Neutrinoless ββ Decay with LEGEND: Pushing the Front-End ASIC Performance Envelope

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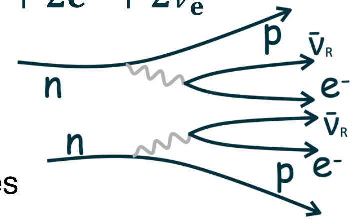
Double-beta decay

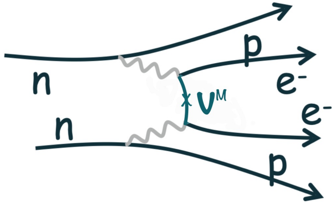
$2\nu\beta\beta: (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

- ΔL=0
- SM allowed
- observed in many isotopes
- $T_{1/2} \sim (10^{18} - 10^{24})$ yr

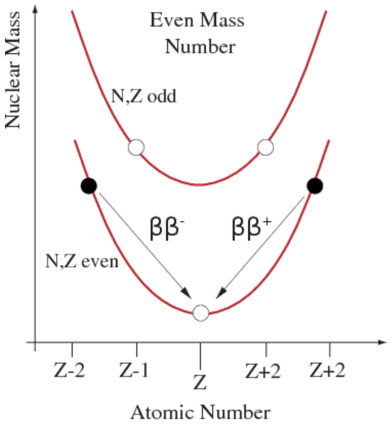


$0\nu\beta\beta: (A, Z) \rightarrow (A, Z+2) + 2e^-$

- ΔL=2
- beyond SM
- Majorana mass component
- via light Majorana ν exchange or other L-violating processes



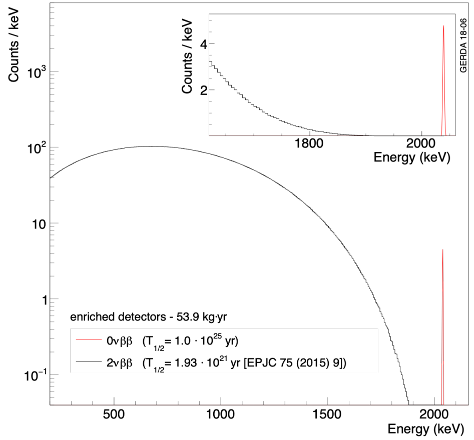
double-beta decay is possible when energetically favored



measure sum energy spectrum of electrons

- 2νββ ➞ continuum
- 0νββ ➞ mono-energetic peak @ $Q_{\beta\beta}$

$Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e$



Neutrinoless Double Beta Decay Detection

Experimental goal is to measure mono-energetic peak at $Q_{\beta\beta}$:

$$\mathbf{0}\nu\beta\beta: (\mathbf{A}, \mathbf{Z}) \rightarrow (\mathbf{A}, \mathbf{Z}+\mathbf{2}) + \mathbf{2e^-}$$

Lepton number violation

measure sum energy spectrum of electrons

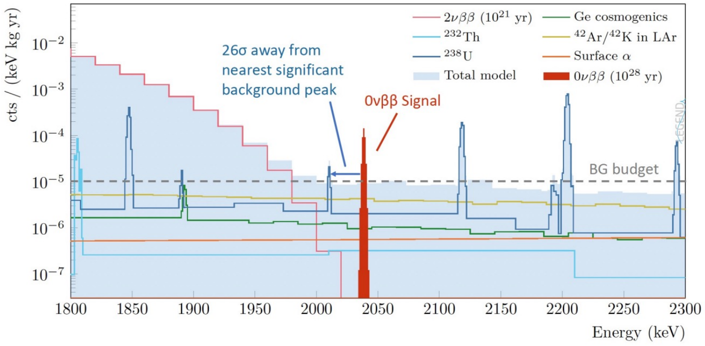
- 2νββ ➞ continuum
- 0νββ ➞ mono-energetic peak @ $Q_{\beta\beta}$

But this signal is buried under other backgrounds…

Experimental sensitivity:

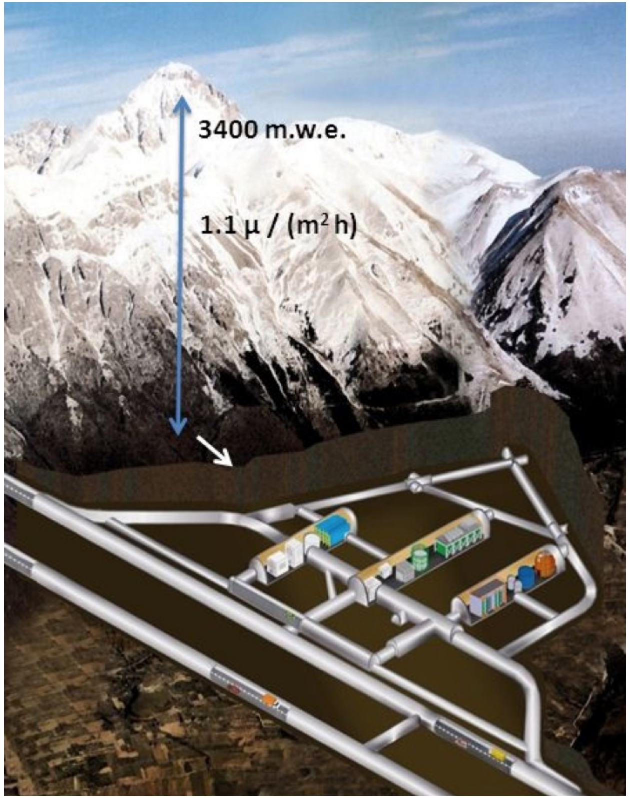
background (BI) > 1:

$$T_{1/2}^{0\nu} \propto \varepsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$



→ **increase sensitivity** by **background reduction (BI)** at $Q_{\beta\beta}$ and simultaneous increase of **mass (M)** and improvement of the **energy resolution (ΔE)**

The LEGEND Experiment



Large **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless double-beta **D**ecay

"…aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years…"

~250 scientists spread over 11 countries and 48 institutes

The LEGEND Experiment

Mission: The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results.

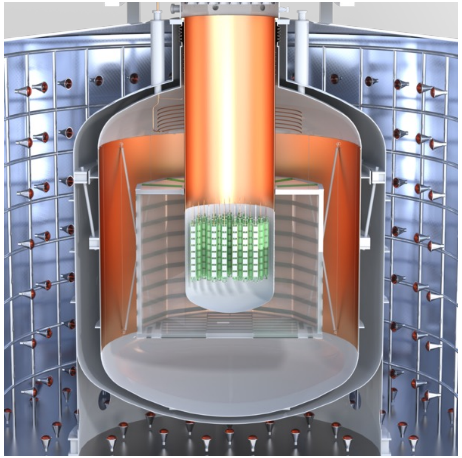
Select best technologies, based on what has been learned from GERDA and MJD, as well as contributions from other groups and experiments.

