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Novel Ge Detector Geometries and Readouts

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Applied Nuclear Physics

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Novel Ge Detector Geometries and Readouts

- The Berkeley Semiconductor Detector Fabrication Laboratory
- Pushing the limits in the operation of HPGe detectors – Position, Count rates, noise
- Towards 0.1 mm 3-D position resolution – very brief
- Towards > 1Mcps
- Towards “zero” noise
- Conclusions

Applied Nuclear Physics

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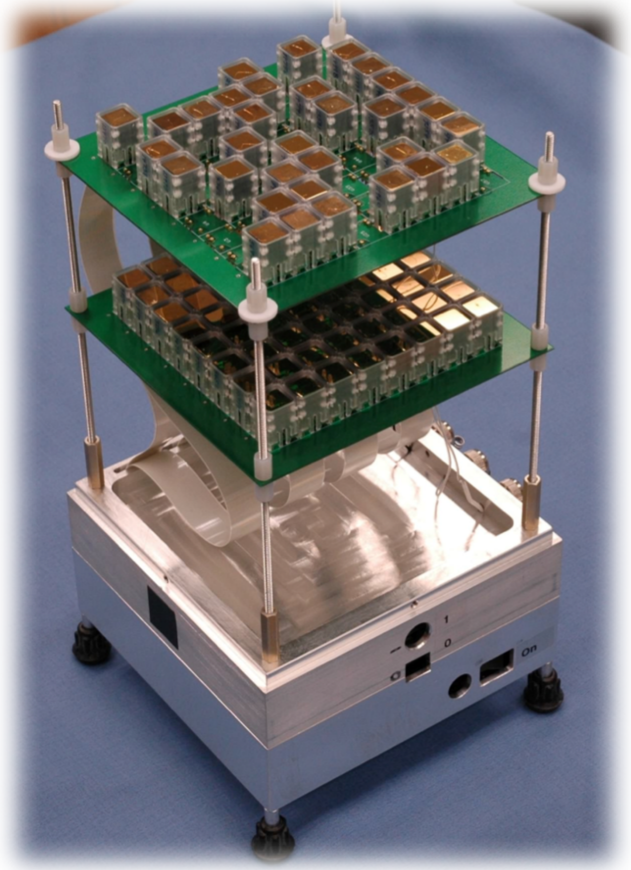
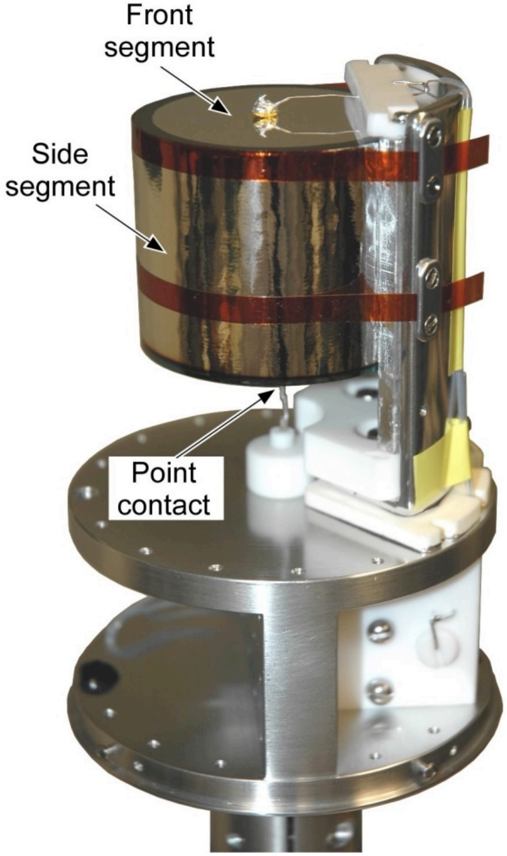
LBNL Semiconductor Detector Lab

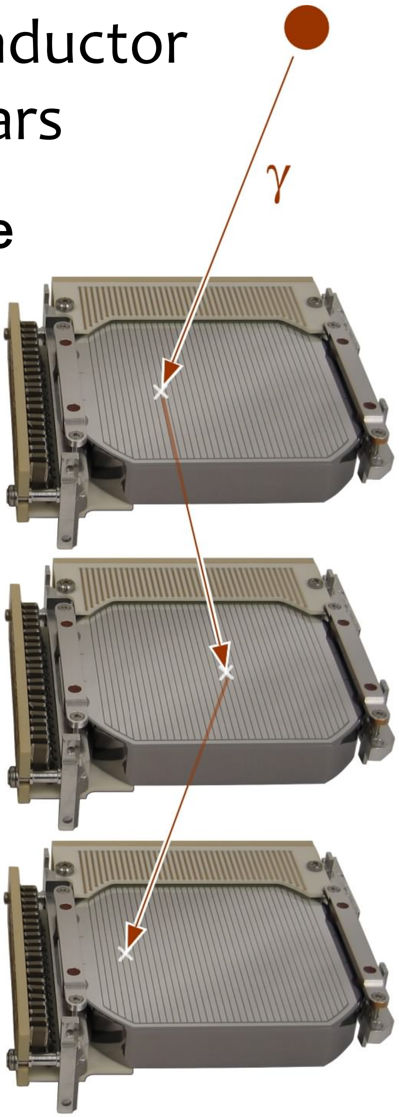
The SDL has been at the forefront of semiconductor detector innovation since for over 50 years

CdZnTe



High-purity Ge





Historical accomplishments with significant impact to radiation detector technology

- **One of first groups to develop lithium-drifted Si detectors (early 1960's)**
- **One of two groups that originally developed high-purity Ge crystal growth (early 1970's)**
- **First Si and Ge drift detectors produced in our laboratories**
- **Fabrication technologies developed include: amorphous semiconductor contact, implanted contact, and surface passivation**
- **Developed position-sensitive Si and Ge detectors**
- **Invented shaped-field point-contact Ge detector (1989)**
- **Invented coplanar-grid technique for CdZnTe-based detectors (1994)**

Recent accomplishments with significant impact to radiation detector technology

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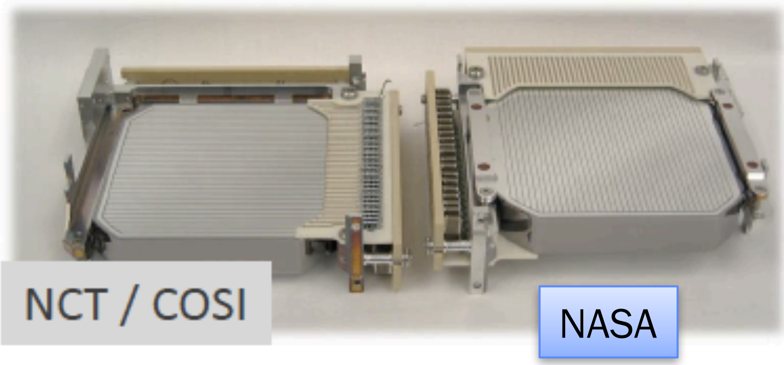
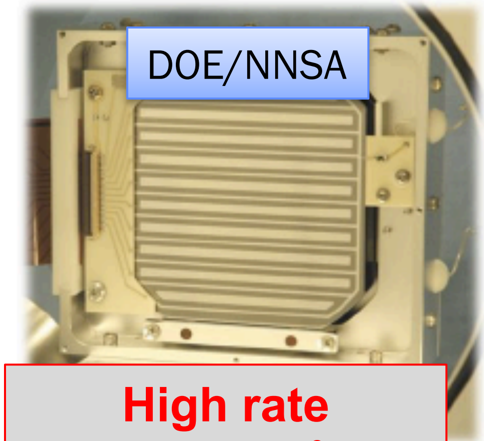
- Fabrication technologies developed include: amorphous semiconductor contact, implanted contact, and surface passivation
- Developed position-sensitive Si and Ge detectors
- Invented shaped-field point-contact Ge detector (1989)
- Invented coplanar-grid technique for CdZnTe-based detectors (1994)
- **Invented proximity charge-sensing readout technique (2009)**
- **Invention of portable gamma-ray imager (2011)**
- **Developed ultra-low-noise system for Ge detectors (2015)**
- **Developed high-count rate Ge detectors (2016)**

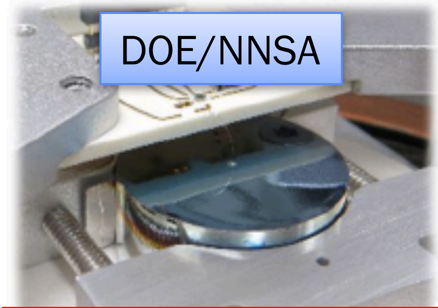
Recent Advances in HPGe Detector Technologies

