



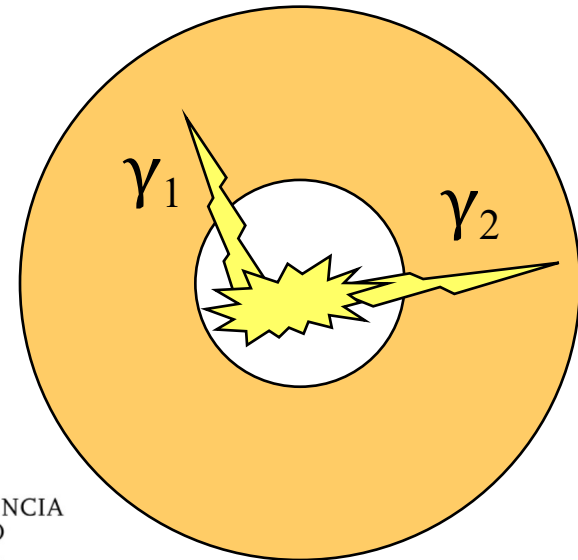
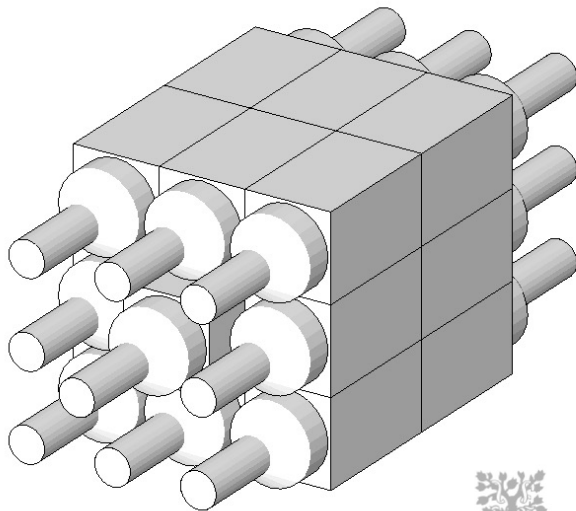
Paradise Lost, John Milton (earlier illustrations of the book)

Total Absorption Detectors (and the technique behind)

A. Algora

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

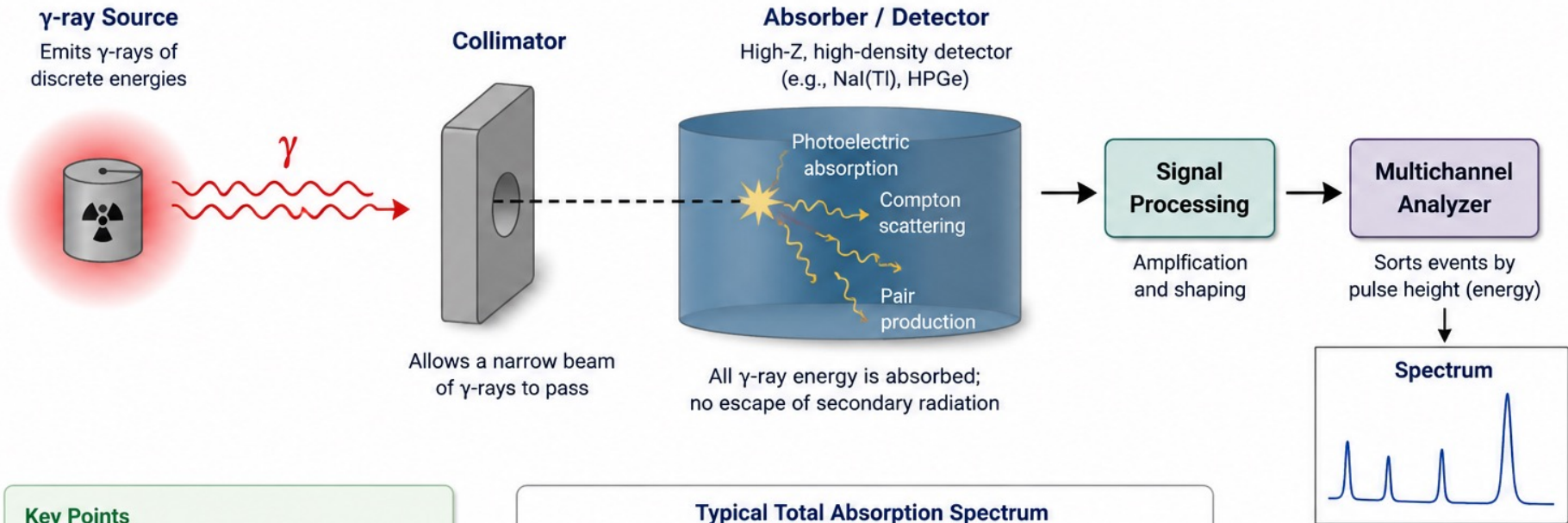
TIDPAN, June 2026



I asked ...

Total Absorption Spectroscopy

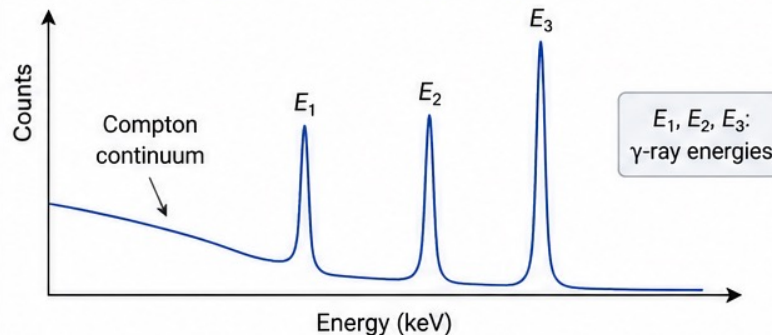
All γ -rays emitted by the source are completely absorbed in the detector.
The measured spectrum shows full-energy (photopeak) lines.



Key Points

- Total absorption occurs when the full energy of the γ -ray is deposited in the detector.
- The spectrum consists of photopeaks at the γ -ray energies.
- Peak intensity is proportional to the emission probability and detection efficiency.
- High detector efficiency is essential for good total absorption.

Typical Total Absorption Spectrum



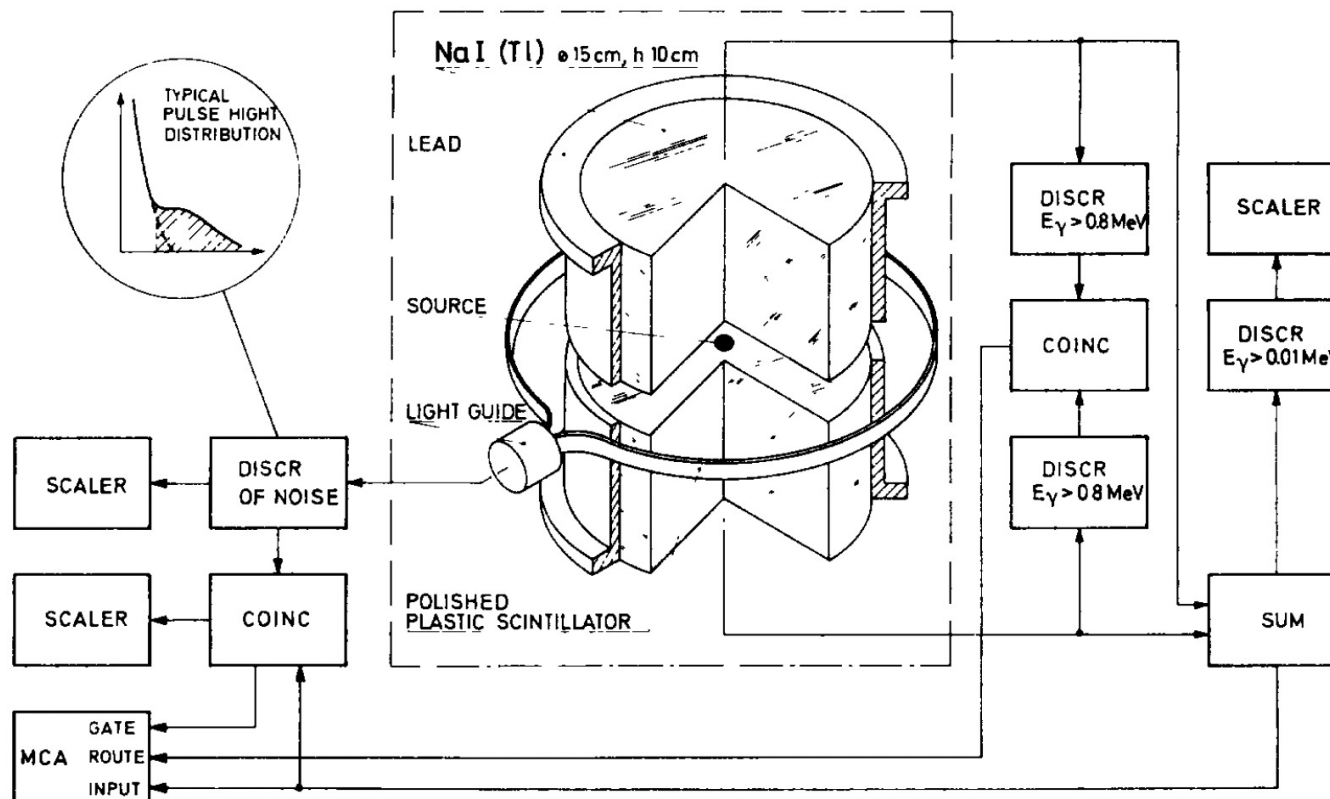
The first total absorption spectrometer

Duke et al, Nucl. Phys. A151 (1970) 609

Johansen et al., Nuclear Physics A203 (1973) 481

Goal:

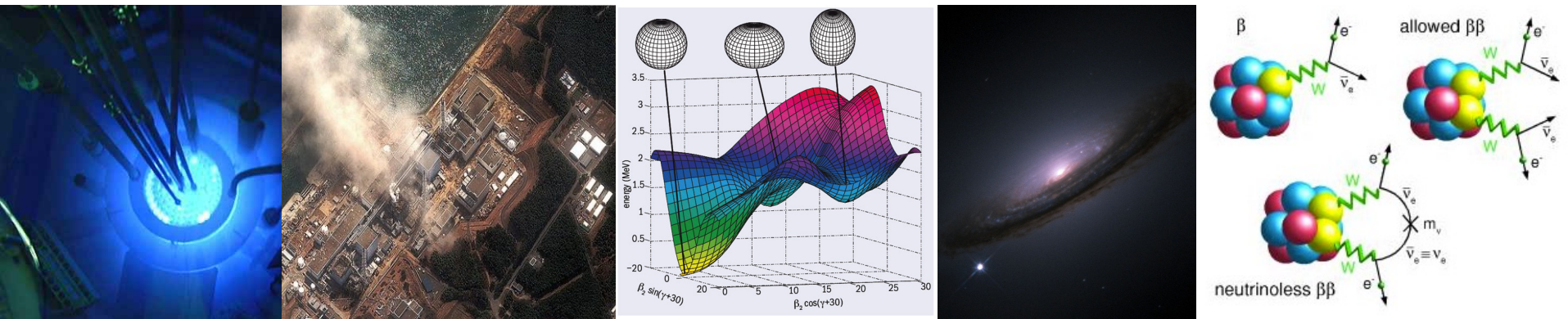
- Maximize the sum of gamma cascades. Take into account incomplett summing
- Minimize the effect of beta penetration and Brehmstrahlung



They called the technique: **incomplete absorption**

Outline

- Beta decay introduction, why we need the total absorption technique?
- Examples of detectors
- Challenges, and how the analysis is done
- Reactor applications (decay heat and neutrino physics)
- Astrophysical applications
- Ground state feeding determination (if enough time)



The ubiquitous beta decay

BROOKHAVEN
NATIONAL LABORATORY

National Nuclear Data Center

Approx. 288 stable
Approx 3000 known produced in
labs and reactors (and stars !!!)
Expected 6900 (500)
[J. Erler *et al.* Nature 486, 11188]

Beta decay studies are relevant for:

- Nuclear structure
- Nuclear astrophysics
- Fundamental physics
- Medical applications
- Nuclear reactors
- Neutrino physics

The study of the beta decay of exotic nuclei is at the forefront of nuclear physics research

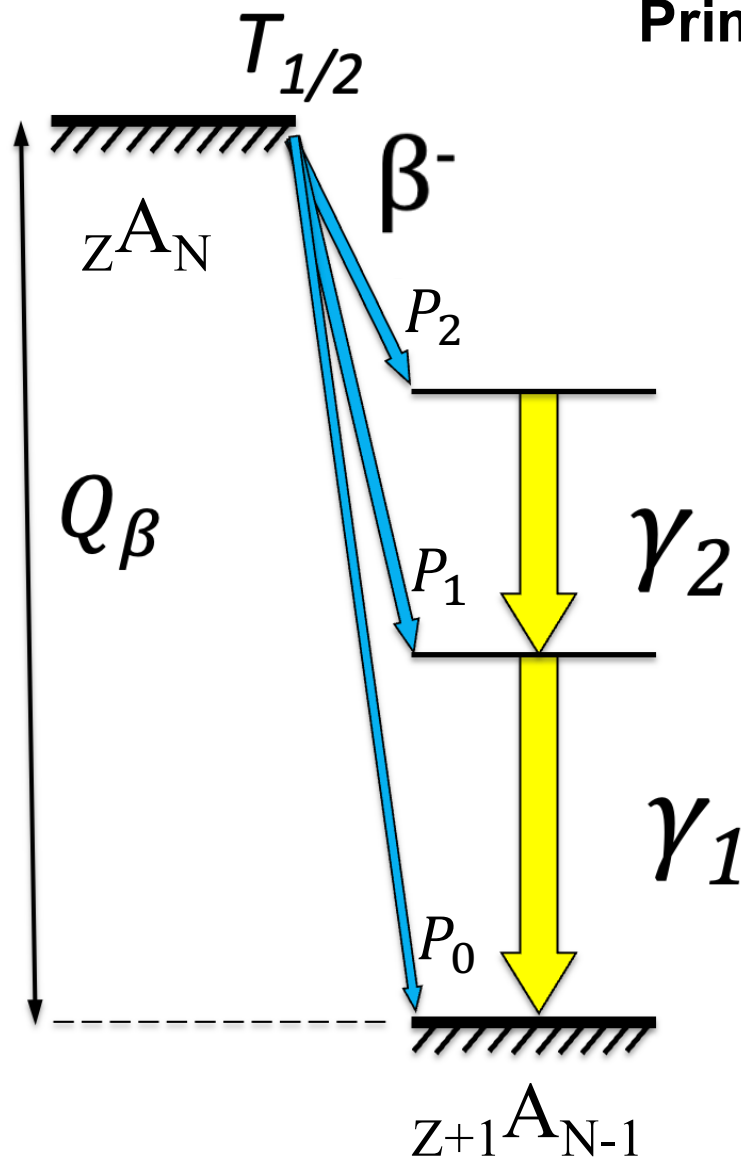
National Nuclear Data Center

National Nuclear Data Center, information extracted from the NuDat 2 database,
<http://www.nndc.bnl.gov/nudat2/>

"Users should feel free to use the information from NuDat 2 (tables and plots) in their work, reports, presentations, articles and books."

1. Question

Data needed for describing properly a beta decay



Primary experimental information needed

- Decay half-life
- Involved masses (Q values)
- Beta decay probabilities (feedings)

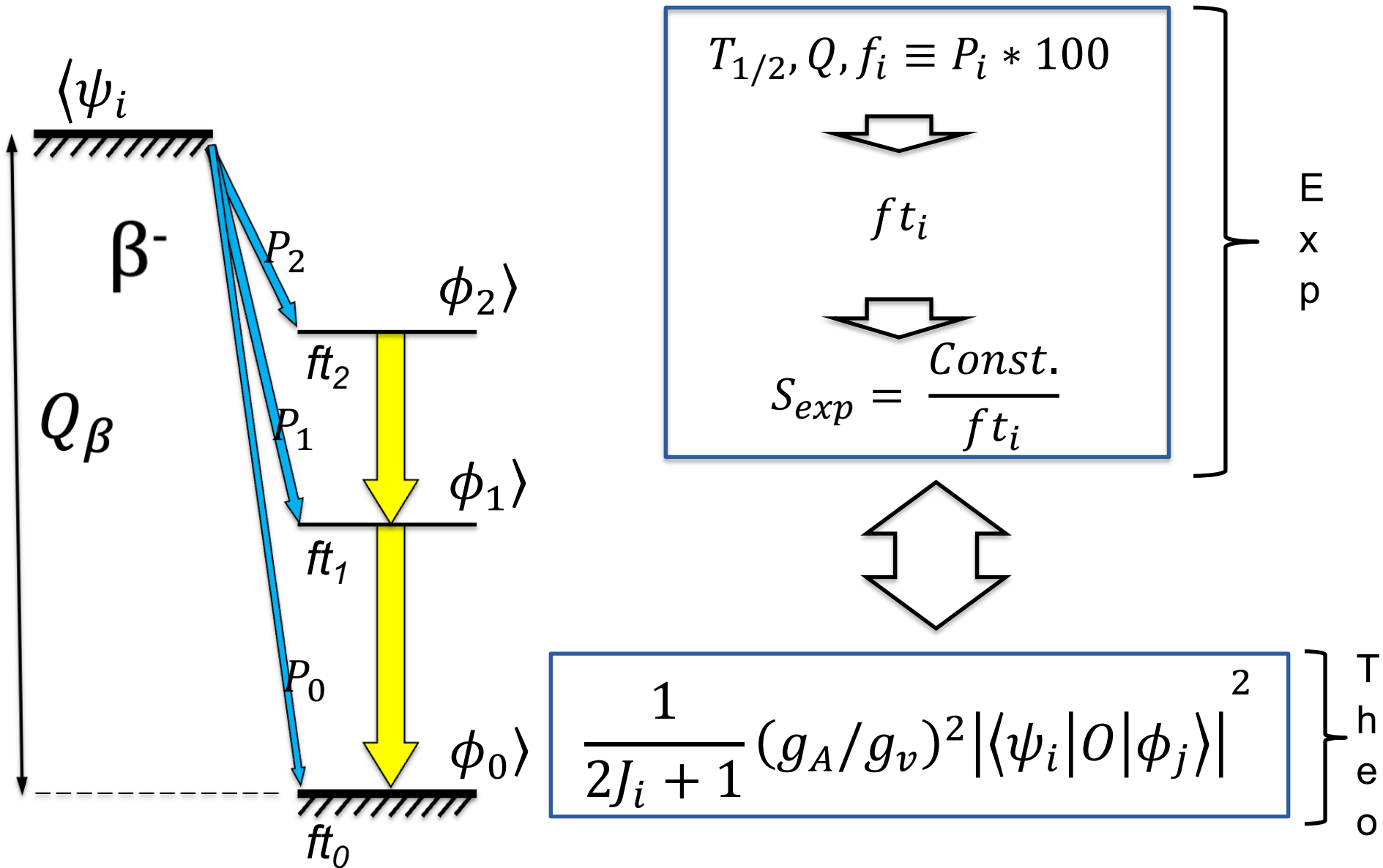
$$T_{1/2}, Q, I_{\beta,i} \equiv P_i * 100$$

$$t_i = \frac{T_{1/2}}{P_i} \quad (\text{partial half-life})$$

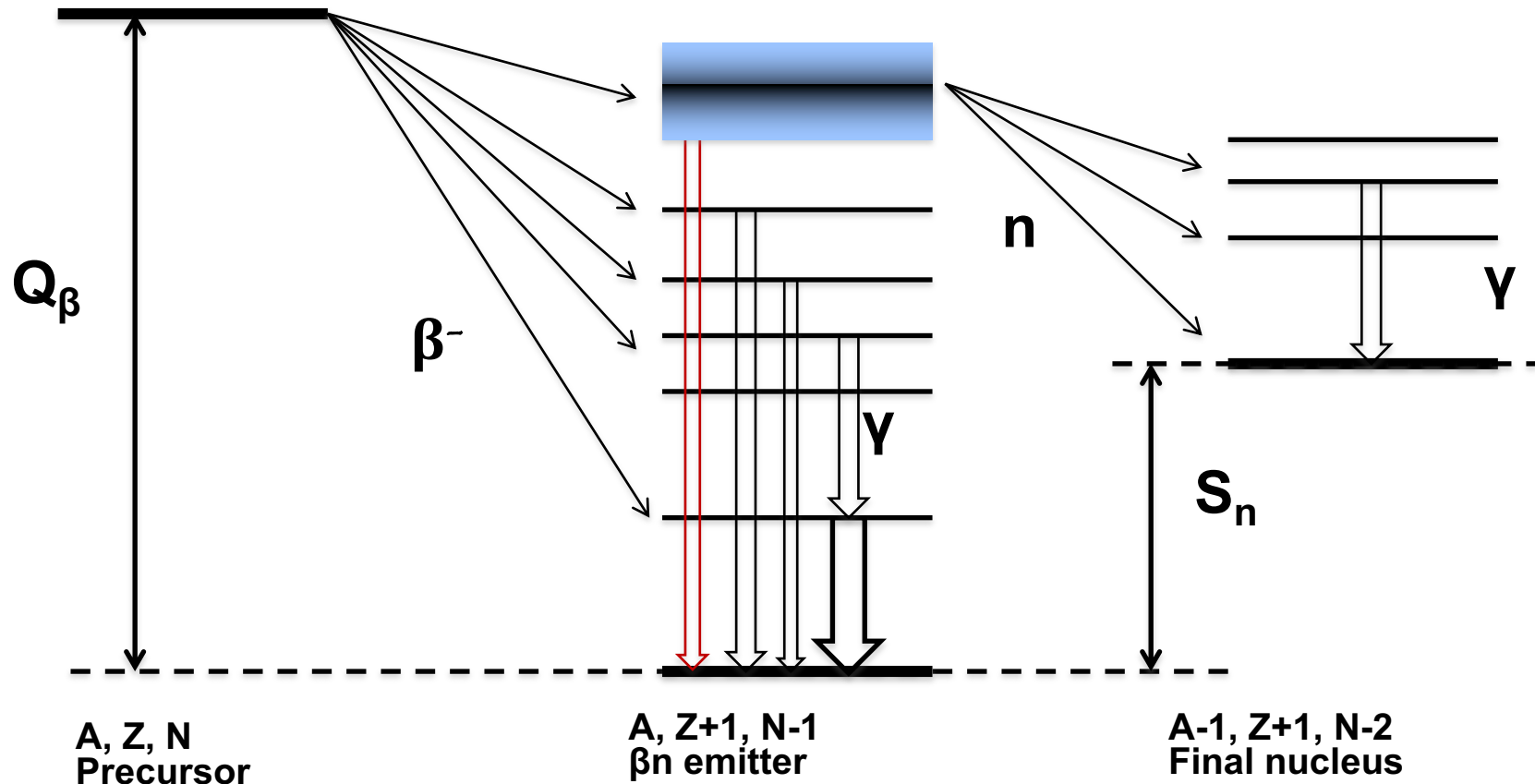
$$f = C \int_0^{p_{max}} F(Z', p) p^2 (Q - E_e)^2$$

$$f t_i \text{ (or } \text{Log } f t_i \text{)}$$

2. What is expected from theory? Beta feedings vs beta strength

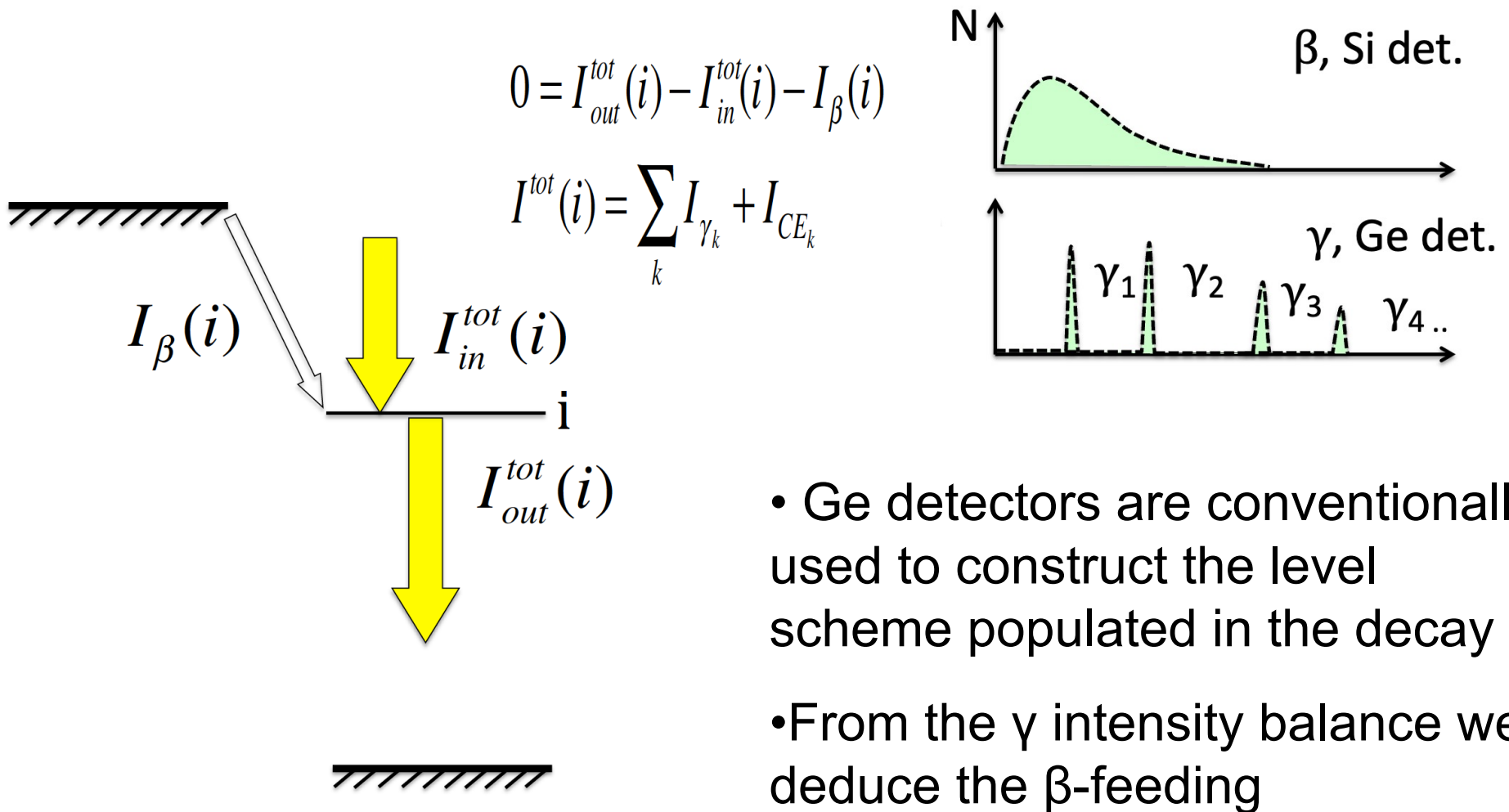


Additional complexity: beta delayed particle emission



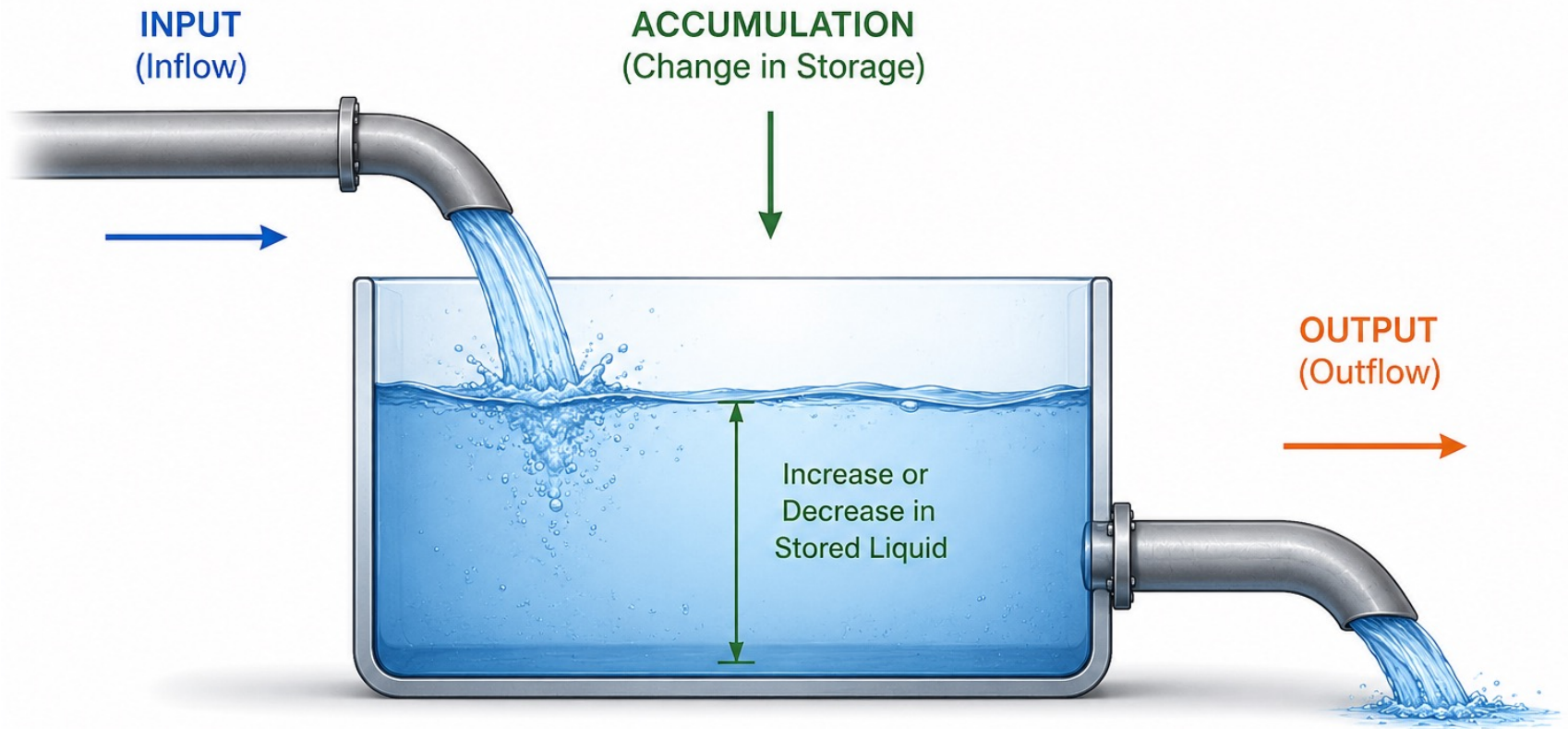
Beta delayed neutrons are possible when $Q_\beta > S_n$
 far enough from stability multiple emission $Q_\beta > S_{xn}$ ($x = 1, 2, 3, \dots$)
 can occur

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



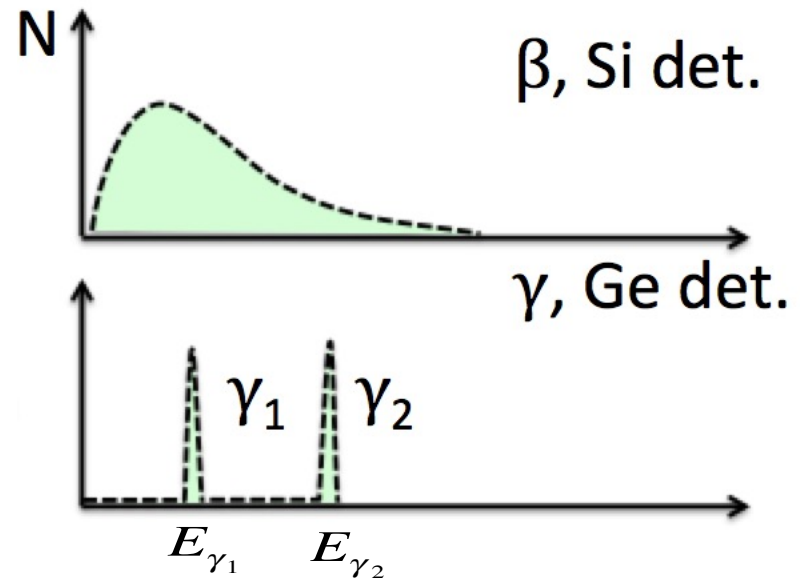
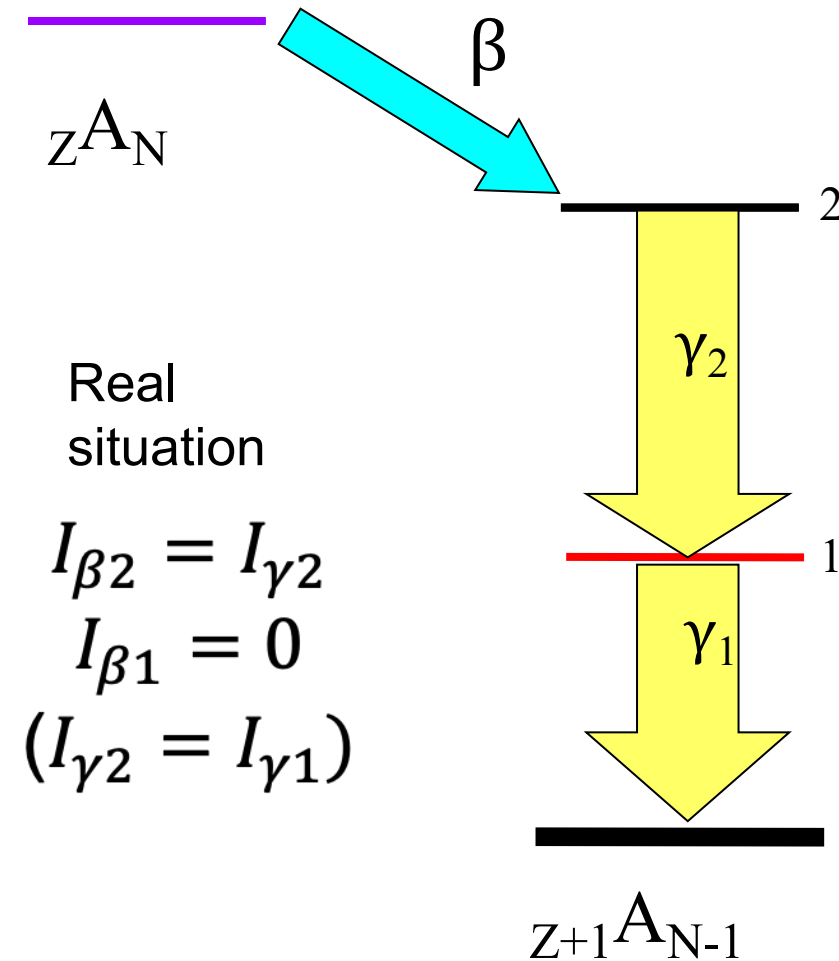
What I just showed is the typical balance equation, which is also valid for chem. react

$$\text{Input} = \text{Accumulation} + \text{Output}$$



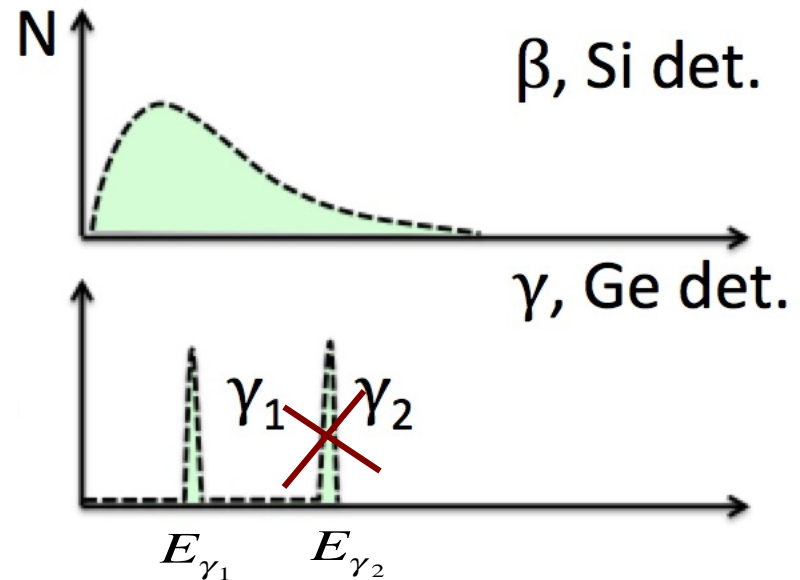
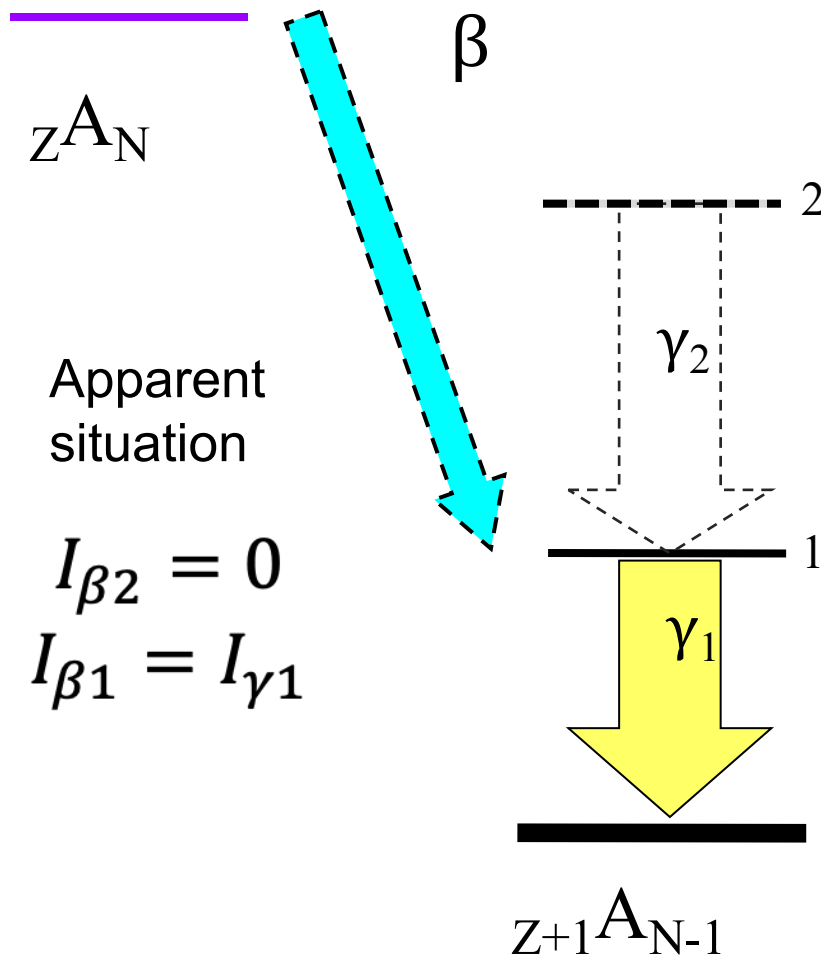
Input (inflow) adds liquid to the system.
Output (outflow) removes liquid from the system.
The difference is the **accumulation** (change in storage).

