Wavelet Transformation for GERDA:
Noise Reduction and Pulse Shape Analysis

Manuel Walter

Universität Zürich UZH

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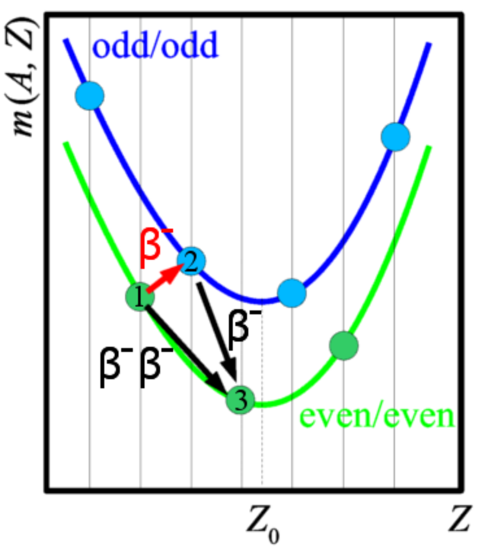
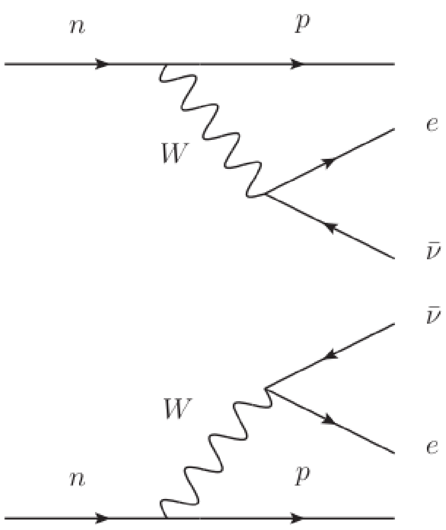
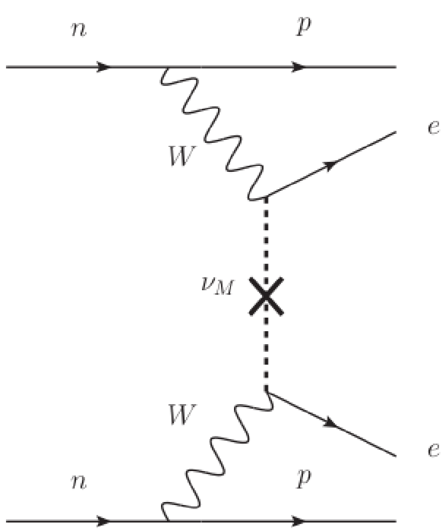
Double Beta Decay





Standard Model 2ν2β decay:

- Known for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, ^{130}Ba, ^{136}Xe
- $T^{1/2}(2\nu)$ in the range of $10^{18\text{-}24}$ yr
- ^{76}Ge: $T_{2\nu} = 1.8^{+0.14}_{-0.10} \cdot 10^{21}$ yr [1]

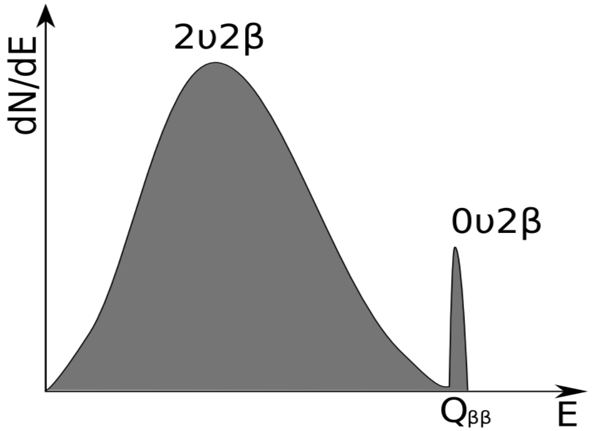


GERDA is searching for the 0ν2β decay.
If it is discovered:

- Lepton number is violated (ΔL = 2)
- Requires physics beyond the Standard Model
- A likely mechanism is ”massive Majorana neutrino exchange”, see e.g. [2]

[1] GERDA Collaboration, J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110
[2] W. Rodejohann, Int. J. Mod. Phys. E20, 1833-1930 (2011)

The GERDA Experiment



- Bare Ge diodes enriched to 86 % of ^{76}Ge:
  - directly immersed in a 5.5 m high 64 m^3 liquid Ar cryostat: cooling and shielding
- Water Cherenkov detector (590 m^3 , 8.5 m heigh) to veto cosmic muons and absorb neutrons
- Plastic scintillator to veto muons going through the neck of the cryostat

Experimental signature:

- Peak at $Q_{\beta\beta} = m(A, Z) - m(A, Z - 2)$
  $= 2039$ keV for ^{76}Ge

Mockup of the GERDA experiment

[GERDA Collab., Eur. Phys. J. C 73 (2013) 2330]

GERDA Sensitivity and Background

Sensitivity:

- $T_{1/2}^{0\nu}(n_\sigma) = \frac{\ln 2 \cdot N_A}{n_\sigma \sqrt{2}} \frac{f_{76} \cdot \varepsilon}{m_A} \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$

  $= const \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$

  M = detector mass

  t = livetime

  BI = background index

  ΔE = energy resolution

- Background reduction is directly increasing the sensitivity

Ways to reduce background:

- Pulse shape discrimination
- Selection of radio-clean materials
- Active veto:
  - Muons
  - γ rays

Background at $Q_{\beta\beta}$ is flat for GERDA (do not expect a background peak at $Q_{\beta\beta}$)

Two Phases:	Mass [kg]	BI [cts/(keV·kg·yr)]	Exposure [kg·yr]	$T_{1/2}^{0\nu}$ Sensitivity [yr]
I (finished)	18	10^{-2}	21.6	$2 \cdot 10^{25}$
II (expected)	38	10^{-3}	100	$2 \cdot 10^{26}$

GERDA Phase I Results

Events at $Q_{\beta\beta}$ ±5 keV

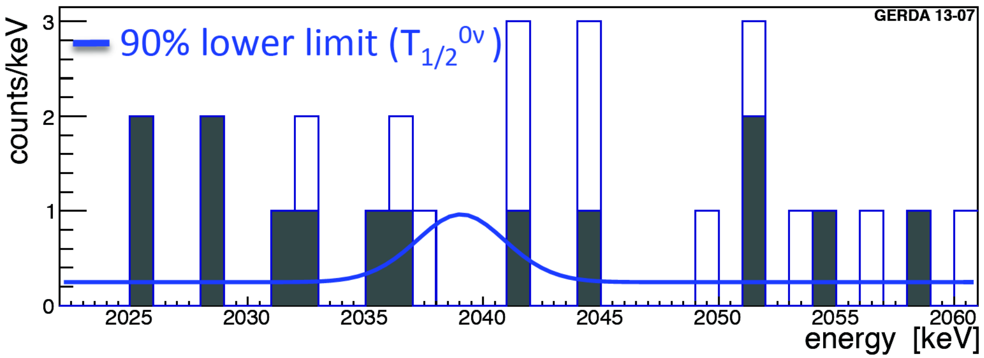
PSD	Dataset	Obs.	Exp. bkg
no	golden	5	3.3
	silver	1	0.8
	BEGe	1	1.0
yes	golden	2	2.0
	silver	1	0.4
	BEGe	0	0.1

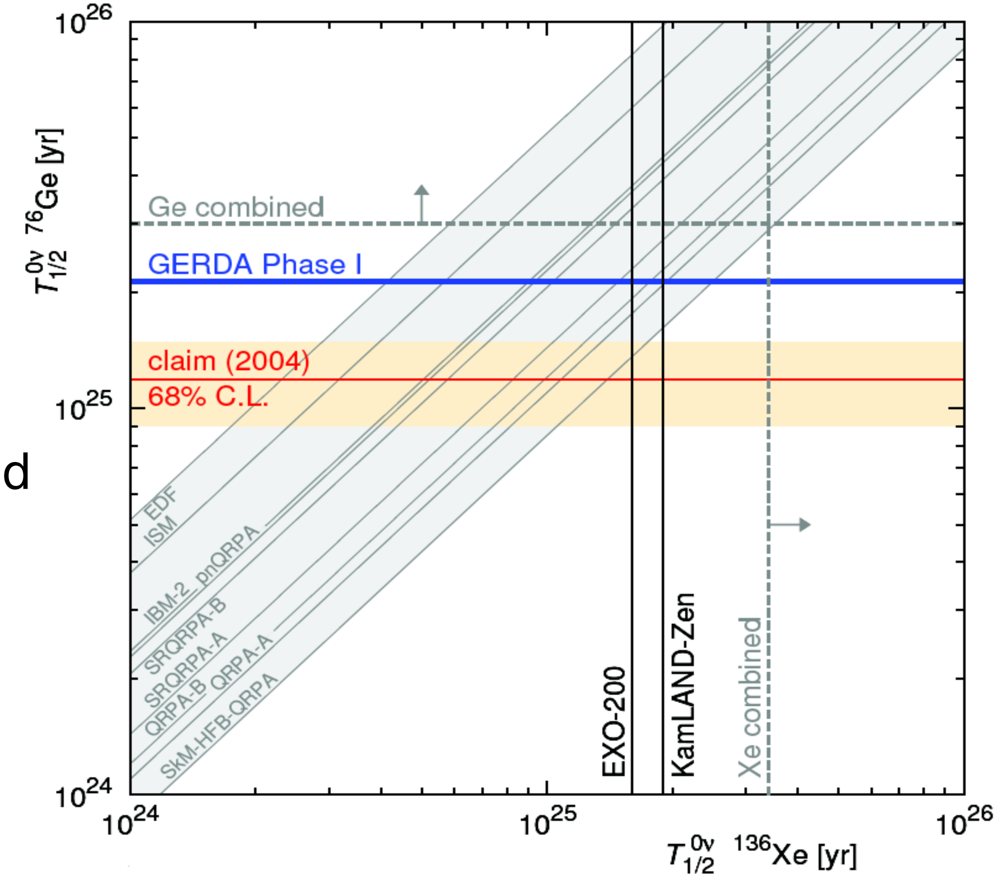
Profile Likelihood Method

- Best fit $N_{0\nu} = 0$
- No excess of signal over background
- 90% C.L. lower limit:

$$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}\,\mathrm{yr}$$

- GERDA Collaboration, Phys. Rev. Lett. 111 (2013) 122503





New EXO (^{136}Xe) result: $T_{0\nu} > 1.1 \cdot 10^{25}$ yr (90%) C.L. [arXiv:1402.6956 [nucl-ex]]

