Benchmarking the High-Spin Capabilities of the 1π AGATA Spectrometer at LNL

The Dawn of The High-Spin Renaissance

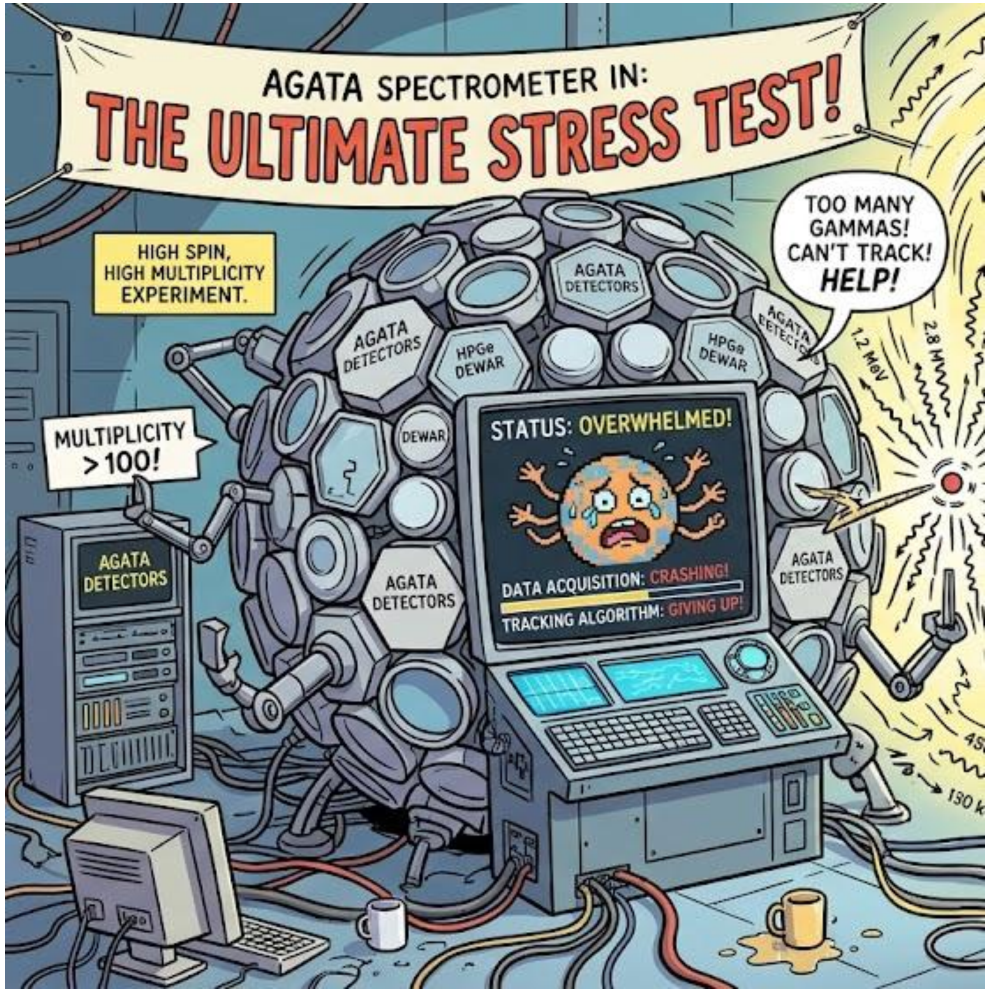
Dr. Conor Sullivan – 11th September 2026

Motivation – Why are high-spin experiments challenging?

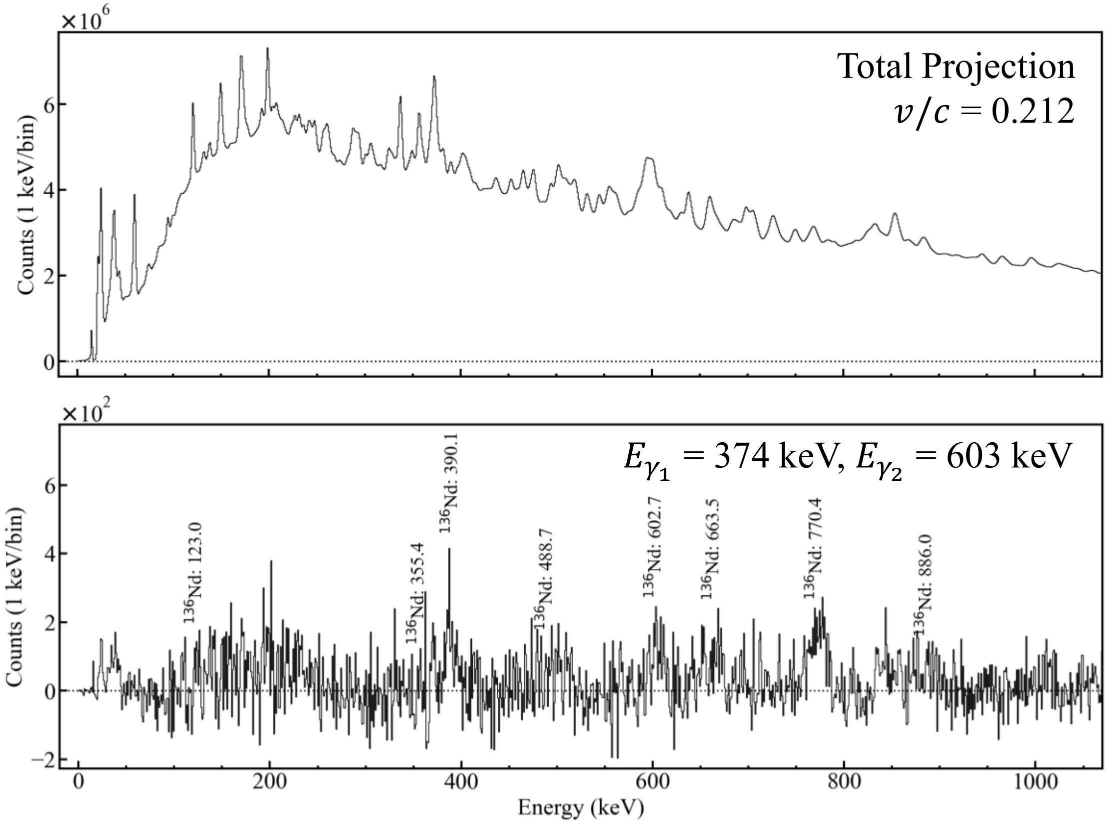
- Deformed nuclei have **long rotational bands == many emitted γ-rays**
- The quantity of emitted γ-rays is referred to as the **γ multiplicity**

- **More γ rays means the system has to work harder!**
  - **High DAQ rates, pressure on trigger system, PSA etc..**
  - **Tracking efficiency decreases with multiplicity**

- In addition… the *interesting* structures at high spin are very weak, often a few percent of the production intensity
  - So we want **high counting rates to maximise counting statistics**



Motivation – Why was this new experiment needed?

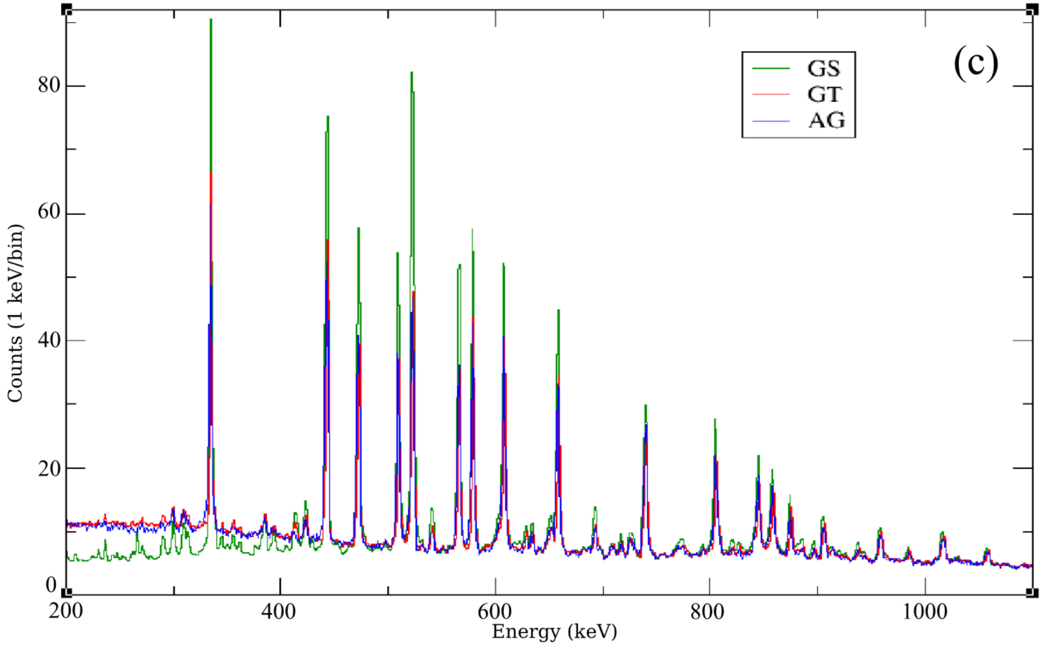


- Spectra from LNL EXP 23.015 (Linking γ rays in ^{136,137}Nd)
- Experiment suffered from **many systematic faults leading** to low "effective" absolute efficiency:
  - Buffer size in the DAQ limited rates to 1 kHz to disk per crystal; **resolved by expanding memory to handle 3-4 kHz per crystal**,
  - GGP backpressure signal triggered prematurely, processing only half of the events; **addressed in principle but needs thorough test**,
  - AGAVA couldn't manage high trigger rates from EUCLIDES, causing long dead-time; **mitigated by distributing the hardware validation across individual GGP's**,
  - Trigger processor struggled with high trigger request volume, causing dead time; **hardware validation mentioned above partially mitigates this but still some dead-time positively correlated with TP data rate.**

A test of AGATA's high-spin capabilities with these fixes ~~is~~ was needed!!

Experimental Methodology – Why ^{158}Er?

A. Korichi, *et al.* Presentation at AGATA Week 2017, Sept. 2017. Milano, Italy.



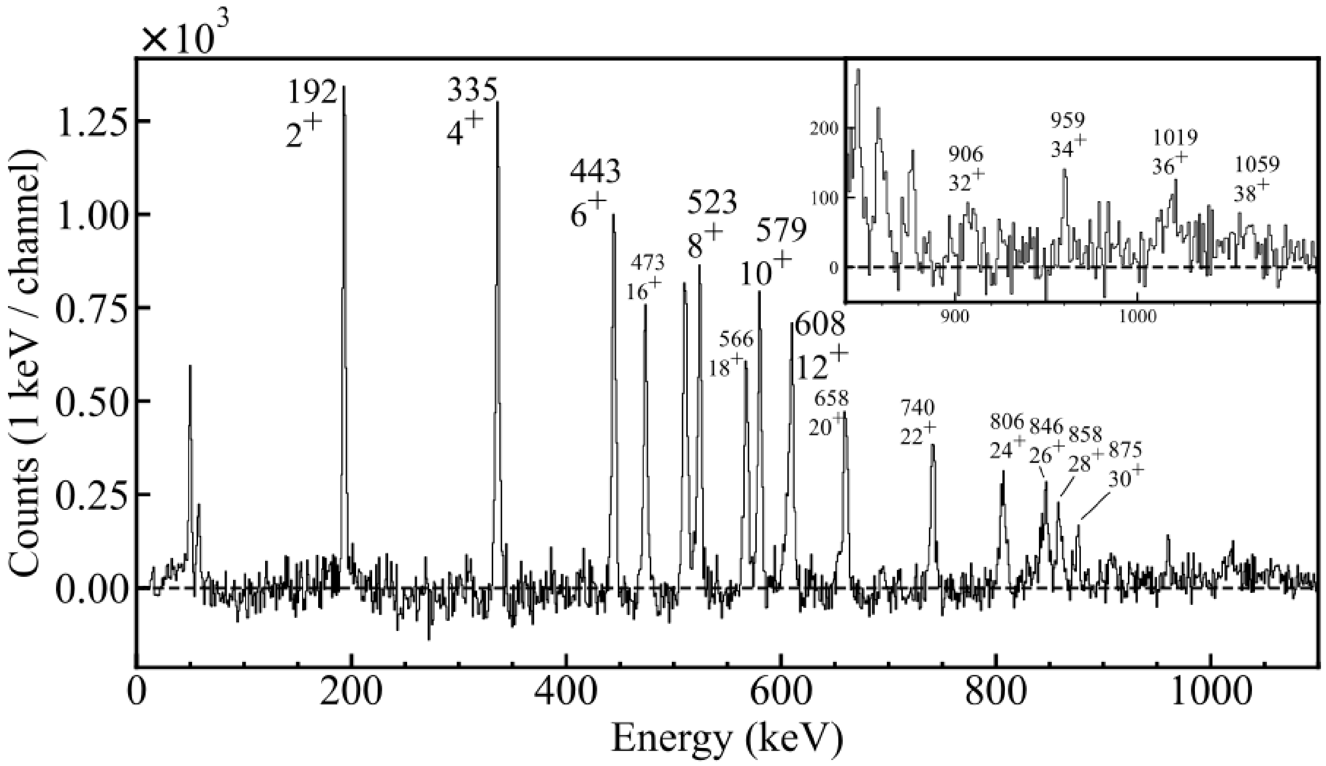
- **Long, intense rotational bands**
- **Relatively easy to produce** with many beam + target combinations available
- Produced with **large production cross-section**

- **Studied many times before** using **EUROGAM, GAMMASPHERE, GRETA and AGATA** (at GANIL) spectrometers

- **Day 1: AGATA Standalone** – ^{32}S beam @ 156 MeV, ^{130}Te target.
  - Various beam currents to allow for characterisation of spectra as a function of event rate.

