

# **DIRECT & COMPOUND INTERACTIONS FOR NEUTRON-INDUCED FISSION CROSS SECTION DETERMINATION**

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# SCOPE

## U-chains, Th-chains

1.  $^{239}\text{U}(23.4 \text{ min})$   $^{238}\text{U}(\text{st})$   $^{237}\text{U}(6.75 \text{ d})$   $^{236}\text{U}(2.3 \times 10^7)$
2.  $^{232}\text{Th}(\text{st})$   $^{231}\text{Th}(25.5 \text{ h})$   $^{230}\text{Th}(6.75 \times 10^4)$   $^{229}\text{Th}(7340 \text{ y})$
3. Neutron data vis. Surrogate data
4. Surrogate data vis. Ratio Surrogate data
5. Hauser-Feshbach vis. Weisskopf-Ewing
6. Fission Barrier structure –transition states influence
7. **Fission probability from PFNS**

# Fission CS model or surrogate/ratio surrogate method deficiency

$^{230}\text{Th}(t, \text{pf})$   $^{232}\text{Th}$ , Younes and Britt, 2003.

$^{232}\text{Th}(^3\text{He}, ^4\text{He})^{231}\text{Th}$  Petit e.a., 2004  $^{230}\text{Th}(n, F)$

$^{236}\text{U}(t, \text{pf})^{238}\text{U}$ , Younes and Britt, 2003  $^{237}\text{U}(n, F)$

$^{238}\text{U}(t, \text{pf})^{240}\text{U}$ , Younes and Britt, 2003

$$\sigma_{\text{nf}}(E_n) = 3.1 P_f^{\text{exp}},$$

$$\sigma_{\text{nf}}(E_n) = q(E_n) \frac{\pi \hat{\lambda}^2}{2(2I+1)} \sum_{lJ\pi} (2J+1) T_{lJ\pi}(E_n) P_f^{\text{exp}}(E_n),$$

$$\mathbf{(n,F)} = \mathbf{(n,f)} + \mathbf{(n,xnf)}$$

$$\sigma_{\text{nF}}(E_n) = \sigma_{\text{nf}}(E_n) + \sum_{x=1}^X \sigma_{\text{n,xnf}}(E_n)$$

$$\sigma_{\text{n,xnf}}(E_n) = \sum_{J\pi}^J \int_0^{U_{\text{max}}} W_{x+1}^{J\pi}(U) P_{f(x+1)}^{J\pi}(U) dU$$

*ratio \_ surrogate \_ data*

$^{238}\text{U}(d, d' f) / ^{236}\text{U}(d, d' f)$  \_ Plettner \_ e.a., 2005

\_  $^{238}\text{U}(\alpha, \alpha' f) / ^{236}\text{U}(\alpha, \alpha' f)$  \_ Burke \_ e.a., 2006

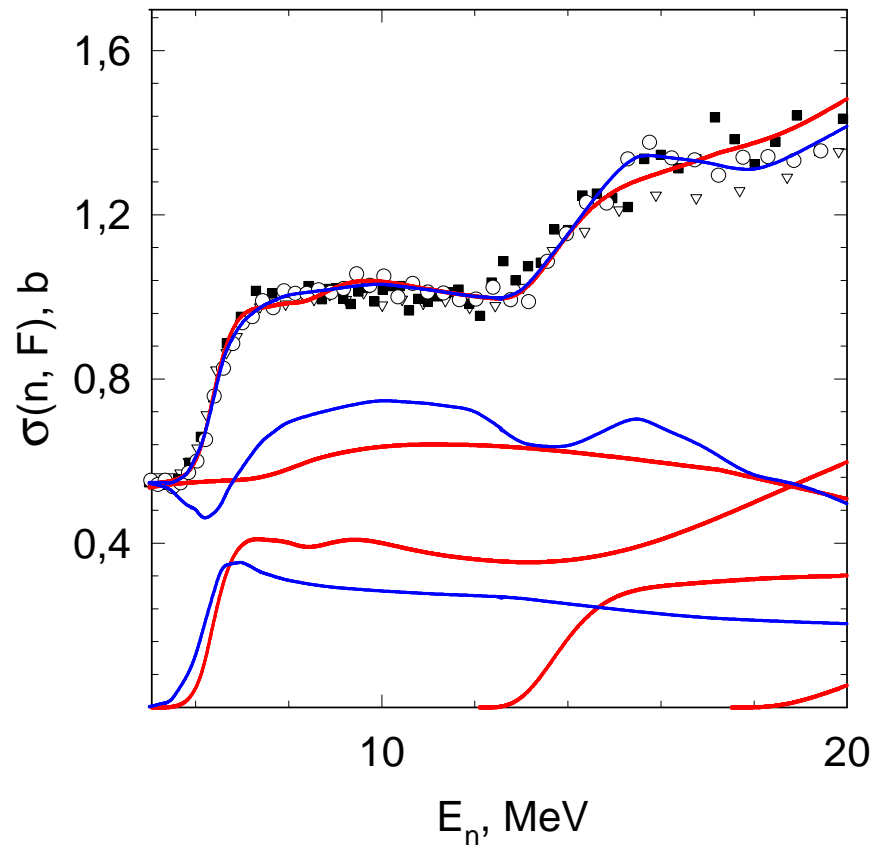
$^{238}\text{U}(^{18}\text{O}, ^{16}\text{O}) ^{240}\text{U}$ , Burke, 2009

*ratio \_ data*

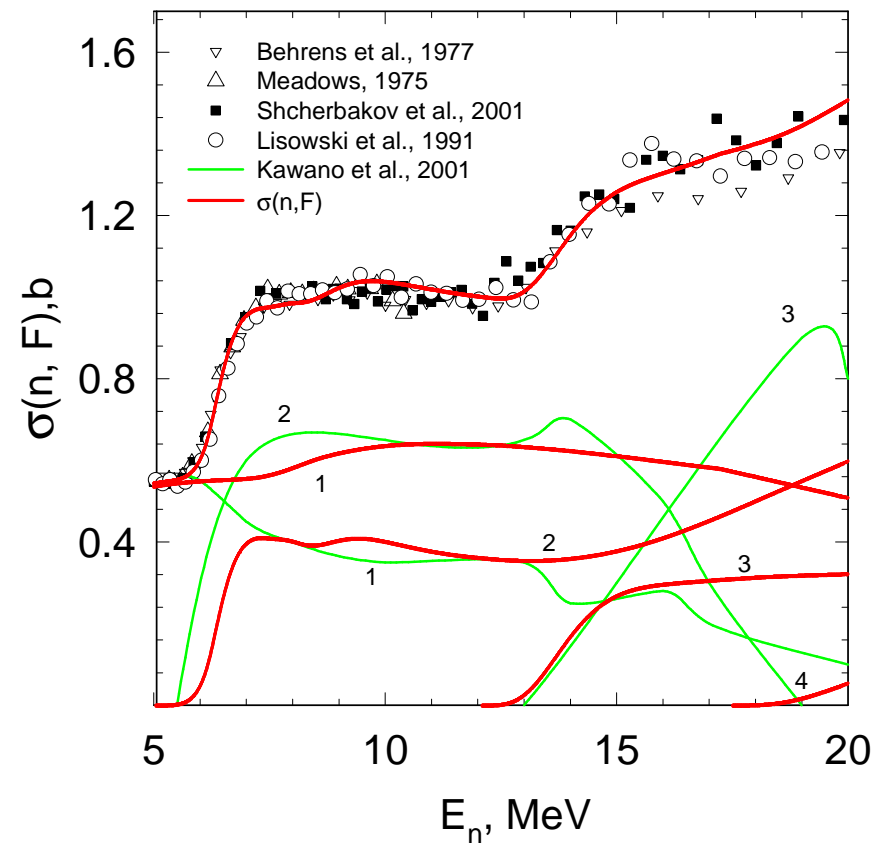
$^{236}\text{U}(t, pf)$ , \_  $^{238}\text{U}(t, pf)$ , \_

# Surrogate vis. direct data for $^{237}\text{U}$

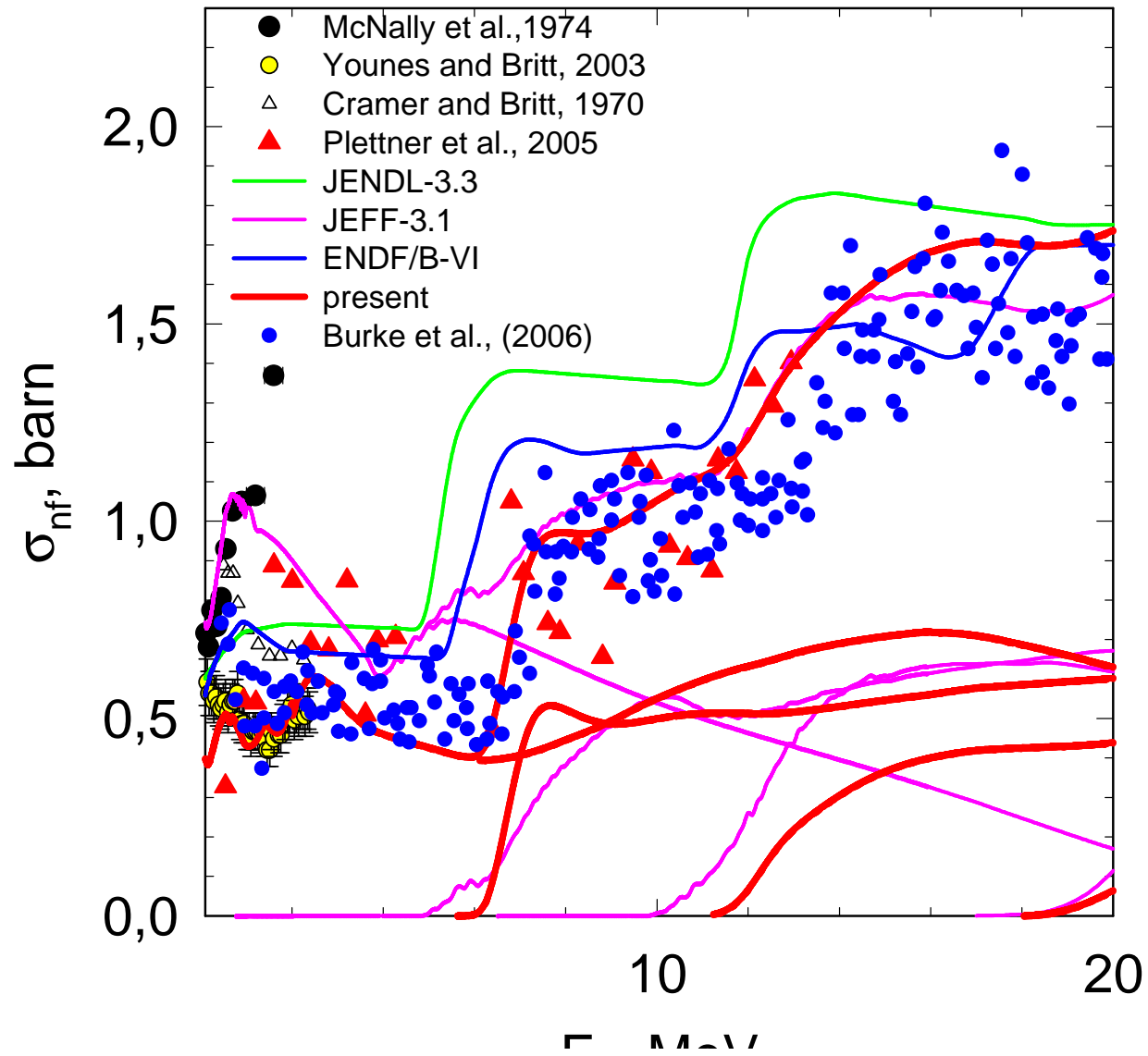
$^{238}\text{U}$  FISSION CROSS SECTION



$^{238}\text{U}$  FISSION CROSS SECTION

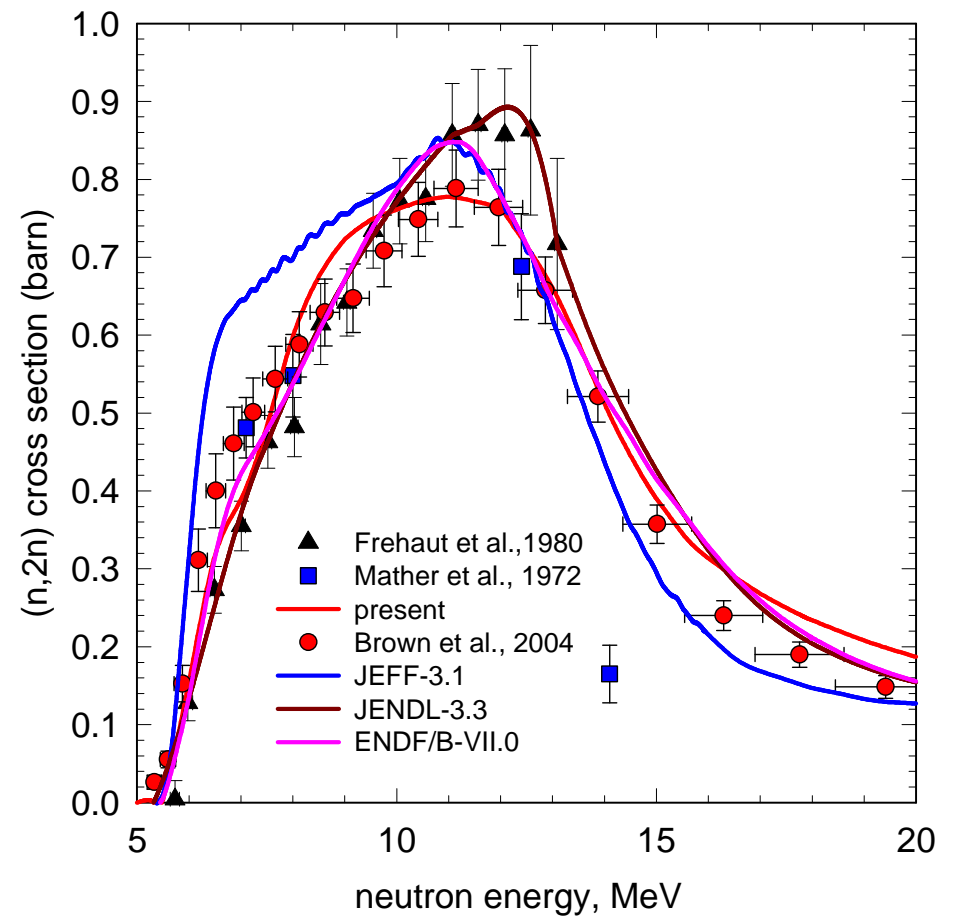
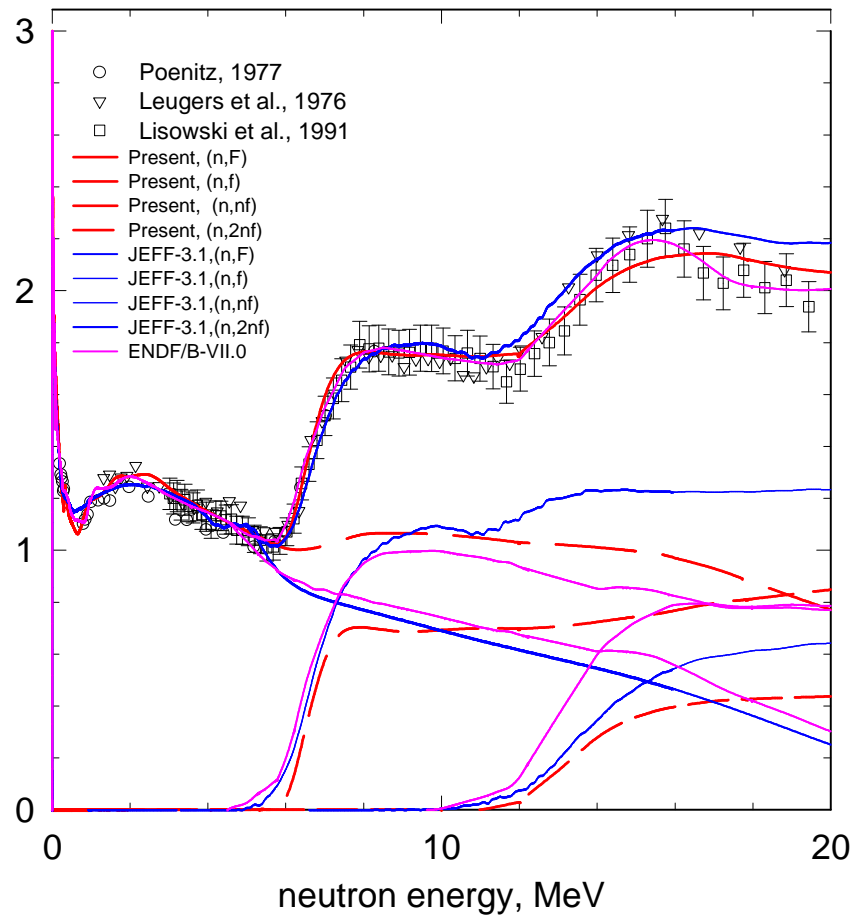


