Update on ^{235}U(n,f) analysis with STEFF

n_TOF Collaboration Meeting
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STEFF campaigns

2012

^{235}U

21 days in PF1B (ILL)

- 100 μg/cm^2 **^{235}U** target
- 50 μg/cm^2 Ni foil
- BARC

2015

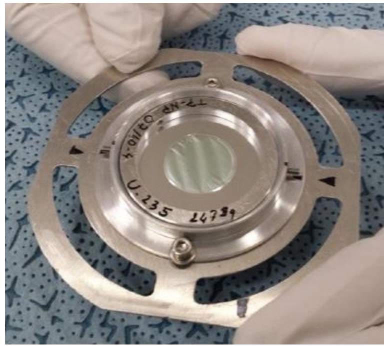
^{235}U

21 days of beam in EAR2

2.2x10^{18} protons on target

Small collimator

- 300 μg/cm^2 **^{235}U** target
- 0.1 μm Al + 1.5 μm mylar backing
- 33 mm diameter active area
- IRMM / CERN



2016

^{235}U

30 days of beam in EAR2

2.4x10^{18} protons on target

Large collimator

- 100 μg/cm^2 **^{235}U** target
- 0.7 μm aluminum backing
- 81 mm diameter active area
- CEA Orsay

2018

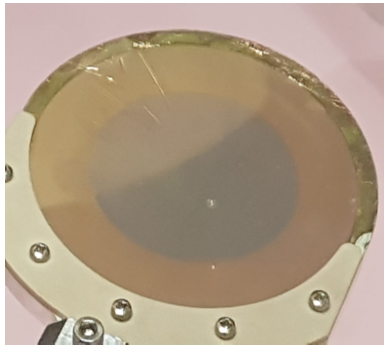
^{239}Pu

51 days of beam in EAR2

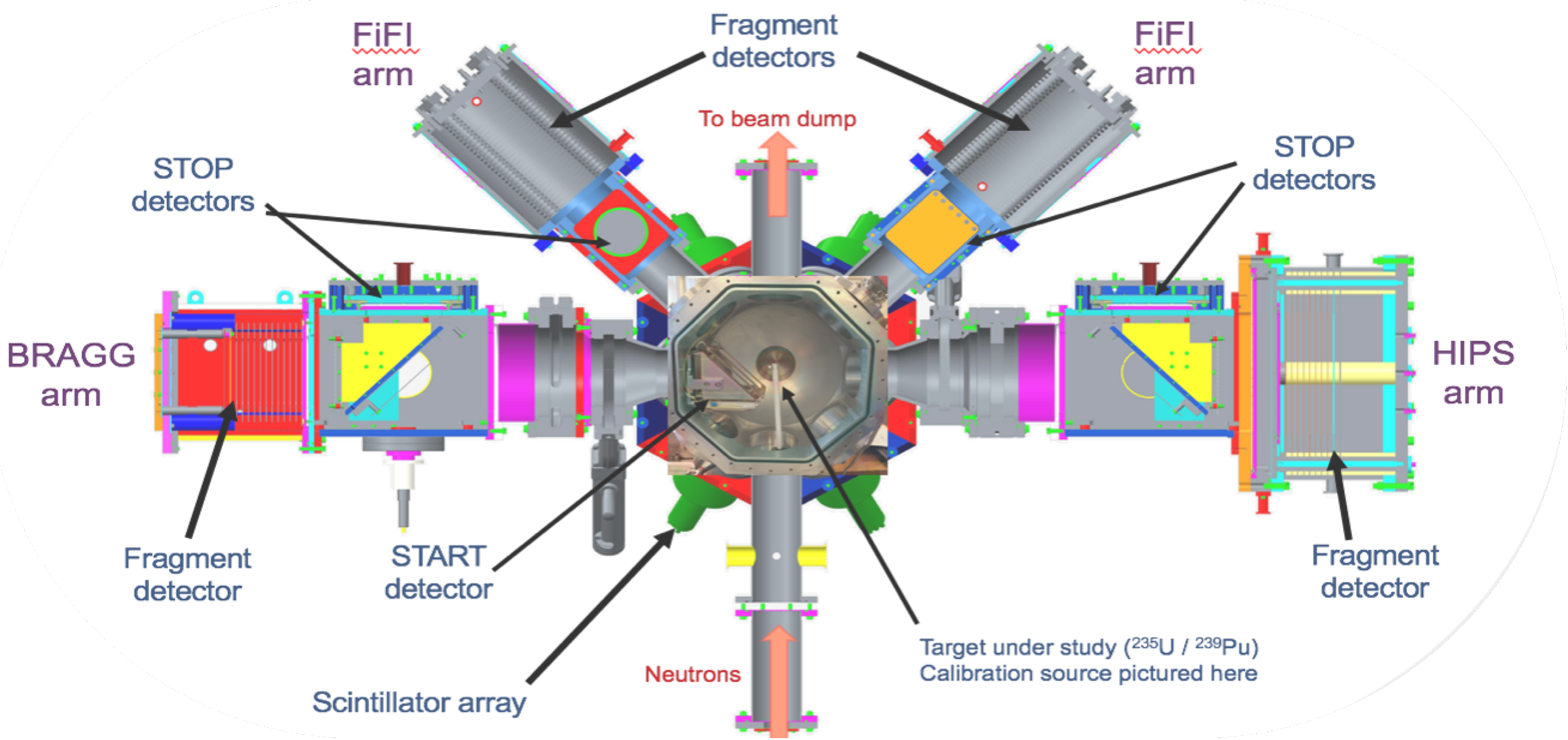
5.1x10^{18} protons on target

Small collimator

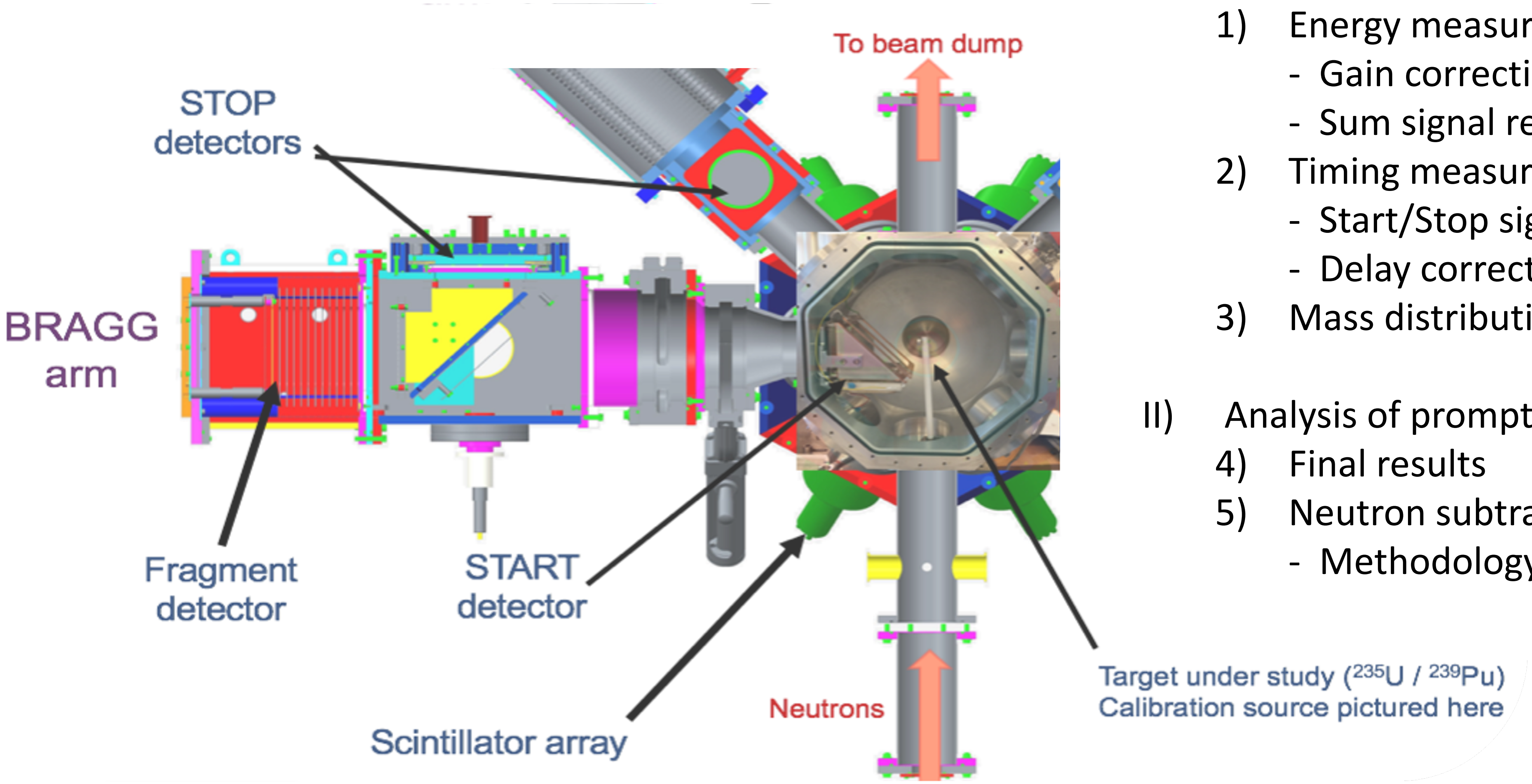
- 24 μg/cm^2 **^{239}Pu** target
- 38 μg/cm^2 mylar support
- 50 mm diameter active area
- JRC Geel



STEFF detectors



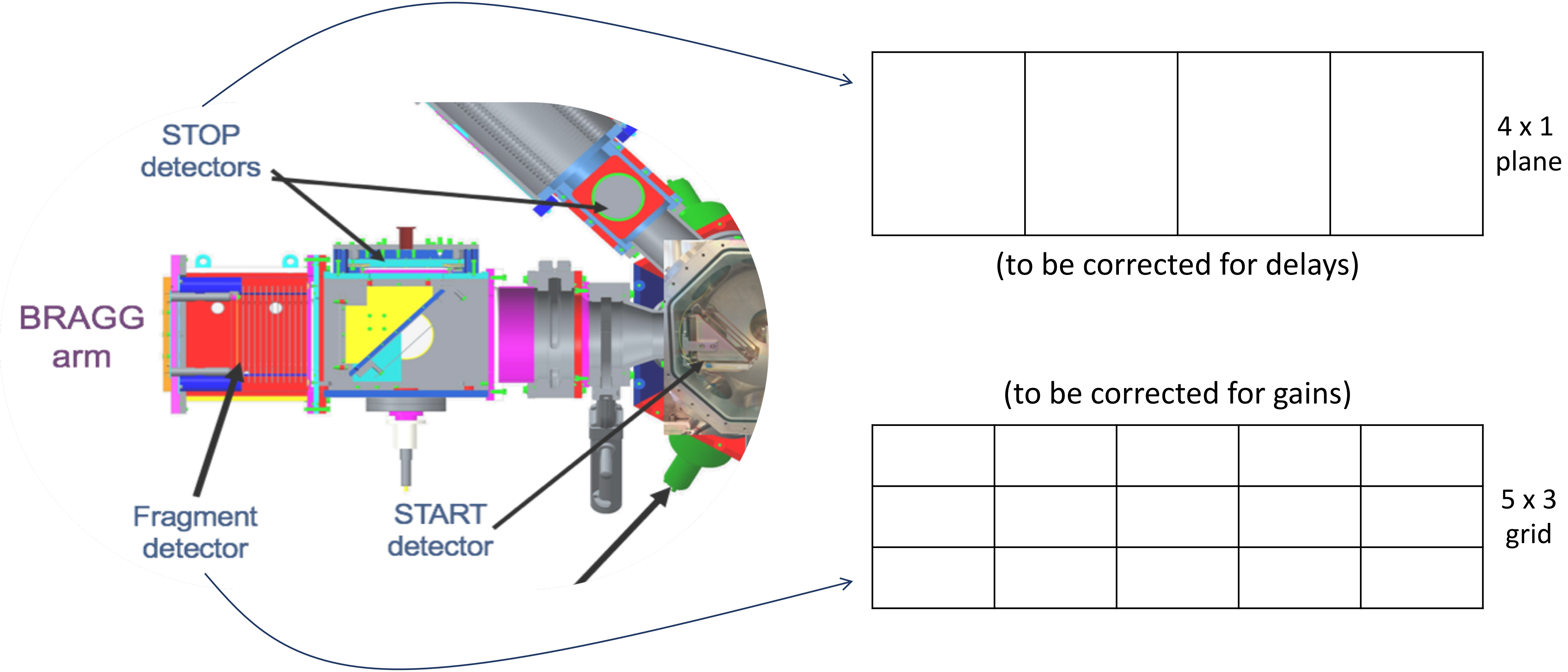
Contents of this talk



I) Analysis of fission fragment distributions
  1) Energy measurement
    - Gain corrections
    - Sum signal reconstruction
  2) Timing measurement
    - Start/Stop signal selection
    - Delay corrections
  3) Mass distribution from E-tof matrices

