Paradise Lost, John Milton (earlier illustrations of the book)

The way to Pandemonium

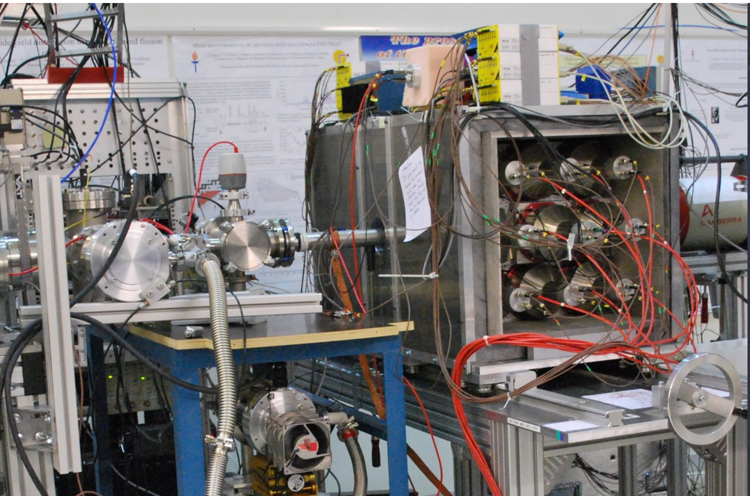
TOTAL ABSORPTION STUDIES FOR REACTOR APPLICATIONS (and beyond): an overview

A. Algora

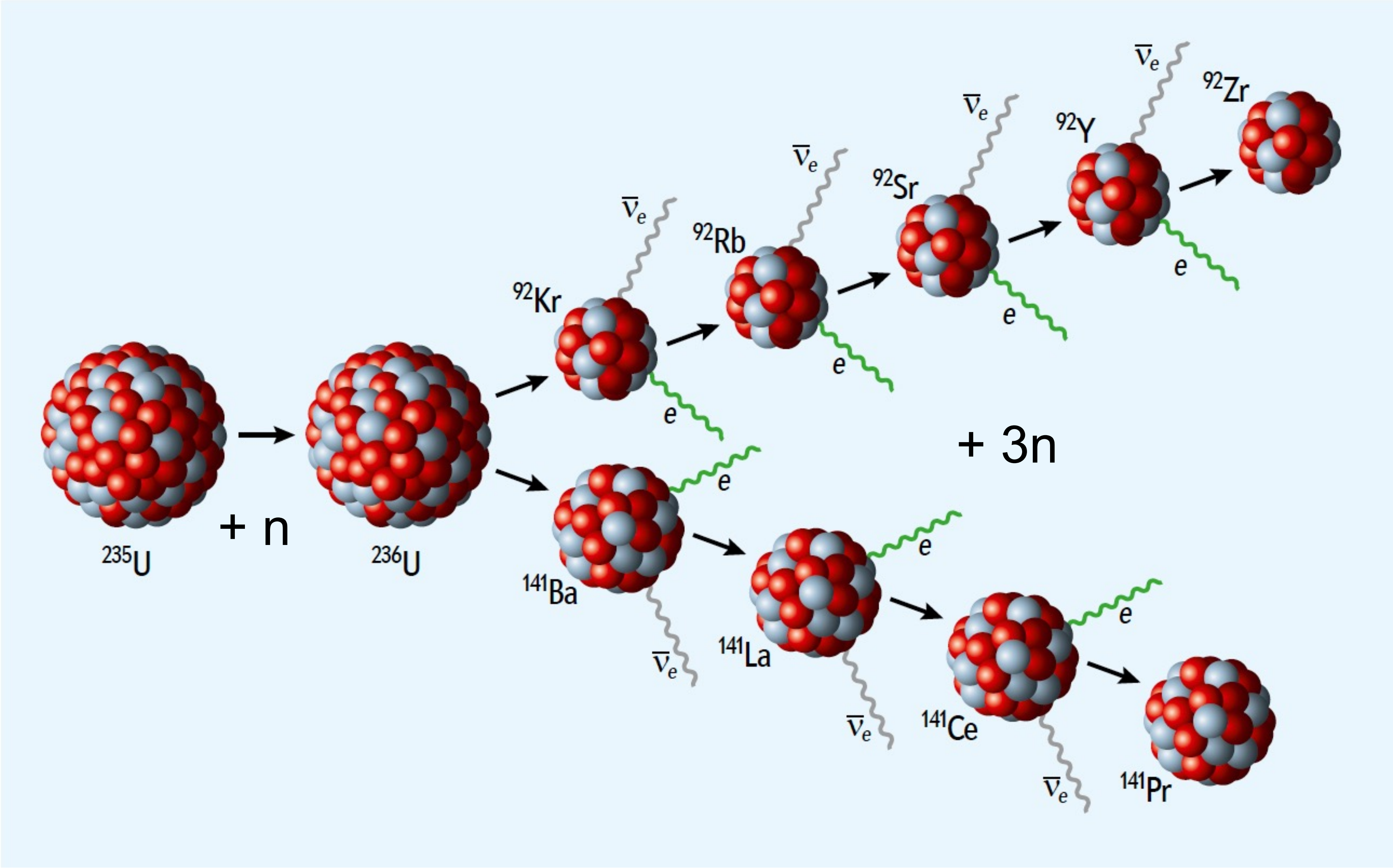
IFIC, CSIC-University of Valencia

and ATOMKI, Debrecen

for the VTAS and DTAS collaborations at JYFL

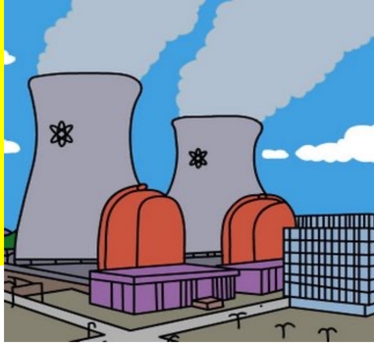


Fission process and beta decay



Every fission is approximately followed by 6 beta decays (sizable amount of energy)
Reactors are the largest (manmade) pacific sources of neutrinos. Produces 2x10^{20} v/s

Decay heat: summation calculations



$$f(t) = \sum_i \boxed{E_i} \lambda_i N_i(t)$$

E_i Decay energy of the nucleus i (gamma, beta or both)

λ_i Decay constant of the nucleus i $\lambda = \frac{\ln(2)}{T_{1/2}}$

N_i Number of nuclei i at the cooling time t

Requirements for the calculations: large databases that contain all the required information (half-lives, mean γ- and β-energies released in the decay, n-capture cross sections, fission yields, this last information is needed to calculate the inventory of nuclides)

How the mean energies are determined ? Measured or deduced (from beta decay studies)

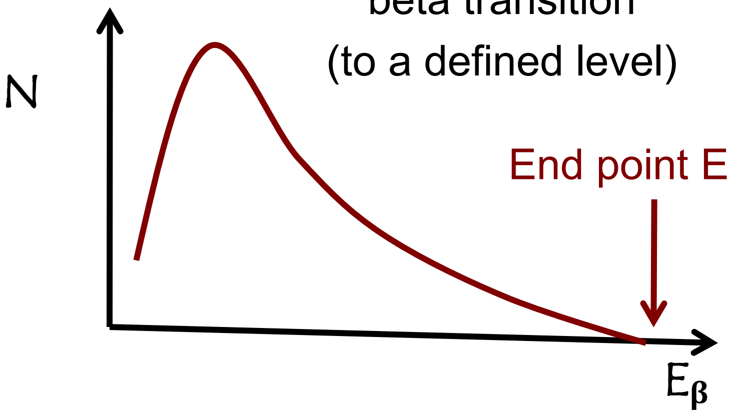
DATA bases:

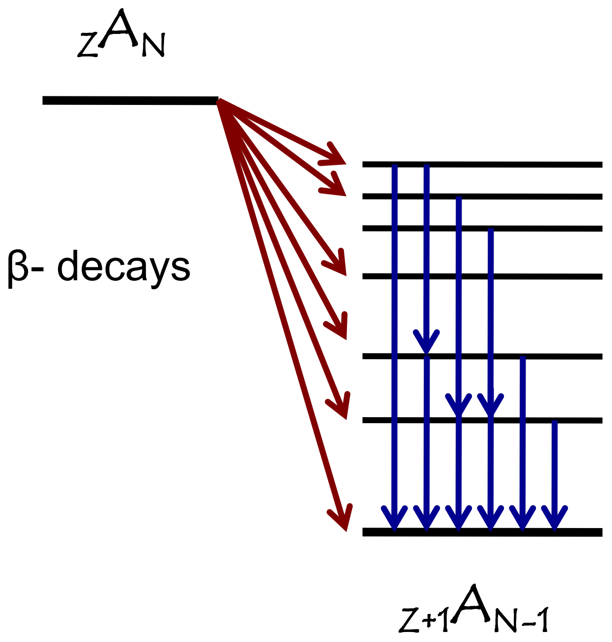
feeding or beta decay prob. distributions

$$f(t)=\sum_i \boxed{E_i}\lambda_i N_i(t)$$

Beta spectrum for a beta transition

(to a defined level)





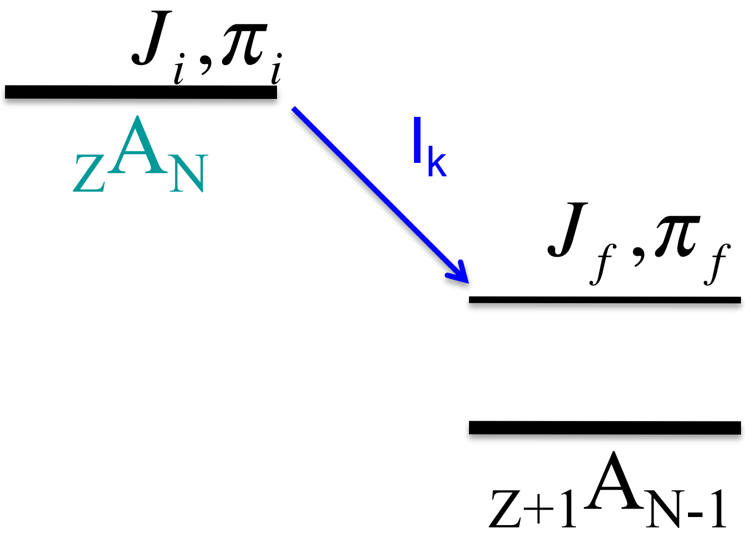
$$\overline{E}_\beta=\sum_i I_\beta(E_i)\langle E_{\beta,i}\rangle$$

$$\overline{E}_\gamma=\sum_i I_\beta(E_i)E_i$$

(Simplified way of calculation)

Neutrino and decay heat summation calculations

Beta decay (β^-)



J_i,π_i

$_{Z}A_{N}$

I_k

J_f,π_f

$_{Z+1}A_{N-1}$

Spectrum for each transition

$$J_i,\pi_i \rightarrow J_f,\pi_f$$

$$S(Q-E_k, J_i\pi_i, J_f\pi_f)$$

Spectrum for the decay (n)

$$S_n(E) = \sum_k I_k S(Q-E_k, J_i\pi_i, J_f\pi_f)$$

Anti-neutrino rate per fission (Vogel, 1981)

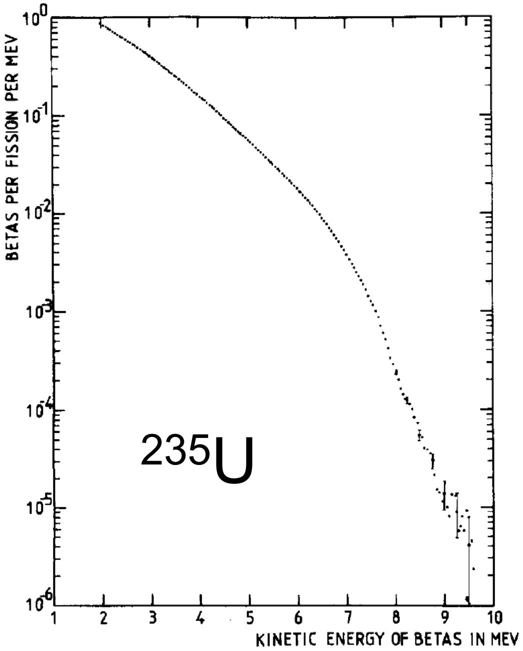
$$S(E) = \sum_n \lambda_n N_n S_n(E)/r = \sum_n CFY_n S_n(E)$$

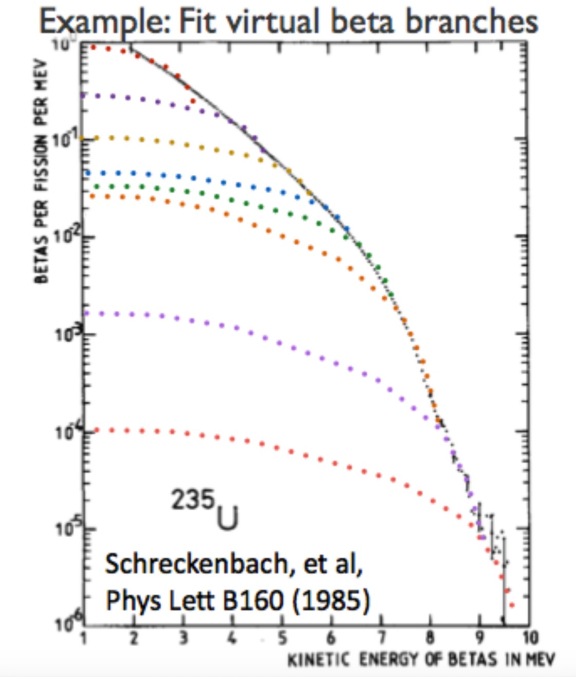
Decay heat summation calculation

$$f(t) = \sum_i E_i \lambda_i N_i(t)$$

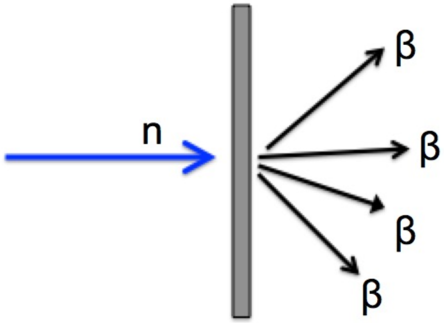
Determination of the primary antineutrino spectrum (1980s): conversion method

- **“Pure conversion procedure**”: using the beta spectrum measured by Schreckenbach et al. from different fissile nuclides (^{235}U,^{239,241}Pu) at ILL and more recently ^{238}U (Haag et al.), which requires complex conversion procedures and assumptions (virtual beta branches, etc.)





Schreckenbach, et al, Phys Lett B160 (1985)



^{235}U,
^{239}Pu,
^{241}Pu

$\sum_i \beta_i$ after fission ⇨ $\sum_i \nu_i$

$$N_\beta(E) = \sum_i a_i \times g_i'\left(E, E_0^{(i)}\right) \times P_i\left[E, E_0^{(i)} \overline{Z}\left(E_0^{(i)}\right)\right]$$

30 hypothetical beta branches,
End point distribution $\left\{a_i, E_0^{(i)}\right\}$, P_i
shapes, $\overline{Z}\left(E_0^{(i)}\right)$, g_i' rad. correction

Modern ways (2011) I:
The Mueller Model, summation + conversion

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

Starting point: based on the ab-initio or summation method, employing an updated database

Summation of all beta branches from all fission products predicted by an evolution code. Estimated uncertainties of the order of 10-20 % because of systematic errors and the incompleteness of the databases.

For the most relevant fisile nuclides 235U, 239Pu, 241Pu they use the measured spectrum of Schreckenbach data to determine the “missing information” from databases. They fit the residuals with a conversion procedure.

The deduced antineutrino spectrum from the fitted beta spectrum shows an increase of 3% in the antineutrino flux

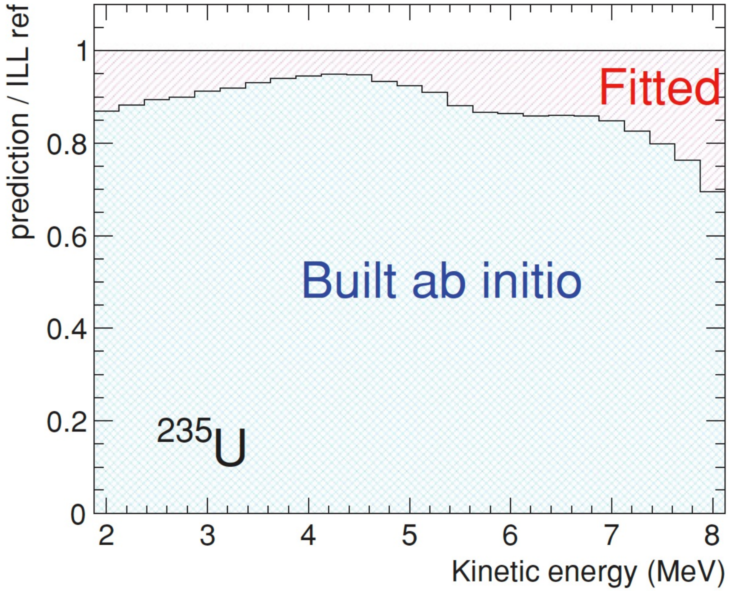


FIG. 5. (Color online) Lower (blue) double hatched area shows the contribution of our *ab initio* prediction (ENSDF + pandemonium corrected nuclei) relative to the ILL reference data. The missing contribution coming from unknown nuclei and remaining systematic effects of nuclear databases [upper (red) hatched area] is fitted using a set of five effective β branches.

Modern ways (2011) II:
The Huber Model, updated conversion method

Starting point: conversion from the data of Schreckenbach applying all “possible” corrections to the beta spectrum and updated information from nuclear databases

Corrections used: finite size, screening, radiative corrections, weak magnetism

Estimation of uncertainties related to the different theoretical corrections of the beta spectrum and with the conversion algorithm. Largest source of uncertainty is associated with the weak magnetism.

The deduced antineutrino spectrum from the fitted beta spectrum shows an increase of 3% in the antineutrino flux, confirming Mueller results. Their predicted spectrum agrees within uncertainties.

P. Huber, Phys. Rev. C 84, 024617 (2011)

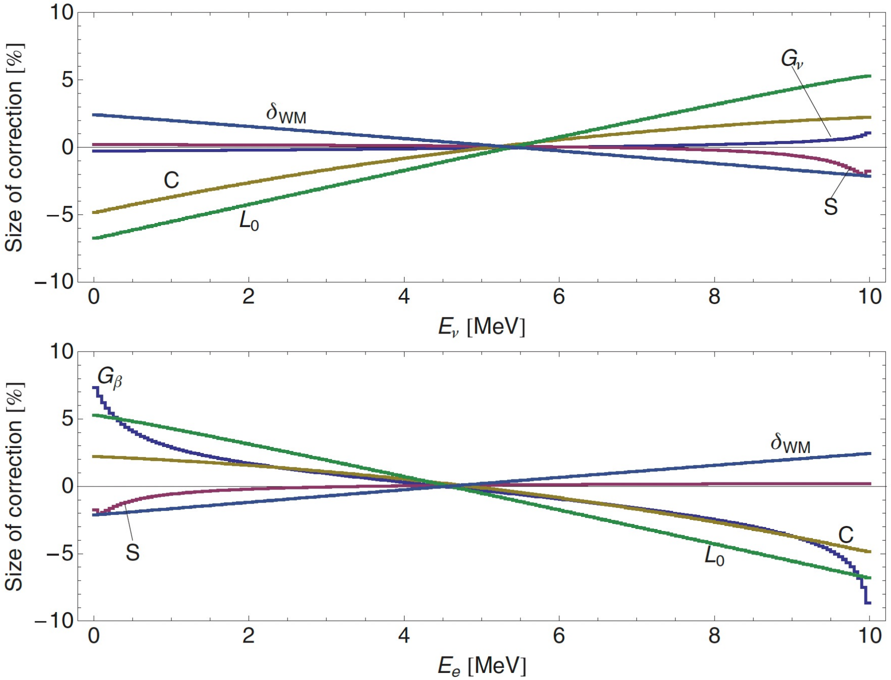
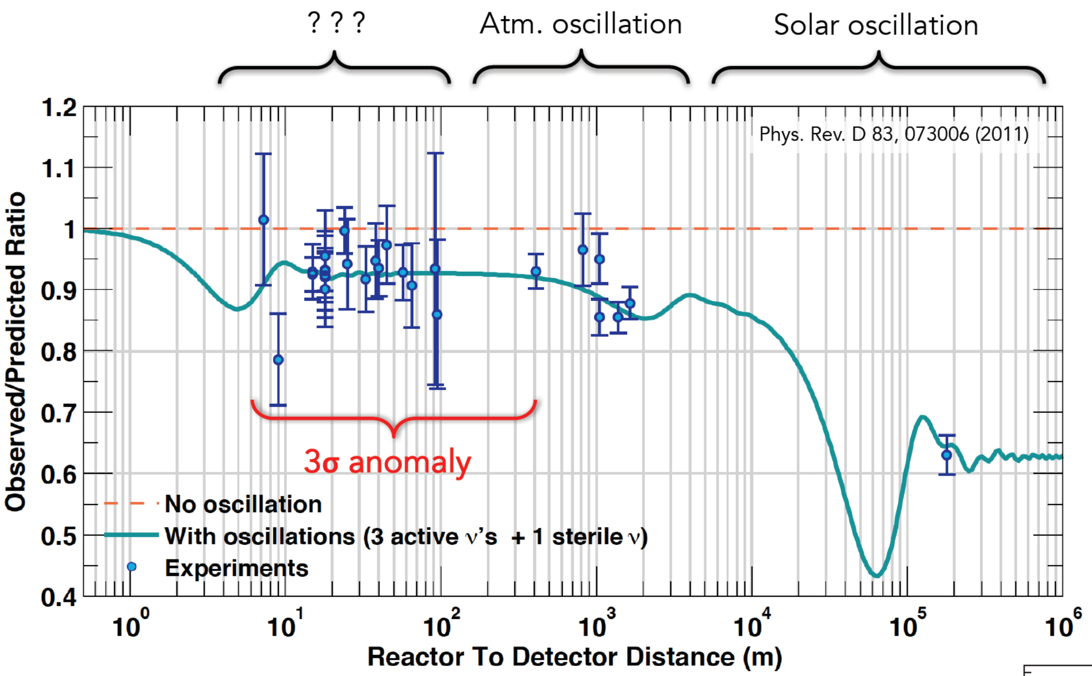


FIG. 1. (Color online) Relative size of the various corrections listed in Eq. (4) for a hypothetical β decay with $Z = 46$, $A = 117$, and $E_0 = 10$ MeV. The top panel shows the effect on the neutrino spectrum, whereas the bottom panel shows the effect on the β spectrum.

Questions related to the antineutrino spectrum



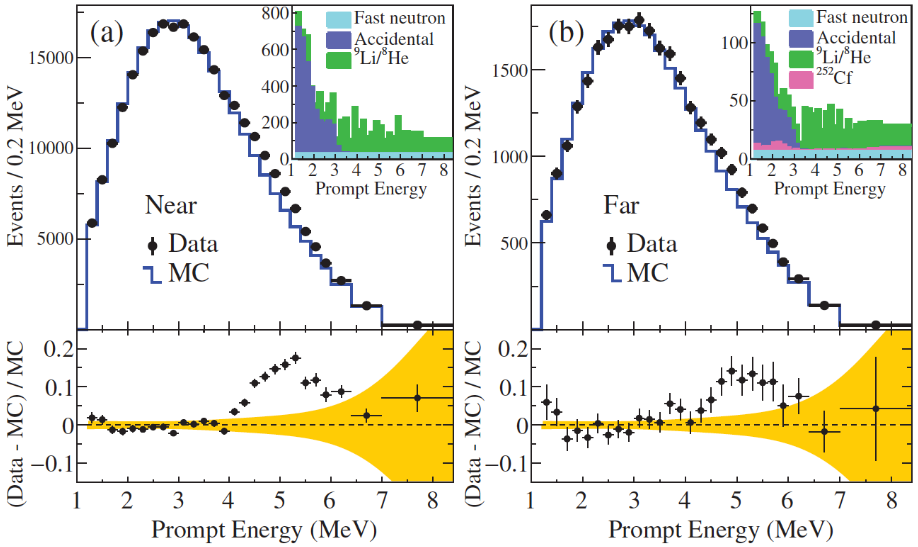
Reactor anomaly ?

Deficit in the number of antineutrinos detected in short base lines, compared with the predictions of the Huber-Muller model. It can be explained by the existence of a sterile neutrino.

Mention et al. PRD 83.073006

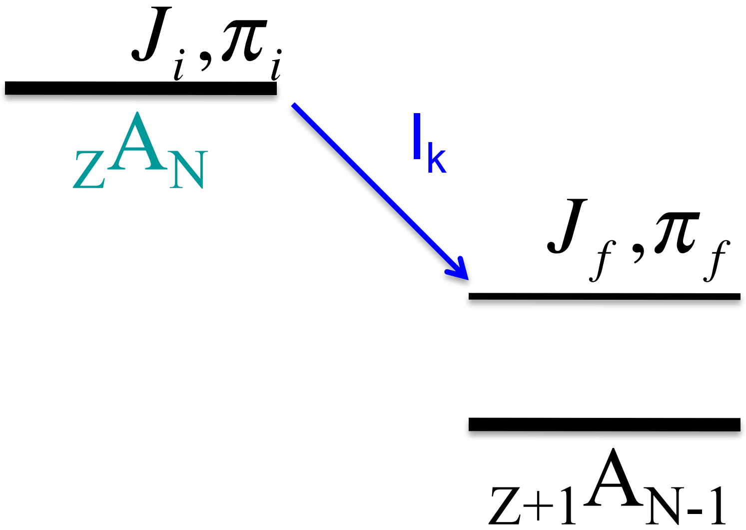
Spectrum distortion (~5 MeV)

RENO results, PRL 116, 211801 (2016)
also seen in DAYA BAY
Many possible explanations have
been discussed, from problems
with the measurements to problems
with the models (fission yields, problems with
the meas. of Schreckenbach et al., etc.)



Nuclear data needs: Q values, beta branches, fission yields, etc.