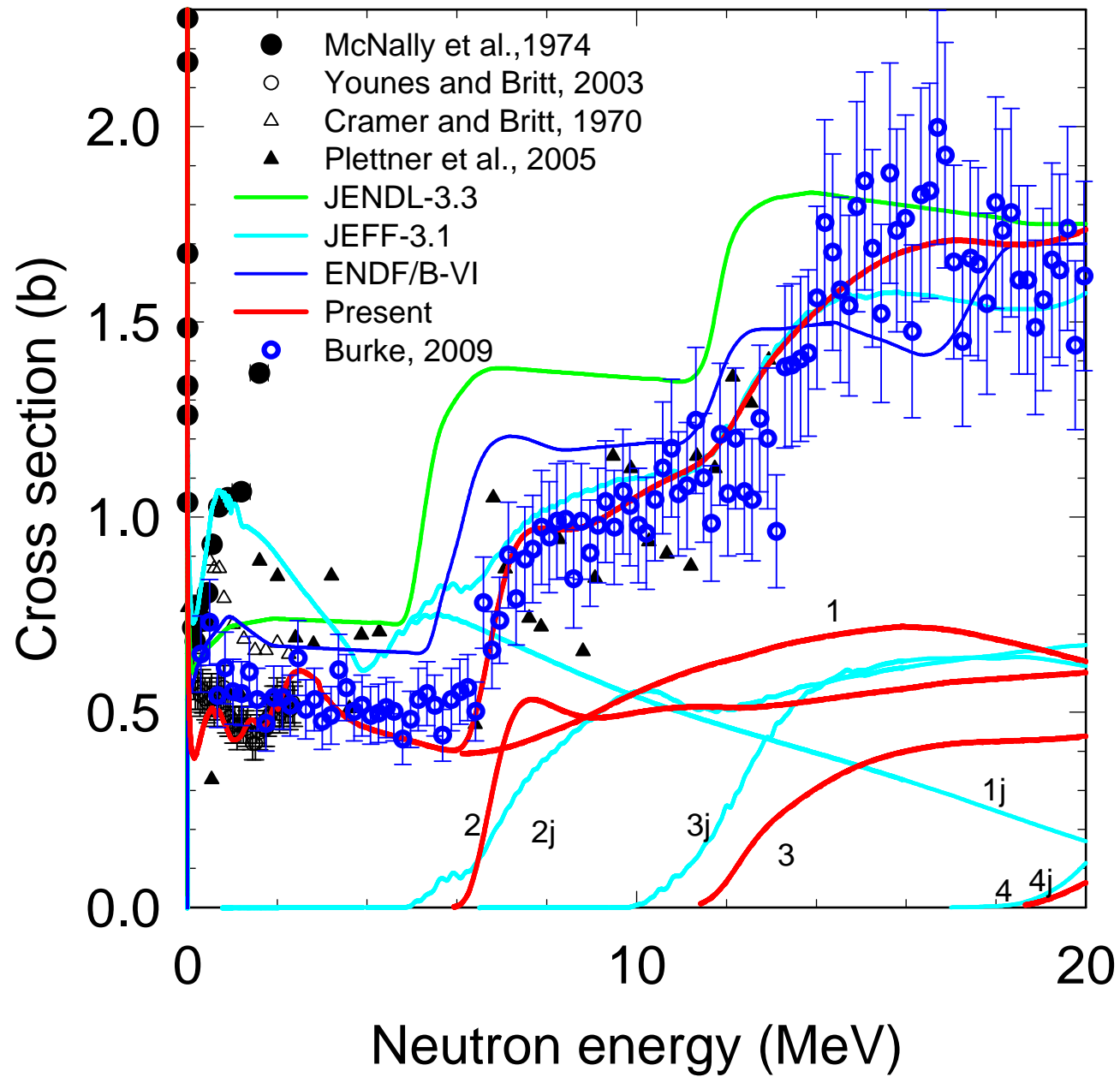
## $^{237}\text{U}$ FISSION CROSS SECTION

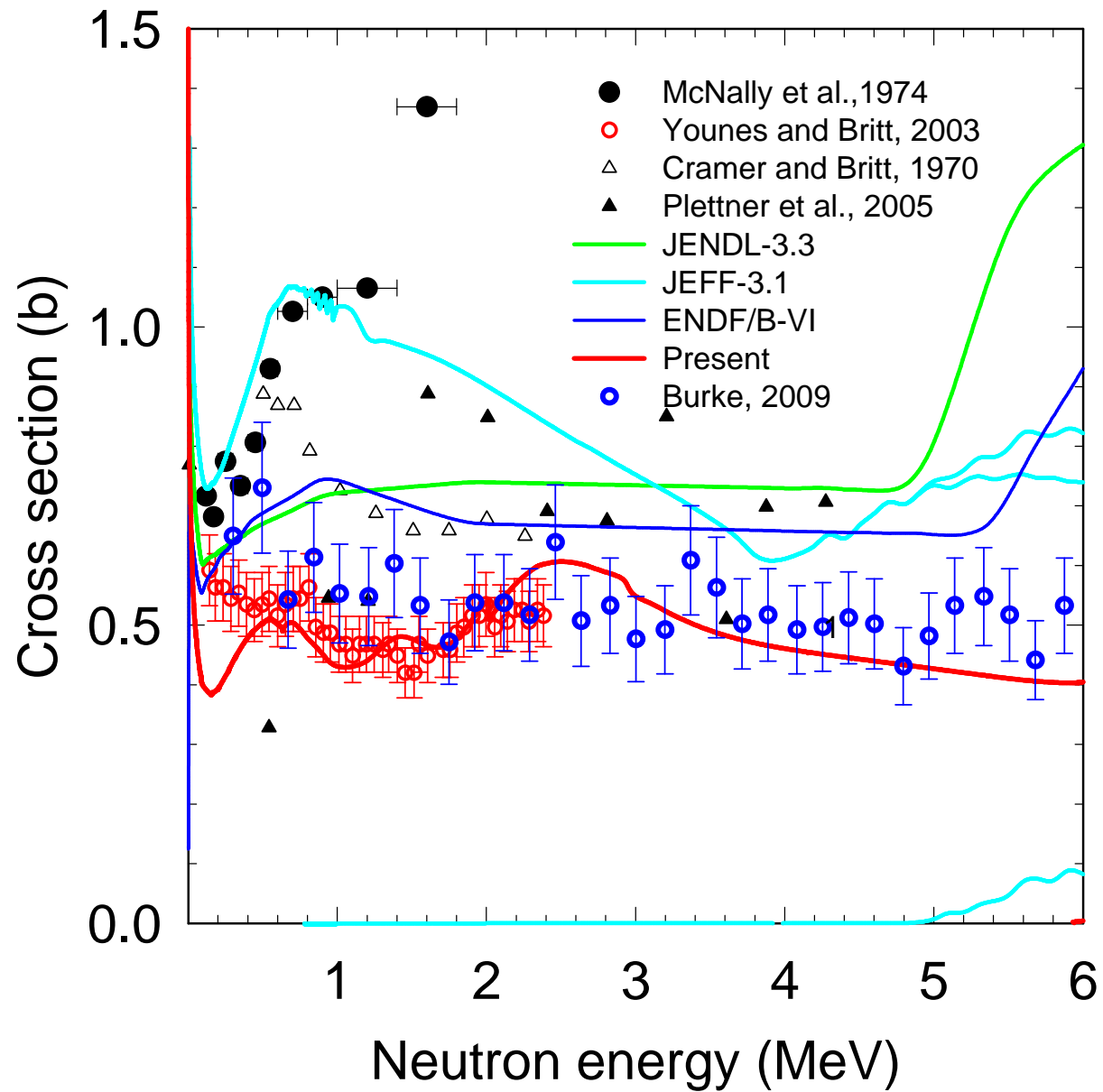


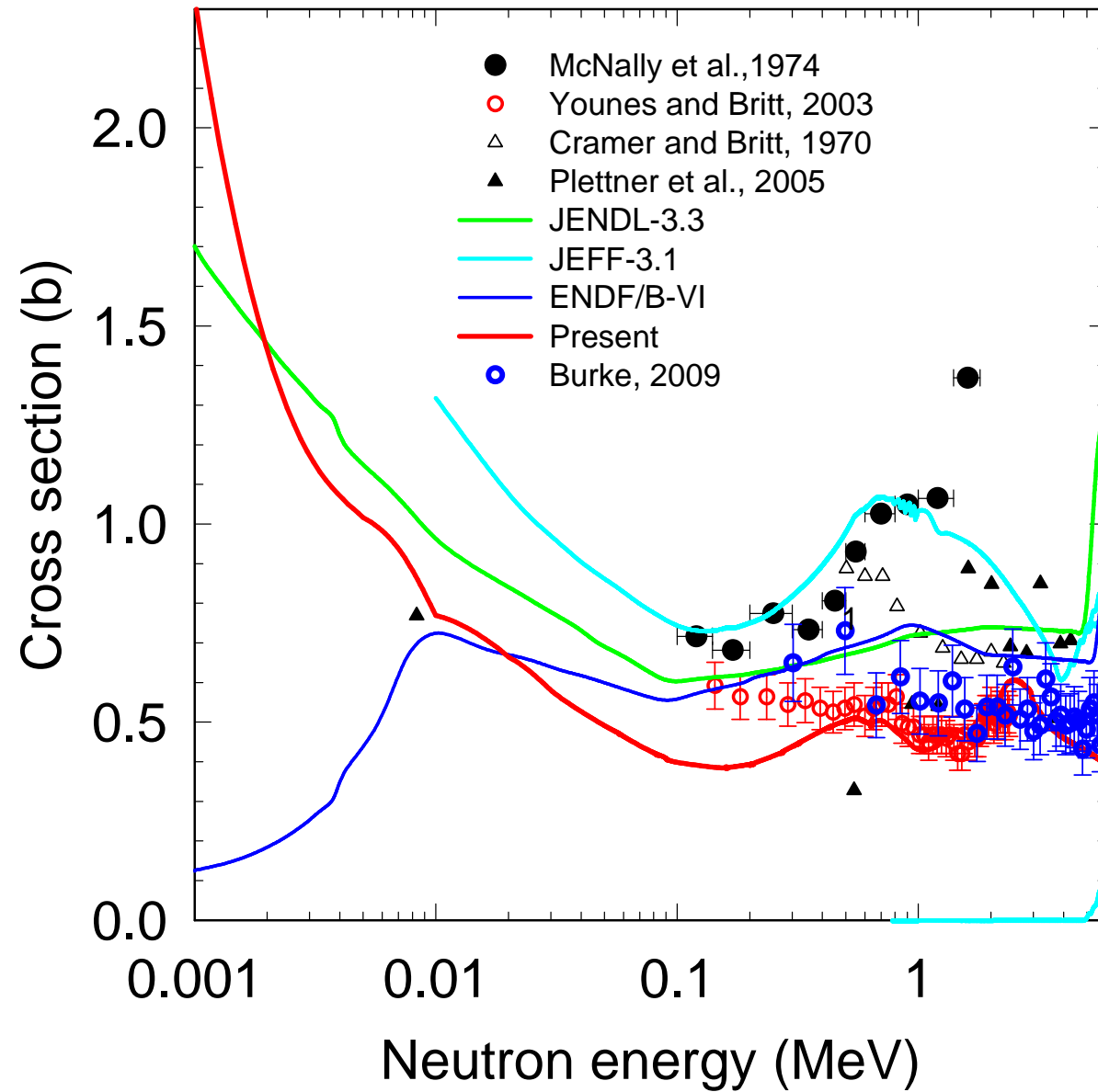
$^{235}\text{U}(n,F)$ 

&amp;

 $^{235}\text{U}(n,2n)$ 




$^{237}\text{U}$  FISSION CROSS SECTION

$^{237}\text{U}$  FISSION CROSS SECTION

## Prompt-fission neutron spectra

superposition of exclusive pre-fission (n,xnf) spectra and post-fission spectra

$$S_{A+2-x}(\epsilon, E_n)$$

$$\begin{aligned} S(\epsilon, E_n) = & \nu^{-1}(E_n)(\nu_1(E_n)\beta_1(E_n)S_{A+1}(\epsilon, E_n) + \\ & \nu_2(E_n)\beta_2(E_n)S_A(\epsilon, E_n) + \beta_2(E_n)\frac{d\sigma_{\text{nnf}}^1(E_n)}{d\epsilon} + \\ & \nu_3(E_n)\beta_3(E_n)S_{A-1}(\epsilon, E_n) + \beta_3(E_n)\left(\frac{d\sigma_{\text{n2nnf}}^1(E_n)}{d\epsilon} + \frac{d\sigma_{\text{n2nnf}}^2(E_n)}{d\epsilon}\right) + \\ & \nu_4(E_n)\beta_4(E_n)S_{A-2}(\epsilon, E_n) + \beta_4(E_n)\left(\frac{d\sigma_{\text{n3nnf}}^1(E_n)}{d\epsilon} + \frac{d\sigma_{\text{n3nnf}}^2(E_n)}{d\epsilon} + \frac{d\sigma_{\text{n3nnf}}^3(E_n)}{d\epsilon}\right)) \end{aligned}$$

## Prompt fission neutron spectra

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

-

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

Kornilov, Kagalenko, Hambusch, YaF, 62, 209, 1999  
**pre-acceleration NE + NE from accelerated fragments**

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

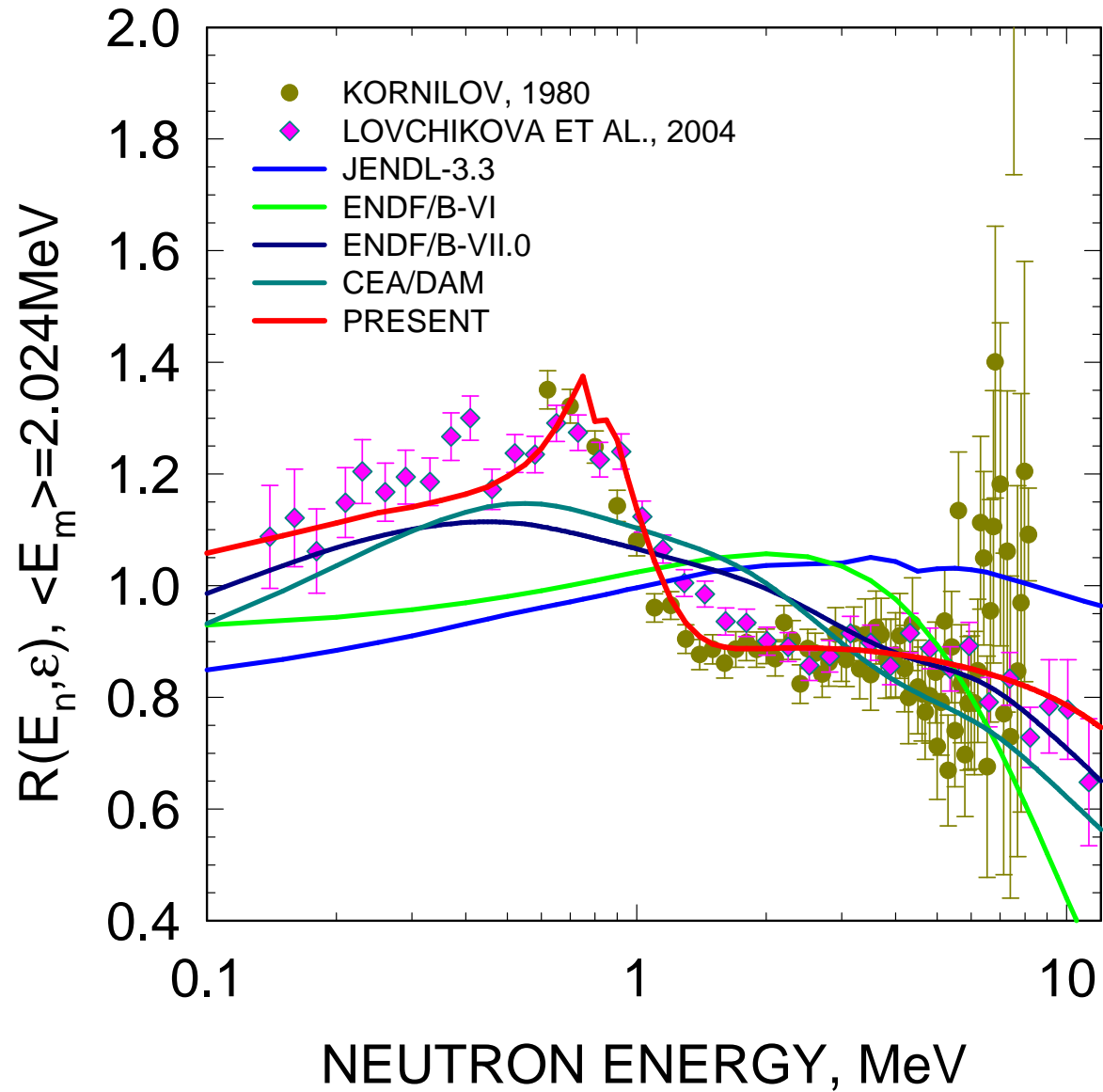
$$b_{ij} = \frac{4E_{vij}^*}{T_{ij}}, T_{ij} = k_{ij} \sqrt{E_r - TKE_i - U_i}$$