II) Analysis of prompt gamma distributions
  4) Final results
  5) Neutron subtraction
    - Methodology

Anode segmentation in Bragg and Bragg Stop



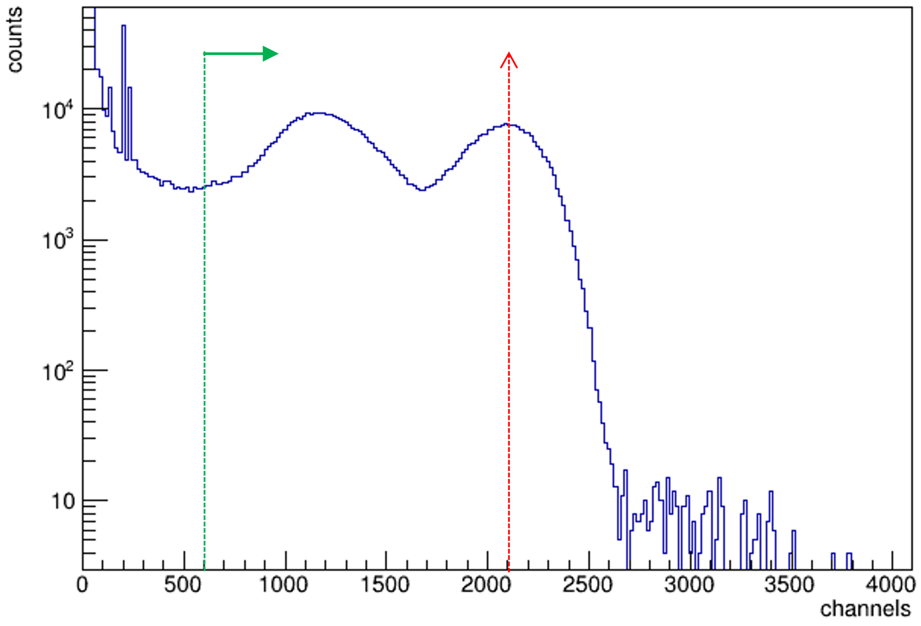
4 x 1 plane

(to be corrected for delays)

(to be corrected for gains)

5 x 3 grid

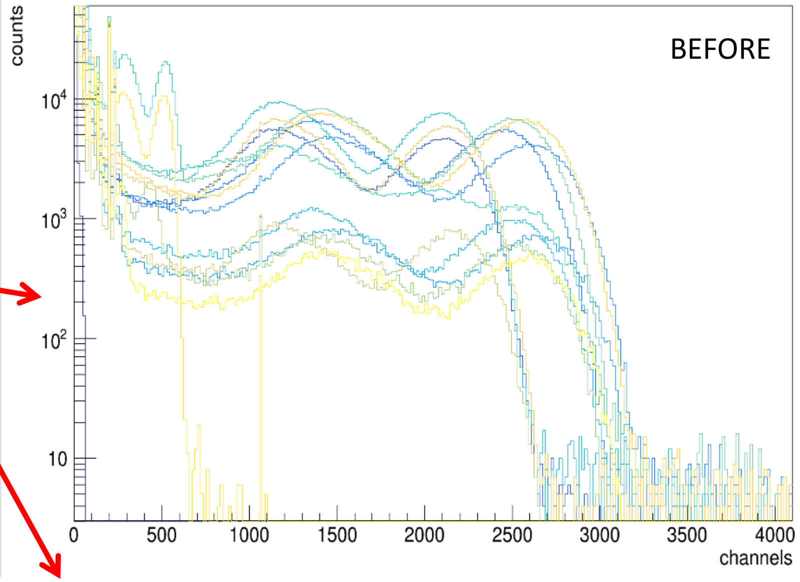
Bragg anode pads gain corrections

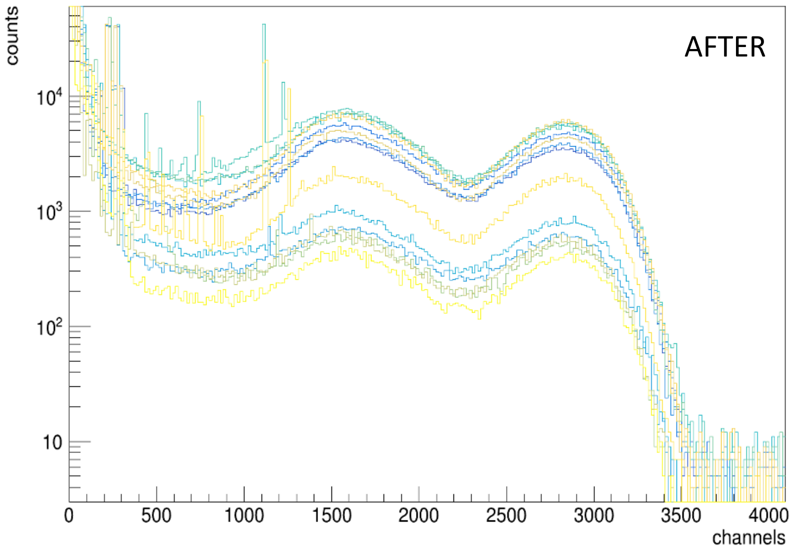


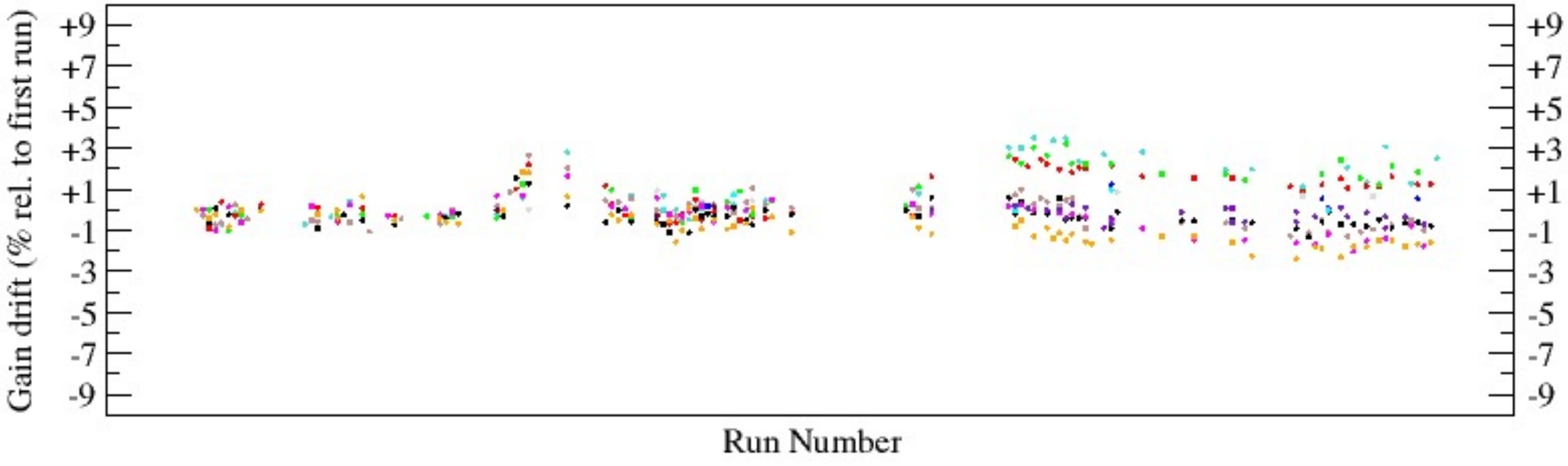
Two types of gain corrections:

1) Matching across pads using position of light peak

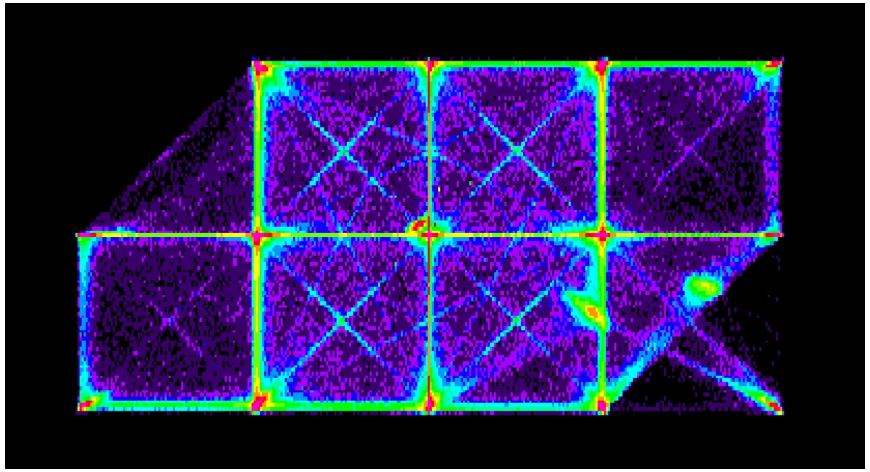
2) Tracking over time using shape of spectrum







