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Delayed γ-ray spectroscopy as a tool for fusion-fission studies

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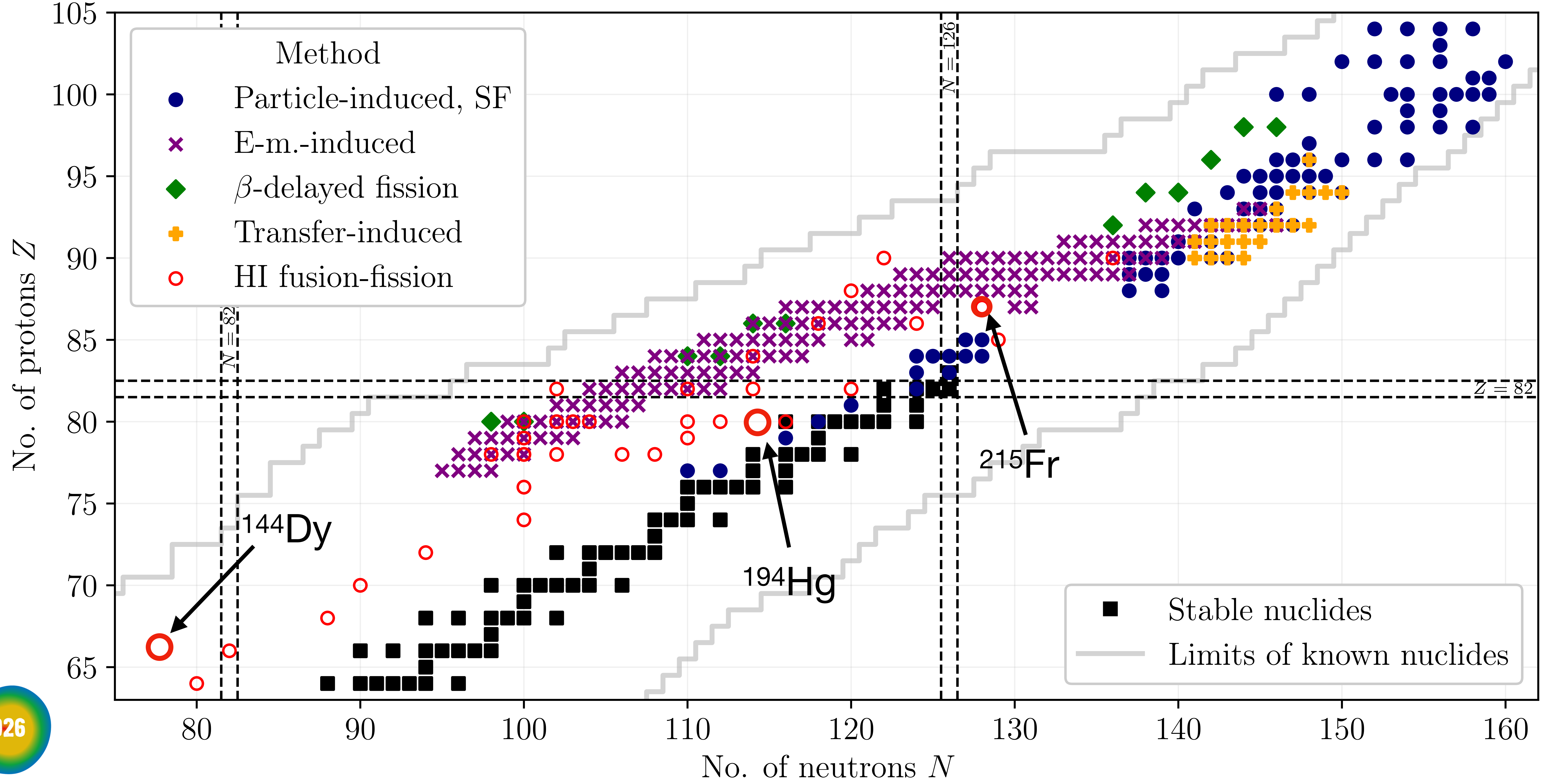
7th Workshop on Nuclear Fission and Spectroscopy of Neutron-Rich Nuclei

Fusion-fission studies

Compound nuclei with measured mass or charge distributions of fission fragments



Fusion-fission studies

Experimental methods

Mass & charge spectrometry

ADVANTAGES

- ✓ High sensitivity
- ✓ Kinetic energy information

LIMITATIONS

- ✗ Limited mass resolution
- ✗ No independent fission yields

γ-ray spectroscopy

ADVANTAGES

- ✓ Precise isotope identification

LIMITATIONS

- ✗ Low sensitivity
- ✗ Systematic corrections required

Activation methods

ADVANTAGES

- ✓ Precise isotope identification
- ✓ High sensitivity

LIMITATIONS

- ✗ Limited to selected isotopes

$^{18}O + ^{197}Au \rightarrow ^{215}Fr^*$ experiment

111 MeV

61.7 MeV

Measurements

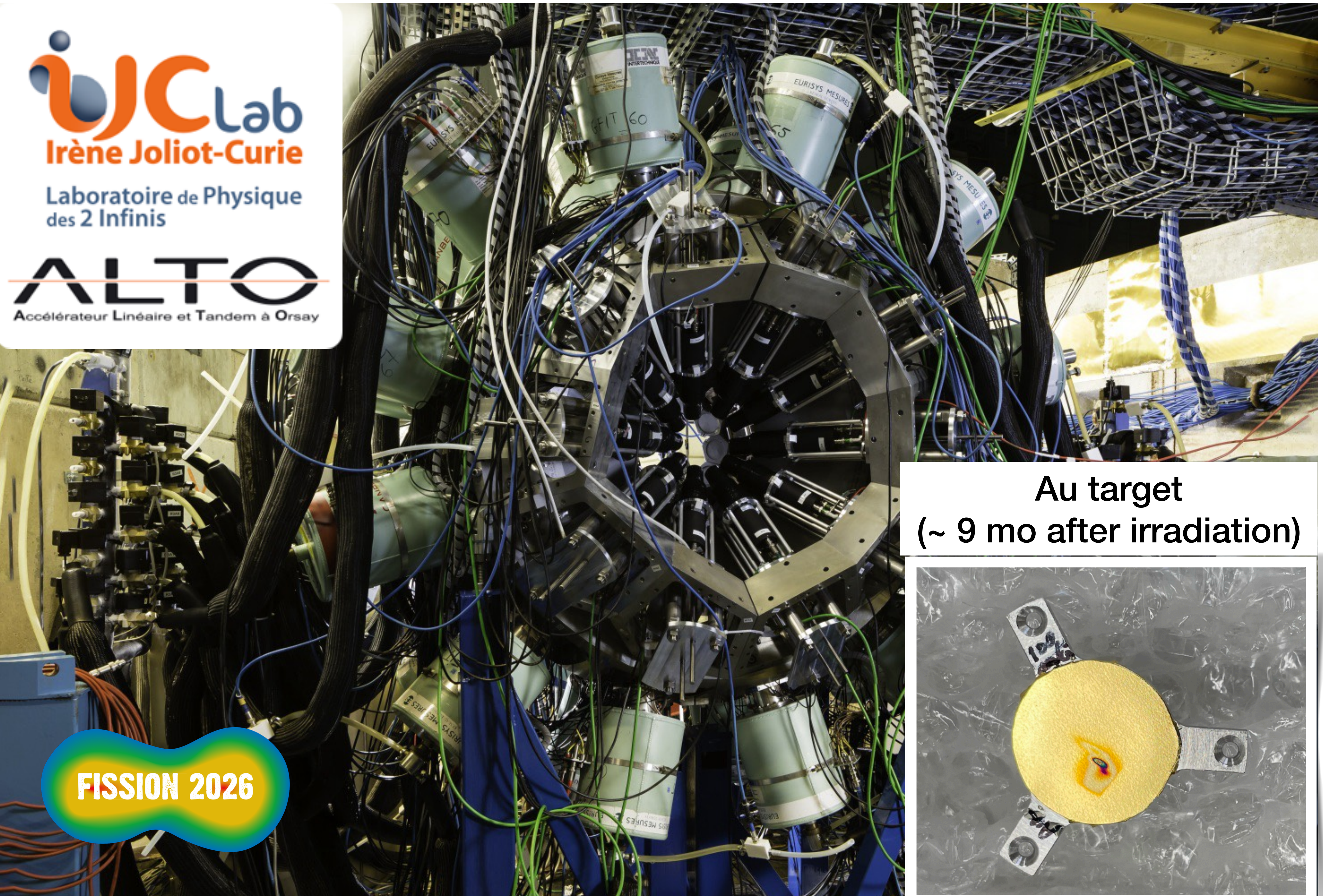
Prompt γ radiation

Analysis by K. Miernik

Classical analysis via $\gamma - \gamma - \gamma$ cascades leading to the g.s. like $4^+ \rightarrow 2^+ \rightarrow 0^+$

Long-lived isotopes at FUW

Alternative method: analysis of decay curves of medium- and long-lived fission products



Au target
(~ 9 mo after irradiation)

ν-ball-2 spectrometer, Credit: J.N. Wilson

$^{18}O + ^{197}Au \rightarrow ^{215}Fr^*$ experiment

111 MeV

61.7 MeV

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Fission of ^{215}Fr studied with γ spectroscopic methods

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Background: Asymmetric fission is known to occur in two regions, the actinides and sublead, and is dependent on the fissioning system excitation energy. Experimental evidence in the sublead region show that this mode is surprisingly persistent with increasing energy and its origin is not fully understood.
Purpose: To experimentally study the fusion-fission reaction of ^{215}Fr at moderate excitation energy and determine previously unknown independent fission yields and other properties.

