Updated Summation Method Model and New Prediction for the Reactor Antineutrino Detected Flux and Energy Spectrum

M. Estienne[1], M. Fallot[1*], A. Algora[2, 3], 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], A. Porta[1], S. Rice[4], B. Rubio[2], J. L. Taín[2], E. Valencia[2], and A.-A. Zakari-Issoufou[1]

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Subatech

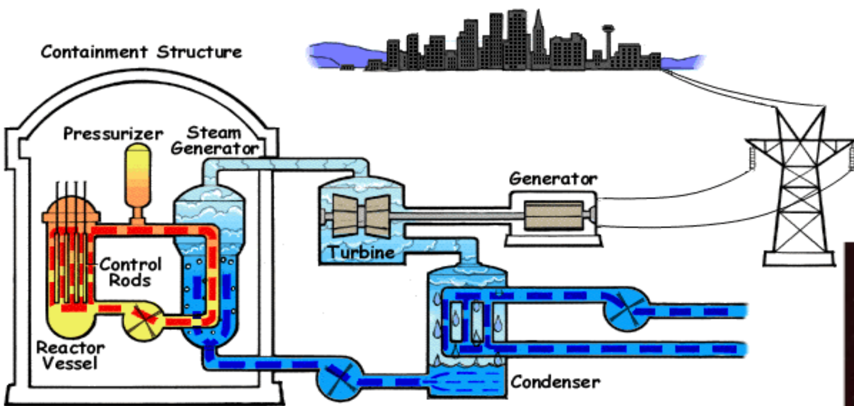
Outline

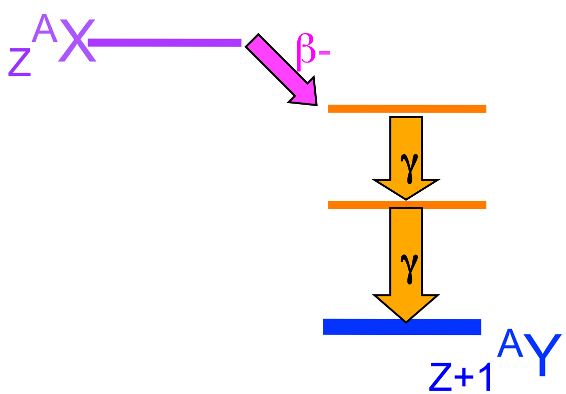
- Introduction & Motivations
- Conversion Method for Reactor Antineutrino Spectra
- Summation Method for Reactor Antineutrino Spectra
- Measurement Caveat
- TAGS Experimental Campaigns
- Updated Summation Model & Comparison with Daya Bay Results
- Conclusions & Outlooks

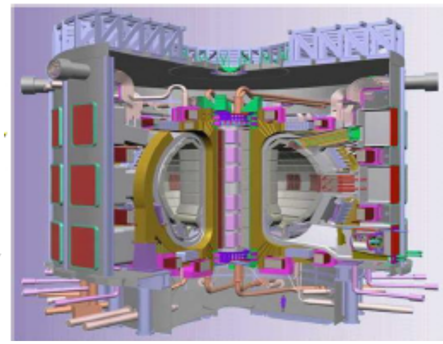
Nuclear Data for …

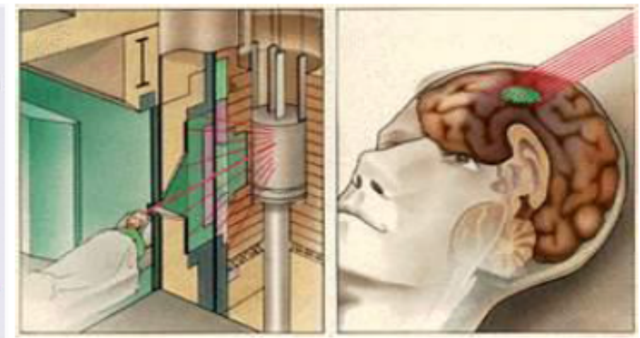
Nuclear fission energy
Nuclear fusion research
Radiation protection
Nuclear medicine
(Nuclear) security

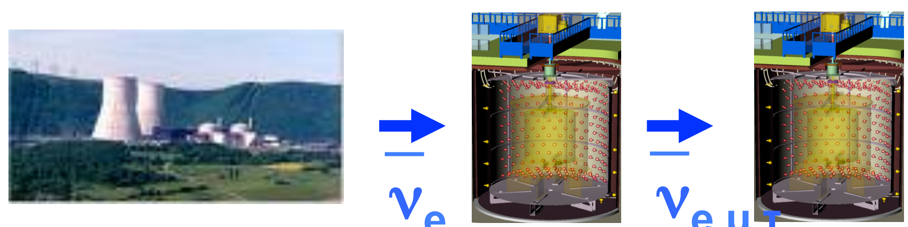
Object and materials analysis
Astrophysics
Basic science









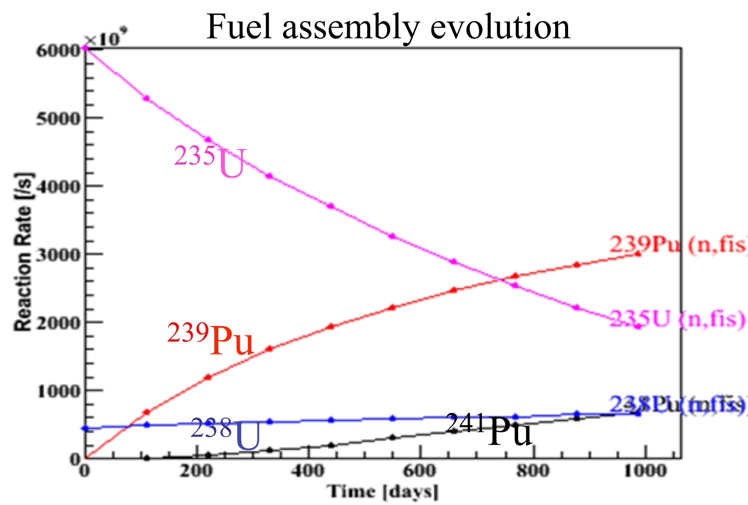


Nuclear Power Station Near detector Far detector

Cf. A. Plompen (CEE) @ PND2 workshop, CEA-DAM Oct. 2014

Reactors and Beta Decay

- In Pressurized Water Reactors, thermal power mainly induced by 4 isotopes:
  - ^{235}U and ^{238}U in fresh fuel
  - Other fissile nuclei (^{239}Pu & ^{241}Pu) created after reactor start by capture and decay processes
  - Burn-up effect => unit GWd/t



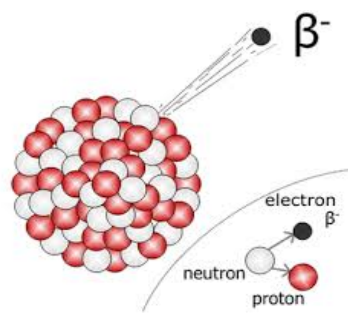
- Fission process gives thermal energy:

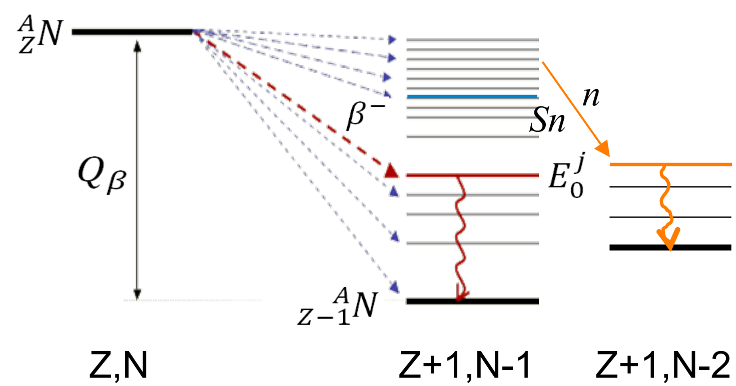
$$n + {}^{235}U \rightarrow {}^{236}U^{*} \rightarrow \mathrm{FP1} + \mathrm{FP2} + \mathrm{neutrons}\,(200 MeV)$$

- The fission products (FP) after the fissions are neutron-rich nuclei undergoing β and β-n decays:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_e$$

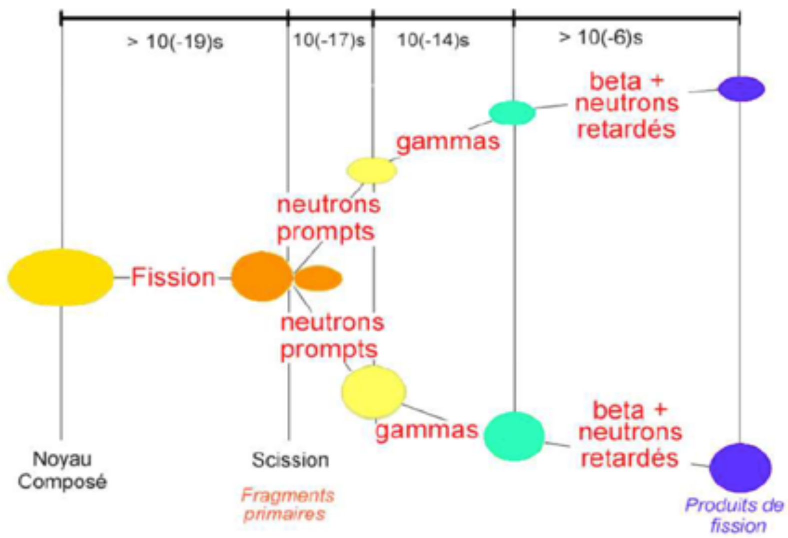
$$ {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s$$



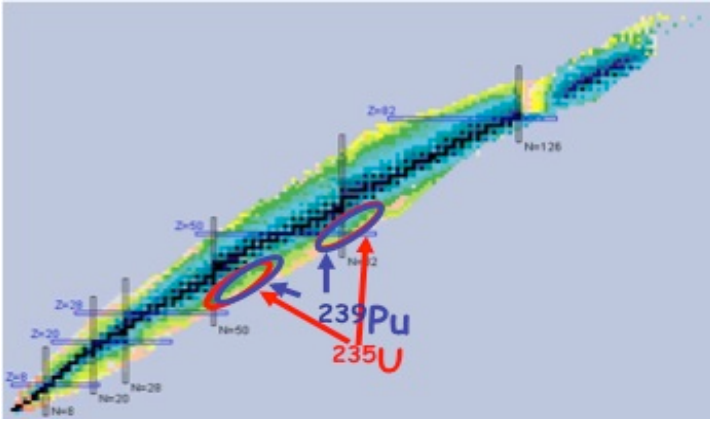


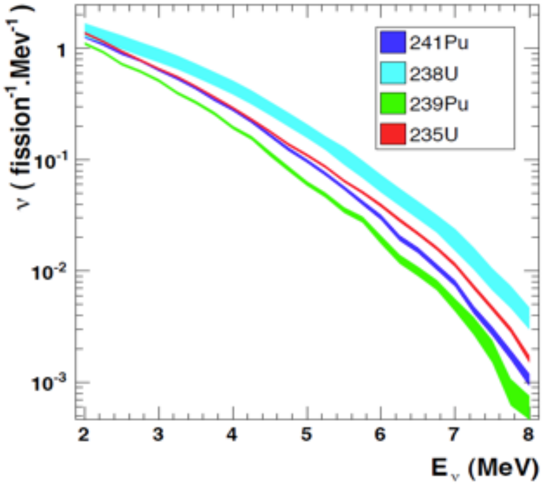
Beta Decay for Present and Future Reactors

