IAEA 60 Years
Atoms for Peace and Development

^{238}U evaluation and validation of neutron induced reactions up to 20 MeV

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International Atomic Energy Agency
Department for Nuclear Sciences and Applications

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Thanks to all collaborators who have contributed: Andrej Trkov (IAEA), Mihaela Sin (University of Bucarest, Romania) Michal W. Herman (BNL, USA), Vladimir G. Pronyaev (PI Atomstandard, Russia), Patrick Talou (LANL, USA), Peter Schillebeeckx (EC JRC Geel), Ivan Sirakov (EC JRC Geel), S.Kopecky (EC JRC Geel), D. Bernard (CEA Cadarache, France), G. Noguere (CEA Cadarache, France), A. Daskalakis (RPI, USA) , Y. Danon (RPI, USA)

Special thanks to my collaborators on optical model: E. Soukhovitskii (JINER, Belarus), J. M. Quesada (Universidad de Sevilla, Spain), Satoshi Chiba (TIT, Japan)

Nuclear Data Sheets

Volume 118, April 2014, Pages 1–25

The CIELO Collaboration: Neutron Reactions on ^{1}H, ^{16}O, ^{56}Fe, ^{235,238}U, and ^{239}Pu

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IAEA contributions (files @ www-nds.iaea.org/CIELO)

- Neutron Standards project
- Actinide PFNS Coordinated Research Project
- Technical work for actinide evaluations
  e.g. OMP developments, ^{238}U and ^{235}U evaluations
- Collaboration with BNL on Fe evaluation

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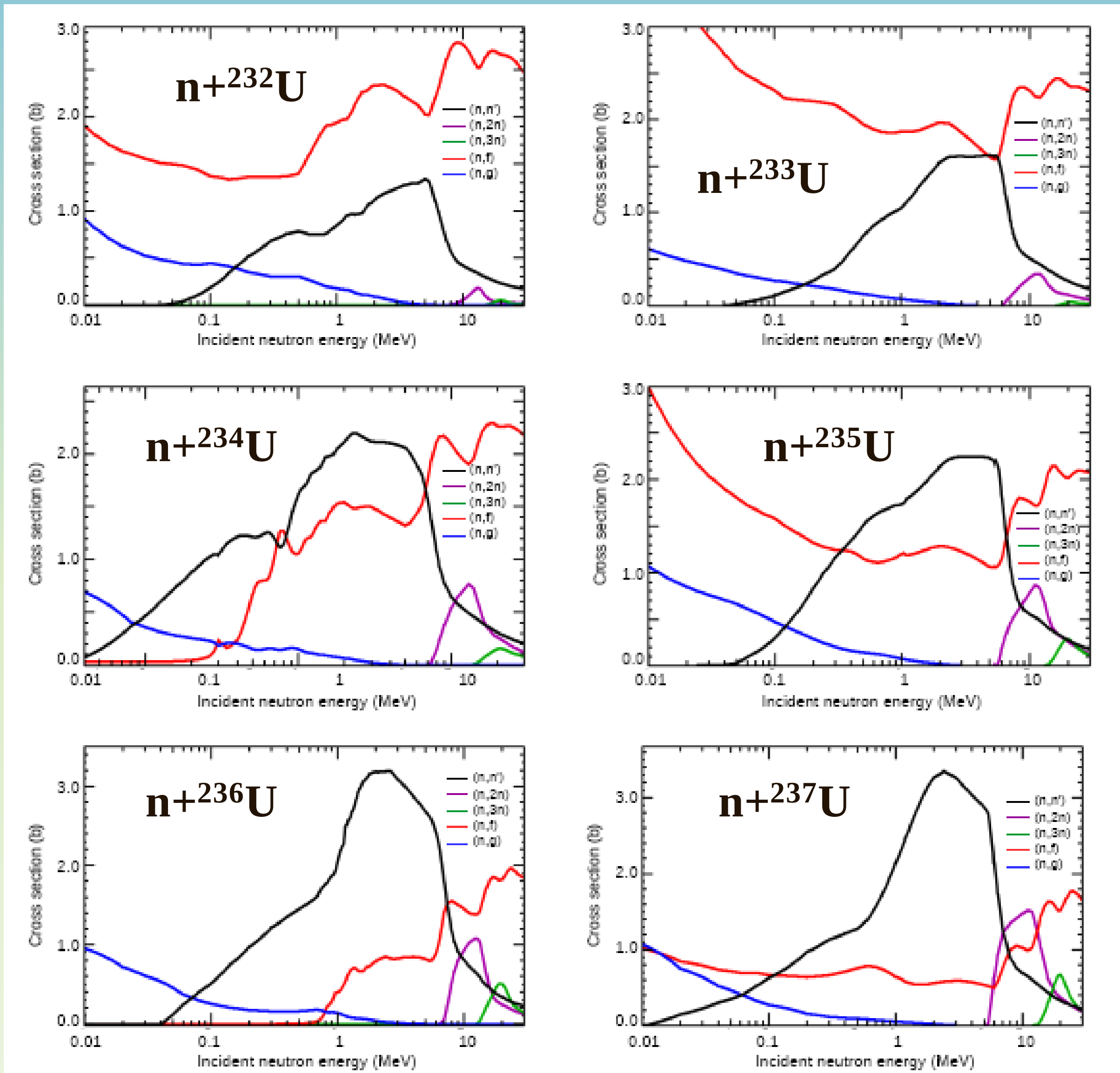
Neutron induced reactions on $^{232\text{-}237}$U



Light isotopes:
(n,f) dominant for all E_n

M. Sin, RC et al, submitted to Nuclear Data Sheets, 08/2016

Heavy isotopes:
(n,n') >> (n,f) > (n,2n) from 100 keV-5 MeV

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Evaluation of n + ^{238}U reaction

RRR (*n*,γ) : Schillebeeckx et al. (R103), E_n<20 keV
URR (*n*,γ) : Schillebeeckx et al. (R103), E_n:20-149 keV

- **(*n*,f), (*n*,γ) from 2006 Neutron Standards**
  to be updated with 2016 Neutron Standards
- **PFNS** adopted from Rising et al, analysis
- **Elastic and inelastic** cross sections based on modelling guided by RPI "quasi-integral" data and integral benchmarks (BIG-10,JEMIMA,Flaptops)
- **(n,2n)** integral benchmark feedback from PROFIL-2(B81) (CEA Cadarache)
- **(n,2n)** TUNL new data (Krishichayan et al)

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IAEA CIELO evaluations vs Wallner AMS

Independent experimental validation

of Neutron Standard fit

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

A. Wallner et al , PRL 2012: 0.391± 0.017 b (4.3%)

✓ **IAEA CIELO: 0.391**

Wallner provided neutron spectra kT ≅ 25 keV

A. Wallner et al, PRL 2012: 0.108±0.004 b (3.7%)

✓ **IAEA CIELO: 0.109**

Wallner provided neutron spectra kT ≅ 426 keV

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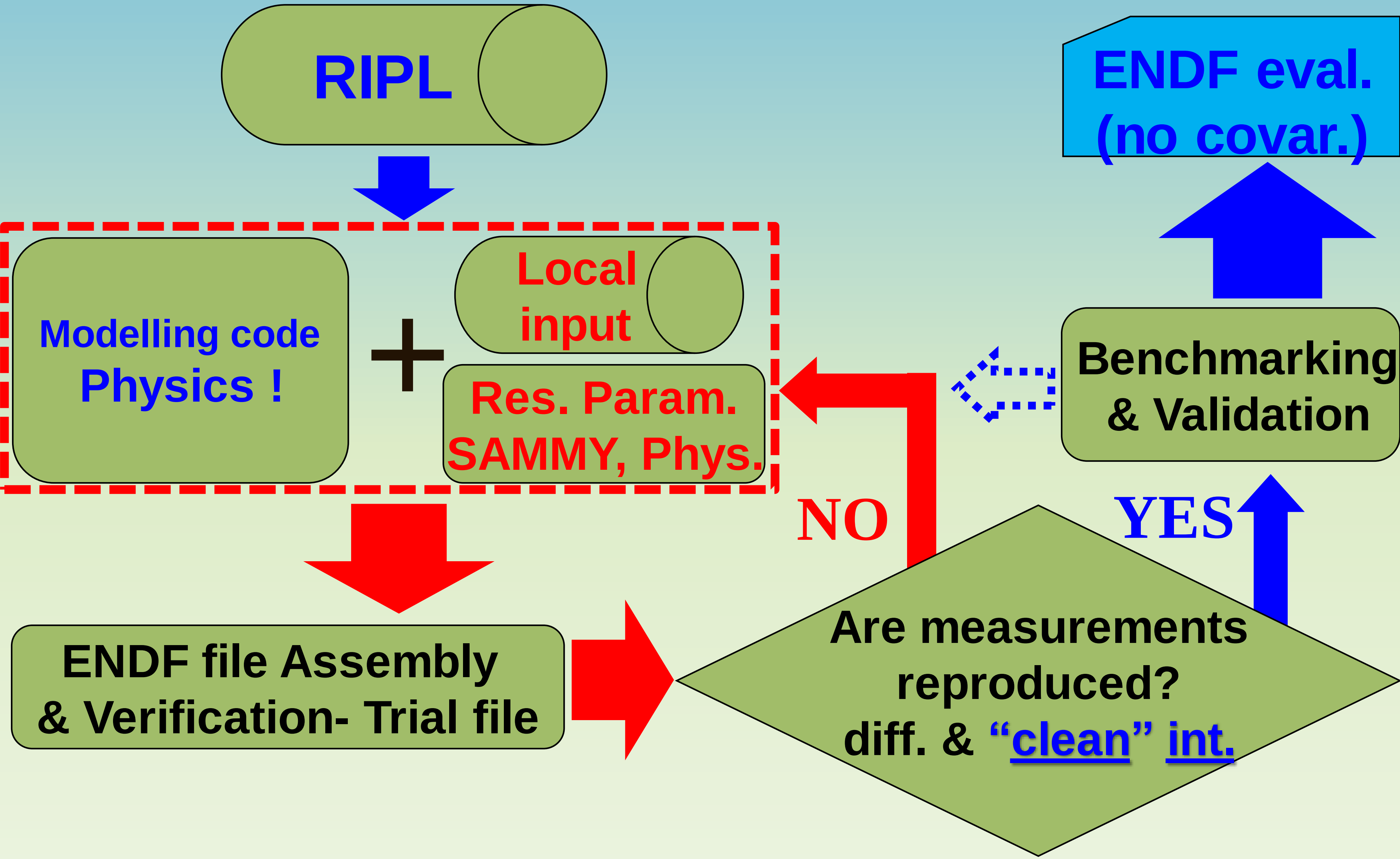
Evaluation process – fast range



