# From Concept to Field Deployment of Advanced Instrumentation for National Security

Gabriella Carini,
Director, Instrumentation Division

carini@bnl.gov
https://www.bnl.gov/instrumentation/

# Overview

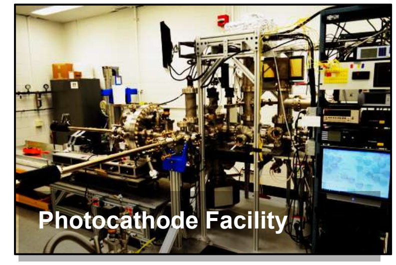
## R&D capabilities, synergistic developments, unique opportunities

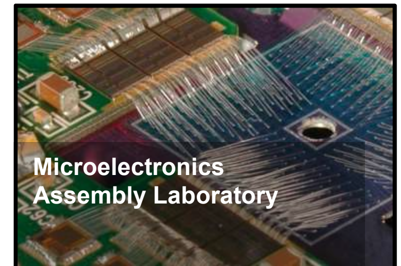
**Sensor Development:** Solid State (Silicon, Germanium, Diamond, Room Temperature Semiconductors), Noble Liquid & Gas, Liquid Scintillator

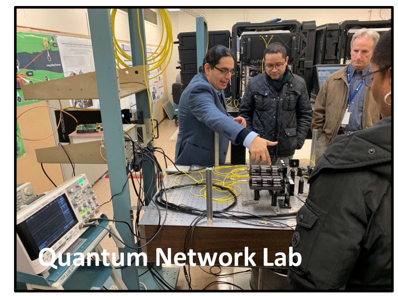
**Integrated Electronics:** ASIC Development, Signal Processing & Electronics, DAQ & Control Systems, PCB Design, High Density Interconnects

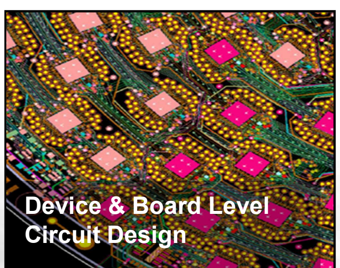
**Systems Development**: Mechanical (Engineering, Fabrication, and Integration), Electrical (Engineering, Assembly, and Integration), Cryogenic & Quantum, Photocathode Systems and Electron Source Development

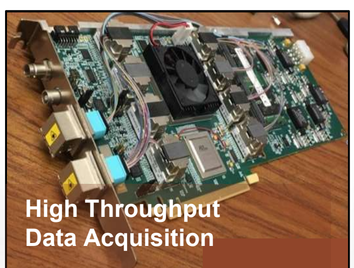
**Infrastructure & Facilities:** Sensor Fabrication & Semiconductor Processing Clean Rooms, Crystal Growth, Irradiation Sources, Ultrafast Lasers, Microscopy, Quantum Lab


Photocathode Facility


Microelectronics Assembly Laboratory

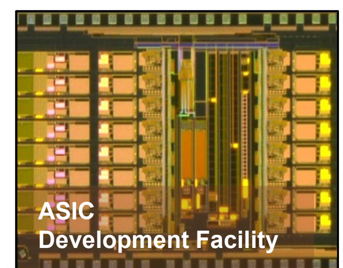

Quantum Network Lab


Device & Board Level Circuit Design

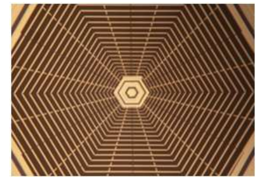
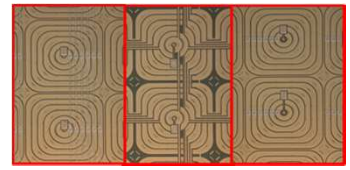
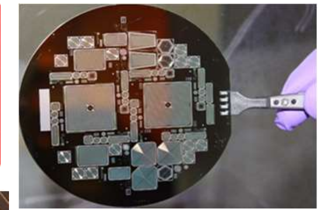

High Throughput Data Acquisition


CCD Detector Assembly & Testing

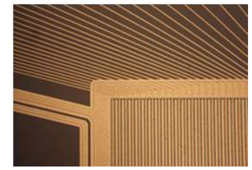
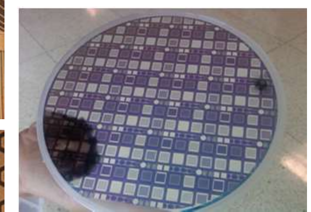

Si Sensor Development Lab


ASIC Development Facility

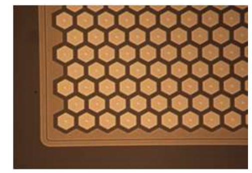
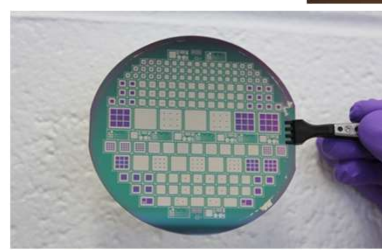
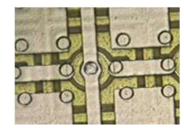
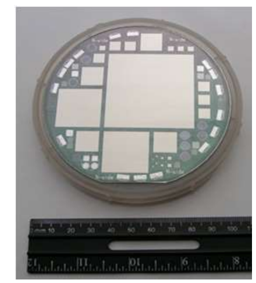
# Silicon sensors

