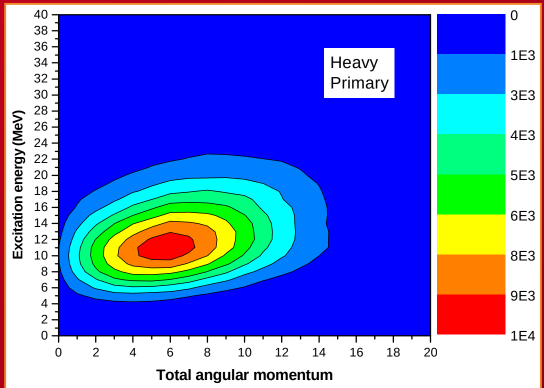
DE LA RECHERCHE À L'INDUSTRIE

CADARACHE



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Prompt particle emission in correlation with fission fragments

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FRANCE

ND-2016, 11-16 september, 2016, Bruges, Belgium.

- ***Model***

  Influence of shell corrections on LDs and PFNS*

- ***Prompt fission neutron observables***

  $\overline{\nu}(A)$ $\overline{\nu}(TKE)$ $\overline{\nu}(TKE;A)$

- ***Prompt fission gamma observables***

  PFGS(A) , PFGS(A,Z)$_{post}$

- ***Conclusion & Outlook***

- ***Model***

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  $\overline{\nu}(A) \quad \overline{\nu}(TKE) \quad \overline{\nu}(TKE;A)$

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- ***Conclusion & Outlook***

Definitions

- Prompt emission : before β^- decay
- Prediction : By establishing the '*as better as possible*' calculation scheme (models, model parameters, hypothesis…) we can reproduce some given 'target observables' (global quantities, e.g. $\overline{\nu_L}$, $\overline{\nu_H}$) and then look at other ones (predicting them):
  $P(\nu)$, $P(M_\gamma), \overline{\nu}(TKE)$, …

Hypothesis

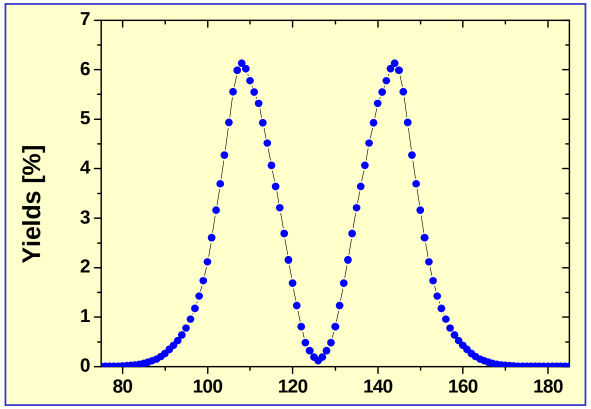
- Binary Fission
- n/γ/e^- emission after FF full acceleration (fragments have recovered their gs deformation)
- NEDA (*A. Matsumoto et al., J. of Nucl. Sc. and Tech. 49, 782 (2012)*) *not accounted for.*
- SN (*N. Carjan et al., Phys. Rev. C 85, 044601 (2012)*) *(see O. Serot presentation)*

Fission Fragment characteristics sampling

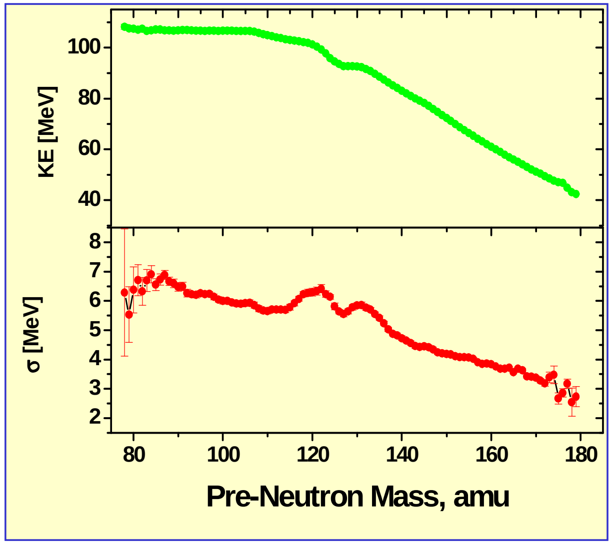
1. Mass (*A*)
2. Kinetic Energy (*KE*)
3. Nuclear Charge (*Z*)
4. Spin, Parity (J^{π})
5. Excitation Energy (*E**)

can be reconstructed from a set of fission mode parameters (MM-RNR)

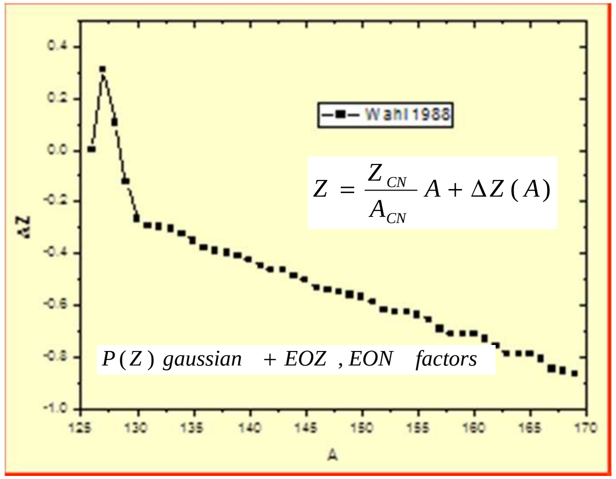
1 ***Pre-neutron mass yields from experiment or fission modes***



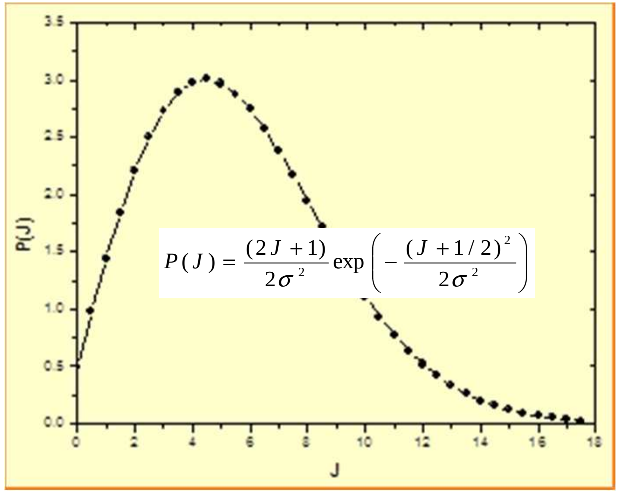
2 ***Pre-neutron kinetic energy distributions as function of mass from experiment or fission modes***



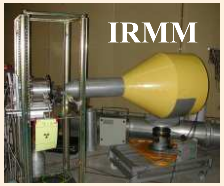
3 ***Nuclear Charge as a function of mass (Wahl model)***



4 ***Spin distribution from models***



***A** & **KE** from experiments…*



… or external codes (SPY, GEF, …)

5 *Excitation energy sharing between fragments*

At scission:

intrinsic excitation energy
+ deformation energy + collective excitation

$$TXE = a_{sc} T_{sc}^{2} + E_{def} + E_{coll}$$

After full acceleration:

the rotational energy is not included
in the intrinsic excitation energy

$$TXE = a_L T_L^2 + a_H T_H^2 + E_{rot}^{L} + E_{rot}^{H}$$

A part of excitation energy at scission is converted in
rotational energy (collective excitation)

Rotating deformed Liquid Drop model

$$E_{rot} = \frac{\hbar^2 J(J+1)}{2\Im}$$

only the intrinsic excitation energy corresponding to

$$TXE - (E_{rot}^{L} + E_{rot}^{H})$$

is partitioned through

$$E_{L,H}^{*} = a_{L,H} T_{L,H}^{2}$$

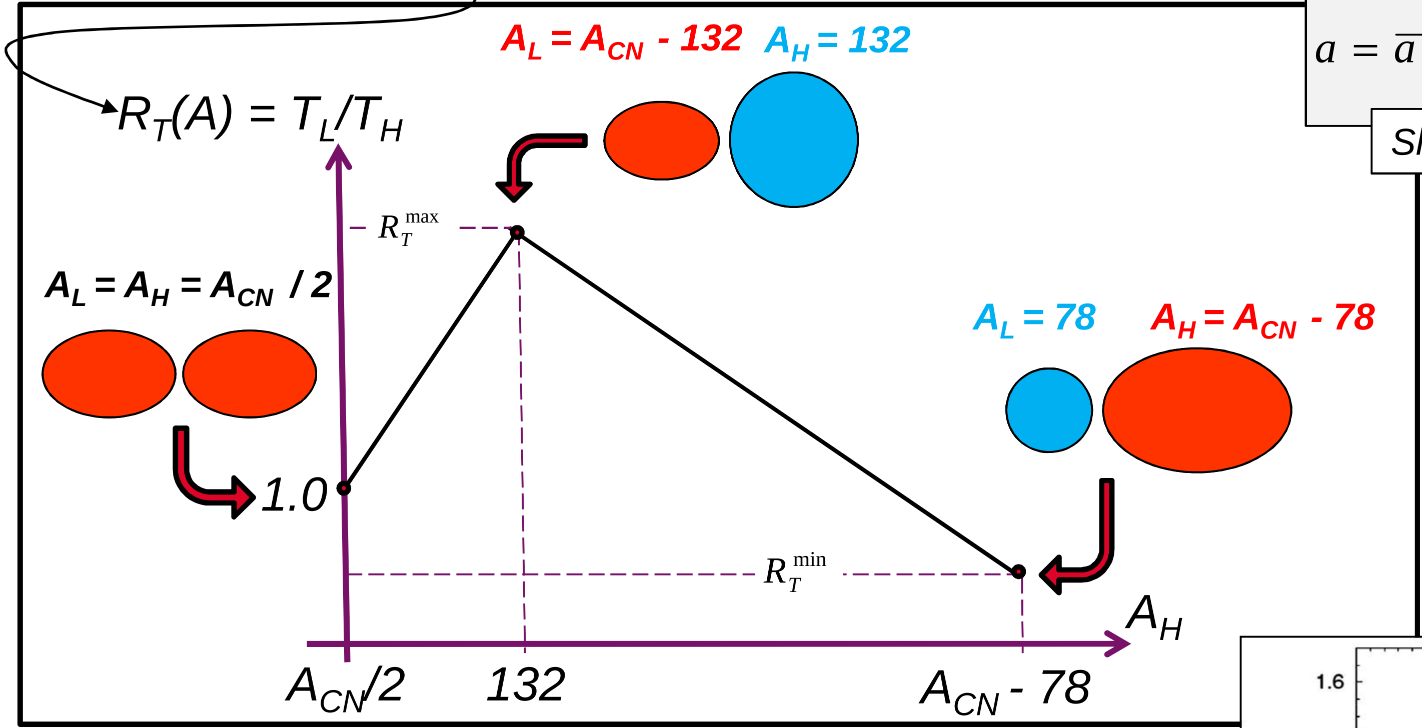
Model

$$\forall\ L,H \quad E^* = a\,T^2$$

Ignatyuk prescription

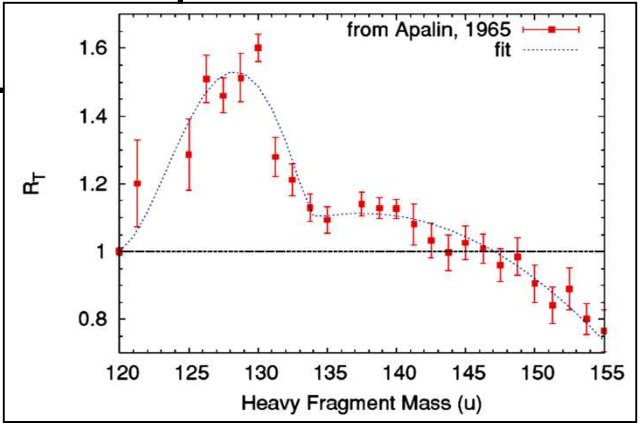
$$a = \bar{a}\left(1 + \delta W\,\frac{\left(1 - e^{-\gamma U^*}\right)}{U^*}\right)$$

Shell corrections, pairing, …



Litaize et al., Phys. Rev. C **82**, 054616 (2010)

- ❑ ***Max $R_T(A_H=130)$?***
- ❑ ***$R_T(Z,N)$?***
- ❑ ***R_T^m ?*** Serot et al., Phys. Proc. **59**, 132 (2014)



Talou et al., Phys. Rev. C **83**, 064612 (2011)

Fission Fragment deexcitation (n/γ coupled mode)

Becvar's Nuclear Realizations (*Becvar, Nucl. Instr. Meth. Phys. Res. **A417**, 434 (1998)*)
Generalized to n/γ coupled emission (*Regnier, Litaize, Serot. Comp. Phys. Comm. **210**, 19 (2016)*)

$E > E_{bin}$

The continuum is described in average (binning)

$E_{cut-off}^{RIPL\ 3} < E < E_{bin}$

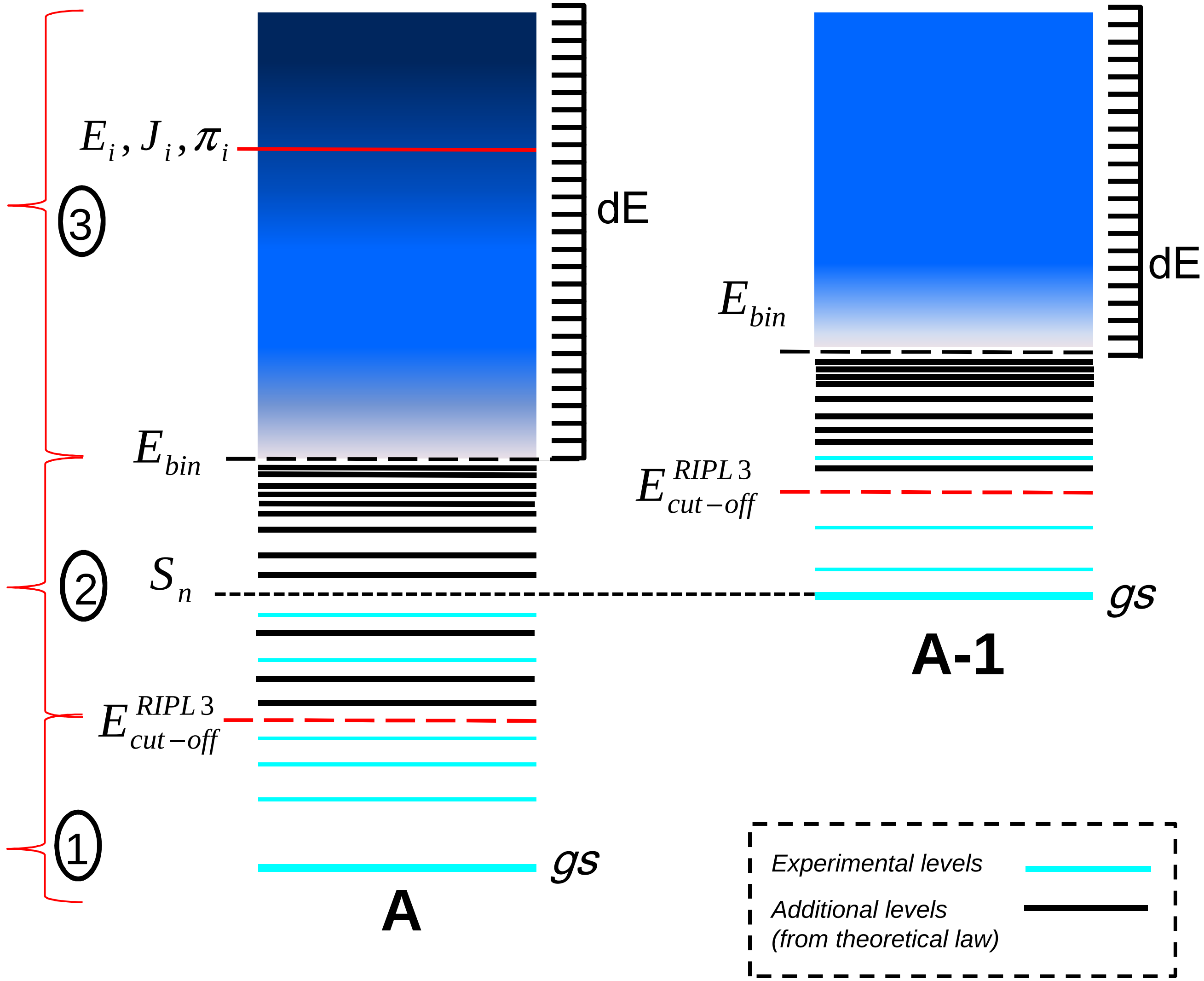
The partial experimental scheme is completed from models up to a given value of the level density (~10^5 MeV^{-1})

$E < E_{cut-off}^{RIPL\ 3}$

The experimental nuclear level scheme is complete:

$I_\gamma^{exp} \cdot (E, J, \pi)_i^{exp} \cdot t_{1/2}^{exp} \cdot \ldots$

are accounted for



Fission Fragment deexcitation (n/γ coupled mode)

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- **Neutron transitions**

Optical model potential :

- BG, KD, JLM, …

(Pre-tabulated T(l,j) FIFRELIN-library usingTalys/Ecis code for roughly 2000 FF)

- **Gamma transitions**

Level Density Models :

- CGCM, CTM, GSFM, HFB-tabulated

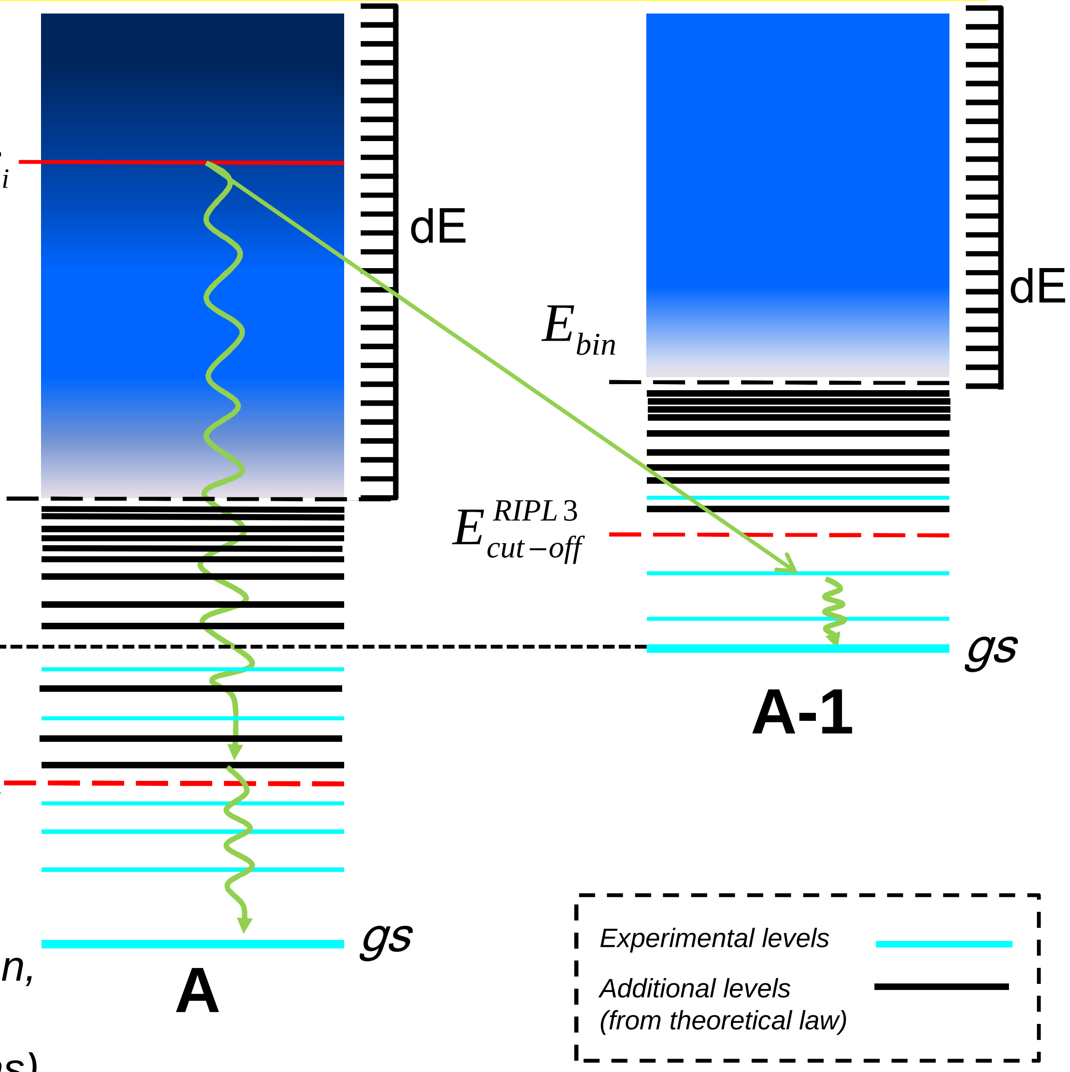
Photon Strength Function Models:

- SLO, EGLO, MLO, QRPA (from HFB or HF+BCS) tabulated

Experimental information (RIPL-3): $E^{RIPL3}_{cut-off}$

- $I_\gamma^{exp.}$, $(E, J, \pi)_i^{exp.}$, $t_{1/2}^{exp.}$ …

❑ *After nuclear level scheme construction, all partial widths are calculated (accounting for Porter Thomas fluctuations).*



The 5 free parameters of the simulation

$k, \sigma_L, \sigma_H, R_T^{min}, R_T^{max}$

- **Fraction (k) of FF moment of inertia $\mathcal{I}$**

  involved in the rotational energy formula $E_{rot} = \hbar^2 J(J+1)/(2\mathcal{I})$

  models for $\mathcal{I}$

  - Rigid spheroid : $\mathcal{I} = k \times \mathcal{I}_{rig.} = k \times 2/5\, AMR^2(1 + 0.31\beta_2 + \cdots)$
  - Hydrodynamical system : $\mathcal{I} = k \times \mathcal{I}_{fluid} = k \times (9/8\pi)\, AMR^2 \beta_2^2$
  - From AMEDEE data base : $\mathcal{I} = \mathcal{I}_{AMEDEE}$

  Hilaire et al. Eur. Phys. J. A33, 237 (2007)

- **Total angular momentum of Primary FF**

$$P(J) = \frac{(J+1/2)}{\sigma^2} \exp\left(-\frac{(J+1/2)^2}{\sigma^2}\right)$$

  - $\sigma^2 \sim \mathcal{I} T / \hbar^2$
  - $<\sigma_L>$, $<\sigma_H>$
  - $<J>(A) \rightarrow \sigma(A)$
  - $<J>(A,E^*) \rightarrow \sigma(A,E^*)$

L. Thulliez, O. Litaize, O. Serot, ,
Eur. Phys. J. W. Conf. 111, 10003 (2016)

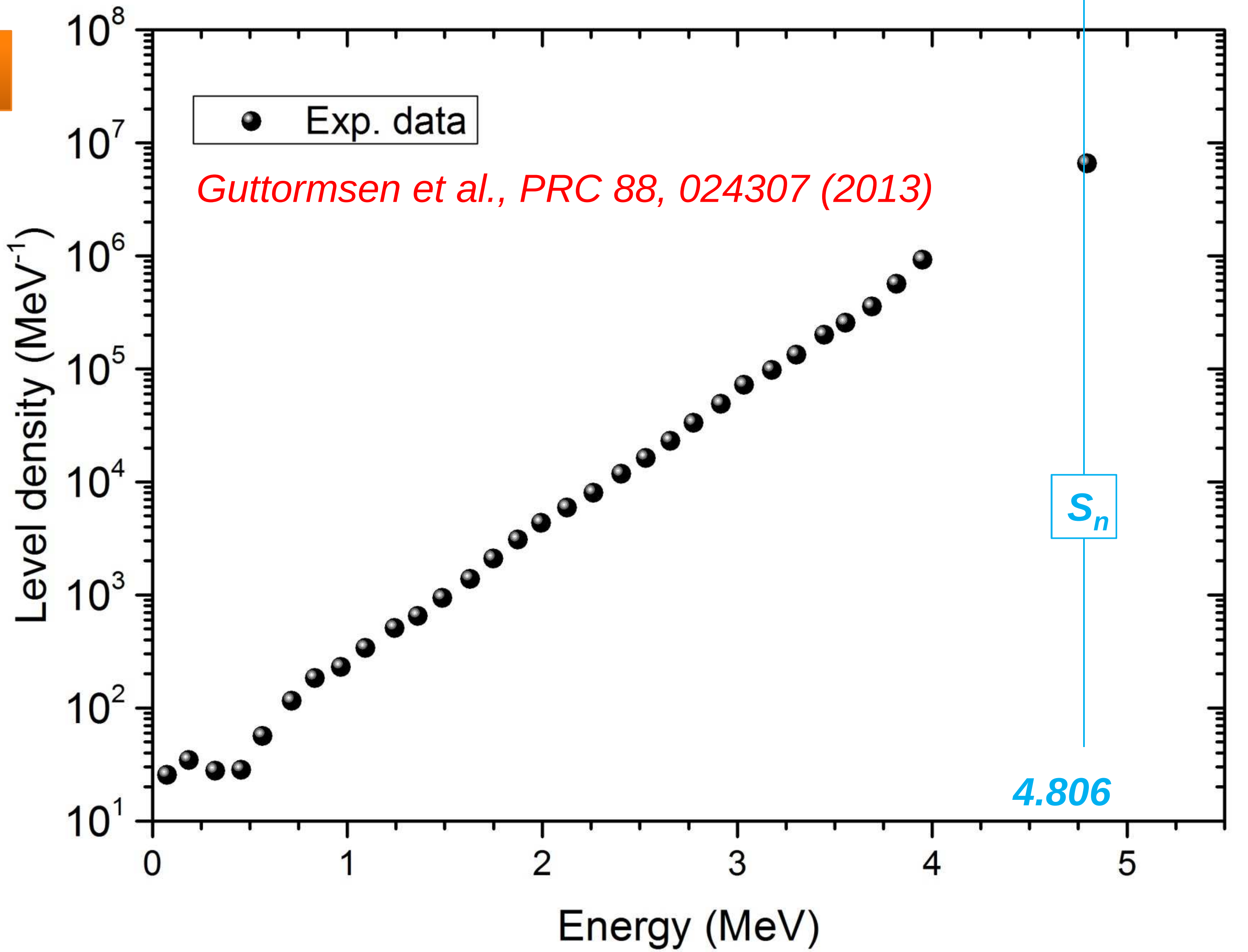
- **Anchor points for Temperature ratio law $R_T(A)$** R_T^{min} , R_T^{max}

DE LA RECHERCHE À L'INDUSTRIE

Influence of shell corrections on level densities

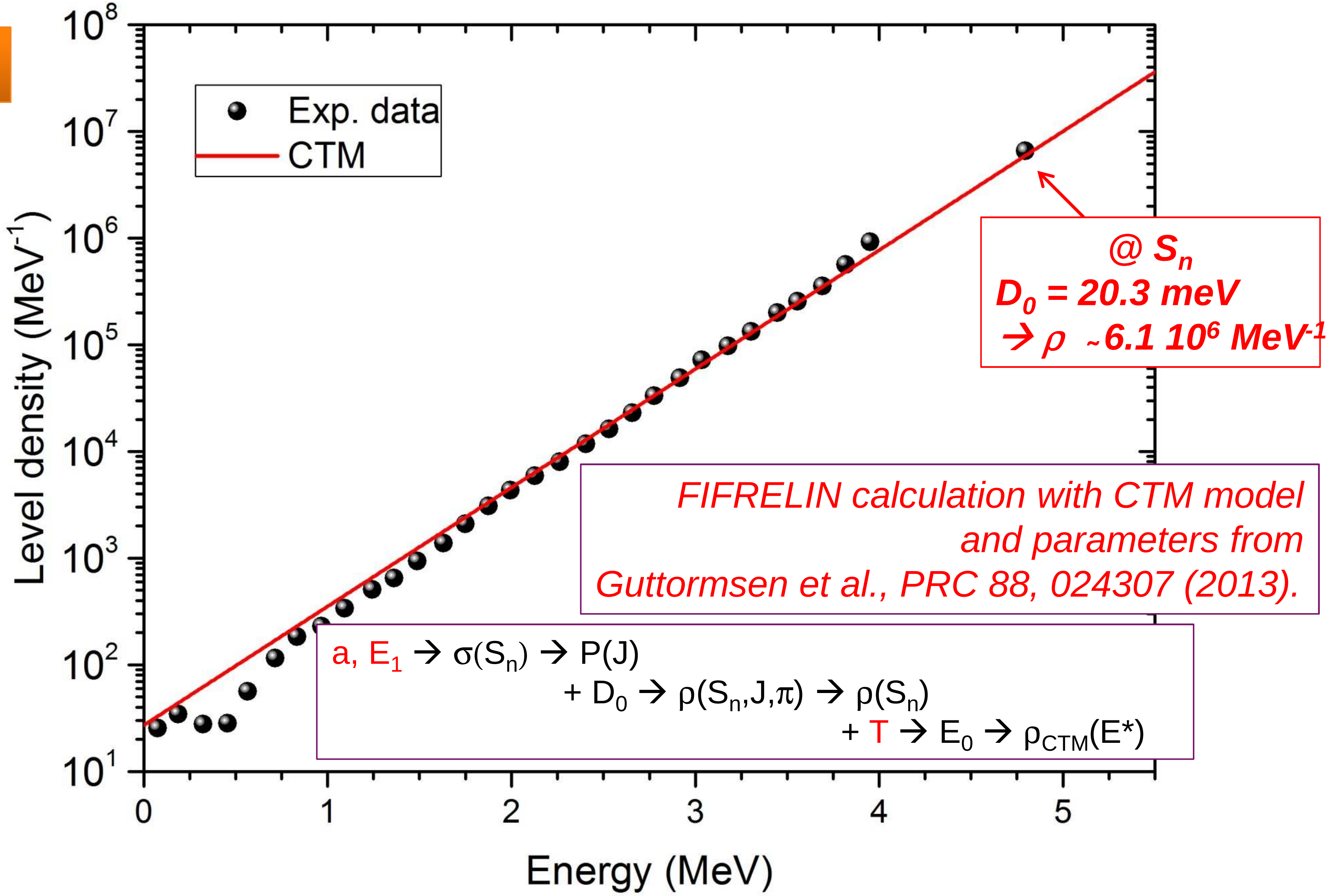
Influence of shell corrections on level densities

^{239}U



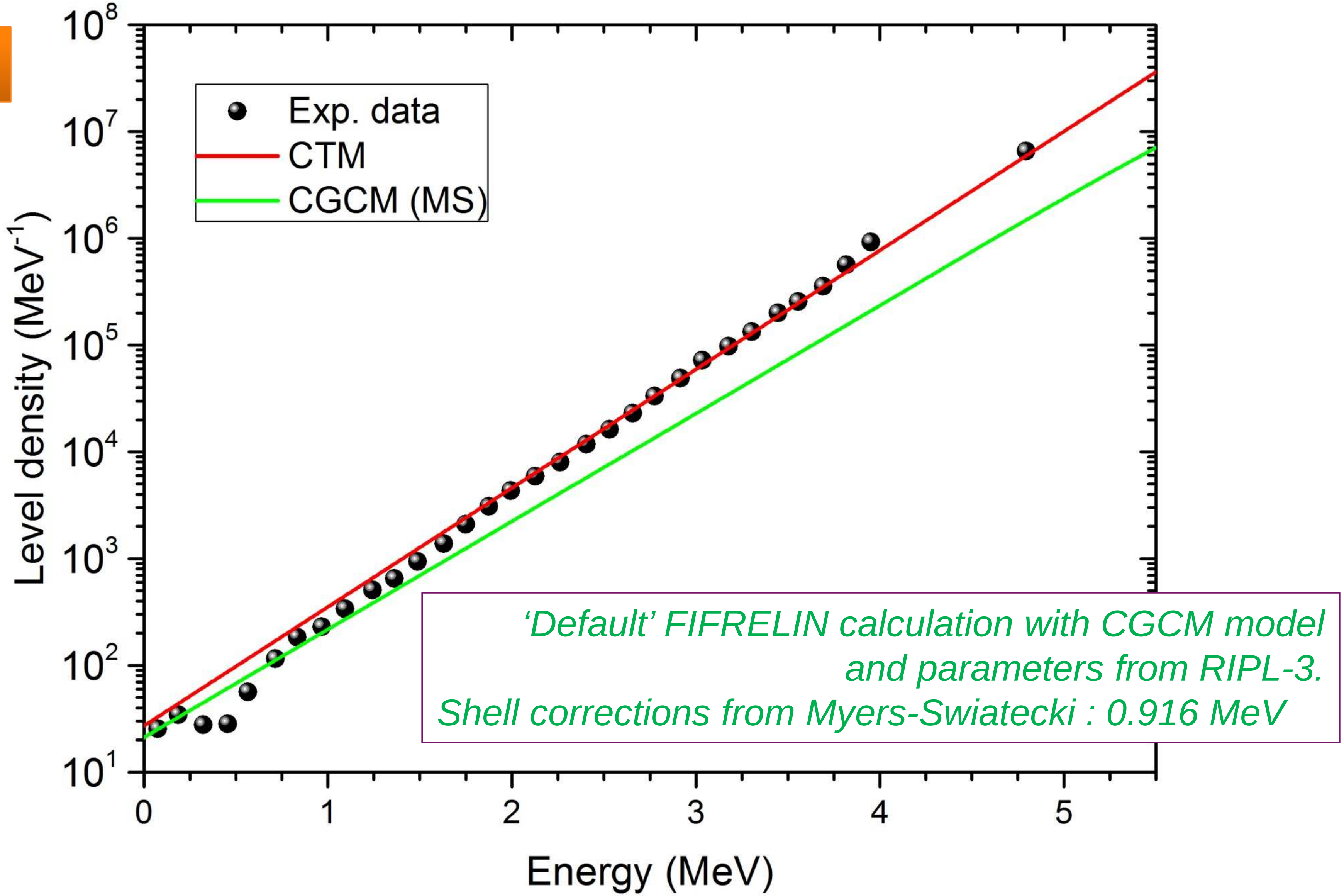
Influence of shell corrections on level densities

