Technology and Science: A two-way street

Gabriella Carini
…with contributions from many colleagues (BNL and other institutions)

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U.S. DEPARTMENT OF ENERGY

@BrookhavenLab

Scientific discovery is enabled by key technologies

"New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. **The effect of a tool-driven revolution is to discover new things that have to be explained**" (Freeman Dyson)

"Measure what is measurable, and make measurable what is not so" (Galileo Galilei)

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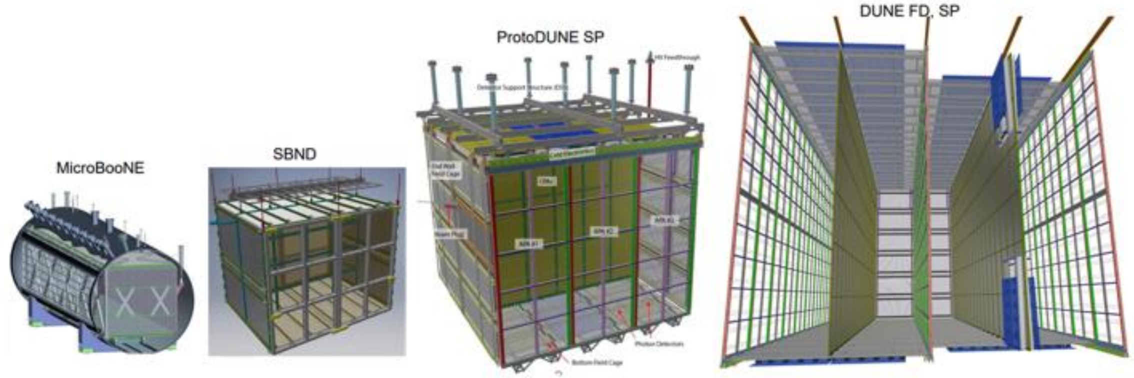
Adaptation from Fleming/Shipsey BRN report presentation

Each of these is a long journey…

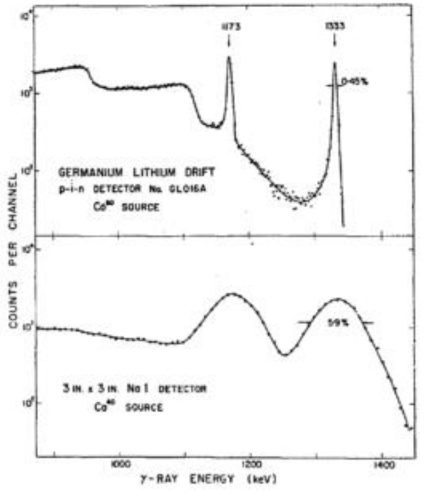


Select events in LAr detector technology development

- Germanium p-i-n detector, Tavendale (1963-4), gamma-ray and x-ray spectroscopy; first cold front end (JFET).
- Liquid Argon Ionization Calorimetry, Willis, Radeka (1972) → CERN ISR → ATLAS
- TPC , Nygren (1974), lasting impact from gas to noble liquid TPCs
- Herbert Chen, C. Rubbia, independently propose TPC with LAr (1977) → leads to ICARUS
- Herbert Chen, (1985) proposal for a large LAr TPC
- Uranium-LAr hadron calorimeter (…), first use of cold electronics (JFETs),(1986)
- Major realizations at FNAL(D0), HERA(H1), SLAC(SLD), (1985-1993)
- LAr, LKr EM calorimeter R&D for GEM/SSC and ATLAS/LHC (1989-1994)
- ATLAS LAr EM calorimeter (2004 -); high speed-high precision; highest confidence limit on Higgs (2012)
- Argoneut (2004); MicroBooNE (MB) proposal (2007) with cold electronics (JFETs);
- MicroBooNE; in 2009 decision to use cold CMOS (LARASIC); in operation 2015-2021;
- Technology selection for DUNE in 2011: LAr TPCs
- MB in operation for 4 years; protoDUNE rapid realization and successful test in 2018;
- Technology path open for DUNE …

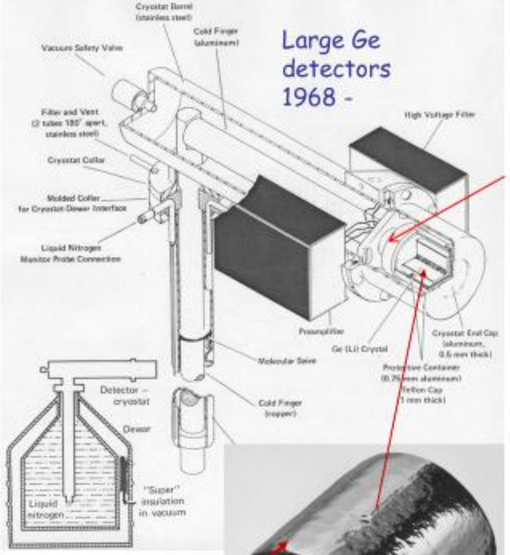
Courtesy of V. Radeka

1963 Germanium Detector Breakthrough

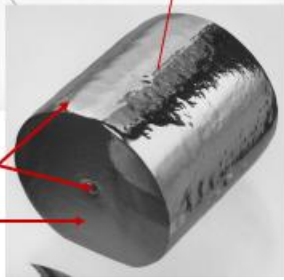


From: A.J. Tavendale (1963)

Large Ge detectors 1968 -



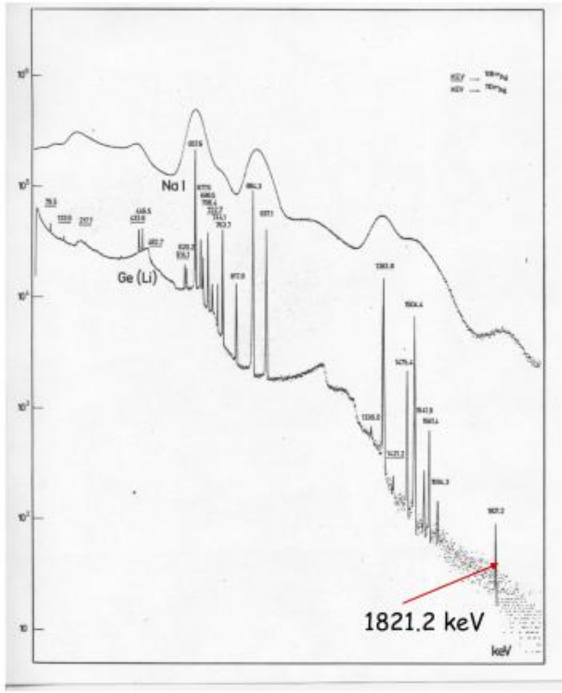
First cold JFET on a detector



Coaxial det.contacts

Ge-crystal ~50-100 cm³

Courtesy of V. Radeka



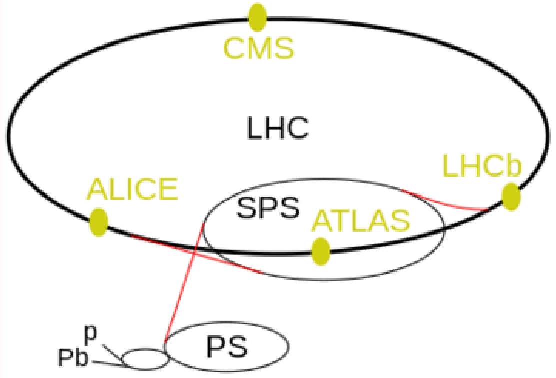
Comparison of Germanium with Sodium Iodide for gamma-ray spectrometry

Low noise electronics and signal processing (for gamma ray energy resolution of ~0.1%) developed for germanium detectors in ~ 1965-1972 provided the basis for later use of these techniques in particle physics, solar neutrino detection, x-ray and neutron detectors … **in LAr calorimeters and later in TPCs …**

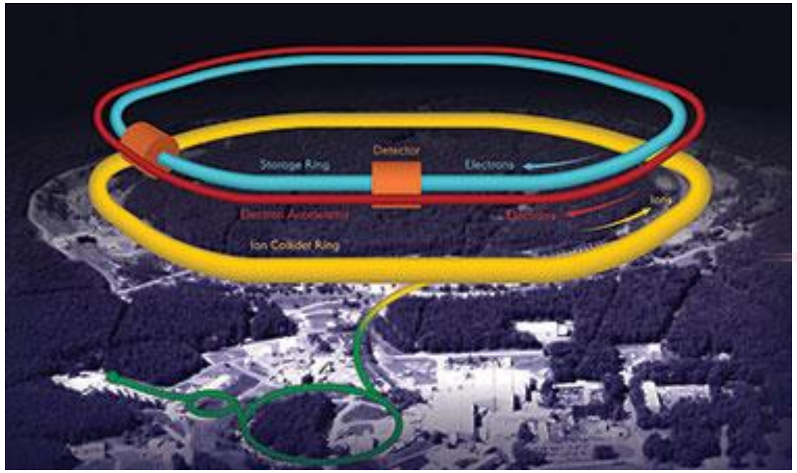
Courtesy of V. Radeka

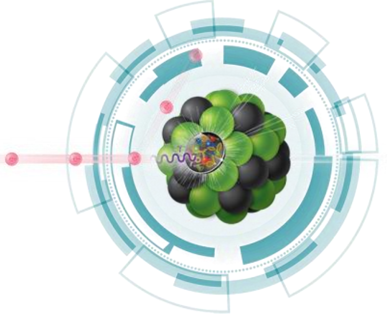
New facilities drive new developments

Large Hadron Collider (LHC) & High Luminosity LHC (HL-LHC), CERN

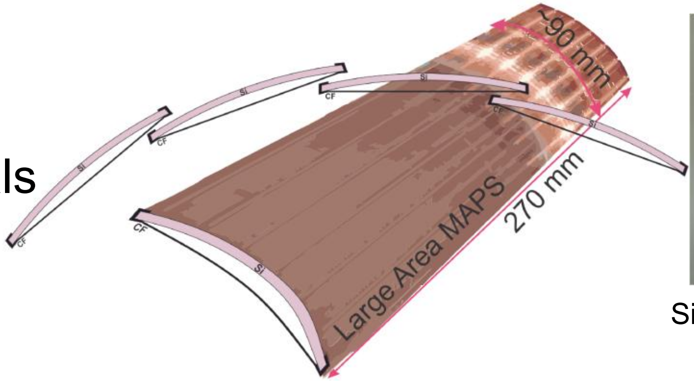


Relativistic Heavy Ion Collider (RHIC) & Electron Ion Collider (EIC), BNL





- Simulation tools (GEANT4, etc.),
- Extreme environments: radiation tolerance and cryogenics
- System integration: lightweight sensor/electronics and new materials
- High-granularity, timing and triggering
- Data deluge: flow, handling, and analytics (ROOT, Python, etc.).



Curved monolithic sensor stave made of stitched MAPS.

Silicon Genesis 20 μm thick wafer

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New technologies enable new capabilities

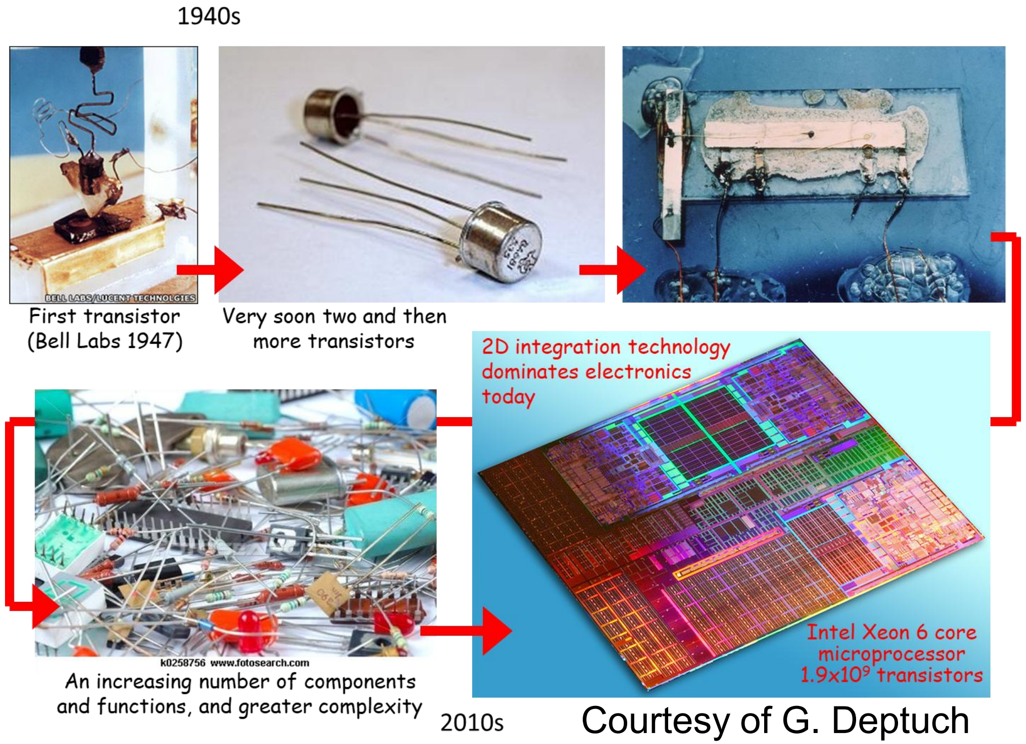
UBIQUITOUS!

- Low-noise, Low-power, Fast timing, High granularity, Functionalities, …

Extreme environments:

- **Radiation-Hardness** immunity to TID, NIEL and SEE effects:
  - process (inherent to process)
  - design (achieved through proper design techniques)
- **Cryogenic operation**
  - readouts for Noble liquid TPCs (long lifetime reliability)
  - spice-type models and characterization of standard cell libraries
  - RF electronics for quantum

Application Specific Integrated Circuit (ASIC)



Courtesy of G. Deptuch

Silicon photomultipliers

Progression as seen from the Nuclear Science Symposium

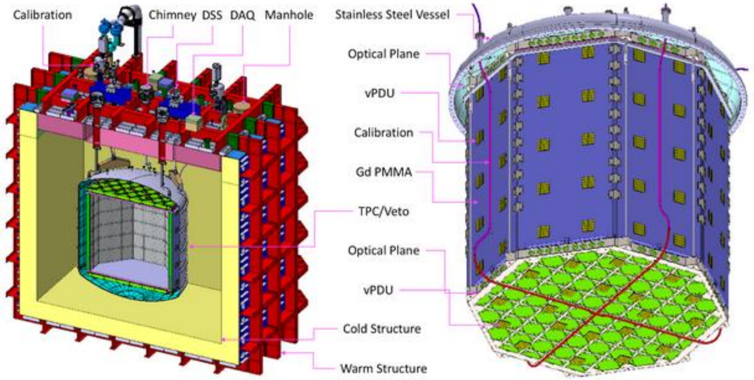
2005 Session on **Photodetectors and Radiation Imaging I**

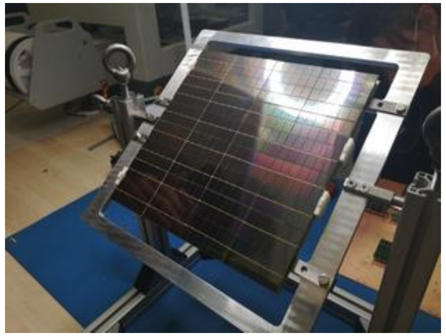
2015 Plenary - **Are SiPMs going to replace your PMTs?,** *Paul Lecoq*, CERN

2022 Plenary **- Adding a New Dimension to Photon Detection: 3D Integrated Single Photon Avalanche Diode Arrays**, Jean-Francois Pratte

2023 Workshops **The Digital SiPM Revolution: Opportunities, New Detector Concepts and Networking (SPAD)**

Challenges: large areas, extreme environments , VUV region



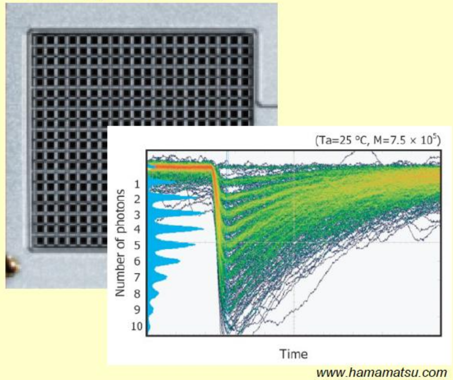


SiPM in liquid Argon for Darkside (https://www.lngs.infn.it/en/darkside)

Sensor evolution: bigger, faster, ultra-sensitive

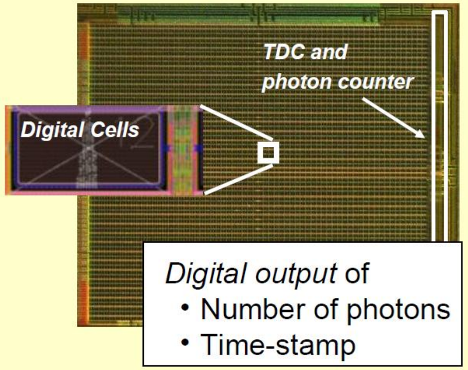
Silicon photomultipliers - SiPM

Analog SiPM



- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

Digital SiPM



- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

CsI scintillators with SiPMs readout for space applications

SensL Array 6 mm x 6mm quad SiPMs

Fully populated beam test hodoscope consisting of 24-element CsI:Tl CDEs.