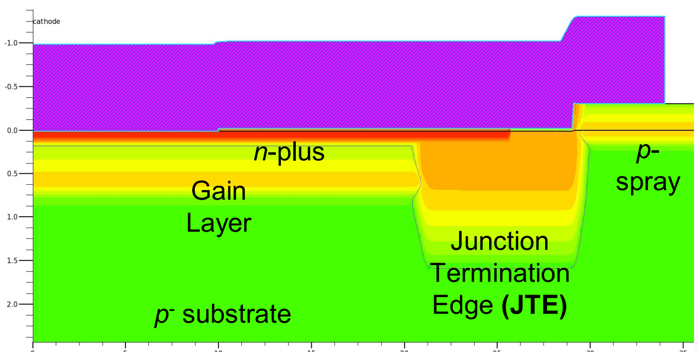




***Design, simulation, fabrication, testing, analysis***

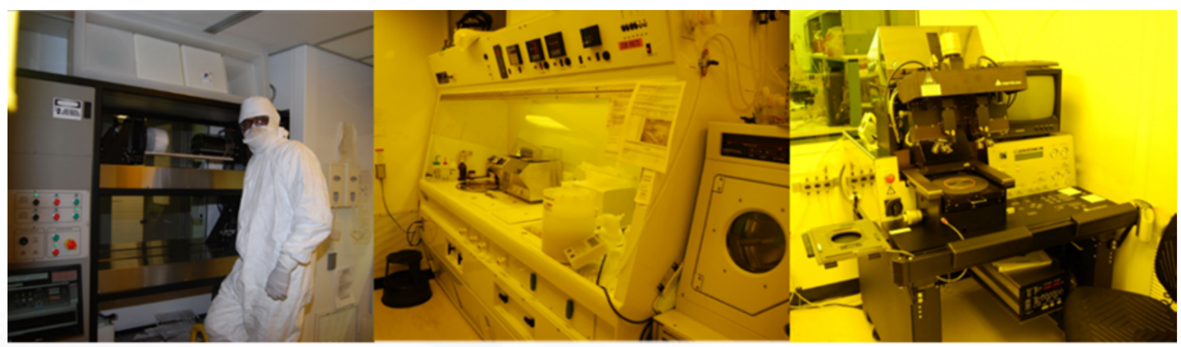




- SDDs: single element and arrays.
- Strips  and microstrips.
- Pixel Array Detectors (square, hexagonal, etc.)
- Active/monolithic pixel detectors (XAMPS, monolithic-SDD, LGAD, etc)
- Low Gain Avalanche Detectors (LGAD)
- Active edge sensors
- Engineered entrance window (nanostructure)




**LGAD simulation**

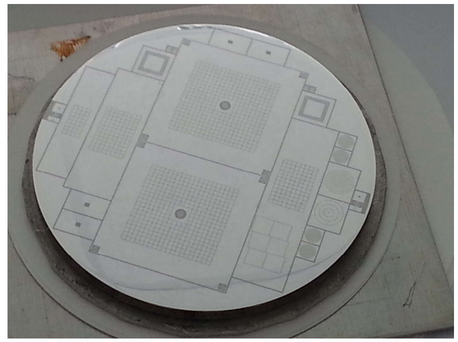


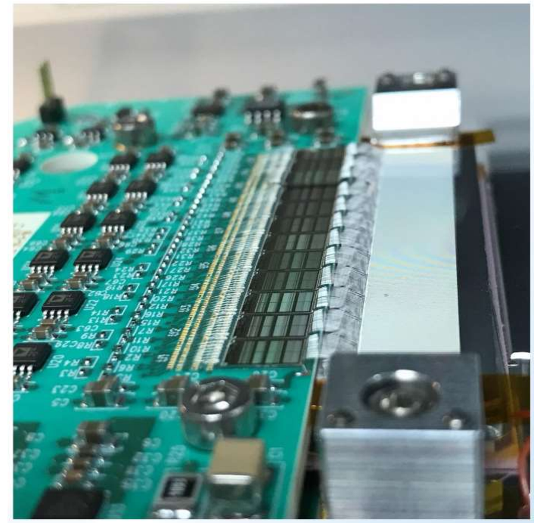
**Pictures of the class-100 Clean room for the silicon processing.**

# Other sensor materials

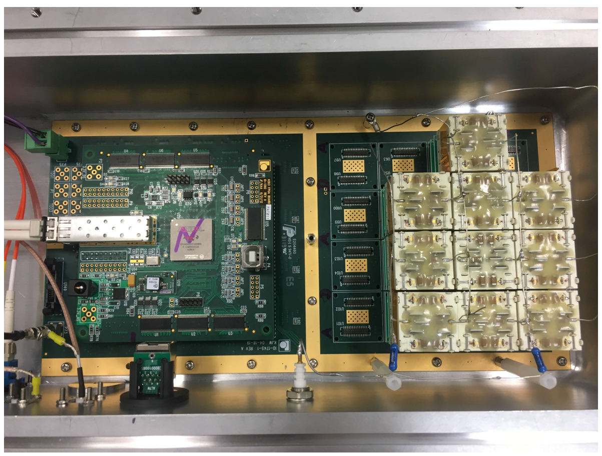
*Design, simulation, fabrication, testing, analysis*

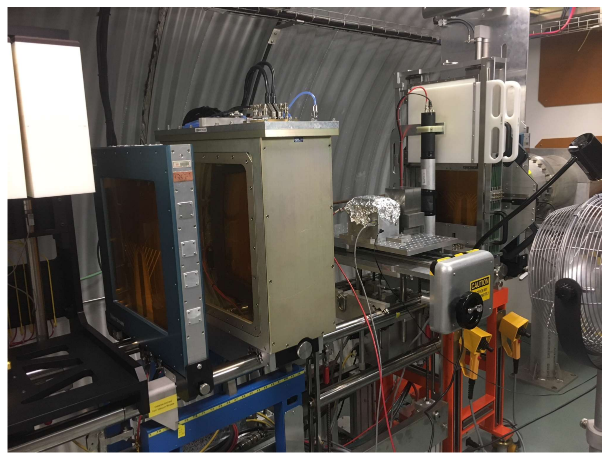
Germanium: strip and pixel
Diamond: quadrant and pixel
Room Temperature
Semiconductors: CdZnTe
Amorphous Selenium



