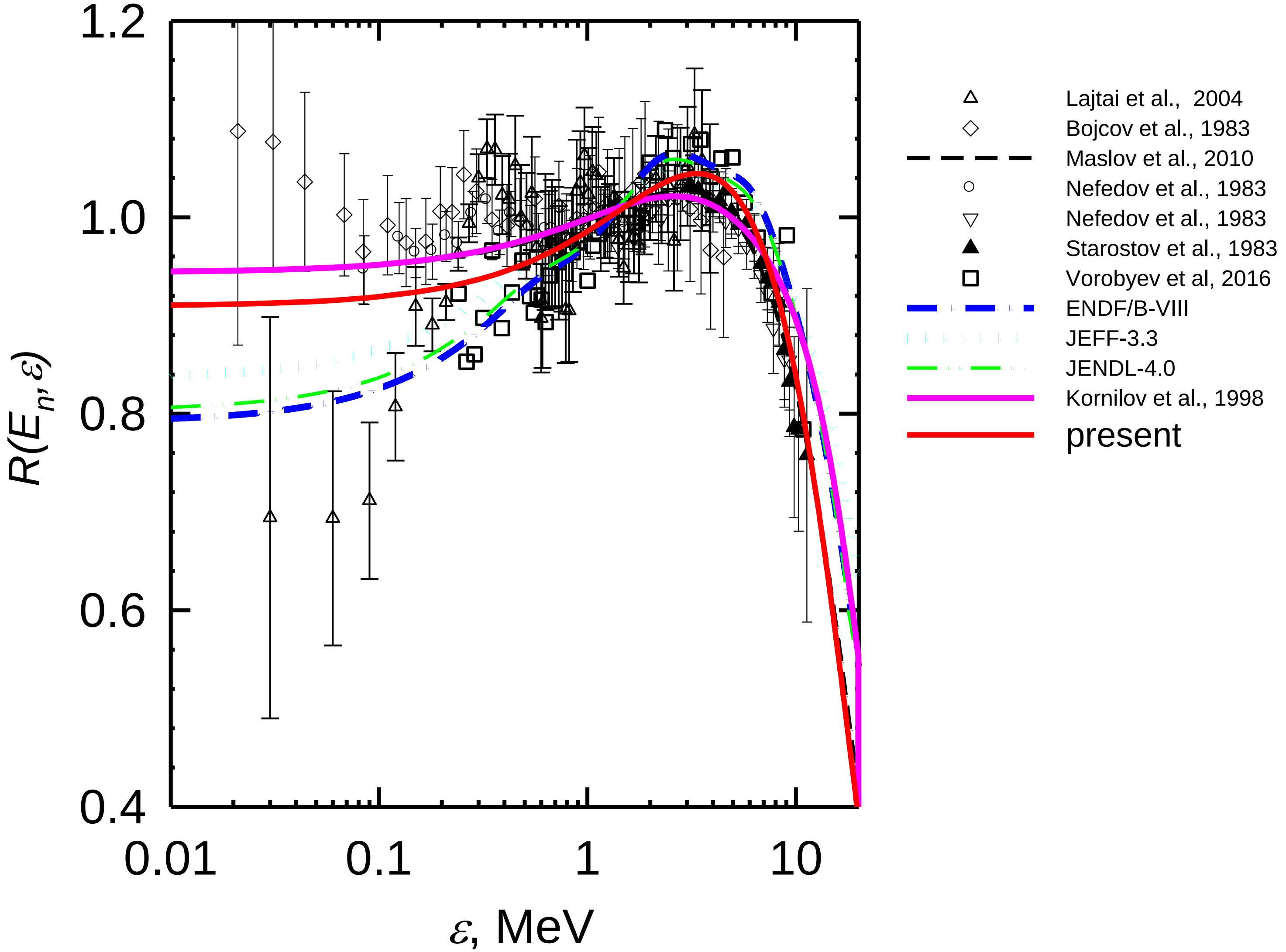


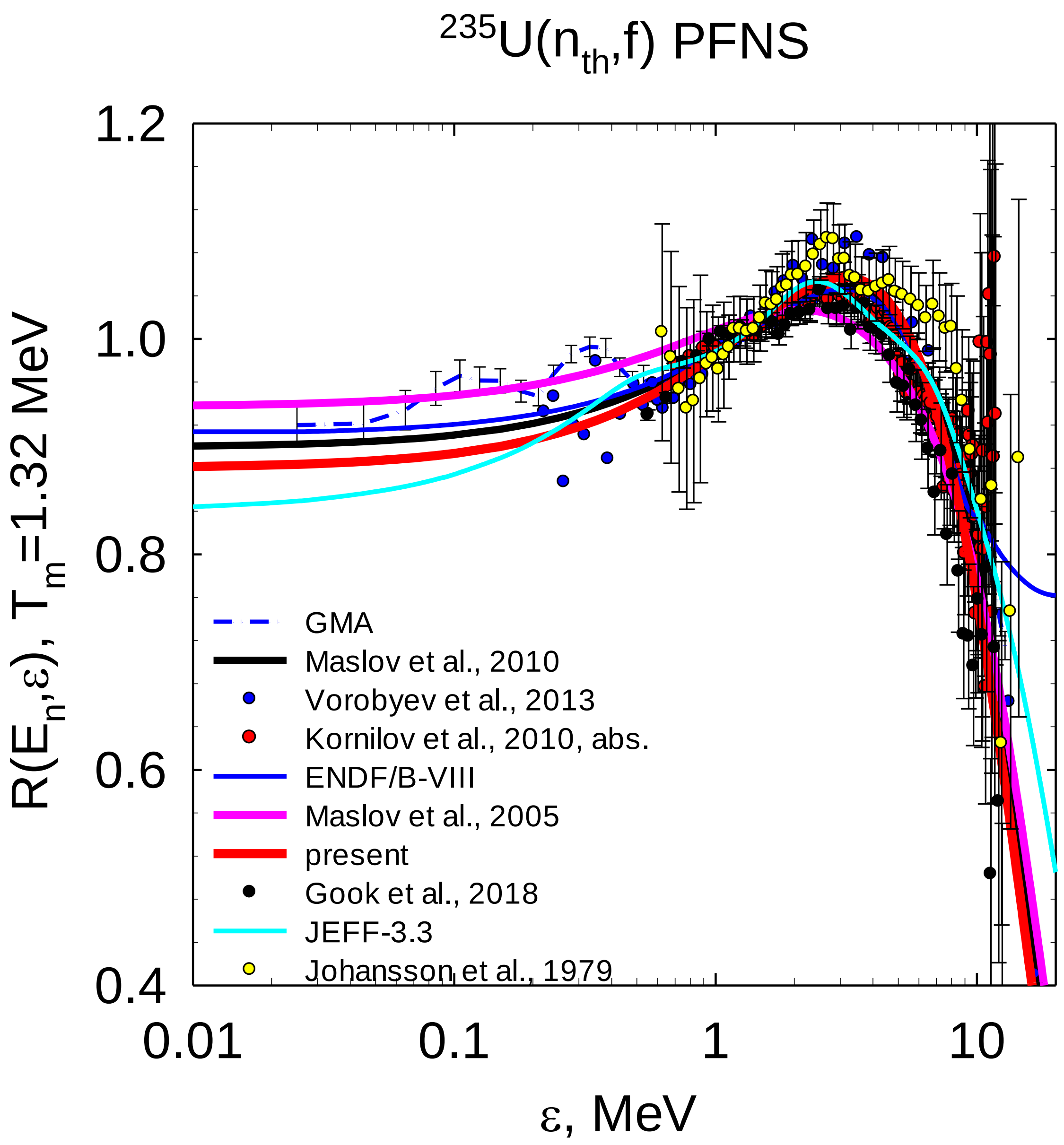
239Pu: <E> (0.01-10 MeV) PFNS
<E>, MeV
2.0
2.1
2.2
2.3
2.4
0
4
8
12
16
20
En, MeV
JEFF-3.3
ENDF/B-VIII.0
JENDL-4.0
Marini et al., 2020
Kelly et al., 2020
Maslov, 2007
Maslov et al., 2010
Vorobyev et al., 2016
Present



^{235}U(n,F) <E> (ε=0.01-10 MeV)
ENDF/B-VIII
JEFF-3.3
JENDL-4.0
Kelly et al., 2020
Maslov et al., 2005
Maslov et al., 2010
Present
Vorobyev et al., 2016
<E>, MeV
2.5
2.4
2.3
2.2
2.1
2.0
1.9
0
2
4
6
8
10
12
14
16
18
20
NEUTRON ENERGY, MeV

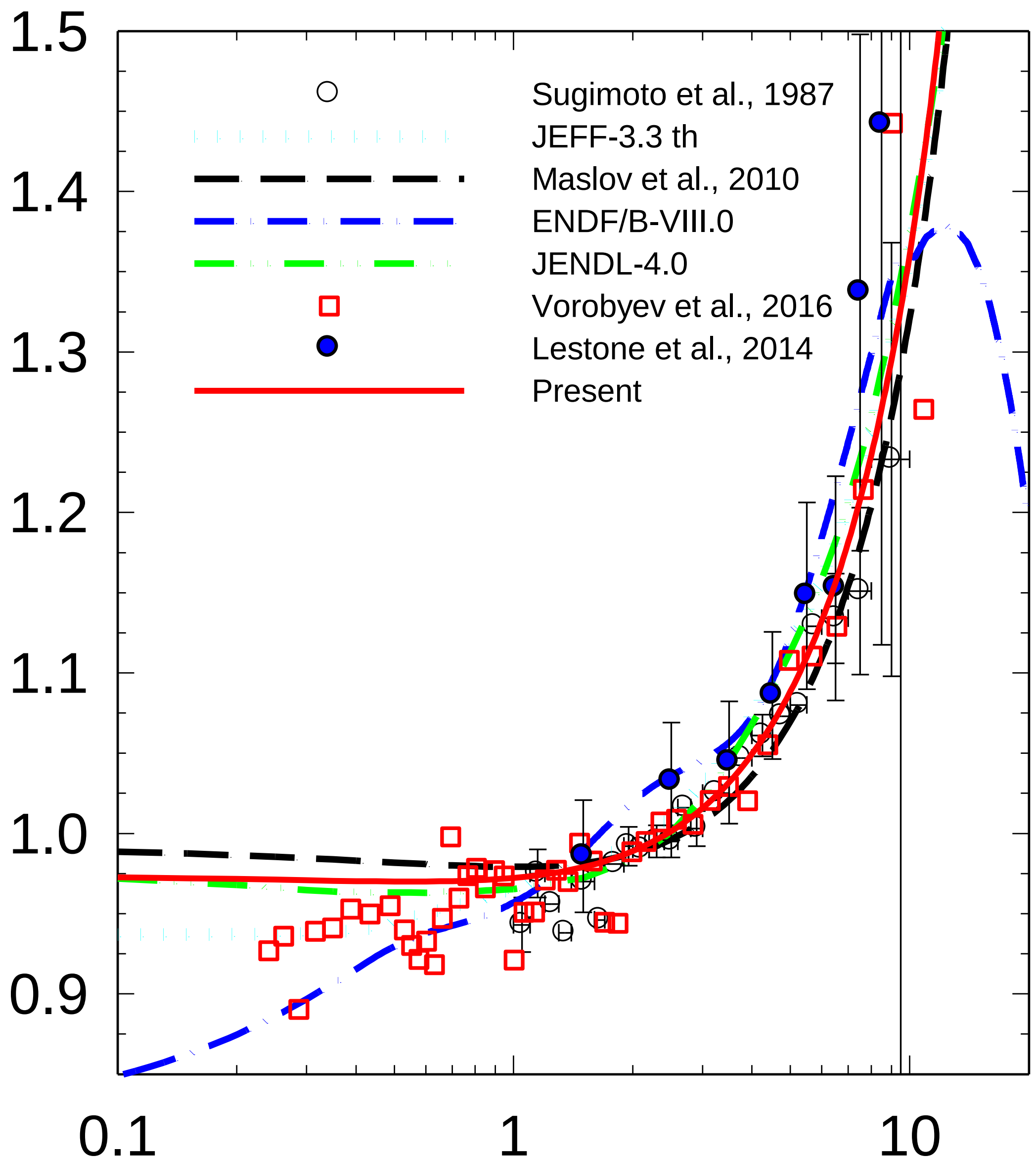
E_th 239-Pu


1.2
1.0
0.8
0.6
0.4
0.01
0.1
1
10
R(En,ε)
ε, MeV
Lajtai et al., 2004
Bojcov et al., 1983
Maslov et al., 2010
Nefedov et al., 1983
Nefedov et al., 1983
Starostov et al., 1983
Vorobyev et al, 2016
ENDF/B-VIII
JEFF-3.3
JENDL-4.0
Kornilov et al., 1998
present

