Snowmass 2021

Instrumentation Frontier Overview

Jinlong Zhang (ANL)
IF Co-conveners: Phil Barbeau (Duke), Petra Merkel (FNAL)

P5 Town Hall Meeting, April 12, 2023

Instrumentation Frontier

The Instrumentation Frontier (IF) is geared to discuss **detector technologies and R&D needs for future experiments in collider physics, neutrino physics, intensity physics and at the cosmic frontier**. It is divided into diagonal topical groups with some overlap among a few of them. Synergies between the different topical groups, as well as with other Frontier groups and research areas outside of HEP will be paid close attention to.

https://snowmass21.org/instrumentation/start

“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

Instrumentation Frontier Topical Groups

IF Co-Conveners: Phil Barbeau (Duke), Petra Merkel (FNAL), Jinlong Zhang (ANL)

Topical Group	**Co-Conveners**			
Quantum Sensors (IF01)	Thomas Cecil (ANL)	Kent Irwin (SLAC)	Reina Maruyama (Yale)	Matt Pyle (Berkeley)
Photon Detectors (IF02)	Carlos Escobar (FNAL)	Juan Estrada (FNAL)	Chris Rogan (KU)	
Solid State Detectors and Tracking (IF03)	Tony Affolder (UCSC)	Artur Apresyan (FNAL)	Steve Worm (DESY)	
Trigger and DAQ (IF04)	Darin Acosta (Florida)	Allison Deiana (SMU)	Wes Ketchum (FNAL)	
Micro Pattern Gas Detectors (IF05)	Bernd Surrow (Temple)	Maxim Titov (SACLAY)	Sven Vahsen (Hawaii)	
Calorimetry (IF06)	Andy White (UTA)	Minfang Yeh (BNL)	Rachel Yohay (FSU)	
Electronics/ASICS (IF07)	Gabriella Carini (BNL)	Mitch Newcomer (Penn)	John Parsons (Columbia)	
Noble Elements (IF08)	Eric Dahl (Northwestern)	Roxanne Guenette (Harvard)	Jen Raaf (FNAL)	
Cross Cutting and System Integration (IF09)	Jim Fast (JLab)	Maurice Garcia-Sciveres (LBL)	Ian Shipsey (Oxford)	
Radio Detection (IF10)	Amy Connolly (OSU)	Albrecht Karle (Wisconsin)		

And some earlier co-conveners: IF02: Maly Sanchez (ISU); IF03: Lucie Linssen (CERN); IF04: Stephanie Majewski (Oregon); IF10: Jim Beatty (OSU), Abigail Vieregg (Chicago).

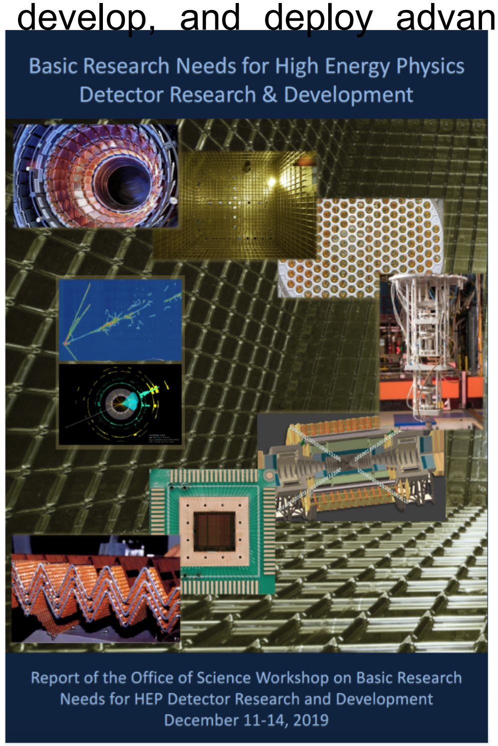
Instrumentation Frontier Liaisons

- High-level and bi-directional communication between IF and other frontiers
- Expertise and experience in both communities
- **IF liaisons**
    - Energy Frontier: Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay)
    - Neutrino Physics Frontier: Mayly Sanchez (ISU), NF10
    - Rare Processes and Precision: Marina Artuso (Syracuse)
    - Cosmic Frontier: Kent Irwin (SLAC), Hugh Lippincott (UCSB)
    - Accelerator Frontier: Andy White (UTA)
    - Computational Frontier: Darin Acosta (Florida)
    - Underground Facilities: Eric Dahl (Northwestern), Maurice Garcia-Sciveres (LBNL)
    - Community Engagement: Farah Fahim (FNAL)
    - Early Career representatives: S. Butalla (FIT), K. Dunne (Stockholm), J. Zettlemoyer (FNAL)

Two Important Inputs

DOE Detector R&D BRN Report

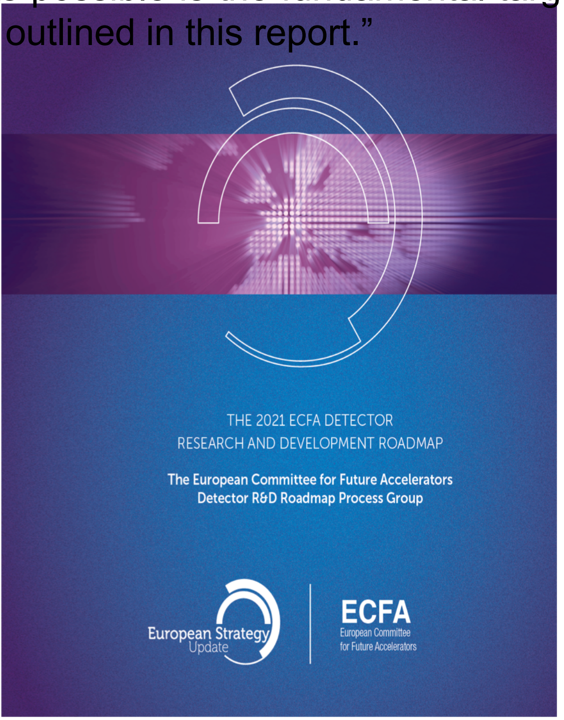
“Transformative discovery in science is driven by innovation in technology. Our boldest undertakings in particle physics have at their foundation precision instrumentation. To reveal the profound connections underlying everything we see from the smallest scales to the largest distances in the Universe, to understand its fundamental constituents, and to reveal what is still unknown, we must invent, develop, and deploy advanced instrumentation”.


Basic Research Needs for High Energy Physics
Detector Research & Development

Report of the Office of Science Workshop on Basic Research Needs for HEP Detector Research and Development
December 11-14, 2019

2021 ECFA Detector R&D Roadmap

“The centrality of experimentation to the scientific method which has led to the discoveries that underpin our current understanding of the Universe, and the technological wonders which have owed from this understanding, cannot be overstated. To appropriately test our current level of understanding requires very high accuracy instrumentation. The degree of confirmation that can be assigned to any hypothesis is determined both by the agreement between theoretical prediction and measurements and the level of precision achievable in each. Enabling future particle physics experiments to achieve the most accurate measurements possible is the fundamental target of all the proposed detector developments outlined in this report.”


THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators
Detector R&D Roadmap Process Group

European Strategy Update
ECFA
European Committee for Future Accelerators

From LOIs to the Final Report

- **IF Report and 10 IF topical group reports**

[Submitted on 28 Sep 2022 (v1), last revised 3 Nov 2022 (this version, v3)]

Report of the Instrumentation Frontier Working Group for Snowmass 2021

Phillip S. Barbeau (1), Petra Merkel (2), Jinlong Zhang (3), Darin Acosta (4), Anthony A. Affolder (5), Artur Apresyan (2), Marina Artuso (6), Vallary Bhopatkar (7), Stephen Butalla (8), Gabriella A. Carini (9), Thomas Cecil (3), Amy Connolly (8), C. Eric Dahl (2, 10), Allison Deiana (11), Katherine Dunne (12), Carlos O. Escobar (2), Juan Estrada (2), Farah Fahim (2), James E. Fast (13), Maurice Garcia-Sciveres (14), Roxanne Guenette (15), Michael T. Hedges (16), Kent Irwin (17), Albrecht Karle (18), Wes Ketchum (2), Scott Kravitz (14), W. Hugh Lippincott (19), Reina H. Maruyama (20), Jess McIver (21), F. Mitchell Newcomer (22), John Parsons (23), Matt Pyle (24), Jennifer L. Raaf (2), Chris Rogan (25), Mayly C. Sanchez (26), Ian Shipsey (27), Bernd Surrow (28), Maxim Titov (29), Sven E. Vahsen (30), Caterina Vernieri (31), Andrew P. White (32), Steven Worm (33, 34), Minfang Yeh (9), Rachel Yohay (26), Jacob Zettlemoyer (2) ((1) Duke University, (2) Fermi National Accelerator Laboratory, (3) Argonne National Laboratory, (4) Rice University, (5) University of California Santa Cruz, (6) Syracuse University, (7) Ohio State University, (8) Florida Institute of Technology, (9) Brookhaven National Laboratory, (10) Northwestern University, (11) Southern Methodist University, (12) Stockholm University, (13) Jefferson Lab, (14) Lawrence Berkeley National Laboratory, (15) University of Manchester, (16) Purdue University, (17) Stanford University, (18) University of Wisconsin Madison, (19) University of California Santa Barbara, (20) Yale University, (21) University of British Columbia, (22) University of Pennsylvania, (23) Columbia University, (24) University of California Berkeley, (25) University of Kansas, (26) Florida State University, (27) Oxford University, (28) Temple University, (29) IRFU, CEA, Université Paris-Saclay, (30) University of Hawaii, (31) Stanford Linear Accelerator Laboratory, (32) University of Texas at Arlington, (33) Deutsches Elektronen-Synchrotron, (34) Humboldt-Universität zu Berlin)