Daniel Shy et al. "Development of a CsI Calorimeter for the Compton-Pair (ComPair) Balloon-Borne Gamma-Ray Telescope", arXiv:2307.11177 [astro-ph.IM].

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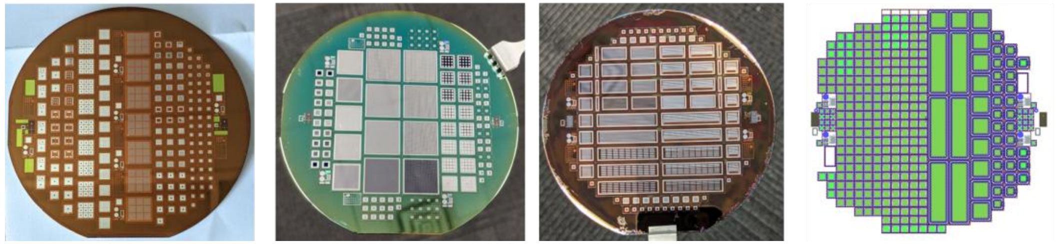
4D detectors – enabling technologies

Layout # 1:
- Based on first LGAD masks

Layout # 2:
- Larger devices

Layout # 3:
- ACLGAD strips

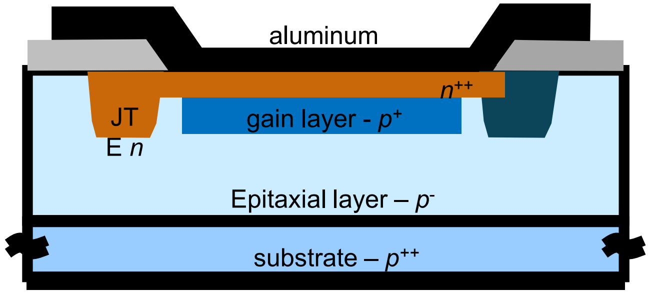
Layout # 4:
- ACLGAD for EIC ROC test



Low Gain Avalanche Detectors: combining timing and position resolution

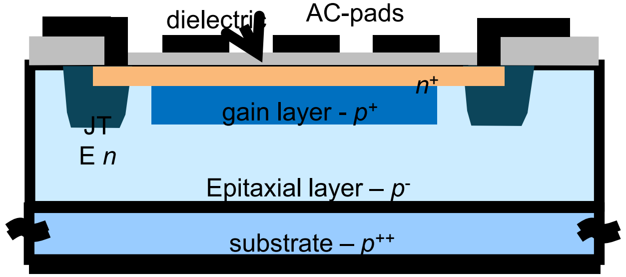
DC-LGAD on thin substrates

Thin substrates (~20-30um) lead to better timing resolution



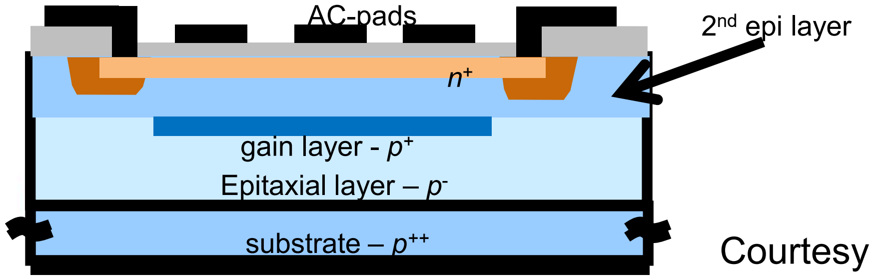
AC-LGAD

Excellent spatial resolution with smart position reconstruction algorithms, possibly for low interaction rates



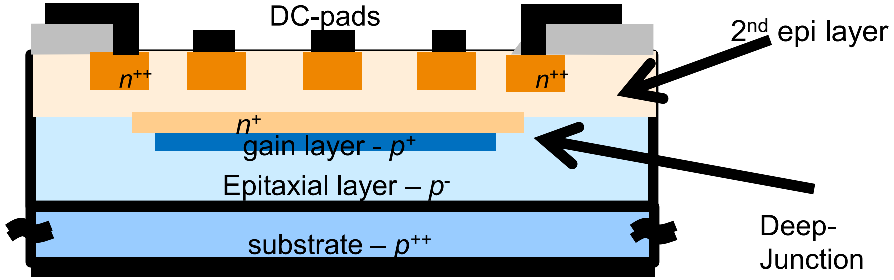
Deep-Layer AC-LGAD

AC-LGAD with a higher rad-hardness



Deep-Junction LGAD

Position resolution given by pitch, as in standard pixel/strip detector



Courtesy of G. Giacomini

How we come across (discover) new technologies? How do we decide what/how to use them?

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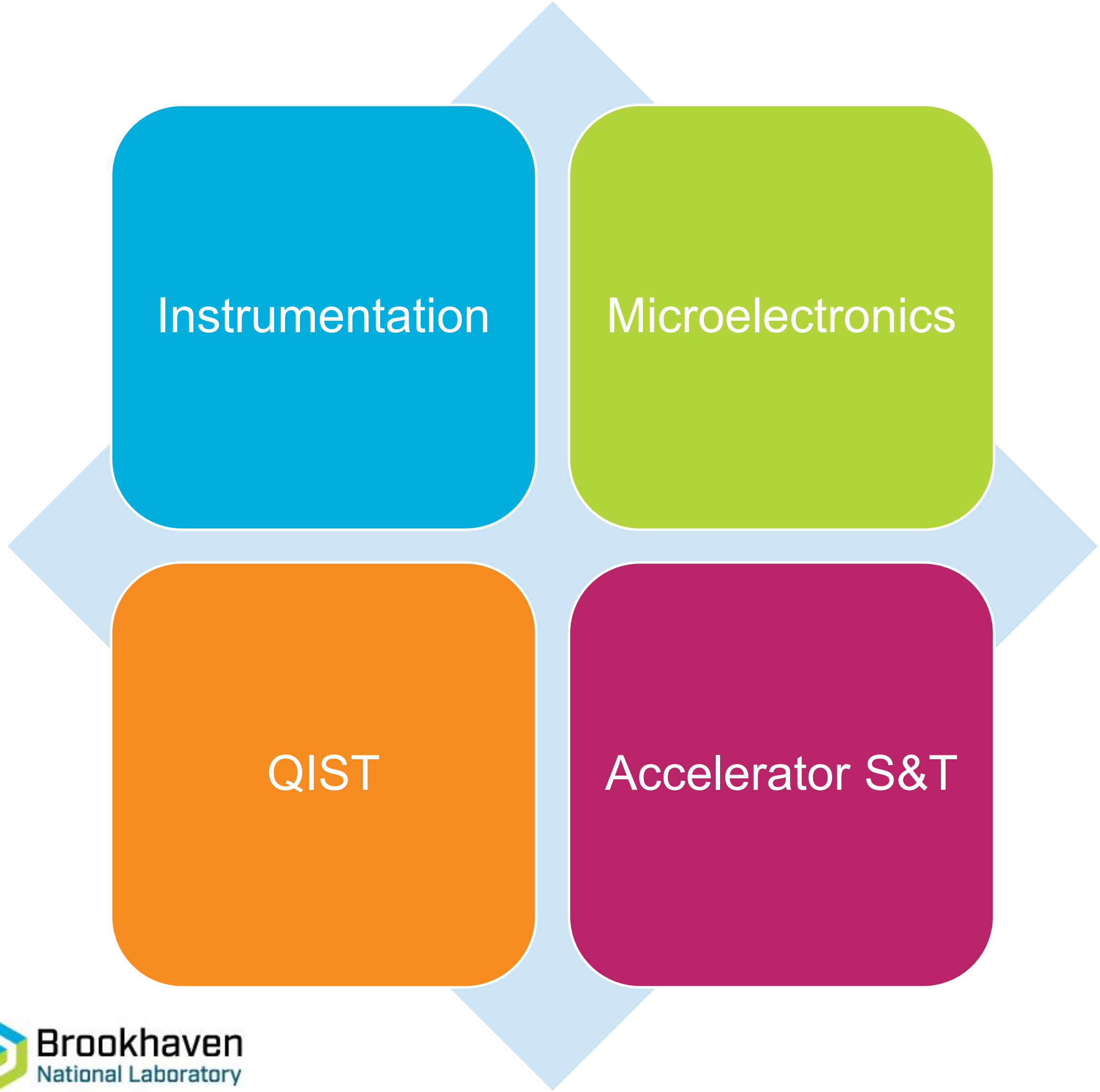
BNL’s Discovery Technologies Directorate



- Unified strategic vision in innovation
- Optimized model for crosscutting research
- Enhanced technological impact

Instrumentation Department

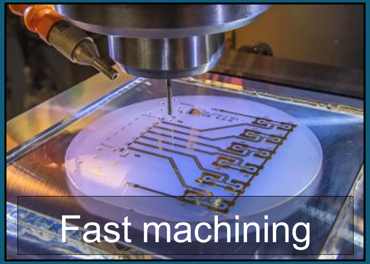
Strategic Thrust: extend capabilities and develop technologies to advance programs in science, energy, security, and industry

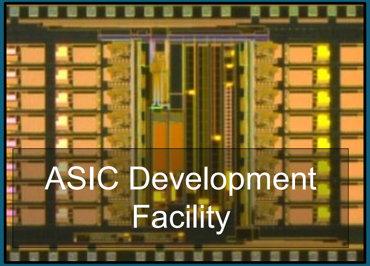
Key Capabilities: design, fabrication, assembly, and testing of detector components and systems; sensors, microelectronics, photocathodes, unique and extreme environments (high radiation, cryogenic)

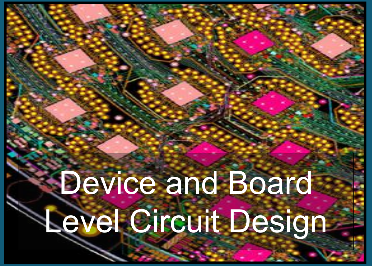
Organization: ~ 90 people, 3 Divisions - Technology Research, Scientific Instrumentation, Instrumentation Facilities

Focus on Emerging Technologies: impact/application driven

Partnerships and Workforce Development: domestic and international





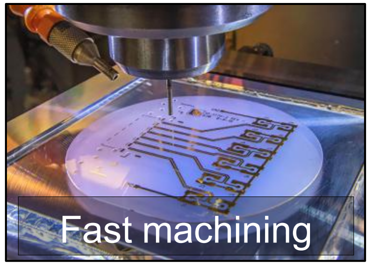


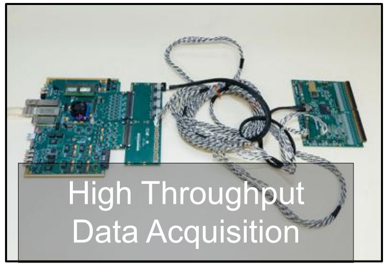
Overview

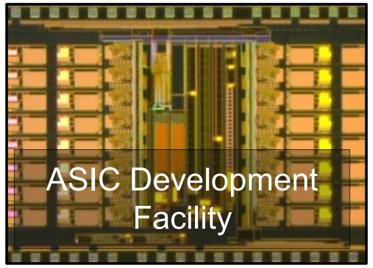
Applied innovation: technology research and scientific instrumentation from concept to product

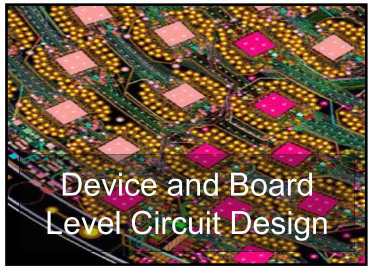
Develop next-generation instrumentation

- **applied research** to advance the state-of-the-art in instrumentation capability and detection systems
- **unique solutions** to enable scientific discovery and technology with societal impact
  - technologies to advance science programs in collider & neutrino physics, cosmology & space science, climate & atmospheric science, at light sources, nuclear nonproliferation and homeland security
  - **scalability enablers**









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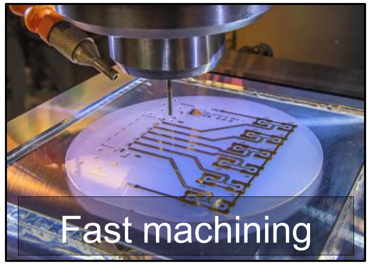
https://www.bnl.gov/instrumentation/

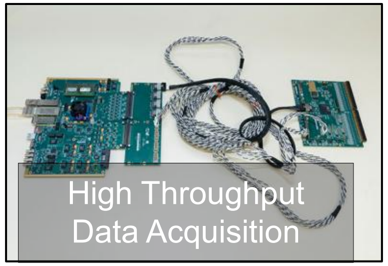
Overview

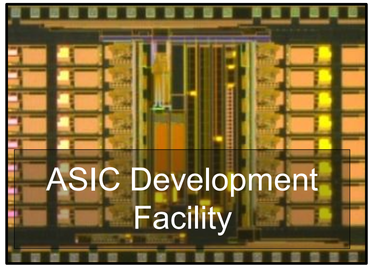
Applied innovation: technology research and scientific instrumentation from concept to product

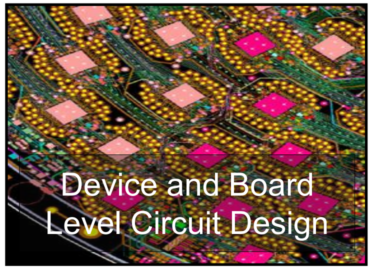
Detector R&D – key ingredients

- **sensing media:** semiconductors (silicon, germanium, diamond, CZT, TlBr, a-selenium, perovskite, scintillators, new materials), noble liquid and gas, liquid scintillators
- **readout electronics:** integrated front-end (ASICs), analog and digital readout electronics (readout boards, DAQ, controls)
- **system integration:** mechanical and electrical engineering, assembly, integration, validation (verification and calibration) – focus on Size Weight and Power (**SWaP**)
- **data acquisition and handling:** signal processing, optimization, feature extraction
- 32 patents in the last 20y (7 pending)









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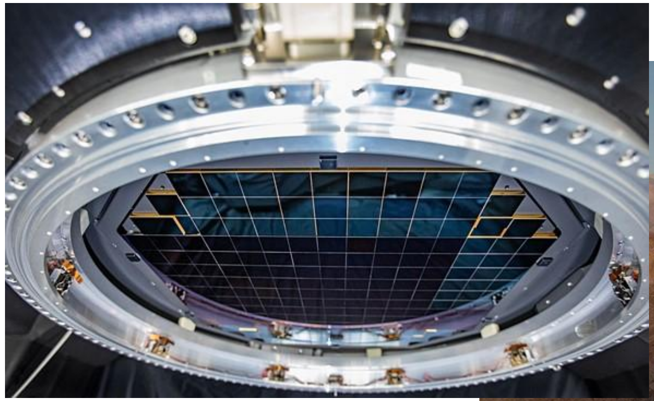
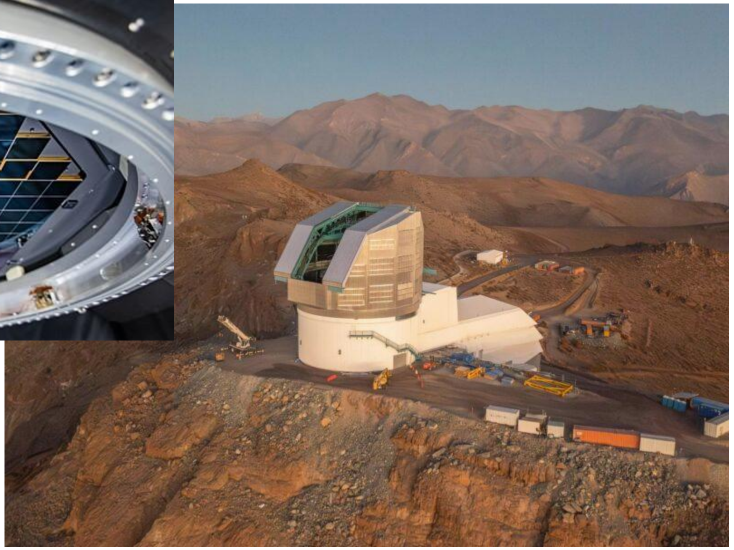
https://www.bnl.gov/instrumentation/