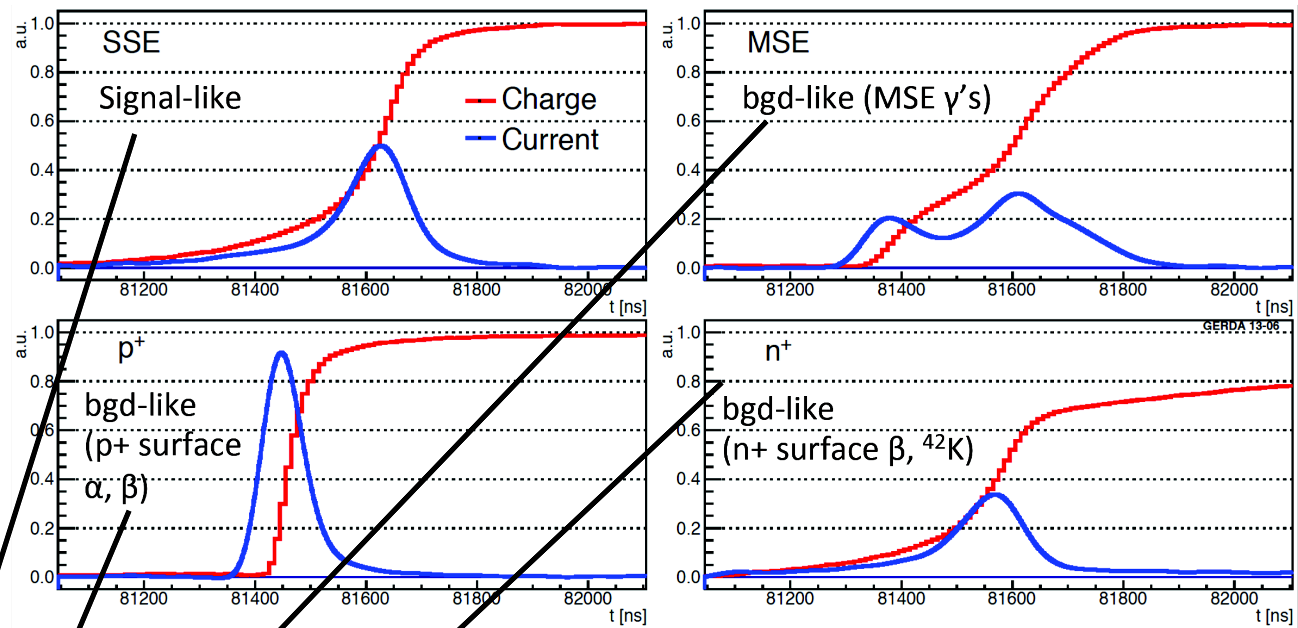
Pulse Shape Discrimination:
Background Rejection

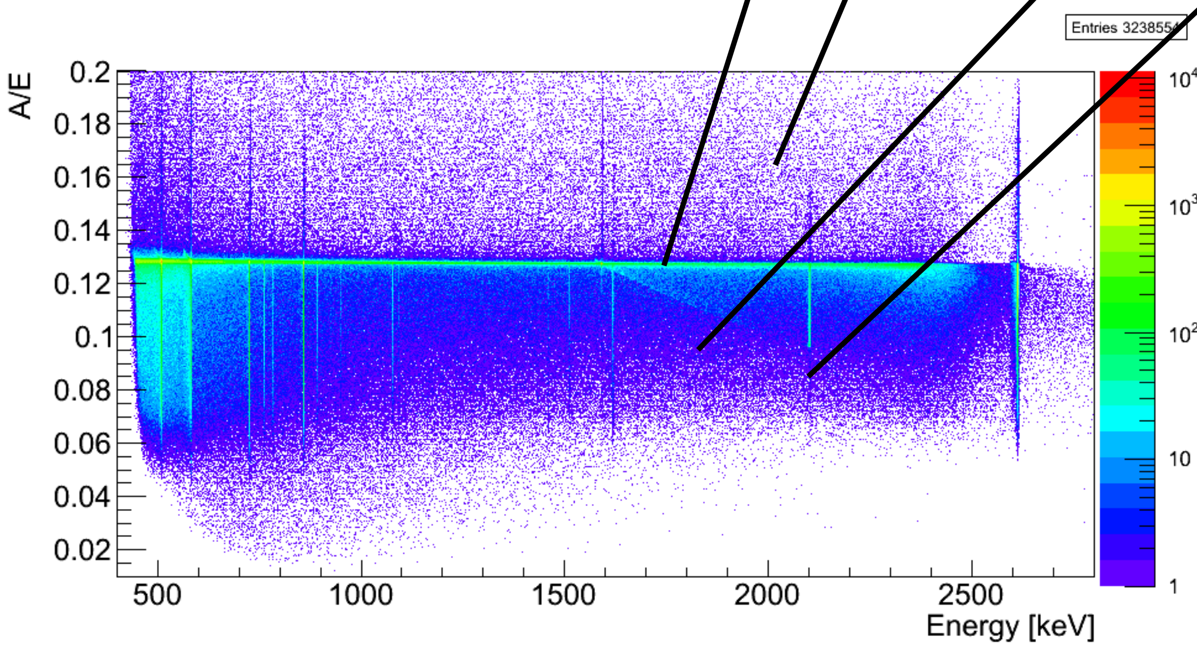
Signal events:

- Single location in the detector bulk (SSE)

Background:

- γ: mostly multiple interaction sites (MSE)
- α and β: mostly surface





Background rejection:

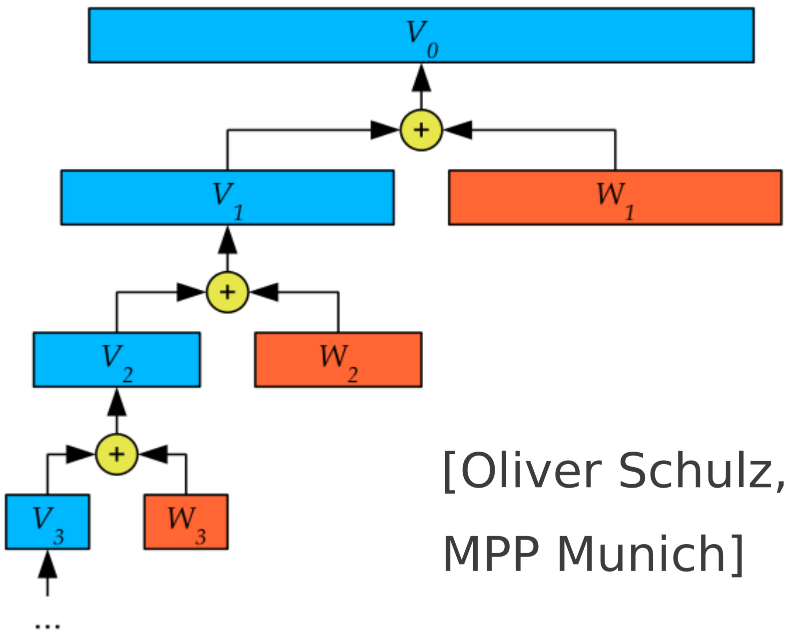
- Cut on amplitude A of current pulse / energy E (amplitude of charge pulse)
- Efficiency strongly dependent on electronic noise

  => Improve noise reduction for Phase II e.g. using wavelets

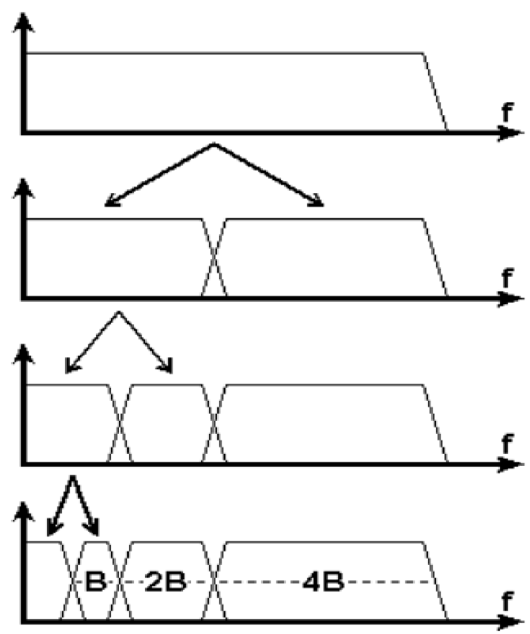
Principle of Wavelet Transformation

Wavelet transformation is a multi resolution decomposition:

- Decomposition is performed convolving the trace with:
  - Wavelet function (high pass)
  - Scaling function (low pass)
- Moved along the trace to obtain local amplitudes of the two functions in the trace:
  - **Wavelet coefficients c**
  - Scaling coefficients
- Use scaling coefficients for next iteration (= scale/level)
- Cutting on decomposed waveform (sets of wavelet coefficients) corresponds to time resolved frequency cuts



[Oliver Schulz, MPP Munich]



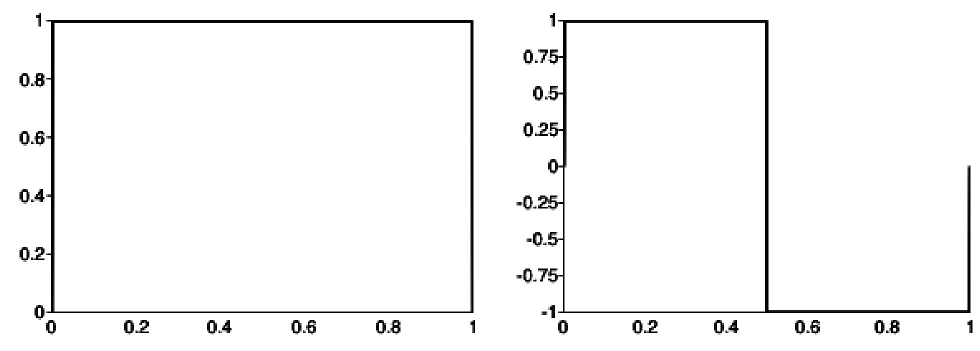
[Michael B. Stewart (of Rader, Fishman & Grauer PLLC)]

Daubechies Wavelet Class

Class of wavelets used in this work: Daubechies Wavelets:

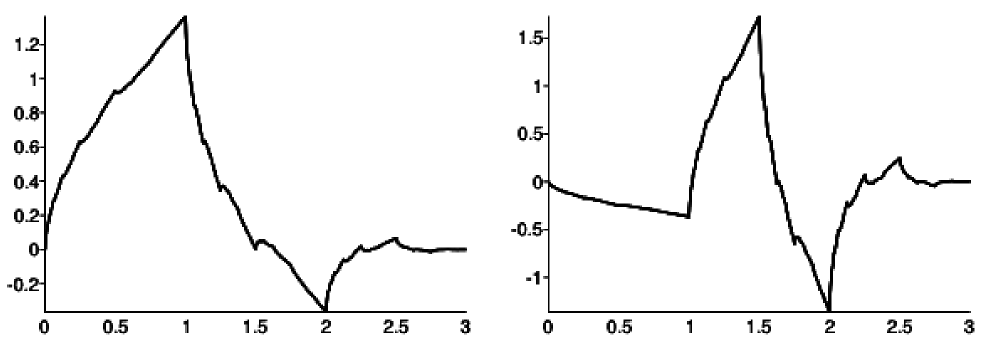
- Forming an orthonormal basis for square integrable functions:
  - Can describe any square integrable signal, like any digitised trace
- Discrete transformation has been implemented into the GERDA analysis software Gelatio

- Wavelet and scaling functions have to be reconstructed from their coefficients, no analytic form (except Daub2)