^{239}U



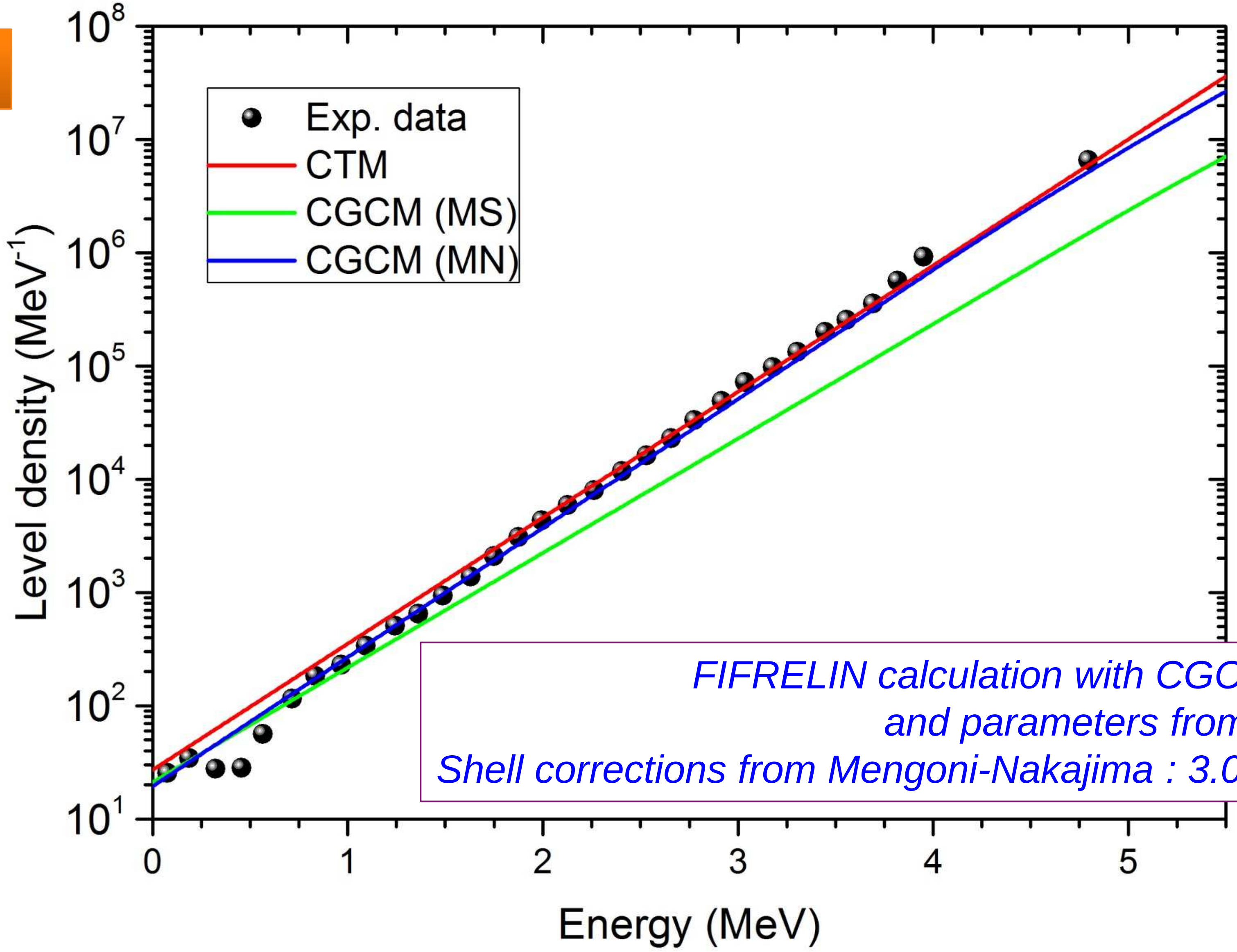
Influence of shell corrections on level densities

^{239}U



Influence of shell corrections on level densities

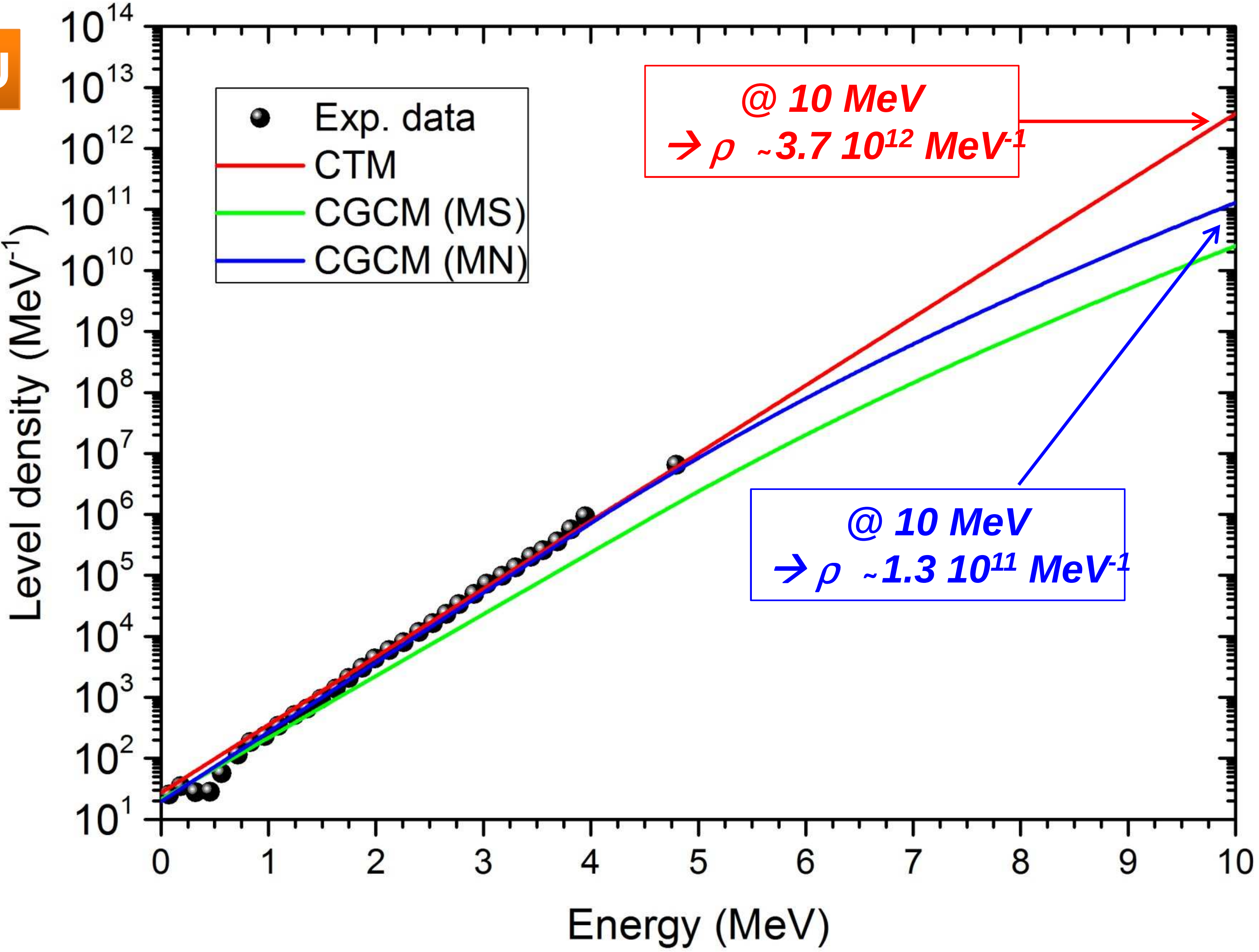
^{239}U



FIFRELIN calculation with CGCM model and parameters from RIPL-3.
Shell corrections from Mengoni-Nakajima : 3.077 MeV

Influence of shell corrections on level densities

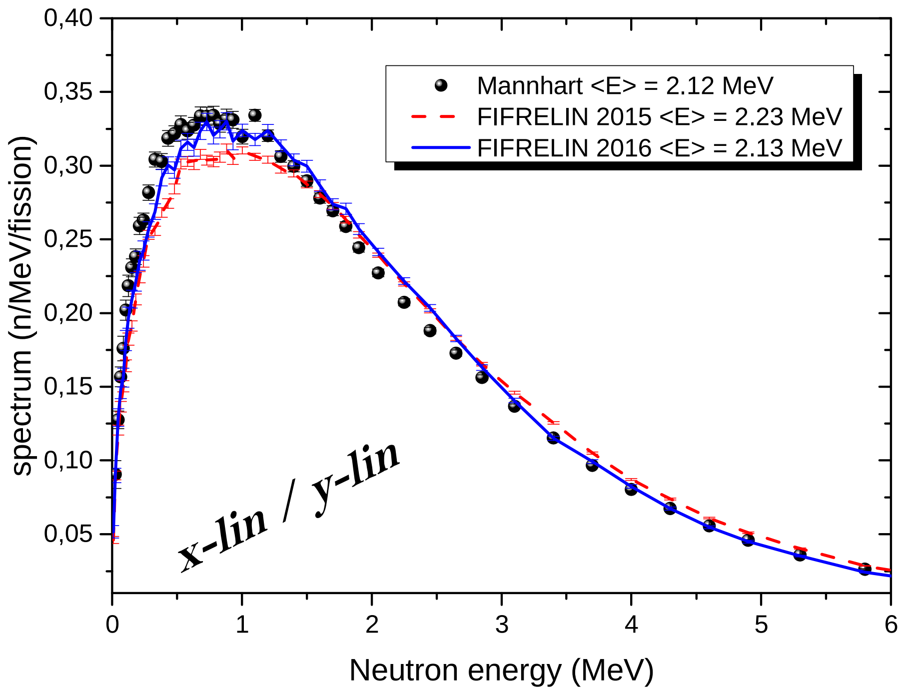
^{239}U

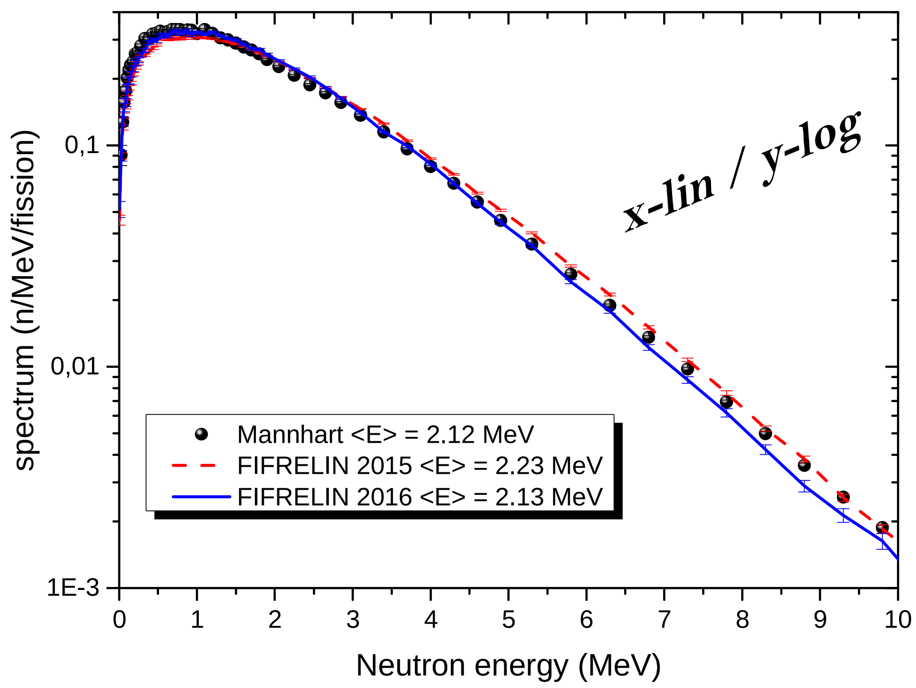


Impact of shell corrections
on prompt fission neutron spectra

$^{252}Cf(sf)$

-- 2015 ≡ shell corrections = Myers-Swiatecki (δW=MS)
-- 2016 ≡ shell corrections = Mengoni-Nakajima (δW=MN)





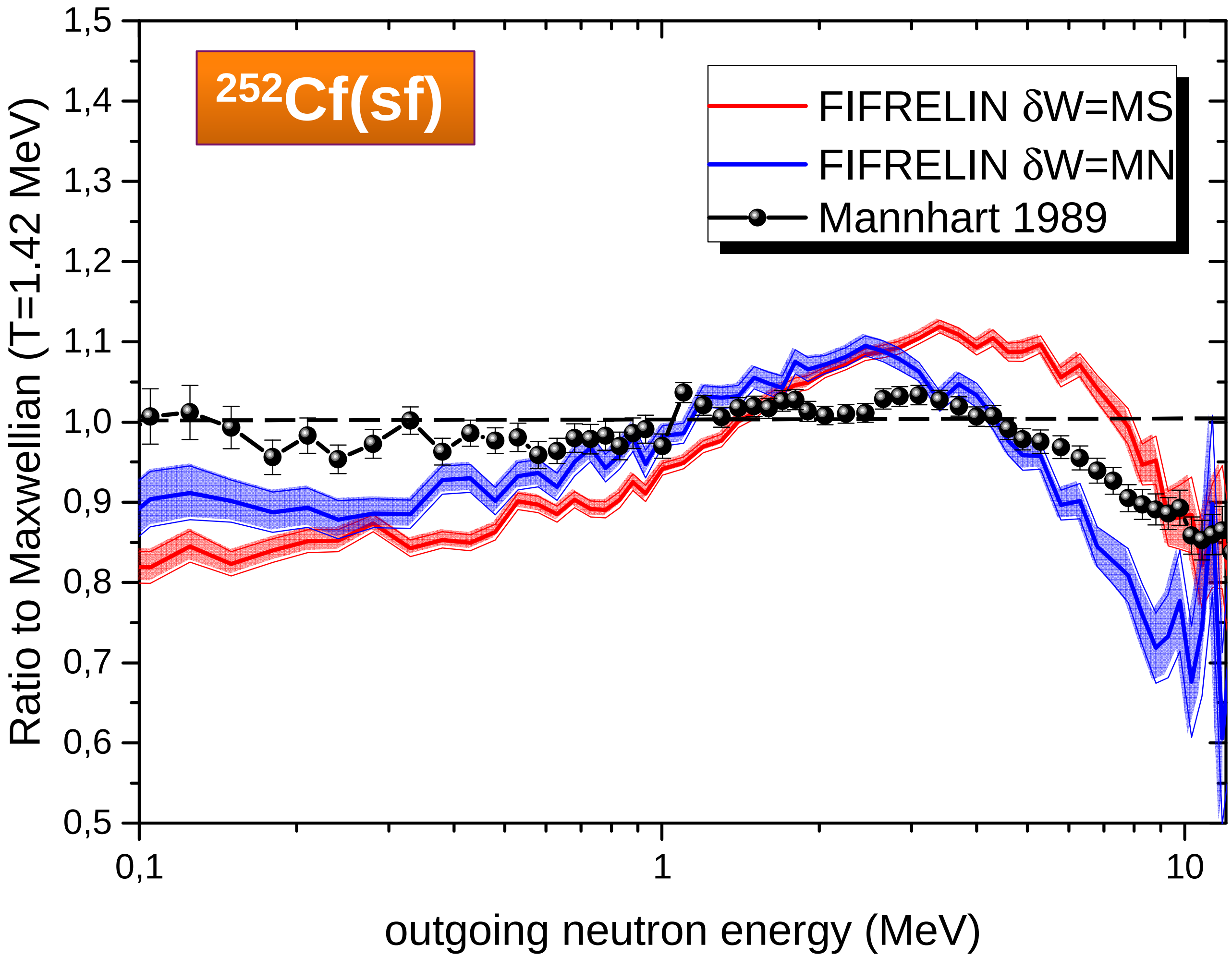
Average neutron energy <E>

Mannhart (non-smooth data):	***2.12 MeV***
Mannhart (smooth evaluation):	***2.13 MeV***
FIFRELIN (δW=MS):	***2.23 MeV***
FIFRELIN (δW=MN):	***2.13 MeV***

- ❑ Level densities increased
- → Low neutron energy transitions increased
- → PFNS softer.

