Digital Pulse Processing of Semiconductor Detector Signals

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GEFÖRDERT VOM

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bcgs

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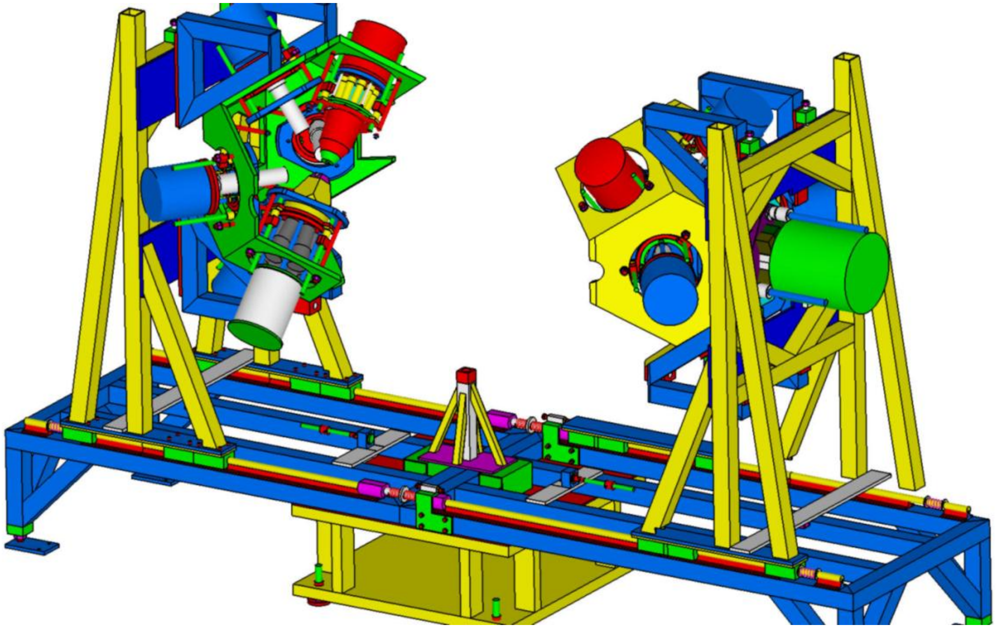
Outline

- Motivation of digital pulse processing
- The DGF-4C module
- Results with HPGe and Silicon detectors
- Summary

The HORUS spectrometer

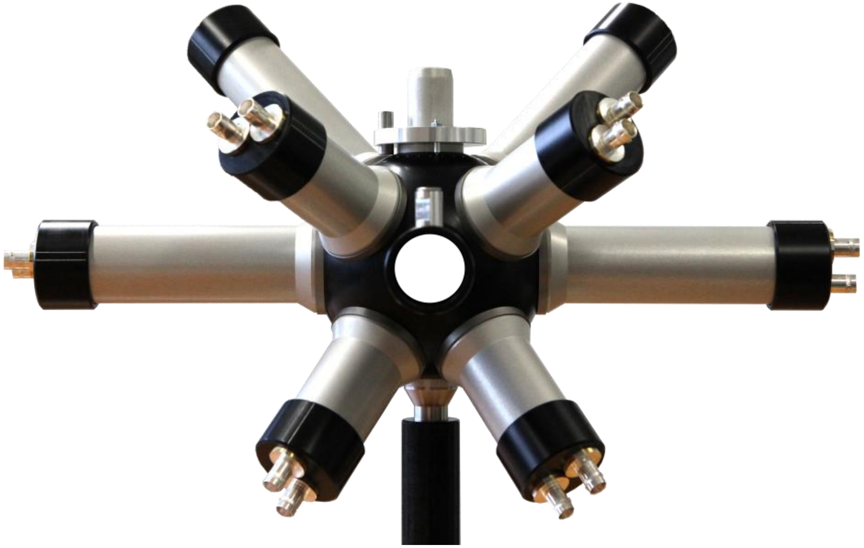


The HORUS spectrometer at the University of Cologne:

- 14 HPGe detectors for high resolution γ spectroscopy
- BGO shields
- Absolute efficiency of up to 5% at 1.33 MeV

The SONIC array:

- 8 ΔE-E sandwich silicon detectors for charged particle spectroscopy
- Particle identification
- Solid angle coverage of 4%



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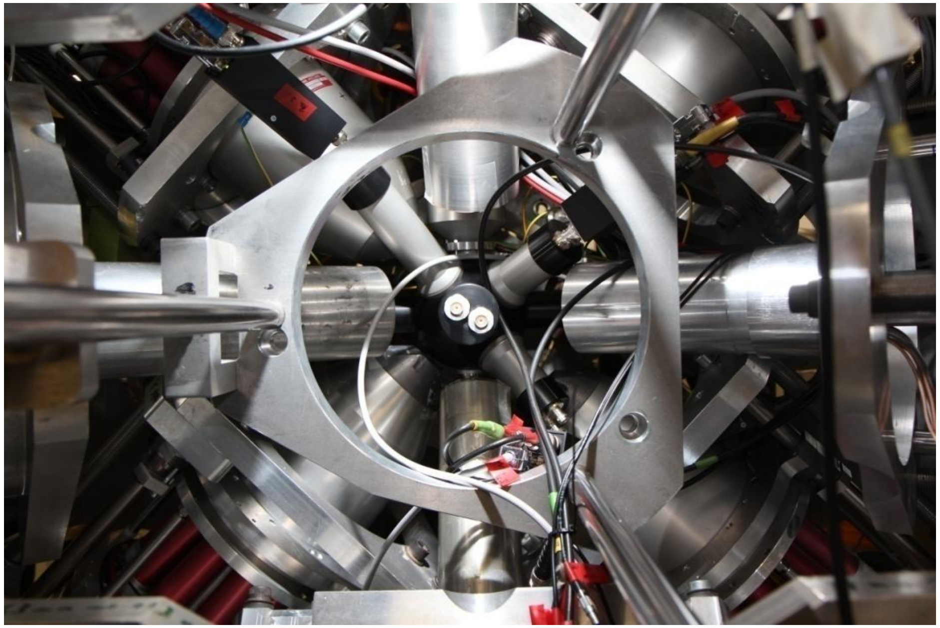

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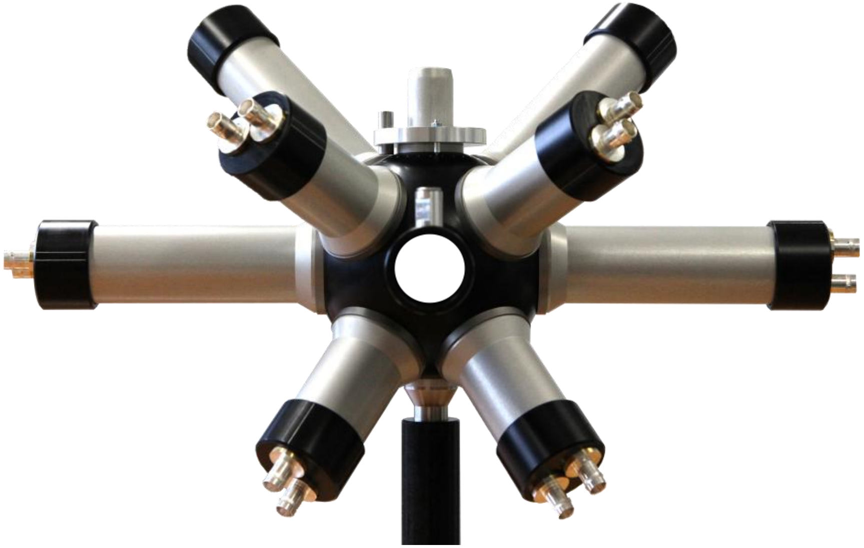


Analog vs. digital spectroscopy

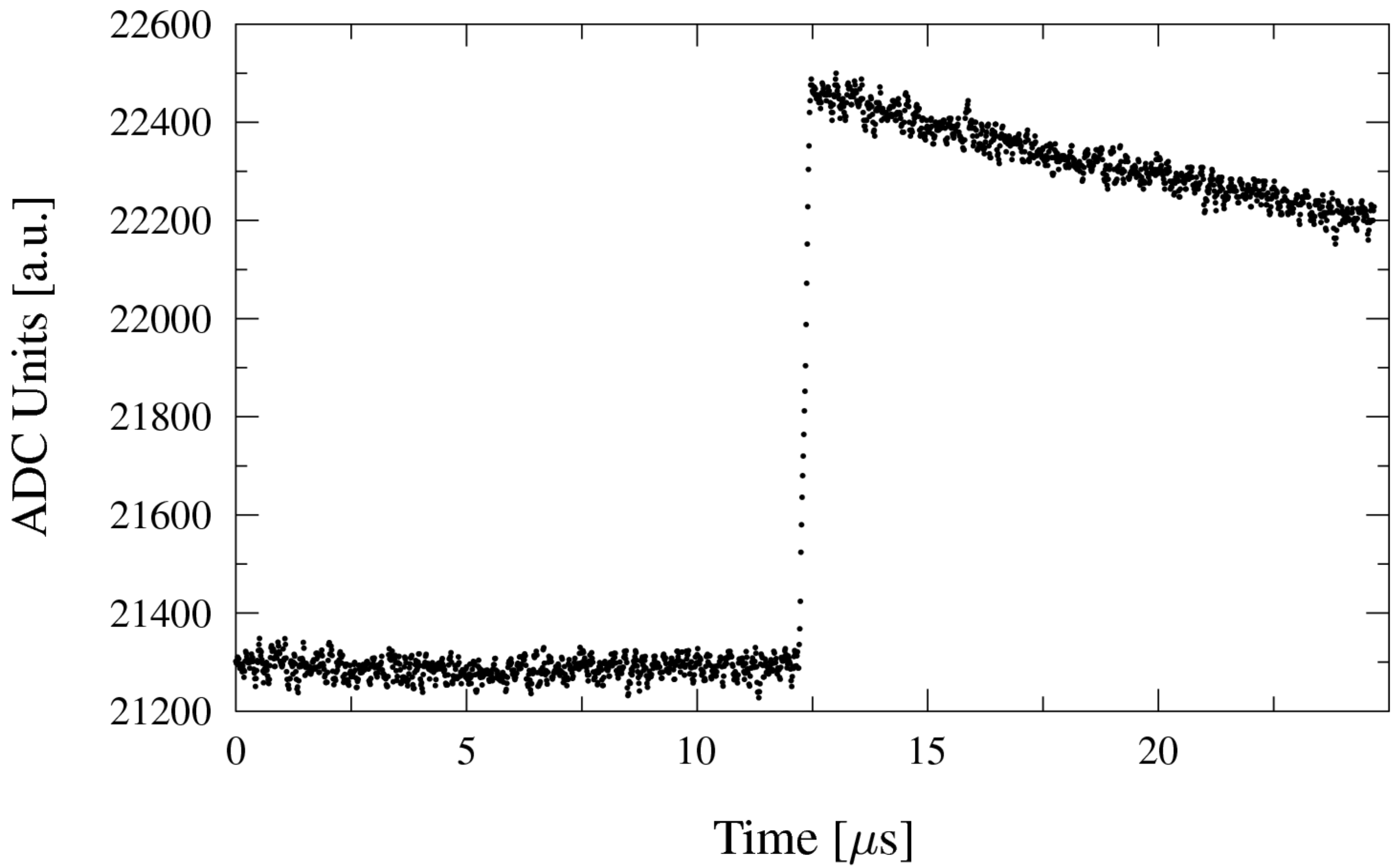
Analog signal processing

- Filtering of signals in different modules to obtain spectroscopic quantities
- Pulse shape analysis hard to implement
- Noise important at all stages
- Highly specialized electronics
- Optimized in ≈ 50 years of use

Digital signal processing

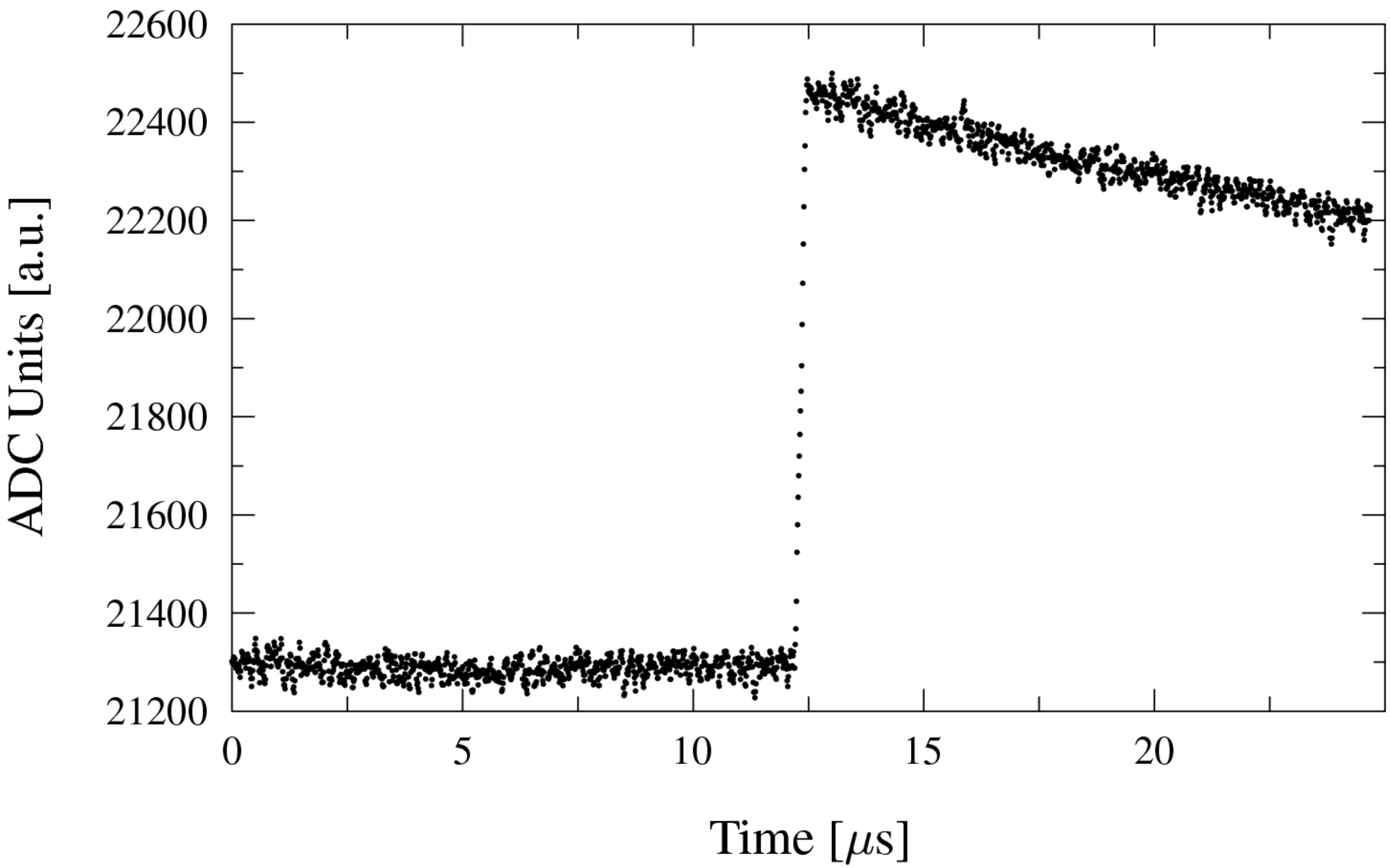
- Sampling of the signal in the MHz regime provides all spectroscopic information
- Pulse shape analysis can be easily implemented
- Noise important only before sampling
- Commonly used components (consumer electronics)

Signal processing - sampling



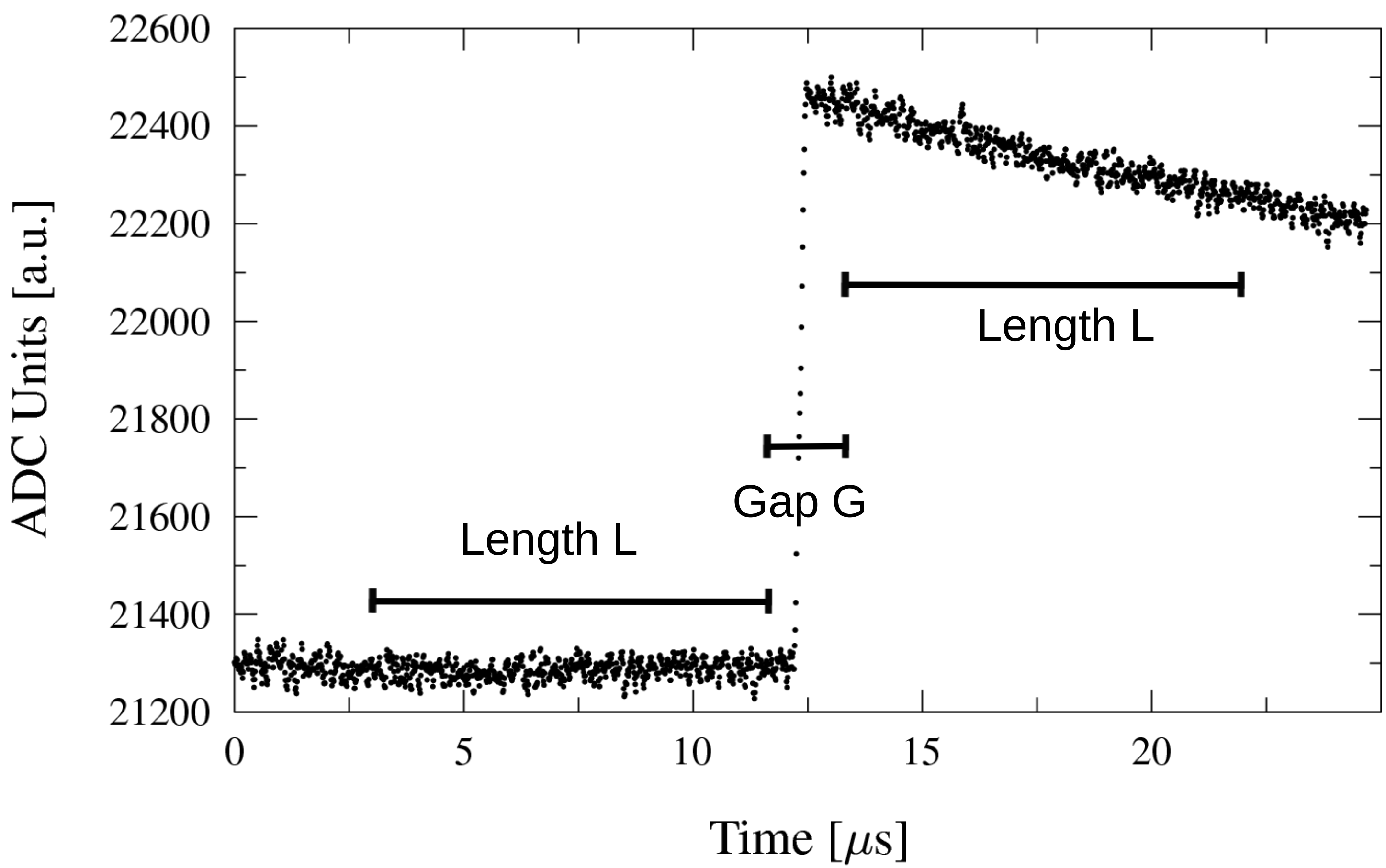
- Sampling of the preamplifier signal at a rate of 10's of MHz

Signal processing - sampling



- Sampling of the preamplifier signal at a rate of 10's of MHz
- Online signal processing using a combination of FPGA and DSP

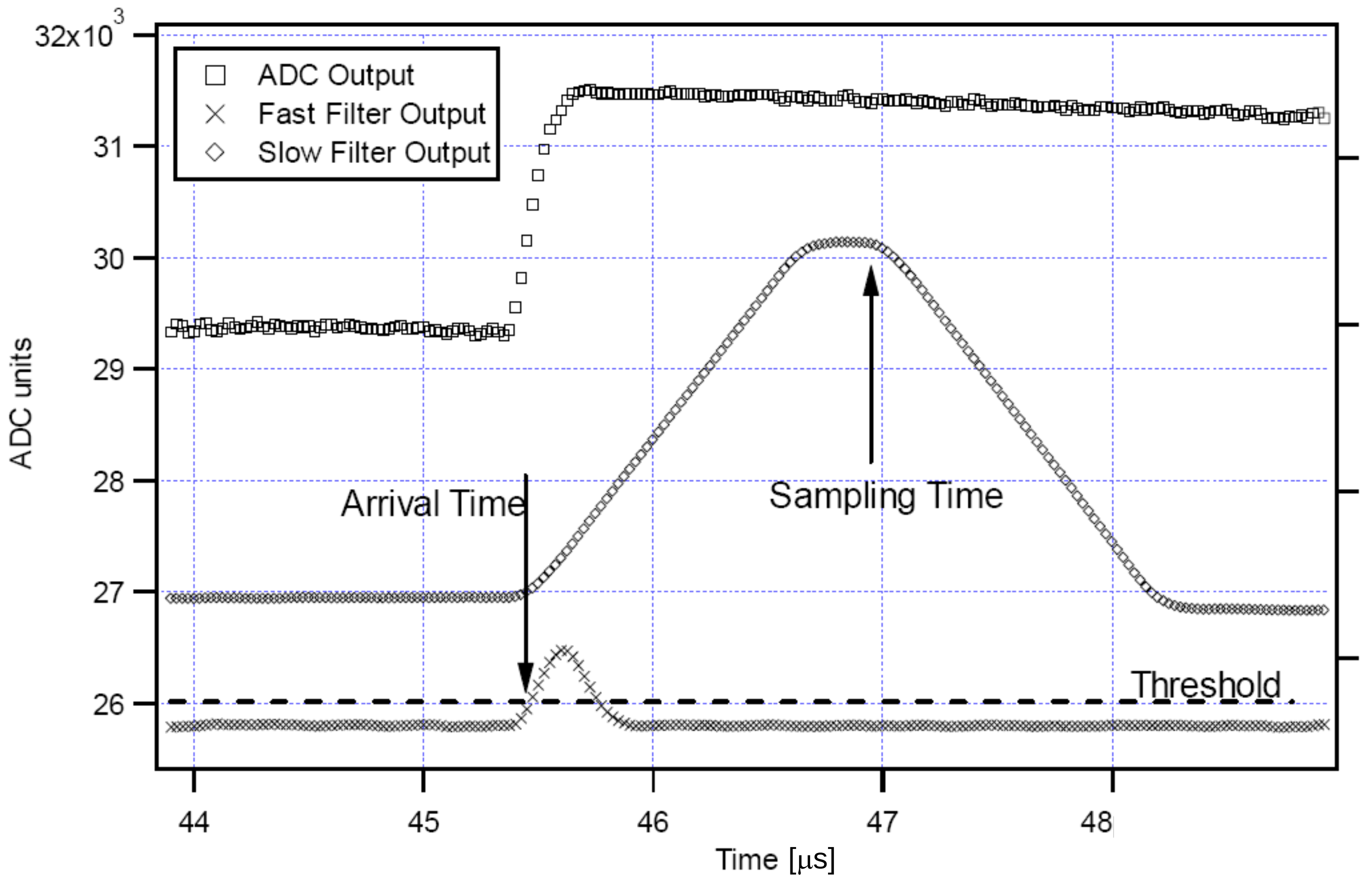
Signal processing - sampling



- Sampling of the preamplifier signal at a rate of 10's of MHz
- Online signal processing using a combination of FPGA and DSP

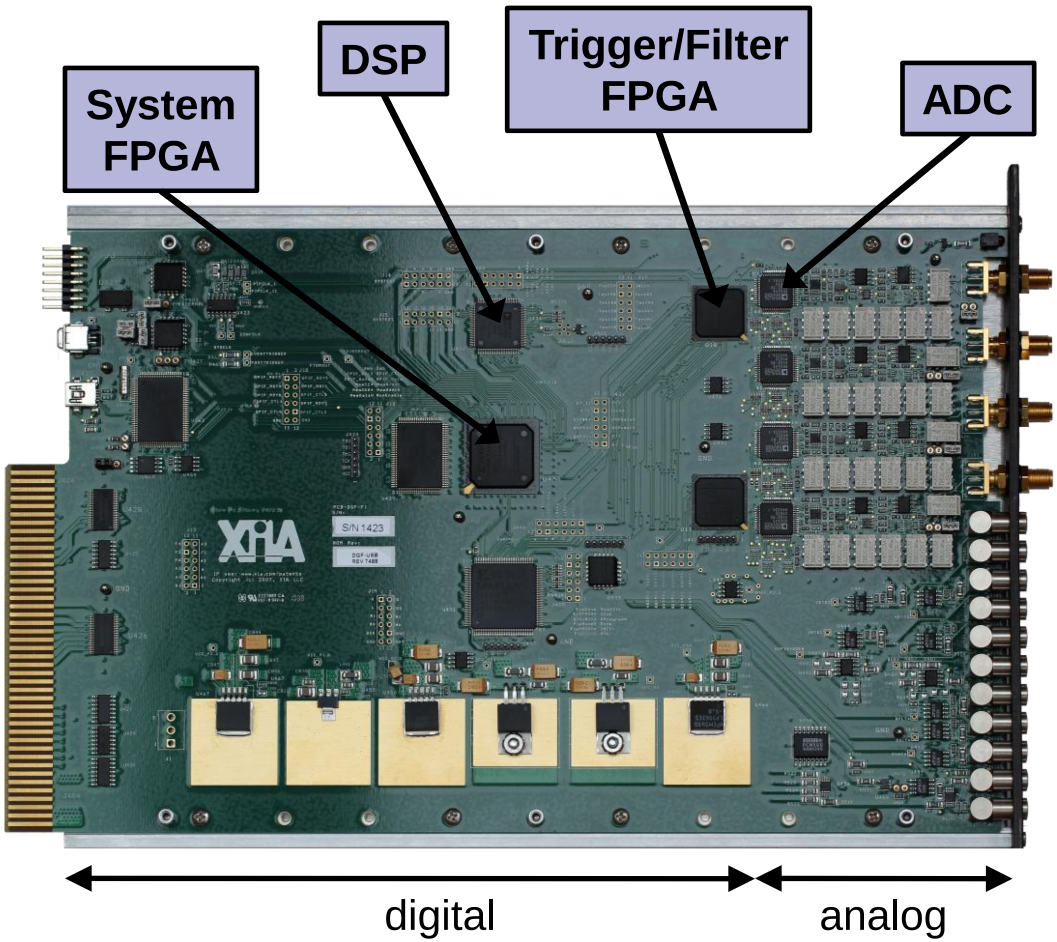
Trapezoidal filter algorithm

- Slow filter: Energy determination → filter amplitude
- Fast filter: Time determination → leading edge trigger
  Trigger to select events of interest (e.g. Pile-up rejection)



The Digital Gamma Finder (DGF-4C) [1,2]

- *Revision F modules*
  cost: about 7000 €
- *Pipeline ADC: digitizing*
  sampling rate 80 MHz
  depth: 14 bit
- *FPGA: filter algorithms*
  signal shaping and
  pile-up rejection
- *DSP: signal processing*
  determination of energy
  and time of the signal
- Readout of the data via USB in event-by-event mode



[1] W.K. Warburton *et al.*, Appl. Rad. and Isot. **53** (2000) 913
[2] XIA LLC, Hayward, CA, USA – http//www.xia.com

