NEUTRINO OSCILLATION WORKSHOP

Spectral Shape of Forbidden β-decays: Recent Results on In-115

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GSSI

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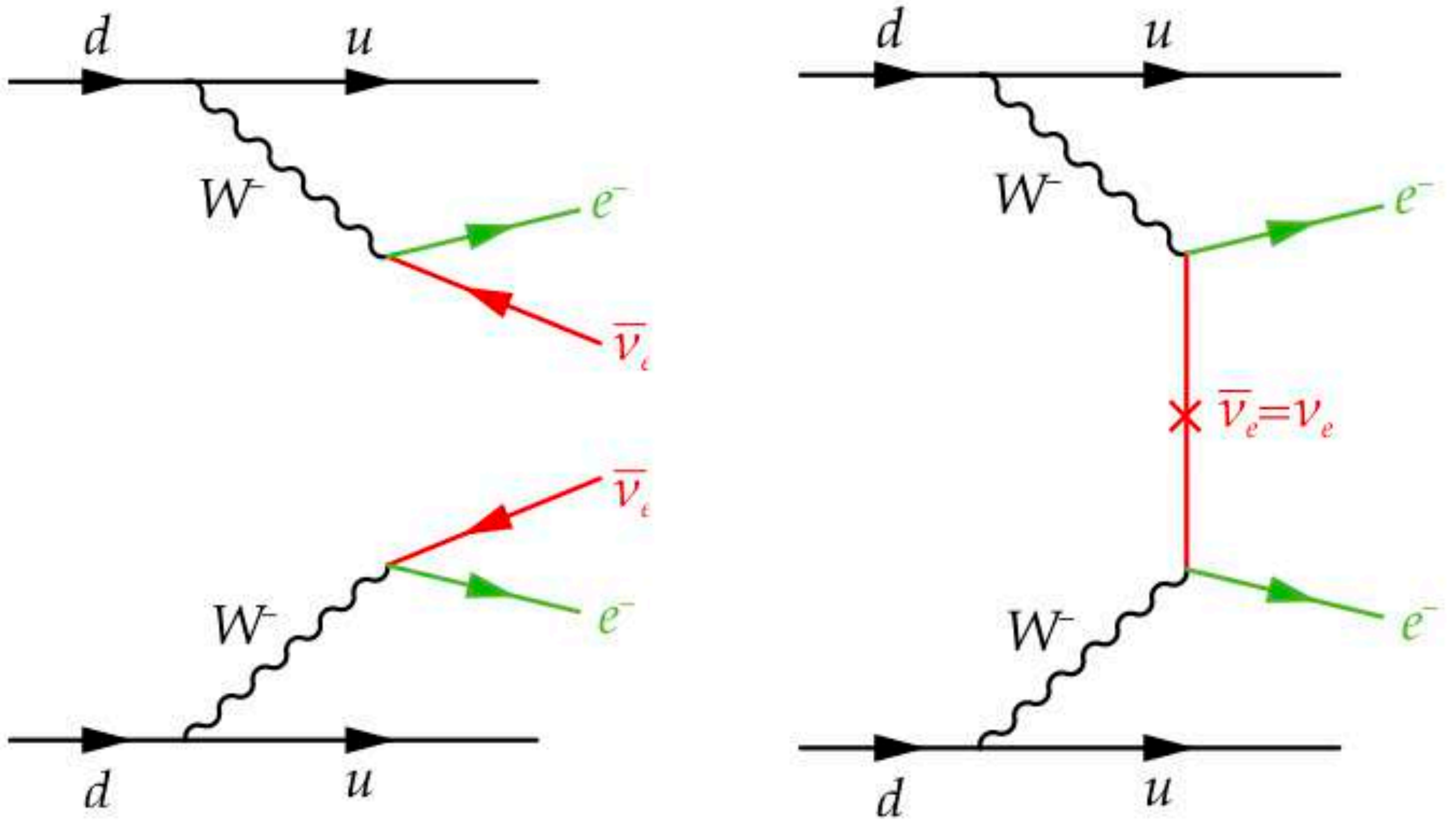
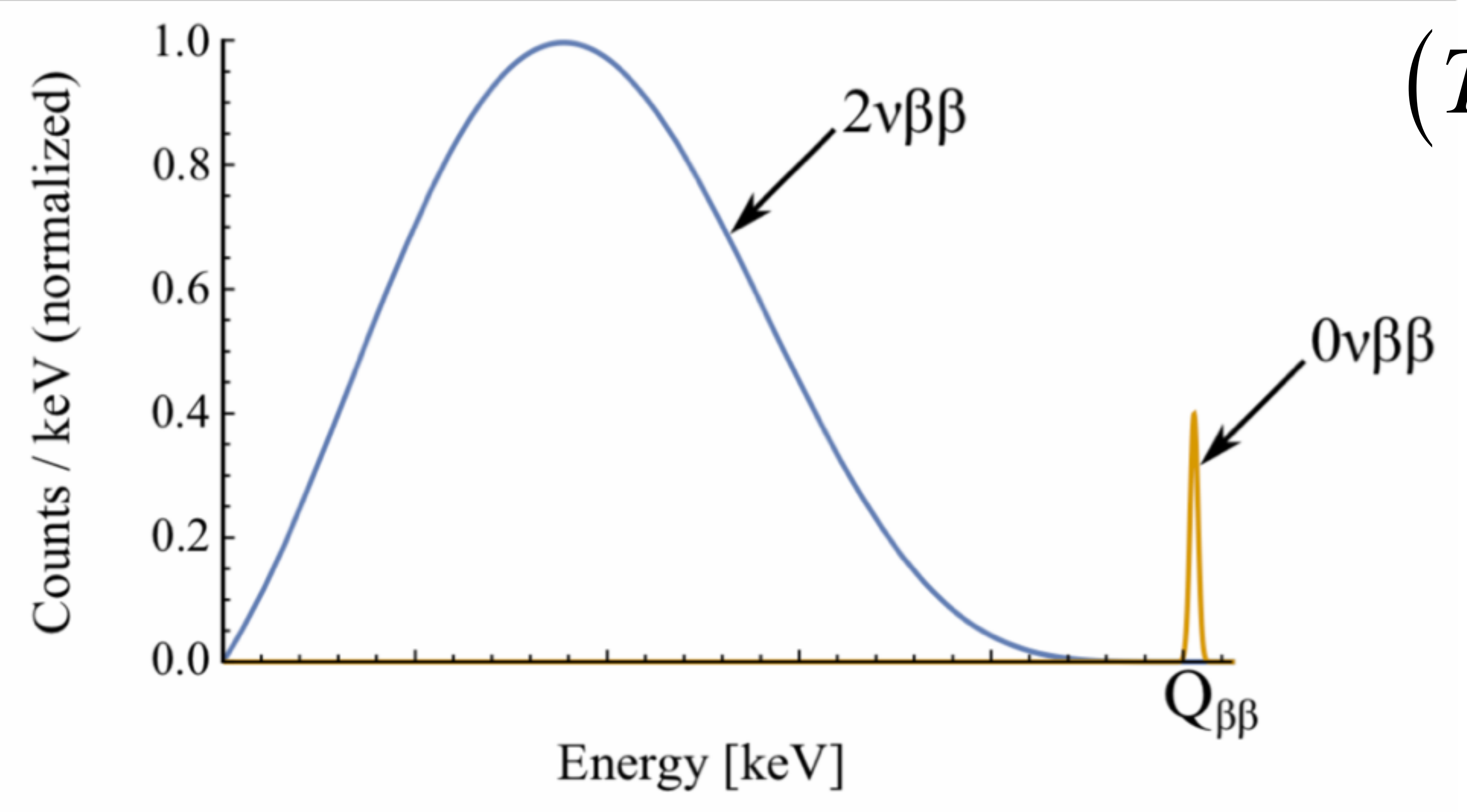
MARIE CURIE ACTIONS

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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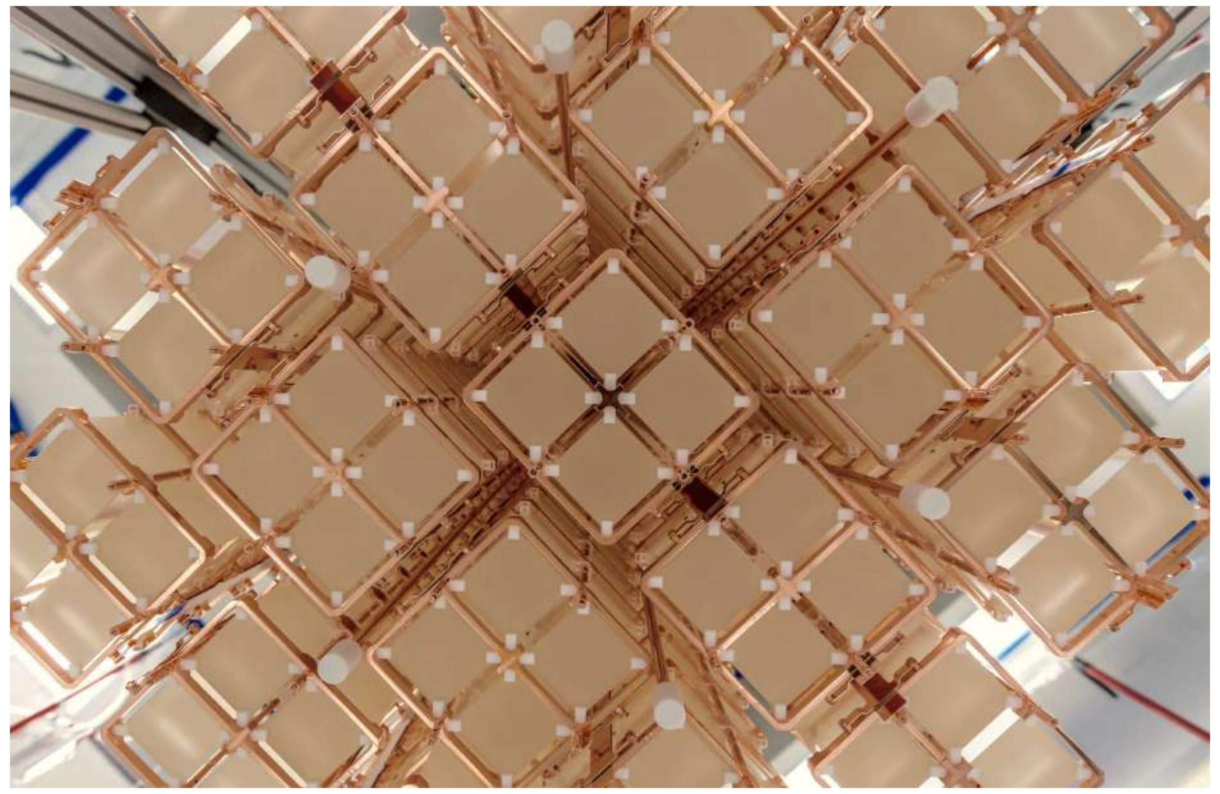
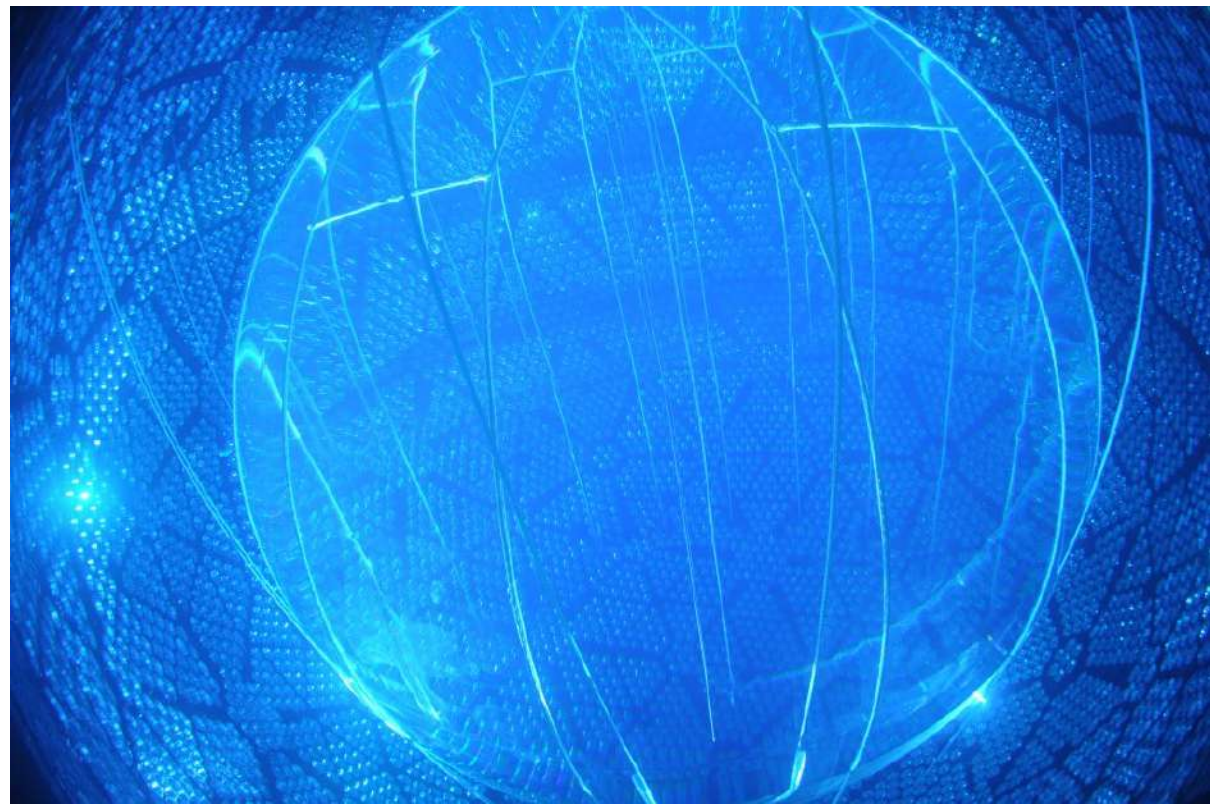


