Future of Detector Development

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U.S. DEPARTMENT OF ENERGY

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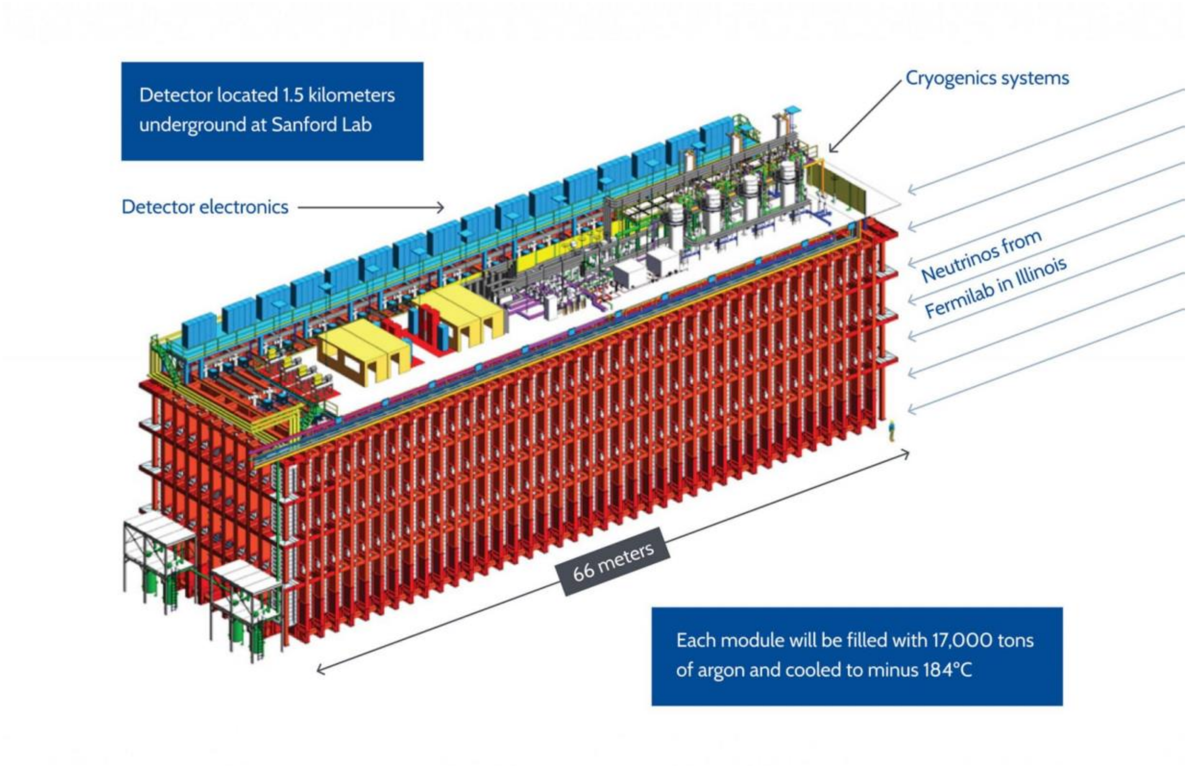
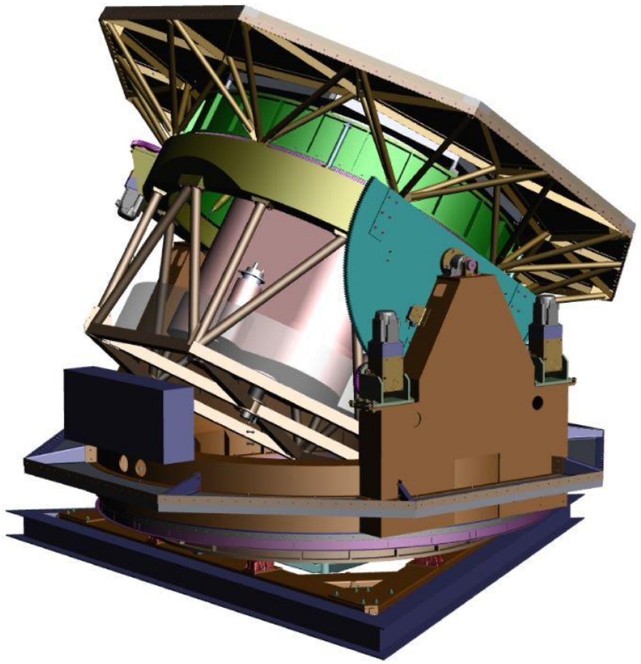
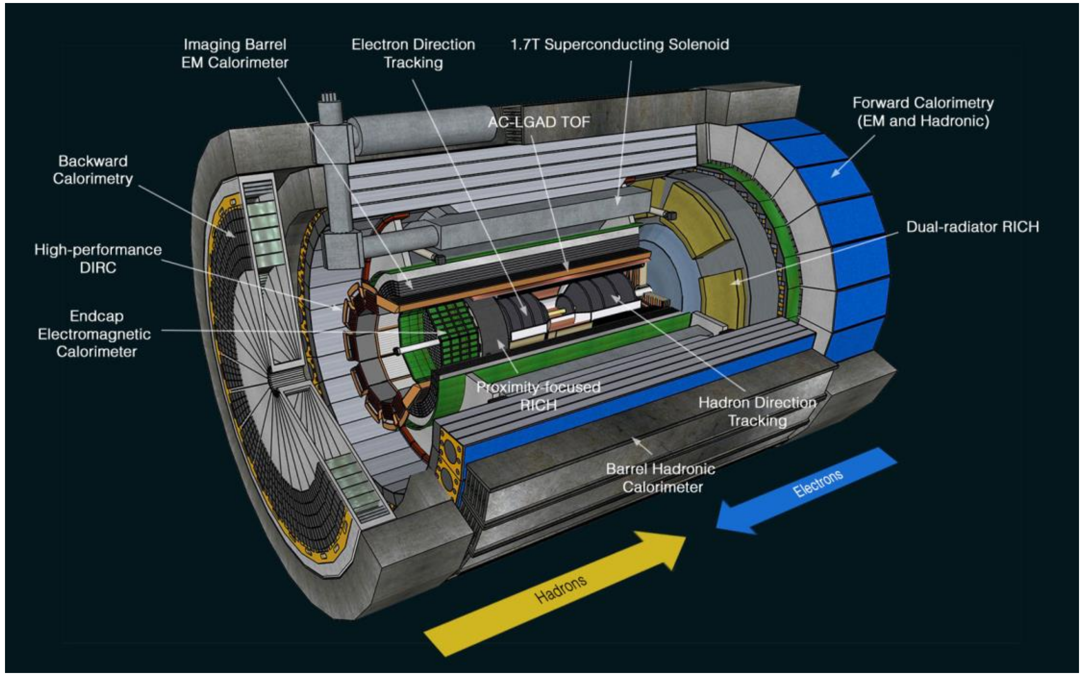
Future Detectors







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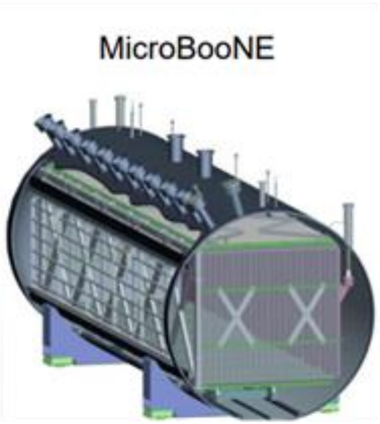
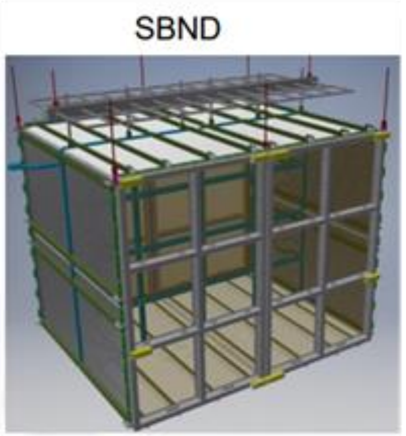
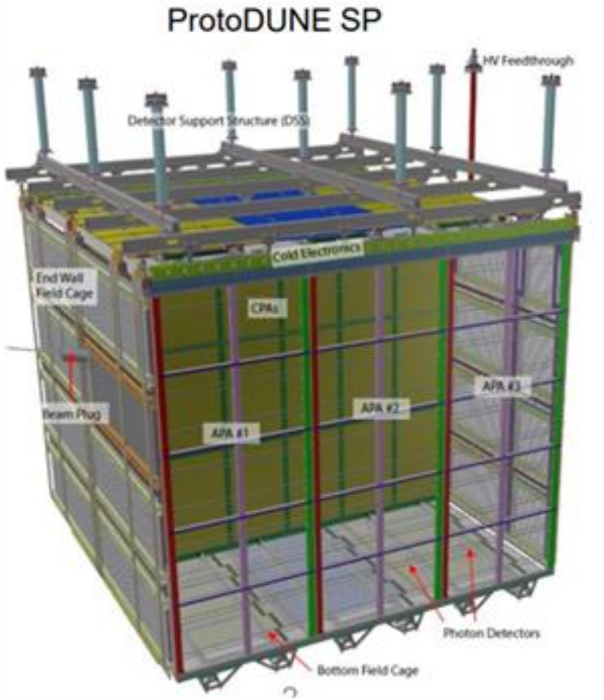
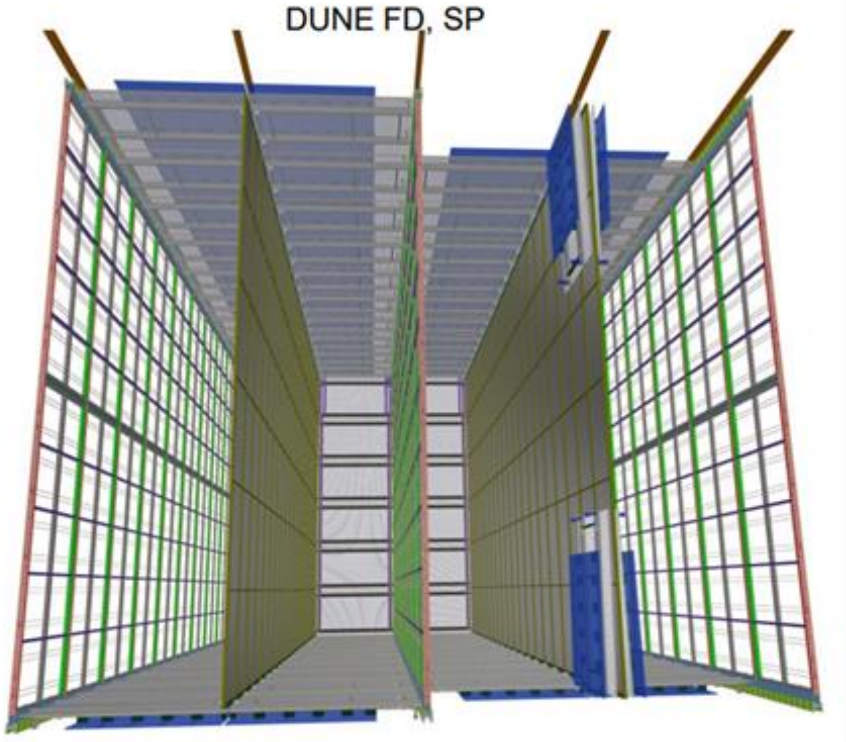
Each of these is a long journey…