- **Days 2 & 3: AGATA + SAURON** – ^{32}S beam @ 156 MeV, ^{130}Te target.
  - Hardware trigger set requiring charged-particle coincidence with SAURON. Dramatic reduction in TP rates (~400 Hz @ 4.5 pnA)

First Results!

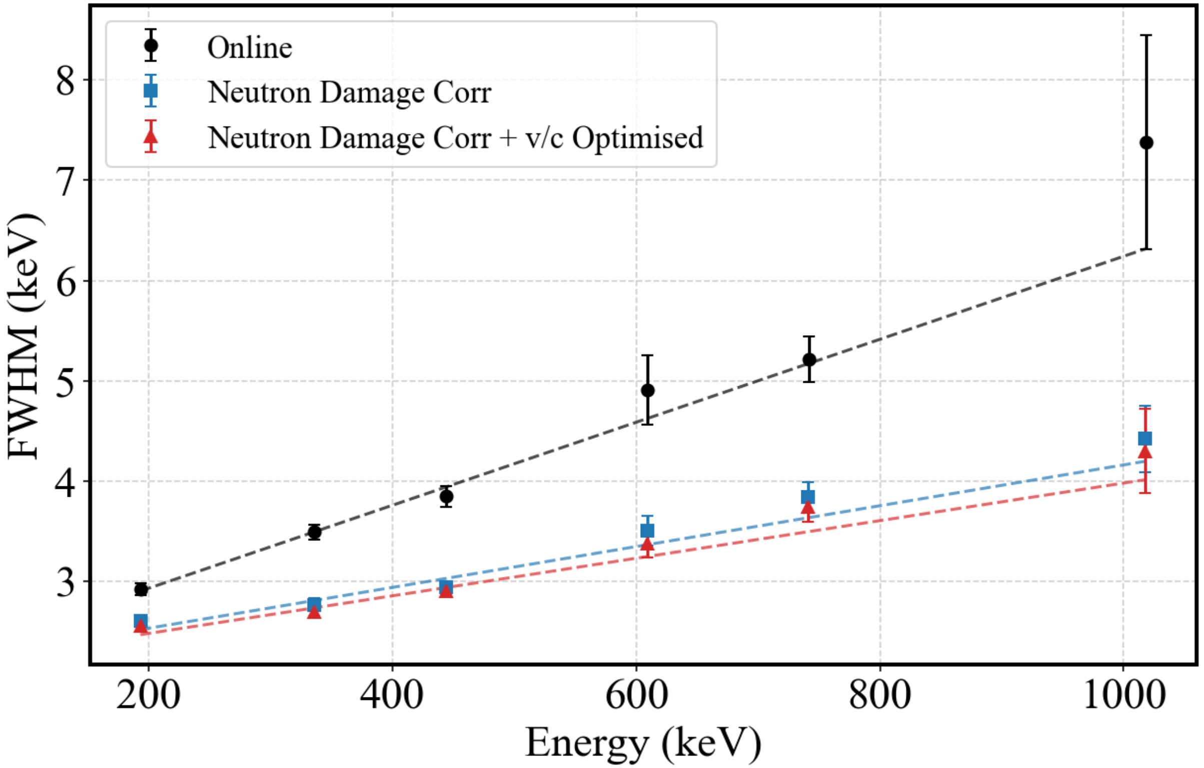


- Spectrum obtained from **cube** (triple-γ coincidence matrix) using the **online configuration** and parameters
- Sum of **double gates** on non-diagonal combinations of energies from the list (192, 335, 443, 523, 579, 608, 473, 566) keV
- Produced from only **5 hours of data** running at 0.5 pnA!!

- **Measurement of the ^{158}Er yrast band up to $I^{\pi} = 38^{+}$**

- Next steps: secondary calibration, neutron-damage correction, v/c correction, fold in the remaining data….
  How high a spin can we go??

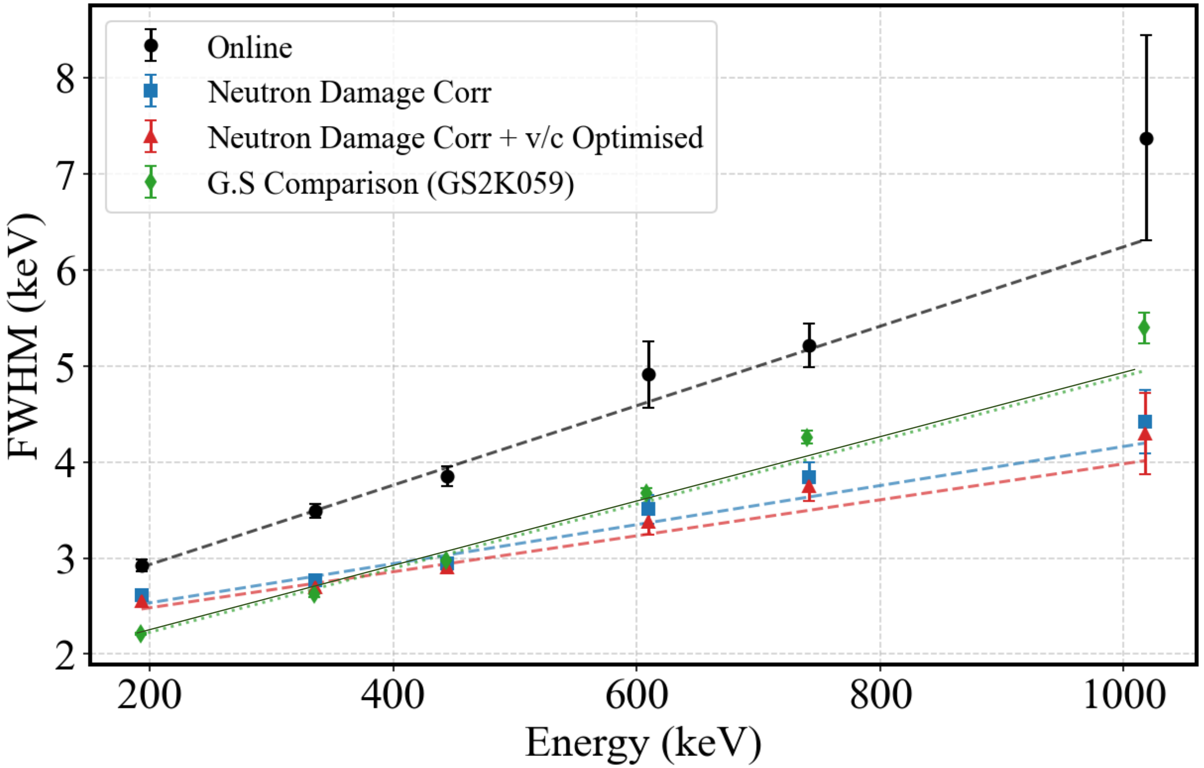
Neutron-Damage Correction



- Essential part of AGATA analysis: **neutron-damage correction**
- Neutron damage in the form of Ge lattice defects causes **low-energy tailing** in γ-ray peaks.
- Position resolution from PSA unaffected by damage:
  - Produce map of correction coefficients as function of position!
    (see e.g Bruyneel, *et al.* https://link.springer.com/article/10.1140/epja/i2013-13061-4)

- Data displayed above is from in-beam runs. Substantial improvement obtained compared to the “online” parameter set.
- Doppler-correction factor also optimised offering smaller – but still measurable – improvement.

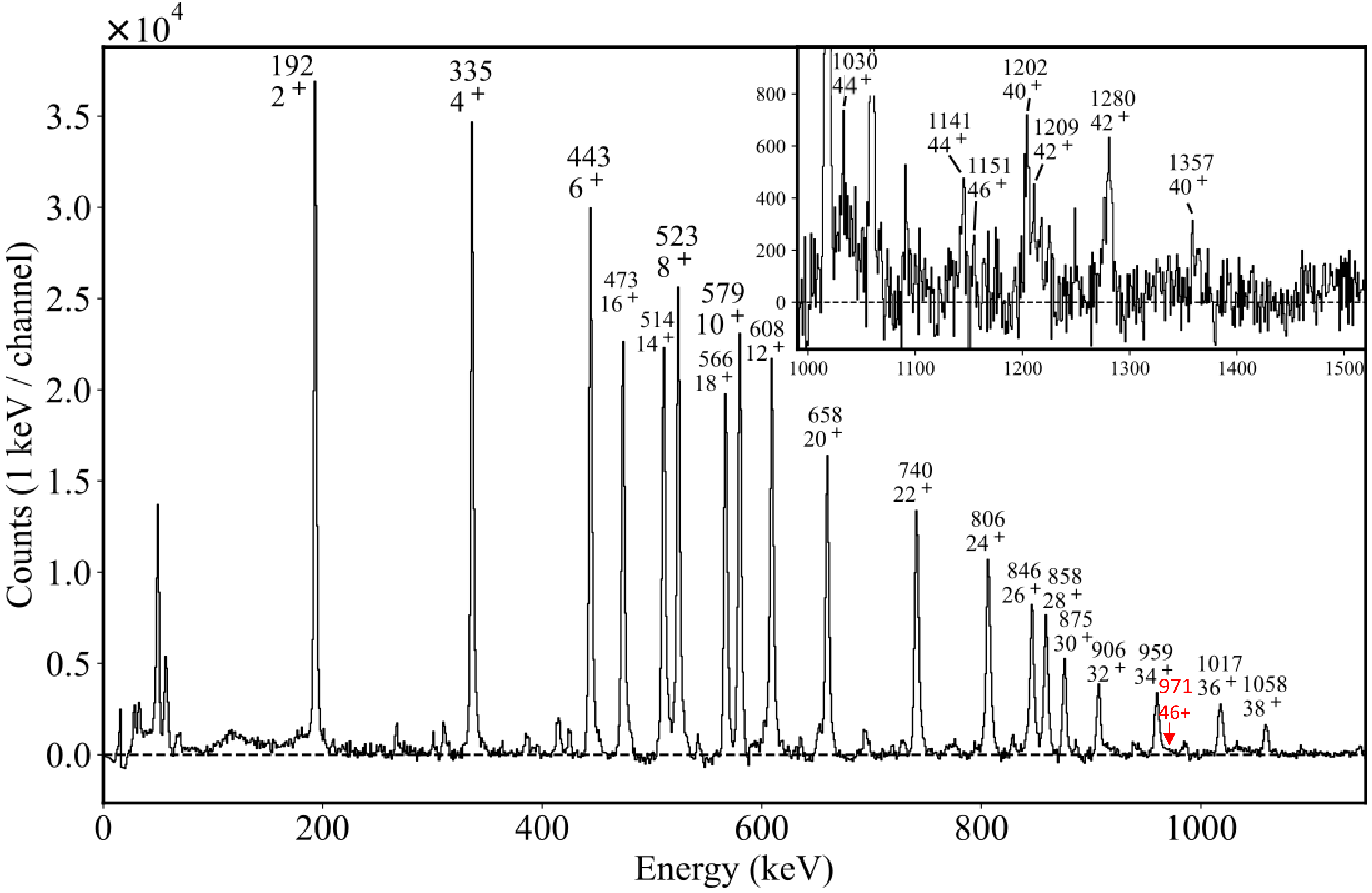
Neutron-Damage Correction



- Comparison with Gammasphere (green line)!
- **AGATA energy resolution superior at high energy**
    - We expect this since AGATA **position sensitivity** results in **lower Doppler broadening**
- BUT, not necessarily "apples and apples comparison":
    - Beam and target not the same between experiments. GS had **faster recoil** therefore **larger Doppler broadening** and expect **worse resolution.**

- How does our ^{158}Er spectrum look with the corrections implemented and all data folded in…?

