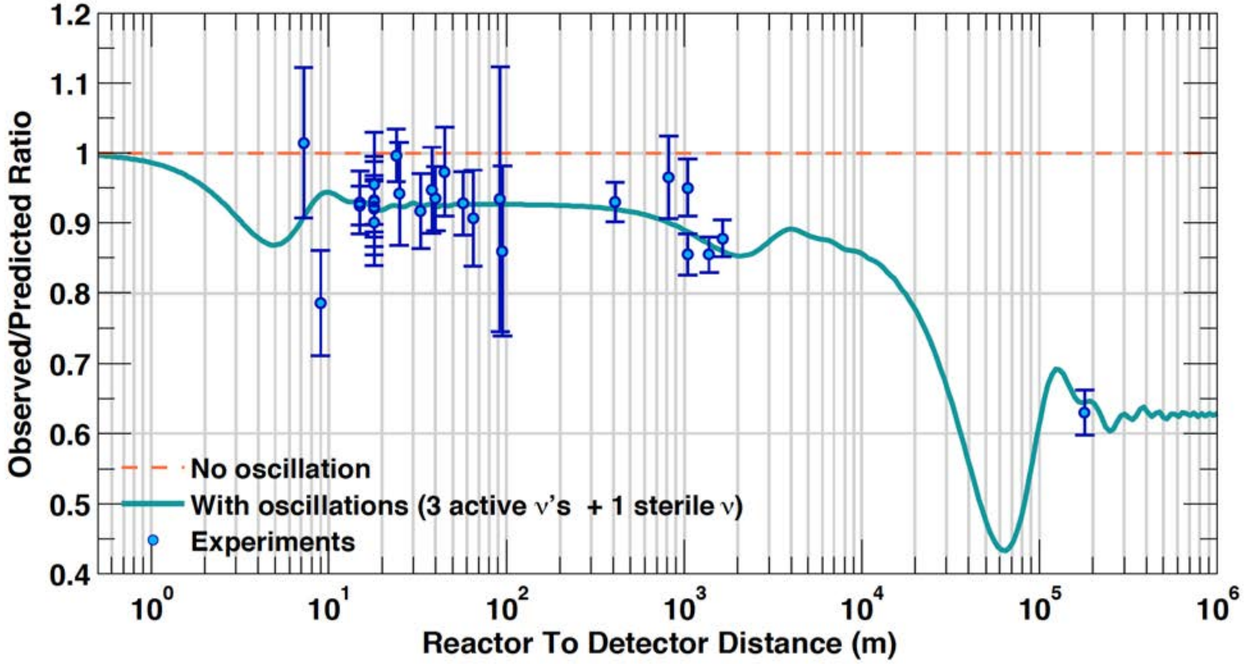
Total Absorption Spectroscopy Measurements for Neutrino Physics

Alejandro Algora

IFIC (CSIC-Univ. Valencia, Valencia), Spain

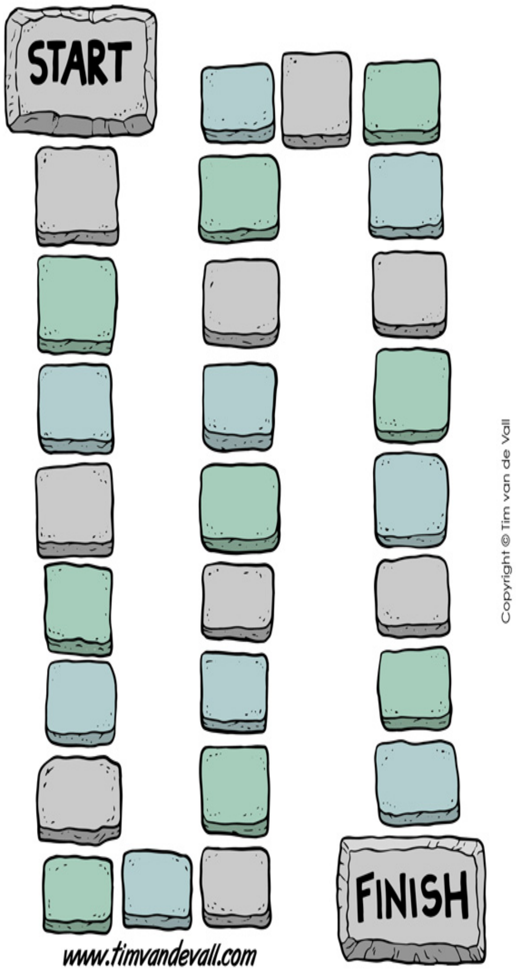
MTA ATOMKI, Hungary

for the Valencia-Nantes-Jyvaskyla-Surrey-et al. collaboration



TASTES, December 2020

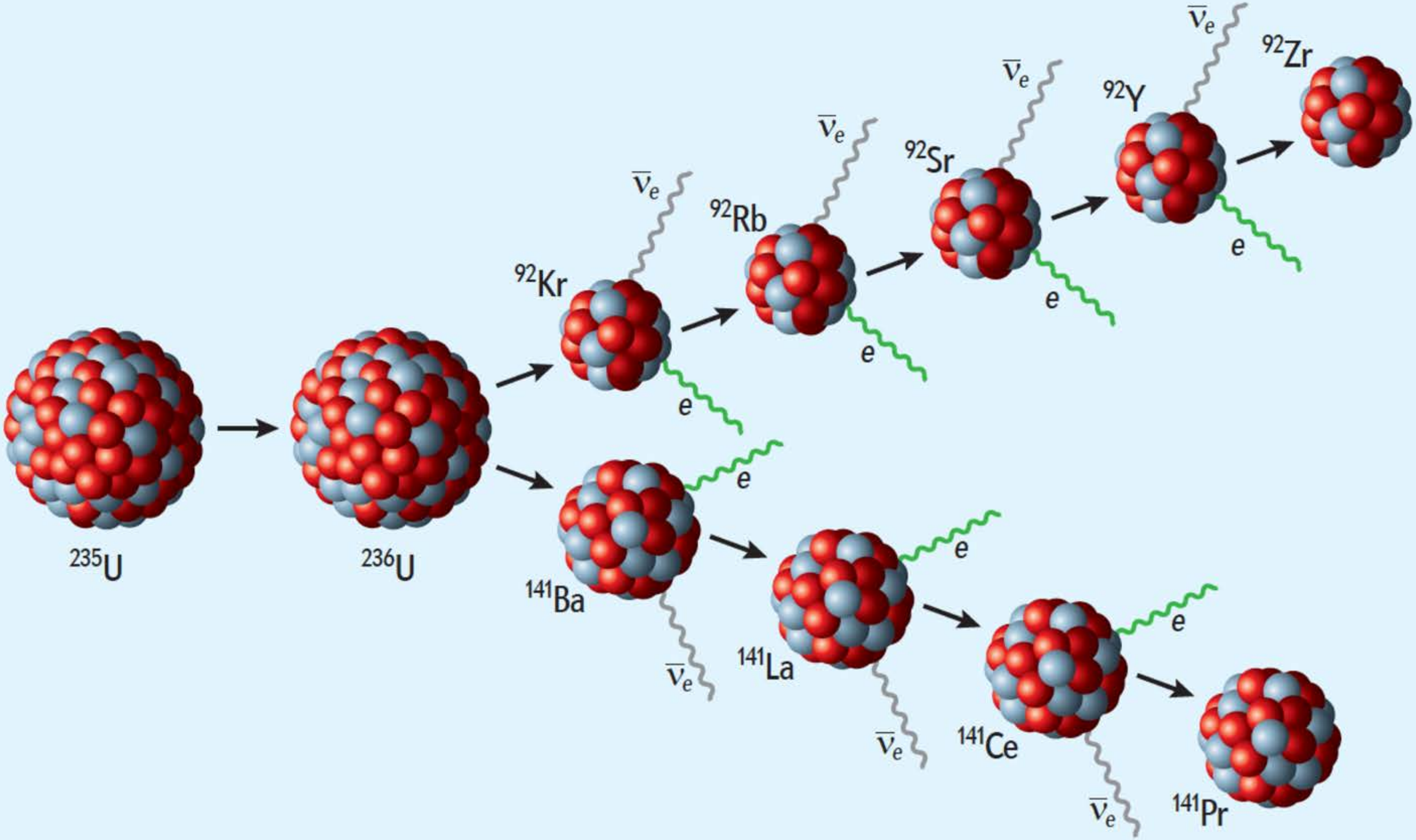
Outline



- Fission, antineutrino
- Antineutrino oscillations
- Antineutrino spectrum, problems
- Beta decay
- Pandemonium
- Total absorption
- Some measurements
- **Goal: the neutrino anomaly?**

Disclaimer: apologies for repeating many trivial things that you know

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 10^{20} ν/s

The relevance of reactors in the discovery, project Poltergeist

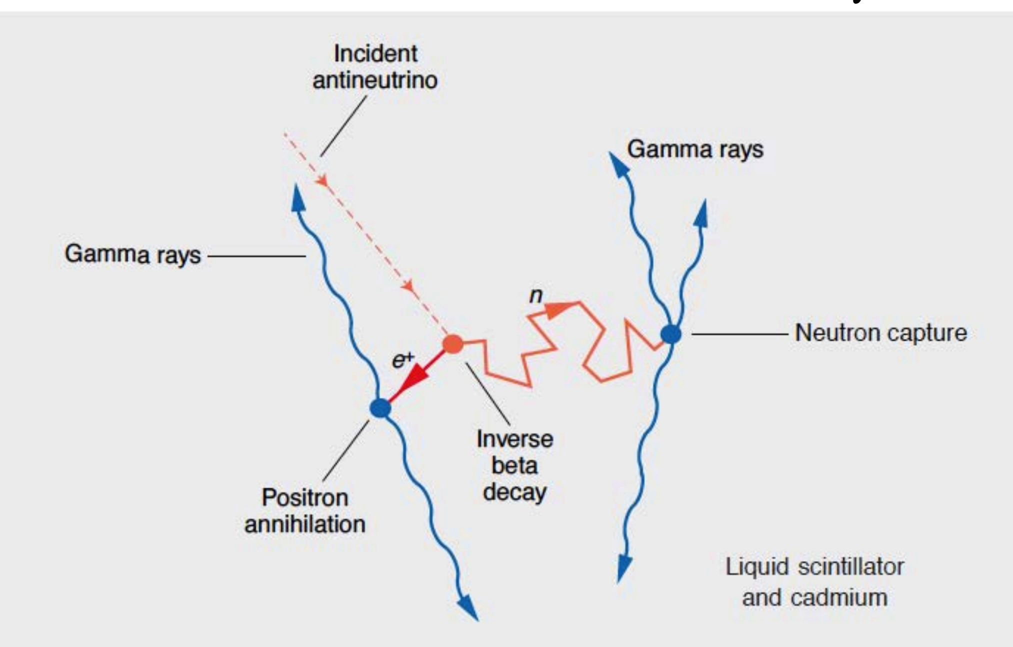
Neutrino postulated by Pauli, 1930

Nuclear reactors are the strongest (peaceful) human source of antineutrinos .

Reines, Cowan,1956

$$\bar{\nu} + p \rightarrow e^{+} + n$$

$$n + {}^{108}Cd \rightarrow {}^{109m}Cd \rightarrow {}^{109}Cd + \gamma$$



Neutrino flux at the *Savannah River* reactor: 5×10^{13} neutrino/s.cm^2

They detected 3 neutrinos/h

Science 20, vol 124 no. 3212 pp. 103-104

(Elusive) neutrino, oscillations, oscillation probability, mixing angles

- In the weak interaction neutrinos are produced and detected in flavours (electron, muon, tau)
- The Hamiltonian (of the propagation) depends on mass (free moving particle)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

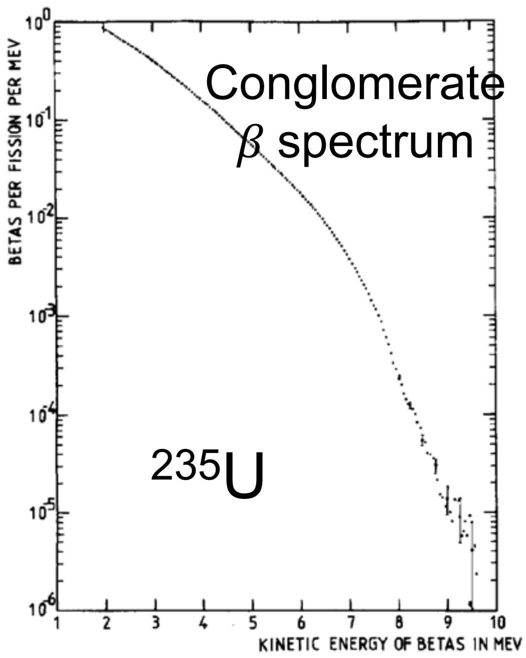
[L in m, E in MeV, Δm^2 in eV^2]

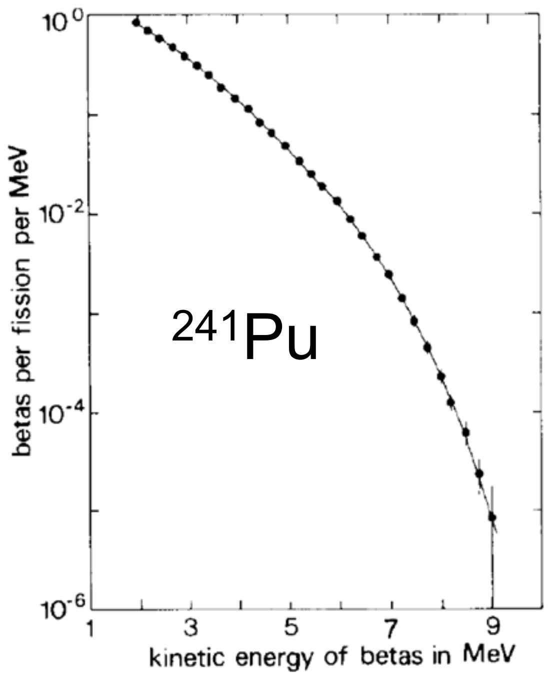
Evidence that there is physics beyond the standard model

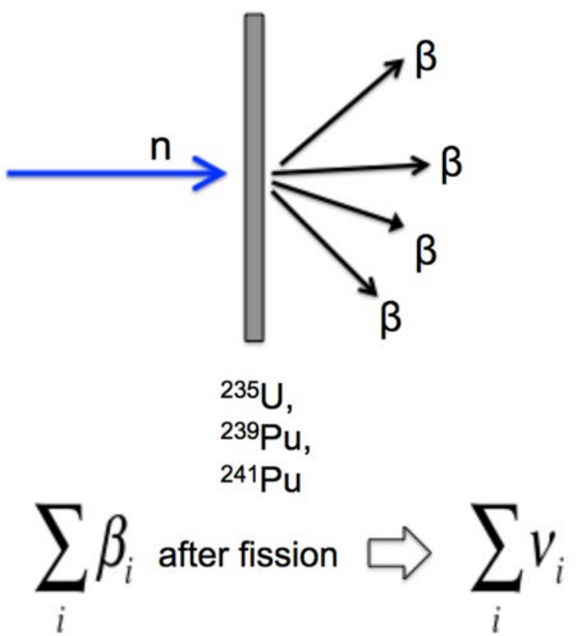
Example of reactor neutrino oscillation experiment: Double Chooz, Θ_{13} (see also Daya Bay, RENO, etc.)

