HADRON 2023

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN LNGS
Istituto Nazionale di Fisica Nucleare

Assessing the Spectral Shape of Forbidden Beta Decays

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MARIE CURIE ACTIONS

Forbidden beta decays

Transition	ΔL	ΔJ	Δπ	log_{10} ft
Fermi “super-allowed”	0	0	0	3-4
Gamow- Teller “allowed”	0	0,1	0	3 - 10
Forbidden	n	n, n+1	0/1	5 -10 (1st) 22-24 (4th)

$$\Delta\pi = (-1)^{\Delta J}$$

Forbidden non-unique

$$\Delta\pi = (-1)^{\Delta J - 1}$$

Forbidden unique*

Forbidenness

K	1	2	3	4	5
ΔJ	0,1,2	2,3	3,4	4,5	5,6
Δπ	-1	1	-1	1	-1

$$\vec{J} = \vec{L} + \vec{S}$$

$$log_{10}ft = log_{10}(f(Z, E_0) \cdot T_{1/2})$$

As a rule of thumb, each degree of forbidenness gives 5-6 orders of magnitude in ~$T_{1/2}$

See *B. Singh et al., Nucl. Data Sheets 84 (1998) 487*.

* defined by only one nuclear matrix element

Spectral shape…the standard approach

$$\rho(E) = \rho_{all}(E) \cdot C(W)$$

$$\rho_{all}(E) \propto F(Z_d, E) \cdot (Q_\beta - E)^2$$

numerically calculated

$C(W)$ empirical correction function

Being W the total energy of the election, while P and Q the momenta of the electron and the anti-neutrino, respectively

Forbidden Non-unique

$$C_1(W) = 1 + \frac{a_1}{W} + a_2 W + a_3 W^2 + a^4 W^3$$

Forbidden Unique

$$C(W) = C_1 \cdot C_2$$

1st $C_2 = P^2 + c_1 Q^2$

2nd $C_2 = P^4 + c_1 Q^2 P^2 + c_2 Q^4$

Spectral shape…a recent approach

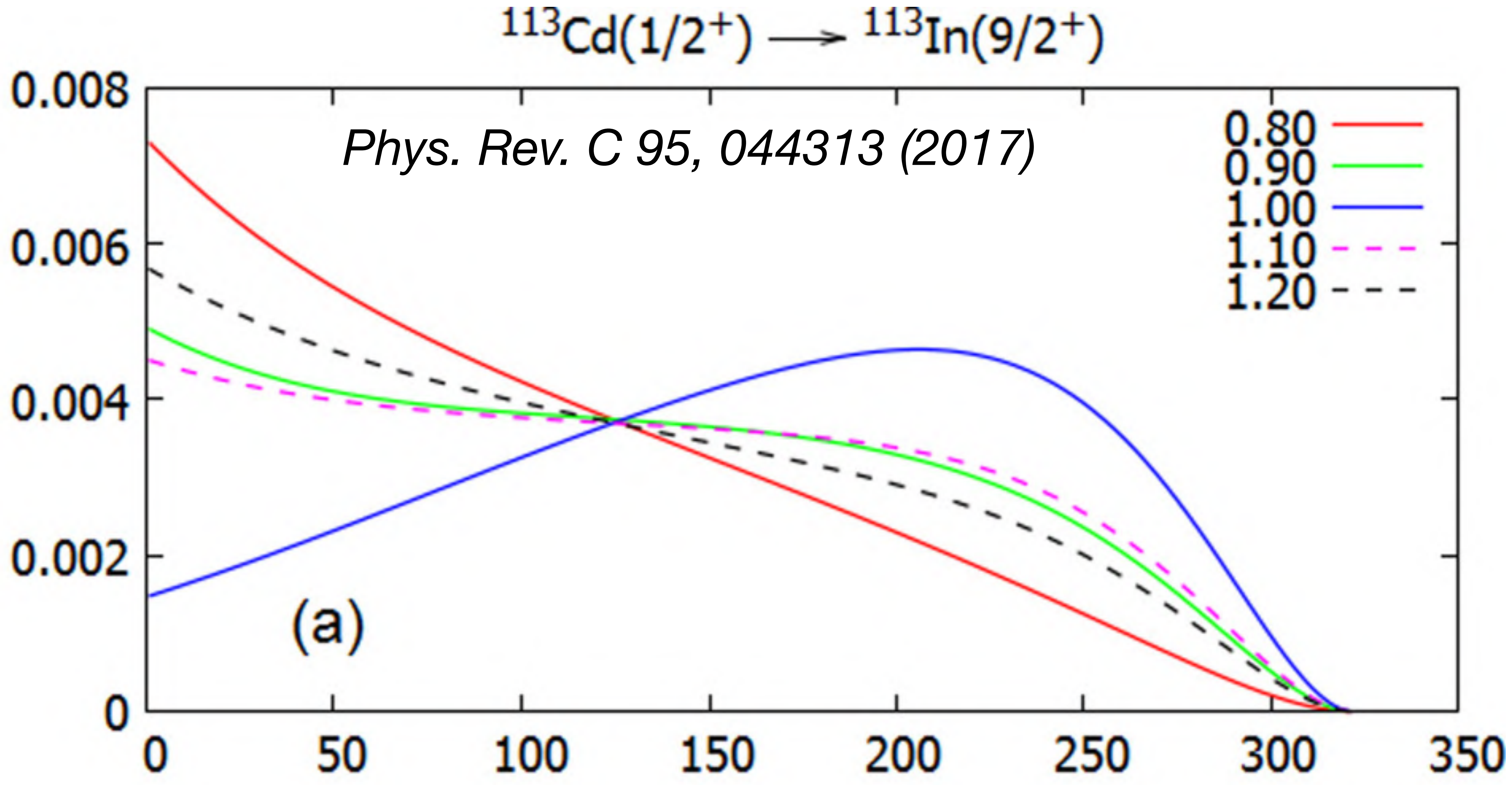
$$\rho(E) = \rho_{all}(E) \cdot C(W)$$

$$\rho_{all}(E) \propto F(Z_d, E) \cdot (Q_\beta - E)^2$$

numerically calculated

$C(W)$ empirical correction function

The "shape factor" encodes the nuclear-structure information and can be decomposed into vector, axial-vector, and vector-axial-vector parts.



$$C(W) = g_A^2 \left[C_A(W) + \left(\frac{g_V}{g_A}\right)^2 + C_V(W) + \frac{g_V}{g_A} C_{VA}(W) \right]$$

Fit the **template spectra** to the experimental data allow us to investigate the g_A values in different decay (aiming at discovering the physics under the phenomenological **g_A-quenching**)

Last development on this line: adding the s-NME as free parameter in the fit

Spectral shape…the most recent approach

From a continuum smooth spectrum (**experimental** or **theoretical**) $S(w_e)$, we can obtain the momenta of the distribution (N = 6 is enough)

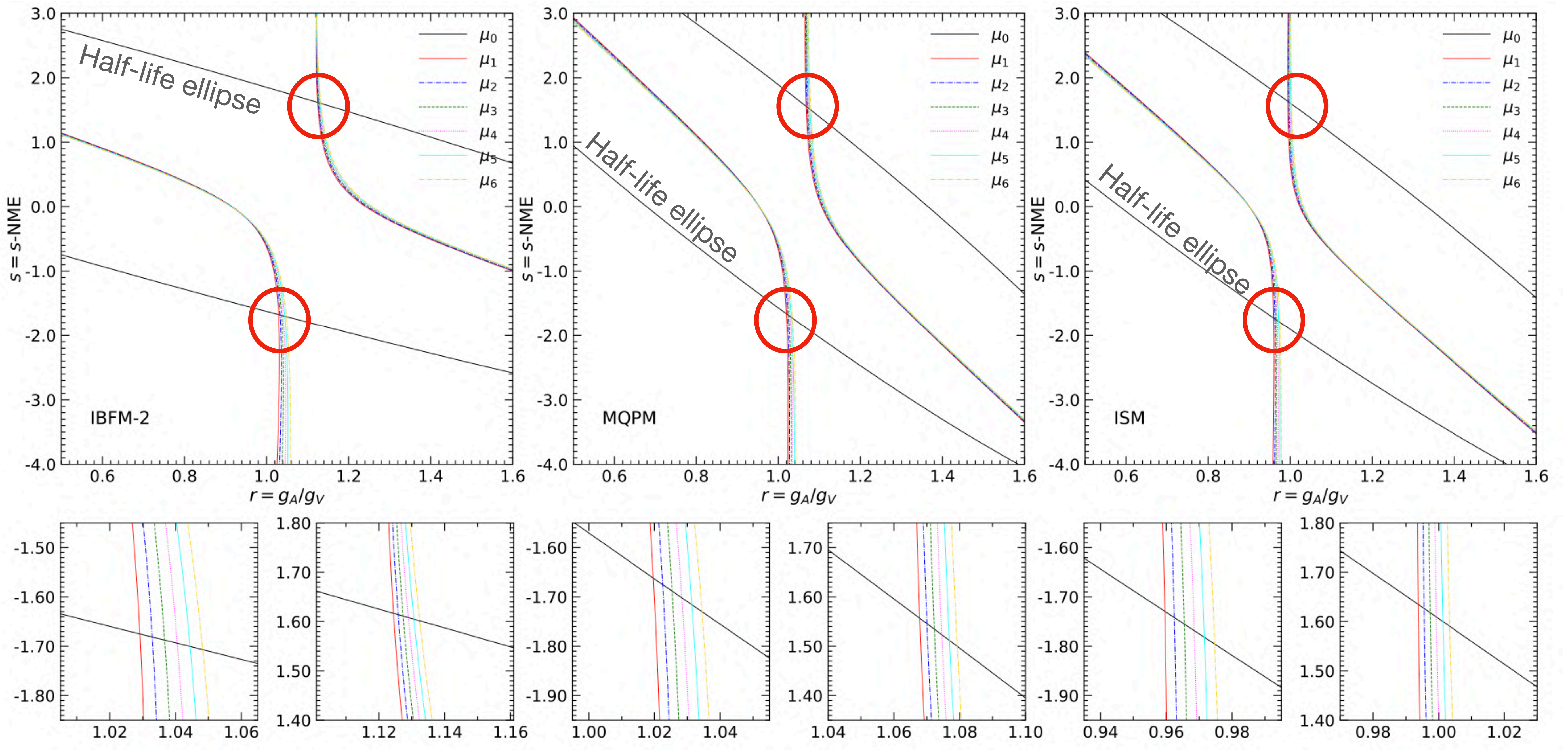
$$\mu_0 = \int_{w_{\rm thr}}^{w_0} S(w_e)\, dw_e$$

Decay rate

$$\mu_n = \frac{\int_{w_{\rm thr}}^{w_0} S(w_e)\, w_e^n\, dw_e}{\int_{w_{\rm thr}}^{w_0} S(w_e)\, dw_e} \quad (n \geq 1)$$

Basically the same approach as before but simpler implementation: one has to reproduce 6 experimental values with 6 theoretical predictions and 2 free parameter (r and s)

Phys.Rev.C 107 (2023) 5, 055502



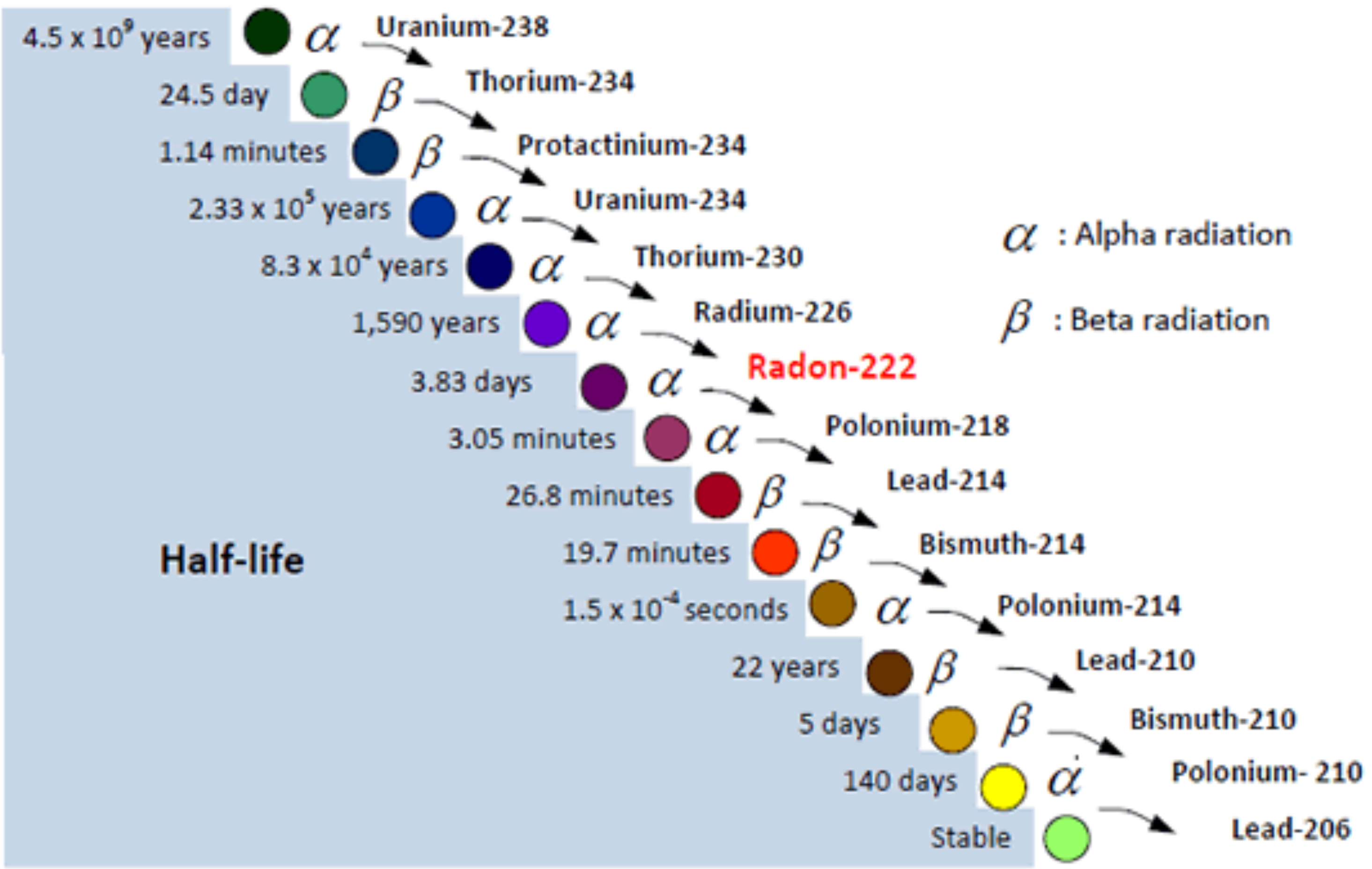
$$r = \frac{g_A}{g_V}$$

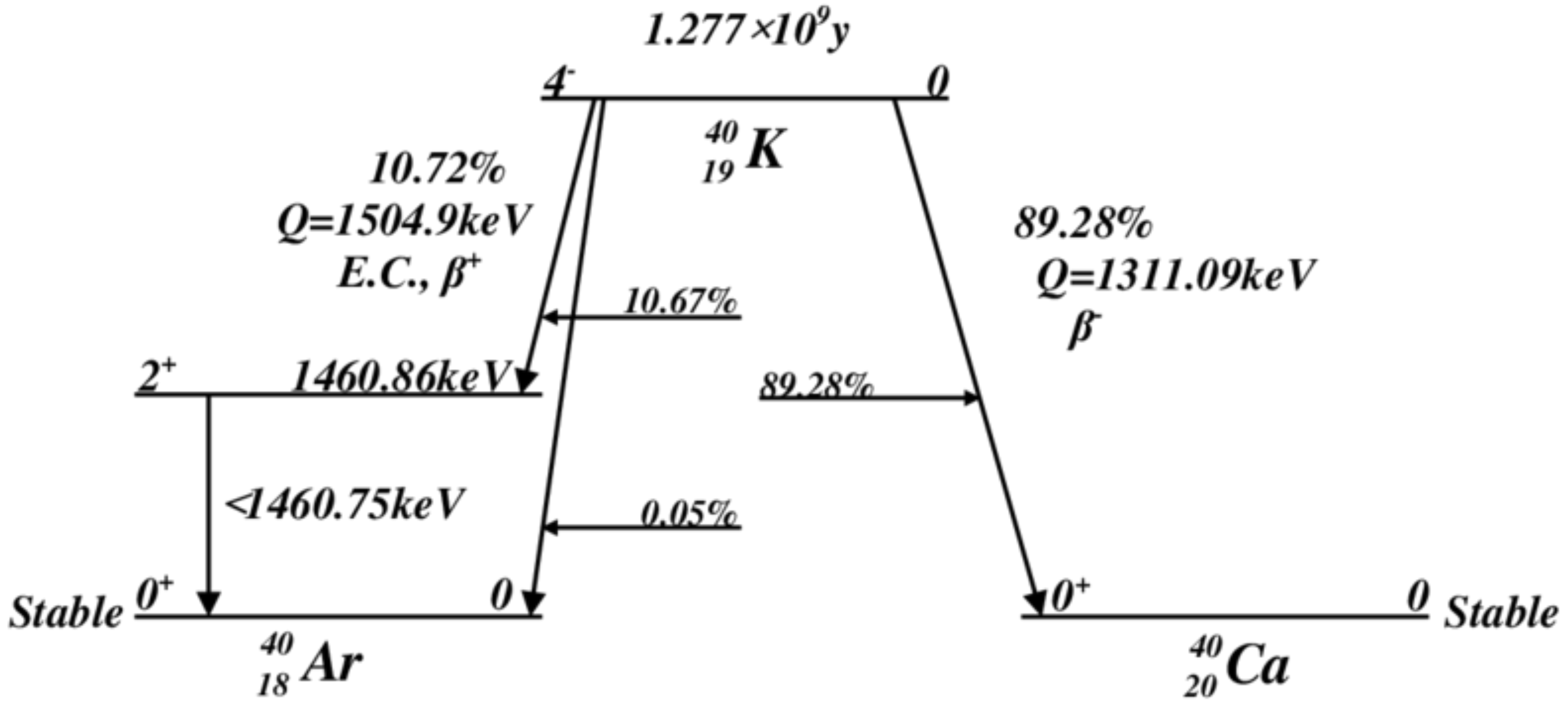
$$s = sNME$$

Small Nuclear Matrix Element

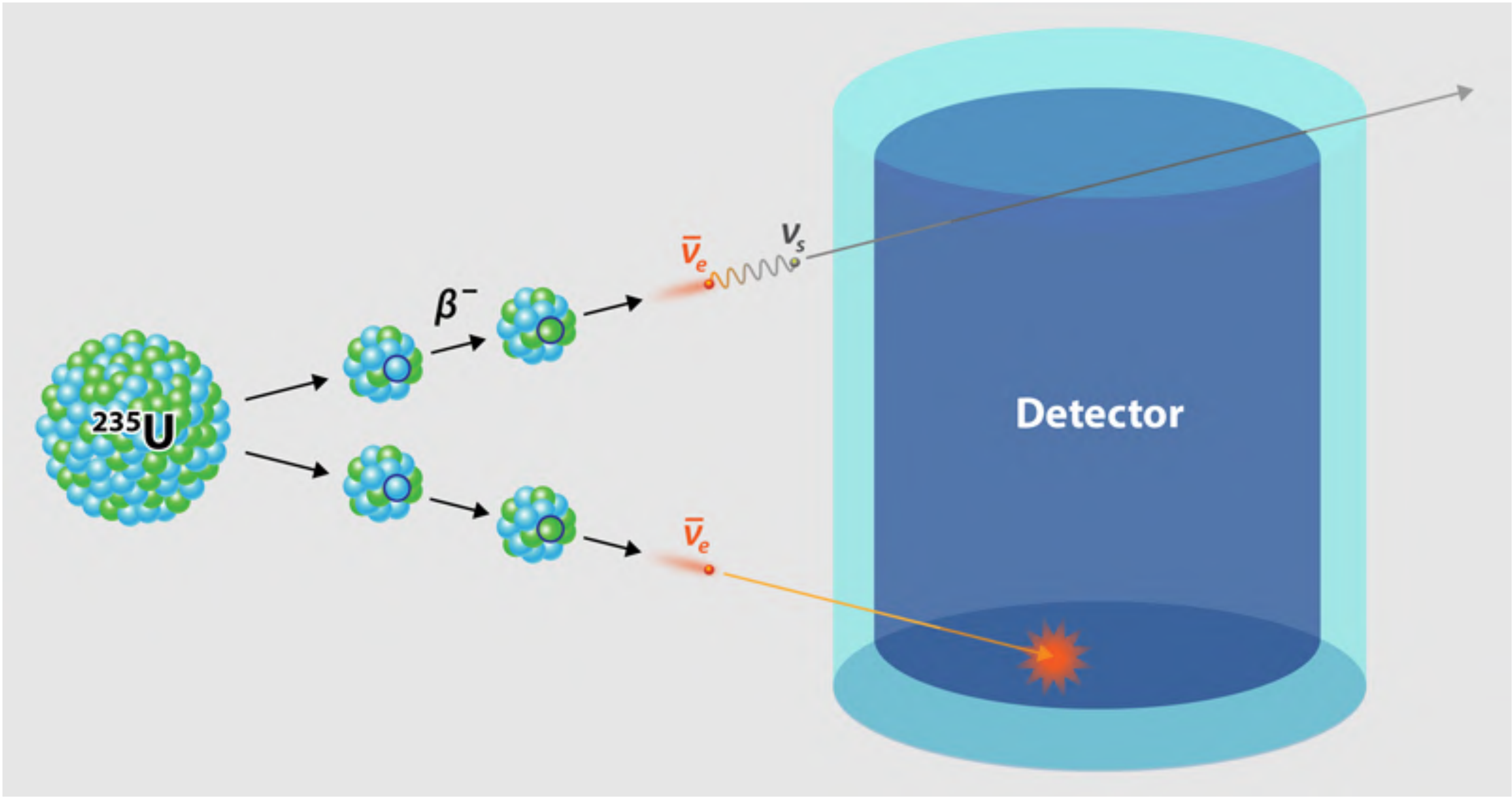
Where we found them?

