CPAD

Coordinating Panel for Advanced Detectors

APS | DIVISION OF PARTICLES & FIELDS

Report from CPAD

HEPAP Meeting

March 13, 2017

Marcel Demarteau
demarteau@anl.gov
Argonne National Laboratory

&

Ian Shipsey
shipsey@physics.ox.ac.uk
Oxford University

The DPF Instrumentation Task Force

From Universities

- Marina Artuso, Syracuse
- Ed Blucher, Chicago
- Bill Molzen, Irvine
- Gabriella Sciolla, Brandeis
- Ian Shipsey*, Purdue
- Andy White, UT Arlington

From laboratories

- Marcel Demarteau*, Argonne
- David Lissauer, Brookhaven
- David MacFarlane, SLAC
- Greg Bock, Fermilab
- Gil Gilchriese, LBNL
- Harry Weerts, Argonne

Ex-officio

- Chip Brock, DPF MSU
- Patty McBride, DPF Fermilab
- Howard Nicholson, DOE Emeritus

Instrumentation in Particle Physics

Commissioned by the Executive Committee of the Division of Particles and Fields, American Physical Society

October 2011

Prepared by the Task Force Members:

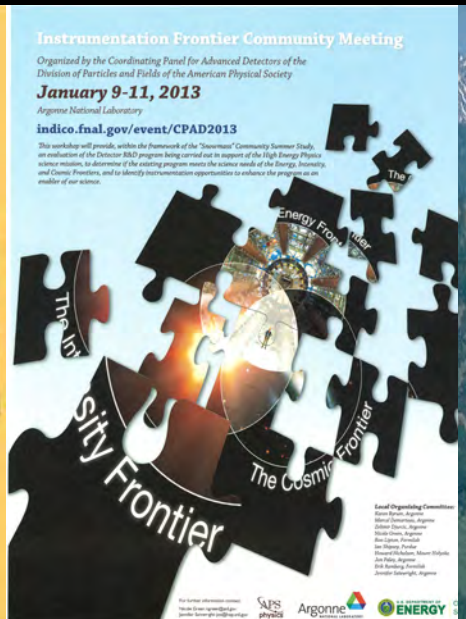
Authors: Marina Artuso (Syracuse), Ed Blucher (Chicago), Ariella Cattai (CERN), Marcel Demarteau (co-chair, ANL), Murdock Gilchriese (LBNL), Ron Lipton (FNAL), David Lissauer (BNL), David MacFarlane (SLAC), Bill Molzon (UCI), Adam Para (FNAL), Bruce Schumm (UCSC), Gabriella Sciolla (Brandeis), Ian Shipsey (co-chair, Purdue), Harry Weerts (ANL). Ex-officio: Chip Brock (Michigan State), Patricia McBride (FNAL), Howard Nicholson (Mount Holyoke).

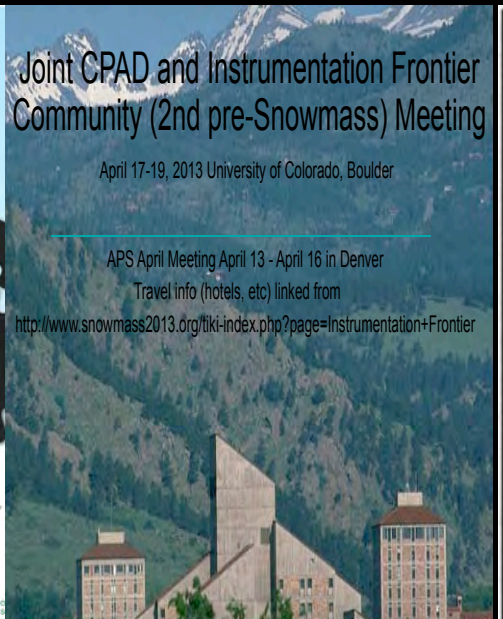
http://www.hep.anl.gov/cpad/docs/dpf_report_v11.pdf

Taskforce created Spring 2011
Report submitted October 2011
- Key recommendation formation of a panel on instrumentation
CPAD formed in 2012

CPAD and Snowmass

- In the fall/summer of 2012 CPAD took a leading role in defining the program of the Instrumentation Frontier for the Community Summer Study (Snowmass)
  - Three conveners of the Instrumentation Frontier were members of CPAD, as was the Chair-Elect of DPF
    - Snowmass planning Meeting, Fermilab, October 11-13, 2012
  - Organized two joint CPAD Snowmass Instrumentation Frontier Workshops
    - Argonne, January 9-11, 2013
    - Boulder, April 17-19, 2013
  - LBL Workshop on IC design for HEP, May 30 – June 1, 2013





Snowmass Report

Instrumentation

Chapter 8: Instrumentation
Conveners: M. Demarteau, R. Lipton, H. Nicholson and I. Shipsey

Working Group Summary (arXiv:1401.6116)

Subgroup Reports:

36. Instrumentation for the Energy Frontier
37. Instrumentation for the Intensity Frontier
38. Sensors
39. Integrated Circuit Design in U.S. High Energy Physics

Planning the Future of U.S. Particle Physics

Report of the 2013 Community Summer Study

Chapter 8: Instrumentation Frontier

Conveners: M. Demarteau, R. Lipton, H. Nicholson, and I. Shipsey

Study Conveners: M. Bardeen, W. Barletta, L. A. T. Bauerdick, R. Brock, D. Cronin-Hennessy, M. Demarteau, M. Dine, J. L. Feng, M. Gilchriese, S. Gottlieb, J. L. Hewett, R. Lipton, H. Nicholson, M. E. Peskin, S. Ritz, I. Shipsey, H. Weerts

Division of Particles and Fields Officers in 2013: J. L. Rosner (chair), I. Shipsey (chair-elect), N. Hadley (vice-chair), P. Ramond (past chair)

CPAD

Coordinating Panel for Advanced Detectors

http://www.hep.anl.gov/cpad/

- CPAD: to promote, coordinate and assist in the research and development of instrumentation for High Energy Physics nationally, and to develop a detector R&D program to support the mission of High Energy Physics for the next decades.

Membership:

- From Universities
  - Marina Artuso (Syracuse)
  - Rick van Berg (Penn)
  - Ulrich Heintz (Brown)
  - Gabriella Sciolla (Brandeis)
  - Ian Shipsey* (Oxford)
  - Wesley Smith (Wisconsin)
  - Matt Wetstein (Iowa)

Former Members
- Jim Alexander (Cornell)
- Bonnie Fleming (Yale)
- Howard Nicholson (Mt. Holyoke)
- Pete Siddons (BNL)

- From Laboratories
  - Clarence Chang (Argonne)
  - Marcel Demarteau* (Argonne)
  - Juan Estrada (Fermilab)
  - Maurice Garcia-Sciveres (LBNL)
  - David MacFarlane (SLAC)
  - Ron Lipton (Fermilab)
  - Vinnie Polychronakos (BNL)
  - Bob Wagner (Argonne)
  - Graham Smith (BNL)

- International
  - Ariella Cattai (CERN)
  - Junji Haba (KEK)

(*) = co-chair

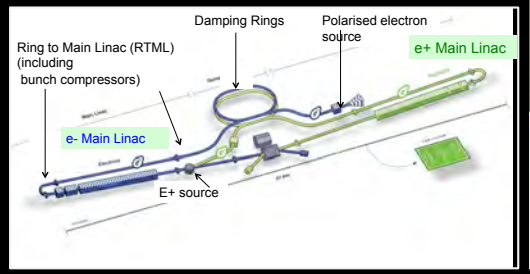
P5 Program

HE-LHC, FCC, CepC,
ILC, CLIC, ...

EF

Phase-I

Phase-II



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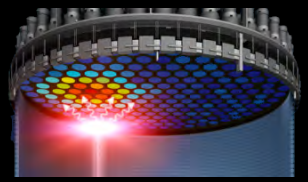
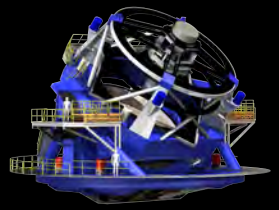
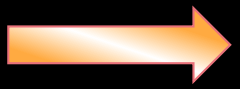




CMB-S4
Next Generation CMB Experiment



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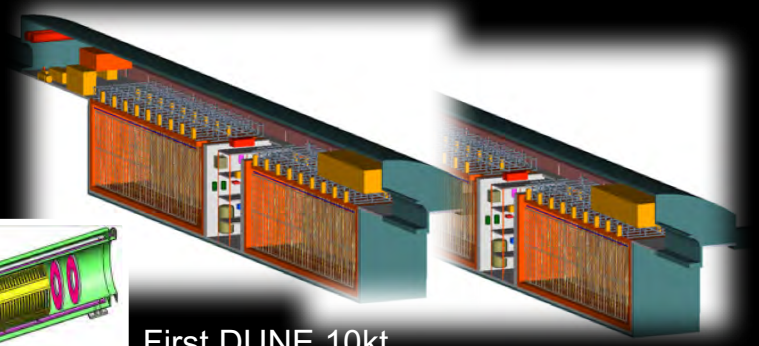
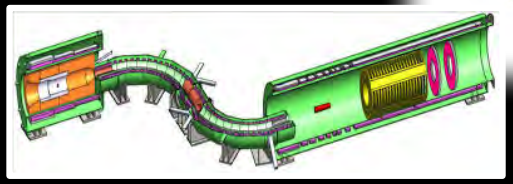
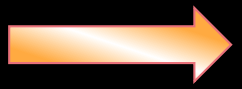




First DUNE 10kt



Today 2020 2025 2030 2035 2040

We are very much in a data driven era !

