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Defense Nuclear Nonproliferation Research & Development

Nuclear Weapons and Material Security Portfolio Review

WMS 2015

Ultra Low Noise Germanium Neutrino Detection Collaboration

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Outline

- **Participants**
- **Project Goals**
- **Progress and Challenges**
- **Future Work**

Participants

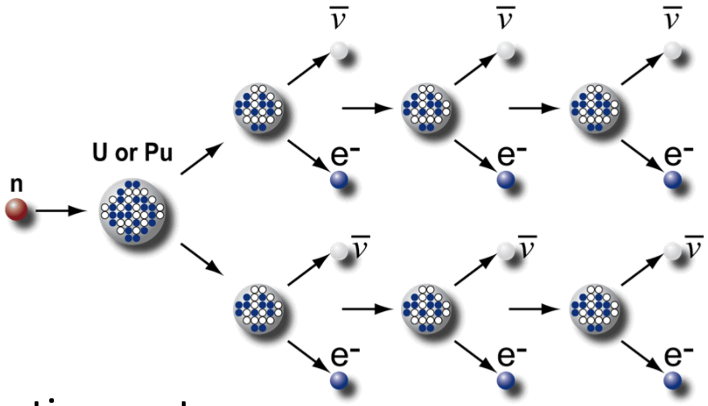
- **Lawrence Berkeley National Laboratory**
  - **PI:** Paul Barton
  - Kai Vetter, Paul Luke, Mark Amman

- **Sandia National Laboratory**
  - **PI:** Belkis Cabrera-Palmer (*see poster*)
  - Craig Tewell, David Reyna

- ~~San Onofre Nuclear Generating Station (**SONGS**)~~
  - now Spallation Neutron Source (**SNS**)
    at Oak Ridge National Laboratory

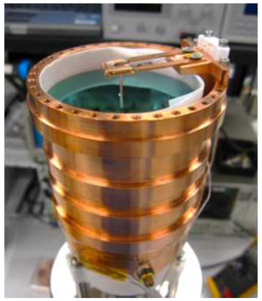
Reactor Monitoring

- **6 antineutrinos** per fission.
- 10^{22} antineutrinos from 3 GWt reactor

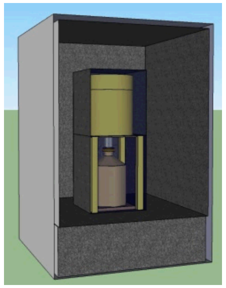


Originally Proposed Goal:

Development, construction, and deployment of the first large-mass High Purity Germanium (**HPGe**) detection system with the required **ultra-low electronic noise threshold** to demonstrate detection of **reactor antineutrinos** via the Coherent Neutrino–Nucleus Scattering (**CNNS**) process.



1 pF, 1pA, <100 eV Ge Detector



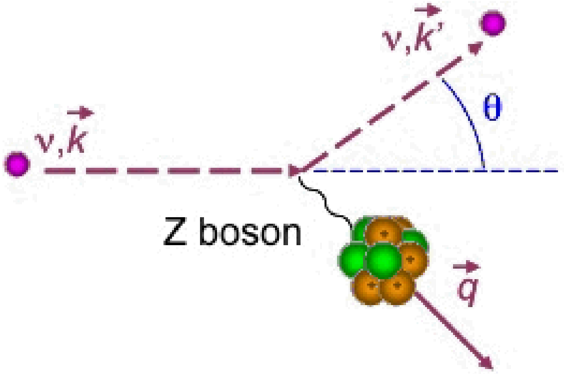
Active / Passive Shielding

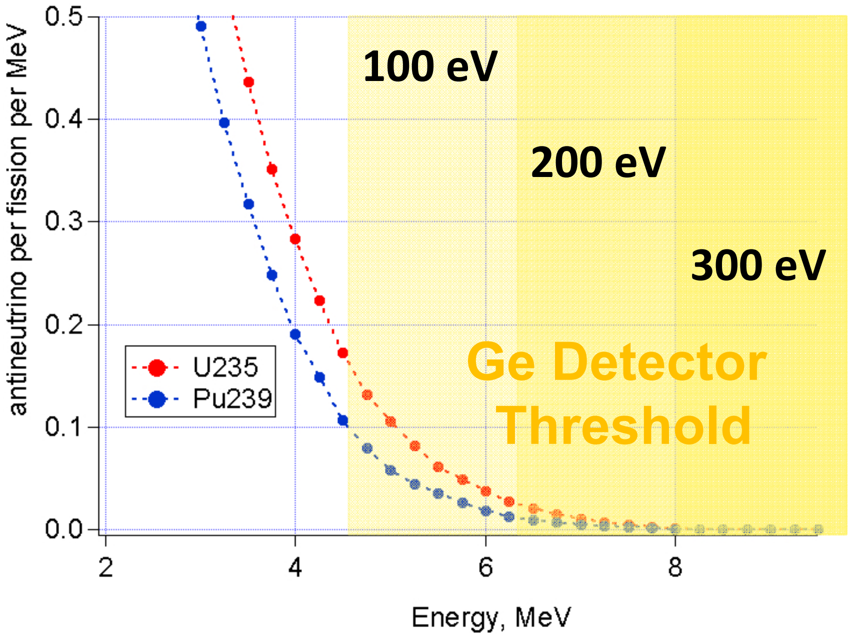
Deployment at Nuclear Power Plant

Coherent Neutrino Nuclear Scattering (CNNS)

- Same for all (anti)neutrino flavors
  - Limit to **<~1 km** distance from reactor due to solar neutrino background.
- Cross-section is **>10^2 times** higher than inverse-beta for reactor antineutrino energies (< 9MeV).
- Small improvement in Ge noise dramatically improves detection sensitivity.

CNNS yet to be observed!





