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TRENDS ON MAJOR ACTINIDES FROM AN INTEGRAL DATA ASSIMILATION

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OUTLINE

I. Context

II. Strategy

III. Integral Data Assimilation

IV. Impact on ASTRID CFV core (BoC)

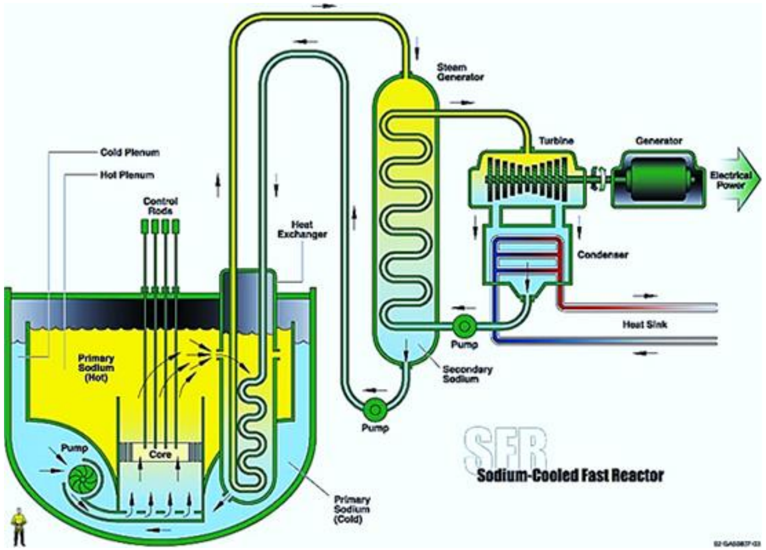
V. Conclusions and Perspectives

I- CONTEXT

ND NEEDS FOR GENERATION IV REACTORS

Five out the six Generation IV concepts are Fast Reactors with **breeding capability (produce Pu out of depleted Uranium) and with the ability to use possibility Pu and MA**, that would otherwise be a waste (Pu from PWR-MOX not suitable for PWR).

- In France, 2006 June 28 act requires the design of a generation of sodium fast reactors, those being the most mature Generation IV concept.



- Nuclear data uncertainties on major actinides as they stand in current nuclear data libraries still do not meet Generation IV core requirements.

ASTRID : NUCLEAR DATA UNCERTAINTY ON CRITICAL MASS

- Uncertainties breakdown (in pcm) on critical mass for the ASTRID core (using **COMACV1** nuclear data covariances) :

Isotope	FISSION	CAPTURE	ELASTIC	INELASTIC	NXN	NU	Fission spectrum	TOTAL
O16	0	110	50	0	0	0	0	120
Na23	0	20	10	10	0	0	0	30
Fe56	0	80	30	50	0	0	0	**100**
U238	439	**869**	30	**649**	30	70	60	**1168**
Pu238	10	20	0	0	0	80	40	100
Pu239	**699**	**190**	10	60	10	100	210	**759**
Pu240	**669**	**300**	0	60	10	20	170	**619**
Pu241	70	90	0	10	0	70	150	200
Pu242	40	50	0	20	0	20	40	80
TOTAL	1069	859	60	649	30	170	320	**1558**

Existing fertile blankets with Uapp induces great sensitivities to U238 XS, notably inelastic.

The use MOx fuel with Pu retrieved from PWR-MOx spent fuel induces high sensitivities not only to Pu239 cross sections but also to other Pu isotopes cross sections (notably Pu240)

II- STRATEGY

PREVIOUS INTEGRAL DATA ASSIMILATIONS

- **Integral data assimilation** has been done with **CARNAVAL IV using the BARAKA approach** (uniform probability law were associated to nuclear data, assuming that most of the problems were coming from normalizations). However, this work resulted in large compensating errors in particular between U238 capture and Pu239 fission.

  →In this work, JEFF3.1.1 for all isotopes with the exception of JEFF3.2 Na23 have been used as a central value of a gaussian probability (COMAC V1 covariances)**.**

- **Integral data assimilation** has been done with **ERALIB1 using gaussian distribution for nuclear data with uncertainties.**
  - ✓ **Approximations** on PFNS, anisotropy, self shielding, etc.
  - ✓ **Nuclear data covariances from expert judgment were used.**
  - ✓ **Numerous experiments were rejected** by assimilation.

  →In this work, reliable experiments have been selected. They are ICSBEP, IRPhE and MASURCA critical masses, PROFIL irradiation experiments and the FCA-IX experimental programme (critical masses and spectral indices).
  →Approximations were marginalized
  → Highly reliable calculation analyses are possible with the use of as-built geometries calculated with the TRIPOLI4 Monte Carlo code.

STRATEGY

- Integral data assimilation can contribute to the nuclear data improvement
- **Parametric studies** have been done so as not be too dependent to the nuclear data **covariance data** that are **still perfectible** or even missing (COMAC V1 used).
- **Marginalization technique** has been **used for light and structural isotopes** for which approximations (anisotropy, secondary neutron energy distribution) in the integral data assimilation technique are rather high.
- **Attention is being given to ways that minimize compensating errors.**
- Compensating errors between U238 capture and Pu239 fission (such as in **CARNAVAL IV**) has been eliminated by using first only U-fueled experiments then adding Pu-fueled experiments.
- A test on whether PFNS needs to fitted or not (such as in **ERALIB1**). It appears that PFNS is a major source of uncertainty and requires to be fitted

CURRENT ASSIMILATION STRATEGY

Nuclear Data evaluations

Associated covariances matrices (COMAC)

Monte-Carlo calculations (TRIPOLI-4)

Deterministic calculations : ECCO/ ERANOS

- **JEFF3.1.1 Na23** (with mistakes) induces R2 and ZONA2 rejection.
- Use of JEFF3.1.1 as prior except for Na23 JEFF3.2
- Use of covariances coming from evaluation processes (COMAC)

$$\frac{C(k_{eff})-E(k_{eff})}{E(keff)}$$

Direct and adjoint ϕ

$$\rightarrow S=\frac{\Delta C / C}{\Delta\sigma / \sigma}$$

$$M_\sigma = \sqrt{S^t D S}$$

Integral data assimilation using Bayesian inference : minimization of a cost function

$$\chi^2_{GLS} = (\sigma-\sigma_{a\ priori})^T M_\sigma^{-1}(\sigma-\sigma_{a\ priori}) + (E - C(\sigma))^T M_E^{-1}(E - C(\sigma))$$

$$\sigma'-\sigma_{a\ priori} = M_\sigma \,.\, S^T(M_E + S.M_\sigma \,.\, S^T)^{-1}.\left(E - C(\sigma_{a\ priori})\right)$$

$$M'_\sigma = M_\sigma - M_\sigma \,.\, S^T(M_E + S.M_\sigma \,.\, S^T)^{-1}\, S.M_\sigma$$

CURRENT ASSIMILATION STRATEGY

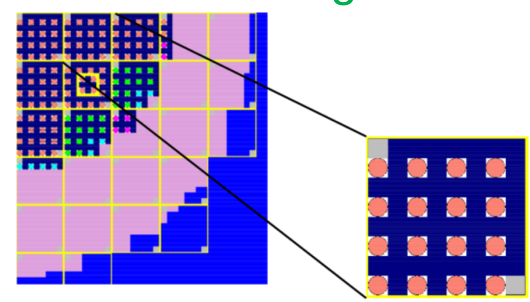
Nuclear Data evaluations

Associated covariances matrices (COMAC)

- Use of TRIPOLI-4 to calculate k_{eff} C/E.
  → Avoid methods bias
- As-built geometry and/or quantified bias
  → No modeling bias

Monte-Carlo calculations (TRIPOLI-4)

Deterministic calculations : ECCO/ ERANOS



$$\frac{C(k_{eff})-E(k_{eff})}{E(keff)}$$

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Integral data assimilation using Bayesian inference : minimization of a cost function

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CURRENT ASSIMILATION STRATEGY

Nuclear Data evaluations

Associated covariances matrices (COMAC)

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Deterministic calculations : ECCO/ ERANOS

$$\frac{C(k_{eff})-E(k_{eff})}{E(keff)}$$

Direct and adjoint ϕ

$$\rightarrow S=\frac{\Delta C/C}{\Delta\sigma/\sigma}$$

Approximations in **sensitivity calculations** :

- We suppose self-shielding factor is not affected.
- Scattering anisotropy and neutron evaporation covariances are missing.

Sensitivity to fission spectra is taken into account.

Integral data assimilation using Bayesian inference : minimization of a cost function

$$\chi^2{}_{GLS} = (\boldsymbol{\sigma}-\boldsymbol{\sigma}_{a\ priori})^T M_{\sigma}^{-1}(\boldsymbol{\sigma}-\boldsymbol{\sigma}_{a\ priori}) + (\boldsymbol{E}-\boldsymbol{C}(\boldsymbol{\sigma}))^T M_E^{-1}(\boldsymbol{E}-\boldsymbol{C}(\boldsymbol{\sigma}))$$

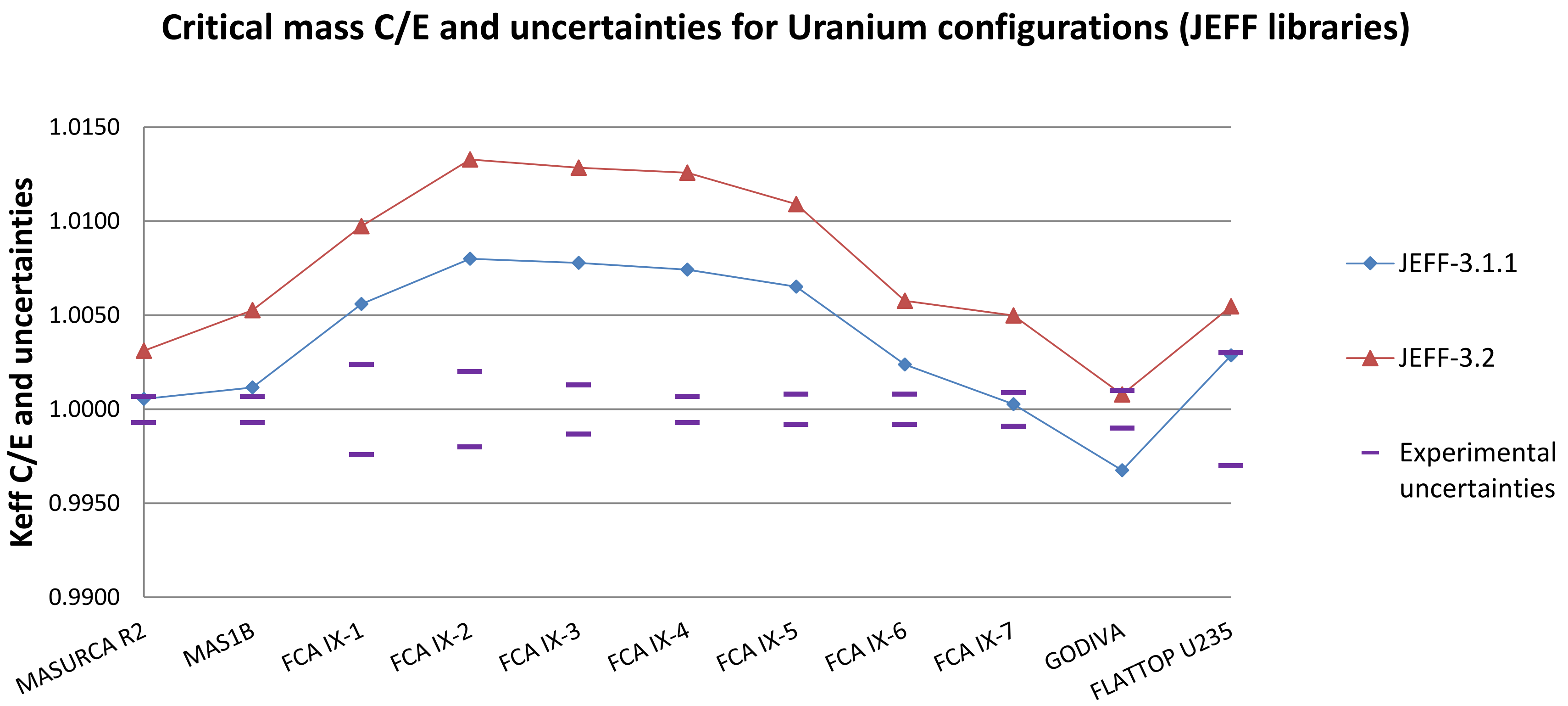
$$\boldsymbol{\sigma}'-\boldsymbol{\sigma}_{a\ priori} = M_{\sigma}\ .\ S^T(M_E + S.M_{\sigma}\ .\ S^T)^{-1}.\left(\boldsymbol{E}-\boldsymbol{C}(\boldsymbol{\sigma}_{a\ priori})\right)$$

$$M'_{\sigma} = M_{\sigma} - M_{\sigma}\ .\ S^T(M_E + S.M_{\sigma}\ .\ S^T)^{-1}\ S.M_{\sigma}$$