Pushing the limits in the operation of “gold-standard” HPGe instruments

- Advanced detectors from HPGe crystals: segmented, high rate, low noise



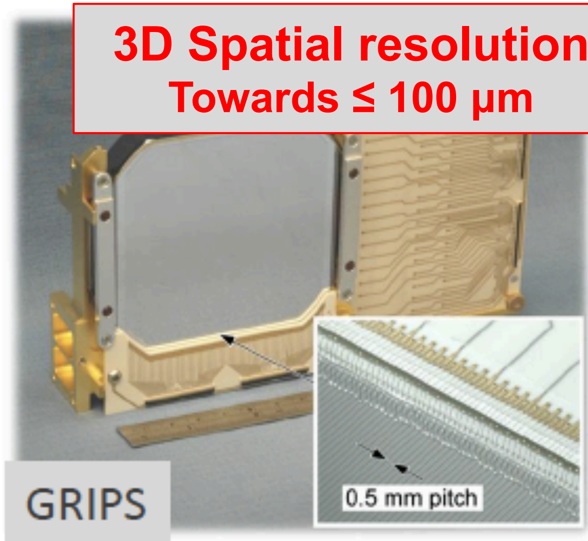


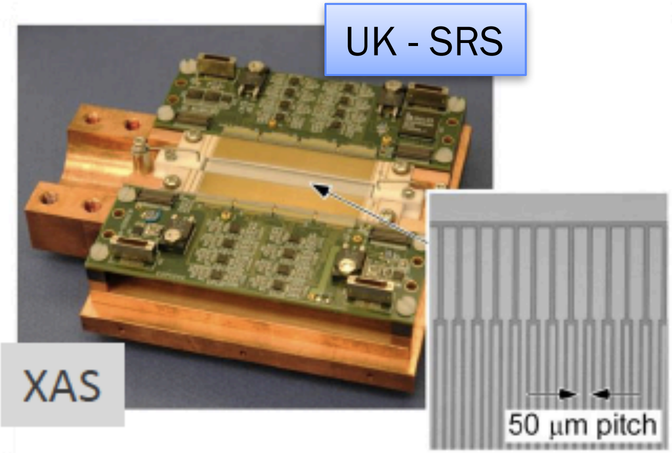


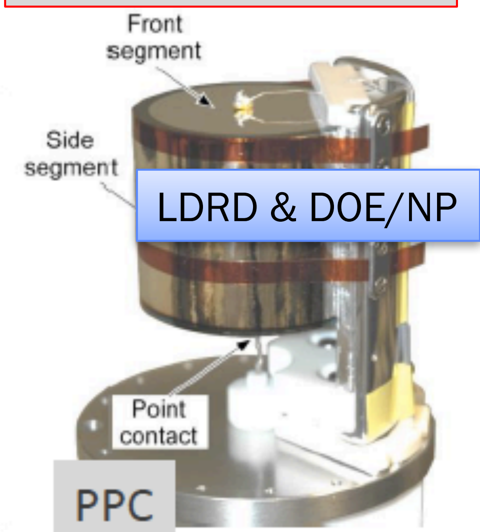
Ultra-low noise
Towards zero

High rate
Towards ≥ 10^6 cps

3D Spatial resolution
Towards ≤ 100 μm







➢ Advanced instruments require parallel development in readout integration.

Ultra-High Count Rate Ge Detector

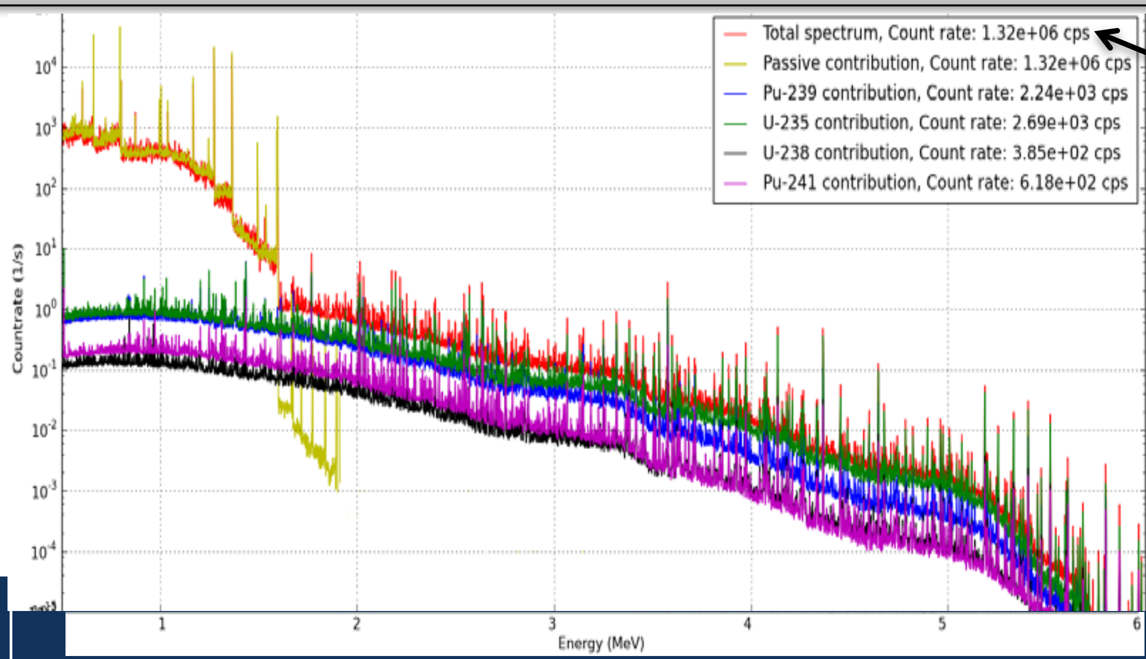
Towards≥ 10^6 cps

- Ge-detectors remain the "gold standard" for high-energy resolution gamma-ray spectroscopy
  - Commercial systems are ruggedized and mechanically cooled, enabling field operations
  - Ongoing improvements in cooling reduce power and weight
- Recent developments in 2-D segmentation of Ge detectors enable gamma-ray imaging in the field (e.g. PhDs)
- One of the remaining limits in the operation of Ge detectors:
  - Operation at count rates above 10 kcps results in significant degradation in energy resolution

Ultra-High Count Rate Ge Detector
Towards≥ 10^6 cps

- Many applications require quantitative spectral analysis in high count rate environments
  - Signal-to-noise ratio may be low
- ***Nuclear safeguards*** has many such applications:
  - Plutonium forensics
  - Passive measurements of spent nuclear fuel
  - Delayed-γ spectroscopy
  - Nuclear resonance fluorescence
- In addition to: Emergency response, nuclear physics, gamma-ray imaging, dosimetry…

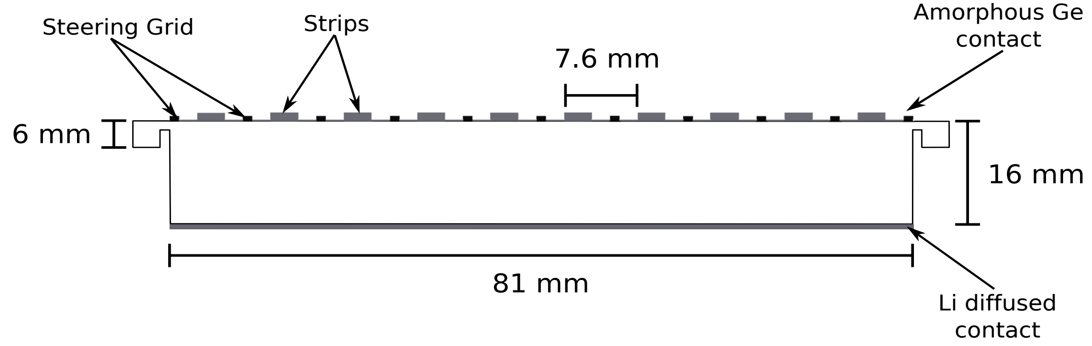
Example: Radio-isotopic identification and quantification of spent nuclear fuel:

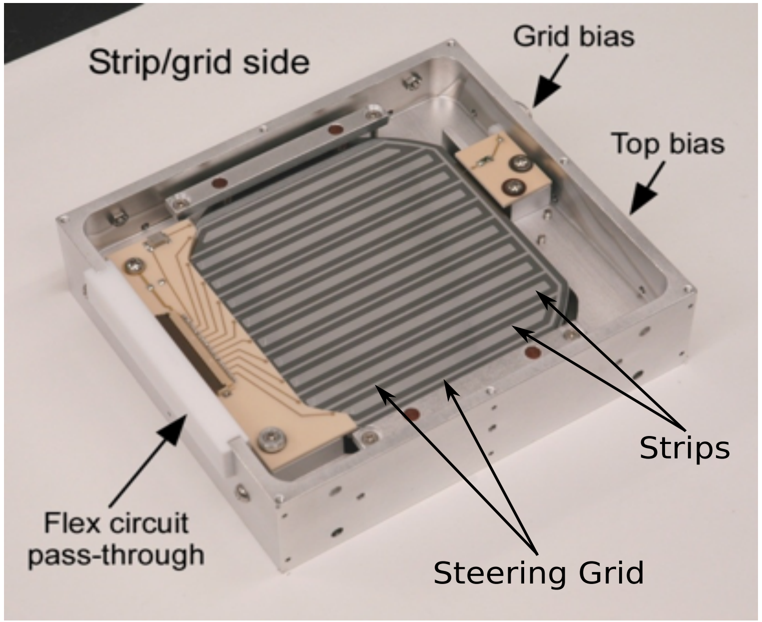


V. Mozin, UCB thesis (now LLNL)

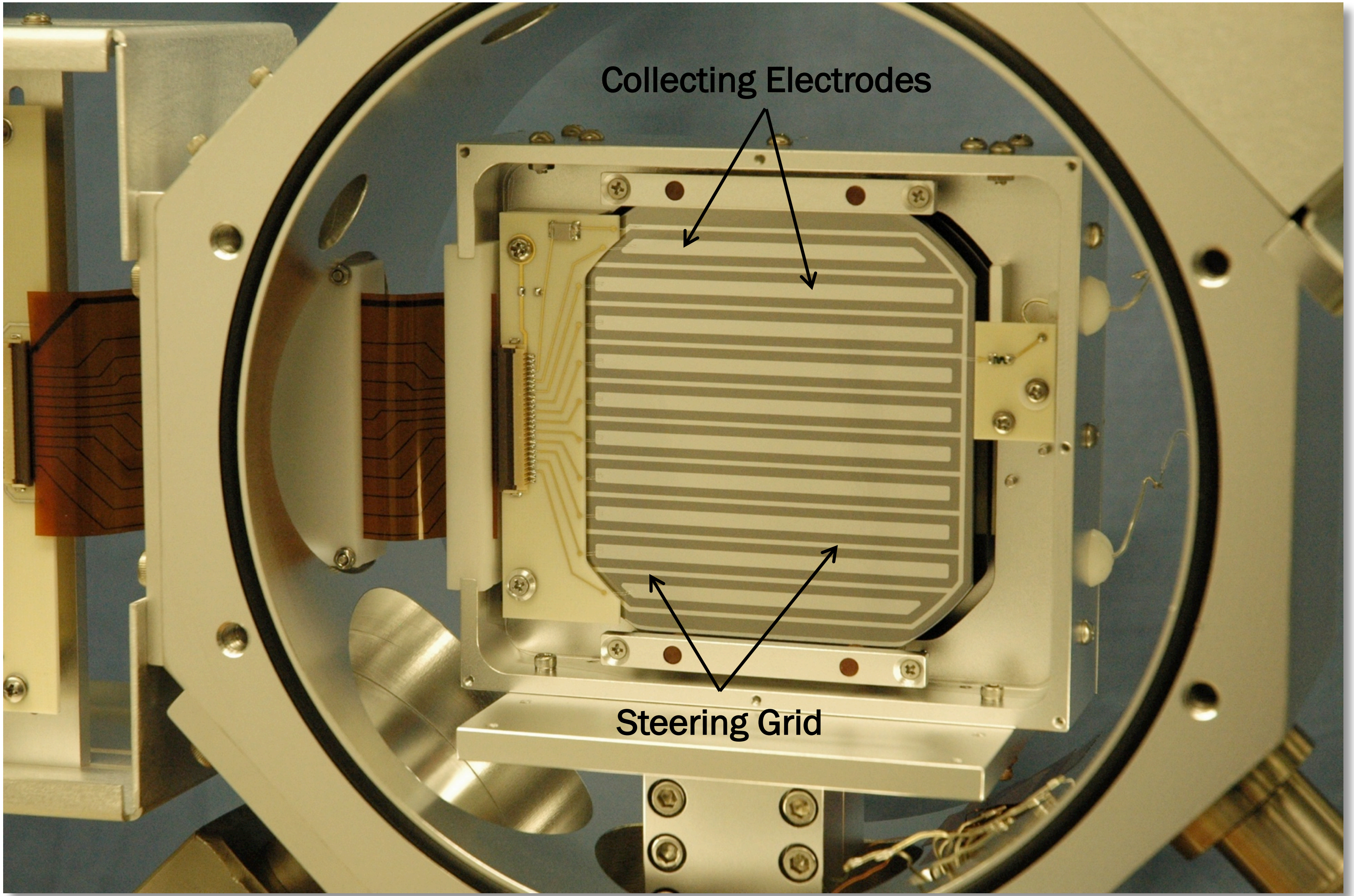
Ultra-High Count Rate Ge Detector
Towards≥ 10^6 cps

- **Design:**
  - Planar configuration
    - High & uniform E-fields with fast rise times
    - Minimum variation in signal shapes & rise times
  - Strip electrodes
    - Distribute count rates across strips
    - Reduce capacitance to allow for shorter peaking times and reduced serial noise by increasing distance between strips
    - Increase charge collection in between strips with steering electrodes
    - Utilize established amorphous Ge contact technologies
  - Utilize state-of-the art digital signal processing (LABZY – nanoMCA)