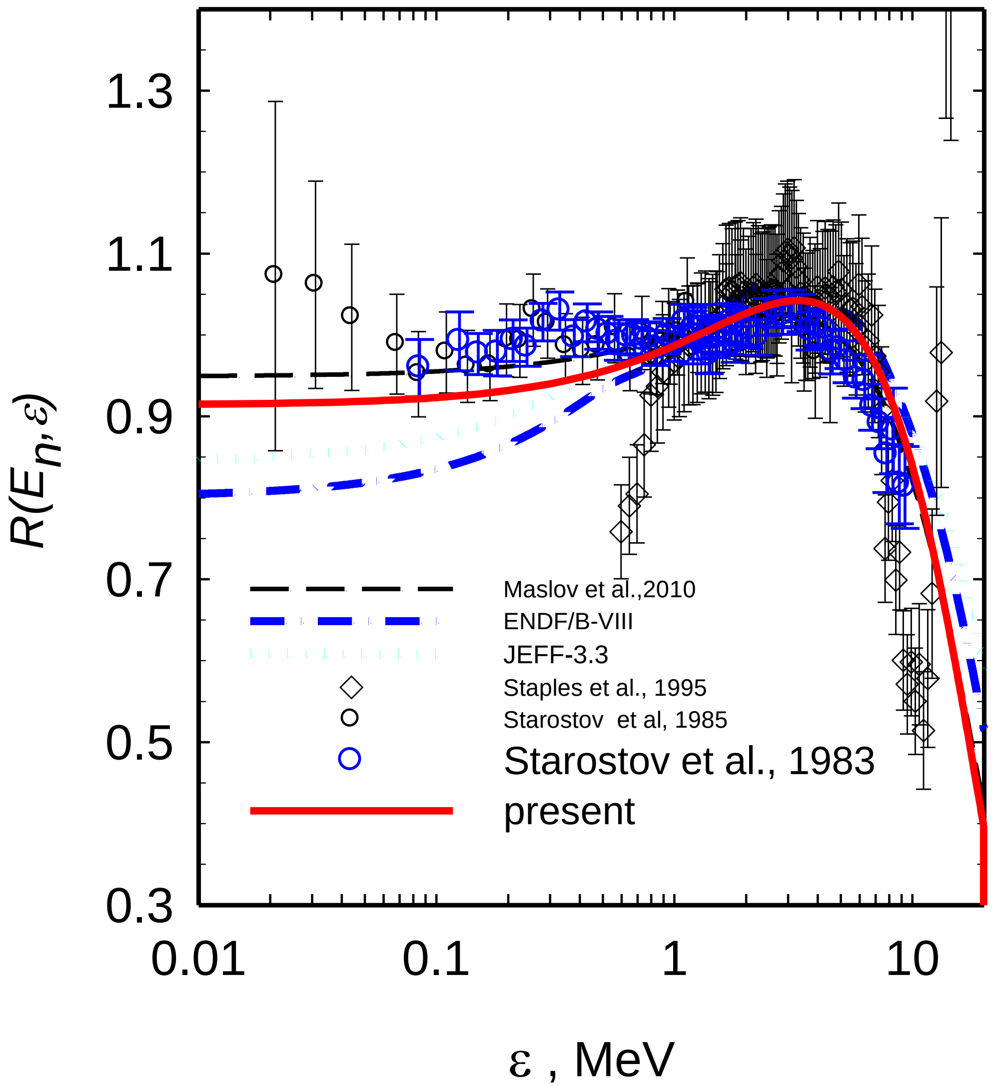


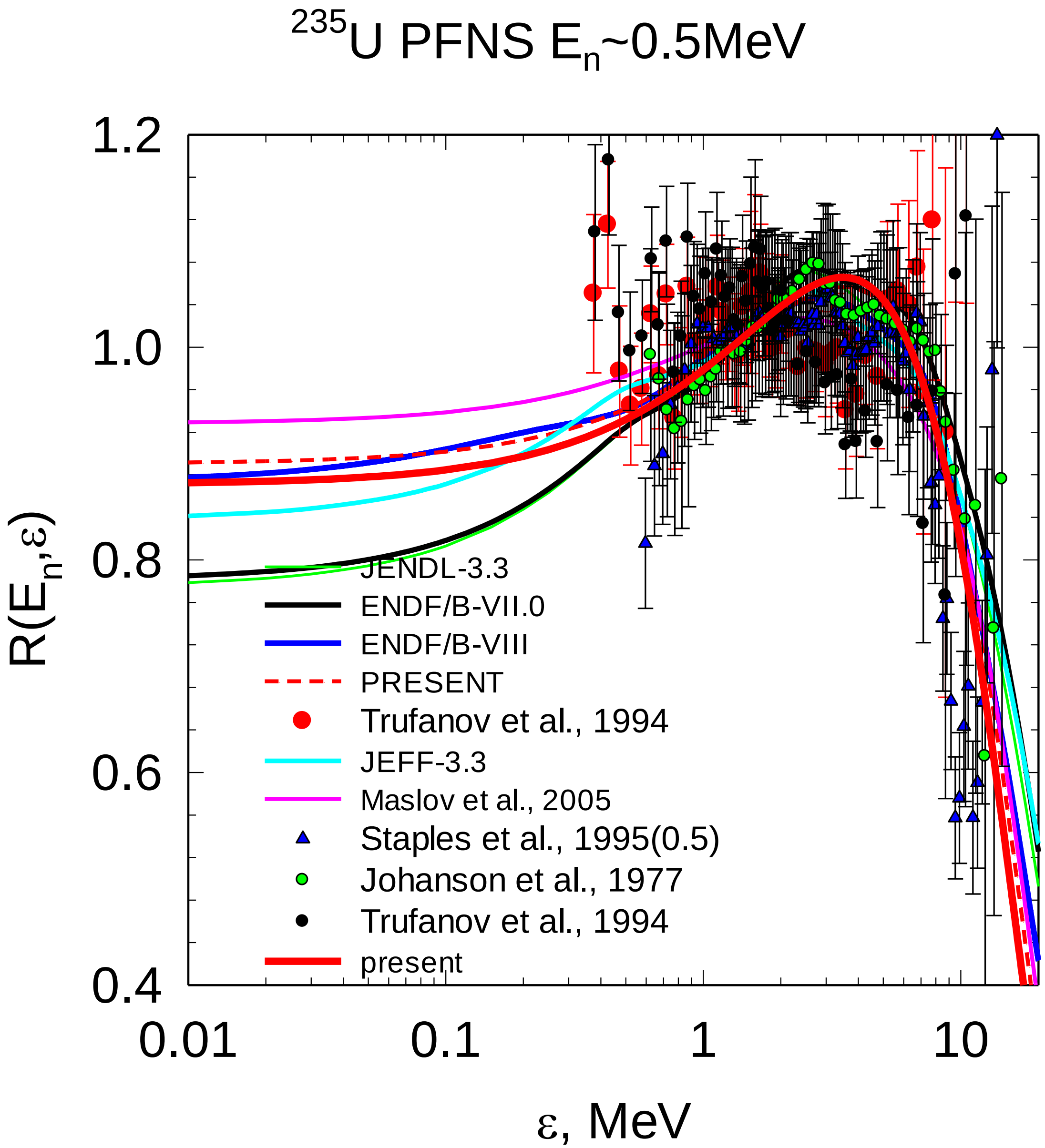
$^{235}U(n_{th},f)$ PFNS
1.2
1.0
0.8
0.6
0.4
$R(E_n,\varepsilon)$, T_m=1.32 MeV
0.01
0.1
1
10
ε, MeV
GMA
Maslov et al., 2010
Vorobyev et al., 2013
Kornilov et al., 2010, abs.
ENDF/B-VIII
Maslov et al., 2005
present
Gook et al., 2018
JEFF-3.3
Johansson et al., 1979