$T_{ij}$  -temperature for light and heavy fragments,  $\alpha = TKE/TKE_\infty$

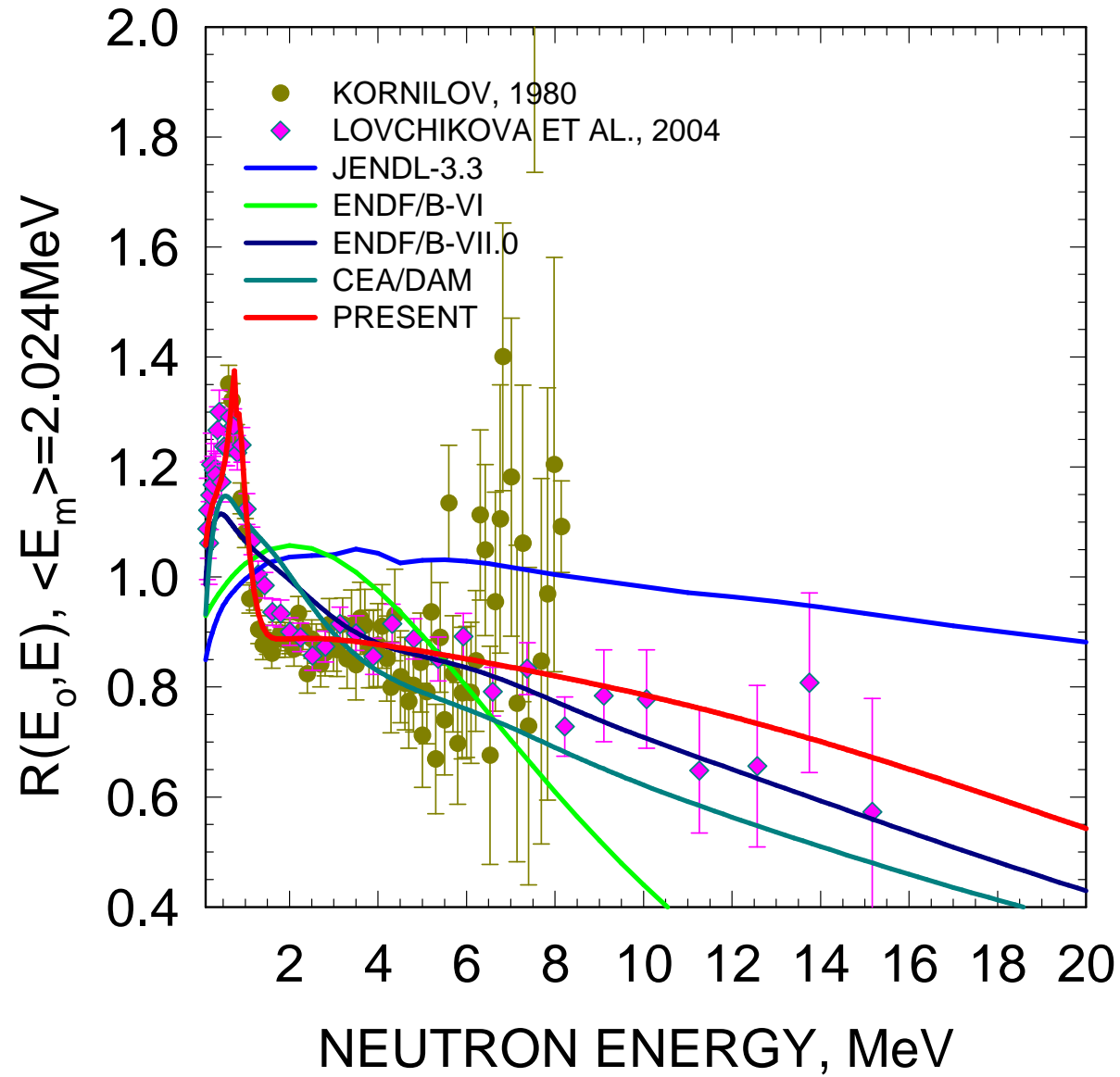
In Watt' equation CMS energy per nucleon -

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

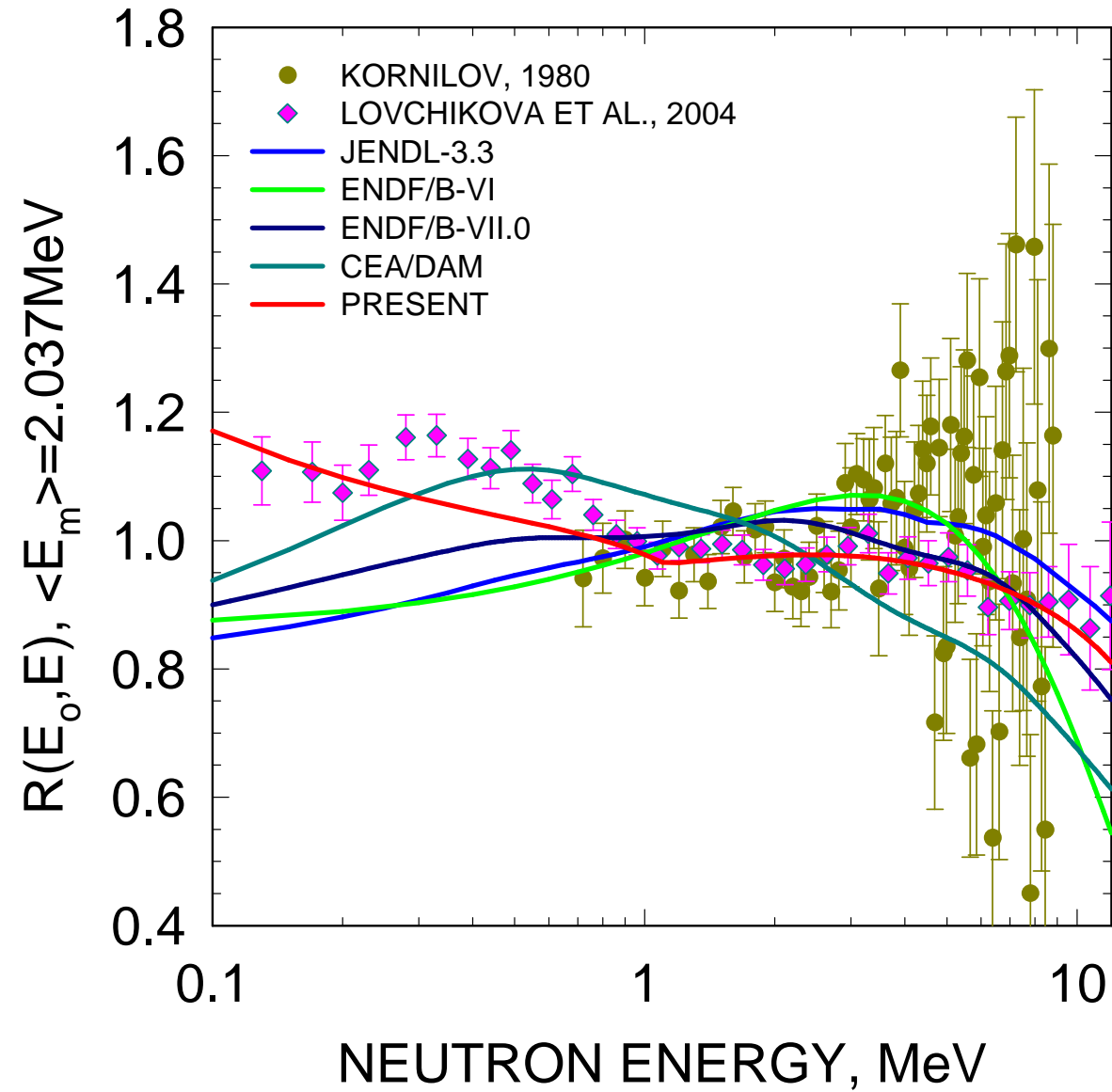
$^{238}\text{U}$  FISSION NEUTRON SPECTRUM  
 $E_n=7$  MeV



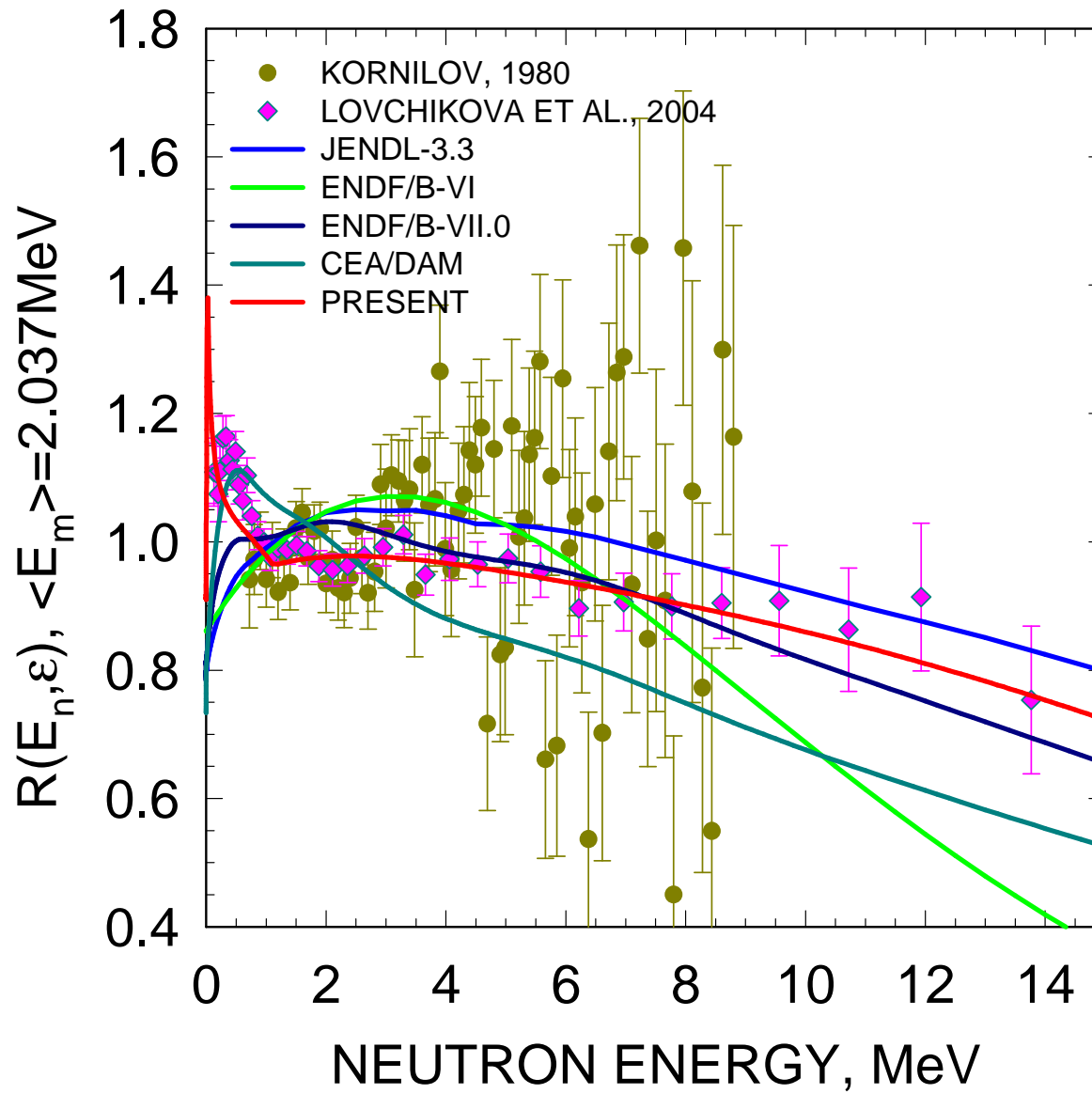
$^{238}\text{U}$  FISSION NEUTRON SPECTRUM  
 $E_0=7\text{ MeV}$



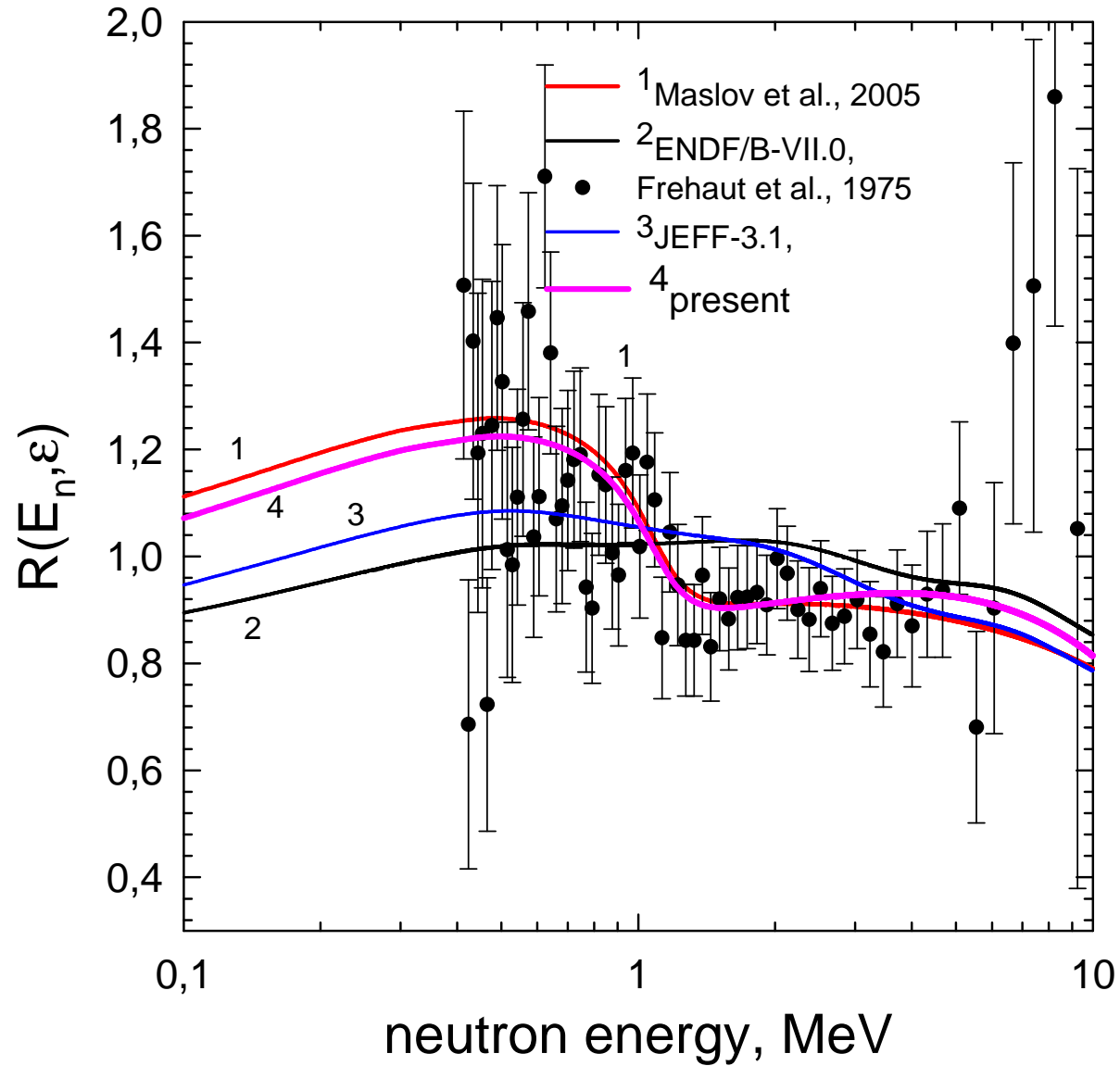
$^{238}\text{U}$  FISSION NEUTRON SPECTRUM  
 $E_0=6\text{ MeV}$