Beta decay (β^-)



Spectrum for each transition

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$$S(Q - E_k, J_i \pi_i, J_f \pi_f)$$

Spectrum for the decay (n)

$$S_n(E) = \sum_k I_k S(Q - E_k, J_i \pi_i, J_f \pi_f)$$

Anti-neutrino rate per fission (Vogel, 1981)

$$S(E) = \sum_n \lambda_n N_n S_n(E) / r = \sum_n CFY_n S_n(E)$$

Decay heat summation calculation

$$f(t) = \sum_i E_i \lambda_i N_i(t)$$

The beginning (for us) …

We got interested in the topic after the work of Yoshida and co-workers (Journ. of Nucl. Sc. and Tech. 36 (1999) 135)

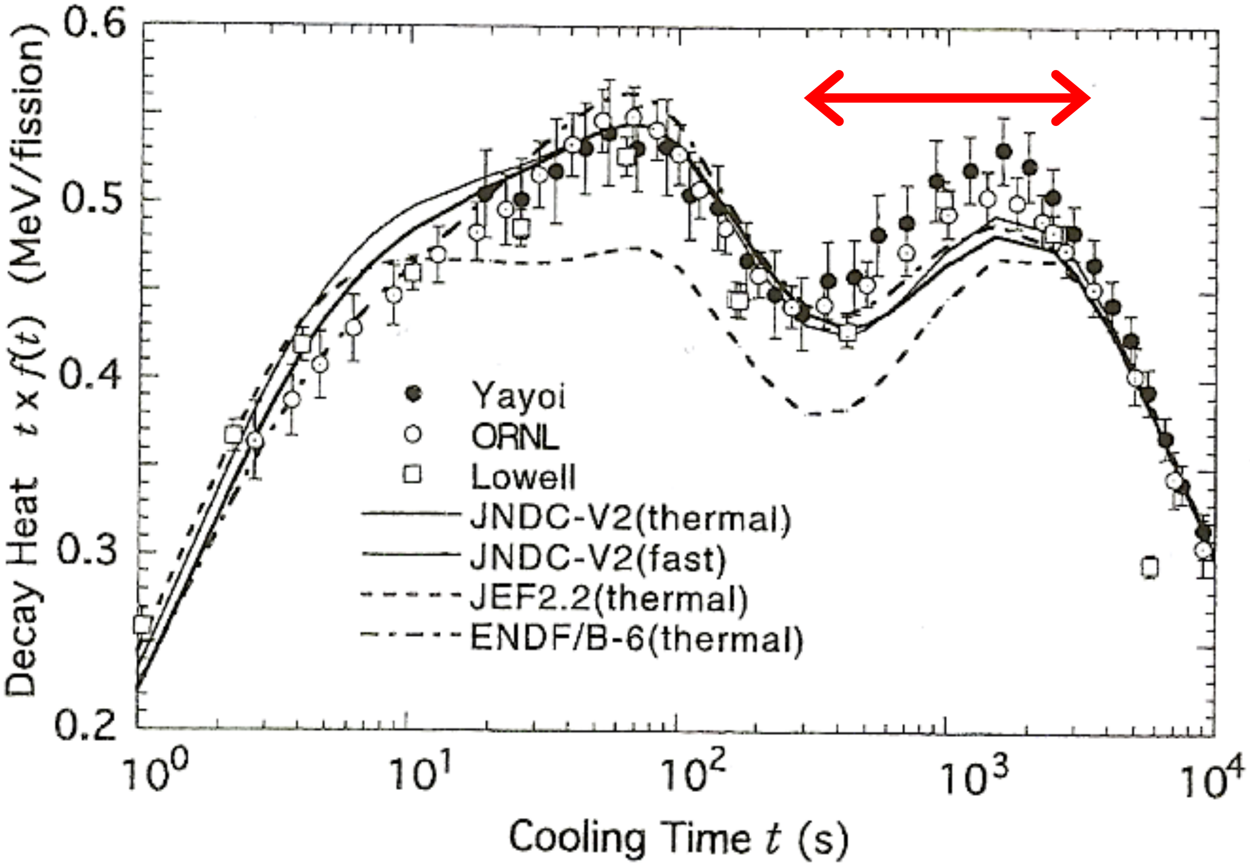
^{239}Pu example (similar situation for ^{235,238}U)

Detective work: identification of some nuclei that could be blamed for the “anomaly” ^{102,104,105}Tc

Suggestion TAGS measurements !!!

^{239}Pu example

(fission pulse decay heat γ component)

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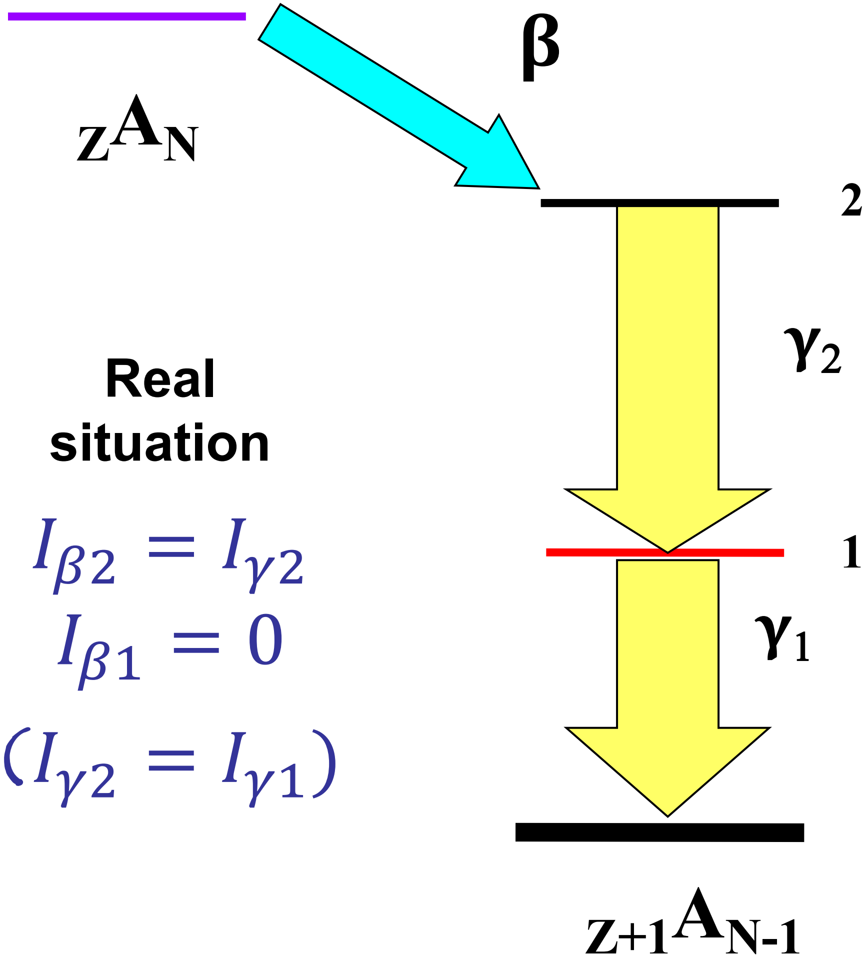
The problem of measuring the β-feeding ($I_\beta = P_\beta * 100$)

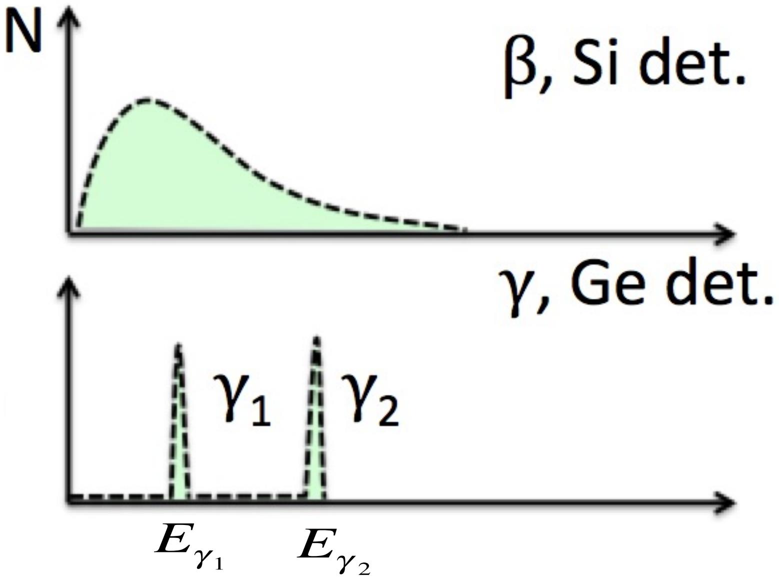


Real situation

$$I_{\beta 2} = I_{\gamma 2}$$

$$I_{\beta 1} = 0$$

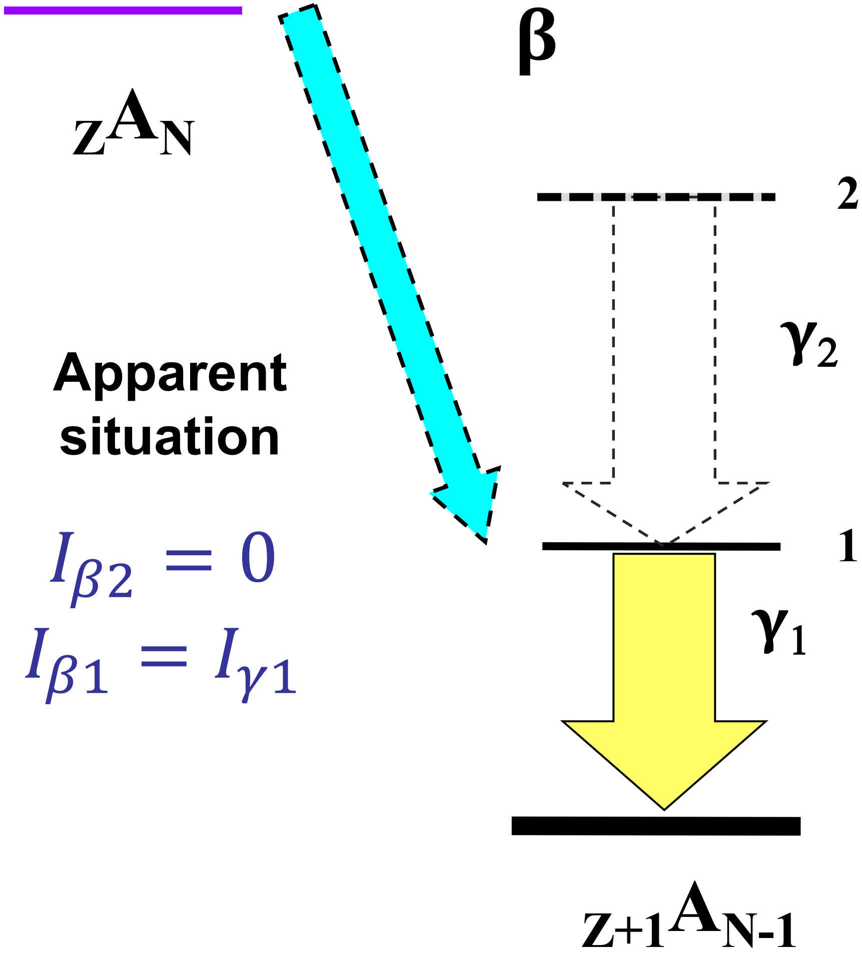
$$(I_{\gamma 2} = I_{\gamma 1})$$



- Ge detectors are conventionally used to construct the level scheme populated in the decay

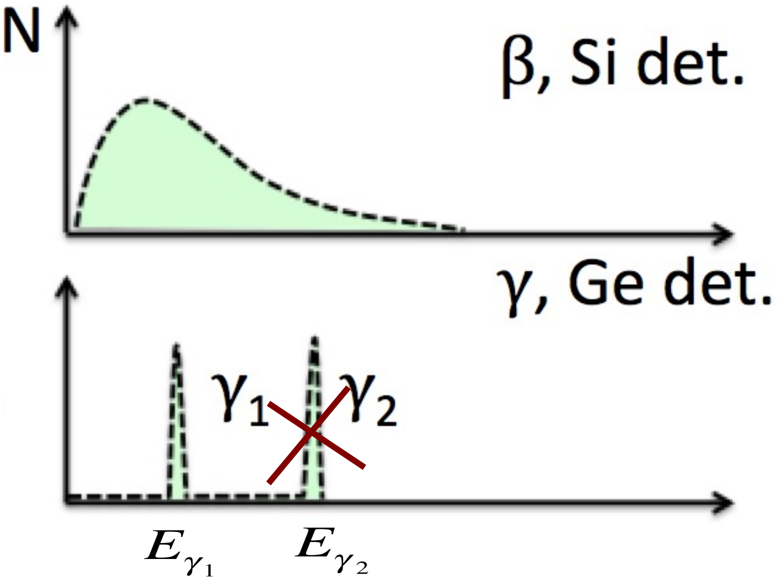
- From the γ intensity balance we deduce the β-feeding

The problem of measuring the β-feeding ($I_\beta = P_\beta * 100$)



Apparent situation

$$I_{\beta 2} = 0$$
$$I_{\beta 1} = I_{\gamma 1}$$

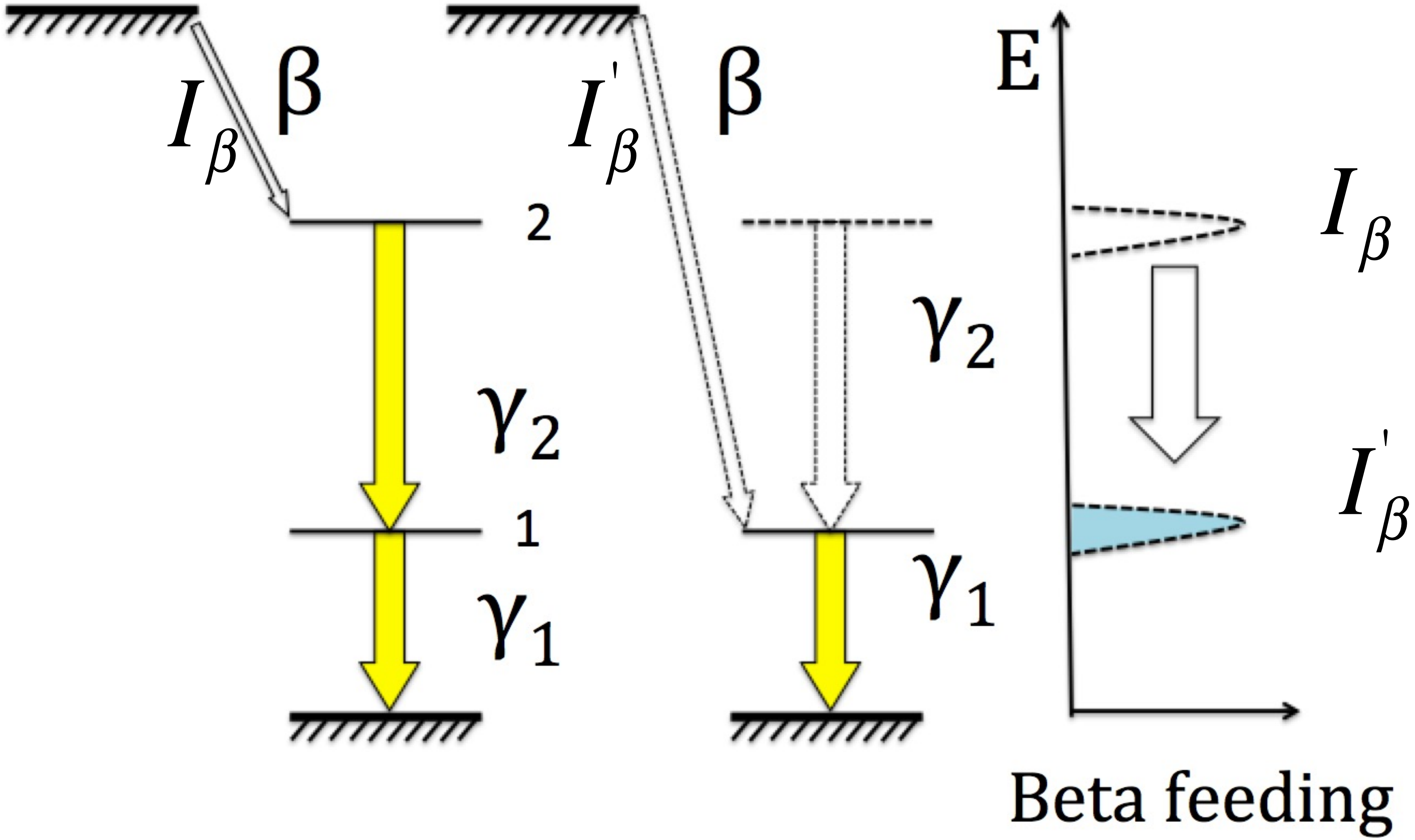


What happens if we miss some intensity?

$$Single\ \gamma \sim \varepsilon$$

$$Coinc\ \gamma_1 \gamma_2 \sim \varepsilon_1 \varepsilon_2$$

Pandemonium effect



Pandemonium (The Capital of Hell)

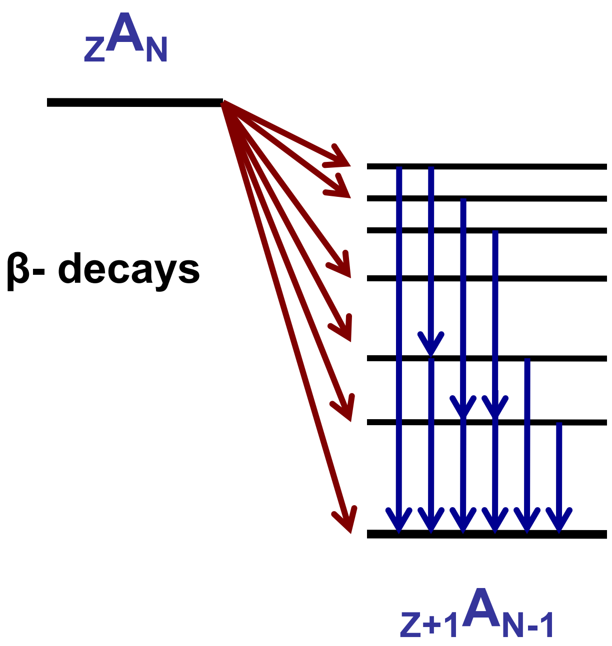
introduced by John Milton (XVII) in his epic poem Paradise Lost

John Martin (~ 1825), presently at Louvre

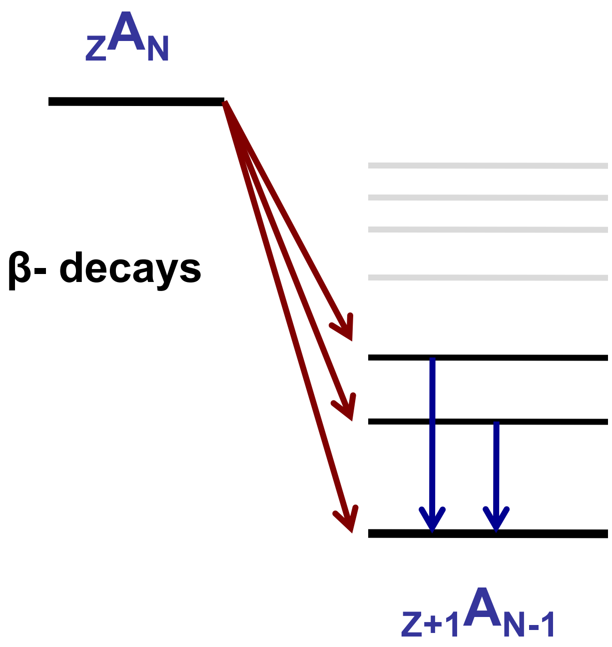
Hardy et al., Phys. Lett. 71B (1977) 307

Effect of Pandemonium on summation calculations

Real situation



Pandemonium situation

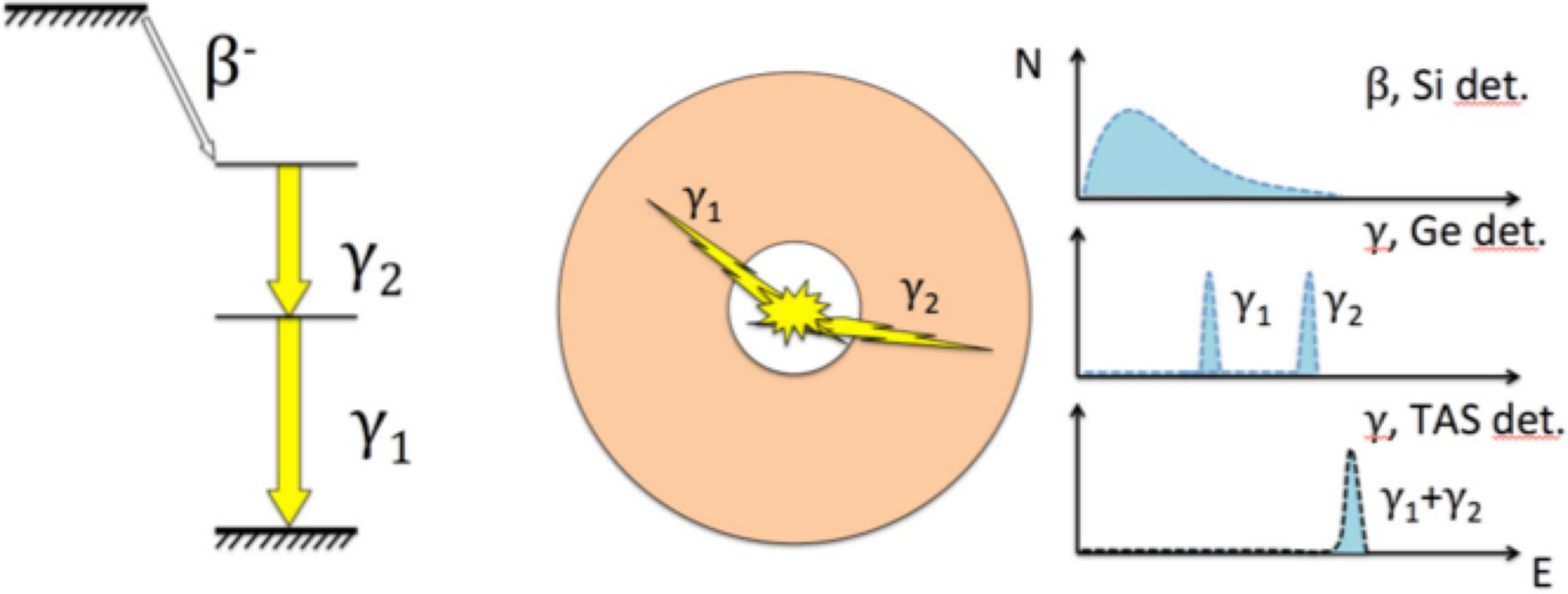


As a result of the Pandemonium, betas are estimated with higher energies from databases. Their spectra is harder. Incomplete level schemes affect the antineutrinos as well.

The gamma mean energies are reduced since you detect less gammas.

This is why you should avoid using data suspicious of suffering from Pandemonium

Total absorption spectroscopy applied to beta decay studies



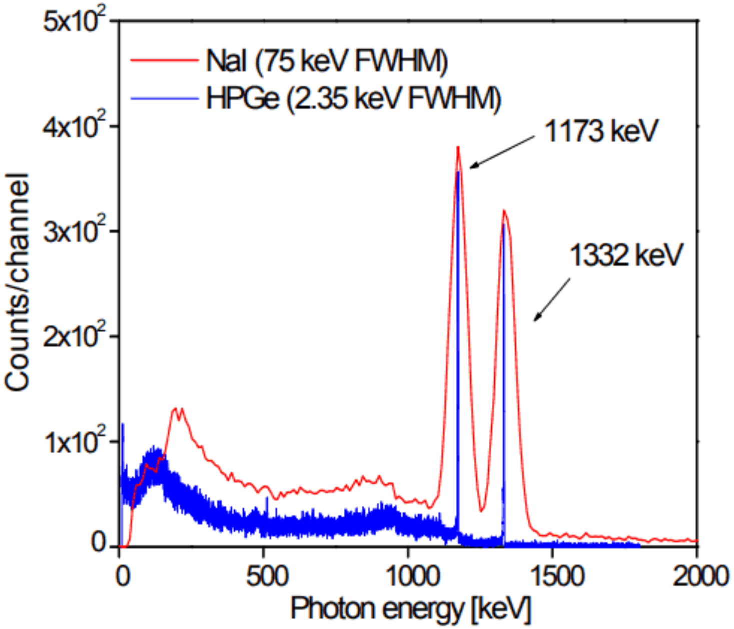
$$d = R(B) \cdot f$$

$(note\ that\ f \equiv I_\beta)$

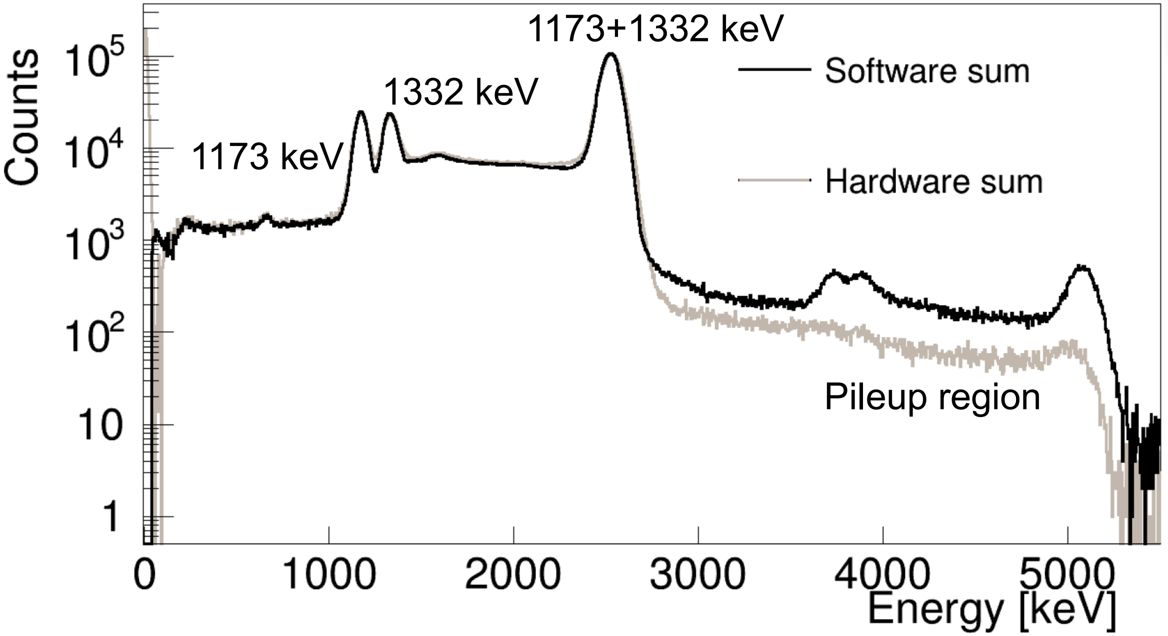
Requirements: clean spectrum or a proper treatment of the contaminants, some knowledge of decay level scheme of the daughter, etc.

