Measurements of the ^{241}Pu capture and fission cross sections at n_TOF and GELINA (Cap-Fiss-Pu241)

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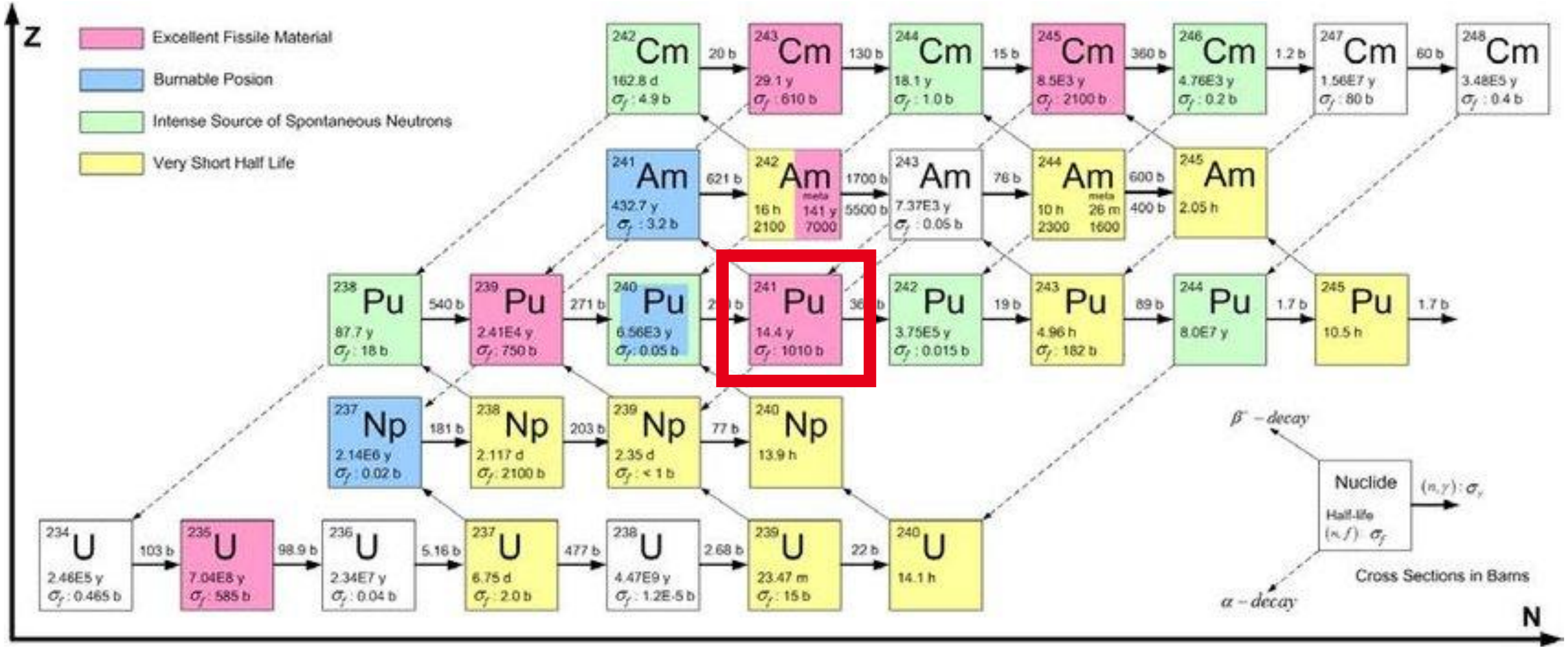
1. Context

Motivations



- Plutonium is produced in reactors, ^{239}Pu and ^{241}Pu both contribute to energy production
- The uncertainty on the reactivity loss with burnup depends on Pu cross section uncertainties
- ^{241}Pu xs are not well known because of its short half-life (~14 years) and the ^{241}Am build-up

Two OECD/NEA high-priority requests

n_TOF

Capture cross section requested with an accuracy of 2-3% (PWR) and ~10% (SFR)

Request ID	33		Type of the request	High Priority request	
Target	**Reaction and process**	**Incident Energy**	**Secondary energy or angle**	**Target uncertainty**	**Covariance**
94-PU-241	(n,g) SIG	0.1 eV-1.35 MeV		See details	Y
Field	**Subfield**	**Created date**	**Accepted date**	**Ongoing action**	**Archived Date**
Fission	Fast Reactors (VHTR)	04-APR-08	12-SEP-08	Y	

Only one available capture xs measurement (Weston and Todd, NSE 65, 454-463, 1978)

n_TOF & GELINA

Fission cross section requested with an accuracy of 3-7% depending on the energy/reactor

Request ID	35		Type of the request	High Priority request	
Target	**Reaction and process**	**Incident Energy**	**Secondary energy or angle**	**Target uncertainty**	**Covariance**
94-PU-241	(n,f) SIG	0.5 eV-1.35 MeV		See details	Y
Field	**Subfield**	**Created date**	**Accepted date**	**Ongoing action**	**Archived Date**
Fission	Fast and Thermal Reactors	04-APR-08	12-SEP-08	Y	

Status of Cap-Fiss-Pu241

Experimental work (2022-2026)

- Production and characterization of ^{241}Pu samples (β-decay to ^{241}Am, $T_{1/2}$ ~14 years)
- Development of compact fission tagging detectors for high counting rates
- Experimental campaigns (within a few months, before ^{241}Am buildup becomes an issue)

  => ND2025 proceedings

- Measurement of the sample homogeneity at JRC-Geel (scheduled in October 2026)

Data reduction/analysis (2025-2028+)

- TAC capture-to-fission ratio (Aline Cahuzac, PhD 2023-2027)

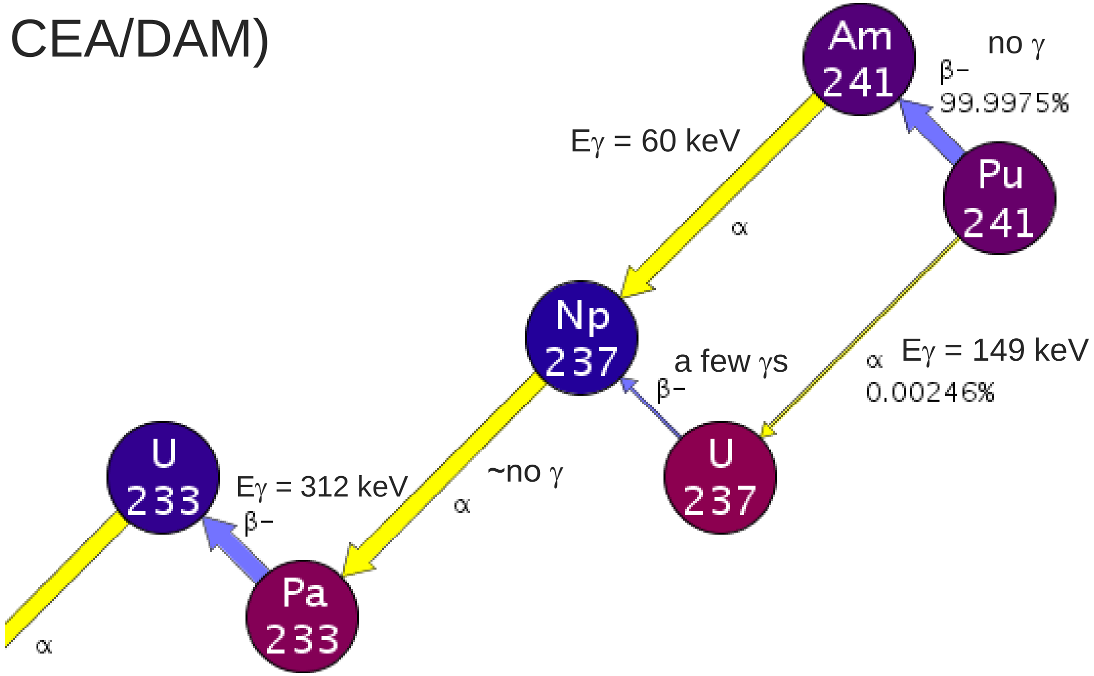
  => Status of the TAC analysis presented at WONDER 2026

- Fission cross section (Michele Spelta, postdoc 2026/06-2028)

2. Samples

Samples production & characterization

- Starting from JRC legacy material (enriched in ^{241}Pu in the 70s)
  - 2022: checking the state of the material (decades old)
  - 2023: Pu-Am separation & characterization
  - 2024: Pu-Np separation & characterization (with CEA/DAM)
  - 2025: Pu-U separation & characterization
- June-July 2025
  - Final Pu-Am separation
  - Samples production by molecular plating
  - Samples mounting in the fission chamber
  - Transport of samples/detectors to CERN



Final samples

- Unique set of 8 plutonium samples (Ø 30 mm) enriched in ^{241}Pu (~6 mg ^{241}Pu)

  ^{238}Pu (0.09%), **^{239}Pu** (6.0%), **^{240}Pu** (23.0%), **^{241}Pu** (53.7%), **^{242}Pu** (17.2%) + **^{241}Am** buildup

  - ~23 GBq of β-activity (from the decay of ^{241}Pu to ^{241}Am)
  - ~33 MBq of total α-activity (mainly from ^{238}Pu and ^{240}Pu)
  - ~5 MBq more α every 2 months (from ^{241}Am buildup)

- + 2 uranium reference samples (Ø 42 mm) highly enriched in ^{235}U (~7.8 mg ^{235}U) produced and characterized by JRC-Geel (on loan from PTB)

3. Detectors

Total Absorption Calorimeter (TAC) for α-ratio

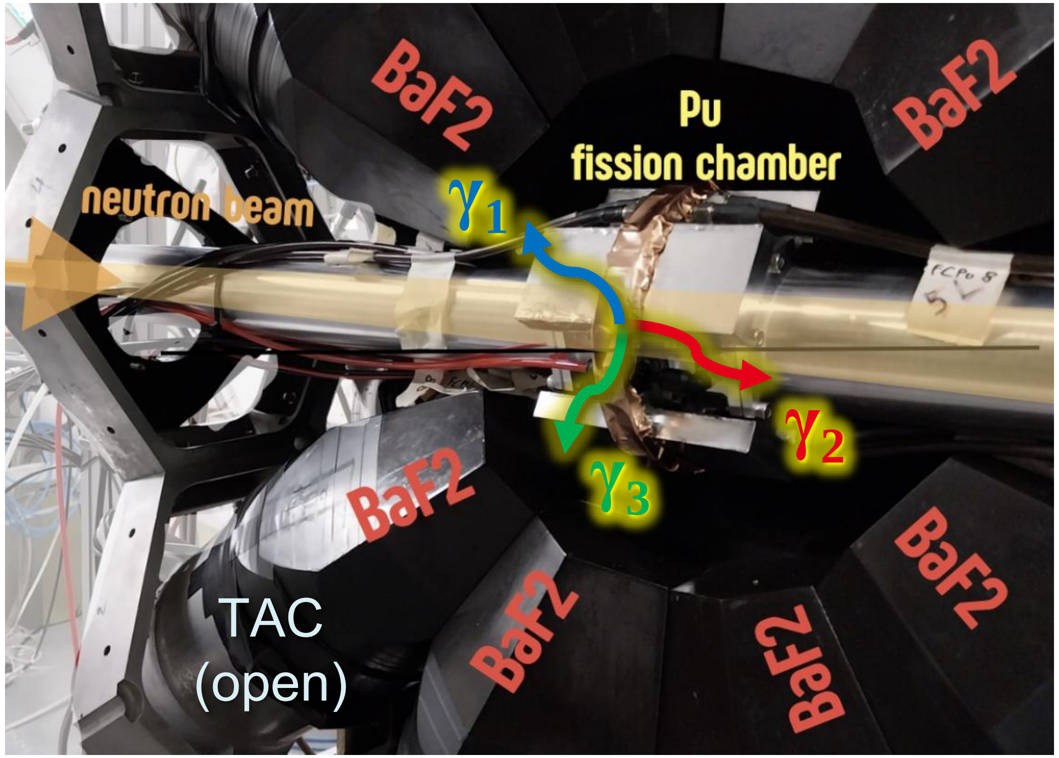
Detection of γ-rays by the TAC (4π calorimeter segmented with 40 BaF_2 crystals)

