Update of the summation calculations for reactor antineutrino spectra & $(NA)^2$STARS project

M. Fallot, M. Estienne, A. Porta, E. Bonnet, S. Bouvier, S. Durand, S. Nandi, J. Pépin, J.-S. Stutzmann (SEN team),
+ TAGS, e-Shape, $(NA)^2$STARS collaborations

Seoul, Korea
April 2025

Subatech, CNRS/IN2P3, Nantes Univ., IMT Atlantique, France

Seoul, Korea
April 2025

- Introduction
- News from recent TAGS & e-Shape Experiments (tbc with A. Algora's talk)
- (NA)^{2}STARS Project
- Some Recent TAGS Results & Summation Method 2025
- Uncertainties with GEF
- Conclusions & Outlooks

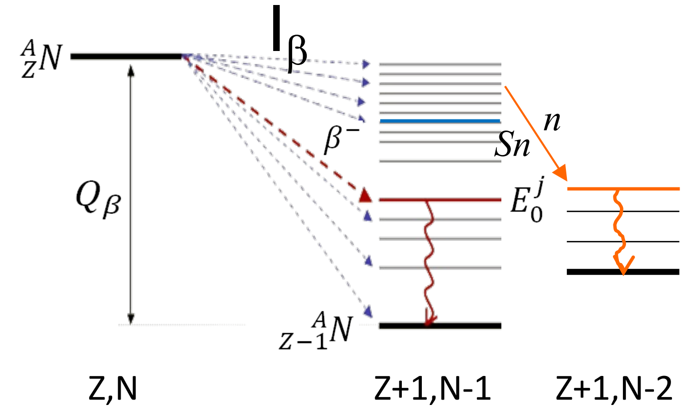
Motivations for Beta Decay Study and its Applications

Applications of Beta Decay from Fission Products

- Getting access to the beta decay properties

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

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



- The exploitation of the products of the beta decay is multifold:

Nuclear Energy

- ❑ The released γ and β contribute to the "**decay heat**" → critical for reactor safety and economy
- ❑ β-n emitters: **delayed neutron fractions** → important for the operation and control of the chain reaction of reactors

Neutrino Physics

- ❑ The **antineutrinos** escape and can be detected → reactor monitoring, potential non-proliferation tool and essential for fundamental physics
  - ✓ But γ and β emission → indirect access to antineutrino energy spectra

Nuclear Astrophysics

- ❑ β–decay plays an important role in the **r-process**: n-capture (n,γ) and (γ,n) photodisintegration equilibrium and β-decay

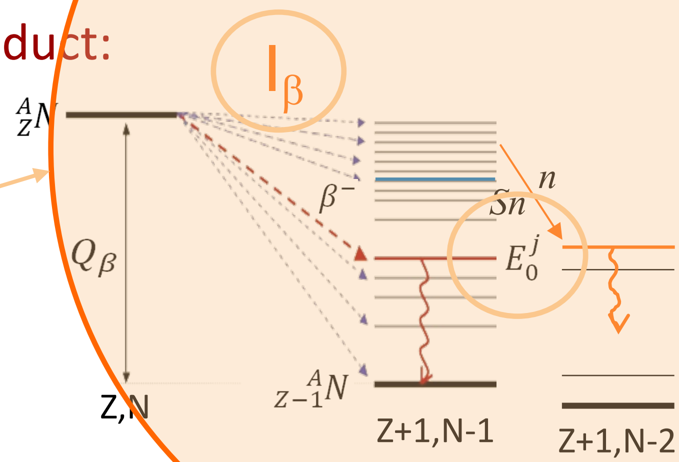
- **γ or β** measurements: **2 experimental methods** → characterize the weak interaction properties, several physics topics in nuclear structure or nuclear astrophysics.

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

- Measurement of well identified fission product:

$$^A_ZX \rightarrow {}^A_{Z+1}Y^* + e^- + \bar{\nu}_e$$

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



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:

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

eShape measurements

Courtesy M. Estienne

γ-Spectroscopy Measurement

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 daughter nuclei (especially with decay schemes with large Q-values)

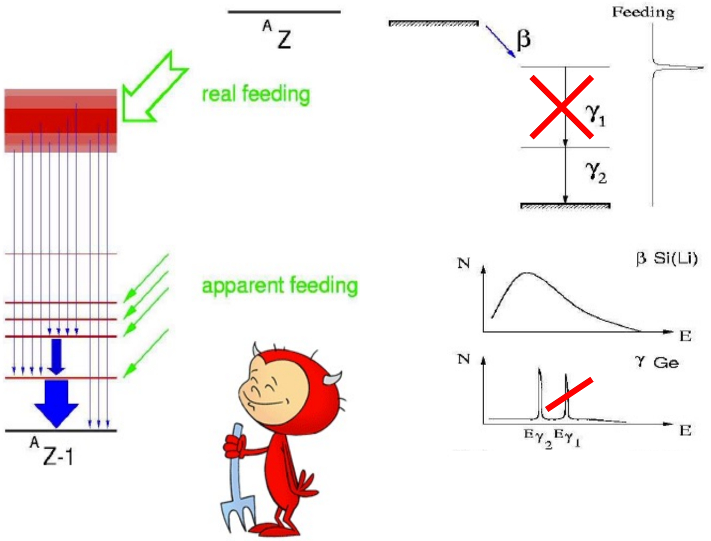
- Incomplete decay schemes: overestimate of the high-energy part of the FP β spectra

- 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** (i.e. indirect effect on summation calculations for DH and anti-ν energy spectra)

Picture from A. Algora



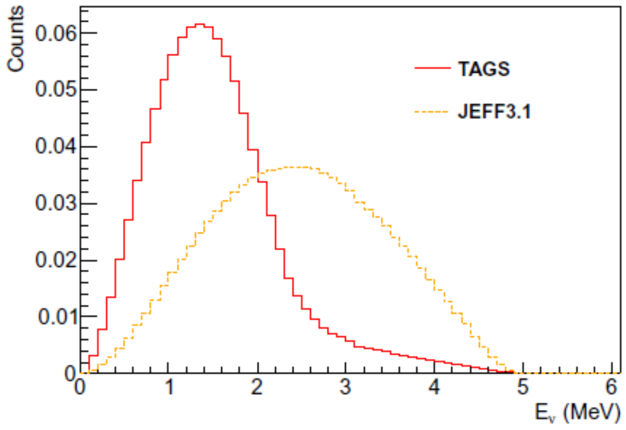
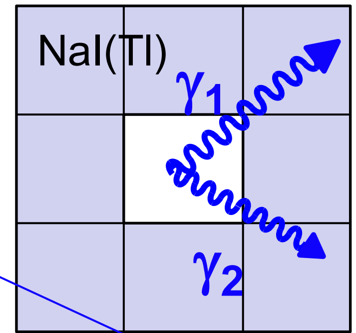
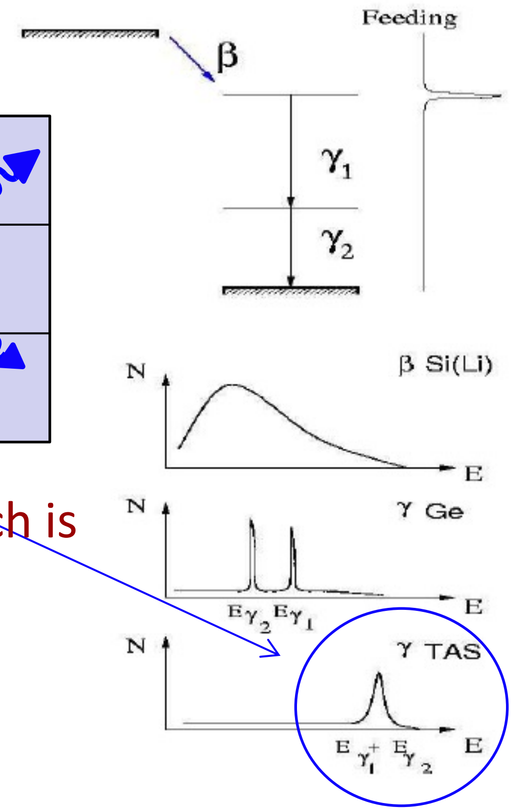


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

TAGS: a Solution to the Pandemonium Effect

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





- An ideal TAS would give directly the β-intensity I_β which is linked with the β-strength S_β:

$$I_i = \frac{f_i}{\sum_k f_k}$$

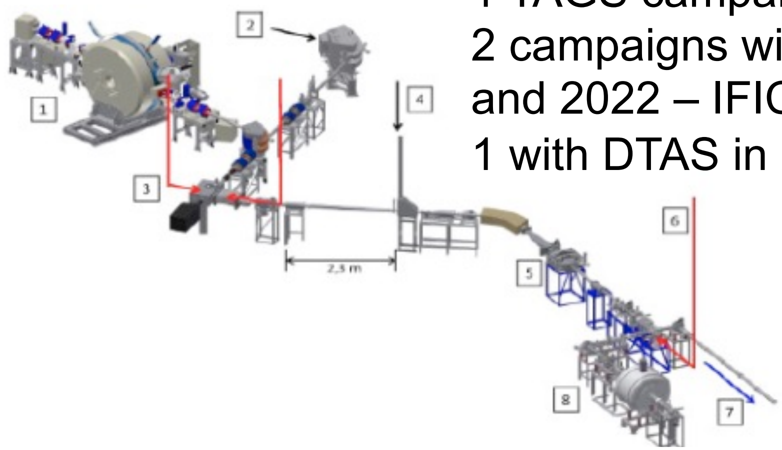
$$\Rightarrow \quad S_i = \frac{I_i}{f(Q_\beta - E_i)T_{1/2}} \quad [s^{-1}]$$

- 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

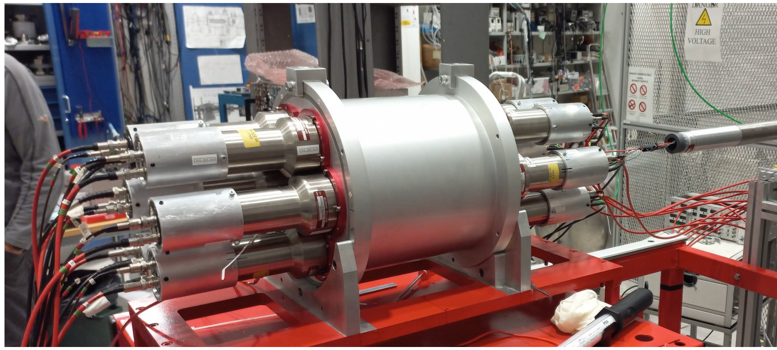
$$d_i = \sum^{m} R_{ij} \cdot f_j$$

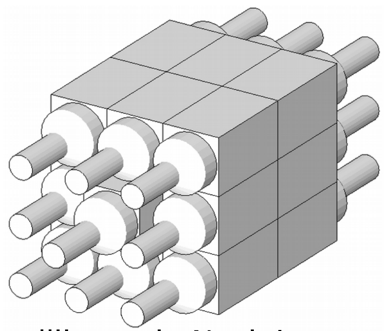
NIM A430 (1999) 333
NIM A430 (1999) 488
NIM A571 (2007) 719
NIM A571 (2007) 728

TAGS Campaigns @ IGISOL



1 TAGS campaign in 2005 IFIC
2 campaigns with Rocinante in 2009 and 2022 – IFIC - Subatech
1 with DTAS in 2014 - IFIC - Subatech



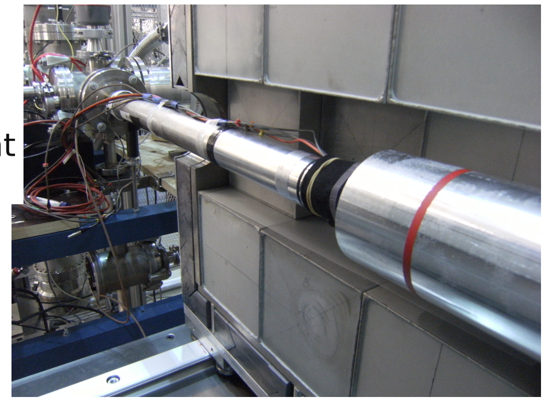


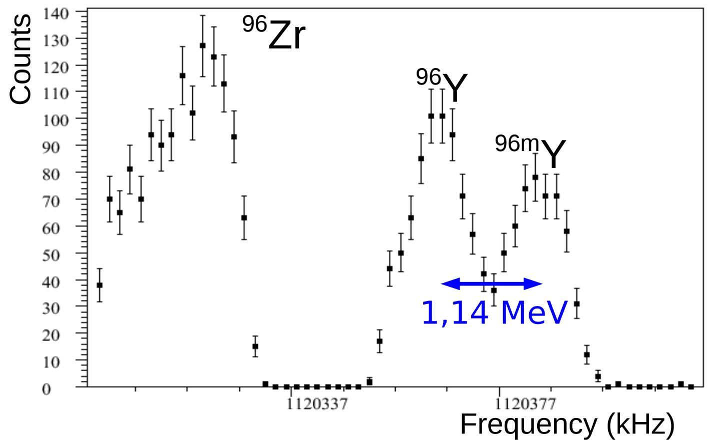
V. Guadilla et al., Nucl. Instrum. Methods B 376 (2016), p. 334

Why @ IGISOL ?
Because of JYFLTrap
$\Delta m/m \sim 10^{-8}$

- DTAS = 18 crystals of NaI(Tl)
  - ~90% efficiency for a 1 MeV gamma-ray
  - $\Delta E/E$ ~ 5% at 1.3 MeV
- β detector = plastic detector
  - In coincidence with γ → background suppression
  - 30% detection efficiency
- HPGe detector
  - Allows identification of possible contaminant coming from the decay chain

+ Implantation on a tape in the center of the TAS

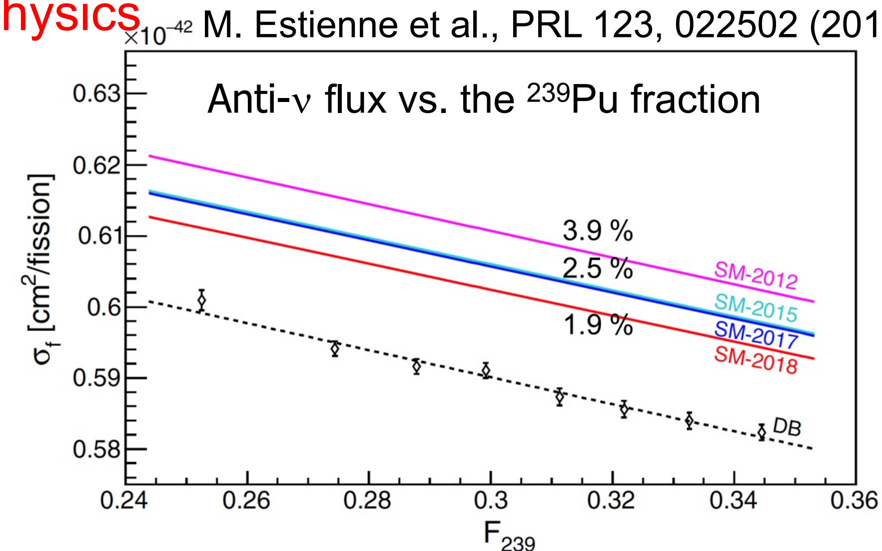




TAGS @IGISOL Jyväskylä

Neutrino Physics

M. Estienne et al., PRL 123, 022502 (2019)

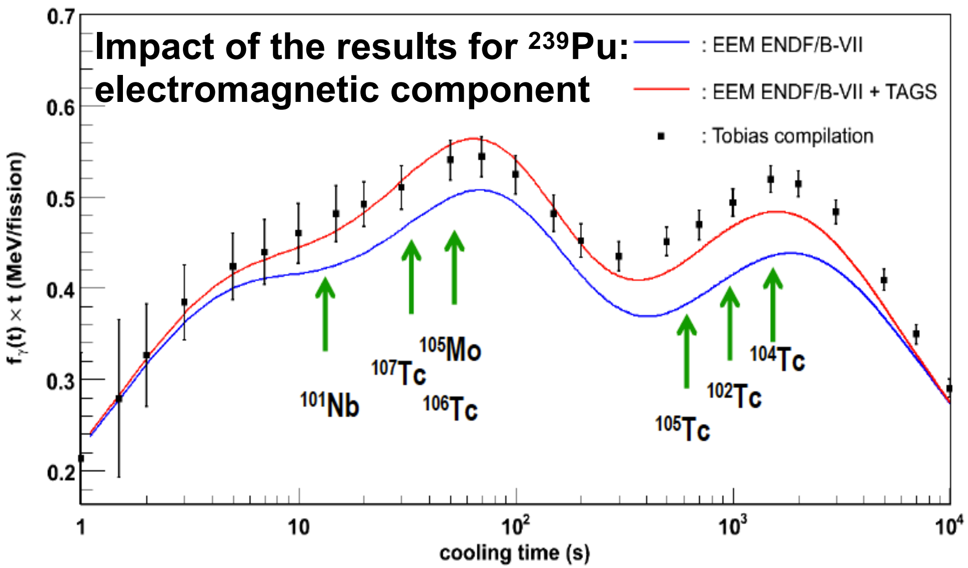


A.Algora et al. PRL 105, 202501 (2010),
M. Fallot et al. PRL 109, 202504 (2012)
D. Jordan et al. PRC 87, (2013) 044318
A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015)
E. Valencia et al., PRC 95, 024320 (2017)
S. Rice et al. PRC 96 (2017) 014320
V. Guadilla et al. PRL 122, (2019) 042502
+ Data vs model in Daya Bay and STEREO recent papers: DB: PRL 130 (2023) 211801, PRL 129 (2022) 041801, STEREO: Nature 613 (2023) 257

Reactor Decay Heat

Review Paper: Algora, Tain, Rubio, Fallot, Gelletly, Eur. Phys. J. A 57, 85 (2021)

A. Nichols et al. Eur. Phys. J. A (2023) **59**: 78
Algora *et al.*, PRL 105, 202501 (2010).



R-process & γ/n competition above Sn

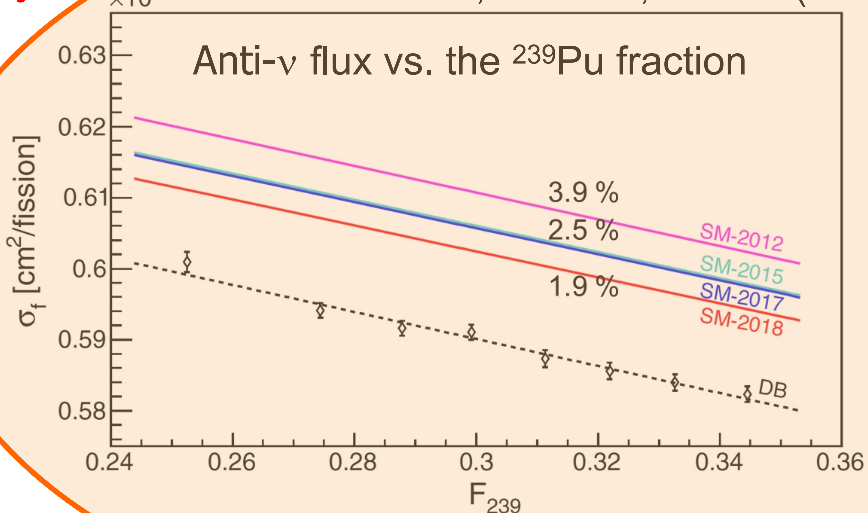
Isotope	$P_\gamma(TAGS)$	P_n
^{87}Br	$3.50^{+0.49}_{-0.40}$	2.60(4)
^{88}Br	$1.59^{+0.27}_{-0.22}$	6.4(6)
^{94}Rb	$0.53^{+0.33}_{-0.22}$	10.18(24)
^{95}Rb	$2.92^{+0.97}_{-0.83}$	8.7(3)
^{137}I	$9.25^{+1.84}_{-2.23}$	7.14(23)

