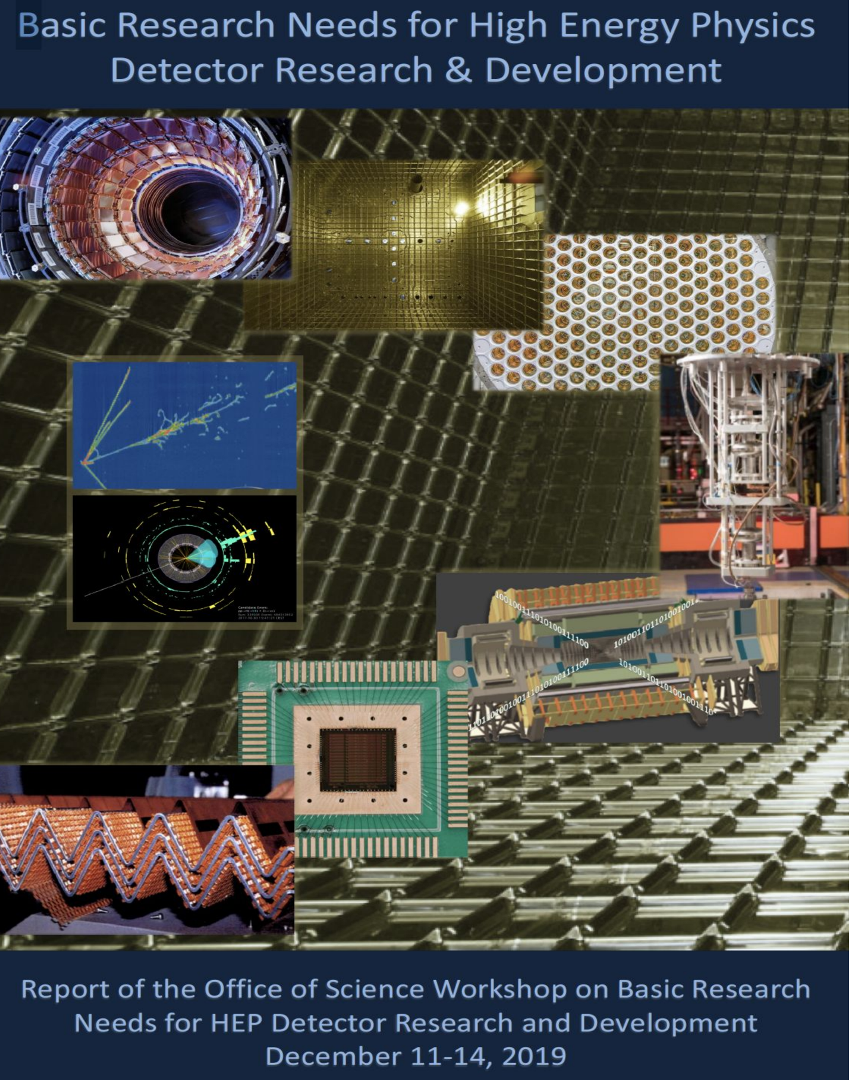

DOE Basic Research Needs Study on Instrumentation

(Report to HEPAP - final draft)

Bonnie Fleming
Ian Shipsey
(on behalf of the BRN Panel)

DOE BRN Instrumentation Panel

Photo credit: DOE

Opportunities for Discovery

Many mysteries to date go unanswered including:

The mystery of the Higgs boson

The mystery of Neutrinos

The mystery of Dark Matter

They mystery of Dark Energy

The mystery of quarks and charged leptons

The mystery of Matter – anti-Matter asymmetry

The mystery of the Hierarchy Problem

The mystery of the Families of Particles

The mystery of Inflation

The mystery of Gravity

Opportunities for Discovery

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The mystery of quarks and charged leptons

The mystery of Matter – anti-Matter asymmetry

The mystery of the Hierarchy Problem

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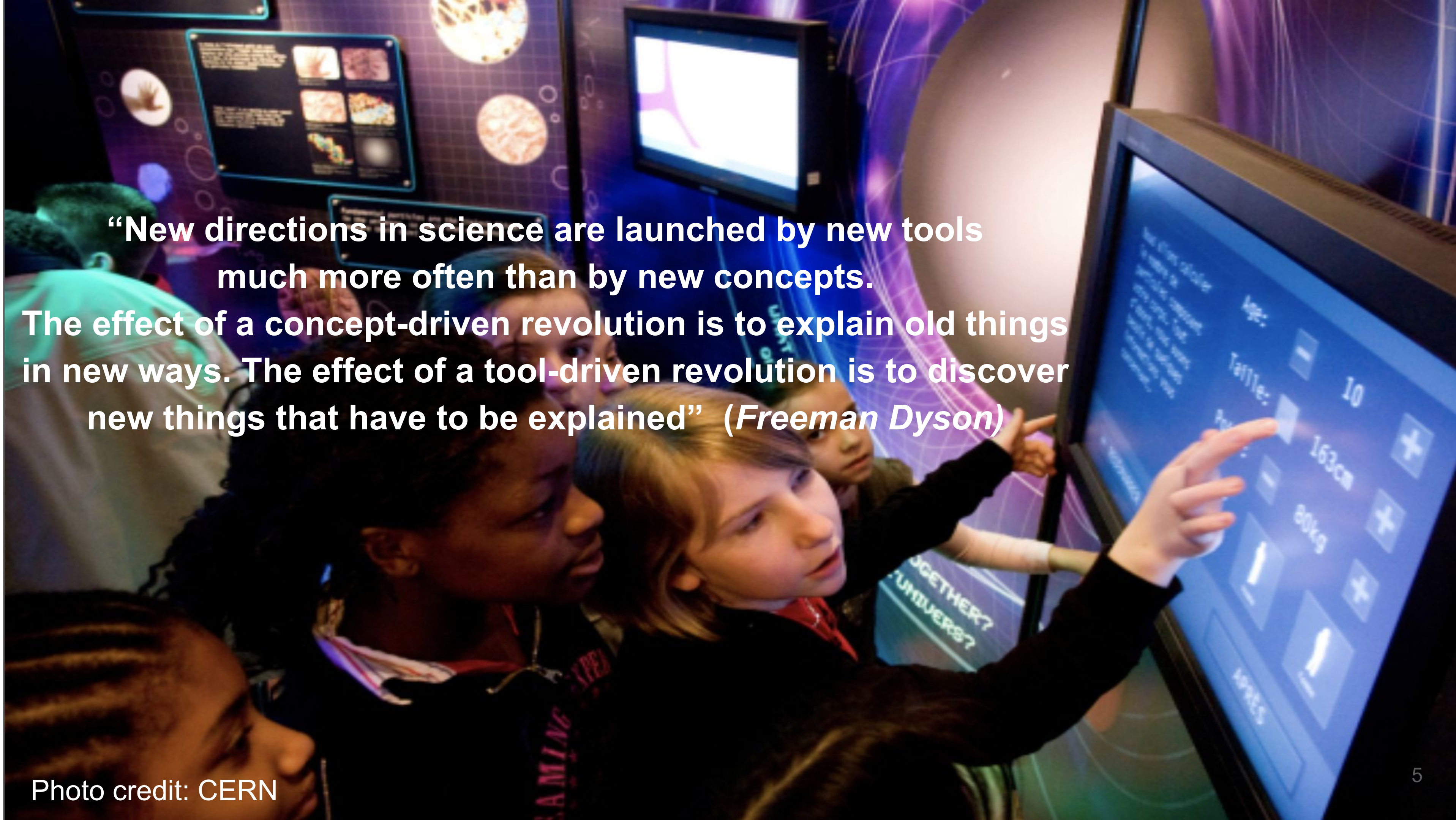
The mystery of Gravity

We are very much in a data driven era !



"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*)

Photo credit: CERN

“Measure what is measurable, and make measurable what is not so” (*Galileo Galilei*)

Photo credit: CERN

Four Grand Challenges encompass this Instrumentation revolution

- **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.*

Charge, audience and goals

- Survey the present state of the HEP technology landscape.
- Identify key capabilities & performance requirements.
- Identify technologies to provide or enhance such capabilities.
- Articulate PRDs to push well beyond the current state of the art, potentially leading to transformative technological advances with broad-ranging applicability.
- Flesh out required R&D efforts with deliverables with notional timelines & key technical milestones. Elucidate the technical infrastructure required to support these efforts.
- Formulate a small set of instrumentation Grand Challenges that could result in game-changing experimental capabilities.

10 Basic Research Needs Study Charge

Department of Energy
Office of Science
Washington, DC 20585

10 July 2019

MEMORANDUM FOR HELMUT MARSISKE

FROM: GLEN CRAWFORD
DIRECTOR, RESEARCH AND TEC[illegible]NOLOGY [illegible]IVISION
OFFICE OF HIGH ENERGY PHY[illegible]ICS (HEP)

SUBJECT: Basic Research Needs Study [illegible] Detector Re[illegible]arch and Development

I request that you organize and carry out a Basic Research Needs (BR[illegible] [illegible]udy to assess the present status of the HEP technology land[illegible]e, and to identify strategic [illegible]nolog[illegible] areas, aligned with the strengths of the US comm[illegible] future long-term resea[illegible]d development (R&D) efforts should focus on in pursuit of [illegible]he HE[illegible]nce drivers identifie[illegible] in the P5 report. For each of these areas, the study should artic[illegible]late and ju[illegible] set of Priority Research Directions (PRDs) to push the technology well beyond [illegible] cur[illegible] of the art, potentially leading to transformative advances with broad-r[illegible]gi[illegible] applicability [illegible] HEP and beyond. Furthermore, the study sho[illegible] identify a small se[illegible] high-impact instrumentation "Grand Challenges" where te[illegible] breakthroughs co[illegible]ld lead to game-changing experimental capabilities in pur[illegible]it of HEP s[illegible]nce goals.

You should [illegible] co-chairs to le[illegible] the study and wor[illegible] with them to select the core group of working group le[illegible] to carry i[illegible] out. [illegible]dy enc[illegible]mpasses responses to the specific charge elements elucidated [illegible] and is expecte[illegible] several months to complete. A focal point of the study should inclu[illegible] workshop, with a[illegible]endance beyond the core group, expected to be held in [illegible] 2019 time fr[illegible] in the Washington, DC area. The study participants are to serve by invitation o[illegible]

The HEP Detector [illegible]D program [illegible]ms to develop cutting-edge, novel instrumentation to enable scientific leadership [illegible] a worldwide experimental program that is broadening into new research areas with ever increa[illegible]ng demands in sensitivity, scale, and cost. To meet this challenge, HEP [illegible] to execute a pro[illegible]am appropriately balanced between incremental, near-term, low-risk [illegible]tor R&D and tr[illegible]sformative, long-term, high-risk detector R&D.

With t[illegible] [illegible]ear-te[illegible] technical challenges of current high-priority P5 projects subsiding, the HEP Detector [illegible] program aims to shift more emphasis towards building a long-term, high-risk high-rewar[illegible] ("Blue Sky") R&D portfolio that holds the promise of transformative advances with broad-ranging applications across HEP as well as other fields of science, medicine, and national security. Crucially, the program must take full advantage of the major advances happening in

Charge, audience and goals

To meet this challenge, HEP
aims to execute a program appropriately balanced between incremental, near-term, low-risk detector R&D and transformative, long-term, high-risk detector R&D

Along with the five science drivers, the 2014 P5 report identifies the importance of Instrumentation R&D in one of its highest level recommendations where it calls for a "balanced mix of short term and long-term R&D" in the current era.

10 Basic Research Needs Study Charge

Department of Energy
Office of Science
Washington, DC 20585

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The BRN does:
- Describe SCIENCE OPPORTUNITIES & TECHNOLOGIES TO REALIZE THEM

(The BRN does not:
- Rank PRD opportunities)

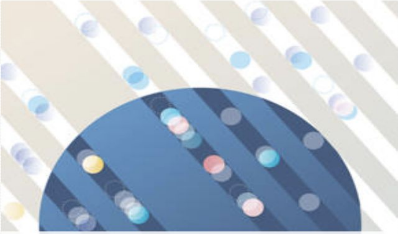
Report should speak to the scientific community, the public, and decision makers

Science opportunities drive the next generation of experiments.

5 Science Panels

The Higgs as a tool for discovery

Conveners:
Jim Hirschauer (FNAL)
Gabriella Sciolla (Brandeis)

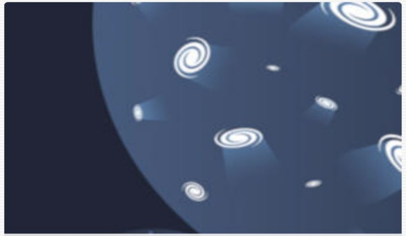


The physics of neutrino mass

Conveners:
Ornella Palamara (FNAL)
Kate Scholberg (Duke)

The new physics of dark matter

Conveners:
Jodi Cooley (SMU)
Dan McKinsey (Berkeley)



Cosmic acceleration: inflation and dark energy

Conveners:
Clarence Chang (ANL)
Brenna Flaugher (FNAL)

Exploring the unknown: new particles, new interactions and physical principles

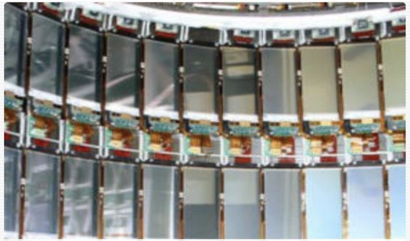
Conveners:
Sarah Demers (Yale)
Monica Pepe-Altarelli (CERN)

An instrumentation revolution is critical to future discoveries

7 Technology Panels

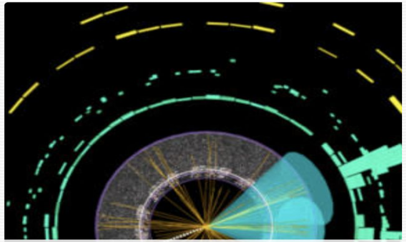
Quantum Sensors

Conveners:
Andy Geraci (Northwestern)
Kent Irwin (Stanford)



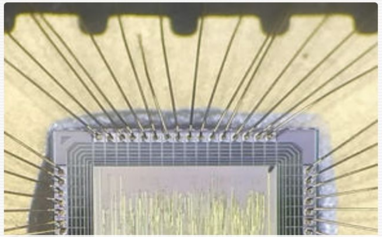
Solid State (including vertexing and tracking)

Conveners:
Marina Artuso (Syracuse)
Carl Haber (LBNL)



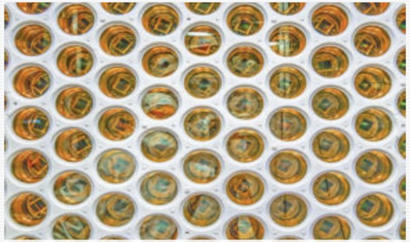
Calorimetry

Conveners:
Francesco Lanni (BNL)
Roger Rusack (Minnesota)



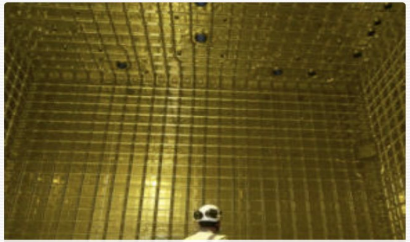
Readout & ASICs

Conveners:
Gabriella Carini (BNL)
Mitch Newcomer (Penn)



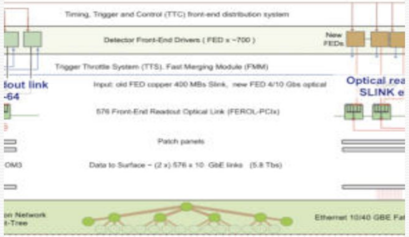
Photodetectors

Conveners:
Lindley Winslow (MIT)
Peter Krizan (Jožef Stefan Institute)



Noble Liquids

Conveners:
Roxanne Guenette (Harvard)
Jocelyn Monroe (RHUL)



TDAQ (including Machine Learning)

Conveners:
Darin Acosta (Florida)
Tulika Bose (Wisconsin)

There is also a **cross-cutting group**.