Improved Spectrum – Higher Spin!!



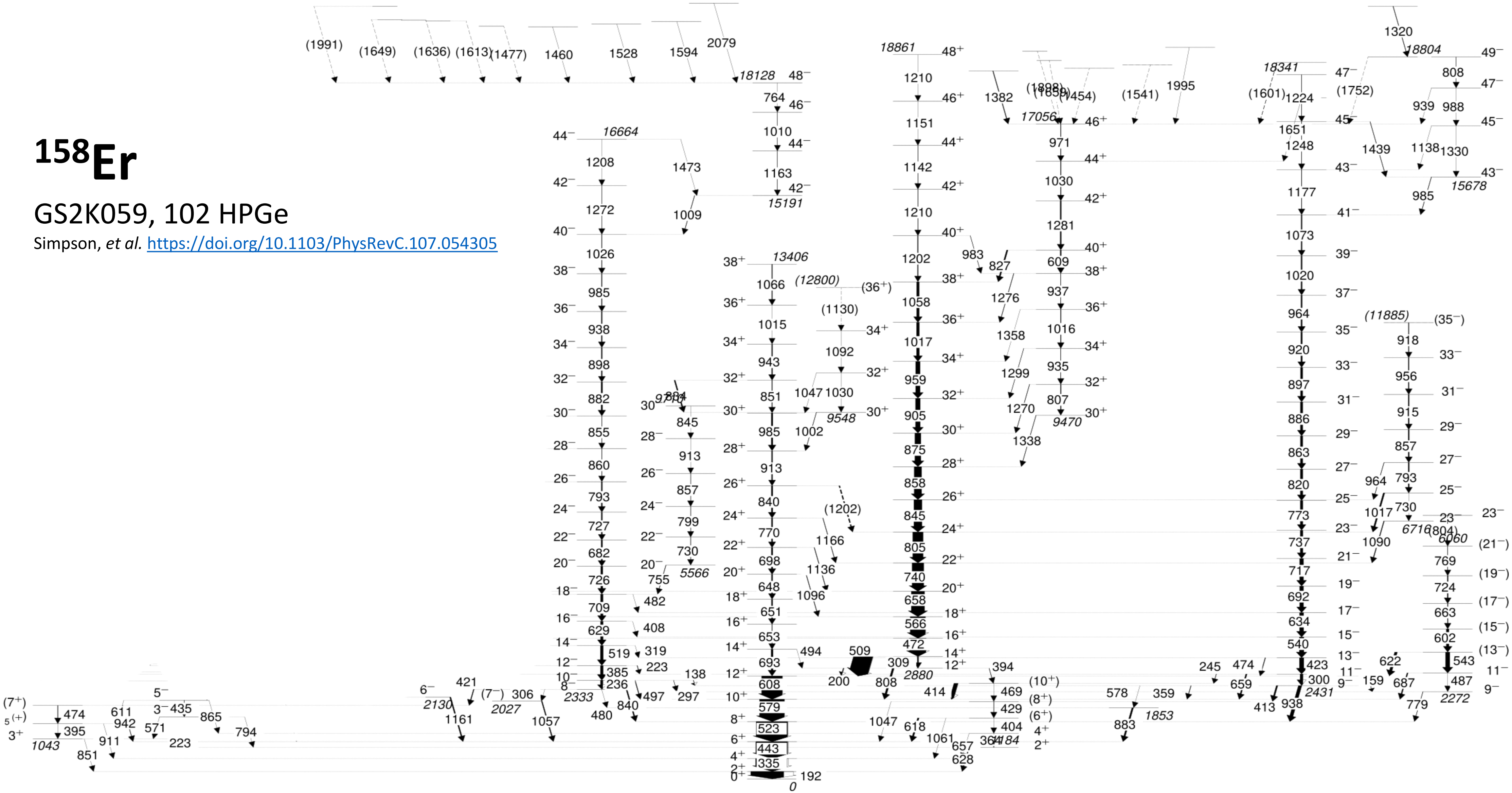
- Spectrum produced using **sum of double gates** on **triple-γ coincidence matrix (cube)**
- ^{158}Er yrast band observed up to spin 46+, the "original" band terminating state!!
- Other band terminating states observed

How do we compare to John, Mark and Eddie?

^{158}Er

GS2K059, 102 HPGe

Simpson, *et al.* https://doi.org/10.1103/PhysRevC.107.054305



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GS2K059, 102 HPGe

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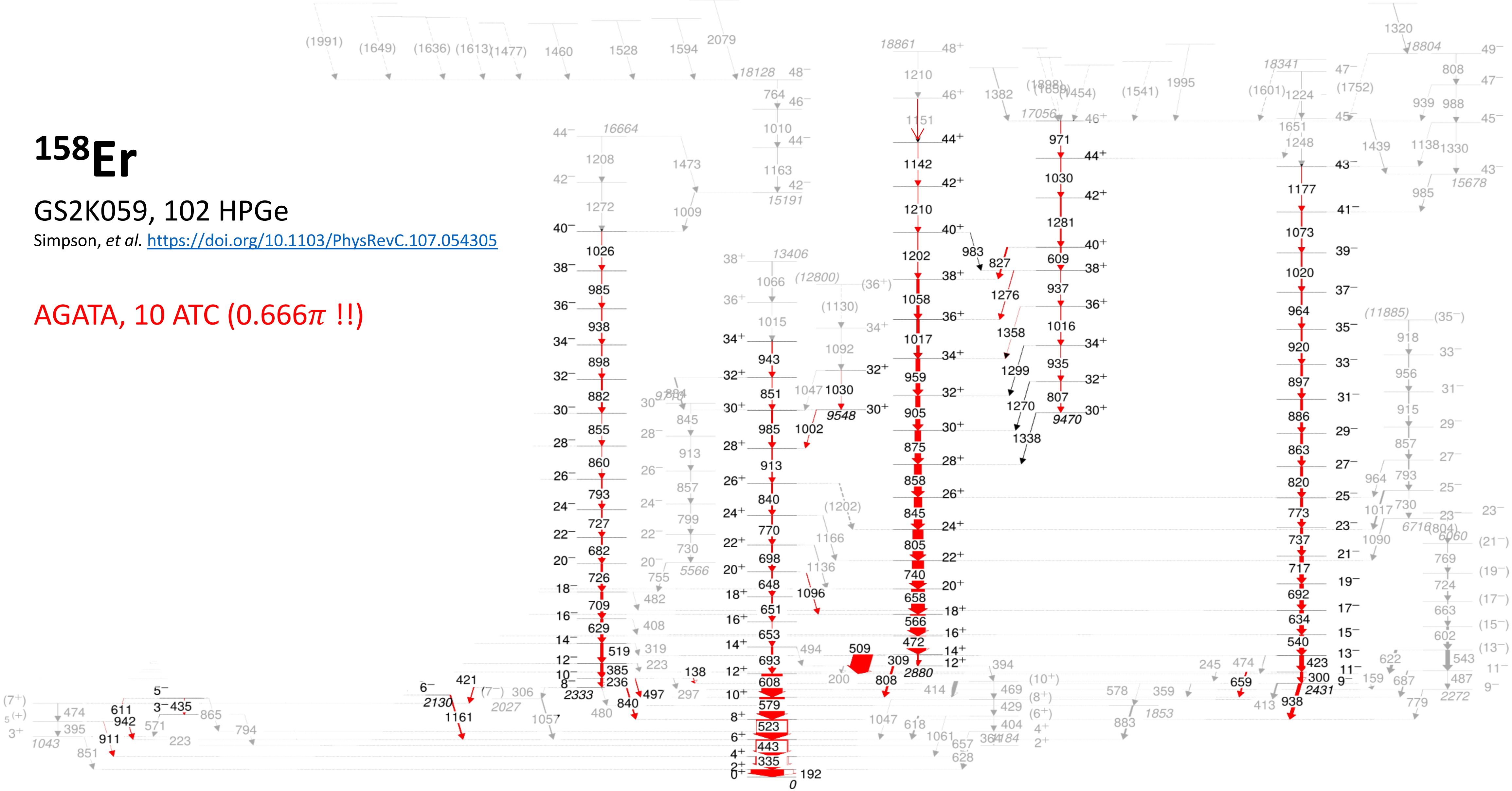
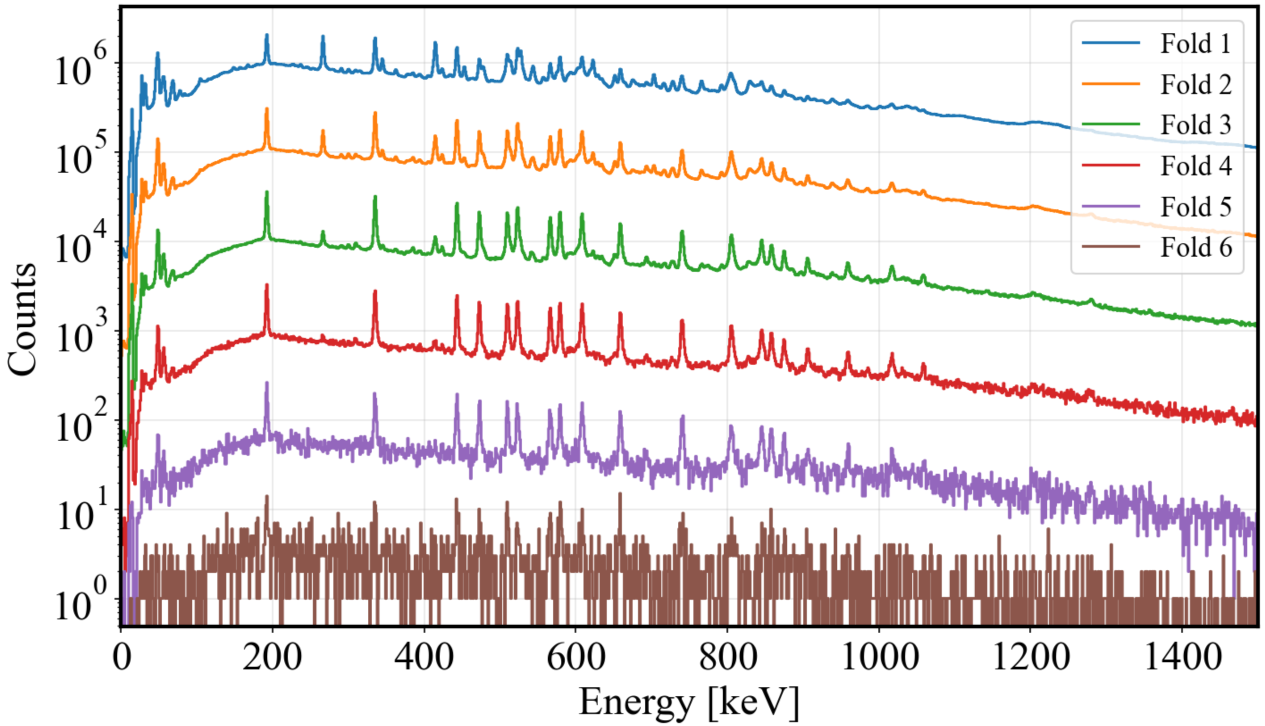
AGATA, 10 ATC (0.666π !!)