III- INTEGRAL DATA ASSIMILATION

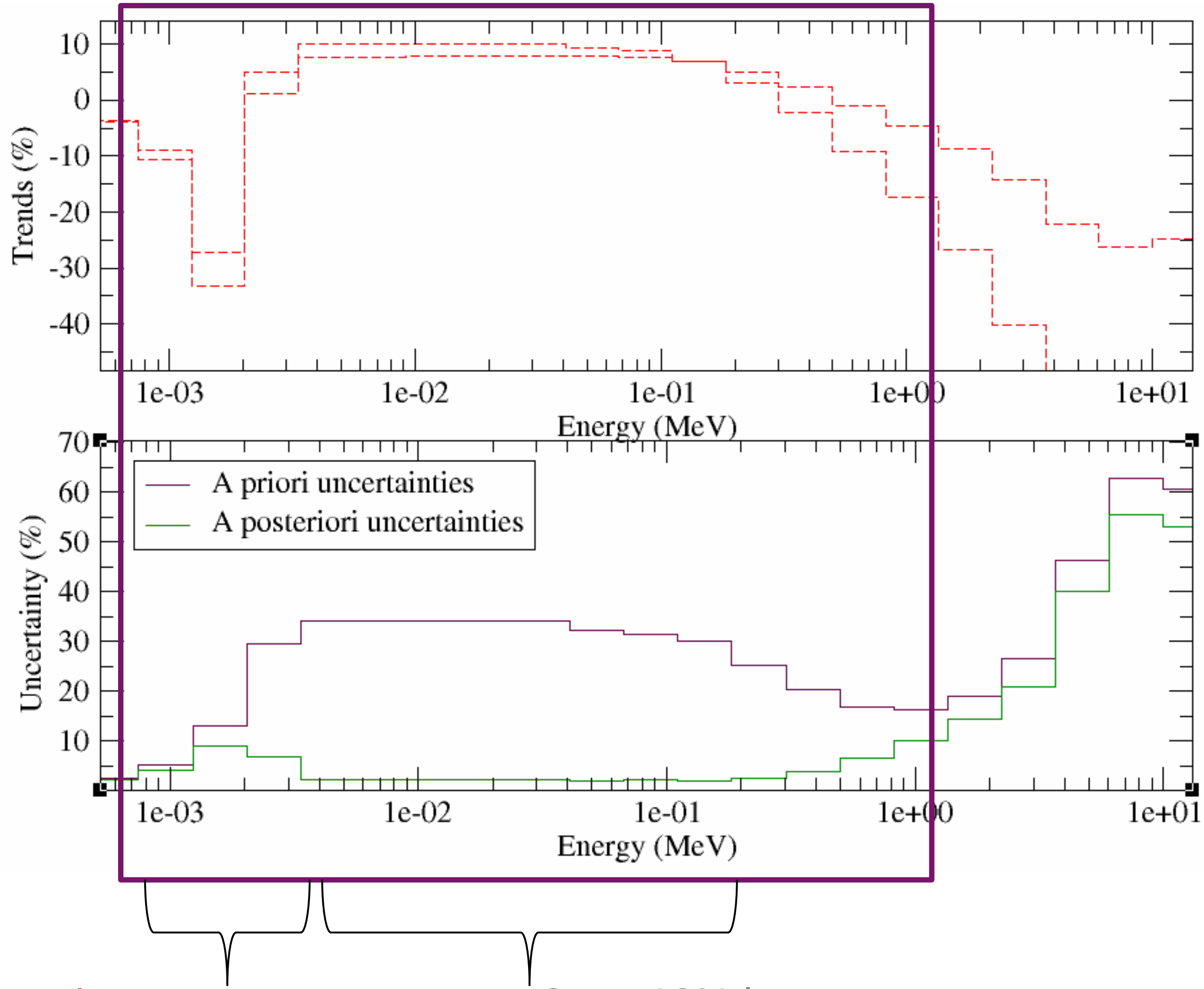
CONTEXT (URANIUM CONFIGURATIONS)

- Critical masses C/Es calculated for different configurations display great dispersion in results. Nuclear Data uncertainties (of the order of 1000 to 2000 pcm) are far beyond experimental uncertainties.



→ Use of integral experiments to identify which reaction and isotopes are responsible for this dispersion (assimilation using Bayesian Inference with CONRAD)

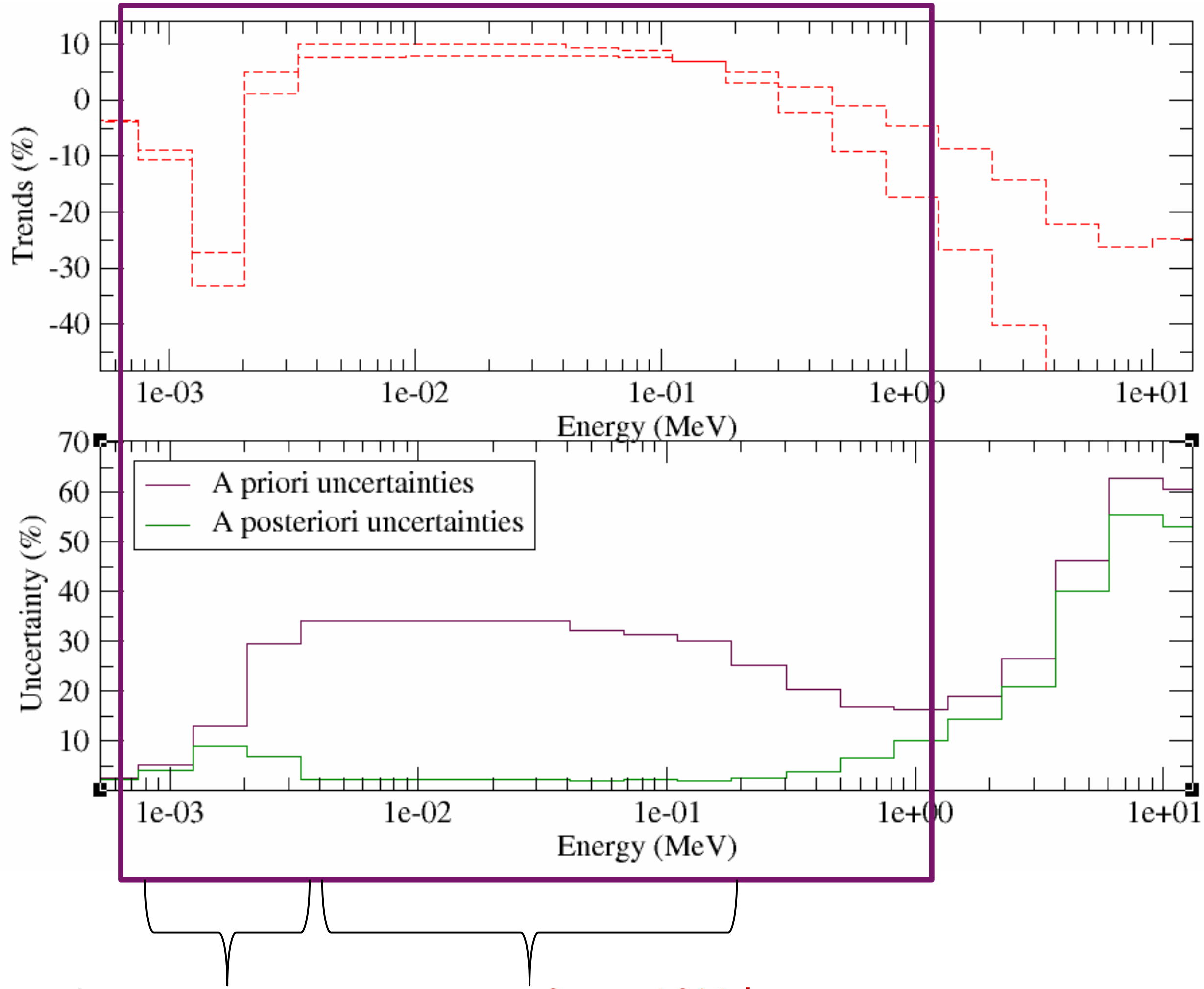
U235-U238 ASSIMILATION RESULTS : TRENDS FOR U235 CAPTURE



-27 to -33 % decrease at 1-2 keV (end of RRR)
→In **agreement with Danon measurements** (2017)

+8 to +10% increase in the 10-100keV region (URR)
→In agreement with Jandel measurements (2012)

U235-U238 ASSIMILATION RESULTS : TRENDS FOR U235 CAPTURE

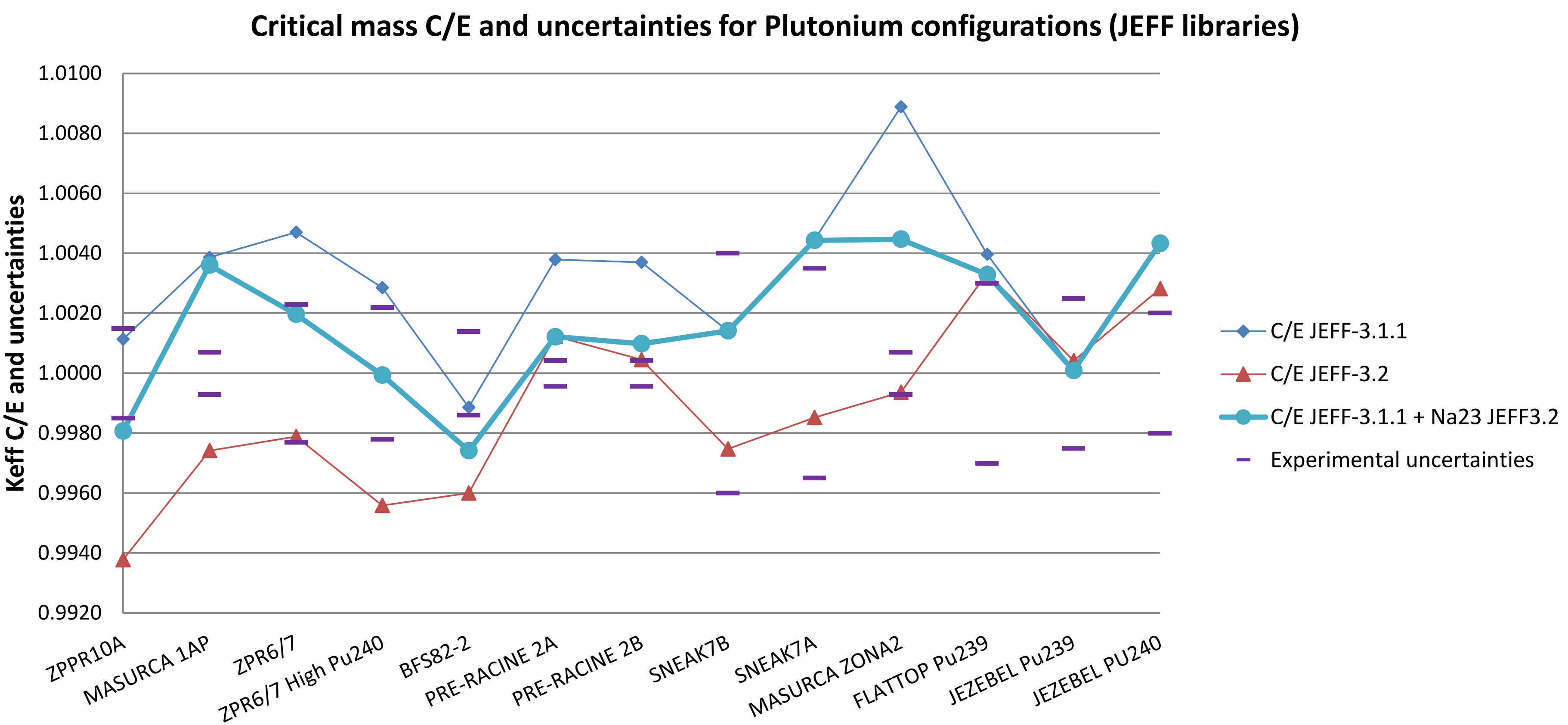


-27 to -33 % decrease at 1-2 keV (end of RRR)
→In agreement with Danon measurements (2017)

+8 to +10% increase
in the 10-100keV region (URR)
→In **agreement with**
Jandel measurements (2012)

