

Study of Beta Decay Spectra Shapes for Predictions of Reactor Antineutrino Spectra

By **Gustavo A. Alcalá E.**
For the **e-shape Collaboration**



XL Reunión Bienal de la RSEF
Sevilla – July 2026



Where the
problems are!

Reactor Antineutrino Spectra

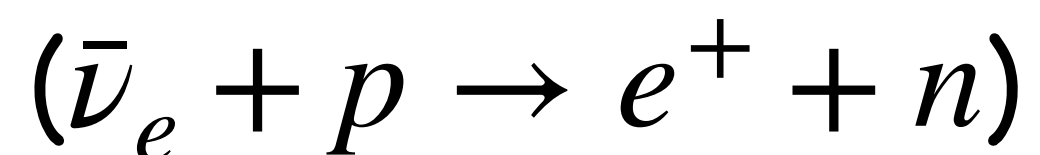
1

Fission products of reactors' fuel
fissile isotopes are

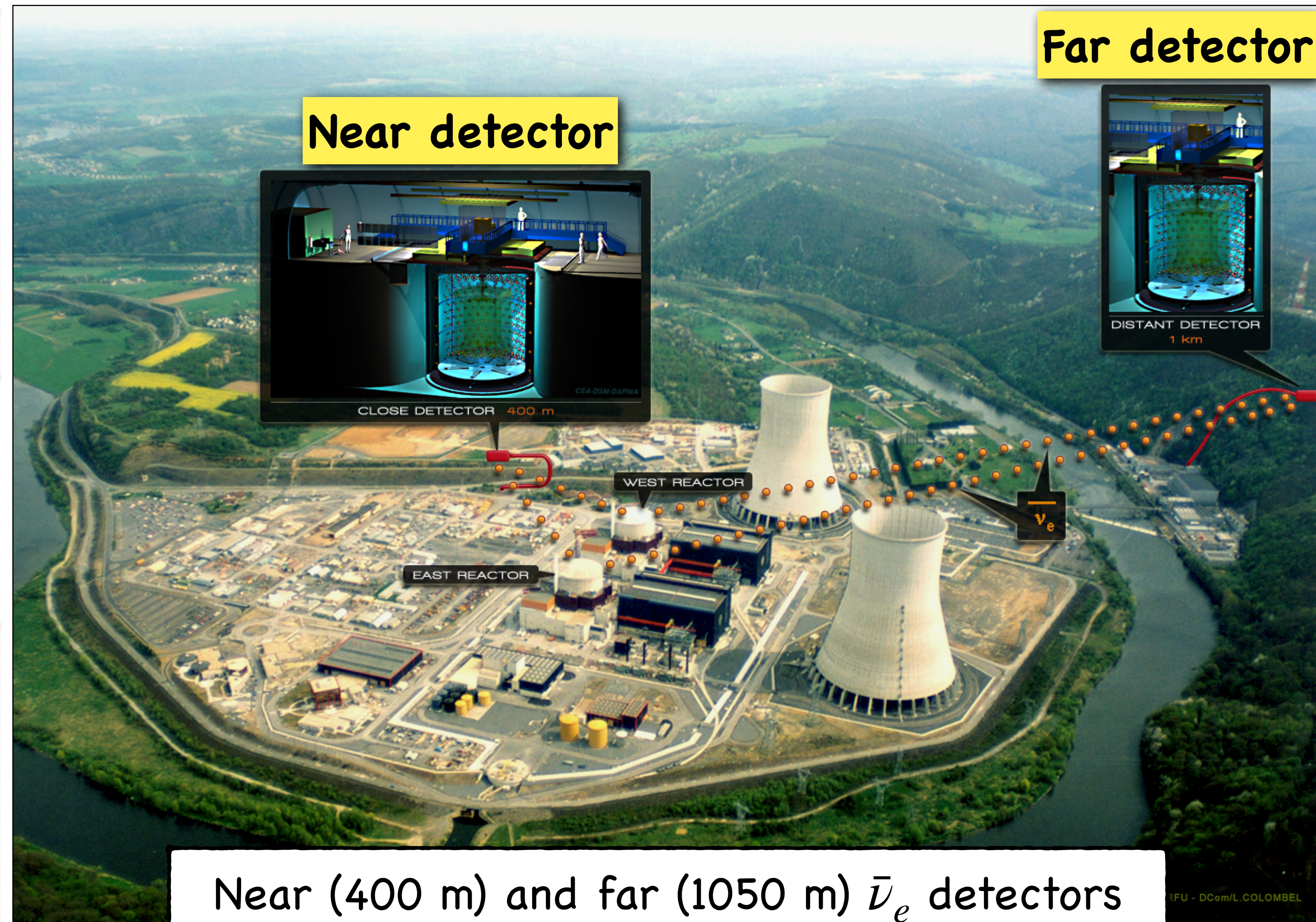
- neutron-rich,
- undergo β^- decay, and
- generate $\bar{\nu}_e$.

$\sim 6 \beta^-$ decays per fission.

Large scintillator detectors use
the Inverse Beta Decay reaction



to detect reactors' $\bar{\nu}_e$.

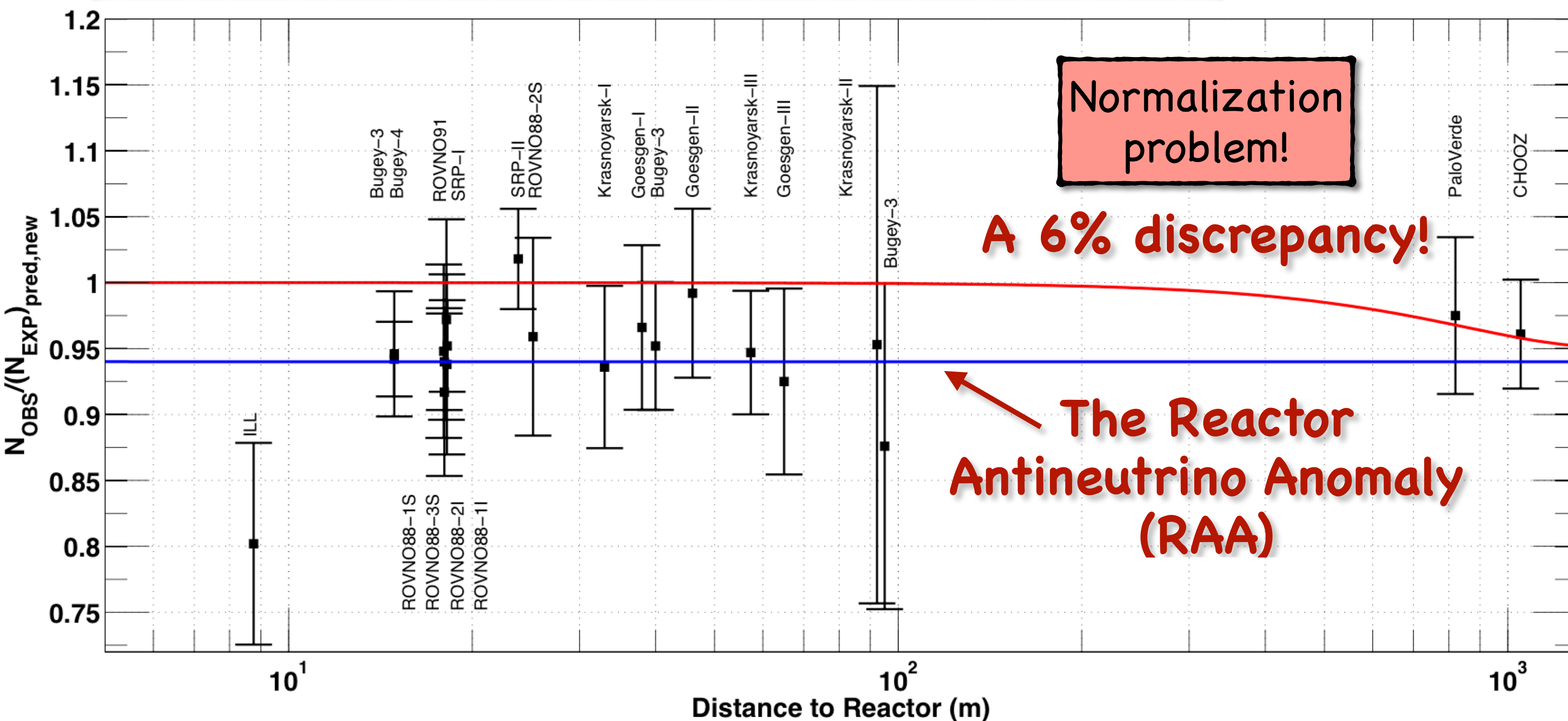


Near (400 m) and far (1050 m) $\bar{\nu}_e$ detectors
placed at the Chooz nuclear power plant.

An anomaly!

Measurements of reactors' $\bar{\nu}_e$ at close distances (near baseline) showed a deficit in the detected $\bar{\nu}_e$ flux compared with predictions.

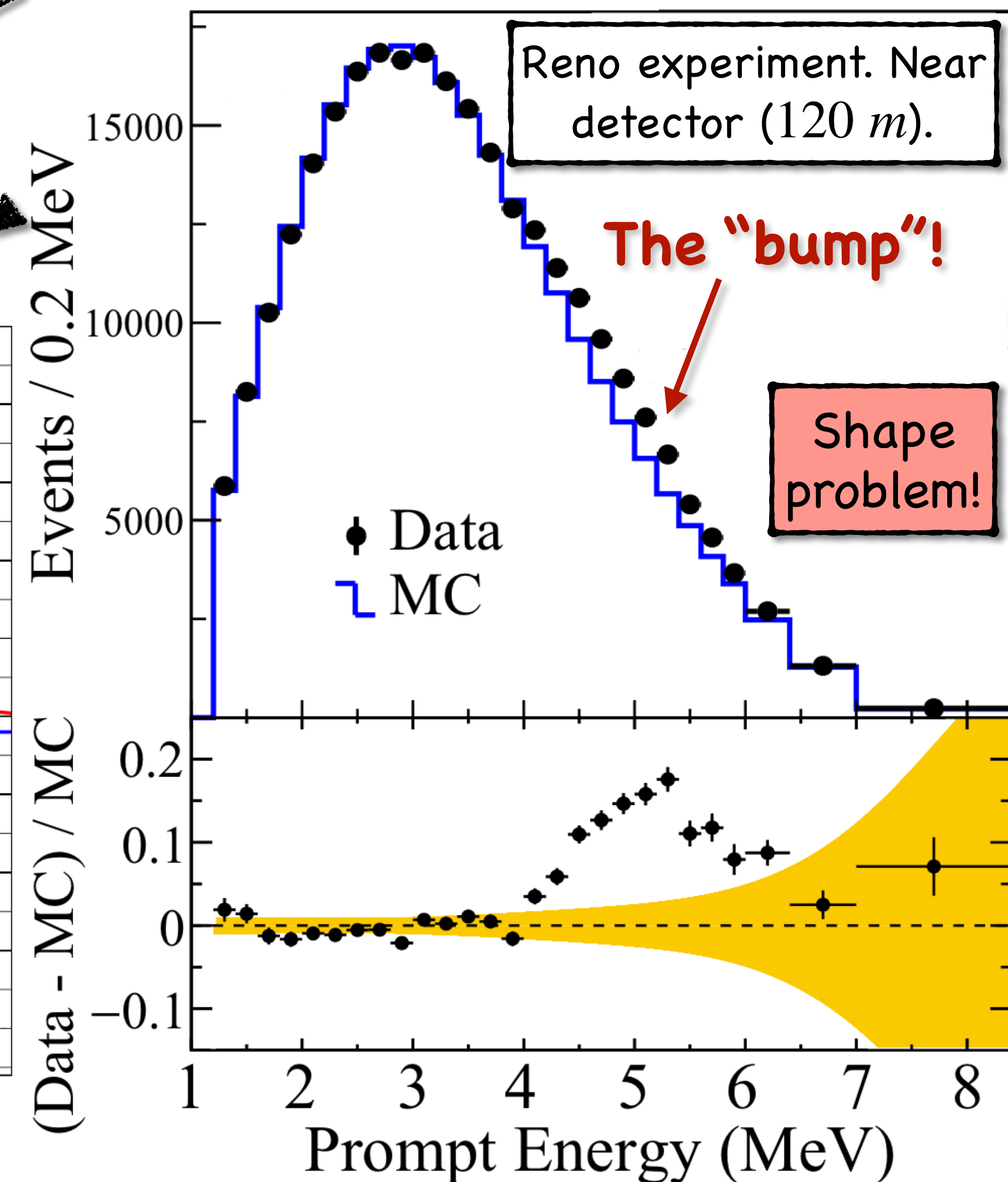
Comparison of flux ratios to theoretical calculations taking into account oscillations of 3 (red line) and 4 (blue line) ν flavors.



Mention et al., PRD **83**, 073006 (2011)

Another problem!

After renormalization, reactors' $\bar{\nu}_e$ energy spectra shapes do not coincide with the predicted spectra everywhere.



Choi et al., PRL **116**, 211801 (2016)

Possible sources of the RAA and the bump

Possible cause explored by the e-shape collaboration!

Incomplete nuclear models and inaccurate relevant nuclear data use for the prediction of $\bar{\nu}_e$ spectra.

Possible solution?

Measure accurate β^- decay spectra of reactors' fuel fission products to calculate reliable $\bar{\nu}_e$ spectra predictions.

How to calculate predictions of reactor $\bar{\nu}_e$ spectra?

Alternative method

The Summation (SM) method (ab initio method). A reactor's $\bar{\nu}_e$ spectrum is constructed from the **sum of all of its contributing β^- ($\bar{\nu}_e$) spectra**.

King & Perkins, PR 112, 963 (1958)

$$S_k = \sum_i A_{k,i} S_i = \sum_{i,b} A_{k,i} f_{i,b} S_{i,b}$$

- S_k : aggregate β^- spectrum of k reactor's fissile isotope.
- $A_{k,i}$: i daughter **isotope activity**.
- $f_{i,b}$: β **feeding** to the b level β branch.
- $S_{i,b}$: b level β **branch β^- spectrum** (S_i).

Vogel et al., PRC 24, 1543 (1981)

**TAGS β
feedings**

TAGS Technique

HPGe detectors facilitate measuring individual γ -rays.

But!

🔥 Pandemonium Effect 🔥

Due to HPGe detectors' low efficiency for low intensity and high-energy γ -rays, β feedings to low-energy levels are **overestimated** because γ -transitions information is lost.

Hardy et al., Phys. Lett. B 71-2, 307 (1977)

The Total Absorption Gamma Spectroscopy (TAGS) technique

TAGS use high efficiency detectors to solve the Pandemonium. Provides better β feedings.