$^{239}Pu/^{235}U$ PFNS ratio, $E_n \sim E_{th}$

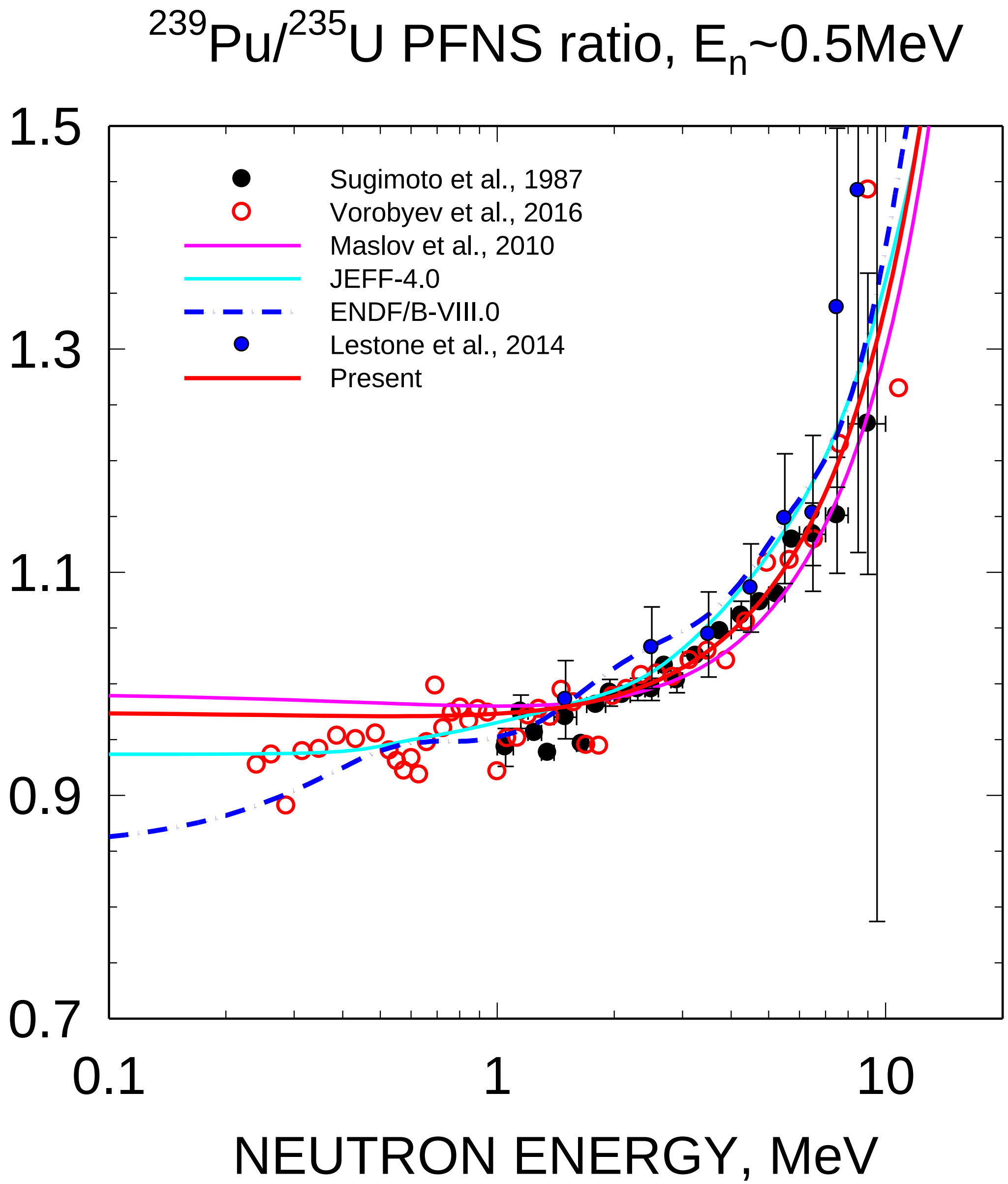


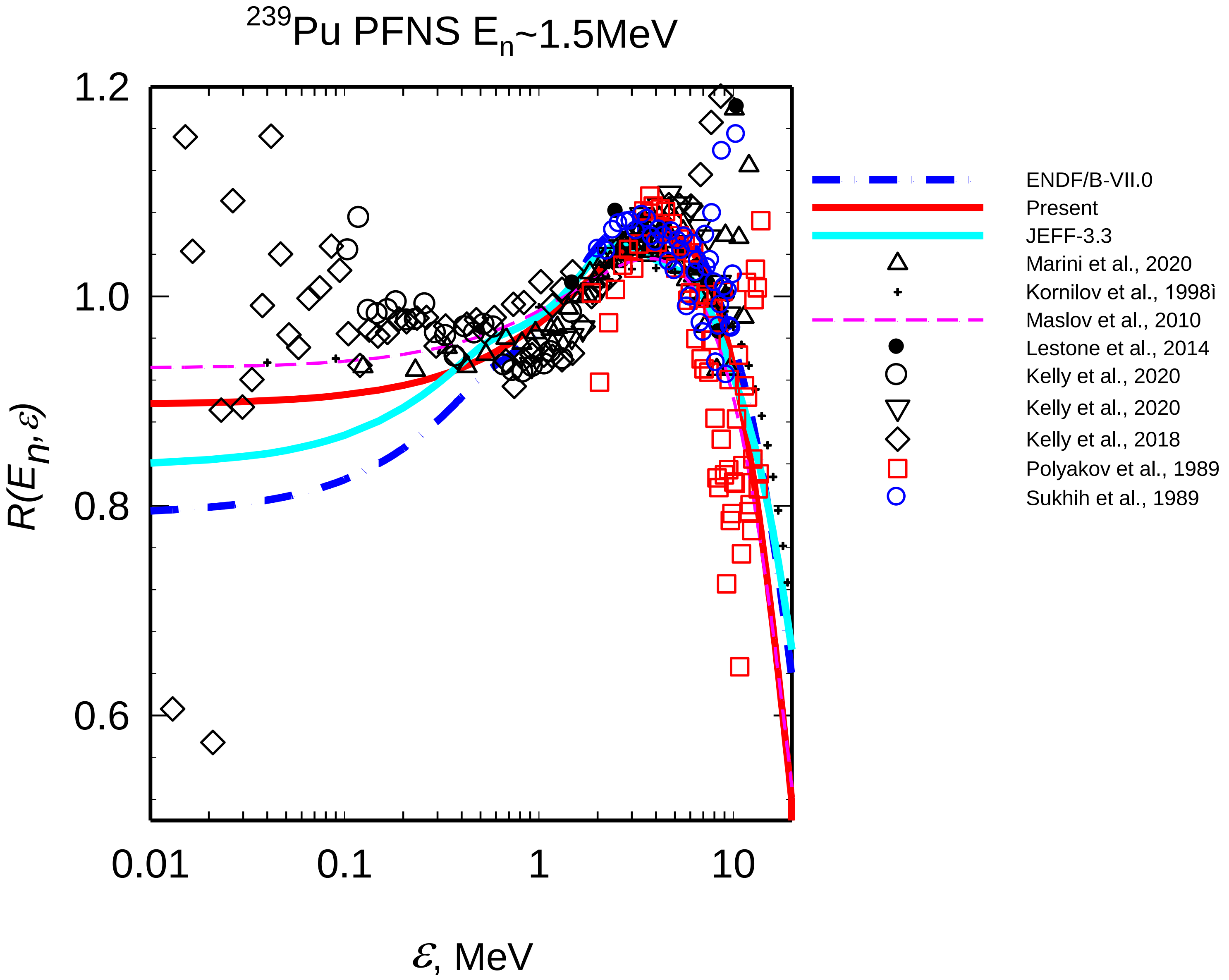
0.5 MeV 239-Pu


1.3
1.1
0.9
0.7
0.5
0.3
0.01
0.1
1
10
$R(E_\eta,\varepsilon)$
ε , MeV
Maslov et al.,2010
ENDF/B-VIII
JEFF-3.3
Staples et al., 1995
Starostov et al, 1985
Starostov et al., 1983
present



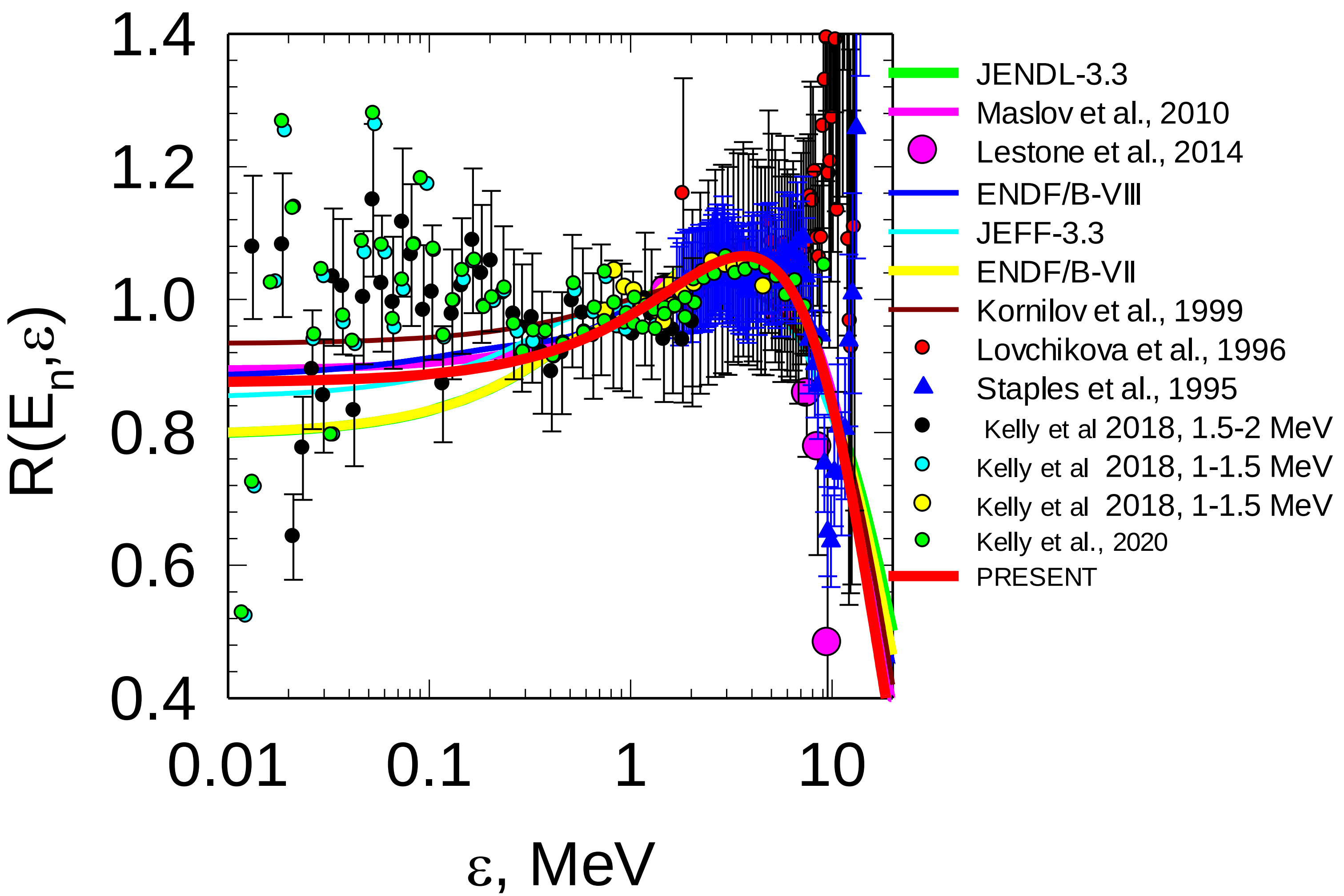
^{235}U PFNS E_n~0.5MeV
R(E_n,ε)
ε, MeV
1.2
1.0
0.8
0.6
0.4
0.01
0.1
1
10
JENDL-3.3
ENDF/B-VII.0
ENDF/B-VIII
PRESENT
Trufanov et al., 1994
JEFF-3.3
Maslov et al., 2005
Staples et al., 1995(0.5)
Johanson et al., 1977
Trufanov et al., 1994
present


239Pu/235U PFNS ratio, En~0.5MeV
Sugimoto et al., 1987
Vorobyev et al., 2016
Maslov et al., 2010
JEFF-4.0
ENDF/B-VIII.0
Lestone et al., 2014
Present
1.5
1.3
1.1
0.9
0.7
0.1
1
10
NEUTRON ENERGY, MeV