Phase I: LEGEND-200

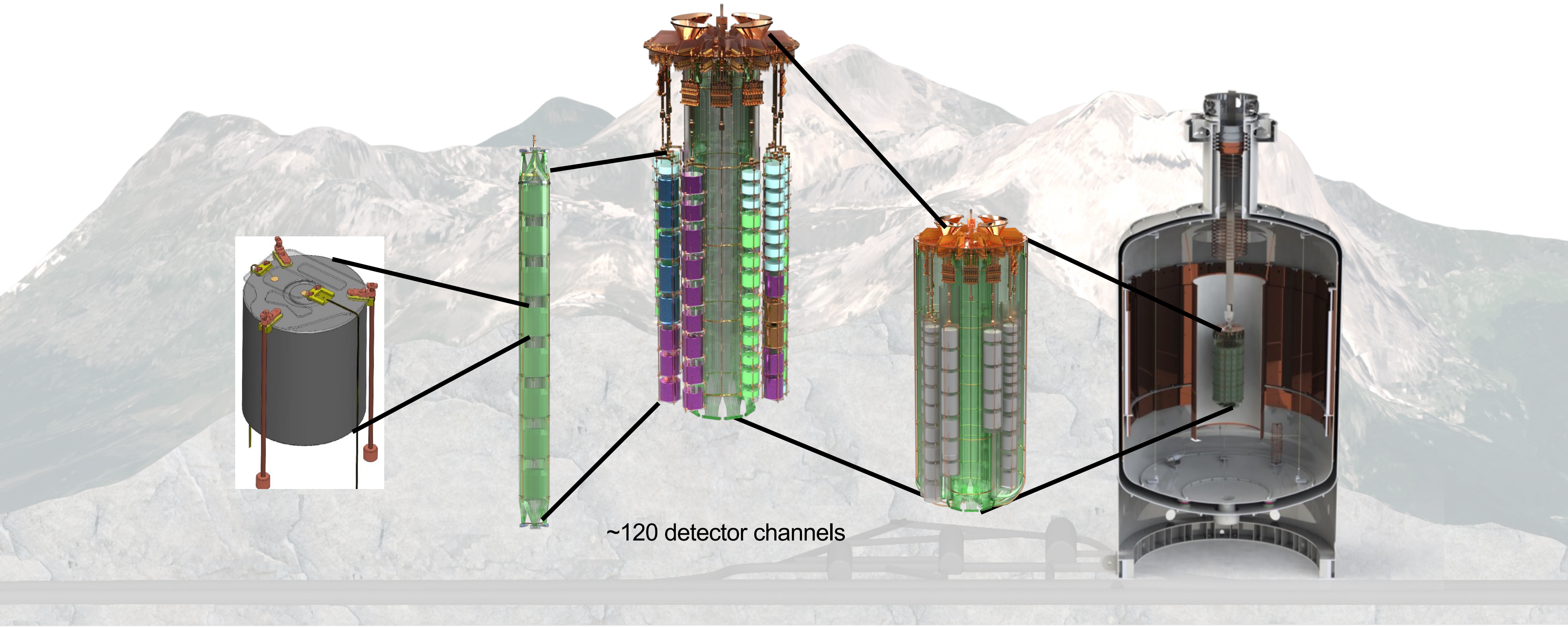
- Up to 200 kg ^{enr}Ge
- Modification of existing GERDA infrastructure at LNGS
- BG x2.5 lower than GERDA
- $T_{1/2} > 10^{27}$ y
- Started in 2021

Phase II: LEGEND-1000

- 1000 kg ^{enr}Ge (staged)
- BG Goal: x50 lower than GERDA
- $T_{1/2} > 10^{28}$ y
- Location: LNGS



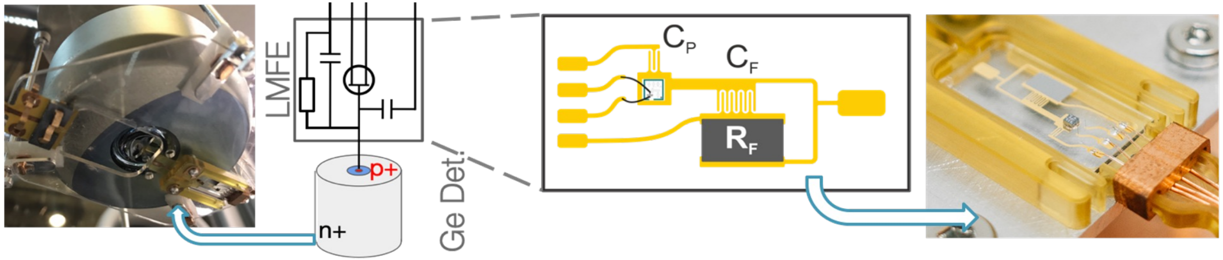
LEGEND-200 Detector Arrays



HPGe Detector Readout in LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Low-Mass Front End (LMFE) for MJD and LEGEND-200



- Specially-designed and fabricated Low-Mass Front End (LMFE)
- Pushes the limits of radiopurity and performance with discrete components.

Tonne-scale LEGEND-1000 will need an ASIC front end…

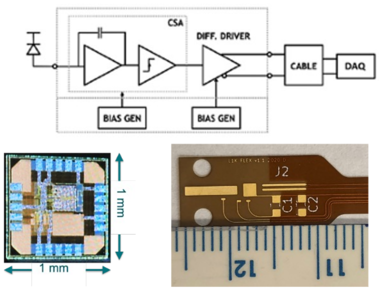
- 1000 kg enr. HPGe detectors
- Background Goal:
  - ~ 6✕ reduction w.r.t. LEGEND-200
  - < 0.1 cts/FWHM/t/y at $Q_{\beta\beta}$ = 2039 keV
- ASIC CSA:
  - Improved noise, resolution
  - Reduced size/mass:
  - Background reduction.

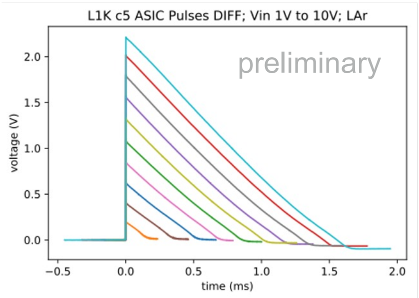
Specifications for LBNL L1K ASIC:

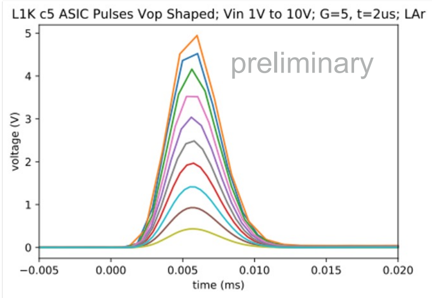
- Low noise/threshold:
  - → L1000 ≲ 1 keV trigger threshold (w/ appropriate max. false hit rate from comparator)
  - → Target noise: 20-200 e^- RMS.
- Large dynamic range:
  - → 9 MeV → 3 ✕ 10^6 e^- → 13 – 16 bits
- Sufficient bandwidth:
  - → 20 – 50 MHZ
- Optimize for few-pF capacitance detectors
- Minimize cabling:
  - → Power, Ground, Diff. Out
- Eliminate external components.
- Single power supply:
  - → Minimize heat dissipation in LAr
  - → 1.8 V, 3.3 V if necessary
- Internal reset.
- Observable leakage current:
  - → < 20 pA
- Testable warm/cold.