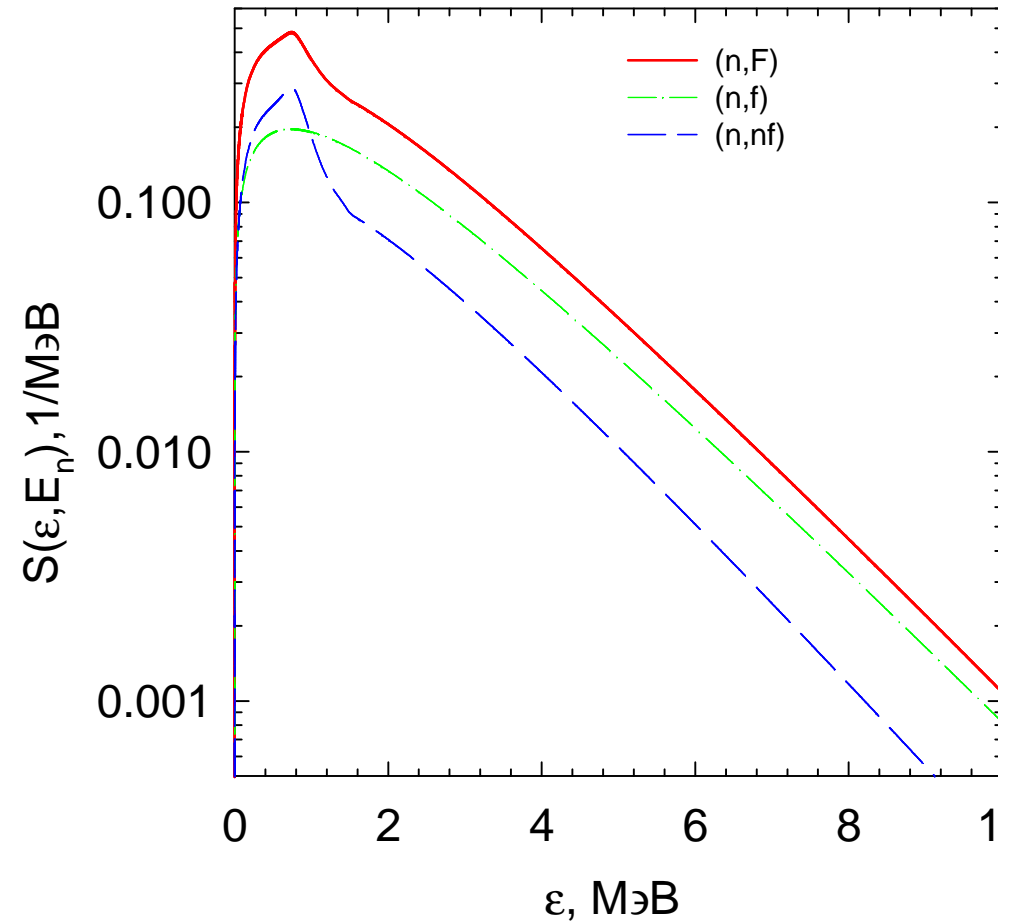
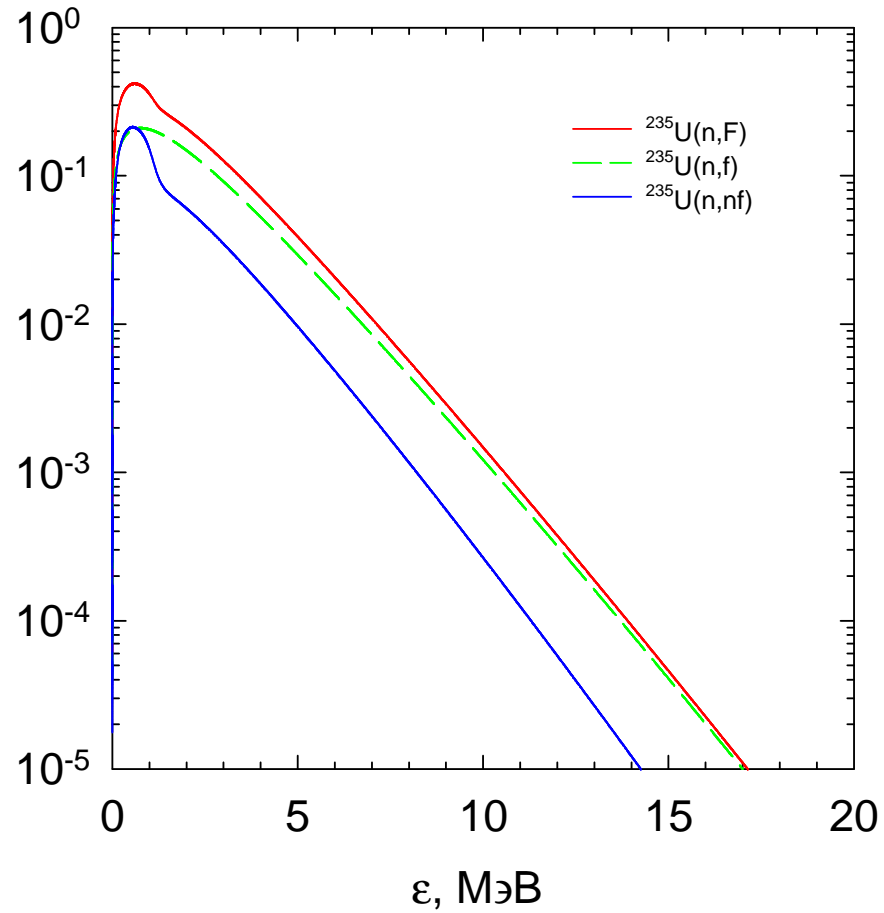


$^{238}\text{U}$  FISSION NEUTRON SPECTRUM  
 $E_n=6$  MeV

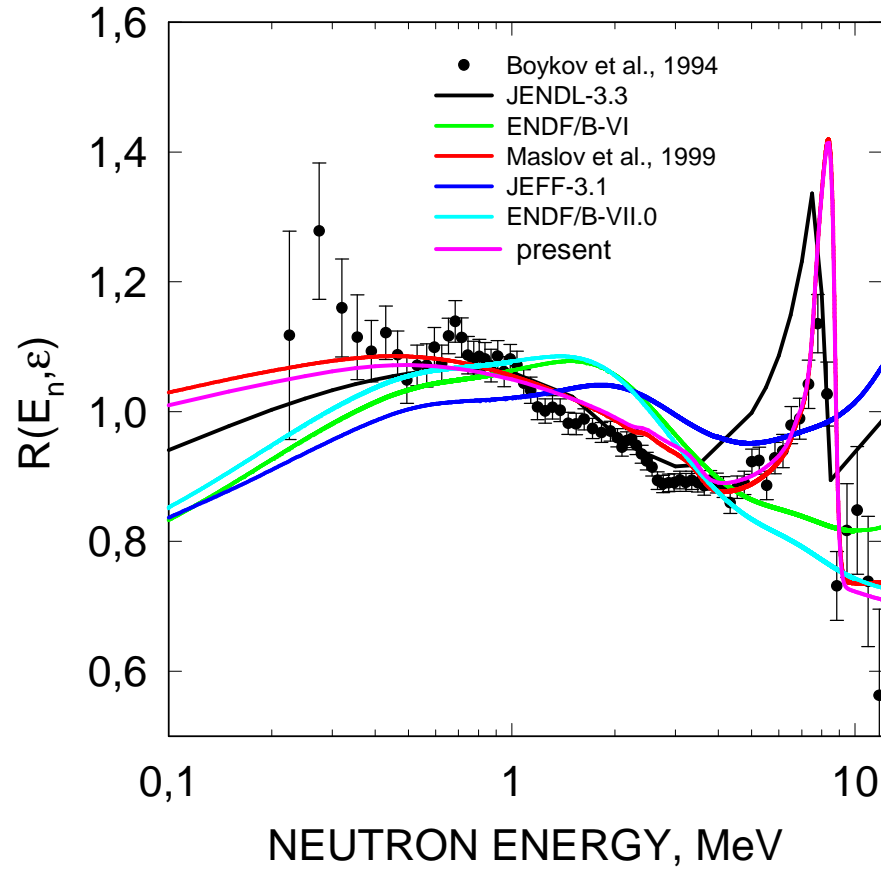


$^{235}\text{U}(n,F)$  FISSION NEUTRON SPECTRUM  
 $E_n=7$  MeV

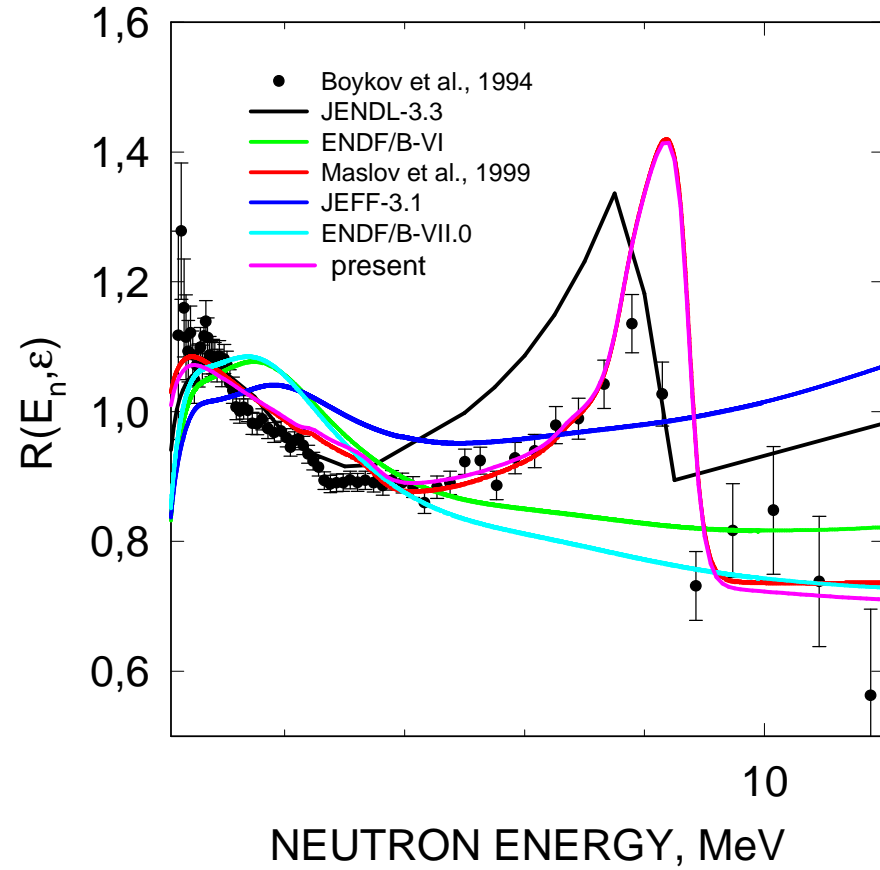


$^{235}\text{U}(n,F)$  [PFNS  $E_n=7$  MeV]  $^{238}\text{U}(n,F)$ 


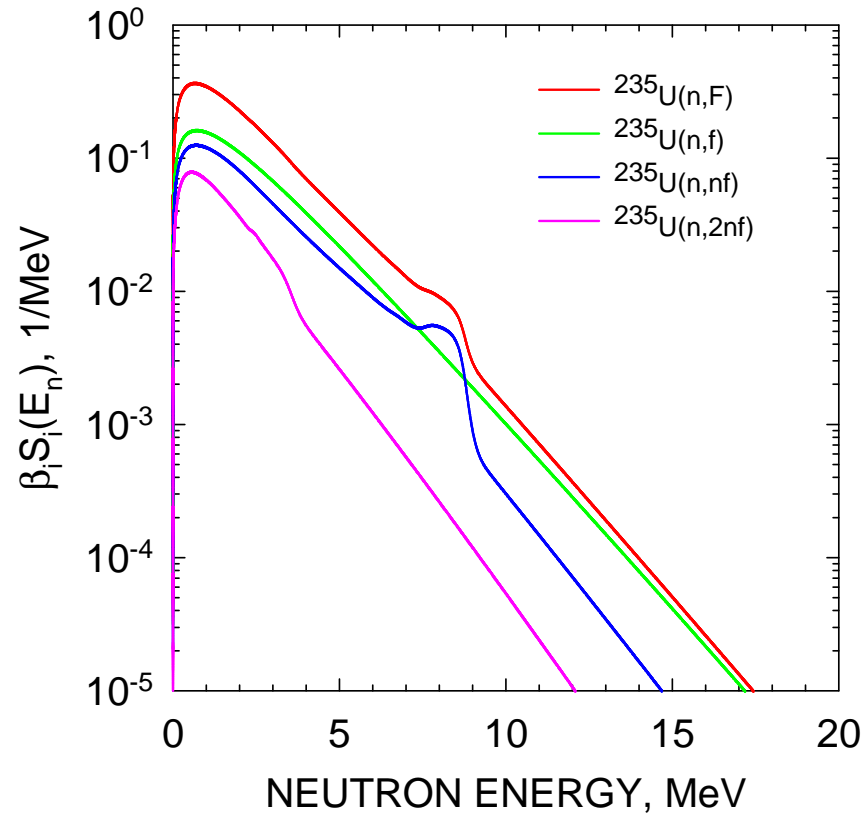
$^{235}\text{U}$  PROMPT FISSION NEUTRON SPECTRUM,  $E_n=14.7$  MeV



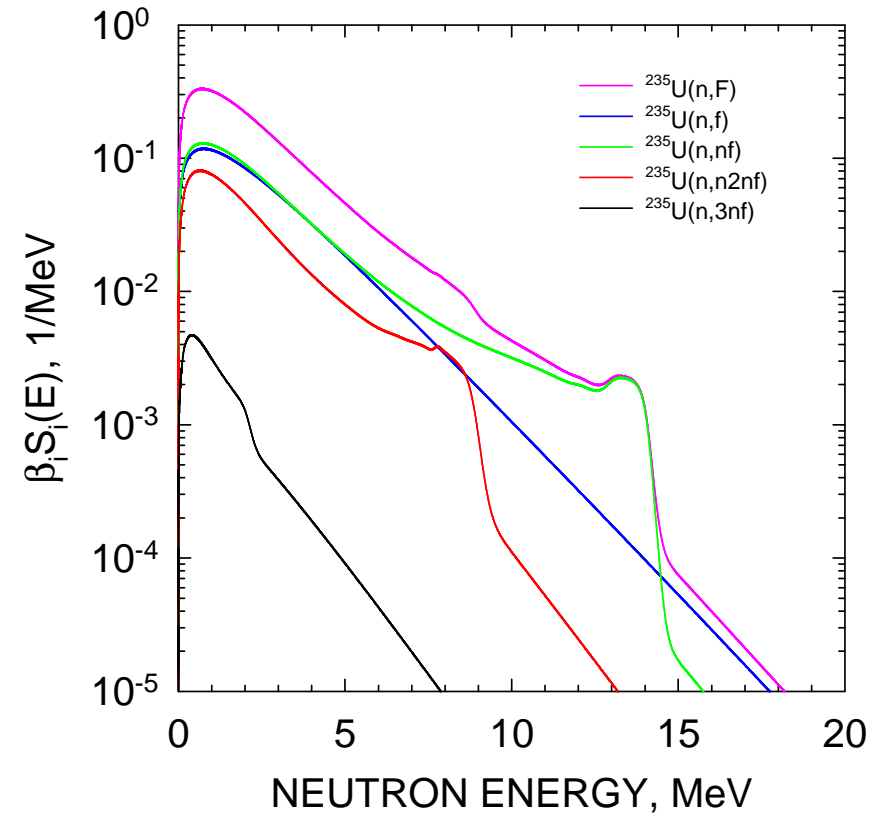
$^{235}\text{U}$  PROMPT FISSION NEUTRON SPECTRUM,  $E_n=14.7$  MeV