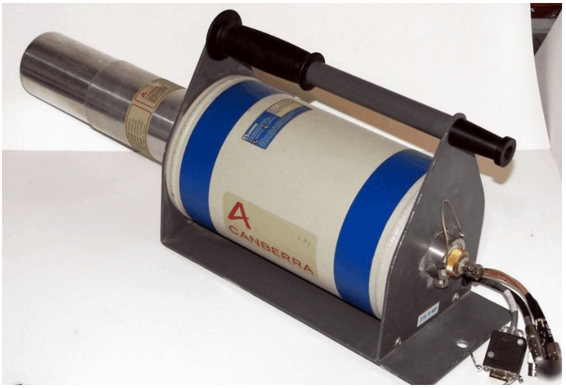
Real gamma spectra from 60Co decay

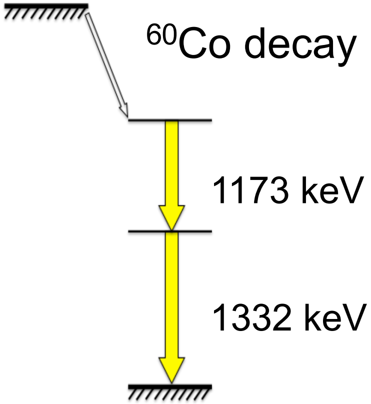
“Small” detectors



Real calorimeter detector



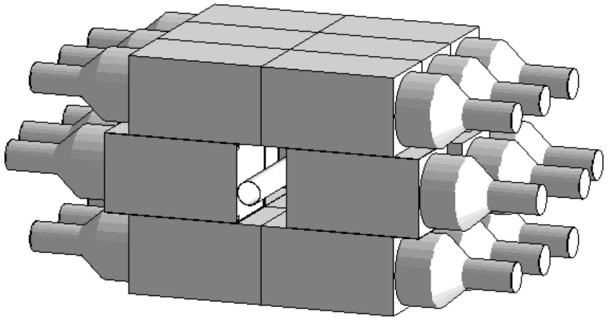




^{60}Co decay

1173 keV

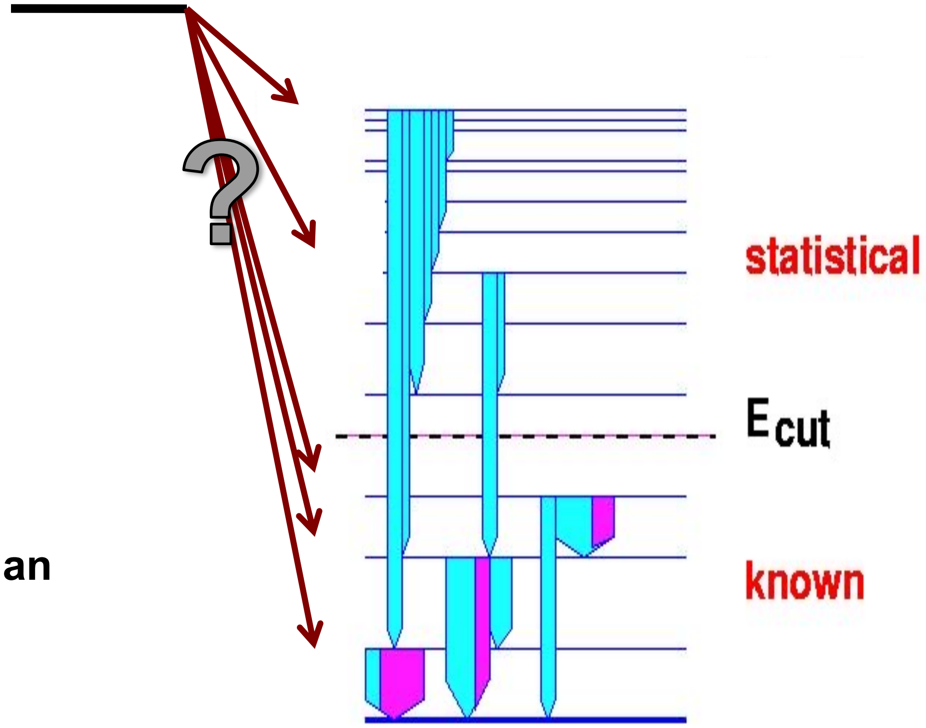
1332 keV



DTAS

The complexity of the TAGS analysis: an ill posed problem

$$d = R(B) \cdot f$$



Steps:

1. **Define B (branching ratio matrix)**
2. **Calculate R(B)**
3. **Solve the equation d=R(B)f using an appropriate algorithm**

Expectation Maximization (EM) method:
modify knowledge on causes from effects

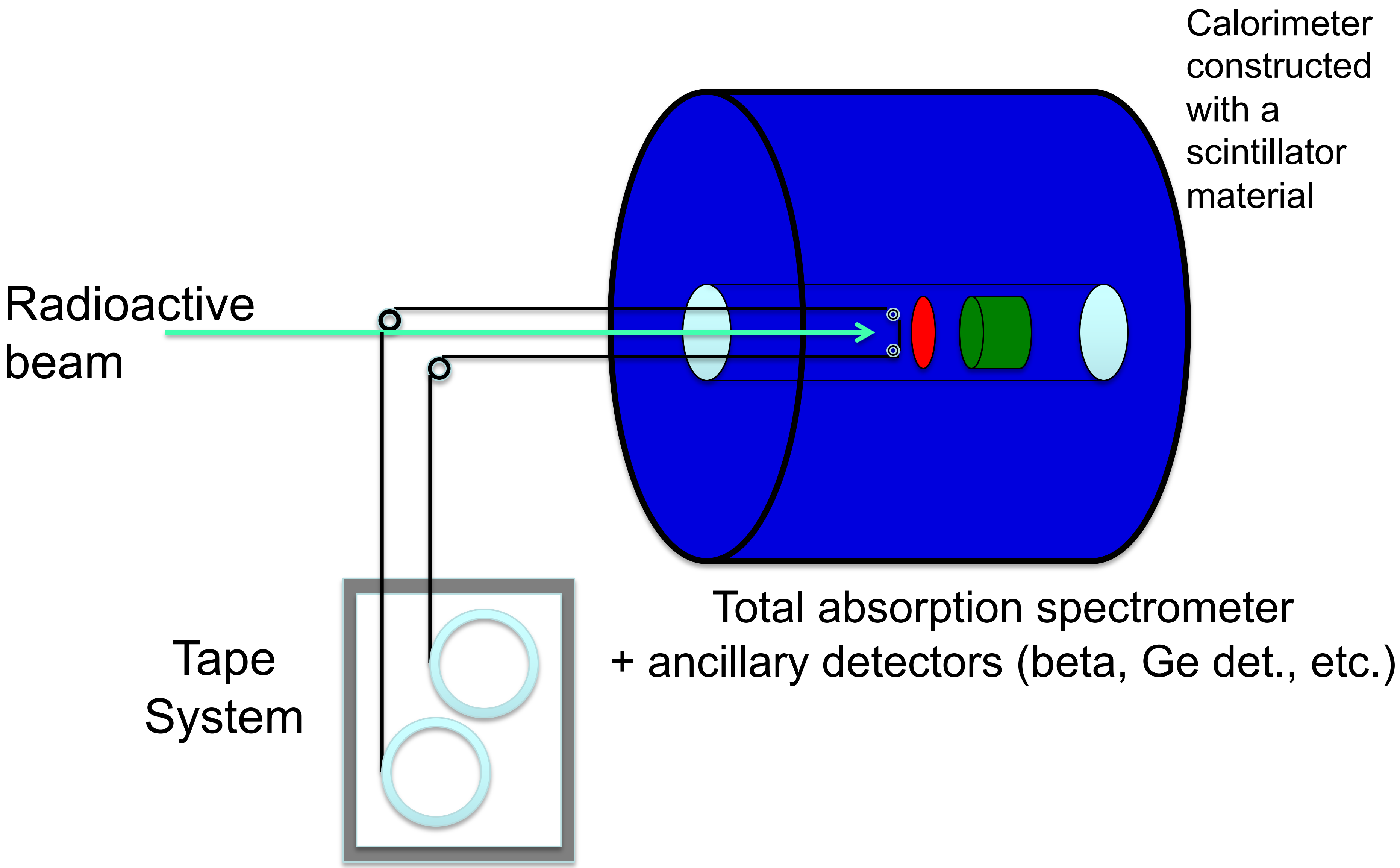
$$\boxed{P(f_j \mid d_i) = \frac{P(d_i \mid f_j)P(f_j)}{\sum_j P(d_i \mid f_j)P(f_j)}}$$

Algorithm:

$$f_j^{(s+1)} = \frac{1}{\sum_i R_{ij}} \sum_i \frac{R_{ij} f_j^{(s)} d_i}{\sum_k R_{ik} f_k^{(s)}}$$

Mathematical formalization by Tain, Cano-Ott

Typical total absorption experiments



Calorimeter
constructed
with a
scintillator
material

Radioactive
beam

Tape
System

Total absorption spectrometer
+ ancillary detectors (beta, Ge det., etc.)

The beginning (for us) …

We got interested in the topic after the work of Yoshida and co-workers (Journ. of Nucl. Sc. and Tech. 36 (1999) 135)

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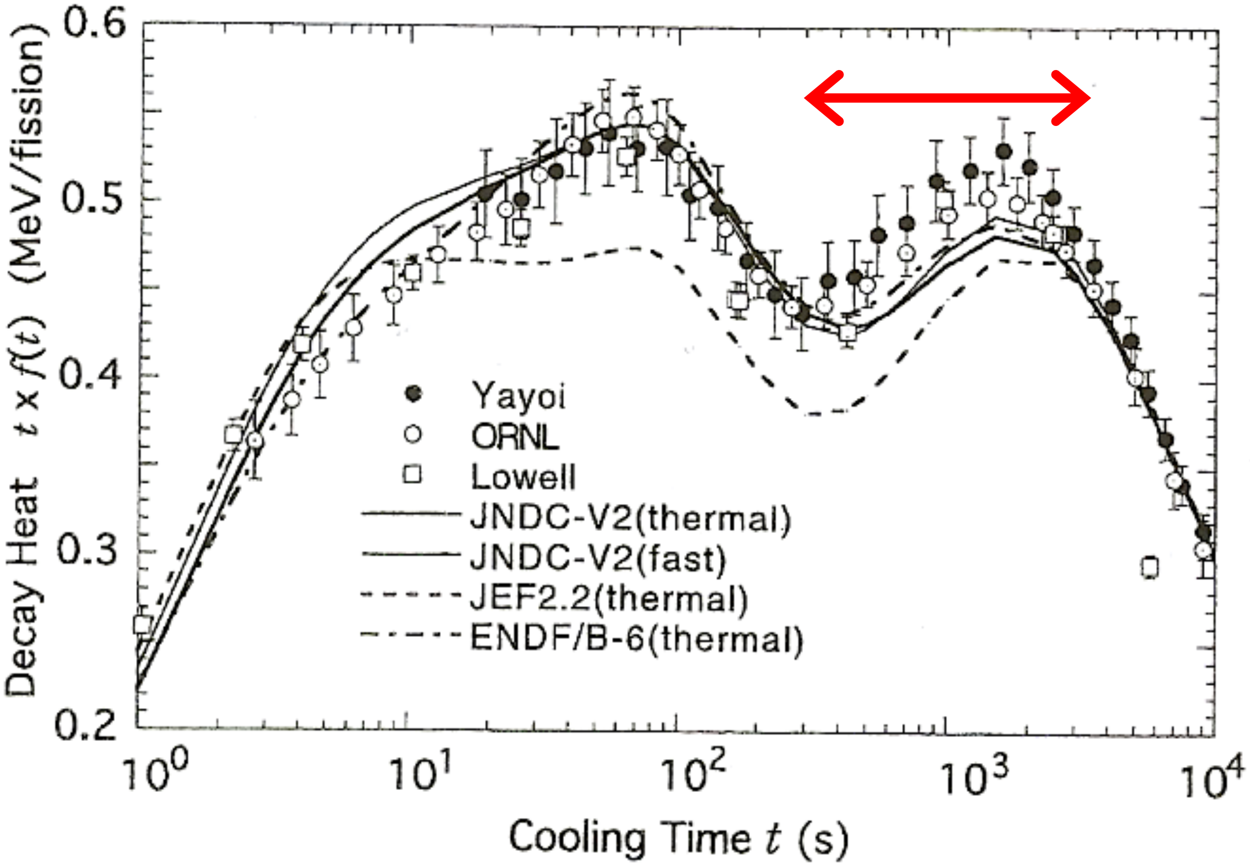
Detective work: identification of some nuclei that could be blamed for the "anomaly" ^{102,104,105}Tc

Suggestion TAGS measurements !!!

^{239}Pu example

(fission pulse decay heat γ component)



The famous list for decay heat (WPEC-25, IAEA working group)

Radionuclide	Priority	Radionuclide	Priority	Radionuclide	Priority
35-Br-86	1	41-Nb-99	1	52-Te-135	2
35-Br-87	1	41-Nb-100	1	53-I-136	1
35-Br-88	1	41-Nb-101	1	53-I-136m	1
36-Kr-89	1	41-Nb-102	2	53-I-137	1
36-Kr-90	1	42-Mo-103	1	54-Xe-137	1
37-Rb-90m	2	42-Mo-105	1	54-Xe-139	1
37-Rb-92	2	43-Tc-102	1	54-Xe-140	1
38-Sr-89	2	43-Tc-103	1	55-Cs-142	3
38-Sr-97	2	43-Tc-104	1	56-Ba-145	2
39-Y-96	2	43-Tc-105	1	57-La-143	2
40-Zr-99	3	43-Tc-106	1	57-La-145	2
40-Zr-100	2	43-Tc-107	2		
41-Nb-98	1	51-Sb-132	1		

37 nuclides, of which 23 were given first priority.

Yoshida and Nichols, NEA report NEA/WPEC-25 (2007) 1., Vol. 25 (NEA No. 6284)

Some published and on-going cases for Decay Heat and Antineutrino Spectrum calculations

Tables extracted from « Beta-decay studies for applied and basic nuclear physics », Algora et al. Eur. Phys. J. A 57 (2021) 85, 2020

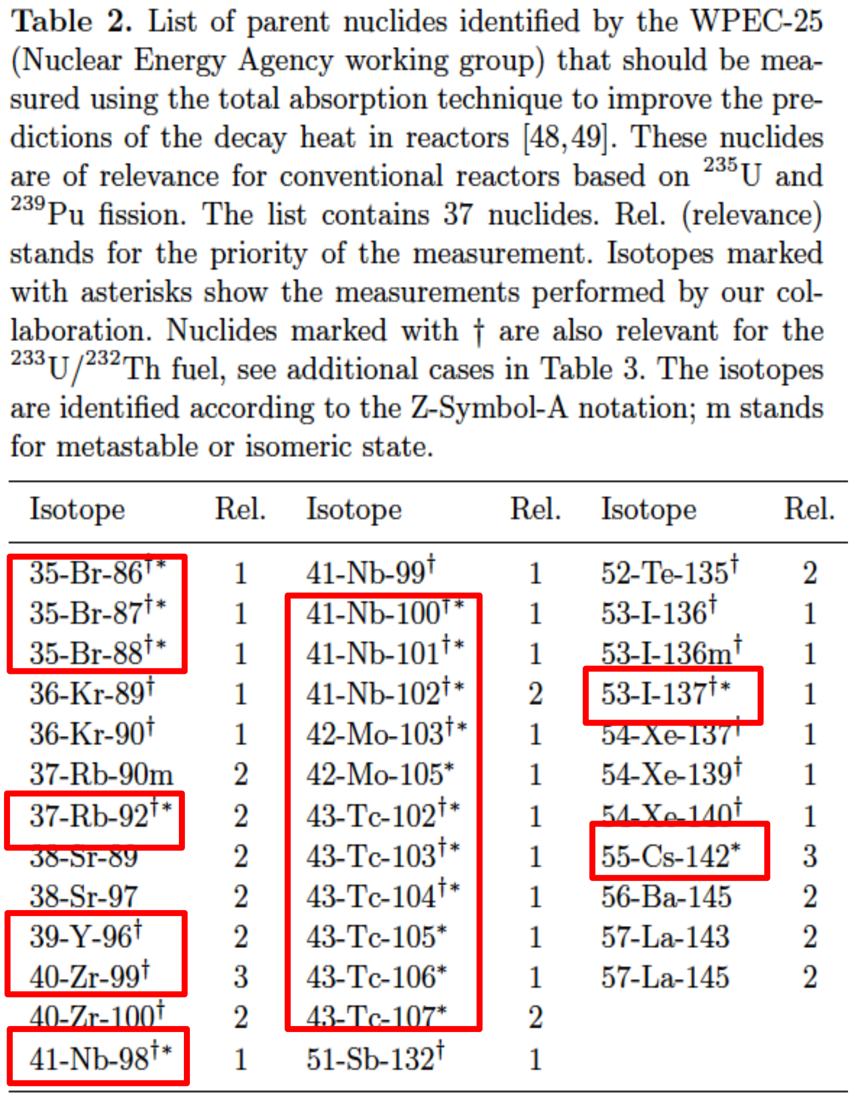


Table 2. List of parent nuclides identified by the WPEC-25 (Nuclear Energy Agency working group) that should be measured using the total absorption technique to improve the predictions of the decay heat in reactors [48,49]. These nuclides are of relevance for conventional reactors based on ^{235}U and ^{239}Pu fission. The list contains 37 nuclides. Rel. (relevance) stands for the priority of the measurement. Isotopes marked with asterisks show the measurements performed by our collaboration. Nuclides marked with † are also relevant for the ^{233}U/^{232}Th fuel, see additional cases in Table 3. The isotopes are identified according to the Z-Symbol-A notation; m stands for metastable or isomeric state.

Isotope	Rel.	Isotope	Rel.	Isotope	Rel.
35-Br-86†*	1	41-Nb-99†	1	52-Te-135†	2
35-Br-87†*	1	41-Nb-100†*	1	53-I-136†	1
35-Br-88†*	1	41-Nb-101†*	1	53-I-136m†	1
36-Kr-89†	1	41-Nb-102†*	2	53-I-137†*	1
36-Kr-90†	1	42-Mo-103†*	1	54-Xe-137†	1
37-Rb-90m	2	42-Mo-105*	1	54-Xe-139†	1
37-Rb-92†*	2	43-Tc-102†*	1	54-Xe-140†	1
38-Sr-89	2	43-Tc-103†*	1	55-Cs-142*	3
38-Sr-97	2	43-Tc-104†*	1	56-Ba-145	2
39-Y-96†	2	43-Tc-105*	1	57-La-143	2
40-Zr-99†	3	43-Tc-106*	1	57-La-145	2
40-Zr-100†	2	43-Tc-107*	2		
41-Nb-98†*	1	51-Sb-132†	1		

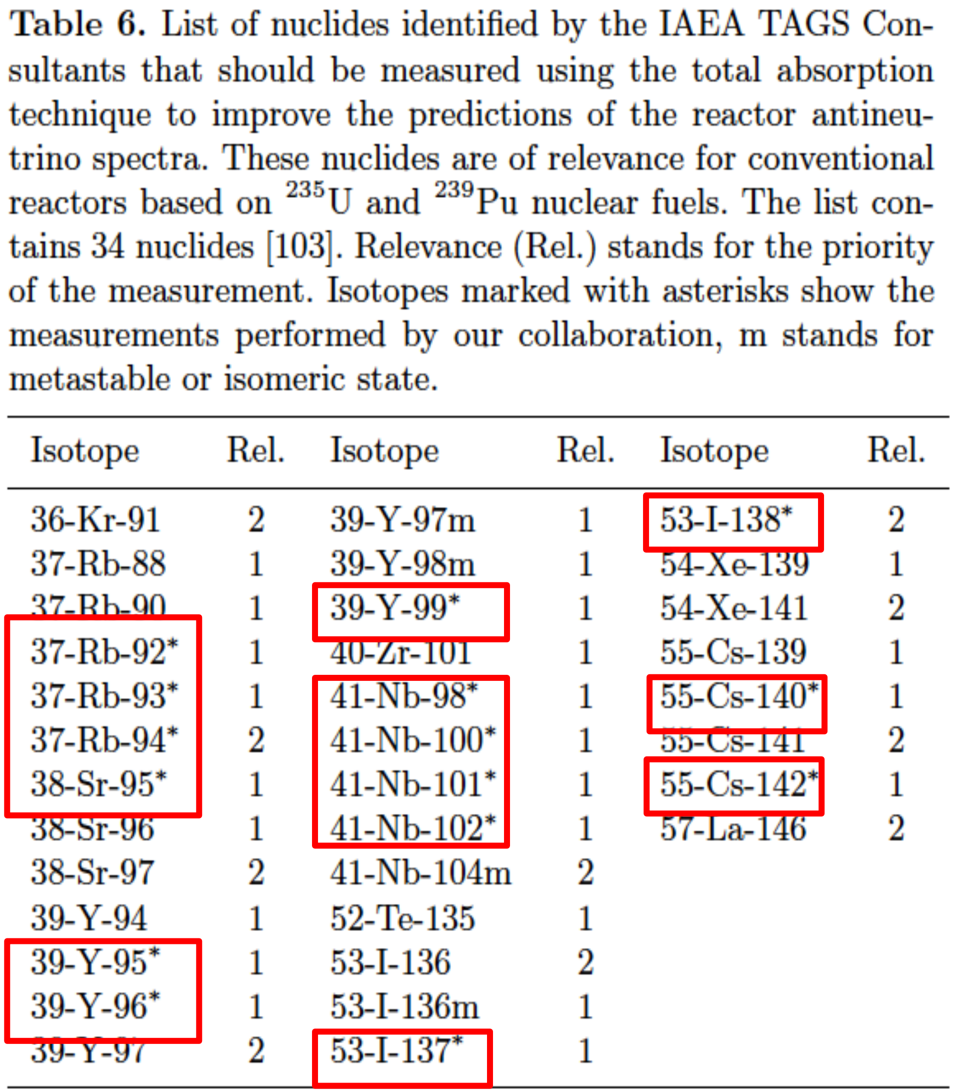
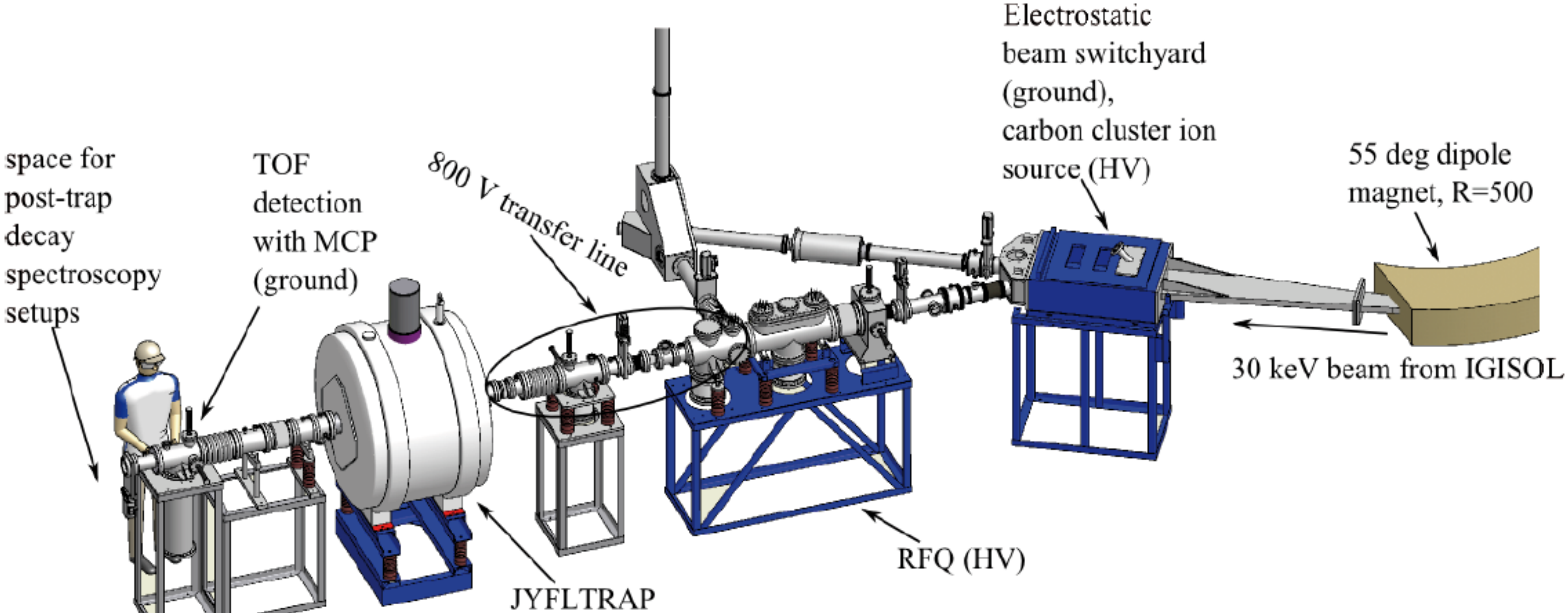


Table 6. List of nuclides identified by the IAEA TAGS Consultants that should be measured using the total absorption technique to improve the predictions of the reactor antineutrino spectra. These nuclides are of relevance for conventional reactors based on ^{235}U and ^{239}Pu nuclear fuels. The list contains 34 nuclides [103]. Relevance (Rel.) stands for the priority of the measurement. Isotopes marked with asterisks show the measurements performed by our collaboration, m stands for metastable or isomeric state.