High-Fold Sorting

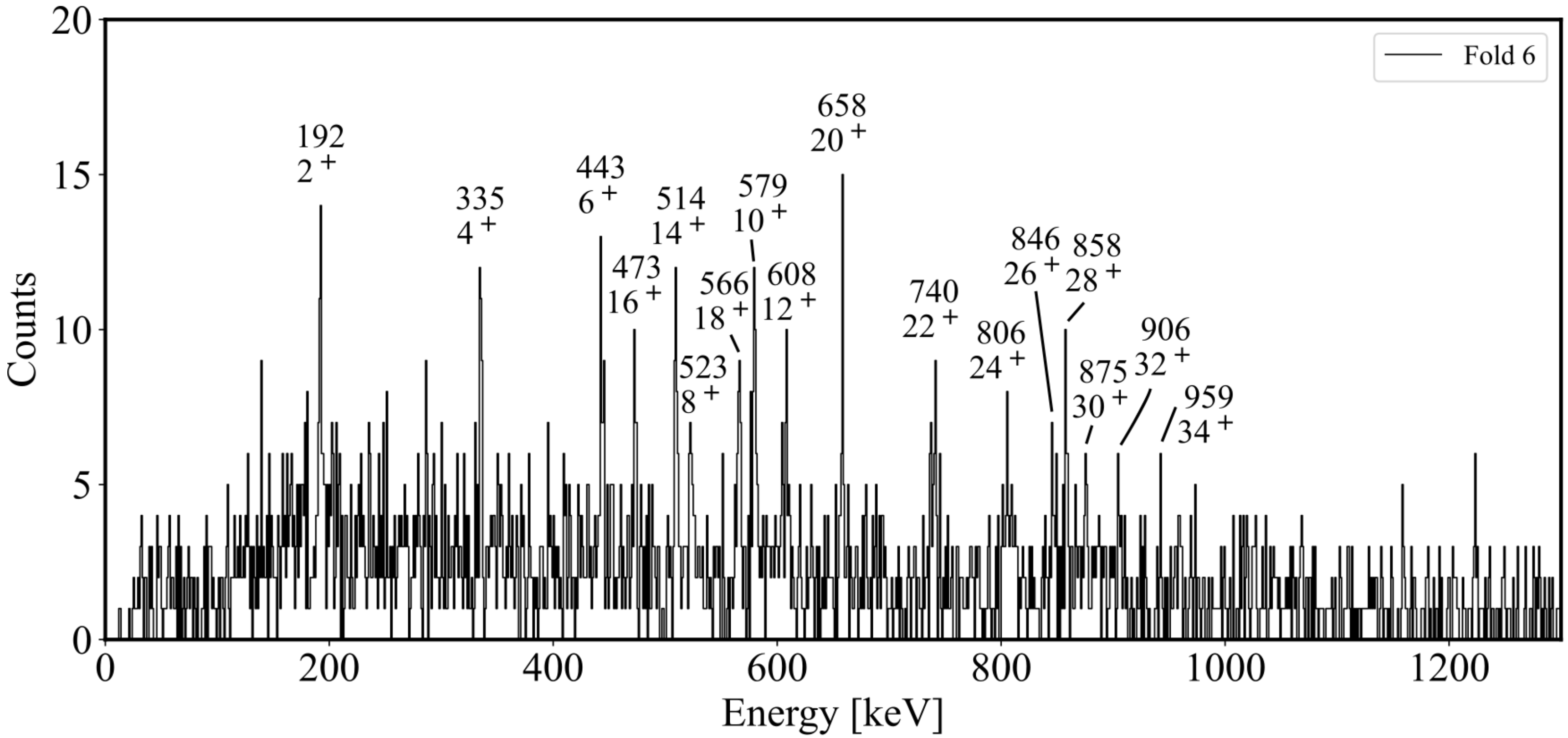


- γ-ray **multiplicity** == amount of γ-rays **emitted in a single cascade**
- γ-ray **fold** == amount of γ-rays **detected (tracked) in a single event**
  - **THIS IS NOT THE SAME AS "FOLD" IN THE PSA SENSE.**
- Define a "gatelist" for band of interest. For ^{158}Er: [192, 335, 443, 523, 579, 608, 510, 473, 566, 659, 740, 806, 846, 858, 876, 906, 959, 1019, 1059]-keV

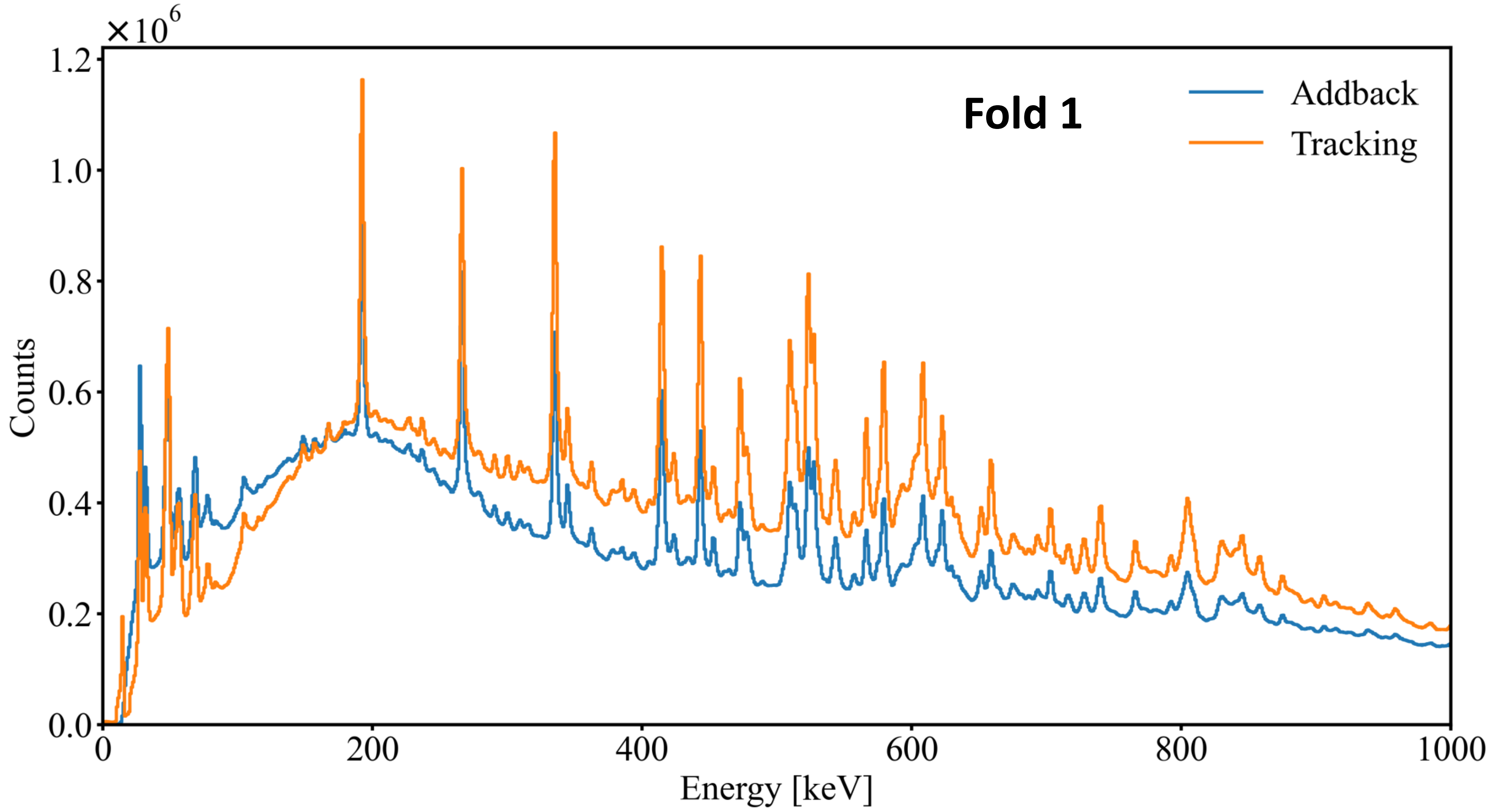
- "Spikeless" high-fold sorting method
  C.W Beausang, *et al.* https://doi.org/10.1016/0168-9002(95)00438-6
  - At least M γ-rays from gatelist must be present in the event to increment the Fold M histogram.

High-Fold Sorting

- **We see clear peaks up to Fold 6!**
- To increment this spectrum requires at least 6 coincident, tracked γ-rays satisfying our gatelist.



Comparison between Addback and Tracking



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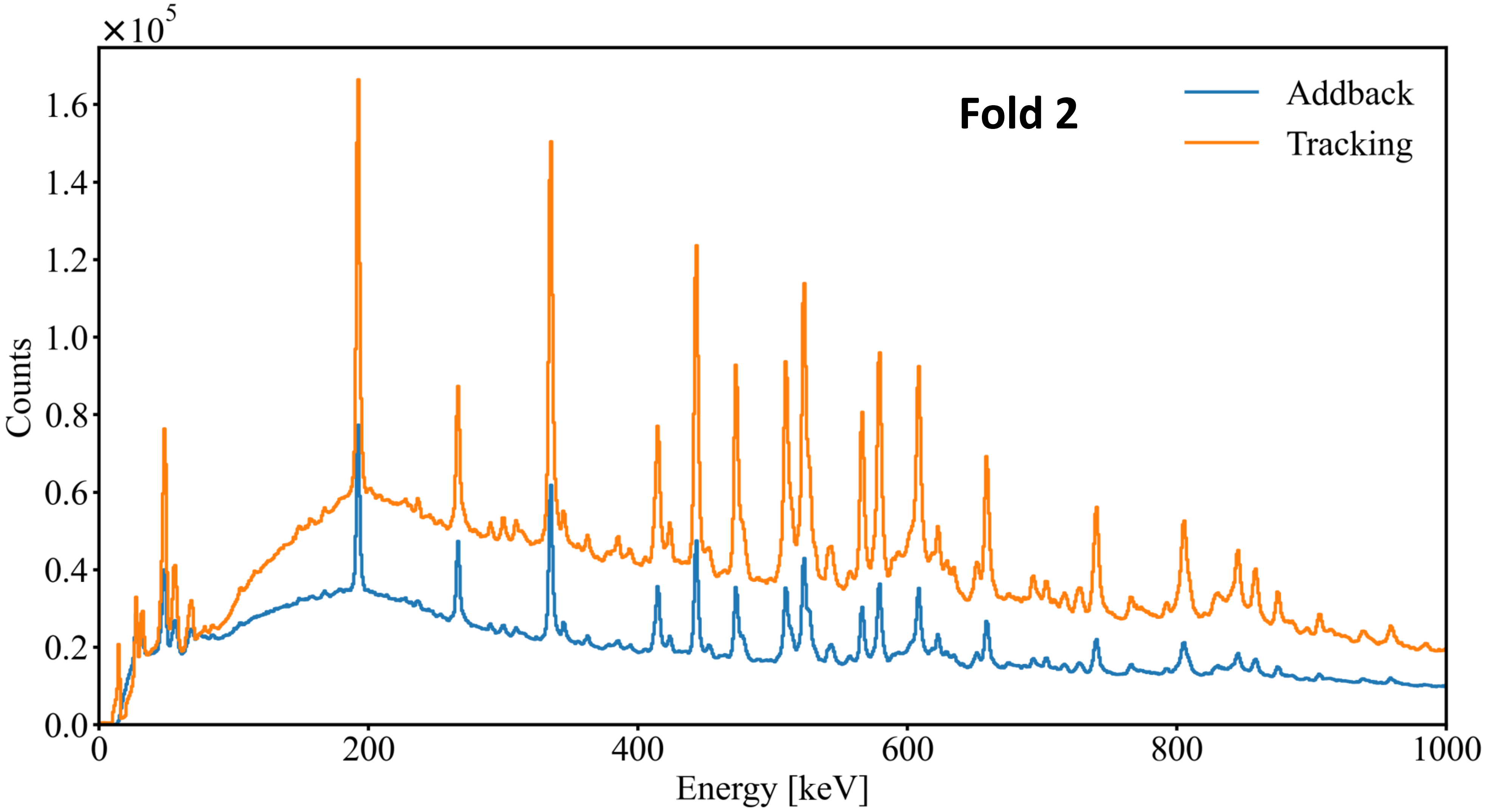