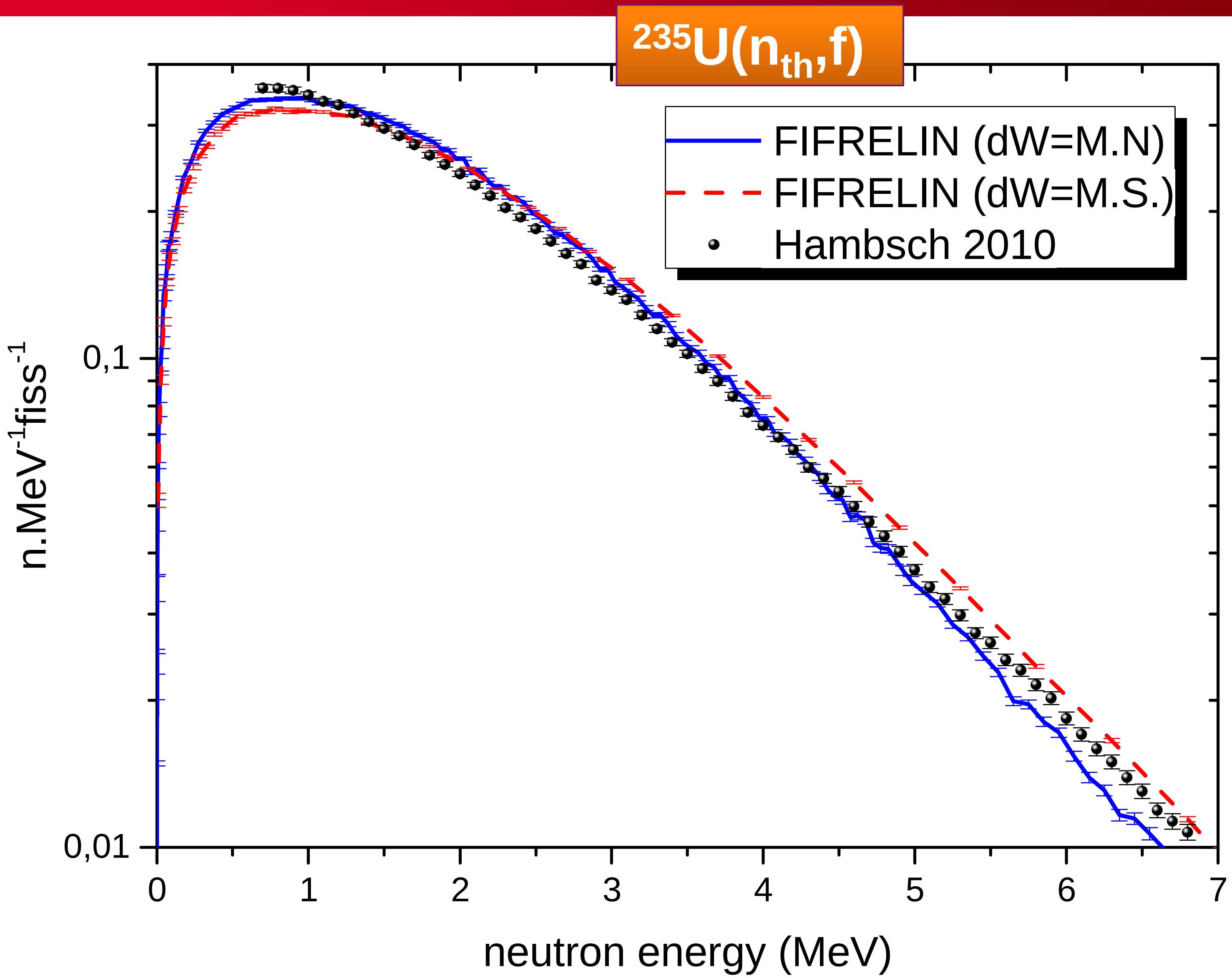
Prompt fission neutron spectra

Ratio to Maxwellian T=1.42 MeV (<E>=2.13 MeV)



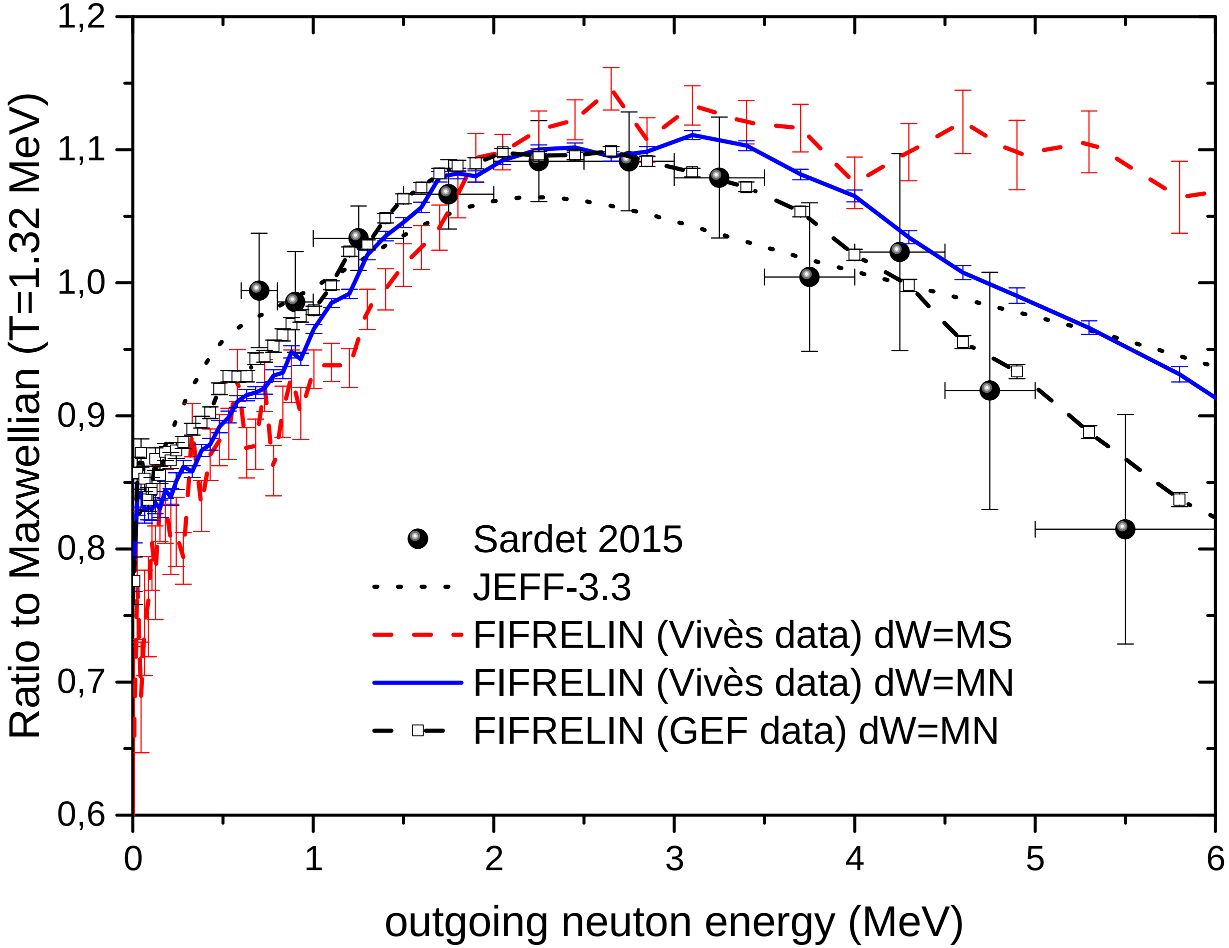
(Mannhart/FIFRELIN)
R < 10% up to 8MeV

Prompt fission neutron spectra



Prompt fission neutron spectra

^{238}U(n,f) @ 2 MeV



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  Influence of shell corrections on LDs and PFNS*

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  $\overline{\nu}(A) \quad \overline{\nu}(TKE) \quad \overline{\nu}(TKE; A)$

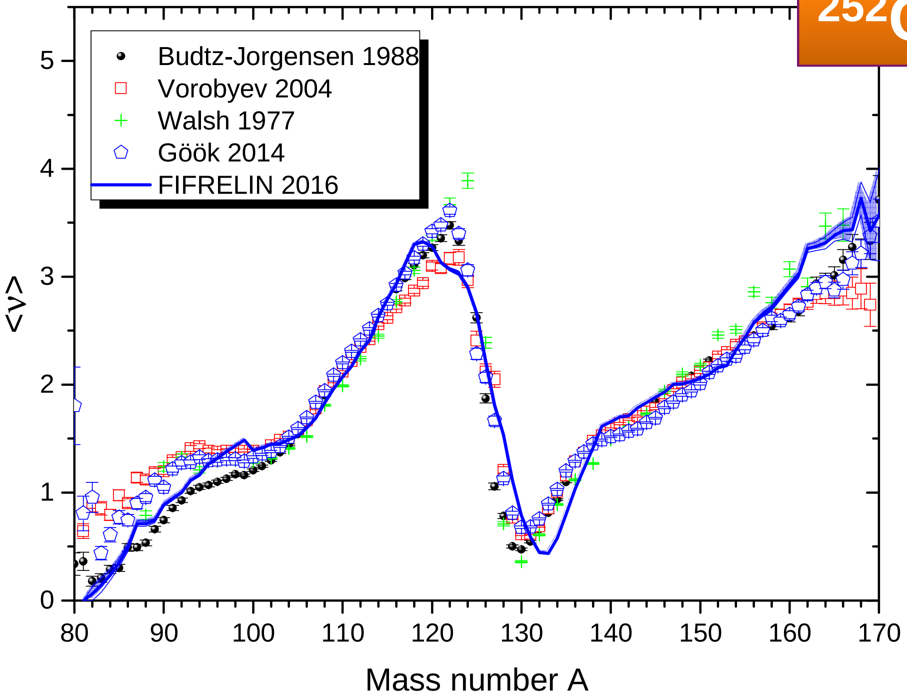
- *Prompt fission gamma observables*

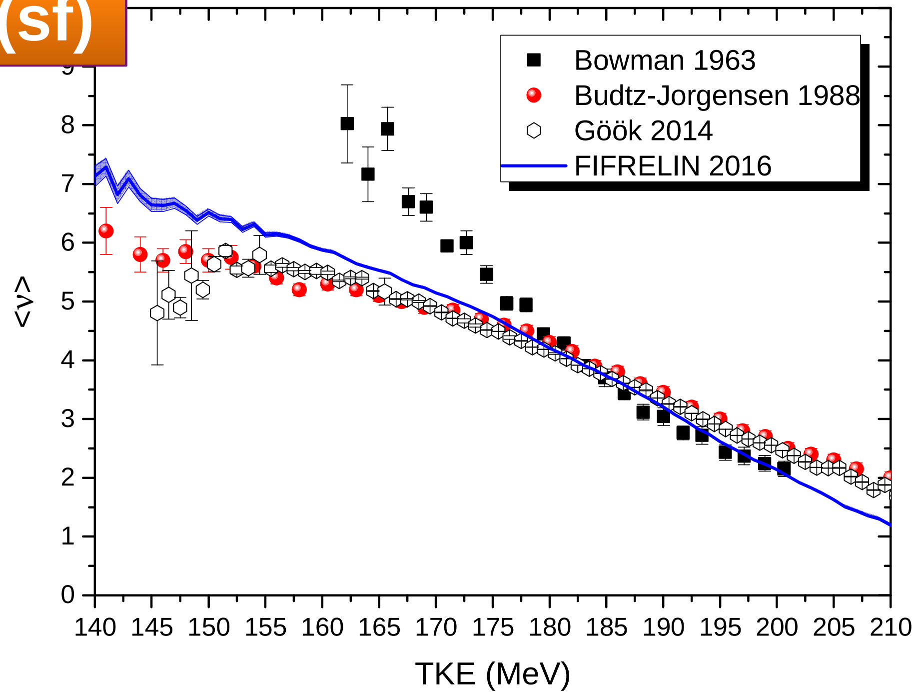
  PFGS(A) , PFGS(A,Z)$_{post}$

- *Conclusion & Outlook*

Average prompt neutron multiplicity as a function of A and TKE

$^{252}Cf(sf)$





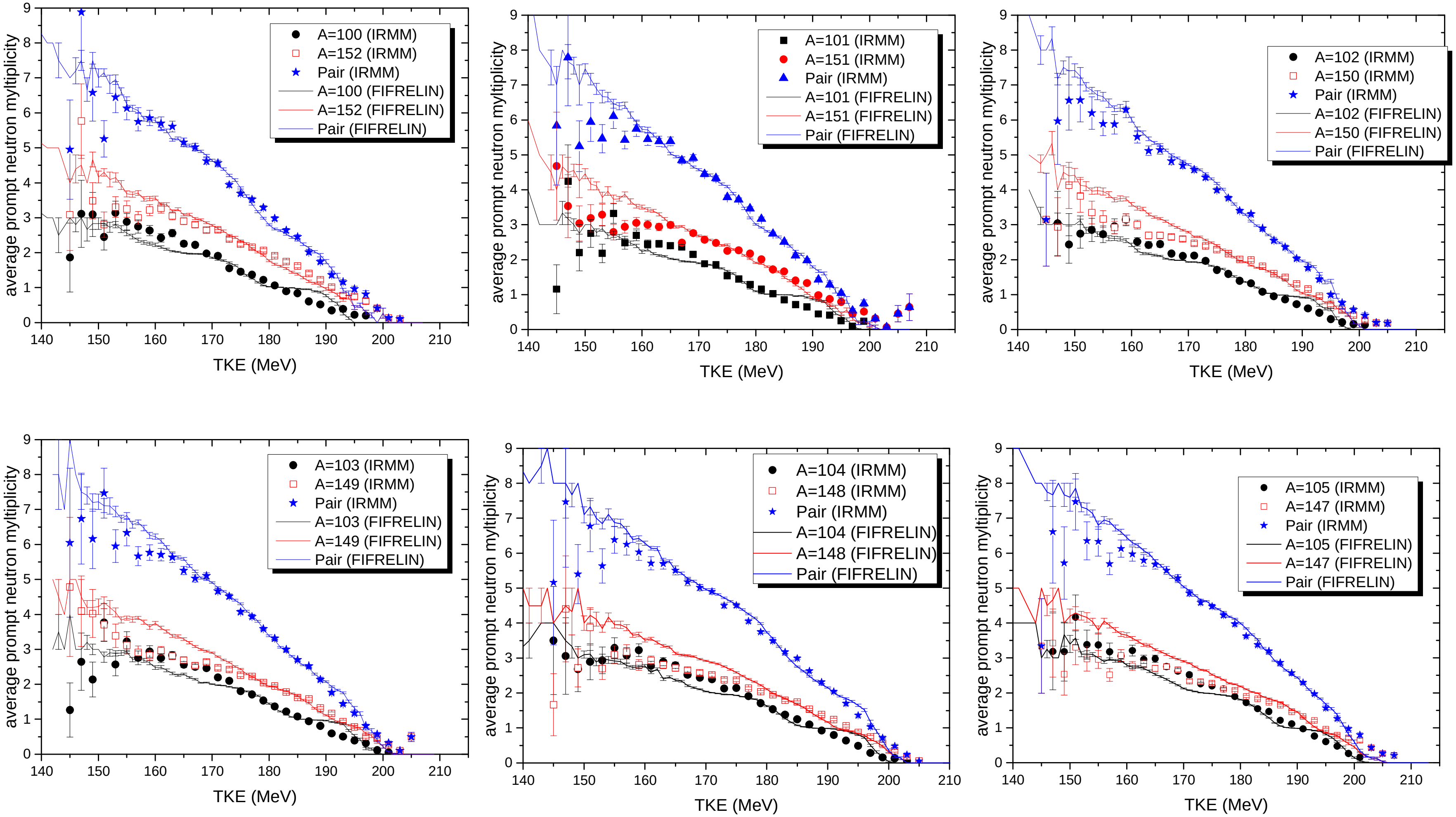
- ❑ Overall good agreement
- ❑ Minimum neutron emission in the heavy peak around mass 132 compared to 130 in experiments *(clearly related to the model)*
- ❑ *Influence of $R_T(A)$ law*

❑ If overestimated calculation at low TKE
→ could be explained by the widths of TKE distributions (*Litaize et al., JEFDOC-1643 (2015)*)

❑ If underestimated measurement at low TKE
→ could be explained by electronic temperature drift (*A. Göök, F.-J. Hambsch, M. Vidali, Phys. Rev. C 90, 064611 (2014)*)