P5 and Beyond

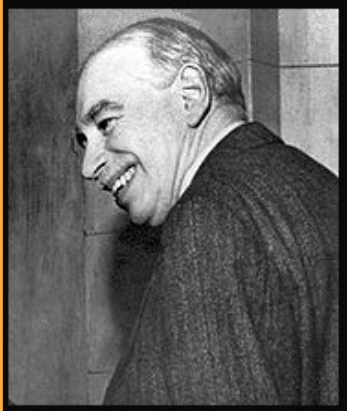
- A new collider, whatever flavor, is very costly and has a long time scale to completion.
- Three 'Stage IV' Cosmic Frontier experiments, which are to first order conclusive experiments of their kind; Three G2 Dark Matter experiments.
- Precision experiments will first have to deliver new results that will need to be confirmed before next series of experiments.
- DUNE is a national flagship program that will run for many years.

- **For (almost) all programs, the next steps will require new ideas and new tools !**

P5 and Beyond

- A new collider, whatever flavor, is very costly and has a long time scale to completion.
- Three 'Stage IV' Cosmic Frontier experiments, which are to first order "ultimate" experiments; Three G2 Dark Matter experiments. No obvious next steps.
- Precision experiments will first have to deliver new results that will need to be confirmed before next series of experiments.
- DUNE is a national flagship program that will run for many years.

- **For (almost) all programs, the next steps will require new ideas and new tools!**



The difficulty lies, not in the new ideas, but in escaping from the old ones, which ramify, for those brought up as most of us have been, into every corner of our minds.

(John Maynard Keynes)

Instrumentation: The Great Enabler !

"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

CPAD Working Groups

1. **The creation of an APS DPF Award for Excellence in Instrumentation Research and Development**
   (Graham Smith, Gabriella Sciolla)
2. **Input to the yearly SBIR/STTR proposal calls**
   (Clarence Chang, Maurice Garcia-Sciveres, Wesley Smith, Rick van Berg)
3. **Creation of a National Instrumentation Fellowship program for both post docs and graduate students**
   (Matt Wetstein, Gabriella Sciolla, Maurice Garcia-Sciveres, Ulrich Heintz, Juan Estrada)
4. **Establish an improved model of an equipment pool that could be used for instrumentation development at U.S. universities and labs**
   (Erik Ramberg, Maurice Garcia-Sciveres)
5. **Coordination of instrumentation resources at National Labs for the HEP community**
   (Graham Smith, David McFarlane, Erik Ramberg)
6. **A program to further develop instrumentation schools and education**
   (Bob Wagner, Rick van Berg, Marina Artuso, Erik Ramberg, Juan Estrada)
7. **Develop a plan to establish and maintain a repository of examples of migration of technologies and instrumentation into high-energy physics and new developments that might benefit HEP**
   (Ron Lipton, Clarence Chang)
8. **Continuation and organization of an, at least, annual national instrumentation workshop for HEP & enhancement of interdisciplinary aspects of instrumentation**
   (Ulrich Heintz, Ron Lipton, Bob Wagner, Matt Wetstein, Rick van Berg)

#1: Award for Excellence in Instrumentation R&D

Message to members of the APS Division of Particles & Fields
Approved by Ian Shipsey, DPF Past Chair

Announcement of the DPF Instrumentation Award

Nomination deadline August 1

Dear Colleagues:

The Division of Particles and Fields of the American Physical Society has established a new award to honor exceptional contributions to instrumentation. This APS Unit Award will be bestowed annually.

The Award will be given for advancing the field of particle physics through the invention, refinement, or application of instrumentation and detectors. In particular, the award will be given for one or more of the following:

- Conceptualization and development of unique instrumentation that has made a significant impact on the field.
- Demonstration of the innovative use of instrumentation.
- Stimulation of other researchers to use new techniques and methods.
- Authorship of research papers or books that have had an influential role in the use of instrumentation.
- Achievement in particle physics instrumentation through dedication over an entire career, or through significant impact at an early career stage.

Award for Excellence in Instrumentation R&D

The 2015 DPF Instrumentation Award
was presented to

David Nygren and Veljko Radeka

•

"For widespread contributions and leadership in the development of new detector technologies and low-noise electronics instrumentation in particle physics as well as other fields, and in particular work leading to the development and instrumentation of large volume liquid argon time projection chambers that are now a key element in the global particle physics program"

2015 Award Committee: Howard Nicholson (Chair, CPAD), Sally Seidel (vice-Chair, DPF) Marina Artuso (CPAD), Karsten Heeger (DPF), Graham Smith (CPAD)

Award for Excellence in Instrumentation R&D

The 2016 DPF Instrumentation Award
was presented to

Steve Holland and Gary Varner

•

"For the development of technologies for detection of signals in frontier experiments, especially the fully depleted charge coupled device and the 'oscilloscope on a chip' integrated circuit."

2016 Award Committee: Sally Seidel (Chair, DPF), Marina Artuso (Vice-Chair, CPAD), David Nygren (2015 Recipient), Veljko Radeka (2015 Recipient), Karsten Heeger (DPF), Howard Nicholson (CPAD), Graham Smith (CPAD)

Award for Excellence in Instrumentation R&D

The 2017 DPF Instrumentation Award
will be presented during the

DPF 2017 Meeting at Fermilab

"Call for nominations will be forthcoming in the next two weeks through DPF email; please send in your nominations! "

https://www.aps.org/units/dpf/awards/instrumentation.cfm

2017 Award Committee: Chair: CPAD Nominee, Steve Holland (2016 Recipient), CPAD Nominee, CPAD Nominee, Gary Varner (2016 Recipient), Member from DPF, Member from DPF

#2: Coordination SBIR/STTR Input

- The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs is a "tax" (3% for 2016) on the budget of the office of science "To support scientific excellence and technological innovation through the investment of Federal research funds in critical American priorities to build a strong national economy… one small business at a time"

Coordination SBIR/STTR Input

- Input to the SBIR/STTR call is coordinated by the SBIR CPAD working group with leads: Maurice Garcia-Sciveres (2015), Rick van Berg (2016) and the OHEP program manager for Detectors and Instrumentation, Helmut Marsiske

U.S. Department of Energy

Small Business Innovation Research (SBIR) and
Small Business Technology Transfer (STTR) Programs

Topics

FY 2017
Phase I
Release 2

Version 3, December 27, 2016

Participating DOE Research Programs

- Office of Defense Nuclear Nonproliferation
- Office of Electricity Delivery and Energy Reliability
- Office of Energy Efficiency and Renewable Energy
- Office of Fossil Energy
- Office of Fusion Energy Sciences
- Office of High Energy Physics
- Office of Nuclear Energy

SBIR·STTR America's Seed Fund

#3: National Instrumentation Fellowship

National Science Foundation
WHERE DISCOVERIES BEGIN

The private sector could also be a source of funding for fellowships

U.S. DEPARTMENT OF ENERGY | Office of Science

National Instrumentation Fellowship

- Have support, analogous to NSF, for a DOE supported graduate student instrumentation fellowship with as goals:
  - To encourage and facilitate greater involvement of physics graduate students in significant instrumentation development.
  - To boost recognition of instrumentation work as a vital part of PhD training.
  - To foster growth of future HEP instrumentation experts in the US.

- Two types of awards:
  - HEP Instrumentation National Graduate Fellowship
    - Funded by DOE OHEP
  - HEP Instrumentation Honorable Mention
    - Funded by budget of DOE funded institution, but overseen through the fellowship program

- One award will be given per year

- **Currently awaiting approval from OHEP for selection of Program Manager. Expected launch date: August 2017.**