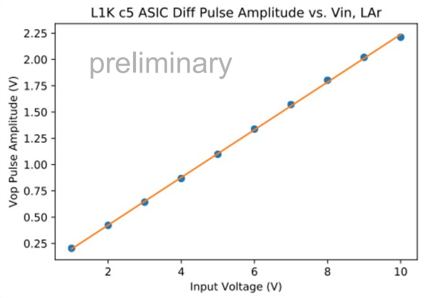
L1Kv1—original/precursor 180 nm prototype

L1Kv1: Differential Charge-Sensitive Amplifier

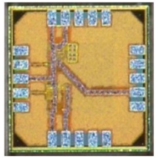


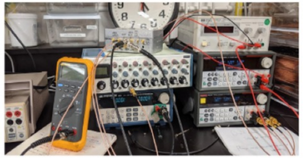






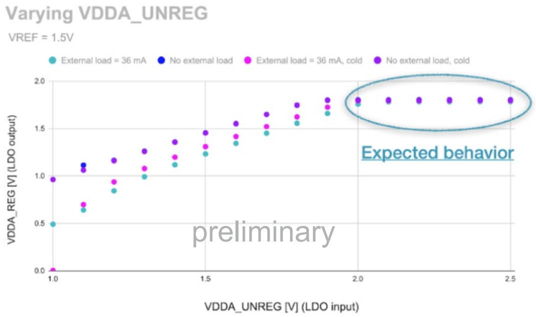
Low-Dropout Voltage Regulator (LDO)

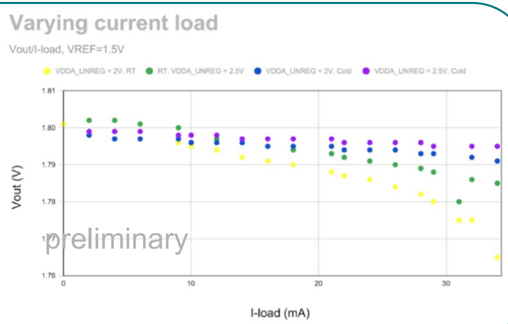




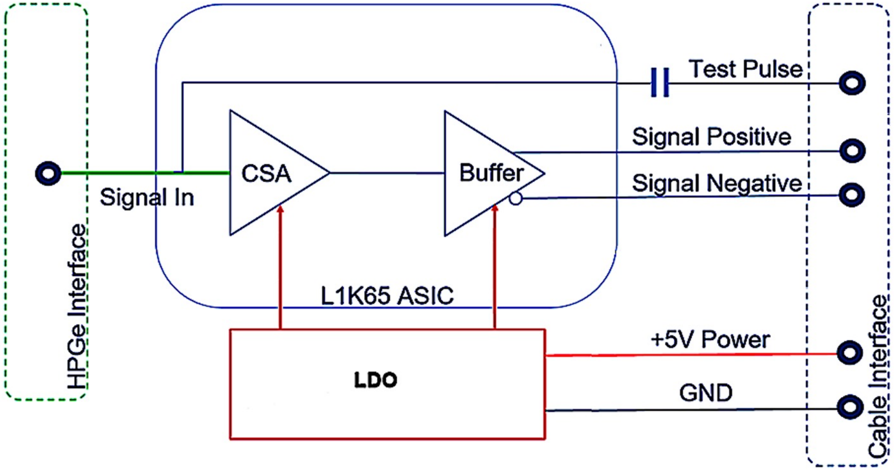
Room temperature testing

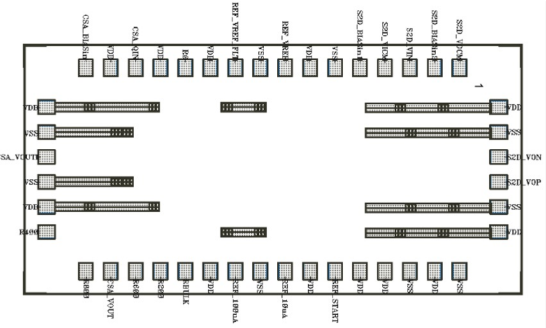
LAr testing

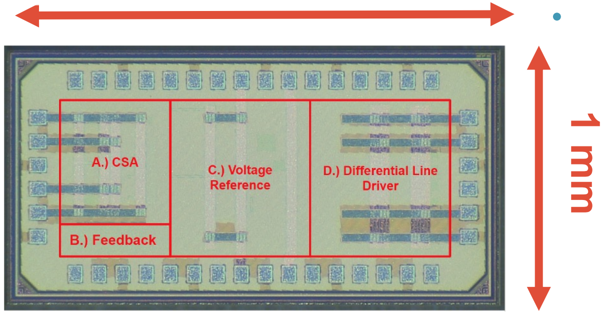




L1K65n ASIC Overview







- This presentation: 1st iteration of 3-spin development cycle
- 2nd iteration being tested now:
  - on-chip low-noise capacitorless LDO
  - innovative feedback circuit
- 65 nm TSMC node
- Intended to be practically usable for LEGEND-1000 and similar applications:
  - $C_{feedback}$ = 540 fF ± 10%
  - 2.5 V – 2.8 V Power supply
  - 30 MHz Bandwidth
  - ENC performance optimized for few-pF detectors
- New collaboration with Mirion.

A - Charge Sensitive Amplifier (CSA)
B - Feedback circuit
C - On-chip voltage references
D - Differential output buffer

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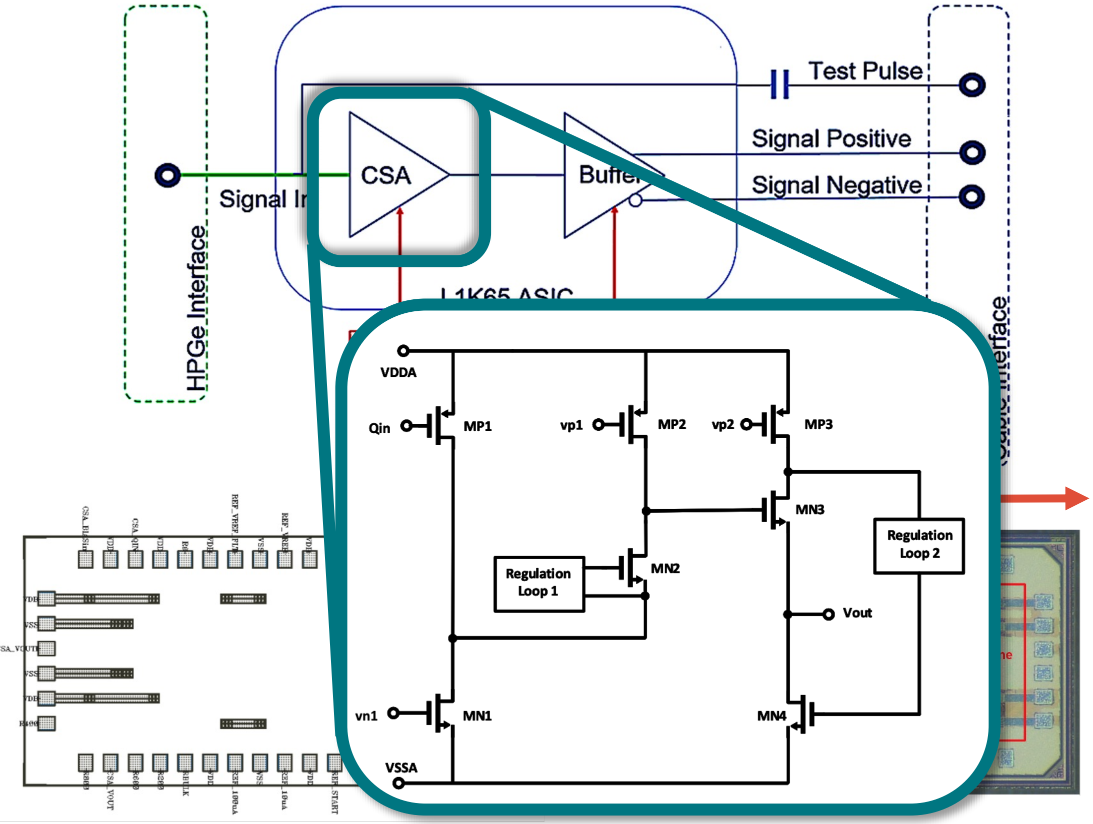
L1K65n ASIC Overview