- The exploitation of the products of the beta decay is threefold:
  - ❑ The released γ and β contribute to the "**decay heat**" → critical for reactor safety and economy
  - ❑ The **antineutrinos** escape and can be detected → reactor monitoring, potential non-proliferation tool and essential for fundamental physics
  - ❑ β-n emitters: **delayed neutron fractions** → important for the operation and control of the chain reaction of reactors



Antineutrinos for Peace





About 6 antineutrinos emitted per fission
→ **About 10^{21} antineutrinos/s emitted by a 1 GW_e reactor**

- Use the discrepancy between antineutrino flux and energies from U and Pu isotopes to infer reactor fuel isotopic composition and power
  - Reactor monitoring, non-proliferation and interest for the IAEA IAEA Report SG-EQGNRL-RP-0002 (2012)
  - Idea born in the 70s, demonstrated in the 80s/90s but developed lately

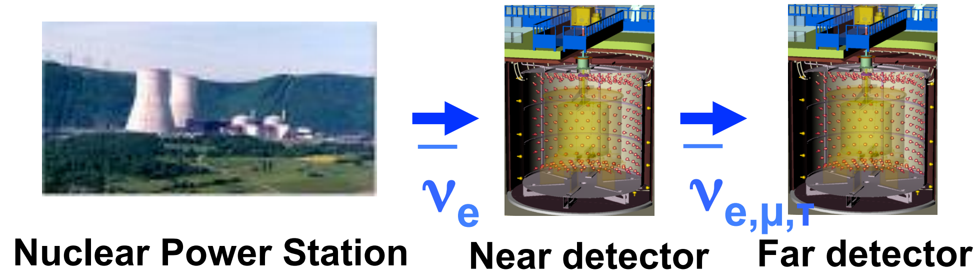
The Summation Method, relying on nuclear data, is the only predictive one (for innovative reactors & fuels):

⇒ The IAEA Nuclear Data section includes the measurements for reactor antineutrino spectra in their Priority lists (CRP meetings, TAGS consultant meetings…see P. Dimitriou et al. INDC(NDS)-0676 (2016))

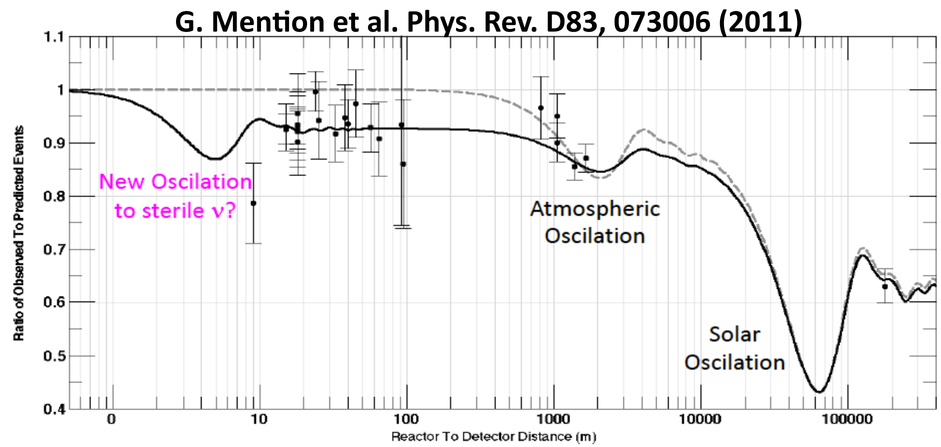
Reactor Antineutrinos are used for

⇒ **Neutrino Fundamental Physics**

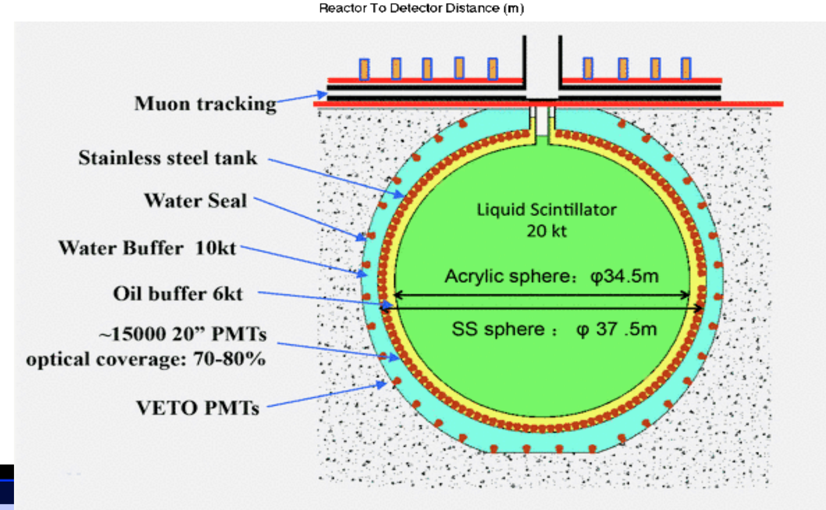
- **Measurement of the θ_{13} oscillation param by Double Chooz, Daya Bay, Reno**



- **Sterile neutrino measurement to explain the "reactor anomaly"**



- **Next generation reactor neutrino experiments like JUNO or background for other multipurpose experiment**



Reactor Antineutrino Spectral Knowledge

- First Double Chooz, Daya-Bay and Reno theta13 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)

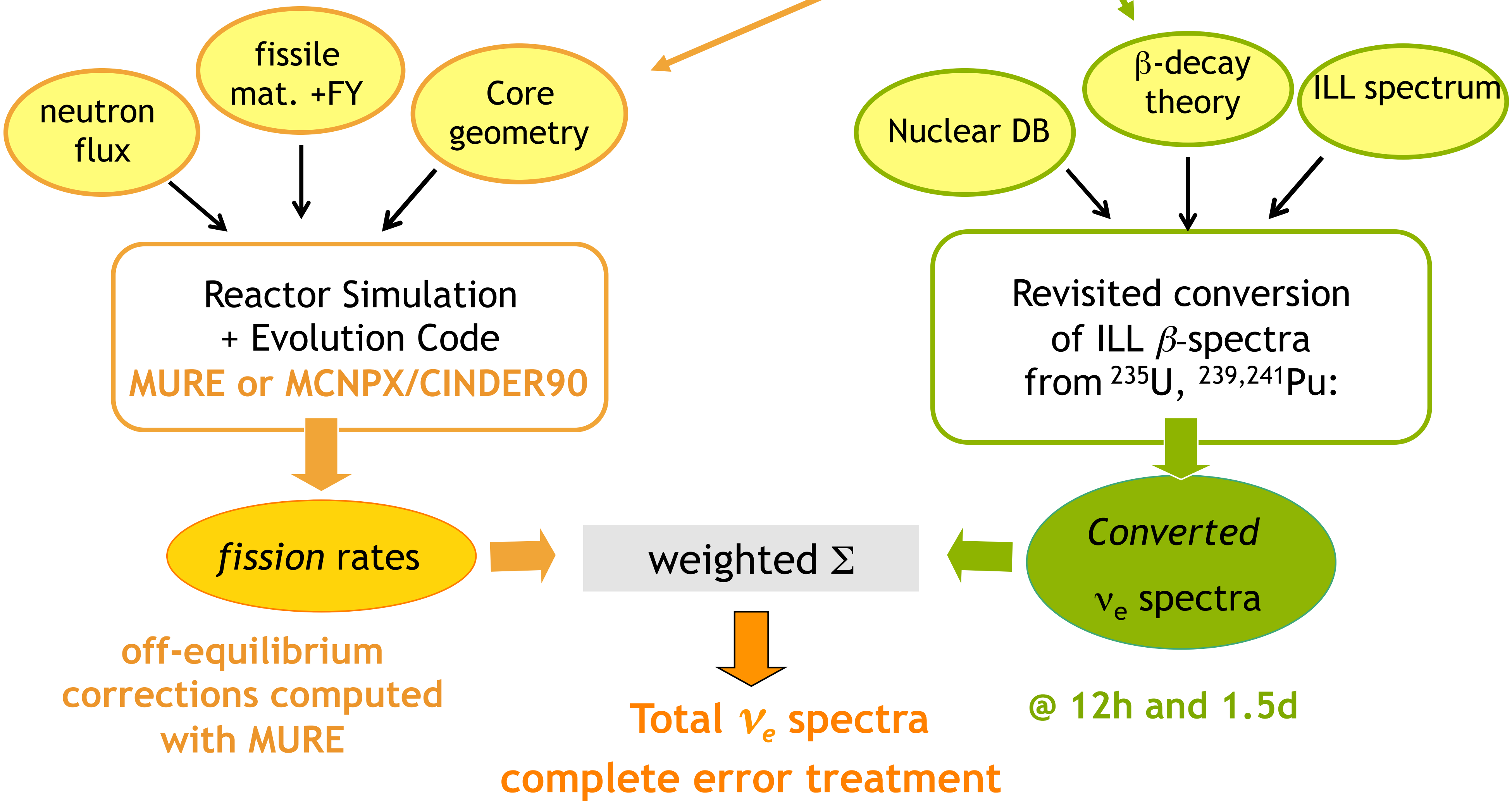
- The Double Chooz experiment has devoted efforts to new computations of reactor antineutrino spectra (mandatory for the 1st phase !!!)