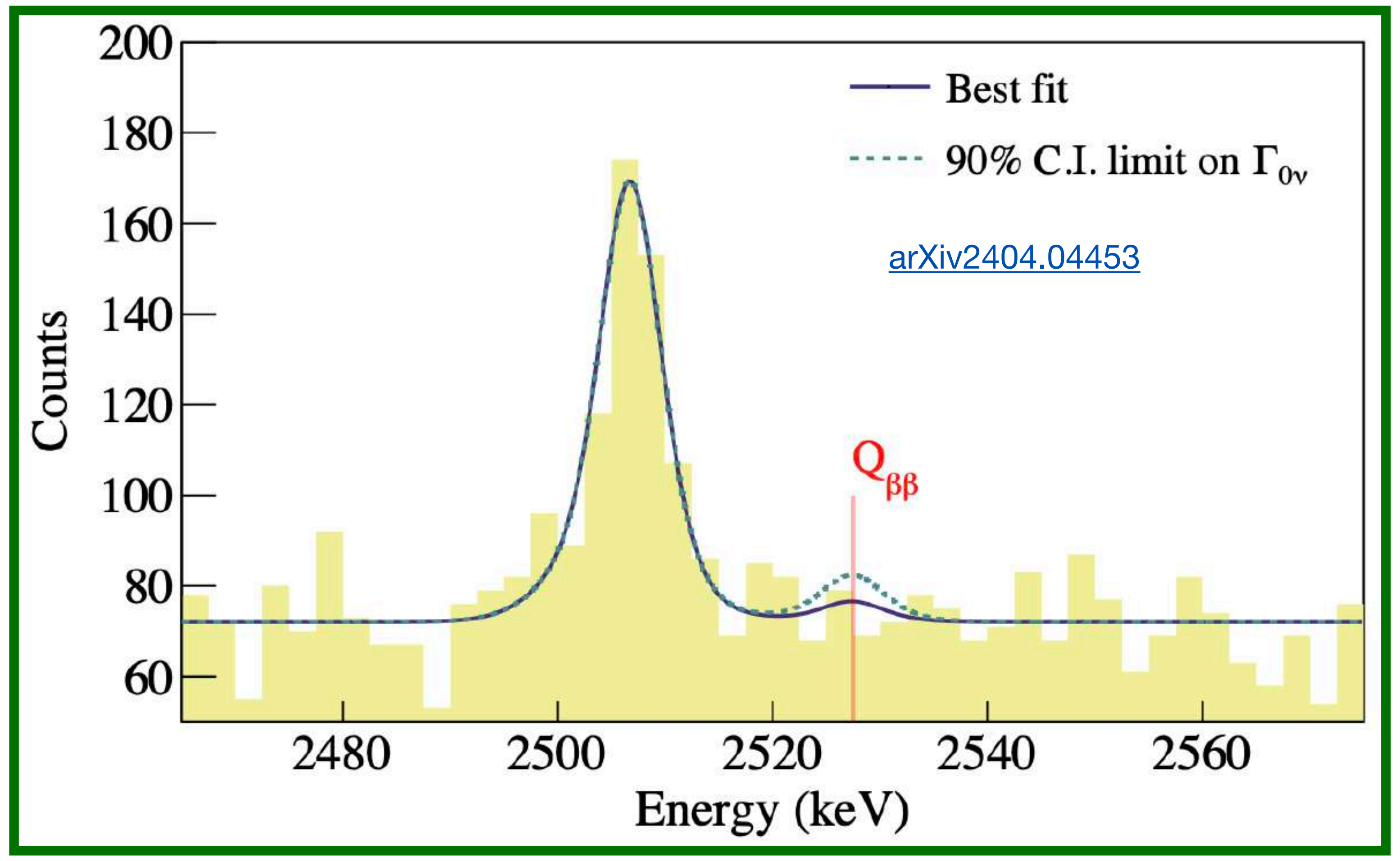


Neutrinoless Double Beta Decay

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

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

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



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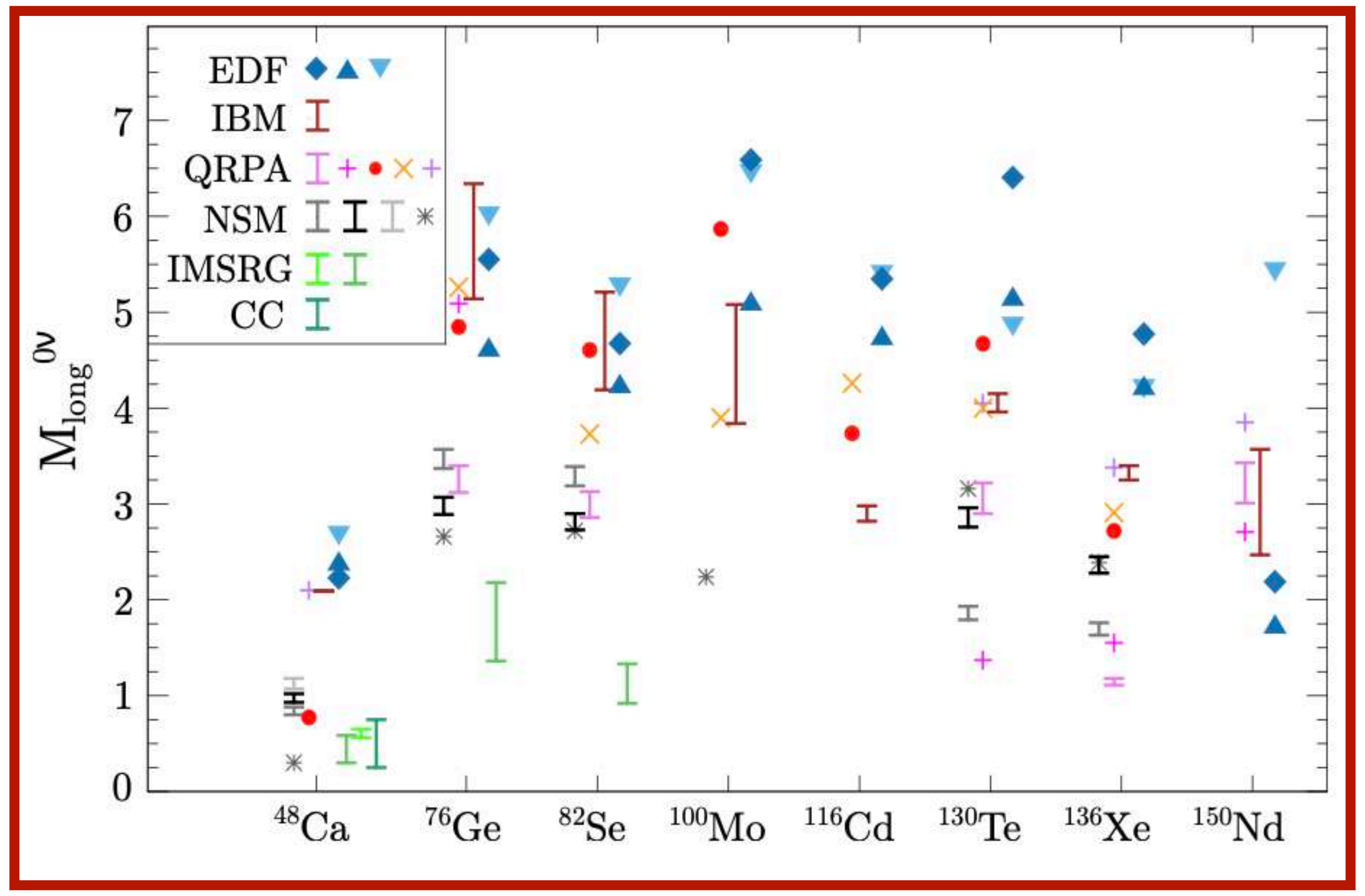

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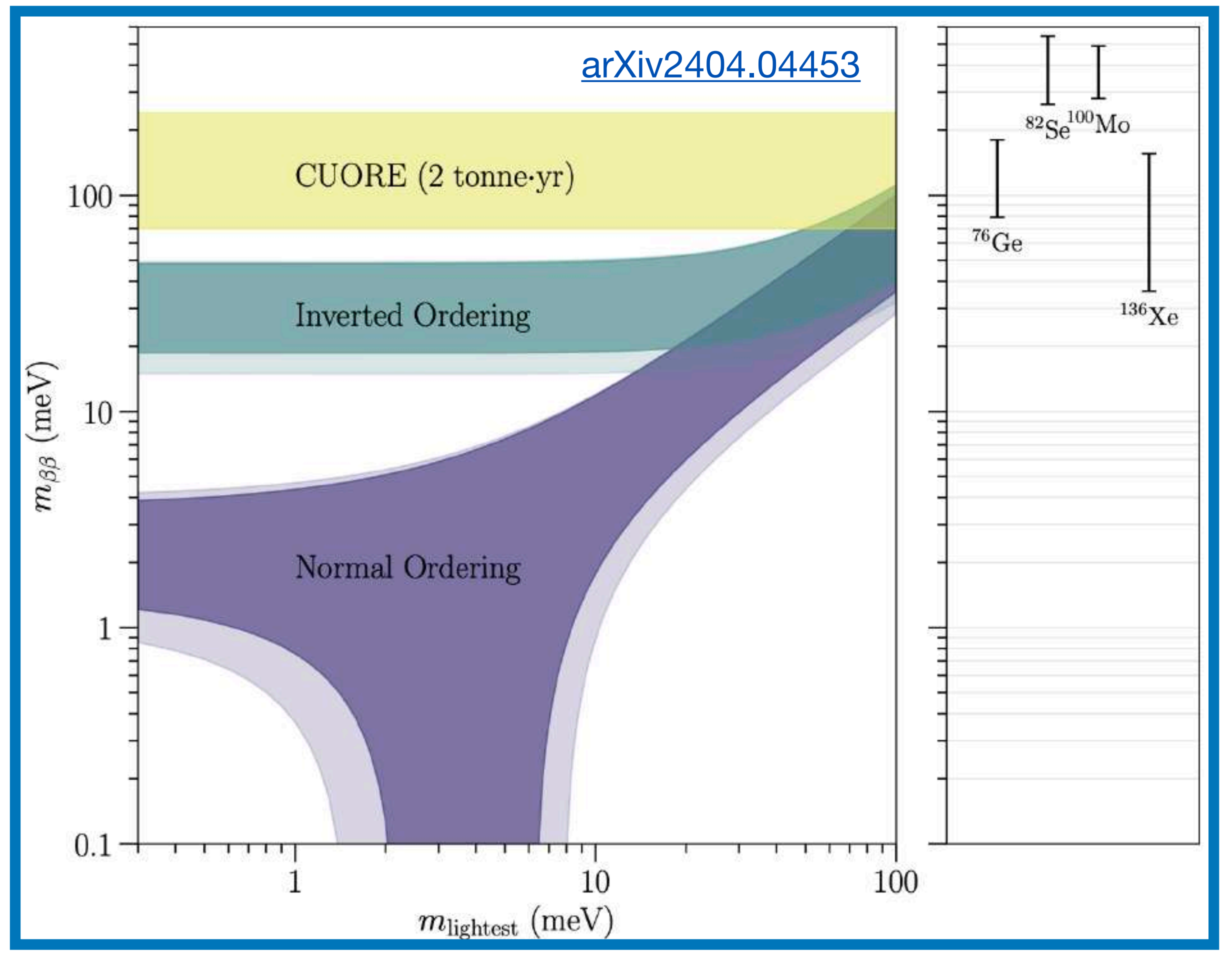


A single experimental limit on the half-life…

…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

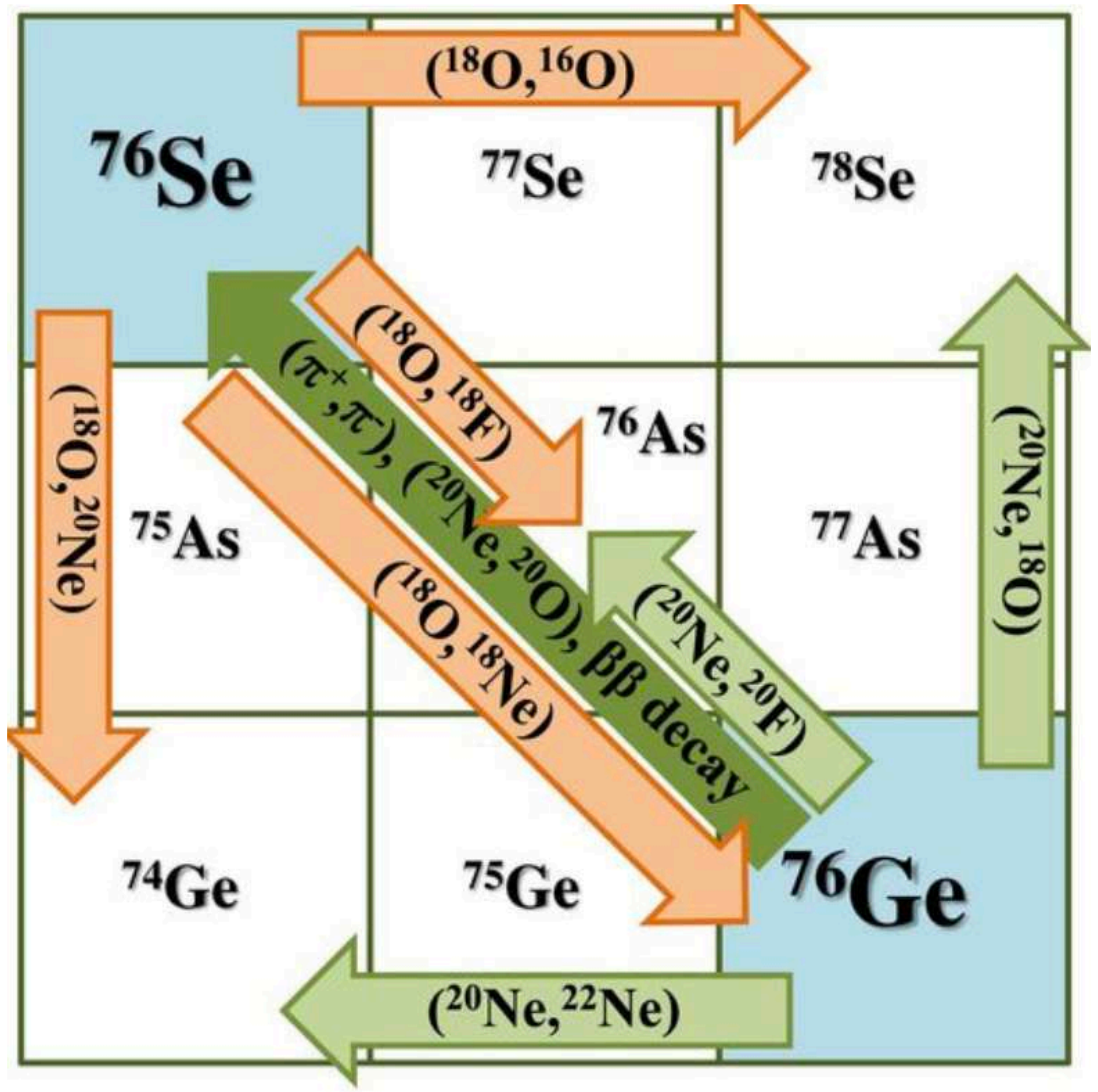
^{82}Se (CUPID-0) - Phys. Rev. Lett., 129(11):111801, 2022

