TRISTAN ADC Non-linearity

TRISTAN Workshop – July 5th 2022
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ADC Non-linearity Goals

- Create and test code for modeling the impact of DAQ systematics on the tritium spectrum
- Calculate spectral distortion induced by unavoidable non-linearities in the DAQ readout system
- Measure ADC non-linearity in benchtop tests to determine necessary mitigation strategies

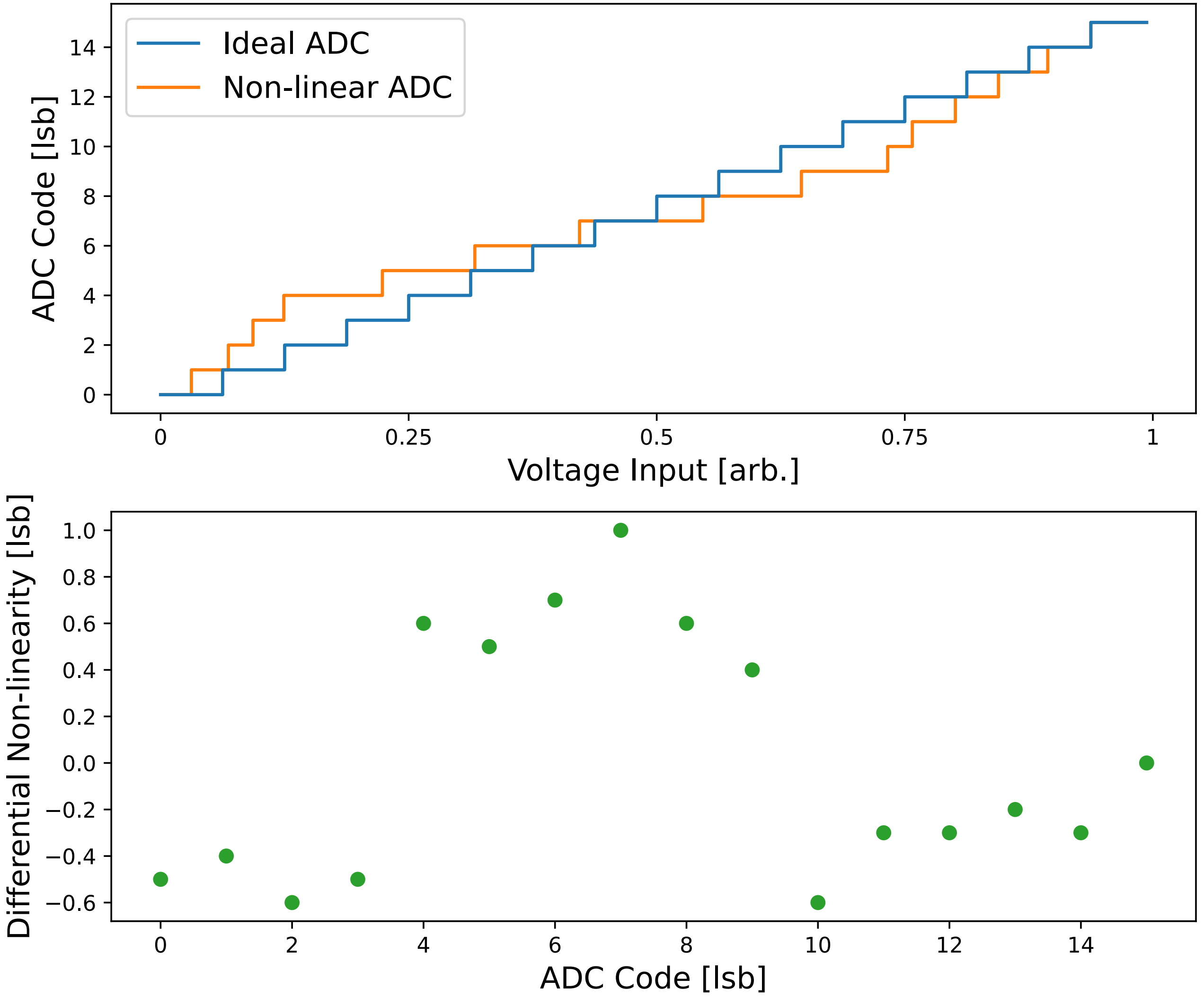
Development splits into three separate categories:

- **Simulation** – development and refinement of code used to produce analysis
- **Hardware development** – adding additional specifications to DAQ board to allow for implementing reduction methods (details included in talk Wednesday by Sascha Wüstling)
- **Bench testing** – non-linearity and spectral measurements

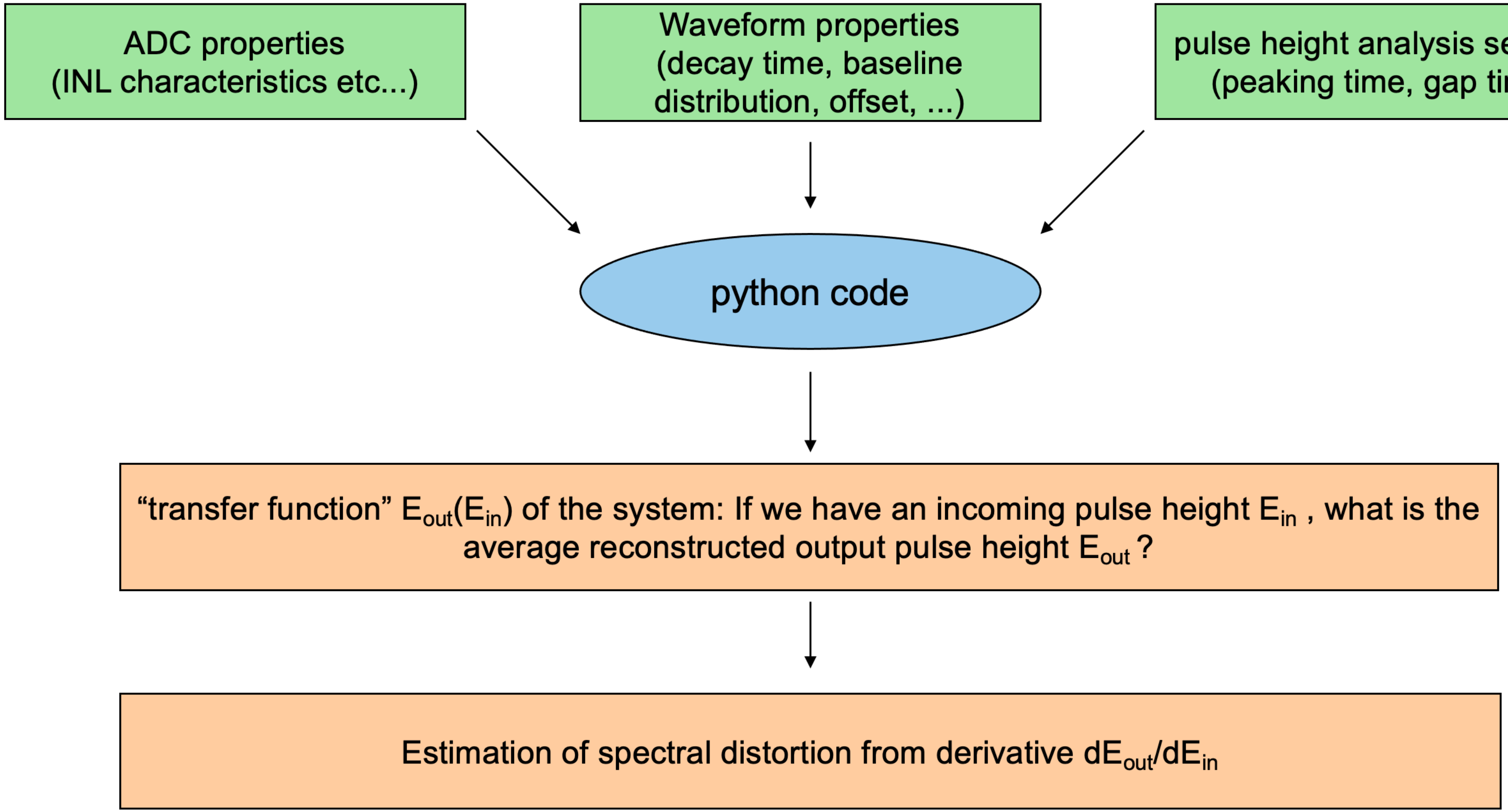
ADC Non-linearity

- All DAQ systems have unavoidable non-linearities which impact performance
- Non-linear 4-bit ADC example shown to the right

- Digitizing pulse with $V_{in} = 0.25, V_f = 0.75$
  - Ideal ADC pulse height = 8 lsb
  - Non-linear ADC pulse height = 5 lsb