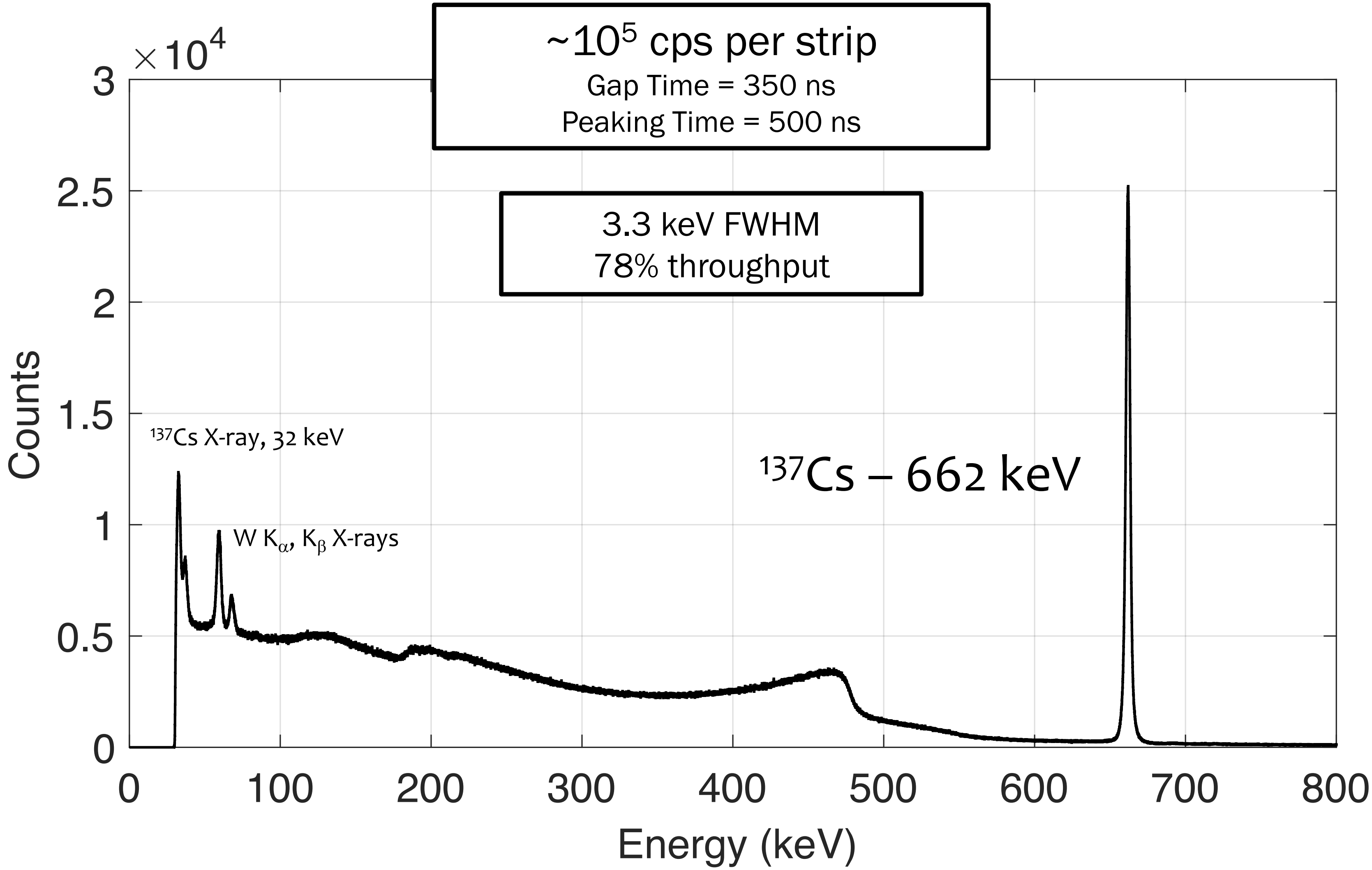


Ultra-High Count Rate Ge Detector – Prototype



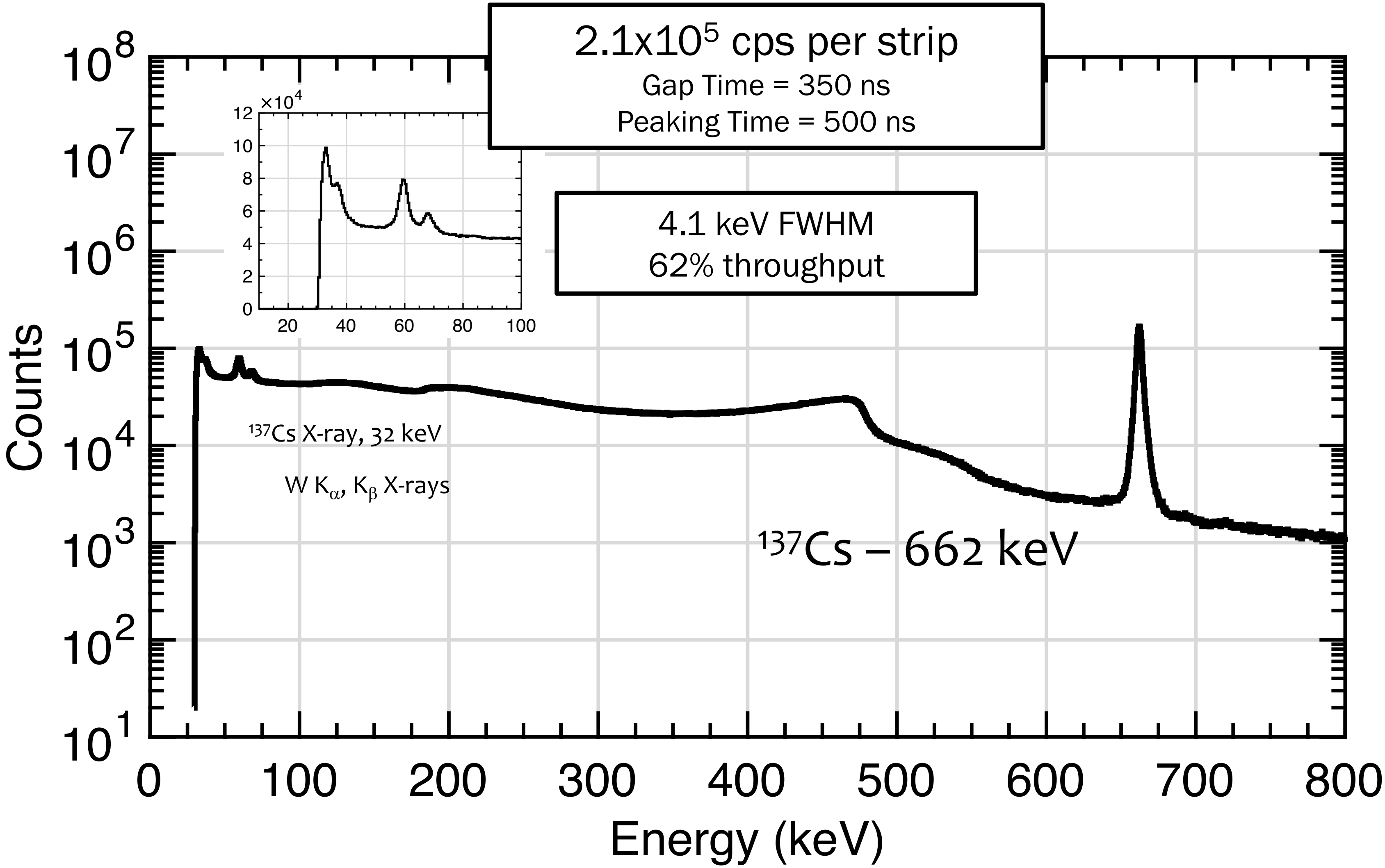
High Rate Spectrum

Single Strip Performance



High Rate Spectrum

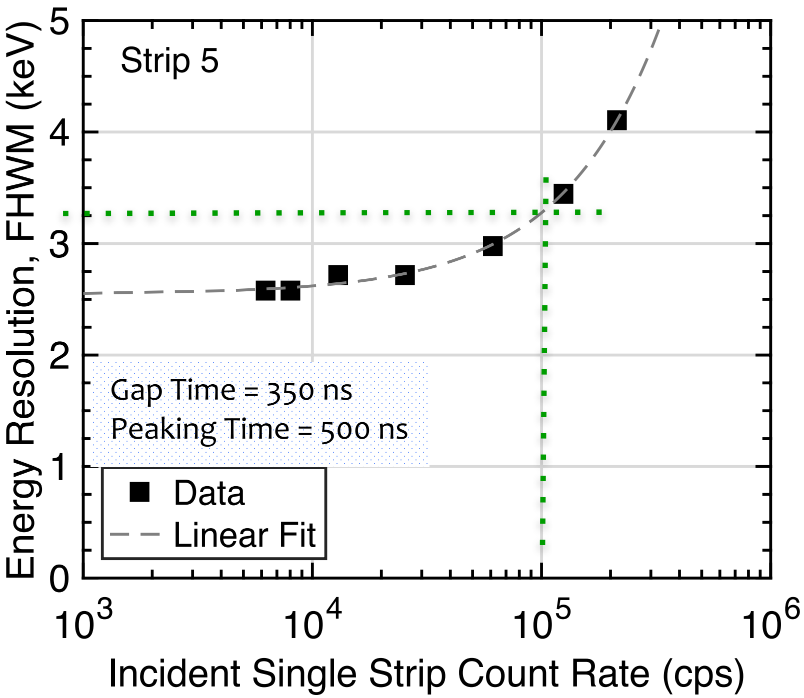
Single Strip Performance

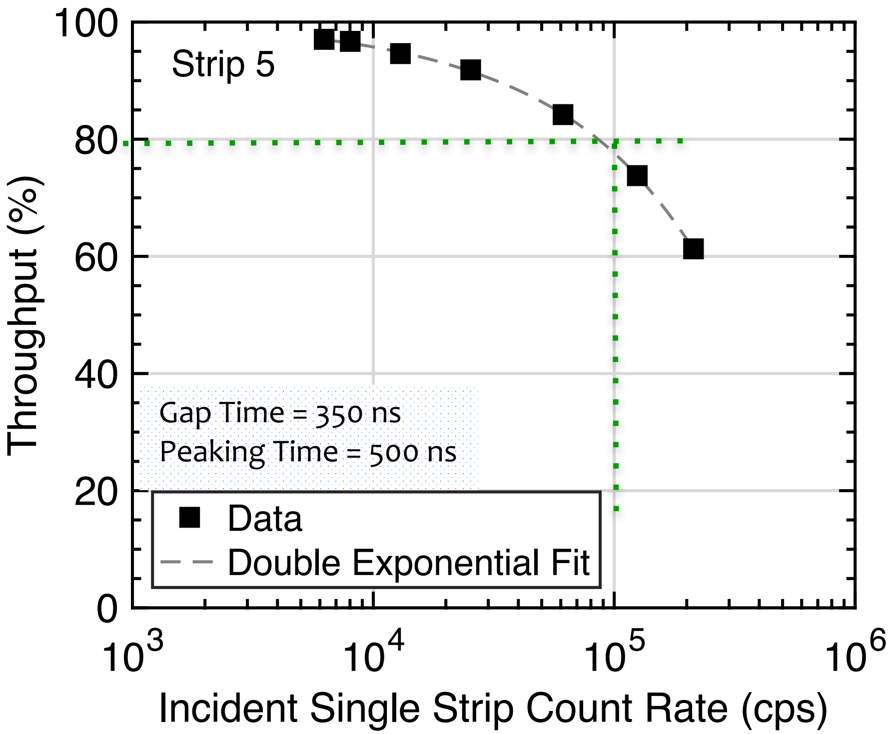


Performance at High Rate

Demonstrated operation at > 10^6 cps with 2 mCi ^{137}Cs source

Commercial electronics and real time, online filtering





- **Achieved 3.2 keV FWHM and 78% throughput at 10^5 cps per strip**

Ultra-Low Noise Ge Detectors
Towards Zero Noise

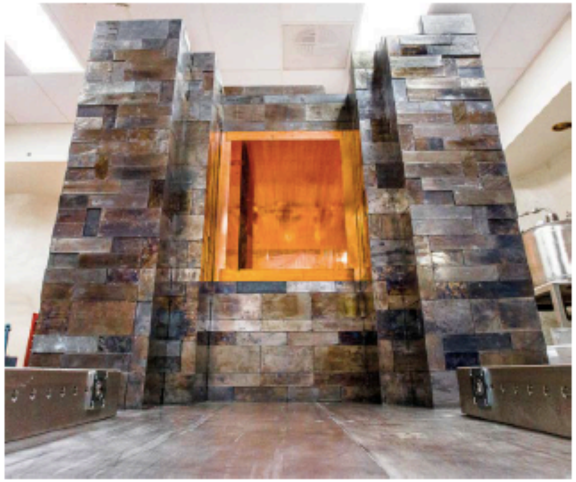
- **Recent advances in the development of so-called P-type Point Contact (PPC) detectors in combination with CMOS readout enable ultra-low noise operation of Ge detectors**
  - Improved energy resolution and low energy threshold
  - Detect low-energy photons and particles, e.g. weakly interacting particles such as (anti) neutrinos from an operational nuclear power plant (NPP)
  - Monitor operation of NPP via coherent neutrino-nucleus scattering (CNNS) in Ge (10'of kg of Ge vs. ton's of scintillator for conventional detection, e.g. Watchman)