- **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 et al. Phys. Rev. C 19 2259 (1979), to Tengblad et al. Nucl. Phys. A 503 (1989)136)

The Conversion Method for Reactor Antineutrinos

Conversion Method

$$N_{\nu}^{emit}(E) = \int_{0}^{T_{run}} P_{th}(t) \times \sum_{i\ fuel\ assemblies} \frac{\alpha_i(t)}{\sum_k f_i^k(t) E_k} \sum_{k\ fissile\ isotopes} N_{\nu}^{k}(E) f_i^k(t) \quad dt$$

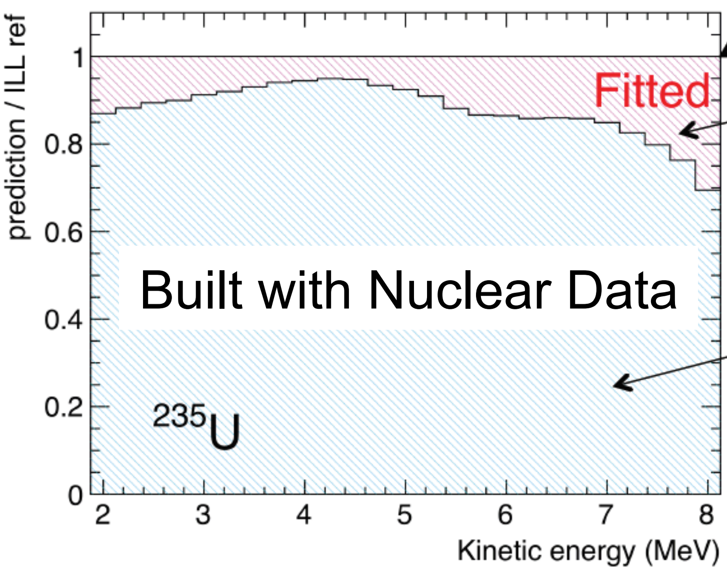


Reactor Antineutrinos: Converted Spectra

- **Calculation of Reactor Antineutrino Spectra from the conversion of the beta spectra measured by Schreckenbach et al. at the ILL reactor in the 80's**
- **Principle: Fit the beta spectrum shape with beta decay branches (nuclear data + fictive branches or only fictive branches), taking into account proper Z distribution of the fission products, proper corrections to Fermi theory and a large enough number of beta branches**

Example: Th.A. Mueller et al, Phys.Rev. C83(2011) 054615:

Ratio of Prediction / Reference ILL data



ILL electron data anchor point

- Fit of residual: five effective branches are fitted to the remaining 10%

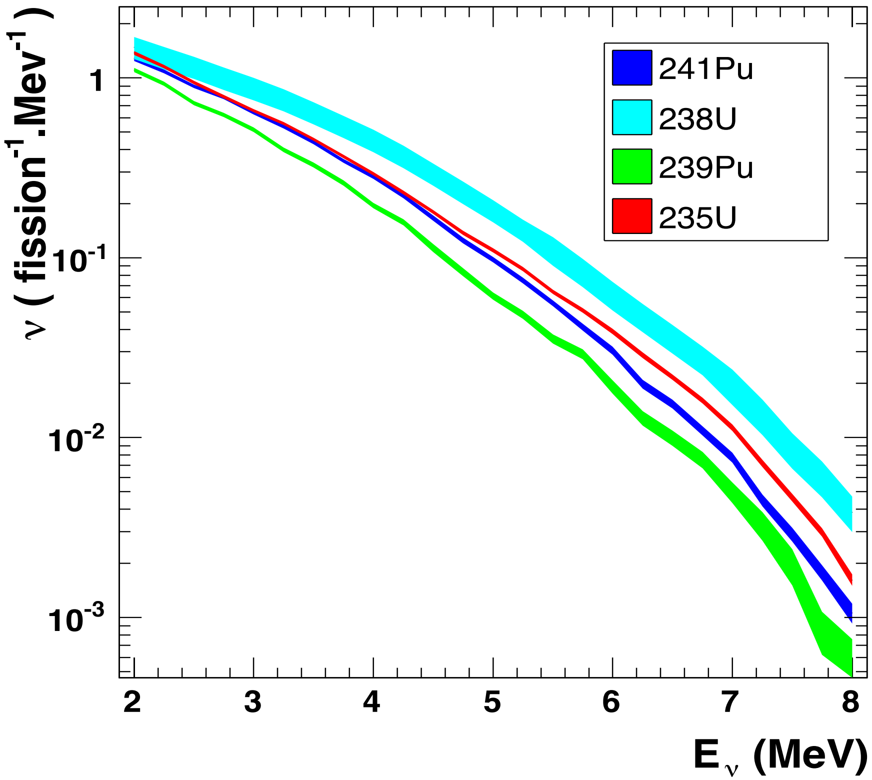
⇒ Suppresses error of full Summation Approach, if assumption that ILL data = only reference

- "true" distribution of all known β-branches describes >90% of ILL e data

⇒ reduces sensitivity to virtual branches approximations

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

Revisited Converted Spectra



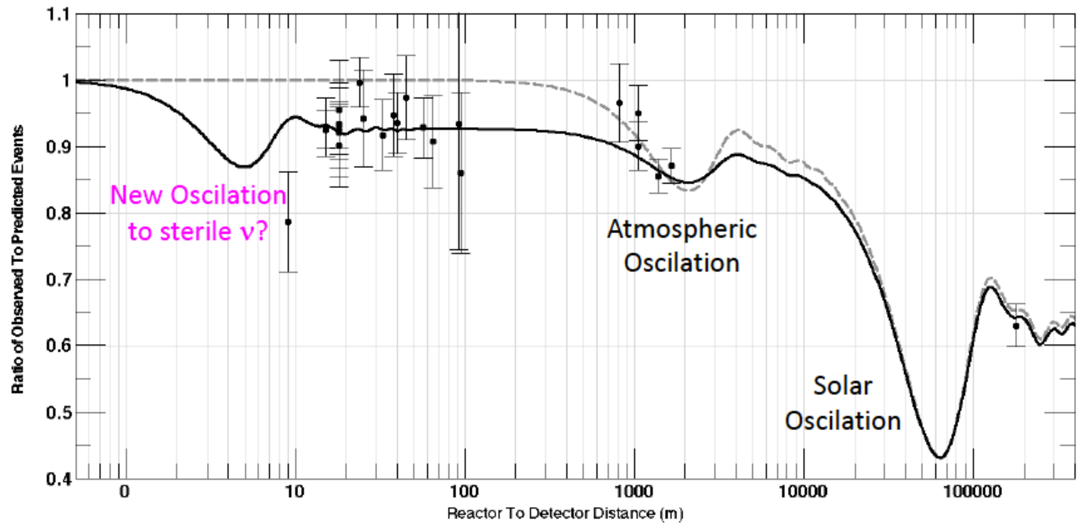
- Recent re-evaluations by
  - ✓ Th.A. Mueller et al, Phys.Rev. C83(2011) 054615.
  - ✓ P. Huber, Phys.Rev. C84 (2011) 024617
- Off-equilibrium corrections included (computed with summation method MURE)
- Summation calculations: provided the used databases for the conversion + a new ^{238}U prediction

Recent works defining new reference on the neutrino flux prediction for neutrino physics

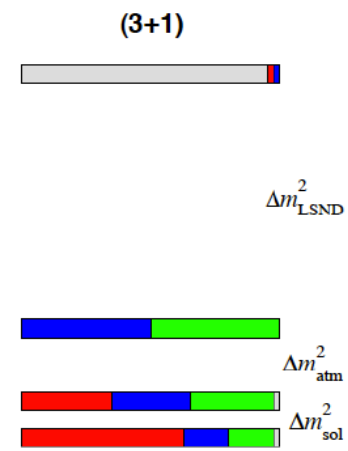
Sterile Neutrino hints ?

- **Reactor Anomaly:**
  - converted ν spectra = ˜+3% normalization shift with respect to old ν spectra, similar results for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)
  - Neutron life-time
  - Off-equilibrium effects

2 flavour simple scheme :
$P_{Osc} = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2_{[eV2]} L_{[m]} / E_{[MeV]})$



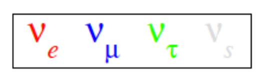
G. Mention et al. Phys. Rev. D83, 073006 (2011)



⇒ **Light sterile neutrino state ?**

could explain L=10-100m anomalies, $\Delta m^2 \approx 1\ eV^2$

Candidate(s) can't interact via weak interaction : constrained by LEP result on 3 families => so can only exist in sterile form



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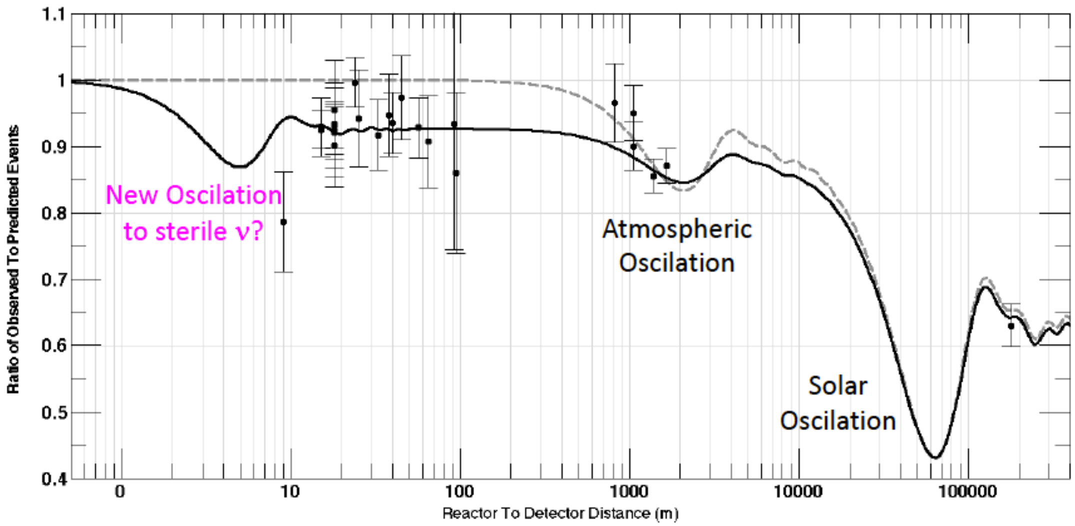


G. Mention et al. Phys. Rev. D83, 073006 (2011)

⇒ Looking for sterile neutrinos as a potential explanation to the reactor anomaly: numerous projects: SoLid (UK-Fr-Bel-US), STEREO (France), Neutrino-4 (Russia), DANSS(Russia), PROSPECT(USA), + Mega-Curie sources in large ν detector… (white paper: K. N. Abazajian et al., http://arxiv.org/abs/1204.5379.)