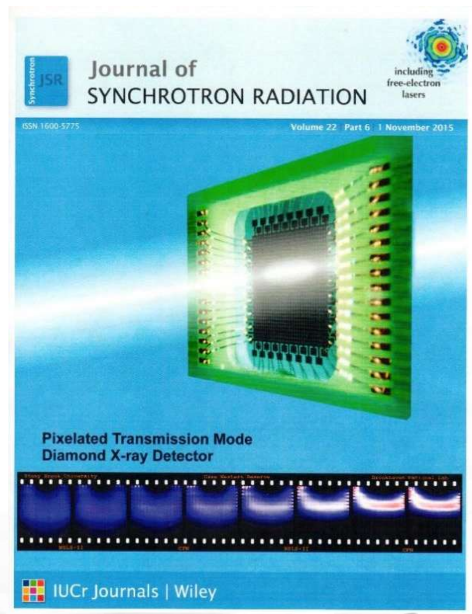


384-strip germanium detector wire-bonded to 12 MARS ASICs





Left: Integrated 10-module CdZnTe calorimeter prototype
Right: CdZnTe detectors in a radiation beam line at NSRL



# Application Specific Integrated Circuit (ASIC)

## Expertise in low-noise, low power, large mixed-signal designs

- hand-in-hand work with in-house TDAQ, PCB, Sensors groups

## Design tools and methodologies

- industry-standard tools for interoperability between analog and digital designs for final tape out (analog on top or digital on top)
- *analog, digital RTL2GDS, library characterization (customs standard cell libraries for handling designs for extreme environments, i.e. cryogenics and radiation),verification, device modeling*
- *f*oundry PDK's: standard and specialized processes
- access to foundries via services and directly

## Low-noise and low-power

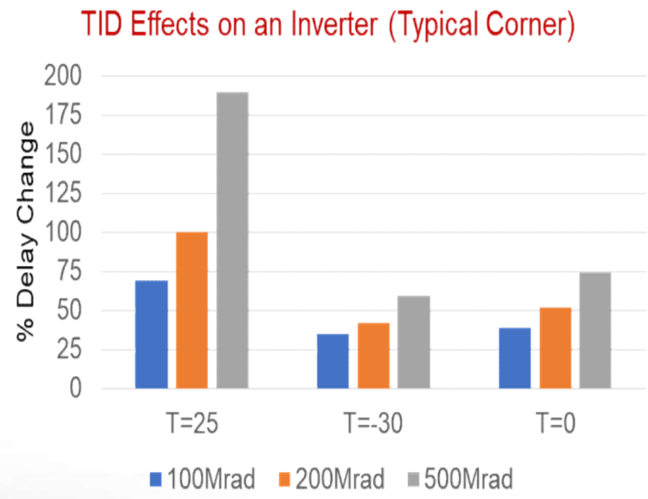
- custom analog front-end matched to a specific sensor
- front-end circuits optimized for amplitude & time-resolution
- data, event driven or zero-suppressed readouts

## Cryogenic operation

- liquid Noble gasses TPCs readouts
- long lifetime reliability

## Radiation-Hard

- immunity to TID, NIEL and SEE effects




Collaborations with academia, national labs, and industry

# Application Specific Integrated Circuit (ASIC)

Hybrid-pixel detectors

- counting and spectroscopic detectors for BES photon science, NNSA applications

3D-IC and High-Density Interconnect

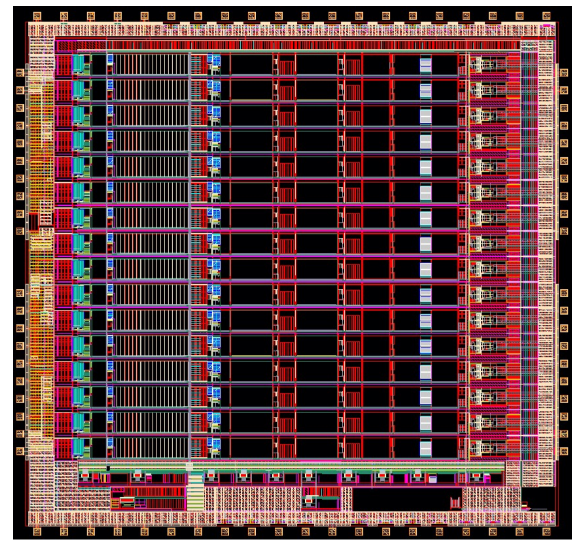
- edgeless and gapless, highly granular pixel detectors with extended functionalities

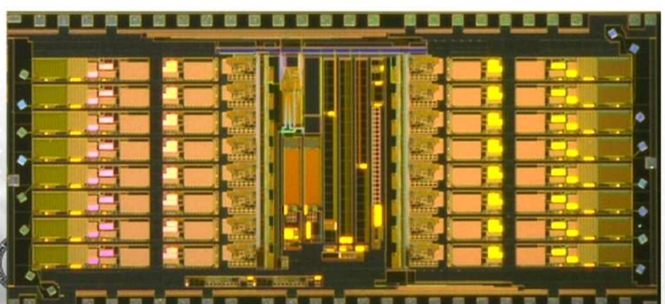
Monolithic Active Pixel Sensors

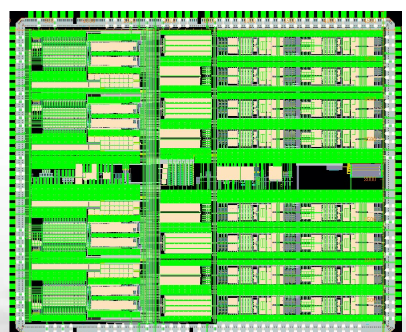
- on HR, thick substrate with full CMOS capability and built-in charge-signal processing

## Emerging technologies

- Quantum Information Science and Technology
  - Control and readout electronics
- High speed electronics for optoelectronic applications
  - High speed switches, DACs and high voltage amplifiers
- AI, Machine Learning for Neuromorphic computing
  - On detector imaging extraction
  - Towards non Von-Neumann architecture