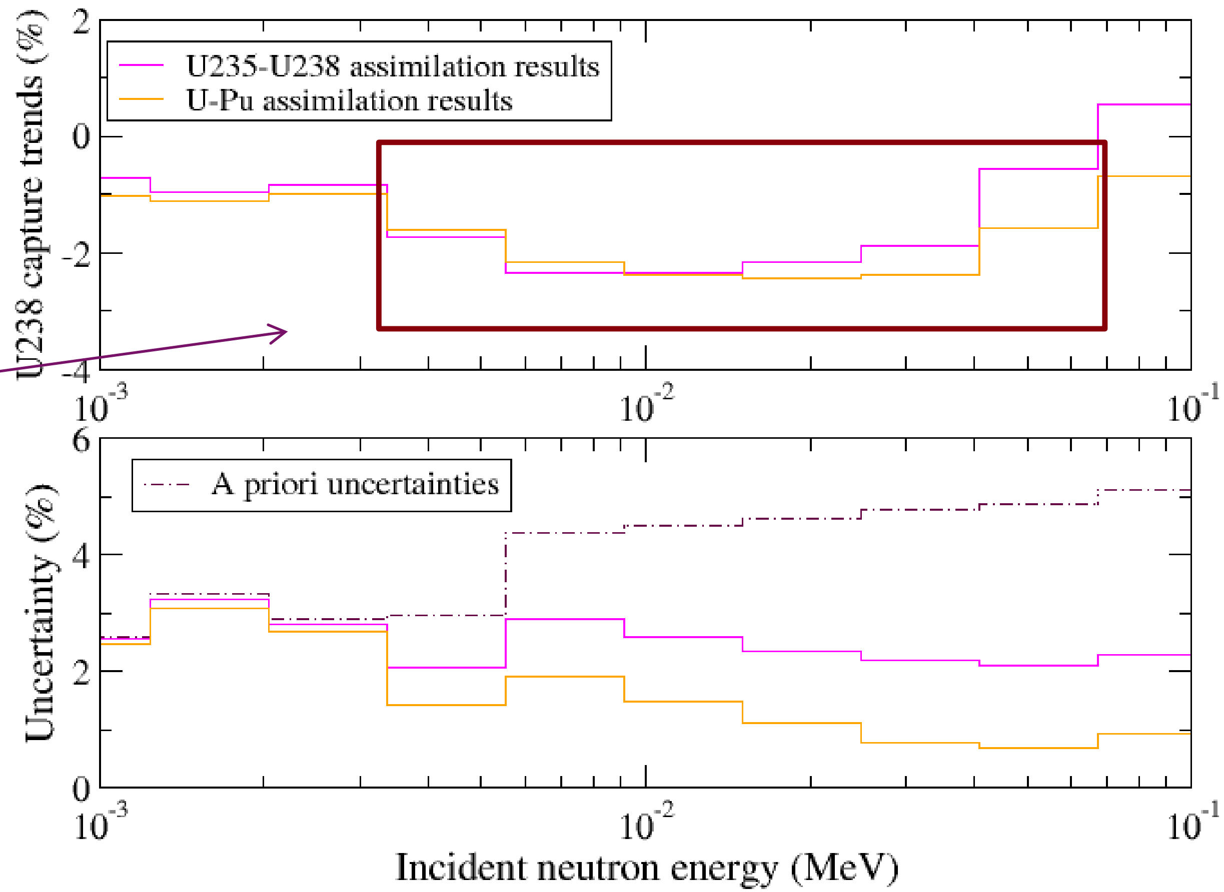
CONTEXT (PLUTONIUM CONFIGURATIONS)

- Critical masses C/Es calculated for different configurations display some dispersion in results. We used as a starting point **JEFF3.1.1 + Na23 JEFF3.2.**



- FCA-IX fission chambers C/Es of Np237, Am241, Am243, Pu238, Pu242, Cm244.
- PROFIL C/E on U238, Pu238, Pu239, Pu240, Pu241, Pu242, Am241, Np237.

U238 CAPTURE

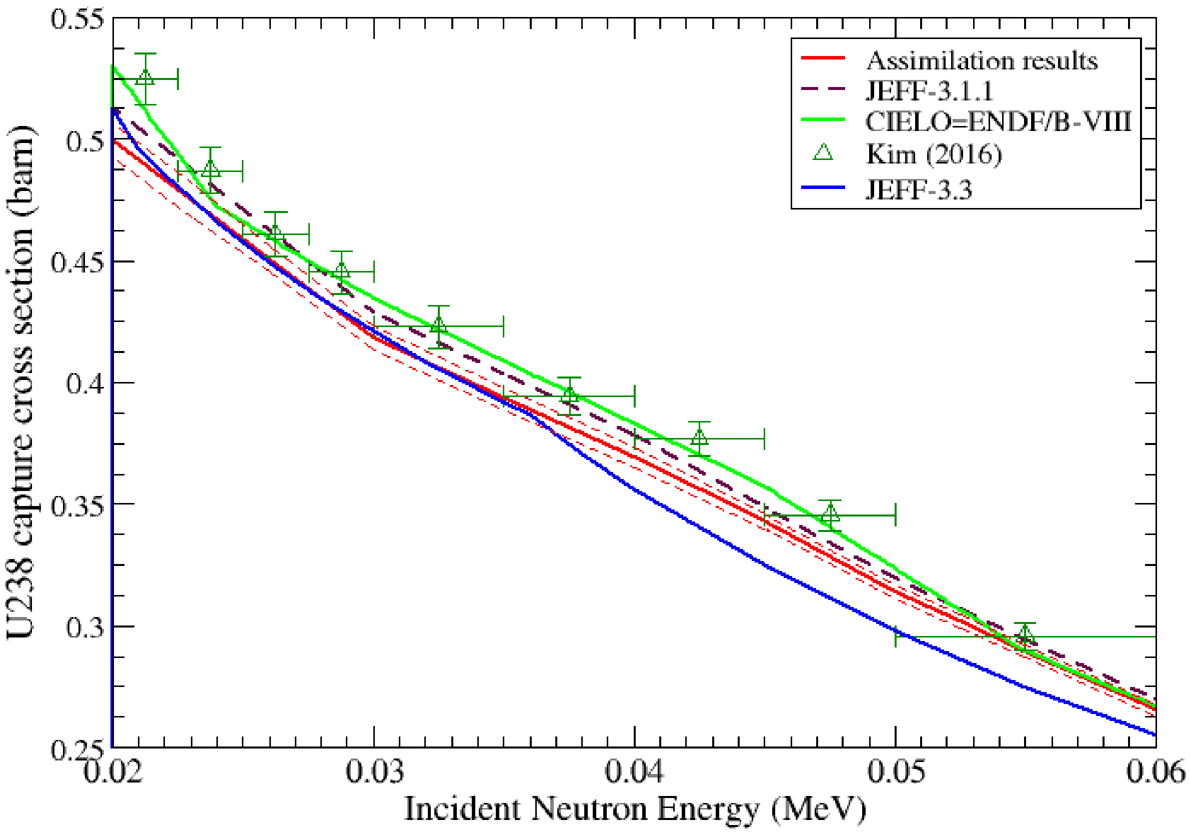


Results from step 1 & 2 are consistent, which means **compensating errors with Pu XS are negligible.**

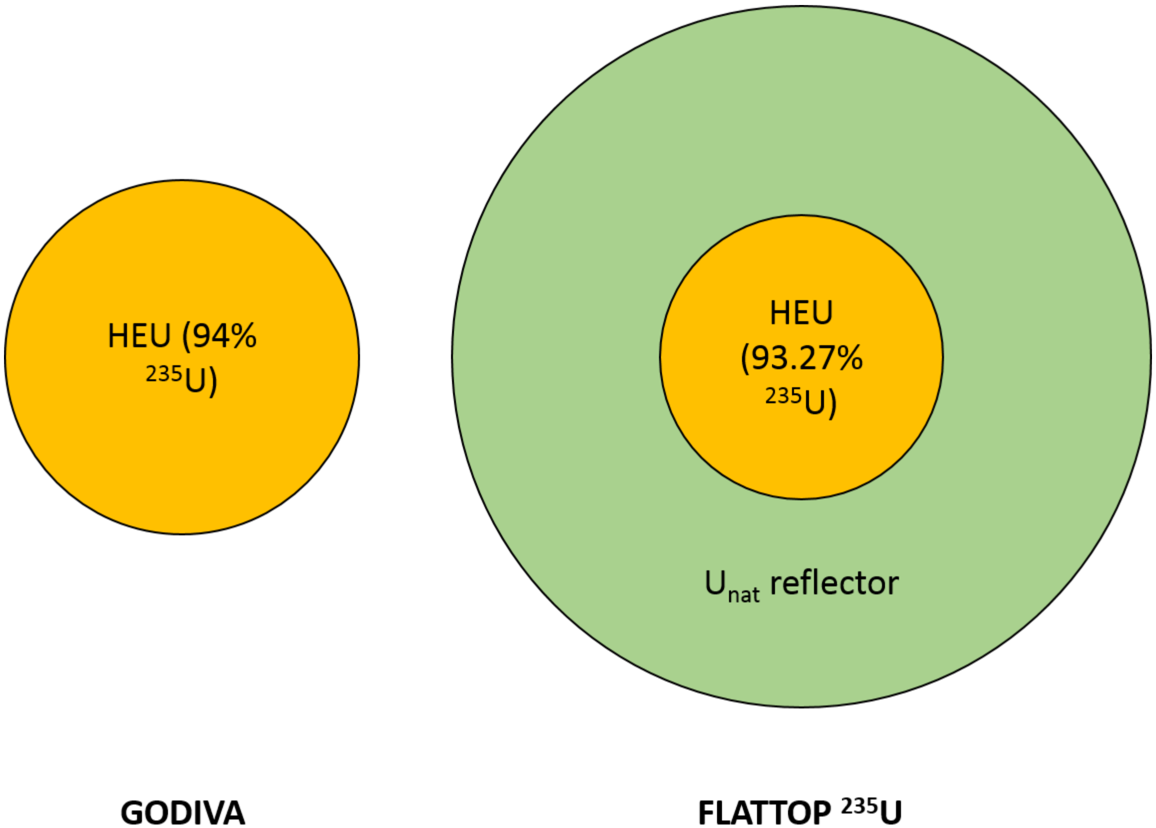
These trends are mainly supported by critical masses and $^{239}Pu/^{238}U$ mass ratios of PROFIL sample experiments.

U238 CAPTURE

Assimilation results for U238 capture compared with differential measurements and with the "a priori" JEFF-3.1.1, CIELO and JEFF-3.3 evaluation. Posterior uncertainties for assimilation results are in dotted line.



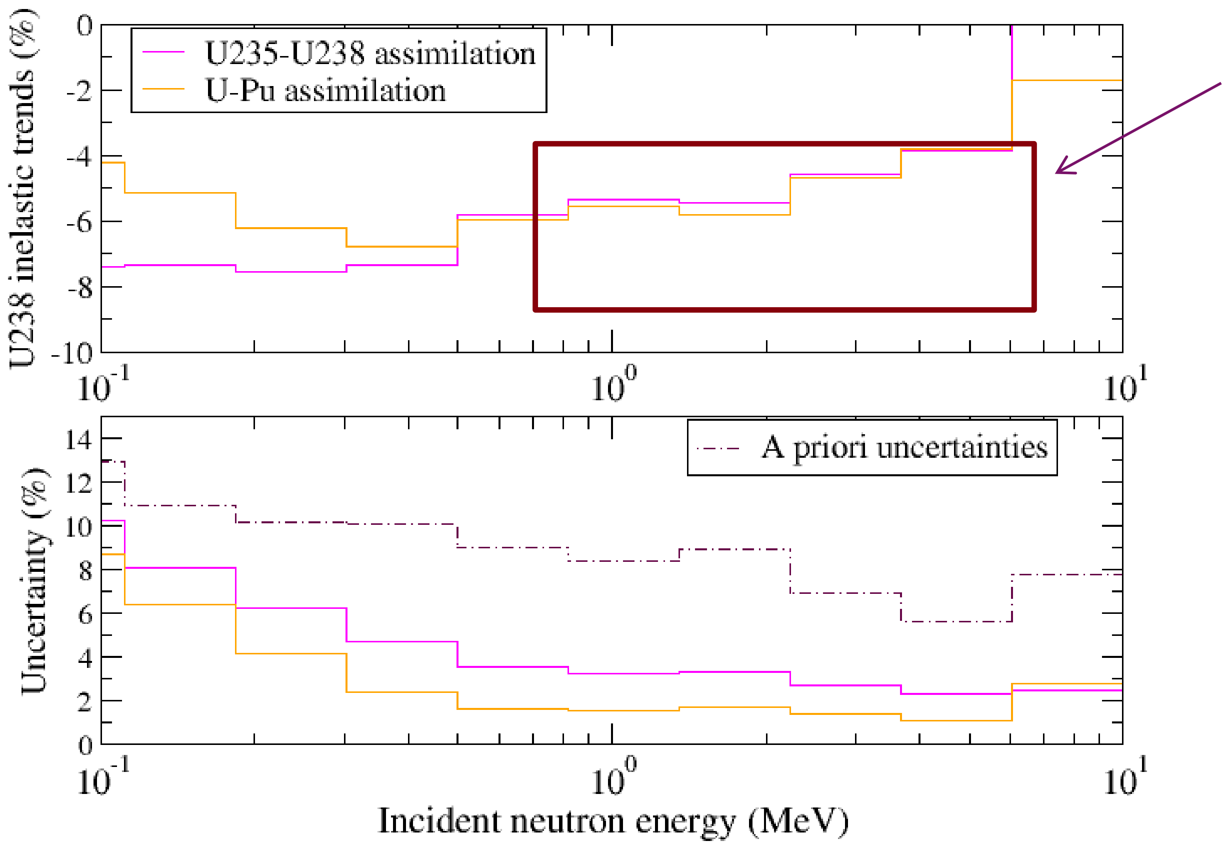
^{238}U INELASTIC



- Notably, the simultaneous use of FLATTOP-U235/GODIVA and FLATTOP-Pu239/JEZEBEL enables us to discriminate contributions from U238 and fissile isotopes. Indeed, GODIVA is a bare U235 sphere while FLATTOP-U235 is surrounded by a U_{nat} blanket. The same for JEZEBEL and FLATTOP-Pu

U238 INELASTIC : COMPARING RESULTS FROM STEP 1 & 2

- U-Pu assimilation (step 2) results are compared to ^{235}U & ^{238}U assimilation (step 1) results :



In the plateau region (~1 MeV to 6 MeV), a 5-6% decrease is suggested.