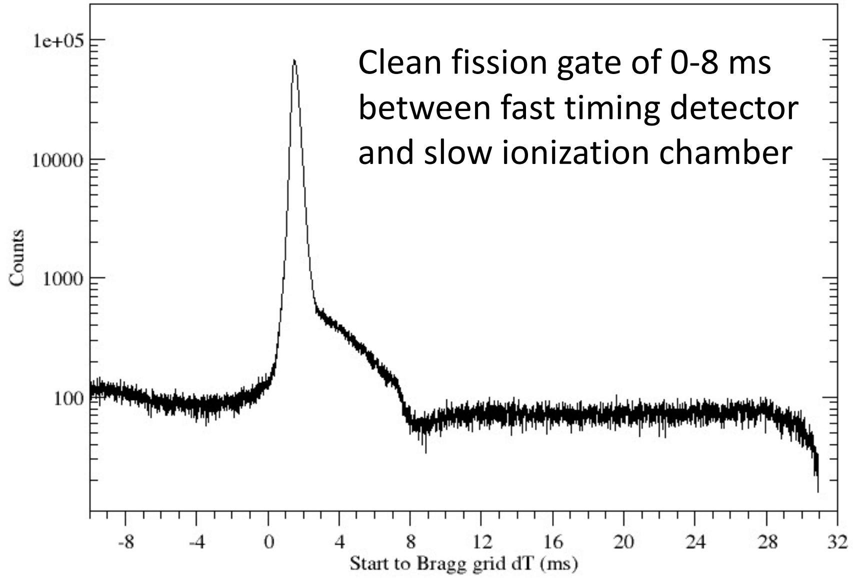
Bragg sum signal reconstruction



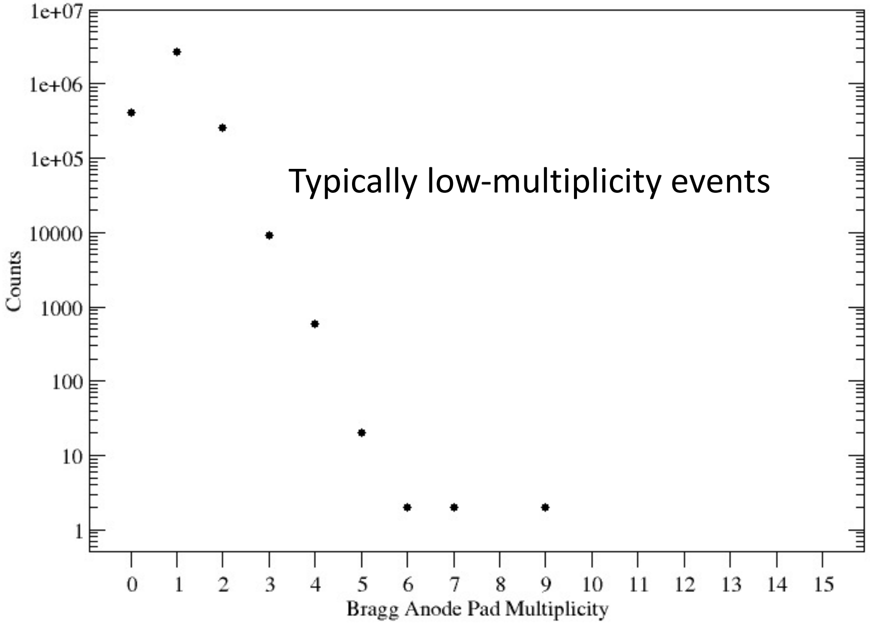
2D map of charge-centres within Bragg chamber

Vertices represent anode pads
Lines indicate charge-sharing

Charge mainly shared between adjacent pads



Clean fission gate of 0-8 ms between fast timing detector and slow ionization chamber

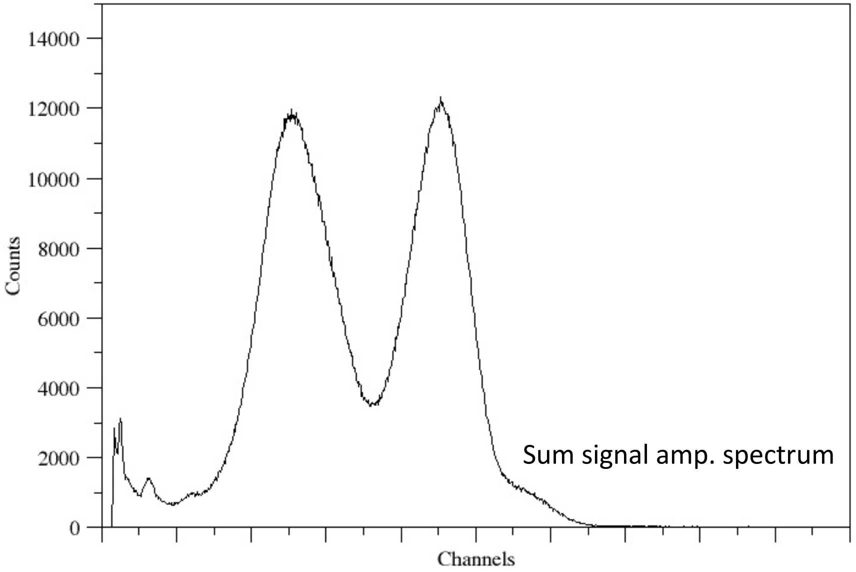


Typically low-multiplicity events

Sum signal reconstruction:

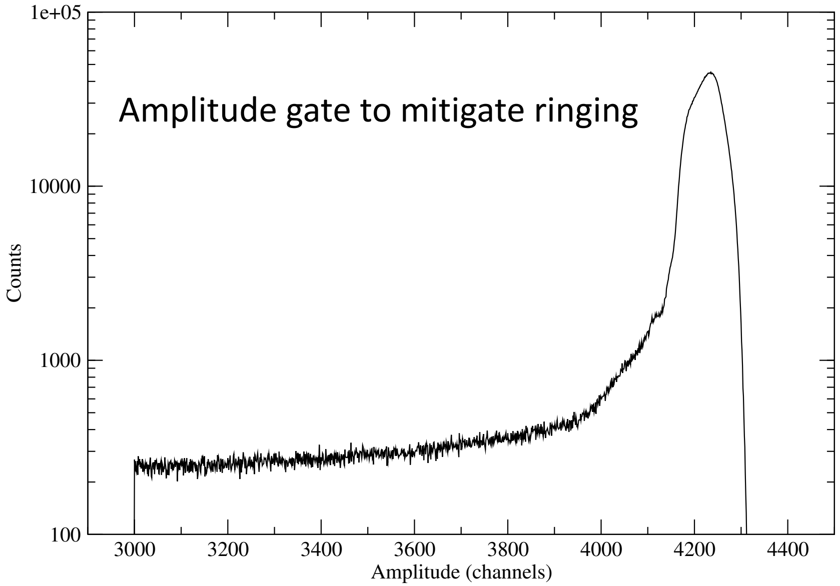
A) Identify anode pad with highest charge collection

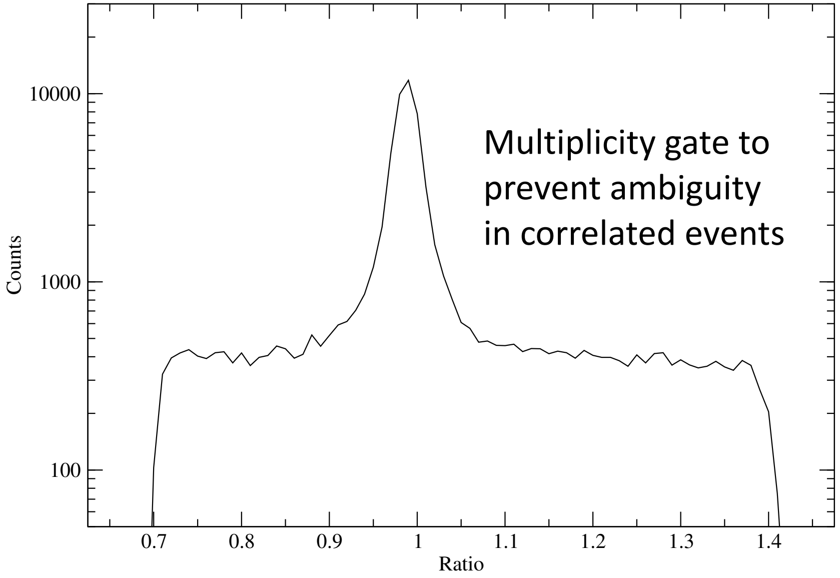
B) Add traces from adjacent pads in a '+' configuration