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



- 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 ($I_\beta = P_\beta \cdot 100$)

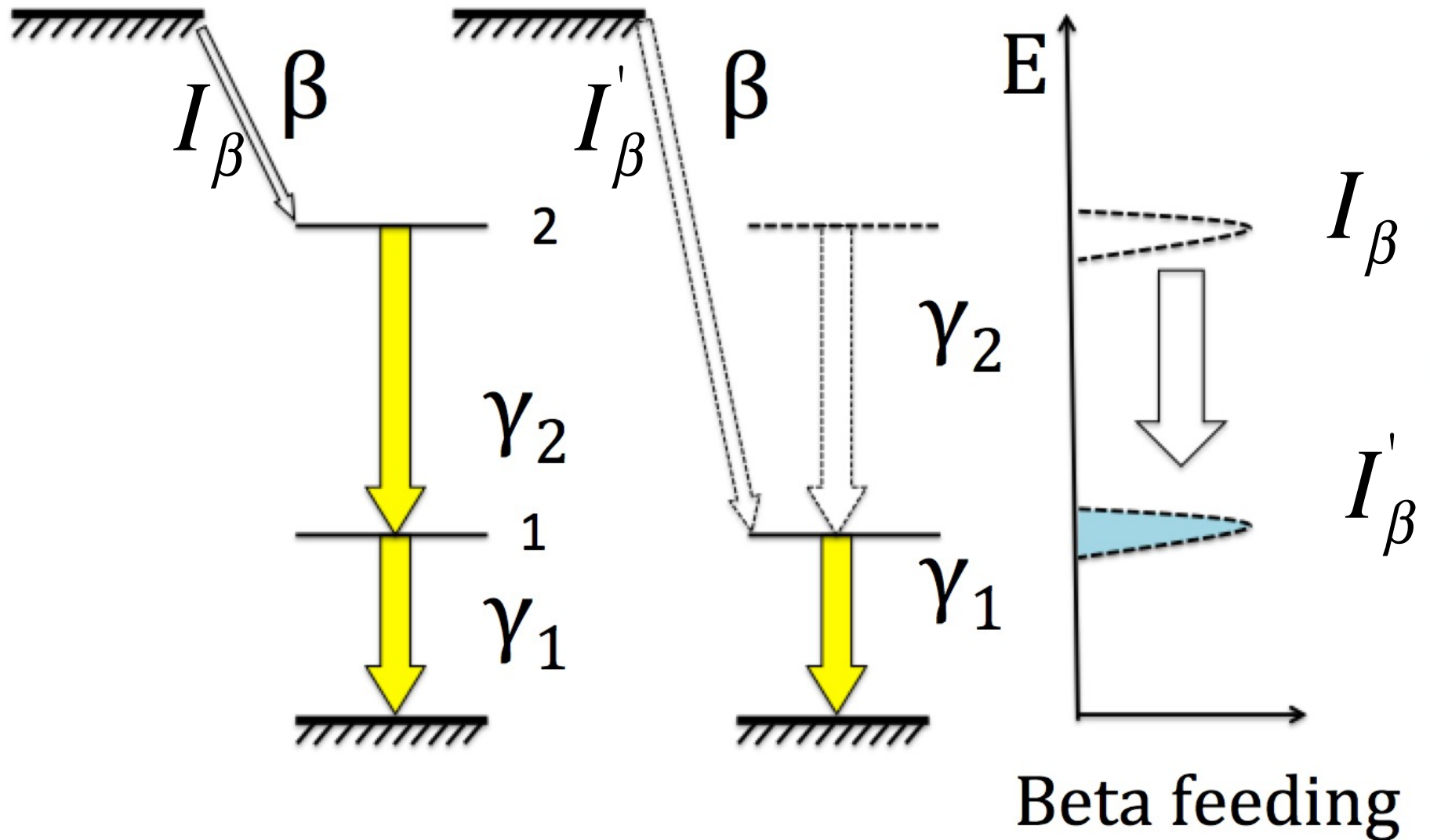


What happens if we miss some intensity?

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*

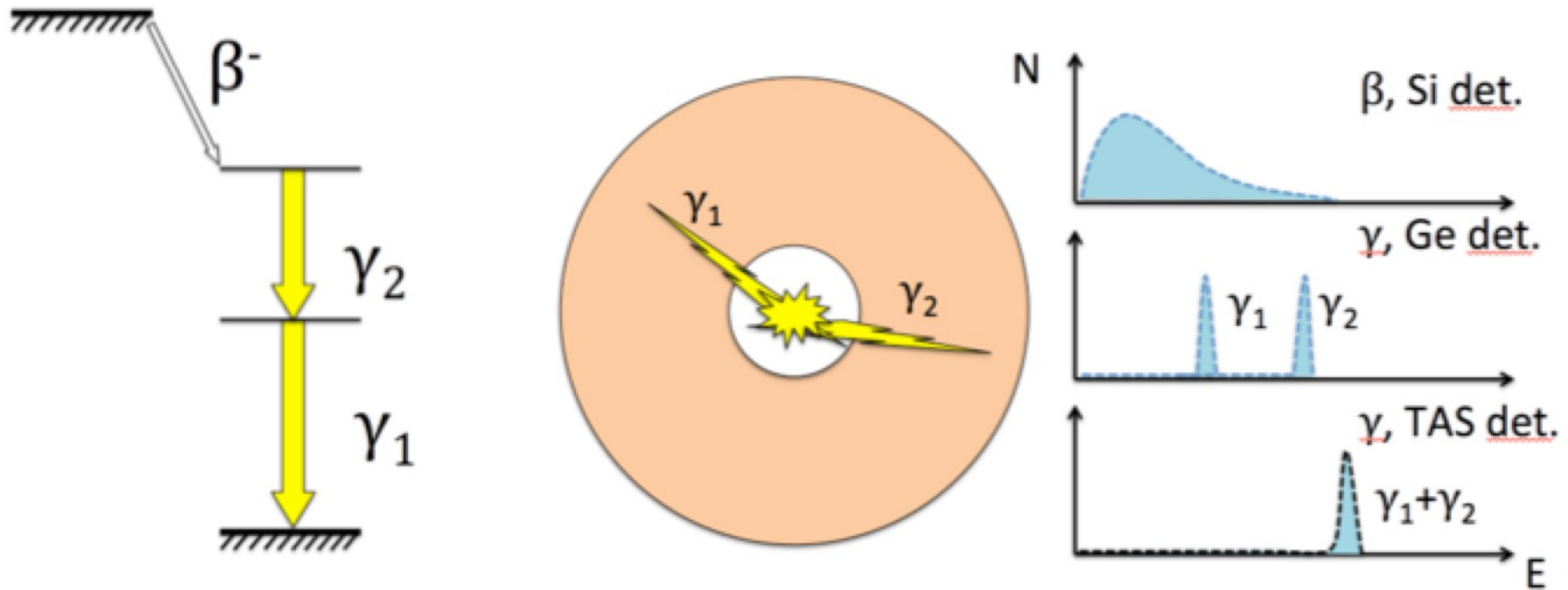


Merriam-Webster definition: wild uproar or unrestrained disorder; tumult or chaos

John Martin (~ 1825), presently at Louvre

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

Total absorption spectroscopy applied to beta decay studies



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

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

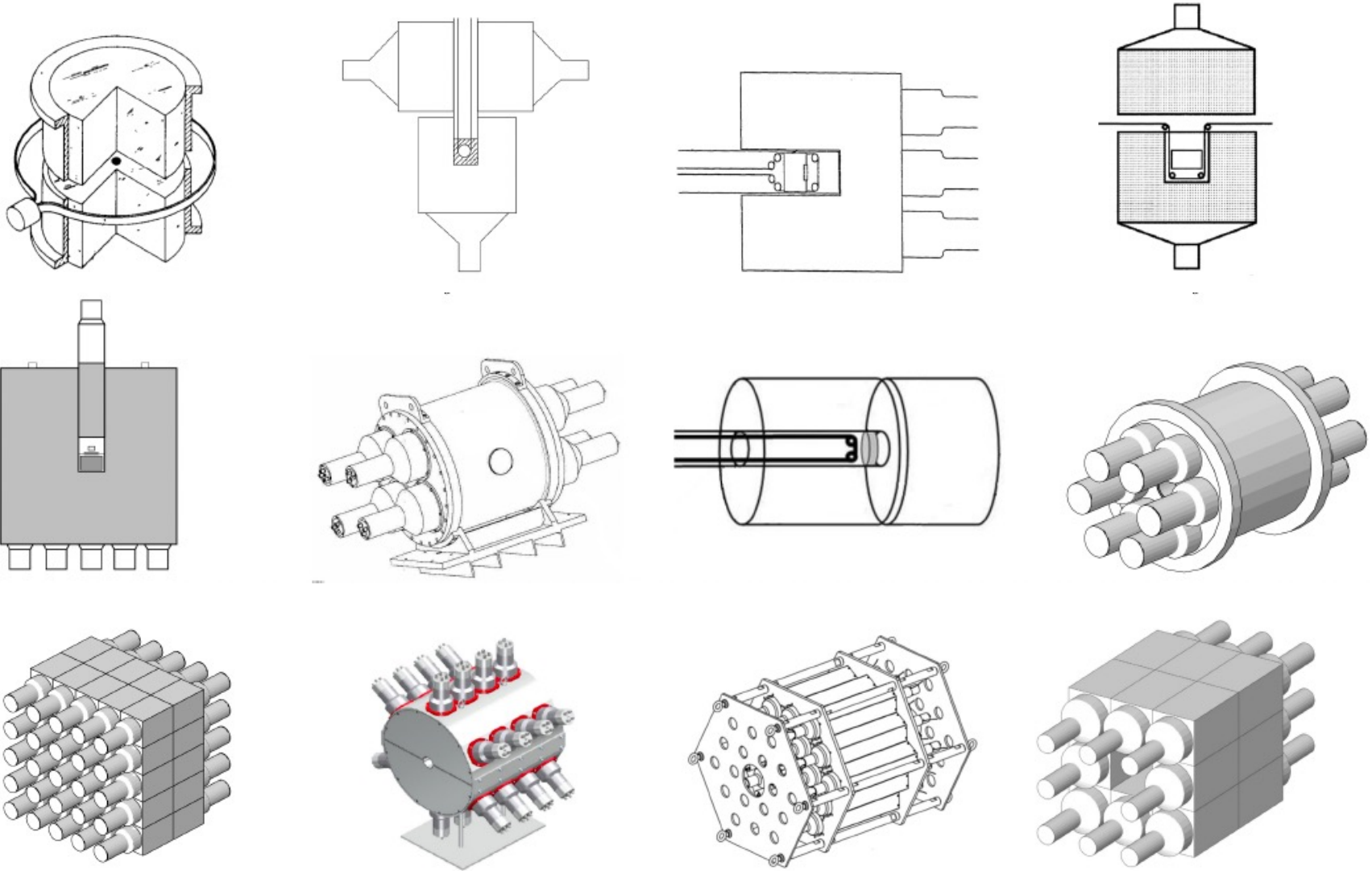
Requirements: clean spectrum or a proper treatment of the contaminants, some knowledge of decay level scheme of the daughter, etc.

The materials

Scintillator Material Comparison

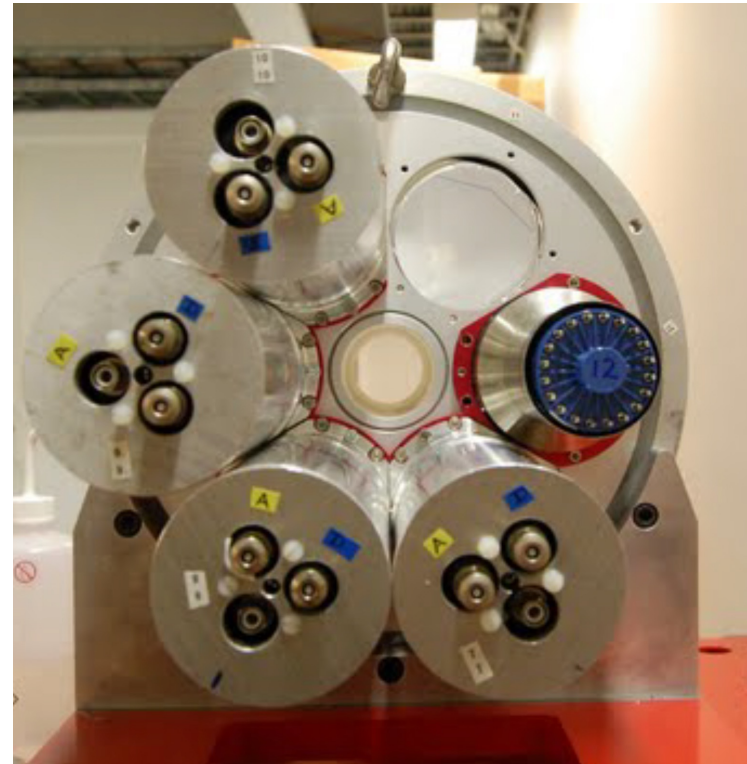
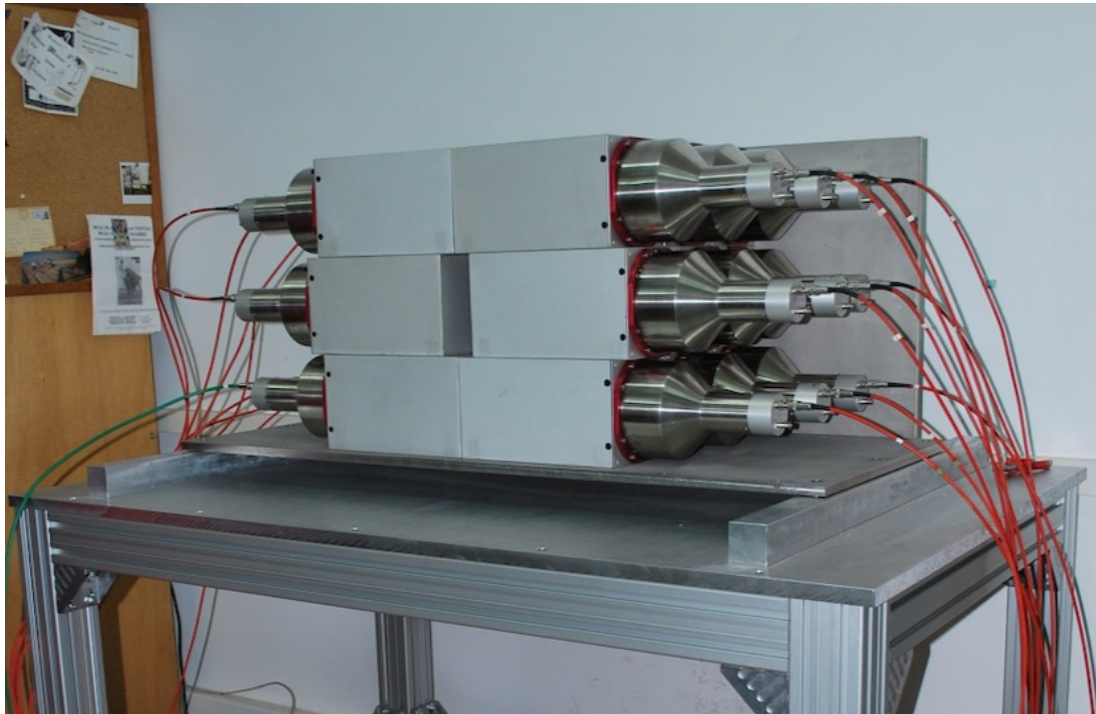
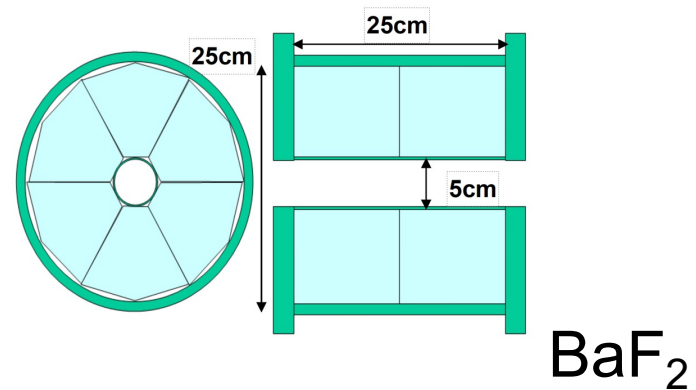
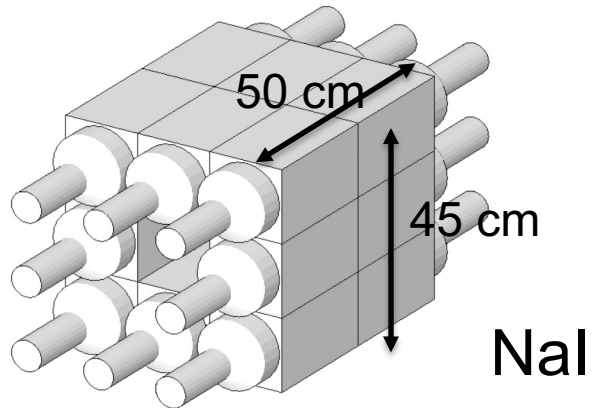
Property	Sodium Iodide (NaI:TI)	Barium Fluoride (BaF ₂)	Lanthanum Bromide (LaBr ₃ :Ce)
Density (g/cm ³)	3.67	4.89	5.08
Effective Atomic Number (Z _{eff})	50	59	47
Decay Time Constant	~250 ns	~0.8 ns (Fast) / 620 ns (Slow)	~16 ns
Light Yield (Photons/MeV)	~38,000	~10,000	~63,000
Energy Resolution @ 662 keV	~6–7%	~10–11%	~2.5–3%
Hygroscopic	Yes (Highly)	No (Practically insoluble)	Yes (Slightly to Moderately)

Time evolution of spectrometers



Taken from Guadilla's thesis, Univ. of Valencia

Valencian design examples: DTAS, Rocinante

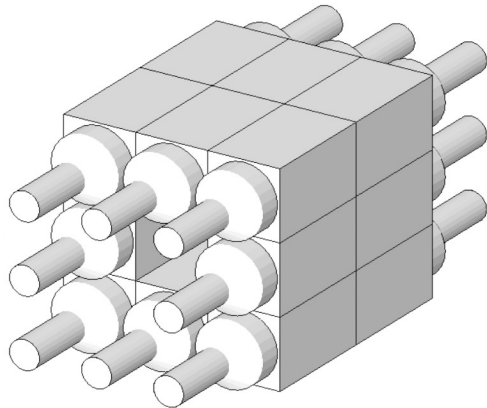


New generation: hybrid detectors

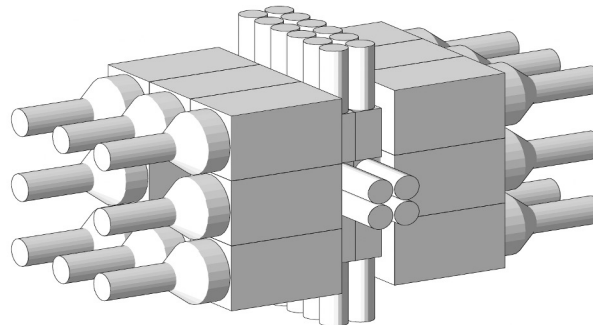
Original design options for DESPEC (FAIR) proposed in the Technical Design Report

16 + (2) modules:

15 x 15 x 25 cm³ **NaI(Tl)**
+ 5" PMT (50% light col.)
V= 95 L, M= 351 kg

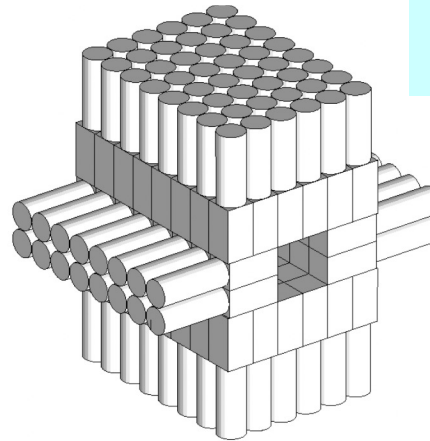


Third generation design
Hybrid detector



128 modules:

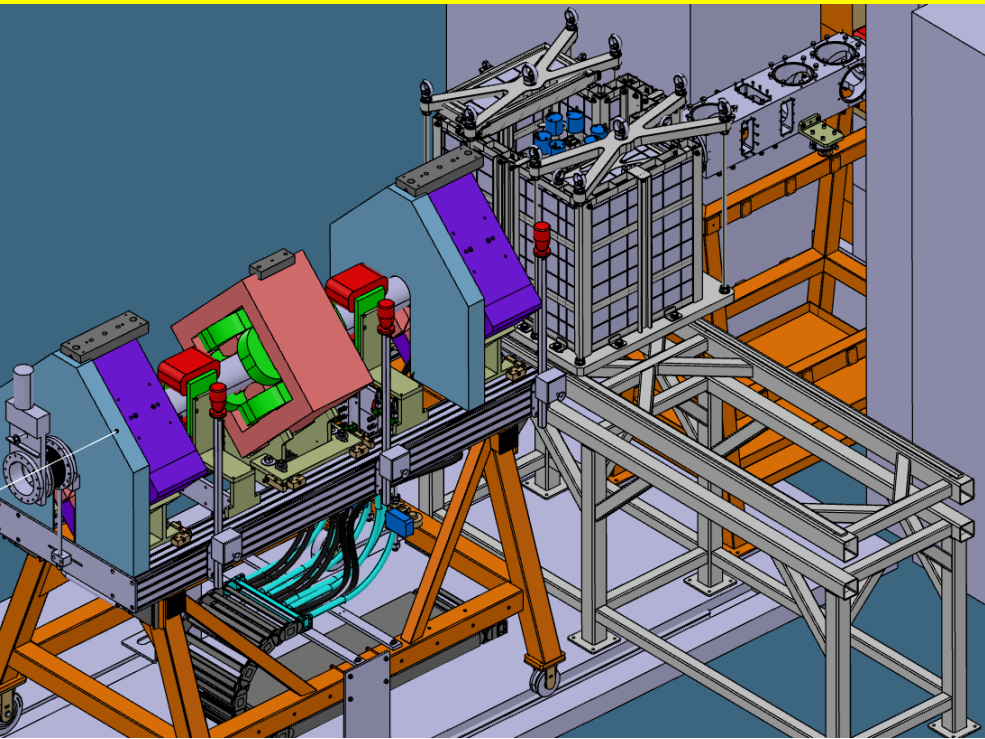
5.5 x 5.5 x 11 cm³ **LaBr3**
+ 2" PMT (90% light col.)



+16 modules:

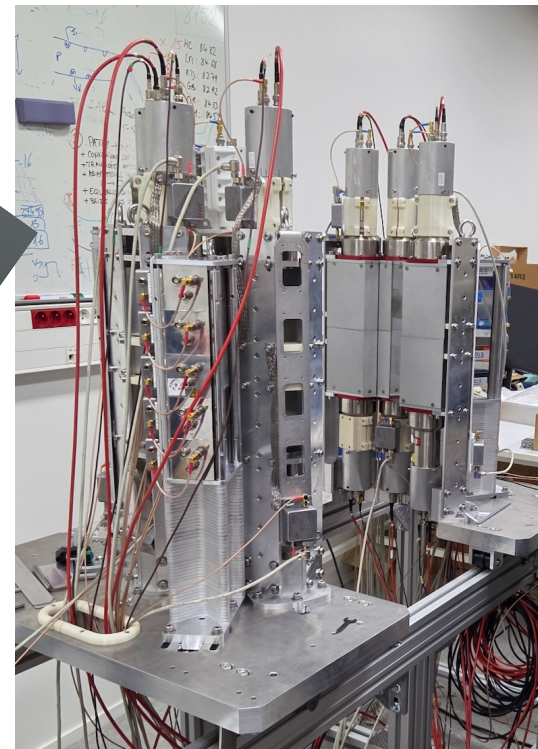
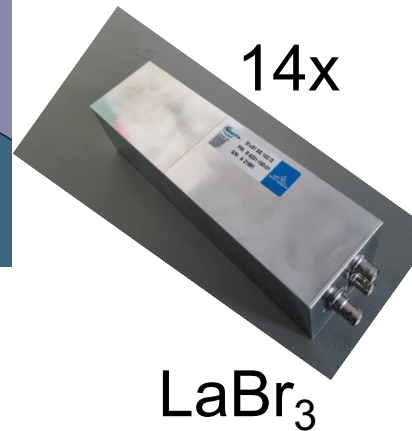
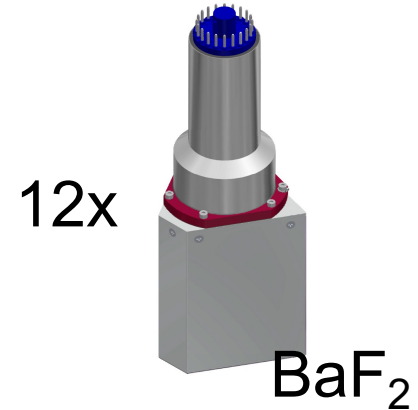
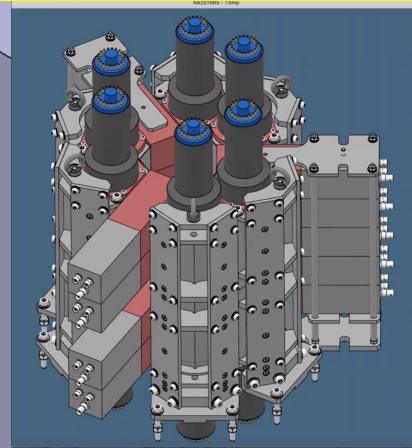
15 x 15 x 25 cm³ **NaI(Tl)**
+
32 LaBr3

New generation: hybrid detectors



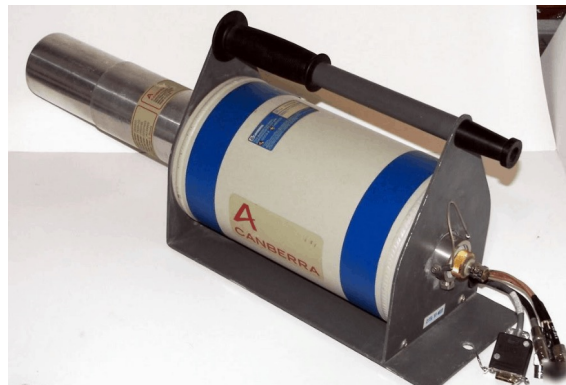
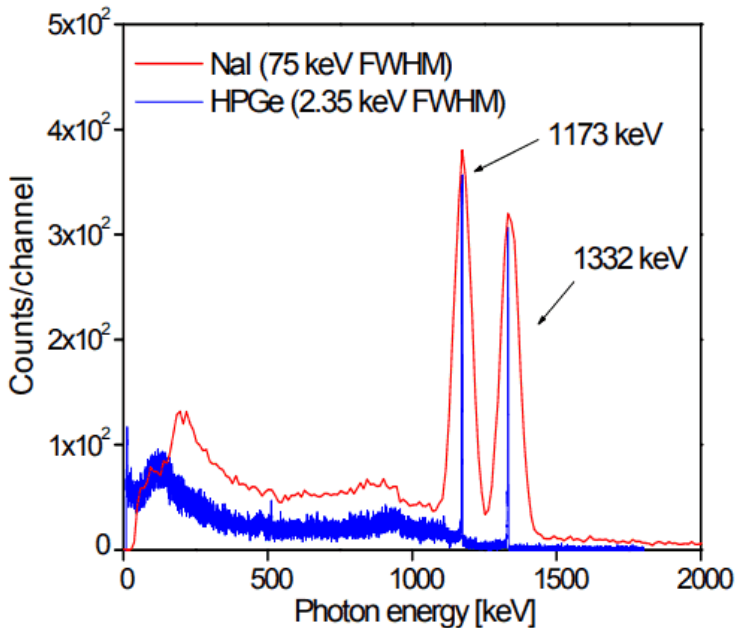
Third generation design
Hybrid detector, 2026
To be deployed at GANIL

NA(2)STARS
IFIC-Subatech-CIEMAT-IEM etc.
Collaboration

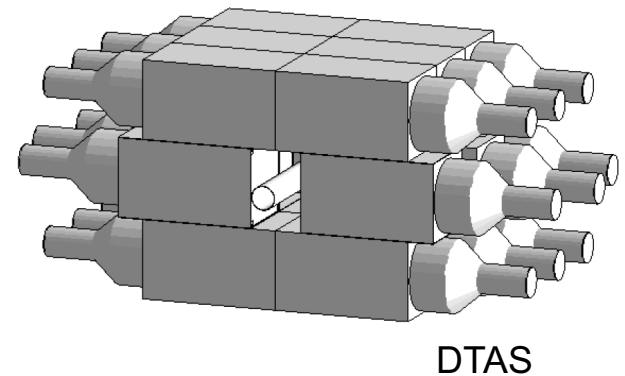
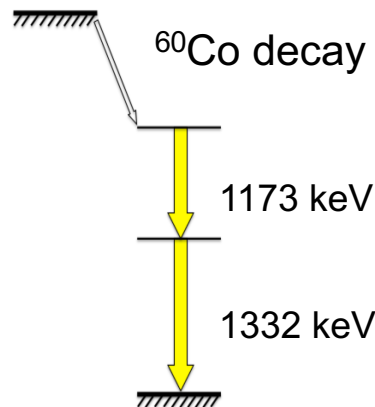
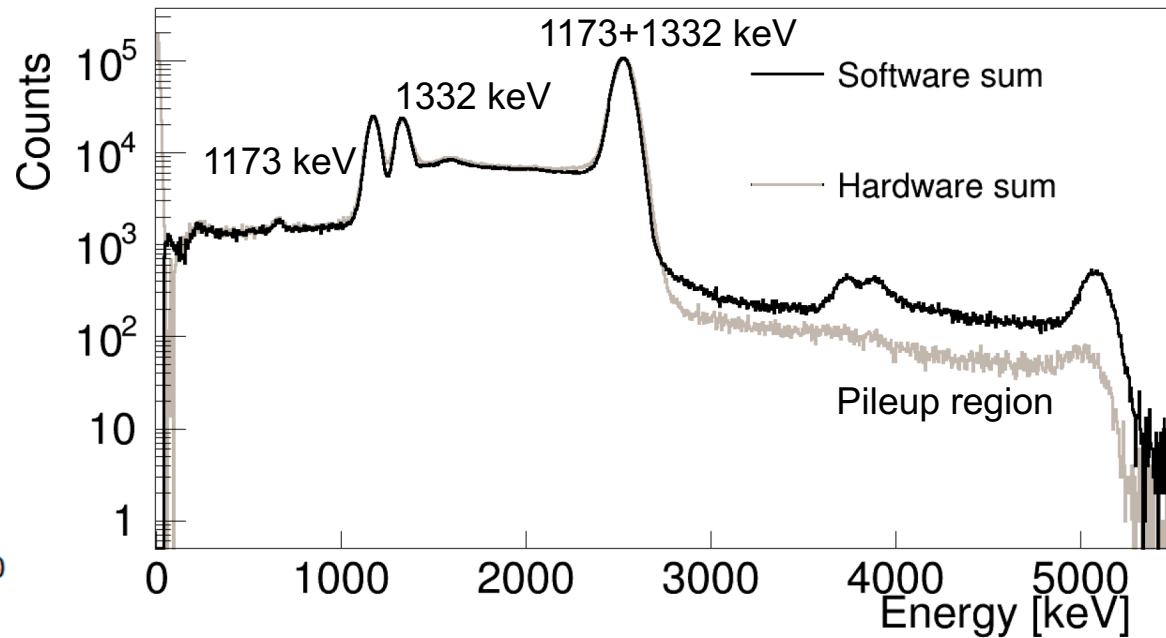