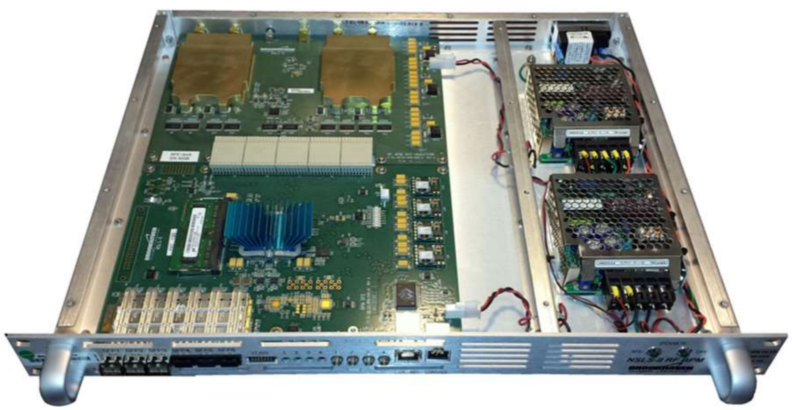
BROOKHAVEN NATIONAL LABORATORY

# Controls and high throughput data acquisition

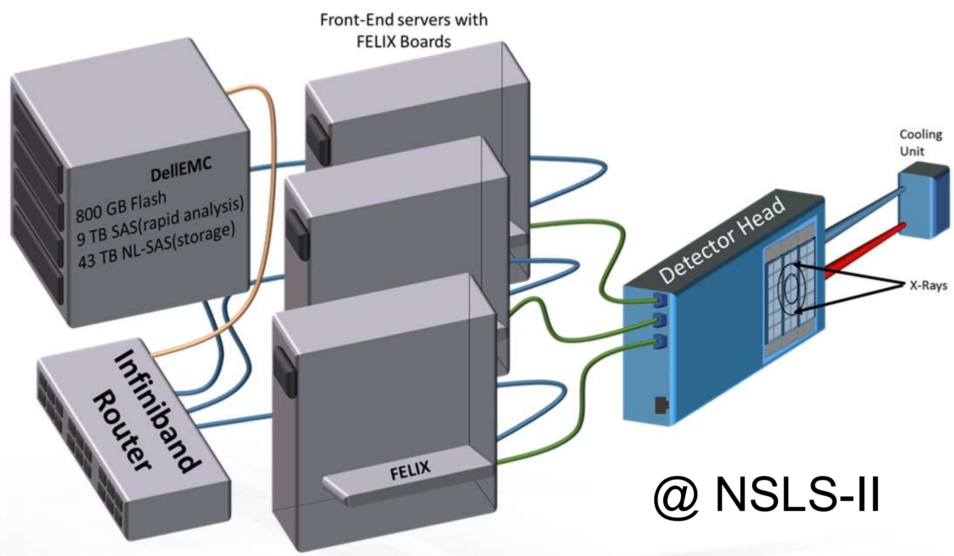
•Factorize front-end electronics from data handling with compact, high-density, scalable, low maintenance, easily upgradeable, commodity-based solution

•Field Programmable Gate Array (FPGA) and system integration experts, highly integrated system level data acquisition systems.

•High performance data acquisition, digital signal processing and data collection. Advanced applications for Nuclear Physics, Particle Physics, & Photon Sciences