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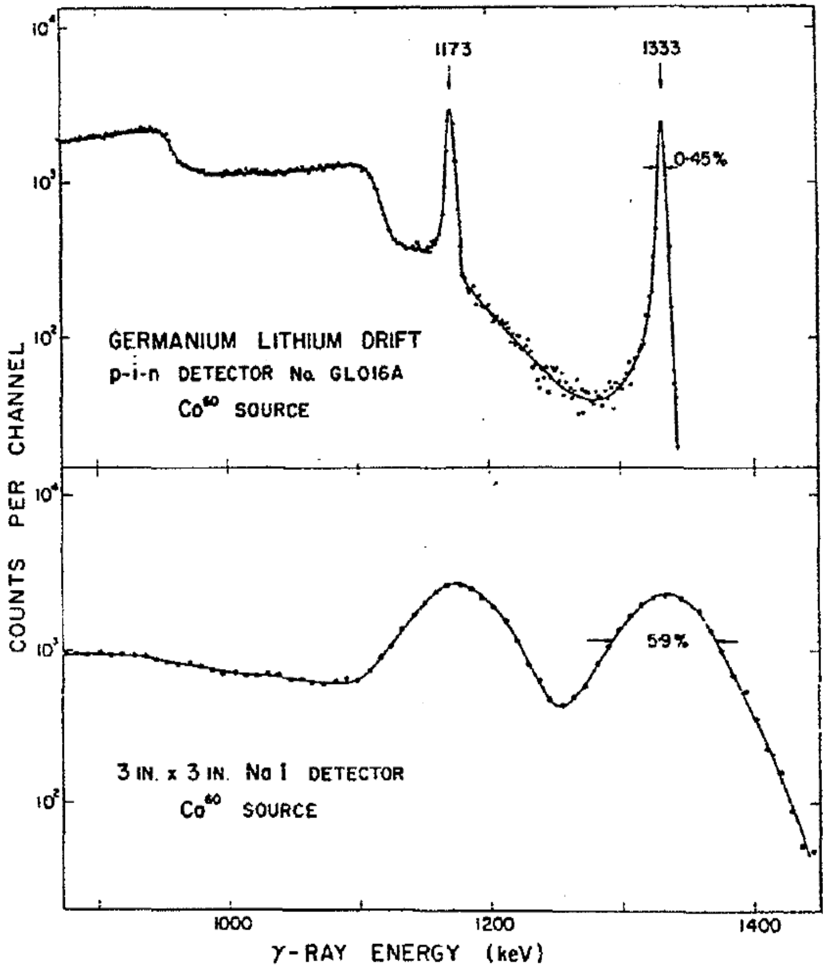
Select events in LAr detector technology development

- 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 …

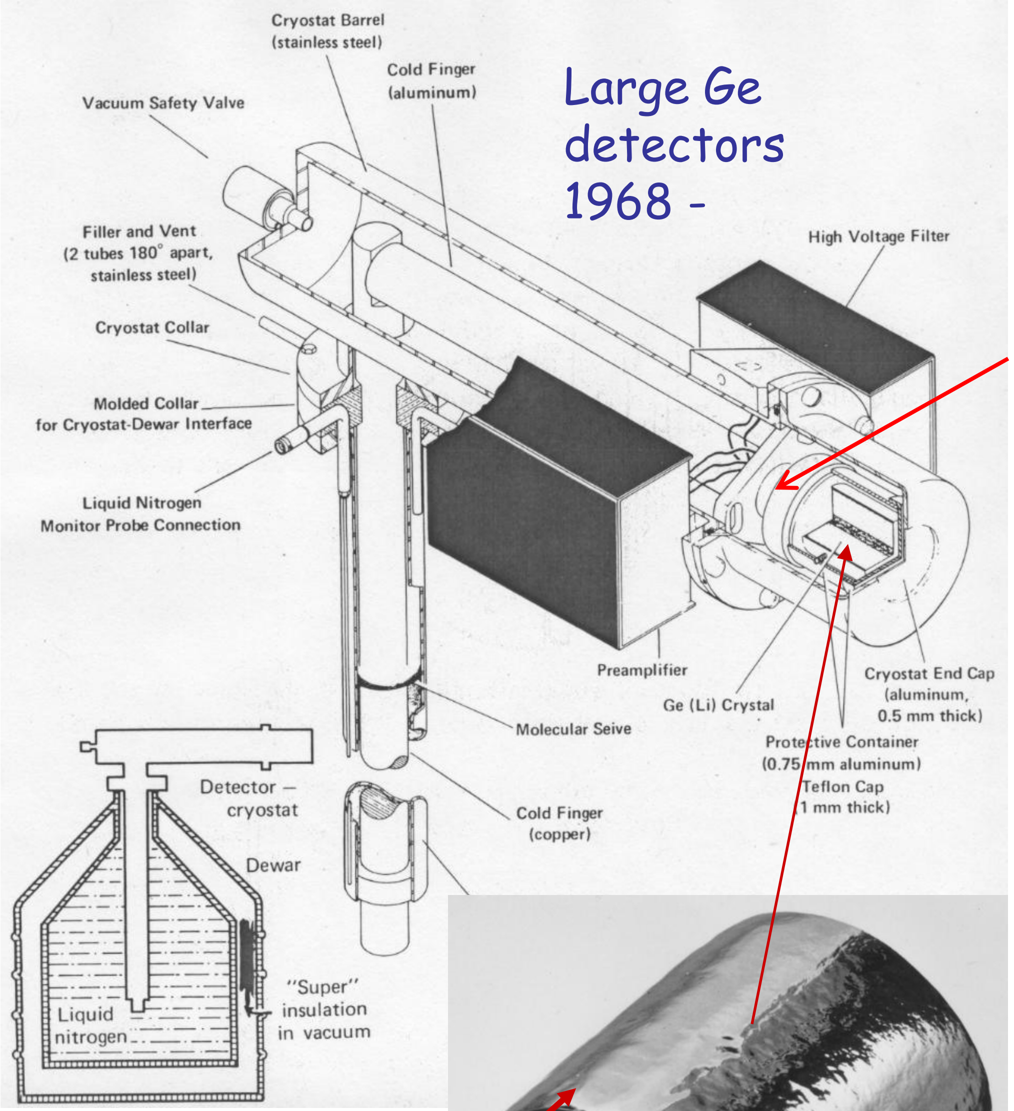
Courtesy of V. Radeka

1963 Germanium Detector Breakthrough

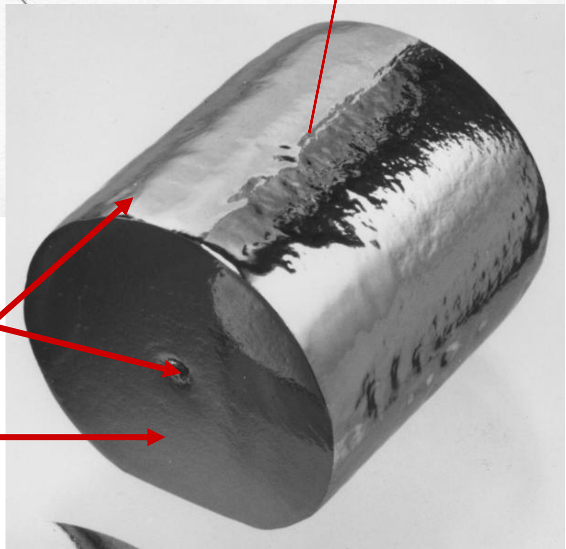


From: A.J. Tavendale (1963)

