Summation Method Model – Nantes

M. Fallot[1*], M. Estienne[1*], A. Algora[2,3], G. Alcala[2], A. Beloeuvre[1], J. Briz-Monago[1], V.M. Bui[1], S. Cormon[1], W. Gelletly[4], L. Giot[1], V. Guadilla[1], D. Jordan[2], L. Le Meur[1], J. Pépin[1], A. Porta[1], S. Rice[4], B. Rubio[2], J. L. Taín[2], E. Valencia[2], and A.-A. Zakari-Issoufou[1]

[*] SEN group, SUBATECH (CNRS/IN2P3, Université de Nantes, IMTA),
4, rue A. Kastler, 44307 Nantes cedex 3, France
fallot@subatech.in2p3.fr
estienne@subatech.in2p3.fr

Subatech

Outline

- Introduction
- Summation Method for Reactor Antineutrinos and Pandemonium Effect
- 2019: Updated Summation Model including most Recent TAGS Results & Comparison with Daya Bay Results
- Ongoing studies and improvements
  - Model ingredients improvements
  - Decay Data and Databases
  - GEF: Fission Yields, Isomers and Predictions for Future Reactors
  - Forbidden Decays and Spectral Shape
- Conclusions & Outlooks

Reactor Antineutrino Spectral Knowledge

- Over the last 45 years, many computations and improvements of the spectra

- First Double Chooz, Daya-Bay and Reno theta 13 results published in Phys. Rev. Lett. In 2012

  Y. Abe et al Phys. Rev. Lett. 108, 131801, (2012)
  F. P. An et al., Phys. Rev. Lett. 108, 171803 (2012).
  J. K. Ahn et al., Phys. Rev. Lett. 108, 191802 (2012)

- The Double Chooz experiment has devoted efforts to new computations of reactor antineutrino spectra (mandatory for the 1st phase !!!)

- Two methods were re-visited:
  - ✓ The **conversion of integral beta spectra of reference measured by Schreckenbach et al. in the 1980's at the ILL reactor** (thermal fission of ^{235}U, ^{239}Pu and ^{241}Pu integral beta spectra): **use of nuclear data for realistic beta branches, Z distribution of the branches…**
  - ✓ The **summation method, summing all the contributions of the fission products** in a reactor core: **only nuclear data : Fission Yields + Beta Decay properties** (several predictions from B.R. Davis, P. Vogel et al. Phys. Rev. C 19 2259 (1979), to Tengblad et al. Nucl. Phys. A 503 (1989)136)

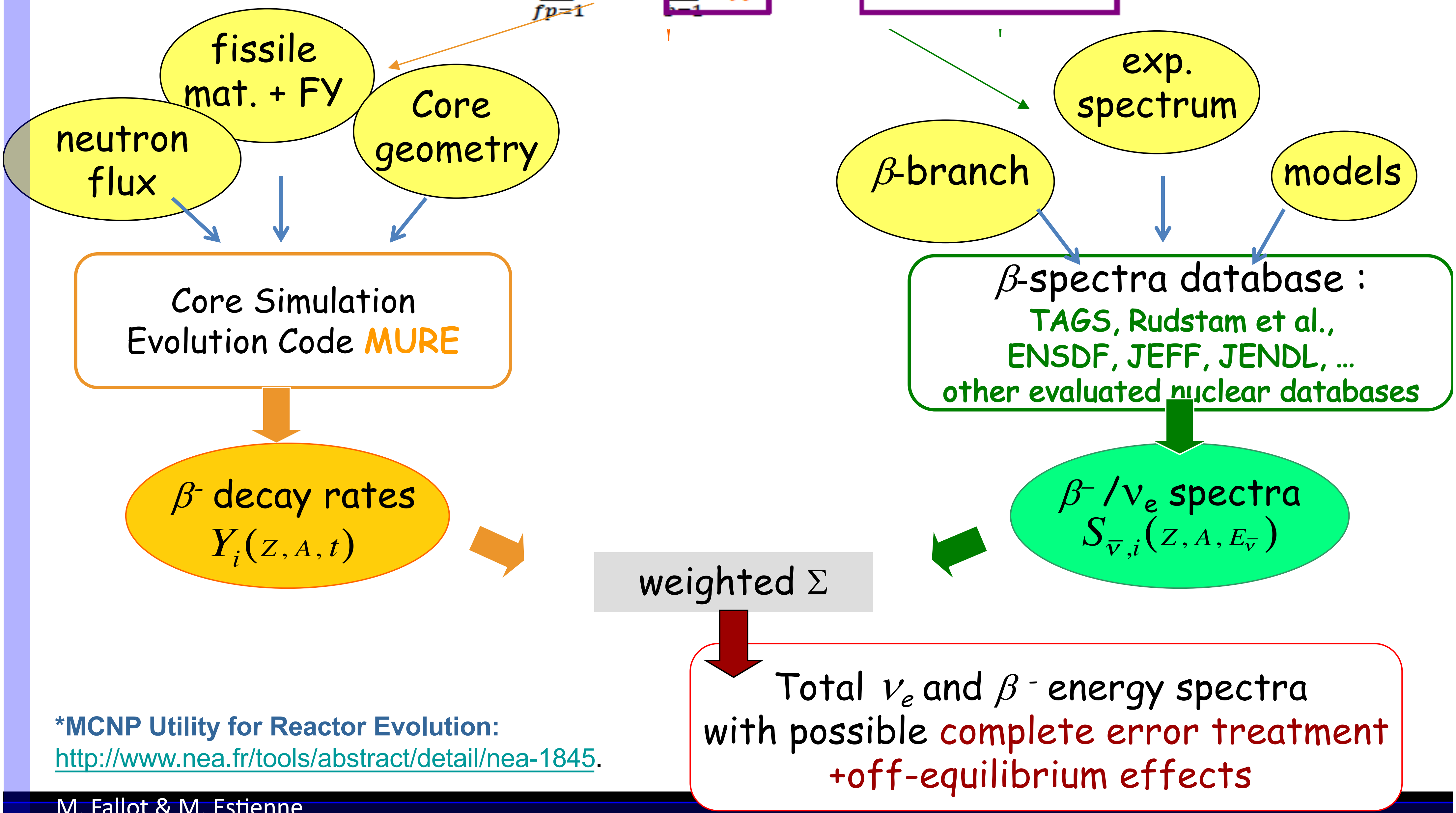
M. Fallot & M. Estienne

Summation Method for Reactor Antineutrinos and Pandemonium effect

Summation Method

$$S_k(Z,A,E) = \sum_{fp=1}^{N_{fp}} A_{fp} \times \sum_{b=1}^{N_b} I_{\beta\, fp}^{\;b} \times S_{fp}^{\;b}\left(Z_{fp}, A_{fp}, E_{0\,fp}^{\;b}, E\right))$$

NUCLEAR DB



*MCNP Utility for Reactor Evolution: http://www.nea.fr/tools/abstract/detail/nea-1845.

What can nuclear data bring to antineutrino spectra ?

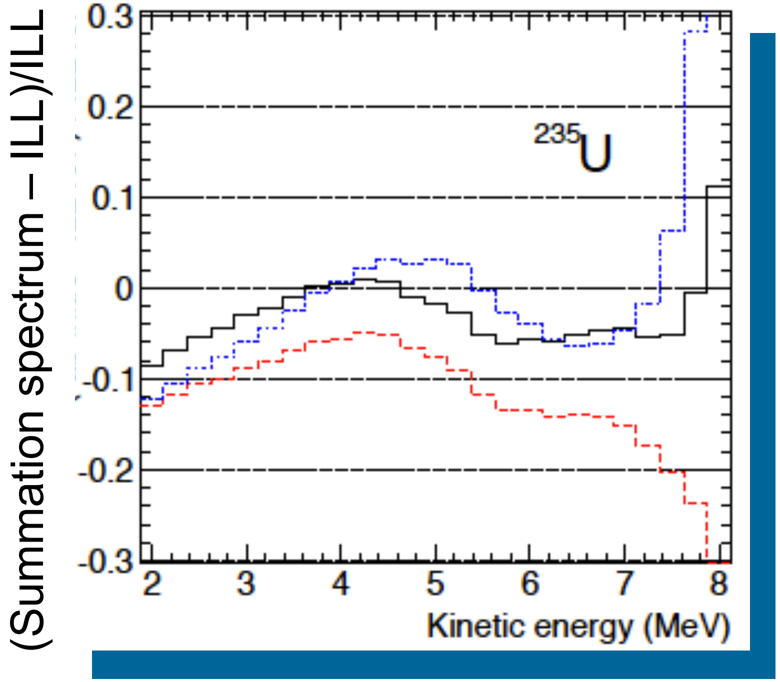
Summation Calculations:

using P. Huber's prescriptions for spectral shape calculations, a careful selection of decay data, and fission yields from JEFF3.1:

$$N(E_\nu) = \sum_n Y_n(Z,A,t) \cdot \sum_i b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)$$

⇒ **Importance of providing decay data to ALL fission yields**

⇒ **Test of various nuclear databases: Pandemonium effect:** **Overestimate of the ILL spectra @ high energy + shape distorsion**



Th. Mueller et al. Phys. Rev. C 83, 054615 (2011), **M. Fallot et al.** Phys. Rev. Lett. 109 (2012) 202504.

γ Measurement Caveat

- Before the 90s, conventional detection techniques: high resolution γ-ray spectroscopy
  - ❑ Excellent resolution but efficiency which strongly decreases at high energy
  - ❑ Danger of overlooking the existence of β-feeding into the high energy nuclear levels of daugther nuclei (especially with decay schemes with large Q-values)

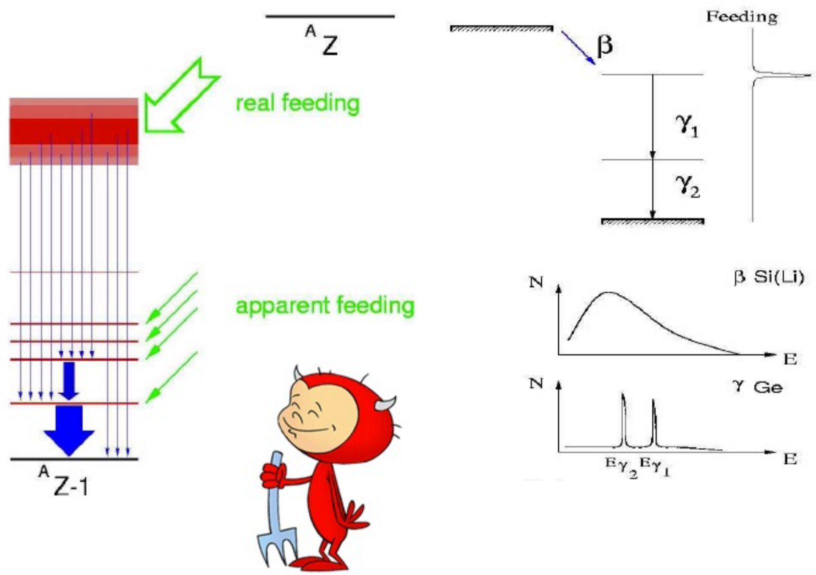
- Incomplete decay schemes: overestimate of the high-energy part of the FP β spectra

- Phenomenon commonly called « pandemonium effect** » by J. C Hardy in 1977

** J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)

➡ **Strong potential bias in nuclear data bases and all their applications**

Picture from A. Algora



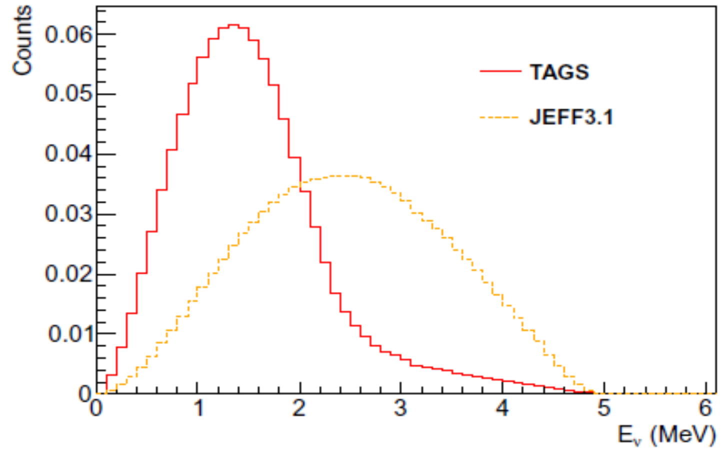


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

What can nuclear data bring to antineutrino spectra ?