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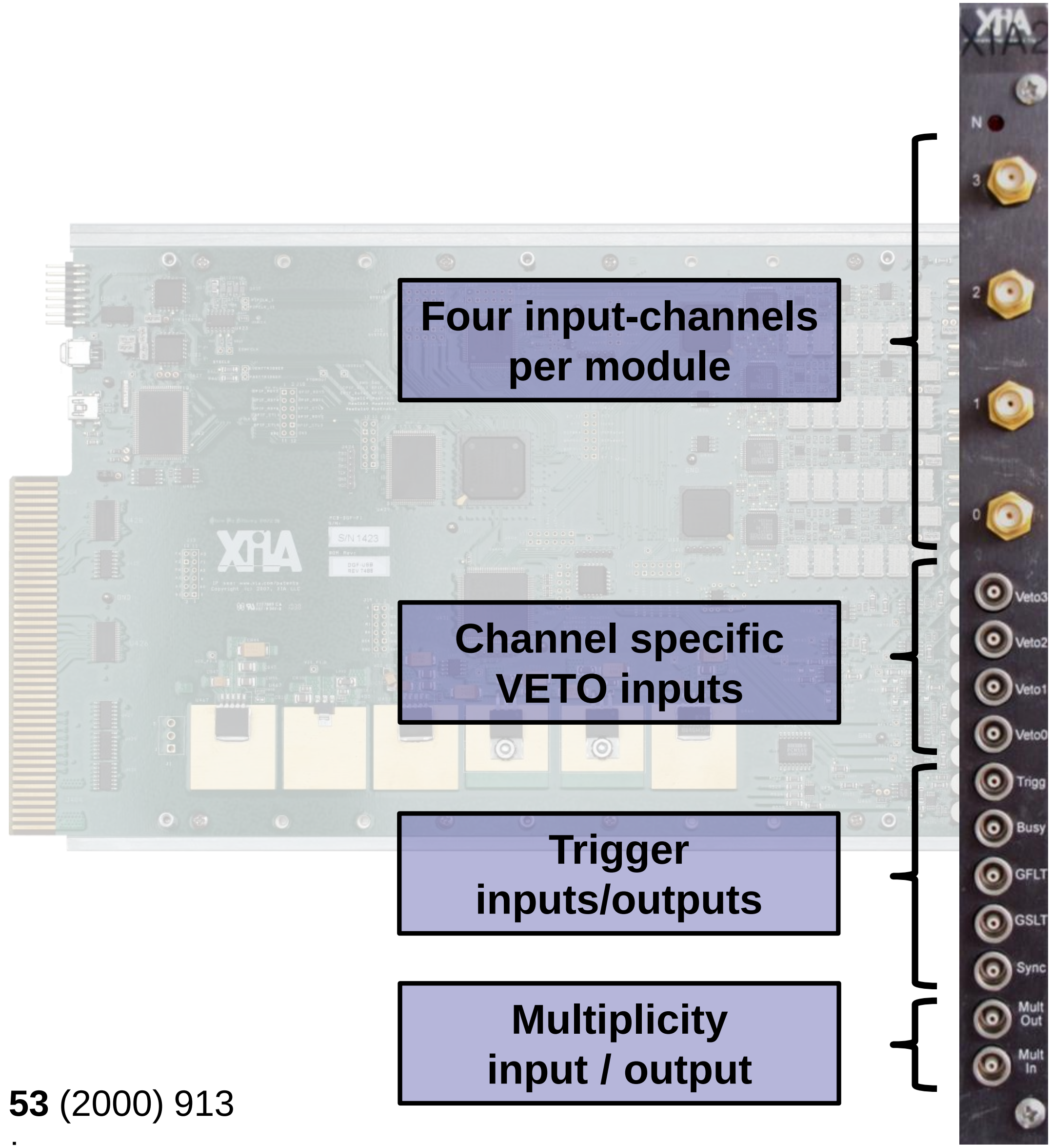

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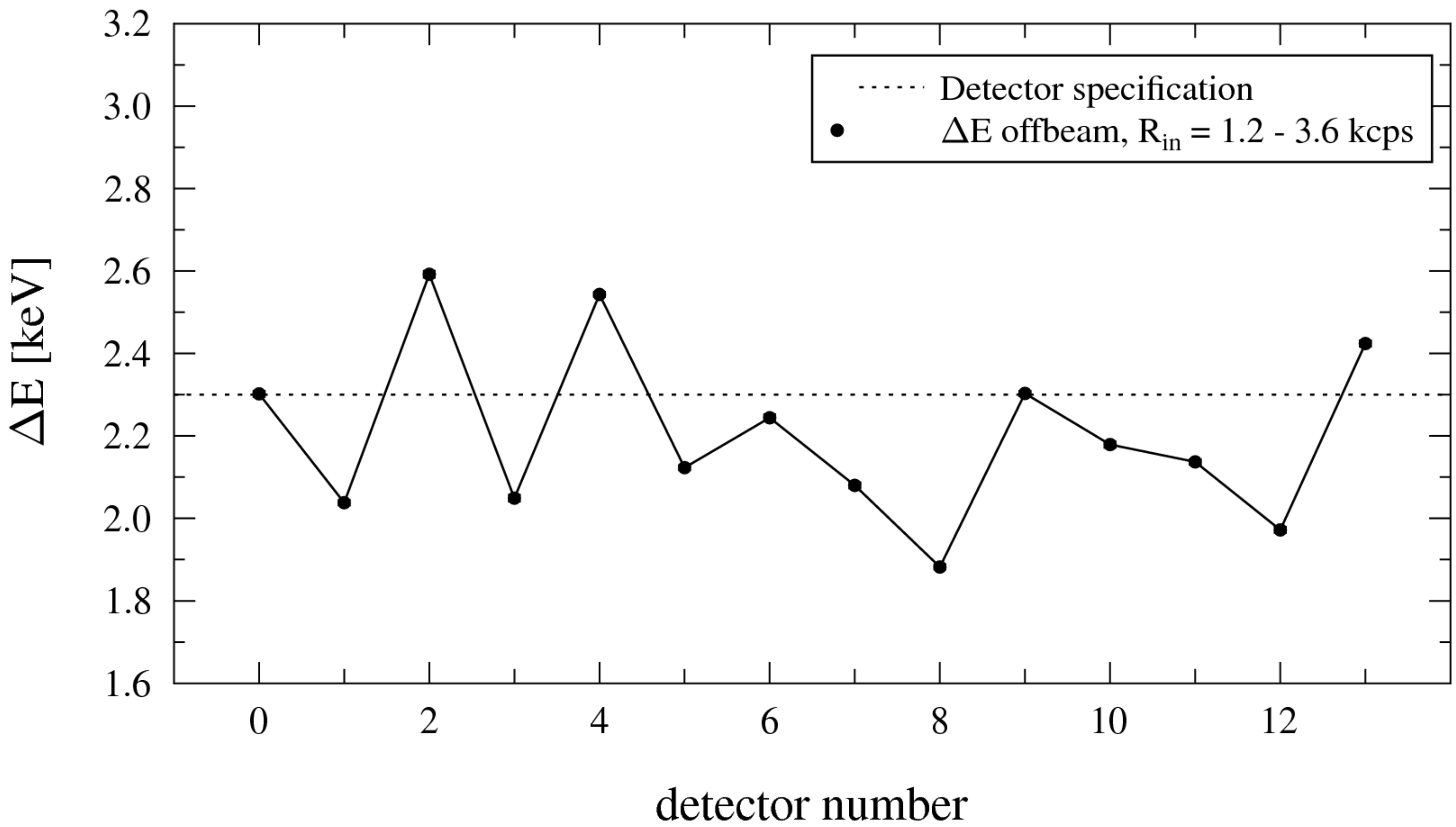
Results - energy resolution

Test with 80% (*) HPGe detectors:



(*) Relative to 3 x 3 inch cylindrical NaI detector

Results - energy resolution

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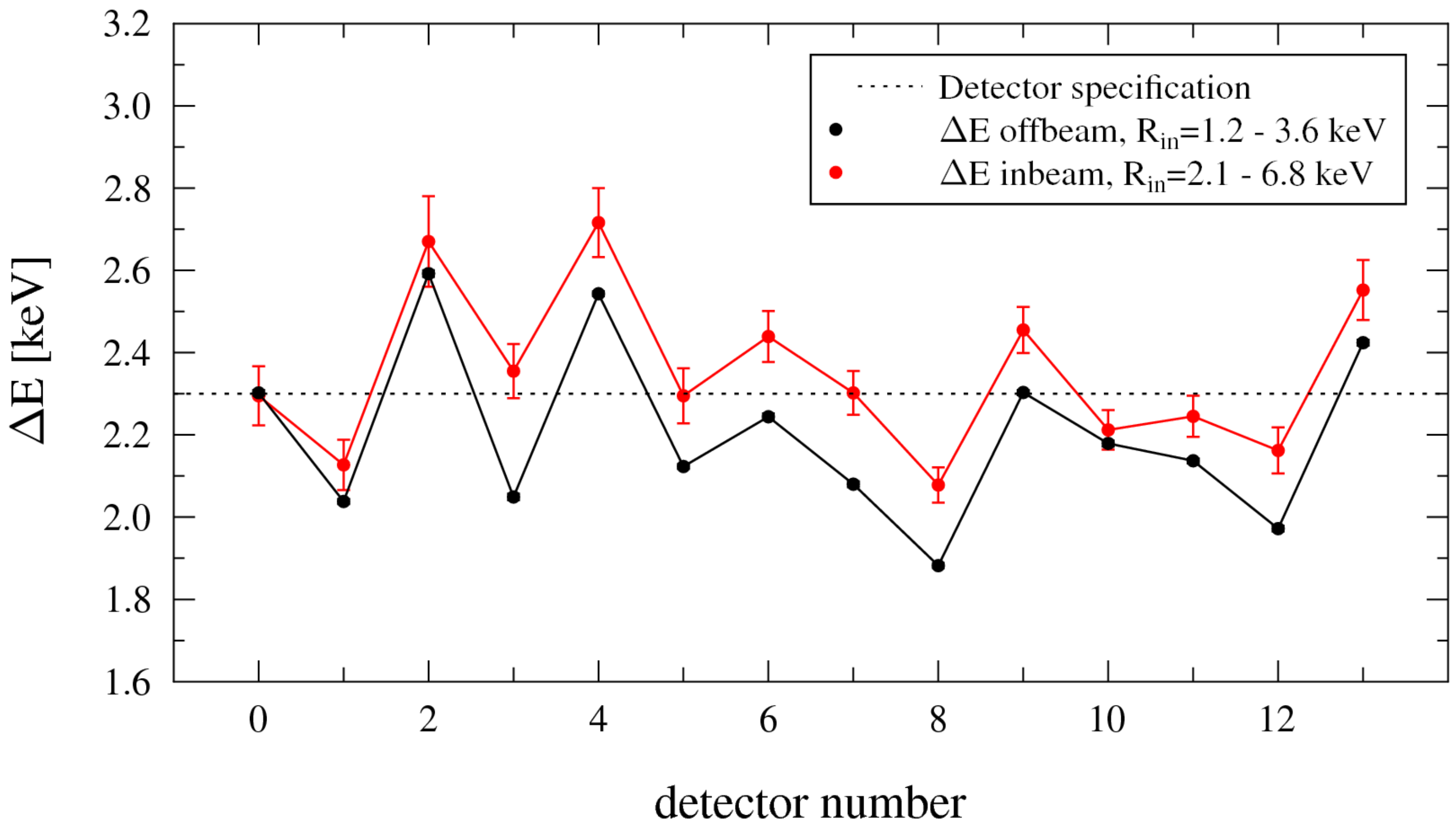


- Energy resolution is slightly worsened due to beam-induced noise and higher countrate

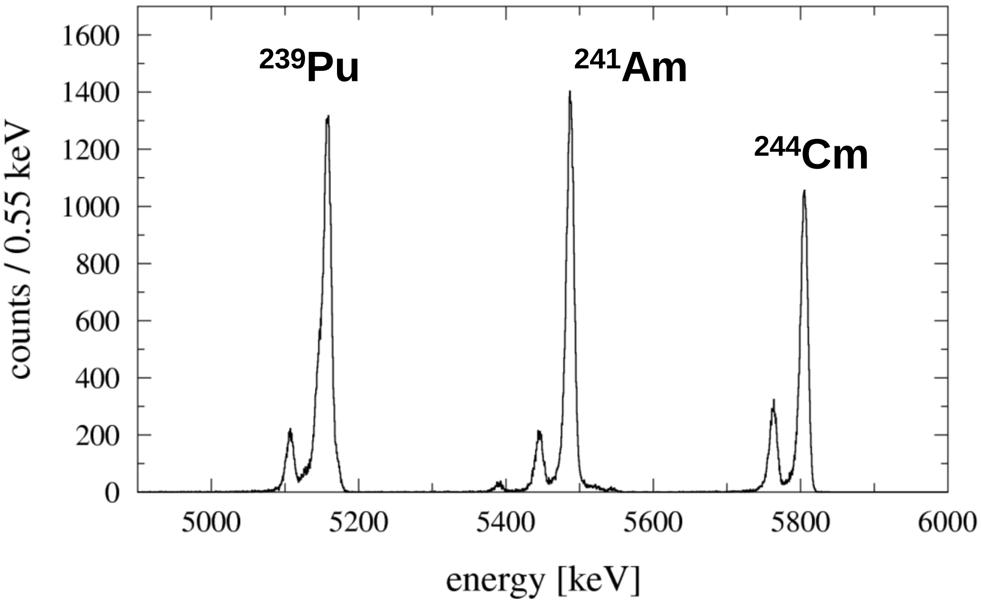
[*] Relative to 3 x 3 inch cylindrical NaI detector

Signal processing of Silicon detector signals

Offbeam test:

- Energy resolution measured with triple-α calibration source:

  ΔE (5486 keV): 12.00(8) keV



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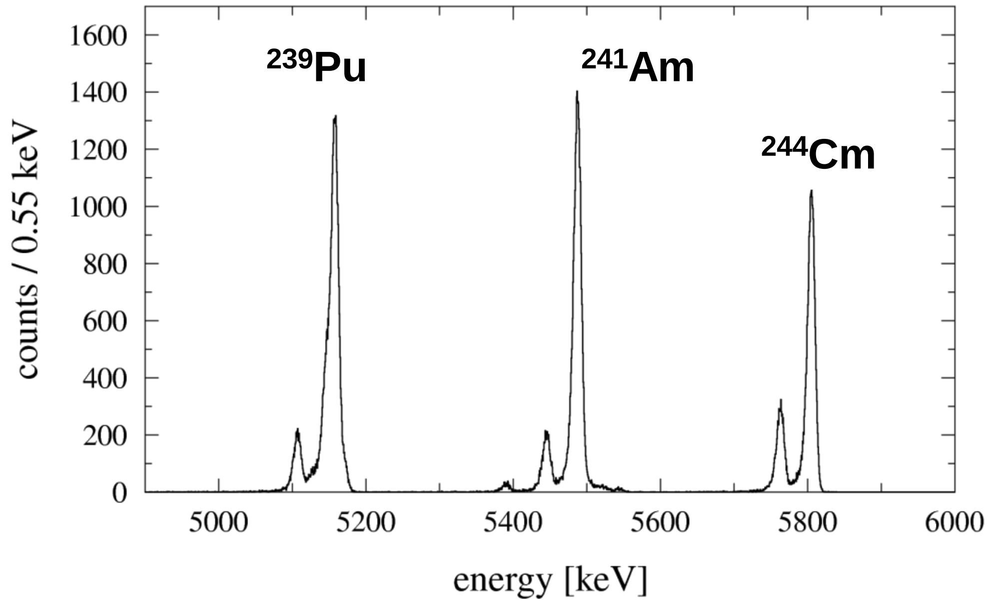
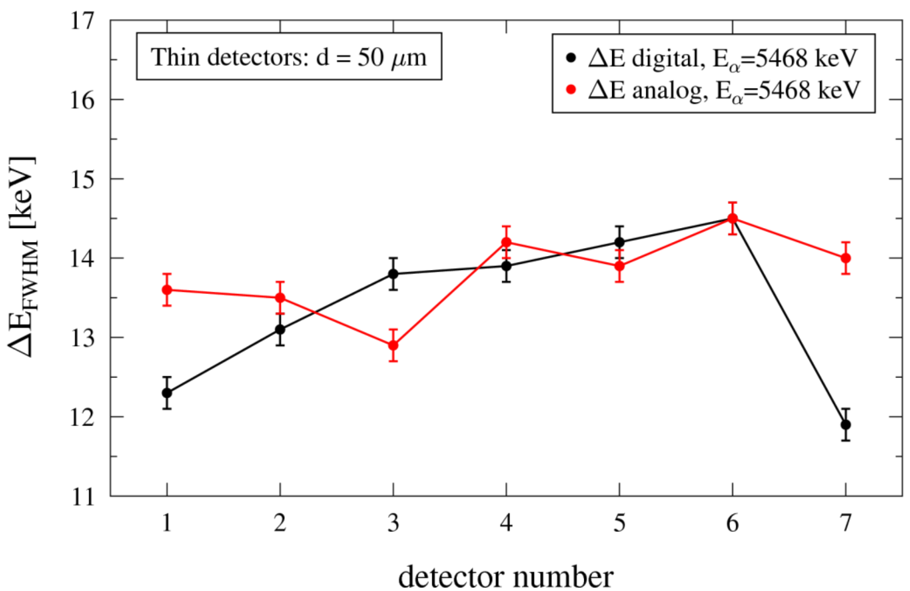
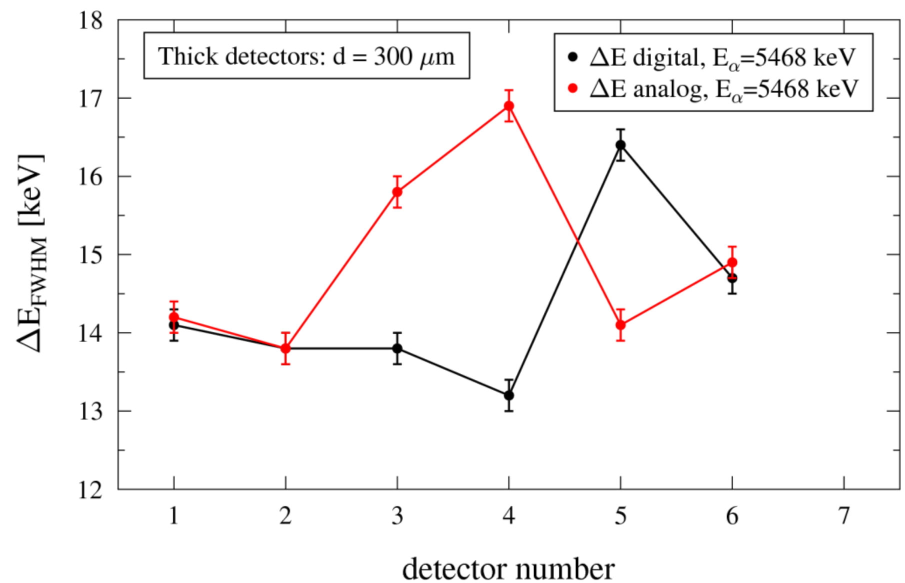


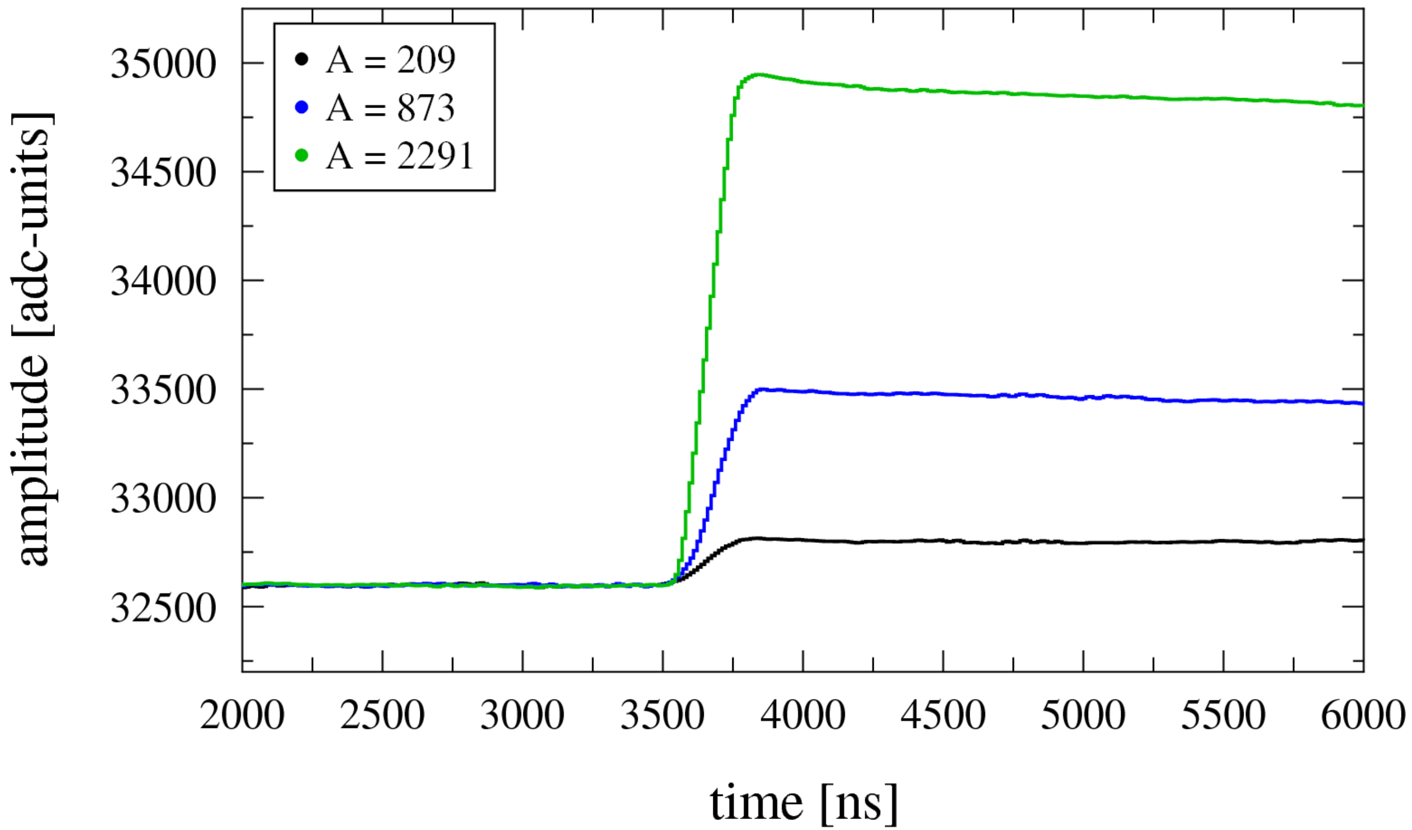




Results – timing resolution

- Time determination in DGF-4C: leading edge trigger

→ Amplitude and risetime-walk effect worsens the timing resolution



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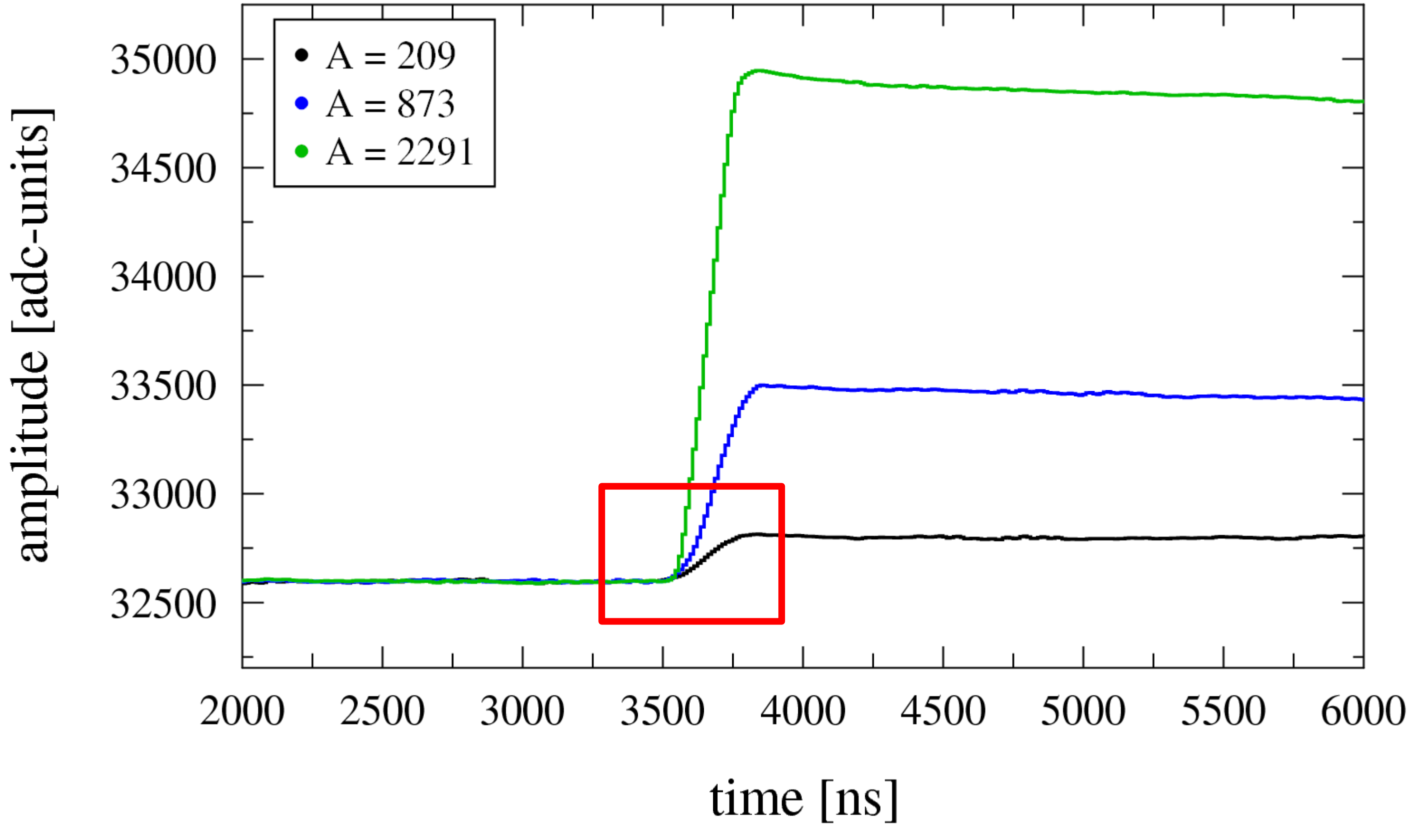