‘Tools’ for cosmological observations

- Rubin Observatory - LSST Camera
  - Largest optical astronomy camera constructed, focal plane assembled and tested at BNL
  - 3.2 Gpix, 15 TB/night, 37 billion stars and galaxies in 10 yr survey

- Baryon Mapping eXperiment (BMX)
  - Technology pathfinder for 21-cm instruments, located at BNL
  - Interferometer array: 4 x 4.5 m dishes, observe HI in galaxies out to z < 0.3 (~1.2 Gpc, 3.5 billion yr ago)





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The journey from the Large Synoptic Survey Telescope (LSST) to the Vera Rubin Observatory

Concept:

- use a telescope to take large format digital images of the sky very quickly and do this repeatedly over 10y

Science:

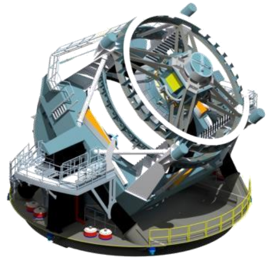
- probe dark energy and matter, observe moving objects and transient & variable phenomena, map Milky Way

Technology enablers:

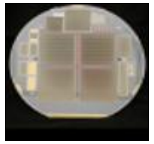
- large – 3.2 Gpix – digital camera, 100’s PB data handling, new types of optical system and telescope mechanical mount

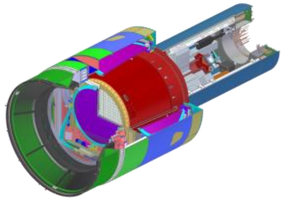
Large Synoptic Survey Telescope

VERA C. RUBIN OBSERVATORY

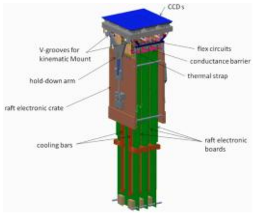


Concept

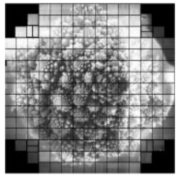




Laying out specifications



Science rafts complete



First images

Mid-1990’s — 2003 — 2018 — 2020 — 2025

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Studying Dark Energy using 21cm intensity mapping

Concept:

- Measure and map the 21cm radio emission of neutral hydrogen as an alternate tracer of large-scale structure of the Universe. Line emission provides accurate, unambiguous redshift measure
- Using precisely calibrated radio interferometers to achieve survey speed is potentially faster and cheaper (per source-equivalent) than an optical survey

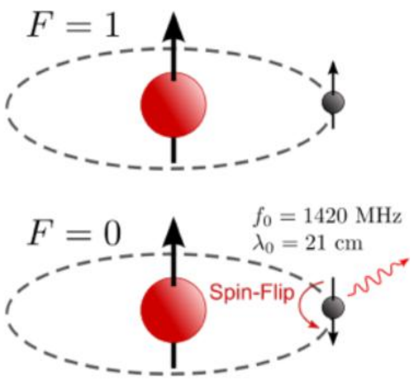
Science:

- Observe source redshifts in the range $0 \leq z \leq 6$ inaccessible to CMB and optical surveys
- Study the evolution of dark energy in the universe

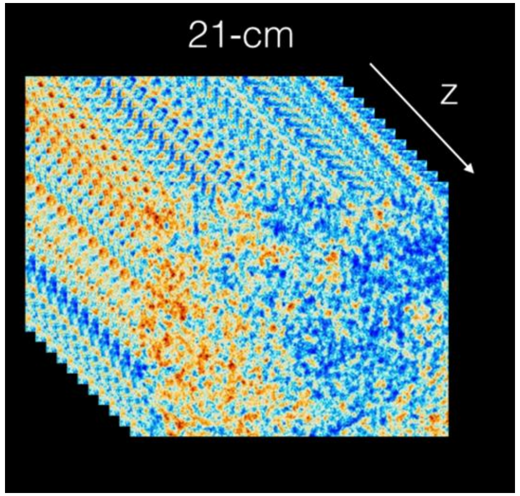
Technology enablers:

- Take advantage of rapid commercial development of digital RF, high-performance computing, and advanced manufacturing technology

Spin-flip transition of neutral hydrogen



Tomographic reconstruction of density field across large volume of space



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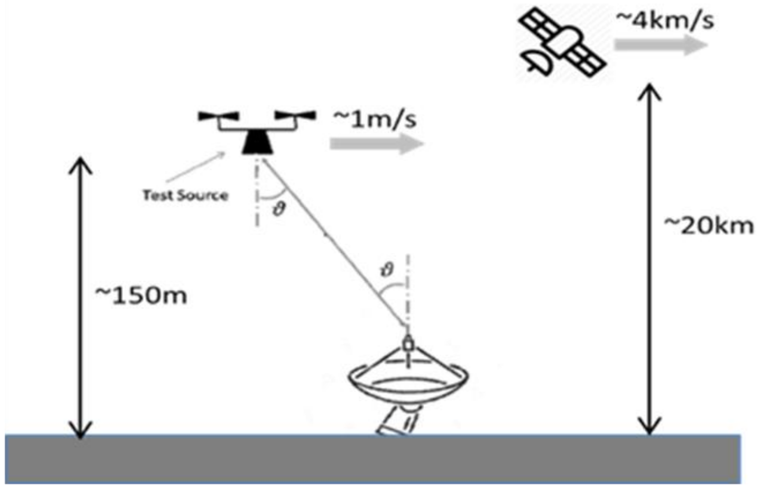
Evolution of technologies: from ground to the moon



- The BMX receivers use PC-hosted digitizers and GPUs to digest the raw data from the antennas and front end electronics, **reducing the data volume from ~190TB to 28GB**.
- **The facility runs 24/7 and is completely autonomous including online and offline reductions**. The recent uptime has been around 70% with interruptions due mainly to weather, power outages, and maintenance/upgrades.
- To date, we have logged around **16,000 hours of data** before QA cuts.

A Joint NASA / DOE Project

The LuSEE (Lunar Surface Electromagnetics Experiment) radio spectrometer will make the most precise measurements of the low-frequency radio sky below 50 MHz (inaccessible from Earth – extreme red-shift 30<z<300), seeking to detect the fossil 21 cm radiation emitted 100 million years after the Big Bang when the first structures were forming.

Our Ride To the Moon*

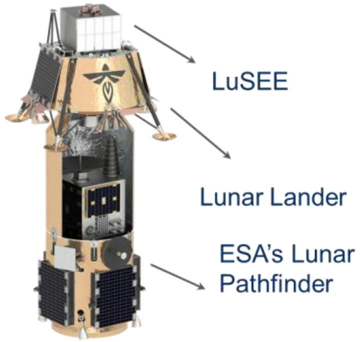
* Supported by NASA Commercial Lunar Payload Services (CLPS)

FIREFLY AEROSPACE

Launch:

Space-X Falcon 9

Journey to the Moon:



Blue Ghost Transfer Vehicle

Landing on the Moon:

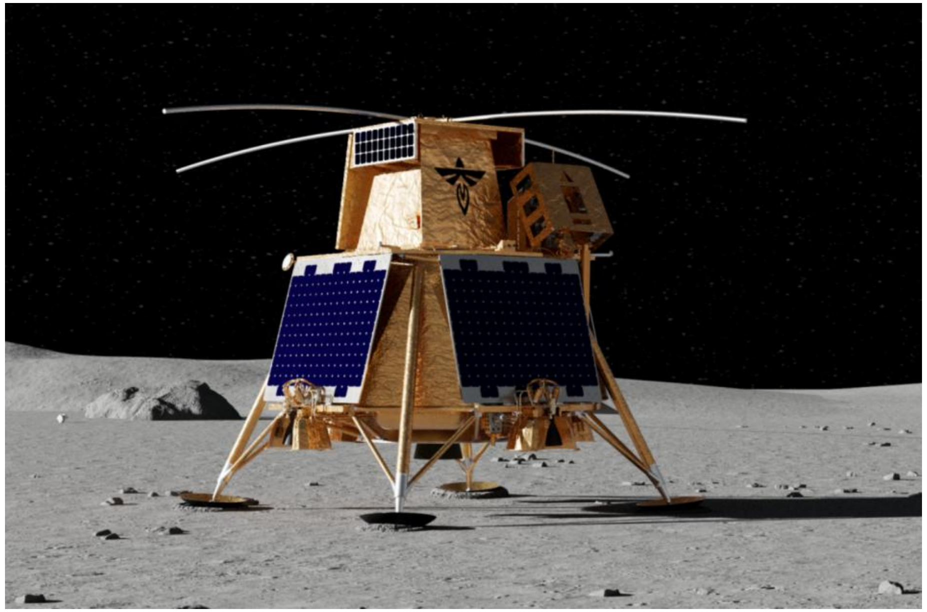
https://fireflyspace.com/blue-ghost-mission-2/

Blue Ghost Lunar Lander

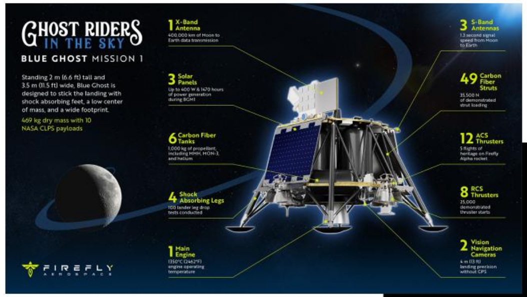
Lunar Surface Electromagnetics Experiment at Night

LuSEE-Night: a NASA-DOE partnership

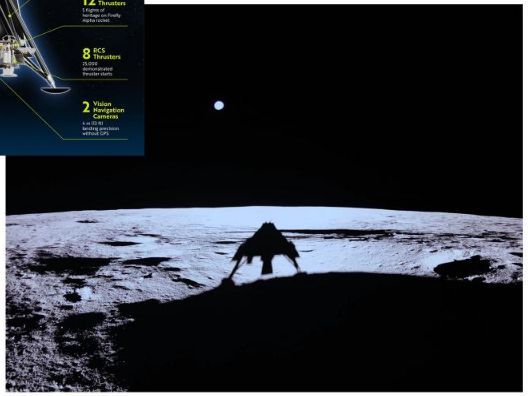
- CLPS CS-3 science payload aboard Firefly Blue Ghost 2 lander
- 4 monopole antennas configured as interferometer, sky noise limited
- Low frequency (0.1 – 50 MHz) spectrometer developed at BNL
- Pathfinder for future lunar observatories to probe Cosmic Dark Ages (400,000 yr – ~200,000,000 yr after Big Bang)



Firefly Blue Ghost Mission 1 landed successfully on the moon March 3rd 2025



FIREFLY AEROSPACE



LuSEE-Night is Firefly BGM2 Launch in DEC 2025

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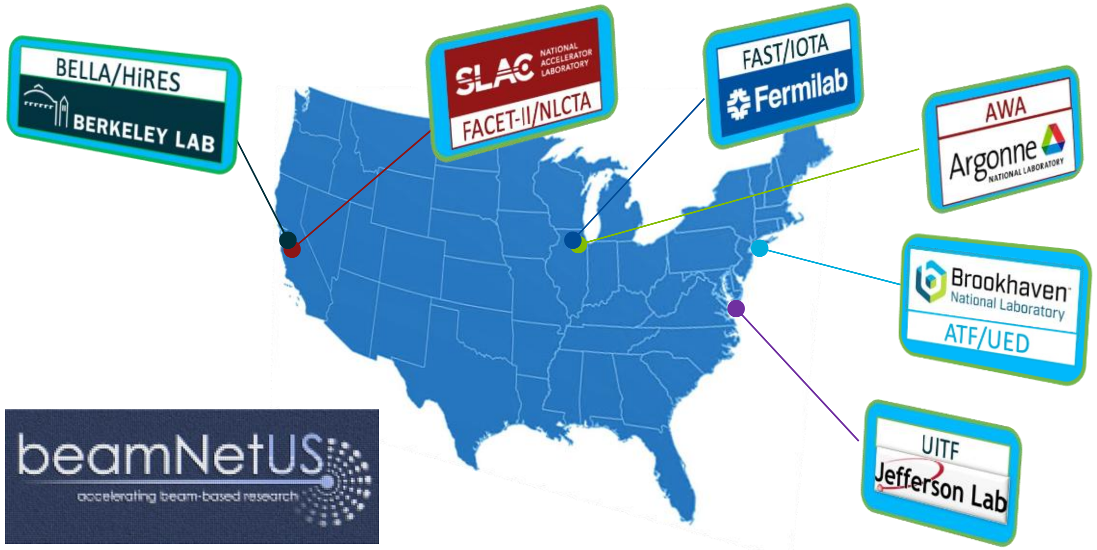
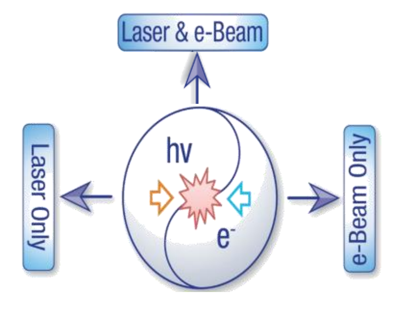
Accelerator Test Facility

DOE Office of Science National User Facility

- Proposal driven, peer reviewed user facility
- Over 30 years of operation for user experiments
- Designated as a flagship facility in Accelerator Stewardship in 2015
- Part of BeamNetUS from 2024
- Unique combination of laser and electron beams drives a diverse program of user experiments.