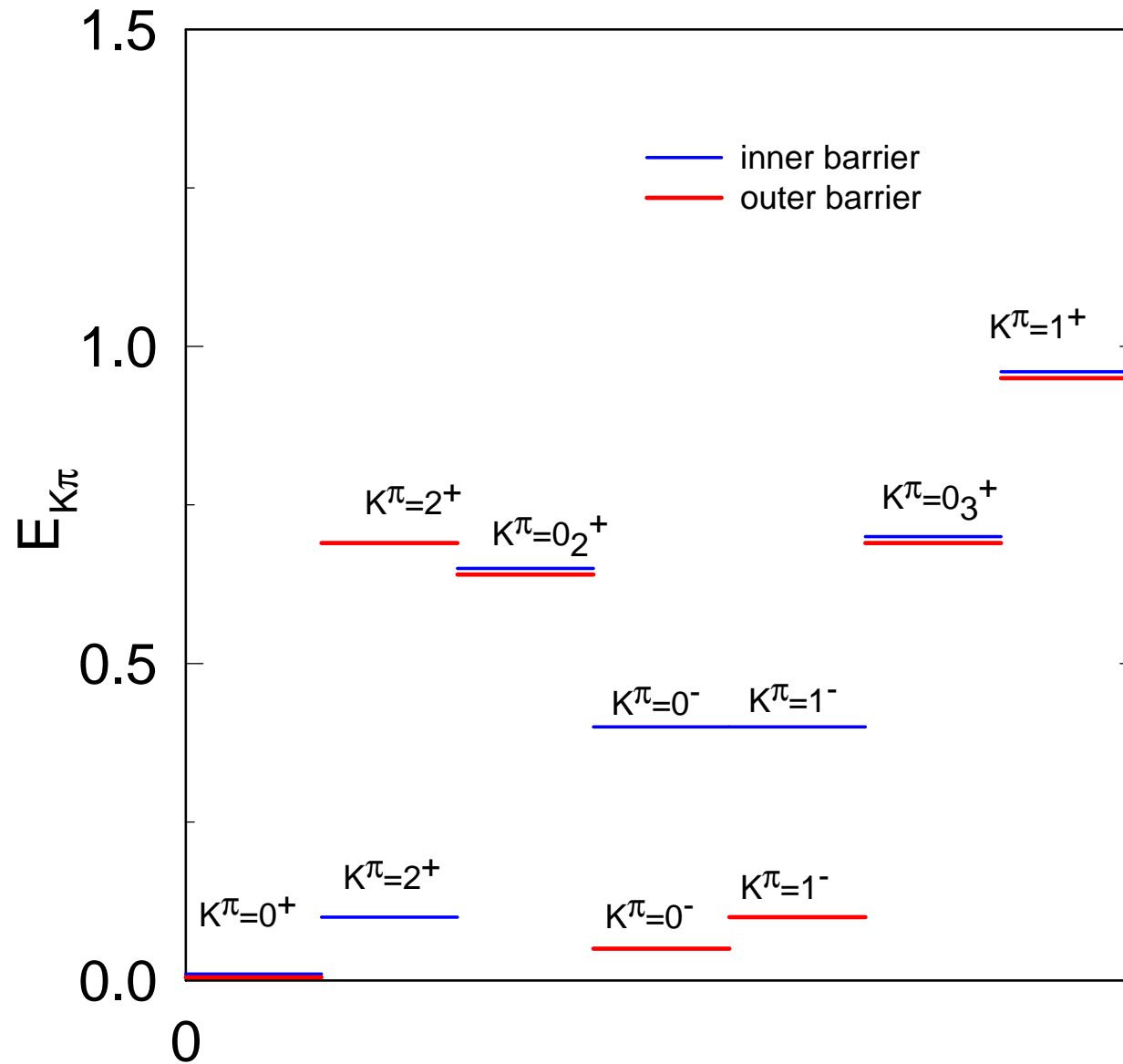


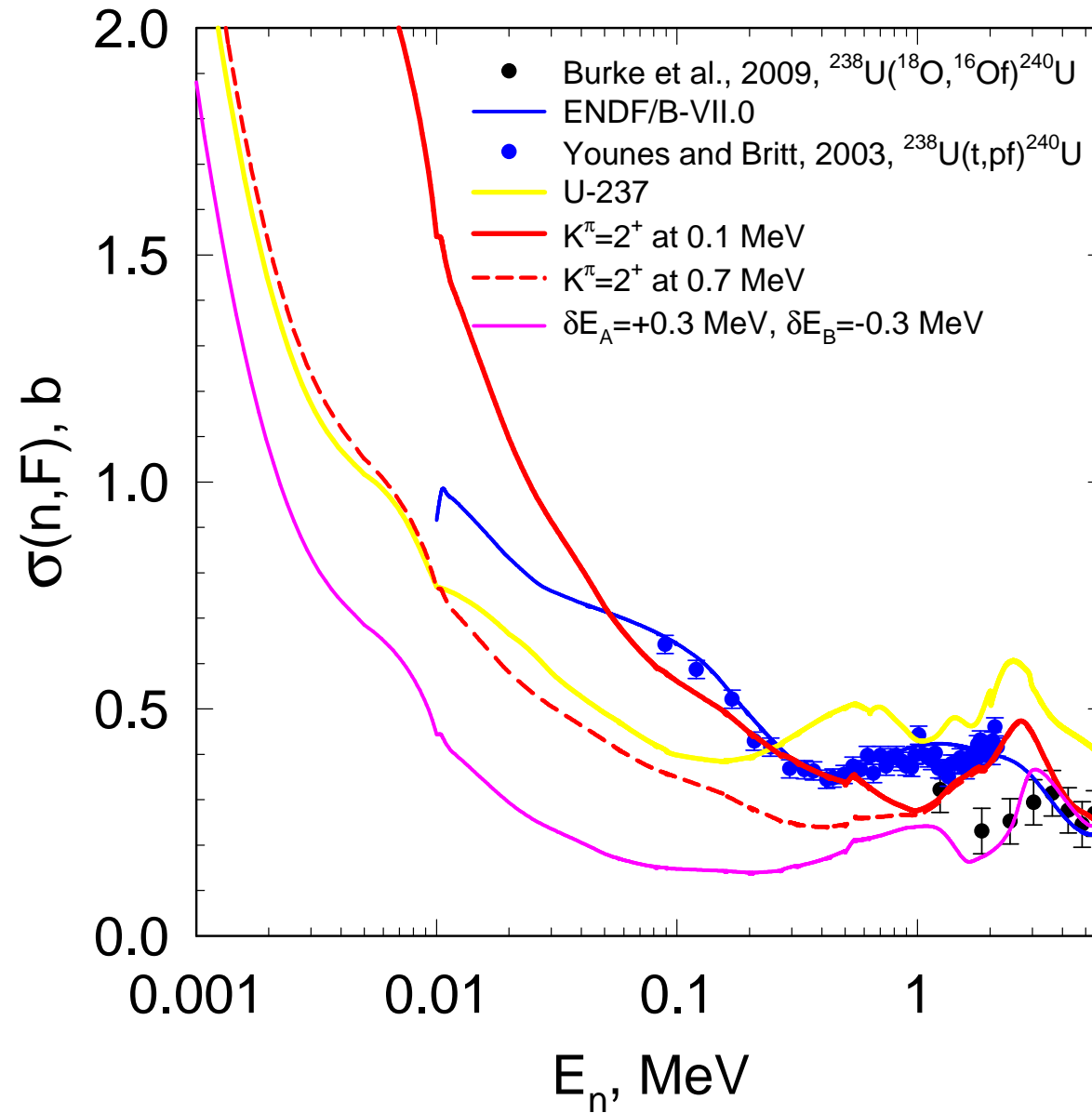
$^{235}\text{U}$  PARTIAL FISSION NEUTRON SPECTRA,  $E_n=14.7$  MeV