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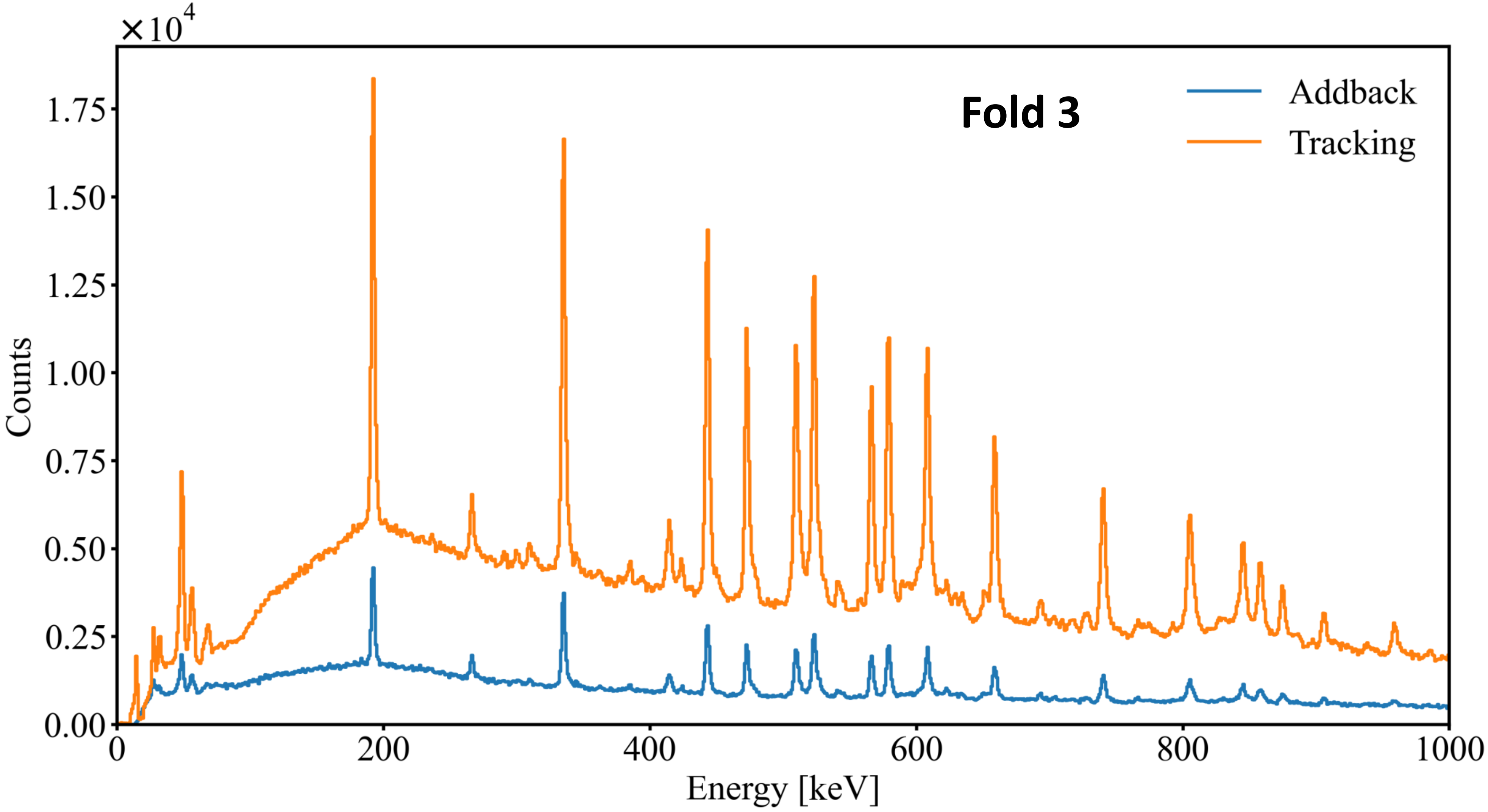
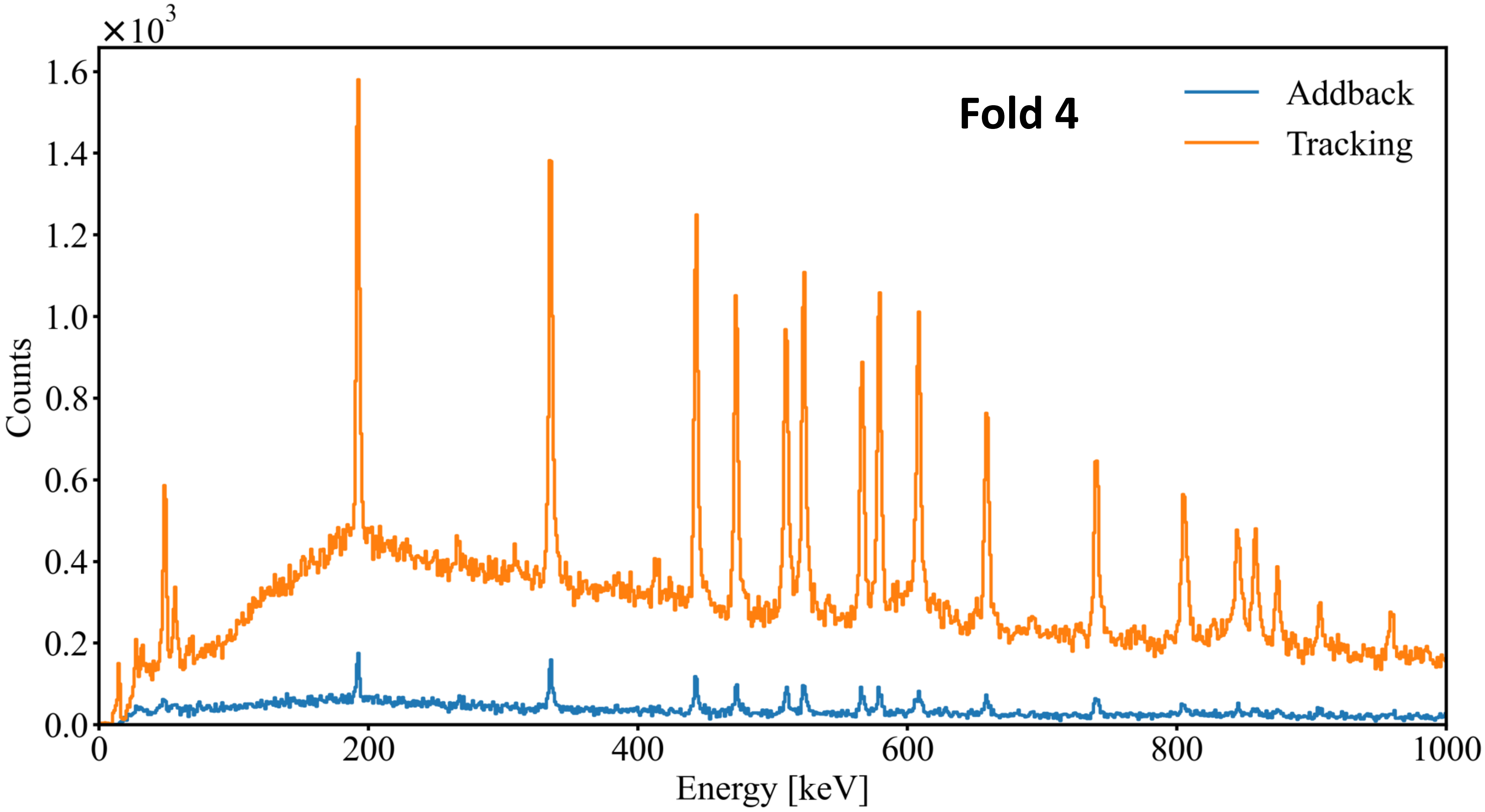
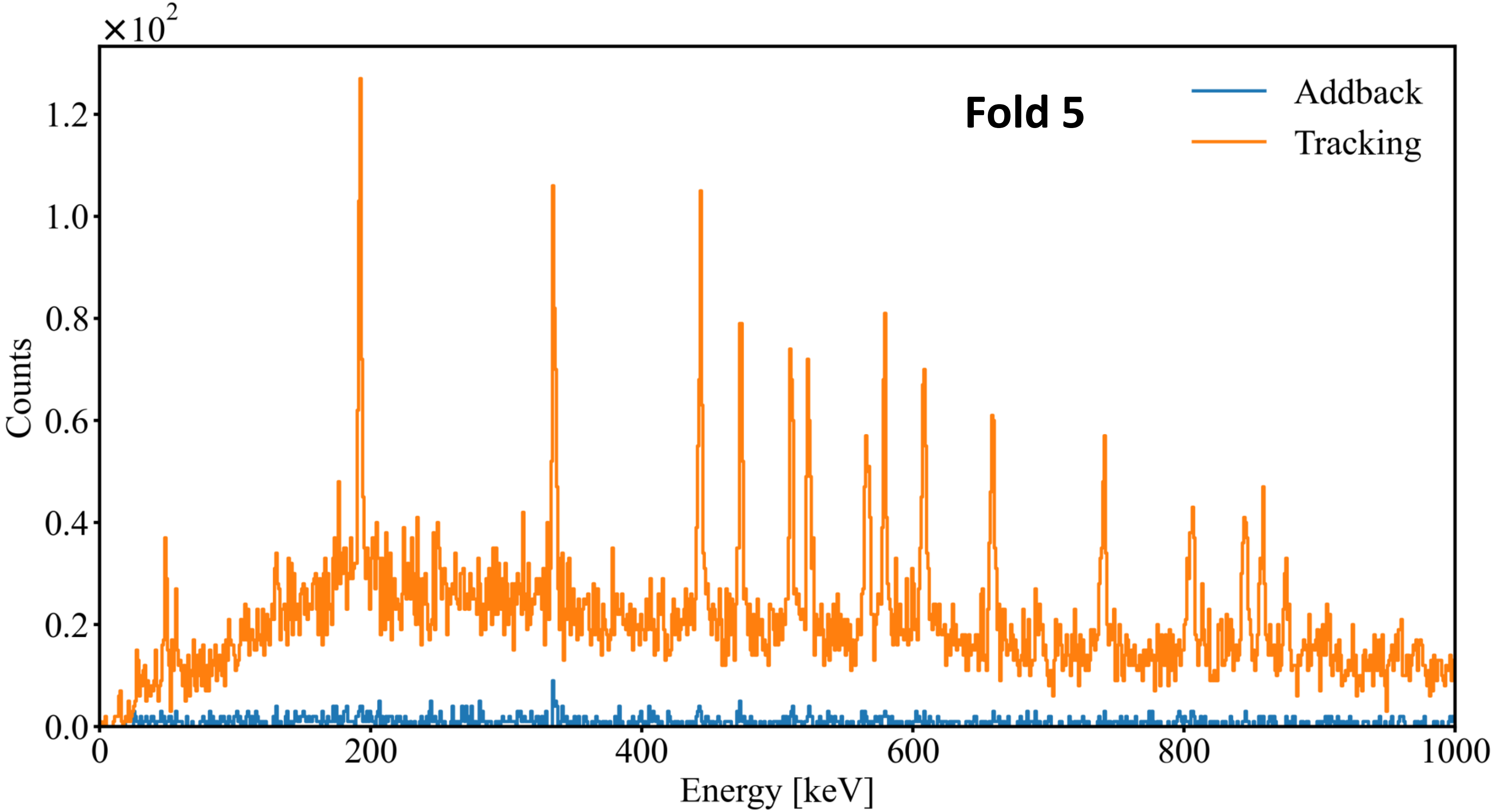