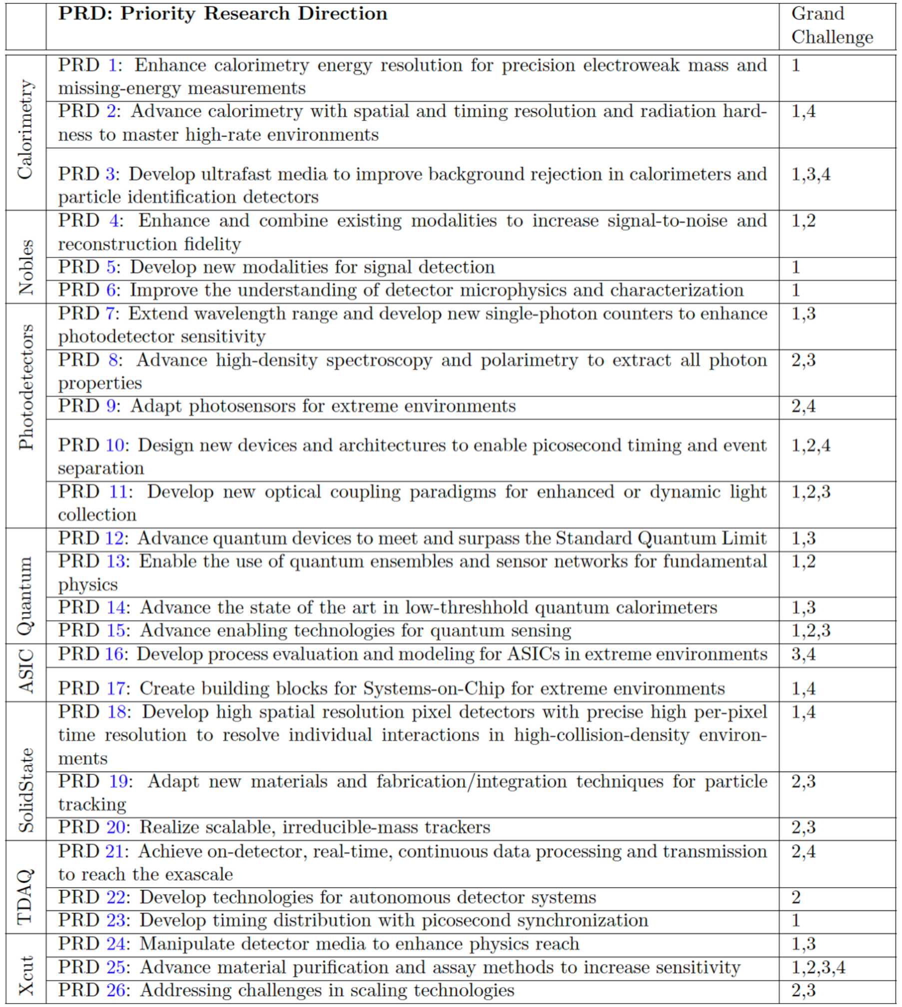
Detector instrumentation is at the heart of scientific discoveries. Cutting edge technologies enable US particle physics to play a leading role worldwide. This report summarizes the current status of instrumentation for High Energy Physics (HEP), the challenges and needs of future experiments and indicates high priority research areas. The Snowmass Instrumentation Frontier studies detector technologies and Research and Development (R&D) needed for future experiments in collider physics, neutrino physics, rare and precision physics and at the cosmic frontier. It is divided into more or less diagonal areas with some overlap among a few of them. We lay out five high-level key messages that are geared towards ensuring the health and competitiveness of the US detector instrumentation community, and thus the entire particle physics landscape.

Comments: 53 pages, 0 figures, contribution to Snowmass 2021
Subjects: **High Energy Physics - Experiment (hep-ex)**; Instrumentation and Detectors (physics.ins-det)
Cite as: arXiv:2209.14111 **[hep-ex]**
(or arXiv:2209.14111v3 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2209.14111

- **Based on 354 LOIs then 91 white papers**

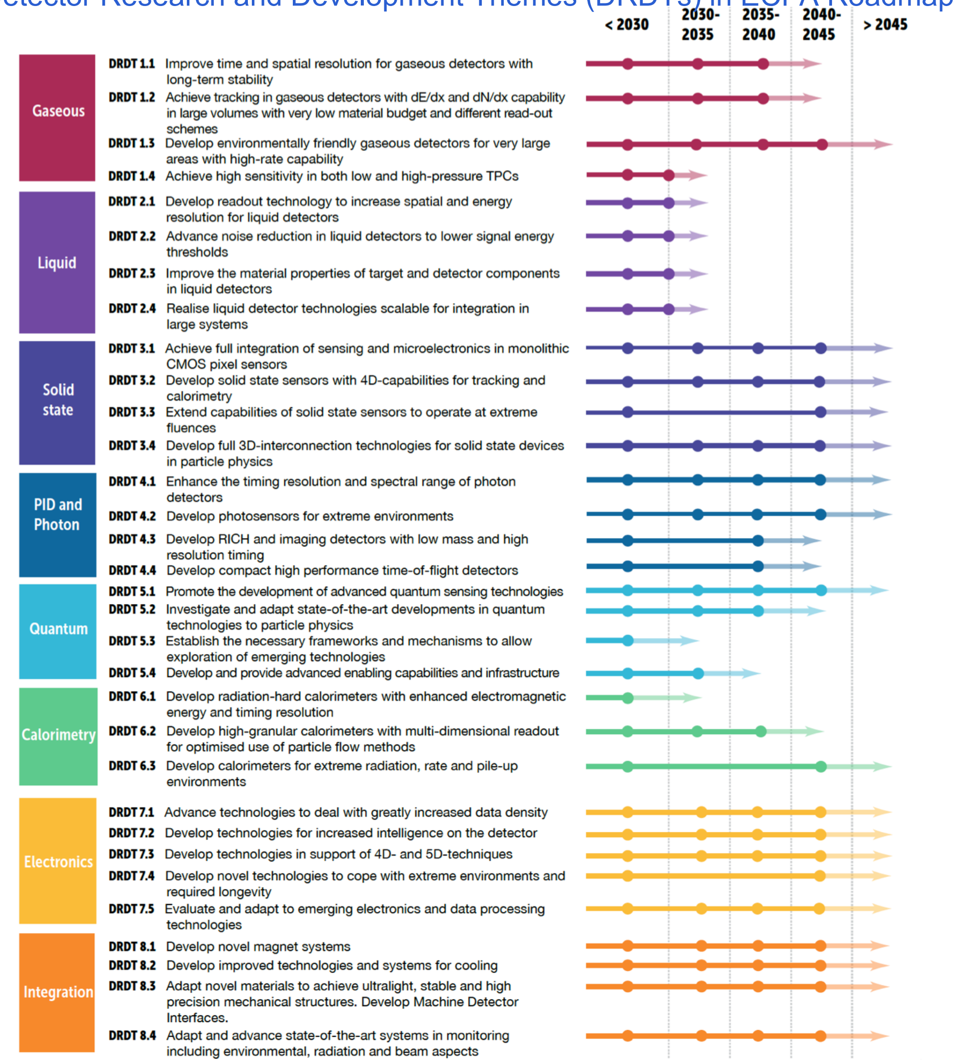
Exciting Technology Challenges Ahead

Priority Research Directions (PRDs) in BRN Report



	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

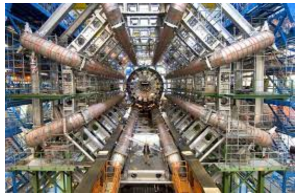
Detector Research and Development Themes (DRDTs) in ECFA Roadmap