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Nuclear Data Sheets **108** (2007) 2655

EMPIRE: Nuclear Reaction Model Code System for Data Evaluation

M. Herman[1,*], R. Capote[2], B.V. Carlson[3], P. Obložinský[1], M. Sin[4], A. Trkov[5], H. Wienke[6], and V. Zerkin[2]
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[2] *Nuclear Data Section, International Atomic Energy Agency, Wagramer Strasse, A-1400 Vienna, Austria*
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[4] *Nuclear Physics Department, Bucharest University, P.O. Box MG-11, Bucharest-Magurele, Romania*
[5] *Jozef Stefan Institute, Reactor Physics Division R-1, Jamova 39, 1000 Ljubljana, Slovenia and*
[6] *Belgonucleaire, Dessel, B2480, Belgium*

+ relevant modelling advances

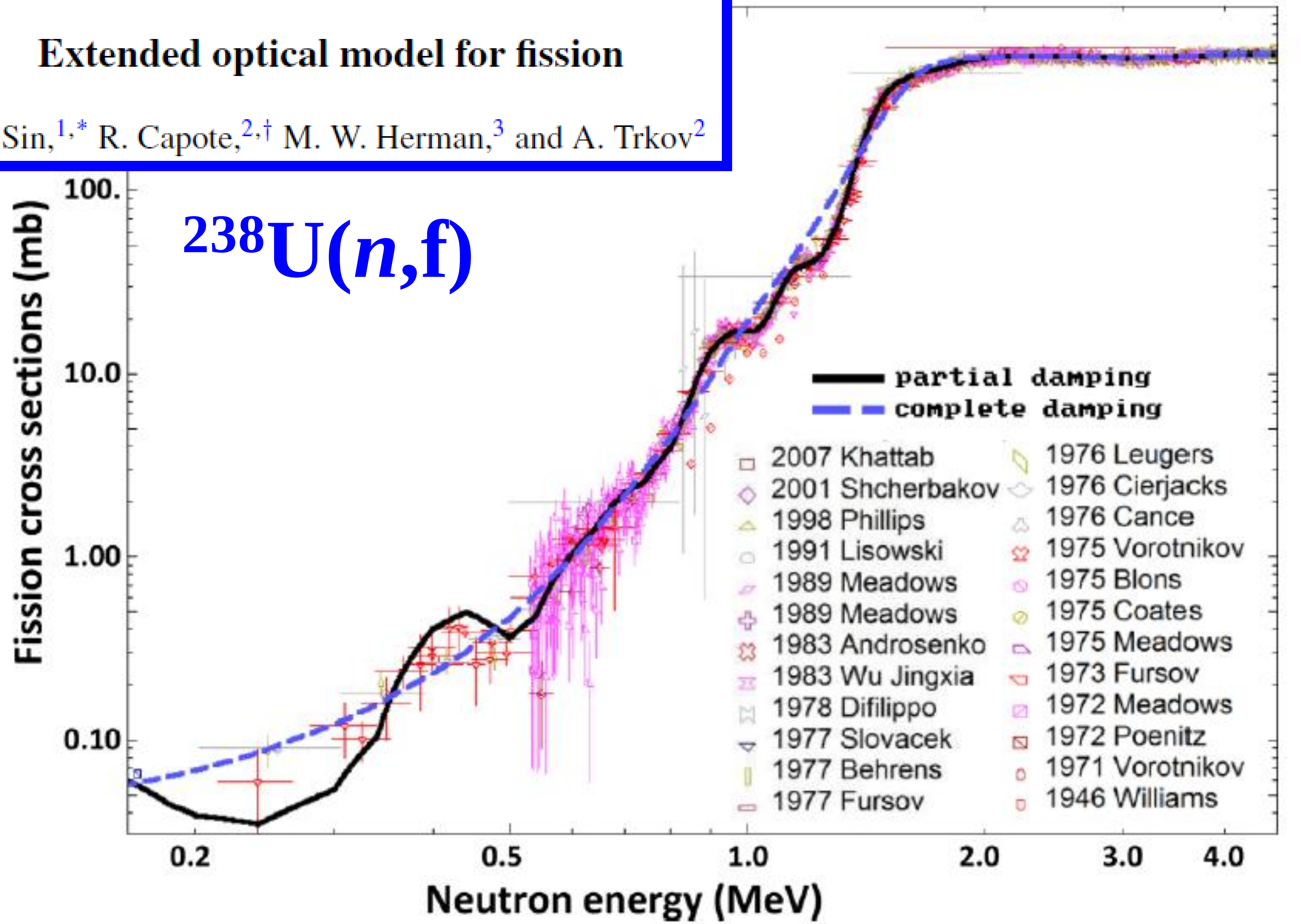
- **Dispersive Lane consistent coupled-channel optical model [1,2] with multiple-band couplings - 21 CC for neutrons, 5 rotational bands + IAS**
- **CN-DIR interference effects [3,4]**
- **neutron elastic and inelastic scattering [5]**
- **extended optical model for fission [6]**

[1] J. M. Quesada, E. Sh. Soukhovitskii, RC, S. Chiba, EPJ Web of Conf. **42**, 02005 (2013).
[2] J. M. Quesada, RC, E. Sh. Soukhovitskii, S. Chiba, Nucl. Data Sheets **118**, 270–272 (2014).
[3] RC, A. Trkov, M. Sin, M. W. Herman, A. Daskalakis, Y. Danon, Nucl. Data Sheets **118**, 26–31 (2014).
[4] T. Kawano, RC, S. Hilaire, P. Chau Huu-Tai, Phys. Rev. C **94**, 014612 (2016).
[5] RC, A. Trkov, M. Sin, M. W. Herman, E. Sh. Soukhovitskii, EPJ Web of Conf. **42**, 00008 (2014).
[6] M. Sin, RC, M. W. Herman, A. Trkov, Phys. Rev. C **93**, 034605 (2016).

PHYSICAL REVIEW C 93, 034605 (2016)

Extended optical model for fission

M. Sin,[1,*] R. Capote,[2,†] M. W. Herman,[3] and A. Trkov[2]



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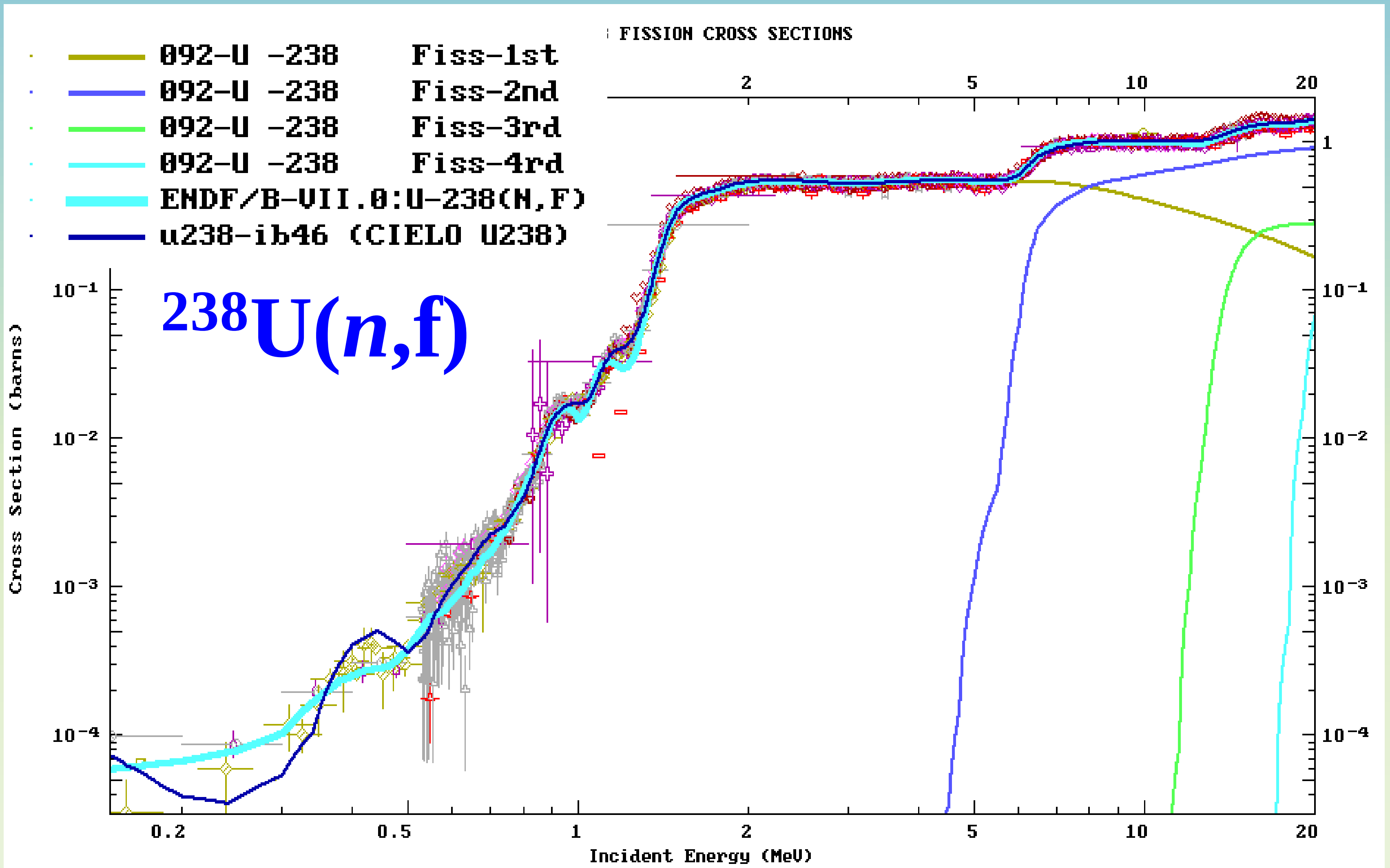
Empire ^{238}U(n,f) vs ENDF/B-VII.1