Average prompt neutron multiplicity as a function of TKE for a given mass split

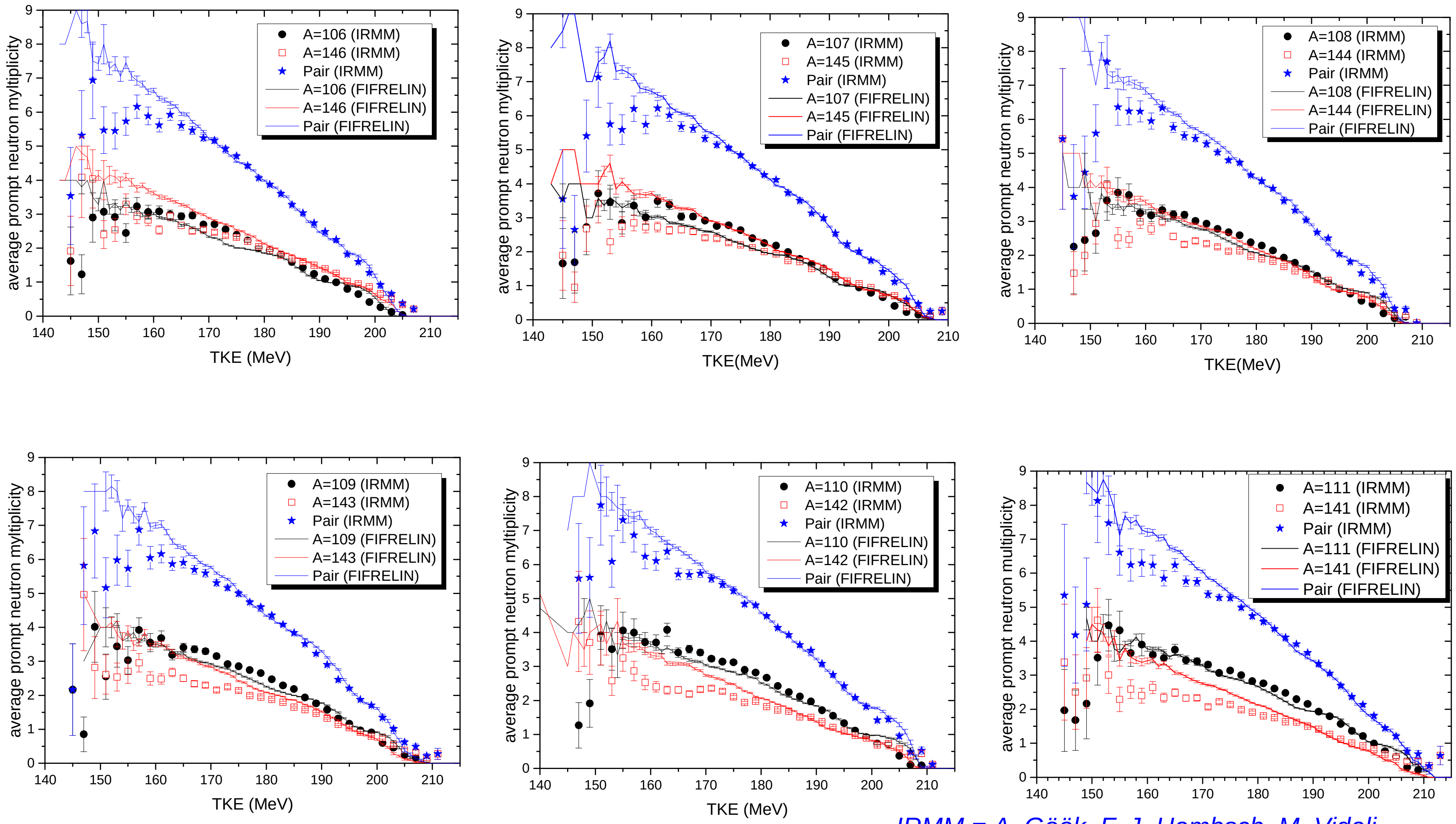
$^{252}Cf(sf)$



IRMM = A. Göök, F.-J. Hambsch, M. Vidali, Phys. Rev. C 90, 064611 (2014)

Average prompt neutron multiplicity as a function of TKE for a given mass split

$^{252}Cf(sf)$



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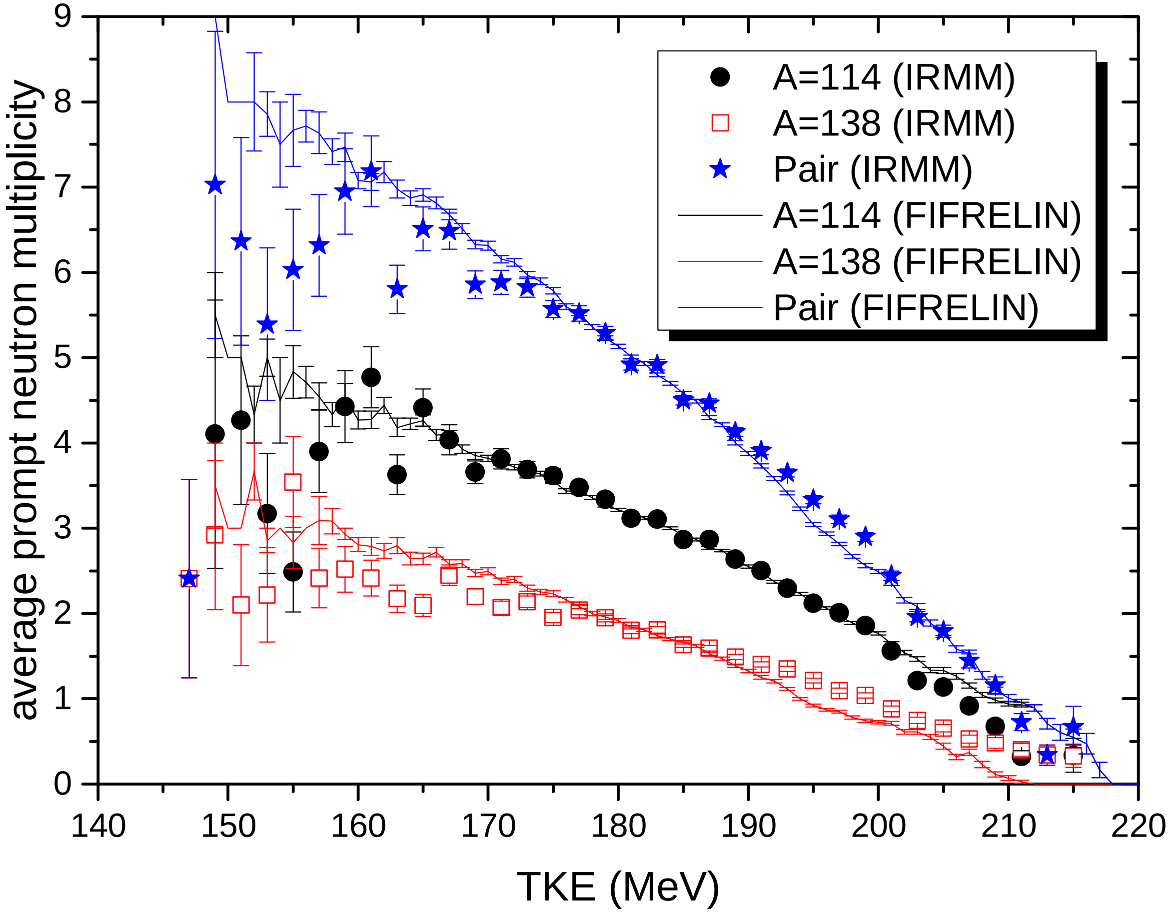
Average prompt neutron multiplicity as a function of TKE for a given mass split

^{252}Cf(sf)

Selected case
$\{ A_L , A_H \} = \{ 114 , 138 \}$

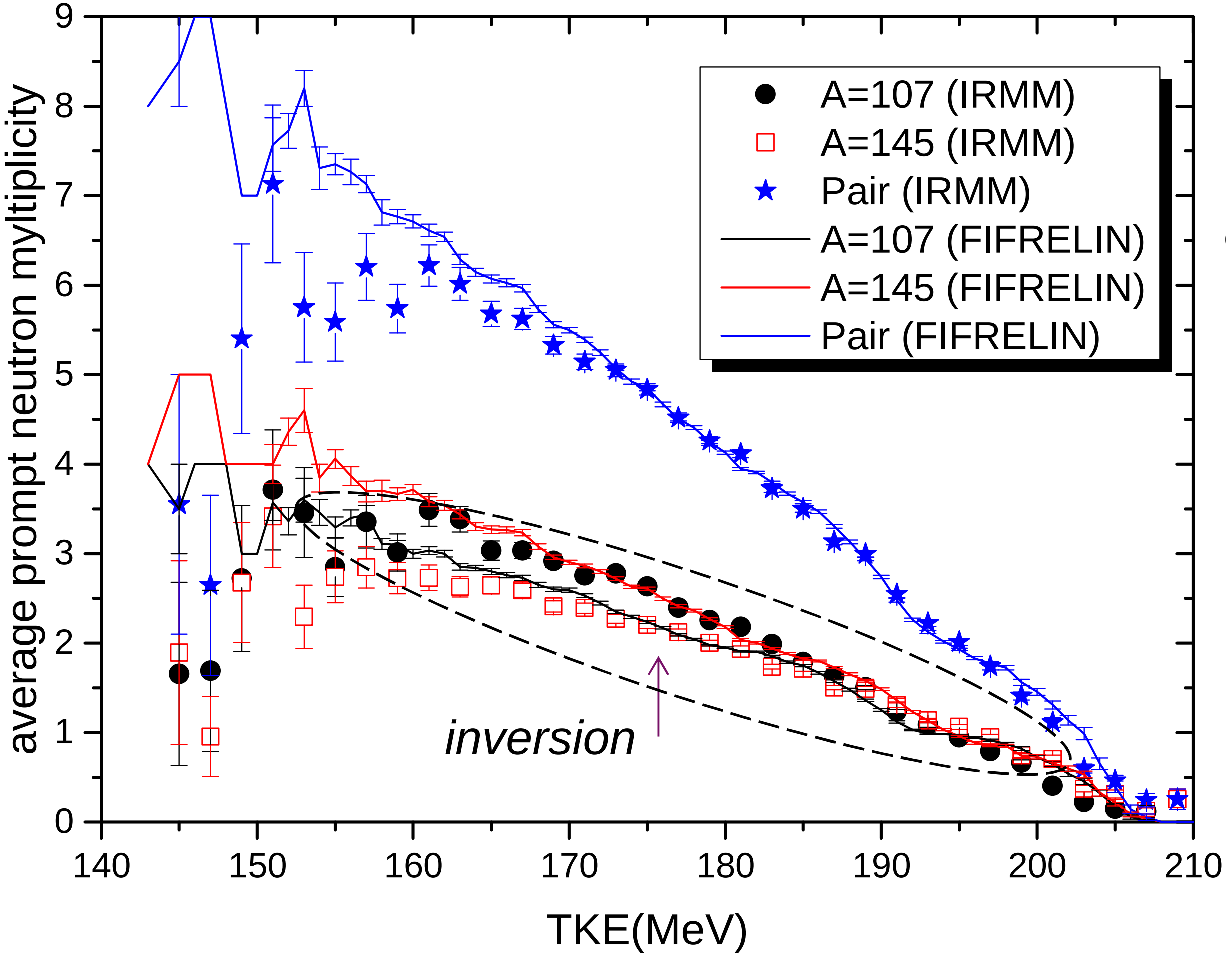


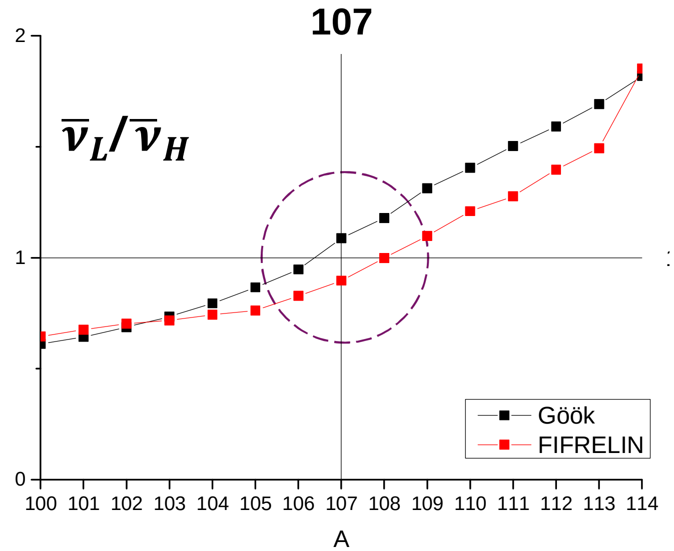
- Quite good over the whole TKE range

IRMM = A. Göök, F.-J. Hambsch, M. Vidali, Phys. Rev. C 90, 064611 (2014)

Average prompt neutron multiplicity as a function of TKE for a given mass split

Selected case
$\{ A_L , A_H \} = \{ 107,145 \}$



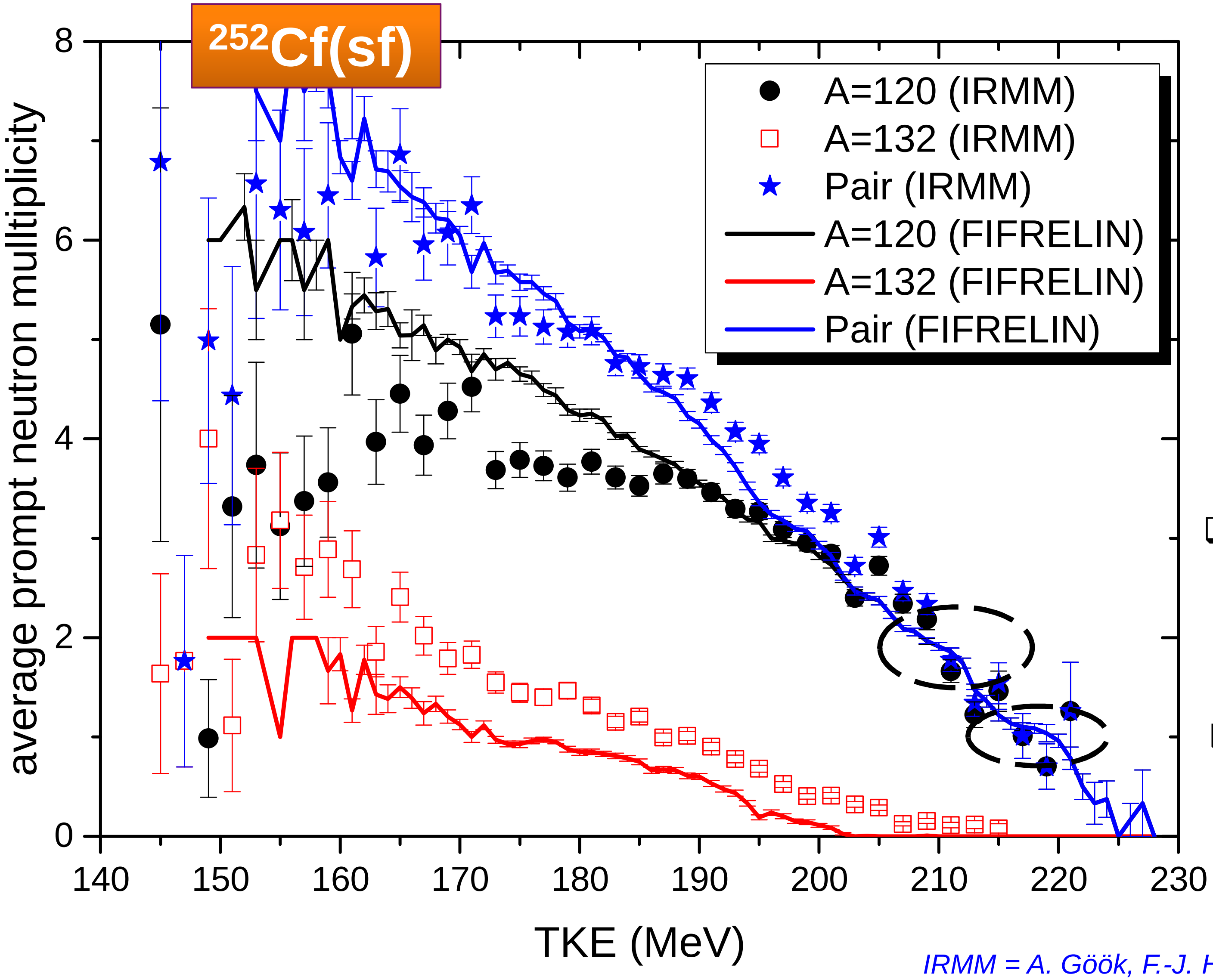


- ❑ Light fragment (A=107) emits less neutron than heavy one (A=145) compared to measurements
  - *Calc* $\bar{\nu}_L/\bar{\nu}_H < 1$
  - *Exp:* $\bar{\nu}_L/\bar{\nu}_H > 1$

This can be observed in the saw-tooth !

This is true for the whole TKE range → R_T(A=107) fails !