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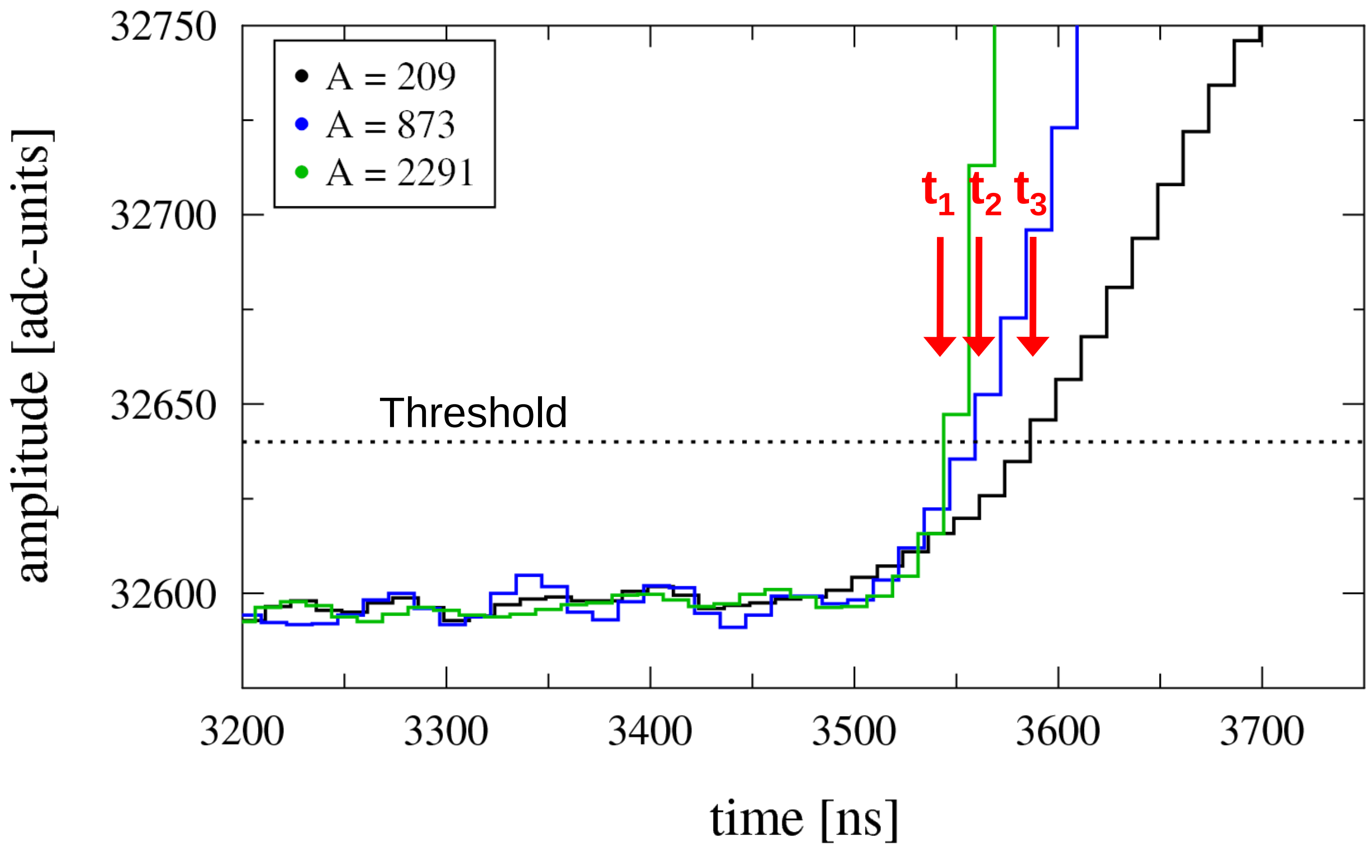
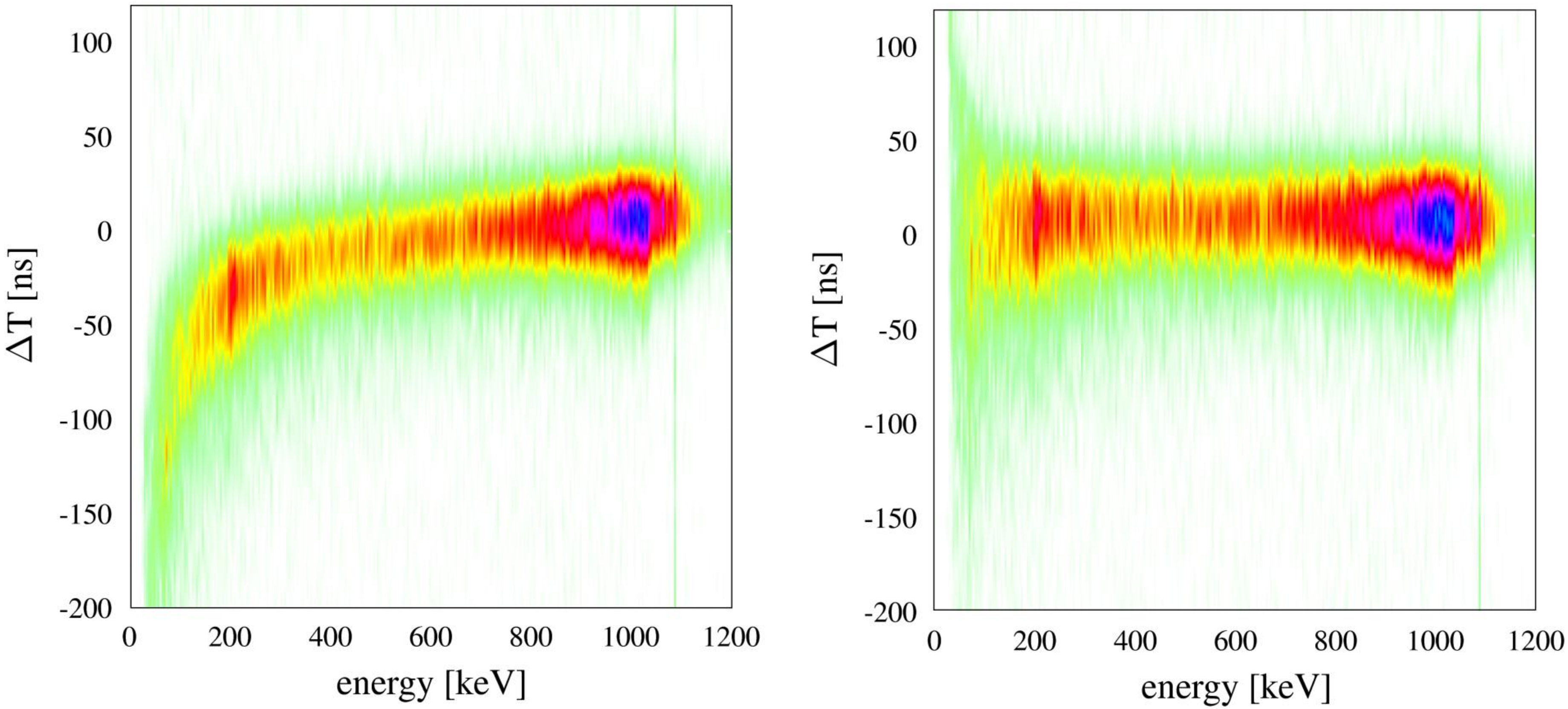


Results – timing resolution

Correction for amplitude walk:



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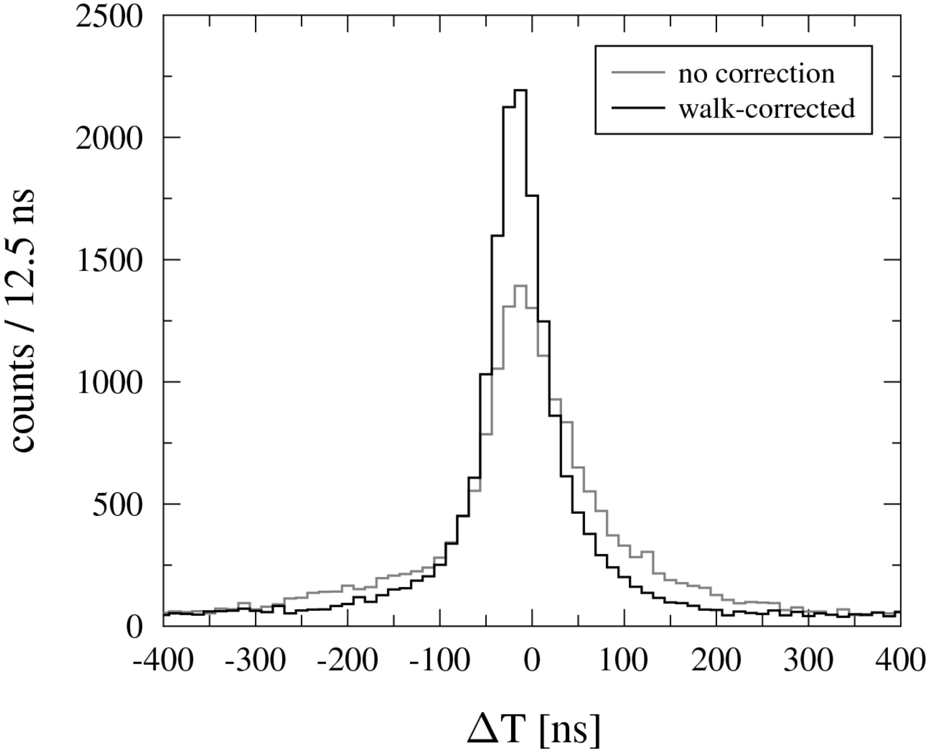

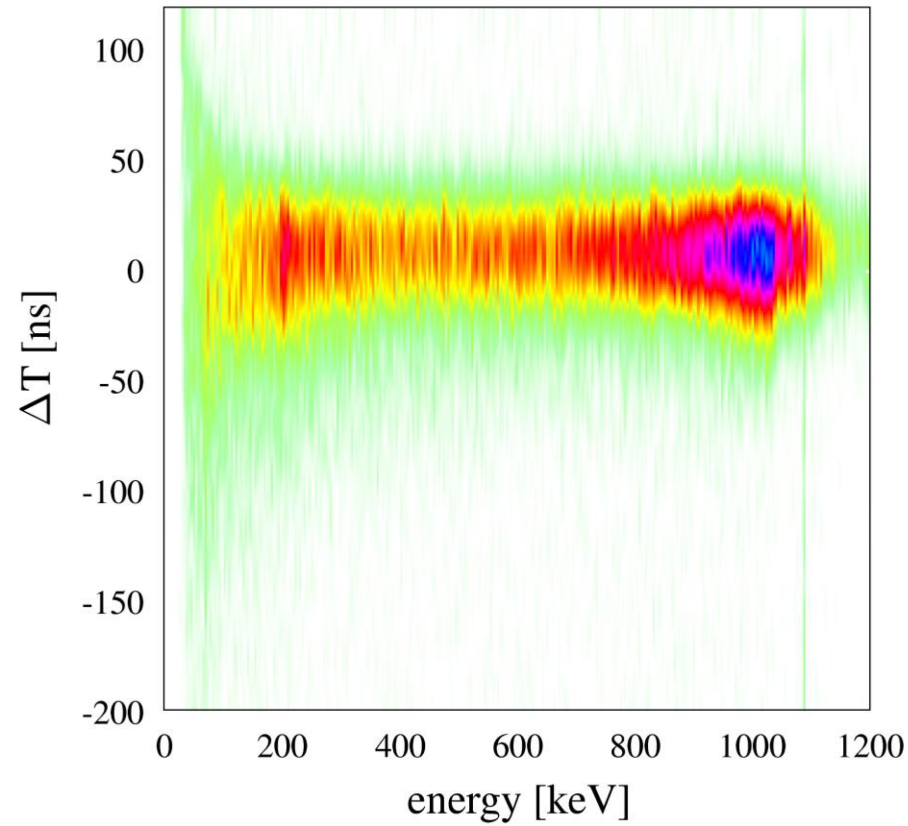

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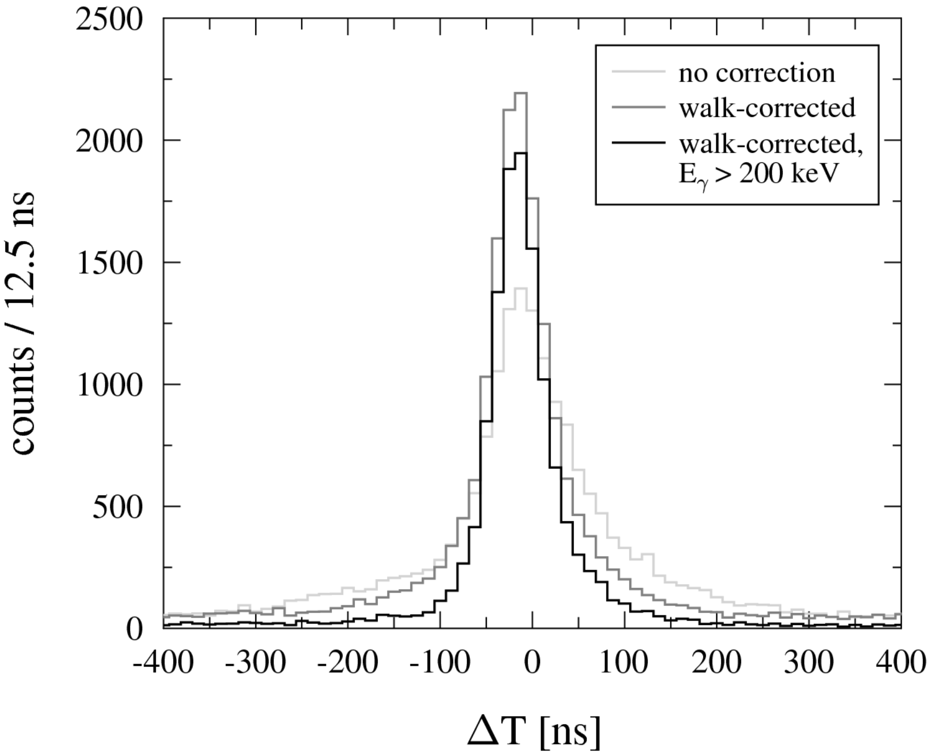
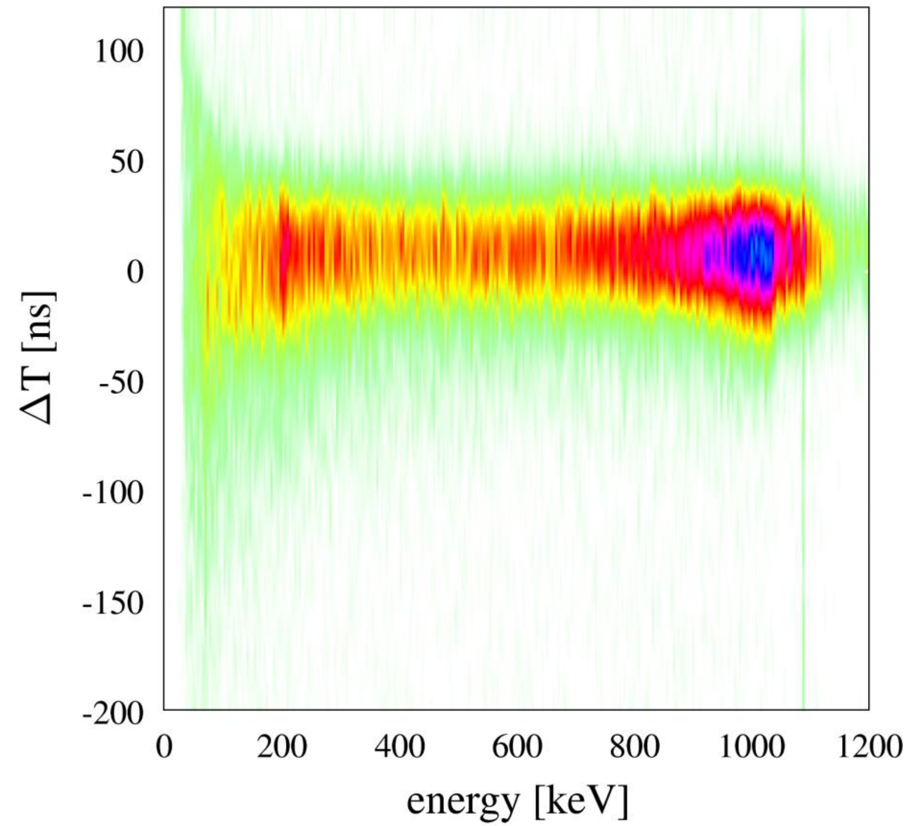




- Timing resolution in coincidence with 1173 keV: $\Delta T \approx 30$ ns
- Improvements with a digital constant fraction algorithm planned [1]

[1] A. Fallu-Labruyere et al., NIM A **579** (2007) 247

Deadtime contribution in the DGF's

Events not processed in the DGF

→ Average values, obtained with ^{226}Ra calibration source

14 detectors at 9.6 kHz (av.) / ch.

- Pile-up rejection in the FPGA
  - Depends on count rate and filter length:

$$R_{out} = R_{in} \cdot \exp(-2T_F \cdot R_{in})$$

with T_F: filter length

12.6 %

- DSP deadtime
  - DSP blocked by signal processing

9.9 %

- Readout deadtime
  - Readout of data from DGF-4C to EM/host

6.3 %

Fraction of events lost per channel in the DGF: **28.8 %**

External gating conditions

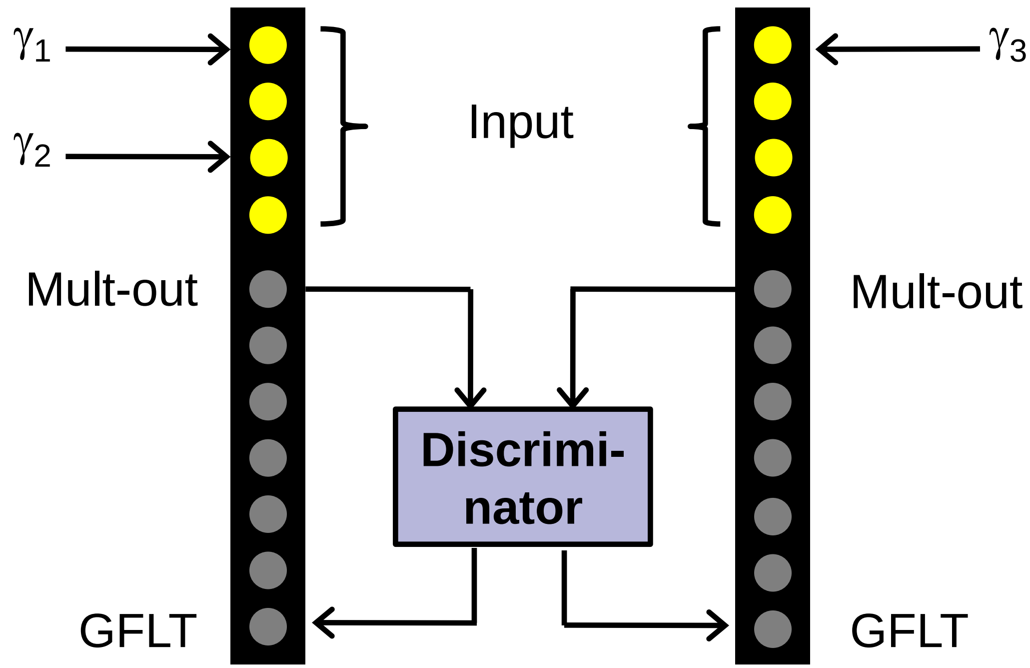
Applications:

- pulsed beam
  → "beam-on" condition
- γγ-coincidence experiments
  → multiplicity filter

Advantages:

- reduced background
- reduced deadtime
  → less data to process for DSP
  → less data to readout

- DGF-4C modules:
  late event validation via GFLT input
- γγ-coincidence experiment:
  number of detected events increased by 30%



Summary

- Digital signal processing yields various benefits compared to analog spectroscopy

  → Easy PSA, low-cost, less bulky setup, ….

- DGF-4C modules for readout of HORUS and SONIC

  → Processing Silicon and Germanium detector signals

  → Channel specific VETO input for BGO suppression

  → Good energy and time resolution

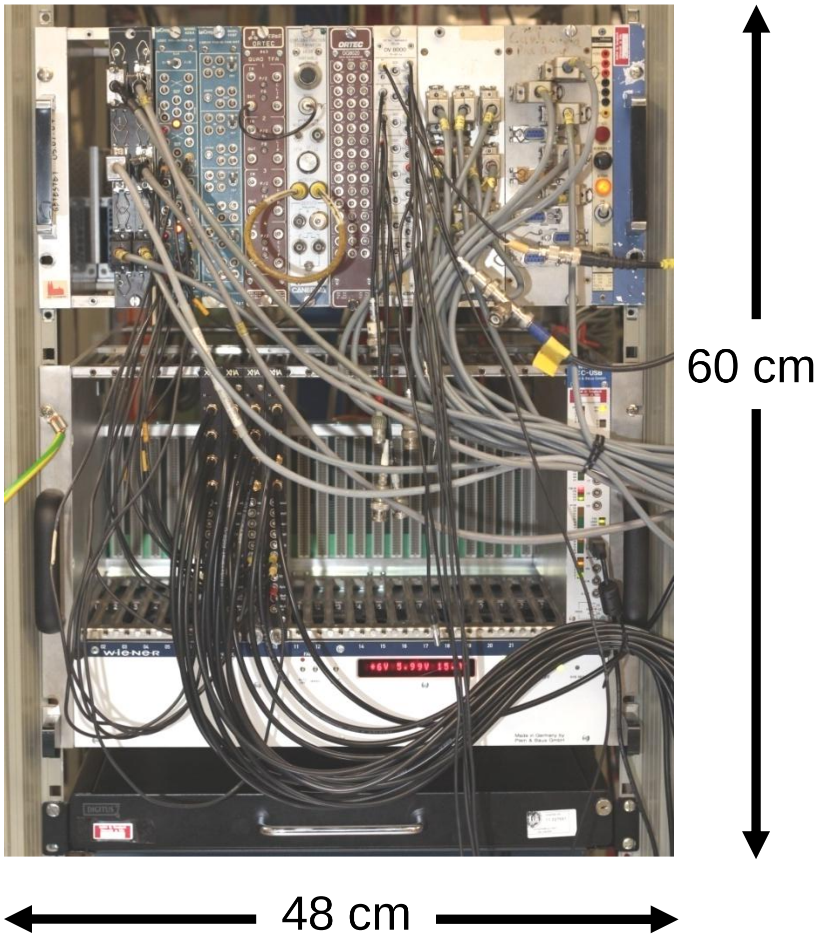
  → Reduced deadtime compared to analog systems

Thanks to:

V. Derya, M. Elvers, J. Endres, C. Fransen, W. Hennig, J. Mayer, L. Netterdon, S. Pascu, G. Pascovici, S. Pickstone, P. Scholz, A. Sauerwein, M. Spieker, T.-M. Streit, N. Warr, M. Weinert and A. Zilges

Advantages of Digital Data Acquisition

- Cost and space saving
- Preamplifier signal is sampled right away
  - ➔ Reduction of signal instabilities
  - ➔ Conservation of signal quality
- Reduced deadtime
  - ➔ Processing of higher countrates
- Comparable energy and timing resolution for Silicon and HPGe detectors



Digital data acquisition with DGF-4C modules

Advantages of Digital Data Acquisition – Deadtime

Contributions to deadtime - analog:

Examples:

- Spectroscopy amplifier — one HPGe at 10 kHz: 10 – 25 %
  - Pile-up rejection
- ADC — one HPGe at 10 kHz: 11%
  - Comparison to reference ladder
- Data acquisition — 20 % at 15 kHz master trigger rate*, 51 % at 5 kHz master trigger rate**
  - Blocked by inhibit logic

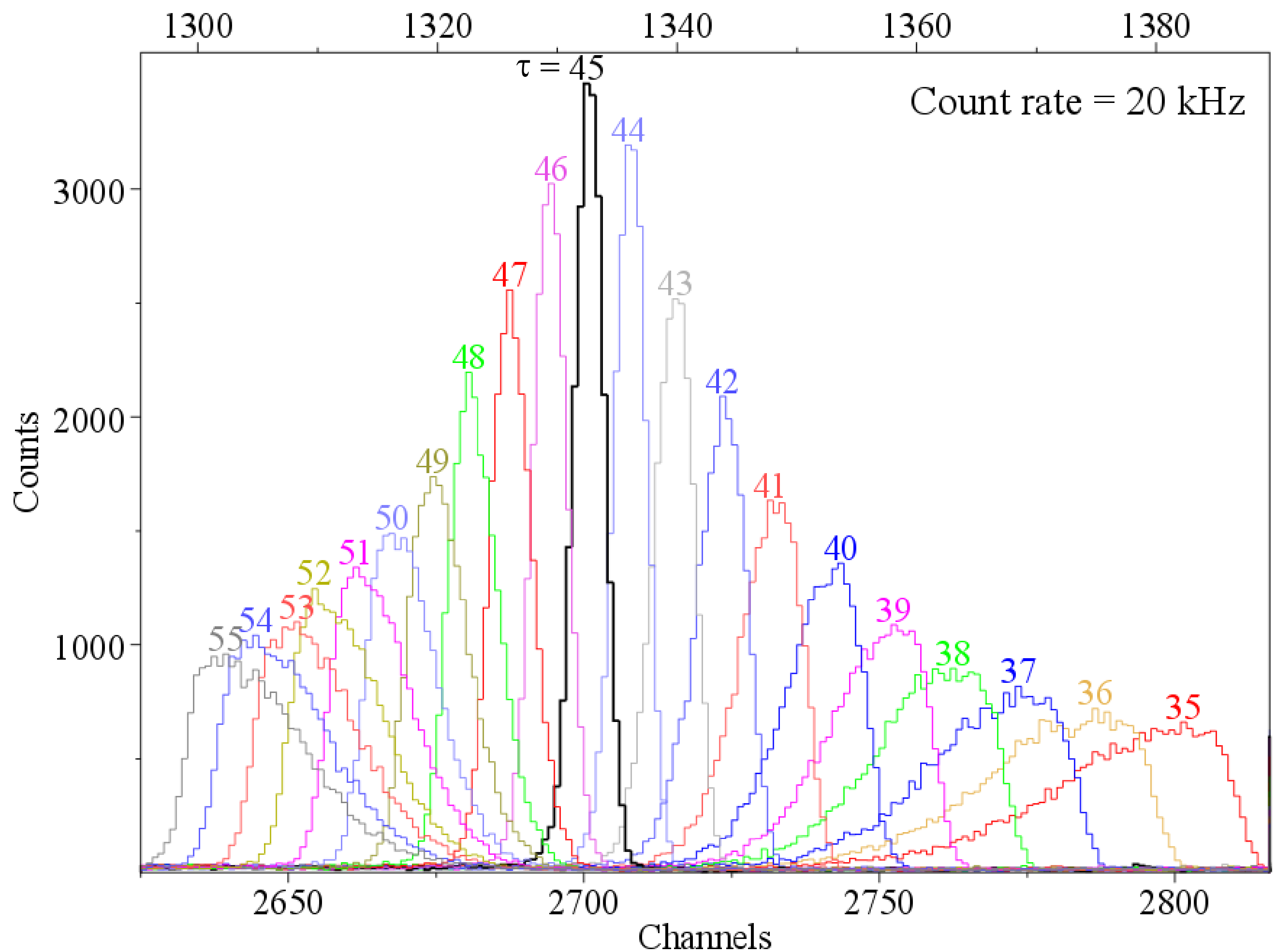
Total: 41-56 % events lost

* measured with a 14 HPGe detector array at the HORUS spectrometer

** measured with a 8 HPGe detector array at KVI Groningen

Energy Resolution – τ Correction

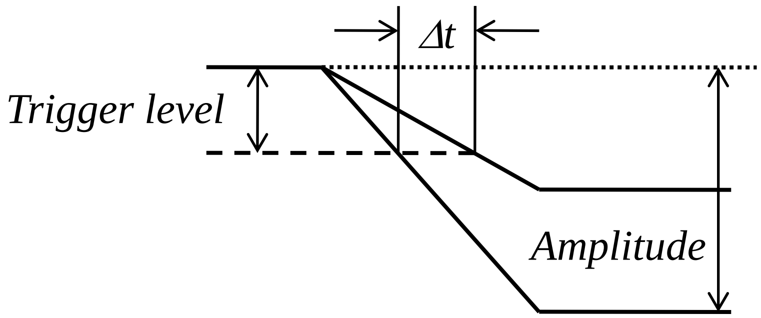
- Time constant τ most important for good energy resolution
- Adjust τ parameter to get best peak shape and resolution

