Assessing Spectral Shape of Forbidden Beta Decays with ACCESS

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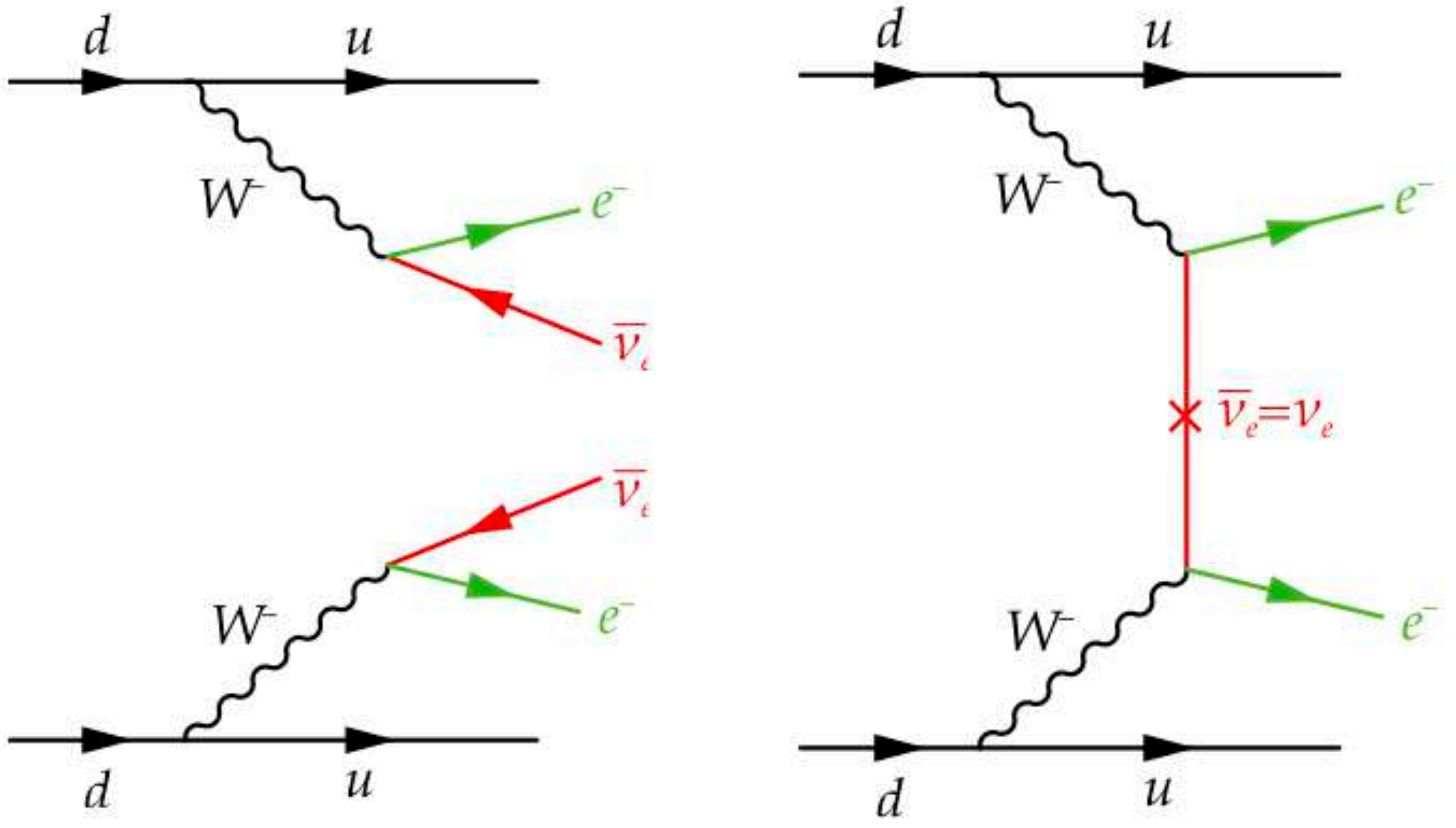
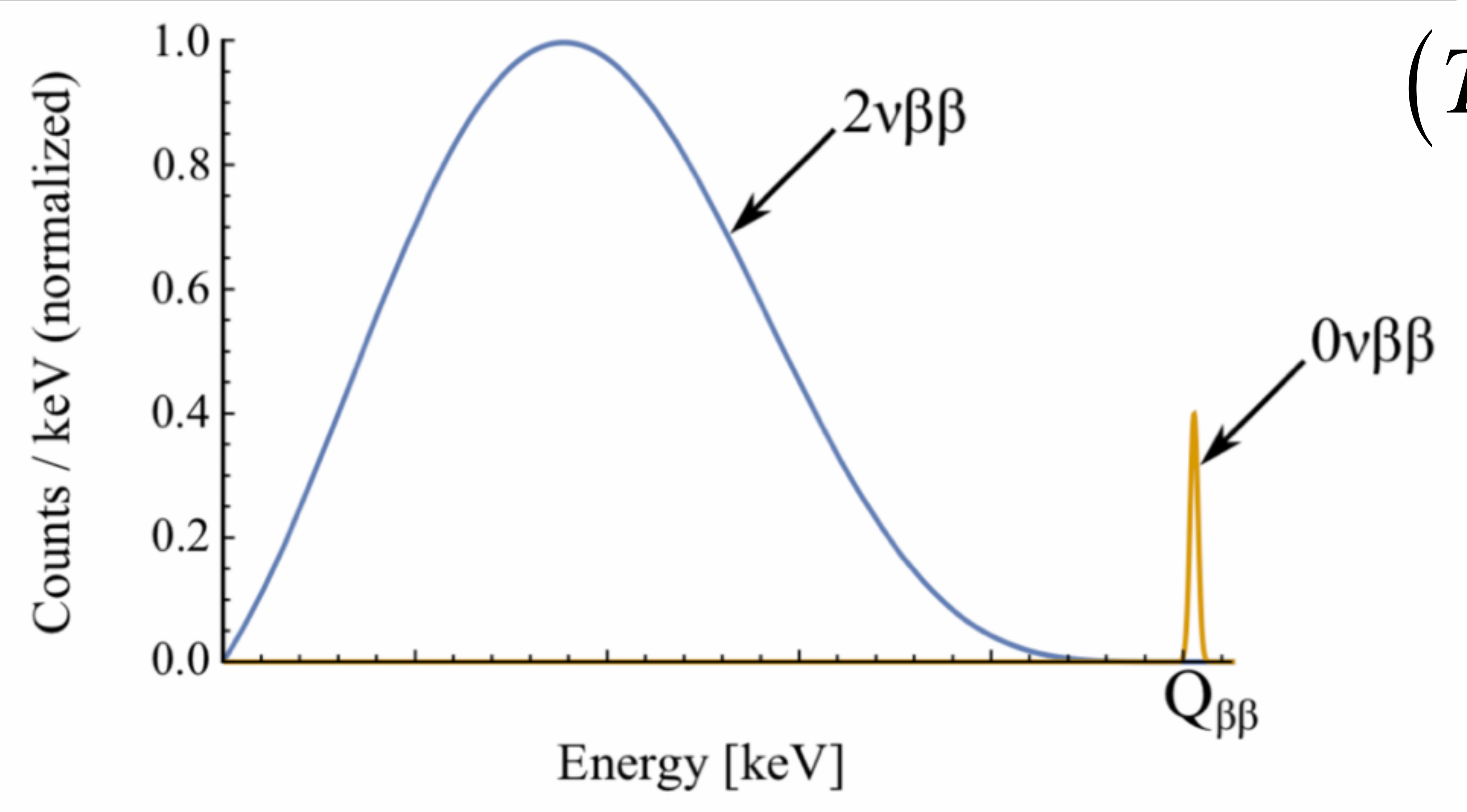
Neutrinoless Double Beta Decay



- It only occurs **if neutrino is a Majorana** particle
- Forbidden by Standard Model: **violation of B-L**
- **Matter creation** (no anti-matter balancing)
- Insights on the **neutrino mass**



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

$$m_{\beta\beta} = \left|\sum_{j=1}^{3} m_j U_{ej}^2\right| = \left|U_{e1}^2 m_1 + U_{e2}^2 e^{i\alpha} m_2 + U_{e3}^2 e^{i\beta} m_3\right|$$

Effective Majorana Mass

Neutrinoless Double Beta Decay

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

AMORE 🇰🇷 🇨🇳 🇩🇪 🇺🇦 🇹🇭 🇮🇩 🇵🇰

CUPID 🇮🇹 🇺🇸 🇫🇷 🇷🇺 🇨🇳 🇺🇦

KamLAND-ZEN 🇯🇵 🇺🇸 🇳🇱

LEGEND 🇩🇪 🇺🇸 🇷🇺 🇨🇳 🇮🇹 🇬🇧 🇨🇳 🇨🇭

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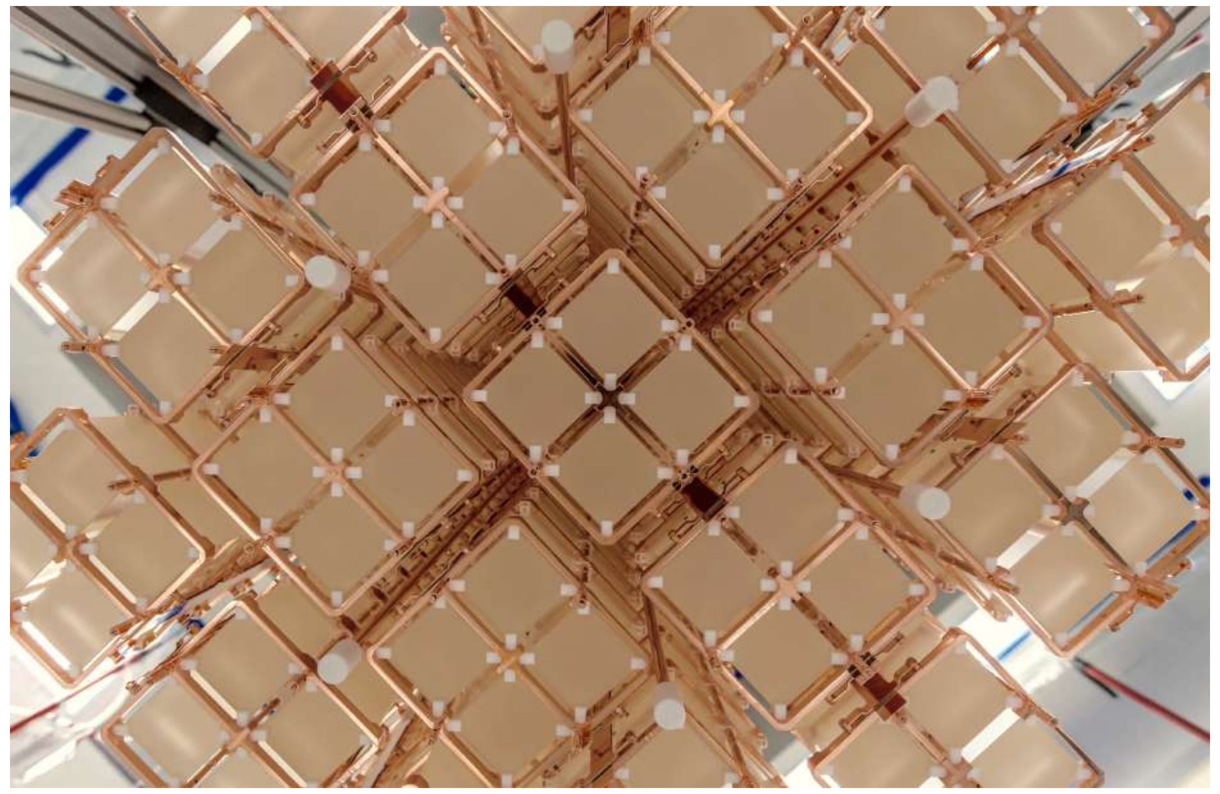
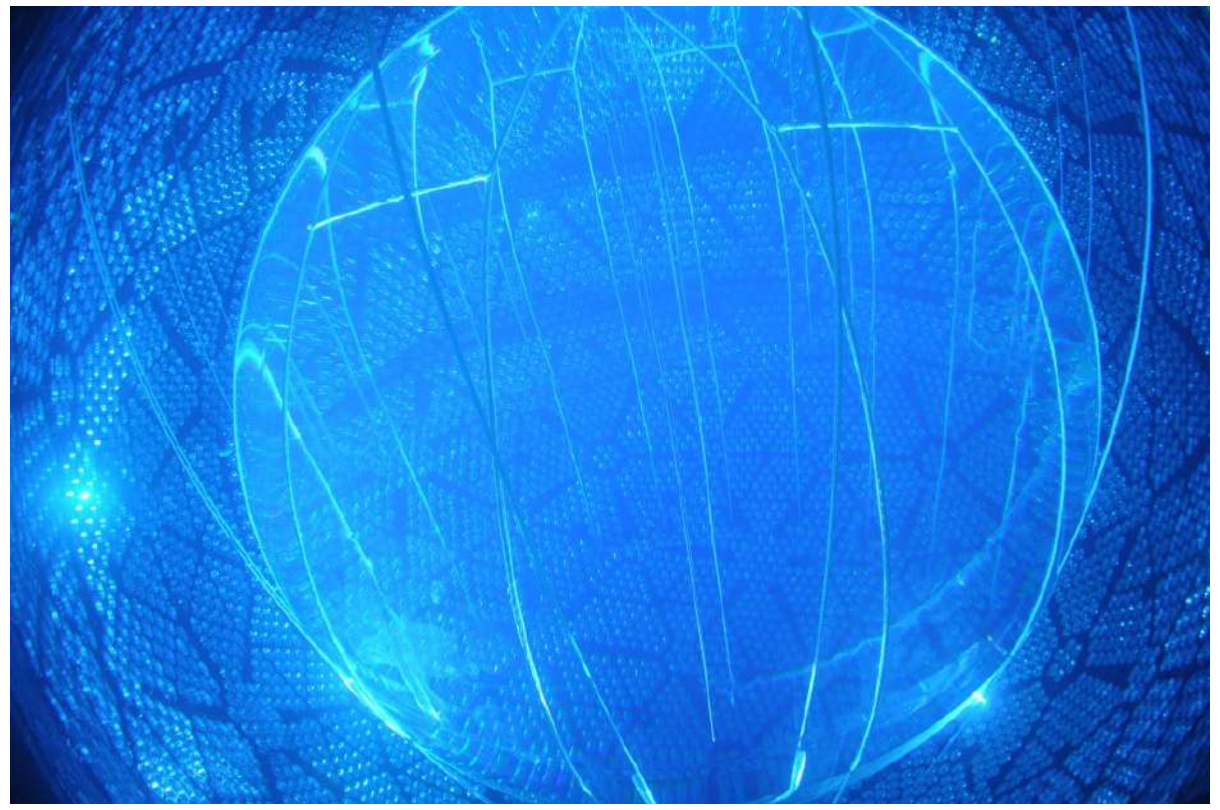




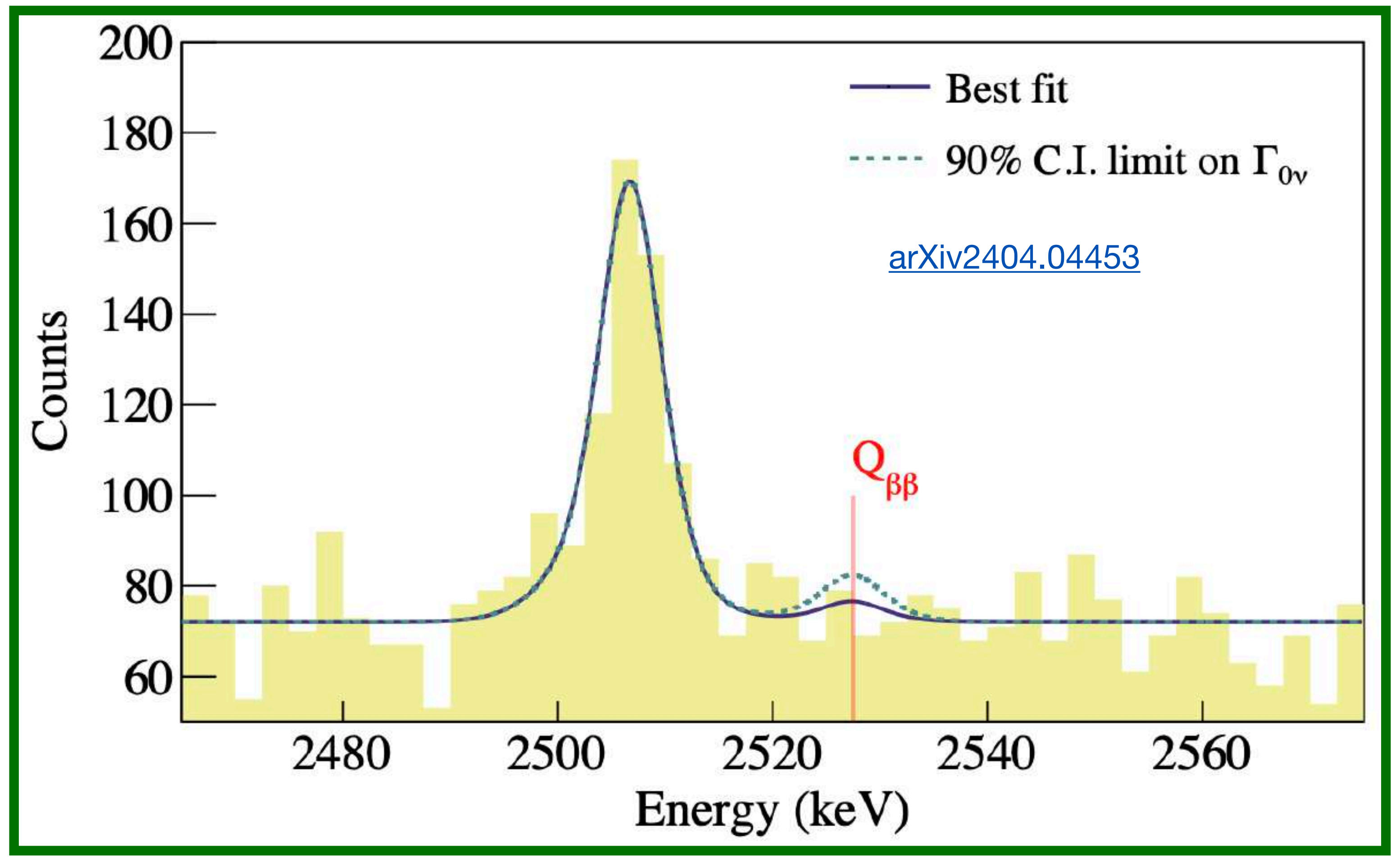
See talks of Biassoni, Brugnera, and Pavan