Summation Calculations:

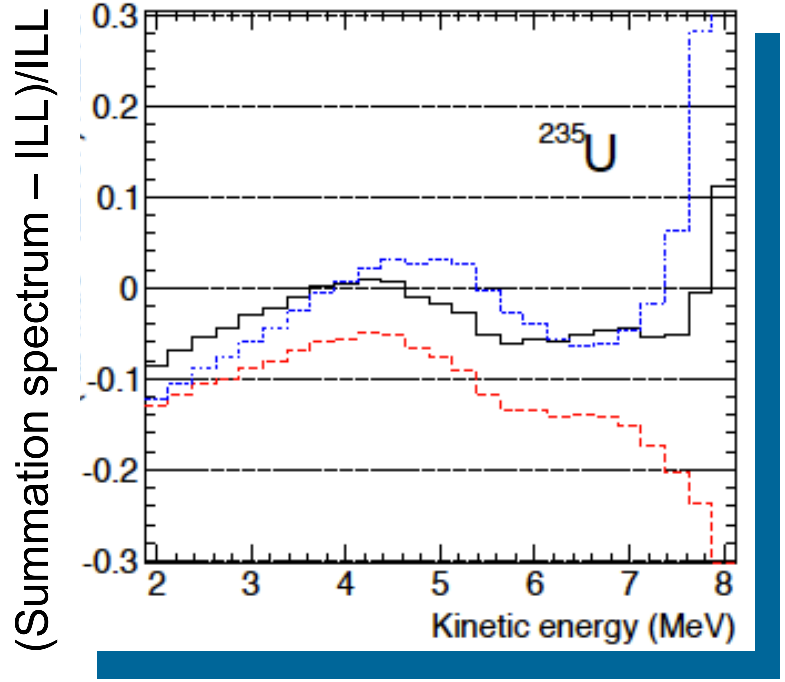
using P. Huber's prescriptions for spectral shape calculations, a careful selection of decay data, and fission yields from JEFF3.1:

$$N(E_\nu) = \sum_n Y_n(Z,A,t) \cdot \sum_i b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)$$

⇒ **Test of various nuclear databases: Pandemonium effect:** Overestimate of the ILL spectra @ high energy + shape distorsion

⇒ Forbiddeness is taken into account when info available except for non-unique transitions (replaced by (n-1)th unique shape)

⇒ **Requires new measurements** of FP beta decay properties



Th. Mueller et al. Phys. Rev. C 83, 054615 (2011), **M. Fallot et al.** Phys. Rev. Lett. 109 (2012) 202504.

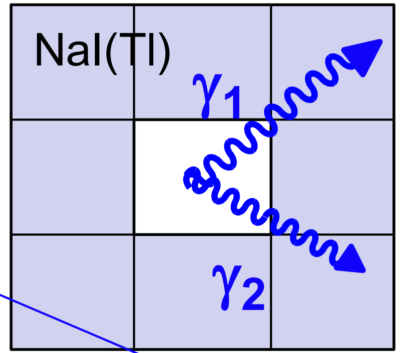
The reactor antineutrino estimates suffer from the Pandemonium Effect: similar to Reactor Decay Heat (Yoshida et al. NEA/WPEC-25 (2007), Vol. 25**)**

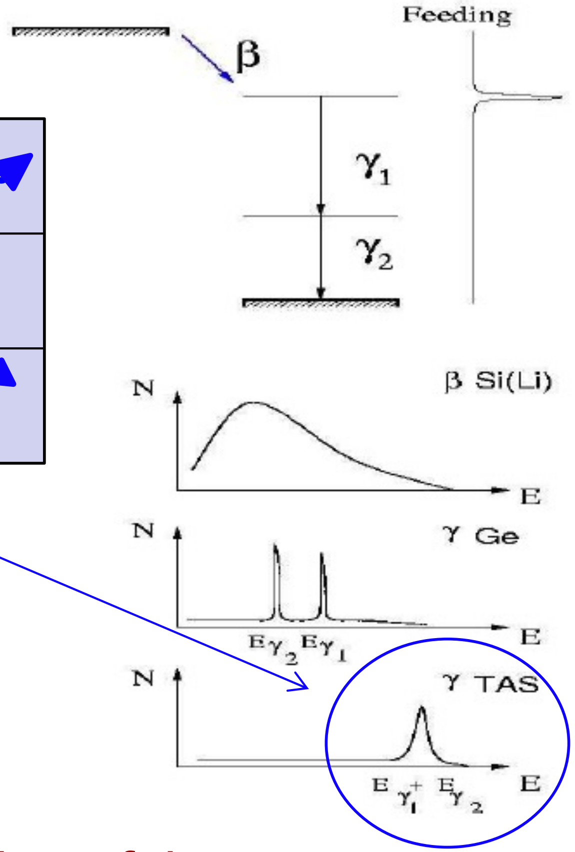
⇒ Importance of the selection of data sets for Summation calculations: i.e. appropriate choice of decay data & fission yields

⇒ Improve systematic errors: list of nuclei to measure with TAS experiments

TAGS: a Solution to the Pandemonium Effect

- Total absorption γ-ray spectroscopy (TAGS)
  - A TAS is a calorimeter
  - It contains big crystals covering 4π
  - Instead of detecting the individual gamma rays, absorbs the full gamma energy released by the gamma cascades in the β-decay process





- First TAS developed in the 70's but too small detectors to be efficient. Development of the TAGS method efficient and systematic since the 90's (Greenwood & al.)

- Calculation of level energy feeding through the resolution of the inverse problem by deconvolution
  - R_{ij} = matrix detector response
  - d_i = measured data
  - Extract f_j the level feeding by deconvolution

$$d_i = \sum_{j=1}^{m} R_{ij} \cdot f_j \Rightarrow I_i = \frac{f_i}{\sum_k f_k}$$

J. L. Tain & D. Cano-Ott, NIMA 571 (2007) 728

First quantification of Pandemonium Data on anti-ν Spectra Calculation

- In 2012, revision of our SM model:
  - ❑ Choice of Nuclear Database cocktail
  - ❑ First quantification of Pandemonium data in an anti-ν spectrum calculation: data taken from TAGS 2007 campain

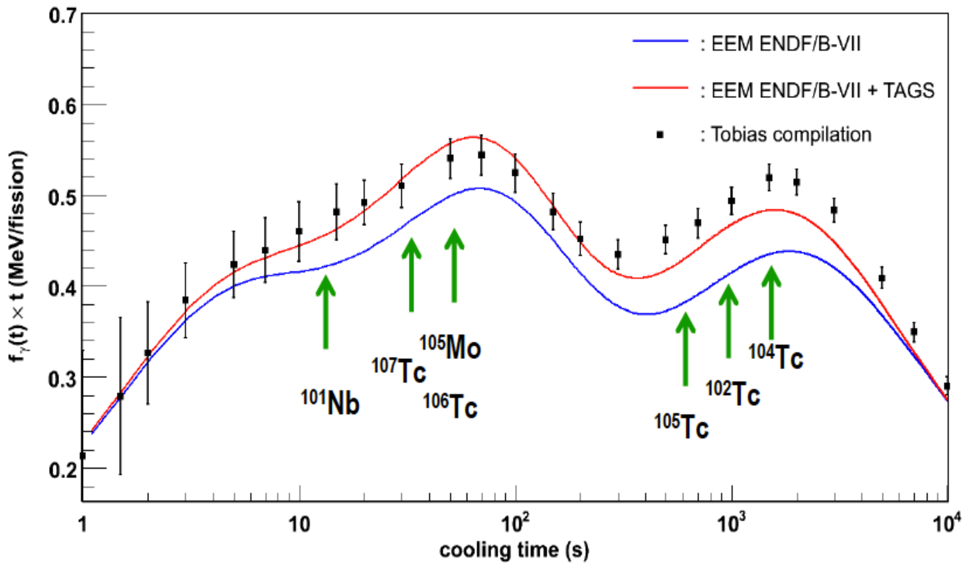
M. Fallot et al., Phys. Rev. Lett. 109 (2012) 202504

- In the 1970s: important discrepancies observed comparing Decay Heat calculation and benchmark experiments ("pandemonium effect")

- Since the 1990s: temporary solution step by step replaced by the use of measured data with a new detection technics: the total absorption spectrometers TAGS (slide 19)

- TAGS campaign in 2007 dedicated to electromagnetic DH puzzle. Seven important nuclei were measured
  - ❑ 5 nuclei were Pandemonium
  - ❑ It solved the electromagnetic DH puzzle

Algora *et al.*, PRL 105, 202501 (2010).

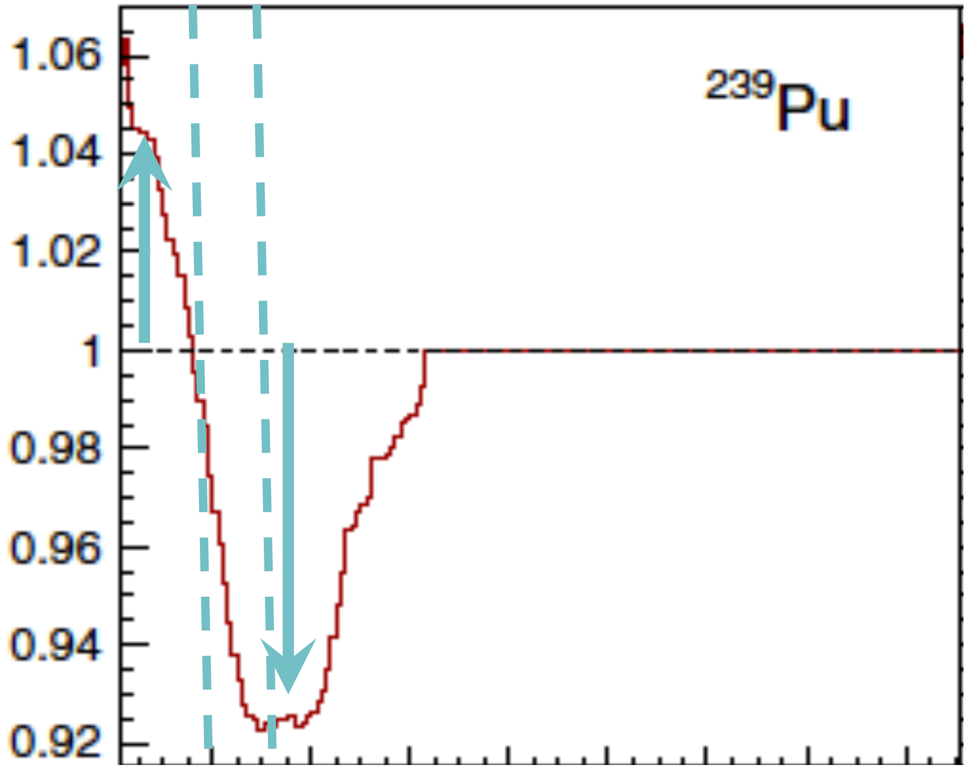


Impact of the results for ^{239}Pu: electromagnetic component

First Impact of 2010 TAS Data on SM calculations

M. Fallot *et al.*, PRL 109, 202504 (2012)

- Taking into consideration the TAS data of the $^{102;104-107}$Tc, ^{105}Mo, and ^{101}Nb isotopes measured @ Jyväskylä by the Valencia team for Decay Heat
  - ~850 nuclei included
  - Noticeable deviation from unity (1.5 to 8% decrease)
  - Change in flux (presented later)



⇒ **Relative Effects of the 2012 TAS data on the Antineutrino Spectra: typical from Pandemonium effect + the inclusion of Pandemonium free data increases the spectrum below 2-3 MeV and decreases it above**

⇒ **The Nantes – Valencia collaboration started with their first TAGS measurements for antineutrino spectra in Jyväskylä as soon as 2009 and later in 2014 and 2022!**

⇒ **Triggered the nuclear experimental efforts**

3 TAS Campains at IGISOL Jyväskylä in 2009, 2014, 2022

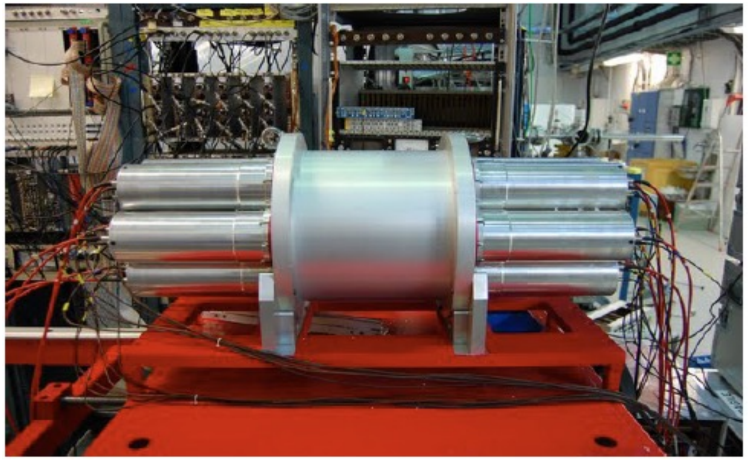
- IGISOL@Jyväskylä:
  - ❑ Proton induced fission ion-guide source
  - ❑ Mass separator magnet
  - ❑ Double Penning trap system to clean the beams

B. Rubio, J. L. Tain, A. Algora et al., Proceedings of the Int. Conf. For nuclear Data for Science and technology (ND2013)

J.L. Tain et al., NIMA 803 (2015) 36
V. Guadilla et al., submitted to NIMA (2018)

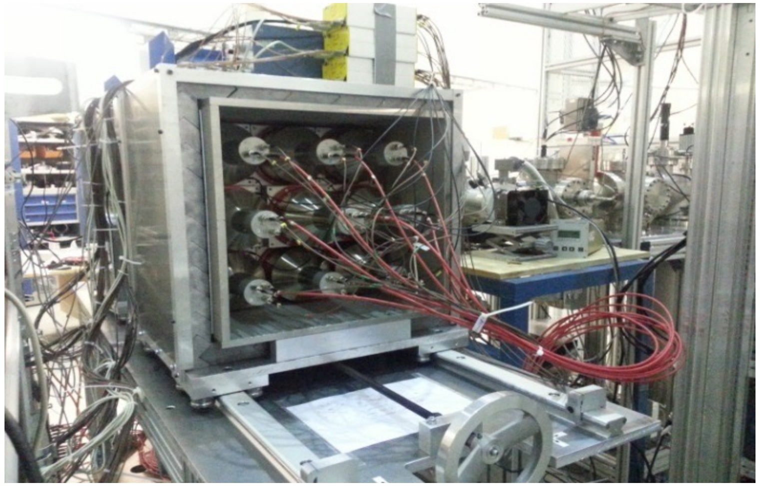
- 2 (segmented) TAS campains :