Measurements

Prompt γ radiation

Analysis by K. Miernik

Classical analysis via $\gamma - \gamma - \gamma$ cascades leading to the g.s. like $4^+ \rightarrow 2^+ \rightarrow 0^+$

Long-lived isotopes at FUW

Alternative method: analysis of decay curves of medium- and long-lived fission products

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Residual activity of ^{215}Fr fission fragments

OBJECTIVE:

Identification of **long-lived** (direct and indirect) products of fission and decay of ^{215}Fr and other isotopes

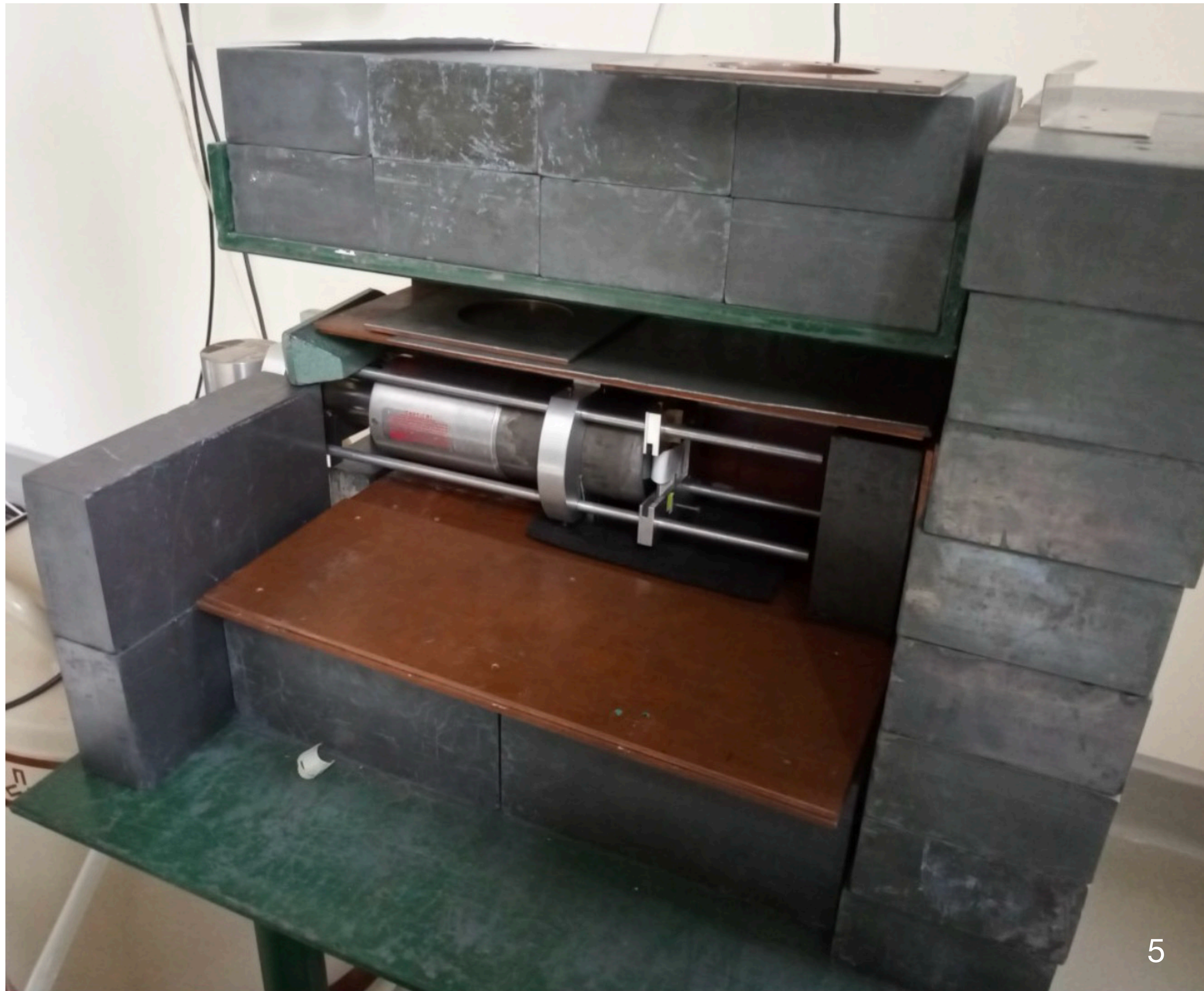
METHOD:

γ-ray spectroscopy with decay analysis

Experimental set-up:

- Target irradiated at ALTO
- **1 HPGe** detector with lead shielding at FUW
- **7 months** of measurements (22.07.22-16.01.23)
- Calibration with standard ^{152}Eu source

HPGe detector with shielding at FUW, Credit: K. Miernik



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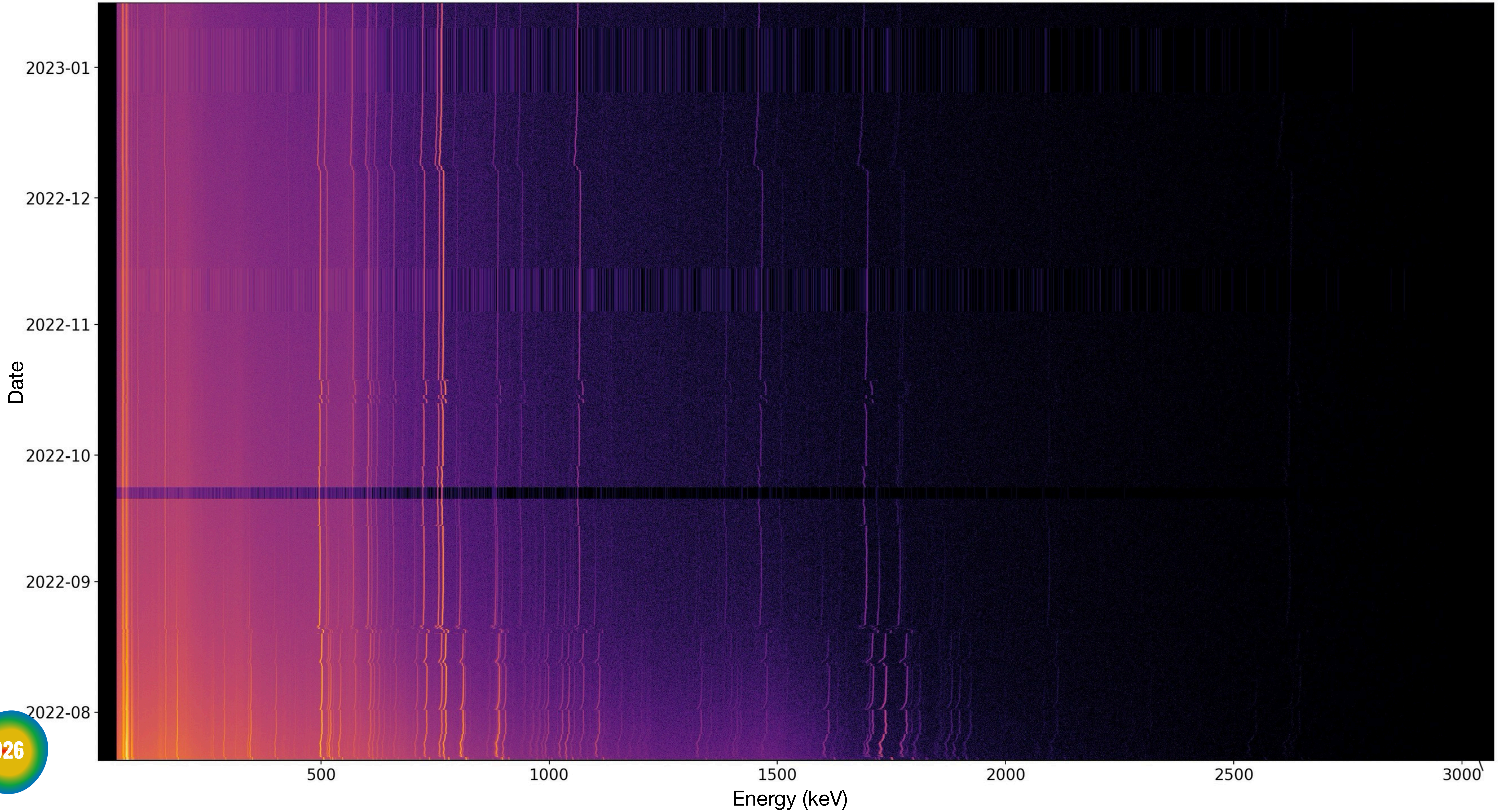
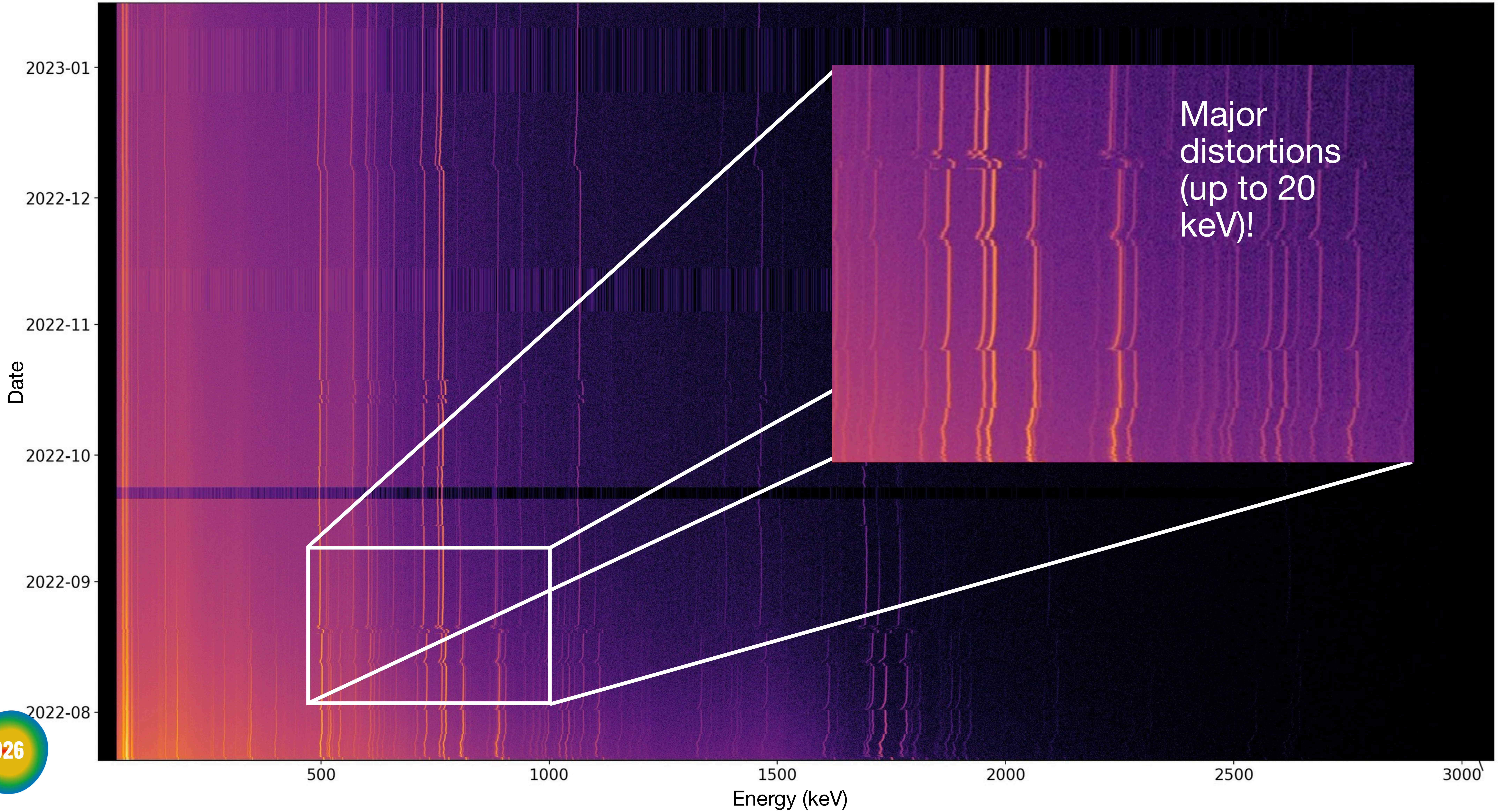
Energy calibration (linear)