Average prompt neutron multiplicity as a function of TKE for a given mass split

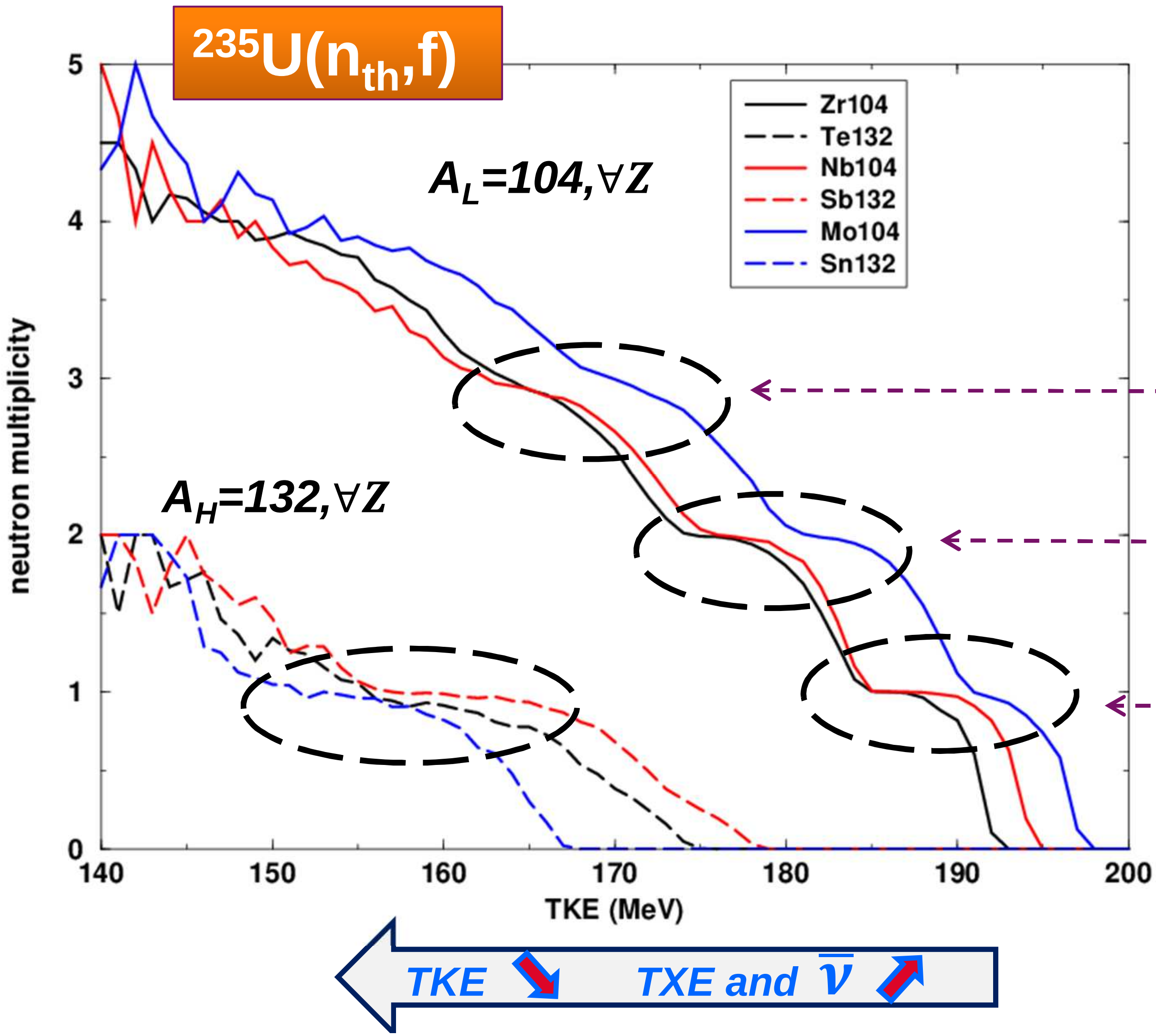


Selected case
$\{A_L, A_H\} = \{120,132\}$

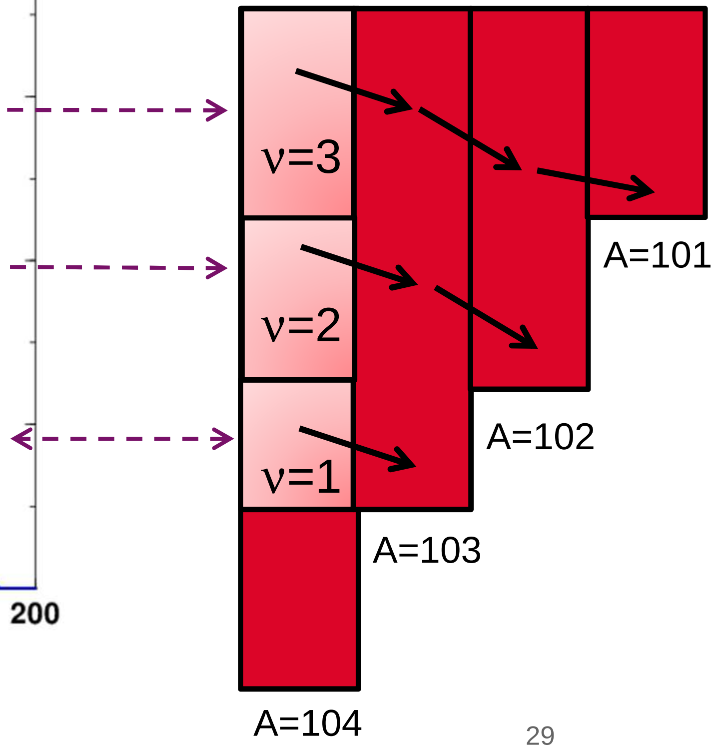
- Overestimation at low TKE for light fragment
- Structures observed in calculation (light fragment)
- Neutron emission underestimated for A=132 over the whole TKE range

IRMM = A. Göök, F.-J. Hambsch, M. Vidali, Phys. Rev. C 90, 064611 (2014)

Average prompt neutron multiplicity as a function of TKE for selected fragments



- Calculated structures are imposed by the nuclear level scheme (S_n and J^{π} set)



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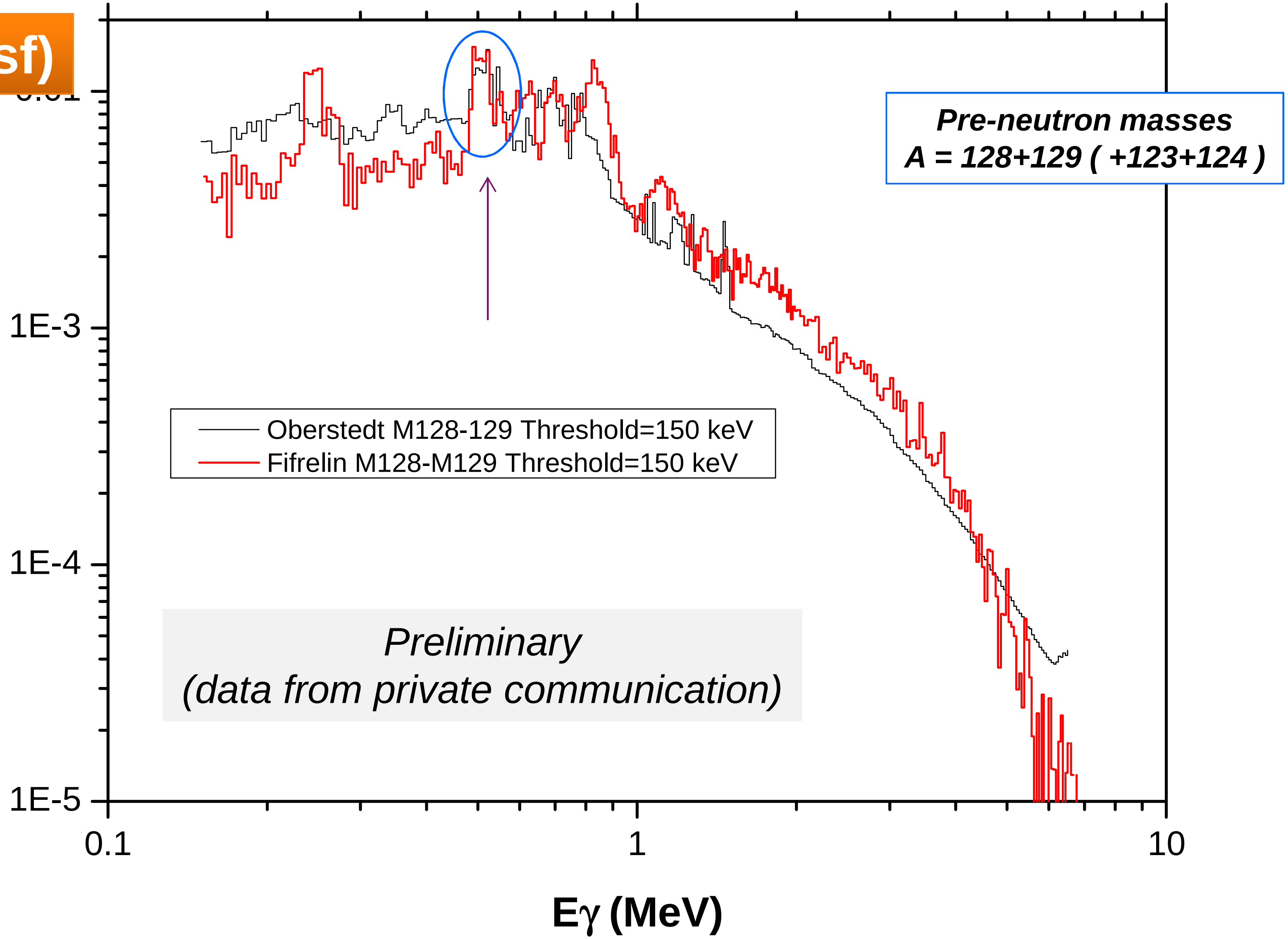
  PFGS(A) , PFGS(A,Z)$_{post}$