Real spectra

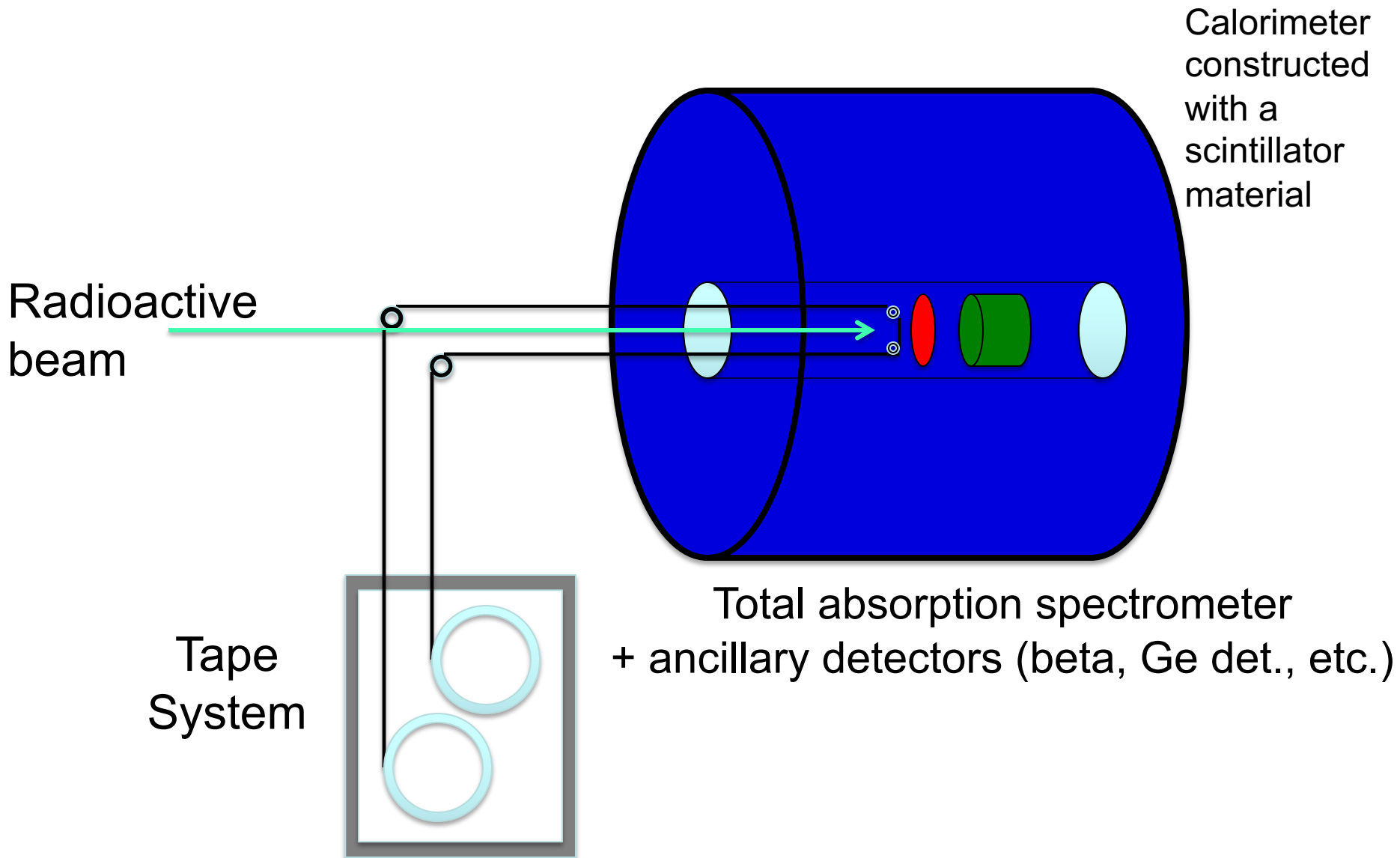
“Small” detectors



Real calorimeter detector



Typical total absorption experiments



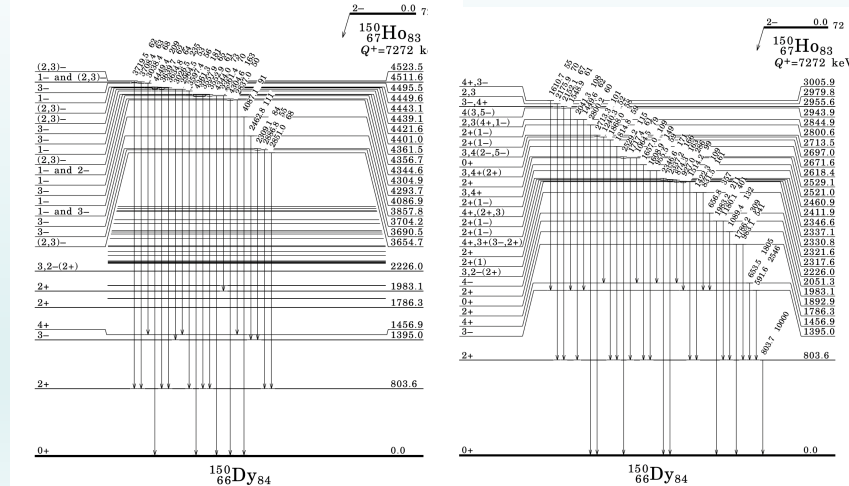
My first Pandemonium experience:

^{150}Ho 2^- isomer decay

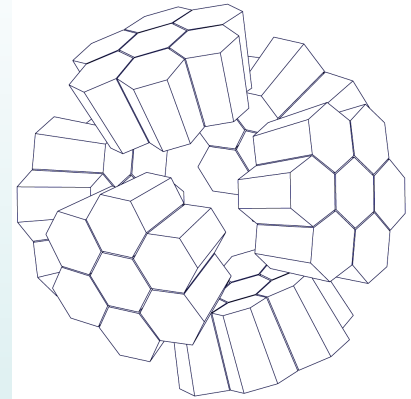
Before 2003

Only 4 gamma rays known

1064 gamma rays, 295 levels
 Algora, Rubio, et al. PRC68.034301



42 Ge capsules



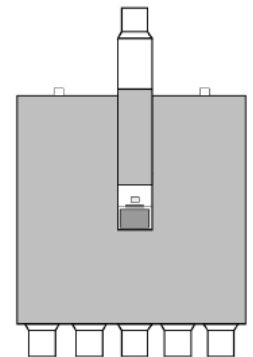
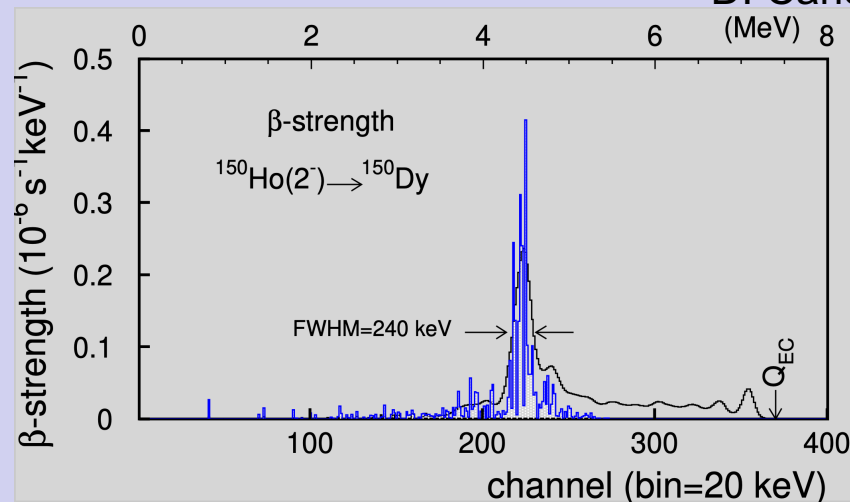
Cluster Cube
 10% eff at Co

Guinness record ?

10 m level scheme
 (1 gamma per cm)

D. Cano-Ott, J. L. Tain et al.

The CC sees
 approx. 50% of the
 total TAS B(GT)



LBL TAS

How these challenging experiments are analyzed?

$$d = R(B).f$$

Measured
spectrum without
contaminants

Response matrix

Beta feeding
distribution
(goal)



Needs/challenges:

Well controled Monte Carlo simulations

Excellent calibration (energy and width)

Knowledge of the (B), branching ratio matrix (level scheme)

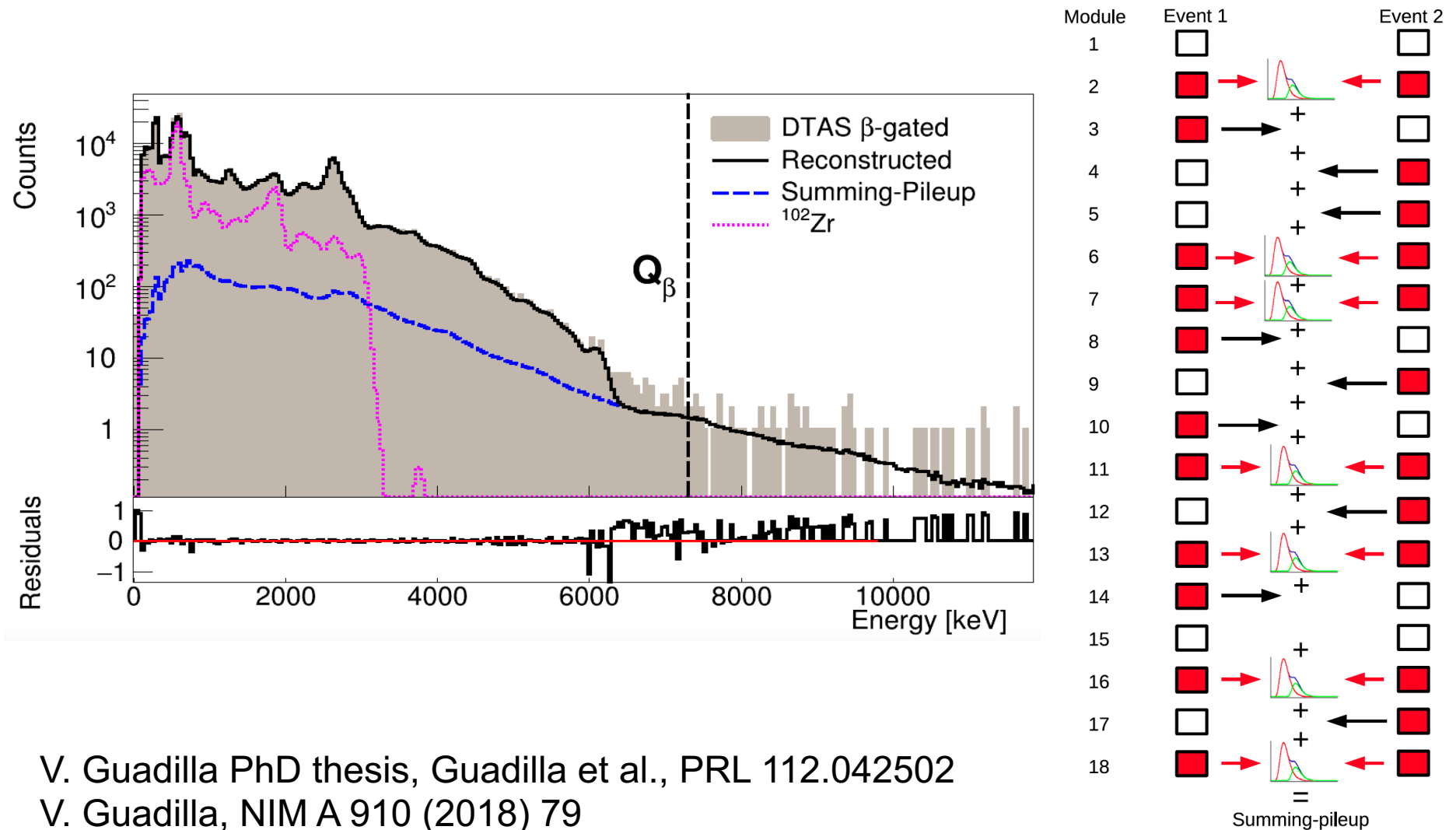
Methods for solving the inverse problem

Control of contaminants

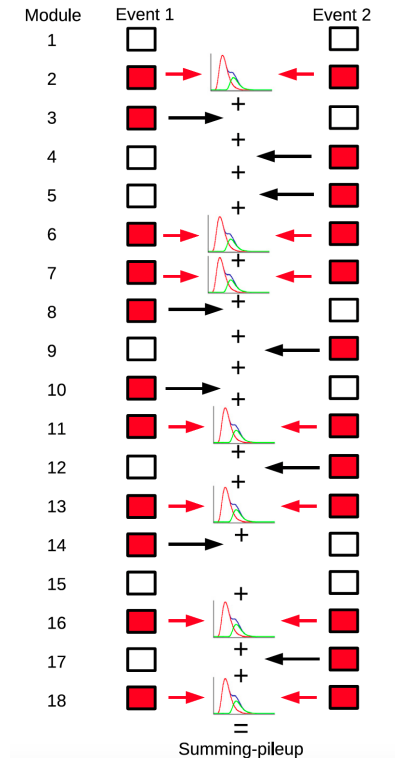
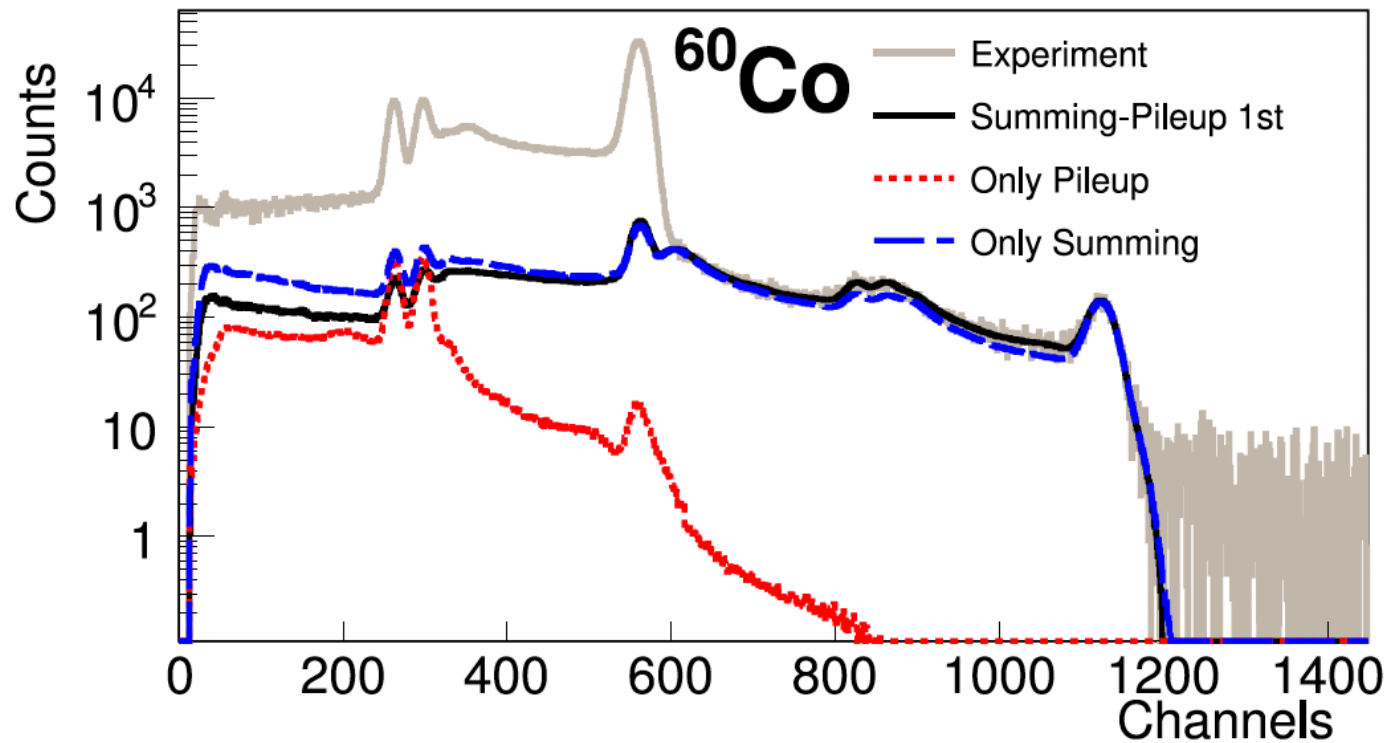
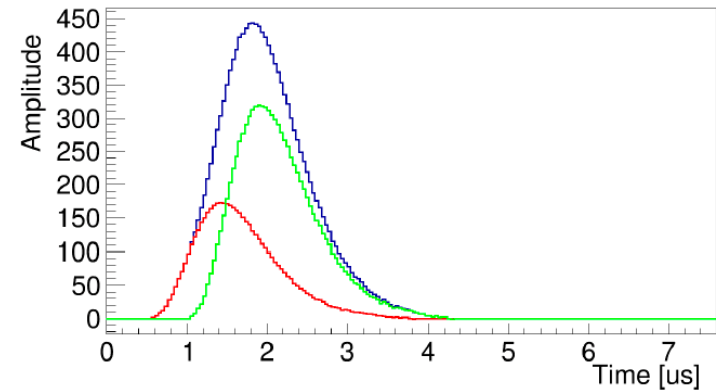
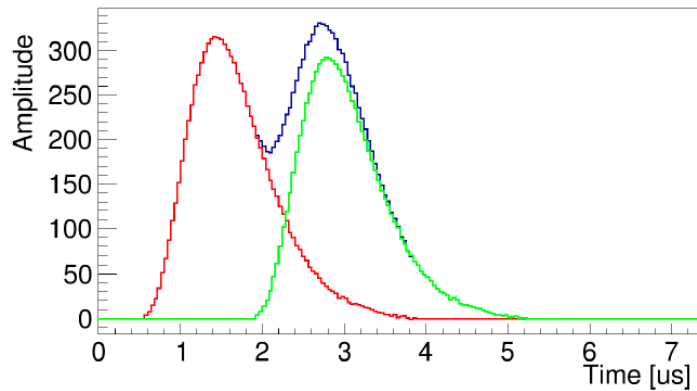
How these challenging experiments are analyzed?

Needs/challenges $d=R(B).f$

Control of contaminants. separate measurements, pile-up



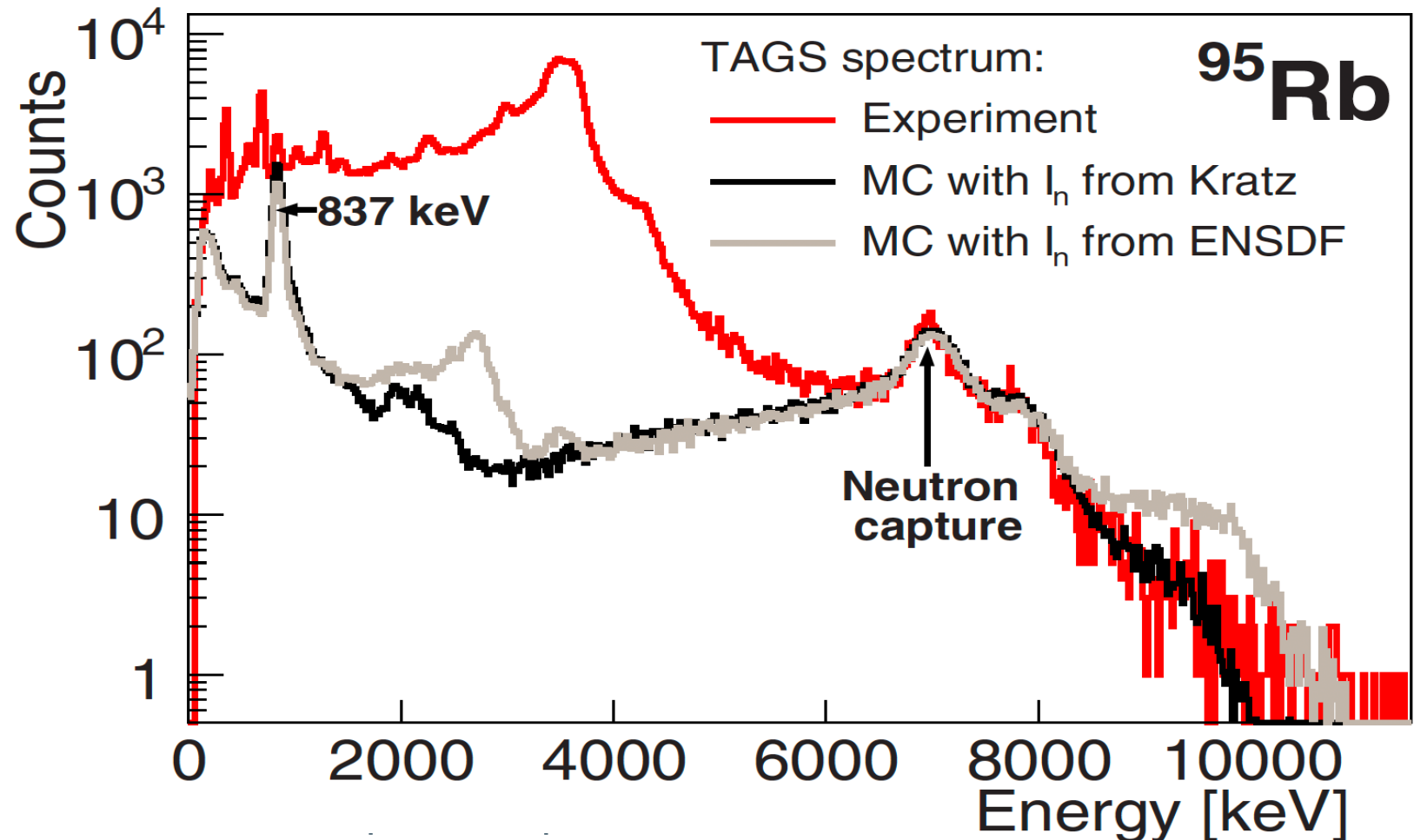
Pileup case: single detector vs sum array



How these challenging experiments are analyzed?

Needs/challenges $d=R(B).f$

Another distortion: beta delayed neutrons, requires additional MC



How these challenging experiments are analyzed?

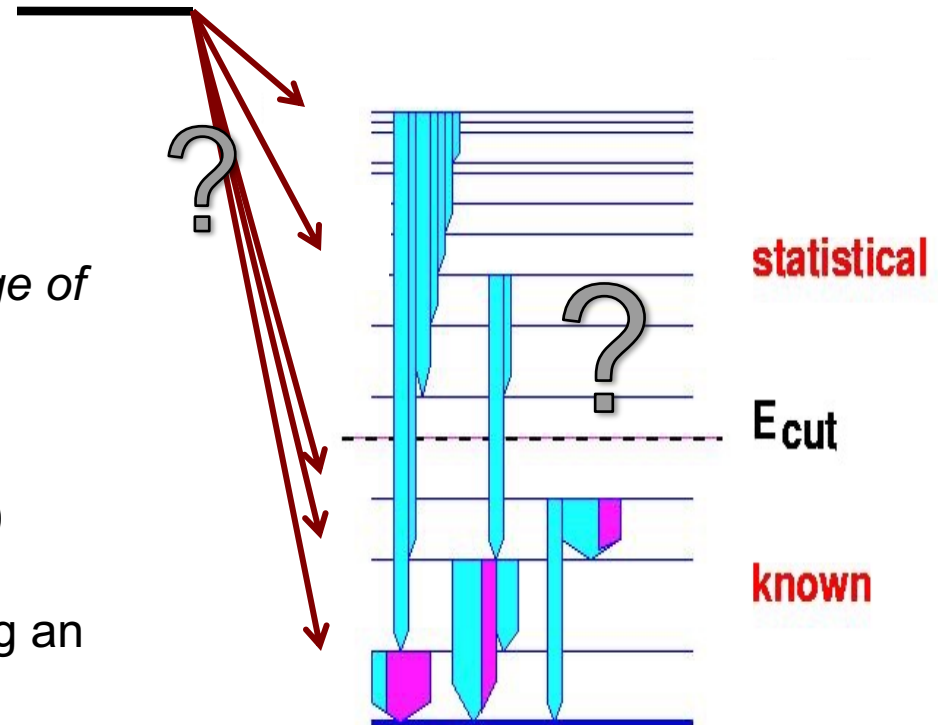
Needs/challenges: response, inverse problem, algorithms

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

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

Algorithm:

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

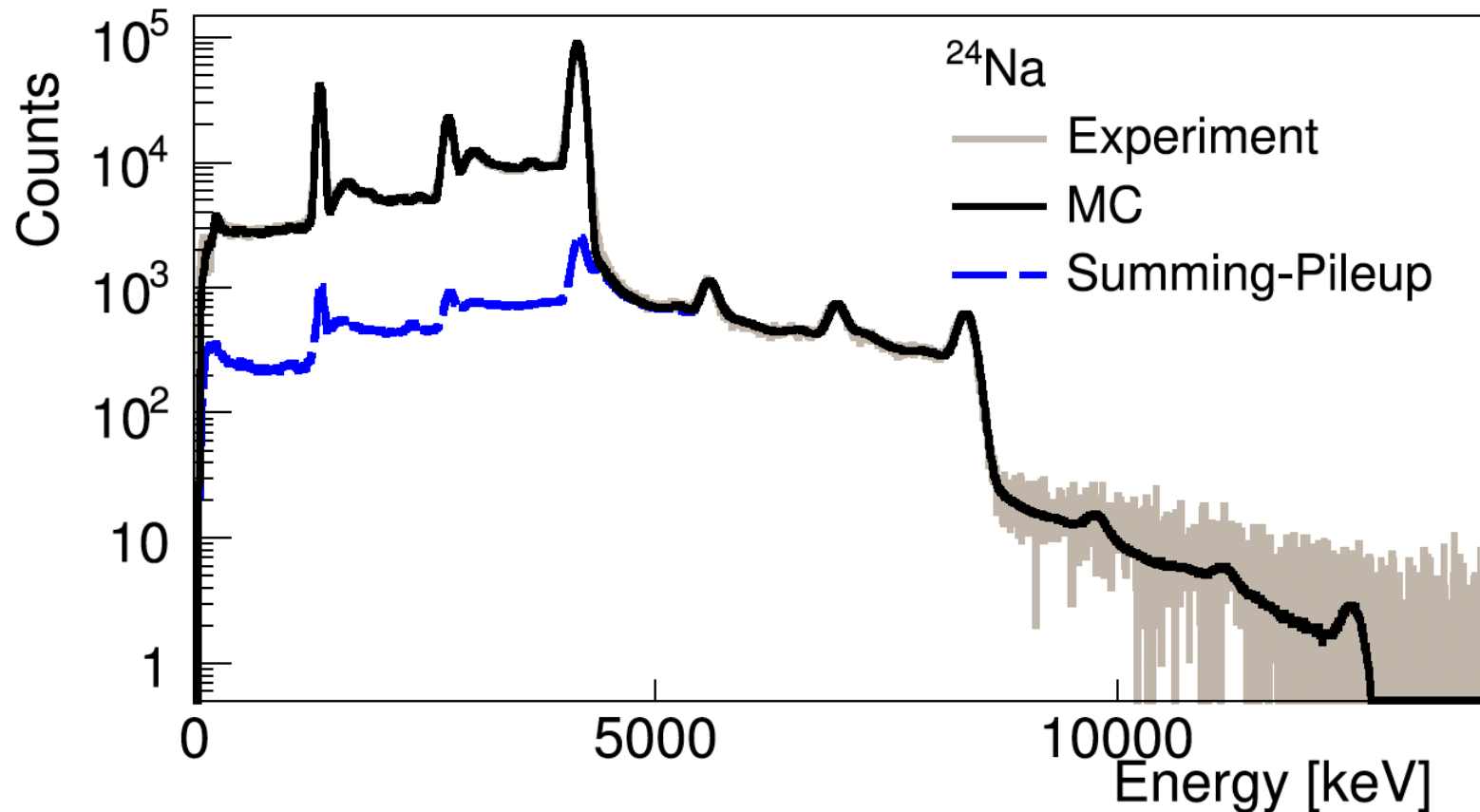
$$P(f_j | d_i) = \frac{P(d_i | f_j) P(f_j)}{\sum_j P(d_i | f_j) P(f_j)}$$

Mathematical formalization by Tain, Cano, et al.

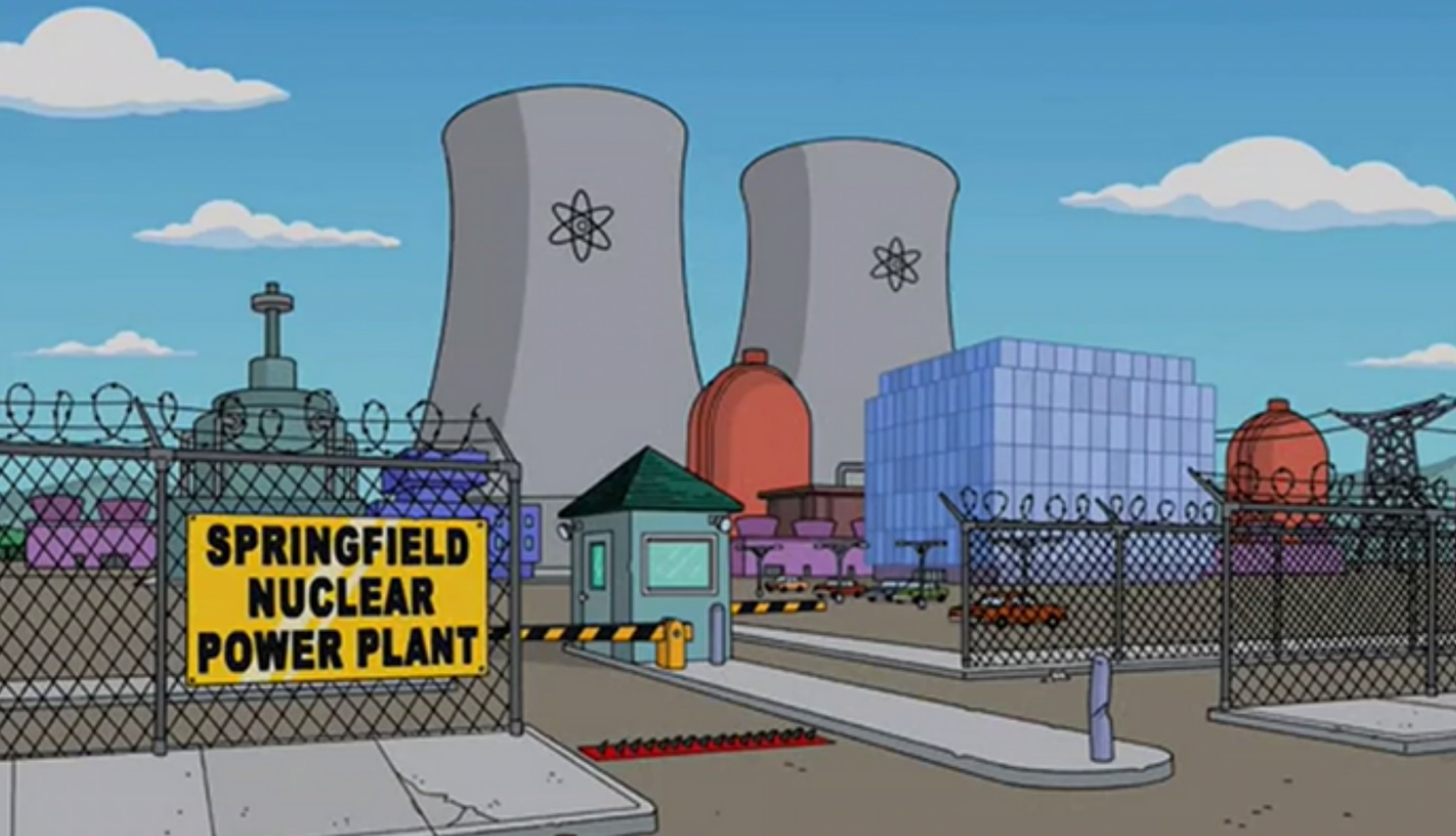
How these challenging experiments are analyzed?

Needs/challenges $d=R(B).f$

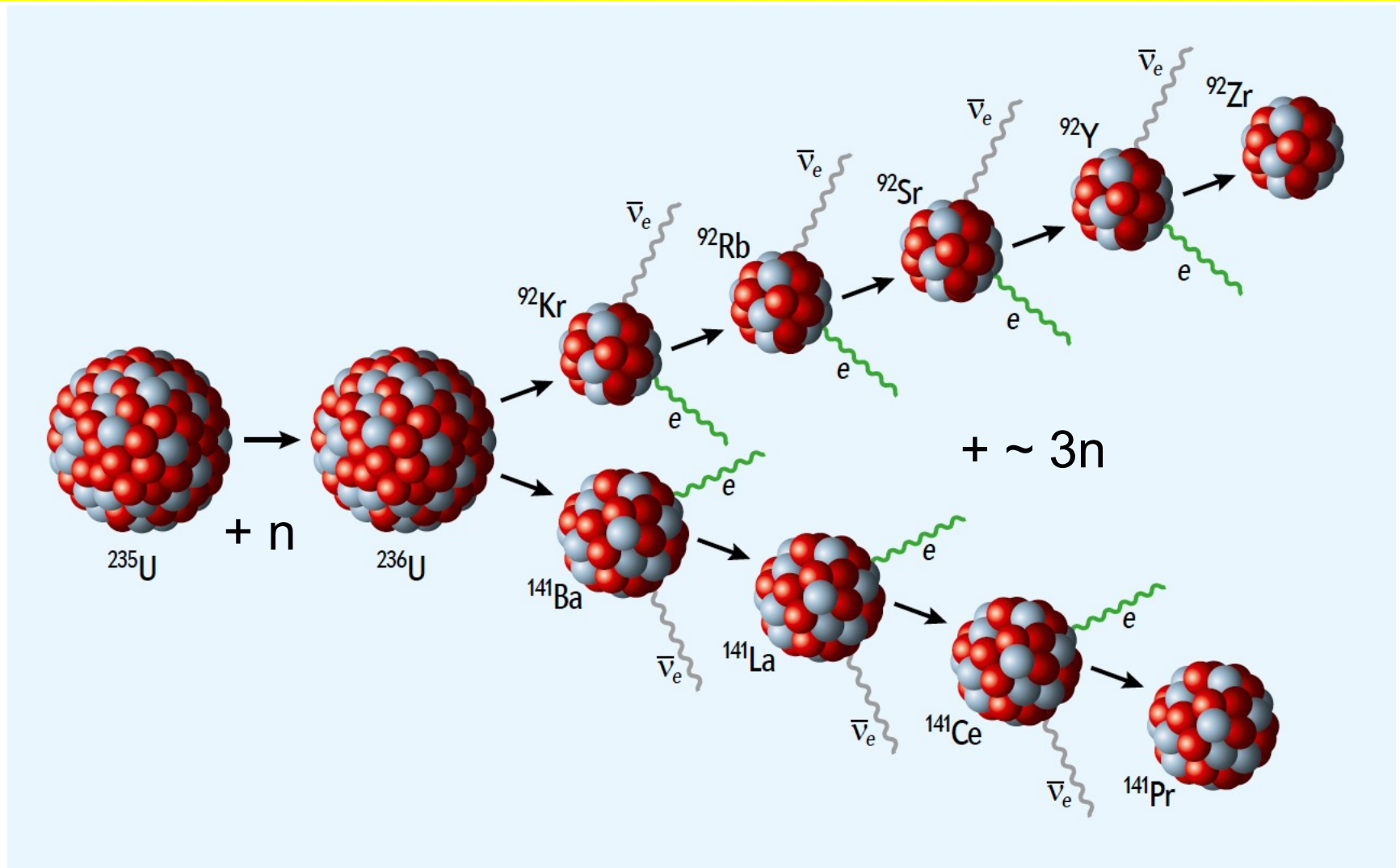
Validation of Monte Carlo simulations with well-know sources
Excellent calibration (energy and width), for both exp. and MC



Reactor applications: decay heat, reactor neutrino physics



Fission process and beta decay: close interconnection



Every fission is approximately followed by 6 beta decays (sizable amount of energy)
Reactors are the largest (manmade) pacific sources of neutrinos. Produces 2×10^{20} v/s



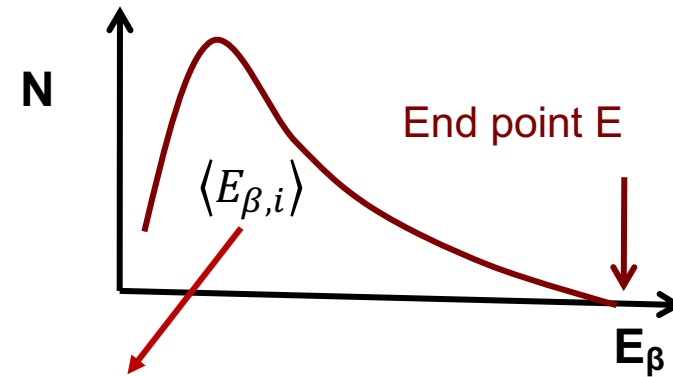
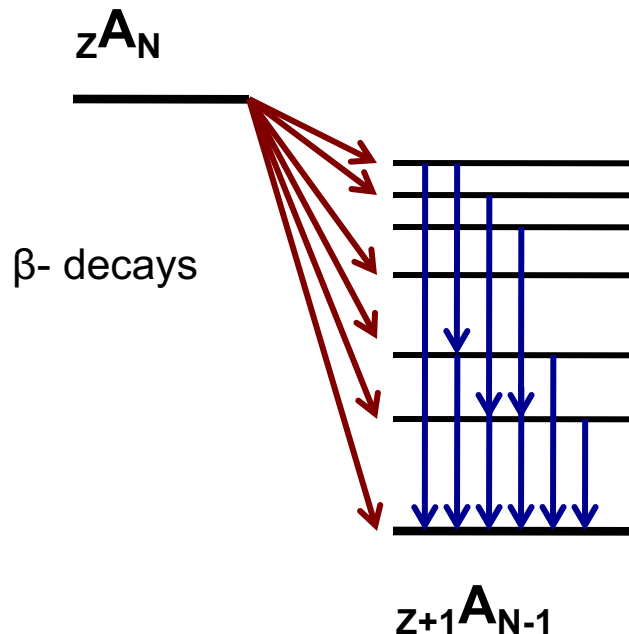
Decay heat summation calculations: Why feedings are needed?