Possible problems with **High Resolution Spectroscopy (HPGe)**!

Real situation

ZX_N

β

Pandemonium effect

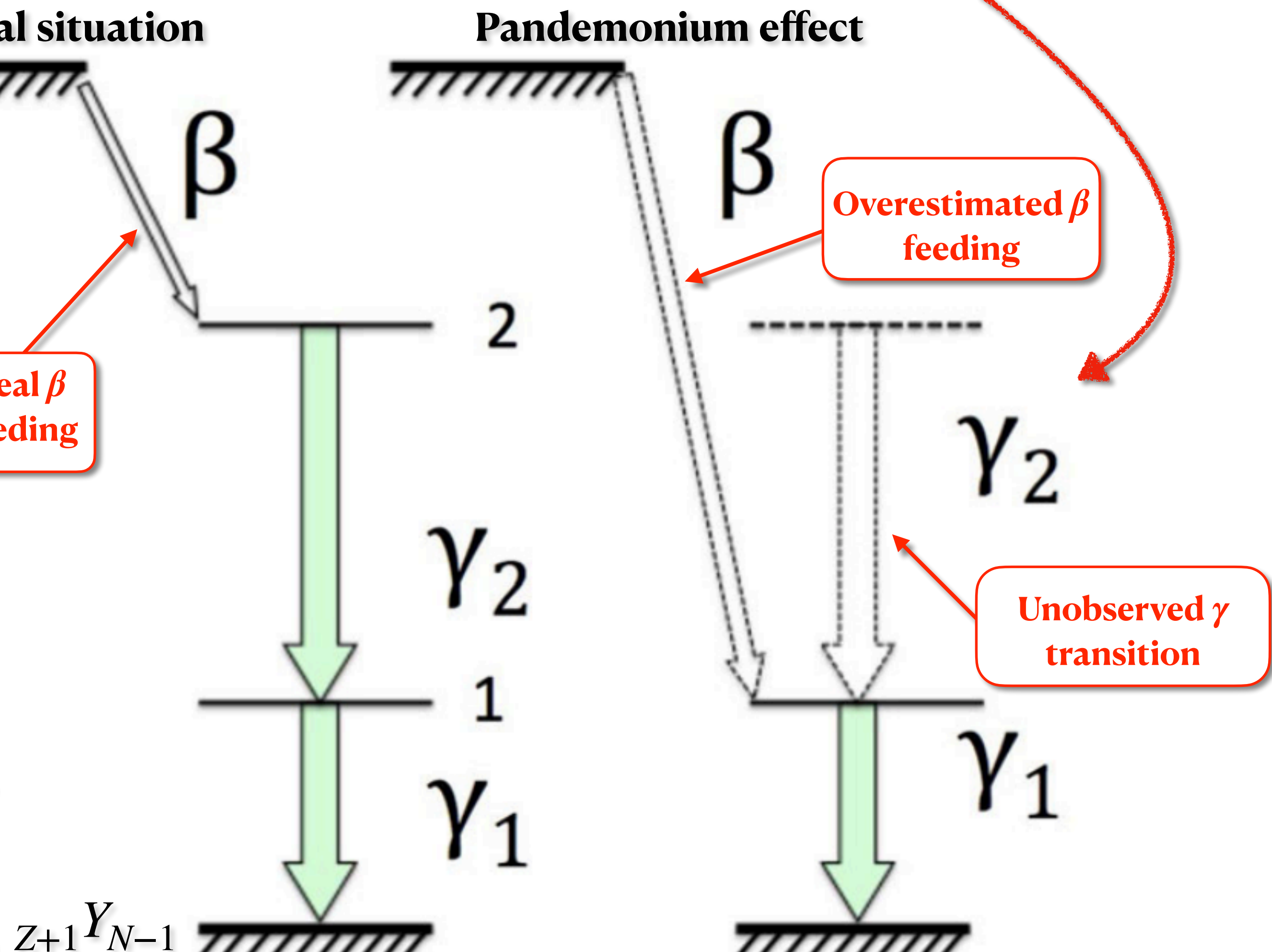
β

Overestimated β feeding

Real β feeding

Unobserved γ transition

$Z+1Y_{N-1}$



Improved β^- spectra shapes

Shape Correction Factors

Shape of β^- decay spectra

Different models of shape correction factors for β^- spectra can be tested to reproduce the experimental data.

$$S_{i,b}(W) \propto \eta W(W_0 - W)^2 F_0(Z, W) \textcolor{red}{C}(Z, W) \textcolor{blue}{K}(Z, M, W_0, W)$$

- $\eta W(W_0 - W)^2$: Statistical factor.
 - $F_0(Z, W)$: Coulomb Fermi function.
 - $\textcolor{red}{C}(Z, W)$: Nuclear shape factor.
 - $\textcolor{blue}{K}(Z, M, W_0, W)$: Other shape correction factors.
- Standard shape

$$W = \frac{E_\beta}{m_e c^2} + 1 \text{ \& } \eta = \sqrt{W^2 - 1}$$

Hayen et al. shape correction factors:

- $\textcolor{blue}{L}_0(Z, W)$: Finite size of the nucleus.
- $\textcolor{blue}{R}(W_0, W)$: Radiative correction.
- $\textcolor{blue}{S}(Z, W)$: Atomic screening.
- $\textcolor{blue}{X}(W)$: Atomic exchange.
- $\textcolor{blue}{r}(Z, W)$: Atomic mismatch.
- $\textcolor{blue}{R}_N(M, W_0, W)$: Nuclear recoil.
- $\textcolor{blue}{Q}(Z, M, W)$: Distorted Coulomb Potential due to Recoil.

Hayen et al., RMP **90**, 015008 (2018)

Huber shape correction factors:

- $\textcolor{blue}{L}_0(Z, W)$: Finite size of the nucleus.
- $\textcolor{blue}{C}_w(Z, W)$: Weak interaction finite size of the nucleus.
- $\textcolor{blue}{G}_\beta(Z, W)$: Radiative correction.
- $\textcolor{blue}{S}_H(Z, W)$: Atomic screening.
- $\textcolor{blue}{H}_{wm}(W)$: Weak magnetism.

Huber, PRC **84**, 024617 (2011)

Nuclear shape factor:

- For allowed transitions, $\textcolor{red}{C}(Z, W) \approx 1$.
- For forbidden transitions, the factors **depend on W** . Require the calculation of matrix elements.

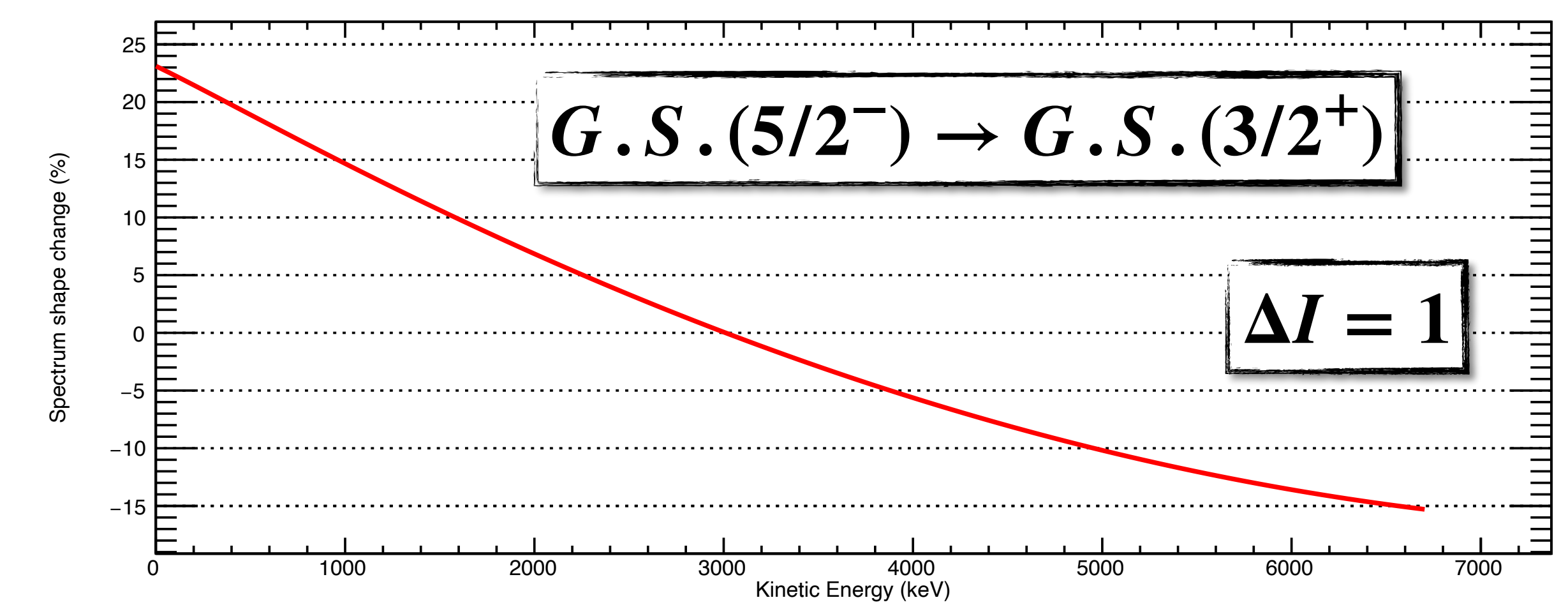
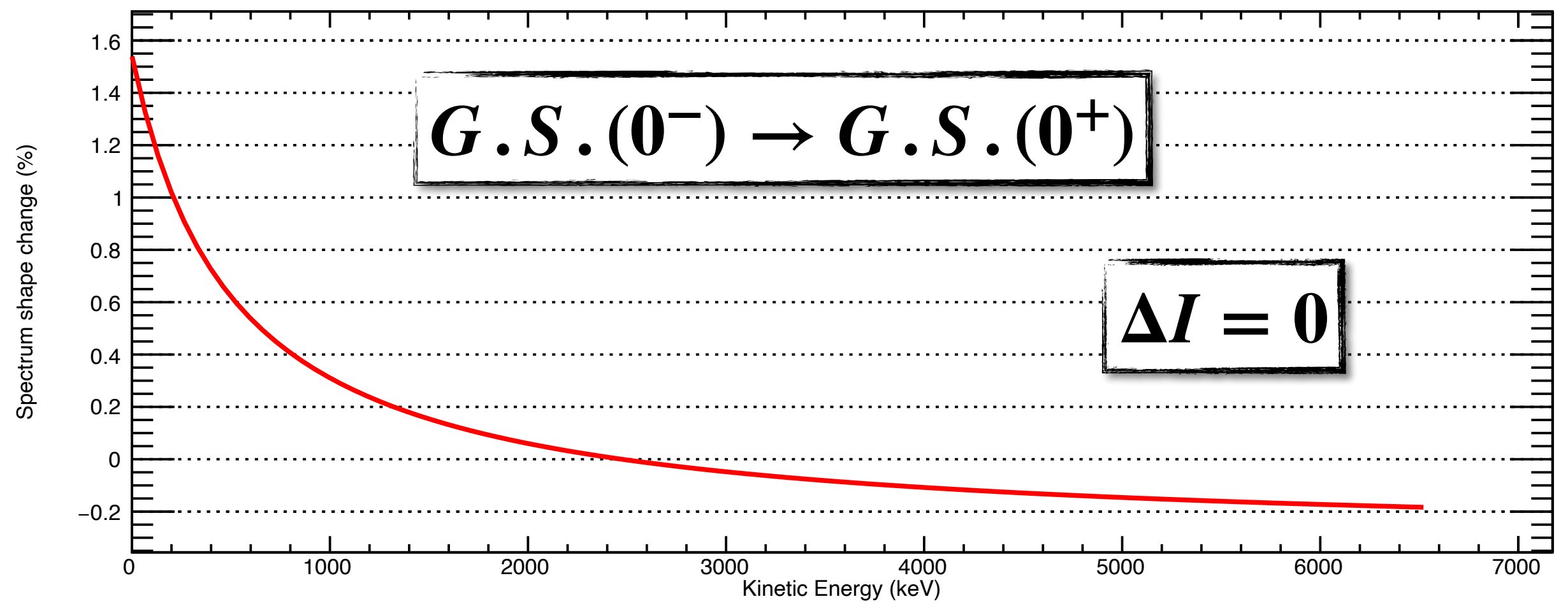
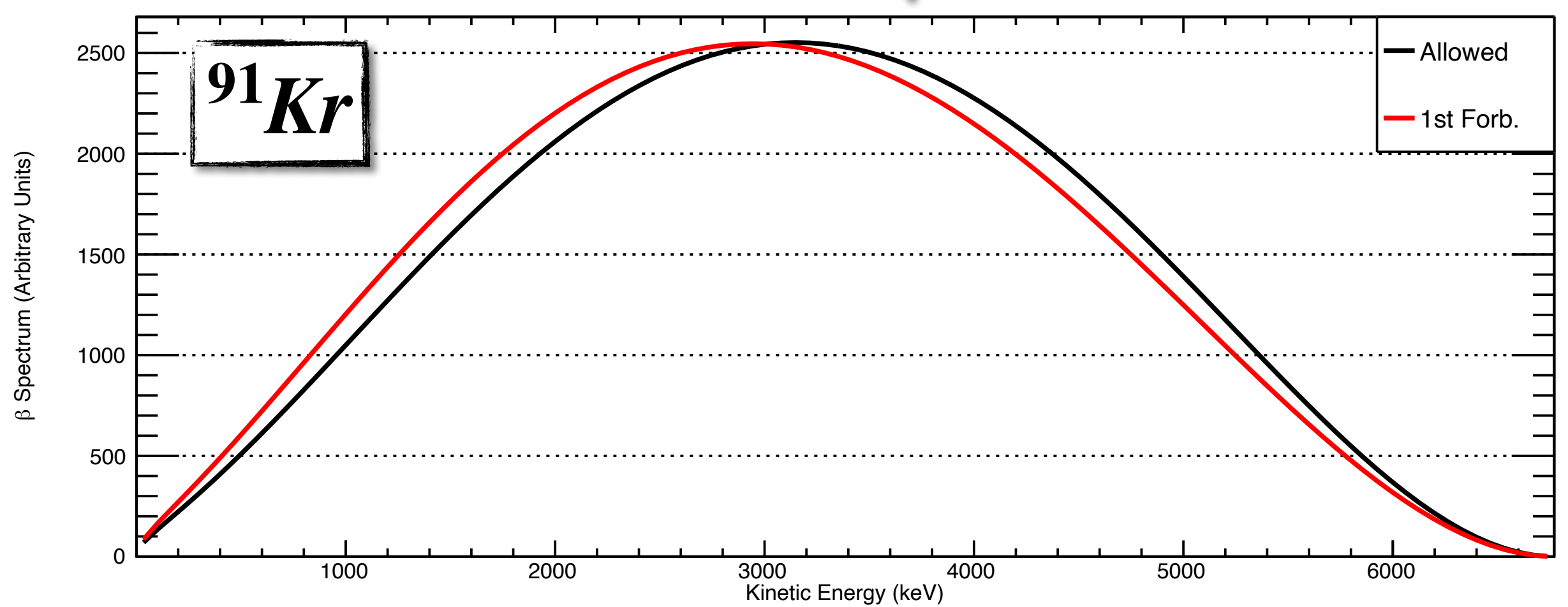
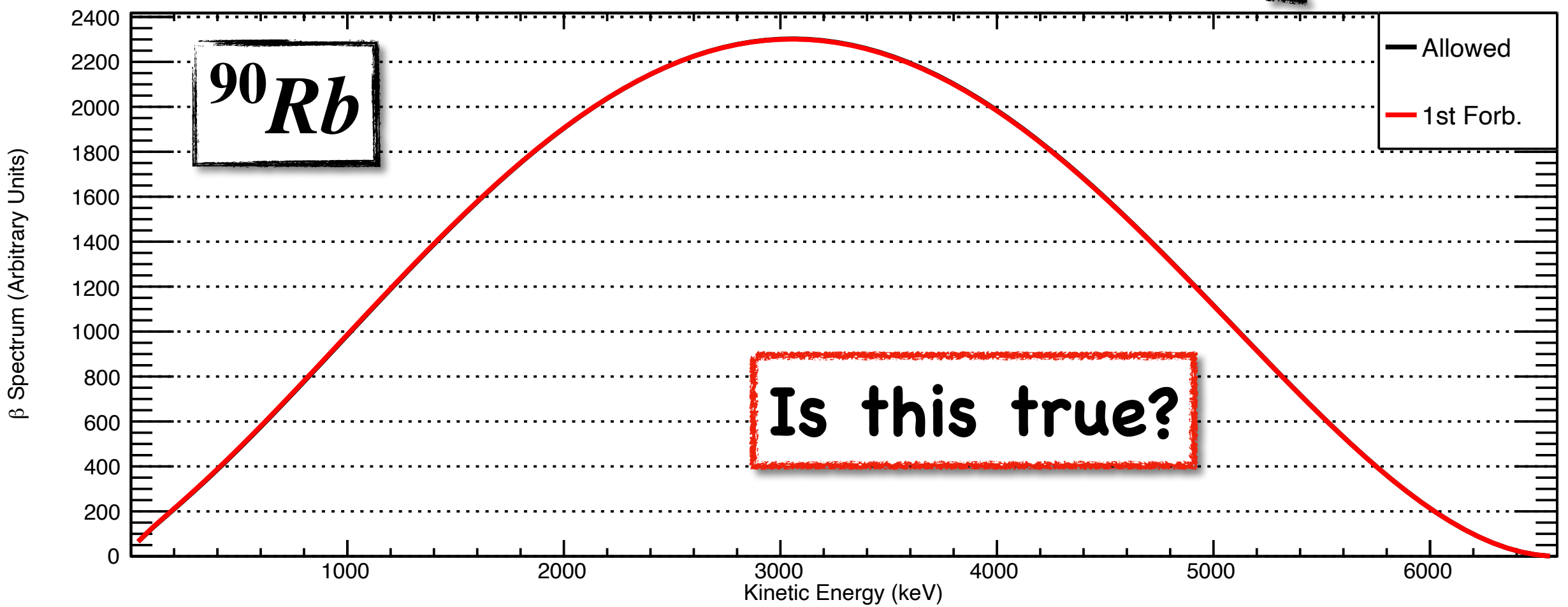
Hayen et al., PRC **100**, 054323 (2019).