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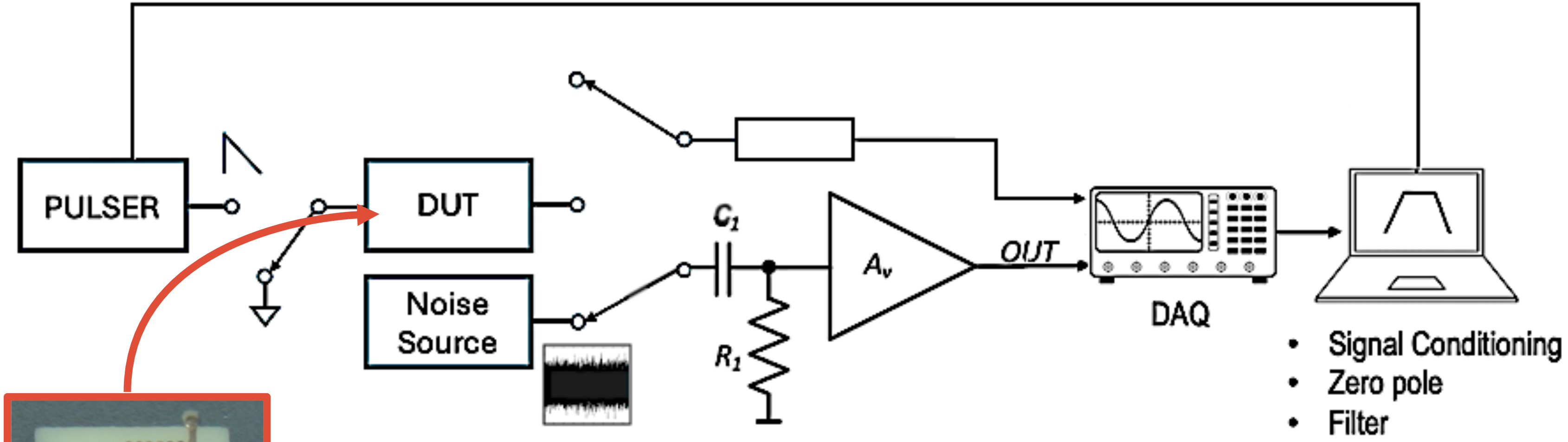
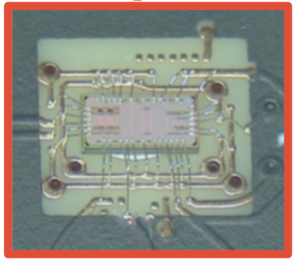
Benchtop Characterization

Test stand schematic





- Benchtop testing to measure:
  - Noise
  - Amplitude v. Energy Linearity
  - Power consumption
  - Load
- Room temperature or 77K with direct LN_2 submersion

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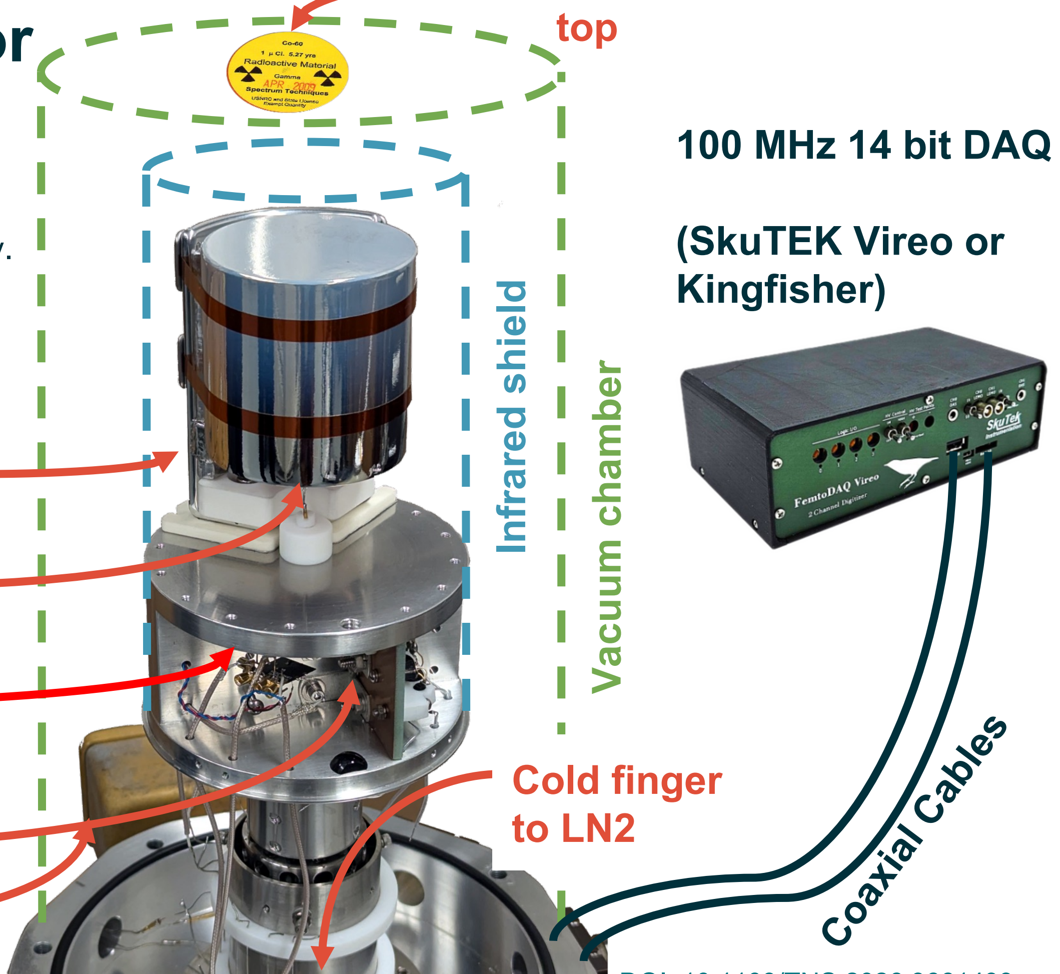
Tests with HPGe Detector

PPC Detector fabricated at LBNL's SDL

- **P**-type **P**oint **C**ontact HPGe detector made in-house in our **S**emiconductor **D**etector **L**aboratory.
- LN_2—cooled "dipstick" cryostat allows operating the detector at ~90K (close to 87K LAr).
  - Vacuum
  - Liquid Ar immersion in the future



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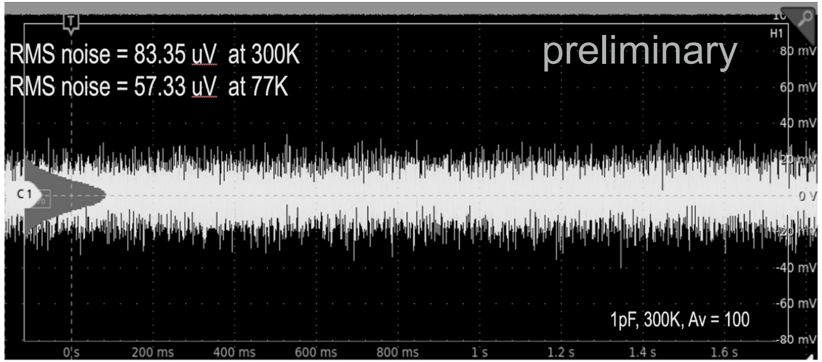
Noise

Benchtop Baseline Noise Characterization



- CSA noise performance meeting specs
  - Still higher than simulation
  - Simulation of external sources may be inadequate:
    - interposer parasitics, feedback resistor…
- Both simulations and measurements use trapezoidal shaper and R_f=500MΩ