Converted Spectra: Underestimated Uncertainties

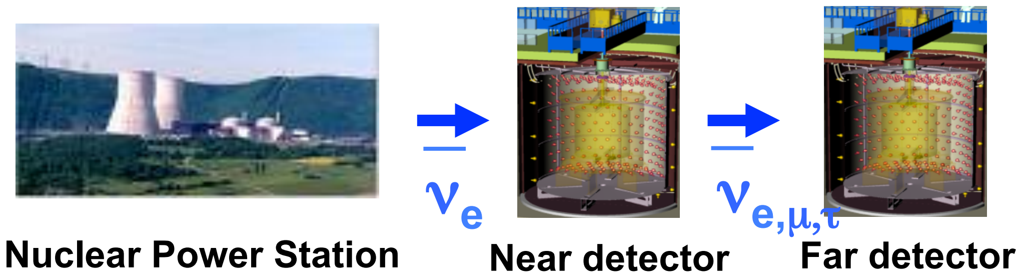
- **Additional sources of systematic errors:**
  - ***ILL data = unique and precise reference*** **=> Need for a second measurement with similar accuracy to exclude potential systematics on the ILL data normalization and shape !!!**
  - ***Large uncertainty for Weak Magnetism term: the*** **most uncertain one among the corrections to the Fermi theory !**

    P. Huber PRC84,024617(2011): could change the normalization of the spectra if very different value…

    D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015): The finite size effects and the weak magnetism corrections obtained in Huber's paper for the allowed (GT) decays are estimated to give a reduction in the number of low energy antineutrinos of 2 – 3%.
  - ***Impact of the conversion method*** **? Quoting A.C. Hayes: depending on the adopted average effective Z distributions used in the fit of the ILL spectra, converted spectra could vary easily by 5%**
  - ***Treatment of forbidden decays => could change normalization & shape of spectra:*** **A. Hayes et al. Phys. Rev. Lett. 112, 202501 (2014), D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015),** X.B. Wang, J. L. Friar and A. C. Hayes **Phys. Rev. C 95 (2017) 064313 and Phys. Rev. C 94 (2016) 034314, L. Hayen et al. Phys. Rev. C 031301(R)(2019)**

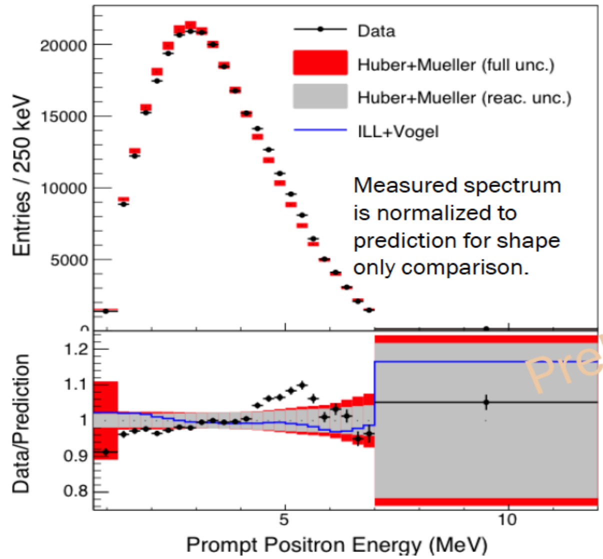
Reactor Antineutrinos & Fundamental Physics

- Measurement of the θ_{13} oscillation param by Double Chooz, Daya Bay, Reno
  - ❑ Independent computation of the anti-ν spectra using nuclear DB: conversion method



- Sterile neutrino measurement to explain the "reactor anomaly"
  - ❑ 6% deficit of the absolute value of the measured flux compared to the best prediction ILL data
  - ❑ Shape anomaly (spectral distorsion) in the full spectrum (btw 4.8-7.3 MeV)
  - ❑ Daya Bay PRL points-out a pb in the converted antineutrino spectra from ^{235}U measured beta spectrum @ILL

✧ Absolute shape comparison of data and prediction: χ^2/ndf = 41.8/21



- Next generation reactor neutrino experiments like JUNO or background for other multipurpose experiment

➡ Putting integral beta measurement of ^{235}U of Scheckenbach *et al.* and sterile neutrinos into question.

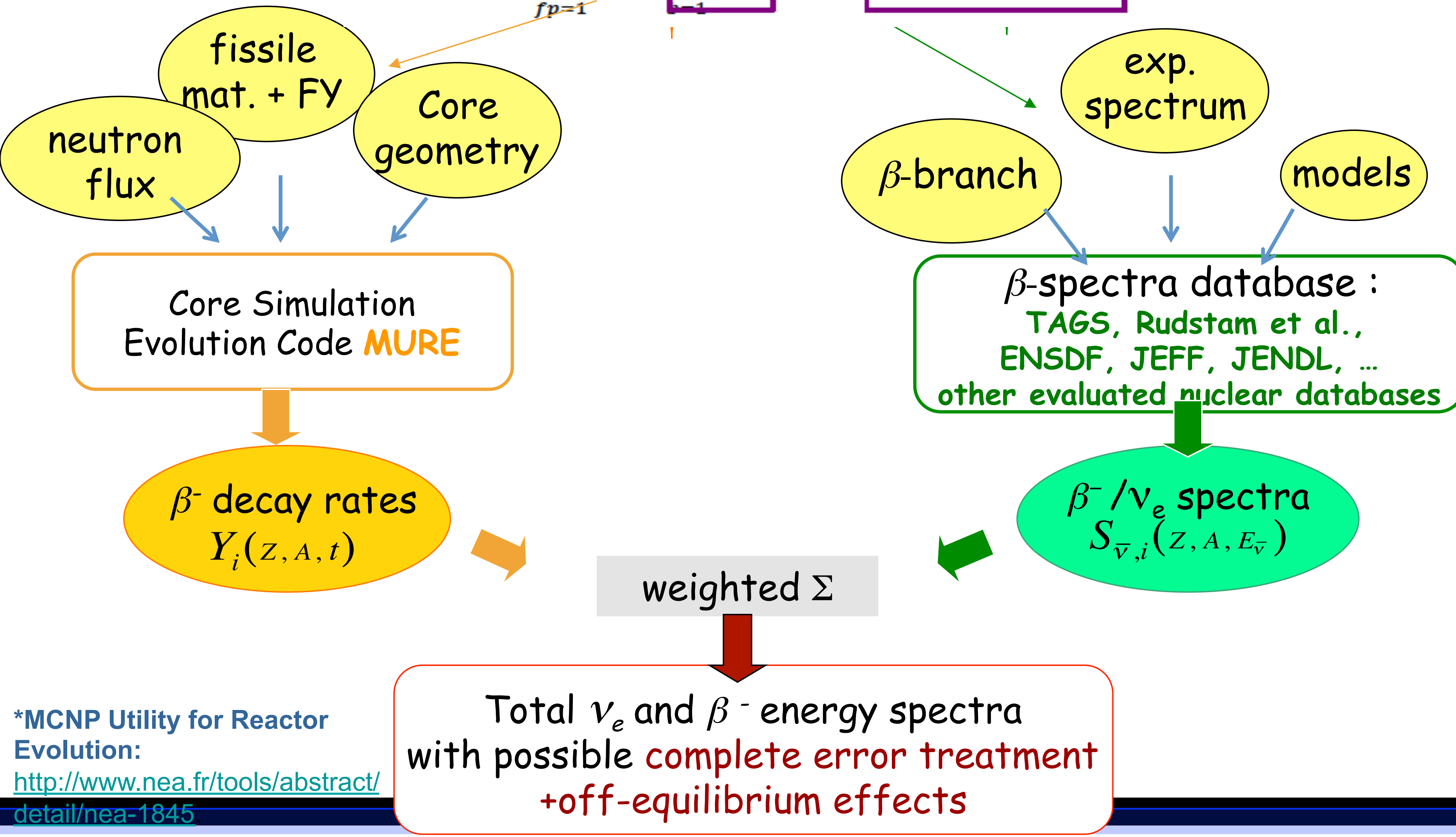
➡ Growing interest in an alternative method: the summation method based on nuclear data

The Summation Method for Reactor Antineutrinos

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 ?

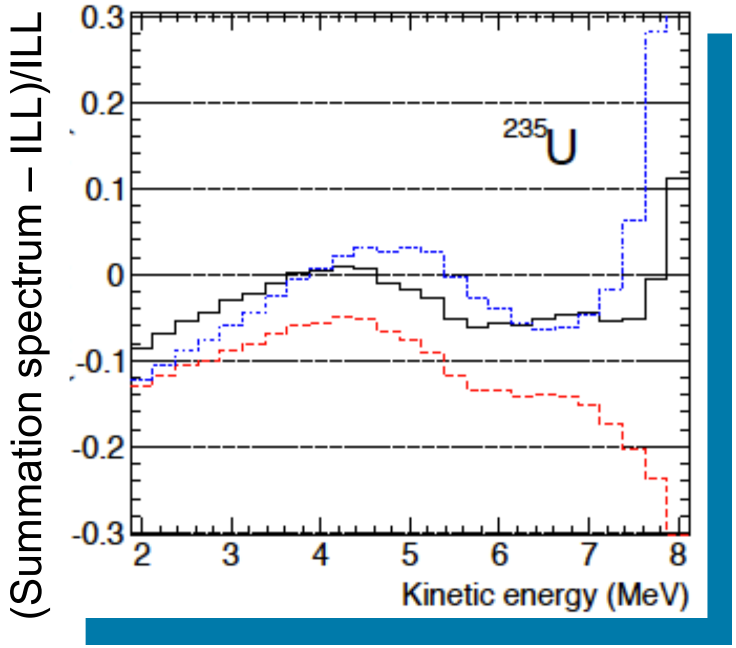
Summation Calculations:

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)

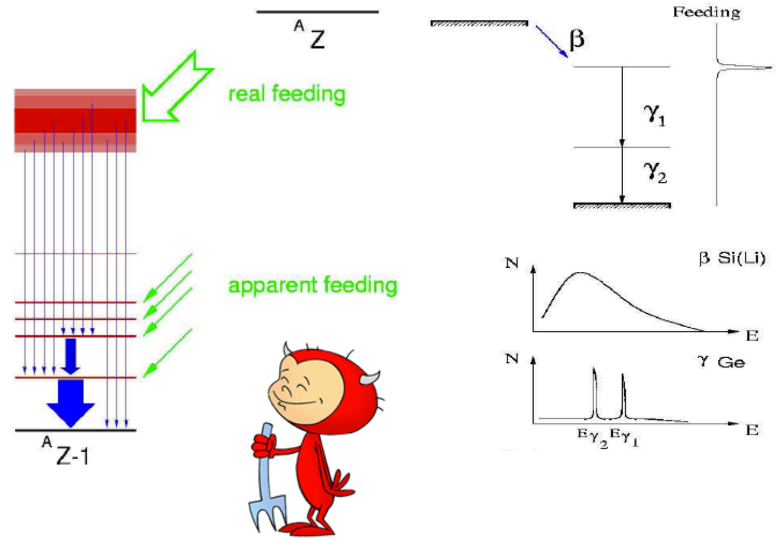
- Incomplete decay schemes: overestimate of the high-energy part of the FP β spectra

- 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



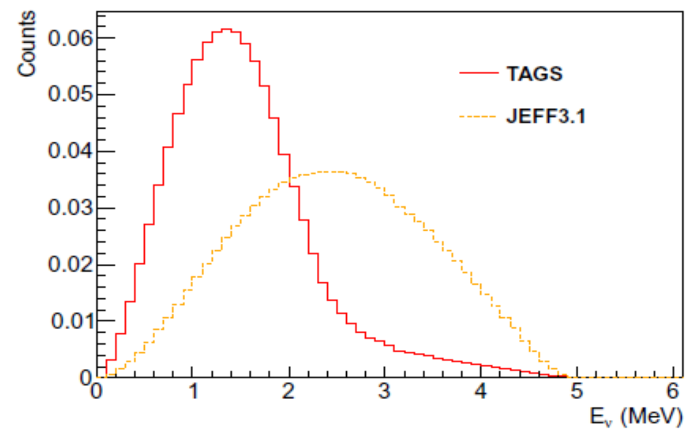


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

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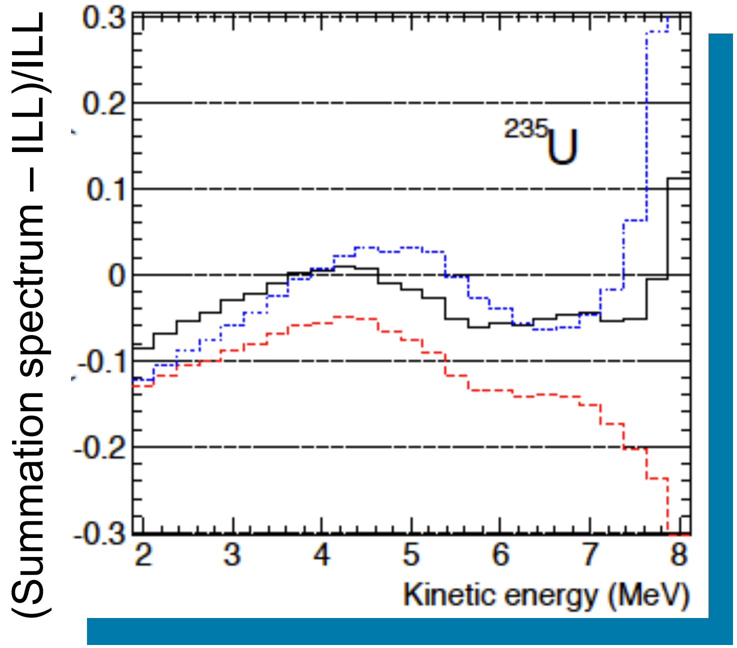
using P. Huber's prescriptions for spectral shape calculations, a careful selection of decay data, and fission yields from JEFF3.1:

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



⇒ **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**

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 (2017): « 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 »

+ A. Sonzogni et al. Phys. Rev. Lett. 116, 132502 (2016) & Phys. Rev. C 98 041323(2018) (2018)

2 TAS Campains at IGISOL Jyväskylä in 2009 and 2014

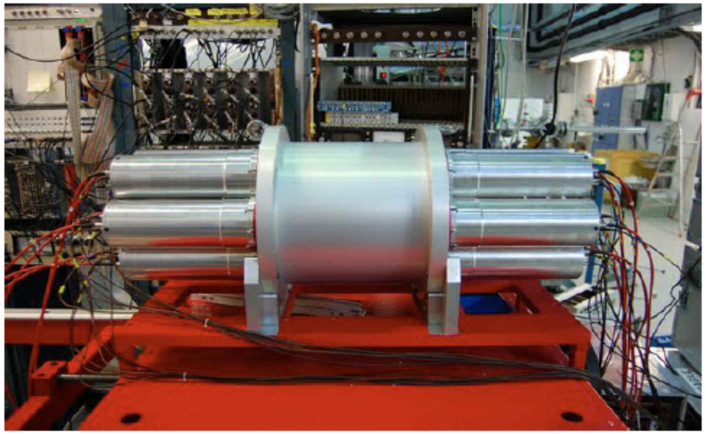
- IGISOL@Jyväskylä:
  - ❑ Proton induced fission ion-guide source
  - ❑ Mass separator magnet
  - ❑ Double Penning trap system to clean the beams

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)

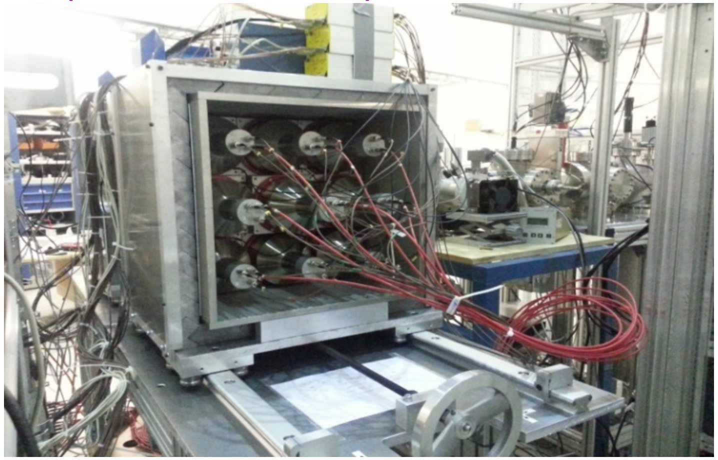
- 2 (segmented) TAS campains :

❑ 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):



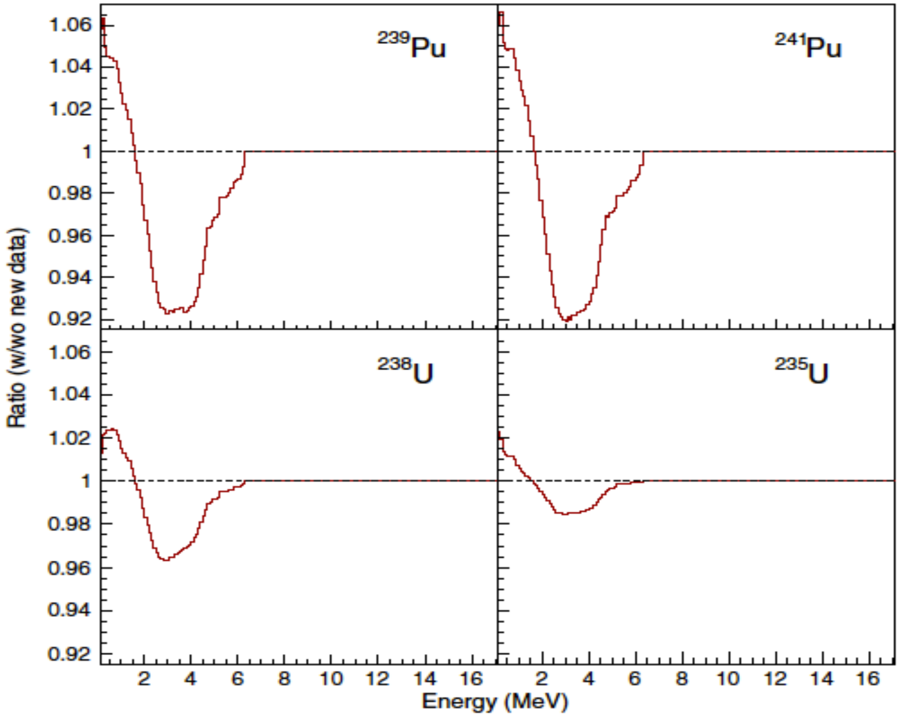
- ✓ 18 NaI(Tl) crystals of 15cm×15cm×25 cm
- ✓ Individual crystal resolutions: 7-8%
- ✓ Total efficiency: 80-90%
- ✓ Coupled with plastic scintillator for β
- ✓ 12 nuclei for anti-ν measured & 11 for DH

Anti-ν Spectra: the Summation Method

Taking into consideration the TAS data of the $^{102;104-107}Tc$, ^{105}Mo, and ^{101}Nb isotopes measured @ Jyväskylä

- ~850 nuclei included
- Noticeable deviation from unity (1.5 to 8% decrease)
- Change in the flux (presented later)

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



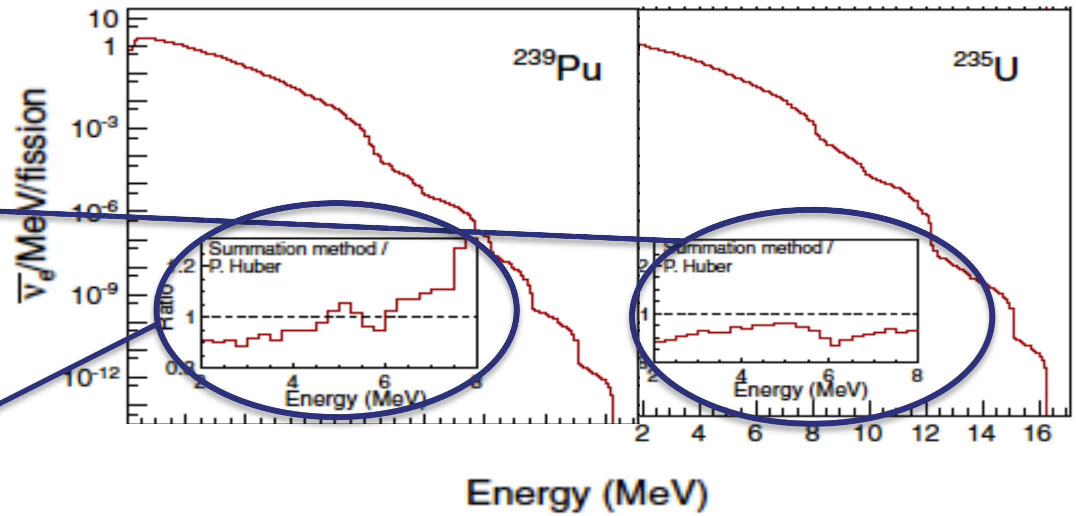
Relative Effects of the 2012 TAS data on the Antineutrino Spectra: typical from Pandemonium: the inclusion of Pandemonium free data increases the spectrum above 2-3 MeV and decreases it above
⇒ Provided the dependence of the IBD cross-section on the energy, this will impact the IBD yield a lot !

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.

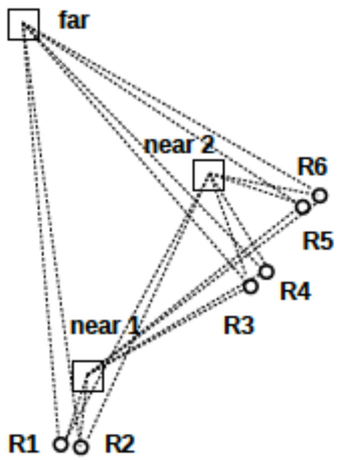


M. Fallot *et al.*, PRL 109, 202504 (2012)

Comparison with the Daya Bay results

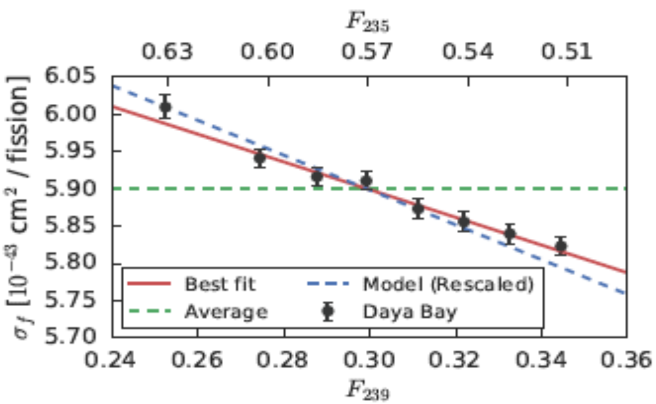
Context by end 2017…

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).
And associated APS Viewpoint by M. Fallot

⇒ 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 with 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 !!!