eBPM & xBPM electronics



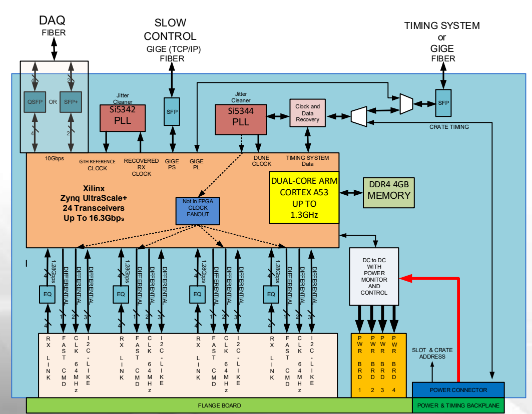

@ NSLS-II

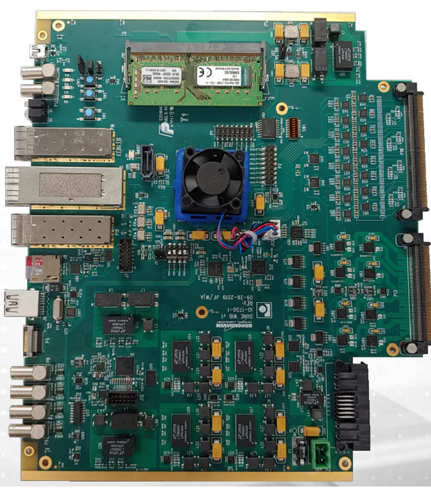
VIPIC readout concepts

# Examples of advanced control boards

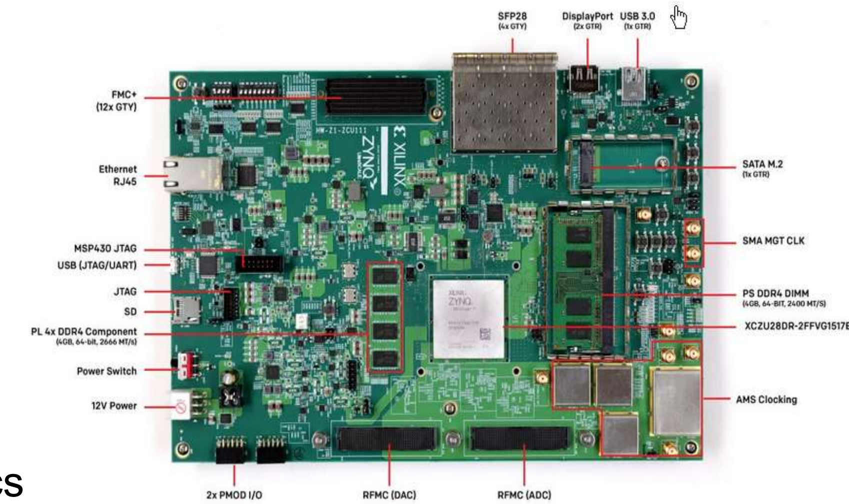
## DUNE Warm Interface Board

- Data streaming and control board for DUNE liquid argon based Time Projection Chamber (TPC)
- Xilinx Zynq Ultrascale+ ZU9EG
- Quad-Core A53 and Dual-Core R5 processors
- Four bidirectional optical links up to 40Gbit/s
- Sixteen 1.25Gbit/s links with external adaptive equalization
- Two TCP/IP Gigabit Ethernet  for system diagnostics and control
- Twenty DC/DC converters with voltage and current monitoring for DUNE cryostat electronics power



## Xilinx Zynq UltraScale+ RFSoC ZCU111



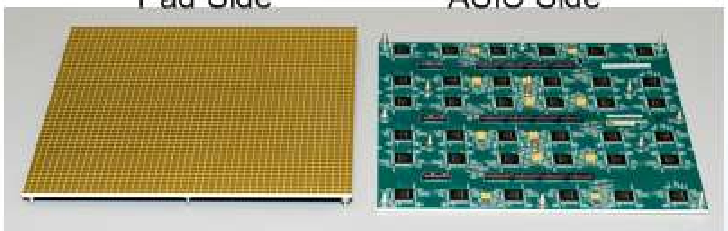

### *RFSoC ZCU111 board*

- Eight 12-bit 4.096GSPS ADCs and Eight 14-bit 6.554GSPS DACs.
- Quad-Core A53 and Dual-Core R5 processors.
- Xilinx XCZU28DR-2FFVG1517E FPGA.
- Flexibility of sampling the ADCs either using the external Phase Locked Loop (PLL) or internal PLL.
- 1GbE and 100 GbE UDP Ethernet Interface.

# 2-dimensional neutron detectors

## Inside the Detector – the Pad Board

Pad Side ASIC Side

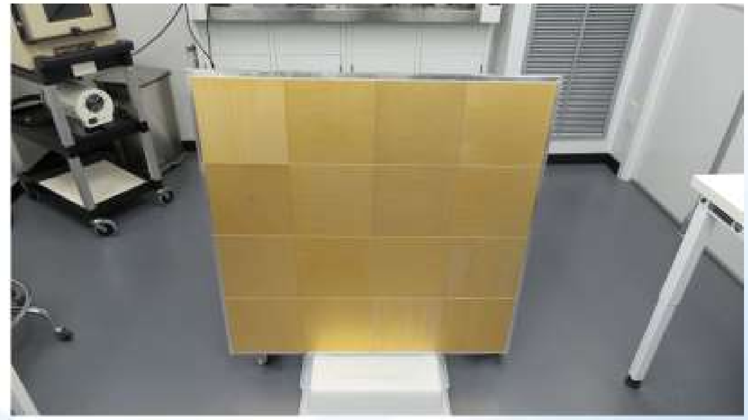


- Pad size: 5mm × 5mm
- Pad board: 24cm × 24cm
- # pads: 48 × 48 = 2304
- # layers: 11
- Board thickness: 2.8 mm (0.011")
- ASIC 64 channels
- # ASICs 36

There are 16 of these boards, in a 4 x 4 array, in the final detector. This represents a 192 x 192 array, or 36,864 channels



16 pad array: heart of 1m x 1m detector



Channels: 16x(48x48) = 192x192 = 36,864



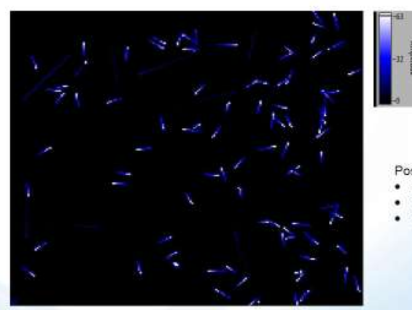
## Assembled Detector

Front of detector

Rear of detector



Several hours of operation in absence of neutron source.
Full 1m x 1m area, 192 x192 pads



Color scaling reflects 6-bit digitization of amplitude of pad charge signal.

Possible phenomena:
- He recoils
- C recoils
- F(n,p) reactions

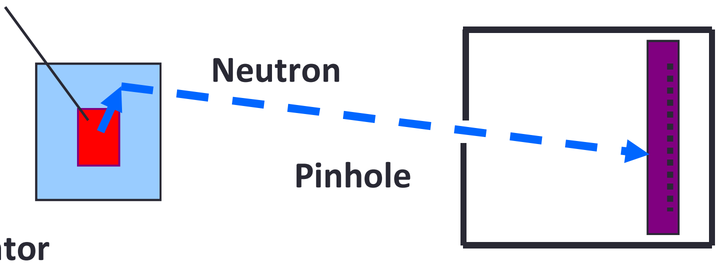


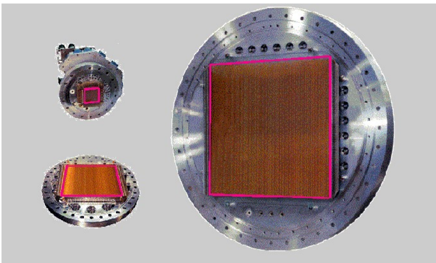
Quokka 20m long x 2m diam. vacuum tank

# Thermal Neutron Imaging concept for National Security

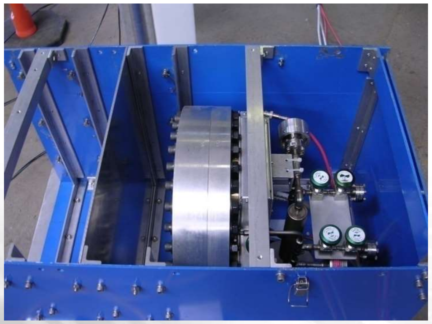
- Fast neutrons are emitted by neutron sources
- Some neutrons are moderated close to the source
- Un-scattered thermal neutrons can be used to form an image of the moderator, using a pinhole
- Many pinholes can be combined to increase efficiency in a Coded Aperture