Isotope	Rel.	Isotope	Rel.	Isotope	Rel.
36-Kr-91	2	39-Y-97m	1	53-I-138*	2
37-Rb-88	1	39-Y-98m	1	54-Xe-139	1
37-Rb-90	1	39-Y-99*	1	54-Xe-141	2
37-Rb-92*	1	40-Zr-101	1	55-Cs-139	1
37-Rb-93*	1	41-Nb-98*	1	55-Cs-140*	1
37-Rb-94*	2	41-Nb-100*	1	55-Cs-141	2
38-Sr-95*	1	41-Nb-101*	1	55-Cs-142*	1
38-Sr-96	1	41-Nb-102*	1	57-La-146	2
38-Sr-97	2	41-Nb-104m	2		
39-Y-94	1	52-Te-135	1		
39-Y-95*	1	53-I-136	2		
39-Y-96*	1	53-I-136m	1		
39-Y-97	2	53-I-137*	1		

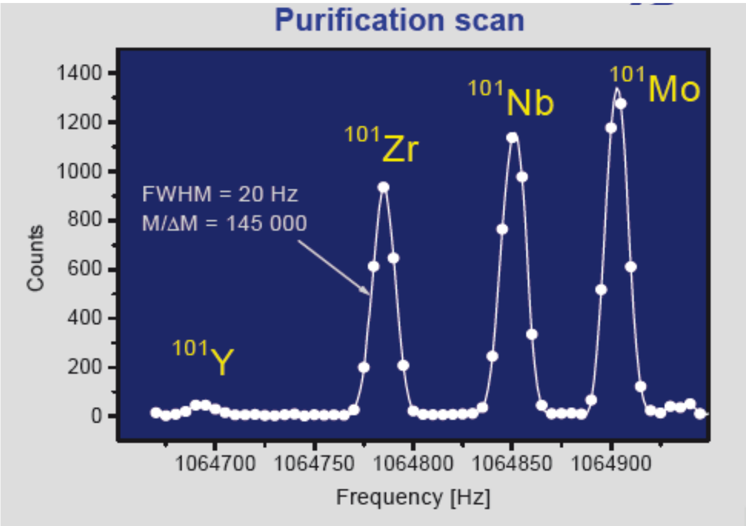
Courtesy: M. Fallot (with some modifications)

Why JYFL(IGISOL)?: ion guide technique + a bonus



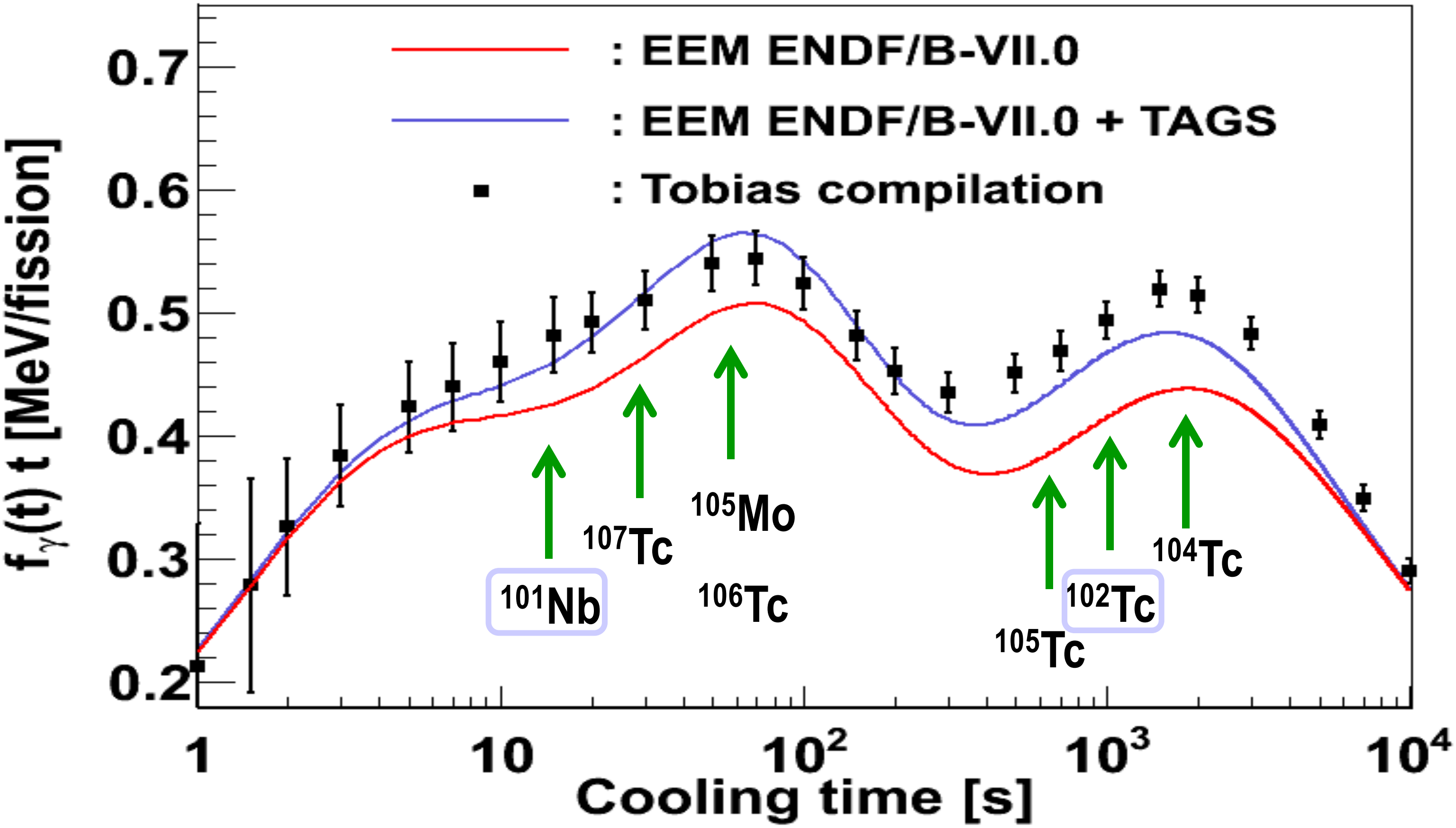
R~100 000

The main reasons are the chemical insensitivity (ion guide technique), high purity by means of purification of the beam using the JYFLTRAP and acceptable yields!


Purification scan

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

Motivated by Yoshida *et al.* (Journ. of Nucl. Sc. and Tech. 36 (1999) 135) and WPEC-25



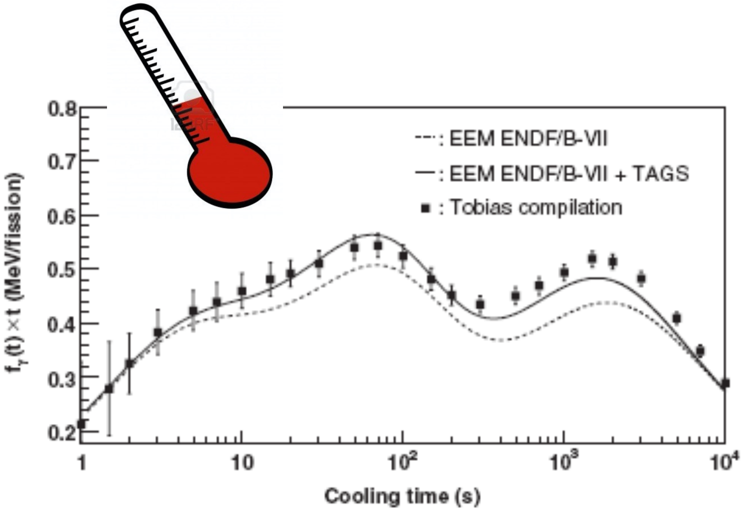
Algora, Phys. Rev. Letts. 105, 202505, PhD Thesis D. Jordan,

K. P. Rykaczewsky, Physics 3, 94 (2011)

DH Courtesy A. Sonzogni

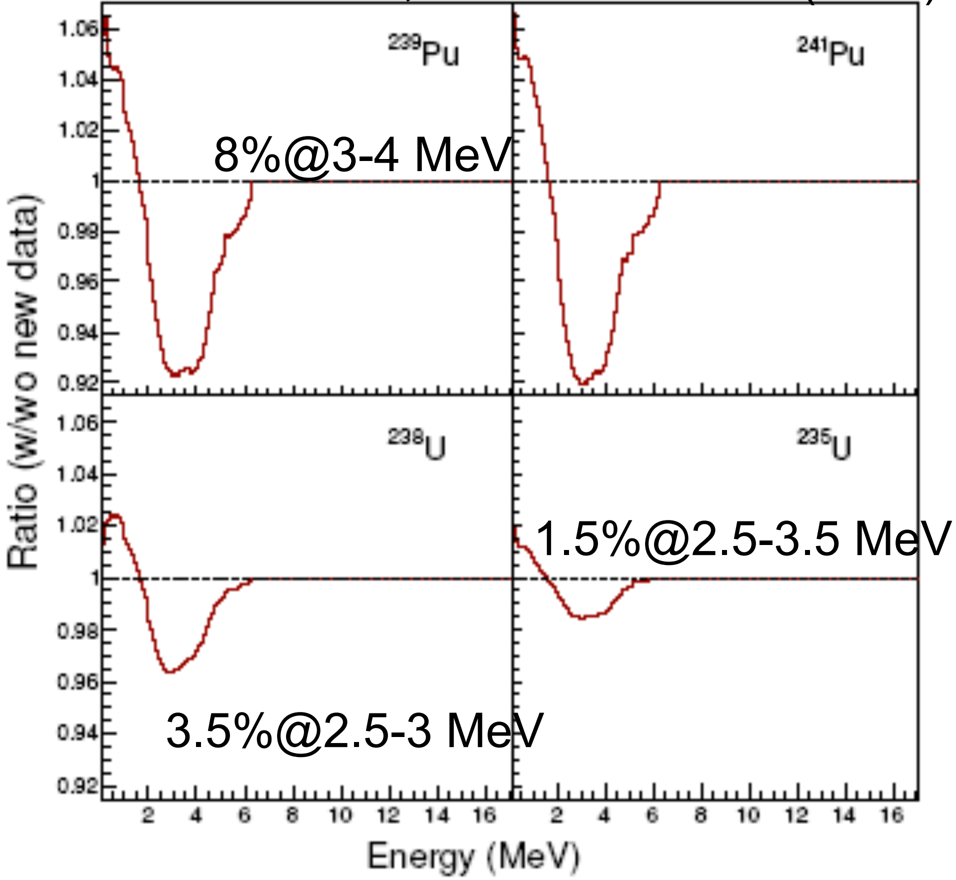
Results also confirmed by R. W. Mills using JEFF 3.1

Impact of some of our earlier data:
^{102,104,105,106,107}Tc, ^{101}Nb, ^{105}Mo



Dolores Jordan, PhD thesis
Algora et al., PRL 105, 202501 (2010)
D. Jordan PRC 87, 044318 (2013)

M. Fallot et al., PRL 109.202504 (2012)



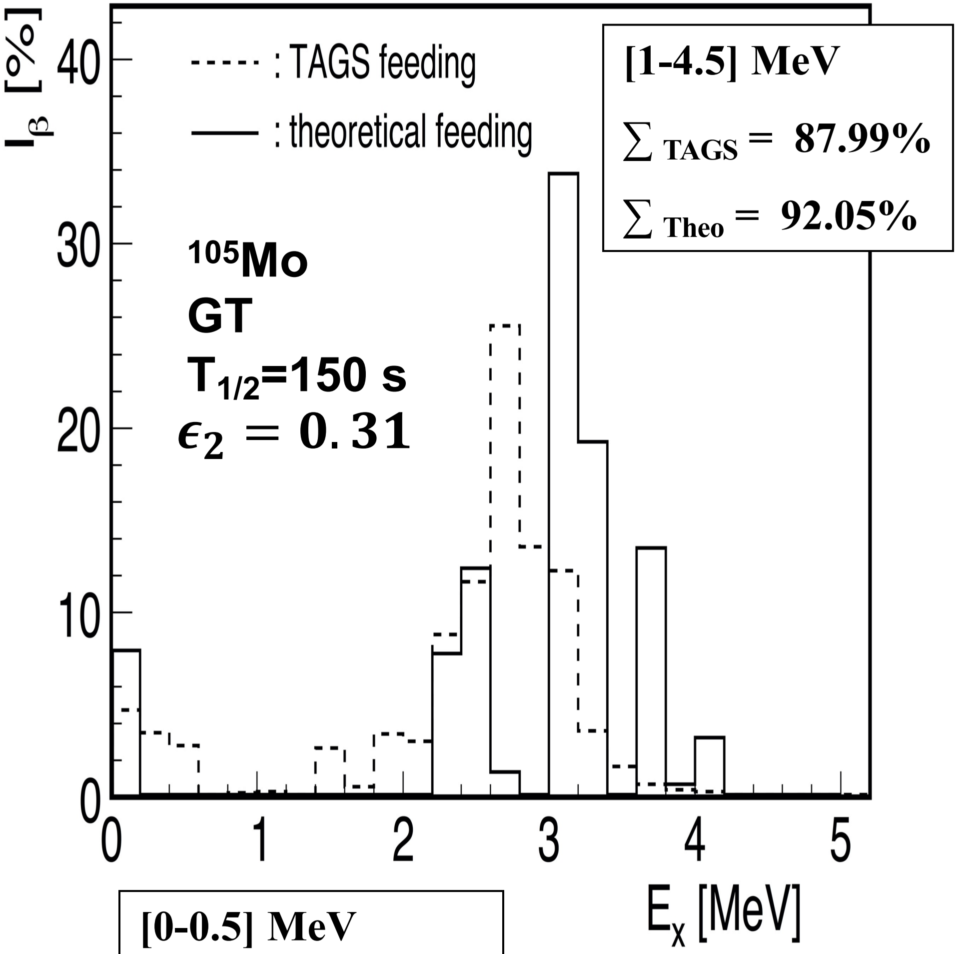
8%@3-4 MeV

1.5%@2.5-3.5 MeV

3.5%@2.5-3 MeV

Ratio between 2 antineutrino spectra built with and without the ^{102,104,105,106,107}Tc,^{105}Mo,^{101}Nb TAS data. Only 5 Pandemonium cases

Nuclear structure example: QRPA calculations ^{105}Mo decay, $T_{1/2}$(exp) = 35.6 s



^{105}Mo
GT
$T_{1/2}$=150 s
$\epsilon_2 = 0.31$

[1-4.5] MeV

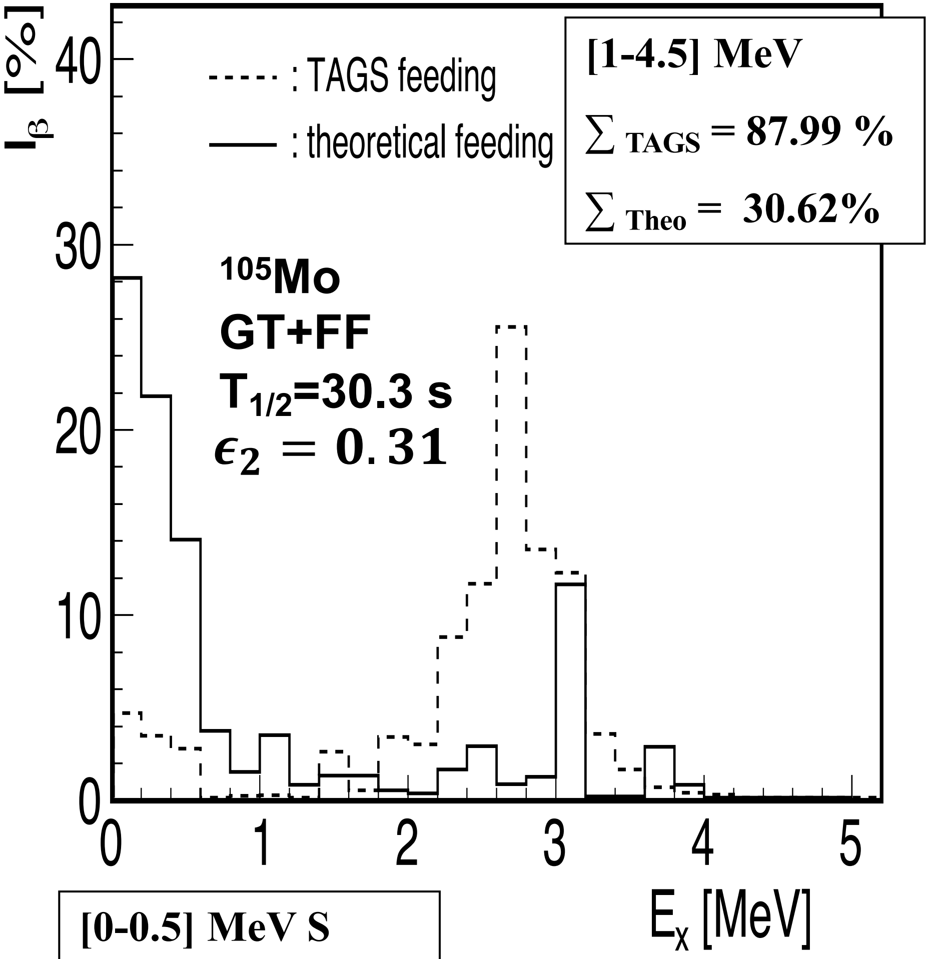
$\sum_{\text{TAGS}} = 87.99\%$

$\sum_{\text{Theo}} = 92.05\%$

[0-0.5] MeV

$\sum_{\text{TAGS}} = 11.51\%$

$\sum_{\text{Theo}} = 7.94\%$



^{105}Mo
GT+FF
$T_{1/2}$=30.3 s
$\epsilon_2 = 0.31$

[1-4.5] MeV

$\sum_{\text{TAGS}} = 87.99\ \%$

$\sum_{\text{Theo}} = 30.62\%$

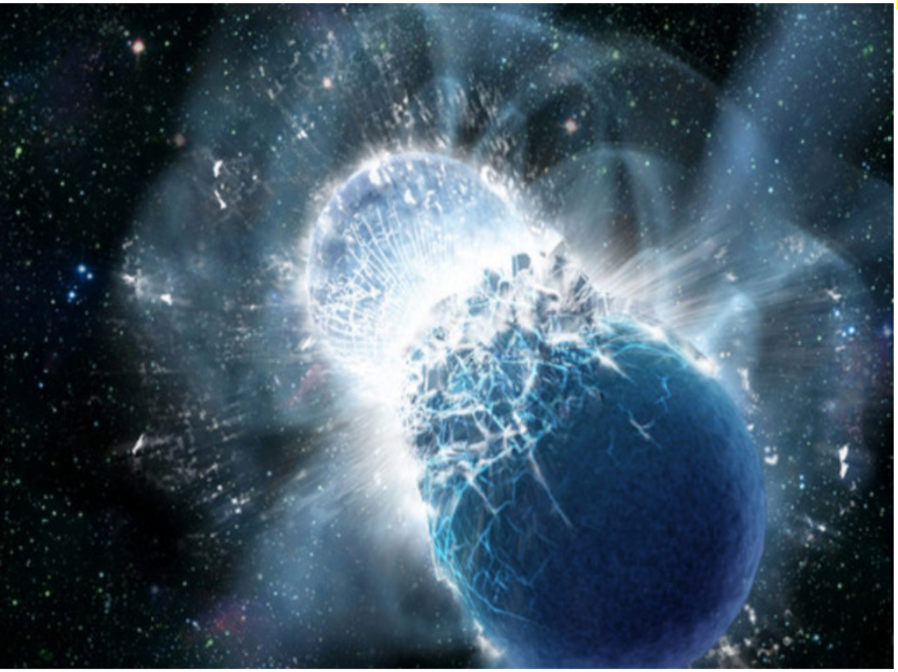
[0-0.5] MeV S

$\sum_{\text{TAGS}} = 11.51\%$

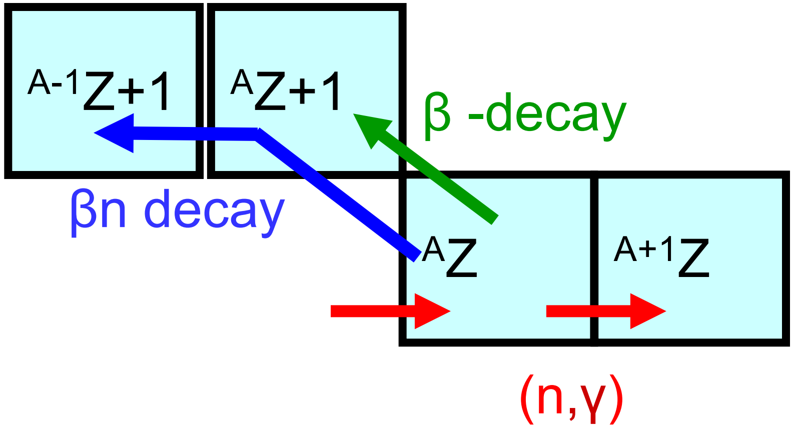
$\sum_{\text{Theo}} = 67.84\ \%$

FRDM-QRPA calc.
Kratz Moeller et al.

Astrophysics I: r-process input from models



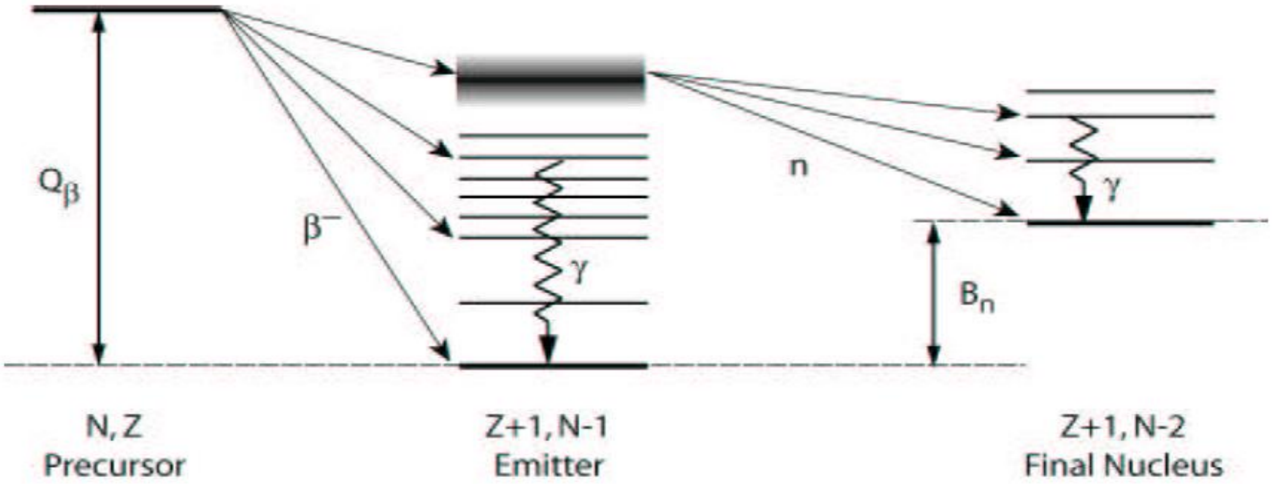
r-process: A short and very high neutron flux produces very neutron-rich nuclei in a short time, which then decay to stability.



- The β-decay half-life determines the speed of the process and shapes the abundance distribution
- The delayed neutron emission probability modifies the abundance distribution

Motivation of most recently analyzed cases: competition between gamma and n emission; antineutrino spectrum

- Competition between gamma and neutron emission above the Sn value
- Relevant cases for the prediction of the antineutrino spectrum
- Some examples of recently published cases: ^{100,102}Nb, ^{95}Rb, ^{103}Tc

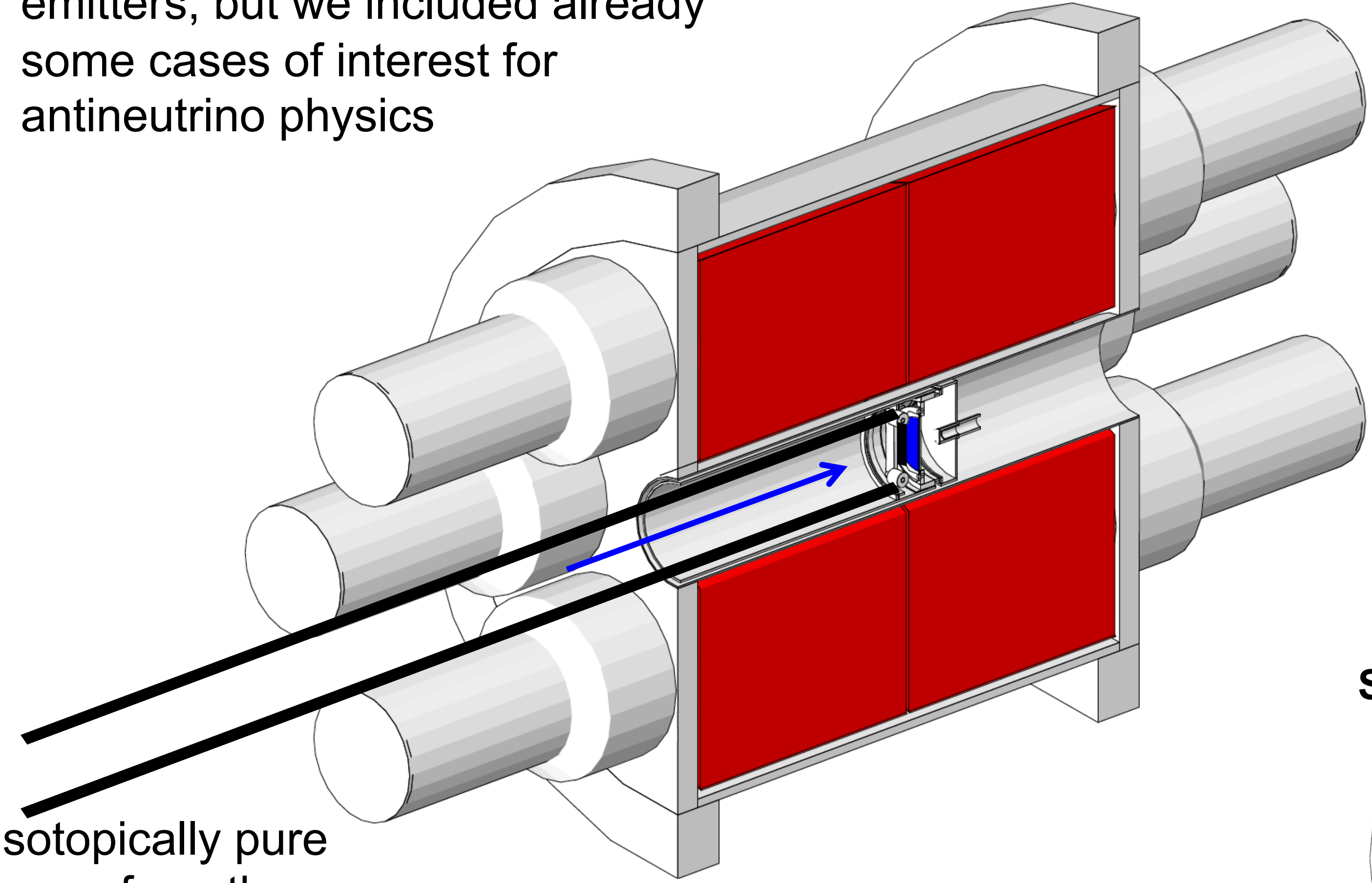


This research has also important implications for nuclear astrophysics for several reasons!!!