Neutrinoless Double Beta Decay

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

Rev.Mod.Phys. 95 (2023) 2, 025002

A. Strumia and F. Vissani, hep-ph/0606054



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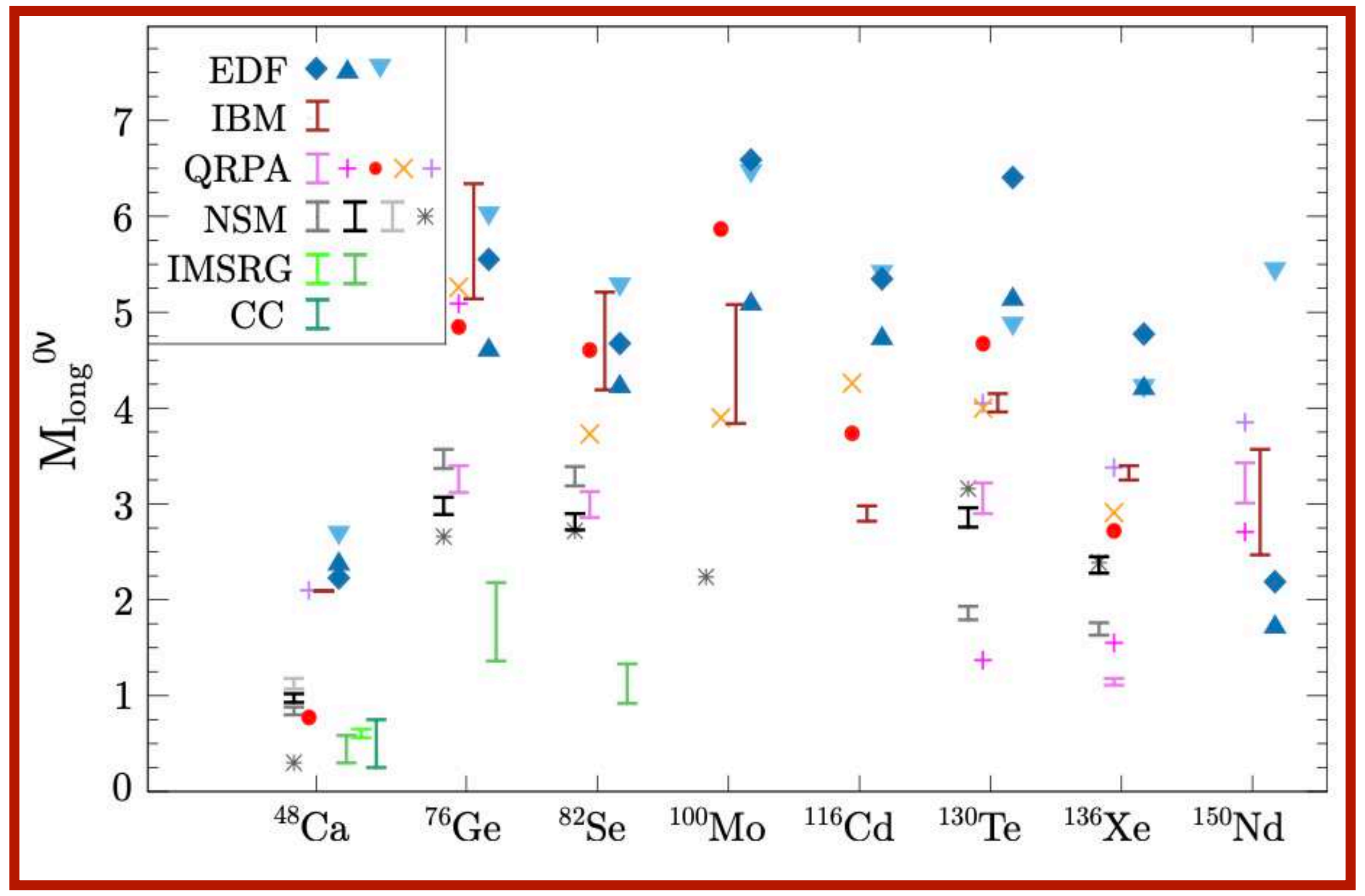

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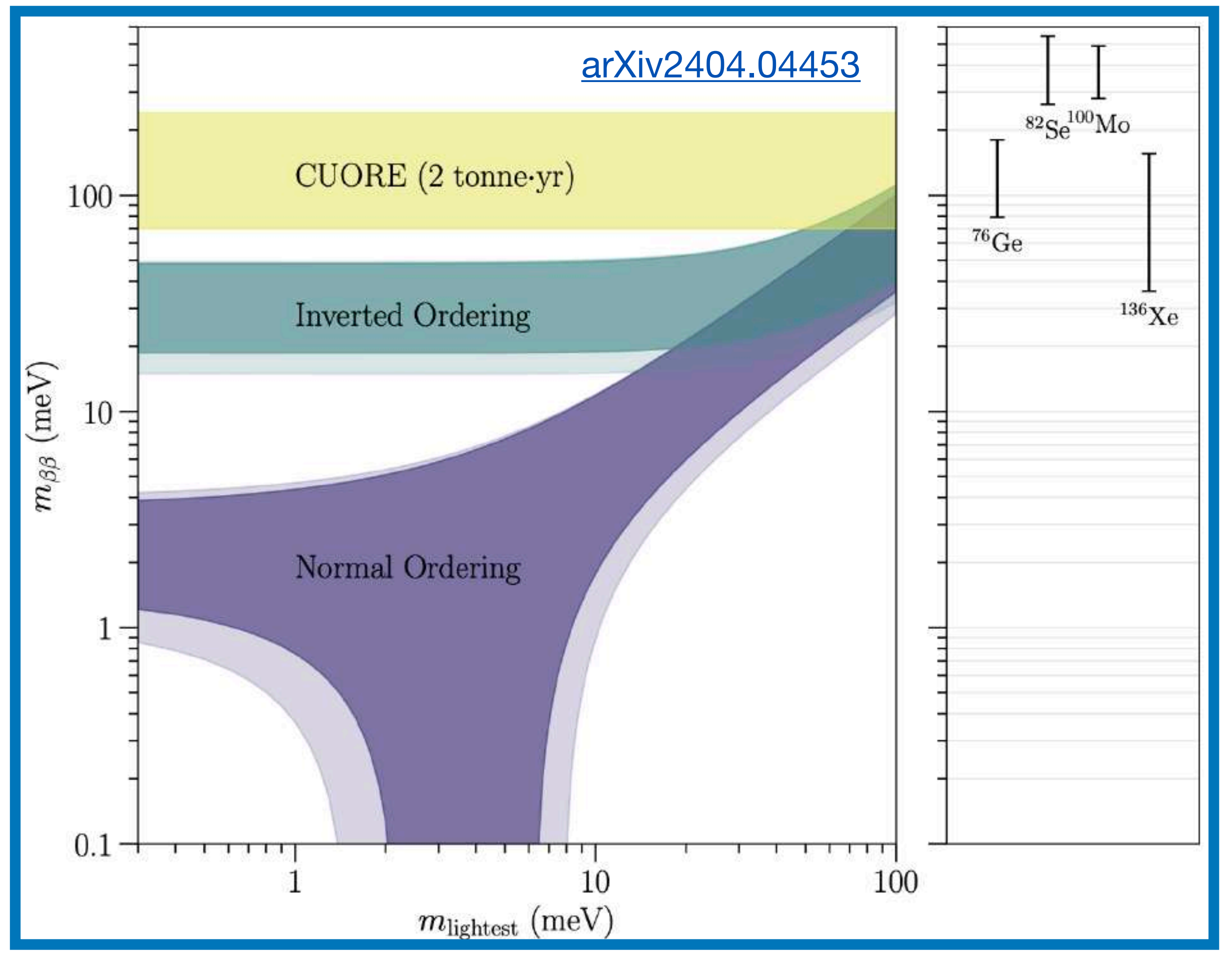


A single experimental limit on the half-life…

…due to the uncertainty on the NME…

…results in a wide interval!

Also the isotope down-selection is affected by this uncertainty!

^{76}Ge (GERDA) - Phys. Rev. Lett., 125:252502, 2020

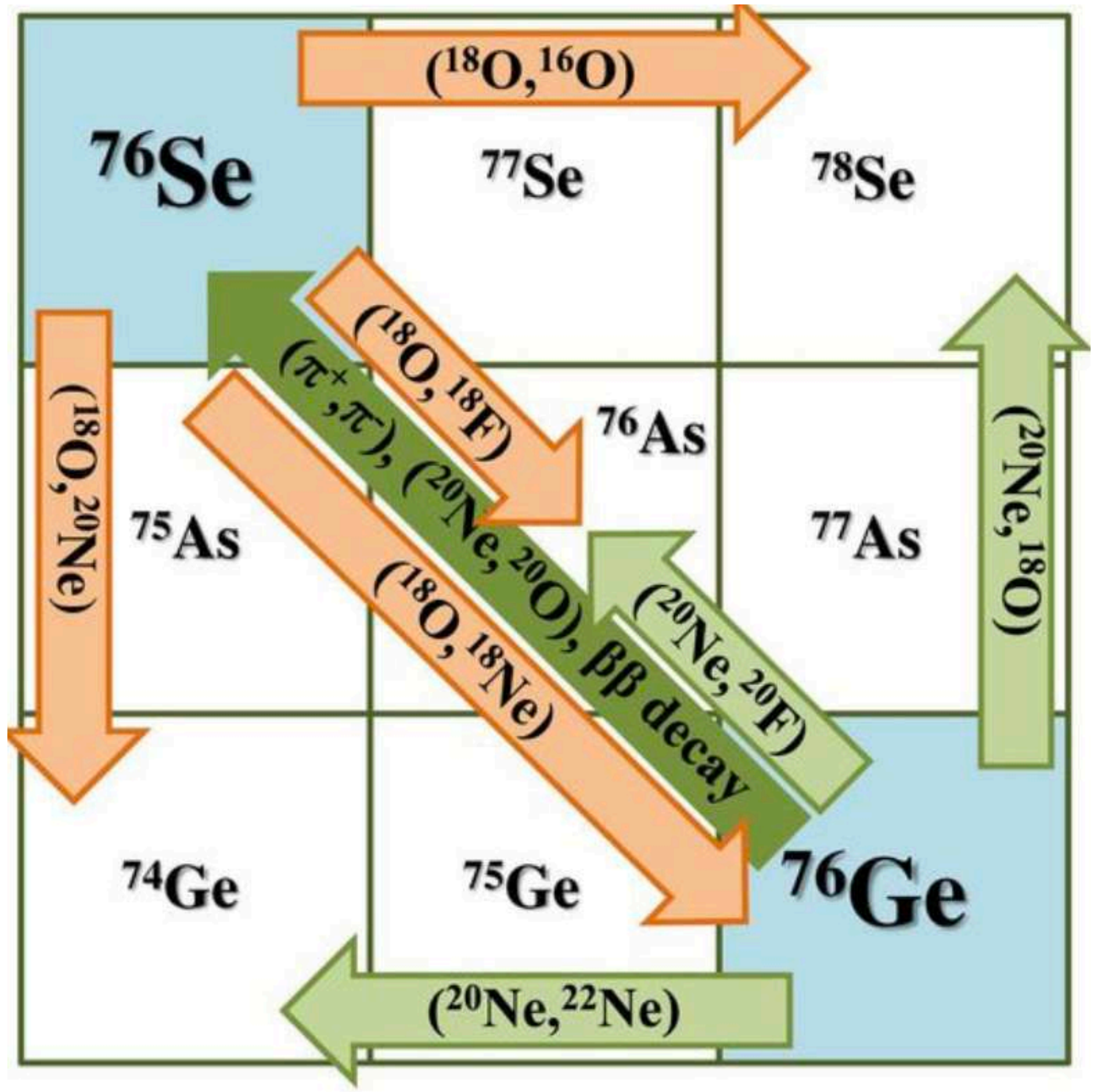
^{82}Se (CUPID-0) - Phys. Rev. Lett., 129(11):111801, 2022

^{100}Mo (CUPID-Mo) - Eur. Phys. J. C, 82(11):1033, 2022

^{136}Xe (KamLAND-Zen) - Phys. Rev. Lett., 130(5):051801, 2023

Data-driven improvements of Nuclear Models

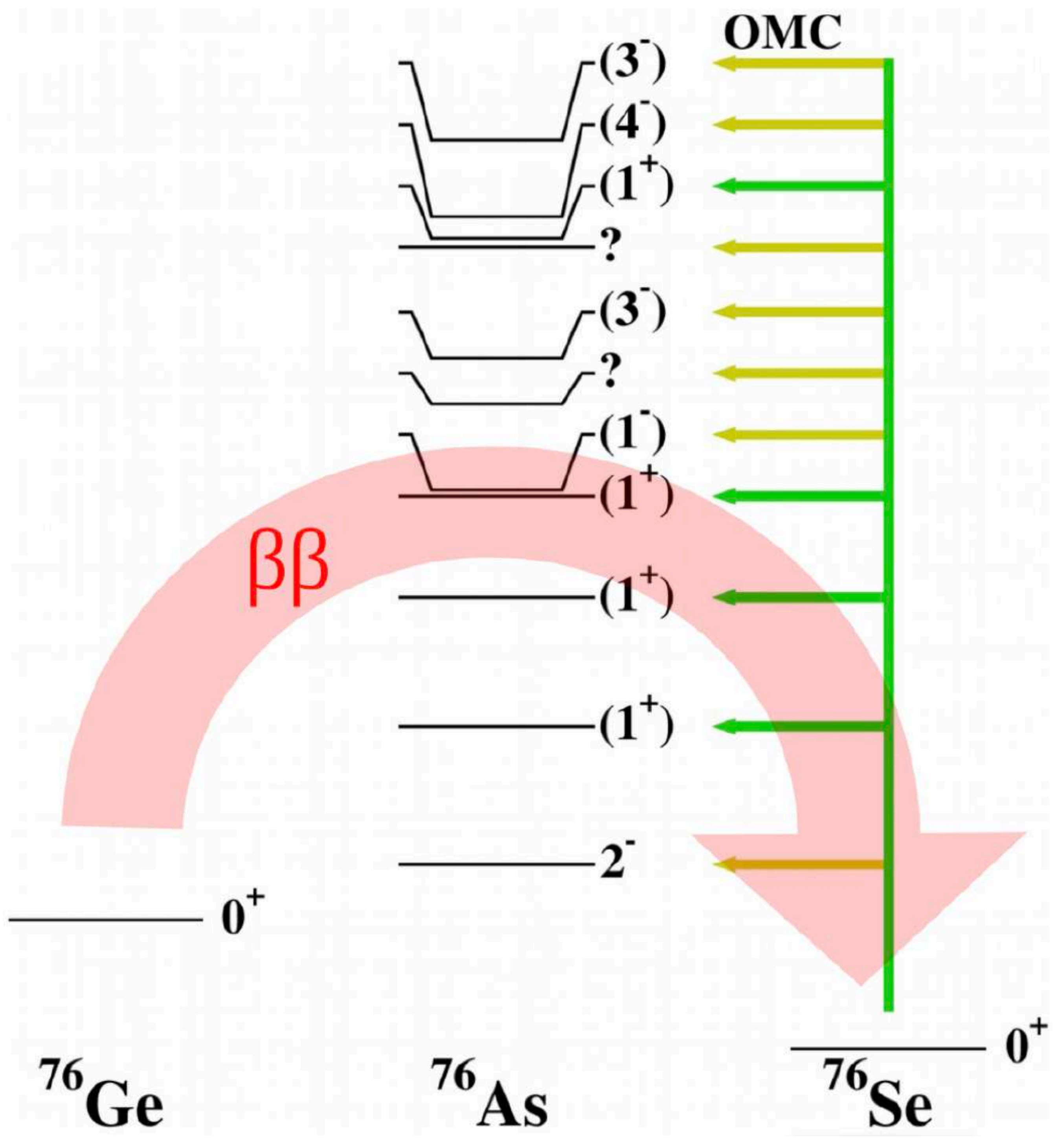
Double Charge Exchange (DCE)