In capture-to-fission ratio measurement, the samples are inside the fission chamber used for fission tagging

Example with the detection of 3 gammas (γ_1, γ_2, γ_3)

- E_{sum} is the total γ-ray energy deposited in the TAC
  - E_{sum} (total E_γ) = $E_1 + E_2 + E_3$
  - In capture, if the TAC detects all γ of the cascade then $E_{sum} = S_n + E_n \approx S_n$
- M_{cr} is the number of crystals detecting a gamma
  - M_{cr} (multiplicity) = 3

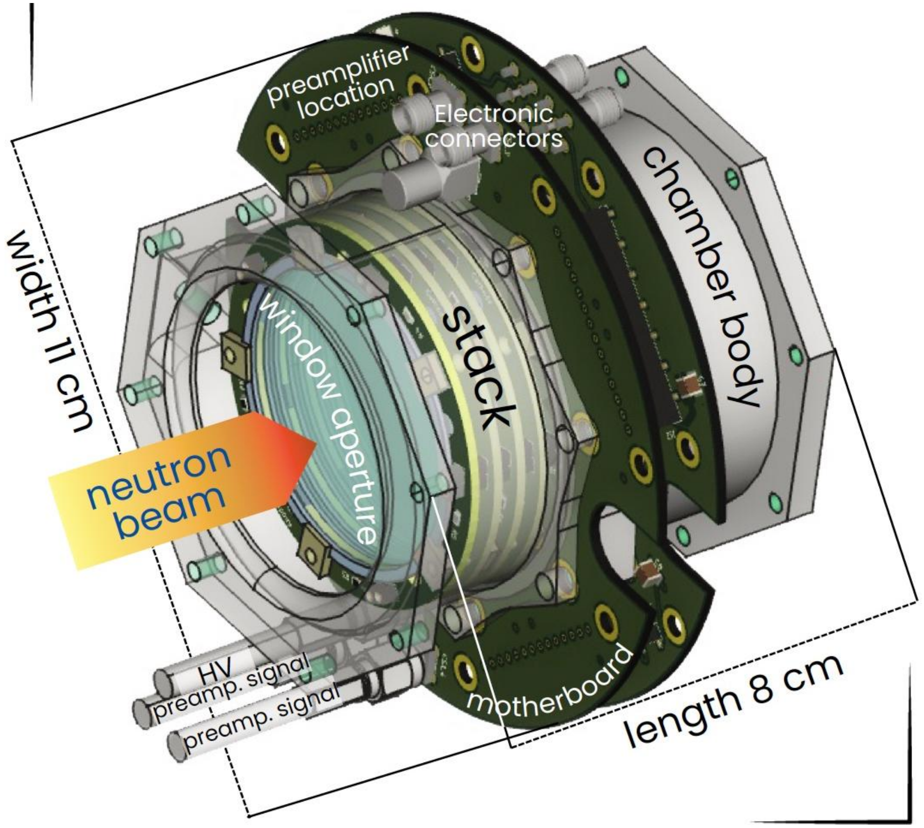
⇨ Selection cuts on E_{sum} and M_{cr} improve S/B ratio



Fission tagging detector

- Main requirements
  - Compact and transparent to neutrons and gammas (for fission-tagging with the TAC 4π calorimeter)
  - High counting rates (for radioactive actinides)
  - Good energy resolution (for α-fission separation)

- Detector design
  - 8 samples/channels to distribute the counting rate
  - Fast preamplifier/shaper minimizing signal widths
  - Gap of 3 mm, low gas pressure, low mass budget



- Fabrication of 3 identical detectors: FICH-Pu241 (Pu samples), FICH-U235 (fission normalization), FICH-dummy (background measurement)

4. Measurements

Data taking in 2025 and early 2026

- Measurements of the ^{241}**Pu capture-to-fission ratio and the fission xs (> ~0.1 eV)**
  - July-Aug. 2025: EAR1 (L ~185 m) with TAC, FICH-Pu241, FICH-U235 + ref. monitors

- Additional measurements of the ^{241}**Pu fission cross section** with FICH-Pu241 and FICH-U235
  - Sept. 2025: EAR2 (L ~18 m) in the thermal and epithermal ranges
  - Feb.-March 2026: GELINA (L ~10 m) in the resolved resonance range

Basic principle of the measurements

Fission cross section

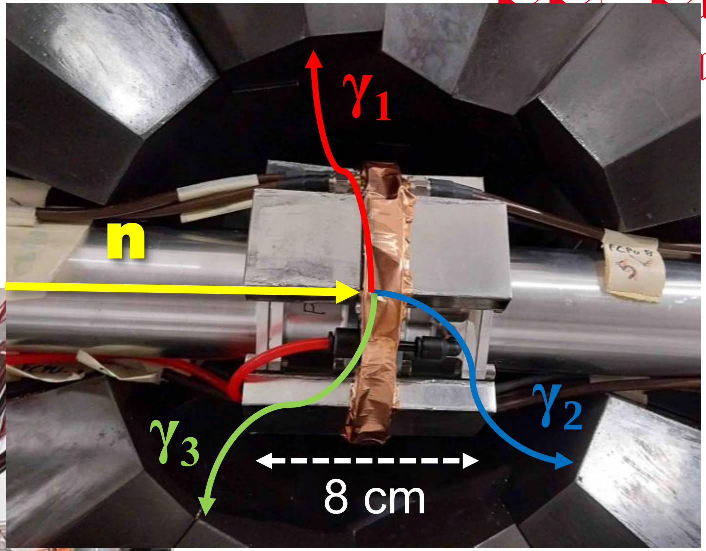
- Fission fragments detected in FICH-Pu241 relative to FICH-U235 reference (+ corrections)
  => absolute measurement of the xs ratio ^{241}Pu(n,f)/^{235}U(n,f)

Capture-to-fission cross section (α-ratio)

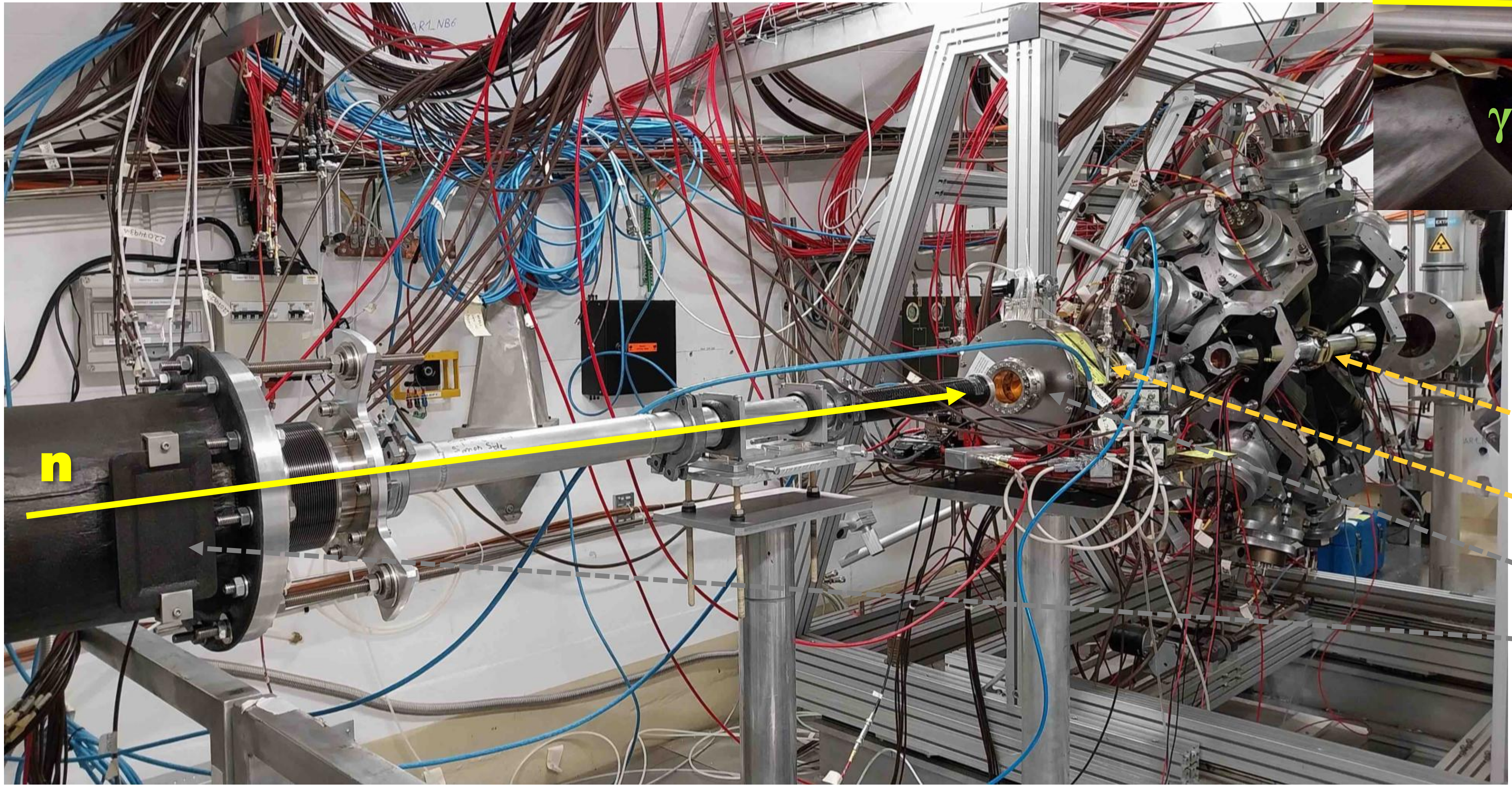
- TAC and FICH-Pu241 in coincidence → gammas from fission
- TAC and FICH-Pu241 in anti-coincidence → gammas from capture (+ background)
- Cuts in gamma energy (E_{sum}) and crystal multiplicity (M_{cr}) to maximize signal/“noise” ratio
- Ancillary measurements to subtract gamma backgrounds
- Corrections for FICH-Pu241 efficiency and cuts
  => absolute measurement of the xs α-ratio ^{241}Pu(n,γ)/^{241}Pu(n,f)

⚠ Small samples requires measurement of the beam interception factor (BIF), i.e. the fraction of the beam intercepted by the sample

n_TOF EAR1 measurement
with the Total Absorption Calorimeter (TAC)
Data taking: 7 weeks in July-August 2025



Zoom on FICH-Pu241 inside the TAC (open)



FICH-Pu241

FICH-U235 (reference)

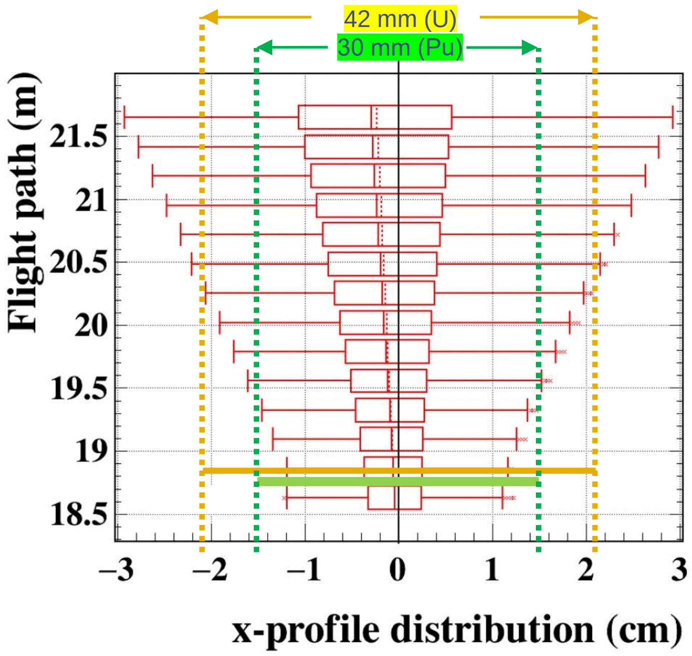
^{235}U PTB LMFC (ref.)