Large Ge detectors 1968 -



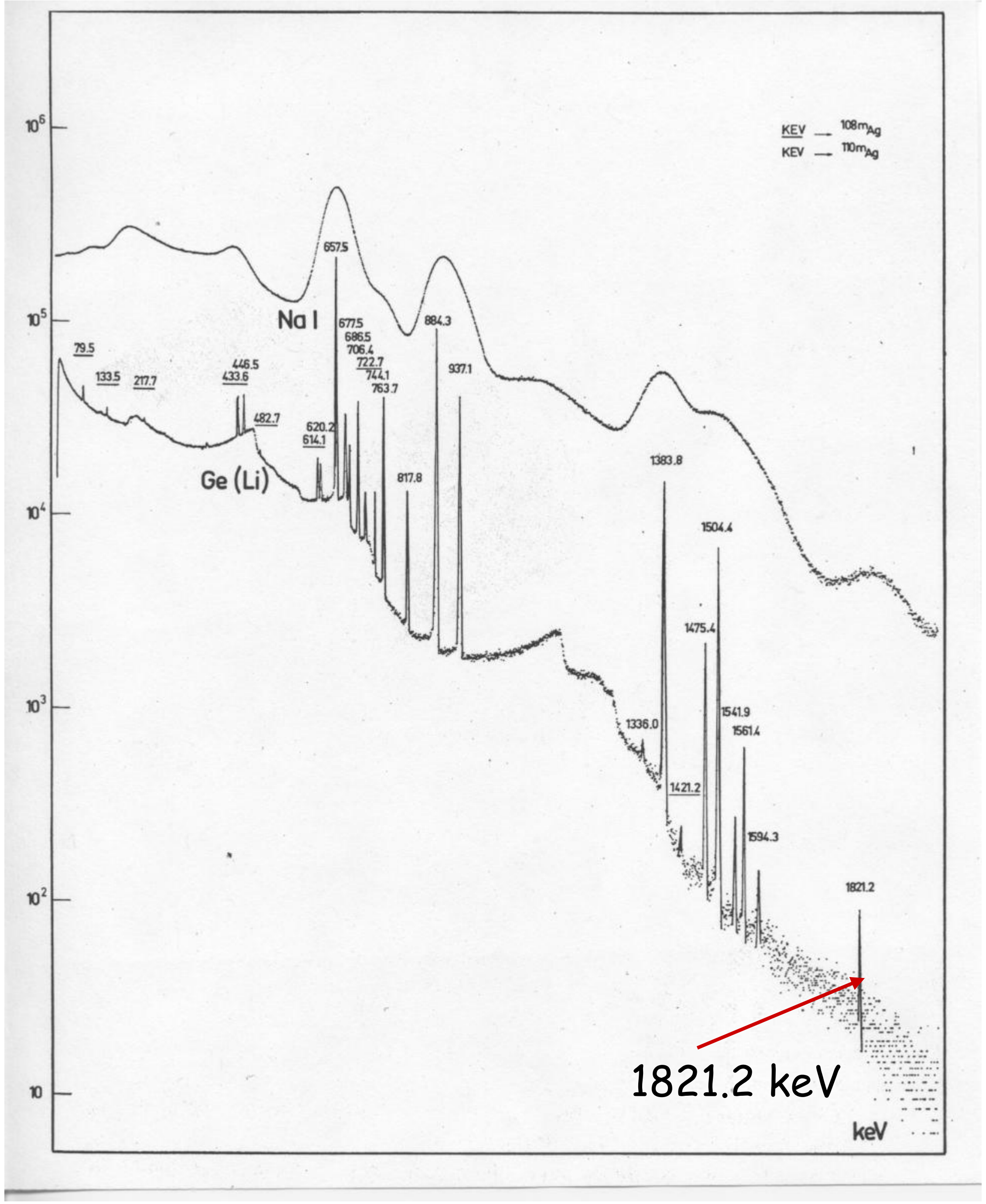
First cold JFET on a detector



Coaxial det.contacts

Ge-crystal
~50-100 cm^3

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

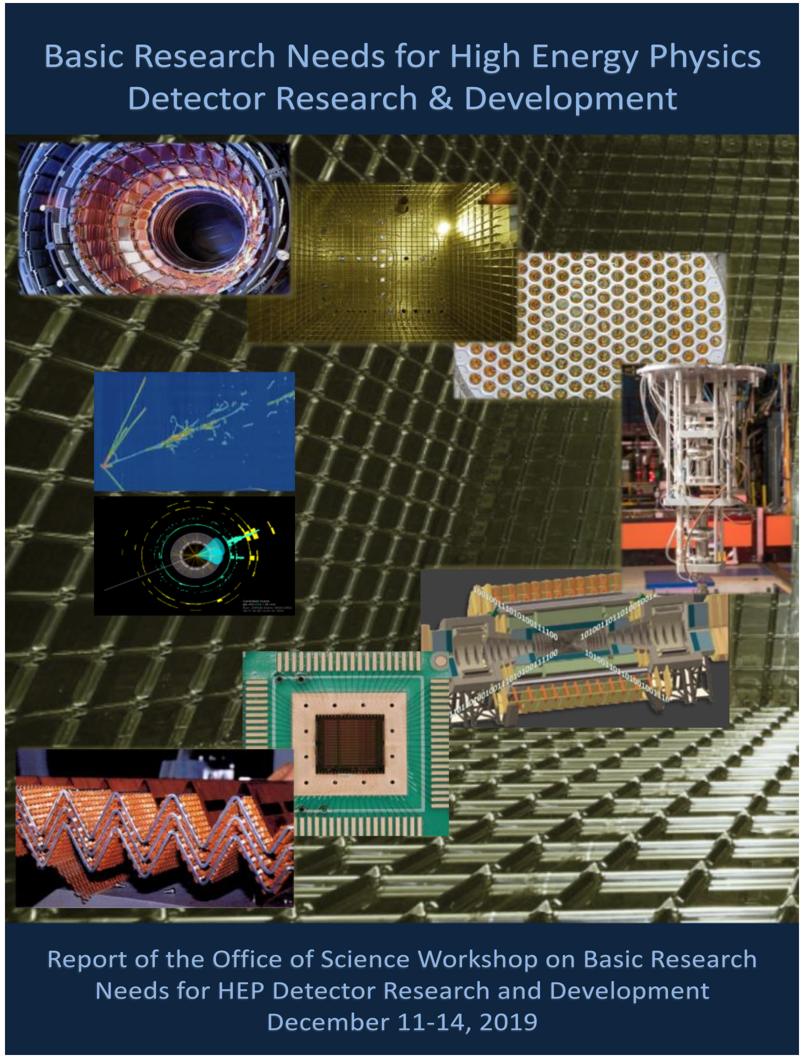
Enabled by key technologies

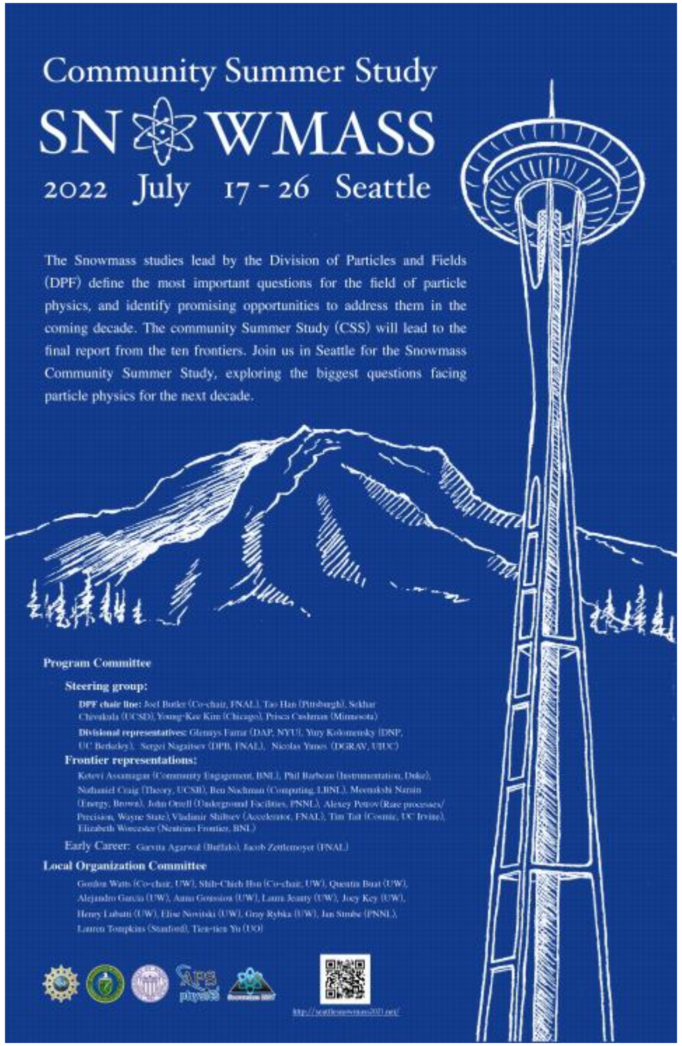
"New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. **The effect of a tool-driven revolution is to discover new things that have to be explained**" (Freeman Dyson)

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

Adaptation from Fleming/Shipsey BRN report presentation

Developing next-generation detectors





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Grand Challenges

1. Advancing HEP detectors to new regimes of sensitivity

2. Using integration to enable scalability for HEP sensors

3. Building next-generation HEP detectors with novel materials and advanced techniques

4. Mastering extreme environments and data rates in HEP experiments

	PRD: Priority Research Direction	Grand Challenge
Calorimetry	PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	1
	PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	1,4
	PRD 3: Develop ultrafast media to improve background rejection in calorimeters and particle identification detectors	1,3,4
Nobles	PRD 4: Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity	1,2
	PRD 5: Develop new modalities for signal detection	1
	PRD 6: Improve the understanding of detector microphysics and characterization	1
Photodetectors	PRD 7: Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity	1,3
	PRD 8: Advance high-density spectroscopy and polarimetry to extract all photon properties	2,3
	PRD 9: Adapt photosensors for extreme environments	2,4
	PRD 10: Design new devices and architectures to enable picosecond timing and event separation	1,2,4
	PRD 11: Develop new optical coupling paradigms for enhanced or dynamic light collection	1,2,3
Quantum	PRD 12: Advance quantum devices to meet and surpass the Standard Quantum Limit	1,3
	PRD 13: Enable the use of quantum ensembles and sensor networks for fundamental physics	1,2
	PRD 14: Advance the state of the art in low-threshhold quantum calorimeters	1,3
	PRD 15: Advance enabling technologies for quantum sensing	1,2,3
ASIC	PRD 16: Develop process evaluation and modeling for ASICs in extreme environments	3,4
	PRD 17: Create building blocks for Systems-on-Chip for extreme environments	1,4
SolidState	PRD 18: Develop high spatial resolution pixel detectors with precise high per-pixel time resolution to resolve individual interactions in high-collision-density environments	1,4
	PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking	2,3
	PRD 20: Realize scalable, irreducible-mass trackers	2,3
TDAQ	PRD 21: Achieve on-detector, real-time, continuous data processing and transmission to reach the exascale	2,4
	PRD 22: Develop technologies for autonomous detector systems	2
	PRD 23: Develop timing distribution with picosecond synchronization	1
Xcut	PRD 24: Manipulate detector media to enhance physics reach	1,3
	PRD 25: Advance material purification and assay methods to increase sensitivity	1,2,3,4
	PRD 26: Addressing challenges in scaling technologies	2,3