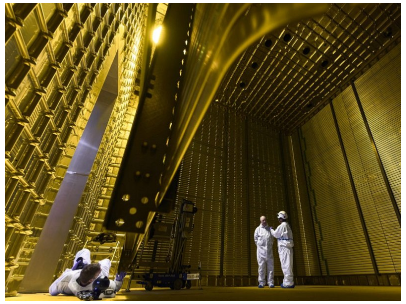


Gaseous	DRDT 1.1	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs
Liquid	DRDT 2.1	Develop readout technology to increase spatial and energy resolution for liquid detectors
	DRDT 2.2	Advance noise reduction in liquid detectors to lower signal energy thresholds
	DRDT 2.3	Improve the material properties of target and detector components in liquid detectors
	DRDT 2.4	Realise liquid detector technologies scalable for integration in large systems
Solid state	DRDT 3.1	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
	DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
	DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics
PID and Photon	DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
	DRDT 4.2	Develop photosensors for extreme environments
	DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
	DRDT 4.4	Develop compact high performance time-of-flight detectors
Quantum	DRDT 5.1	Promote the development of advanced quantum sensing technologies
	DRDT 5.2	Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
	DRDT 5.3	Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
	DRDT 5.4	Develop and provide advanced enabling capabilities and infrastructure
Calorimetry	DRDT 6.1	Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
	DRDT 6.2	Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
	DRDT 6.3	Develop calorimeters for extreme radiation, rate and pile-up environments
Electronics	DRDT 7.1	Advance technologies to deal with greatly increased data density
	DRDT 7.2	Develop technologies for increased intelligence on the detector
	DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
	DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
	DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies
Integration	DRDT 8.1	Develop novel magnet systems
	DRDT 8.2	Develop improved technologies and systems for cooling
	DRDT 8.3	Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
	DRDT 8.4	Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects

Snowmass IF reports did not collate a list like above, but concur most of these items with key messages.

Workforce, Collaborations, Stewards and Partnerships as Critical

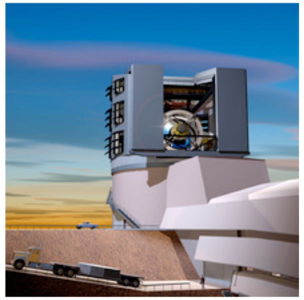




Workforce Development

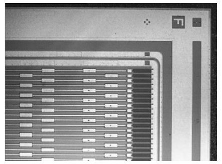
Research Collaborations

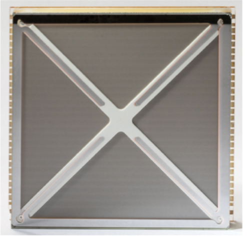
Advanced Detector Development

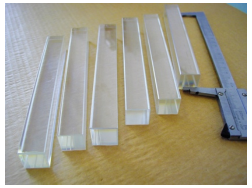


Facility Stewards

Industry Partnerships







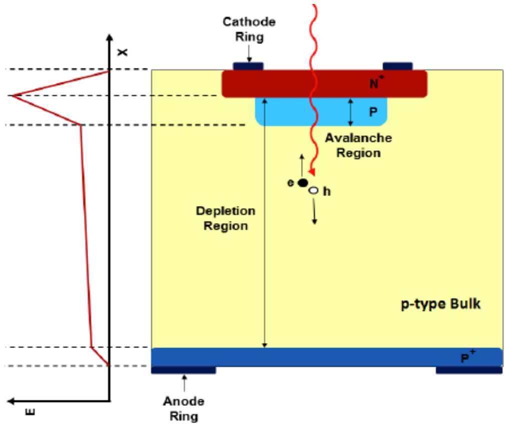
IF Key Messages

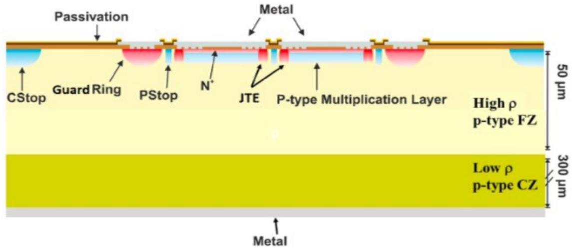
- **IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.**
- **IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.**
- **IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.**
- **IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews.**
- **IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.**

IF Key Messages

- **IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.**
- **IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.**
- **IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.**
- **IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews.**
- **IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.**

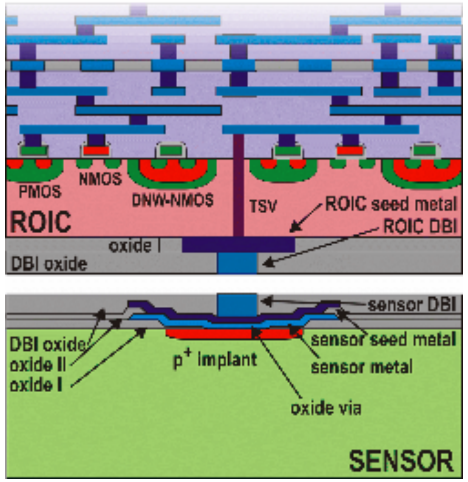
Solid State Detectors and Tracking

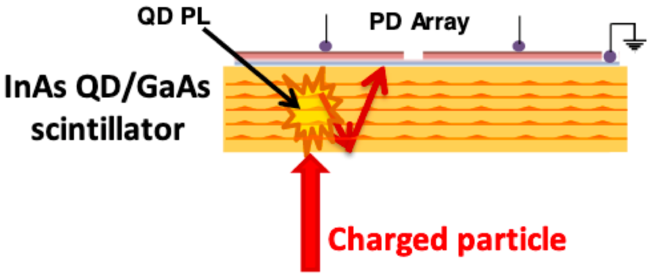


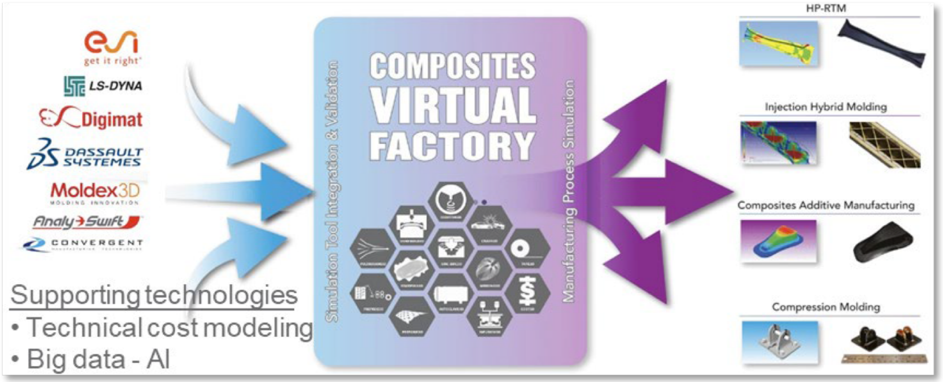


Pursue 4D resolution, low mass and radiation hardness

- Development of sensor technologies
  - Achieve 4D-capability from timing sensors with fine segmentation and able to cope with high occupancies and radiation tolerance
  - Large area sensors with improved uniformity, such as traditional sensors, LGADs, and wafer-scale MAPS
  - Major advances in ASIC development and approaches: bandwidth optimization, low noise, small area and low power dissipation
  - New materials for sensor and electronics
- Advanced packaging and edge-computing paradigms
  - Vertical integration of multi-tier processing electronics and sensors, optimization of detector thickness
  - Industry partnerships and adoption of new technologies
- Radiation hard technologies and more effective cooling
- Cohesive set of simulation tools







