Soustons, France
September 28 2023

The Contribution of Nuclear Physics to Reactor Antineutrino Physics

M. Estienne

Colloque GANIL 2023

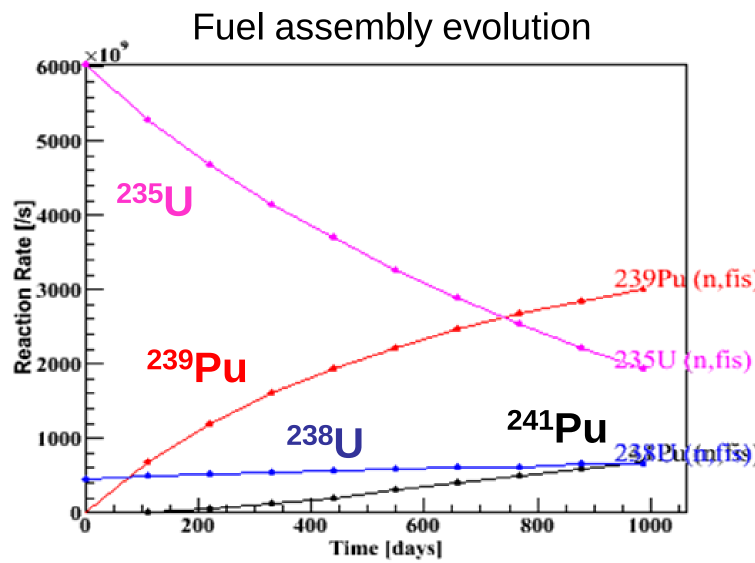
Outline

- Motivations for the Study of Beta Decay
- TAGS: a solution to the Pandemonium Systematic Uncertainty Present in Nuclear Data
- Updated Summation Model and Reactor Anomalies
- E-Shape and the Shape Anomaly
- Conclusions and Outlooks

Motivations for the Study of Beta Decay

Reactor Antineutrinos from Beta Decay

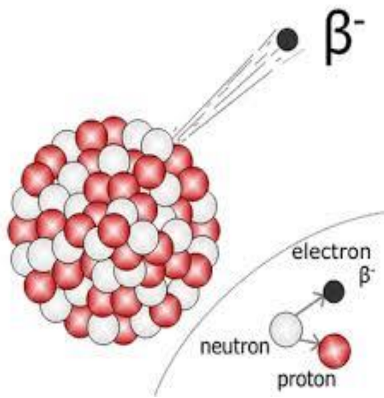
- In Pressurized Water Reactors, thermal power mainly induced by 4 isotopes:
  - ^{238}U = vast majority of the fuel, its fast fission contributes to ~10% of the flux
  - Dominant contribution of ^{235}U at beginning of cycle slowly decreases burnt by the core
  - Other fissile nuclei (^{239}Pu & ^{241}Pu) created after reactor start by β decay/capture process increases



- Fission process gives thermal energy:

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

- The fission products (FP) are neutron-rich nuclei undergoing β⁻ and β-n decays:
  - (~6 β⁻ decays = ~6 electron anti-ν) / fission



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

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

Beta Decay for Present and Future Reactors

- Getting access to the β decay properties and to antineutrino energy spectra

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

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

- The exploitation of the products of the beta decay is multifold:
  - The **antineutrinos** escape and can be detected → reactor monitoring, potential non-proliferation tool and essential for fundamental physics
  - **In laboratory, γ or β** measurements of well identified fission products → characterize the weak interaction properties, several physics topics in nuclear structure or nuclear astrophysics but also indirect access to antineutrino energy spectra

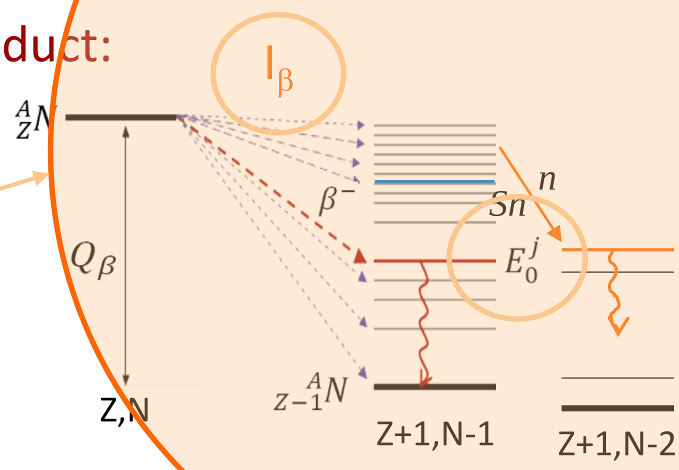
- Beta decay driven by some selection rules regarding the isospin and the spin-parity between the parent and daughter nuclei
  - Fermi in the 30s: $\lambda = \frac{2\pi}{\hbar}\left|V_{fi}\right|^{2}\rho(E_f)$, $V_{fi} \equiv \langle \psi_f | O_\beta | \psi_i \rangle$
  - β decay first formalized for ΔL=0 (allowed transitions):
    - ✓ Fermi transitions (super-allowed) : isospin change and ΔS=0: $O_\beta = O_F = g_V \tau^{\pm}$
    - ✓ Gamow-Teller transitions: ΔS=1: $O_\beta = O_F = g_A \hat{\sigma}_\mu \tau^{\pm}$
  - Forbidden transitions later identified and characterized: ΔL>=1
    - ✓ For first forbidden transitions: O_β includes 6 operators

Getting access to the $\bar{\nu}$ energy spectra of a fp

- Measurement of well identified fission product:

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

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



TAGS measurements

- Total energy spectrum of a fission product:

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

- Energy spectrum of a b branch of a fission product:

$$ S_{fp}^{b}(p) \propto \underbrace{p^2 (Q - T_e)^2}_{\text{Phase space}} \underbrace{F(Z',p)}_{\text{Fermi function}} \underbrace{C(Z,p)}_{\text{Shape factor}} \underbrace{(1 + \delta(Z,A,p))}_{\text{Subdominant corrections}} $$

eShape measurements

Total Antineutrino Spectra and nuclear models

- Over the last 50 years, many computations and improvements of the spectra

- Two methods were re-visited in 2011:
  - **Conversion model**: **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), 2 approaches in good agreement:
    - ✓ **Use of nuclear data for realistic beta branches, Z distribution of the branches, 5 fictive beta branches…**
    - ✓ **30 fictive beta branches and nuclear data for realistic Z distribution of the branches**
    - ✓ **Correction for weak magnetism and coulomb effect in both approaches**

    } H-M model

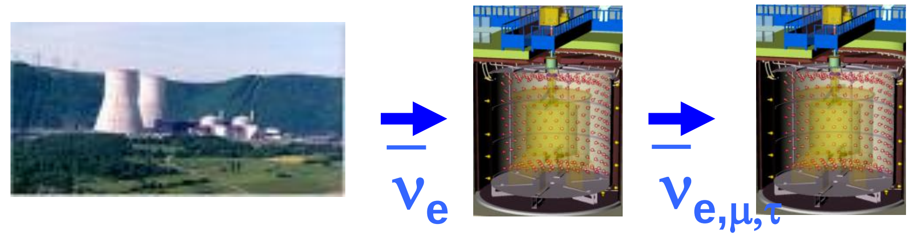
  - **Summation method: summing all the contributions of the fission products** in a reactor core**: totally rely only nuclear data : Fission Yields + Beta Decay properties** (several predictions from B.R. Davis et al. Phys. Rev. C 19 2259 (1979), to Tengblad et al. Nucl. Phys. A 503 (1989)136)
    - ✓ Only alternative to H-M
    - ✓ Independant from the integral measurement of Schreckenbach et al. at ILL.
    - ✓ Predictive for future reactor

    } Present work

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

Reactor Antineutrinos Spectral Knowledge

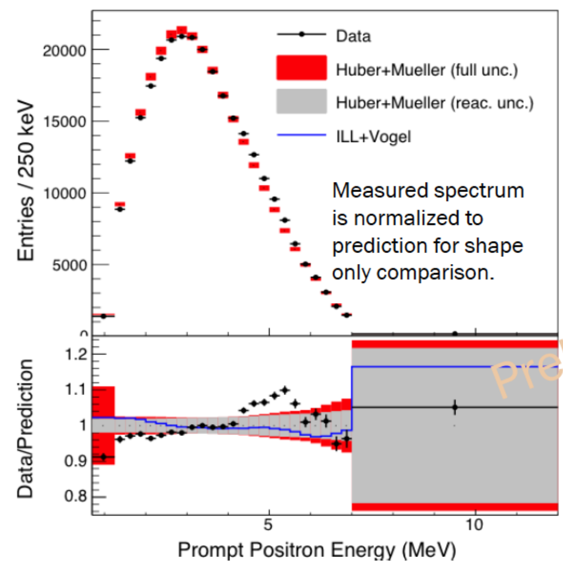
- Measurement of the θ_{13} oscillation param by Double Chooz, Daya Bay, Reno in 2012
  - Independent computation of the anti-ν spectra using nuclear DB: conversion method
- Converted anti-ν spectra revisited
  - 6% deficit of the absolute value of the measured flux compared to the best prediction ILL data
  - Reactor anomaly
  - Numerous projects searching for the existence of a sterile neutrino
- Bump (spectrum distortion) in the full spectrum (btw 4.8-7.3 MeV)
- Next generation reactor neutrino experiments like JUNO or background for other multipurpose experiment