^{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

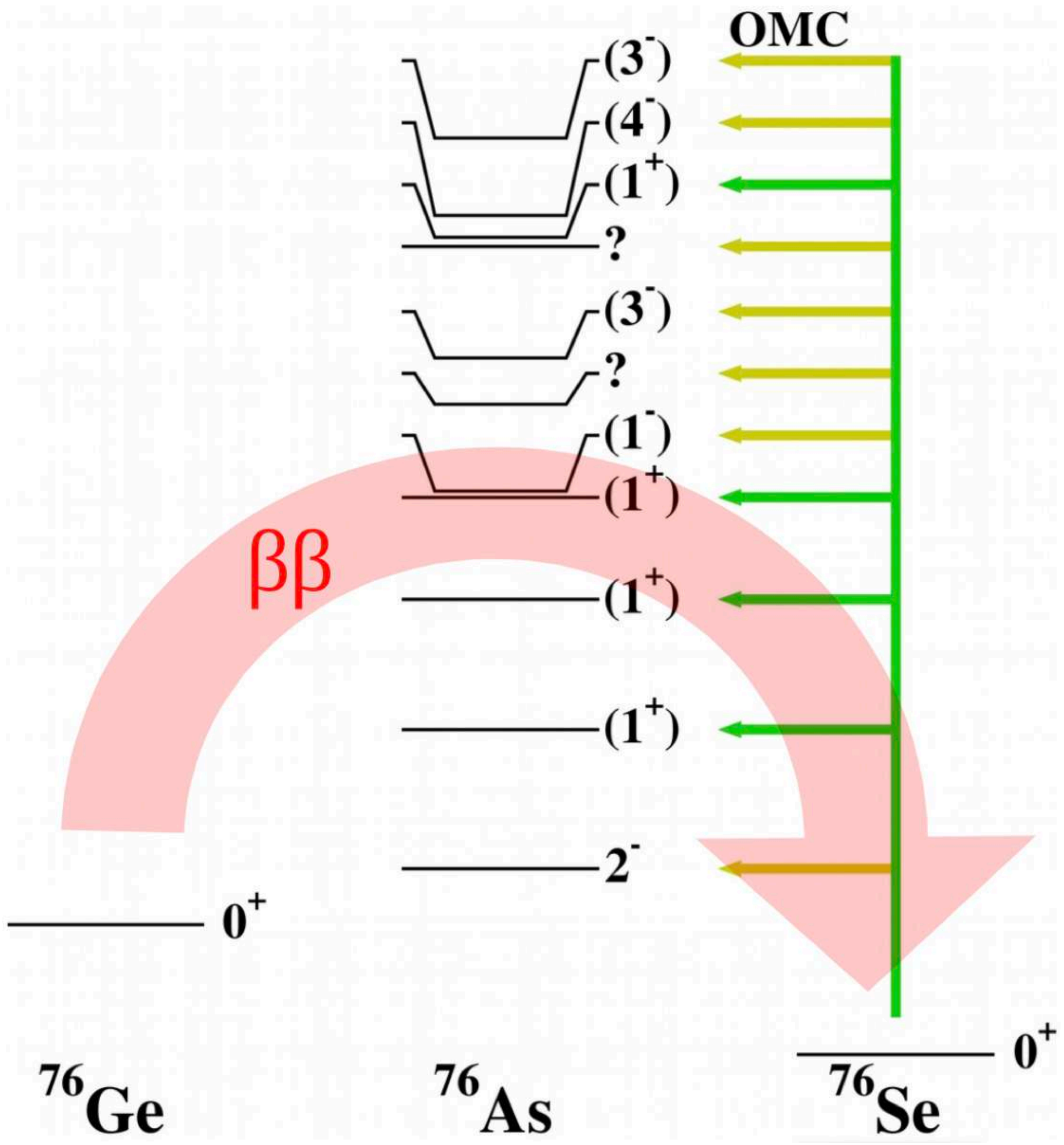
Double Charge Exchange (DCE)



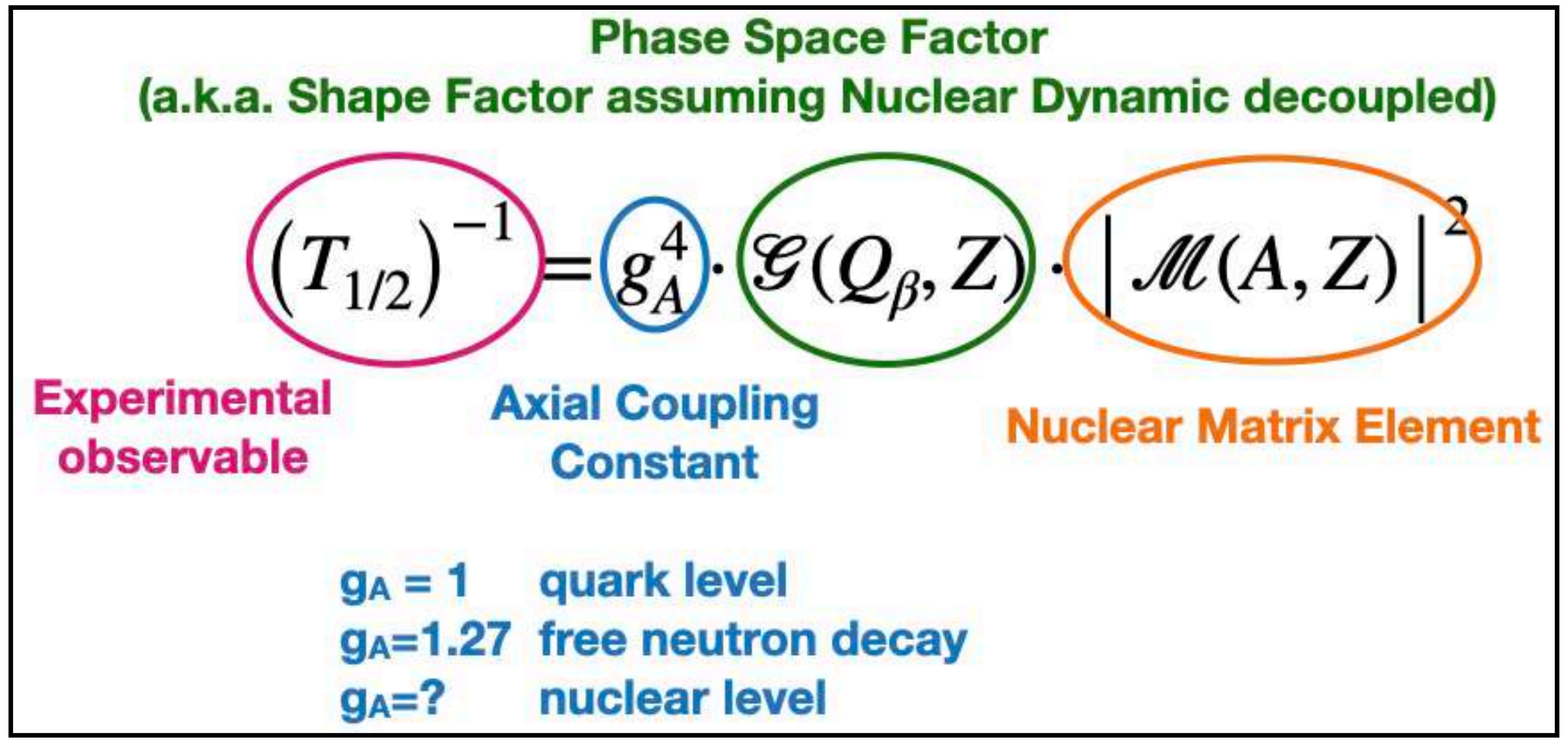
See Clementina Agodi's talk on NUMEN

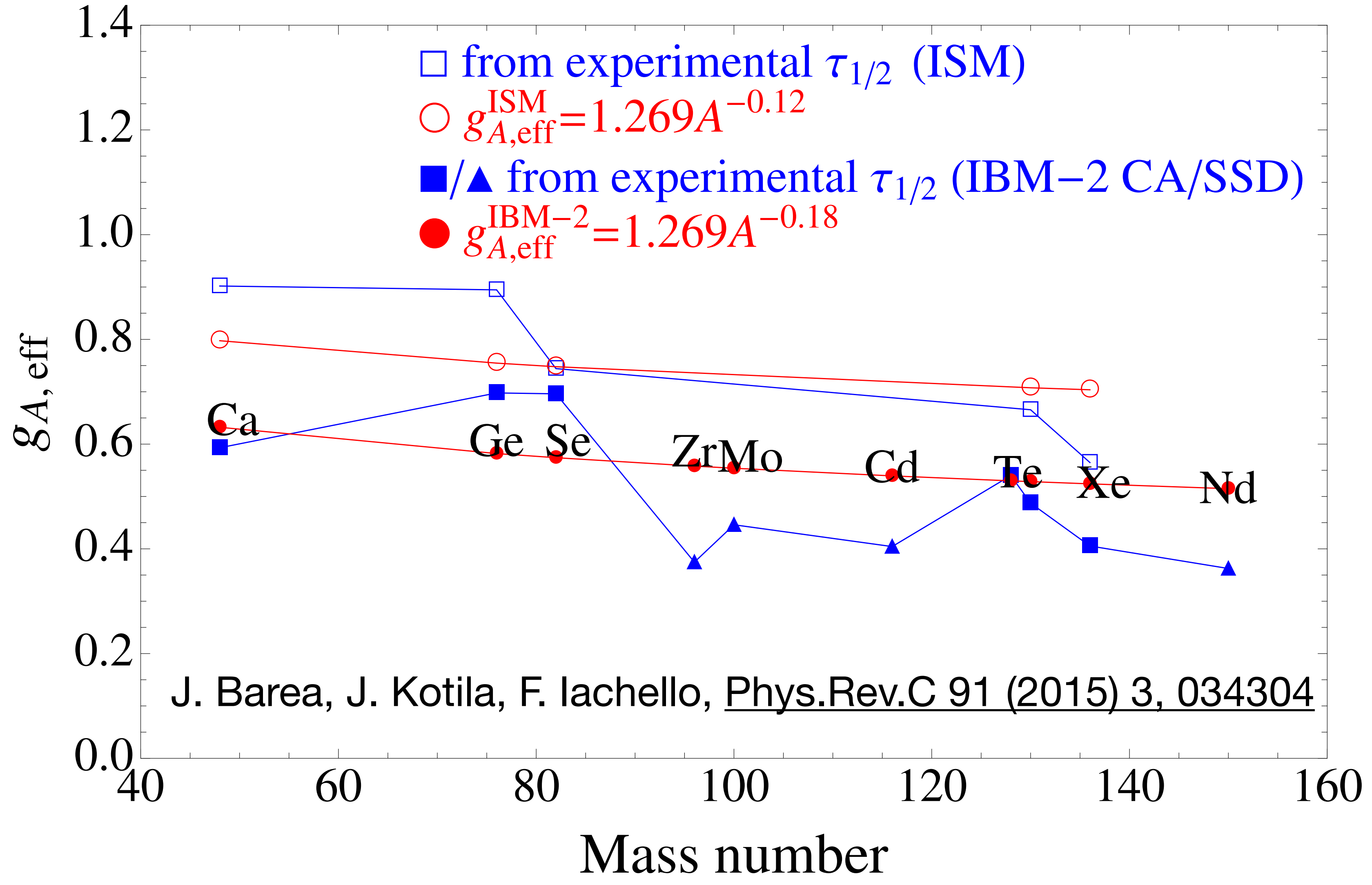
Ordinary Muon Capture (OMC)