Determination of the primary antineutrino spectrum

- **"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

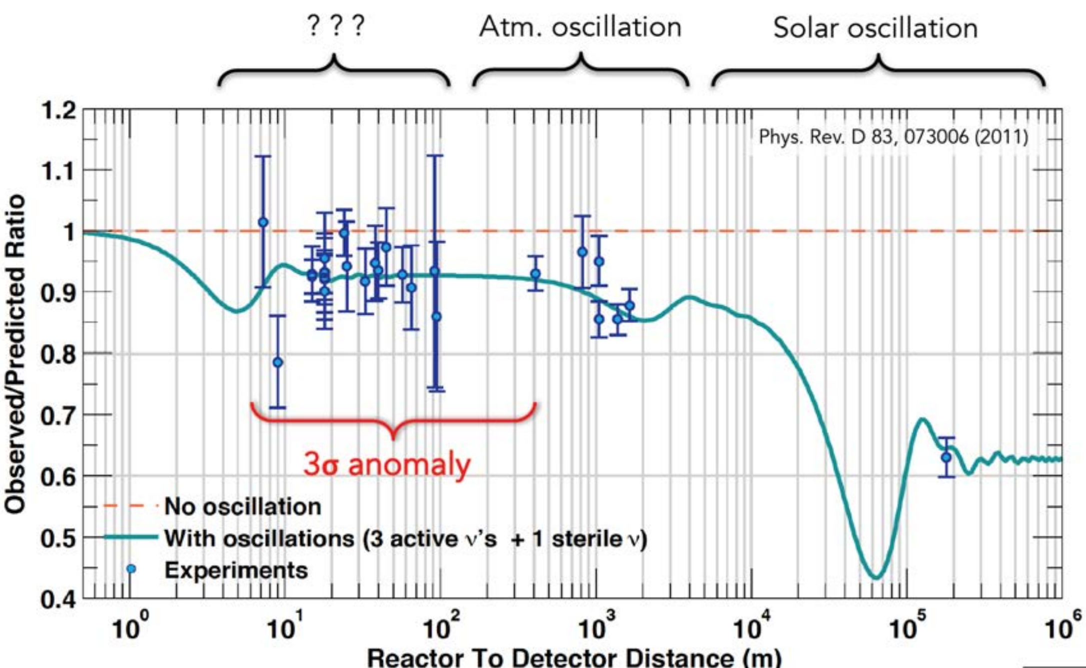






- **"Huber-Mueller model"**: revision in 2011 of the conversion proc.
- **"Summation calculations":** for many years the only posibility for ^{238}U

Remaining problems with the antineutrino spectrum



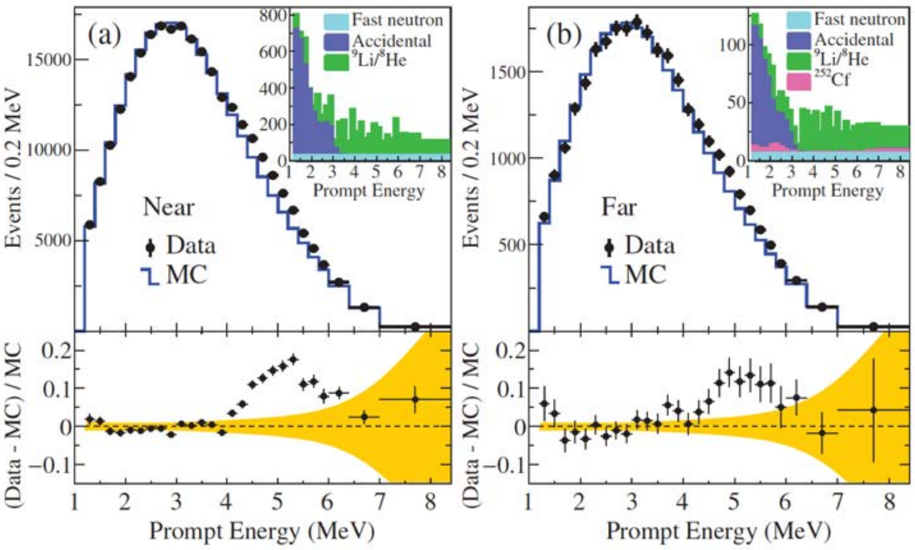
Reactor anomaly

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

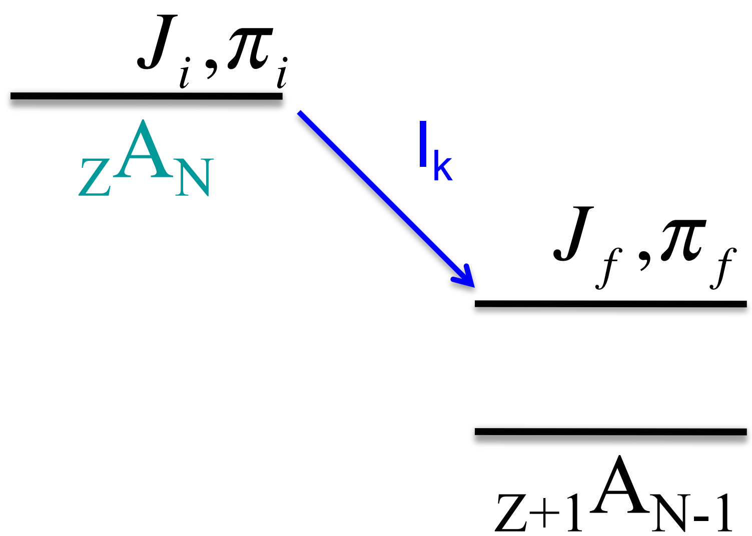
Spectrum distortion (~5 MeV)

RENO results, PRL 116, 211801 (2016)
also seen in DAYA BAY



Summation calculations for the antineutrino spectrum and decay heat

Beta decay (β^-)



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)

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

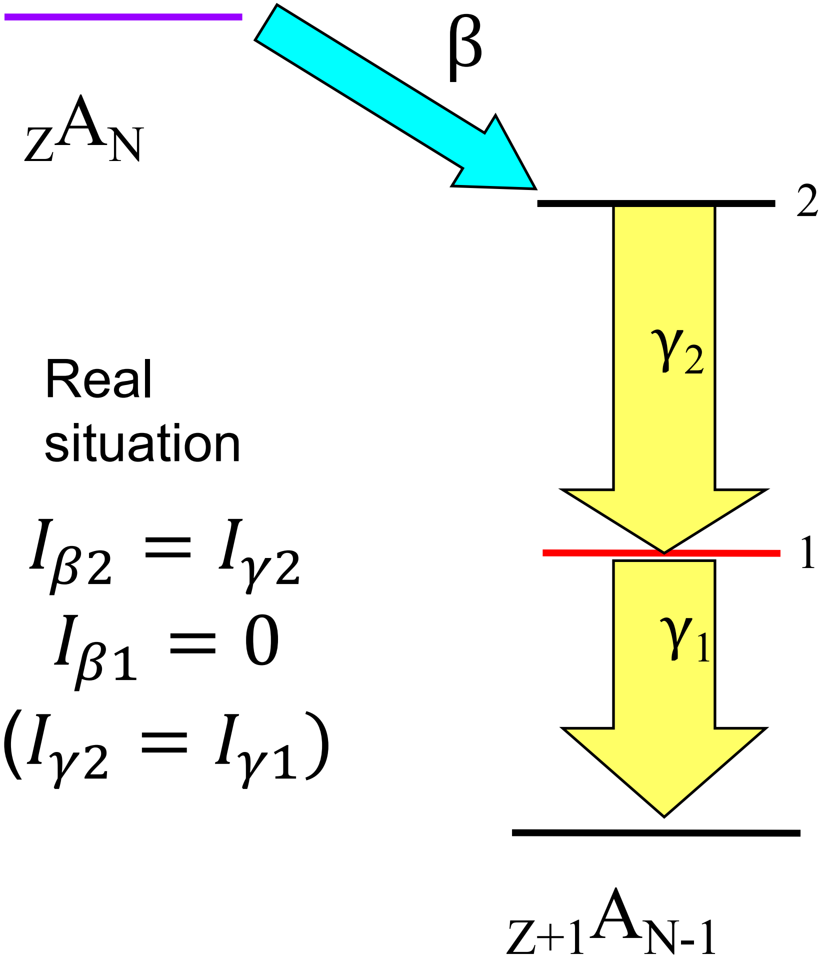
Anti-neutrino rate per fission (see Vogel 1981)

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

Decay heat summation calculation

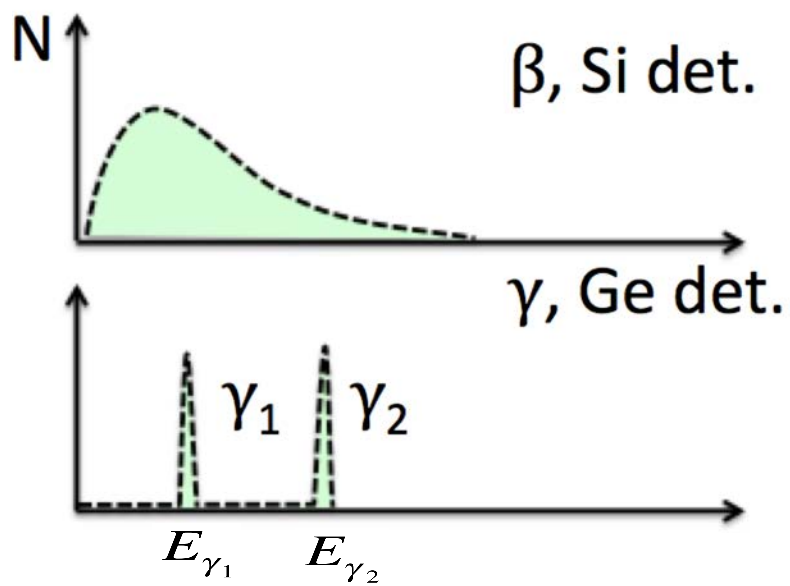
$$f(t) = \sum_i E_i \lambda_i N_i(t)$$

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



Real situation

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

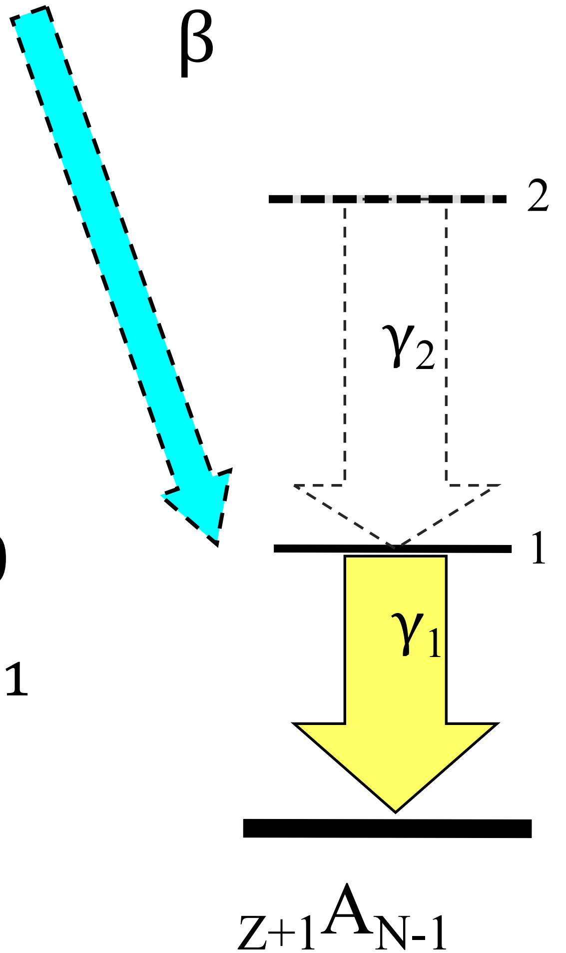


- Ge detectors are conventionally used to construct the level scheme populated in the decay

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

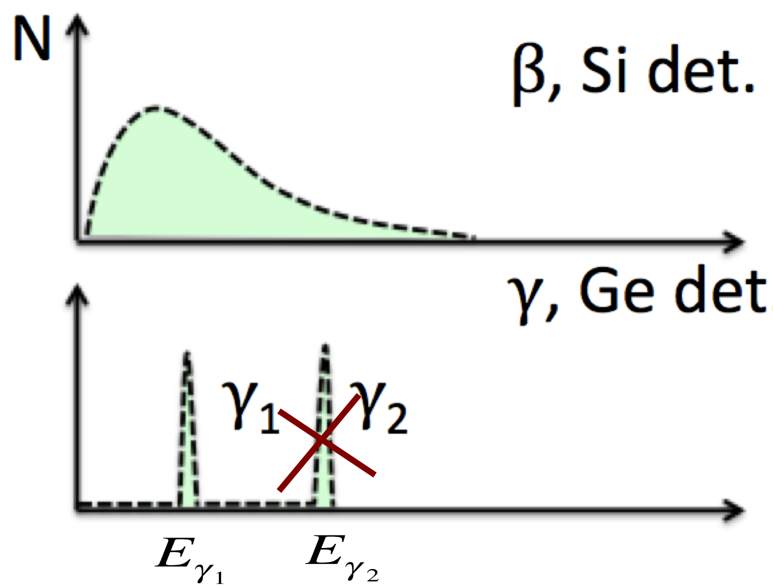
The problem of measuring the β-feeding ($I_\beta = P_\beta * 100$)

$_{Z}A_{N}$



Apparent situation

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



What happens if we miss some intensity?

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

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

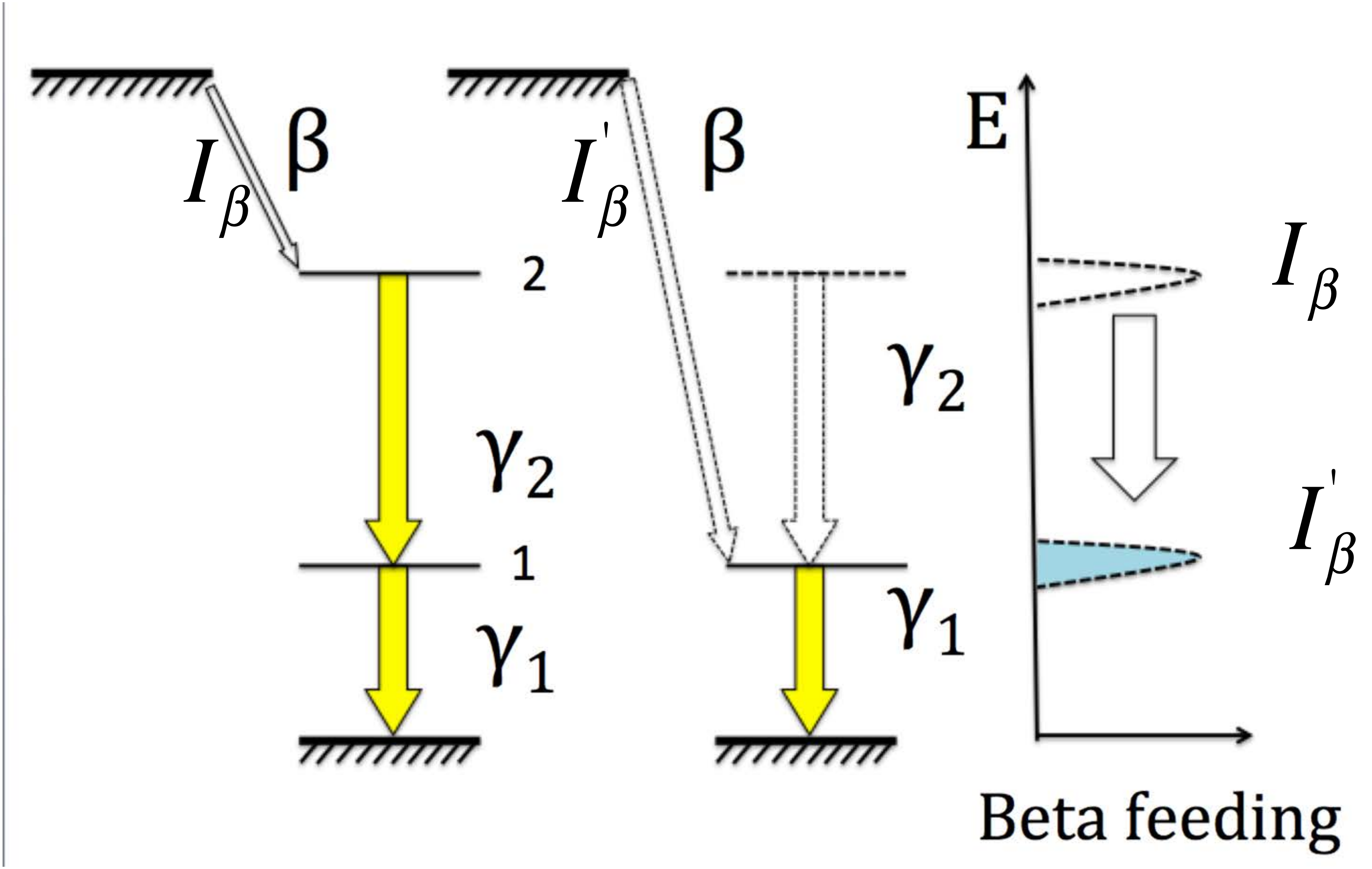
Pandemonium (The Capital of Hell)