Example: Neutrino-Less Double Beta Decay in ^{76}Ge
Majorana Demonstrator + GERDA = LEGEND

Low-noise PPC detectors achieve the best energy resolution and lowest background to date:

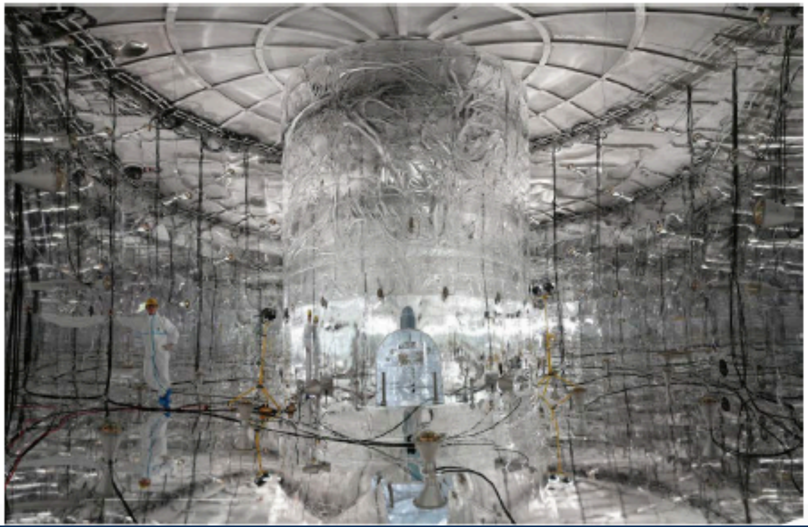
MAJORANA

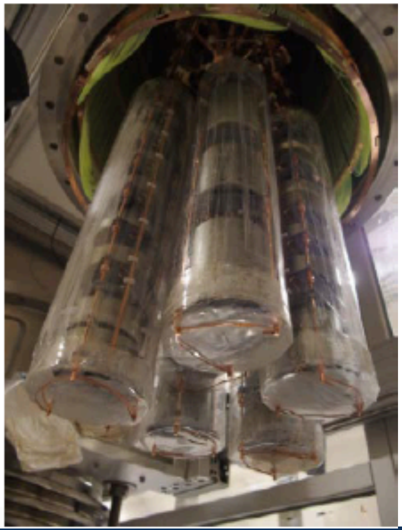
Vacuum cryostats in a passive graded shield with ultra-clean materials



GERDA

Direct immersion in active LAr shield





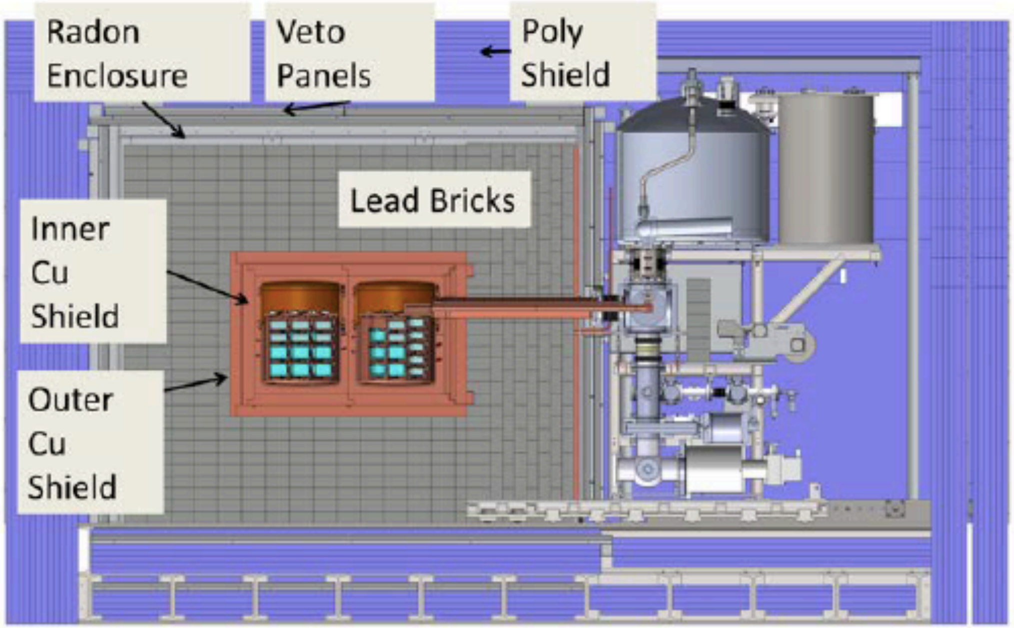
Example: Neutrino-Less Double Beta Decay in ^{76}Ge

Majorana Demonstrator

Goals:

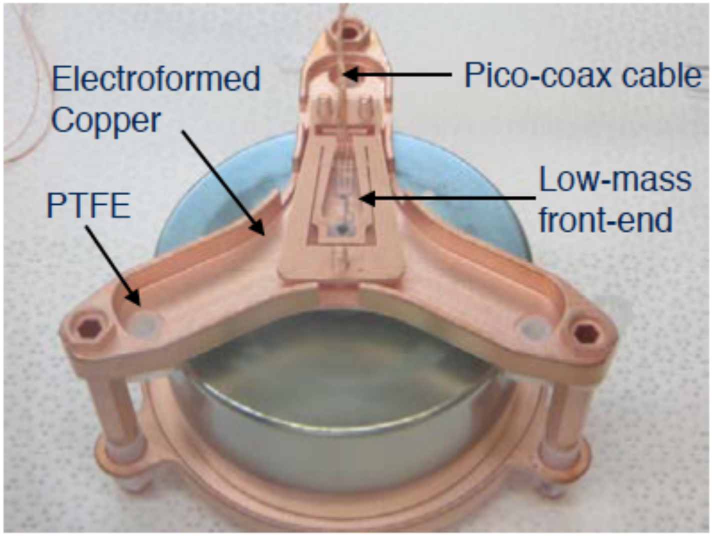
- ***Demonstrate backgrounds low enough*** *to justify building a tonne scale experiment.*
- ***Establish feasibility*** *to construct & field modular arrays of Ge detectors.*
- ***Searches for additional physics beyond the standard model.***

- Located underground at 4850' Sanford Underground Research Facility
- 44-kg of Ge detectors in two independent cryostats
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge crystals
- **Highest energy resolution** among all 0νββ detector technology
- ~0.1% FWHM at Q(^{76}Ge)=2039 keV



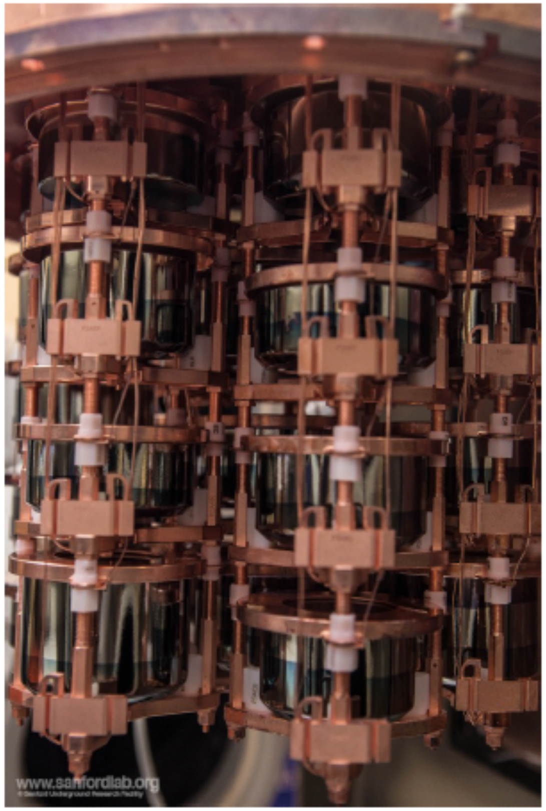
Example: Neutrino-Less Double Beta Decay in ^{76}Ge