VTAS in Jyväskylä (November 2009)

$^{86,87,88}\mathrm{Br}$, $^{\mathbf{91},\mathbf{92},\mathbf{93},94}\mathbf{Rb}$

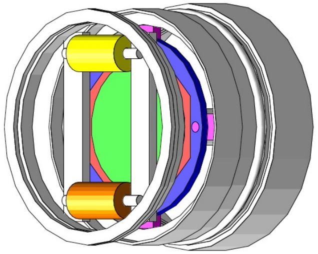
Main goal: beta delayed neutron emitters, but we included already some cases of interest for antineutrino physics



Isotopically pure beam from the JYFL trap

Segmented BaF2 detector with optically separated crystals

Si detector endcup

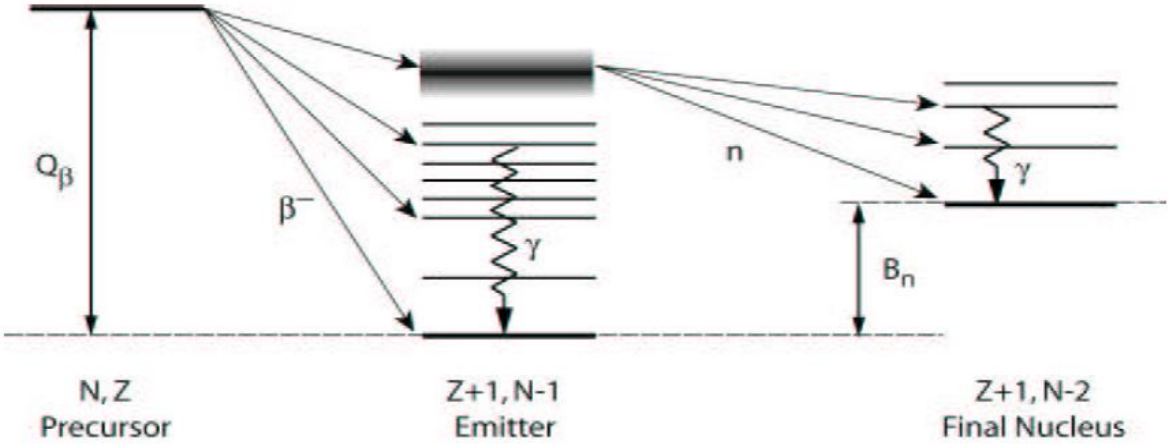


A problem of astrophysical interest

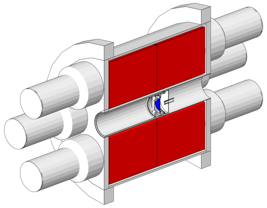
Competition between gamma and neutron emission above the Sn value

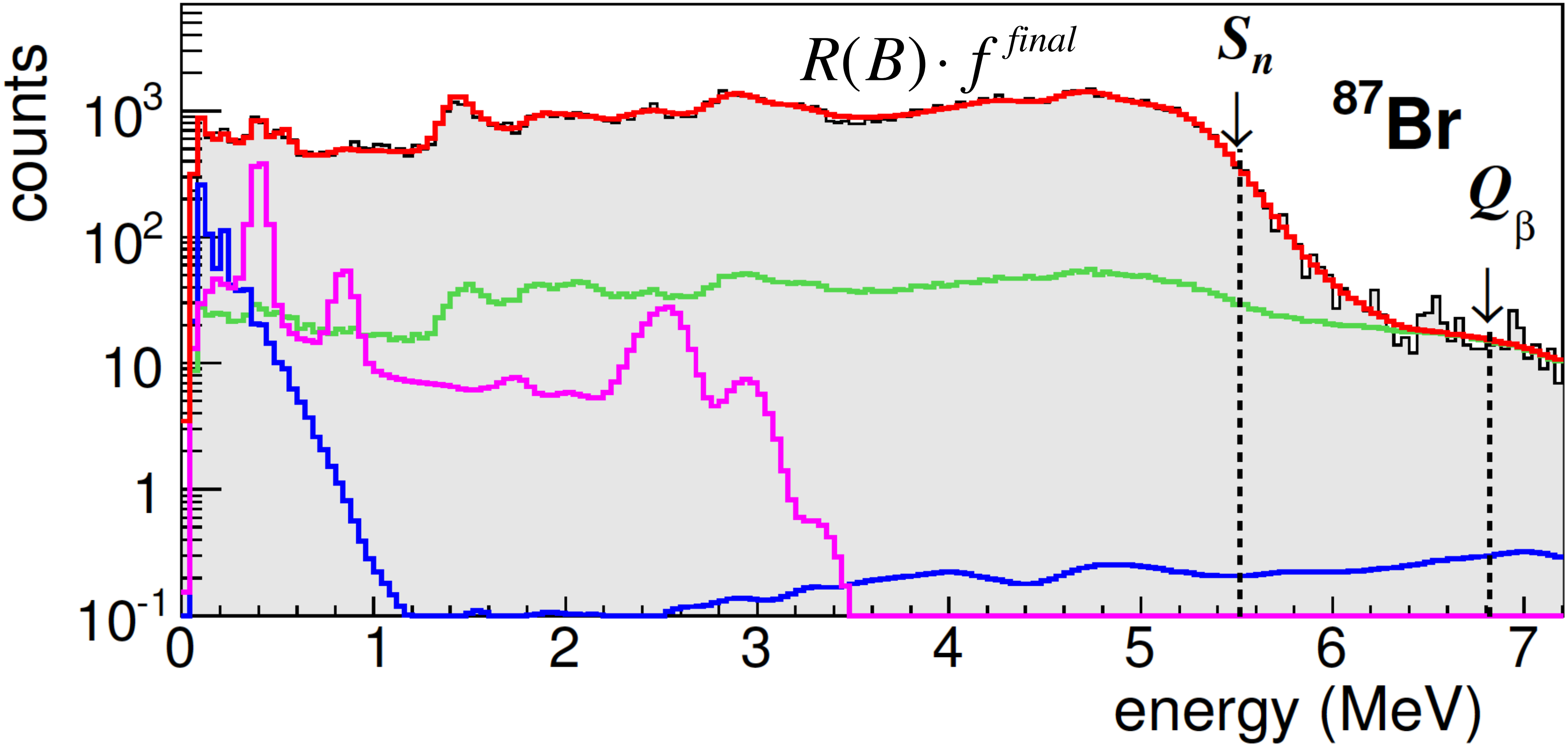
$$\frac{1}{T_{1/2}} = \int_{0}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\,dE_x$$

$$P_n = \frac{\int_{S_n}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\cdot \frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma}\,dE_x}{\int_{0}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\,dE_x}$$



Beta delayed neutron emitters, example: ^{87}Br

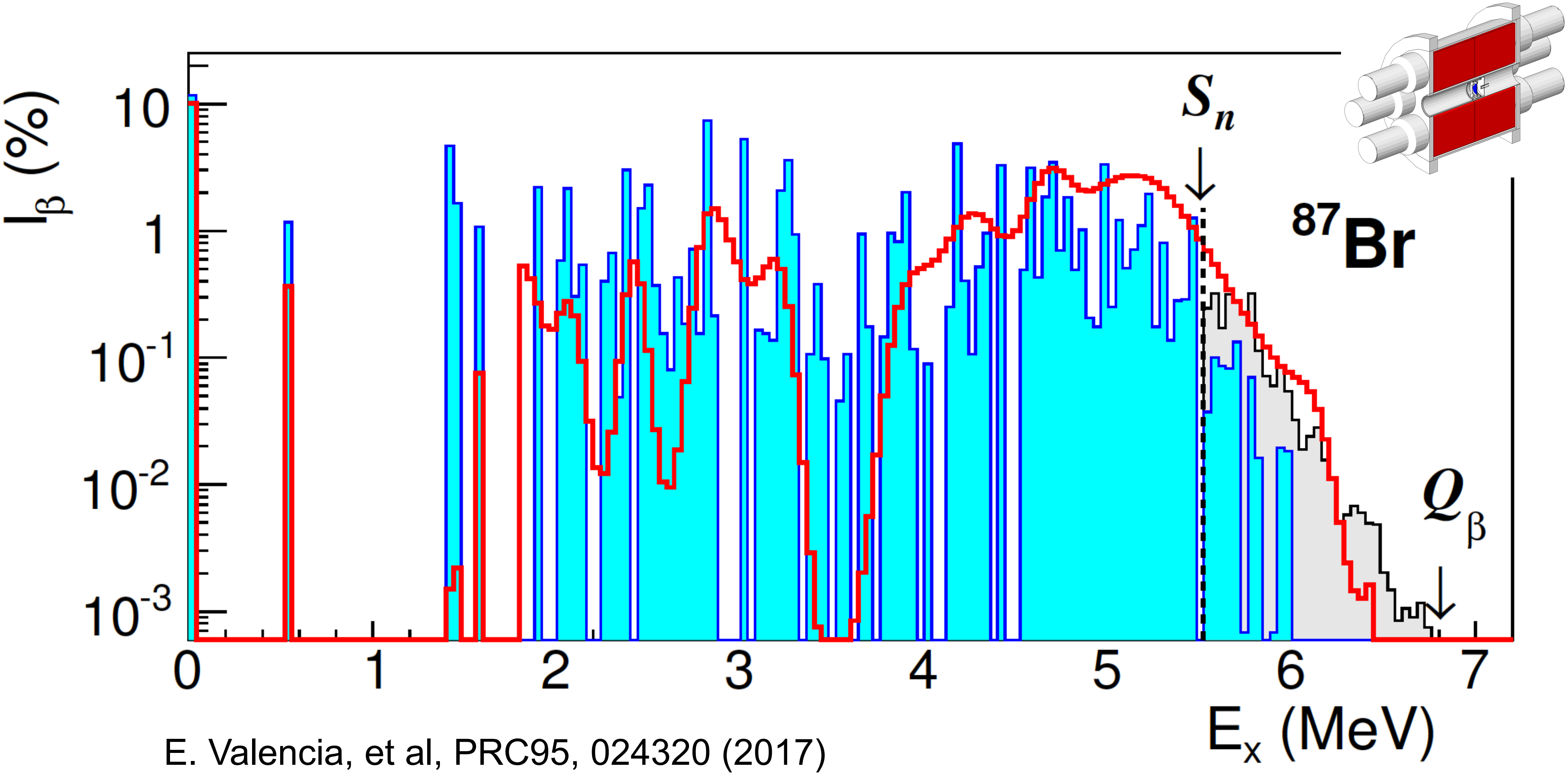




E. Valencia, et al, PRC95, 024320 (2017)

J. L. Tain et al. PRL 115, 062502

Beta delayed neutron emitters, example: 87Br



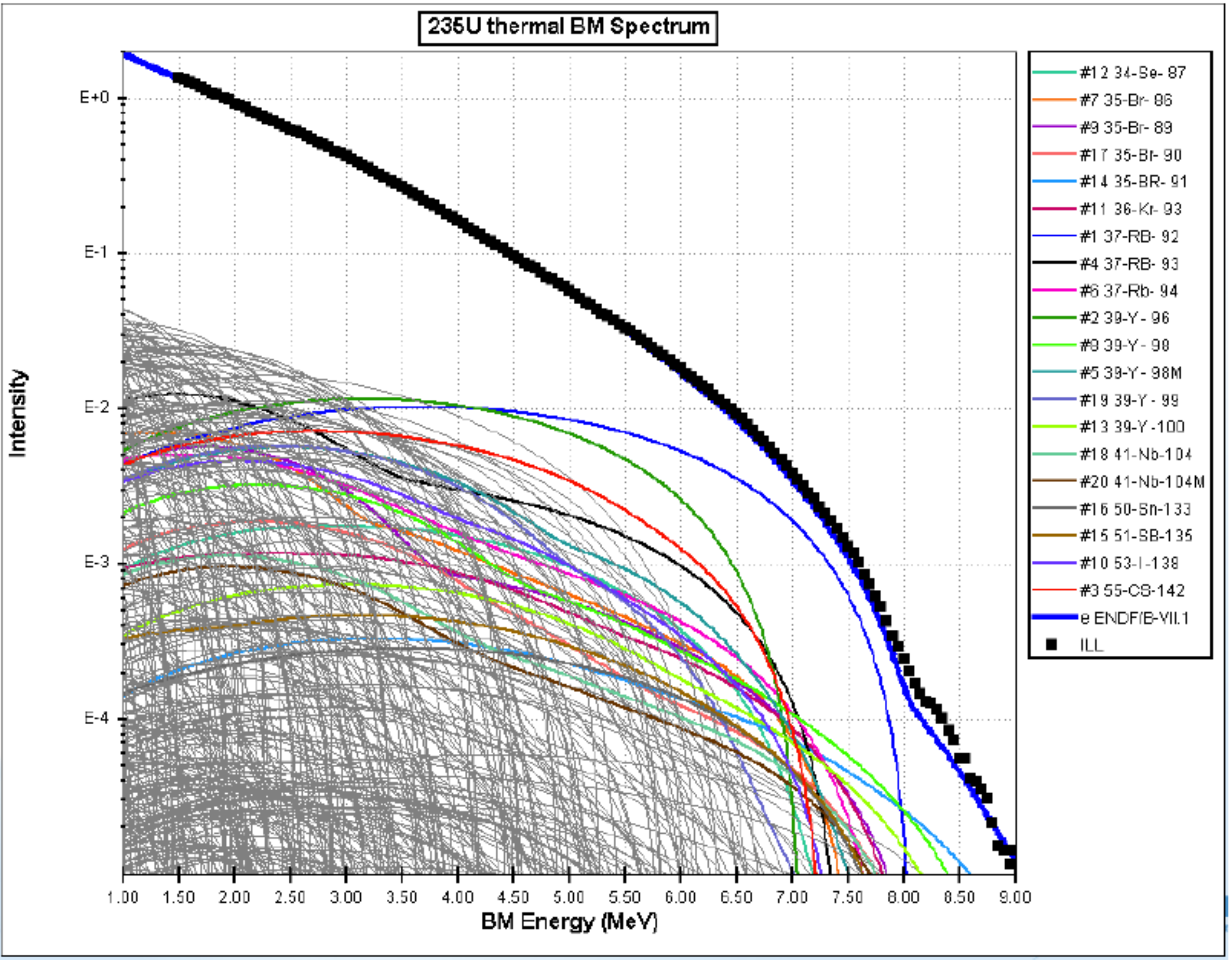
E. Valencia, et al, PRC95, 024320 (2017)
J. L. Tain et al. PRL 115, 062502

$$\frac{I_{\beta\gamma}}{I_{\beta\gamma}+I_{\beta n}} \Leftrightarrow \left\langle \frac{\Gamma_\gamma}{\Gamma_\gamma+\Gamma_n} \right\rangle$$

Pγ=3.50 (+49-40) %

Pn=2.60 (4) %

Is this feasible?: role of individual decays



How to identify
the main players

- Large cum. fission yields
- Large decay Q_{beta}
- Large beta feeding to gs

Taken from A. Sonzogni
using ENDF VII.1

75% of the spectrum can be accounted by 50 or fewer transitions (E> 3 MeV)
Sonzogni et al., PRL 119, 112501 (2017) (not all decays are equal, reminds me of G.Orwell)

^{92}Rb: star case, nuclear data matters

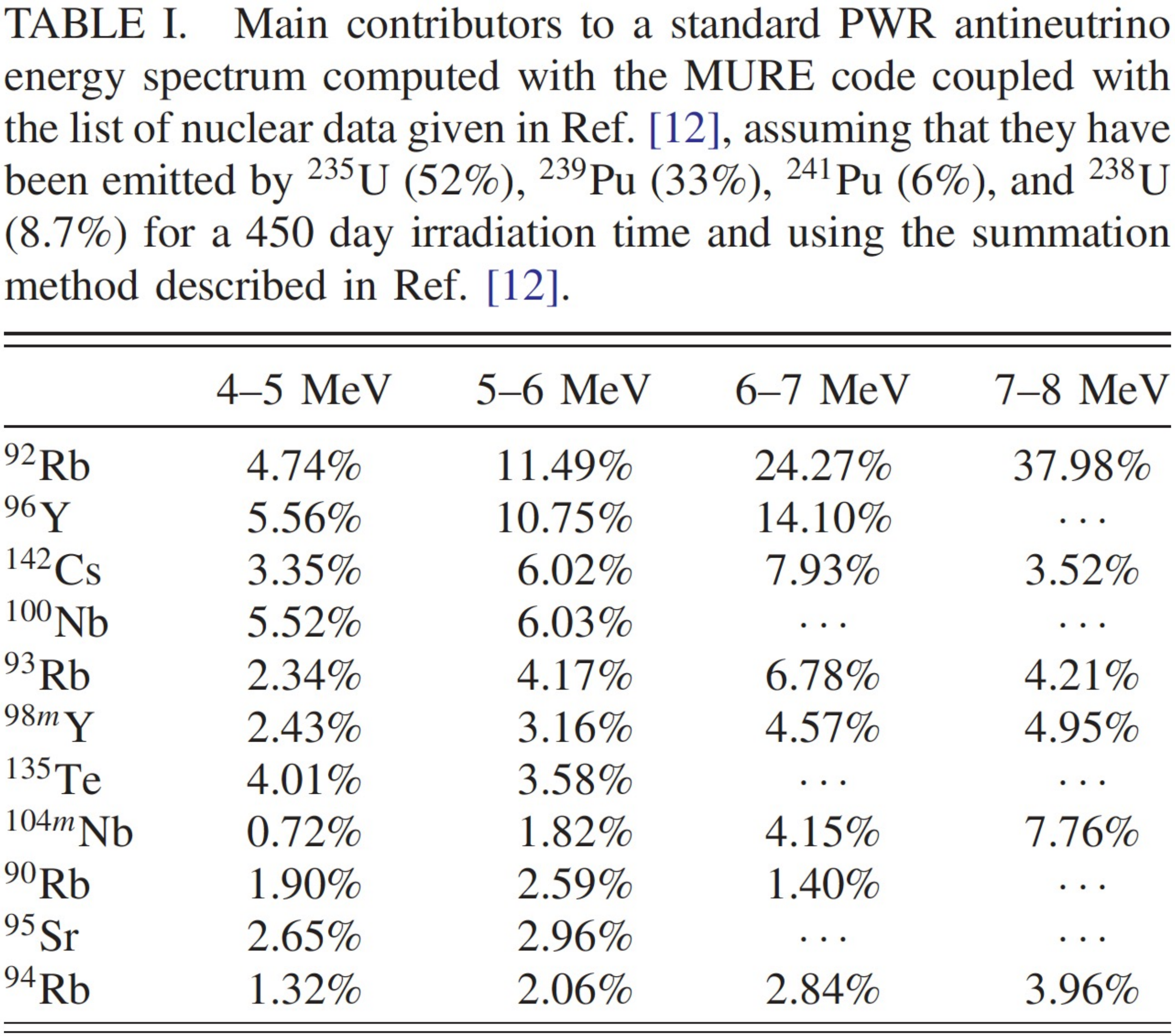


TABLE I. Main contributors to a standard PWR antineutrino energy spectrum computed with the MURE code coupled with the list of nuclear data given in Ref. [12], assuming that they have been emitted by ^{235}U (52%), ^{239}Pu (33%), ^{241}Pu (6%), and ^{238}U (8.7%) for a 450 day irradiation time and using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

Identification of the most relevant players by the Nantes Group

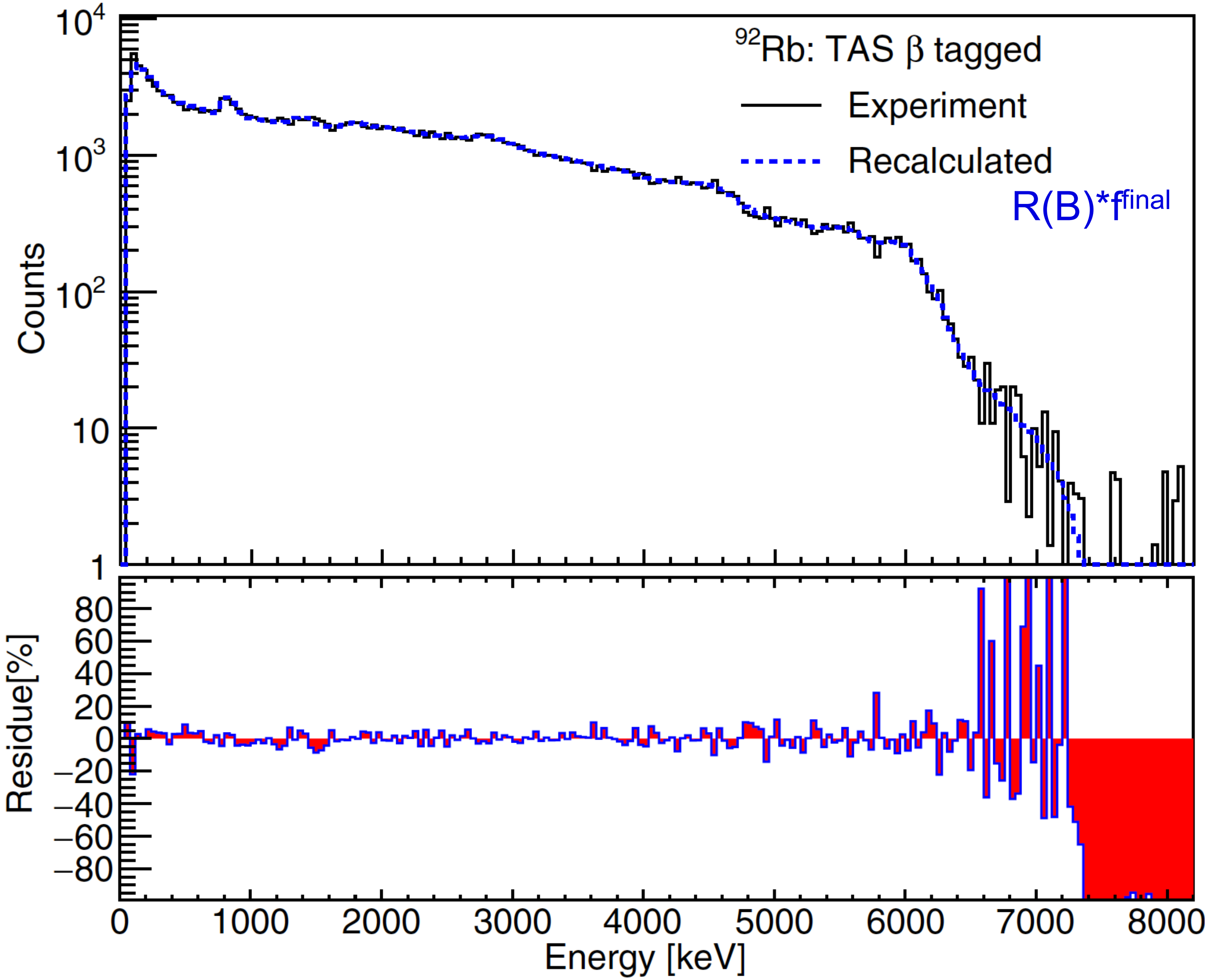
92Rb GS to GS feeding Evolution

94(+6−20)(<2000)
Olson et al.
51(18) % (<2012)
NDS 2000
95.2(7) % (2012)
NDS 2012
G. Lhersonneau
(PRC74 (2006)017308)
New experiment ????

Table from
Zakari-Issoufou et al.
PRL 115.102503(2015)

92Rb contributes alone to 16% of the spectrum in the 5-8 MeV range

^{92}Rb: TAS measurement (2009 exp.) Analized by the Nantes group

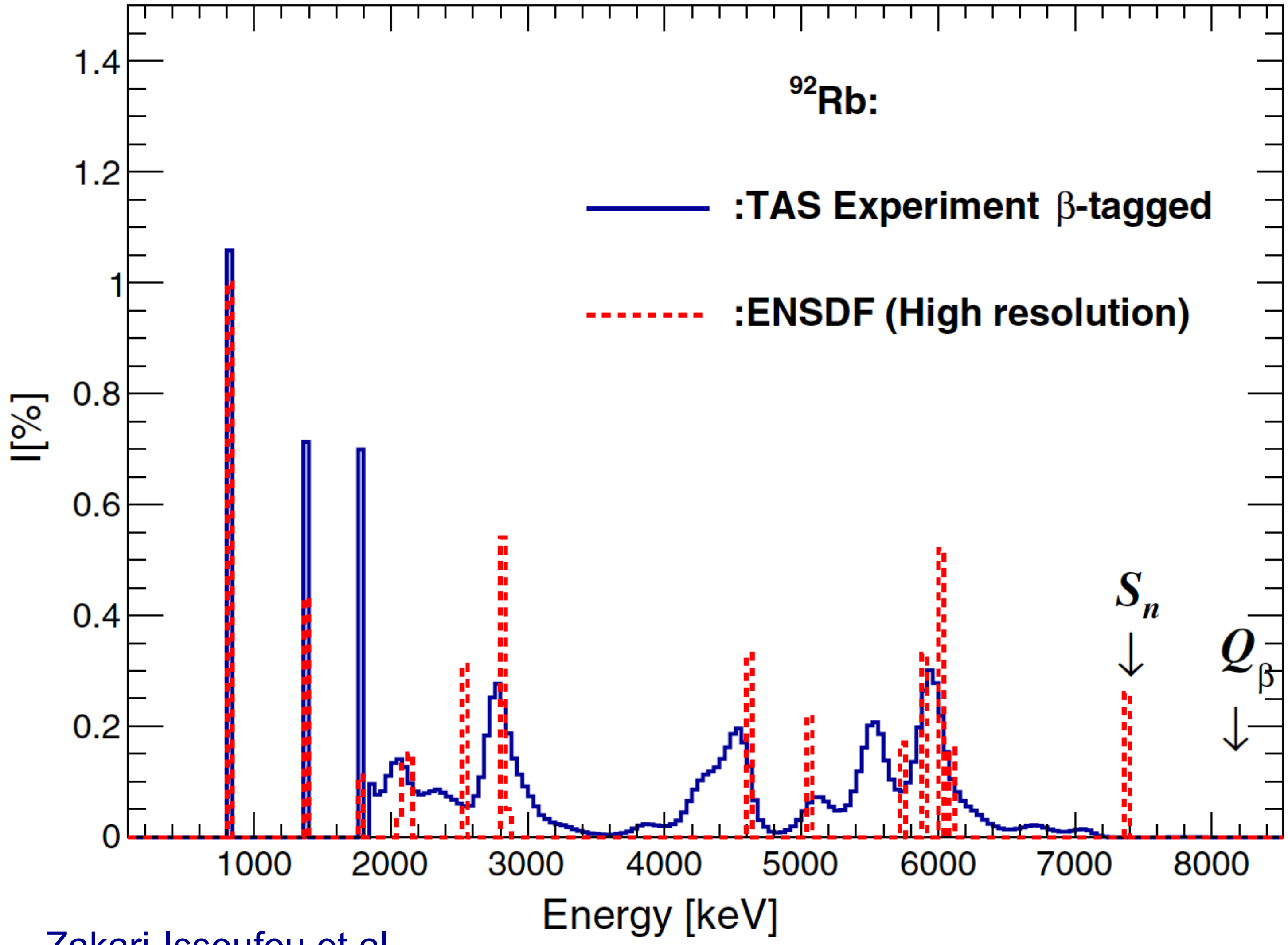


Zakari-Issoufou PhD thesis, Nantes

Zakari-Issoufou et al. PRL 115.102503(2015)

Another recent measurement by Rasco et al. PRL 117.092501 (2016) (Oak Ridge group)

92Rb: star case, not really a Pandemonium case



Gs to gs feeding Evolution

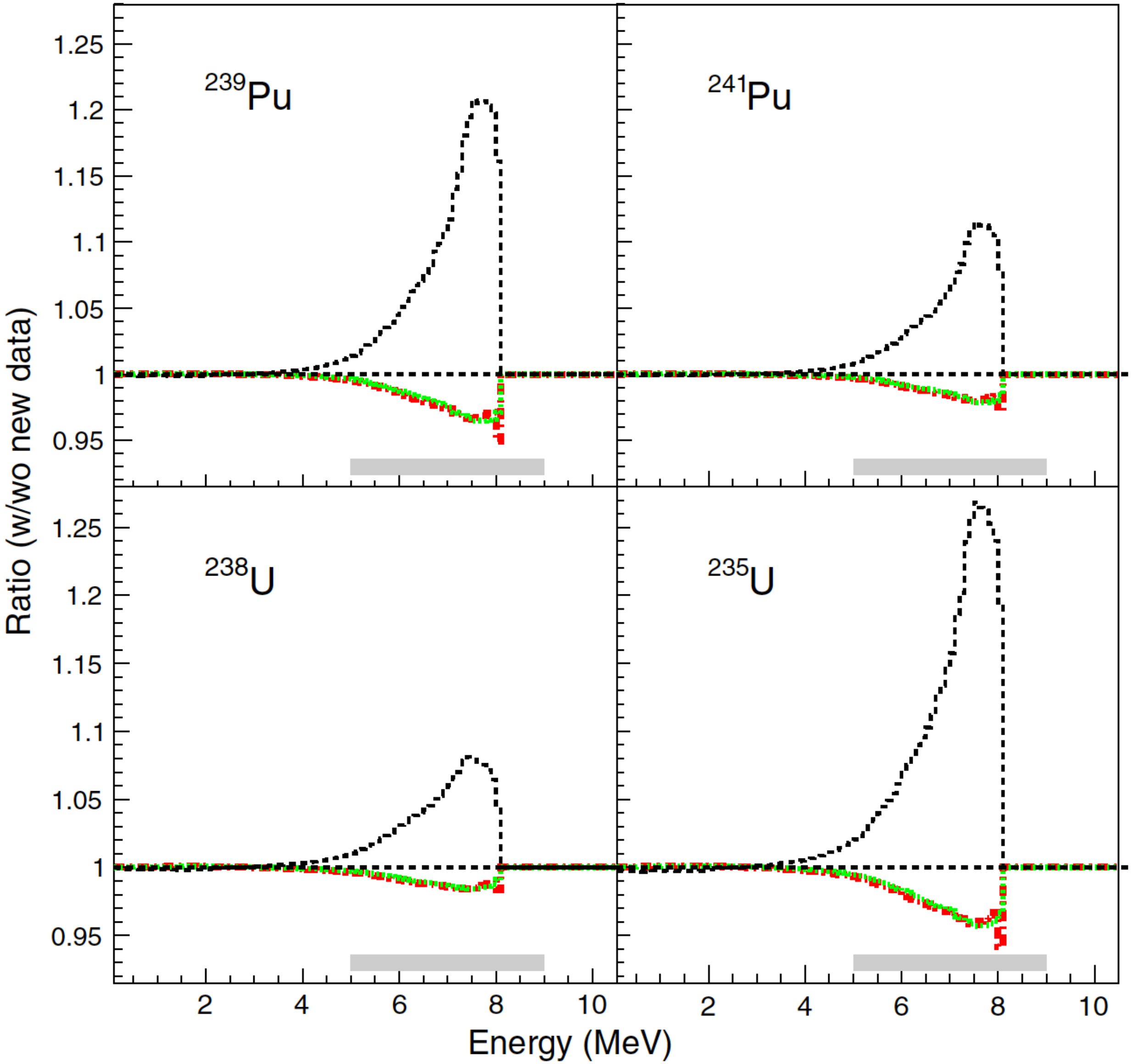
94(+6−20)(<2000)
Olson et al**.**
51(18) % (<2012)
NDS 2000
95.2(7) % (2012)
NDS 2012
G. Lhersonneau
(PRC74 (2006)017308)