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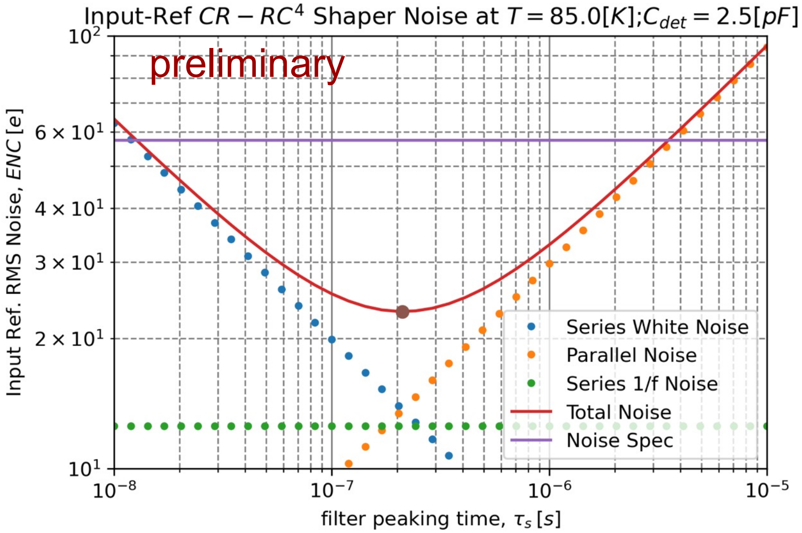
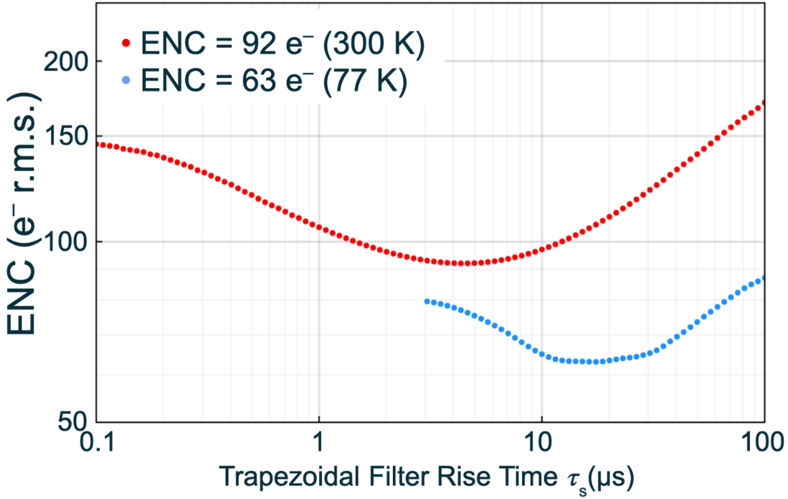
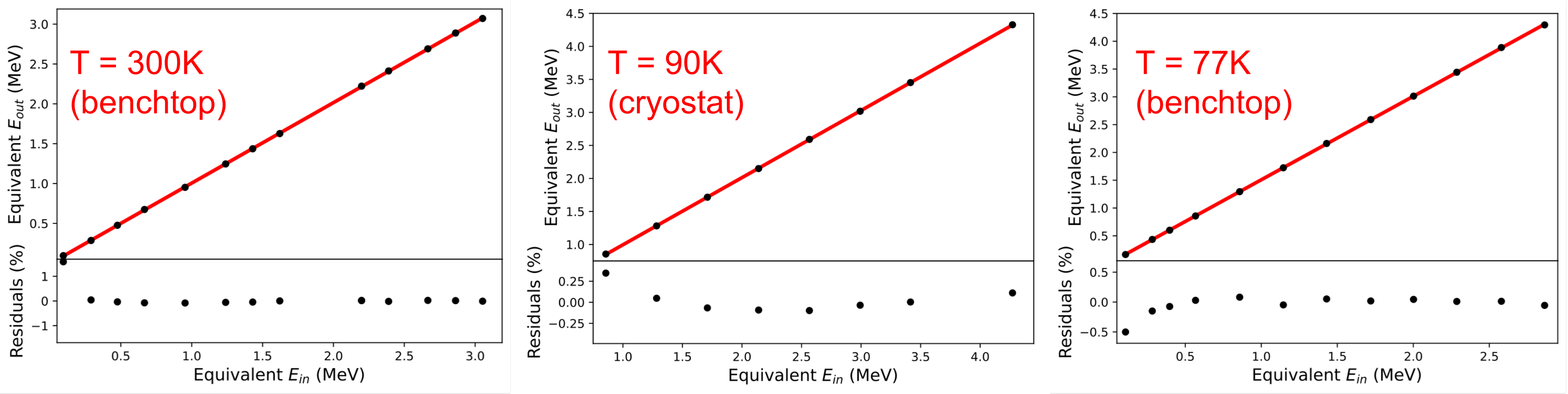




Linearity

Benchtop and in-Cryostat Amplitude v Energy Linearity Evaluation with Pulser



- Measured amplitude v. energy linearity is within 0.5% at cryogenic operating temperatures.
- Observed systematic trends are likely setup-dependent.

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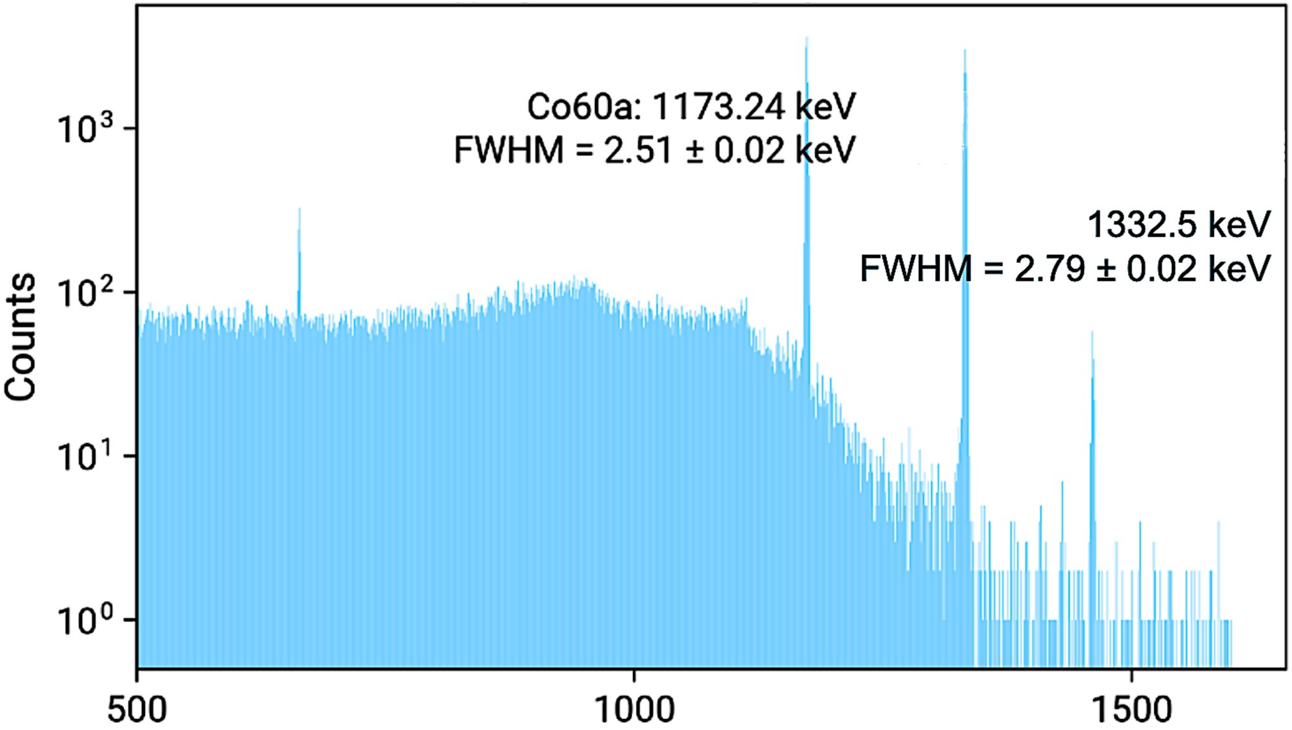
Energy Resolution