❑ ROCINANTE (IFIC Valencia/Surrey):



- ✓ 12 BaF_2 covering 4π
- ✓ Detection efficiency of γ ray cascade >80% (up to 10 MeV)
- ✓ Coupled with a Si detector for β
- ✓ 7 nuclei (4 delayed neutron emitters) measured (6 for DH and 2 for anti-ν)

❑ DTAS (IFIC Valencia):



- ✓ 18 NaI(Tl) crystals of 15cm × 15cm × 25 cm
- ✓ Individual crystal resolutions: 7-8%
- ✓ Total efficiency: 80-90%
- ✓ Coupled with plastic scintillator for β
- ✓ 12 nuclei for anti-ν measured & 11 for DH

See A. Algora's talk

A Reduced List of Important Contributors

A.-A. Zakari-Issoufou, PRL 115, 102503 (2015)

TABLE I. Main contributors to a standard PWR antineutrino energy spectrum computed with the MURE code coupled with the list of nuclear data given in [12], assuming that they have been emitted by ^{235}U (52%), ^{239}Pu (33%), ^{241}Pu (6%)and ^{238}U (8.7%) for a 450 day irradiation time and using the summation method described in [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	-
^{95}Sr	2.65%	2.96%	-	-
^{94}Rb	1.32%	2.06%	2.84%	3.96%

- Summation calculations give the following priority list of nuclei, with a large contribution to the PWR antineutrino spectrum in the high energy bins

The number of contributors in these bins is small enough to give the hope to produce summation calculations with reduced systematic errors due to decay data at a relatively short time scale

+ Quoting A. A. Sonzogni, E. A. McCutchan, and A. C. Hayes Phys. Rev. Lett. 119, 112501: « in order to confirm the existence of the reactor neutrino anomaly, or even quantify it, precisely measured electron spectra for about 50 relevant fission products are needed »

TAGS' Consultant Meeting

Coordinated by P. Dimitriou, IAEA ND section

IAEA
International Atomic Energy Agency

INDC(NDS)-0676
Distr. EN, ND

INDC International Nuclear Data Committee

Total Absorption Gamma-ray Spectroscopy for Decay Heat Calculations and Other Applications

Summary Report of Consultants' Meeting

IAEA Headquarters
Vienna, Austria

15-17 December 2014

Prepared by

Paraskevi Dimitriou and Alan L. Nichols

IAEA Nuclear Data Section
Vienna, Austria

Contains table of priorities for decay heat, antineutrino spectra and info about β-n emitters

Table 3. Summary of priorities for TAGS measurements of importance in decay-heat calculations for U/Pu and Th/U fuel cycles and for determining the antineutrino spectra produced by standard nuclear power plants. Radionuclides that have already been studied by means of TAGS are ticked in the 5th column, where the initials stand for the experimental groups responsible for measurements: V for IFIC-Univ. Valencia group, N for Subatech-Univ. Nantes group, O for Oak Ridge National Laboratory group.

Radionuclide	Q_β-value (keV)	Half-life	Comments	TAGS measurements	Priority		
					U/Pu fuel	Th/U fuel	Antineutrinos Total [3-8] MeV
37-Rb-92	8095(6)	4.492 s	small (β^-,n) branch	✓ V-N, O	2	2	1
37-Rb-93	7466(9)	5.84 s	(β^-,n) branch	✓ V-N			1
39-Y-99	6969(12)	1.484 s	(β^-,n) branch				1

Antineutrino tables were made using the Summation Model frpm M. Fallot et al. PRL 2012, that is in agreement with A. Sonzogni et al. PRC 91, 011301(R) (2015)

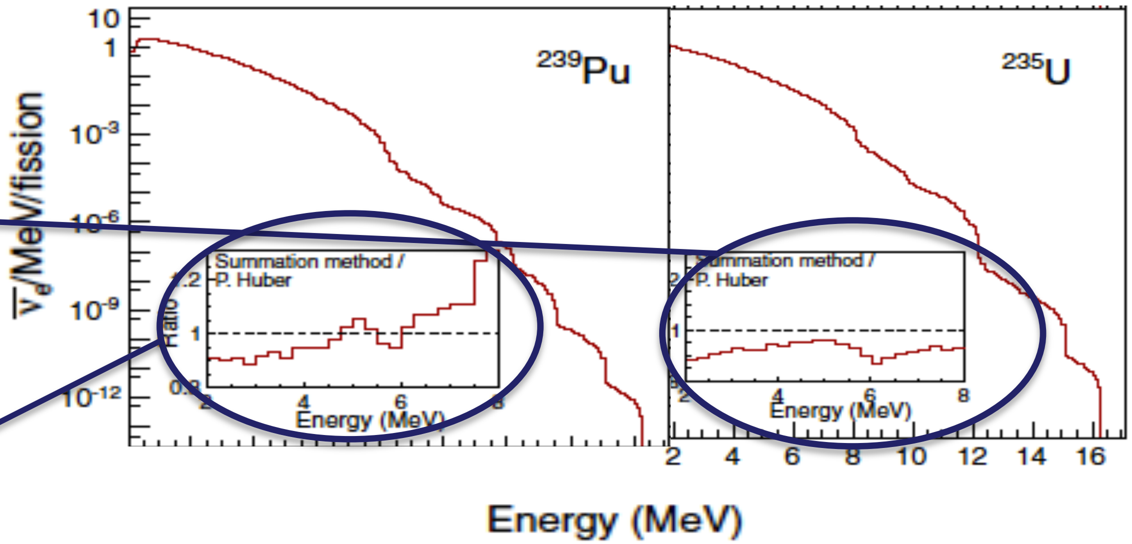
The meetings organized by IAEA-NDS gather evaluators, experimentalists and theoreticians around a given topic. Part of the job consists in sitting together and **go through the data of each selected nucleus to critically assess the quality of the existing data.**
The quality of Summation Method models relies mainly on the quality of the data. If two models include the state of the art of the nuclear data, they should agree to a certain extent which reflects the limit of knowledge, but should not differ by more in principle.
⇒ **the Summation Method model evolves with the advances of nuclear data**

2019: Updated Summation Model including most Recent TAGS Results & Comparison with Daya Bay Results

Comparison with the ILL Reference

- **2012 Ratio between spectra calculated with summation method and converted spectra from ILL measurements**

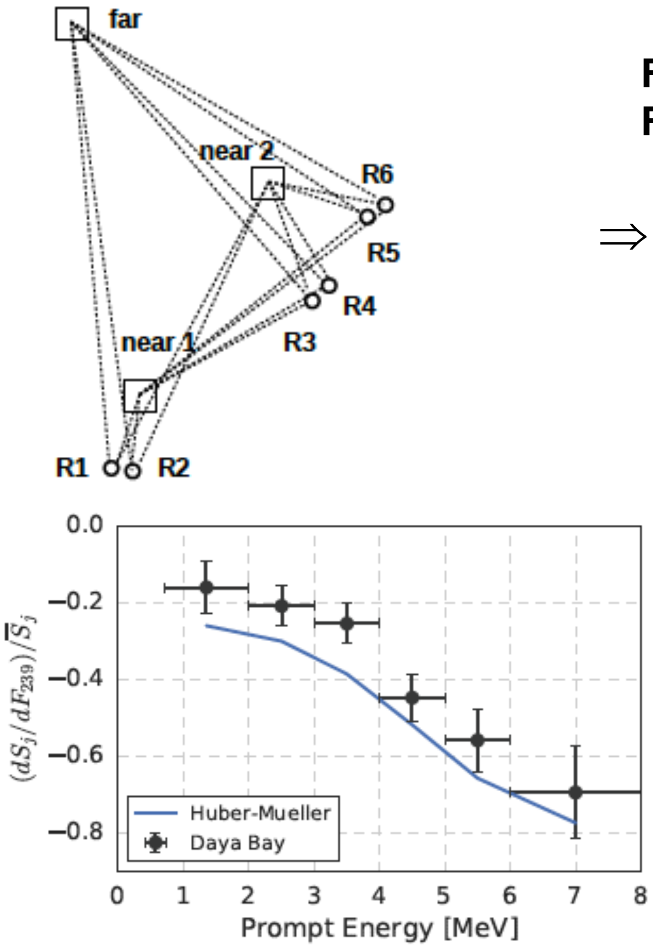
  - For ^{235}U: the summation is 5 to 10% below the conversion. Goes in the direction of Daya Bay's new 2017 result on the reactor anomaly: pb is in the ^{235}U spectrum!!!
  - Summation spectra still not pandemonium free requiring new TAS measurements.



M. Fallot *et al.*, PRL 109, 202504 (2012)

Context by end 2017…

In 2017: Daya Bay's new result about the reactor anomaly: [pb is in the ^{235}U spectrum!!!]



F. P. An et al. (Daya Bay Collaboration), ``Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay," Phys. Rev. Lett. 118 (2017).

⇒ Measured antineutrinos from **six 2.9-thermal-gigawatt reactor cores**, which were located either at Daya Bay or at the Ling Ao power plant in China

⇒ **Deficit in detected antineutrinos** compared to predictions **depends on the relative fractions of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu** in the reactor.

⇒ **^{235}U fissions produced 7.8% fewer antineutrinos than predicted**—enough of a discrepancy to explain by itself the entire antineutrino anomaly !!!

⇒ In contrast, the discrepancy = **almost zero for ^{239}Pu fissions.**

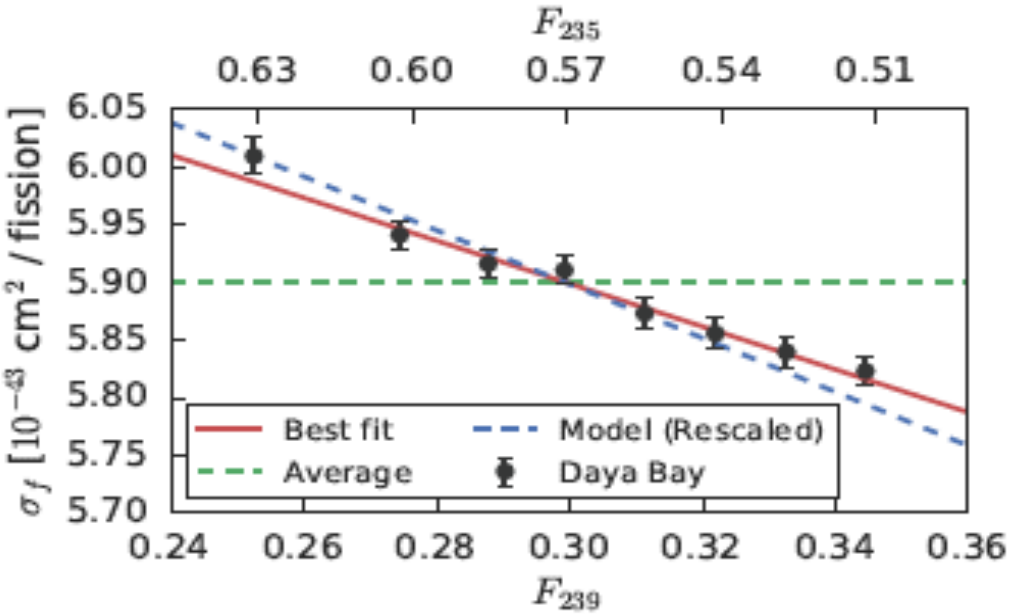
Previous hints were pointing to ^{235}U: ArXiv:1609.03910, 1608.04096, 1512.06656.

BUT https://arxiv.org/abs/1709.04294: **sterile neutrino hypothesis cannot be rejected based on global data**

Daya Bay Inverse Beta Decay (IBD) Yield

- The deficit observed in measured flux with respect to different predictions does not result from equal fractional deficits from the primary fission isotopes
- The evolution of the antineutrino flux detected per fission = the measured IBD yield per nuclear fission σ_f was studied as a function of the effective fission fractions $F_i(t)$.
- σ_f is a simple sum of IBD yields from the individual isotopes (product of the IBD cross section and the antineutrino flux per fission): $\sigma_f = \sum_i F_i \sigma_i$

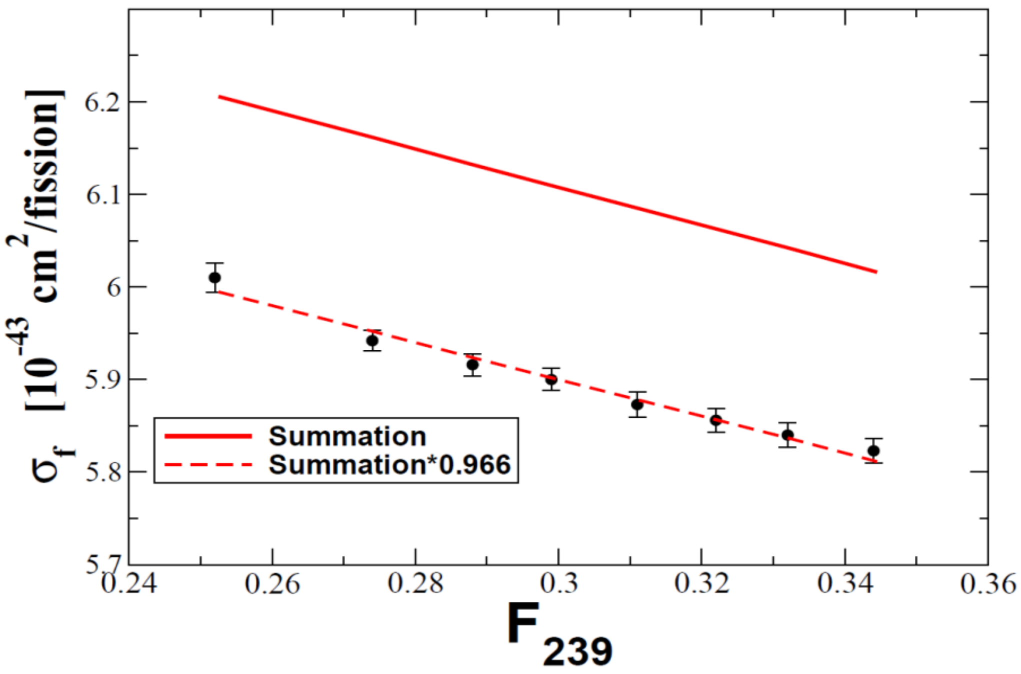
F. P. An et al., Daya Bay Collaboration PRL 118 (2017) 251801