Nuclear Power Station **Near detector** **Far detector**

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)

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



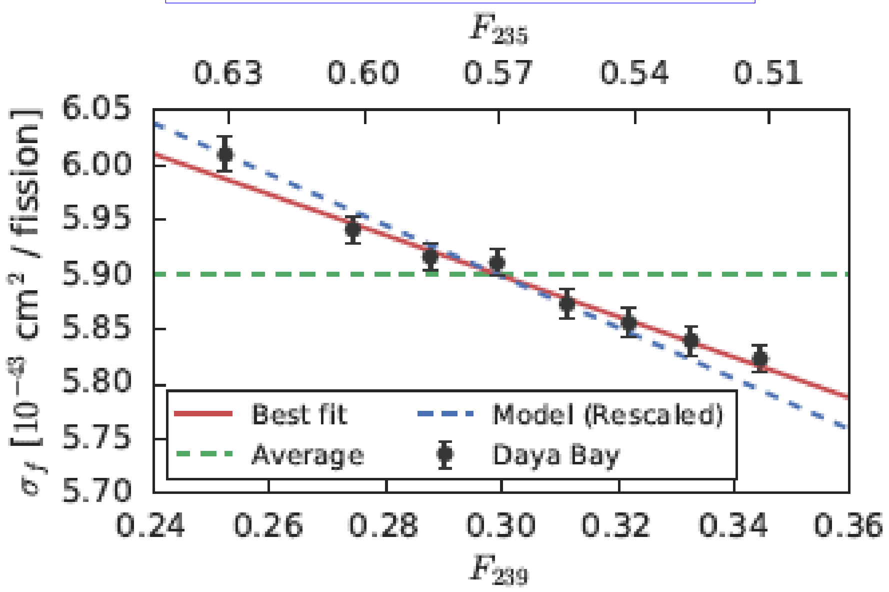
➡ Growing interest in summation method to calculate anti-ν spectra

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. (DB Collaboration), ``Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay," PRL 118 (2017).
And associated APS Viewpoint by M. Fallot

σ_f = IBD yield per fission = anti-ν flux per fission



- Slope in ~agreement with H-M but global deficit of 5.1%
- 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.
- Flux deficit quasi all taken by ^{235}U — 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 ^{235}U?**

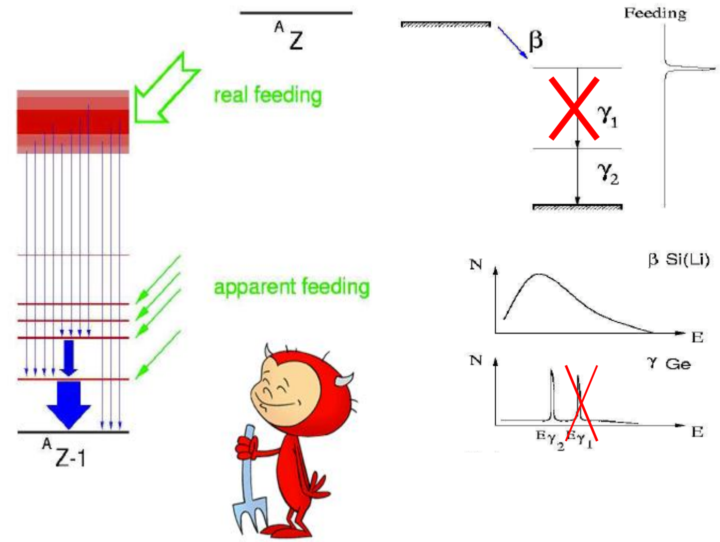
New DB (ArXiv:1904.07812) **and RENO** (PRL 122 (2019) 232501) **papers re-inforce previous results**

➡ **Growing interest in summation method to calculate anti-ν spectra**

TAGS Solution to the Pandemonium Systematic Uncertainty

γ Measurement Caveat

Picture from A. Algora



- Before the 90s, conventional detection techniques: high resolution γ-ray spectroscopy
  - Excellent resolution but efficiency which strongly decreases at high energy or because of small acceptance
  - Danger of overlooking the existence of β-feeding into the high energy nuclear levels of daughter nuclei
- Incomplete decay schemes: overestimate of the high-energy part of the FP β spectra
- Phenomenon commonly called « pandemonium effect** »

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

➡ Expected distortion of the antineutrino energy spectra computation with SM

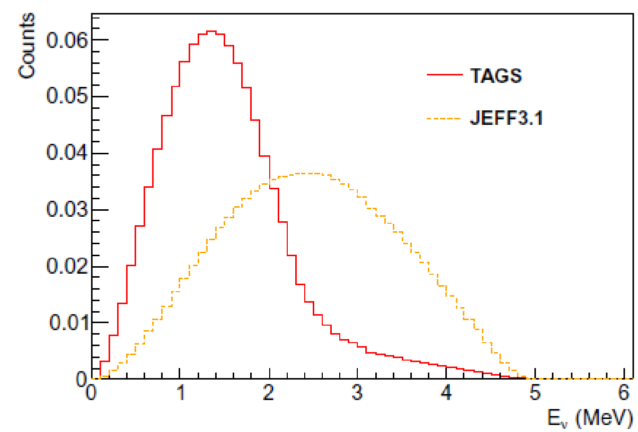
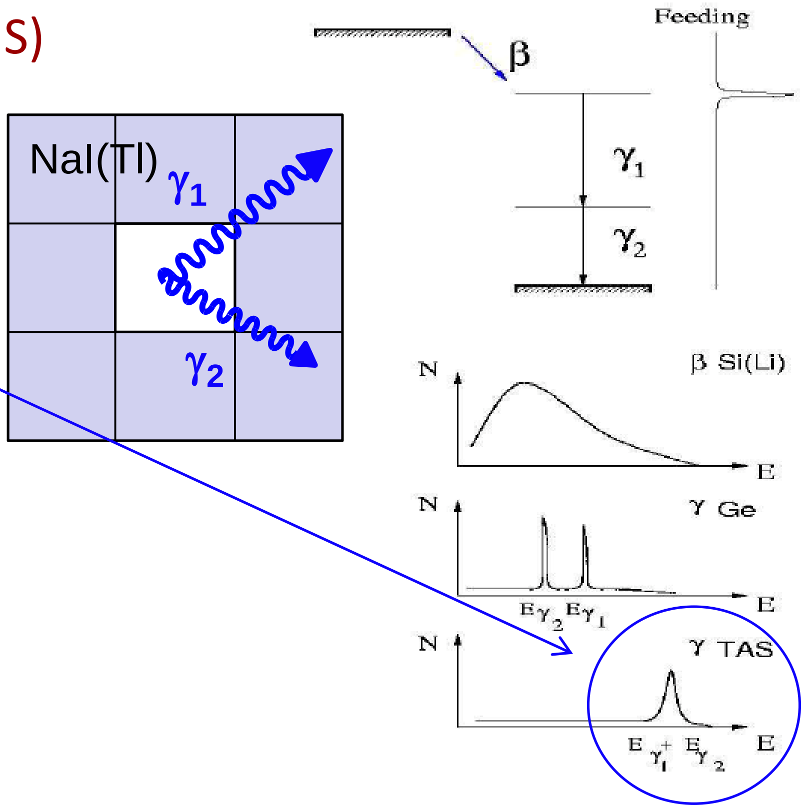


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

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

3 TAS Campains at IGISOL Jyväskylä in 2009, 2014 and 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)

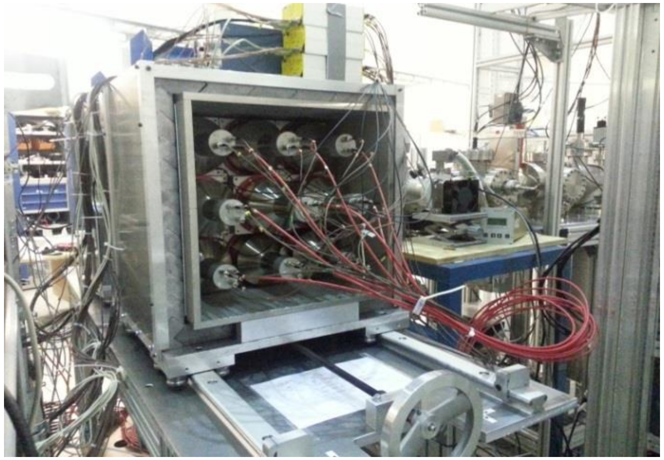
- 2 (segmented) TAS campains :