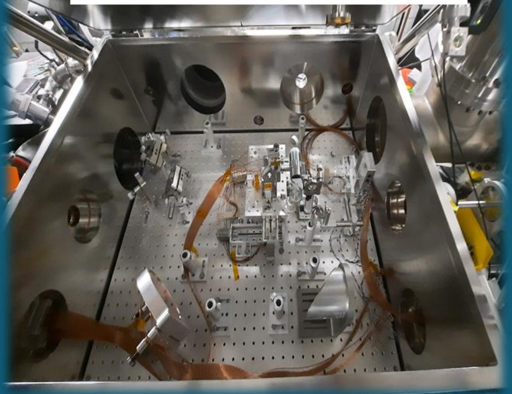


beamNetUS
accelerating beam-based research



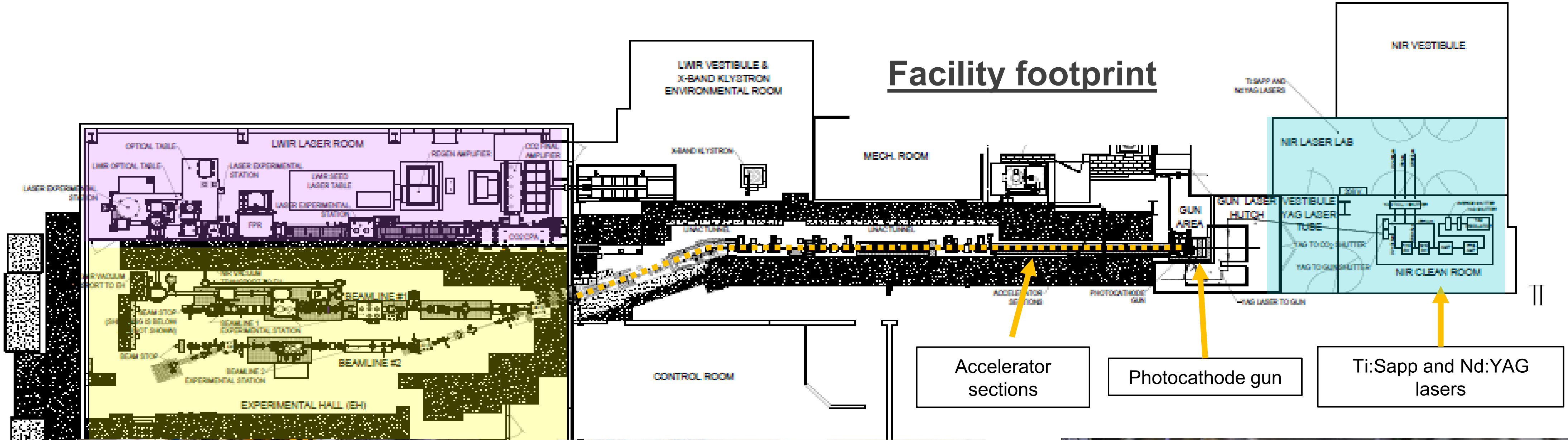
High-power lasers

Interaction Chamber

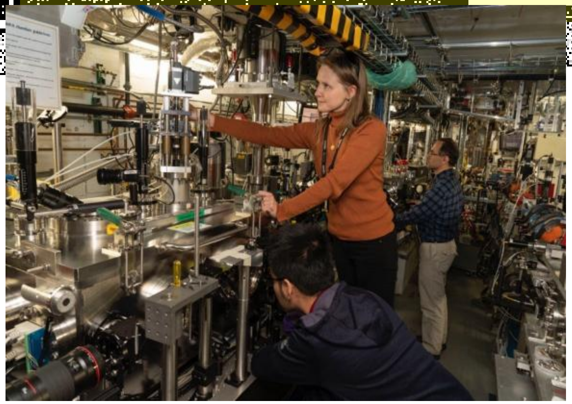


Electron Linac

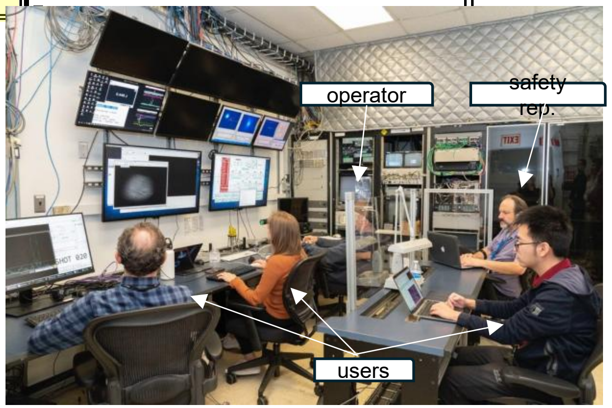
Combination of high-peak-power lasers and a high-brightness electron linac



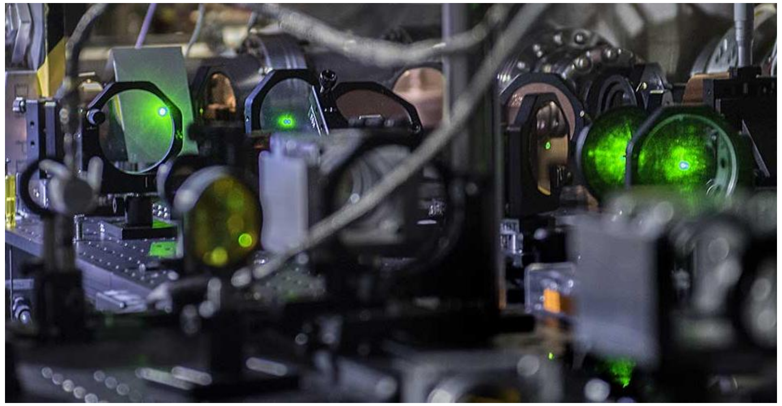
Facility footprint



Experimental hall



Control room

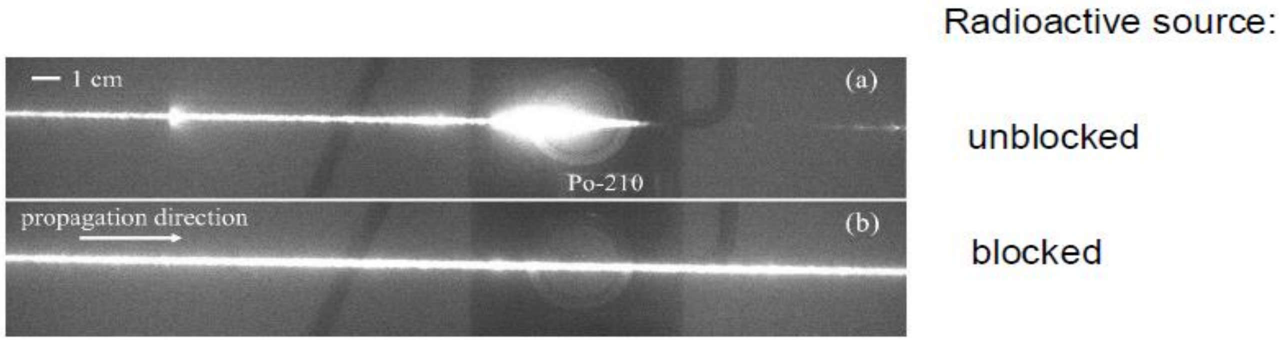


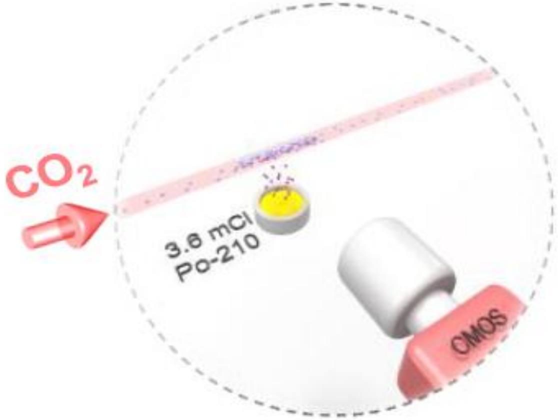
Lasers

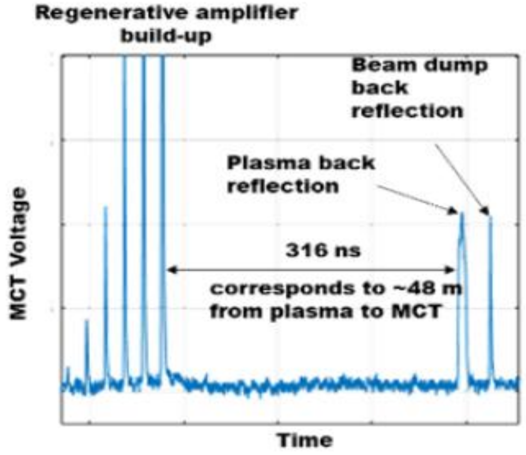
Brookhaven National Laboratory

Remote detection of radioactive material using a short-pulse CO_2 laser

- The experiment capitalizes on abilities of LWIR radiation to propagate a strong light filament over the km distance and to reach optical breakdown in air by enhancing the initial local ionization produced by a radioactive source.
- The location of the breakdown is visible with naked eye, and the distance can be accurately measured by the return signal.
- Field deployment is possible.







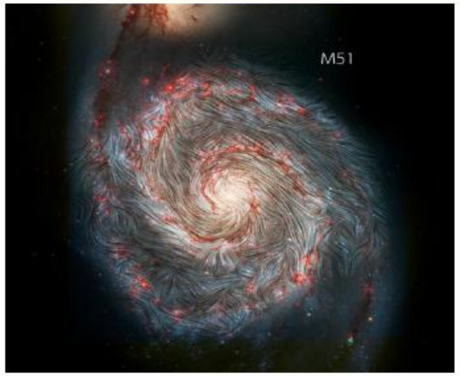
Experiment conducted by: University of Maryland, Los Alamos National Laboratory, Lawrence Livermore National Laboratory

Brookhaven National Laboratory

Probing of B-fields generated by plasma instabilities

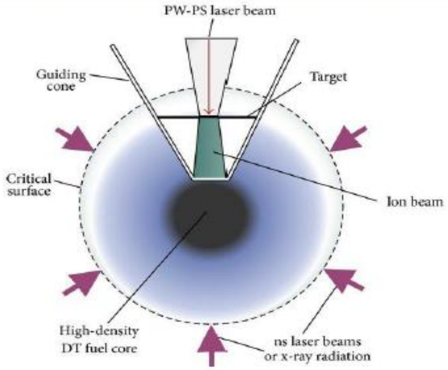
- Pioneering studies of dense plasma instabilities lead to better understanding of galactic and fast fusion ignition.
- LWIR driver is ideal because it strongly affects plasma temperature, $T_e \sim \lambda E^2$, and has a low critical plasma density, $n_{cr} \sim \lambda^{-2}$, allowing optical diagnostic in gas plasma.

ASTROPHYSICS

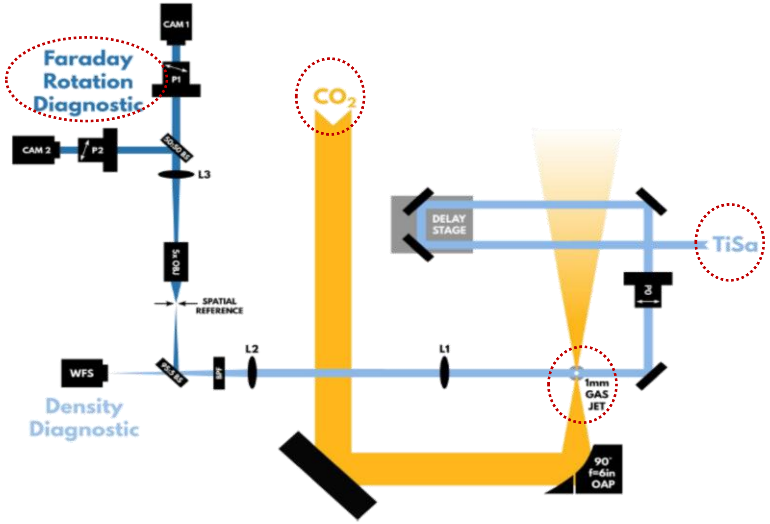


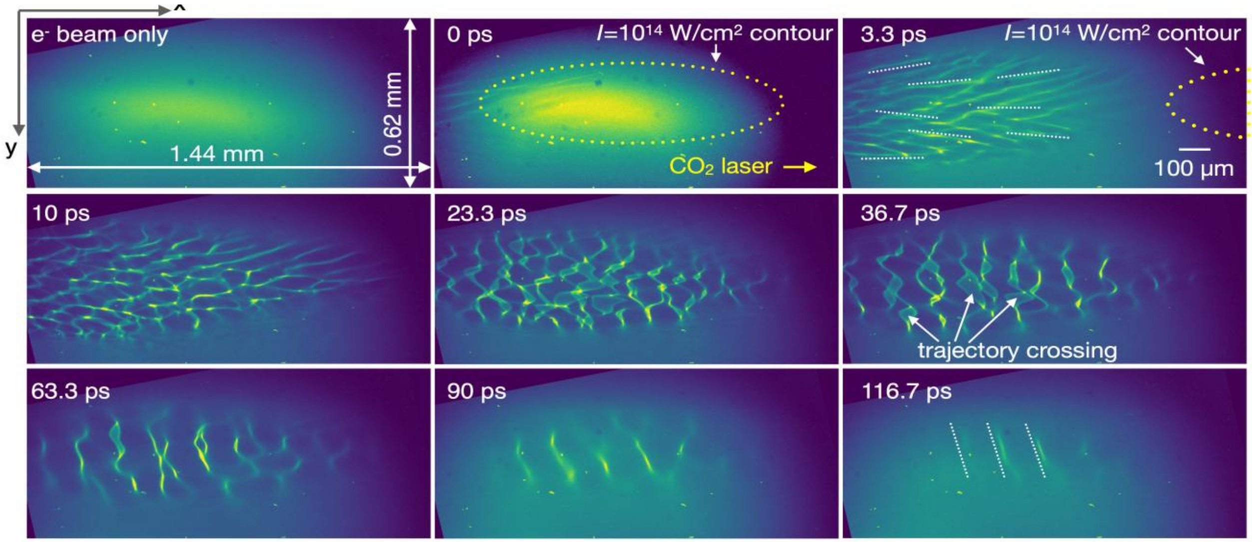
Seed fields for galactic dynamo mechanism, γ-ray bursts

ENERGY



Laser-driven fusion schemes: fast ignition, indirect drive

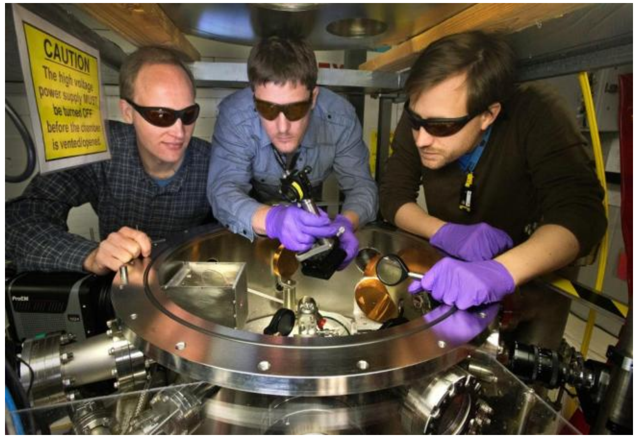




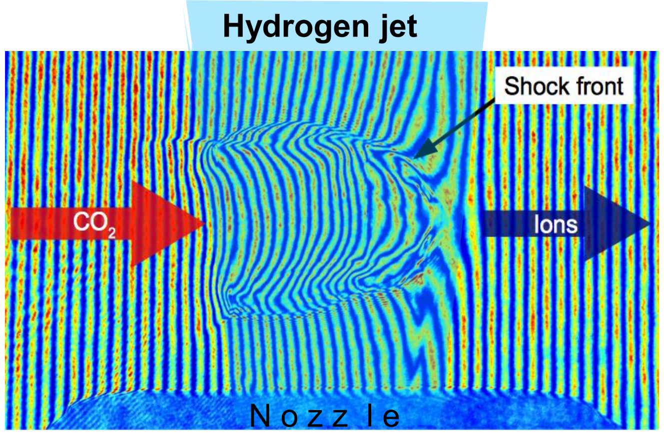
Experiment conducted by UCLA

Proton beam generation from supersonic hydrogen gas jet

- Low critical plasma density allows driving ions out of gas.
- New, shock wave mechanism of monoenergetic acceleration.
- Need 100 times higher laser intensity to reach proton energies for cancer treatment.

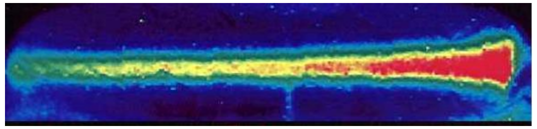


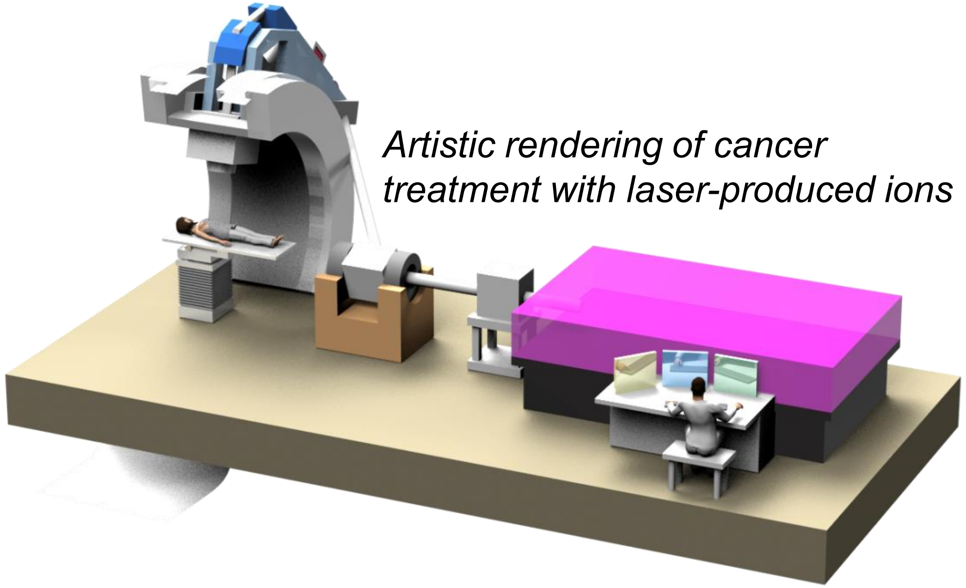
Optical diagnostic



Laser-induced electrostatic shock reflects protons upon its propagation through the ionized H_2 jet.