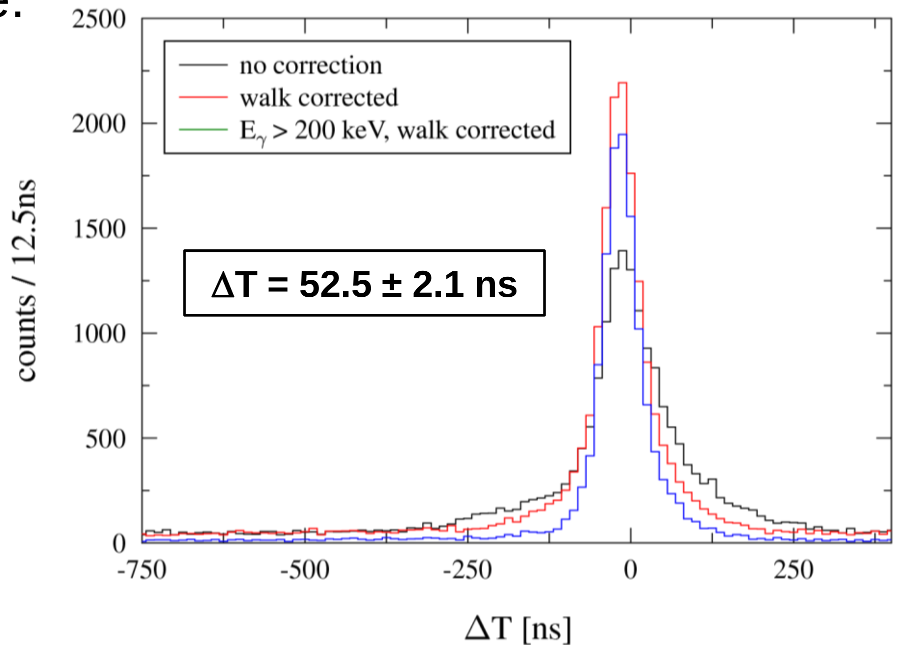


courtesy of N. Warr

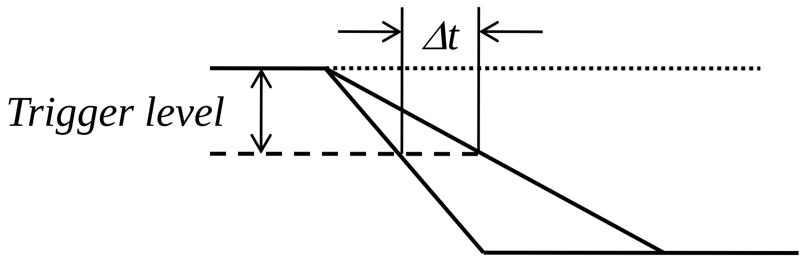
Timing Properties

- Time determination in DGF module: *leading edge trigger*
- Amplitude walk: Depending on the energy deposited in the crystal





- Risetime walk: Depending on the interaction point in the crystal

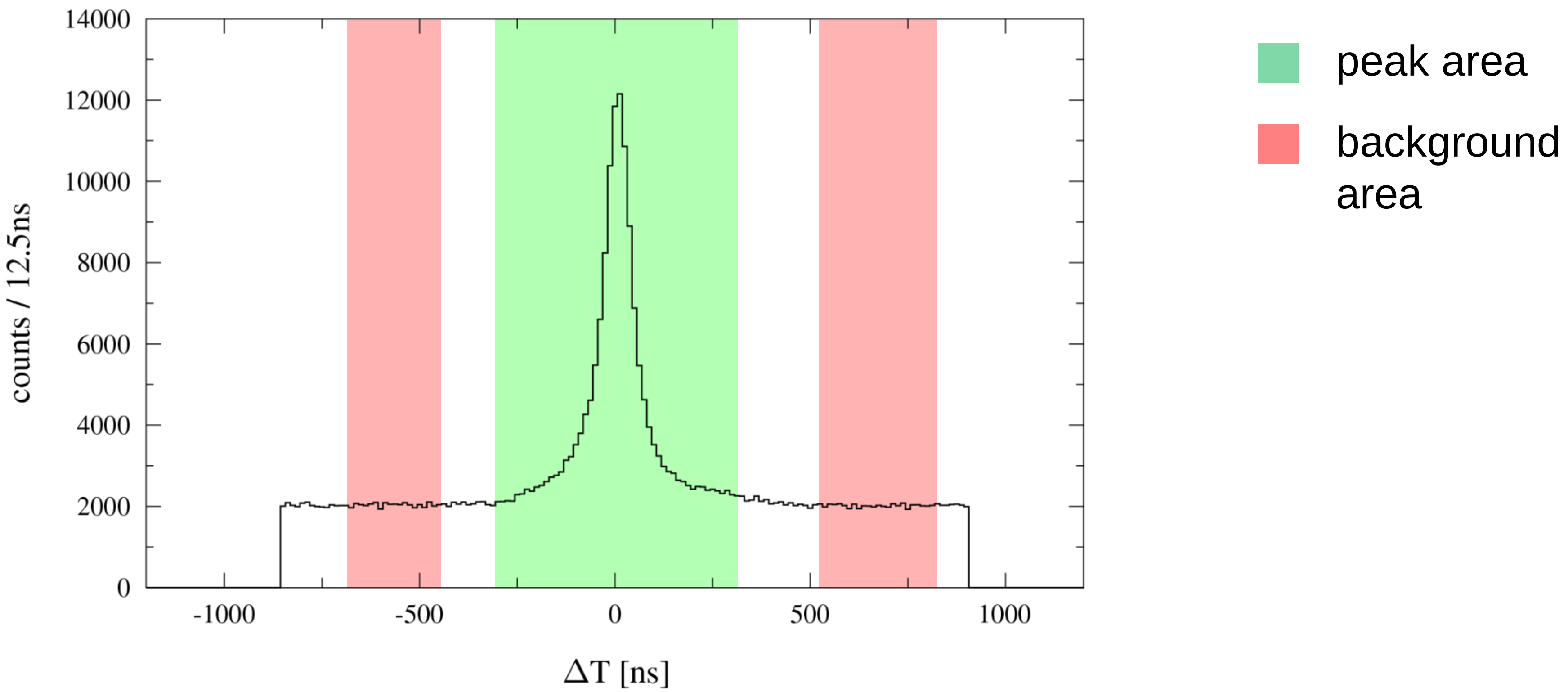


- Improvement of timing resolution with a digital constant fraction algorithm planned [1]

[1] A. Fallu-Labruyere et al.,
Nucl. Instr. Phys. Res. A **579** (2007) 247

Treatment of Random Coincidences

Timedifference spectrum between two detectors:



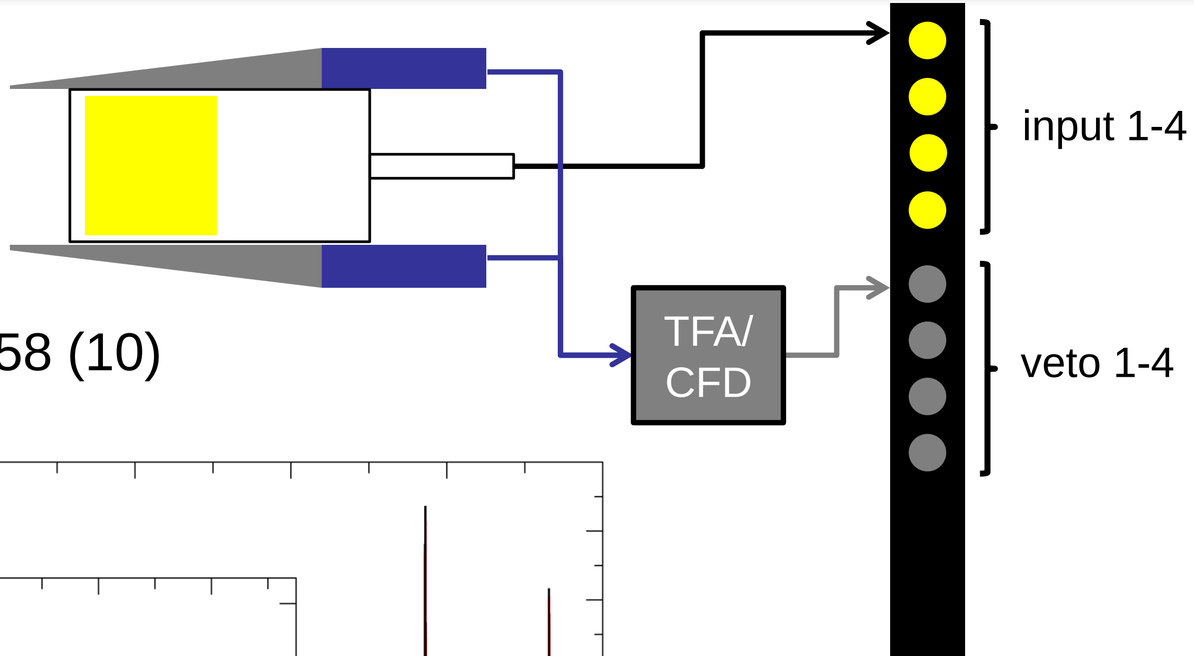
- Create peak and background matrices

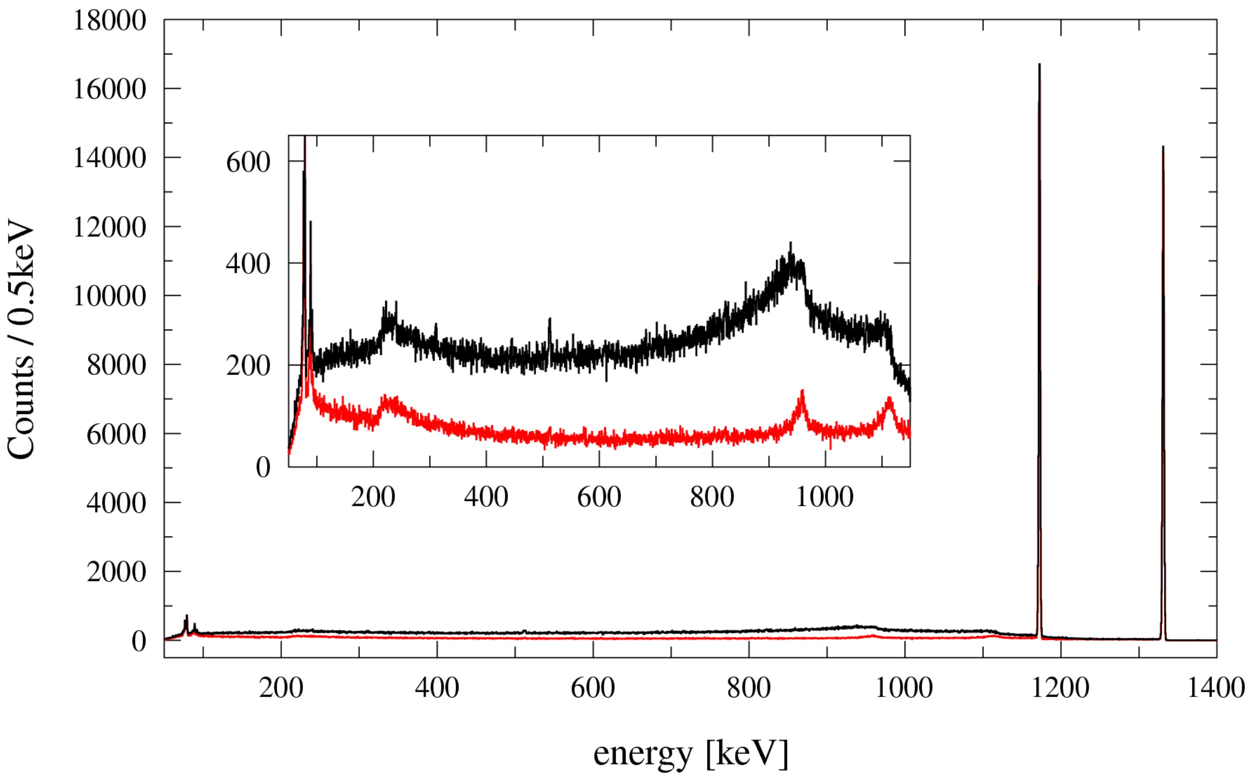
➡ Final matrix: difference of peak and background matrix

Active Compton Suppression

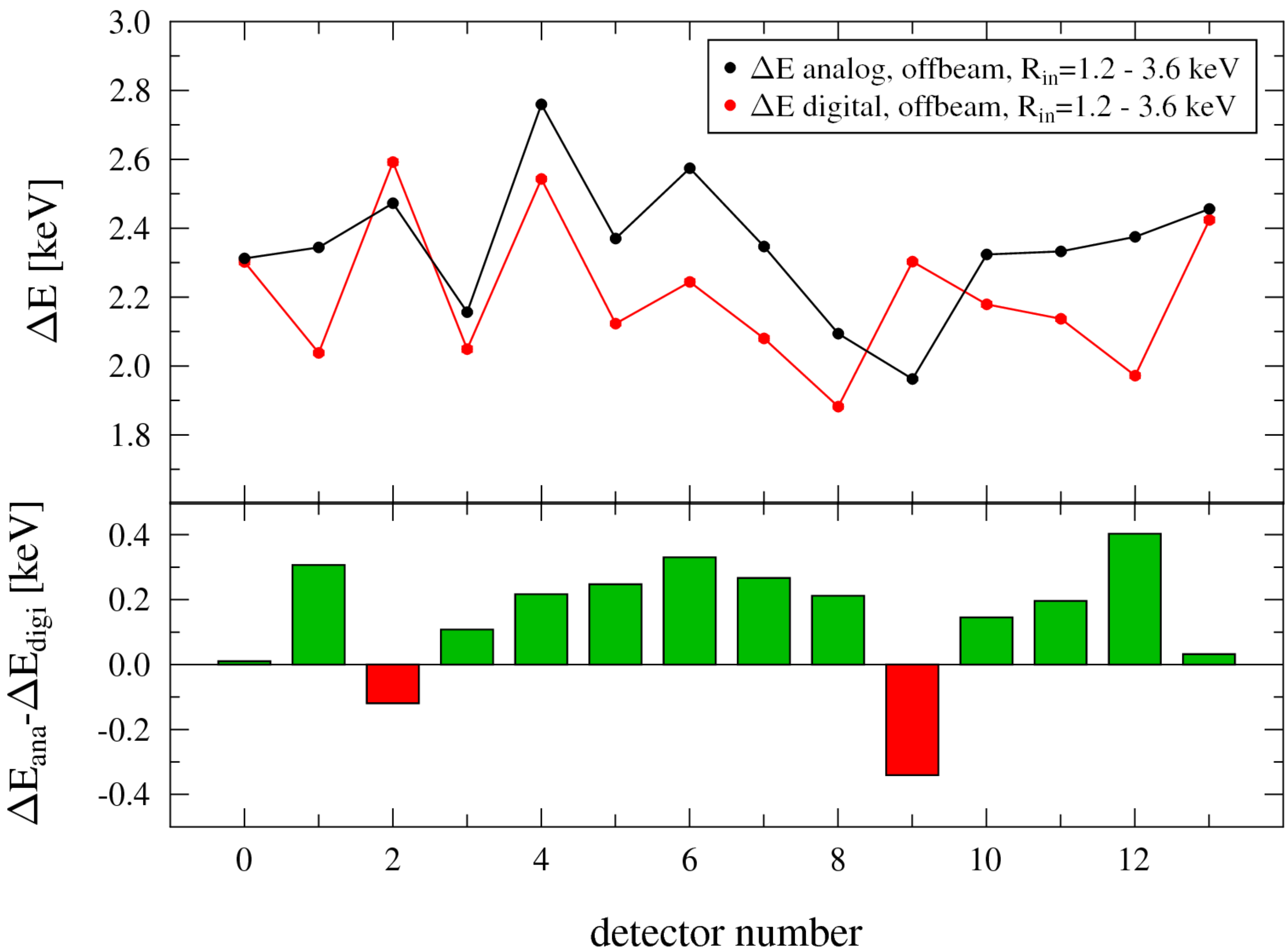
Four veto channels for Compton suppression

Reduction factor: 3.358 (10)



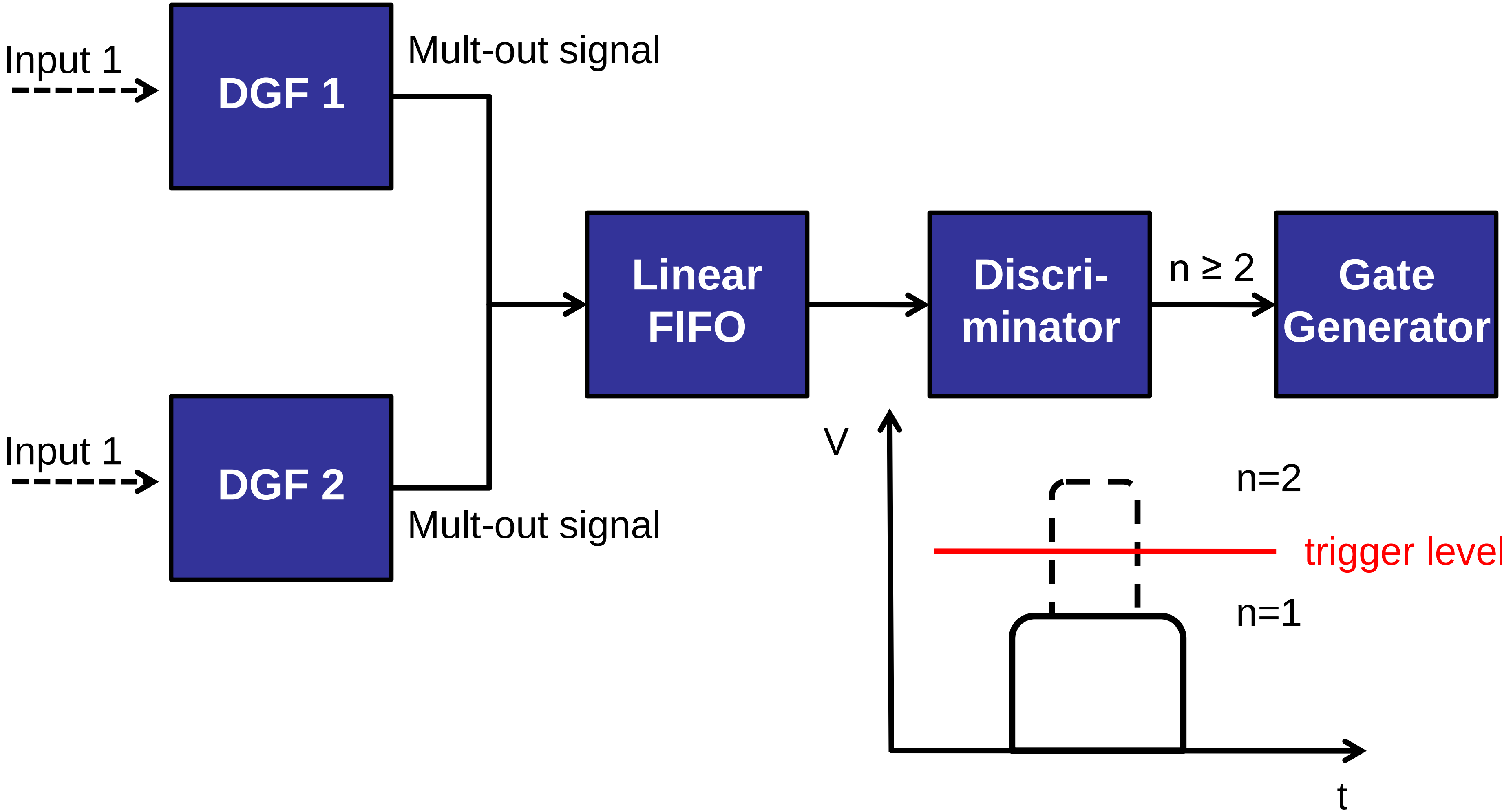


Energy Resolution – Analog vs. Digital



External Trigger Conditions

Late event validation using the GFLT



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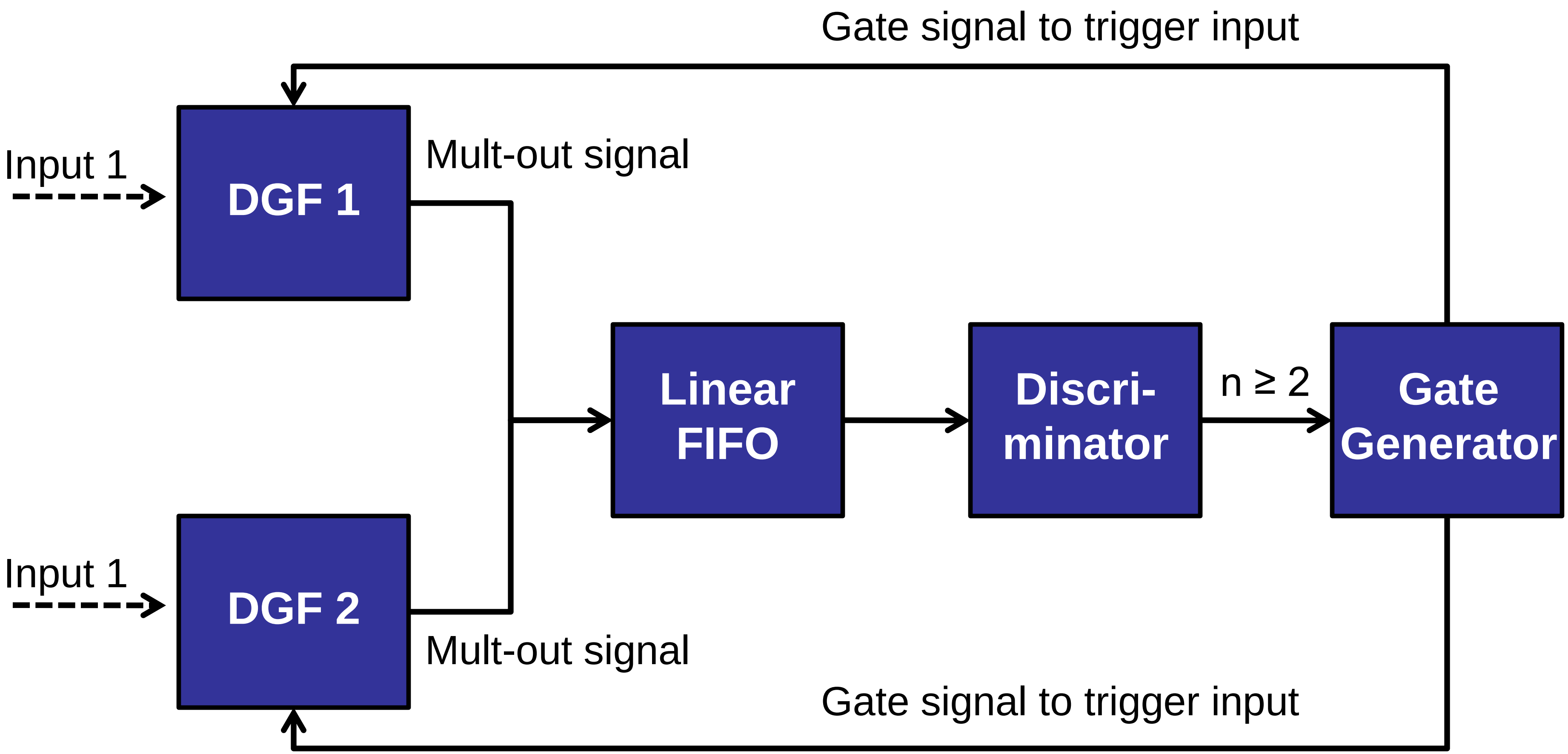
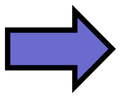




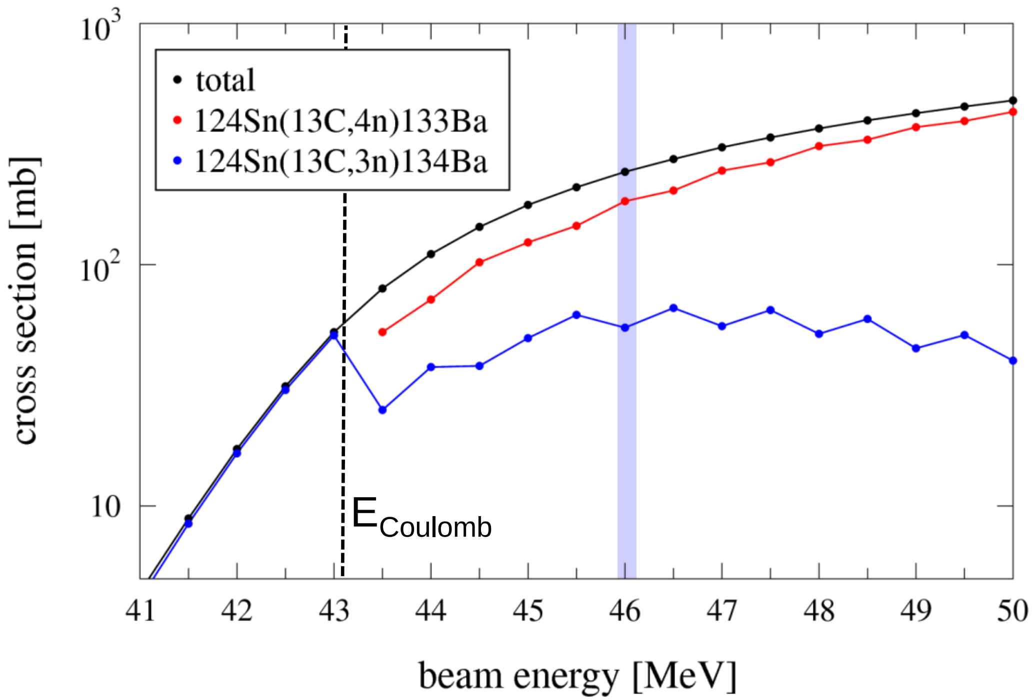
Readout deadtime reduced to 0.9%

The $^{124}Sn(^{13}C,3n)^{134}Ba$ Experiment

γγ-Coincidence Experiment

Reaction: $^{124}Sn(^{13}C,xn)^{137-x}Ba$

- Use of 13 HPGe detectors
- Production of well studied nuclei ^{133}Ba [1,2] and ^{134}Ba [3,4]
- Beam energy: 46 MeV, calculation with CASCADE



Aim of the test experiment:

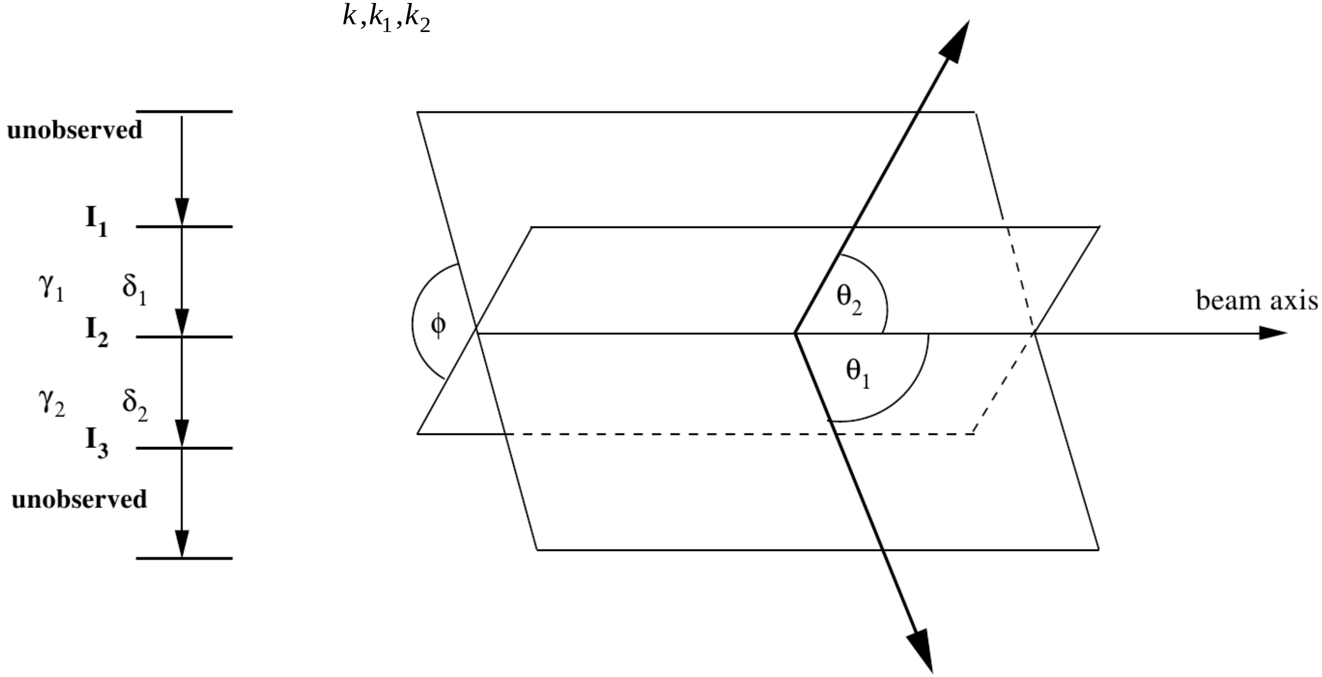
- Acquisition of γγ coincidences
- Investigation of energy and timing resolution
- Reproduction of angular correlations of coincident γ-rays