Nuclear shape factors
calculated for relevant
1st forbidden transitions
with $g_A = 0.70$.

Hayen et al., PRC 100, 054323 (2019)

Nuclear shape factors

$$C(Z_d, W) = \sum_{k_e, k_\nu, K} \lambda_{k_e} \left(M_K^2(k_e, k_\nu) + m_K^2(k_e, k_\nu) - \frac{2\mu_{k_e} \gamma_{k_e}}{k_e W} M_K(k_e, k_\nu) m_K(k_e, k_\nu) \right)$$



Precedents

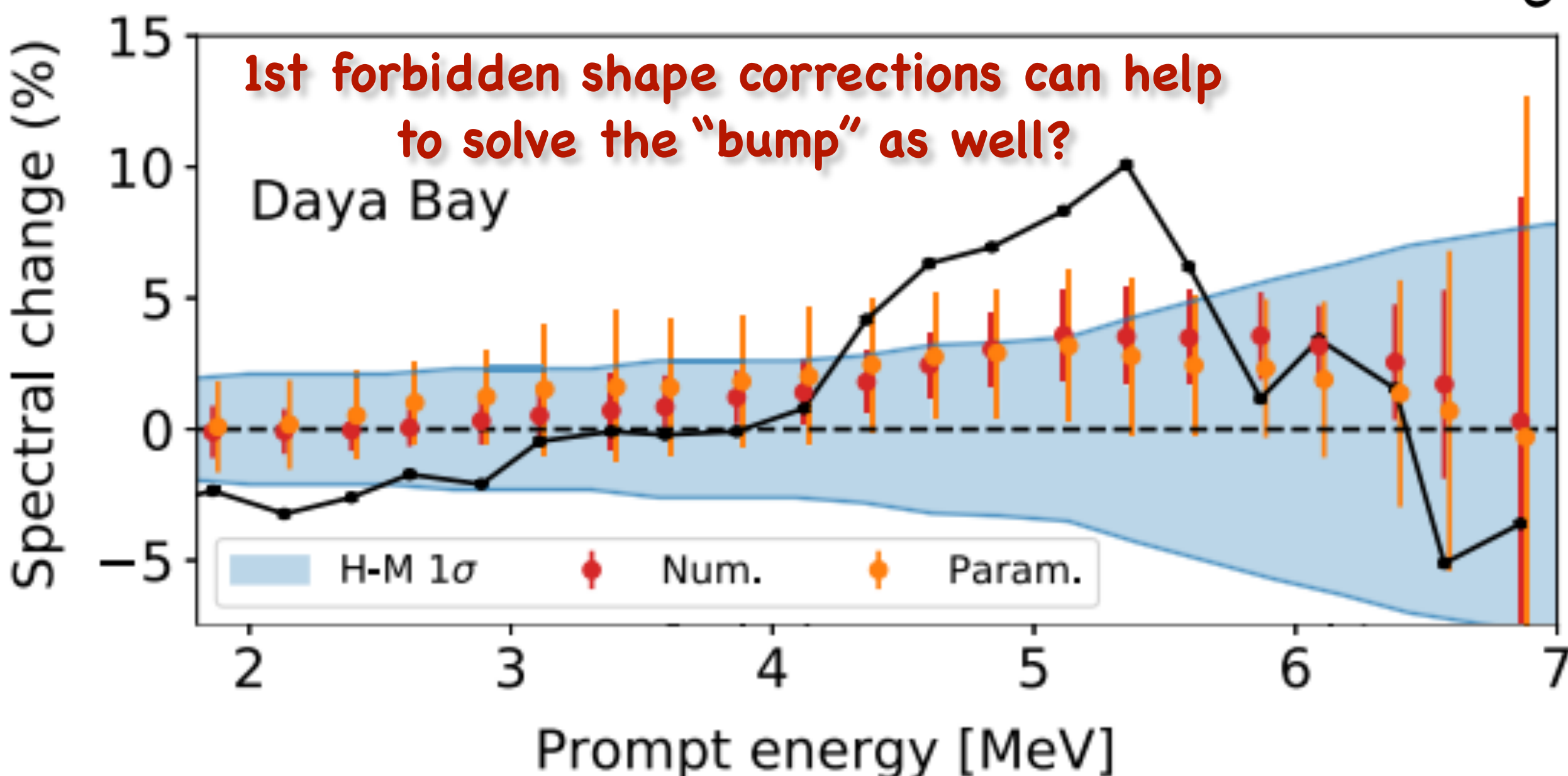
Fixing Reactors $\bar{\nu}_e$ spectra

Summation calculations with TAGS data have **partially solved reactors' $\bar{\nu}_e$ flux discrepancies** respect to previous predictions.

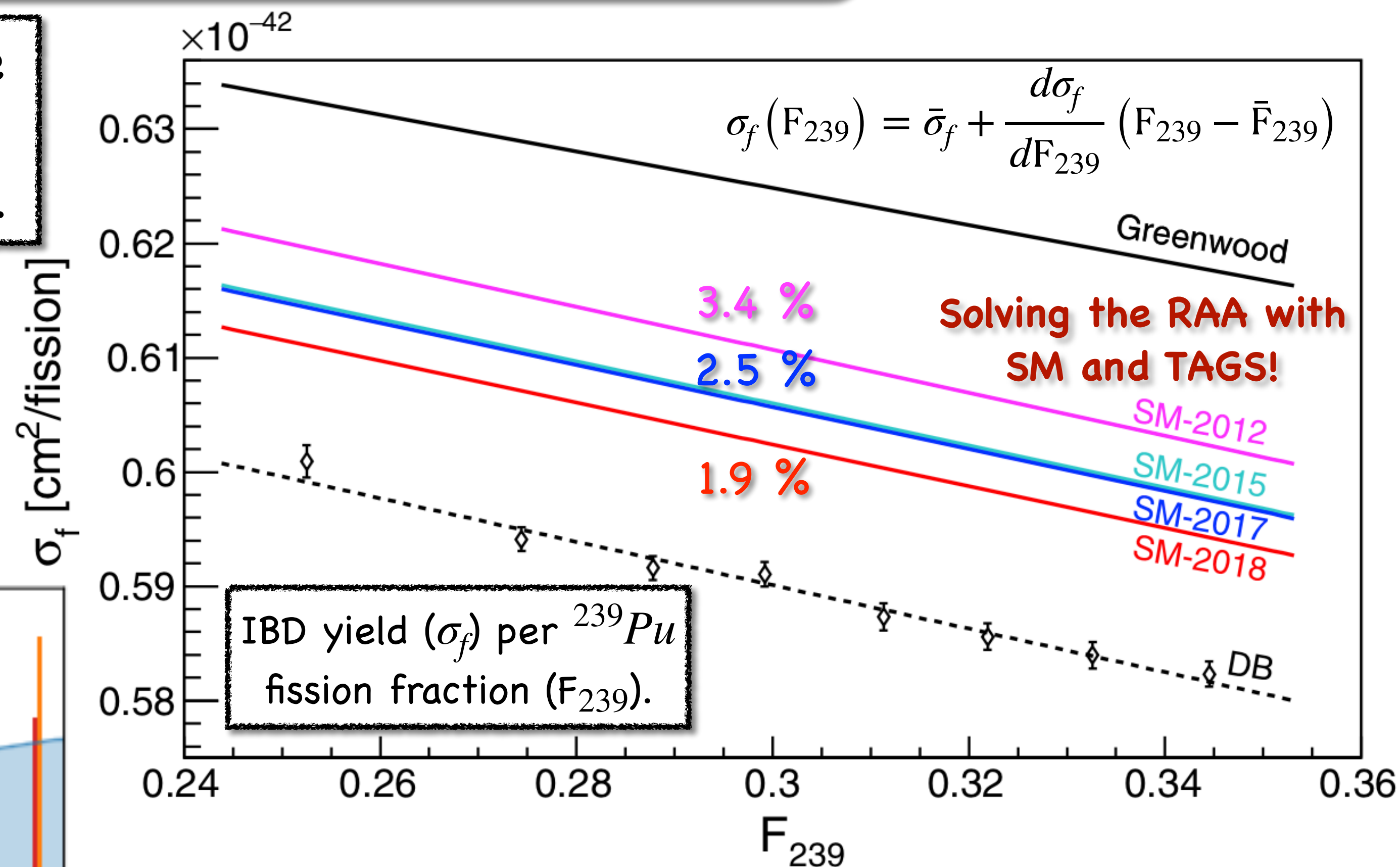
TAGS achievement

$\bar{\nu}_e$ flux difference reduced up to **1.9%** with subsequent TAGS data!

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



Hayen et al., PRC **100**, 054323 (2019)

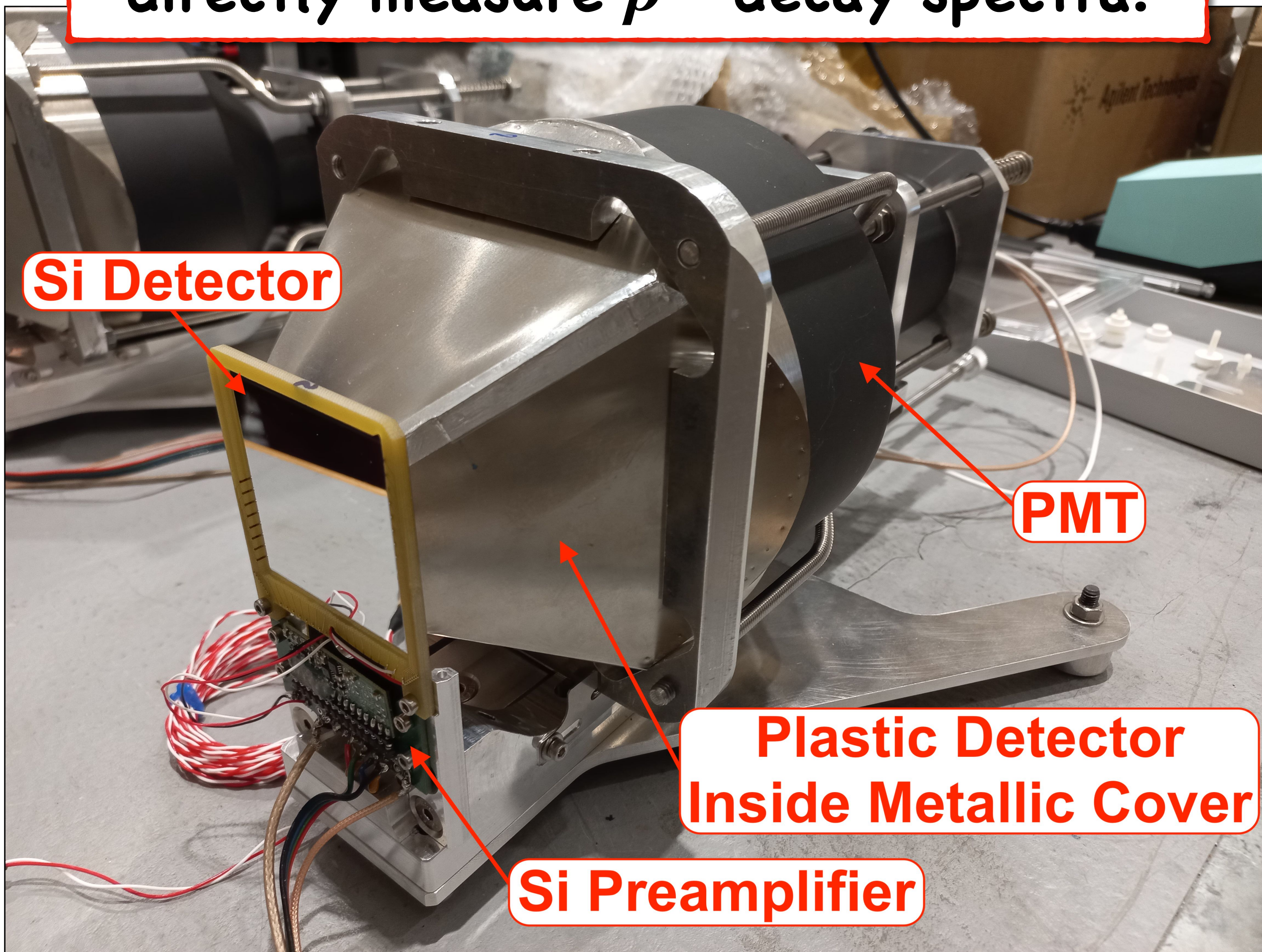


Theory expectations

β^- decay shape correction factors accounting for 1st forbidden transitions can be **essential** to solve $\bar{\nu}_e$ anomalies in reactors.