^{238}U(n,f)-ib46 = (ENDF-B/VII.1 incl. IAEA STD)

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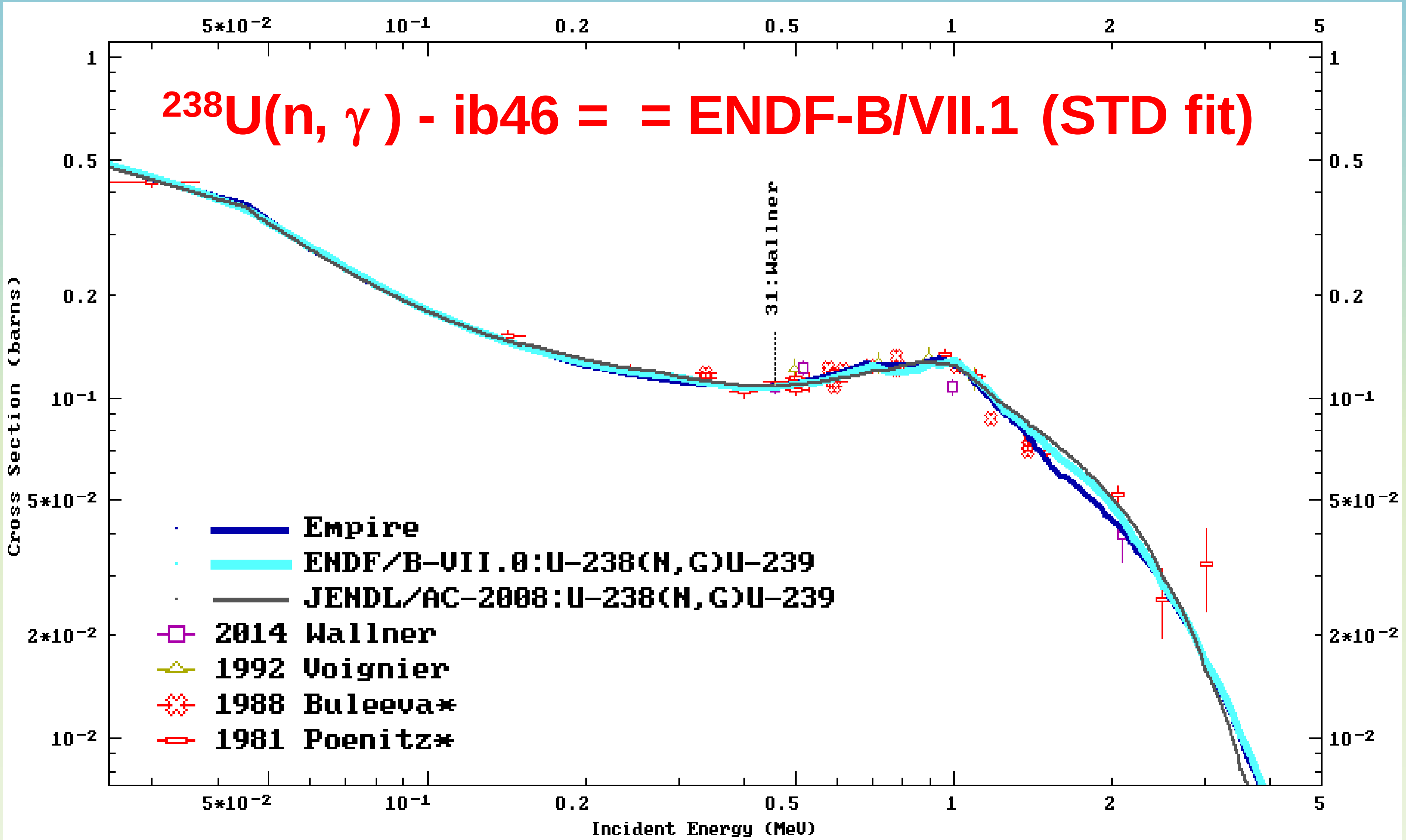
Empire $^{238}U(n,\gamma)$ vs ENDF/B-VII.1



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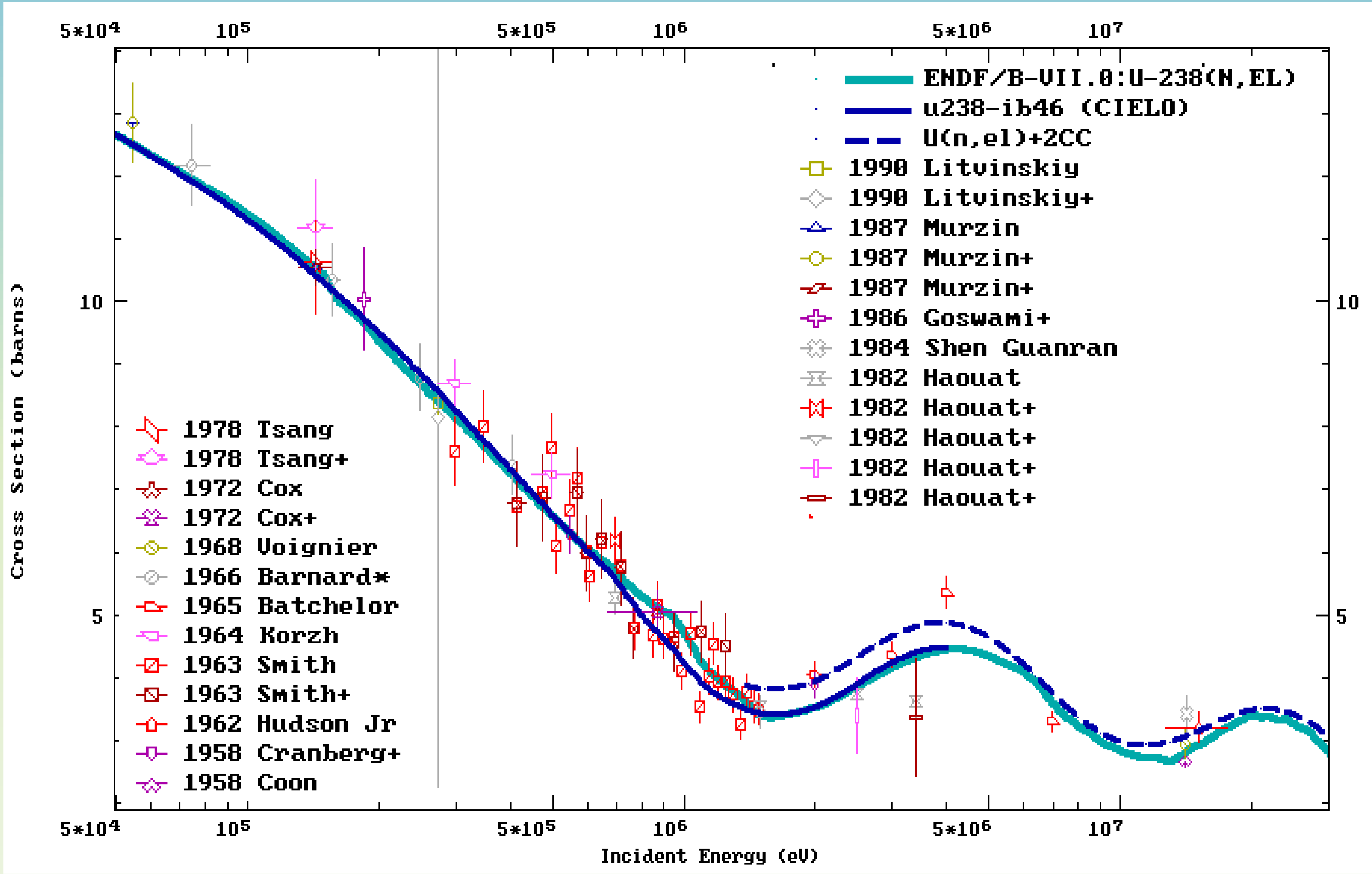
^{238}U(n,el), ^{238}U(n,sct) el+2 inel