National Instrumentation Fellowship

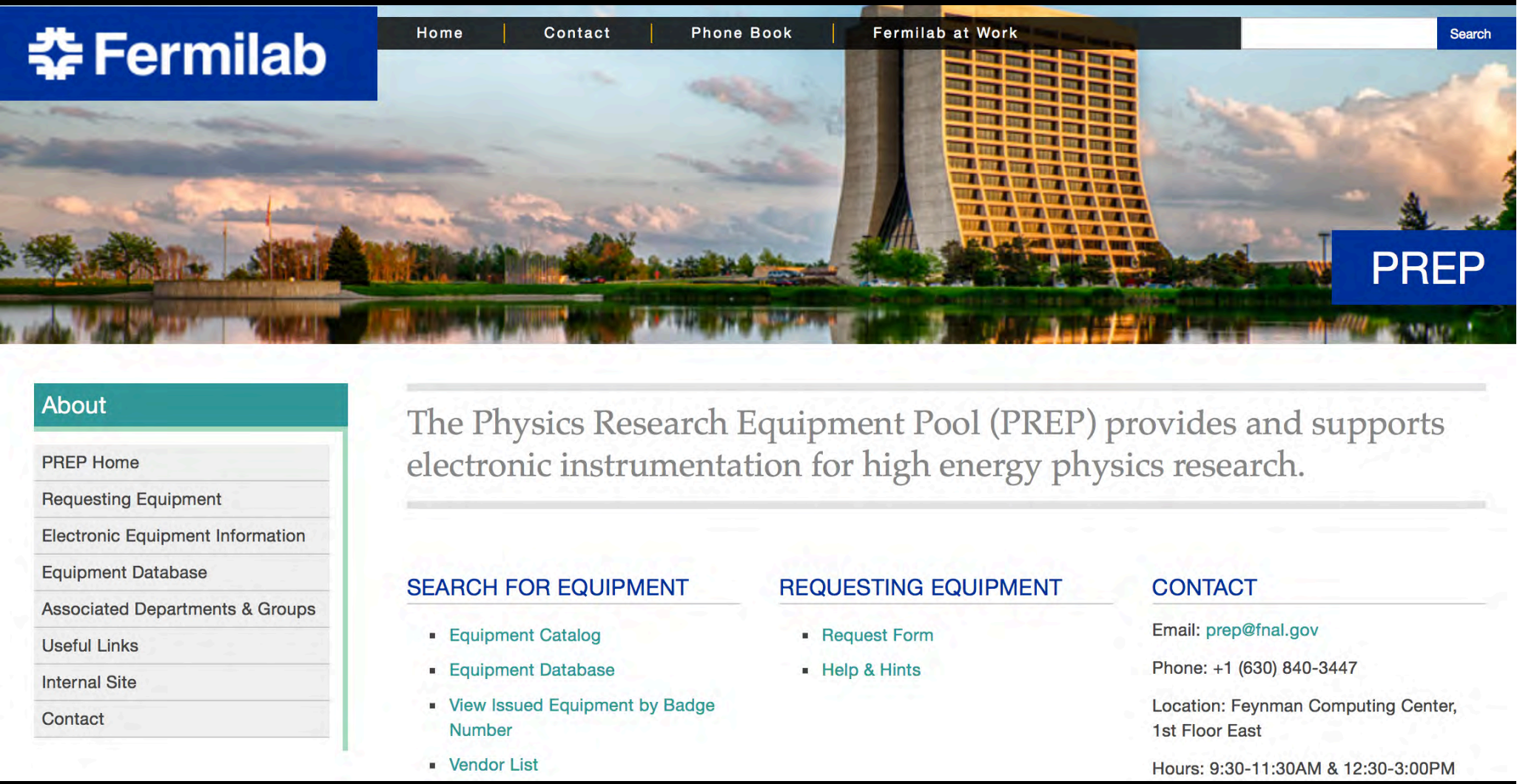
Protocol for Fellowships:

- All students enrolled in accredited US Physics PhD programs are eligible.
- Fellowship must be taken consecutively for 12 months.
- Student may not take classes for credit during the fellowship. Auditing and professional training courses are allowed, as necessary for instrumentation work.
- No obligation to seek renewal, but the fellowship duration is capped at 3 years.
- Fellowship program overseen by Fellowship Program Manager.
- Applications reviewed by a 5-member Selection Panel; at least one new member inducted in selection panel each year; no member can serve more than 5 consecutive years.

- Performance metric: one instrumentation publication of per year of fellowship in a refereed journal
  - Paper must contain a significant fraction of the student's original work
  - review papers not acceptable

- Funding will match NSF Fellowship award
  - currently annual NSF stipend of $34,000 along with a $12,000 cost of education allowance for tuition and fees (paid to the institution).

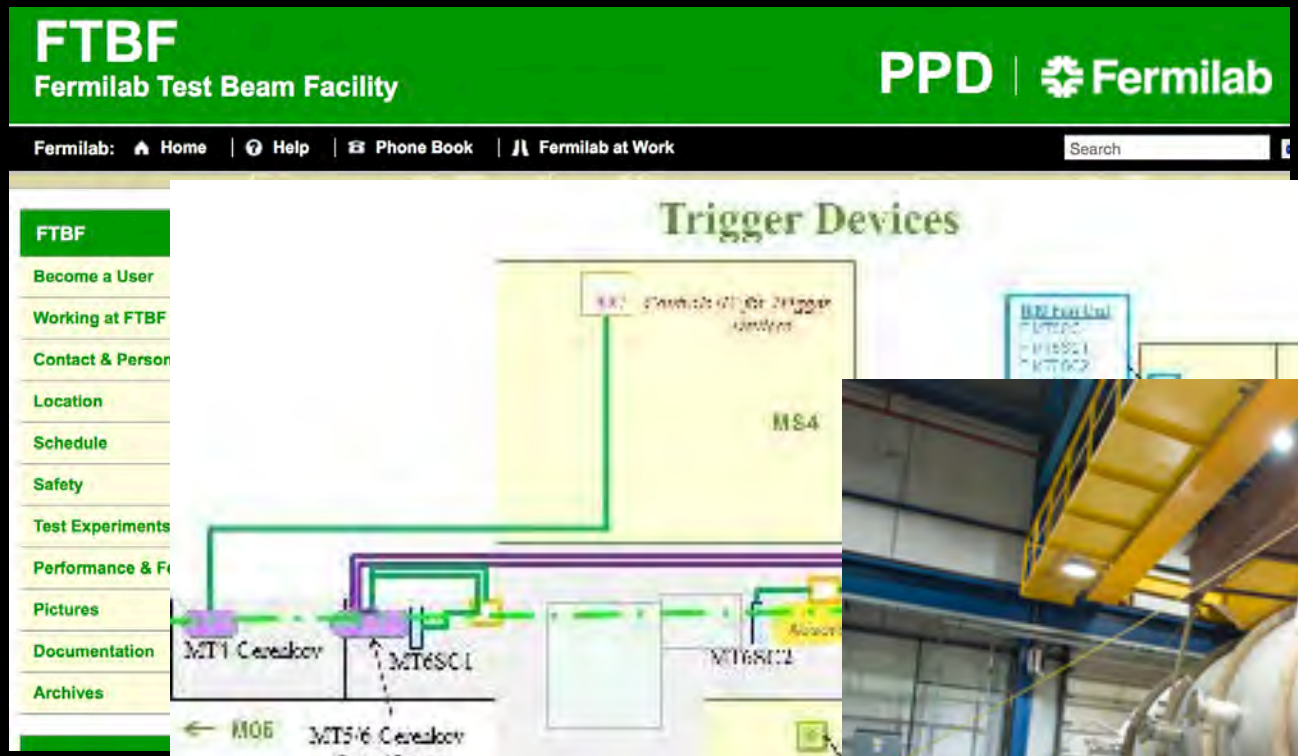
#4: Improved model of an equipment pool



- Various issues with the equipment pool at Fermilab have been addressed
- Pool is fully supported by Fermilab to serve the community

#5: Coordination of Resources

- Coordination of instrumentation resources (including engineering) at National Labs for the HEP community at the universities and the National Labs



Coordination of Resources

- Coordination of resources has been limited to bringing about an awareness of the available resources within the community
  - Dedicated overview talks at the workshops on available facilities

- Issues regarding access to engineering resources require stronger mandate, given the budgetary implications

- OHEP is currently engaged in an inter-laboratory 'optimization process' and in inter-laboratory discussions on Detector R&D to make progress on the overall coordination of resources. CPAD is engaged helping facilitate the coordination of resources.

#6: Schools

- A program to further develop instrumentation schools and education

Schools

- In collaboration with other regions, supported organizing the EDIT schools: Excellence in Detectors and Instrumentation Technologies
- 2011 @ CERN

- 2012 @ FNAL with Test Beam !