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

❑ 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
- ✓ **2009**: **7 nuclei measured** (6 for DH and 2 for anti-ν) **all published**
- ✓ **New measurements in 2022**: ~15 cases with a focus on isomers and beta-n decays

❑ 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: some published and some analyses still ongoing

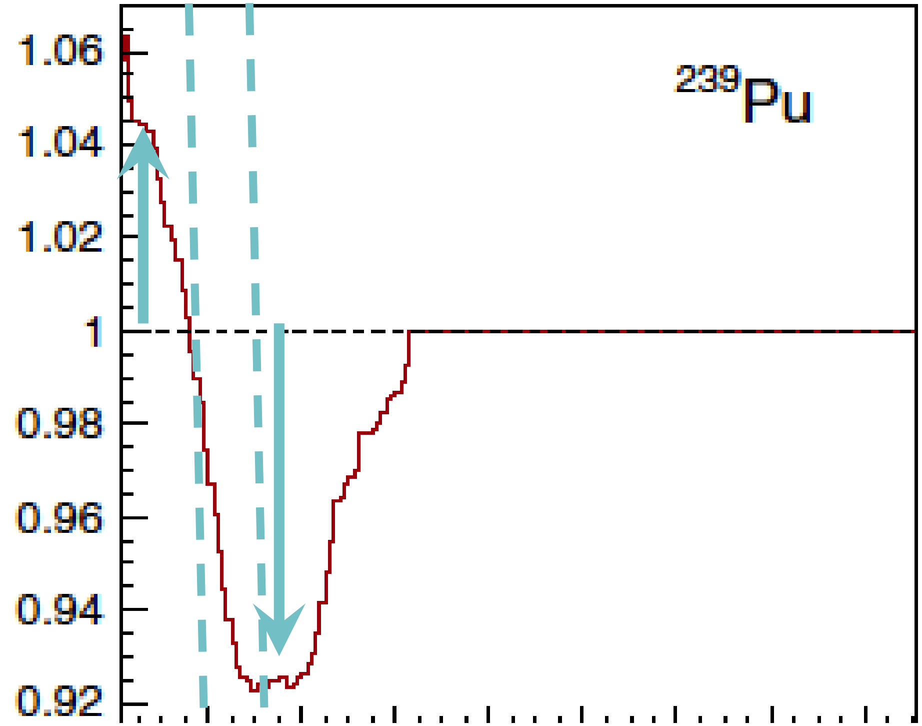
First Impact of 2010 TAS Data on SM calculations

- Taking into consideration the TAS data of the $^{102;104-107}$Tc, ^{105}Mo, and ^{101}Nb isotopes measured in 2007 @ Jyväskylä

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

  - ❑ ~850 nuclei included
  - ❑ Noticeable deviation from unity (1.5 to 8% decrease)

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



Relative Effects of the 2007 TAS data (published 2010) on the Antineutrino Spectra:

<u>typical from Pandemonium</u>: the inclusion of Pandemonium free data increases the spectrum before 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 !

Updated Summation Model and Reactor Anomalies

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

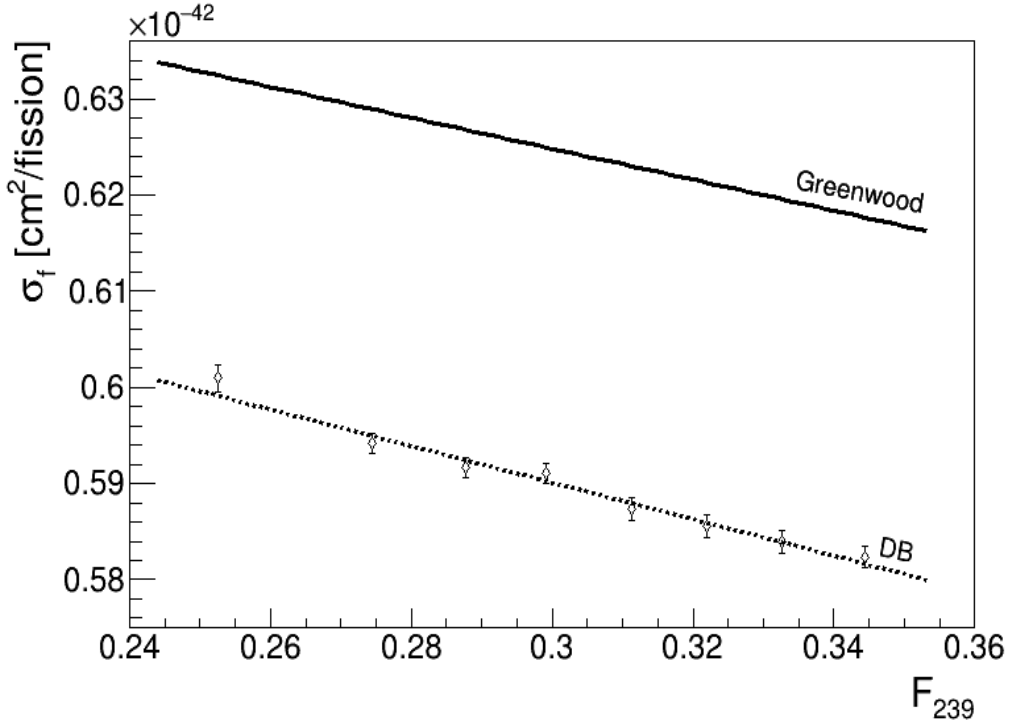
*T. Yoshida, T. Tachibana, S. Okumura, and S. Chiba, Phys. Rev. C 98, 041303(R) (2018).

- 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 F_{239} including TAGS data published in 2012, 2015, 2017 and 2019 has been calculated using our summation calculation

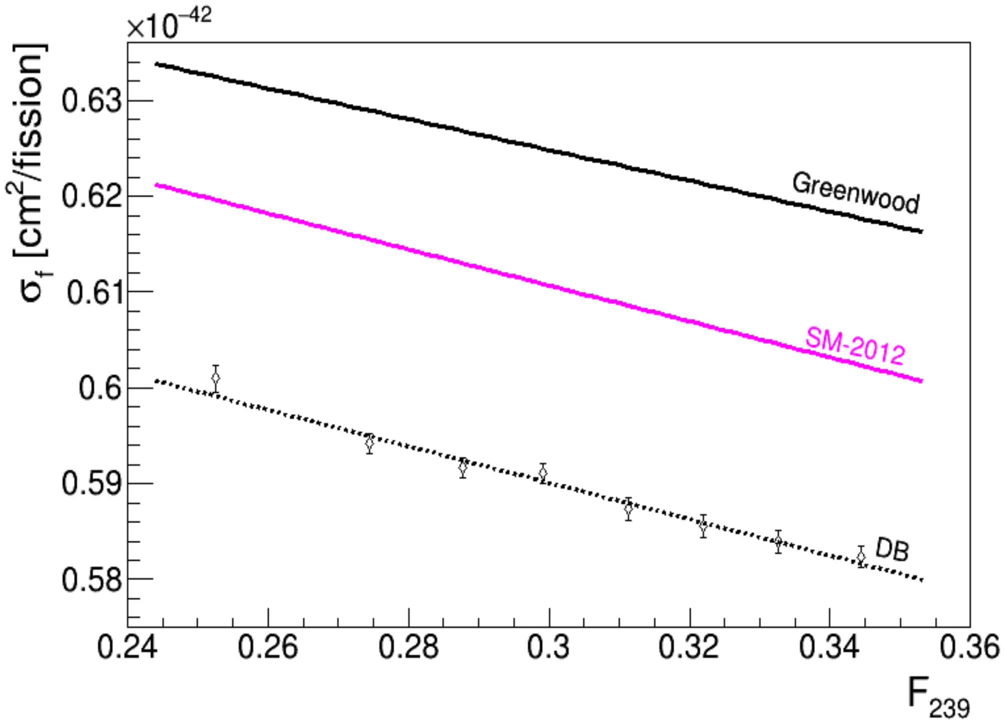


- Impact of the inclusion of the TAGS data (Pandemonium free):

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

Our IBD Yield Calculation Including TAGS vs DB

- The IBD yields dependency with F_{239} including TAGS data published in 2012, 2015, 2017 and 2019 has been calculated using our summation calculation