Hayes et al., PRL **112**, 202501 (2014)

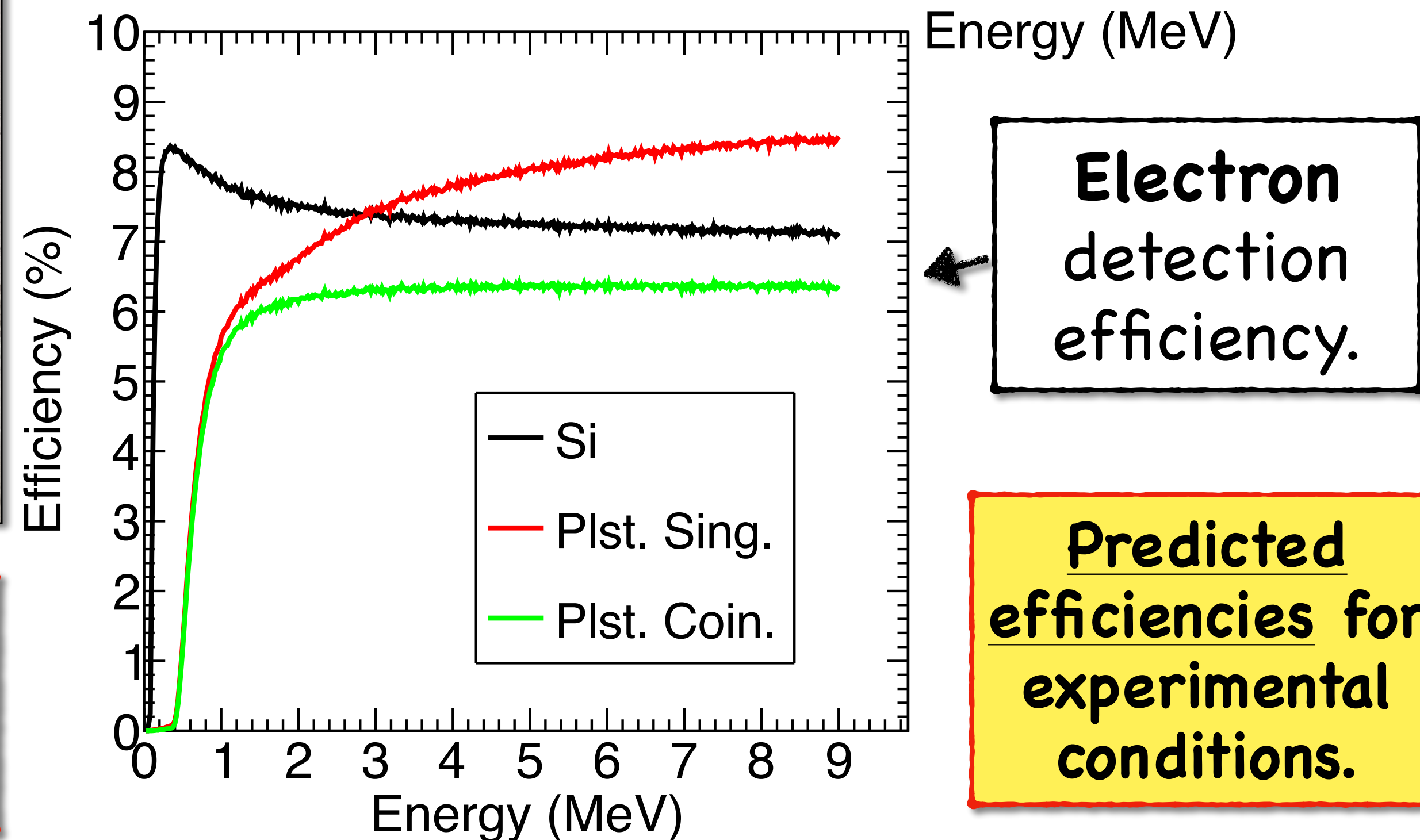
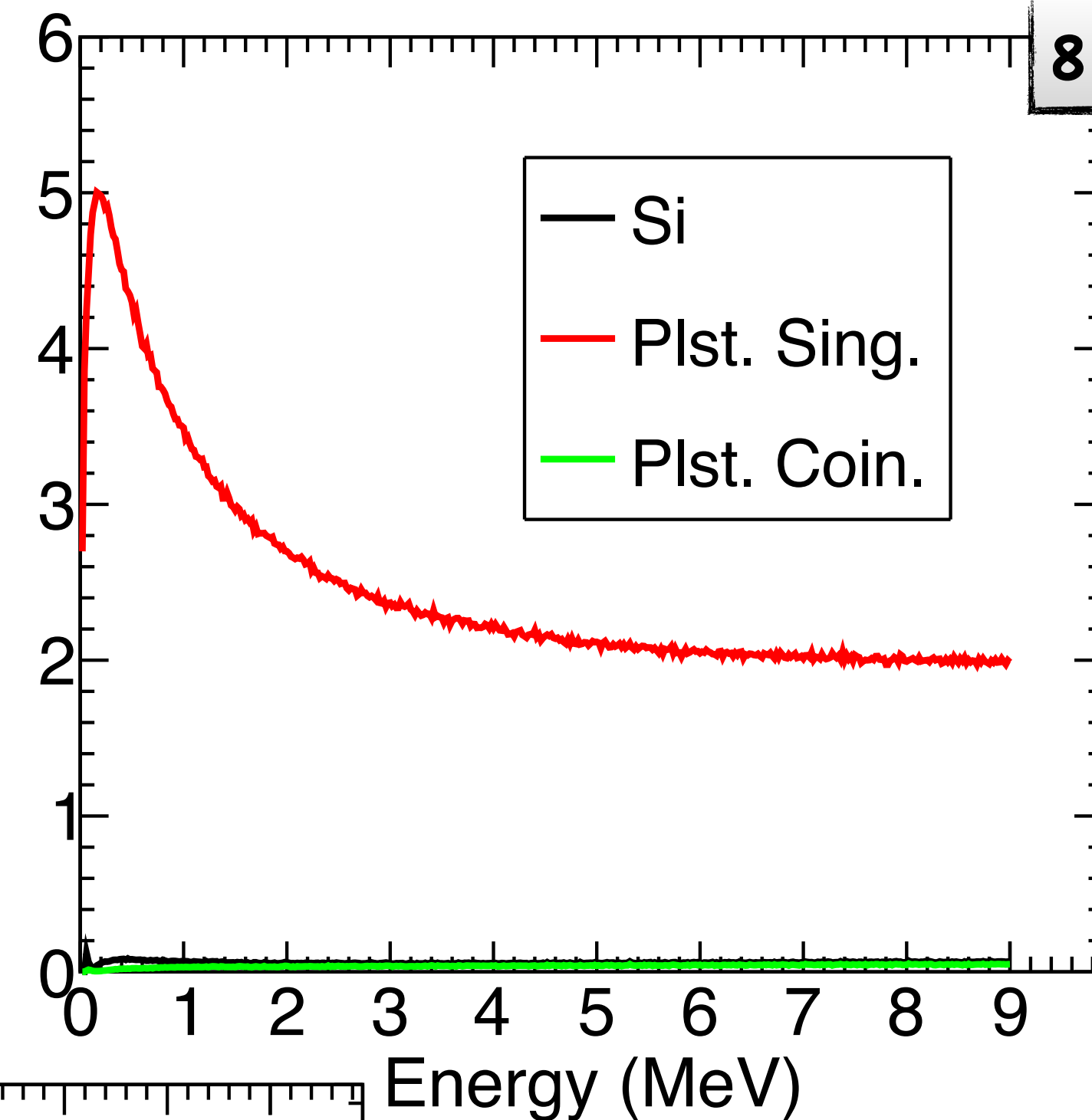
The $\Delta E - E$ electron detectors directly measure β^- decay spectra.



e-shape detectors

γ -ray
detection
efficiency.

Efficiency (%)



**Electron
detection
efficiency.**

Plastic-Si coincidence spectra are dominated by electrons, as γ -rays are rejected due to the small thickness (0.527 mm) of the Si detector.

**Predicted
efficiencies for
experimental
conditions.**

IGISOL at JYFL

We need clean radioactive beams composed of the **isotopes of interest** to measure their β^- decay spectra without contaminations.



The IGISOL facility (University of Jyväskylä, Finland) can provide isotopically pure radioactive beams that suit our needs!

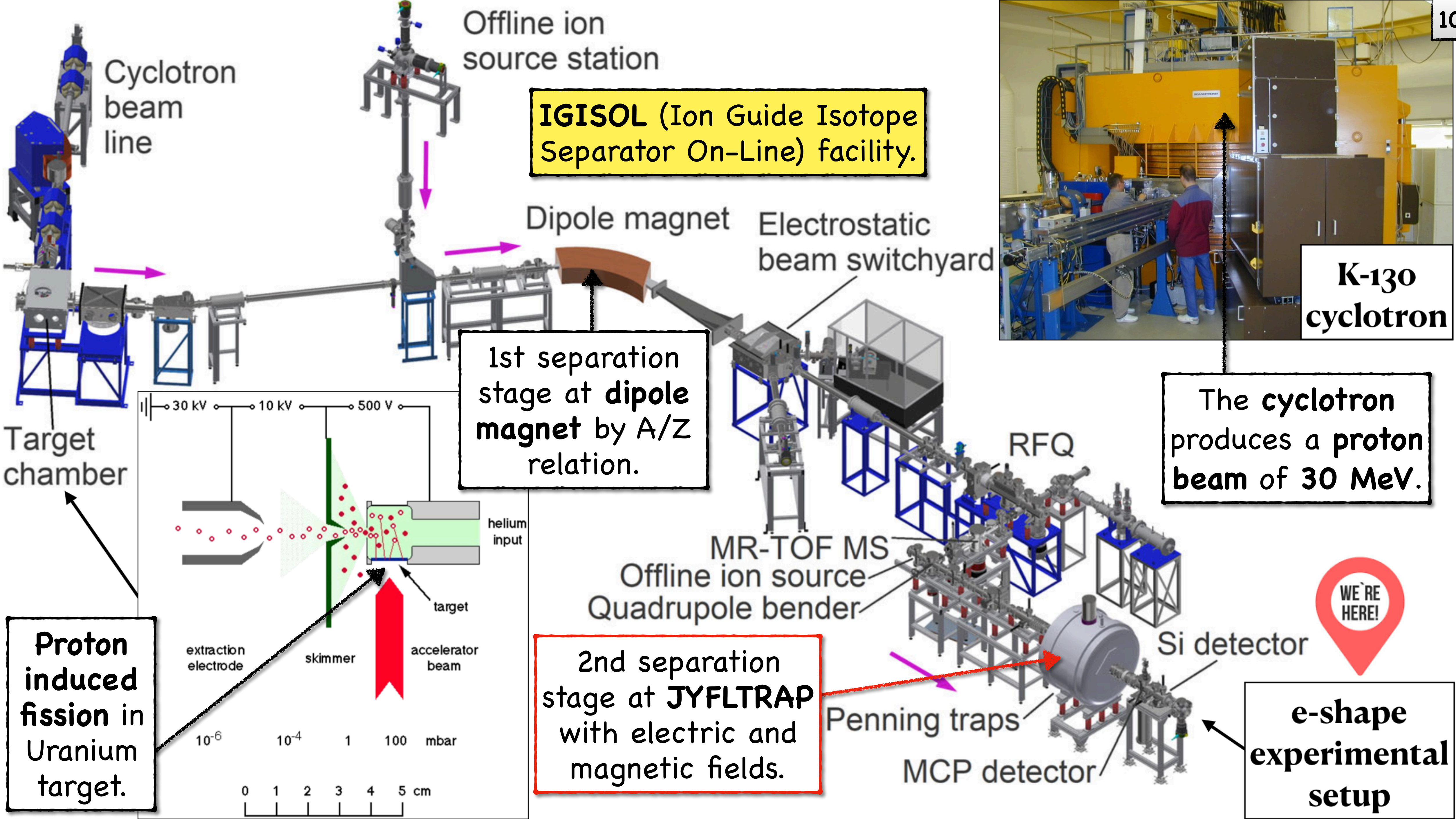
Table of relevant 1st forbidden β^- transitions for solving the RAA and "bump".