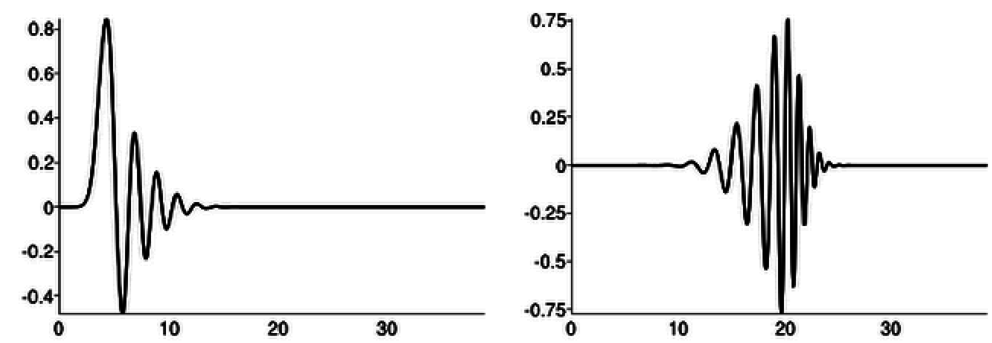
Scaling function φ   Wavelet function ψ

Daubechies 2



Scaling function φ   Wavelet function ψ

Daubechies 4

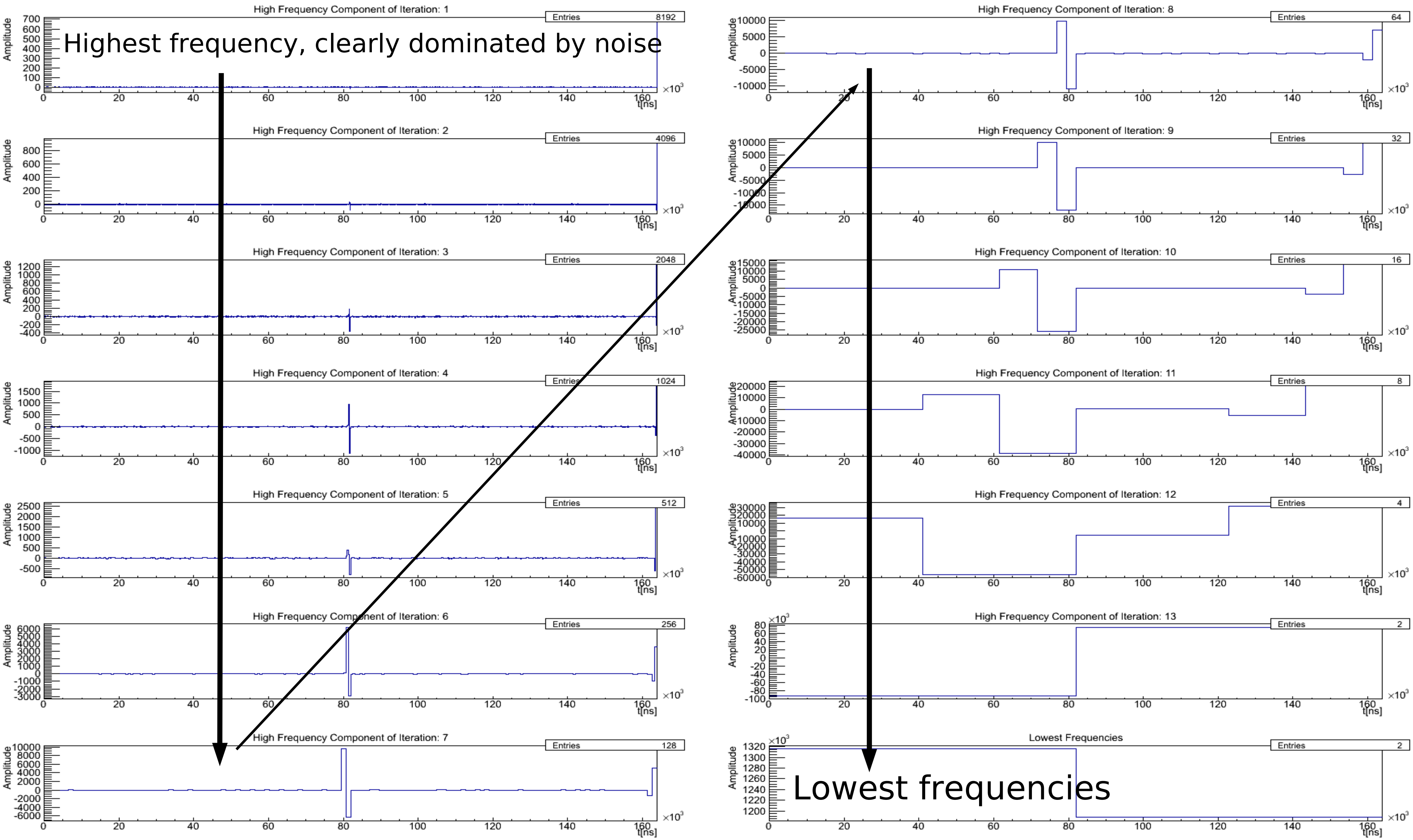


Scaling function φ   Wavelet function ψ

Daubechies 20

[Plots from http://wavelets.pybytes.com/]

One Example Decomposed Waveform



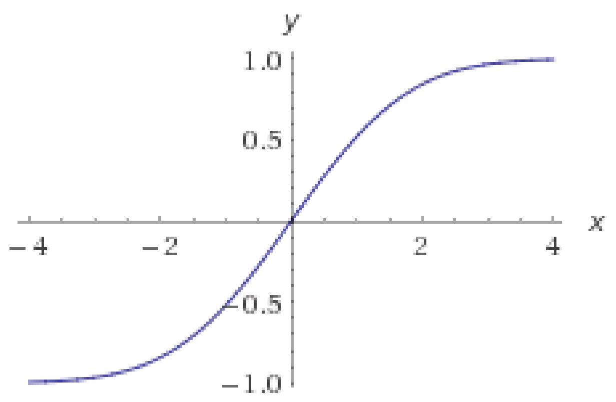
Complete set of wavelet coefficients needed to descibe one event

(one trace = one scale) Here: 2147 keV

Cut Procedure for Denoising

Implemented different types of threshold

- Hard threshold:
  - Set wavelet coefficients (c) below threshold to 0
  - Subtract threshold value from coefficients (c) above threshold
- Soft threshold:
  - $c_{cut} = c_{orig} \bullet \mathrm{erf}(c_{orig} / (th. \bullet \sqrt{2}))$



Two options for height of threshold

- Calculate event by event for each scale
- Set a fixed threshold for all events

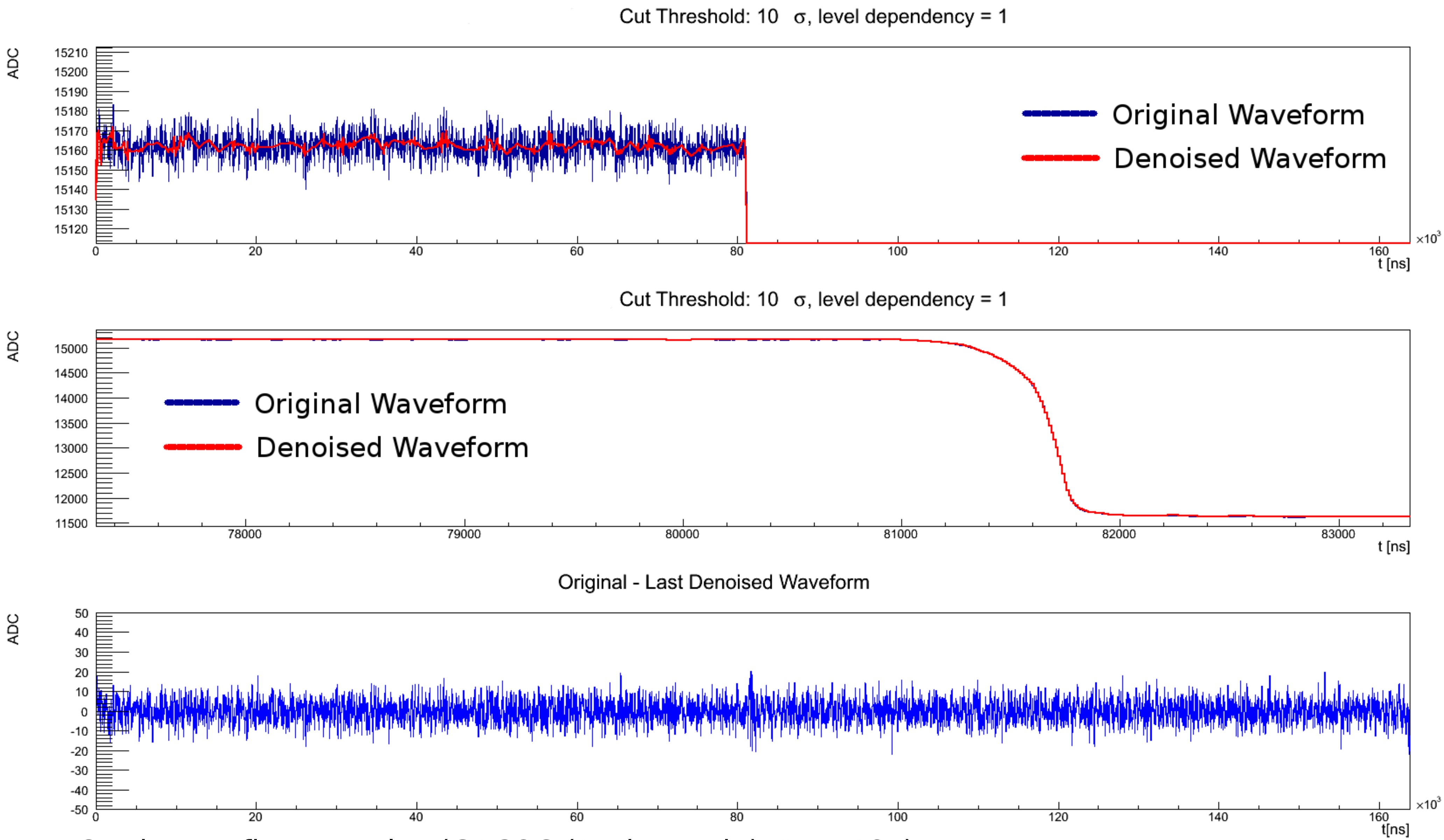
Different thresholds for different scales

- No. of high frequency scales to cut on
- And level dependency: $th.[scale] = th._{given/calculate}[scale] / scale^{leveldep.}$

Parameter to scan:

- Wavelet type, threshold level and type, level dependency, No. of levels to cut

Example Denoised Waveform
(Daubechies 6 Wavelet)

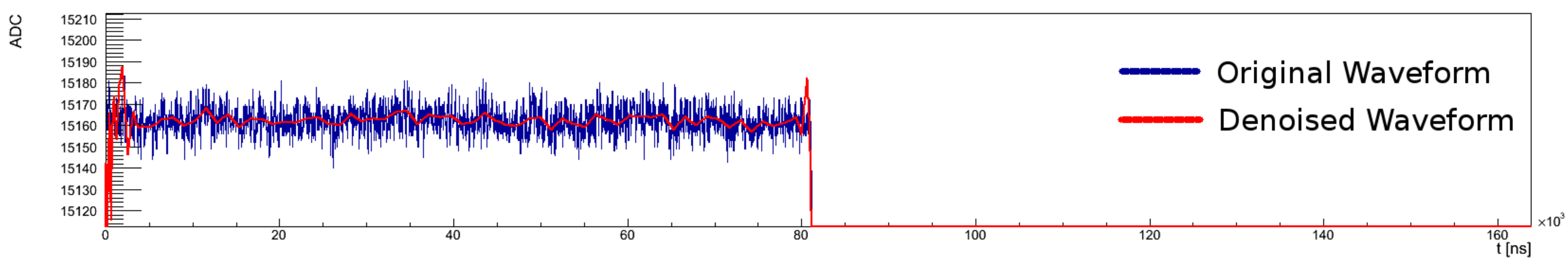


Cutting on first 7 scales (GD32C (Andromeda), Run 46a)