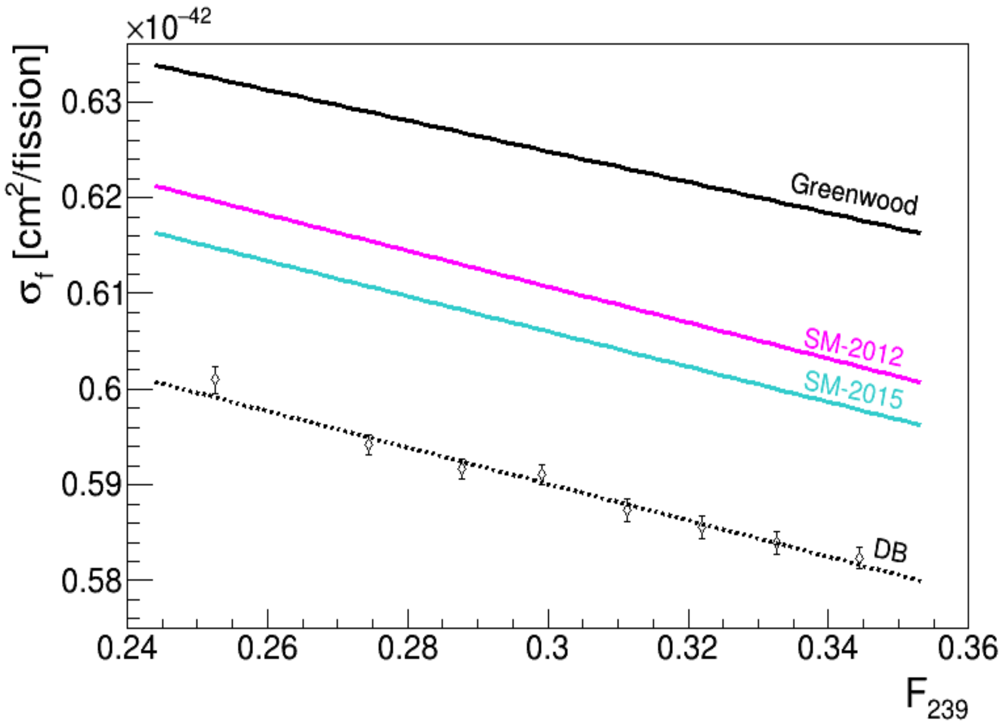


M. Estienne et al., **Phys. Rev. Lett. 123 (2019) 022502**

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

Our IBD Yield Calculation Including TAGS vs DB

- The IBD yields dependency with F_{239} including TAGS data published in 2012, 2015, 2017 and 2019 has been calculated using our summation calculation

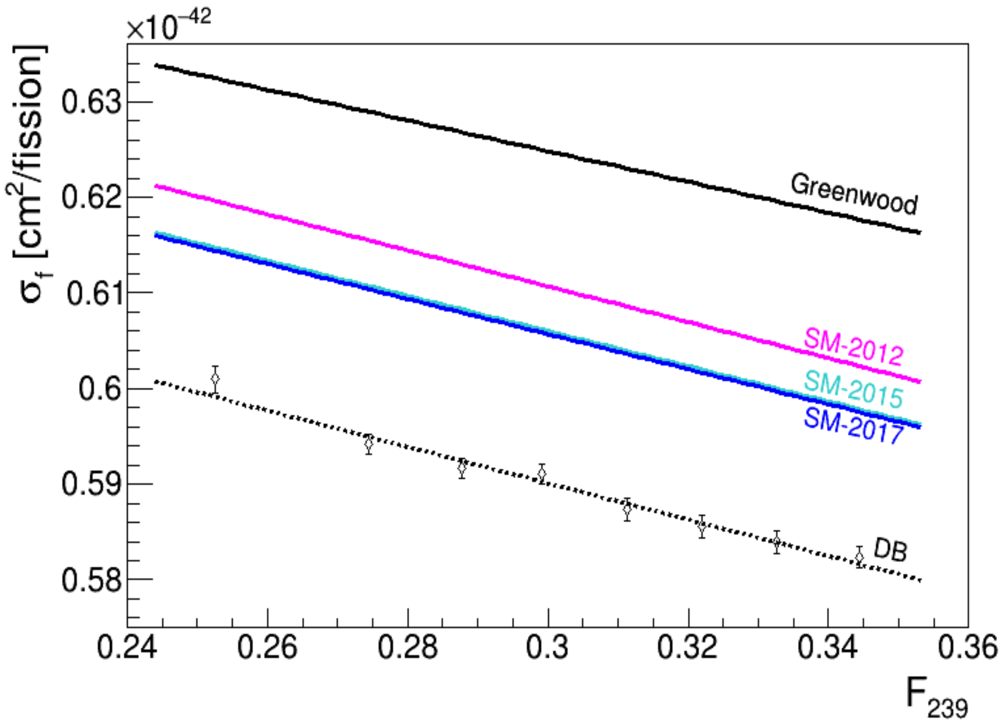


- Impact of the inclusion of the TAGS data (Pandemonium free):

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

Our IBD Yield Calculation Including TAGS vs DB

- The IBD yields dependency with F_{239} 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):

$\Rightarrow$ Systematic reduction of the detected flux

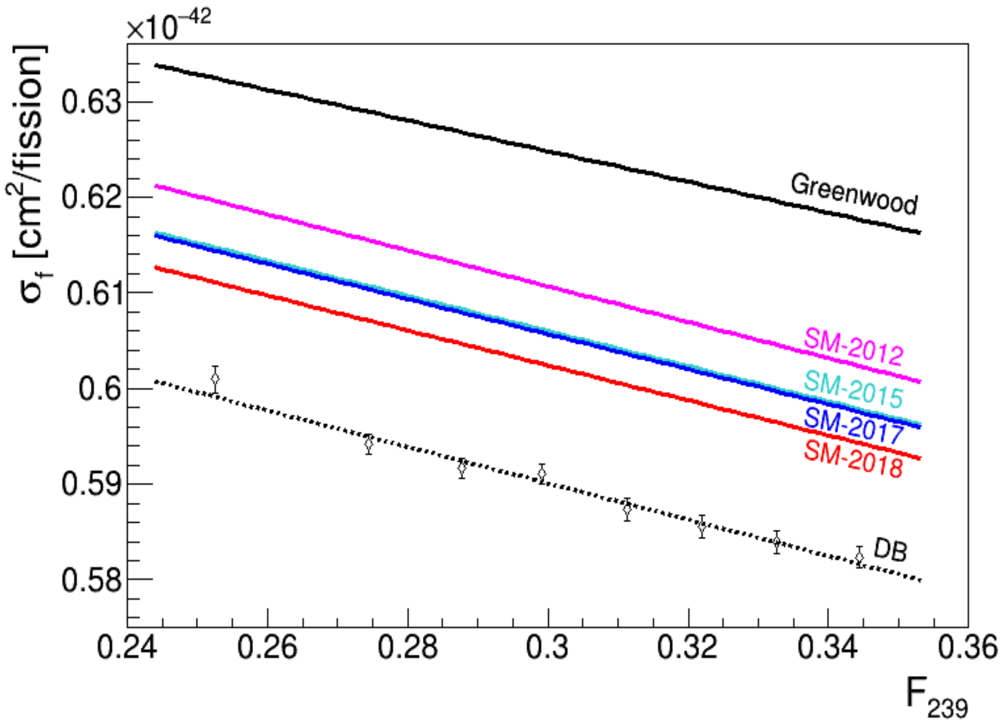
$\Rightarrow$ Systematic reduction of the discrepancy with Daya Bay results

$\Rightarrow$ 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 IBD yields dependency with F_{239} 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):

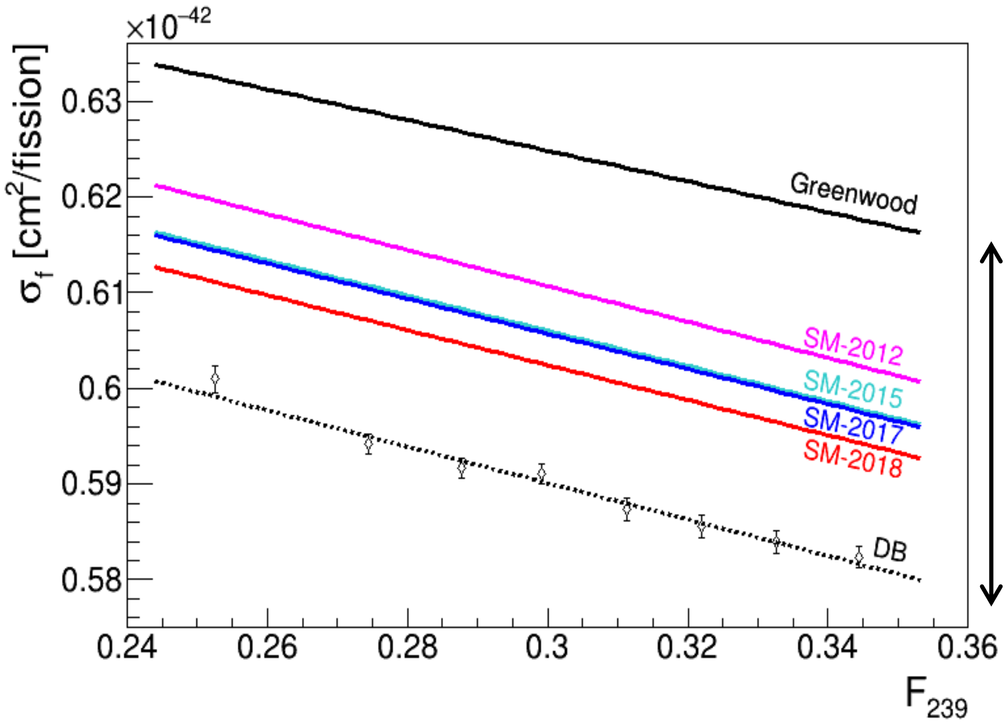
$\Rightarrow$ **Systematic reduction of the predicted flux**