- ❑ Still 6% discrepancy with Huber-Mueller prediction
- ❑ Slope of the IBD yield with burnup quite well reproduced by H-M model but not exactly the same
- ❑ Extraction of the individual contributions of the fissioning nuclei: **flux deficit quasi all taken by ^{235}U, while ^{239}Pu one in good agreement with H-M model**
- ❑ **Potential issue in Schrekenbach measurement or H-M model for U5 ?**

First Comparison with a SM model

A. C. Hayes et al. PRL 120 (2018) 022503



- Summation calculation by Hayes et al. compared with Daya Bay IBD yield evolution with ^{239}Pu fission fraction
- Compatible dependence of the flux vs F239 between the calculation and Daya Bay
- But, still a deficit observed in DB data but smaller than with converted model

➡ 3.5% deficit is still large enough to say that the reactor anomaly exists

Our New Summation Method: Update of Ingredients

- Decay data updated with **the latest published TAS data = 15 nuclei Pandemonium free**

Nuclei	Model names	Publications
$^{102;104-107}$Tc, ^{105}Mo & ^{101}Nb	SM-2012 M. Fallot et al. PRL 109, 202504 (2012)	A. Algora et al. PRL 105, 202501 (2010), D. Jordan et al. PRC 87, (2013) 044318
+ ^{92}Rb	SM-2015	A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015)
+ ^{87,88}Br and ^{94}Rb + ^{86}Br and ^{91}Rb	SM-2017	E. Valencia et al., PRC 95, 024320 (2017) S. Rice et al. PRC 96 (2017) 014320
+ ^{100,100m,102,102m}Nb	SM-2018 M. Estienne et al., PRL 123, 022502 (2019)	V. Guadilla et al. PRL 122, (2019) 042502

- **Then nuclear decay databases** in decreasing priority order:

The Greenwood TAS data set, the experimental data measured by Tengblad et al., experimental data from the evaluated nuclear databases JEFF3.3, ENDFB-VIII.0 and Gross theory spectra from JENDL2018* and the "Q_β" approximation for the remaining unknown nuclei

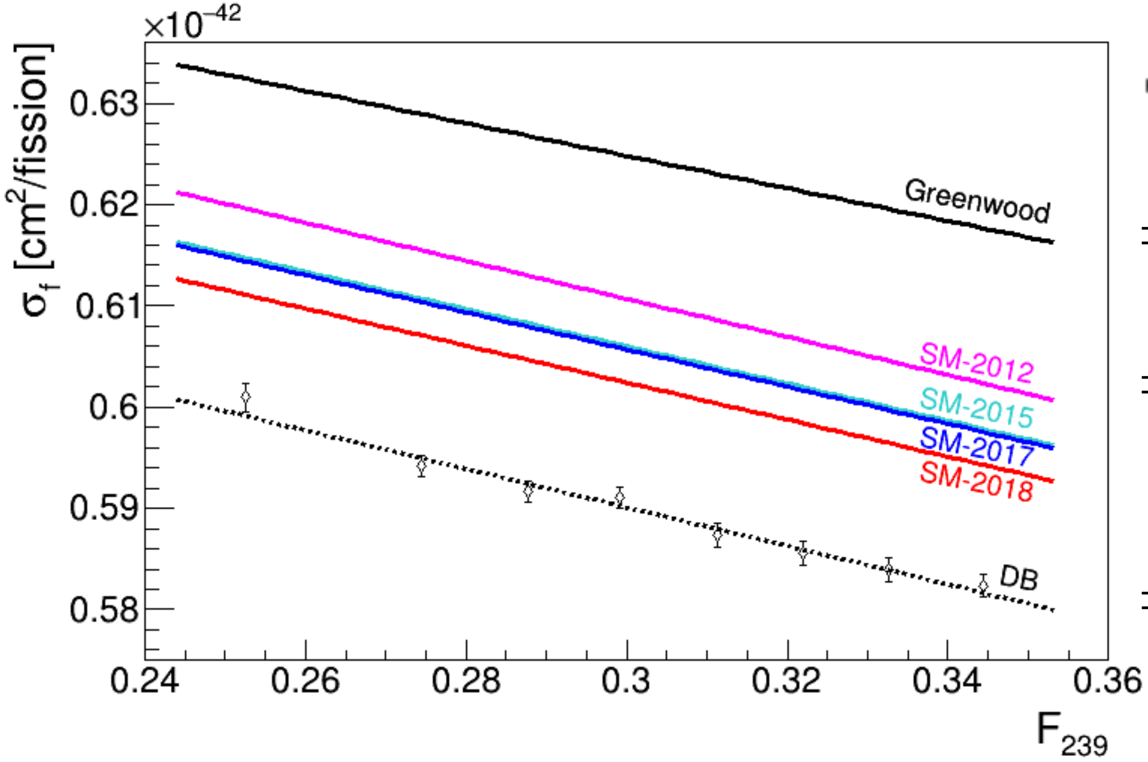
*T. Yoshida, T. Tachibana, S. Okumura, and S. Chiba, Phys. Rev. C 98, 041303(R) (2018).

- Fission yields database: JEFF3.1.1

- Irradiation times with MURE: 12 h for ^{235}U, 1.5 d for $^{239;241}$Pu, and 450 d for ^{238}U.

Our IBD Yield Calculation Including TAGS vs DB

- The IBD yields dependency with F239 including TAGS data published in 2012, 2015, 2017 and 2019 has been calculated using our summation calculation



- Impact of the inclusion of the TAGS data (Pandemonium free):

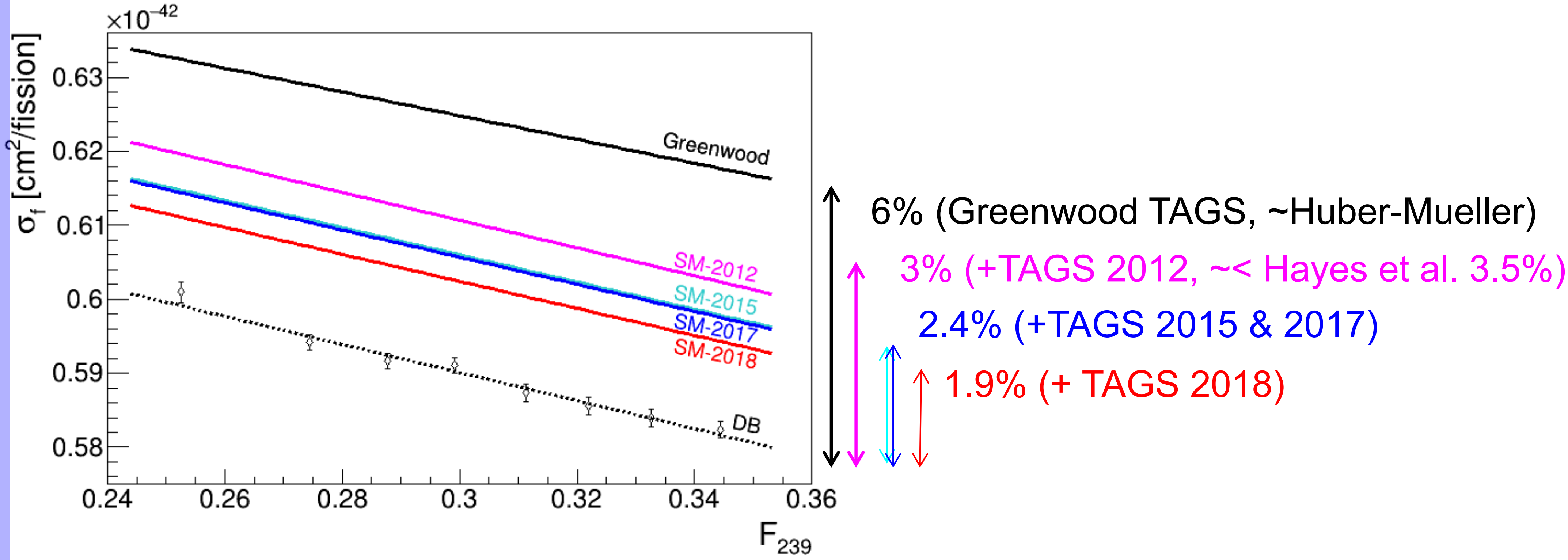
⇒ **Systematic reduction of the detected flux**

⇒ **Systematic reduction of the discrepancy with Daya Bay results**

⇒ Implies an increasingly smaller discrepancy with the inclusion of future TAGS data, **leaving less and less room for a reactor anomaly**.

M. Estienne et al., **Phys. Rev. Lett. 123 (2019) 022502**

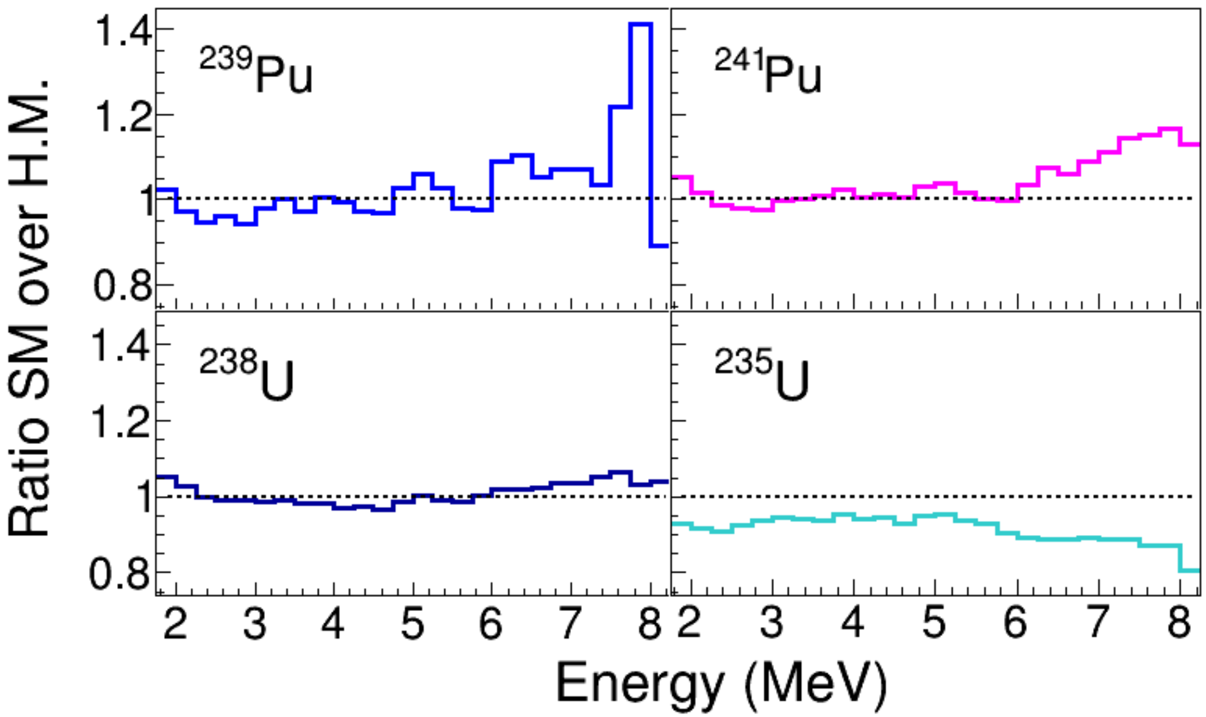
Our IBD Yield Calculation Including TAGS vs DB



- The remaining discrepancy with the Daya Bay flux reduces to only 1.9% compared with the 6% discrepancy of the H-M model (percentage at the origin of the reactor anomaly) and the 3.5% quoted by Hayes et al.
- **Key point: the use of new nuclear databases and the use of Pandemonium free data.**

M. Estienne et al., **Phys. Rev. Lett. 123 (2019) 022502**

Comparison with H-M individual spectra



M. Estienne et al., **Phys. Rev. Lett. 123 (2019) 022502**

- The ratios with converted spectra have become flatter up to ~6 MeV compared with SM-2012
- The normalisation of ^{235}U still disagrees (same as in 2012), confirming Daya Bay's result
- ^{238}U: ratio w.r.t. Mueller et al 's version of the SM: spectrum remains stable with the update of databases and inclusion of new TAGS results up to ~6 MeV

⇒ Overall the SM model shows a fairly good shape agreement with Huber's spectra up to 6 MeV (in the error bars of the converted spectra in this energy range, except for ^{239}Pu)

⇒ **The shape anomaly is not explained**

⇒ **The energy range matters indeed, because the antineutrino data are also more uncertain above 6 MeV: pandemonium, unknown decay schemes, fission yields, isomers**

IAEA Technical Meeting 2019

- Technical Meeting on Antineutrino Spectra and Applications, Organized by the Nuclear Data Section of IAEA April 23-26 2019 – ***Report INDC(NDS)786 2019***
- ~30 participants, representatives nearly from all reactor neutrino experiments (Daya Bay, Reno, Juno, Juno-Tao, Double Chooz, SoLid, Prospect, DANSS, Neutrino-4, NEOS, Coherent, Chandler, …) + representatives from modelling side (theorists, nuclear data specialists) + representatives nuclear experimentalists from US and Europe

IAEA
International Atomic Energy Agency

INDC(NDS)-0786
Distr. G, EN, ND

INDC International Nuclear Data Committee

Antineutrino spectra and their applications

Summary of the Technical Meeting

IAEA Headquarters, Vienna, Austria
23-26 April 2019

Prepared by

M. Fallot
Laboratoire SUBATECH-University of Nantes
Nantes, France

B. Littlejohn
Illinois Institute of Technology
Chicago, USA

P. Dimitriou
IAEA
Vienna, Austria

Summary Conversion– Report INDC(NDS)786 2019

«

- Several publications since 2011 have pointed out that the total uncertainties were significantly underestimated

- The conversion procedure itself suffers from larger uncertainties than expected due to the distribution of the average effective Z of the beta branches used in the fit of the ILL beta spectra.