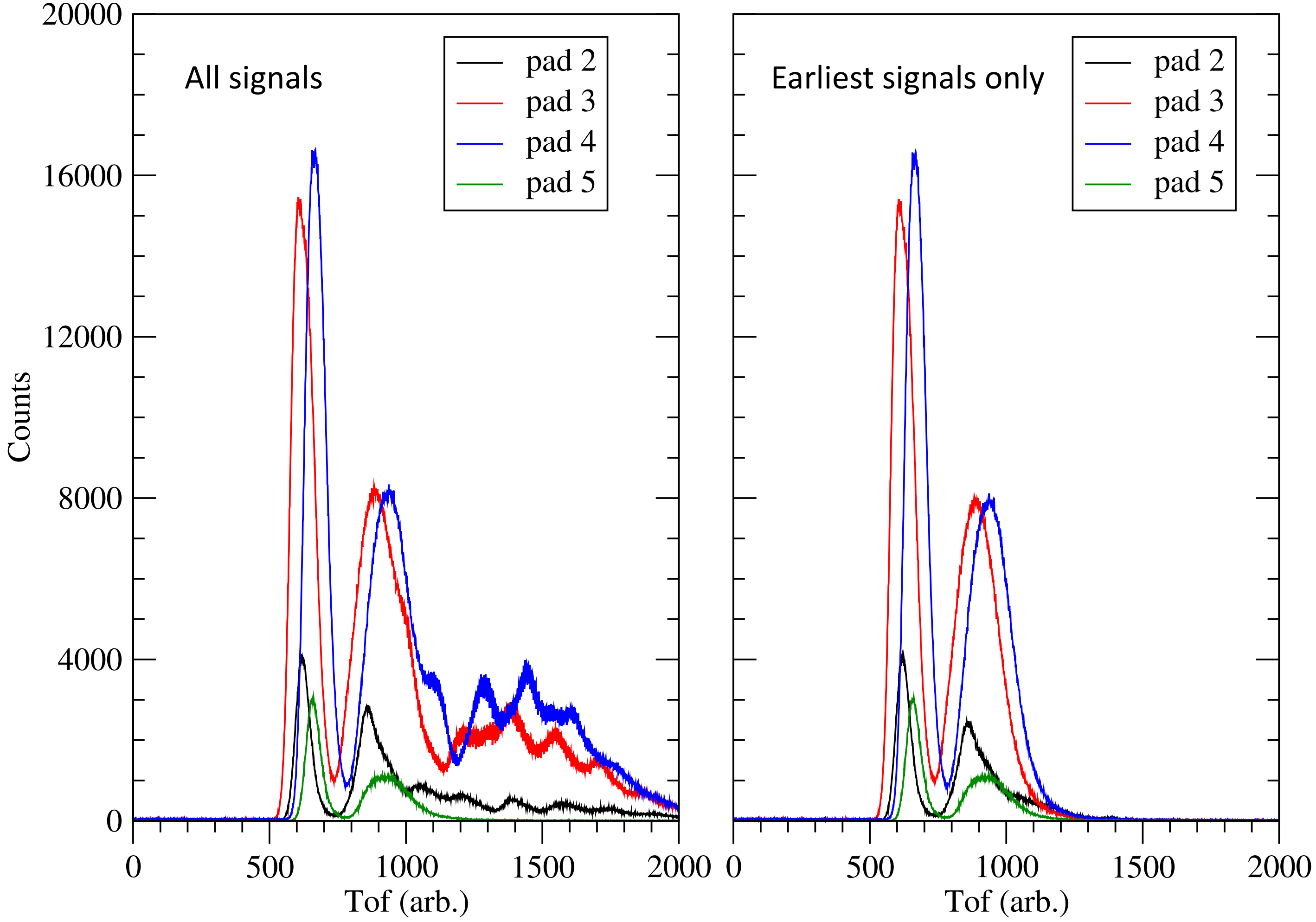
Sum signal amp. spectrum

Start Timing signals selection Stop

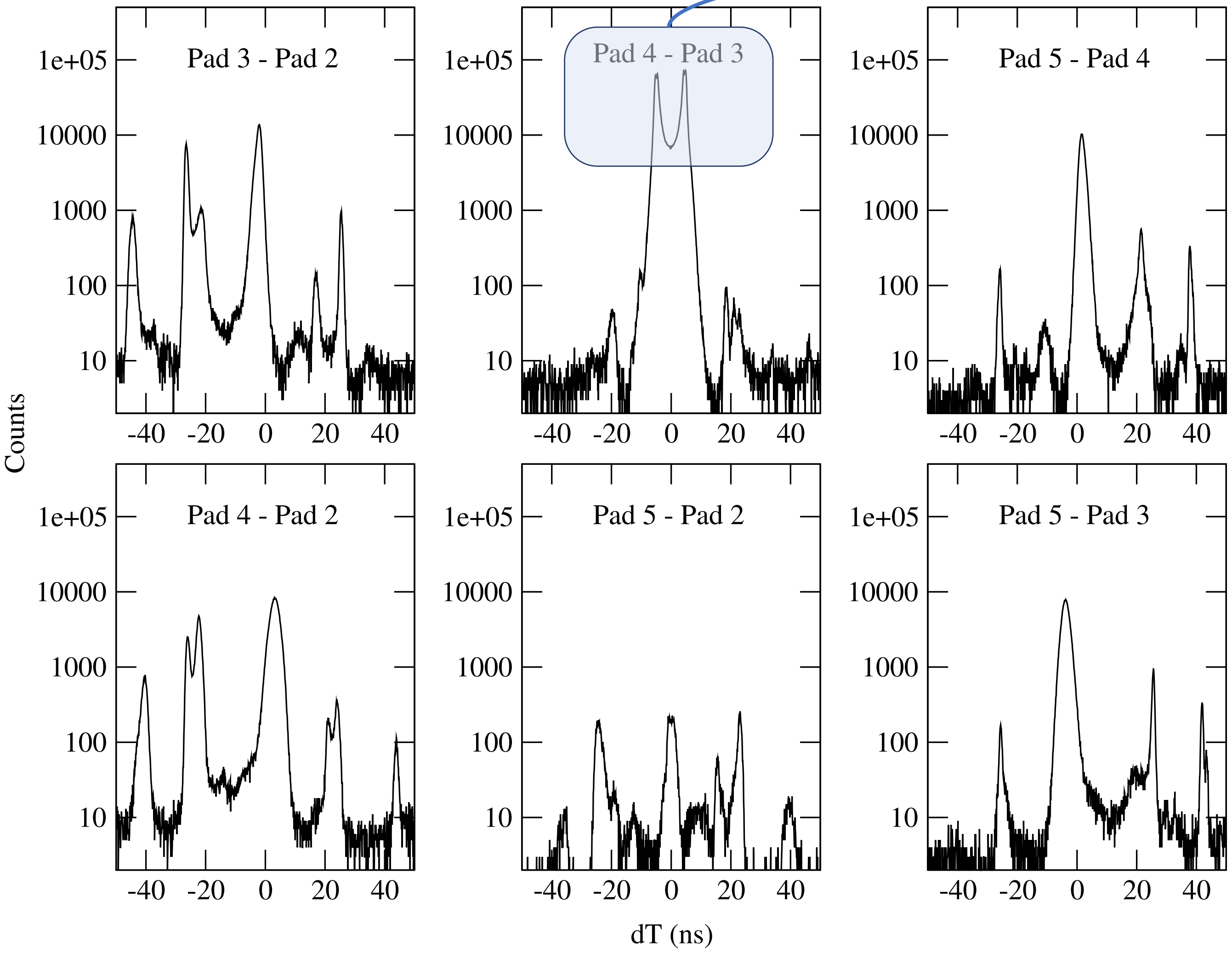

Amplitude gate to mitigate ringing


Multiplicity gate to prevent ambiguity in correlated events

Anode segmented into four –{ Treat earliest signal on each pad as primary
Treat all subsequent signals as secondaries



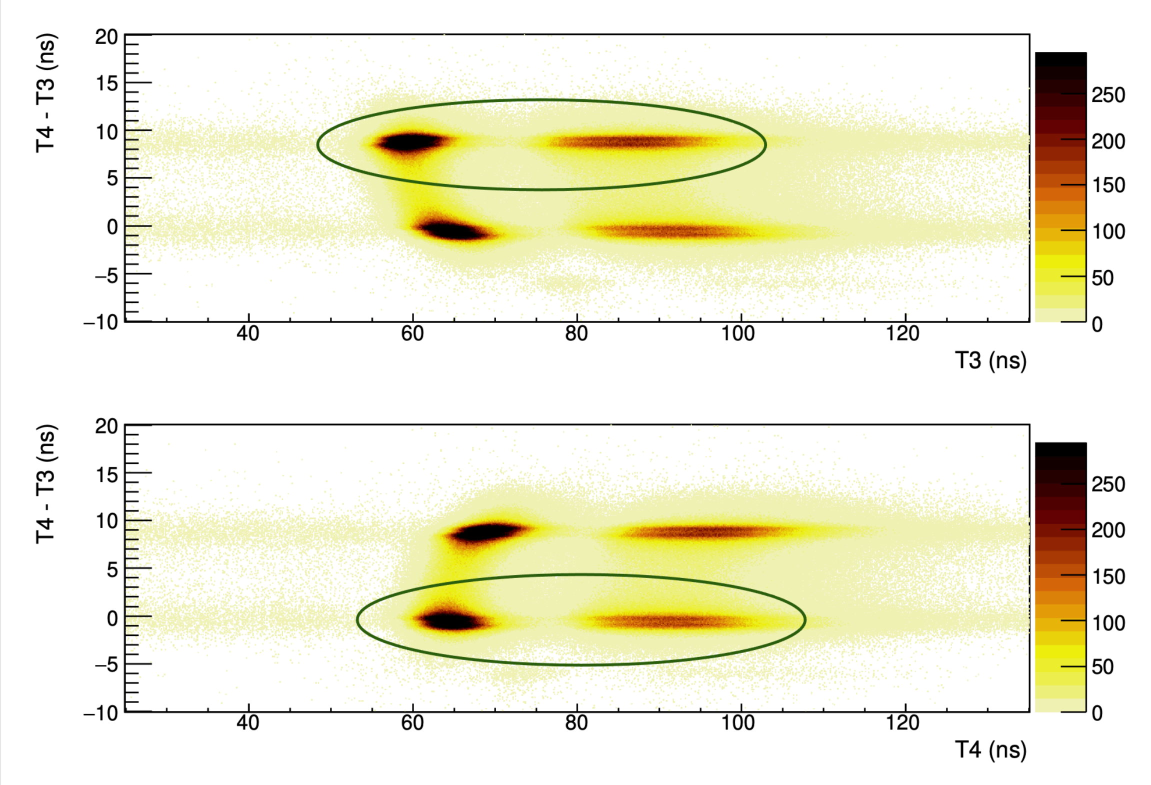
Bragg Stop anode delay corrections



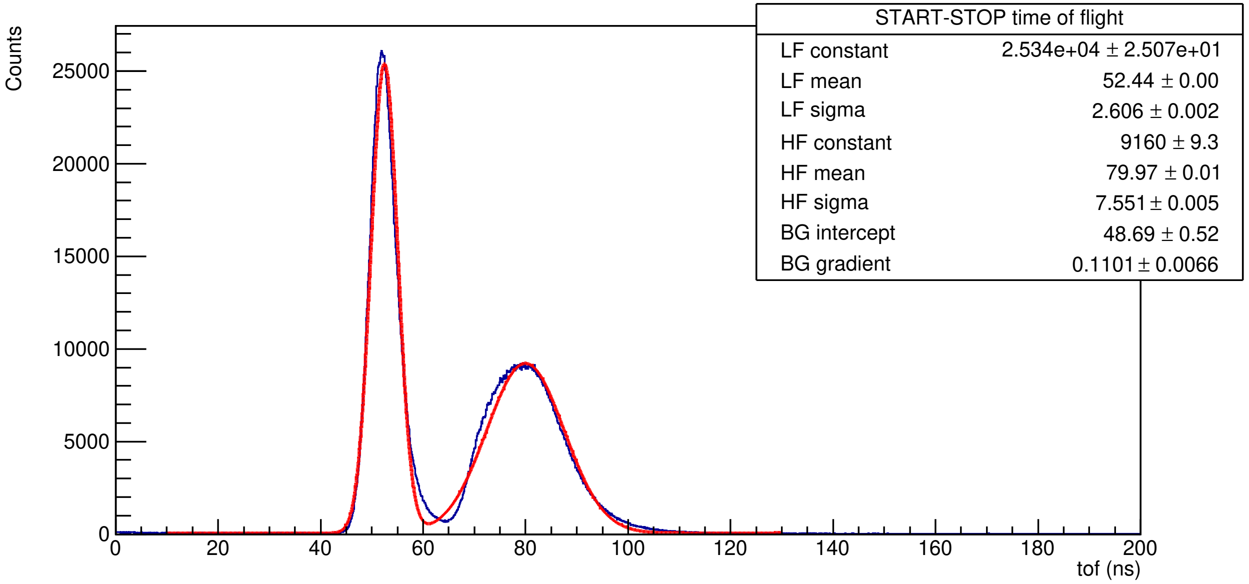
Align pads using “synchronous” multipad events

But it appears to be a signal-echo pair instead

Stick to philosophy of considering earliest signal

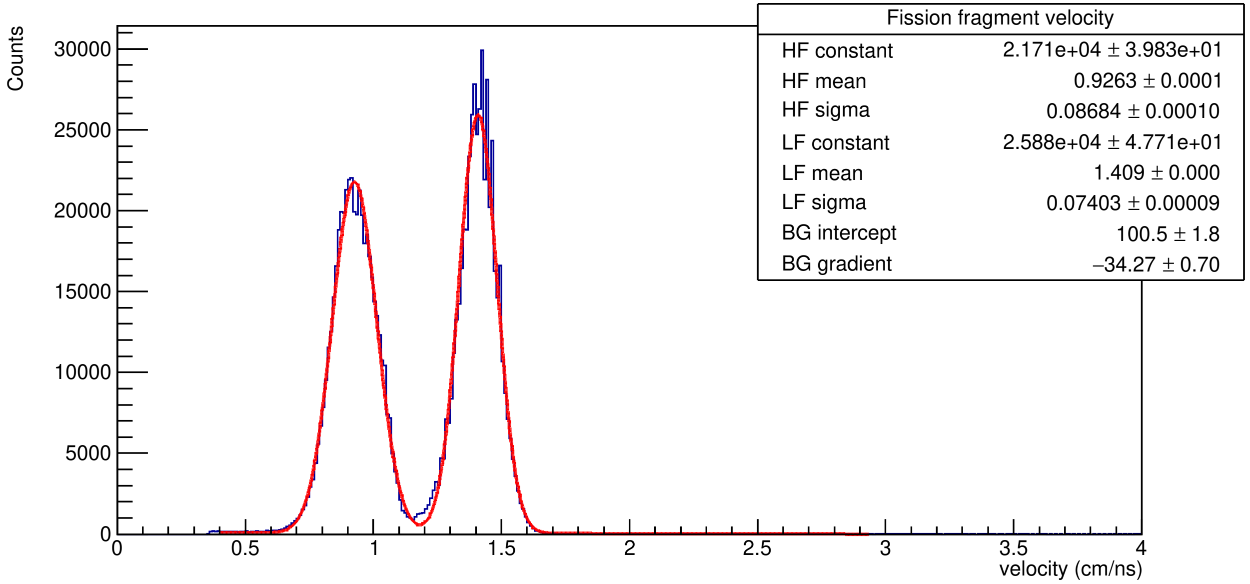


FF tof and velocity spectra



START-STOP time of flight

LF constant	2.534e+04 ± 2.507e+01
LF mean	52.44 ± 0.00
LF sigma	2.606 ± 0.002
HF constant	9160 ± 9.3
HF mean	79.97 ± 0.01
HF sigma	7.551 ± 0.005
BG intercept	48.69 ± 0.52
BG gradient	0.1101 ± 0.0066



Fission fragment velocity

HF constant	2.171e+04 ± 3.983e+01
HF mean	0.9263 ± 0.0001
HF sigma	0.08684 ± 0.00010
LF constant	2.588e+04 ± 4.771e+01
LF mean	1.409 ± 0.000
LF sigma	0.07403 ± 0.00009
BG intercept	100.5 ± 1.8
BG gradient	−34.27 ± 0.70