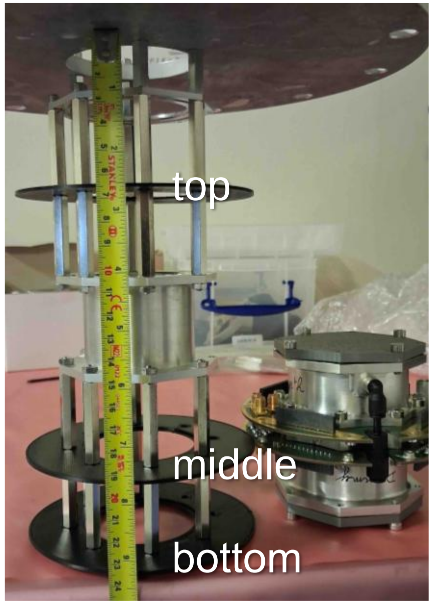
SiMon (reference)

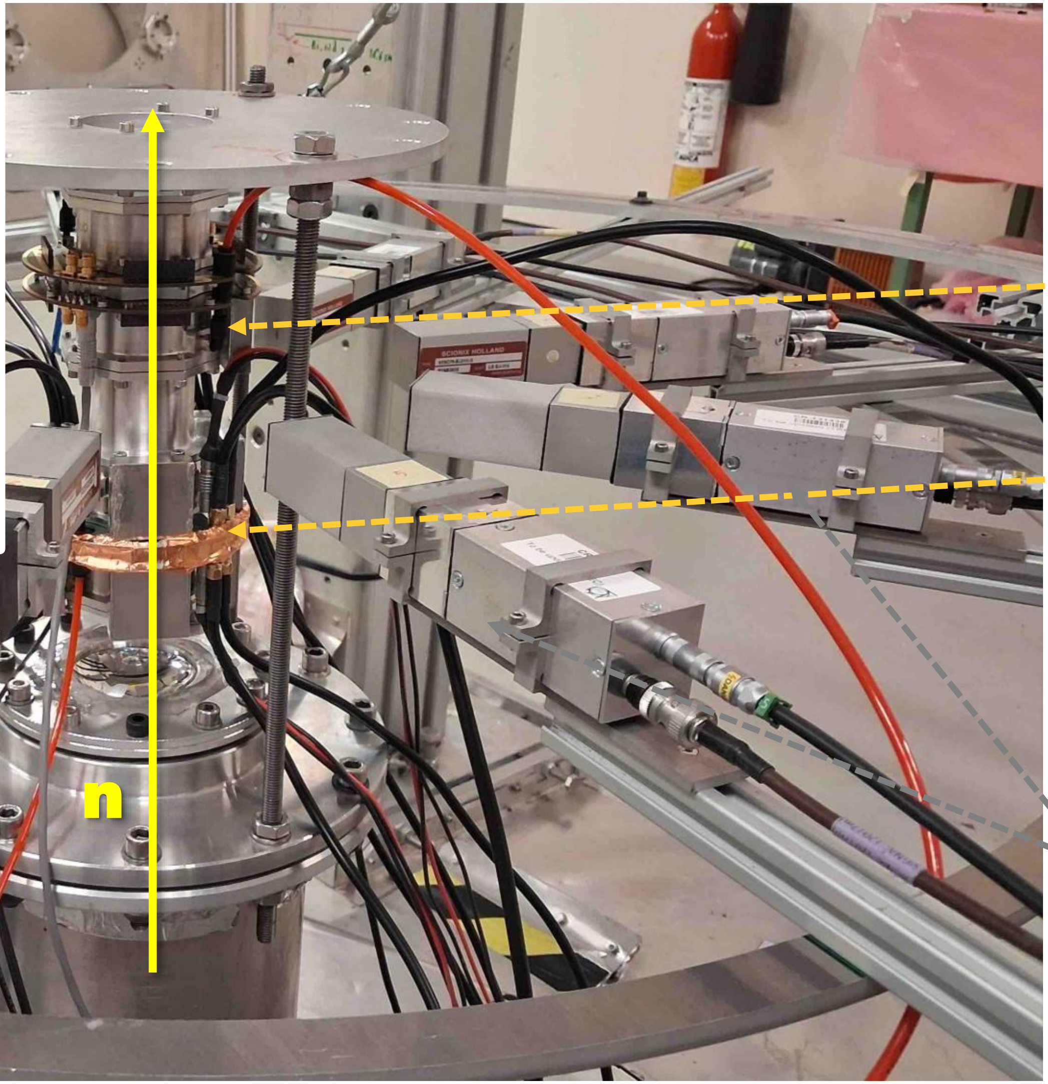
n_TOF EAR2 measurement (thermal fission)

Data taking:

1 week in Sept. 2025





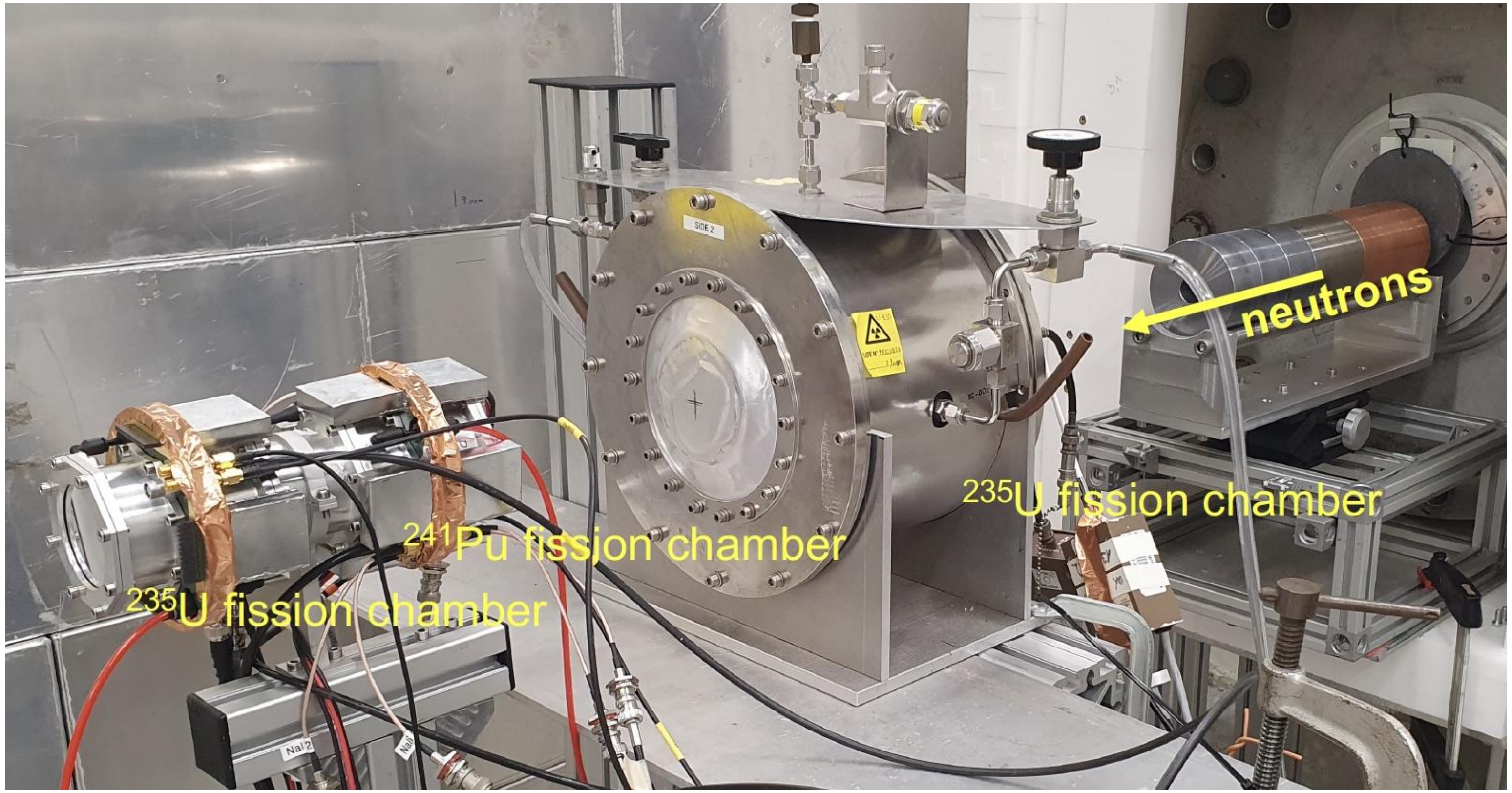


GELINA measurement (fission resonances)

Data taking at FP2/10m

Started in Nov. 2025

Completed in Feb-Mar. 2026



5. Analysis (ongoing)

EAR1 capture-to-fission ratio (A. Cahuzac)

- 2 PB of raw data (2 TB pre-processed data)
- 61 channels: TAC (40), FICH-Pu241 (8), FICH-U235 (2), LMFC (6), SiMon (4), PKUP (1)

- TAC data processing
  - ✓ Calibration of the 40 TAC BaF_2 crystals
  - ✓ Synchronization of TAC crystals (^{88}Y source)
  - ✓ Synchronization with PKUP (beam signal)
  - ✓ Separation of α and noise from gammas
  - ✓ Clusterization (pulses $\rightarrow$ events)

- FICH-Pu241 data processing
  - ✓ Separation of α and fission fragments

- Fission tagging
  - ✓ Synchronization between FICH and TAC
  - ✓ Tag γ events

- Capture-to-fission (work in progress)
  - Selection cuts in M_{cr} and E_{sum}
  - Subtraction of backgrounds
  - Correction for fission tagging efficiency and cuts