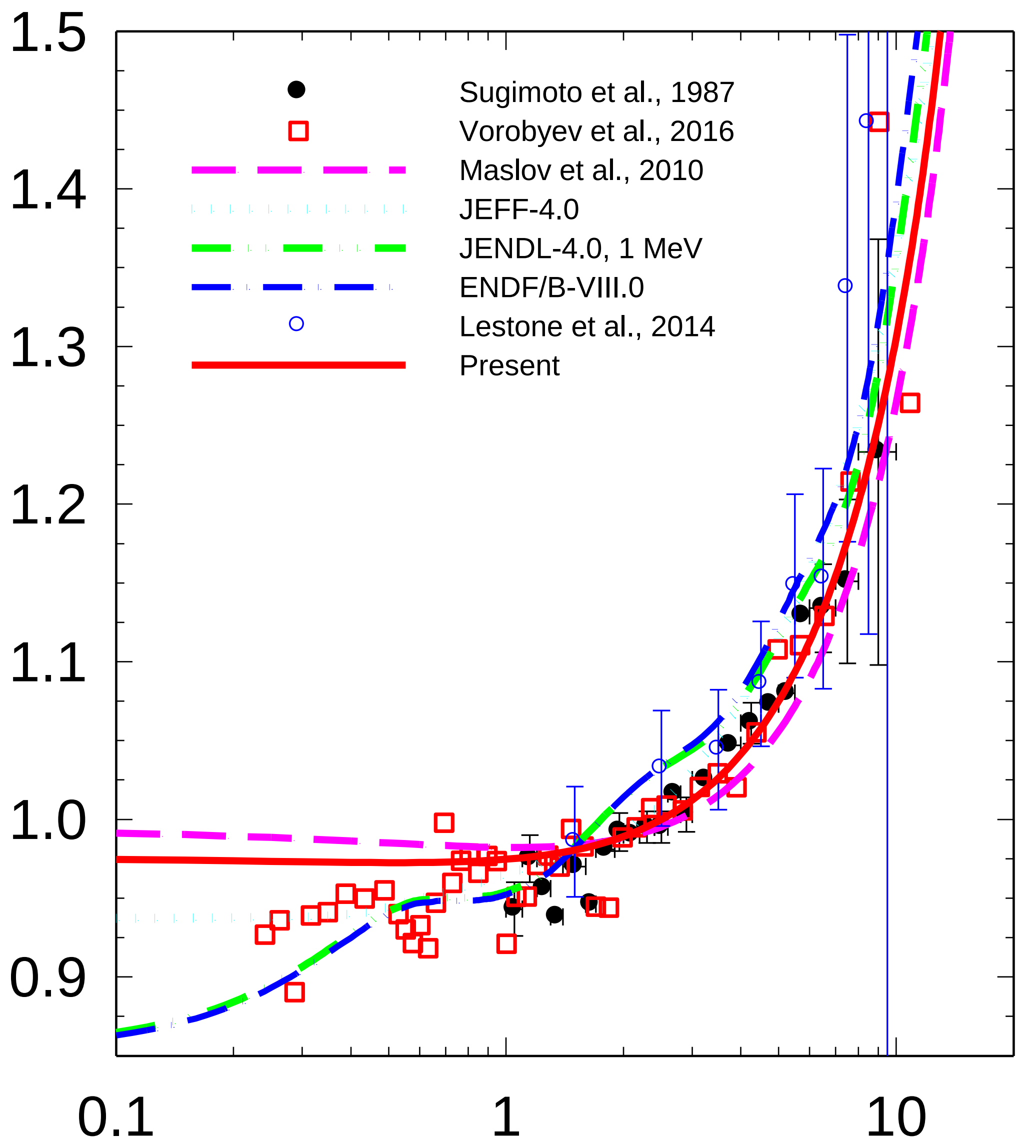


^{239}Pu PFNS E_n~1.5MeV
1.2
1.0
0.8
0.6
$R(E_n,\varepsilon)$
0.01
0.1
1
10
ε, MeV
ENDF/B-VII.0
Present
JEFF-3.3
Marini et al., 2020
Kornilov et al., 1998ì
Maslov et al., 2010
Lestone et al., 2014
Kelly et al., 2020
Kelly et al., 2020
Kelly et al., 2018
Polyakov et al., 1989
Sukhih et al., 1989

^{235}U FISSION NEUTRON SPECTRUM
E_n~1.5MeV



^{239}Pu/^{235}U PFNS ratio, E_n~1.5MeV



Prompt fission neutron spectra

$S(\varepsilon, E_n)$ - sum of two Watt distributions:

-

$$\mathrm{S}(\varepsilon, \mathrm{E_n}) = 0.5 \sum_{i=1}^{2} W_i(\varepsilon, E_n, T_{ij}(E_n), \alpha)$$

Kornilov, Kagalenko, Hambsch, YaF, 62, 209, 1999

pre-acceleration NE + NE from accelerated fragments

$$W_i(\varepsilon, E_n, T_{ij}(E_n), \alpha) = \frac{2}{\sqrt{\pi} T_{ij}^{3/2}} \sqrt{\varepsilon} \exp(-\frac{E^*_{vij}}{T_{ij}}) \frac{sh(\sqrt{b_{ij}\varepsilon})}{\sqrt{b_{ij}\varepsilon}}$$

-

$$b_{ij} = \frac{4E^*_{vij}}{T_{ij}}, T_{ij} = k_{ij}\sqrt{E_r - TKE_i - U_i}$$

T_{ij} **-temperature for light and heavy fragments, α =TKE/TKE$_\infty$**

In Watt' equation CMS energy per nucleon -

$$E^*_{vij} = \alpha E_{vij}$$

GMA-analysis with code by Poenitz at al., 1997

1. Model-independent PFNS of
$^{235}U(n_{th},f)$, $^{233}U(n_{th},f)$, $^{239}Pu(n_{th},f)$, $^{252}Cf(sf)$-
2. "Smoothed" combined evaluation of 4 PFNS
   a) $^{252}Cf(sf)$ PFNS was smoothed,
   b) non-smoothed $^{252}Cf(sf)$ –4th pseudo- exp. data set
3. Model' fits of model-independent PFNS

In Major Data Libraries PFNS at thermal E_n suffer from

1. Deficiency of soft neutrons,
2. Excess of neutrons with ε=1~3 MeV
3. Excess of hard-tail neutrons

Prompt-fission neutron spectra

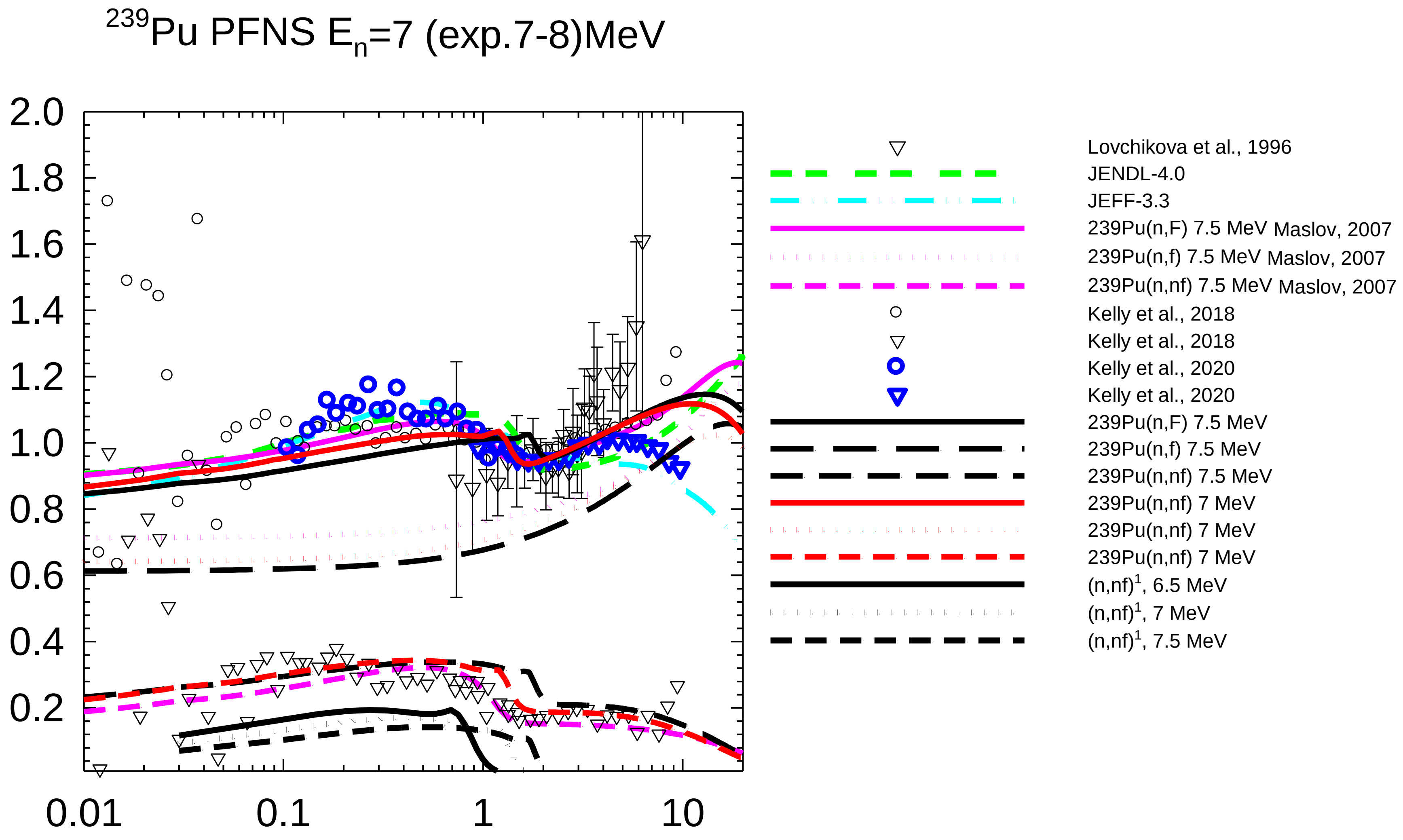
superposition of exclusive pre-fission (n,xnf) spectra and post-fission spectra $S_{A+2-x}(\varepsilon,E_n)$

$$\mathrm{S}(\varepsilon,\mathrm{E_n}) = \nu^{-1}(E_n)(\nu_1(E_n)\beta_1(E_n)\mathrm{S_{A+1}}(\varepsilon,\mathrm{E_n}) +$$

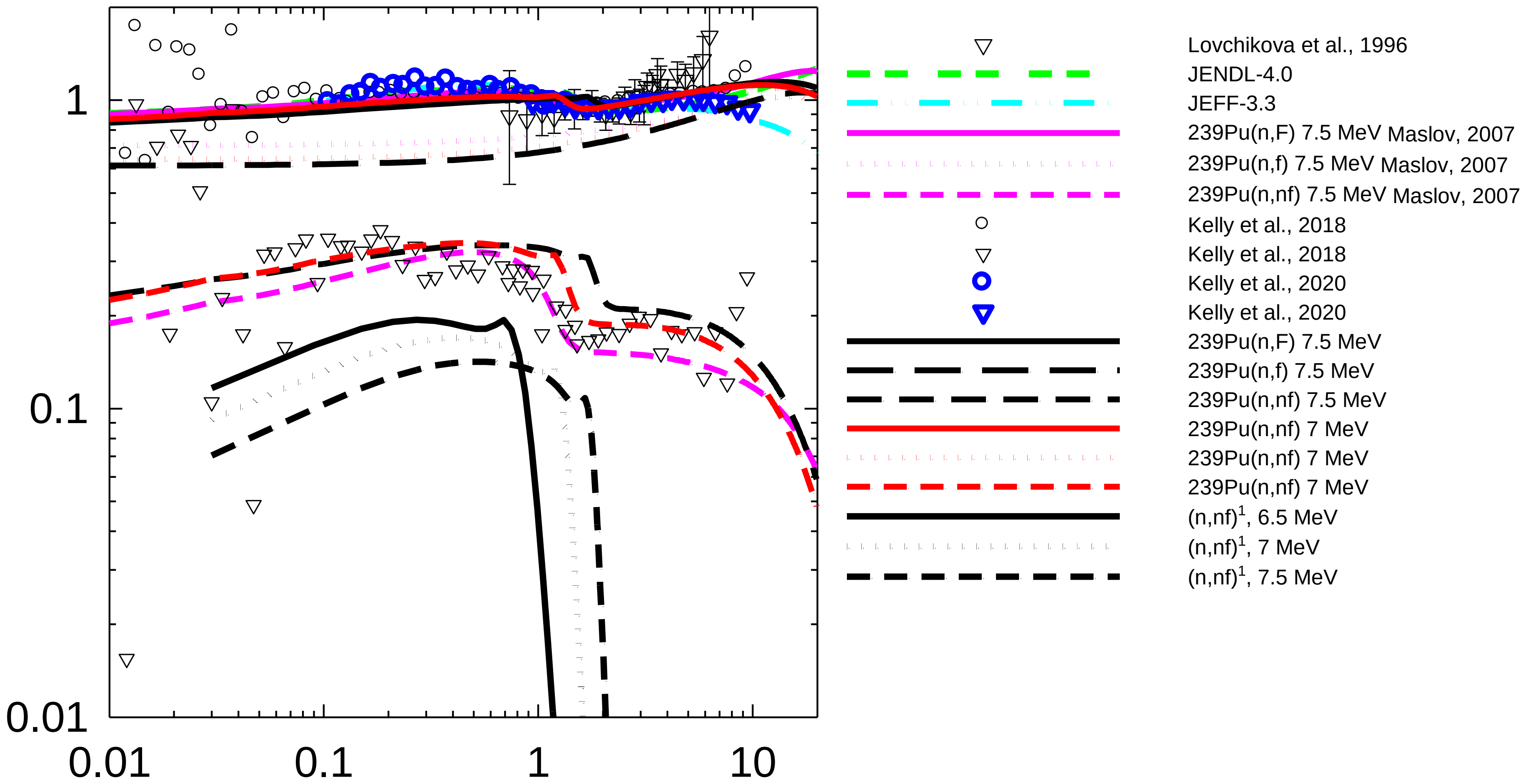
$$\nu_2(E_n)\beta_2(E_n)\mathrm{S}_A(\varepsilon,\mathrm{E_n}) + \beta_2(E_n)\frac{d\sigma^1_{\mathrm{nnnf}}(E_n)}{d\varepsilon} +$$