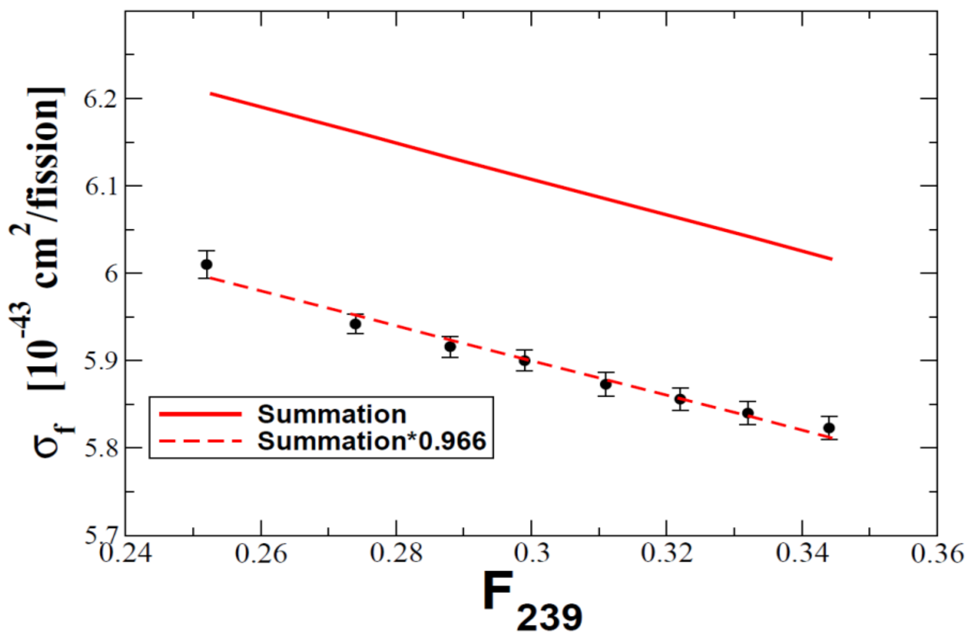
⇒ In contrast, the discrepancy = **almost zero for ^{239}Pu fissions**.

➡ **Potential issue in Schreckenbach measurement or H-M model for 235U?**

New DB paper on ArXiv:1904.07812 re-inforces previous results

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

Summation Method: Update of Ingredients

- **Considered nuclear decay databases** ordered by decreasing priority:

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

⇒All fission products in the JEFF3.1.1 fission yields databases taken into account

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

Taking into consideration:

⇒the latest published TAS data of the $^{102;104–107}Tc$, ^{105}Mo, and ^{101}Nb isotopes from A. Algora et al. PRL. 105, 202501 (2010), D. Jordan et al. Phys. Rev. C 87, (2013) 044318, this constitutes the SM model from M. Fallot et al. Phys. Rev. Lett. 109,202504 (2012), called **SM-2012**

⇒ + ^{92}Rb A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015), called **SM-2015**

⇒ + $^{87,88}Br$ and ^{94}Rb E. Valencia et al., Phys. Rev. C 95, 024320 (2017)

⇒ + ^{86}Br and ^{91}Rb S. Rice et al. Phys. Rev. C 96 (2017)014320 called **SM-2017**

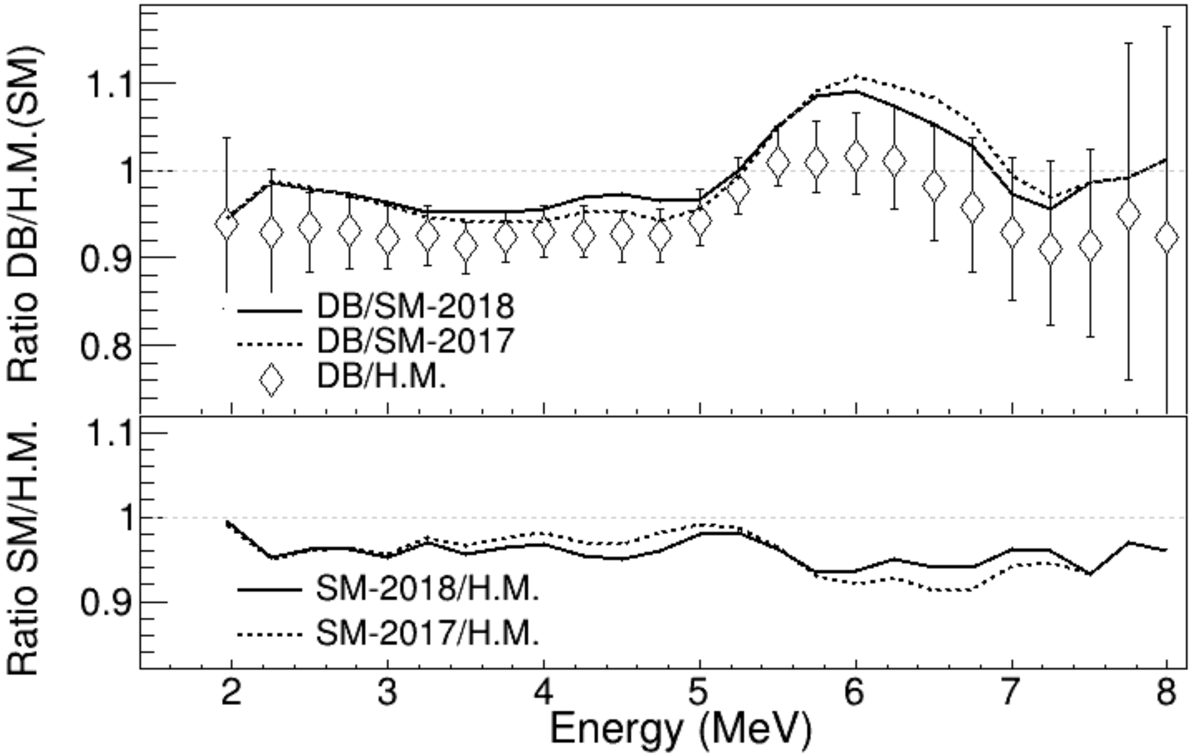
⇒ + $^{100,100m,102,102m}Nb$ Guadilla et al. Phys. Rev. Lett. 122, (2019) 042502 called **SM-2018**

See M. Estienne et al. http://arxiv.org/abs/1904.09358

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

Comparison with Daya Bay results and H-M Predictions

M. Estienne et al. http://arxiv.org/abs/1904.09358 **accepted in Phys. Rev. Lett.**



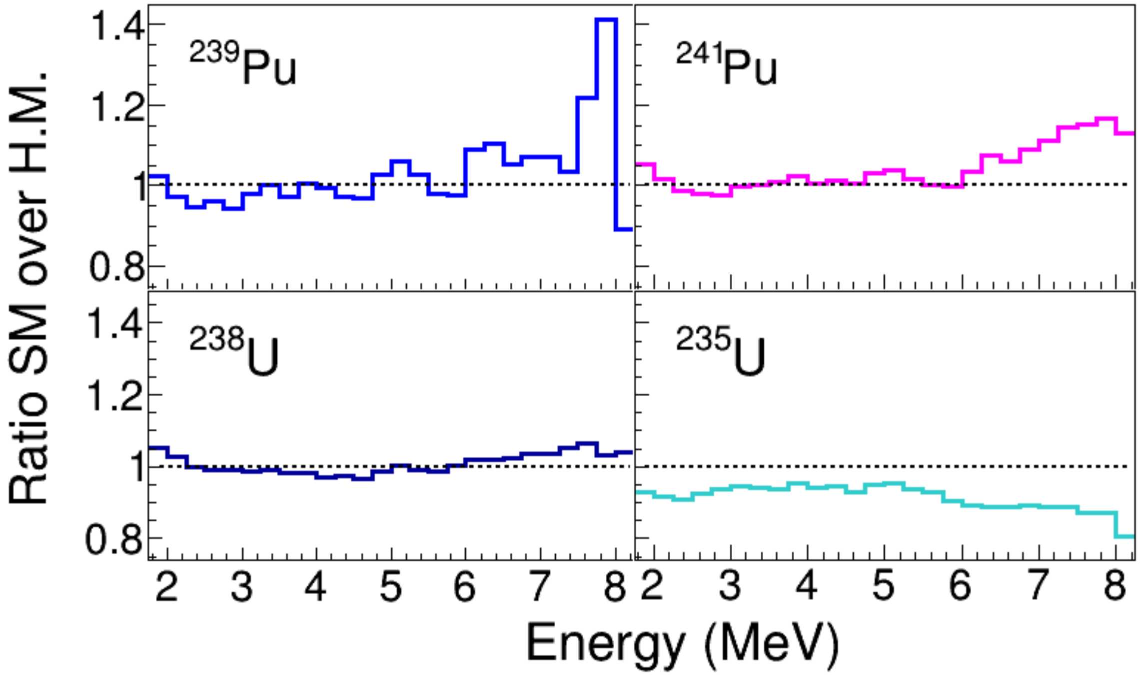
- Comparison of the full detected antineutrino energy spectrum obtained with the summation model, without any renormalization, with the measurements from Daya Bay.
- The 2018 data improve the agreement with Daya Bay (ratio DB/SM closer to 1)

.

- Even with the inclusion of the 2018 TAGS data, the bump is still there i.e. for the moment, it still cannot be explained by ingredients of the nuclear databases.

Comparison with H-M individual spectra

M. Estienne et al. http://arxiv.org/abs/1904.09358 accepted in Phys. Rev. Lett.



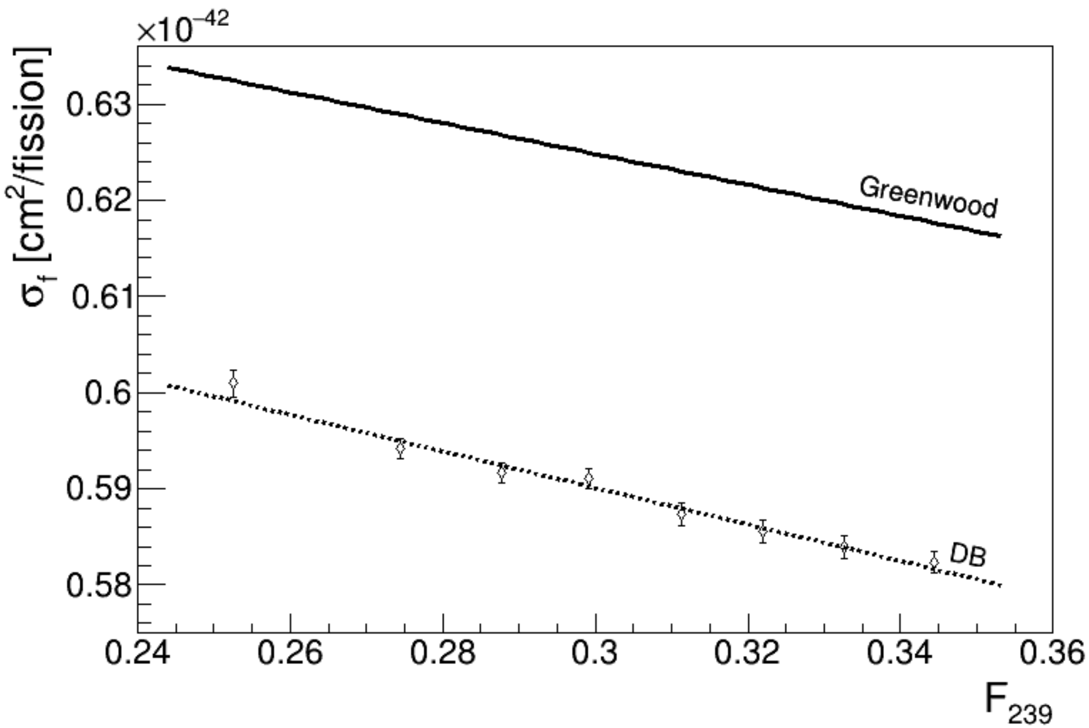
- The ratios with converted spectra have become flatter up to ~6 MeV compared with SM-2012
- The normalisation of ^{235}U still disagrees (same as in 2012), confirming Daya Bay's result
- ^{238}U: ratio w.r.t. Mueller et al 's version of the SM: spectrum remains stable with the update of databases and 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 energy range matters indeed, because the antineutrino data are also more uncertain above 6 MeV

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. http://arxiv.org/abs/1904.09358 accepted in Phys. Rev. Lett.