Dark Matter & Rare event searches

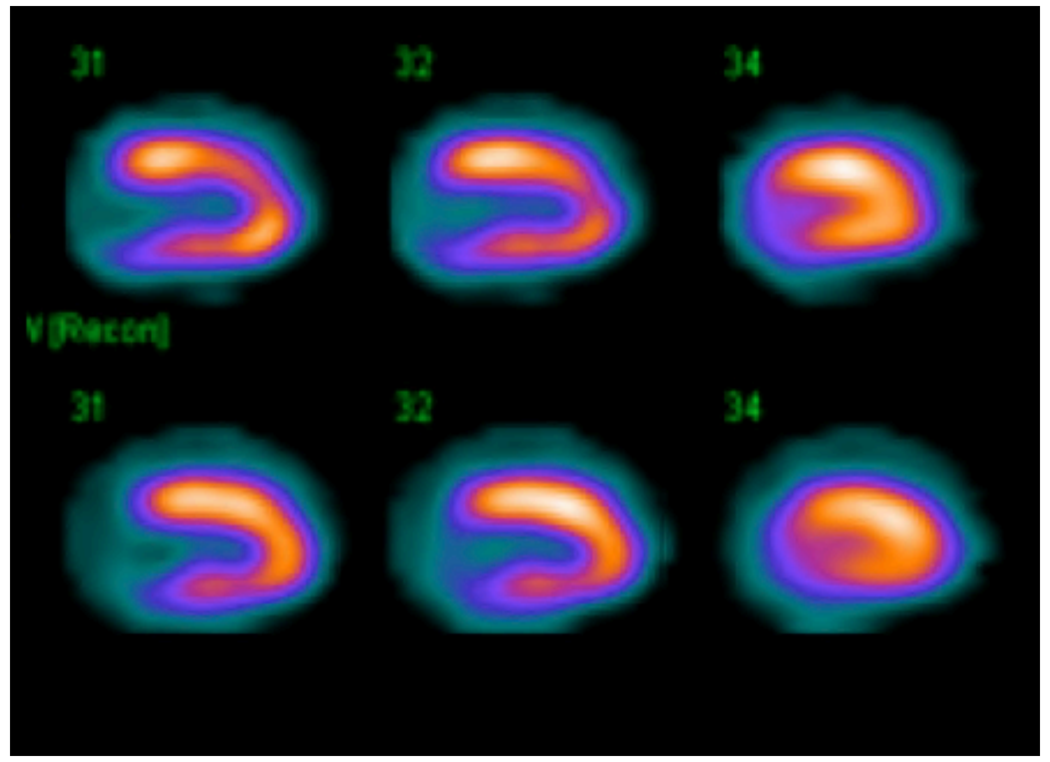




Neutrino physics at reactor



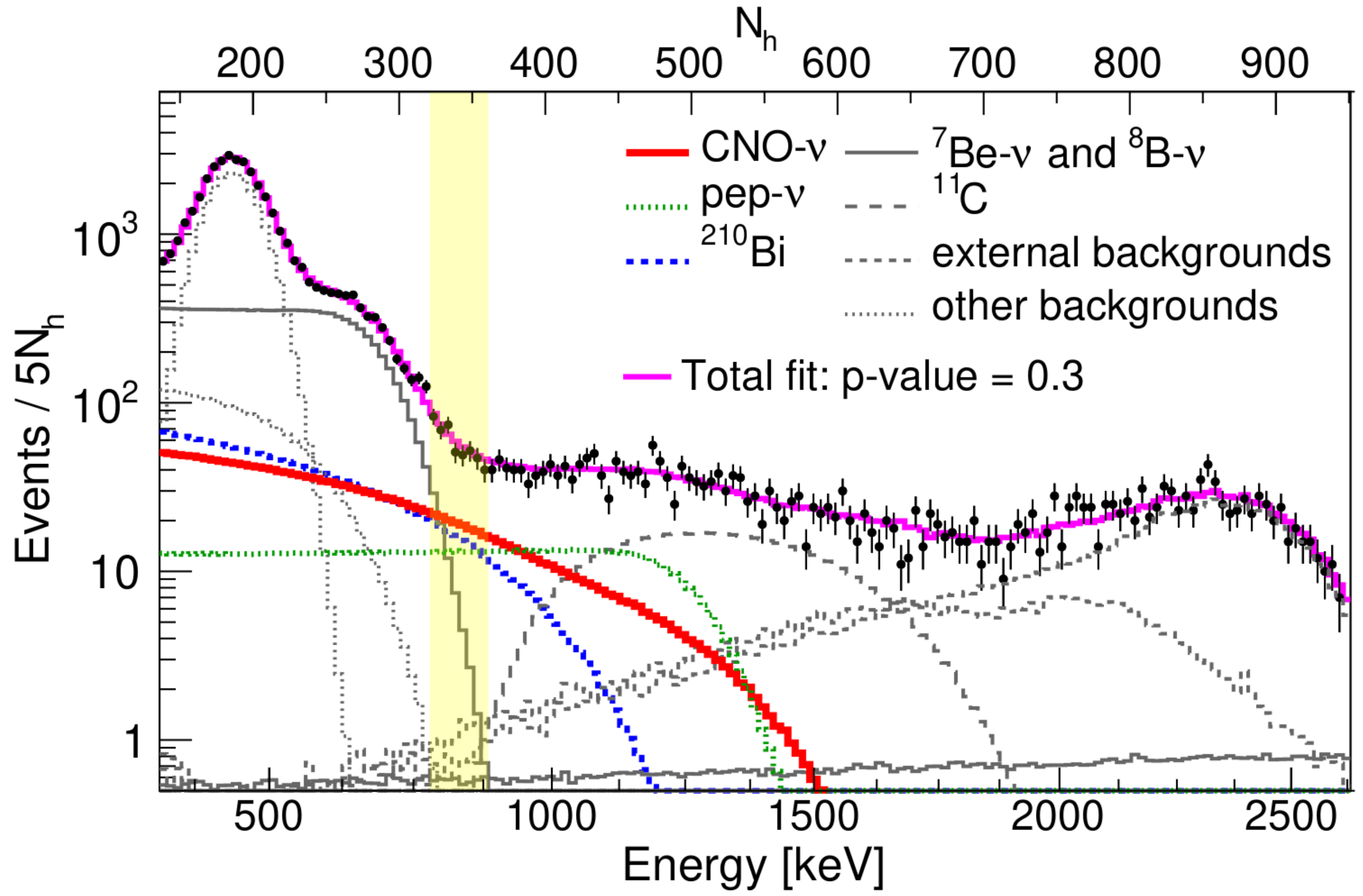
Medical diagnostics



Motivations - Why so much interest?

1. Background or source of uncertainty in rare event search

- Background source in dark matter search => ^{40}K, ^{42}Ar, ^{39}Ar
- Ingredients in NLDBD background modeling => ^{90}Sr/^{90}Y, ^{210}Bi
- Background in Neutrino experiment => ^{210}Bi

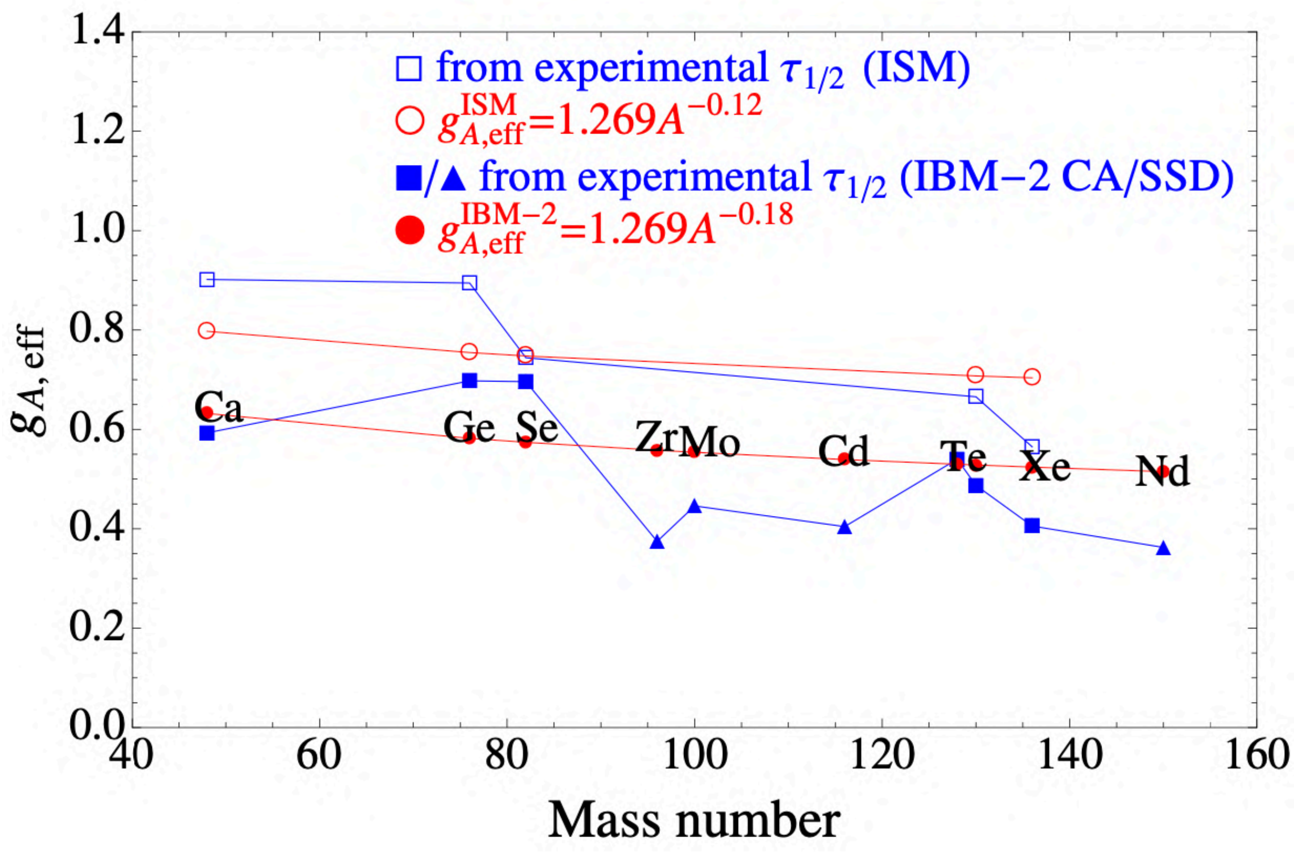


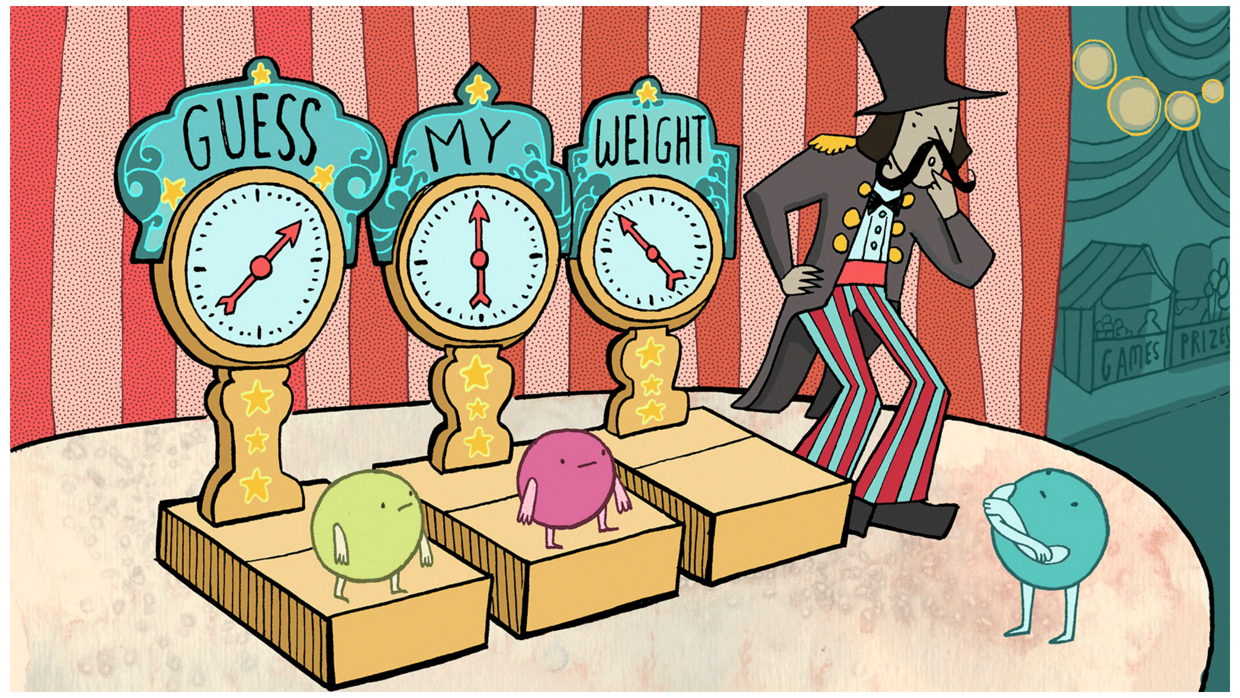
2. Low Q-value decay

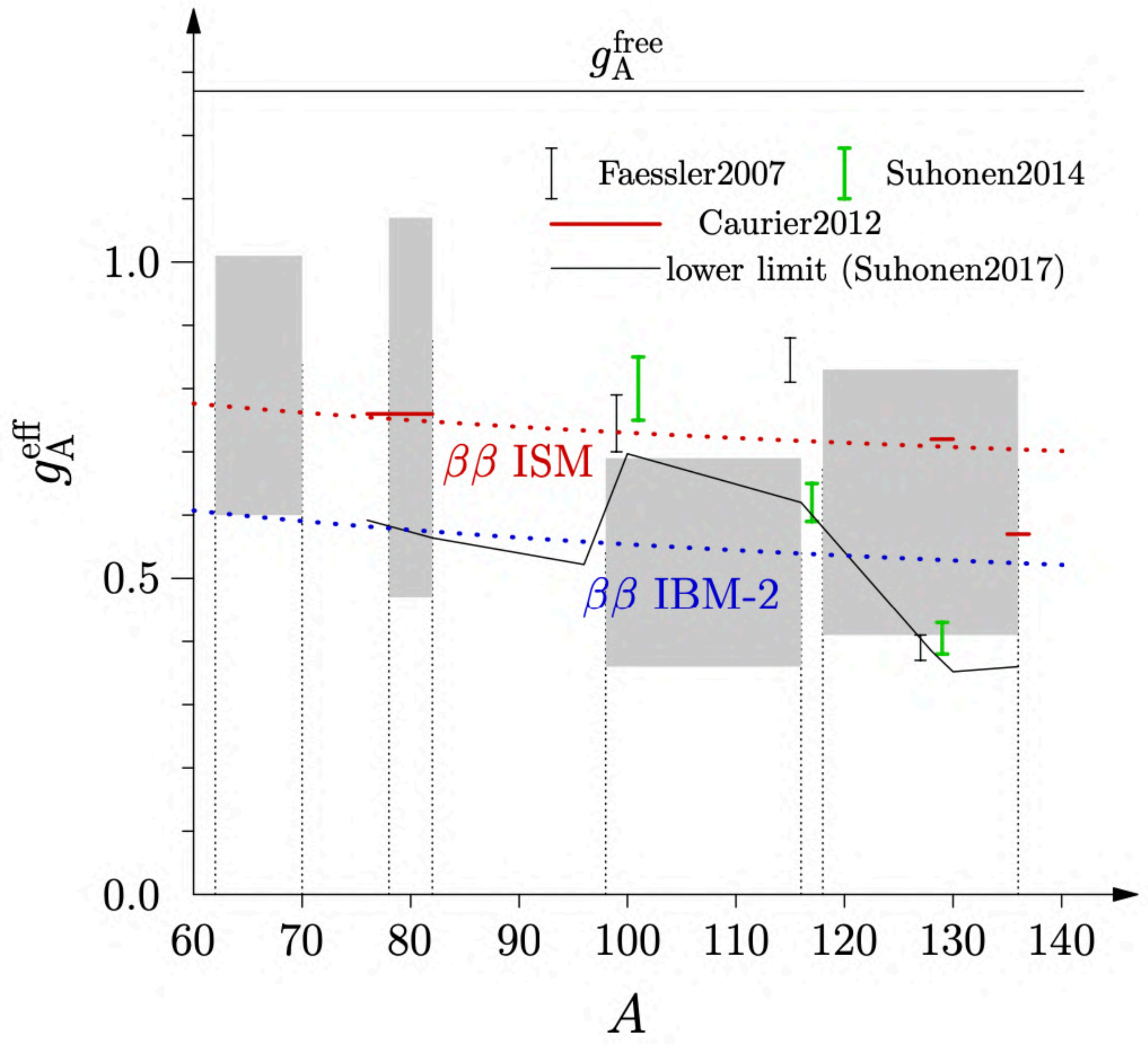
- Cosmic Neutrino Background detection => ^{151}Sm, ^{171}Tm
- Neutrino mass => ^{115}In*

3. Gym for Nuclear Models

1. Opportunity to solve the long standing g_A quenching
2. Opportunity to improve Nuclear Model for NME calculations => NLDBD







Motivations

The international effort to observe neutrinoless double beta decay is increasing and new experiments are growing

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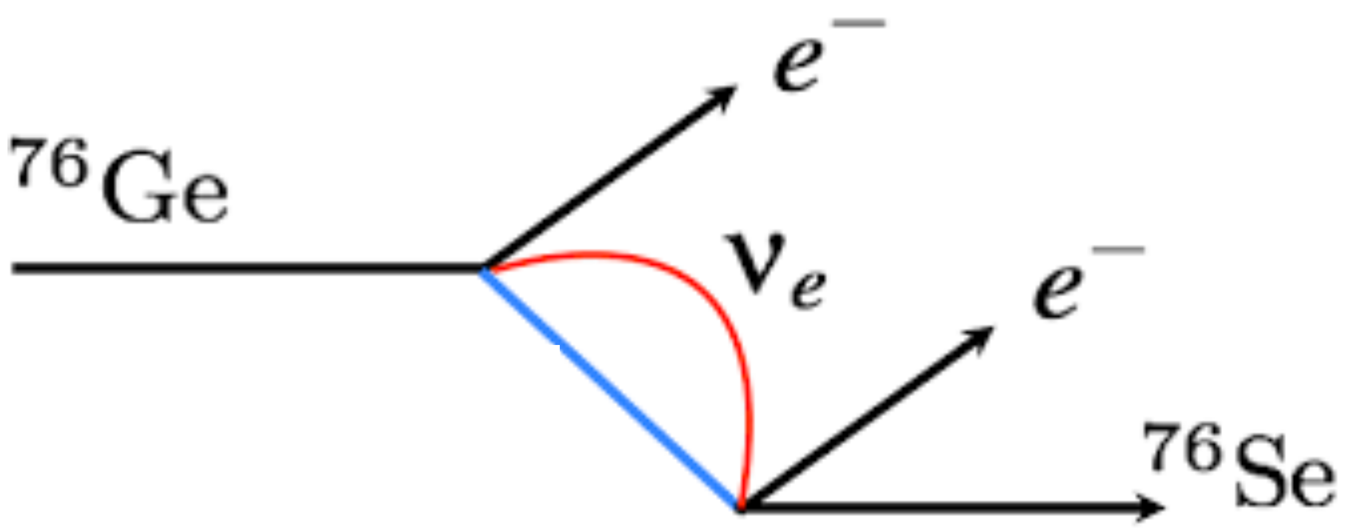
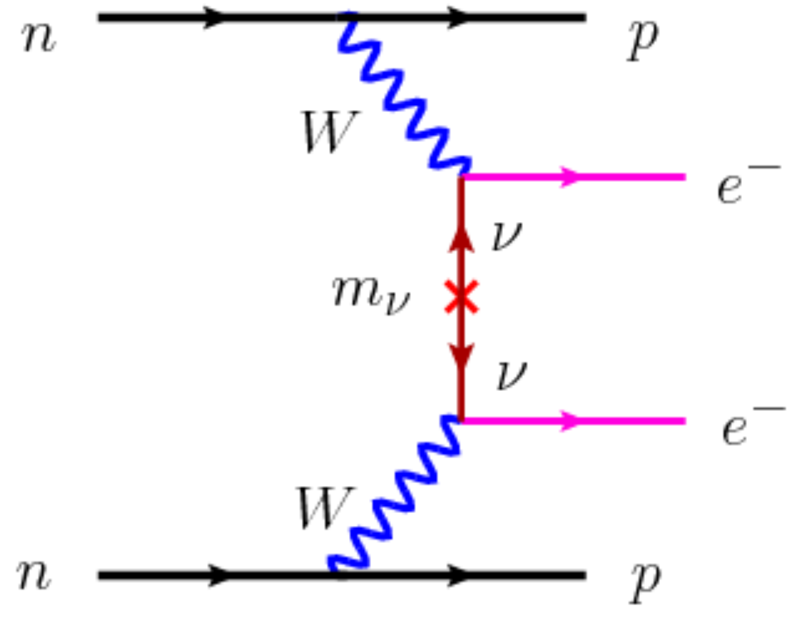
See yesterday talks by Claudia Tomei, and Stefano Dell’Oro