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

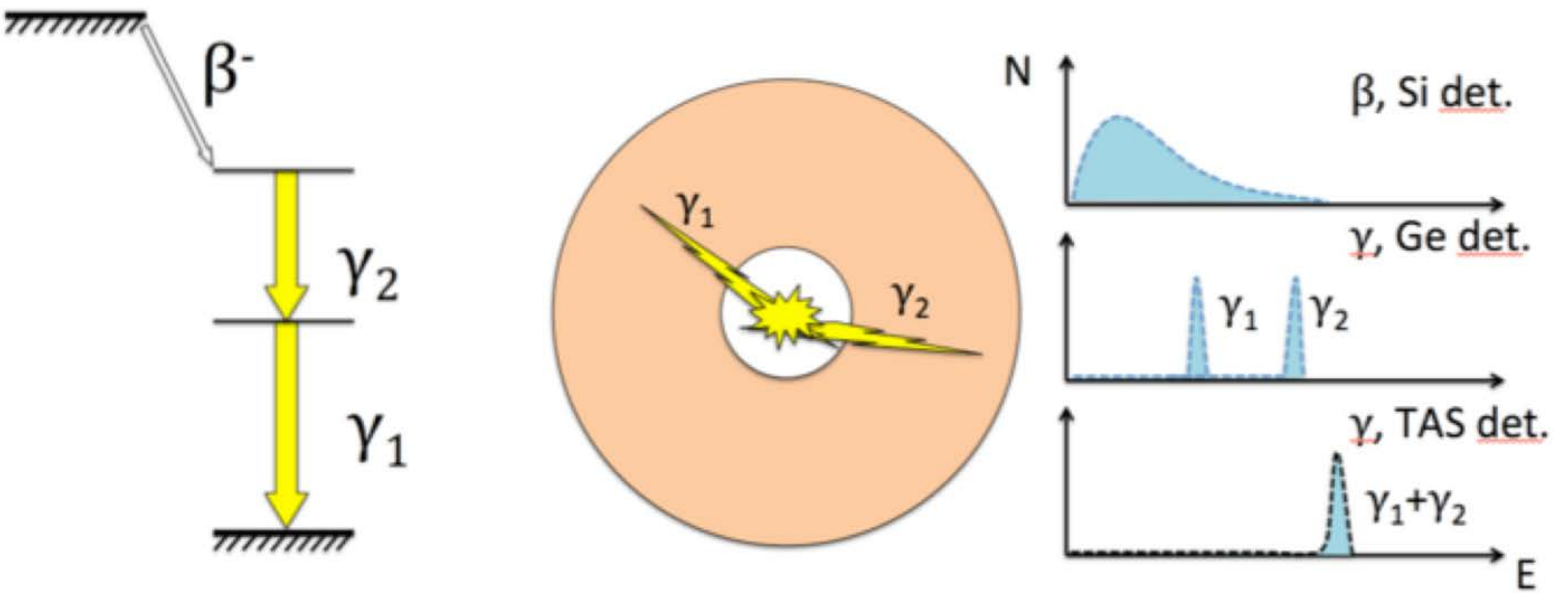
John Martin (~ 1825), presently at Louvre

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

Pandemonium effect



Total absorption spectroscopy (applied to beta decay studies)



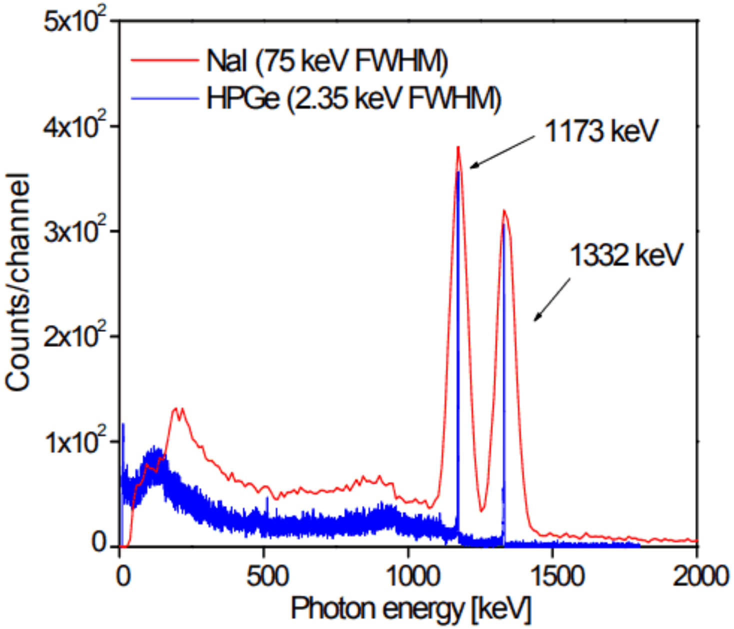
$$d = R(B) \cdot f$$

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

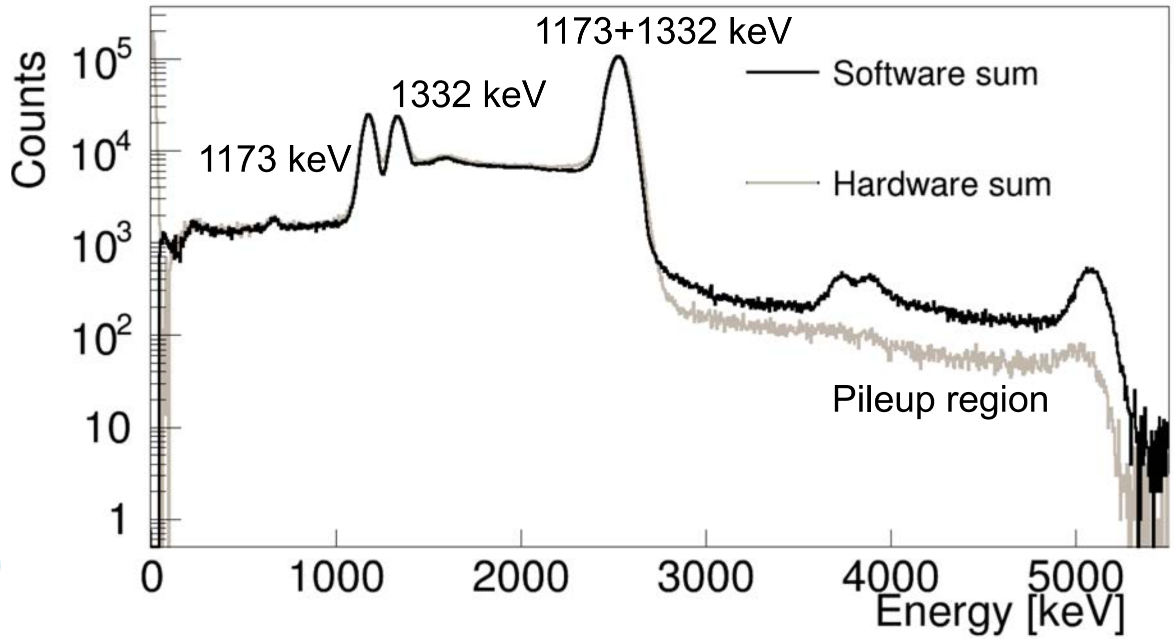
Requirements: clean spectrum or a proper treatment of the contaminants, some knowledge of decay level scheme of the daughter, etc.

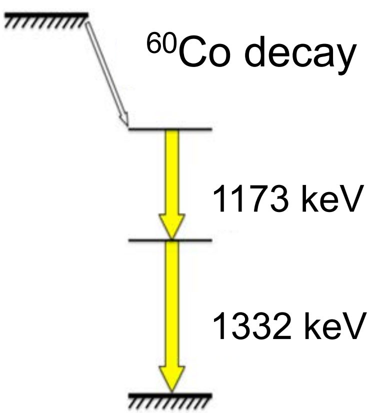
Real spectra

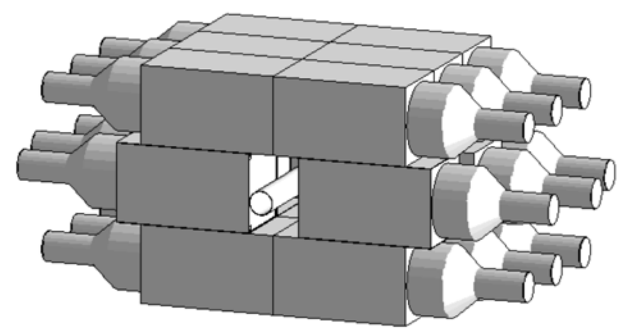
"Small" detectors



Real calorimeter detector

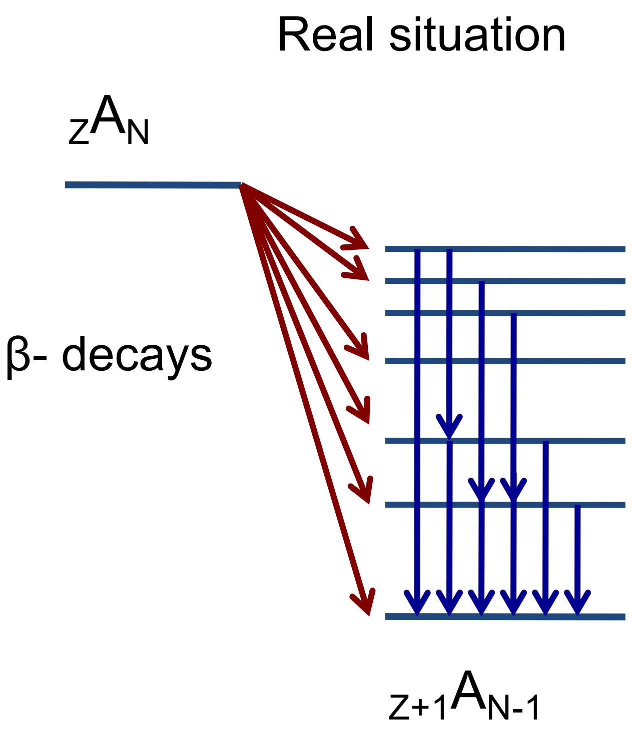


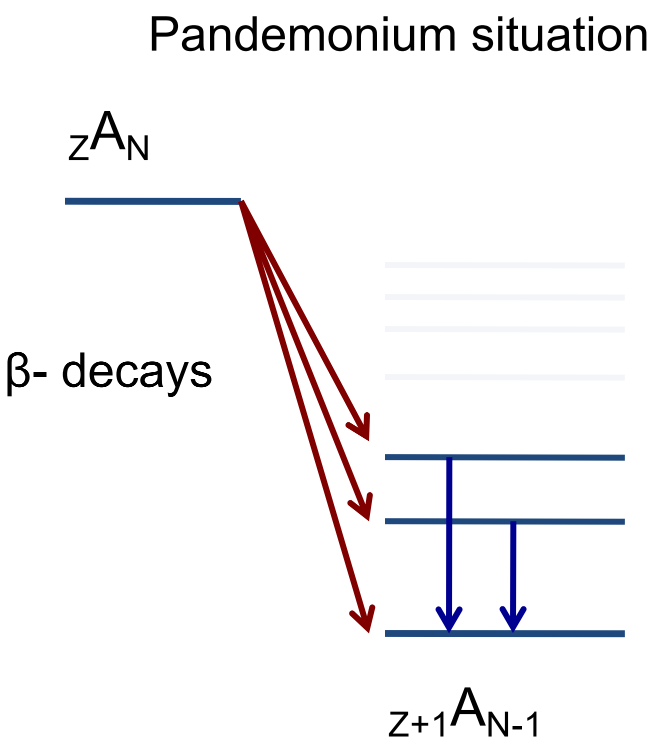




DTAS

Pandemonium and summation calculations for decay heat and antineutrino





As a result of the Pandemonium, betas and neutrinos are estimated with higher energies from databases. This is why TAS data is very important

$\overline{E}_{\beta}$ overestimation

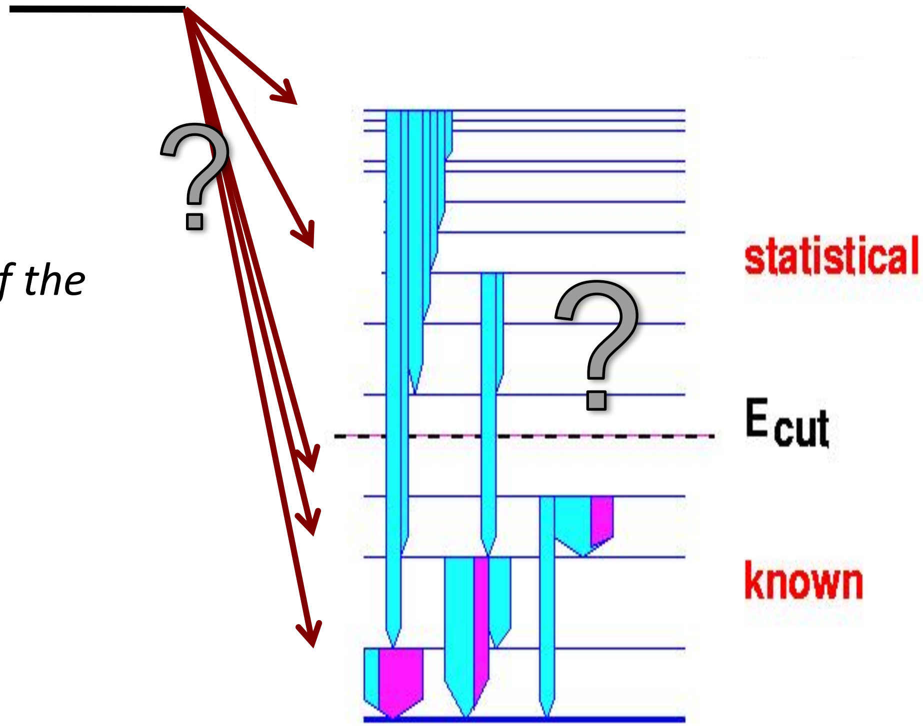
$\overline{E}_{\gamma}$ underestimation

The complexity of the TAGS analysis: an ill posed problem

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

Primary question: f determination
but there is an incomplete knowledge of the level scheme populated

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



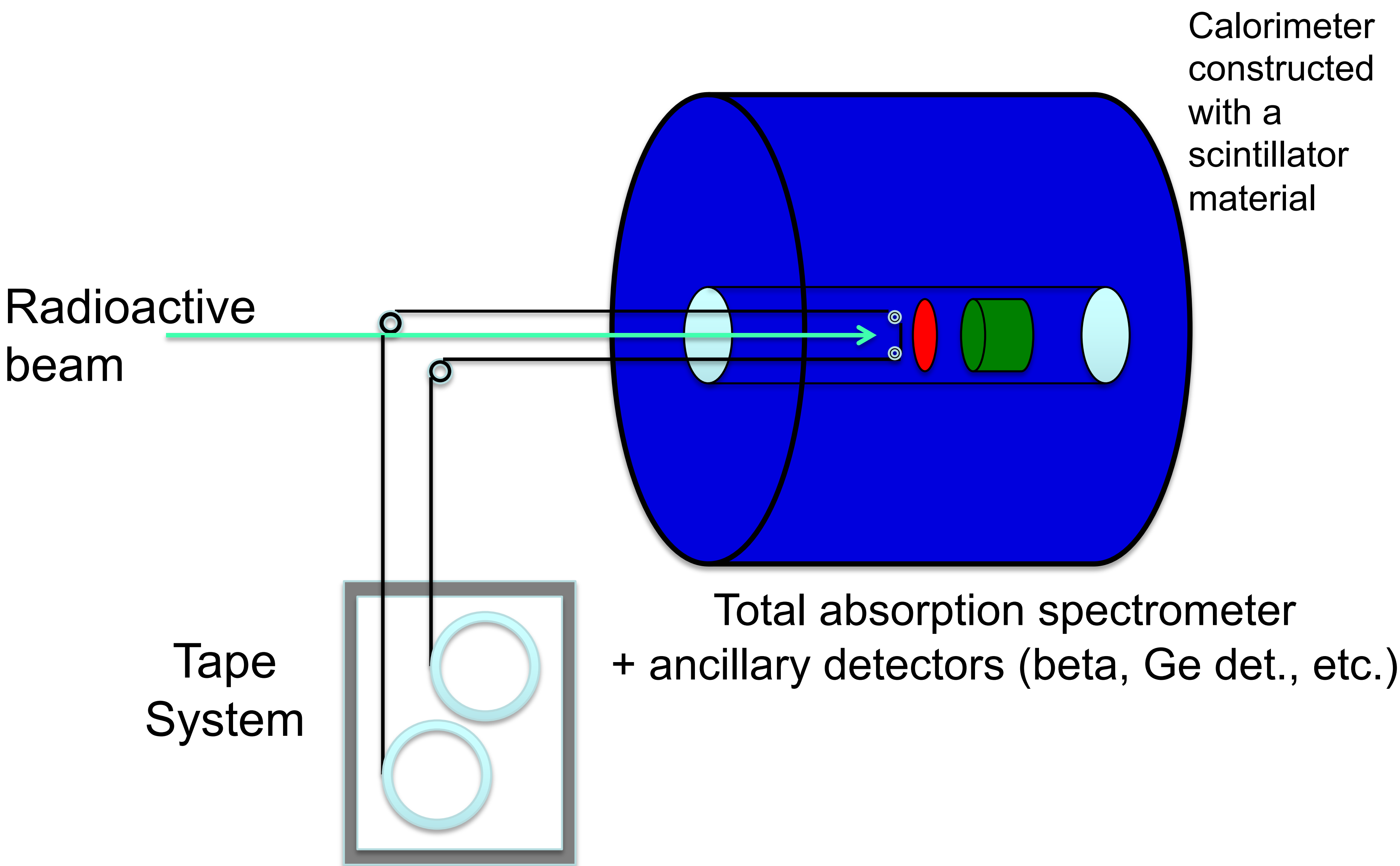
Expectation Maximization (EM) method:
modify knowledge on causes from effects

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

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, et al.