See Alessandro Spatafora's talk on NUMEN

Ordinary Muon Capture (OMC)

$$^{76}\mathrm{Se} + \mu^- \rightarrow {}^{76}\mathrm{As} + \nu_\mu$$



See Songlin Lyu's talk

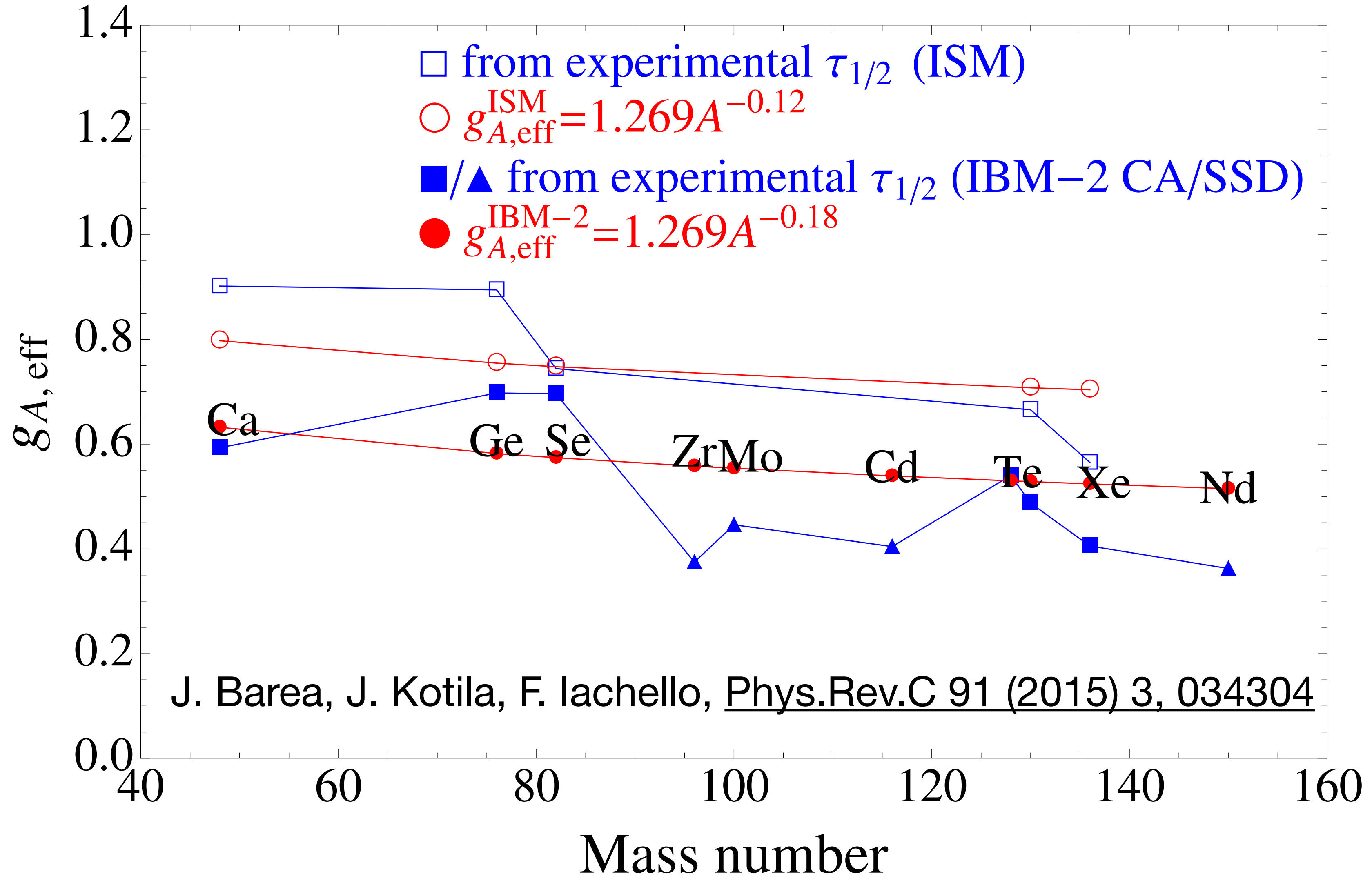
Two-neutrinos Double Beta Decay

Phase Space Factor
(a.k.a. Shape Factor assuming Nuclear Dynamic decoupled)

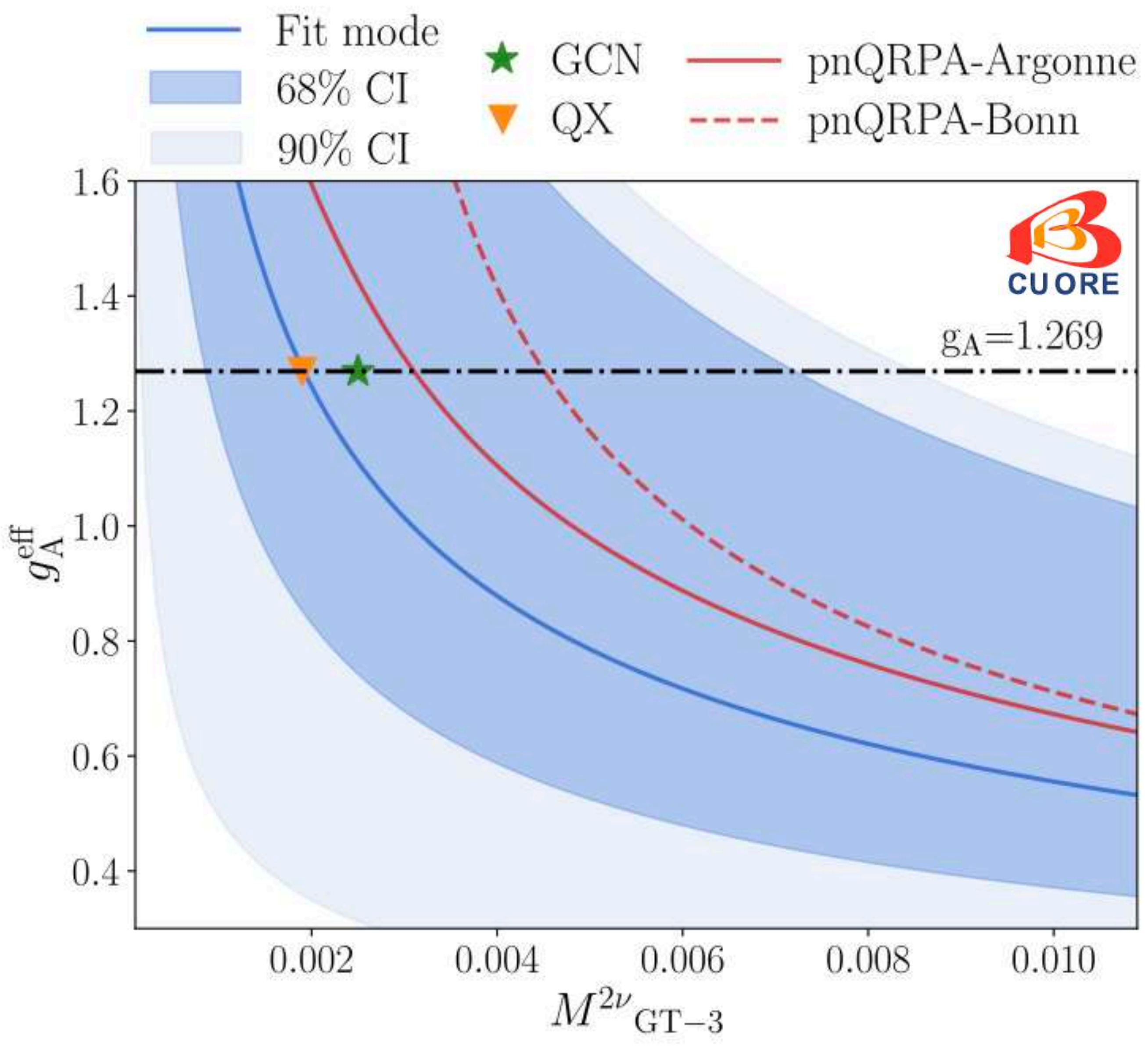
$$\left(T_{1/2}\right)^{-1} = g_A^4 \cdot \mathcal{G}(Q_\beta, Z) \cdot \left|\mathcal{M}(A,Z)\right|^2$$

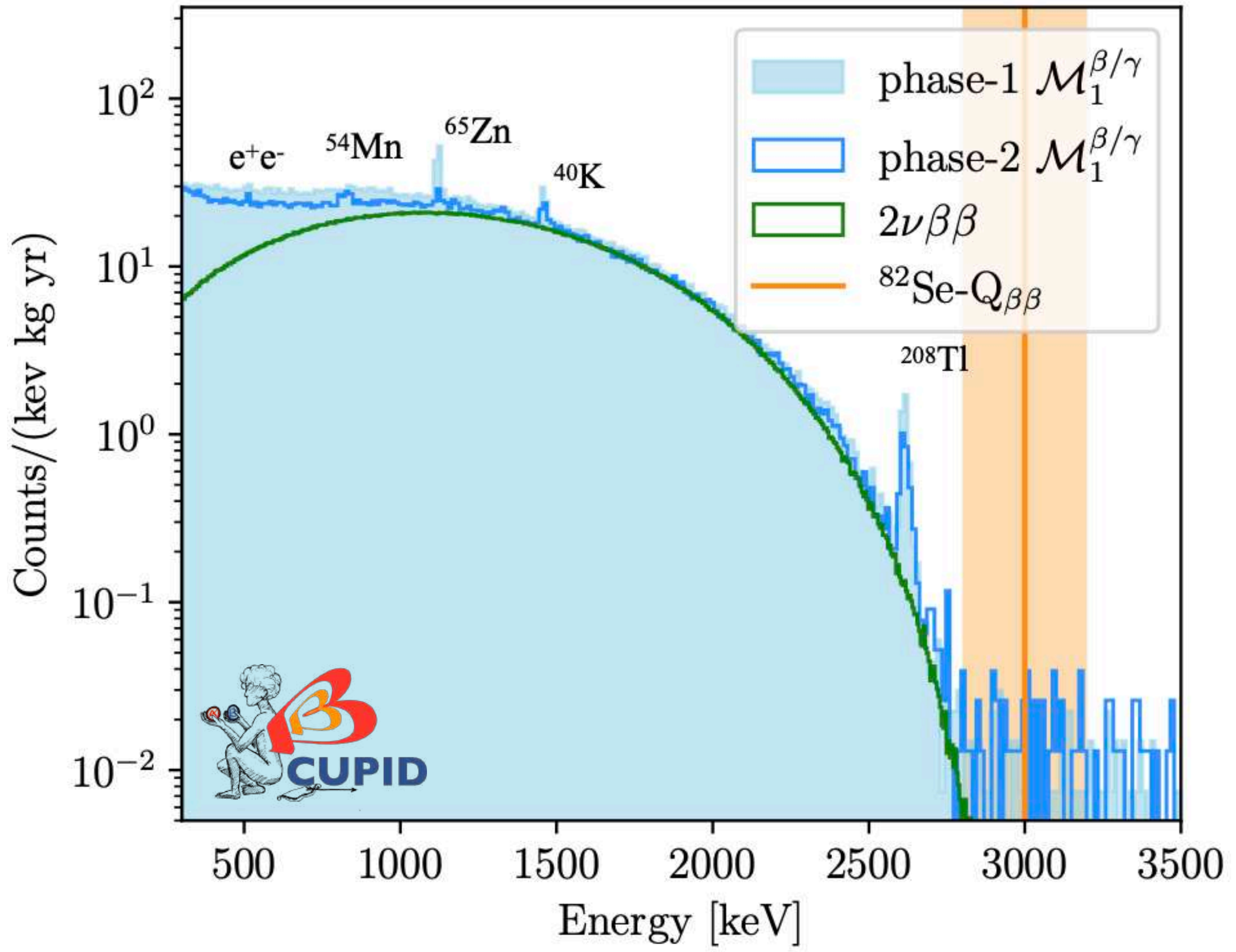
Experimental observable — **Axial Coupling Constant** — **Nuclear Matrix Element**

g_A = 1 quark level
g_A=1.27 free neutron decay
g_A=? nuclear level



g_A modeling based on experimental 2νββ half-lives only





Precision **Spectral Shape** Studies of 2νββ
^{136}Xe (KamLAND-Zen) - Phys.Rev.Lett. 122 (2019) 19, 192501
^{82}Se (CUPID-0) - Phys.Rev.Lett. 131 (2023) 22, 222501
^{100}Mo (CUPID-Mo) - Phys.Rev.Lett. 131 (2023) 16, 162501
^{130}Te (CUORE) - Submitted to PRL

+

Using the **improved description** of 2νββ presented in
F. Šimkovic *et al.* - Phys.Rev.C 97 (2018) 3, 034315

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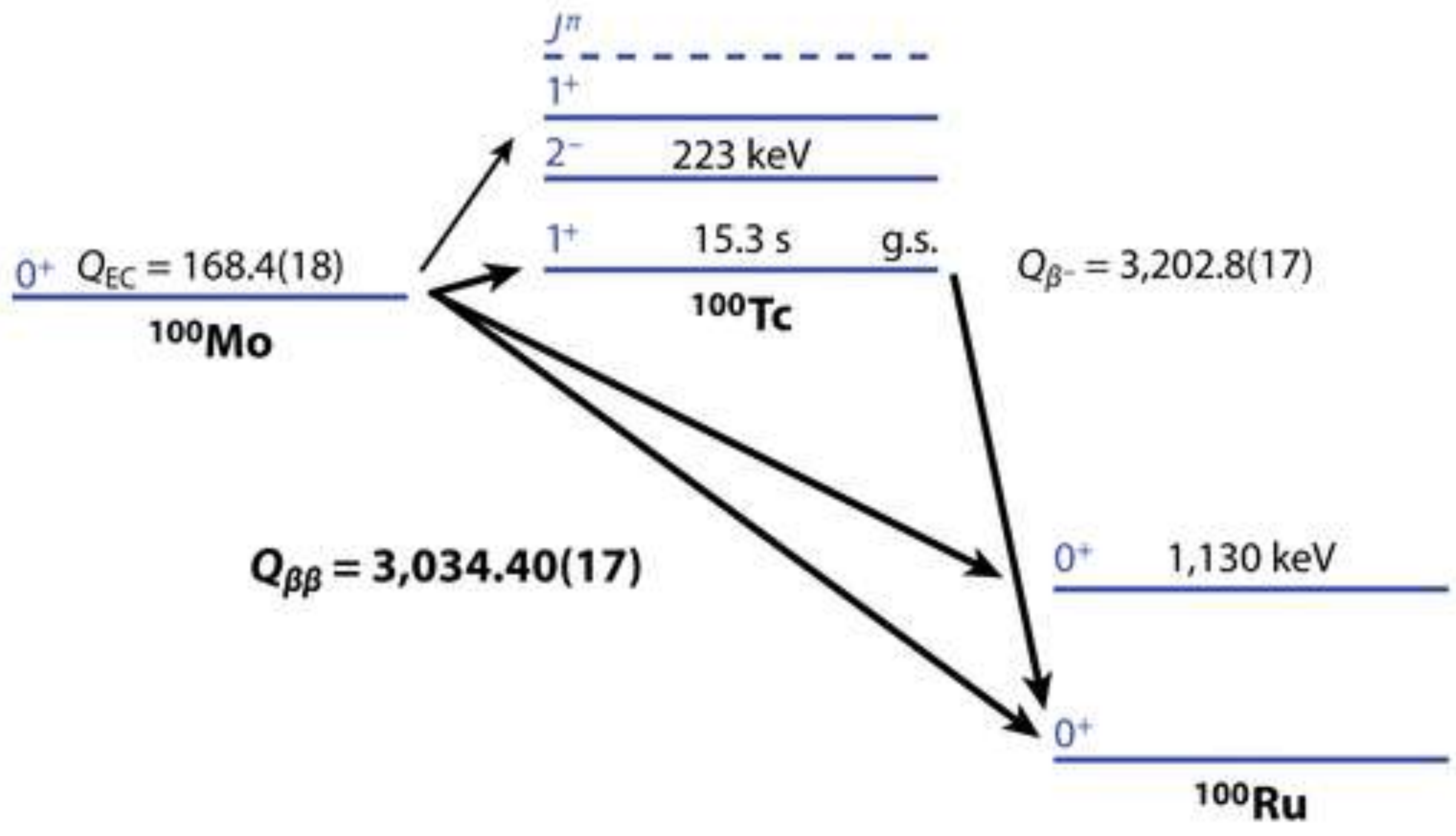
Deeper comparison with theory
Effective nuclear matrix elements as a function of g_A

Forbidden transitions in NLDBD



Forbidden β-decays are interesting for NLDBD since it **proceeds through forbidden virtual β-transitions** involving the excited states in the intermediate nucleus with **high multi-polarities**.