J.L. Tain et al., PRL 115, 062502 (2015)
E. Valencia et al., Phys. Rev. C 95, 024320 (2017).
V. Guadilla et al., Phys. Rev. C 100, 044305 (2019)

TAGS @IGISOL Jyväskylä

- Neutrino Physics

M. Estienne et al., PRL 123, 022502 (2019)



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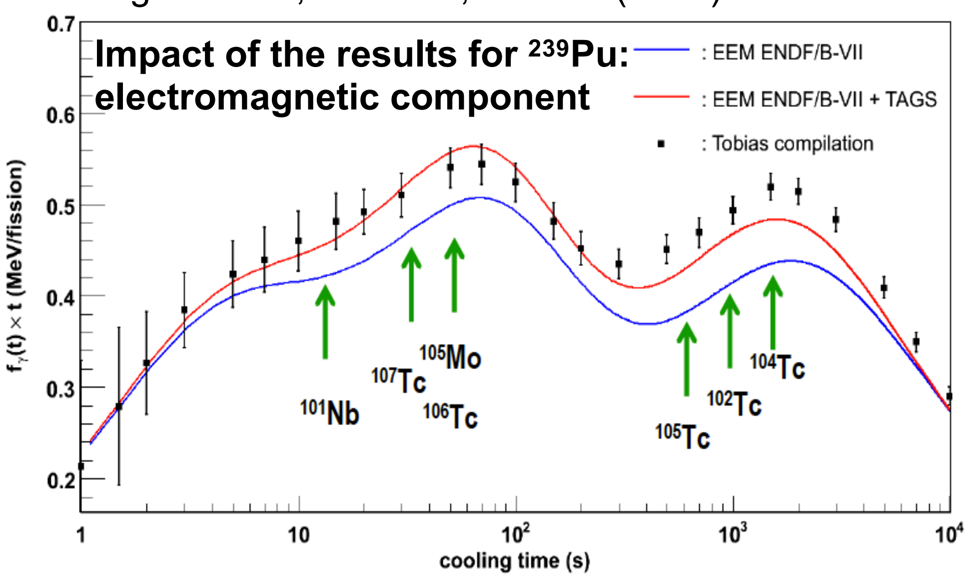

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V. Guadilla et al., Phys. Rev. C 100, 044305 (2019)

Anomalies of Reactor Antineutrino Energy Spectra

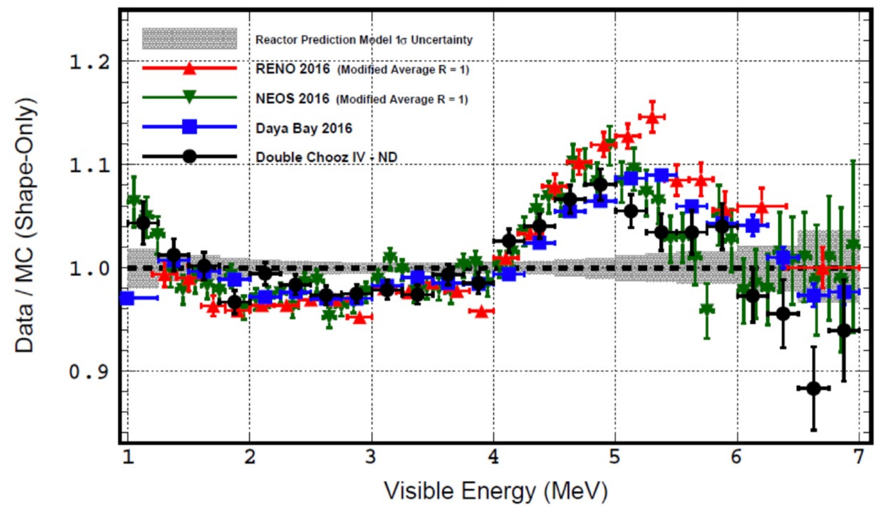
- Measurement of the θ_{13} oscillation parameter by Double Chooz, Daya Bay, Reno in 2012
  - Independent evaluation of anti-ν energy spectra using BDNs
  - 6% deficit in the absolute value of the measured flux compared with the best prediction based on ILL data: reactor anomaly
  - Numerous projects in search of the existence of sterile neutrinos

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)

- In 2014, the same three experiments highlighted a spectrum distortion between 4.8-7.3 MeV compared to nuclear models again! (Shape anomaly)
- **Since 2023, issue with the ^{235}U measurement from Schrekenbach et al. confirmed** by Daya Bay, Reno, STEREO, Prospect, Double Chooz, etc. and by **summation calculations based on nuclear data**
- **Research path put forward: first forbidden β-decays could be responsible for the distortion.**

- Experimental requirement: direct measurement of electron energy spectra of β decays of well-identified fission products (also known as form factors).
  → e-Shape experiment
- Theoretical requirement: take these form factors into account in our calculations for summing antineutrino energy spectra.
- Still more TAGS data: especially for high energy part & future comparison with Juno-TAO, and other forthcoming measurements
  → TAGS experiments

Nature Physics 558–564 (2020)

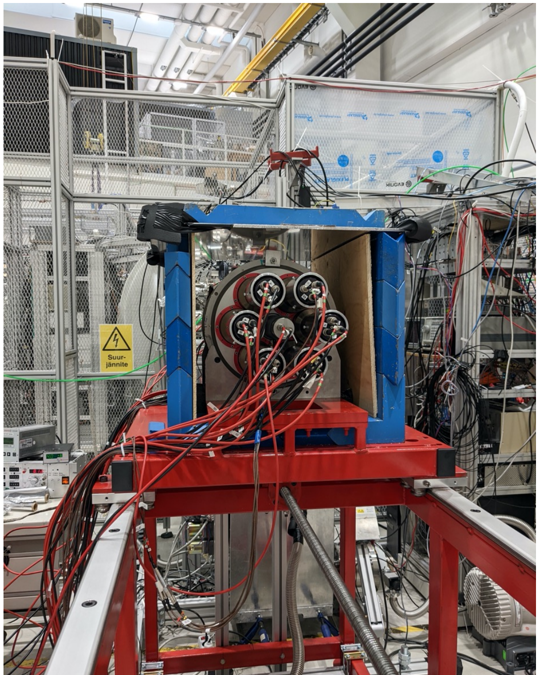


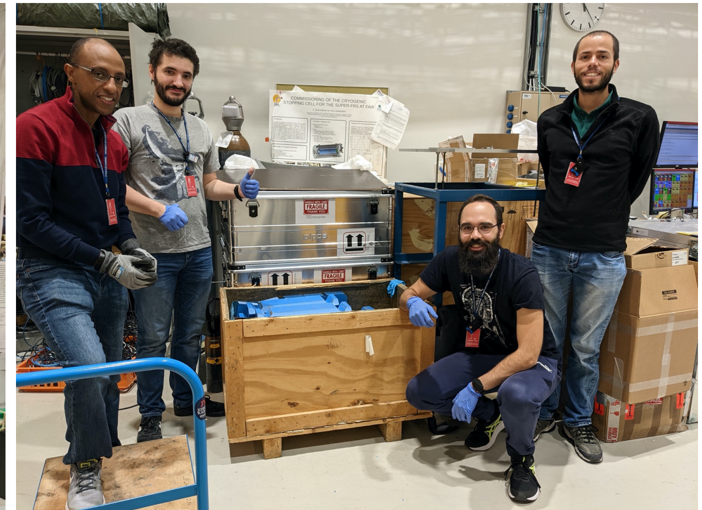
C. Zhang, X. Qian, M. Fallot, Prog. Part. Nucl. Phys. 136 (2024) 104106

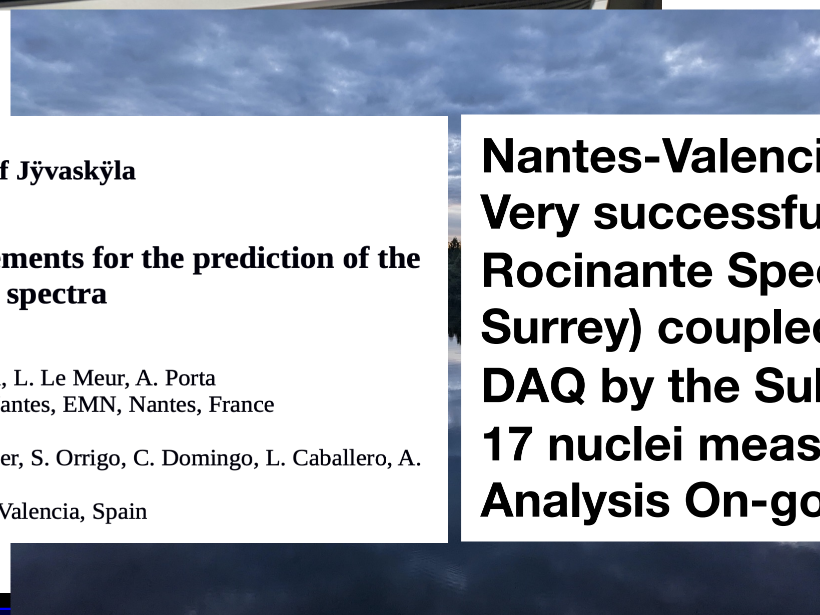
News from Pandemonium-free Experiments

TAGS Experiments

2022 TAGS Campaign @ Jyväskylä







Proposal to the PAC of Jÿvaskÿla

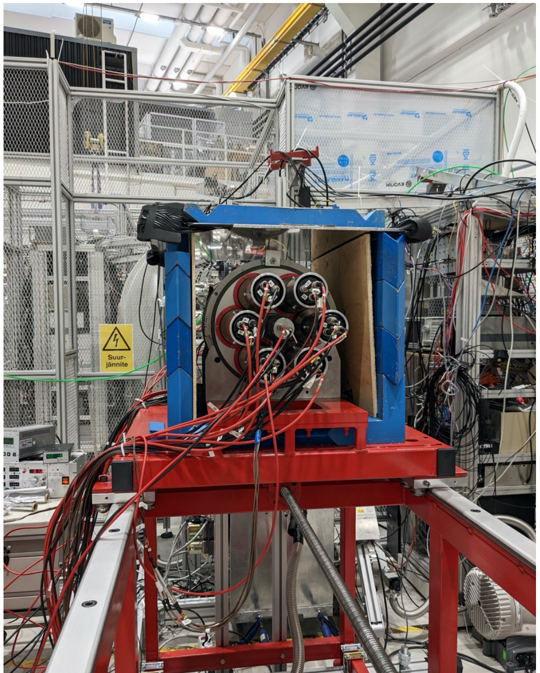
Total absorption spectroscopy measurements for the prediction of the reactor antineutrino spectra

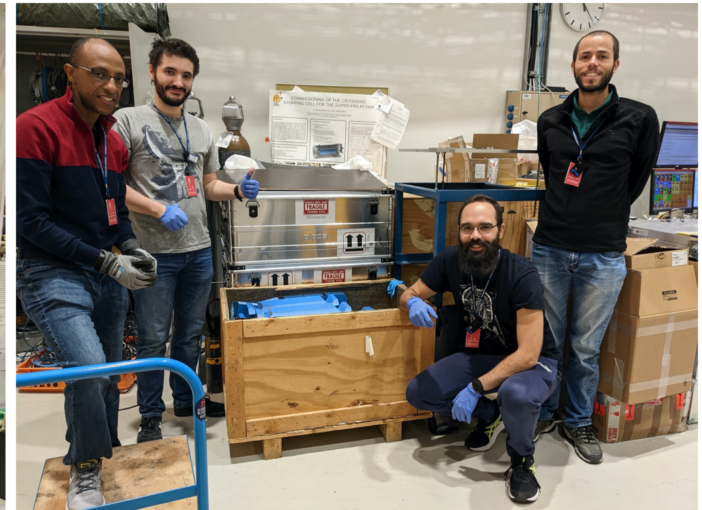
M. Estienne, M. Fallot, V. Guadilla, L. Le Meur, A. Porta
Subatech, CNRS/IN2P3, University of Nantes, EMN, Nantes, France

A. Algora, J. L. Taín, B. Rubio, J. Agramunt, A. Montaner, S. Orrigo, C. Domingo, L. Caballero, A. Tolosa
IFIC,CSIC-Univ. Valencia, Valencia, Spain

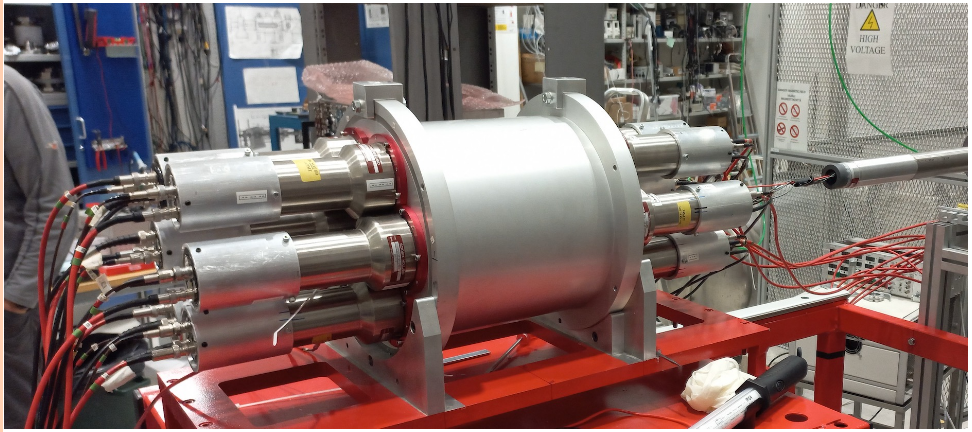
Nantes-Valencia proposal,
Very successful experiment,
Rocinante Spectrometer (IFIC-Surrey) coupled to the FASTER DAQ by the Subatech team
17 nuclei measured with TAGS
Analysis On-going…

2022 TAGS Campaign @ Jyväskylä



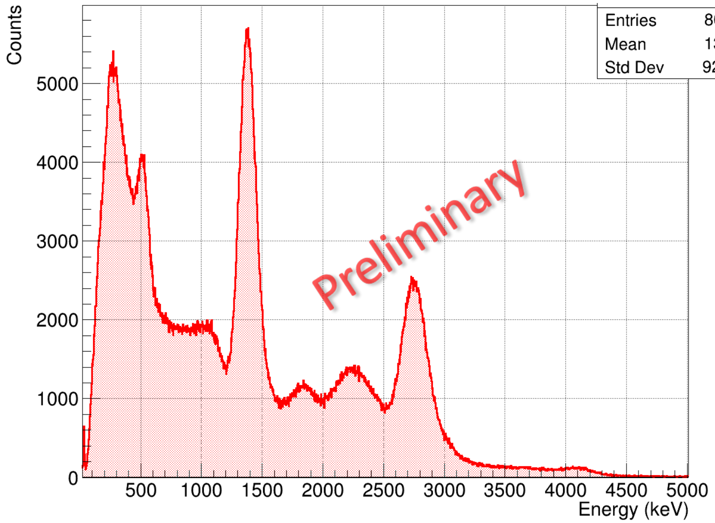


TAGS Campaign @ Jyväskylä Sept. 2022

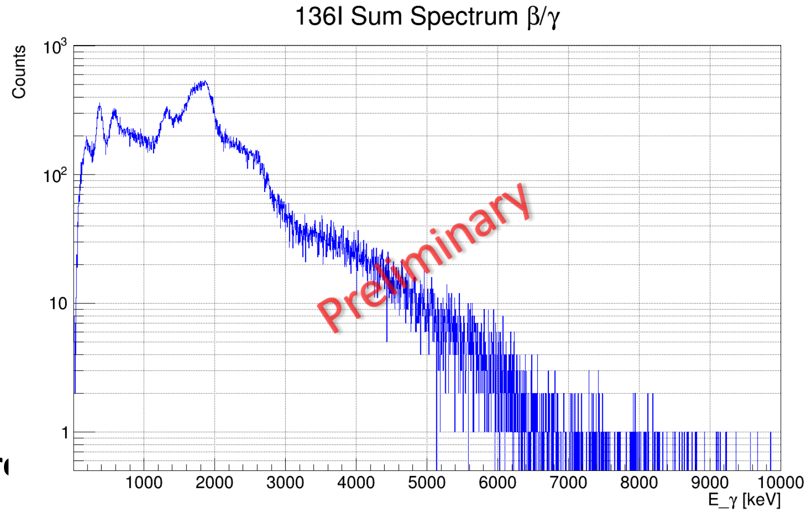


- **Analysis performed by Julien Pépin**, co-supervised Subatech - IFIC **and Soumen Nandi**, post-doc Subatech Nov. 2023 – March 2025
- **New analysis codes of** raw data (alignment of cristals, energy calibration): automation
- **Calibration phase over**, simulation Geant4 developed and pile-up subtraction.