- 2013 @ KEK

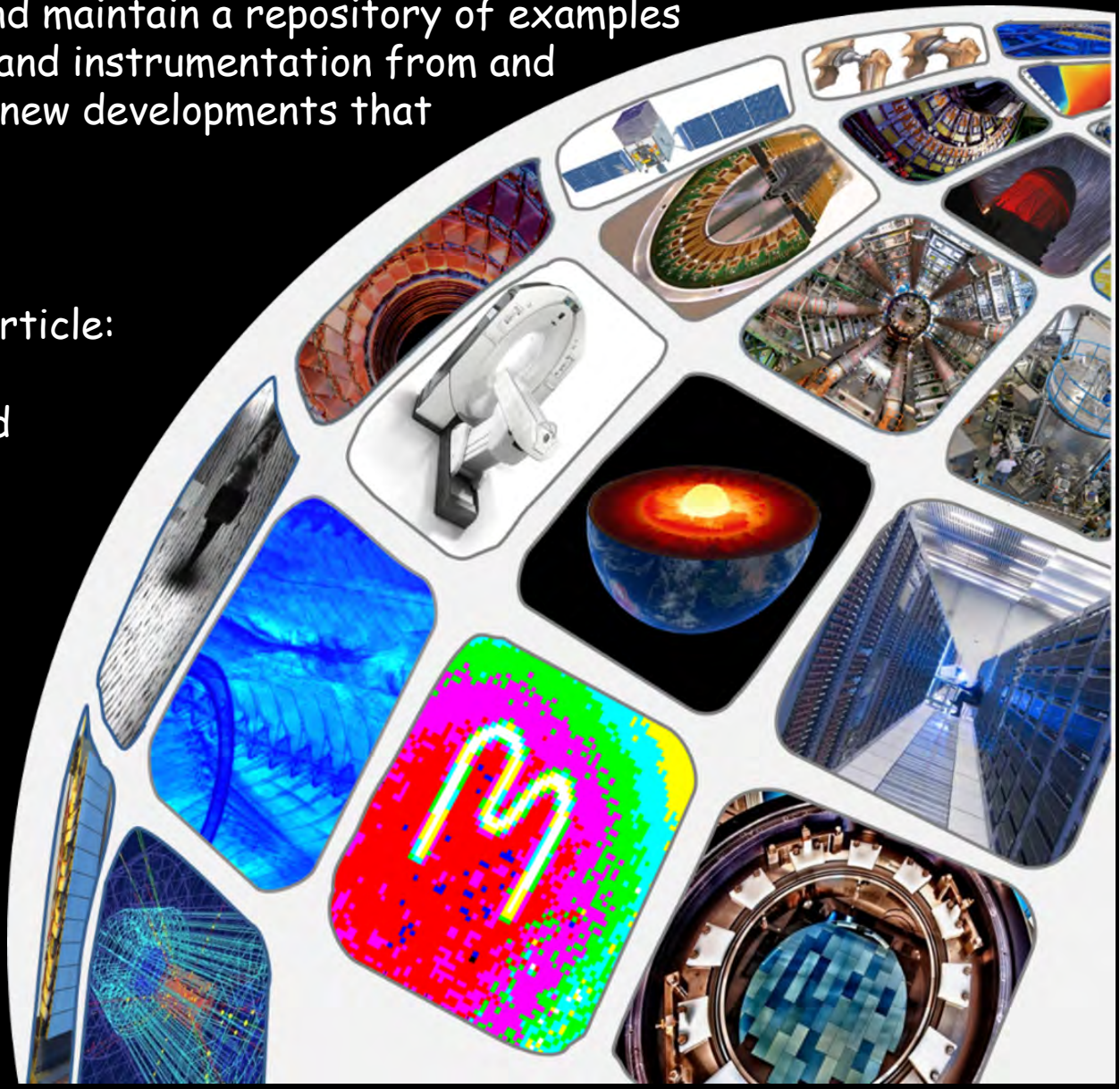
- 2015 @ Frascati

- 2018 @ FNAL — 5-16 March, 2018; open to 48 students (had to be postponed by a year due to Fermilab's 50th anniversary)
- Little activity in organizing national schools on instrumentation and advancing interdisciplinary education.

#7: Migration of Technologies

- Develop a plan to establish and maintain a repository of examples of migration of technologies and instrumentation from and into high-energy physics and new developments that might benefit HEP

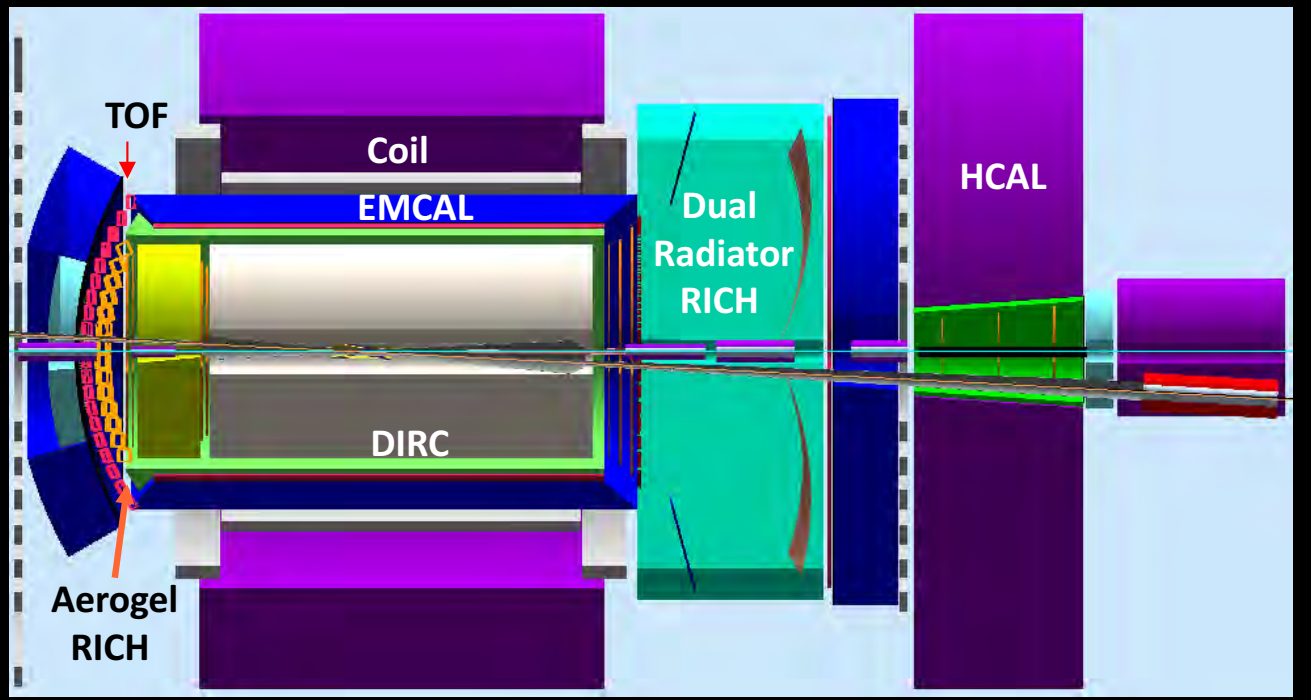
- Four CPAD members wrote a Reviews of Modern Physics Article: "Particle and nuclear physics instrumentation and its broad connections"
  Rev. Mod. Phys. 88, 045007
  Published 20 December 2016



http://journals.aps.org/rmp/abstract/10.1103/RevModPhys.88.045007

Migration of Technologies

- The long-range plan for Nuclear Physics calls for the construction of an Electron-Ion Collider. Experiments at this machine are looking more and more like particle physics experiments.
- Invitation to attend the CPAD workshops is extended to the Nuclear Physics Community.
- Coordination between the offices in SC is being encouraged
  - Thomas Ullrich (BNL), Abhay Deshpande (Stony Brook) and Marcel Demarteau (ANL) visited ONP in November 2016 to advocate for stronger collaboration between the two communities in the area of detector R&D



#8: Annual Workshop

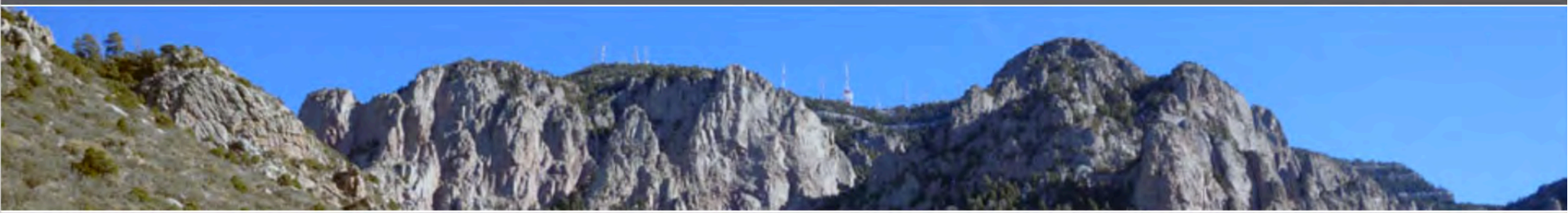
NEW TECHNOLOGIES FOR DISCOVERY

Organized by the Coordinating Panel for Advanced Detectors of the Division of Particles and Fields of the American Physical Society

October 5 - 7, 2015 - University of Texas at Arlington

Next Annual Workshop

UNM | CPAD 2017
October 12-14 Albuquerque, New Mexico



http://physics.unm.edu/CPAD2017/

- Two bids for hosting the 2018 workshop from east-coast universities being considered.

#8: Annual Workshop

- Goal: #1: Evaluation of the Detector R&D program being carried out in support of the High Energy Physics science mission, to determine if the existing program meets the science needs of the 5 P5 science drivers within the twenty year P5 vision.

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

Annual Workshop

- Goal #2: proposing new ideas for detection technologies and identifying instrumentation opportunities to enhance the program as an enabler of our science: *grand challenges for our field*

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

Workshop Structure

- Structure of the workshop to meet goals:
- Day 1:
  - Plenary overview session addressing technological barriers in P5 science drivers
  - Five P5 science driver parallel sessions
- Day 2:
  - Six technology parallel sessions
  - Talk(s) on inter-disciplinary science projects
- Day 3: (1/2 day)
  - Summary of 11 parallel sessions
- 2015: Total of ~100 talks 120 participants
- 2016: Total of ~150 talks 155 participants
- The outcome of the workshop: a formulation of the needs of the field to ensure a vibrant future.

Linkage between science drivers and technologies

The P5 Science Drivers:

The Higgs as a tool for discovery

Physics associated with neutrino mass

The nature(s) of dark matter

Early and late time cosmic acceleration

Exploring the unknown

Technologies:

Noble Liquids

Tracking and vertex detectors & muon detectors

Photodetectors

Solid State Detectors/ Quantum sensors

Calorimetry

Trigger and DAQ

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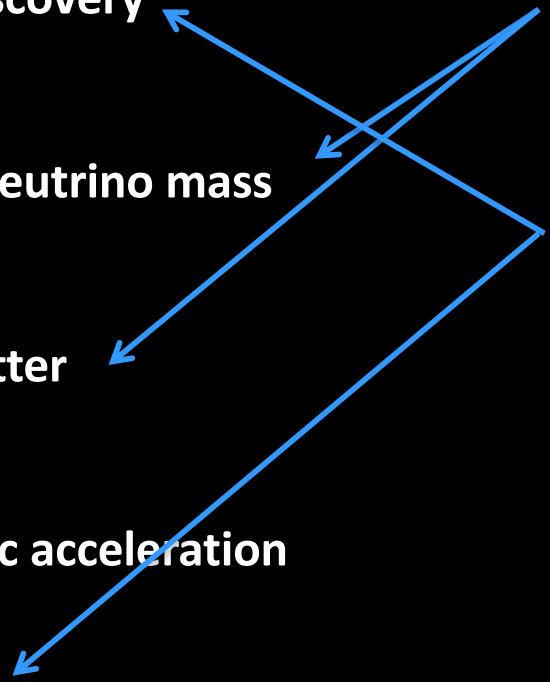