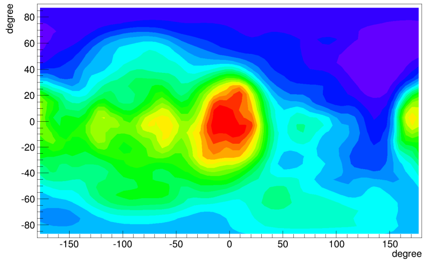
Project Goals (SNL)

- Started with simulation work to understand background in energy region relevant to reactor antineutrinos (0.1 - 3 keVee), and specify shielding for deployment at the SONGS tendon gallery.
- The permanent shutdown of SONGS forces us to search for other feasible reactors and neutrino sources.

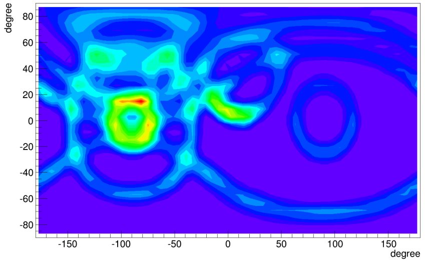
- The Spallation Neutron Source (SNS) at ORNL produces neutrinos of greater energies (10x) that would allow a deployment with existing Ge technology.
- SNL and LBNL are part of the multi-institutional **COHERENT collaboration** to measure CNNS at the SNS.
- The SNS can provide first-time confirmation of the existence of CNNS, which is of extraordinary relevance to the continued pursuit of its application for reactor monitoring.

SNS Background for CNNS

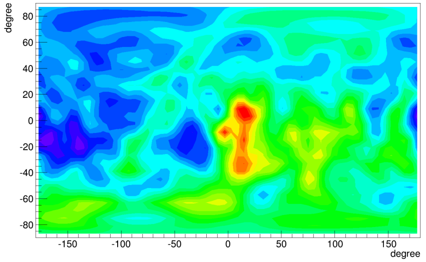
- Measured neutron fluxes at the candidate SNS locations are used as input for shield design simulations.
- Use of Sandia's Neutron Scatter Camera to measure neutron spectrum and image at SNS available locations.
- In the 3 locations measured so far, beam-related neutrons coincident with the neutrino signal, exceed the local cosmic neutron background.
- Next candidate location is only 12 m from the SNS target: stronger neutrino signal necessary for system with ~10 kg of Ge.
- See poster 13 by B. Cabrera-Palmer for more.



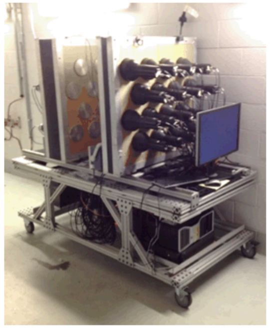
Beam Line 14a



Basement 2.5

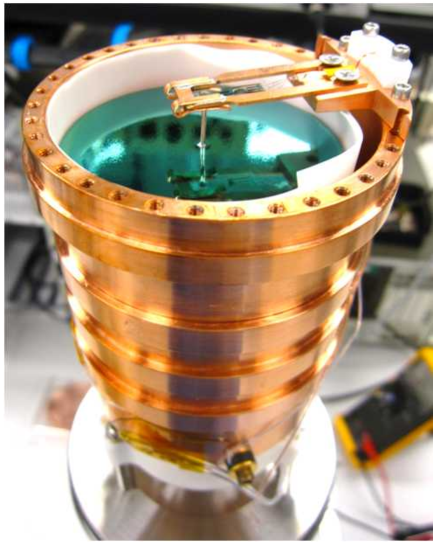


Basement 11



Project Goals (LBNL)

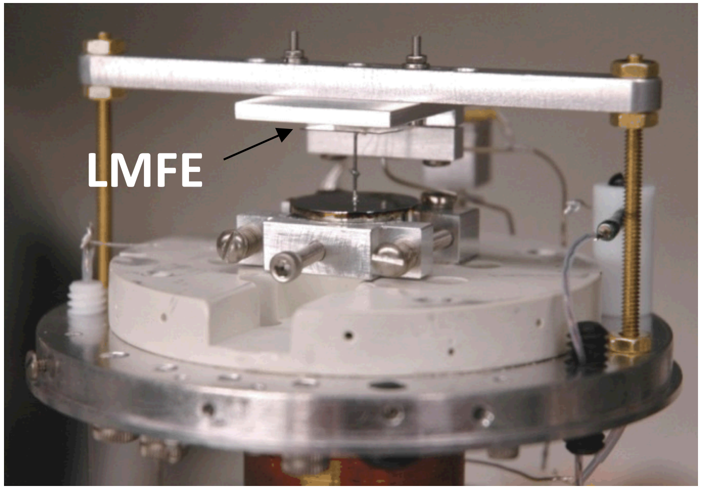
- Advance low noise germanium readout
  - Optimize noise of JFET-based front-end (< 150 eV-FWHM)
  - Demonstrate advantages of alternative readout technologies (e.g. CMOS)
  - Evaluate benefits at low temperature (10-80 K)
- Leverage other low-background low-noise germanium collaborations (Majorana, GERDA, CDMS)
- Demonstrate a low-threshold detector suitable for observation of reactor antineutrinos and other weakly interacting particles.