^{24}Na source : energy spectrum of Crystal 1



Example of TAGS spectrum:



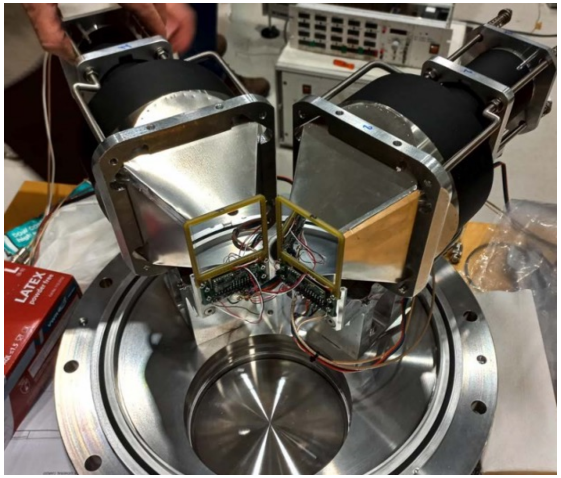
A. Porta et al. BARRANDE Workshop 2023 Oct. 10.-12., workshop NEEDS/Nacre Jan. 2024

J. Pépin et al.: 2 poster presentations @ EJC 2023 and @ Colloque GANIL 2023

Electron Spectra Measurement

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

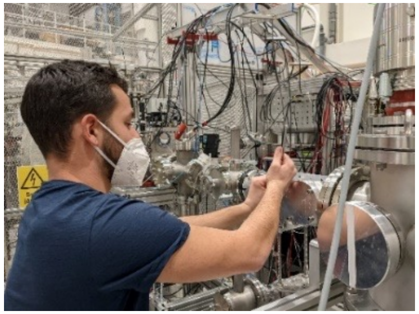
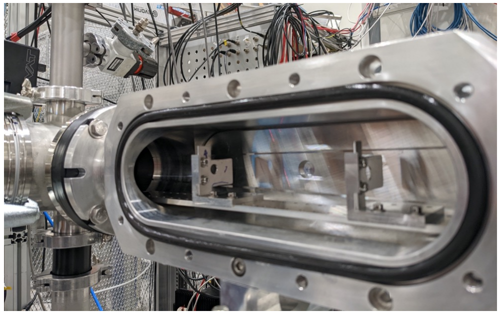
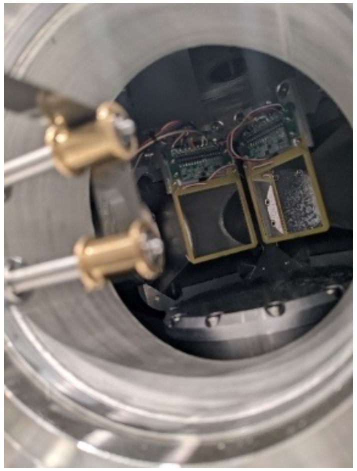
- ΔE – E telescopes to measure the beta spectrum of selected decays using isotopically pure beams at Jyväskylä with Si and plastic detectors in coincidence
- In vacuum chamber
- Description of the telescopes:
  - **ΔE**: 500 (or 300) μm thickness Si detector, active area 50x50 mm^2
  - **E**: Pl truncated cones, height 110 mm



- Ancillary detectors for gammas: HPGe and $CeBr_3$
- DAQ: successful use of FASTER DAQ (LPC Caen)
- I206, I233, I233Add IGISOL proposals Univ. of Jyväskylä, Spokespersons: A. Algora, M. Fallot, W. Gelletly, local contact: Tommi Eronen
- First commissioning @ex-CENBG Bordeaux, March 2019 and I206@Jyväskylä May 2019
  - Detector Paper arXiv:2305.13832 V. Guadilla et al. 2024 JINST 19 P02027

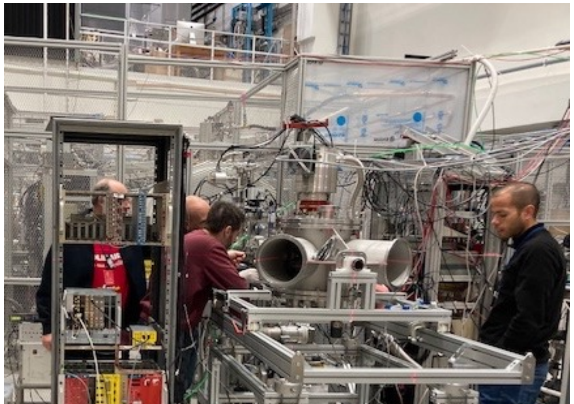
Several works and publications emphasize the need of such measurements:
Hayes et al. PRL 112.202501 (2014), Hayen et al. PRC 99.031311 (2019)
Technical Meeting (IAEA, 2019), Report INDC-NDS-0786, Sonzogni et al. , PRL 119.112501 (2017)

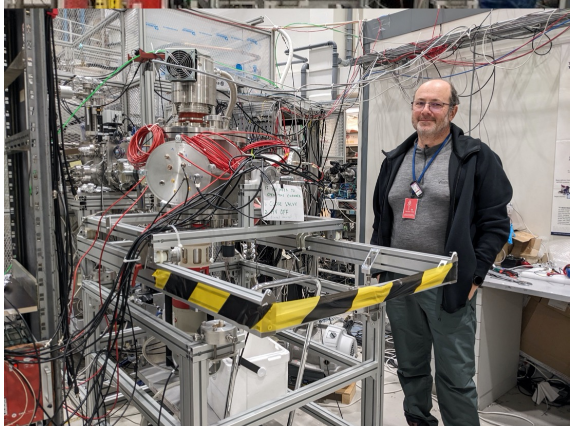
Experimental campaigns in 2022 & 2023


- **IGISOL @ Jyväskylä** for purified beams
- e-Shape improvements after **commissioning I206** in **2019**: **electronical threshold** of Si detectors
- e-Shape **experimental campaign I233 in 2022**: A dozen nuclei measured including nuclei for the detector calibration.
- Analyses: **2 defended PhD thesis**: G. Alcala (IFIC Valencia) and A. Beloeuvre (Subatech)
- Some issues in Jan. 2022 to tune properly the beam => **I233Add**
- **2023: technical improvements + successful (**re-)measurement of nuclei
- PhD thesis in Subatech (Samuel Durand) & Postdoc in IFIC (Gustavo Alcala) started in fall 2024

E-Shape Campaigns @ Jyväskylä





⇒ See Alejandro Algora's talk for the first results !!!

The $(NA)^2$STARS Project

Neutrinos, Applications and Nuclear Astrophysics with a Segmented Total Absorption with higher Resolution Spectrometer: the (NA)^{2}STARS Project

(NA)^{2}STARS Collaboration
SUBATECH: E. Bonnet, S. Durand, M. Estienne, M. Fallot, S. Nandi, J. Pépin, A. Porta
IFIC Valencia: A. Algora, E. Nacher, S. Orrigo, B. Rubio, J.-L. Tain
GANIL : J.-C. Thomas, U. Guérin, B. Ribeiro
CIEMAT Madrid: D. Cano-Ott
CSIC Madrid: T. Kurtukian Nieto
IP2I: C. Ducoin, N. Millard-Pinard, O. Stézowski
Surrey: W. Gelletly, Z. Podolyak
U. Istanbul: E. Ganioğlu Nutku, L. Şahin Yalçın, M. Yalçınkaya
U. Huelva: A. M. Benitez-Sanchez
NPI CAS: A. Cassissa, J. Mrazek, E. Simeckova

The $(NA)^2$STARS project

<u>GOAL:</u> Upgrade of the existent TAS spectrometers **DTAS** and **Rocinante** with **16 $LaBr_3$(Ce) modules** 2”x2”x4”

- Large efficiency of DTAS/Rocinante **+** very good energy resolution and timing of $LaBr_3$
  - Higher segmentation: γ-γ coincidences, angular correlations, γ-cascade multiplicity
  - n/γ discrimination through timing
- Broad physics case: exotic nuclei further away from stability => nuclear structure and astrophysics on the p-rich (p/γ competition >S_p, p-process, rp-process, SNe…) and n-rich sides (n/γ competition >S_n), decay heat, reactor neutrinos…

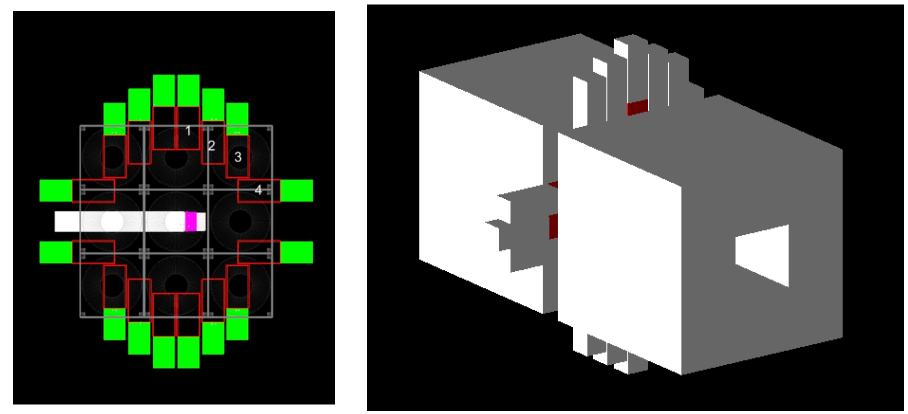


Fig. 4 : view of possible arrangement of the 16 LaBr3:Ce (red) in the middle of the NaI crystals (grey) (courtesy A. Beloeuvre).

Neutrinos, Applications and Nuclear Astrophysics with a Segmented Total Absorption with higher Resolution Spectrometer

A combination of calorimetric and spectroscopic tools for beta decay and in-beam measurements

Total Absorption Spectroscopy for Nuclear Structure and Nuclear Astrophysics

Spokespersons: M. Fallot[1], S. E. A. Orrigo[2], A. M. Sánchez Benítez[3],

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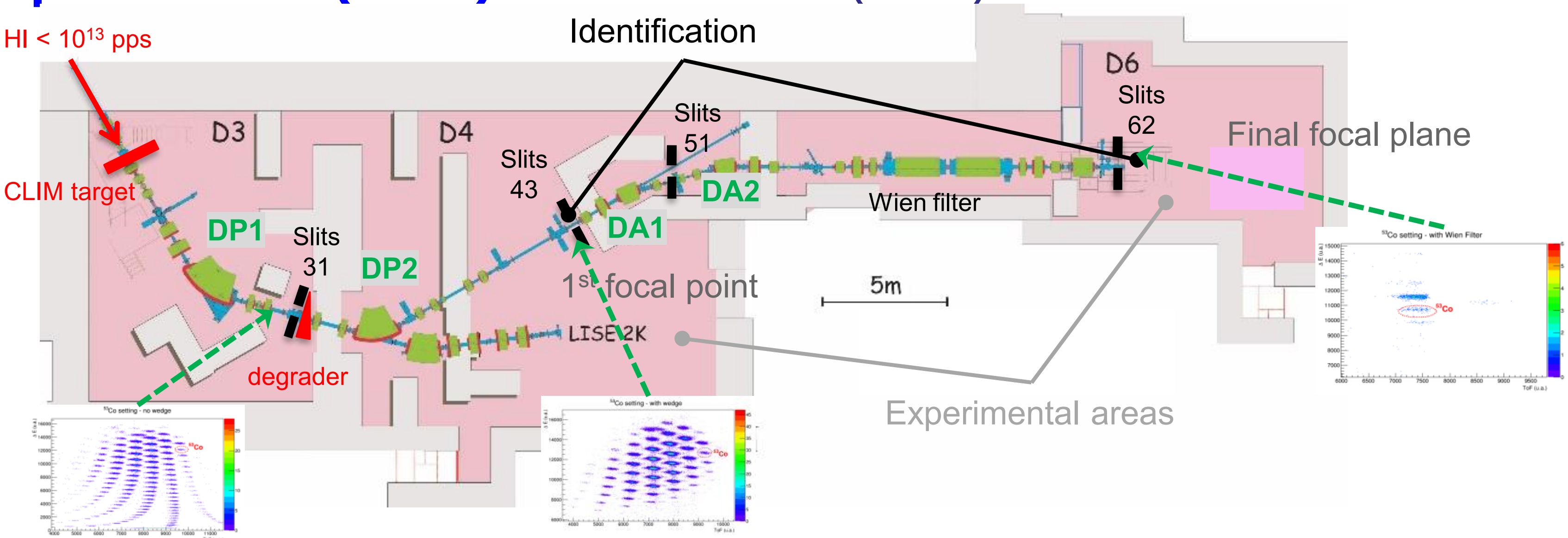
(NA)²STARS ‘ proposal @ GANIL

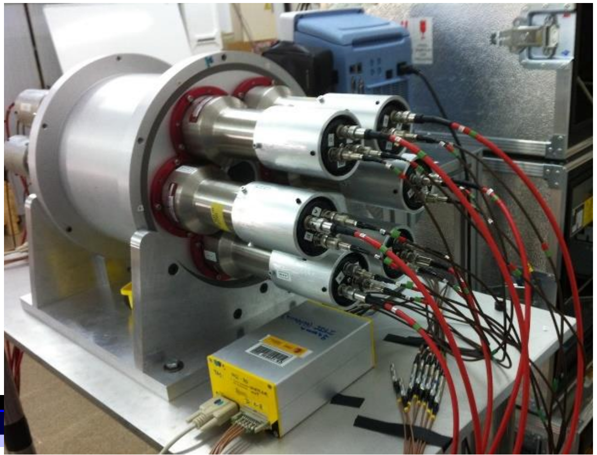
The LISE spectrometer (44 m) similar to e556a (2010)



New DSSSD (GANIL) +

1 mm-thick, 40x40 mm2, 1 mm pitch

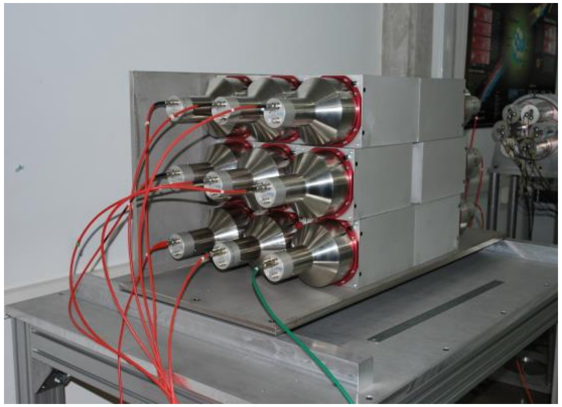
“Rocinante” TAS



(NA)²STARS: TAS upgrade with $LaBr_3$ modules

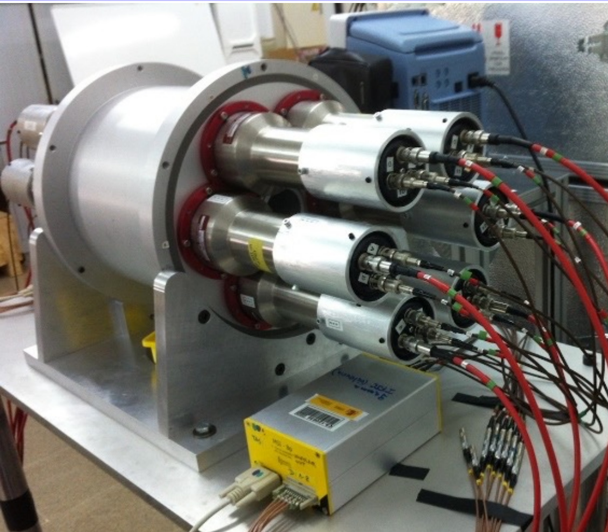
- Compact 12-fold segmented BaF_2 spectrometer (to be refurbished)
- Cascade multiplicity information
- Good timing

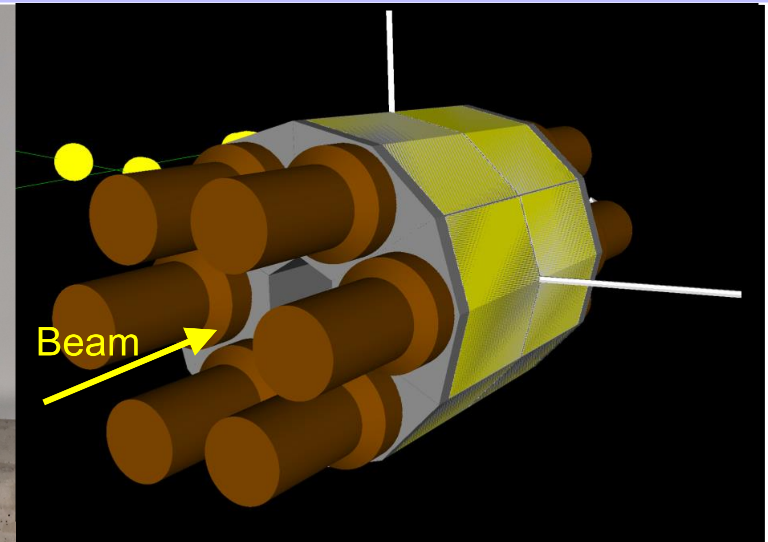
DTAS (NUSTAR)

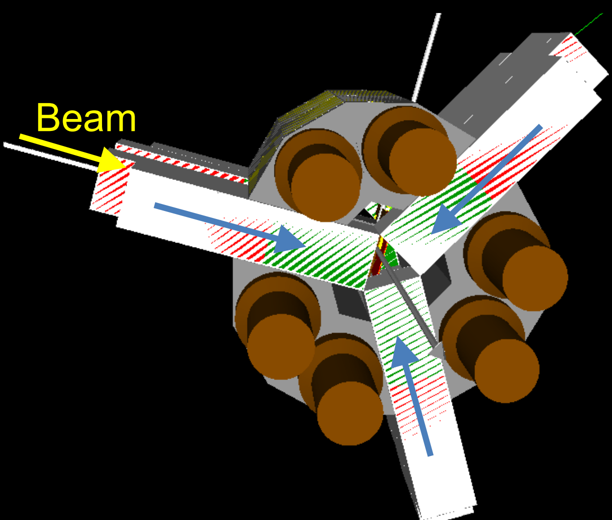


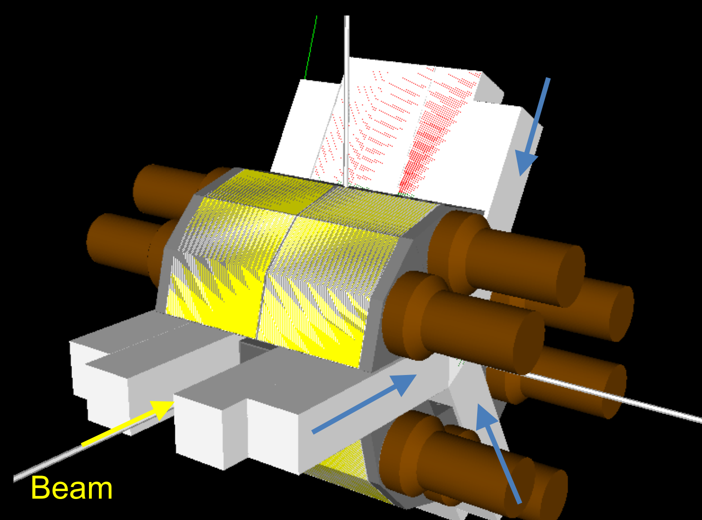
- Large 18-fold segmented NaI spectrometer
- Cascade multiplicity information

The $(NA)^2$STARS project









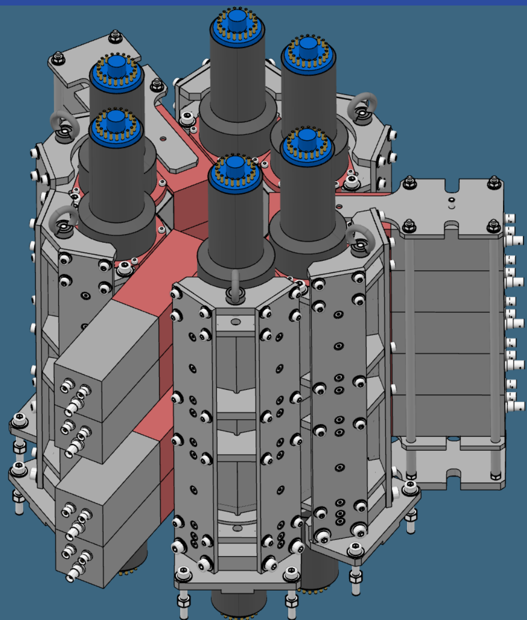
BaF_2: ρ= 4.893 g/cm^3, τ_{decay}= 0.6 and 620ns, energy resolution ~10 %@1332 keV