<u>Caveat for extrapolation to NLDBD:</u>

- only 1^+ states of the intermediate nucleus partecipate in the 2νββ (apparently only the first - Single State Dominance)
- β-decays and 2νββ feature a lower transferred momentum with respect to NLDBD

Forbidden Beta Decays:
Indium-115

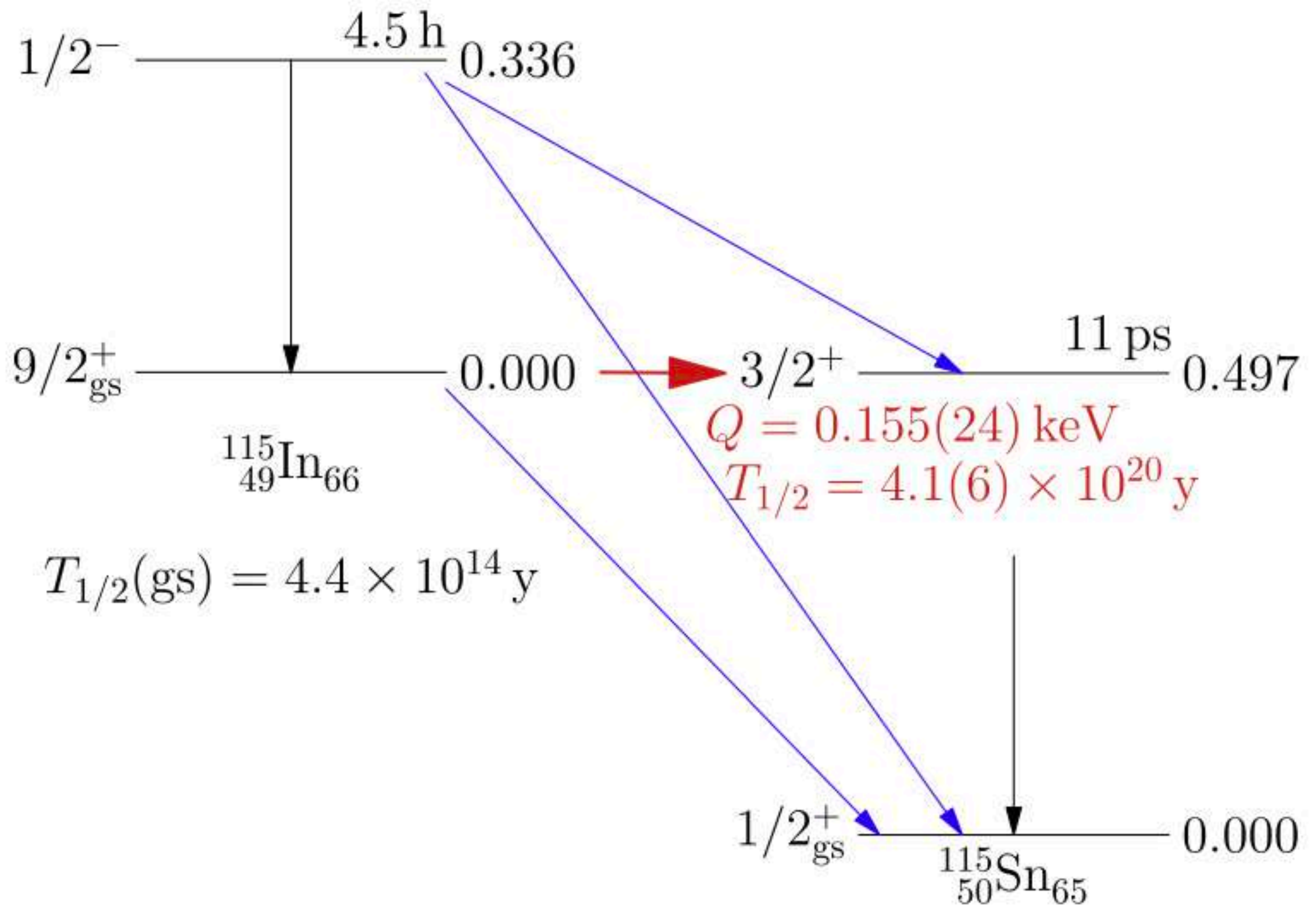
Indium-115

Q-value	Half-life	Classification
496 keV	4.41x10^{14} yr	$\frac{9}{2}^+ \rightarrow \frac{1}{2}^+ \quad \Delta J^{\Delta\pi} = 4^+$

Situation in *2022*

Only three *historical* measurements:

- *G.B. Beard and W. H. Kelly, PR 122 (1961) 1576*
  - $T_{1/2}$ = (6.9 ± 1.5) x 10^{14} yr
  - Threshold 50 keV
  - **No spectral shape**
- *D. E. Watt, R. N. Glover, Phil.Mag 7, 105 (1962)*
  - $T_{1/2}$ = (5.1 ± 0.4) x 10^{14} yr
  - **No spectral shape**
- *L. Pfeiffer et al., PRC 19 (1979) 1035*
  - $T_{1/2}$ = (4.41 ± 0.25) x 10^{14} yr
  - Spectral shape but with not clear background subtraction
  - Threshold not clear



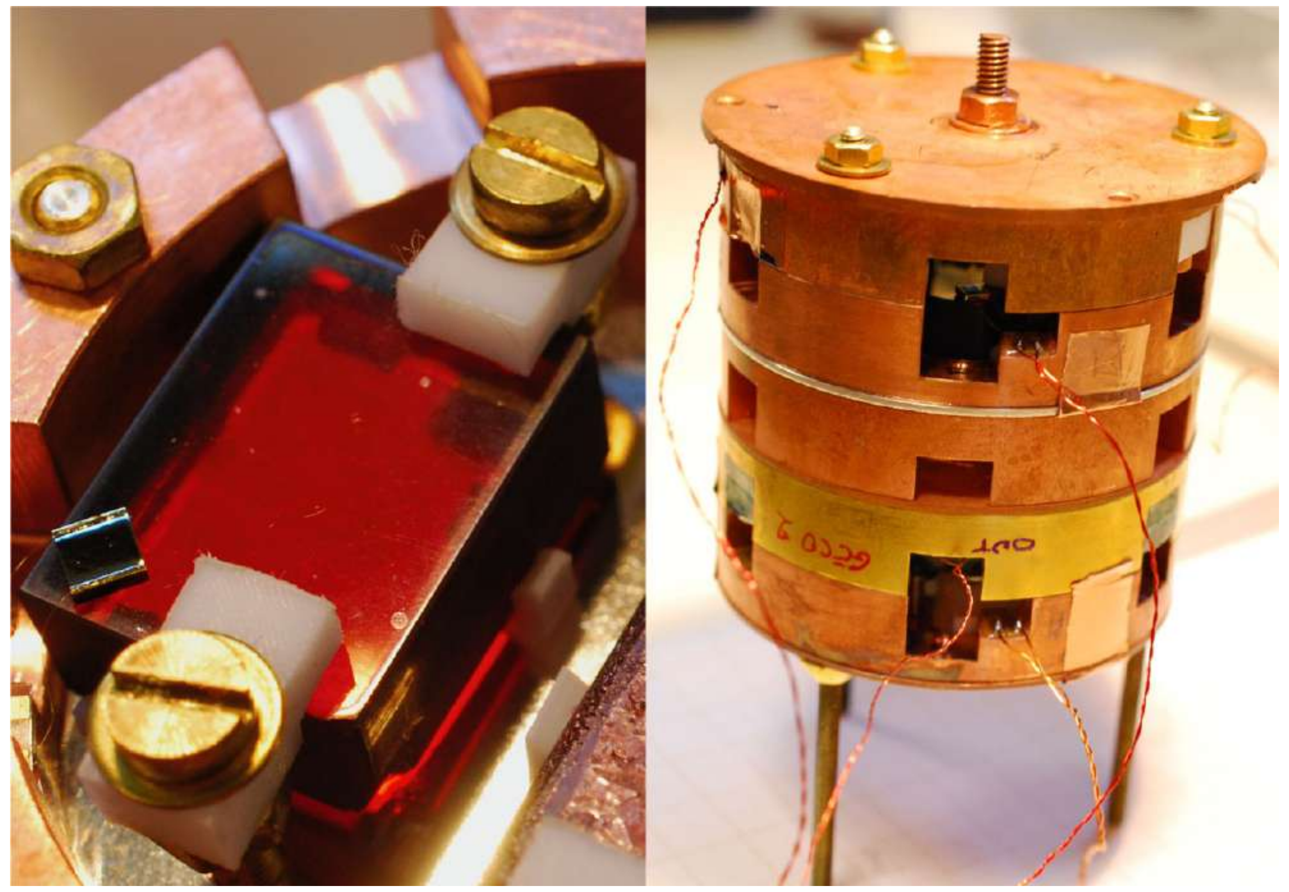
New low-background measurements needed!

Very good experimental conditions:

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

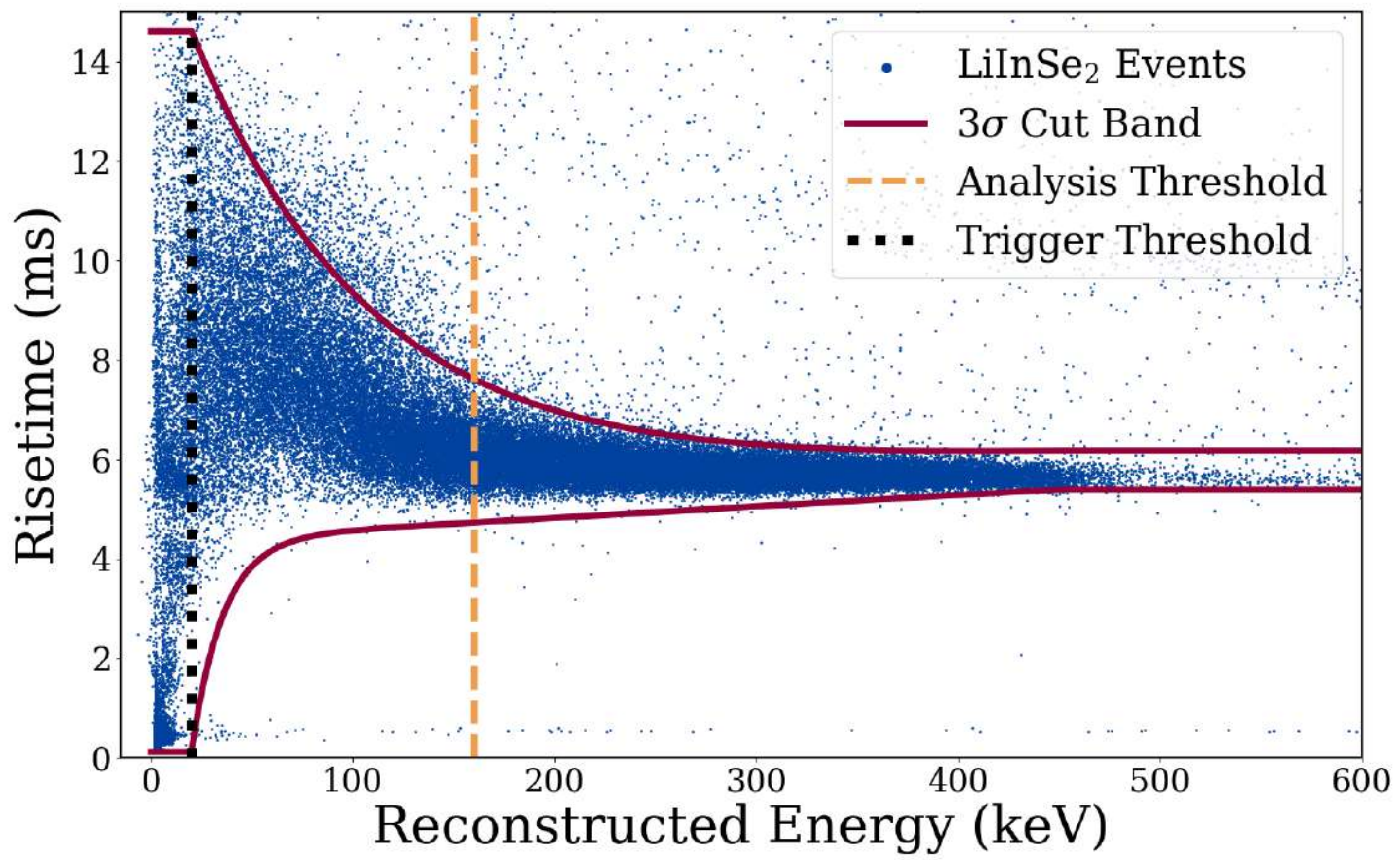
A new measurement (MIT/Berkeley/CNRS)

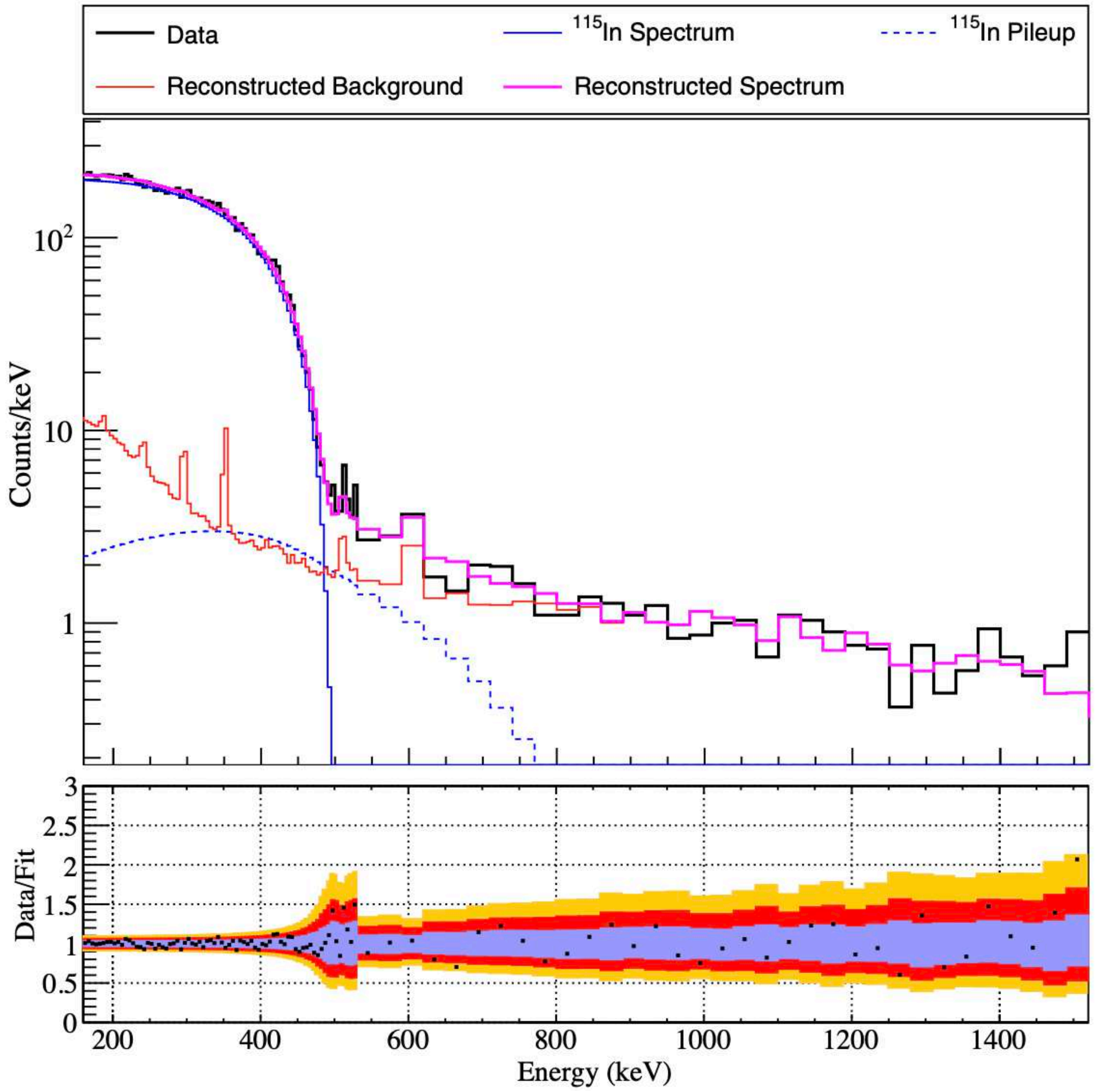
- $LiInSe_2$ operated as cryogenic calorimeter
- Excellent performance but high rate at low energy
- High analysis threshold (160 keV)

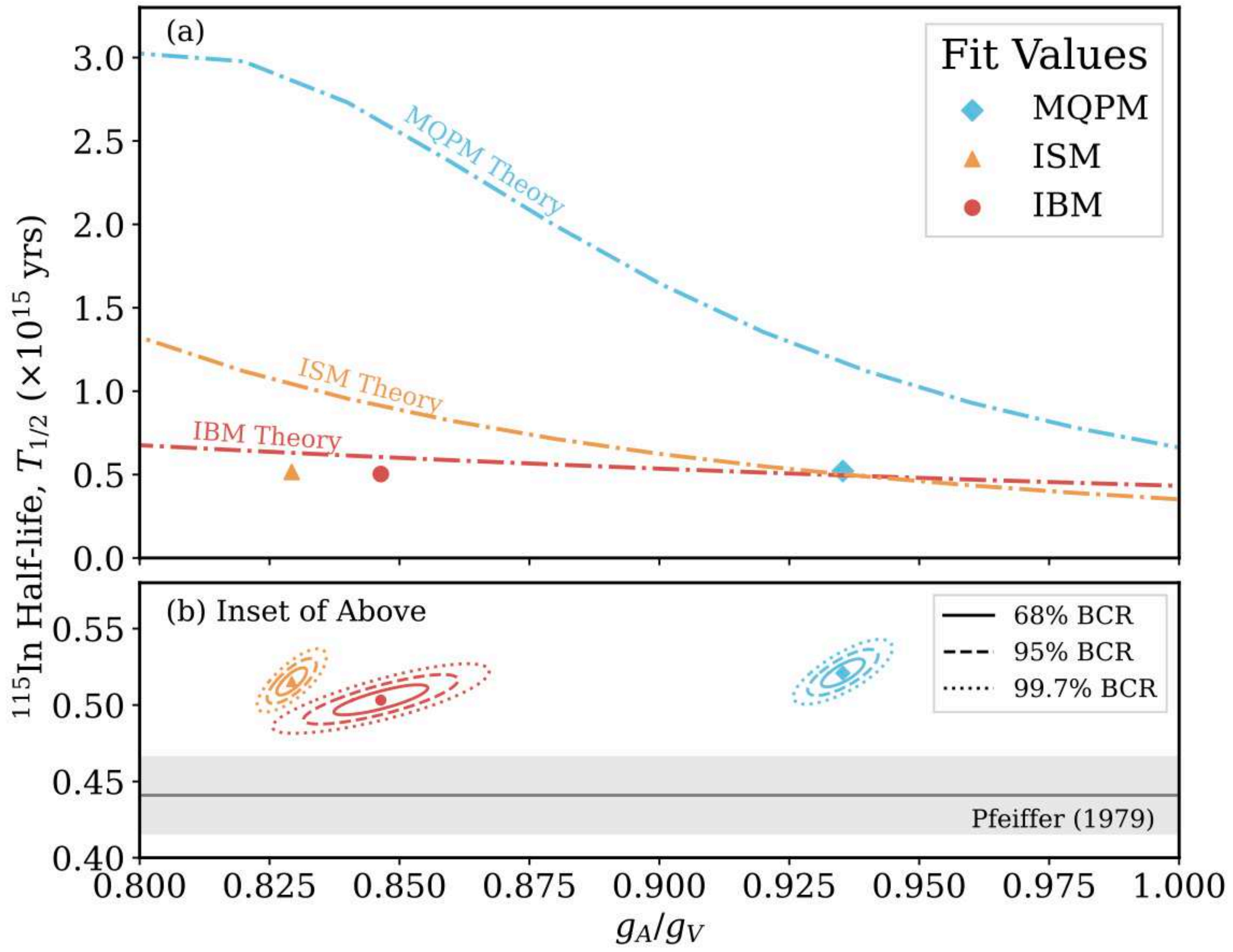


Phys. Rev. Lett. 129, 232502 (2022)