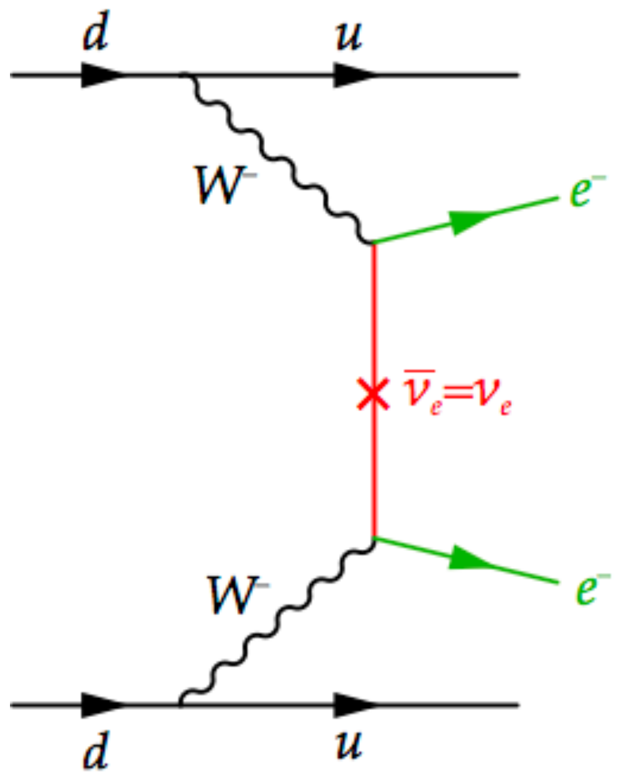
Neutrinoless double beta decay



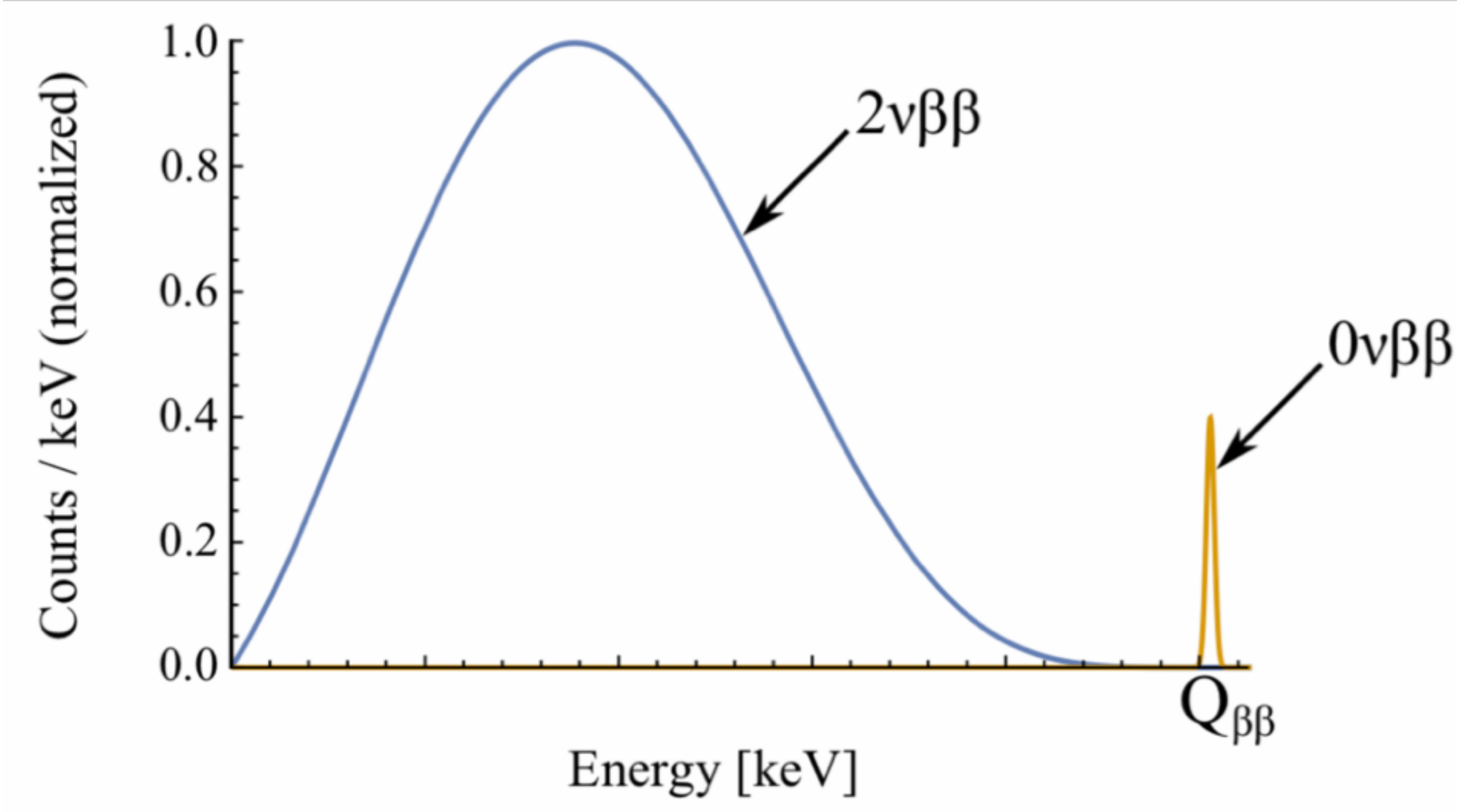
...atomic level



...nuclear level

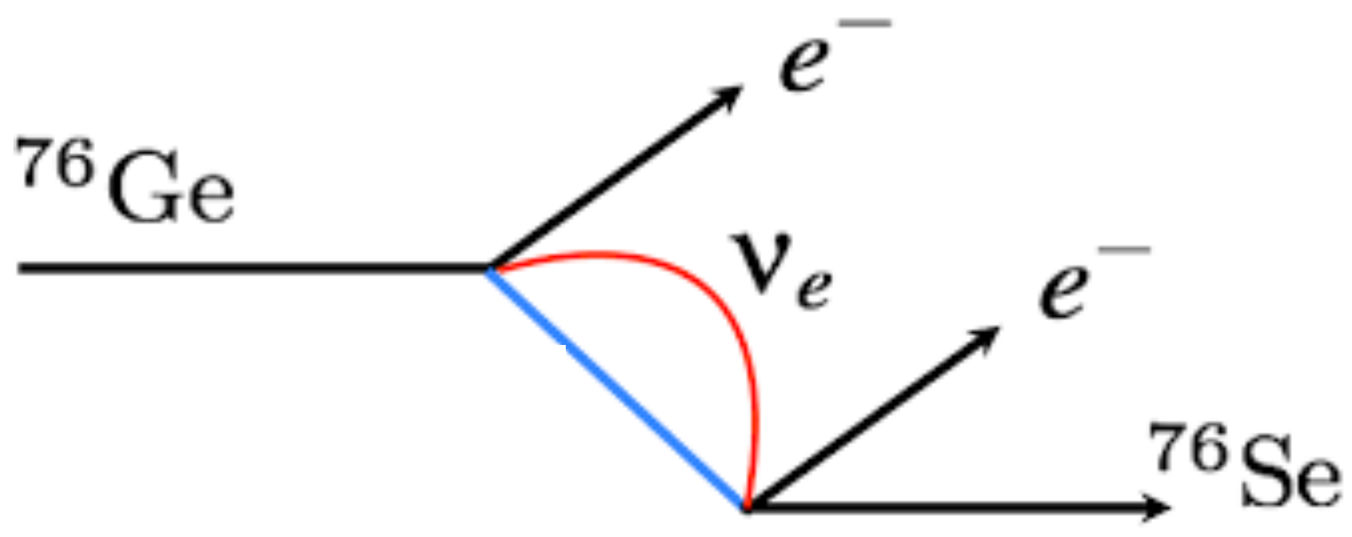


...particle level



$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4 \cdot \mathcal{G}^{0\nu}(Q_{\beta\beta}, Z) \cdot \left|\mathcal{M}^{0\nu}(A, Z)\right|^2 \cdot \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Neutrinoless double beta decay



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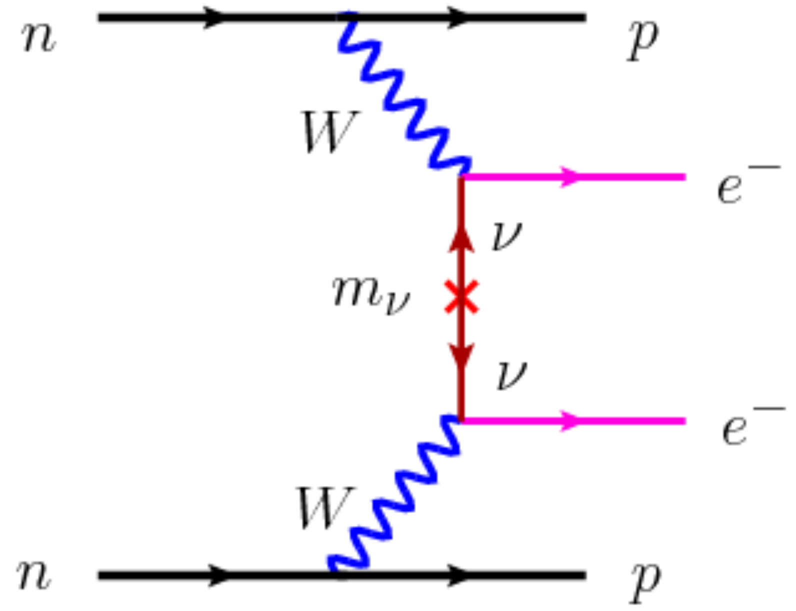

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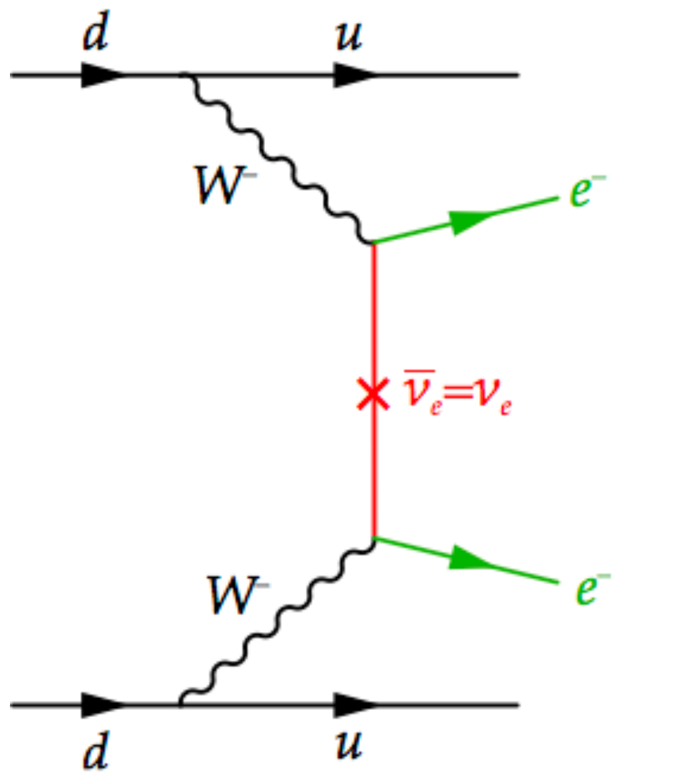

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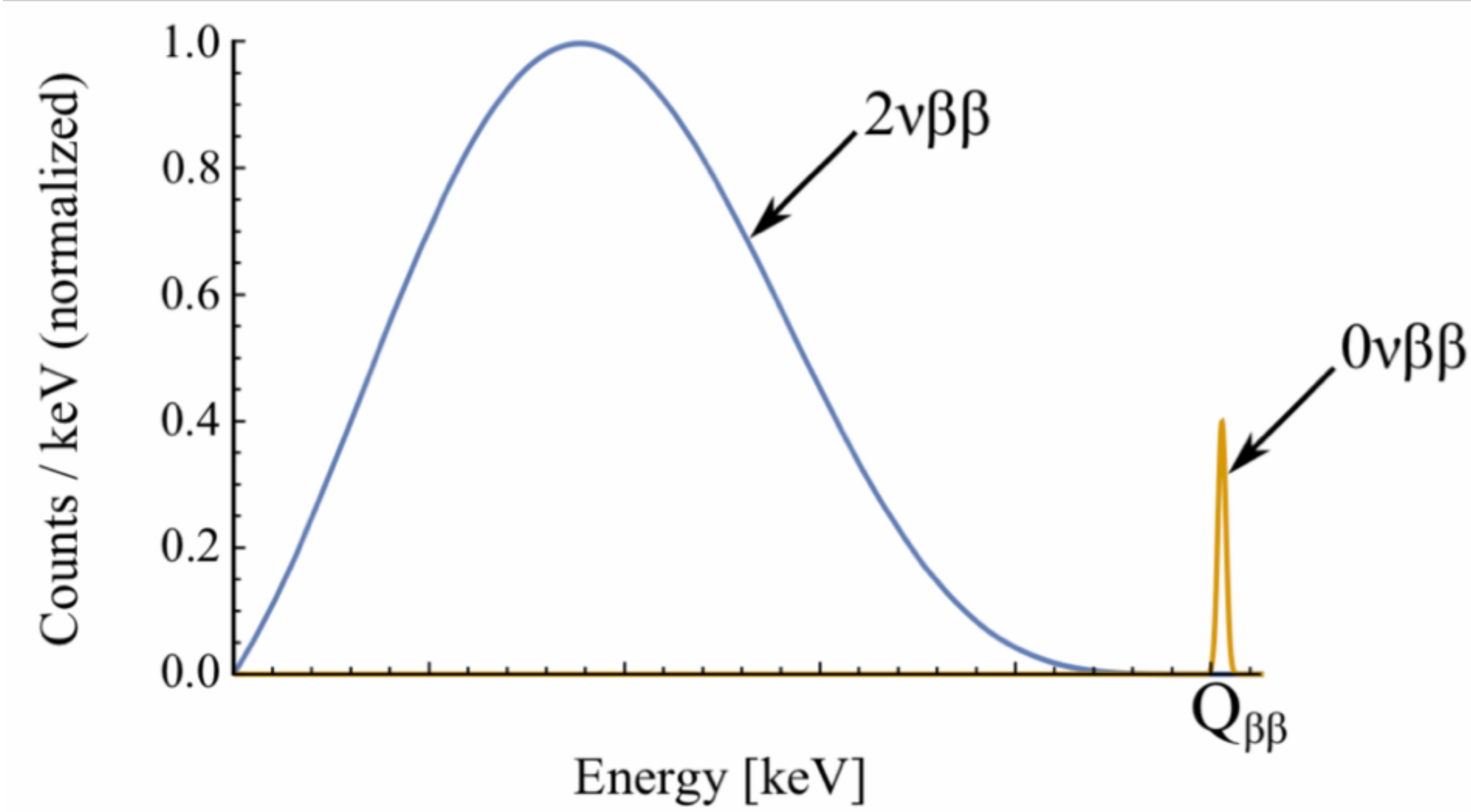


Effective Majorana Mass

New physics parameter

Half-life from experiments

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \cdot \mathcal{G}^{0\nu}(Q_{\beta\beta}, Z) \cdot \left|\mathcal{M}^{0\nu}(A, Z)\right|^2 \cdot \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Phase Space Factor

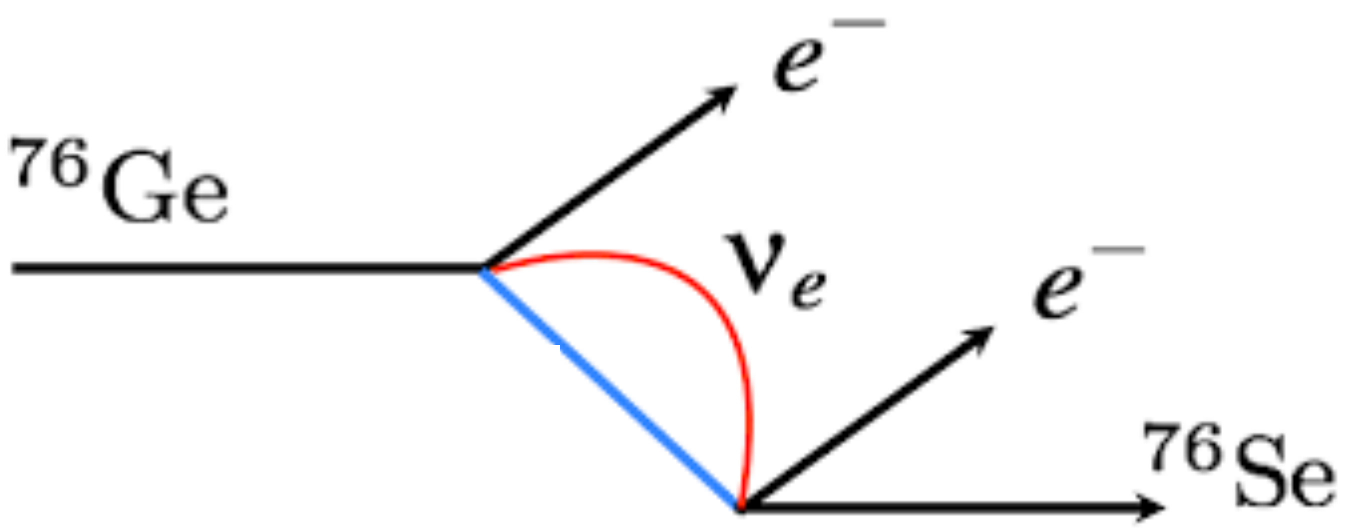
precisely evaluated

Nuclear Matrix Elements

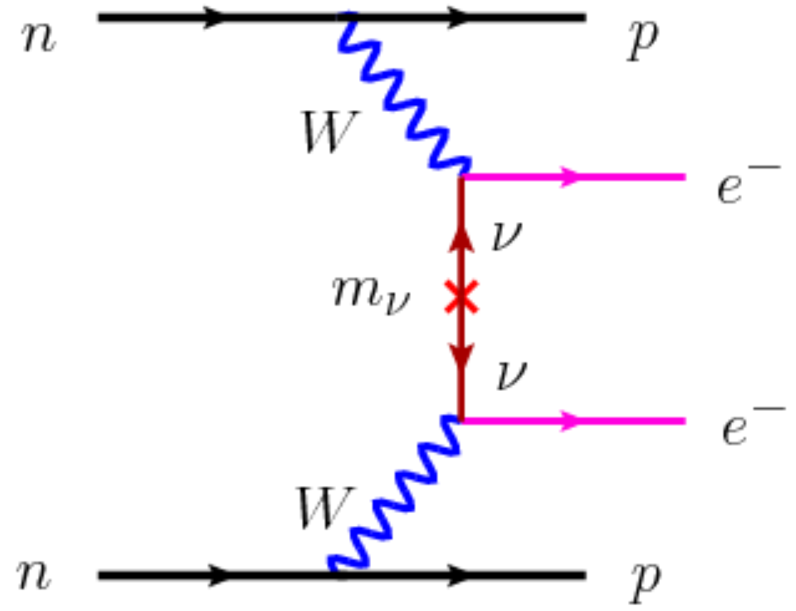
from NuclearModels

(large uncertainty)

Neutrinoless double beta decay



...atomic level



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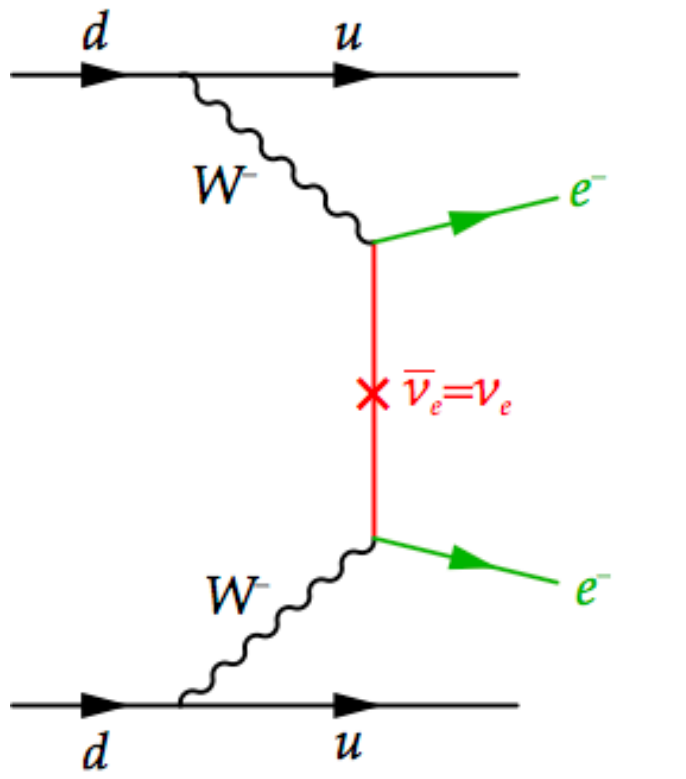

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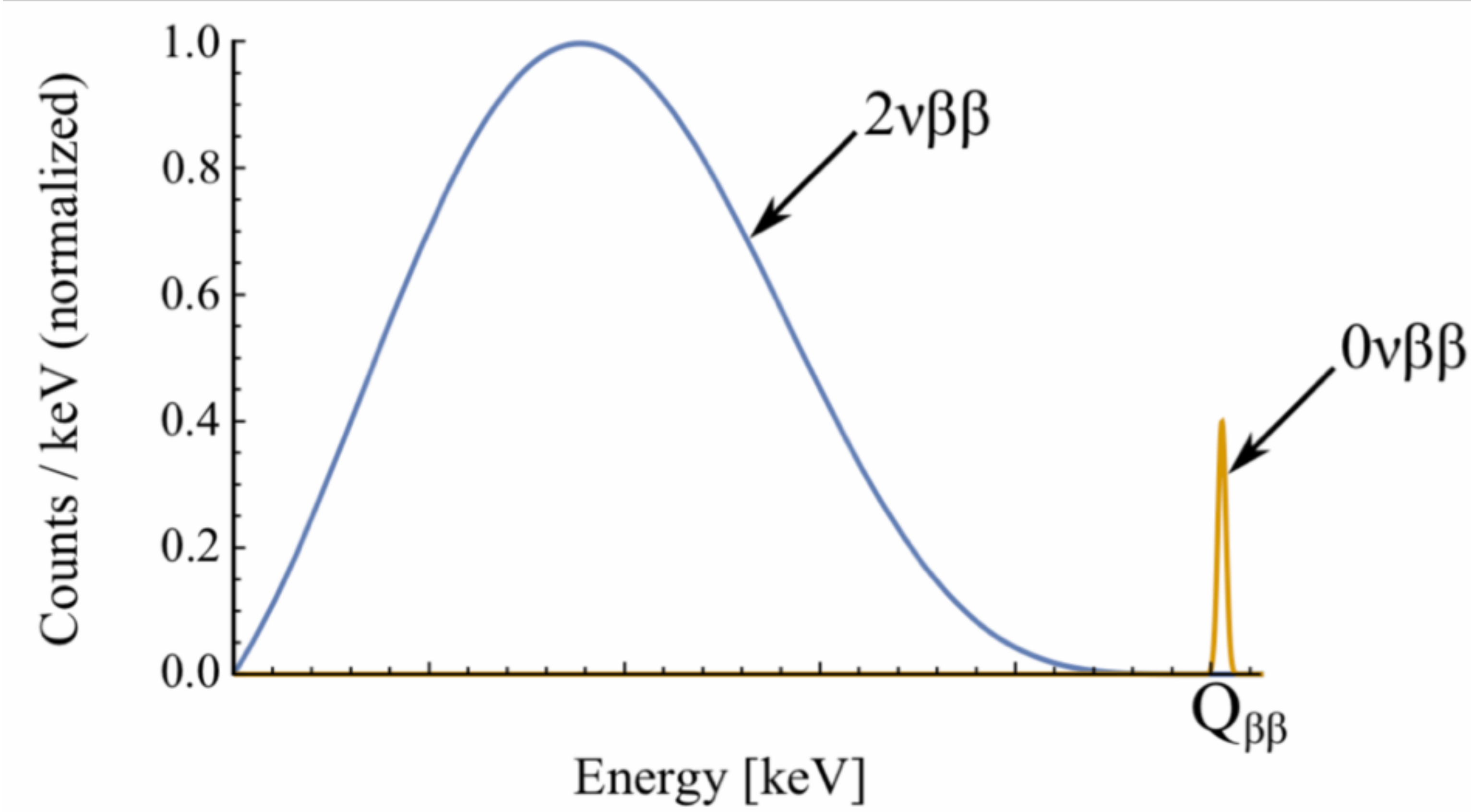


$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \cdot \mathcal{G}^{0\nu}(Q_{\beta\beta}, Z) \cdot \left|\mathcal{M}^{0\nu}(A, Z)\right|^2 \cdot \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Nuclear Matrix Elements (NMEs) are fundamental for two reasons:

1. If we observe 0νββ, we will need precise value of NME to **convert the half-life to Majorana mass**.
2. A further **isotope down-selection** is prevented by NME uncertainties (only knowing the NMEs we can identify a set of golden-candidates, e.g. $G_{0\nu} \propto Q^5$)