- There are also large uncertainties in the treatment of high Q-value forbidden non-unique transitions. The effect of these uncertainties is still not well understood.

»

Summary Summation– Report INDC(NDS)786 2019

«

- There has been significant improvement in the Summation Method (SM) calculations which rely heavily on nuclear data for fission yields and fission product decay data.
- A large concerted experimental effort driven by several nuclear physics groups has resulted in a series of targeted Total Absorption Gamma-ray Spectroscopy measurements of a large number of isotopes relevant to anti-neutrino spectra. The new TAGS decay data have led to significant improvement in the quality of the summation.
- There have also been efforts to improve the fission yield data with the works performed by Sonzogni et al. and Schmidt et al.

»

US TAGS measurements: B. C. Rasco et al., Phys. Rev. Lett. 117, 092501 (2016), B.C. Rasco et al. Phys. Rev. C 95, 054328 (2017), A. Fijalkowska et al. Phys. Rev. Lett. 119, 052503 (2017)

A. Sonzogni et al. Phys. Rev. Lett. 116, 132502 (2016), A. A. Sonzogni et al. PRL 119, 112501 (2017), PRC 98 041323(2018) (2018)

M. Fallot et al. PRL 109,202504 (2012), A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015), E. Valencia et al., PRC 95, 024320 (2017), S. Rice et al. PRC 96 (2017)014320, V. Guadilla et al. PRL122, (2019) 042502, M. Estienne et al. **PRL 123, (2019) 022502,**

P. Dimitriou et al. INDC(NDS)-0676 (2016)

Impact of recent TAGS data on Reactor Antineutrinos

Figures extracted from « β-decay studies for applied and basic nuclear physics », Algora et al., *Eur. Phys. J. A* **57,** 85 (2021) https://arxiv.org/pdf/2007.07918.pdf

Calculations by M. Estienne

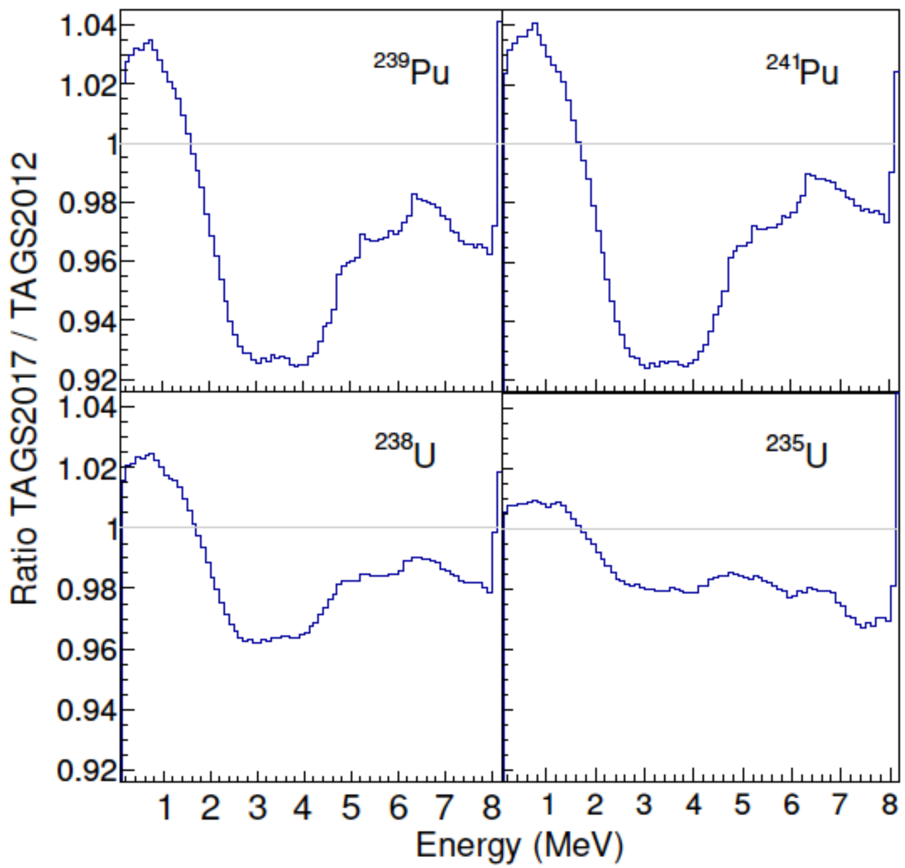


Fig. 17. Accumulated impact of the beta intensities of the ^{86,87,88}Br and ^{91,92,94}Rb [24,62,67] decays measured with the total absorption spectrometer *Rocinante* on the antineutrino spectra with respect to that published in [99] (relative ratios) for the thermal fissions of ^{235}U, ^{239}Pu and ^{241}Pu, and the fast fission of ^{238}U [107].

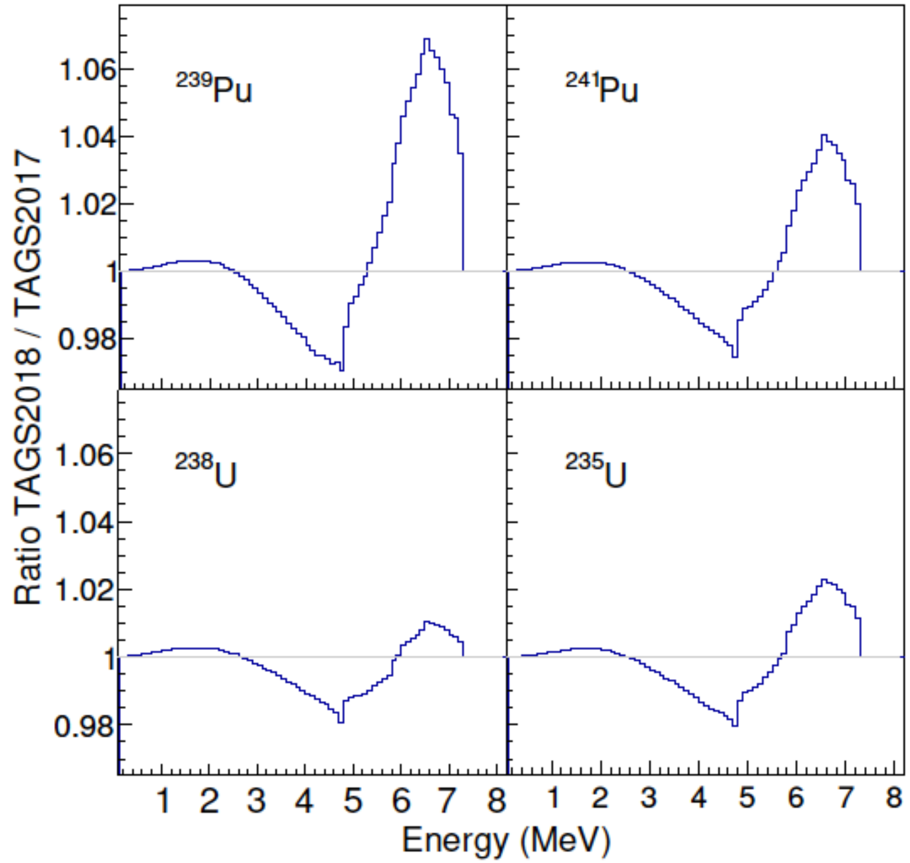


Fig. 18. Accumulated impact of the beta intensities measured with the DTAS detector on the antineutrino spectra with respect to that presented in Figure 17 (relative ratios) for the thermal fissions of ^{235}U, ^{239}Pu and ^{241}Pu, and the fast fission of ^{238}U [107]. The figure represents the relative impact of the ^{100,100m,102,102m}Nb decays [13].

Outstanding Issues and Recommendations:

From *Report INDC(NDS)786 2019:*

- **Obtain realistic estimates of the uncertainties in the SM. The propagation of uncertainties associated with the decay data and the fission yields on the summation method spectra is being investigated for the effect of uncertainty correlations.**
- **Improve with more TAGS results,**
- **Measurement of electron shapes**
- **Improve the treatment of forbidden non-unique shape factors of the beta decay spectra.**
- **Improve fission yields data**
- **Provide an assessment of the published values of the different sub-contributions to the total uncertainties of the conversion models**
- **Improve the predictive power of nuclear models for the beta decay or the fission process**

On going studies and improvements:

- Model ingredients,
- Decay Data and NDB,

Summation calculations: on-going work

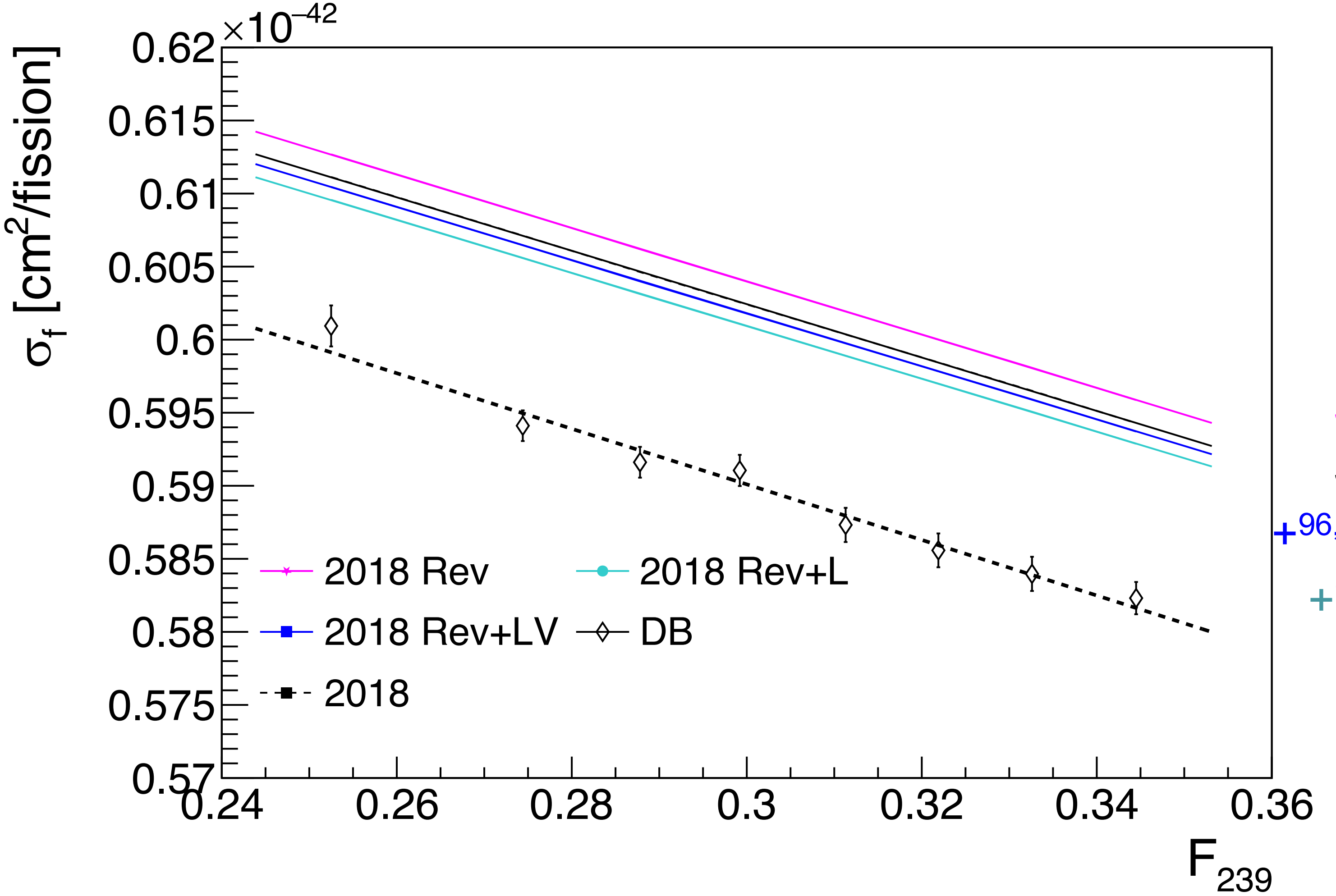
- Collaboration with L. Hayen:
  - ❑ Compare our ingredients and corrections (on-going)
    - ➢ Modifications in our model core calculation:
      - 1keV energy bins
      - Screening corrections: Rose replaced by Salvat (**L. Hayen, N. Severijns et al. Rev. Mod. Phys. 90, 015008 (2018)**)
      - Nubase 2020 for Q_β approximation

⇒ Small change in the global flux (~0.25%)