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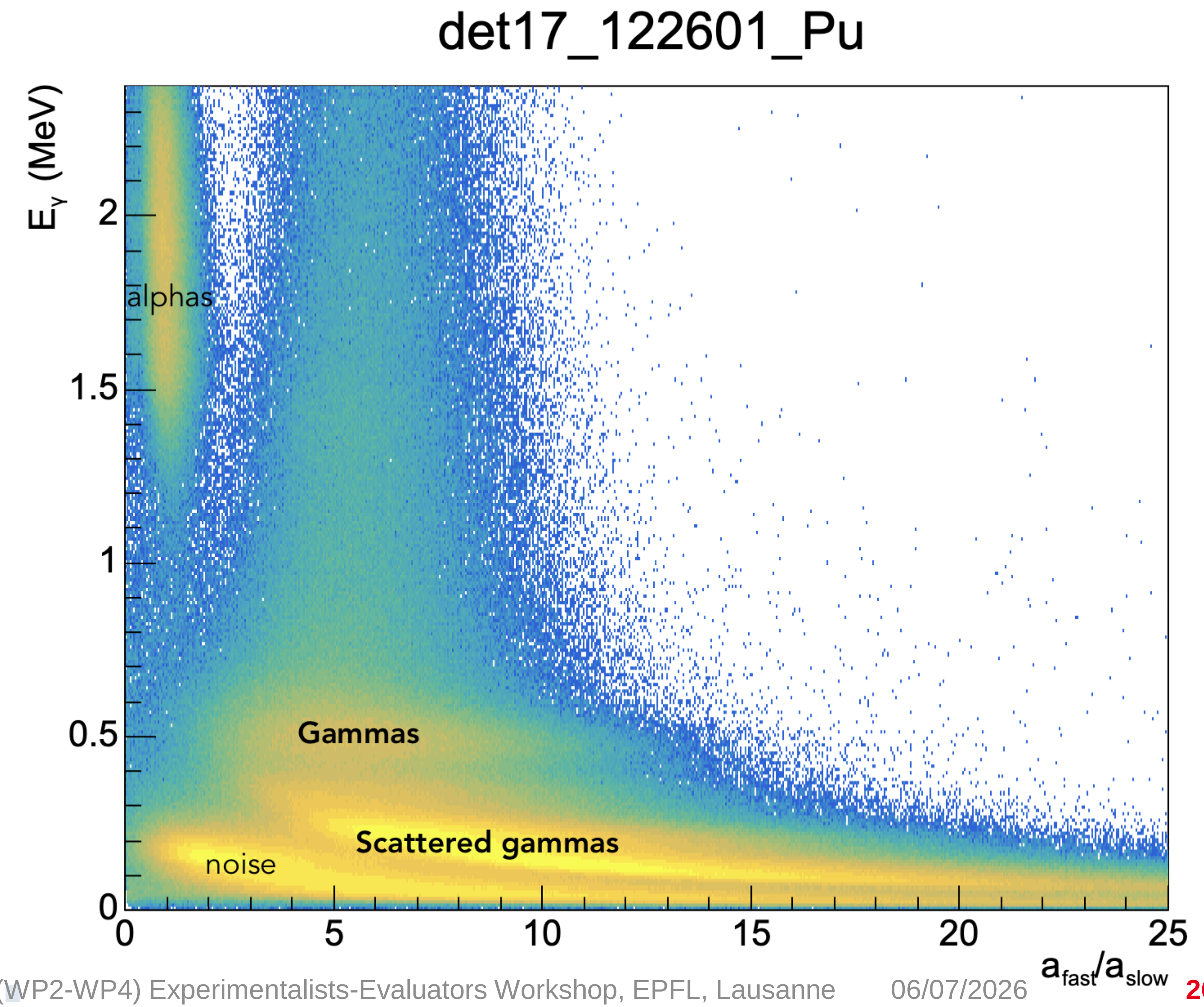
EAR1 capture-to-fission ratio (A. Cahuzac, Wonder 2026)

PSD of alphas (from Radium), noise, and gammas in BaF_2



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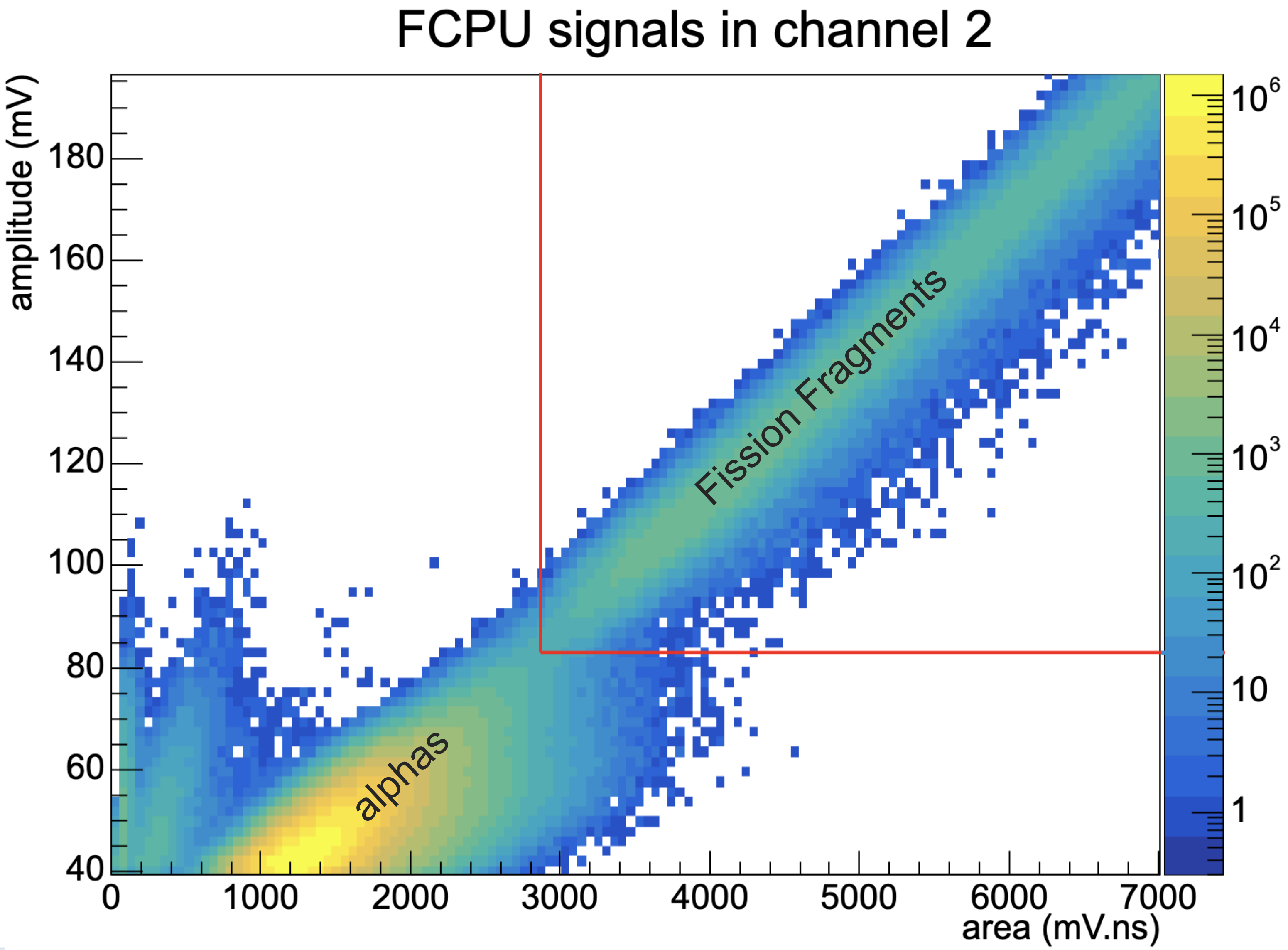
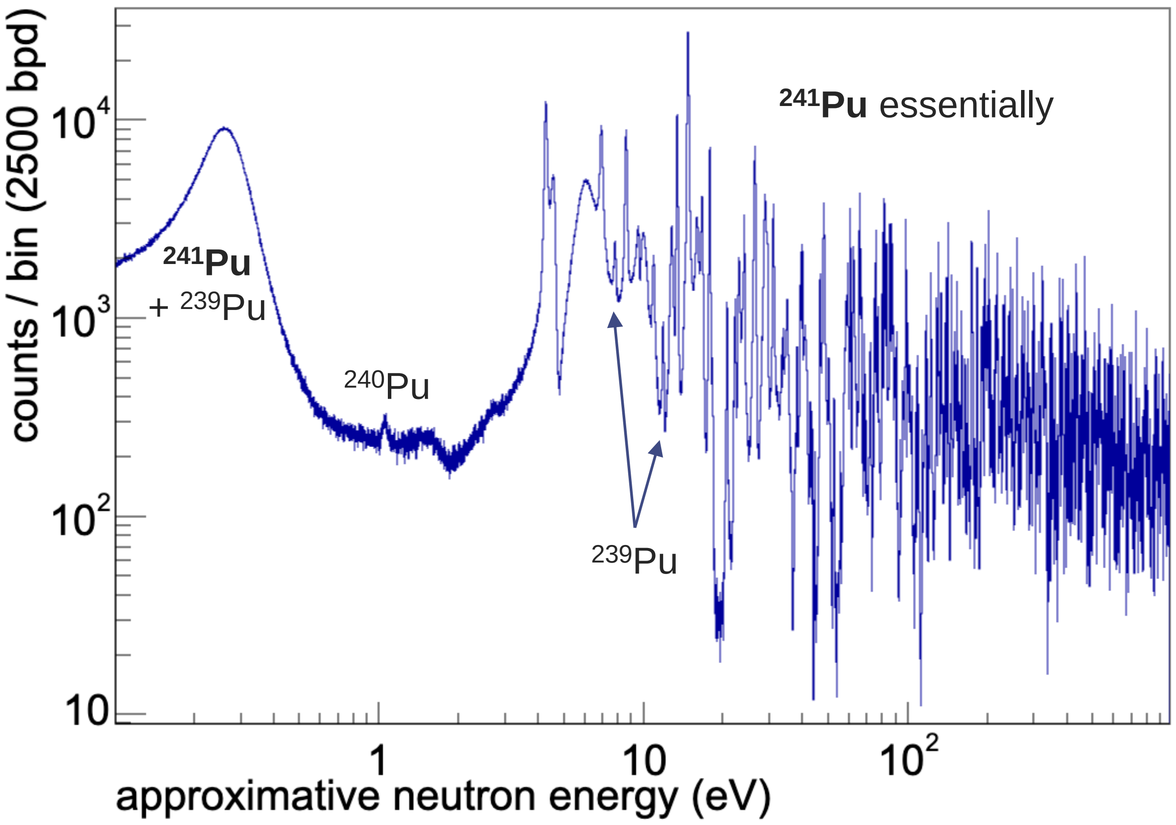
EAR1 capture-to-fission ratio (A. Cahuzac, Wonder 2026)

Separation between alphas (mainly from $^{238,240}Pu$, ^{241}Am) and fission fragments in FICH-Pu241

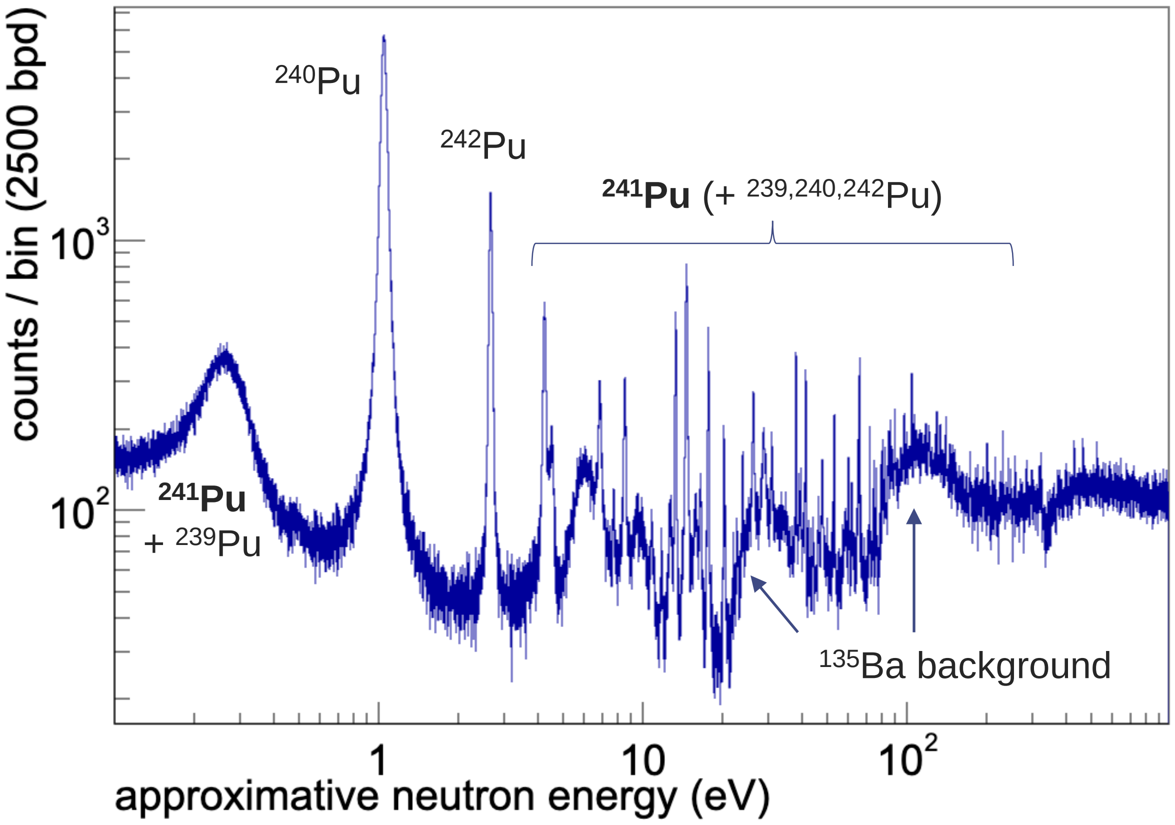


EAR1 raw data (E. Berthoumieux, A. Cahuzac)