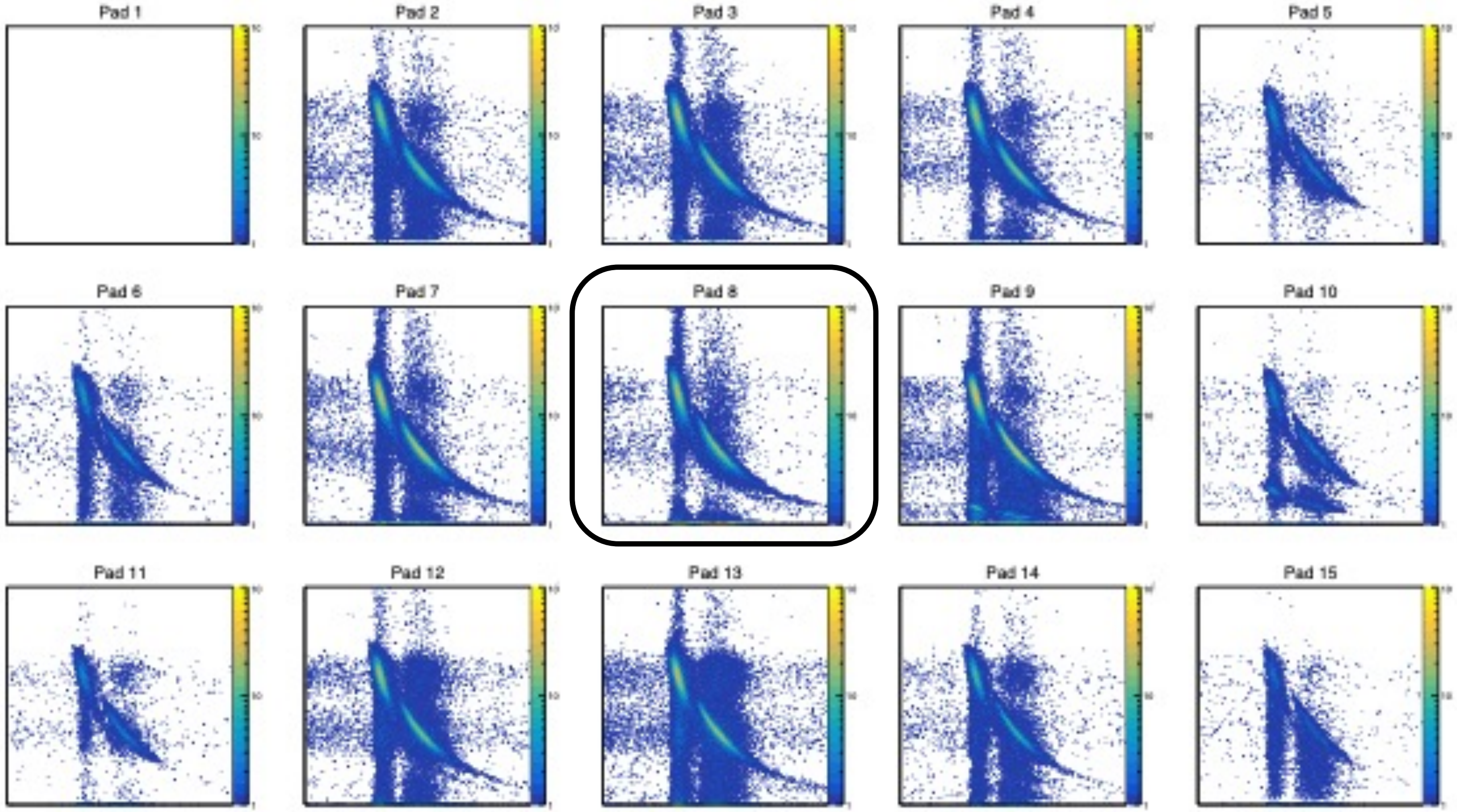
Alignment done using light ff tof peak
Spread in heavy ff peaks under 0.5 ns

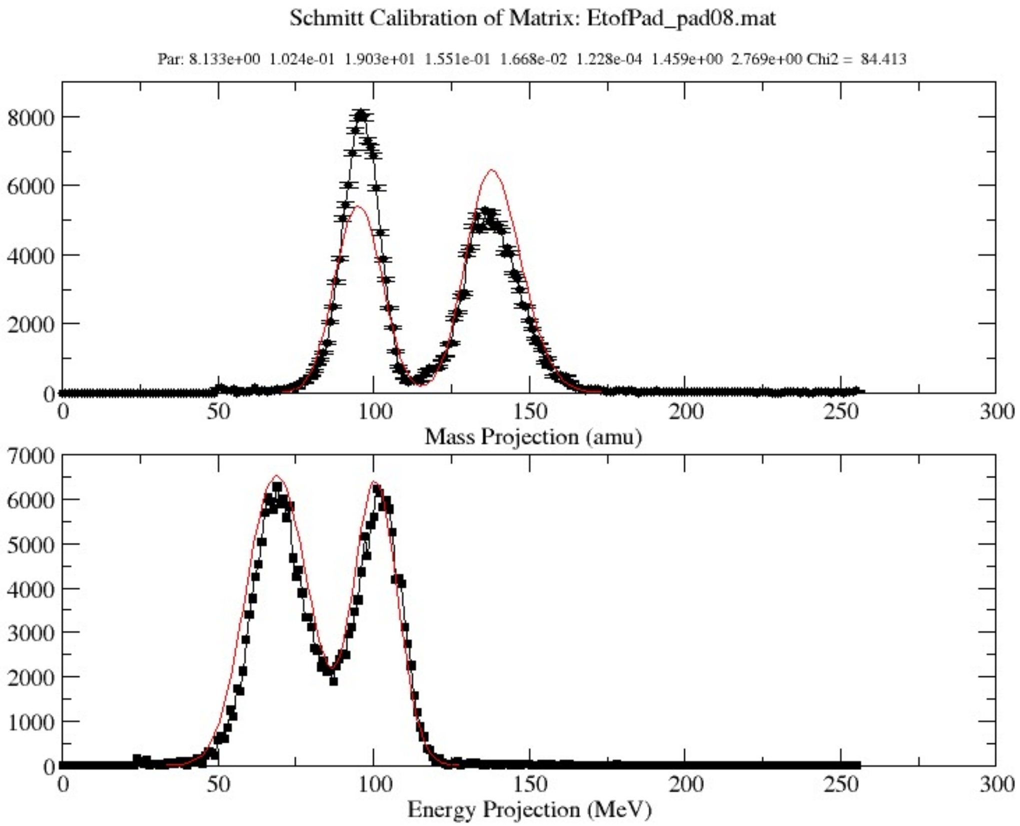
Comparable to spread in signal rise times
(calculated by S. Warren to be 0.48 ns)

Time resolution of start-stop system is 1.76 ns

	STEFF (preliminary)	**Shiraishi and Hosoe (1973)**	**Andritsopoulos (1967)**	**Milton and Fraser (1962)**
T_L (ns/cm)	0.71 ± 0.04	0.70 ± 0.03	0.71 ± 0.02	0.71 ± 0.02
T_H (ns/cm)	1.08 ± 0.10	1.04 ± 0.09	1.02 ± 0.09	1.03 ± 0.10
v_L (cm/ns)	1.41 ± 0.07	1.42 ± 0.06	1.42 ± 0.05	1.41 ± 0.06
v_H (cm/ns)	0.93 ± 0.09	0.97 ± 0.08	0.97 ± 0.09	0.97 ± 0.07