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



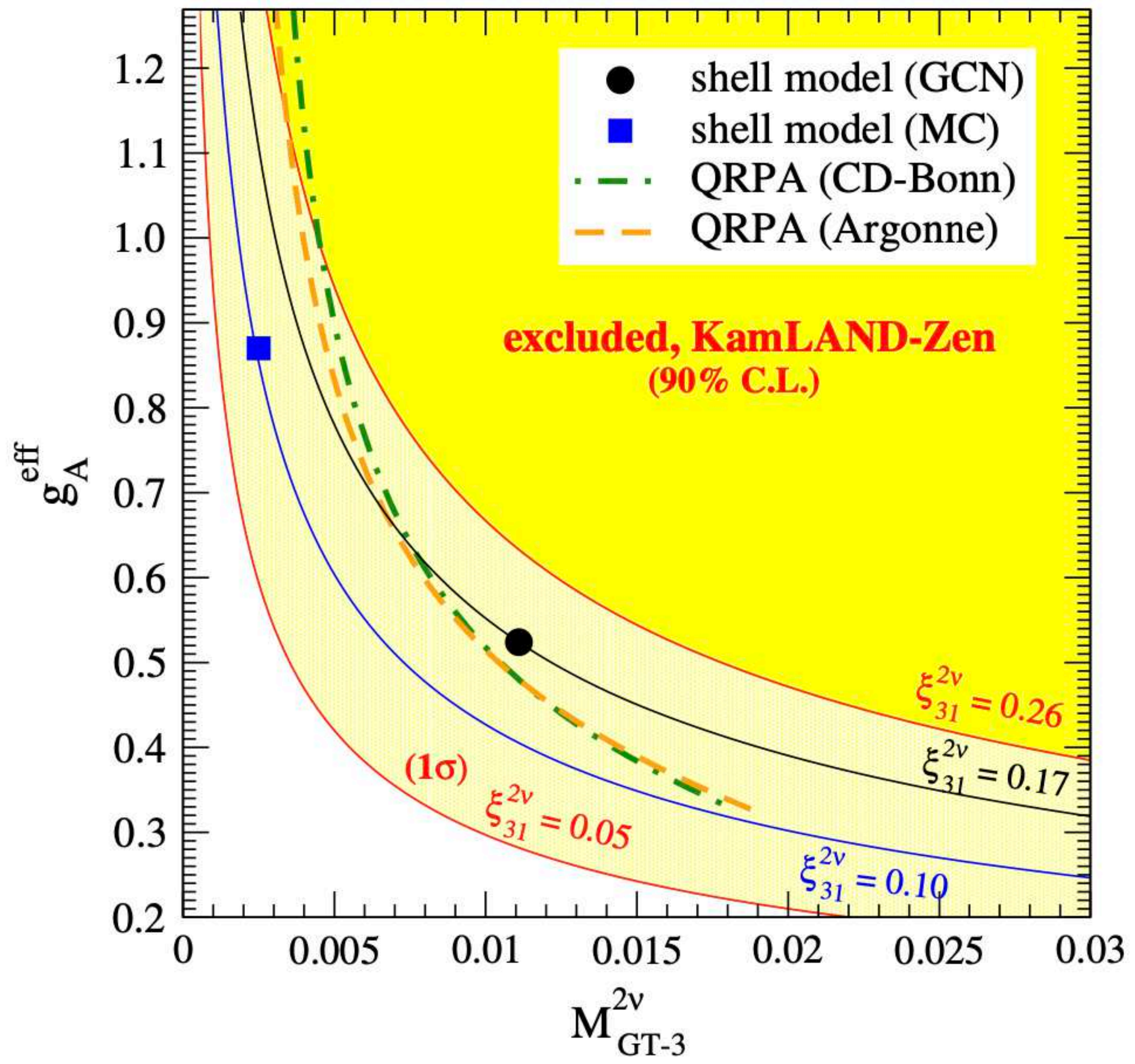
Two-neutrinos Double Beta Decay

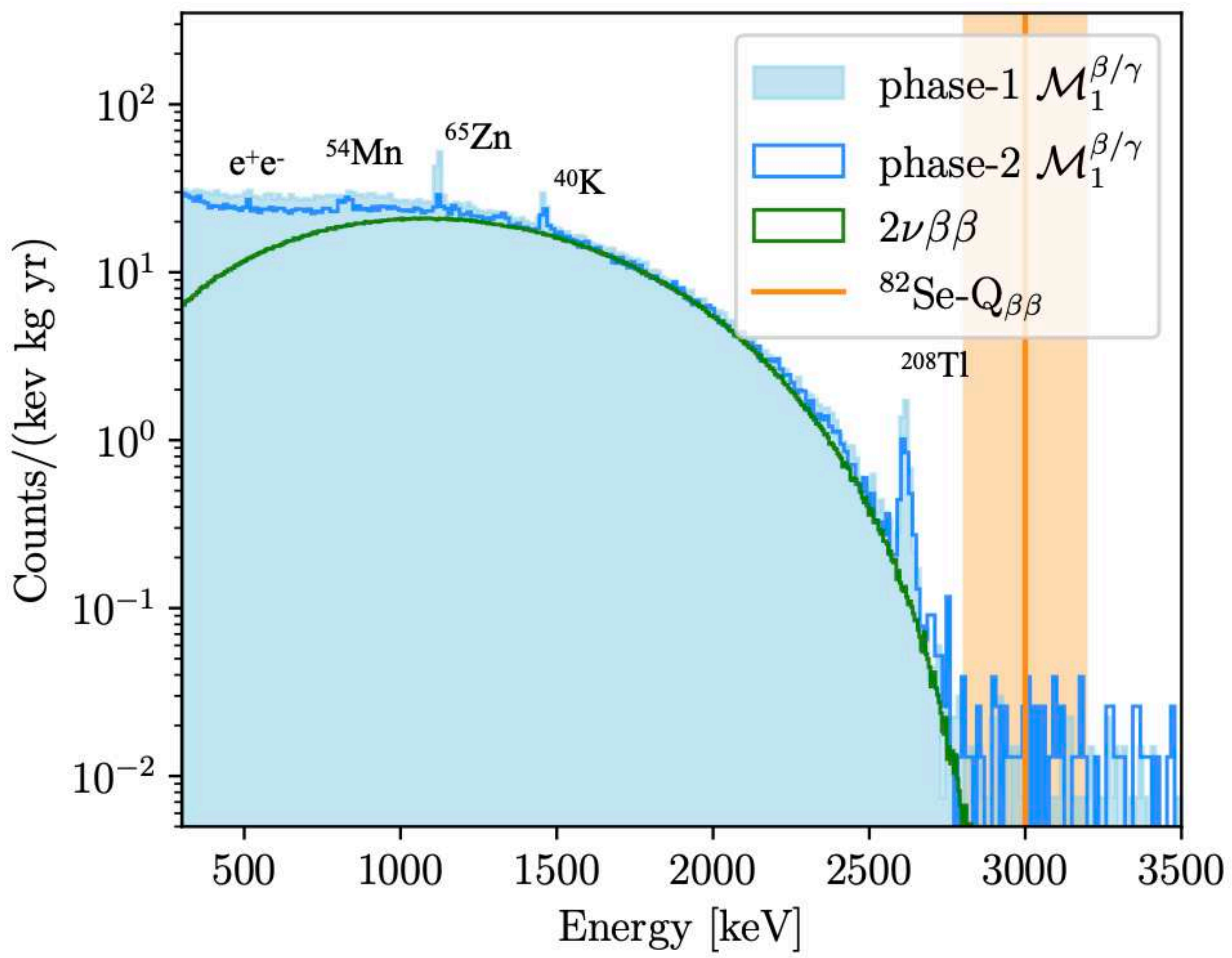




J. Barea, J. Kotila, F. Iachello, Phys.Rev.C 91 (2015) 3, 034304

gA 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

+

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

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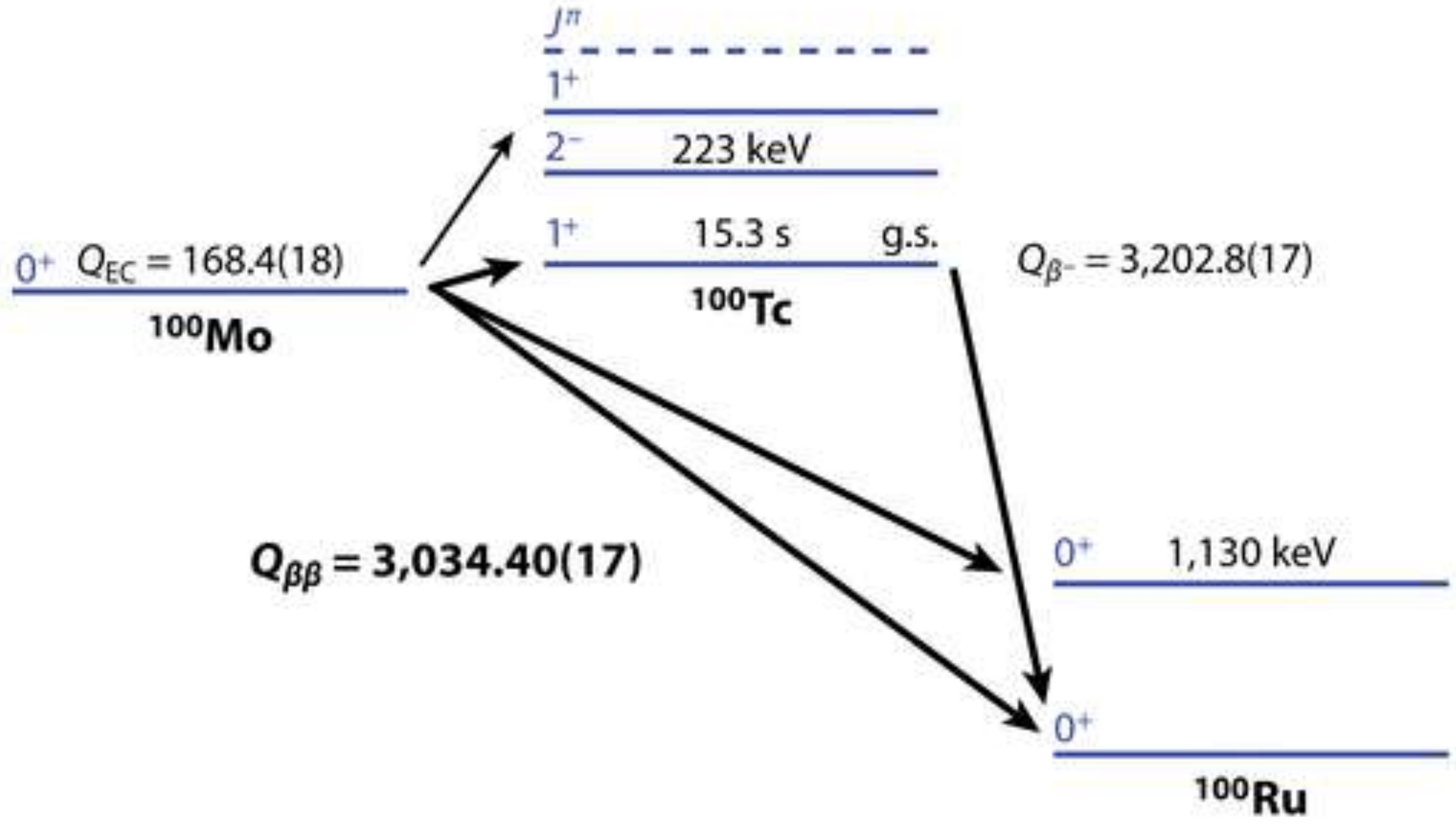
Deeper comparison with theory

Effective nuclear matrix elements as a function of gA

Forbidden transitions in NLDBD



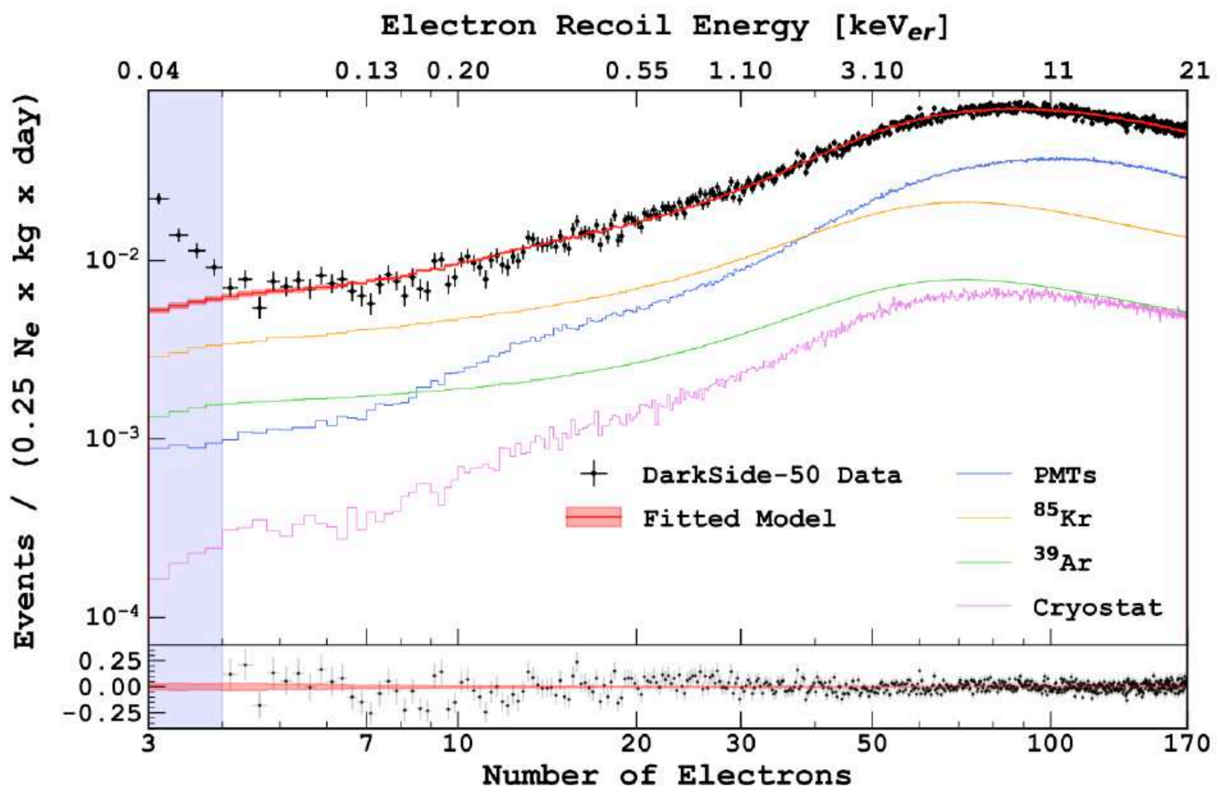
Forbidden β-decays are interesting for NLDBD since it **proceeds through forbidden virtual β-transitions** involving the excited states in the intermediate nucleus with **high multi-polarities**.

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

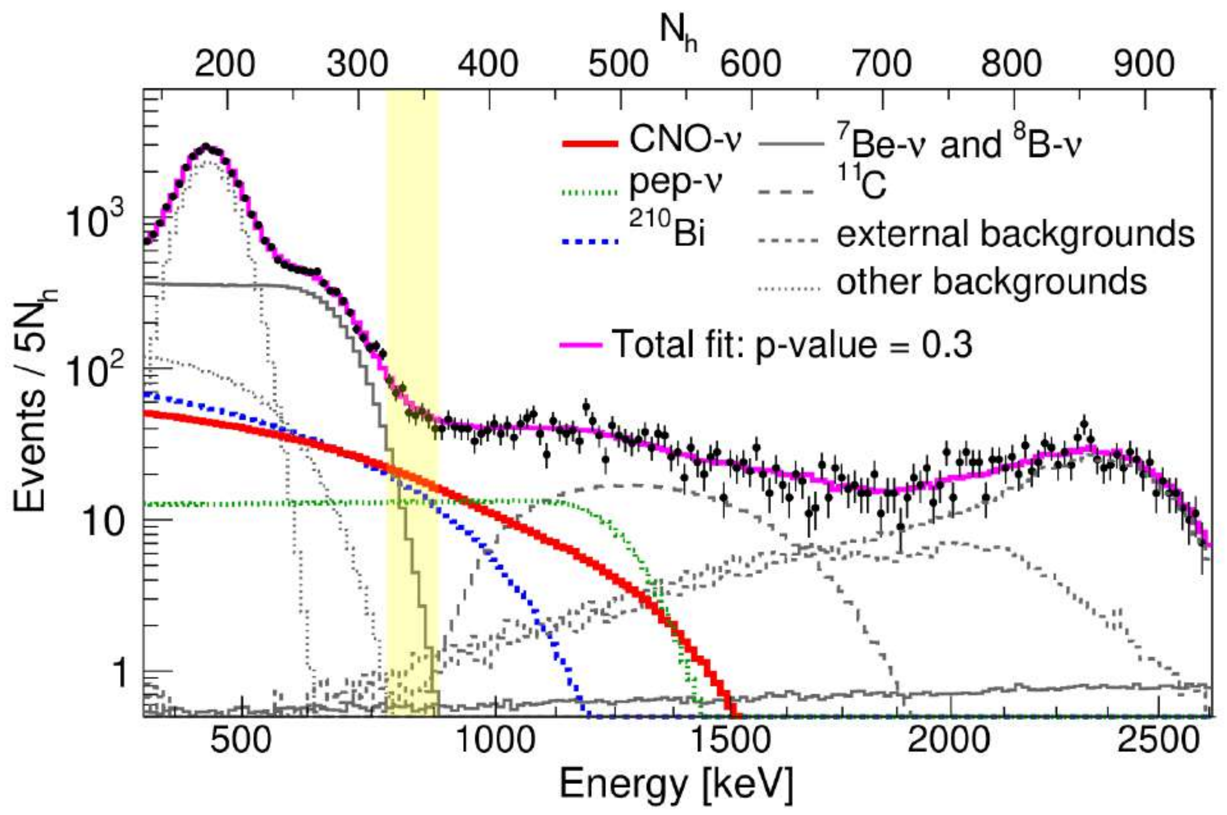
- only 1^{+} states of the intermediate nucleus partecipate in the 2νββ (apparently only the first - Single State Dominance)
- β-decays and 2νββ feature a lower transferred momentum with respect to NLDBD