FICH-Pu241: fission fragments



TAC: gammas from fission, capture, and bgd



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  - Selection cuts in M_{cr} and E_{sum}
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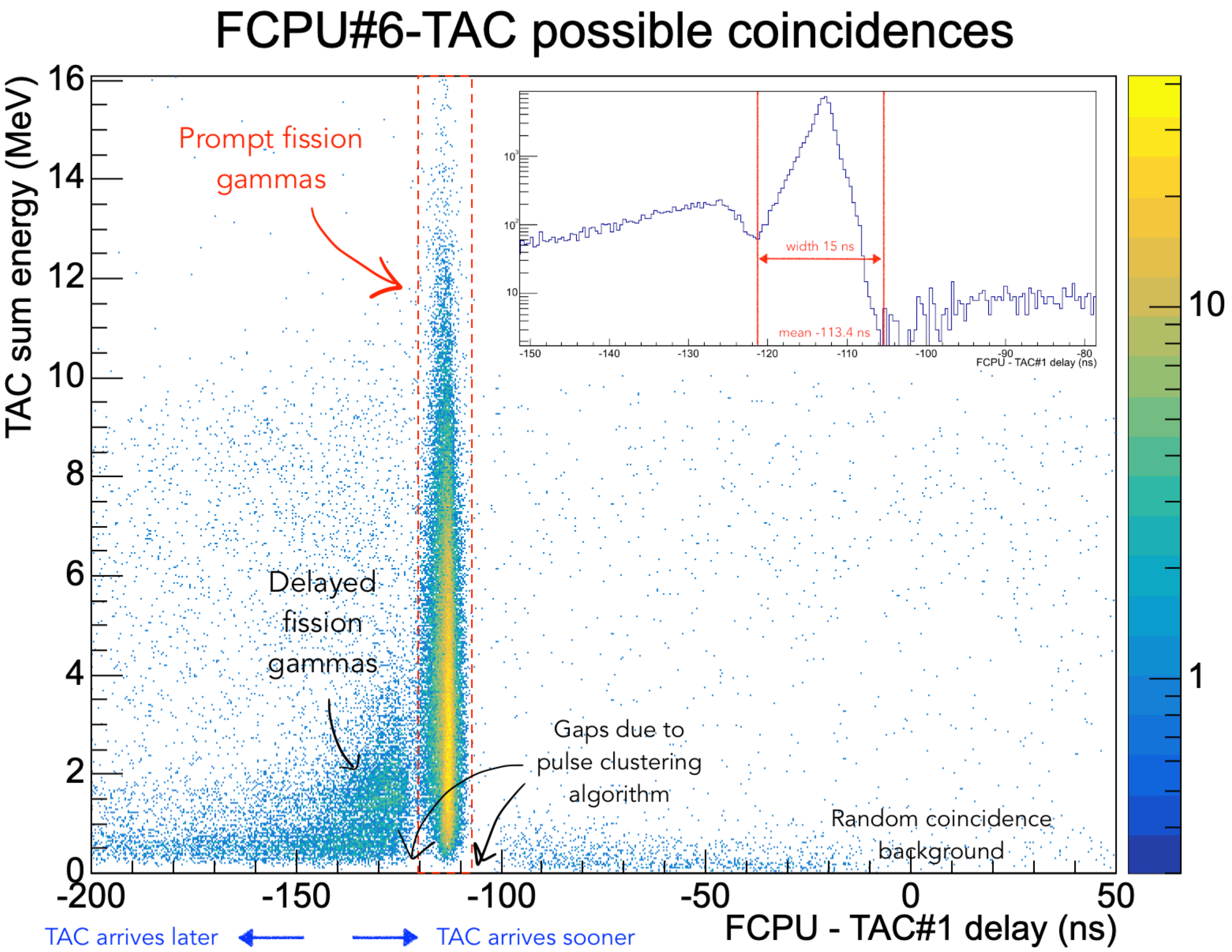
EAR1 capture-to-fission ratio (A. Cahuzac, Wonder 2026)

FICH vs. TAC timing

=> Fission tagging of gammas
in a 15 ns coincidence window



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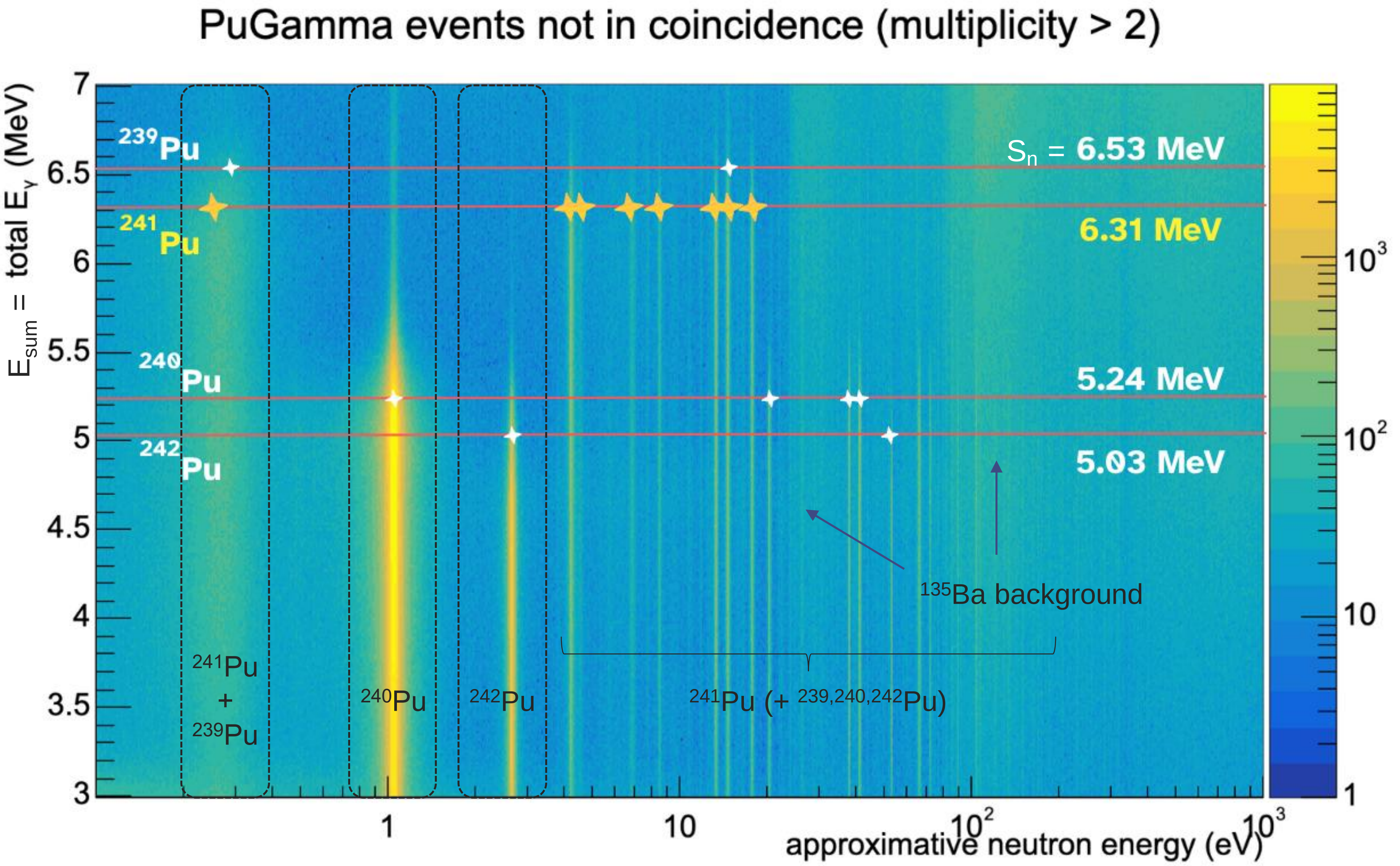
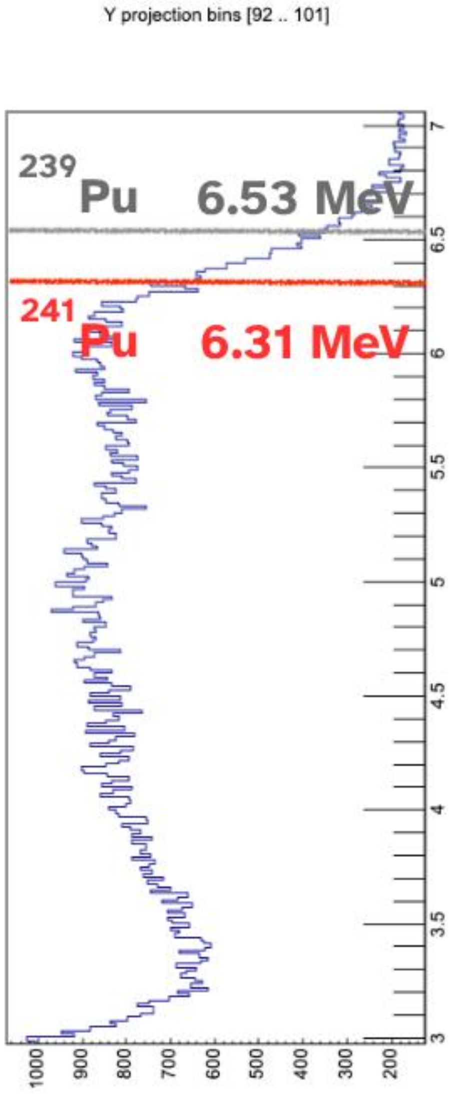
EAR1 capture-to-fission ratio (A. Cahuzac, Wonder 2026)