Energy calibration (linear)



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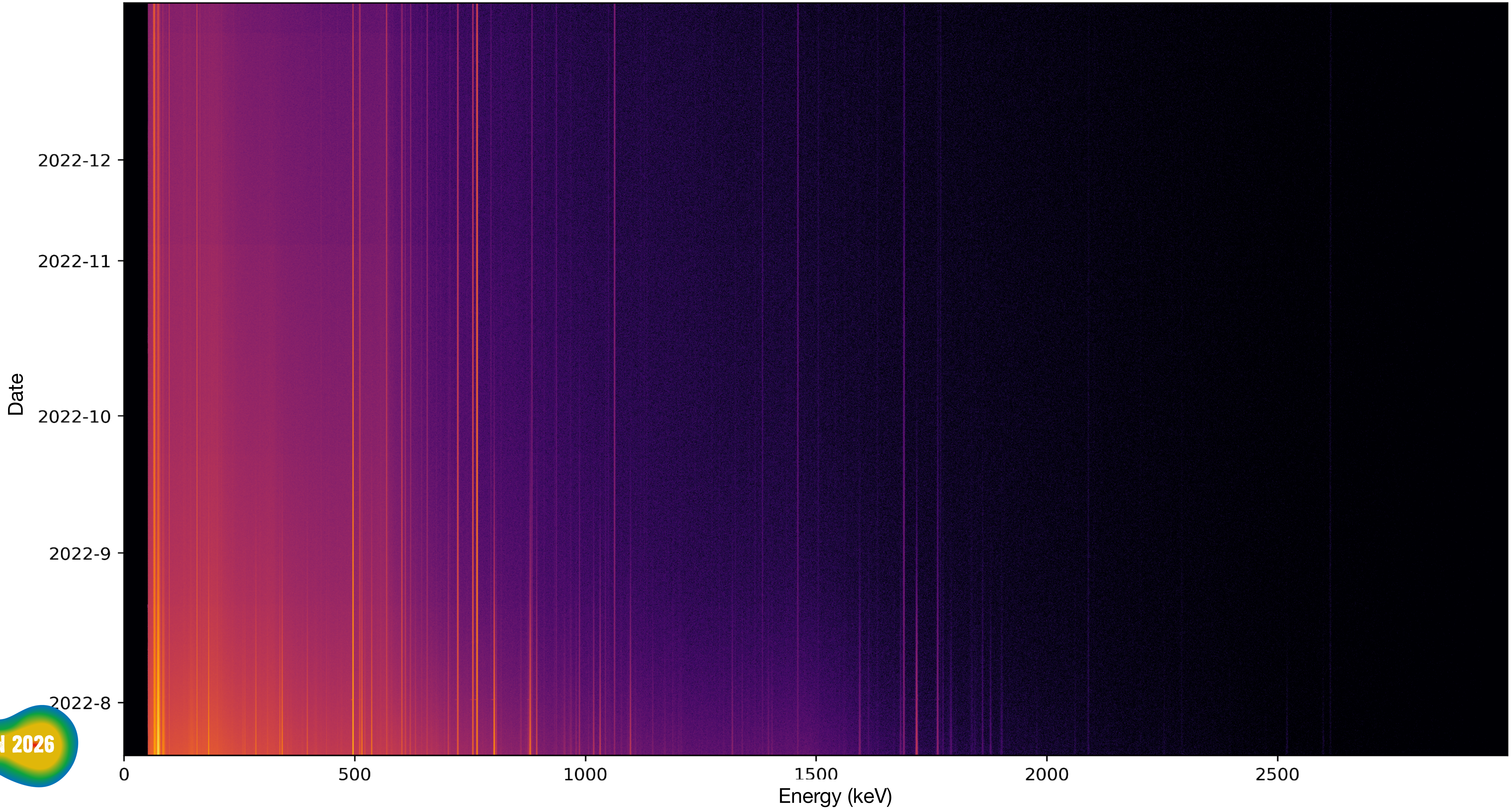
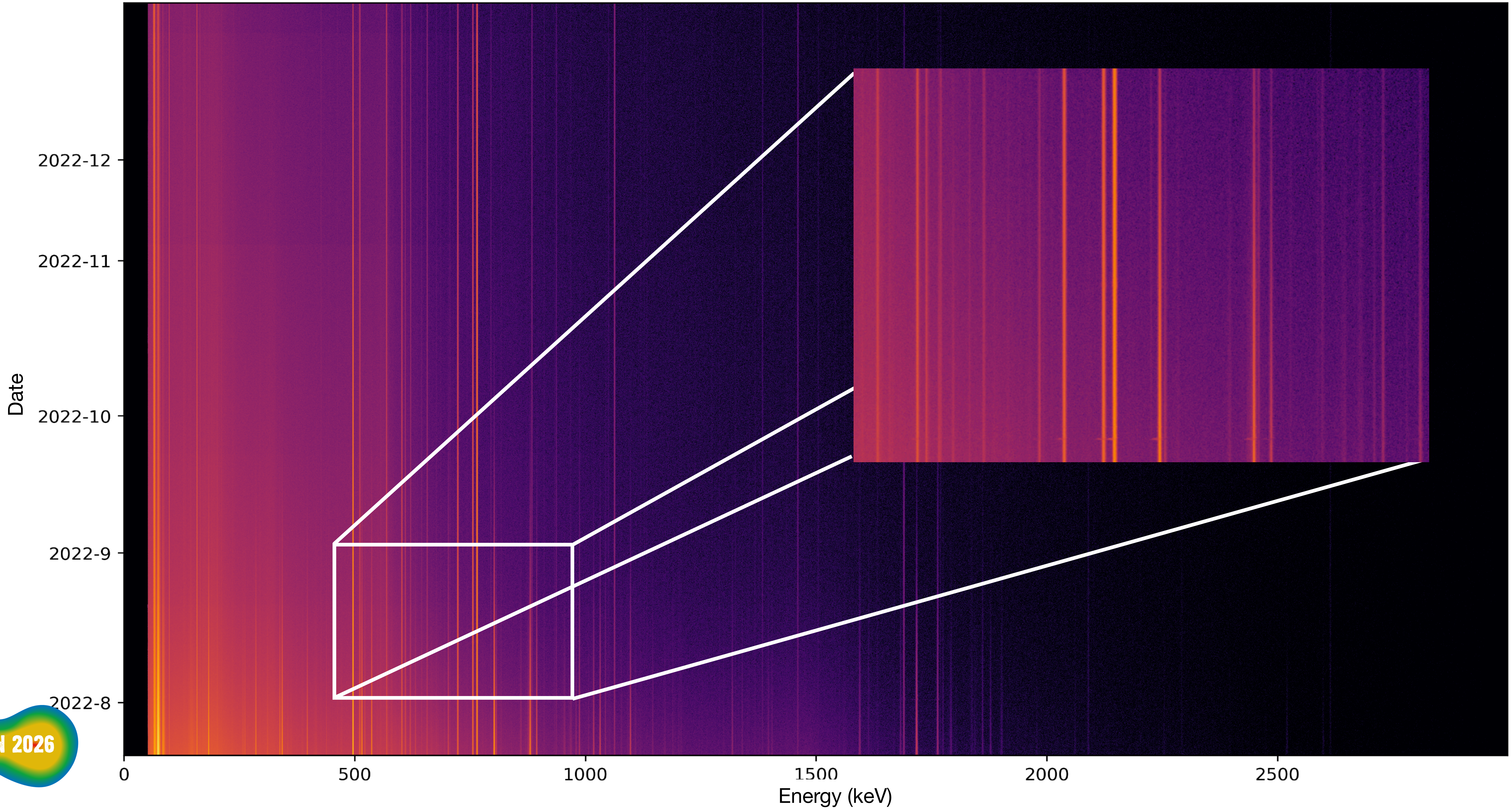
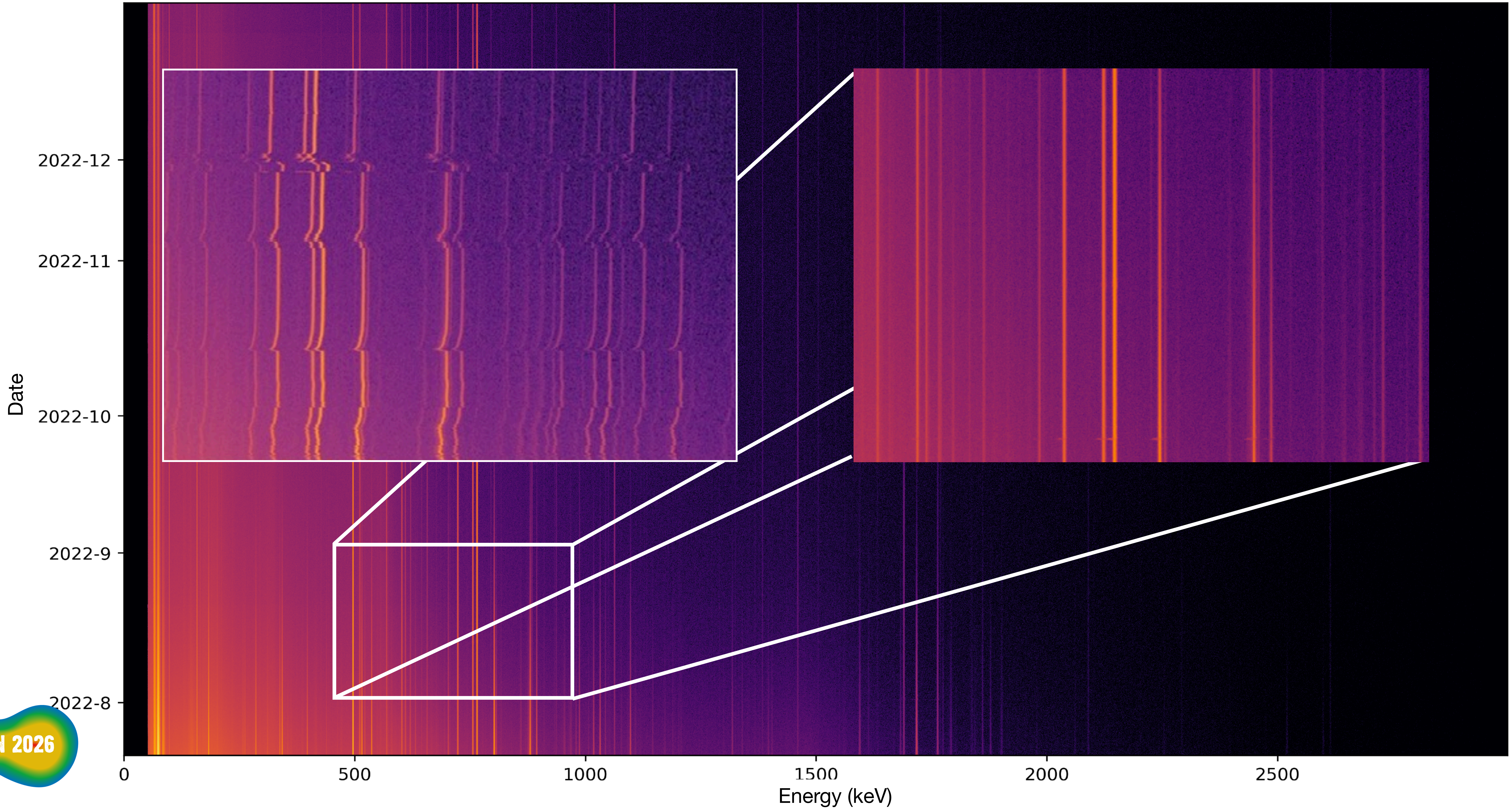
Energy calibration (linear + corrections)



Energy calibration (linear + corrections)



Energy calibration (linear + corrections)