$\Rightarrow$ **Systematic reduction of the discrepancy with Daya Bay results**

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

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

Our IBD Yield Calculation Including TAGS vs DB



6% (Greenwood TAGS, ~Huber-Mueller)

3% (+TAGS 2012, ~< Hayes et al. 3.5%)

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

2.4% (+TAGS 2015 & 2017)

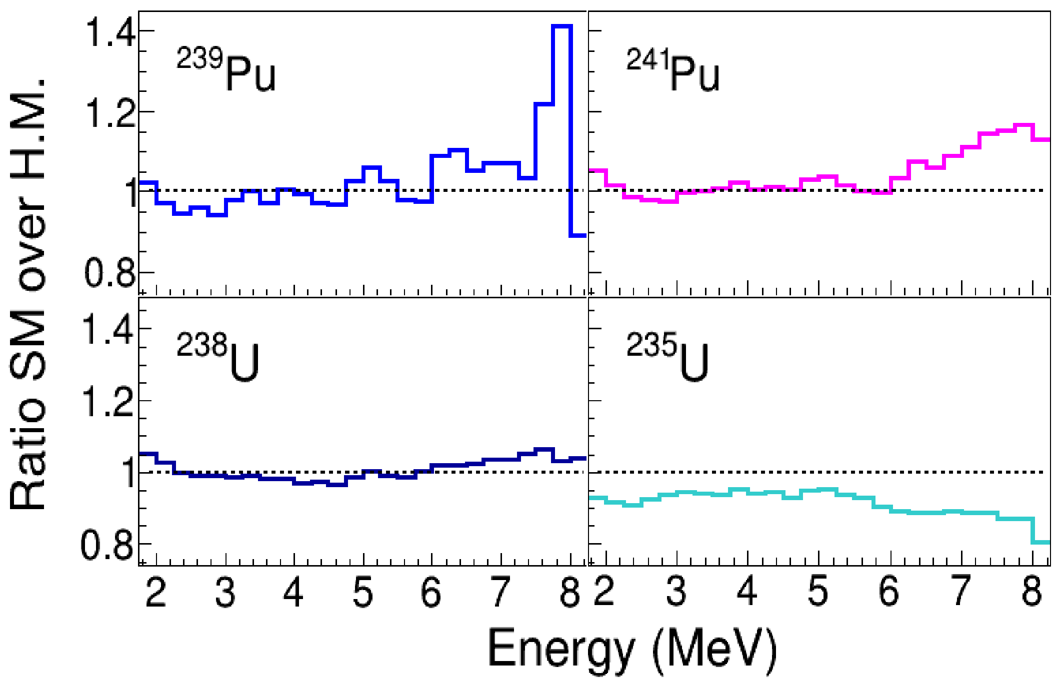
1.9% (+ TAGS 2018)

- 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.**
- **It is a systematic effect!**

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

Comparison with H-M individual spectra in 2019

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' 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

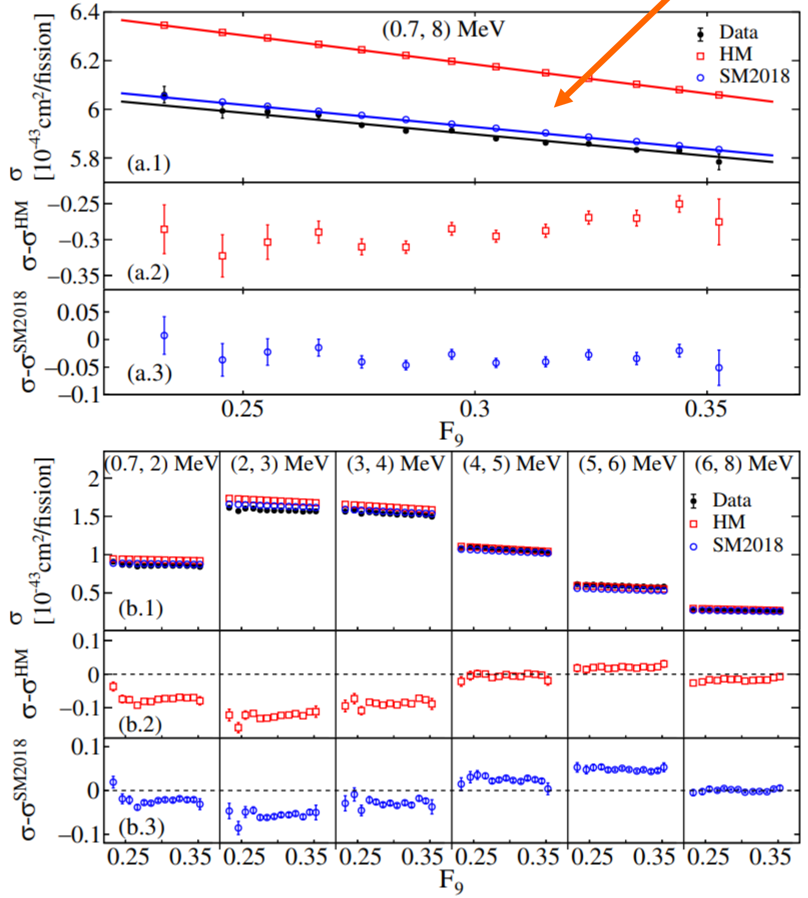
⇒ **Overall the SM model shows a fairly good shape agreement with Huber's spectra up to 6 MeV and the shape anomaly is still there !**

Recent Results from Daya Bay

- Measured antineutrinos from six 2.9-thermal-gigawatt commercial reactor cores, which were located either at Daya Bay or at the Ling Ao power plant in China.
- Eight antineutrino detectors (AD).
- Using of 1958-day data sample (~6 years of measurement since 2011), study of the total IBD yield and energy differential IBD yield (6 energy bins).
- Spent nuclear-fuel contribution and out-of-equilibrium effect taken into account as a function of antineutrino detector and time.
- No extra uncertainties due to unfolding method done before.
- Data sorted into 13 groups of ^{239}Pu fission fraction.

Best fit lines

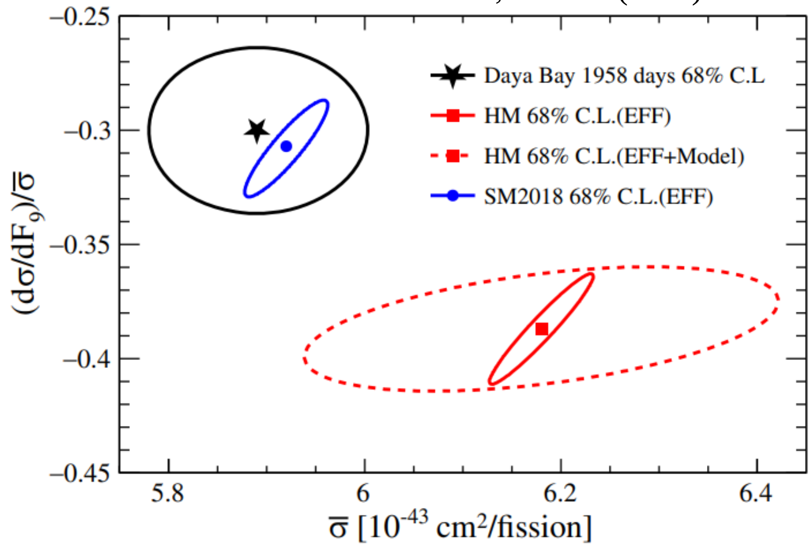
DB collaboration, PRL 130 (2023) 211801



Evolution of the total and energy differential IBD yield vs F9

2022 & 2023 Results from Daya Bay

DB collaboration, PRL 10 (2023) 211801



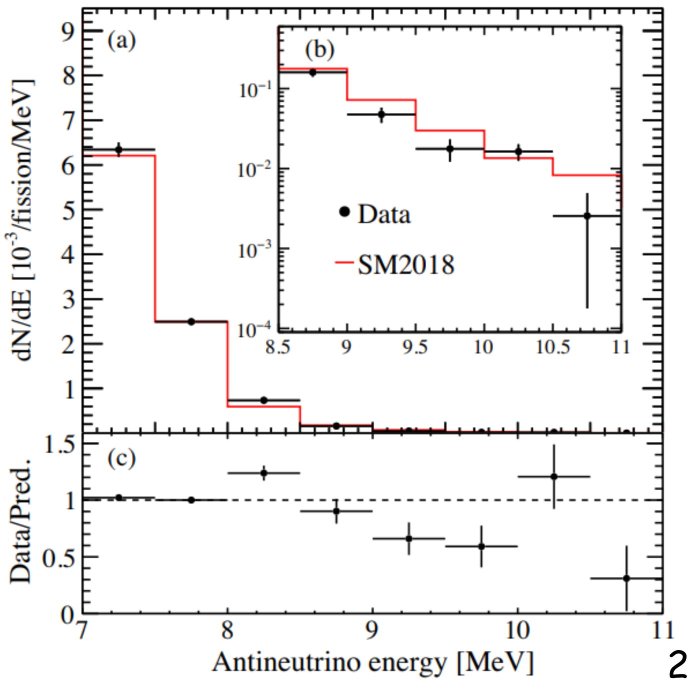
- H-M predictions for $\bar{\sigma}$ and $[\frac{d\sigma}{dF_9}]/\bar{\sigma}$ rejected at 3.6 and 3 standard deviations.
- SM18 consistent with DB