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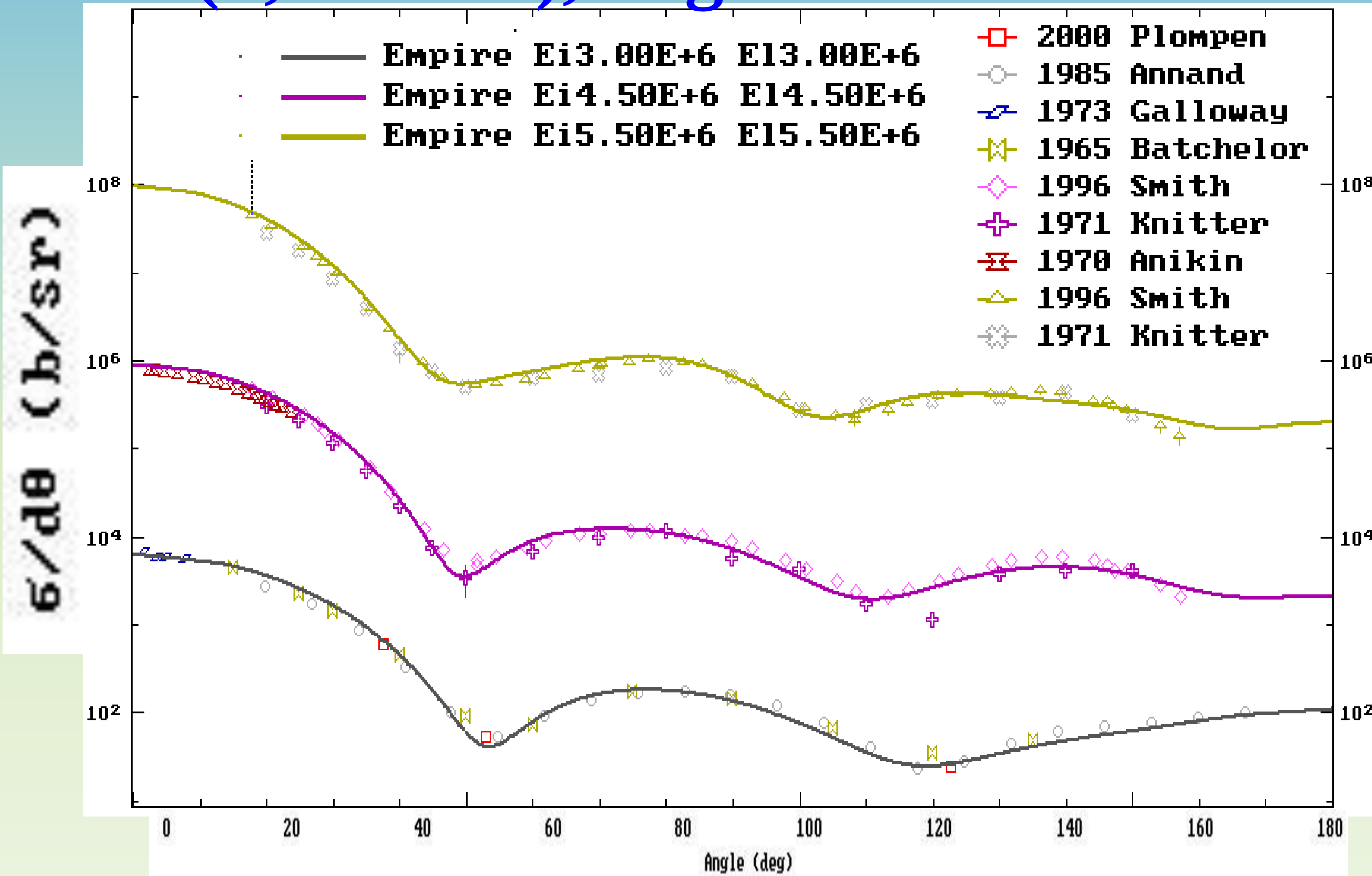
^{238}U(n,el+2CC), angular distributions



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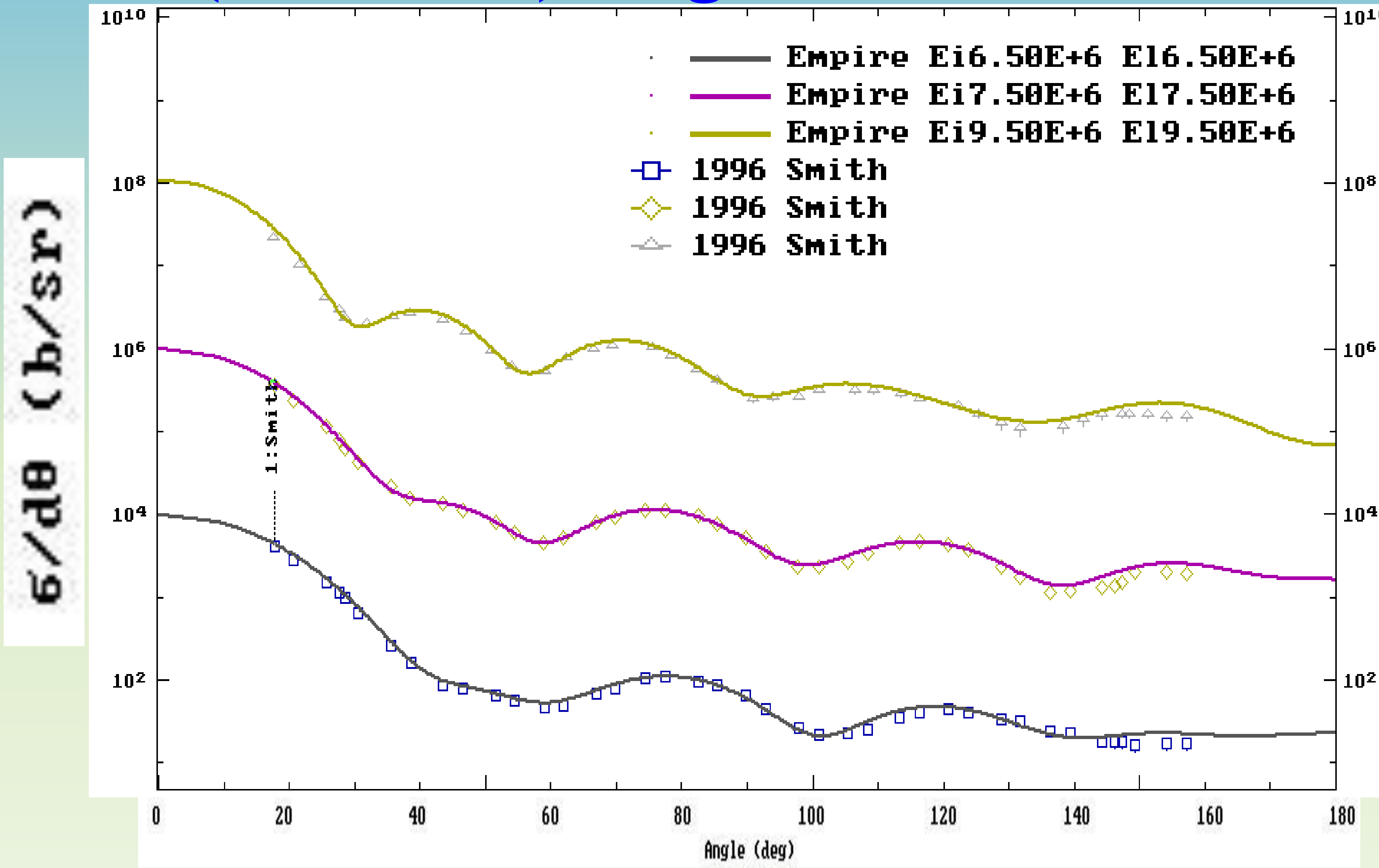
^{238}U(n,el+2CC), angular distributions



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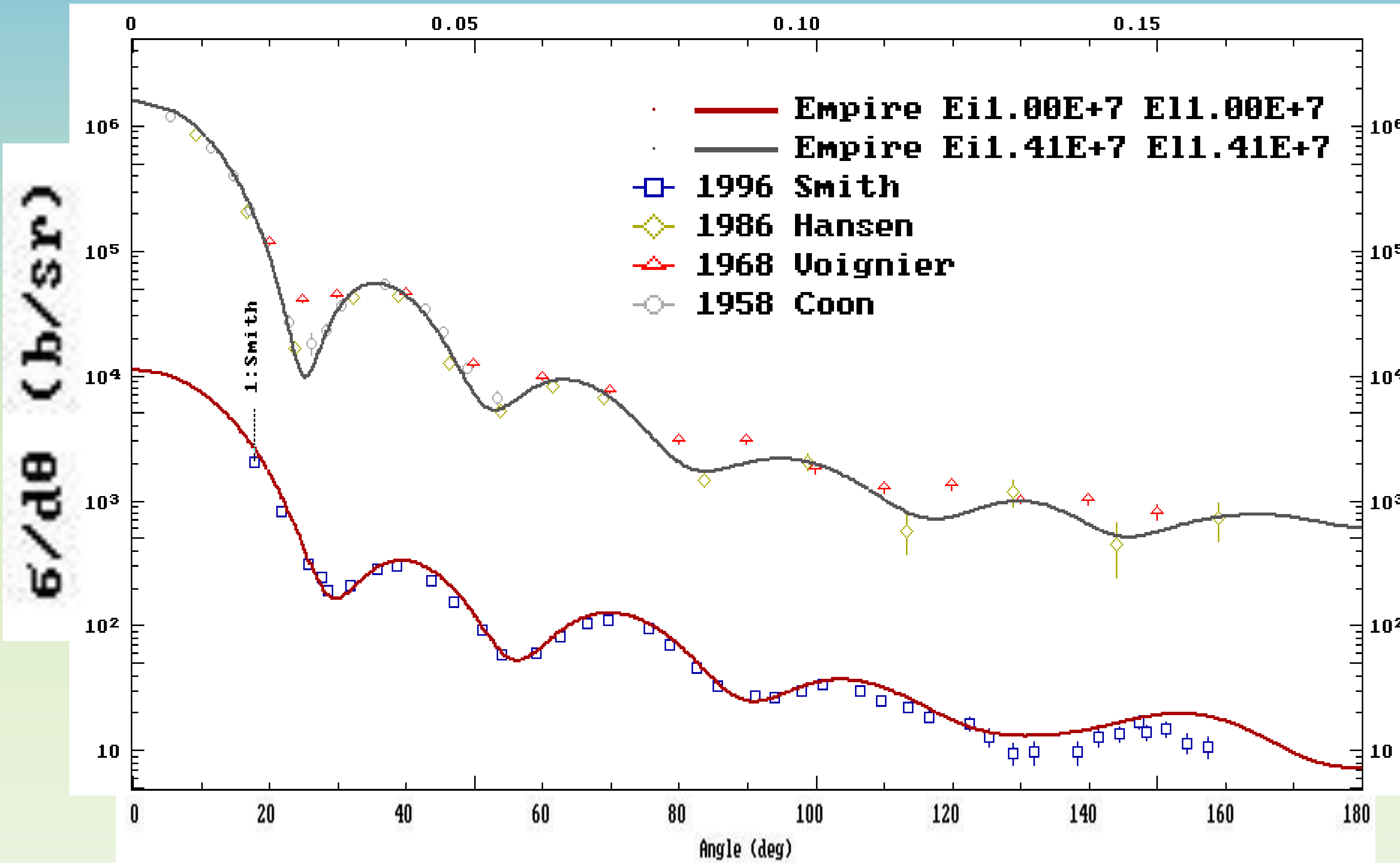
^{238}U(n,el+2CC), angular distributions