New decay data taken into account

- 2014 TAGS campaign: quantification of the impact of 7 new nuclei (see A. Algora's presentation – Wednesday 01/18):
  - ^{95}Rb et ^{137}I: 2 nuclei from V. Guadilla et al. **Phys. Rev. C 100, 044305 (2019)**
  - ^{96gs}Y and ^{96m}Y (Pandemonium): 2 nuclei from V. Guadilla et al. **Phys. Rev. C 106, 014306 (2022)**
  - ^{99}Y, ^{142}Cs and ^{138}I: 3 Pandemonium nuclei from L. Le Meur et al., in preparation, see A. Algora's presentation

New decay data taken into account



SM-2018 Rev: 2.1%

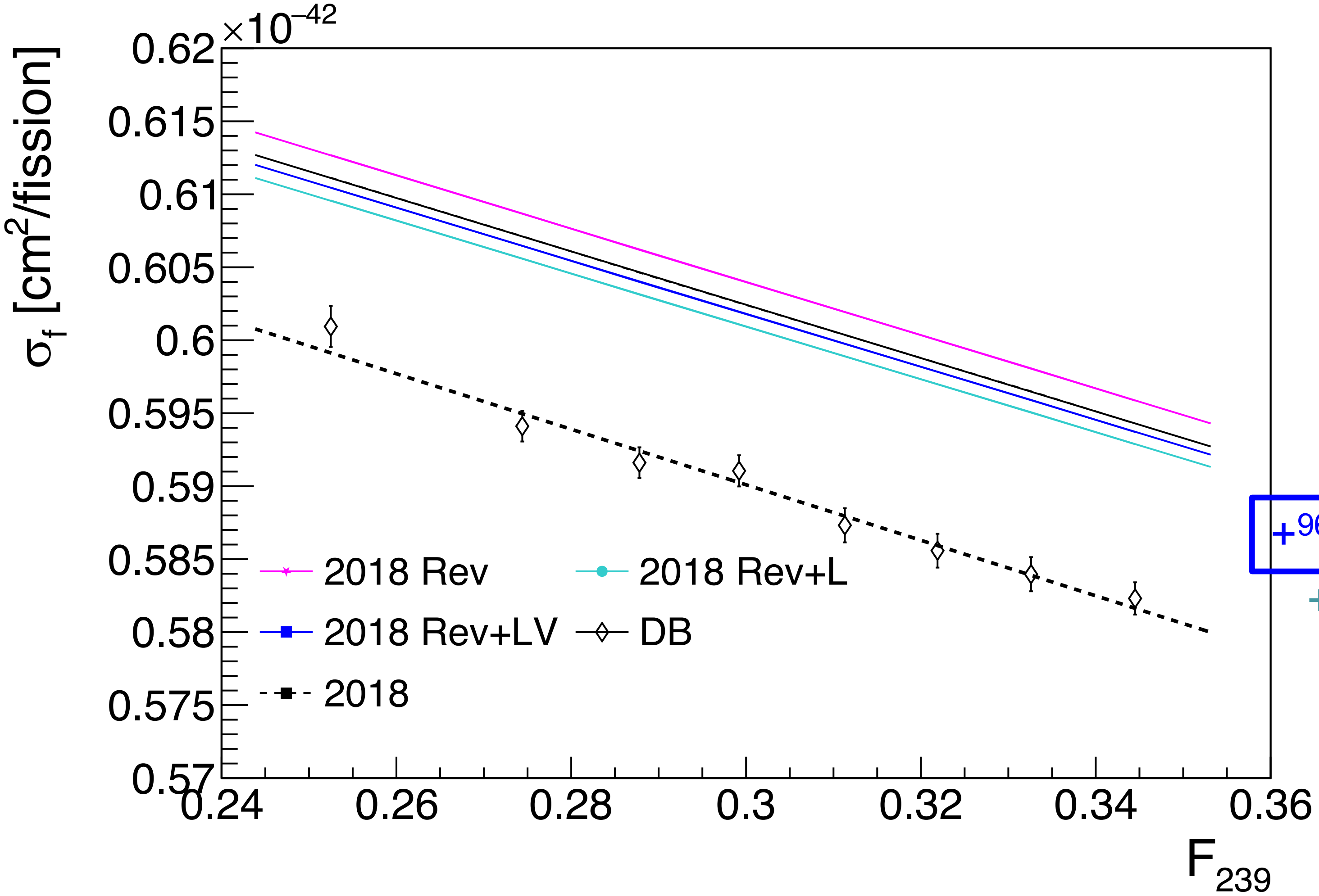
SM-2018: 1.9%

$+^{96,96m}Y$, ^{95}Rb, ^{137}I: 1.8%

$+^{99}Y$, ^{138}I, ^{142}Cs: 1.7%

- Still systematic trend reducing the flux including pandemonium free data
- TAGS also allows to correct other biases present in NDB
- More to come with new TAGS campaign (**see A. Algora's talk**)

New decay data taken into account



SM-2018 Rev: 2.1%

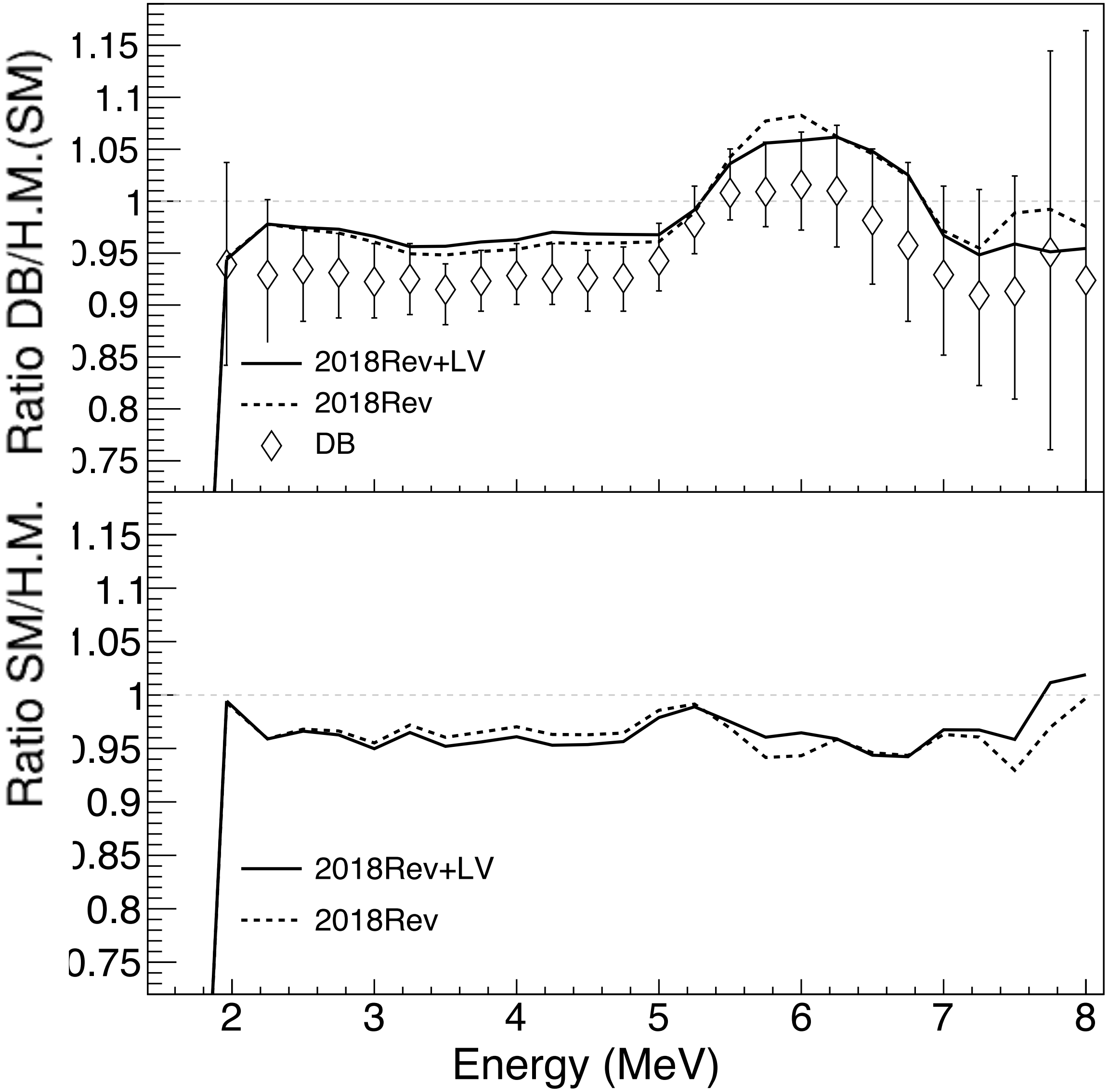
SM-2018: 1.9%

+^{96,96m}Y, ^{95}Rb, ^{137}I: 1.8%

+^{99}Y, ^{138}I, ^{142}Cs: 1.7%

- Still systematic trend reducing the flux including pandemonium free data
- TAGS also allows to correct other biases present in NDB
- More to come with new TAGS campaign (**see A. Algora's talk**)

New decay data taken into account

- 

⇒ **The energy range matters indeed, because the antineutrino data are also more uncertain above 6 MeV: pandemonium, unknown decay schemes, fission yields, isomers**

On going studies and improvements:

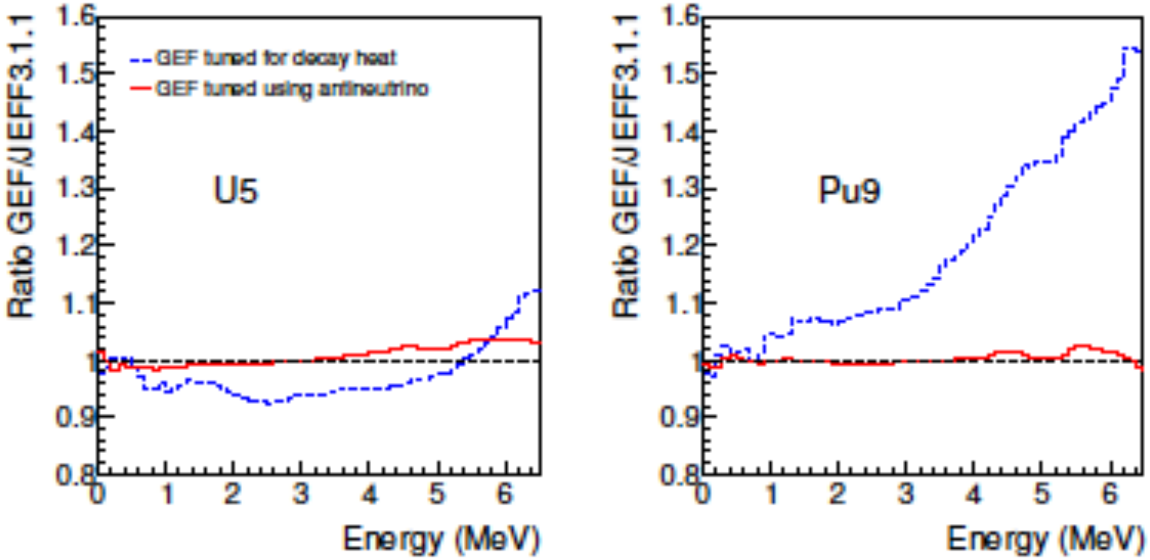
- Model ingredients,
- Decay Data and NDB,
- GEF: Fission Yields, uncertainties, isomers and predictions for future reactors,

Fission Yields & the GEF Code

- The SM spectra need uncertainties: not trivial ! Because:
  - ❑ Decay data: Pandemonium effect needs to be eliminated, otherwise the quoted uncertainties in the databases have no meaning;
  - ❑ Fission Yields: need covariance matrices ;
- Collaboration with Karl-Heinz Schmidt in Subatech in order to use the GEF code to study antineutrino spectra with the propagation of uncertainties:

The GEF code prediction capability for the fission yields was not good enough for antineutrino spectra:

For the first time a careful analysis and a systematic comparison of data from different sources and evaluations with GEF have been performed to sort out the more reliable and the less trustworthy values ;



⇒Reactor Antineutrino spectra combined with the GEF model provide a useful tool to assist fission yield data evaluation

Fission Yields & Antineutrinos

- **Collaboration with K.-H. Schmidt** (author of GEF with B. Jurado) for several years with the purpose to use the GEF FY with their uncertainties. Results are:
  - **a new version of the GEF code improved thanks to the antineutrino spectral studies**
  - **an assessment of the experimentally available fission yields with the GEF model showing that the discrepancies btw FY from JEFF3.1.1 and JEFF3.3 are not always understood**
  - **The ^{238}U spectrum is obtained using a realistic PWR neutron flux in GEF (improves agreement with JEFF FY)**
  - New predictions compared with the DB flux
  - New predictions of actinide antineutrino spectra for applications