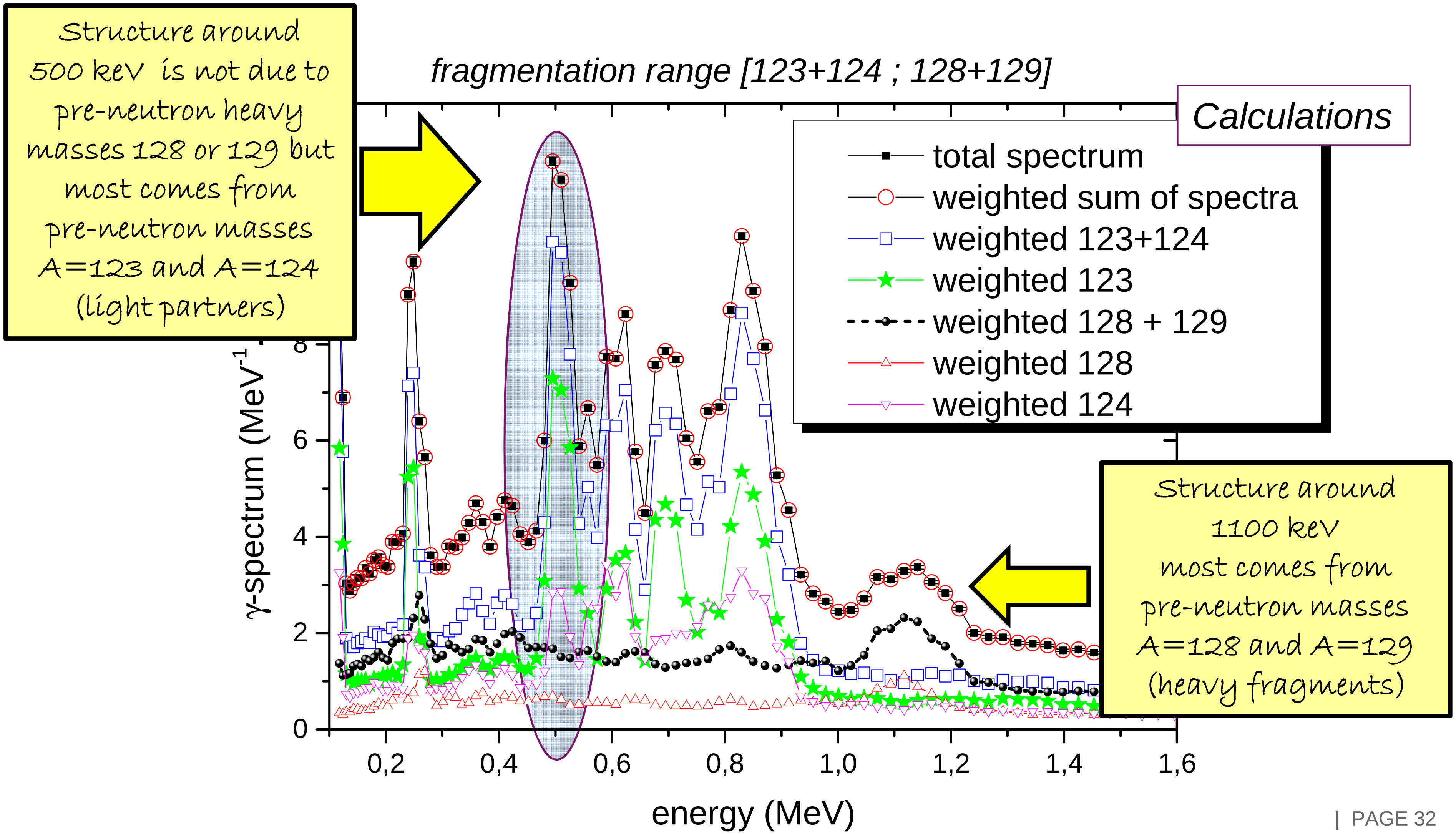
- ***Conclusion & Outlook***

Prompt fission gamma spectra for a given mass range

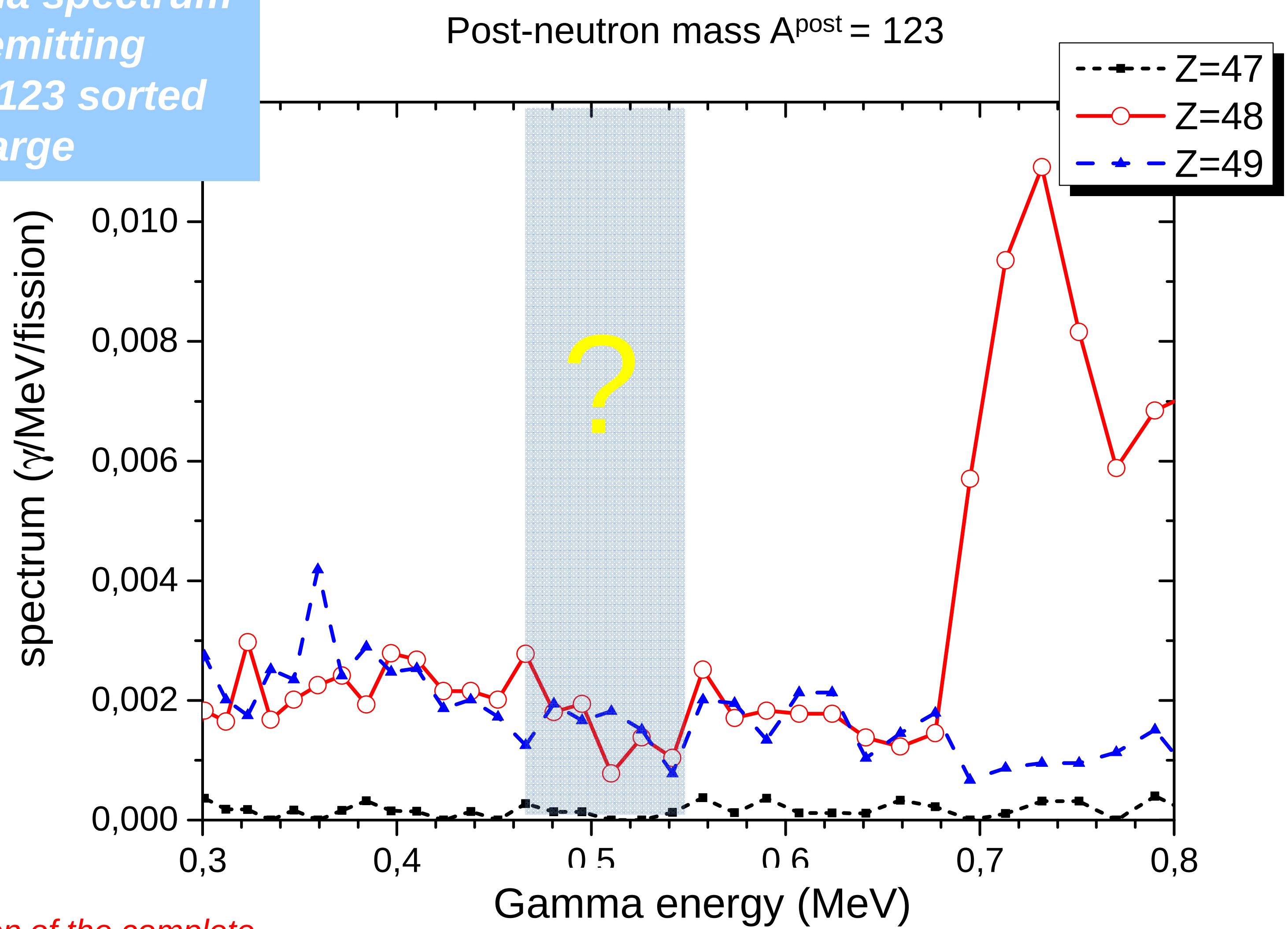
$^{252}Cf(sf)$



Calculated results for a restricted initial fragmentation range

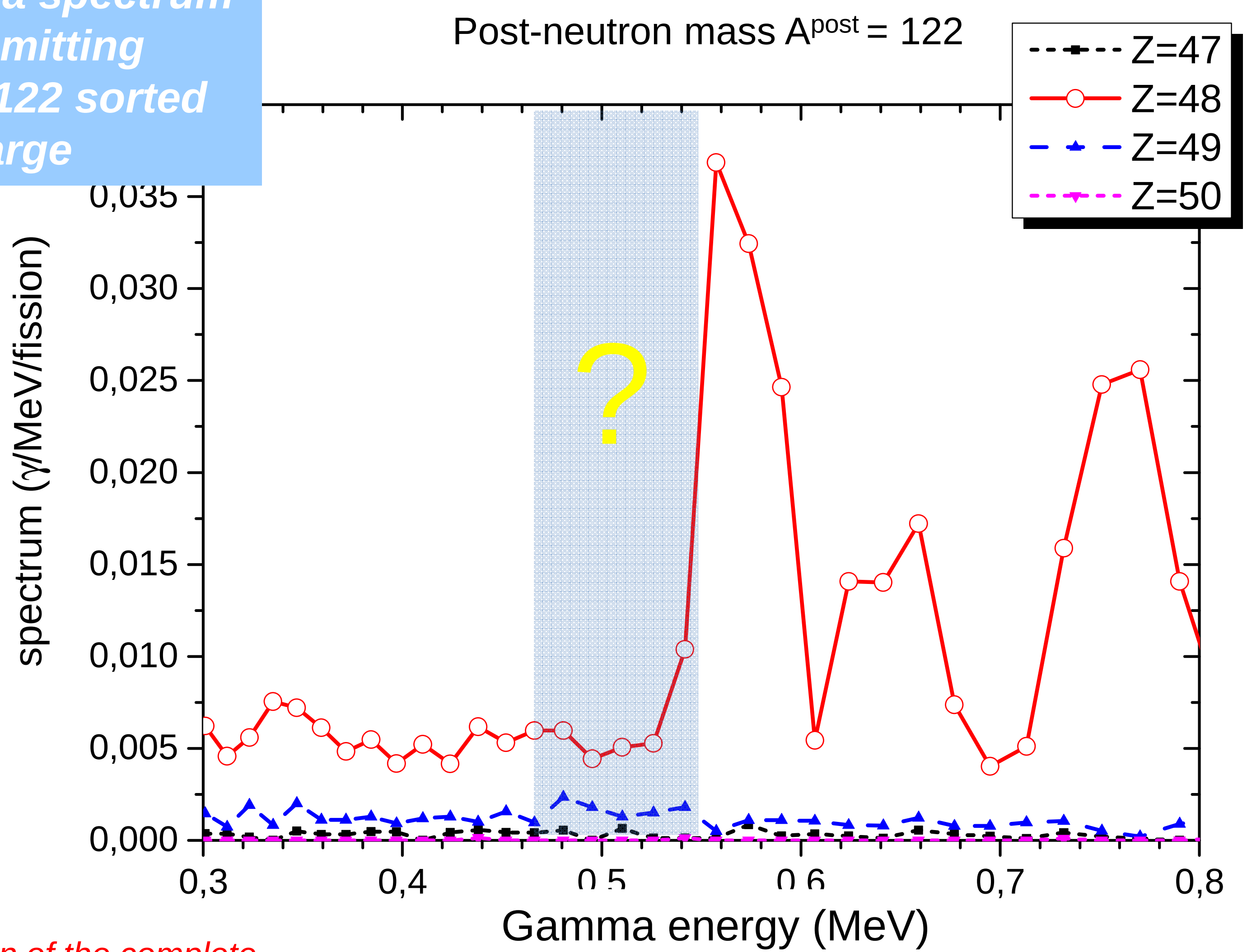


Gamma spectrum from emitting mass 123 sorted by charge



Simulation of the complete initial mass range

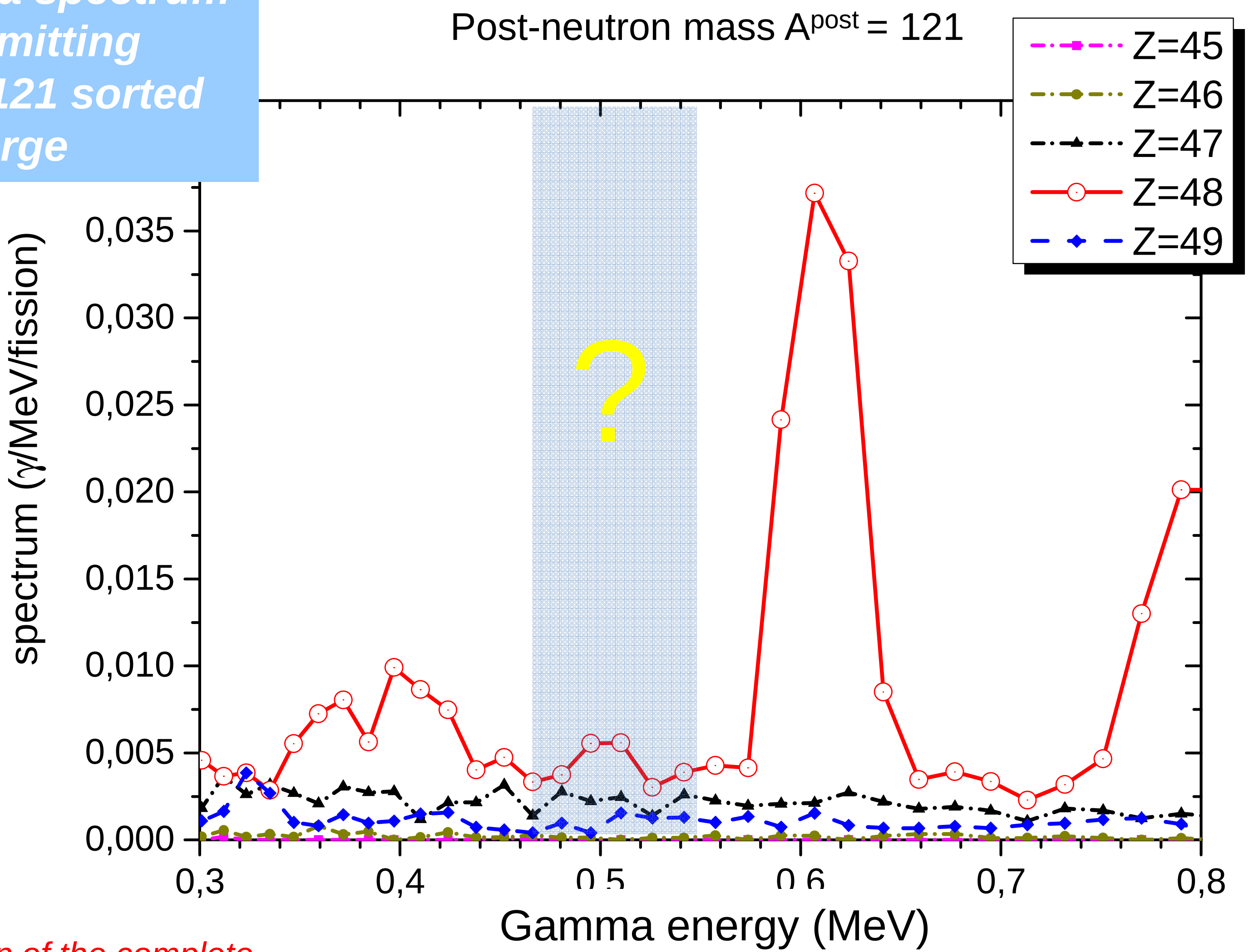
Gamma spectrum from emitting mass 122 sorted by charge



Simulation of the complete initial mass range

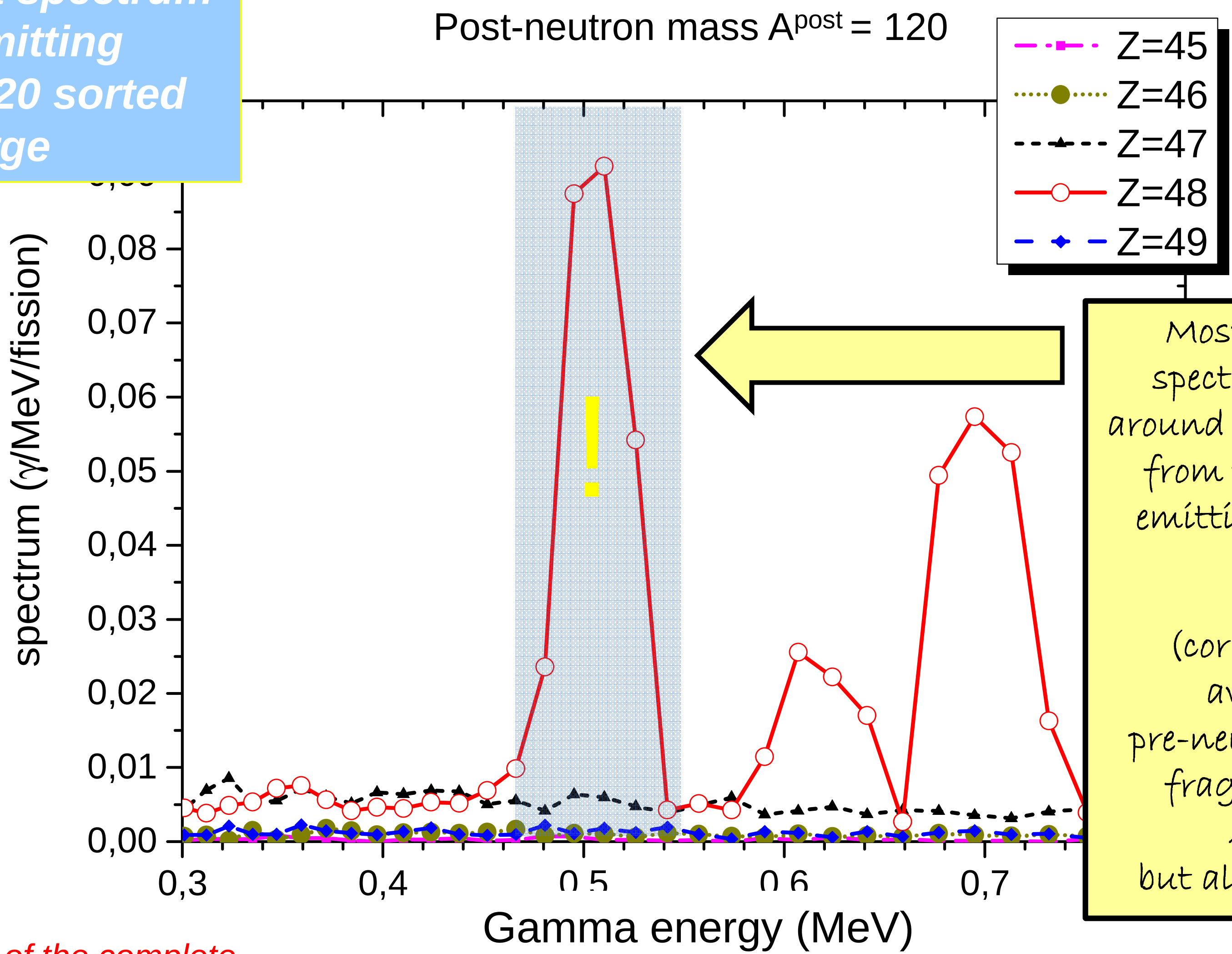
Prompt fission gamma spectra for a given mass range

Gamma spectrum from emitting mass 121 sorted by charge



Simulation of the complete initial mass range

Gamma spectrum from emitting mass 120 sorted by charge



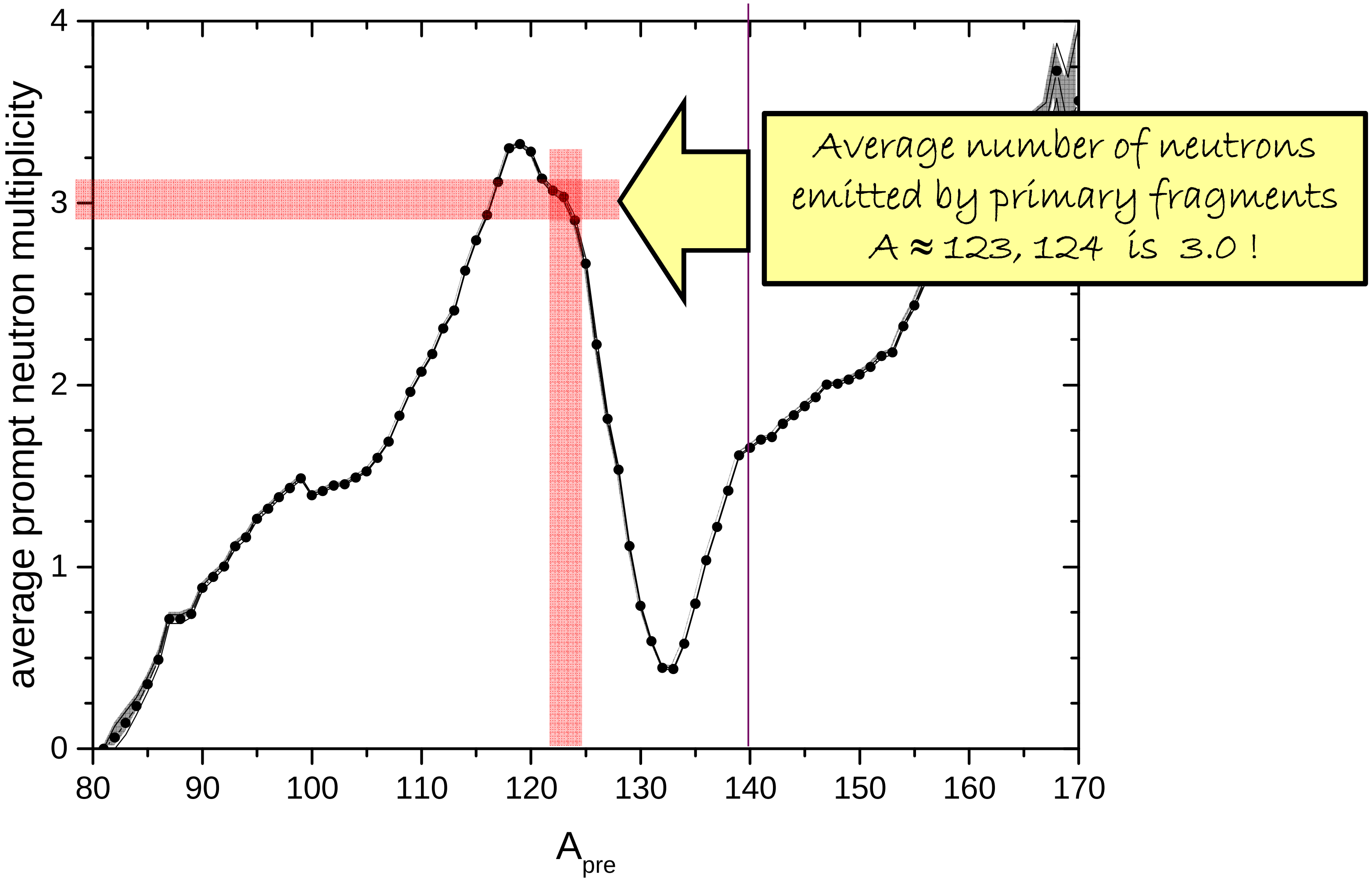
Most part of the spectrum in peak around 500 keV comes from post-neutron emitting fragment

$^{120}_{48}\mathrm{Cd}$

(corresponds in average to pre-neutron primary fragment mass A=123 but also A=124...)