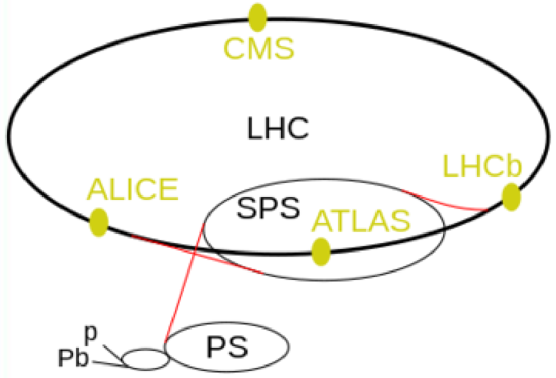
The Grand Challenges

- Advancing HEP detectors to new regimes of sensitivity: To make the unmeasurable measurable will require the development of sensors with exquisite sensitivity with the ability to distinguish signal from noise…. **Research will be needed to develop these sensors with maximal coupling to the quanta to be sensed and push their sensitivities to ultimate limits**.
- Using Integration to enable scalability for HEP sensors: Future HEP detectors for certain classes of experiments will require massive increases in scalability to search for and study rare phenomena ... **A key enabler of scalability is integration of many functions on, and extraction of multidimensional information from, these innovative sensors.**
- Building next-generation HEP detectors with novel materials & advanced techniques: Future HEP detectors will have requirements beyond what is possible with the materials and techniques which we know. **This requires identifying novel materials … that provide new properties or capabilities and adapting them & exploiting advanced techniques for design & manufacturing**.
- Mastering extreme environments and data rates in HEP experiments: Future HEP detectors will involve extreme environments and exponential increases in data rates to explore elusive phenomena. ... **To do so requires the intimate integration of intelligent computing with sensor technology.**

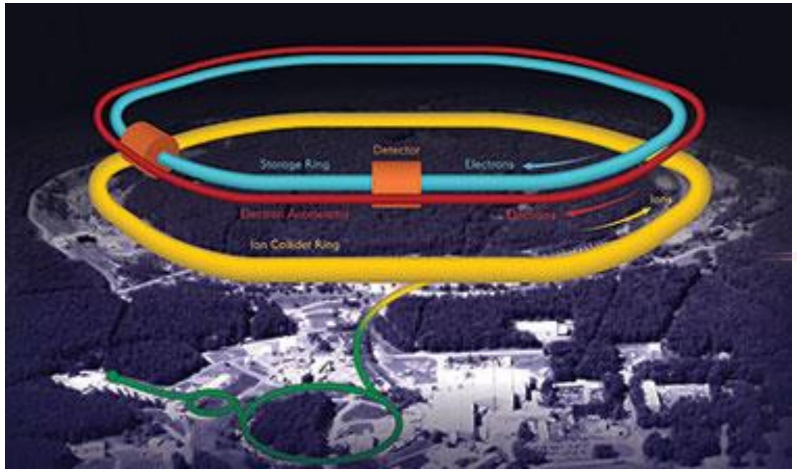
https://doi.org/10.2172/1659761

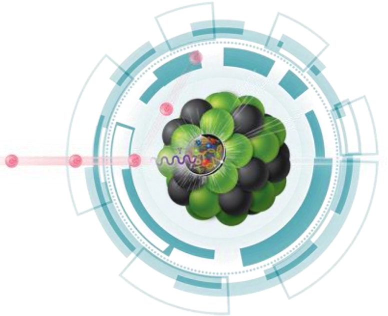
New facilities drive new developments

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

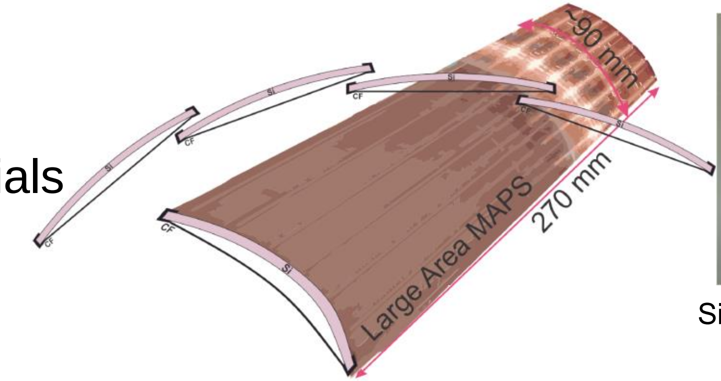


Relativistic Heavy Ion Collider (RHIC) & Electron Ion Collider (EIC), BNL





- 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

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

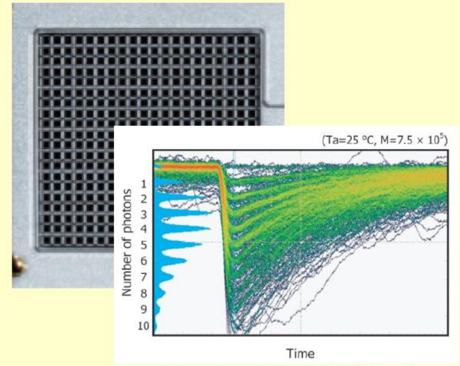
2022 Plenary **- Adding a New Dimension to Photon Detection: 3D Integrated Single Photon Avalanche Diode Arrays**, Jean-Francois Pratte

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

Sensor evolution: bigger, faster, ultra-sensitive

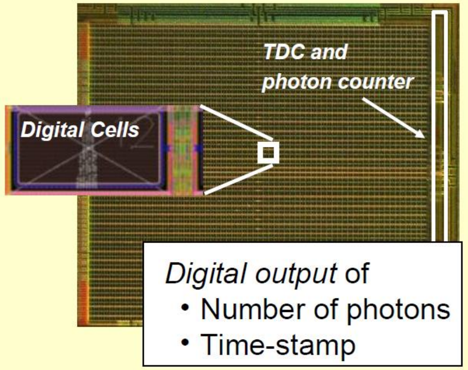
Silicon photomultipliers - SiPM

Analog SiPM



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

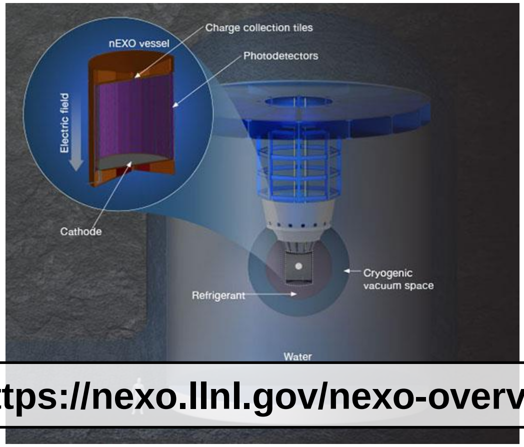
Digital SiPM



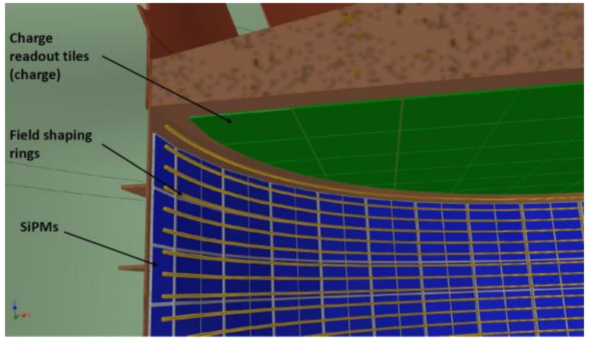
Digital output of
- Number of photons
- Time-stamp

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

Challenge: SiPMs to cover large areas



https://nexo.llnl.gov/nexo-overview



- Charge collection on the anode plane
- Light collection on the barrel behind field shaping rings

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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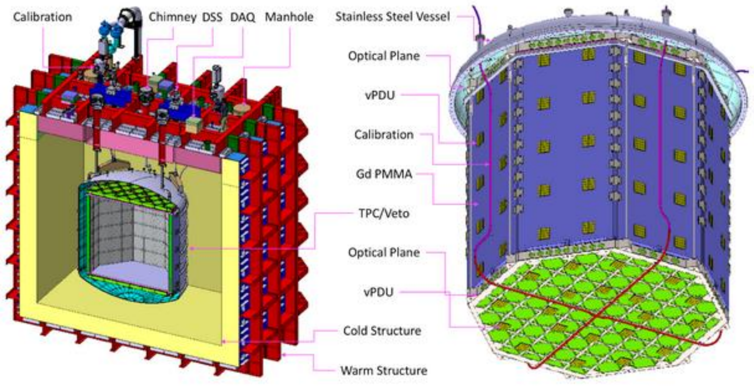
SiPM: Extend to the VUV region for noble element detectors

Current and proposed High-Energy Physics and Nuclear Physics experiments that need high QE in VUV range

nEXO	LXe	178 nm	~4 m2 (4x10^4 SiPMs)
DarkSide	LAr	128 nm	~14 m2 (14x10^4 SiPMs)
PETALO (PET)	LXe	178	~10^4 SiPM
MEG II	LAr	128 nm	~1 m2 (1x10^4 SiPMs)
Pioneer	LXe	178 nm	~5 m2 (5x10^4 SiPMs)
Darwin (XENIN,LZ)	LXe	178 nm	~21 m2 (12x10^4 SiPMs)
FLARE	LAr	128 nm	~1 m2 (10^4 SiPMs)
THEIA	WbLS	~200 nm	
High-pressure He-4 gas detectors for neutrons	He-4	175 nm or WLS	100 of SiPMs
High-pressure Xe detectors for gammas and neutrons	Xe	175 nm	100 of SiPMs

Extreme Environments



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

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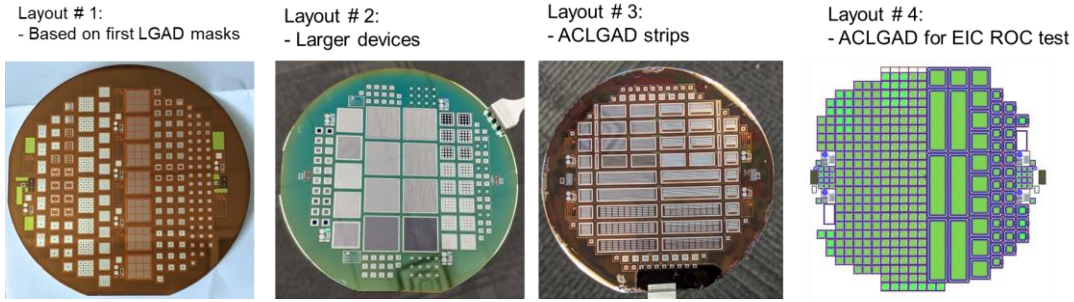
Courtesy of S. Rescia