Further Motivations

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

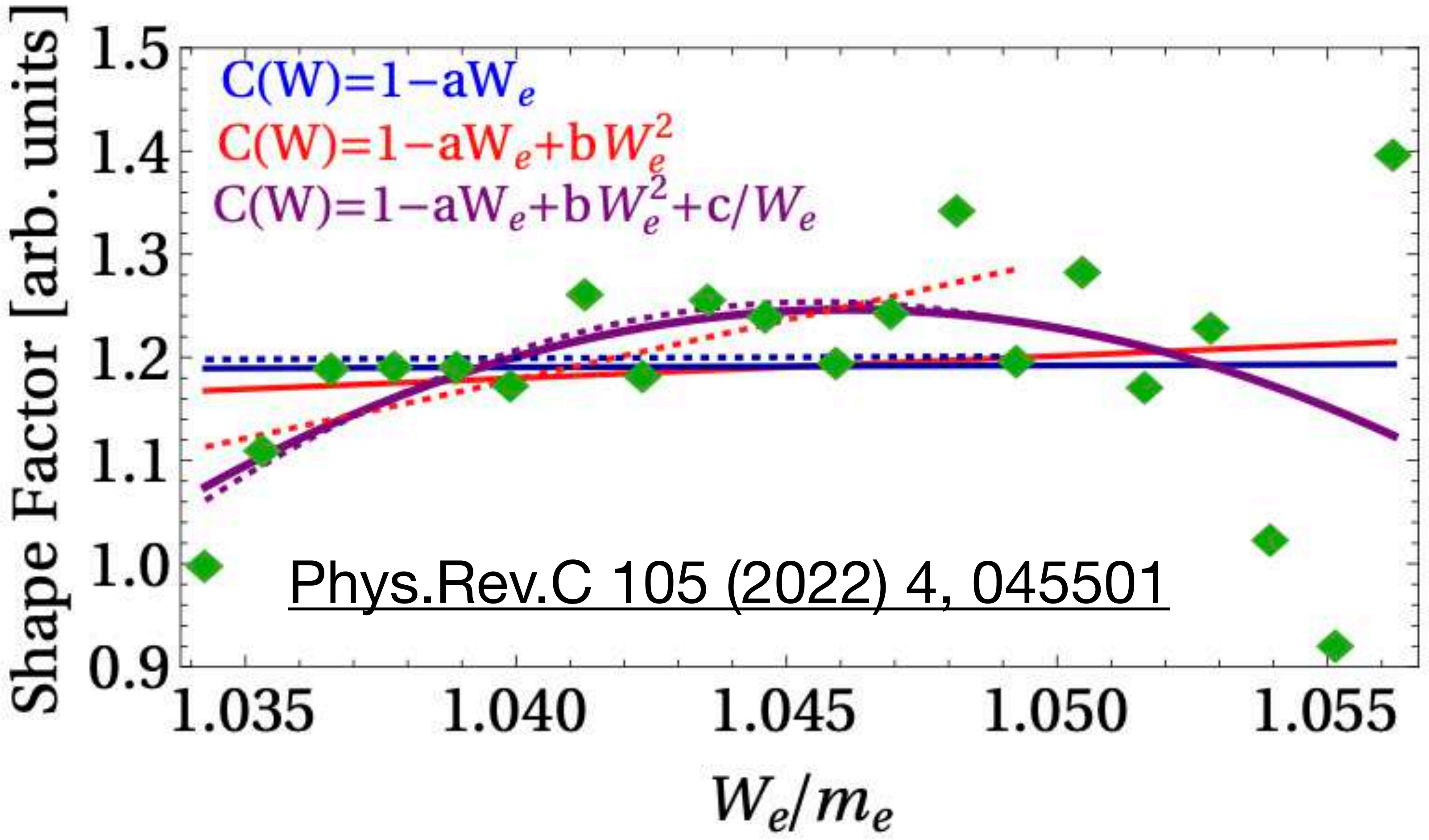


^{39}Ar in Ar-based detector

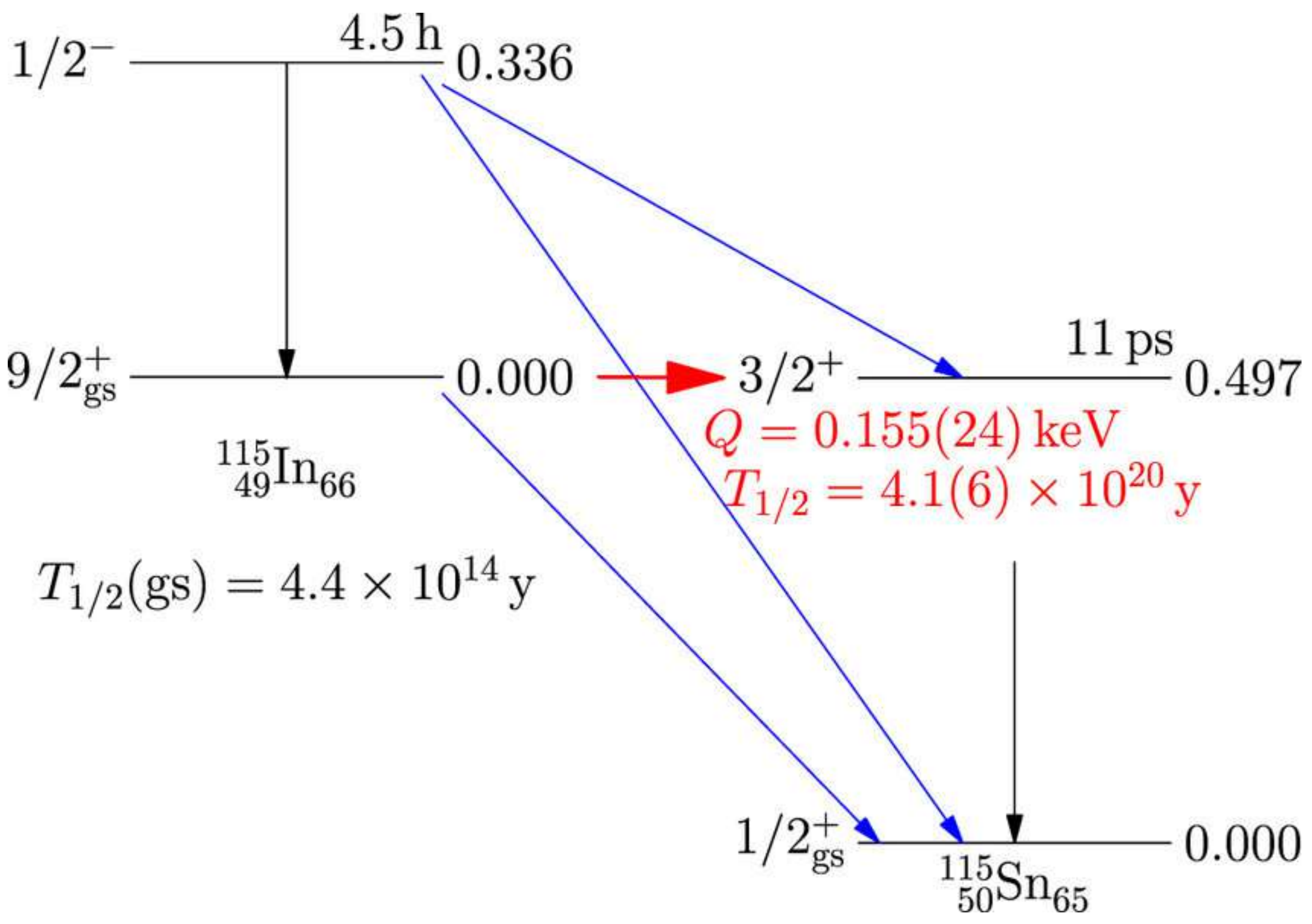


^{210}Bi in Liquid Scintillators

- **Low Q-value decays**
  - Cosmic Neutrino Background detection => ^{151}Sm, ^{171}Tm
  - Neutrino mass => ^{115}In decay on ^{115}Sn*



^{171}Tm shape factor



Forbidden Beta Decays: Indium-115

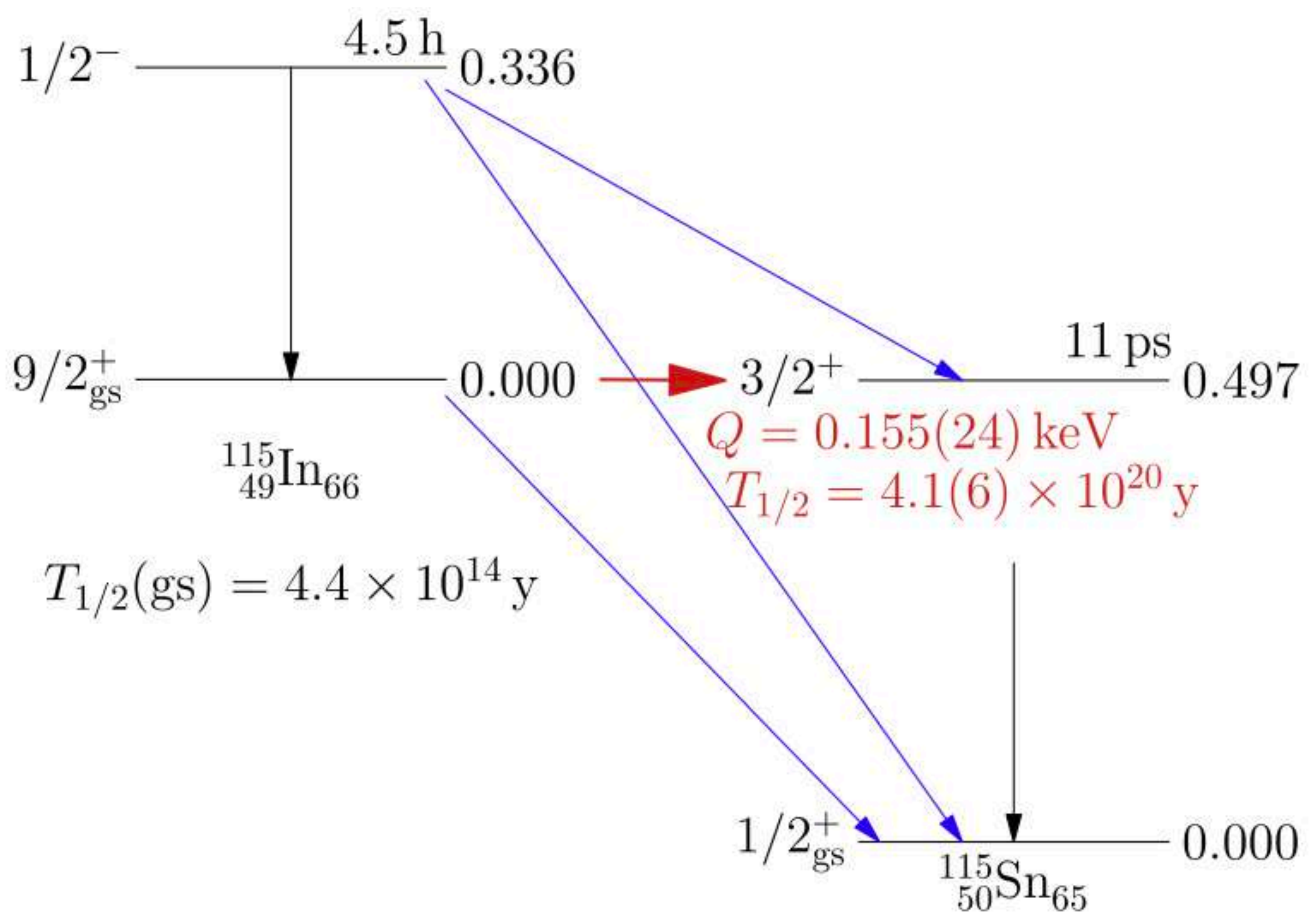
Indium-115

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



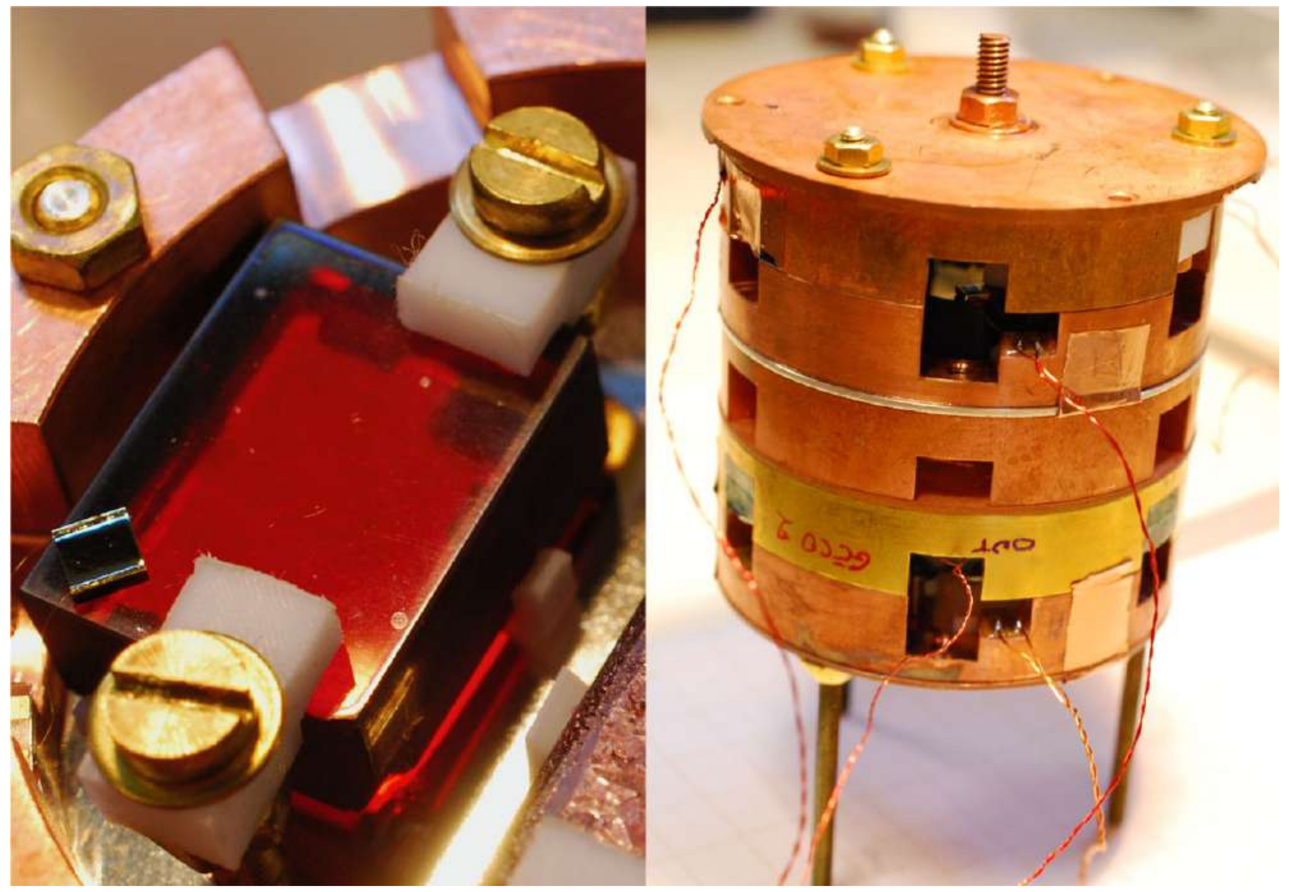
New low-background measurements needed!