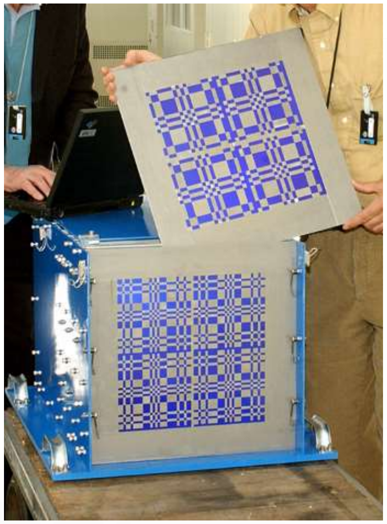
**n+ $^{3}$He → p+$^{3}$H +764 keV (25 × 10$^{3}$ electrons)**



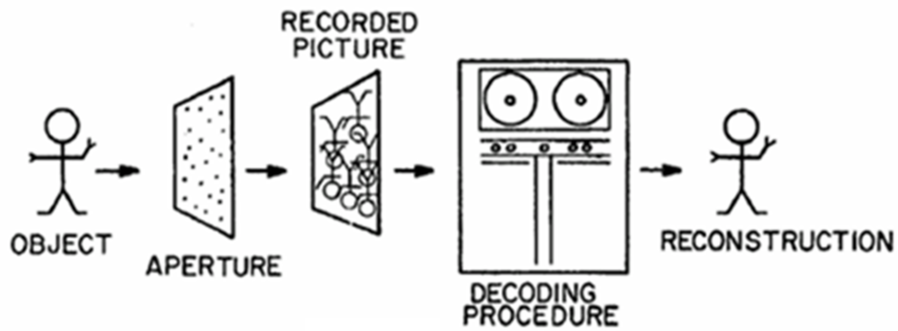
Position-sensitive $^{3}$He wire or pad detector





0.4 mm thick Cd masks on Al

*Coded aperture imaging of non-focusable radiation*

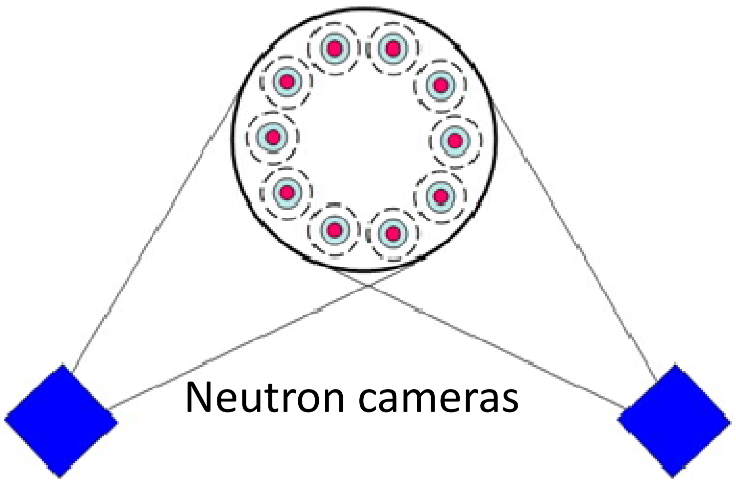



E. E. Fenimore and T. M. Cannon, Coded aperture imaging with uniformly redundant arrays. United States Patent 4360797 1980

# Thermal Neutron Imaging concept for National Security

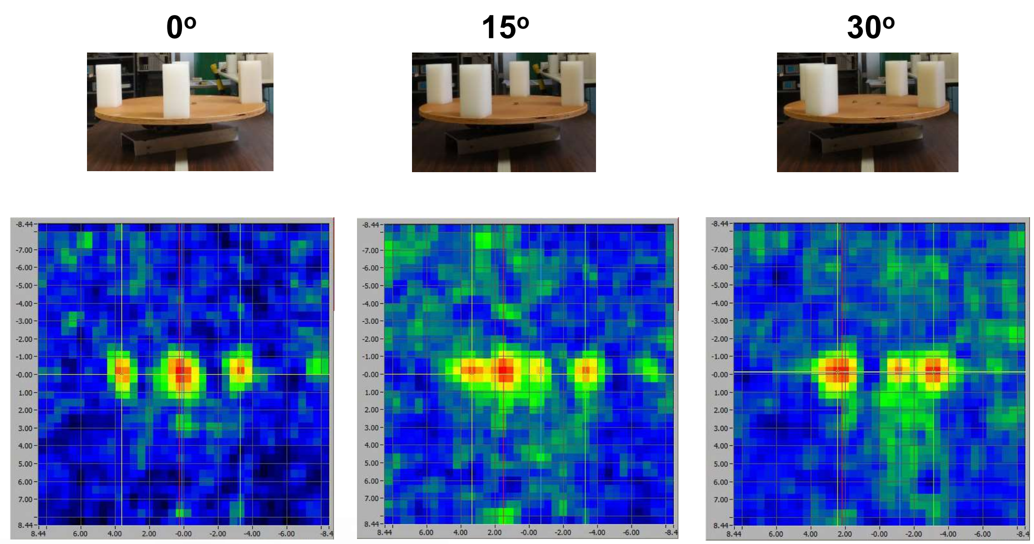
## Multi-view imaging in warhead counting