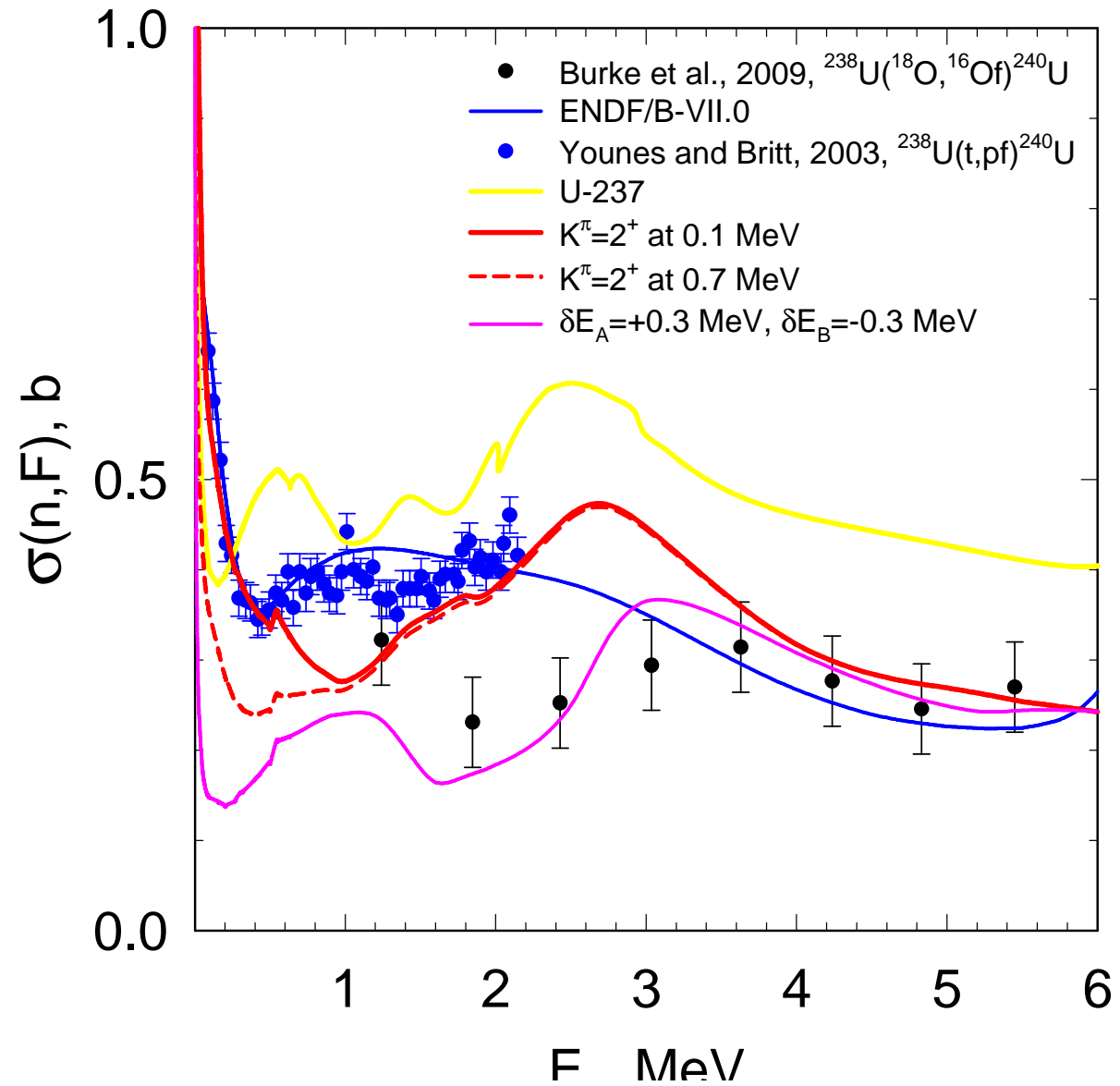


$^{235}\text{U}$  PARTIAL FISSION NEUTRON SPECTRA,  $E_n=20$  MeV

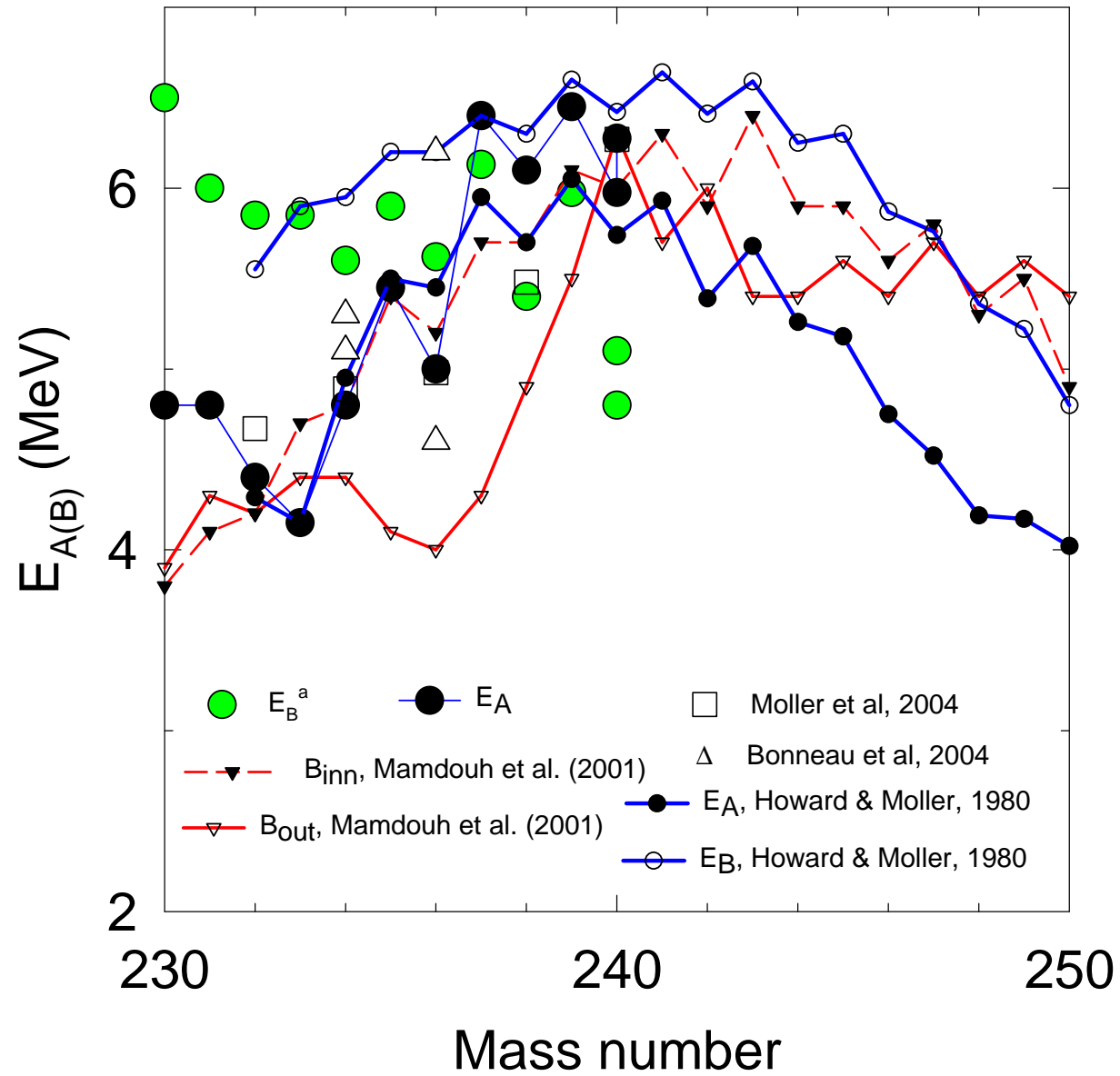


$^{238}\text{U}$  transition states

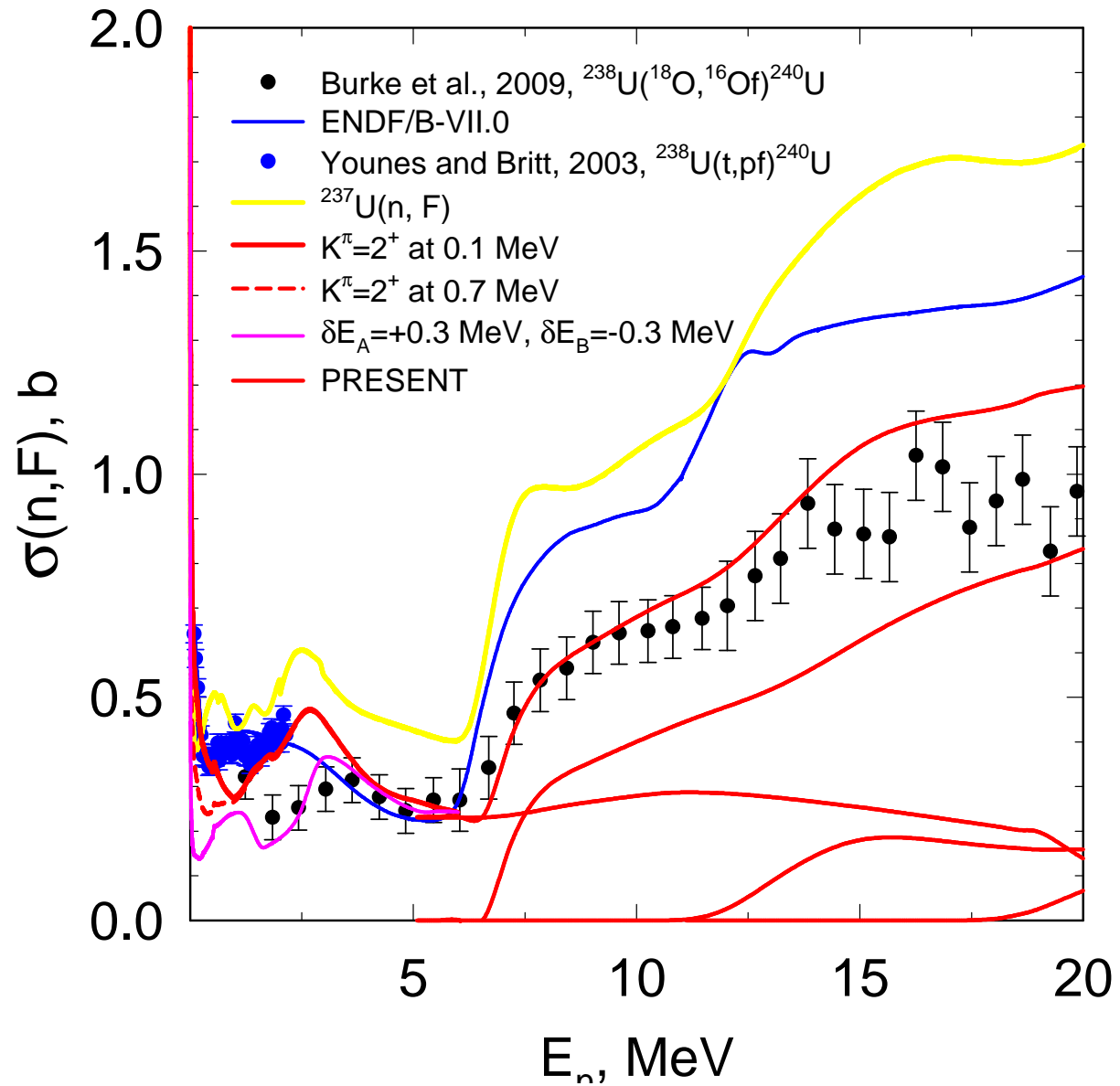
$^{239}\text{U}$  FISSION CROSS SECTION

$^{239}\text{U}$  FISSION CROSS SECTION

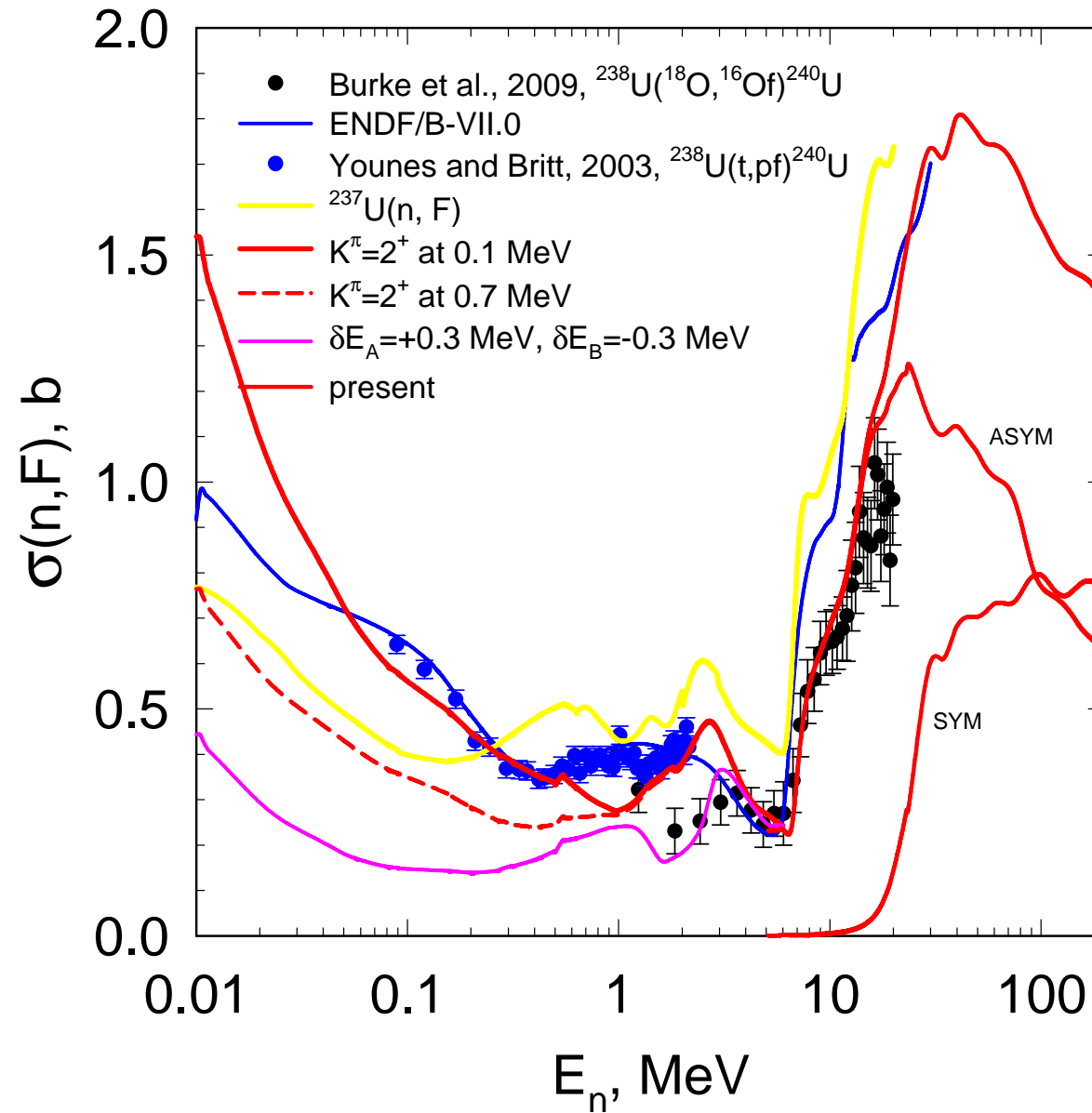
## U FISSION BARRIERS

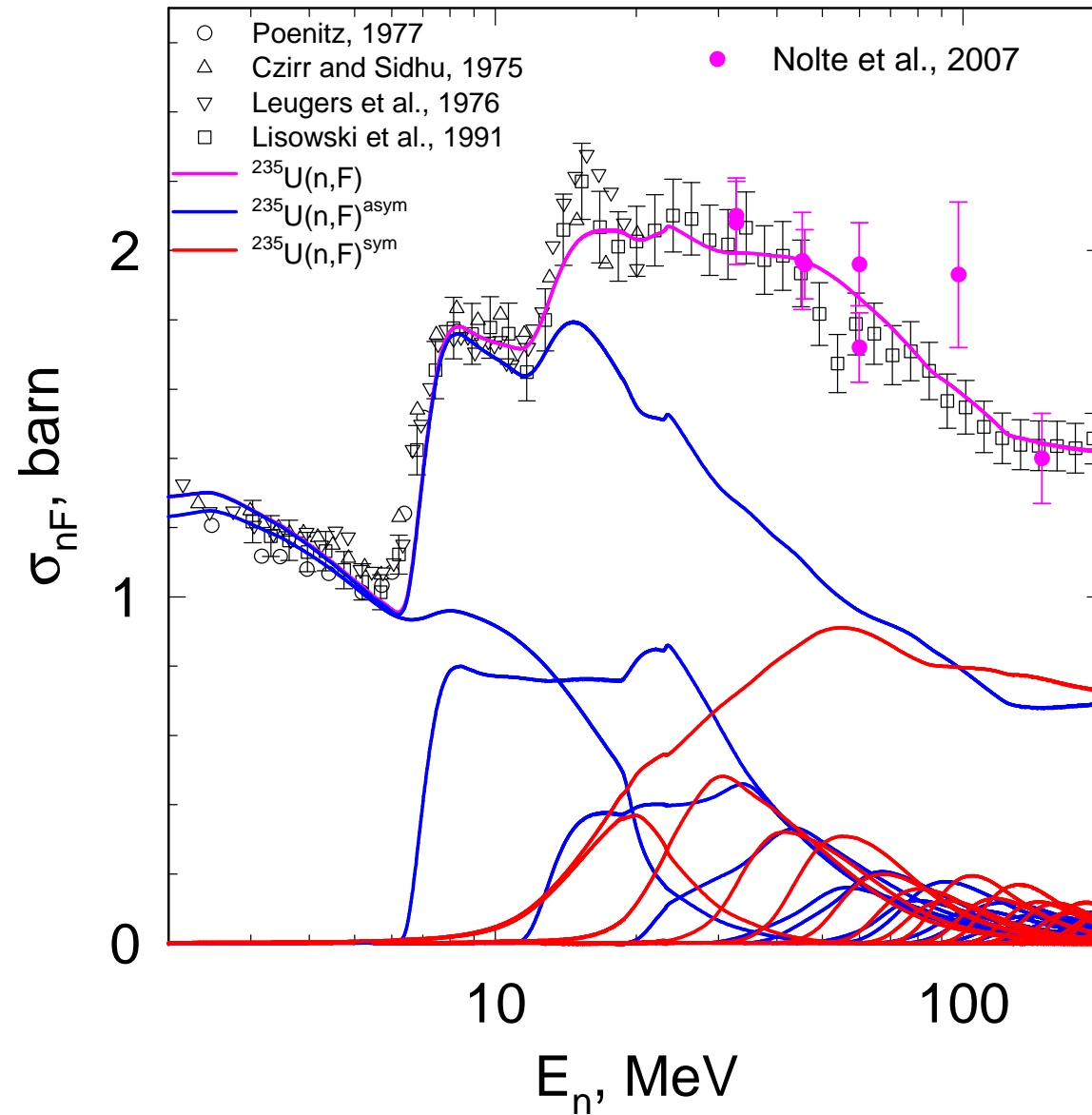


## $^{239}\text{U}$ FISSION CROSS SECTION



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$^{235}\text{U}$  FISSION CROSS SECTION

*ratio \_ surrogate \_ data*

$^{232}\text{Th}(^3\text{He}, ^3\text{He})^{232}\text{Th}, \text{vis. } ^{236}\text{U}(^3\text{He}, ^3\text{He})^{236}\text{U}, \text{Goldblum _ e.a., 2009}$

$^{232}\text{Th}(^3\text{He}, ^4\text{He})^{231}\text{Th}, \text{vis. } ^{236}\text{U}(^3\text{He}, ^4\text{He})^{235}\text{U}, \text{Goldblum _ e.a., 2009}$

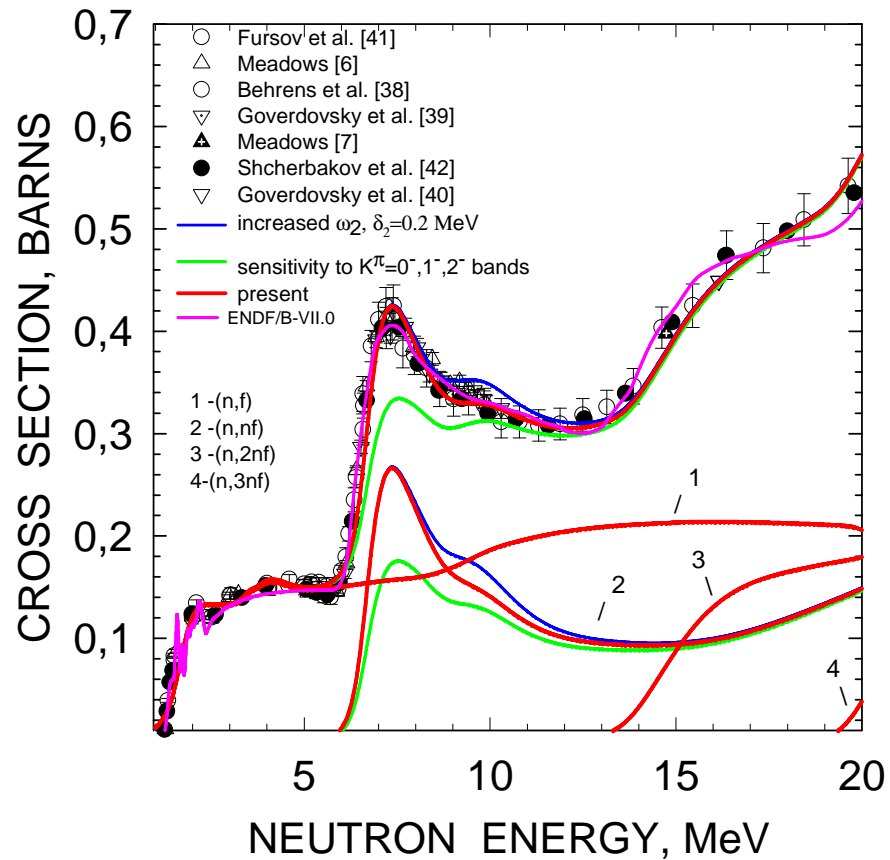
$^{232}\text{Th}(^6\text{Li}, ^4\text{He})^{234}\text{Pa} / ^{232}\text{Th}(^6\text{Li}, d)^{236}\text{U} \text{ _ Nayak _ e.a., 2008}$

*ratio \_ data*

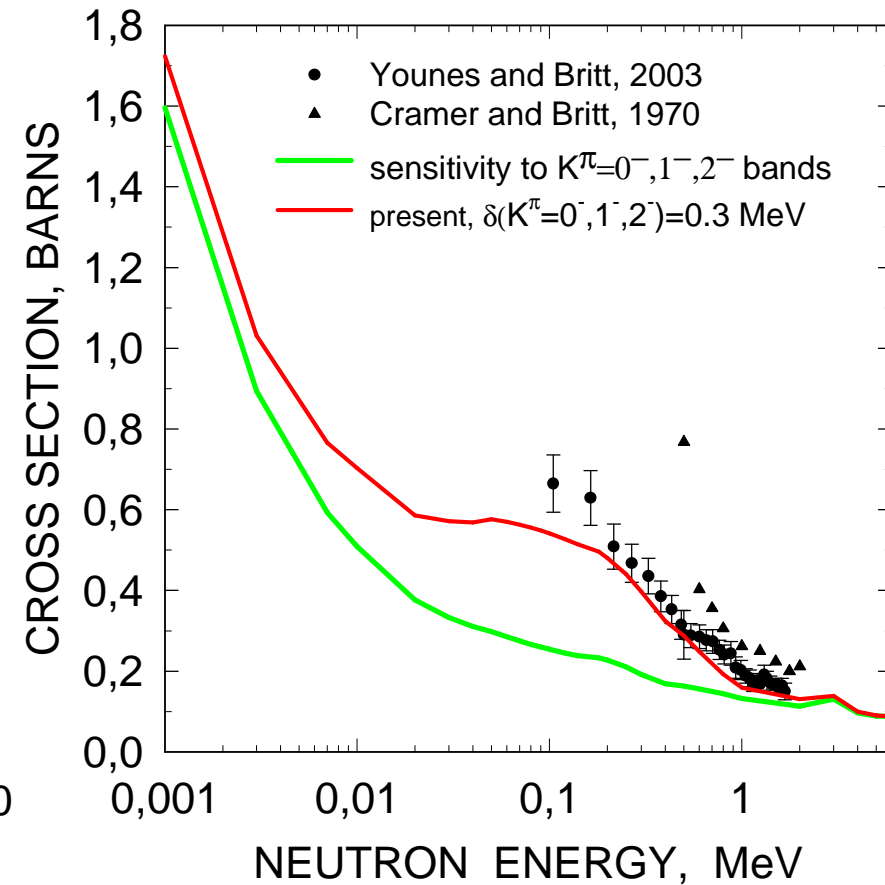
$^{230}\text{Th}(t, pf), \text{ _ } ^{232}\text{Th}(t, pf)$