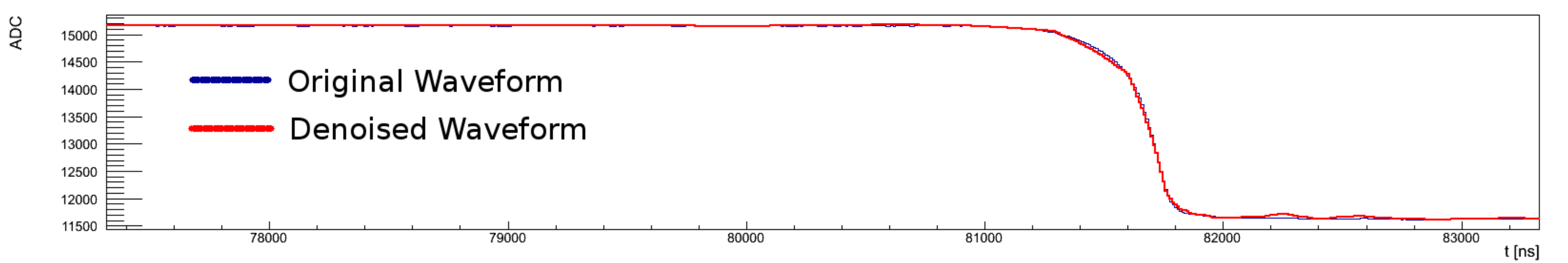
Good signal description and significant noise reduction

Effect of Level Dependency

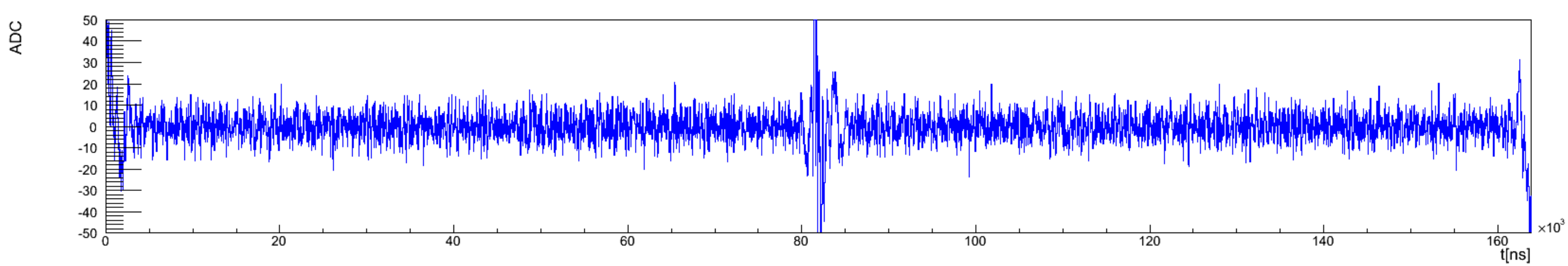
Cut Threshold: 10 σ, level dependency = 0



Cut Threshold: 10 σ, level dependency = 0



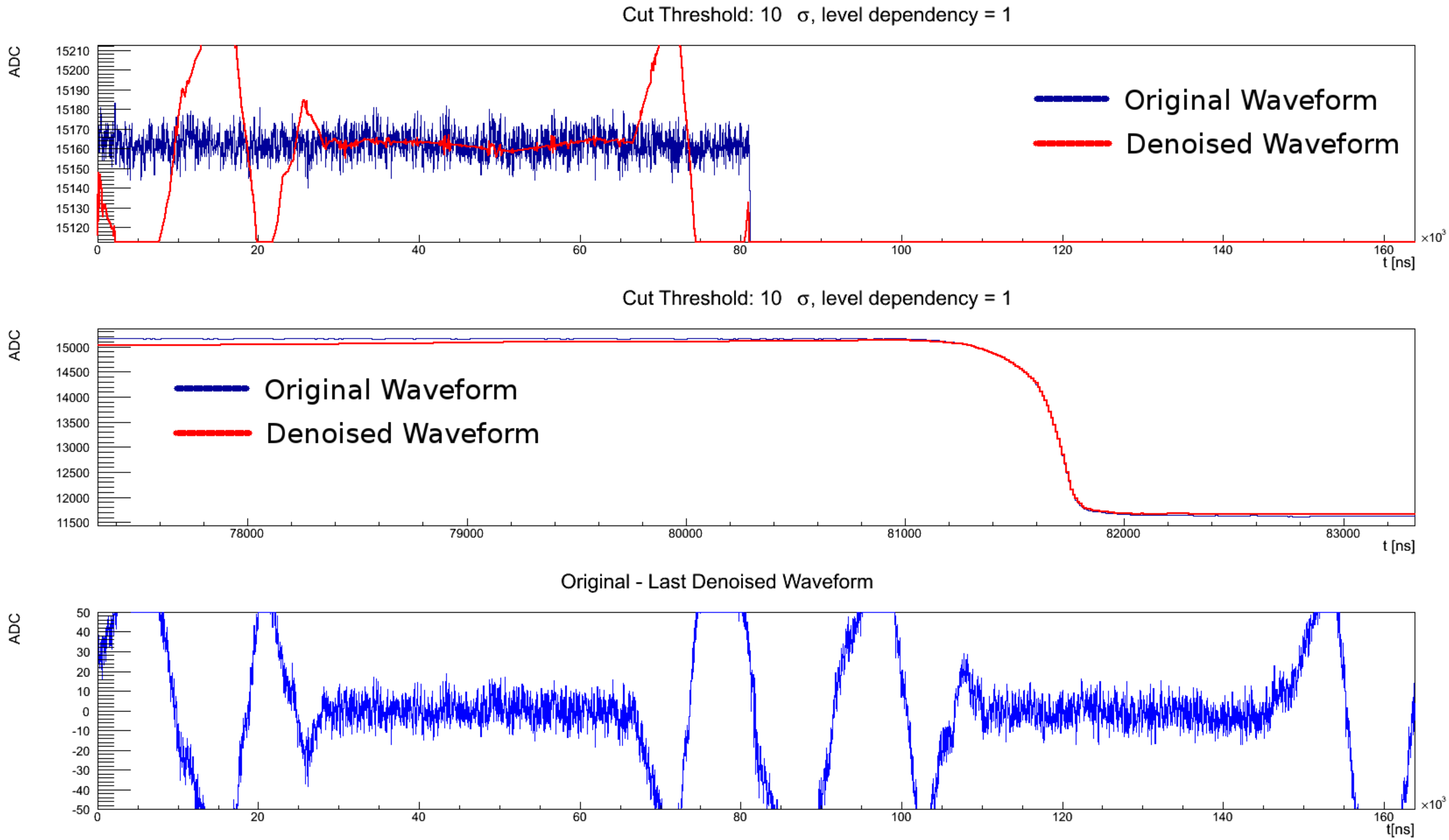
Original - Last Denoised Waveform



No dependency instead of 1

=> Difference of denoised signal to original waveform clearly larger than noise

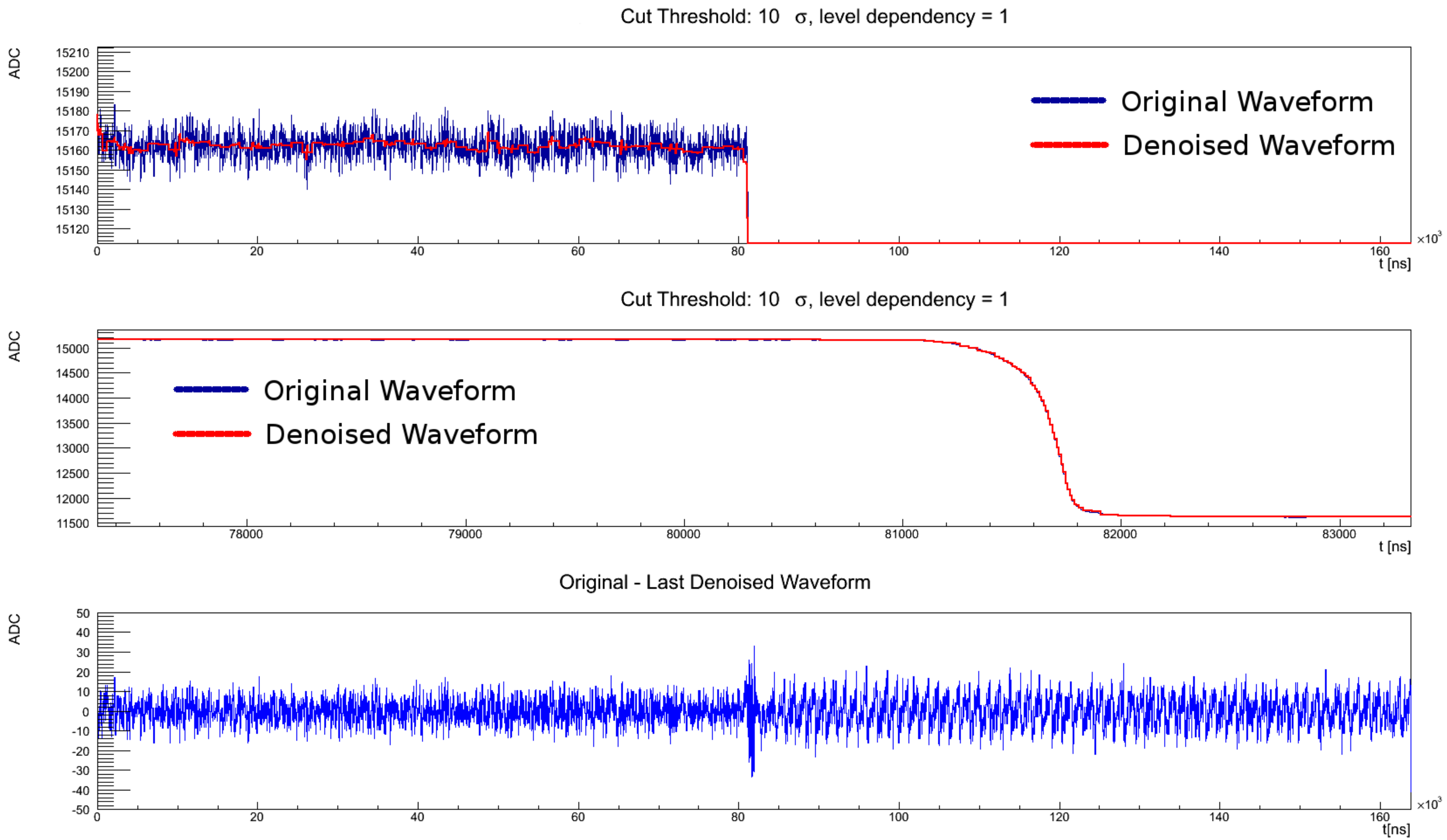
Effect of Low Frequencies



Cutting on the first 10 scales instead of 7

=> low frequencies clearly needed to describe the signal

Daubechies 2 Wavelets



Using Daub 2 => unsteady signal description

A/E After Wavelet Denoising

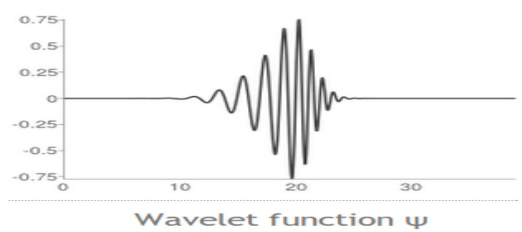
Event based determination fails on our standard calibration traces with a length of 400 samples (10 ns/sample):