Results from step 1 & 2 are consistent, which means **compensating errors with Pu XS are negligible.**

- This decrease trend is in agreement with recent evaluations (CIELO and JEFF-3.3).

U238 INELASTIC

- Assimilation results for U238 inelastic compared with the "a priori" JEFF-3.1.1, CIELO and JEFF-3.3 evaluation. Posterior uncertainties for assimilation results are in dotted line.

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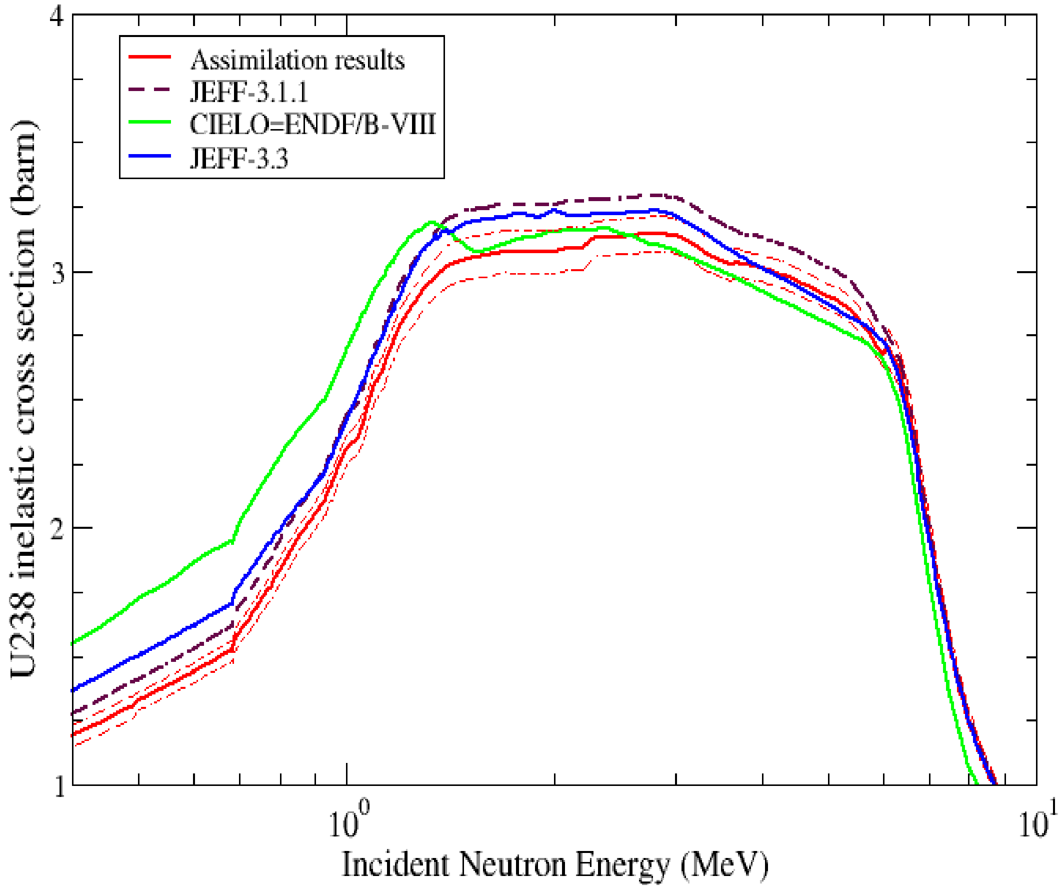
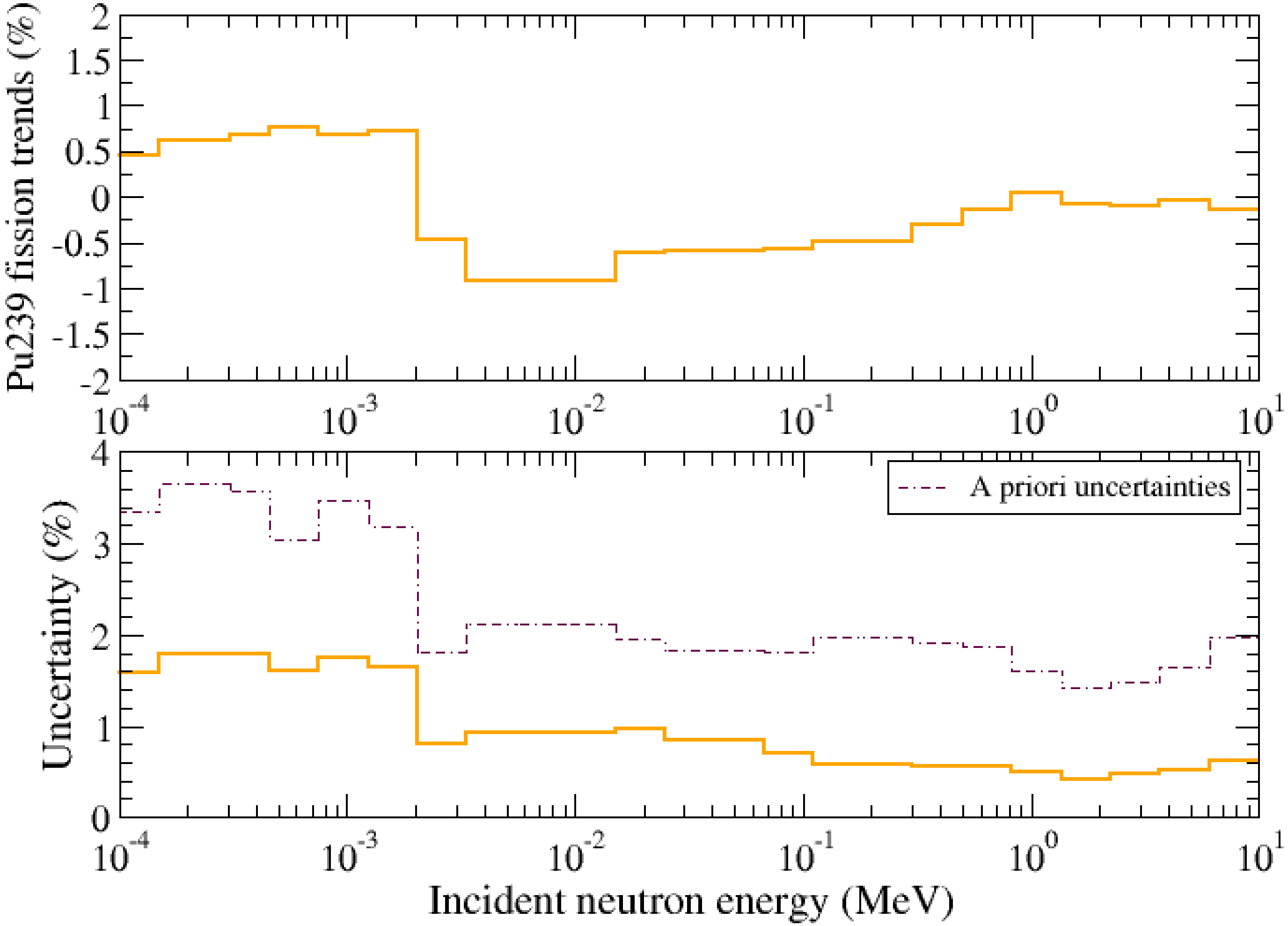


PU ISOTOPES

- Summary of trends for XS which can have a significant impact for ASTRID :

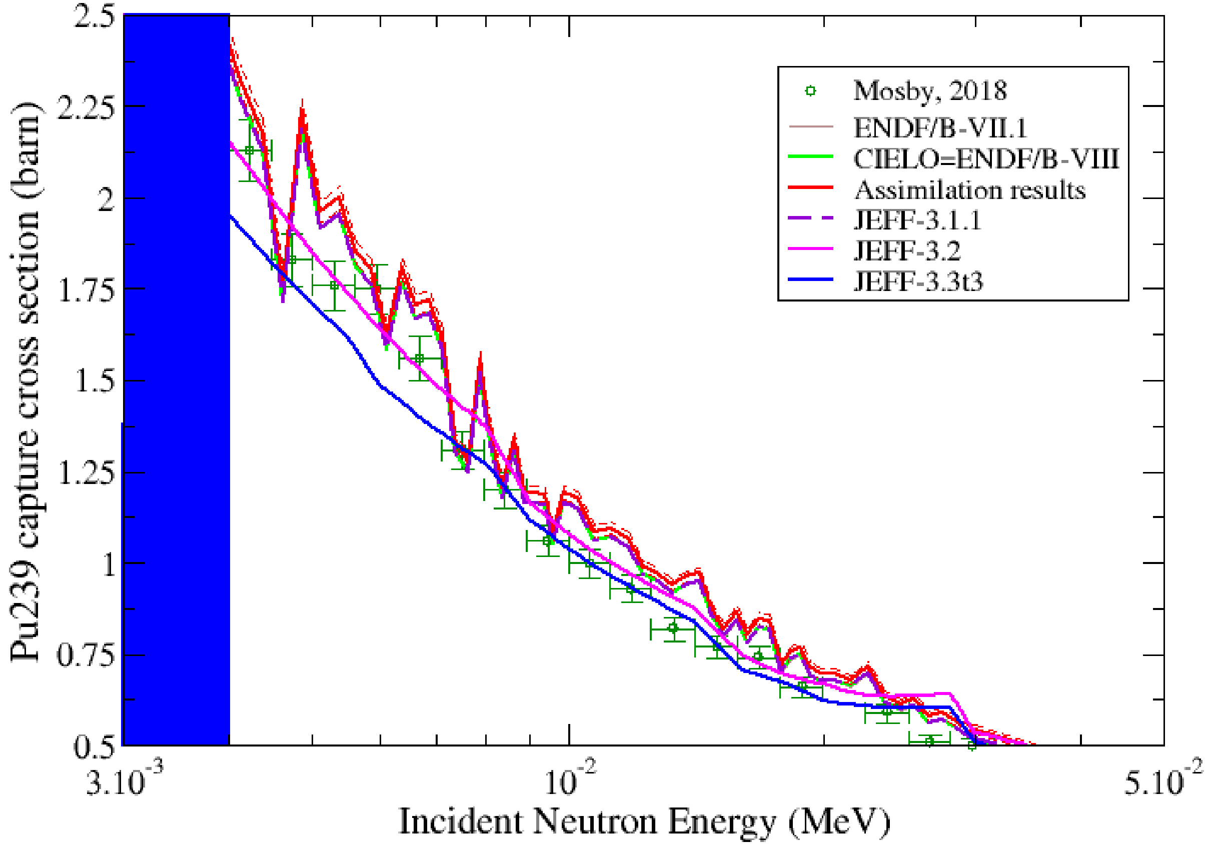
Cross section	Trends (%)	Energy range	Experiments	Comments
^{239}Pu fission	<1% (+/- 1.7% or less)	0.1 keV- 500 keV	Pu-fueled critical masses	Trends included in posterior unc.
^{239}Pu capture	from -1.4 to -4.8 % (+/- 2-5%)	0.04 keV - 300keV	PROFIL and critical masses	
^{240}Pu fission	**from - 7.5 to -9.6% (+/-8-11%)**	**0.75 keV-100 keV**	**Mostly JEZEBEL- ^{240}Pu**	**Risk of compensating errors with multiplicity and PFNS. Trends are close to posterior uncertainties.**
	from -3.5 to -4.6% (+/- 4-7%)	**1 keV-3.7 MeV**		
^{240}Pu capture	from 2.5 to -4.2 % (+/- 2-4.5%)	0.7 keV - 100 keV	PROFIL	
^{242}Pu fission	**- 10% (+/- 3.5%)**	**500 keV- 4 MeV**	**FCA-IX IS**	**Underestimated prior uncertainties (~2% in the plateau region)**
^{242}Pu capture	from -3 to -9% (+/- 2-5%)	3 keV - 300 keV	Trends are driven by PROFIL (C/E~1.14).	IDA trends have an unreliable energy breakdown due to Covariances
	around -20 % (+/- 12%)	0.4 keV- 3 keV		