Typical total absorption experiments



Our favorite place for “polar” experiences

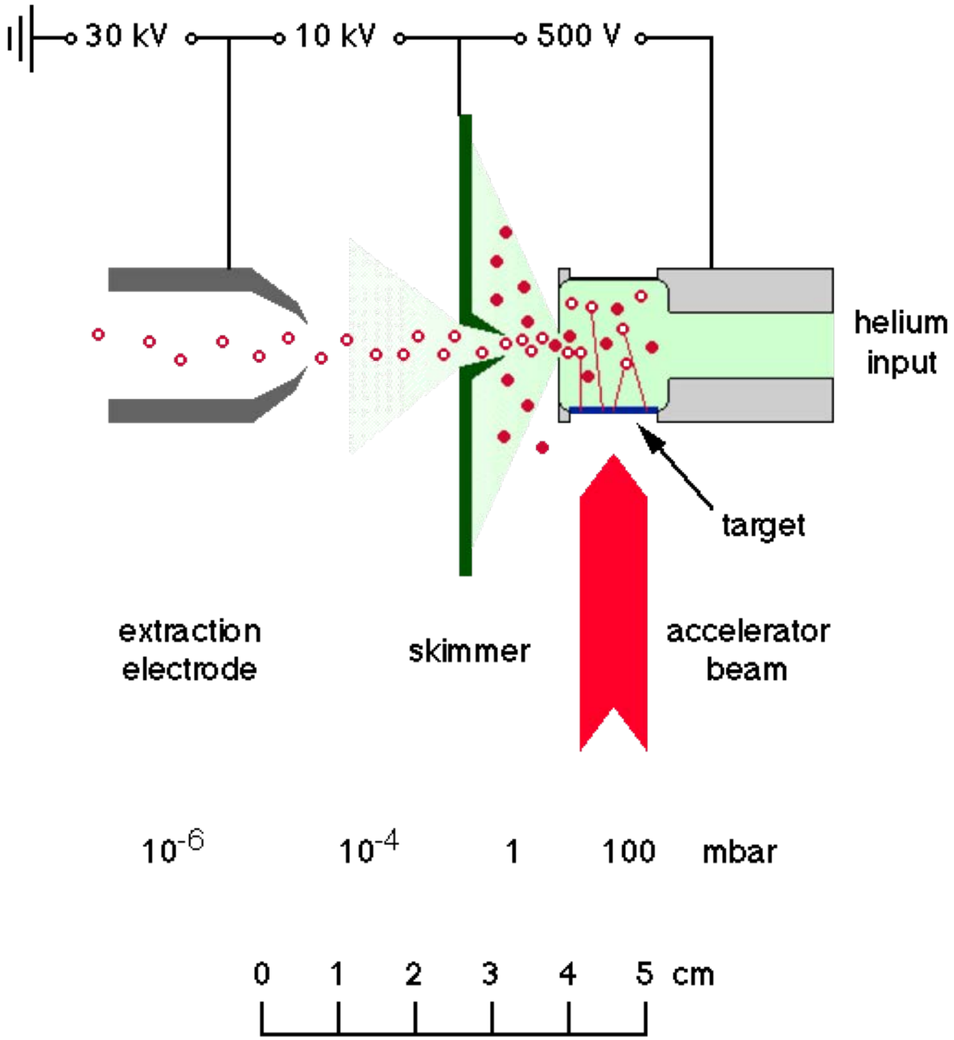
Published cases until know:

^{102,104,105,106,107}Tc, ^{105}Mo, ^{101}Nb

^{86,87,88}Br, ^{91},^{92,94}Rb,^{100gs,m}Nb, ^{102gs,m}Nb

Ongoing: ^{142}Cs, ^{96}Y, etc, … see INDC-NDS-0676

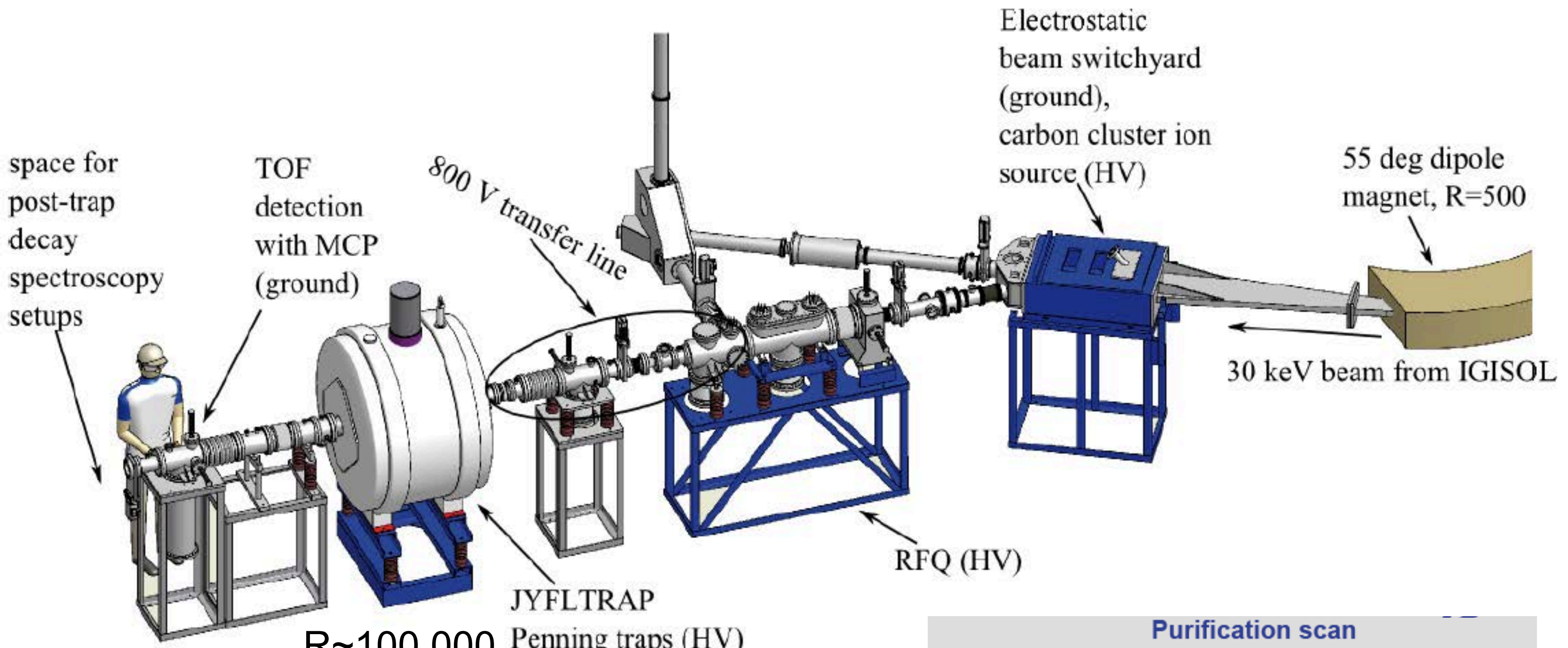
Odd ISOL case: The ion guide technique



Generic ion guide: the nuclear reaction products are stopped in a gas and are transported through a differential pumping system into the accelerator stage of the mass separator.

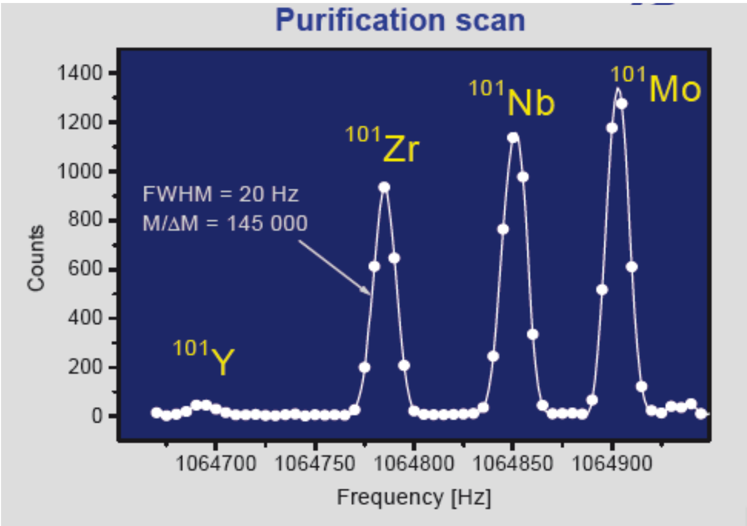
The process is fast enough for the ions to survive as single charged ions. The system is chemically insensitive and very fast (sub-ms).

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



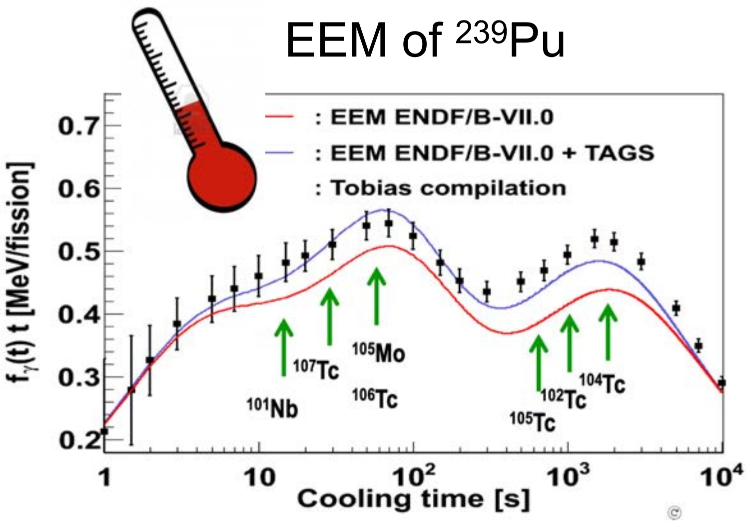
R~100 000

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!



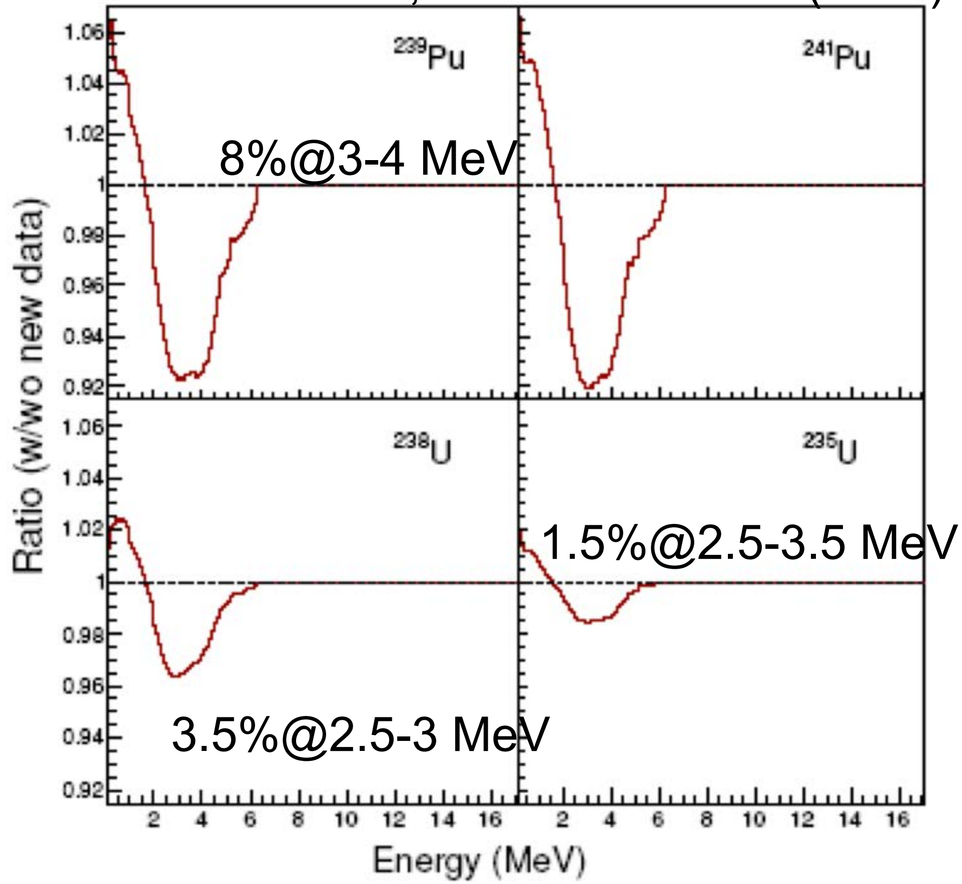
Impact of some of our earlier data:
$^{102,104,105,106,107}Tc$, ^{101}Nb, ^{105}Mo