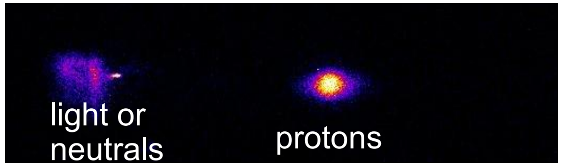
Bragg absorption of 200 MeV protons in 10 cm of water





Artistic rendering of cancer treatment with laser-produced ions

Energy spectrum



- Energy spread 4% (record-narrow for laser acceleration)
- Spectral brightness 10^{12} proton/MeV/str
- Proton energy up to 3.2 MeV

Experiments conducted by Imperial College London and Naval Research Laboratory

Brookhaven National Laboratory

Magnet Division

58,000 sq. ft. facility, ~50 staff members

Capabilities:

Coil Winding – NbTi, Nb_3Sn, HTS

- Unique direct wind capability for high precision specialty and IR magnets

Vacuum Impregnation

Coil Reaction

Flexible vertical test stand

- Operation down to 1.9K

Magnetic measurements

BNL Facility Northwest (High) Bay Area

Test Facility

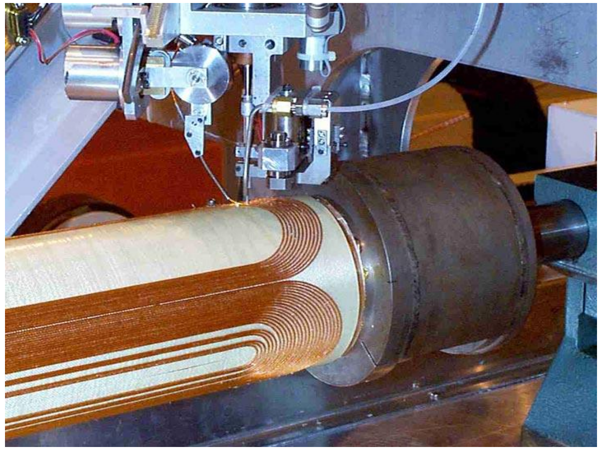
Brookhaven National Laboratory

https://www.bnl.gov/magnets/

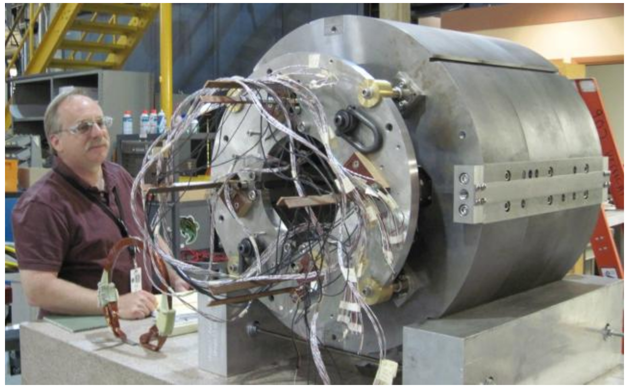
Magnets for accelerators around the world

Relativistic Heavy Ion Collider – BNL

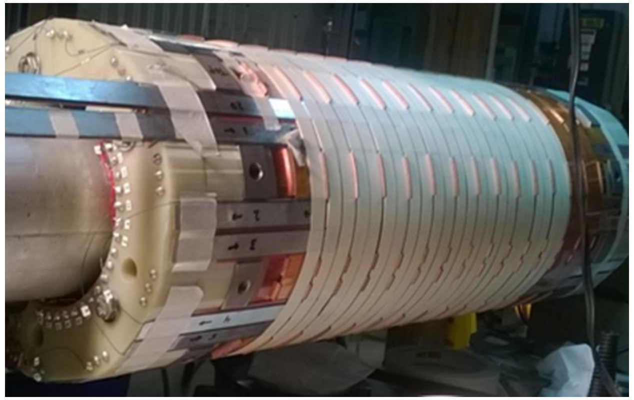
Magnets for Large Hadron Collider – Geneva, Switzerland



Hadron Electron Ring Accelerator magnet – Hamburg, Germany



High temperature superconducting magnet for Facility for Rare Isotope Beams, Michigan State



High temperature superconducting magnetic energy storage device

Brookhaven National Laboratory

https://www.bnl.gov/magnets/

Testing magnets

Typical Test Sequence

Incoming inspection of Magnet (Warm measurements)

Magnet is Upright and attached to top hat

Ready with all power and instrumentation connection-transported to test Dewar

Magnet in Test Dewar and Field Measurement Probe

Brookhaven National Laboratory

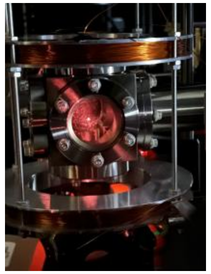
Direct winding

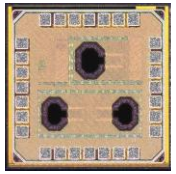
https://www.bnl.gov/magnets/

Quantum Information Science, Technology, and Engineering

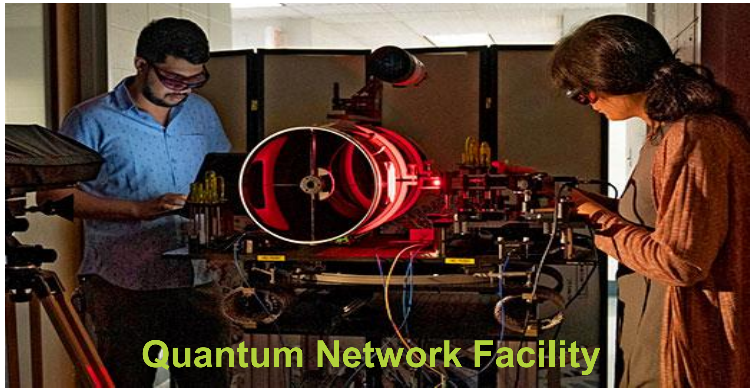
Brookhaven National Laboratory

Summary



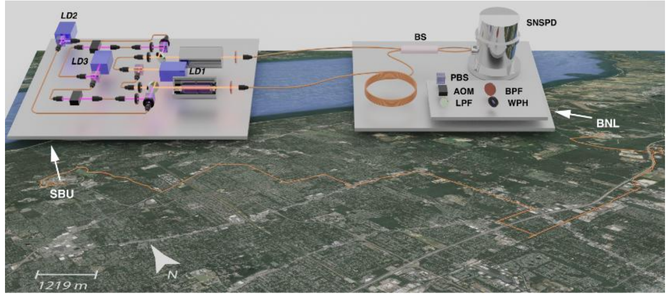


- One of 5 DOE ‘Quantum Centers’
- Develop large quantum entanglement distribution networks (Quantum Internet)
- World class facilities, including **Quantum Network Facility**
- Enabling technologies: **cryo-CMOS**, photonics, new materials, lasers, UHV, integration
- R&D toward quantum networks of sensors and quantum enhanced sensing



Quantum Entangled Network

- **Longest** and most **advanced** quantum networks in the U.S. since 2020
- 161 miles and 5 distinct nodes

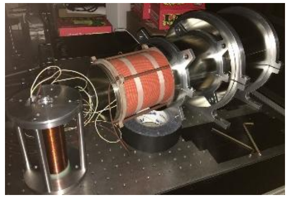


Elements of QIST at BNL

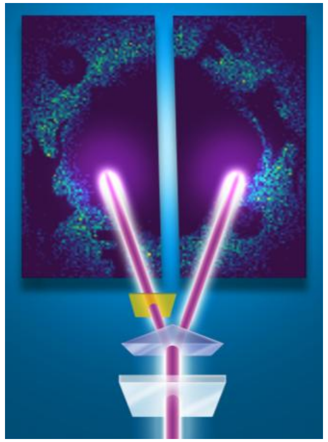
- Co-design Center for Quantum Advantage
- Quantum network lab and testbed
- Interdisciplinary teams focused on next-gen quantum materials
- Quantum-enabled facilities and instruments
  - Quantum algorithms and computation
  - Partnership and workforce

Quantum Networks of Sensors and Quantum Enhanced Sensing

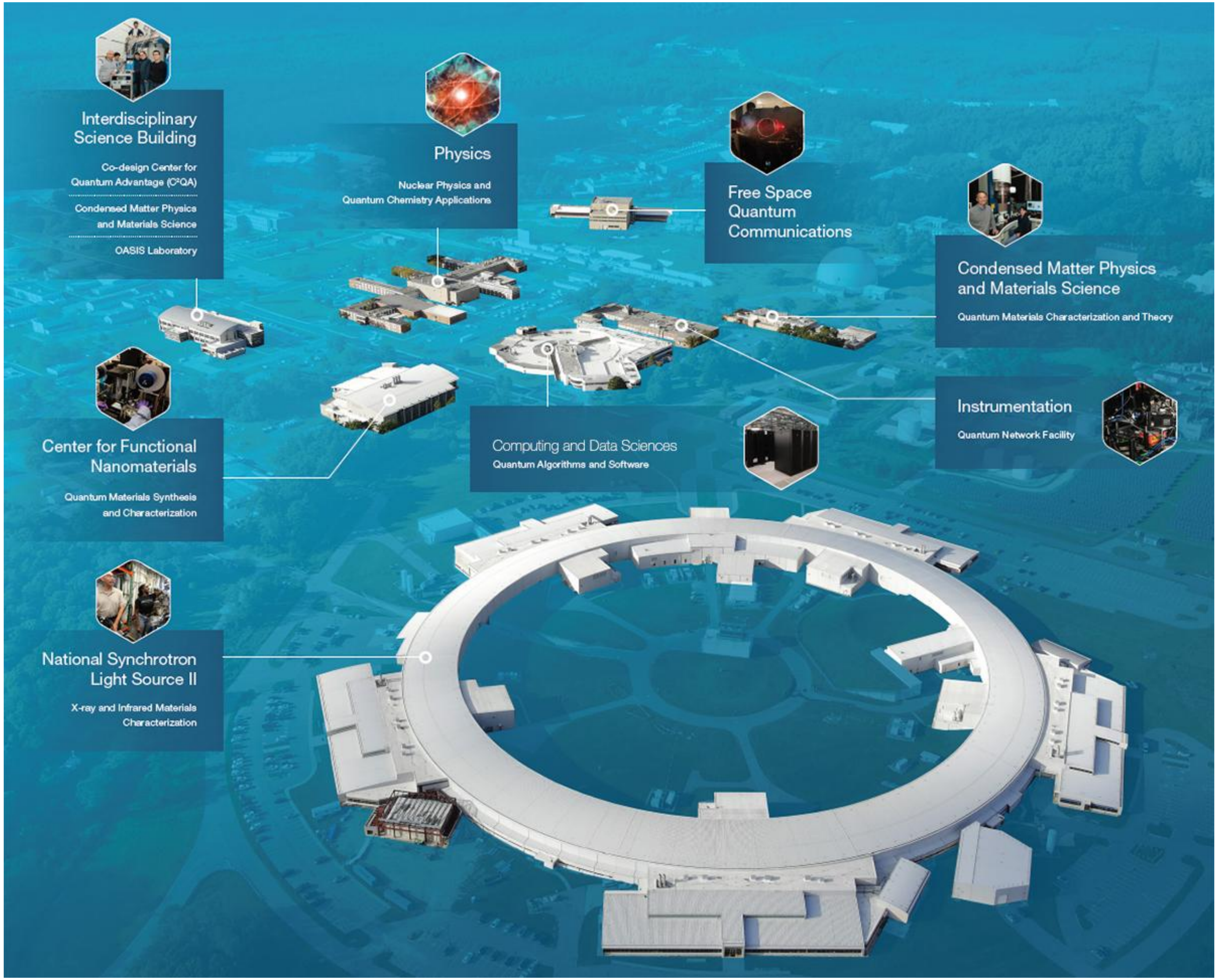
- Network of spatially separated magnetometers to demonstrate improved sensitivity to EM fields



- Ongoing R&D:
- develop quantum-enabled x-ray microscopy for ghost imaging
- quantum astrometry demonstrator
- enhance lidar with quantum technology



Quantum Innovation Ecosystem at Brookhaven National Lab



Brookhaven National Laboratory

C^2QA 2024 Impact by the Numbers (as of November 6, 2024)

QIS Career Fair: Connected 1,620 Jobseekers with over 85 Hiring Managers since 2021

Over 485 papers (including 267 publications*, 210 preprints…and counting!

8 subject inventions and 11 open-source software packages attributed to C^2QA

300+ people working on 100+ projects to advance quantum computing

4 educational outreach programs offered including Quantum Thursdays and Speakers Colloquia

27 institutions (including 2 affiliates) from national labs, industry, and academia

88 Principal Investigators and Research Scientists

8 summer school offerings for K-12, undergrads, grad students, postdocs & faculty

1 of 5 U.S. Department of Energy National QIS Research Centers addressing quantum challenges

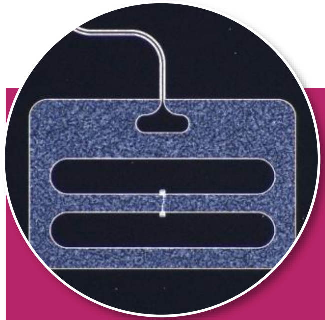
3 technical areas (thrusts) and 1 crosscutting team focused on software, devices, & materials co-design

With additional support from

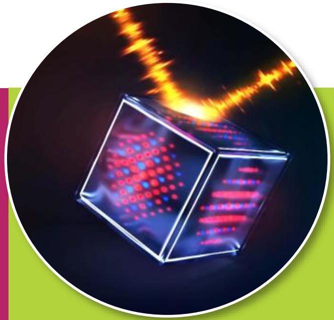
Affiliates

* *Including peer-reviewed conference proceedings*

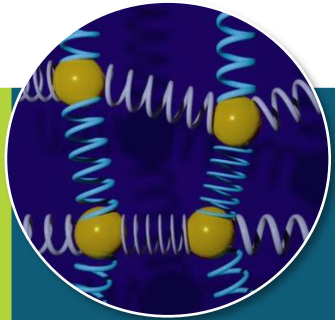
Key Achievements



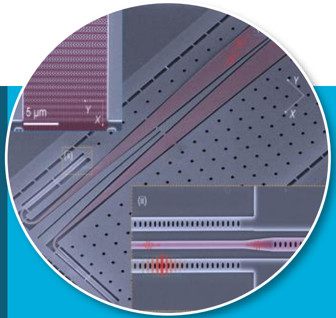
Enhanced lifetime enables quantum calculations that could not be done before



Error correction strategies are essential for accurate quantum computers



Algorithms are crucial for leveraging the potential of quantum computing



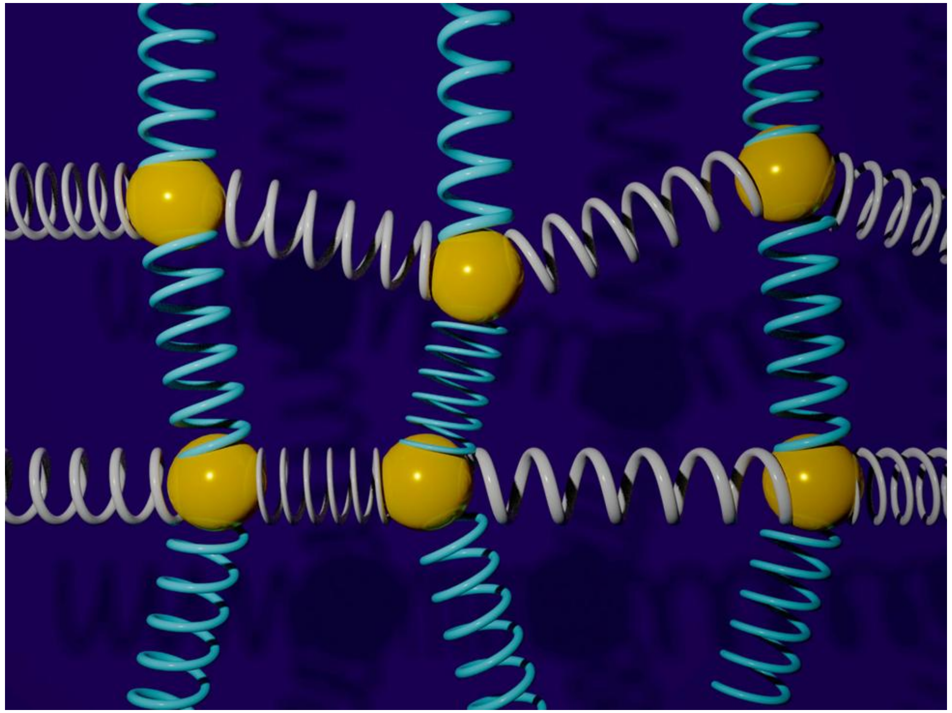
Enables distributed quantum computing which is the key to scaling to a quantum supercomputer

Google credits C2QA as a driver of progress in quantum computing.