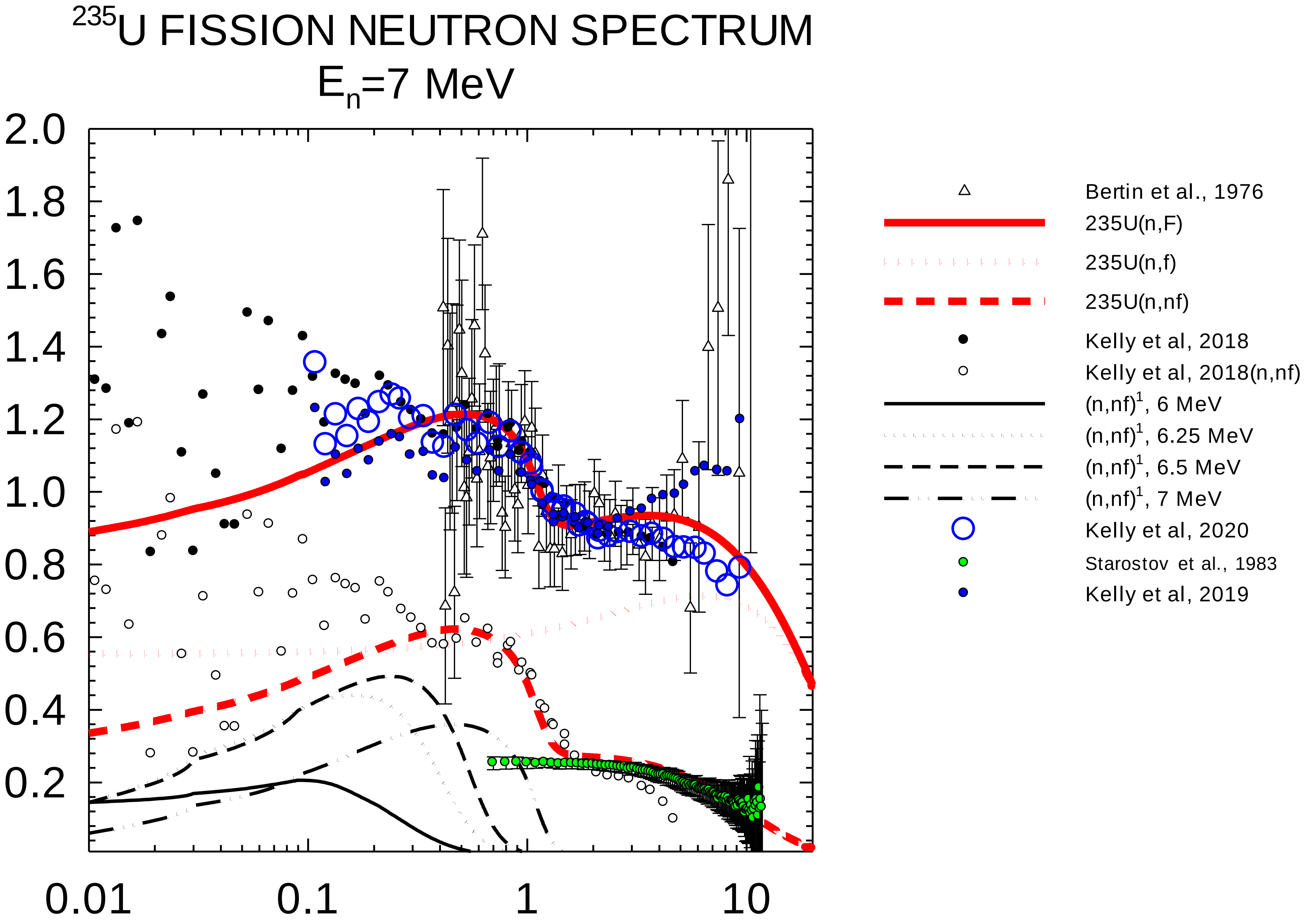
$$\nu_3(E_n)\beta_3(E_n)\mathrm{S}_{A-1}(\varepsilon,\mathrm{E_n}) + \beta_3(E_n)\left(\frac{d\sigma^1_{\mathrm{n2nnf}}(E_n)}{d\varepsilon} + \frac{d\sigma^2_{\mathrm{n2nnf}}(E_n)}{d\varepsilon}\right) +$$

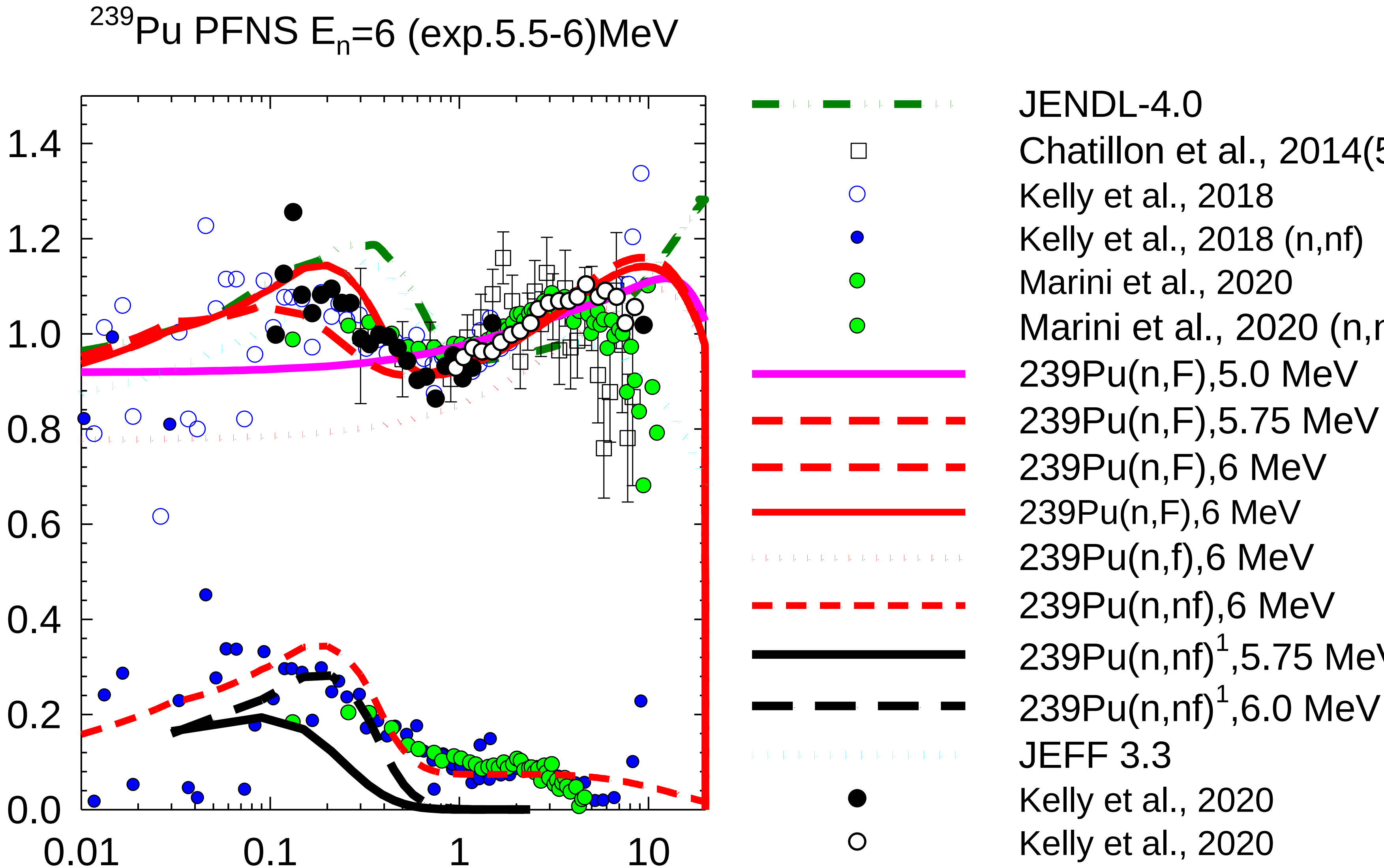
$$\nu_4(E_n)\beta_4(E_n)\mathrm{S}_{A-2}(\varepsilon,\mathrm{E_n}) + \beta_4(E_n)\left(\frac{d\sigma^1_{\mathrm{n3nnf}}(E_n)}{d\varepsilon} + \frac{d\sigma^2_{\mathrm{n3nnf}}(E_n)}{d\varepsilon} + \frac{d\sigma^3_{\mathrm{n3nnf}}(E_n)}{d\varepsilon}\right))$$


239Pu PFNS En=7 (exp.7-8)MeV
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.01
0.1
1
10
Lovchikova et al., 1996
JENDL-4.0
JEFF-3.3
239Pu(n,F) 7.5 MeV Maslov, 2007
239Pu(n,f) 7.5 MeV Maslov, 2007
239Pu(n,nf) 7.5 MeV Maslov, 2007
Kelly et al., 2018
Kelly et al., 2018
Kelly et al., 2020
Kelly et al., 2020
239Pu(n,F) 7.5 MeV
239Pu(n,f) 7.5 MeV
239Pu(n,nf) 7.5 MeV
239Pu(n,nf) 7 MeV
239Pu(n,nf) 7 MeV
239Pu(n,nf) 7 MeV
(n,nf)1, 6.5 MeV
(n,nf)1, 7 MeV
(n,nf)1, 7.5 MeV