[1] J. Gizon et al., Nucl. Phys A **252** (1975) 509
[2] S Juutinen et al., Phys. Rev. C **51** (1995) 51
[3] M. Behar et al., Nucl. Phys. A **192** (1972) 218
[4] T. Lönnroth et al., JYFL Ann. Rep. **89-90** (1990) 99

$\gamma\gamma$ Angular Correlations

Angular distribution of γ-ray emission from an aligned nucleus:

$$W(\theta_1,\theta_2,\phi) = \sum_{k,k_1,k_2} B_{k_1}(I_1) A_k^{k_1,k_2}(\gamma_1) A_{k_2}(\gamma_2) H_{k_1,k,k_2}(\theta_1,\theta_2,\phi)$$

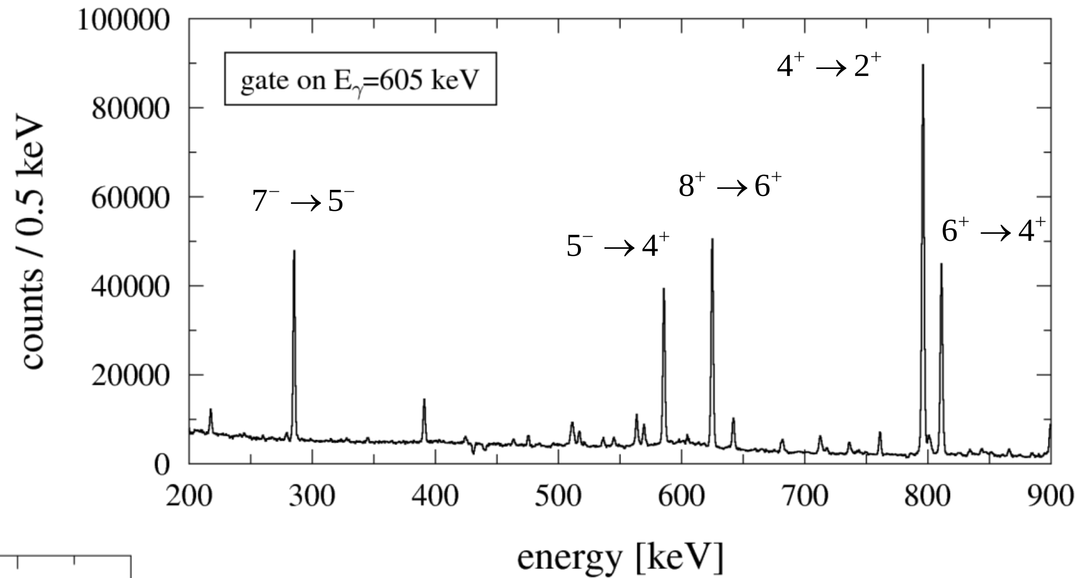


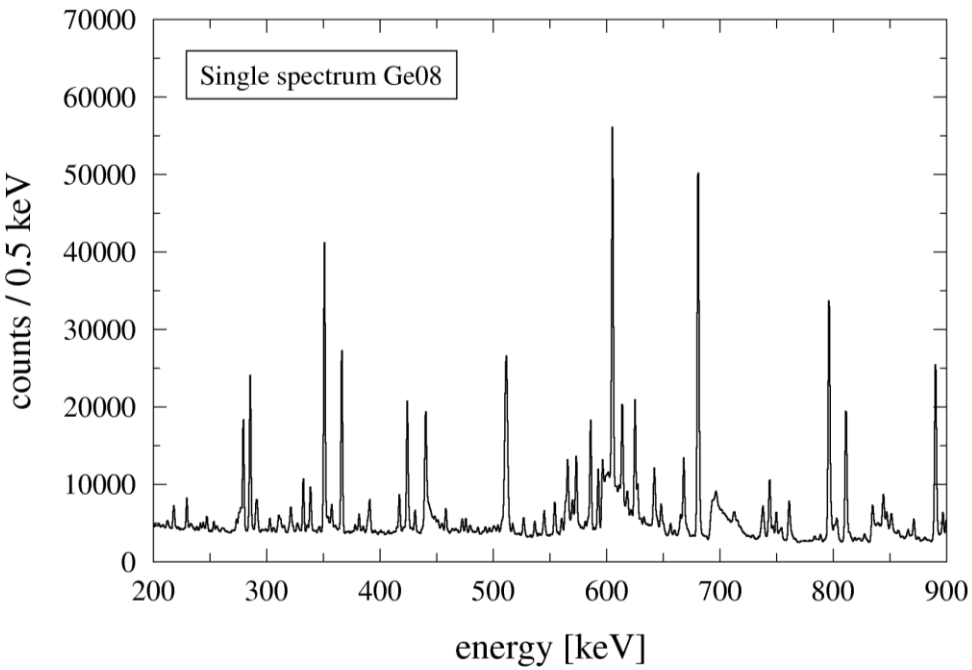
- Sorting of detector pairs in 17 correlation groups that share the same angles ϕ,θ_1,θ_2
- Fit of $W(\theta_1,\theta_2,\phi)$ to intensities in correlation groups

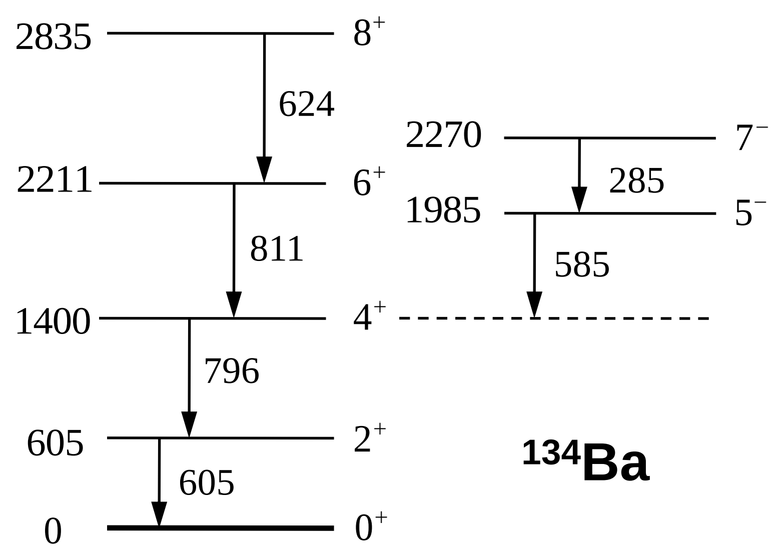
Test of the Data Acquisition

Reaction: $^{124}Sn(^{13}C,4n)^{133}Ba$

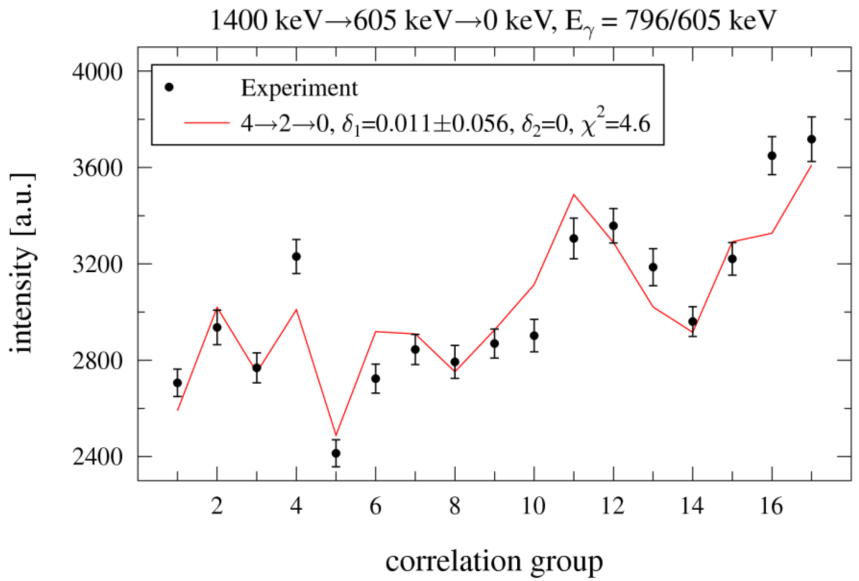
- Beam energy: 46 MeV
- Beam current: 10 pnA
- HPGe count rates: 5 -14 kHz
- ΔE_{FWHM} : 1.9 to 2.4 keV

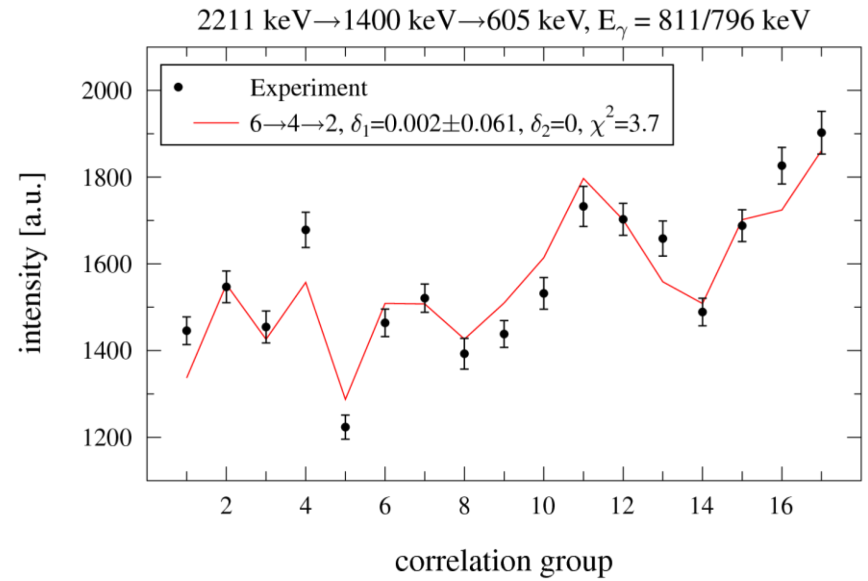


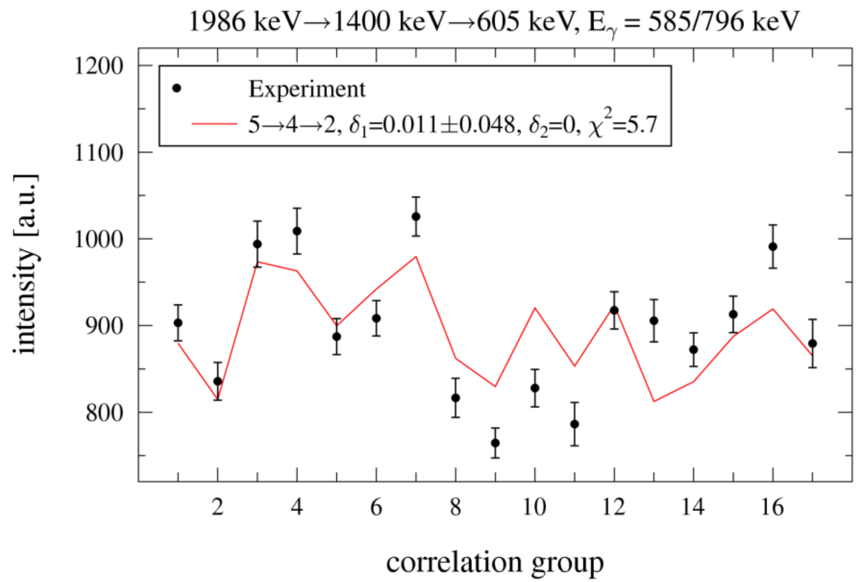


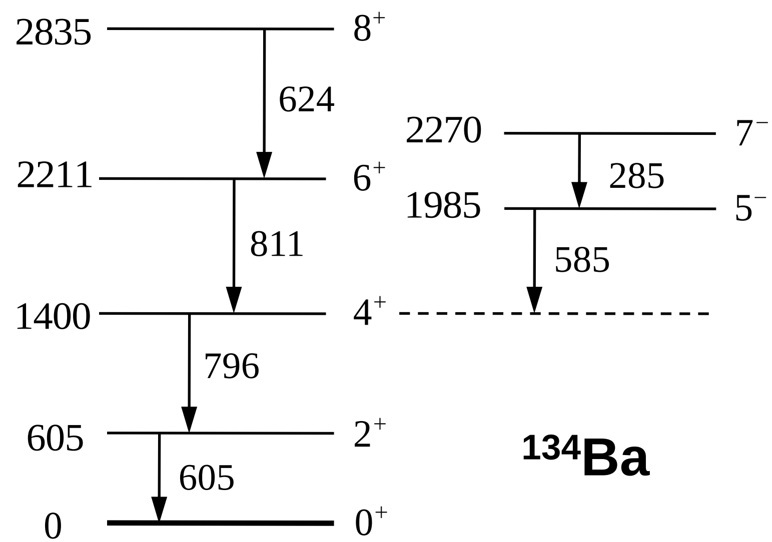


γγ Angular Correlations in ^{134}Ba









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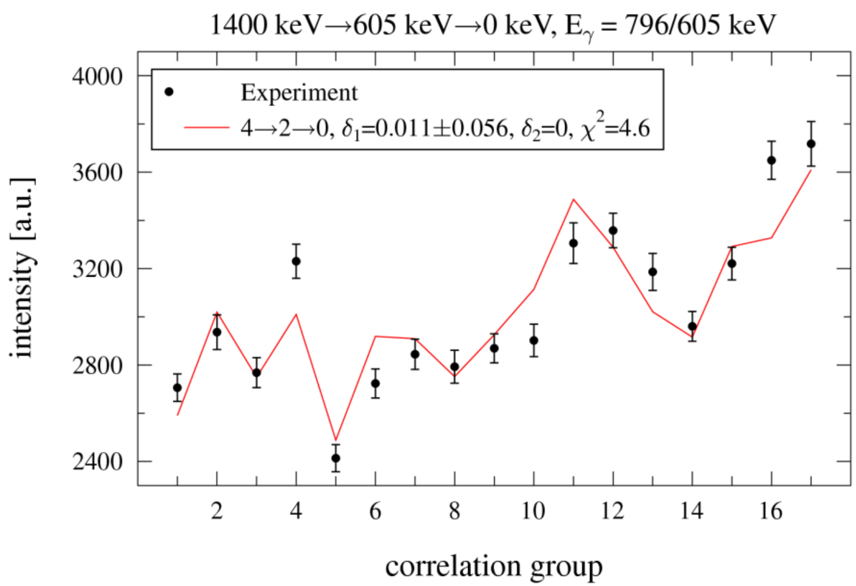
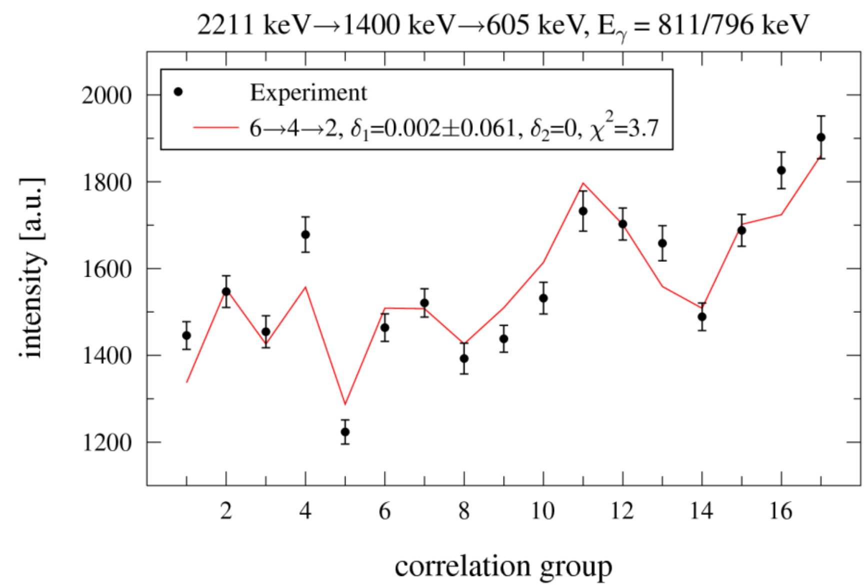
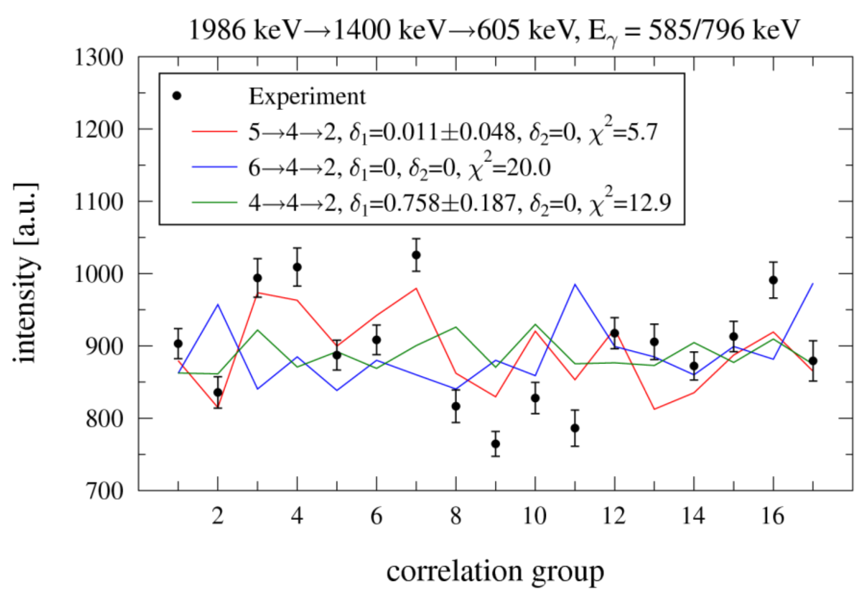
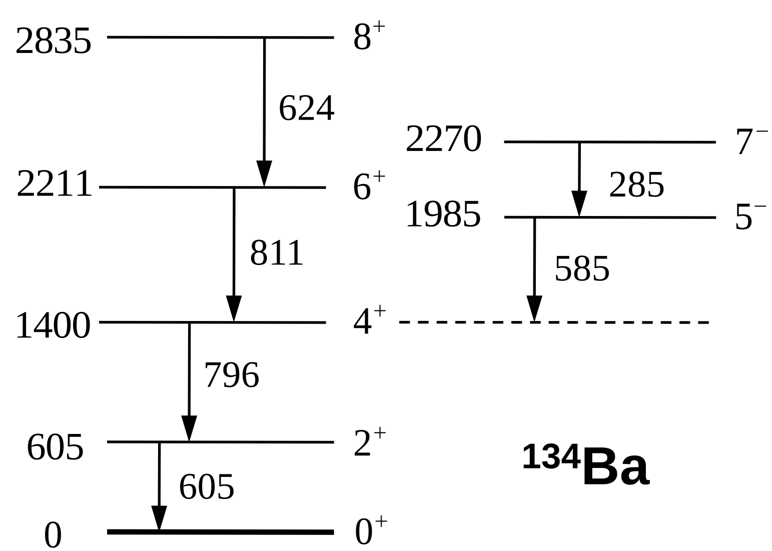
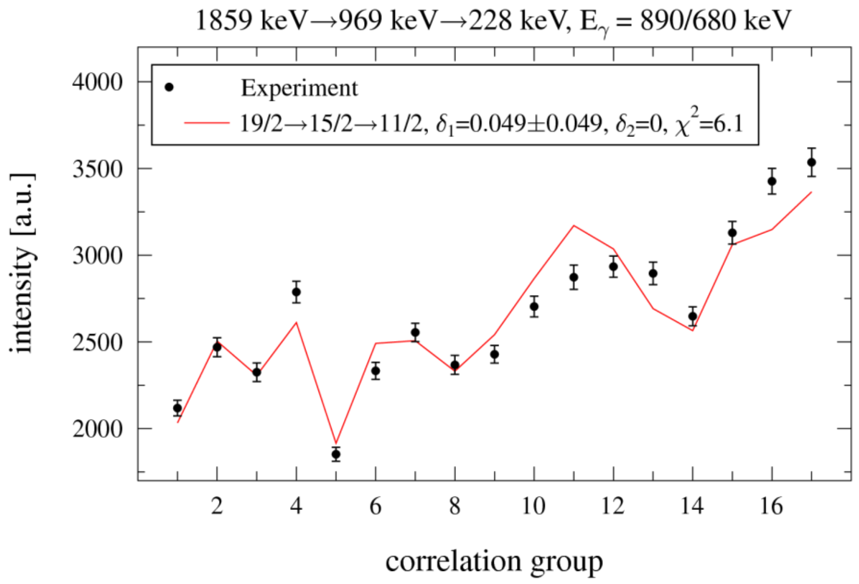


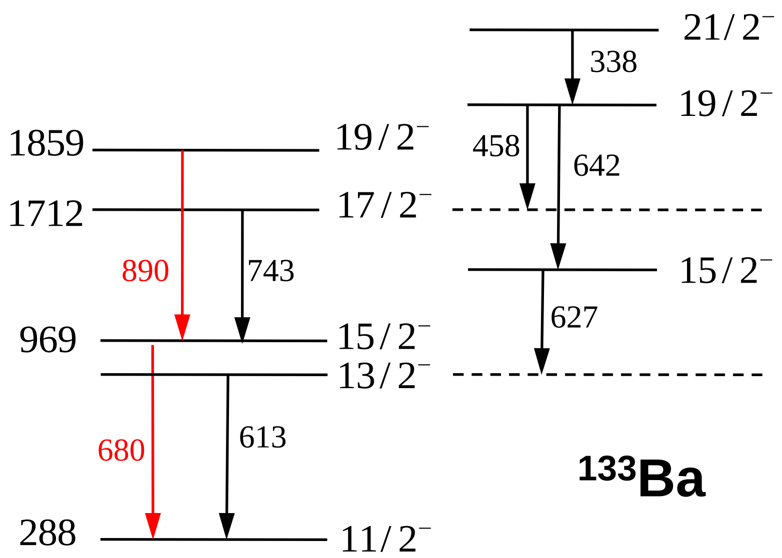




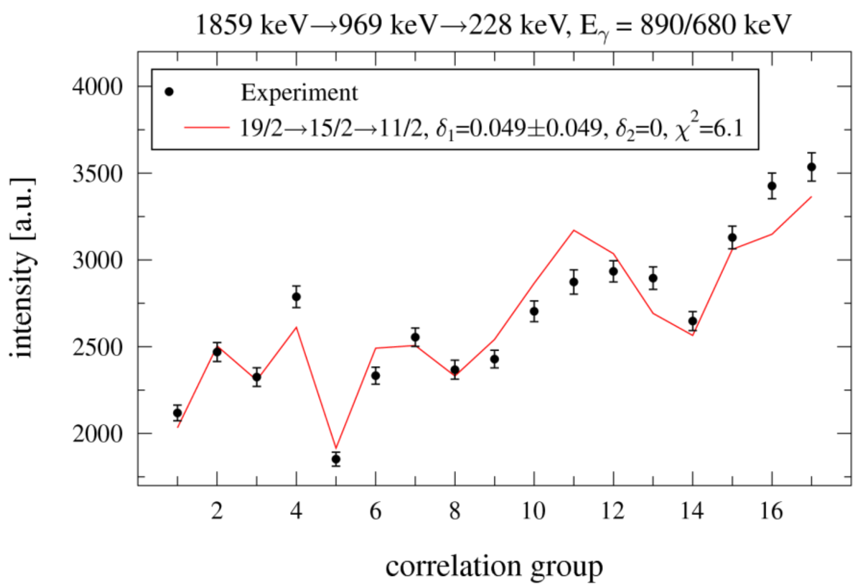


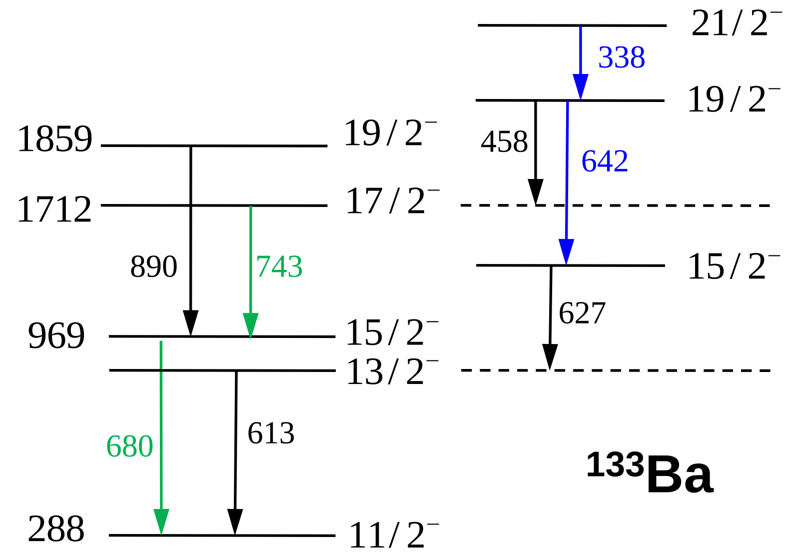
$\gamma\gamma$ Angular Correlations in ^{133}Ba