DATA bases:
feeding or beta
decay prob.
distributions

$$f(t) = \sum_i \mathbf{\textcolor{blue}{E}_i} \lambda_i N_i(t)$$

Beta spectrum for a
beta transition
(to a defined level)

Key ingredient:
beta feedings

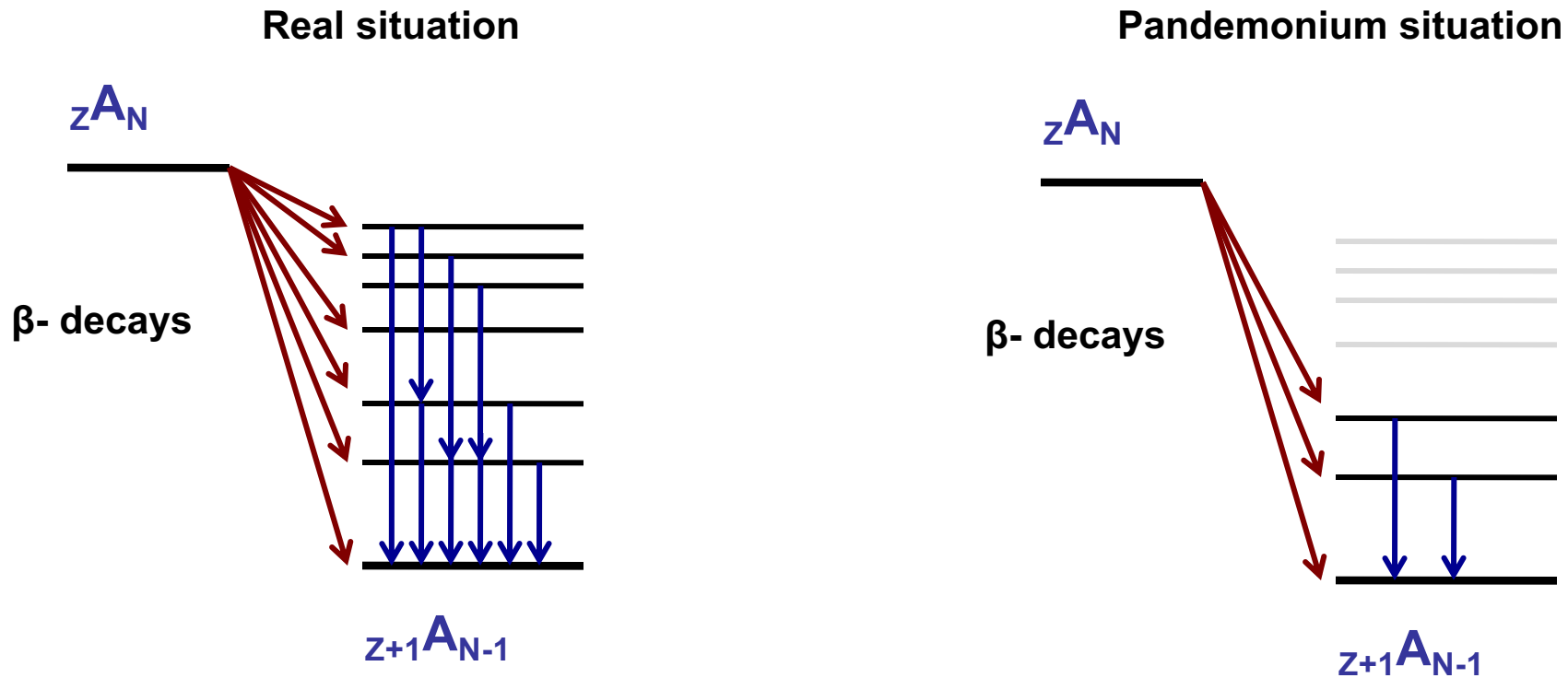


$$\bar{E}_\beta = \sum_i I_\beta(E_i) \underline{\langle E_{\beta,i} \rangle}$$

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

(Simplified way of calculation)

Effect of Pandemonium on summation calculations (decay heat example)



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

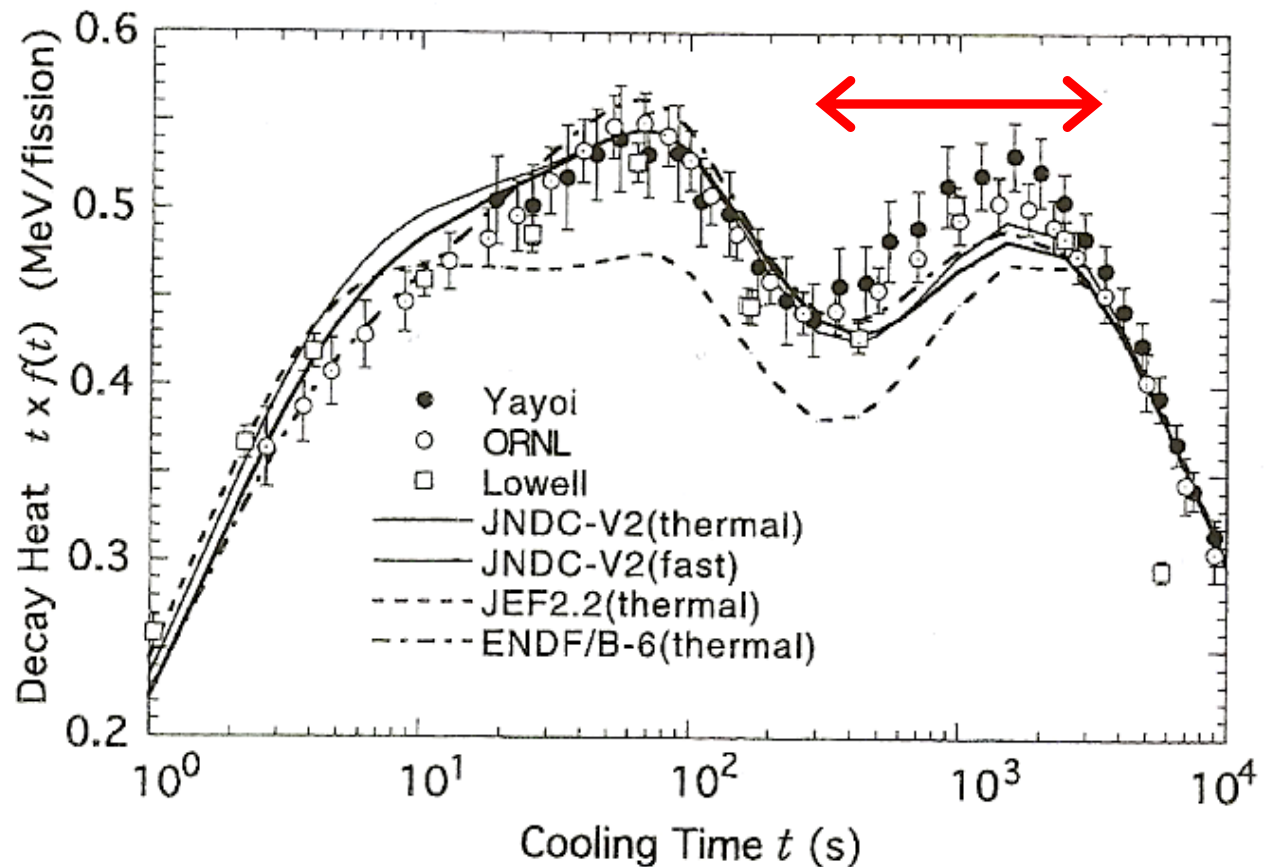
The beginning (for us) ...

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 $^{235,238}\text{U}$)

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

^{239}Pu example (γ component)



The famous list

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.

Our favorite place for “polar” experiences

Published cases until know:

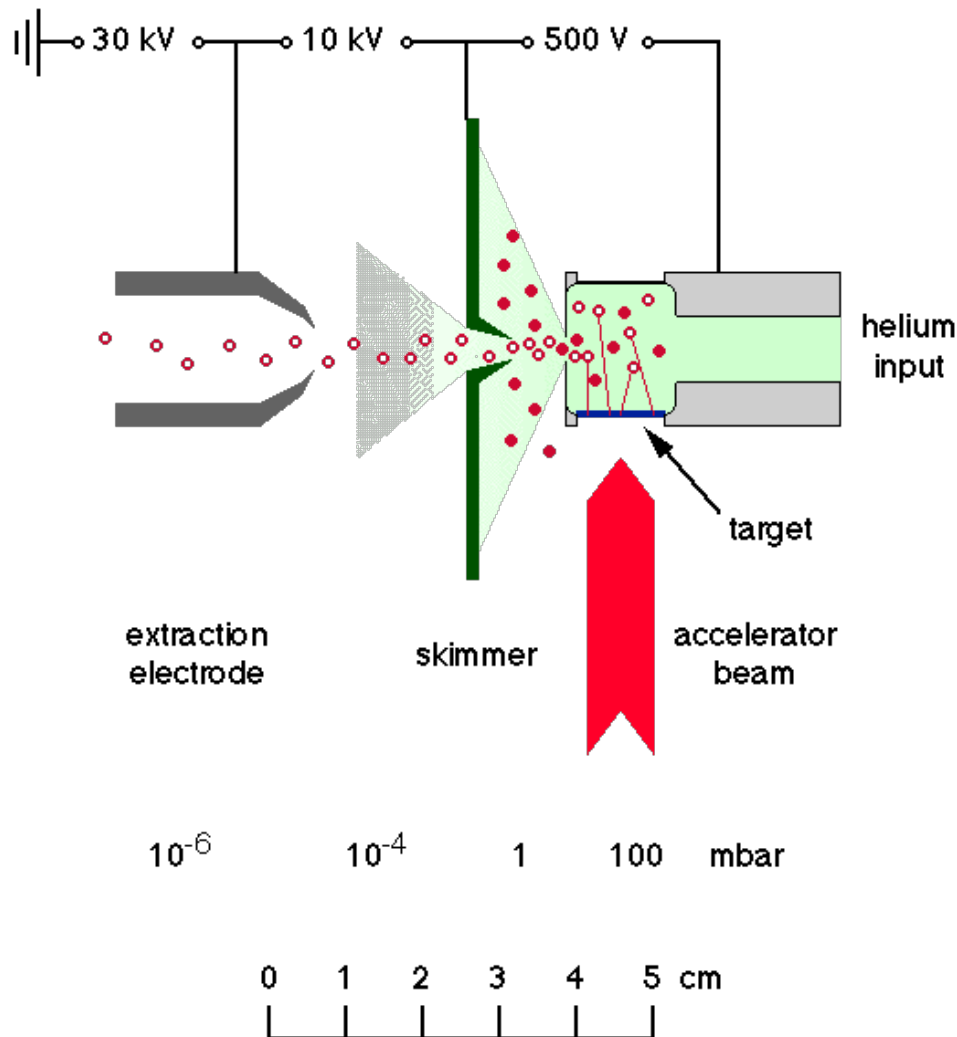
$^{102,104,105,106,107}\text{Tc}$, ^{105}Mo , ^{101}Nb

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

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



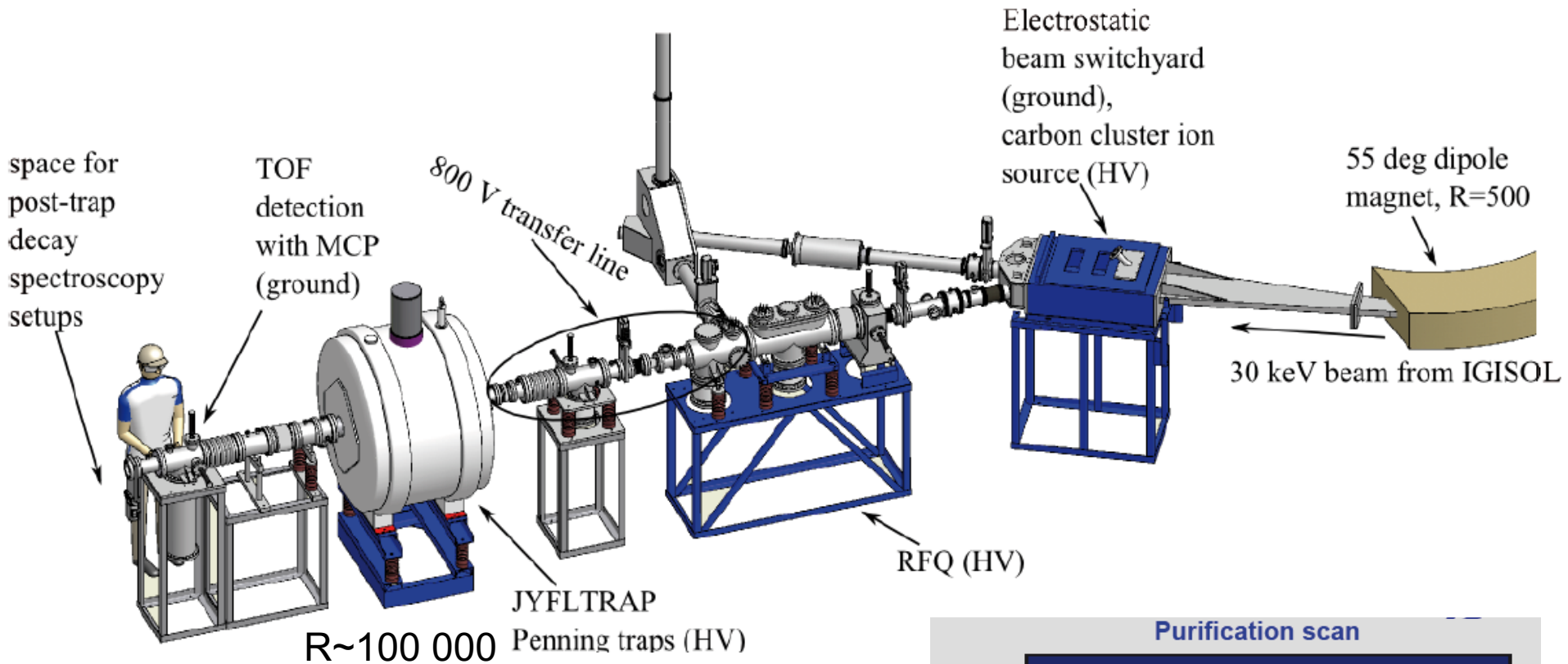
Odd ISOL case: The ion guide technique



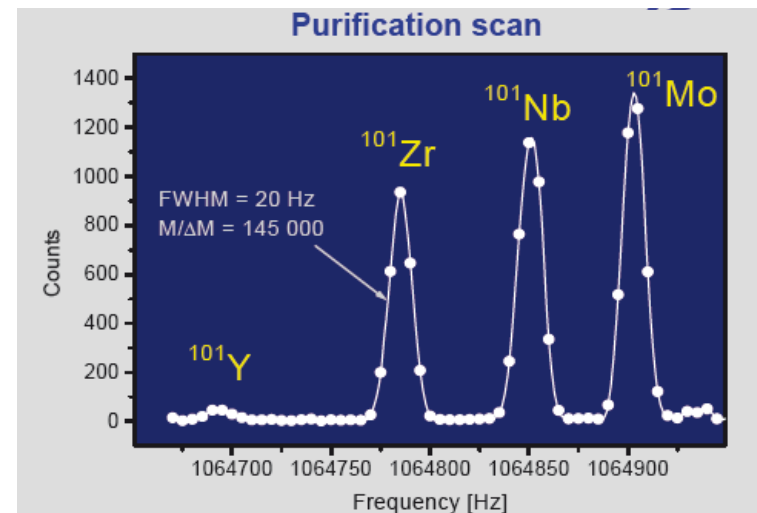
Generic ion guide: the nuclear reaction products are stopped in a gas and are transported through a differential pumping system into the accelerator stage of the mass separator.

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

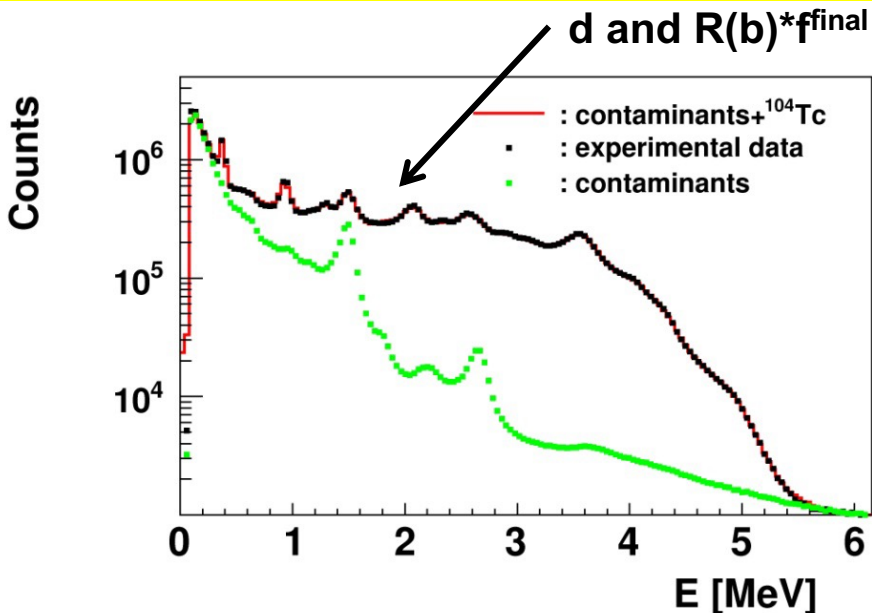
Why JYFL?: IGISOL + a bonus



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!



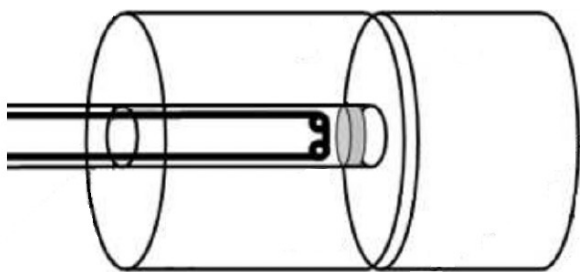
Results of the analysis for ^{104}Tc



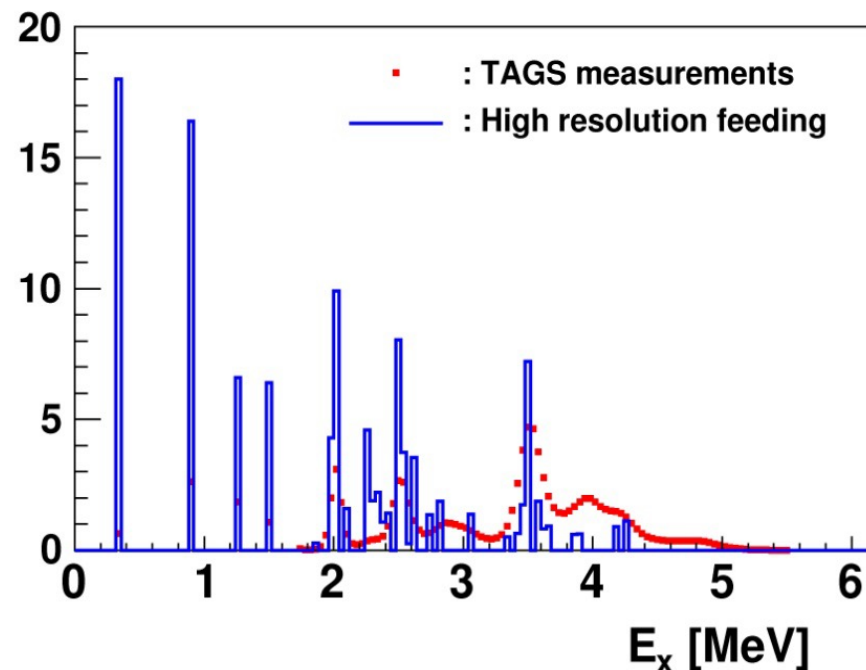
$$T_{1/2} = 1098(18) \text{ s}; Q_{\beta} = 5516(6) \text{ keV}$$

$$\left. \begin{array}{l} E_{\beta}(\text{TAGS}) = 931(10) \text{ keV} \\ E_{\beta}(\text{JEFF-3.1}) = 1595(75) \text{ keV} \end{array} \right\} \Delta E_{\beta} = -664 \text{ keV}$$

$$\left. \begin{array}{l} E_{\gamma}(\text{TAGS}) = 3229(24) \text{ keV} \\ E_{\gamma}(\text{JEFF-3.1}) = 1890(31) \text{ keV} \end{array} \right\} \Delta E_{\gamma} = 1339 \text{ keV}$$

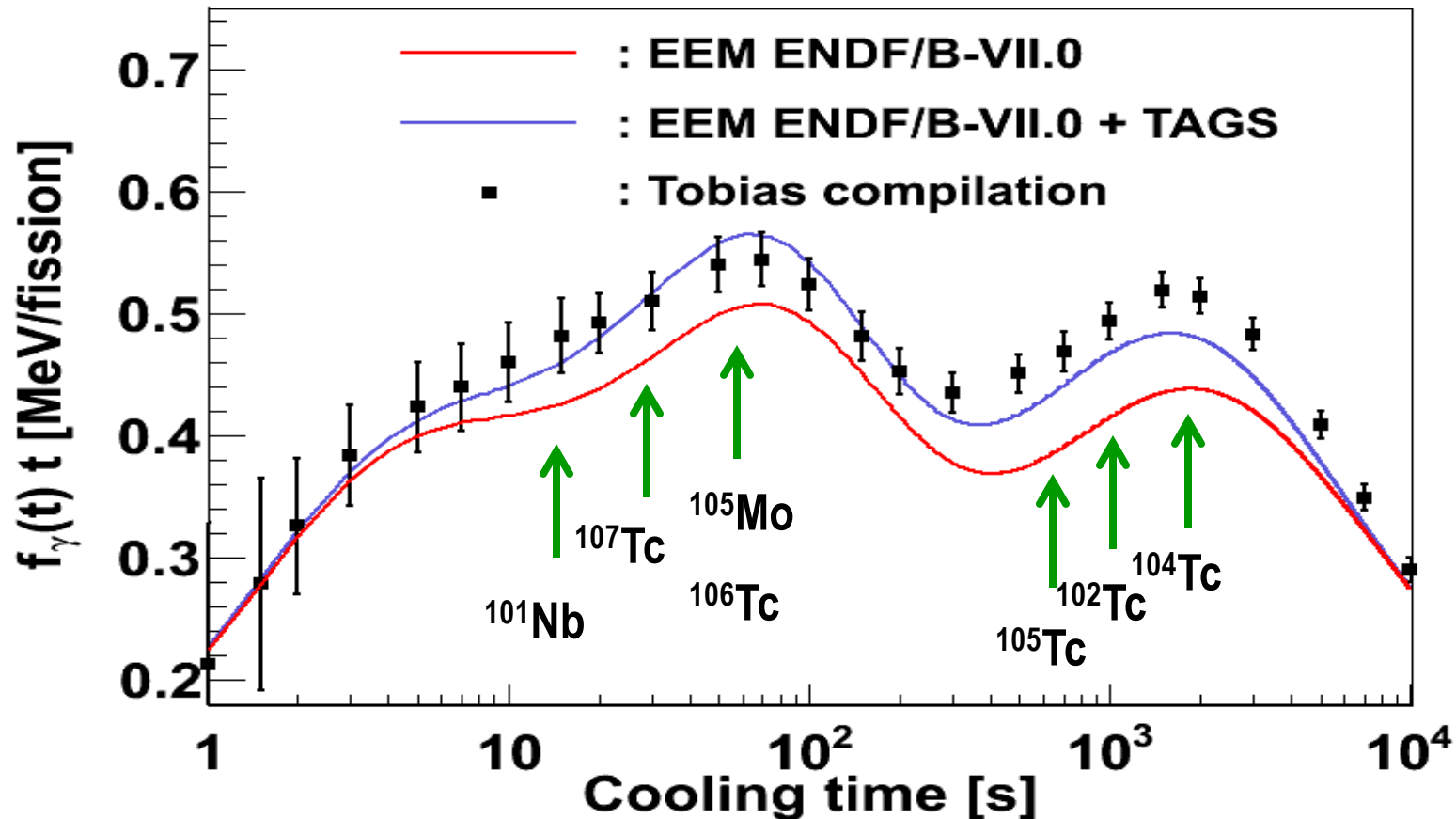


Feeding



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

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



PhD Thesis D. Jordan , A. Algora, Phys. Rev. Letts. 105, 202505,
K. P. Rykaczewsky, Physics 3, 94 (2011)

DH Courtesy A. Sonzogni

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

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

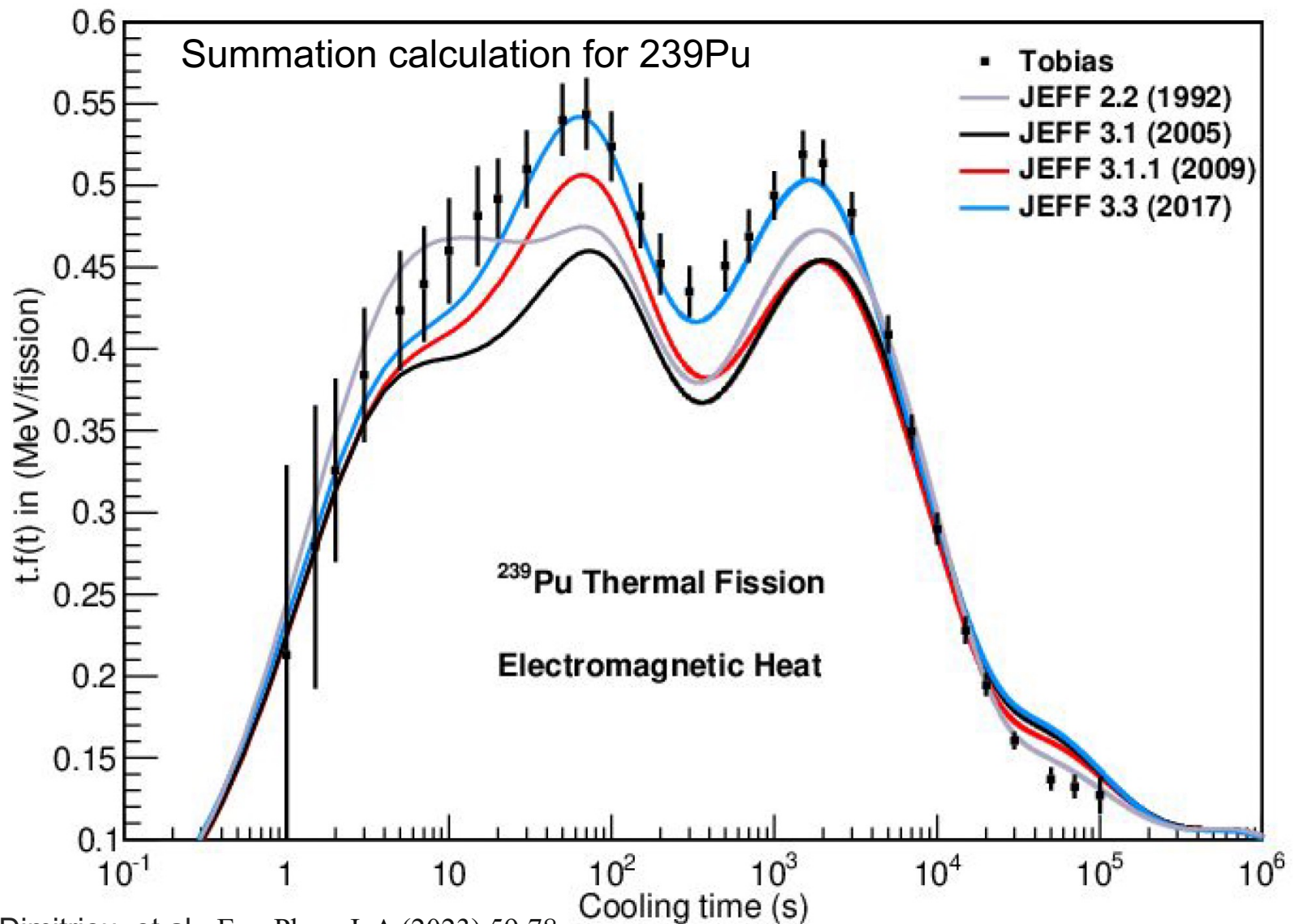
Table 2. List of parent nuclides identified by the WPEC-25 (Nuclear Energy Agency working group) that should be measured using the total absorption technique to improve the predictions of the decay heat in reactors [48,49]. These nuclides are of relevance for conventional reactors based on ^{235}U and ^{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 $^{233}\text{U}/^{232}\text{Th}$ 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		

Decay heat impact of the measurements



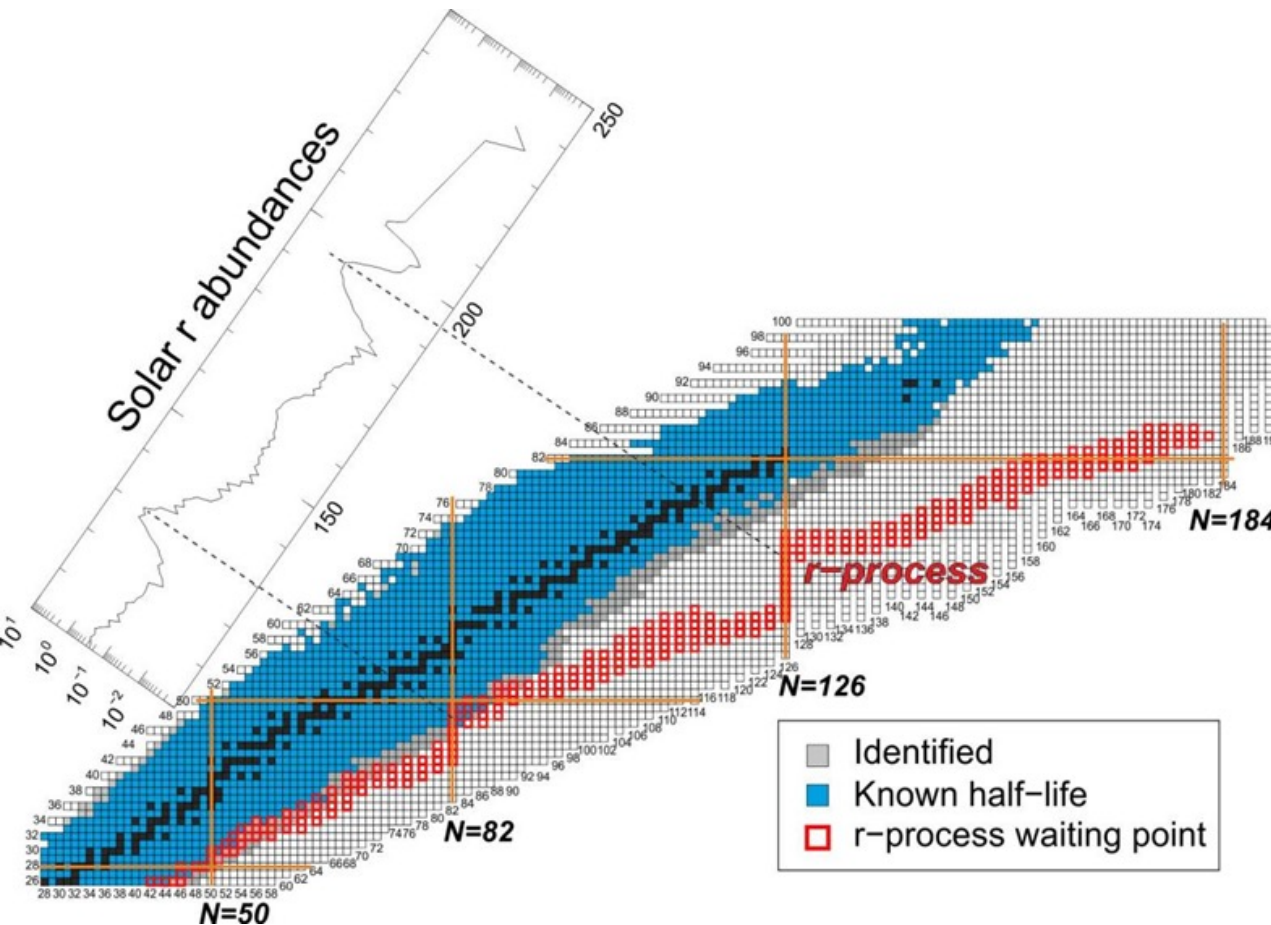
Nichols, Dimitriou, et al., Eur. Phys. J. A (2023) 59:78

<https://arxiv.org/abs/2212.10335>

Courtesy of L. Giot with SERPENT

Astrophysics: r-process input from models

Scenarios: core collapse supernova (hypernova), neutron star mergers



Requirements
(r-process):