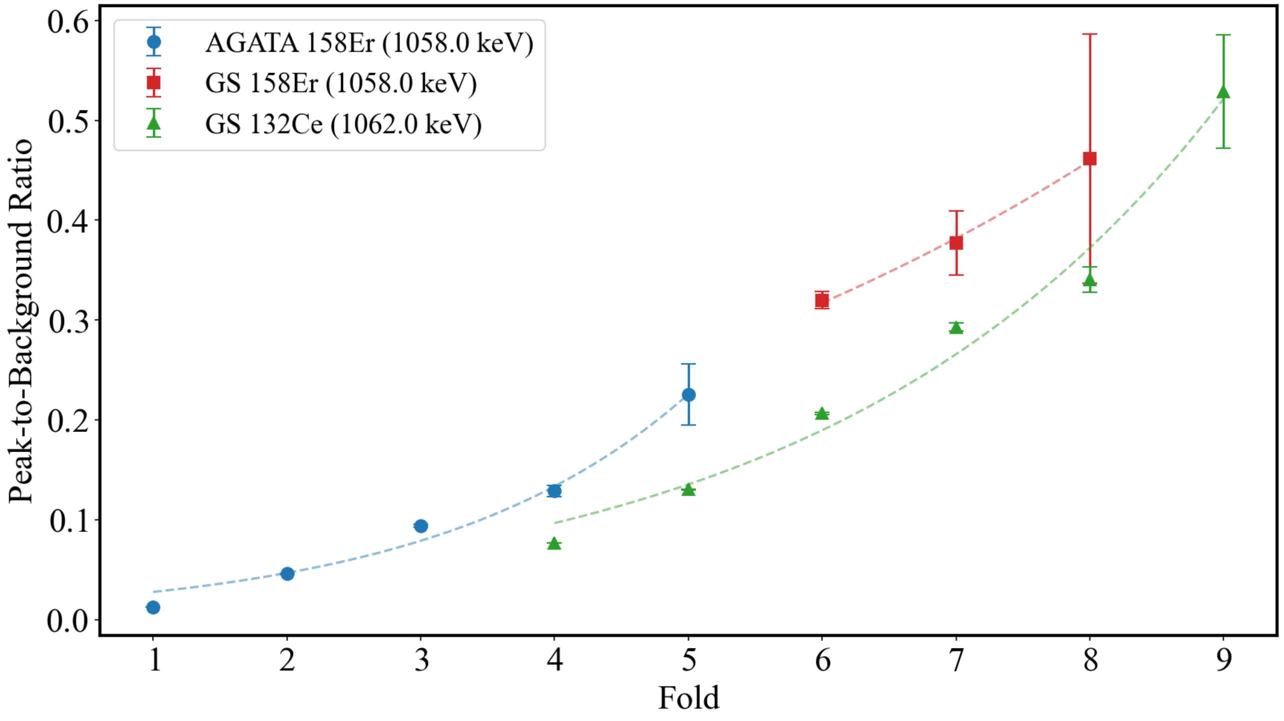
Comparison between Addback and Tracking



Comparison between Addback and Tracking



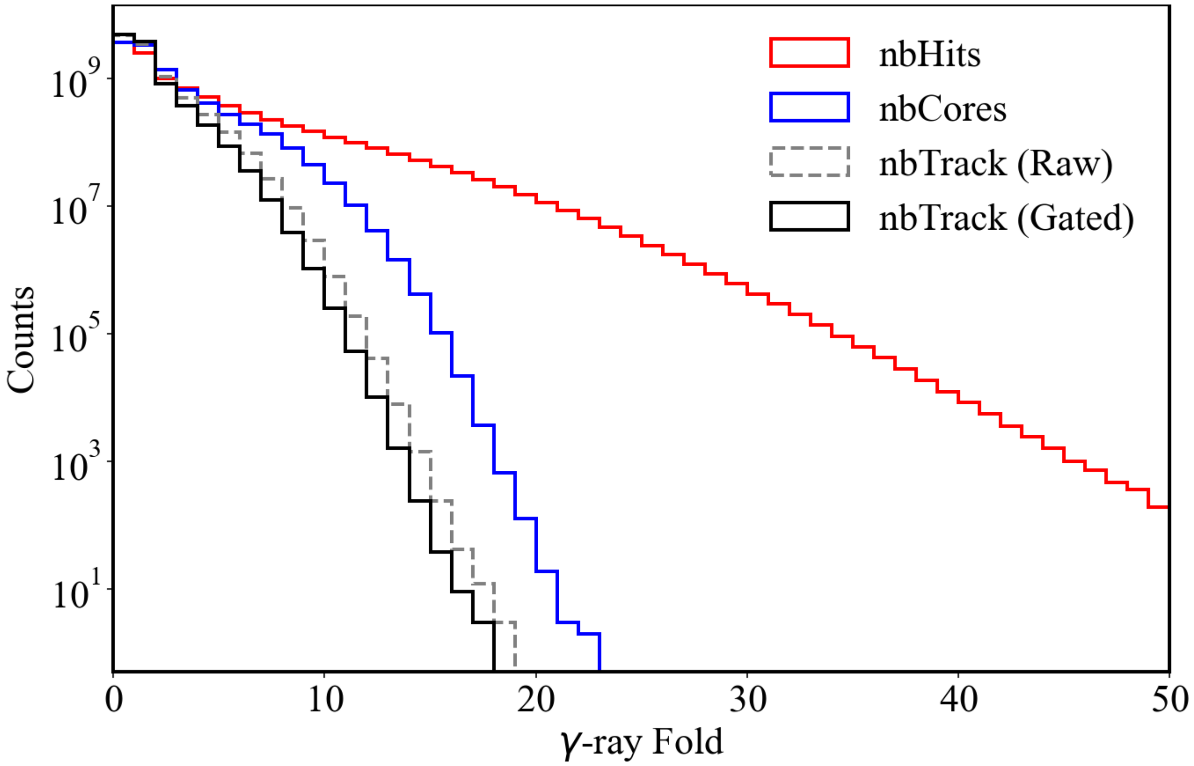
High-Fold Sorting



- Peak-to-background ratio increases **exponentially** with fold.
  - See also e.g Brinkmann, *et al.* https://doi.org/10.1063/1.41218
- Moreover, **high-fold events can be unfolded into combinations of lower fold events** for a dramatic increase in **spectra quality** and **counting statistics**
  - e.g. A fold-7 event unfolds into 35 fold-3 events. A fold-9 event into 84!!

- **Comparable performance between AGATA and Gammasphere** but again must be careful when comparing and especially *extrapolating* such simple models… Let's look at a more general case!

High-Fold Sorting



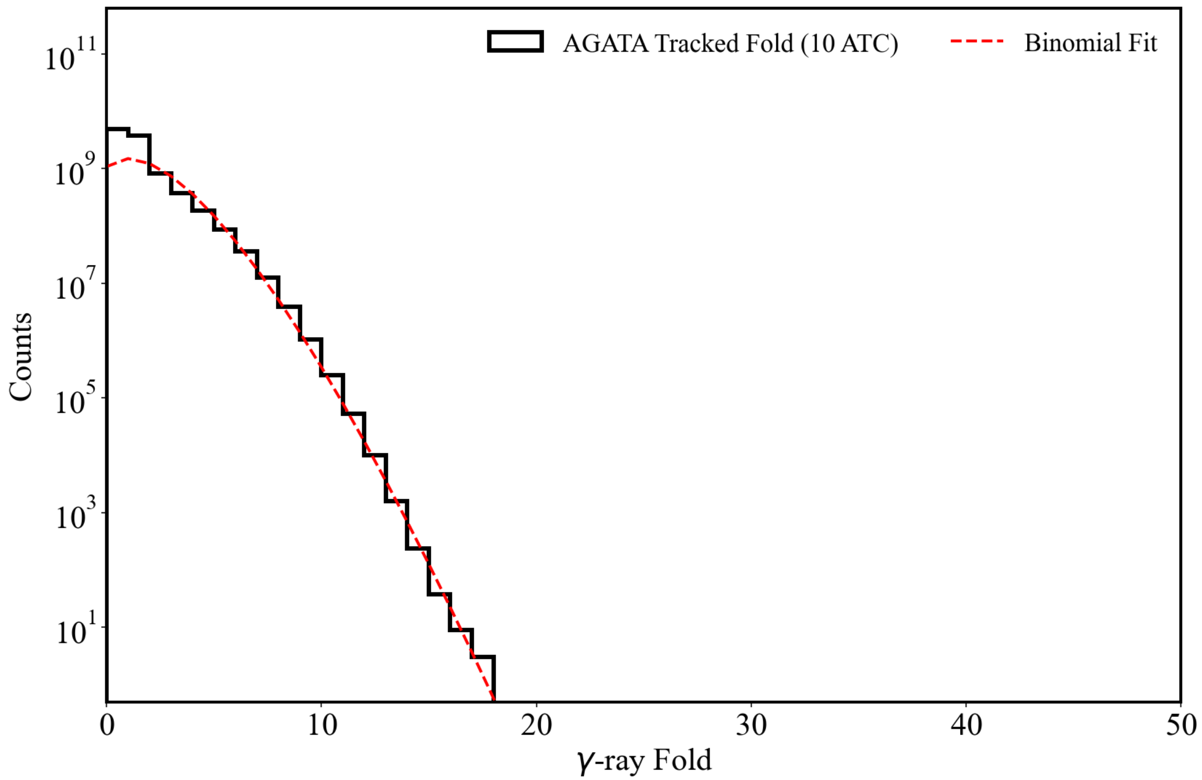
- The graph displays the AGATA γ-ray fold at various stages of the data processing chain

- nbHits represents the number of segments fired in a single event
- nbCores represents the number of cores fired in a single event
- nbTrack is the number of tracked γ rays in a single event

- A gate is placed on energy (0 – 5 MeV) and timing (0 – 100 ns) for further processing

- **What can this tell us about the future performance of the array?**

High-Fold Sorting



- The tracked fold distribution is well-described by a convoluted Gaussian-binomial model:

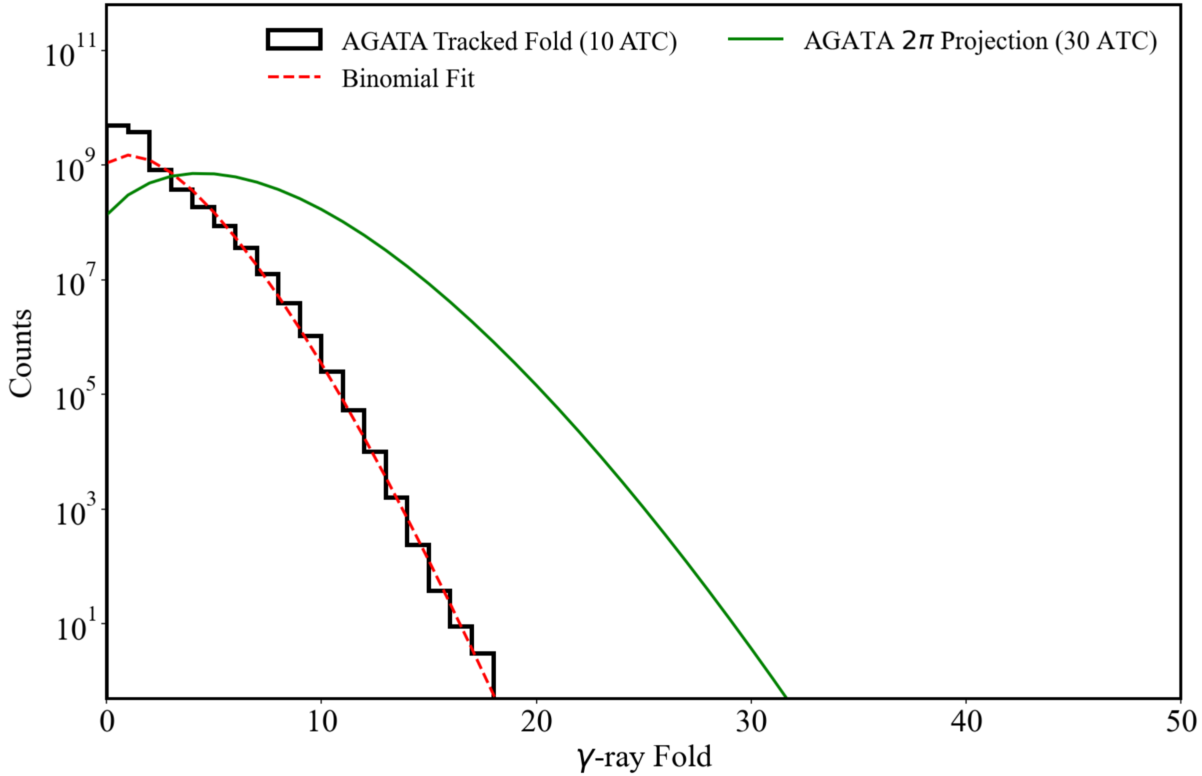
$$P(n) = A \sum_{M=n}^{M_{Max}} \left[\frac{1}{\mathbb{N}} e^{-\frac{(M-\mu_M)^2}{2\sigma_M^2}} \times \left(\binom{M}{n} \epsilon^n (1-\epsilon)^{M-n} \right) \right]$$

where M is the “true” number of γ rays emitted, μ_M is the average event multiplicity, σ_M is the average spread of that multiplicity, n is the number of detected γ rays (i.e fold), ϵ is the average efficiency of the array and A, $\mathbb{N}$ are scaling and normalisation factors

- The fit yields $M = 35,\ \mu_M = 15$ for $\epsilon = 4\%$.

- **Now let’s extrapolate this model for a future, larger AGATA array…**

High-Fold Sorting

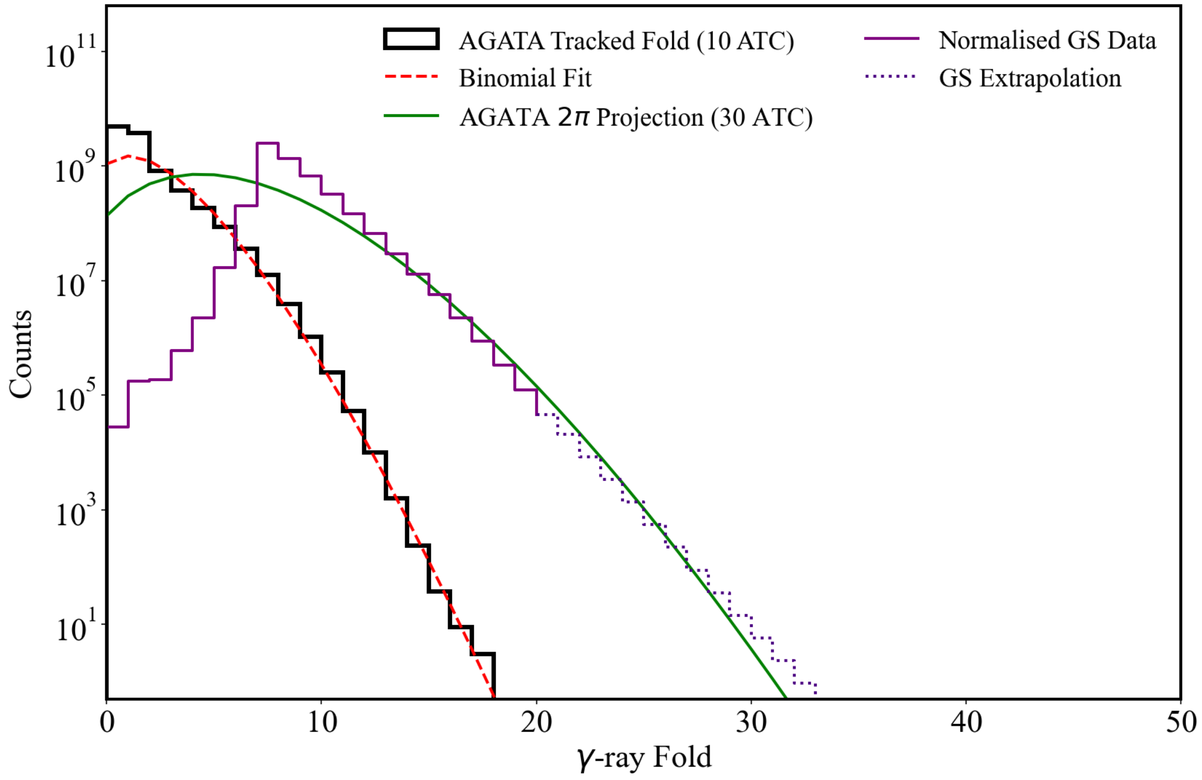


- **Extrapolated model is promising, but is it realistic?**

- 2π AGATA will have 30 ATCs. So to get a rough estimate of the efficiency we simply scale by 3!!
  - $\boldsymbol{\epsilon_{2\pi} \sim 12\%}$