87.5(2.5)% (2015)
Zakari-Issoufou et al.
PRL 115.102503(2015)
VTAS result

Later, Rasco et al.
PRL 117, 092501(2016)
91(3)%, MTAS

Zakari-Issoufou et al.
PRL 115.102503(2015)

^{92}Rb: comparison of the impact with respect to earlier used gs to gs feeding values



92Rb impact
Zakari-Issoufou et al.
PRL 115.102503(2015)

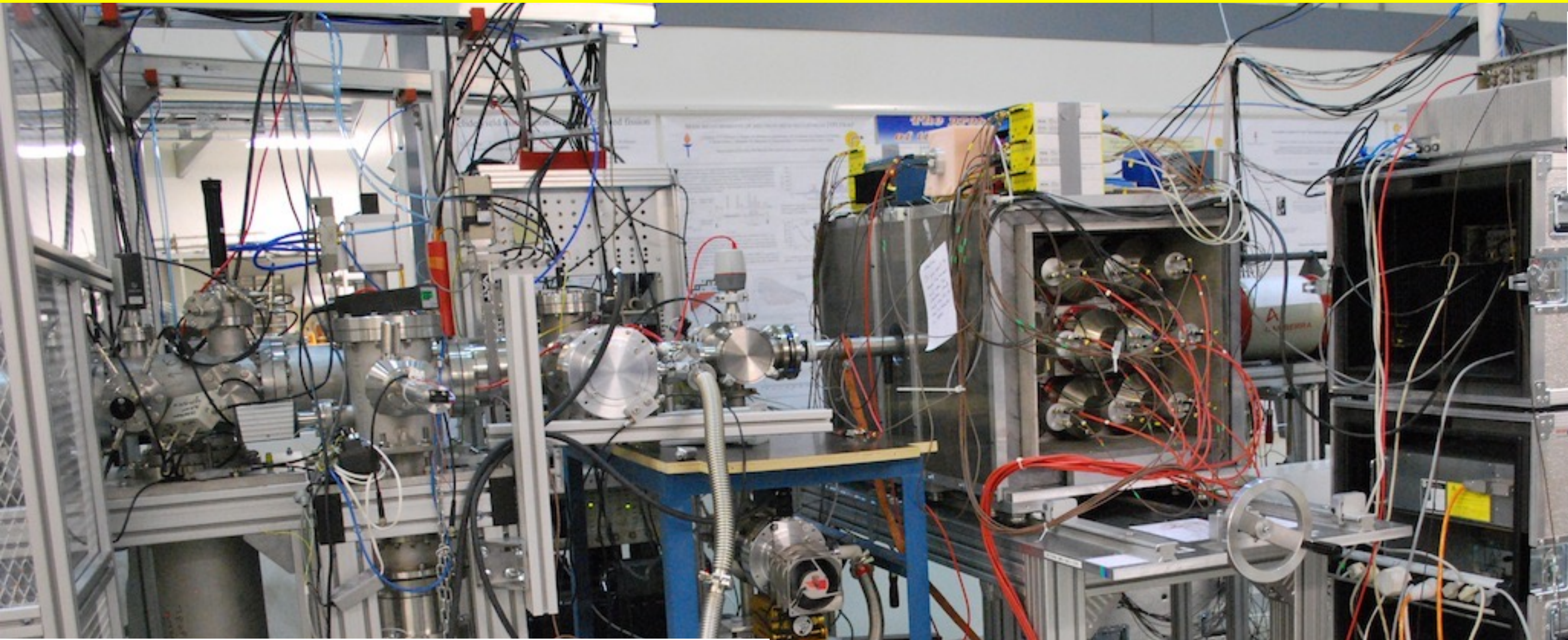
Black: with respect to the value used in D. A. Dwyer et al. PRL 114,012502 (used 51% gs feeding, earlier ENSDF)

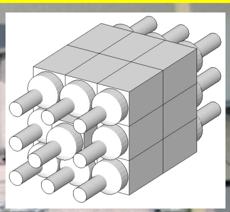
Green: with respect to A. A. Sonzogni et al. PRC 91, 011301(R) (used 95 % gs feeding)

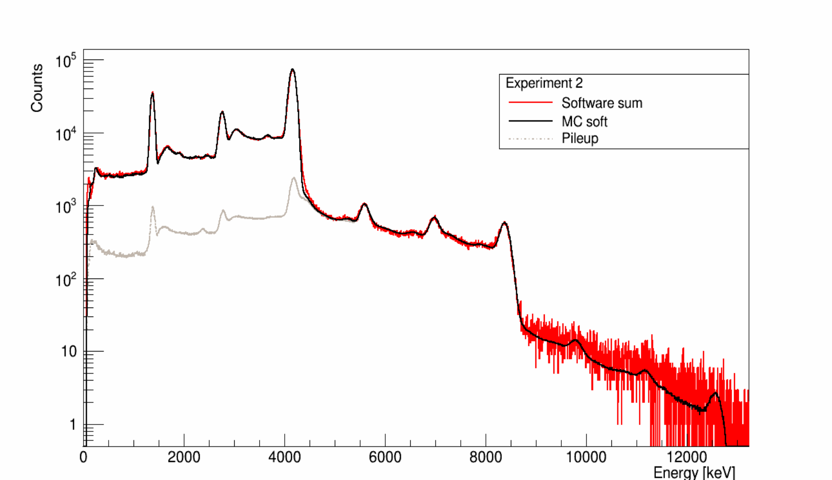
Red: with respect to M. Fallot et al., PRL 109, 202504 (previously Rudstam data was used)

DTAS at Jyväskylä (Feb. 2014)

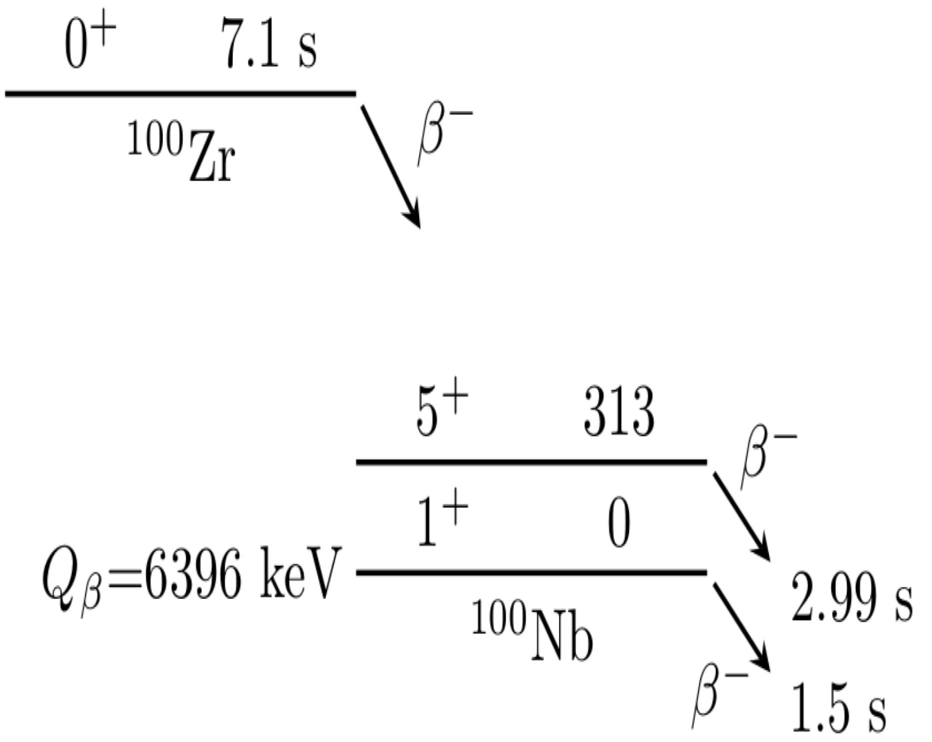
(collaboration with Subatech, spokespersons: Fallot, Tain, Algora)

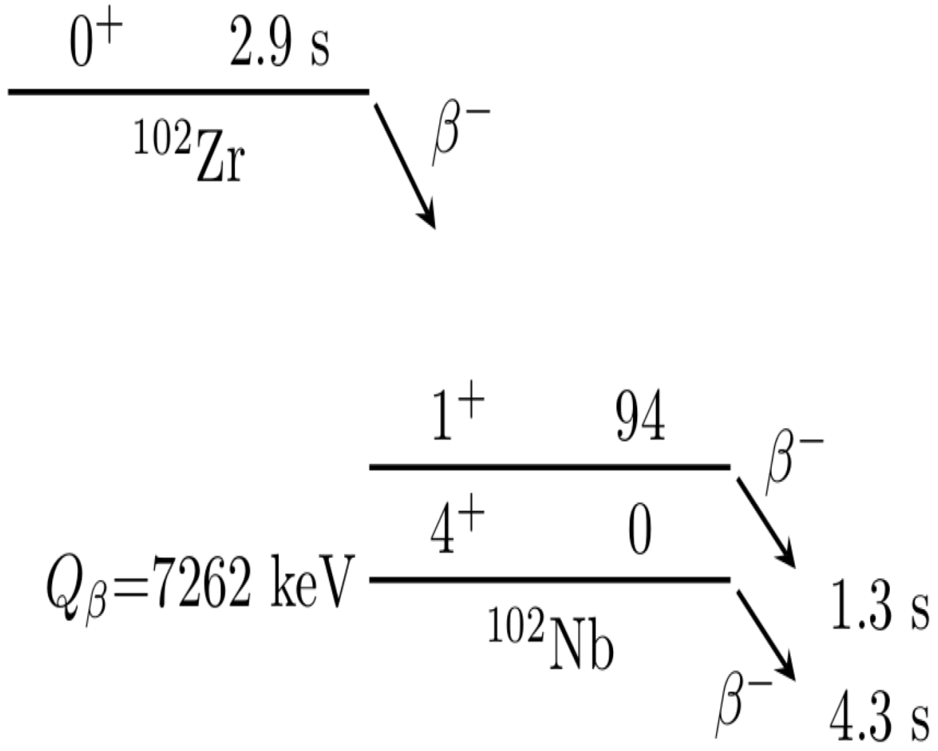






Example: the challenging ^{100,102}Nb cases (from 18(+5) relevant decays measured)



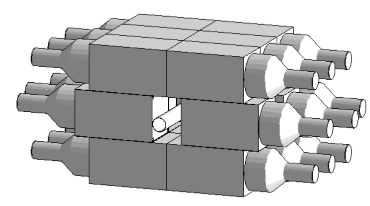


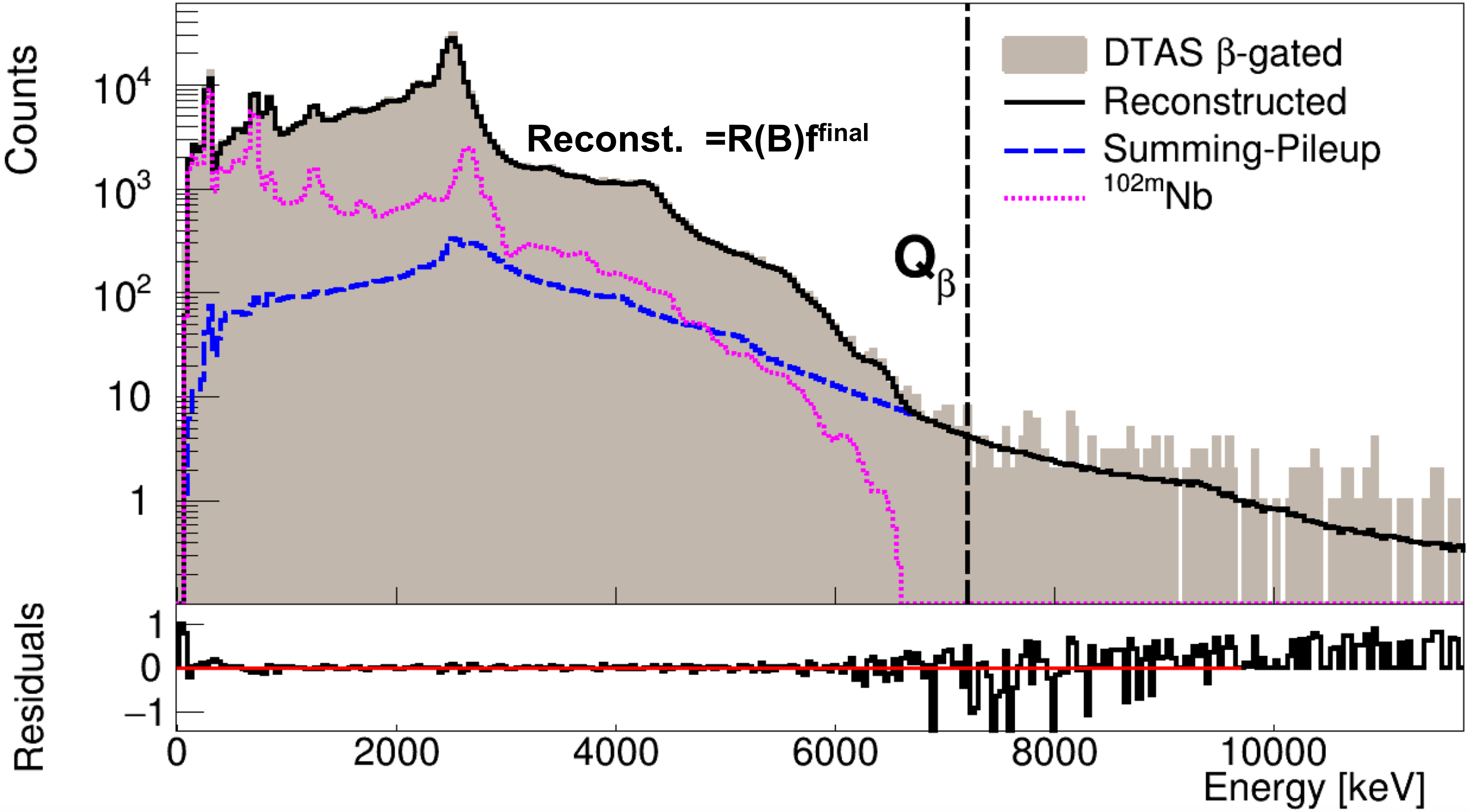
CFY of the order of 5%
and ~1 % respectively
(for both 235U and 239Pu)

Challenge: small separation energy, similar half-lives

Tricks: Production through the parent, purification cycles in the Penning Trap (Ramsey cleaning), separation using different sorting times

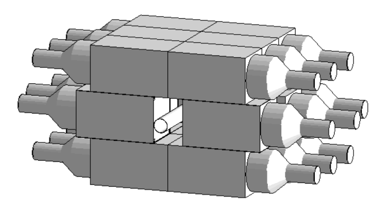
^{102gs}Nb decay (4+ state)

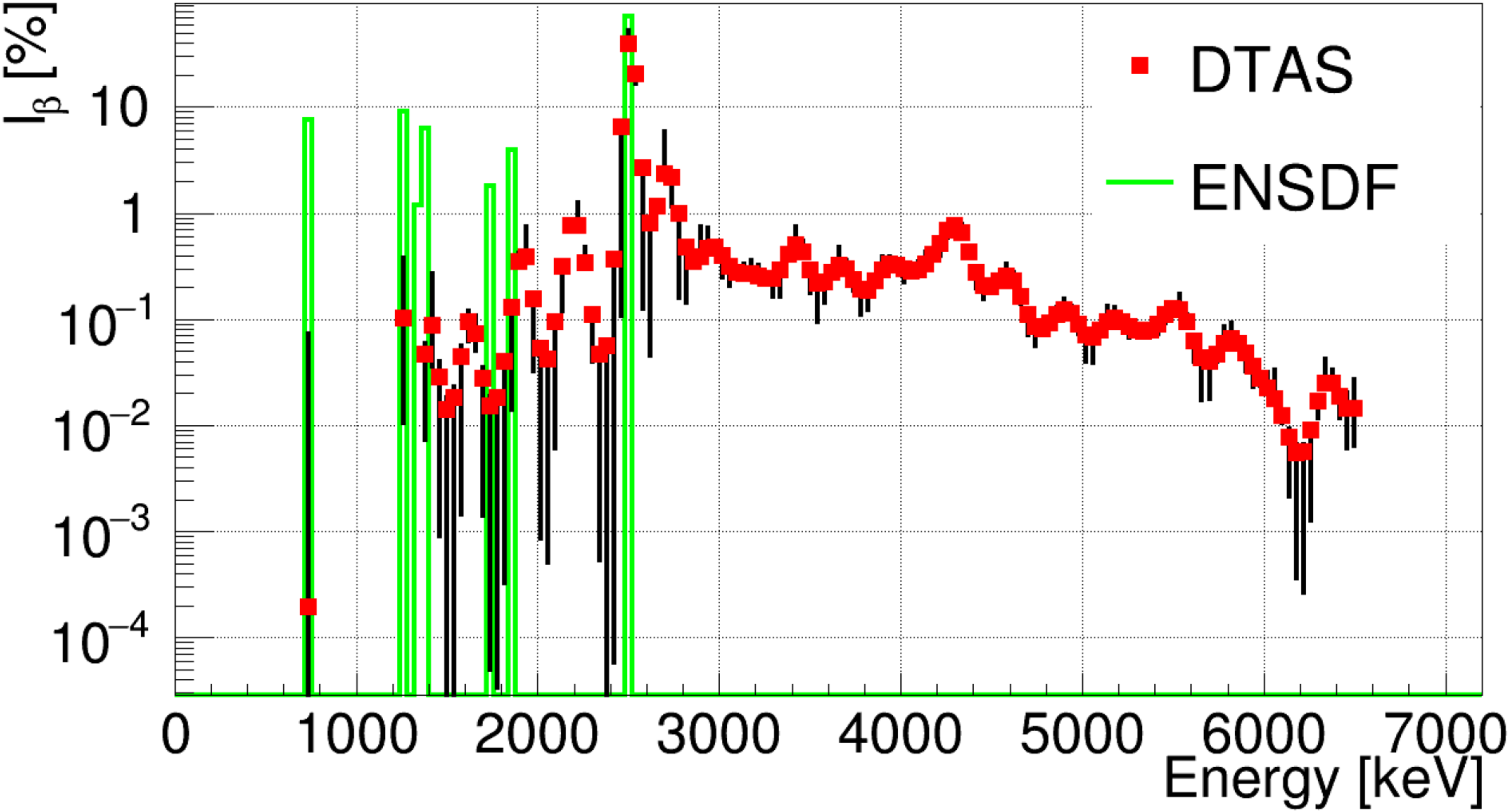




V. Guadilla et al., PhD thesis and V. Guadilla et al., PRL 112.042502

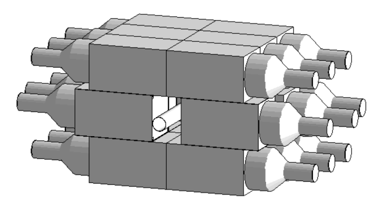
^{102gs}Nb decay (4+ state)

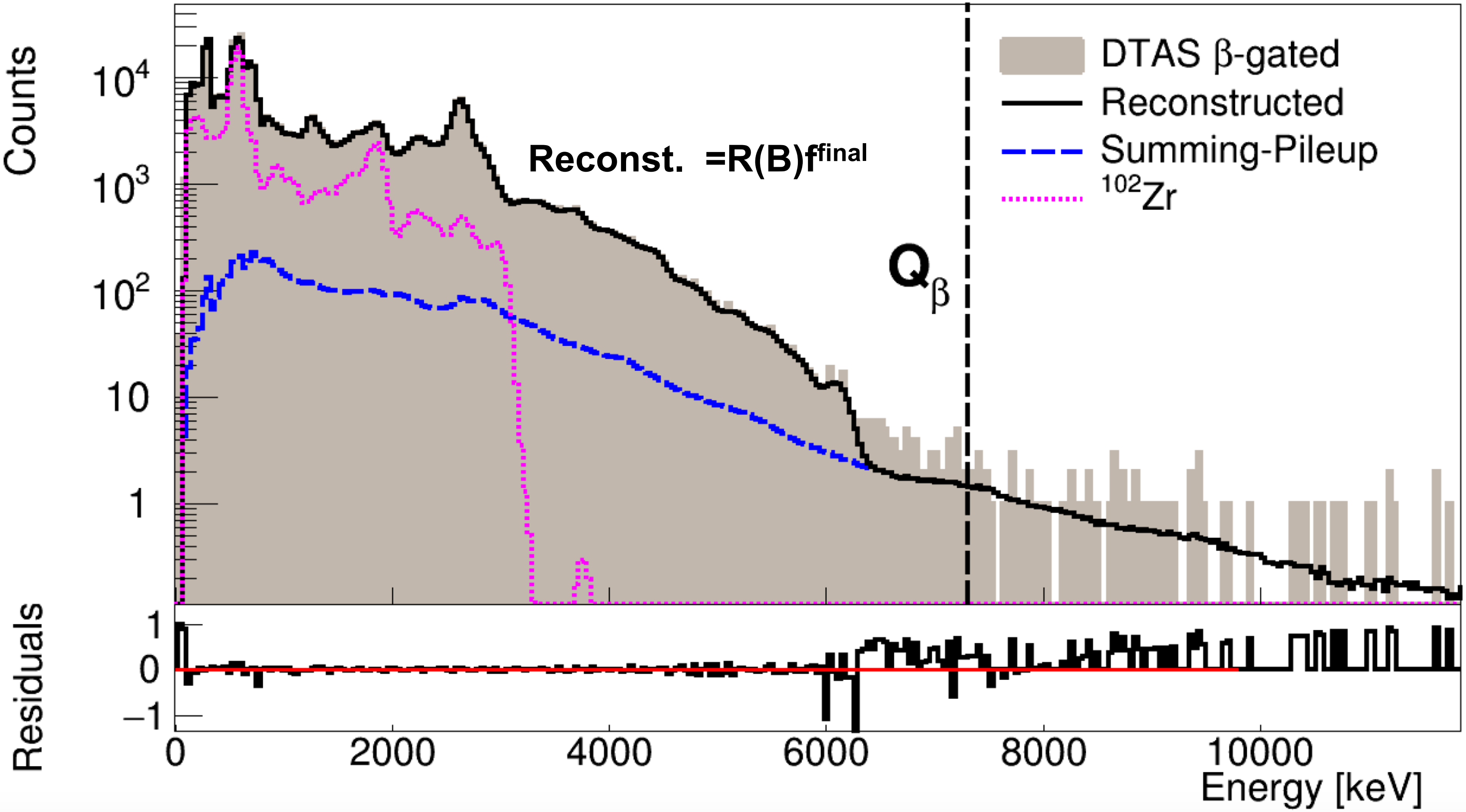




V. Guadilla et al., PRL 112.042502

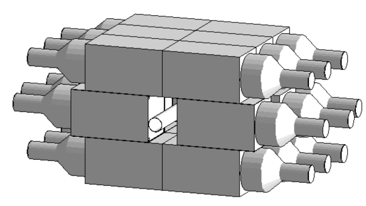
^{102m}Nb decay (1+ state, 94 keV)

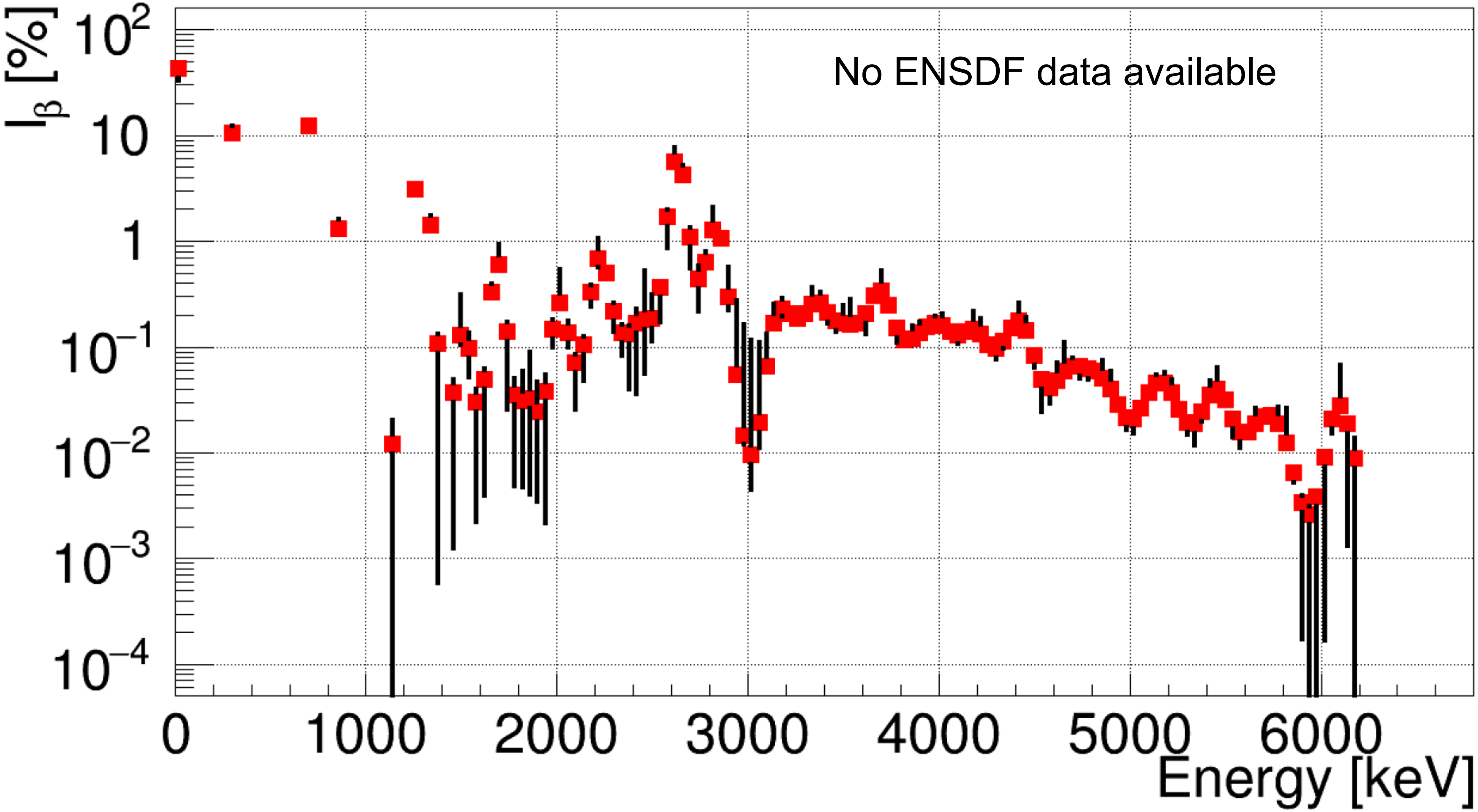




V. Guadilla et al., PhD thesis

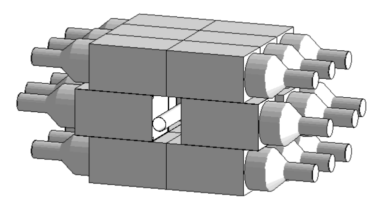
^{102m}Nb decay (1+ state, 94 keV)