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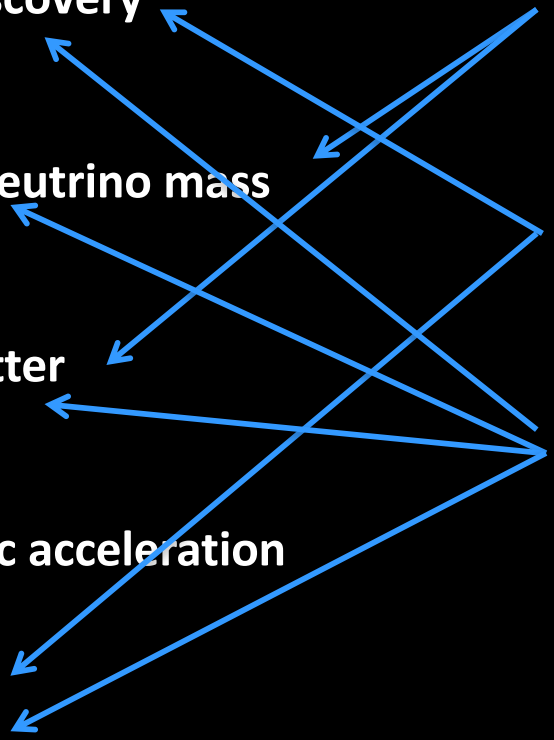

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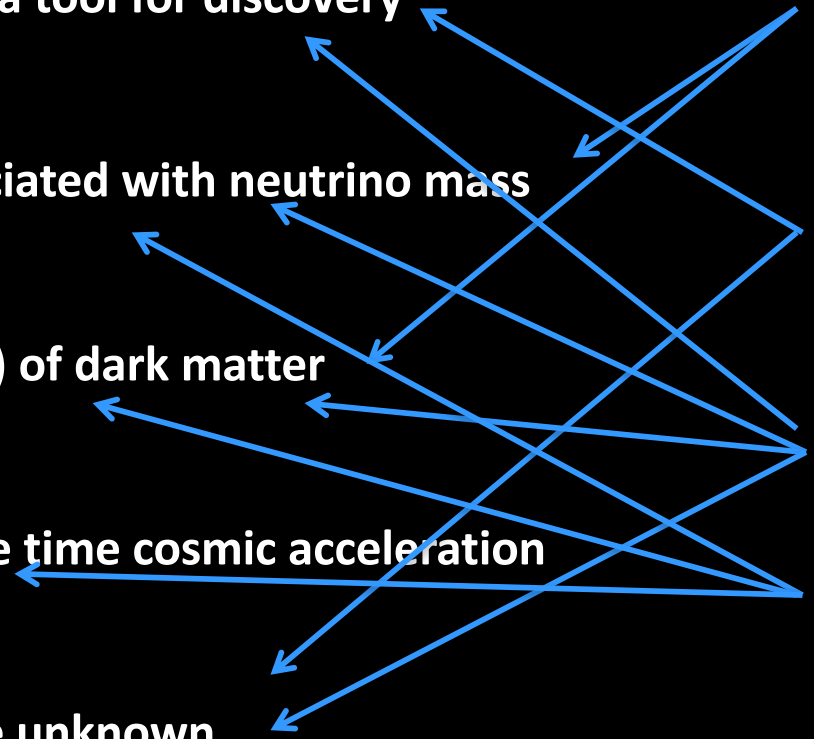

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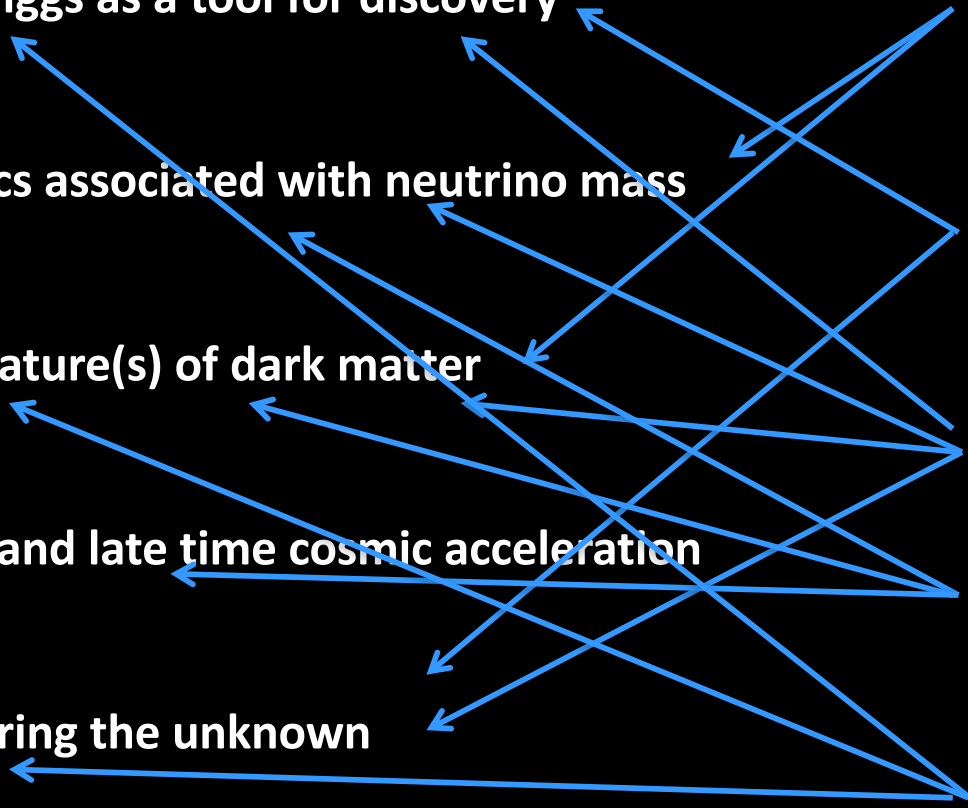

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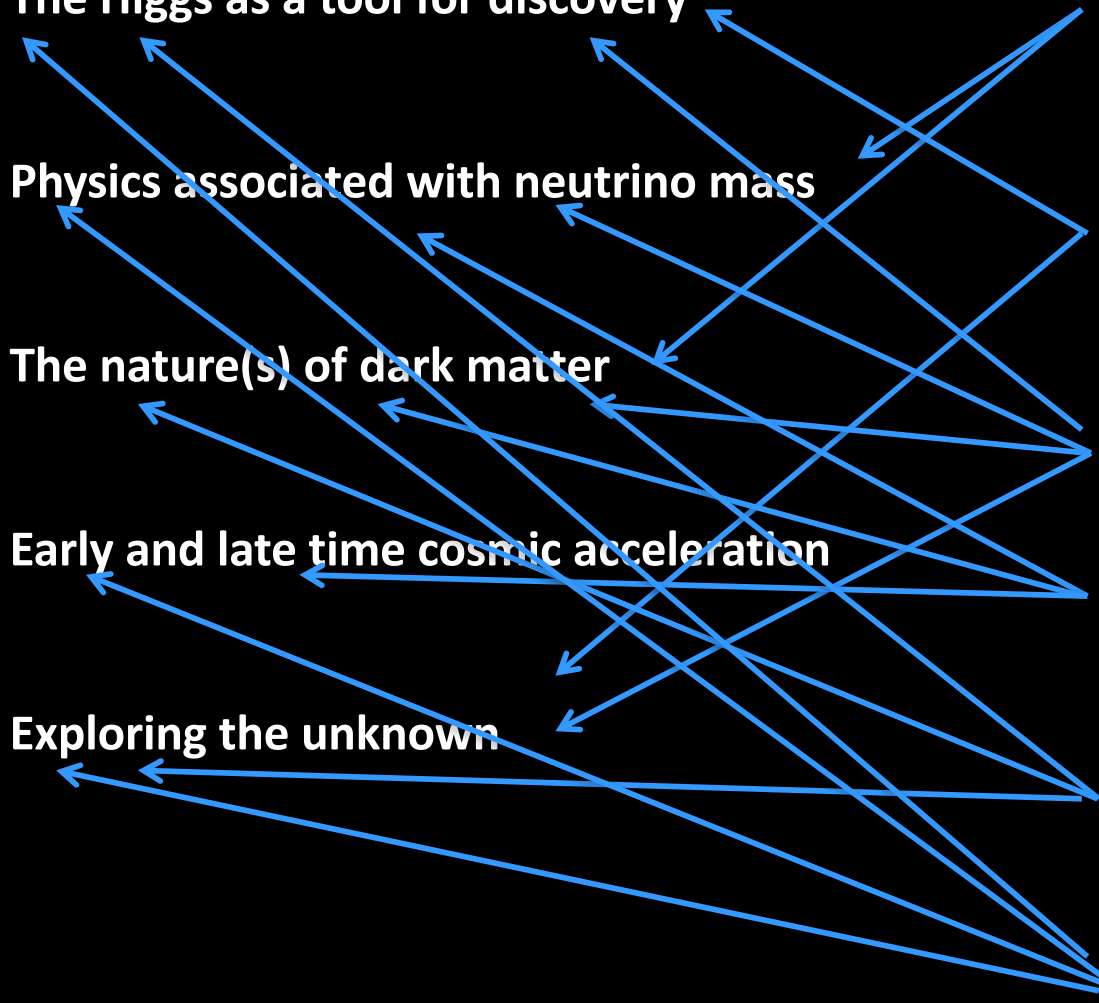