New and Better Quantum Algorithms

C²QA discovered the first new class of quantum algorithms in more than a decade, enabling the simulation of coupled complex systems.

We are lowering the barrier to achieving quantum advantage by efficient design of calculations.



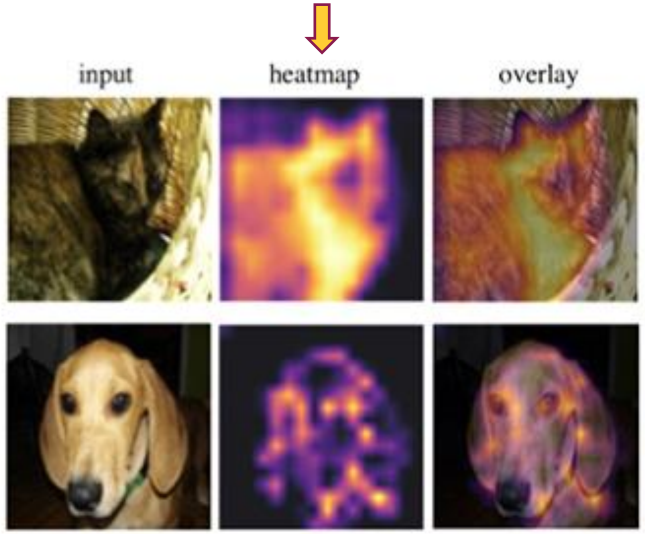
A new quantum algorithm was developed to improve the simulation of coupled oscillators (*Physical Review X,* **13**, (4))

Brookhaven National Laboratory

Making Quantum AI Accountable

Quantum Explainable AI (xAI) focuses on one goal: *understanding* and *trusting* the decisions made by quantum computers.

Our first-of-its-kind work answers: *How did the AI get this solution*?



Simple "heatmaps" visually highlight the exact information the AI used to make its choice.

Why is Brookhaven Lab's Quantum xAI Work Critical?

- **Builds Trust for Critical Missions**: For national security, healthcare, and finance, we must be able to verify that AI reasoning is sound and reliable.
- **Reduces Risk and Bias**: Helps to find and fix hidden flaws or biases in an AI system, ensuring fair and accurate outcomes.
- **Secures U.S. Tech Leadership**: By pioneering transparent AI, the United States can set the global standard for responsible and trustworthy next-generation technology.

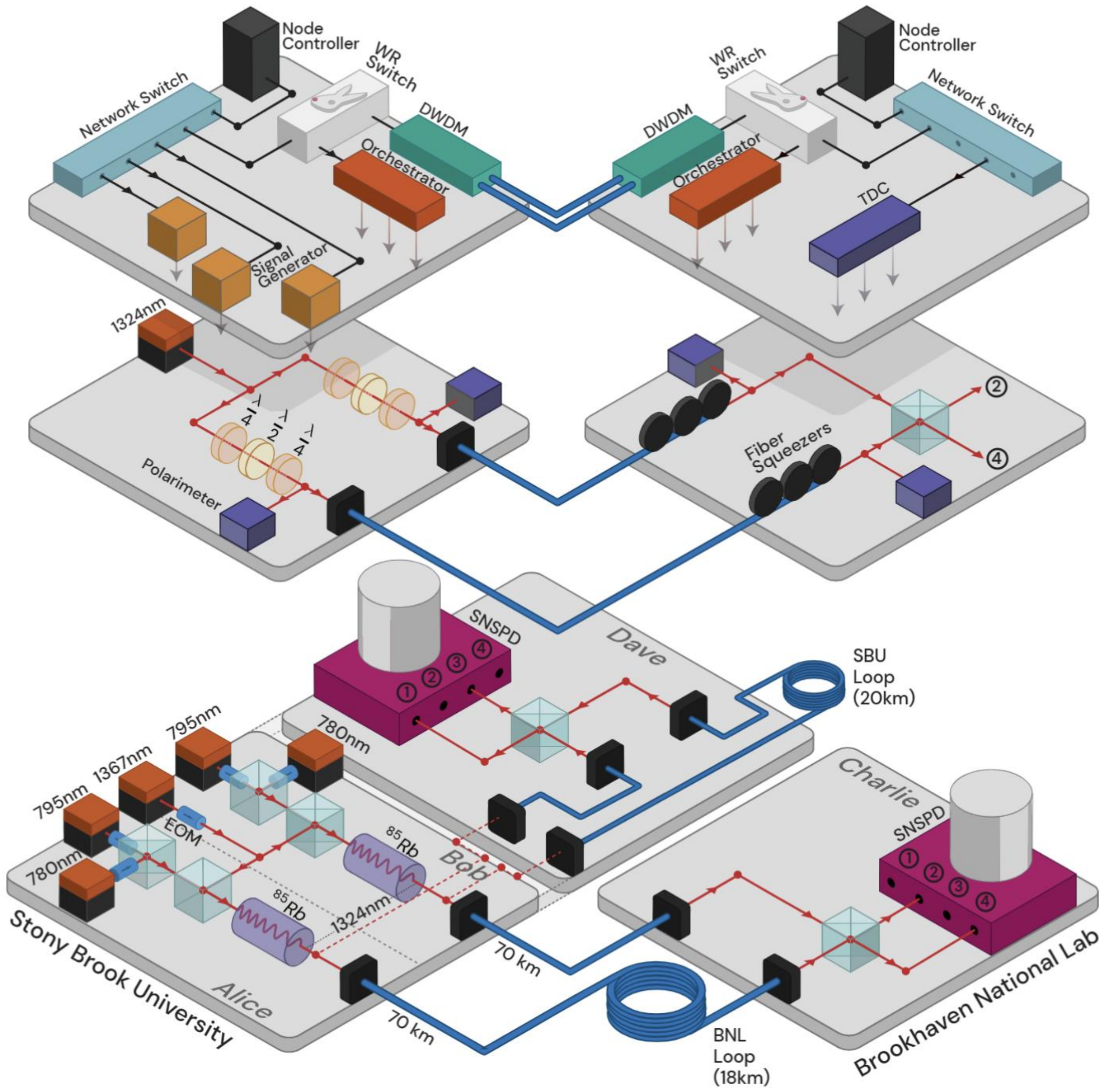
Brookhaven National Laboratory

Stony Brook University

161 miles, **5** nodes in **5** different locations, includes quantum memories and remote-control capability

Stack-driven quantum network

- Experimentally-inspired (*bottom up*) and application-driven (*top down*)
  - Construction of a ***layered*** quantum network
- Short-term quantum network-assisted applications
  - ***Controllable*** quantum nodes
- Technology development: hardware/software building blocks (sim, algorithm, protocols)
  - ***Interoperable*** quantum hardware
- Towards the construction of long-distance fiber/free-space quantum network
  - Quantum ***repeaters*** and satellite ***free space quantum*** links

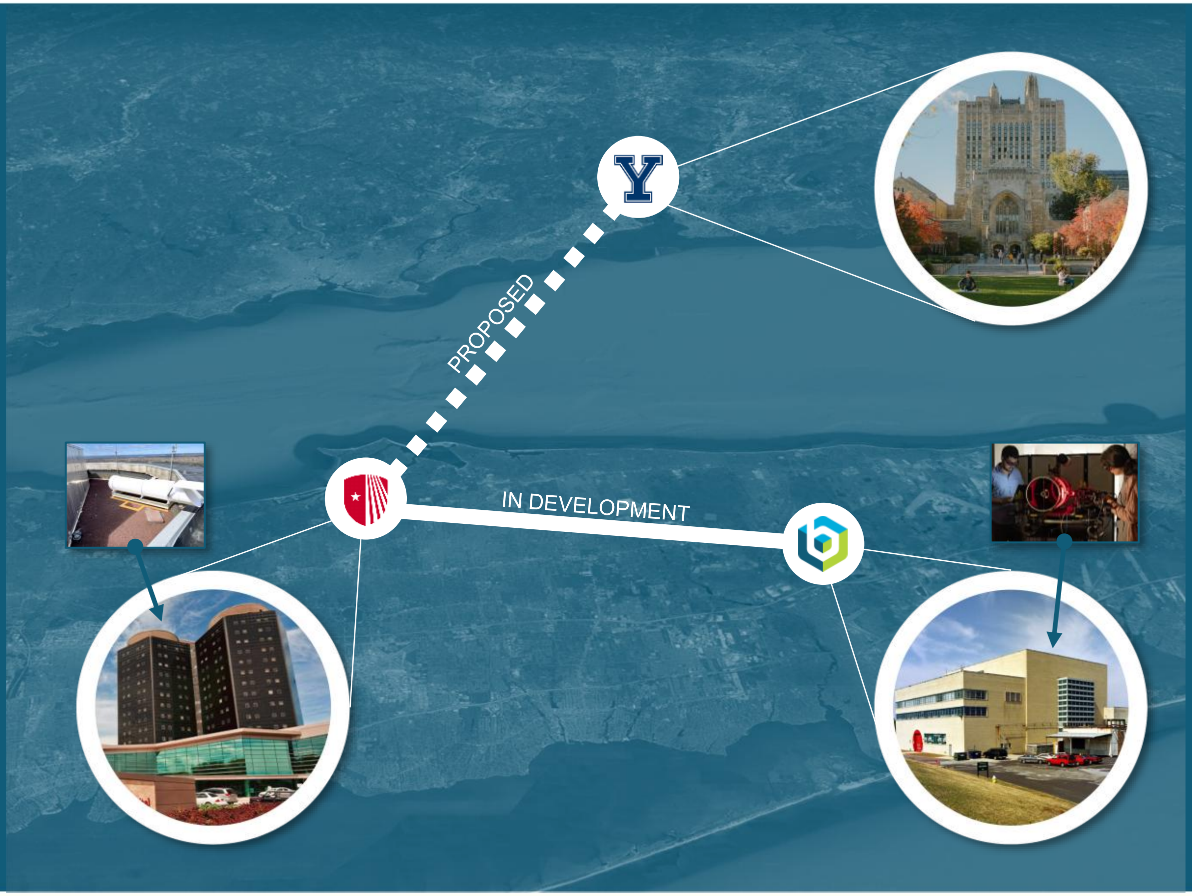


arXiv:2101.12742v3 (2024)

*Partners co-authoring 5 white papers submitted, accepted and presented at the ASCR workshop (July 2023)