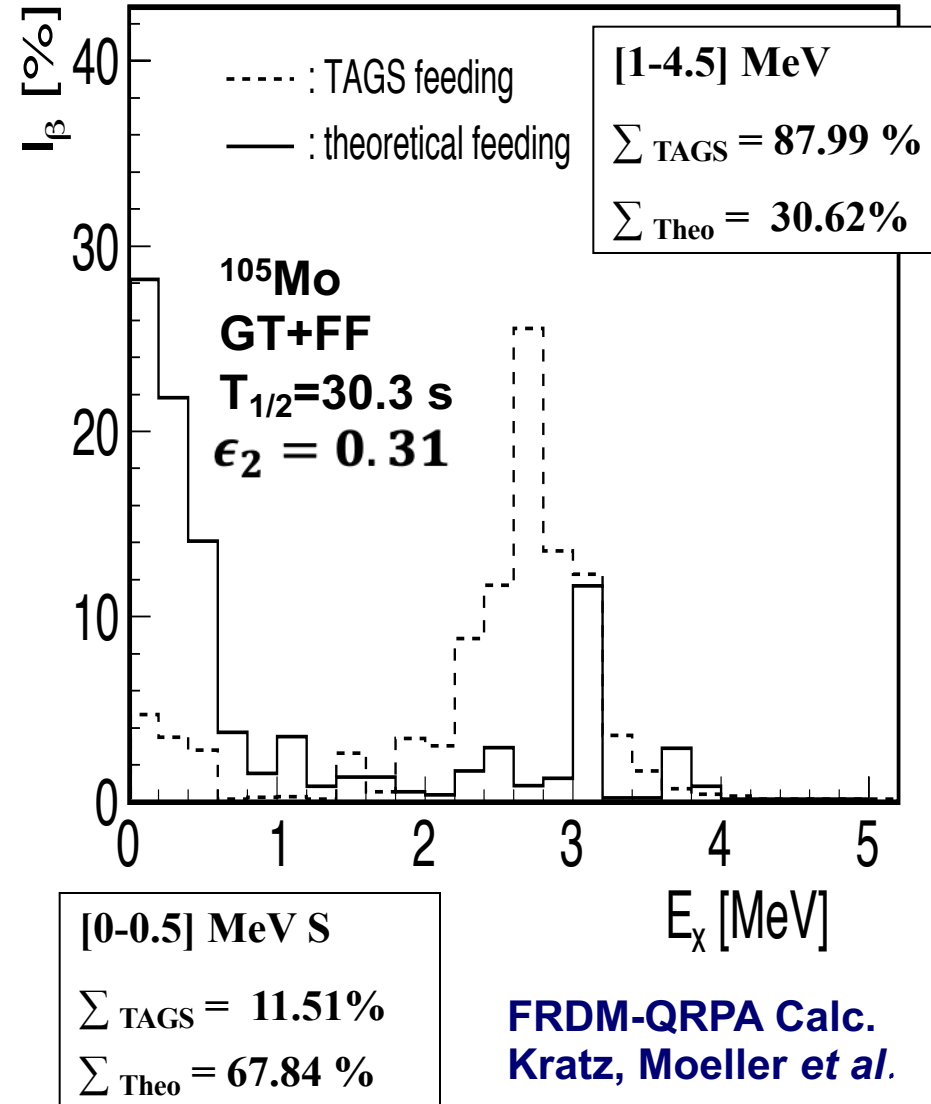
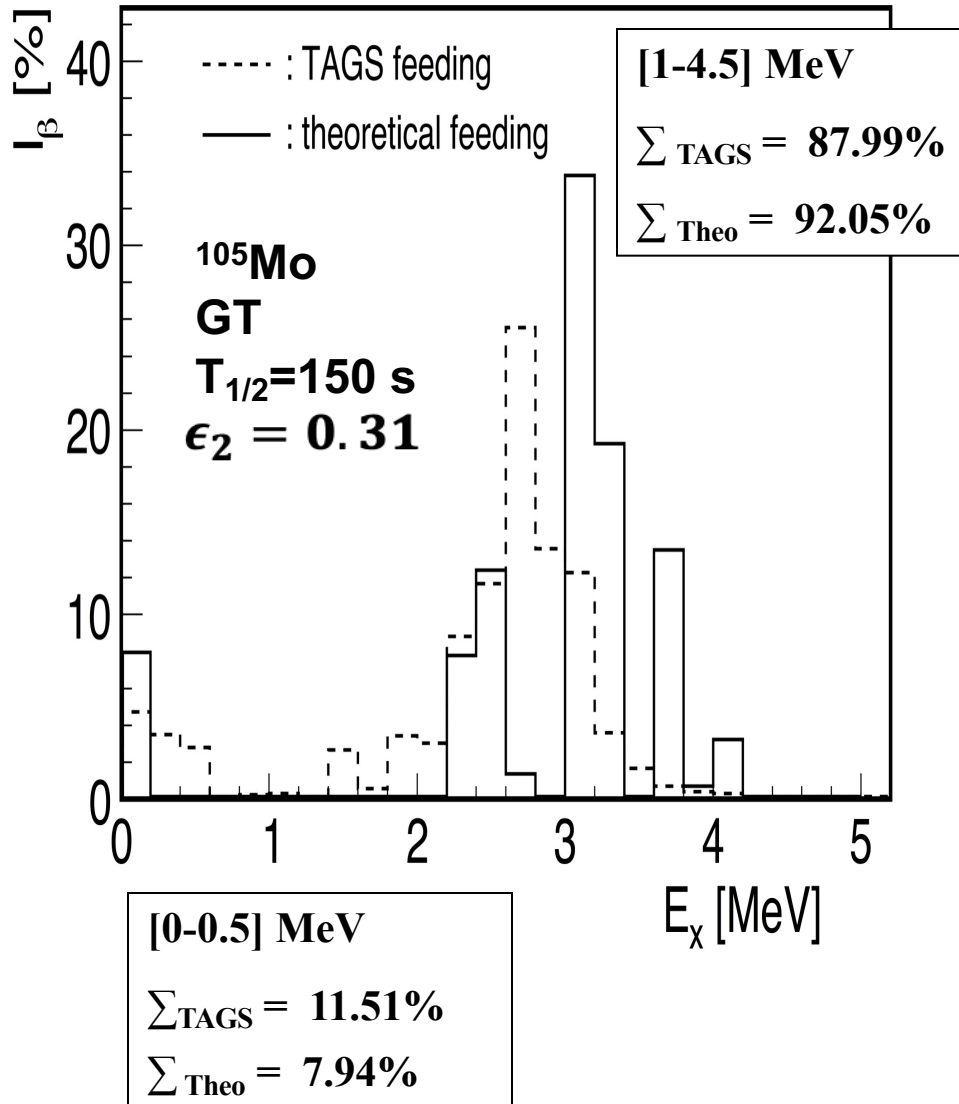
- Masses
- Half-lives
- n emission probabilities,
- (n,gamma) cross-sec.
- Fission probabilities

D. Siegel, see recent Nature review

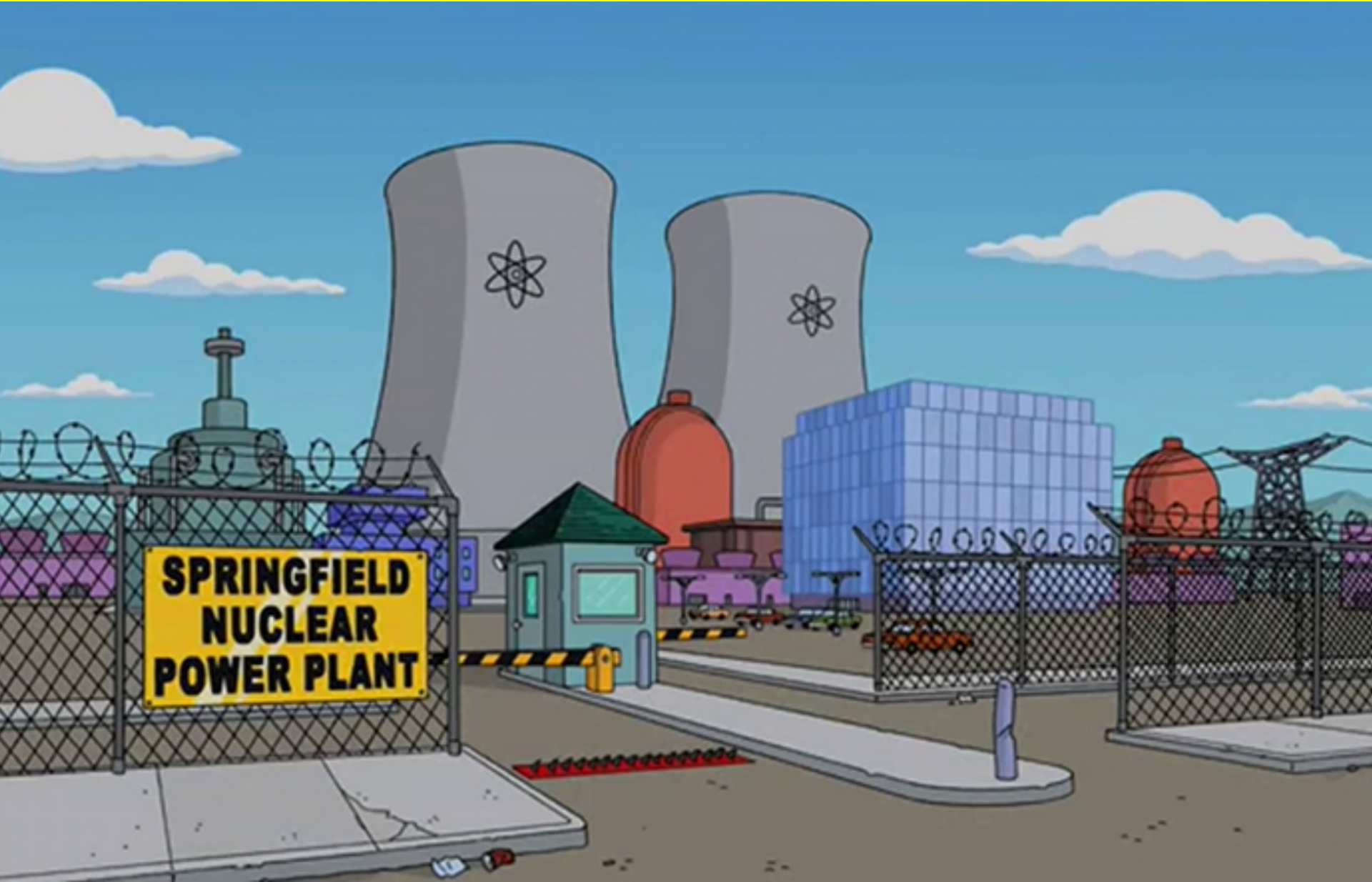
Accessability to the r-process path data ?
Validation of theoretical calculations ?

Nuclear structure example: QRPA calculations

^{105}Mo decay, $T_{1/2}(\text{exp}) = 35.6 \text{ s}$



TAS and reactor neutrinos

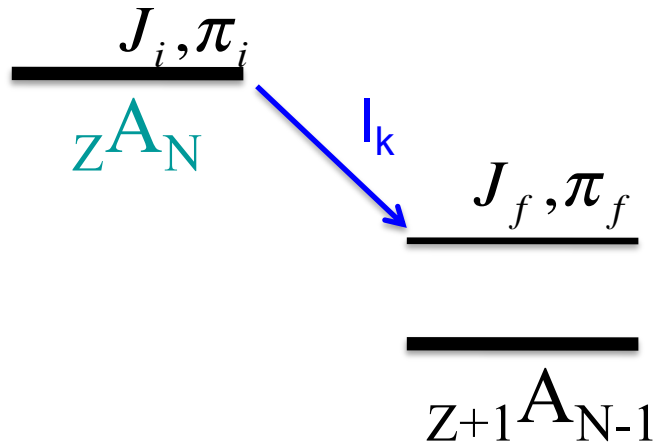


Is summation a feasible alternative for antineutrino spectrum calculations?

Remember the decay heat summation calculation formula

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

Beta decay (β^-)



Spectrum shape 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 decay (n)

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

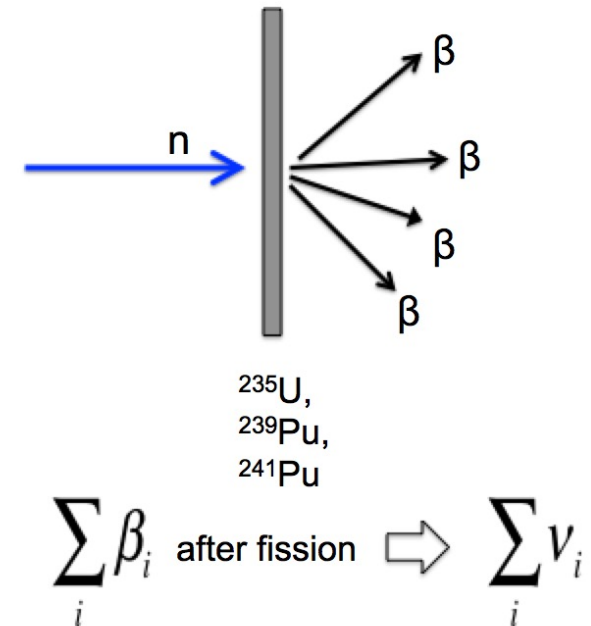
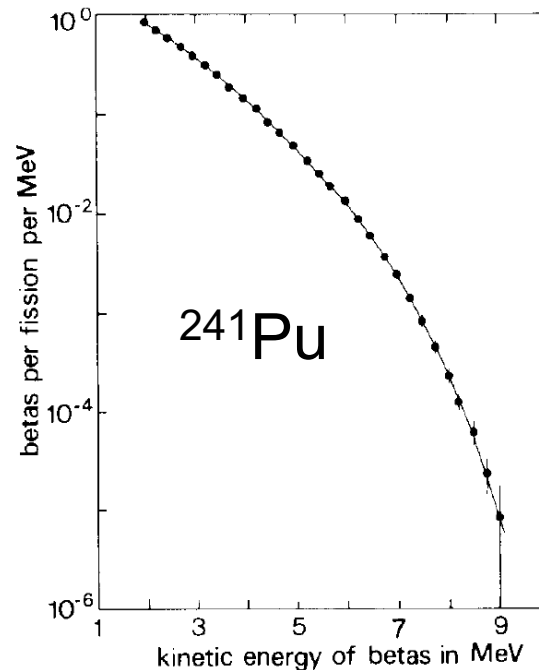
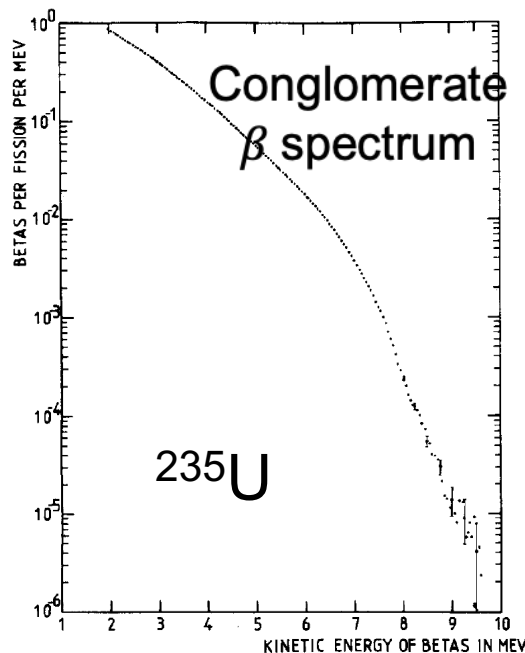
Beta Branch, or feedings

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

Anti-neutrino rate per fission (Vogel, 1981)

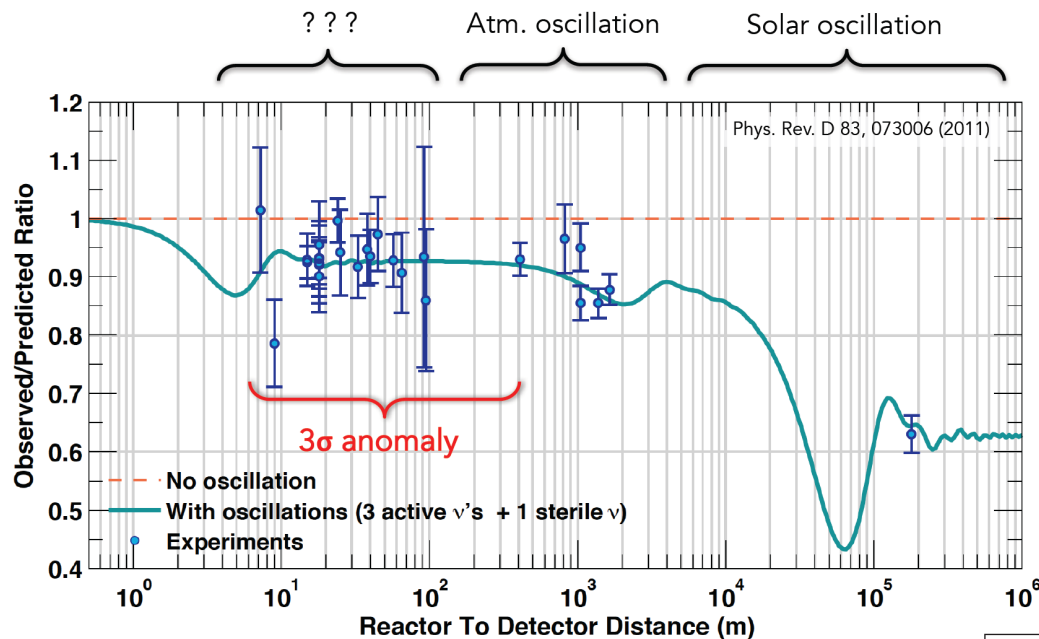
Determination of the primary antineutrino spectrum

- **“Pure conversion procedure”**: using the beta spectrum measured by Schreckenbach et al. from different fissile nuclides (^{235}U , $^{239,241}\text{Pu}$) 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”**

Black clouds in the reactor antineutrino field



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.

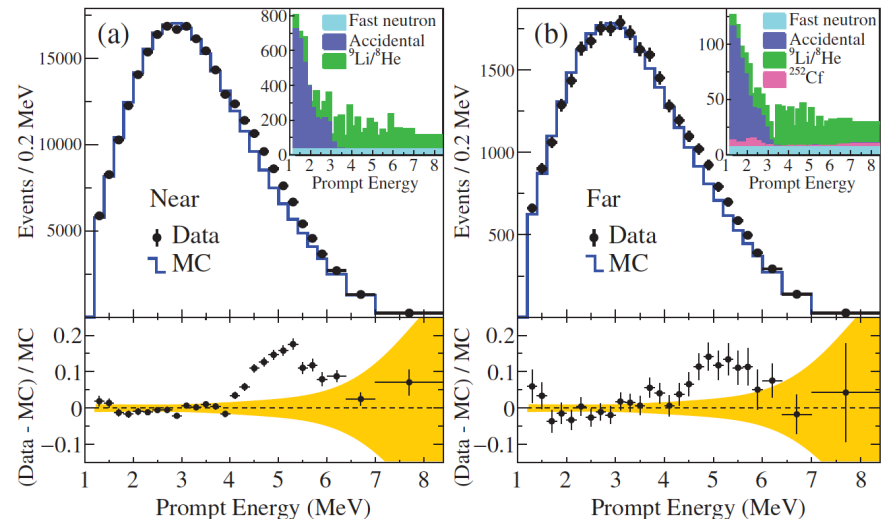
Mention et al. PRD 83.073006

Spectrum distortion (~5 MeV)

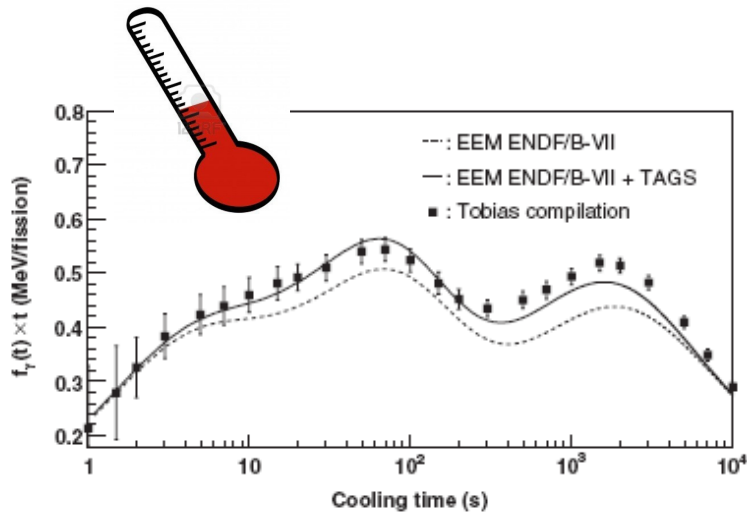
RENO results, PRL 116, 211801 (2016)

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.)

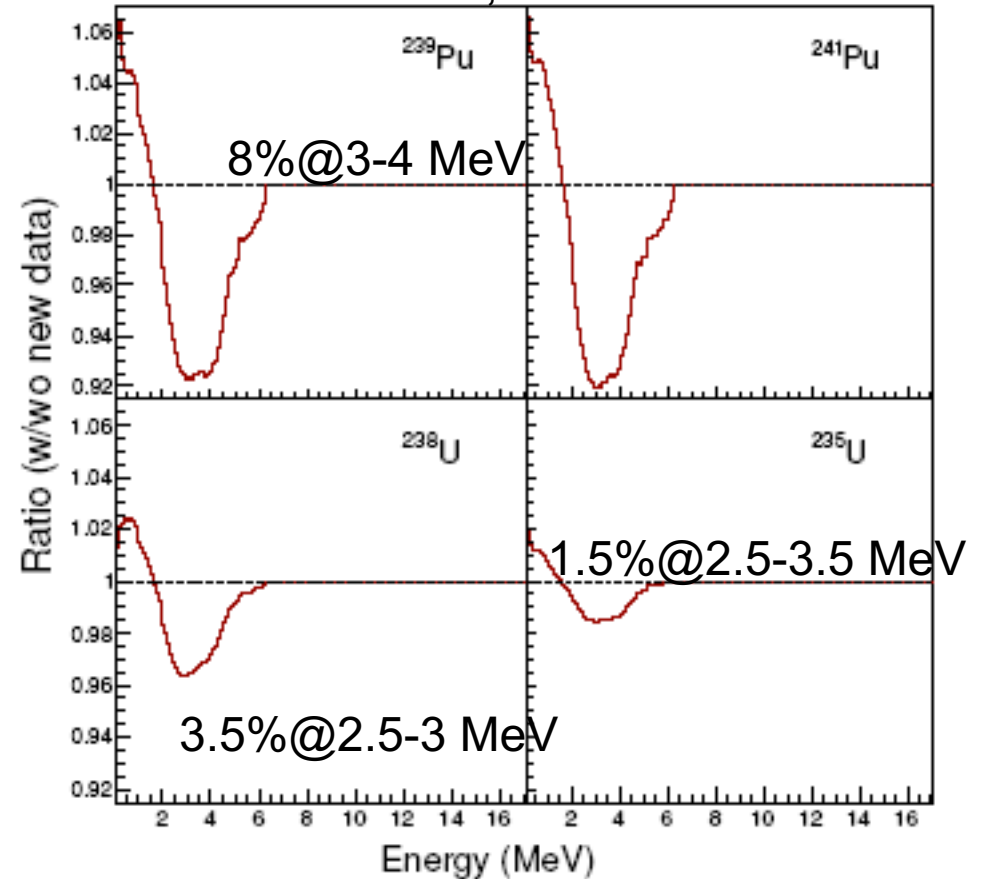


Impact of our first data for decay heat



Dolores Jordan, PhD thesis
 Algorta et al., PRL 105, 202501, 2010

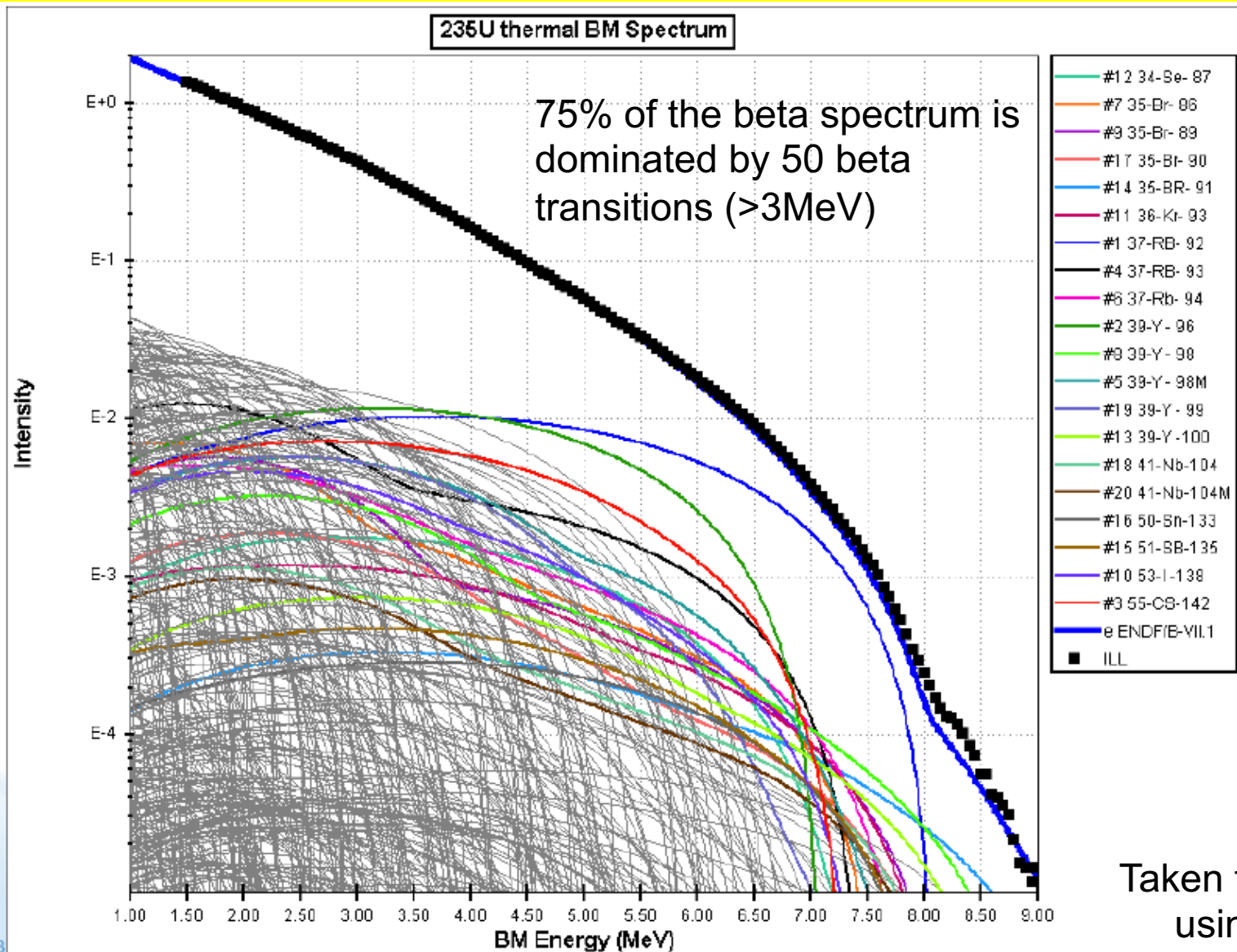
M. Fallot et al., PRL 109.202504



Ratio between 2 antineutrino spectra built with and without the $^{102,104,105,106,107}\text{Tc}$, ^{105}Mo , ^{101}Nb TAS data



1000-s of fission products: is this feasible?

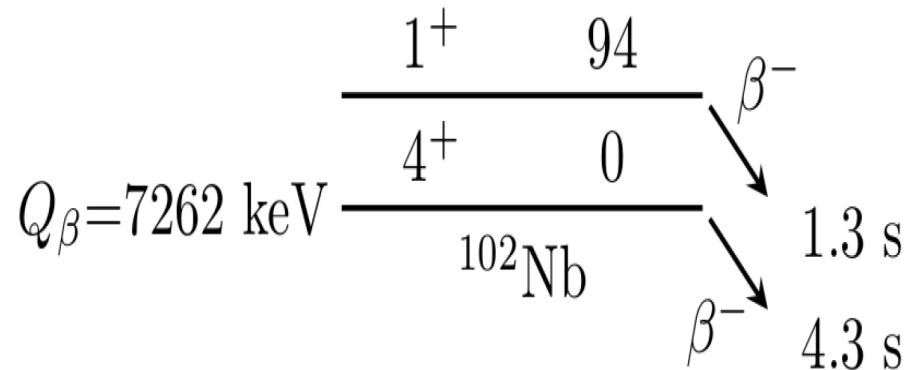
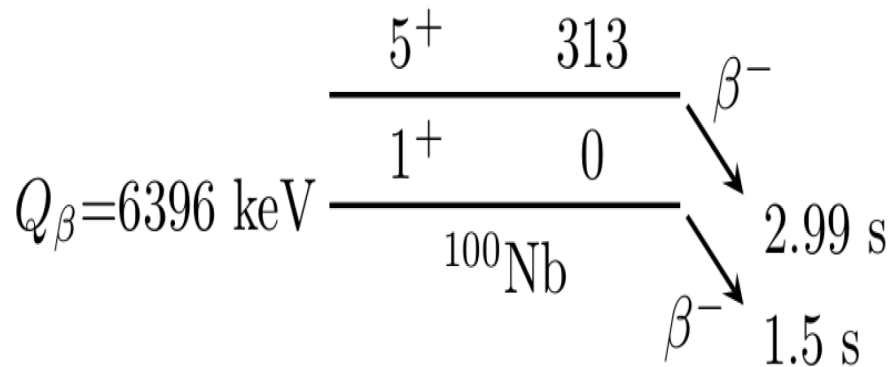
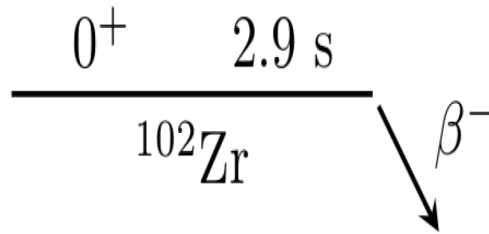
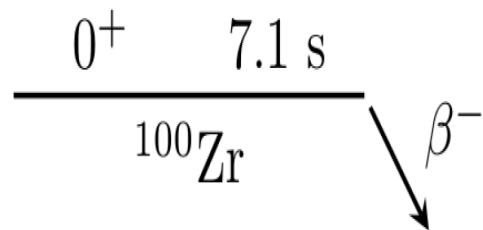


How to identify
the main players

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

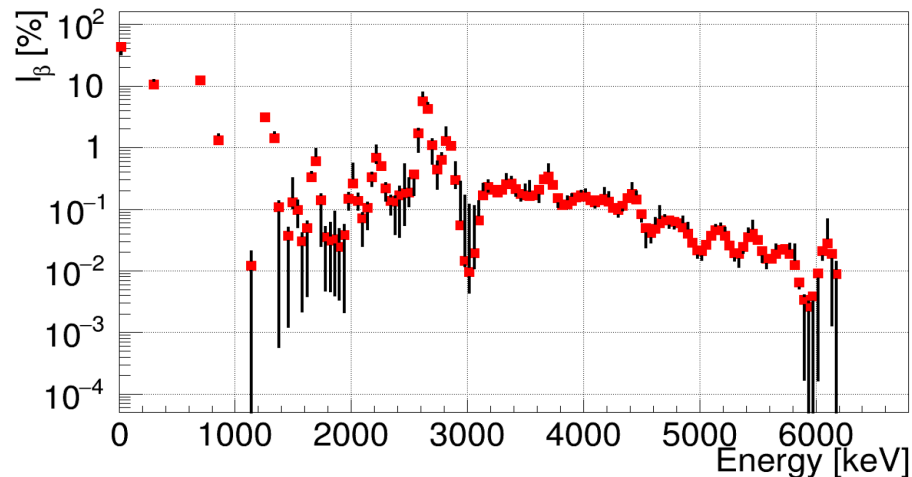
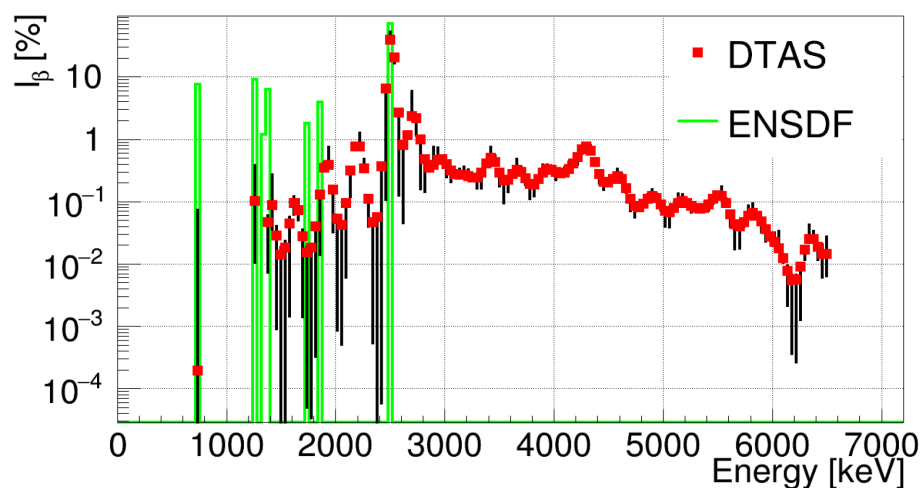
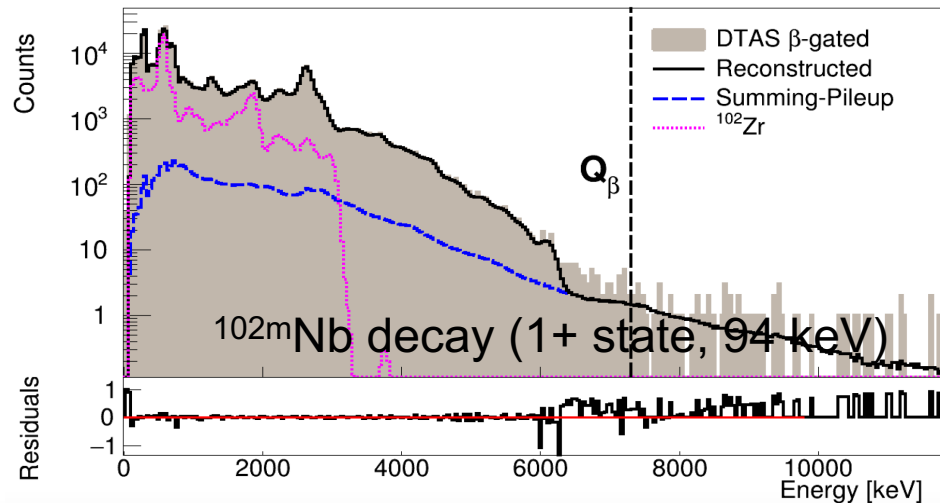
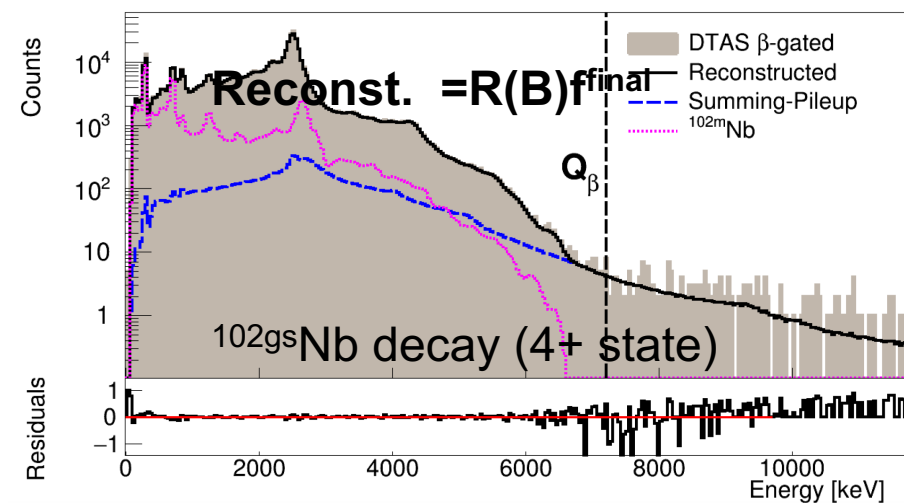
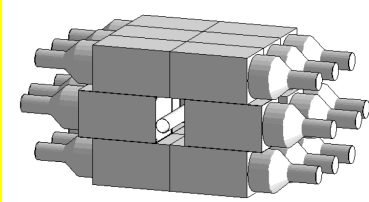
Taken from A. Sonzogni
using ENDF VII.1

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

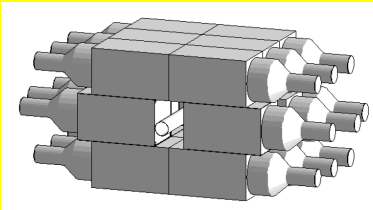


CFY of the order of 5%
and ~1 % respectively
(for both ^{235}U and ^{239}Pu)