Community Engagement

The P5 Science Drivers:

- The Higgs as a tool for discovery — 2015: Rick van Kooten, Ulrich Heinz, Ariel Schwartzman; 2016: Anadi Canepa, Anyes Taffard
- Physics associated with neutrino mass — 2015: Jae Yu, Kate Scholberg; 2016: Roxanne Guenette, Ornella Palamara
- The nature(s) of dark matter — 2015: Priscilla Cushman, Rupak Mohapatra; 2016: Carmen Carmona, Tali Figueroa-Feliciano
- Early and late time cosmic acceleration — 2015: Brad Benson, Mike Niemack; 2016: Elisabeth Krause, Eduardo Rozo
- Exploring the unknown — 2015: Jim Alexander, Doug Glenzinski; 2016: Bob Bernstein, David Moore

Technologies:

- Noble Liquids — 2015: Marty Breidenbach, Cristiano Galbiati, Tom Shutt; 2016: Angela Fava, Hugh Lippincott, Brian Rebel
- Tracking, vertex & muon detectors — 2015: Marina Artuso, Ron Lipton; 2016: Maurice Garcia-Sciveres, Petra Merkel, Sally Seidel
- Solid State Detectors — 2015: Clarence Chang, Yury Kolomensky, Kent Irwin; 2016: Amy Bender, Juan Estrada, Matt Pyle
- Calorimetry — 2015: Burak Bilki, Roger Rusack, Erik Ramberg; 2016: Artur Apresyan, Adi Bornheim, RenYuan Zhu, Craig Woody
- Photodetectors — 2015: Adam Para, Bob Svoboda, Matt Wetstein; 2016: Michey Chiu, Bob Svoboda, Hiro Tanaka
- Trigger and DAQ — 2015: Wesley Smith, Mike Huffer; 2016: Tulika Bose, Hucheng Chen

CPAD Report

- The report identifies opportunities and "grand challenges" for investment by OHEP to deliver new capabilities for HEP and science and society more generally.
- Summaries of the 11 sessions at the 2015 workshop, which give a status of each area and help to place the grand challenges in context
- Grand challenges form an important element of the report

CPAD Report

- The CPAD report is a living document
- It is not the intent to write a new report each year, but rather update and enhance the report each year as ideas arise or are further developed at the CPAD workshops

- The update of the current report is expected to be completed in April

- The report includes “grand challenges” as major deliverable

Grand Challenges

- A grand challenge is one or more specific critical barrier(s) that, if removed, would enable addressing one of the important science questions with a high likelihood of great impact through discovery and widespread implementation.

Grand Challenges

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- Advantages:
  - Provides a sharp focus
  - By articulating important challenges, it brings the best minds to the table
  - Builds and strengthens the instrumentation communities of innovators
  - They capture the imagination
  - They serve as a platform for global participation

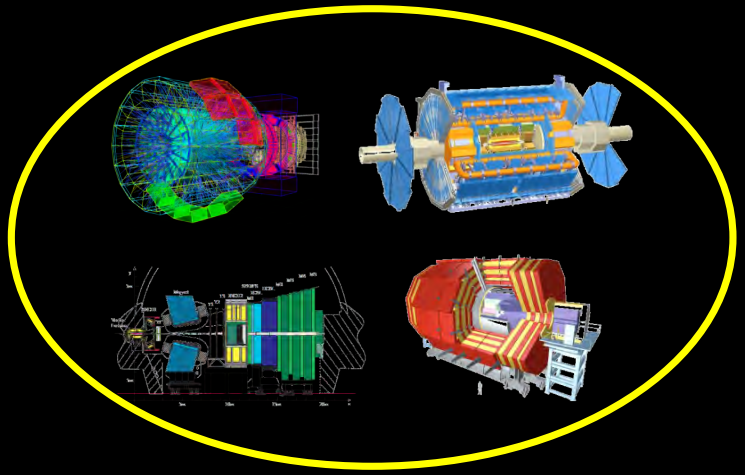
- Risk:
  - Dilution of truly significant challenges
  - No guarantee of success (but this is exactly what we want!)

Grand Challenges To Date

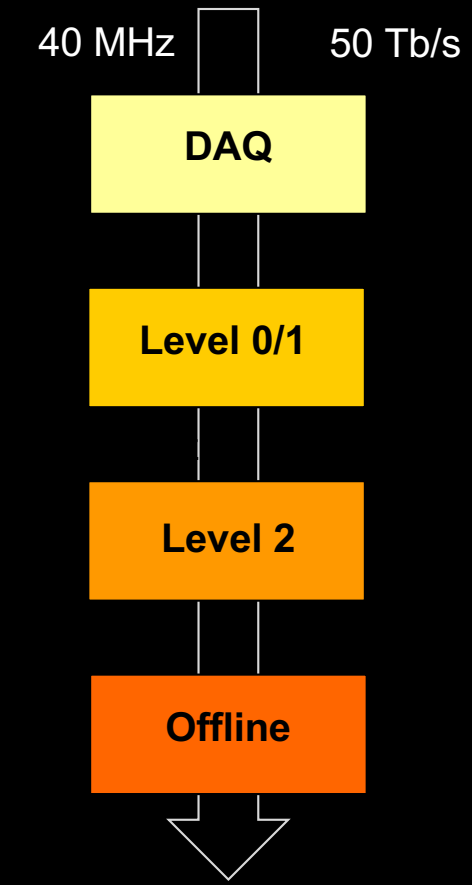
- While the grand challenges in the current report are ambitious and disruptive if realized, they are based on evolutionary research:
  - Quantum Sensors
  - Large-Area Photodetectors
  - Breaking the pico-second time barrier
  - Deadtimeless TDAQ
  - Ultra-low mass/power rad hard silicon detectors

- It has been difficult for the community to shed current paradigms and propose even more ambitious challenges that call for “blue sky" R&D that have the potential to be disruptive.

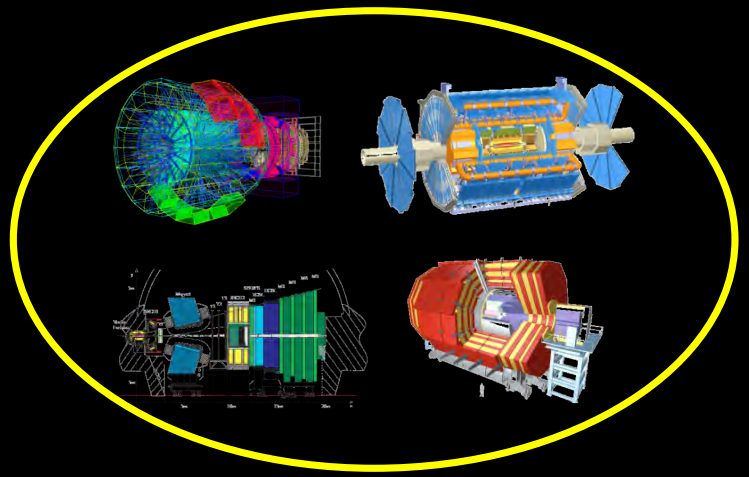
Example:



TDAQ Today



Deadtimeless TDAQ



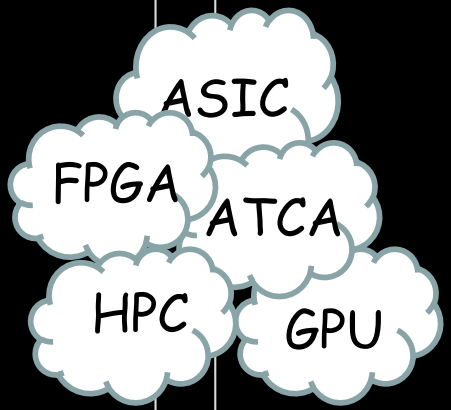
Exascale
Heterogenous
Neuromorphic

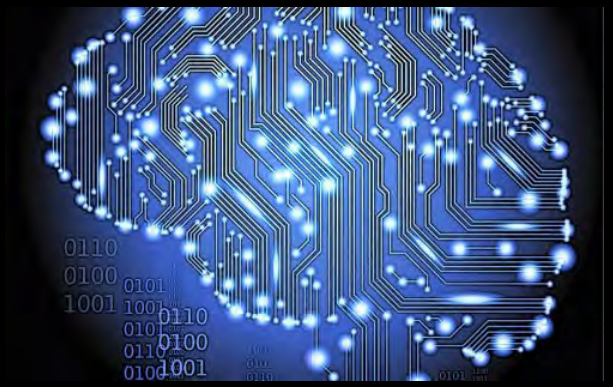
Computing

40 MHz

50 Tb/s

Exascale computing by 2025
Machine Learning



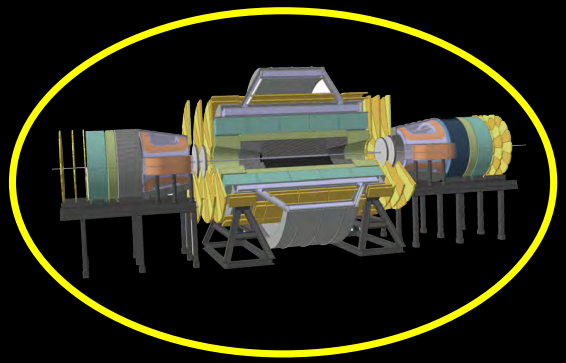


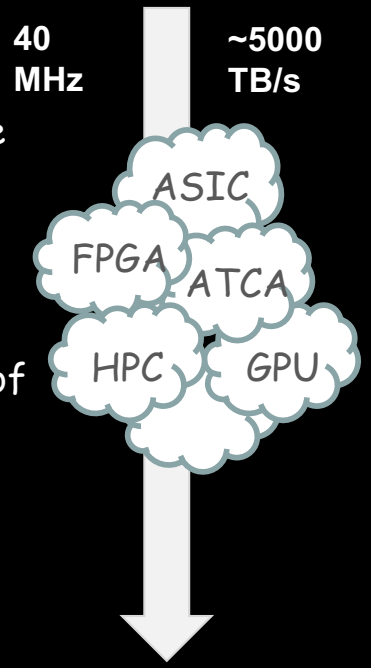
FPGA-accelerated
heterogeneous computing