TRENDS ON ^{239}PU FISSION XS



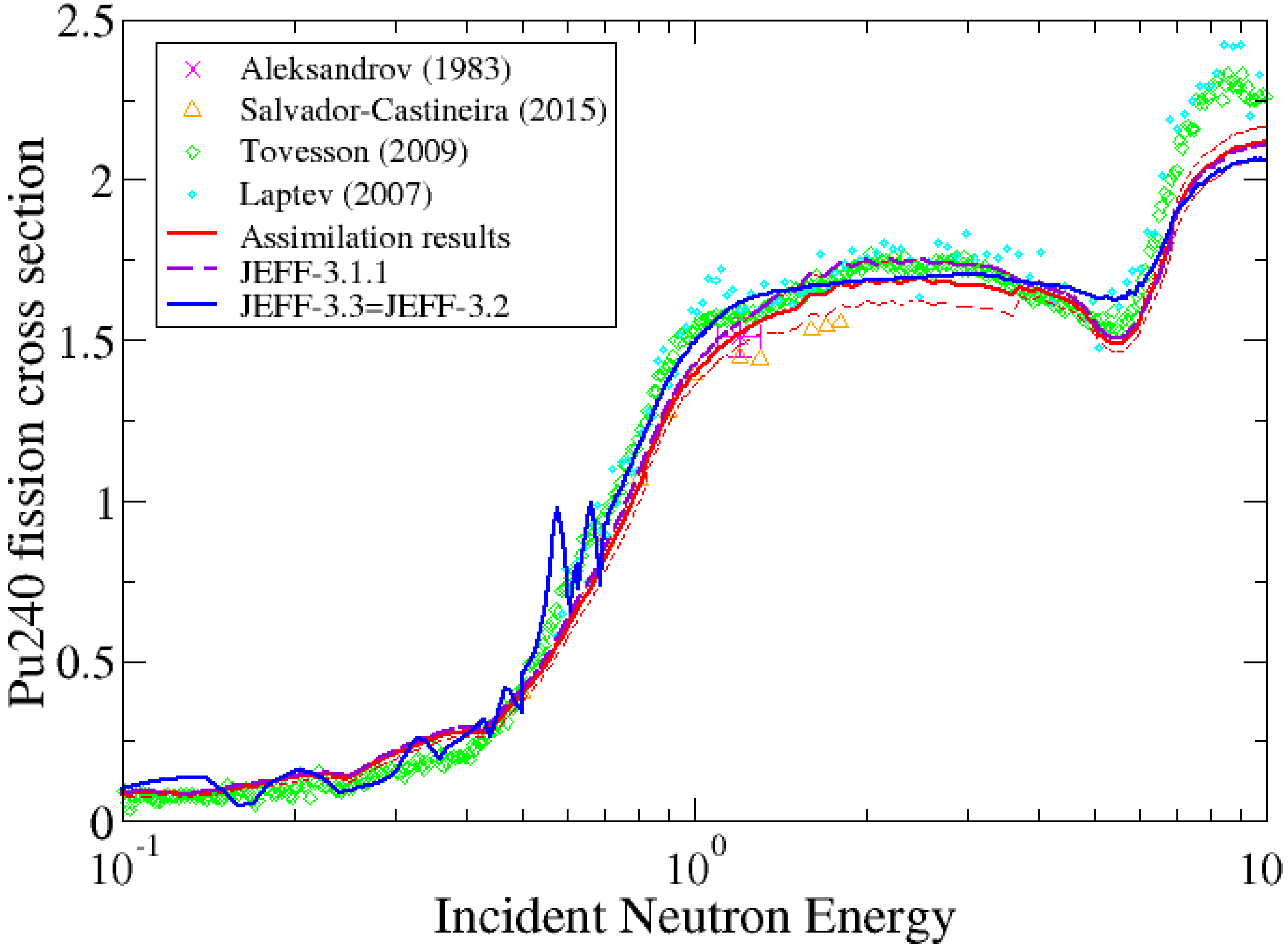
TRENDS ON ^{239}PU CAPTURE XS

Assimilation results do not go in the same direction as the JEFF-3.3 evaluation.



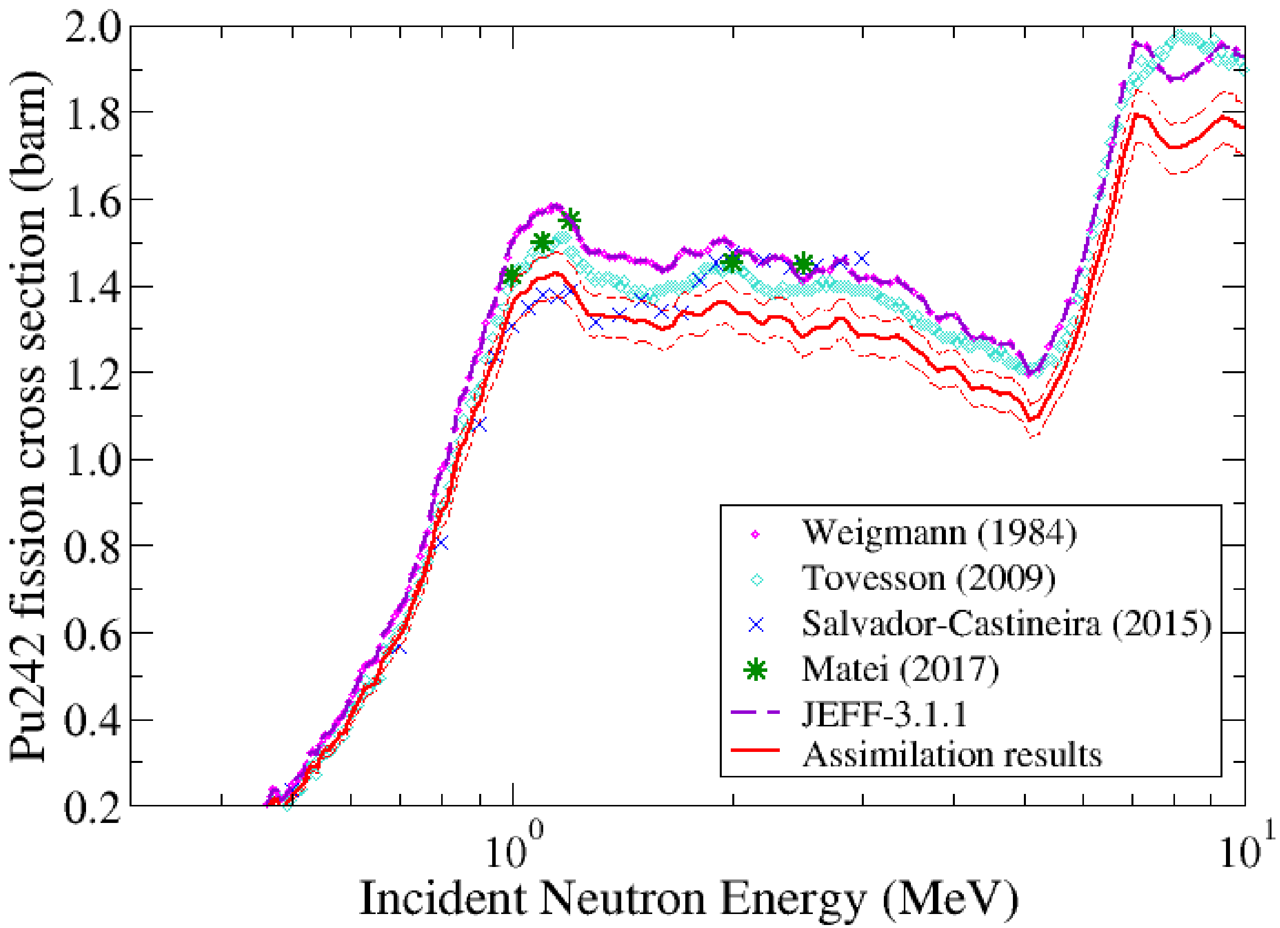
From 4keV up to 30 keV, the ENDF/B-VIII evaluation corresponds to JEFF-3.1.1.

TRENDS ON ^{240}PU FISSION XS



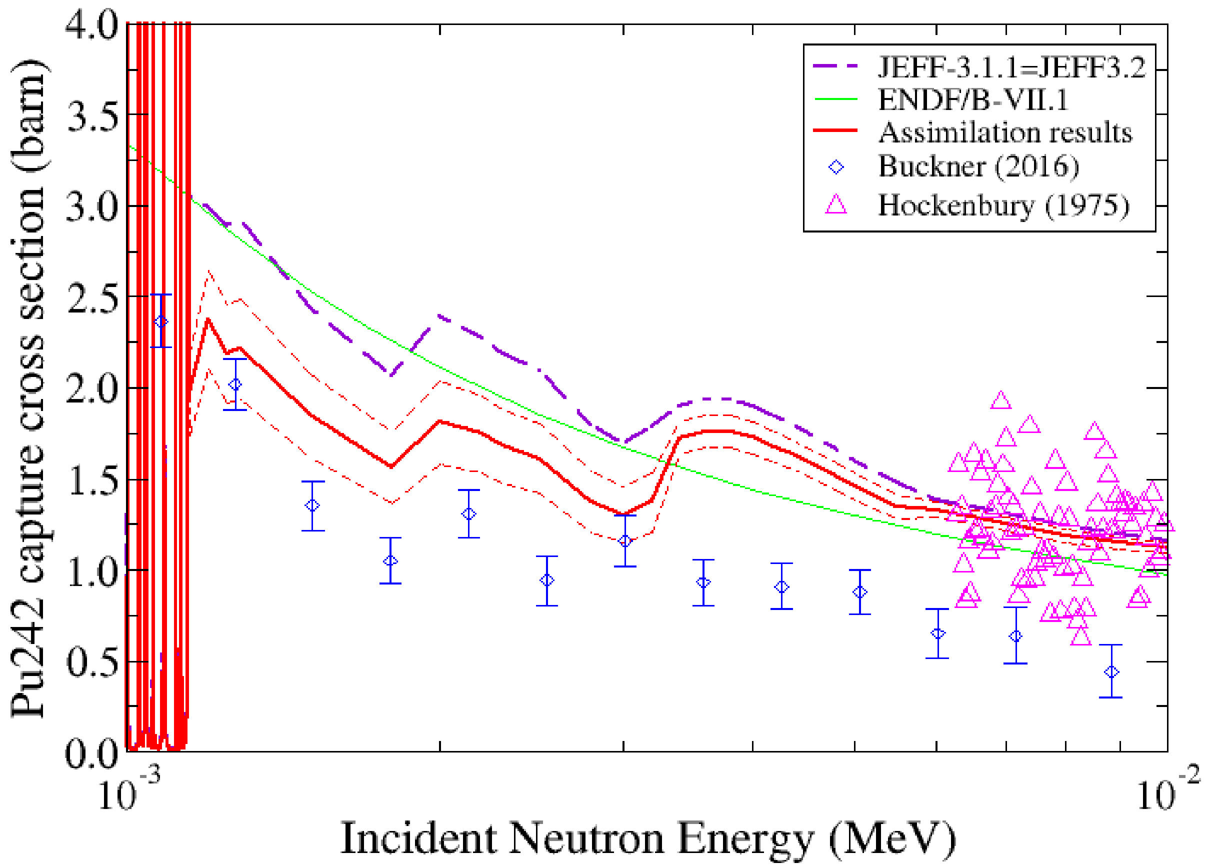
^{242}PU FISSION

- C/E values for FCA-IX spectral index ^{242}Pu/^{239}Pu ratio are highly overestimated (C/E~1.12). Integral data are in better agreement with Tovesson measurements than Weigmann's:



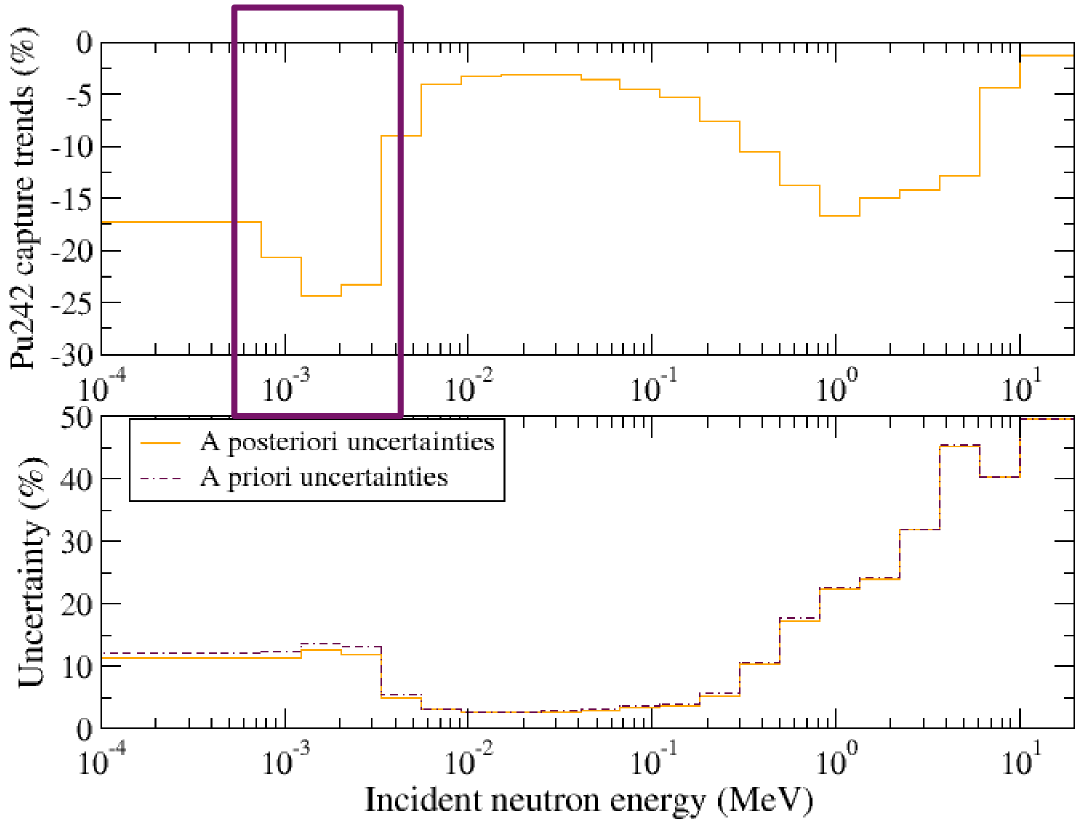
^{242}PU CAPTURE

- Trends are driven by PROFIL (C/E~1.14).



^{242}PU CAPTURE

- Trends are driven by a single integral information: PROFIL (C/E~1.14 with JEFF-3.1.1) and follow prior uncertainties.
- IDA trends hence have an unreliable energy breakdown with prior uncertainty greatly **underestimated below 4keV (beginning of the URR)**.



IV- IMPACT ON THE ASTRID CFV CORE

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IMPACT ON ASTRID CRITICAL MASS PREDICTION

all values in pcm	Impact on k_{eff}	Posterior associated uncertainty contribution	Prior associated uncertainty contribution
U238_CAPTURE	249	180	869
U238_NU	0	40	70
U238_FISSION_SPECTRUM	12	40	60
U238_ELASTIC	-7	30	30
U238_INELASTIC	342	60	649
Pu238_CAPTURE	6	10	20
Pu238_FISSION	-82	20	10
Pu239_CAPTURE	-96	20	190
Pu239_FISSION	**-143**	120	699
Pu239_NU	-49	40	100
Pu239_FISSION_SPECTRUM	-37	50	210
Pu240_CAPTURE	-100	40	300
Pu240_FISSION	**-323**	170	669
Pu240_NU	-2	10	20
Pu240_FISSION_SPECTRUM	-66	90	170
Pu241_CAPTURE	7	70	90
Pu241_FISSION	-8	60	70
Pu241_NU	-6	60	70
Pu241_FISSION_SPECTRUM	-29	130	150
Pu242_CAPTURE	99	30	50
Pu242_FISSION	-197	20	40
Total actinides (pcm)	**-435**	**490**	**1558**

Significant impact of U238 capture and inelastic, Pu239, Pu240 and Pu242 fission XS.

Prior keff =0.99882
(JEFF-3.1.1 for all isotopes except Na23 for which JEFF3.2 is used: Impact of using Na23 evaluation from JEFF-3.2 instead of JEFF-3.1.1 on the ASTRID core reactivity: -250 pcm.)
Posterior keff =0.99449

The Integral Data Assimilation reduces uncertainties associated to nuclear data with, in particular, a significant reduction on Pu239 and Pu240 fission XS.

V- CONCLUSIONS AND PERSPECTIVES

CONCLUSION

- Integral data assimilation in this work has proved to be efficient in identifying the sources of possible normalization problems in the differential measurements

- The trends on the JEFF3.1.1 ^{235}U capture cross section are quite consistent with recent differential measurements. The information comes from the simultaneous use of PROFIL sample irradiation analyses and various ^{235}U enriched critical masses.

- Assimilation results suggest also a 2.5% decrease for ^{238}U capture from 3 keV to 60 keV, and a 4-5% decrease for ^{238}U inelastic in the plateau region. For this energy range, uncertainties are respectively reduced from 3-4 to 1-2% and from 6-9% to 2-2.5% for ^{238}U capture and ^{238}U inelastic.

- The increase trend on ^{239}Pu capture cross section of around 3% in the [2 keV-100 keV] energy range is driven by an underestimation of the PROFIL ^{240}Pu/^{239}Pu ratio C/E.

- For ^{240}Pu capture cross section, the increase is of around 4% in the [3 keV-100 keV] energy range and is suggested by PROFIL C/E. This trend goes in the same direction as the recent ENDF/B.VIII evaluation though at a much lower level.

PERSPECTIVES

- Integral data assimilation in this work has identified the lack of differential measurements, in particular for prompt fission neutron spectrum or U238 inelastic.

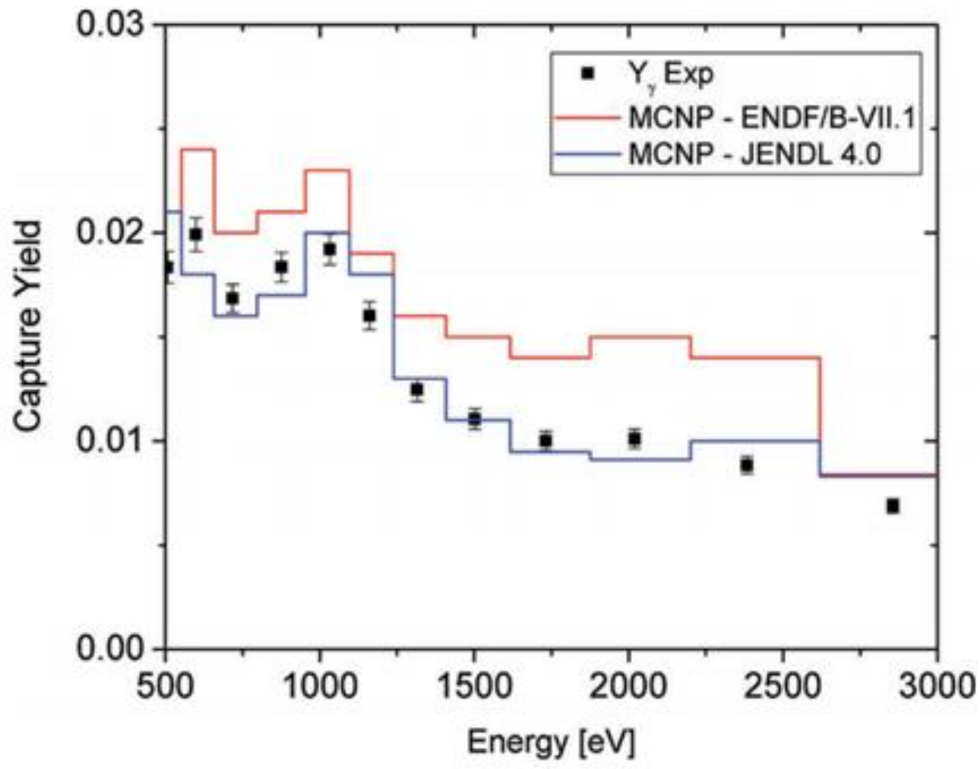
- Parametric studies have shown that nuclear data covariance data with better reliability are required (for PFNS and some capture cross sections).

- Marginalization has been used for anisotropy of scattering and distribution of secondary energy neutrons since covariance data is missing. Hence, there is a request to have those covariance in particular for light and structural isotopes.

- Improve Integral Data Assimilation by
  - incorporating all sources of uncertainties such as anisotropy of scattering and distribution of secondary energy neutrons
  - adding more experiments in the data base

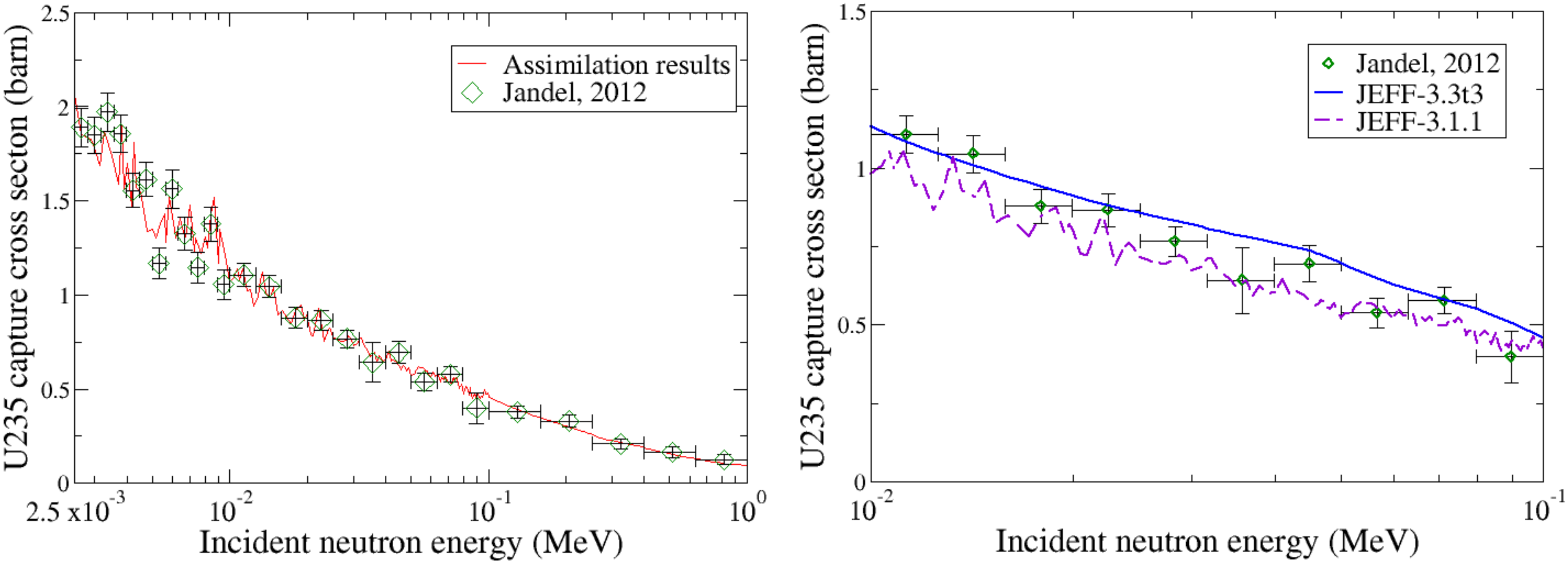
^{235}U CAPTURE

- Results of differential measurements from Danon et al. from reference U235 capture from 0.5 to 3 keV, compared with ENDF/B-VII.1(=JEFF3.1.1) and JENDL-4.0 evaluations.