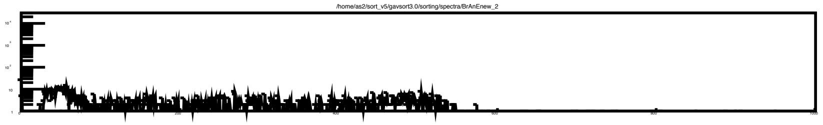
E-tof matrices and E,m distributions



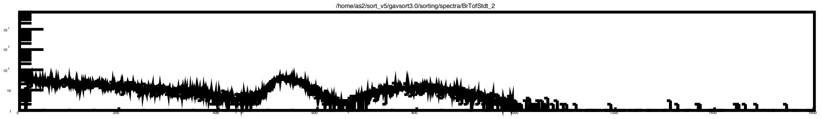


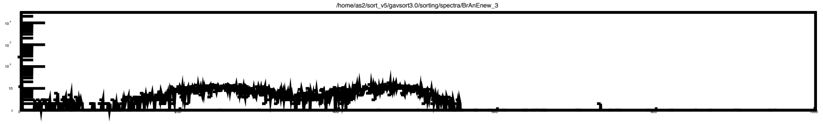
Extending to higher neutron energies

Bragg E

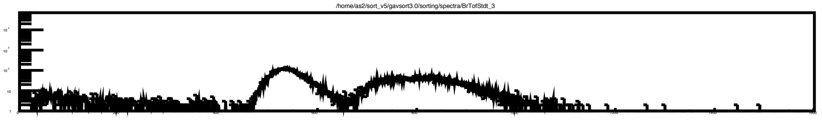


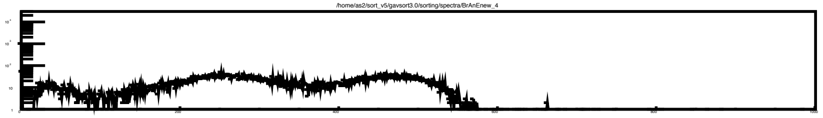
10 keV – 10 MeV



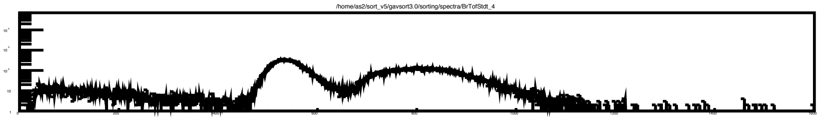


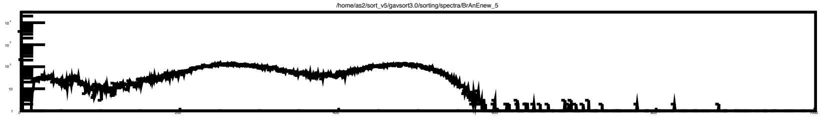
1 – 10 keV



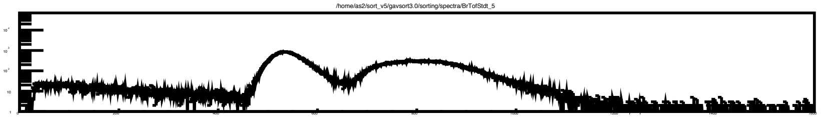


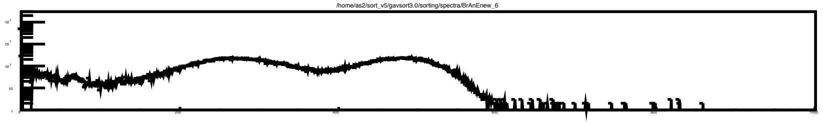
100 eV – 1 keV



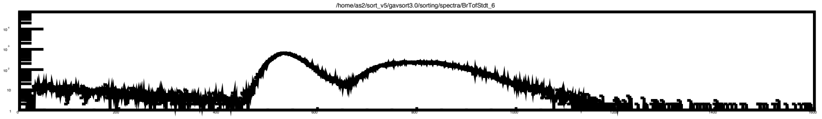


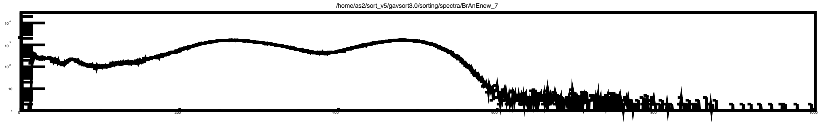
10 – 100 eV



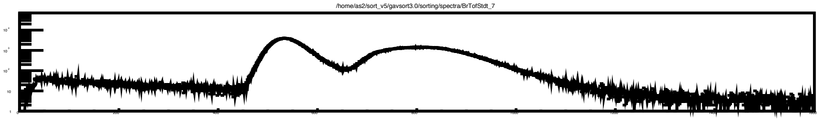


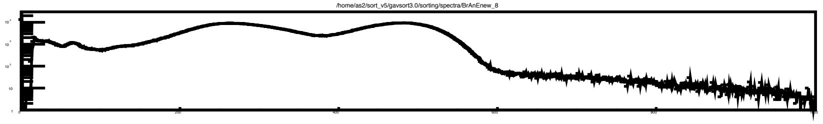
1 – 10 eV



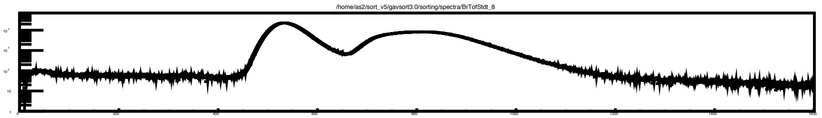


100 meV - 1 eV

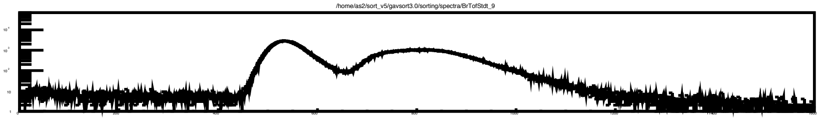




10 – 100 meV

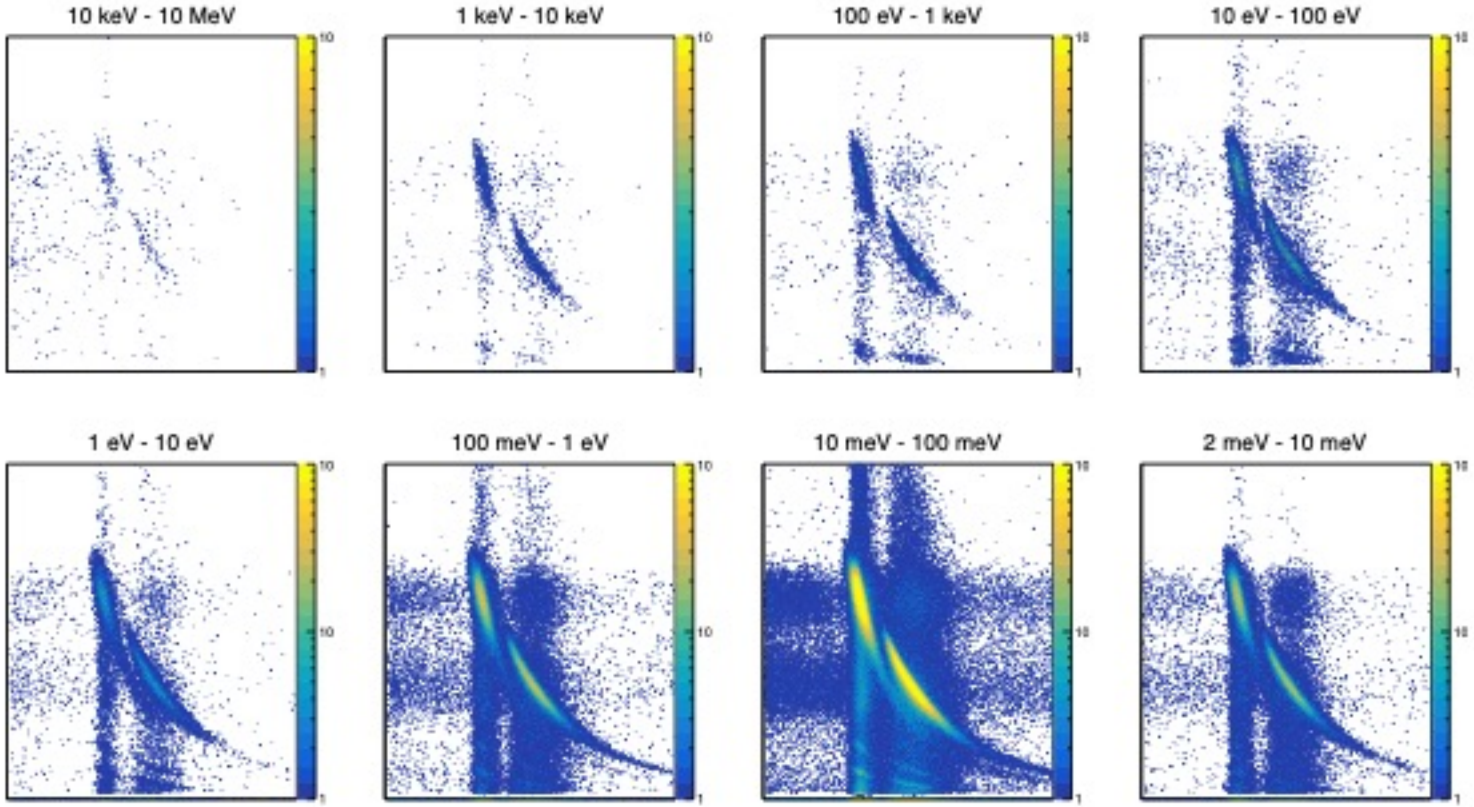


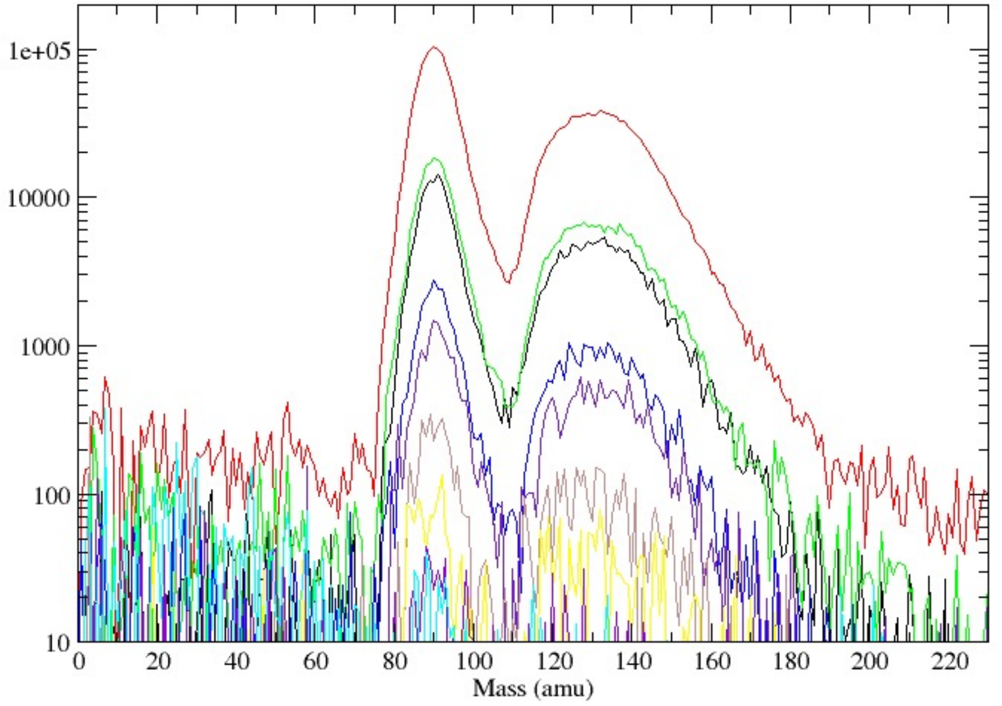
2 – 10 meV



Start-Stop tof

Consistency across neutron energies





(PRELIMINARY)

Summary + Next steps

- Bragg anode pads have been gain-corrected and sum signal has been reconstructed

- Bragg Stop anode pads have been delay-corrected and start-stop pairs have been identified
- Time of flight and velocity results are consistent for literature values with similar setups

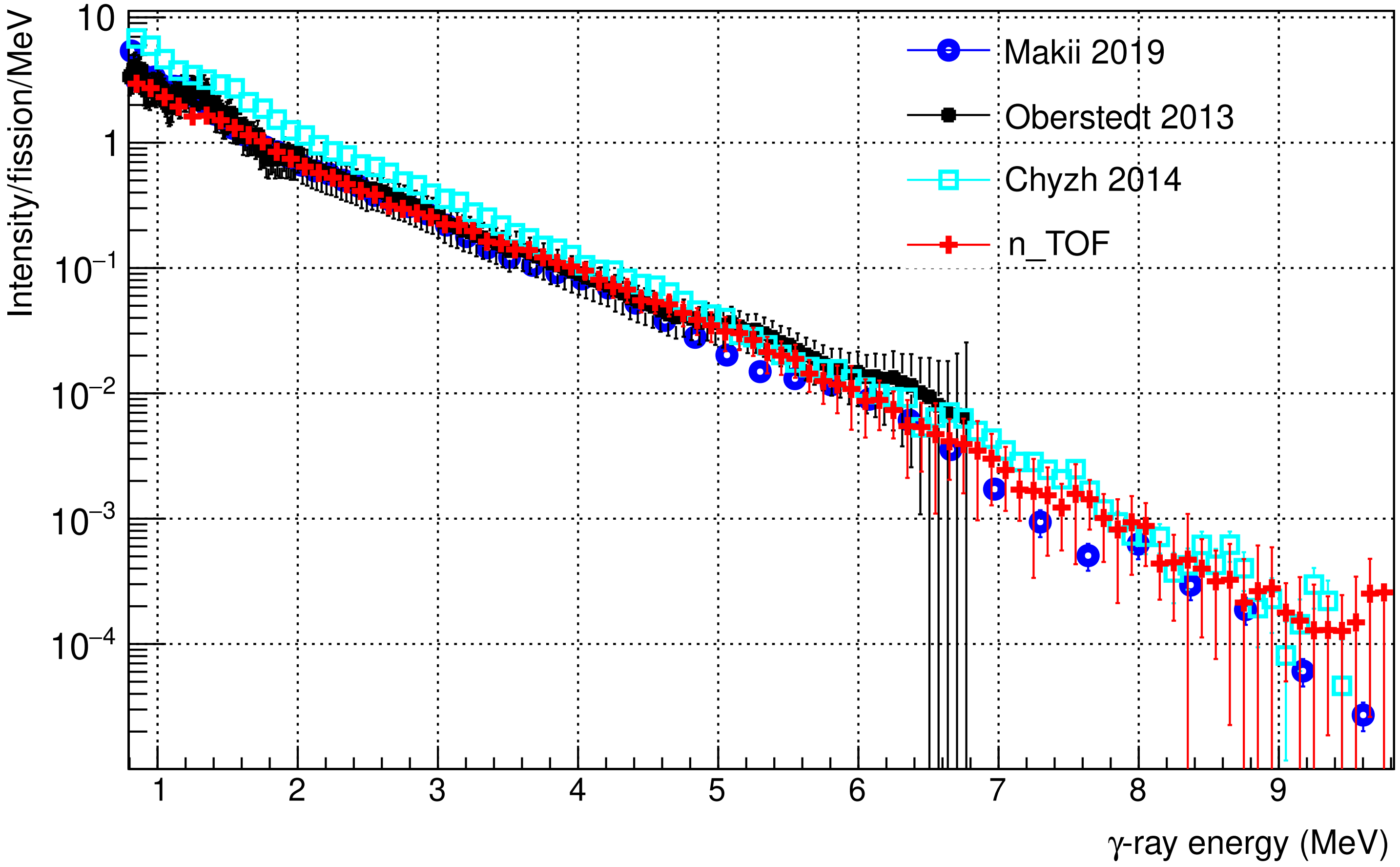
- Energy-tof matrices show consistency across the segmented anode pads
- Energy-tof matrices show consistency across neutron energy decades