Supporting technologies
- Technical cost modeling
- Big data - AI

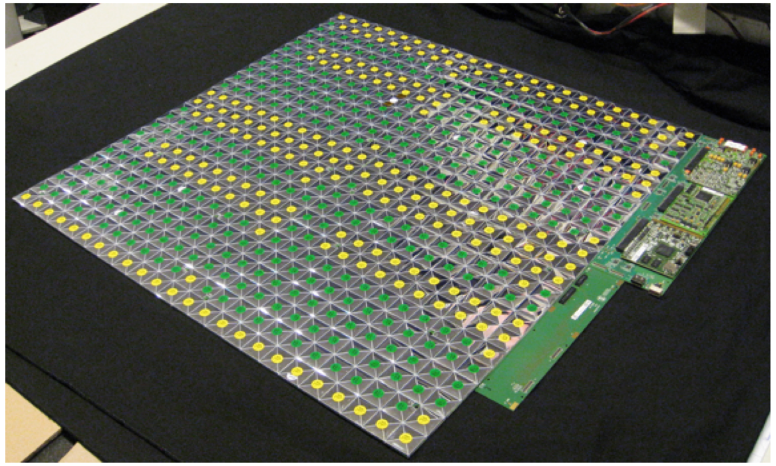
Calorimetry

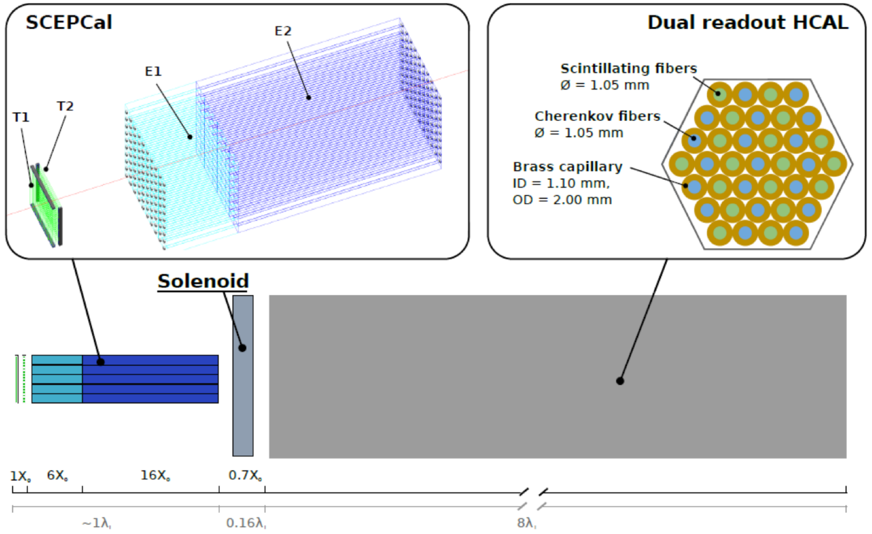
Two major approaches: particle flow (PF) and dual readout (DR)

- Recent addition of precision timing information
- Development of new, radiation-hard active materials
- Challenges remain:
    - PF: scaling to 10-100M channels while maintaining the required quality
    - PF: power budget and cooling load of electronics
    - PF: compact design with minimizing gaps between sampling layers
    - DR: mechanics, integration, costing of a realistic spaghetti calorimeter
    - DR: red-sensitive SiPMs and novel optical materials to boost the Cherenkov signal/noise in homogeneous crystal setups
    - … …

high density, good optical quality, high light-yield, fast decay time, good radiation hardness and low cost

- Materials for Future Calorimeters



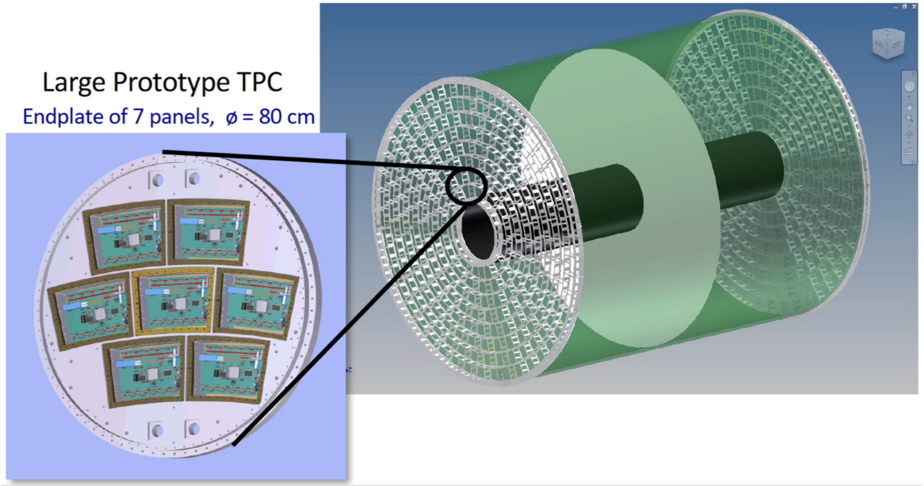


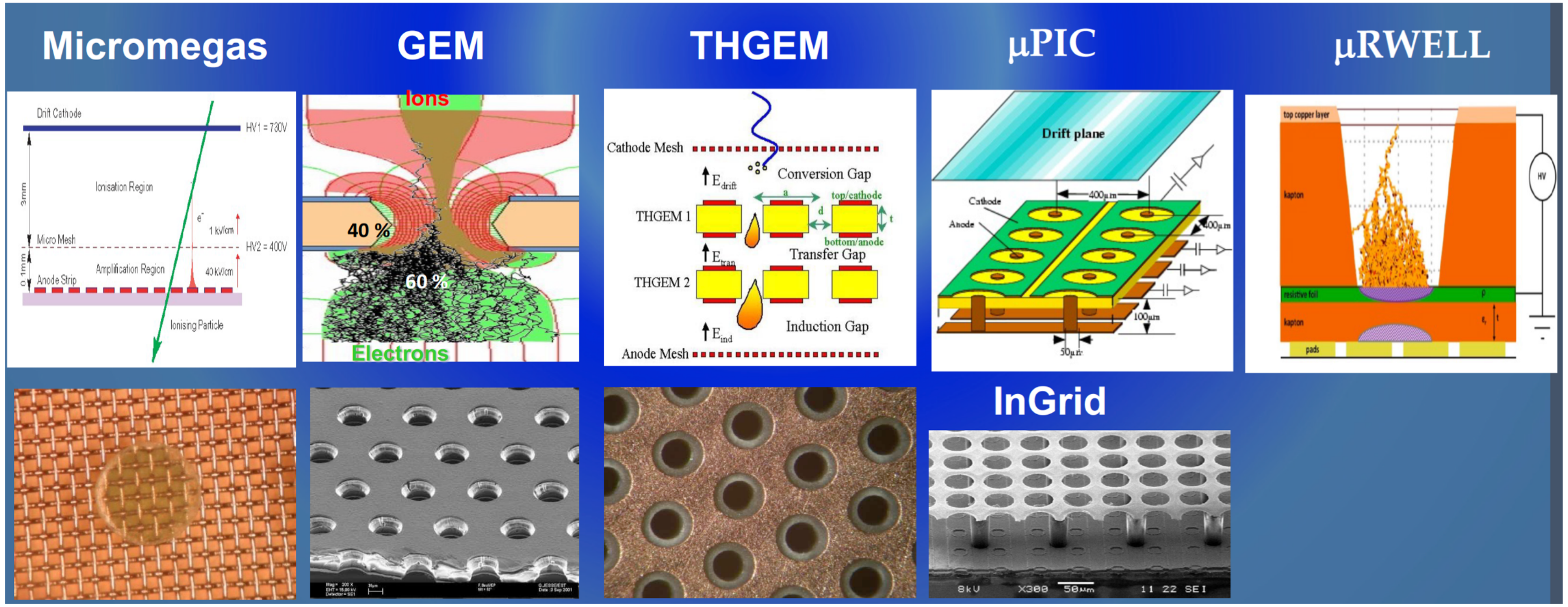
Micro Pattern Gas Detectors

- Micro Pattern Gas Detectors (MPGDs) constitute an enabling technology that is key for large segments of the future US Nuclear Physics (NP) and HEP programs, and which also benefits other communities. MPGDs provide a flexible go-to solution whenever particle detection with large area coverage, fine segmentation, and good timing is required.
    - TPC, muon detector system, …
- The technology is relatively young and should be advanced to performance limits to enable future HEP experiments. Support of generic and blue-sky R&D is required to achieve this.
- In order to maintain and expand US expertise on MPGDs, The US NP and HEP communities would benefit strongly from a joint MPGD development and prototyping facility in the US.