- A special calibration was taken with 4096 samples in a vacuum cryostat

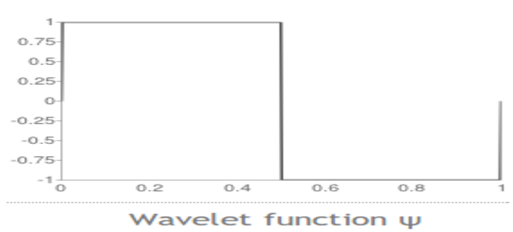
Fluctuations in A/E for strong cuts:

- Examples using:

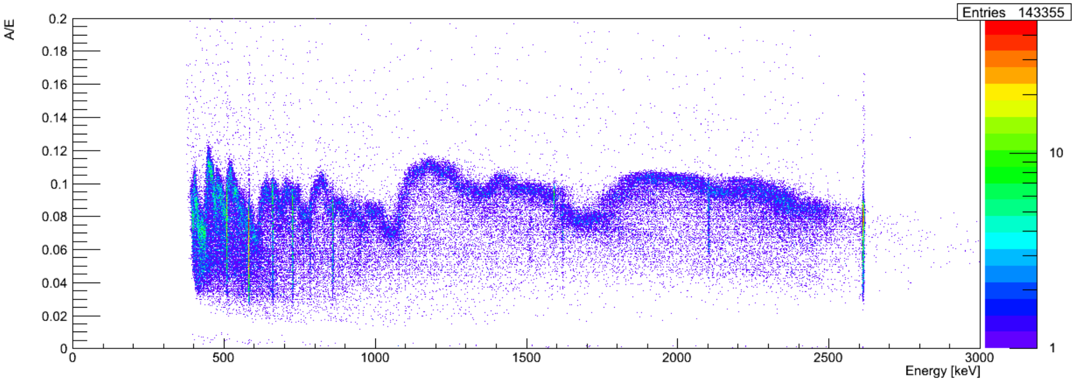
Daub 20

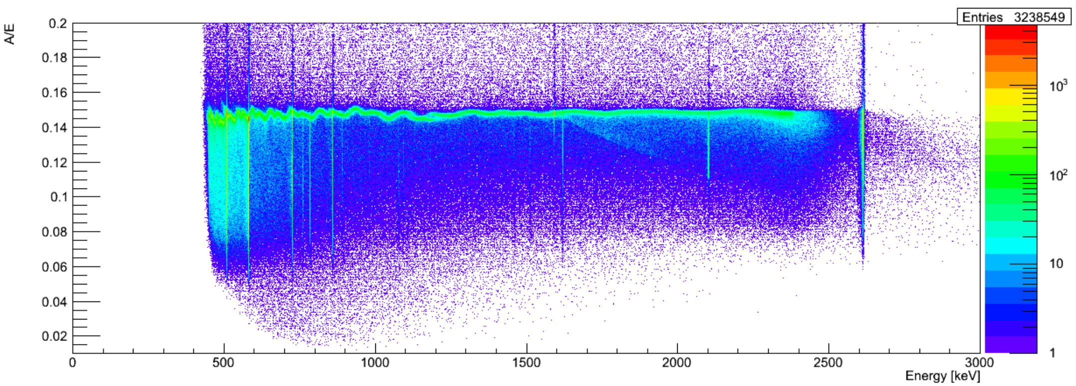


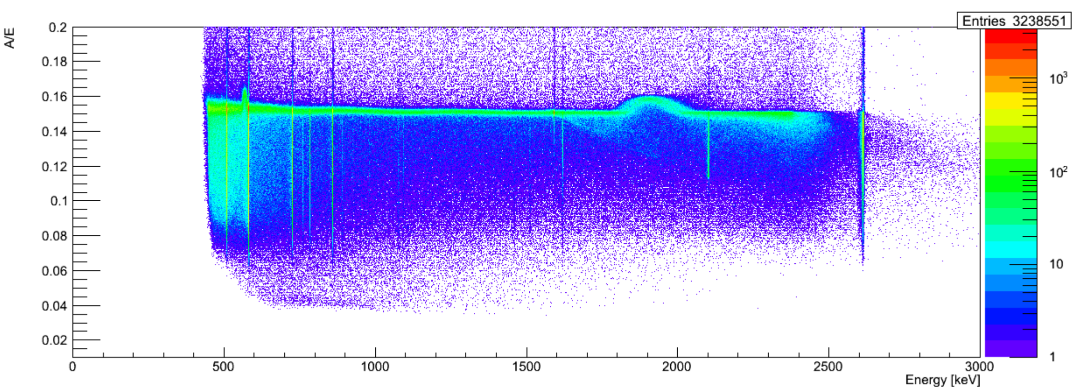
Daub 2



Probably caused by energy dependent trace position (trigger)





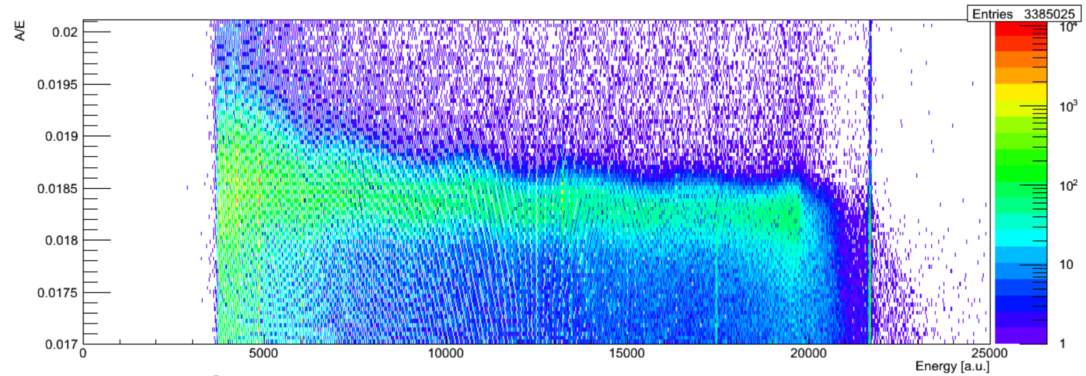


Fluctuations of A/E

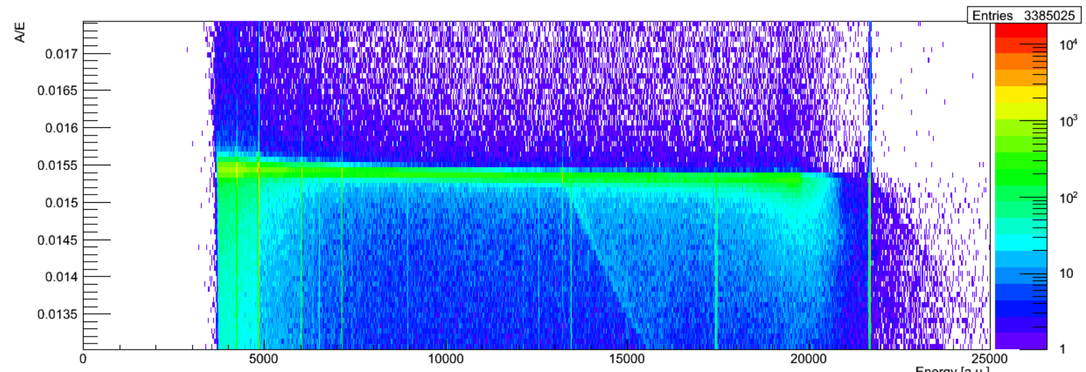
- Small fluctuations also present when applied to unshaped (raw) traces
- Use only parameter sets with fluctuations at most as big as for unshaped traces
- Fluctuations smaller using Daub 2 and 20 than using other Daub types
- Fluctuations smaller with soft than hard threshold

Parameter optimisation:

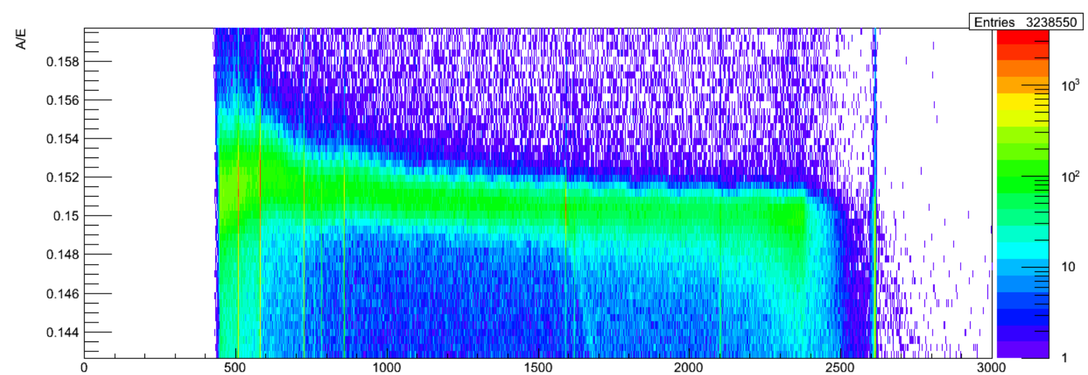
- Fix 90 % survival in the signal like ^{208}Tl DEP at 1592 keV
- Use survival fraction of (background like) events in the 1620.5 keV γ peak for optimisation