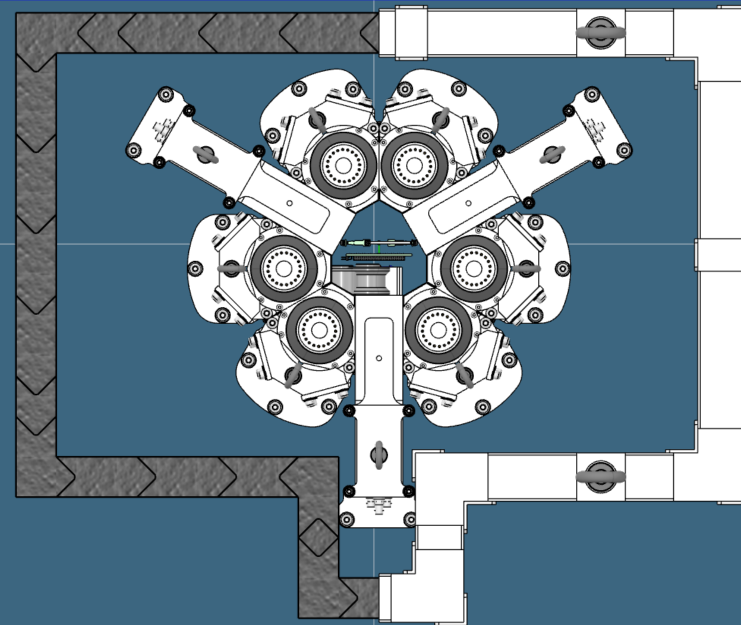
$LaBr_3$: ρ=5.08 g/cm^3, τ_{decay}=17 ns, energy resolution ~3 %@662 keV

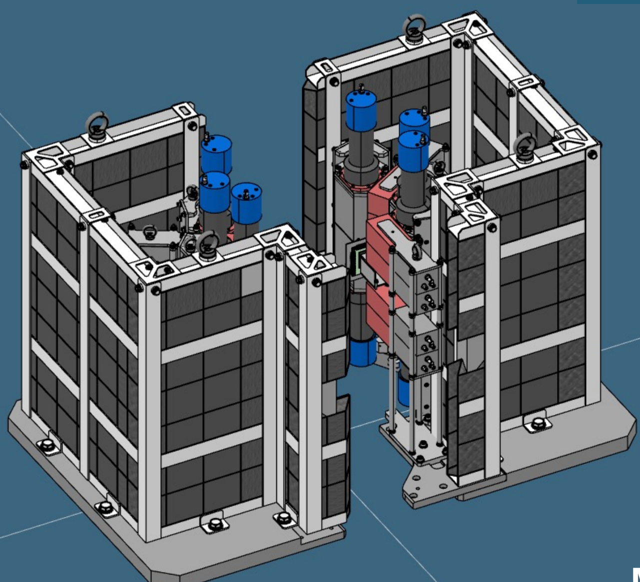
On-going work…

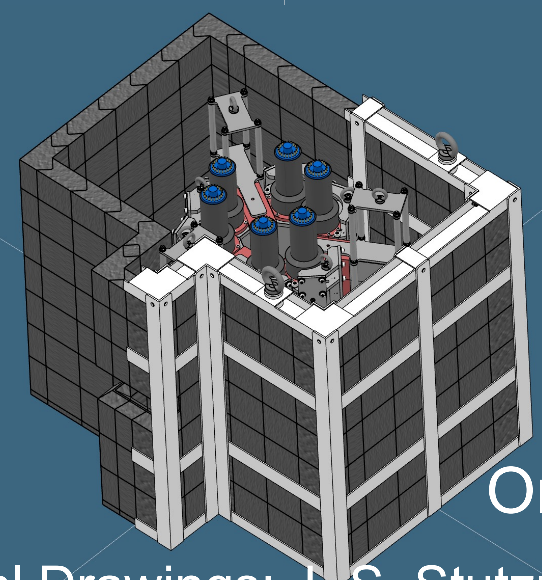
Pictures A. Algora & Simulations M. Estienne

The $(NA)^2$STARS project





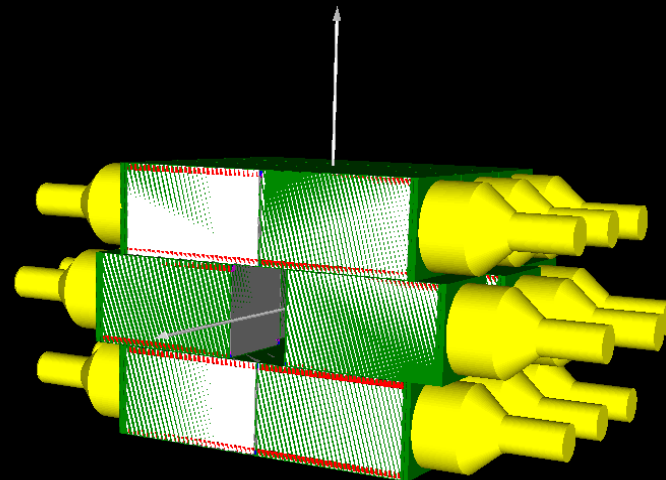




On-going work…

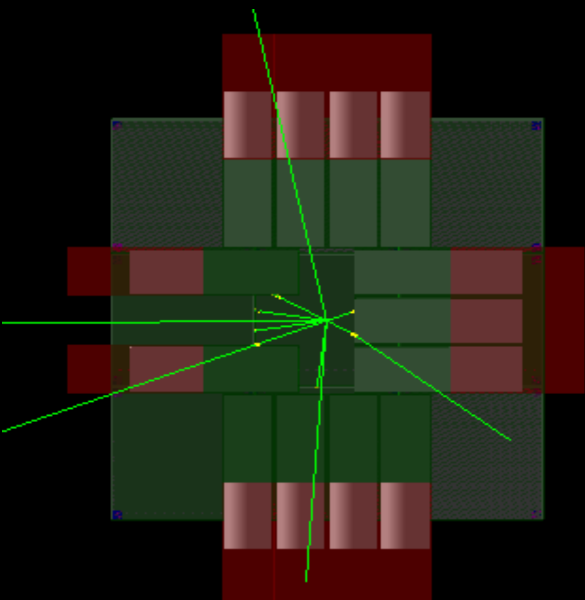
Mechanical Drawings: J.-S. Stutzmann & B. Madiot

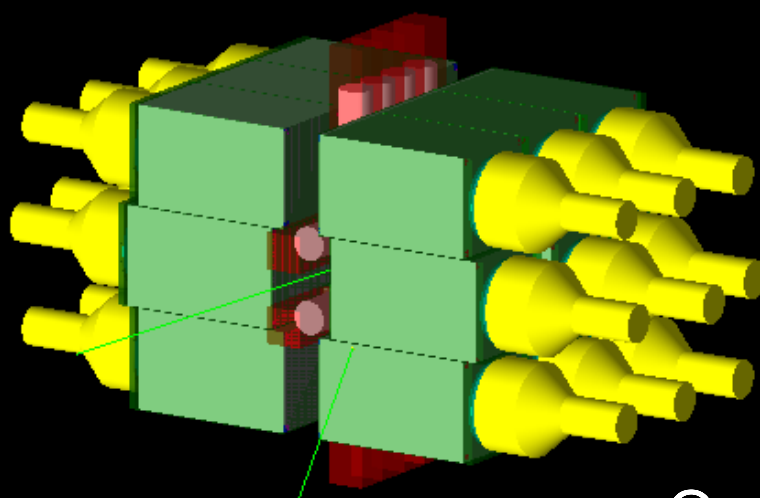
The $(NA)^2$STARS project



NaI: ρ=3.67 g/cm^3, τ_{decay}=230 ns, energy resolution ~7 %@662 keV

$LaBr_3$: ρ=5.08 g/cm^3, τ_{decay}=17 ns, energy resolution ~3 %@662 keV

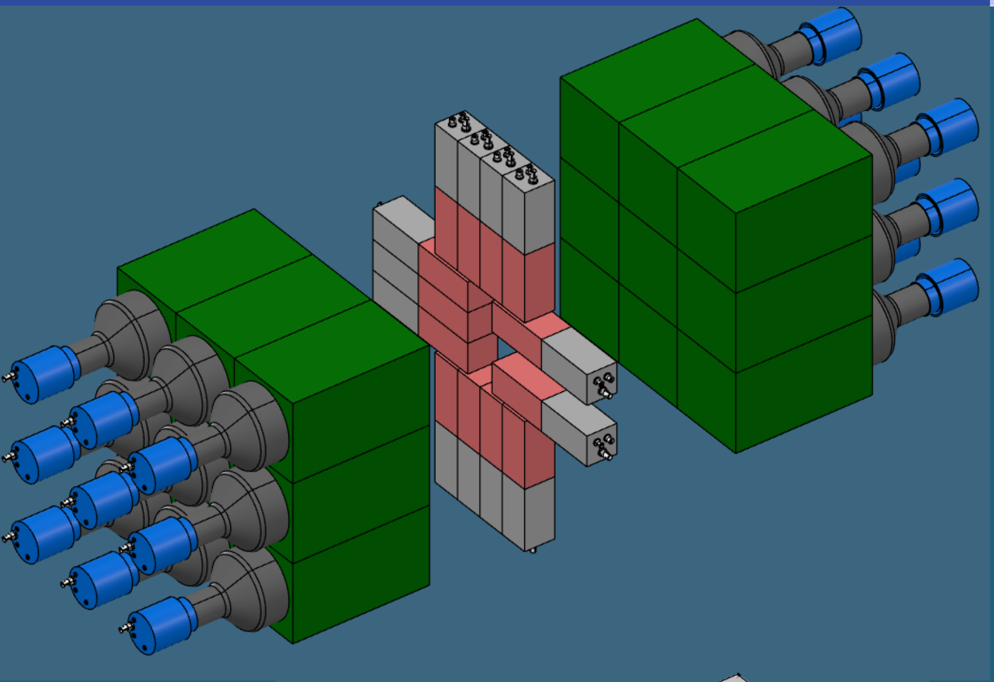


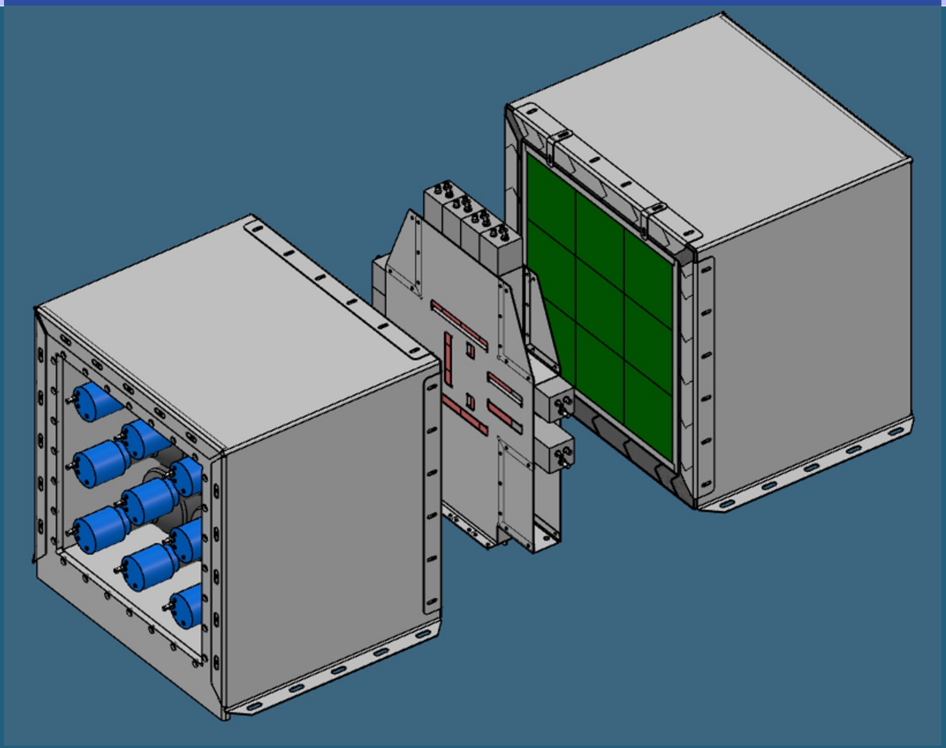


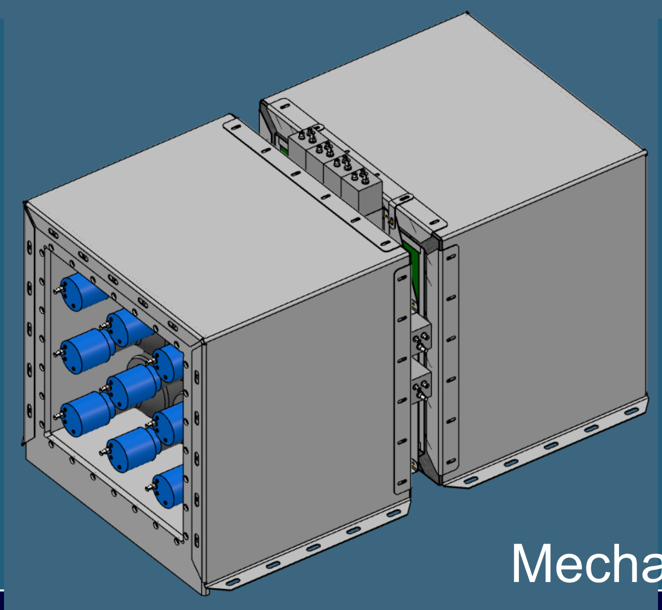
On-going work…

Pictures A. Algora & Simulations M. Estienne, A. Porta

The (NA)^{2}STARS project





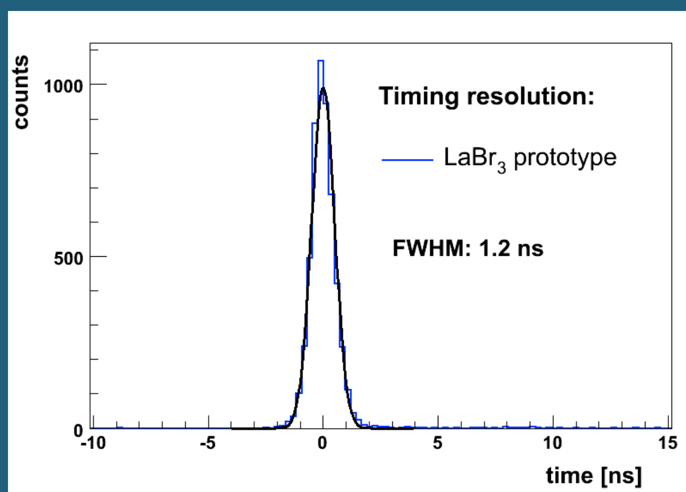


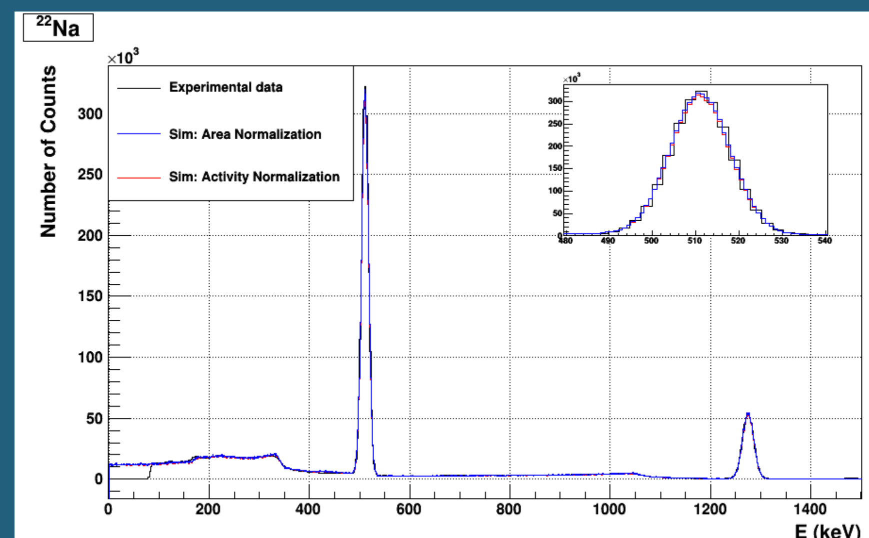
On-going work…

Mechanical Drawings: J.-S. Stutzmann & B. Madiot

The (NA)^{2}STARS project

- R&D on-going also on DSSSD det.
- Electronics & DAQs, @ GANIL and Subatech (S. Bouvier, H. Guérin, B. Rebeiro, J.-C. Thomas et al.)
- Individual module tests by CIEMAT and IFIC, design based on design studies performed for DESPEC TAS (DTAS)





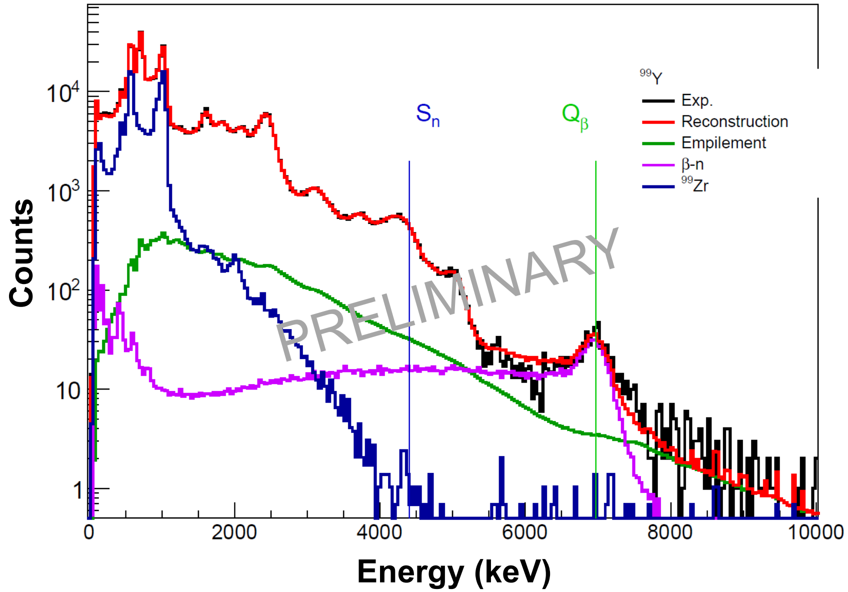
Neutrinos ucture and
Astrophysics pectroscopy:

Kick-Off (NA)^{2}STARS Meeting
Subatech

First in-person meeting in Dec. 2024 @ Subatech - Nantes

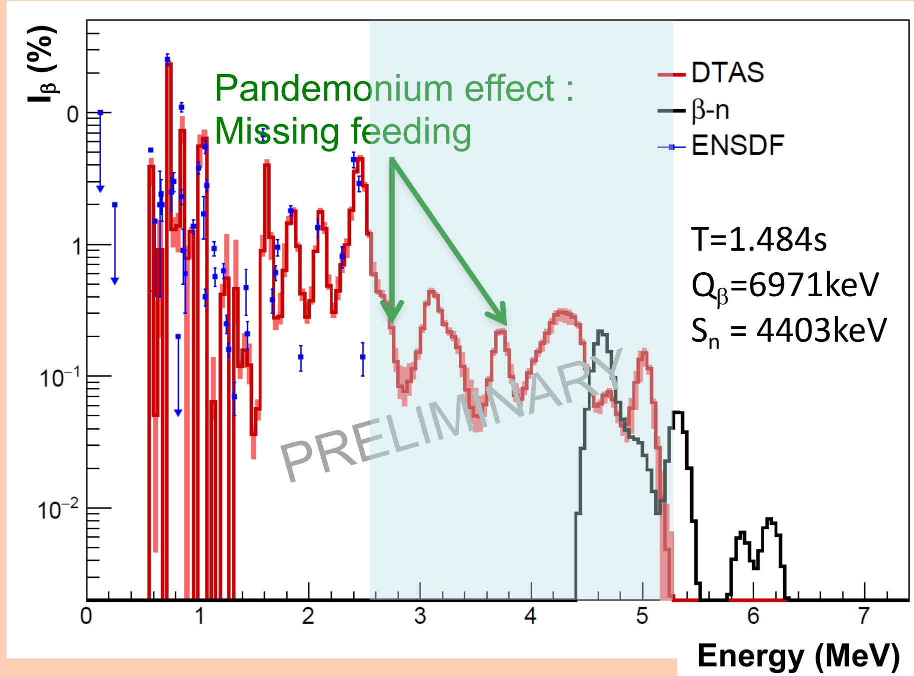
Recent Results of TAGS experimental campaign at IGISOL

The Case of ^{99}Y



- β–γ coincidences
- $T_{1/2}$ = 1.484s, Q-value: 6971(12) keV
- Contaminants : daughter, pile-up, β-n branch
- $^{99}Y \to {}^{99}Zr$ GS to GS feeding 0%
- Assume Pn value given in ENSDF: 1.77(19)%.