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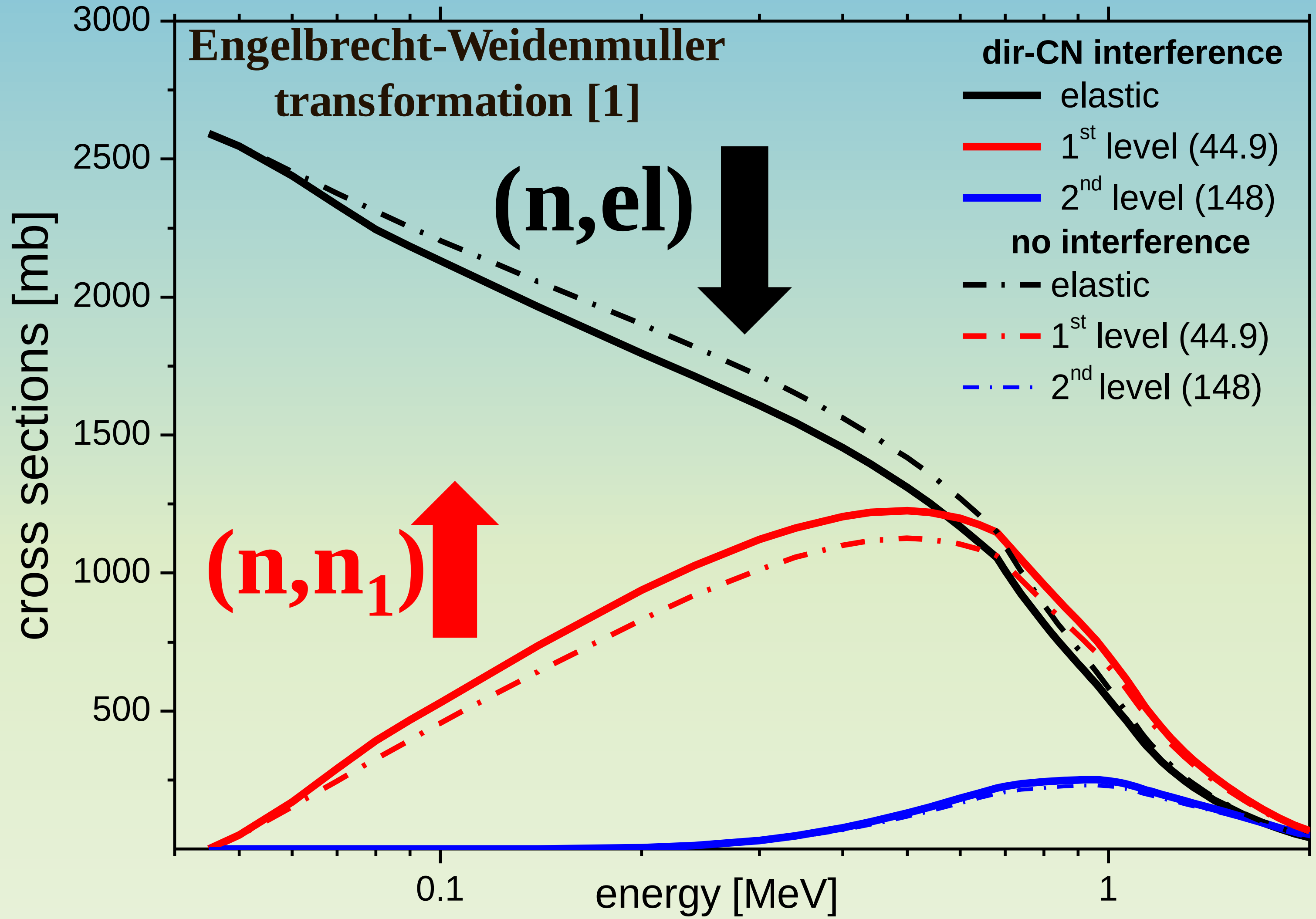
Effects of direct reactions on CN



[1] C.A. Engelbrecht, H.A. Weidenmuller, "Hauser--Feshbach theory and Ericson fluctuations in the presence of direct reactions", Phys.Rev. **C8**, 859-862 (1974).

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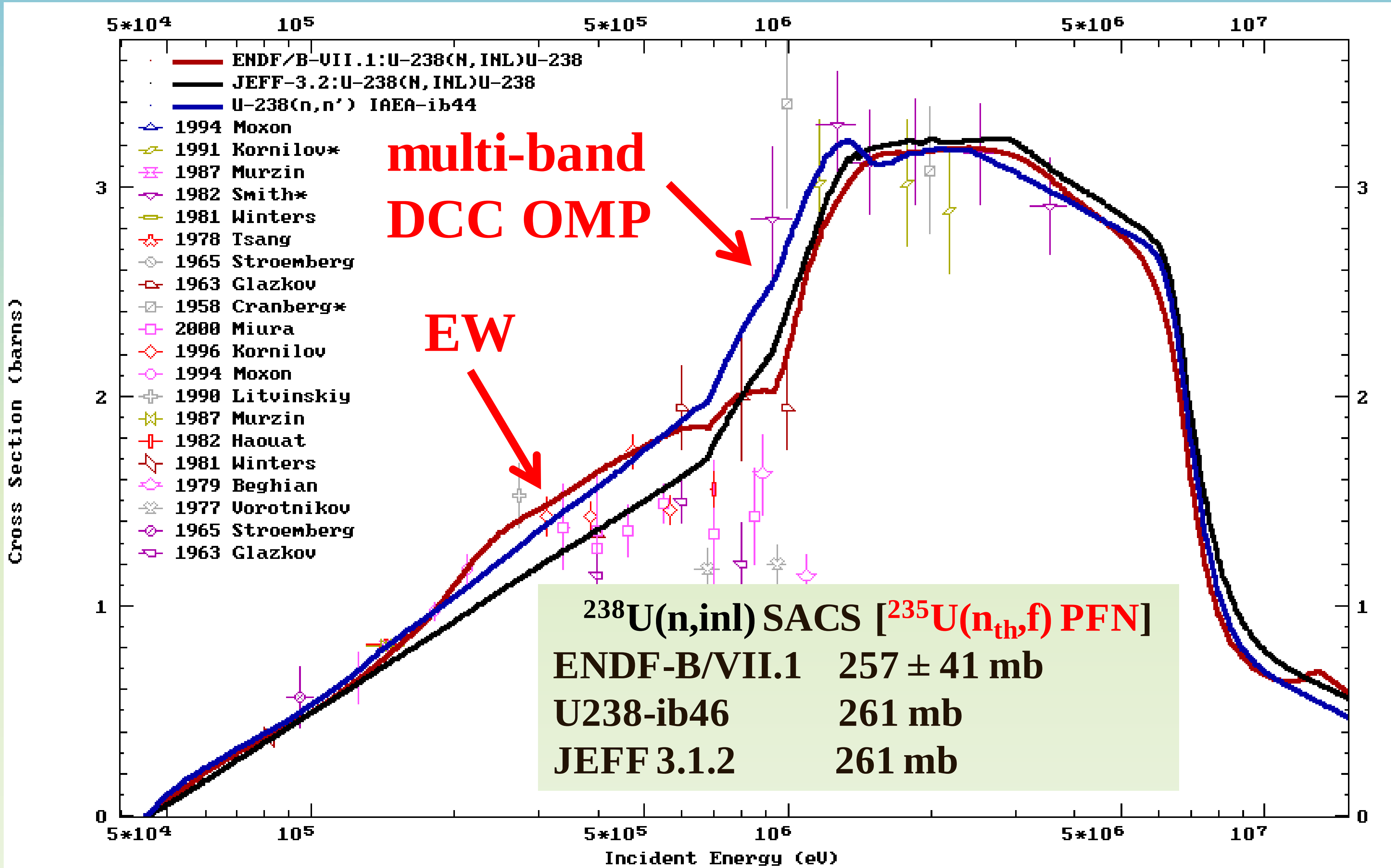
σ(inel), new physics: EW, 21-CC OMP



^{238}U(n,inl) SACS [^{235}U(n_{th},f) PFN]	
ENDF-B/VII.1	257 ± 41 mb
U238-ib46	261 mb
JEFF 3.1.2	261 mb