TRModel INL Code

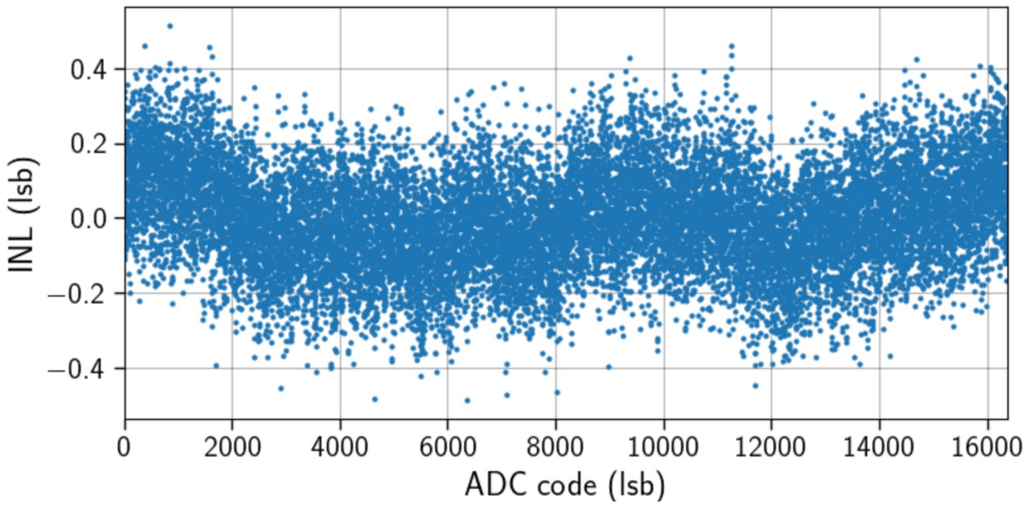


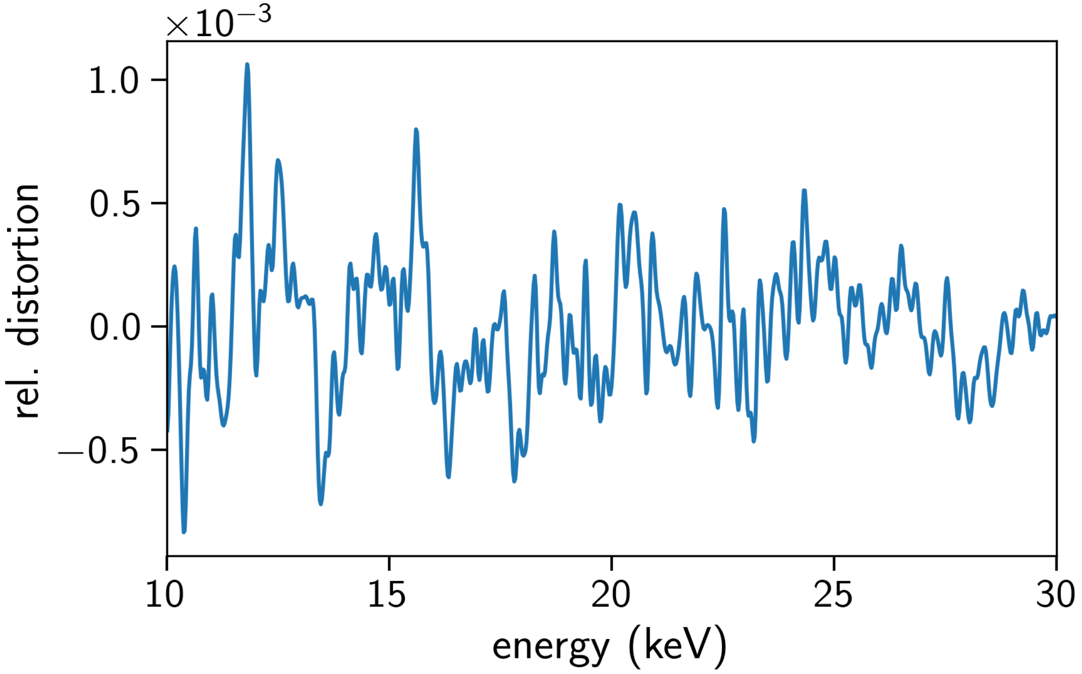
Single Pixel Distortion

- Simulated non-linearity consistent with reported values of AD9257 ADC and measured structure

- TRModel Scenario 1:
    - 10 keV post-acceleration
    - 10 kcps
    - Normal waveform decay and pulse height analysis

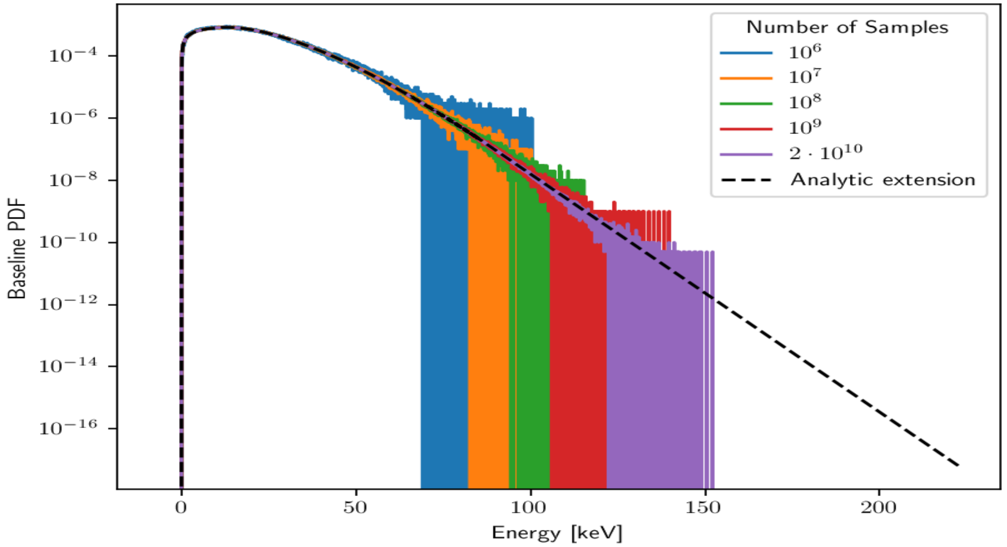
- Overall distortion occurs at the level of 10^{-3}, which must be reduced to $\approx 10^{-6}$ measure shape distortion from sterile neutrino

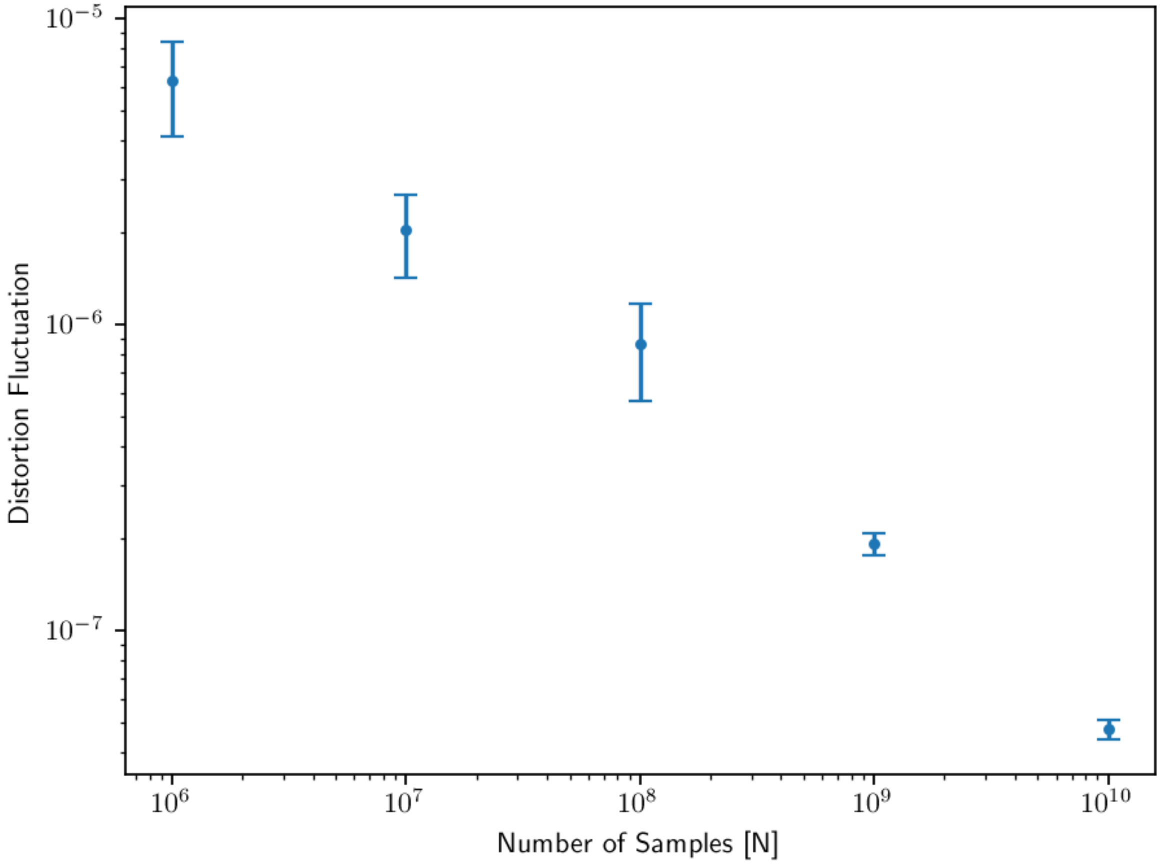




Distortion Sample Dependence

- Number of baseline samples taken determines the precision of the baseline distribution and distortion
- High sampling number, or analytical extension of baseline distribution needed to reach required simulation sensitivity