⇒ RAA relieved by SM2018

- Issue with the ^{235}U measurement from Schrekenbach et al. Confirmed

- A challenging measurement: rare signal above 8.5 MeV and dominated by cosmogenic backgrounds.
- A fine statistical treatment of the background
- Comparison with SM2018:
  - deviation above 8 MeV
  - 29% difference in IBD rate in the prompt energy region 8-11MeV

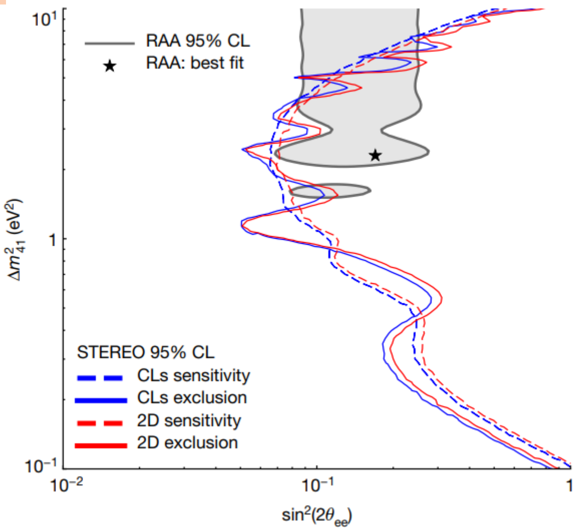
DB collaboration, PRL 129 (2022) 041801

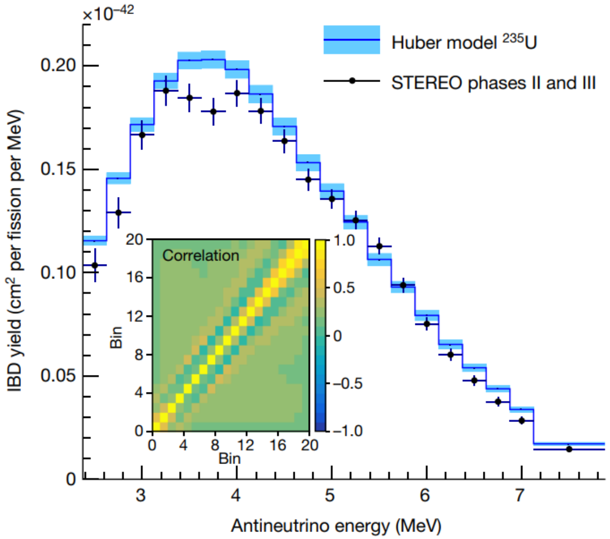


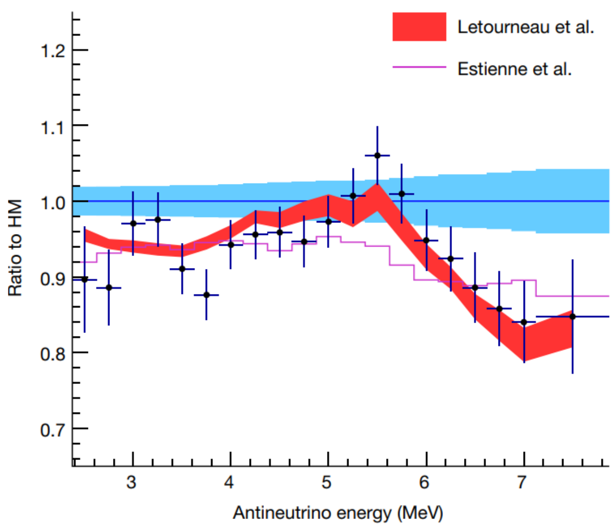
2023 Results from STEREO

- Short baseline experiment built to test the existence of a sterile neutrino state
- Installed in 2016 at the ILL high-flux research reactor
- Full statistic (~107600 detected antineutrinos) from Oct 2017 to Nov 2020
- **Three main results:**

STEREO Collaboration, Nature 613 (2023) 257







1) Rejection of the sterile neutrino hypothesis:

- Parameter space favoured by the RAA excluded up to a few eV^2 at 95% CL or greater
- Data compatible with the no oscillation hypothesis

2) Reference pure ^{235}U antineutrino spectrum:

- Shape and absolute normalization studied by combining the 6 measured spectra w.r.t. E_p.
- Deconvolution to get the spectra w.r.t. E_ν.

3) RAA and shape anomaly:

- 5.5% deficit with respect to H-M and better agreement with SM2018
- Role of the ^{235}U in the RAA.
- Shape distortion confirmed: Pandemonium bias in NDB

Ongoing Work E-F Summation model

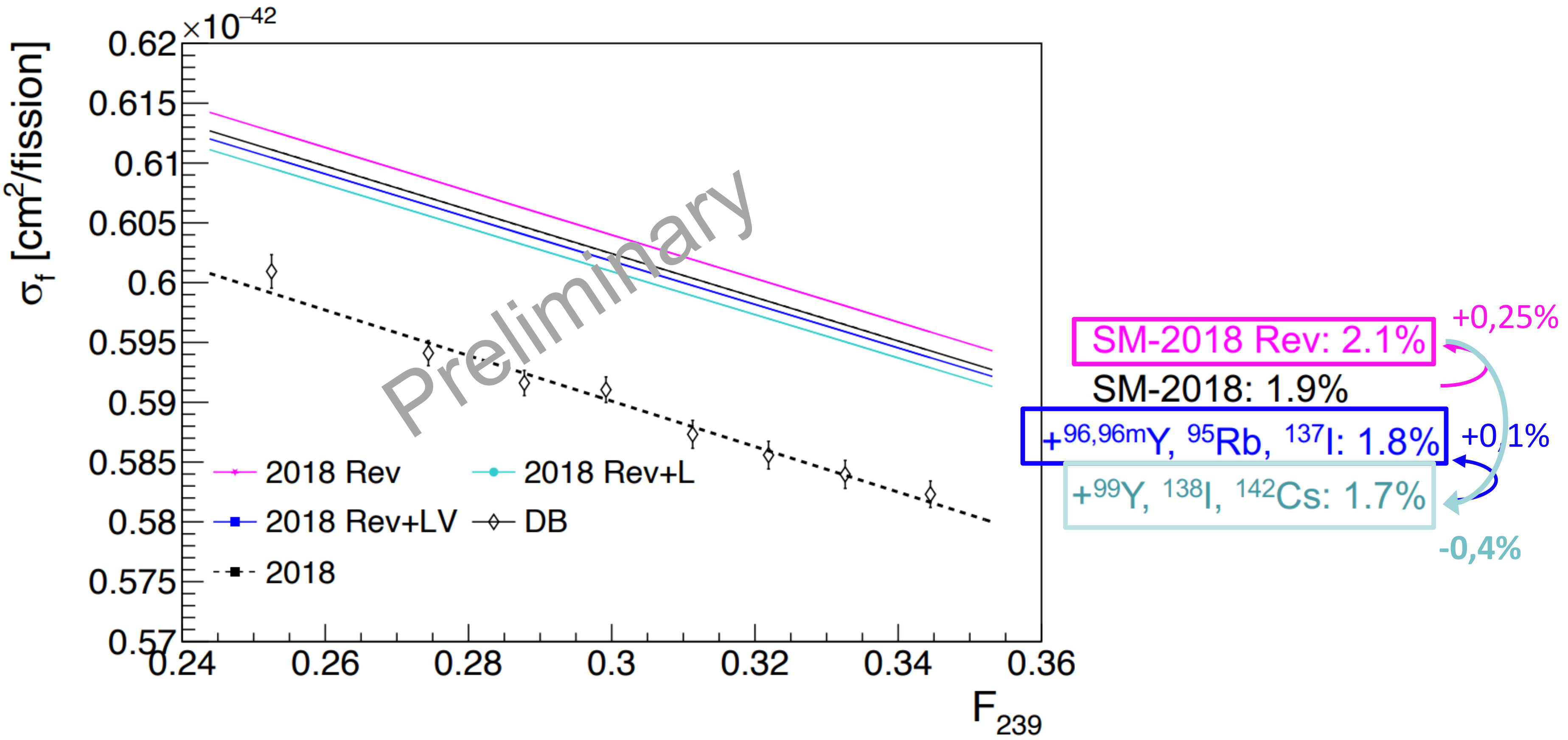
- New collaboration with L. Hayen
  - Compare our ingredients and corrections (on-going)
    - ✓ Modifications in our model core calculation:
      - 1keV energy bins
      - Screening corrections: Rose replaced by Salvat (L. Hayen, N. Severijns et al. Rev. Mod. Phys. 90, 015008 (2018))
      - Nubase 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
    - ✓ ^{95}Rb et ^{137}I: 2 nuclei from V. Guadilla et al. Phys. Rev. C 100, 044305 (2019)
    - ✓ ^{96gs}Y and ^{96m}Y: 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