Hayen et al., PRC 100, 054323 (2019)

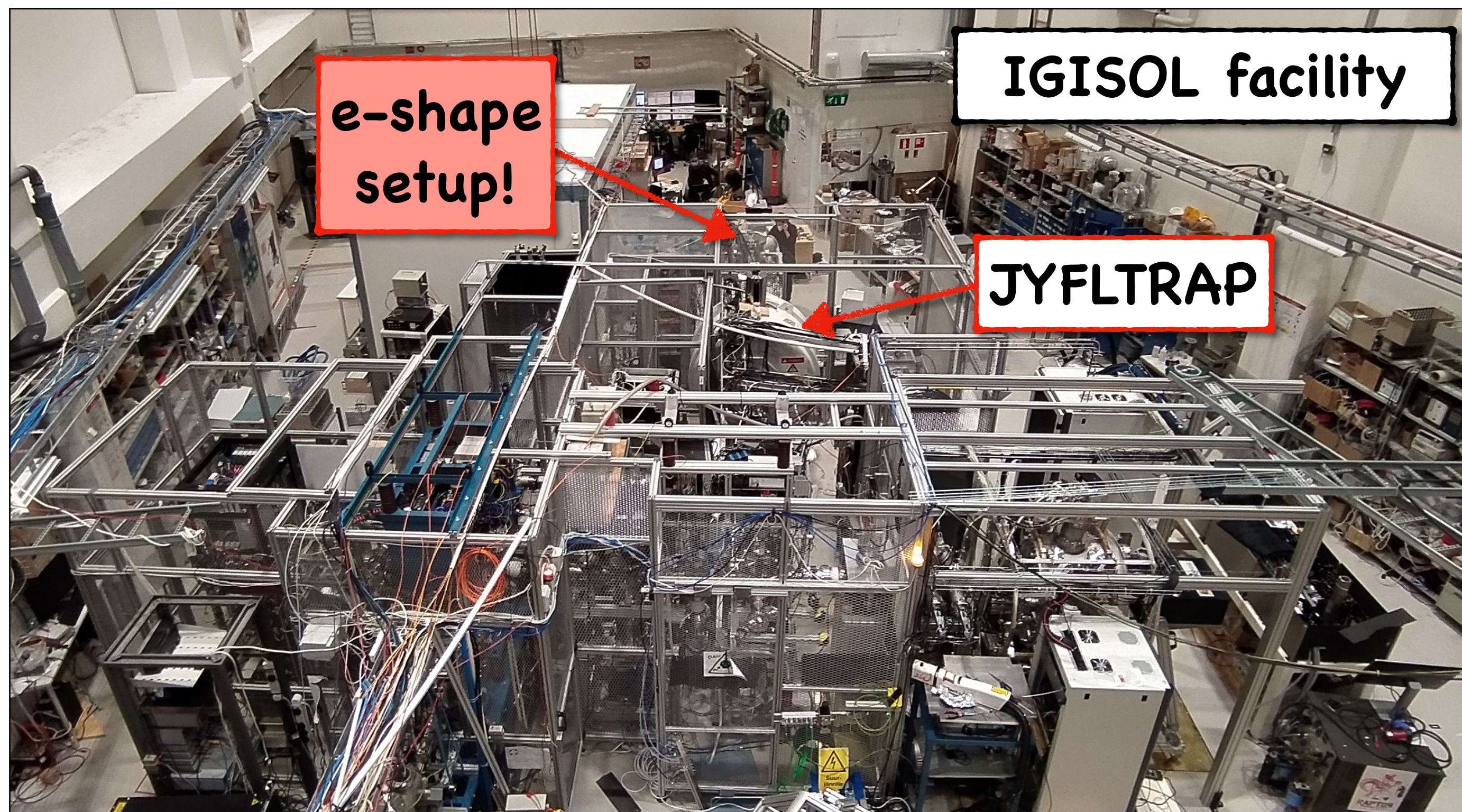
❄️ Quasi-Polar expedition! ❄️



Nuclide	Q_β (MeV)	E_{ex} (MeV)	BR (%)	$J_i^\pi \rightarrow J_f^\pi$	FY (%)	ΔJ
^{89}Br	8.3	0	16	$3/2^- \rightarrow 3/2^+$	1.1	0
^{90}Rb	6.6	0	33	$0^- \rightarrow 0^+$	4.5	0
^{91}Kr	6.8	0.11	18	$5/2^+ \rightarrow 5/2^-$	3.5	0
^{92}Rb	8.1	0	95.2	$0^- \rightarrow 0^+$	4.8	0
^{93}Rb	7.5	0	35	$5/2^- \rightarrow 5/2^+$	3.5	0
^{94}Y	4.9	0.92	39.6	$2^- \rightarrow 2^+$	6.5	0
$^{95}\text{Rb}^a$	9.3	0.68	5.9	$5/2^- \rightarrow 5/2^+$	1.7	0
^{95}Sr	6.1	0	56	$1/2^+ \rightarrow 1/2^-$	5.3	0
^{96}Y	7.1	0	95.5	$0^- \rightarrow 0^+$	6.0	0
^{97}Y	6.8	0	40	$1/2^- \rightarrow 1/2^+$	4.9	0
^{98}Y	9.0	0	18	$0^- \rightarrow 0^+$	1.9	0
^{133}Sn	8.0	0	85	$7/2^- \rightarrow 7/2^+$	0.1	0
^{135}Te	5.9	0	62	$(7/2^-) \rightarrow 7/2^+$	3.3	0
^{135}Sb	8.1	0	47	$(7/2^+) \rightarrow (7/2^-)$	0.1	0
^{136m}I	7.5	1.89	71	$(6^-) \rightarrow 6^+$	1.3	0
^{136m}I	7.5	2.26	13.4	$(6^-) \rightarrow 6^+$	1.3	0
^{137}I	6.0	0	45.2	$7/2^+ \rightarrow 7/2^-$	3.1	0
^{142}Cs	7.3	0	56	$0^- \rightarrow 0^+$	2.7	0
^{86}Br	7.3	0	15	$(1^-) \rightarrow 0^+$	1.6	1
^{86}Br	7.3	1.6	13	$(1^-) \rightarrow 2^+$	1.6	1
^{87}Se	7.5	0	32	$3/2^+ \rightarrow 5/2^-$	0.8	1
^{89}Br	8.3	0.03	16	$3/2^- \rightarrow 5/2^+$	1.1	1
^{91}Kr	6.8	0	9	$5/2^+ \rightarrow 3/2^-$	3.4	1
$^{95}\text{Rb}^a$	9.3	0.56	6.0	$5/2^- \rightarrow (7/2^+)$	1.7	1
^{95}Rb	9.3	0.68	5.9	$5/2^- \rightarrow 3/2^+$	1.7	1
^{134m}Sb	8.5	1.69	42	$(7^-) \rightarrow 6^+$	0.8	1
^{134m}Sb	8.5	2.40	54	$(7^-) \rightarrow (6^+)$	0.8	1
^{136}Te	5.1	0	8.7	$0^+ \rightarrow (1^-)$	3.7	1
^{138}I	8.0	0	26	$(1^-) \rightarrow 0^+$	1.5	1
^{140}Xe	4.0	0.08	8.7	$0^+ \rightarrow 1^-$	4.9	1
^{140}Cs	6.2	0	36	$1^- \rightarrow 0^+$	5.7	1
^{143}Cs	6.3	0	25	$3/2^+ \rightarrow 5/2^-$	1.5	1
^{88}Rb	5.3	0	76.5	$2^- \rightarrow 0^+$	3.6	2
^{94}Y	4.9	0	41	$2^- \rightarrow 0^+$	6.5	2
^{95}Rb	9.3	0	0.1	$5/2^- \rightarrow 1/2^+$	1.7	2
^{139}Xe	5.1	0	15	$3/2^- \rightarrow 7/2^+$	5.0	2



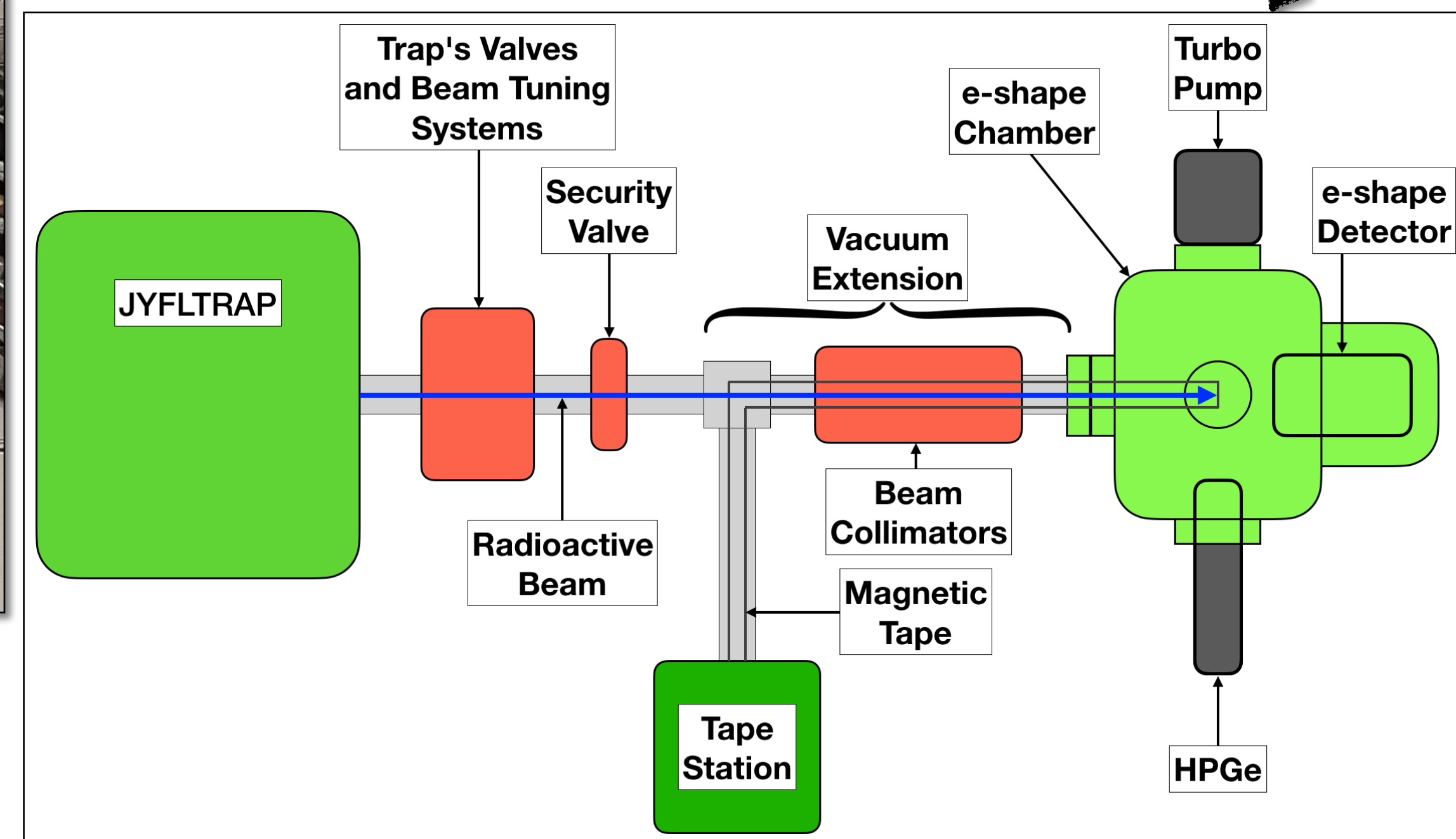
I233 Experiment



The I233 experiment ran for 2 weeks. Jan-Feb 2022.

We measured the β^- spectrum of the ^{92}Rb and ^{142}Cs , among other cases of interest and calibration.