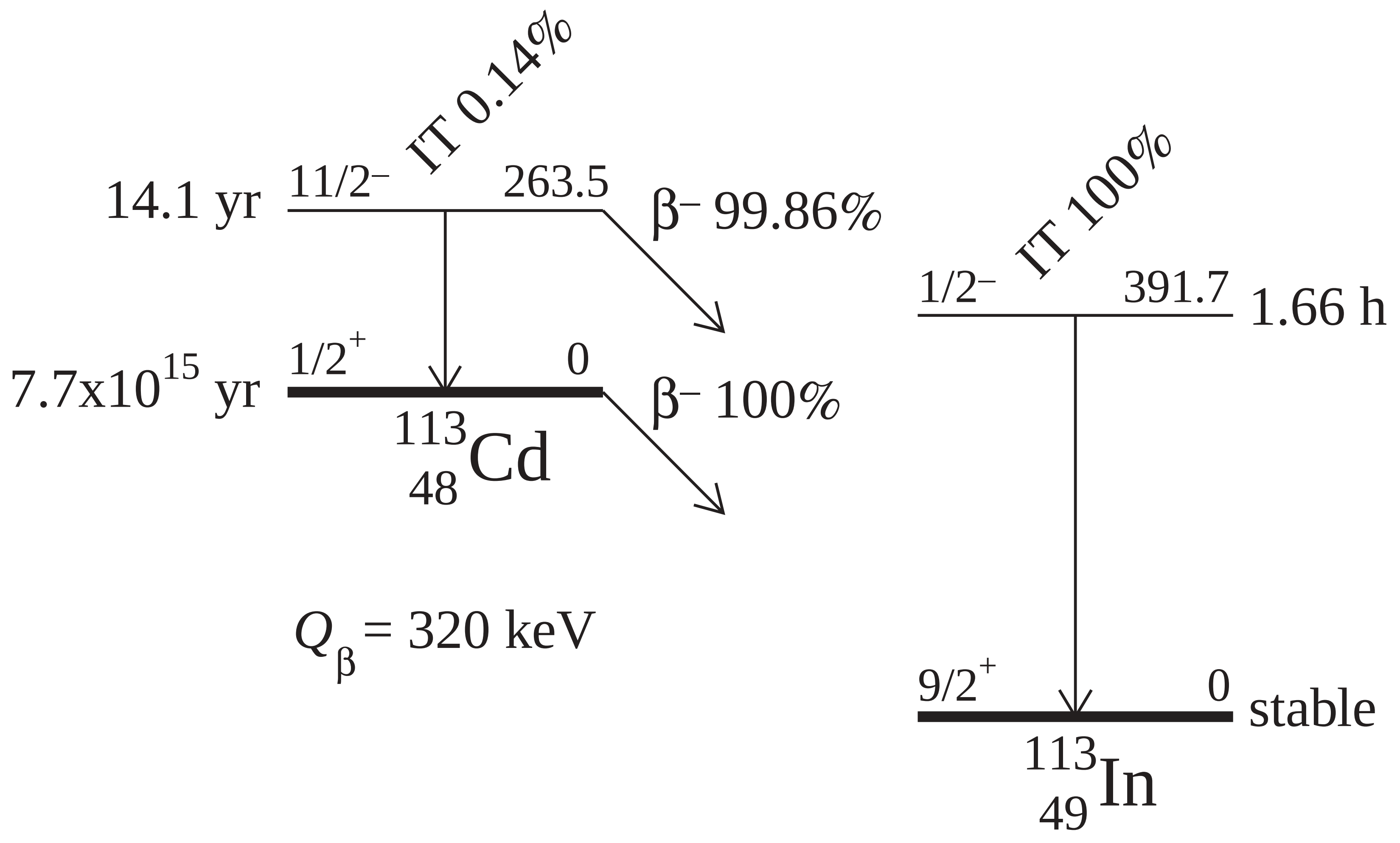
Forbidden Beta Decays of Natural Isotopes

Cadmium-113

Q-value	Half-life	Classification
320 keV	8x10^{15} yr	$\frac{1}{2}^+ \rightarrow \frac{9}{2}^+$ $\quad \Delta J^{\Delta\pi} = 4^+$

"Golden candidate" due to experimental conditions:

- Good natural abundance i.a. = 12.22%
- Embedded in **$CdWO_4$ crystal**
  - excellent scintillator for NLDB (by DAMA group)
  - excellent bolometer for DM (by CRESST)
- Embedded in **semiconductors** (CdTe, CdZnTe)
  - interesting for NLDB (by COBRA)
- Good intrinsic radiopurity



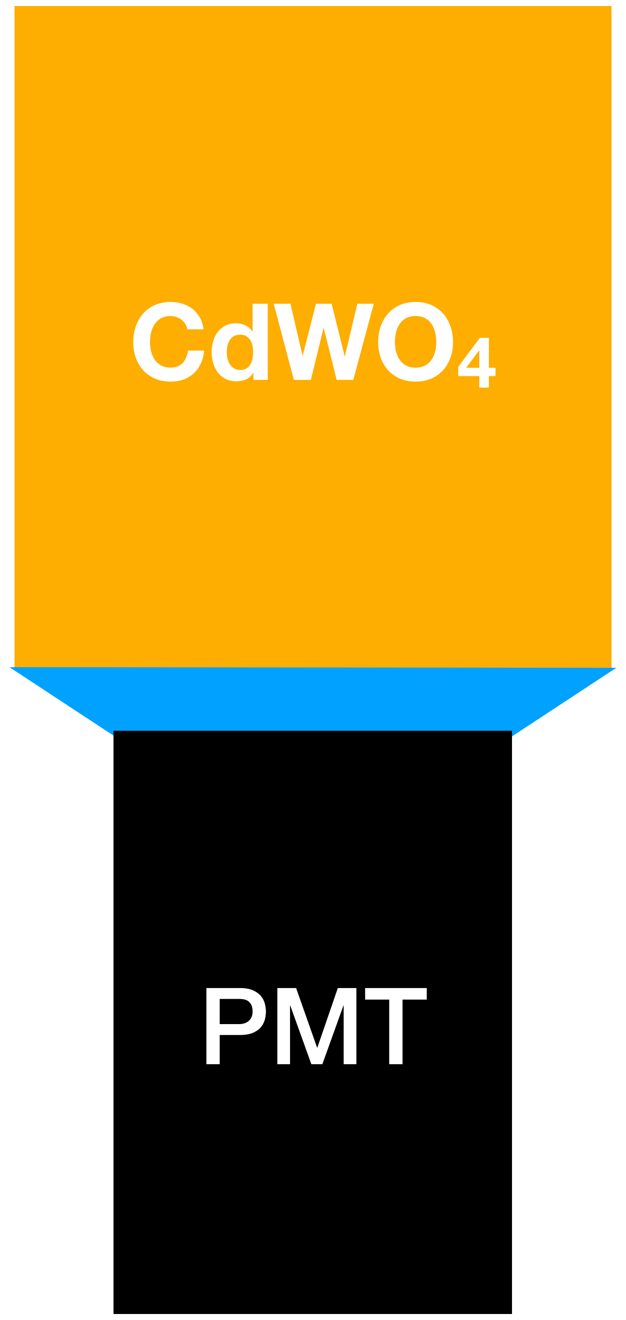
Phys. Lett. B 800 (2020) 135092

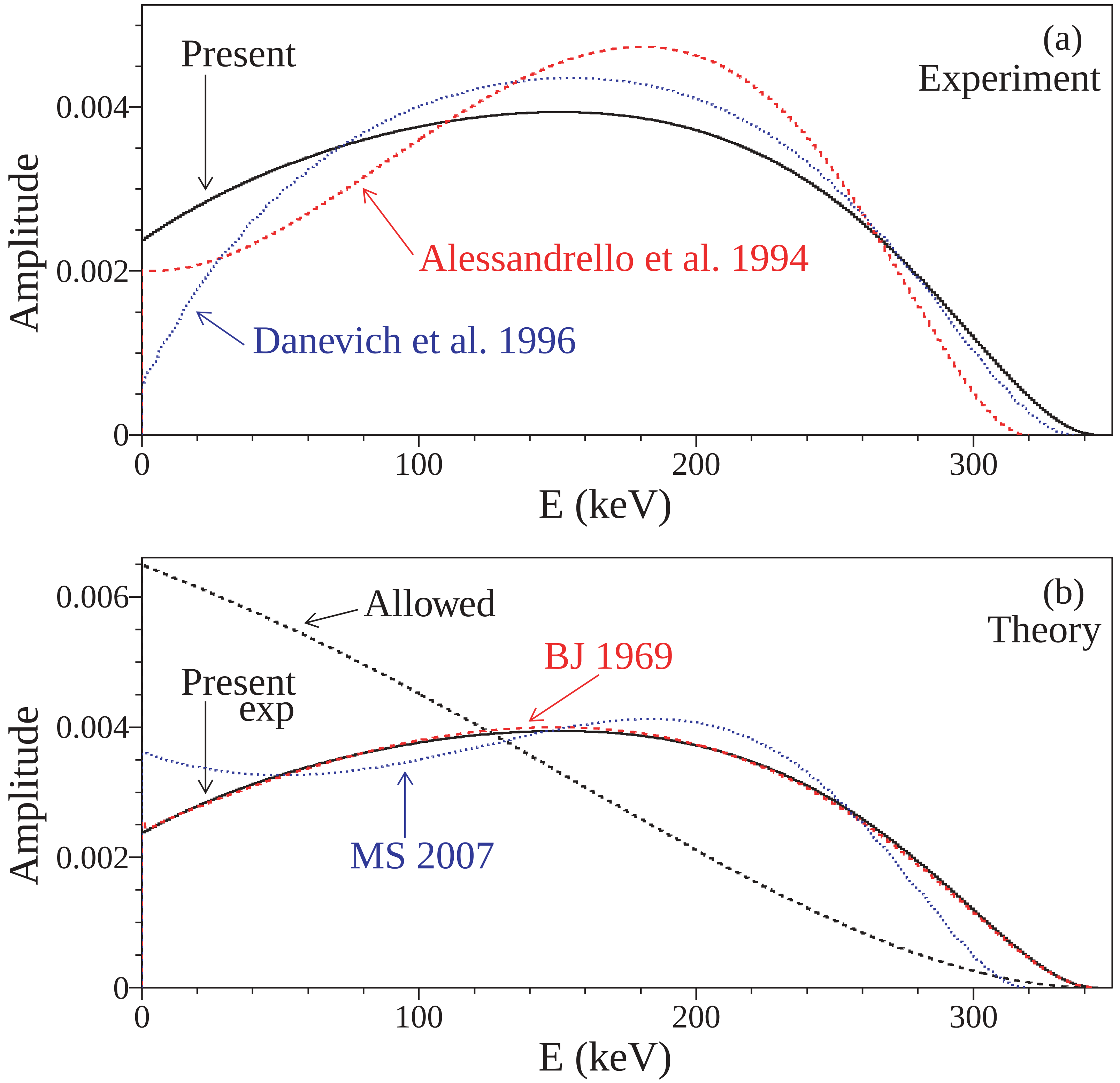
Detector material	E_{th} / keV	isotop. exp. / kg d	FWHM / keV	S/B ratio	$T_{1/2}$ / 10^{15} yrs	Ref., year
$CdWO_4$, 454 g	44	0.31	~49	~50	7.7 ± 0.3	[48], 1996
CdZnTe, 3×5.9 g	100	0.05	~43	~8	$8.2^{+0.3}_{-1.0}$	[49], 2005
$CdWO_4$, 434 g	28	1.90	~47	~56	8.04 ± 0.05	[41], 2007
CdZnTe, 11×6.5 g	110	0.38	~20	~9	8.00 ± 0.26	[50], 2009
CdZnTe, 45×6.0 g	84	2.89	~18	~47	–	present work

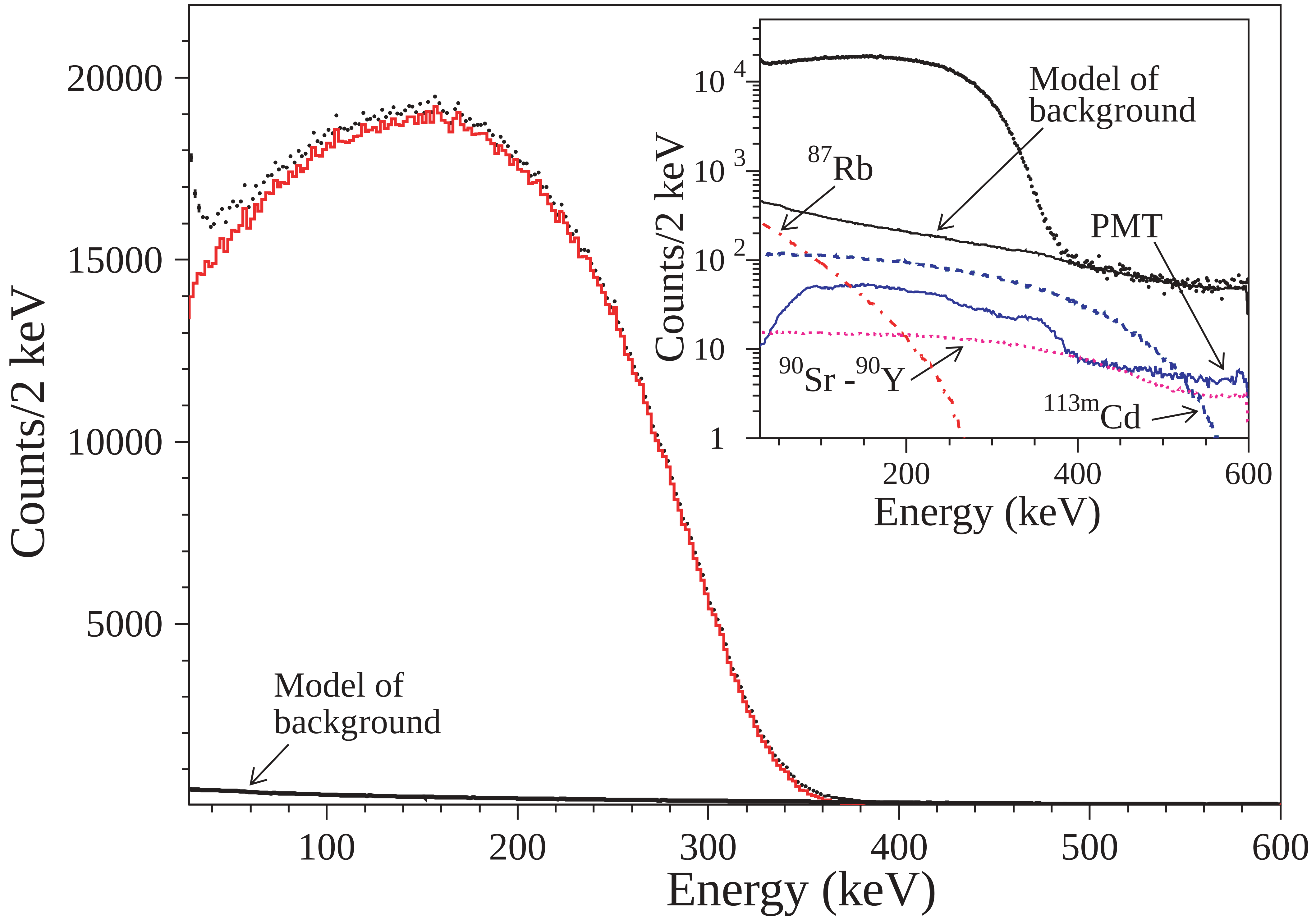
Cd-113 by DAMA

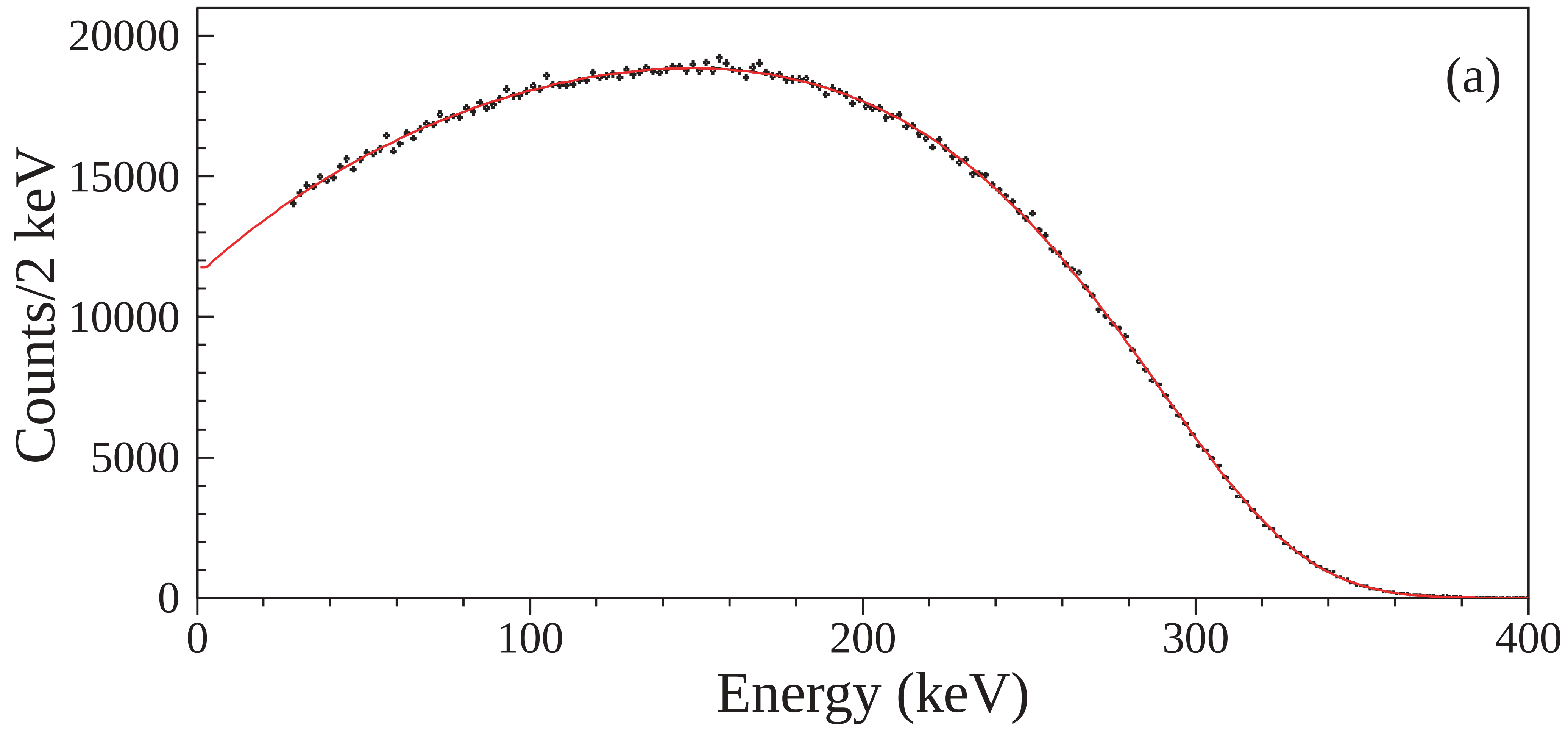
PHYSICAL REVIEW C **76**, 064603 (2007)

- CdWO4 scintillating crystal
- Q-value = (343.1 ± 0.6) keV [Kurie Plot - tension]
- Half-life = (8.04 ± 0.05)x10^{14} yr
- Spectral shape with polynomial coefficients
- Detailed comparison with theory