Morphing new computing paradigms to address pressing HEP issues

100 TeV

Larger detectors
Higher granularity
More data





- Tracking and calorimeter each have raw data rates of ~2,000 TB/s
- Using 10Gb/s modularity, 4M optical links
- Implies an event-building network of 50Pb/s capacity
- Note: largest Google data center is currently ~1Pb/s

100 TeV

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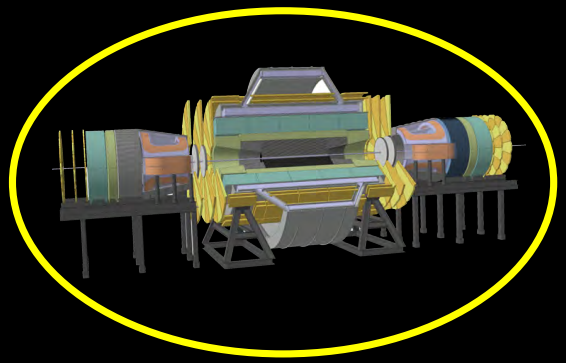
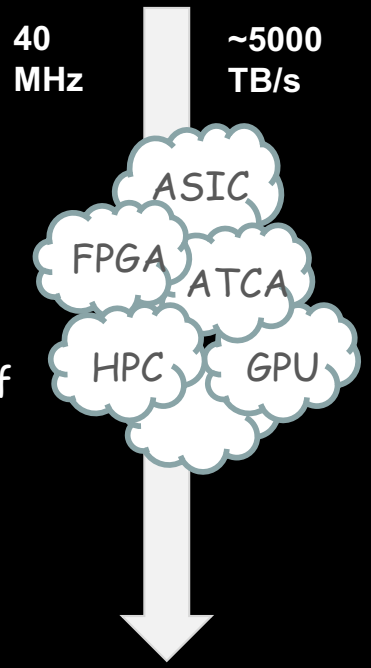
Higher granularity
More data





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- Using 10Gb/s modularity, 4M optical links
- Implies an event-building network of 50Pb/s capacity
- Note: largest Google data center is currently ~1Pb/s

- Power budget for links, based on best current devices (~500mW for 5Gb/s): 2MW for links alone
- Substantial R&D required for low-mass, rad-hard, low-power, low-cost, ultra fast devices with no guaranteed commercial applications

Next Steps

- CPAD workshops have been very effective bringing the community together
  - Almost 1:1 ratio of participants and presenters
  - Good participation of industry
- Participants expressed a desire to change the format to limit the number of parallel sessions and have more interaction among the participants.
  - Extend workshop to three days (from 2.5) with more discussion sessions
  - More plenary sessions to stimulate exchange of ideas
- Considering addition of short courses or academic lectures, especially on developments in other science disciplines

Visibility of Instrumentation

- The urgent need for investment in instrumentation is being recognized, but much more work remains.

- The University of Hawaii at Manoa, with a strong track record and strong faculty in instrumentation, has an opening for a tenure-track faculty member at the Assistant Professor or Associate Professor level in experimental high energy physics who will lead a program on the Instrumentation Frontier.
  - "The new faculty member should contribute to and enhance the physics programs of one or more of the Department's efforts in high energy physics and train the next generation of students and postdocs to build experimental devices."
  - http://inspirehep.net/record/1501626?ln=en

- There are 21 applicants for the position !

CPAD Working Groups

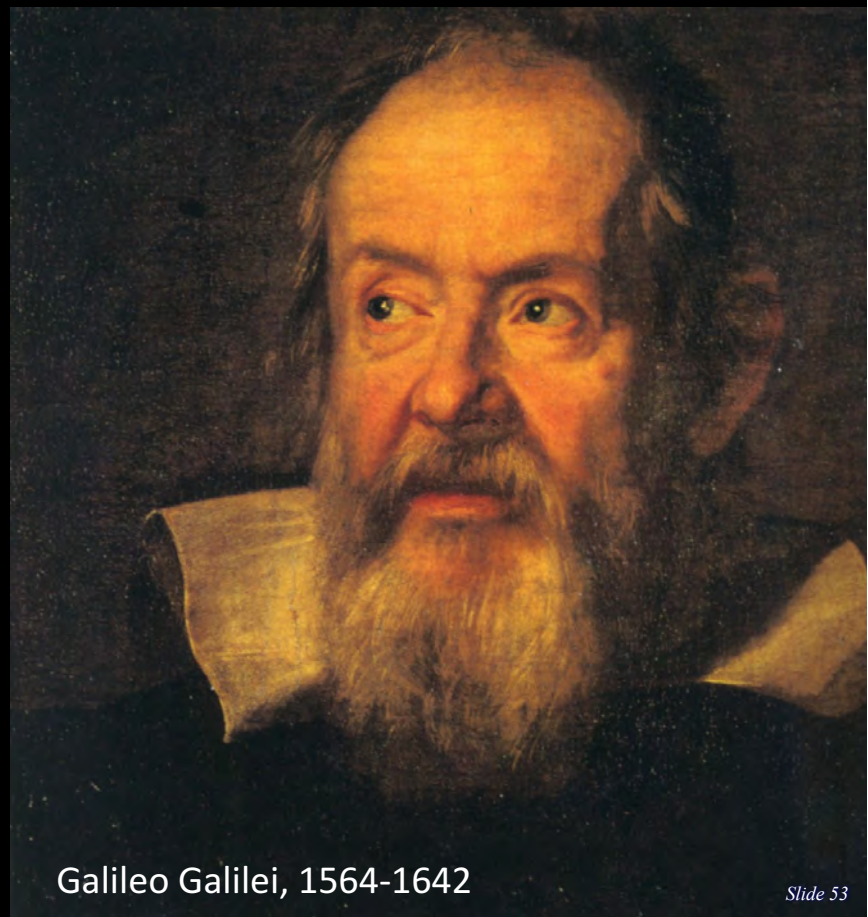
1. **The creation of an APS DPF Award for Excellence in Instrumentation Research and Development** ✓
2. **Input to the yearly SBIR/STTR proposal calls** ✓
3. **Creation of a National Instrumentation Fellowship program for both post docs and graduate students** ✓
4. **Establish an improved model of an equipment pool that could be used for instrumentation development at U.S. universities and labs** ✓
5. **Coordination of instrumentation resources at National Labs for the HEP community** ...
6. **A program to further develop instrumentation schools and education** ✓
7. **Develop a plan to establish and maintain a repository of examples of migration of technologies and instrumentation into high-energy physics and new developments that might benefit HEP** ✓
8. **Continuation and organization of an, at least, annual national instrumentation workshop for HEP & enhancement of interdisciplinary aspects of instrumentation** ✓

Summary

- Much work has been done, but much work remains to be done, to enable the discoveries that help us understand the universe.
- We can be optimistic of a bright future for the field of particle physics, but continued strong participation and support will be required.
- CPAD has a lot of very talented people, but some members terms are now coming to an end including the co-Chair (Ian) and we are looking forward to have many new members to help us realize our goals.

"Measure what is measureable and make measureable what is not so."