Commack Node:1st Quantum Node in a Commercial Colocation Data Center

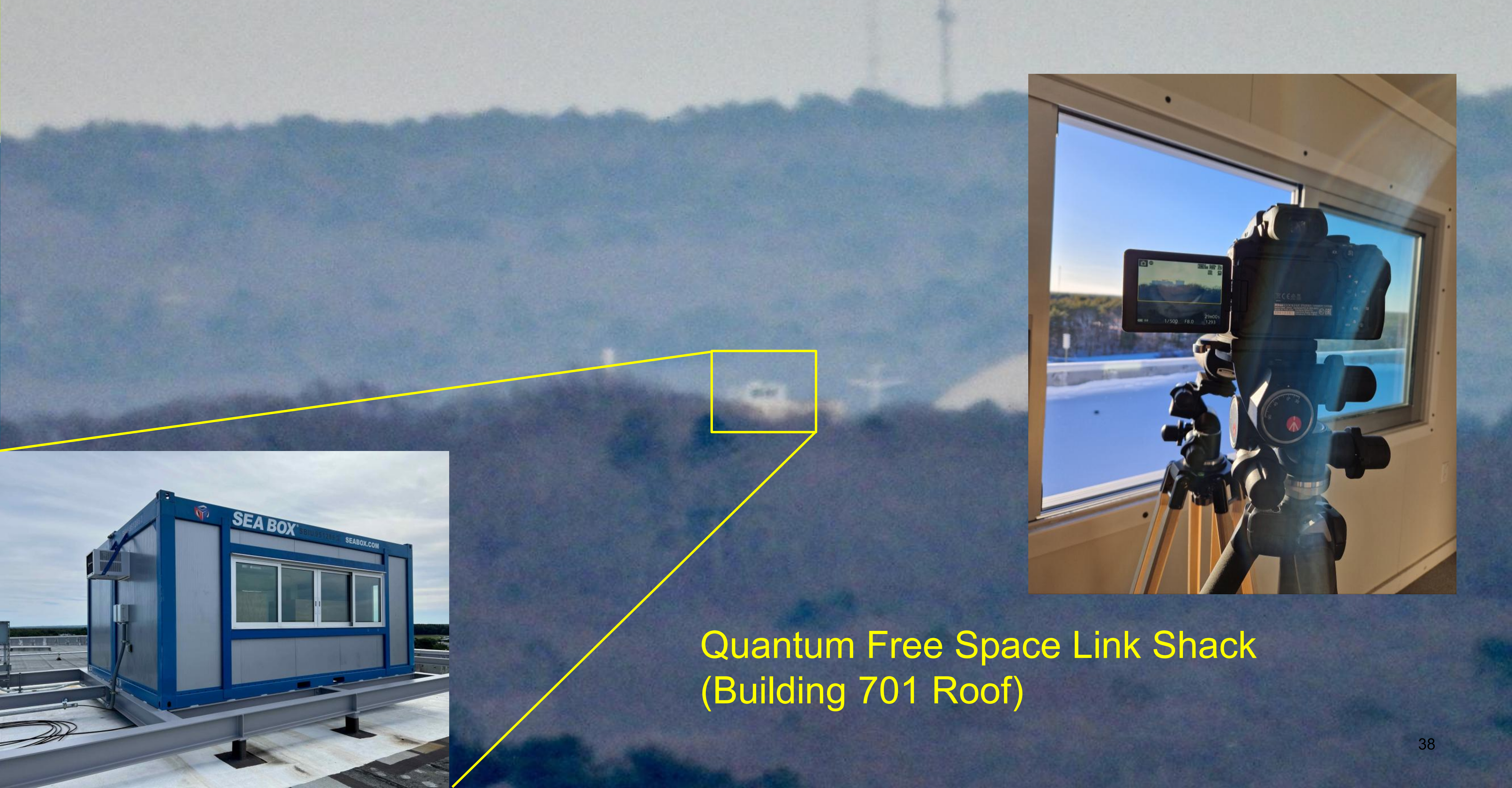
The Free Space Optical link



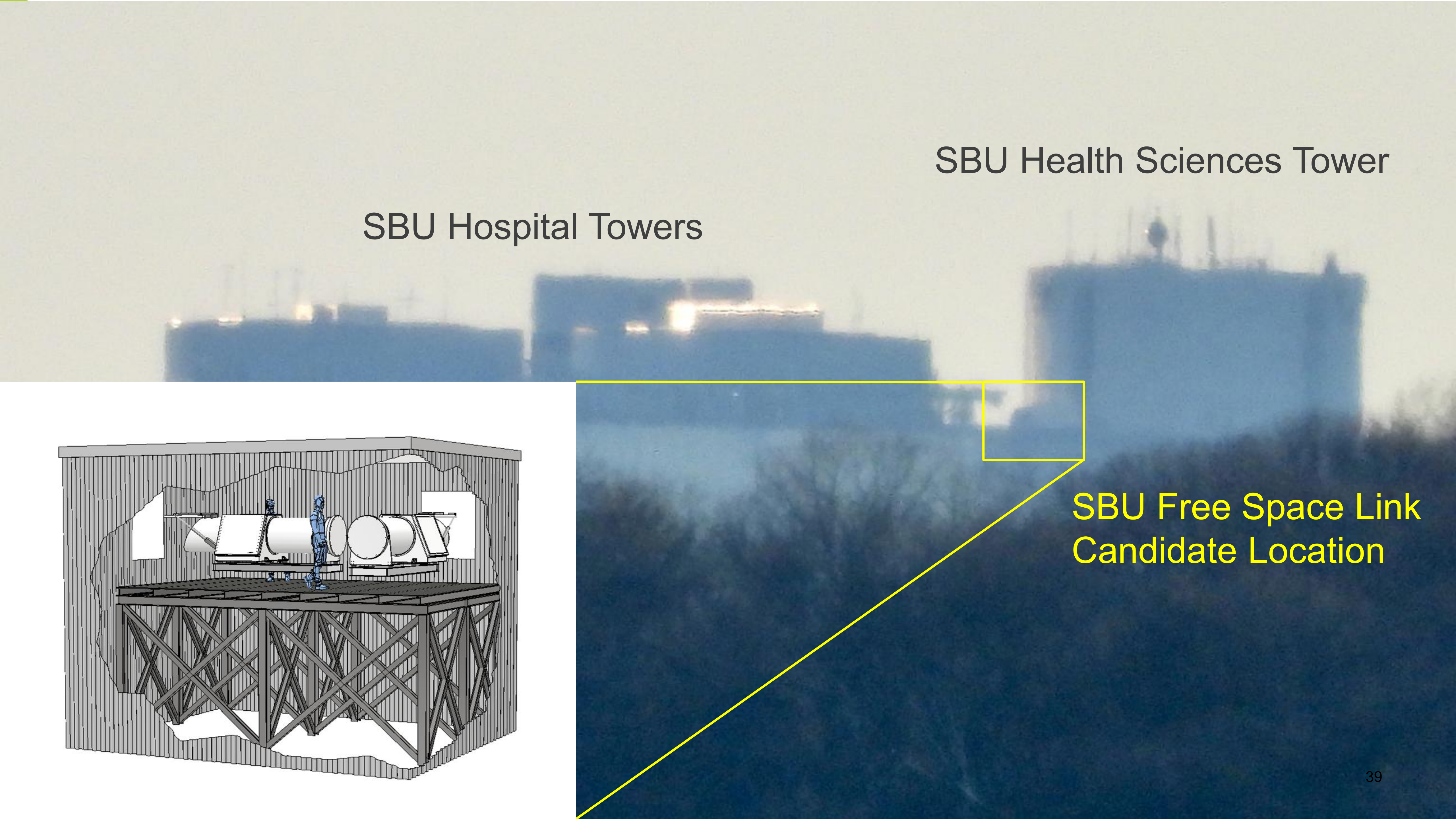
Brookhaven National Laboratory

Stony Brook University

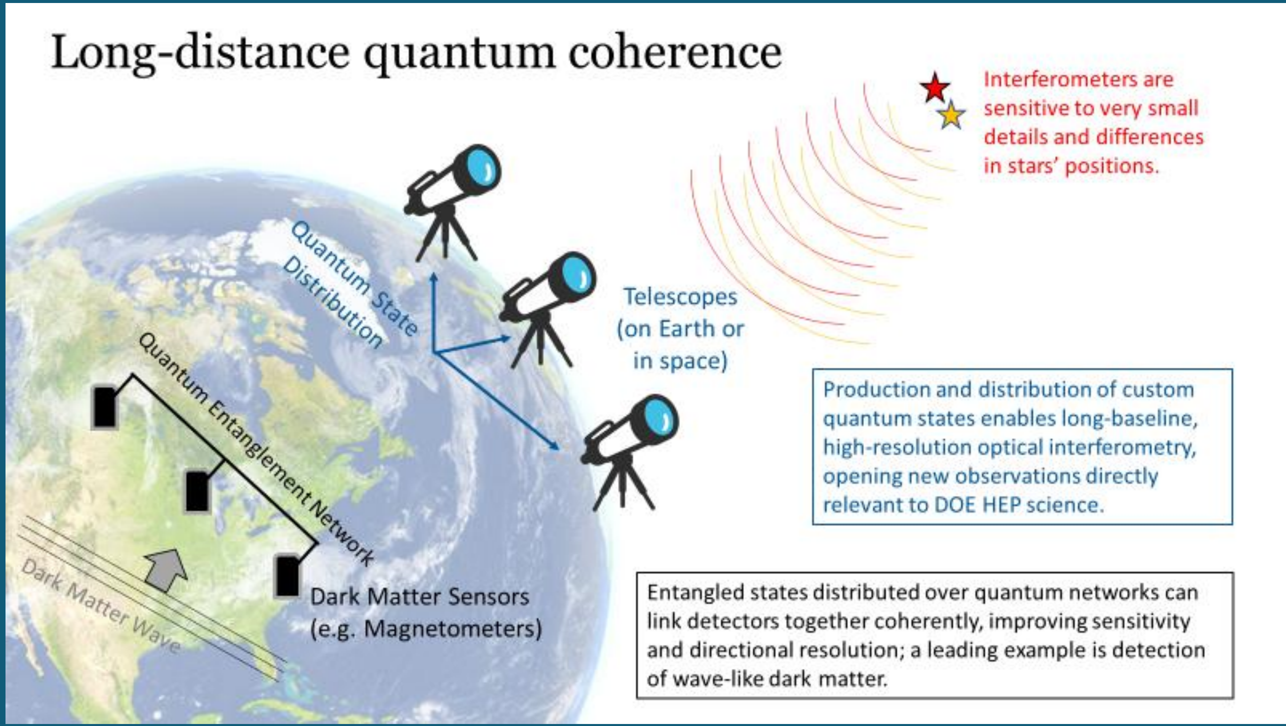
As seen from SBU Candidate Location



Quantum Free Space Link Shack
(Building 701 Roof)


SBU Health Sciences Tower
SBU Hospital Towers
SBU Free Space Link
Candidate Location

Scientific applications



Brookhaven National Laboratory

Distributed quantum entanglement

Astrometry

- Studying QIS techniques of two-photon interferometry to **enable practically arbitrarily large synthesized apertures**
- Experimenting several practical implementations of the technique to demonstrate how this can be deployed for cosmological and astronomical measurements

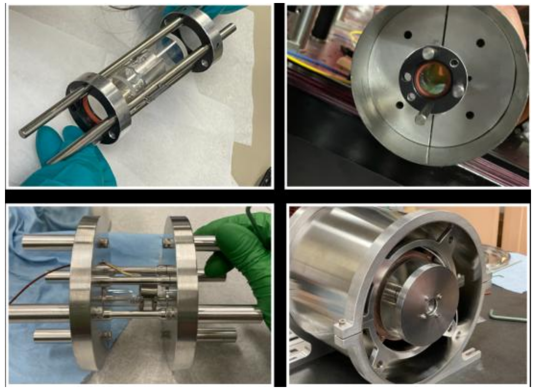
P. Stankus *et al*., Instr. Meth. Astrophysics, vol 5 (2022)

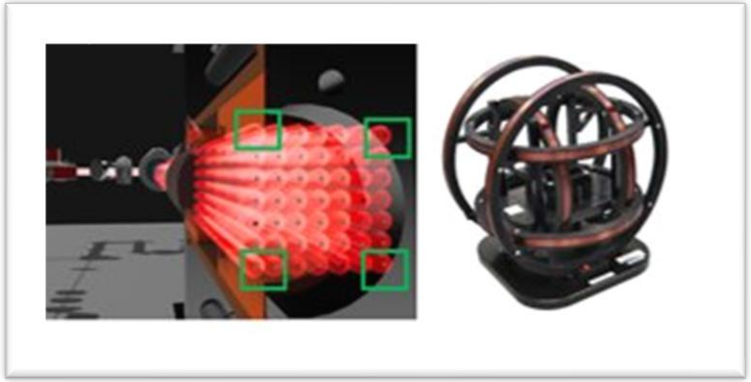
Network of sensors

- Atomic systems are excellent candidates to sense changes in electric and magnetic fields expected from the passage of axion-like dark matter
- Studying how to entangle a network of magnetometers and its improved sensitivity
- Unmanned aerial vehicles and satellites

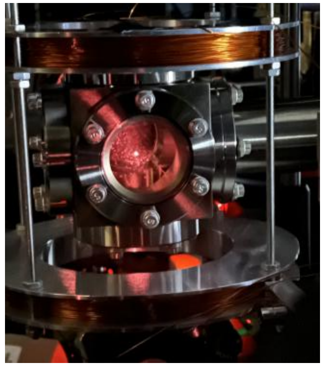
Atomic sensing

Currently, developing an array of 7x7 atom magnetometers



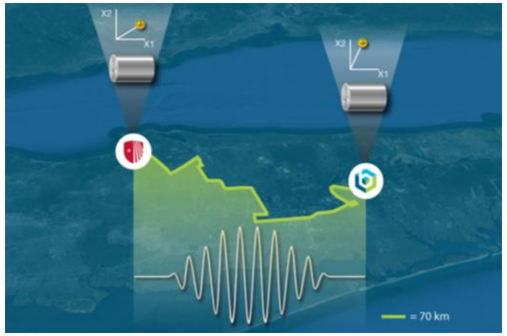


Next: Explore arrays of atomic clocks



Developed atomic cold cloud (~500 μK)

Long term: Long-distance (~70 km) entanglement of atomic systems to study its possible connection to gravitational diffusion (quantum nature of gravity)



We can reach **sub-nT** resolution for B-field sensing using high fidelity (>99%)

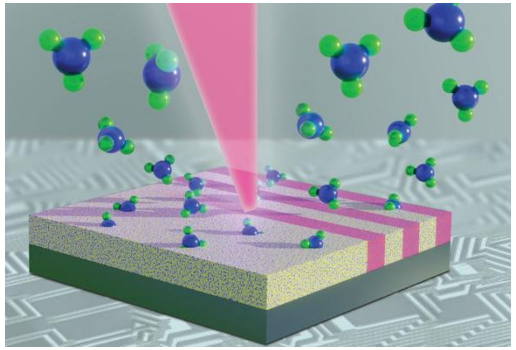
Brookhaven National Laboratory

Courtesy of P. Stankus and J. Martinez-Rincon

Microelectronics

Re-envision semiconductor R&D

Novel Materials

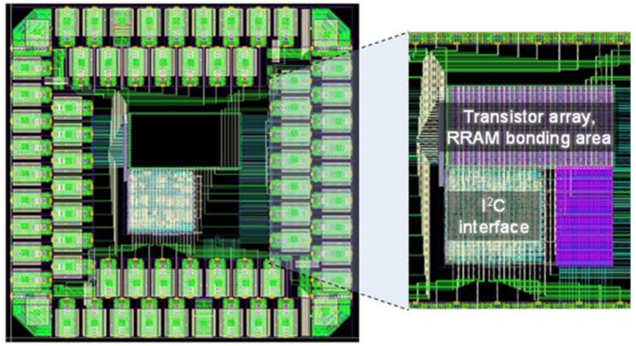


Hybrid EUV resists and memristors

Characterization & Metrology

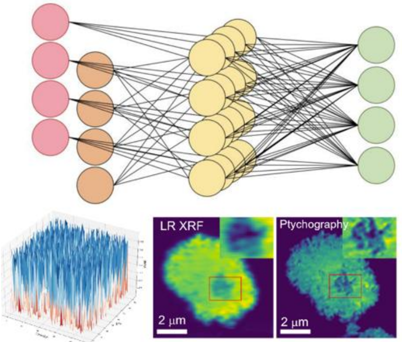
Phase change memory imaging

Circuits & Architecture



Memristor-ASIC integration

Modeling & Algorithms



Mod-sim and machine learning

BNL strengths

- + New electronic materials; new patterning materials & processes
- + World-leading X-ray imaging, spectroscopy
- + Electron microscopy; electrical, electronic, structural, optical characterization
- + Device modeling
- + ASIC design (low noise, low power) & fab; cryo CMOS
- + Algorithms
- + Architecture, subsystem, and system simulation; codesign tools
- + Facilities for characterization (extreme environments)

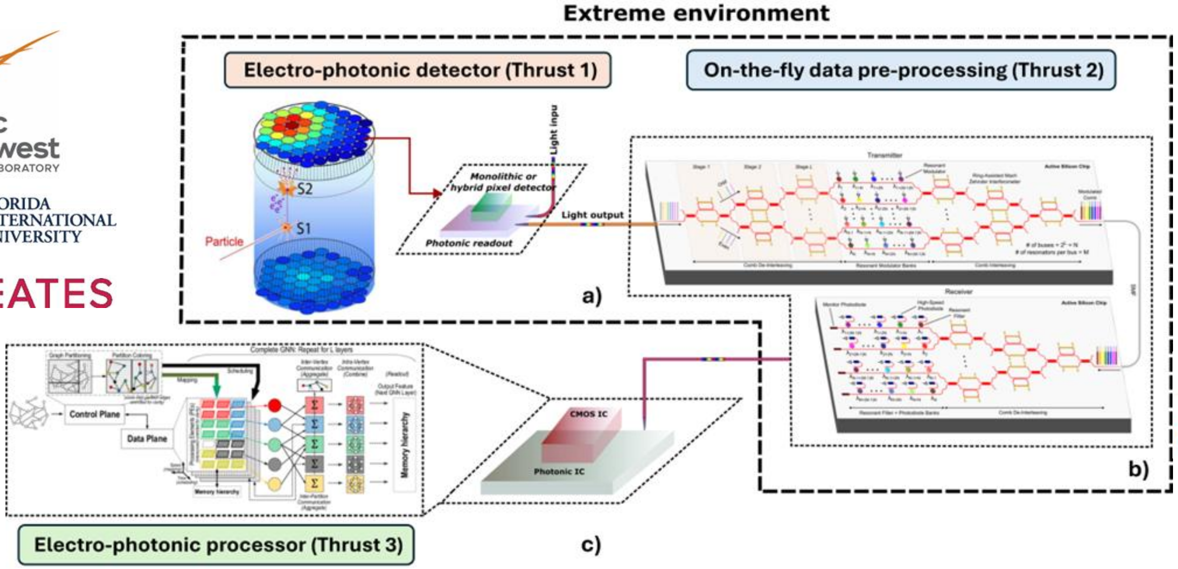
Brookhaven National Laboratory

Energy efficient microelectronics center integrating innovations across materials, devices, information handling modalities, and system architectures

Intelligent end-to-end codesign

Nanoscale materials → Neuromorphic architecture → In-transit Data processing → Heterogeneous integration

Brookhaven National Laboratory
Columbia University in the City of New York
CUNY The City University of New York
cadence
Pacific Northwest National Laboratory
FIU Florida International University
NYCREATES

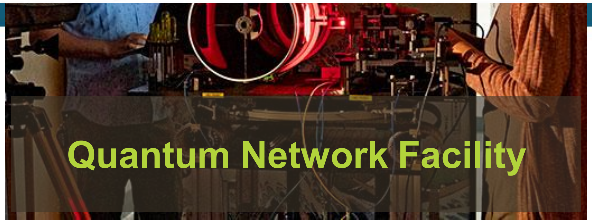


EI-Pho: Electro-Photonic Integrated Platform for Near-Sensor Processing in Extreme Environments