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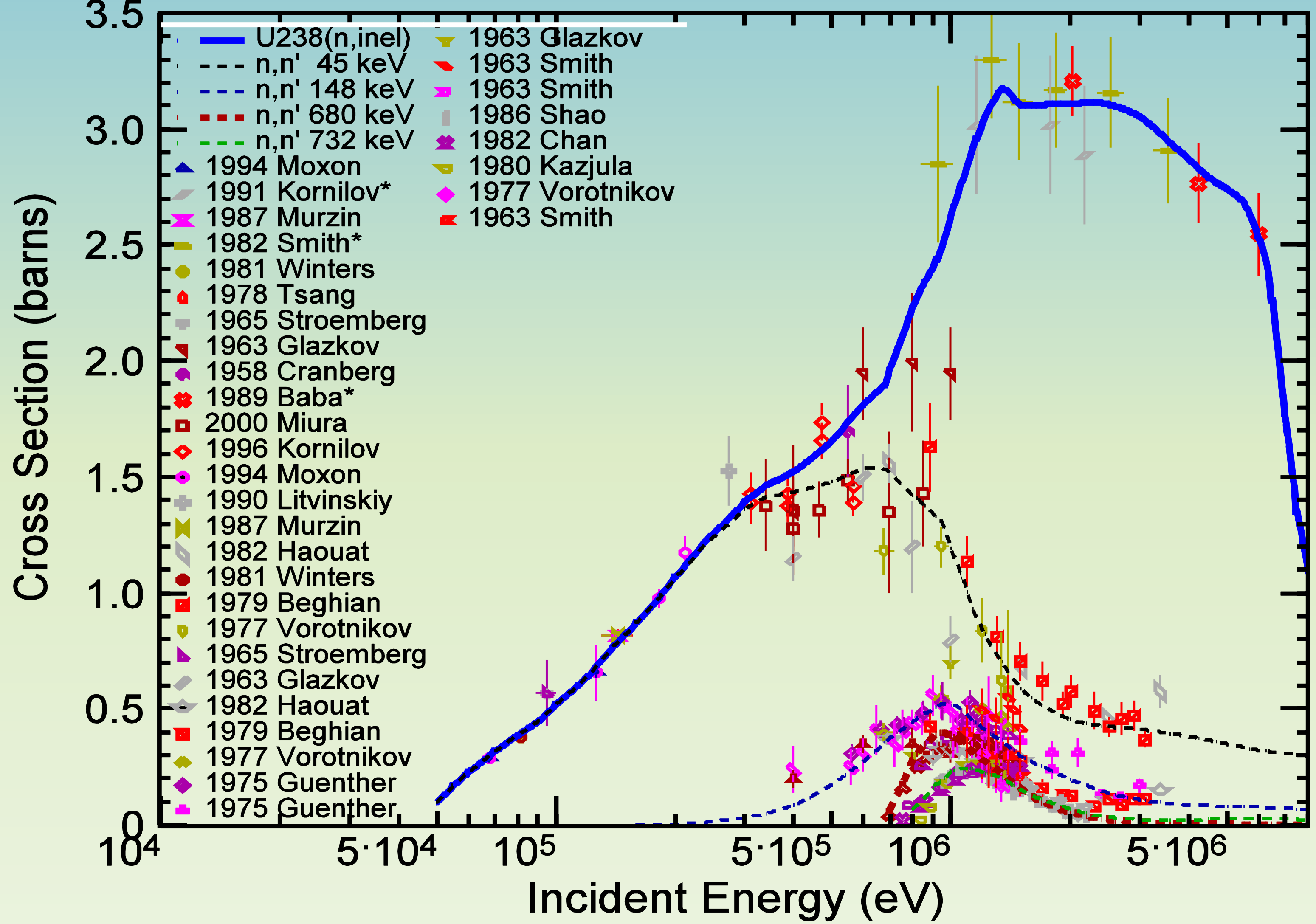
σ_{in}(tot), σ_{in} (2^+), σ_{in} (4^+) , σ_{in} (1^-) , σ_{in} (3^-)...

R. C., M. Sin, A. Trkov, M. W. Herman, D. Bernard, G. Noguere, A. Daskalakis, and Y. Danon.
NEMEA-7 proceedings, NEA SG-40 (2014) "Evaluation of neutron induced reactions on ^{238}U nucleus"



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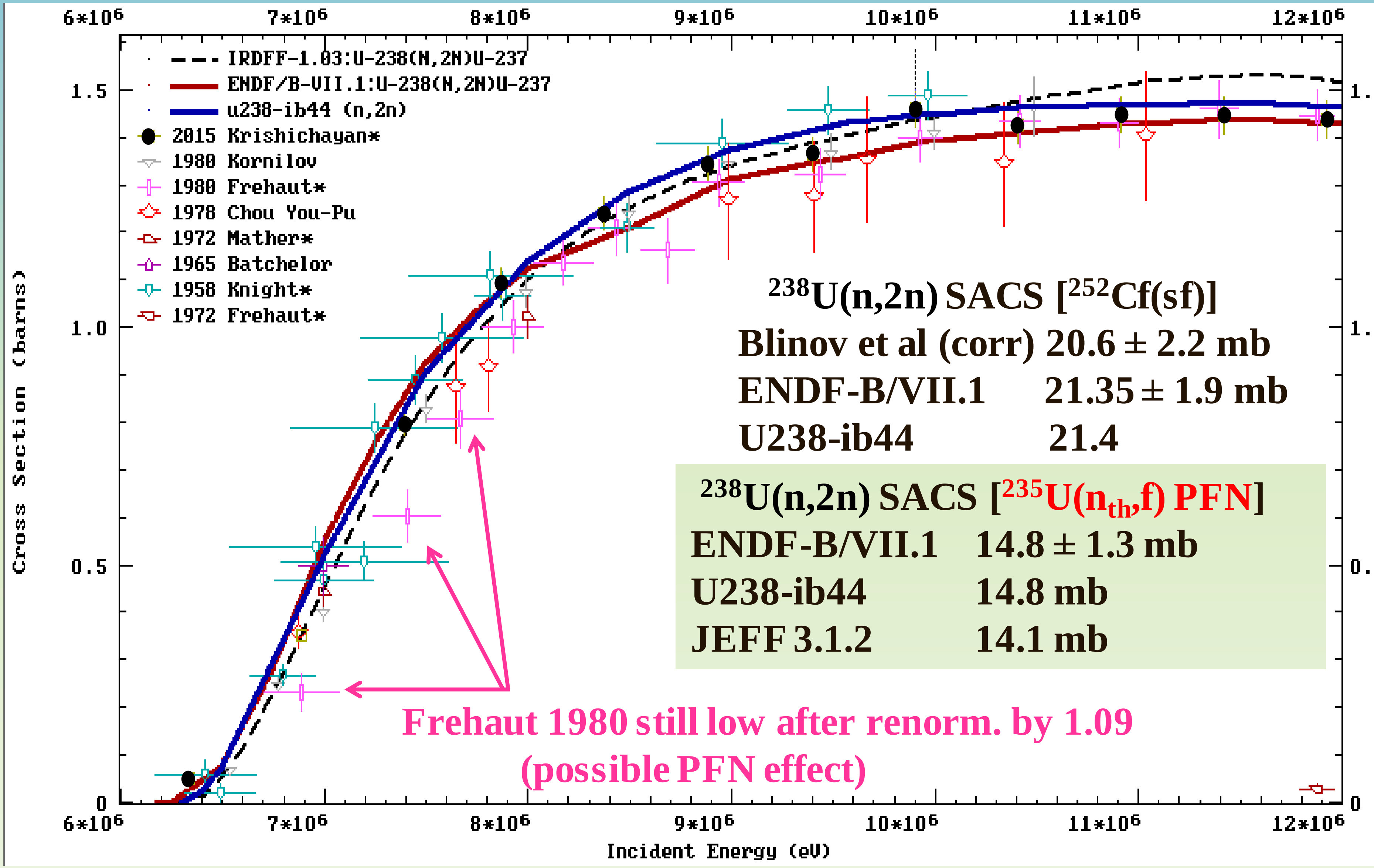
σ(n,2n) vs TUNL and SACS



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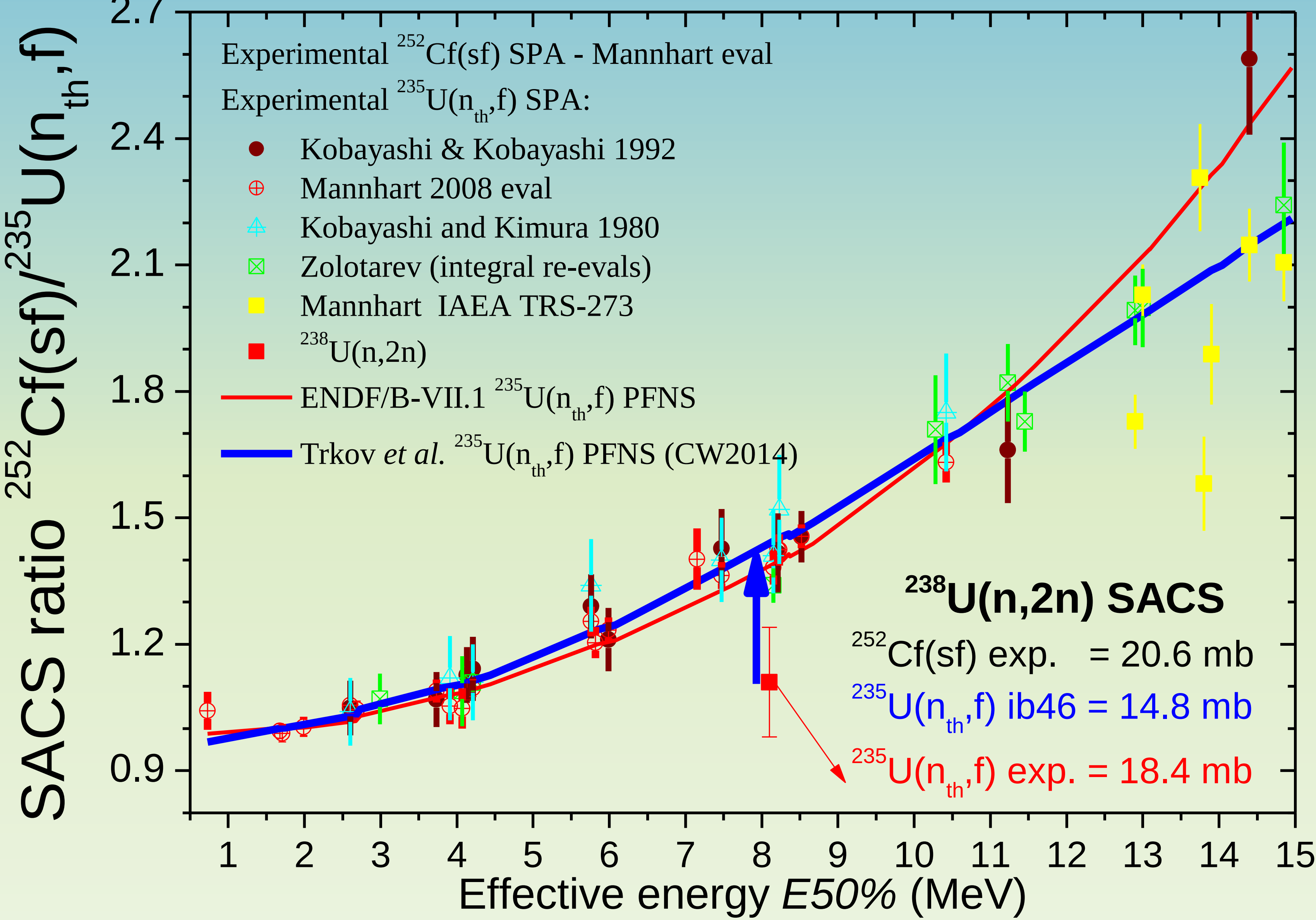
SACS(n,2n) confirmed by SACS ratio syst.