$^{102}\text{gs,mNb}$ decays



Impact on the neutrino summation calculations

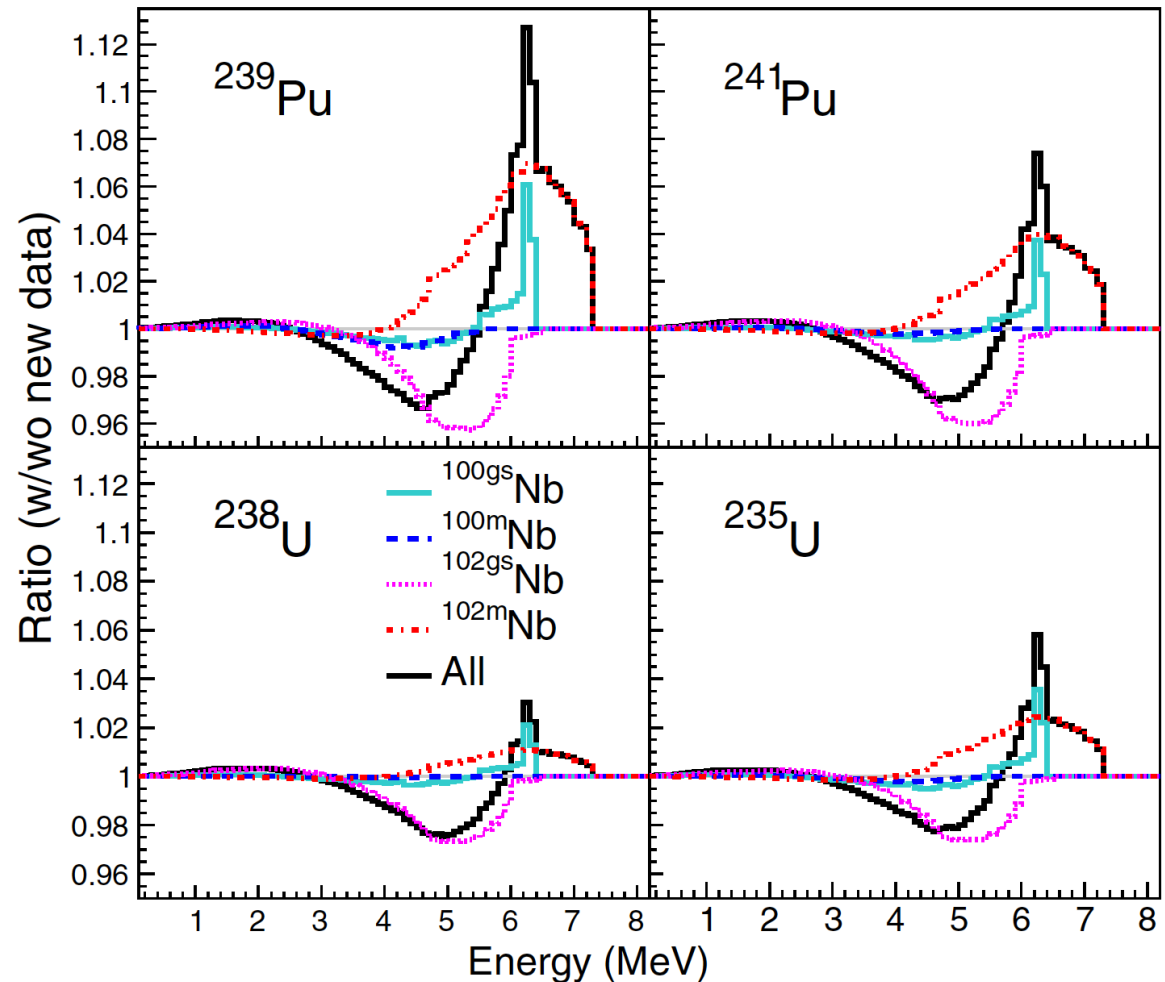


Neutrino summation
calculation

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

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

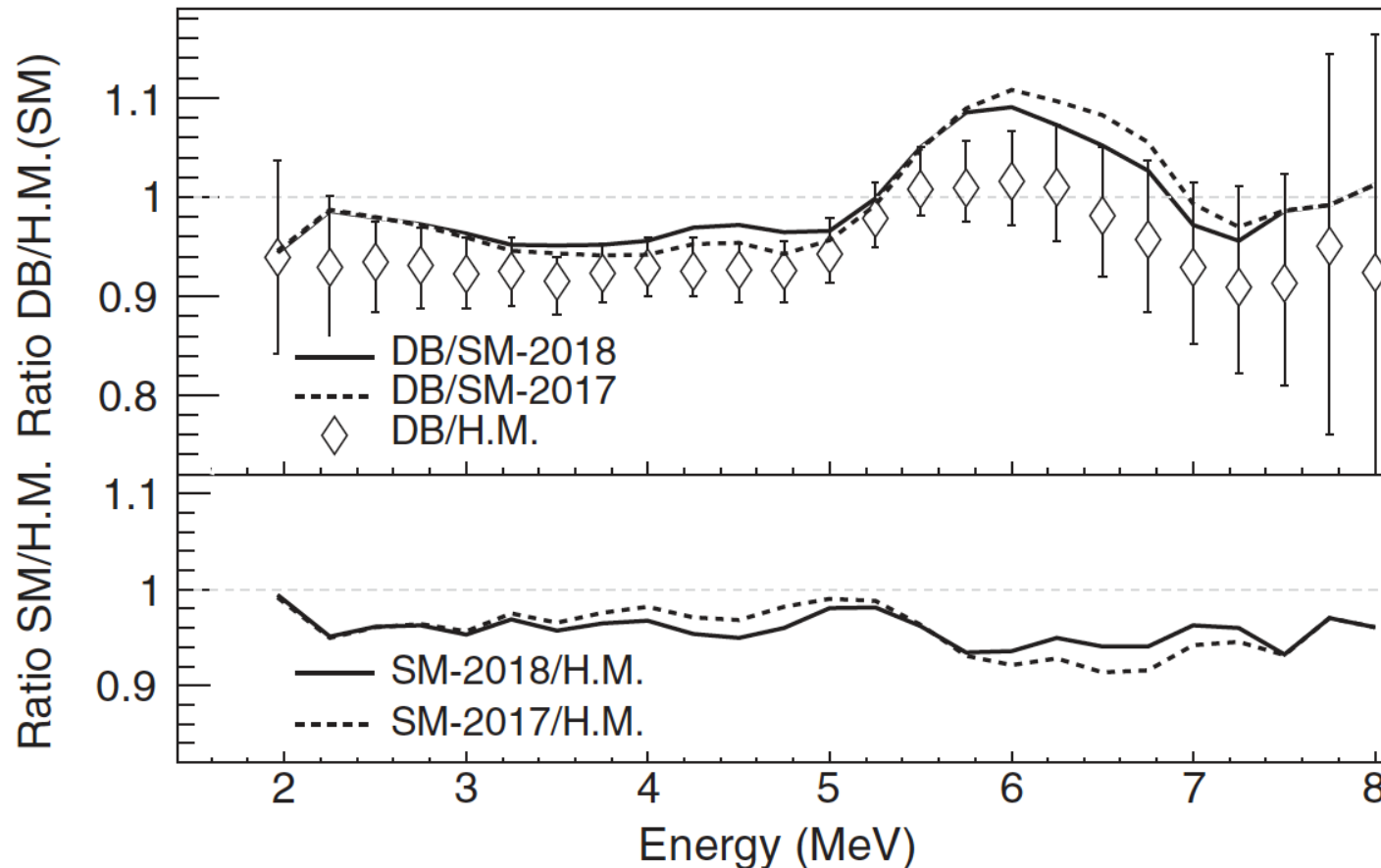
**Large impact in the
region of the spectral
distortion !!!**



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)

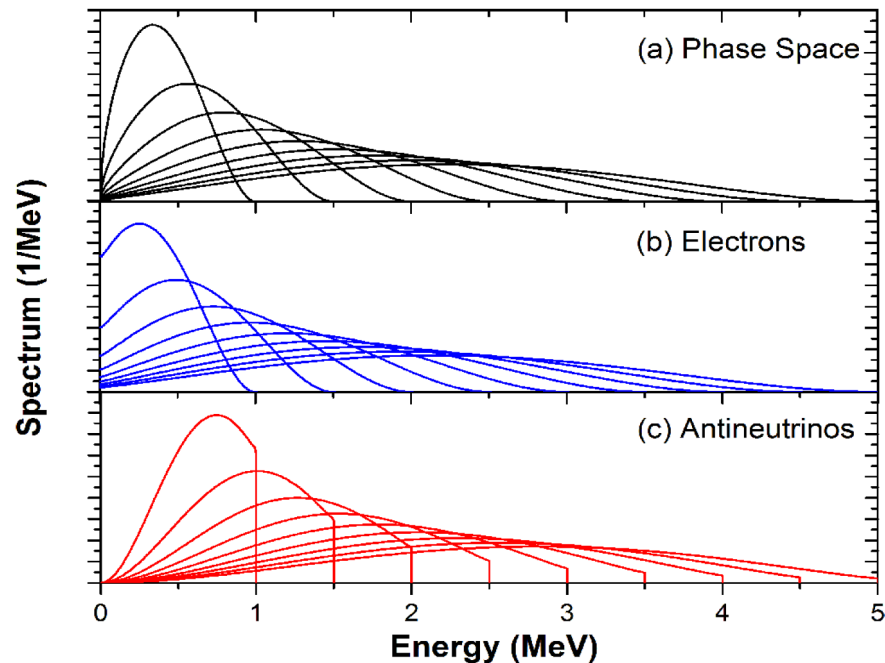


Subatech
Calculations
Estienne,
Fallot, et al.

Summation is
now better
than the
Hueber-
Mueller
conversion
model

Antineutrino 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

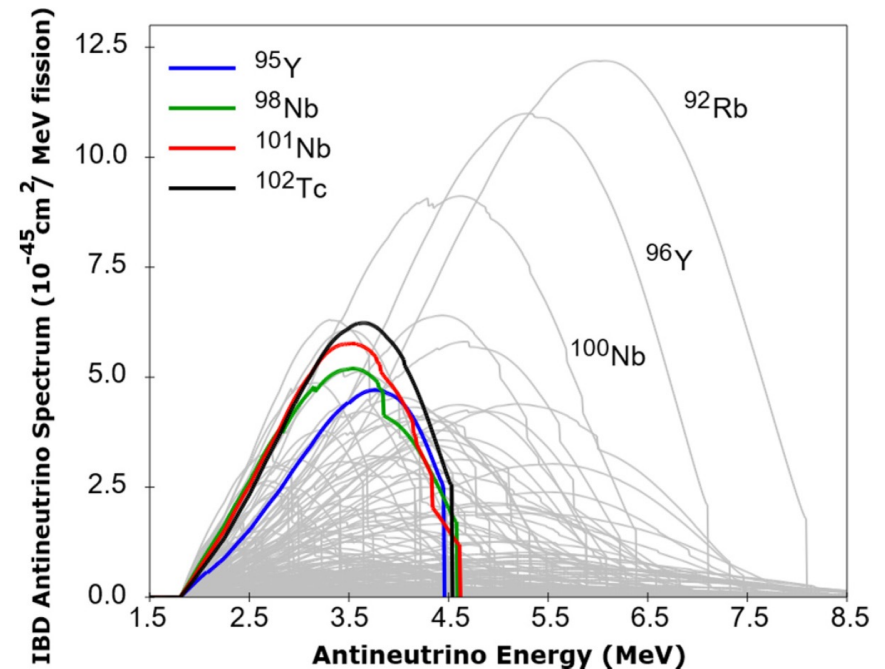
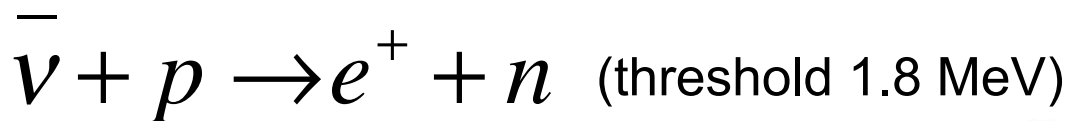


FIG. 6. Calculated Daya Bay IBD antineutrino spectra from all the fission products, highlighting the ^{95}Y , $^{98,101}\text{Nb}$, and ^{102}Tc ones.

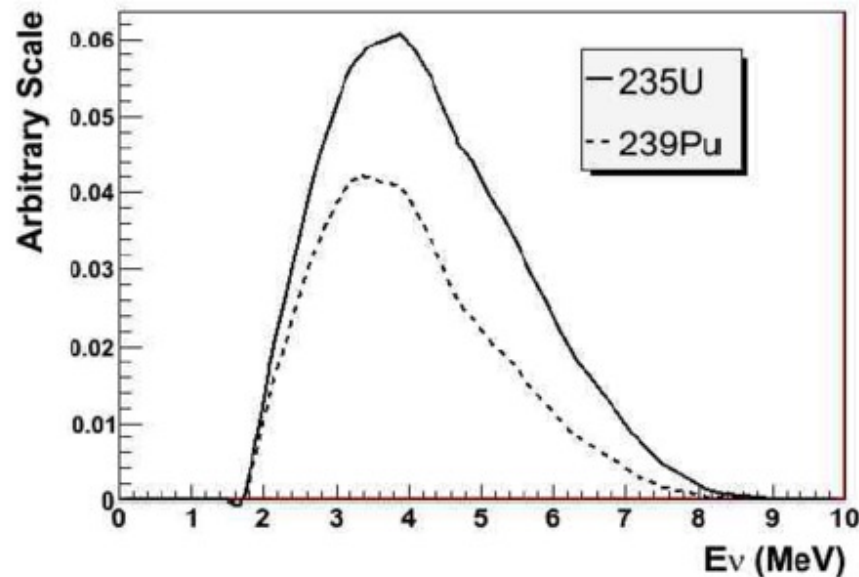
Window to “new physics” and applications: it can be also relevant for antineutrino experiments of new generation like JUNO and TAO, that address fundamental questions like the mas hierarchy

Prediction of the antineutrino spectrum from reactors for non-proliferation

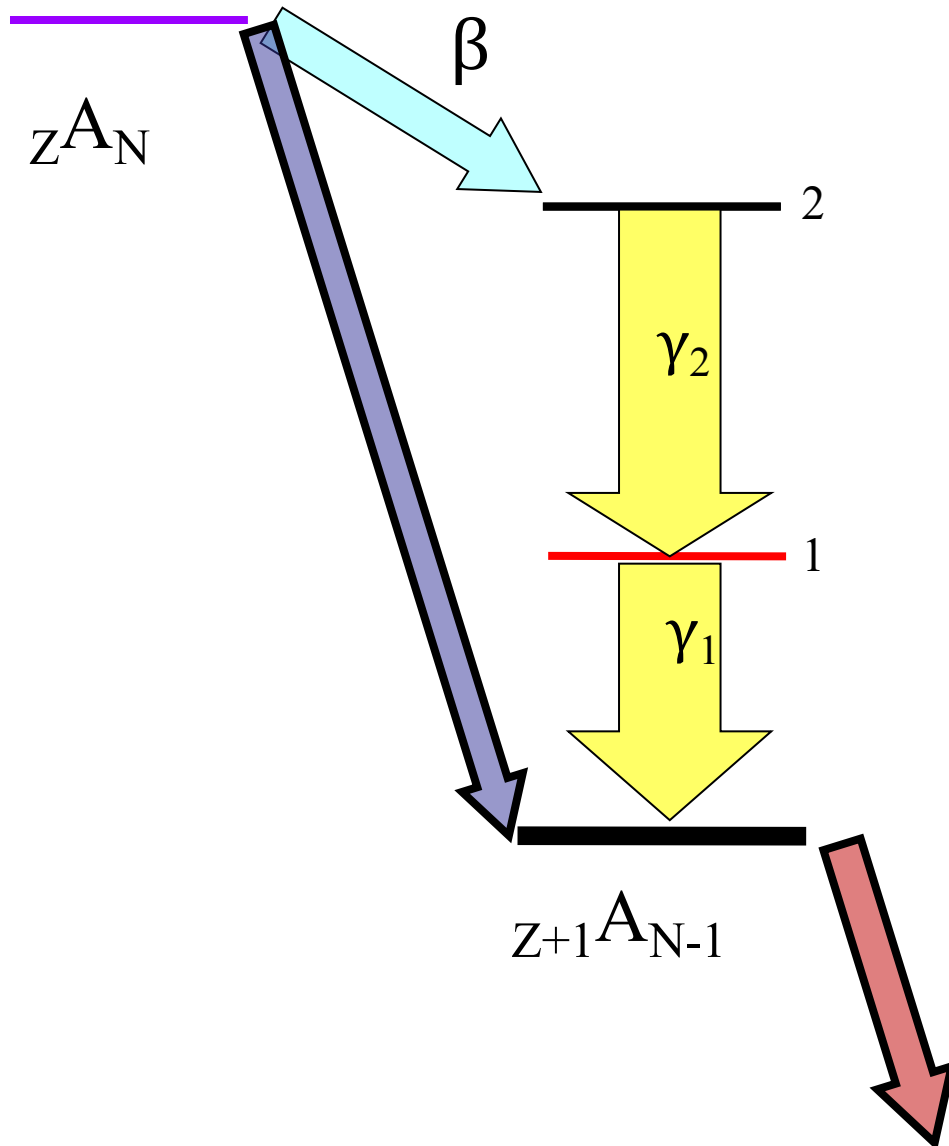
	235U	239Pu
Released E per fission	201.7 MeV	210.0 MeV
Mean neutrino E	2.94 MeV	2.84 MeV
Neutrinos/fission >1.8 MeV	1.92	1.45
Aver. Int. cross section	$3.2 \times 10^{-43} \text{cm}^2$	$2.8 \times 10^{-43} \text{cm}^2$



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.



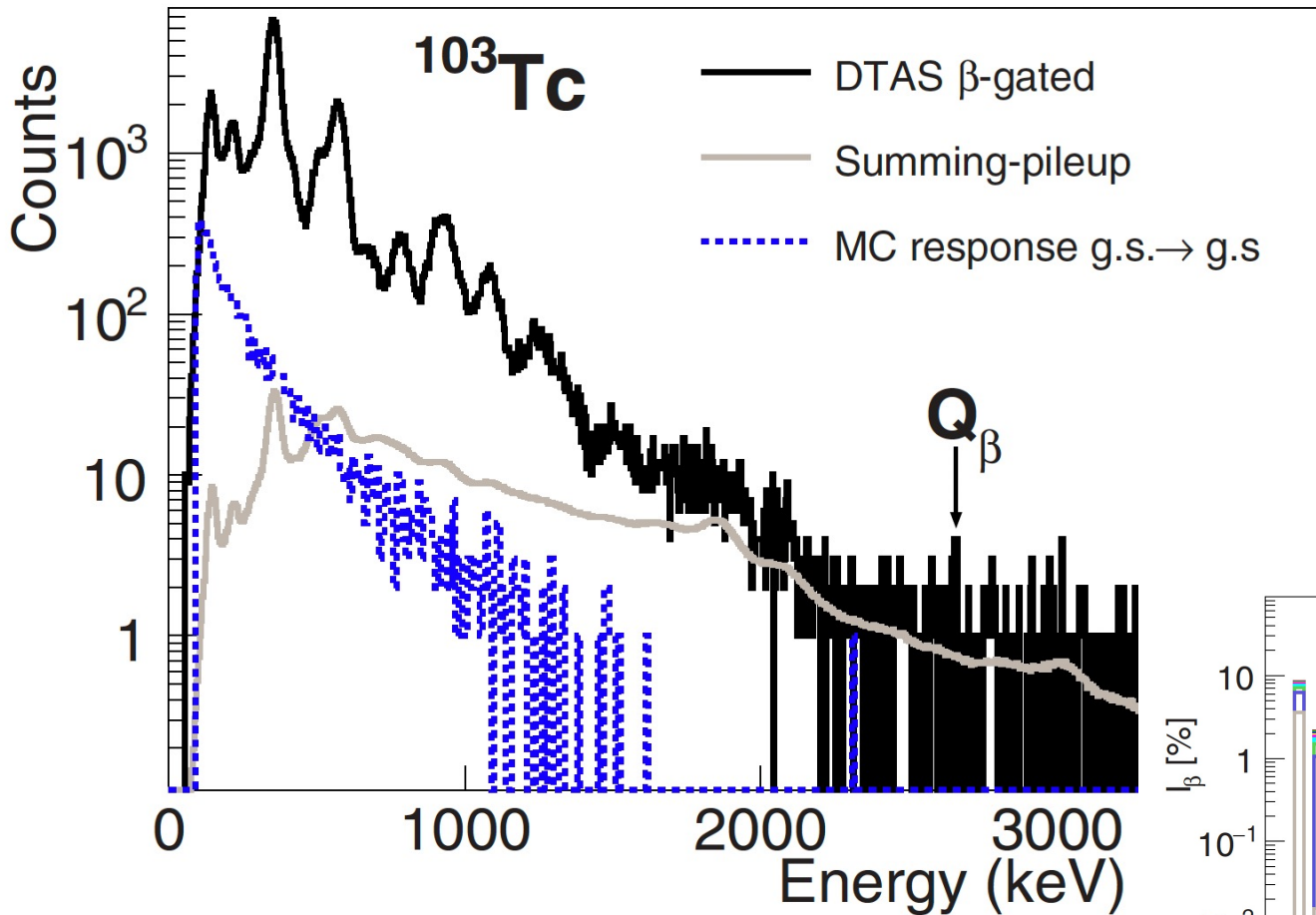
One last challenge: gs to gs feeding



Decay to the ground state is not accompanied by beta delayed gamma emission

Several options exist, but they can suffer from Pandemonium, and you need to count all the beta particles. Complex procedure.

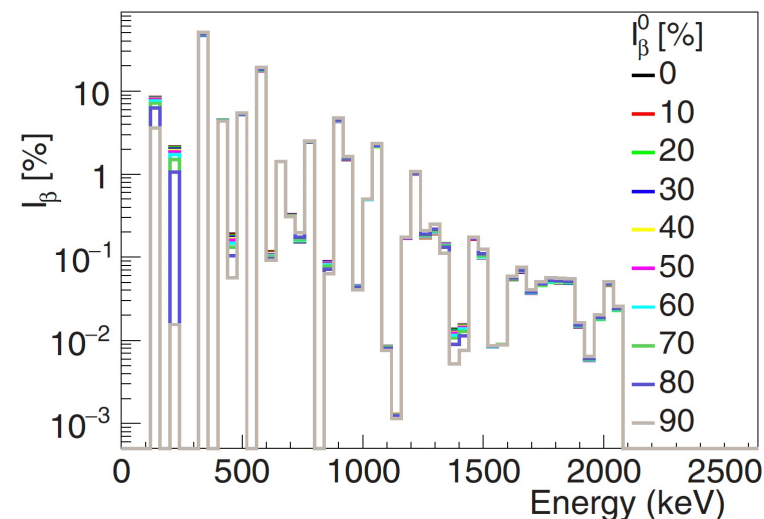
^{103}Tc decay (an odd TAGS case) Bad luck or serendipity?



Is it possible to determine
gs to gs feeding from
TAGS measurements?

Yes, but there might be
exceptions

TAGS analysis insensitive
to the assumed ground
state feeding



A new method for determining the gs to gs feeding from TAGS exp.

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 ($N_{\beta\gamma}$)

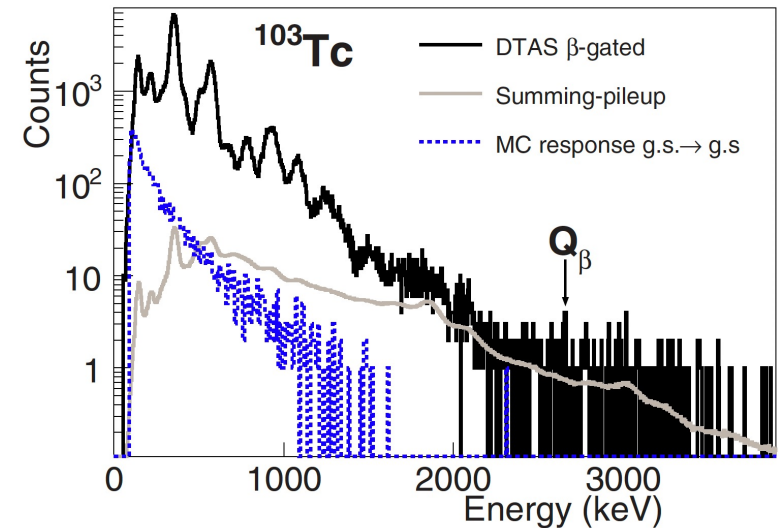
$$I_\beta^0 = \frac{1 - \frac{N_{\beta\gamma}}{N_\beta} \frac{\bar{\varepsilon}_\beta^*}{\bar{\varepsilon}_{\beta\gamma}^*}}{1 + \frac{N_{\beta\gamma}}{N_\beta} \frac{\varepsilon_\beta^0 - \bar{\varepsilon}_\beta^*}{\bar{\varepsilon}_{\beta\gamma}^*} - \frac{\varepsilon_{\beta\gamma}^0}{\bar{\varepsilon}_{\beta\gamma}^*}}.$$

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

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

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

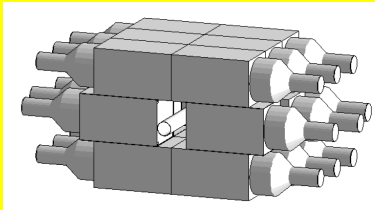
The method was tested with synthetic data.



$$I_\beta^0(^{103}\text{Tc}) = 45.6(+1.5-0.9)$$

ENSDF value 34(8)

Ground state feedings obtained the new method



Isotope	I_{β}^0 (%)		
	ENSDF	TAGS	$4\pi\gamma - \beta$
^{95}Rb	≤ 0.1	$0.03^{+0.11}_{-0.02}$	$-0.2(42)$
$^{100\text{gs}}\text{Nb}$	50(7)	46^{+16}_{-15}	40(6)
$^{102\text{m}}\text{Nb}$	—	$42.5^{+9.3}_{-10.0}$	44.3(28)
^{100}Tc	93.3(1)	93.9(5)	92.8(5)
$^{103}\text{Tc}^{\text{a}}$	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)

^aFor 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)

Can be useful for cases that are relevant for fundamental applications

Some “trivial” conclusions

I hope I have shown you that total absorption technique is a necessary technique for beta decay studies.

There is a large potential for nuclear structure, astrophysics and practical applications.

But, in reality we need a combination of techniques to obtain the full picture: high resolution, beta spectrum shapes, not covered here

THANK YOU

All this work has been possible thanks to the students and postdocs working on the field, my colleagues from Valencia, Jyväskylä, Nantes, Surrey, etc.



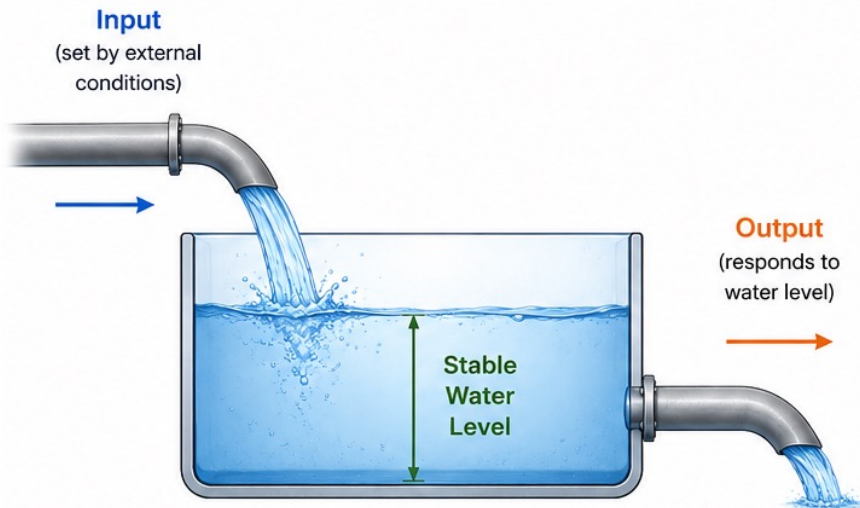
Pandemonium effect (I asked again ...)

The Pandemonium Effect

When a process responds to changes in its own output, it can create a self-reinforcing cycle that leads to instability or runaway behavior.

Without Pandemonium (Balanced System)

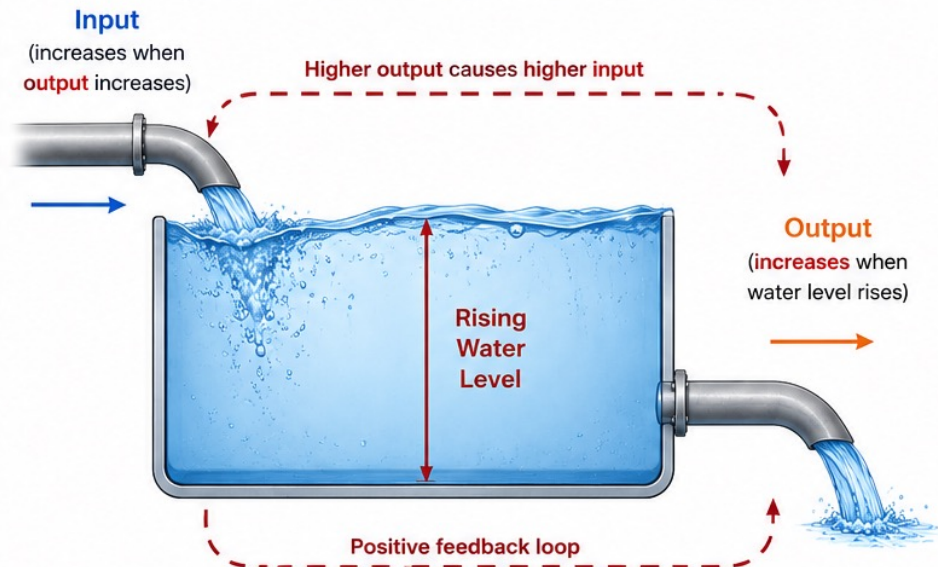
$$\text{Input} = \text{Accumulation} + \text{Output}$$



Output adjusts to the water level but does not affect the input.
The system reaches equilibrium.

With Pandemonium (Self-Reinforcing Loop)

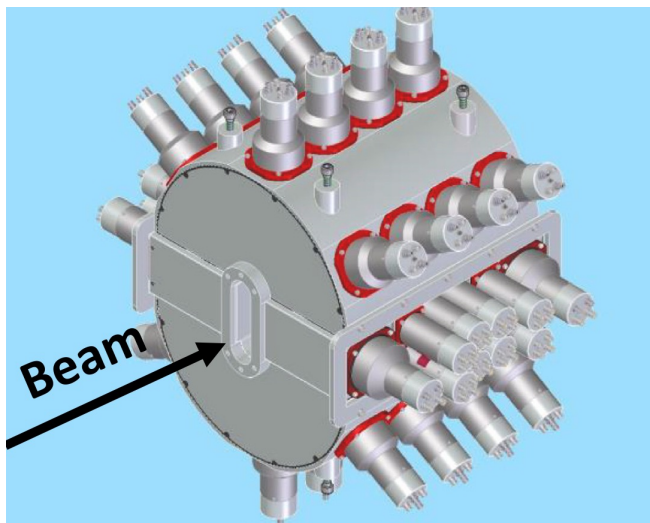
$$\text{Input} = \text{Accumulation} + \text{Output}$$



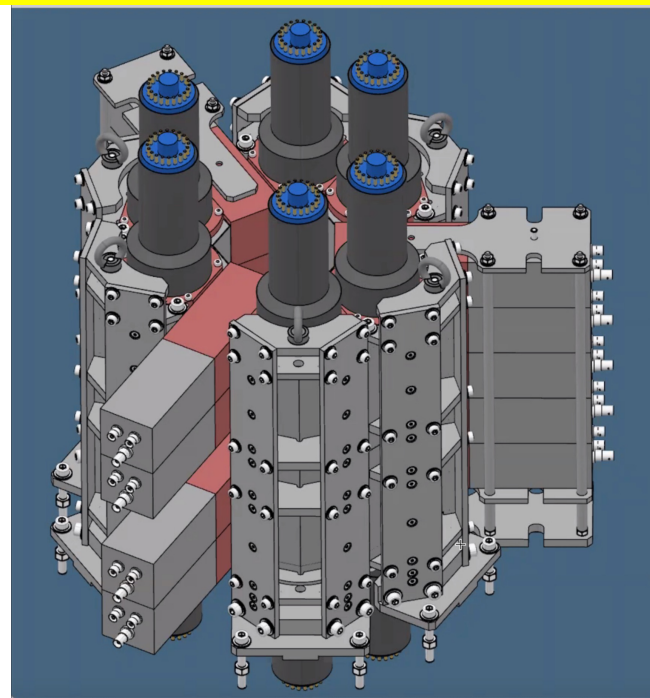
As water level rises, output increases, which causes input to increase even more.
The system spirals out of control.

Key Insight: When the output of a system influences its own input, it can create a reinforcing feedback loop called the **Pandemonium Effect**.

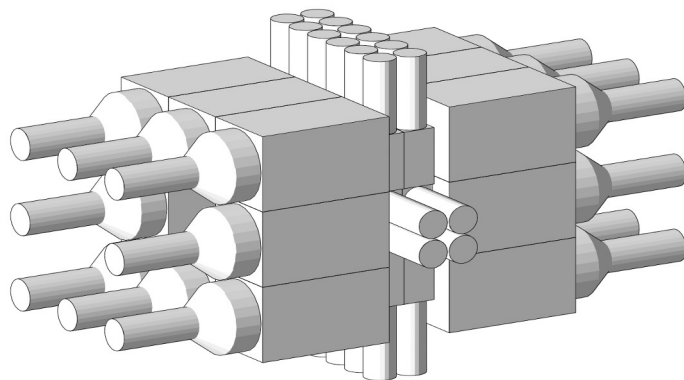
Latest fashion models: hybrids



SuN++:
NaI + CeBr₃

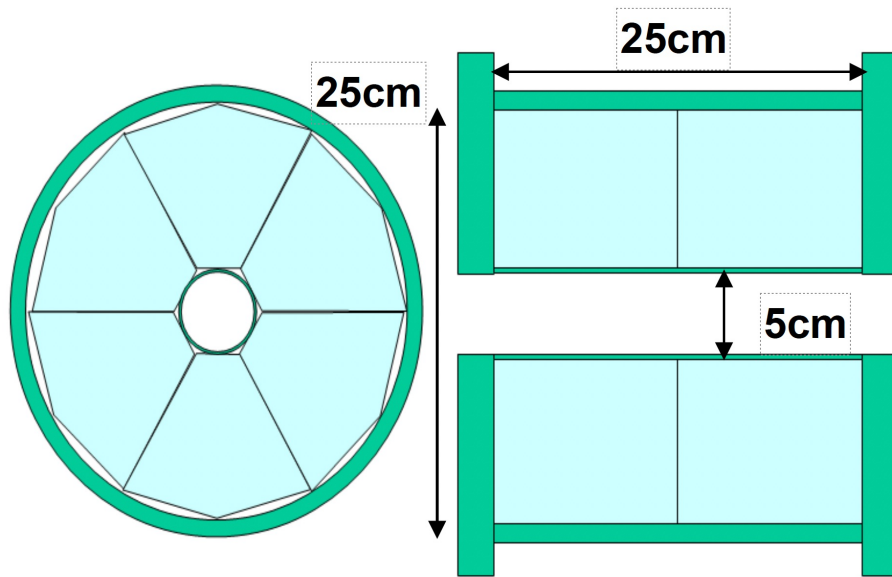


Rocinante + NA2STARS:
NaI+LaBr₃

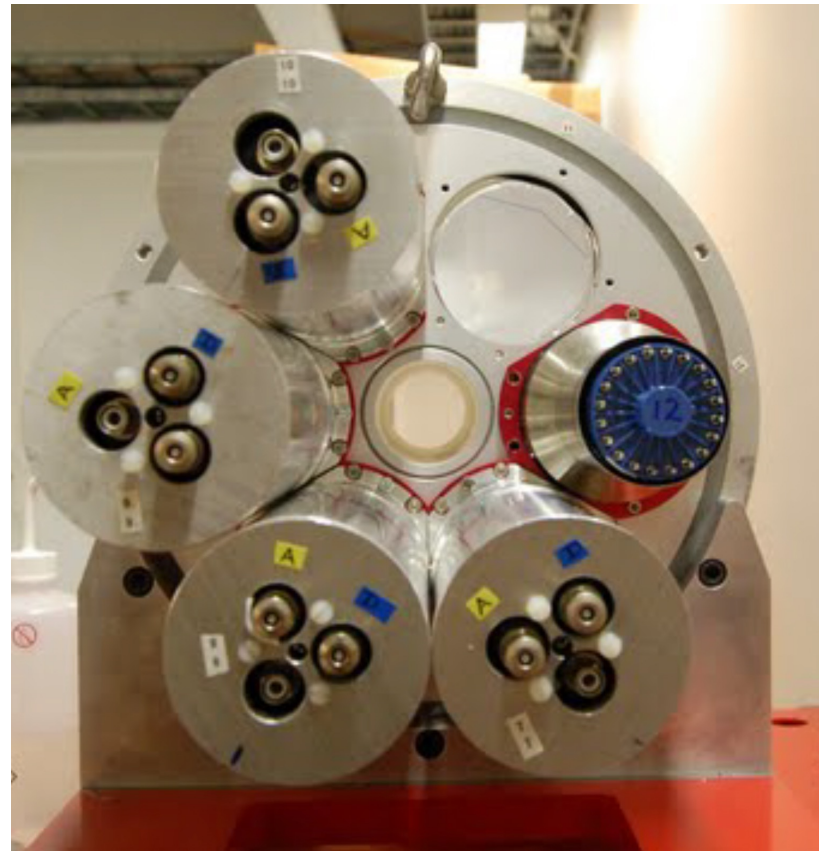
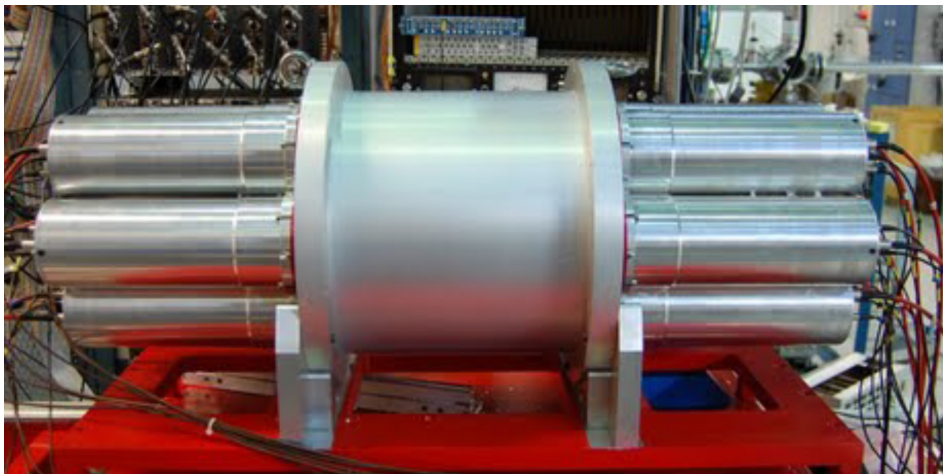


DTAS ++?