Cross Cut

Conveners:
Marcel Demarteau (ORNL)
Abe Seiden (UCSC)

Study Process and timeline

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- Community input through CPAD, community surveys, town hall meetings, small targeted workshops

Panelists

Co-Chairs

Bonnie Fleming, Yale
Ian Shipsey, Oxford

Cross-Cut Panel

Marcel Demarteau, ORNL
James Fast, JLab
Sunil Golwala, CalTech
Young-Kee Kim, Chicago
Abraham Seiden, UCSC

Physics Panels

Energy Frontier
James Hirschauer, Fermilab (Lead)
Gabriella Sciolla, Brandeis (Lead)
Michael Begel, Brookhaven
Meenakshi Narain, Brown

Neutrinos
Ornella Palamara, Fermilab (Lead)
Kate Scholberg, Duke (Lead)
Daniel Dwyer, Berkeley Lab
Amy Connolly, OSU

Dark Matter
Jodi Cooley, SMU (Lead)
Dan McKinsey, Berkeley (Lead)
Andrew Sonnenschein, Fermilab
Reyco Henning, UNC

Cosmic Acceleration
Clarence Chang, Argonne (Lead)
Brenna Flaugher, Fermilab (Lead)
Kyle Dawson, Utah
Laura Newburgh, Yale

Explore the Unknown
Sarah Demers, Yale (Lead)
Monica Pepe-Altarelli, CERN, EONR (Lead)
Matthew Reece, Harvard
Nicola Serra, Universität Zürich

Technology Panels

Calorimetry
Francesco Lanni, Brookhaven (Lead)
Roger Rusack, Minnesota (Lead)
Nural Akchurin, Texas Tech
Sarah Eno, UMD
Paolo Rumerio, Alabama
Ren-Yuan Zhu, CalTech

Noble Liquids
Roxanne Guenette, Harvard (Lead)
Jocelyn Monroe, U London (Lead)
Jennifer Raaf, Fermilab
Andrea Pocar, UMass
Jonathan Asaadi, UT, Arlington
Hugh Lippincott, UCSB

Photodetectors
Lindley Winslow, MIT (Lead)
Peter Krivzan, ULJ / JSI (Lead)
Graham Giovanetti, Williams College
Adriana Lita, NIST
Felix Sefkow, DESY

Quantum Sensors
Andrew Geraci, Northwestern (Lead)
Kent Irwin, Stanford (Lead)
Gretchen Campbell, JQI/UMD
Alexander Sushkov, BU
Ronald Walsworth, Harvard
Anna Grassellino, Fermilab

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Mitch Newcomer, Penn (Lead)
Angelo Dragone, SLAC
Maurice Garcia-Sciveres, Berkeley Lab
Terri Shaw, Fermilab
Julia Thom-Levy, Cornell

Solid State & Tracking
Marina Artuso, Syracuse (Lead)
Carl Haber, Berkeley Lab (Lead)
Alessandro Tricoli, Brookhaven
Petra Merkel, Fermilab

TDAQ
Darin Acosta, Florida (Lead)
Tulika Bose, UW, Madison (Lead)
Wesley Ketchum, Fermilab
Jinlong Zhang, Argonne
Paul O'Connor, Brookhaven
Georgia Karagiorgi, Columbia

2 co-Chairs, 24 panel leads, 35 panel members, 5 cross cutters= 66

Balance is important

University - National Lab

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University (60%) National Labs (40%)

Balance is important

Gender (Female - Male)

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Female (44%) Male (56%)

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arXiv.org > physics > arXiv:1908.00194

Physics > Instrumentation and Detectors

New Technologies for Discovery

A report of the 2018 DPF Coordinating Panel for Advanced Detectors (CPAD) Community Workshop

Report of the 2018 CPAD workshop was a primary input to the 2019 DOE BRN study on HEP Detector R&D

CPAD INSTRUMENTATION FRONTIER WORKSHOP 2019

University of Wisconsin-Madison

Goal: provide a community forum to communicate with the BRN panel , timed to be just before the BRN workshop

12 plenary speakers Day 1 were mostly BRN panel members. Townhalls provided further opportunities for dialog

Time	Talk	Speaker	Location	Slot
			Monona Terrace Convention Center	08:00 - 09:00
09:00	Welcome	Kimberly PALLADINO	Monona Terrace Convention Center	09:00 - 09:15
	The Higgs as a tool for discovery	Jim HIRSCHAUER	Monona Terrace Convention Center	09:15 - 09:30
	Dark Matter	Jodi COOLEY	Monona Terrace Convention Center	09:30 - 09:45
	DE and Inflation Instrumentation BRN working group	Dr. BRENNA FLAUGHER	Monona Terrace Convention Center	09:45 - 10:00
10:00	Exploring the Unknown	Sarah DEMERS	Monona Terrace Convention Center	10:00 - 10:15
	Neutrinos and Neutrino Mass	Amy CONOLLY	Monona Terrace Convention Center	10:15 - 10:30
	Photodetectors	Junqi XIE	Monona Terrace Convention Center	11:40 - 11:52
12:00	Quantum Sensors	Tim KOVACHY	Monona Terrace Convention Center	11:52 - 12:04
	Noble Liquid detectors	Dr. Hugh LIPPINCOTT	Monona Terrace Convention Center	12:04 - 12:16
	Trigger and DAQ	Prof. Tulika BOSE		
	Solid State and tracking	Carl HABER	Meeting Rooms K-R, Monona Terrace Convention Center	13:30 - 13:45
	Calorimetry	Roger RUSACK	Meeting Rooms K-R, Monona Terrace Convention Center	13:45 - 14:00
14:00	Readout and ASICs	Mitch NEWCOMER	Meeting Rooms K-R, Monona Terrace Convention Center	14:00 - 14:15
	Plenary Townhall: BRN process		Monona Terrace Convention Center	14:15 - 15:00

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HEP Basic Research Needs Workshop on Detector Research and Development

December 11 – 14, 2019
Hilton Washington DC/Rockville Hotel & Executive Meeting Center
1750 Rockville Pike
Rockville, MD 20852

- Attendees: Panel conveners and members, Agencies (DOE, NSF)
- Plenaries on the first day live streamed to community
- Parallel sessions and working groups to work through the substance and first draft of the report

08:30 → 09:10 **DOE Introduction**
Speaker: Helmut Marsiske (DOE)
DetectorBRN_11dec... DetectorBRN_11dec...

09:10 → 09:40 **Higgs and Energy Frontier** ¶
Speakers: Gabriella Sciolla (Brandeis University (US)), Jim Hirschauer (Fermi National Accelerator Lab. (US))
hirschauer_higgsAn...

09:40 → 10:10 **Neutrinos**
Speakers: Amy Connolly (The O ... a (L
BRN_neutrino_plena...

10:10 → 10:40 **Dark Matter**
Speakers: Daniel Mckinsey, Jo
2019_1210_BRN_D...

10:40 → 11:00 **Break**

Roxanne Guenette, Harvard

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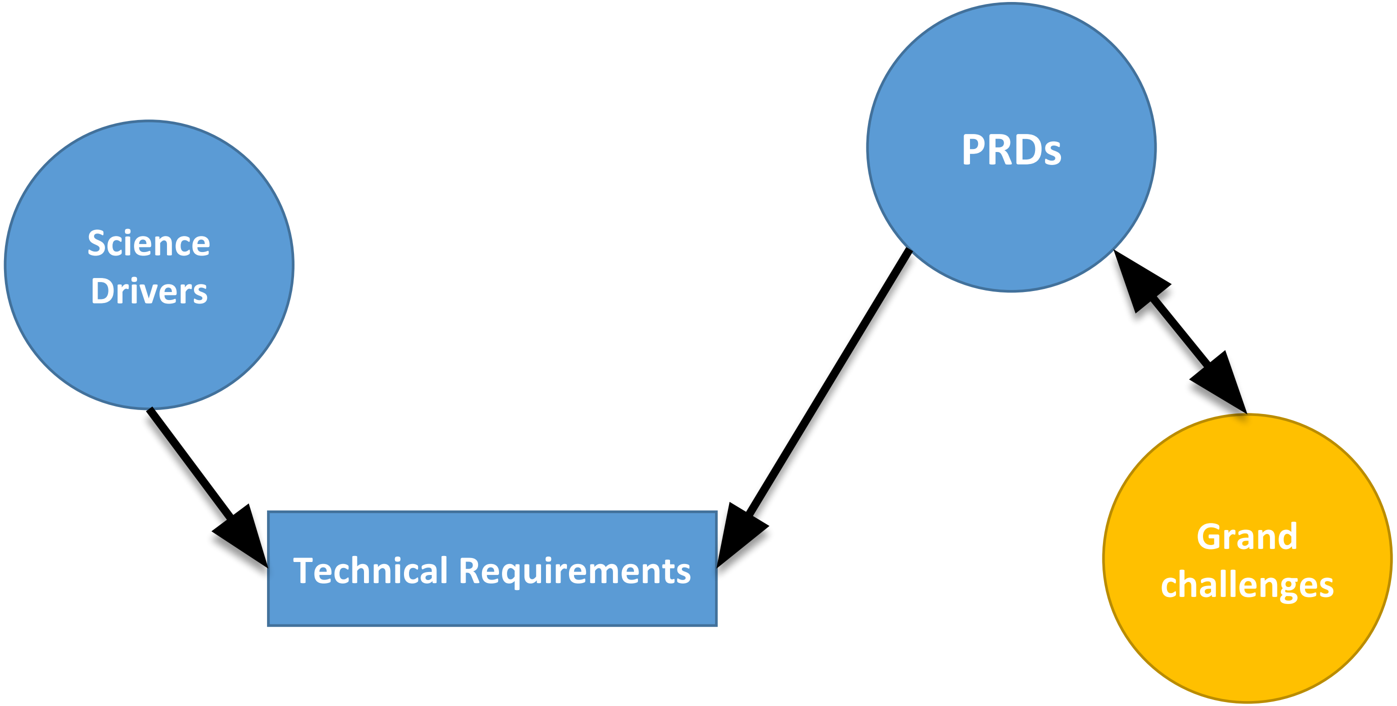
- Summer 2019: DOE charged co-Chairs. Conveners, panel members and additional members identified.
- Fall 2019: Regular telecons began to conduct the ground work leading up to December BRN workshop.
- Interim report laid the foundations of the panel's work and informed interactions at CPAD
- December 11-14, 2019: BRN Workshop in the Washington D.C. area. The workshop was attended by all BRN Study members and a number of observers: DOE Program Managers from HEP and related programs, and from NSF. The plenary talks on the first day were live-streamed to the community.
- July 2020: Presentation to HEPAP

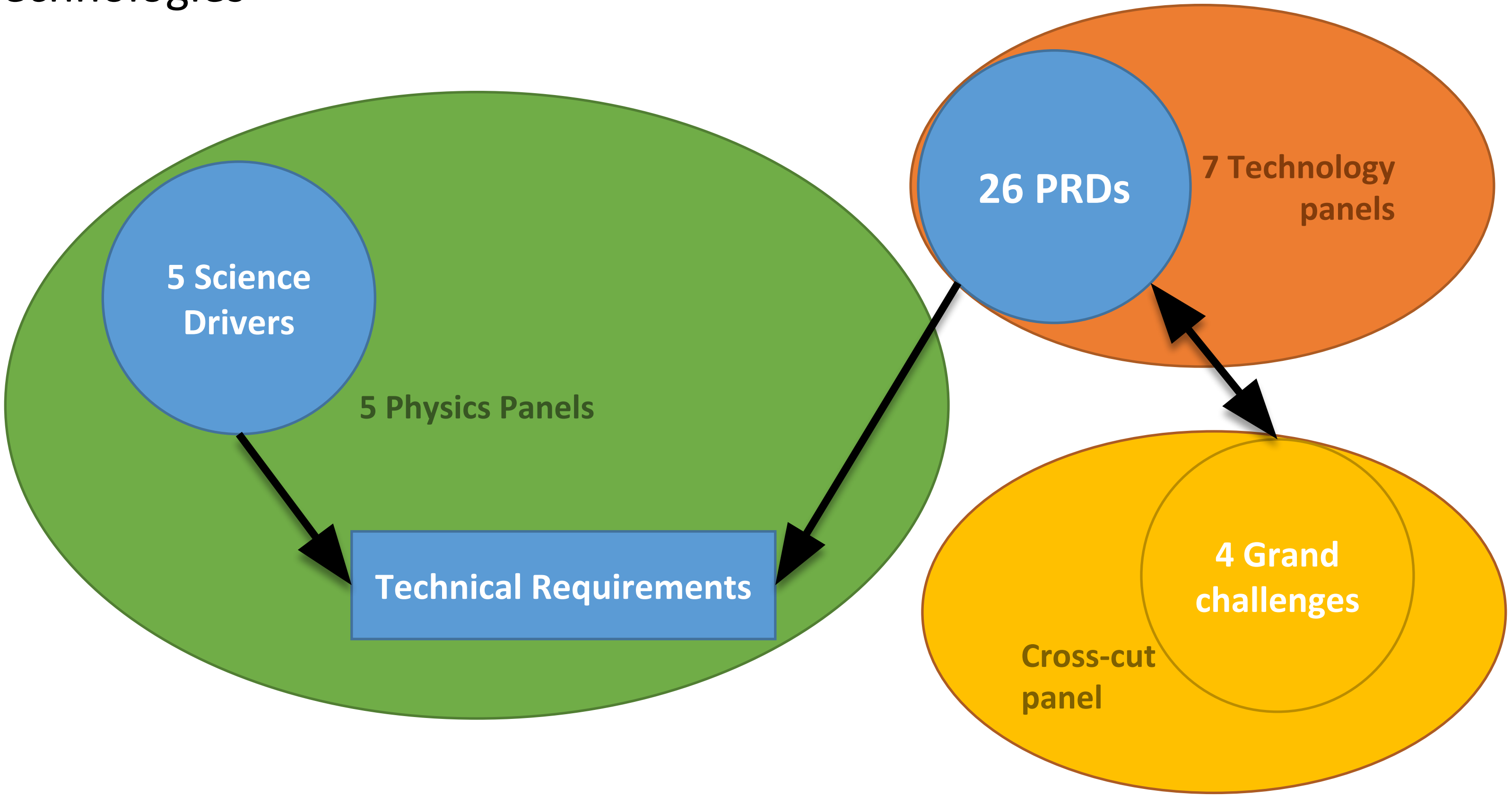
Study hallmarks:

- Close interaction between physics and technology groups. Cross cutting group across all areas to identify foundational issues and synergies
- Community input through CPAD, community surveys, town hall meetings, small targeted workshops

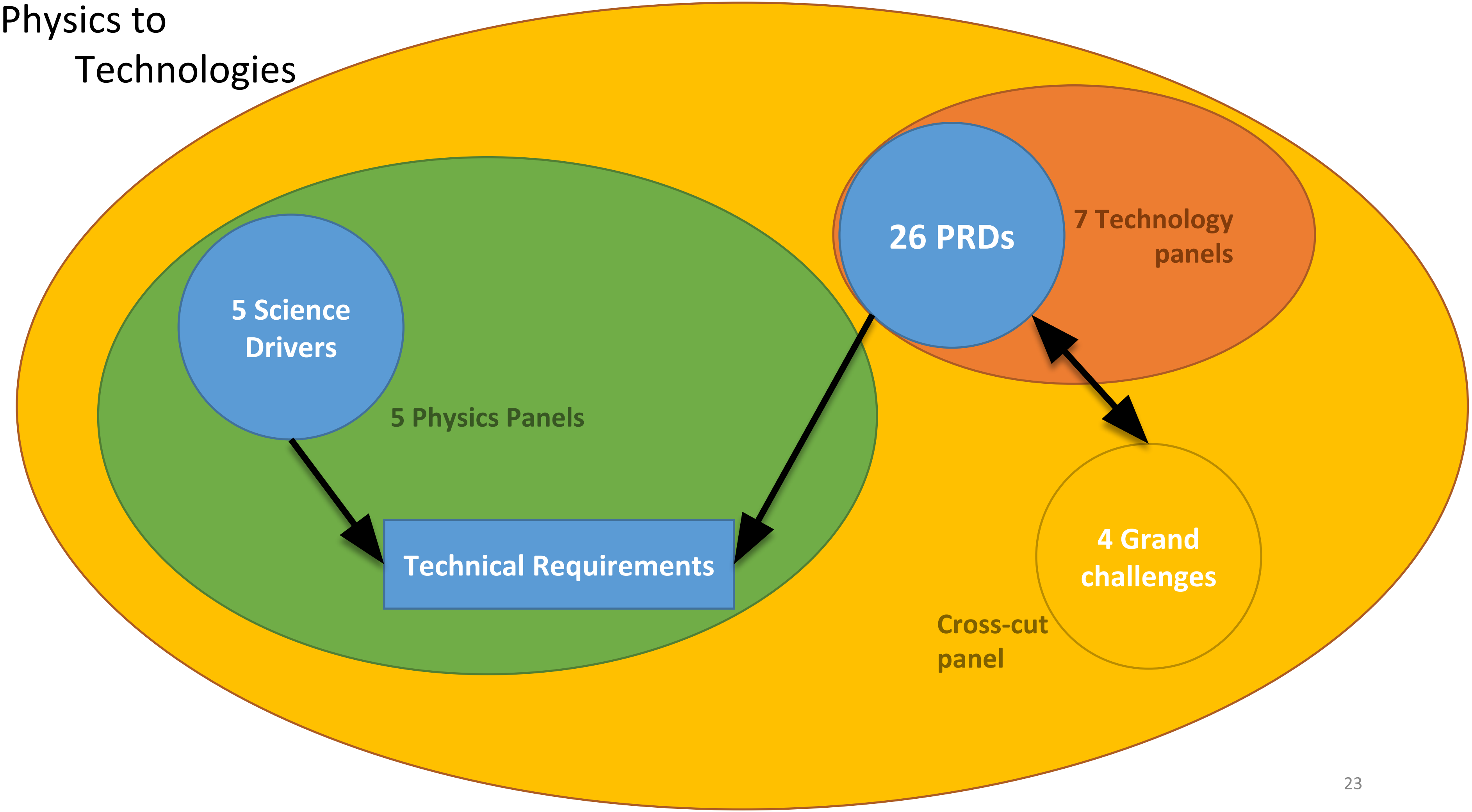
Physics to Technologies



Physics to Technologies



Physics to Technologies



Four Grand Challenges encompass this Instrumentation revolution

- **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.*

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- **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.*

Instrumentation Development Ecosystem

Key to the success of this tool revolution are **people**, **facilities and resources**, and **connections and collaborations**

1. Advanced workforce
2. Unique capabilities and facilities
3. Connections to other programs, other offices, other agencies, private foundations, commercial partners, global collaborations

A Commitment to Equality, Diversity and Inclusion in HEP Instrumentation R&D

Excellence and innovation come most effectively from diverse teams of people.

To accomplish the best science, we must commit, as a community, to action, to overcome the social injustices in our own backyard, and realize the impact of a diverse workforce. We must find, develop, and invent new ways to attract, encourage, recruit, and support a diverse community. We must enact an inclusive environment within instrumentation and within particle physics at all levels and across the areas in which we work and that we touch including academia, in universities and national laboratories, and in industry.

Some small steps are being taken to draw young people from diverse backgrounds to instrumentation.

- Outreach programs at universities and national labs and to the public
- Undergraduate research opportunities (NSF Research Experience for Undergraduates)
- Graduate Instrumentation Research Awards (award winners and honorable mentions, 2018 GIRA)

Recipients of the DPF Instrumentation Awards 2019. Left to Right Hanguo Wang (UCLA), Ettore Segreto, and Anna Amelia Machado (both of the University of Campinas in Brazil)

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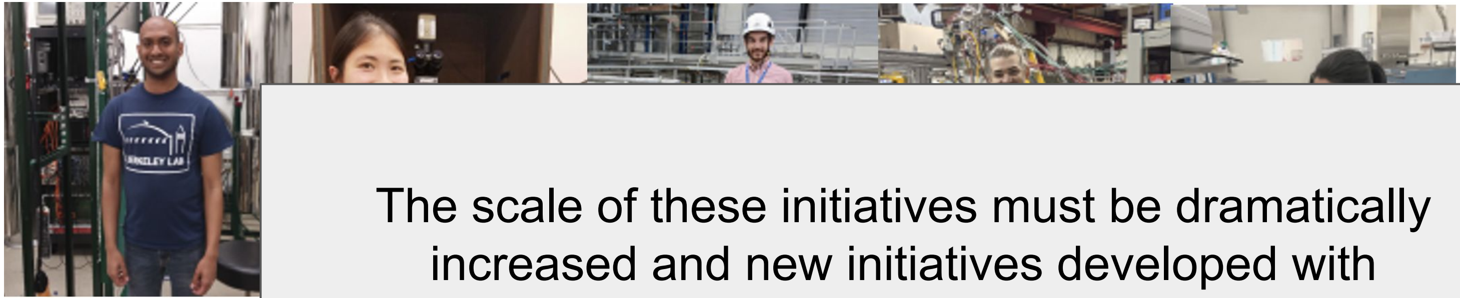
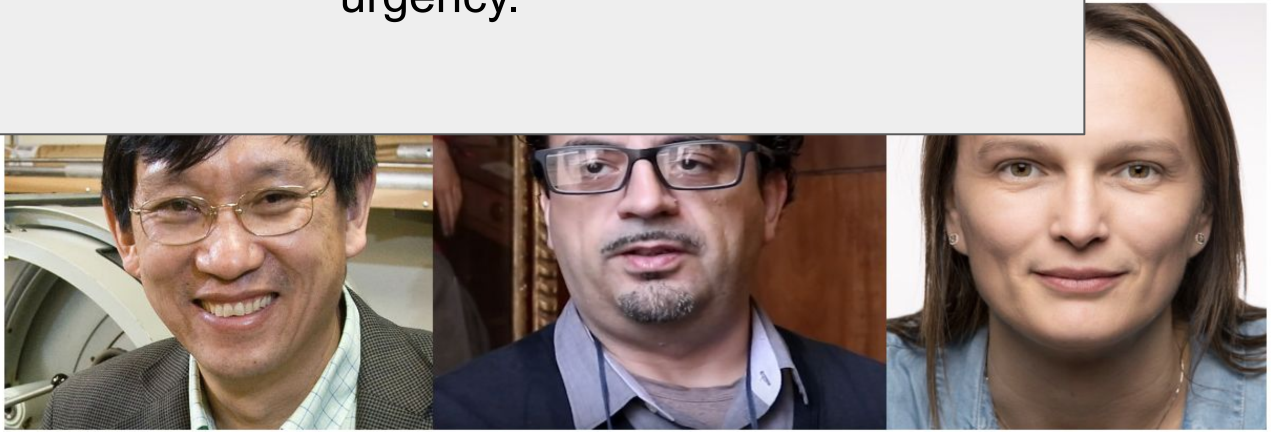


The scale of these initiatives must be dramatically increased and new initiatives developed with urgency.



Recipients of ... Instrumentatio ... 2019. Left to Right Hanguo Wang (UCLA), Ettore Segreto, and Anna Amelia Machado (both of the University of Campinas in Brazil)

Workforce requirements

Many areas require expertise and cross-disciplinary work (electronics, CS, DAQ, Mechanical engineering, cryogenic systems, composites design and fabrication, microfab and assembly, analytic chemistry, materials science, ...

To succeed in creating tools and new technologies, we need to succeed in excellence in the current and next generation of people

- diverse pipeline (in US, international)
- University/lab partnerships
- connections to other disciplines
- appropriate recognition

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

Instrumentation Development Ecosystem

Key to the success in this tool revolution are **people**, **facilities and resources**, and **connections and collaborations**

1. Advanced workforce
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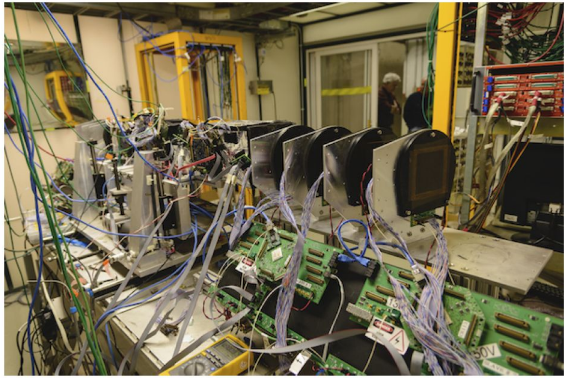
3. Connections to other programs, other offices, other agencies, private foundations, commercial partners, global collaborations

Maintain core facilities

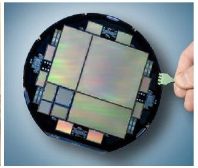
- SiDET
- Noble Liquid Test Facility
- Micro Systems Lab
- FTBTF
- Test beams at SLAC




Lithography


Etching


Film Deposition


CCD Wafer

	Higgs and Energy Frontier	Neutrinos	Dark Matter	Cosmic Acceleration	Unknown
Irradiation, ionizing and non-ionizing	✓	✓			✓
Test Beams	✓	✓			✓
Test Stands at Ultra-low Temperature			✓	✓	✓
Calibration Facilities	✓	✓	✓	✓	✓
Low Background Materials and Assay		✓	✓		✓
Ultra-light Composites	✓				✓
Novel CCD Development			✓	✓	
Superconducting Detector and Device Foundry			✓	✓	
Microelectronics Engineering and Foundry Access	✓	✓	✓	✓	✓
Simulation Framework	✓	✓	✓	✓	✓

Table 23: Capability needs for the five science drivers.