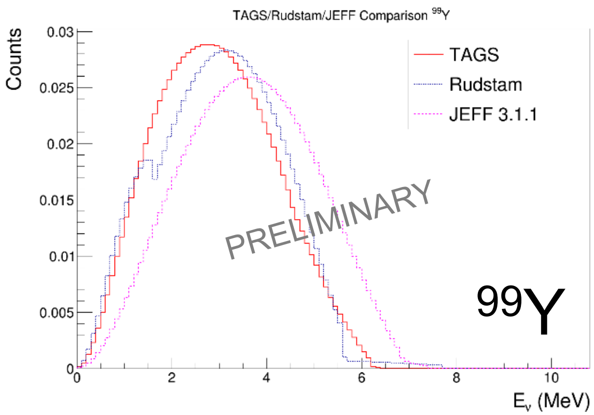
- Physics Motivations for their measurement:
  - Nuclear Structure: ^{99}Y known to be strongly deformed (β2 0.4 + in a region (N=60) of large shape dis- continuity in the Ytrium isotopes
  - Antineutrino spectra: priority 1

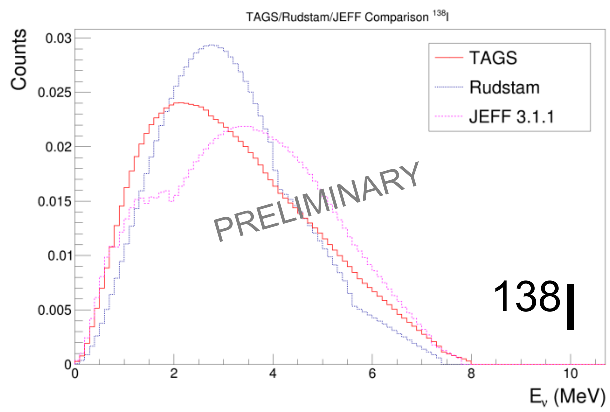


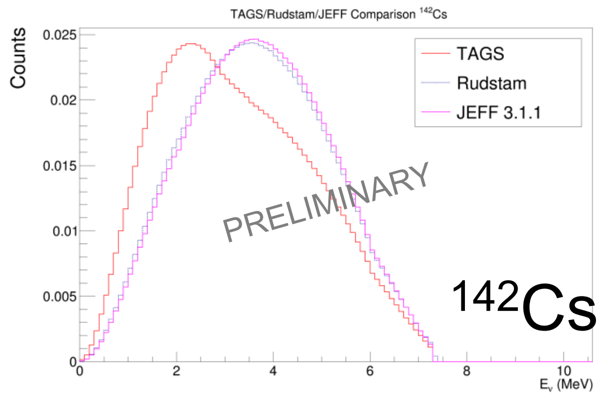
PhD Thesis work:
Loïc Le Meur (Subatech, Nantes)
Publication in preparation

Individual Anti-ν Energy Spectra: ^{99}Y, ^{138}I and ^{142}Cs

- Comparison of the individual antineutrino energy spectra between DTAS and the preferred nuclear database that was used for our previous calculation (Rudstam).
  - Rudstam β spectra converted
  - Non pandemonium free data in JEFF 3.1.1
  - Shift vs low energy in TAS: apparent biases in Rudstam measurement and large error bars
  - Impact the total antineutrino spectrum







PhD Thesis work:
Loïc Le Meur (Subatech, Nantes)
Publication in preparation

Decay	$\overline{E}$	DTAS [keV]	JEFF [keV]	ENDF [keV]
^{142}Cs	γ	1526.3^{+83}_{-54}	676.48	952.37
	β	2535.0^{+25}_{-39}	2919(178)	2919(179)
^{99}Y	γ	1584^{+46}_{-31}	917	1006
	β	2379^{+15}_{-22}	2949(146)	2931(208)
^{138}I	γ	2005^{+106}_{-99}	1325	1420
	β	2475^{+64}_{-33}	2721(125)	3068(290)

Summation Method - 2025

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

Our TAS data set, 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

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

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

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

- Taking into consideration: **the latest published TAS data = 15+7 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

Summation Method - 2025

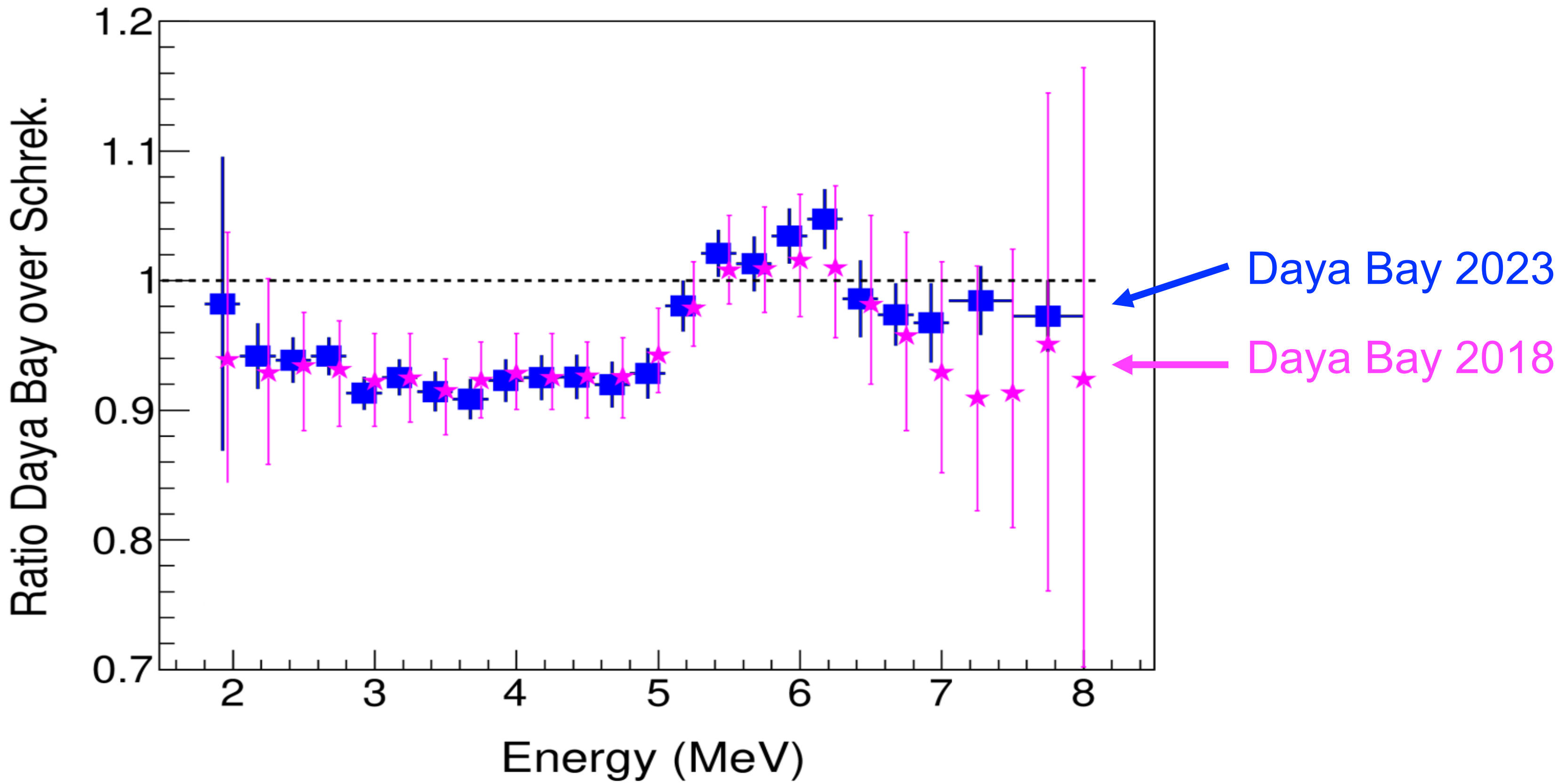
- Ingredients of our model core calculation: :
  - 1keV energy bins
  - Collaboration with L. Hayen: Screening corrections: Rose replaced by Salvat (**L. Hayen, N. Severijns et al. Rev. Mod. Phys. 90, 015008 (2018)**)
  - Nubase 2020 for Q_β approximation
  - 65 nuclei from Rudstam / Tengblad et al. (elimination of those in agreement with JEFF/ENDFB8, and a few « odd » ones)

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

- 2014 TAGS campaign: quantification of the impact of 7 new nuclei (see A. Algora's presentation):
  - ^{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

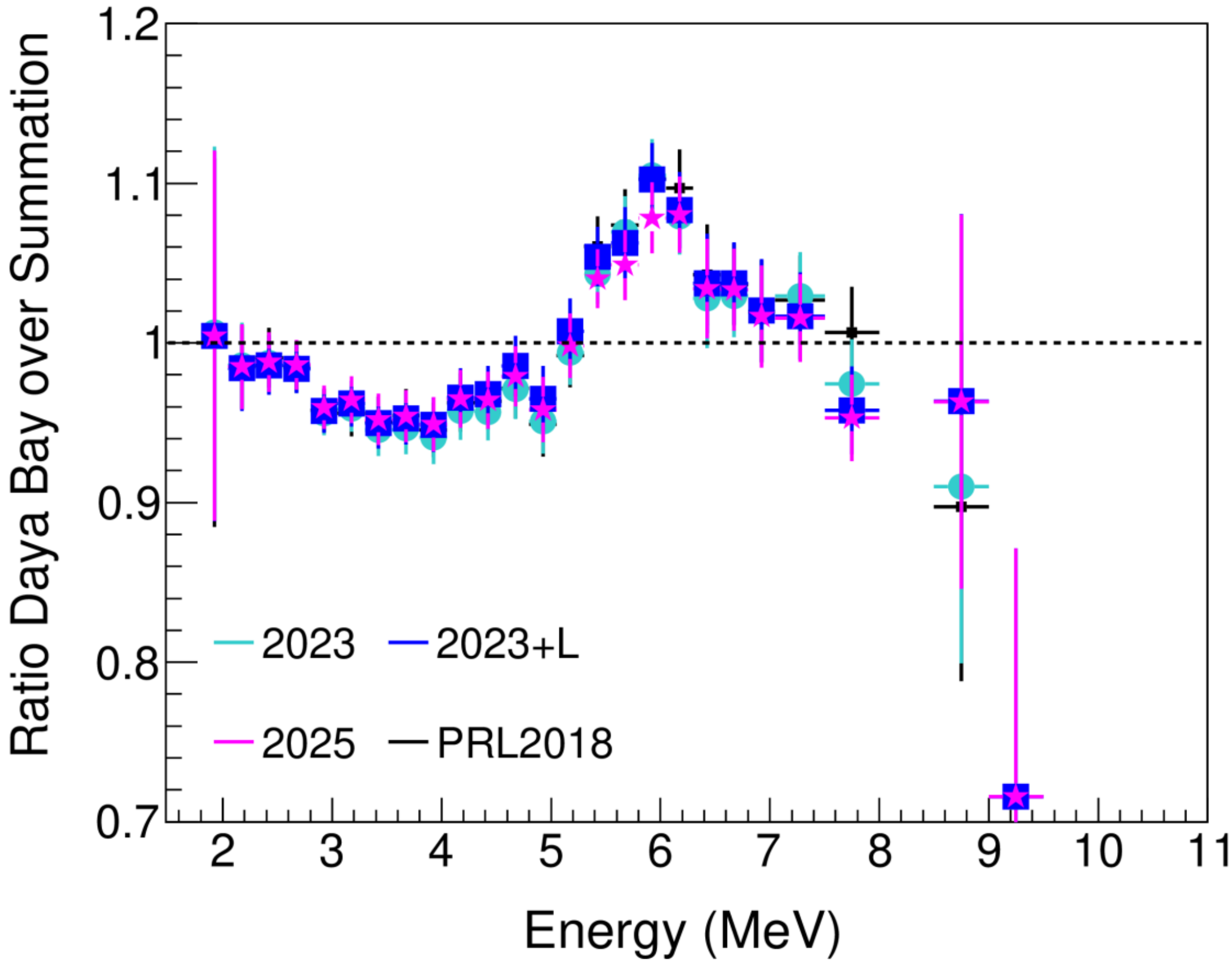
Daya Bay Spectrum 2023

- Ratio Daya Bay Spectrum 2023 over HM



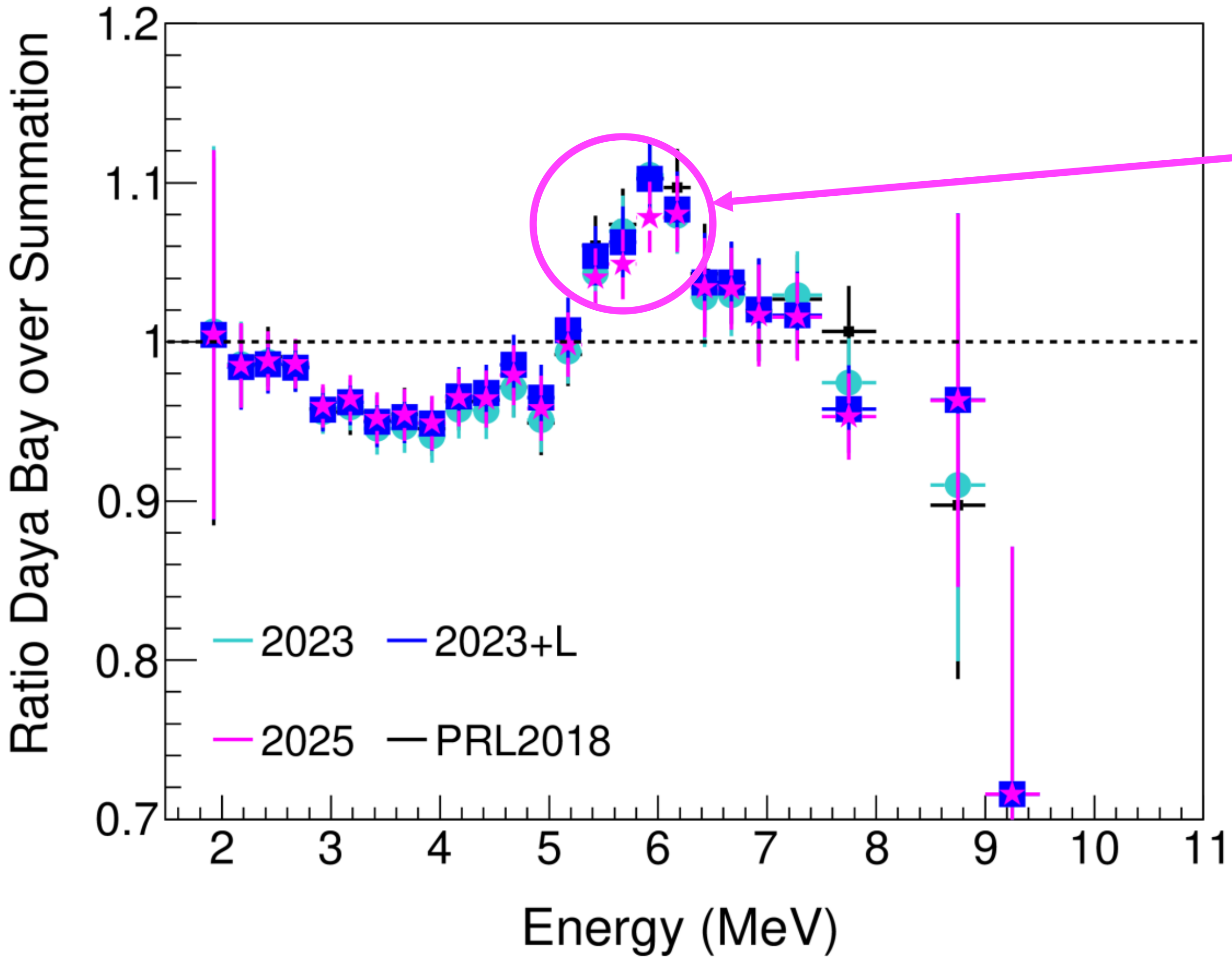
Summation Method - 2025

- Ratio Daya Bay Spectrum 2023 over SM25



Summation Method - 2025

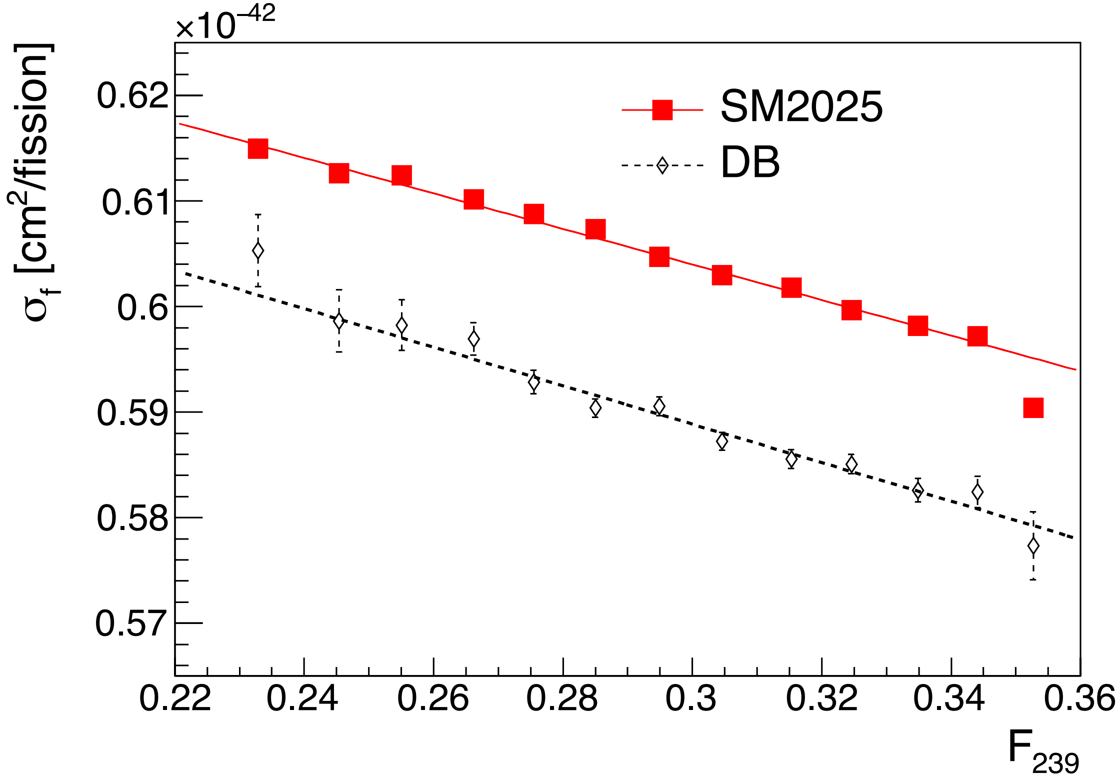
- Ratio Daya Bay Spectrum 2023 over SM25