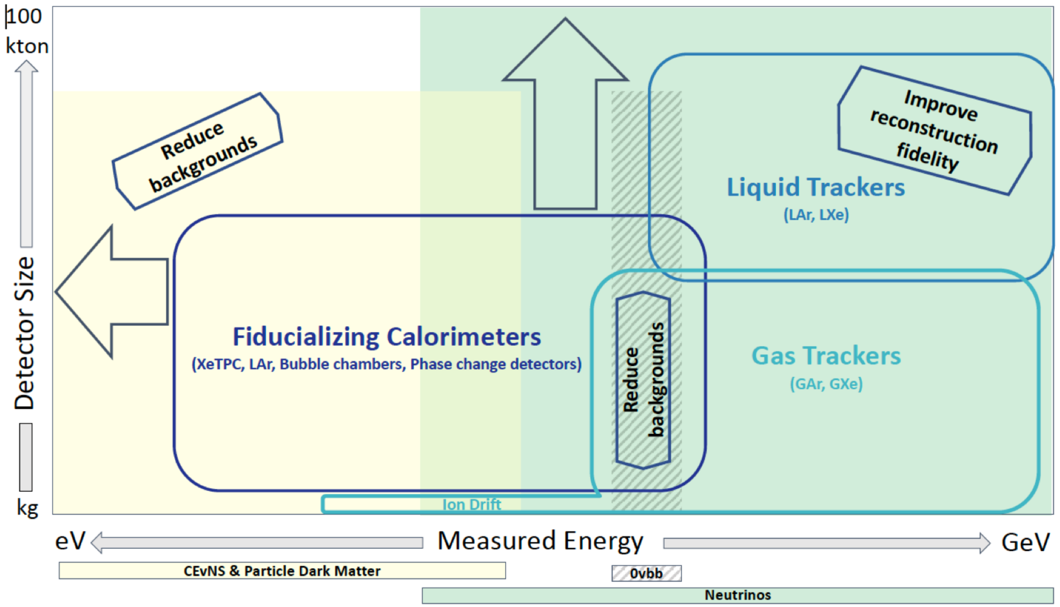
Large Prototype TPC

Endplate of 7 panels, ⌀ = 80 cm



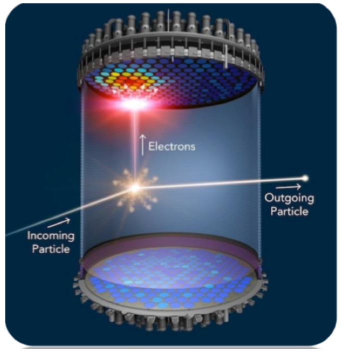


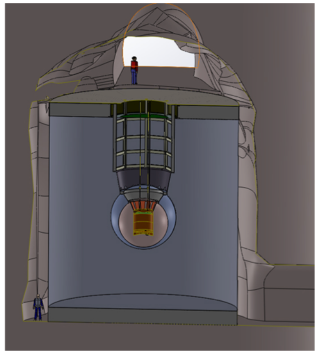
Noble Element Detectors

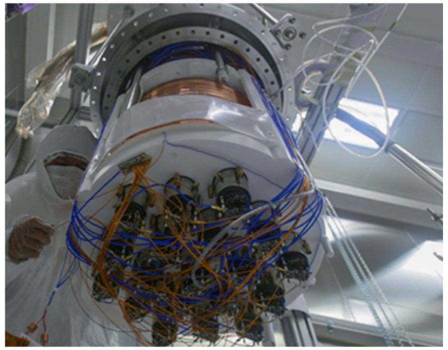


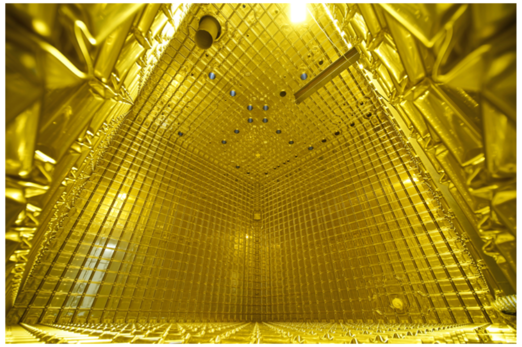
Synergies between Dark Matter searches and neutrino physics

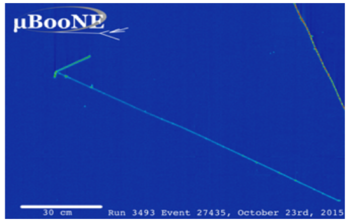
- Increase signal-to-noise and reconstruction fidelity
- Develop signal detection, including methods based on ion drift, metastable fluids, solid-phase detectors and dissolved targets
- Improve the understanding of detector microphysics and calibrate detector response in new signal regimes
- Address the scaling challenges, including material purification, background mitigation, large-area readout and magnetization



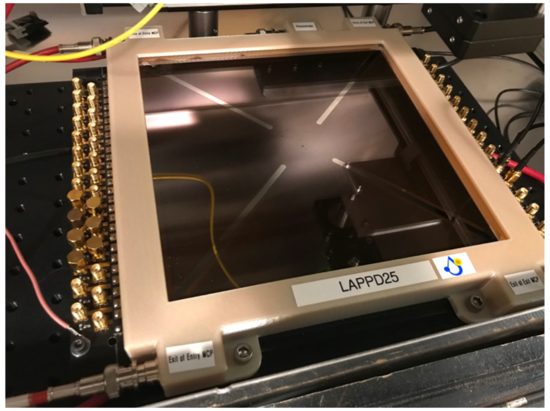








Photon Detectors

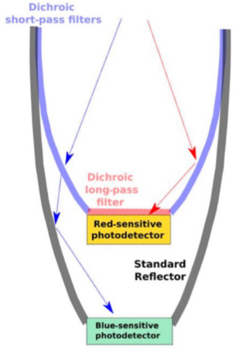


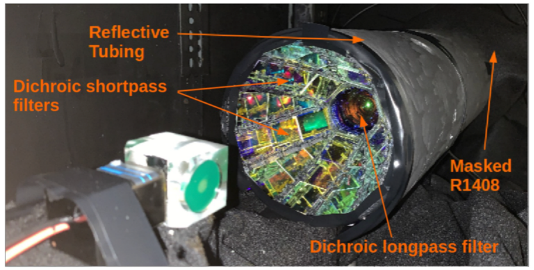
Wide-field multi-object spectroscopy cosmological facilities

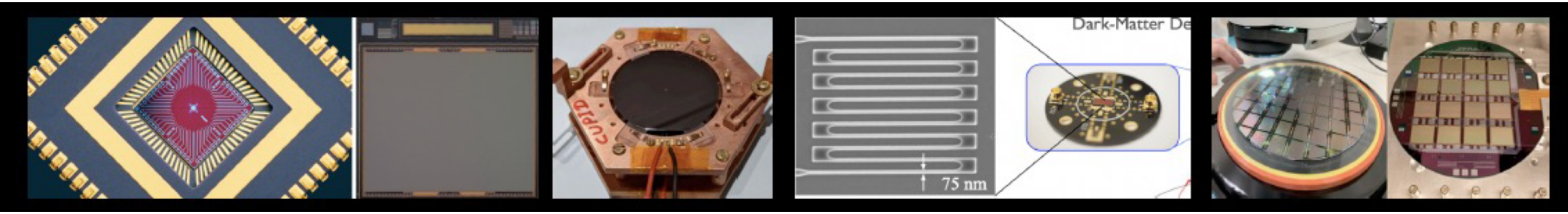
- Photon counting sensors
  - Superconducting sensors, such as MKIDs, TES, SNSPDs
  - Semiconducting sensors, such as skipper-CCDs, in CMOS, photon-to-digital converters (PDC)
- Extending wavelength coverage, both IR and UV

Photon-based Neutrino experiments

- large-scale, monolithic detectors that use either Cherenkov or scintillation light continuing; hybrid Cherenkov-scintillation detectors started
  - New photon sensors such as LAPPDs
  - New photon collectors such as Dichroicons

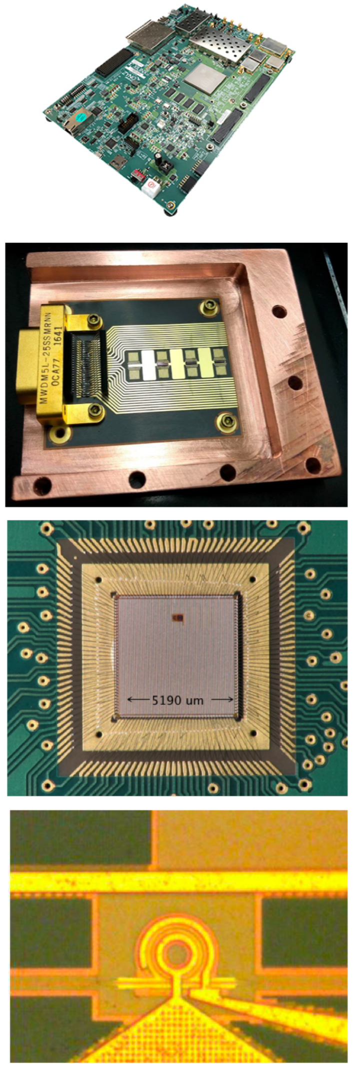






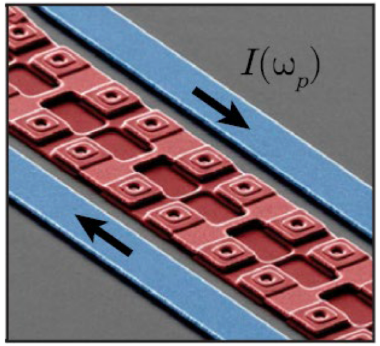
Electronics/ASICs, Trigger/DAQ

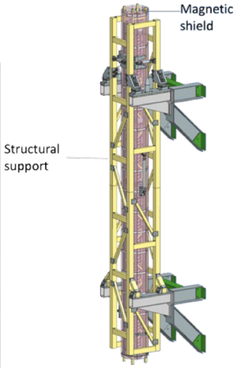
- Electronics/ASICs
  - Improve mechanisms for **shared access to advanced technology** providing broader access by the community to foster real exchange of information and accelerate development.
  - Continue to develop methodologies to **adapt the technology for operation in extreme environments.** Deep cryogenics, ultra-radio pure materials, radiation-harsh environments with limited power budget and long lifetime for all cases.
  - Develop novel techniques to manage very **high data rates**. Data reduction and optimization needs to be as close as possible to the generation point with acceptable power consumption.
  - Create framework and platform for **easy access to design tools.** Develop specialized online resources for the HEP community. Provide the basis for true co-design R&D efforts: from simulation to verification and implementation.