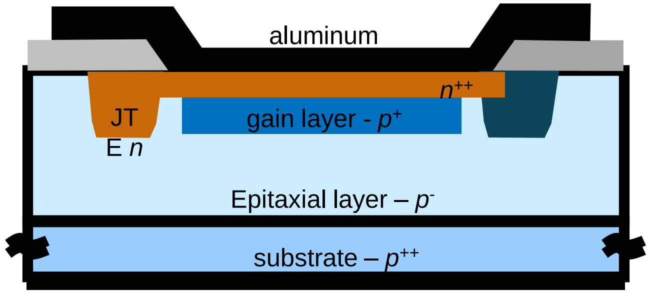
4D detectors – enabling technologies



Low Gain Avalanche Detectors: combining timing and position resolution

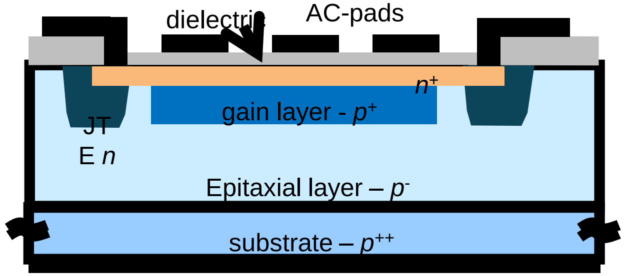
DC-LGAD on thin substrates

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



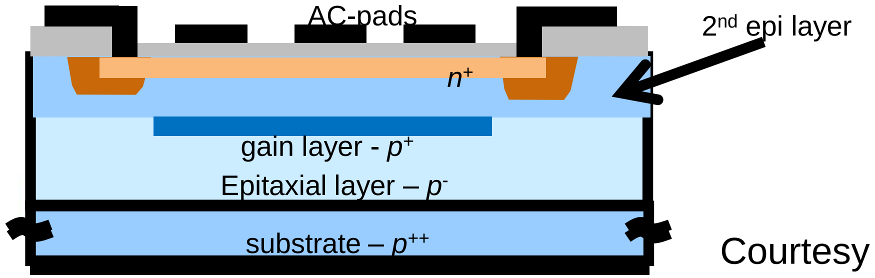
AC-LGAD

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



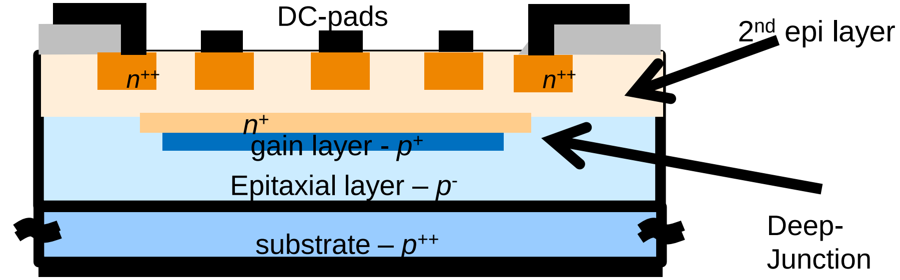
Deep-Layer AC-LGAD

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

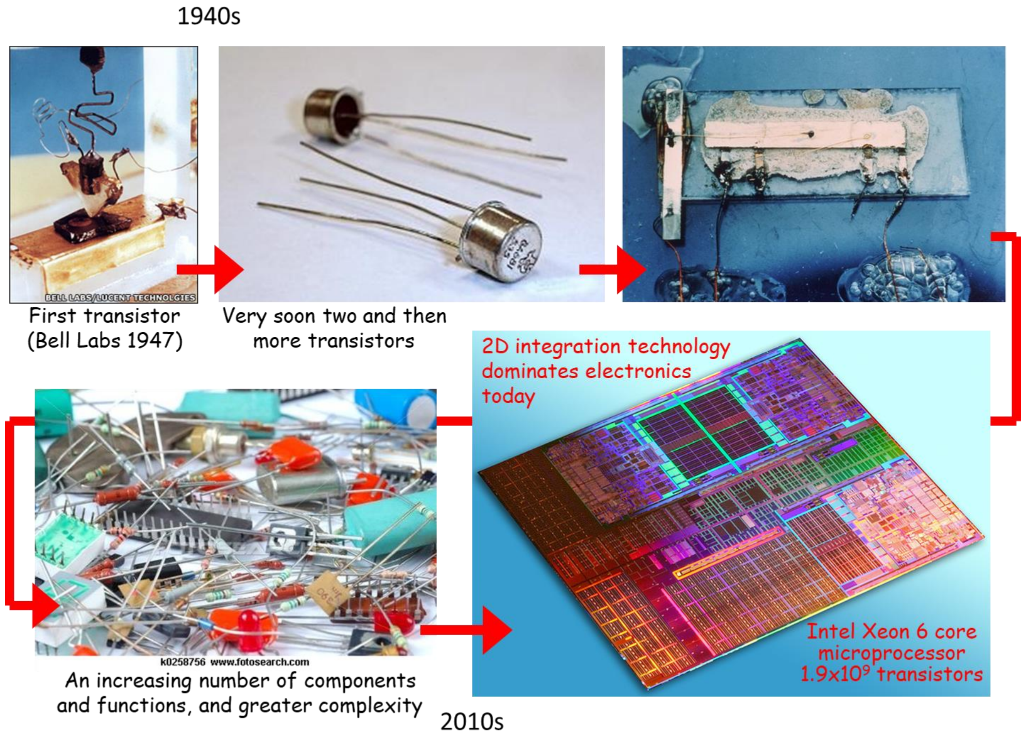
Application Specific Integrated Circuits

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



Courtesy of G. Deptuch

Beyond standard CMOS

3D vertical integration

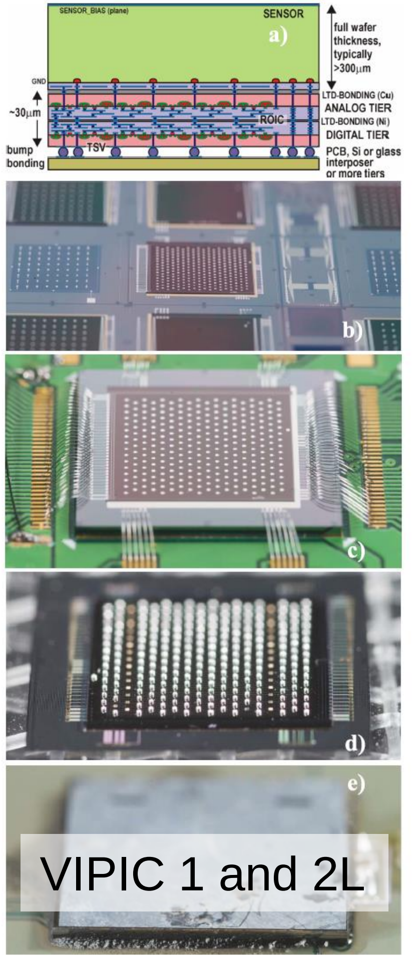
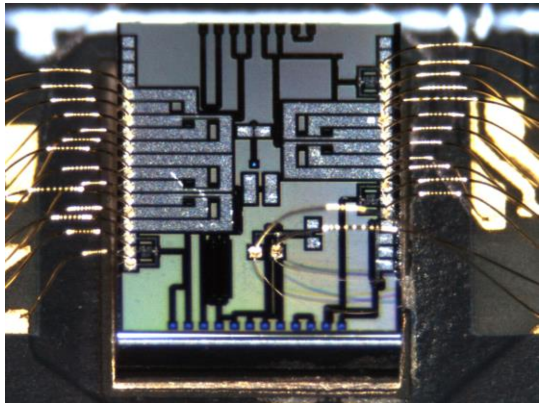


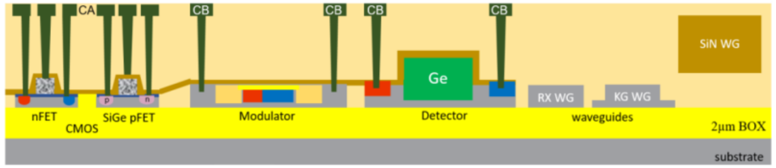
Fig. 1. (a) Cartoon of a fully 3-D integrated pixel detector. (b) VIPIC1 LTD-bonded on the sensor wafer with the back-side bump-bonding pads exposed before wafer dicing. (c) VIPIC1 LTD-bonded on the sensor with the wirebonding connections to the PCB using traces on the sensor. (d) VIPIC1 LTD-bonded to the sensor with the bump-bonding Sn–Pb balls deposited on the back. (e) VIPIC1 LTD-bonded on the sensor bump-bonded upside down on the precision PCB.

Deptuch, IEEE 2016

Photonics



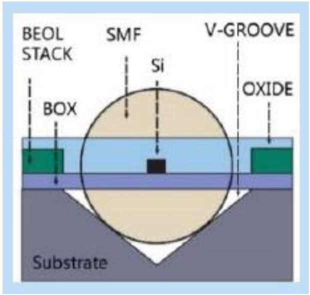
P. Arseanult, IEEE 2022
Silicon photonics test chip – V1
Université de Sherbrooke



GlobalFoundries 45SPCLO process cross-section

Entirely Galvanically Isolated (GalIsol) detector system

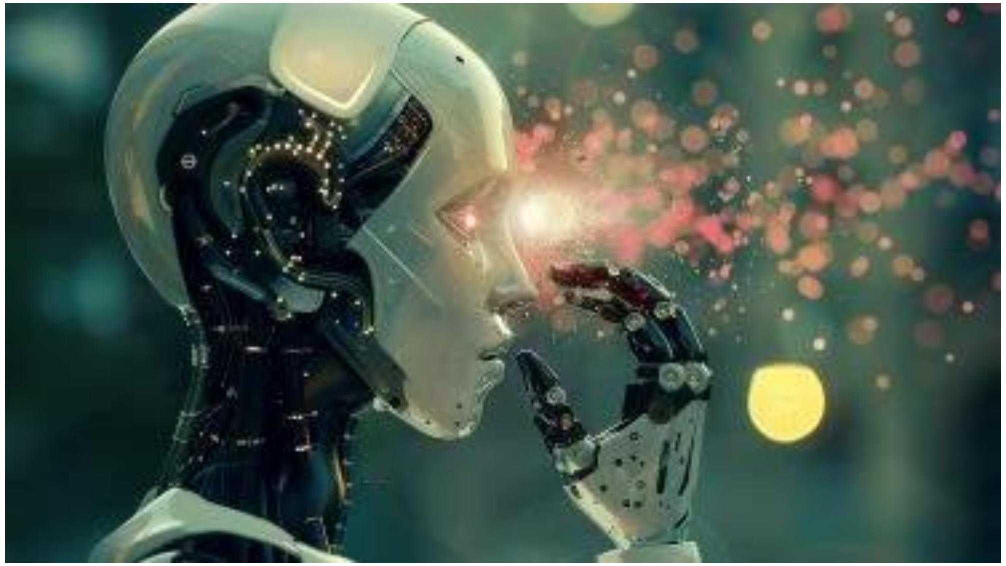
- **Power -** by light on fiber (PoF) and PV cells;
- **Slow Control and Reference Clock** - delivered on fiber
- **High-Speed data -** on fiber, wavelength multiplexed, EOM = Photonic IC (PIC)