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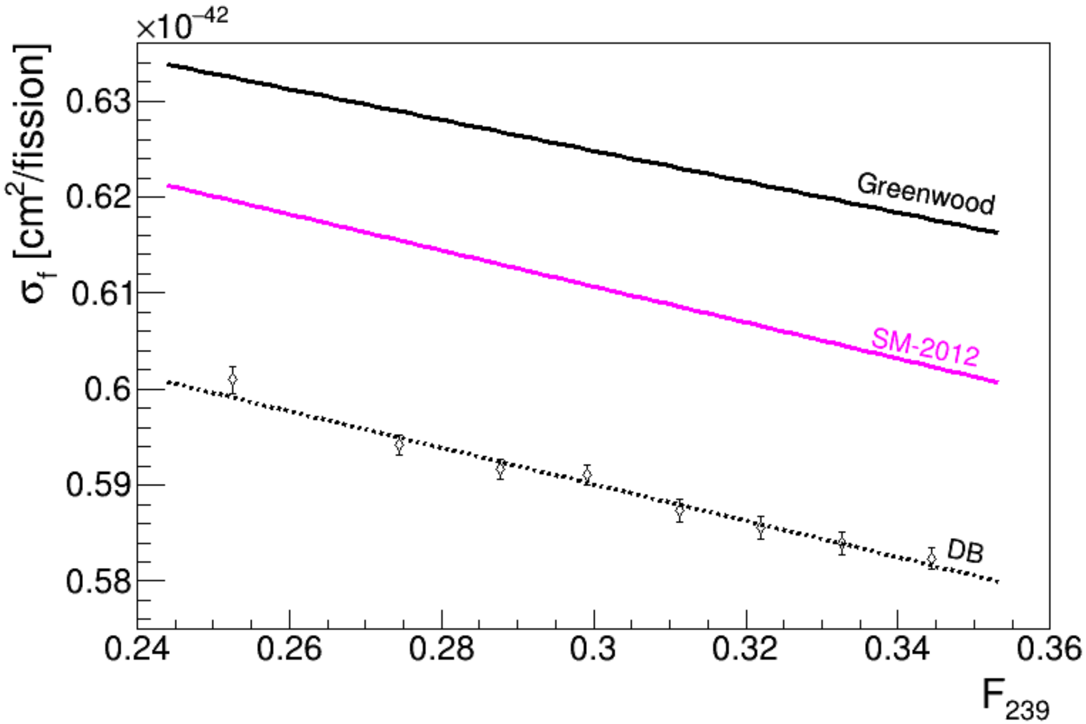

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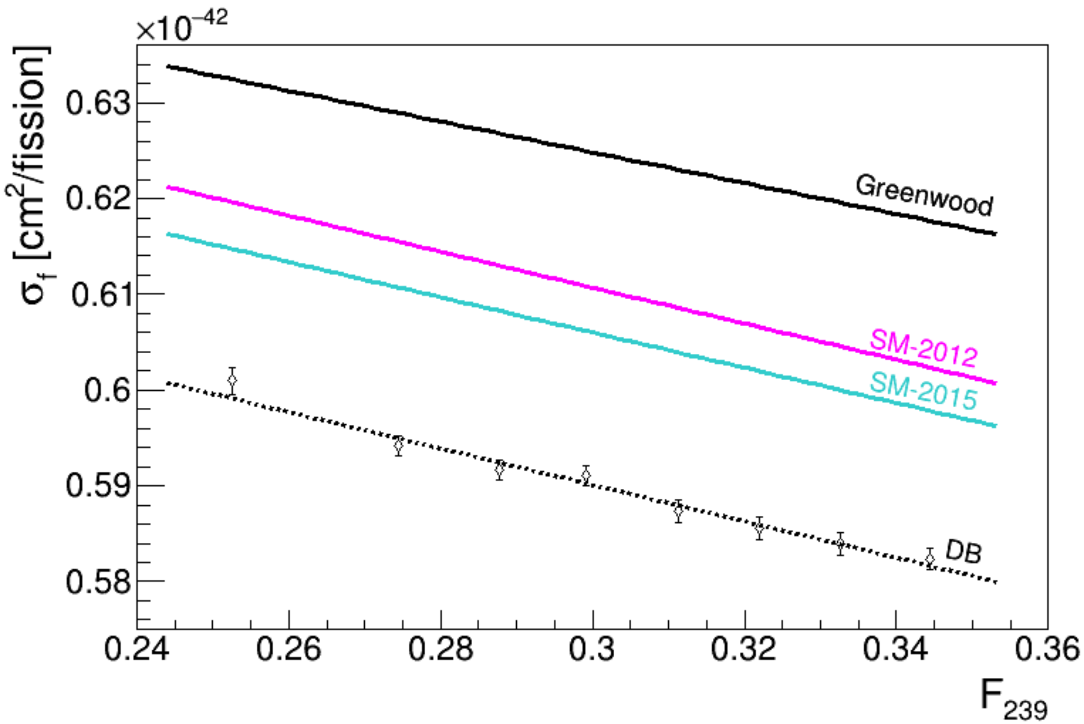

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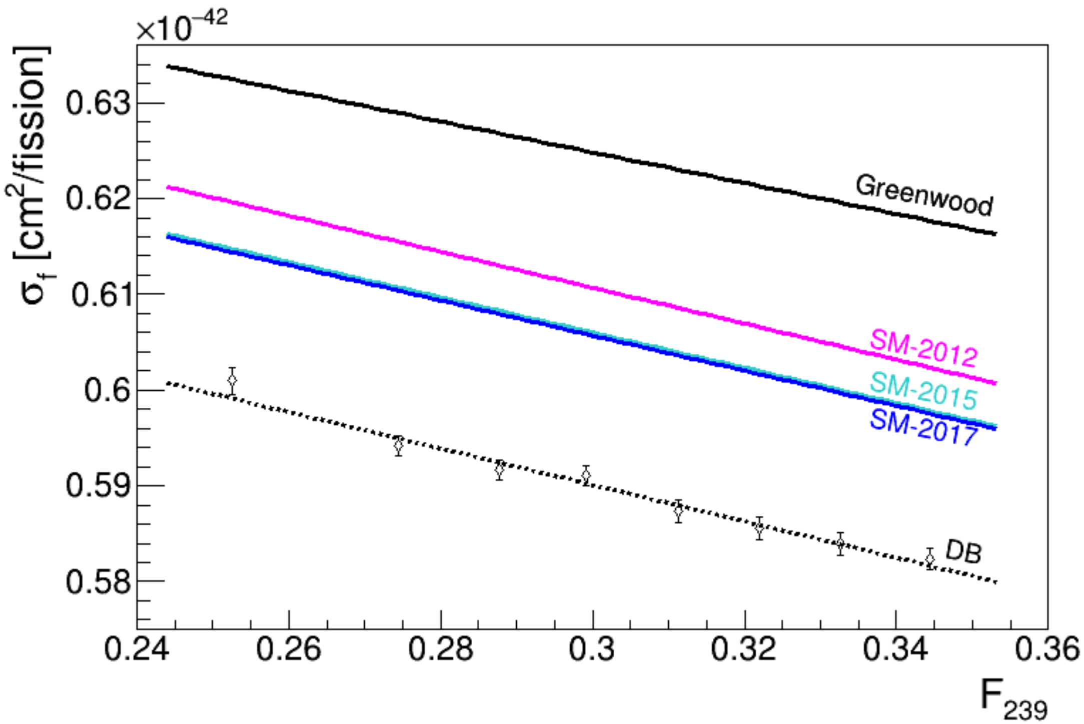

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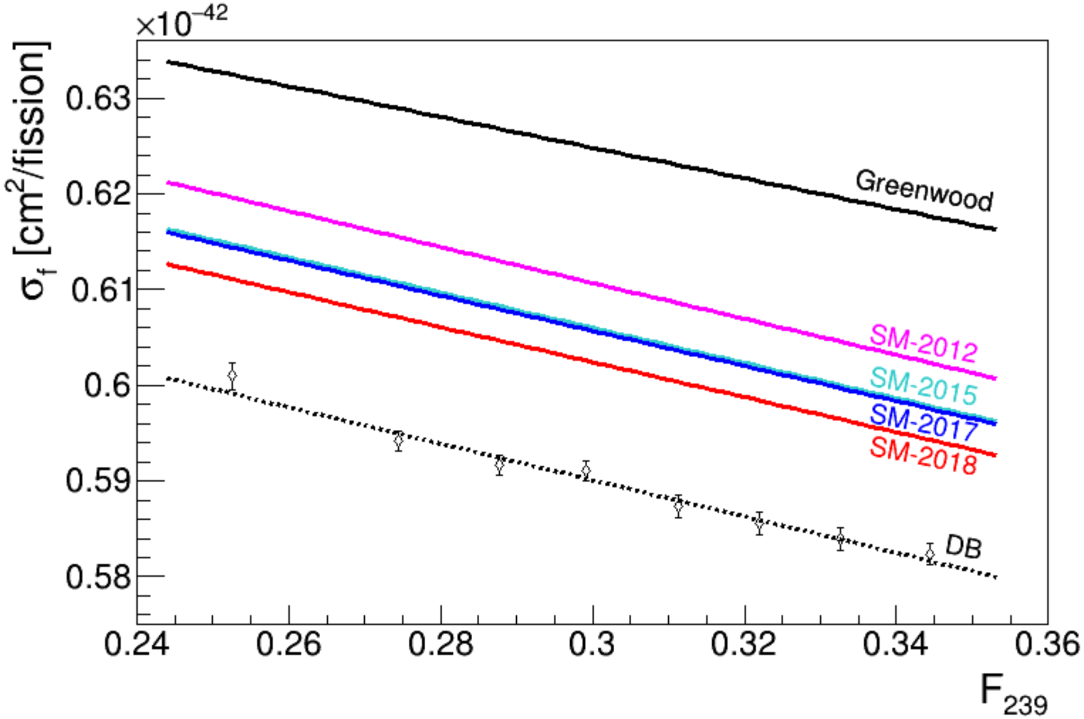


- Impact of the inclusion of the TAGS data (Pandemonium free):