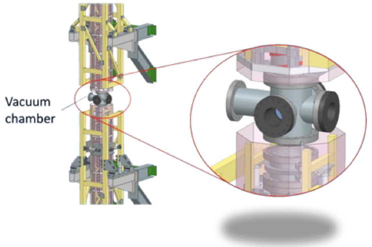


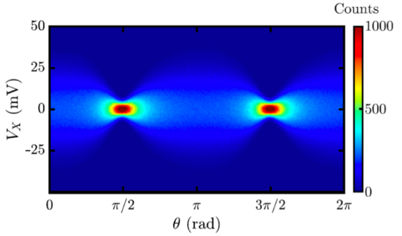
- Trigger/DAQ (TDAQ)
  - Pursue innovations in the application of Machine Learning (ML) to TDAQ systems, particularly in the co-design of hardware and software to apply ML algorithms to real-time hardware and in other novel uses to improve the operational efficiency and sensitivity to new physics of future experiments;
  - Invest in the design of TDAQ system architectures that leverage new technologies, techniques, and partnerships to enable more intelligent aggregation, reduction, and streaming of data from detectors to higher-level trigger systems and offline data processing;
  - Develop improved readout technologies that increase data bandwidth and are capable of operating in extreme environments, while fitting the material and power constraints of future experiments.

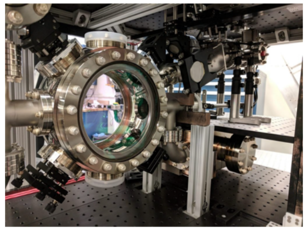
Quantum Sensors

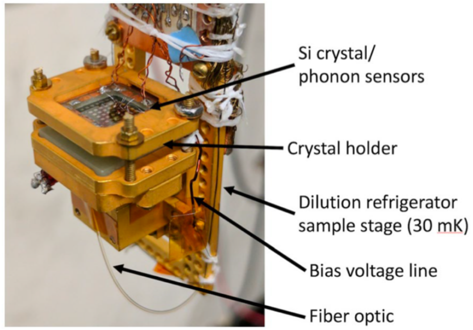


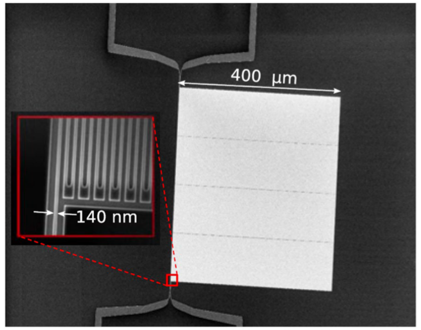












- Wide range of science impact: dark matter, new particles or forces, the electric dipole moment (EDM), variations in fundamental constants, gravitational wave, space-time symmetries, and neutrino masses
- Broad spectrum of technologies: atomic interferometers, optomechanical sensors, optical clocks, spin-dependent sensors, quantum calorimeters, and superconducting sensors
- Key avenue for improvement includes back action evasion schemes and squeezing techniques to push beyond standard quantum limit (SQL)
- Need strong Theory support to address issues of materials and measurement methods

IF Key Messages

- IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.
- **IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.**
- IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.
- IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews.
- IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.

Technical Workforce

Many areas of required expertise and multi-disciplinary work, such as electronics, DAQ, mechanical engineering, composites design and fabrication, microfabrication and assembly, cryogenic systems, analytic chemistry, radiochemistry, materials science, ...

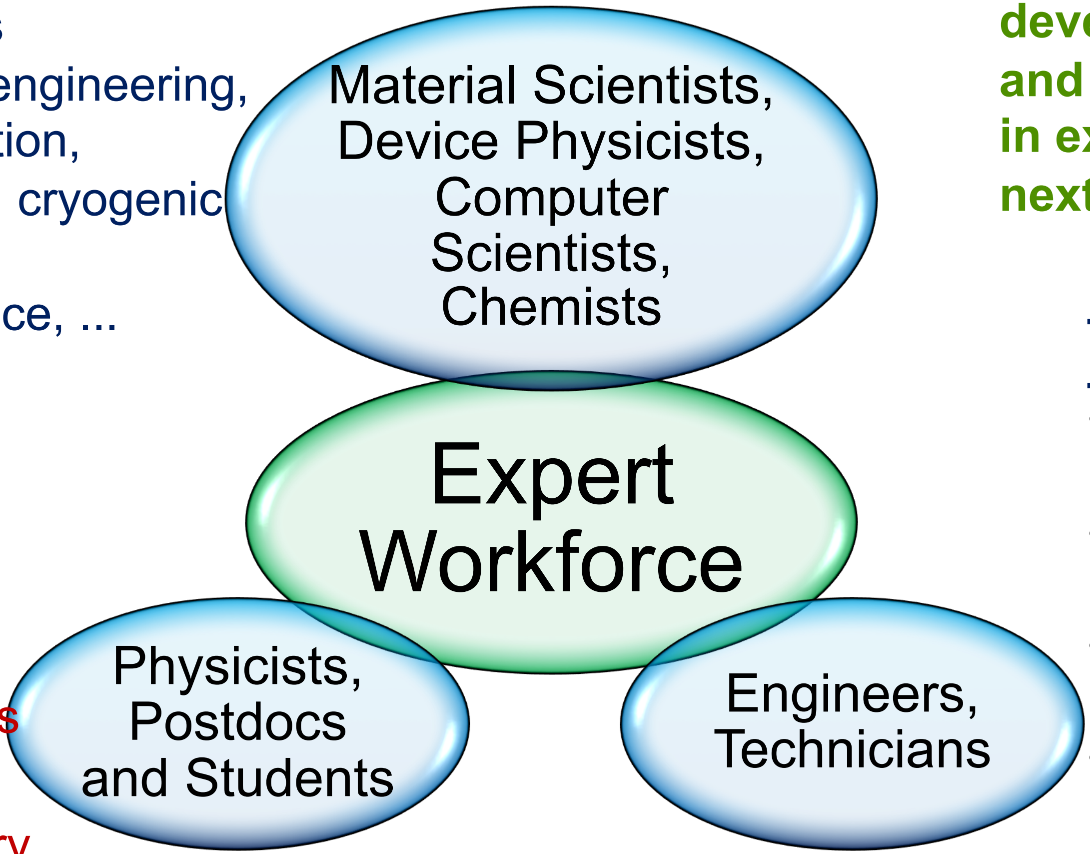
Diverse pipeline (in US, international)

Instrumentation traineeship programs (DOE 2021)
University/lab partnerships

Connections to other disciplines

Supporting alternative career paths including multi-disciplinary

Appropriate recognition across all of the workforce


Material Scientists, Device Physicists, Computer Scientists, Chemists

Expert Workforce

Physicists, Postdocs and Students

Engineers, Technicians

To succeed in advanced detector development in the next decade and beyond, we need to succeed in excellence in the current and next generation of people

Fostering careers in instrumentation

- Historically challenging career path for HEP instrumentation in the U.S.
- CPAD has spearheaded some changes in recent years
- Physics faculty positions focused on instrumentation are uncommon
- Several Nuclear Engineering departments have strong support for instrumentation experts

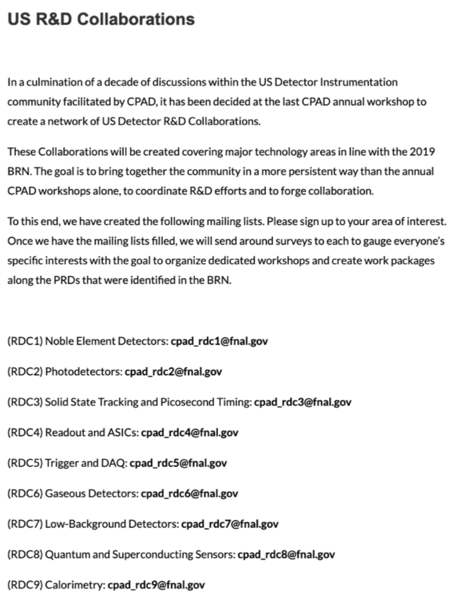
These experts, in turn, educate the next generation in advanced HEP instrumentation techniques and development transforming not only HEP but other fields too.

IF Key Messages

- IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.
- IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.
- **IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.**
- IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews
- IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.

R&D Collaboration

- Coordinating Panel for Advanced Detectors (CPAD) found in 2012
  - A standing body under the auspices of the executive committee of the DPF, seeks to promote, coordinate and assist in the research and development of instrumentation and detectors for high energy physics experiments
    - Annual Instrumentation Workshop
    - DPF Instrumentation Awards (early career and senior), Graduate Instrumentation Research Awards
    - Coordination SBIR/STTR Input when requested by DOE
  - Improved status and coordination of the US instrumentation community
    - Coordinating the formation of US detector R&D collaborations to address key technology areas that were identified in the 2019 Detector R&D BRN report.