Sketch of a missile with warheads




- Multiple view (stereo or higher order) has higher accuracy and less uncertainty in resolving complicated structures
- It can resolve neutron sources which are blocked on one view only

four Cf-252 sources embedded in polyethylene blocks



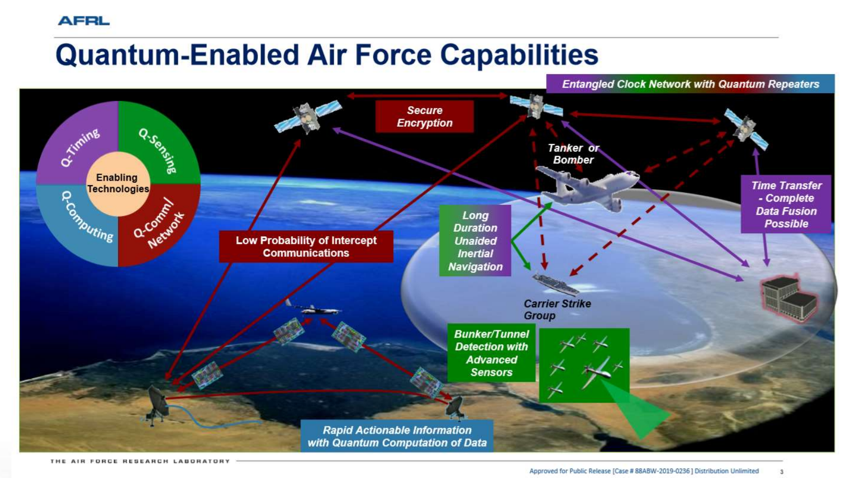

Stereo images

# Quantum Networks

**MOTIVATION**: secure communication

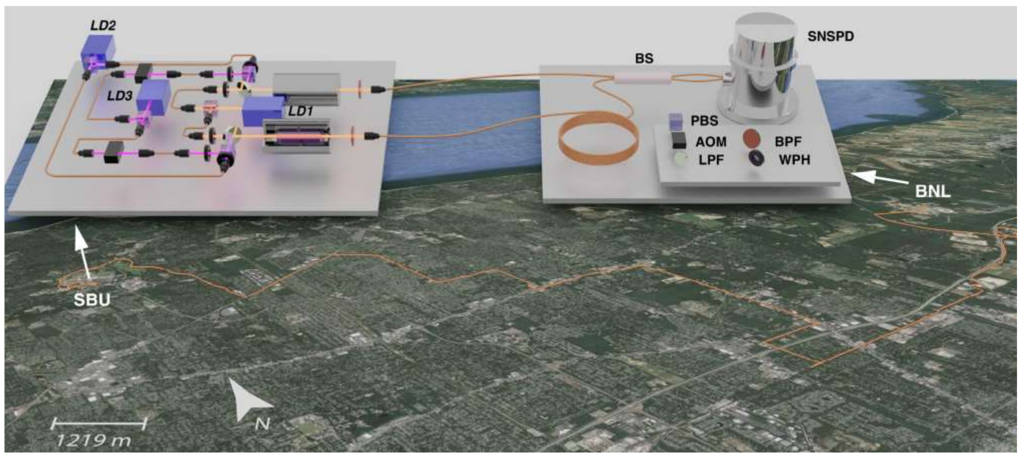
- *A quantum network provides the basis for*:
  - trading, personal data handling, transport and power grid security
  - secure position tracking
- *Quantum internet and the future of cybersecurity*
- Disruptive technology with tremendous scientific and economic impact.

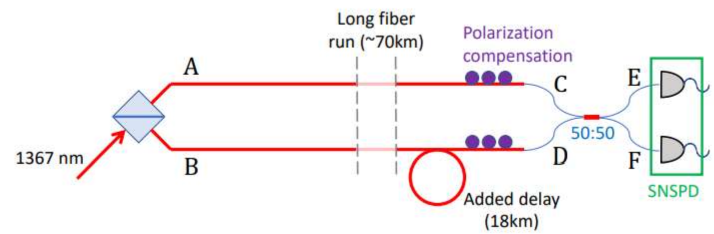
Drones have been used to send quantum internet signals
Hua-Ying Liu et al

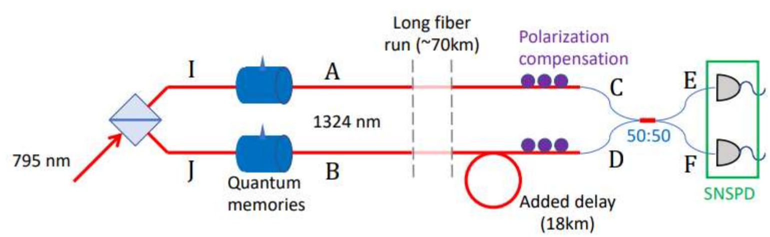



# An elementary 158 km long quantum network connecting room temperature quantum memories

arXiv 2101.12742 Figueroa *et al.*



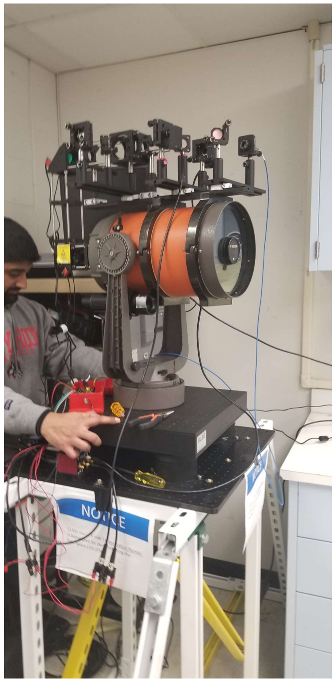




- LONG DISTANCE QUANTUM INTERFERENCE EXPERIMENTS
  - SINGLE PHOTON (SP) MACH-ZEHNDER INTERFEROMETRY
  - TWO-PHOTON (TP) HONG-OU-MANDEL INTERFEROMETRY