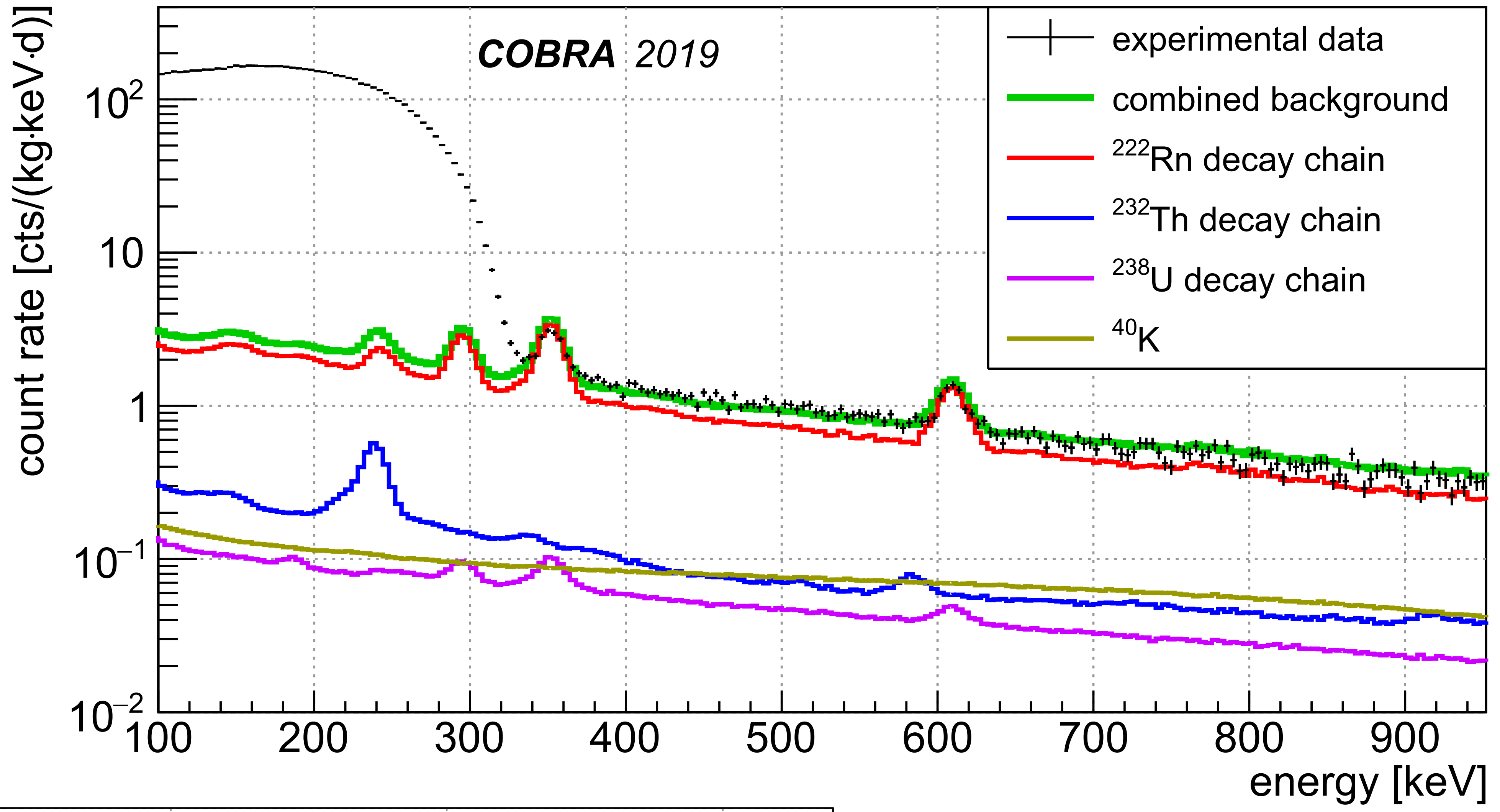








Cd-113 by COBRA

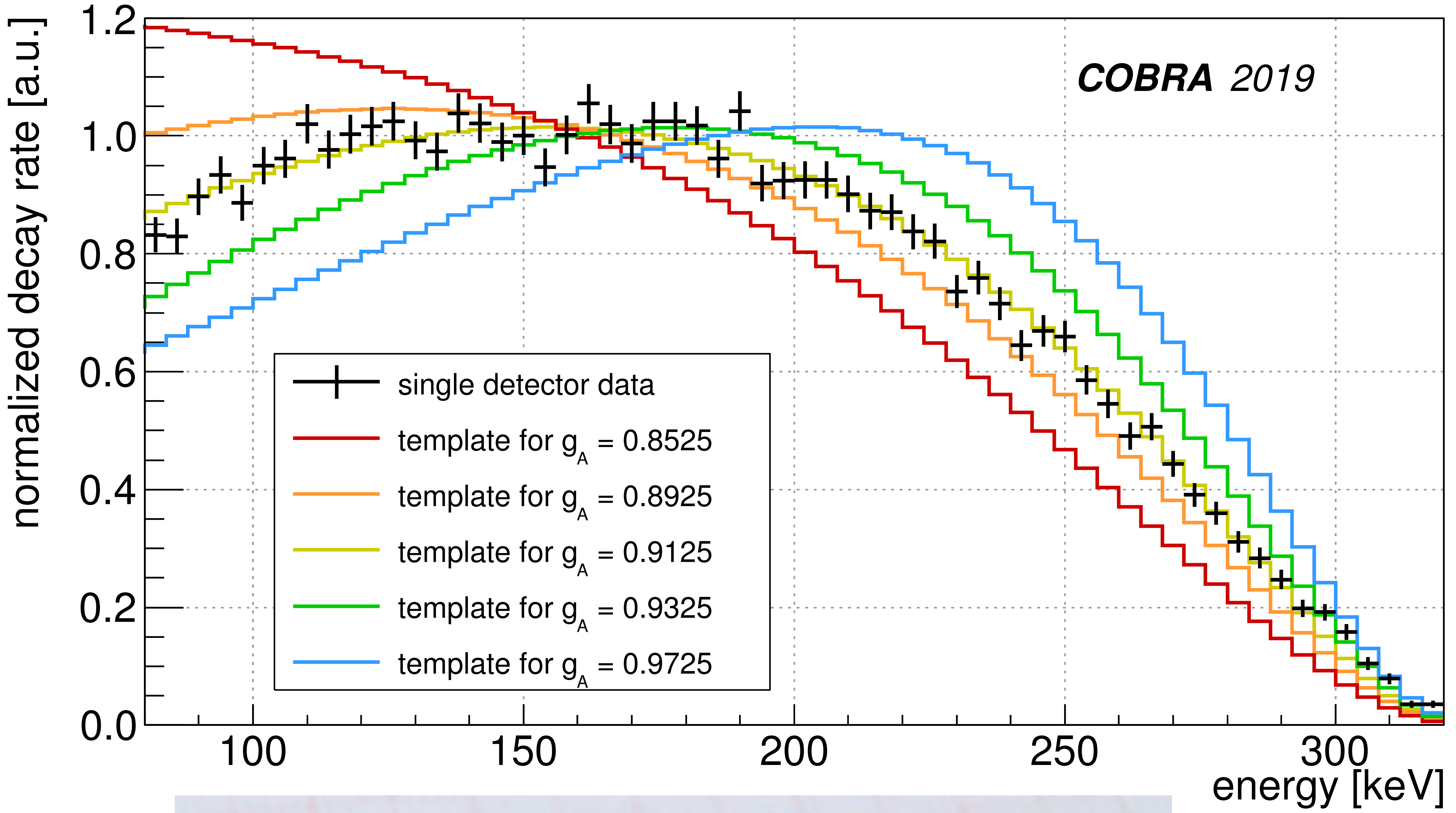


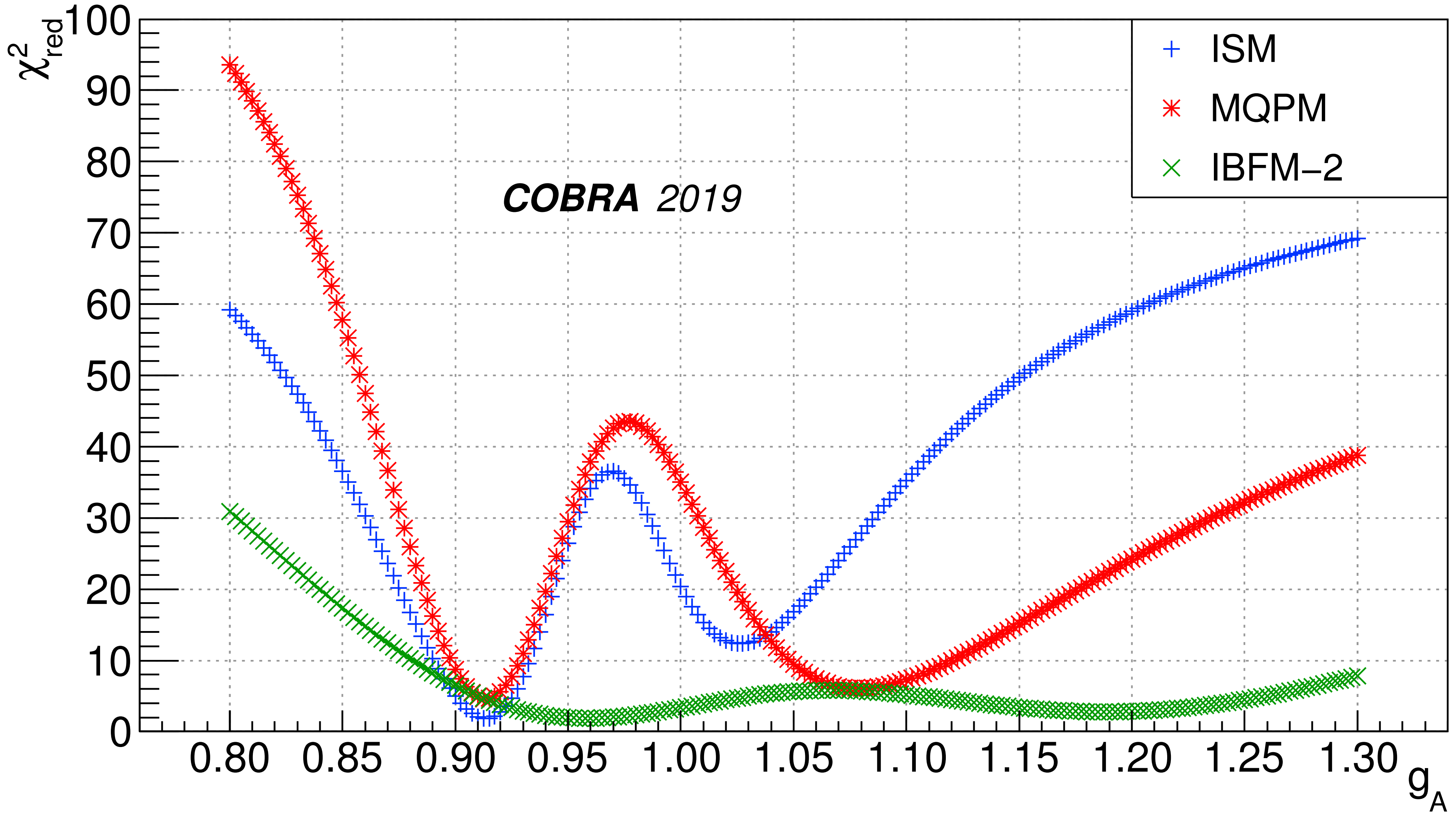
- Spectral shape reproduced by theory, varying g_A

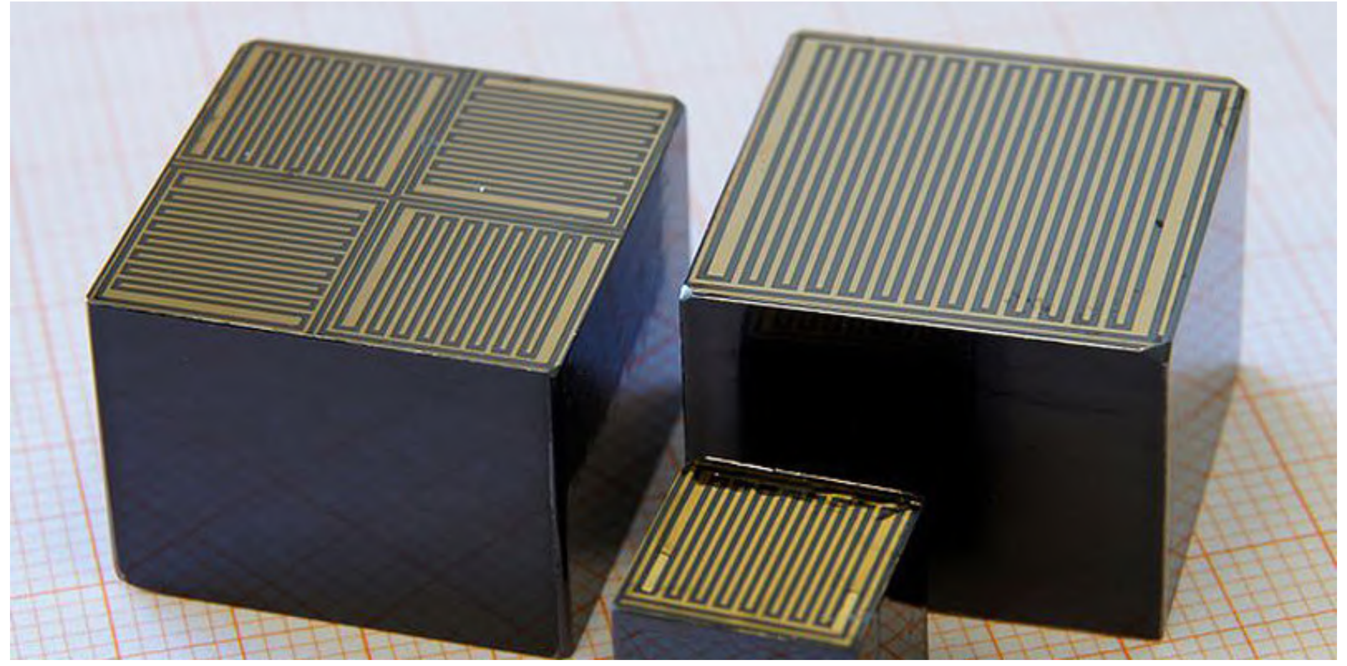
BUT

- no Q-value measurement
- no Half-life measurement

Physics Letters B 800 (2020) 135092



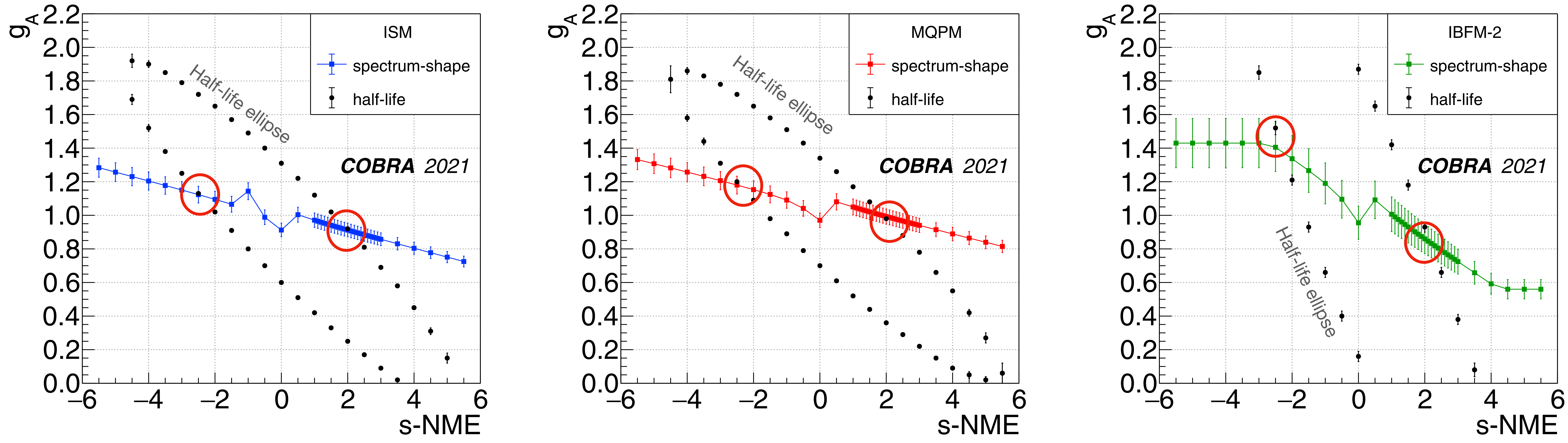




CdZnTe semiconductors

Cd-113 (COBRA reanalysis)

A novel approach to simultaneously reproduce the **spectral shape** and the **half-life** introducing as free parameter the s-NME (small Nuclear Matrix Element).

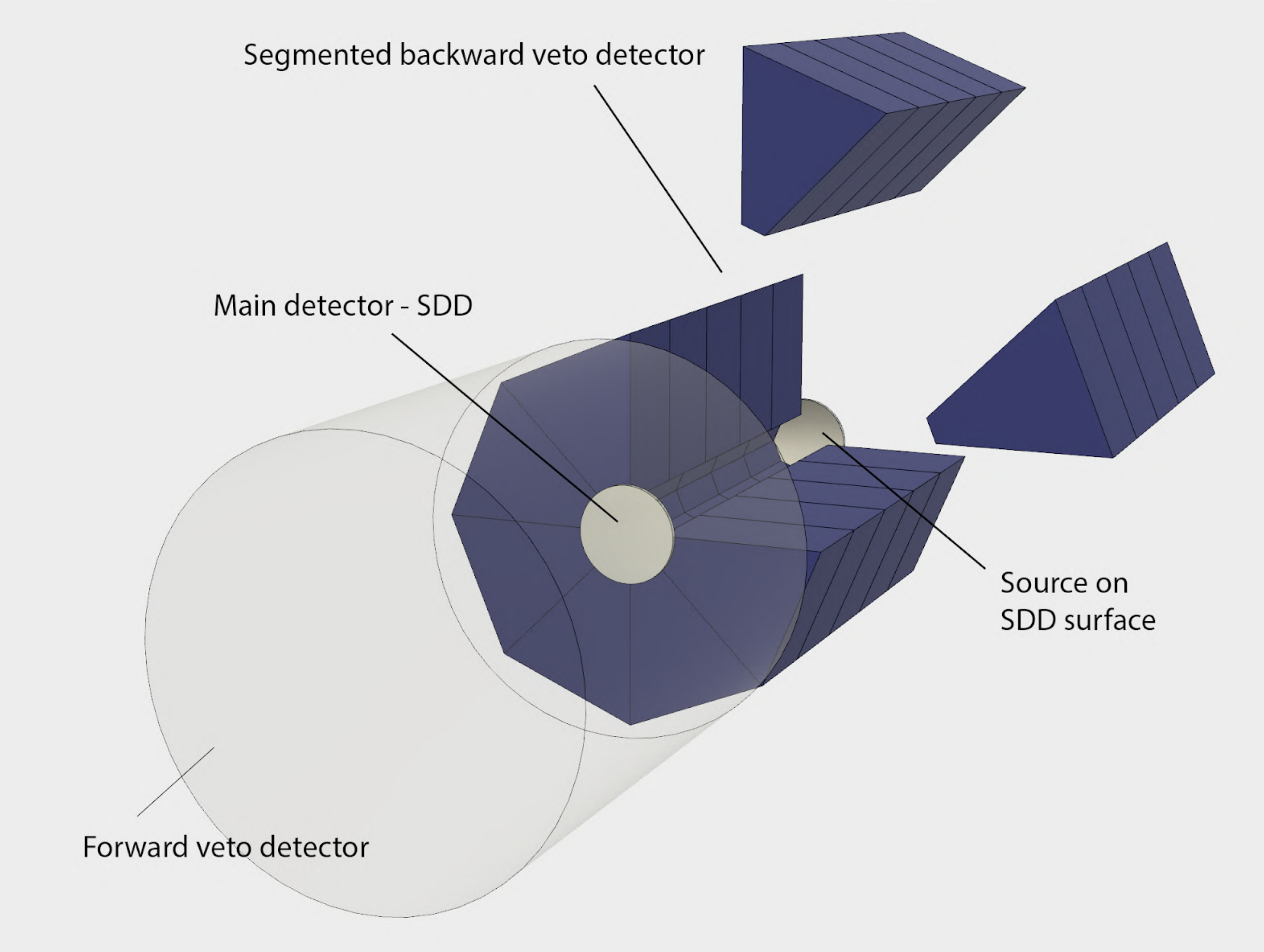


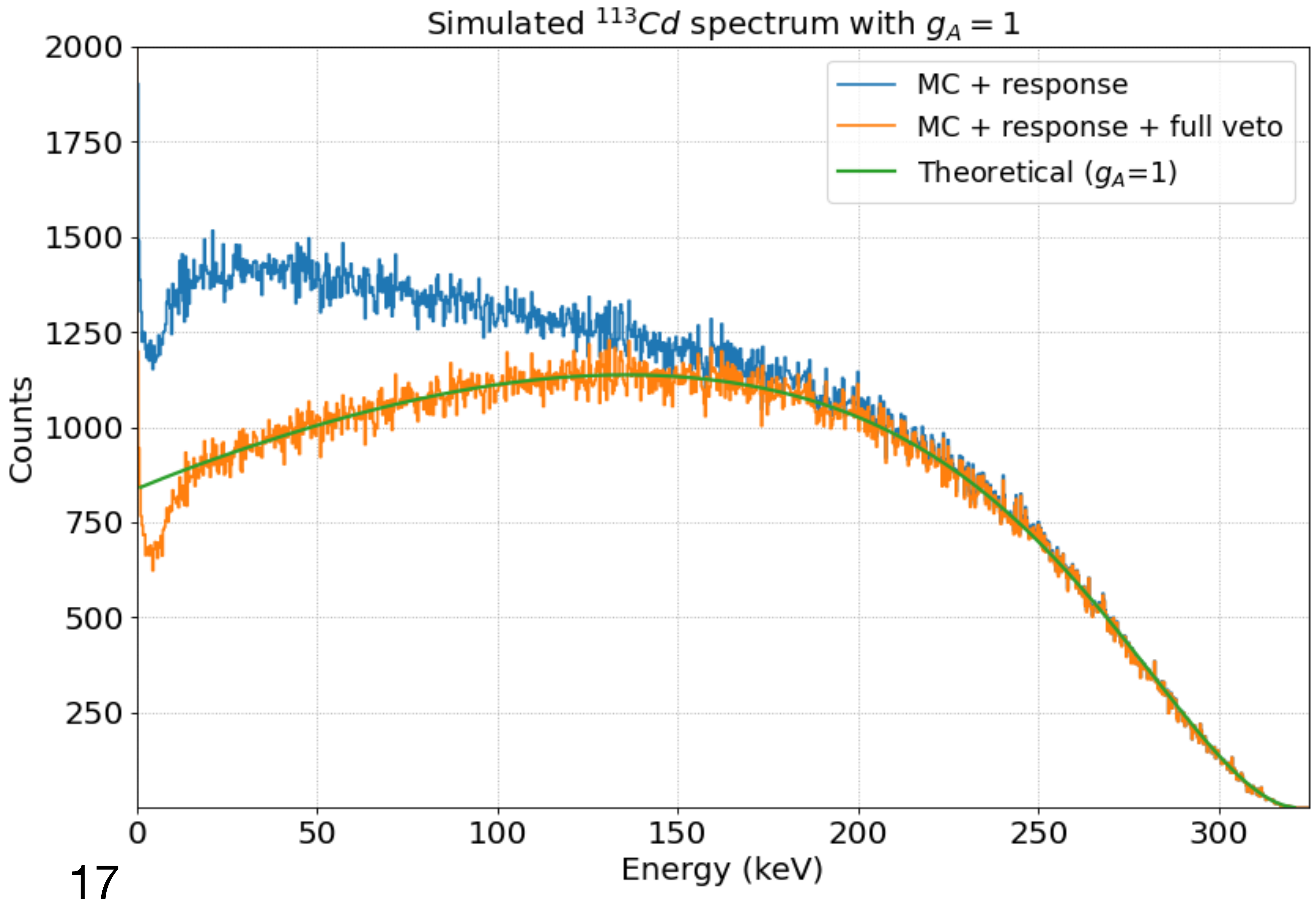
Phys. Lett. B 822 (2021) 136652

Cd-113 with Silicon Drift Detectors

Journal of Physics: Conference Series ***2453*** *(2023) 012020*

- Source ≠ detector
- On the surface of an SDD acting as veto
- Electrons detected by a second SDD
- Active veto for backscattered electrons