Measured with 60Co source

Energy resolution of ^{60}Co γ lines measured with PPC detector read out with L1K65n ASIC (100k events):

- 2.51 ± 0.02 keV @ 1173 keV
- 2.79 ± 0.02 keV @ 1332 keV



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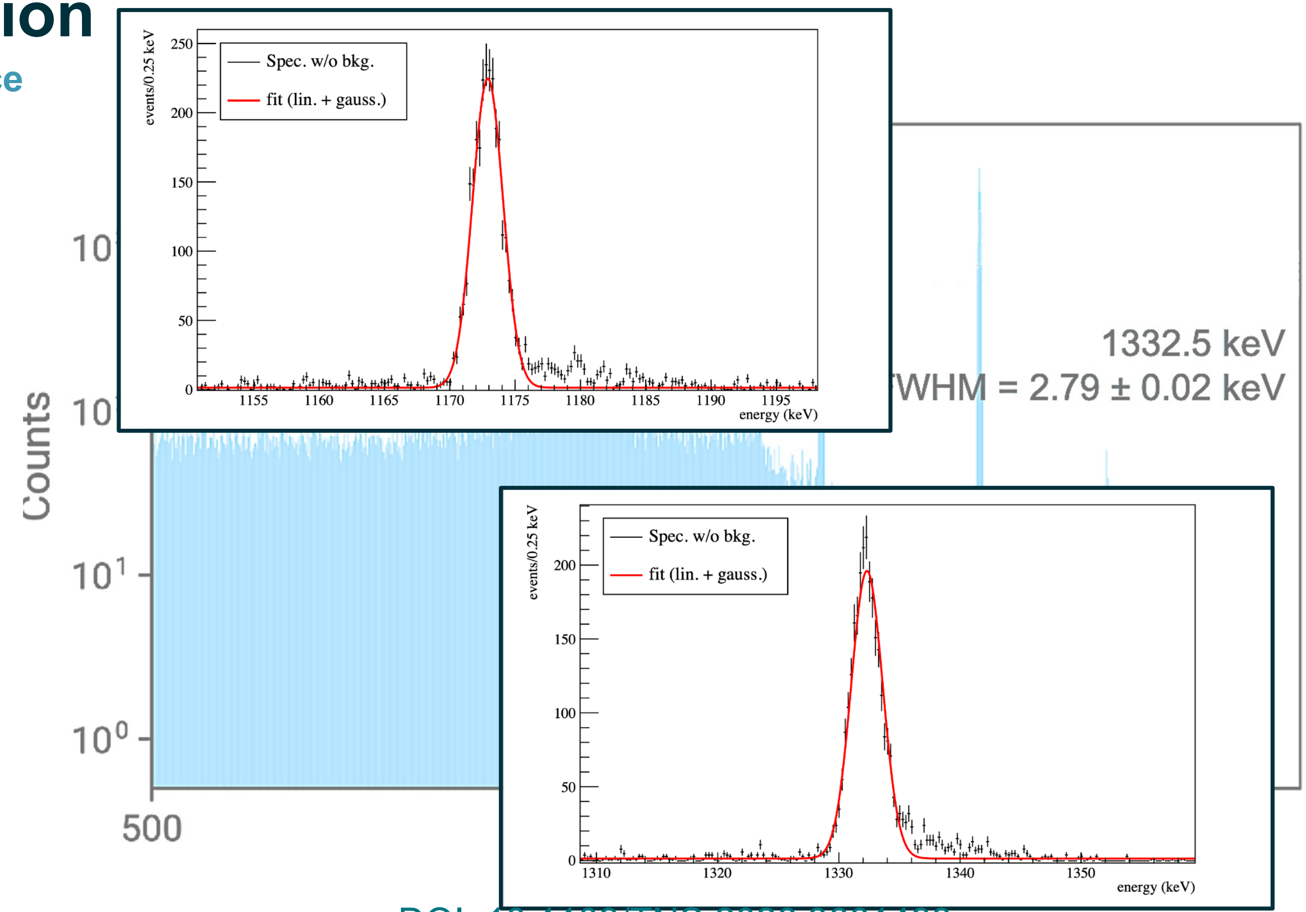
Same or better than this detector read out with qAMP discrete CSA:

- 2.75 ± 0.05 keV @ 1173 keV
- 3.05 ± 0.06 keV @ 1332 keV



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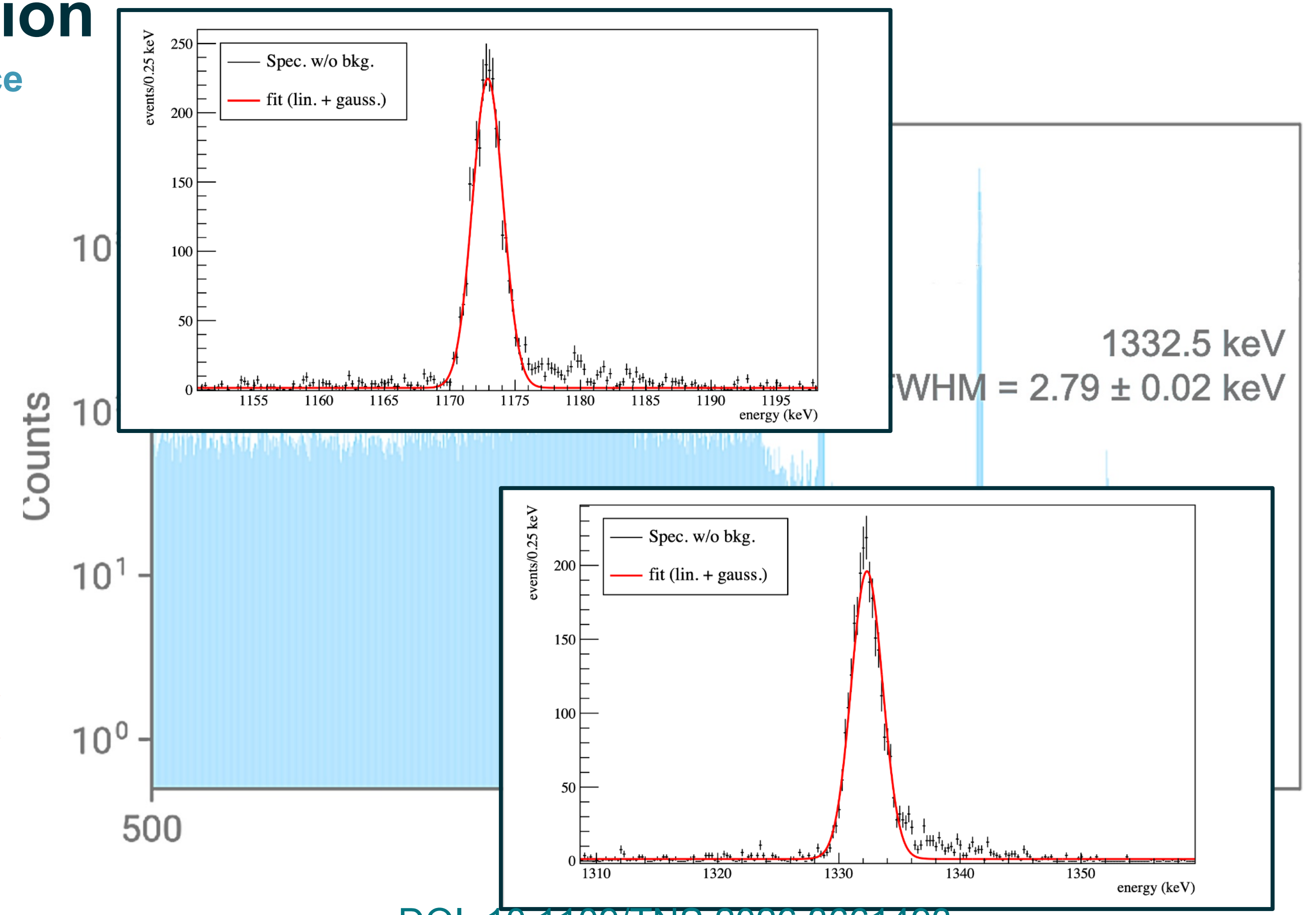
Same or better than this detector read out with qAMP discrete CSA:

- 2.75 ± 0.05 keV @ 1173 keV
- 3.05 ± 0.06 keV @ 1332 keV

Detector & Setup Limited:

- Non-Fano contribution:
  - 281 e− RMS @ 1173 keV
  - 320 e− RMS @ 1333 keV
  - *63 e− RMS benchtop test*
- Two legs of diff. out digitized separately → + ~40% noise



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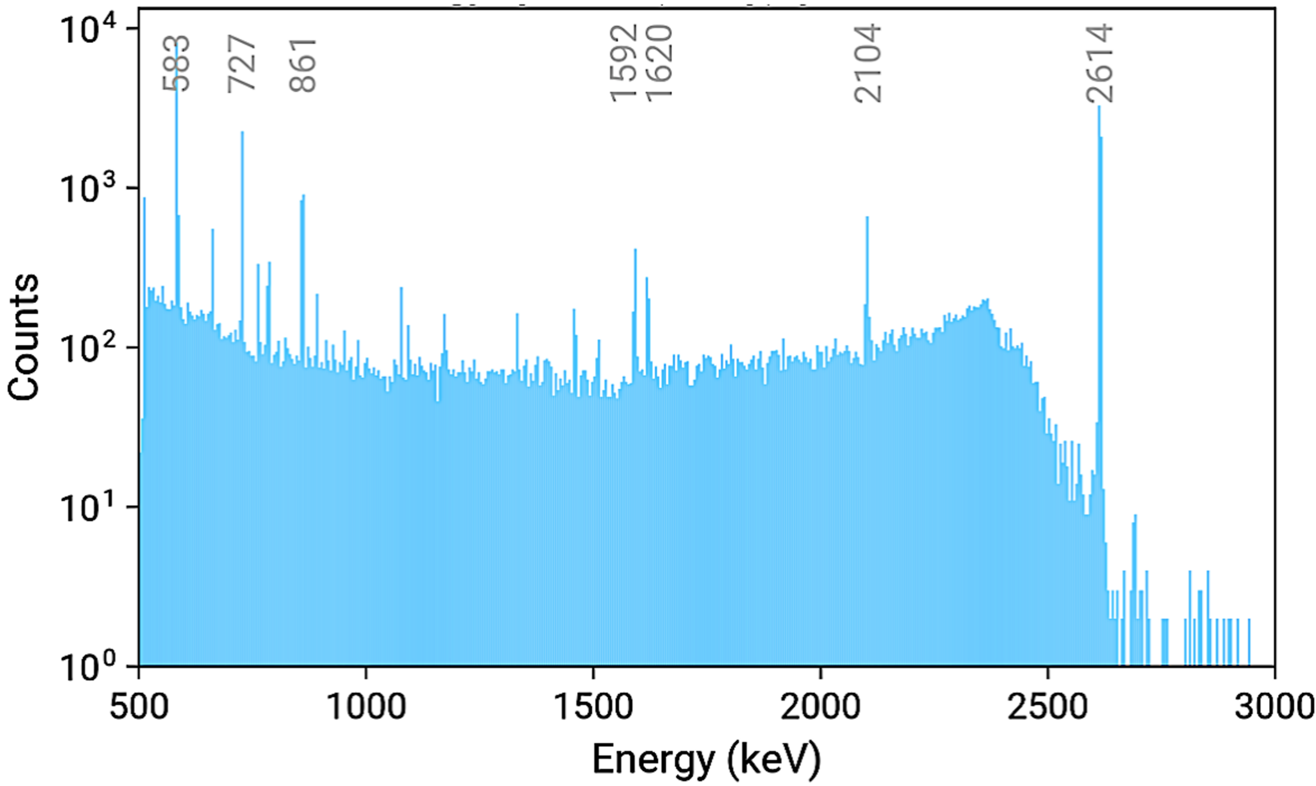
Energy Calibration

232Th Spectrum Measurement

^{232}Th γ spectrum measured with PPC detector read out with L1K65n ASIC (100k events).

Multiple γ lines between 0.5 and 3 MeV allow for a good calibration fit.



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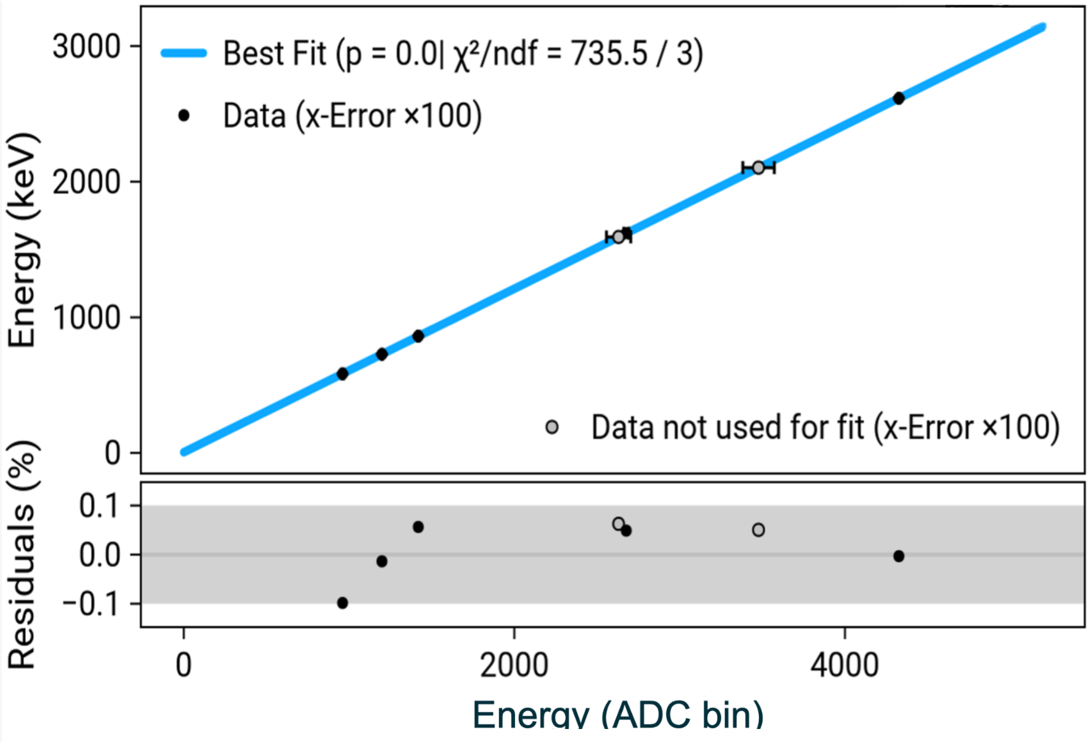
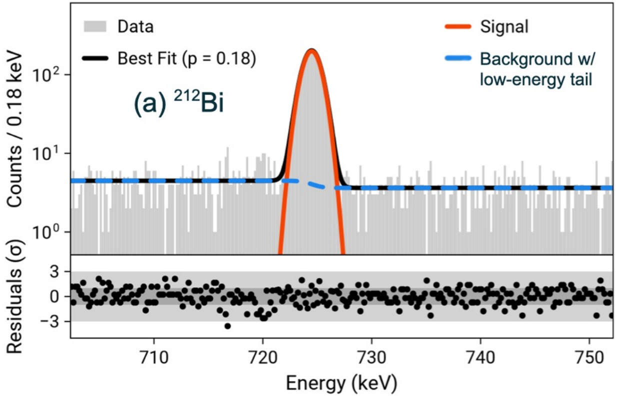
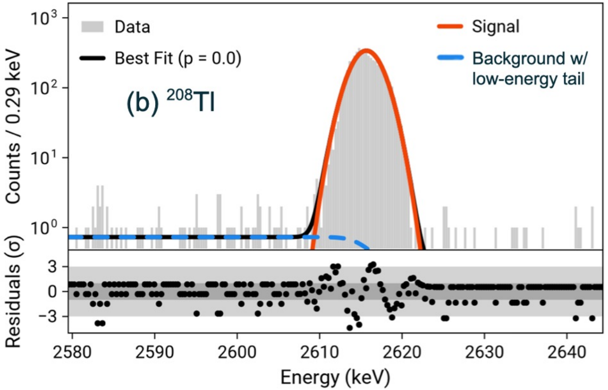
Energy Calibration