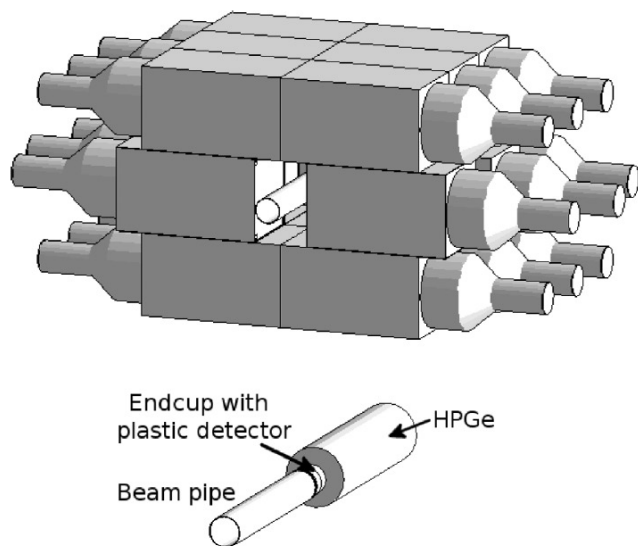
Original setup



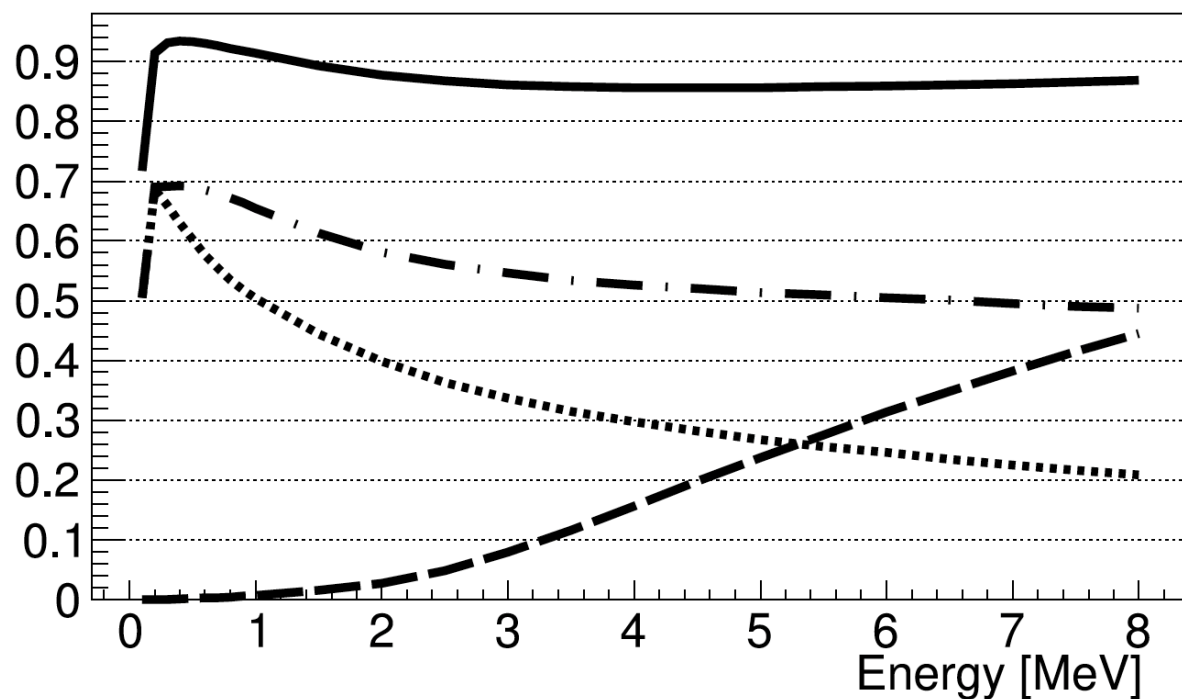
Crystals are optically separated.



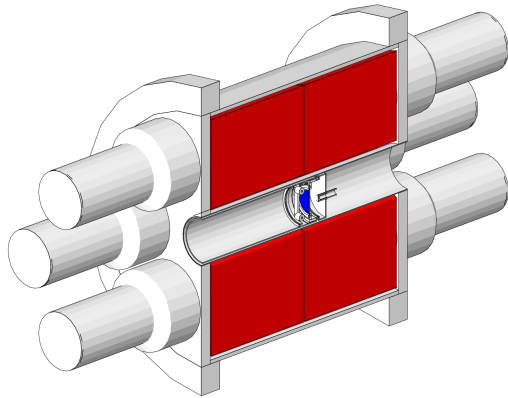
DTAS efficiency



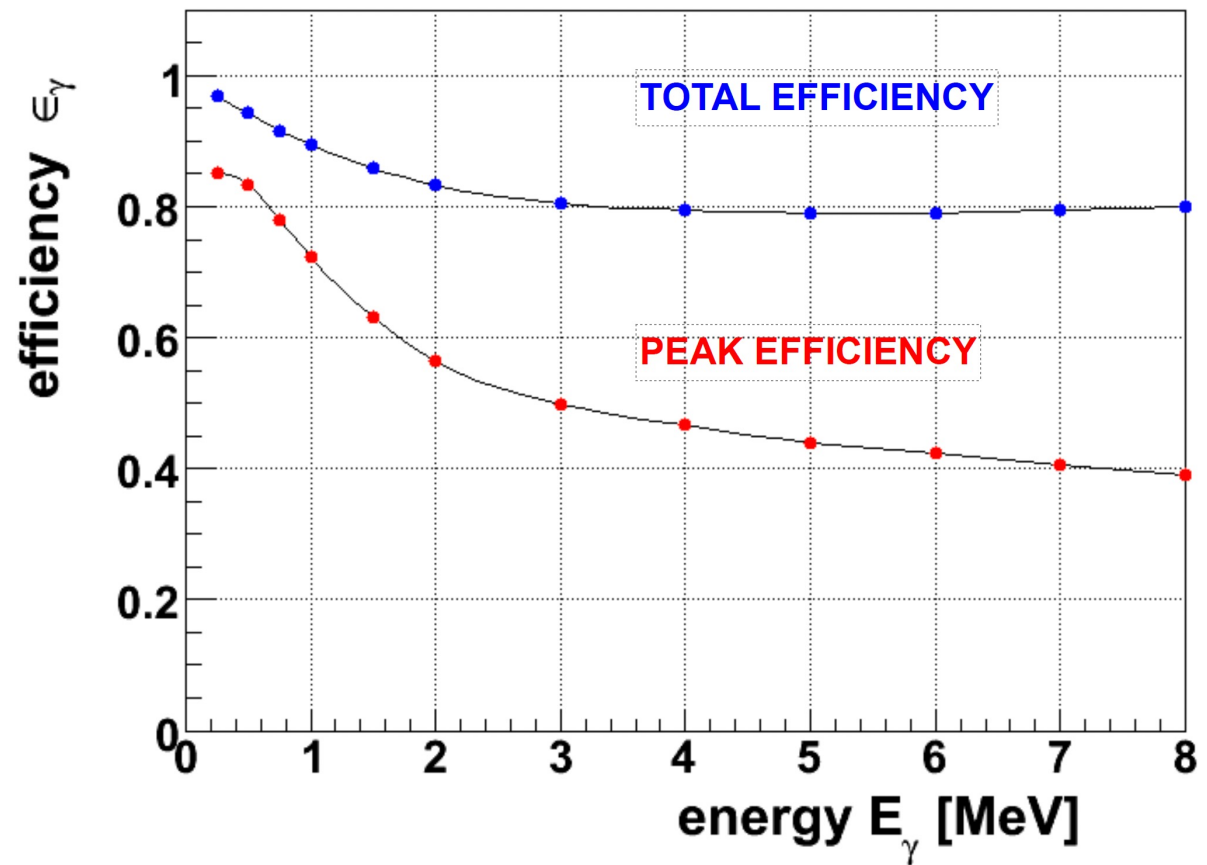
Simulated MC efficiency



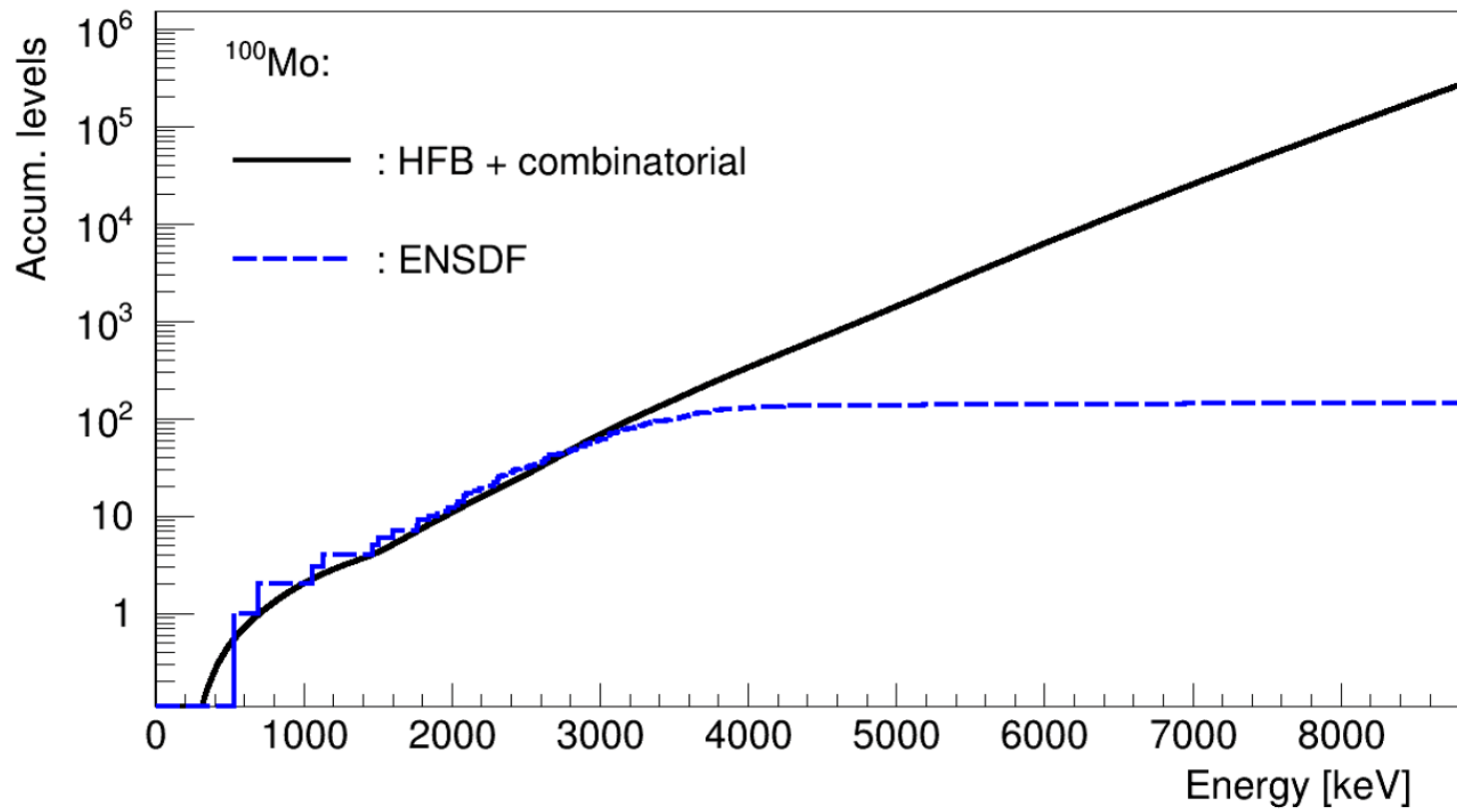
Original setup: compact and highly efficient



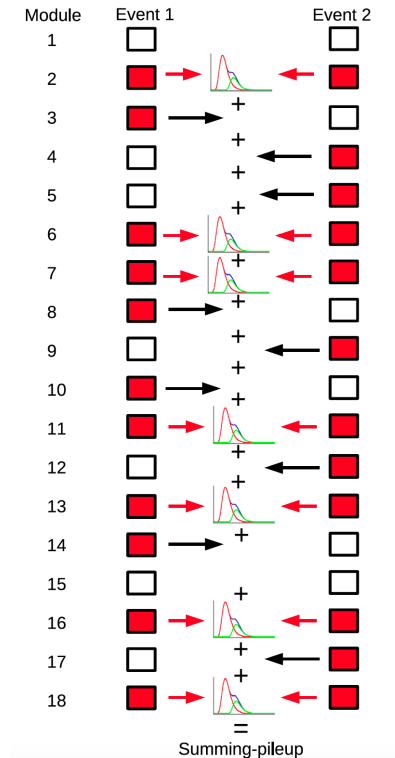
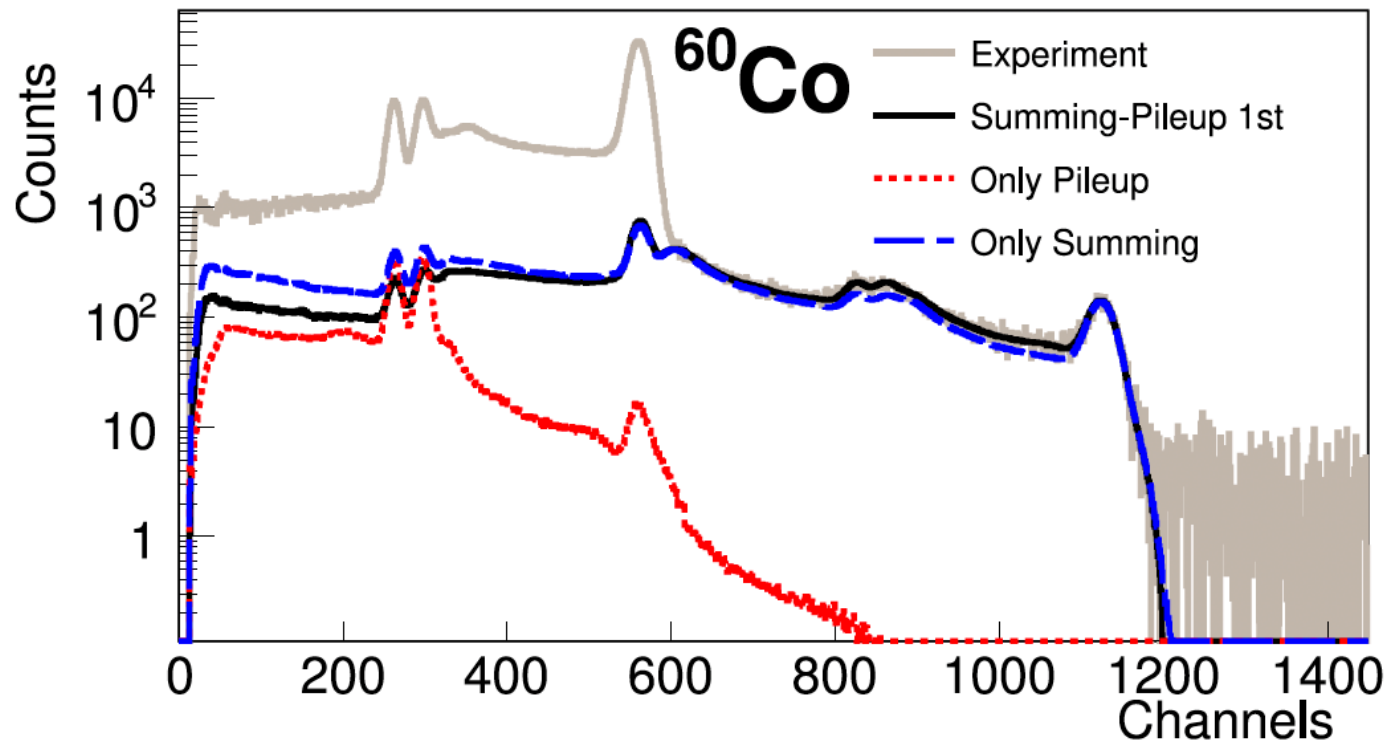
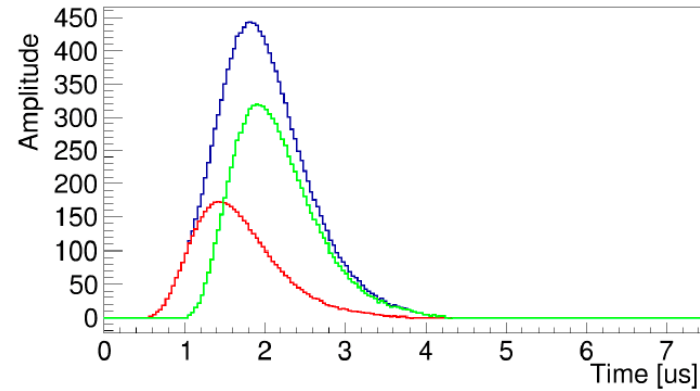
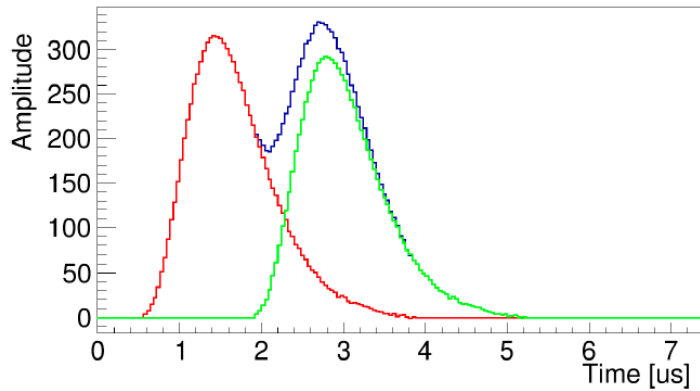
Simulated MC efficiency



Level density

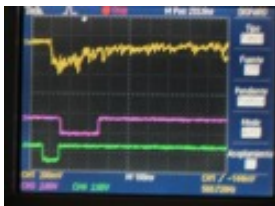
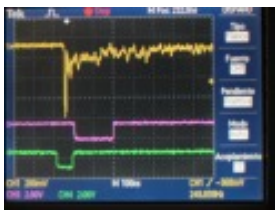
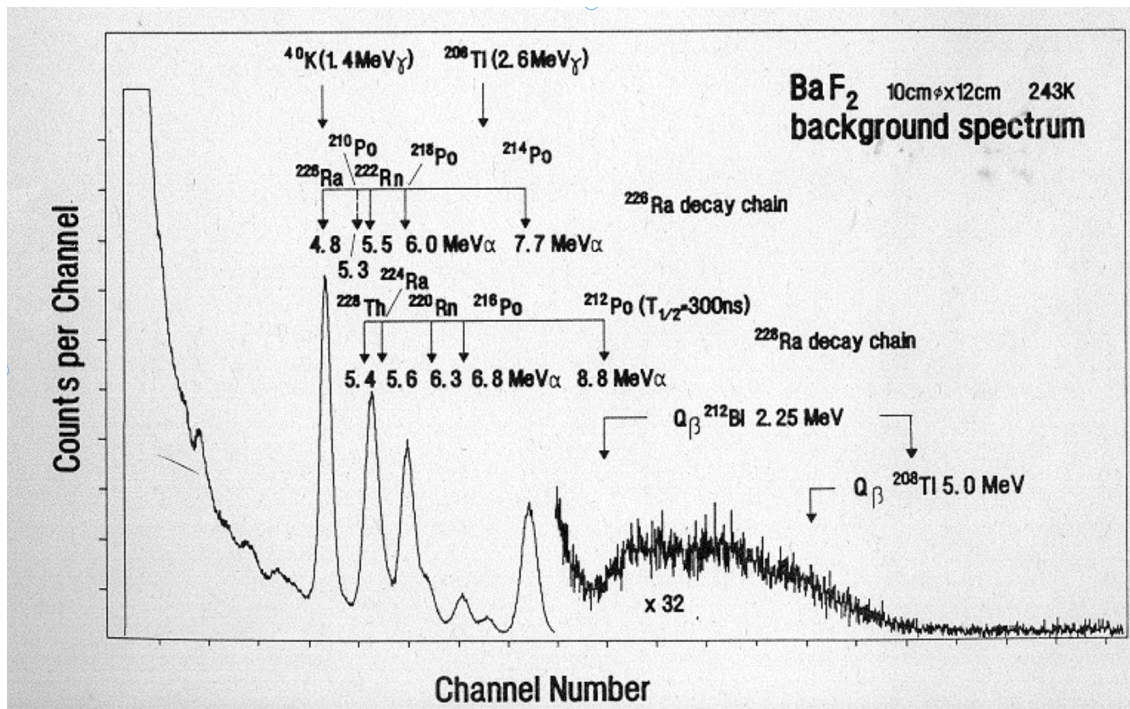
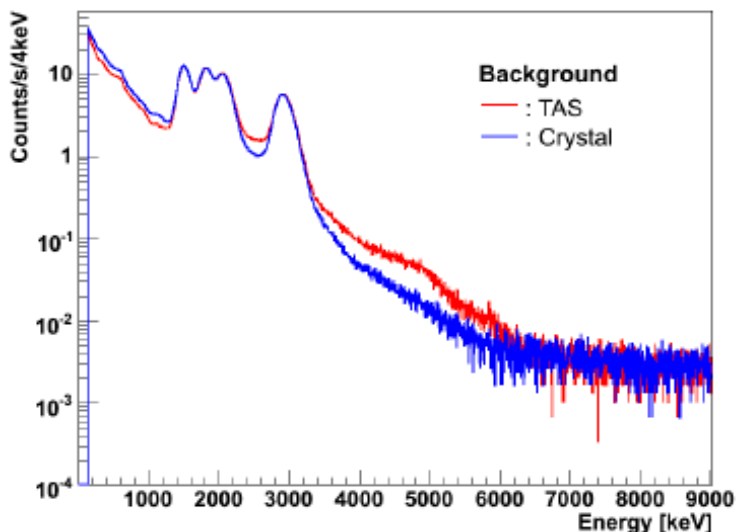


Pileup



Setup limitations: contamination, resolution

Internal alpha contamination of the crystals

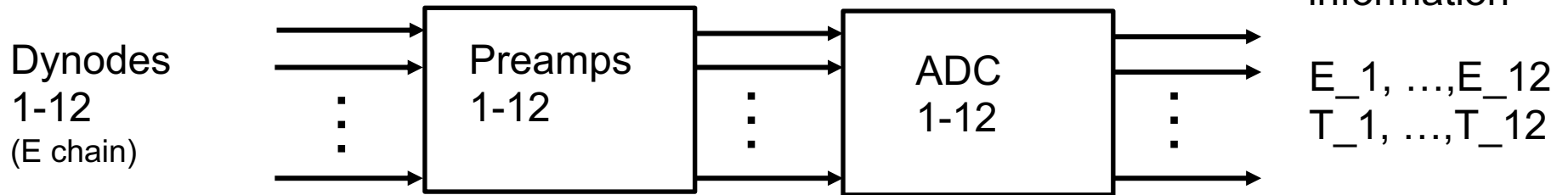


Positive side: with puls discrimination we can do gain matching

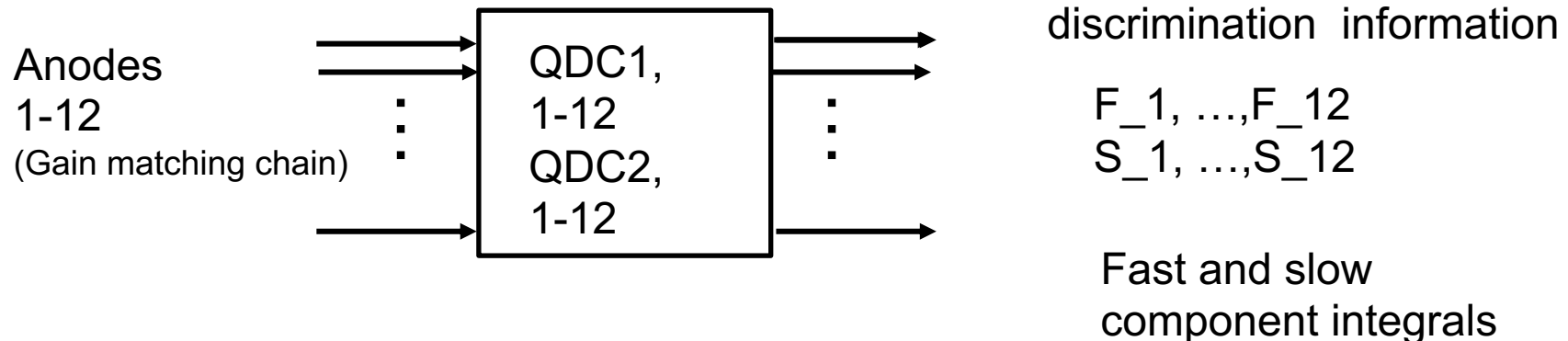
Typical problem: we need to replace often the optical grease

How the gain matching is done (over-simplified)

Energy-time branch using preamps + ADCs

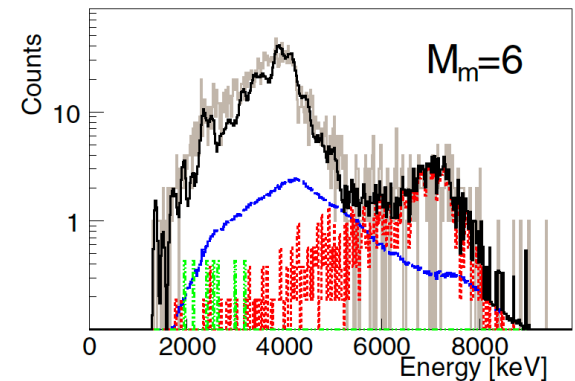
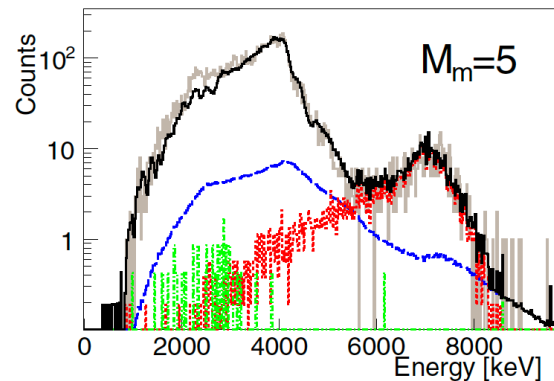
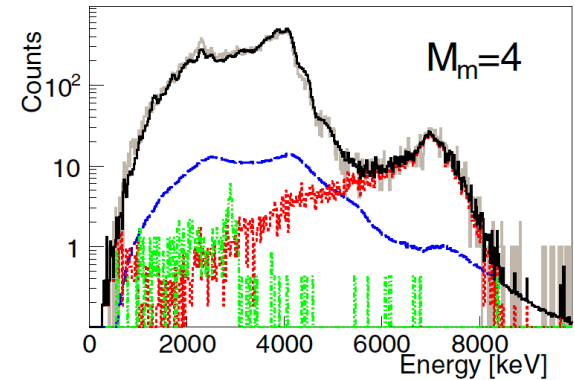
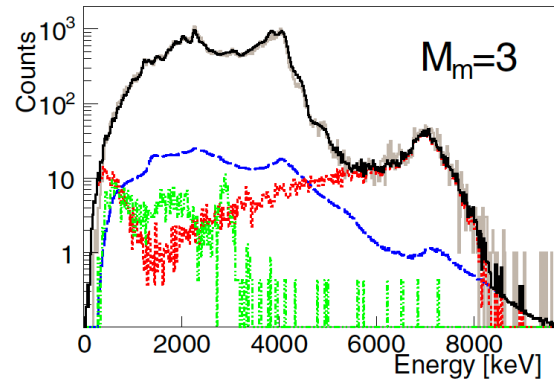
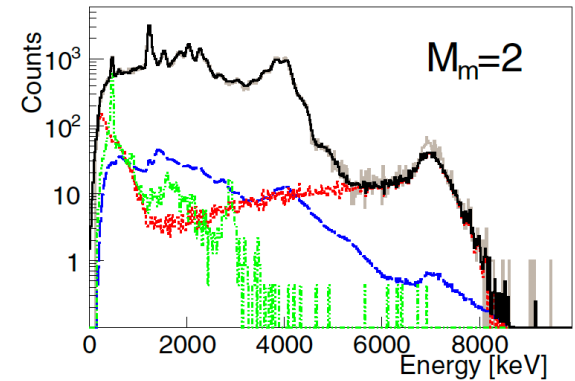
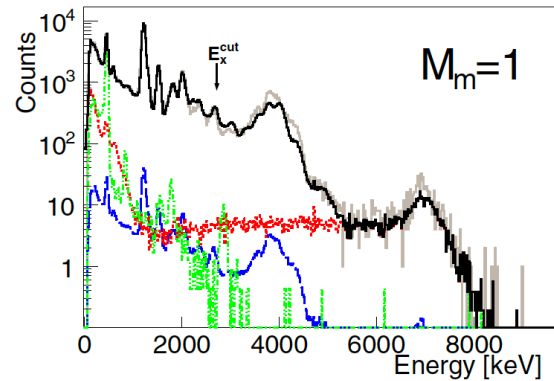


Pulse shape discrimination branch using QCDs

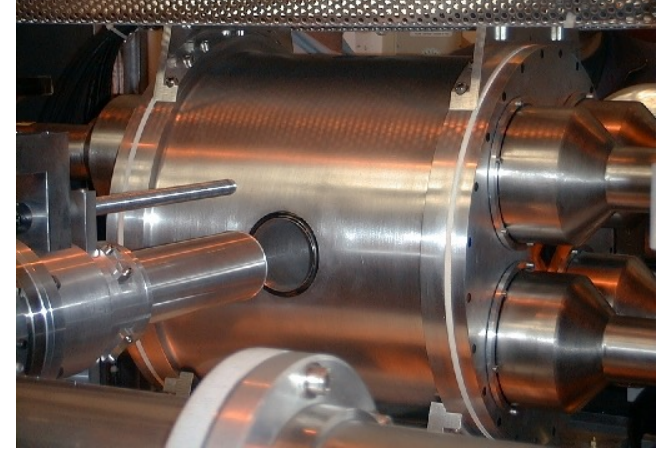
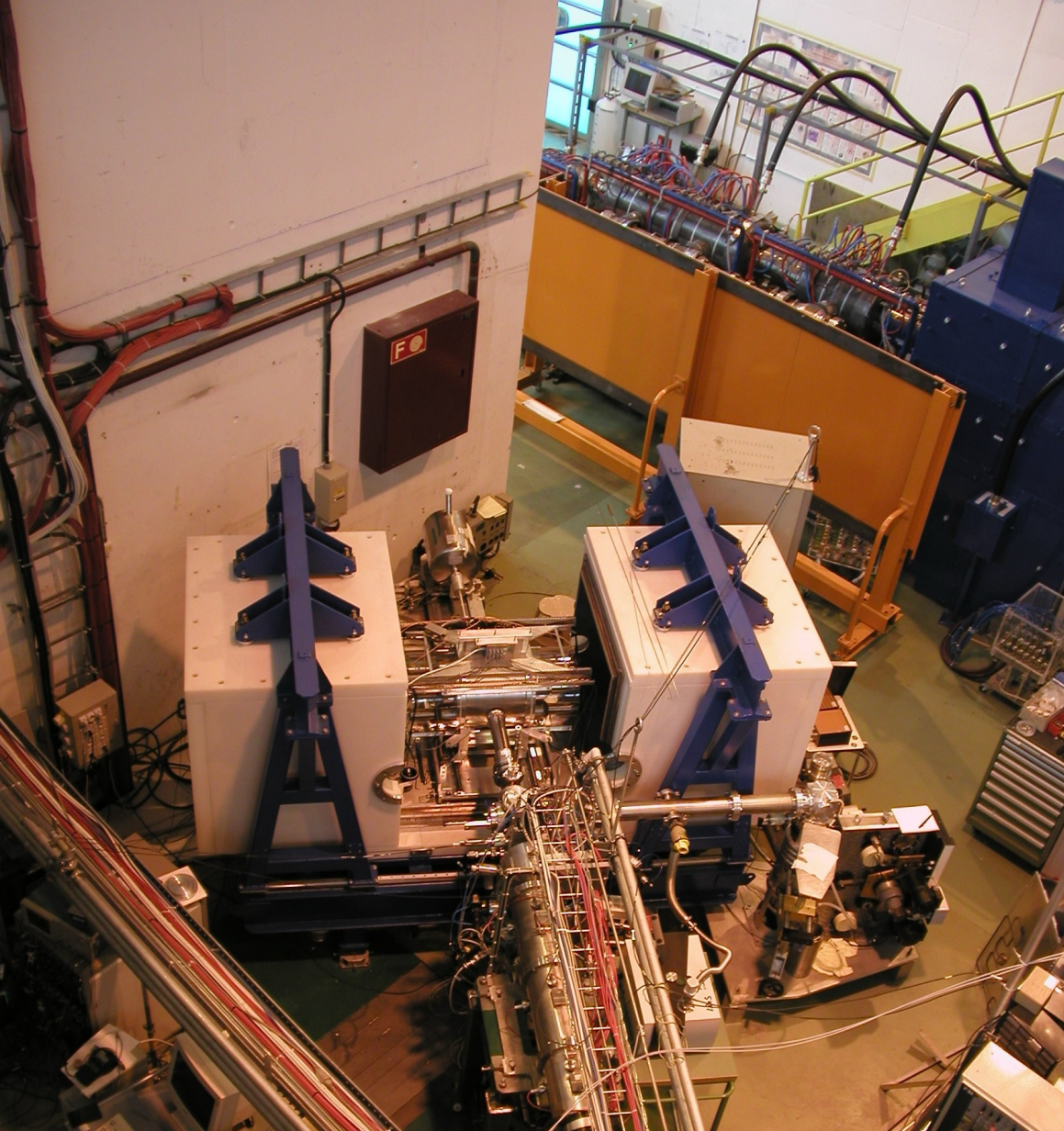


Multiplicity reproduction after the analysis

137I decay

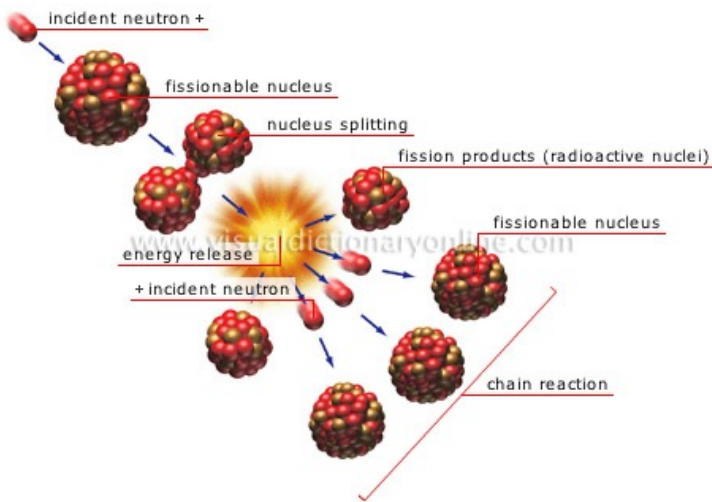


Lucrecia: the TAS at ISOLDE (CERN) (Madrid-Strasbourg-Surrey-Valencia)



- A large NaI cylindrical crystal 38 cm Ø, 38cm length
- An X-ray detector (Ge)
- A β detector
- Possibility of collection point inside the crystal

Fission process energy balance

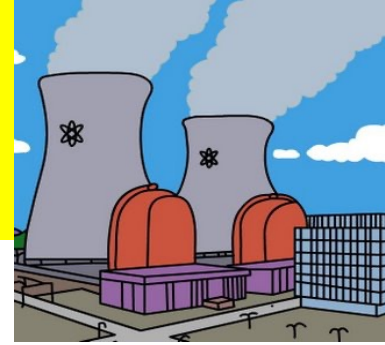


Each fission is approximately followed by 6 beta decays (sizable amount of energy)
A reactor produces 10^{20} v/s

Energy released in the fission of ^{235}U	
Energy distribution	MeV
Kinetic energy light fission fragment	100.0
Kinetic energy heavy fission fragment	66.2
Prompt neutrons	4.8
Prompt gamma rays	8.0
Beta energy of fission fragments	7.0
Gamma energy of fission fragments	7.2
Subtotal	192.9
Energy taken by the neutrinos	9.6
Total	202.7

James, J. Nucl. Energy 23 (1969) 517

Decay heat: how to determine it ?