Model	g_A/g_V	$T_{\frac{1}{2}}^{^{115}In}$ (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	

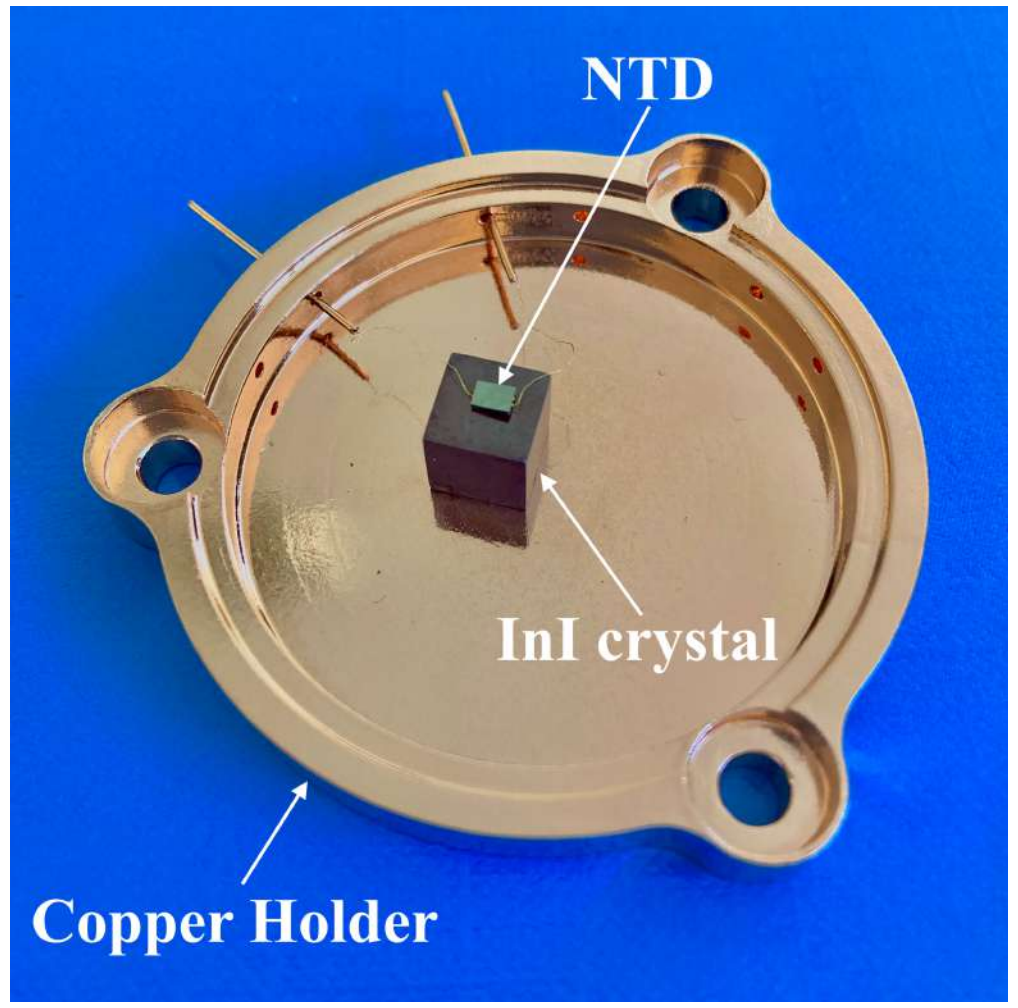






Theory ≠ Experiment

In-115 by ACCESS

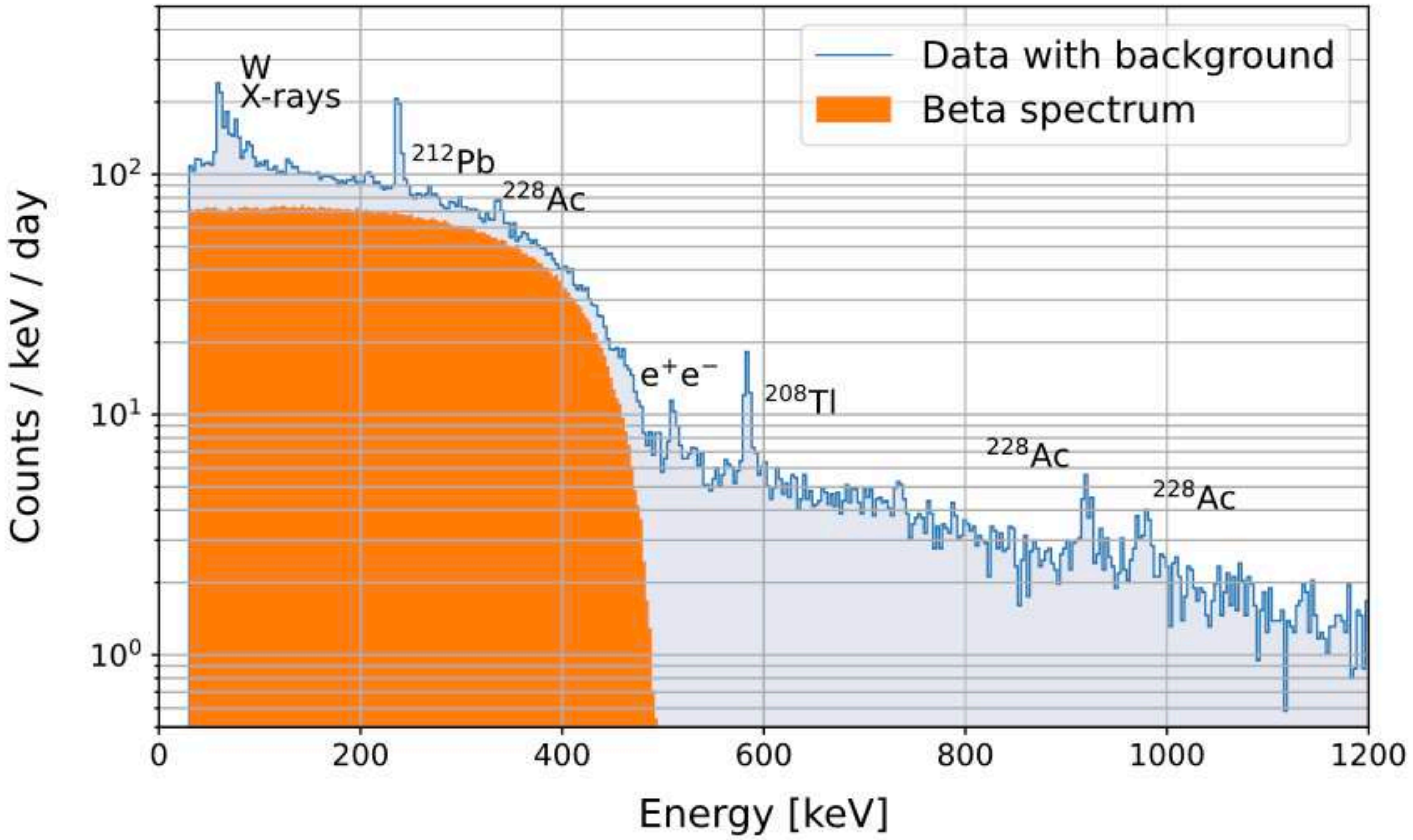


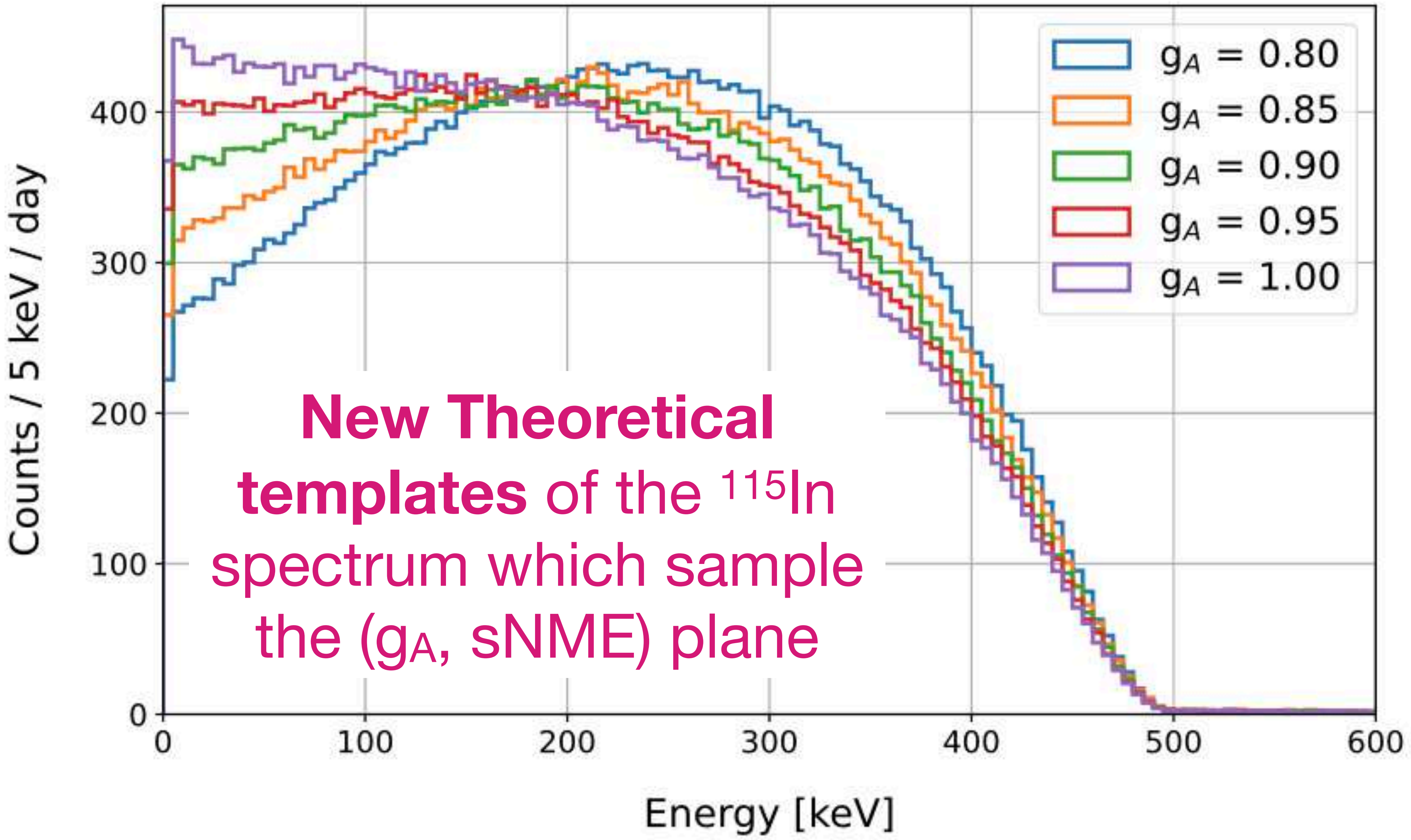
- **Cryogenic calorimeter**
  - Indium Iodine (InI) crystal - m = 1.91 g - 7x7x7 mm^3
  - Semiconductor sensor (CUPID-0 like)
  - Calibration source with ^{232}Th

- **Very good performance**
  - 138 hours of stable data taking
  - Energy threshold of 3.4 keV
  - Energy resolution of 3.9 keV FWHM @ 238.6 keV

ACCESS webpage

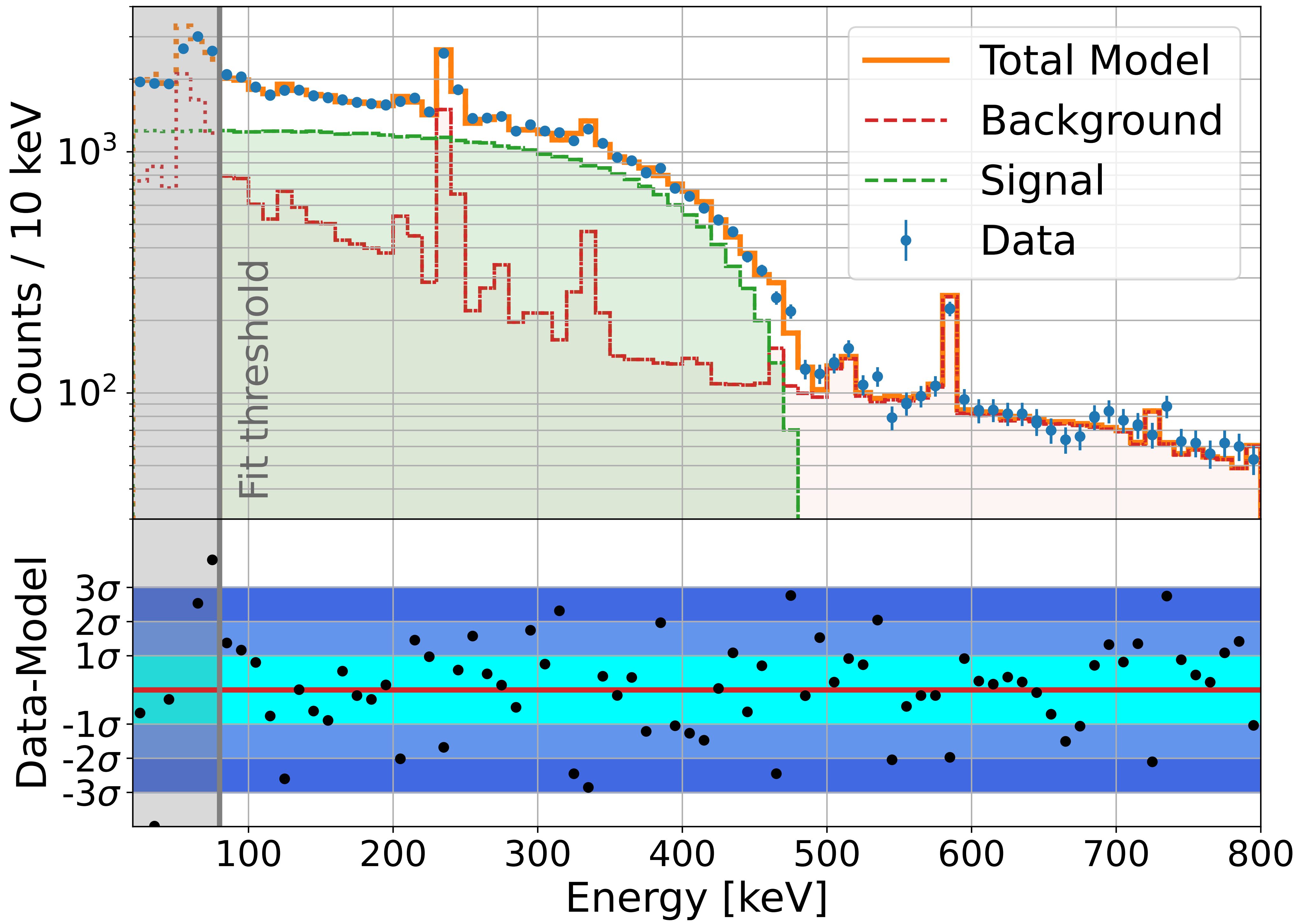
Eur.Phys.J.Plus 138 (2023) 5, 445





New Theoretical templates of the ^{115}In spectrum which sample the (g_A, sNME) plane

In-115 by ACCESS - Best Fit



Bayesian fit based on BAT with 5 free parameters:

- 2 bkg components due to the calibration source
- half-life of ^{115}In
- g_A in the range [0.60, 1.39]
- sNME in the range [-5.9, 5.9]

Full results in: Phys. Rev. Lett. 133, 122501

Model	g_A	sNME	$T_{1/2}$ [$\times 10^{14}$ yr]	χ^2_{red}
Best fit				
ISM	$0.964^{+0.010}_{-0.006}$	$1.75^{+0.13}_{-0.08}$	5.26 ± 0.06	1.55
MQPM	$1.104^{+0.019}_{-0.017}$	$2.88^{+0.49}_{-0.71}$	5.26 ± 0.07	1.65
IBFM-2	$1.172^{+0.022}_{-0.017}$	$0.81^{+0.52}_{-0.24}$	5.25 ± 0.07	1.66

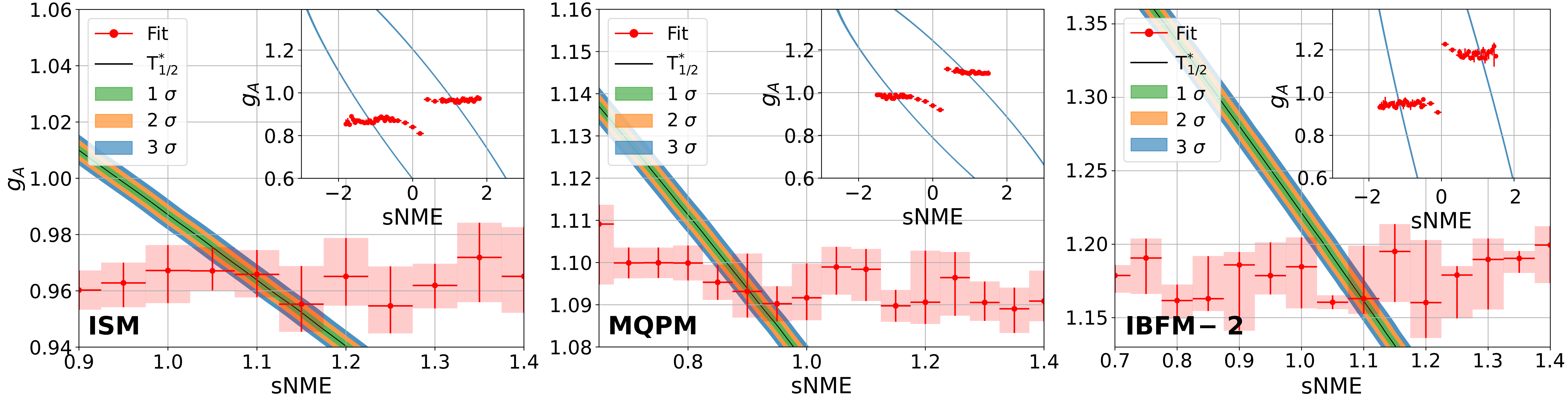
- Different values of g_A for different models
- Lower quenching ($g_A \approx 1$)
- sNME not fixed

- Stable and precise evaluation of $T_{1/2}$
- Theory ≠ Experiment for $T_{1/2}$

In-115 by ACCESS - Matched Fit

For each value of sNME, we run the fit to choose the best value of g_A (red points).