A/E of raw traces



Standard analysis chain with 3 · 50 ns MWA

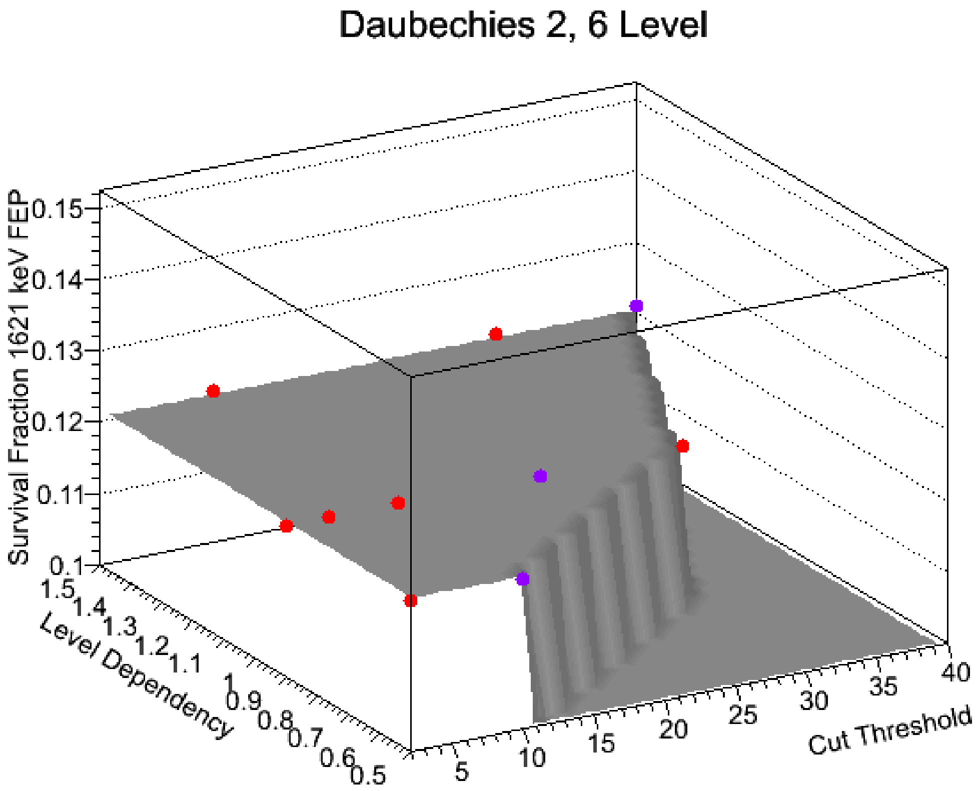


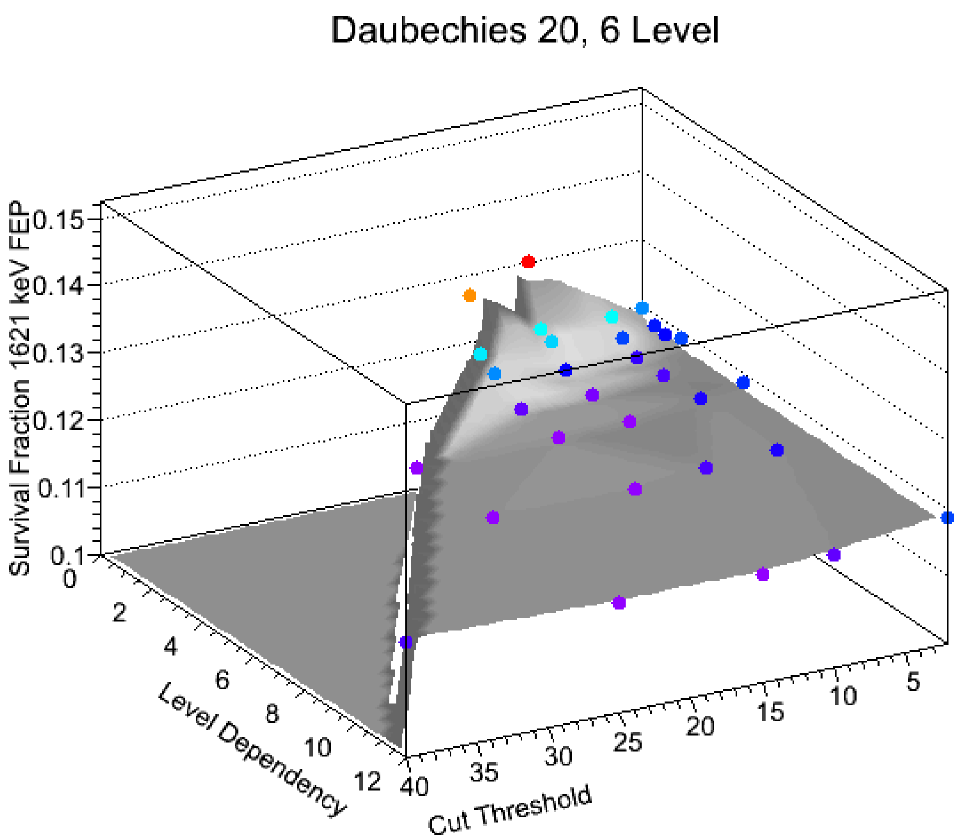
Daub 20, thresh. 10, level dep. 4, 6 scales

Preliminary Results

Survival fraction of 1620.5 keV peak:

- Without denoising: 12.1 %
- With (optimised) 3 · 50 ns MWA: 11.2%
- Daub 6, 8, 10: worse than without denoising





Daub 2: 12.1 %

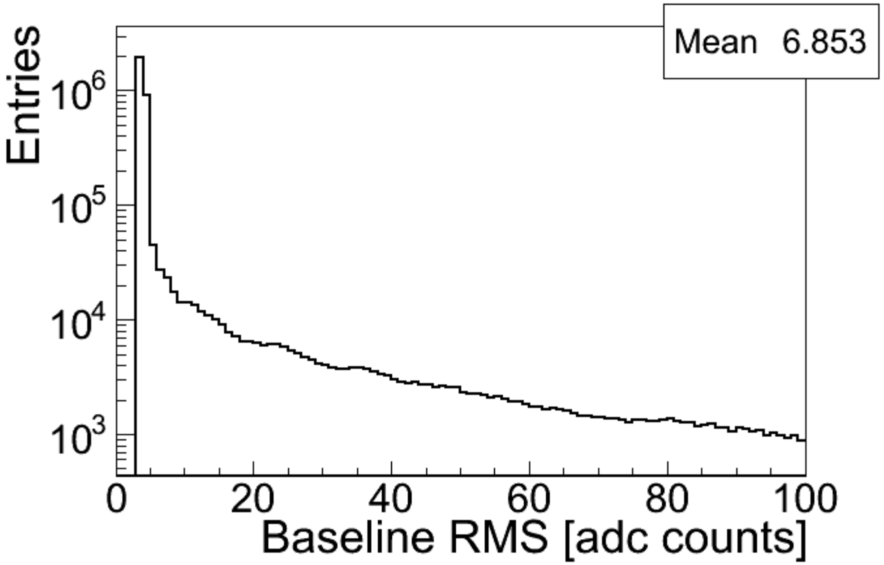
- No effect, despite reduced noise

Daub 20: Up to 11.7 %

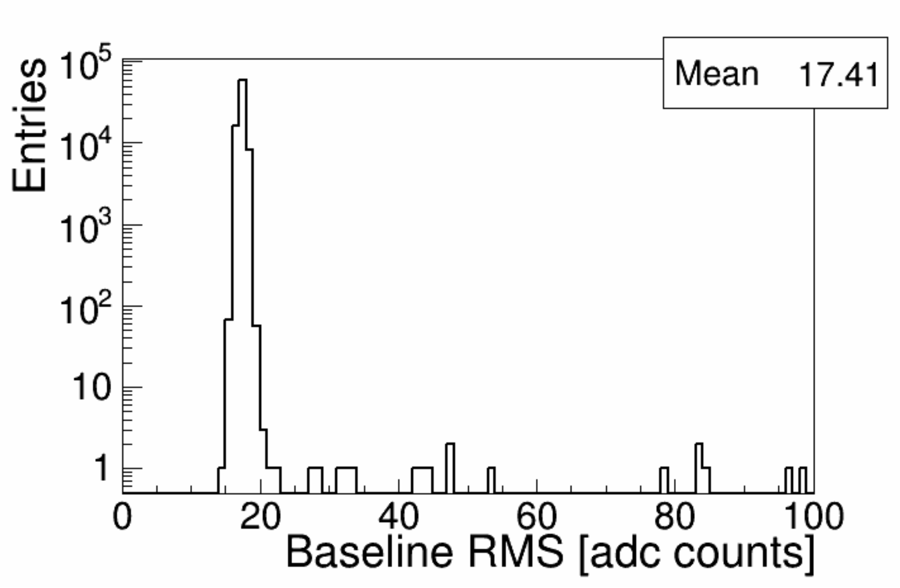
- **Improvement**

Context to GERDA Data

Comparison of Noise conditions:



Low noise level in data used for optimisation



High noise level in GERDA physics data due to long cables

A larger effect of denoising is expected for GERDA like noise conditions

Conclusion and Possible Improvements

Conclusions:

- Wavelet denoising implemented into the GERDA analysis software Gelatio
- Rejection efficiency improved from 12.1% to 11.7%, smaller than with optimised MWA filter 11.2%, so far

Outlook:

- Room for improvements of the filter:
  - Apply to current pulse instead of the charge pulse
  - Correct for energy dependent trigger
  - Find cut directly in transformed waveform
- Improved background rejection efficiency

  => increased sensitivity for Phase II

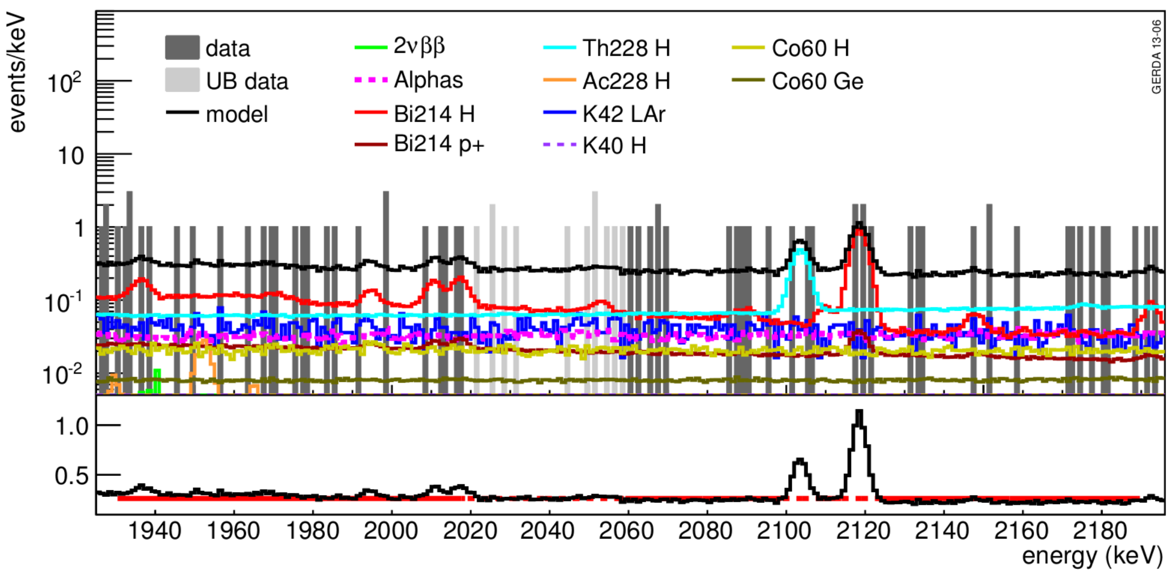
Thank you for your attention!