- Measure it (lacks flexibility and it is costly)
- Try to predict or calculate in the best way
 - Statistical method (the first solution)

Way and Wigner, Phys. Rev. 73 (1948) 1318

$$B(t) = 1.26t^{-1.2} \text{ MeV} / s$$

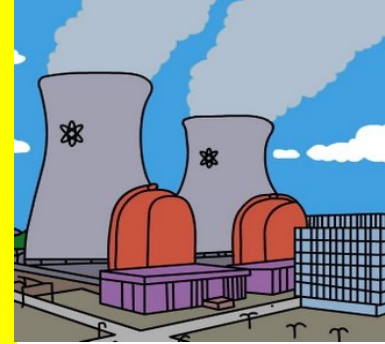
$$\Gamma(t) = 1.40t^{-1.2} \text{ MeV} / s$$

later, Griffin, Phys. Rev. 134 (1964) B817

- Summation calculations (next slide)

The inventory of nuclides:

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

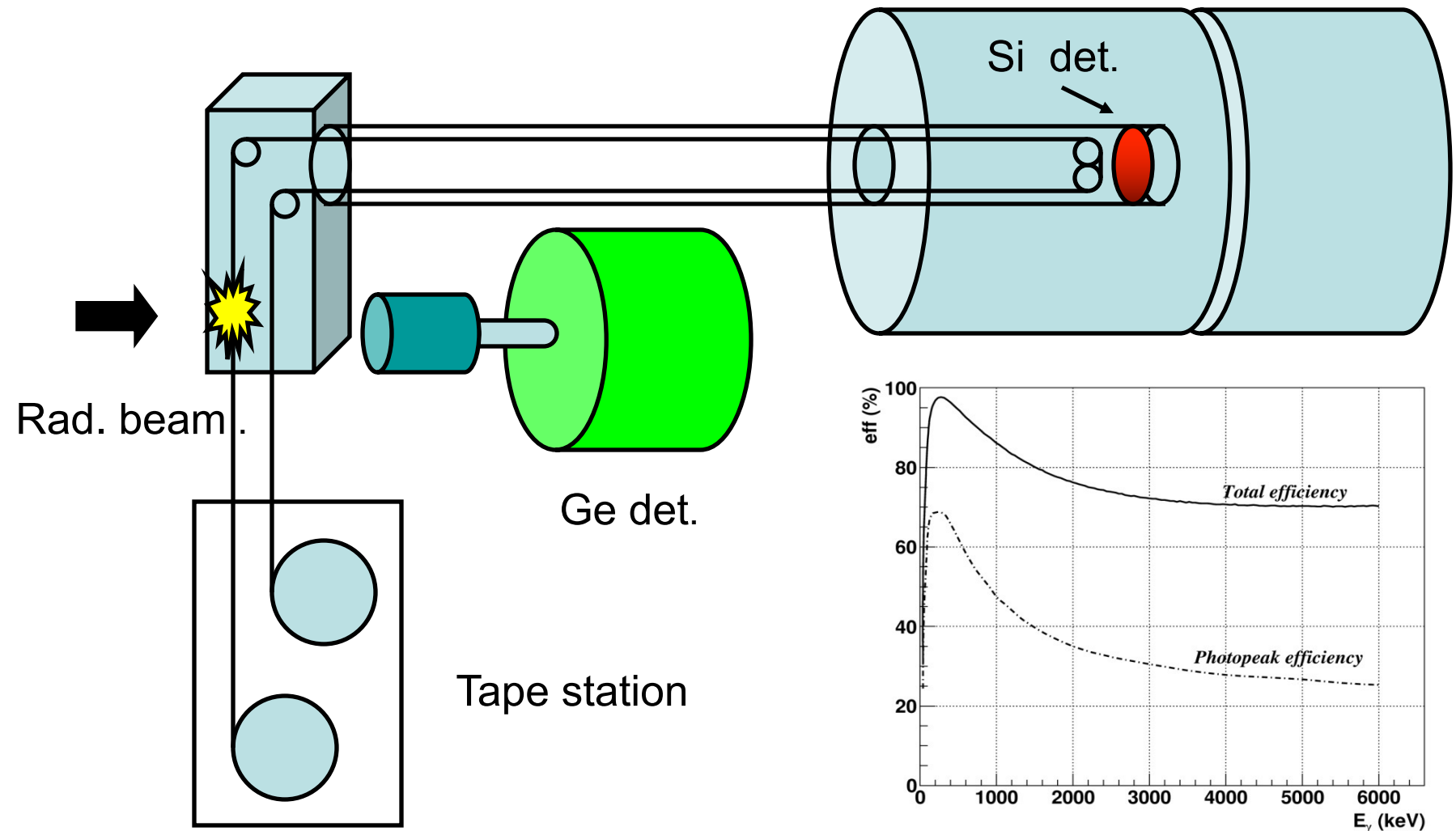


Solve a linear system of coupled first order differential equations

$$\begin{aligned} \frac{dN_i}{dt} = & -(\lambda_i + \sigma_i \phi) N_i + \sum_j f_{j \rightarrow i} \lambda_j N_j \\ & + \sum_k \mu_{k \rightarrow i} \sigma_k \phi N_k + y_i F \end{aligned}$$

N_i	Number of nuclides i	$f_{i \rightarrow j}$	branching ratio of j to i decay
λ_i	decay constant i	$\mu_{k \rightarrow i}$	{ production rate of i per one neutron capture of k
σ_i	capture cross section i	y_i	
ϕ	neutron flux	F	fission rate

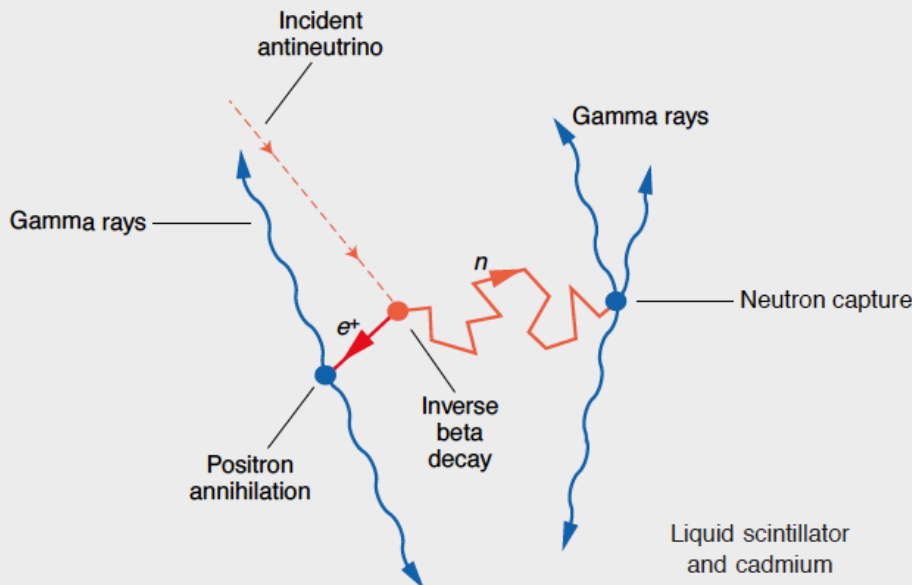
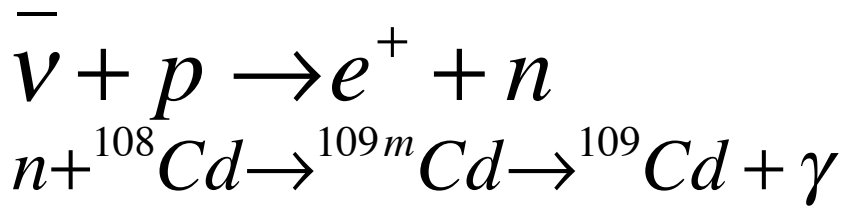
First experimental setup at Jyväskylä



Nuclear reactors and neutrino physics I

Neutrino postulated by Pauli, 1930
Nuclear reactors are the strongest
(peaceful) human source of
antineutrinos.

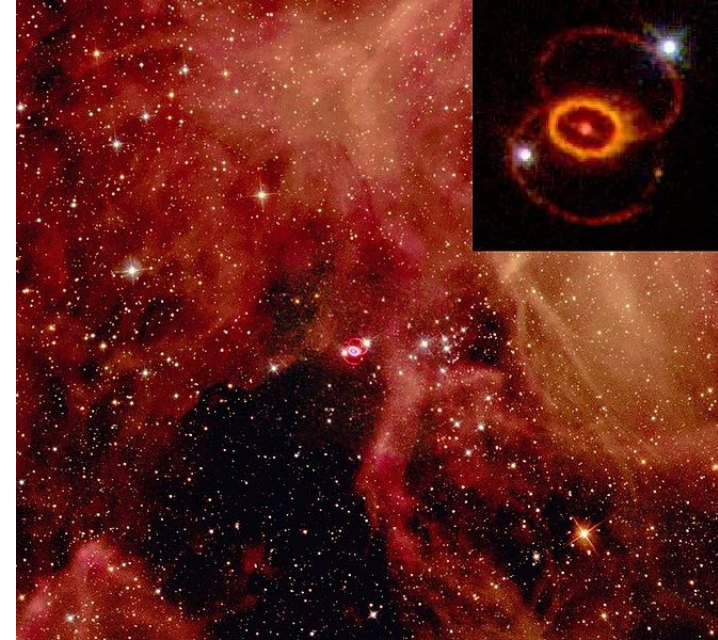
Reines, Cowan, 1956



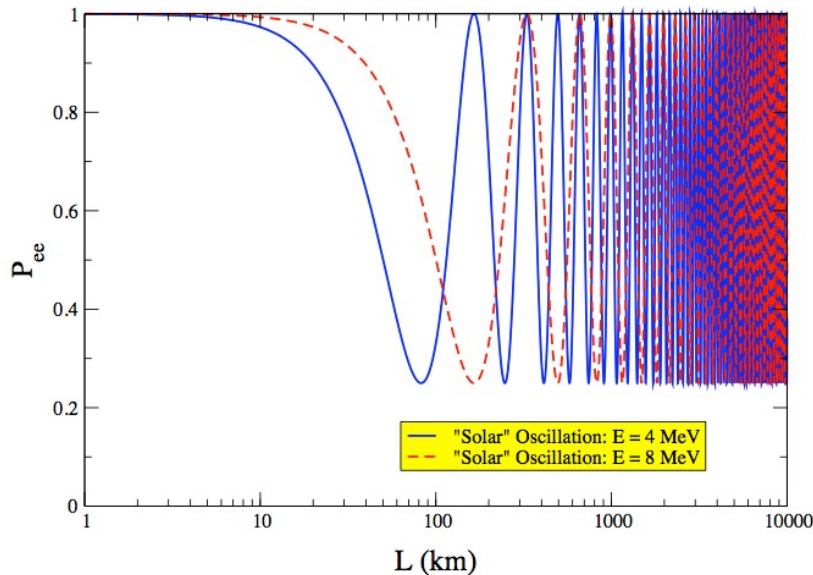
Neutrino flux at the *Savannah River*
reactor: 5×10^{13} neutrino/s.cm²
They detected 3 neutrinos/h
Science 20, vol 124 no. 3212 pp. 103-104

Why worth studying: neutrinos as messengers

- We hear about many types of neutrinos: solar neutrinos, geo-neutrinos, atmospheric neutrinos, supernova neutrinos, Big Bang neutrinos, reactor neutrinos, etc., etc.
- They can provide information about the processes that happen inside those objects, because they can travel very long distances without interaction.
- Quantum effects at macroscopic scales



Supernova SN1987A



Oscillations !!!
(solar neutrino deficit, atm. neutrino deficit, ^{238}U , ^{232}Th , ^{40}K content, etc.)

Neutrino oscillations

FOR
DUMMIES



- 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)

(including myself !)

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

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

$$\Delta m^2 = m_2^2 - m_1^2 \quad [L \text{ in m, } E \text{ in MeV, } \Delta m^2 \text{ in eV}^2]$$

In three flavours we need the Pontecorvo-Maki-Nakagawa-Sakata unitary matrix !!!

Example of reactor neutrino oscillation experiment: Double Chooz, Θ_{13}



^{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

^{92}Rb 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 ????

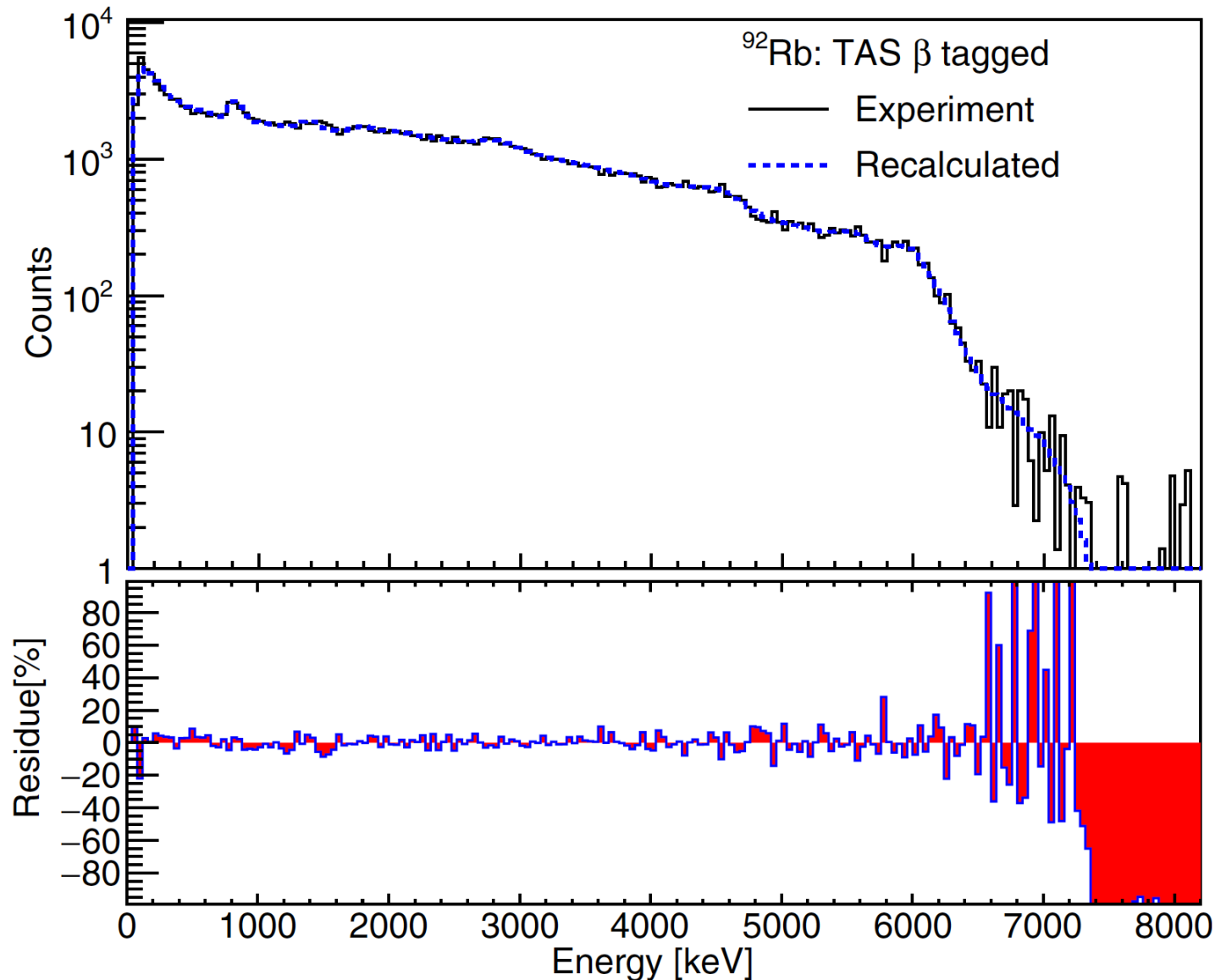
Table from

Zakari-Issoufou et al.

PRL 115.102503(2015)

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

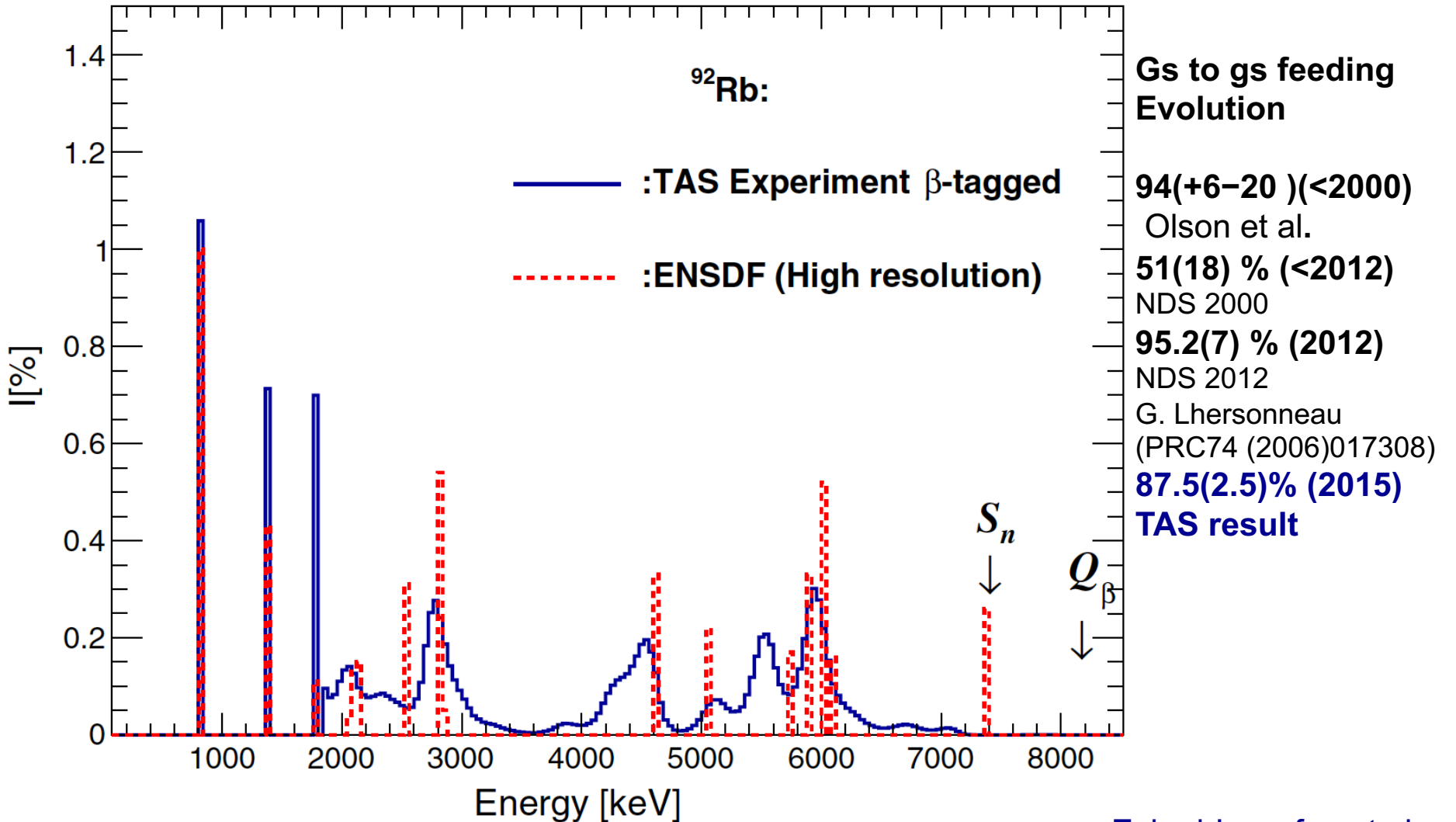
^{92}Rb : TAS measurement, 2009 exp. Analyzed by the Nantes group



Zakari-Issoufou et al.
PRL 115.102503(2015)

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

^{92}Rb : star 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

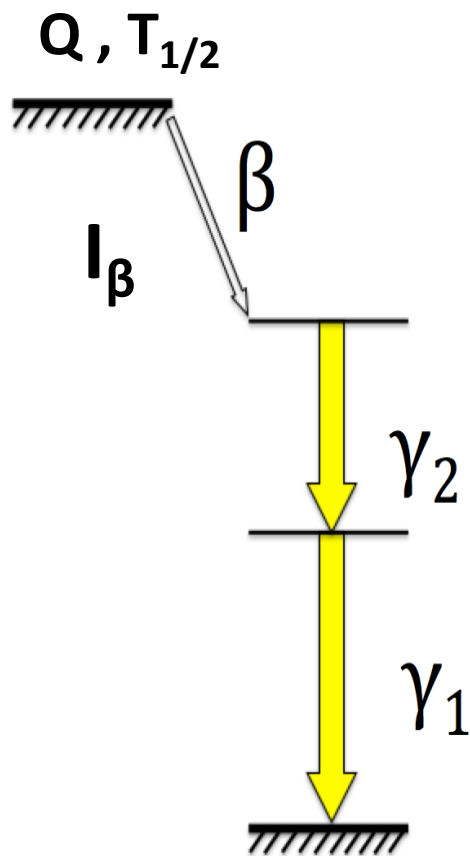
(PRC74 (2006)017308)

87.5(2.5)% (2015)

TAS result

Zakari-Issoufou et al.
PRL 115.102503(2015)

Beta feeding vs beta strength



Feedings

$$\text{Feeding} := I_{\beta} = P_{\beta} \cdot 100$$

Other experimental ingredients: $T_{1/2}$; Q

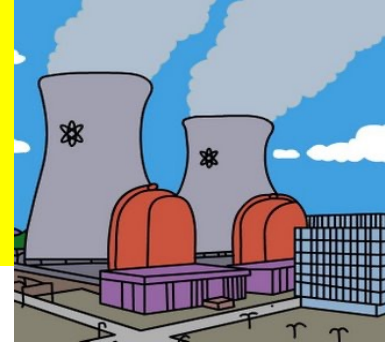
$$f(Z', Q) = \text{const} \cdot \int_0^{p_{\max}} F(Z', p) p^2 (Q - E_e)^2 dp; \quad t = \frac{T_{1/2}}{P_{\beta}}$$

$$S_{\beta}(E) = \frac{P_{\beta}(E)}{f(Z', Q_{\beta} - E) T_{1/2}} = \frac{1}{ft(E)}$$

Strength

$$ft = \text{const}' \frac{1}{|M_{if}|^2}$$

Decay heat: summation calculations



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

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

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

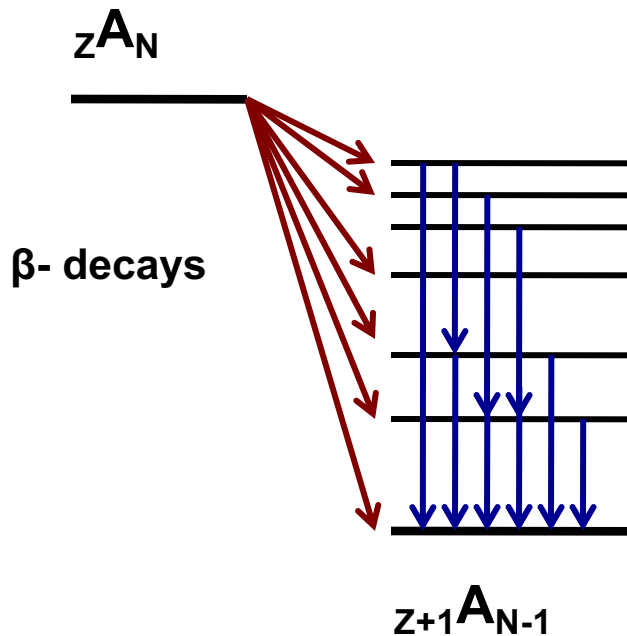
N_i Number of nuclei i at the cooling time t

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)

Mean energies and Pandemonium

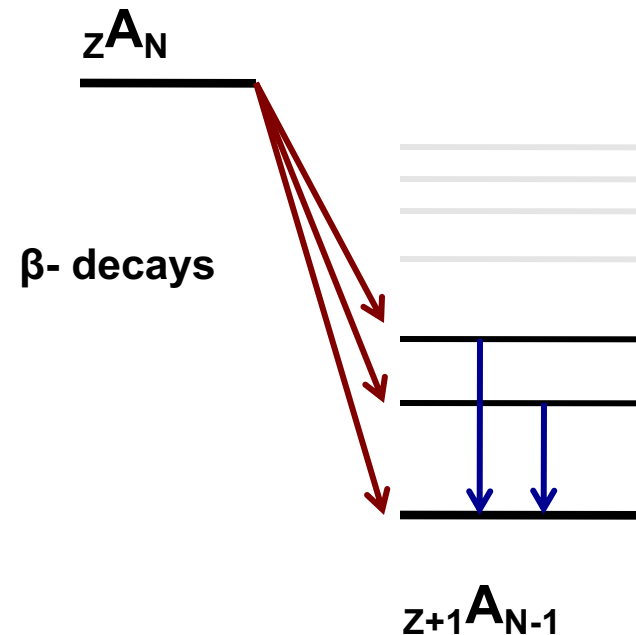


$$f(t) = \sum_i \textcircled{E_i} \lambda_i N_i(t)$$



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

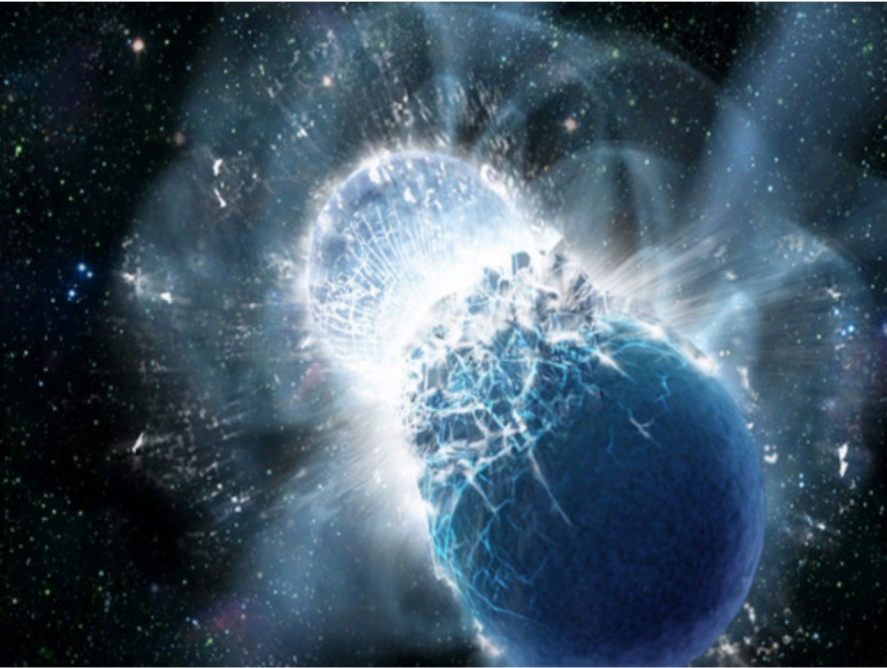
$$\overline{E}_\gamma = \sum_i I_\beta(E_i) E_i$$



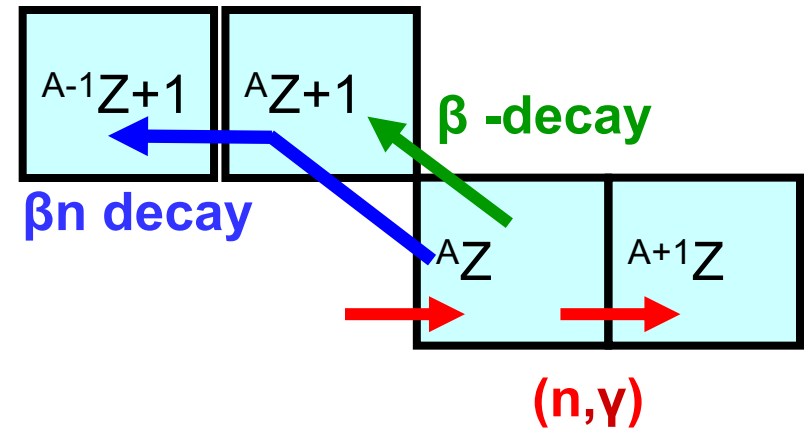
$\overline{E}_\beta$ overestimation

$\overline{E}_\gamma$ underestimation

Astrophysics I: r-process input from models



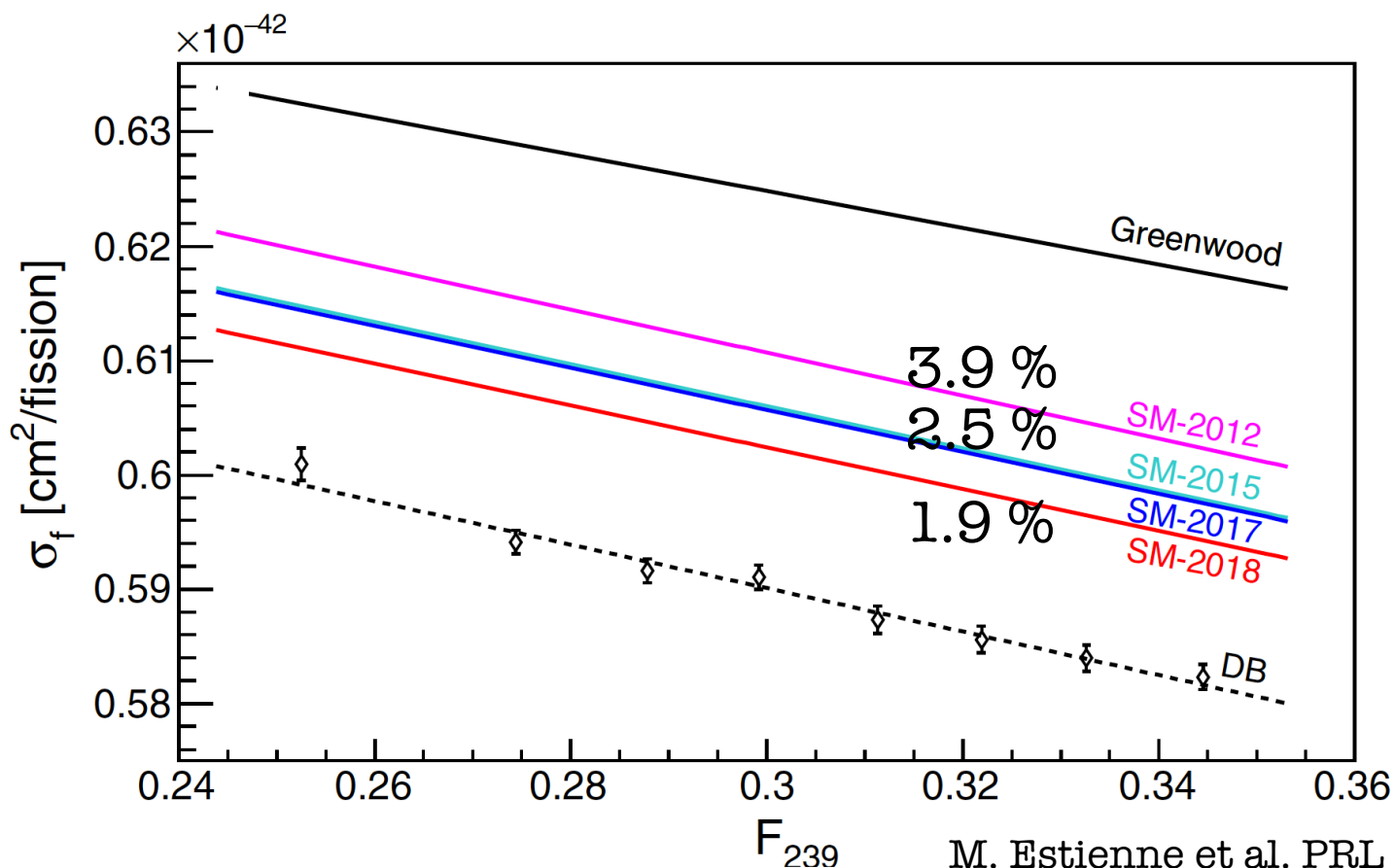
r-process: A short and very high neutron flux produces very neutron-rich nuclei in a short time, which then decay to stability.



- ◇ 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

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:
102,104,105,106,107Tc,
105Mo, and 101Nb

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

SM-2017:
91Rb, 86Br

SM-2018:
100,100m,102,102mNb

DB: Daya Bay

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

Nuevo exp. in 2022
(>10 nuevos casos)
Tesis: Julien Pepin