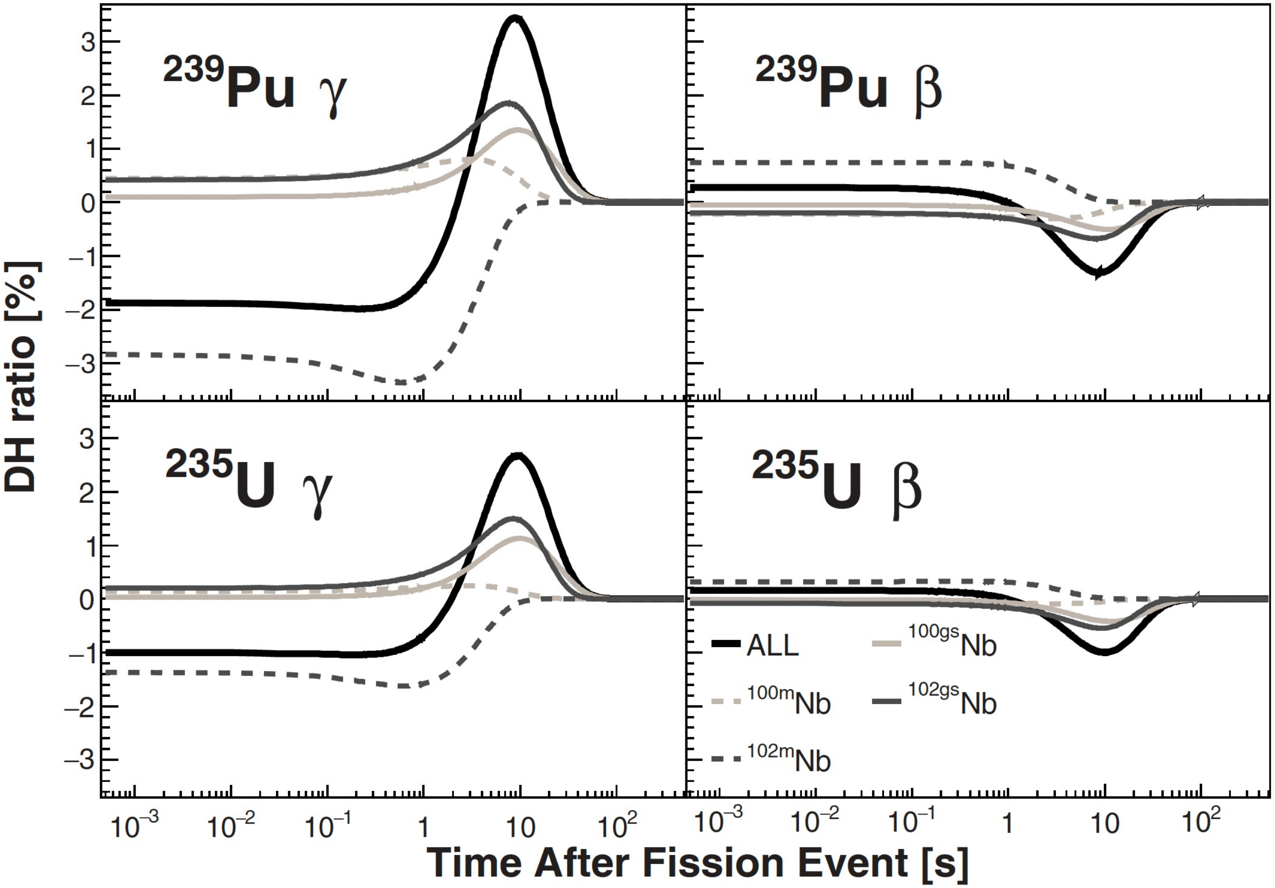


V. Guadilla et al., PRL 112.042502

Impact on the decay heat summation calculations



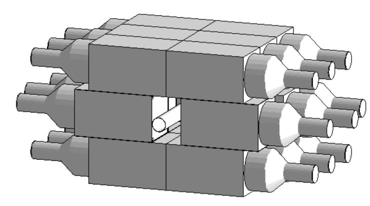
DH summation calculation Courtesy of A. Sonzogni PhD thesis of V. Guadilla



Impact of the 4 new Nb decay studies, with decaying isomers.

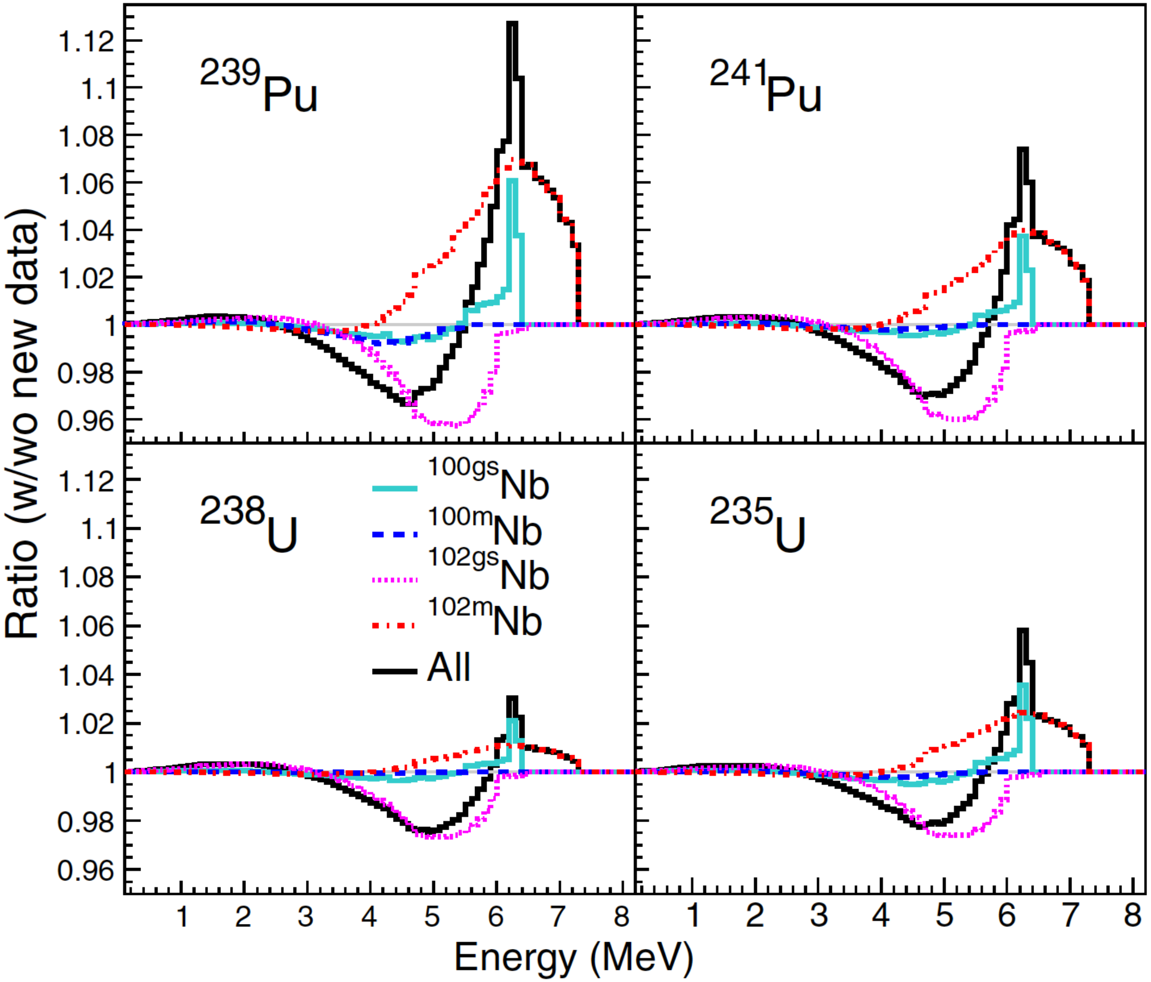
V. Guadilla et al., PRC 100, 024311 (2019)

Impact on the neutrino summation calculations



Neutrino summation calculation
Courtesy of M. Fallot, M. Estienne et al, PhD thesis of V. Guadilla

Impact of the 4 new Nb decay studies, with decaying isomers.
Large impact in the region of the spectral distortion !!!

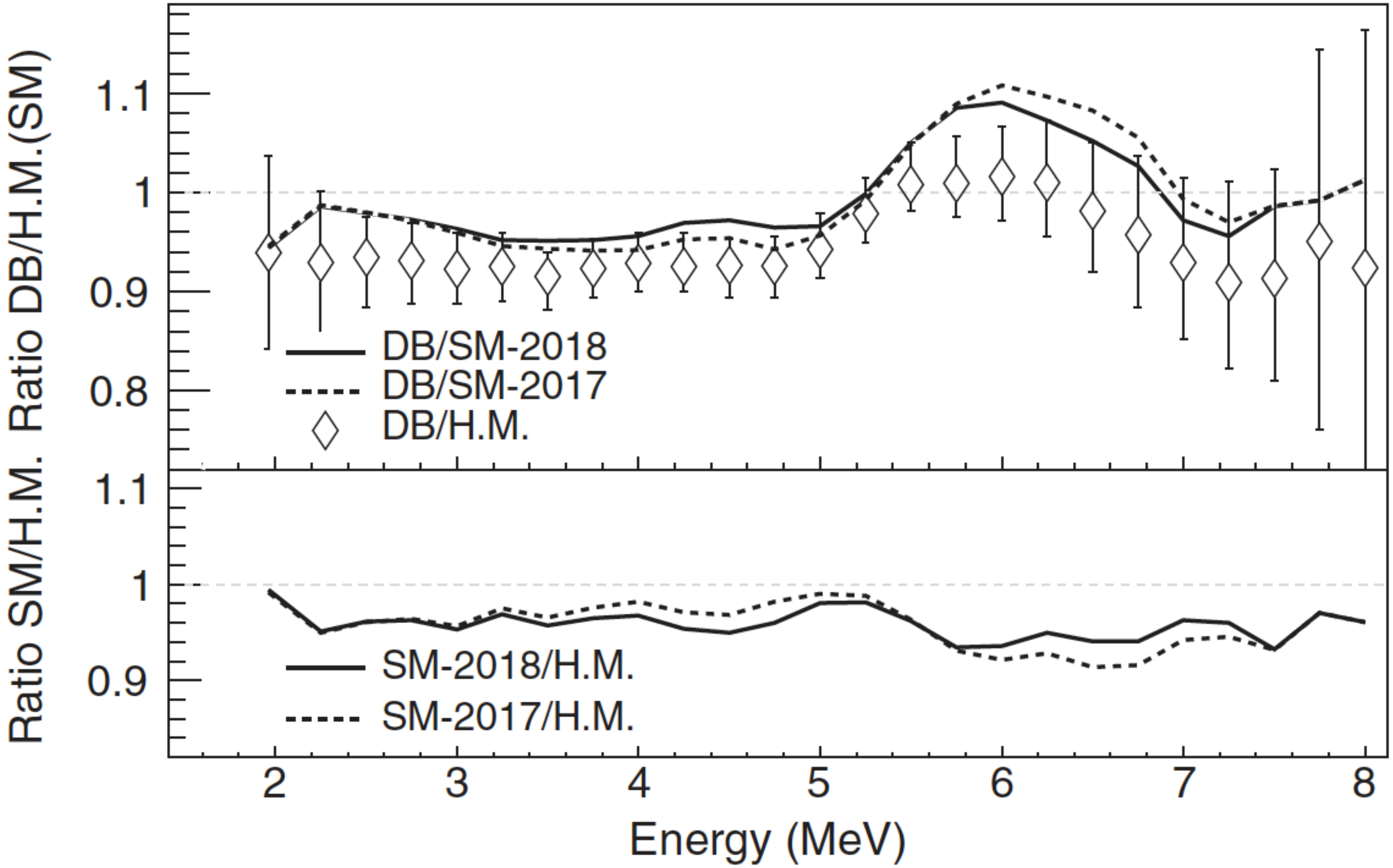


V. Guadilla et al., PRL 112.042502

Is the reactor anomaly dead?

Results from the application of a new summation calculation including all our TAS measurements. The discrepancy with the antineutrino meas. within this model is of the order of 2 %

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

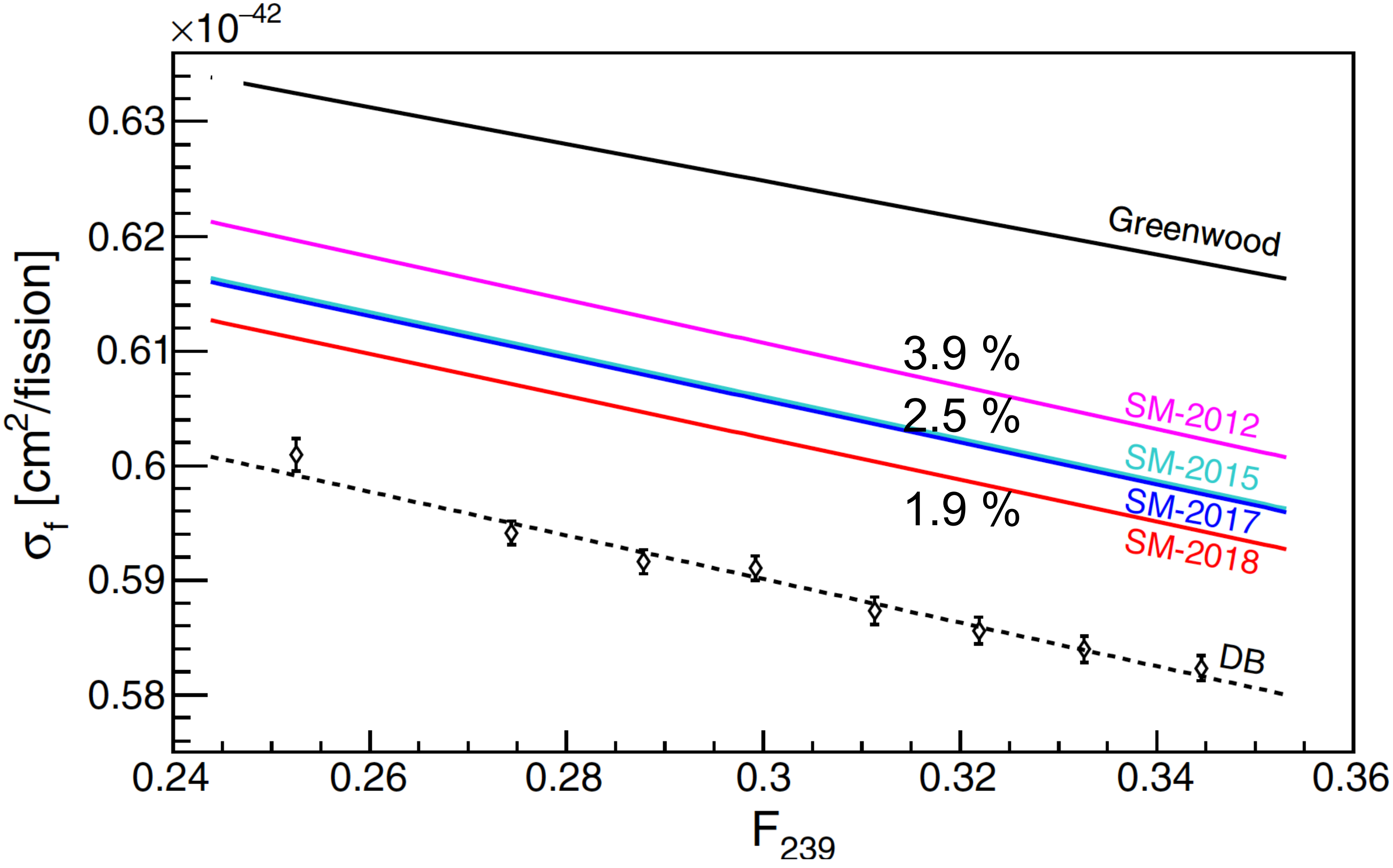


Subatech Calculations Estienne, Fallot, et al.

Summation is slightly better than the Hueber-Mueller conversion in the 2-5 MeV range,

Reactor anomaly?

Effect of the successive inclusion of TAS data (Pandemonium free data) in the summation model (flux)



Careful selection of the pandemonium free data + TAS data

SM-2012: ^{102,104,105,106,107}Tc, ^{105}Mo, and ^{101}Nb

SM-2015: ^{92,94}Rb, and ^{87,88}Br

SM-2017: ^{91}Rb, ^{86}Br

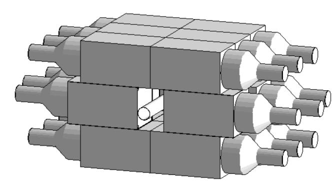
SM-2018: ^{100,100m,102,102m}Nb

DB: Daya Bay

$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \bar{F}_{239}).$$

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

A new method for determining the gs to gs feeding

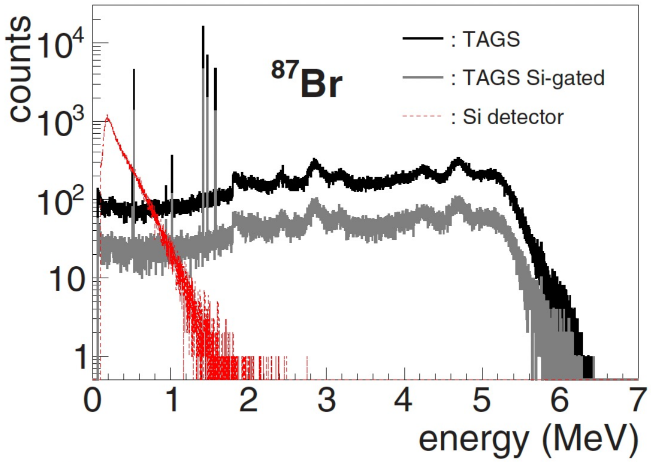


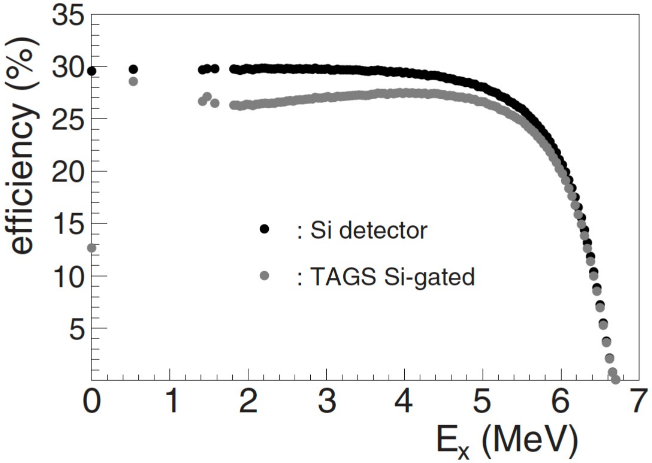
Based on a comparison of the number of counts detected in the beta detector（N_β）with the number of counts detected in the TAS in coincidence with the betas ($N_{\beta\gamma}$)

$$I_\beta^0 = \frac{1 - \frac{N_{\beta\gamma}}{N_\beta}\frac{\bar{\varepsilon}_\beta^*}{\bar{\varepsilon}_{\beta\gamma}^*}}{1 + \frac{N_{\beta\gamma}}{N_\beta}\frac{\varepsilon_\beta^0 - \bar{\varepsilon}_\beta^*}{\bar{\varepsilon}_{\beta\gamma}^*} - \frac{\varepsilon_{\beta\gamma}^0}{\bar{\varepsilon}_{\beta\gamma}^*}}.$$

ε_β^*, $\varepsilon_{\beta\gamma}^*$ are average efficiencies to excited states

ε_β^0, $\varepsilon_{\beta\gamma}^0$ average efficiencies to gs



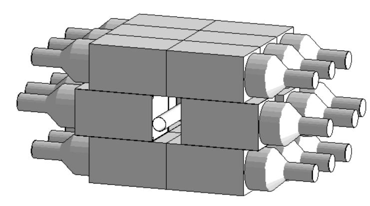


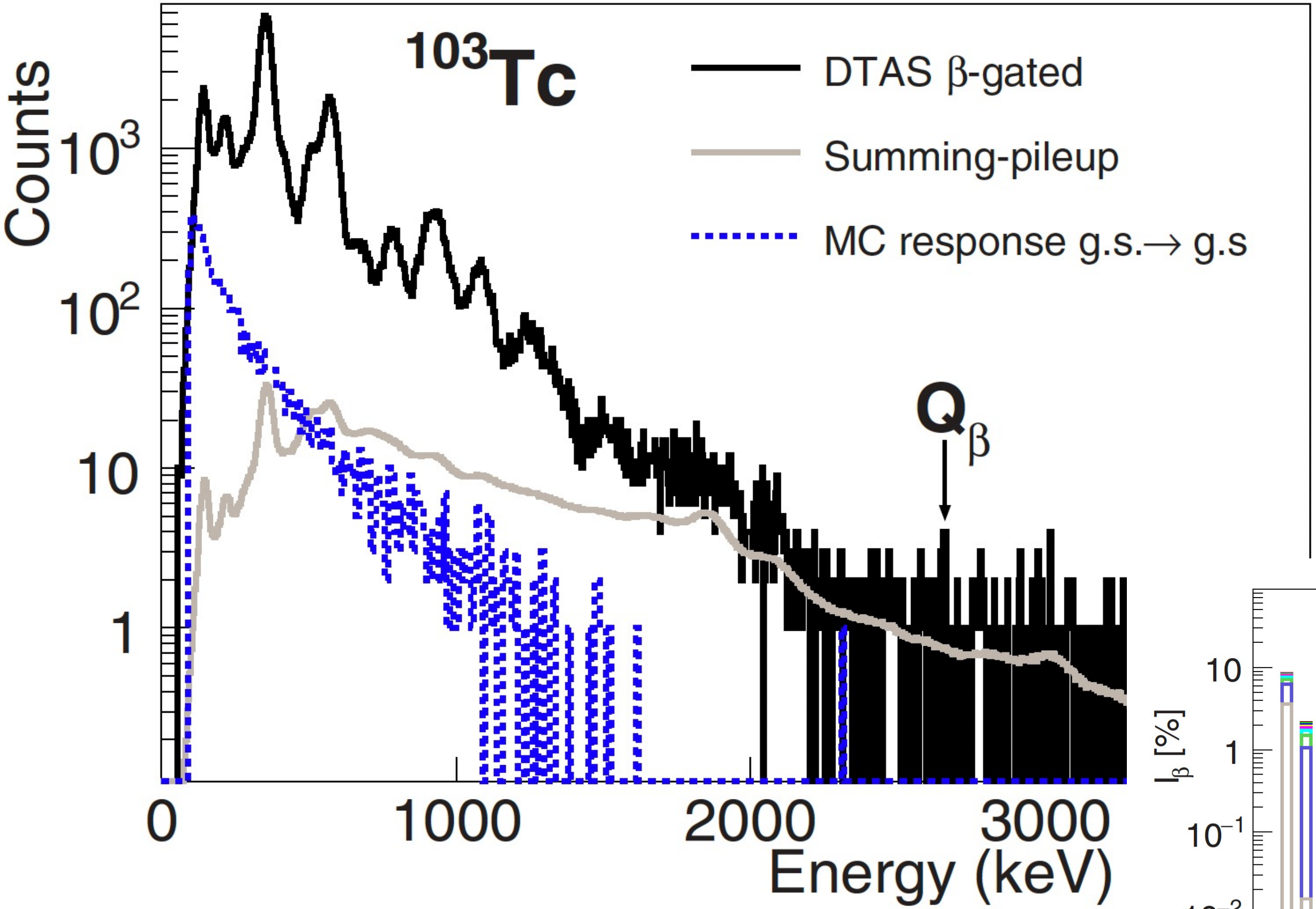
Corrected form in comparison with the earlier work of Greenwood et al. NIM A317 (1992) 175

The method was tested with synthetic data.