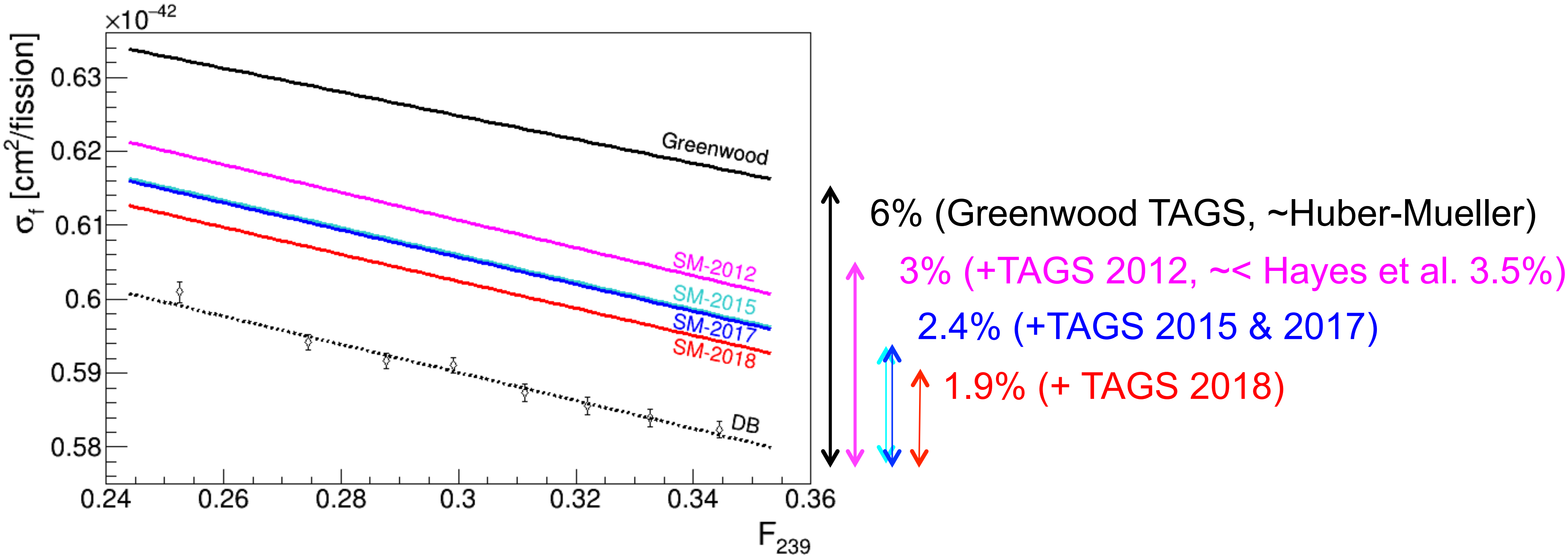
⇒ **Systematic reduction of the detected flux**

⇒ **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. http://arxiv.org/abs/1904.09358 accepted in Phys. Rev. Lett.

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. http://arxiv.org/abs/1904.09358 accepted in Phys. Rev. Lett.

« Robustness » of the prediction

Table extracted from Mueller et al. Phys. Rev. C 83, 054615 (2011)

Kinetic E (MeV)	Nuclear databases	Forbid. treatment	$A_{C,W}$ corrections	Missing info.
2.00	1.2	0.2	0.1	10
2.25	1.3	0.2	0.2	10
2.50	1.3	0.1	0.3	10
2.75	1.3	0.1	0.3	10
3.00	1.4	0.4	0.4	10
3.25	1.6	0.7	0.5	10
3.50	1.7	0.1	0.5	10
3.75	1.9	1.3	0.6	10
4.00	2.2	1.6	0.6	10
4.25	2.5	1.6	0.7	10
4.50	2.8	1.4	0.8	10
4.75	3.2	1.0	0.8	10
5.00	3.8	0.5	0.9	10
5.25	4.4	0.2	0.9	10
5.50	5.2	0.2	0.9	15
5.75	6.1	0.2	0.9	15
6.00	7.1	0.2	1.0	15
6.25	8.0	0.3	1.0	15
6.50	9.0	0.4	1.1	15
6.75	10.1	0.4	1.1	15
7.00	10.9	0.5	1.1	20
7.25	11.0	0.7	1.1	20
7.50	10.7	0.8	1.1	> 20
7.75	11.1	0.8	1.2	> 20
8.00	13.3	1.2	1.3	> 20

TABLE II. Sources of errors in the ^{235}U electron spectrum as predicted by the *ab initio* approach. All errors are given in percent at 1σ (68% CL).

- **The agreement of the SM-2018 spectra with the shape of the H-M spectra is better than 5-10% !**
- **it is rather ±2-3% on the energy range dominating the flux**
- Robustness of the SM w.r.t the choice of decay data data tested:

⇒ **remains robust in the 2 to 5 MeV range at the 2% level, i.e. a much better situation than the “10%” of missing information published in 2011 in Mueller et al.**

⇒ **The level of agreement is confirmed by the 1.9% discrepancy with the DB flux**

⇒ will allow computing associated decay data uncertainties (only possible if Pandemonium effect is not too strong!)

IBD Average Yields

	DB	SM 2018	SM 2017	SM 2012	SM from [42]	H-M
σ_f (10-43cm^2)	5.9±0.13	6.01	6.05	6.10	6.11	6.22±0.14
$\frac{d\sigma_f}{dF_{239}}$(10-43cm^2)	-1.86±0.18	-1.82	-1.83	-1.87	-2.05	-2.46±0.06
σ_5 (10-43cm^2)	6.17± 0.17	6.28	6.31	6.38	6.49	6.69±0.15
σ_9 (10-43cm^2)	4.27± 0.26	4.42	4.44	4.47	4.49	4.36±0.11
σ_8 (10-43cm^2)	10.1±1.0	10.14	10.20	10.27	10.2	10.1±1.0
σ_4 (10-43cm^2)	6.04±0.6	6.23	6.27	6.29	6.4	6.04±0.6
σ_5/σ_9	1.445±0.097	1.421	1.421	1.427	1.445	1.53± 0.05

- The agreement of the individual contributions of ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U with the detected antineutrino flux and of the slope of the IBD yield with the burnup with that measured by the DB experiment is improved by our new model.

- With the SM model, no huge discrepancy in the flux w.r.t. DB for one specific fissioning nucleus: 2.5-3% for ^{235}U and ^{239}Pu (contrary to H.-M.) and about 1% for ^{238}U and ^{241}Pu

M. Estienne et al. http://arxiv.org/abs/1904.09358 accepted in Phys. Rev. Lett.

Conclusions & Perspectives

- TAGS data (Pandemonium free) measured over a decade at Jyväskylä: see Victor Guadilla's contribution tomorrow

⇒ Impact of the inclusion of these TAGS on the antineutrino flux: systematic reduction of the detected flux, remaining discrepancy with Daya Bay = 1.9%

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

⇒ Says also how much the quality of the summation model has been improved during this decade.

⇒ Less Pandemonium effect means that computing associated decay data uncertainties becomes possible

- First comparison of the full detected antineutrino energy spectrum obtained with the summation model, without any renormalization, with the measurements from Daya Bay.
- Robustness of the SM model: predictions of the SM model remain robust in the 2 to 5 MeV range at the 2% level, i.e. a better situation than the "10%" of missing information published in 2011 in Mueller et al.
- Even with the inclusion of the latest TAGS data, the bump is still there meaning that for the moment, it still cannot be explained by ingredients of the nuclear databases. - Note that the shape anomaly may be de-correlated from the reactor anomaly
- The agreement of the individual contributions of ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U with the detected antineutrino flux and of the slope of the IBD yield with the burnup with that measured by the DB experiment is improved by our new model.

IAEA Technical Meeting 2019

Participants

- Leendert Hayen
- Jun Cao
- Liangjian Wen
- Yufeng Li
- Zeyuan Yu
- Fengpeng An
- Liang Zhan
- Cecile Jollet
- Muriel Fallot
- Madalina Wittel
- Karl-Heinz Schmidt
- Tadashi Yoshida
- Soo-Bong Kim
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- Marek Karny
- Marzena Wolinska
- Dmitry Svirida
- Alejandro Algora
- Jose Tain
- Antonin Vacheret
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- Toshihiko Kawano
- Filip Kondev
- Krzysztof Rykaczewski
- B.S. Rasco
- Anna Hayes-Sterbenz
- Jonathan Link
- Bryce Littlejohn
- Yuri Efremenko
- Patric Huber
- Karsten Heeger
- Nathaniel Bowden
- Frederik Tovesson
- Patric Huber
- Karsten Heeger
- Nathaniel Bowden

Technical Meeting on Nuclear Data for Anti-neutrino Spectra and Their Applications

23-26 April 2019, IAEA Headquarters, Vienna, Austria

The Nuclear Data Section of the International Atomic Energy Agency is holding a Technical Meeting on Nuclear data for anti-neutrino spectra and their applications, from 23 to 26 April 2019.

The idea is to bring together experts from the broad spectrum of physics, theory and measurements, related to anti-neutrino studies for basic sciences (mixing angle in neutrino oscillations) and for applications (reactor monitoring with anti-neutrino detection), to review the current status of:

-neutrino anomalies and the sterile neutrino hypothesis
-existing measurements of integral beta spectra
-recent Daya Bay, Double Chooz and Reno results on spectra measurements
-results from short baseline experiments Prospect, SoLid, Neutrino-4/DANSS, NEOS
-conversion method and uncertainties, corrections
-summation method and impact of nuclear data (beta decay data; fission yield data; uncertainties and correlations)
-nuclear data libraries (ENDF/B; JEFF; JENDL)

The goal is to (a) assess the sensitivity of the observations to uncertainties affecting large and short-baseline anti-neutrino measurements, (b) address the limitations and uncertainties of the theoretical methods (conversion vs summation), (c) estimate their dependence on the available data (beta spectra, decay data, fission yields), and finally (d) make recommendations for the existing measurements, theories and evaluations and e) new proposals for the future where needed.

The meeting will start on Tuesday 23 April in the afternoon, and finish on Friday 26th April again in the afternoon.

The meeting will include presentations from experts covering the above listed topics and discussions that will lead to a list of recommendations for the relevant scientific community. A summary report of the meeting will be published as an INDC(NDS) report.

A list of abstracts is given below. Presentations will be uploaded as they become available.

Preliminary Agenda

Abstracts

#	Author	Title	Link
1	P. Huber	Antineutrino spectrum prediction and nuclear data	DOC

IAEA Technical Meeting 2019

- Technical Meeting on Antineutrino Spectra and Applications, Organized by the Nuclear Data Section of IAEA April 23-26 2019 – ***Report in preparation***
- ~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
- All Communities acknowledged the huge experimental effort with TAGS, « Bringing the Summation Method to another level »
- Outlooks:
  - **of course keep improving with remaining TAGS results,**
  - **measurement of electron shapes**
  - **High stats Highly Enriched Uranium reactor measurements crucial for understanding**
  - **Significant improvement in energy resolution proposed by JUNO-TAO could constitute a benchmark for nuclear data, evidencing the individual components of the fission products**
  - **Bump not understood yet**

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

THANK YOU