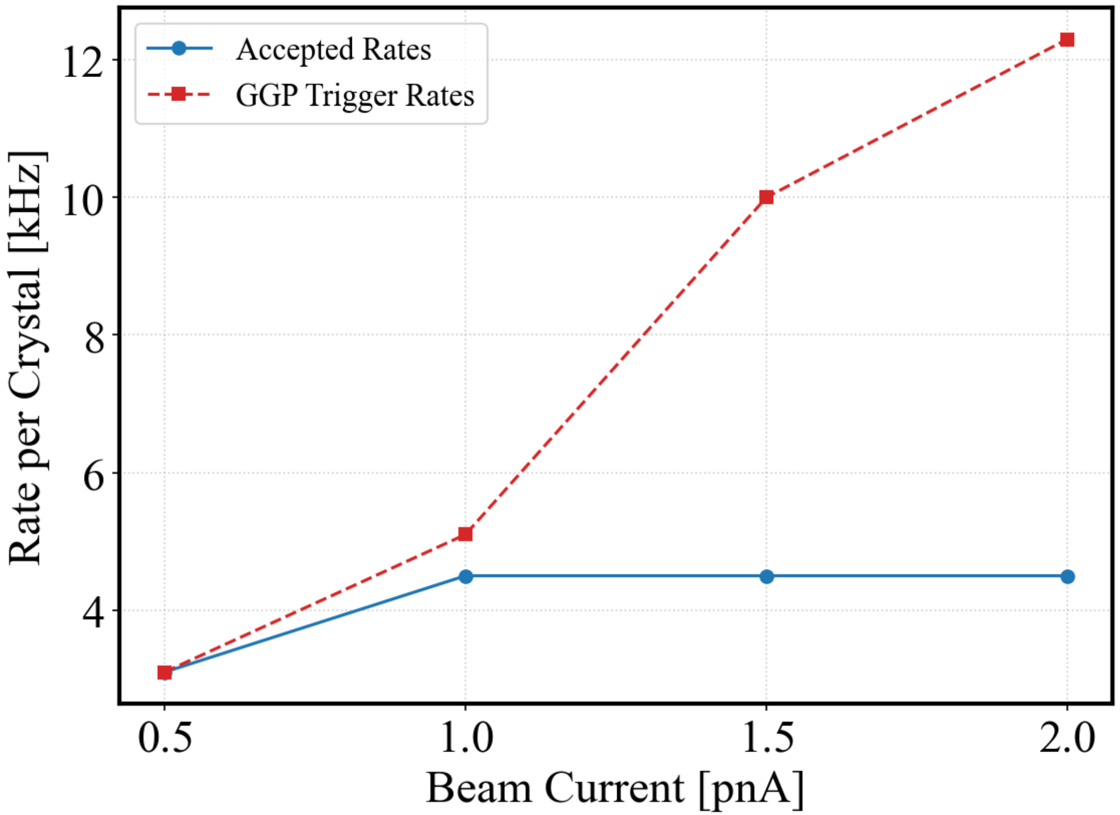
- Real 2π AGATA should have even higher efficiency than this since proportionally fewer γ rays escape out of the sides…

High-Fold Sorting



- Compare once again to John, Mark and Eddie's fantastic GS data…
- **Normalise their observed fold distribution to our total number of events**
  - Caveats: they set a **minimum fold threshold of 7** (show offs!); events with fold < 7 are from invalid events in some detectors for that event (pile up, energy, timing etc)
  - Hard cut off at fold 20, so the line is extrapolated beyond this
- **The extrapolated AGATA distribution is consistent with the Gammasphere one!**

Impact of Rates



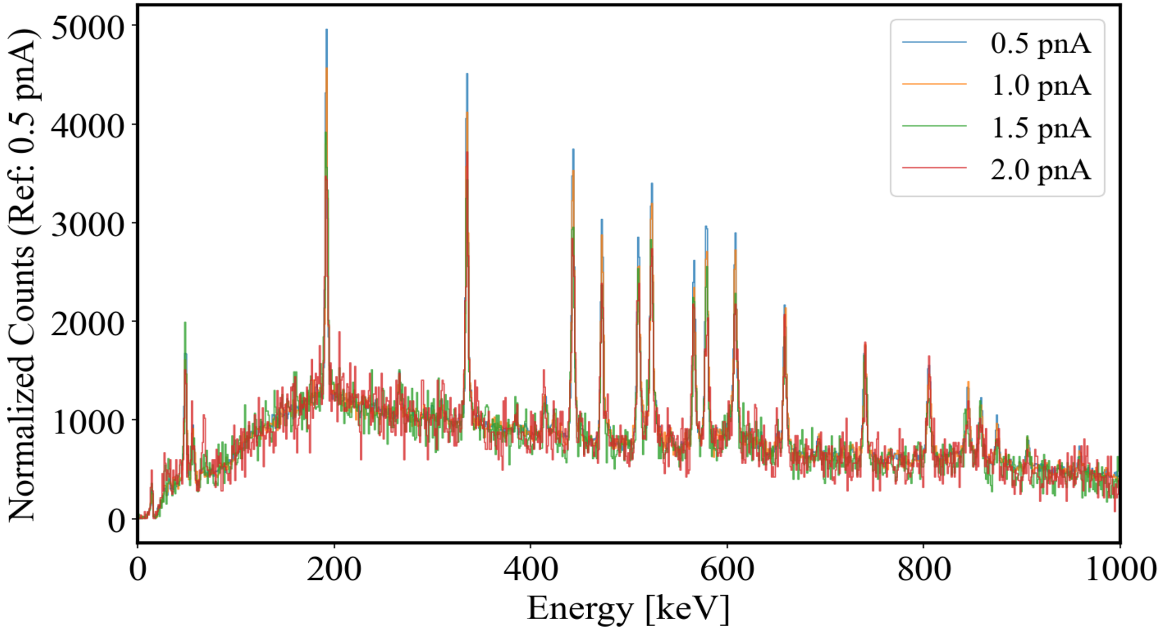
- Trigger Processor can handle **a maximum of ~4-5 kHz** incoming trigger requests per crystal.

- For trigger request rates beyond this, the trigger processor starts to **reject (throw away) valid events**

    - **Disaster** for a tracking array – how do you track a γ ray with missing hits in the track?

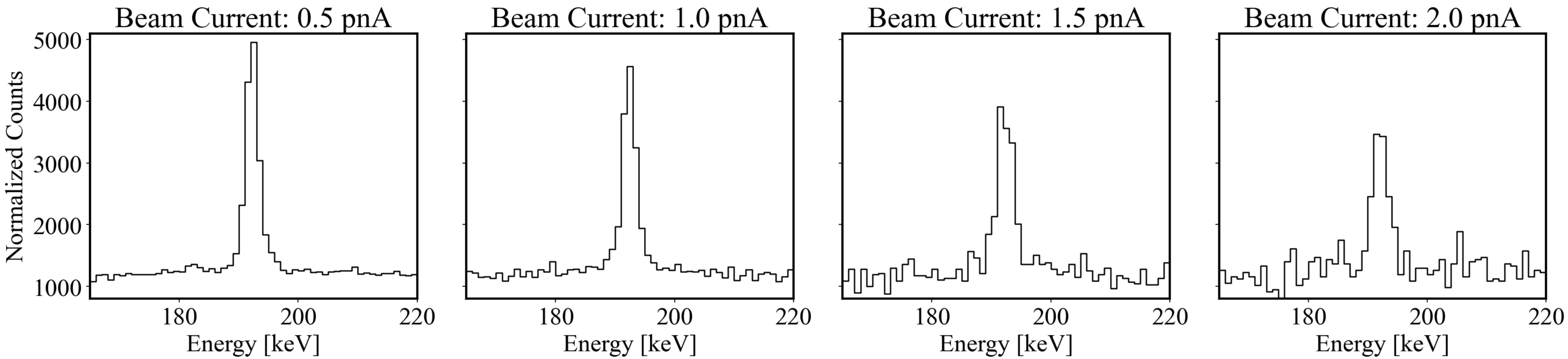
- **How does this affect the spectra?**

Impact of Rates

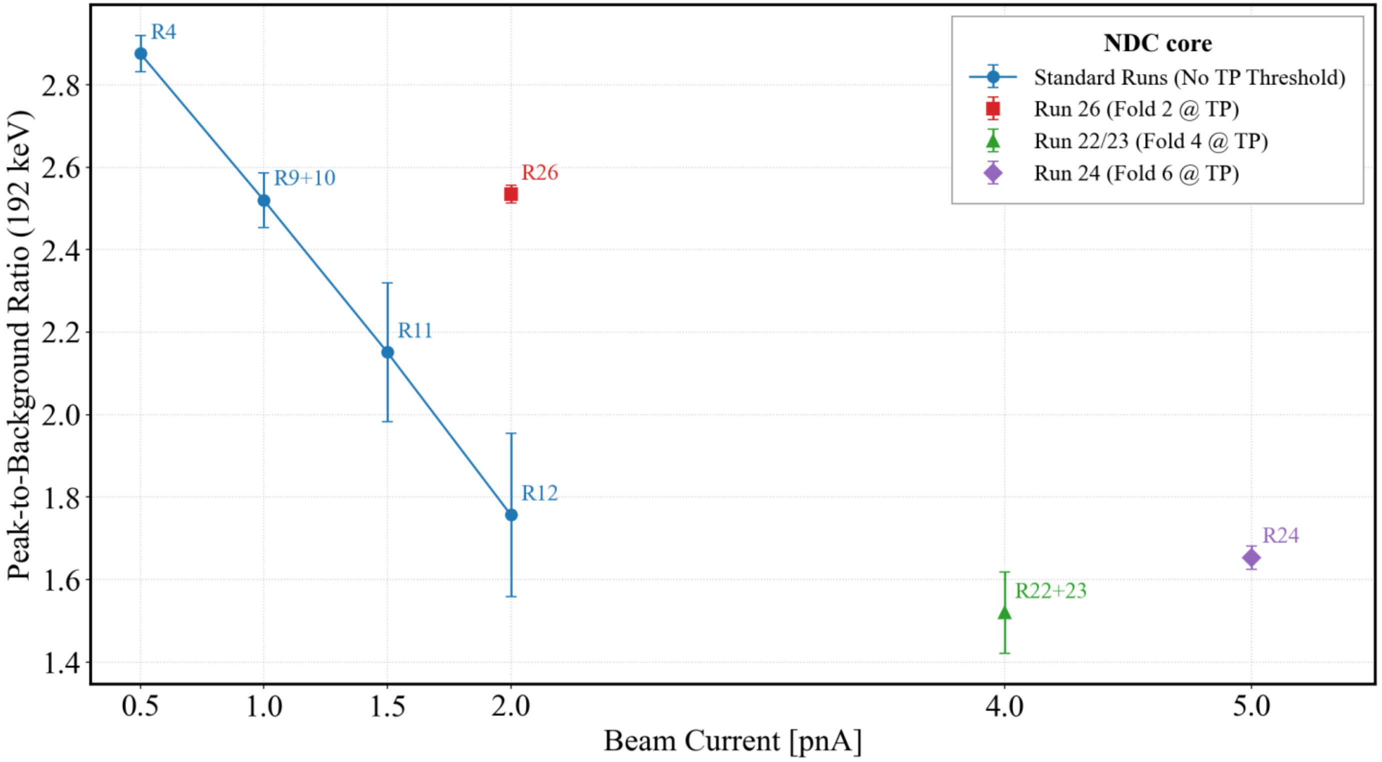


- γ-ray spectra measured using **AGATA standalone** at **various beam currents**
- The spectra have been **normalised** so the background between 100-180 keV and 200-280 keV is equal
- Measure peak to background of 192 keV peak in ^{158}Er