- Corrections for foils and windows to be done (SRIM)
- Mass distributions to be extracted and calibrated (Schmitt method)

- Analysis has to be extended to the Hips arm (aim to write paper on this analysis in early 2024)
- Analysis to be extended to the ^{239}Pu dataset (new PhD student starting in January 2024)

Prompt Fission Gamma Ray Results

- Data from NaI scintillators analysed – only for sub-thermal neutron energy induced fission to avoid gamma-flash induced gain effects
- Background from prompt fission neutrons subtracted based on expected detected counts distribution in time
- Results in good agreement with other recent works, publication submitted to EPJA



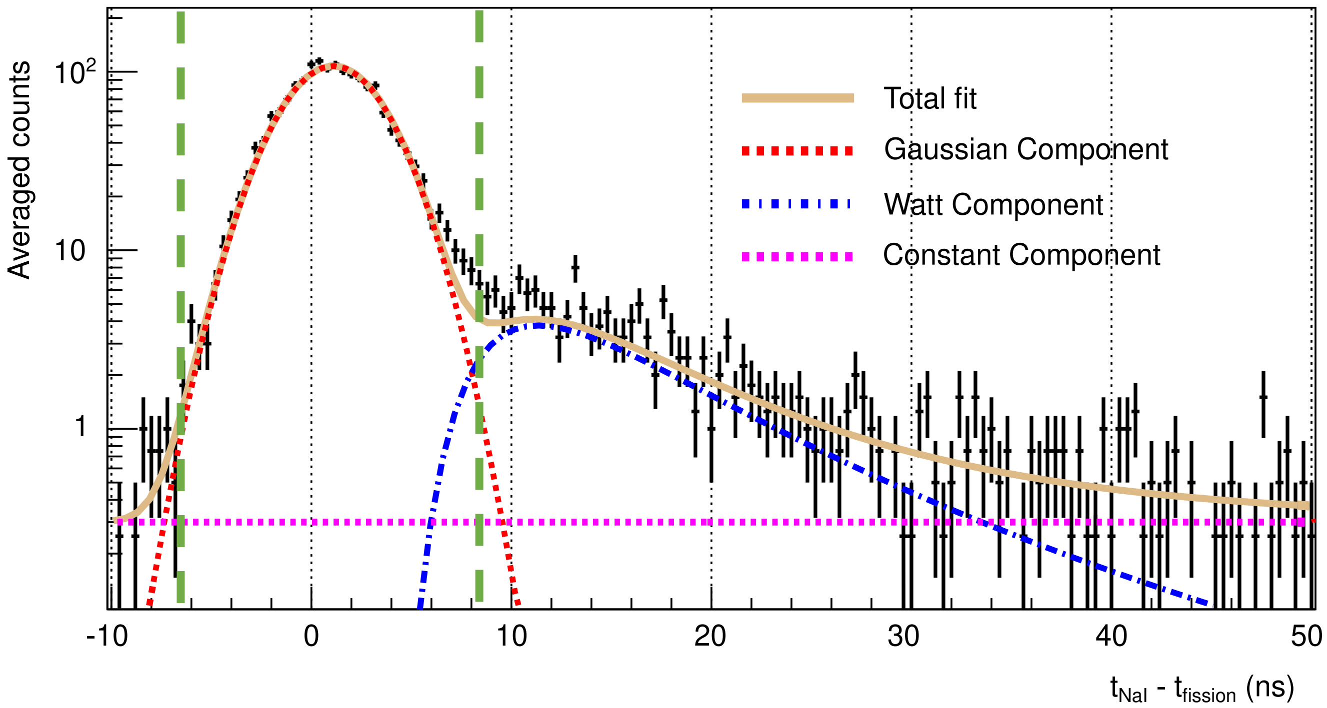
Reference	$\bar{E}_\gamma$ (MeV)	$\bar{\nu}_\gamma$	$\bar{E}_\gamma \times \bar{\nu}_\gamma$ (MeV)
Oberstedt *et al.*[10]	1.64(4)	2.99(4)	4.9(1)
Chyzh *et al.*[11]	1.56(4)	3.24(15)	5.1(3)
Makii *et al.*[14]	1.56(4)	3.04(7)	4.7(2)
n_TOF	1.68(4)	2.63(24)	4.4(4)

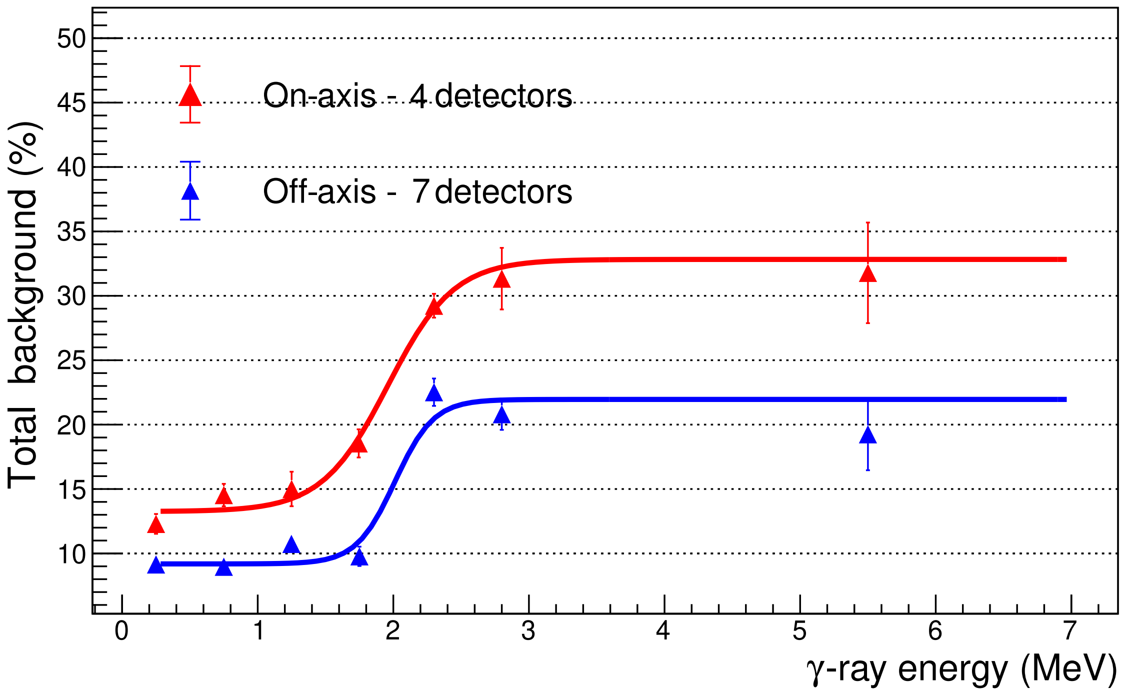
[9] Oberstedt, A., Belgya, T., Billnert, R., Borcea, R., Bryś, T., Geerts, W., Göök, A., Hambsch, F.-J., Kis, Z., Martinez, T., Oberstedt, S., Szentmiklosi, L., Takàcs, K., Vidali, M.: Improved values for the characteristics of prompt-fission γ-ray spectra from the reaction ^{235}U(n_{th}, f). Phys. Rev. C **87**, 051602 (2013). https://doi.org/10.1103/PhysRevC.87.051602

[11] Chyzh, A., Wu, C.Y., Kwan, E., Henderson, R.A., Bredeweg, T.A., Haight, R.C., Hayes-Sterbenz, A.C., Lee, H.Y., O'Donnell, J.M., Ullmann, J.L.: Total prompt γ-ray emission in fission of ^{235}U, ^{239,241}Pu, and ^{252}Cf. Phys. Rev. C **90**, 014602 (2014). https://doi.org/10.1103/PhysRevC.90.014602

[14] Makii, H., Nishio, K., Hirose, K., Orlandi, R., Léguillon, R., Ogawa, T., Soldner, T., Köster, U., Pollitt, A., Hambsch, F.-J., Tsekhanovich, I., Aïche, M., Czajkowski, S., Mathieu, L., Petrache, C.M., Astier, A., Guo, S., Ohtsuki, T., Sekimoto, S., Takamiya, K., Frost, R.J.W., Kawano, T.: Effects of the nuclear structure of fission fragments on the high-energy prompt fission γ-ray spectrum in ^{235}U(n_{th}, f). Phys. Rev. C **100**, 044610 (2019). https://doi.org/10.1103/PhysRevC.100.044610

Neutron subtraction



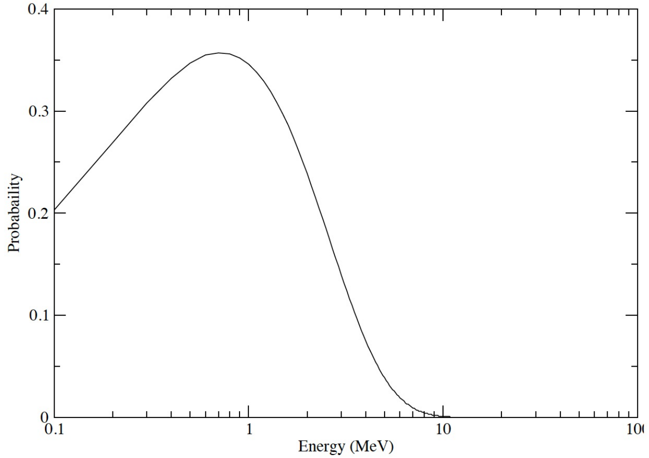


- Referee’s main points:
  - Is the ‘Watt component’ really a reasonable physical description of the detectors response to neutrons? Does it work at specific angles since it describes the energy distribution averaged over all emission angles?
  - Is taking the counts in the full time window reasonable? Why choose to include so many background counts?