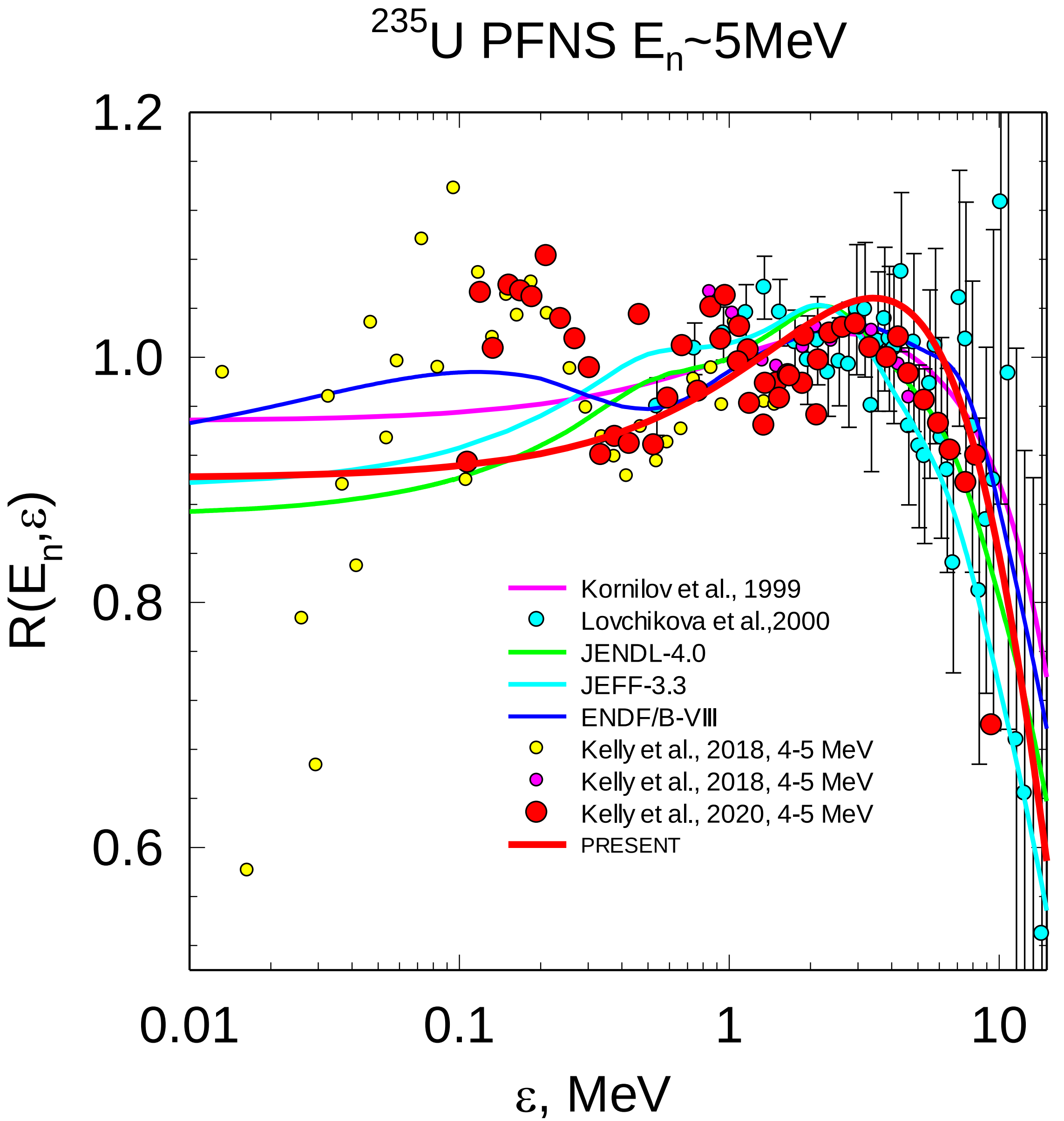
^{239}Pu PFNS E_n=7 (exp.7-8)MeV



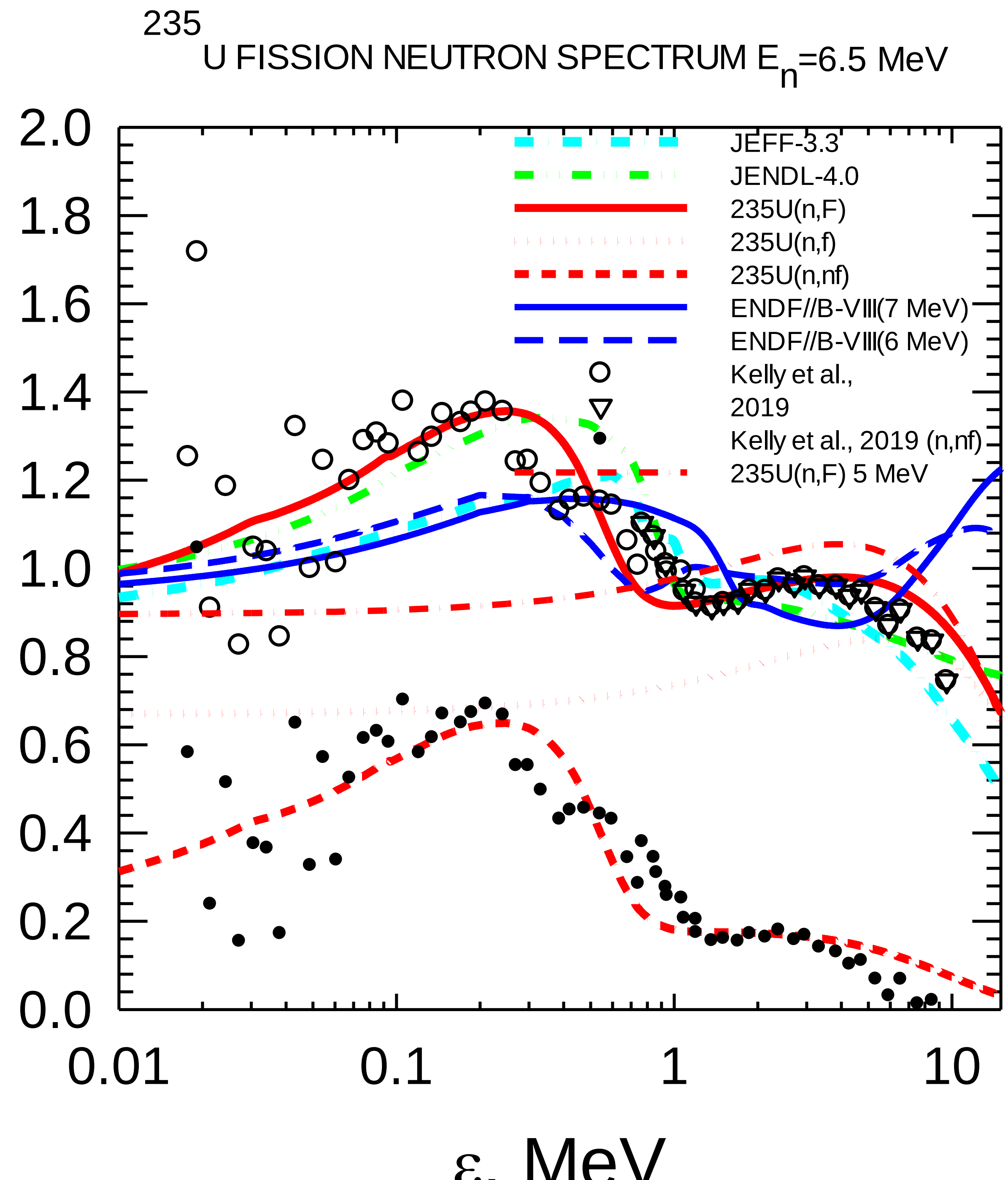

235U FISSION NEUTRON SPECTRUM
En=7 MeV
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.01
0.1
1
10
Bertin et al., 1976
235U(n,F)
235U(n,f)
235U(n,nf)
Kelly et al, 2018
Kelly et al, 2018(n,nf)
(n,nf)1, 6 MeV
(n,nf)1, 6.25 MeV
(n,nf)1, 6.5 MeV
(n,nf)1, 7 MeV
Kelly et al, 2020
Starostov et al., 1983
Kelly et al, 2019



239Pu PFNS En=6 (exp.5.5-6)MeV
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
10
JENDL-4.0
Chatillon et al., 2014(5
Kelly et al., 2018
Kelly et al., 2018 (n,nf)
Marini et al., 2020
Marini et al., 2020 (n,n
239Pu(n,F),5.0 MeV
239Pu(n,F),5.75 MeV
239Pu(n,F),6 MeV
239Pu(n,F),6 MeV
239Pu(n,f),6 MeV
239Pu(n,nf),6 MeV
239Pu(n,nf)1,5.75 MeV
239Pu(n,nf)1,6.0 MeV
JEFF 3.3
Kelly et al., 2020
Kelly et al., 2020



^{235}U PFNS E_n~5MeV
R(E_n,ε)
ε, MeV
1.2
1.0
0.8
0.6
0.01
0.1
1
10
Kornilov et al., 1999
Lovchikova et al.,2000
JENDL-4.0
JEFF-3.3
ENDF/B-VIII
Kelly et al., 2018, 4-5 MeV
Kelly et al., 2018, 4-5 MeV
Kelly et al., 2020, 4-5 MeV
PRESENT

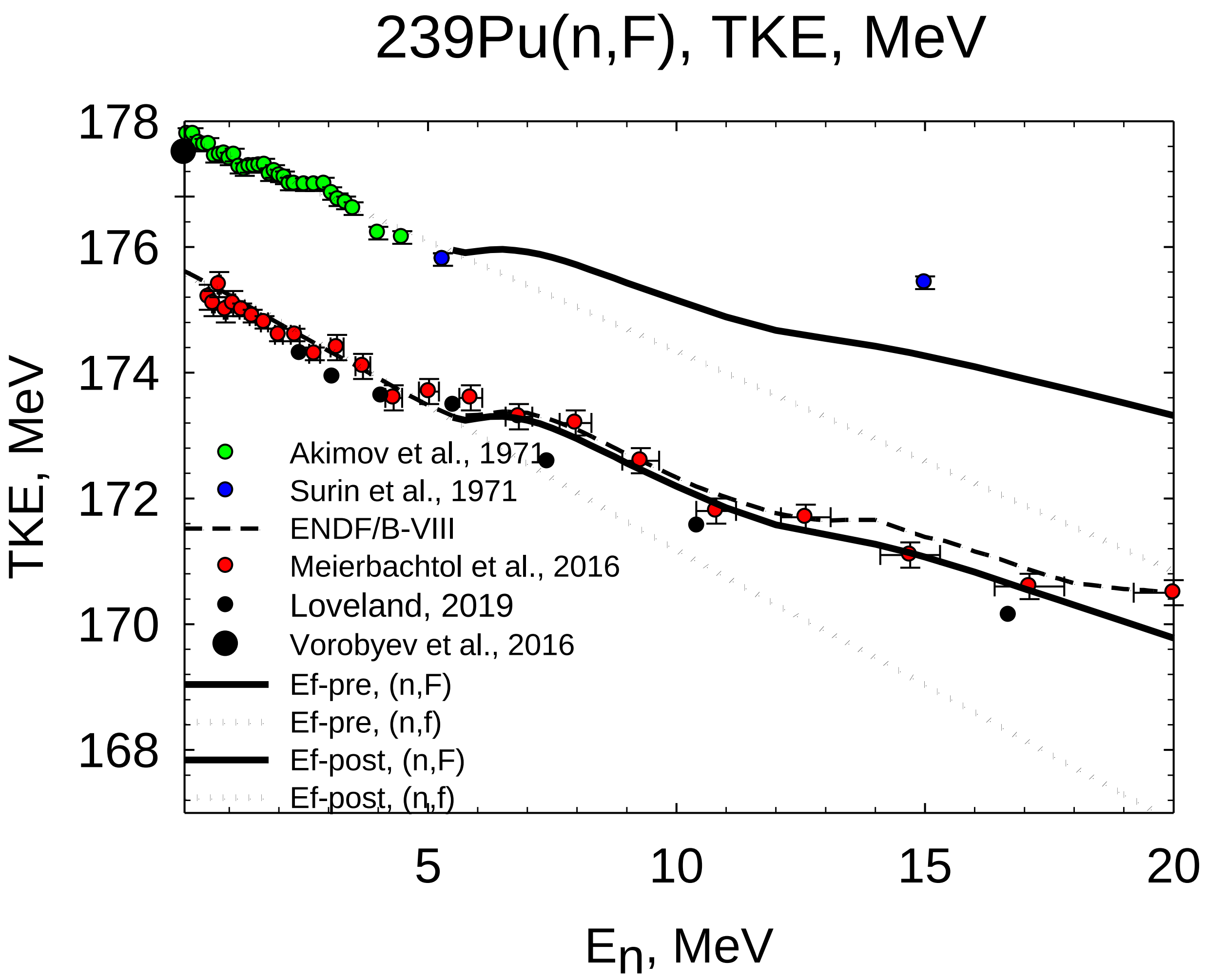


^{235}U FISSION NEUTRON SPECTRUM E_n=6.5 MeV
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
10
JEFF-3.3
JENDL-4.0
235U(n,F)
235U(n,f)
235U(n,nf)
ENDF//B-VIII(7 MeV)
ENDF//B-VIII(6 MeV)
Kelly et al., 2019
Kelly et al., 2019 (n,nf)
235U(n,F) 5 MeV
ε, MeV