- **Clear decrease in peak-to-background ratio with increasing beam current!!**

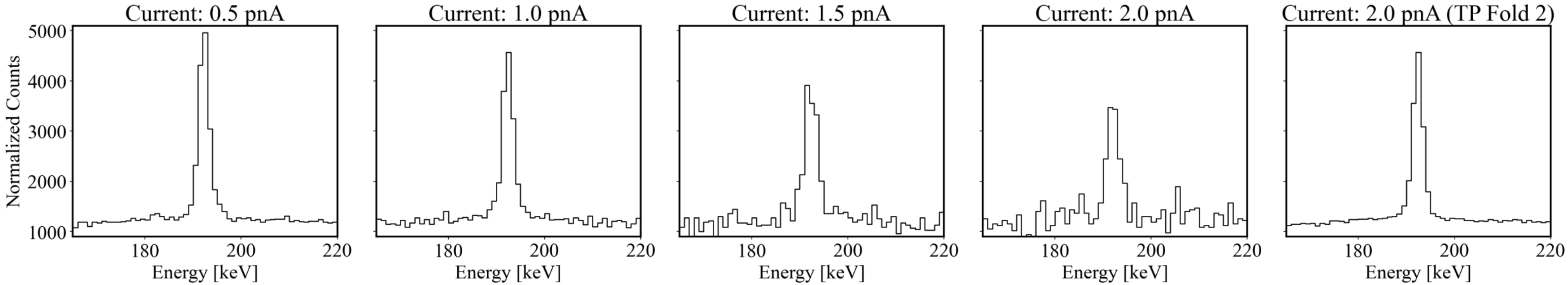


Impact of Rates

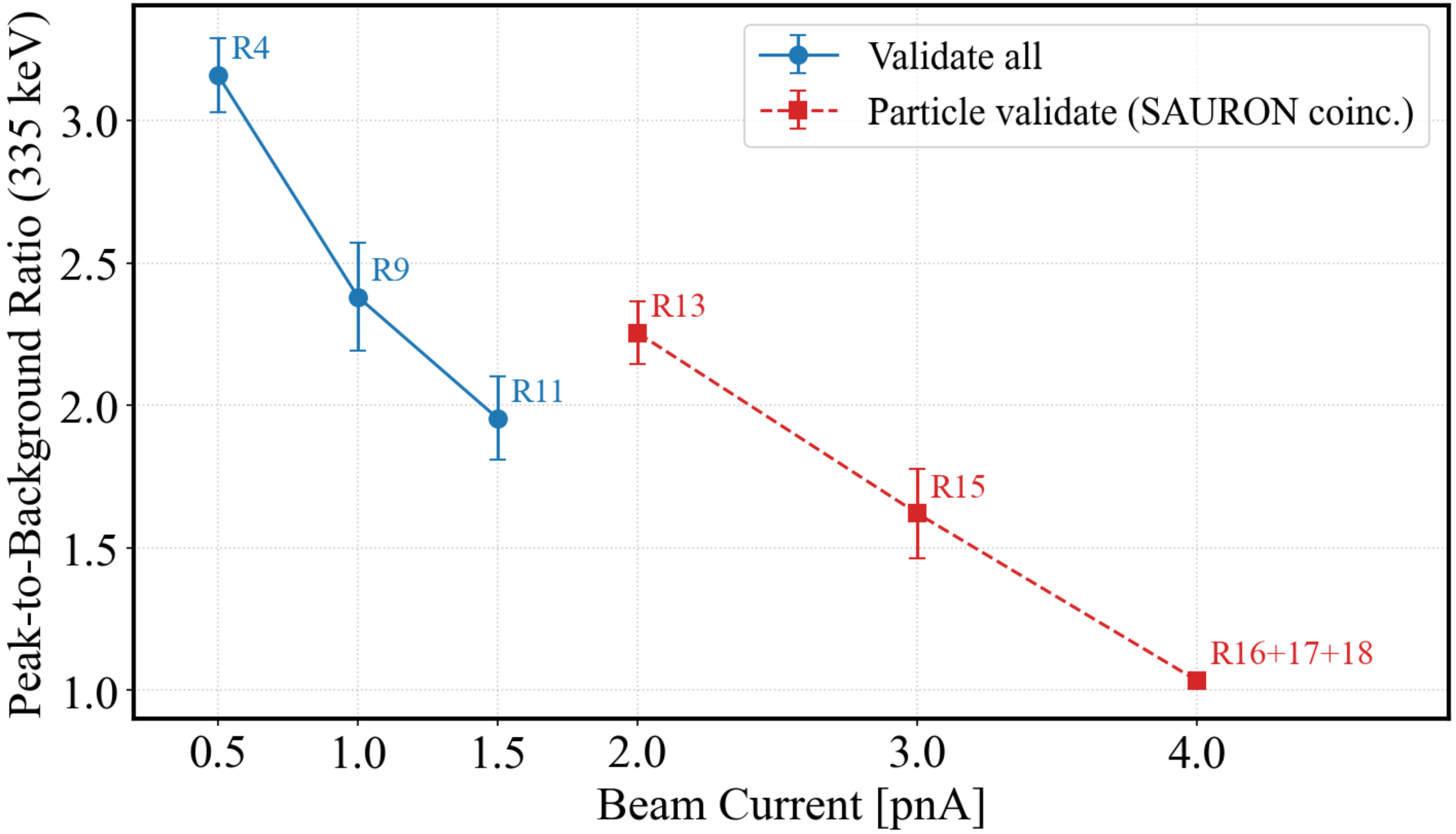


- **Peak-to-background under high beam intensity can be recovered to some extent by setting a minimum “fold” threshold at the trigger processor**

- Still not *quite* as good as for low rates. Why?
- **At high rates PtB is poor *even with TP threshold. Why?***



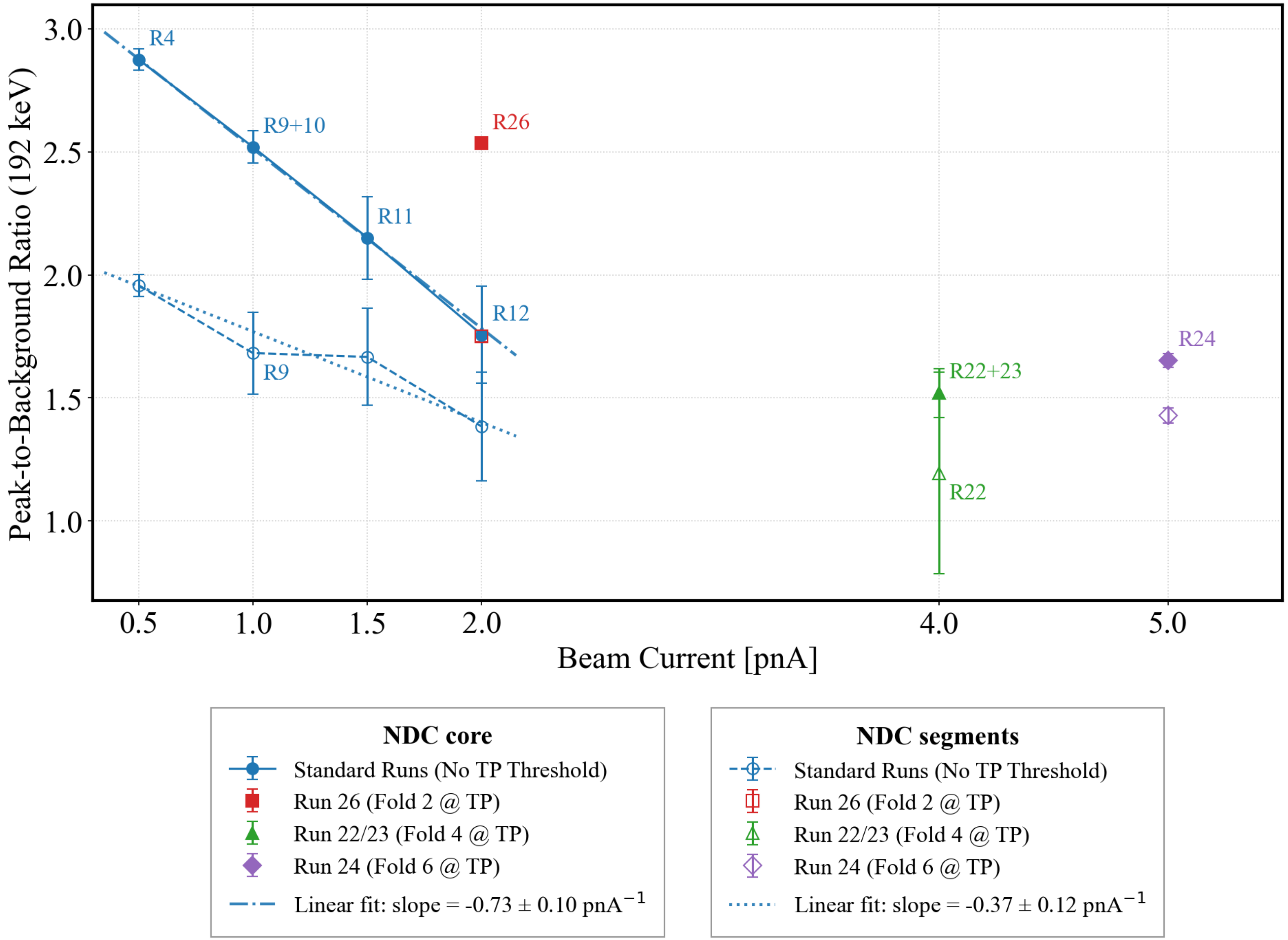
Impact of SAURON



- Peak to background measured using ^{155}Dy 335 keV line – not directly comparable to the ^{158}Er 192 keV line on previous slide.
- Spectra obtained with 1α gate set at SAURON.
- **Hardware trigger has similar improvements for PtB for the same beam current, but still we get deteriorated PtB at high rates.**

- **Could this be related to the PSA?**

Impact of ForceSegmentsToCore



- Back to the 192 keV peak in ^{158}Er
- **Comparison between NDC on CC only with ForceSegmentsToCore turned on and NDC on SG only with ForceSegmentsToCore turned off.**
- In general, PtB performance for segments is worse
- However the ***deterioration*** of PtB with increasing rates is **less for the segments**
- ***Evidence of PSA struggling with high intensity experiments***

Conclusion and Future Outlook

- Outlook for this experiment
  - **Tracking**:
    - Machine Learning Tracking
    - How does high multiplicity affect the tracking efficiency?
    - Tracking parameter optimisation
  - **Neutron damage correction**
    - Joa's basis vs Regular basis
  - **γ-ray angular distributions with AGATA**
  - Comparison with GRETA/GRETINA

- Outlook for the future
  - High-spin spectroscopy with AGATA possible but limitations at high rates need solutions

C.M. Sullivan[1], G. de Angelis[2], A. Astier[3], H. Ayatollahzadeh[4], M. Balogh[2], M.A. Bentley[5], G. Benzoni[6], A.J. Boston[1], S. Bottoni[6], A.D. Briscoe[1], D. Brugnara[2], F. Camera[6], B. Cederwall[7], J.A. Chadderton[1], E. Clement[8], F.C.L. Crespi[6], D. Curien[9], F. Didierjean[9], G. Duchene[9], L.P. Gaffney[1], A. Goasduff[2], A. Gottardo[2], H. Hilton[1], B. Hogg[4], F. Holloway[1], P. Jodidar[3], D.T. Joss[1], J. Keatings[4], A. Korichi[3], M. Labiche[10], T. Lauritsen[11], S. Leoni[2], J. Ljungvall[9], A. Lopez-Martens[3], A. McCarter[1], D. O'Donnell[4], R.D. Page[1], E.S. Paul[1], J. Pellumaj[2], R.M. Perez-Vidal[12], C.M. Petrache[3], N. Redon[13], P. Reiter[14], M. A. Riley[15], M. Rocchini[16], J. Simpson[10], J.F. Smith[5], J.J. Valiente-Dobòn[2], T.D. Wonderley[1], L. Zago[2], I. Zanon[7], and M. Zielinska[17]

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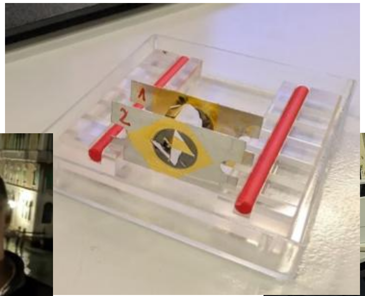
+ D. Stramaccioni and S. Carollo the best liaisons you could want & M. Loriggiola for his excellent target production & TANDEM Beam Operators!



Thanks for listening! Any questions?