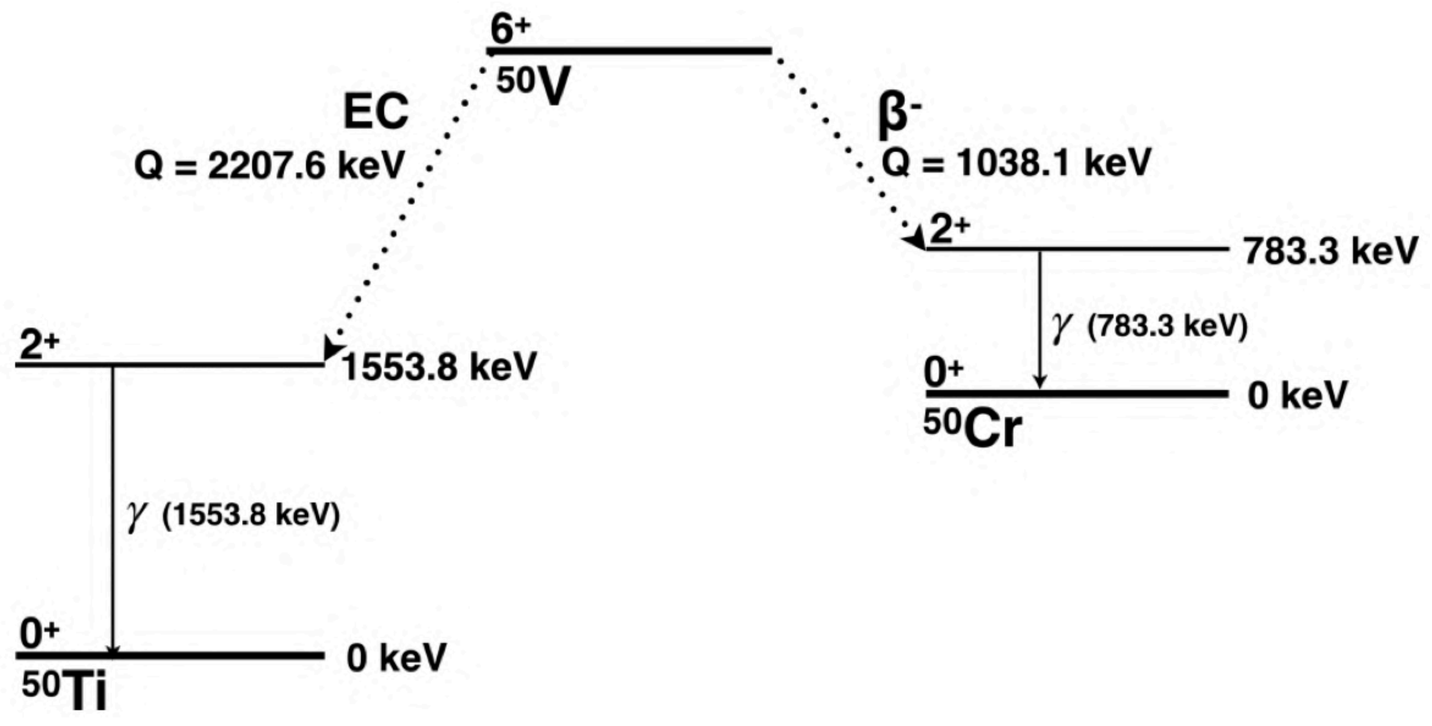


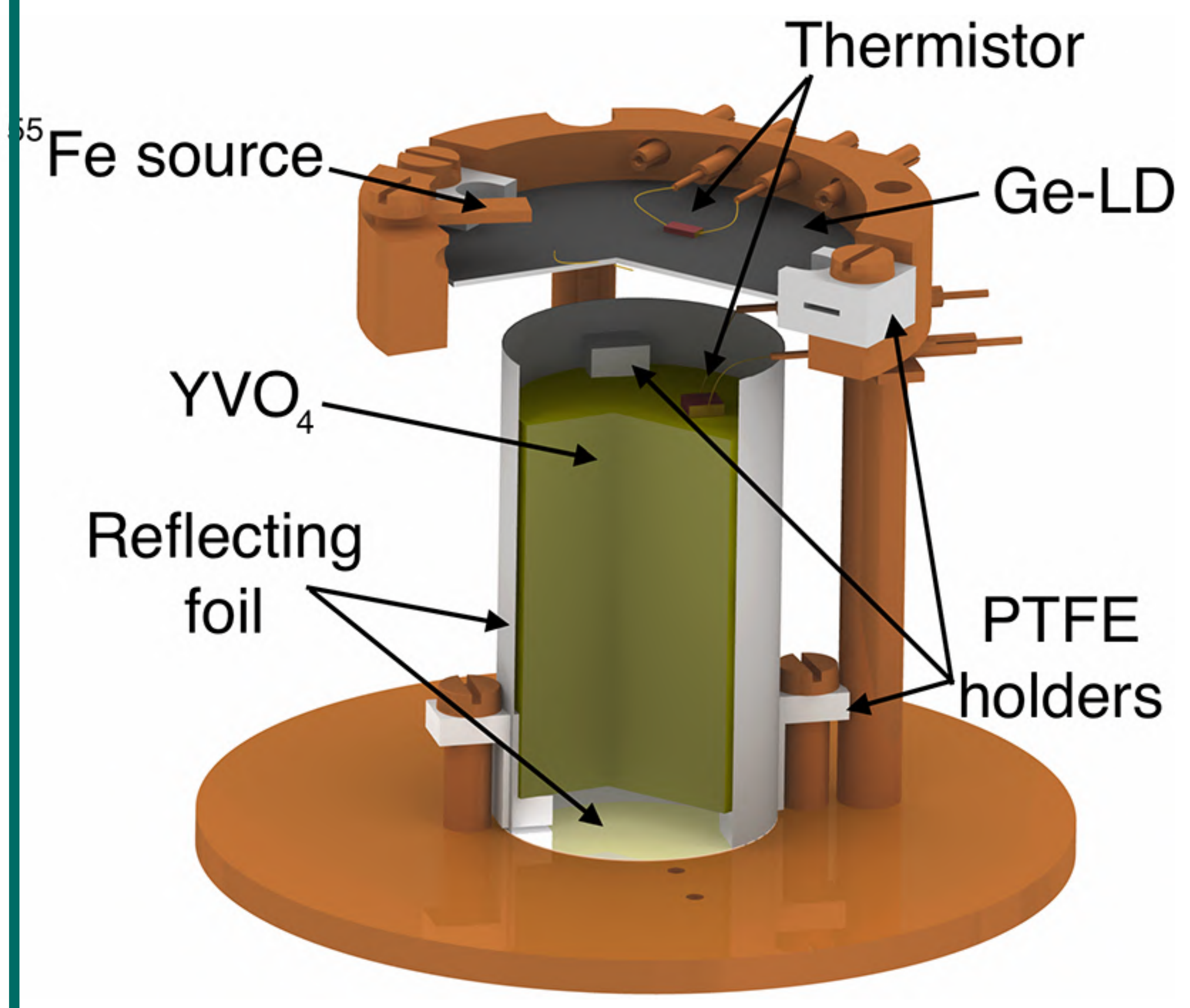
Vanadium-50

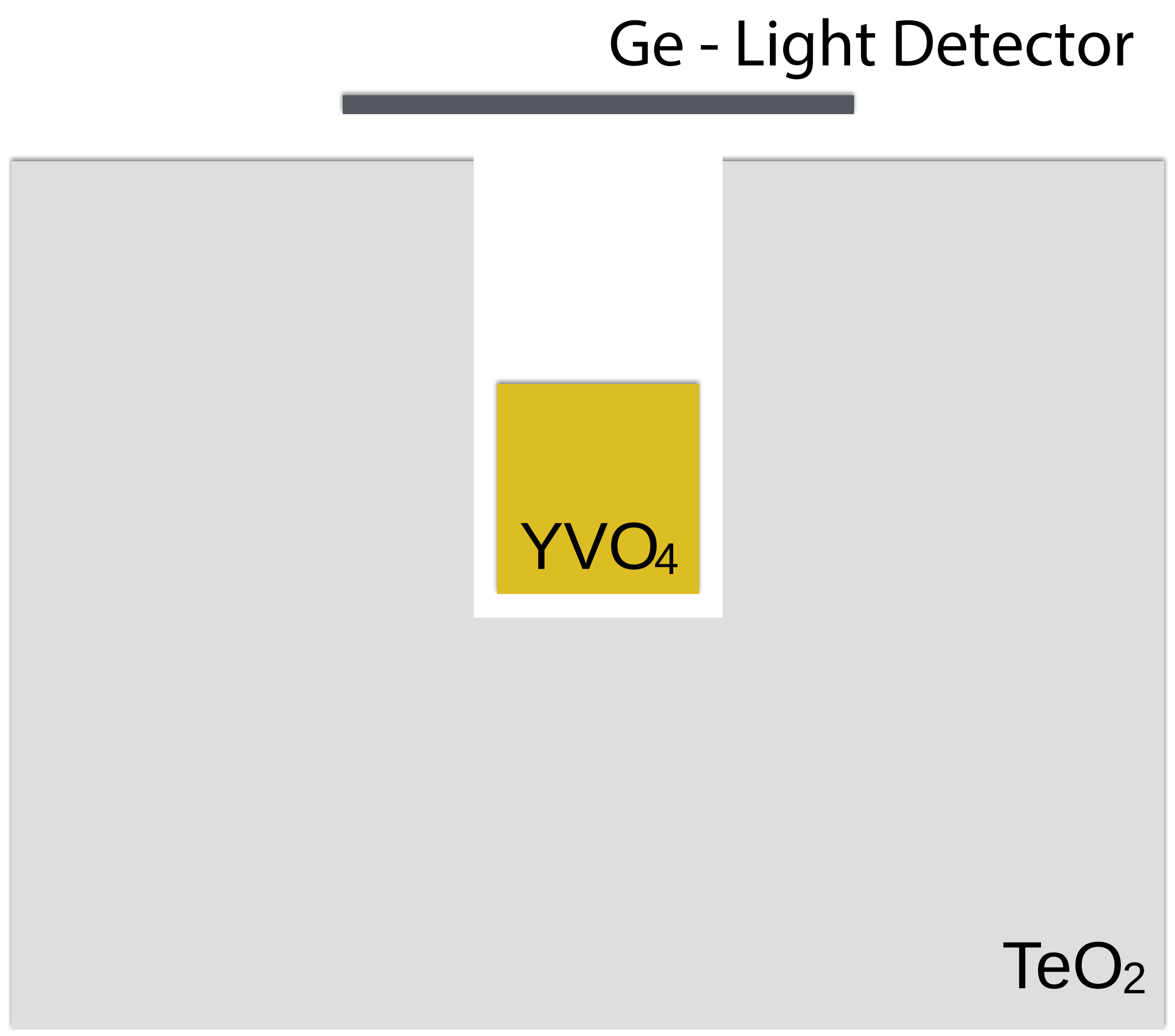
Q-value	Half-life	Classification
1038 keV	>1.9×10^{19} yr	$6^+ \rightarrow 2^+ \quad \Delta J^{\Delta\pi} = 4^+$

Opposite situation wrt Cd113:

- Low natural abundance i.a. =0.250%
- Observed only the EC branch
- Most stringent limit by HPGe detector measurement
- New measurement with HPGe and optimized setup
- Attempt with scintillators and cryogenic calorimeters







Sample for HPGe spectrometry

Recent developments:

- *Eur.Phys.J.A 54 (2018) 5, 79* (Bolometers)
- *PHYSICAL REVIEW C 99, 045501 (2019)* (HPGe)

Indium-115

Good experimental situation:

- High natural abundance i.a. = 95.71%
- Embedded in crystal as InI, InO, $LiInSe_2$
- Good radiopurity levels

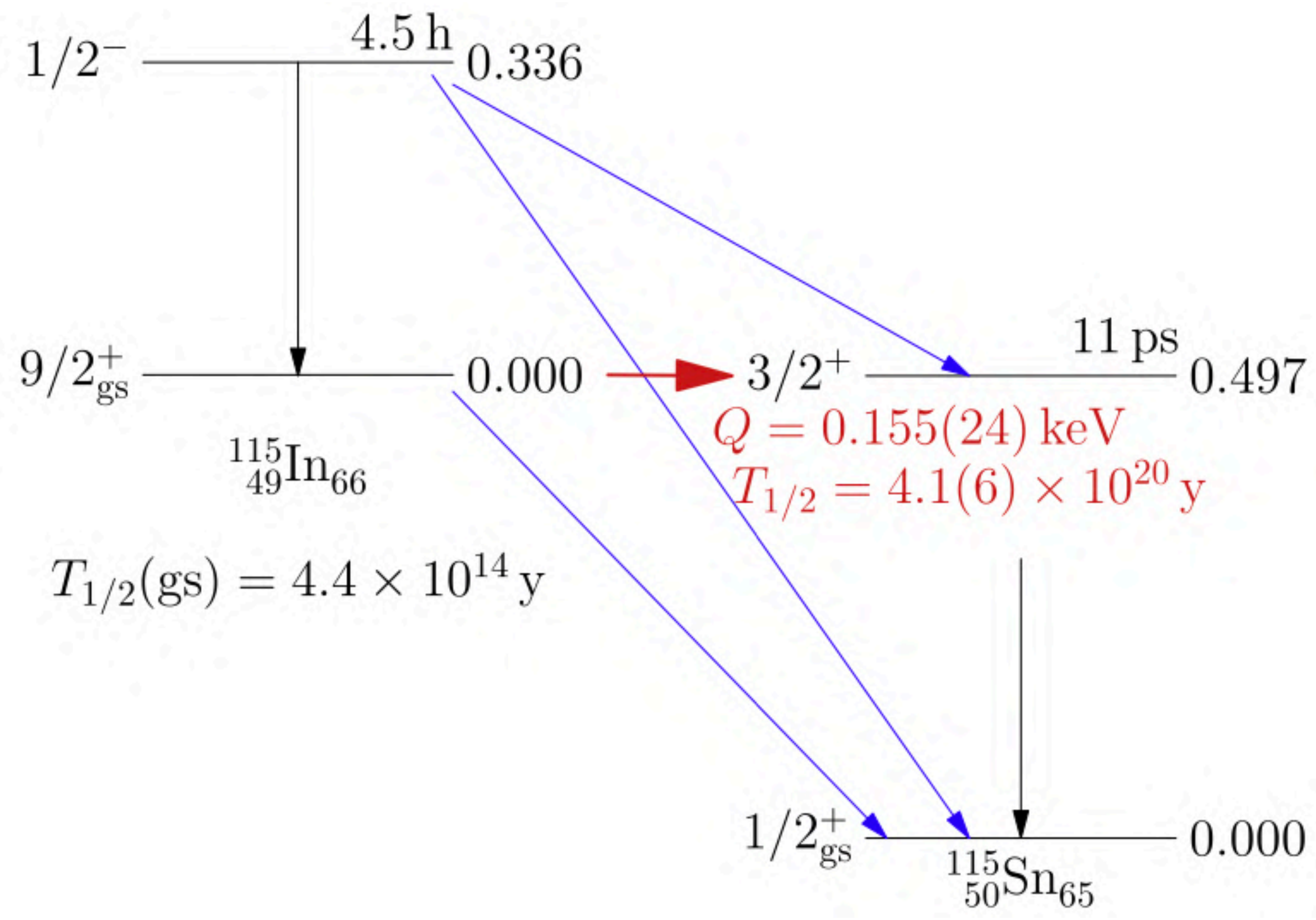
Q-value	Half-life	Classification
496 keV	4.41×10^{14} yr	$\frac{9}{2}^+ \rightarrow \frac{1}{2}^+ \quad \Delta J^{\Delta\pi} = 4^+$

Spectrum shape was measured **only in one work**: L. Pfeiffer et al., PRC 19 (1979) 1035

- Disagreement with previous results

  G.B. Beard et al., PR 122 (1961) 1576

  $T_{1/2} = (6.9 \pm 1.5) \times 10^{14}$ yr
- Energy threshold ~50 keV

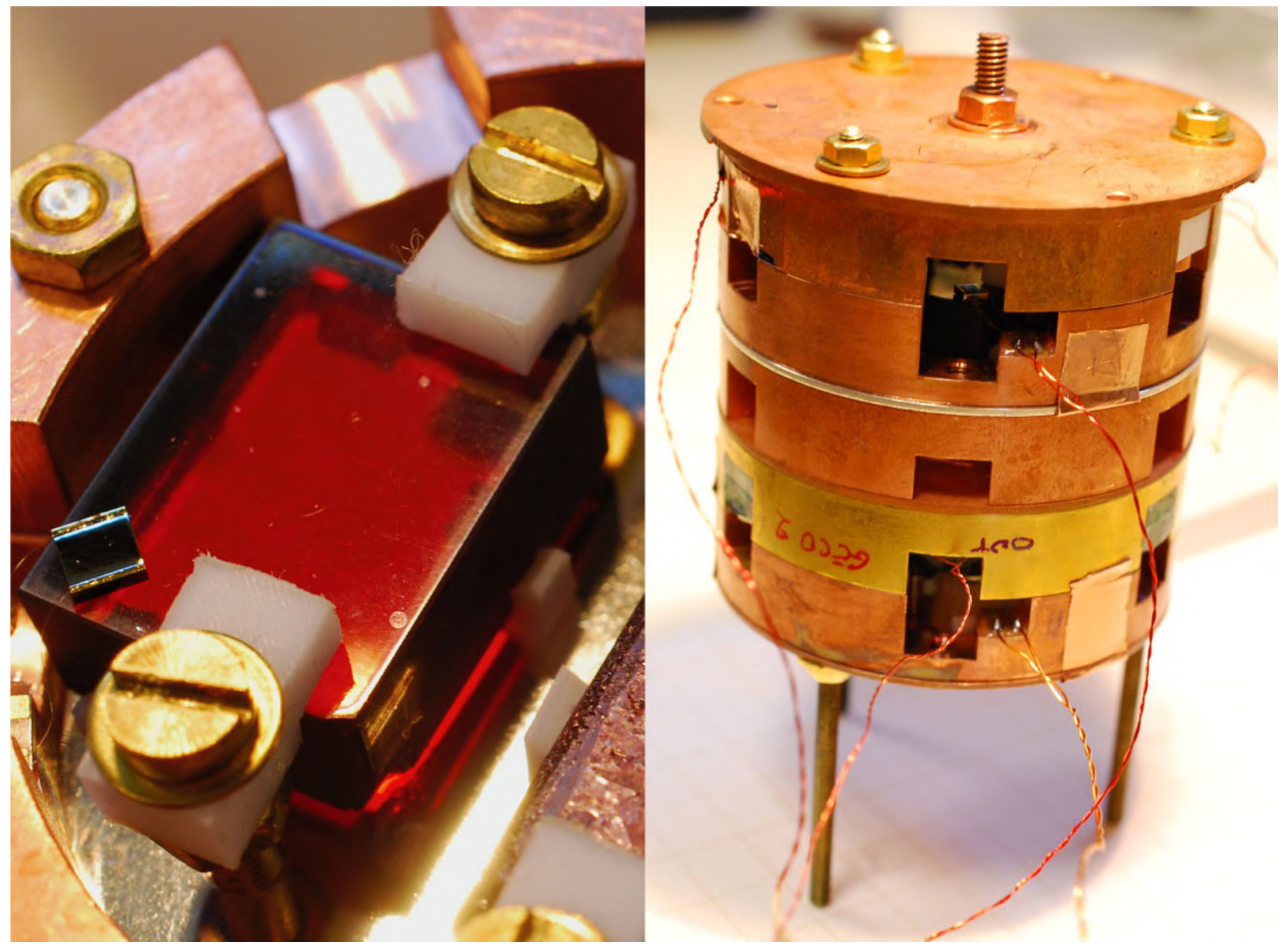


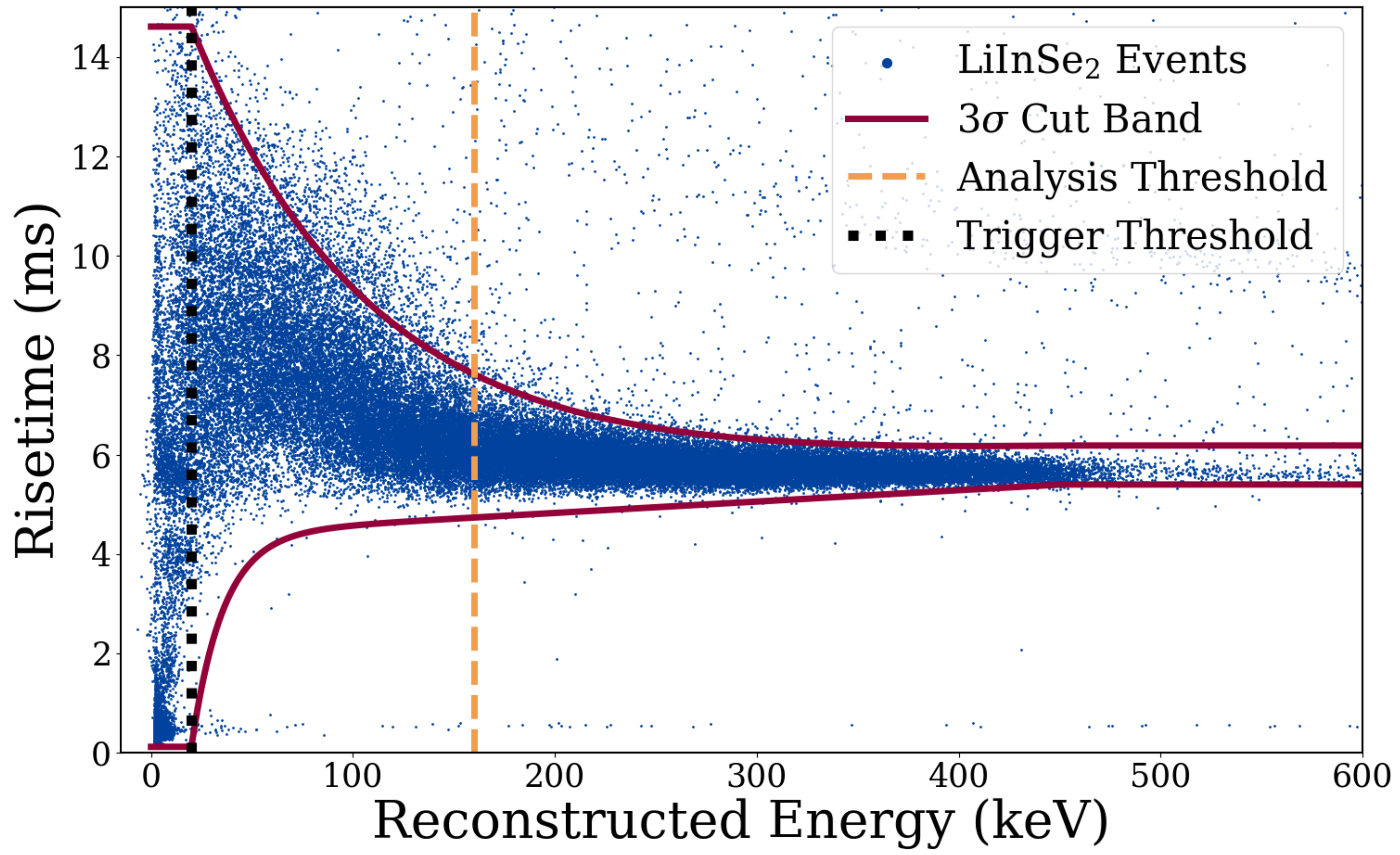
New low-background measurements are needed!