Attractive for noble liquid detectors

Deptuch, HEPIC 2024

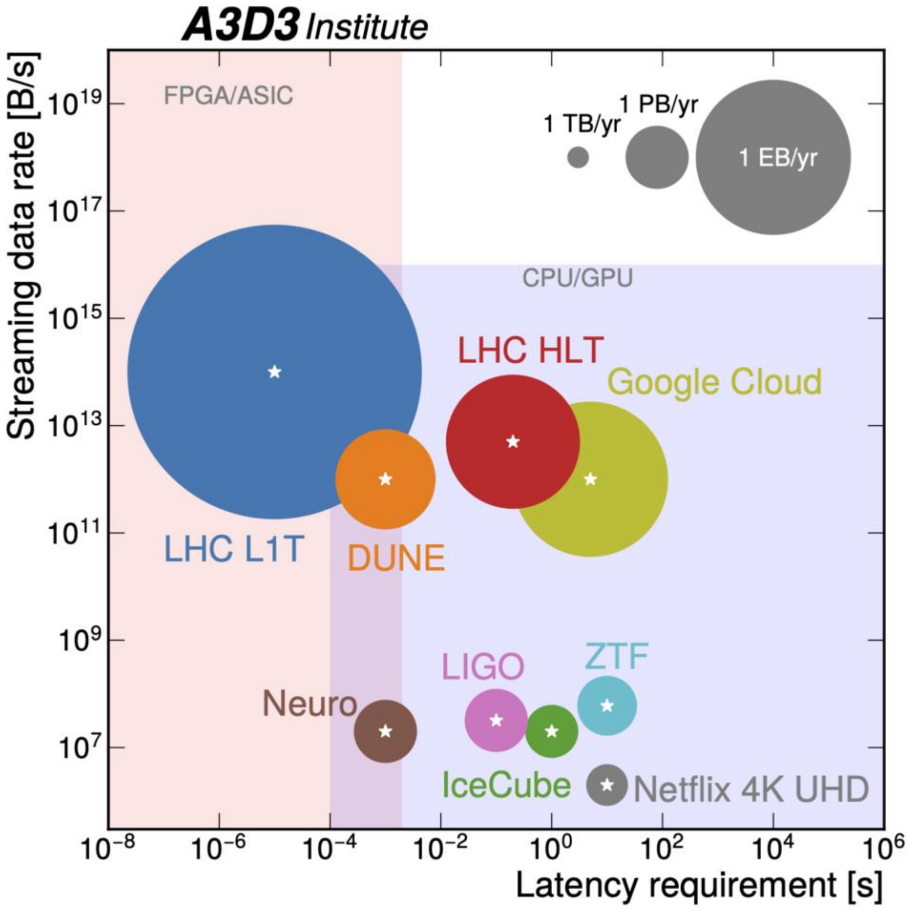
Artificial Intelligence (AI)



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/

Opportunities for AI/ML

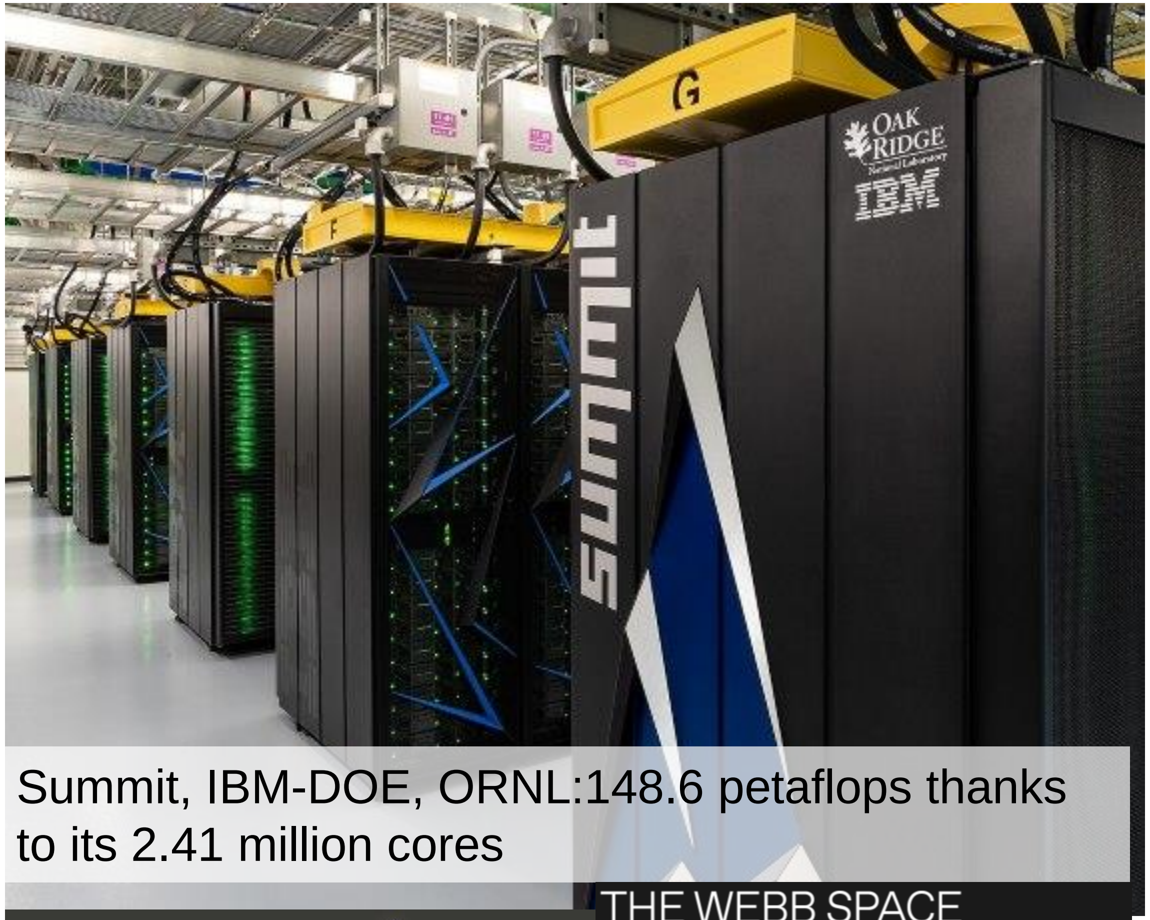
Energy efficiency

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

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

What's next? More AI!

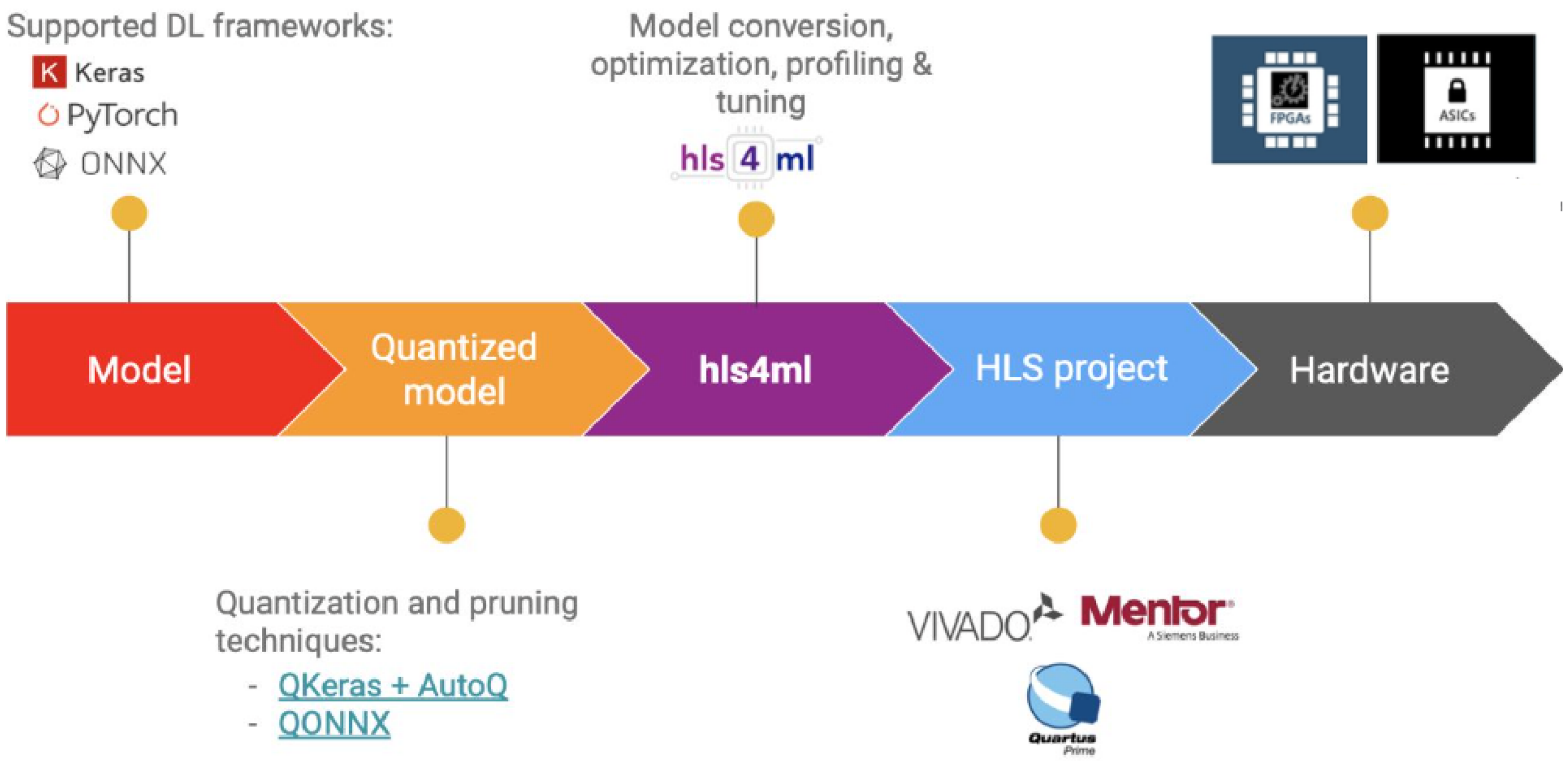
On-chip processing with modern data-science-driven co-design