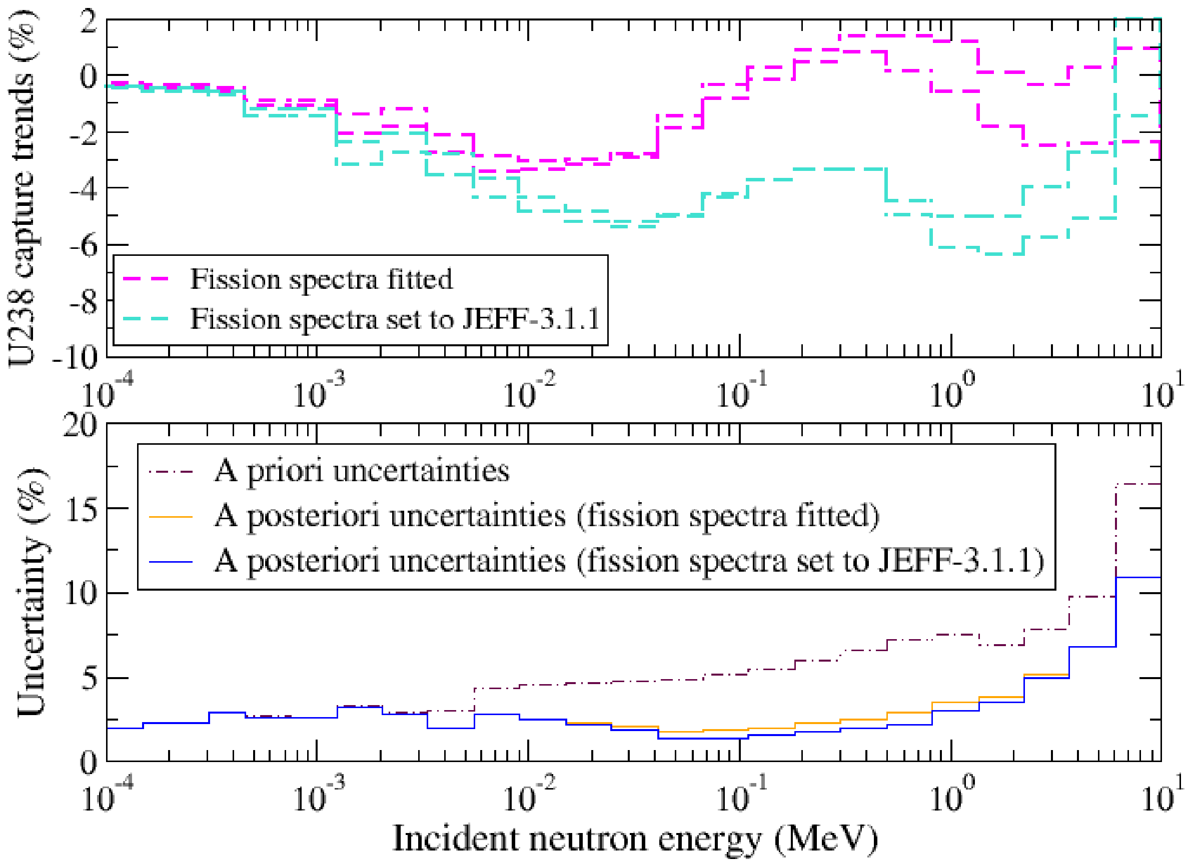
^{235}U CAPTURE

- Results of differential measurements from Jandel et al. for ^{235}U capture from 3keV to 1MeV.



IMPACT OF FISSION SPECTRUM ON ^{238}U CAPTURE TRENDS.

- Trends noticeably differ **depending on whether fission spectrum is fitted or not.**



→ Fission spectra have been identified as the **main source of uncertainties** in our assimilation work.

IMPACT OF FISSION SPECTRUM ON ^{238}U INELASTIC TRENDS.

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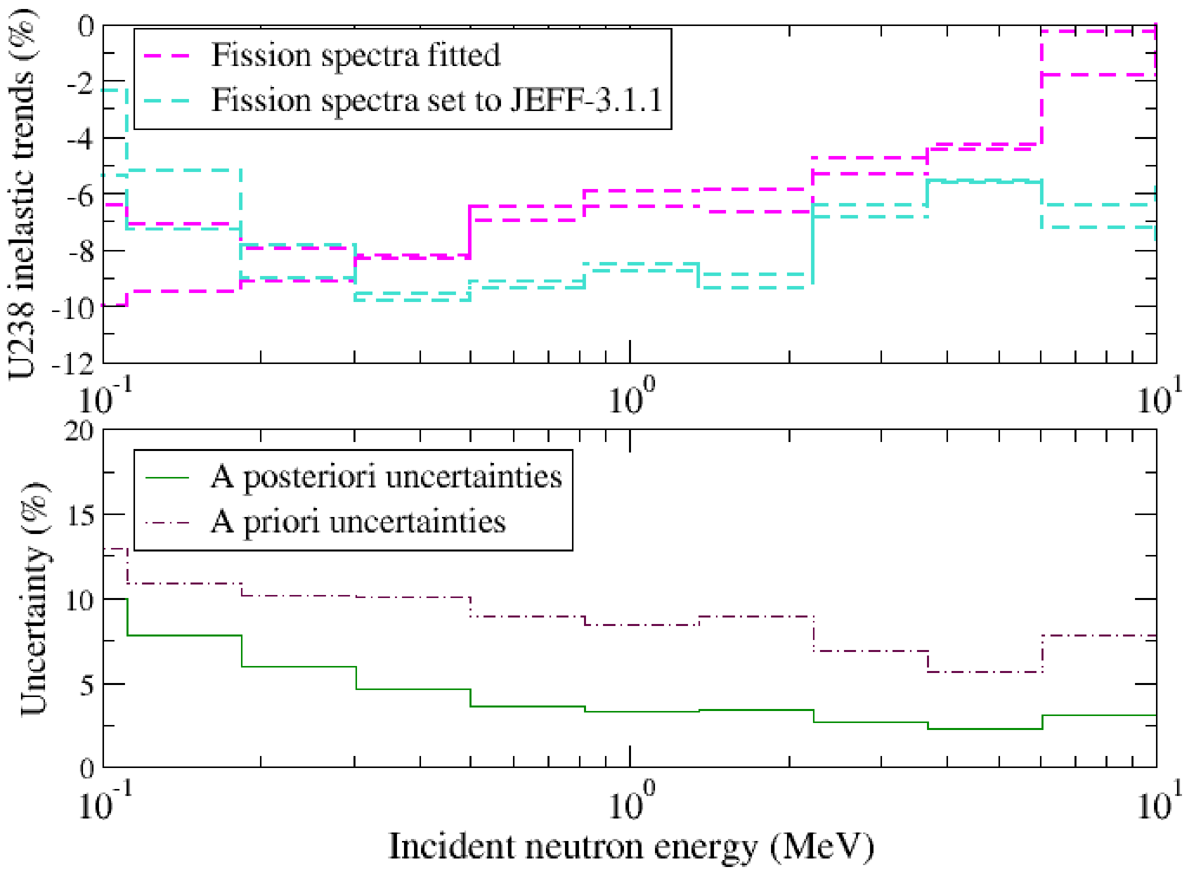
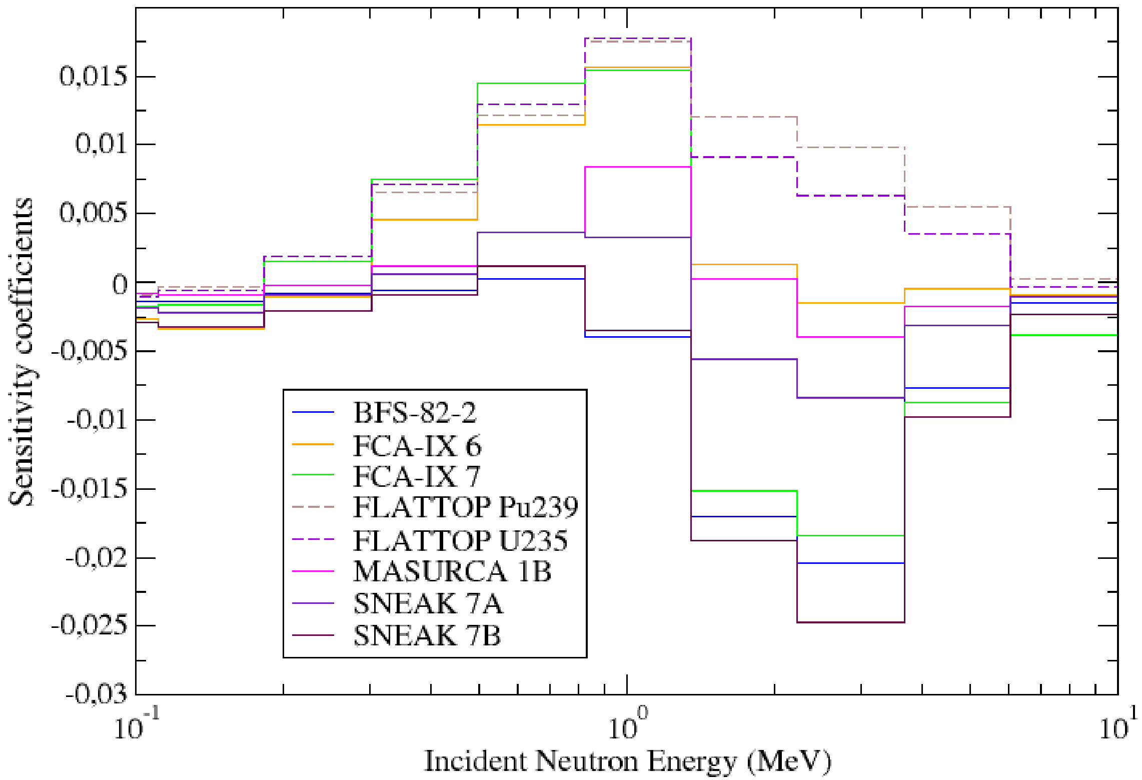


→ Fission spectra have been identified as the **main source of uncertainties** in our assimilation work.

^{238}U INELASTIC

- Sensitivity profile of several critical masses to U238 inelastic cross sections.