AIM Photonics
GlobalFoundries
Tower Semiconductor

Brookhaven National Laboratory

BNL User Facilities: microelectronics & QIST



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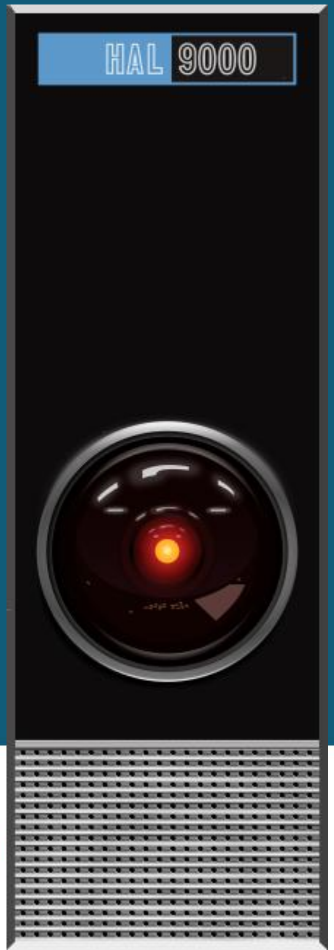
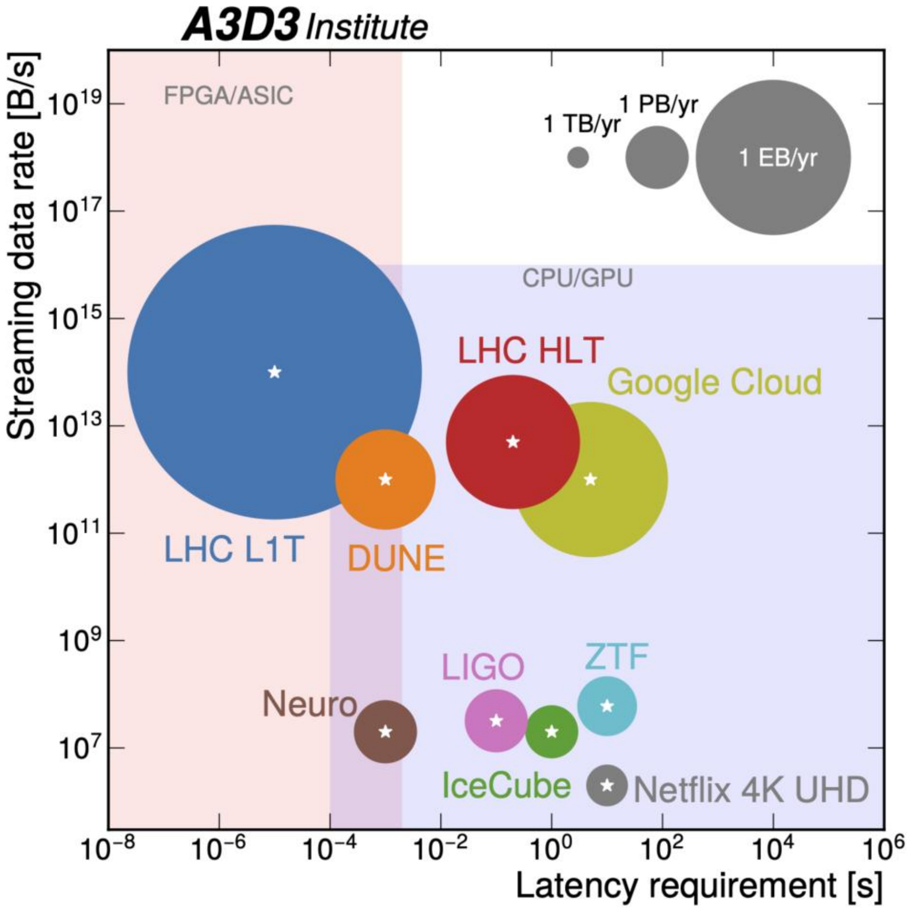


Artificial Intelligence (AI)

From automated to
autonomous

AI for science

- Large and complex scientific data sets
- Processing and analysis challenge
- Existing processor technologies are suitable for AI algorithms
  - graphics processing units (GPUs) and field-programmable gate arrays (FPGAs)



Latency, throughput, and estimated dataset sizes for a number of scientific and industry real-time AI applications, provided by the A3D3 NSF institute

https://a3d3.ai/about/

Brookhaven National Laboratory

Opportunities for AI/ML

Energy efficiency

*It is estimated that the U.S. light sources will generate **exabytes (EB)** of data over the next decade, requiring tens to **1,000 PFLOPS** of peak on-demand computing resources, and utilization of billions of core hours per year**

Edge processing, Fast feedback, Self calibration, Operations

Data quality (filtering, conditioning, etc.), Identification, Reduction

Better design with generative AI

Summit, IBM-DOE, ORNL:148.6 petaflops thanks to its 2.41 million cores

IEEE Spectrum

Brookhaven National Laboratory

*N. Schwarz et al., Revised Selected Papers 17; 2020: Springer. 305 35

What's next? More AI!

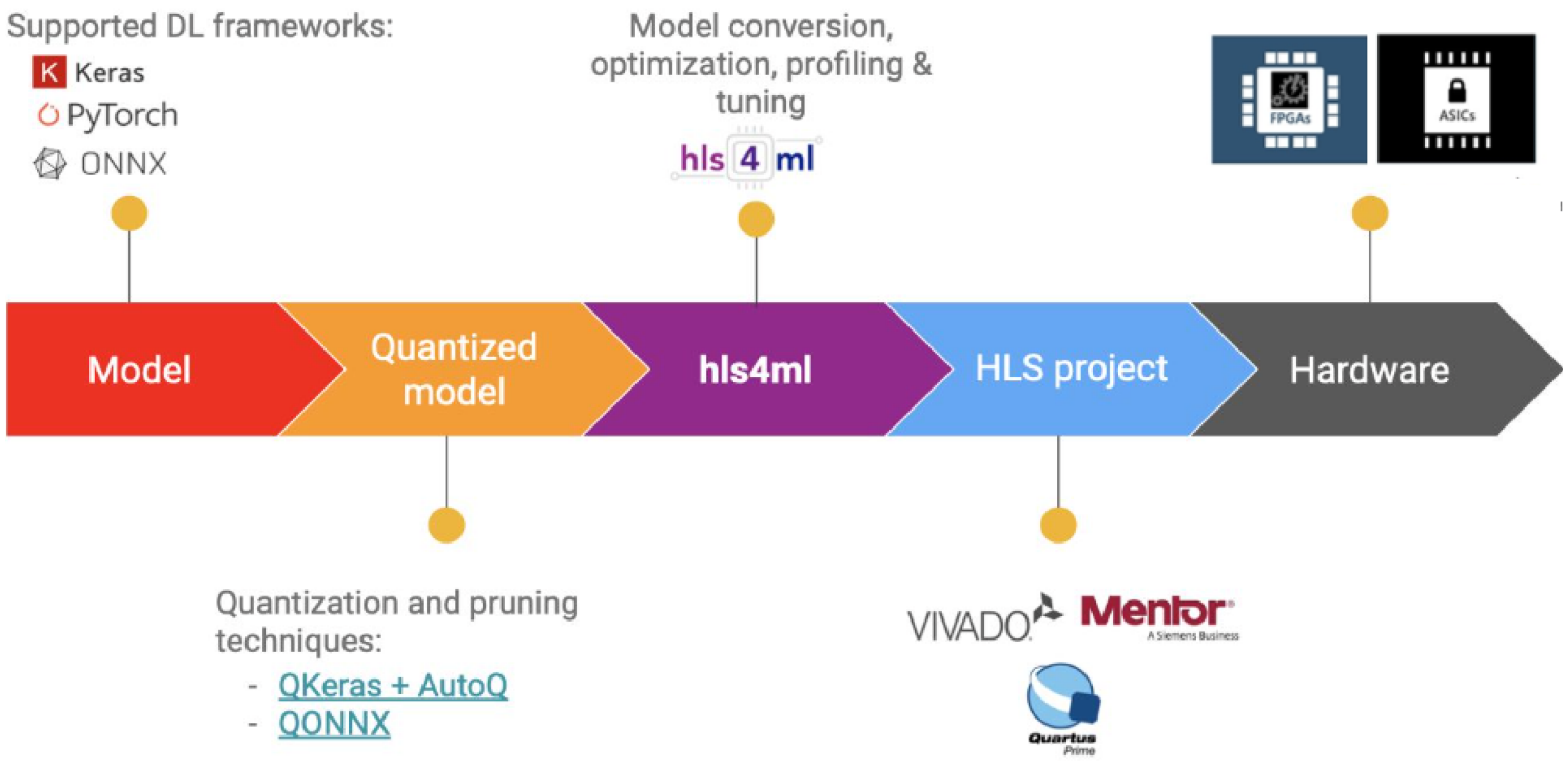
On-chip processing with modern data-science-driven co-design

Advancing AI in near-detector electronics is a natural evolution

- Improve data quality and reach
  - enable powerful and efficient non-linear data reduction or feature extraction techniques
- Reduce complexity of down stream processing systems
  - aggregate less overall information all the way to offline computing
- Increase efficiency and reduce complexity
  - enable real-time data filtering and triggering like at colliders (e.g., LHC, EIC)
  - use less data bandwidth
- Enable faster feedback loops
  - control or operations loop for particle accelerators

Enabled by new tools…

Software-hardware codesign with hls4ml[1]



A typical workflow to translate an ML model into an FPGA or ASIC implementation using hls4ml.

The red boxes (left) describe the model training and compression steps performed within conventional ML software frameworks.

The configuration and conversion steps are shown in the blue boxes (center). [2]

[1]https://fastmachinelearning.org/hls4ml/concepts.html

[2]arXiv:2204.13223v1 [physics.ins-det]

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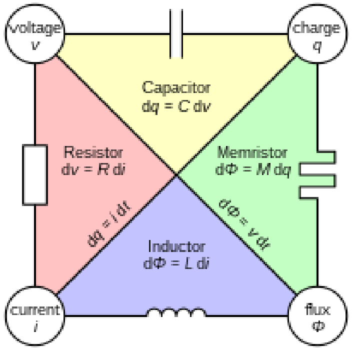
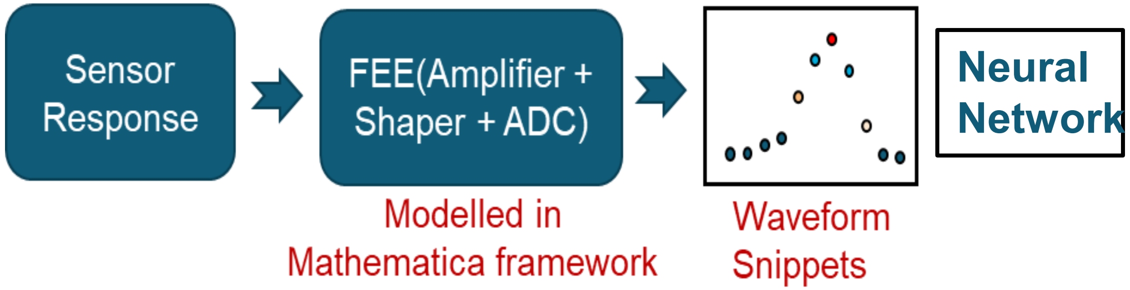
… may require new devices



Implementation on analog signals

- Highly-digital and ML-assisted front-end allow signal processing and data quality not achievable in pure analog processing[1]
- High energy efficiency can be achieved with analog AI circuits and neuromorphic algorithms



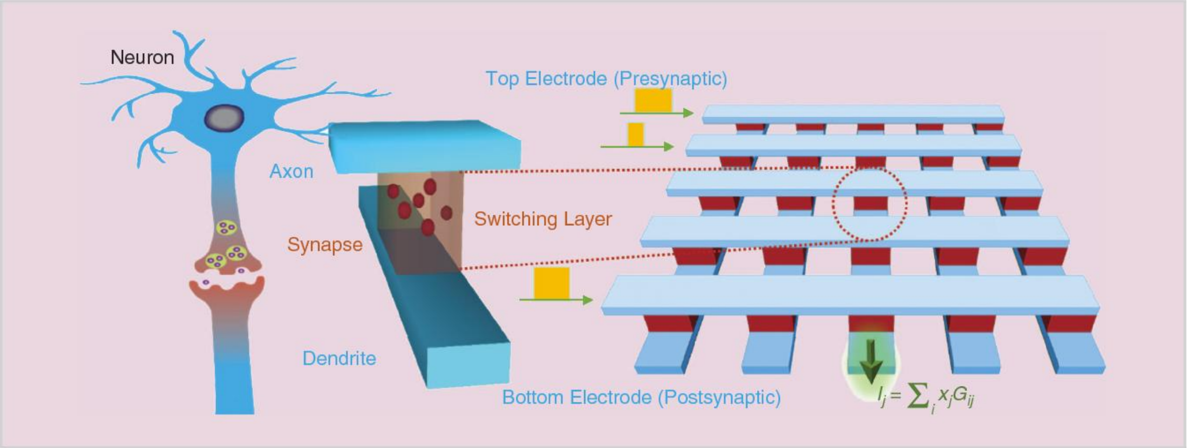


FIGURE 1 An illustration of the similarities between biological and memristor-based artificial synapses and networks.

Neural Networks (NN) circuital solutions for extraction of features from digitized pulses on frontend ASICs (signal amplitude, time-of-arrival, charge deposition, etc.) [2]

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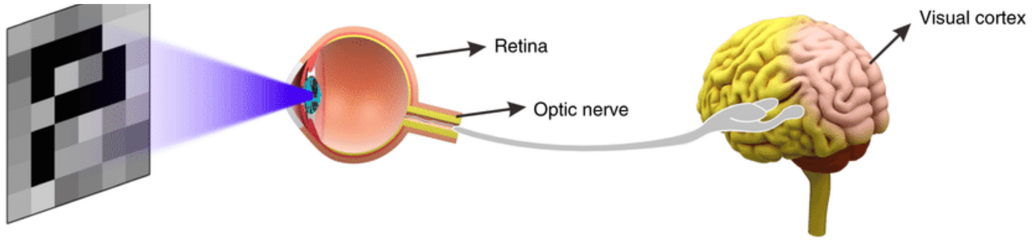
[1]S. Mandal, et al., "Real-Time Feature Extraction for Readout ASICs: Algorithms and On-Chip Implementations," 2023 IEEE NSS MIC RTSD; [2]arXiv:2204.13223v1 [physics.ins-det], [3] Y. Jeong, W. Lu, IEEE Nanotechnology, **12**, 6, 2018

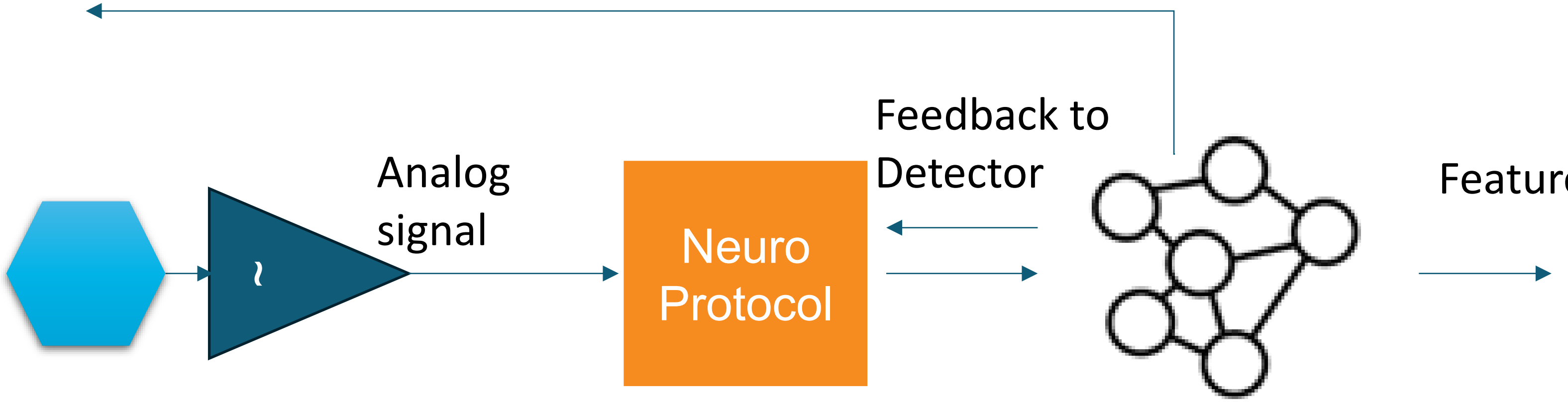
Idea of a New Concept of a Smart Detector

AI is aware of the detector (HEP Hardware) and has access to individual pixels for detector control (such as gain and speed) and to experiment control (such as brightness and position)

Particles hitting sensor | Eye | Brain



Feedback to Experiment



MAPS Sensor

Courtesy of P. Maj

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Binary Readout
High occupancy (10 Mcps)
Low noise (10 el.)
Low Power (100nW)
Small Area (20um)

Biologically inspired
Event based
Frameless
Low Latency
Single Pixel access

Neuromorphic Processor - “brain” of the detector
Event / Address protocol (supported by SNN)
Real-time features extraction (as Trigger primitives – coincidence in time, neutrino oscillation amplitudes or time-resolved spectra)

Questions?


NO WHEELS HERE
NO NEW TECHNOLOGY
NO
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