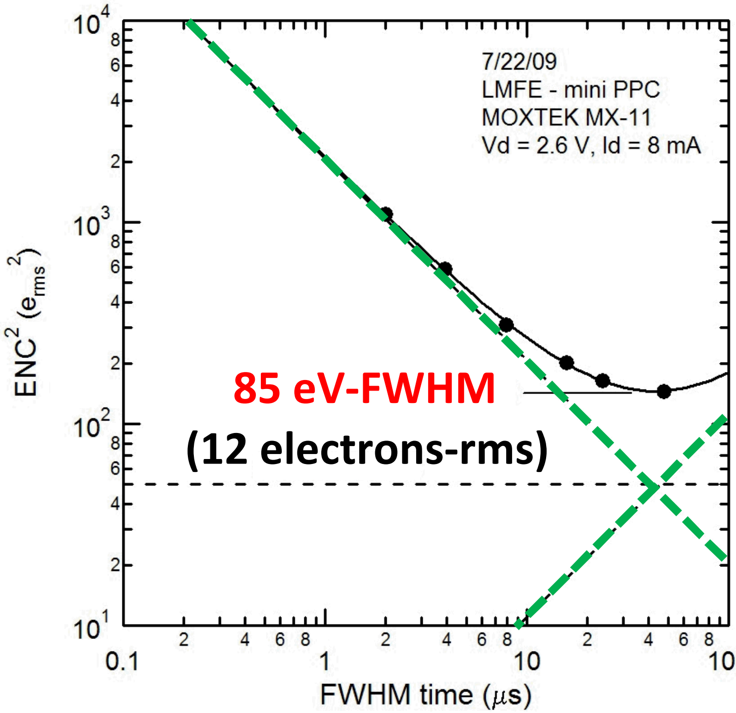


0.9 kg LBNL PPC

Low Noise Germanium

Mini-PPC w/ **Low Mass Front End**
2009 Paul Luke, LBNL





85 eV-FWHM
(12 electrons-rms)

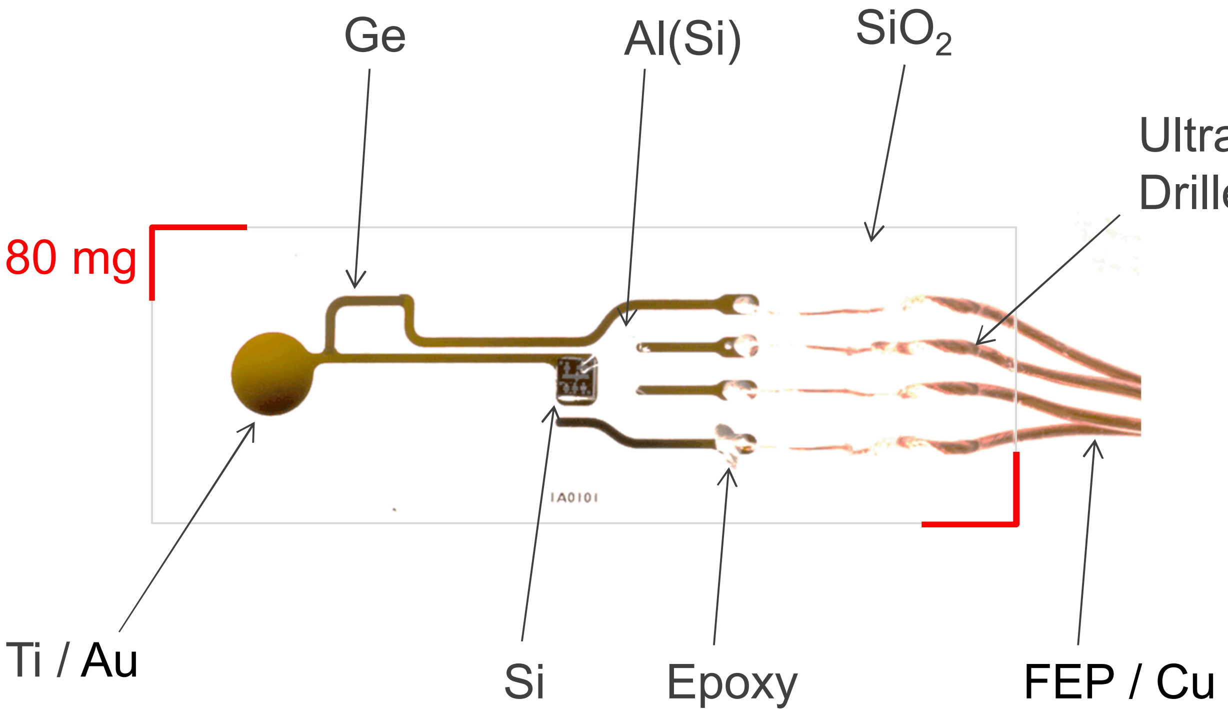
LN_2 Cryostat
Lower temperature (80 K)
than dipstick (95-105 K).

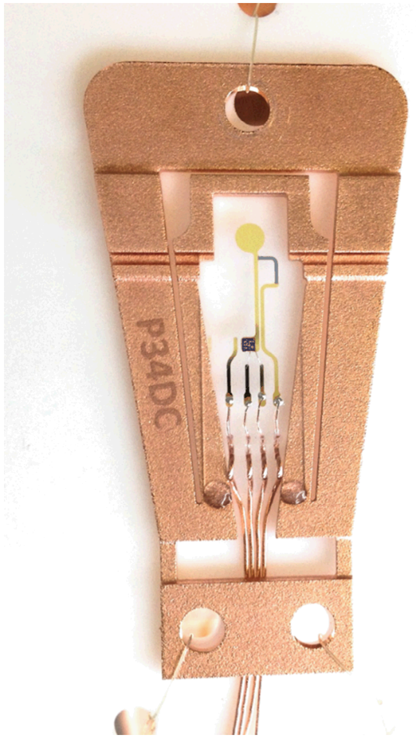
Long shaping time requires:

- low microphonics
- low leakage current
- high feedback resistance

Prior Front End Development

- Low-mass (radioactive background) developed for MAJORANA by Paul Luke.
- Current performance (preliminary) <300 eV-FWHM (MAJORANA target = 1 keV).
- Technology transferred / modified by ULGeN in FY13 to **95 eV-FWHM**.