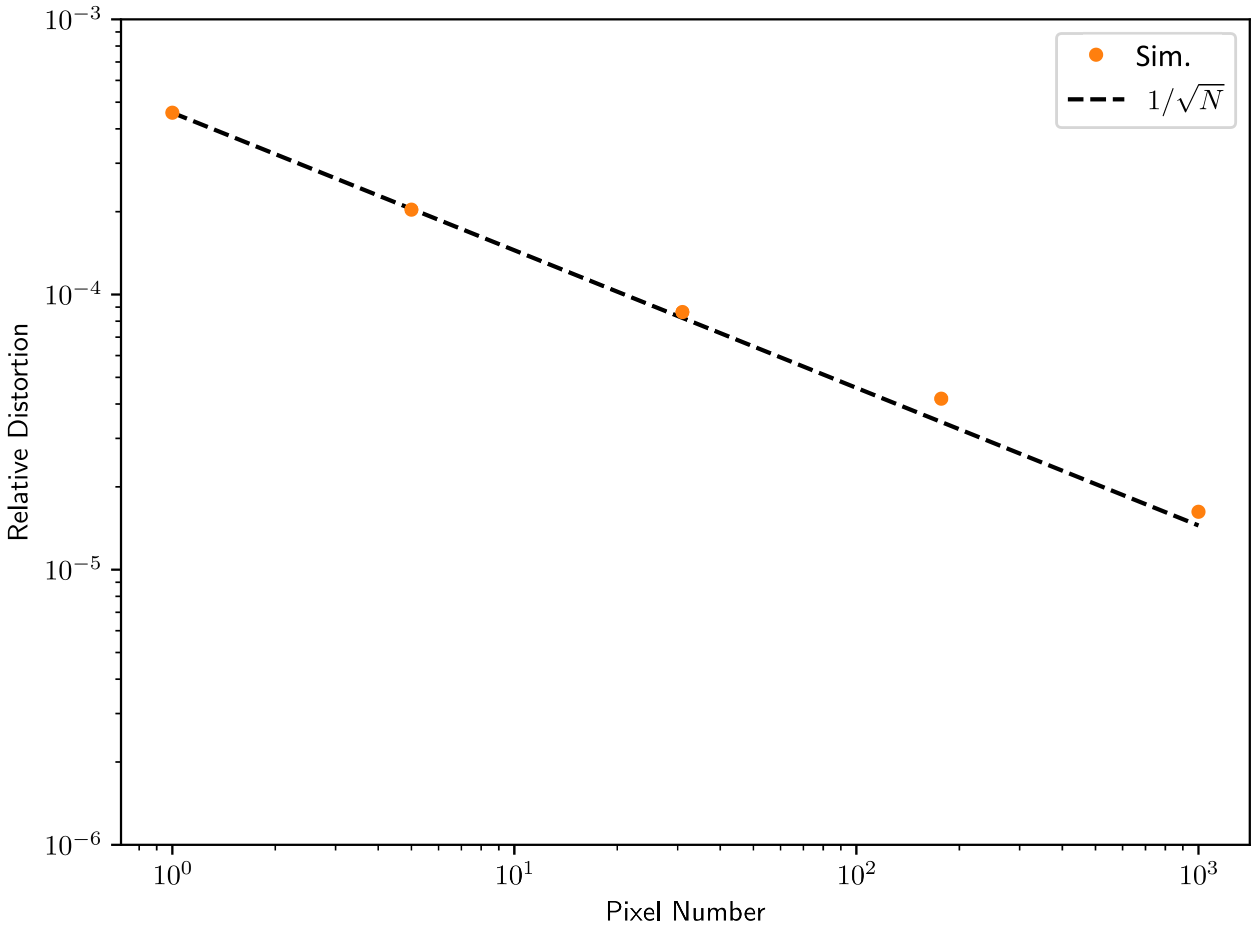
Mitigation Methods

Averaging (finished)
- Goal is to average out the non-linearity experienced by the spectrum
  - Averaging pulses from different readout channels
  - Pulses occurring at different ADC ranges (increasing count rate, Gatti slider)
  - Pulses having variable heights (varying PAE)

Correction (in progress)
- Goal is to precisely measure non-linearity and apply correction
  - Correct digitized signals before applying energy filter
  - Apply correction on energy filter
  - Spectrum level correction afterwards

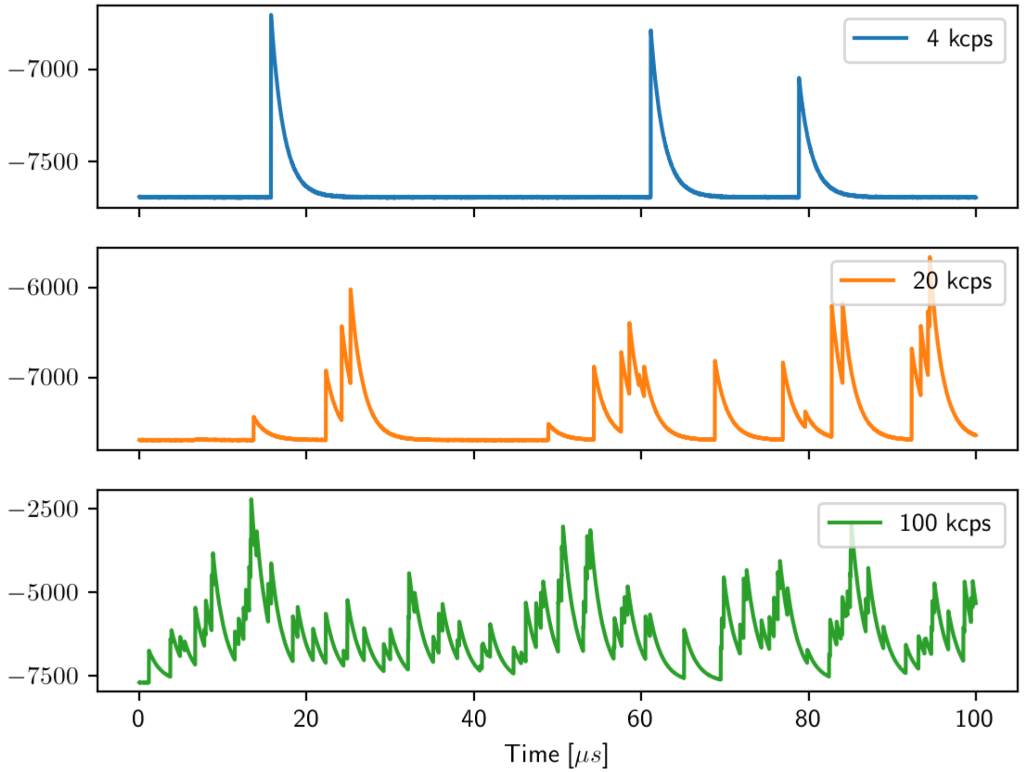
Pixel Averaging

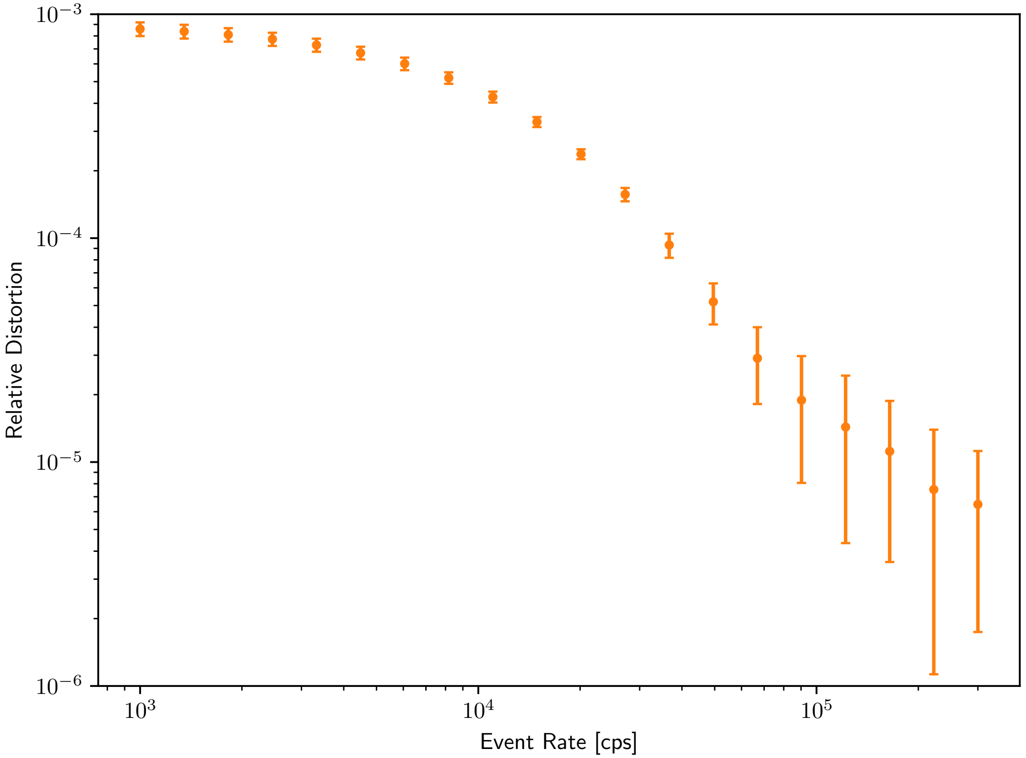
- Averaging of multiple pixel's spectrum decreases distortion by $\approx N^{-1/2}$ if the non-linearity of the ADC channels are uncorrelated
- TRISTAN Design
  - Phase 1: $2.5 \cdot 10^{-2}$ reduction
  - Phase 2: $1.7 \cdot 10^{-2}$ reduction
- Would decrease ability to do ring-wise/patch-wise fitting



Count Rate

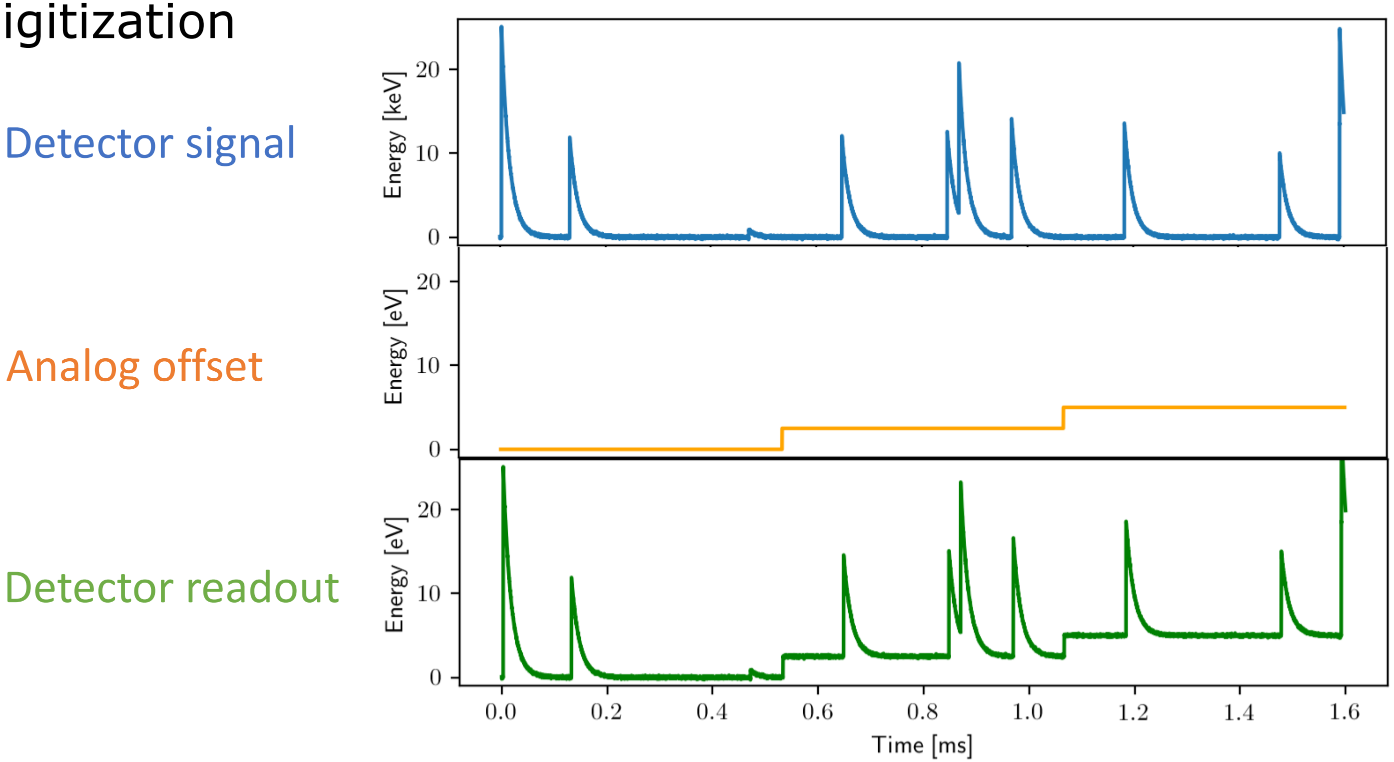
- Increased count rates broaden the baseline distribution and randomize the starting ADC value of the pulse