US R&D Collaborations

In a culmination of a decade of discussions within the US Detector Instrumentation community facilitated by CPAD, it has been decided at the last CPAD annual workshop to create a network of US Detector R&D Collaborations.

These Collaborations will be created covering major technology areas in line with the 2019 BRN. The goal is to bring together the community in a more persistent way than the annual CPAD workshops alone, to coordinate R&D efforts and to forge collaboration.

To this end, we have created the following mailing lists. Please sign up to your area of interest. Once we have the mailing lists filled, we will send around surveys to each to gauge everyone's specific interests with the goal to organize dedicated workshops and create work packages along the PRDs that were identified in the BRN.

(RDC1) Noble Element Detectors: **cpad_rdc1@fnal.gov**

(RDC2) Photodetectors: **cpad_rdc2@fnal.gov**

(RDC3) Solid State Tracking and Picosecond Timing: **cpad_rdc3@fnal.gov**

(RDC4) Readout and ASICs: **cpad_rdc4@fnal.gov**

(RDC5) Trigger and DAQ: **cpad_rdc5@fnal.gov**

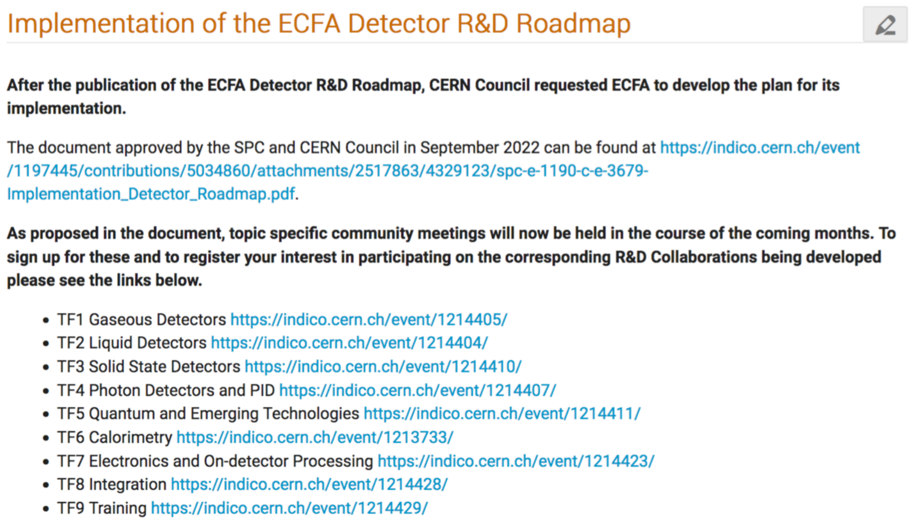
(RDC6) Gaseous Detectors: **cpad_rdc6@fnal.gov**

(RDC7) Low-Background Detectors: **cpad_rdc7@fnal.gov**

(RDC8) Quantum and Superconducting Sensors: **cpad_rdc8@fnal.gov**

(RDC9) Calorimetry: **cpad_rdc9@fnal.gov**

- CERN RD Collaboration Model
  - Topical collaborations around specific technology Developments, originated in 1990 with RD-1 and now at RD-53
  - ECFA Detector R&D Roadmap (2021) identified a set of detector R&D areas and defined the most important themes (DRDTs), and made general strategic recommendations (GSR)
  - The implementation plan proposed to organize long-term R&D efforts into newly established Detector R&D (DRD) Collaborations
  - The US HEP community is welcome to, and engaging broadly and early in the DRD process



Implementation of the ECFA Detector R&D Roadmap

After the publication of the ECFA Detector R&D Roadmap, CERN Council requested ECFA to develop the plan for its implementation.

The document approved by the SPC and CERN Council in September 2022 can be found at https://indico.cern.ch/event/1197445/contributions/5034860/attachments/2517863/4329123/spc-e-1190-c-e-3679-Implementation_Detector_Roadmap.pdf.

As proposed in the document, topic specific community meetings will now be held in the course of the coming months. To sign up for these and to register your interest in participating on the corresponding R&D Collaborations being developed please see the links below.

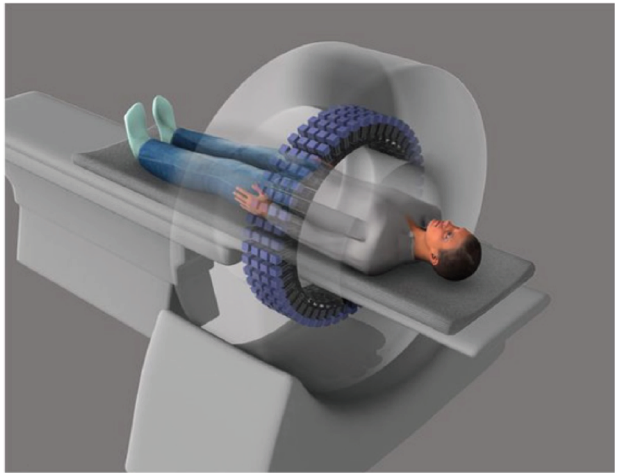
- TF1 Gaseous Detectors https://indico.cern.ch/event/1214405/
- TF2 Liquid Detectors https://indico.cern.ch/event/1214404/
- TF3 Solid State Detectors https://indico.cern.ch/event/1214410/
- TF4 Photon Detectors and PID https://indico.cern.ch/event/1214407/
- TF5 Quantum and Emerging Technologies https://indico.cern.ch/event/1214411/
- TF6 Calorimetry https://indico.cern.ch/event/1213733/
- TF7 Electronics and On-detector Processing https://indico.cern.ch/event/1214423/
- TF8 Integration https://indico.cern.ch/event/1214428/
- TF9 Training https://indico.cern.ch/event/1214429/

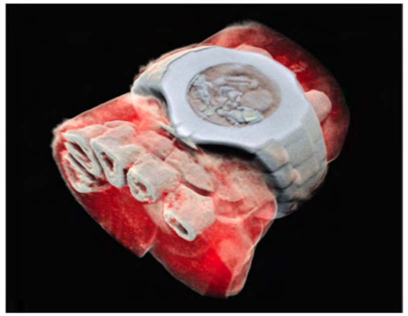
IF Key Messages

- IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.
- IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.
- IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.
- **IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews.**
- IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.

Importance of Blue-Sky R&Ds

- Could not have been anticipated, but “Blue-sky” developments in particle physics have often been of broader application and had immense societal benefit. Examples include
    - Development of the World Wide Web
    - Magnetic Resonance Imaging, Positron Emission Tomography
    - X-ray imaging for photon science
- The invention of MPGD is another example (with very large-scale systems now being installed), as are the more recent new technologies for 4D tracking
- It is essential that adequate resources be provided to support more speculative “Blue-Sky” R&Ds
    - Less directly goal-driven R&Ds should be recognized and have funding lines
    - This should include supporting the careers of junior scientists pursuing high-risk, high-reward ideas



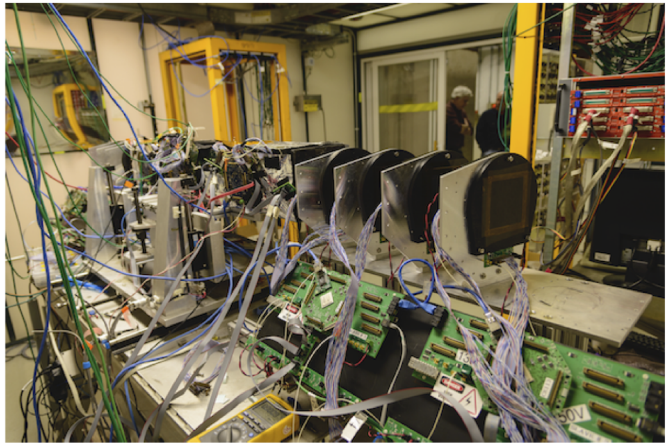


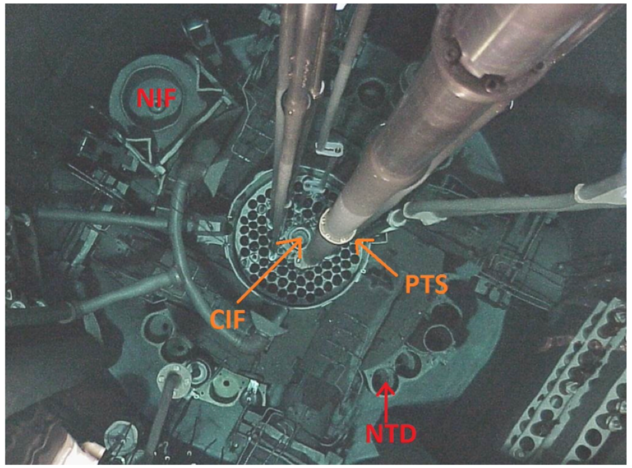
IF Key Messages

- IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.
- IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.
- IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.
- IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews.
- **IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.**