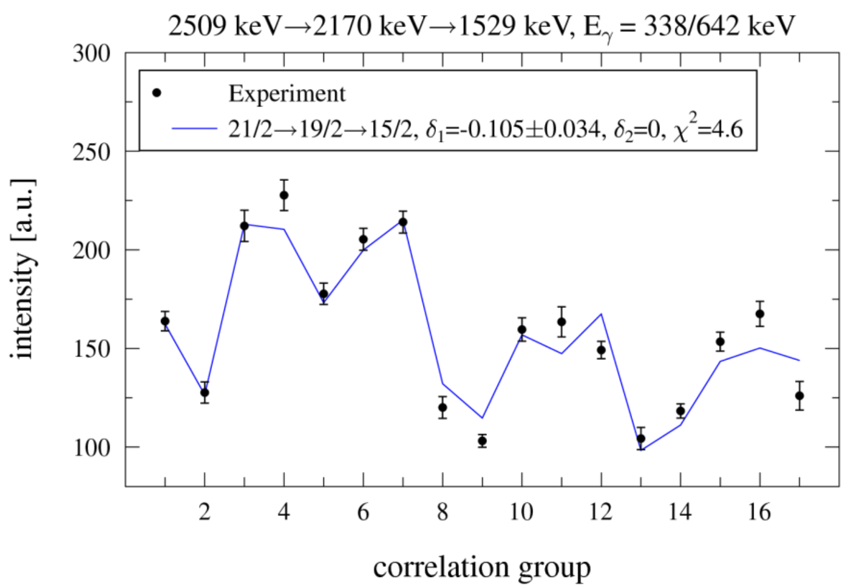


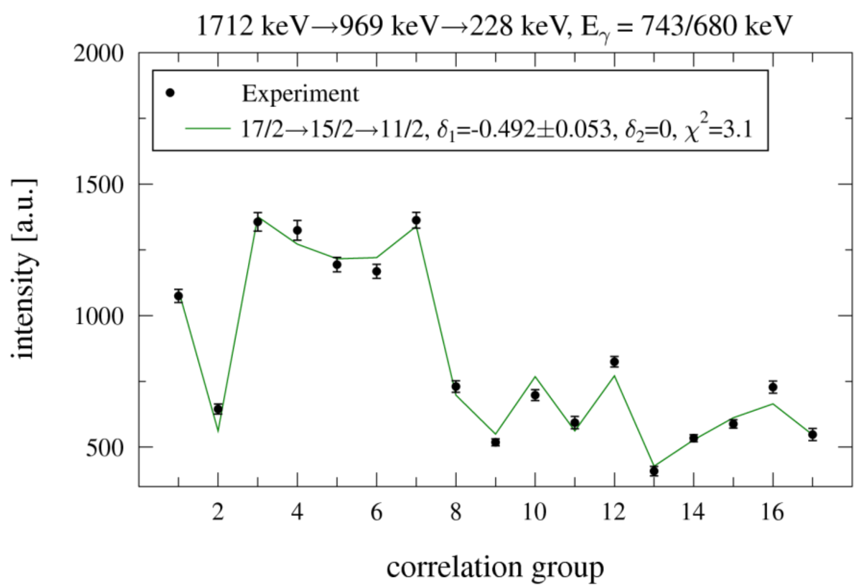


γγ Angular Correlations in ^{133}Ba





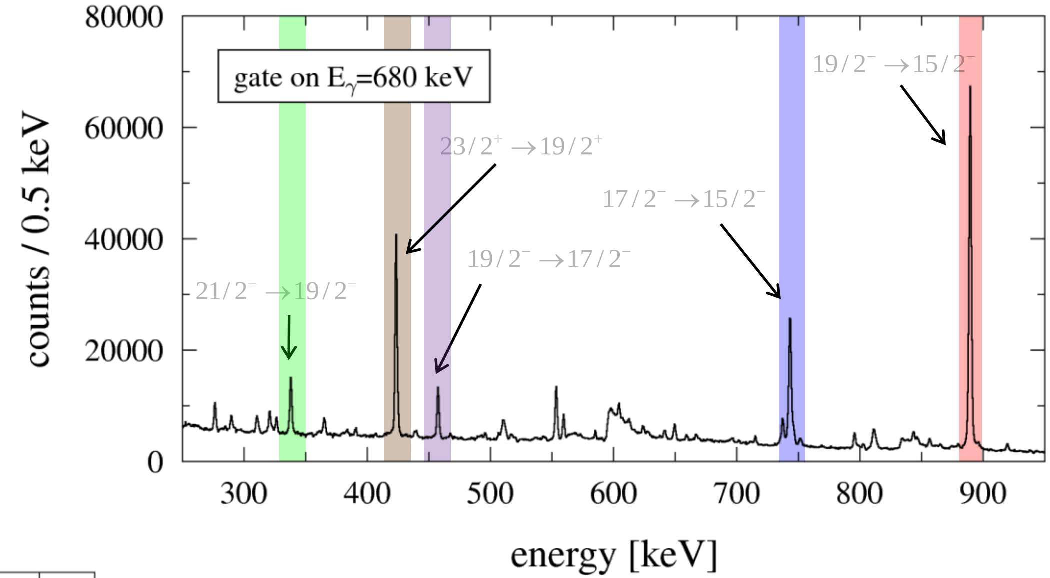


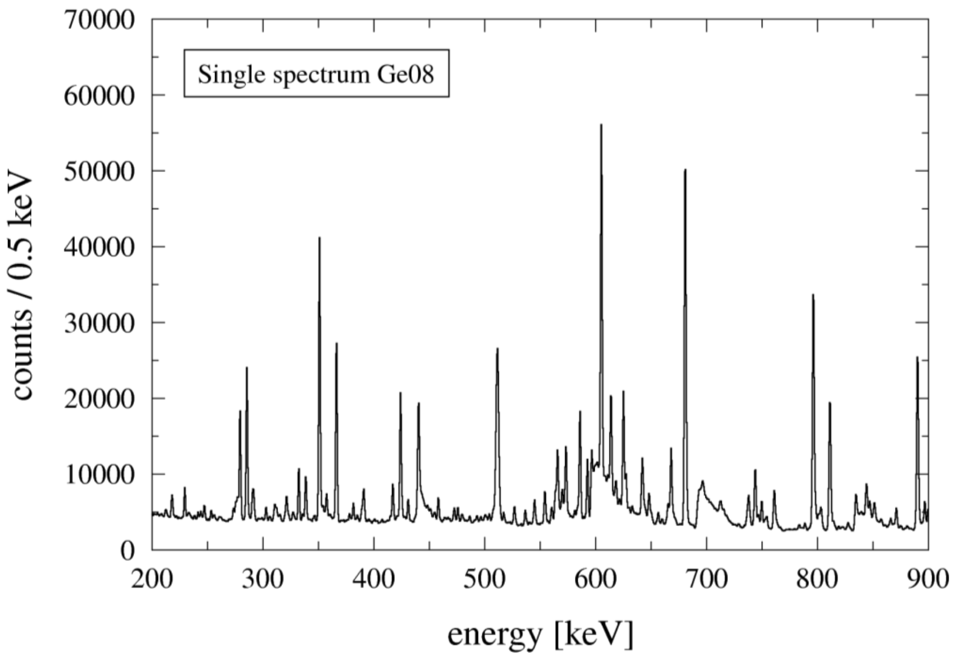


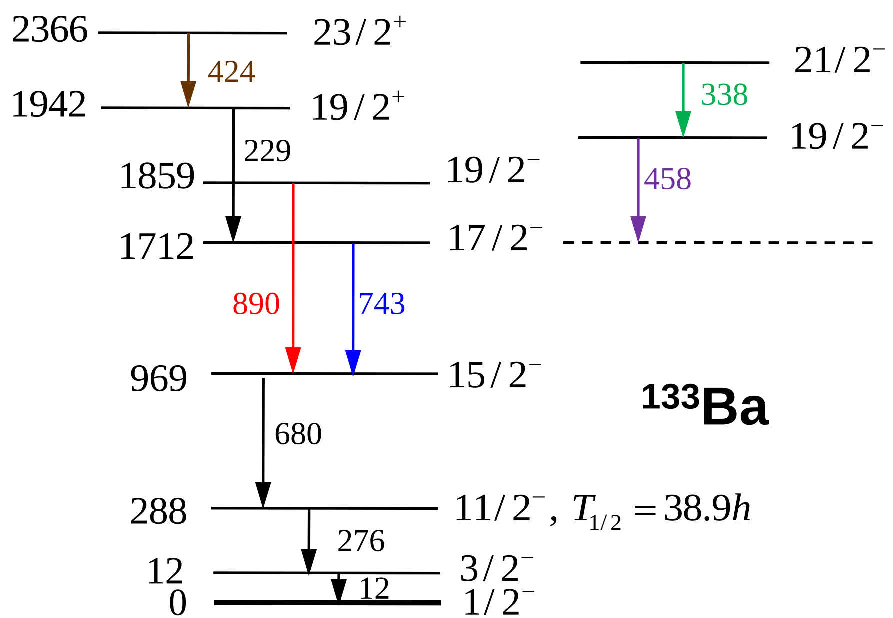
Test of the Digital Data Acquisition System

Reaction: $^{124}Sn(^{13}C,4n)^{133}Ba$

- Beam energy: 46 MeV
- Beam current: 10 pnA
- HPGe count rates: 5 -14 kHz
- ΔE_{FWHM} : 1.9 to 2.4 keV



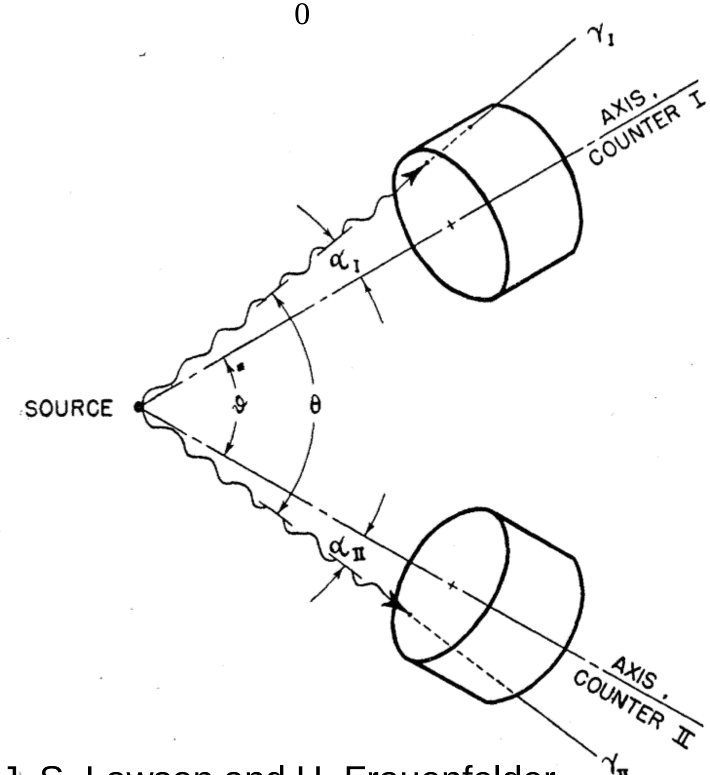




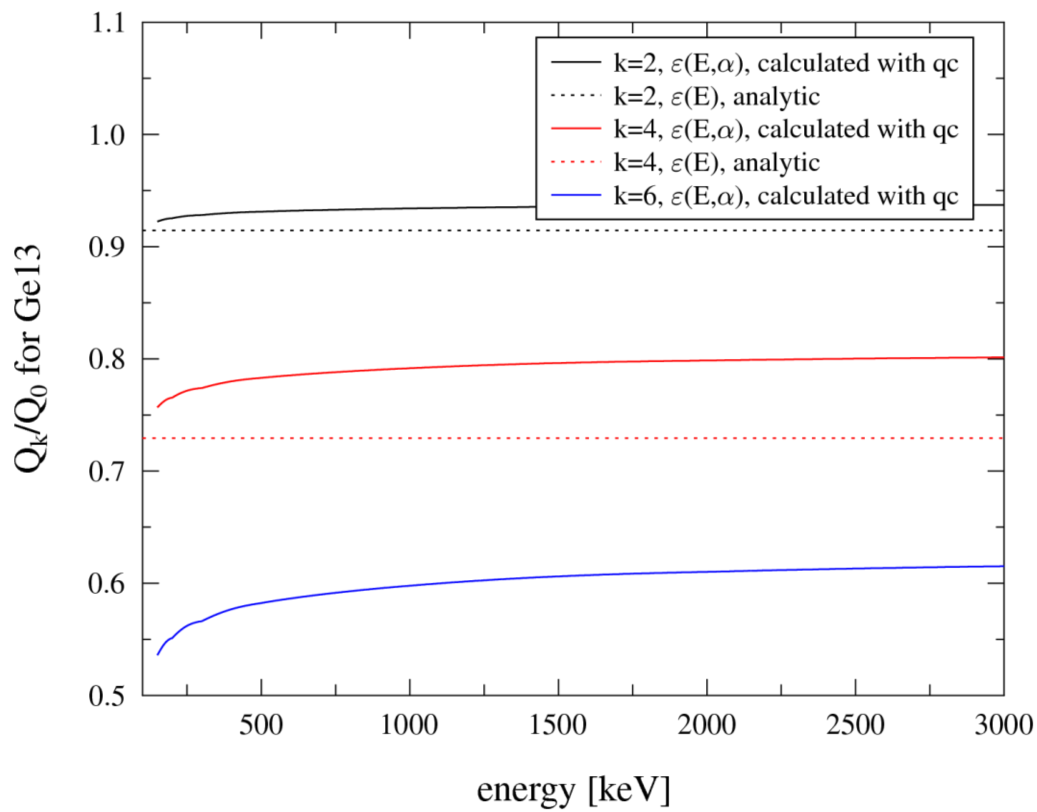
Correction for Solid Angle Coverage

Neglecting the extension of the source: $A_{kk} = A_{kk}^{\exp} / Q_{kk}$

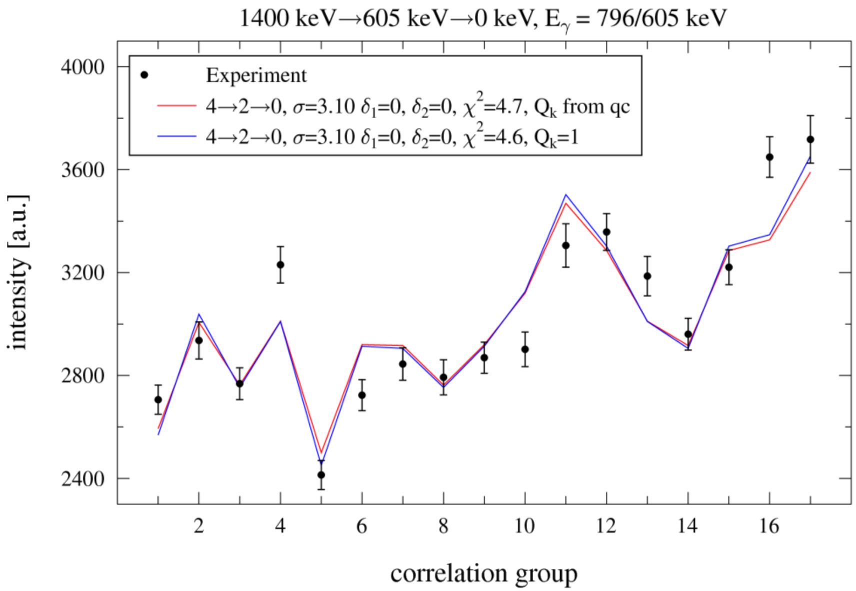
- Attenuation factors $Q_{kk} = Q_k(1) \cdot Q_k(2)$ with $Q_k(i) = J_k(i) / J_0(i)$
- $J_k(i) = \int_0^{1/2\pi} \varepsilon_i(E,\alpha) \cdot P_k(\cos\alpha)\, |\sin\alpha|\, d\alpha$

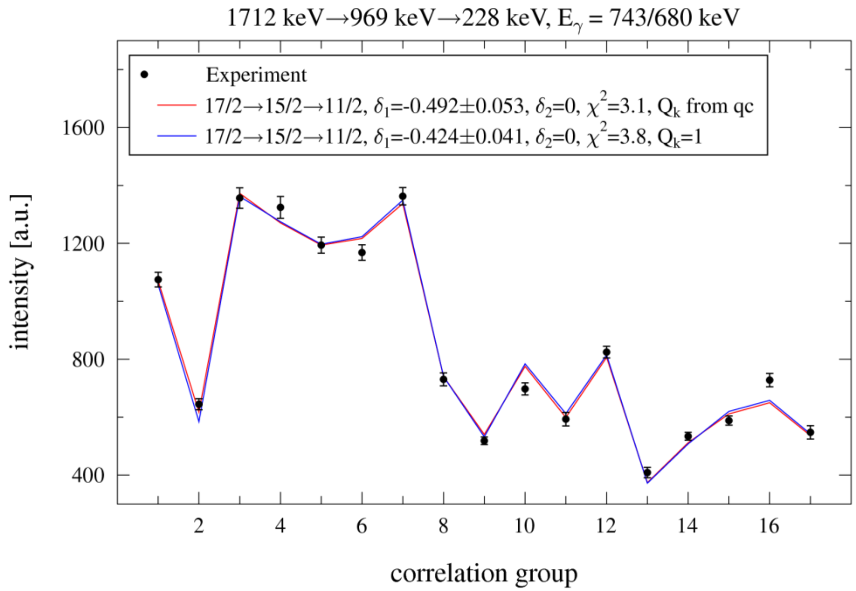


J. S. Lawson and H. Frauenfelder,
Phys. Rev. **91** (11953) 649



Correction for Solid Angle Coverage

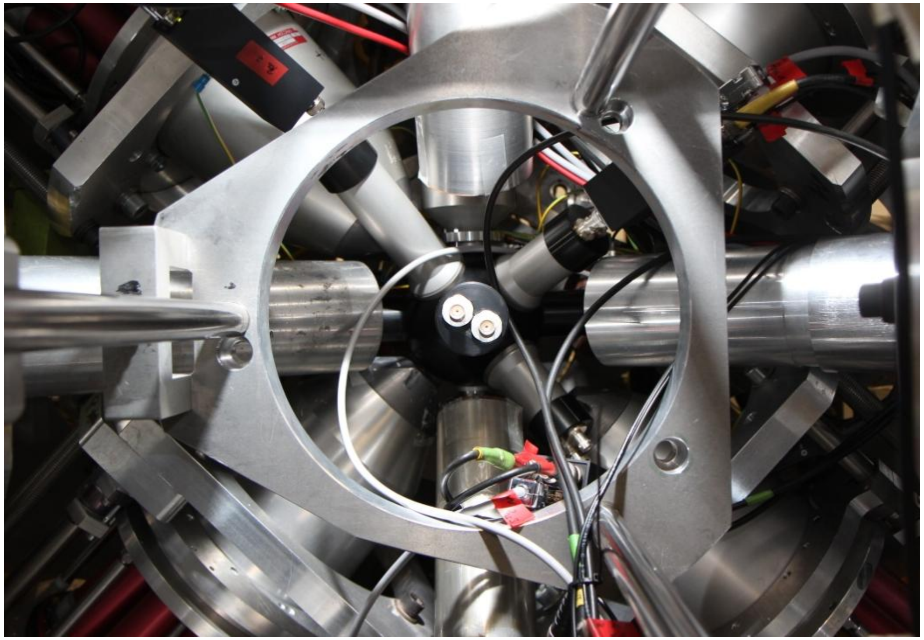




- Effect of solid angle correction with statistical error bars
- Minor changes in determined multipole mixing ratios

The $^{140}Ce(p,p'\gamma)$ Experiment

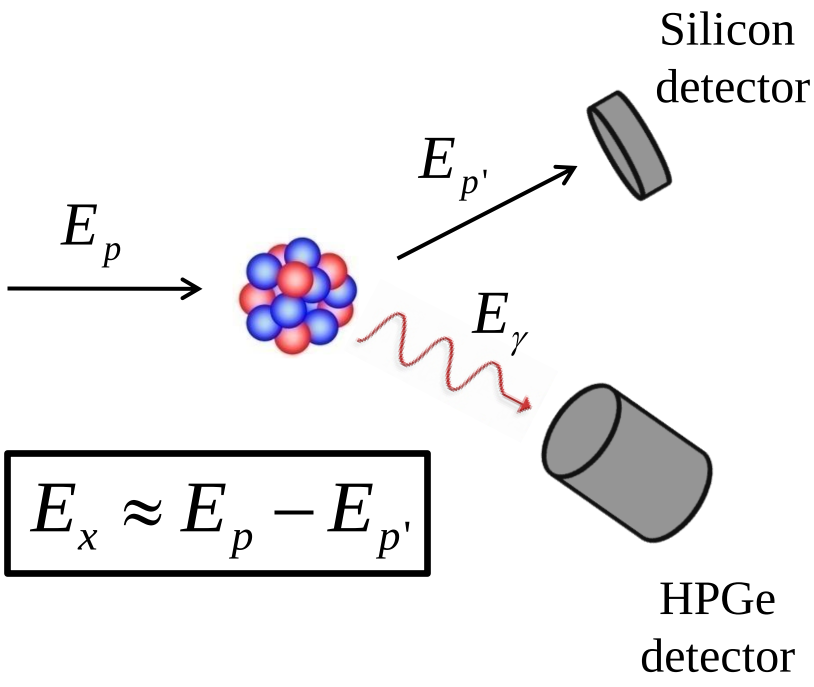
Particle-γ Coincidence Experiment



- Coincident detection of scattered proton and deexciting γ ray
- Particle detector array SONIC embedded into HORUS spectrometer

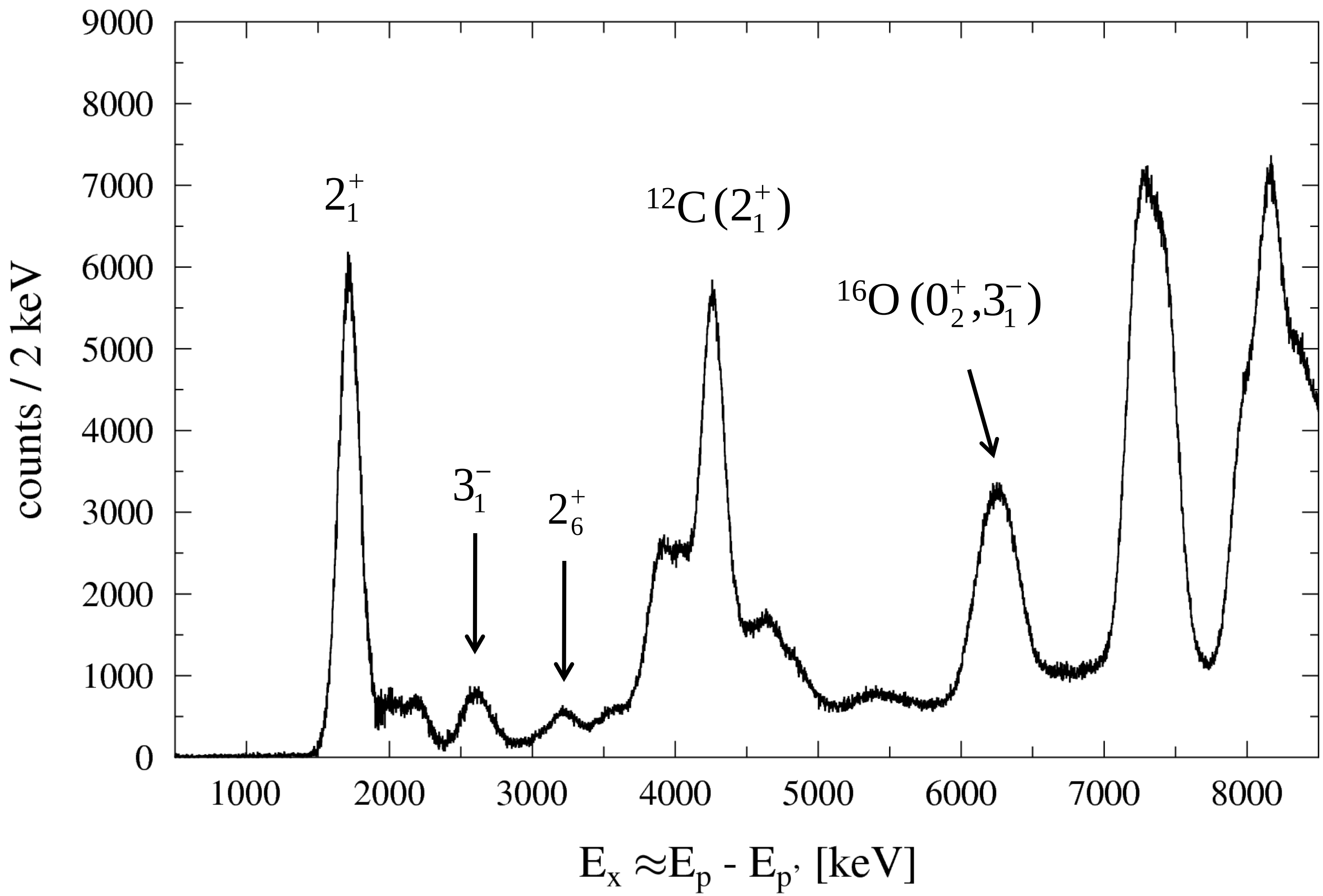
Reaction: ^{140}Ce(p,p'γ)

- Beam energy: E_p = 10.4 MeV
- Beam current: I_p = 0.5 pnA



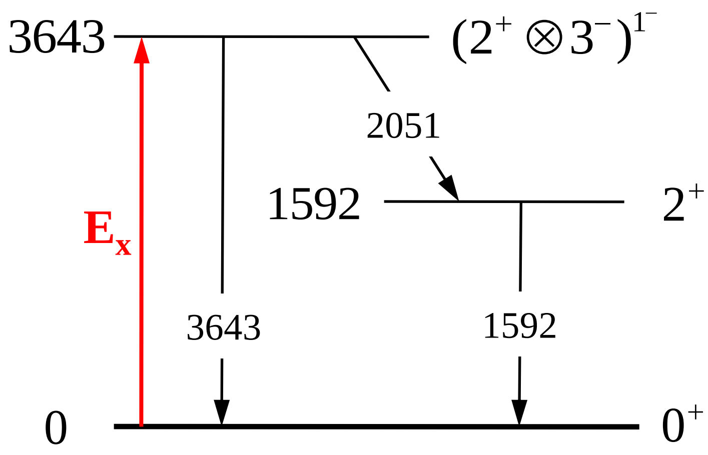
$$E_x \approx E_p - E_{p'}$$

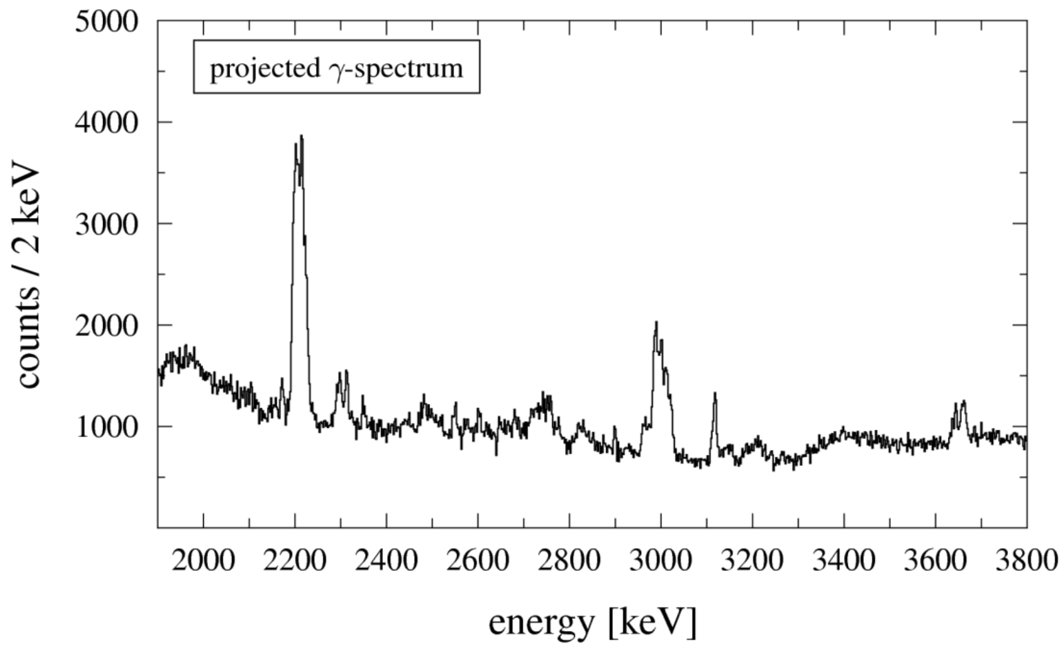
Excitation spectrum in ^{140}Ce



Decay of Two-Phonon State in ^{140}Ce

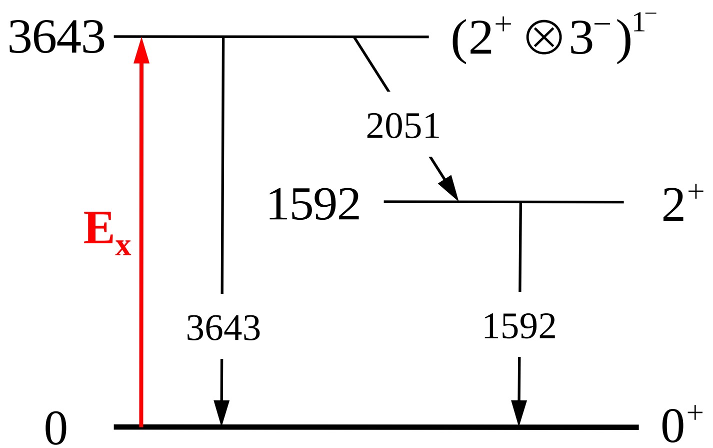
- Two-phonon 1^- state in ^{140}Ce:

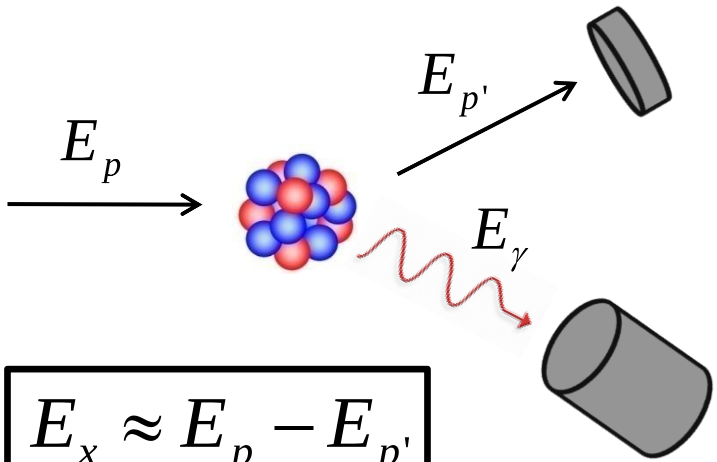




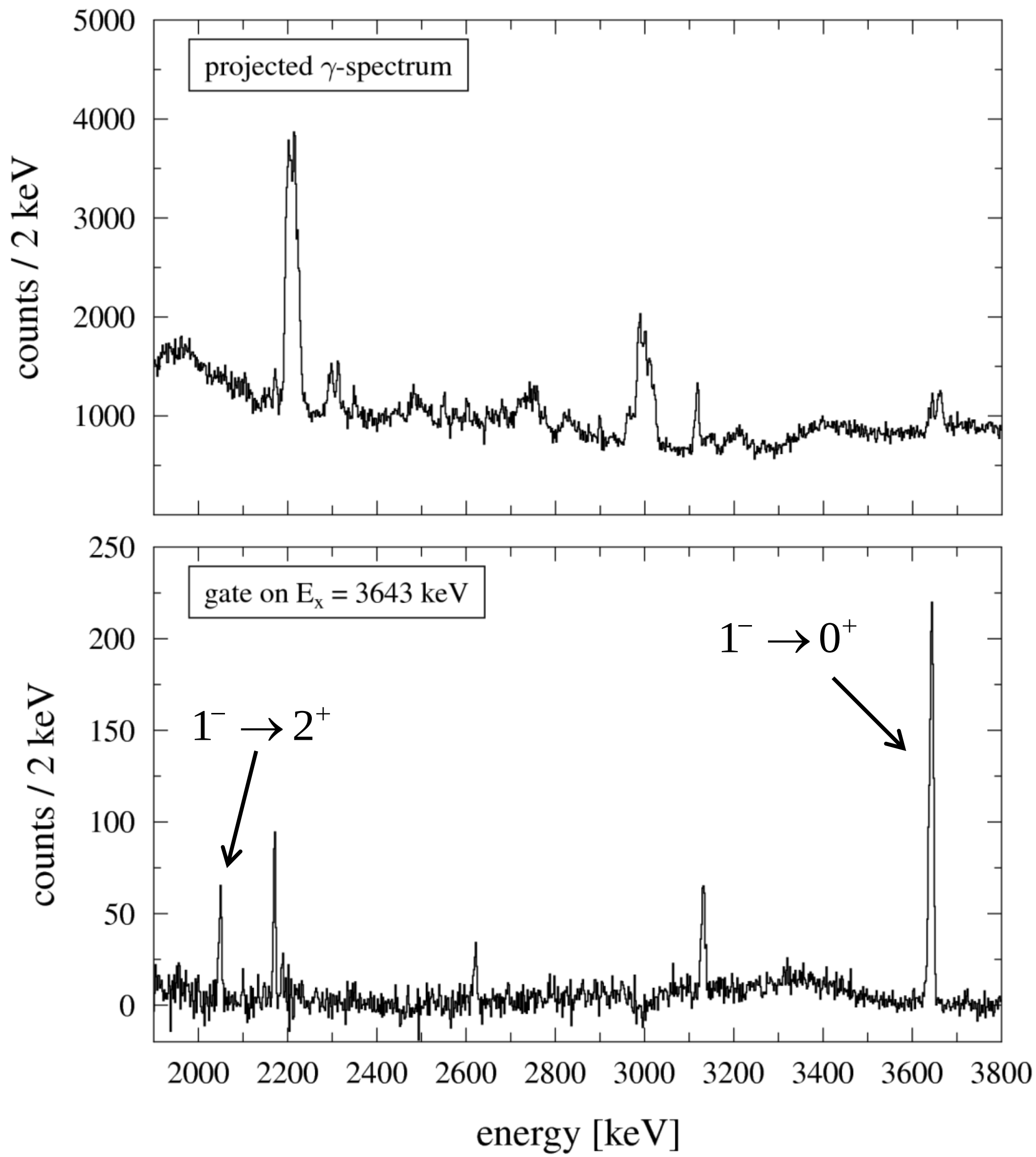
Decay of two-phonon state in ^{140}Ce

- Two-phonon 1^- state in ^{140}Ce:





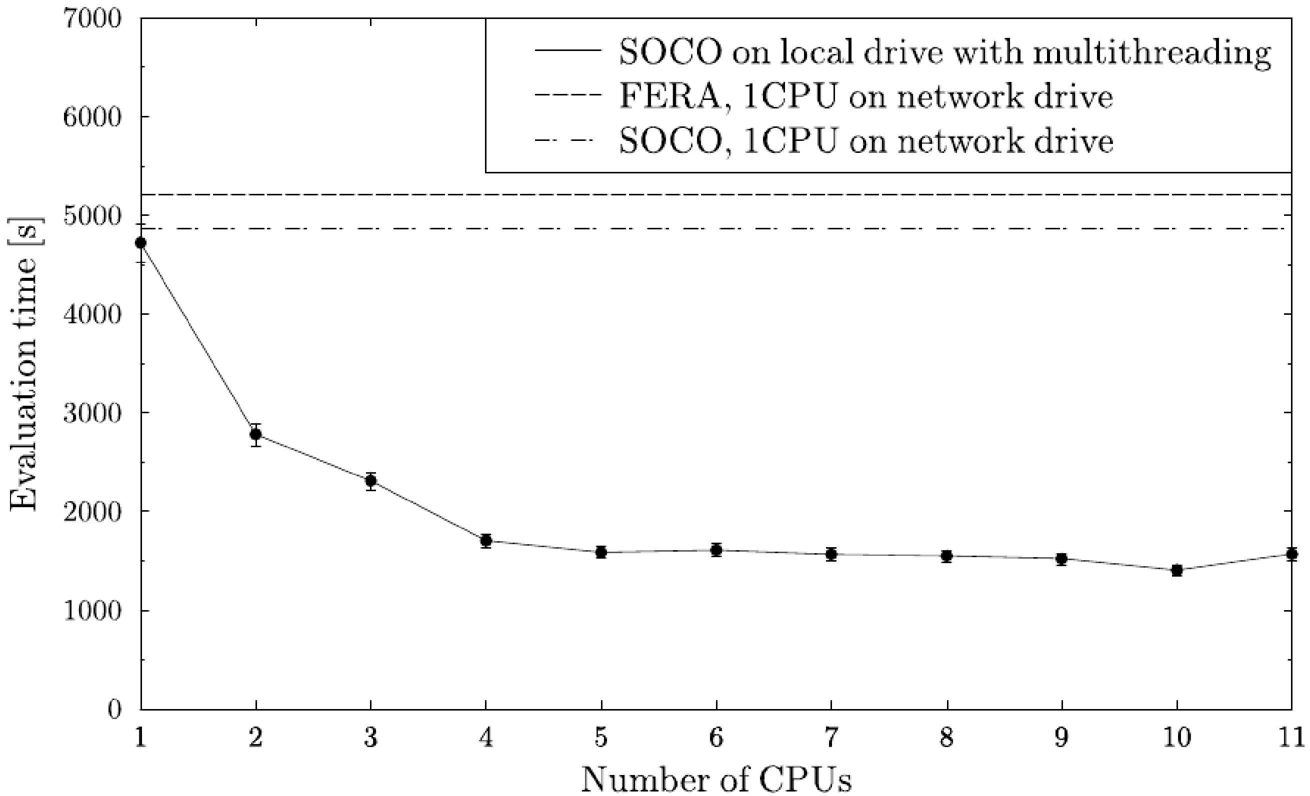
$$E_x \approx E_p - E_{p'}$$



The sorting code SOCO

SOrting code COlogne (SOCO)[1]

- Evaluation software for double coincidence listmode data
- Features:
  - Use of multiprocessing



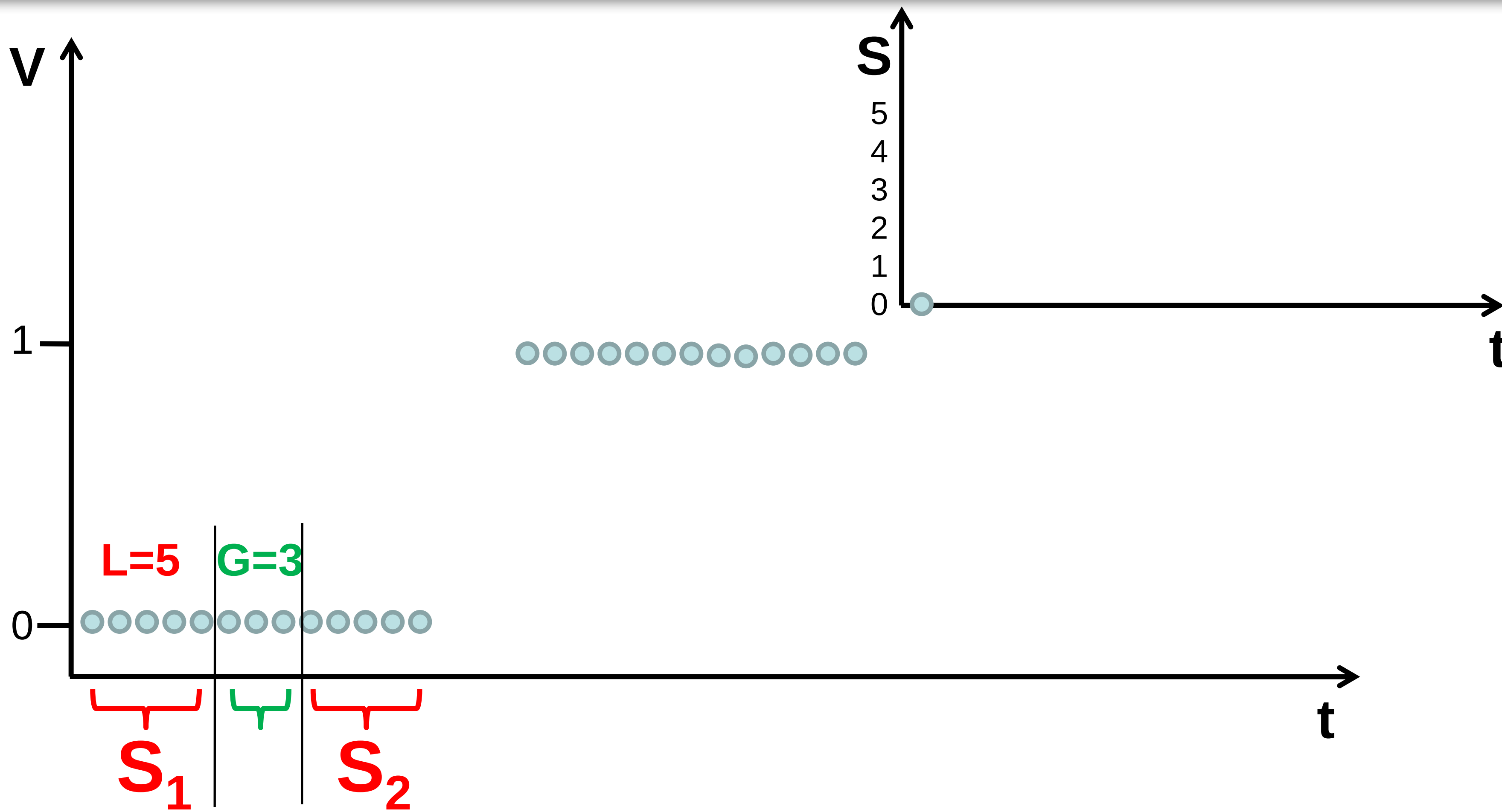
[1] M. Elvers, PhD thesis, University of Cologne (2011)

SOrting code COlogne (SOCO) [1]

- Evaluation software for double coincidence listmode data
- Features:
  - Use of multiprocessing
  - Provides matrices, single spectra and projections, as well as time-difference spectra
  - Support of different listmode formats:
    - ***FERA*** *(old cologne data format)*
    - ***XIA*** *(data format for the new digital data acquisition)*
    - ***GASP*** *(INFN Legnaro, IFIN-HH Bucharest)*

[1] M. Elvers, PhD thesis, University of Cologne (2011)