Gatti Slider Method

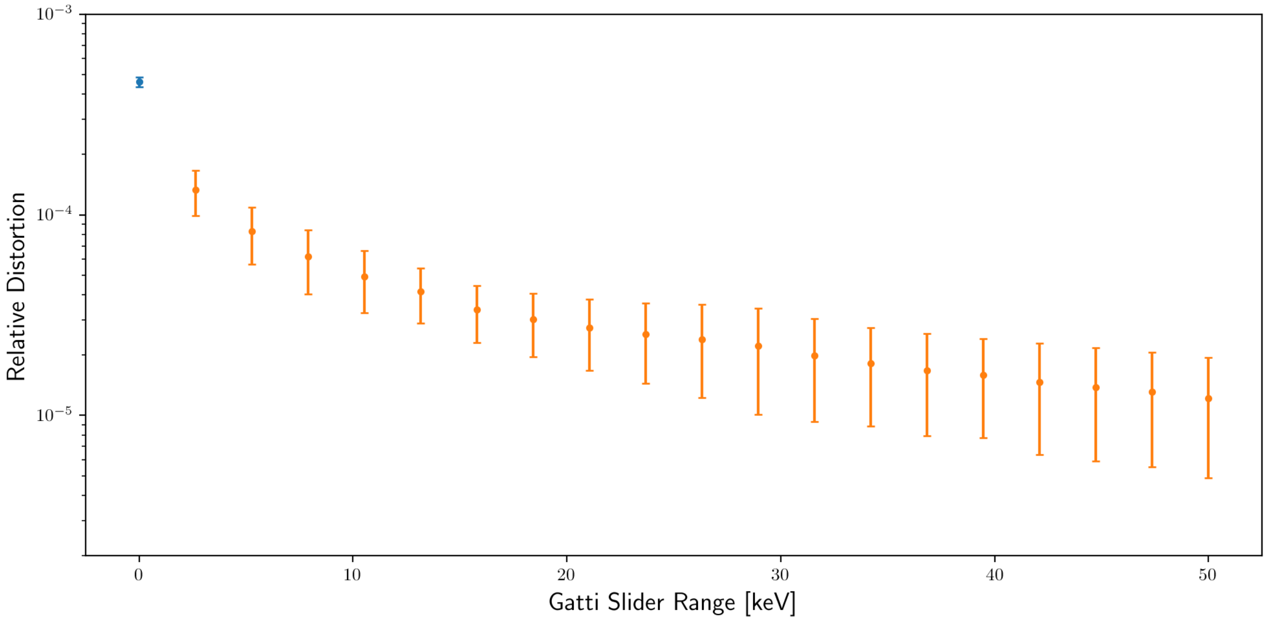
- Artificially alter the baseline by adding a known analog offset to the detector signal before digitization



- Simulation shows discrete ADC steps reduce distortion at same level as continuously sliding offset

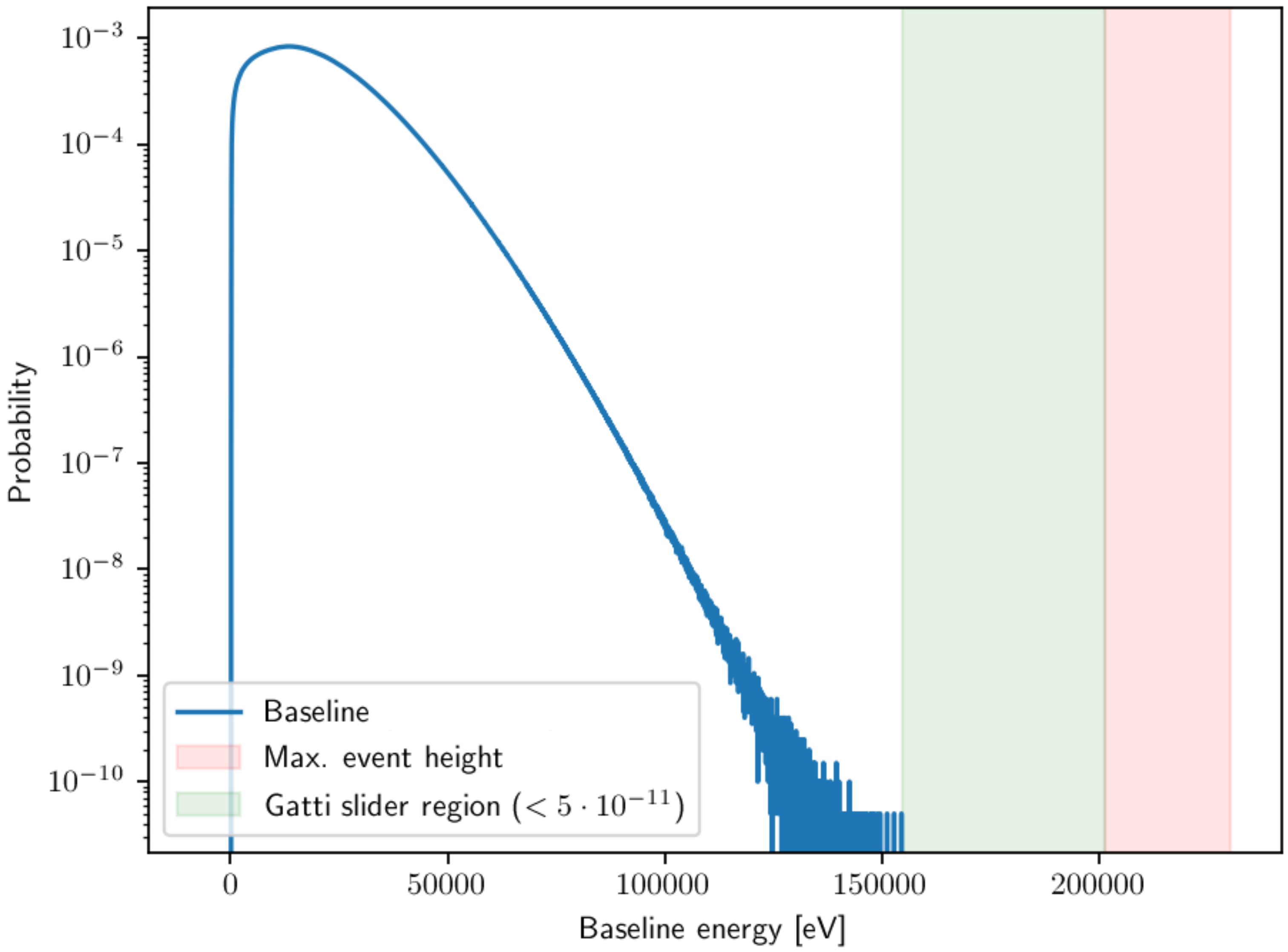
Gatti Slider Implementation

- Voltage offset is applied to detector readout signal before ADC board
- Implemented on the main tile board as a global voltage offset changed during detector reset
  - Information must be communicated through the FPGA, as the FPGA must later correct for the known offset
- Discrete steps of voltage offset applied