Erosion of the bump: -2% on 4 points, without moving the low energy part (not just global shift downward)

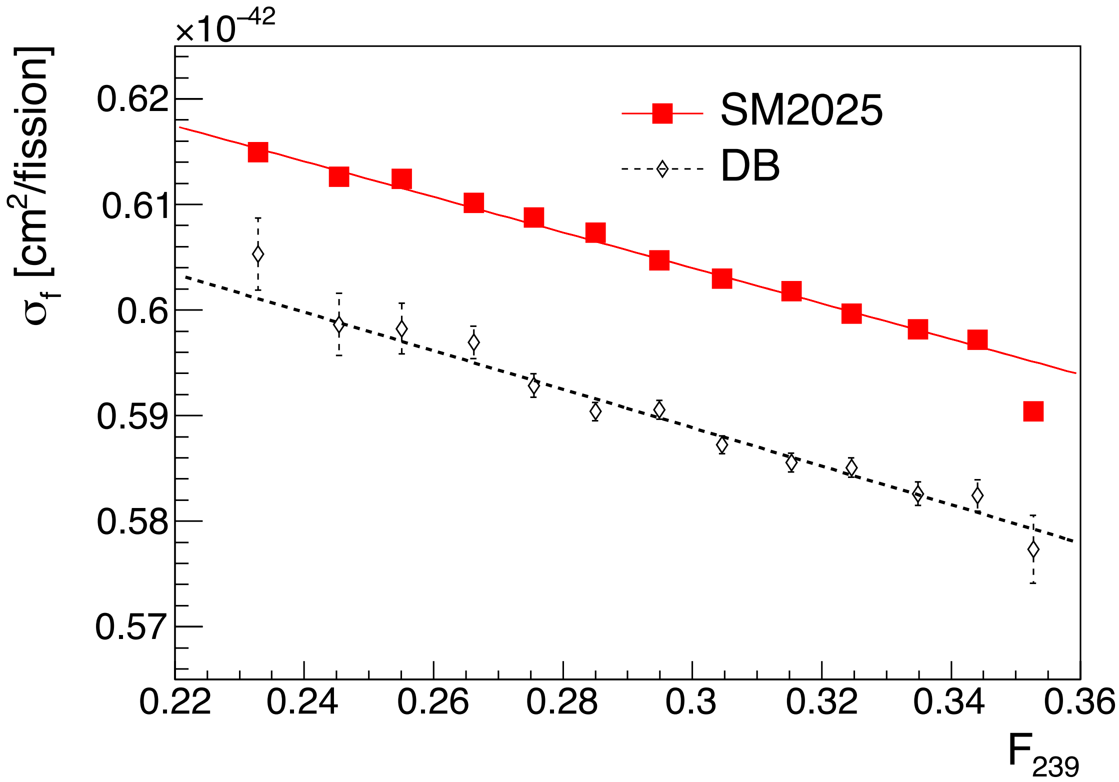
Summation Method - 2025

- Ratio Daya Bay 2023 IBD flux vs SM25



Summation Method - 2025

Ratio Daya Bay 2023 IBD flux vs SM25



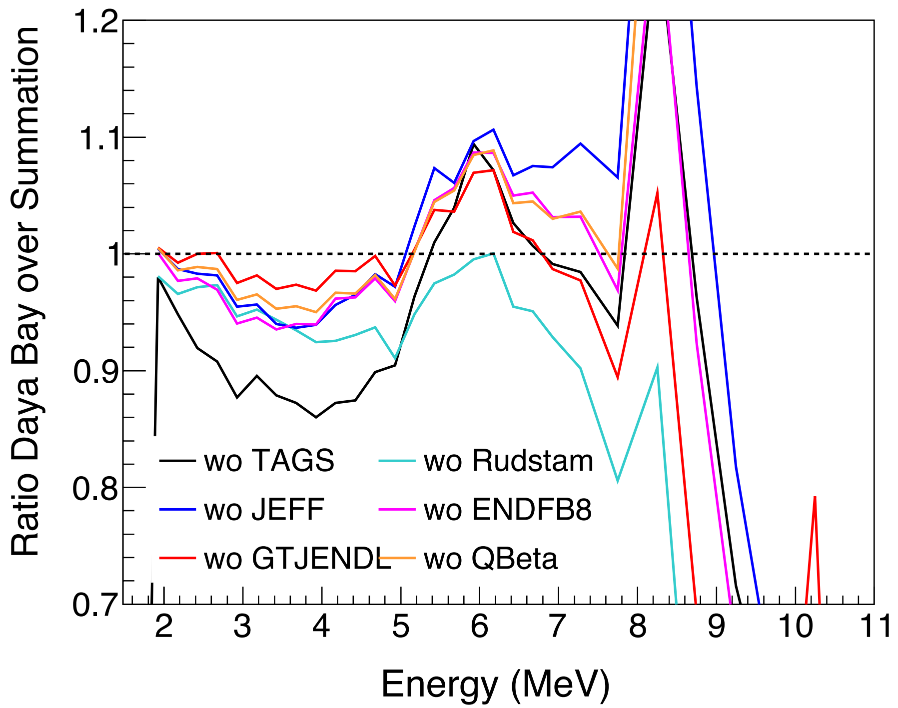
- SM25 is 2.5% above DB2023:

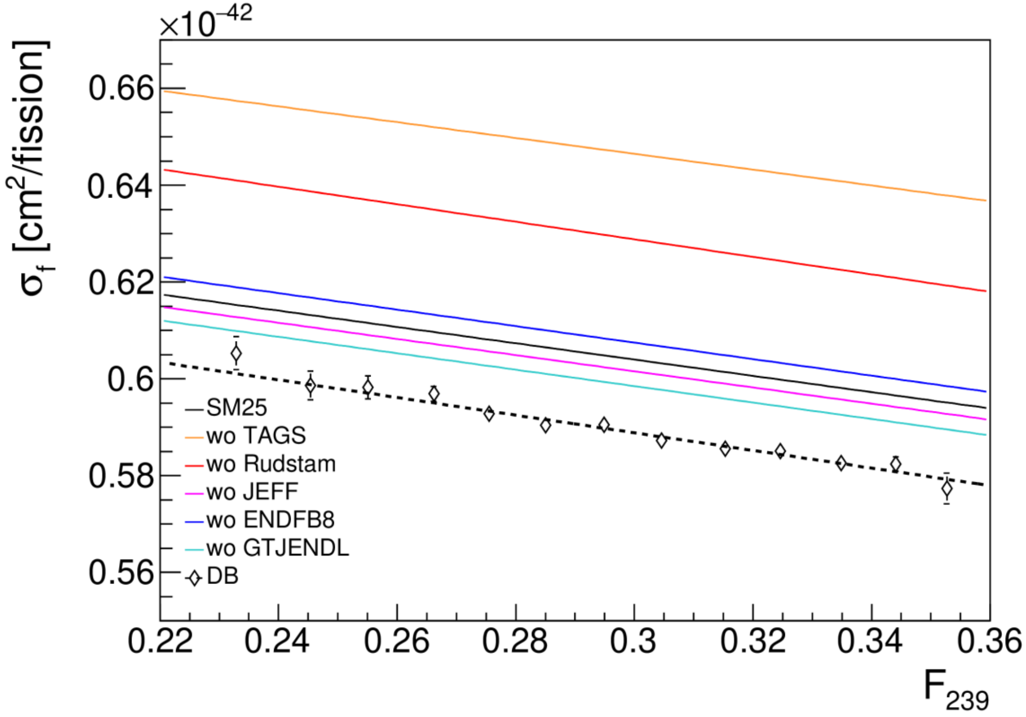
- +0.25% increase due to update of the model
- -0.6% due to ^{142}Cs, ^{138}I and ^{99}Y
- +0.25% due to $^{96,\,96m}Y$, ^{137}I and ^{95}Rb
- +0.25% due to new Daya Bay points

- Pandemonium correction still decreases the discrepancy but some nuclei are corrected from other systematic effect (i.e. w.r.t. Rudstam or new data for isomer)

Summation Method - 2025

Impact of the DDB ingredients:





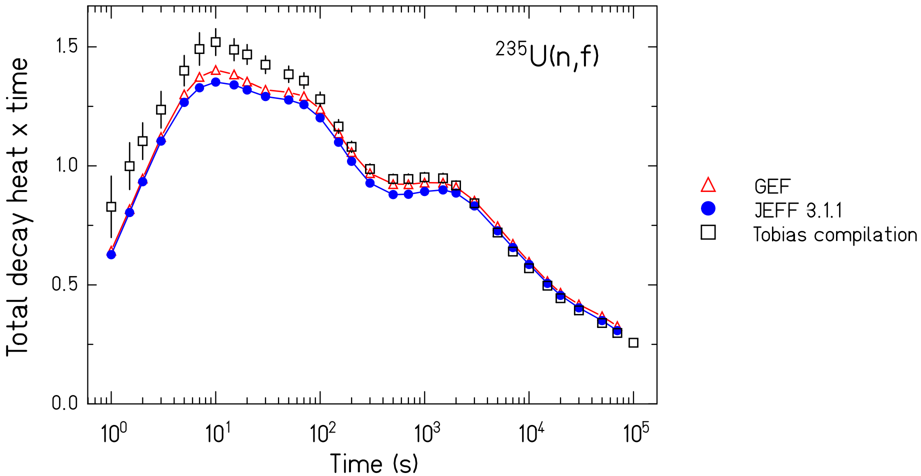
Uncertainties

Antineutrinos & 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:

Decay heat



K.-H. Schmidt et al. Nuclear Data Sheets 131 (2016) 107–221

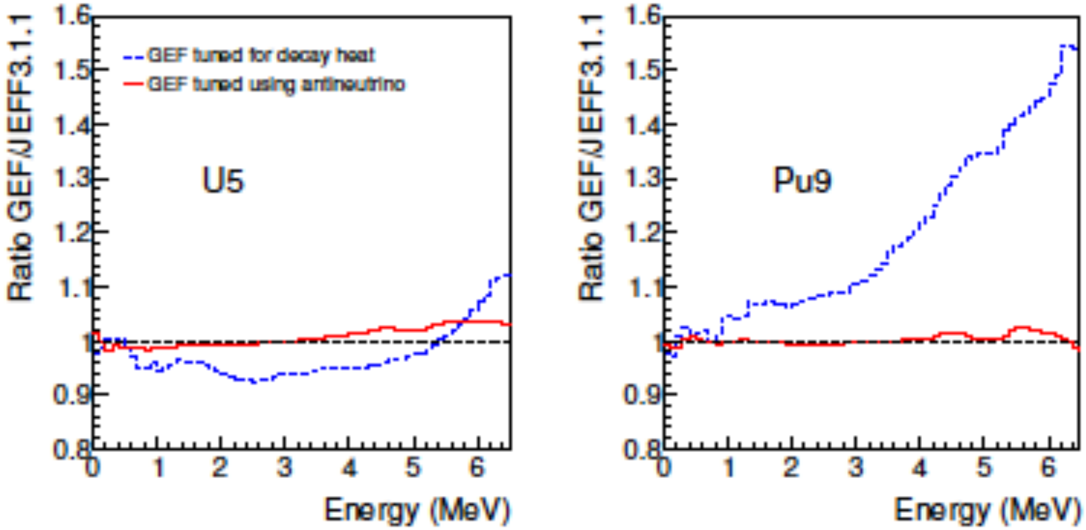
- Starting with the GEF code that obtained very good results for decay heat calculations

Antineutrinos & 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:

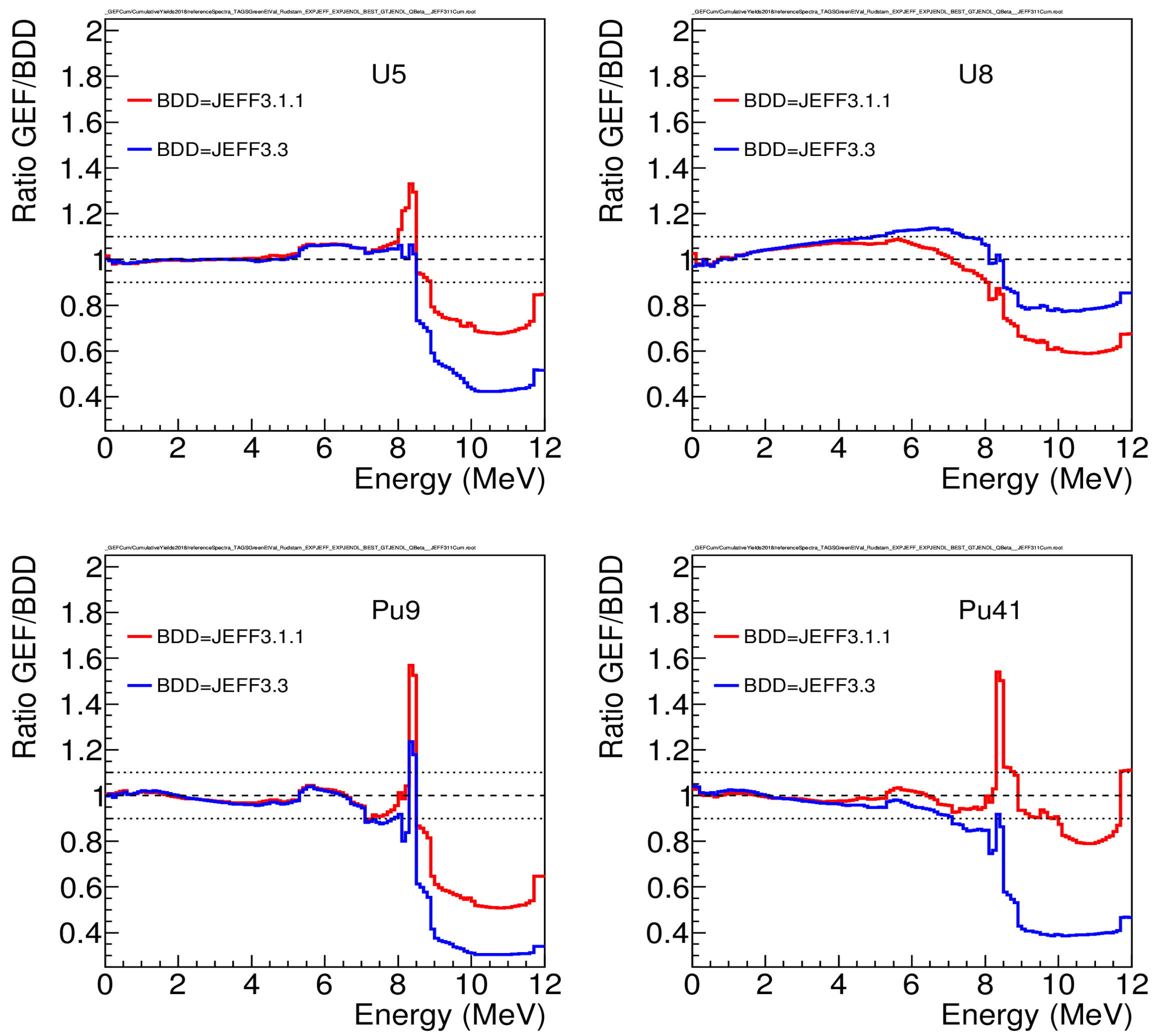
For the first time a careful analysis and a systematic comparison of data from different sources and evaluations with GEF have been performed to sort out the more reliable and the less trustworthy values ;



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

K.-H.Schmidt, et al., Nuclear Data Sheets Volume 173, (2021),

Antineutrinos & the GEF Code

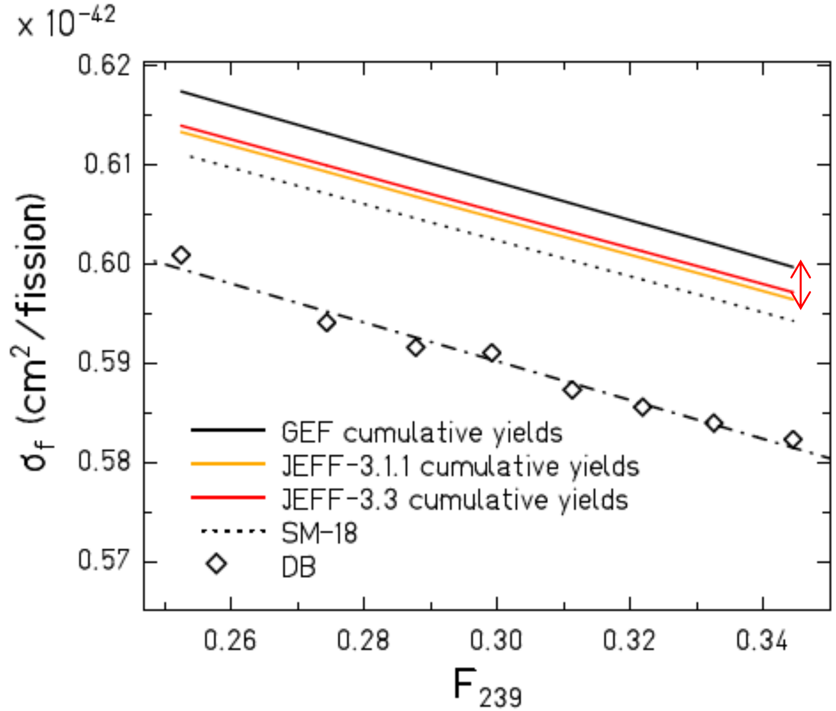


Different isomeric ratios btw GEF and JEFF are partly responsible for the large deviation at high energy. But also btw JEFF3.1.1 and JEFF3.3 !