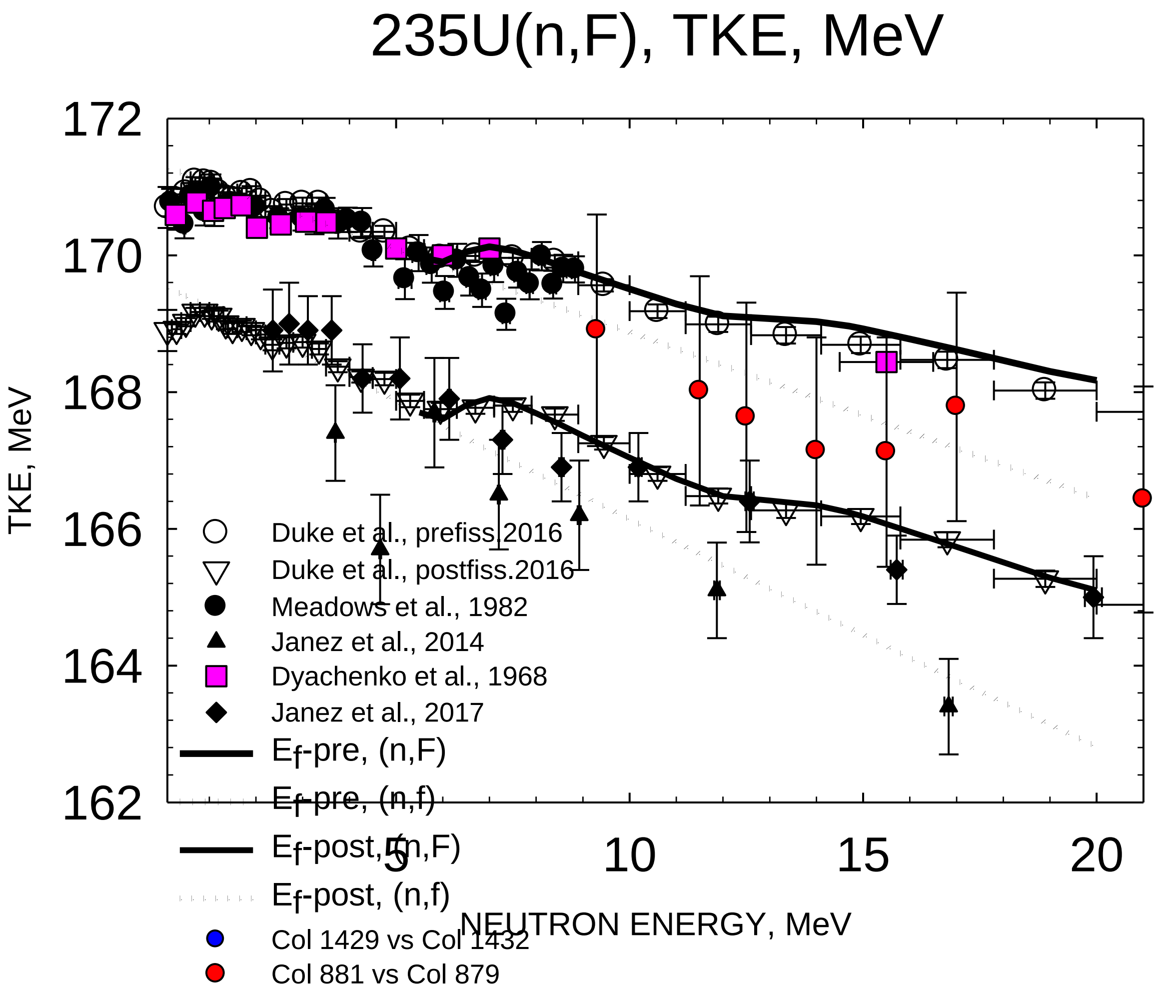
$$E_f^{post} \approx E_f^{pre}\left(1 - \nu_{post} / \left(A - \nu_{pre}\right)\right)$$

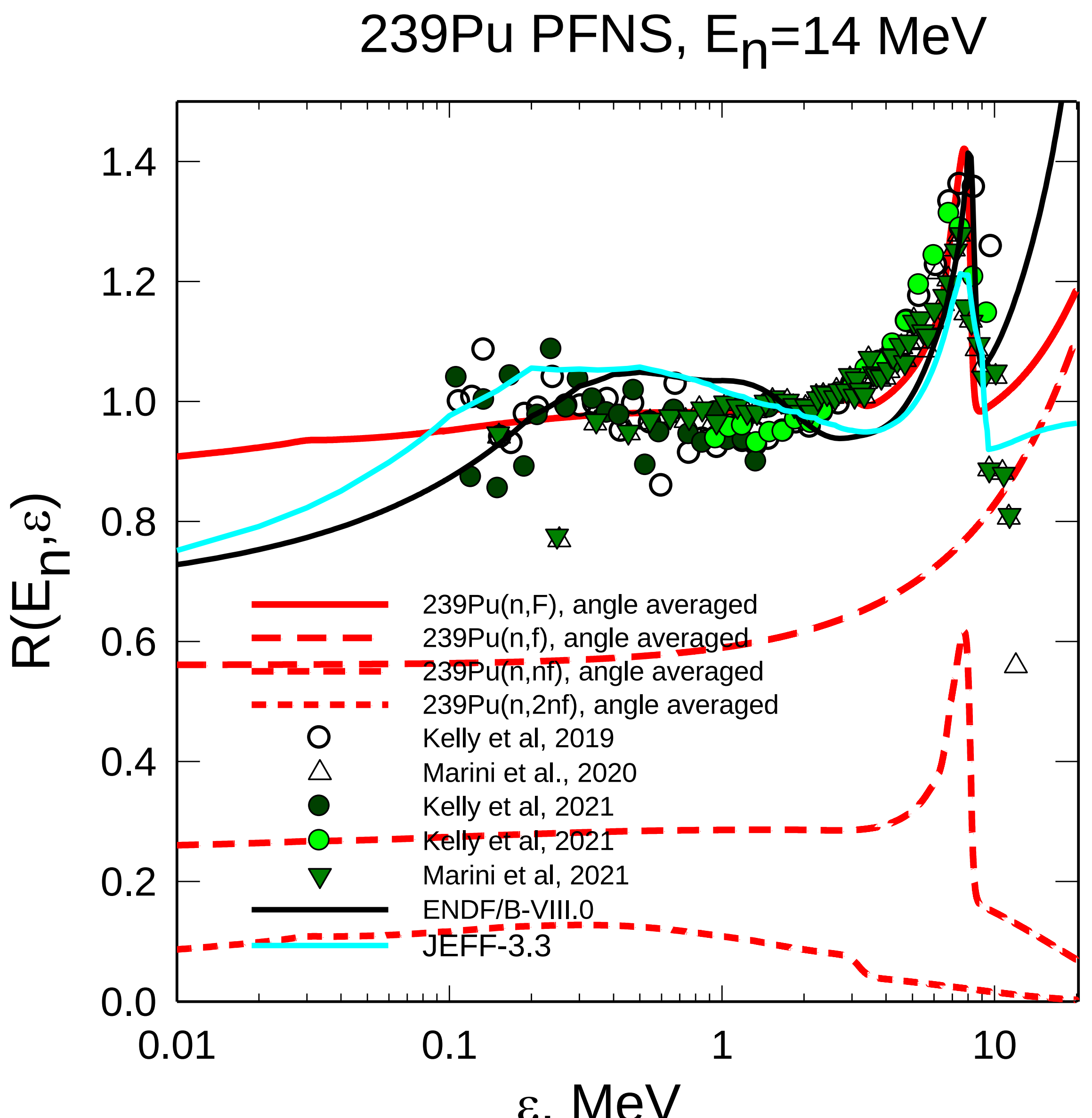
$$E_f^{pre}(E_n) = \sum_{x=0}^{X} E_{fx}^{pre}(E_{nx}) \cdot \sigma_{n,xnf} / \sigma_{n,F},$$

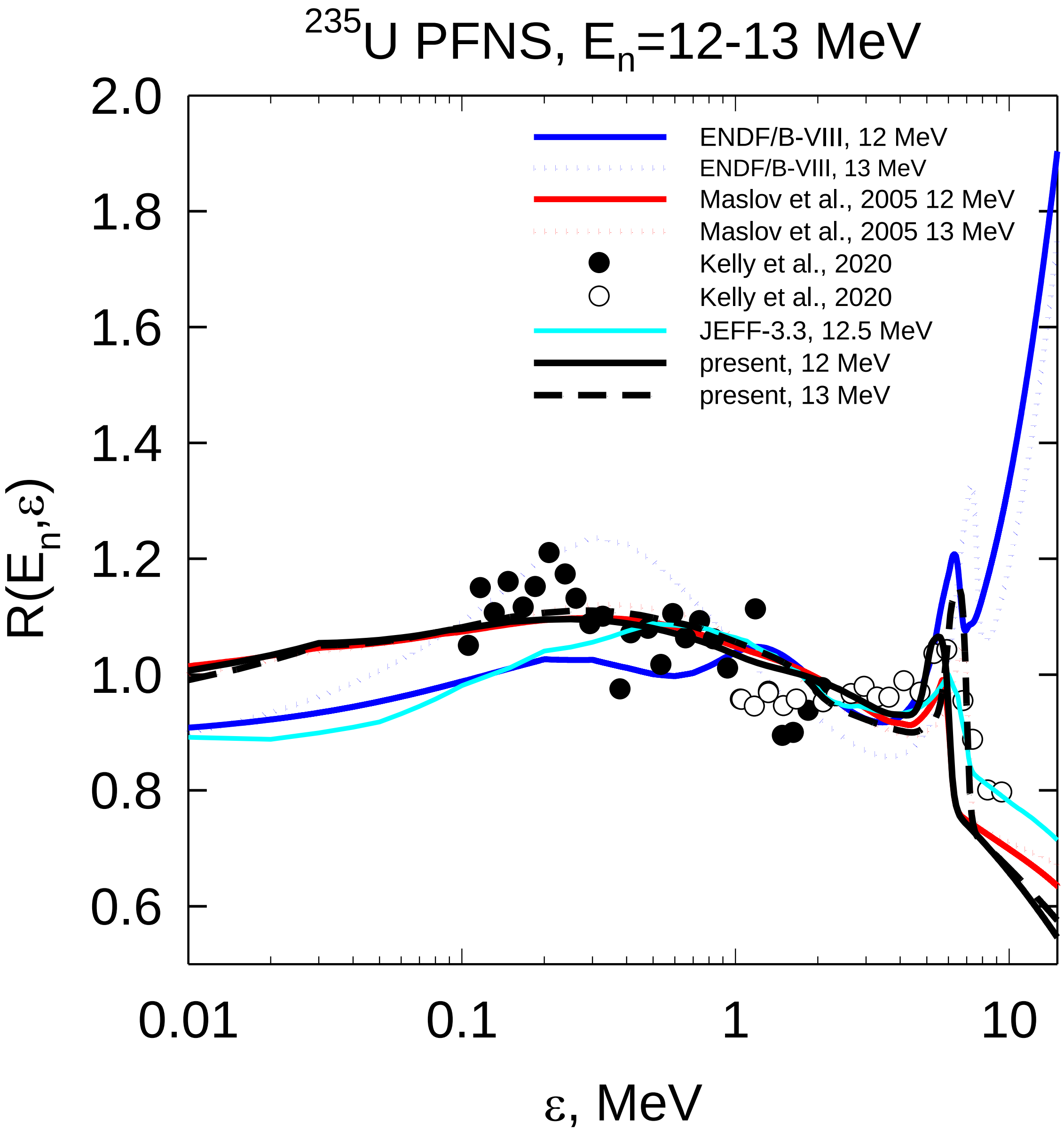
$$E_{nx} = E_n + B_n - \sum_{x=0, 1 \le j \le x}^{X} \left(\left\langle E_{n,xnf}^{j} \right\rangle + B_x \right)$$