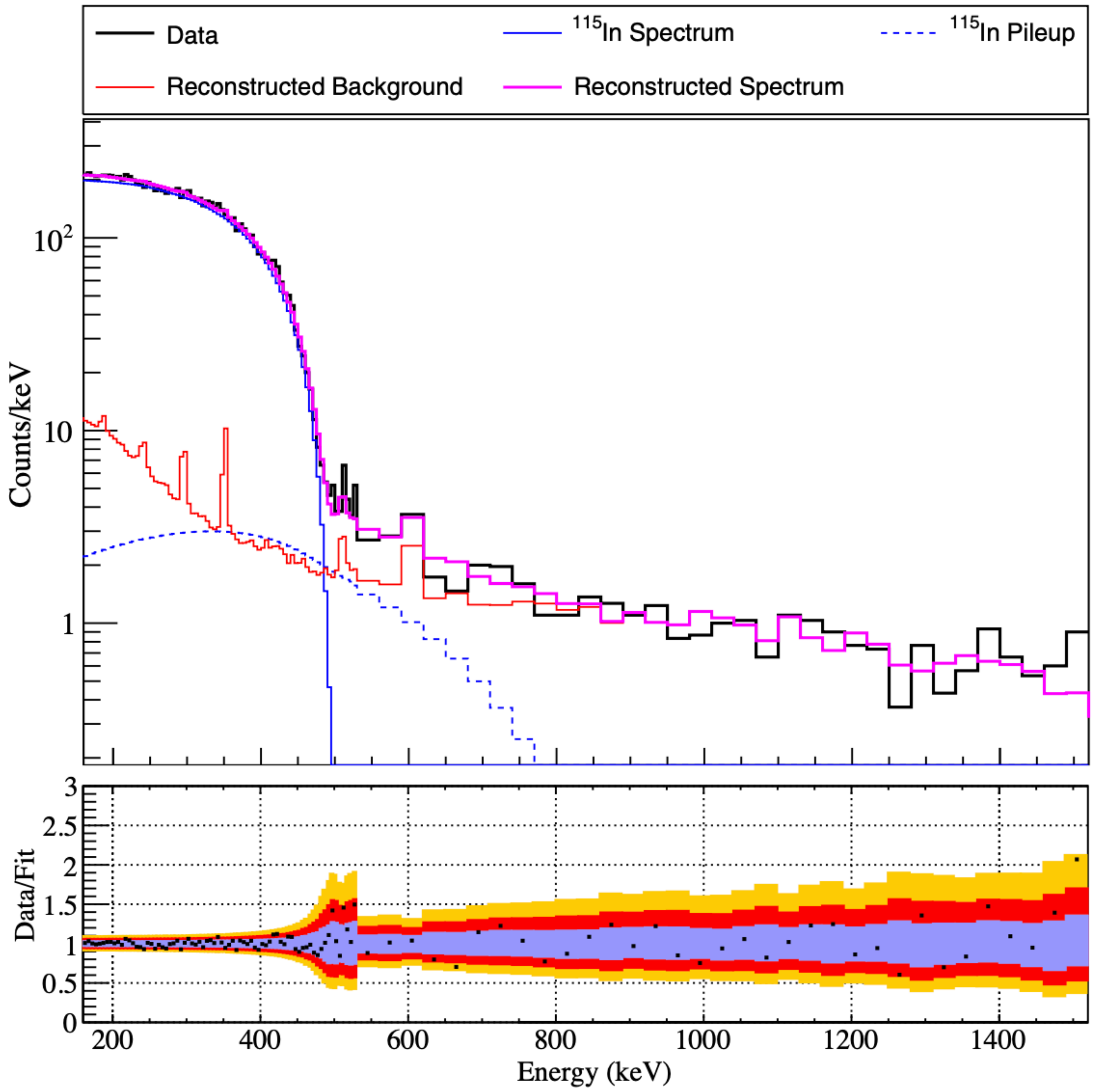
In-115

Phys. Rev. Lett. 129, 232502 (2022)

- $LiInSe_2$ measured as cryogenic calorimeter
- Excellent performance but high rate at low energy

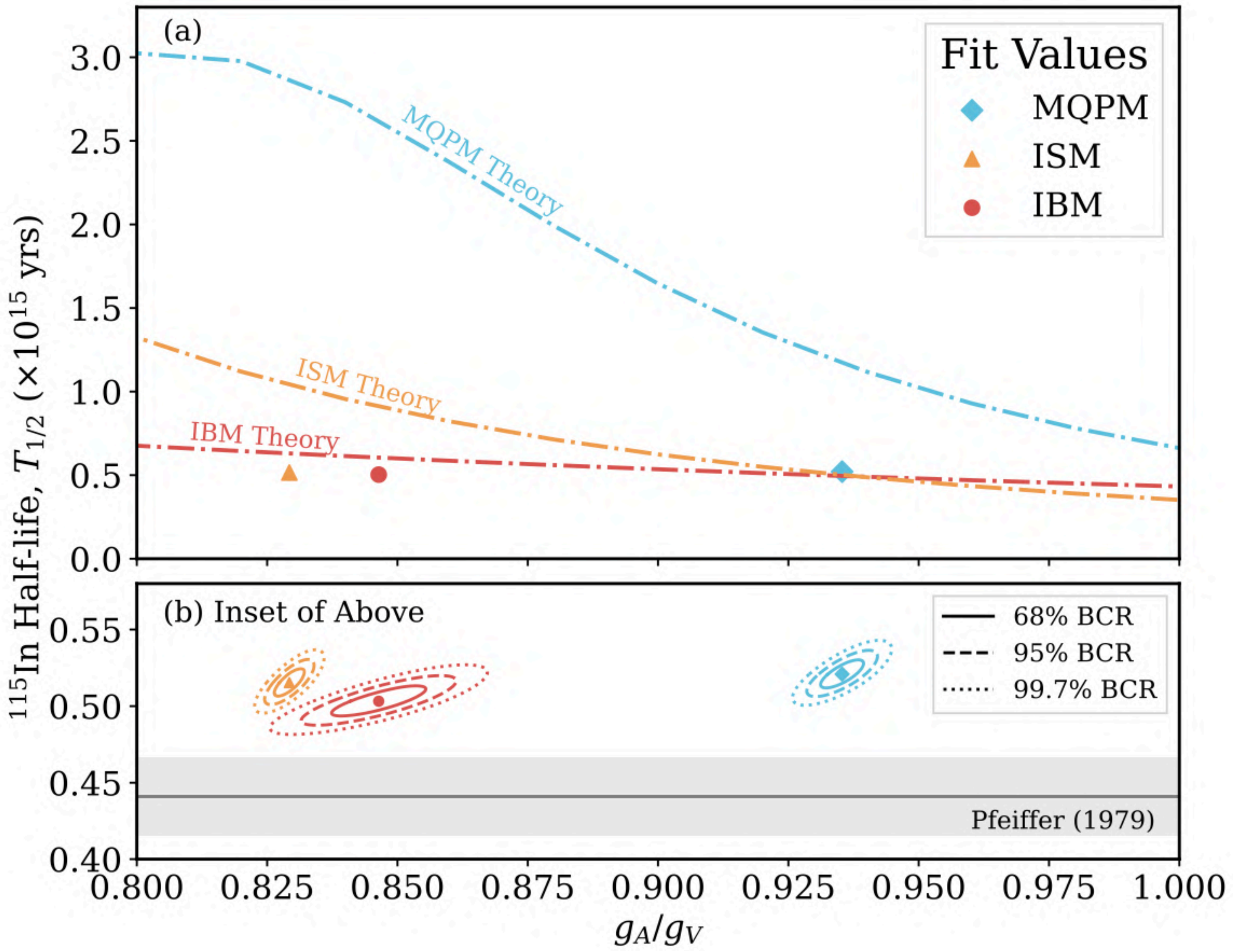






Detector parameter	$LiInSe_2$ crystal
Crystal dimensions	$1.3 \times 1.6 \times 0.7$ cm
Total crystal mass	10.3 grams
Effective ^{115}In mass	4.1 grams
Noise level	1.1 keV (1σ)
Avg. energy resolution	2.4 keV (1σ)
100% Trigger threshold	20.0 keV
Analysis threshold	160 keV
Containment efficiency	96.6% @ 497 keV
Data selection cut efficiency	47.6(2)% (160–500 keV)
Livetime fraction	52.54(8)%
Total exposure	39.7 g days

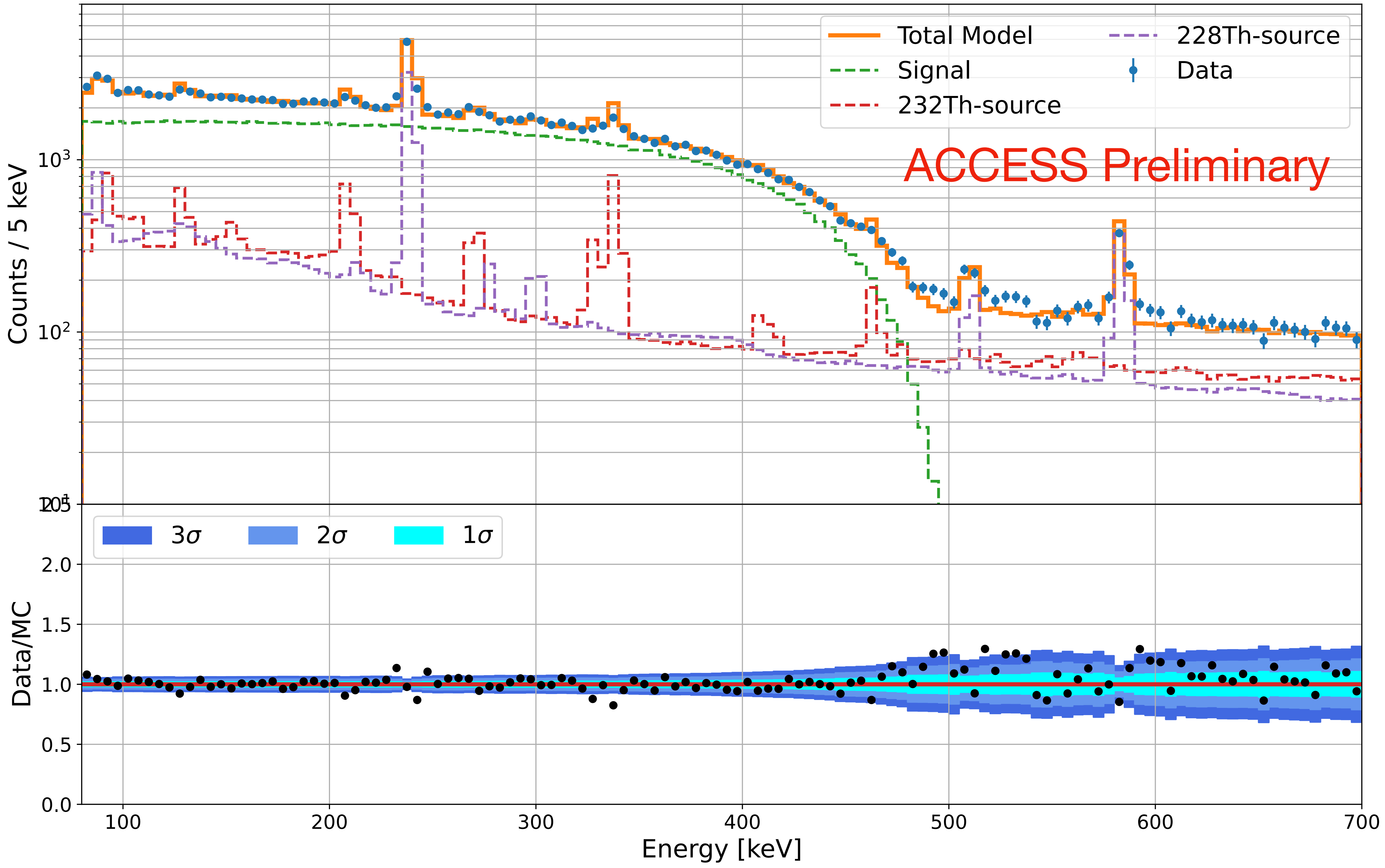
Model	g_A/g_V	$T_{\frac{1}{2}}^{115\mathrm{In}}$ (10^{14} yr)	Reduced χ^2
ISM	0.830 ± 0.002	5.177 ± 0.060	1.58
IBM	0.845 ± 0.006	5.031 ± 0.065	1.50
MQPM	0.936 ± 0.003	5.222 ± 0.061	1.60
Pfeiffer *et al.* [42]		4.41 ± 0.25	
Watt and Glover [70]		5.1 ± 0.4	
Beard and Kelly [71]		6.9 ± 1.5	

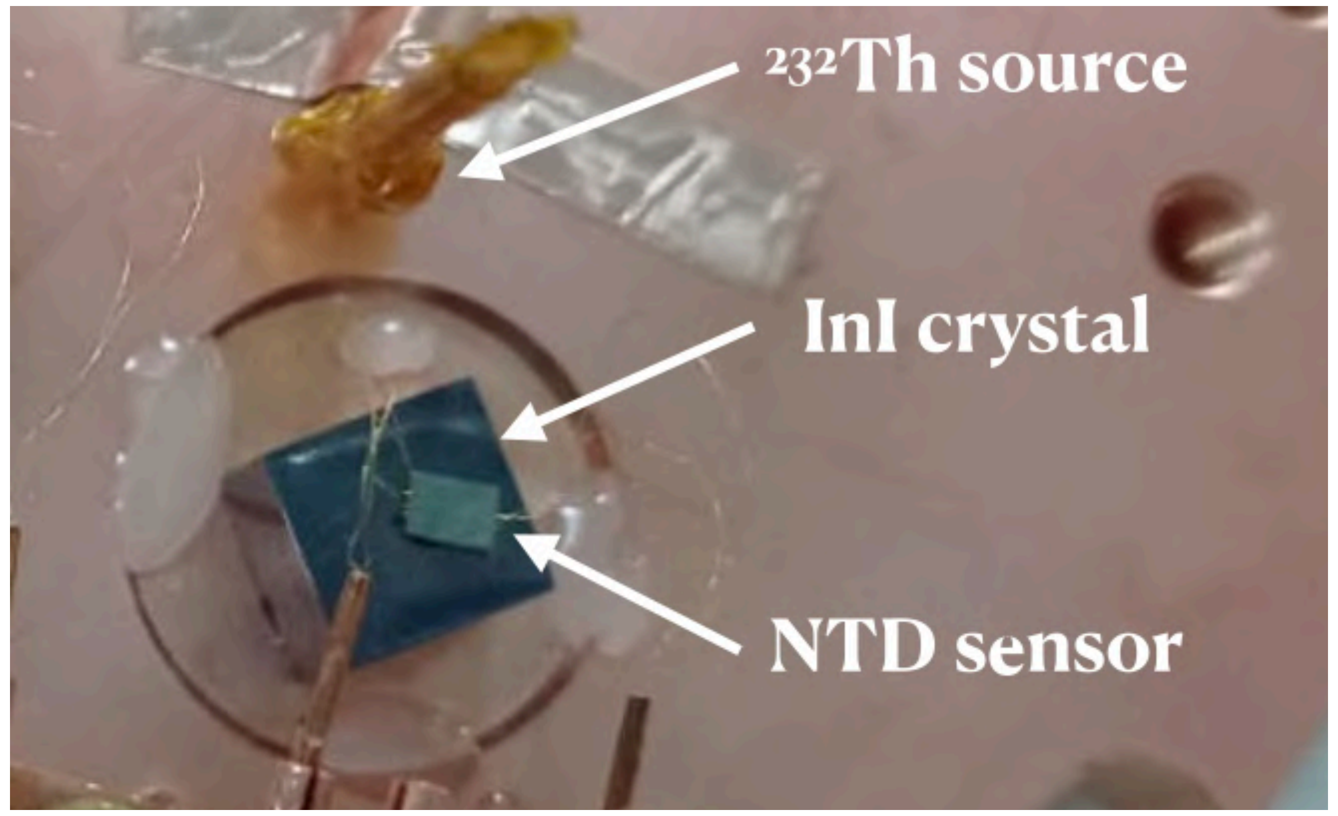


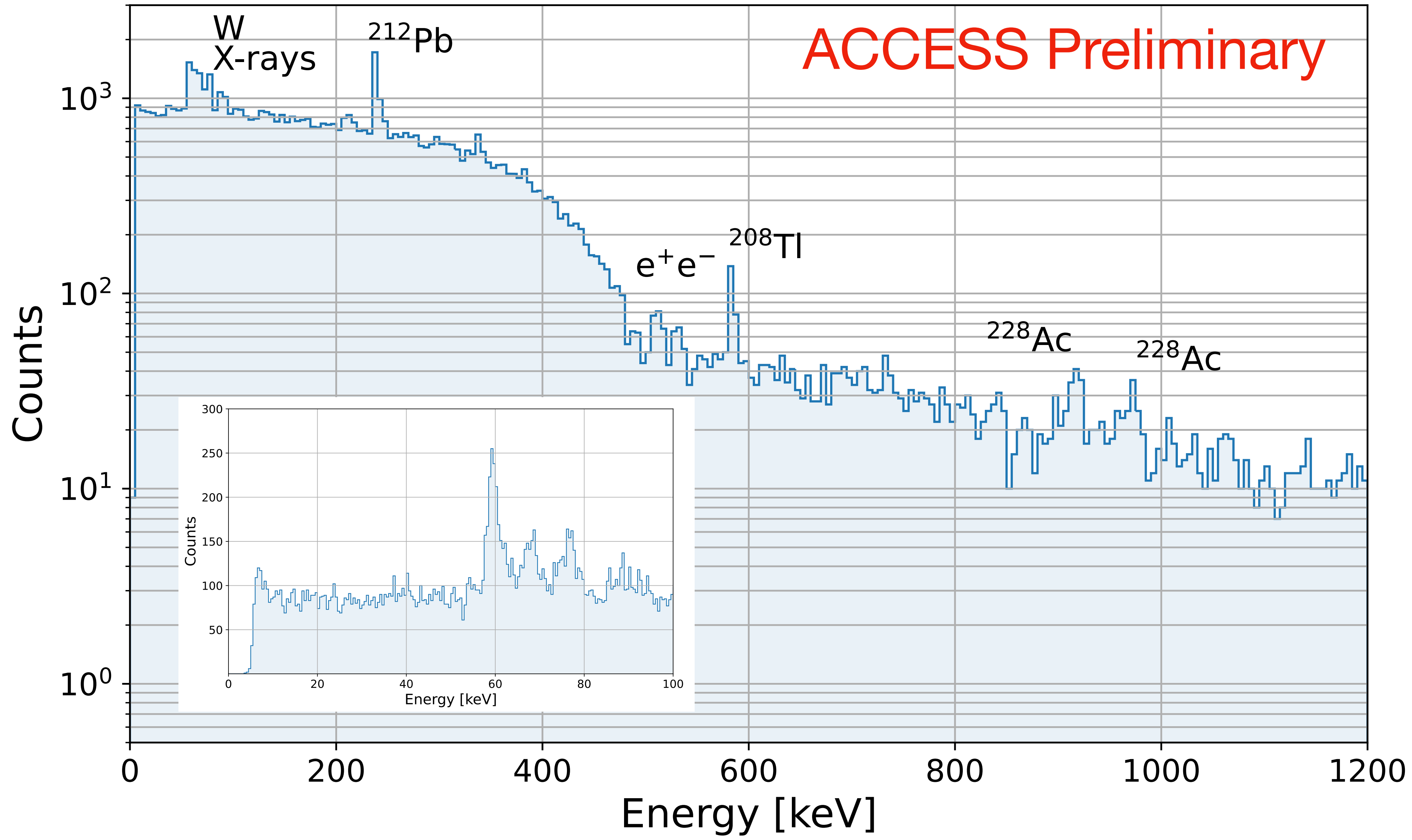
In-115 by ACCESS

- Indium Iodine (InI) crystal measured as cryogenic calorimeter
- Excellent performance
  - Threshold ~7 keV
  - 3.1 keV FWHM at 60 keV
  - Half-life = 4.77×10^{14} yr