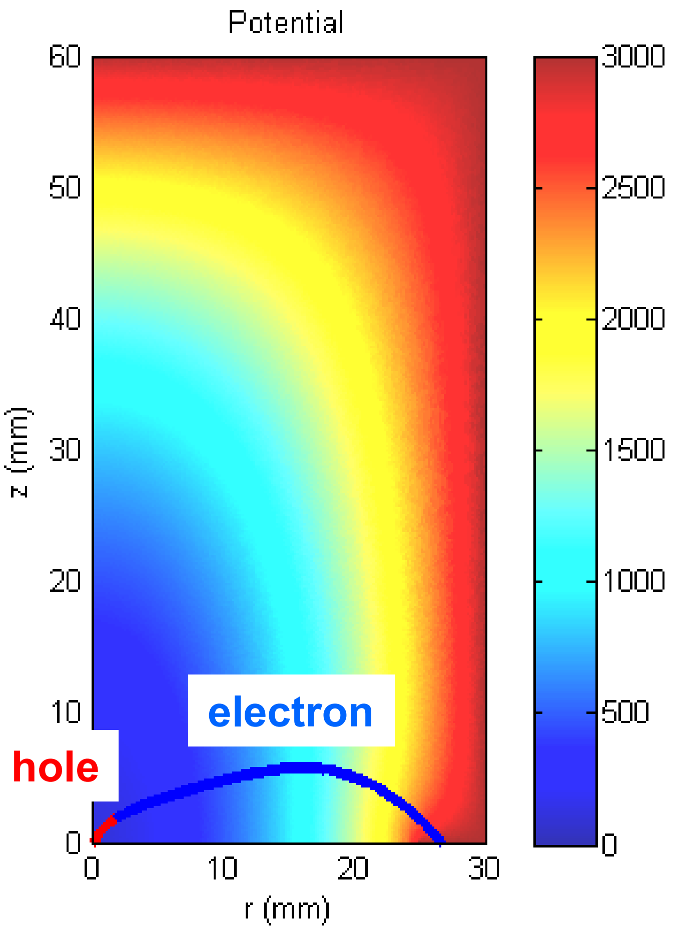


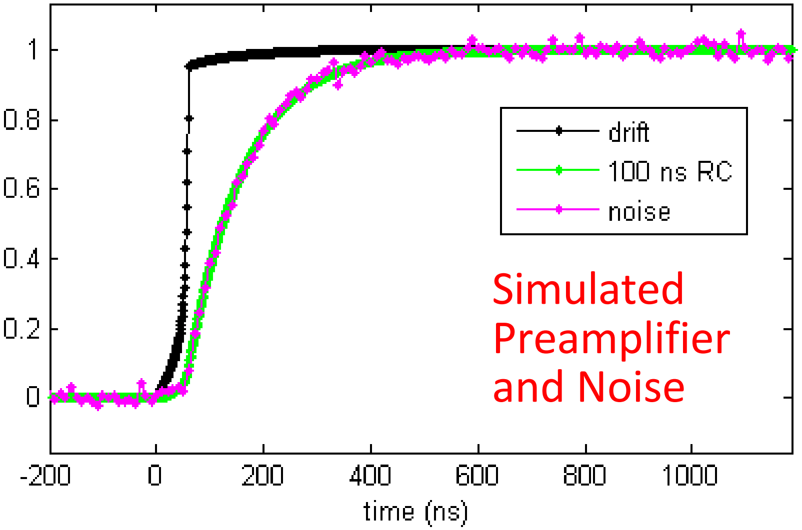


Mounted in Spring Clip

Progress: Signal Simulation

- In FY13, developed extensible / validated Ge signal **simulation framework**, based on COMSOL and MATLAB.





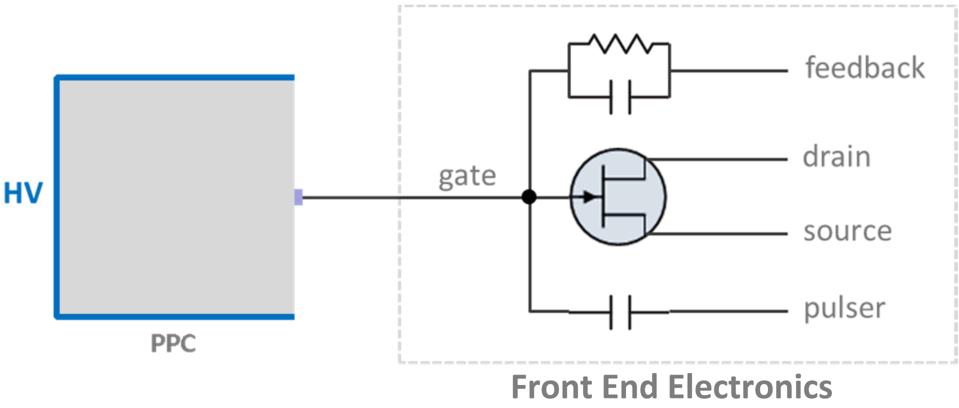
Simulated Preamplifier and Noise

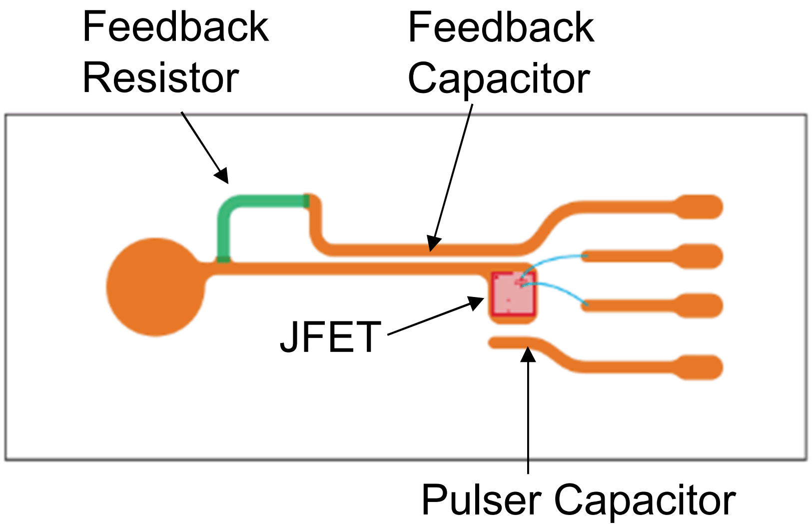
FY14 Additions to Framework:

1. Charge trapping
2. Lithium dead layer
3. Crystallographic dependence
4. Surface channels

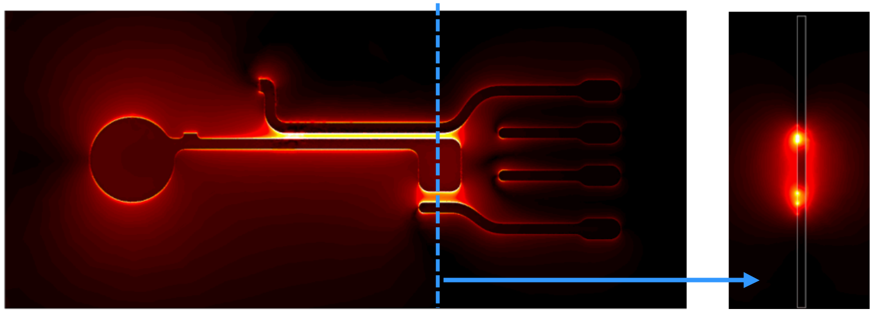
Low Mass Front End Concept

- **Goal:** Improve low capacitance charge amplification with minimum mass of radio-assayed materials. Take advantage of low temperature.

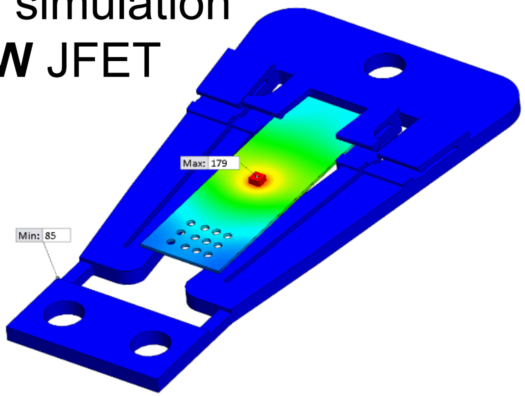




3D electric field simulation for extraction of **inter-strip capacitance** (5 fF accuracy)

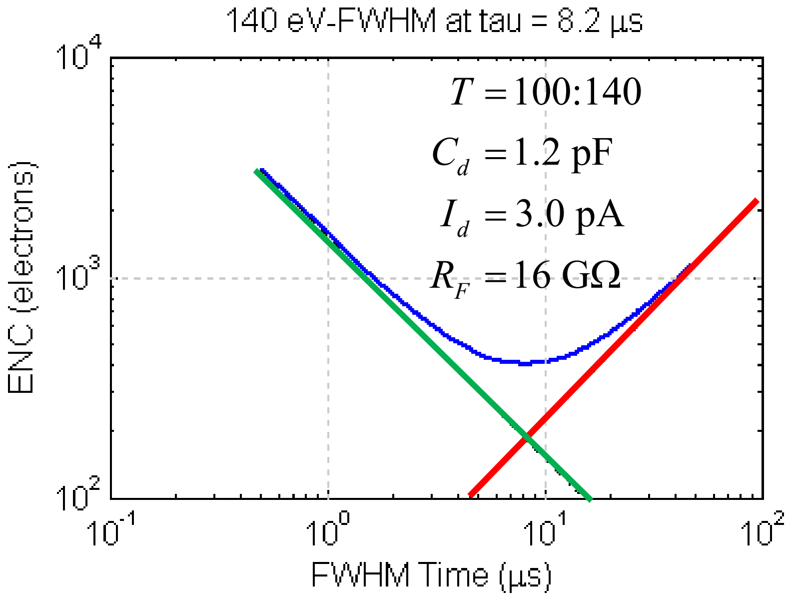


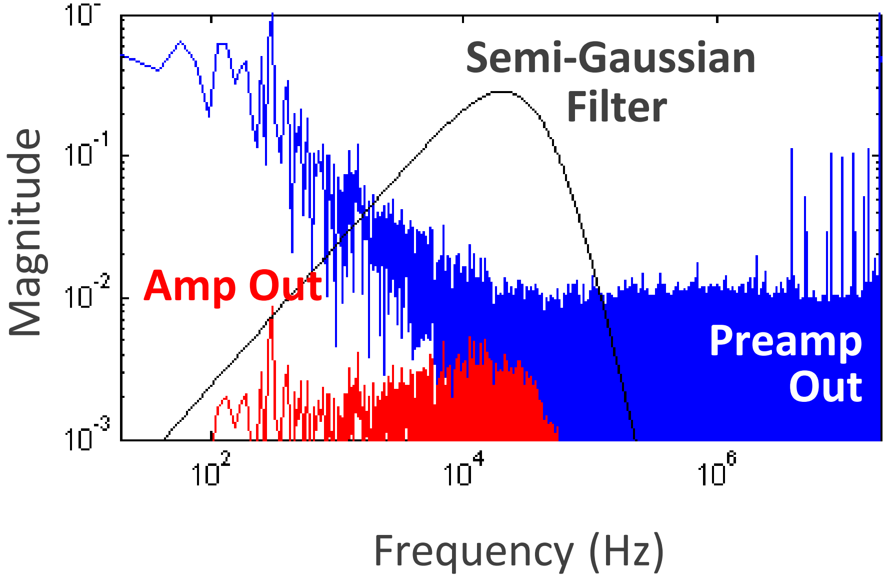
Thermal simulation of **20 mW** JFET power.



Challenge:
Electronic Noise Reduction

Tasks: Modify front end, crystal, cryostat, etc. to **lower ENC**.