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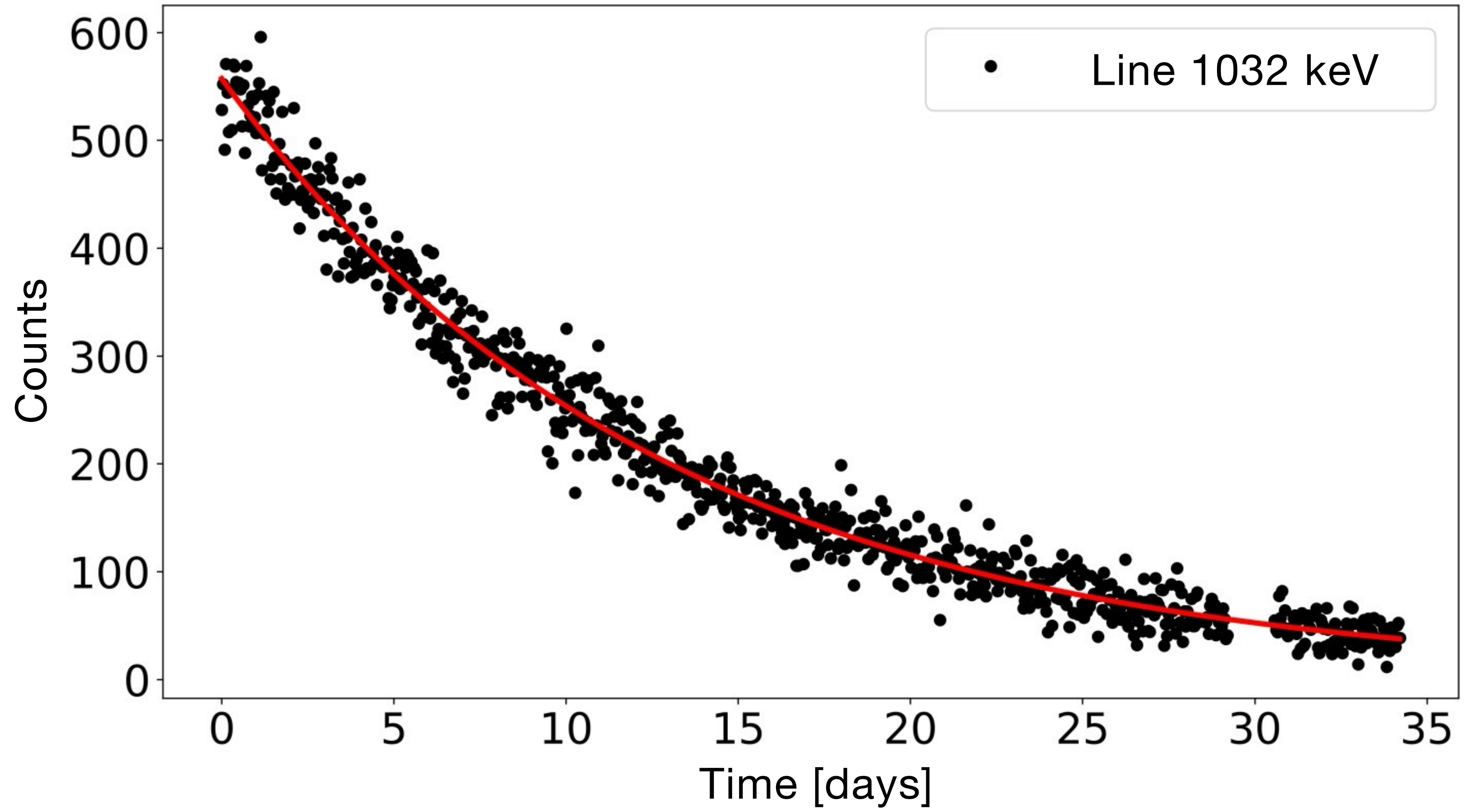
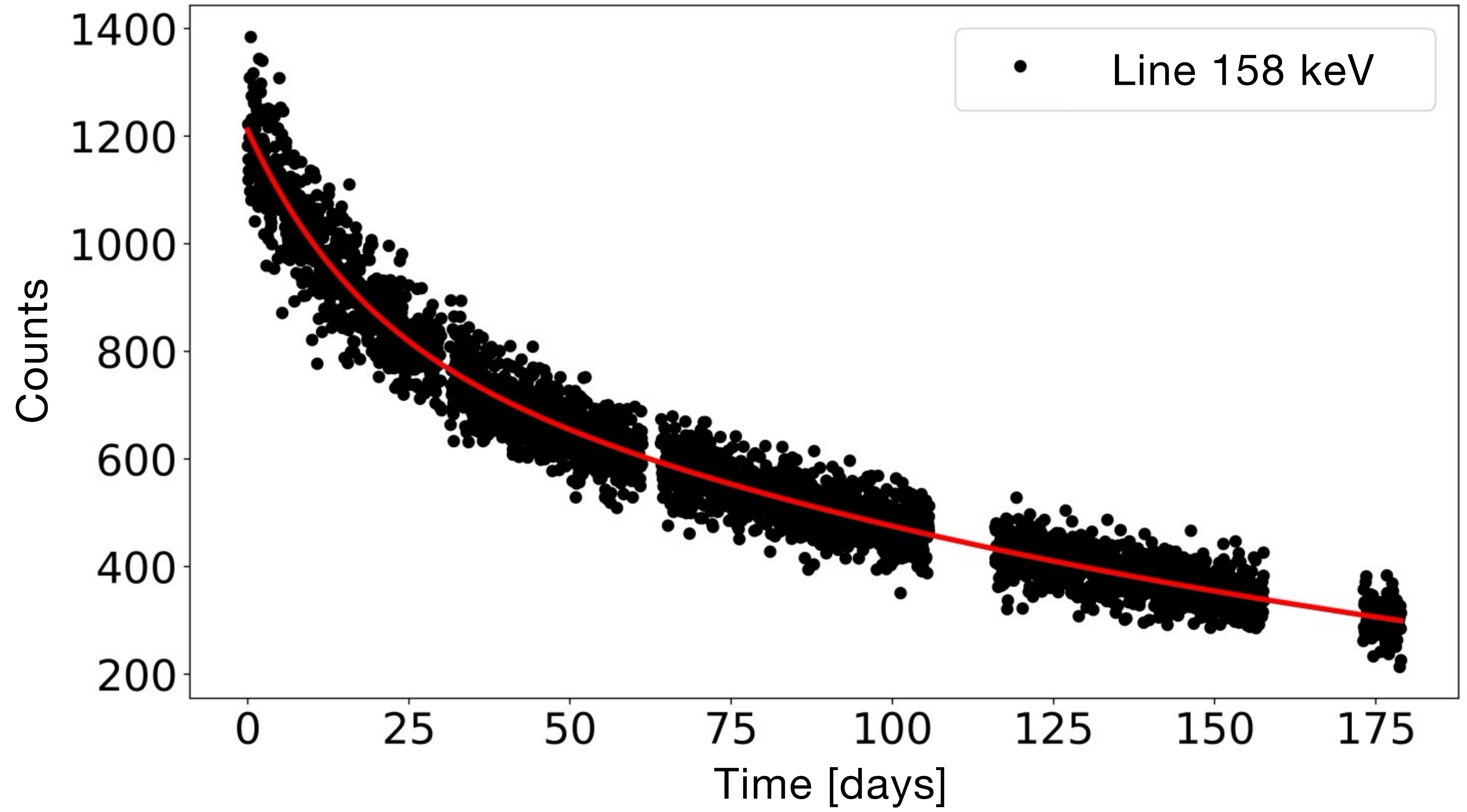
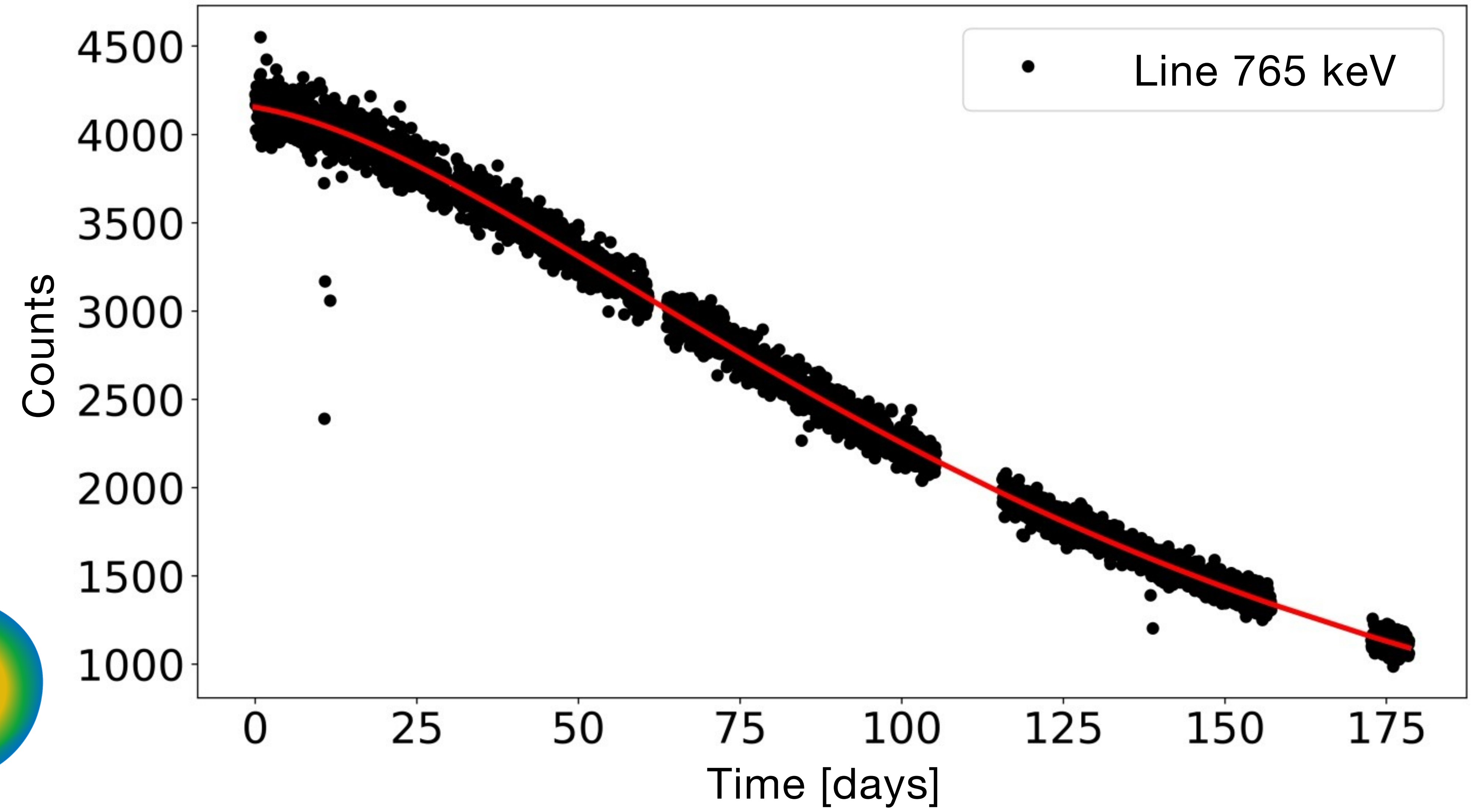
Isotopes identification via decay curves