K.-H.Schmidt, et al., Nuclear Data Sheets Volume 173, (2021),

Antineutrinos & the GEF Code

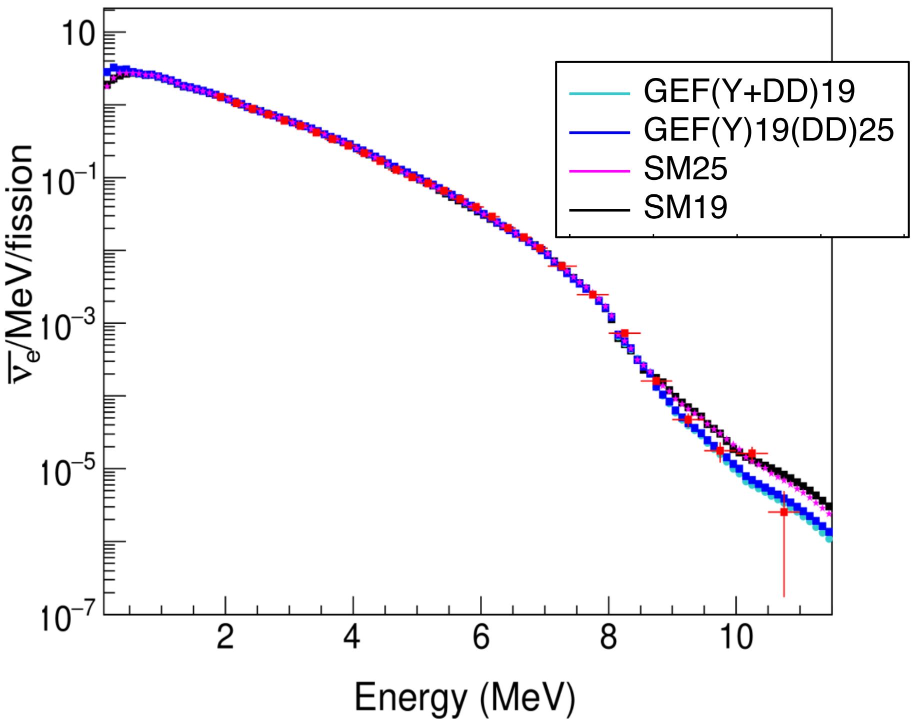
- **Collaboration with K.-H. Schmidt** (author of GEF with B. Jurado) for several years with the purpose to use the GEF FY with their uncertainties. First results are:
  - ➢ a new version of the GEF code improved thanks to the antineutrino spectral studies
  - ➢ an assessment of the experimentally available 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

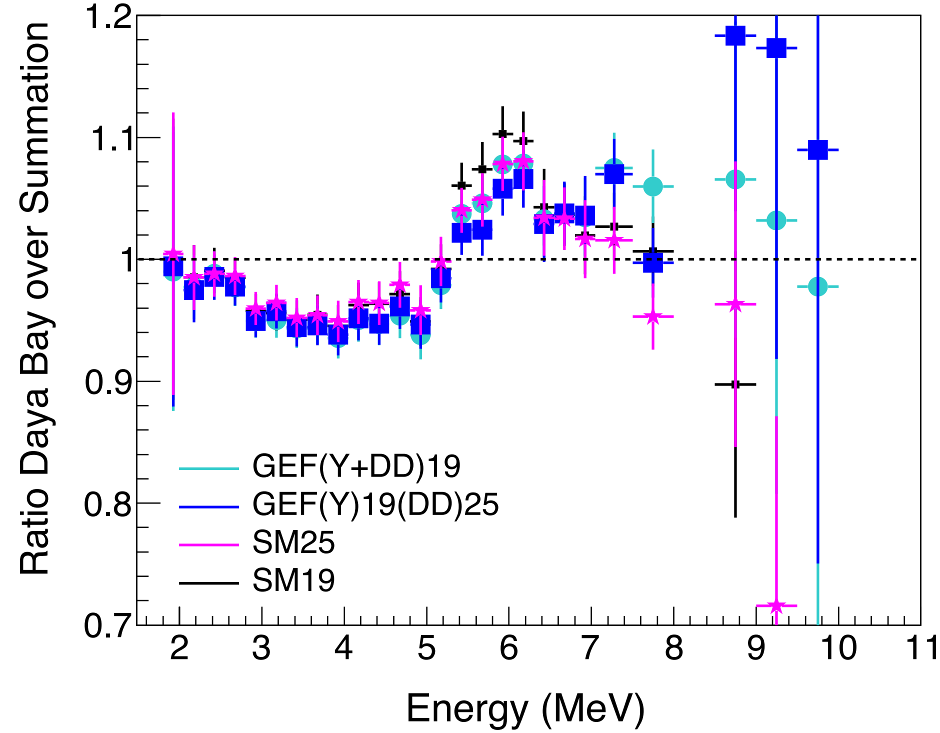


↕ : impact of off-equilibrium effects w.r.t cumulative FY: 0.5%

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

SM with GEF





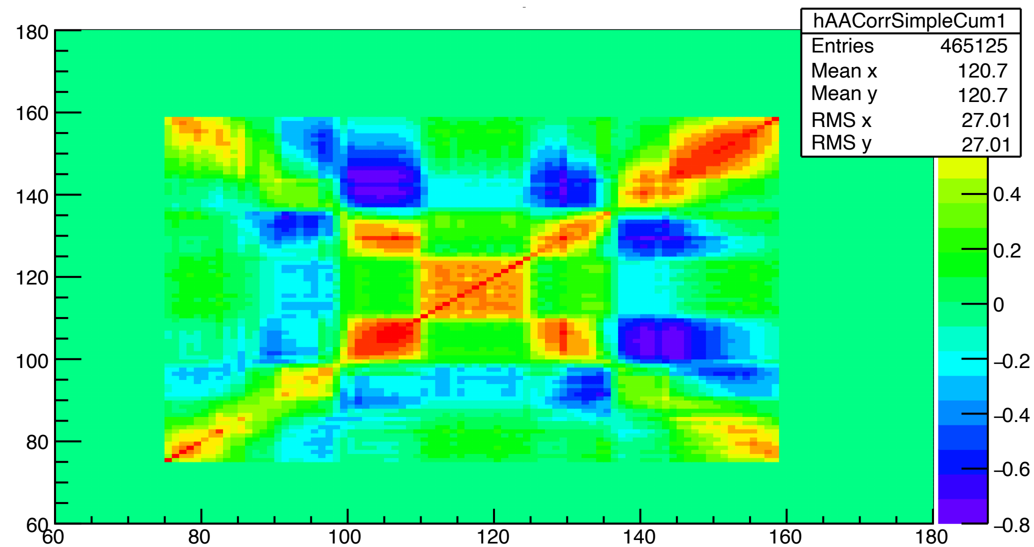
Different isomeric ratios btw GEF and JEFF: large deviation at high energy

⇒ **GEF yields do better at high energy with the Daya Bay points**

GEF Correlations btw cumulative yields

- The GEF version optimized with antineutrino spectra achieves an excellent agreement with the SM based on JEFF yields for a model
- We consider it as **representative enough to be able to compute the flux and spectrum with their associated uncertainties thanks to GEF covariance matrices in a consistent way**
- The uncertainties of the calculated fission quantities are determined by their fluctuations in a large number of calculations with different sets of perturbed parameters.

- Examples of GEF yields and associated uncertainties:
  - ^{92}Rb: 0.043714 +- 4%
  - ^{96}Y: 0.04656 +- 3.3%
  - ^{96m}Y: 0.011347+- 21%
  - ^{104}Nb: 0.7393187 +- 23.5%
  - ^{104m}Nb: 0.02308596 +- 50%



Propagation of Yield Uncertainties

- Using the (improved) GEF covariance matrices
- Analytical error propagation
- **Study of the dependence on beta decay uncertainties which are underestimated in nuclear DDB in many cases: assuming 4 uncertainties, all the same for all nuclei: 5, 10, 15, 20%**

Δ_{DD} = 5%	**Δ_{DD} = 10%**	**Δ_{DD} = 15%**	**Δ_{DD} = 20%**
$\Delta\sigma_f$ = +-1.00%	**$\Delta\sigma_f$ = +-1.33%**	**$\Delta\sigma_f$ = +-1.70%**	**$\Delta\sigma_f$ = +-2.2%**

- **Note that this calculation was performed a long time ago…**
  - Yields are very correlated
  - Final uncertainty is quite small, even when assuming 20% on all decay data

⇒ **On-Going work, preliminary**

⇒ **Truth is some BDD should have less than 20% and some more (100%)**

Conclusions & Perspectives

- The theoretical and experimental studies of β decays are important for several domains of physics including decay heat and antineutrinos from reactors and nucleosynthesis
- β–intensity can be obtained through γ-ray spectroscopy and electron shape measurements
- New TAGS results: publications in preparation + See other results in Alejandro Algora's talk
- TAGS Data Analysis on-going on the newly available data: Julien Pépin's co-directed PhD (IFIC – Subatech) and Soumen Nandi's postdoc (Subatech).
- e-Shape Detector built and operated, Data Analysis on-going,
  - A. Beloeuvre's PhD thesis defended October 2023.
  - G. Alcala's PhD thesis in Valencia defended October 2024
  - New PhD started in Oct. 2024 at Subatech Samuel Durand
  - New Postdoc started at IFIC 2025 Gustavo Alcala

  ⇒ See first results in Alejandro Algora's talk
- $(NA)^2$STARS upgrade of the ROCINANTE & DTAS: detector is being developed, MC simulations, mechanical simulations, & laboratory tests on-going. First commissioning mid-2026 at GANIL.
- Update of the Summation Methode SM18 => SM25 with new TAGS data, comparison to all published reactor neutrino spectra + uncertainty calculation: on-going work

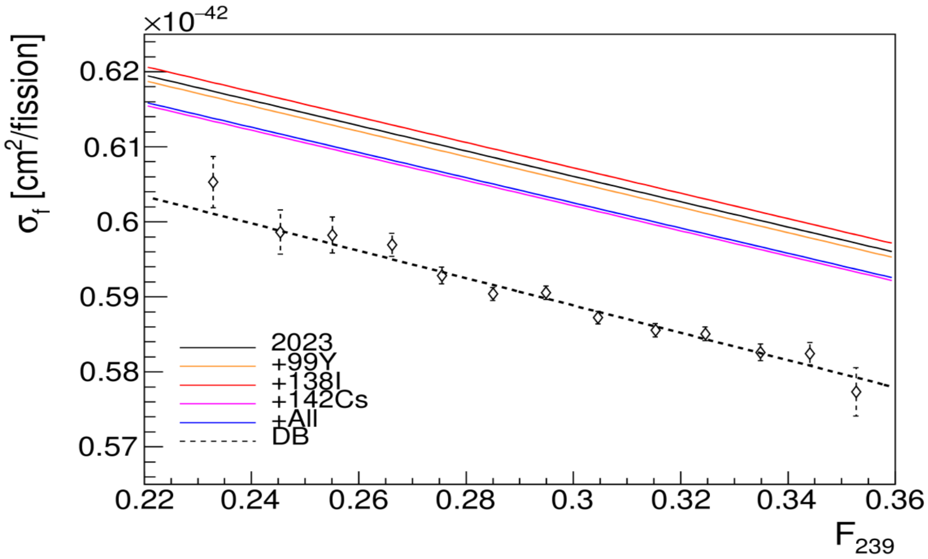
E-Shape & TAGS COLLABORATION

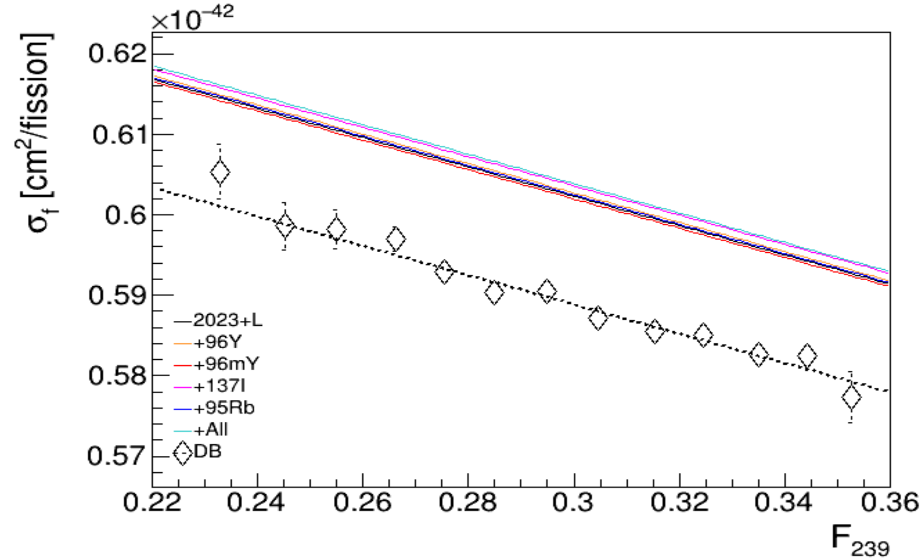
IFIC Valencia: A. Algora, B. Rubio, J.A. Ros, J.L. Tain, E. Valencia, A.M. Piza, S. Orrigo, M.D. Jordan, J. Agramunt
SUBATECH Nantes: E. Bonnet, S. Bouvier, S. Durand, M. Estienne, M. Fallot, S. Nandi, J. Pépin, A. Porta, J.-S. Stutzmann
U. Surrey: W. Gelletly
IGISOL Jyväskylä: H. Penttilä, Äystö, T. Eronen, A. Kankainen, V. Eloma, J. Hakala, A. Jokinen, I. Moore, J. Rissanen, C. Weber
CIEMAT Madrid: D. Cano, T. Martinez, L.M. Fraile, V. Vedia, E. Nacher
IJCLab: M. Lebois, J. Wilson
BNL New-York: A. Sonzogni
Istanbul Univ.: E. Ganioglu
GANIL: B. Rebeiro, J.-C. Thomas

Special thanks to my close collaborators from Subatech who were (and are stil!) involved in the instrumental developments for the recent experimental campaigns or new projects making them possible

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

Thank you!


×10^-42
σ_f [cm²/fission]
0.62
0.61
0.6
0.59
0.58
0.57
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
F_239
2023
+99Y
+138I
+142Cs
+All
DB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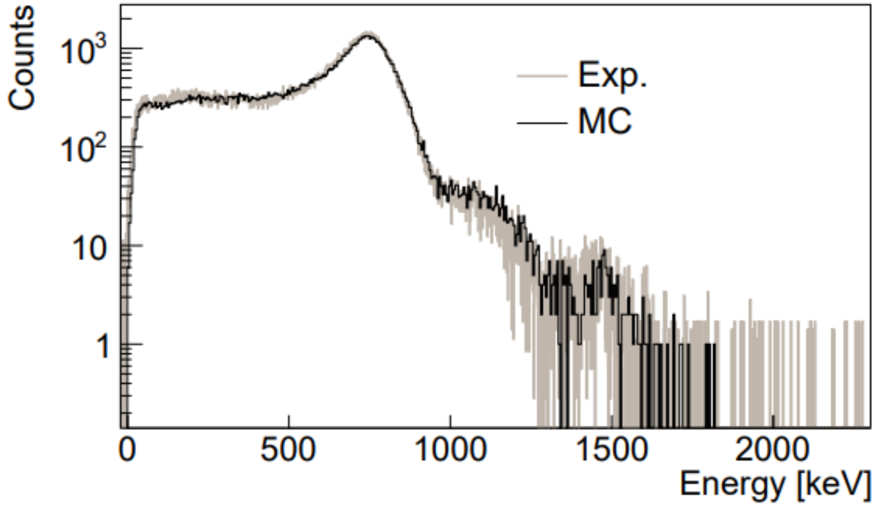
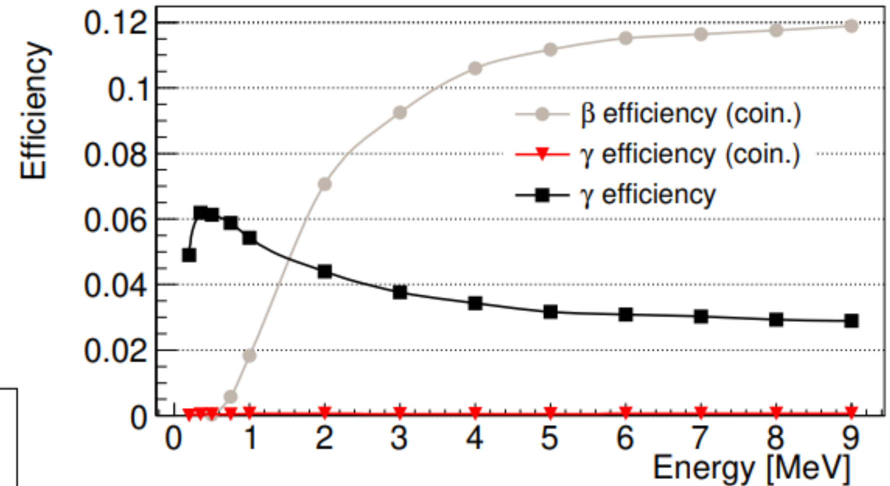
0.32
0.34
0.36
F_239
2023+L
+96Y
+96mY
+137I
+95Rb
+All
DB

The e-Shape experiment: Detection principle

- **Detection principle:**
  - ❑ ΔE-E system provides very high gamma rejection efficiency
  - ❑ 12% efficiency for β measurements using coincidences



MC reproduction of the ^{207}Bi source at the lab. Plastic detector in coincidence with the silicon detector

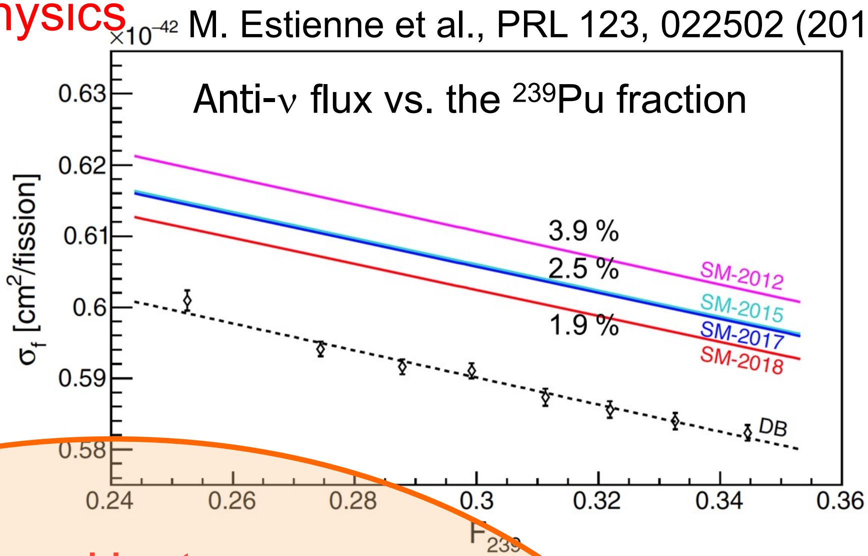


- **First commissioning @ex-CENBG Bordeaux, March 2019.**
  - ❑ Monoenergetic electron sources
  - ❑ Detector Paper arXiv:2305.13832 V. Guadilla et al. 2024 JINST 19 P02027