Very good experimental conditions:

- High natural abundance i.a. = 95.71%
- Embedded in crystal as InI, InO, LiInSe$_2$
- Excellent radiopurity levels

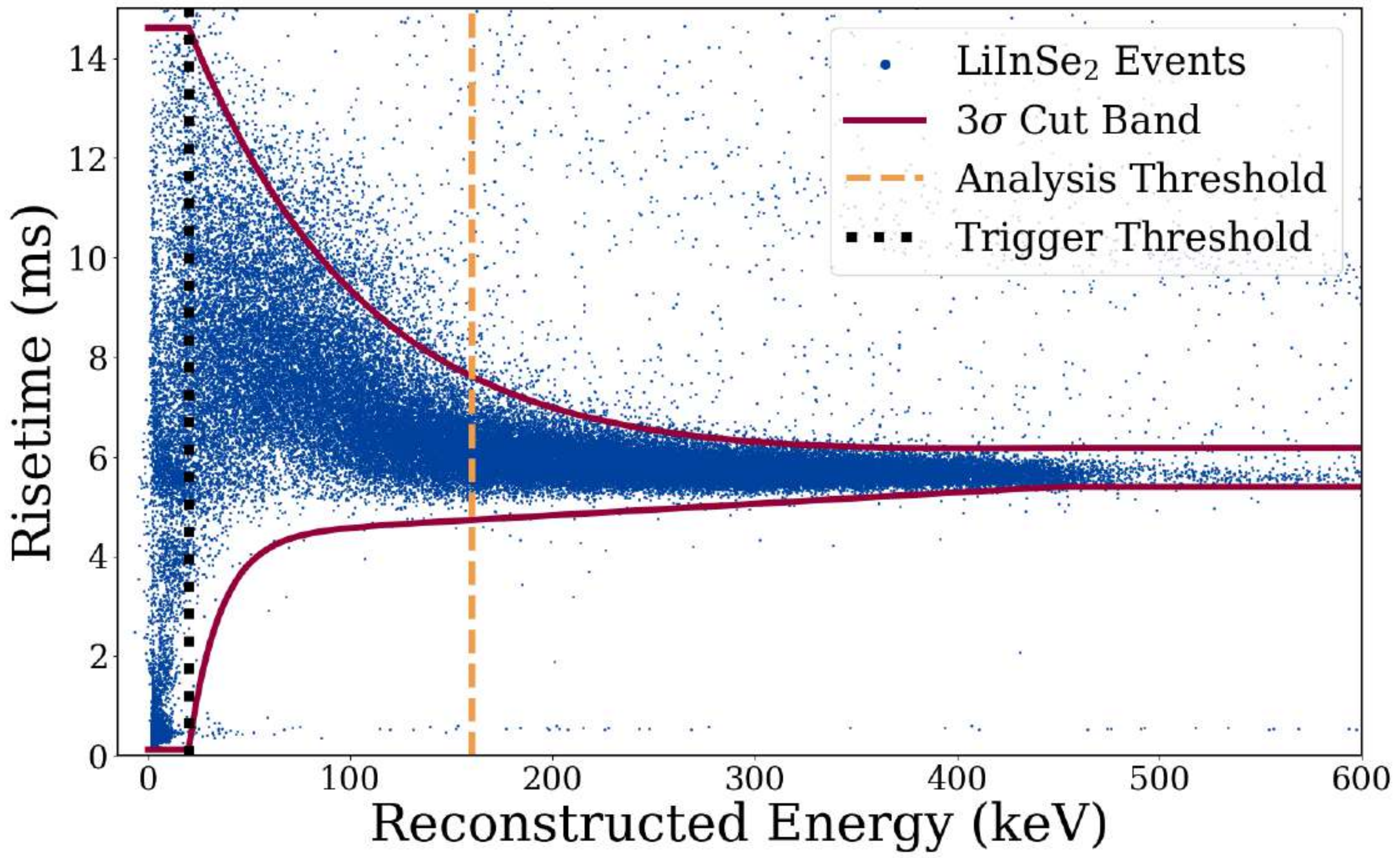
A new measurement (MIT/Berkeley/CNRS)

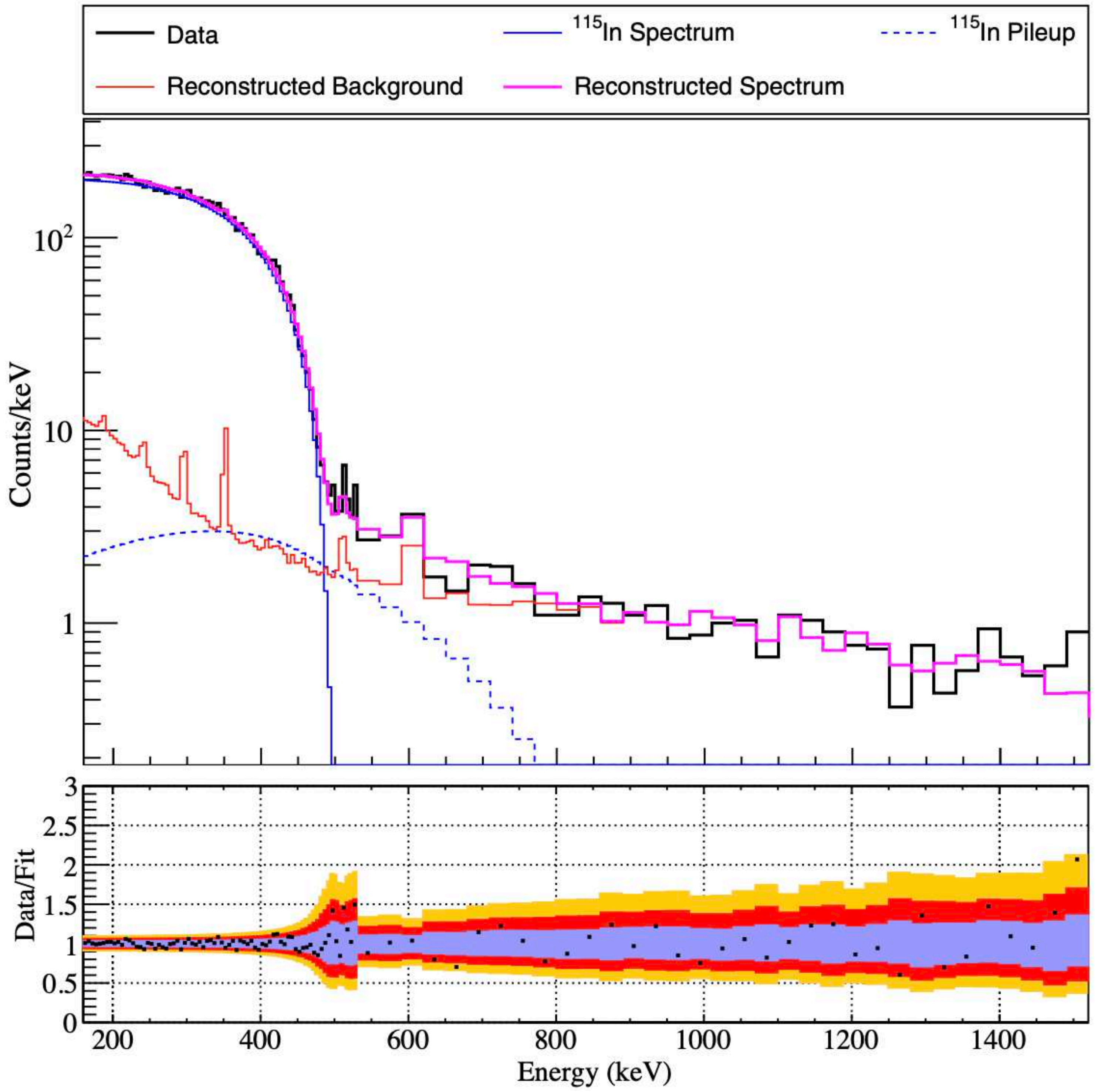
- $LiInSe_2$ operated as cryogenic calorimeter
- Excellent performance but high rate at low energy
- High analysis threshold (160 keV)

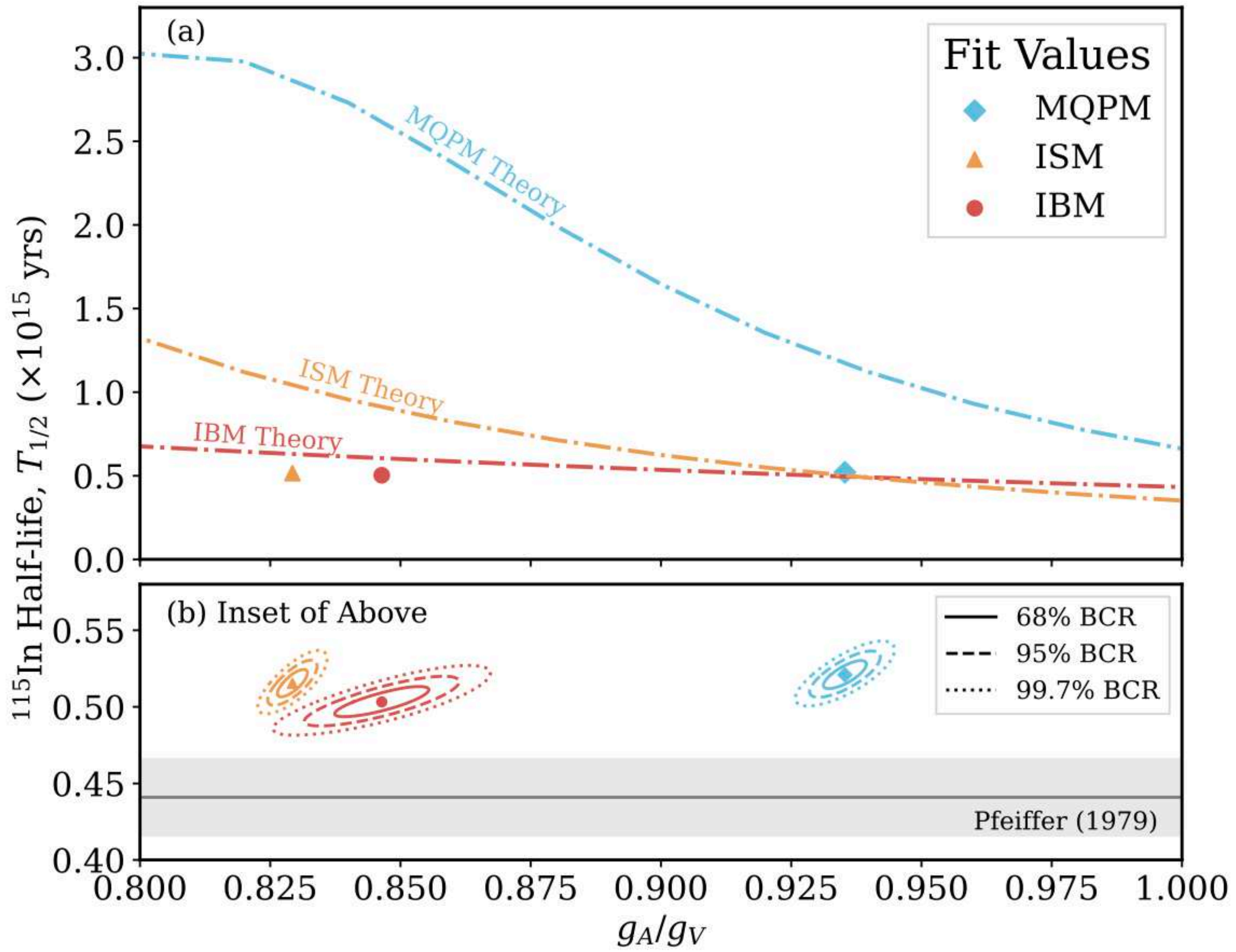


Phys. Rev. Lett. 129, 232502 (2022)