The solution in the (g_A, sNME) plane is given by the interception of the red line (exp.) and the half-life ellipse (theory).

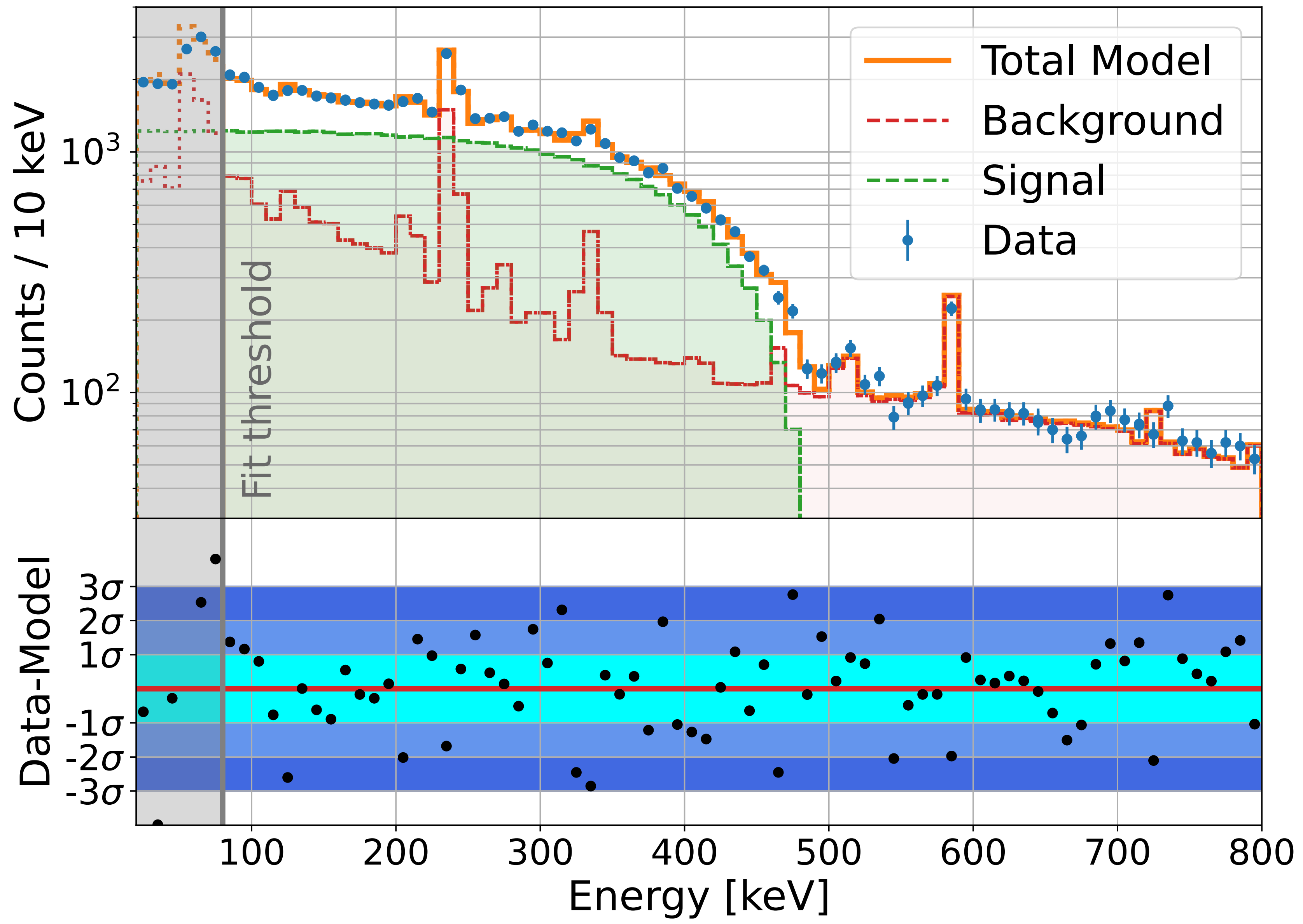


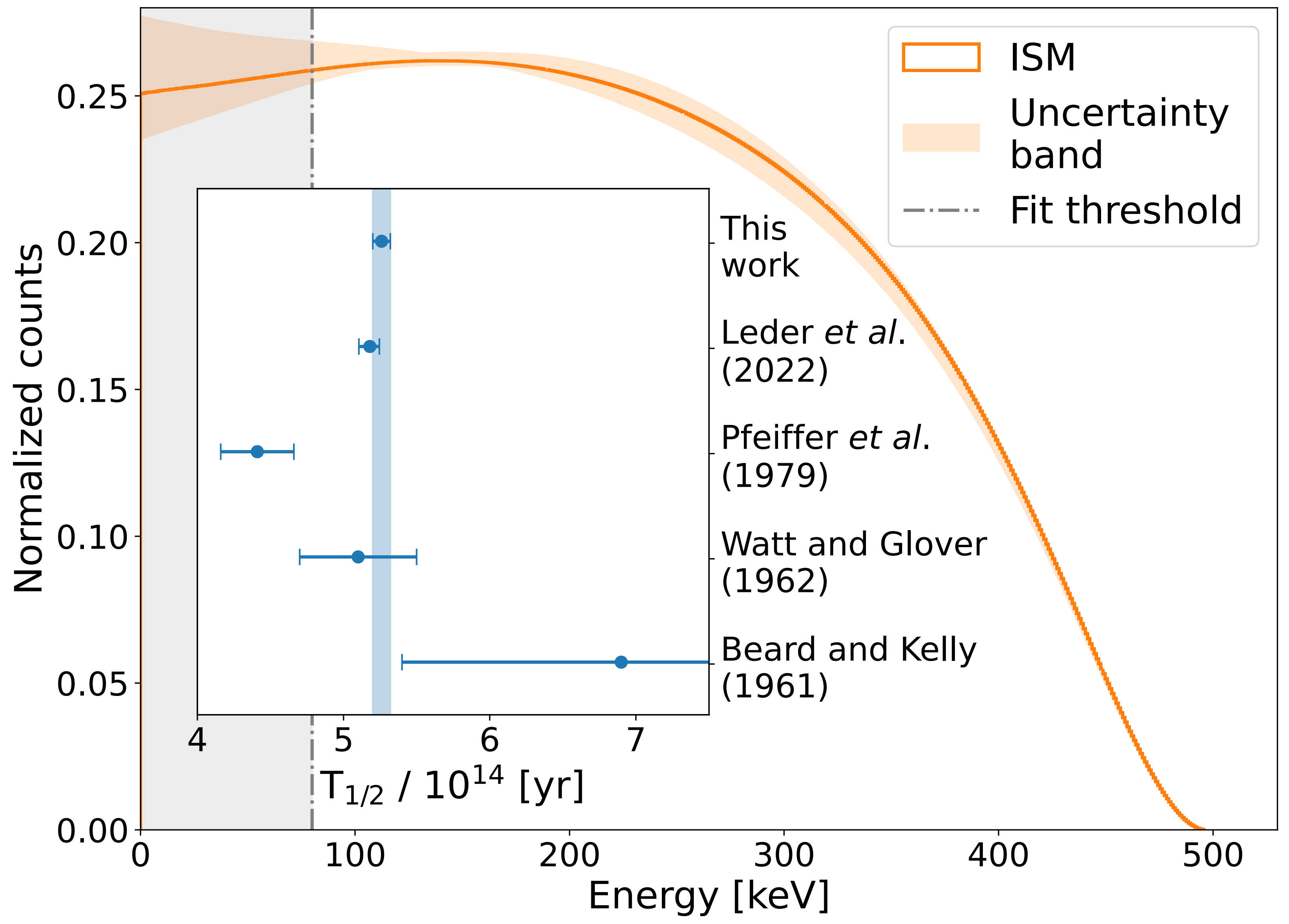
Phys. Rev. Lett. 133, 122501

Model	g_A	sNME	$T_{1/2}$ [$\times 10^{14}$ yr]	χ^2_{red}
Matched half-life				
ISM	$0.965^{+0.013}_{-0.010}$	1.10 ± 0.03	5.20 ± 0.07	1.78
MQPM	$1.093^{+0.009}_{-0.007}$	0.90 ± 0.03	5.05 ± 0.06	2.32
IBFM-2	$1.163^{+0.036}_{-0.010}$	1.10 ± 0.03	5.28 ± 0.06	1.67

- g_A values compatible with the best fit
- sNME fixed by the ellipse interception to similar values
- Theory = Experiment for $T_{1/2}$
- Bias from previous $T_{1/2}$ in the ellipse

In-115 by ACCESS





Phys. Rev. Lett. 133, 122501

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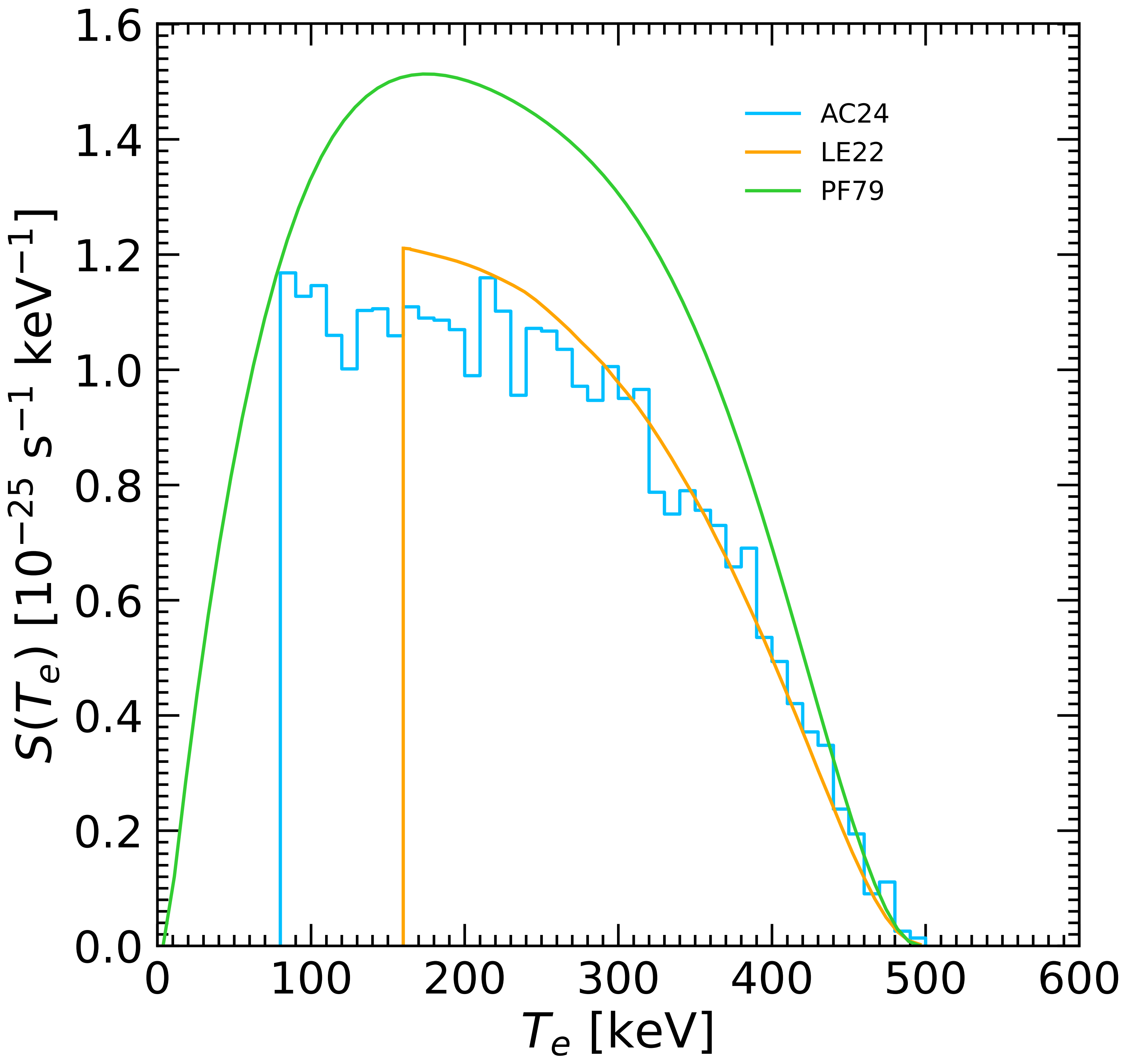
Outcomes:

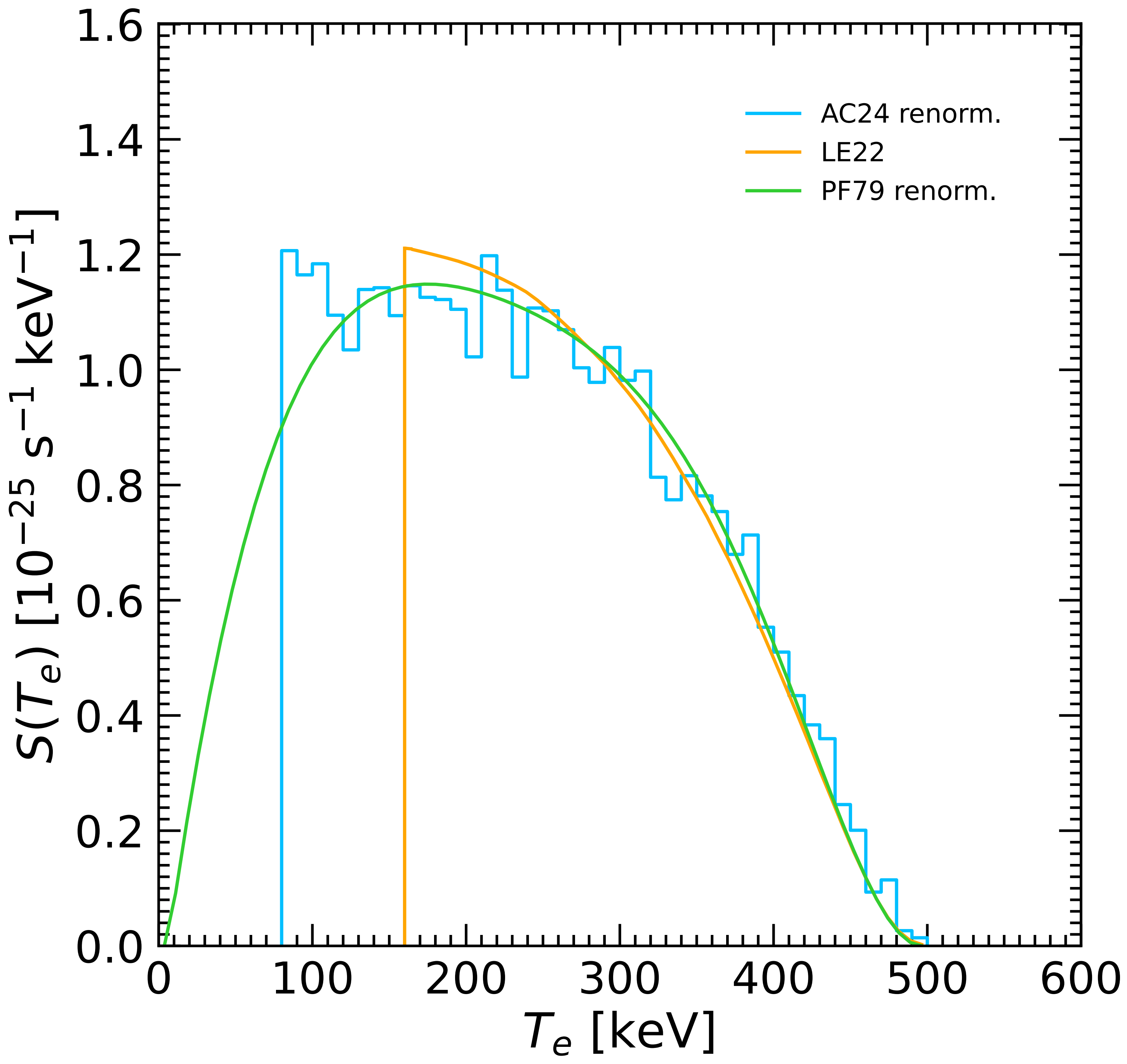
- Stable and precise estimate of $T_{1/2}$
- Evaluation of the spectral shape

Less model dependent!