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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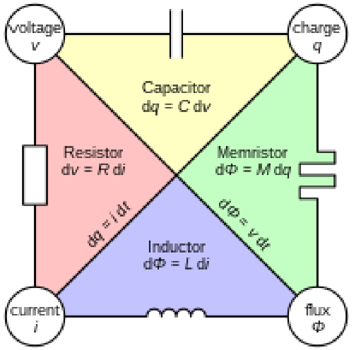
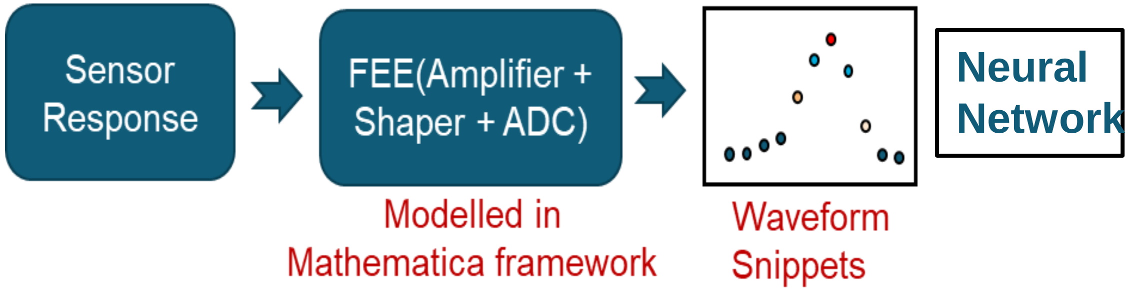


… may require new devices

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



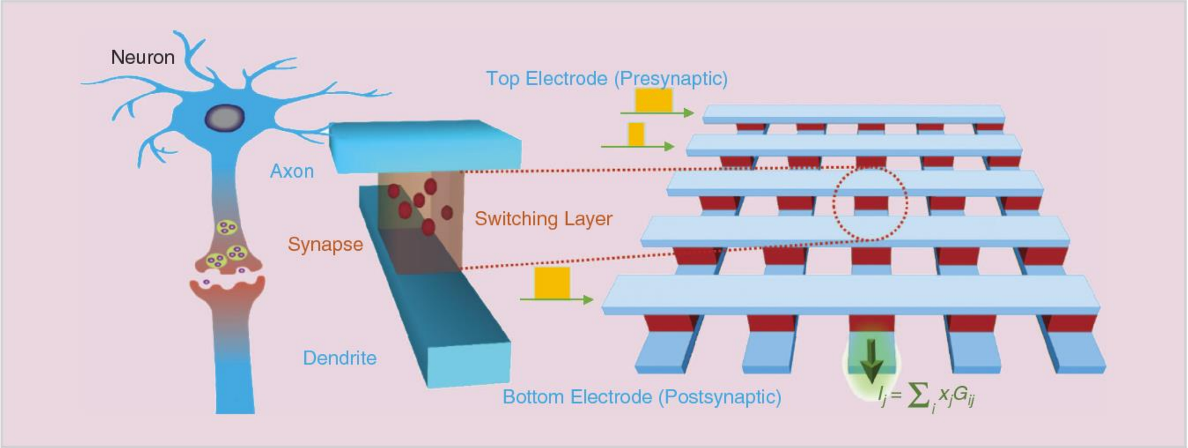


FIGURE 1 An illustration of the similarities between biological and memristor-based artificial synapses and networks.

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

[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

Scientists Propose New Way To Search for Dark Matter

TOPICS: Astronomy Astrophysics Dark Matter DOE Popular SLAC National Accelerator Laboratory

By SLAC NATIONAL ACCELERATOR LABORATORY MAY 6, 2024

Physicists at SLAC National Accelerator Laboratory are exploring a new method to detect dark matter using quantum devices, focusing on a lesser-known form called thermalized dark matter. Their approach involves utilizing quantum sensors, traditionally disrupted by unexplained energy intrusions, to potentially detect dark matter's subtle energy impacts. This innovative research leverages the unique capabilities of quantum technology to potentially solve the long-standing mystery of dark matter detection. Credit: SciTechDaily.com

"Dark Matter Induced Power in Quantum Devices" by Anirban Das, Noah Kurinsky and Rebecca K. Leane, 22 March 2024, *Physical Review Letters*.

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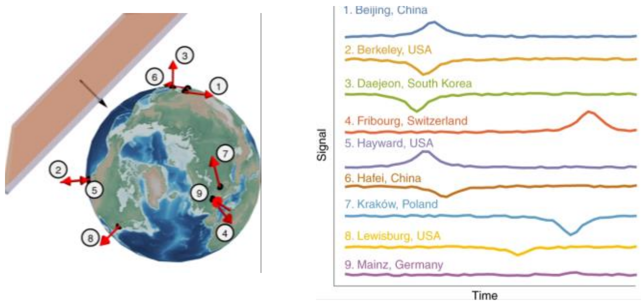
Distributed quantum entanglement

There are two planned networks of atom interferometers for searches of gravitational waves and/or ultra-light DM:

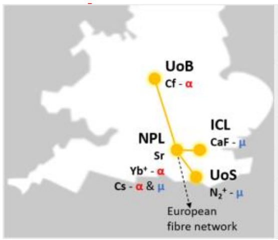
- Atom Interferometric Observatory and Network (AION) collaboration (UK) - connection with MAGIS100 (USA)
- Zhaoshan long-baseline Atom Interferometer Gravitation Antenna (ZAIGA) collaboration (China)

- *Global Network of Magnetometers for Searches of Exotic Physics (GNOME):* An axion-like particle (ALP) “wall” can be seen as an effective Zeeman shift in the nuclear spin:

$$H_{\rm lin} = -(\hbar c)^{3/2} \frac{\xi}{f_{\rm SB}} \frac{\mathbf{S}}{\|S\|} \cdot \nabla a(\mathbf{r}, t)$$



- *Networked Quantum Sensors for Fundamental Physics* (QSNET) collaboration in the UK: network of seven atomic and molecular clocks of different species designed to search for deviations in the fine structure constant and the electron-to-proton mass



Clock	Kα	Kμ
Yb^+ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^+ (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

α: fine structure “constant”

μ: electron-to-proton mass

Open Question: Can (and how in practice) quantum entanglement improve the sensitivity and spatial resolution of these networks of distributed atomic sensors? HEP goals still require better bounds that what the above efforts promise!

Courtesy of J. Martinez-Rincon

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Distributed quantum entanglement

Astrometry

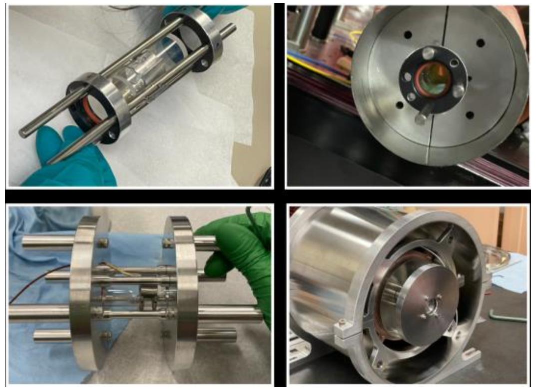
- Studying QIS techniques of two-photon interferometry to **enable practically arbitrarily large synthesized apertures**
- Experimenting several practical implementations of the technique to demonstrate how this can be deployed for cosmological and astronomical measurements

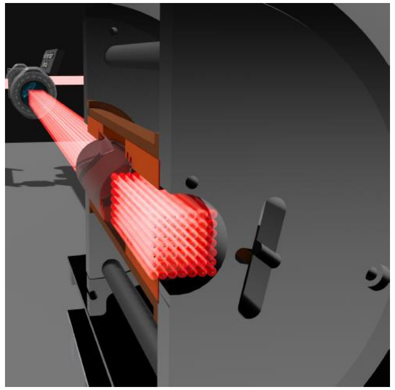
Network of sensors

- 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

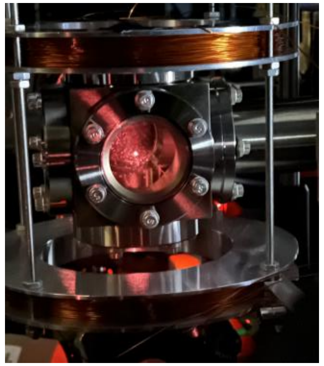
Atomic sensing

Currently, developing an array of 7x7 atom magnetometers



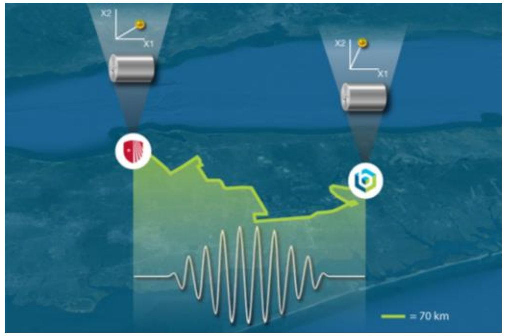


Next: Explore arrays of atomic clocks



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)



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Courtesy of P. Stankus and J. Martinez-Rincon

EDIT School 2023 - Excellence in Detector and Instrumentation Technologies
Hosted by Brookhaven National Laboratory, October 10-20, 2023

Locations: BNL (Upton, NY) and Danfords (Port Jefferson, NY)

Numbers: 2 weeks, 48 students (31% female, 63% non-US - all continents), 40+ BNL staff, 7 topics

- **Silicon Sensors: Design, Fabrication, and Testing**
- **Integrated Electronics for Detector Readouts**
- **Data Acquisition Systems for Quick Prototyping of Detectors Readout and an Experiment**
- **Liquid Argon Detectors: Physics, Design, and Operation**
- **Liquid Scintillators: Properties, Fabrication, and Analysis**
- **RF Cosmology: Techniques, Instrumentation, and Data**
- **Quantum Network: Concepts, Components, and Capabilities**

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https://www.bnl.gov/icfa-editschool/

HEPIC – activities and workshop

IC Design Traineeship Program With Applications In High Energy Physics

The HEPIC Traineeship Program provides graduate students from participating Universities interested in integrated circuit design with an opportunity to learn about the types of experiments conducted at Department of Energy (DoE) national laboratories around the country which work on high energy physics (HEP) including various particle accelerators. It introduces the trainees to the HEP design community, the scientific ASIC design challenges they face, and other students across the country who are part of the same program.