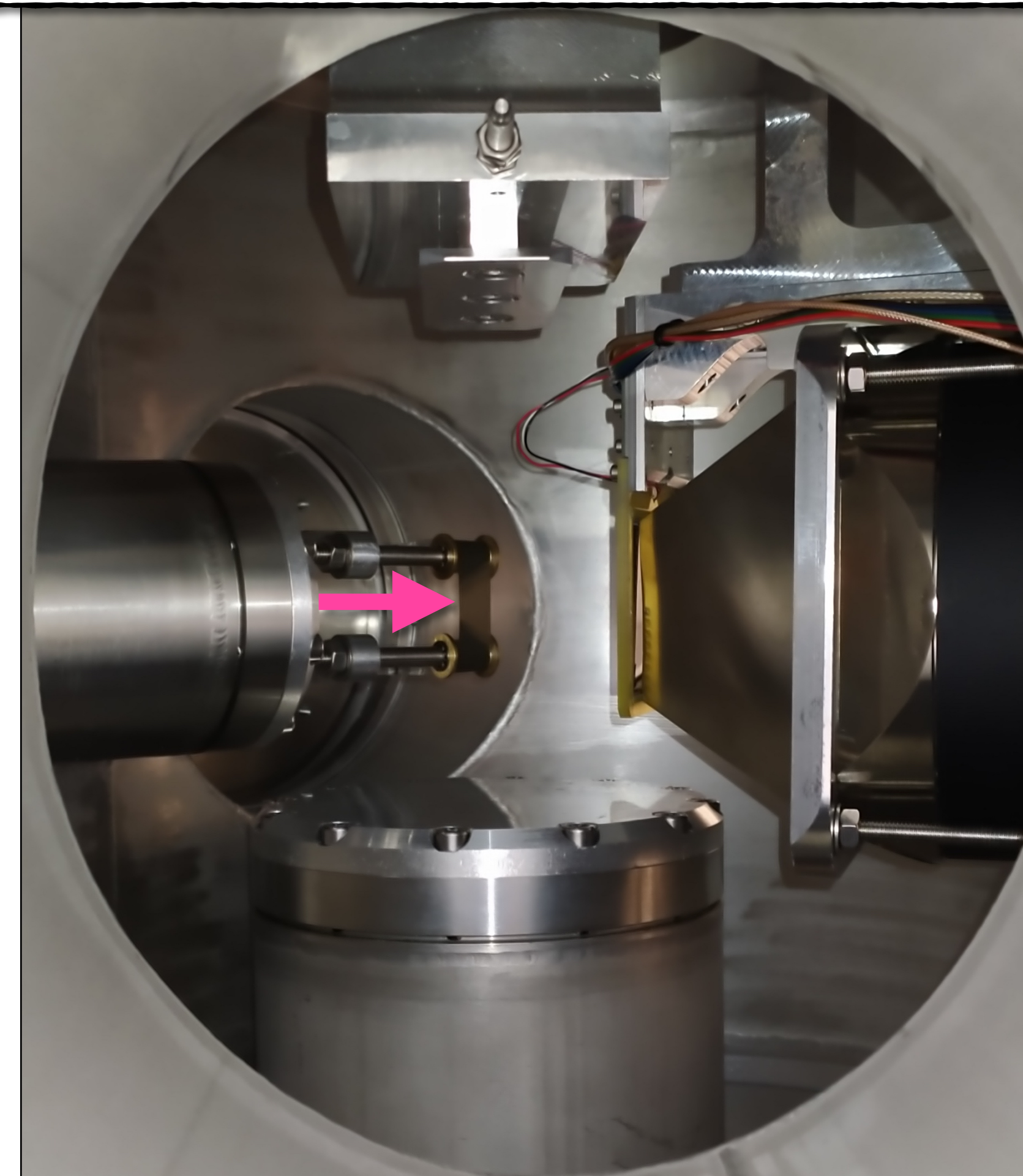
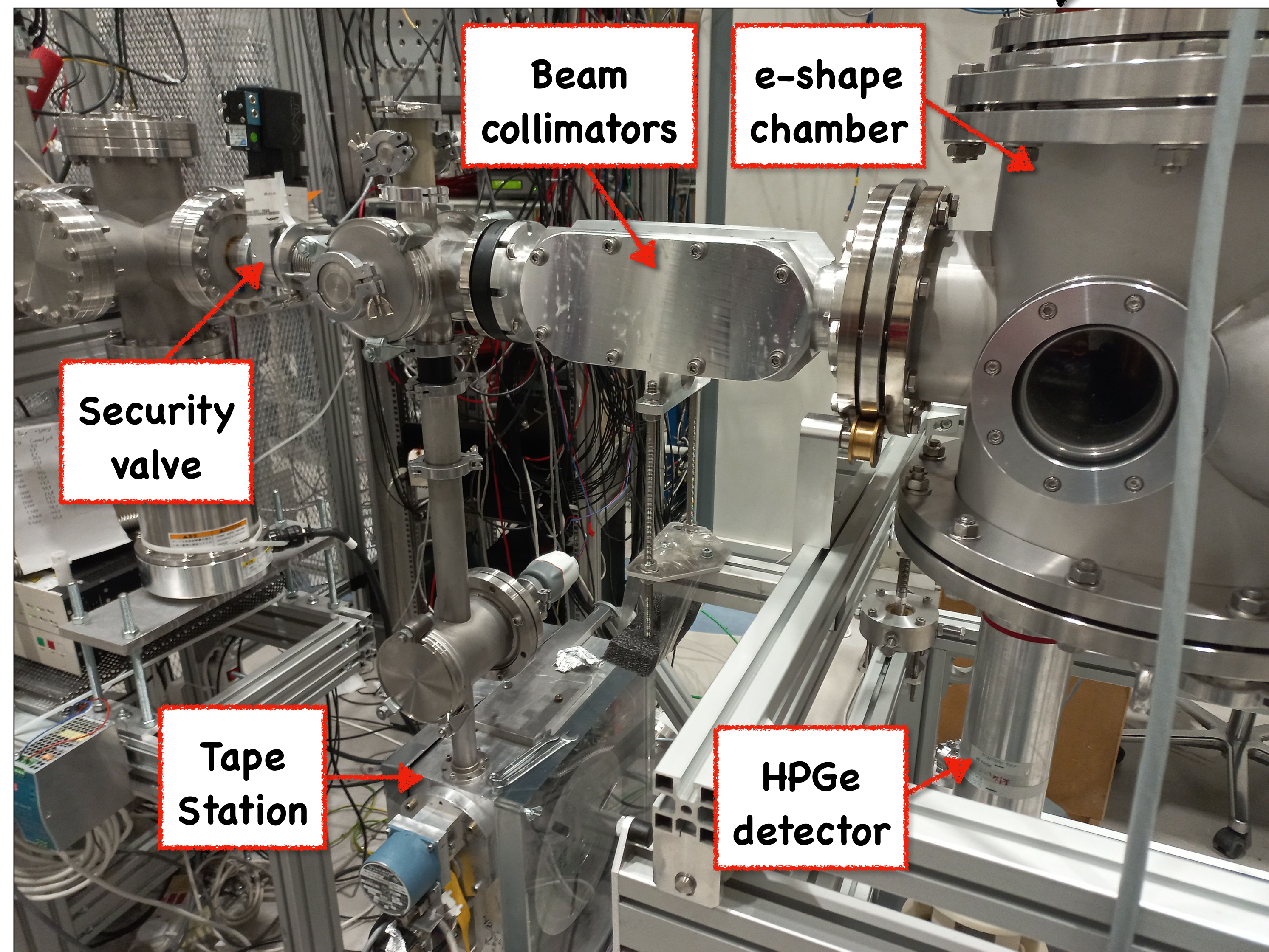
Schematic representation of the e-shape setup.



Lateral view from the right side of the perspective of the radioactive beam.

e-shape setup during the I233 experiment.

Internal view of the e-shape chamber, with one detector installed.



The **radioactive beam** is implanted in a movable magnetic tape inside the chamber.

Tools for
the analysis!

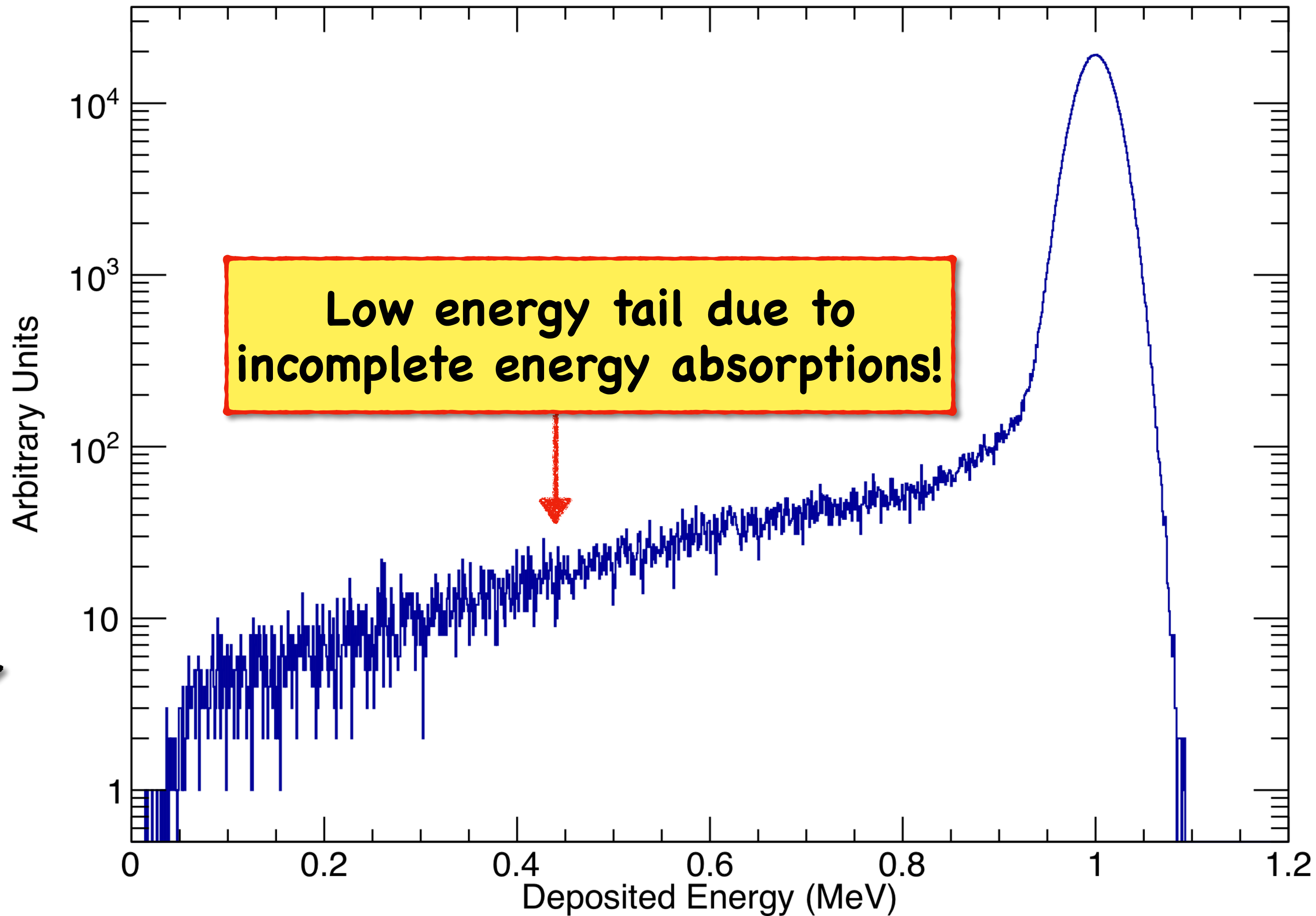
Deconvolution of the Data

Careful!

Measured β^- decay spectra are deformed due to the energy distribution of electrons in the plastics detector!

Example

1 MeV simulated monoenergetic electron spectrum in the plastic detector.



To obtain the original β^- spectrum (o) from the measured β^- spectrum (d), the inverse problem must be solved with an iterative deconvolution algorithm.

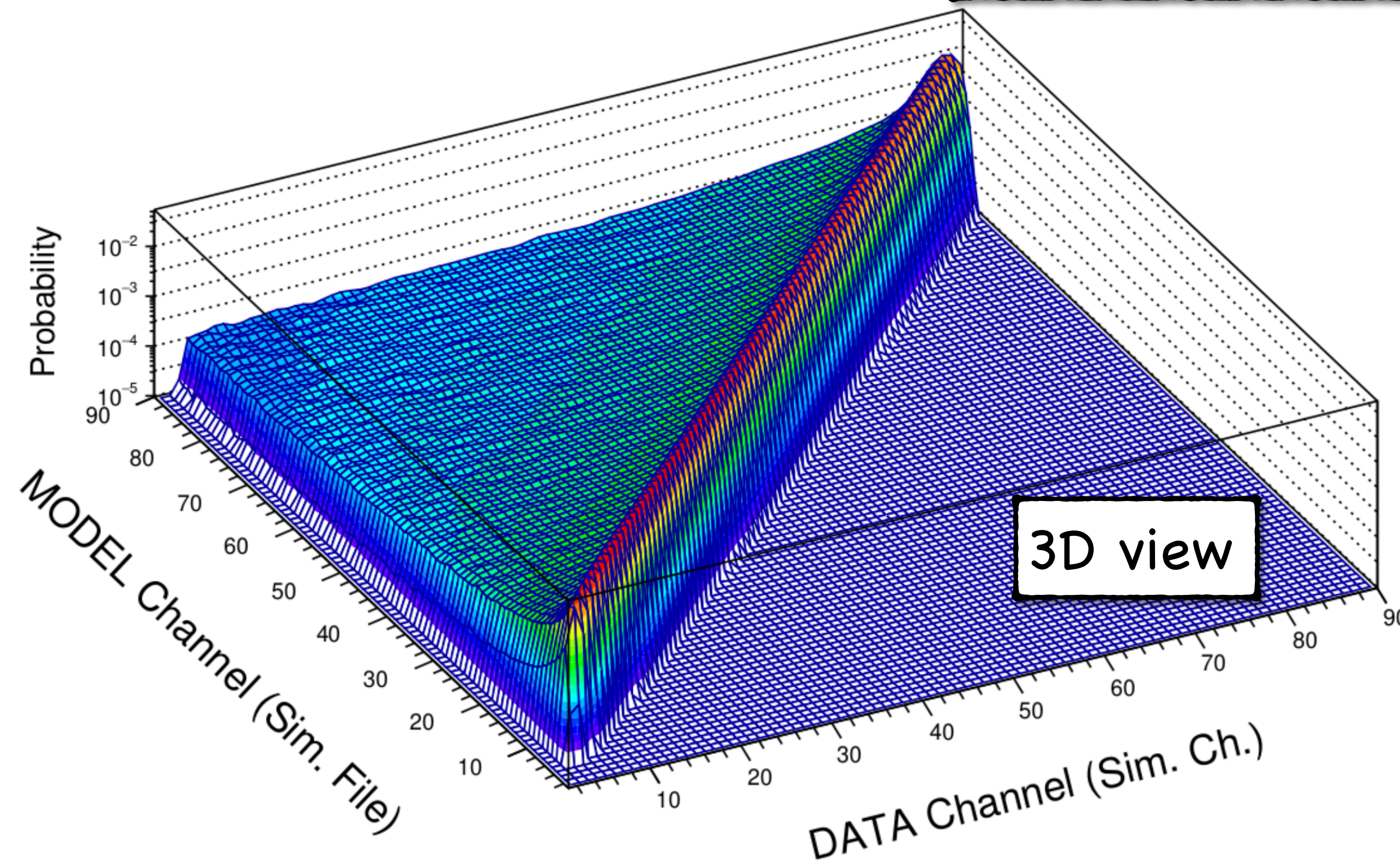
Tain & Cano-Ott, NIMPR A 571, 728 (2007)

The Expectation-Maximization (E-M) deconvolution method was used.

The E-M method is implemented using the Bayes theorem.

$$d_i = \sum_{j=j_{min}}^{j_{max}} \mathcal{R}_{i,j} o_j + C_i$$

- R : Response Matrix of the detector.
- C : Spectrum of contaminations.



$$o_j^{(s+1)} = \frac{o_j^{(s)}}{\sum_{i=i_{min}}^{i_{max}} \mathcal{R}_{i,j}} \sum_{i=i_{min}}^{i_{max}} \frac{\mathcal{R}_{i,j} d_i}{\sum_{k=j_{min}}^{j_{max}} \mathcal{R}_{i,k} o_k^{(s)}}$$

Tain & Cano-Ott, NIMPR A 571, 728 (2007)

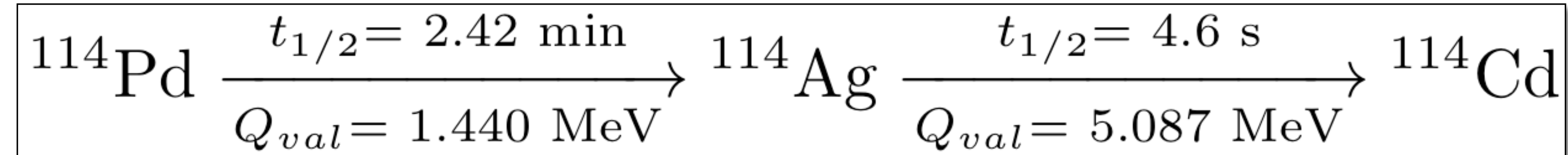
Response Matrix

Plastic coincidence spectra of simulated monoenergetic electron.