- g_A quenching still needed but reduced (wrt slide 11)
- Positive solutions (sNME>0) are always favored
- sNME fixed only with the $T_{1/2}$ match
- Theoretical $T_{1/2}$ compatible with experimental one

In-115: measurement comparison





Very useful comparison:

- AC24 (our data) and LE22 fully compatible
- PF79 very different (possible issues in the background subtraction)

See details in J. Kostensalo, E. Lisi, A. Marrone and J. Suhonen, Phys.Rev.C 110 (2024) 4, 045503

Theory progress: an example

G. De Gregorio, R. Mancino, L. Coraggio, N. Itaco, Phys.Rev.C 110 (2024) 1, 014324

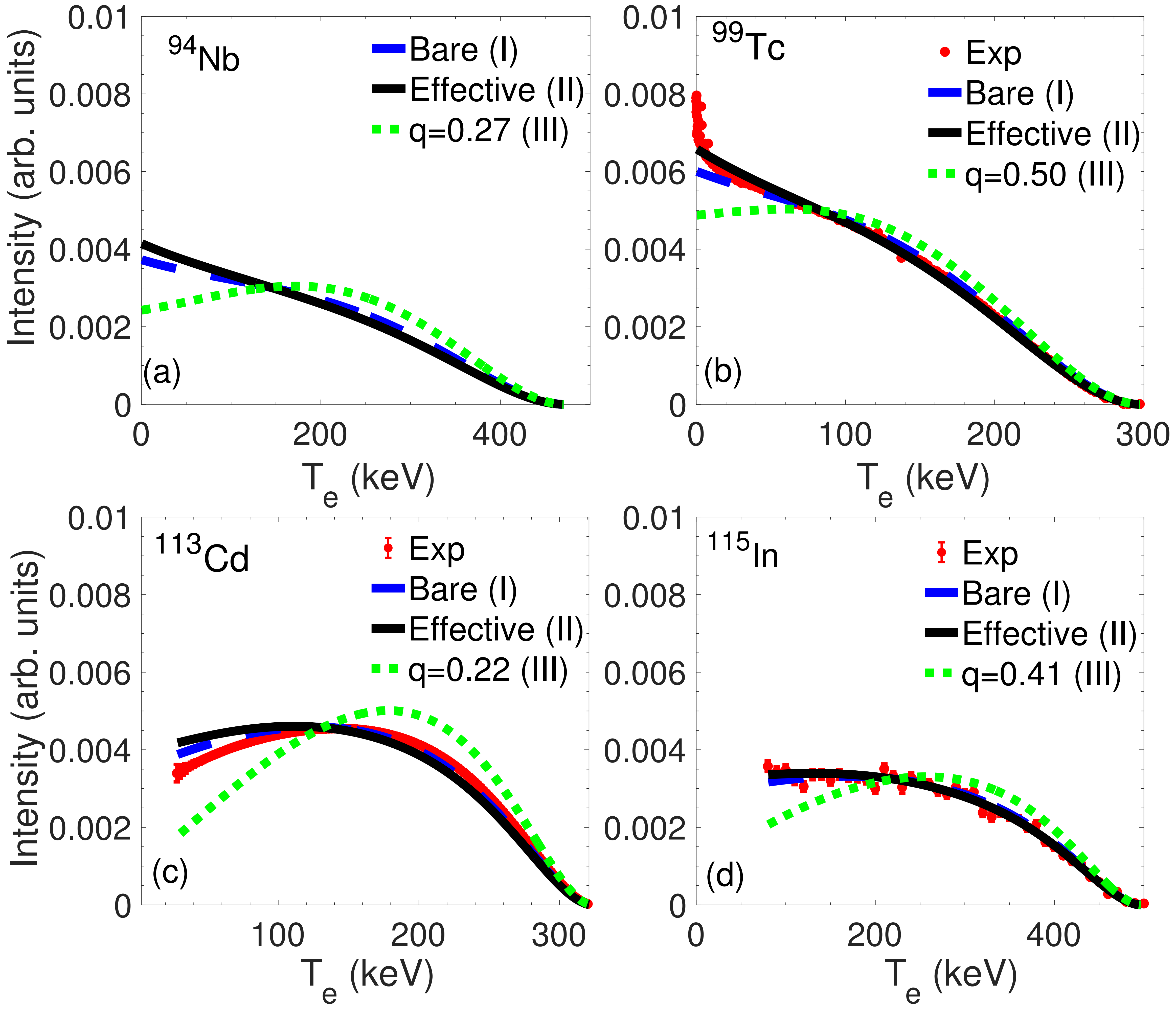
In a recent paper, the data presented were used as a term of comparison with theoretical calculations within the **Realistic Shell Model**.

Very good match of the spectral shape ➡ **without g_A quenching**

Half-life is underestimated (factor of 2 - 8)

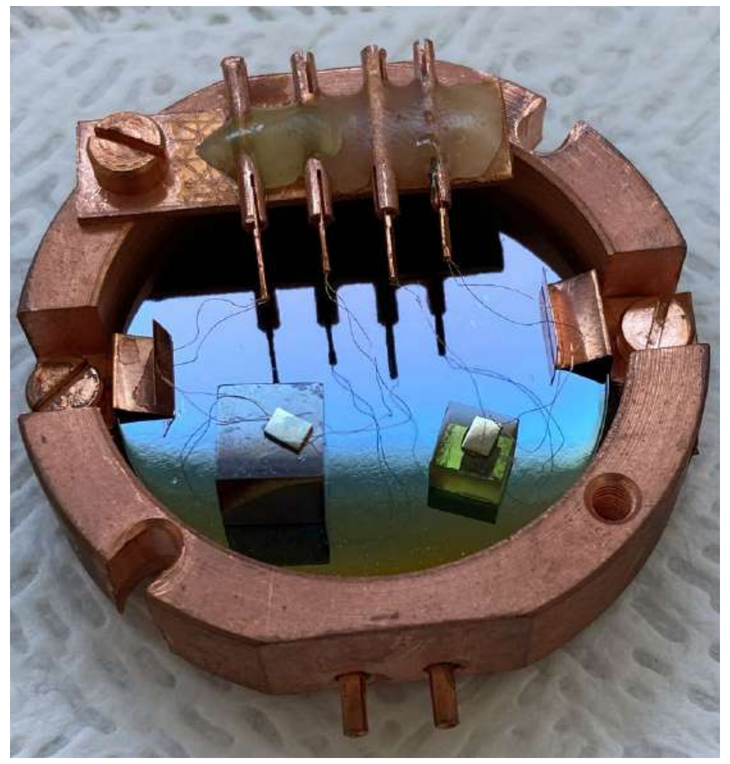
⬇

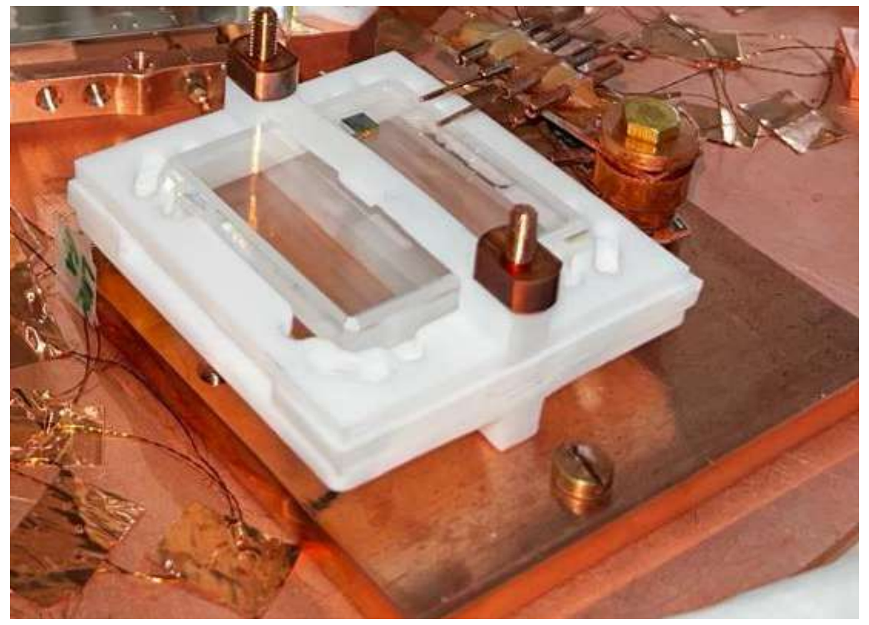
	log(ft) Bare	log(ft) Effective	log(ft) Exp.
^{94}Nb	11.30	11.58	11.95 (7)
^{99}Tc	11.580	11.876	12.325 (12)
^{113}Cd	21.902	22.493	23.127 (14)
^{115}In	21.22	21.64	22.53 (3)



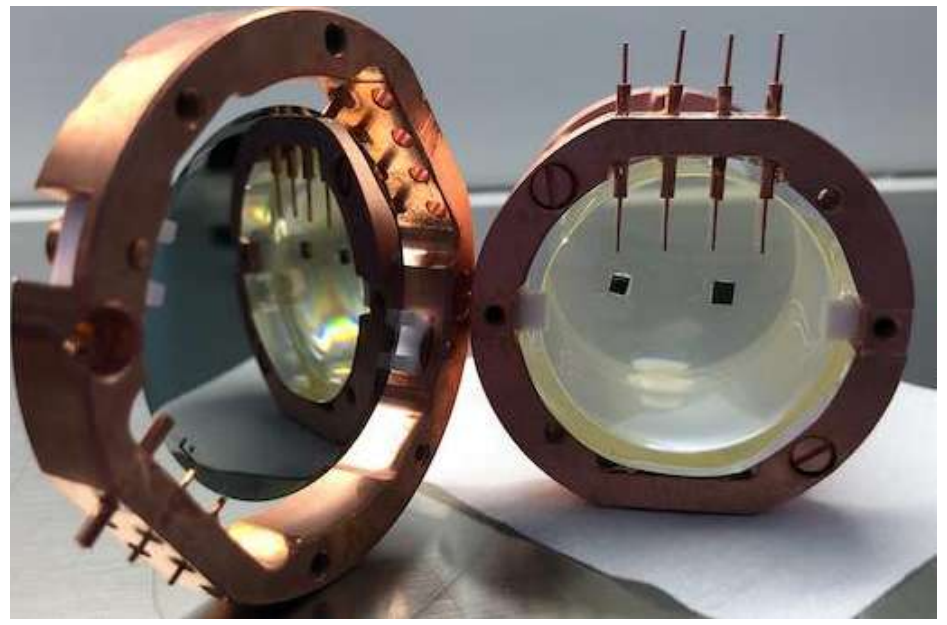
Next steps

- **^{115}In with InI and In_2O_3**
  - Refined measurement with optimized setup (shielded in IETI)
  - LED/Heater for temperature gain stabilization
  - External or removable calibration source





- **^{99}Tc with SourceOnPEN**
  - Assess the background of the two TeO slabs
  - Add proper shielding and the ^{99}Tc source in the next run
  - LED/Heater for temperature gain stabilization
  - External or removable calibration source



- **^{210}Bi/^{210}Pb with $PbWO_4$**
  - See what we can extract from the RES-NOVA crystals

- **^{36}Cl with NaCl (irradiated)**
  - To be tested within 2026

- **^{113}Cd with $CdWO_4$**
  - Natural crystal, never measured (m = 195 g)

Summary

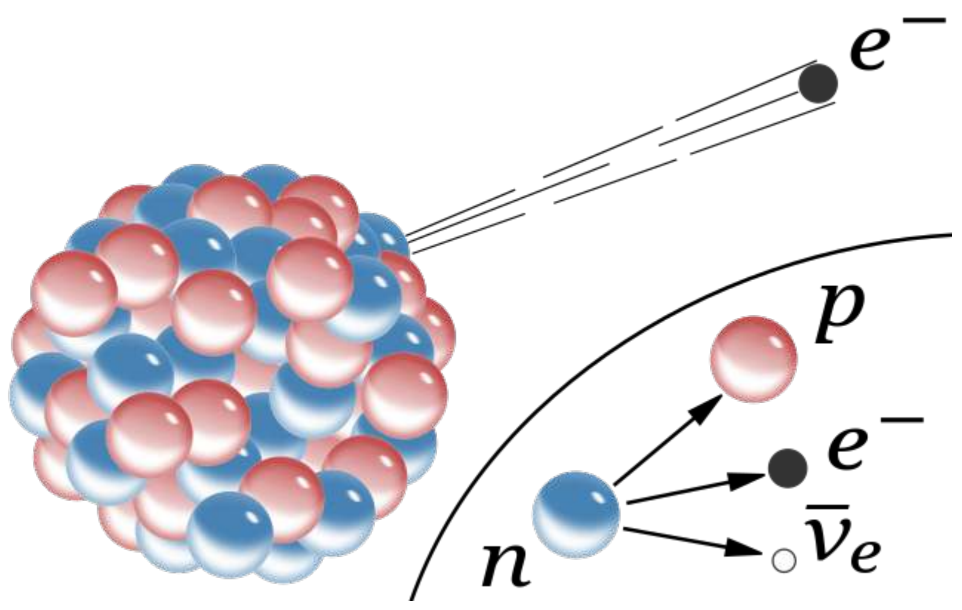
- **Forbidden beta decays**, and in particular their spectral shape, **challenge nuclear models**
- **Nuclear models** and **computation techniques** have improved a lot
- Renewed experimental efforts are ongoing to provide **novel high-quality data**

Mapping the spectral shape of several forbidden β-decays in terms of effective nuclear parameters

We could shed light on the nuclear physics behind the phenomenological g_A quenching and try to avoid it

Backup slides

Forbidden β-decays



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

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

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

Forbidden non-unique

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

Forbidden unique*

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)**

Forbidenness index

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

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

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

* defined by only one nuclear matrix element

Spectral shape description - 1

$$S(E) = C(E) \cdot S_{all}(E)$$

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

numerically calculated

$C(E)$ ➡ empirical correction function

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

Forbidden Non-unique

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

Forbidden Unique

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

1st $C_1 = P^2 + c_1 Q^2$

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

Spectral shape description - 2

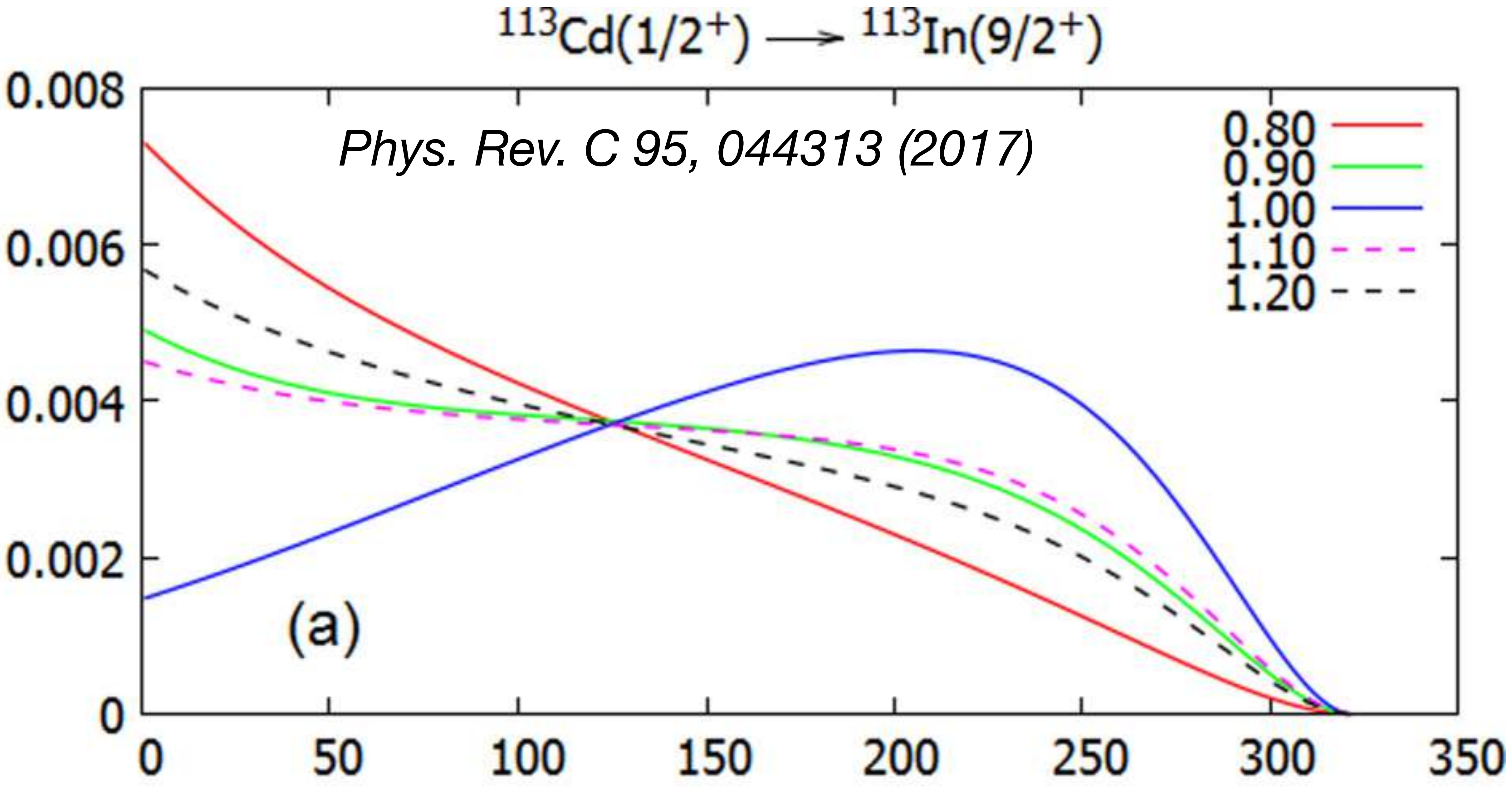
$$S(E) = C(E) \cdot S_{all}(E)$$

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

numerically calculated

$C(E)$ ➡ empirical correction function

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



Template spectra can be produced within Nuclear Models as a function of **nuclear parameters (g_A)** or with **different approximations**, and then **compared with experimental data.**