EEM of ^{239}Pu



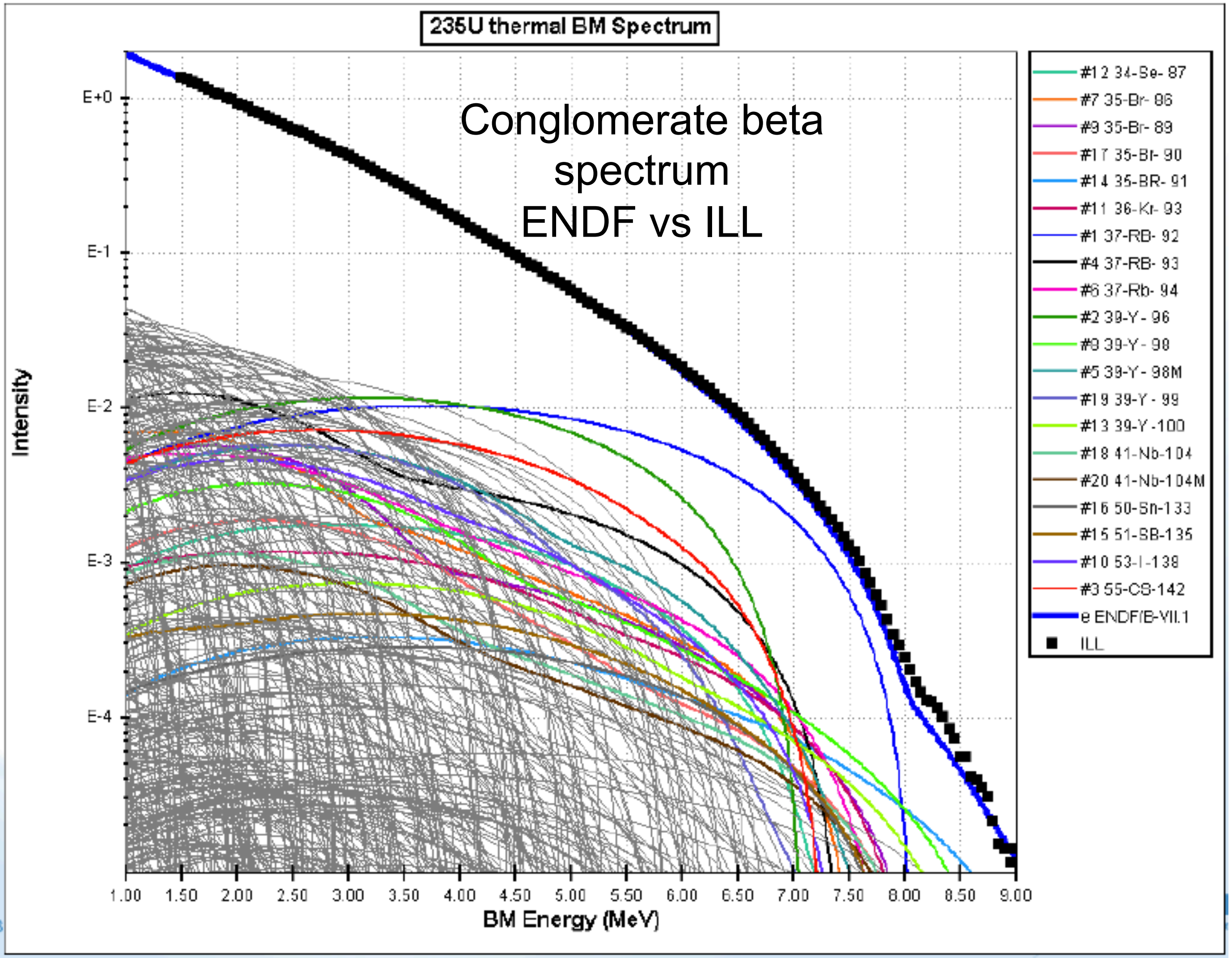
Dolores Jordan, PhD thesis
D. Jordan PRC 87, 044318 (2013)
Algora et al., PRL 105, 202501, 2010

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



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

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
Sonzogni et al., PRL 119, 112501 (2017) (not all decays are equal, remains 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

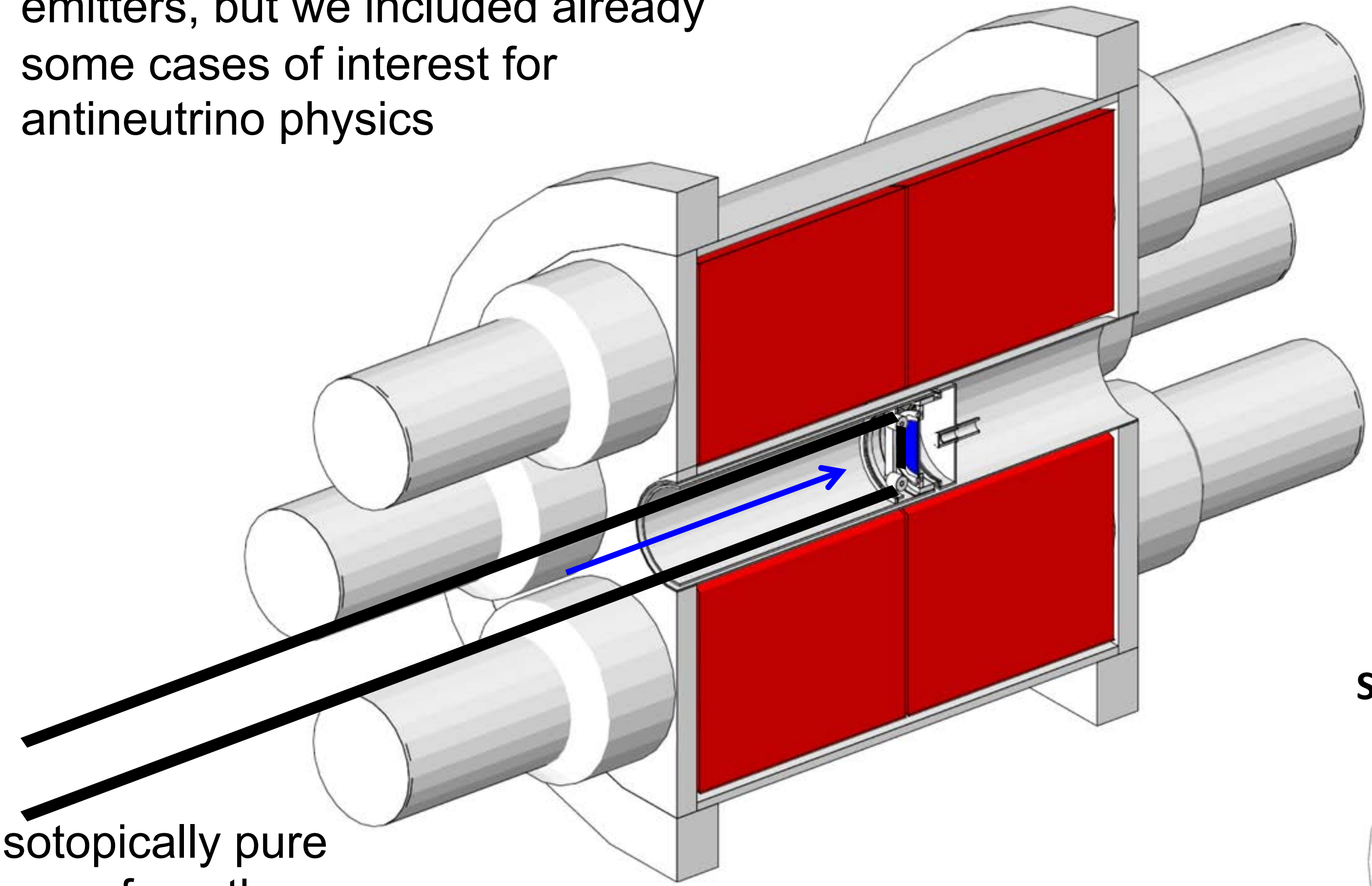
94(+6−20)(<2000)
Olson et al.
51(18) % (<2012)
NDS 2000
95.2(7) % (2012)
NDS 2012
G. Lhersonneau
(PRC74 (2006)017308)
New experiment ????

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

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

VTAS in Jyväskylä (November 2009)
^{86,87,88}Br, $^{\mathbf{91},92,\mathbf{93},94}$**Rb**

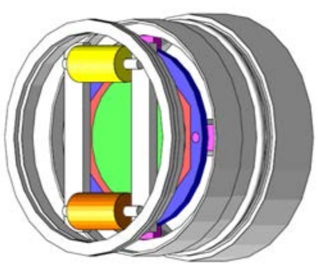
Main goal: beta delayed neutron emitters, but we included already some cases of interest for antineutrino physics



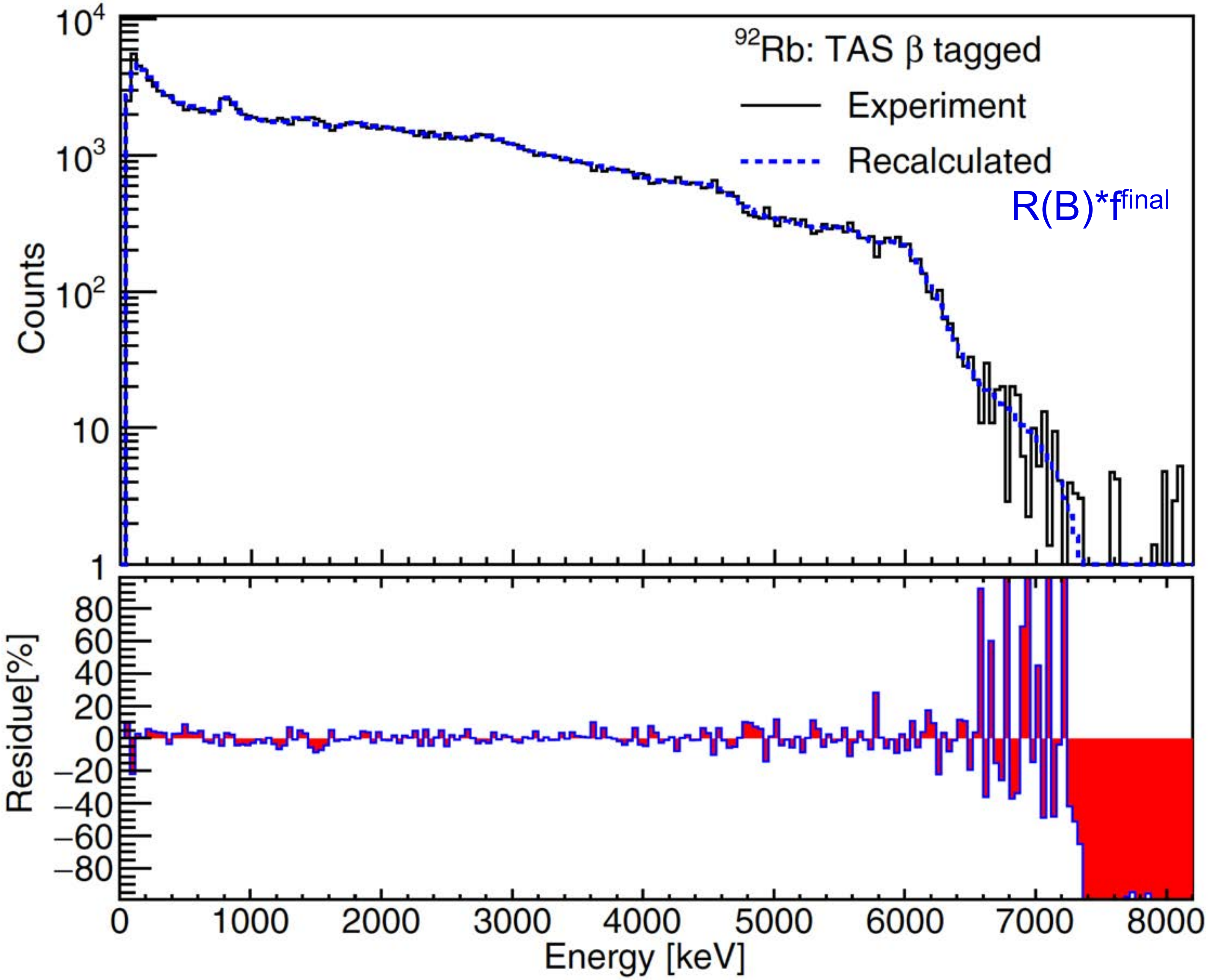
Isotopically pure beam from the JYFL trap

Segmented BaF2 detector with optically separated crystals

Si detector endcup



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

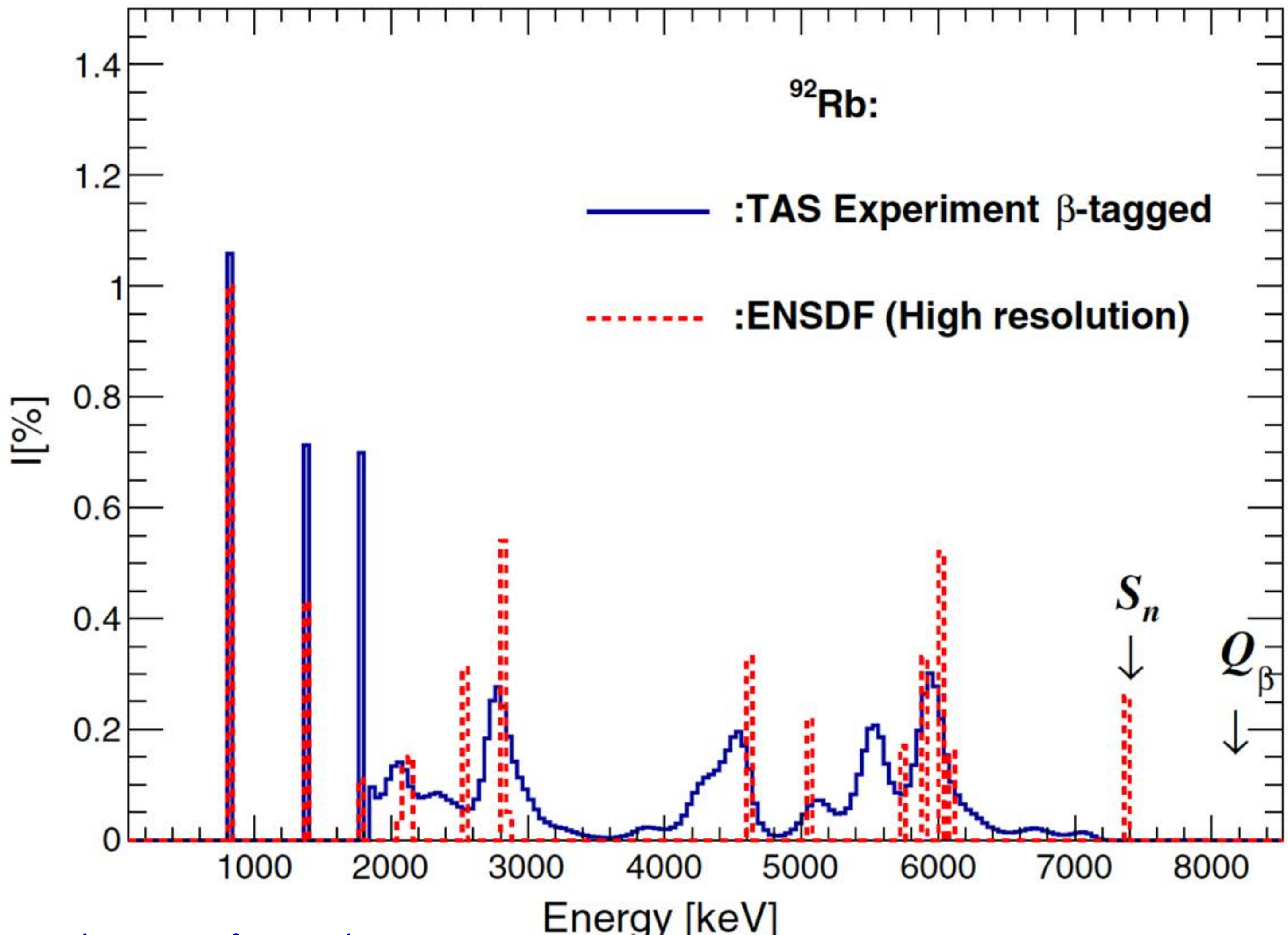


Zakari-Issoufou PhD thesis, Nantes

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



Zakari-Issoufou et al.
PRL 115.102503(2015)