Backup Slides

GERDA Phase I Background at $Q_{\beta\beta}$

Phase I finished May 2013, Background Models:

- Minimum model containing only known and visible background sources
- Alternative (maximum model) containing the same isotopes but more possible locations
- Both models predict a flat background at $Q_{\beta\beta}$



$[10^{-3}$cts/(keV·kg·yr)]	GOLD-coax	SUM-BEGe
interpolation	17.5[15.1, 20.1]	36.1[26.4, 49.3]
minimum	18.5[17.6, 19.3]	38.1[37.5, 38.7]
maximum	21.9[20.7, 23.8]	-
after PSD	11[9, 13]	5[2, 9]

For $0\nu2\beta$ analysis:

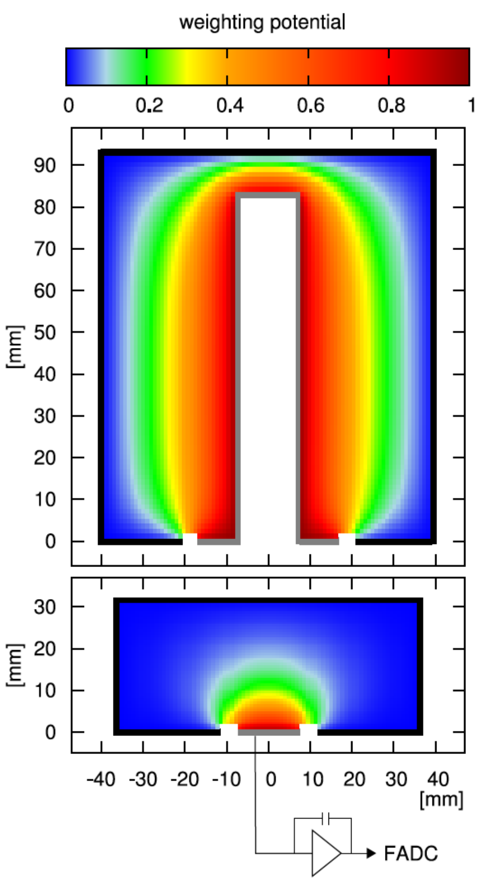
- Use an interpolation of the background by a constant excluding known γ peaks at 2104 (^{208}Tl SEP) and 2119 keV (^{214}Bi). Value is consistent with models
- Table:
  BI before and after Pulse Shape Discrimination (PSD) in ROI

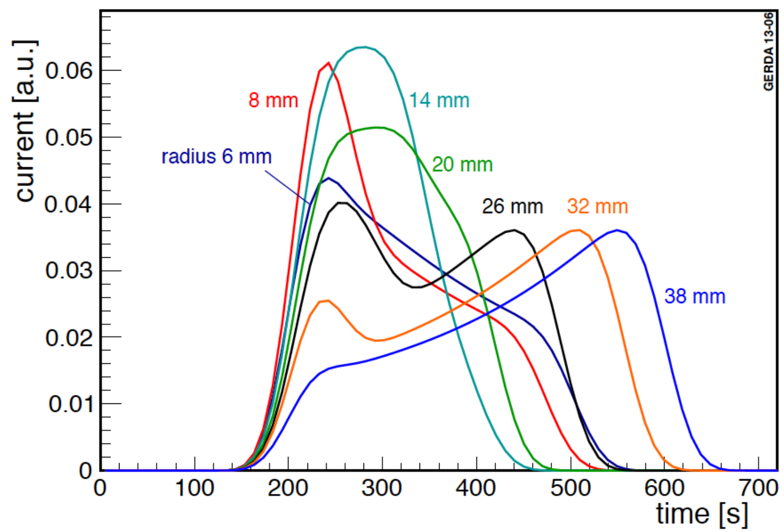
PSD, BEGe and Coaxial Detector

PSD: distinguish between SSE (like many 0ν2β events), MSE and surface events (like many background events)

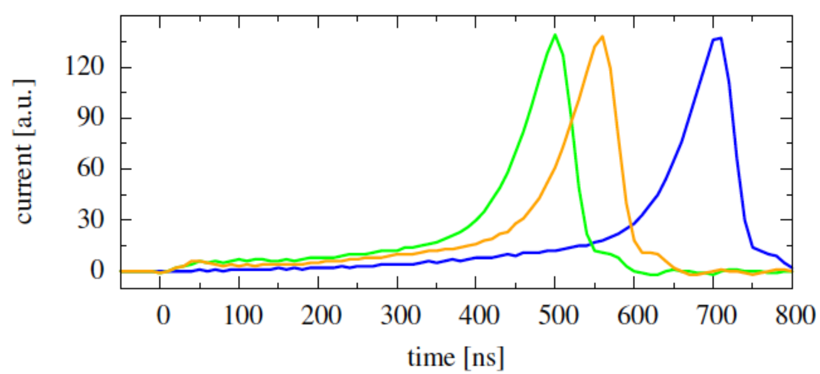
BEGe and Coaxial geometry result in different el. fields and pulse shapes

- Require different PSD methods





- Simulated SSE current pulse in coaxial detector
- Difficult to distinguish from MSE

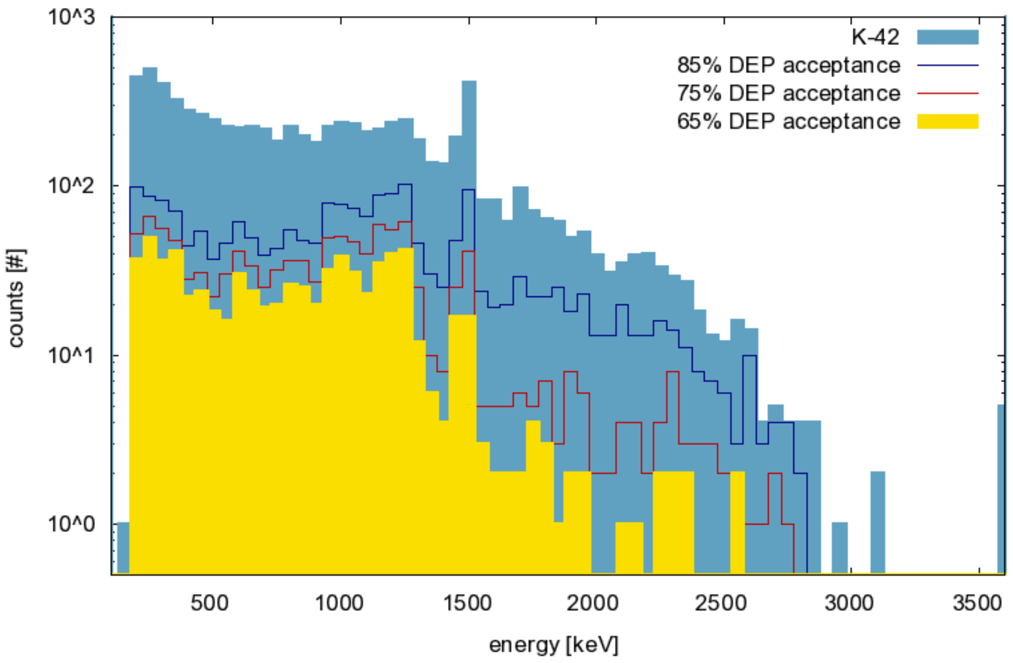


- Simulated SSE current pulse in BEGe
- “Easy” to distinguish from MSE

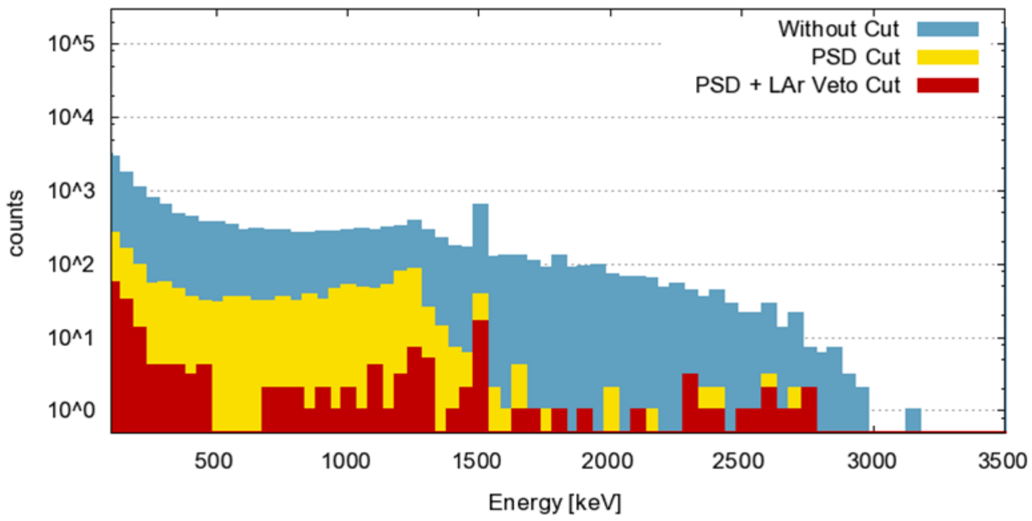
Noise Dependency of Rejection Efficiency