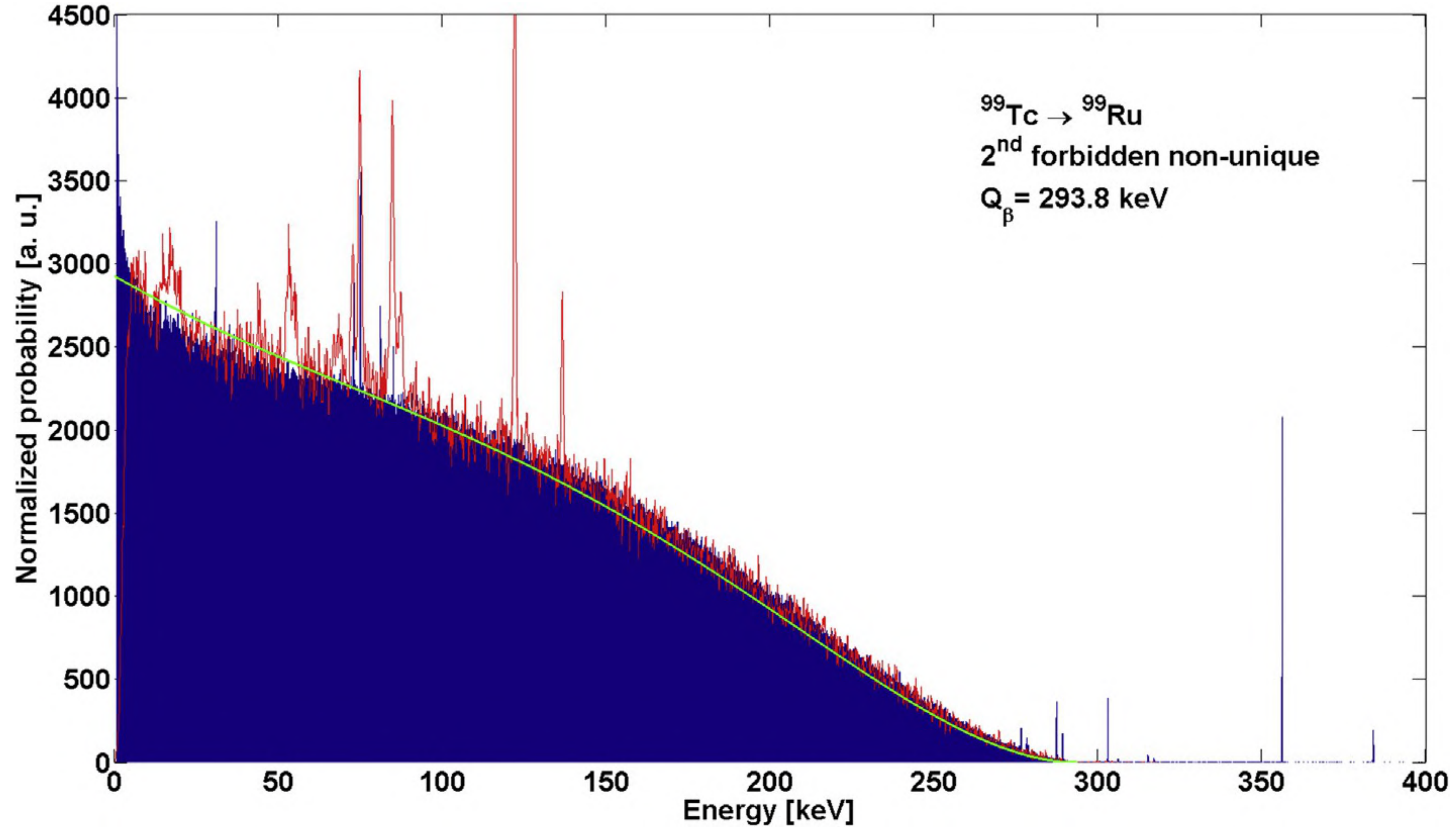
Eur.Phys.J.Plus 138 (2023) 5, 445

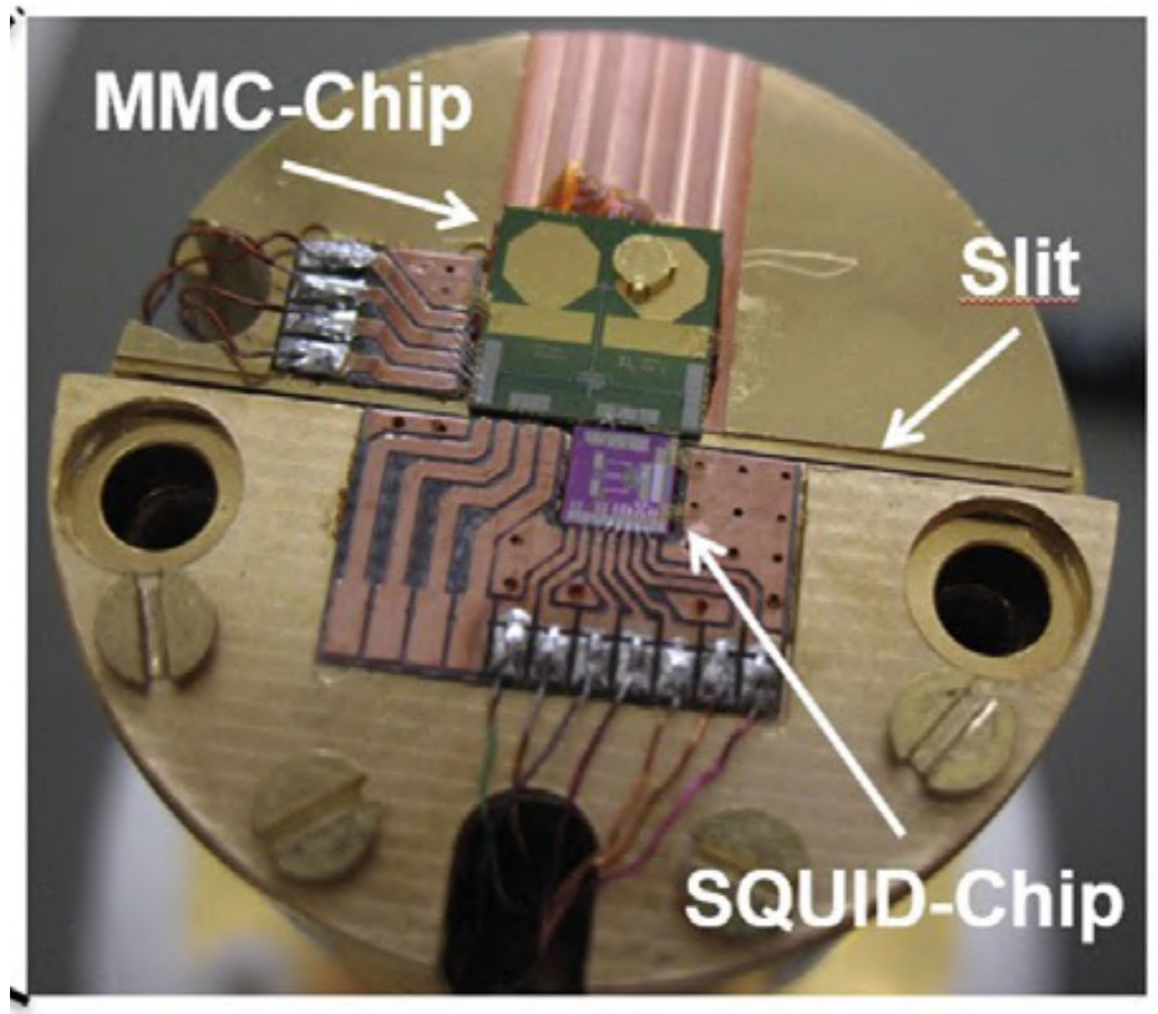


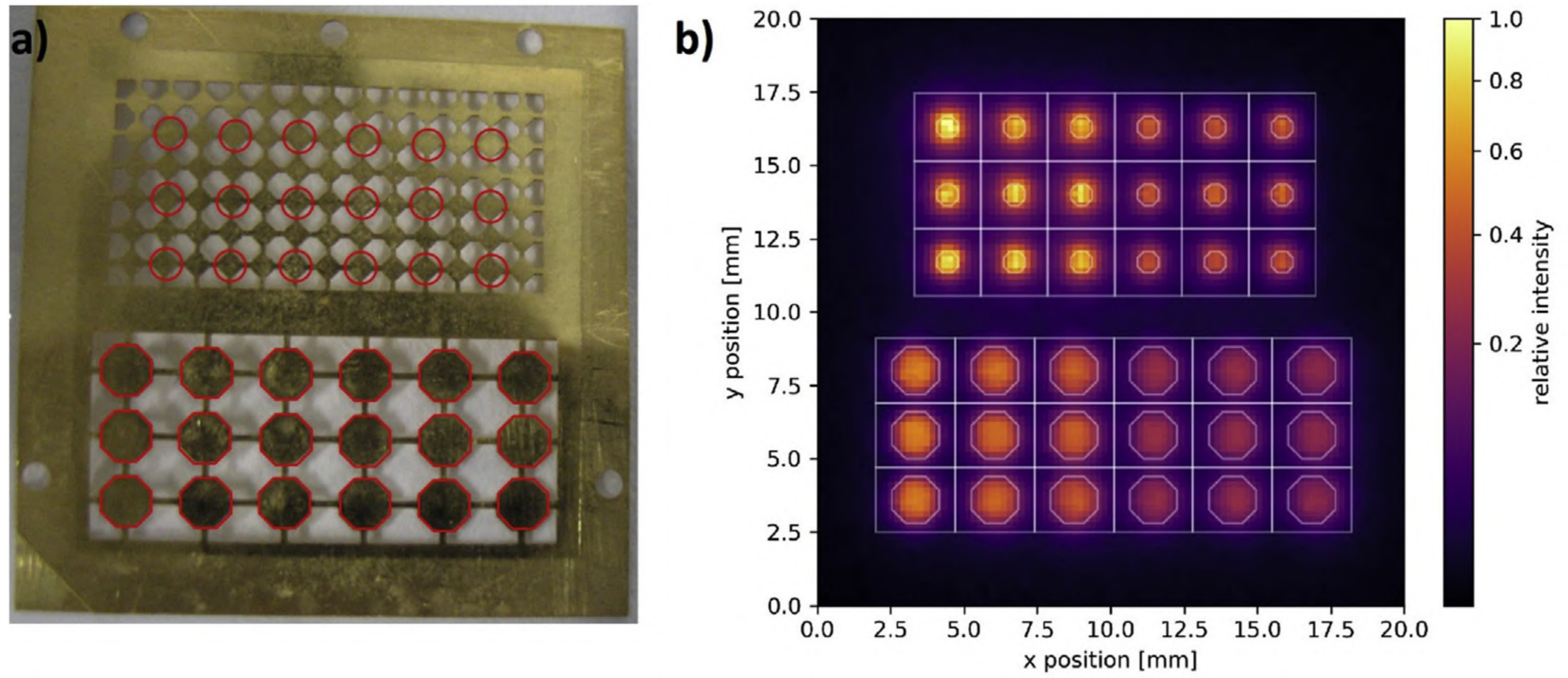


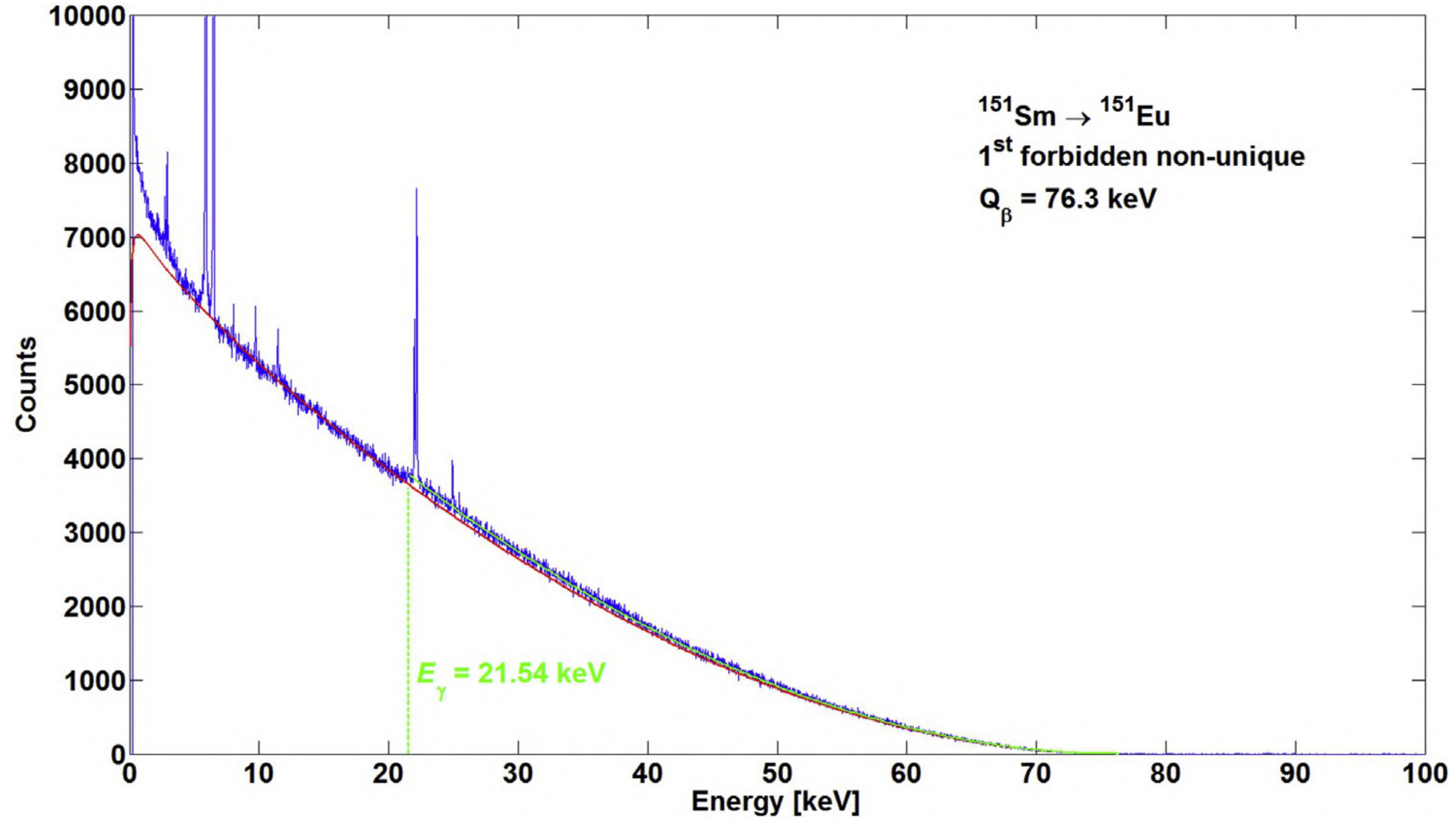


Artificial Isotopes









MetroBeta project => ^{99}Tc, ^{151}Sm (and others) electrodeposited on silver foils or dropped on gold foils than used as an **absorber coupled to a MMC** (Metallic Magnetic Calorimeter)

App. Rad. Iso. 153 (2019) 108830

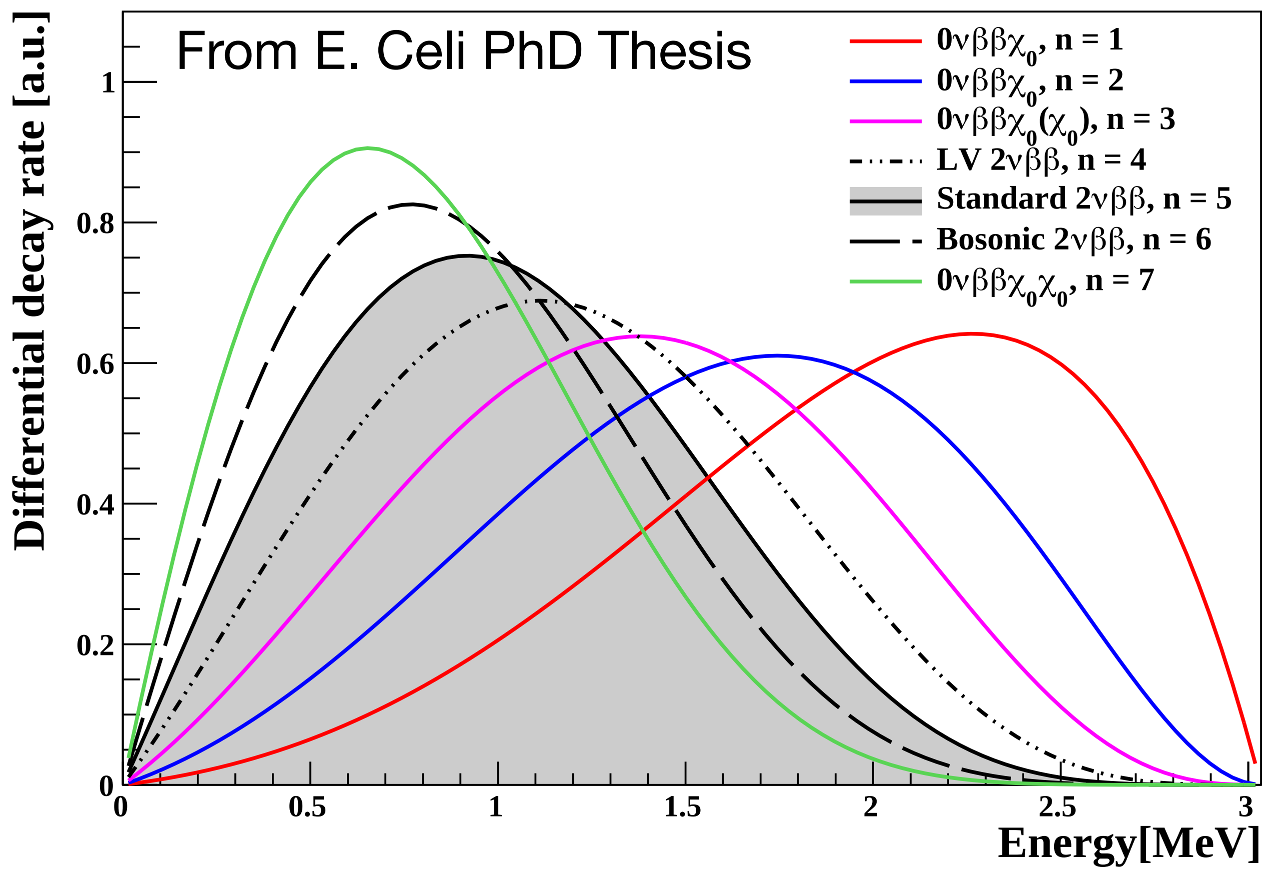
App. Rad. Iso.185 (2022) 110237

BetaShape code => used to reproduce the spectra

http://www.lnhb.fr/rd-activities/spectrum-processing-software/

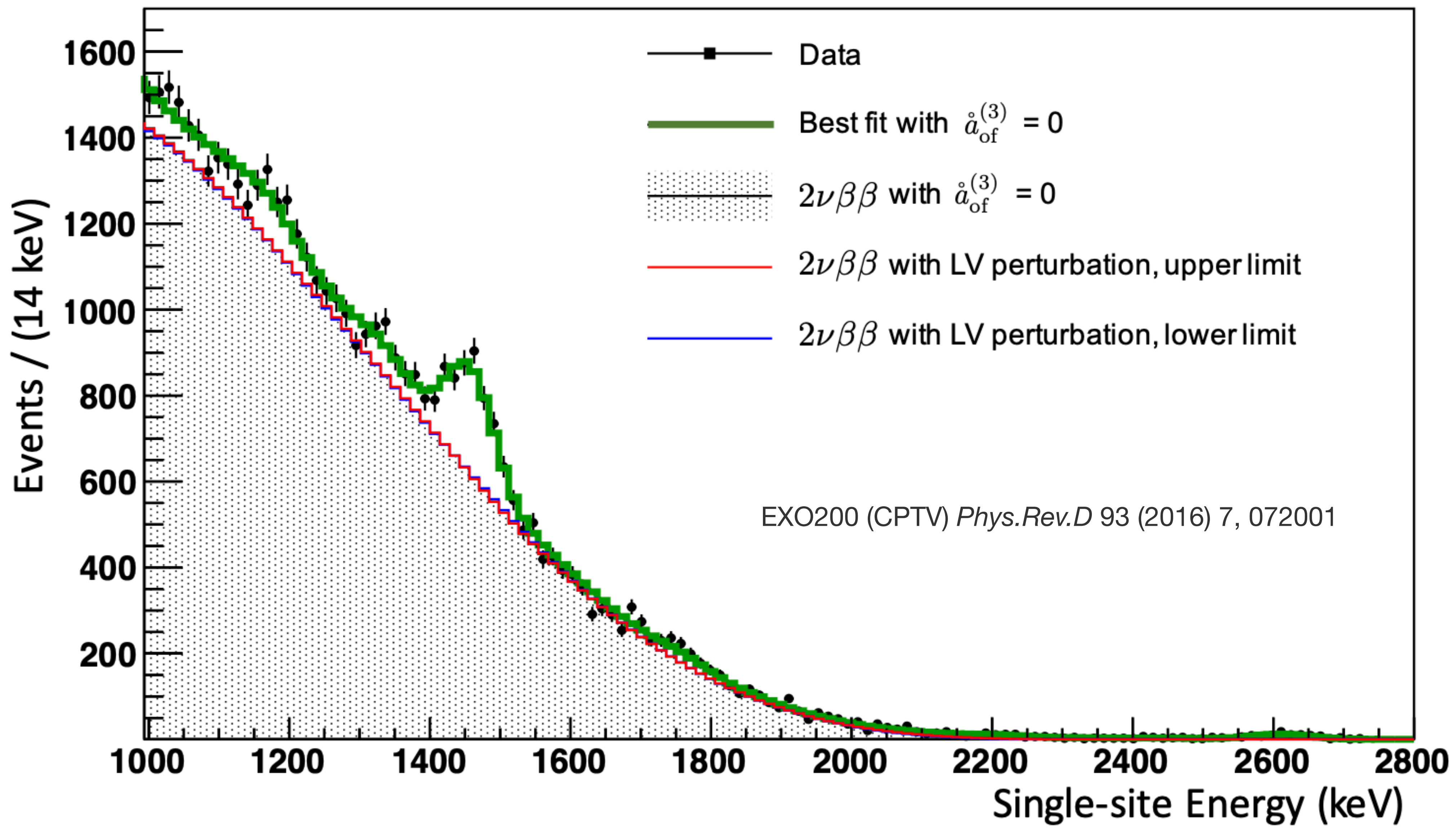
Spectral shape of 2νββ decay

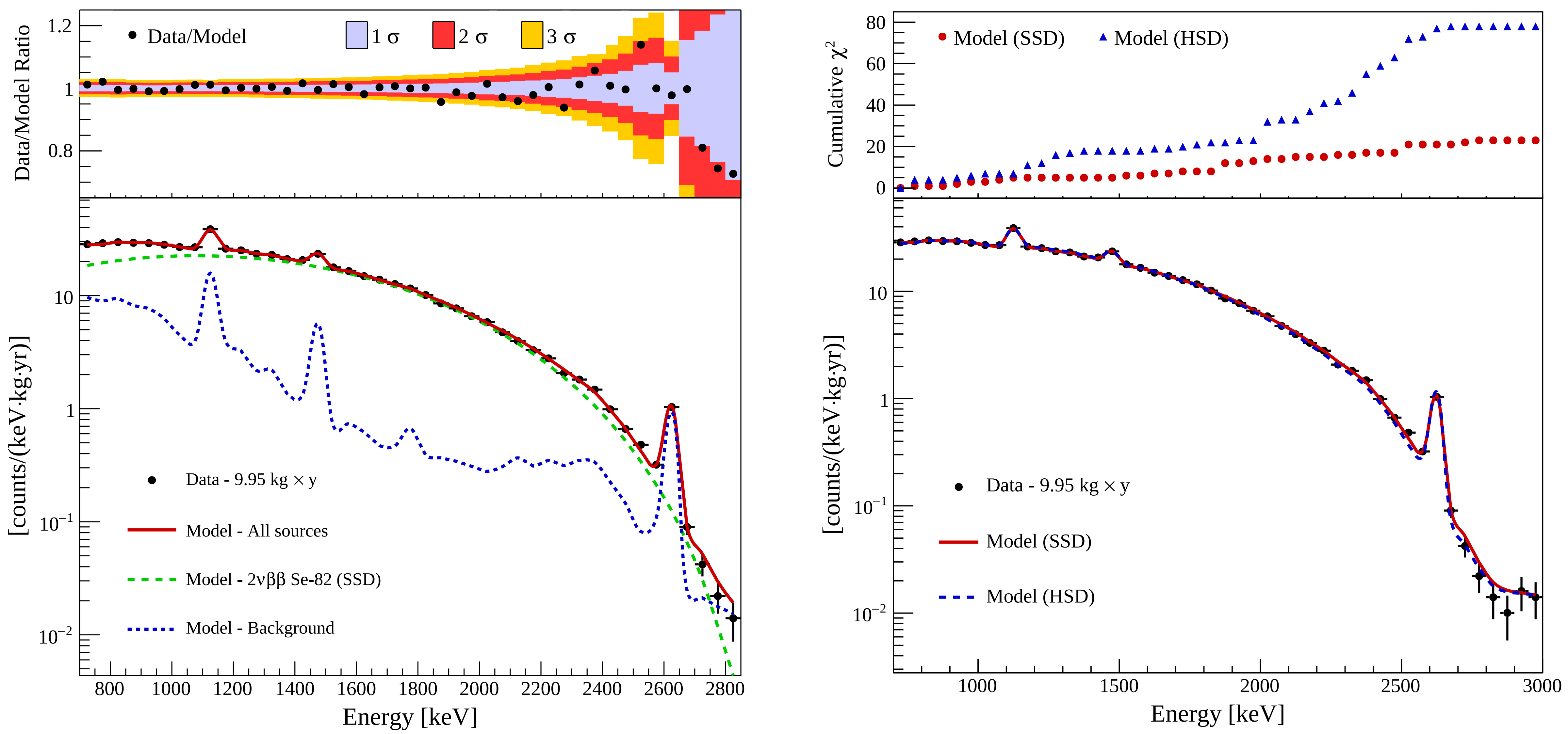
Neutrinoless double beta decay experiments ➪ **huge statistics of 2νββ** ➪ **spectral shape studies**



Goals:

- 2νββ modeling in Nuclear Theory
  - Single State Dominance vs Closure Approximation
  - Improved description
- distortion due to Beyond Standard Model Physics
  - CPT violation
  - ν-Self Interactions





Summary

- **Forbidden beta decays**, and in particular their spectral shape, **challenge the nuclear models**
- **Nuclear models** and **computation techniques** have evolved a great deal
- Renewed experimental efforts ongoing to provide **new high-quality data**

Mapping the spectral shape of several forbidden beta decays in terms of effective g_A

We could shed light on the nuclear physics behind the phenomenological g_A quenching