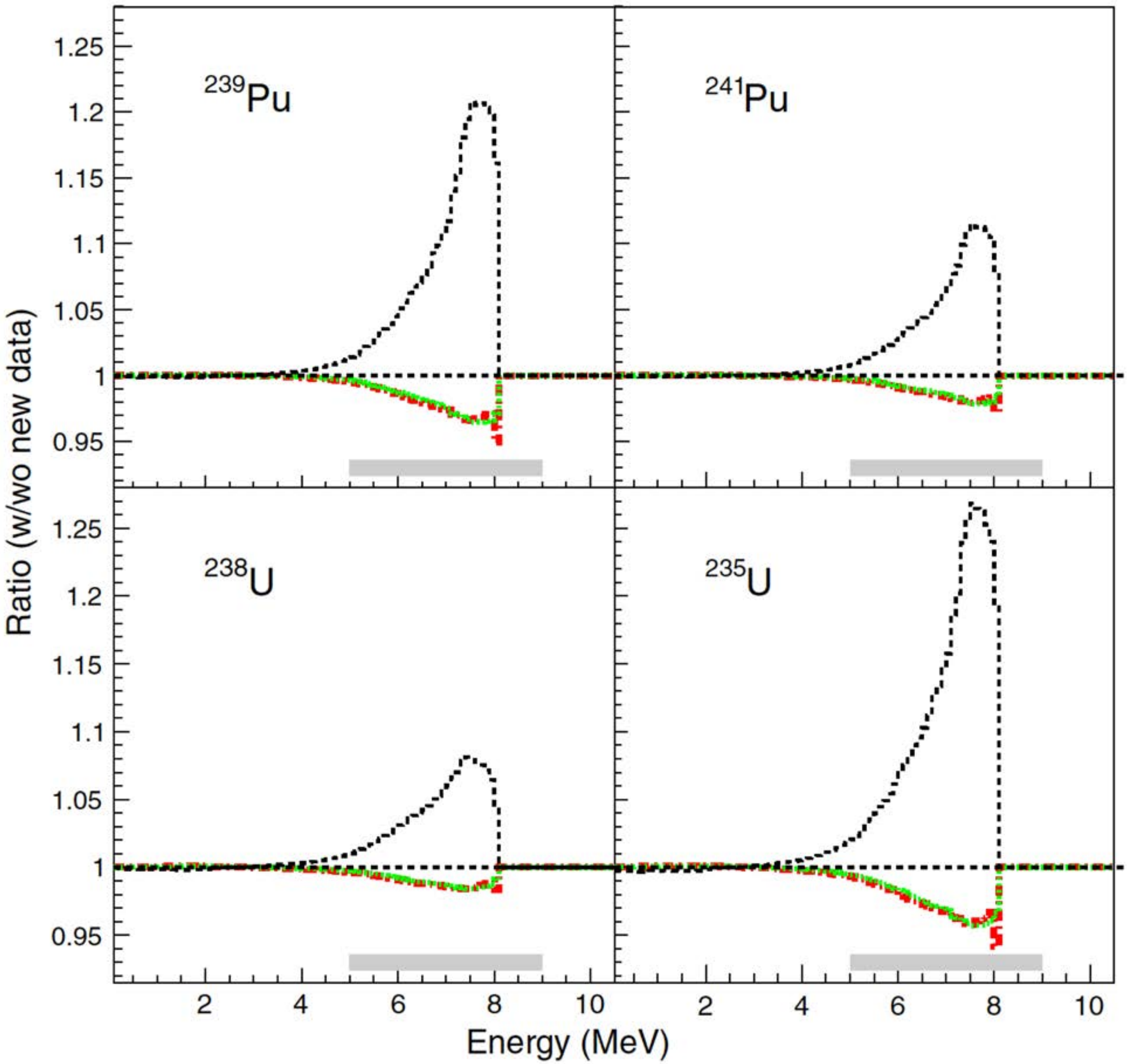
Gs to gs feeding Evolution

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

^{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)

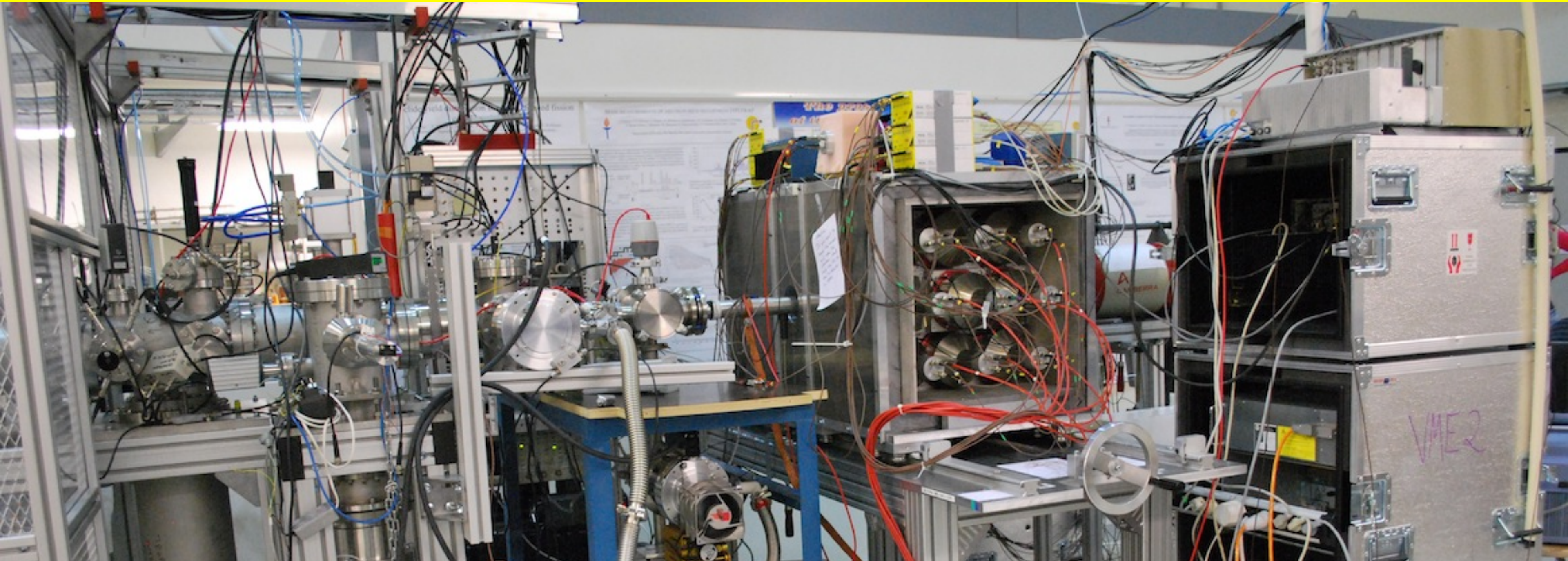
Black: with respect to the value used in D. A. Dwyer et al. PRL 114,012502 (used 51% gs feeding, earlier ENSDF)

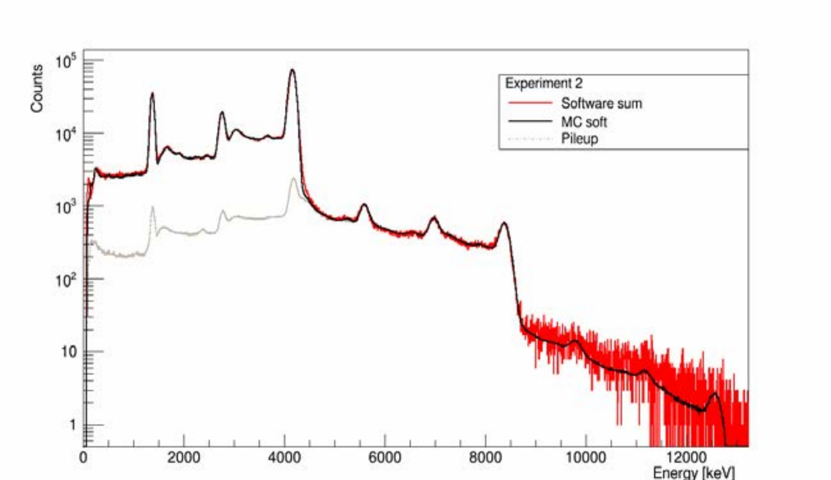
Green: with respect to A. A. Sonzogni et al. PRC 91, 011301(R) (used 95 % gs feeding)

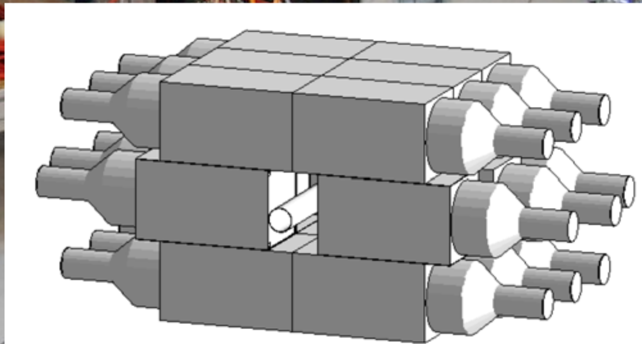
Red: with respect to M. Fallot et al., PRL 109, 202504 (previously Rudstam data was used)

DTAS at Jyväskylä (Feb. 2014)

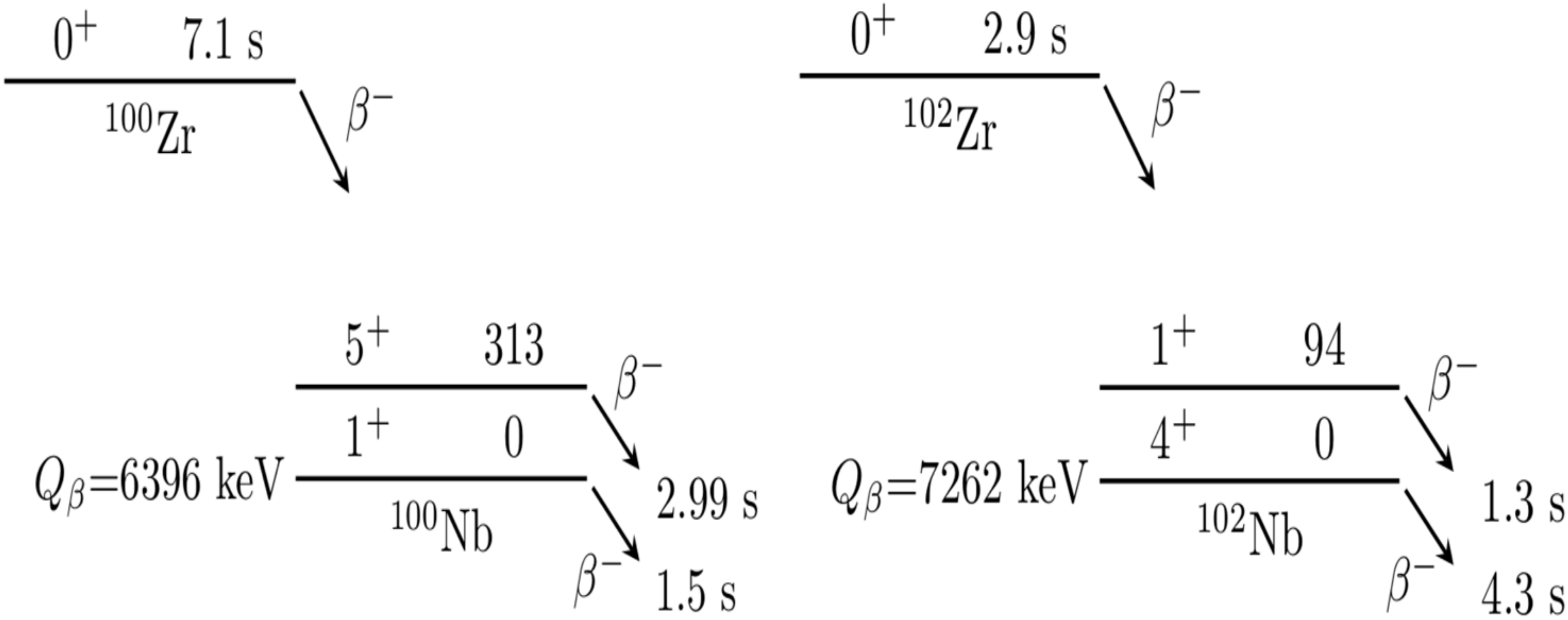
(proposal with Subatech, spokespersons: Fallot,Tain, Algora)





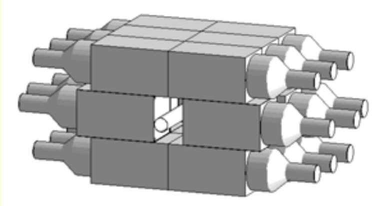


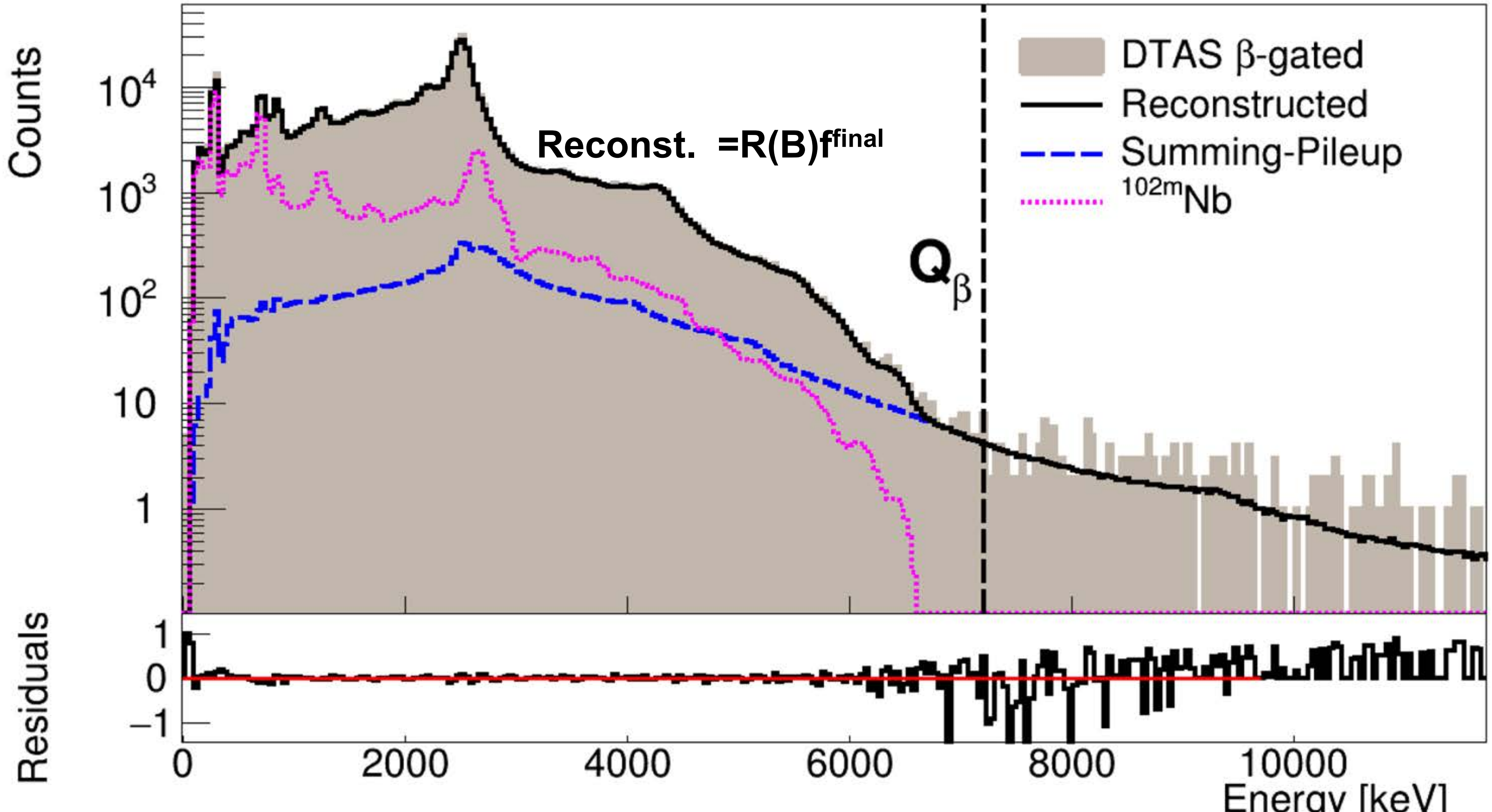
Example: the challenging ^{100,102}Nb cases (from 18(+5) relevant decays measured)



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

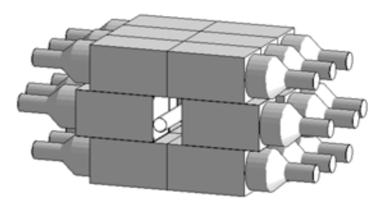
^{102gs}Nb decay (4+ state)