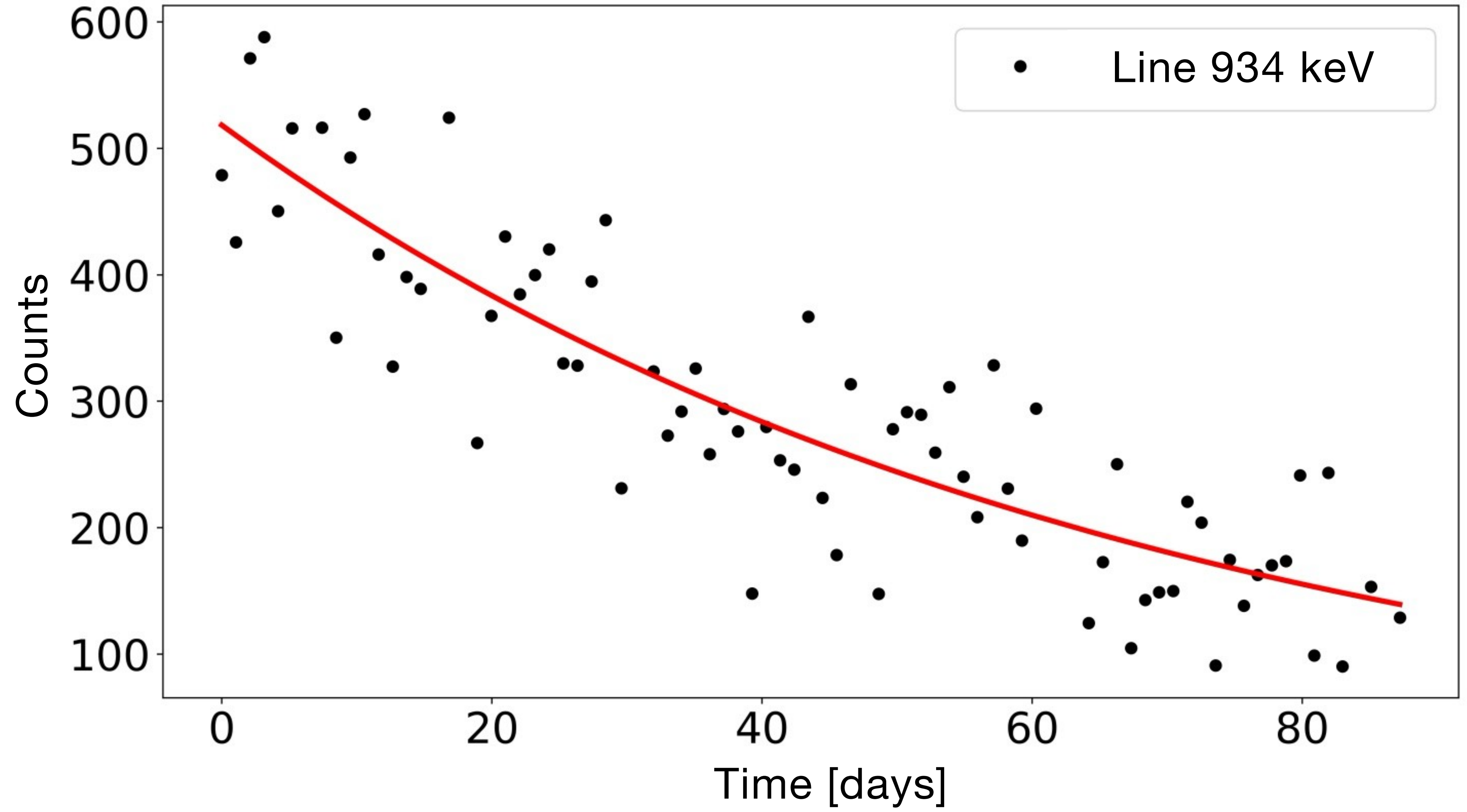




Parallel ^{123}Te & ^{117}Sn decay

^{95}Zr ↓ ^{95}Nb decay chain





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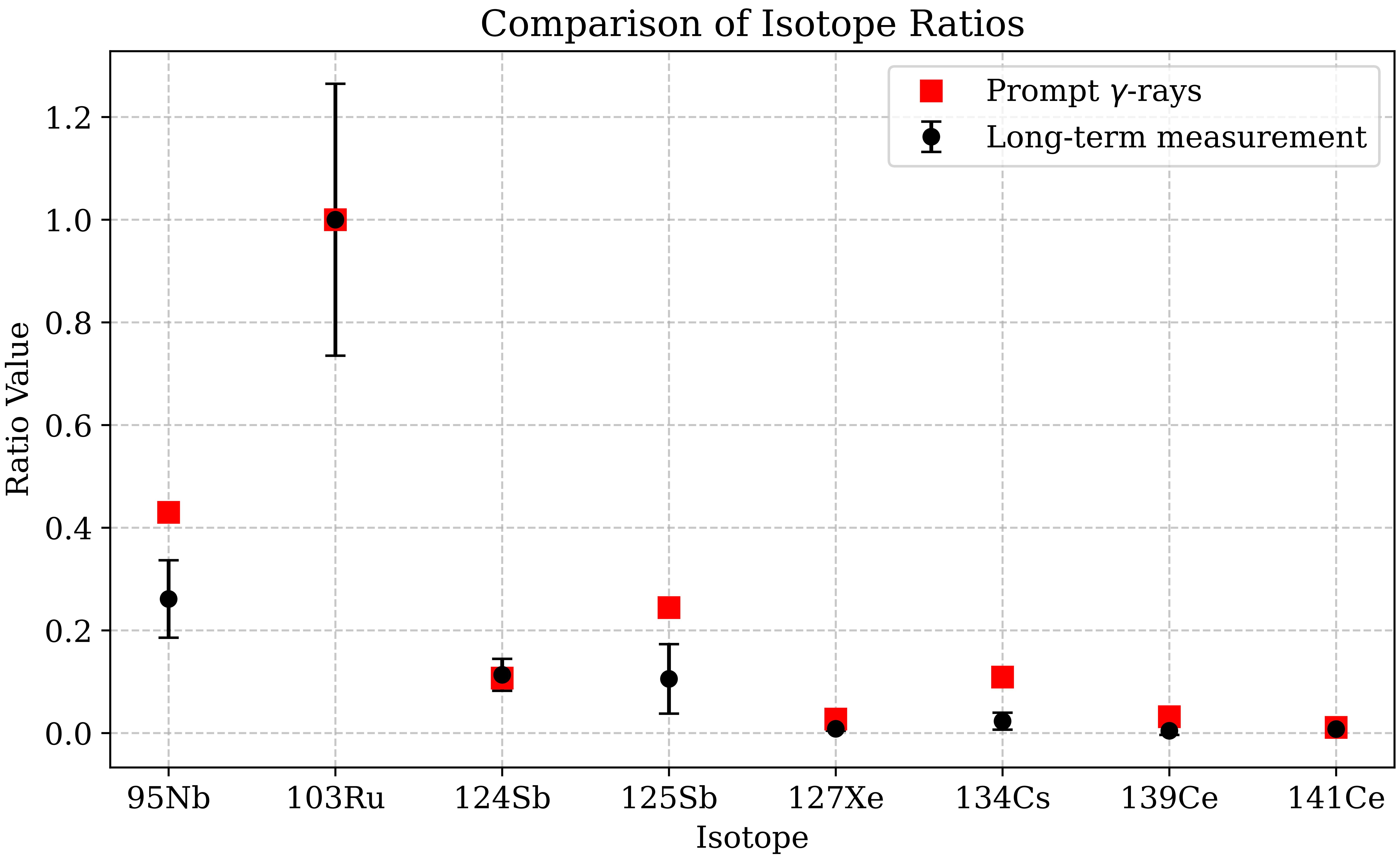
Comparison with prompt γ-rays analysis

Yields relative to ^{103}Ru:

- Production probability based on prompt γ-ray analysis propagated to the start of the long measurement (MLE + decay)
- Residual activity measurement (67 d post-ALTO)



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^{12}C + ^{182}W → ^{194}Hg* experiment

87.5 MeV

60.9 MeV

Measurements

Prompt γ radiation (ALTO, IJCLab)

8 h post-irradiation *in situ* (ALTO, IJCLab)

Long-lived isotopes at FUW

Analysis by K. Miernik

Analysis by M. Kurzelewski

Classical analysis via $\gamma - \gamma - \gamma$ cascades leading to the g.s. like $4^+ \rightarrow 2^+ \rightarrow 0^+$

Alternative method: analysis of decay curves of medium- and long-lived fission products

Gamma spectroscopy of ^{12}C + ^{182}W fusion-fission reaction

K. Miernik,[1,*] P. Garczyński,[1] A. Korgul,[1] J.N. Wilson,[2] A. Algora,[3] M. Chotkowski,[4] S. Czajkowski,[5] N. Dzysiuk,[6] L. M. Fraile,[7] C. Hiver,[2] T. Kurtukian-Nieto,[5,8] K. Komuda,[1] M. Lebois,[2] A. Lopez-Martens,[2] J. Ljungvall,[2] L. Mathieu,[5] J. A. B. Monago,[7] G. Pasqualato,[2] W. Poklepa,[1] P. Połczyński,[4] H. A. Rösch-Kabadayi,[9] K. Solak,[1] I. Tsekhanovich,[5] and S. Zajda[1]

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(Dated: November 3, 2025)

Background: The fission character changes along the mercury isotopic chain, from asymmetric (^{180}Hg), through slightly asymmetric (^{190}Hg), to symmetric (^{198}Hg). Mercury isotopes have been studied using complementary techniques such as β-delayed fission and fusion-fission, but the isotope ^{194}Hg has not been investigated until now.