Surface event rejection

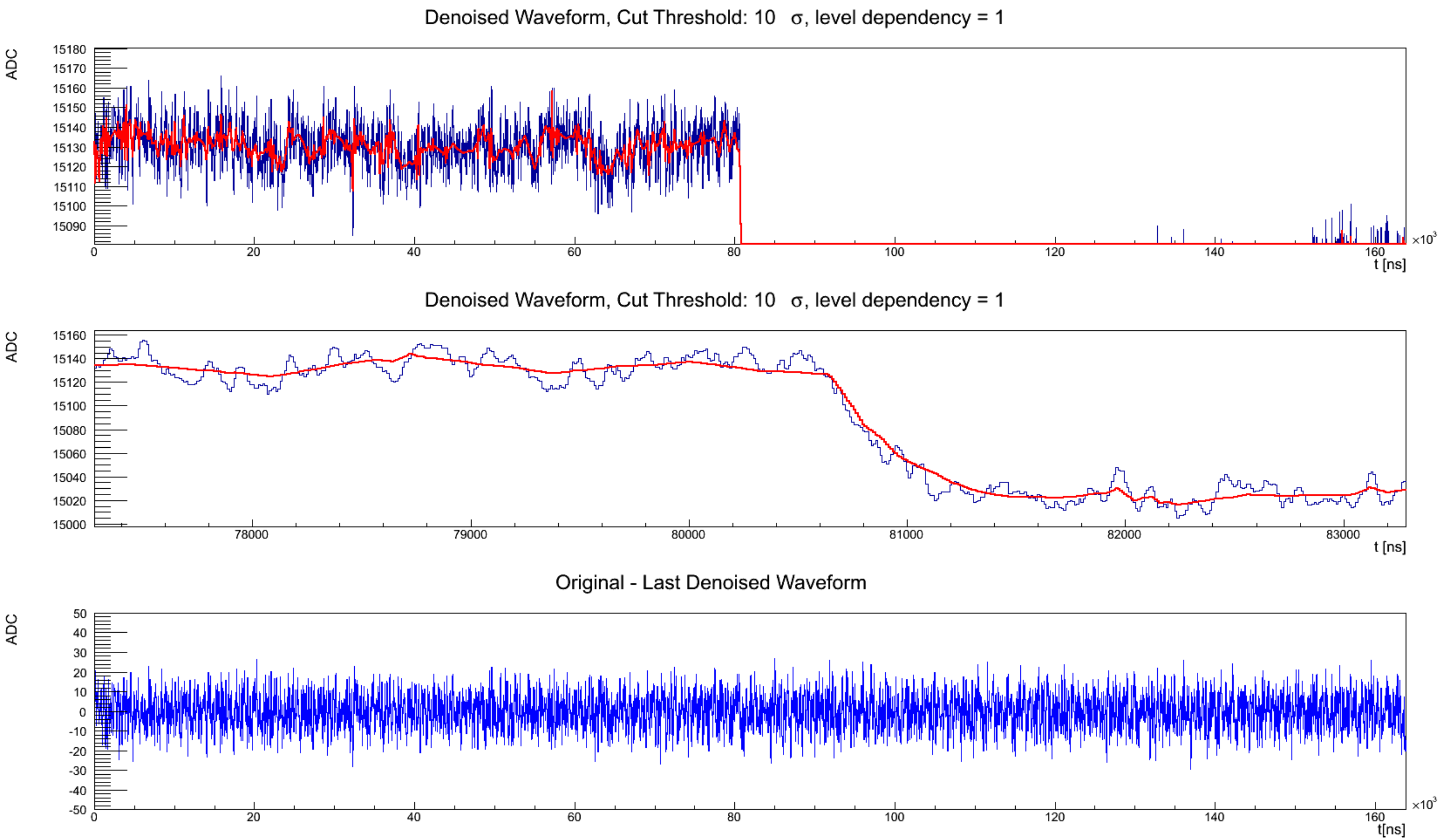
- High noise



- Low noise

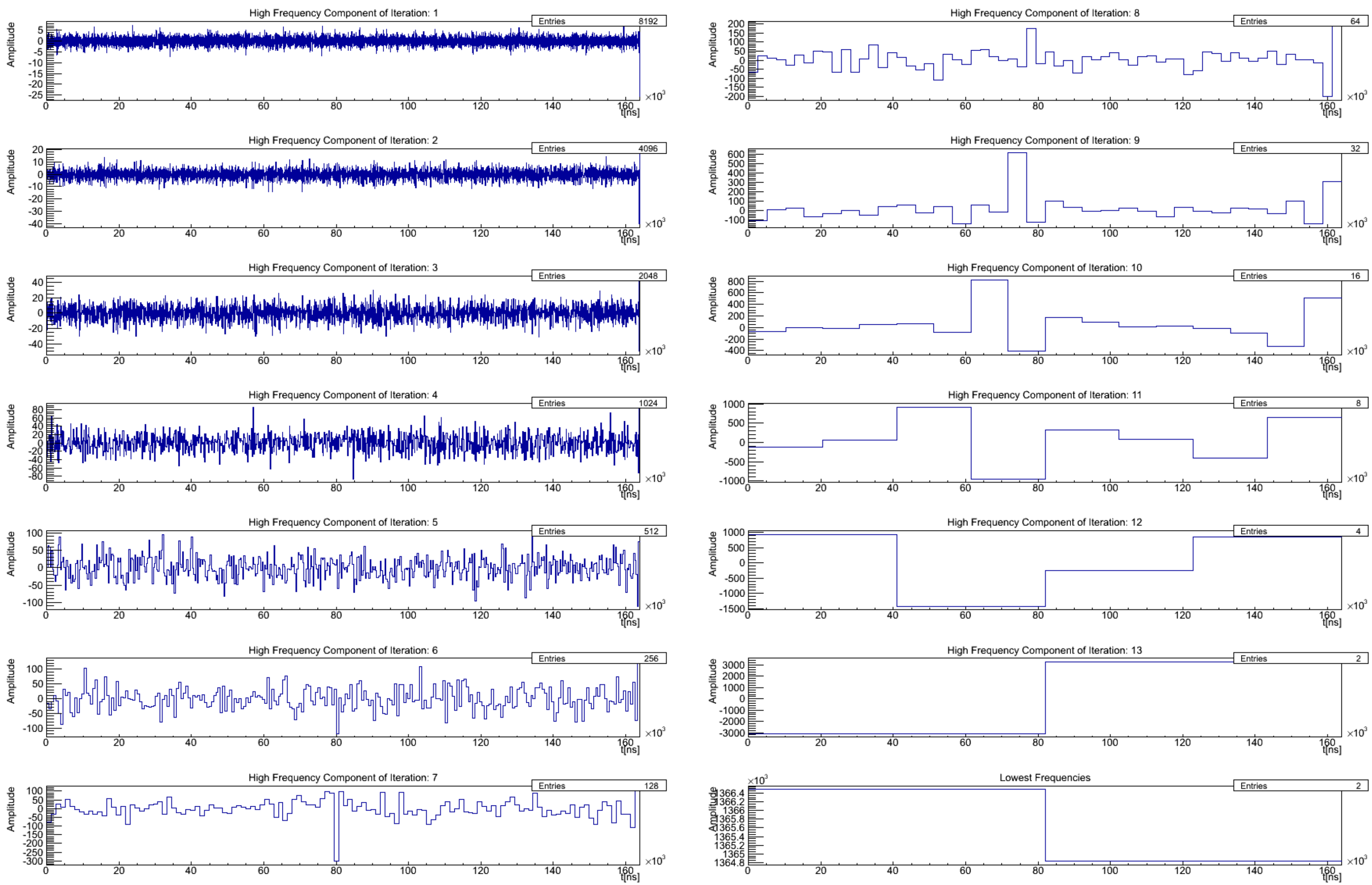


Application to low Energy Events

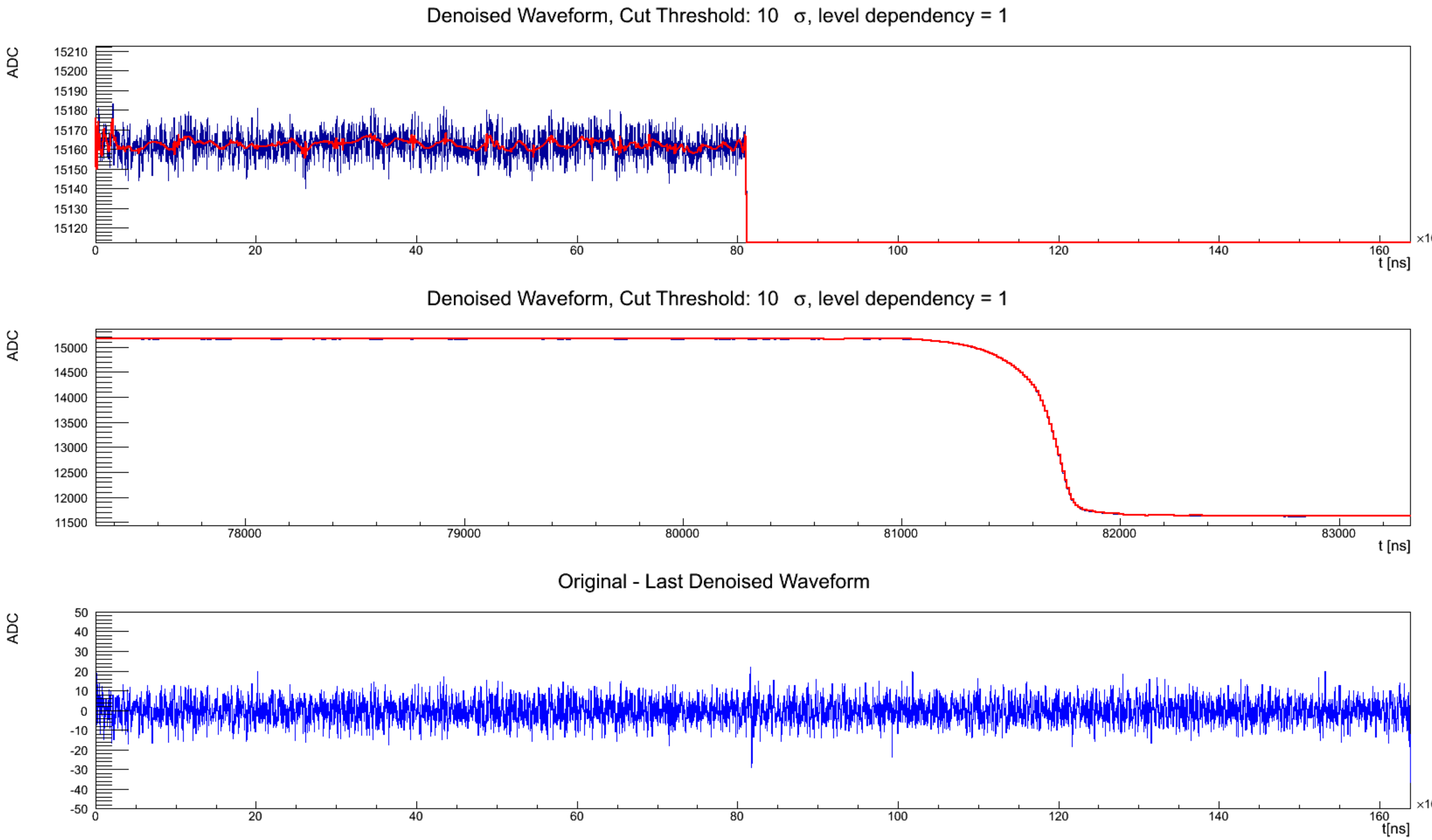


Working well also for low energy events.

Transformed WF of low E Event

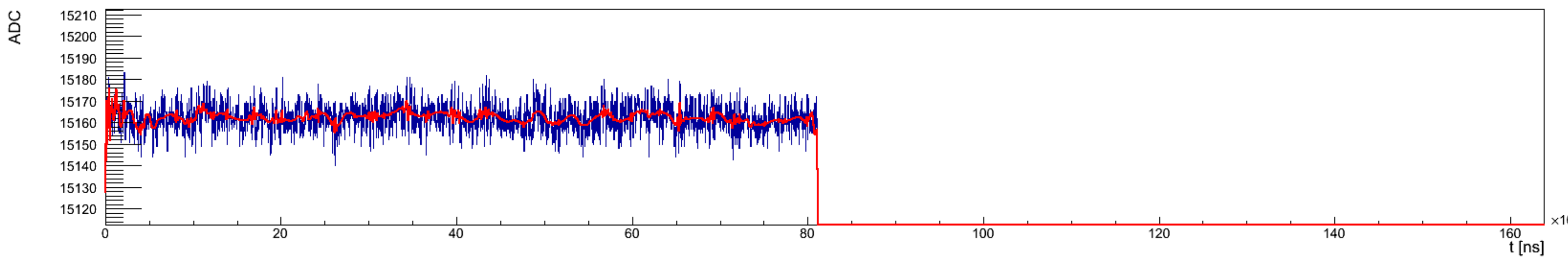


Daubechies 8



Daubechies 10

Denoised Waveform, Cut Threshold: 10 σ, level dependency = 1



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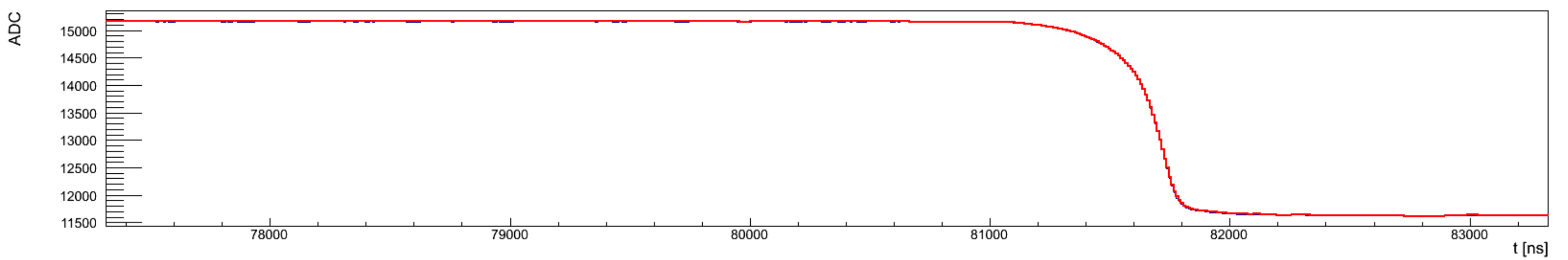

Original - Last Denoised Waveform