Majorana Demonstrator – Detector strings and modules



Final design

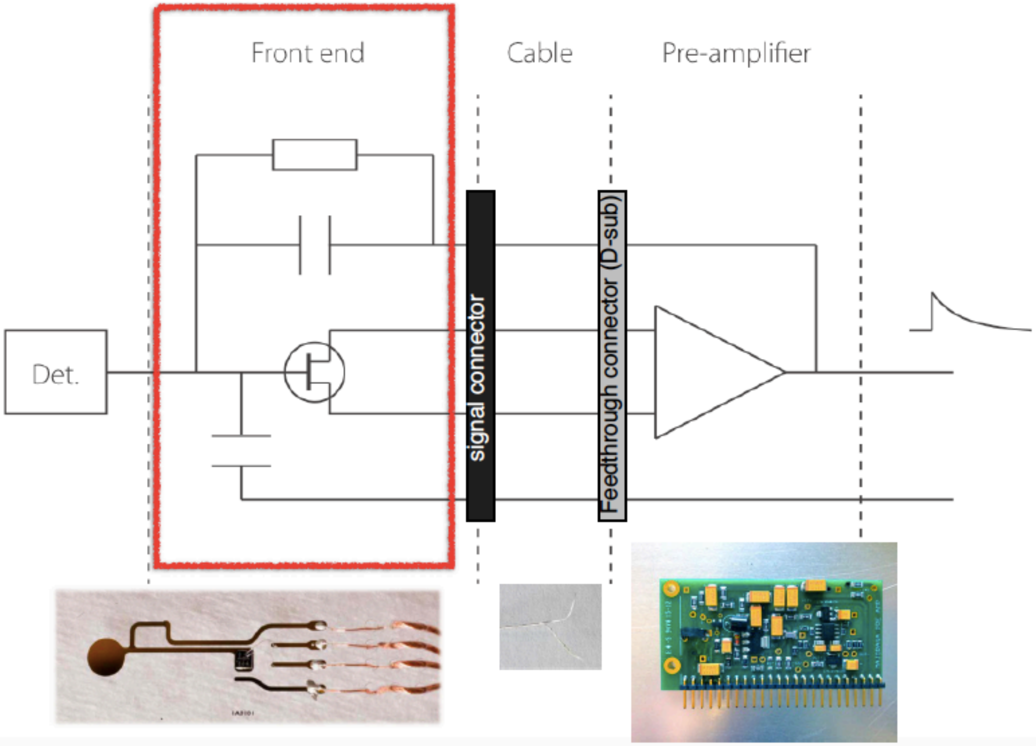
Detector String
3 - 5 DU / string

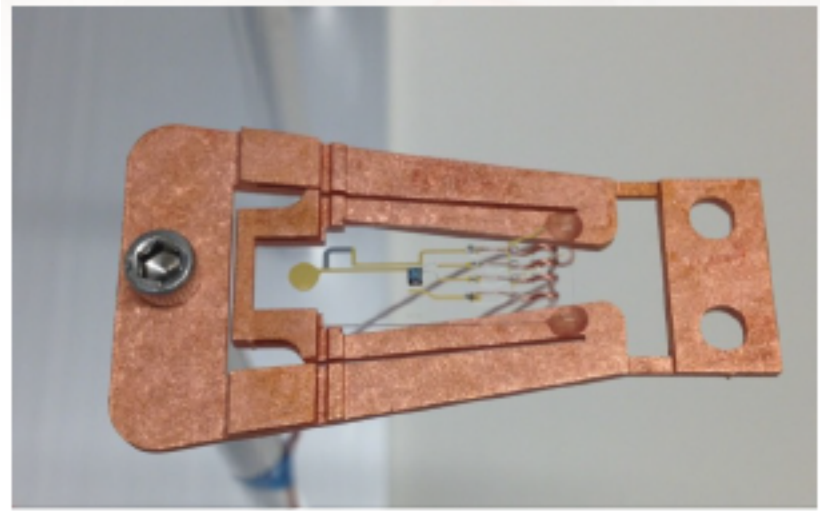


Detector Module
7 strings / module x
2 modules

Example: Neutrino-Less Double Beta Decay in ^{76}Ge

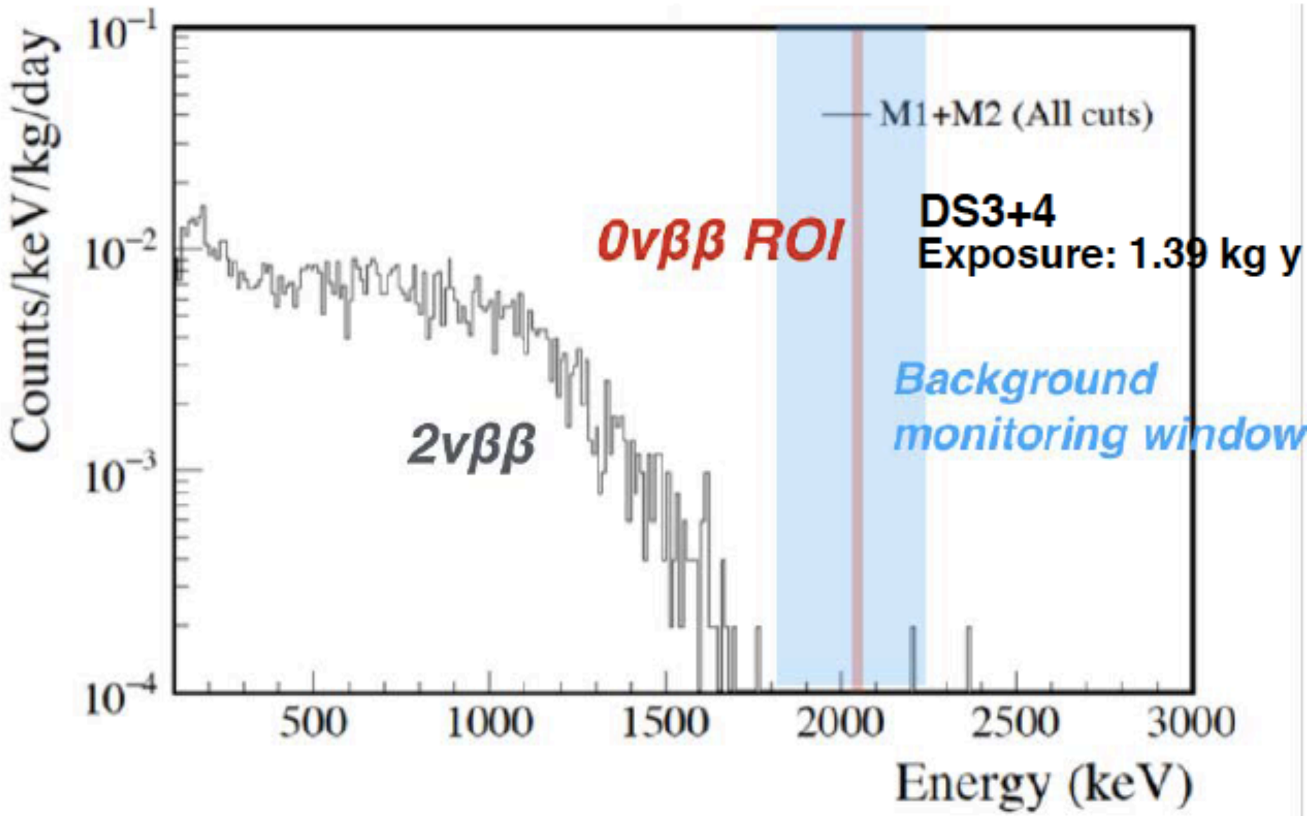
Majorana Demonstrator – Low-Mass Front End (LMFE)