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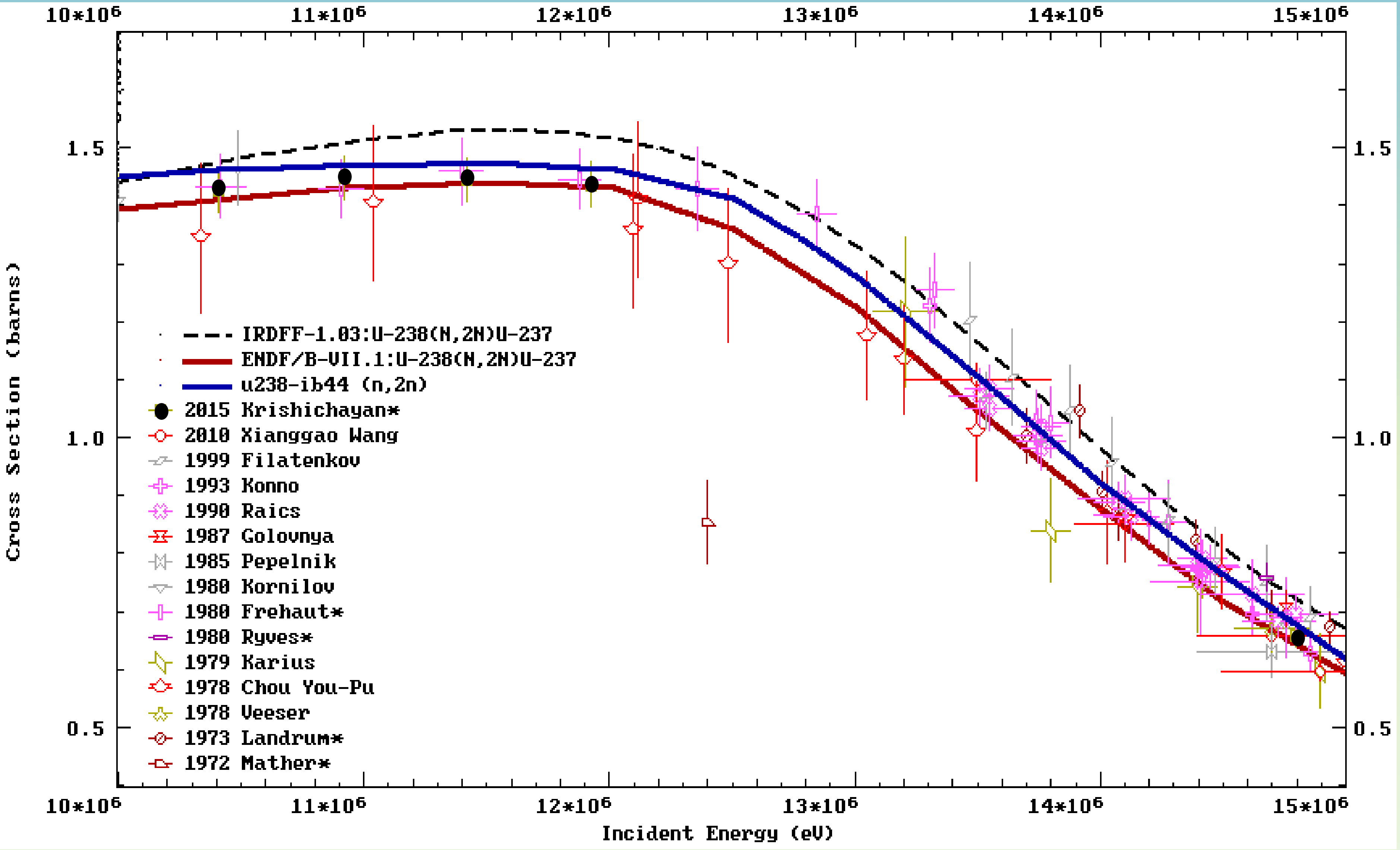
σ(n,2n) vs TUNL (above 10 MeV)



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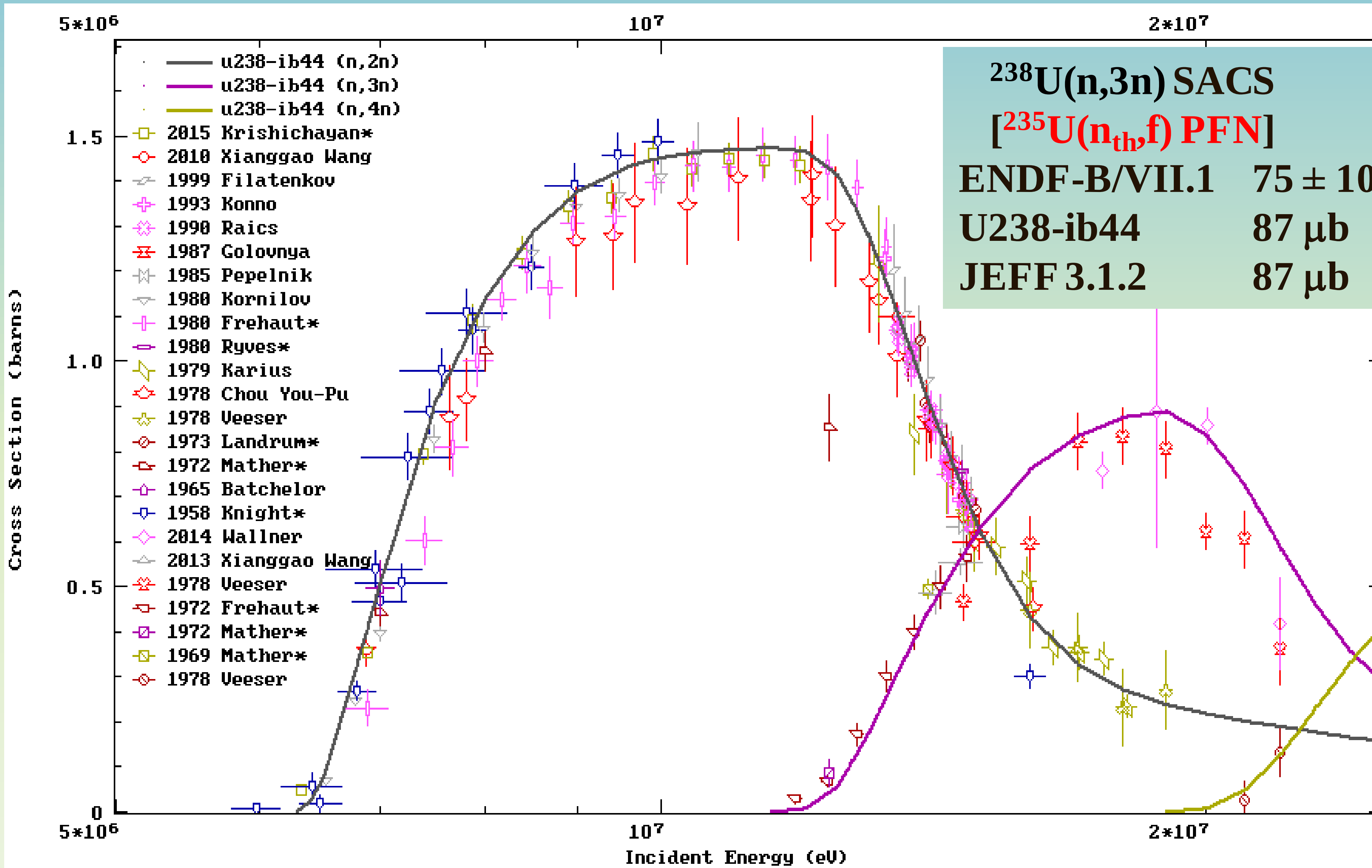
σ(n,2n), σ(n,3n), σ(n,4n)



$^{238}U(n,3n)$ SACS

[$^{235}U(n_{th},f)$ PFN]

ENDF-B/VII.1	75 ± 10 μb
U238-ib44	87 μb
JEFF 3.1.2	87 μb

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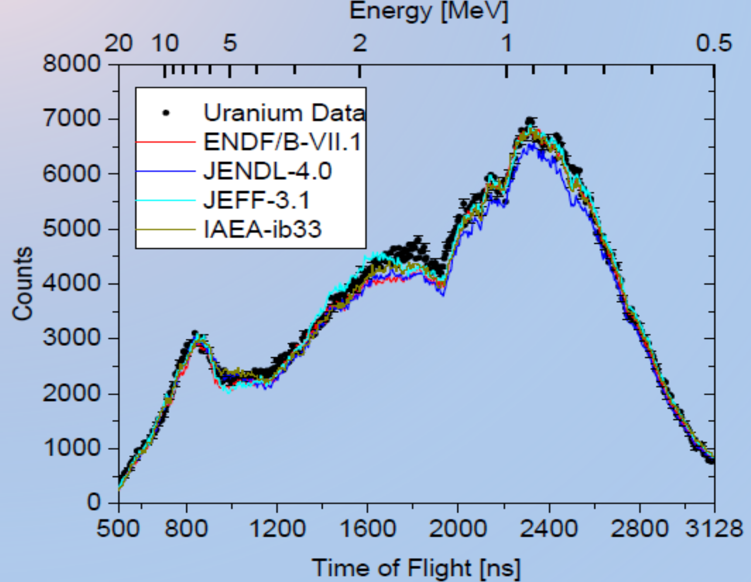
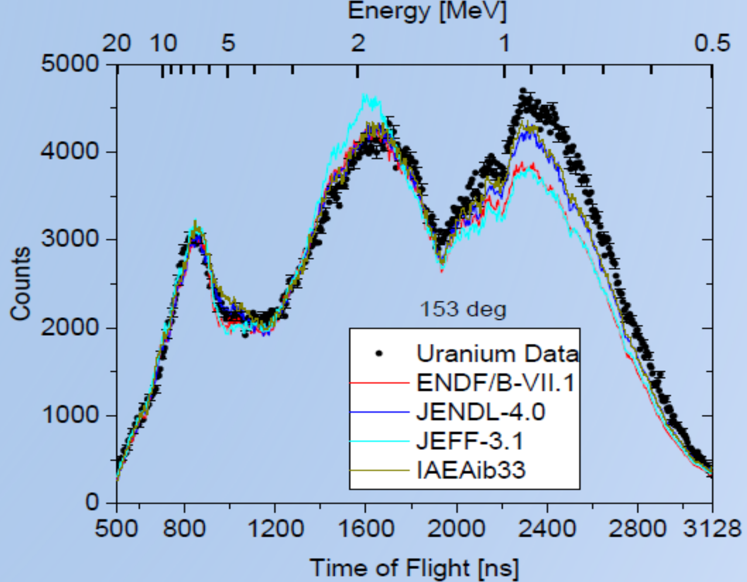
RPI exp. essential to define $d^2\sigma_{el}/dEd\Omega$