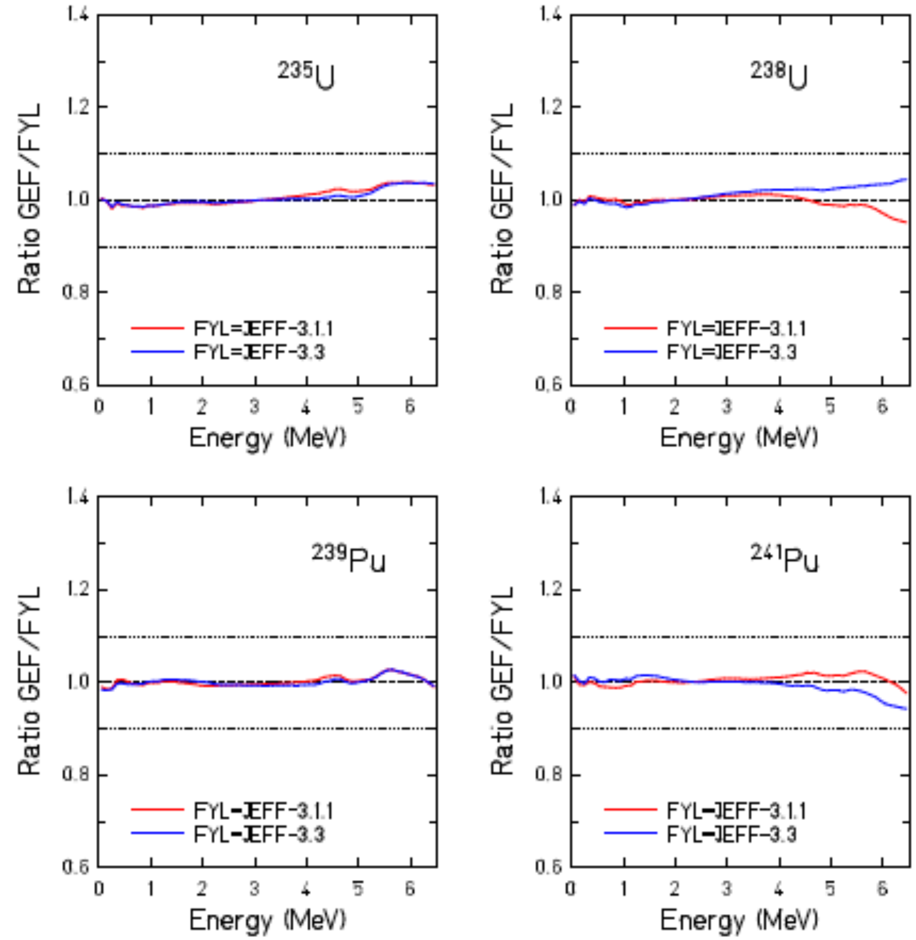
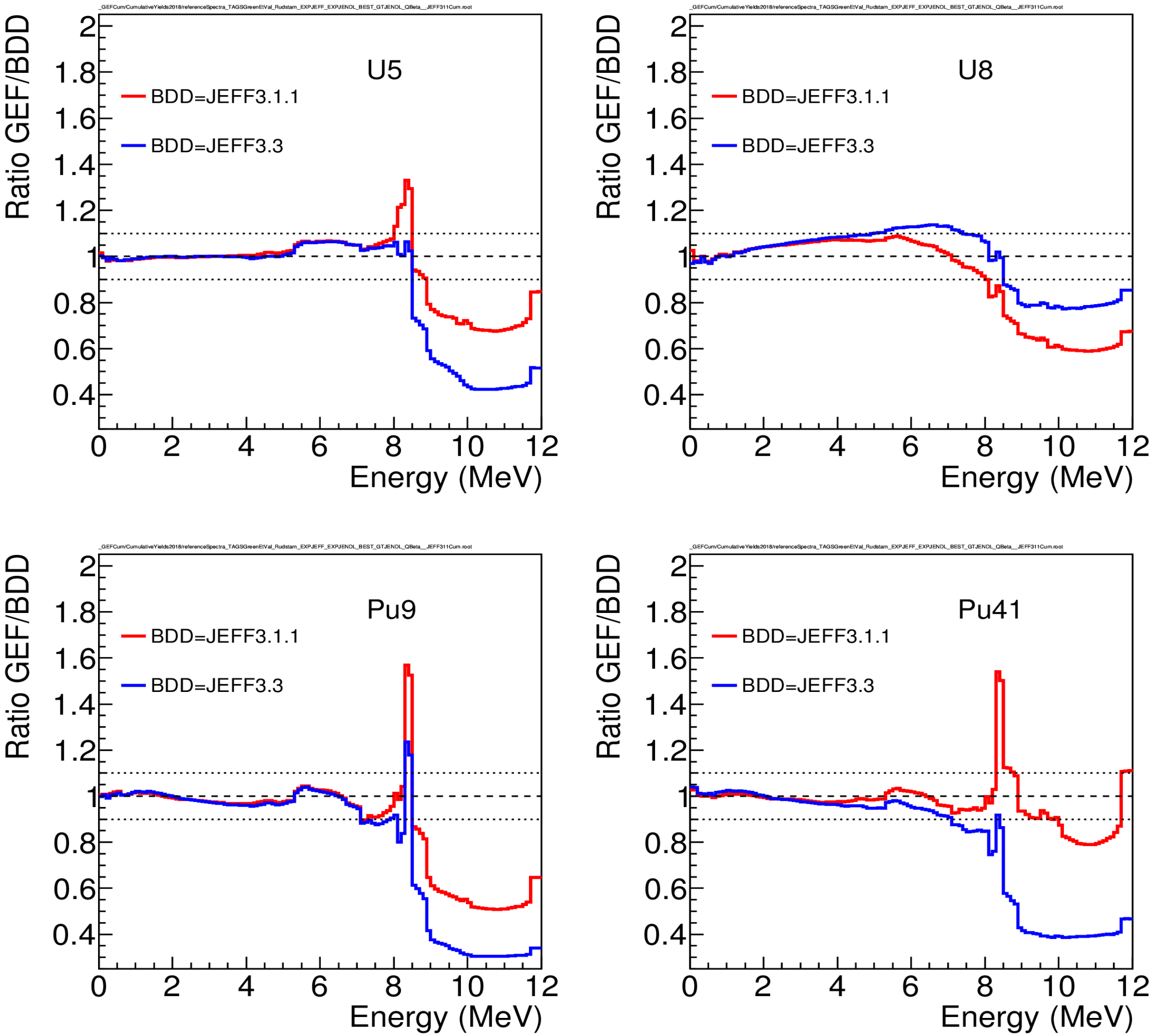


FIG. 63. Ratio of the antineutrino spectra calculated with yields from GEF and from the fission-yield libraries (FYL) JEFF-3.1.1, respectively JEFF-3.3, after tuning.

Extensive study of the quality of fission yields from experiment, evaluation and GEF for antineutrino studies and applications, K.-H.Schmidt, M.Estienne, M.Fallot, et al., Nuclear Data Sheets Volume 173, (2021), Pages 54-117, https://doi.org/10.1016/j.nds.2021.04.004

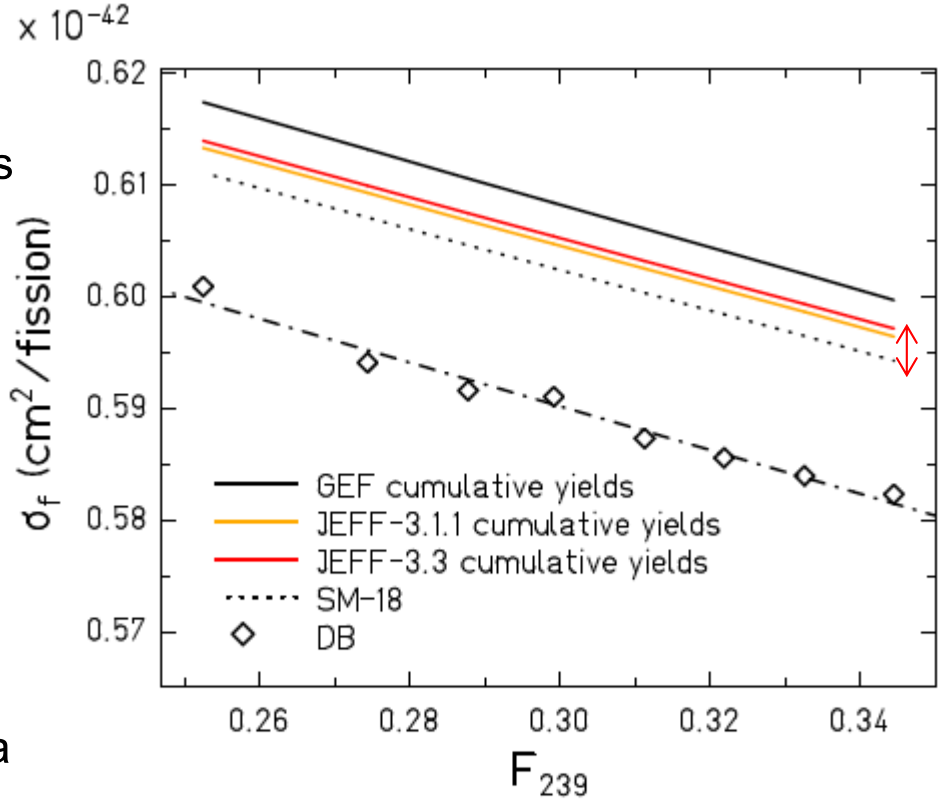
Fission Yields & Antineutrinos



Different isomeric ratios btw GEF and JEFF are partly responsible of the large deviation at high energy.
But also btw JEFF3.1.1 and JEFF3.3 !

Fission Yields & Antineutrinos

- **Collaboration with K.-H. Schmidt** (author of GEF with B. Jurado) for several years with the purpose to use the GEF FY with their uncertainties. First results are:
  - a new version of the GEF code improved thanks to the antineutrino spectral studies
  - an assessment of the experimentally available fission yields with the GEF model showing that the discrepancies btw FY from JEFF3.1.1 and JEFF3.3 are not always understood
  - The ^{238}U spectrum is obtained using a realistic PWR neutron flux in GEF (improves agreement with JEFF FY)
  - **New predictions compared with the DB flux**
  - New predictions of actinide antineutrino spectra for applications

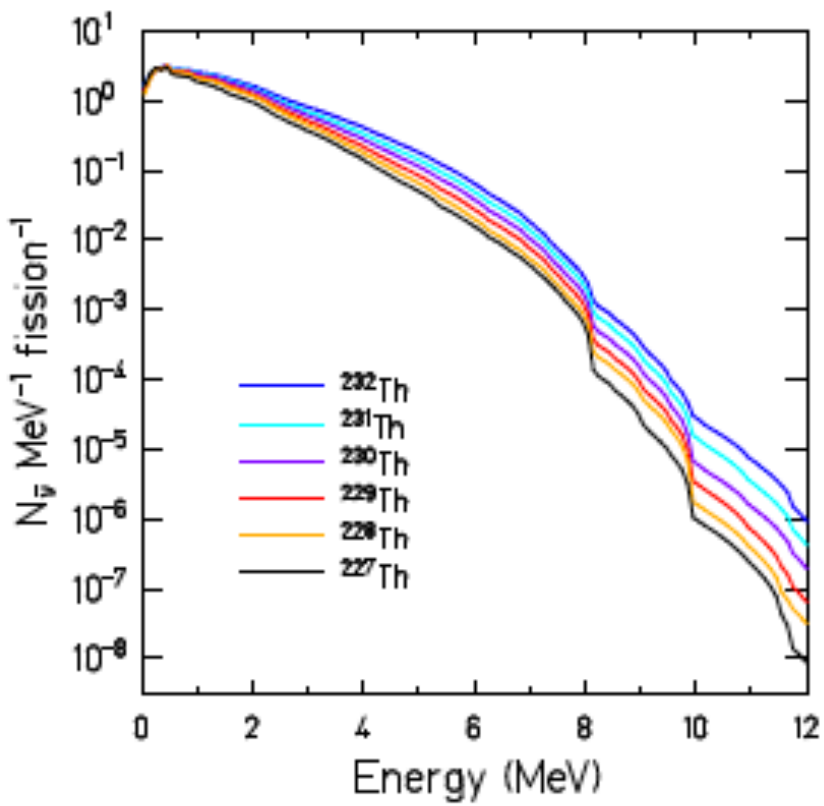


↕ **: impact of off-equilibrium effects w.r.t cumulative FY: 0.5%**

Extensive study of the quality of fission yields from experiment, evaluation and GEF for antineutrino studies and applications, K.-H.Schmidt, M.Estienne, M.Fallot, et al., Nuclear Data Sheets Volume 173, (2021), Pages 54-117, https://doi.org/10.1016/j.nds.2021.04.004

Fission Yields & Antineutrinos

- **Collaboration with K.-H. Schmidt** (author of GEF with B. Jurado) for several years with the purpose to use the GEF FY with their uncertainties. First results are:
  - **a new version of the GEF code improved thanks to the antineutrino spectral studies**
  - an assessment of the experimentally available fission yields with the GEF model showing that the discrepancies btw FY from JEFF3.1.1 and JEFF3.3 are not always understood
  - The ^{238}U spectrum is obtained using a realistic PWR neutron flux in GEF (improves agreement with JEFF FY)
  - New predictions compared with the DB flux
  - **New predictions of actinide antineutrino spectra for applications**



Extensive study of the quality of fission yields from experiment, evaluation and GEF for antineutrino studies and applications, K.-H.Schmidt, M.Estienne, M.Fallot, et al., Nuclear Data Sheets Volume 173, (2021), Pages 54-117, https://doi.org/10.1016/j.nds.2021.04.004

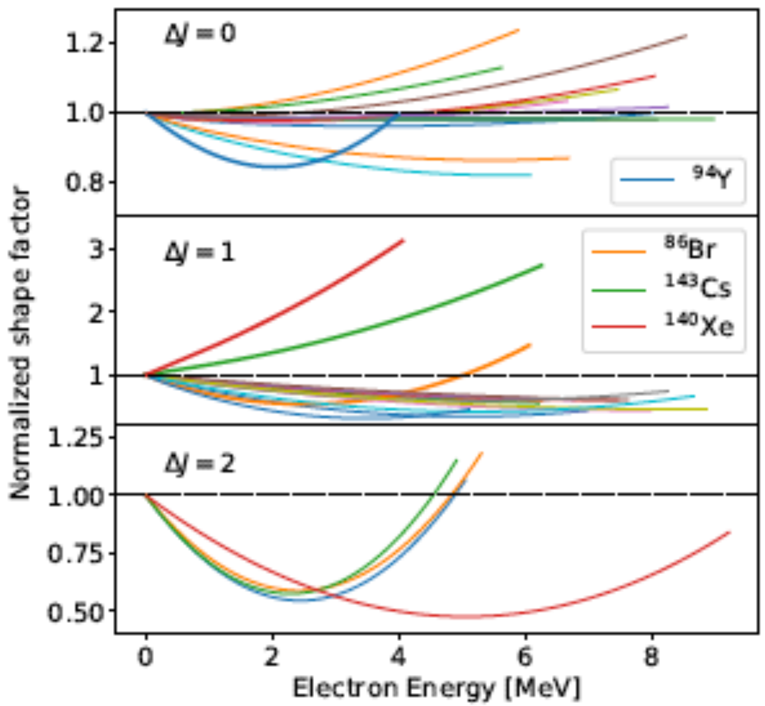
On going studies and improvements:

- Model ingredients,
- Decay Data and NDB,
- GEF: Fission Yields, uncertainties, isomers and predictions for future reactors,
- Forbidden decays and spectral shape

Explanation for the shape anomaly ?