Develop new capabilities, collaborate where possible

Instrumentation Development Ecosystem

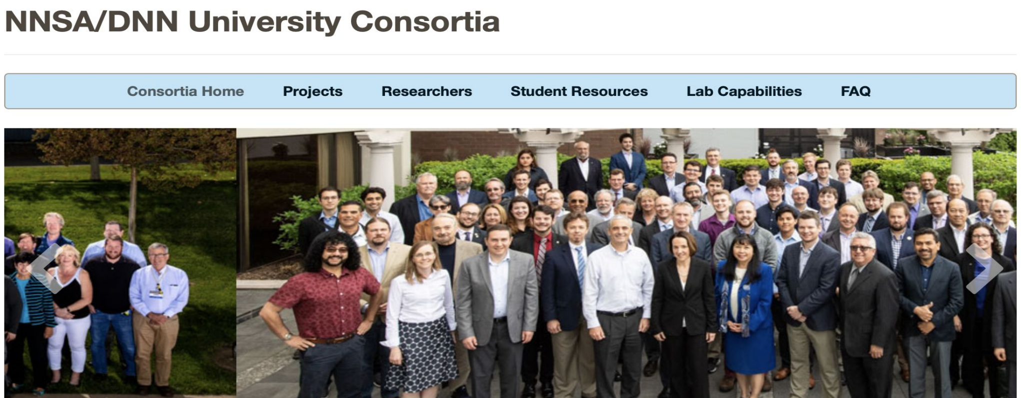
Key to the success in this tool revolution are **people**, **facilities and resources**, and **connections and collaborations**

1. Advanced workforce
2. Unique capabilities and facilities
3. Connections to other programs, other offices, other agencies, private foundations, commercial partners, global collaborations

R&D connections and collaborations

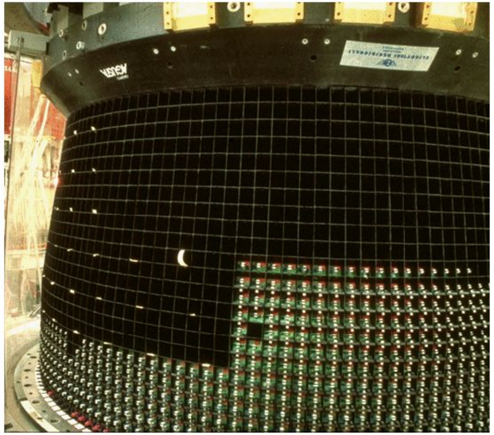
- Connections within OHEP, with the DOE Office of Science, between federal agencies, Universities & National Labs, with industry, & philanthropic foundations
- Need organizational structures to bring together technical areas.
- Rotating leadership, National labs provide homes
- Models: CERN R&D collaborations,
- DOE NNSA R&D consortia

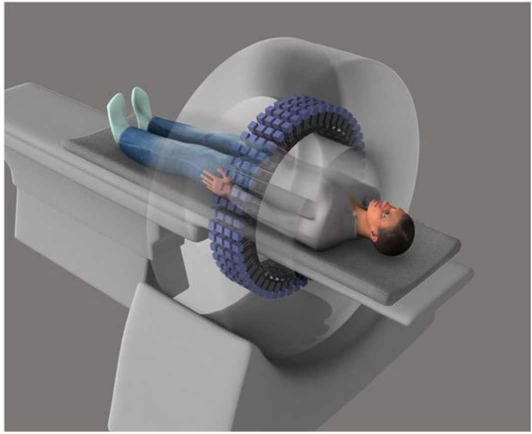
RD-53 Collaboration Home



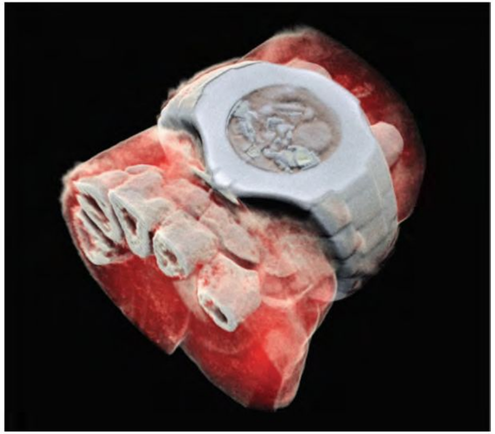
Connections to other disciplines: Benefits to Society

The development of the manufacturing process of BGO crystals for the calorimeter of the L3 experiment at the LEP collider at CERN (left) has contributed significantly to the advancement of Positron Emission Tomography (PET) scanners





(photo credit: CERN and S.R. Cherry/U.C. Davis)



The development of large-area hybrid pixel detectors for high energy physics experiments led to the realization of the potential of this new technology to provide noise-hit-free single-photon counting impactful for development of sophisticated integrated circuits with timing. The circuit is being used in medical imaging, X-ray science, materials analysis, space dosimetry and climate studies among others

The instrumentation plan described in this report will lead to the development of new technologies that hold the promise to be as broadly applicable and equally transformative.

Four Grand Challenges encompass this Instrumentation revolution

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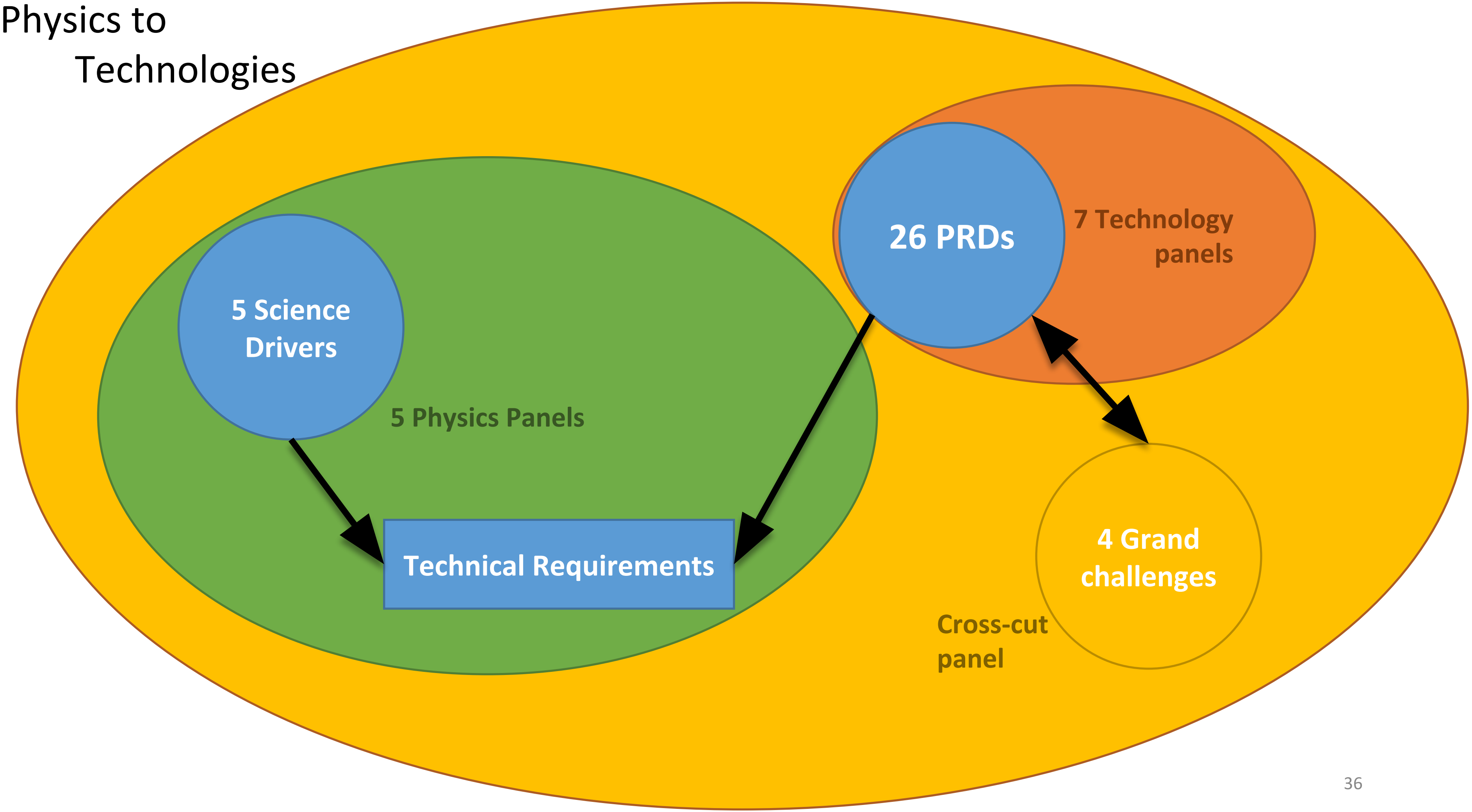
Physics to Technologies



Higgs and the Energy Frontier:

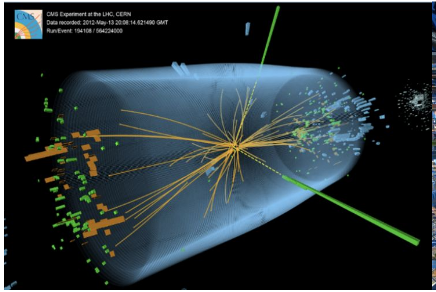
Next generation energy frontier colliders & detectors are precision measurement machines & discovery machines. The transformative physics goals include 4 inspiring & distinct directions:

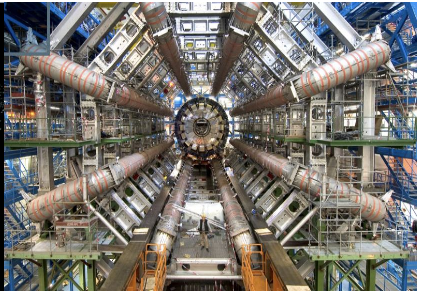
Higgs properties with sub-percent precision

Higgs self-coupling with 5% precision

Higgs connection to dark matter

New particles and phenomena at multi-TeV scale





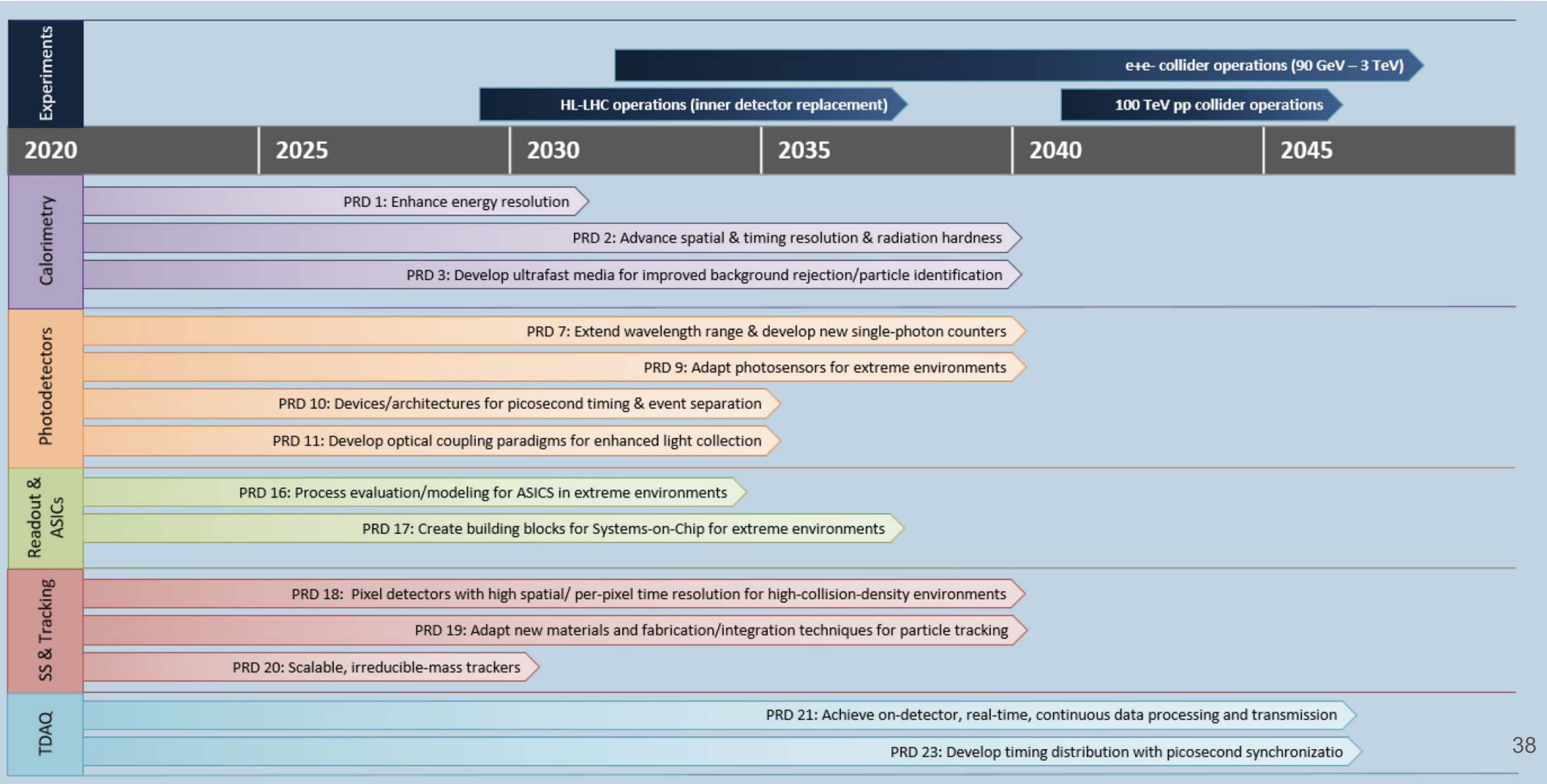
Science	Measurement	Technical Requirement	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\text{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\text{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\text{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	18, 19, 20, 23
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8 \times 10^{17}\ \text{n}_{\text{eq}}/\text{cm}^2$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	16, 17, 18, 19, 20, 23, 26
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of $0.5 \times 0.5\ \text{cm}^2$, hadronic cells of $1 \times 1\ \text{cm}^2$ TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	1, 3, 7, 10, 11, 23
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) $\text{n}_{\text{eq}}/\text{cm}^2$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	1, 2, 3, 7, 9, 10, 11, 16, 17, 23, 26
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8 \times 10^{17}\ \text{n}_{\text{eq}}/\text{cm}^2$	16, 17, 21, 26

Ta … er
an…

Jim Hirschauer Gabriella Sciolla (leads)
Michael Begel Meenakshi Narain

Technical Requirements to enable the physics program for Higgs and the Energy Frontier and map to Priority Research Directions.

Timeline: Higgs → Technologies to Discovery



Neutrinos

- Push the three-flavor paradigm into the regime of high-precision measurements of all parameters.
- Explore unknown territory in neutrino energy range, types of neutrino sources, and faint source intensities.
- Hunt for evidence of new particles and phenomena in the neutrino sector, and in other sectors using neutrino detectors.

Figure I: Neutrino sources. Typical neutrino energy is shown.

Science	Measurement	Technical Requirement	PRD
Neutrino mixing matrix unitarity	Measure tau neutrino appearance with high efficiency/purity	TR 2.1: Resolve short tracks (0.1 mm at 10 GeV) in 10 kton detectors	**4,6,10, 11,16,21,22, 23,25,26**
Measure neutrinos at macroscopic energies from cosmic distances for BSM searches	Sensitivity to neutrino fluxes 1/km^2/decade at low energy threshold	TR 2.2: Low power ($\ll$ 1 W) digitizers sampling at >3 GHz, triggering at $\mathcal{O}(1)$S/N	**16,17**
Resolve solar/ reactor Δm^2_{12} tension	Measure solar ^{8}B, hep and neutrino regeneration in the Earth with S/B>1 above a few MeV	TR 2.3: Radiogenic background reduction by a factor of 100-1000 in argon TR 2.4: <1 cm spatial, TR 2.5: < 10% energy resolution at kton scale	**4,6,21,22, 23,24,25,26**
Measure all flavor components of a supernova burst in real time	Flavor tagging with >90% efficiency, 5-50 MeV; measure CEvNS glow/buzz in large LAr or scintillator	TR 2.3, 2.4, 2.5 TR 2.6: Photodetector efficiency improvement by factor of 10 TR 2.7: Photosensor dark noise reduction by factor of 100	**4,6,7,9,10, 11,16,21,22 23,24,25,26**
BSM physics with sub-MeV (or sub-keV) neutrinos (geoneutrinos, pp neutrinos, solar thermal neutrinos, artificial radioactive sources)	Sensitivity to very low energy nuclear or electronic recoils in real time	TR 2.8: 10 eV nuclear recoil threshold at multi-ton to kton scale TR 2.9 Few degree recoil directionality	**5,6,7,9,11, 12,14,24,25,26**
Cosmic relic neutrino background, test of cosmological models	Measure cosmic relic neutrino capture on nuclei	TR 2.10: 10 meV energy resolution at beta endpoint, $\mathcal{O}$(1 kg) source with TR 2.11: <10 meV energy loss distortion at endpoint	**12,14,26**

Table 3: Technical Requirements to enable example neutrino physics topics and map to Priority Research Directions.