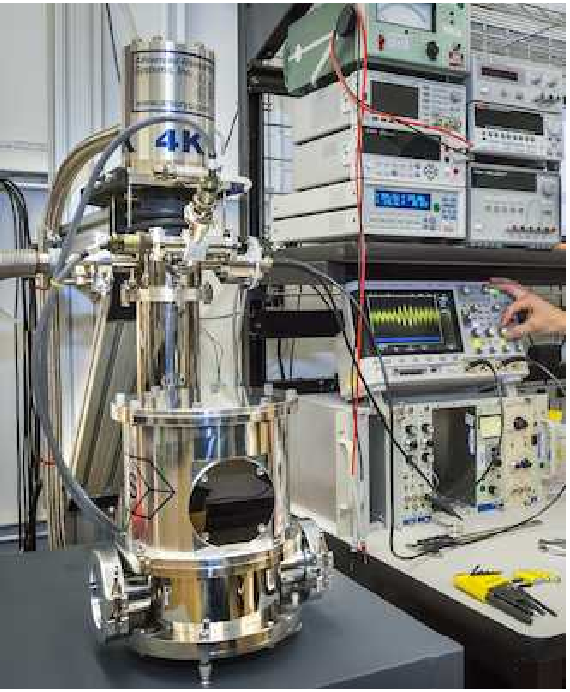
simple CR-RC Shaper

Voltage (series) **1/f** **Current (parallel)**

$$ENC^2 = Q_n^2 = \left(\frac{e^2}{8}\right)\left[\boxed{\left(\frac{4kT}{g_m} + e_{na}^2\right)\frac{C_d^2}{\tau}} + \boxed{4A_f C_d^2} + \boxed{\left(2q_e I_d + \frac{4kT}{R_F} + i_{na}^2\right)\tau}\right]$$

Cold Germanium

- LN-cooled cryostats for shielded deployment operate too warm (near 100 K) for PPC.
- At **lower temperatures**, Ge surfaces become more resistive, reducing leakage current.
- MOSFET voltage noise improves continuously from 300 K down to ~4 K.
- HPGe charge carrier mobility / velocity increases at temperatures below that of LN.



Operating at **7.8 K**

Relevant FY14-15 Tasks

1. 10 K ARS Cryostat (**NSSC supported**) delivered in FY14
2. Low vibration performance verified
3. Ge contact technology characterization (10-100 K)
4. Detector leakage current and capacitance reduction
5. MOSFET and JFET noise optimization at low temperatures

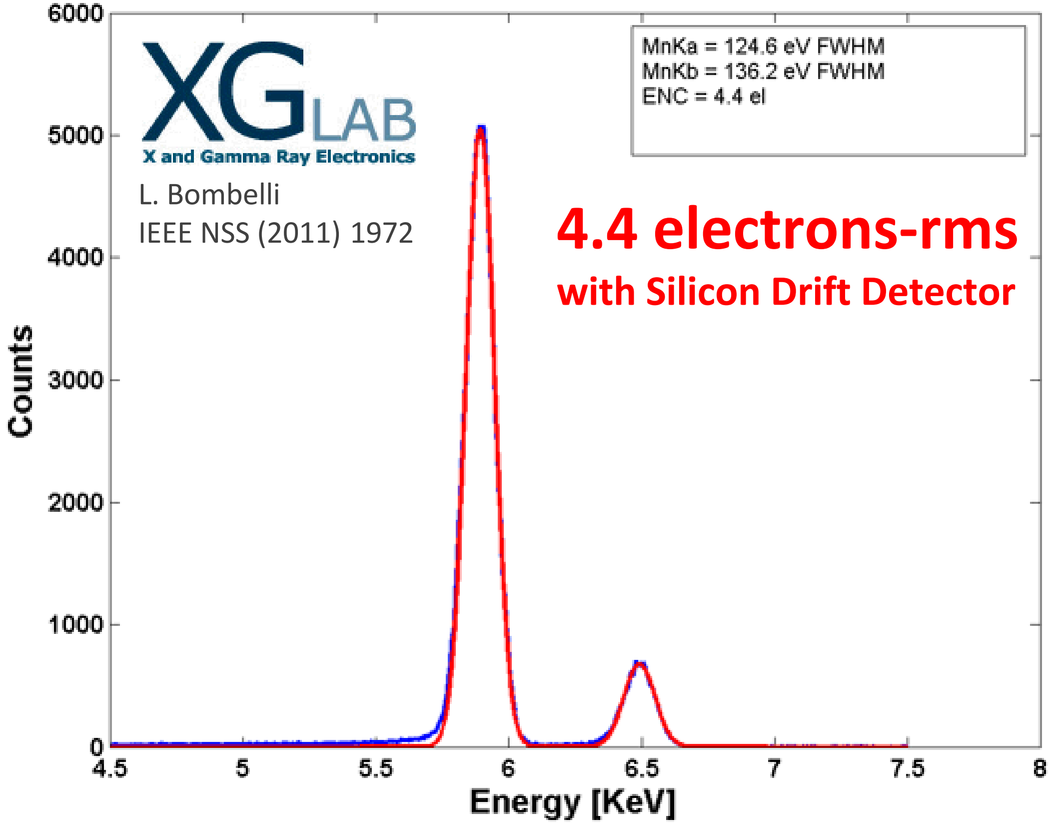
MOSFET vs. JFET

Investigating cold (10-80 K) CMOS options:

XGLab CUBE ASIC
Originally for SDD
Functional at 4 K

Pulsed-Reset
0.75 x 0.75 mm^2
3.4 electrons-rms alone

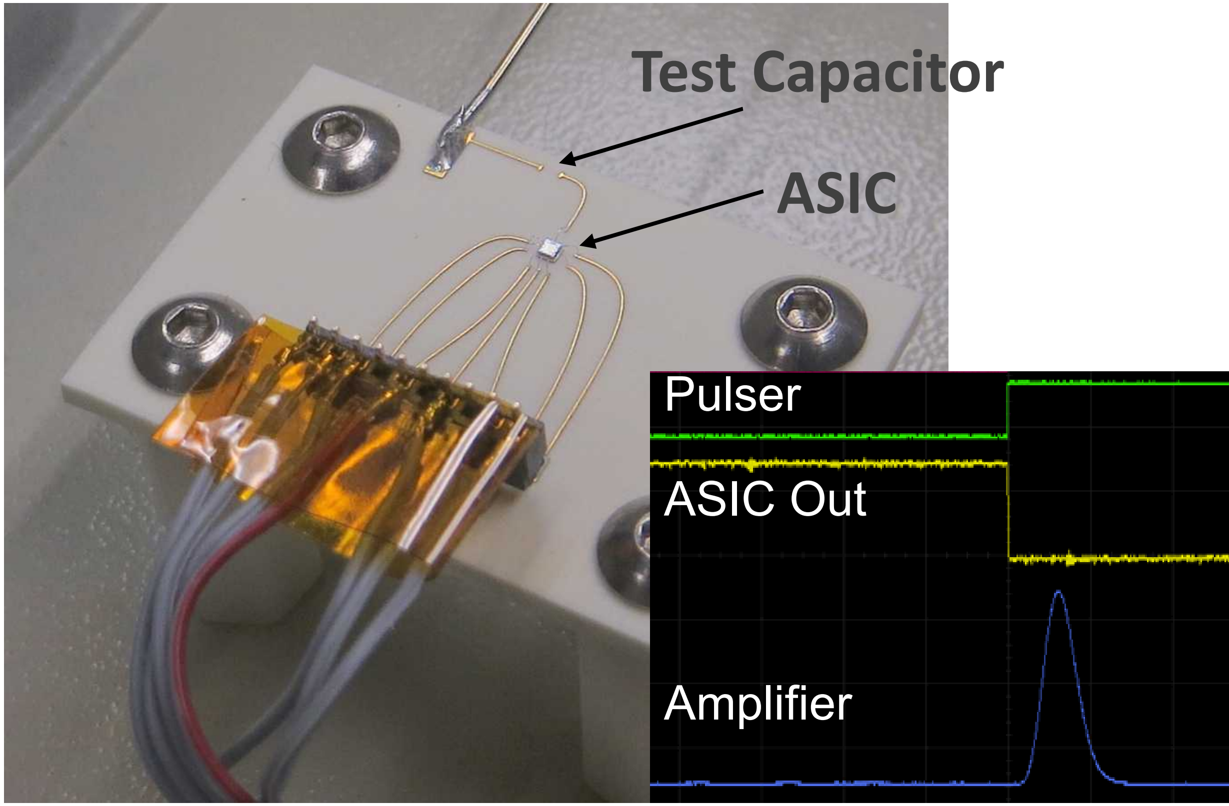
…would be 24 eV-FWHM in Ge,
for a safe threshold of 62 eV!



L. Bombelli
IEEE NSS (2011) 1972

4.4 electrons-rms
with Silicon Drift Detector

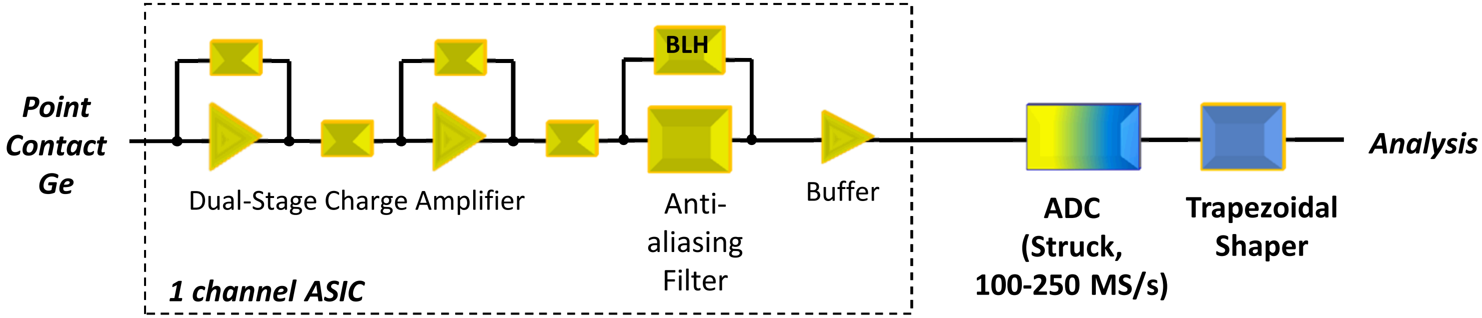
CMOS Integration



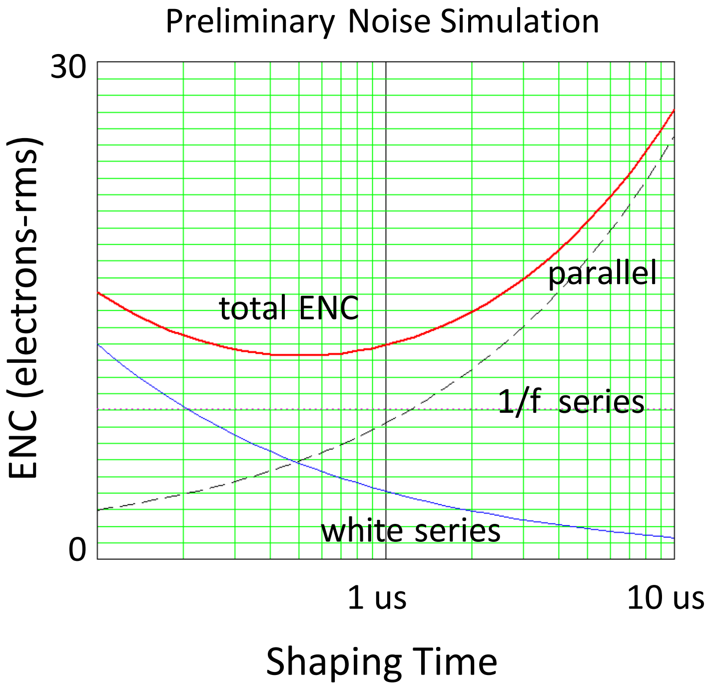
- Shielded test enclosure
- Bias board (filtering, pulse reset, buffering)
- CUBE ASIC mounted on low-loss PCB
- Integrated test capacitor (75 fF)

Optimizing filtering and grounding with XGLab support.