Analysis of the Experiment

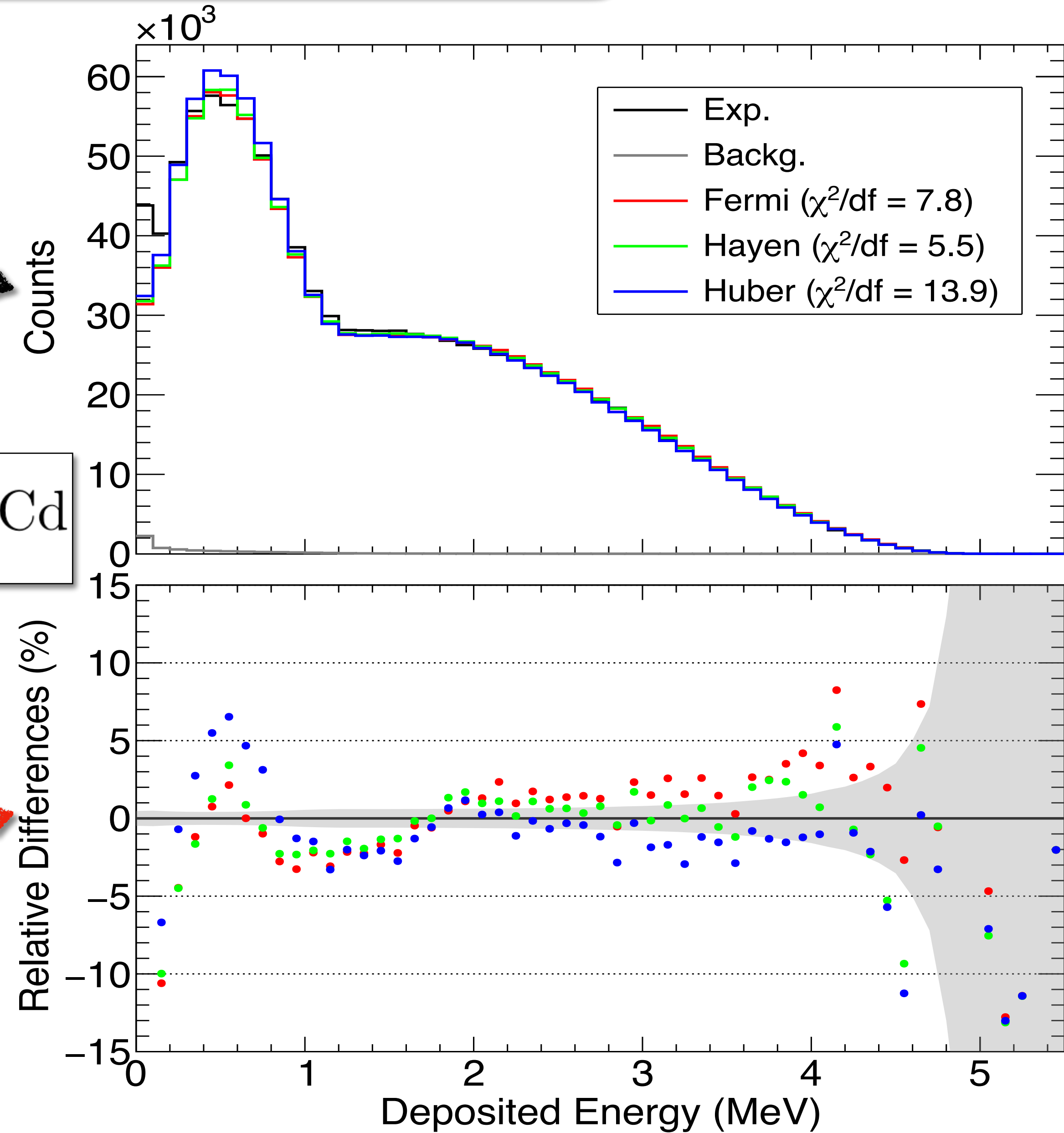
Simulations must be **validated**

The $^{114}\text{Pd} + ^{114}\text{Ag}$ allowed β^- decay was measured to **validate the Monte Carlo model** for the deconvolutions.



The relative differences are lower than $\sim 3\%$ when Hayen et al. shape corrections are applied.

Criterion for validation fulfilled!



Results vs. models

^{92}Rb deconvolution

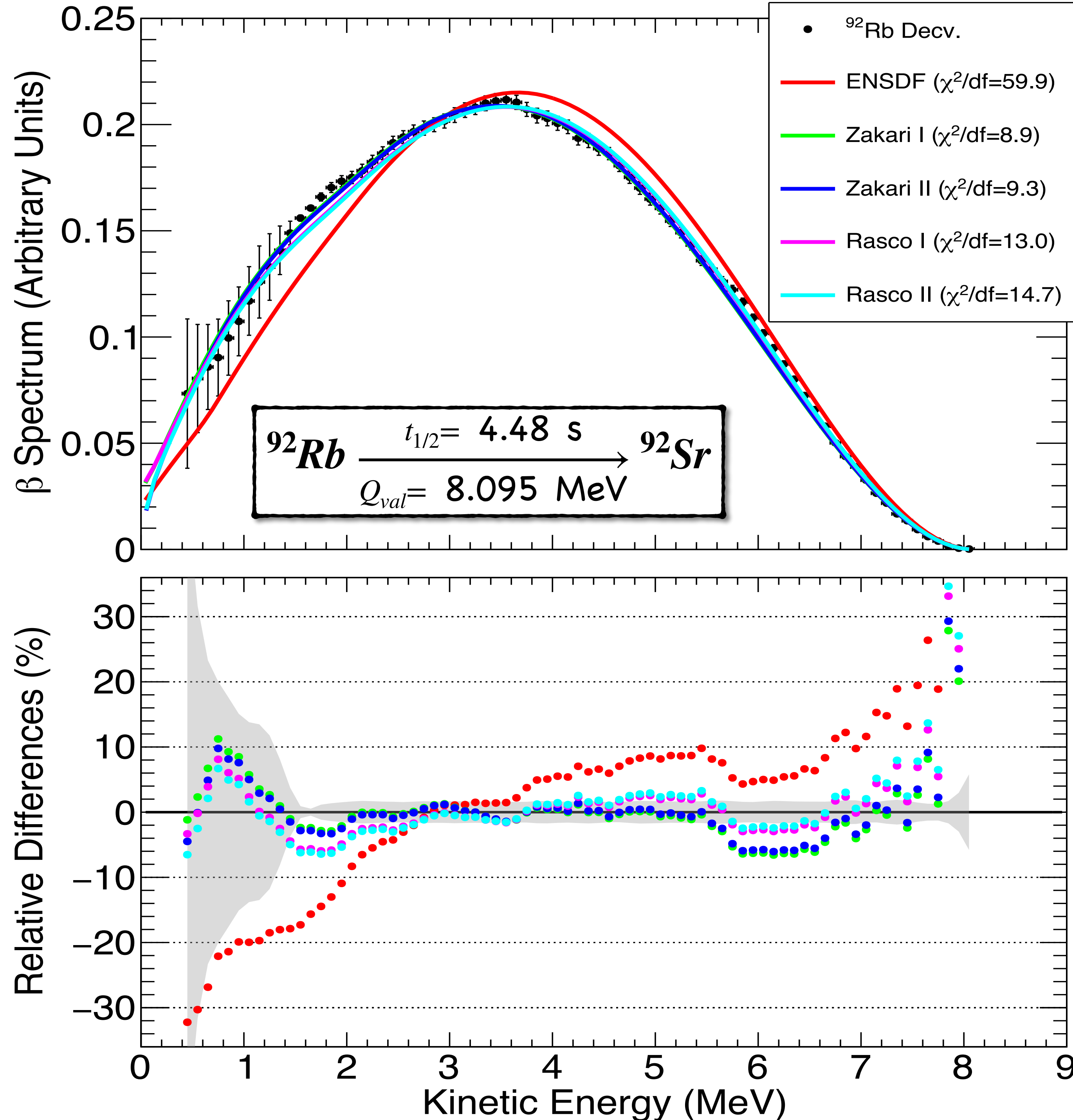
^{92}Rb G.S. to G.S. β feeding:

- ENSDF $\rightarrow$ 95.2(7)%
- Zakari et al. $\rightarrow$ 87.5(25)%
(PRL 115, 102503 (2015))
- Rasco et al. $\rightarrow$ 91(3)%
(PRL 117, 092501 (2016))

ENSDF G.S. to G.S. β feeding (red)
not properly determined due to the
Pandemonium effect.

The experimental
spectrum coincide
with predictions
associated with TAGS
measurements.

Hayen (I) and
Huber (II) shape
corrections yield
similar results.



^{142}Cs deconvolution

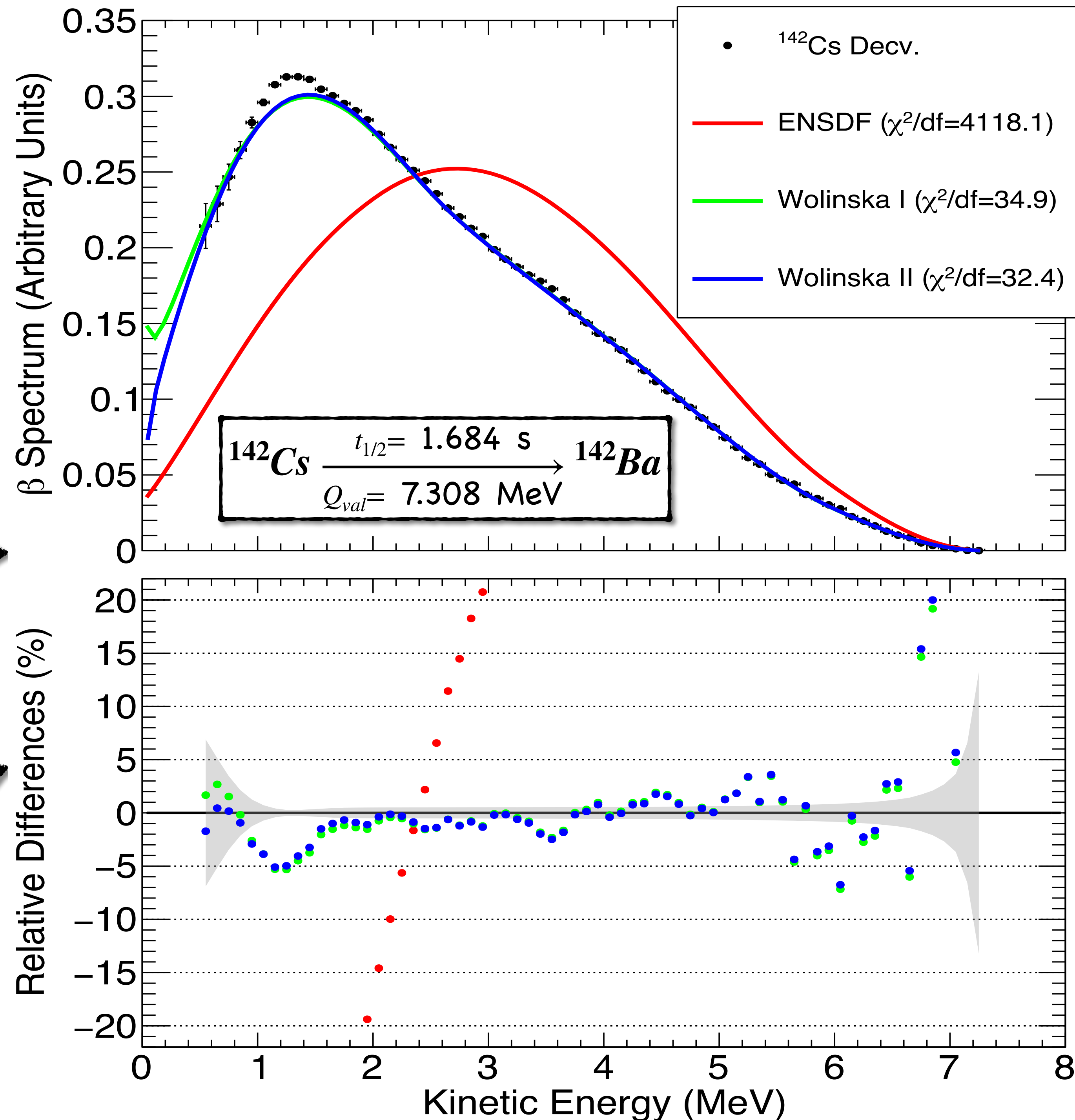
^{142}Cs G.S. to G.S. β feeding:

- ENSDF $\rightarrow$ 56(5)%
- Wolinska et al. $\rightarrow$ 40.6(20)%
(PRC 107, 034303 (2023))

ENSDF β feedings (red) suffer from the Pandemonium effect.

The experimental spectrum coincide with predictions associated with TAGS measurements.

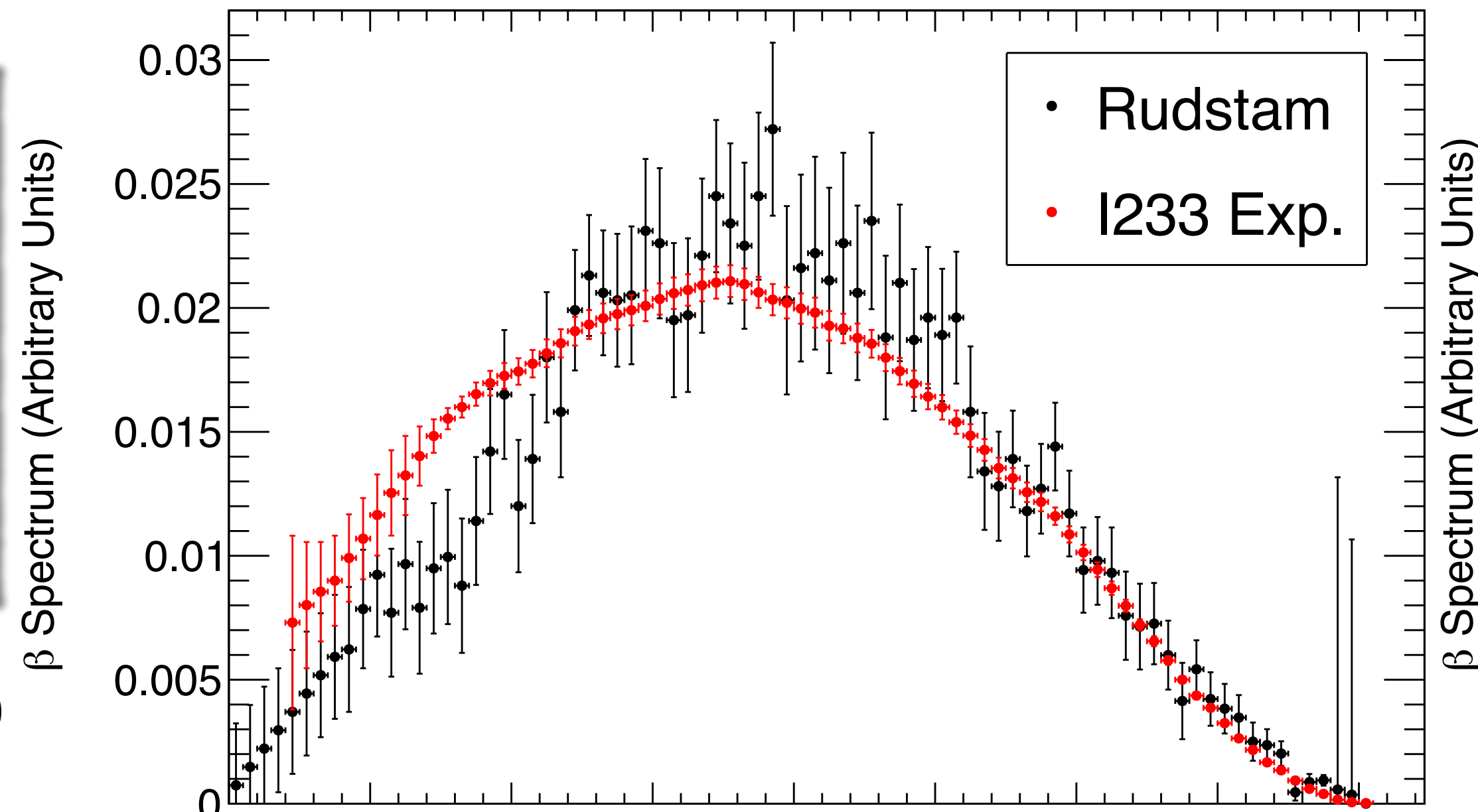
Hayen (I) and Huber (II) shape corrections yield similar results.