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	

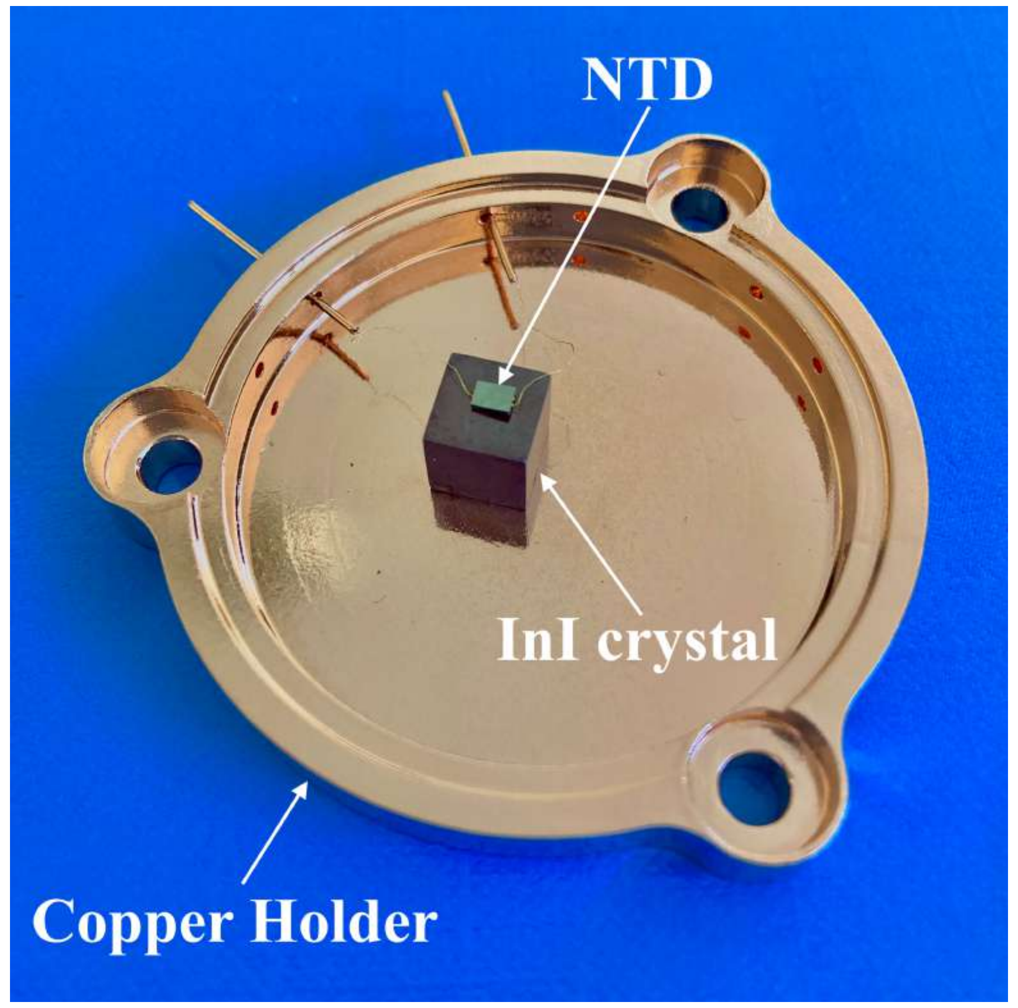






Theory ≠ Experiment

In-115 by ACCESS

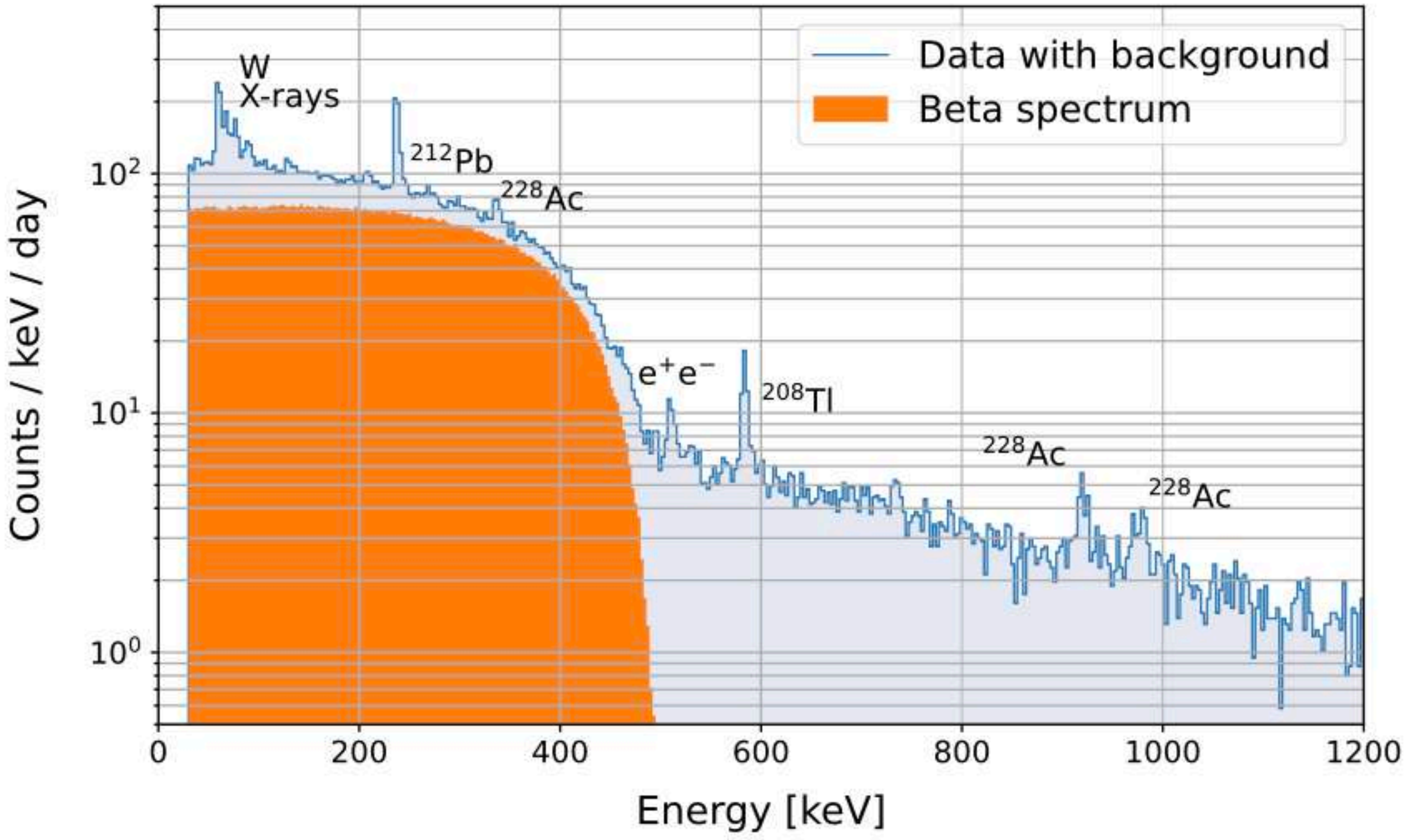


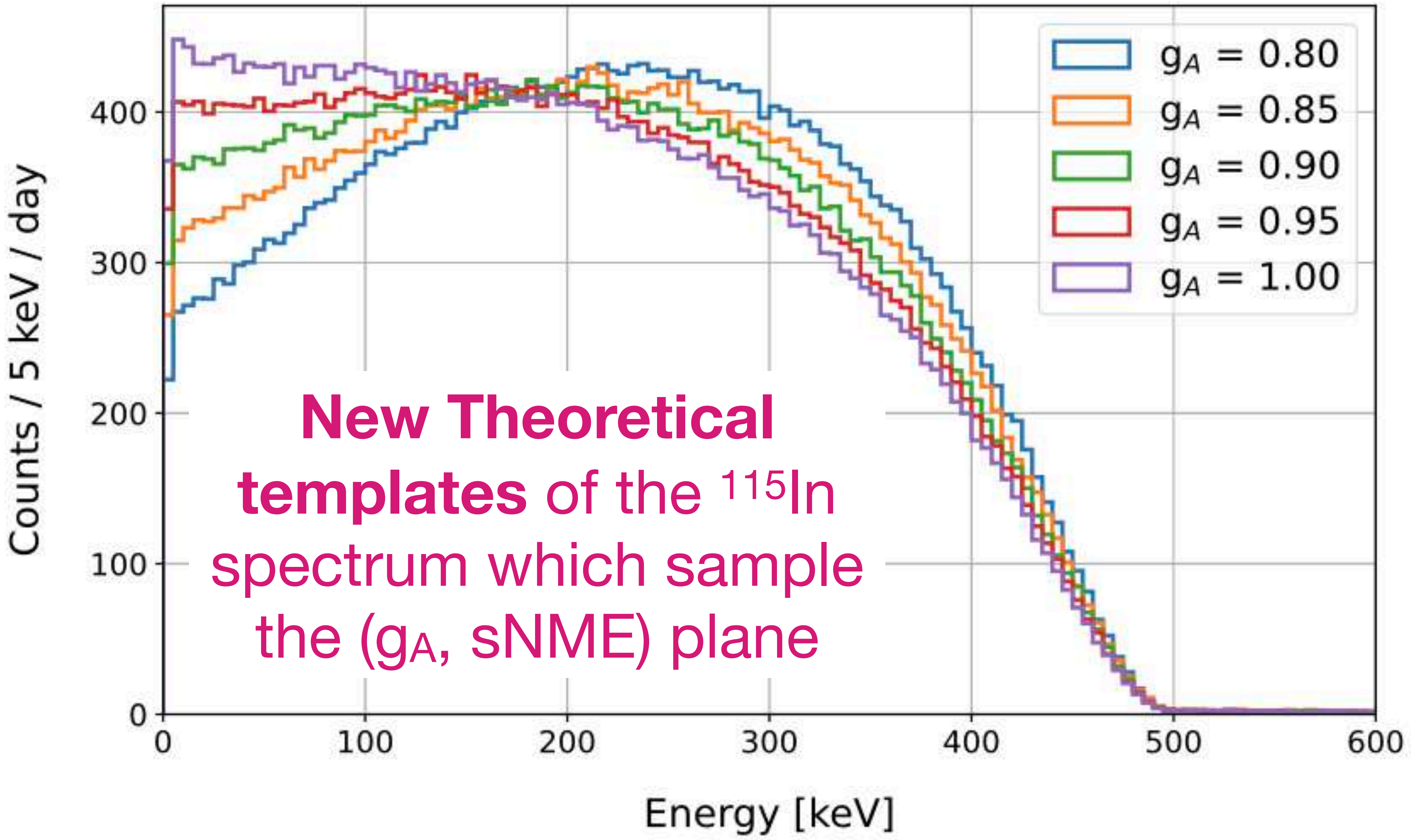
- **Cryogenic calorimeter**
  - Indium Iodine (InI) crystal - m = 1.91 g - 7x7x7 mm^3
  - Semiconductor sensor (CUPID-0 like)
  - Calibration source with ^{232}Th

- **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

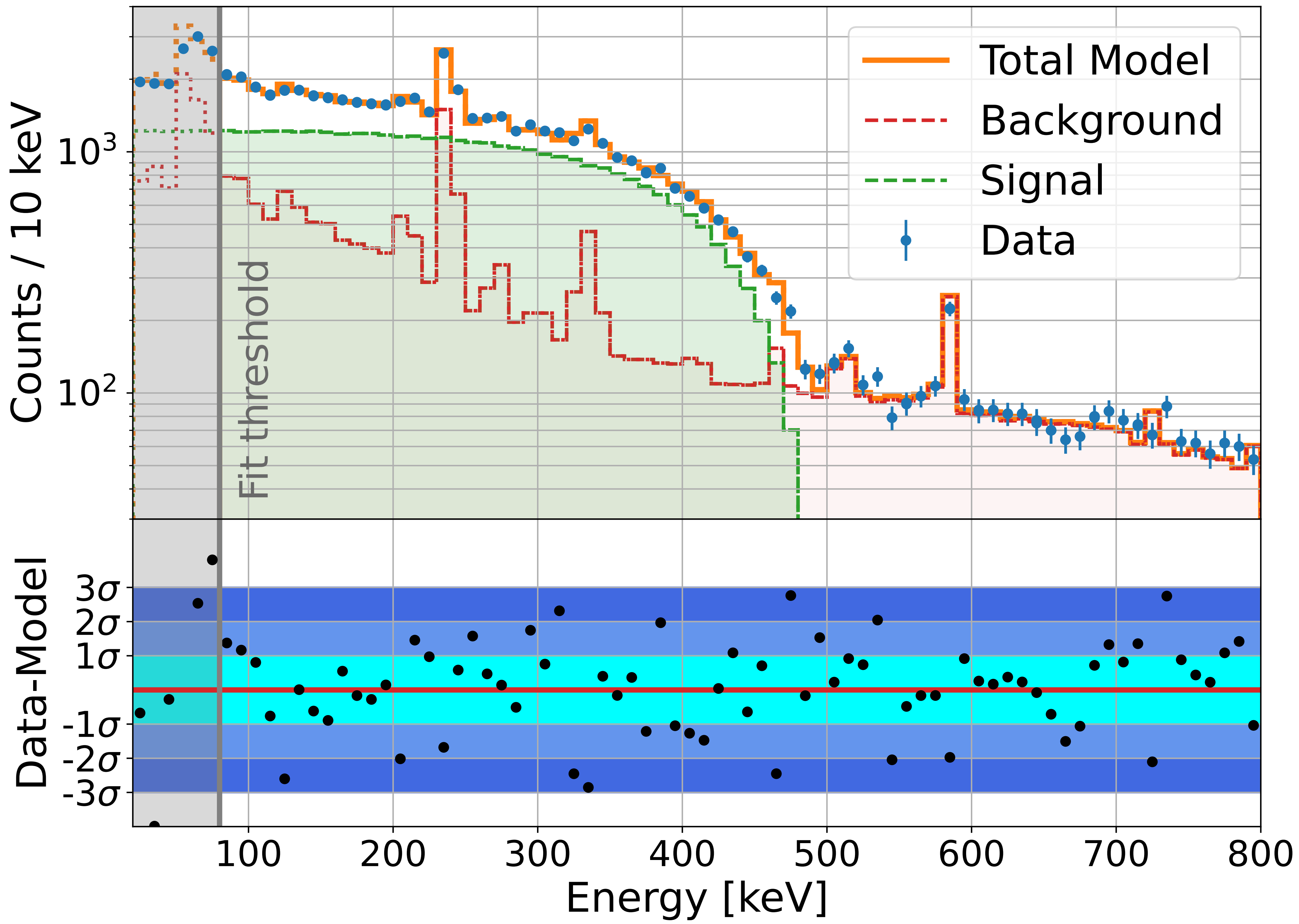
Eur.Phys.J.Plus 138 (2023) 5, 445





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

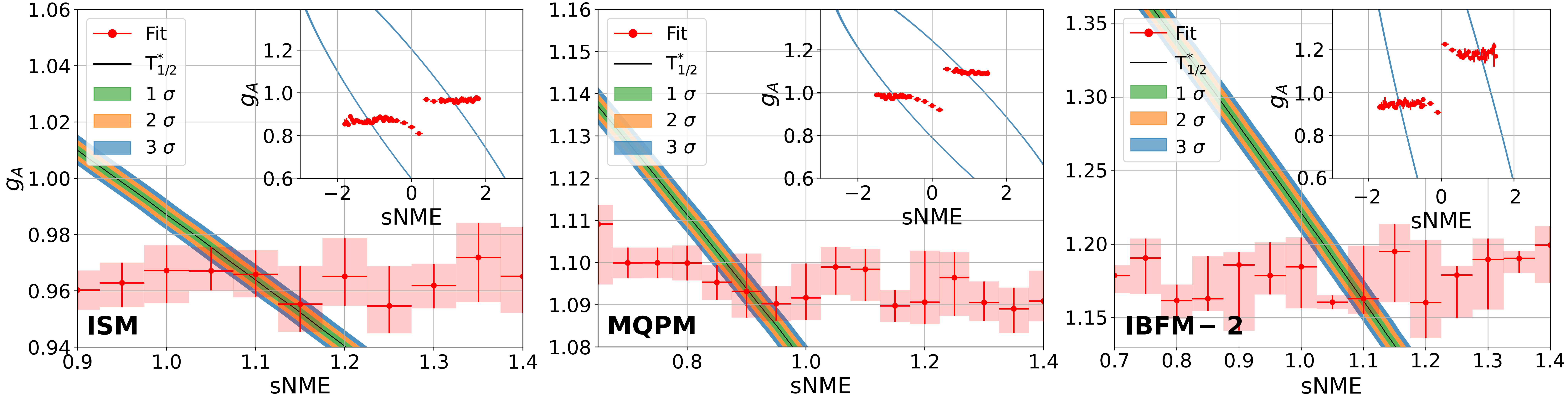
- Different values of g_A for different models
- Lower quenching ($g_A \approx 1$)
- sNME not fixed

- 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).