⇨ ~ -0.4% change in the global flux

Impact on the IBD yield



- 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

E-Shape and the Shape Anomaly

Motivation for the study of forbidden transitions

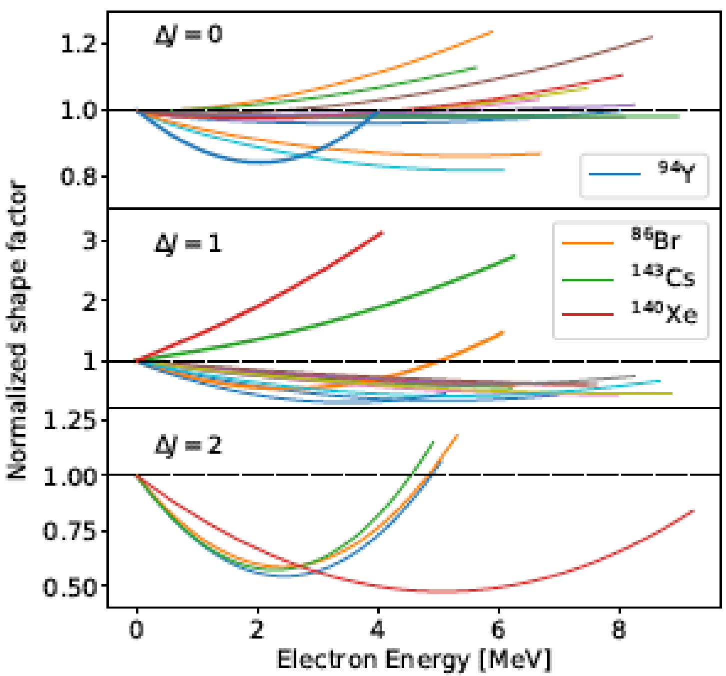
- First-forbidden β decays represent 25-30% of the decay branches of the fission products
- The inclusion of forbidden decays in nuclear models for calculating reactor antineutrino energy spectra can change the normalization & shape of reactor antineutrino energy spectra.
- In the case of first forbidden transitions, the form factor depends on the energy and is the combination of 6 transition matrix elements
  - The energy spectrum of electrons from forbidden transitions can differ profoundly from the shape of a spectrum from permitted transitions only, depending on which matrix element(s) dominate(s) a given transition.

Twofold motivation:
- Electron energy spectrum measurement for well defined FP
- Theoretical computation of the forbidden decay operators and inclusion in microscopic models

Collaboration with S. Péru (CEA, DAM) and M. Martini, A. Beloeuvre PhD thesis

Several Form Factor Predictions

- Form factor calculations for forbidden transitions: several models disagree, with the broadest predictions coming from L. Hayen et al.



L. Hayen et al., PRC.100.054323

- Predictions not all in agreement...:
  - 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)
  - J. Petković, T. Marketin, G. Martínez-Pinedo, N. Paar, J. of Physics G: NPP 2019, ISSN: 1361-6471

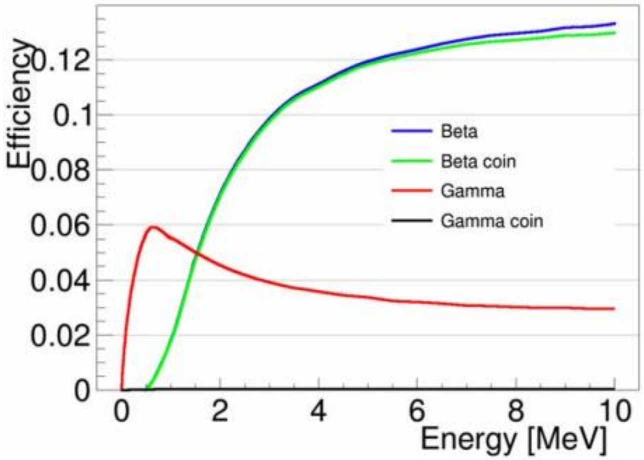
- Some of these groups also perform large-scale r-process calculations.

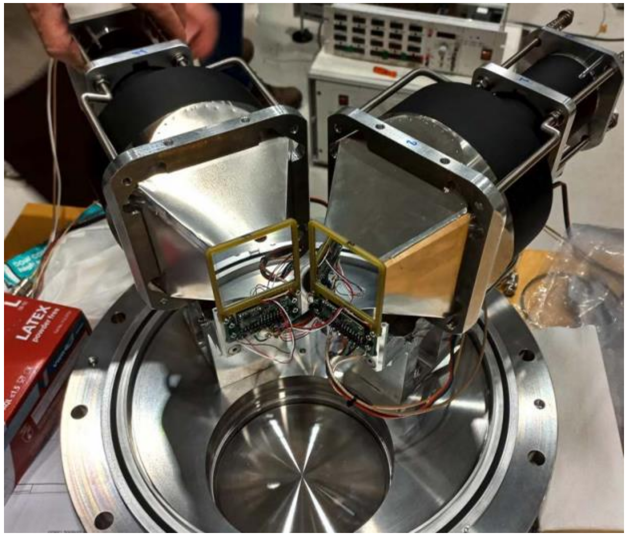
Ex.: T. Marketin, L. Huther, and G. Martínez-Pinedo, Phys. Rev. C 93, 025805 (2016).

➡ **Form factor measurements for the most important forbidden decays are needed to constrain the models.**

The e-Shape experiment: Nantes-Surrey-Valencia Collaboration

- ΔE – E telescopes to measure the beta spectrum of selected decays using isotopically pure beams at Jyväskylä with Si and plastic detectors in coincidence
- In vacuum chamber: two **ΔE-E telescopes** as close as possible (solid angle and better efficiency)
- Description of the telescopes:
  - **ΔE**: 500μm thickness Si detector, active area 50x50 mm2
  - **E**: Pl truncated cones, height 110 mm
- Ancillary detectors for gammas: HPGe and CeBr3
- DAQ: successful use of FASTER from LPC Caen

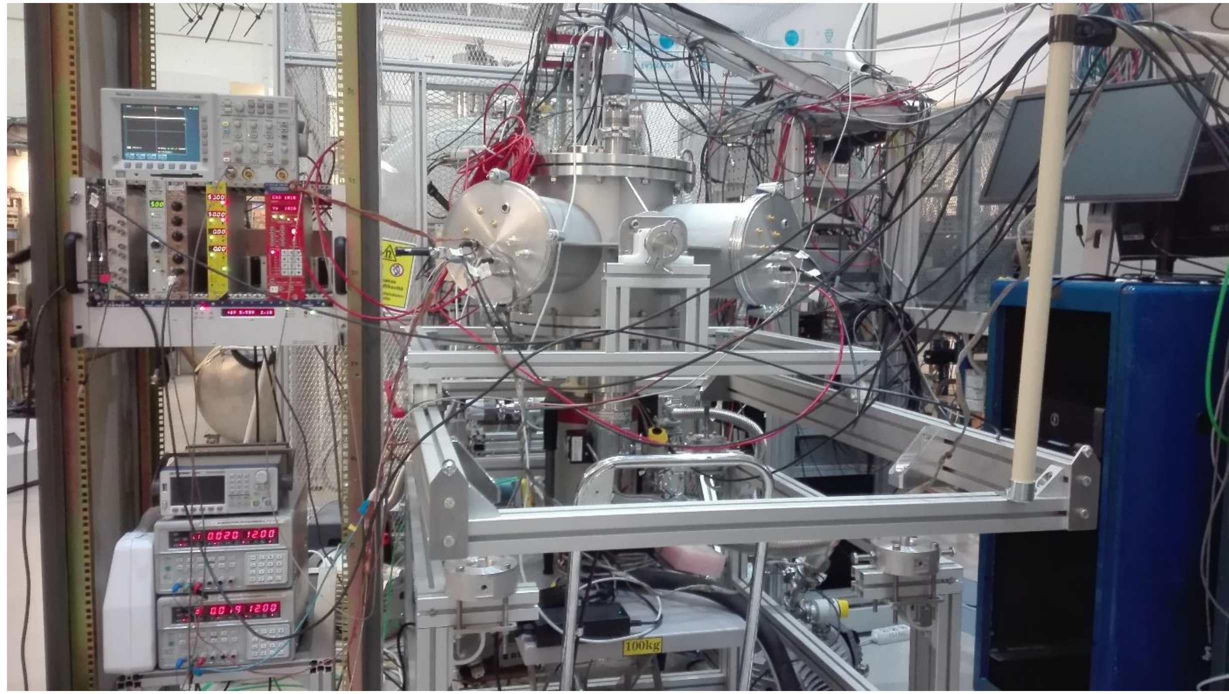




- Detection principal:
  - ΔE-E system provides very high gamma rejection efficiency

e-Shape Assembly and Commissioning

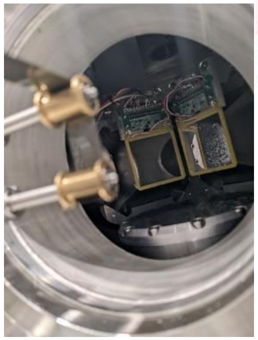
- What has been done so far?