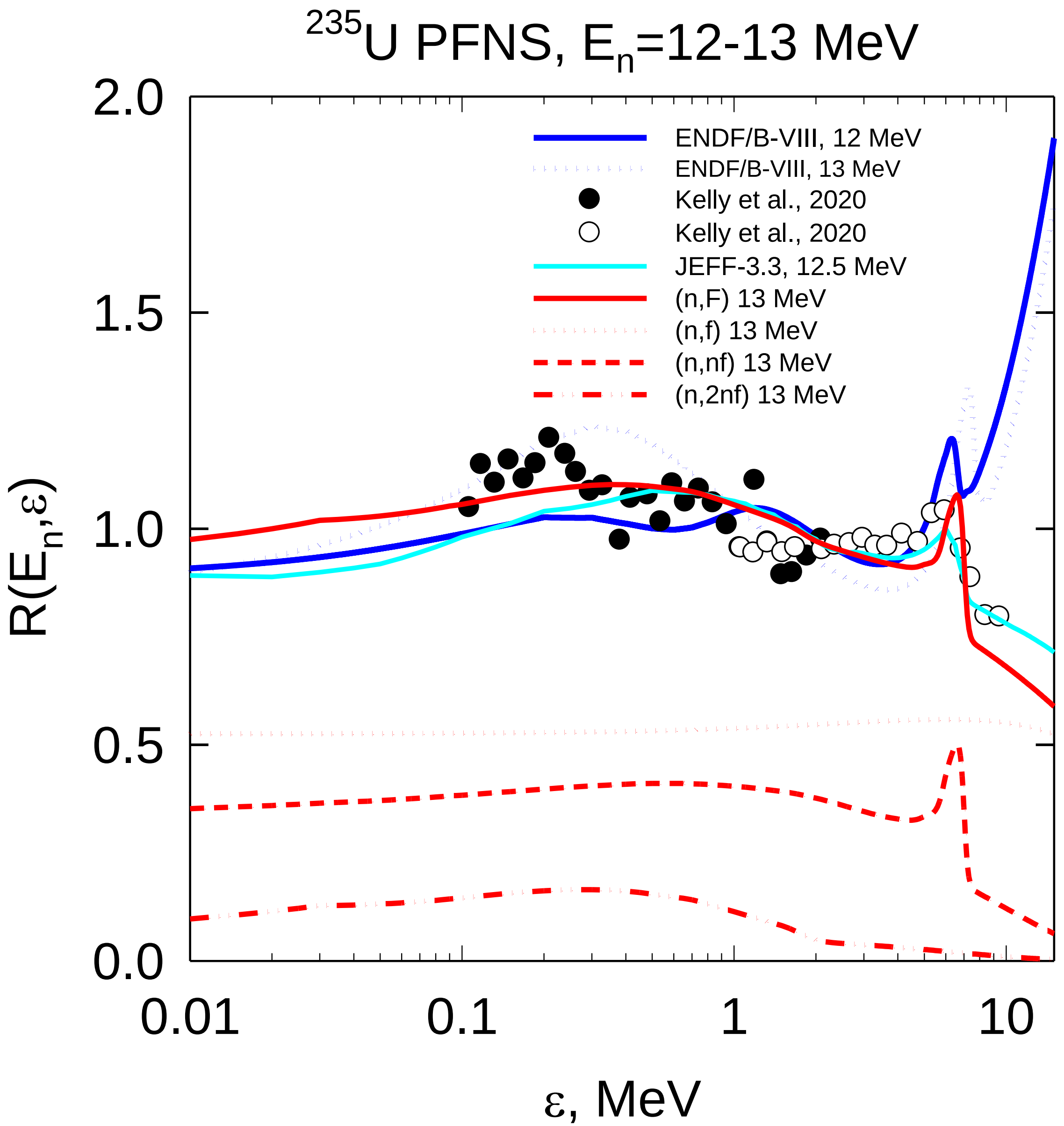
239Pu(n,F), TKE, MeV
TKE, MeV
178
176
174
172
170
168
5
10
15
20
En, MeV
Akimov et al., 1971
Surin et al., 1971
ENDF/B-VIII
Meierbachtol et al., 2016
Loveland, 2019
Vorobyev et al., 2016
Ef-pre, (n,F)
Ef-pre, (n,f)
Ef-post, (n,F)
Ef-post, (n,f)


235U(n,F), TKE, MeV
TKE, MeV
172
170
168
166
164
162
5
10
15
20
NEUTRON ENERGY, MeV
Duke et al., prefiss.2016
Duke et al., postfiss.2016
Meadows et al., 1982
Janez et al., 2014
Dyachenko et al., 1968
Janez et al., 2017
Ef-pre, (n,F)
Ef-pre, (n,f)
Ef-post, (n,F)
Ef-post, (n,f)
Col 1429 vs Col 1432
Col 881 vs Col 879

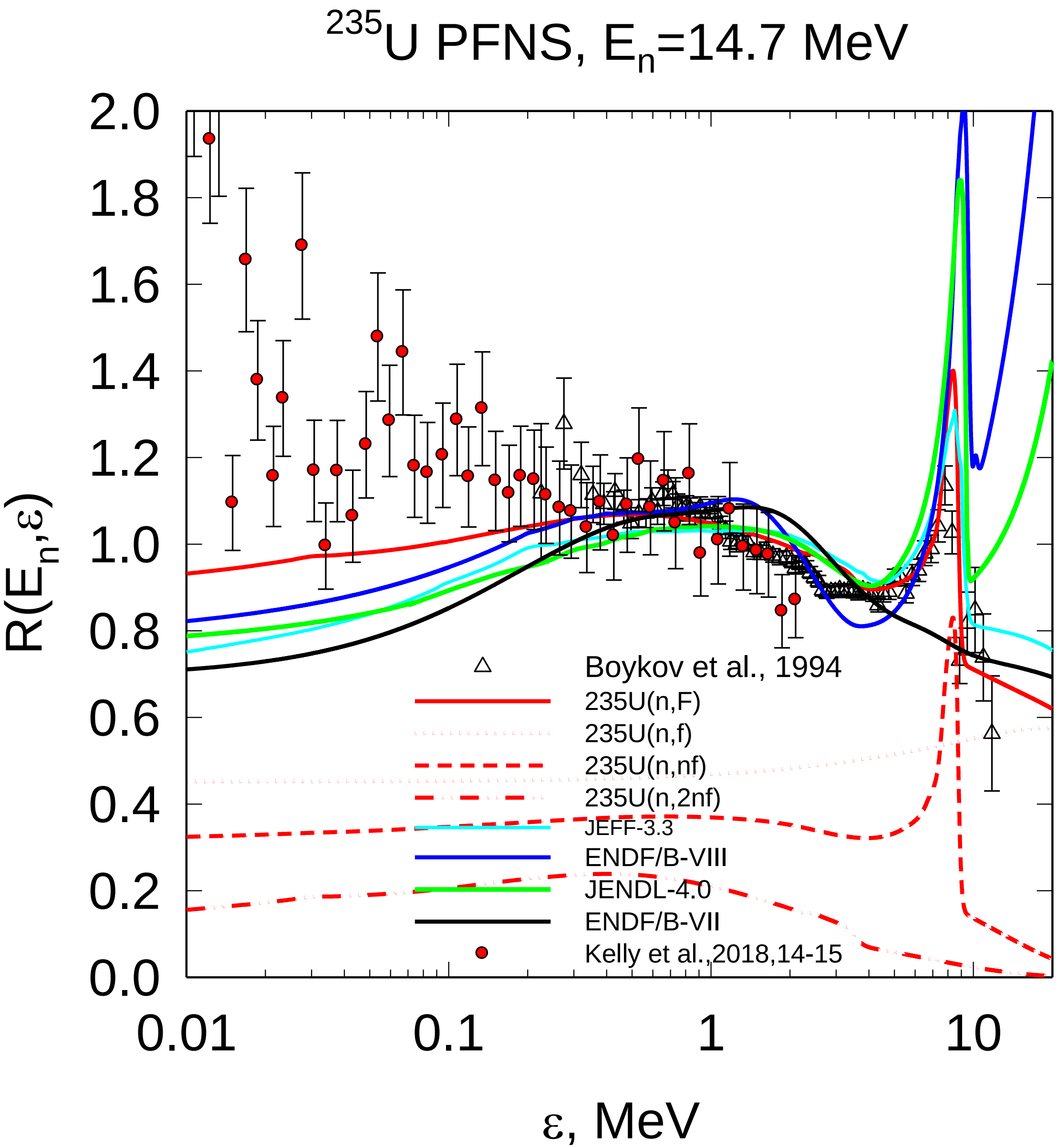

239Pu PFNS, E_n=14 MeV
R(E_n,ε)
ε, MeV
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.01
0.1
1
10
239Pu(n,F), angle averaged
239Pu(n,f), angle averaged
239Pu(n,nf), angle averaged
239Pu(n,2nf), angle averaged
Kelly et al, 2019
Marini et al., 2020
Kelly et al, 2021
Kelly et al, 2021
Marini et al, 2021
ENDF/B-VIII.0
JEFF-3.3



^{235}U PFNS, E_n=12-13 MeV
ENDF/B-VIII, 12 MeV
ENDF/B-VIII, 13 MeV
Maslov et al., 2005 12 MeV
Maslov et al., 2005 13 MeV
Kelly et al., 2020
Kelly et al., 2020
JEFF-3.3, 12.5 MeV
present, 12 MeV
present, 13 MeV
R(E_n,ε)
ε, MeV
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.01
0.1
1
10



^{235}U PFNS, E_n=12-13 MeV
2.0
1.5
1.0
0.5
0.0
R(E$_n$,ε)
ENDF/B-VIII, 12 MeV
ENDF/B-VIII, 13 MeV
Kelly et al., 2020
Kelly et al., 2020
JEFF-3.3, 12.5 MeV
(n,F) 13 MeV
(n,f) 13 MeV
(n,nf) 13 MeV
(n,2nf) 13 MeV
0.01
0.1
1
10
ε, MeV



235U PFNS, En=14.7 MeV
R(En,ε)
ε, MeV
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
10
Boykov et al., 1994
235U(n,F)
235U(n,f)
235U(n,nf)
235U(n,2nf)
JEFF-3.3
ENDF/B-VIII
JENDL-4.0
ENDF/B-VII
Kelly et al.,2018,14-15

Conclusions

1. GMA +phenomenological fit,
2. The energy balance model is validated for $E_{th}<E_n<20$ MeV, describing fission cross sections, nu_bar, TKE & PFNS.
3. Pre-fission neutrons are interpreted at $5<E_n<20$ MeV

Why these clues eluded the NDXXXX'community?

Relative success of previous models' for
LCT,HEU-MET-FAST was mainly due to

Compensation of
deficiency of soft neutrons
with
excess of neutrons with ε=1~3 MeV.
Excess of hard-tail neutrons
was justified by some
integral CSS, which are sensitive to ε=10~15 MeV

Conclusions

Present PFNS have no

deficiency of soft neutrons

have no

excess of neutrons with ε=1~3 MeV.

have no excess of hard-tail neutrons.