TAGS @IGISOL Jyväskylä

- Neutrino Physics

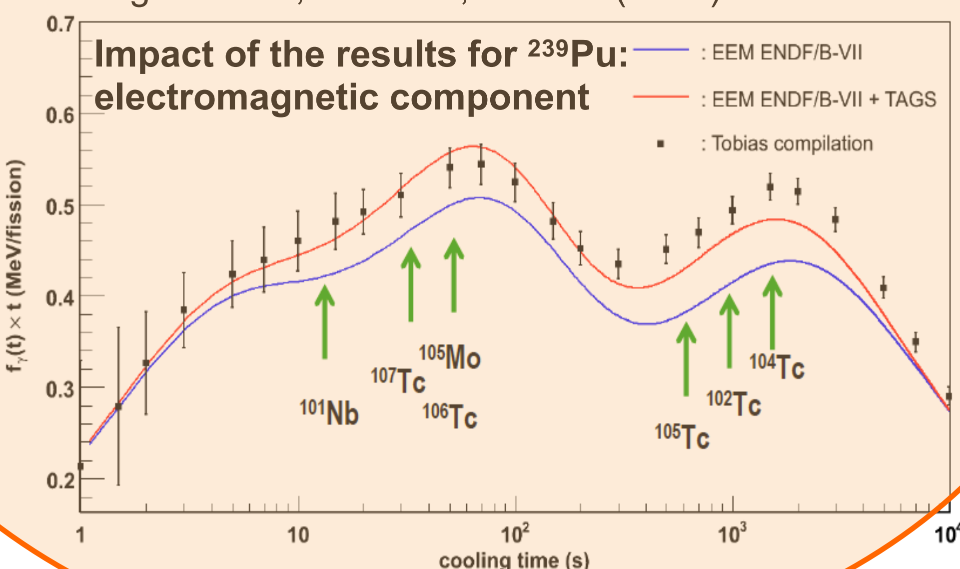
M. Estienne et al., PRL 123, 022502 (2019)



A.Algora et al. PRL 105, 202501 (2010),
M. Fallot et al. PRL 109, 202504 (2012)
D. Jordan et al. PRC 87, (2013) 044318
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. PRL 122, (2019) 042502
+ Data vs model in Daya Bay and STEREO recent papers: DB: PRL 130 (2023) 211801, PRL 129 (2022) 041801, STEREO: Nature 613 (2023) 257

- Reactor Decay Heat

A. Nichols et al. Eur. Phys. J. A (2023) **59**: 78
Algora *et al.*, PRL 105, 202501 (2010).



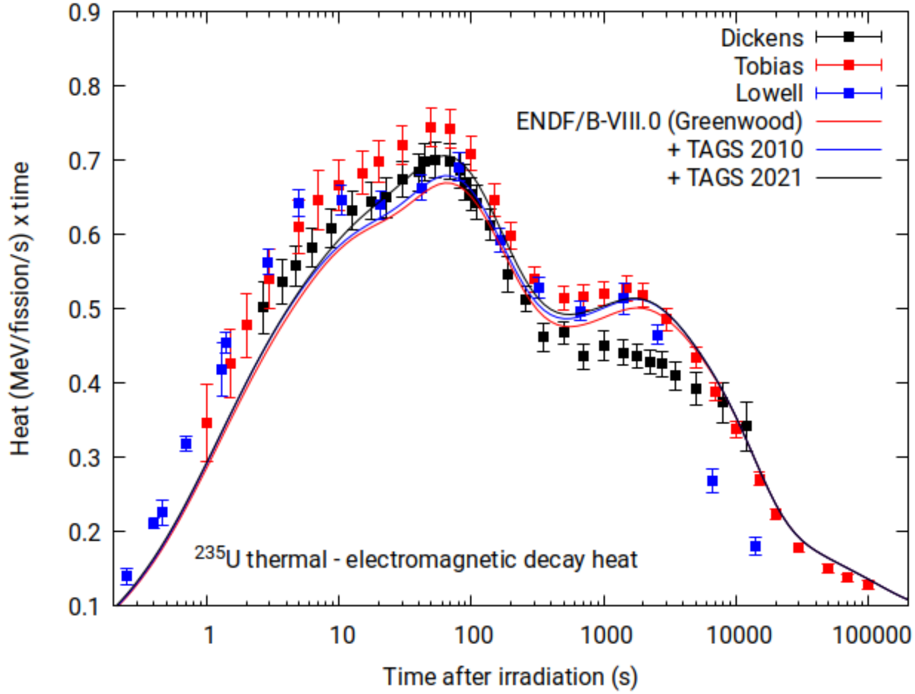
- R-process & γ/n competition above Sn

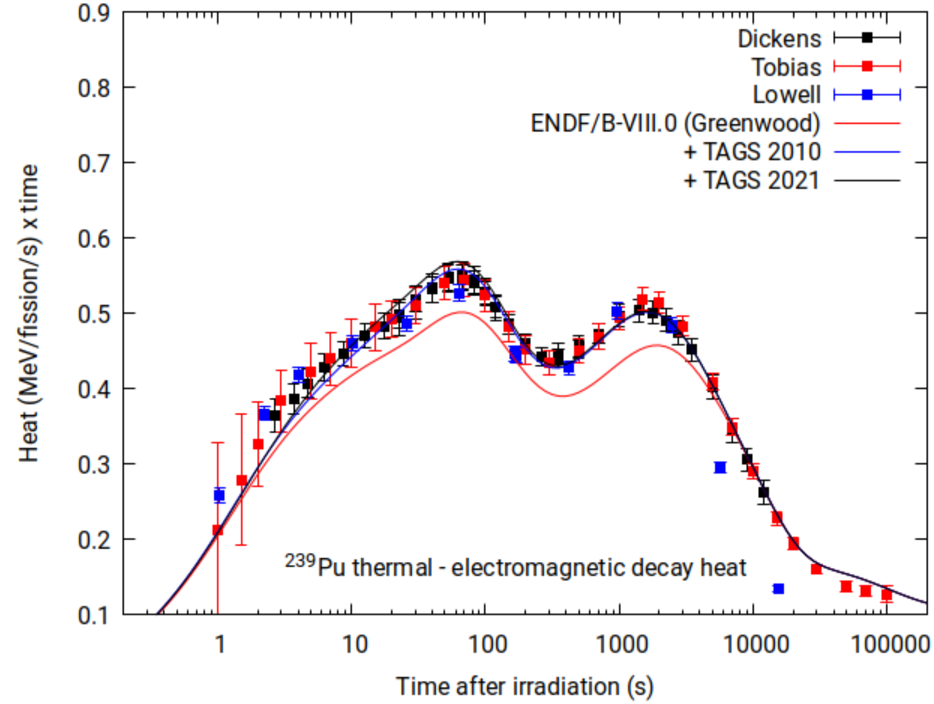
Isotope	$P_\gamma(TAGS)$	P_n
^{87}Br	$3.50^{+0.49}_{-0.40}$	2.60(4)
^{88}Br	$1.59^{+0.27}_{-0.22}$	6.4(6)
^{94}Rb	$0.53^{+0.33}_{-0.22}$	10.18(24)
^{95}Rb	$2.92^{+0.97}_{-0.83}$	8.7(3)
^{137}I	$9.25^{+1.84}_{-2.23}$	7.14(23)

J.L. Tain et al., PRL 115, 062502 (2015)
E. Valencia et al., Phys. Rev. C 95, 024320 (2017).
V. Guadilla et al., Phys. Rev. C 100, 044305 (2019)

Impact of TAGS measurements over the decade

- Improving Fission-product Decay Data for Reactor Applications: Part I - Decay Heat , A. Nichols, P. Dimitriou et al. Eur. Phys. J. A (2023) 59: 78



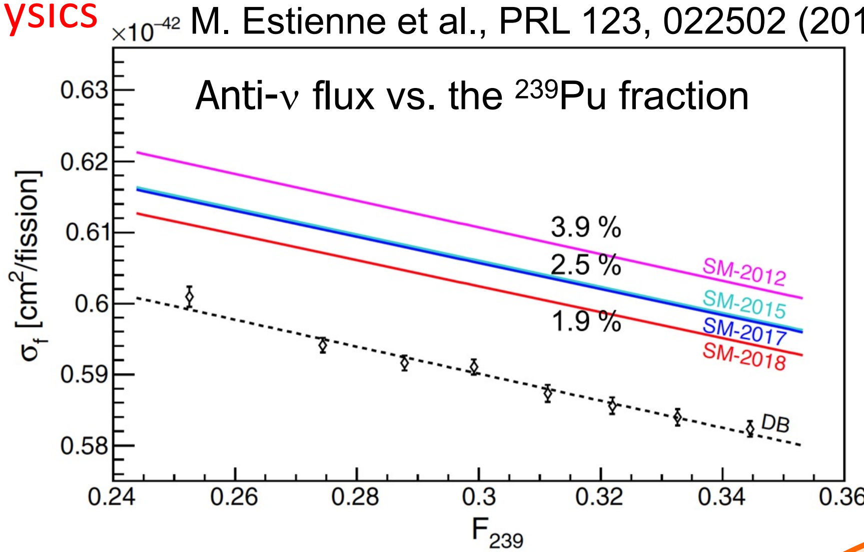


- TAGS 2021 includes decay data with recent measured TAGS data published or communicated before the cut-off date of February 2022: clear impact in ^{235}U thermal electromag DH
- TAGS 1st priority: ^{99}Zr, ^{98,99}Nb, ^{106}Tc, ^{130m,132}Sb, ^{138}Cs, ^{142,143}La

TAGS @IGISOL Jyväskylä in 2009, 2014 and 2022

Neutrino Physics

M. Estienne et al., PRL 123, 022502 (2019)



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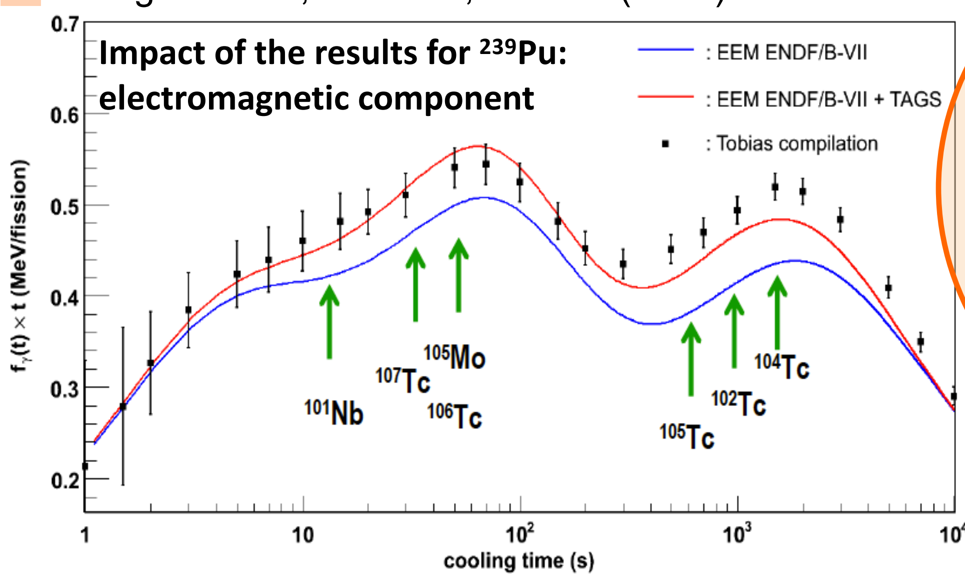

R-process & γ/n competition above Sn

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V. Guadilla et al., Phys. Rev. C 100, 044305 (2019)

Electron Shape Measurements From Forbidden Decays

- Measurement of the θ_{13} oscillation parameter by Double Chooz, Daya Bay, Reno in 2012
  - ❑ Independent evaluation of anti-ν energy spectra using BDNs
  - ❑ 6% deficit in the absolute value of the measured flux compared with the best prediction based on ILL data: reactor anomaly
  - ❑ Numerous projects in search of the existence of sterile neutrinos

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)

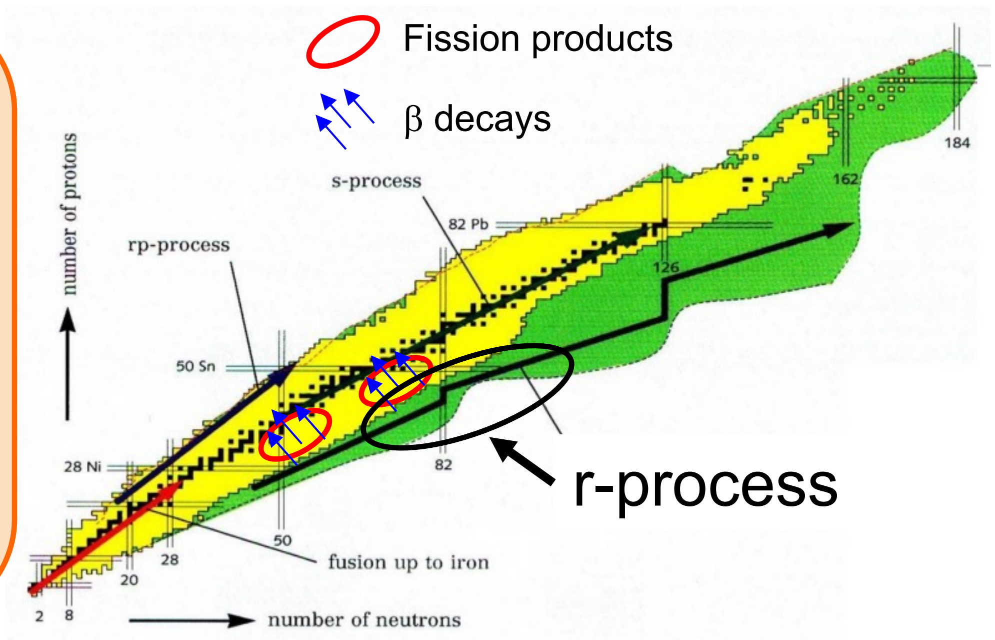
- In 2014, the same three experiments highlighted a spectrum distortion between 4.8-7.3 MeV compared to nuclear models again! (Shape anomaly)

- **Research path put forward: first forbidden β-decays could be responsible for the distortion.**

- Experimental requirement: direct measurement of electron energy spectra of β decays of well-identified fission products (also known as form factors).
  ⇒ e-Shape experiment

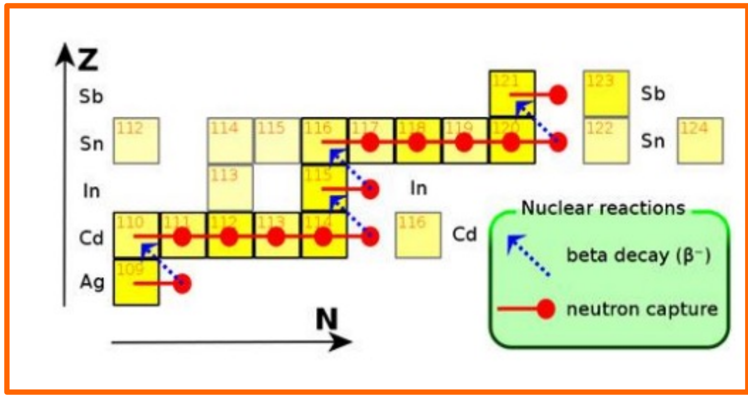
- Theoretical requirement: take these form factors into account in our calculations for summing antineutrino energy spectra.

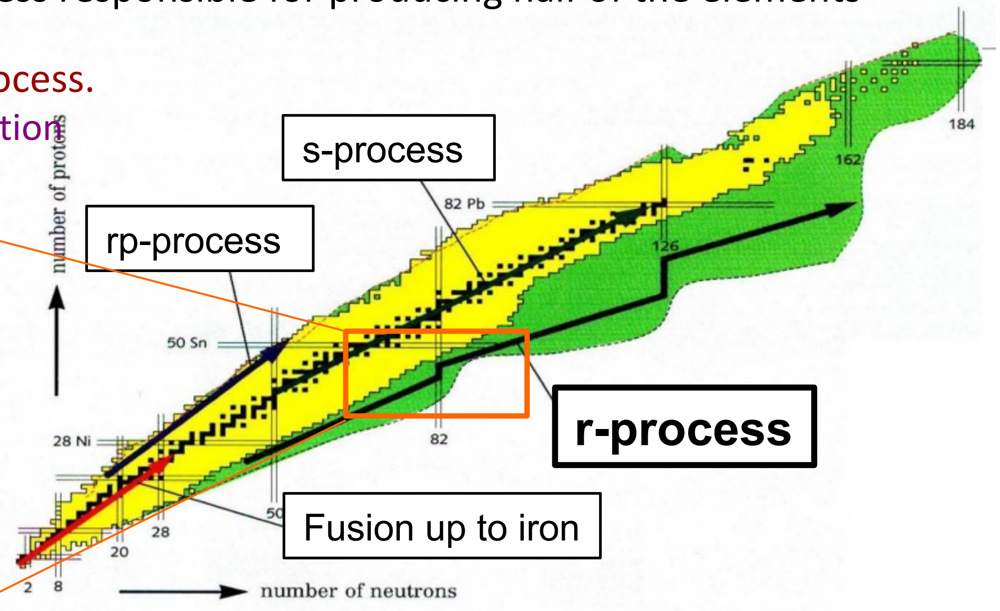
- Still more TAGS data: especially for high energy part & future comparison with Juno-TAO
  ⇒ TAGS experiments



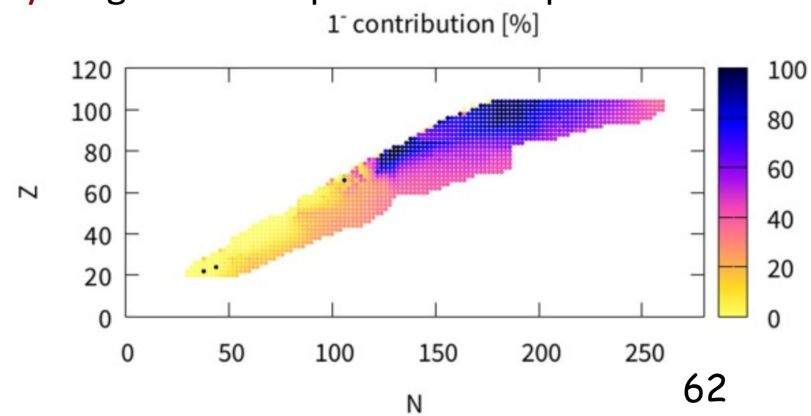
Electron Shape Measurements From Forbidden Decays

- Understanding nucleosynthesis: the r-process responsible for producing half of the elements heavier than iron in the universe
- ß decay plays an important role in the r-process.
  - n-capture (n,γ) and (γ,n) photodisintegration equilibrium and β-decay





- Half-life is an important parameter in r-process models. It represents an integral measure of β-strength.
- First forbidden β decays account for 1⁄3 to ½ of β decays: significant impact on the r-process.



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