Ornella Palamara Kate Scholberg (leads)
Amy Connolly Dan Dwyer

Timeline: Neutrinos to technologies

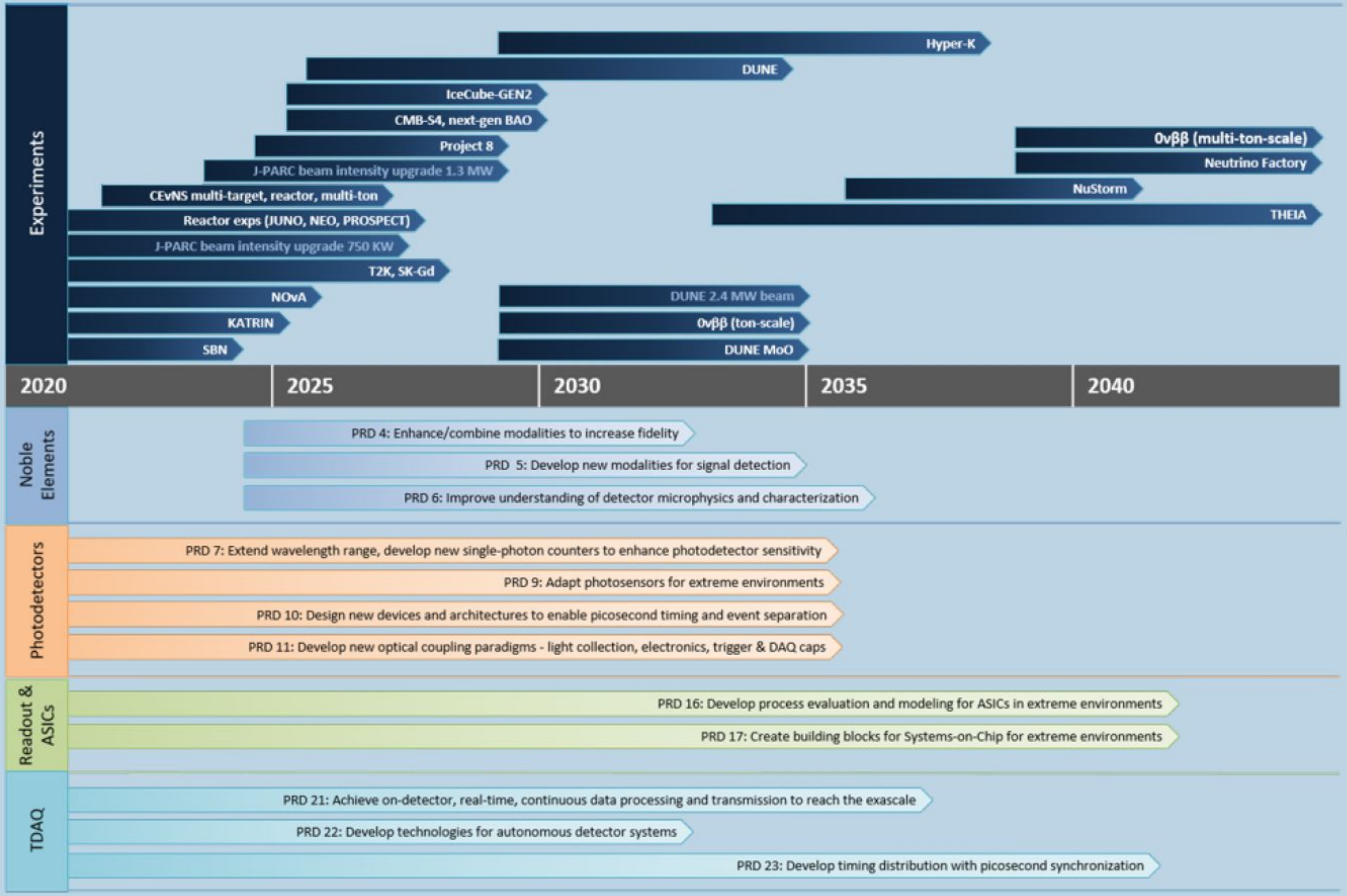


Figure II: Timeline of neutrino experiments.

Dark Matter

- Search for WIMP dark matter towards the neutrino floor
- Searching for particle dark matter with low masses
- Searching for wave-like dark matter
- Searching for the annihilation or decay products of dark matter interactions

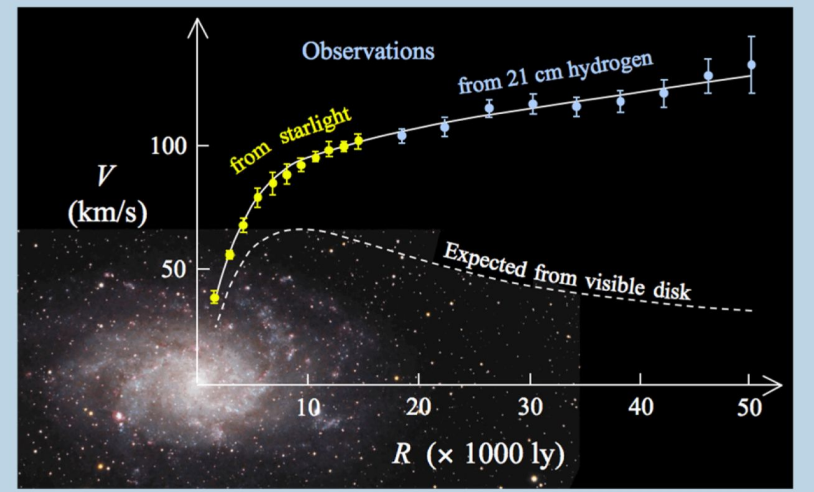


Figure I: Galaxy M33 illustrating how a gravitation force, in addition to that from the visible stars, is needed to explain the speed of stars at the outer edge of this galaxy. Creative Commons Attribution 3.0 Unported. Asher Yahalom, 2019. The Effect of Retardation on Galactic Rotation Curves. Journal of Physics: Conference Series

Jodi Cooley Dan McKinsey (leads)

Reyco Henning Andrew Sonnenshein

Science	Measurement	Technical Requirement	PRDs
Test for dark matter particles with mass >1 GeV	Search for nuclear recoils arising from scattering of >1 GeV dark matter with normal matter via spin-independent and spin-dependent couplings to nucleons	**Mass 1 - 10 GeV** TR 3.1(SI),TR 3.7(SD): Background rate < coherent scattering rate of solar neutrinos TR 3.2(SI), TR 3.8(SD): Target mass ~100 kg TR 3.3(SI), TR 3.9(SD): Energy Threshold: ~100 eV **Mass > 10 GeV** TR 3.4(SI), TR 3.10(SD): Background rate < coherent scattering rate of atmospheric neutrinos TR 3.5(SI), TR 3.11(SD): Target mass ~100 tonnes TR 3.6(SI), TR 3.12(SD): Energy Threshold: ~10 keV	5, 6, 24, 25 6, 7, 9, 11, 25, 26

Science	Measurement	Technical Requirement	PRDs
Test for peV–neV QCD axion dark matter	Search for peV–neV QCD axion dark matter via axion-nucleon coupling with nuclear magnetic resonance	**Near Term:** TR 3.21 $P \geq 0.05$ TR 3.23 $N\tau = 10^{24}$ sec. **Long Term:** TR 3.22 $P \geq 0.3$ TR 3.24 $N\tau = 10^{25}$ sec.	12, 13, 15 12, 13, 15
Test for neV–μeV QCD axion dark matter	Search for neV–μeV QCD axion dark matter using axion-photon conversion in lumped-element electromagnetic resonators	**Near Term:** TR 3.25 $Q_L \geq 10^6$ GeV TR 3.27 $\eta \leq 20$ TR 3.29 $BV \geq 4\,\mathrm{T}\cdot\mathrm{m}^3$ **Long Term:** TR 3.26 $Q_L \geq 10^8$ TR 3.28 $\eta \leq 0.1$ TR 3.30 $BV \geq 10\,\mathrm{T}\cdot\mathrm{m}^3$	12, 15 12, 15
Test for μeV–meV QCD axion dark matter	Search for μeV–meV QCD axion dark matter using axion-photon conversion in cavity electromagnetic resonators	**Near Term** TR 3.31 $Q_C \geq 10^5$ TR 3.33 $\eta \leq 1$ TR 3.35 $B \geq 10\,\mathrm{T}$, $V \geq 100l$ **Long Term:** TR 3.32 $Q_C \geq 10^6$ TR 3.34 $\eta \leq 10^{-6}$ TR 3.36 $B \geq 30\,\mathrm{T}$, $V \geq 1l$	12, 15 12, 15

Complete tables in text...

Timeline: Dark Matter → Technologies to Discovery

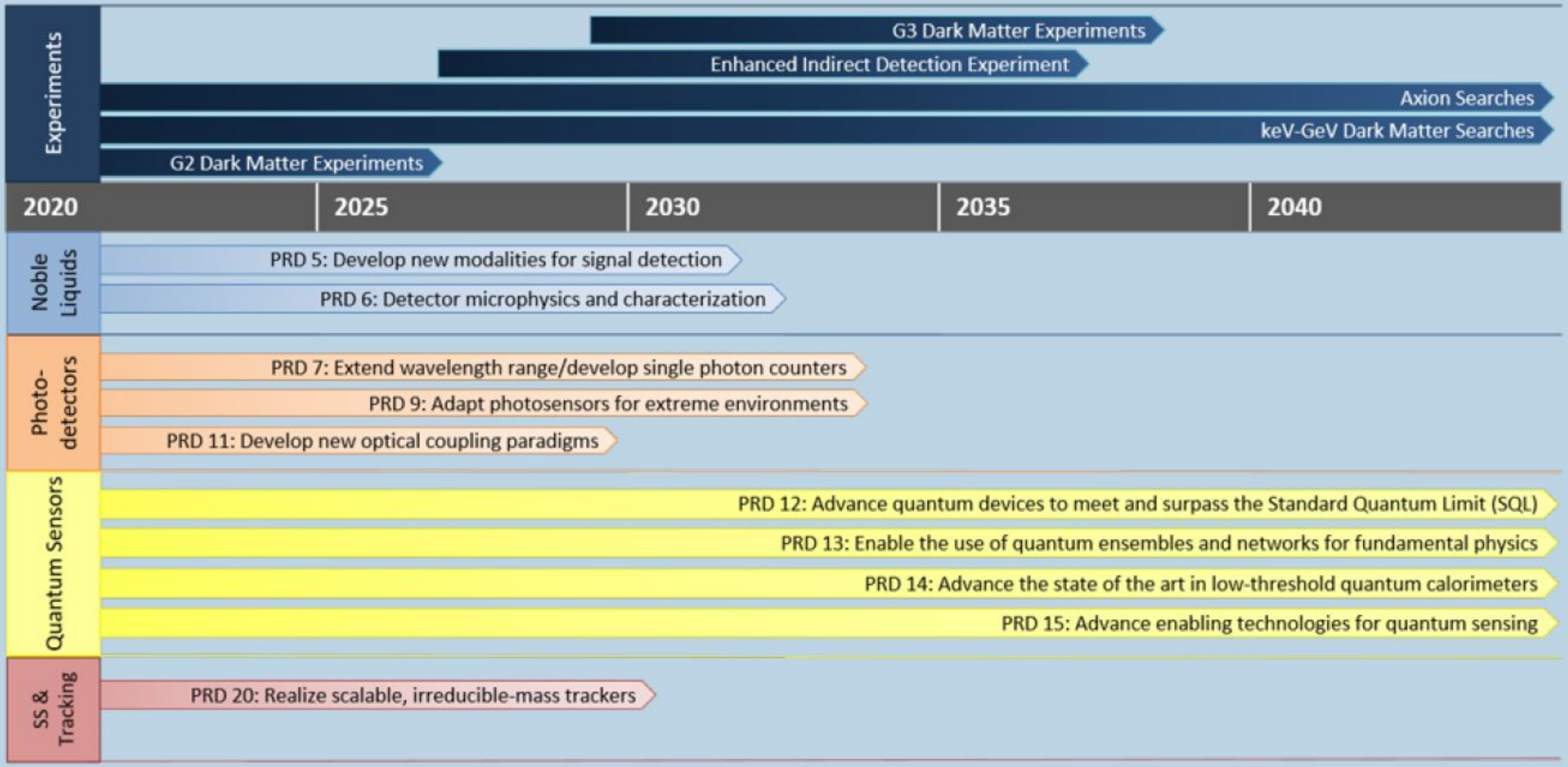
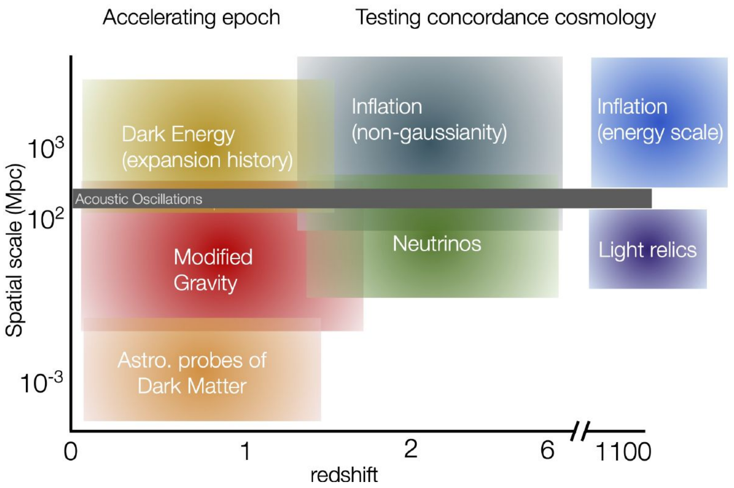