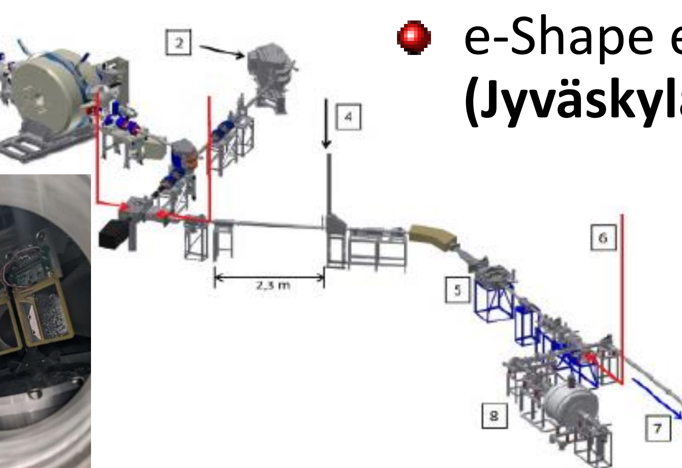


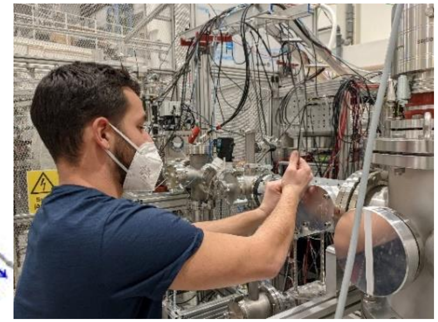
- Mechanical design, electronics and detector assembly @Subatech
- First tests @CENBG in march 2019
- Commissioning experiment in may 2019 @Jyväskylä (Finlande), analyses ongoing (R. Kean, **G. Alcala PhD @Valencia**)

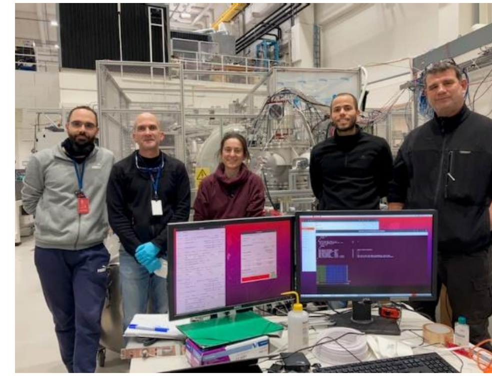
Experimental campaign in 2022 and ongoing analyses

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









- A dozen nuclei measured for first forbidden decay interest including nuclei for the detector calibration
- Analyses ongoing: 2 PhD thesis: G. Alcala (Valencia) and A. Beloeuvre (Subatech)
- Simulation: Implementation of a complex event generator for the simulation of complex beta decays in GEANT4 (Hayen et al. or Huber's corrections). Validation of the MC for the ^{114}Ag.
- Calibration: close to be finalized
- Next step**:** Analysis using deconvolution techniques of the most relevant contributors using our setup and deduce the spectrum shape for comparison with theoretical predictions.

Conclusions & Perspectives

- TAGS data (Pandemonium free) measured over more than a decade at Jyväskylä: correct NDB from Pandemonium effect

- First comparison of the full detected antineutrino energy spectrum from Daya Bay with the summation model, without any renormalization.

- Robustness of the SM model: predictions of the SM model remain robust in the 2 to 5 MeV range at the 2% level.

- Systematic trend to reduce the predicted flux by correcting the Pandemonium bias. Improvements to come with new TAGS data analyzed!

- Fundamental reactor antineutrino experiments:
  - All: issue in the absolute normalization of ILL β spectrum from ^{235}U
  - BD: RAA relieved with SM2018.
  - STEREO: rejection of the sterile neutrino hypothesis and for ^{235}U agreement with SM2018
  - PROSPECT: shape anomaly in ^{235}U and not explained by an isotope in particular

- Shape anomaly still there: focus on the experimental and theoretical studies of first forbidden decays:
  - Ongoing: forbidden operators computation and inclusion into a pnQRPA approach
  - e-Shape experiment performed and analysis ongoing
  - New e-Shape experimental campaign next Dec. 2023 in Jyväskylä

Thank you!

TAGS 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: A. Beloeuvre, J.A. Briz, M. Estienne, M. Fallot, V. Guadilla, A. Porta, A.-A. Zakari-Issoufou,_T. Shiba, A.S. Cucoanes

U. Surrey: W. Gelletly

IGISOL Jyväskylä: 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

IJCLab: M. Lebois, J. Wilson

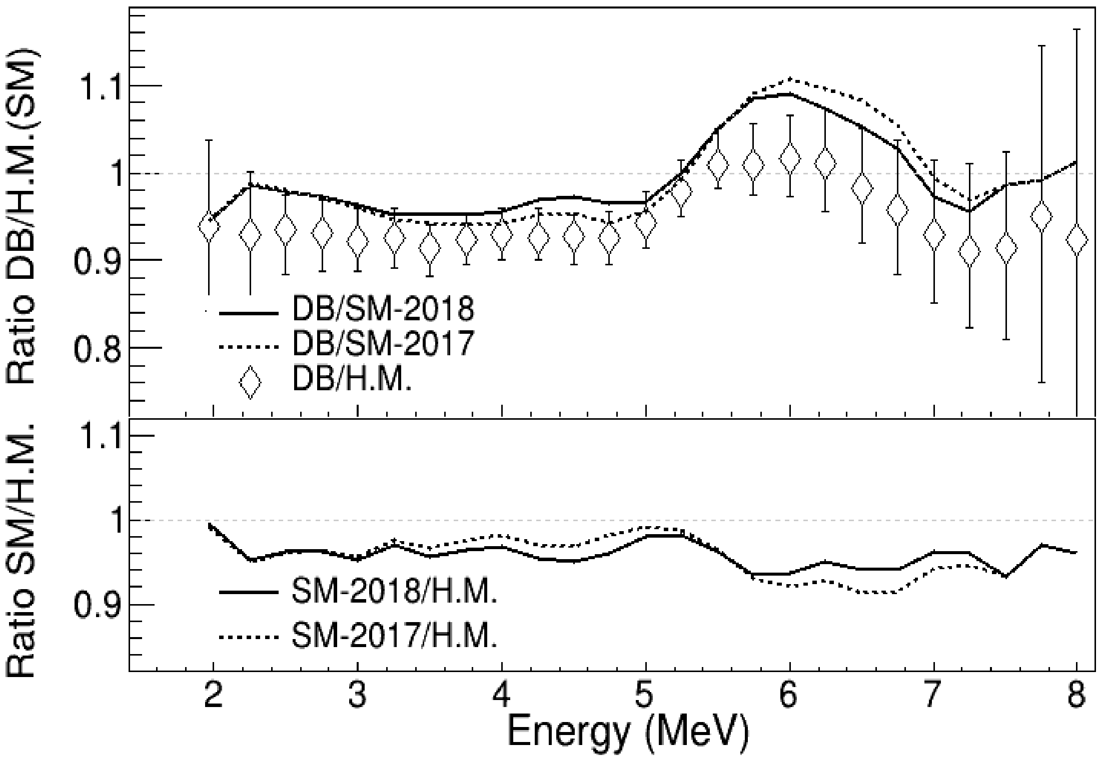
BNL New-York: A. Sonzogni

Istanbul Univ.: E. Ganioglu

Special thanks to the young researchers working in the project:
A. Beloeuvre, R. Kean, L. Le Meur, J.A. Briz, V. Guadilla, J. Pépin, E. Valencia, S. Rice, A. -A. Zakari-Issoufou
Discussions with and slides from: A. Algora, J. L. Tain, B. Rubio, S. Orrigo, W. Gelletly, C. Ducoin, O. Stezowski, J.-C. Thomas, P. Chauveau, P. Delahaye, H. Savajol, F. de Oliveira, B. Blank, B. Bastin, A. Sanchez, E. Bonnet, M. Fallot, L. Giot, A. Porta, …are acknowledged

Comparison with Daya Bay results and H-M Predictions

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



- For the first time! 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.