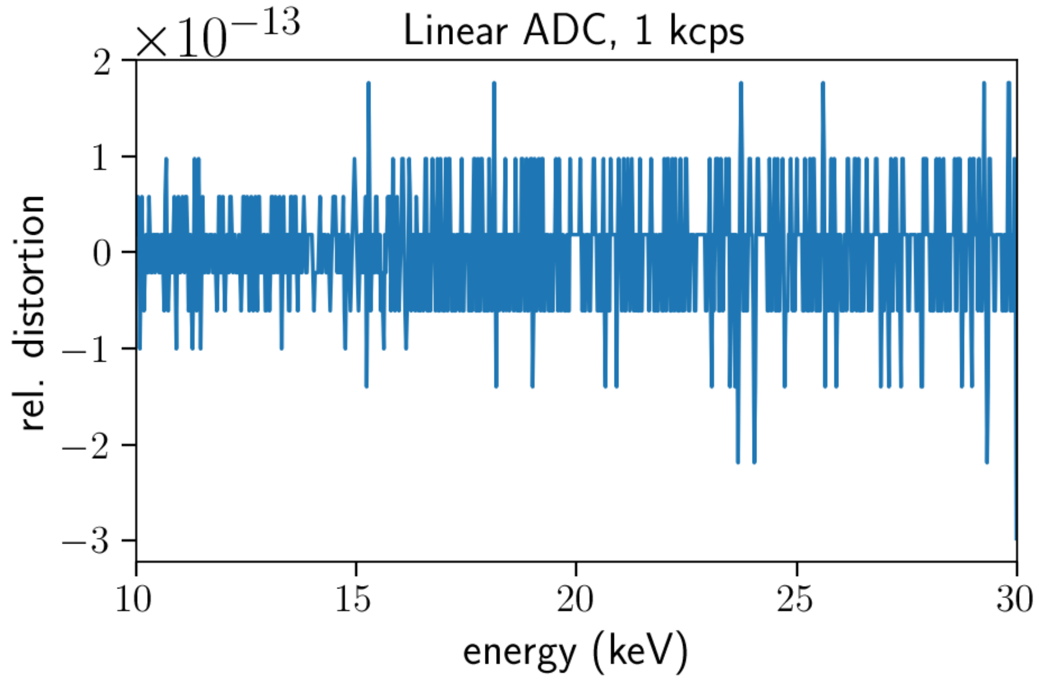
Gatti Slider Limitation

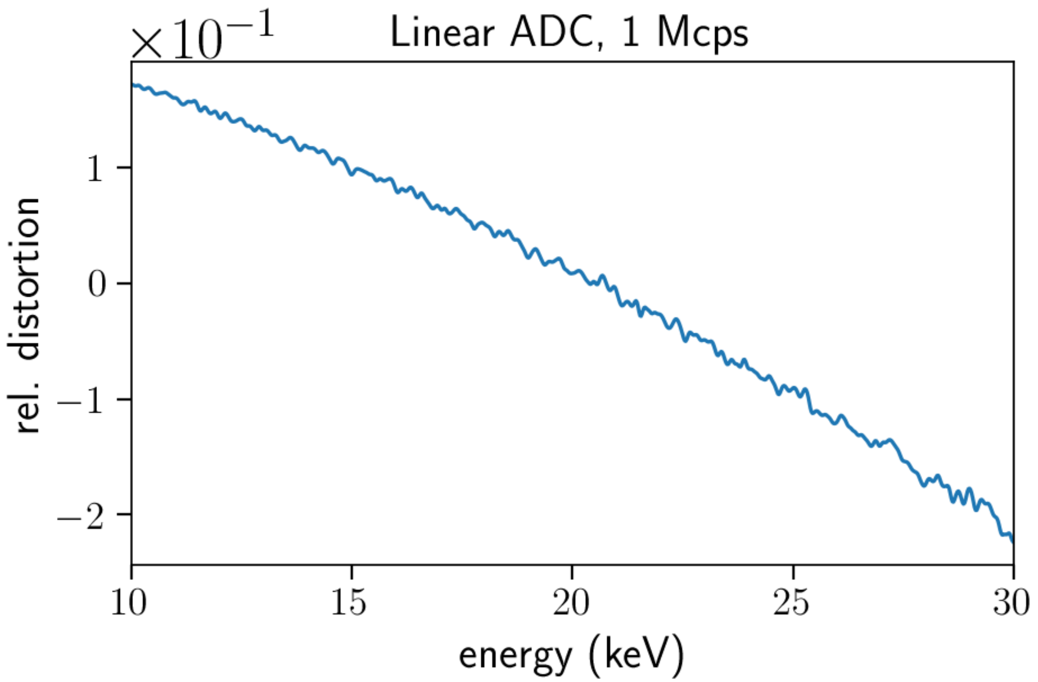
- 100 kcps count rate
- Simulated $2 \cdot 10^{10}$ baseline points, with no distortion with perfect linearity
- Difference between baseline distribution maximum and railing sets limit on Gatti slider range



Distortion Calculations

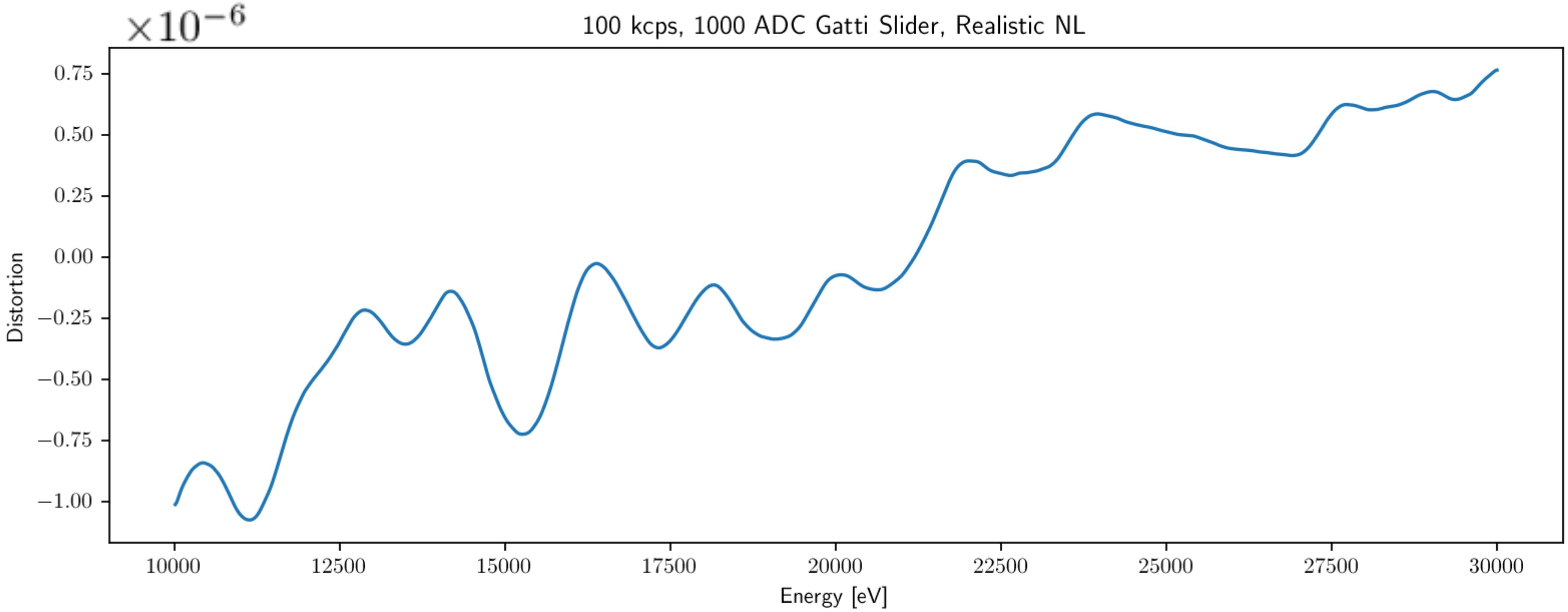
- Implementing strategies that broaden the baseline can also introduce distortions from events railing
- Inherently biases against larger energy events, correlated between detectors
- Test by running INL code to validate with no non-linearity





Distortion Calculations

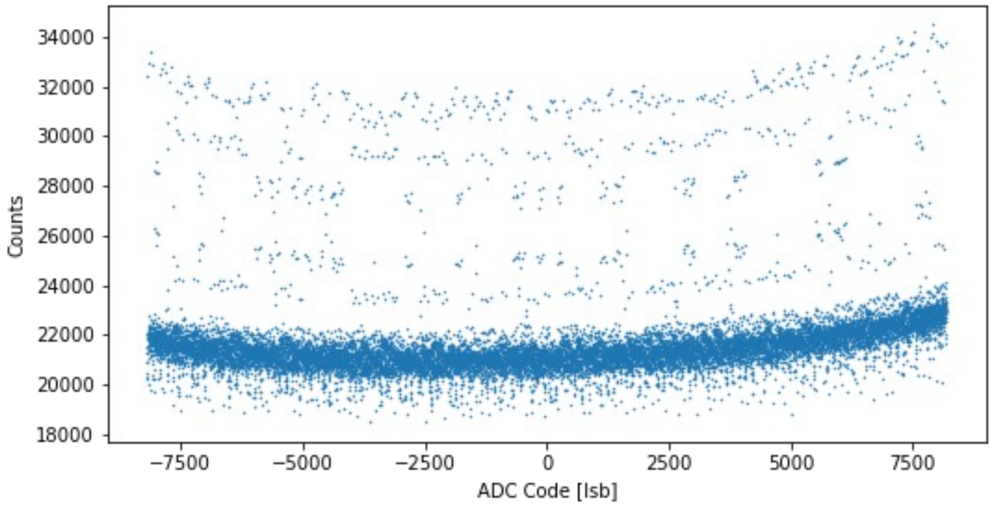
- First implementation of high statistics baseline calculation for single pixel with realistic ADC non-linearity

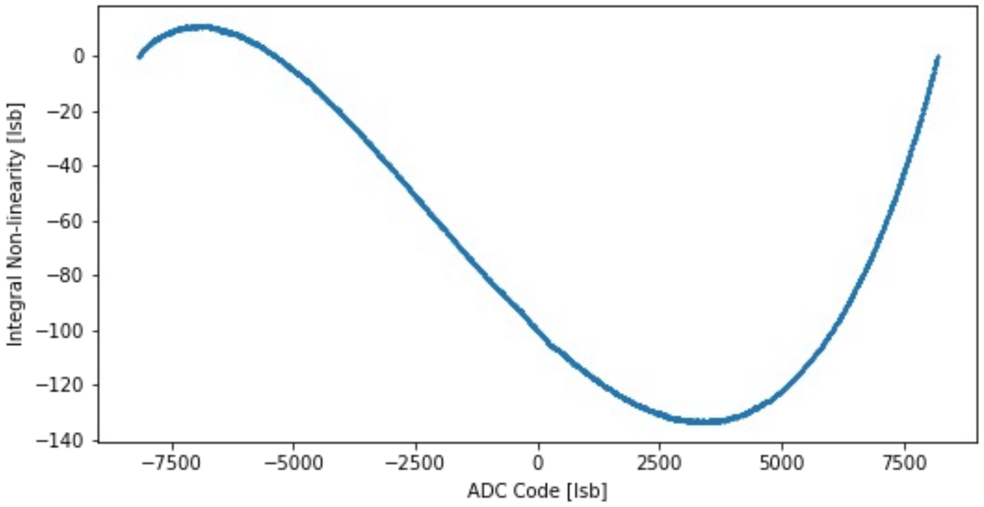


ADC Non-linearity Preliminary Measurements

- ADC NL measurement needed for TRModel propagation
- If NL is stable over time, spectral correction must be made
  - Time must be allotted to perform repeated measurements of ADC response to know ramp/sine signal to measure NL