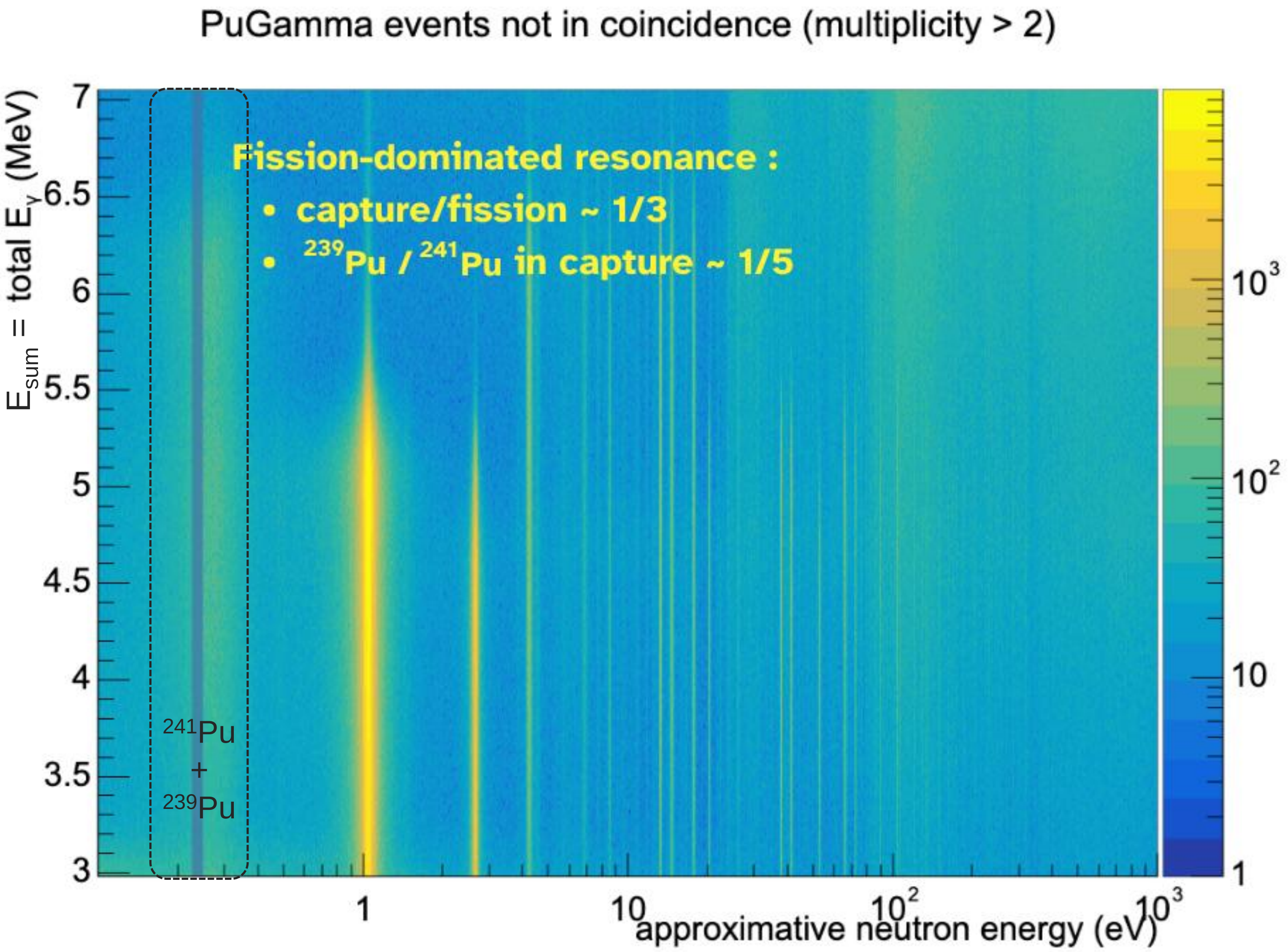
TAC: Gammas from capture and background



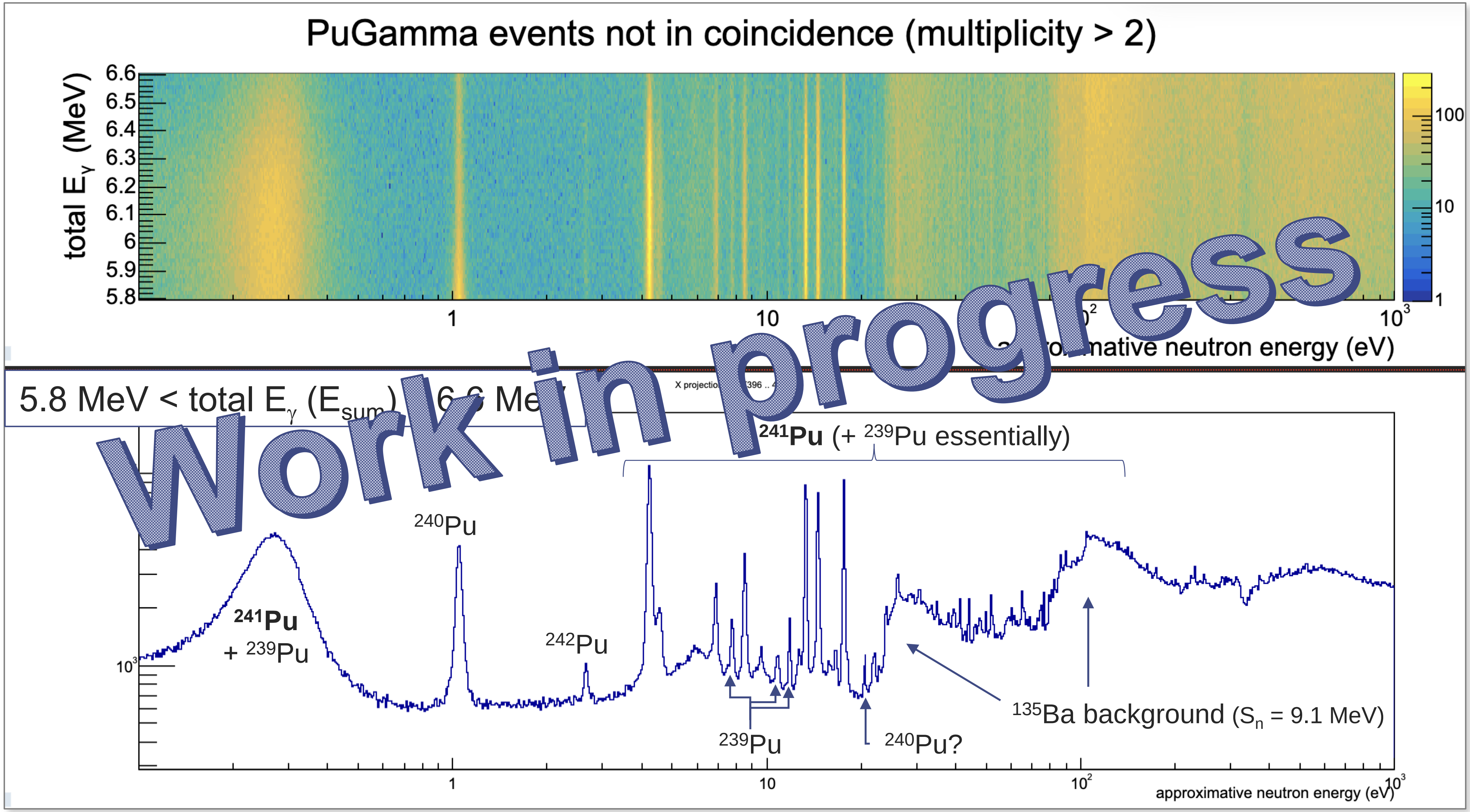
EAR1 capture-to-fission ratio (A. Cahuzac, Wonder 2026)

E_{sum} spectra in the first large ^{241}Pu resonance



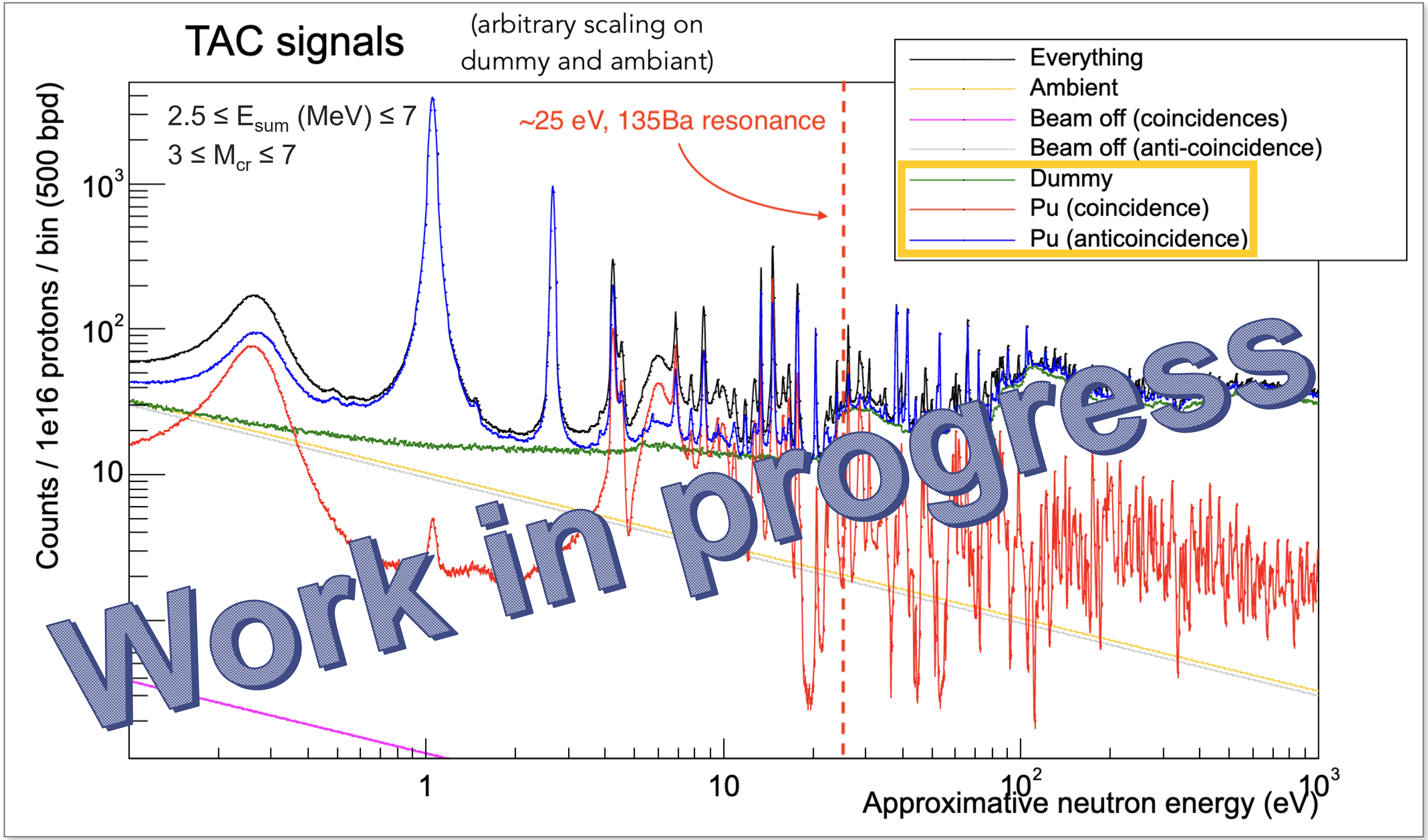


EAR1 capture-to-fission ratio (A. Cahuzac, Wonder 2026)



Cuts on ^{241}Pu sum peak

EAR1 capture-to-fission ratio (A. Cahuzac, Wonder 2026)



Fission data (E. Berthoumieux, M. Spelta)

- Consistency checks done on EAR1 and EAR2 fission data
  - ✓ α-fission discrimination
  - ✓ Stability check
  - ✓ Beam-off subtraction
  - ✓ Sample's beam interception factor determination
  - ✓ Check with respect to samples
    - spontaneous fission (sensitive to total mass)
    - neutron-induced fission (sensitive to areal density)
    - areal density uniformity check on spare samples
  - ✓ Normalization to ^{235}U fission chamber (assuming the same efficiency)