Example: Neutrino-Less Double Beta Decay in ^{76}Ge

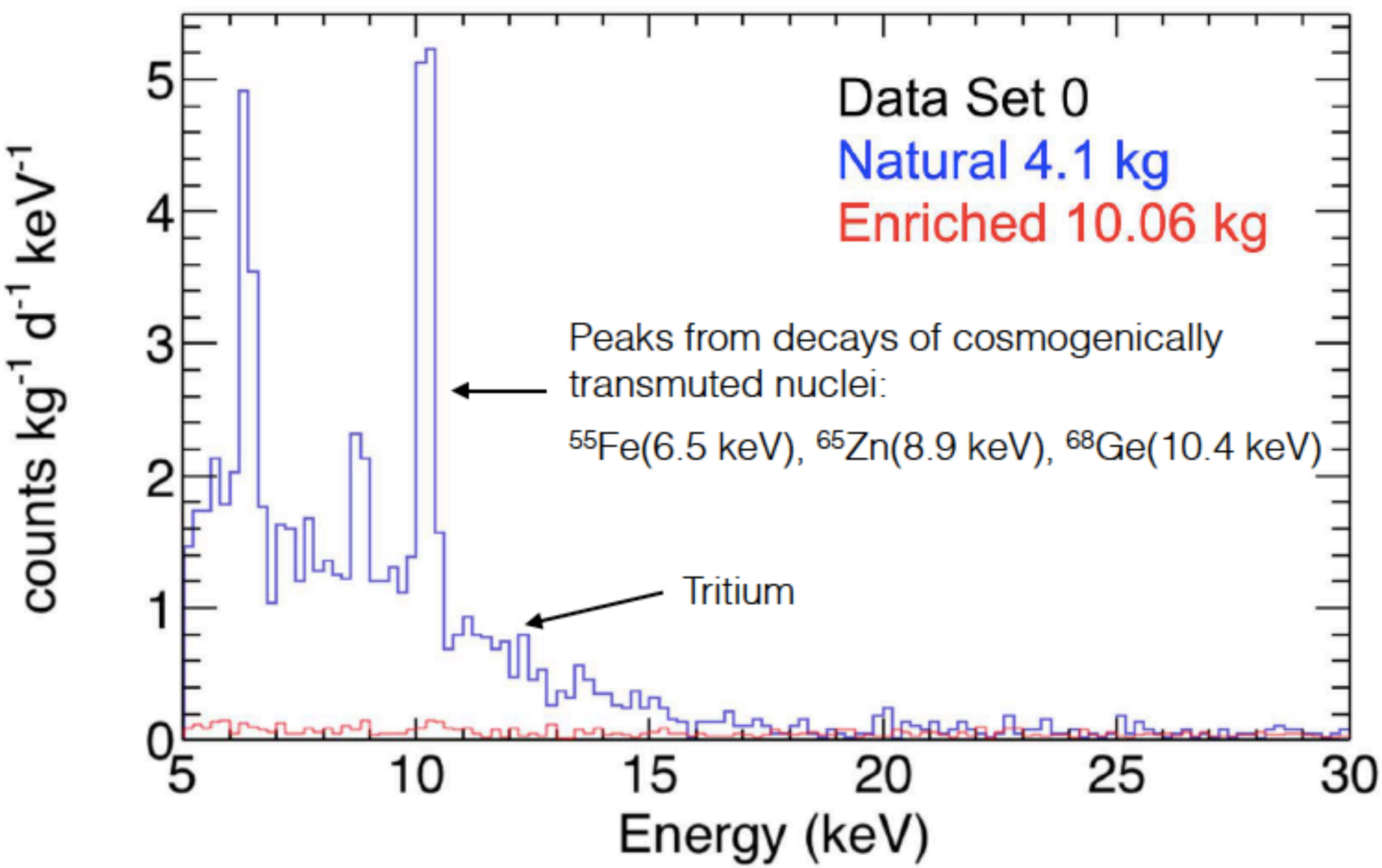
Majorana Demonstrator – Preliminary results at Q-value (2039 keV)



- Only 1 event survived in 400 keV window. Background rate is $5.1^{+8.9}_{-3.2}$ counts/(ROI t y) for a 3.1-keV ROI, (68% CL).
- Background index is **$(1.8^{+3.1}_{-1.1})\times10^{-3}$ counts/(keV kg y)**.
- Through mid-May, we have 10x more exposure in hand. Analysis is in progress.

Example: Neutrino-Less Double Beta Decay in ^{76}Ge

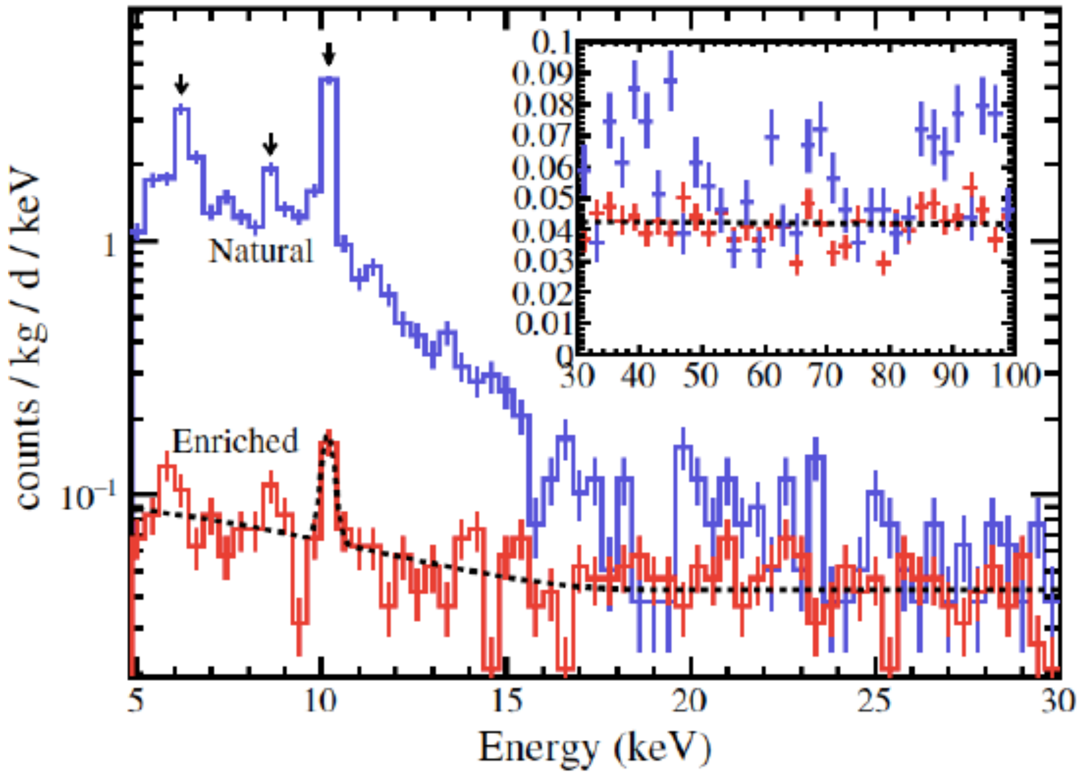
Majorana Demonstrator – Preliminary results at low energies



Example: Neutrino-Less Double Beta Decay in ^{76}Ge
Majorana Demonstrator – Preliminary Results

MJD 478 kg-d data

Phys. Rev. Lett. 118, 161801



$FWHM_{noise}$ ~ 250 eV
$E_{threshold}$ ~ 600 eV

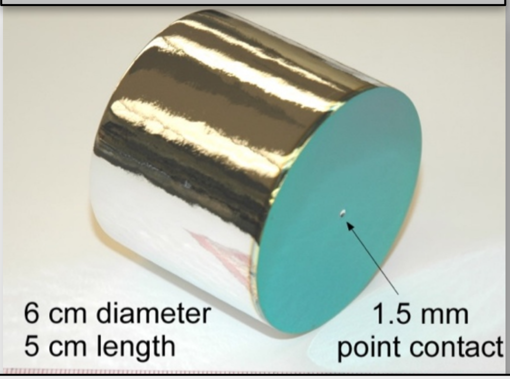
Low background in low-energy regime + low energy threshold:
- Extended low-energy physics program to search for physics beyond the Standard Model
- Can we go lower?

Ultra-low noise HPGe ionization detector

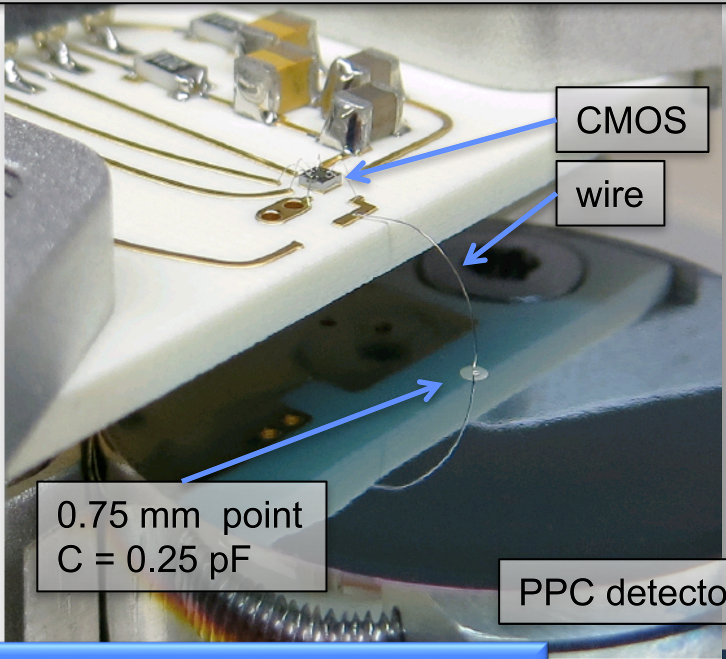
- Combine low capacitance in detector and readout with low noise amplification at low temperature:
  - Point contact detector with small point
  - Wire bonding
  - CMOS readout
  - Ultra-low vibration mechanical cooling

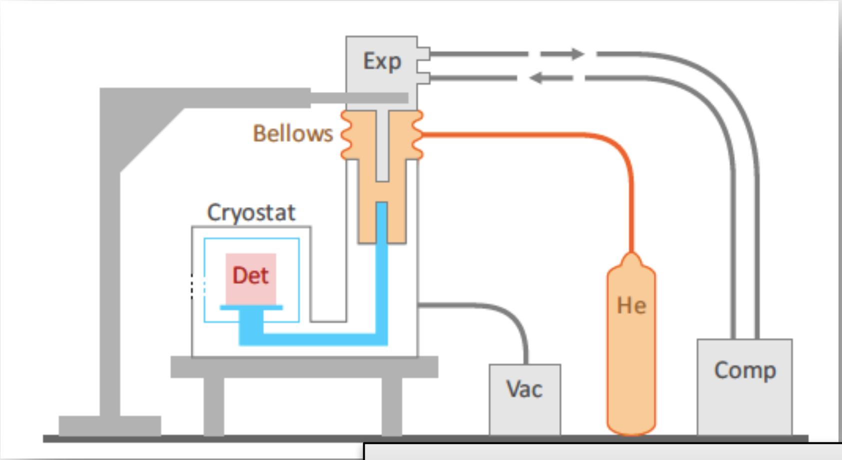
  + Potentially “radio-pure” readout

PPC detector



PPC detector and CUBE ASIC wire bonded to low dielectric loss PCB with power supply filters