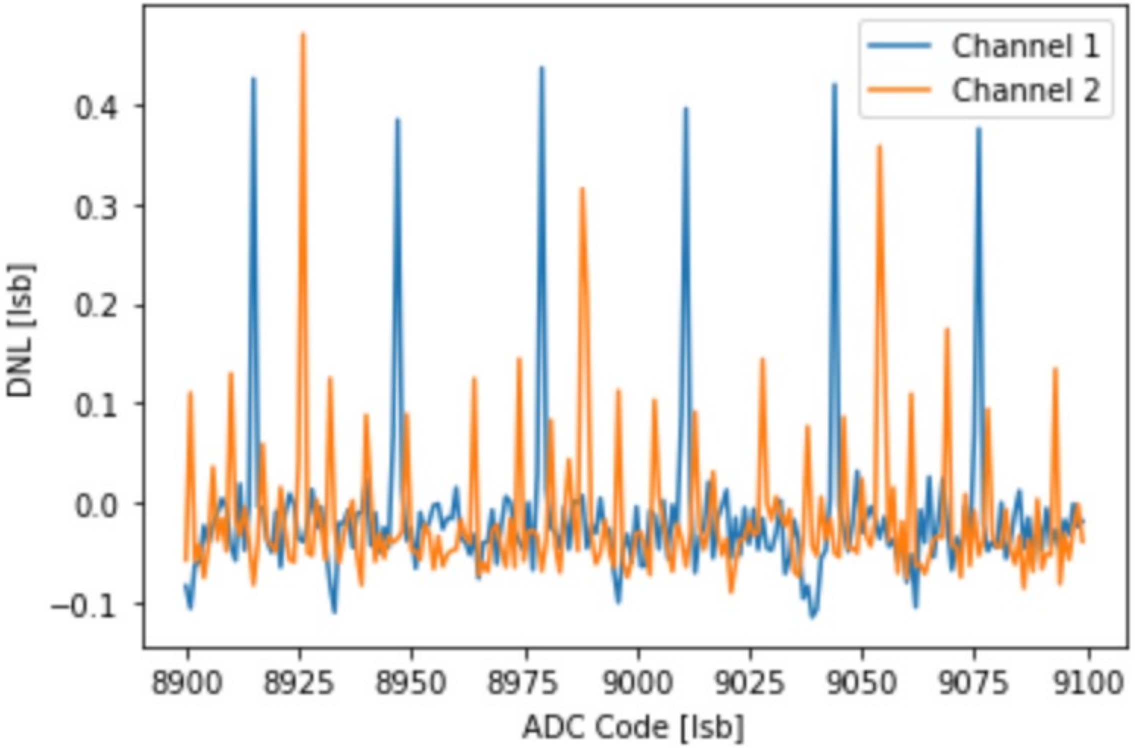
- First measurements of ADC non-linearity performed using a UPV Audio Analyzer with a 24-bit D/A converter
- Slow linear ramp signal input into the Anpassnetz board

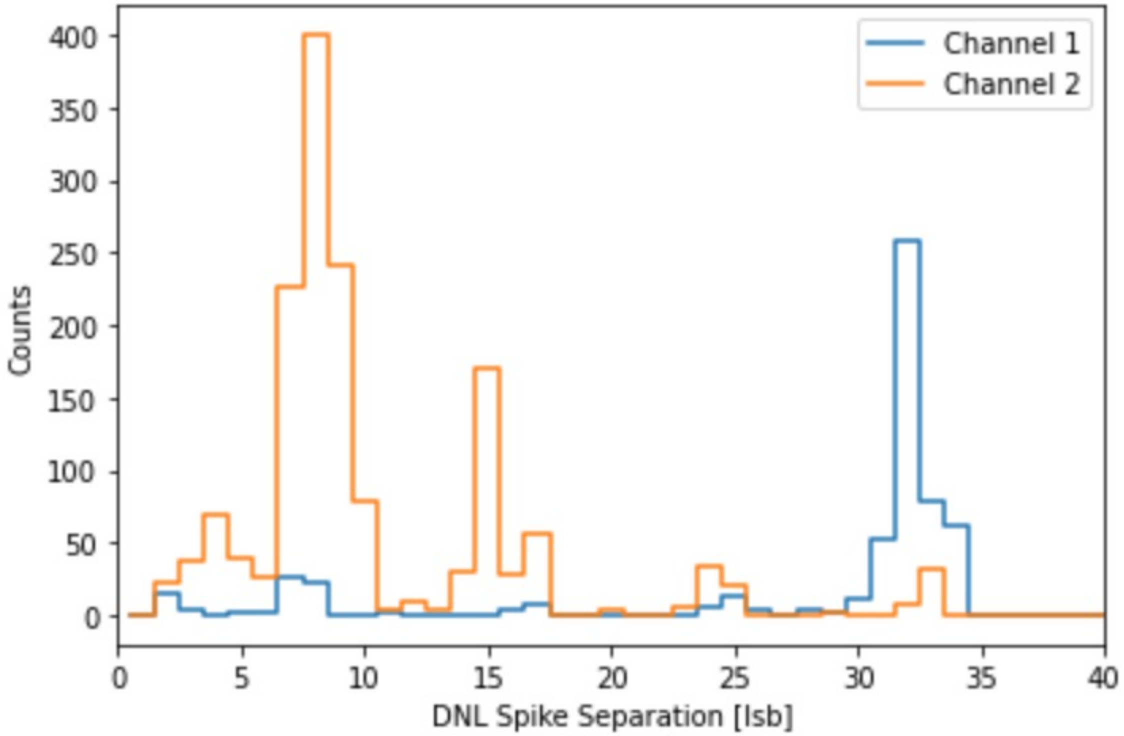




DNL Structure Comparison

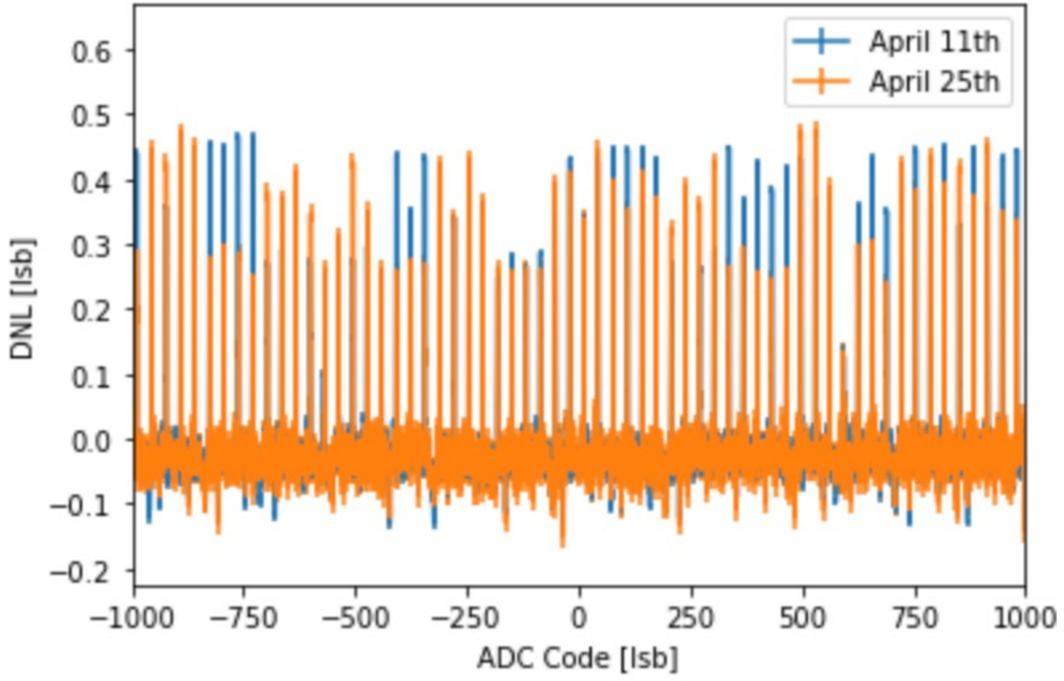
- Two ADC channels from the same ADC board, with large non-linearity removed
- One has structure that is defined by 3-bits, other 5-bits (uncorrelated)

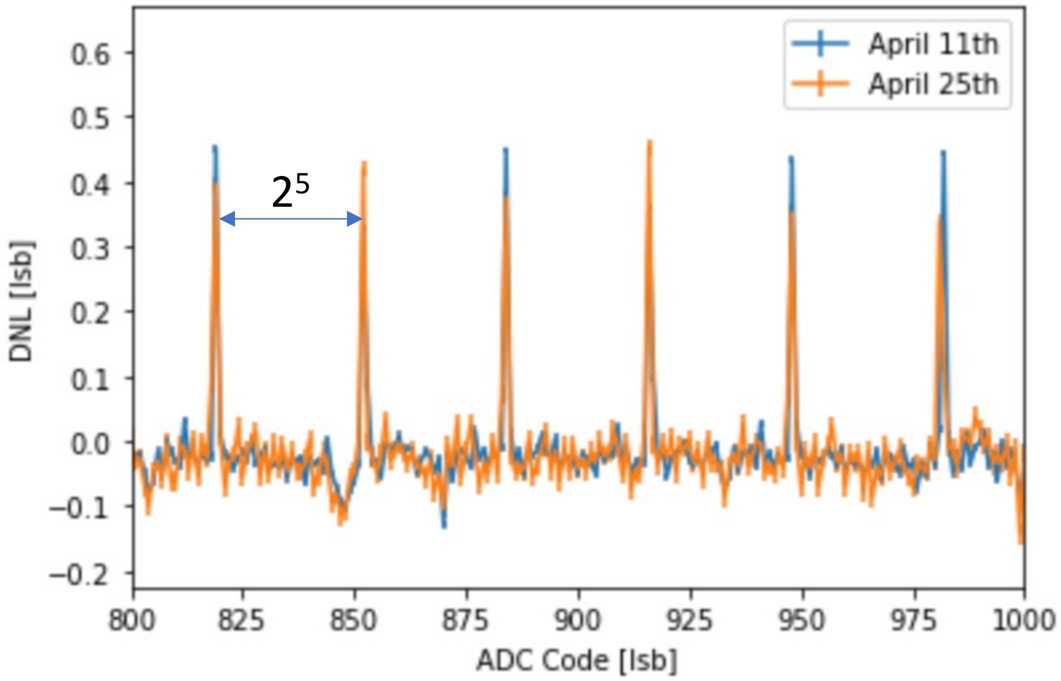




DNL Measurement Stability

- First tests of stability of ADC non-linearity show some evidence that a correction could be applied over a long term
- Further testing needed to determine the precision of stability





ADC Non-linearity Measurement Options

- ADC NL measurement needed for TRModel propagation
- If NL is stable over time correction can be made on the level of digitized signals, filter output, or spectrum