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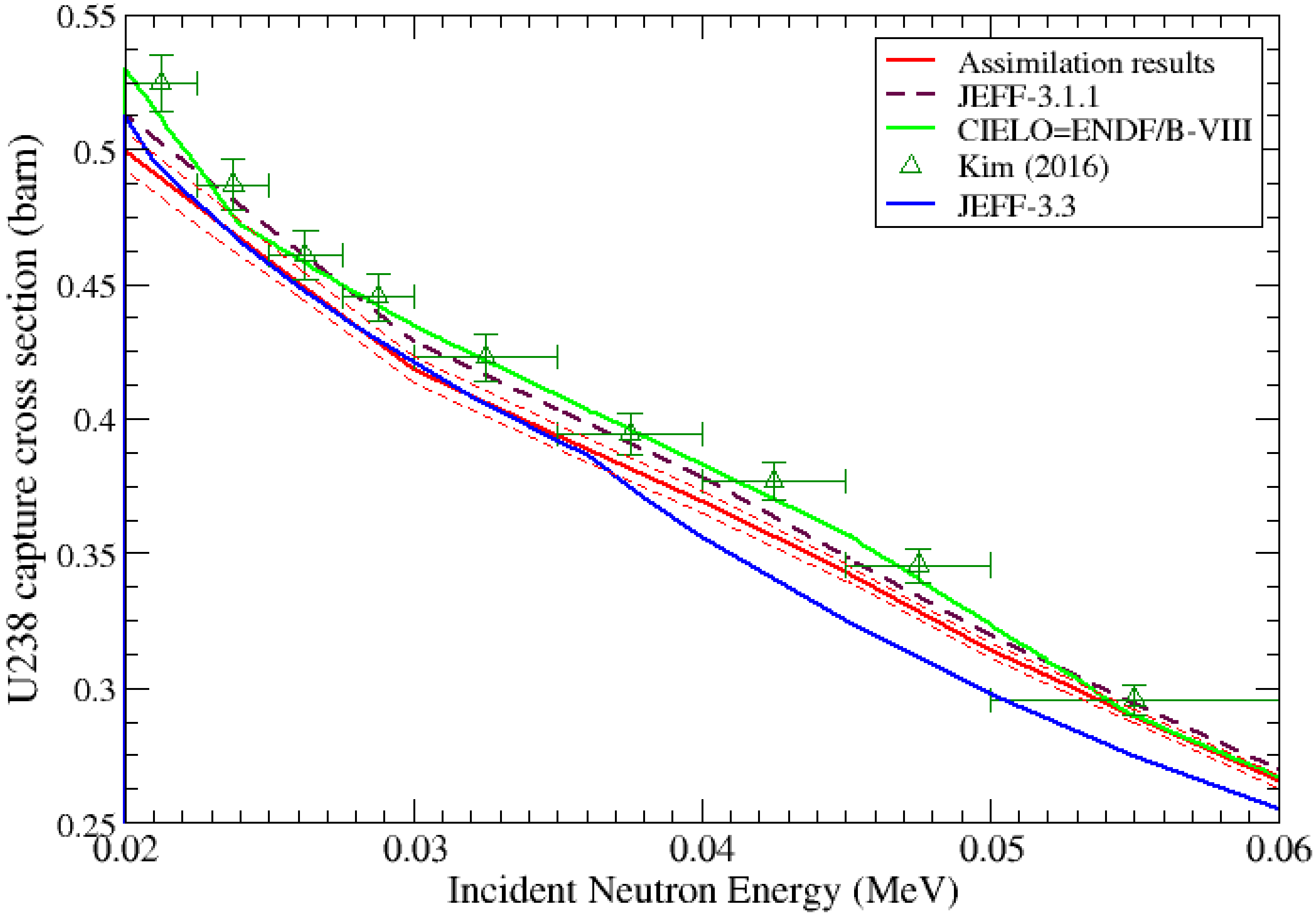
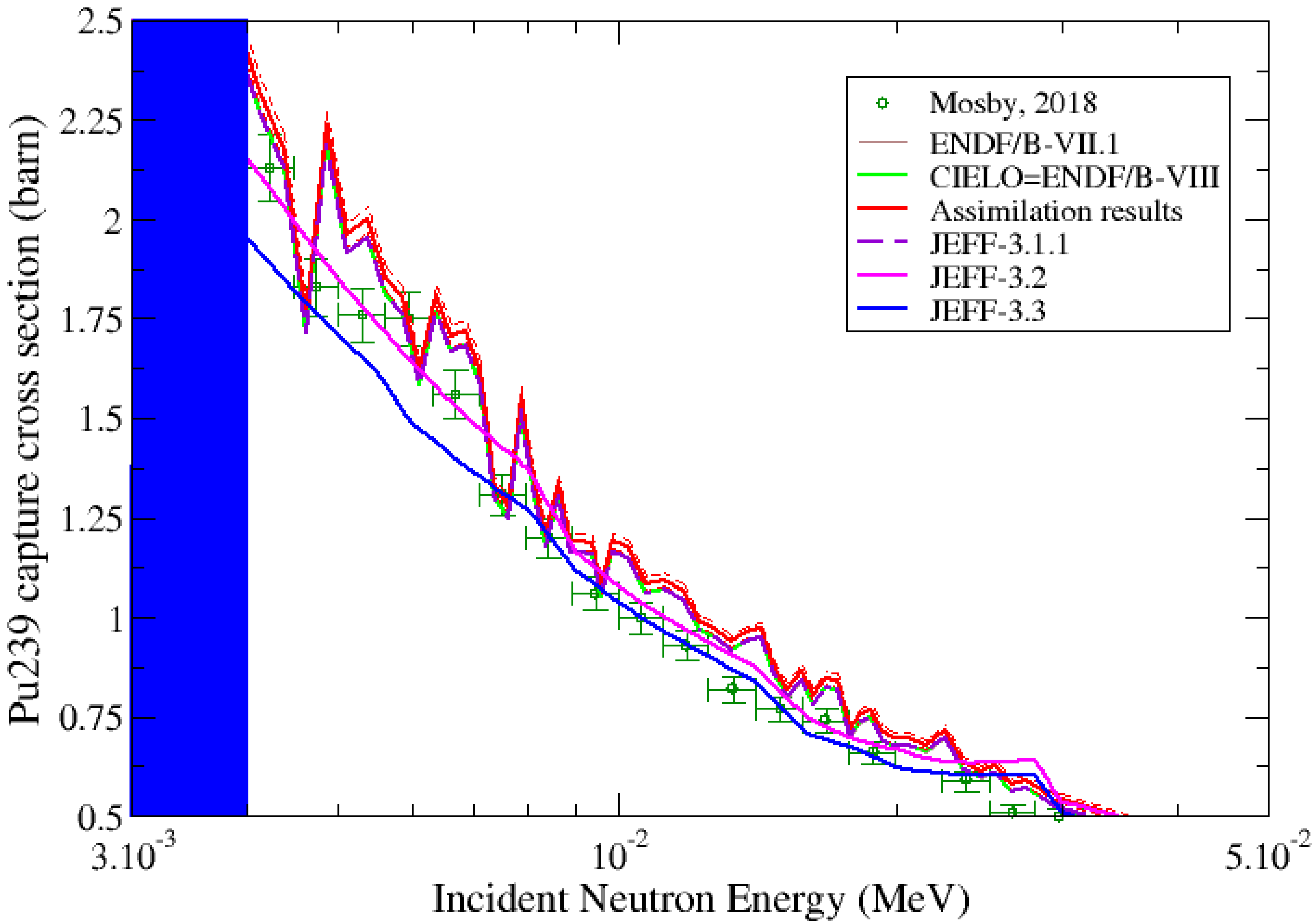
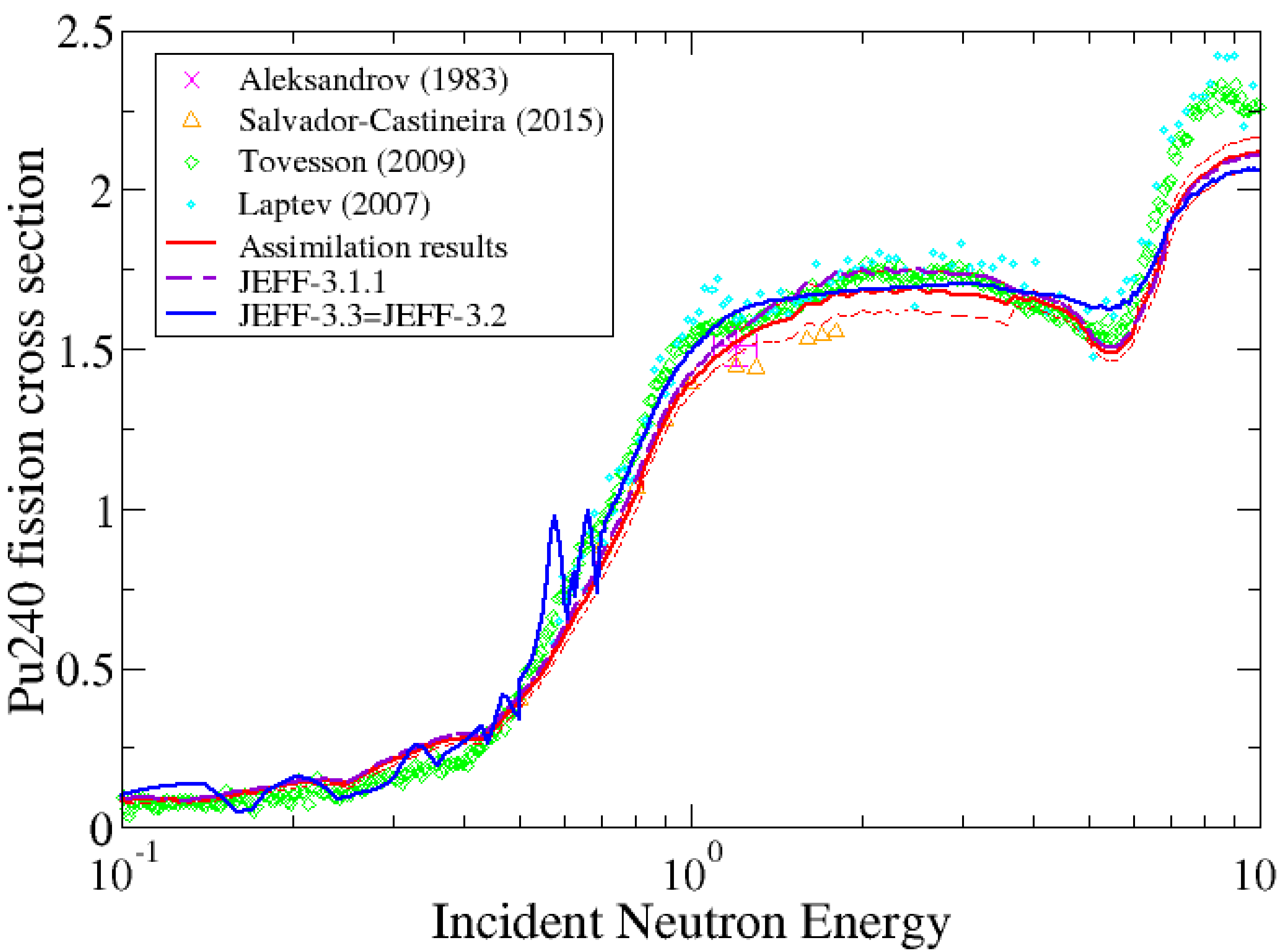
TRENDS ON ^{238}U CAPTURE XS



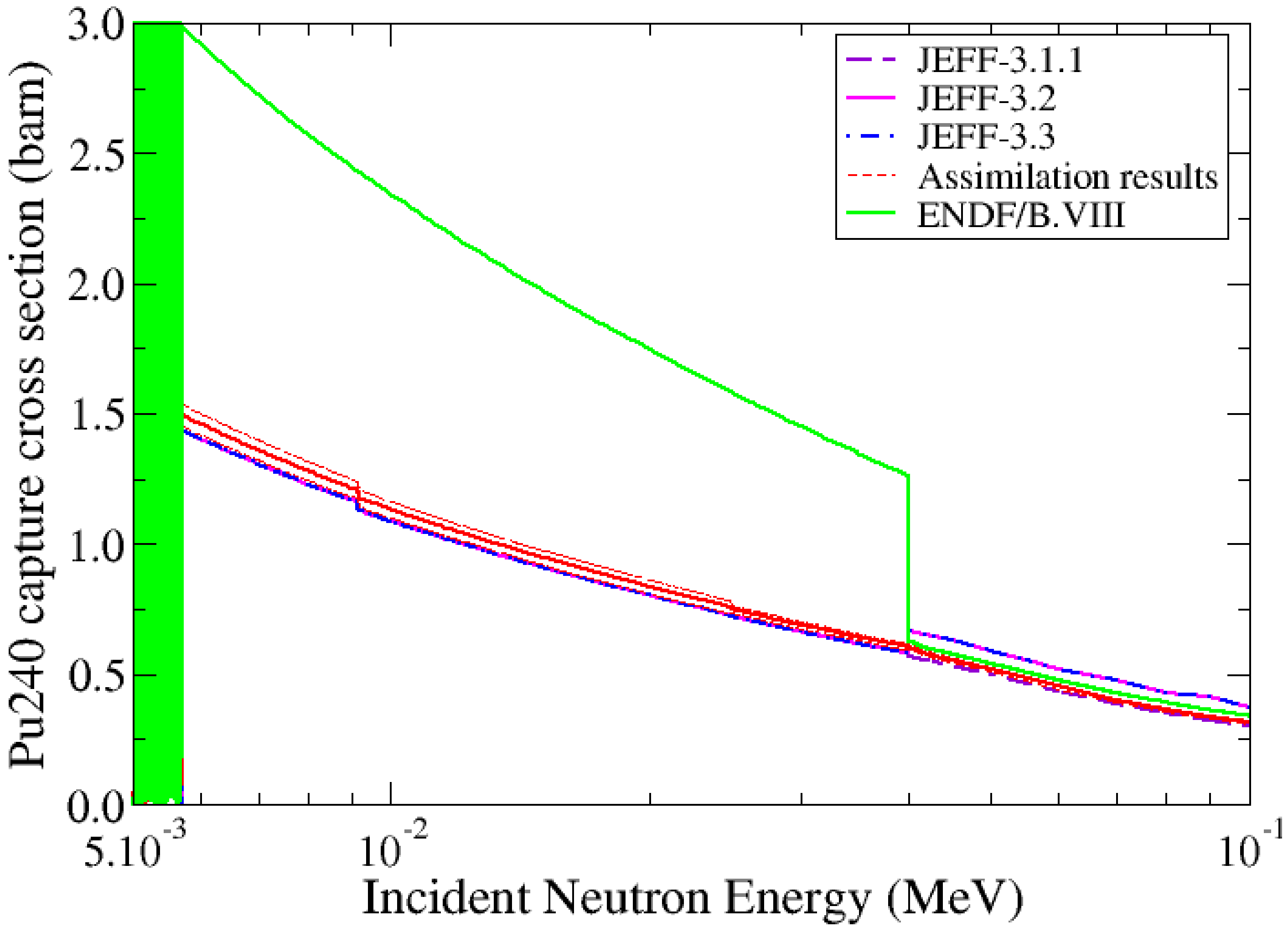
TRENDS ON ^{239}PU CAPTURE XS



TRENDS ON ^{240}PU FISSION XS



TRENDS ON ^{240}PU CAPTURE XS



^{238}U INELASTIC XS