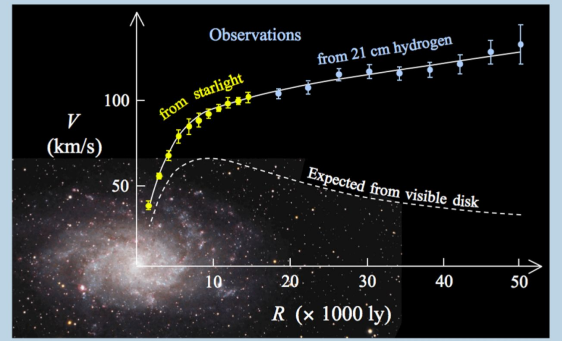
Figure II: Dark Matter Timeline

Cosmic Acceleration: Dark Energy & Inflation

- Drive cosmological measurements to new spatial and temporal scales
- Explore the properties of inflation, dark energy, and dark matter
- Study neutrino physics in a context complementing terrestrial techniques
- Test our concordance cosmological model in new regimes

Science Goal	Measurement	Technical Requirement	PRD
Fully sample the epoch of late-time cosmic acceleration	500M Galaxy spectra (R∼3000) to z<4	For Optical/IR spectroscopy TR 4.1: Sensitivity at wavelengths beyond the 1eV Silicon cutoff. TR 4.2: Ten-fold increase in multiplexing relative to current experiments	7, 11, 26
Distinguish between single vs. multi-field inflation by measuring f_{NL} down to 1	Multiple Intensity mapping surveys to measure flux from 2.9B galaxies to z<6	For 21-cm Intensity Mapping: TR 4.3: Pico-second timing synchronization across ∼km TR 4.4: Direct digitization and real-time calibration	21, 22, 23, 26
		For mm-wave Intensity Mapping: TR 4.5: On-chip mm spectrometers with R>200 TR 4.6: Fabrication and readout of 1M detectors	7, 8, 26





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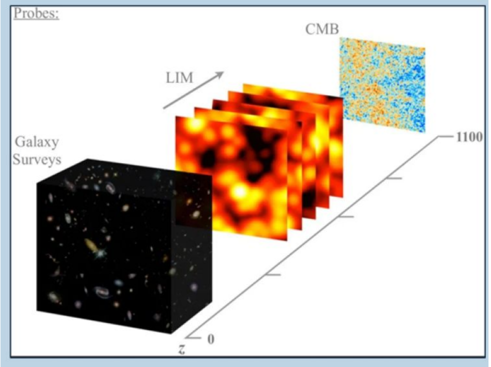


Clarence Chang Brenna Flaugher (leads)
Kyle Dawson Laura Newburgh

Timeline: Cosmic Acceleration → Technologies to Discovery

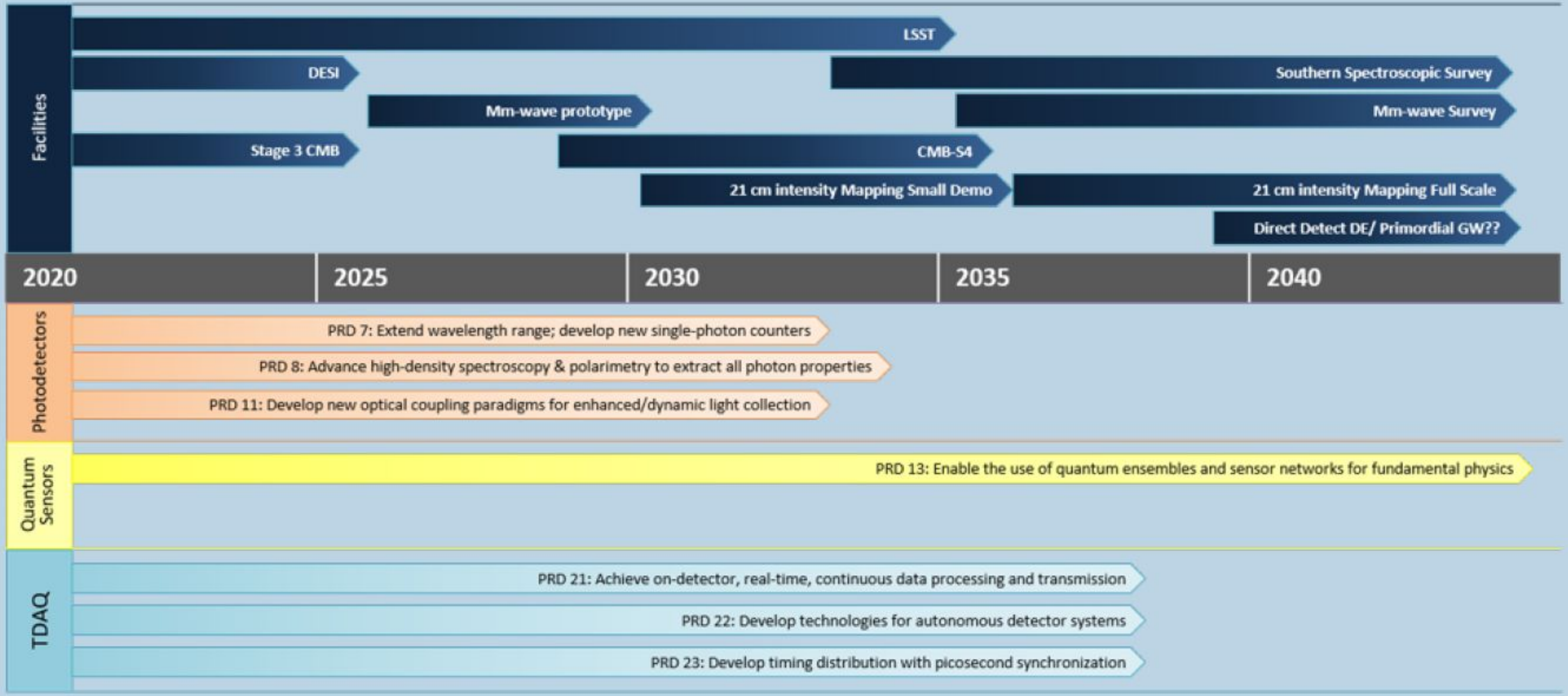
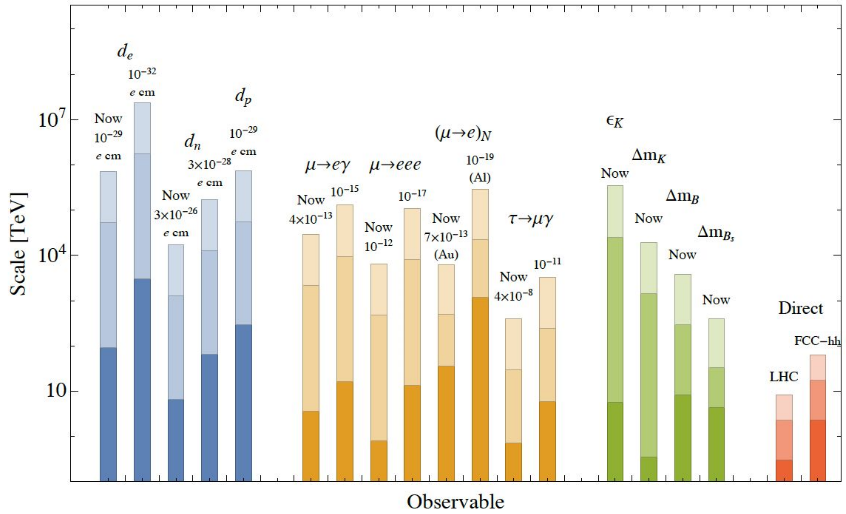


Figure IV: Dark Energy and Inflation Timeline

Explore the Unknown

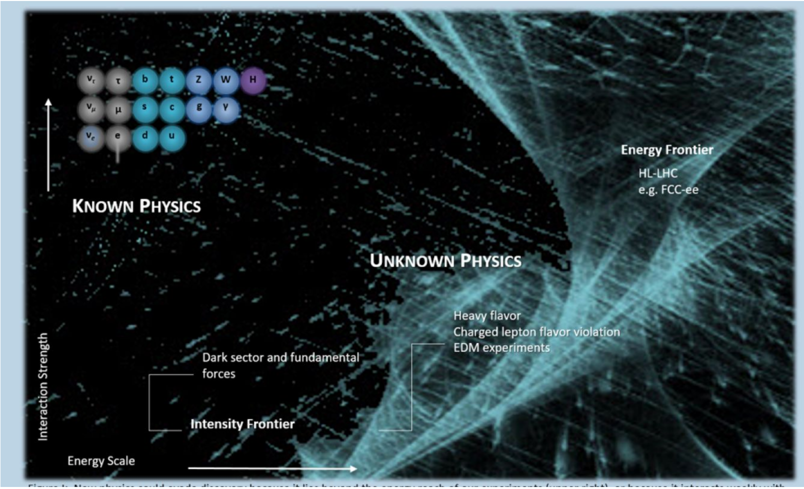
- Precision measurements in heavy flavor decays
- Searching for charged lepton flavor violation in rare decays of muons and kaons
- Tests of CP violation through electric dipole moment searches
- Probes of the dark sector and hunts for new fundamental forces



Science	Timescale	Technical Requirement	PRD
Search for new physics though rare flavor interactions	medium term	TR 5.1: Timing resolution at the level of 10 – 30 ps per hit in the silicon-pixel vertex detectors and 10 – 30 ps per track for both PID detectors (RICH, TORCH) and electromagnetic calorimeters	2, 10, 18
	medium term	TR 5.2: Development of radiation-hard, fast and cost-effective photosensors for TORCH and RICH detectors and tracking systems with optical readout	9, 11
	medium term	TR 5.3: Development of the next generation ASICS to extract the large data rate (and possibly pre-process it) out of inner pixel layer detectors in a very challenging radiation environment	16, 17
Tests of the CKM quark mixing matrix description	medium term	TR 5.4: Radiation-hard silicon pixel detectors (fluences of 5×10^{16} n_{eq}/cm^2)	18, 20
	medium term	TR 5.5: Cost-effective electromagnetic calorimeter with granularity of typically 2×2 cm^2, resolution of $\frac{\sigma(E)}{E}\sim\frac{10\%}{\sqrt{E}}\oplus1\%$ and timing resolution of a few tens of ps; total radiation dose of $\sim$ 200 Mrad	1
	medium term	TR 5.6: Real-time processing of large amount of data (400-500 Tb/sec) and development of radiation-hard, high-rate optical links, with tight constraints of low-power consumption and low mass	16, 17, 21, 22
	long term	TR 5.7: Fast-timing resolution at the level of 1 ps per track for $\pi/K/p$ separation up to 50 GeV	3, 10
Studies of Lepton Flavor Universality	long term	TR 5.8: Further ASICS development to extract and pre-process on detector the large data rate of inner layers detectors in an extreme radiation environment	16, 17
	long term	TR 5.9: Radiation-hard, ultra-fast silicon pixel detectors (fluences of 10^{18} n_{eq}/cm^2)	18, 19, 20
	long term	TR 5.10: Very high granularity calorimeters preserving an energy resolution of $\frac{\sigma(E)}{E}\sim\frac{10\%}{\sqrt{E}}$	1, 2, 7, 9
		TR 5.11: Real-time processing of large amount of data	16, 17, 21, 22, 23

Sarah Demers Monica Pepe-Altarelli (leads)
Matthew Reece Nicola Serra

Timeline: Explore the Unknown → Technologies to Discovery



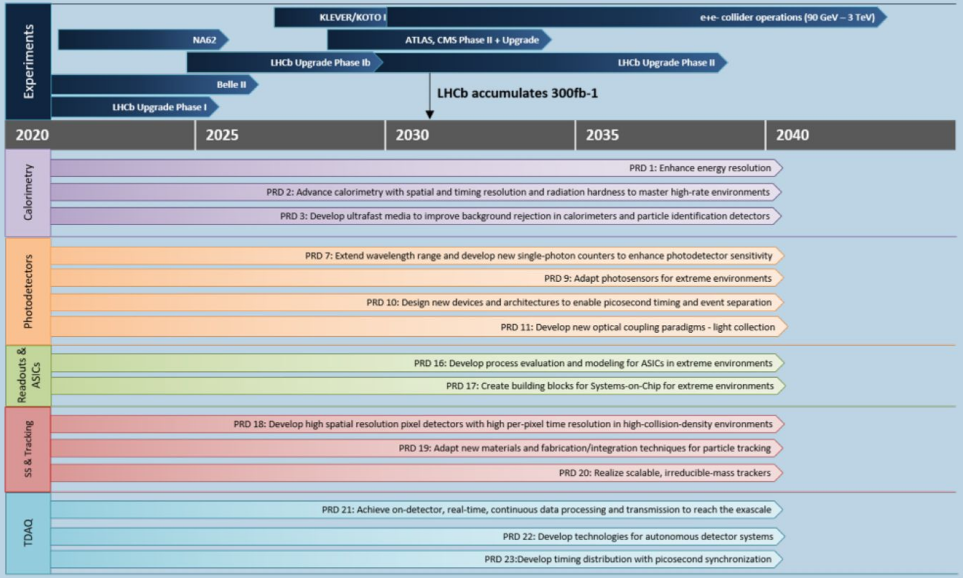


Figure III: Flavor physics timeline. The arrows that extend until the 2040s indicate instrumentation PRDs that will enable the flavor physics program at proposed future e+e- colliders at the energy frontier such as the FCC-ee, CEPC, ILC and CLIC.

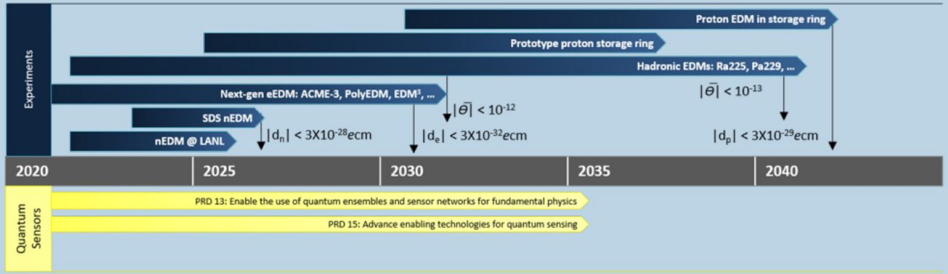


Figure VI: EDM Experiments Timeline, where d_n refers to the EDM of the neutron, d_p refers to the EDM of the proton, d_e refers to EDM of the electron, and theta is the strong CP phase.