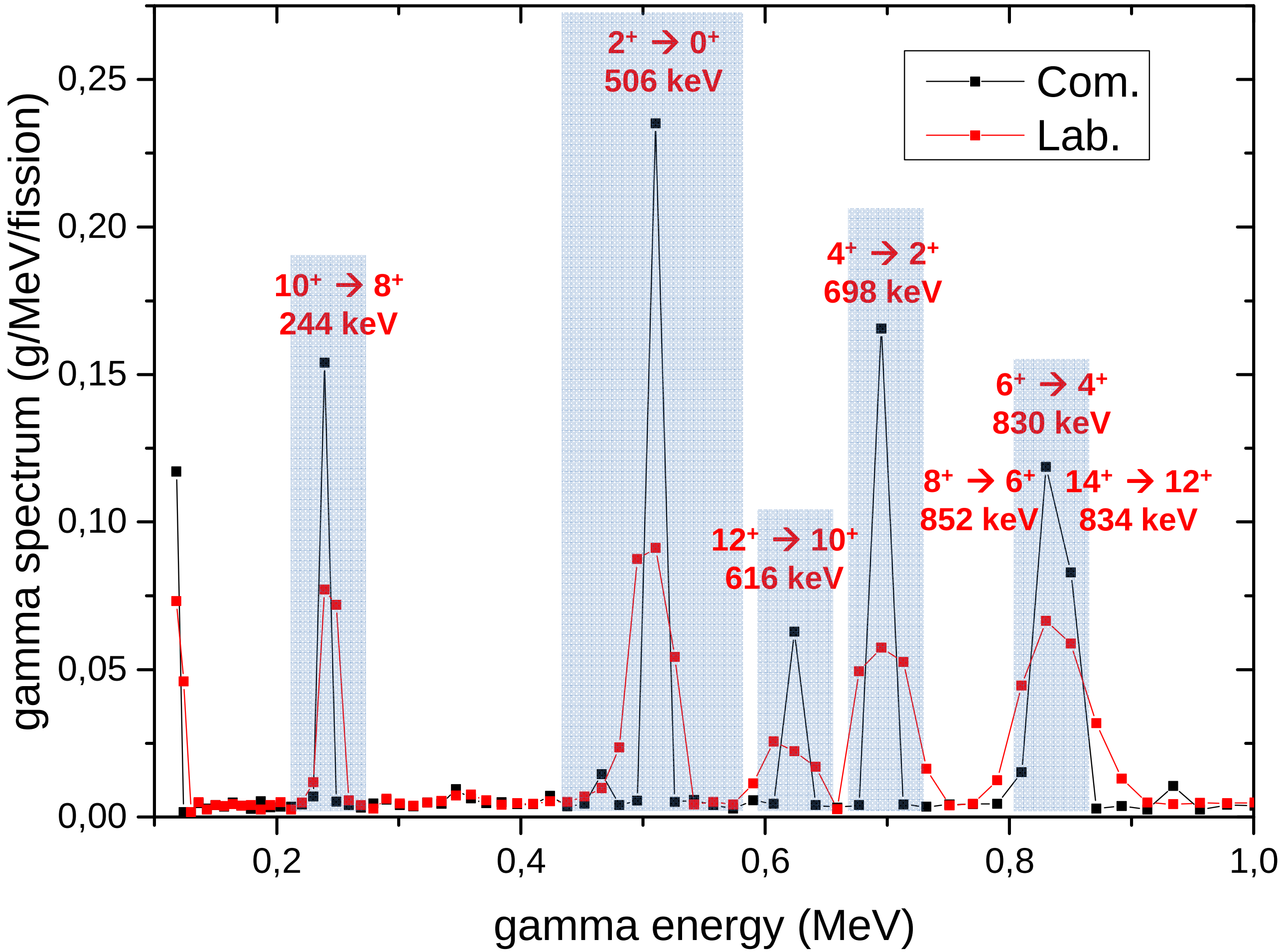
Simulation of the complete initial mass range

… which is consistent with the saw-tooth $\bar{\nu}(A)$

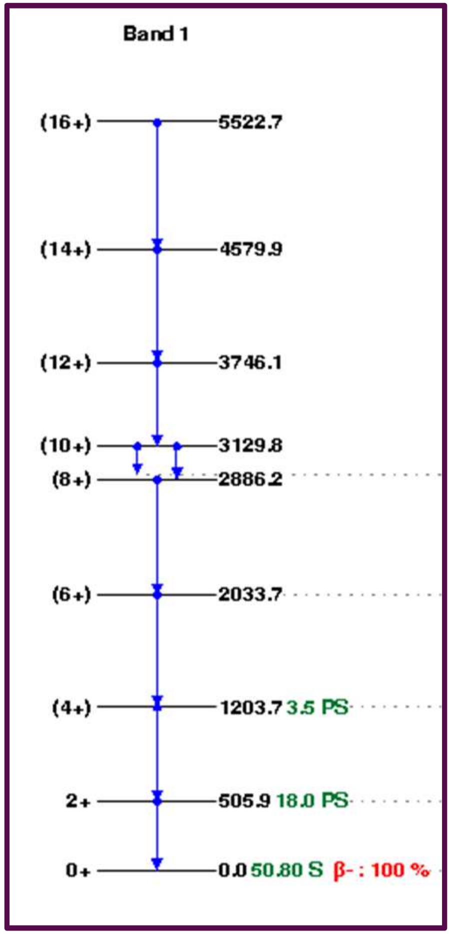


Prompt fission gamma spectra for a given mass range

^{120}Cd gamma spectrum below 1MeV

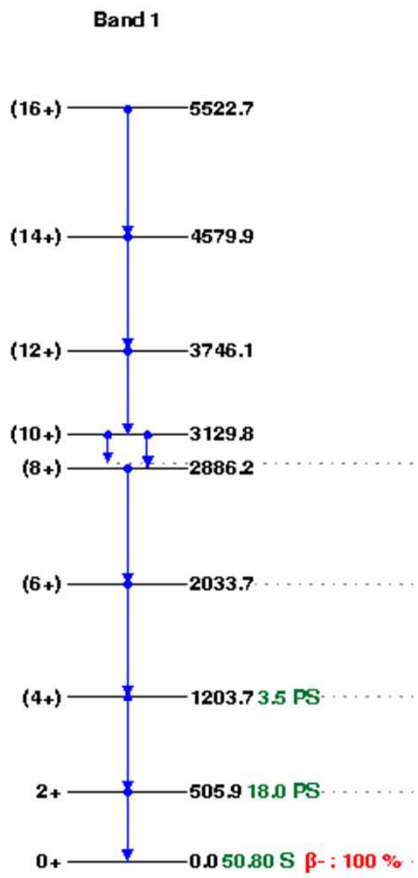


Nuclear level scheme



Prompt fission gamma spectra for a given mass range

- It is possible to disantangle which fragment is behind a structure in the prompt gamma spectrum (sorted by mass ranges).
- The presence of a structure (several transitions in a peak for a given resolution) is imposed by the nuclear level scheme (mostly the experimental part).
- Models (PSF, LD, Spin cut-off, …) can influence the relative intensity of a peak compared to another one (different feeding of different bands). Influence of primary yields cannot be neglected. Poor knowledge of nuclear structure (level scheme) can influence position of peaks (bad spin/parity assignment for instance)



Remember that models are used

- *to determine the (E*,J$^\pi$) entry zone (for primary fragments)*
- *to construct the level scheme*

- *Model*

  Influence of shell corrections on LDs and PFNS*

- *Prompt fission neutron observables*

  $\overline{\nu}(A)$ $\overline{\nu}(TKE)$ $\overline{\nu}(TKE;A)$

- *Prompt fission gamma observables*

  PFGS(A) , PFGS(A,Z)$_{post}$

- ***Conclusion & Outlook***

Conclusion

- PFNS improved (Mengoni-Nakajima shell corrections) .
- More and more experimental data, more and more sensitive (PFGS(A) or PFNM(TKE) for selected mass splits... very useful for model testing purpose.
- Nuclear level scheme can be modified (spin/parity assignment) through FIFRELIN code to reproduce experimental differential data.
- The TKE range of the $\nu(A)$ over/underestimation can be adressed.
- Primary TKE distributions impact neutron/gamma emission (by modifying the (E^*,J) entry zone for primary FF).

Trees of fission events are generated in the actual release of the FIFRELIN code
(not fully exploited yet).

Any kind of fission observable can be analyzed through a dedicated software (Energy and time thresholds can be tuned in the software 'offline' to reproduce the experimental conditions).

APPLICATIONS

- Kinetic energy dependent Isomeric ratio measured at LOHENGRIN spectrometer.

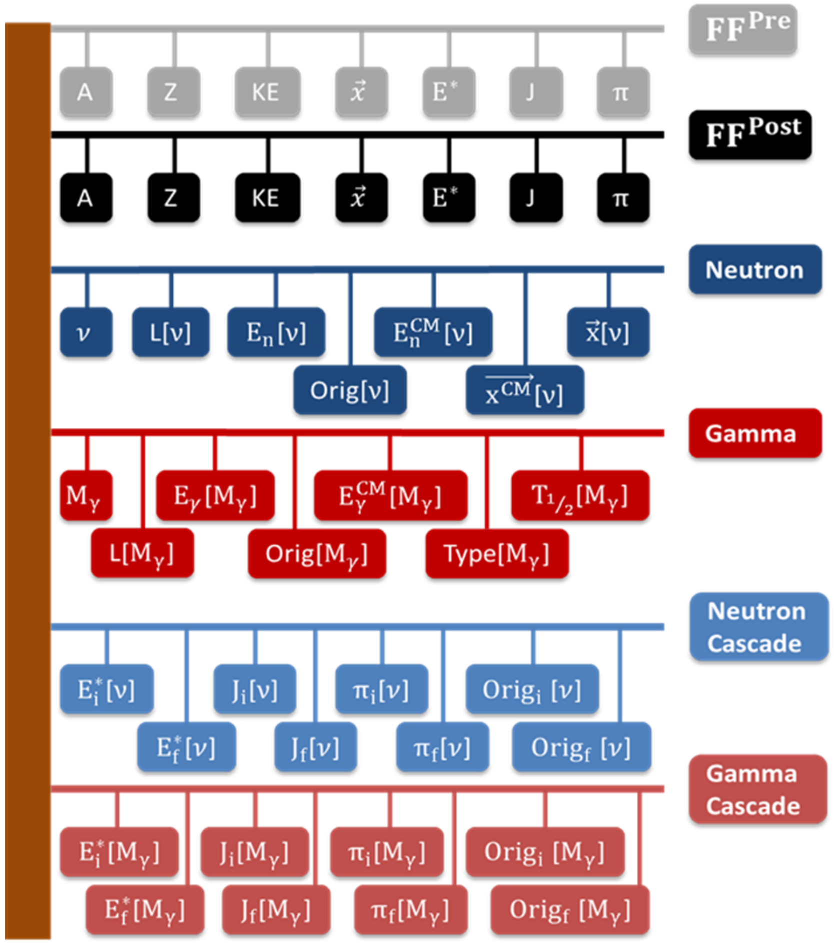
  A. Chebboubi et al. ,
  Eur. Phys. J. W. Conf. ***111****, 08003 (2016)*

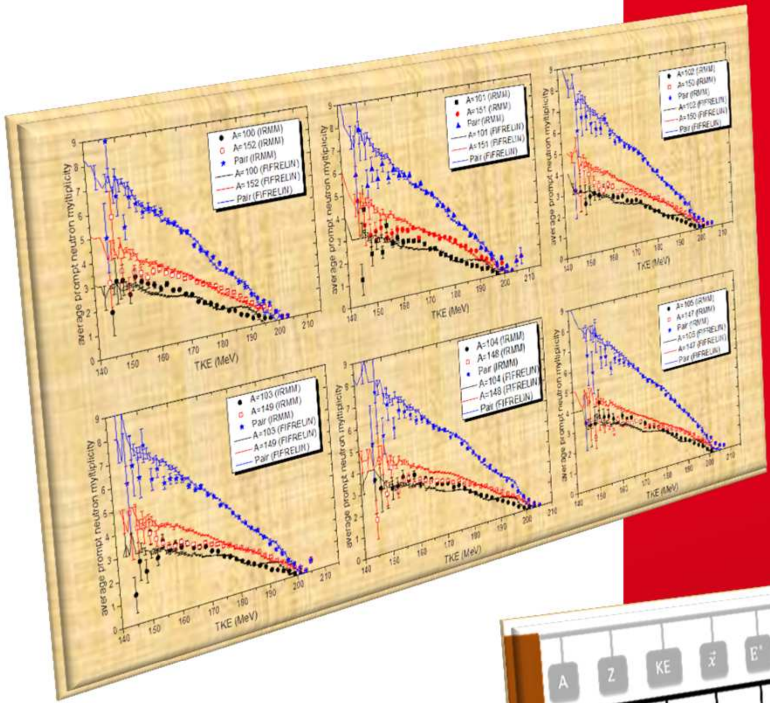
- Yields of correlated fragment pairs

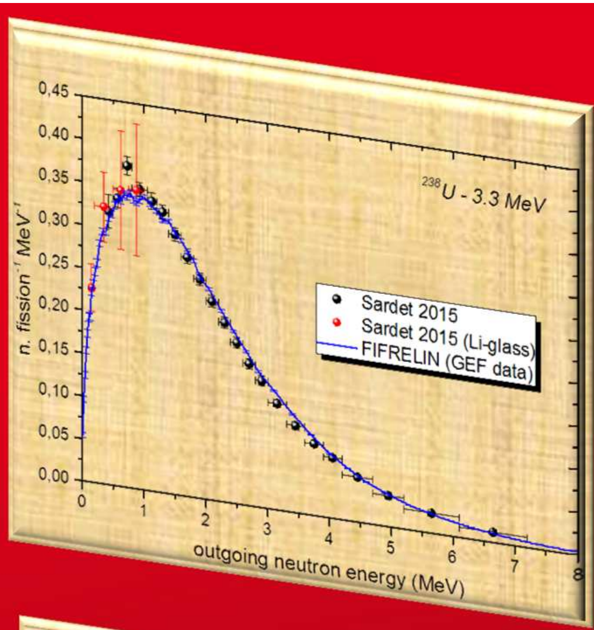
  T. Materna et al. ,
  Eur. Phys. J. W. Conf. ***93****, 02020 (2015)*

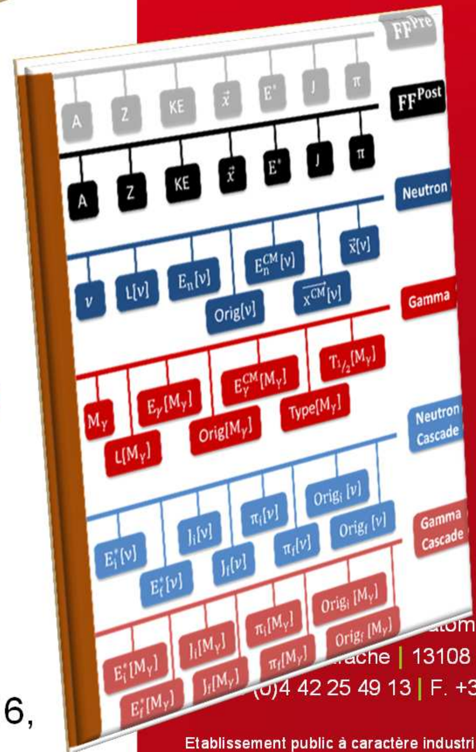
- Analog fission in transport codes

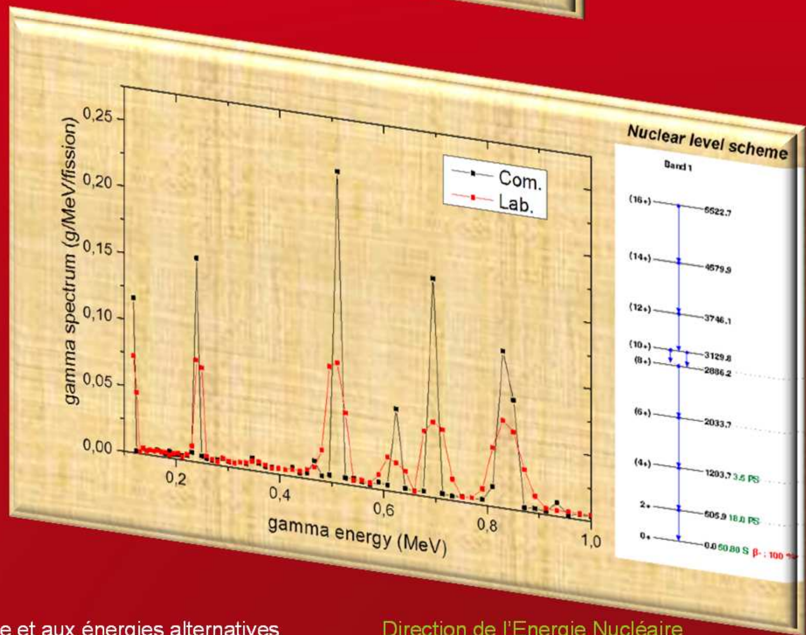
  O. Petit et al., Proc. of ICRS13 & RPSD 2016, Paris











Merci
pour votre attention

ND-2016, 11-16 september, 2016,
Bruges, Belgium.