PI Contact: Mark Horovitz

SLAC · BERKELEY LAB · Stanford University · UC SANTA CRUZ · Brookhaven National Laboratory · Fermilab · UC DAVIS


HEPIC 2024

HEP-IC

April 30, 2024 to May 2, 2024
Brookhaven National Laboratory
US/Eastern timezone

Enter your search term

Registration is now closed. Please contact the event coordinator to see if you can still register.

- Overview
- Scientific Program
- Call for Abstracts
- Timetable
- Registration

Indico
- hepic24@brookhavenLa…
- scapp@bnl.gov
- dgorni@bnl.gov

HEP-IC Workshop 2024 is the fourth in a series of workshops designed to bring together US scientists and engineers involved in developing integrated circuit electronics for particle physics and related applications. Participants from US laboratories and Universities will have an opportunity to learn about the latest activities and developments of the various groups, trends in IC design and fabrication, and new technologies that will be needed to enable future scientific goals. The workshop will also promote collaborations, exchange of ideas on innovative circuit techniques, and provide a forum to discuss new approaches to partnerships and optimizing the use of technical resources. This workshop should provide a high-level overview of activities, together with opportunities for discussions and exploration of new ideas and partnerships to address the technical challenges posed by the next generation of HEP experiments.

BNL website (registration)

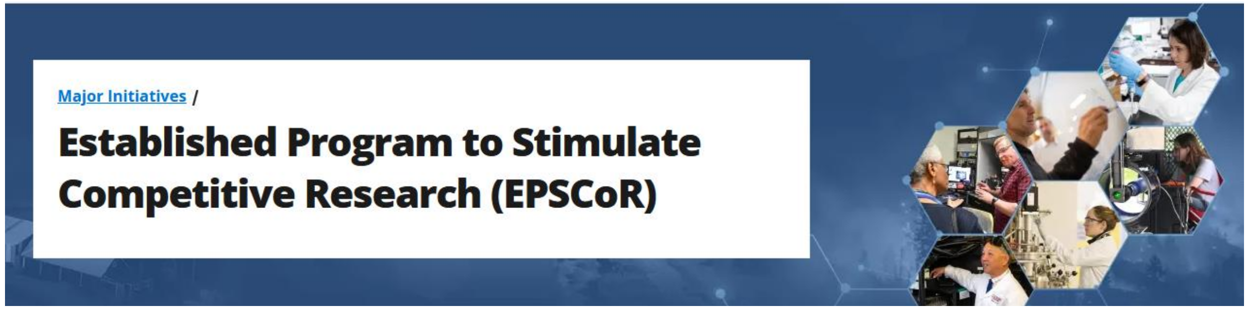
Innovation through diversity

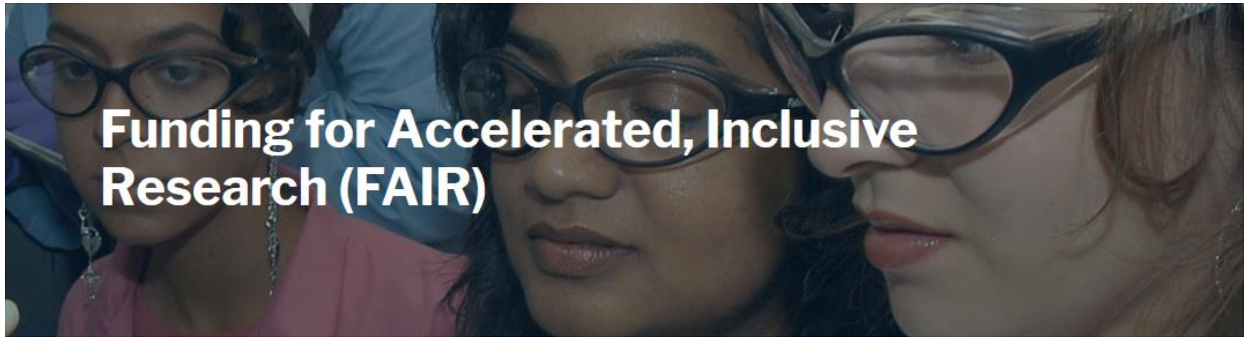
Why Diverse Teams Are Smarter

by David Rock and Heidi Grant

Harvard Business Review, Nov 4, 2016

Striving to increase workplace diversity is not an empty slogan — it is a good business decision. A 2015 McKinsey report on 366 public companies found that those in the top quartile for ethnic and racial diversity in management were 35% more likely to have financial returns above their industry mean, and those in the top quartile for gender diversity were 15% more likely to have returns above the industry mean.

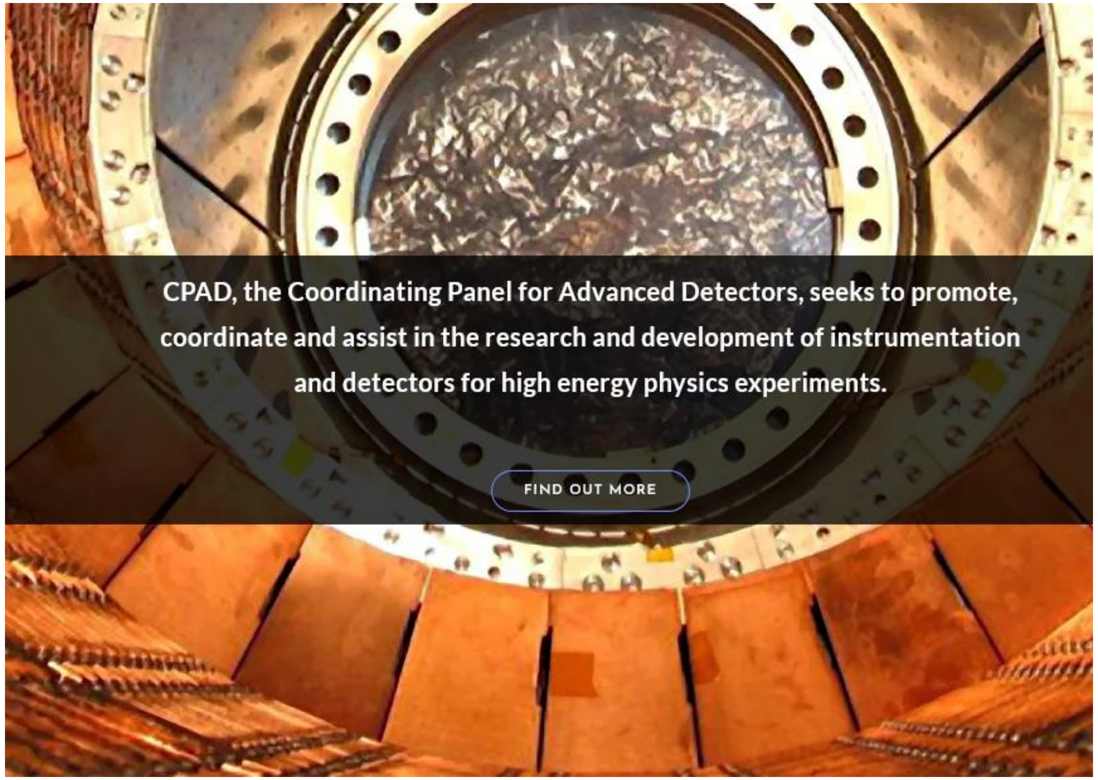




Coordinating Panel for Advanced Detectors

The American Physics Society (APS) and Division of Particles and Fields (DPF) Coordinating Panel for Advanced Detectors (CPAD)

- The Coordinating Panel for Advanced Detectors (CPAD), seeks to promote, coordinate and assist in the research and development of instrumentation and detectors for high energy physics experiments. CPAD's representatives come from the national high-energy physics laboratories and the university community.
- By helping to coordinate the development of both evolutionary and transformative detector instrumentation across the national laboratories and with the university community, CPAD works to ensure the future of high-energy physics experiments. CPAD was formed in spring 2012 in response to an 18-month-long study by a task force appointed to address the organization of high-energy physics instrumentation.



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Coordinating Panel for Advanced Detectors

Formation of Research and Development Collaborations (RDC's) within CPAD

2024 RDC Collaborative Proposals

- CPAD and the RDC's aim to put forward a small number of university lead, multi-institutional proposals focused on generic "blue-sky" R&D

RDC#	TOPIC	COORDINATORS	MAILING LIST
1	Noble Element Detectors	Jonathan Asaadi, Carmen Carmona	cpad_rdc1@fnal.gov
2	Photodetectors	Shiva Abbaszadeh, Flavio Cavanna	cpad_rdc2@fnal.gov
3	Solid State Tracking	Anthony Affolder, Sally Seidel	cpad_rdc3@fnal.gov
4	Readout and ASICs	Angelo Dragone, Mitch Newcomer	cpad_rdc4@fnal.gov
5	Trigger and DAQ	Zeynep Demiragli, Jinlong Zhang	cpad_rdc5@fnal.gov
6	Gaseous Detectors	Prakhar Garg, Sven Vahsen	cpad_rdc6@fnal.gov
7	Low-Background Detectors	Daniel Baxter, Guillermo Fernandez-Moroni, Noah Kurinsky	cpad_rdc7@fnal.gov
8	Quantum and Superconducting Sensors	Rakshya Khatiwada, Aritoki Suzuki	cpad_rdc8@fnal.gov
9	Calorimetry	Marina Artuso, Minfang Yeh	cpad_rdc9@fnal.gov
10	Detector Mechanics	Eric Anderssen, Andreas Jung	cpad_rdc10@fnal.gov
11	Fast Timing	Gabriele Giacomini, Matt Wetstein	cpad_rdc11@fnal.gov

Public-private partnerships accelerate HEP innovations

There are barriers to effective HEP-Industry partnerships

- Small Business Innovation and Research (SBIR)
- Programs Enabling Deep Tech Transfer from National Labs
- Partnership Intermediaries (PI) can accelerate commercialization
- Entrepreneurial Leave Programs (ELP)
- Building relationships with venture capitalists (VC)

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arxiv:2203.08973v1 arXiv:2211.13210v1

Thanks!

Acknowledgments: help from many colleagues from the Instrumentation Department (BNL) and the community at large