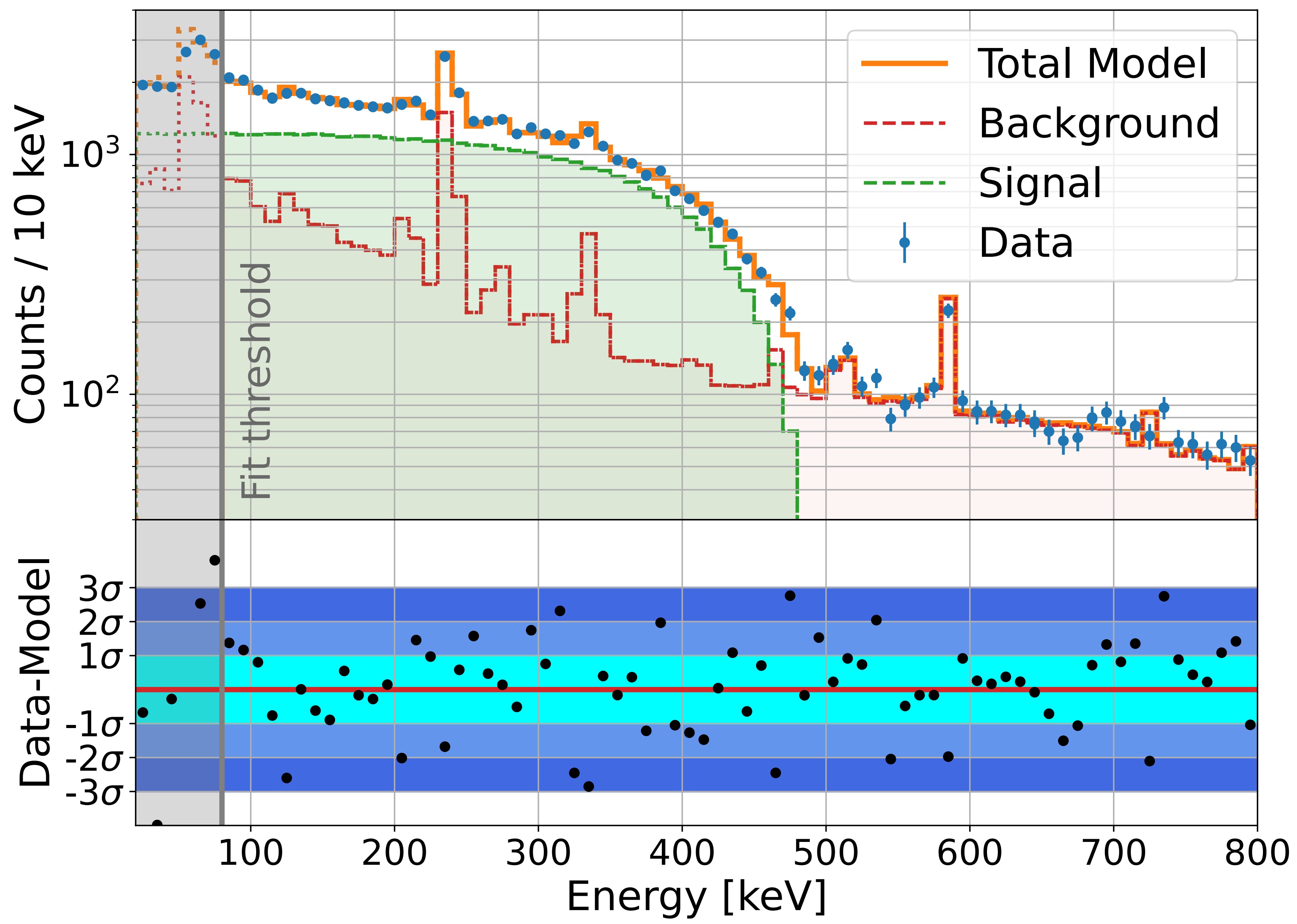


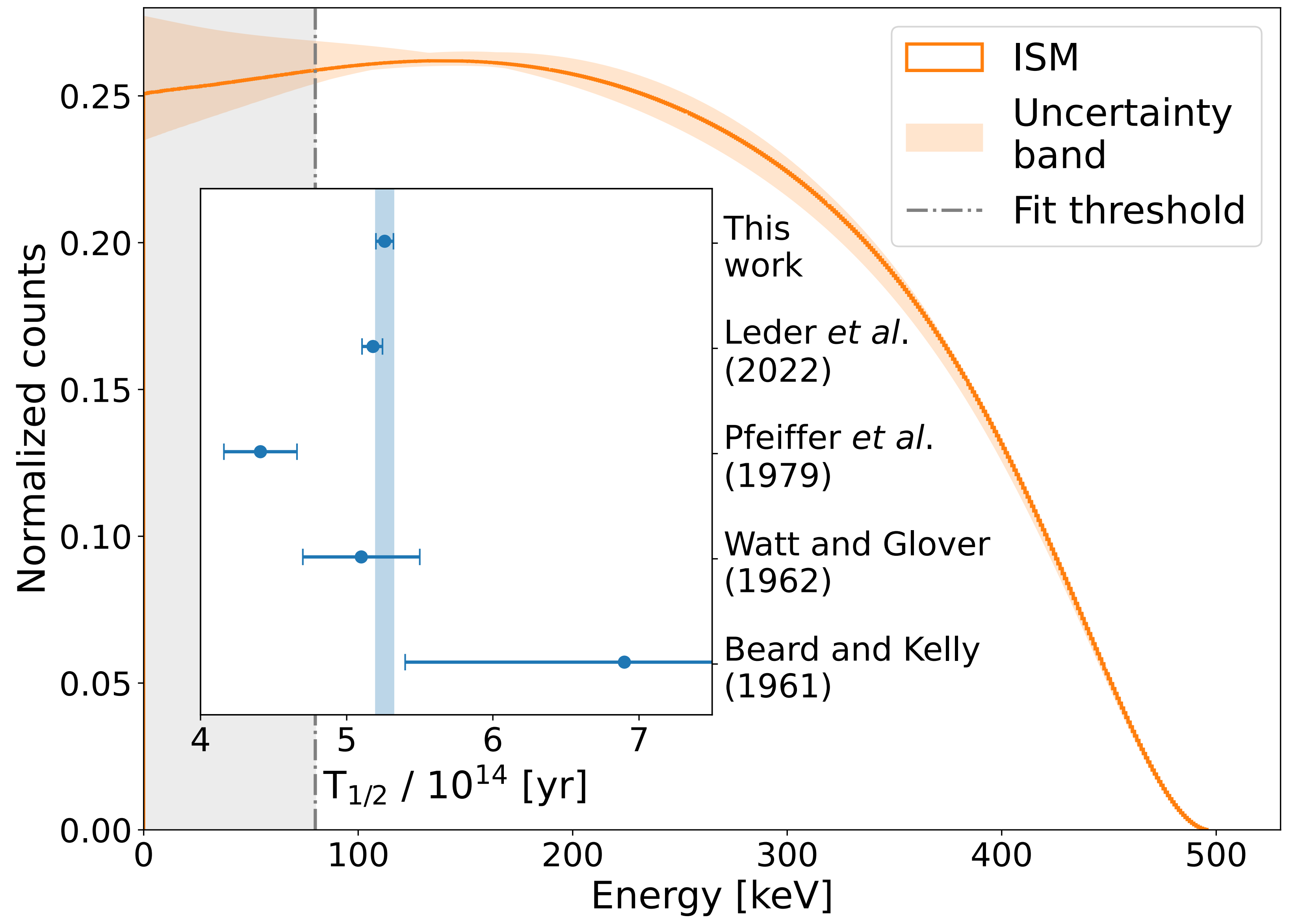
Phys. Rev. Lett. 133, 122501

Model	g_A	sNME	$T_{1/2}$ [$\times10^{14}$ 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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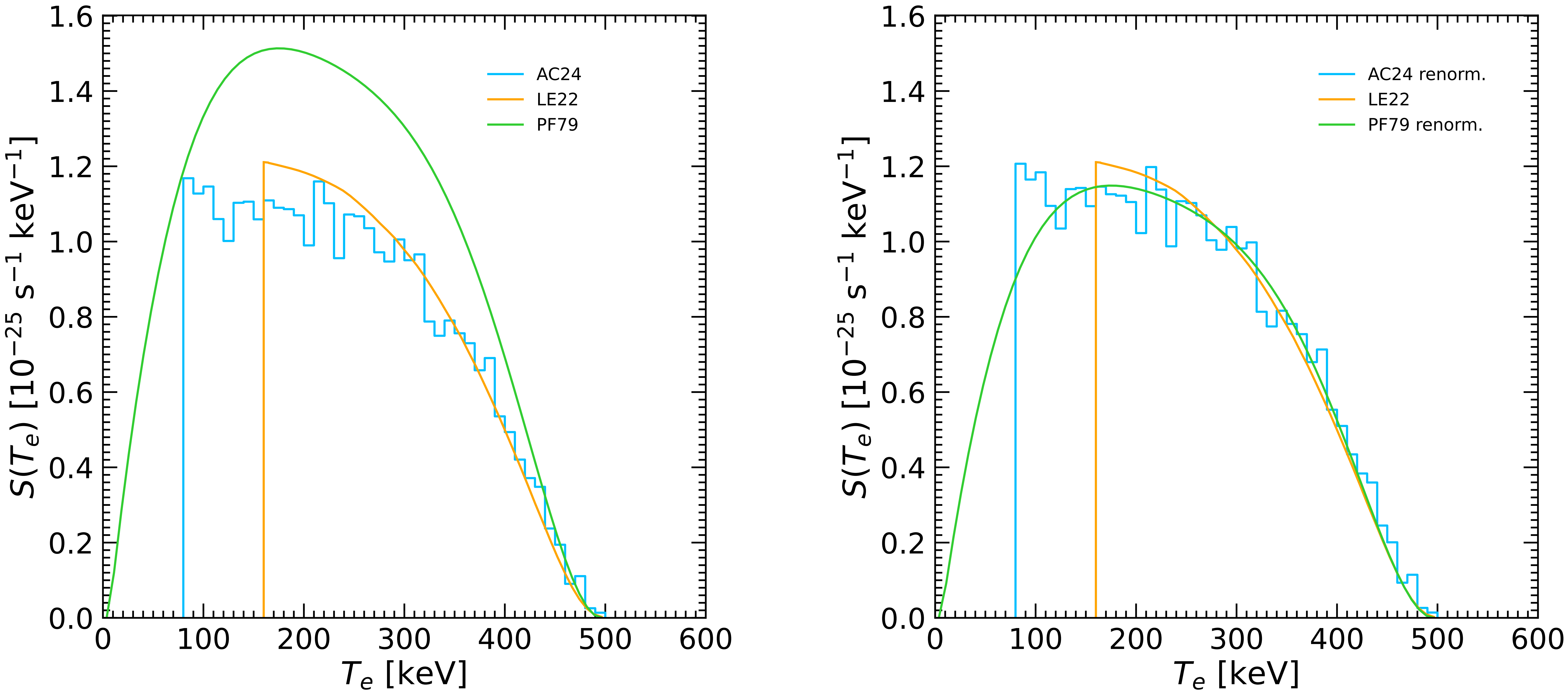
Outcomes:

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

- 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 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, [arXiv 2405.11920]

Theory progress: an example

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

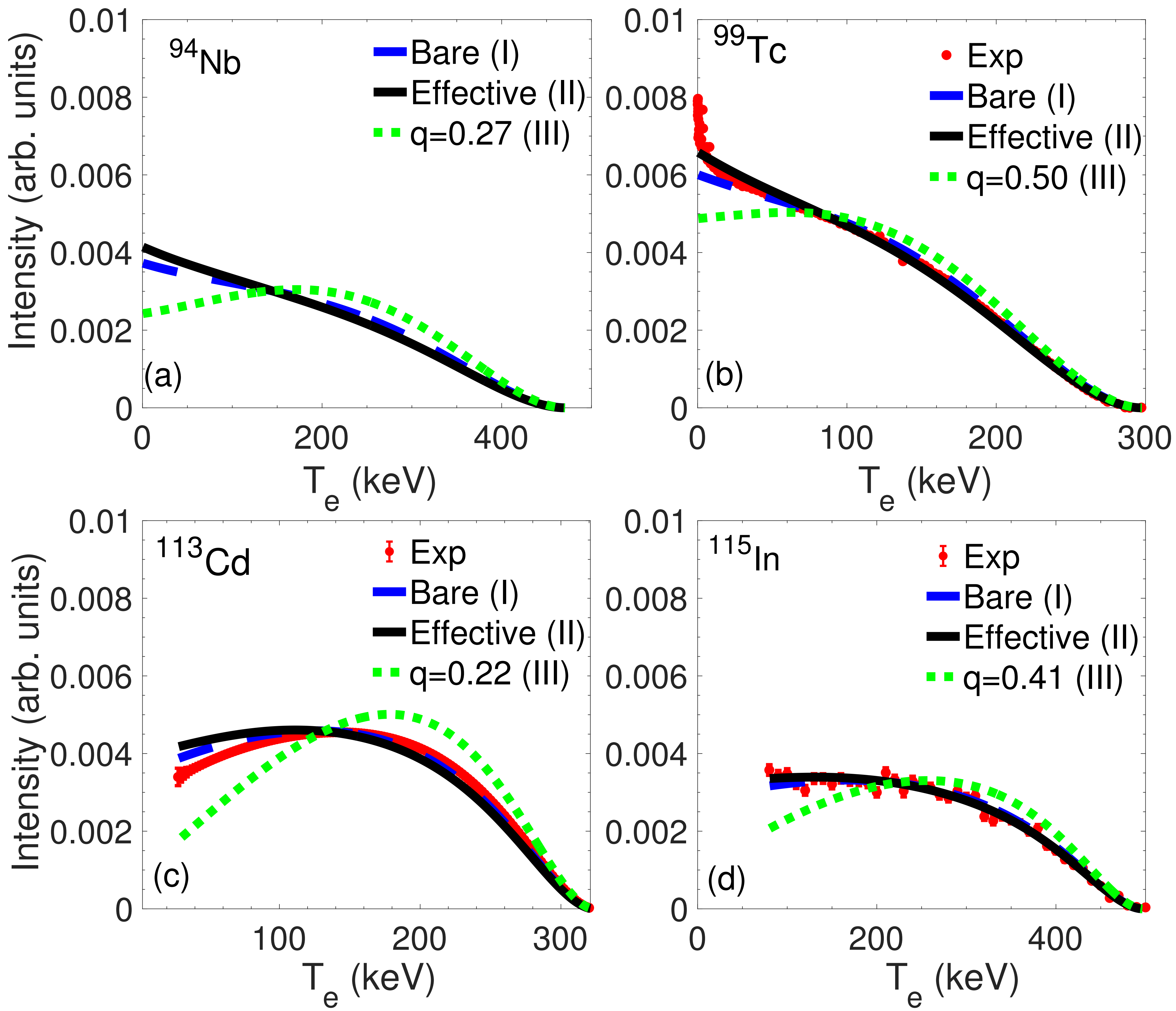
In a recent paper, the data presented were used as a term of comparison with theoretical calculations within the **Realistic Shell Model**.

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

Half-life systematically 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)



Summary

- **Forbidden beta decays**, and in particular their spectral shape, **challenge the nuclear models**
- **Nuclear models** and **computation techniques** improved a lot
- Renewed experimental efforts 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