# Surrogate vis. direct data for $^{231}\text{Th}(n,F)$

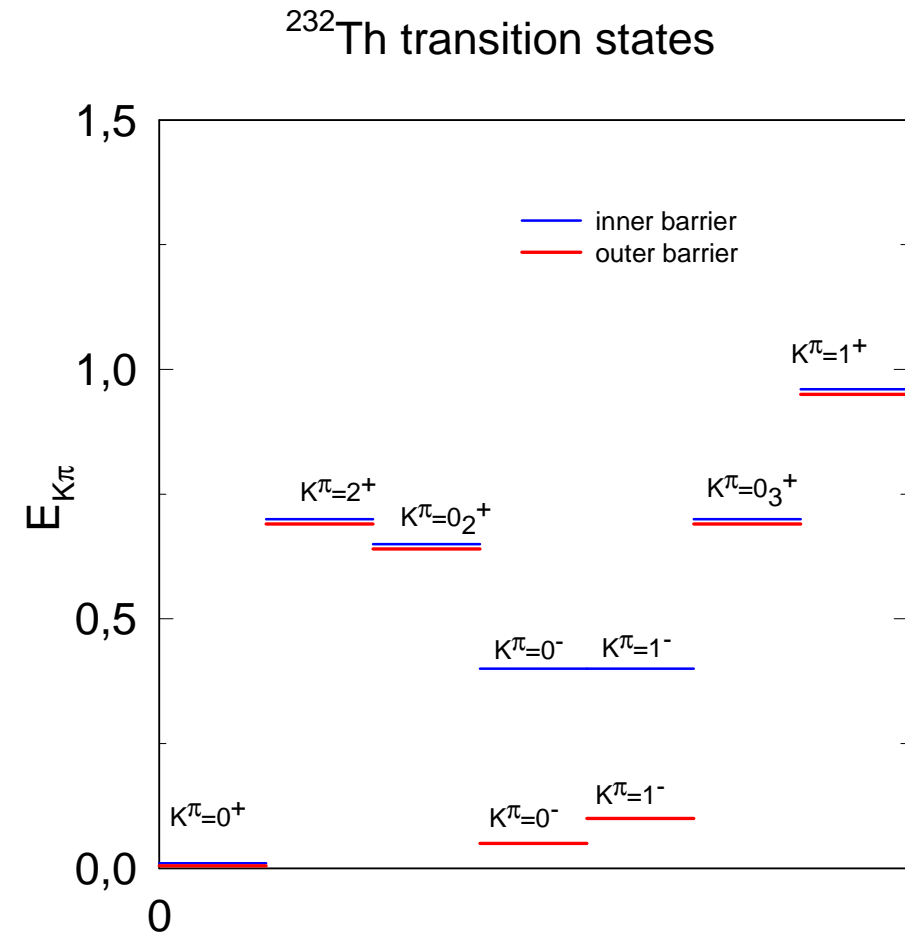
## $^{232}\text{Th}$ FISSION CROSS SECTION

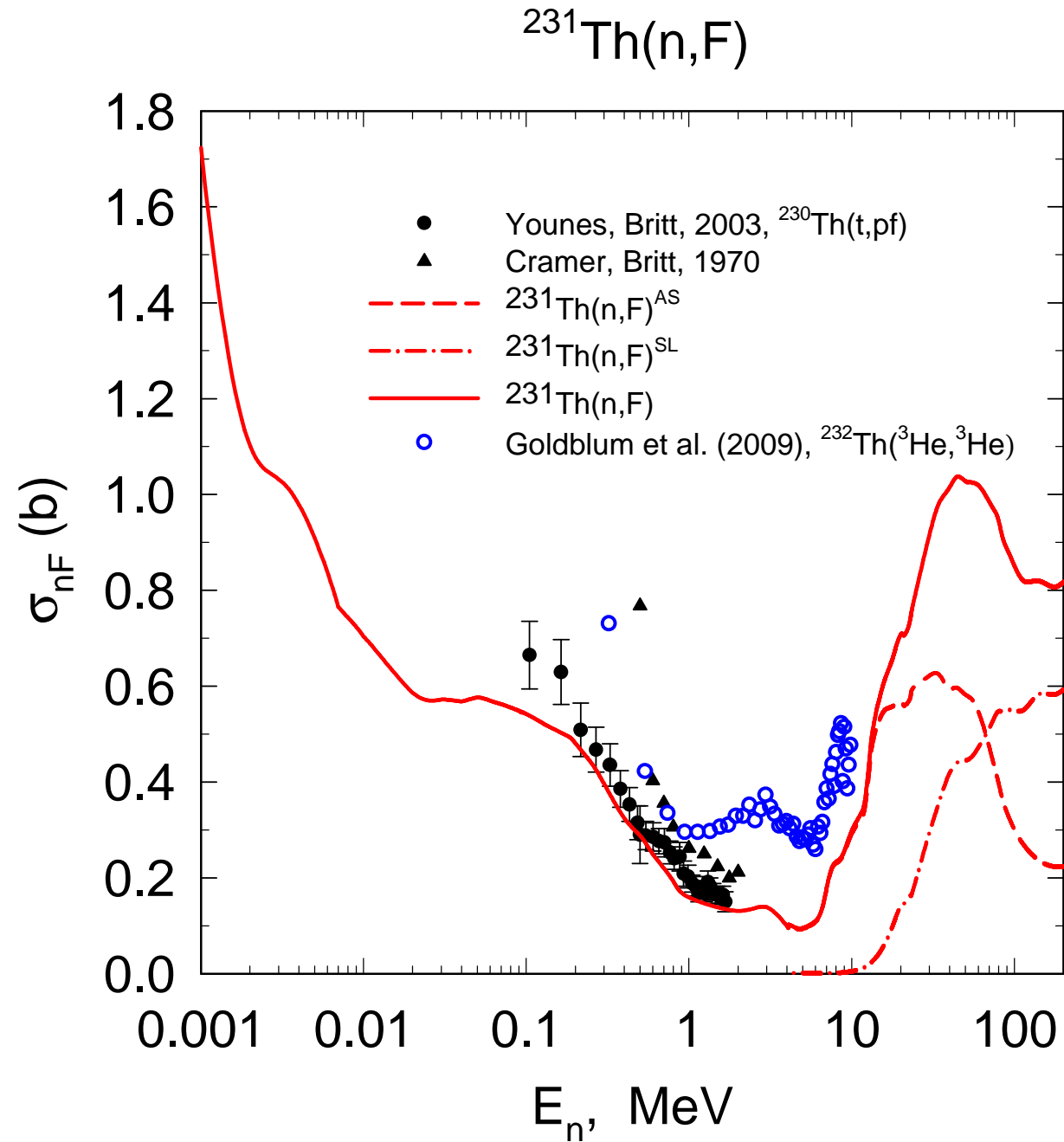


## $^{231}\text{Th}$ FISSION CROSS SECTION

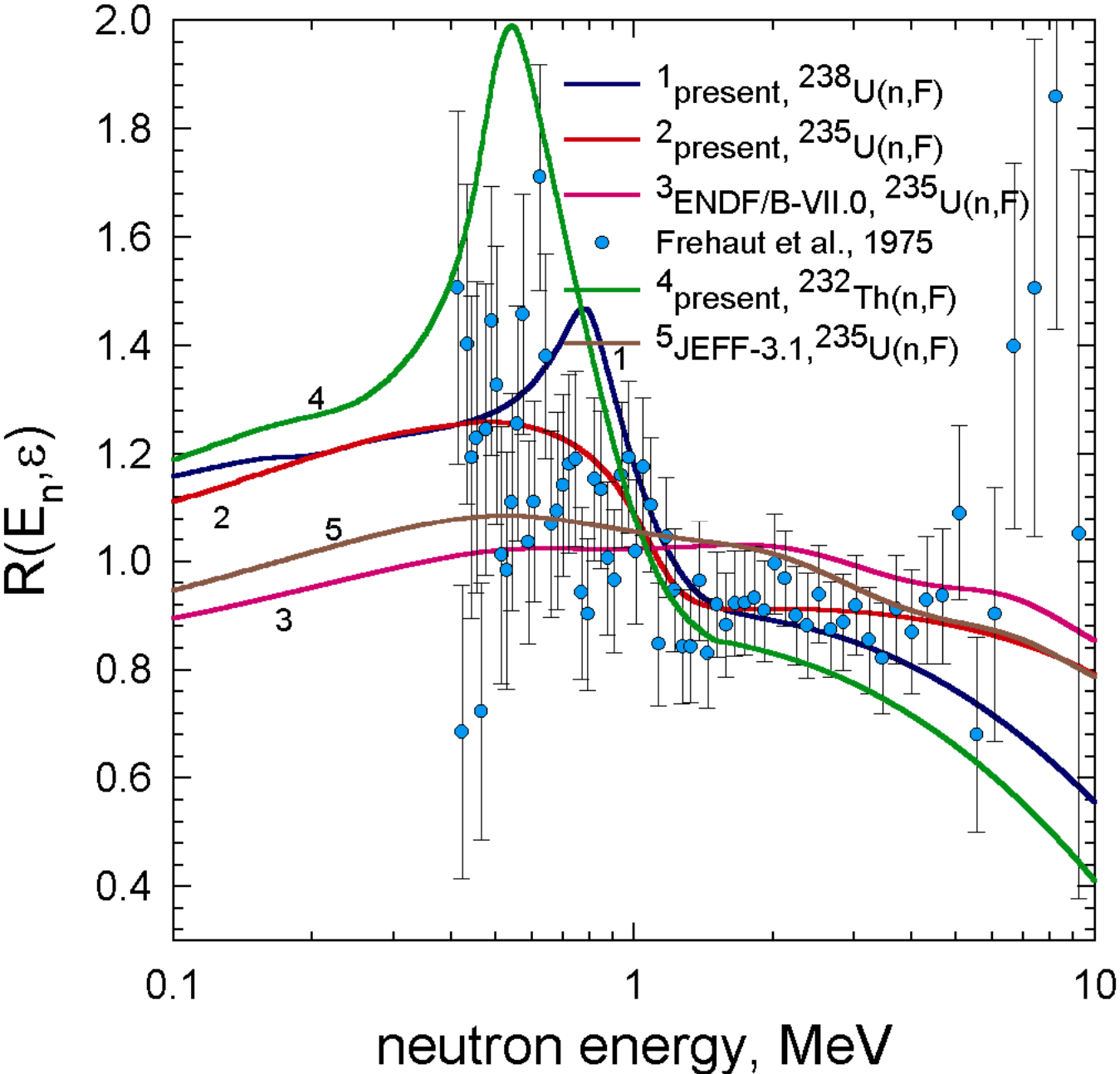


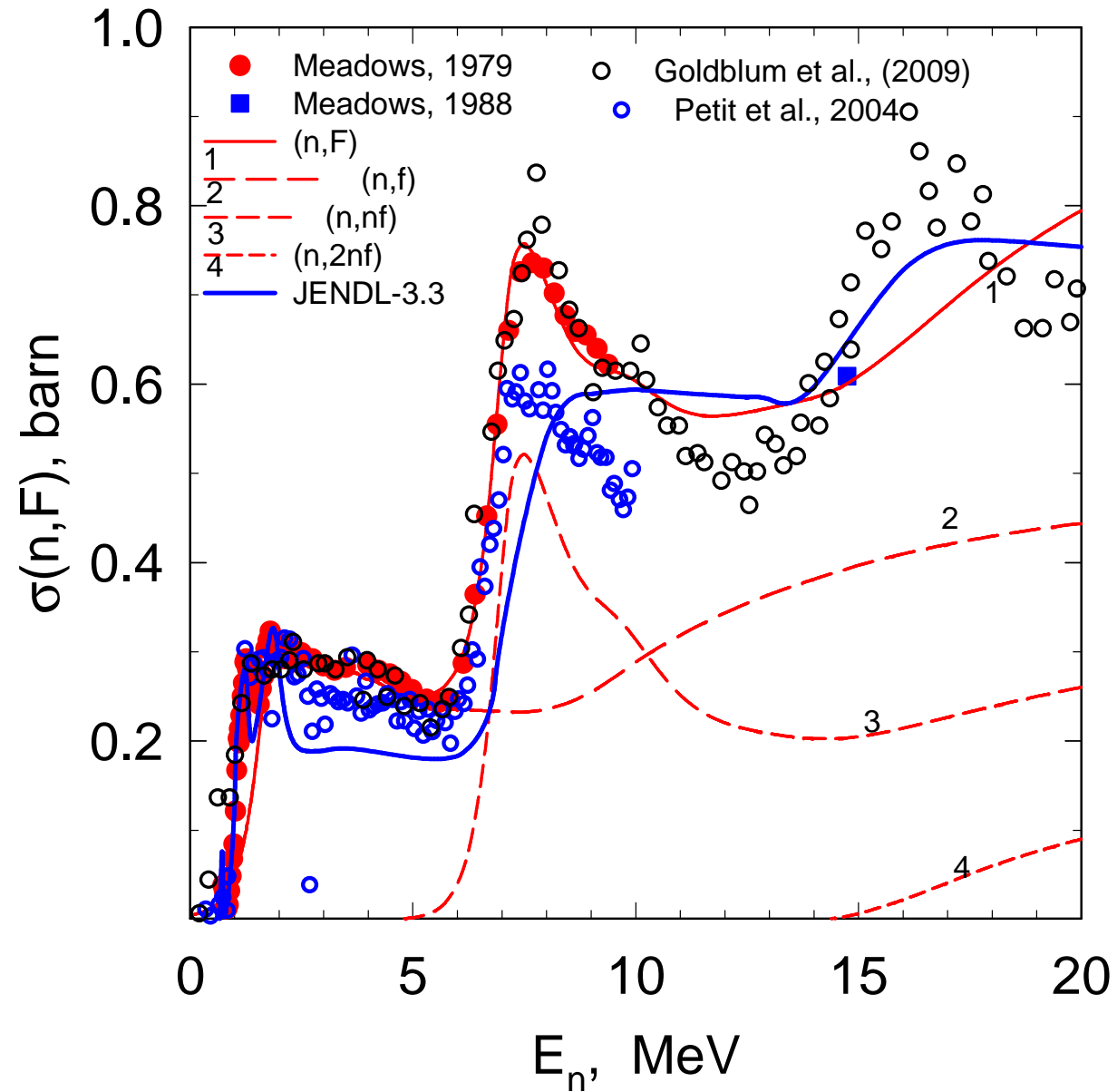
for mass-asym. shapes  
lowering  
of  $K^\pi = 0_1^-$ ,  $K^\pi = 1_1^-$



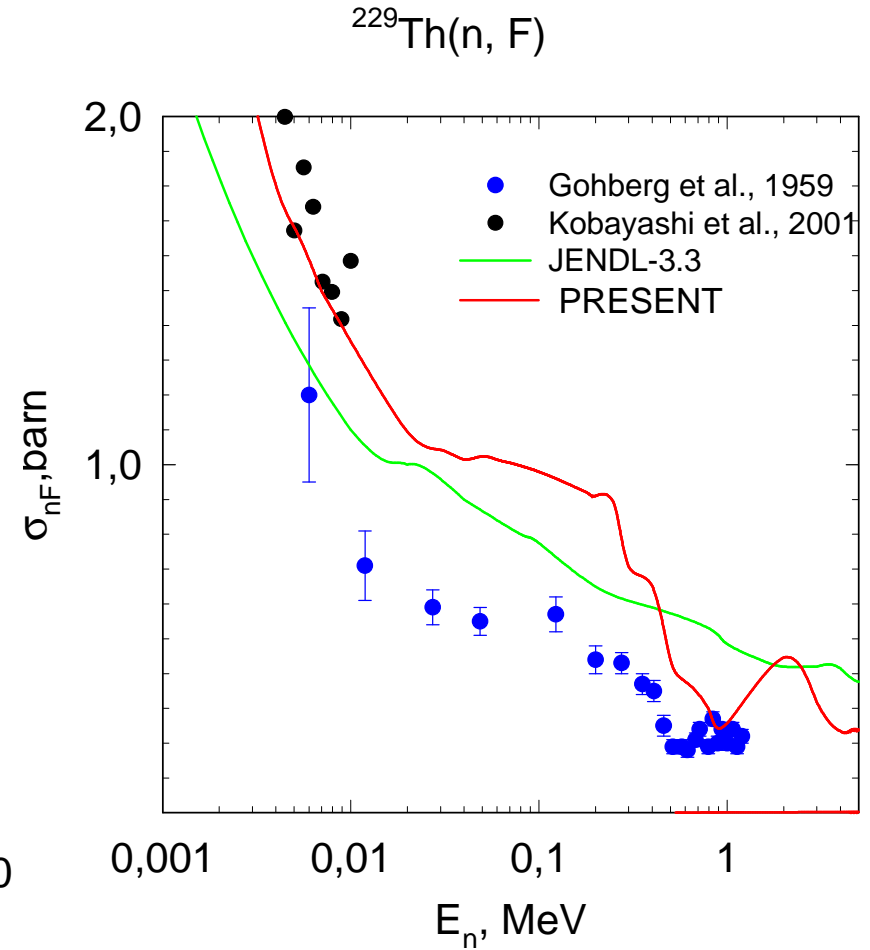
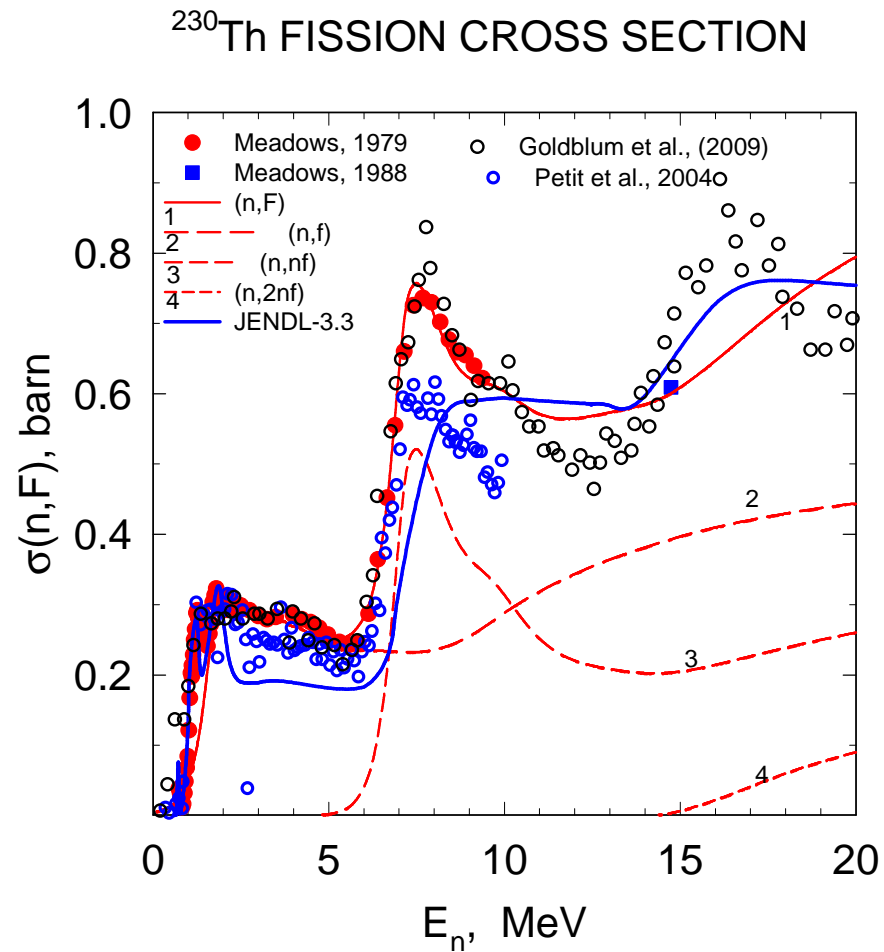