232Th Line Fits + Energy Calibration Curve







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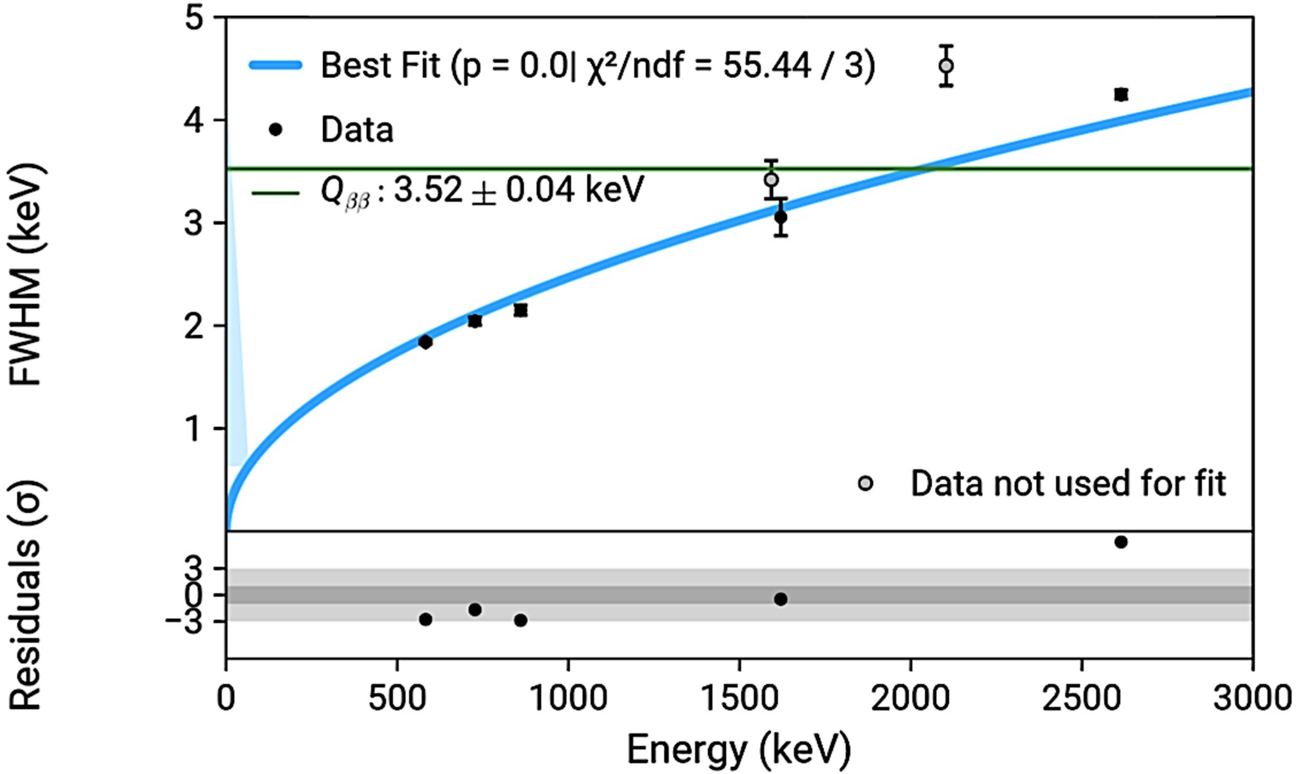
Energy Calibration

Resolution vs Energy Curve



- Plot and fit measured peak FWHM values vs. literature ^{232}Th γ line energies.
- Square root of a first-order polynomial
- Energy resolution at $Q_{\beta\beta}$ (^{76}Ge) = 3.52 ± 0.04 keV FWHM
- As noted before, this is a detector/setup-limited value:
  - non-Fano contribution of 408 e− RMS, vs
  - L1K65n's 63 e−RMS ENC measured on the benchtop

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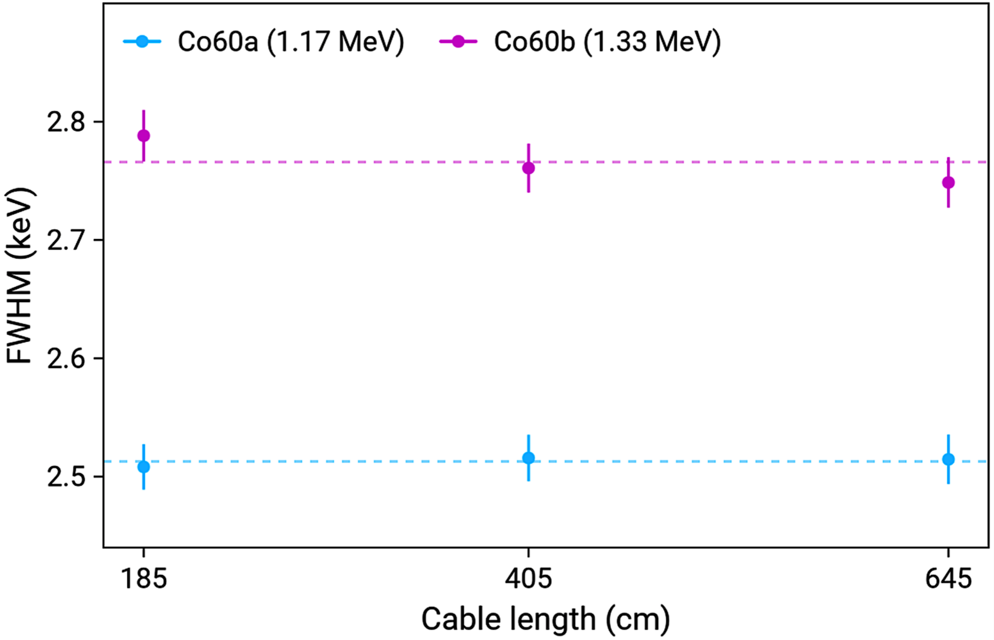
The Effect of Cable Length

- Long cables between preamplifier and digitizer, shaper etc. are an important challenge in LEGEND and other large detector arrays.
- L1K65n ASIC'S differential driver successfully address this.



Cable length (cm)	FWHM @ 1173 keV (keV)	FWHM @ 1333 keV (keV)
185	2.51 ± 0.02	2.79 ± 0.02
405	2.52 ± 0.02	2.76 ± 0.02
645	2.52 ± 0.02	2.75 ± 0.02

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Next Steps

- Test L1K65n v2 chips
  - Novel feedback solution
  - On-chip LDO
  - Other improvements
  - Already delivered and ready for testing
- Test with detector(s) submerged in LAr, as in LEGEND
- Test with other/better detectors, e.g. ICPC
- Design and produce L1K65n v3 (pre-)final iteration
- Develop our collaboration with Mirion

Thank you!