Shape Function: g_A and sNME

$$T_{1/2} = \frac{6289}{\tilde{C}}$$

Decay half-life

$$\tilde{C} = \int_0^{Q_\beta} S(E) \cdot dE$$

Integrated shape function

$$S(E) = C(E) \cdot p \cdot E \cdot (Q_\beta - E)^2 \cdot F(Z_d, E)$$

Shape Function

$$C(E) = g_V^2 C_V(E) + g_A^2 C_A(E) + g_V g_A C_{VA}(E)$$

Shape Function Decomposition

Nuclear Matrix Elements enter the Shape Functions!

s-NME l-NME

$${}^V\mathcal{M}^{(0)}_{KK-11} = \left(\frac{\frac{(-M_n c^2 + M_p c^2 + W_0) \times R}{\hbar c} + \frac{6}{5}\alpha Z}{\sqrt{K(2K+1)} \times R} \right) \times {}^V\mathcal{M}^{(0)}_{KK0}$$

$M_{n/p}$ = neutron/proton mass K = order of forbiddenness

Z = atomic number of the daughter nucleus

R = atomic radius W_0 = Q-value

Formula valid only in the ideal case:

- infinite valence spaces
- perfect nuclear many-body theory

l-NME fixed by the nuclear calculations

sNME is treated as free parameter

NLDBD vs Heavy Ion DCER

Credits to
Horst Lenske

1. **Initial and final states:** Parent/daughter states of the $0\nu\beta\beta$ are the same as those of the target/residual nuclei in the DCE;

2. **Spin-Isospin mathematical structure** of the transition operator: Fermi, Gamow-Teller and rank-2 tensor together with higher L components are present in both cases;

3. **Large momentum transfer:** A linear momentum transfer as high as 100 MeV/c or so is characteristic of both processes;

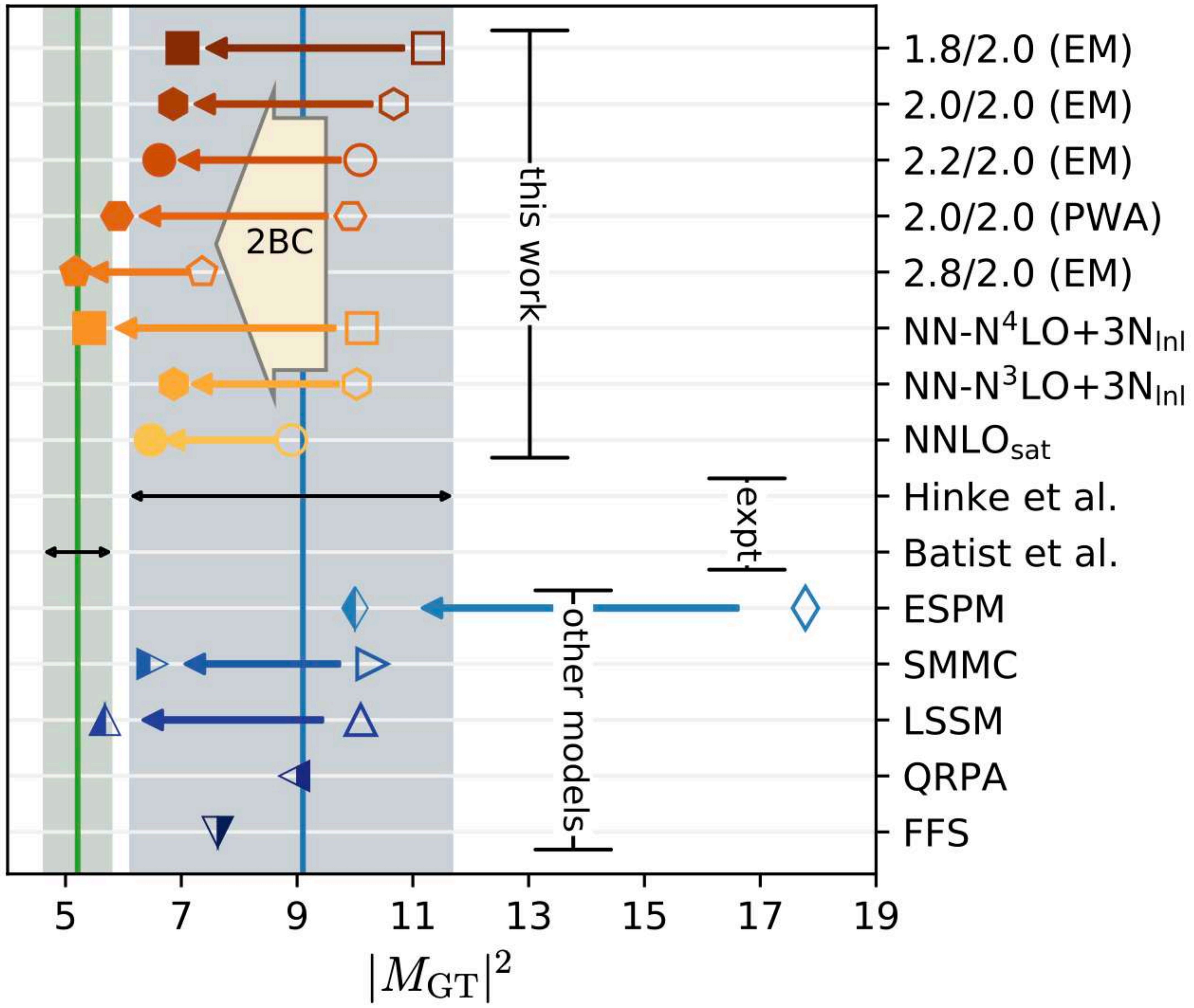
4. **Non-locality**: both processes are characterized by two vertices localized in two valence nucleons. In the ground to ground state transitions in particular a pair of protons/neutrons is converted in a pair of neutrons/protons so the non-locality is affected by basic pairing correlation length;

5. **In-medium** processes: both processes happen in the same nuclear medium, thus **quenching** phenomena are expected to be similar;

6. Relevant **off-shell propagation** in the intermediate channel: both processes proceed via the same intermediate nuclei off-energy-shell even up to 100 MeV.

Ab initio calculations

(^{100}Sn) P. Gysbers et al, Nature Phys. 15 (2019) 5, 428-431



Ab initio calculations including **2 body currents** improve the match with the half-life for **Gammow-Teller transitions**.

it is unclear what's happen for spectral shape and for forbidden decay.

In-115 by ACCESS: Full Numerical Results

	Positive solution				Negative solution			
Model	g_A	sNME	$T_{1/2}$ [$\times 10^{14}$ yr]	χ^2_{red}	g_A	sNME	$T_{1/2}$ [$\times 10^{14}$ yr]	χ^2_{red}
Best fit								
ISM	$0.964^{+0.010}_{-0.006}$	$1.75^{+0.13}_{-0.08}$	5.26 ± 0.06	1.55	$0.774^{+0.046}_{-0.042}$	$-5.43^{+0.40}_{-0.22}$ (*)	5.40 ± 0.07	2.27
MQPM	$1.104^{+0.019}_{-0.017}$	$2.88^{+0.49}_{-0.71}$	5.26 ± 0.07	1.65	$0.978^{+0.022}_{-0.021}$	$-5.40^{+0.38}_{-0.53}$ (*)	5.46 ± 0.07	2.26
IBFM-2	$1.172^{+0.022}_{-0.017}$	$0.81^{+0.52}_{-0.24}$	5.25 ± 0.07	1.66	$0.739^{+0.069}_{-0.058}$	$-5.20^{+0.63}_{-0.41}$ (*)	5.40 ± 0.06	1.97
Matched half-life								
ISM	$0.965^{+0.013}_{-0.010}$	1.10 ± 0.03	5.20 ± 0.07	1.78	$0.869^{+0.004}_{-0.004}$	-1.15 ± 0.03	5.50 ± 0.06	2.94
MQPM	$1.093^{+0.009}_{-0.007}$	0.90 ± 0.03	5.05 ± 0.06	2.32	$0.992^{+0.004}_{-0.004}$	-1.00 ± 0.03	5.64 ± 0.07	3.22
IBFM-2	$1.163^{+0.036}_{-0.010}$	1.10 ± 0.03	5.28 ± 0.06	1.67	$0.958^{+0.012}_{-0.015}$	-1.15 ± 0.03	5.46 ± 0.07	2.28

ACCESS

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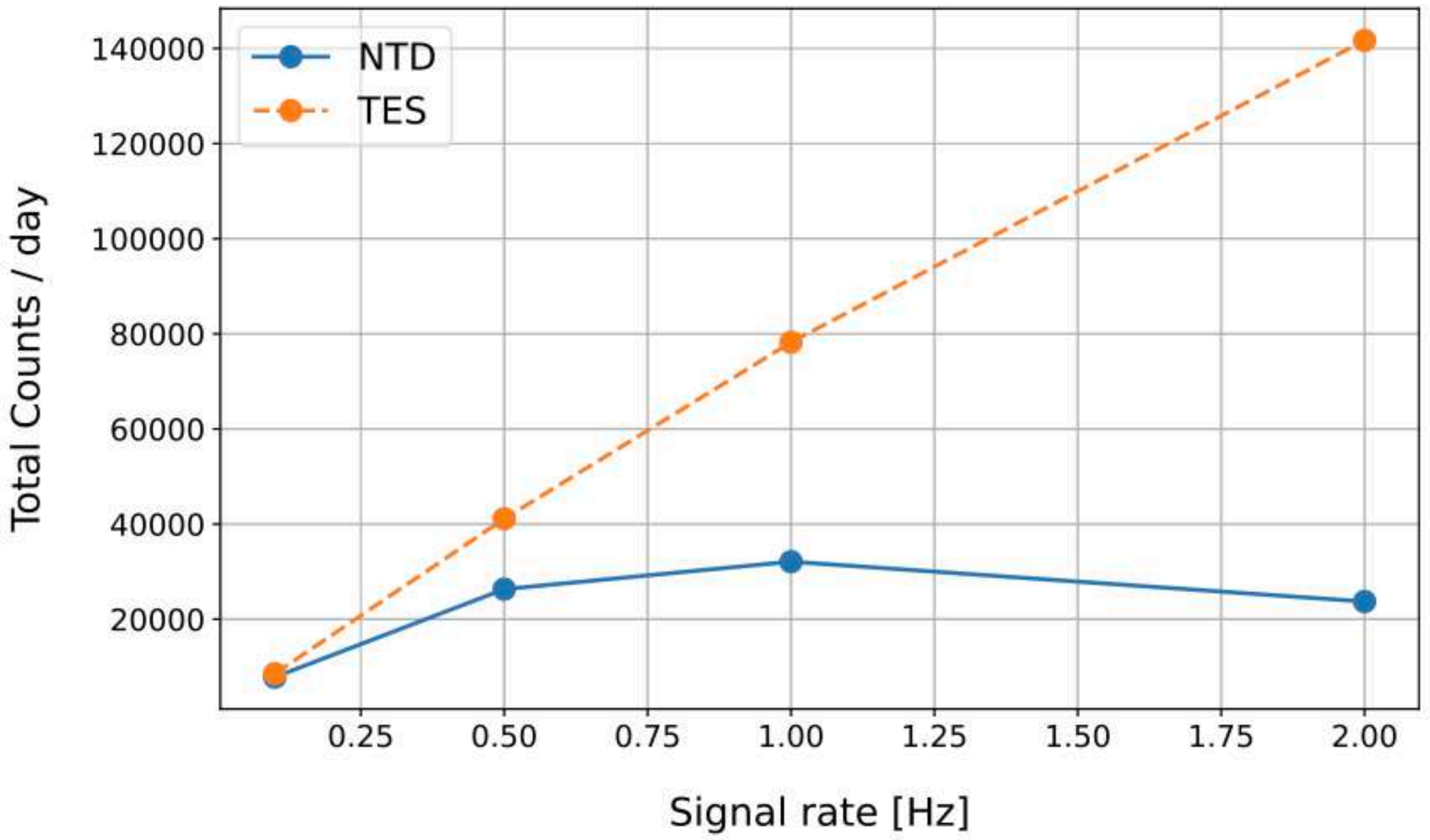
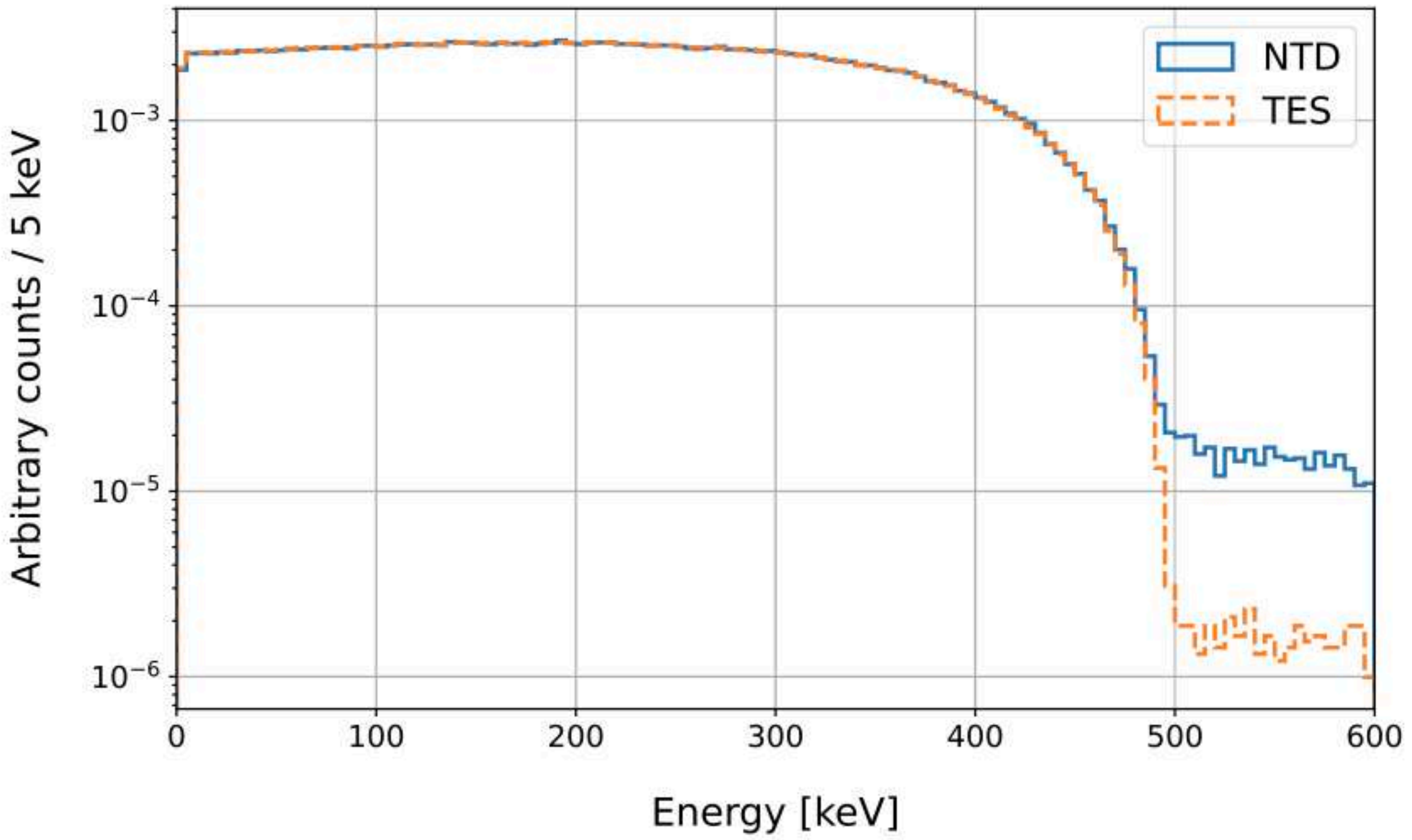
Next steps with increasing challenges:

- ^{113}Cd with natural $CdWO_4$
- ^{99}Tc with Li_2MoO_4, $Na_2Mo_2O_7$ irradiated at nuclear reactor / doped
- move from semiconductor sensors (NTD) to superconductive sensors (TES)
  - better threshold, energy resolution and detection efficiency (pile-up)





Beyond ACCESS:

- ^{37}Cl with irradiated NaCl irradiated at nuclear reactor
- ^{97}Zr with irradiated ZrO_2 irradiated at nuclear reactor

https://sites.google.com/gssi.it/access