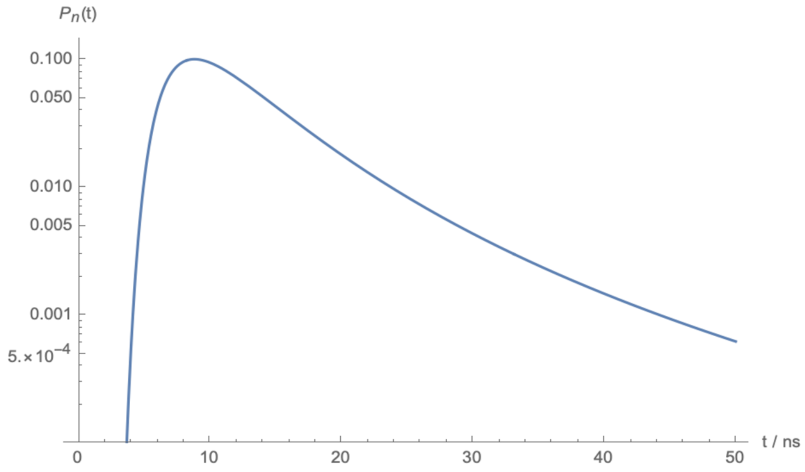
Neutron Subtraction – Methodology

Thermal neutron induced fission on ^{235}U results in the prompt fission neutrons – their energy spectrum is well characterized experimentally and can be described by the Watt distribution with known parameters

$$P(E) = a\sinh(\sqrt{2.29E})e^{-(bE)}MeV^{-1}$$



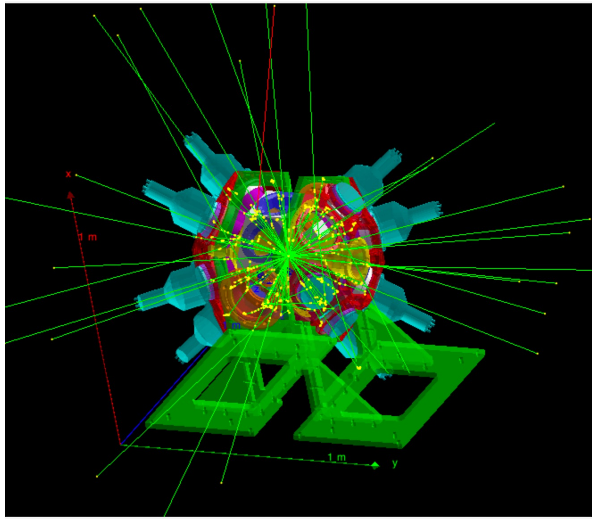
Distribution in energy

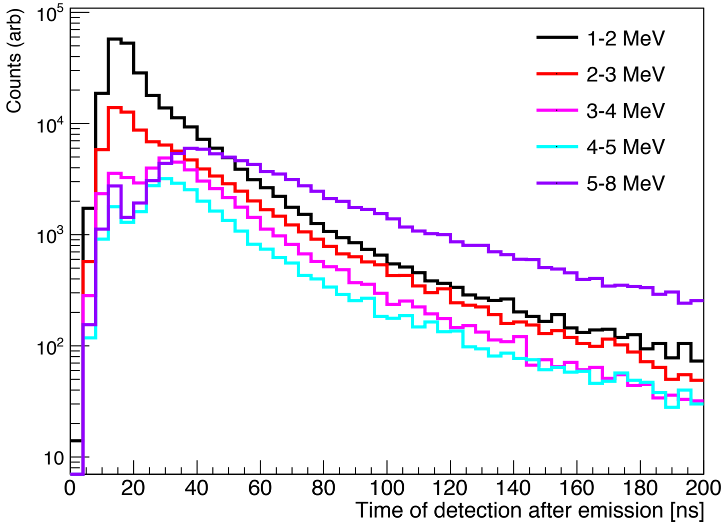


Distribution in time the neutron reaches the scintillator

Use Geant4 to simulate the detectors response to neutrons emitted at the target position with a Watt distribution in energy

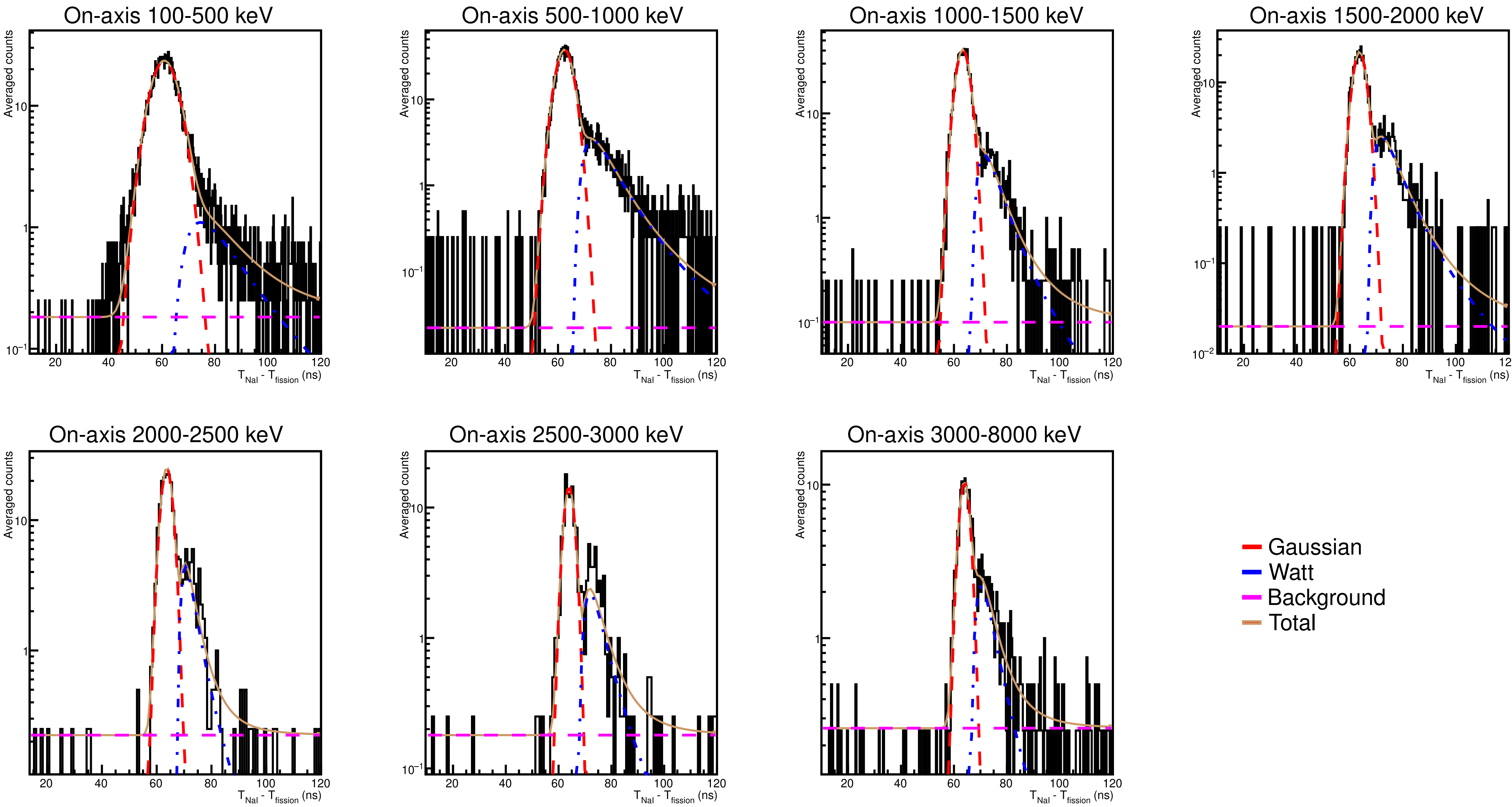
- ➢ The distribution mean moves to higher times as the detected gamma-ray energy increases – this is what we see in our data
- ➢ The shape seems to stay reasonably similar to that of the Watt distribution in time





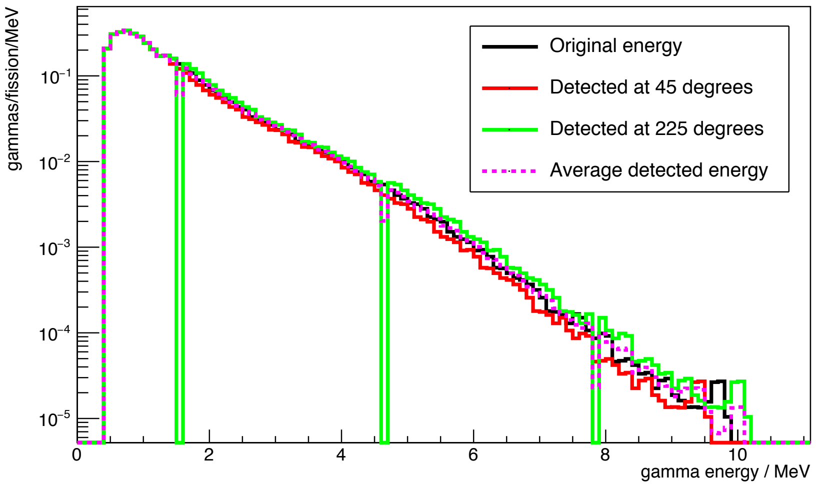
Neutron Subtraction – Methodology

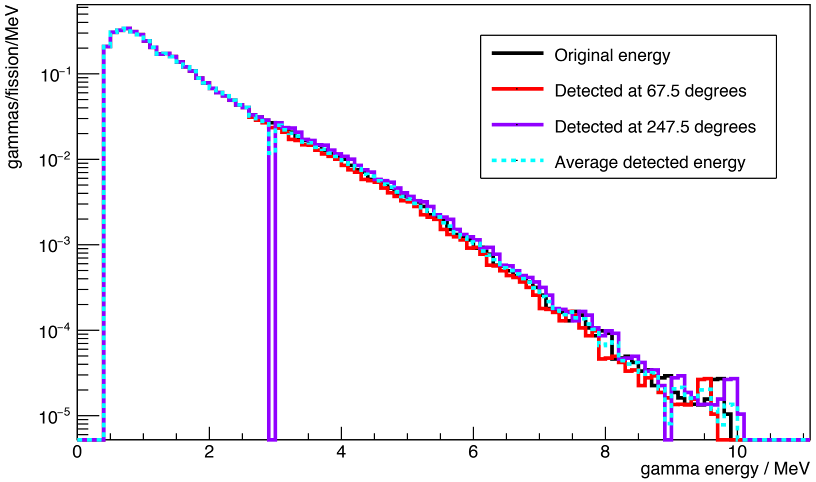
The data is well represented by our choice of Gaussian + Watt + Constant giving confidence to the methodology.

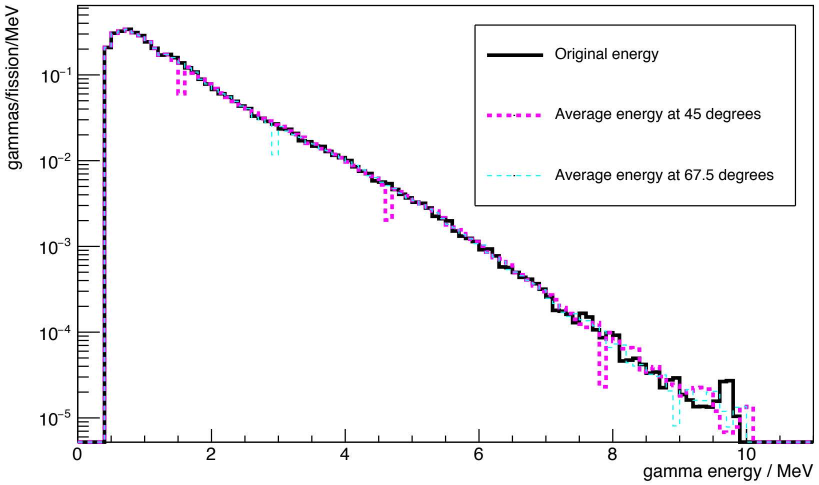


Doppler shift of gamma-rays

- Doppler shift of detected gamma-rays will be different at different fixed angles of detection
- 1% effect, however, uncertainty introduced in detected energy







Final thoughts

- Estimation of neutron contribution can be defended
- The benefits of using the wide time window to include ‘all’ counts from PFGs are likely outweighed by the disadvantages due to the large background subtraction at high gamma-ray energies. Further, ‘delayed’ PFGs will originate from a FF which has travelled some unknown distance along the fission axis therefore our response matrix for gamma-rays originating from the target position is no longer valid
- Analysis with a narrow (2 sigma) window around the PFG peak is underway and the paper will be resubmitted. The final results are likely to not change very much.

Acknowledgements

- University of Manchester STEFF team (present and past)
    - A.G. Smith, T. Wright, N. Sosnin, S. Bennett, A. Sekhar, A. McFarlane, A. Smith, P.J. Davies, S. Warren, J. Ryan

- n_TOF local teams 2016 & 2018
- M.A. Millan-Callado (Universidad de Sevilla)

- National Nuclear Laboratory (NNL) Advanced Fuel Cycle Program (AFCP)
- UK Nuclear Data Network (UKNDN)

- Science and Technology Facilities Council (STFC)
- Engineering & Physical Sciences Research Council (EPSRC)

Thank you