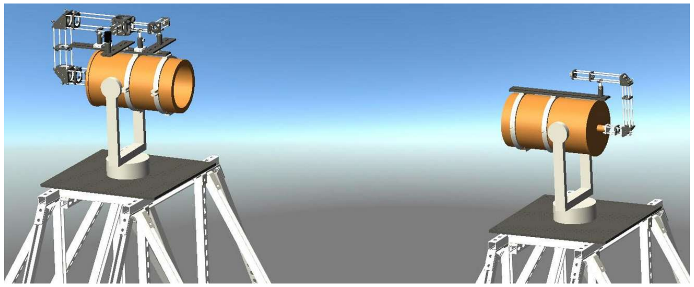
U.S. DEPARTMENT OF ENERGY

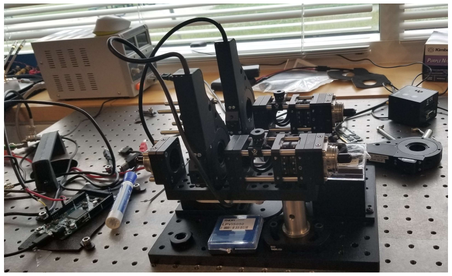
BROOKHAVEN NATIONAL LABORATORY

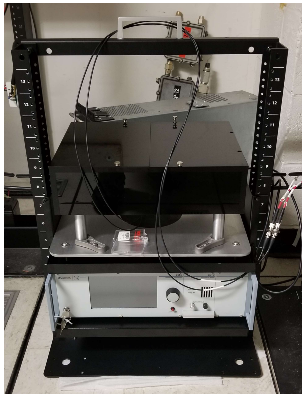
# Free Space Optical Link for Entangled Photon Distribution Over Long Distances



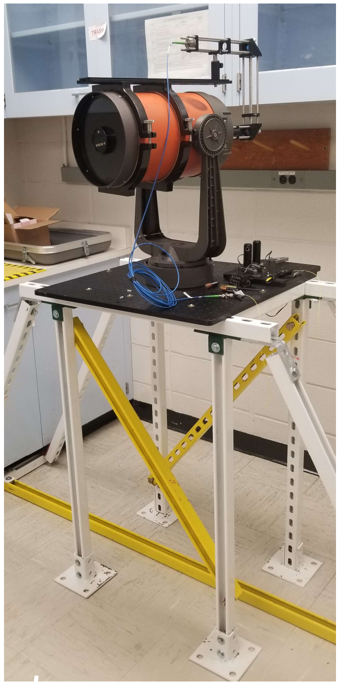
Quantum Receiver







Entanglement detection (left) and source (right)

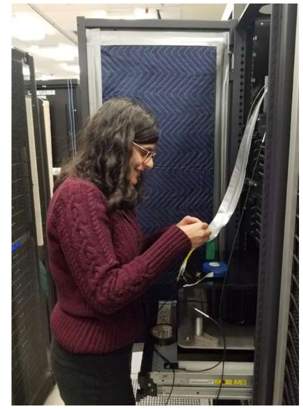


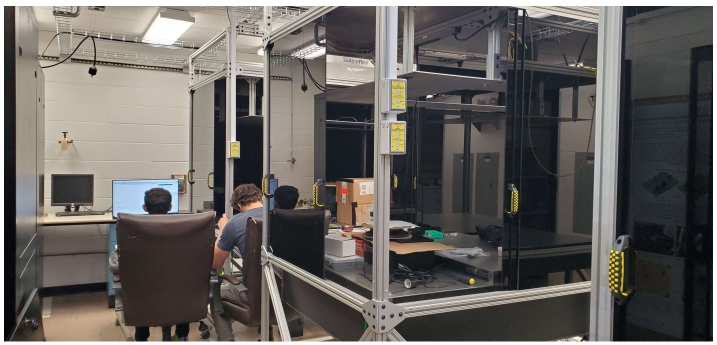
Quantum Transmitter

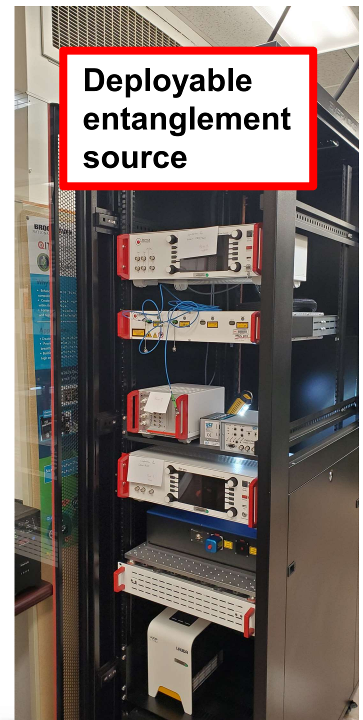

U.S. DEPARTMENT OF ENERGY

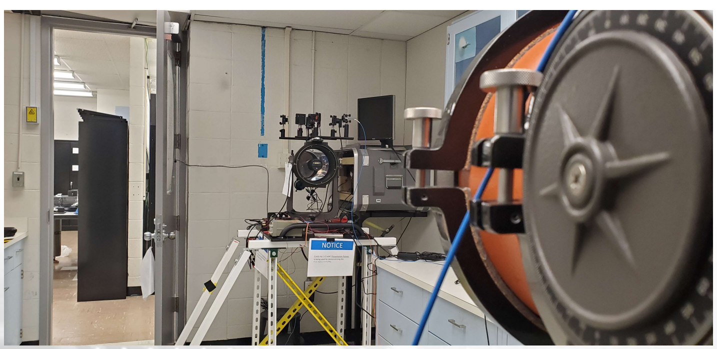
BROOKHAVEN NATIONAL LABORATORY

# A tour of the QIST lab







Portable laser rack with master and locking lasers

Quantum network, quantum lidar, quantum astrometry

# Summary

- *Instrumentation Division is a vibrant organization*
- *Broad set of capabilities*
- *Diverse portfolio*
- *Natural set for collaborations and interships*

# Questions?