Gifford-McMahon Cryocooler (Advanced Research Systems)

➢ Achieve low noise and study charge transport down to < 10 K

Ultra-low noise HPGe ionization detector

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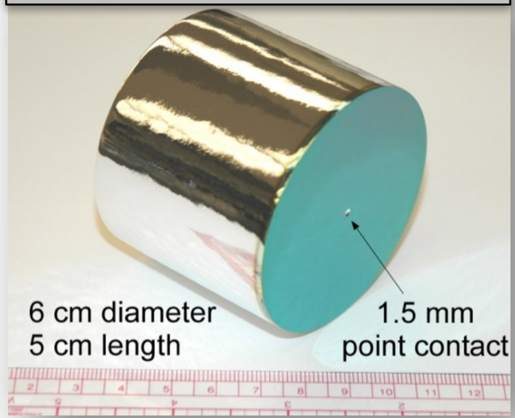
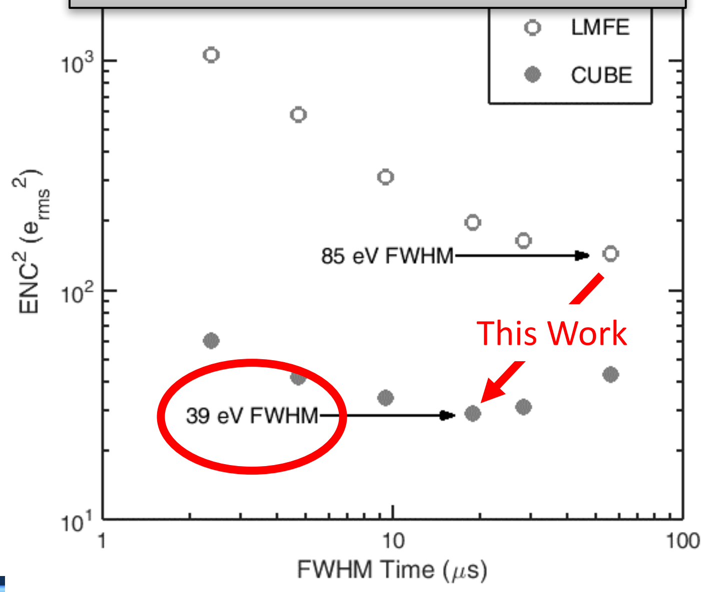
  - Wire bonding
  - CMOS readout
  - Ultra-low vibration mechanical cooling
  + Potentially "radio-pure" readout

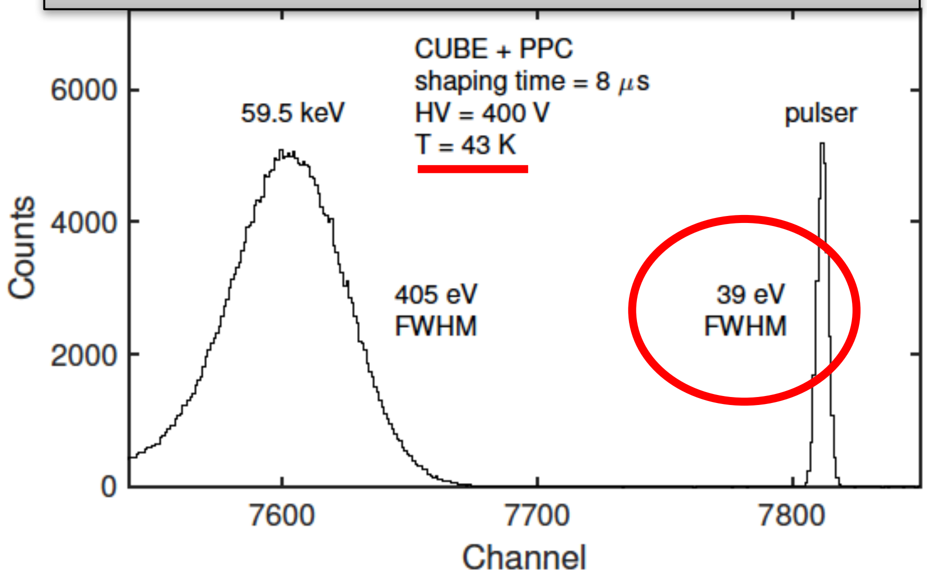
PPC detector



Equivalent Noise Charge



Spectrum of ^{241}Am (59.5 keV) and pulser peak

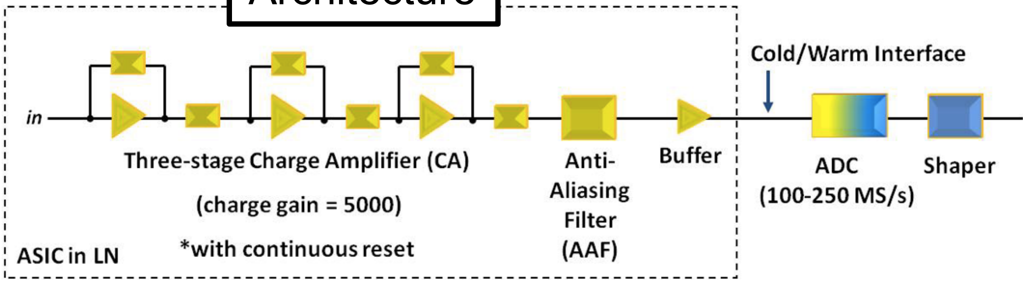


➢ New low-noise record in HPGe ionization detector: ~5.6 electrons RMS!

New Ultra Low-Noise ASIC for HPGe PPC Detector

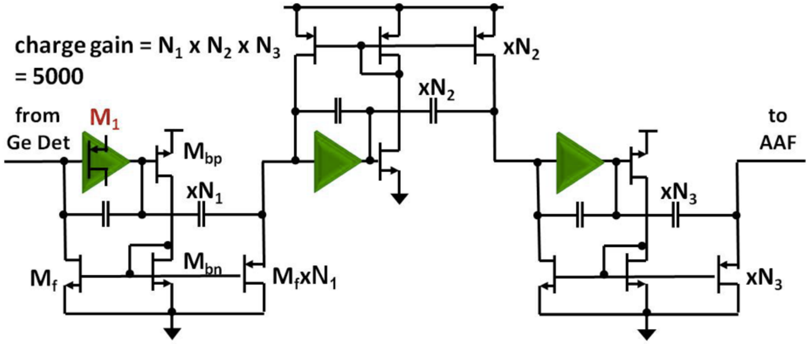
- Lower Noise ASIC Goals
  - Low Noise, Low Threshold
  - Optimize for down to 0.1 pF detectors
  - Minimize Cabling
  - Reduce External Components

Architecture

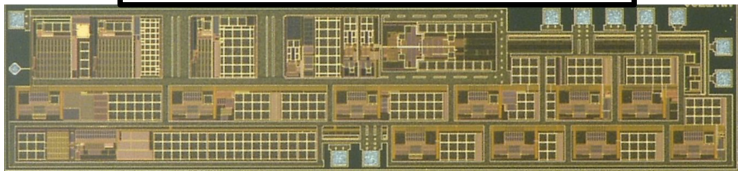


- Developed improved preamp-on-a-chip ASIC with BNL: The *Low-Noise Low-Capacitance* (LNC) Preamplifier
  - Single Power Supply, *internally filtered*
  - No Reset Signal, No Rfeedback (*internal reset*)
  - 4 Connections: [Power, Ground, In, Out]
  - 50 MHz bandwidth
  - 27 eV-FWHM (100 fF HPGe), < 4 e-rms (at 78K)
  - Operational in LAr

Simplified Schematics



ASIC (2.6 mm x 0.6 mm)



Conclusions

- Although Ge detectors have been the gold-standard in gamma-ray spectroscopy for many decades, technological advances continue and enhance the performance and range of applications.

- Towards zero noise:
  - The recent realization of (inverted) PPC geometries in combination with CMOS and high radio-purity signal readout provide ultra-low noise and ~background-free operation of large HPGe detectors;
- Towards >1 Mcps:
  - Refined segmentation schemes and digital readouts enable operation with detector throughputs of > 1Mcps
- **Towards < 100um resolution:**
  - Refined segmentation schemes and integrated readouts will enable <0.5 mm 3-D spatial resolution
- **Example for future: Combine 0.5 mm pitch DSSD with high count rate capability**


Thank you !