I233 experiment results compared with previous experiments.

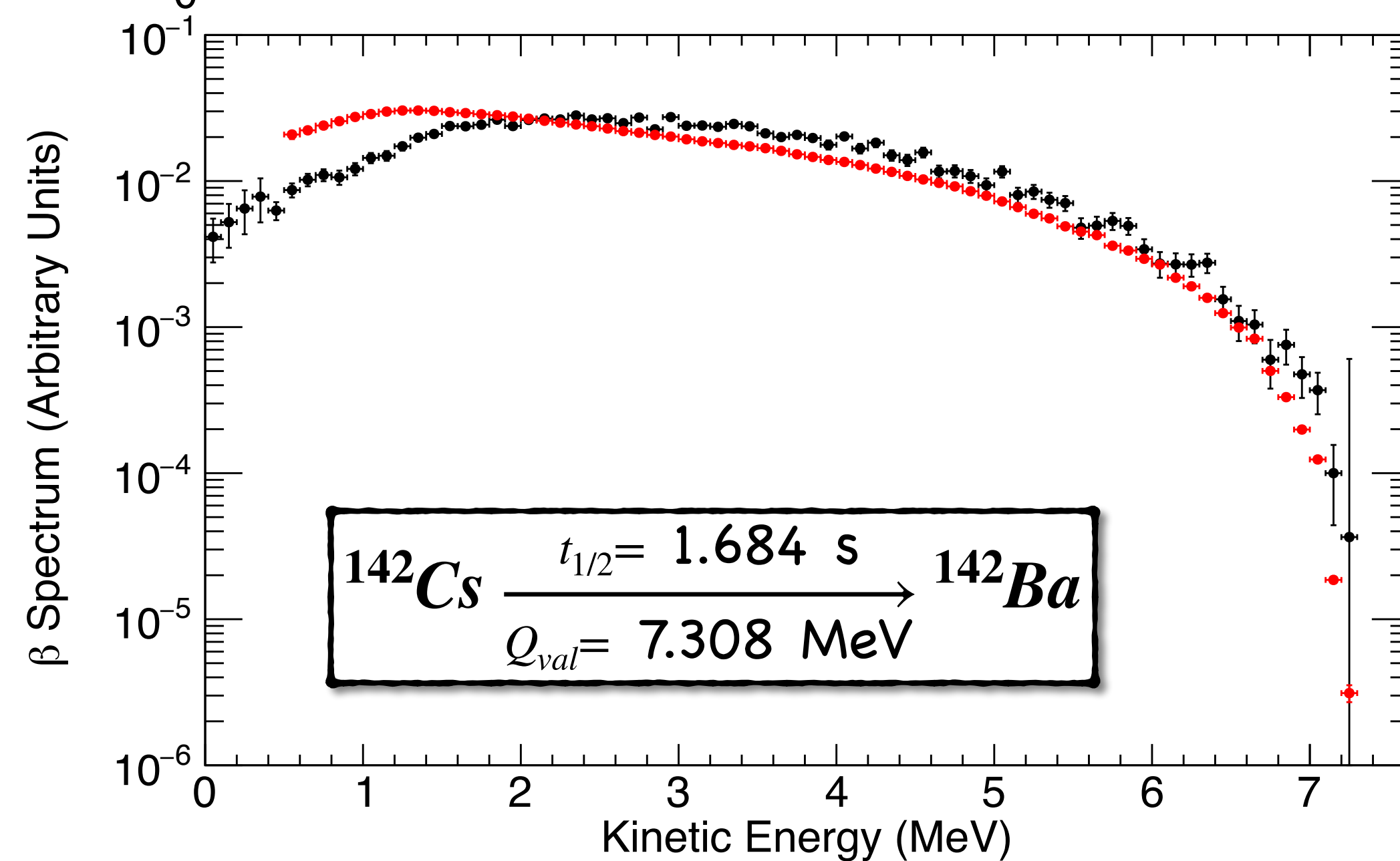
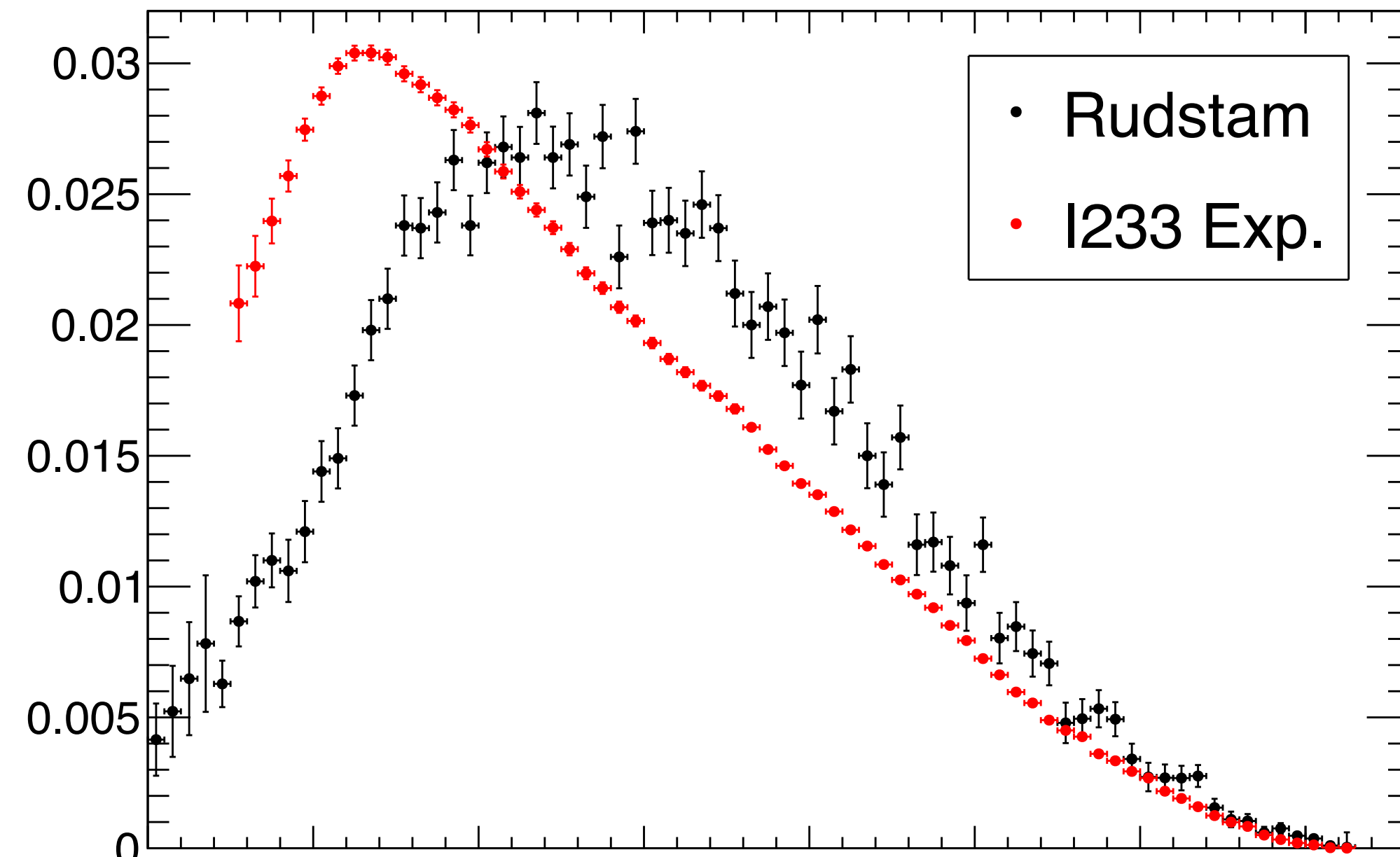
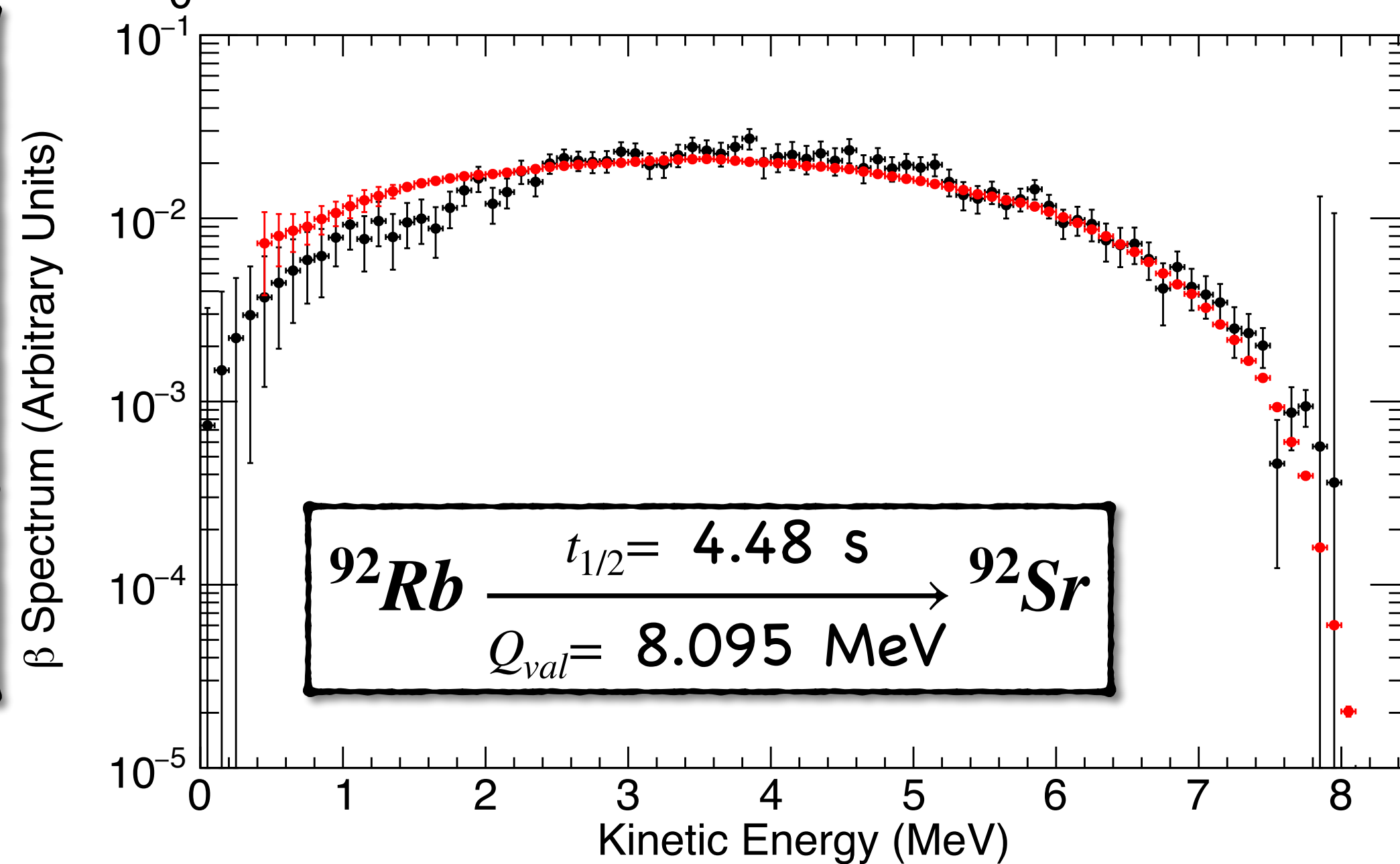
The shapes of the ^{123}I β^- spectra differ from those previously reported.

Rudstam et al.,
ADNDT **45**, 239 (1990)



Rudstam et al. spectra are based on Tengblad et al. measurements, conducted more than 37 years ago.

Tengblad et al.,
NPA **503**, 136 (1989)



Final remarks

- e-shape detectors record accurate β decay spectra.
- TAGS data is essential to describe the β^- spectra of isotopes relevant for the RAA and “bump”.
- 1st forbidden ($\Delta\pi = -1$) nuclear shape factors for $\Delta J = 0$ are negligible.

Complementary experiments conducted at IGISOL-4

- I241: TAGS experiment with Rocinante (Sep. 2022) → Improve β feedings of isotopes of interest for the RAA and “bump”.
- I233add: e-shape experiment (Dic. 2023) → Measure β^- spectra not recorded in the I233.

Muchas gracias!

Special thanks to

A. Algora, M. Fallot, V. Guadilla, M. Estienne, T. Eronen, W. Gelletly, J-S. Stutzmann, S. Bouvier, S. Rinta-Antila, A. Porta, J. Agramunt, A. Beloeuvre, E. Bonnet, D. Ettase, L. Giot, A. Laureau, J. A. Victoria, Y. Molla, and A. Jaries

for their collaboration and involvement in these measurements.



The authors acknowledge support from the European Union NextGenerationEU and Generalitat Valenciana in the call PRTR PC I+D+i ASFAE/2022/027