^{238}U Scattering Measurement





Library	FOM
ENDF/B-VII.1	3.8
JEFF-3.1	3.0
JENDL-4.0	5.5
IAEA-ib33	3.5

Library	FOM
ENDF/B-VII.1	18.8
JEFF-3.1	20.4
JENDL-4.0	7.7
IAEA-ib33	7.0

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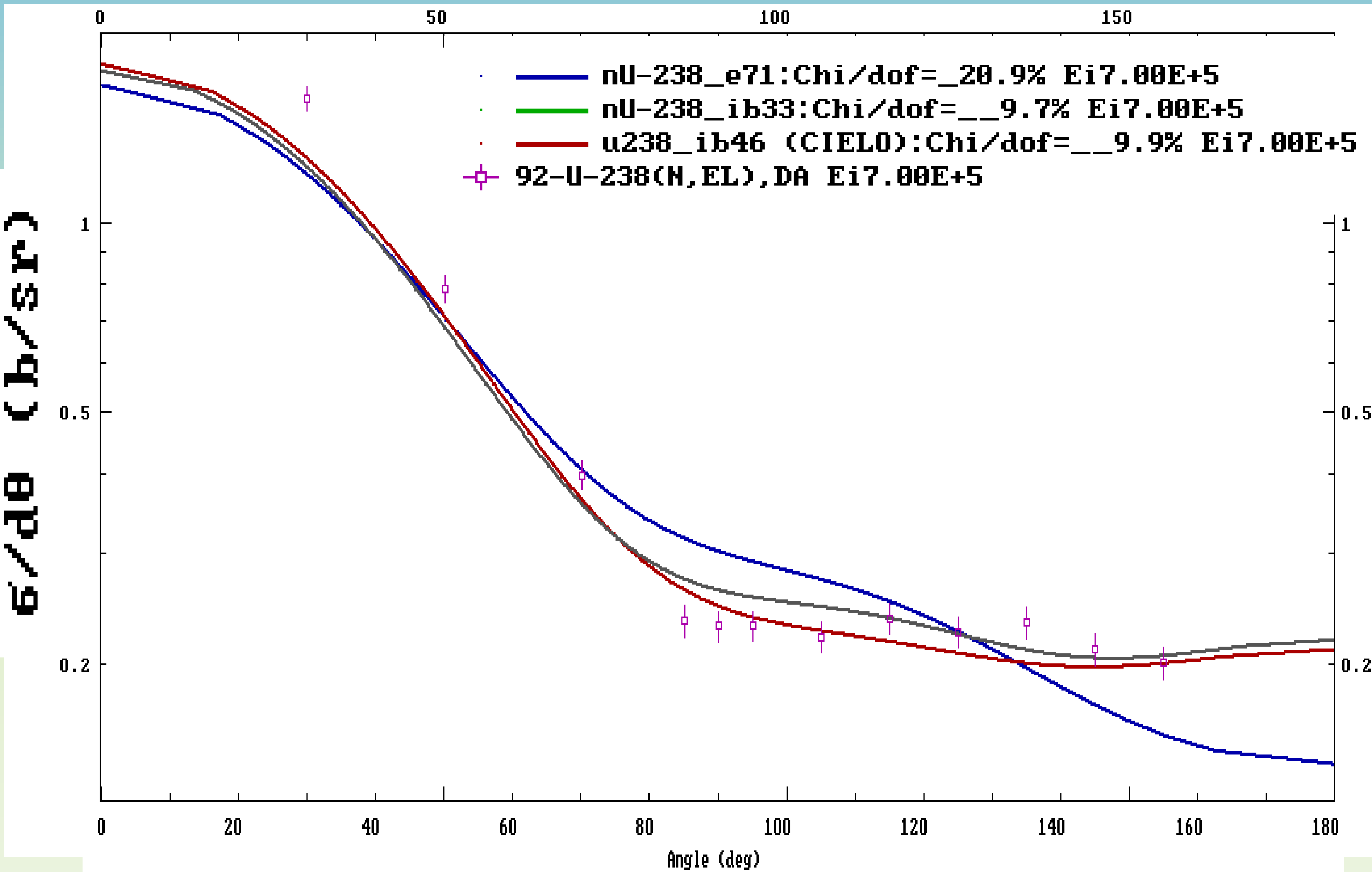
$^{238}U(n,el)$, E_n=700 keV, ang. distributions



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Conclusions: IAEA CIELO ^{238}U file ready

- Resonance range: New measurements and REFIT analysis lead to a better evaluation
- URR also improved by new measurements & evaluation (20-150 keV)
- Capture and fission in fast region from Neutron Standards (GMA fit)
- New GMA fit within STD - (n,γ): excellent agreement with Wallner
- PFNS adopted from Rising et al, 2013 (LAM) for all incident energies
- New fast evaluation with elastic/inelastic improvements
- RPI quasi-diff. data - a big help for fast region scattering
- Better multiple neutron emission (CEA Cadarache feedback, LANL feedback, inelastic + diff. TUNL data)
- Good agreement between B/VII.1 SACS and new evaluations

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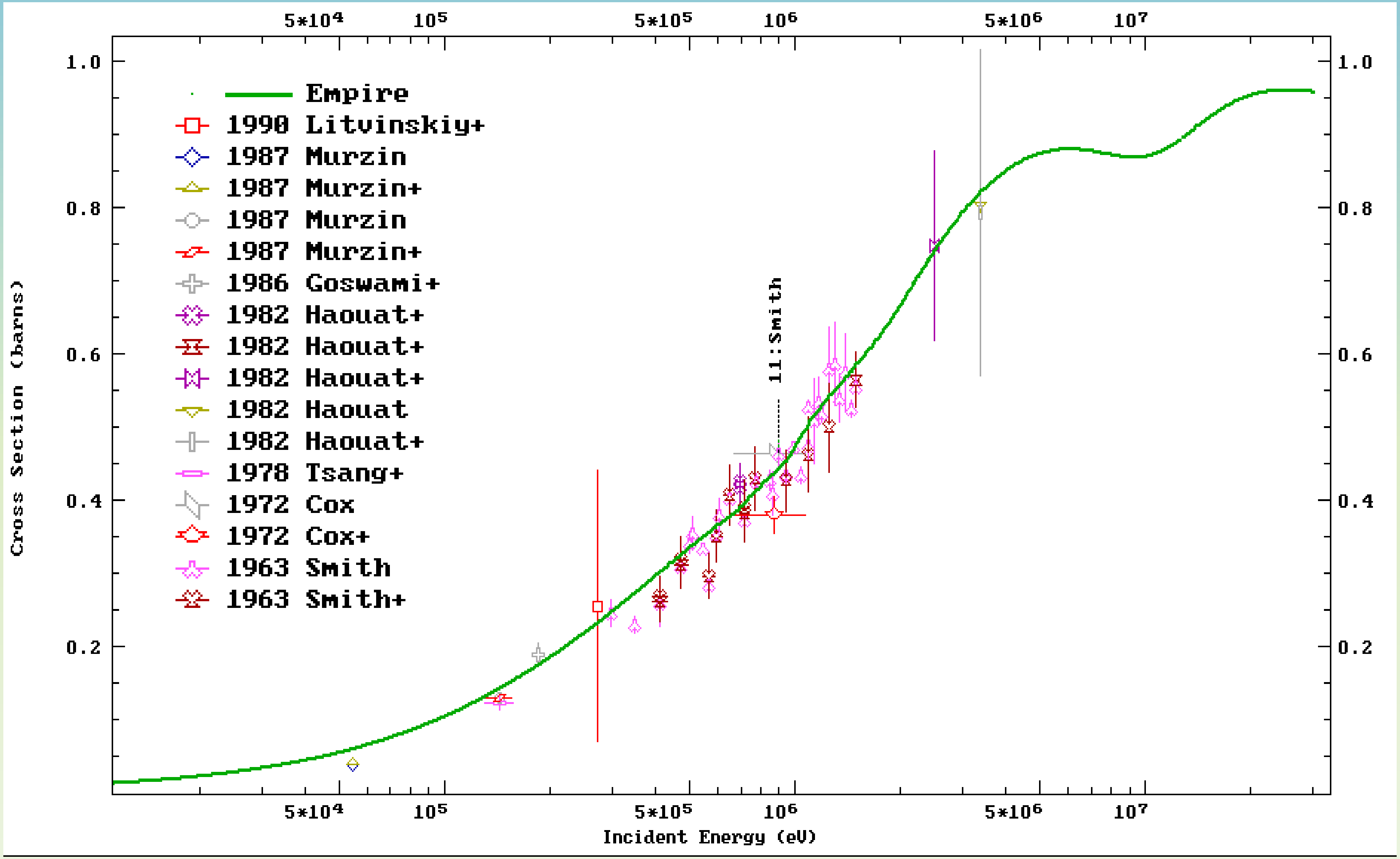
^{238}U elastic μ-bar



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