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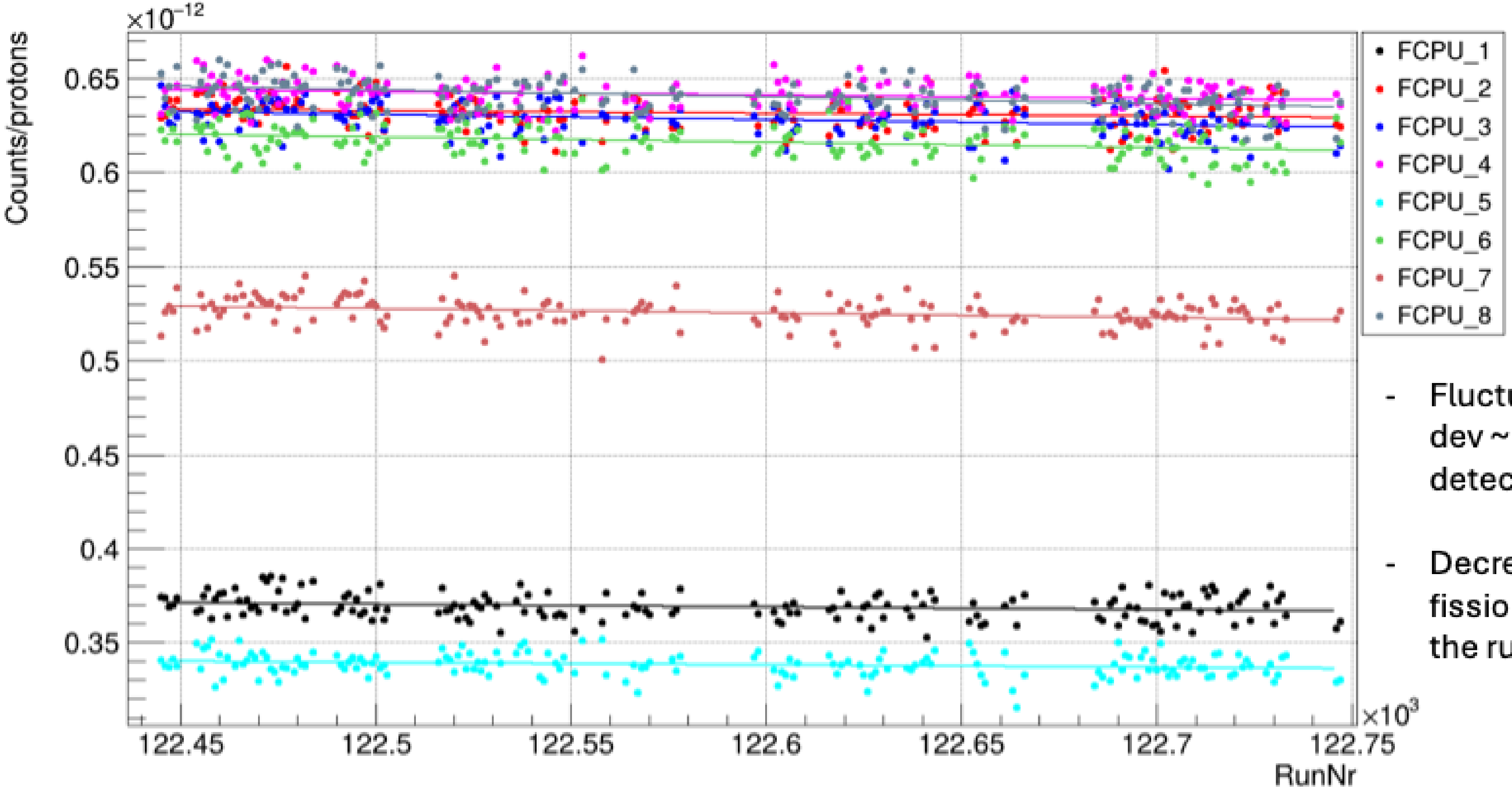
Fission data (M. Spelta)

Stability of the measurement

Selected Fission Fragments with preliminary constant threshold .



- Fluctuations with std dev ~ 1.5% for each detectors
- Decrease of ~ 1.2% of fission counts during the run

Fission data (E. Berthoumieux, M. Spelta)

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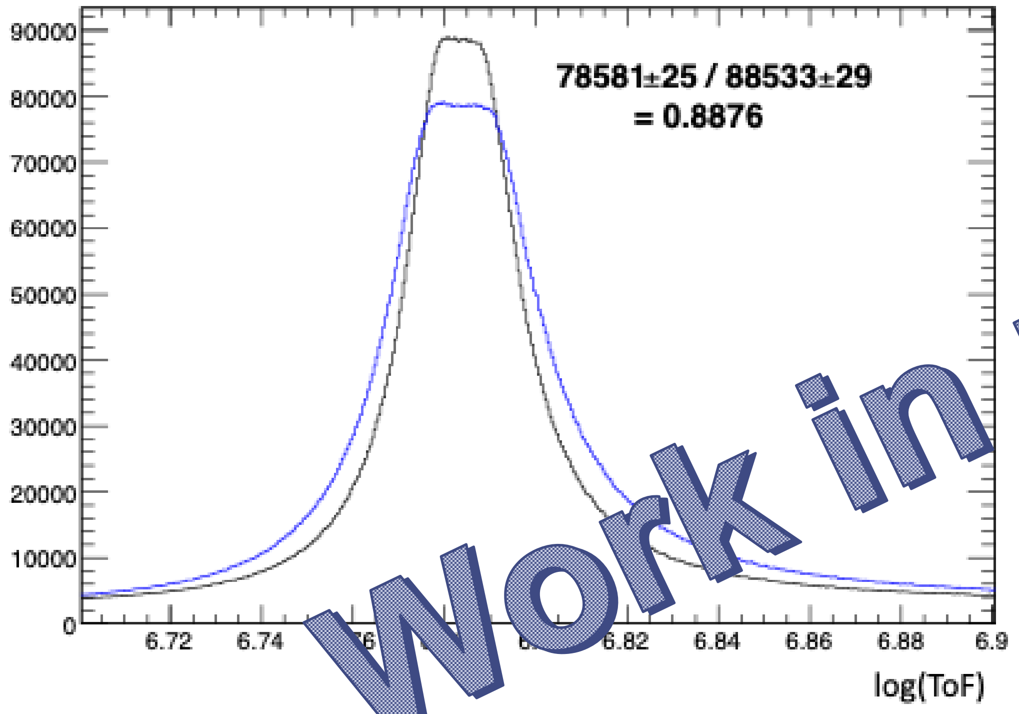
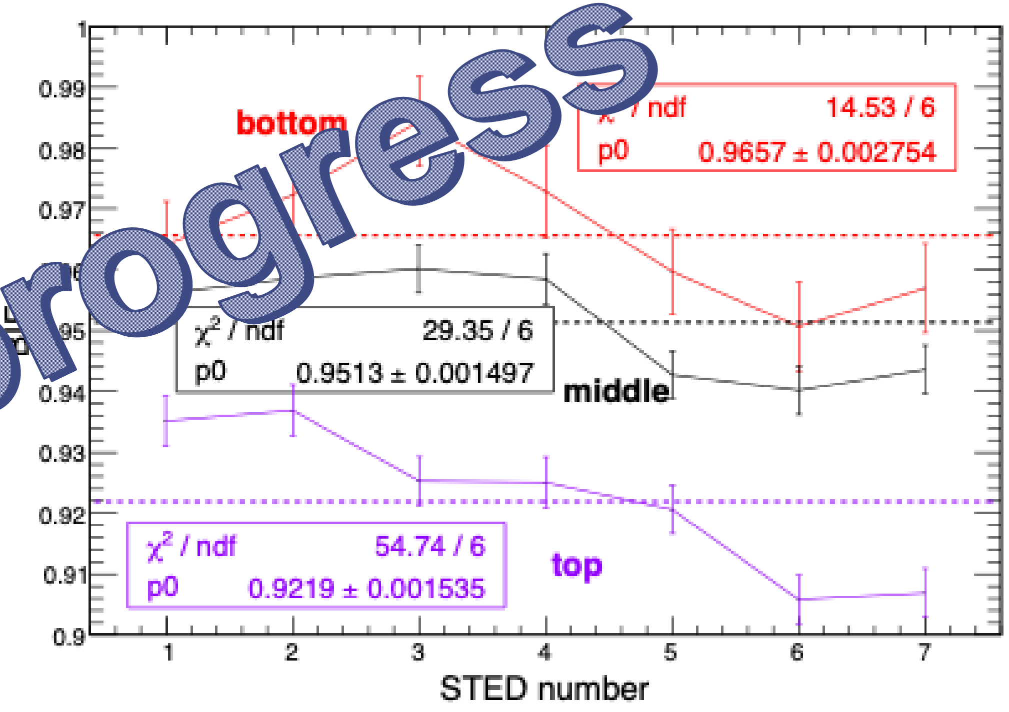
Fission data (E. Berthoumieux, n_TOF Meeting, Vienna, Dec. 2025)

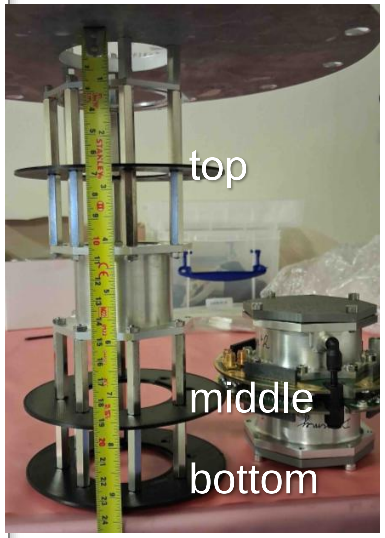
Beam interception factor => Counts of Au-30mm (Pu ∅) / Au-45mm (BIF=100%)



EAR1 : BIF using TAC counts in 1st gold resonance

BIF = 88.7 %





EAR2 : BIF using STED counts in 1st gold resonance

BIF = 95.1 % (middle position = mid of Pu chamber)

Fission data (E. Berthoumieux, M. Spelta)

- Consistency checks done on EAR1 and EAR2 fission data
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  - ✓ Stability check
  - ✓ Beam-off subtraction
  - ✓ Sample's beam interception factor determination
  - ✓ Check with respect to samples
    - spontaneous fission (sensitive to total mass)
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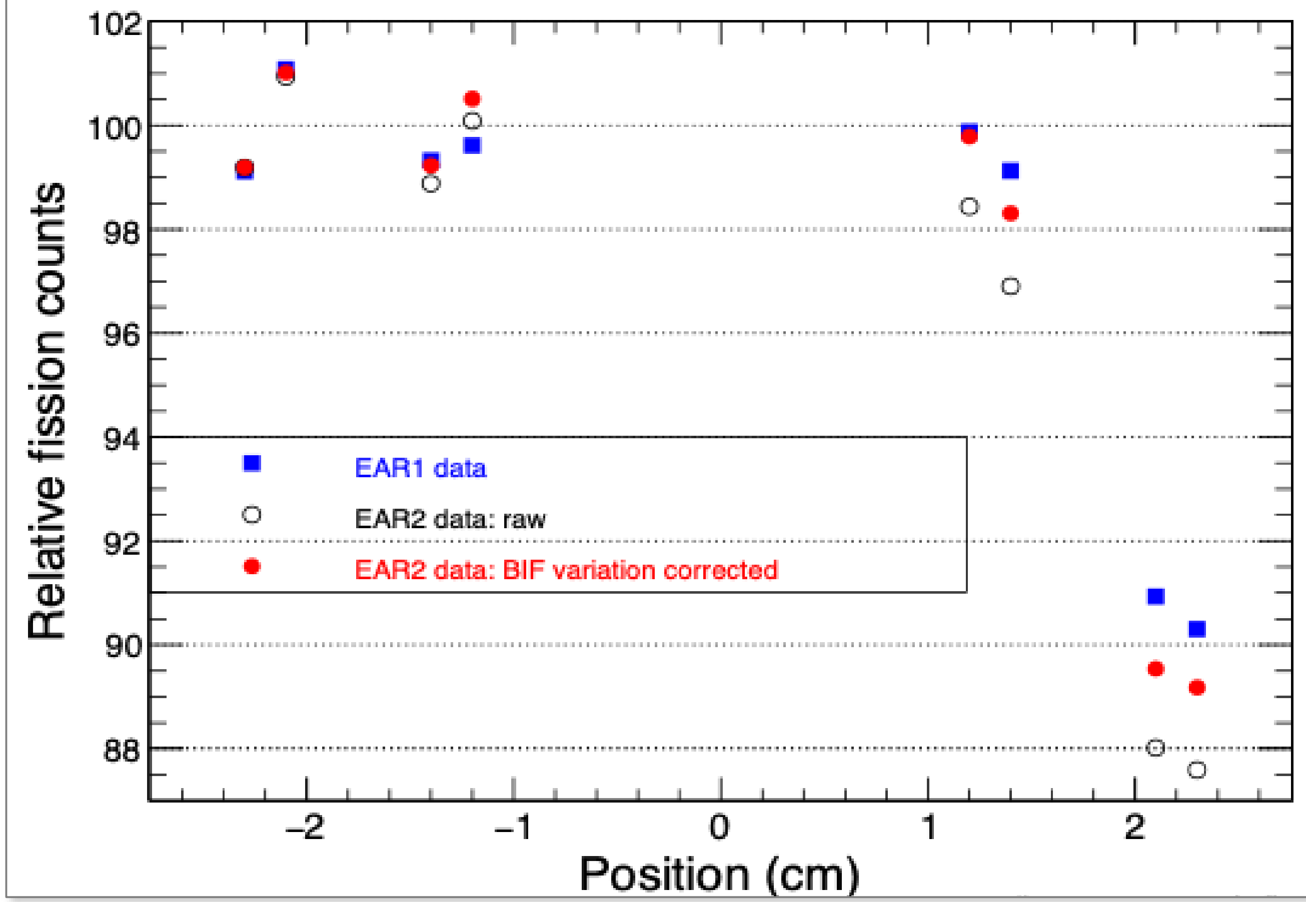
Fission data (E. Berthoumieux, n_TOF Meeting, Vienna, Dec. 2025)