Purpose: To experimentally study the fusion-fission reaction of ^{194}Hg at moderate excitation energy and to determine previously unknown independent fission yields and properties of emitted neutrons and γ-rays.

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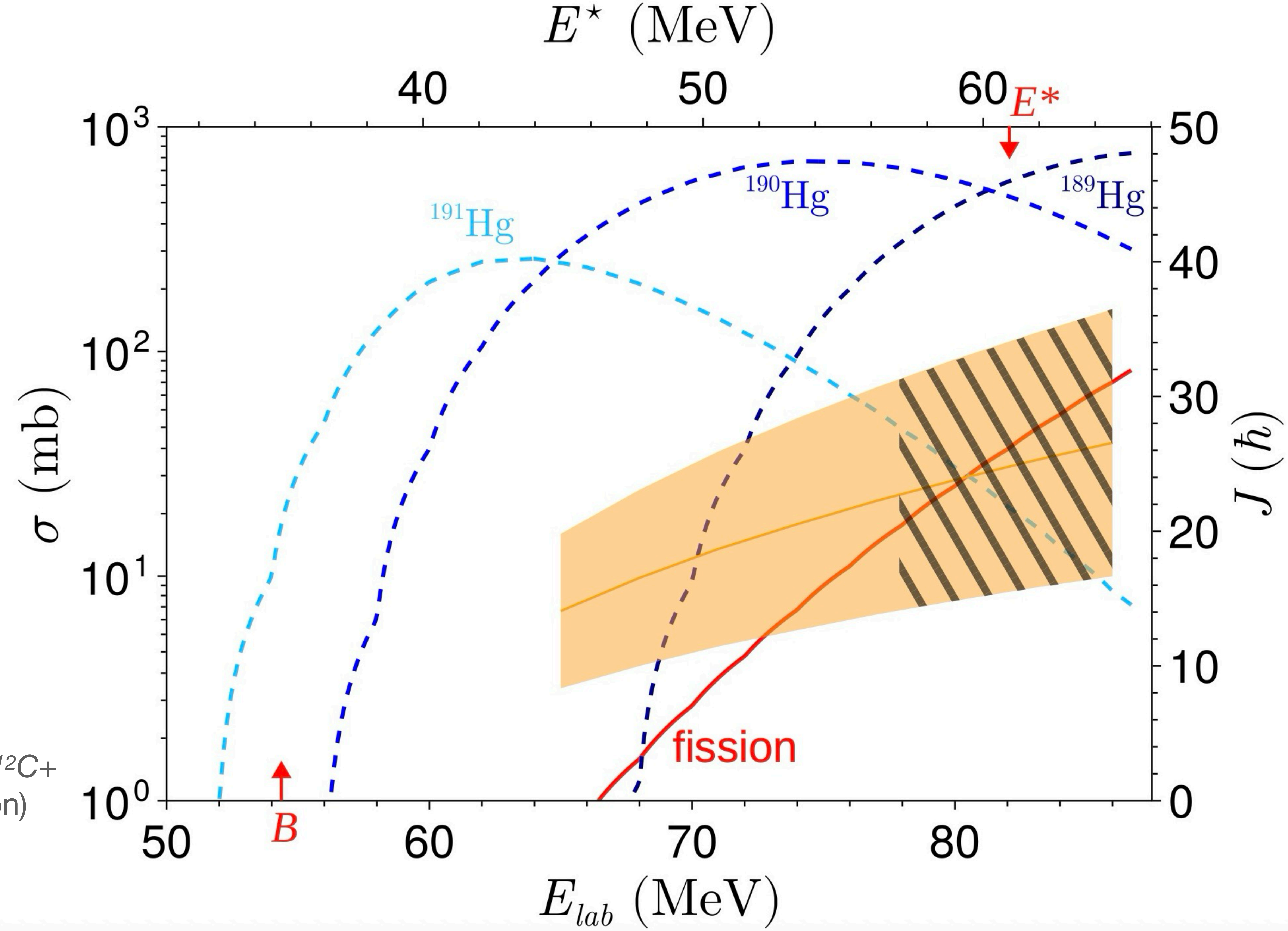
(in preparation)

$^{12}C + ^{182}W \rightarrow ^{194}Hg^*$ experiment

Theoretical cross-sections (HIVAP) for different deexcitation channels from CN $^{194}Hg^*$

Fusion-evaporation channels much more populated than fission

K.Miernik in., *Gamma spectroscopy of the ^{12}C+ ^{182}W fusion–fission reaction* (in preparation)



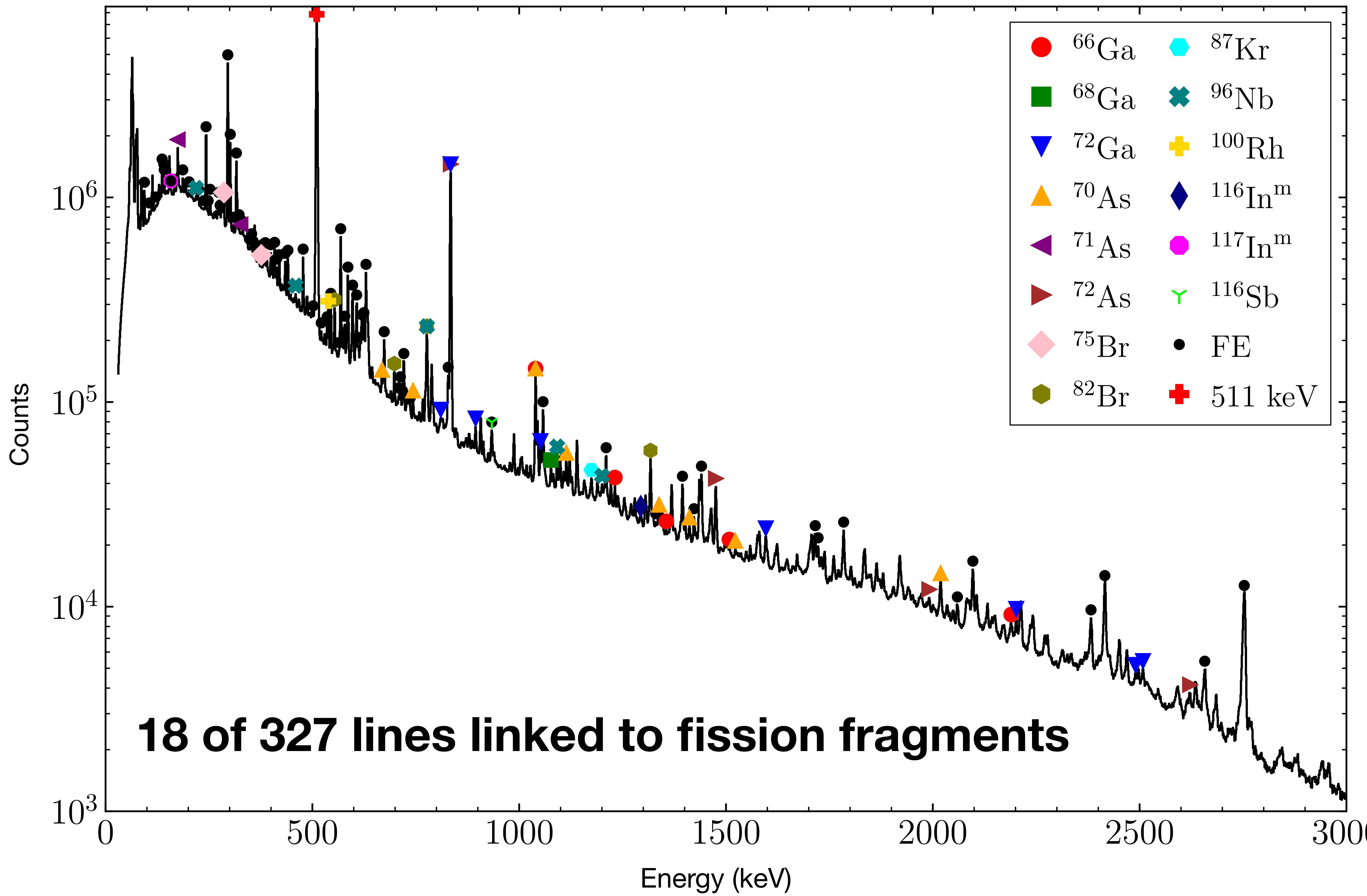
$^{12}C + ^{182}W \rightarrow ^{194}Hg^*$ — decay analysis results

Results

- 26 isotopes identified, $T_{½}$ from minutes to tens of hours:
  - 7 fission fragments
  - 11 fusion-evaporation products
  - 8 from other beam reactions
- **FF signals insufficient** for yields comparison with prompt data
- For 6 FE products we obtained improved $T_{½}$ precision estimation

Lesson learned:

Future campaigns should **extend the post-irradiation counting period**



Spectrum of a 8 h measurement after beam shut down

^{12}C + ^{182}W → $^{194}Hg^*$ — decay analysis results

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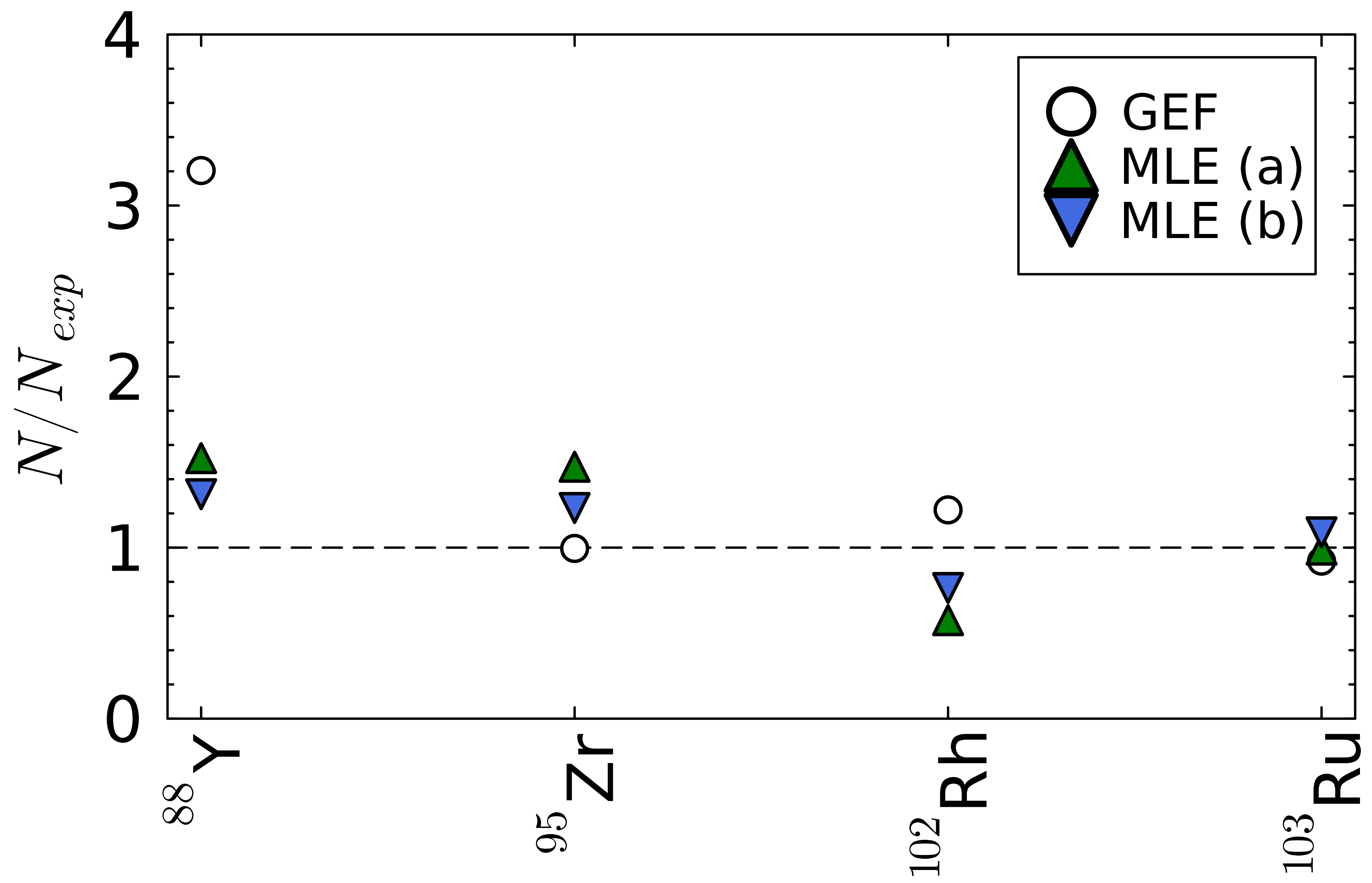

Ratios of theoretical and prompt experimental populations of isotopes to the values obtained in the long-term measurement at FUW. Credit: K. Miernik

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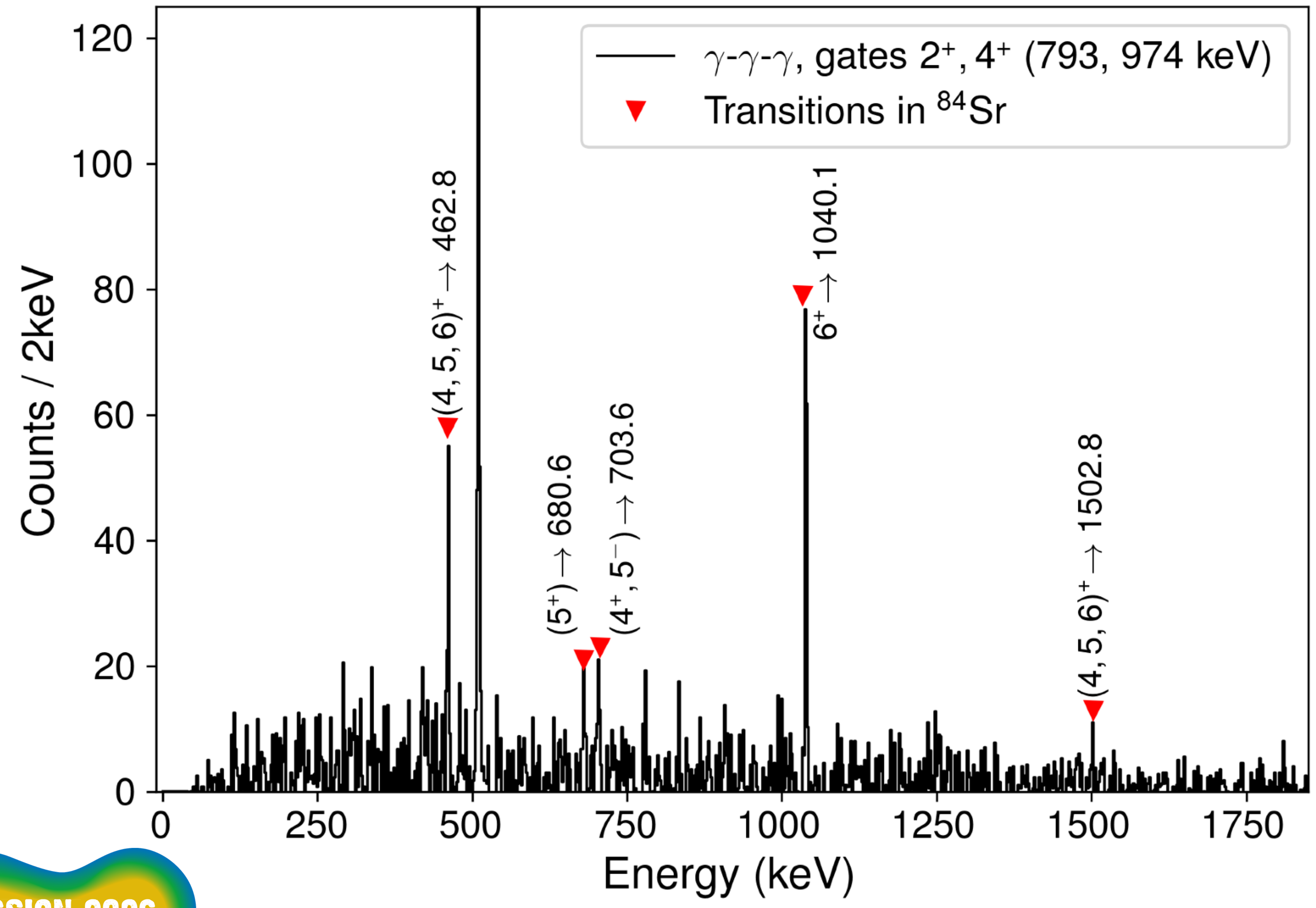
Further studies: ^{32}S + ^{112}Sn → ^{144}Dy*

EXPERIMENTAL SET-UP AT HIL, UW:

EAGLE (HPGe x 15) + **DIAMANT** (charged particles) + **NEDA** (neutrons)



MEASUREMENT IN 2024/25:

— **180 h on-line**

— **27 h post-beam**

— **long-term at FUW**

The following isotopes has been identified by M. Kurzelewski (bachelor):

^{54}Mn, ^{56,58,60}Co, ^{65}Zn, ^{75}Se, ^{83}Rb, ^{85}Sr, ^{88}Y

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Summary

Measurement of the irradiated target is a valid method of verification of results obtained with γ-ray spectroscopy, but:

- Sensitive to the reaction choice (dominant fusion-evaporation channels will complicate the analysis)
- Months-long measurement required in simple setup version

Collaboration:
K. Miernik, A. Korgul, J. N. Wilson, A. Algora, J.A. Briz, G. Charles, M. Chotkowski, S. Czajkowski, P. Czyż, N. Dzysiuk, A. Fijałkowska, L.M. Fraile, K. Hauschild, C. Hiver, T. Kurtukian-Nieto, M. Lebois, M. Llanos, A. Lopez-Martens, K.M. Deby Treasa, J. Ljungvall, M. Kurzelewski, I. Matea, L. Mathiew, J. Mielczarek, J.A.B. Monago, J.R. Murias, G. Pasqualato, W. Poklepa, P. Połczyński, H.A. Rösch-Kabadayi, A. Skruch, K. Solak, K. Szlęzak, K. Stoyachev, I. Tsekhanovich, S. Zajda

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Thank you!