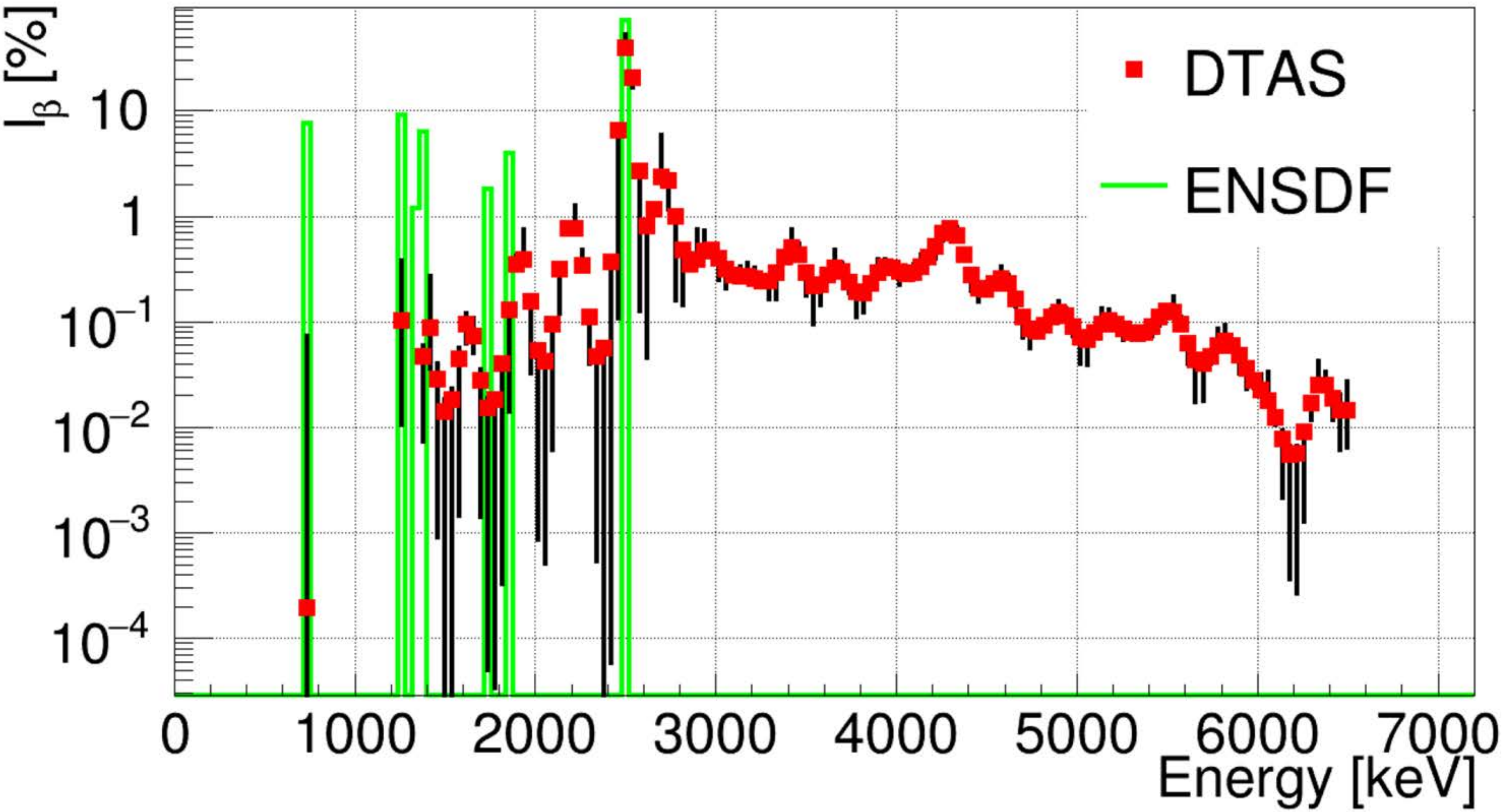




V. Guadilla et al., PhD thesis

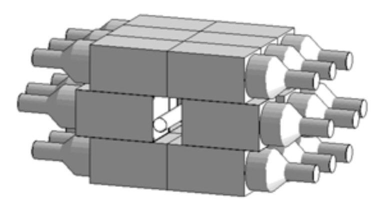
^{102gs}Nb decay (4+ state)

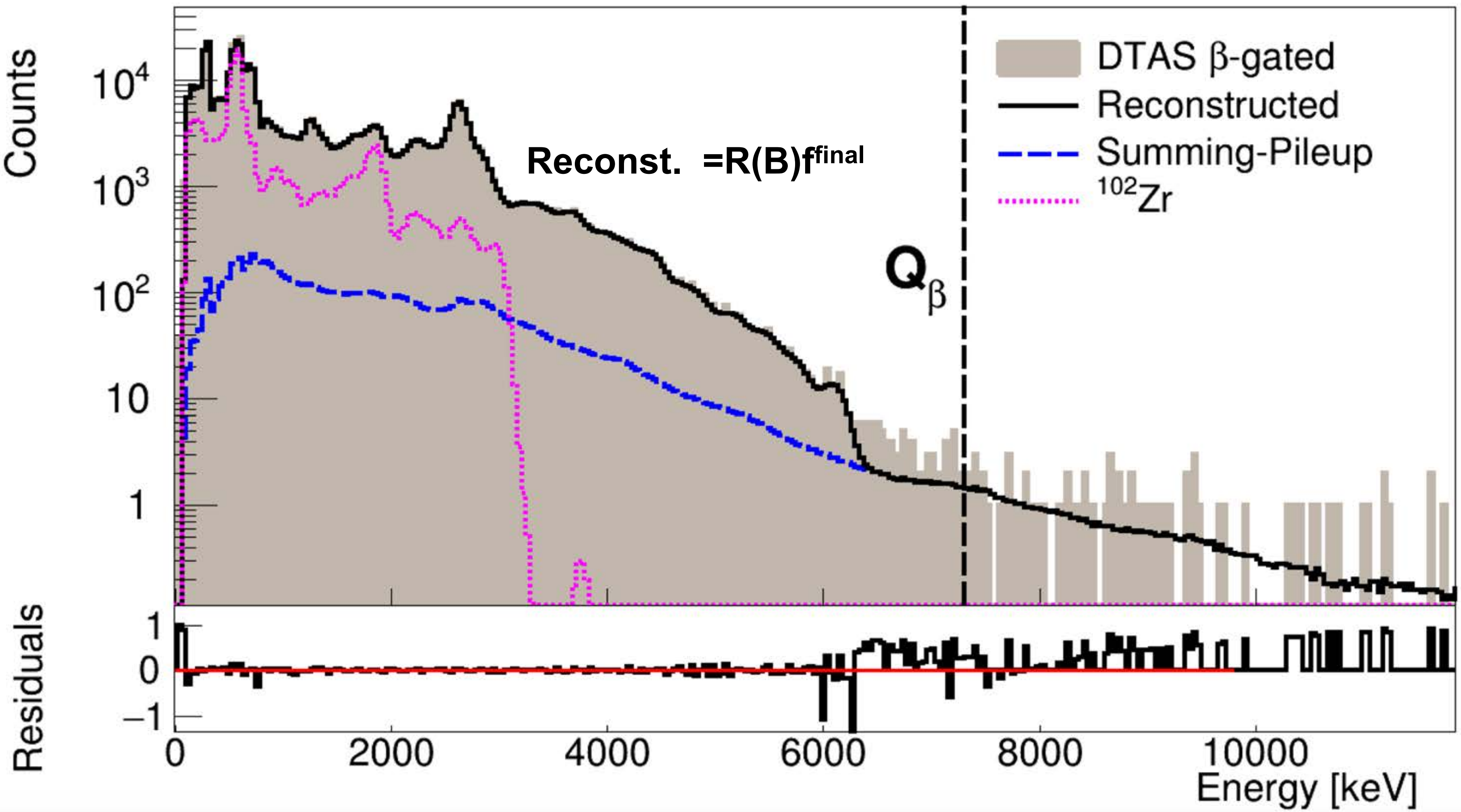




V. Guadilla et al., PRL 112.042502

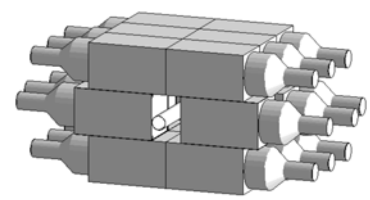
^{102m}Nb decay (1+ state, 94 keV)

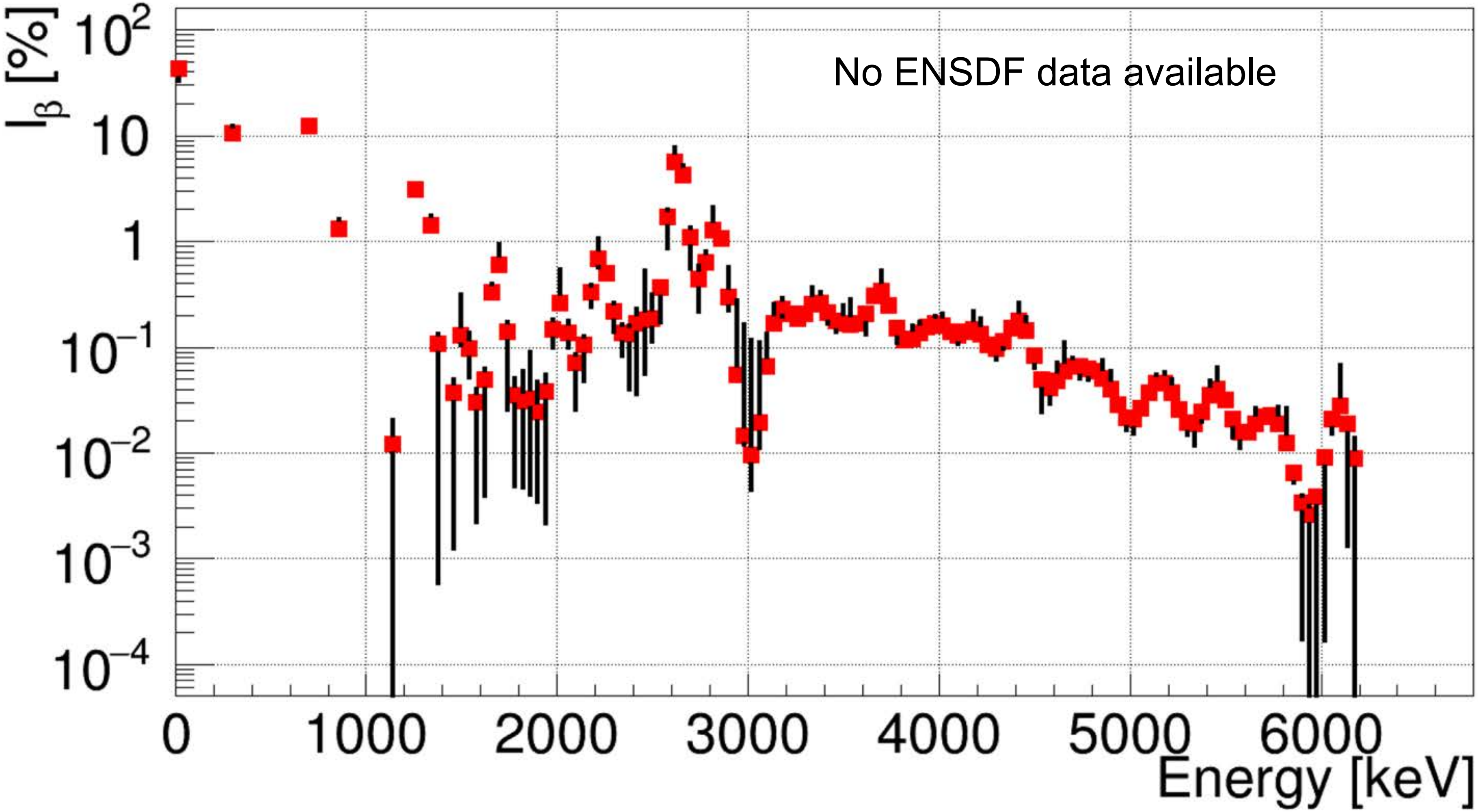




V. Guadilla et al., PhD thesis

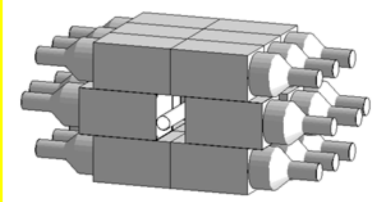
^{102m}Nb decay (1+ state, 94 keV)





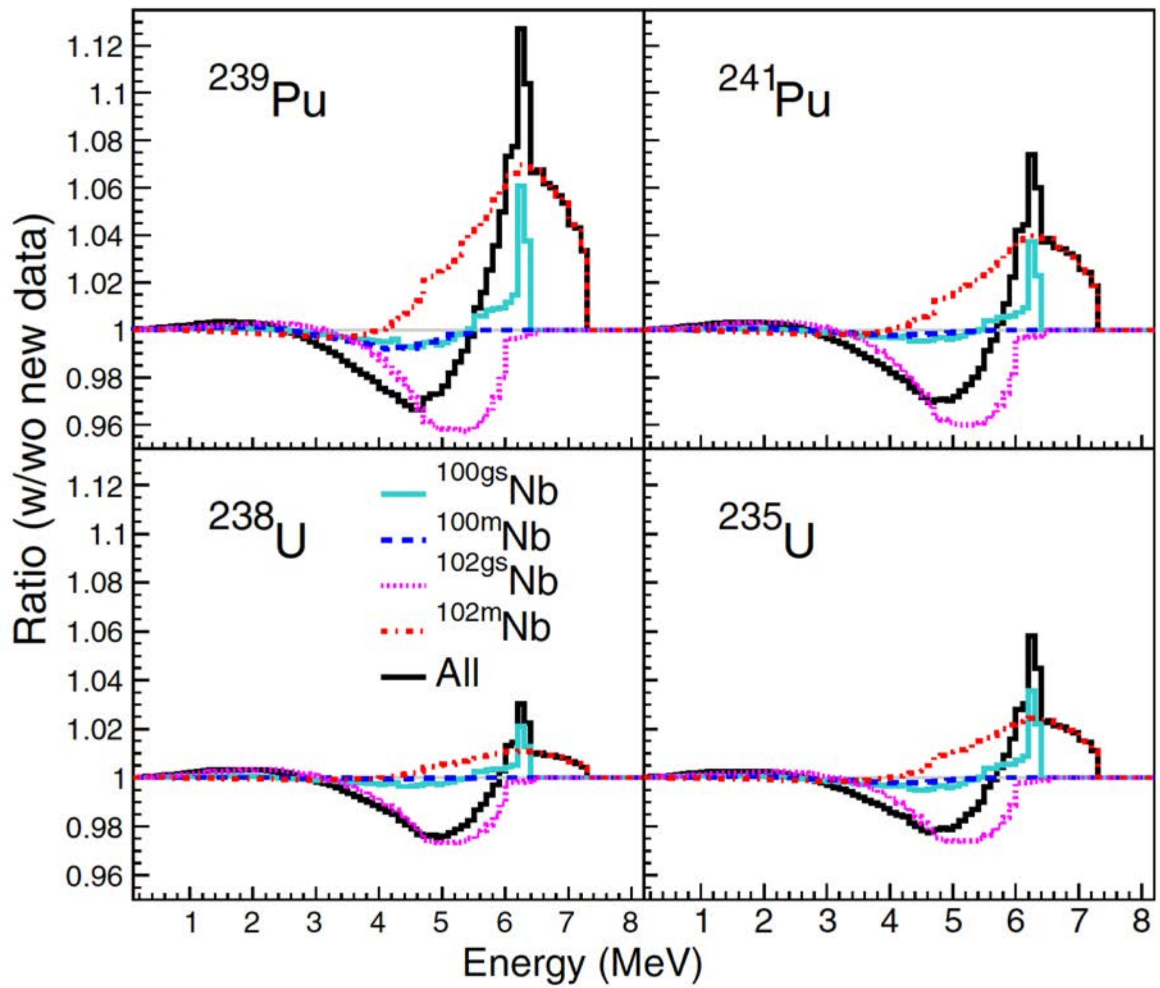
V. Guadilla et al., PRL 112.042502

Impact on the 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 !!!