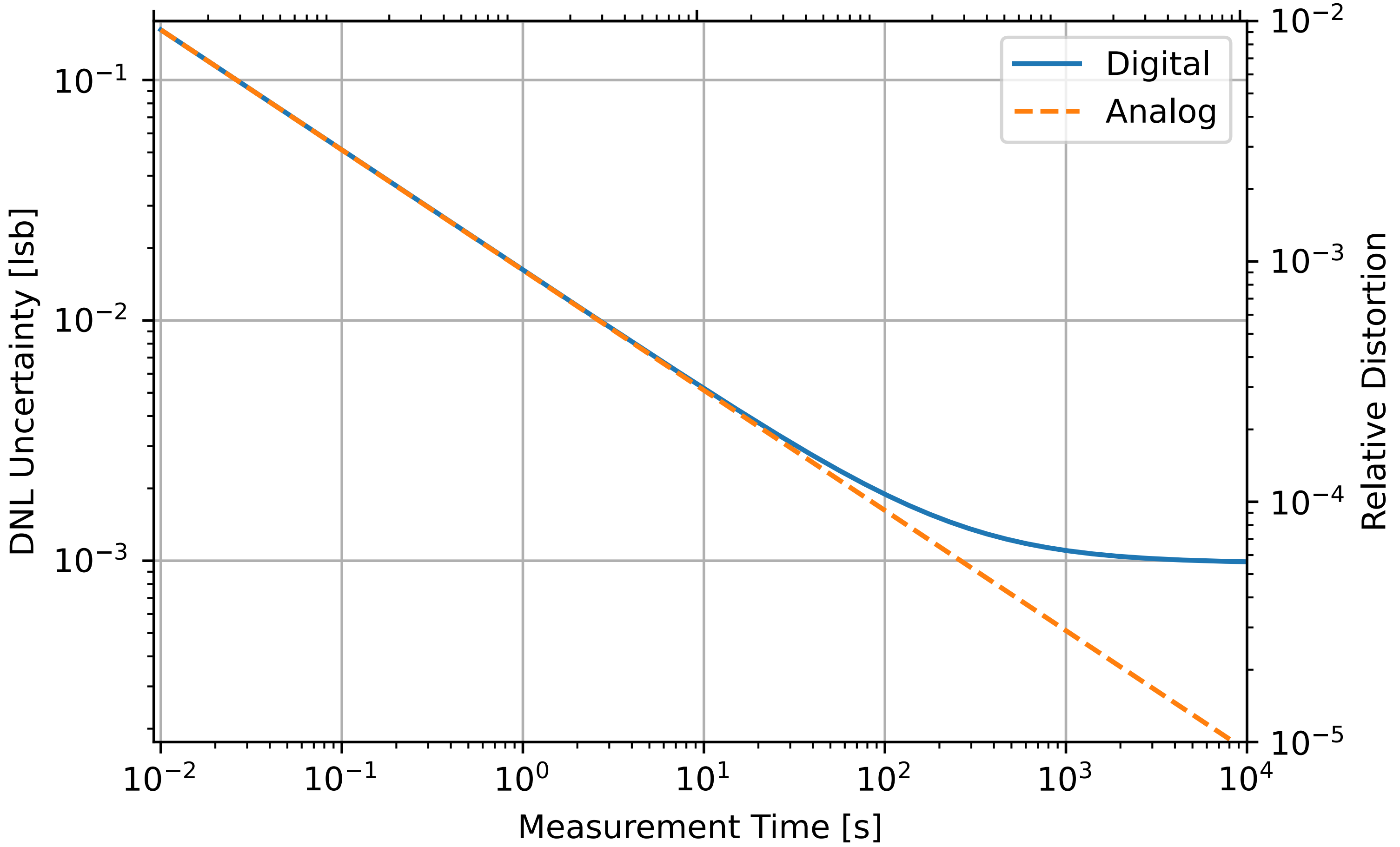
	Instable	Stable
One Measurement	Set overall scale (easy implementation)	Correction (medium implementation)
Repeated Measurement (in-situ)	Distortion reduction (hard implementation)	Correction (hard implementation)

Ramp Measurement Timing

- DNL uncertainty is determined by total number of counts measured (measurement time)

- For a desired initial distortion, we can calculate the amount of non-linearity data needed to be taken

- Frequency and required uncertainty will introduce restrictions on measurement time



Upcoming DAQ Non-linearity Tasks

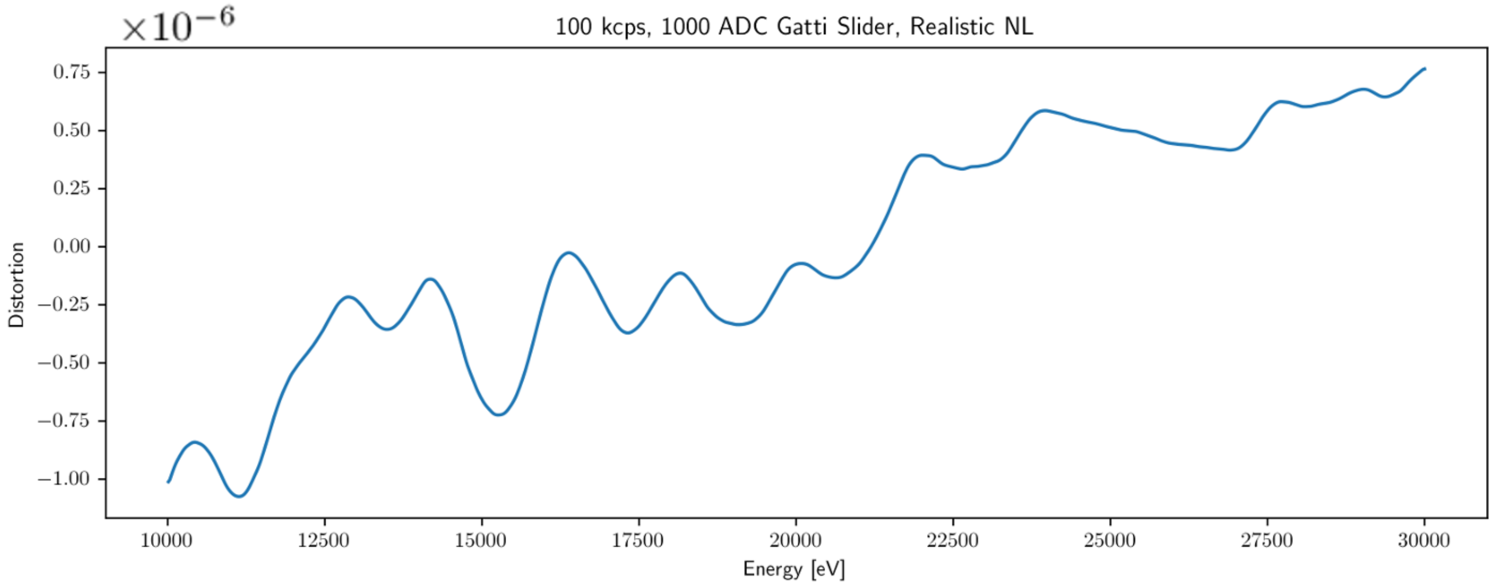
- DAQ Hardware Development
  - New ADC boards without highly non-linear programmable gain amplifier
  - Main tile board voltage offset for implementing Gatti slider

- DAQ Testing
  - Spectrum distortion testing with Americium and Iron using existing ADC boards, leveraging large non-linearity to validate trains_inl predictions
  - Repeated, high statistics linearity testing of DAQ readout channels
    - Stability and correlation tests for non-linearity structure

- In-situ Testing
  - Recording high statistics baseline to be used as input for trains_inl
  - Possible recurring non-linearity measurement using either the main tile board voltage offset or detector leakage current

Upcoming Distortion Simulations

- Calculating distortion for complete Phase-0 and Phase-1 detector system with the high statistics baseline sampling
- Use measured ADC of RADC-40 board as input into simulations for single pixel distortions, and apply pixel averaging propagation to create final distortion projection
- Investigate sensitivity impact from additional spectral shape uncertainty introduced by ADC non-linearity effects



Conclusion and Outlook

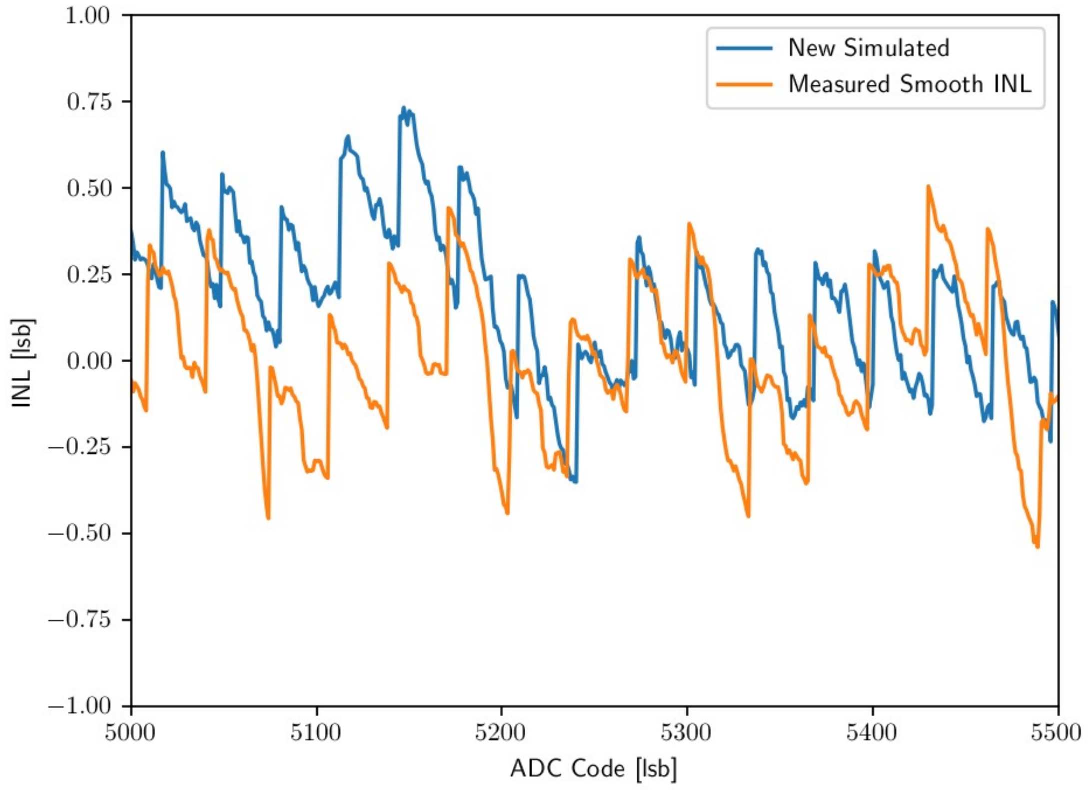
- Combination of mitigation strategies allows for reduction of non-linearity induced distortion below the desired level of 10^{-6}
  - Exact implementation to be determined by upcoming testing of non-linearity and TRISTAN detector operating conditions
  - Ideal: 100 kcps, pixel averaging, and Gatti slider, without the need of non-linearity measurement correction