BNL Preamp ASIC for Ge

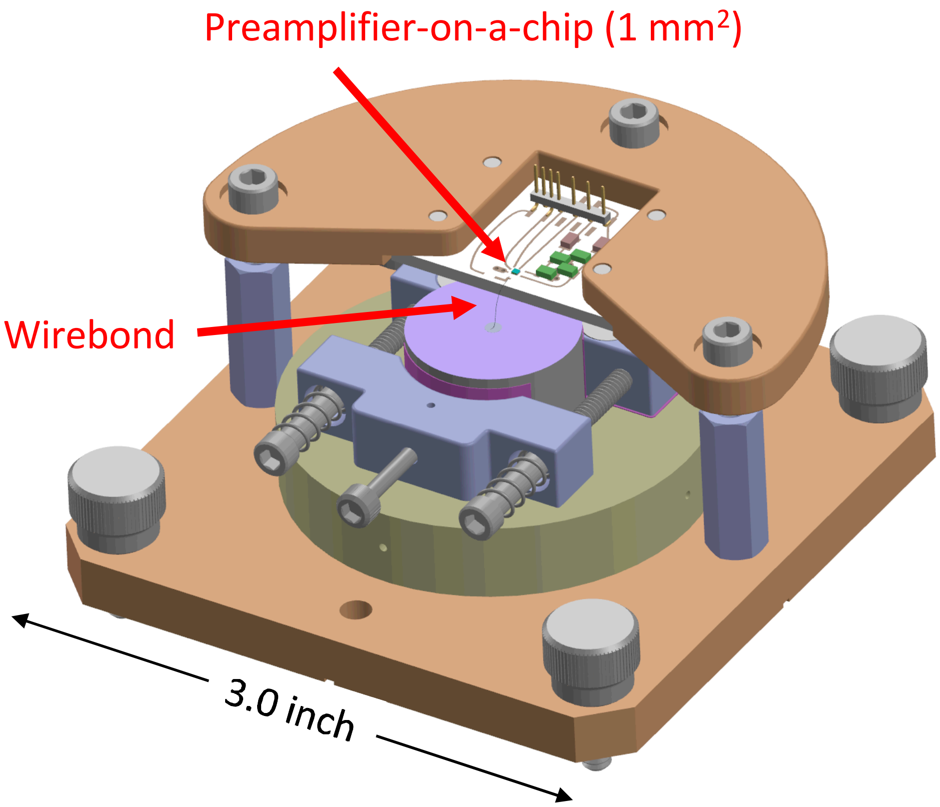


- Would like to evaluate multiple CMOS processes vs. temperature to identify lowest 1/f noise front end.
- Commissioned BNL to design an **ultra-low noise preamplifier ASIC** for low-capacitance point contact Ge detectors.
- BNL's specific expertise with ASICs for radiation detectors will enable custom features (shaping, BLR, driving long cables, etc.), opening up new physics frontiers with Ge detectors.
- Design and simulations started FY15Q2. Fabrication by end of FY15Q3.



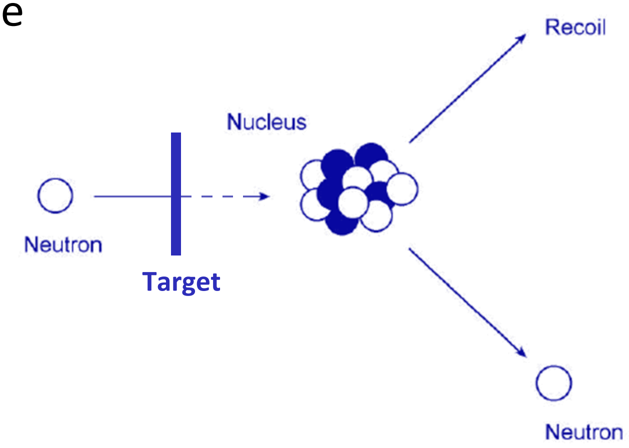
Wirebonded Point Contact Ge

- Wire-bonding provides robust access to a smaller (lower capacitance) point contact.
- Point contact size reduction ultimately limited by higher electric fields.
- Robust bonding guaranteed by previous stress tests in double-sided strip Ge.
- Opens pathway to **multiple**-point contacts for a position-sensitive PPC, improving surface event discrimination.



Neutron Detection

- Many of the nuisance particles in our CNNS region of interest (0.2-3 keVee = 1-15 keVnr) are in fact neutrons.
- By lowering the threshold of the large volume Ge PPC, we are enabling the sensitive direct detection of neutron-induced Ge recoils.
- It is now possible to examine an incoming spectrum of scattered neutrons for scattering or “absorption” notches, indicating the presence of an isotope.
- Simulation work is underway to determine detection and identification sensitivies for various candidate isotopes.



Summary and Future Work

- SNL actively engaged in collaboration to demonstrate **CNNS at the SNS**, with background measurements to validate ULGeN simulations.
- Demonstrated **95 eV-FWHM** JFET-based readout of 0.9 kg PPC at 101 K. Transformational noise threshold unlikely w/o exploratory research below.
- **Wire bonding** point contact to provide lower capacitance / noise. Low temperature (**10-80 K**) evaluation of CMOS charge preamplifiers from various foundries.
- Motivate need for **multi-point** contact Ge for gamma imaging and surface event discrimination.
- Explore applicability of Ge recoil (0.2-3 keVnr) detection for isotope identification from notches in a **scattered neutron** spectrum.