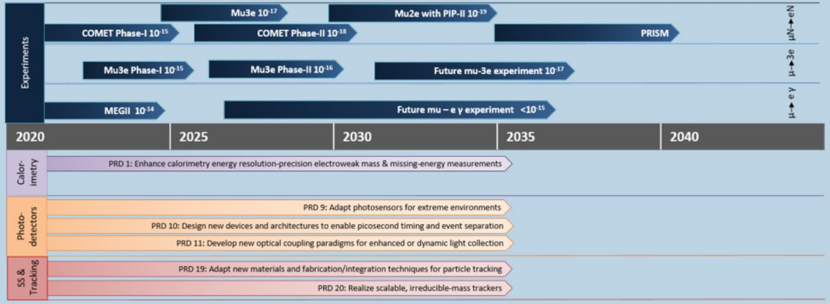


Figure IV: Rare Muon Experiments Timeline

Technology Panels

↓

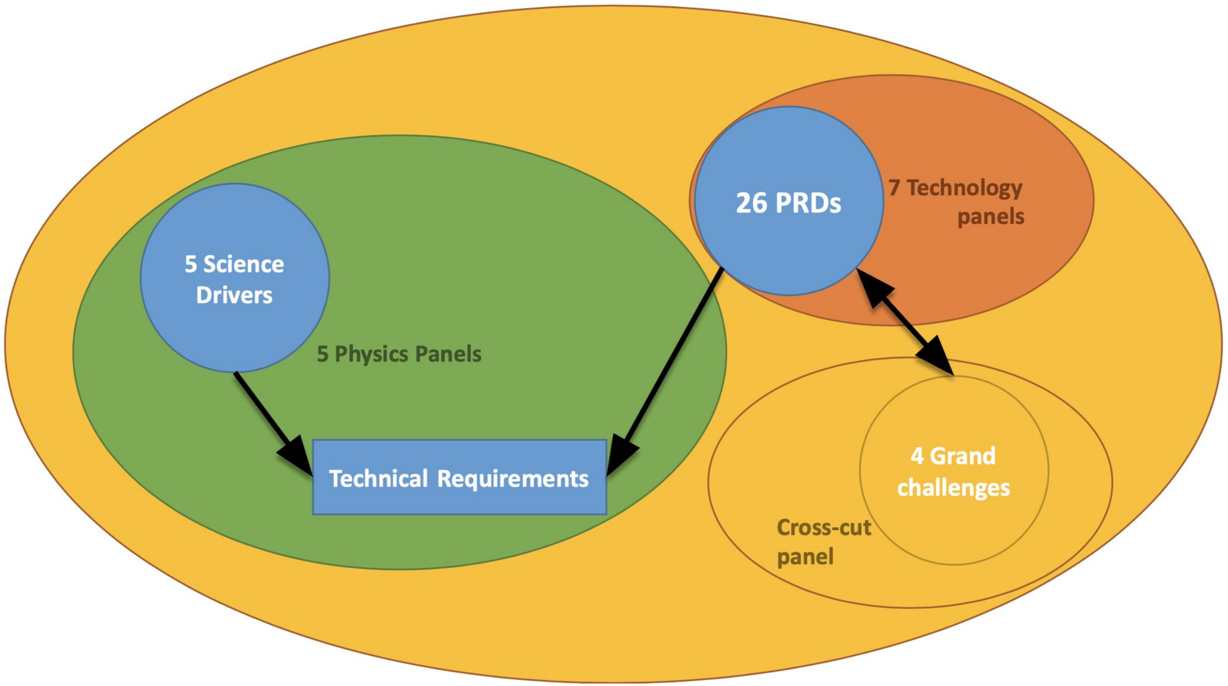
Priority Research Directions

↓

Thrusts delineated

↓

Actionable Research plans



Calorimetry

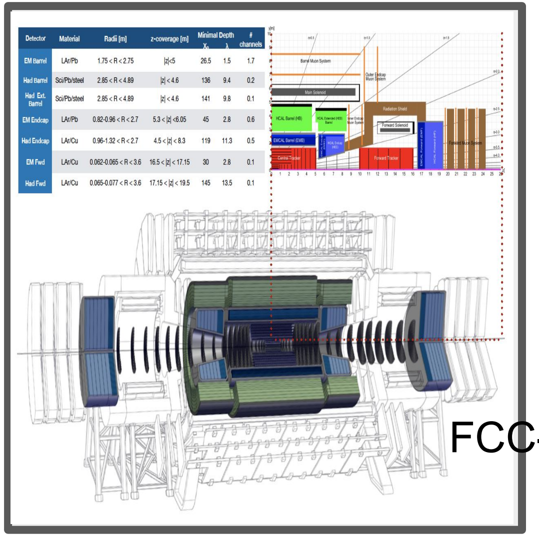
Priority Research Direction	Technical Requirements
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	TR 1.3, TR 1.4, TR 5.1, TR 5.5, TR 5.10
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	TR 1.4, TR 5.7
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification	TR 1.3, TR 1.4, TR 5.7

Connections outside of HEP:

- The detection of photons, electrons, and hadrons beyond HEP. Eg: experiments at EIC
- Development of organic scintillators for medicine and national security

Facilities and Capabilities (existing and needed)

- Detailed, reliable simulation studies (GEANT4)
- Irradiation facilities to qualify materials, test beams
- Characterizing precision timing systems.
- Studies of data rate, rad tolerance, improved or alternate power delivery systems.
- Expertise: Research scientists at universities



Detector	Material	Radii [m]	z-coverage [m]	Minimal Depth X_0	Minimal Depth λ	# channels
EM Barrel	LAr/Pb	1.75 < R < 2.75	|z|<5	26.5	1.5	1.7
Had Barrel	Sci/Pb/steel	2.85 < R < 4.89	|z| < 4.6	136	9.4	0.2
Had Ext. Barrel	Sci/Pb/steel	2.85 < R < 4.89	|z| < 4.6	141	9.8	0.1
EM Endcap	LAr/Pb	0.82-0.96 < R < 2.7	5.3 < |z| <6.05	45	2.8	0.6
Had Endcap	LAr/Cu	0.96-1.32 < R < 2.7	4.5 < |z| < 8.3	119	11.3	0.5
EM Fwd	LAr/Cu	0.062-0.065 < R < 3.6	16.5 < |z| < 17.15	30	2.8	0.1
Had Fwd	LAr/Cu	0.065-0.077 < R < 3.6	17.15 < |z| < 19.5	145	13.5	0.1

FCC-hh

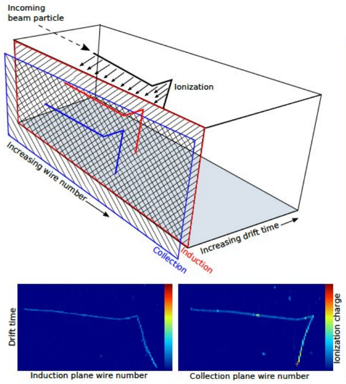
Francesco Lanni Roger Rusack (leads)
Nural Akchurin Sarah Eno Paolo Rumerio Ren-Yuan Zhu

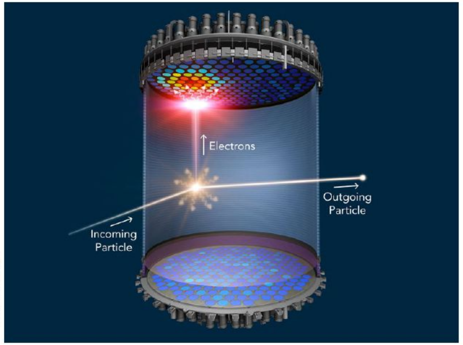
Noble Elements

Priority Research Direction	Technical Requirements
PRD 4: Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity PRD 5: Develop new modalities for signal detection	TR 1.3.3, 2.1, 2.4, 2.5, 2.7, 2.9, 3.3, 3.6, 3.9, 3.12, 3.13, 3.15, 3.17, 3.19
PRD 6: Improve the understanding of detector micro-physics and characterization to increase signal-to-noise and reconstruction fidelity	TR 2.8, 2.9, 3.3, 3.6, 3.9, 3.12, 3.13, 3.15, 3.17, 3.19
PRD 25: Advance material purification and assay methods to increase sensitivity	TR 2.3, 3.1, 3.4, 3.7, 3.10
PRD 26: Addressing challenges in scaling technologies	TR 2.1, 2.3, 2.4, 2.7, 2.9, 3.2, 3.5, 3.8, 3.11 , 3.14, 3.16, 3.18, 3.20, 3.45a, 3.45b

Connections outside of HEP:
- Double beta decay experiments (NP)
- Impact on Astrophysics (eg: SN and solar nus)
- Dedicated R&D for medical imaging

Facilities and Capabilities (existing and needed)
- Low background screening
- Cryogenic platforms (materials, optical properti HV….)
- Test beams
- Engineering expertise





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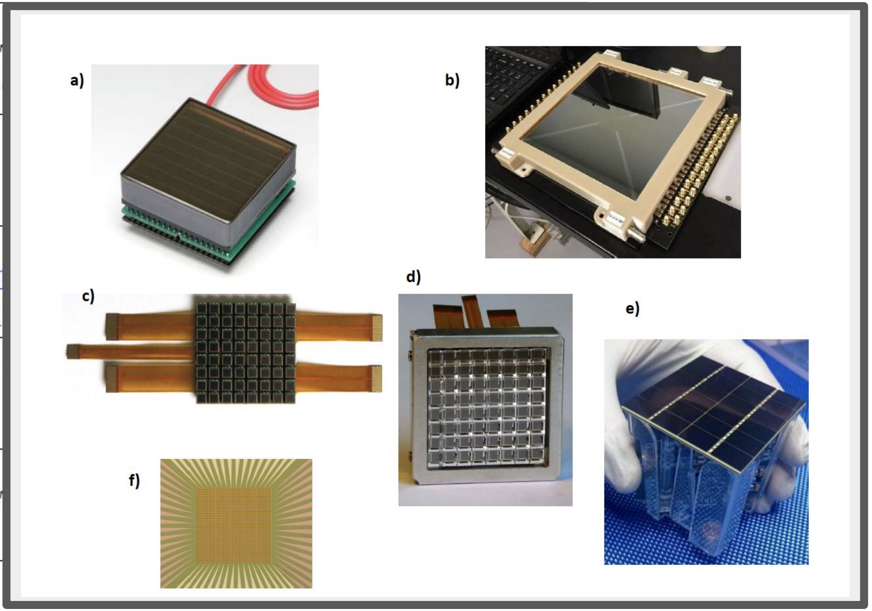
Jennifer Raaf Andrea Pocar Jonathan Asaadi Hugh Lippincott

Photodetectors

Priority Research Direction	Technical Requirements
PRD 7: Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity	TR 1.3, TR 1.4, TR 2.8, TR 2.9, TR 3.6, TR 4.1, [cut]
PRD 8: Advance high-density spectroscopy and polarimetry to extract all photon properties	TR 4.1, TR 4.2
PRD 9: Adapt photodetectors for extreme environments	TR 1.4, TR 2.3, TR 2.9, TR 2.[cut] TR 5.10, TR 5.1[cut]
PRD 10: Design new devices and architectures to enable picosecond timing and event separation	TR 1.3, TR 1.4, TR 2.7, TR 4.3, [cut]
PRD 11: Develop new optical coupling paradigms for enhanced or dynamic light collection	TR 1.3, TR 1.4, TR 2.7, TR 2.8, TR 3.5, TR 3.6, [cut]



Connections outside of HEP

- **physics experiments and detectors at the light sources and in Astronomy**
- **Time-Of-Flight (TOF) PET medical imaging, biology, quantum computers, national security**

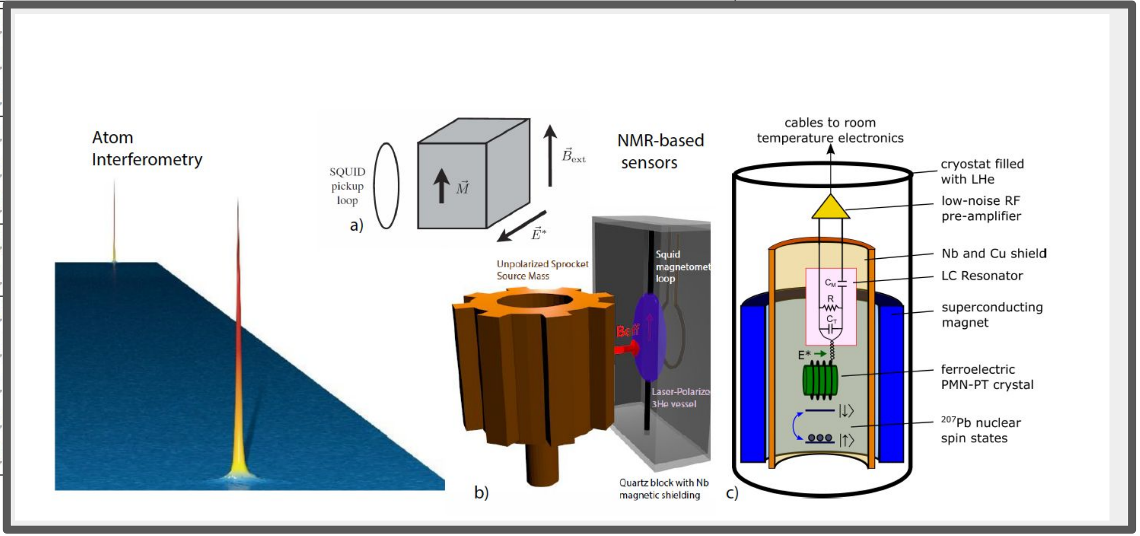
Facilities and Capabilities

- **close connections to industry for fabrication of devices and the procurement of materials.**
- **new infrastructure through upgrades at existing DOE facilities or partnerships with other federal facilities and industry. (eg: Ge CCD R&D, development of readout and ASICs**

Lindley Winslow Peter Krivzan (Leads) Graham Giovanetti Adriana Lita Felix Sefkow

Quantum Sensors

Priority Research Direction	Technical Requirements
PRD 12: Advance quantum devices to meet and surpass the Standard Quantum Limit	TR TR TR
PRD 13: Enable the use of quantum ensembles and sensor networks for fundamental physics	TR TR TR
PRD 14: Advance the state of the art in low-threshold quantum calorimeters	TR TR
PRD 15: Advance enabling technologies for quantum sensing	TR TR TR TR TR

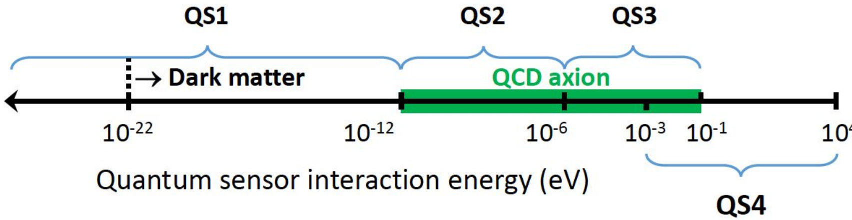


Connections outside of HEP:

- quantum information science, quantum computing, materials science, and biology

Facilities and Capabilities (existing and needed

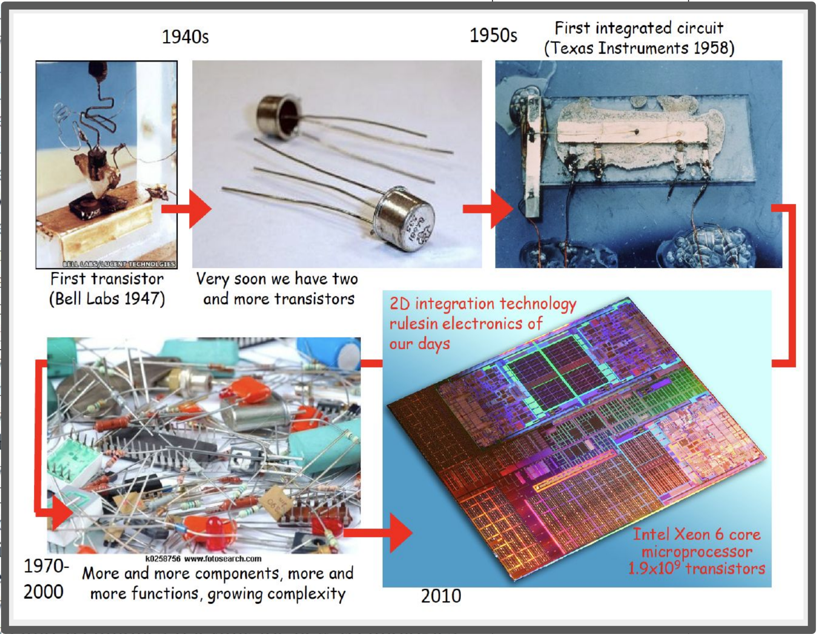
- Large volume high field magnets in solenoidal and toroidal geometries
- Faster turnaround, cheaper, larger mK dilution refrigerators

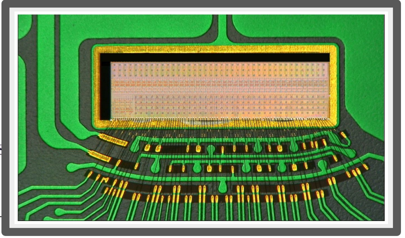


Andrew Geraci Kent Irwin (Leads) Gretchen Campbell
Alexander Sushkov Ronald Walsworth Anna Grassellino

Readout and ASICs

Priority Research Directions	Thrusts	Technical Requirements
PRD 16: Evaluate process technology and develop models for ASICs in extreme environments	Develop models, standard cell libraries, and demonstrators for extreme rate and radiation; Develop models, standard cell libraries, and Dev and and Inve and Inve pho Inve tech asse Add Art	
PRD 17: Create building blocks for Systems-on-Chip for extreme environments	Dev high Dev wit Dev (DC Cir desi inte Dev flows and techniques relevant for new technologies; Develop analog and multiplexing blocks for 4K environments and below; Develop fault tolerant communications for long lifetime inaccessible readout; Develop precision clock and timing circuits (PLL, DLL, Timing Discriminators, Delay Lines, Picosecond TDCs); Develop multi-channel RF digitizers	TR 5.2 TR 5.6





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Angelo Dragone Maurice Garcia-Sciveres
Terri Shaw Julia Thom-Levy

Connections outside of HEP:

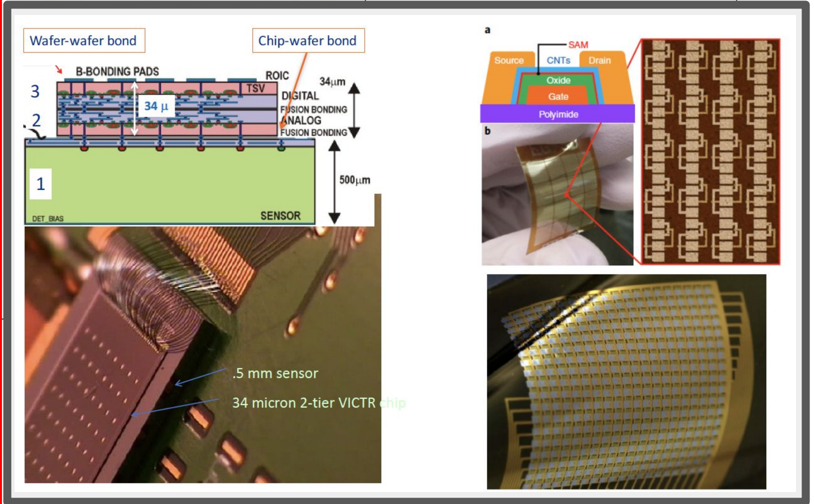
- Instrumentation for Basic Energy Sciences, NASA, stockpile stewardship program

Facilities and Capabilities (existing and needed)

- Foundry access, including design tools and third party intellectual property
- Long-term, diverse, HEP workforce
- Collaboration with other sponsors

Solid State and Tracking

PRD	Thrust	Technical Requirements
PRD 18: Develop high spatial resolution pixel detectors with high per-pixel time resolution to resolve individual interactions in high-collision-density environments	Thrust 1:Lepton colliders, re- ... dustrial partnerships	
PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking	Thrust 2: Development of rea out electronics matched to n sensor characteristics, includi new processing such as 3 integration	
PRD 20: Realize scalable, irreducible-mass trackers	Thrust 1: Highly integrat monolithic, active sensors Thrust 2: Scaling of low-m detector system Thrust 3: Systems for spec applications: space-based tra ing detectors and dedicat	



Marina Artuso Carl Haber (Leads)
Alessandro Tricoli Petra Merkel

Connections outside of HEP:

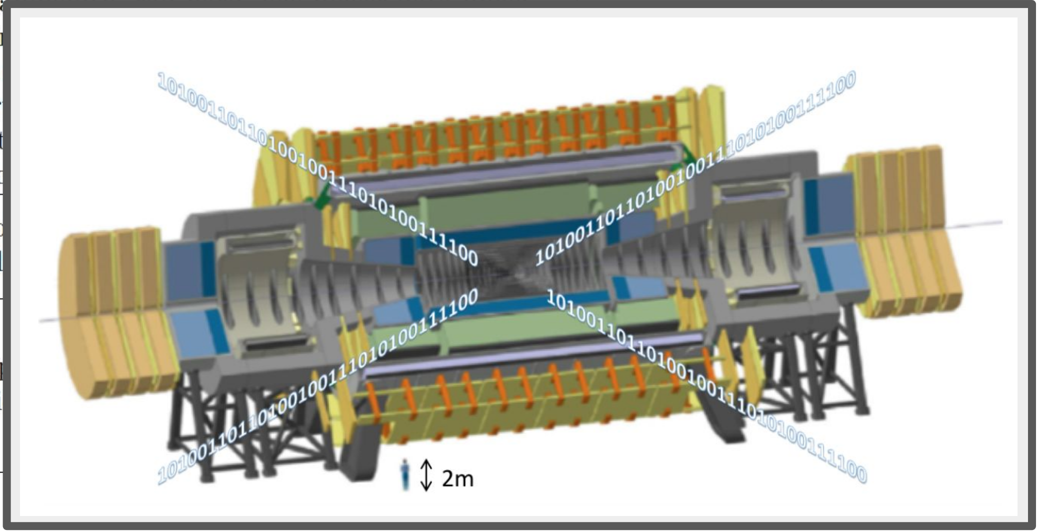
- Nuclear (eg: EIC), astroparticle, medical, materials, homeland security science and engineering.

Facilities and Capabilities (existing and needed)

- specialized infrastructure: test beam and **irradiation facilities**, silicon processing labs, electronic packaging and assembly, metrology, and composites fabrication facilities
- engineering expertise in ASIC design and test, simulation, verification, and low power systems, and mechanical design and composite fabrication.

Trigger and DAQ

Priority Research Directions	Thrusts	Technical Requirements
PRD 21: Achieve on-detector real-time, continuous data processing and transmission to reach the exascale	High-b[illegible] Real-ti Online Fast ar comput Advanc	
PRD 22: Develop technologies for autonomous detector systems	Autono Self-cal	
PRD 23: Develop timing distribution with picosecond synchronization	Develop with pi	



Connections outside of HEP:

- DOE Nuclear Physics and DOE Basic Energy Sciences.
- Machine-learning and implementation overlap with technology industry: Aeronautics, smart power grids, autonomous vehicles...

Facilities and Capabilities (existing and needed)

- partnerships between U.S. national laboratories and universities for tool, ASIC, and TDAQ development
- irradiation facilities, integration test facilities

Darin Acosta Tulika Bose (Leads)
Wesley Ketchum Jinlong Zhang Paul O'Connor Georgia Karagiorgi

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

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

What to do with this report and why now #1

During the course of this BRN study the Division of Particles and Fields of the American Physical Society announced the year-long U.S. Particle Physics Community Planning Exercise Snowmass 2021. This will be followed by a new meeting of the Particle Physics Project Prioritization Panel (P5).

We encourage the particle physics community to build on the research plans presented in this BRN study by developing and refining them further and introducing and developing new instrumentation ideas during Snowmass 2021.

Welcome to Snowmass 2021

The Particle Physics Community Planning Exercise (a.k.a. “Snowmass”)

What to do with this report and why now #2

The ESU states: *The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels."*

We support the stance the ESU articulates towards instrumentation.

We encourage the U.S. particle physics community through the Snowmass process to play a role in the proposed global detector R&D roadmap exercise by contributing U.S. input.

CPAD should continue to play a role in developing this international roadmap and can be the vehicle for the realization of the program outlined in this report.

Acknowledgments

Many contributed at various stages of the Basics Research Needs study that led to this report. We are grateful to those who played roles beyond the report authors. We acknowledge with gratitude:

The 142 other members of the particle physics community who contributed their time and ideas to the BRN study in the months leading up to the workshop. (See back-up for individual names.)

The Report's "readers" gave us critical feedback and provided fact checking during the final stages of preparation. Dan Akerib (SLAC National Laboratory), Myron Campbell (University of Michigan), Andy Lankford (University of California Irvine), Ritchie Patterson (Cornell University), Steve Ritz (University of California Santa Cruz) and Heidi Schellman (University of Oregon).

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“The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark” *(Michelangelo)*

Aim high or we will not realize the potential of our field, discovery will be stalled and we betray ourselves and the next generation.

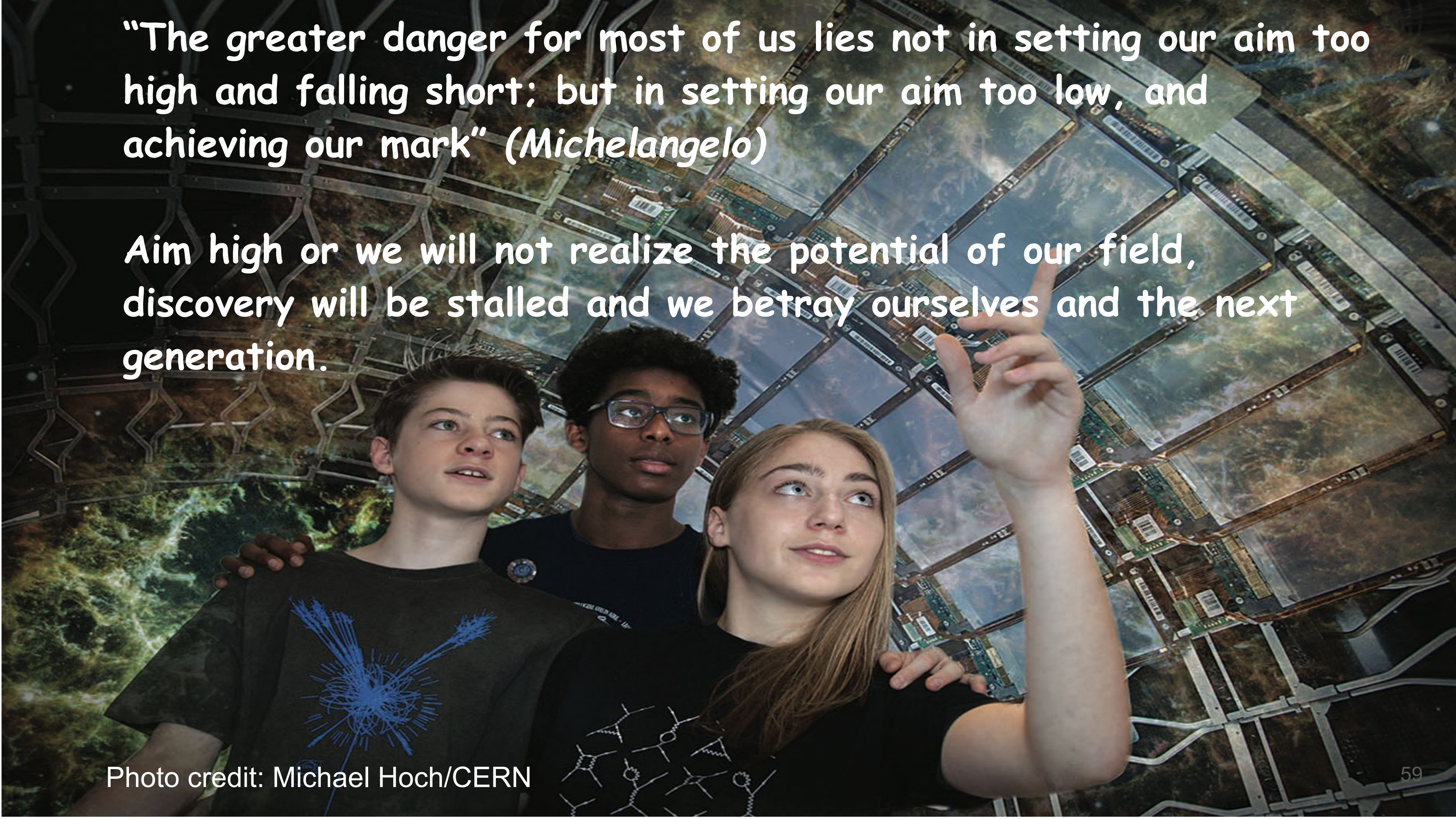

Photo credit: Michael Hoch/CERN

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In addition to the members of the BRN panel many other members of the particle physics community contributed their time and ideas to the BRN study in the months leading up to the workshop. We acknowledge with gratitude:

Energy Frontier: Artur Apresyan (Fermi National Accelerator Laboratory), James Brau (University of Oregon), Martin Breidenbach (SLAC National Accelerator Laboratory), Sarah Eno (University of Maryland), Zhen Liu (University of Maryland), Alessandro Tricoli (Brookhaven National Laboratory);

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In addition to the members of the BRN panel many other members of the particle physics community contributed their time and ideas to the BRN study in the months leading up to the workshop. We acknowledge with gratitude:

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