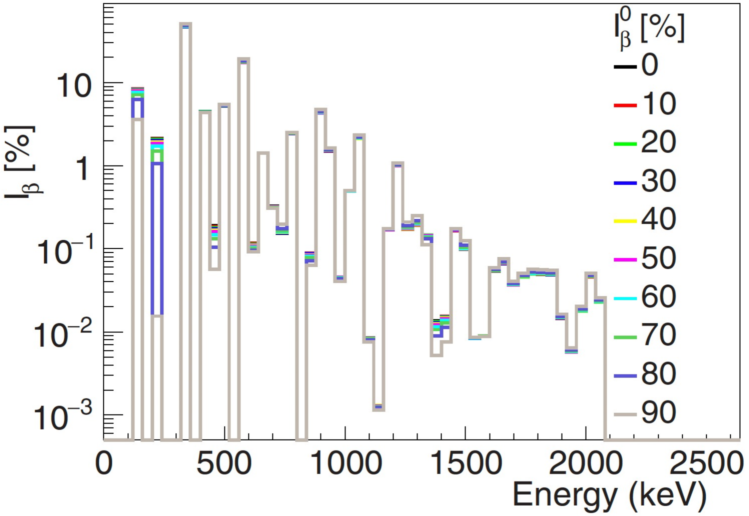
Guadilla et al. PRC 102, 064304 (2020)

^{103}Tc decay (an odd TAGS case)



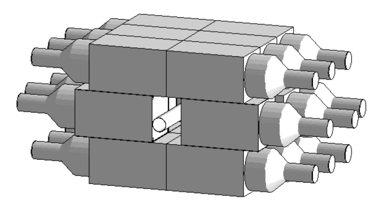


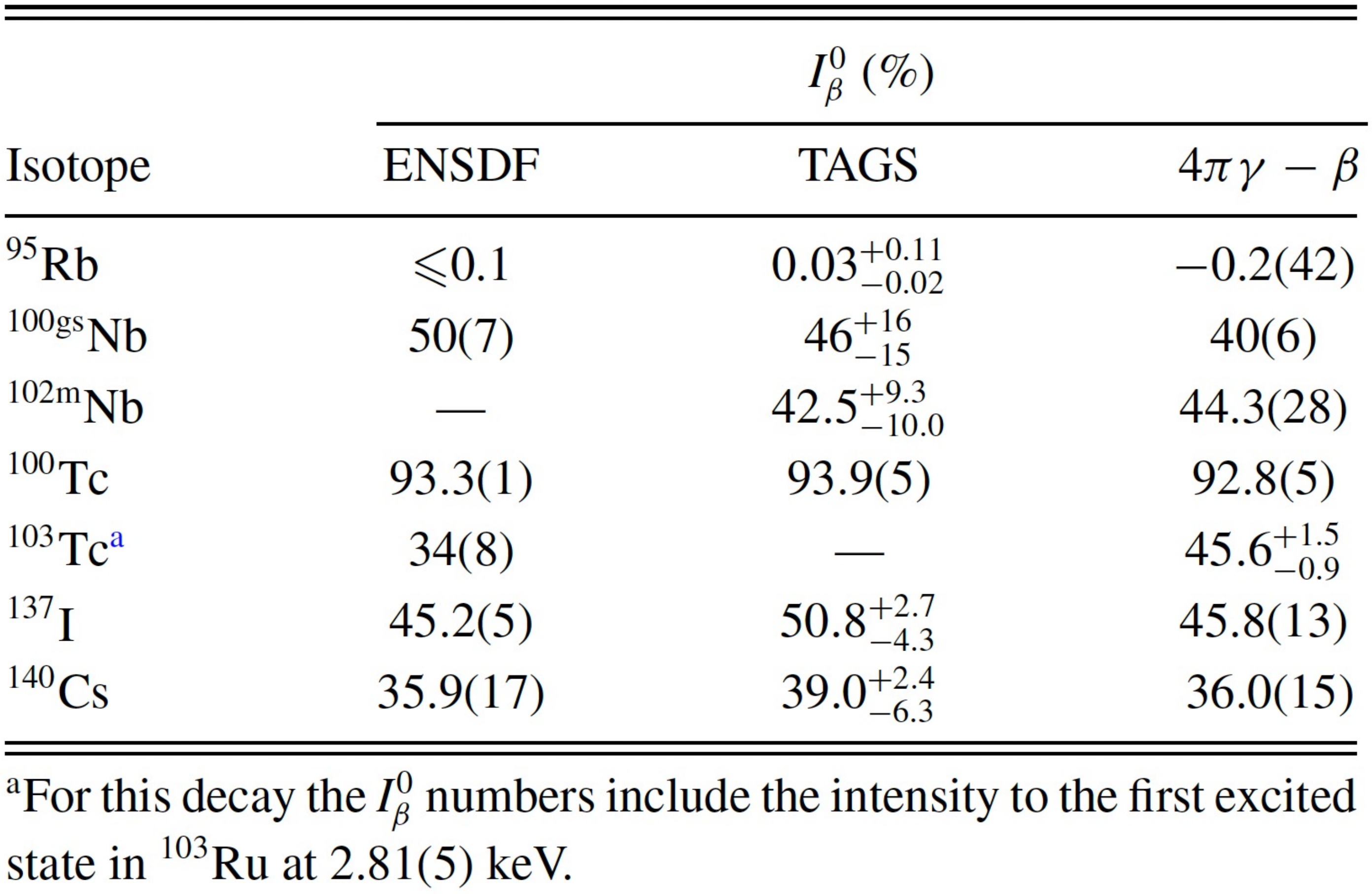
TAGS analysis insensitive to the assumed ground state feeding



Guadilla et al. PRC 102, 064304 (2020)

Ground state feedings obtained the new method





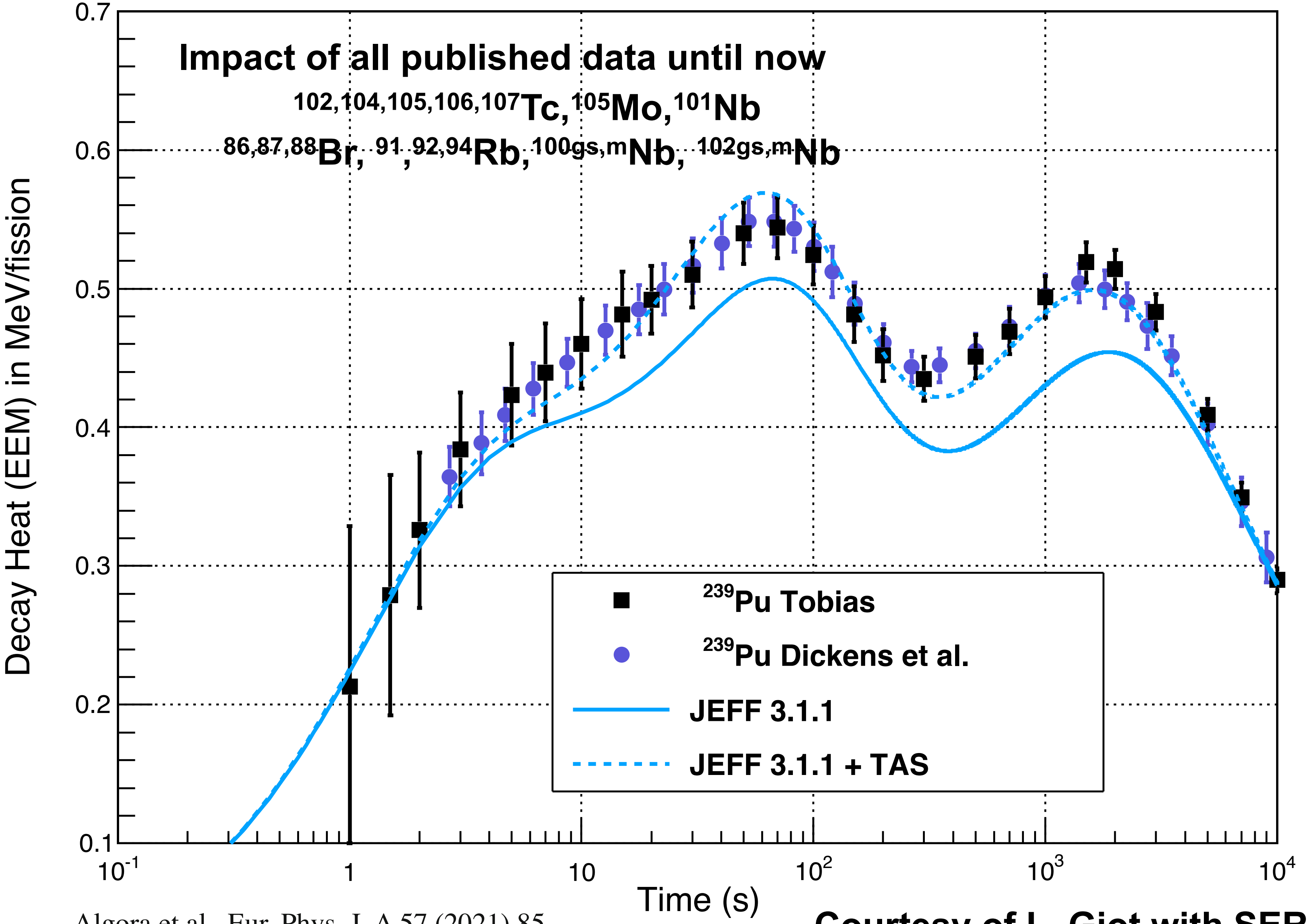
Isotope	I_β^0 (%) ENSDF	 TAGS	 $4\pi\gamma-\beta$
^{95}Rb	$\leqslant 0.1$	$0.03^{+0.11}_{-0.02}$	$-0.2(42)$
^{100gs}Nb	50(7)	46^{+16}_{-15}	40(6)
^{102m}Nb	—	$42.5^{+9.3}_{-10.0}$	44.3(28)
^{100}Tc	93.3(1)	93.9(5)	92.8(5)
^{103}Tc[a]	34(8)	—	$45.6^{+1.5}_{-0.9}$
^{137}I	45.2(5)	$50.8^{+2.7}_{-4.3}$	45.8(13)
^{140}Cs	35.9(17)	$39.0^{+2.4}_{-6.3}$	36.0(15)

[a] For this decay the I_β^0 numbers include the intensity to the first excited state in ^{103}Ru at 2.81(5) keV.

Reduced uncertainties and consistency with the TAGS results

Guadilla et al. PRC 102, 064304 (2020)

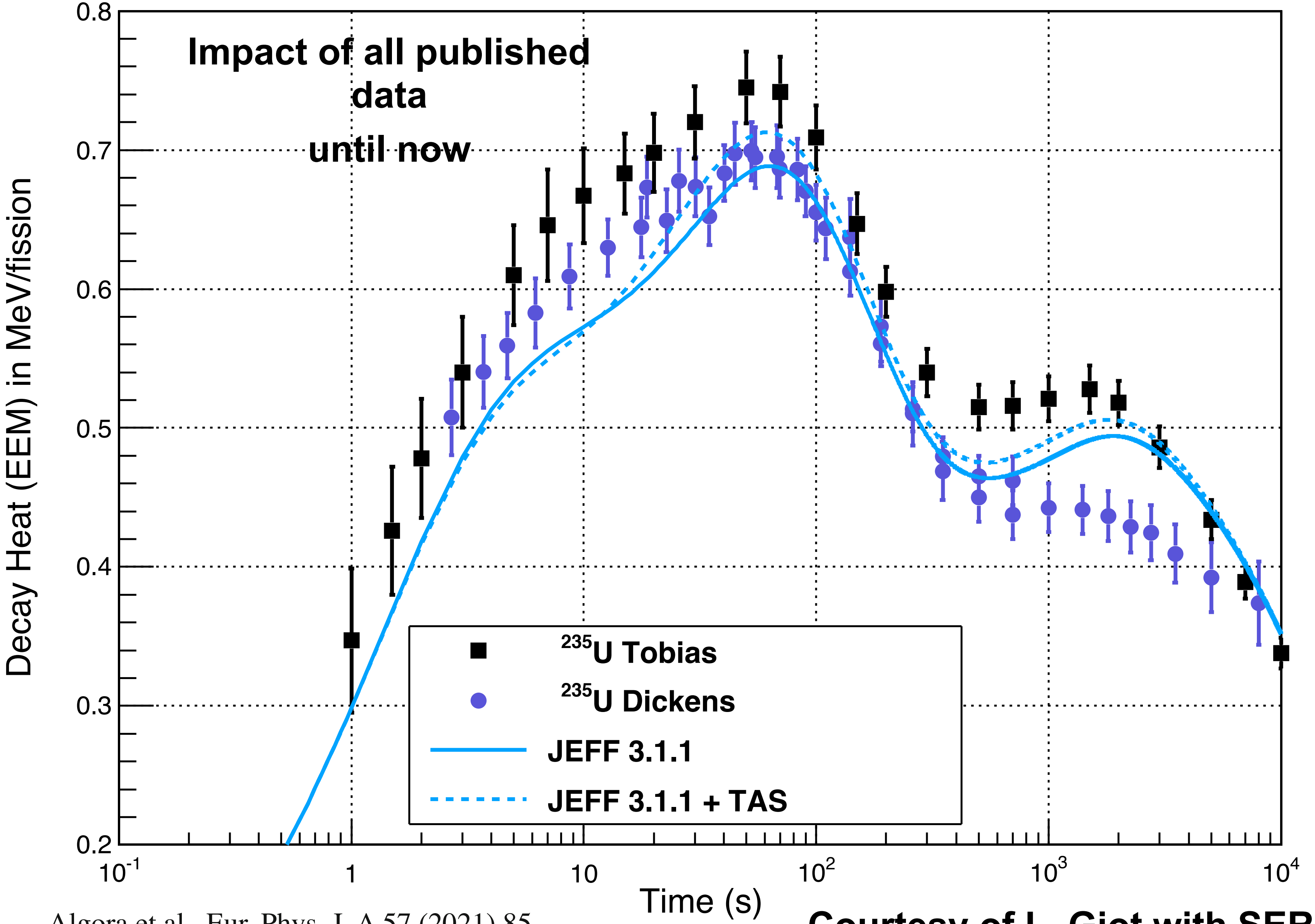
Impact of the measurements for ^{239}Pu



Algora et al., Eur. Phys. J. A 57 (2021) 85

Courtesy of L. Giot with SERPENT

Impact of the measurements for ^{235}U



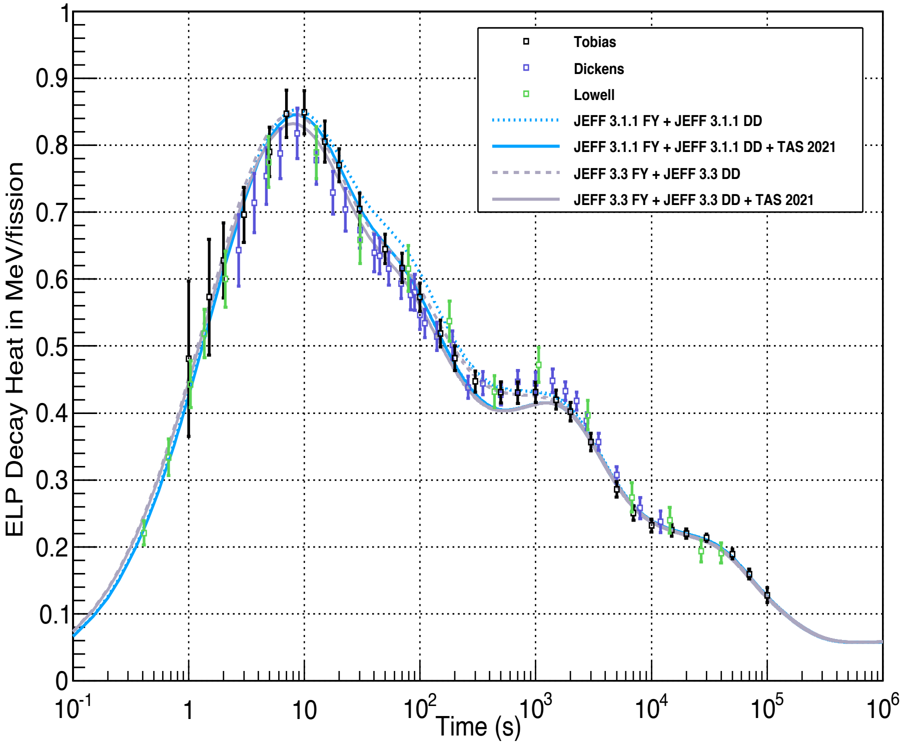
Algora et al., Eur. Phys. J. A 57 (2021) 85

Courtesy of L. Giot with SERPENT

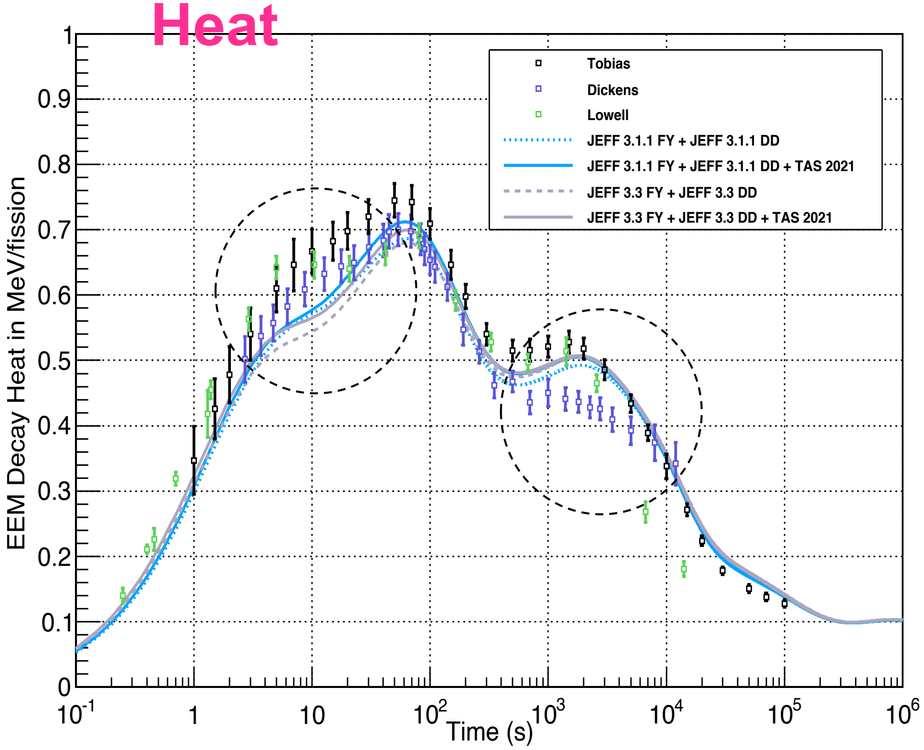
III. TAGS measurements and Impact

$^{235}U_{thermal}$

Light Particles Heat



Electromagnetic Heat



28 TAGS measurements added to JEFF3.1.1 ref lib

19 TAGS measurements added to JEFF3.3 ref lib (^{87}Br, ^{88}Br, ^{92}Rb, ^{94}Rb, ^{105}Mo, ^{104,105,106,107}Tc already included)

IAEA Report in preparation

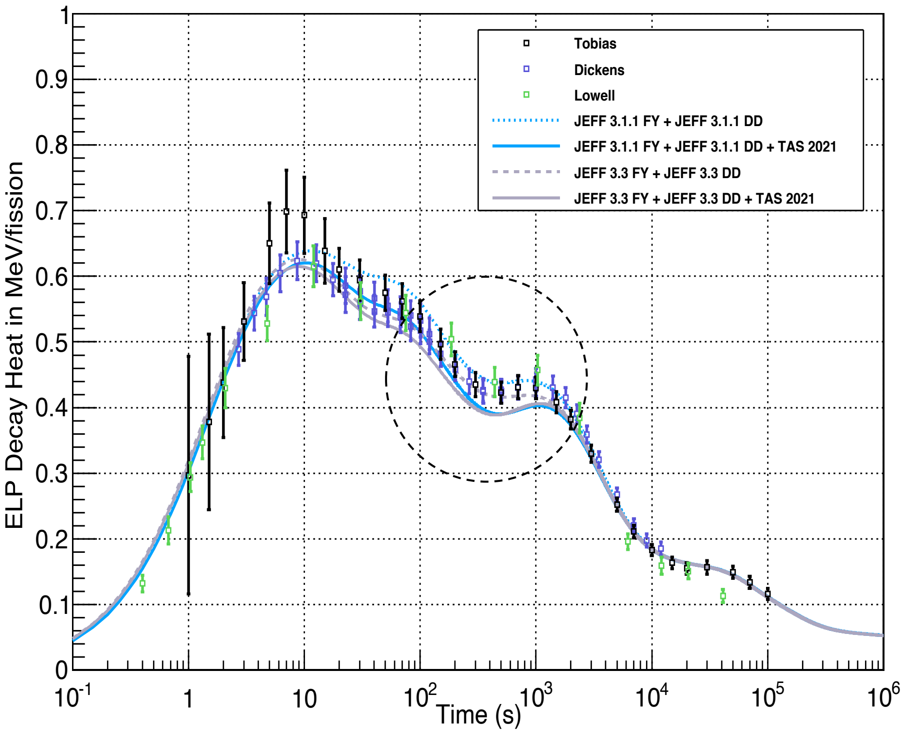
Courtesy of L. Giot

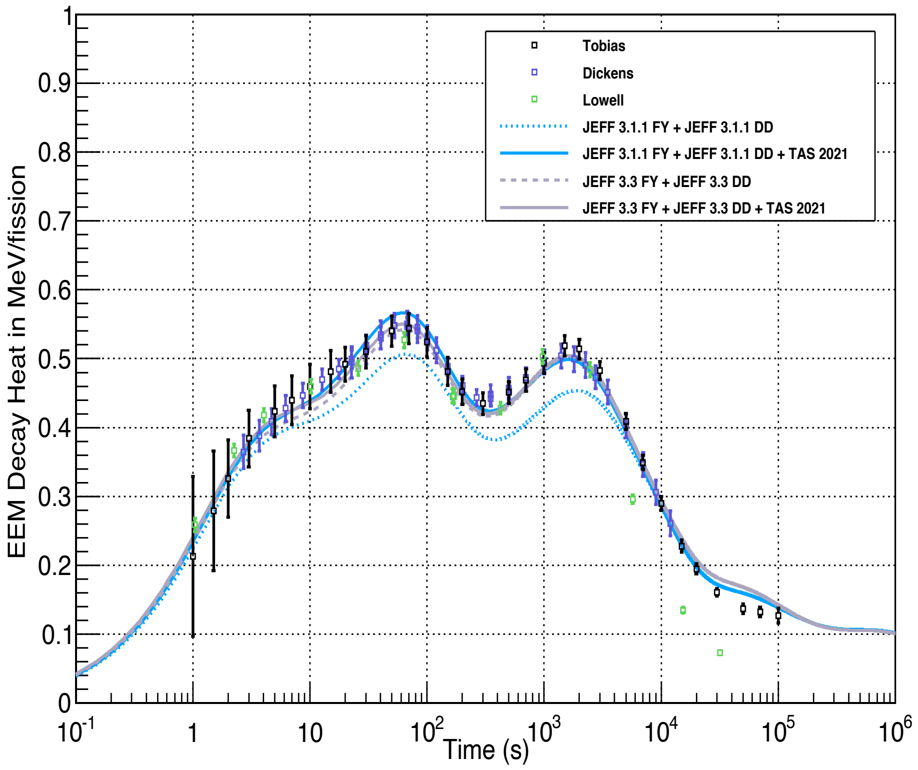
III. TAGS measurements and Impact

$^{239}Pu_{thermal}$

Light Particles Heat

Electromagnetic





28 TAGS measurements added to JEFF3.1.1 ref lib
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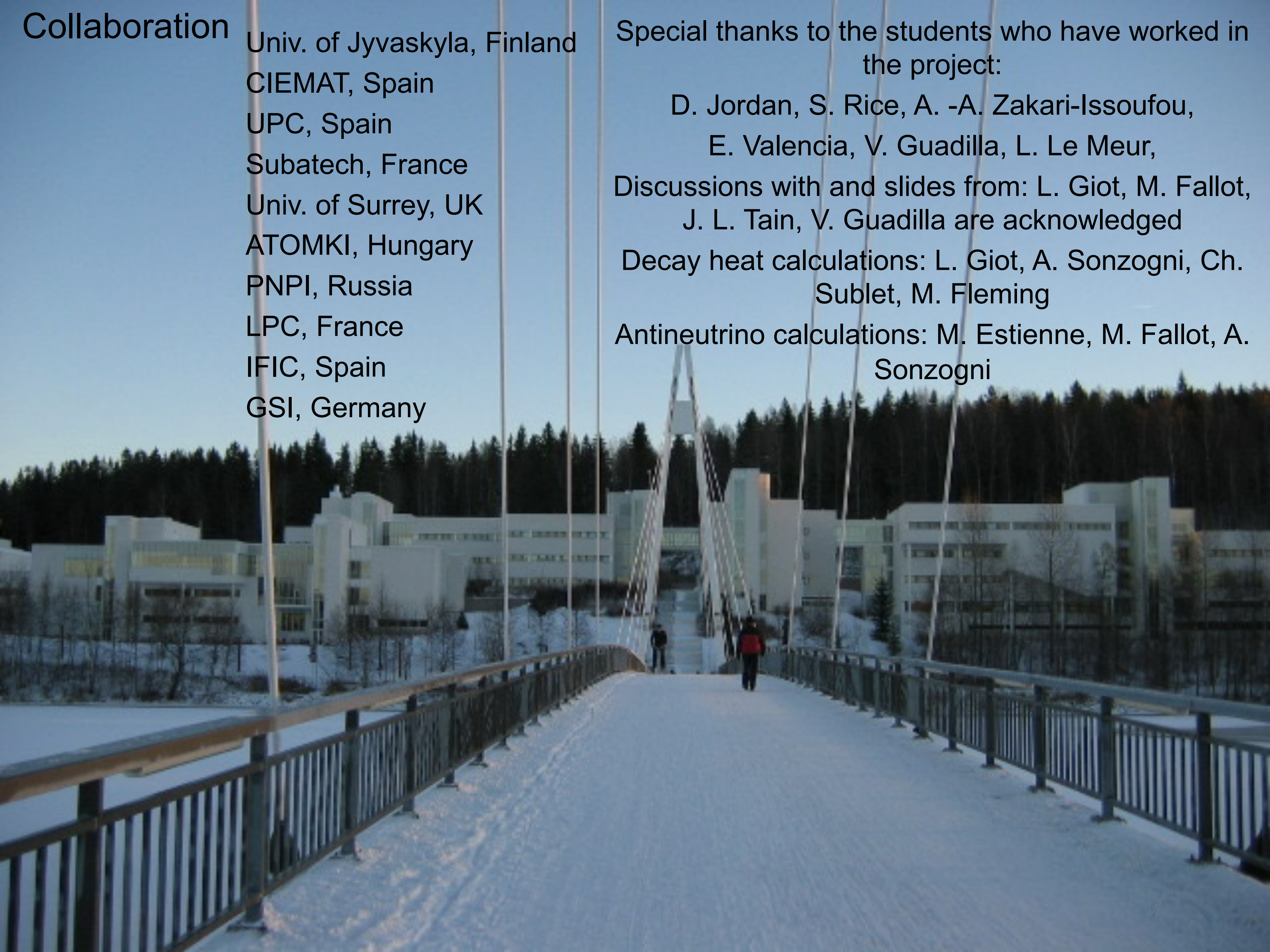
IAEA Report in preparation

Courtesy of L. Giot

Conclusions

- We hope we have shown that total absorption measurements can provide useful data for applications related to nuclear reactors, in particular for decay heat calculations and for anti-neutrino physics applications
- We are running a research program related to this topic, that can also have an impact in nuclear structure and astrophysics (not discussed in detail here)
- We hope to perform, in collaboration with Nantes, a new experiment in Jyvaskyla this year to measure the in next order relevant cases for both decay heat and neutrino spectrum prediction.



Collaboration

- Univ. of Jyvaskyla, Finland
- CIEMAT, Spain
- UPC, Spain
- Subatech, France
- Univ. of Surrey, UK
- ATOMKI, Hungary
- PNPI, Russia
- LPC, France
- IFIC, Spain
- GSI, Germany

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E. Valencia, V. Guadilla, L. Le Meur,

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Decay heat calculations: L. Giot, A. Sonzogni, Ch. Sublet, M. Fleming

Antineutrino calculations: M. Estienne, M. Fallot, A. Sonzogni

Full list of contributors

Total absorption study of beta decays relevant for reactor applications

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