- RADC-40 DAQ system will be tested with board improvements to verify the ADC non-linearity structure and voltage offset feature
  - Hopefully will rule out the need for in-situ measurement and correction

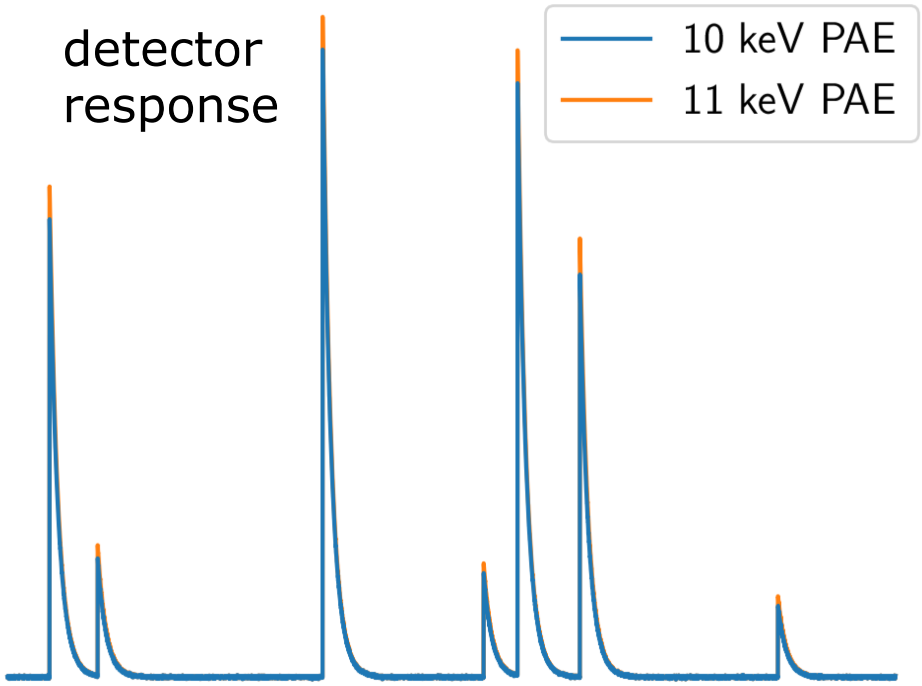
Additional Slides

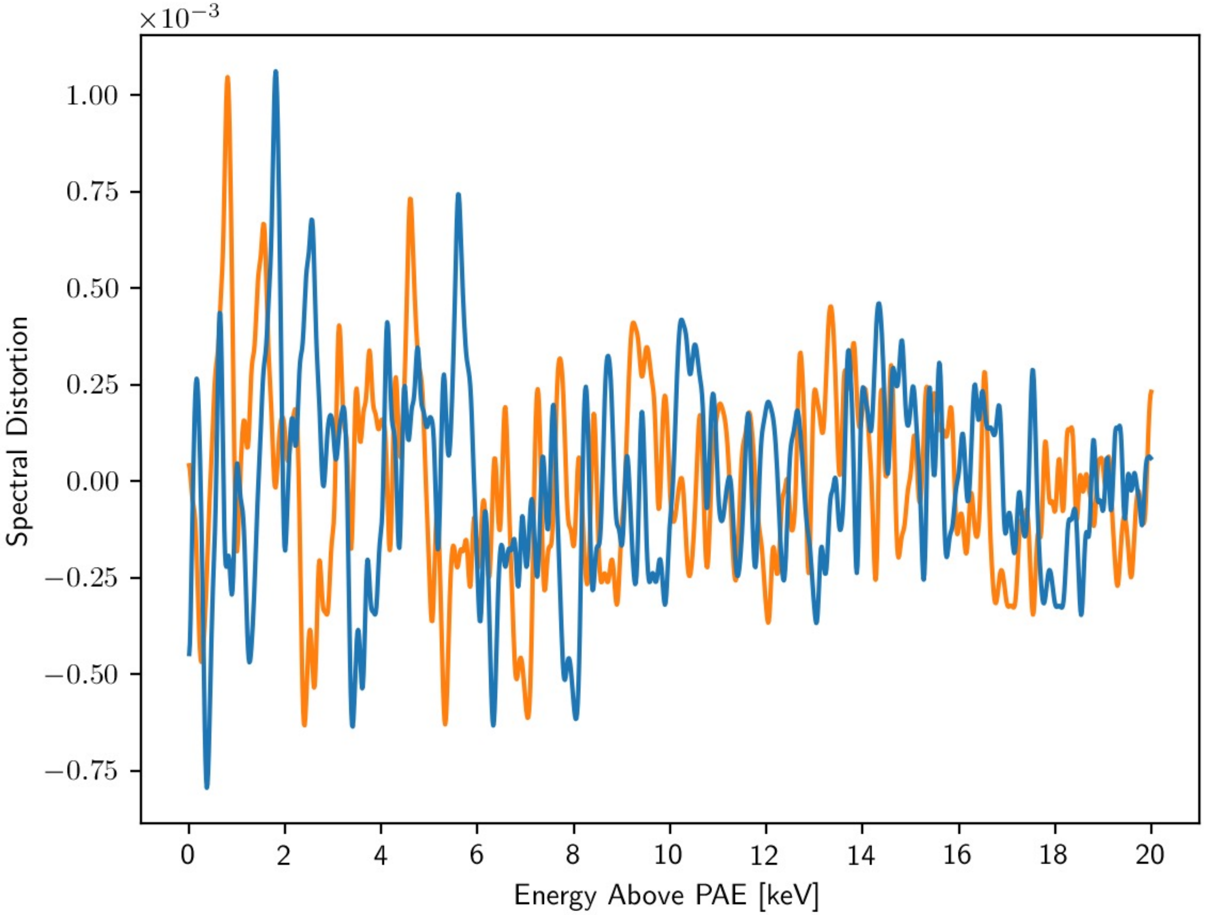
Realistic INL Simulation

- Mimic observed INL structure from measurement
- Randomize DNL spike separation and offset from within the range of options from 4 measured INL structures



Sliding post-acceleration

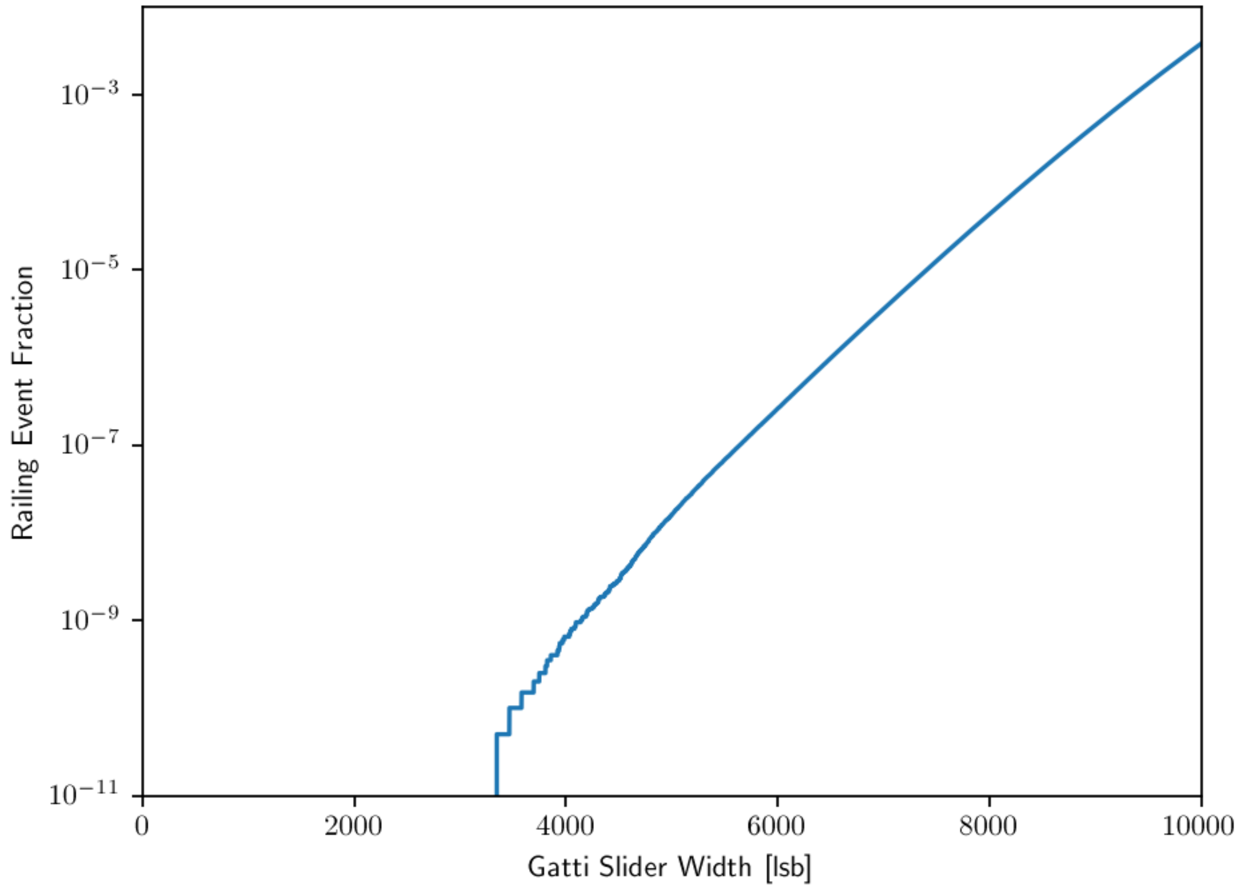




- Changing PAE shifts ADC non-linearity distortion by the amount PAE is changed
- Similar reduction to analog Gatti slider, but limited ability due to sensitivity studies needing higher PAE

Gatti Slider Limitation

- Gatti slider width of less that 3500 ADC keeps impacted events below $5 \cdot 10^{-11}$
- Proposed 1000 ADC Gatti slider of 1000 ADC impacts less than 10^{-12}



Discrete Gatti Slider Impact