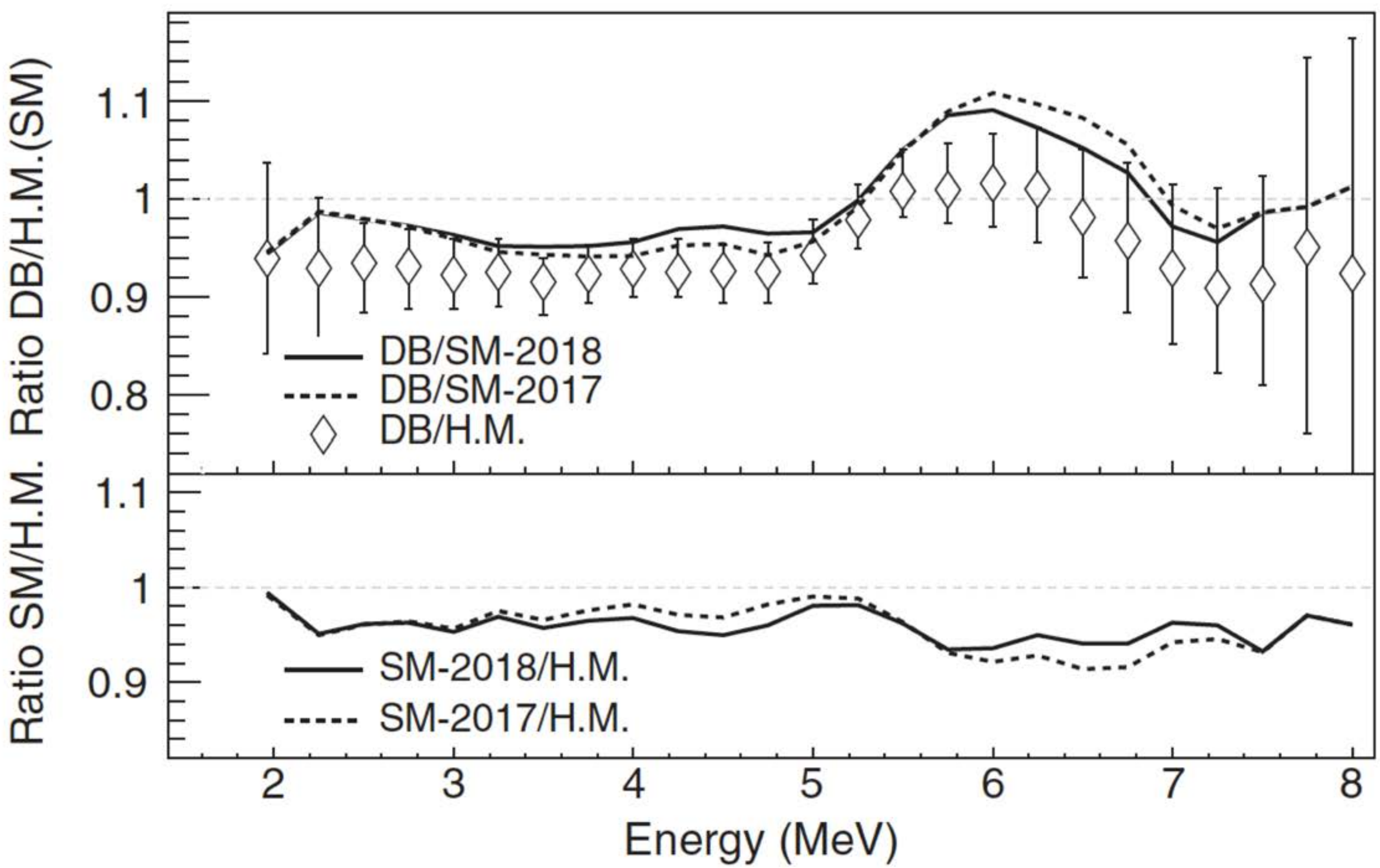


V. Guadilla et al., PRL 112.042502

Is the reactor anomaly dead?

Results from the application of a updated summation calculation including all our TAS measurements. The discrepancy with the antineutrino meas. within this model is of the order of 2 % in the region that dominates the flux

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

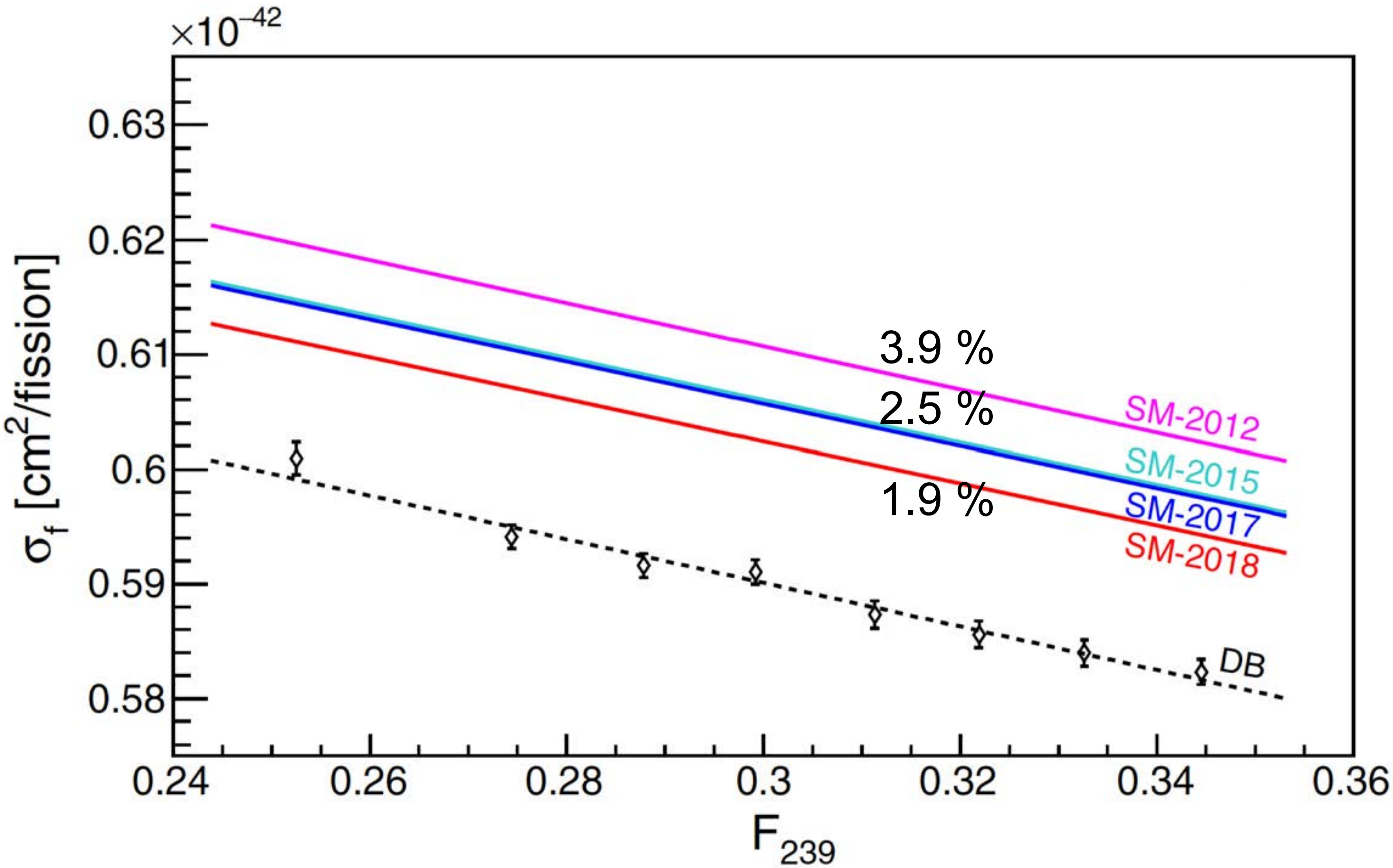


Subatech Calculations Estienne, Fallot, et al.

Summation is now better than the Hueber-Mueller conversion model

Is the reactor anomaly dead?

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



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

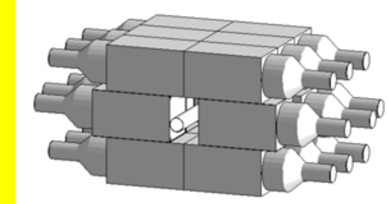
SM-2018: $^{100;100m;102;102m}$Nb

DB: Daya Bay

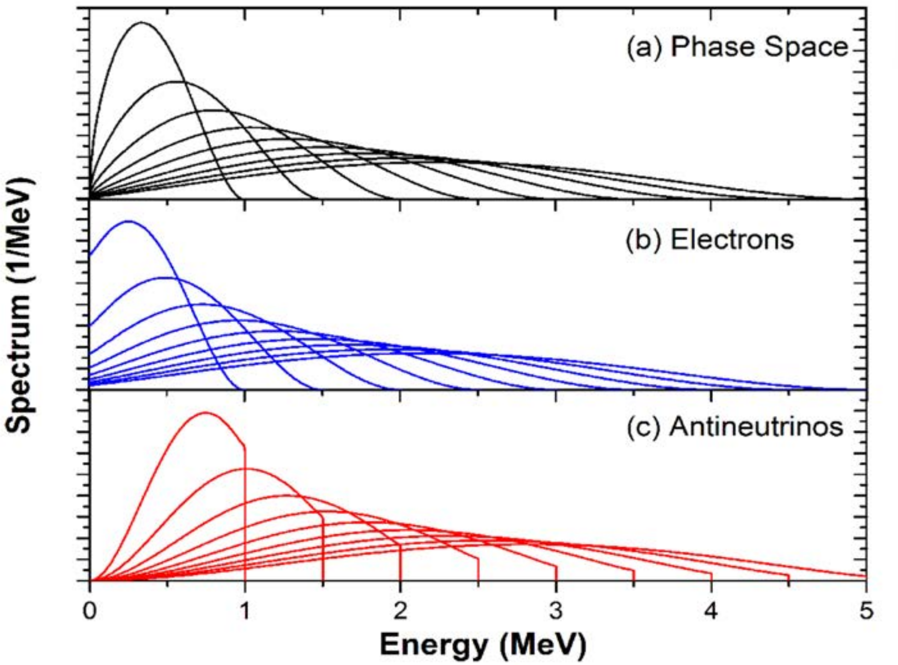
$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \bar{F}_{239}).$$

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

Antieutrino summation calculations: reactor spectroscopy



Fine structure of the antineutrino spectrum from a reactor reflects what is going on inside a reactor



A. Sonzogni et al., PRC 98.014323

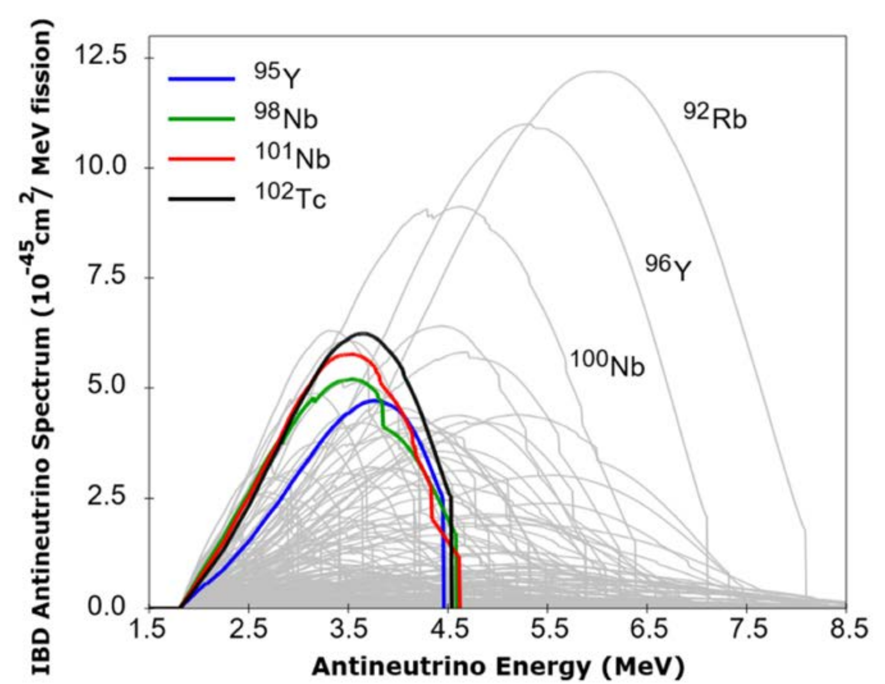


FIG. 6. Calculated Daya Bay IBD antineutrino spectra from all the fission products, highlighting the ^{95}Y, ^{98,101}Nb, and ^{102}Tc ones.

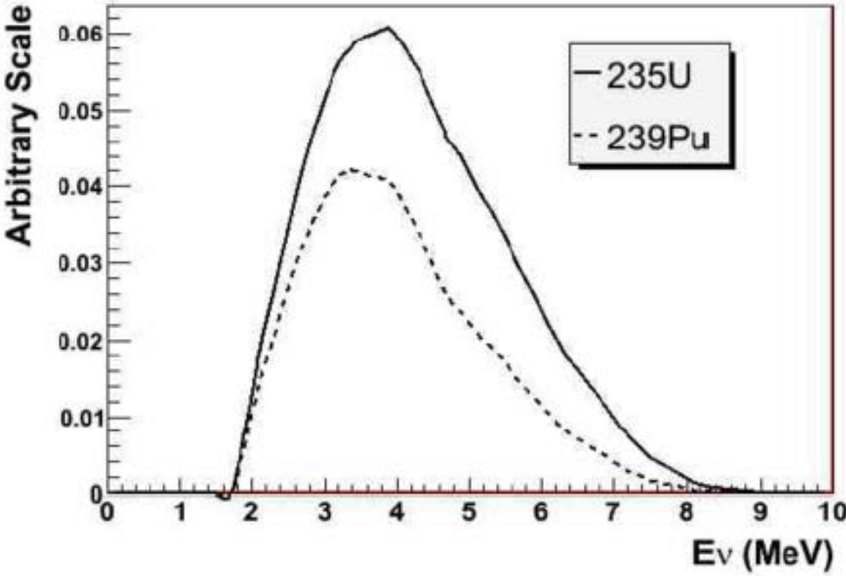
Window to "new physics" and applications: it can be also relevant for antineutrino experiments of new generation like JUNO and TAO, that address fundamental questions like the mas hierarchy

Another application: prediction of the neutrino spectrum from reactors for non-proliferation

	235U	239Pu
Released E per fission	201.7 MeV	210.0 MeV
Mean neutrino E	2.94 MeV	2.84 MeV
Neutrinos/fission >1.8 MeV	1.92	1.45
Aver. Int. cross section	$3.2 \times 10^{-43} cm^2$	$2.8 \times 10^{-43} cm^2$

$$\bar{\nu} + p \rightarrow e^{+} + n$$ (threshold 1.8 MeV)

Relevance for non-proliferation studies (working group of the IAEA). Neutrino flux can not be shielded. Study to determine fuel composition and power monitoring. Non-intrusive and remote method.



Message

- I hope that I have shown that the TAS technique can contribute to the improvement of nuclear data for neutrino applications, in particular for summation calculations.
- Our results come from careful measurements and analyses. Special care have been devoted to the purity of the beams (trap assisted spectroscopy) and to the characterization of the detectors
- There are still several cases measured to be published from the top contributors to the neutrino spectrum, but we are working on that, since this is part of our highest priority research lines. New proposal approved for JYFL. Other groups are also working on the topic (Oak Ridge group)
- We thank the IAEA for the continous support of the related activities

THANK YOU

V. Guadilla, L. Le Meur, Z. Issoufou, S. Rice, E. Valencia, M. D. Jordan, J. L. Tain, M. Fallot, M. Estienne, J. Agramunt, A. Porta, J. A. Briz, A. A. Sonzogni, T. Eronen, L. M. Fraile, E. Ganioglu, W. Gelletly, D. Gorelov, J. Hakala, A. Jokinen,, V. Kolkinen, J. Koponen, L. Lebois, T. Martinez, A. Montaner, I. Moore, E. Nácher, S. Orrigo, H. Penttilä, I. Pohjalainen, J. Reinikainen, M. Reponen, S. Rinta-Antila, B. Rubio, T. Shiba,, V. Vedia, A. Voss, J. N. Wilson, A. Algora, …

What is TASTES? The TASTES anomaly

Even Bohr was challenged by the question
Inspired by the quantum mechanical teachings of J. Wood
(and also a bit by shape coexistence, and two level mixings)

$$\psi_{TASTES} = \phi_{SCHOOL}\ ?$$

$$\psi_{TASTES} = \phi_{CONFERENCE}\ ?$$

$$\psi_{TASTES} = \alpha\phi_{SCHOOL} + \sqrt{1-\alpha^2}\,\phi_{CONFERENCE}$$

$$what\ is\ the\ value\ of\ \alpha\ ?$$