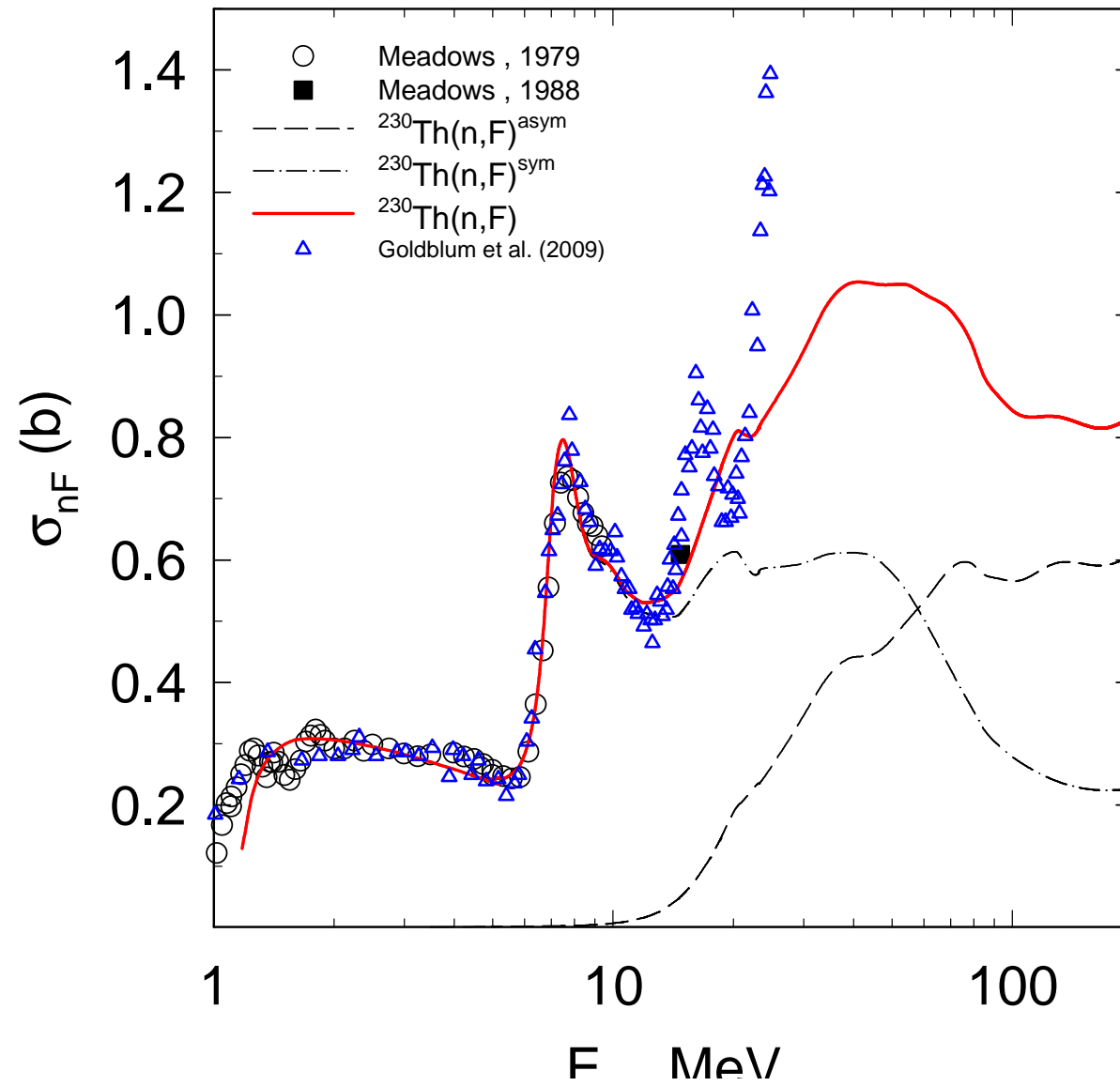
$E_n=7$  MeV  $^{235}\text{U}$

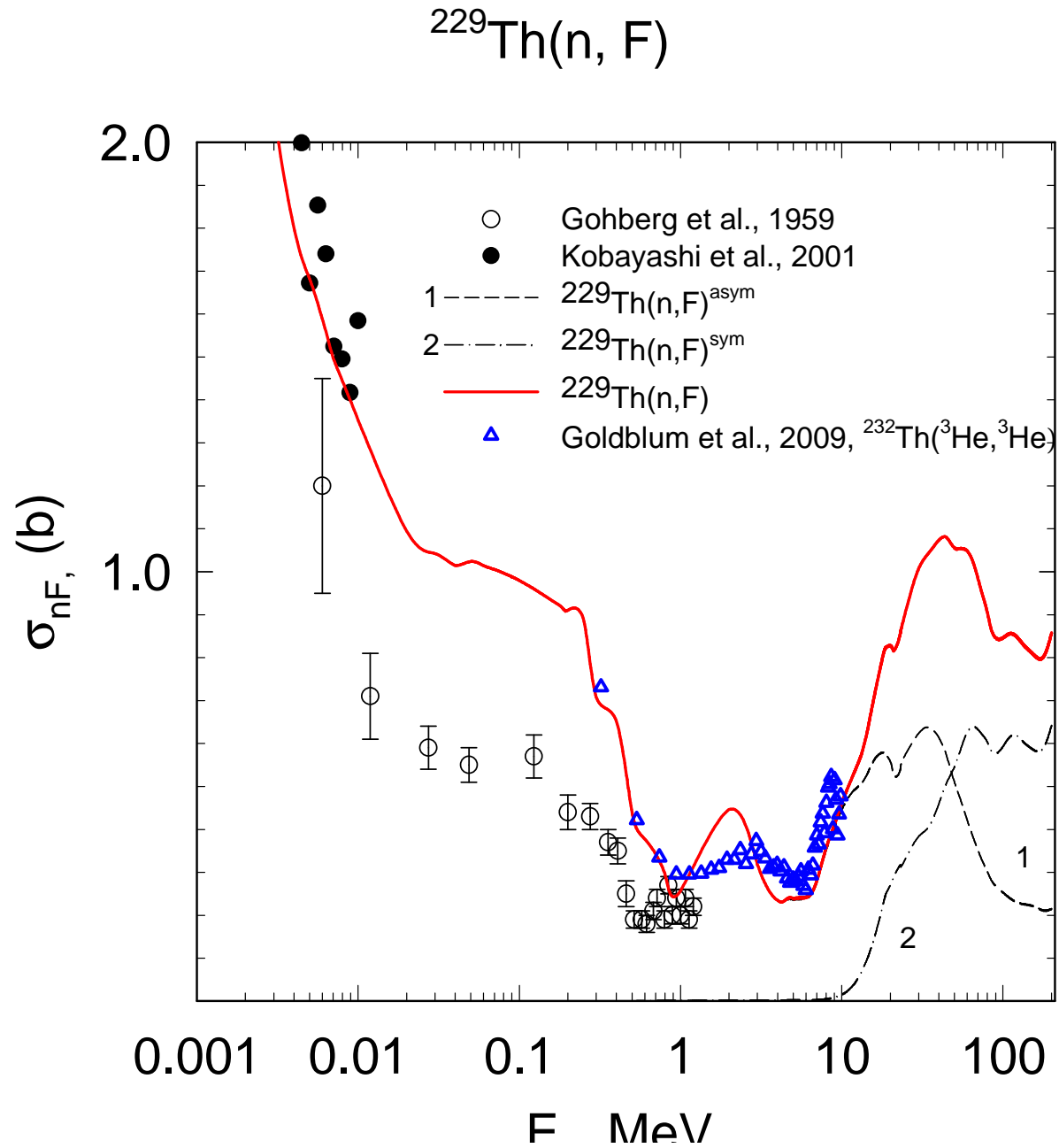


$^{230}\text{Th}$  FISSION CROSS SECTION

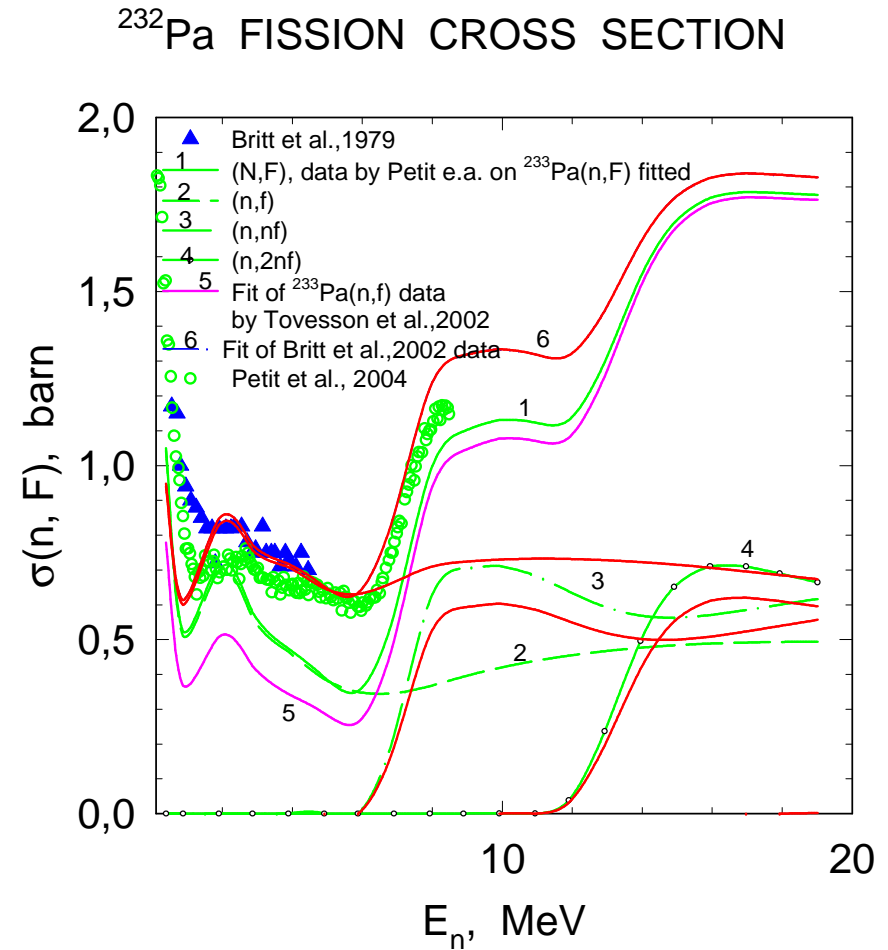
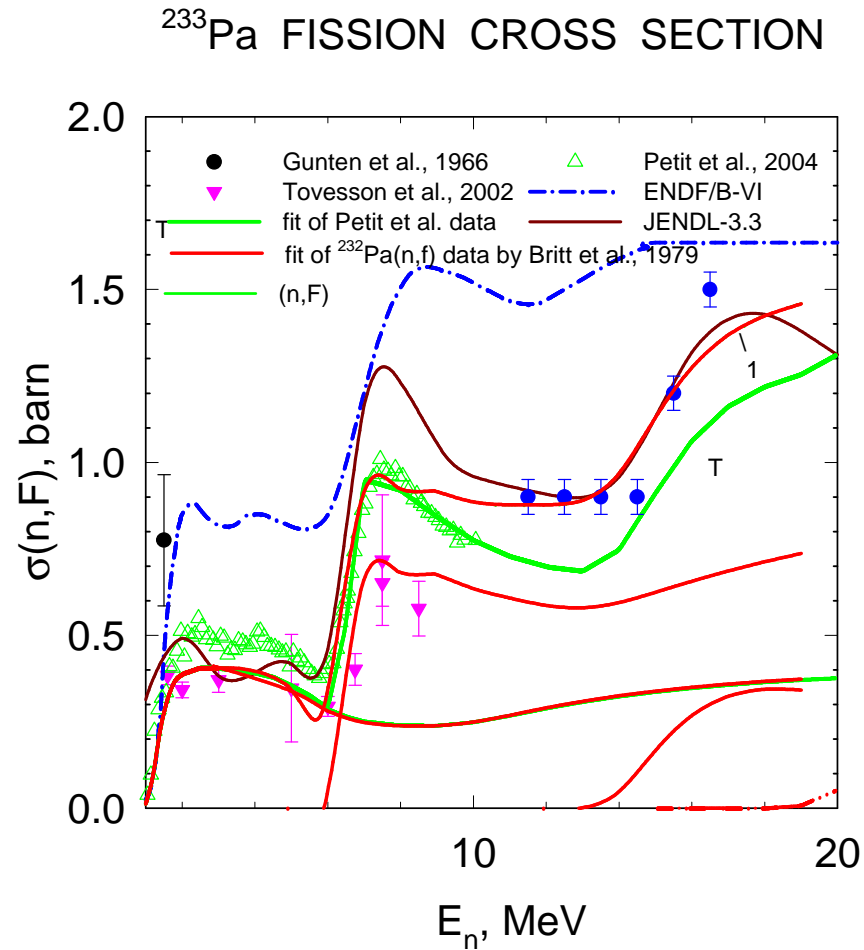
# Surrogate vis. direct data for $^{230}\text{Th}(n,F)$ & $^{229}\text{Th}(n,F)$



$^{230}\text{Th}$  FISSION CROSS SECTION



$^{232}\text{Th}(^6\text{Li}, ^4\text{He})^{234}\text{Pa} / ^{232}\text{Th}(^6\text{Li}, d)^{236}\text{Pa}$  \_Nayak\_ e.a., 2008



# Conclusions

1. **SRD (d,d'f) & ( $\alpha$ ,  $\alpha'$ F) & ( $^{18}\text{O}$ ,  $^{16}\text{O}$ ) for the  $^{237}\text{U}(\text{n}, \text{F})$  &  $^{239}\text{U}(\text{n}, \text{F})$  support present approach (PA).**
2. **Discrepancy of SD and SRD data for  $^{231}\text{Th}(\text{n}, \text{F})$  is of systematic character, SRD is inconsistent with neutron data base.**
3. **SRD data of  $^{232}\text{Th}({}^3\text{He}, {}^4\text{He})^{231}\text{Th}$ , support PA and discard ratio data for the emissive fission domain.**
4. **Importance of fission barrier structure and transition state spectroscopy is demonstrated.**
5. **First-chance fission cs. energy dependence is important.**