Fission (n induced) normalized to sample mass

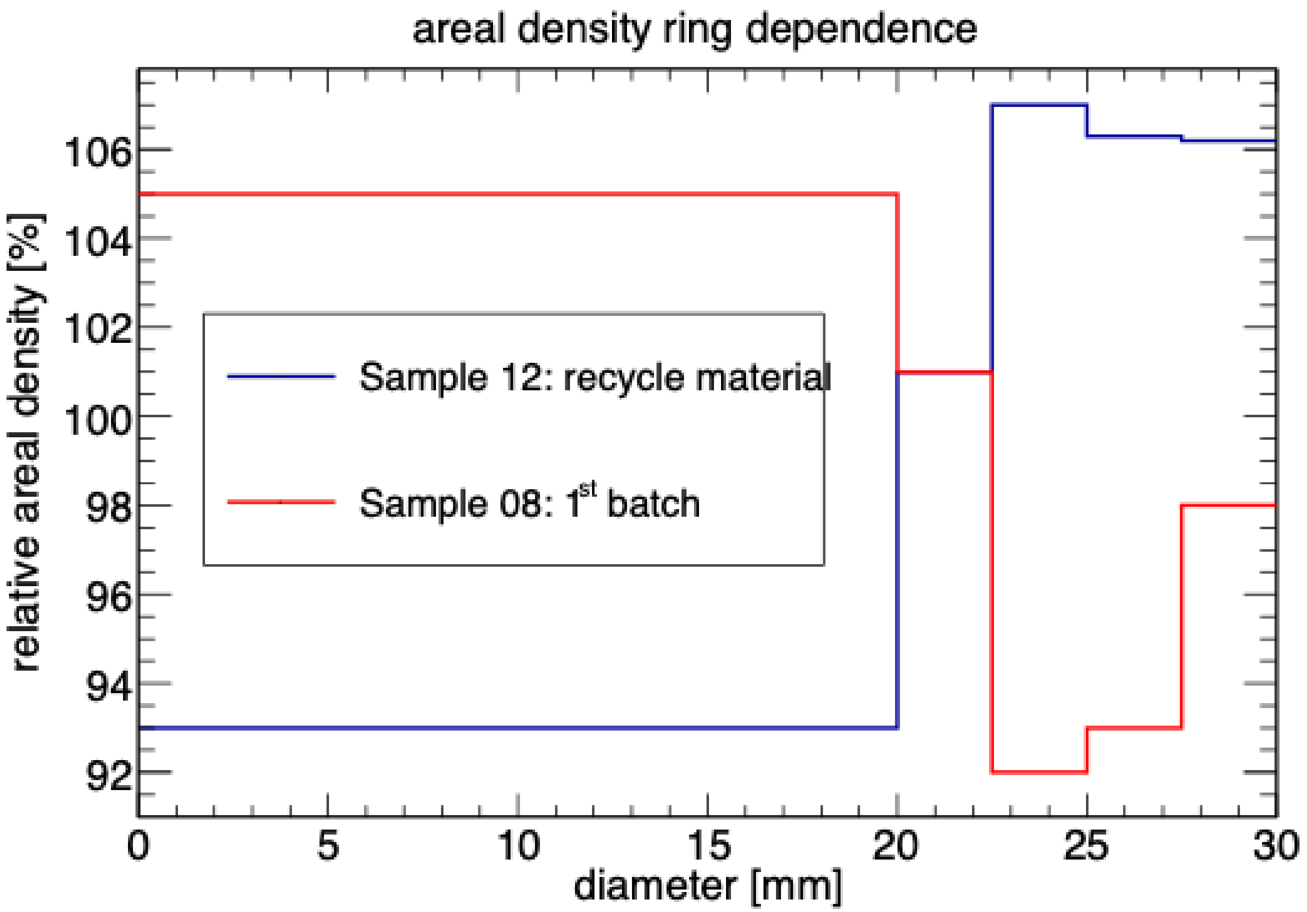


No efficiency correction performed

- BIF in EAR2 correction made by linear inter/extra/polation of Au BIF meas. at bottom and middle position
- Excellent agreement except for last 2 samples (made with recycling material) that show ~9% fission less compared to others samples
- Efficiency seems sample areal density independent : 05-10 is only 130 μg/cm² (~220 μg/cm² for others)

Fission data (E. Berthoumieux, n_TOF Meeting, Vienna, Dec. 2025)

Areal density non uniformity measurement



JRC-Geel performed additional α spectrometry measurements on similar Pu samples (with and without recycled material) with various mask diameter (20, 22.5, 25, 27.5, 30 mm)

- Non recycle material show overconcentration in the middle
- Recycle material show underconcentration in the middle

- To be convoluted with the beam shape to check observed discrepancy in the n induced fission rate (but seems consistent)

- Effect to be considered as well for ^{235}U samples (as in E. Pirovano *et al.* 2023 JINST 18 P11011)?

Fission data (E. Berthoumieux, M. Spelta)

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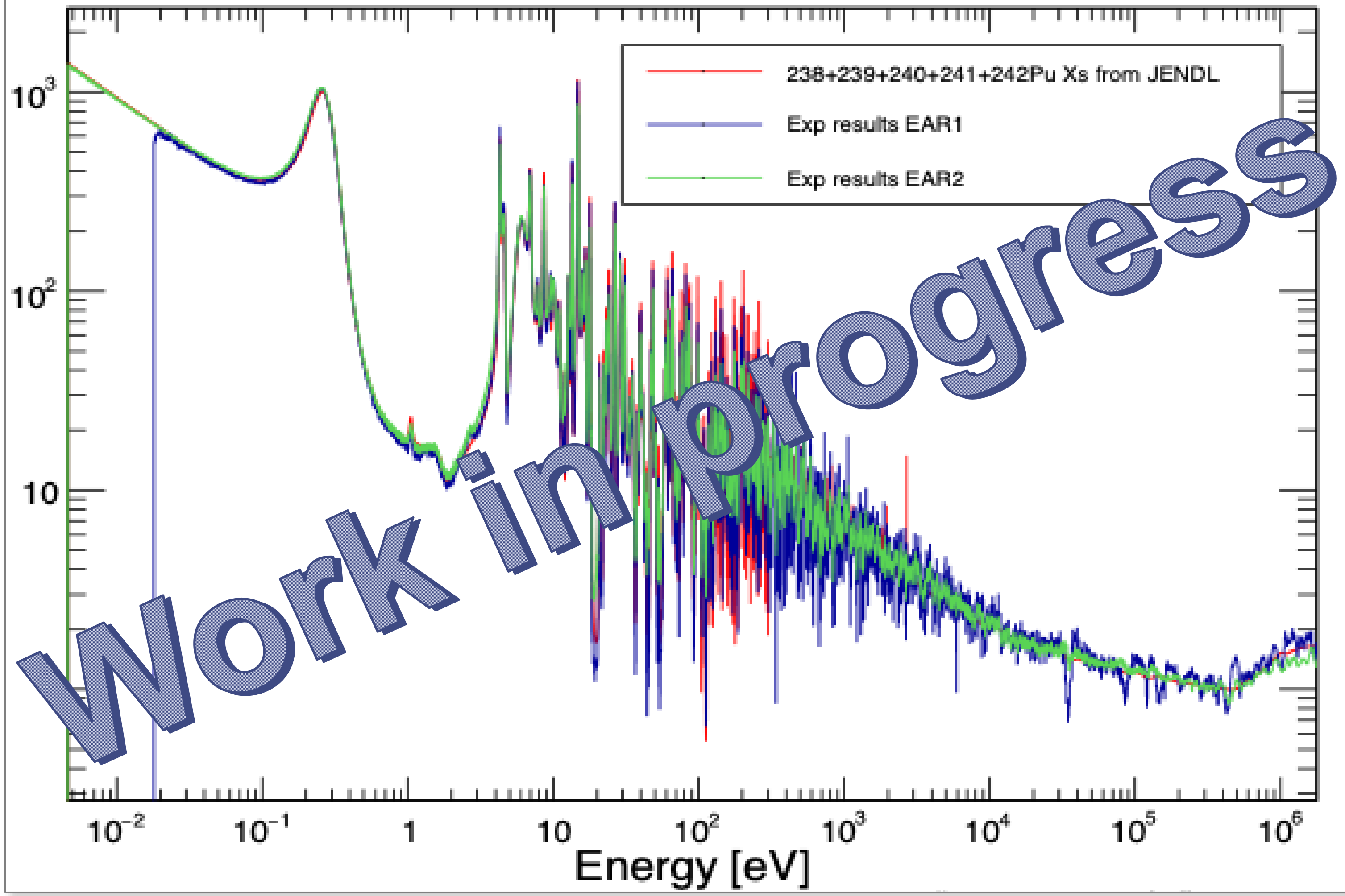
Fission data (E. Berthoumieux, n_TOF Meeting, Vienna, Dec. 2025)



No arbitrary scaling performed:

- Using (modified) evaluated flux and 90% efficiency
- Experimental BIF : 0.951 (BIF position dependance not considered here)
- 2% correction factor to account for ~9% fission rate loss on 2 samples

Overall good agreement with evaluation from thermal to ~800 keV

Precise comparison should be done by taking care of the resolution function in EAR2

Fission data (E. Berthoumieux, M. Spelta)

- Consistency checks done on EAR1 and EAR2 fission data
  - ✓ α-fission discrimination
  - ✓ Stability check
  - ✓ Beam-off subtraction
  - ✓ Sample's beam interception factor determination
  - ✓ Check with respect to samples
    - spontaneous fission (sensitive to total mass)
    - neutron-induced fission (sensitive to areal density)
    - areal density uniformity check on spare samples
  - ✓ Normalization to ^{235}U fission chamber (assuming the same efficiency)

=> Overall consistency with evaluated data from thermal to ~800 keV ✓

⚠ Still a lot of work to provide accurate data! (=> Michele Spelta, postdoc 2026-2028)

6. Outlook

Outlook of the ^{241}Pu measurements

- Experimental part completed (but samples homogeneity measurement in October 2026)
  - Ongoing analysis shows consistent data
- Still work in progress…
  - Capture-to-fission α-ratio (Aline Cahuzac, PhD 2023-2027)
  - Fission cross section (Michele Spelta, post-doc 2026/06-2028)
  - Spectra and multiplicity of prompt gamma from fission and capture reactions (TBC)
- Outcome (by 2028+)
  - PhD thesis
  - Publications
  - Data in EXFOR (α-ratio and fission xs)
- Collaboration with evaluators
  - Preliminary data expected in 2027

Impact of the new data

Current ^{241}Pu evaluation (JEFF-4.0)

- RRR: E < 300 eV
- URR: E < 30 keV
- Capture channel based on one single capture-to-fission ratio measurement (Weston, 1978)

Evaluation update

- new data up to 100-200 eV for the capture-to-fission ratio
- new data up to ~1 MeV for the fission cross section

Status of SAMMY / REFIT / CONRAD

- n_TOF resolution function (EAR1, but also EAR2)?
- Adjustment of resonance parameters on α-ratio?

Thank you for your attention

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