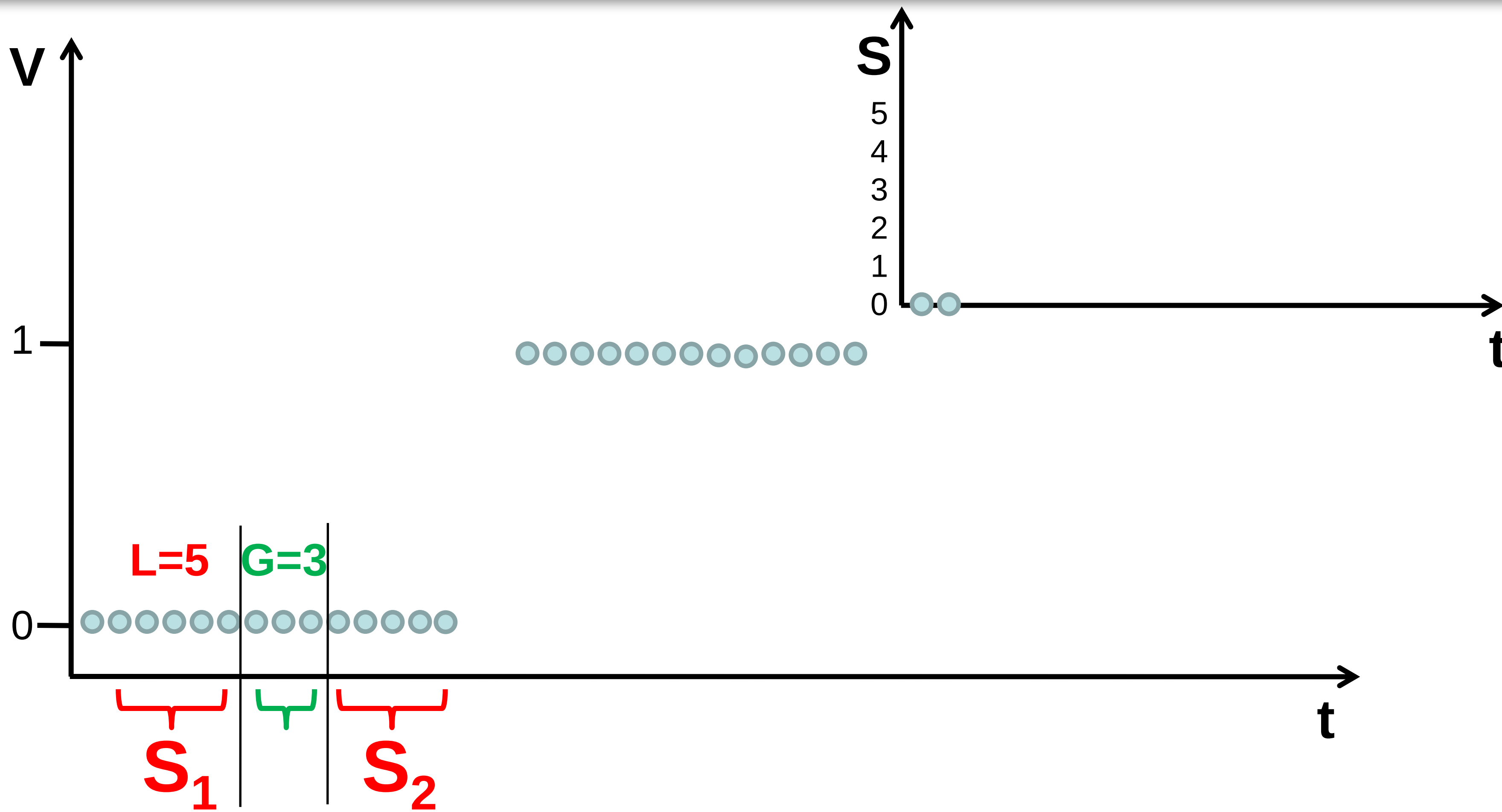
Trapezoidal filter algorithm



$$S = S_2 - S_1 = 0$$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

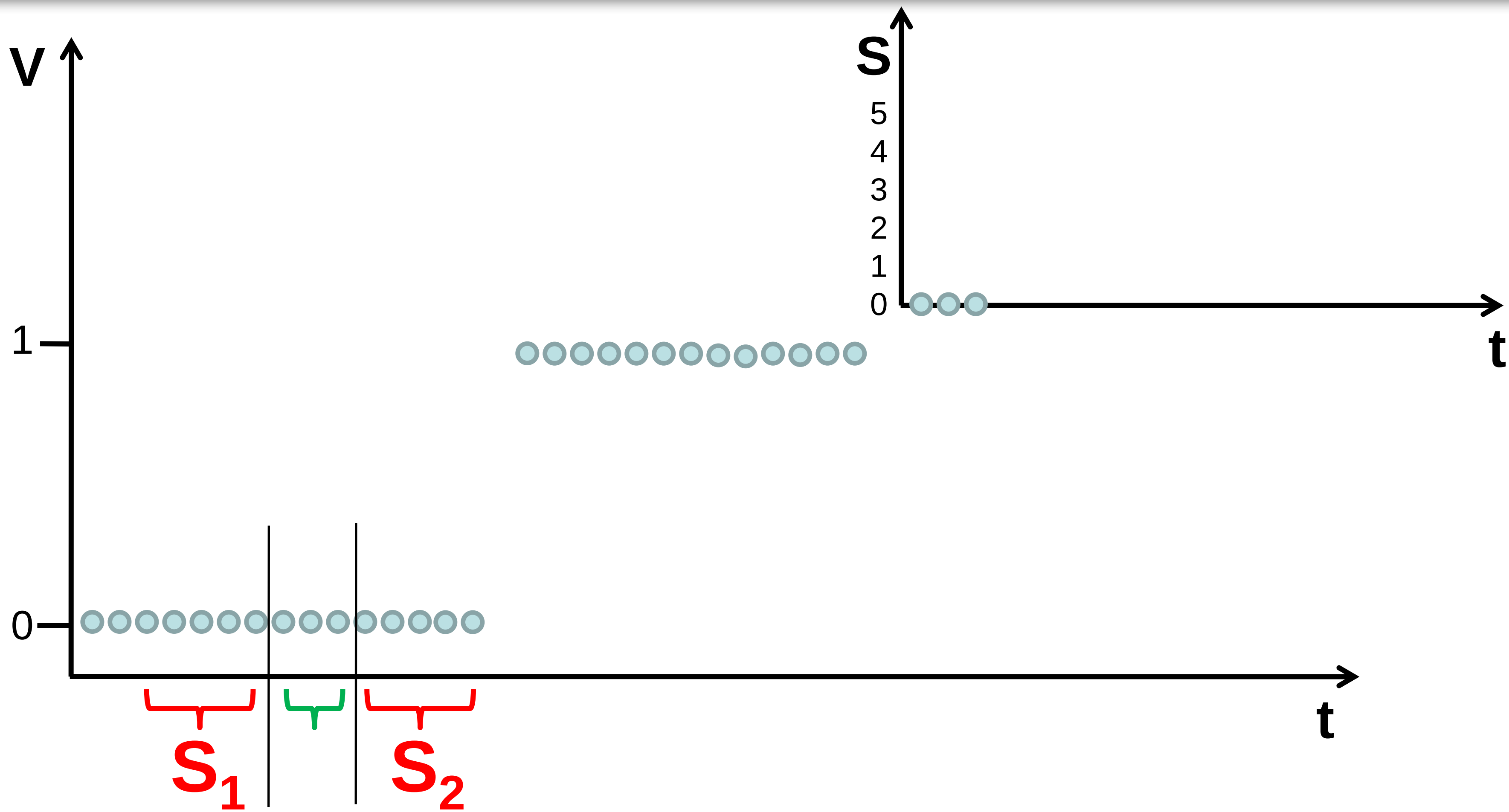
Trapezoidal filter algorithm



$$S = S_2 - S_1 = 0$$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

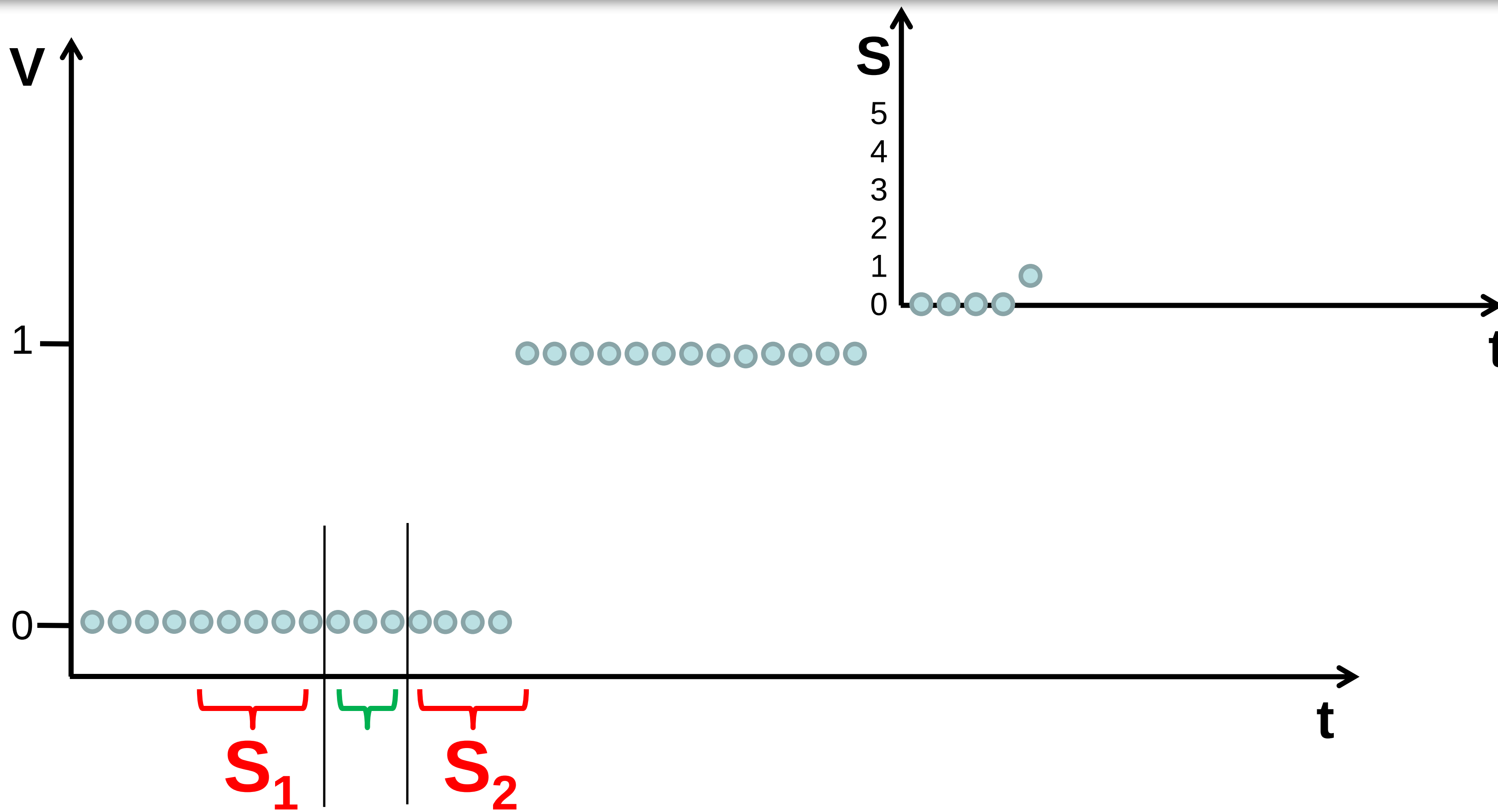
Trapezoidal filter algorithm



$$S = S_2 - S_1 = 0$$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

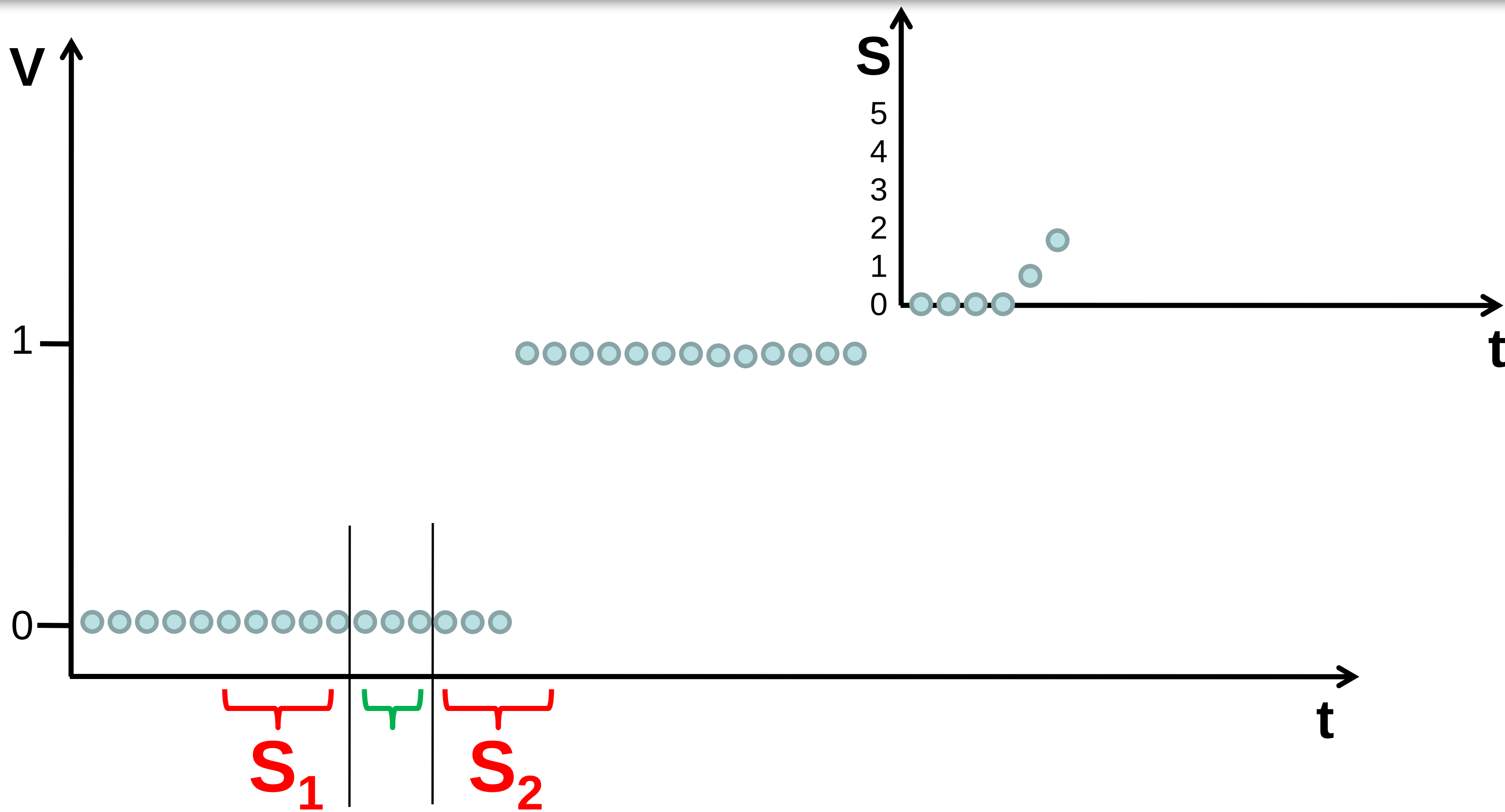
Trapezoidal filter algorithm



$$S = S_2 - S_1 = 1$$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

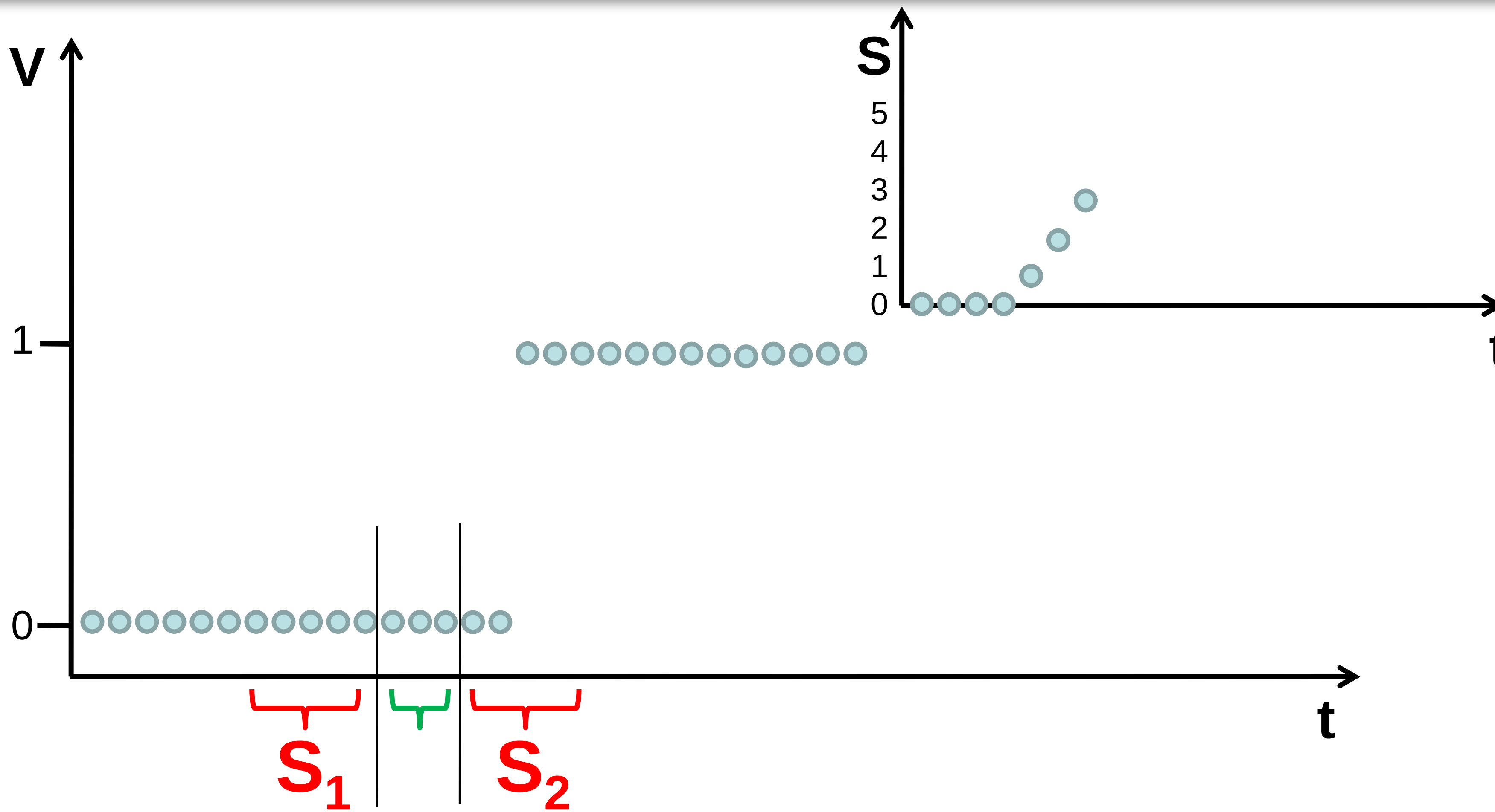
Trapezoidal filter algorithm



$S = S_2 - S_1 = 2$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

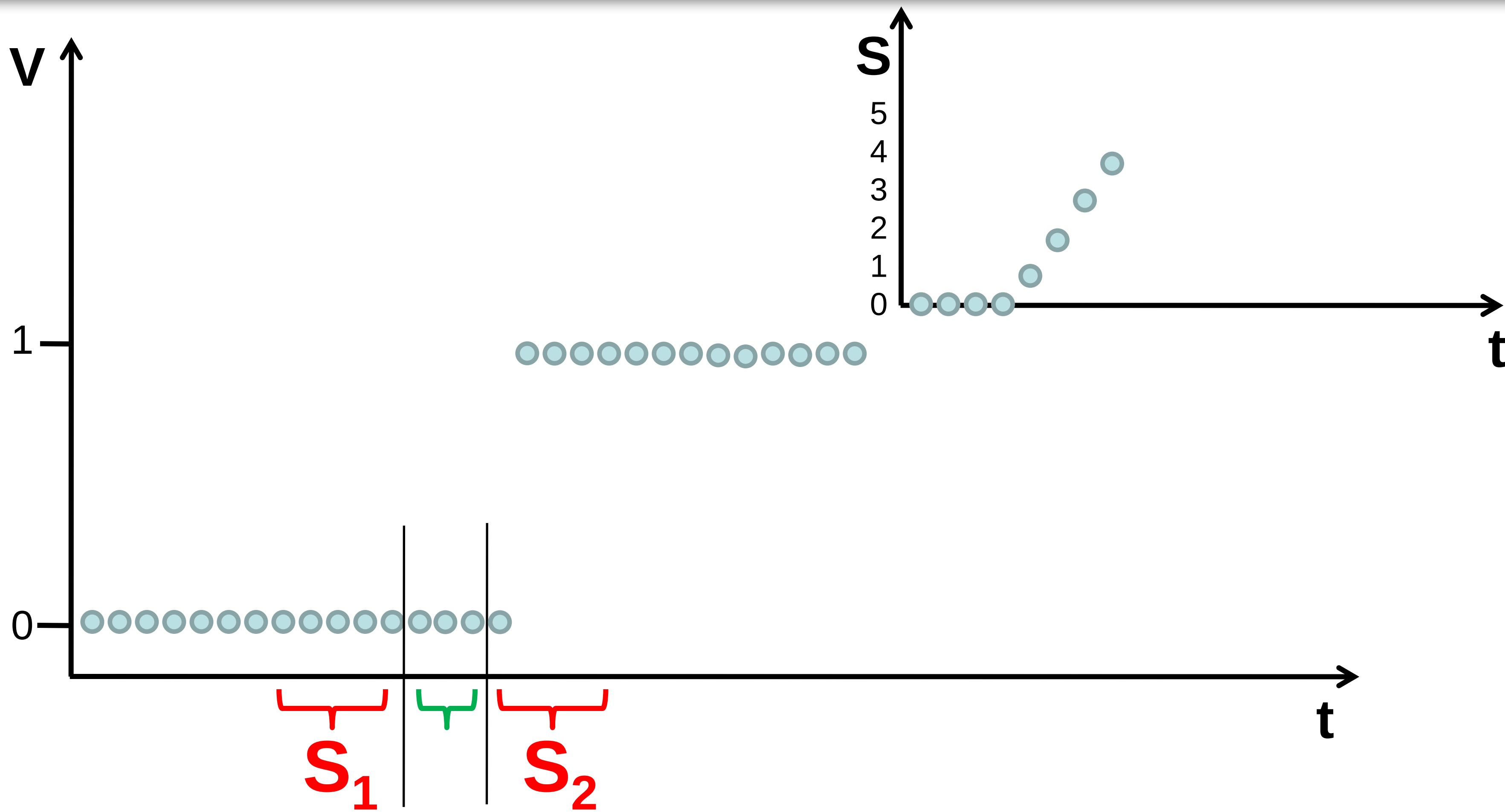
Trapezoidal filter algorithm



$S = S_2 - S_1 = 3$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

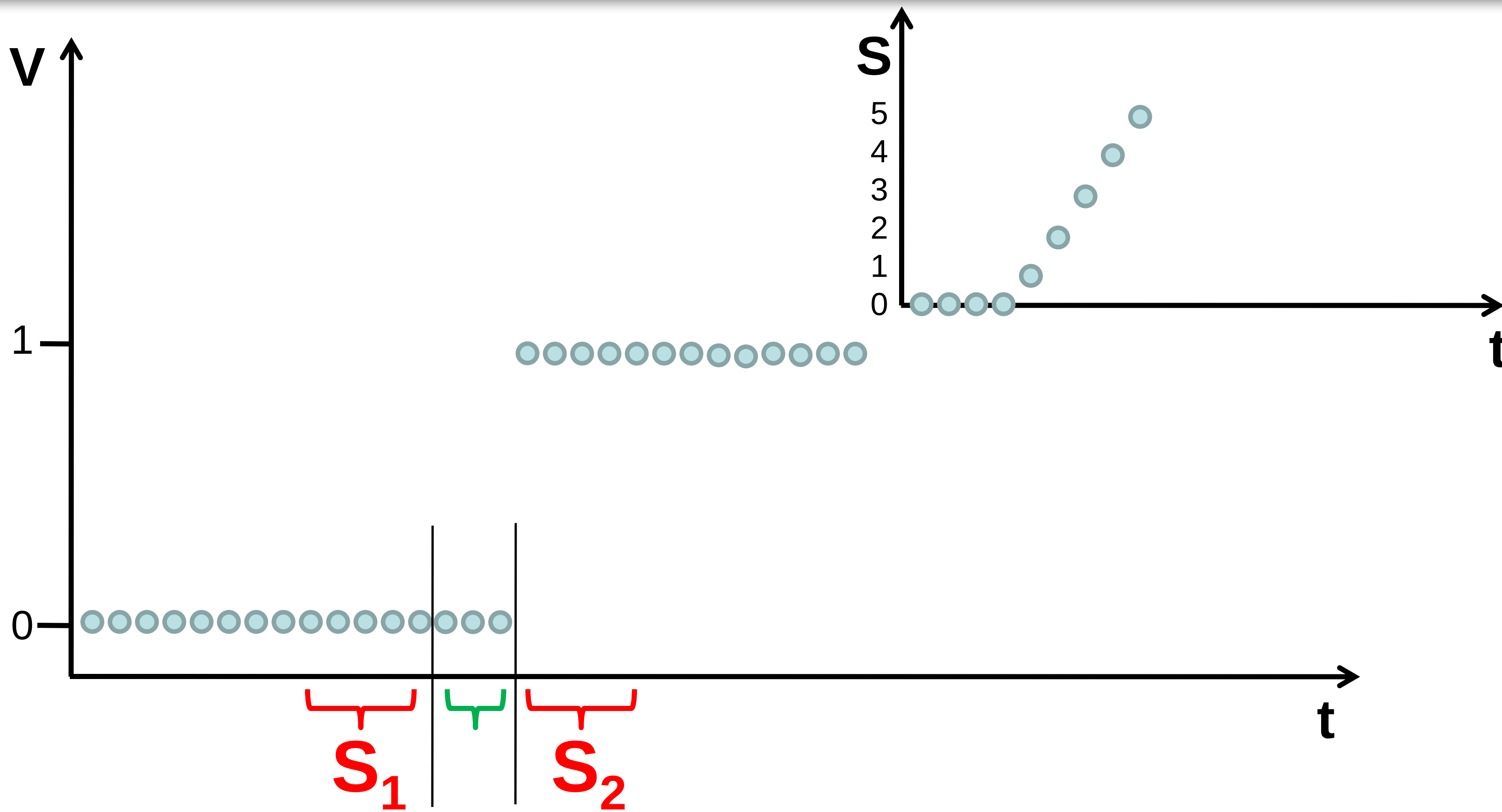
Trapezoidal filter algorithm



$$S = S_2 - S_1 = 4$$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

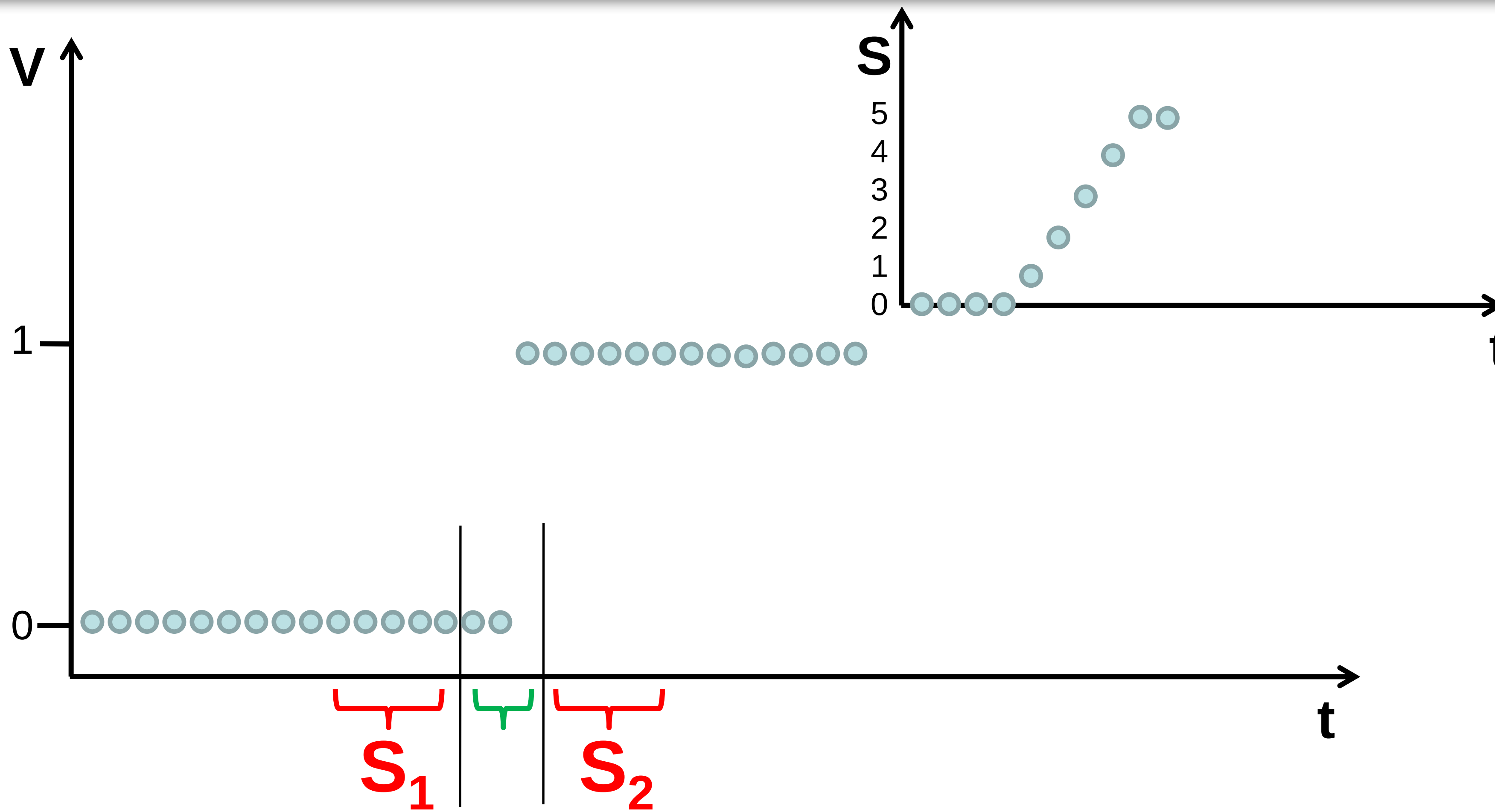
Trapezoidal filter algorithm



$$S = S_2 - S_1 = 5$$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

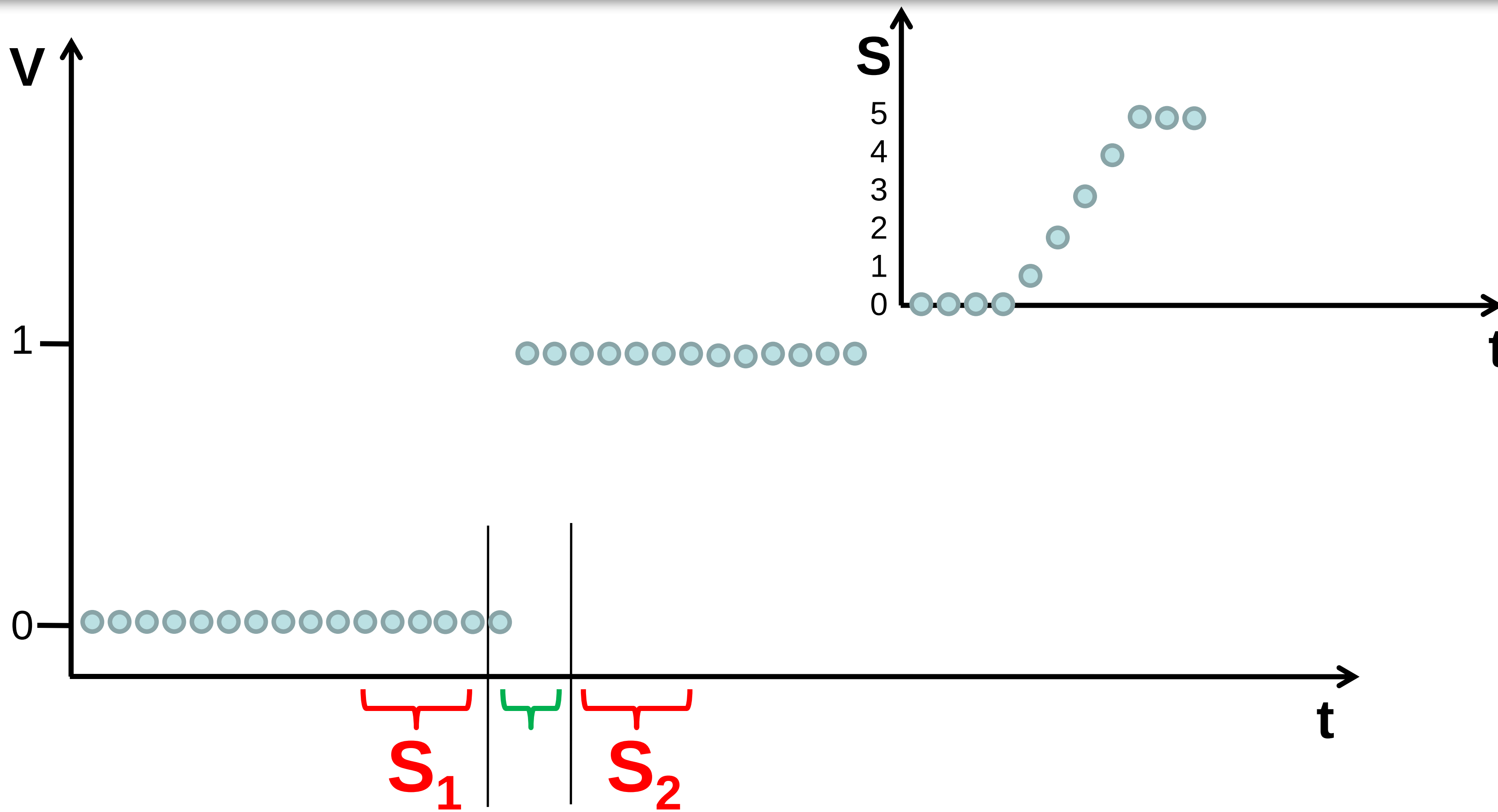
Trapezoidal filter algorithm



$$S = S_2 - S_1 = 5$$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

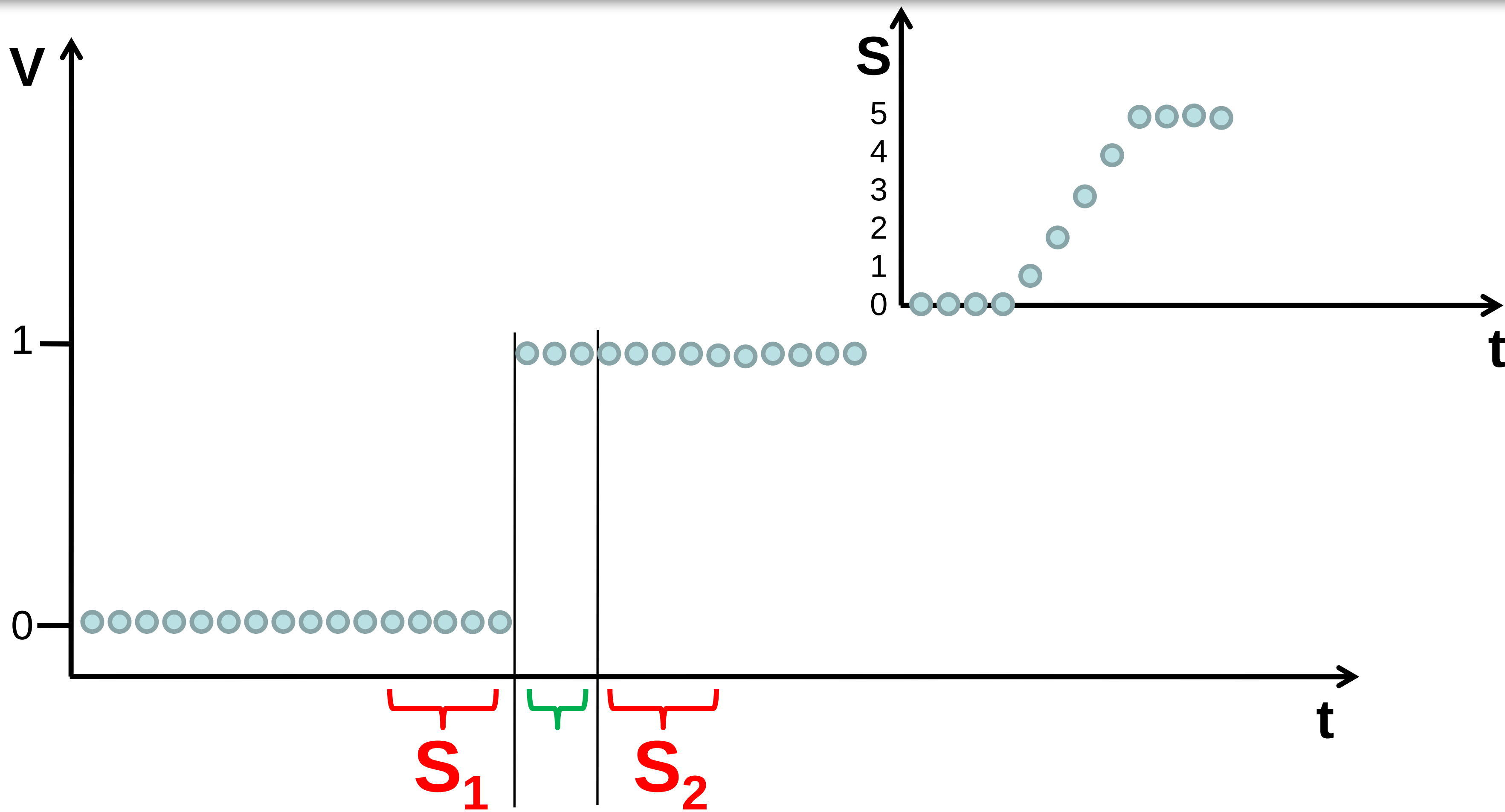
Trapezoidal filter algorithm



$S = S_2 - S_1 = 5$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

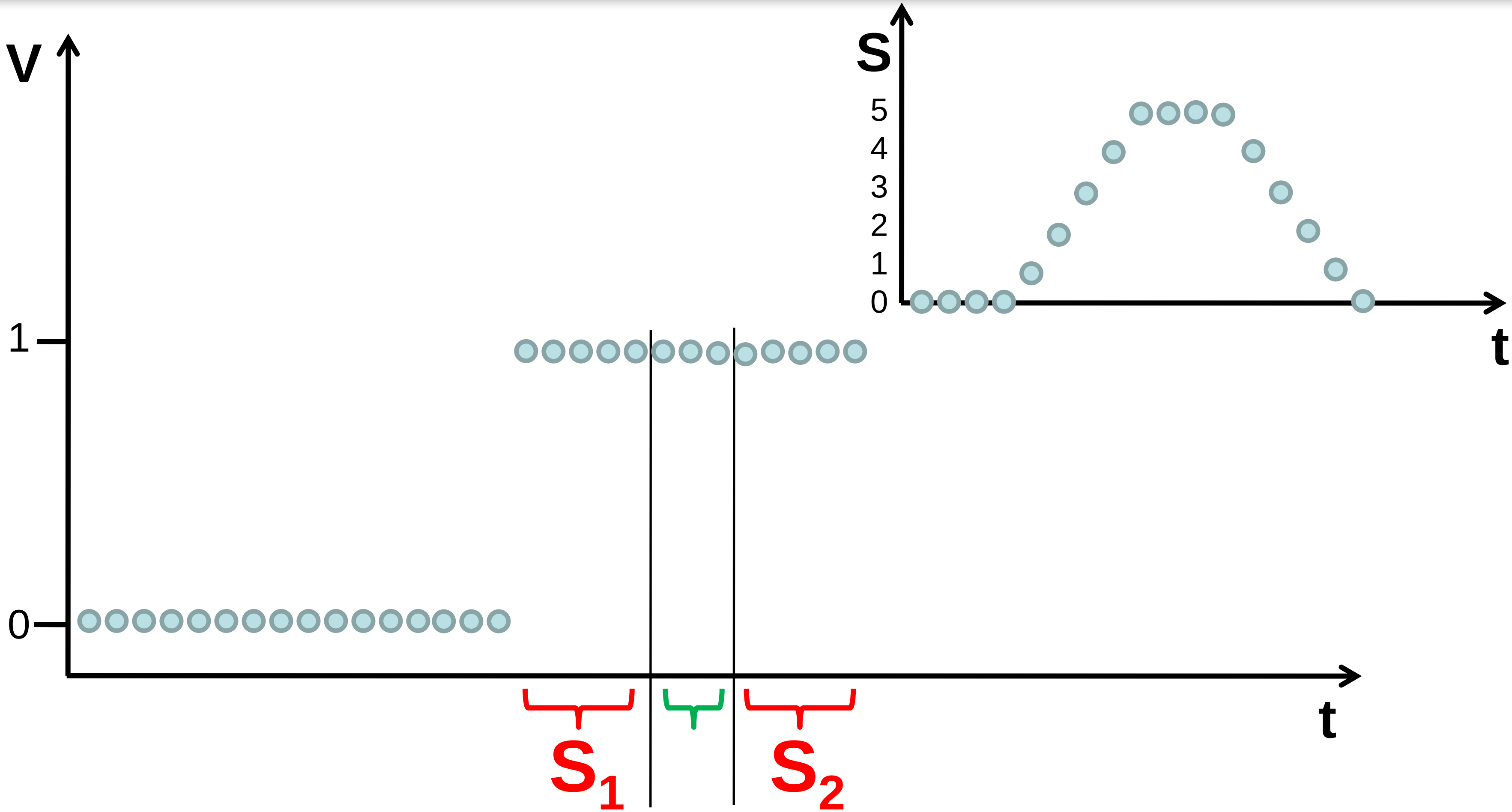
Trapezoidal filter algorithm



$$S = S_2 - S_1 = 5$$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$

Trapezoidal filter algorithm



$$S = S_2 - S_1 = 0$$

$$LV_{x,k} = -\sum_{i=k-2L-G+1}^{k-L-G} V_i + \sum_{i=k-L+1}^{k} V_i$$