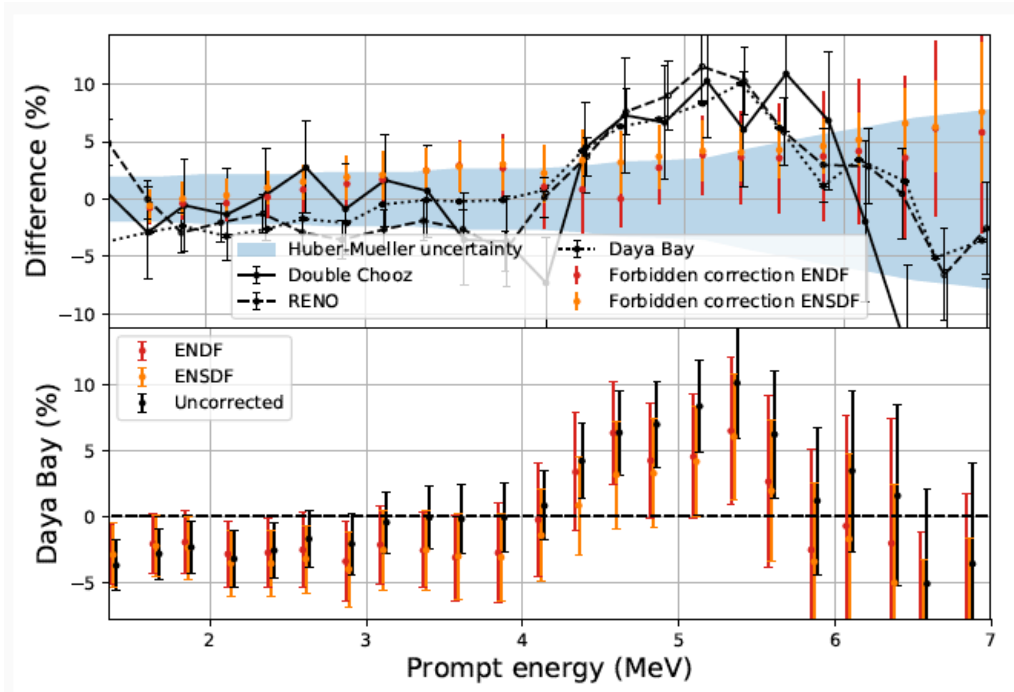
- **About 25% of decay branches of the fission products**
- **Treatment of forbidden decays => could change normalization & shape of reactor antiν spectra**

Calculation of the shape factors for forbidden decays: discrepancies among models, largest shape factors from L. Hayen et al.



L. Hayen et al., PRC.100.054323

Bump signicantly mitigated, still further research



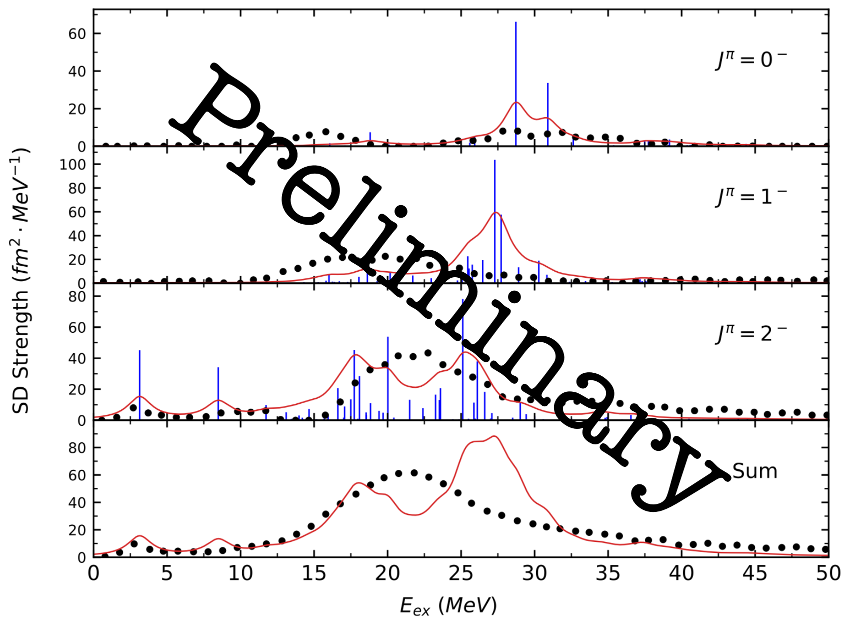
L. Hayen et al., PRC 99 (2019) 031301(R)

➡ **Measurements of the shape factors for the most important forbidden decays are needed to disentangle models, and understand the shape anomaly**

First-forbidden ß decay description through the pnQRPA approach

- Implementation and self-consistent calculation of charge-exchange operators corresponding to first-forbidden ß decays in the pnQRPA approach (charge-exchange quasiparticle random phase approximation)
- Code developed by the CEA DAM (Martini, Péru, 2014)
- Treatment of deformed nuclei and use of a unique nuclear force (Gogny D1M) to describe both ground and excited states for all nuclei
- Compare with TAGS and E-Shape measurements
- Compare with L. Hayen's shape factors

- The six first-forbidden ß operators $\mathcal{O}_\beta$ can be written as:
  - The anti-analog dipole operator: $\hat{O}_{r\mu} = rY_{1\mu}\tau_\pm$
  - The spin-dipole operators $(0^+ \to 0^-, 0^+ \to 1^-, 0^+ \to 2^-)$: $\hat{O}_{rs\lambda\mu} = r[Y_1 \otimes \sigma]_{\lambda\mu}\tau_\pm$
  - The pseudoscalar-axial vector operator: $\hat{O}_{ps0} = \sigma \cdot \nabla\tau_\pm$
  - The tensor-polar vector operator: $\hat{O}_{p\mu} = [Y_0 \otimes \nabla]_{1\mu}\tau_\pm$



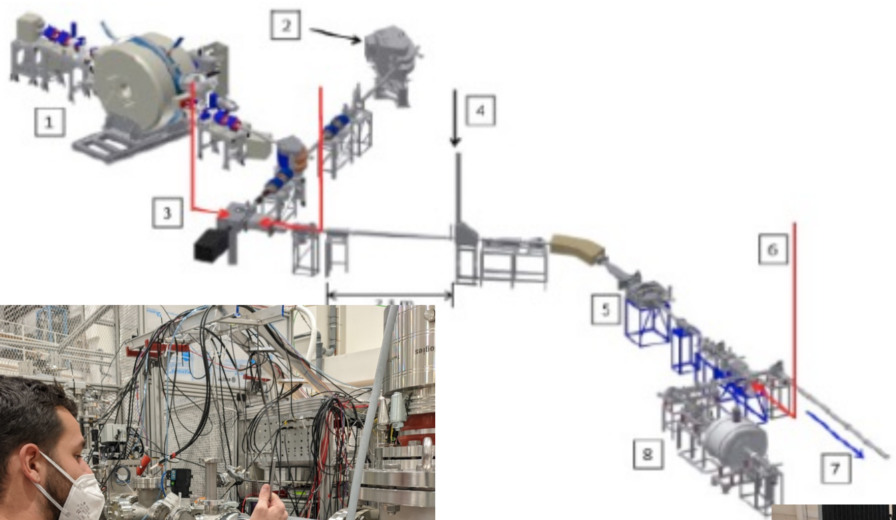
^{208}Pb Spin-Dipole strengths for each multipolarity. The bars in blue are the pnQRPA strengths, the line in red is the folded Spin-Dipole strength and the points in black are the available experimental data (Wakasa, 2010)

Courtesy A. Beloeuvre (Subatech), collaboration with S. Péru and M. Martini

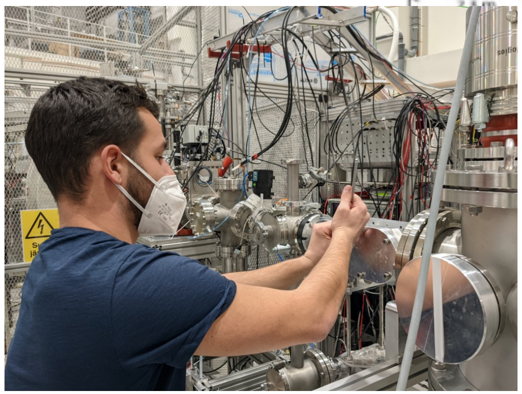
E-Shape (Nantes-Valencia-Surrey) 2022

- : **E-Shape campaign @IGISOL (Jyväskylä) in Jan. 2022:**

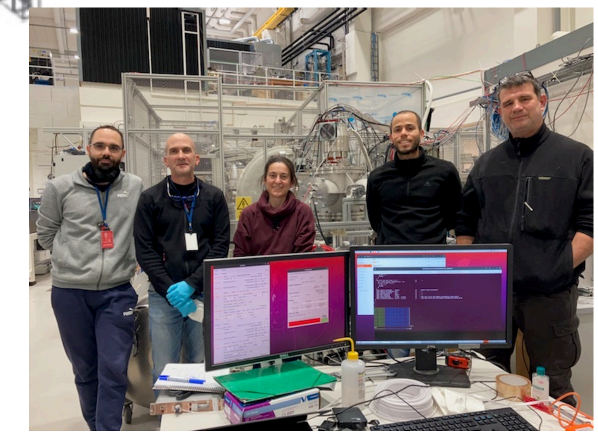
E-Shape Motivations: measure electron spectral shapes from First-Forbidden β-decays for Reactor Antineutrinos and Nuclear Structure and Astrophysics

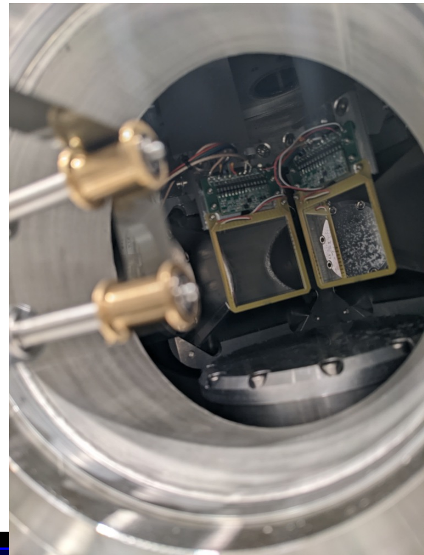


See A. Algora's talk



2 PhD students:
G. Alcala (Valencia) and A. Beloeuvre (Nantes)





Huge technical involvement by Subatech (Technical Services and SEN team): Mechanics + Electronics (Faster DAQ) very successful

Conclusions & Outlooks

Work on-going about:

- **Neutrino spectral formulation with L. Hayen**
- **Forbidden shape factors: theory & experiment (2022!)** **See A. Algora's talk**
- **More TAGS results with 7 more nuclei measured with the TAGS technique included in the summation model**
  - ❑ **New SM prediction lying at 1.8% above DB flux**
- **Uncertainty propagation with the GEF code**
- **New TAGS measurements performed (Sept. 2022!)** **See A. Algora's talk**

Yes we need new TAGS measurements, new shape measurements, Juno-TAO measurements, more nuclear structure insight => to understand the shape anomaly, at least ! + reactor monitoring

TAS COLLABORATION

IFIC Valencia: A. Algora, B. Rubio, J.A. Ros, V. Guadilla, J.L. Tain, E. Valencia, A.M. Piza, S. Orrigo, M.D. Jordan, J. Agramunt

SUBATECH Nantes: J.A. Briz, M. Fallot, A. Porta, A.-A. Zakari-Issoufou, M. Estienne, T. Shiba, A.S. Cucoanes

U. Surrey: W. Gelletly

IGISOL Jyvaskyla: H. Penttilä, Äystö, T. Eronen, A. Kankainen, V. Eloma, J. Hakala, A. Jokinen, I. Moore, J. Rissanen, C. Weber

CIEMAT Madrid: T. Martinez, L.M. Fraile, V. Vedia, E. Nacher

IPN Orsay: M. Lebois, J. Wilson

BNL New-York: A. Sonzogni

Istanbul Univ.: E. Ganioglu

Special thanks to the young researchers working in the project:
L. Le Meur, J.A. Briz, V. Guadilla, E. Valencia, S. Rice, A. -A. Zakari-Issoufou
Discussions with and slides from: A. Algora, J. L. Tain, B. Rubio, S. Cormon, A. Cucoanes, M. Estienne, M. Fallot, L. Giot, A. Porta, T. Shiba, …are acknowledged