Facilities and Capabilities

- Calibration and Test Beams
  - High-quality electron beams
  - High-energy (TeV scale) hadron beams
  - High-dose facility access
- Low-noise and environmentally stable facilities
  - Low seismic/vibration noise
  - Low RF/EM noise
  - Low radioactive background
- Cryogenic test facilities
  - Low temperature test
  - LAr test capacity
- TDAQ facilities
  - Integration testing
  - Develop and maintain knowledge base
- Dedicated detector development labs
  - Silicon (e.g., SiDet, MSL), Noble elements (e.g., NLTF)
  - Microelectronics
- Semiconductor foundry access
  - Access is getting more complex and costly for advanced (<45 nm) technology nodes
  - HEP timelines are long and volumes are low compared to industry drivers

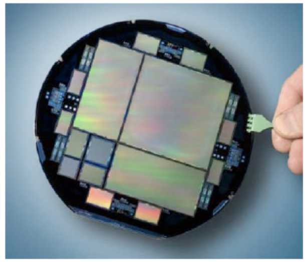





Lithography


Etching

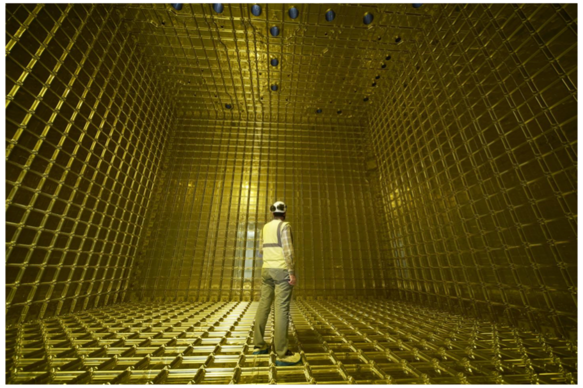

Film Deposition


CCD Wafer

Instrumentation Development Ecosystem

Keys to the success of this enterprise are **people**, **facilities and resources**, and **connections and collaborations**

- Advanced workforce and research collaborations
- Unique facilities and capabilities
- Connections to other programs, other offices/agencies, private foundations/commercial partners, and global collaborations



1979

1983 A LONG RANGE PLAN FOR NUCLEAR SCIENCE

1989 Nuclei, Nucleons, Quarks
Nuclear Science in the 1990's

1996 Nuclear Science: A Long Range Plan

2002

2007

REACHING FOR THE HORIZON

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

Roundtable on
Producing and Managing Large Scientific Data with Artificial Intelligence and Machine Learning

FUTURE OF ELECTRON SOURCES

Neuromorphic Computing: From Materials to Systems Architecture

Report of a Roundtable Convened to Consider Neuromorphic Computing Basic Research Needs

Neutron and X-ray Detectors

Report of the Basic Energy Sciences Workshop on Neutron and X-ray Detectors.
August 1-3, 2012

ENERGY
Office of Science

Basic Energy Sciences Roundtable
Opportunities for Basic Research for Next-Generation Quantum Systems
October 30–31, 2017

Basic Research Needs for
Microelectronics

Report of the Office of Science Workshop on Basic Research Needs for Microelectronics
October 23 – 25, 2018

U.S. DEPARTMENT OF ENERGY

NSF National Science Foundation

NASA

DTRA DEFENSE THREAT REDUCTION AGENCY
Detect. Deter. Defeat.

GlobalFoundries™

RMD
A Dynasil Company

skywater

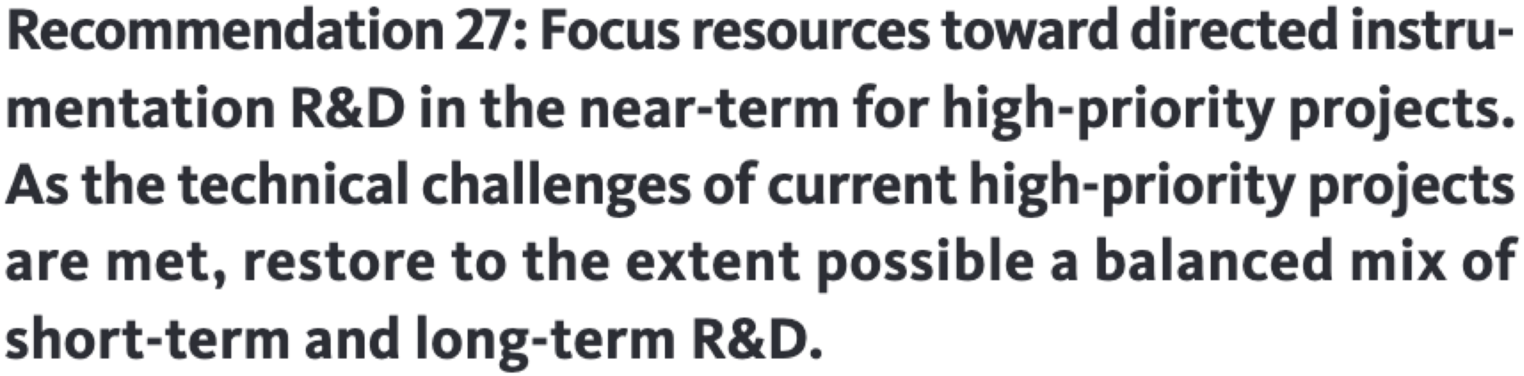
INCOM
BRIGHT IDEAS

Tower Semiconductor
Where **Analog** and **Value** Meet

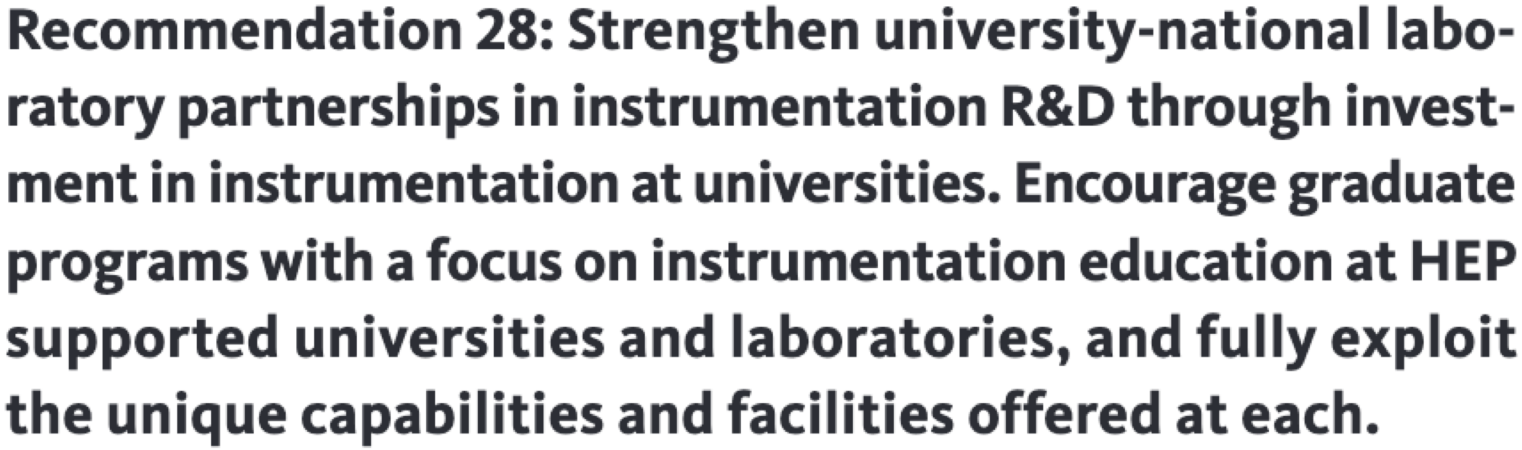
MIT LINCOLN LABORATORY

SenseICs

Recommendations by the Previous P5


Recommendation 27: Focus resources toward directed instrumentation R&D in the near-term for high-priority projects. As the technical challenges of current high-priority projects are met, restore to the extent possible a balanced mix of short-term and long-term R&D.

- Did not yet happen,
  we need do better


Recommendation 28: Strengthen university-national laboratory partnerships in instrumentation R&D through investment in instrumentation at universities. Encourage graduate programs with a focus on instrumentation education at HEP supported universities and laboratories, and fully exploit the unique capabilities and facilities offered at each.

Instrumentation Frontier Summary

A strong need for much increased technology development, in preparation for the next big step in facilities and experiments while we exploit the ones we are currently developing/building