Two inseparable sides of the same coin

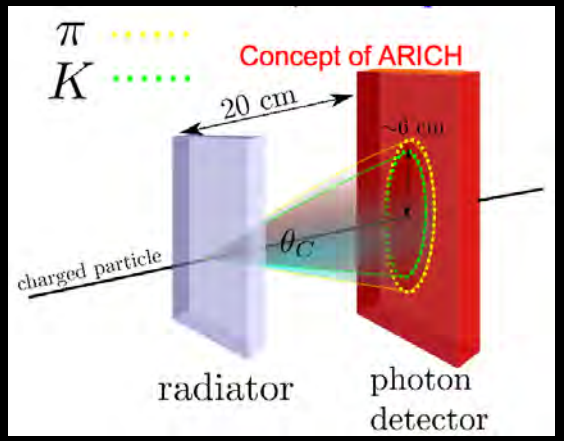


Galileo Galilei, 1564-1642

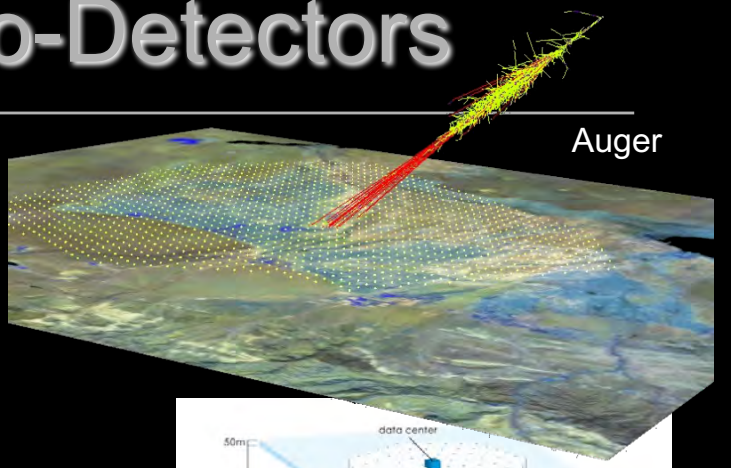
Backup Slides

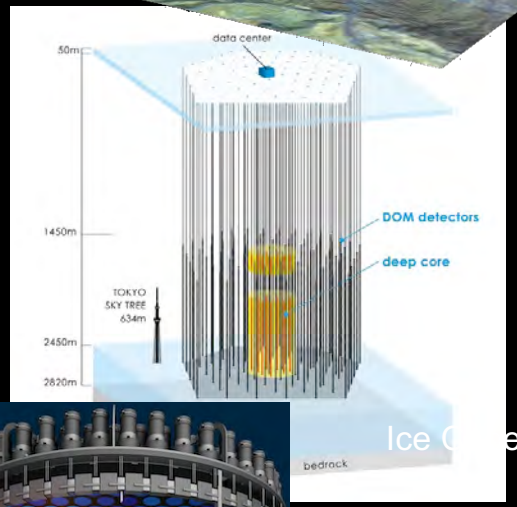
The Broad Reach of Photo-Detectors

BELLE-II



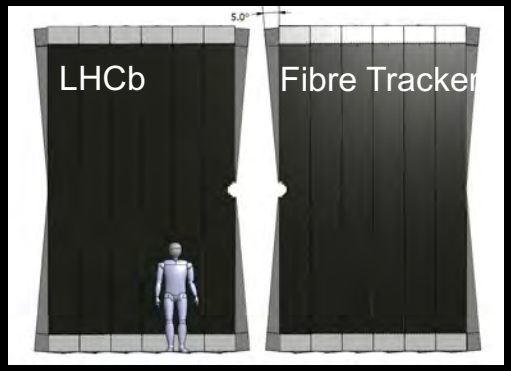

DES


Auger



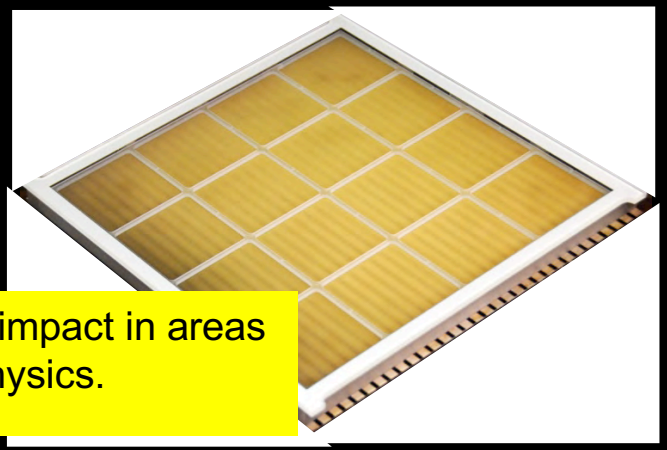
Ice C e

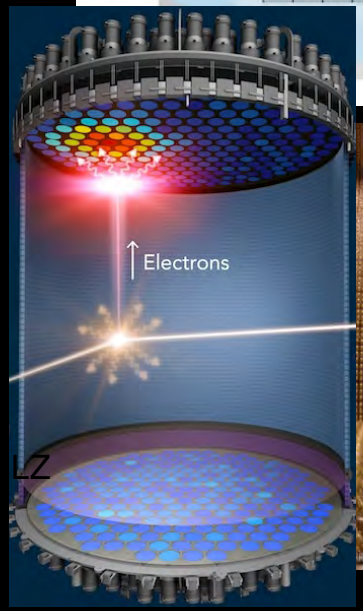
Photon detection is ubiquitous over wide range of wavelengths & signal times

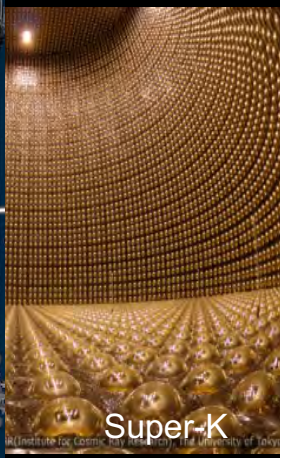


Development of large-area devices, radiopure, cryogenic stability and high QE within appropriate wavelength sensitive window


CMS PWO Ecal

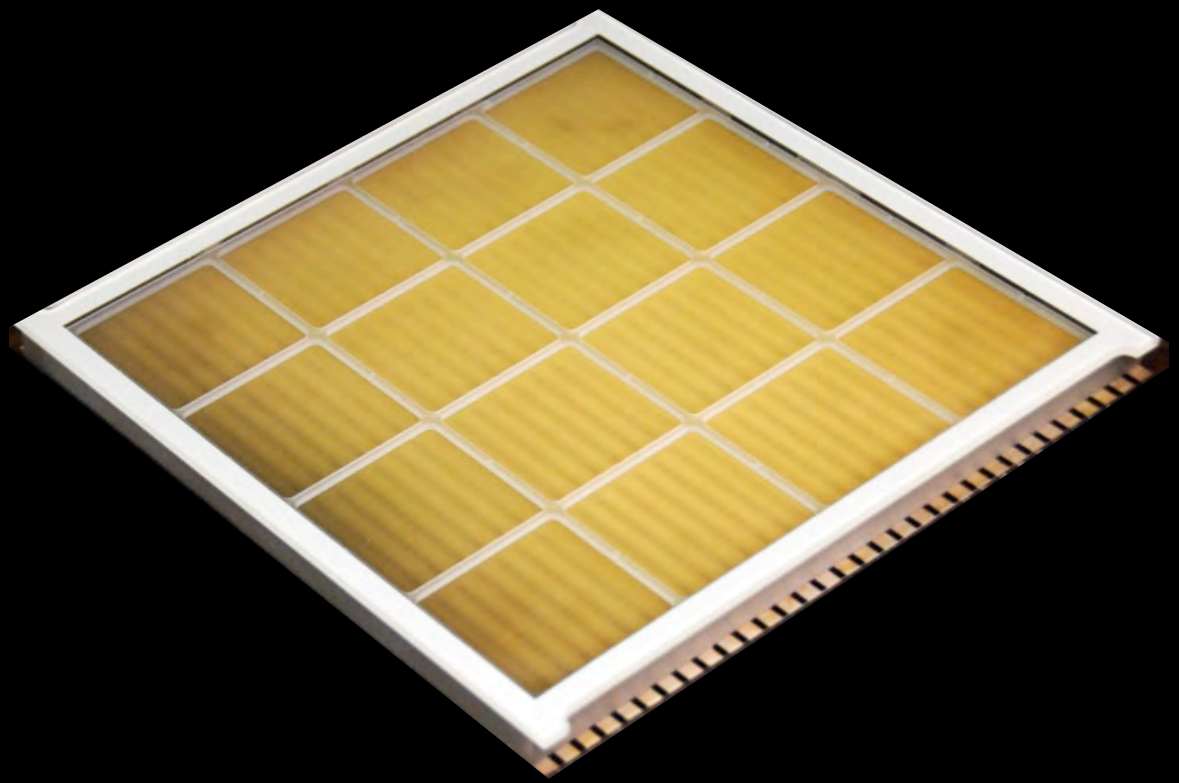





Super-K

a "game-changer" with significant impact in areas outside of high energy physics.

Photon Detection



- $1/cm^2$
- Production format $1m^2$
- QE in VUV of 400% using Perovskites / Trans Metal Di-chalcogenides
- PDE of 90%
- 3d printed Micro-Channel Plates
- Timing resolution ~1ps
- Position resolution 5μm

Photosensors a grand challenge

Applications:
dark matter
neutrino experiments
Rare decays
collider detectors
medicine, industry, and other scientific fields.

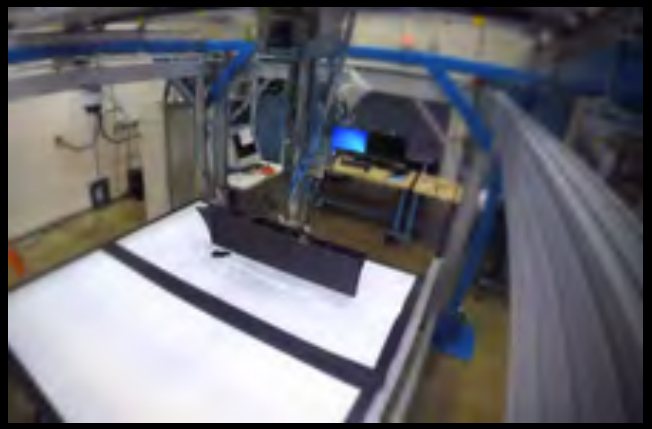
Speed, spectral response,
radiation hardness, cryogenic adaptation,
radiopurity, cost

Specialization for a specific use. E.g. SiPM's are not low cost compared to PMT's performance is selling point if cost is not a major part of the total cost of the experiment.

Large-area fast photosensors: 50-100 picosecond, inexpensive photo-detectors would be a "game-changer" for large, homogeneous detectors for neutrino oscillations and neutrino astrophysics, and also for neutrinoless double beta decay. They would also have significant impact in areas outside of high energy physics.

Additive Manufacturing

A New Era of Possibilities



Print

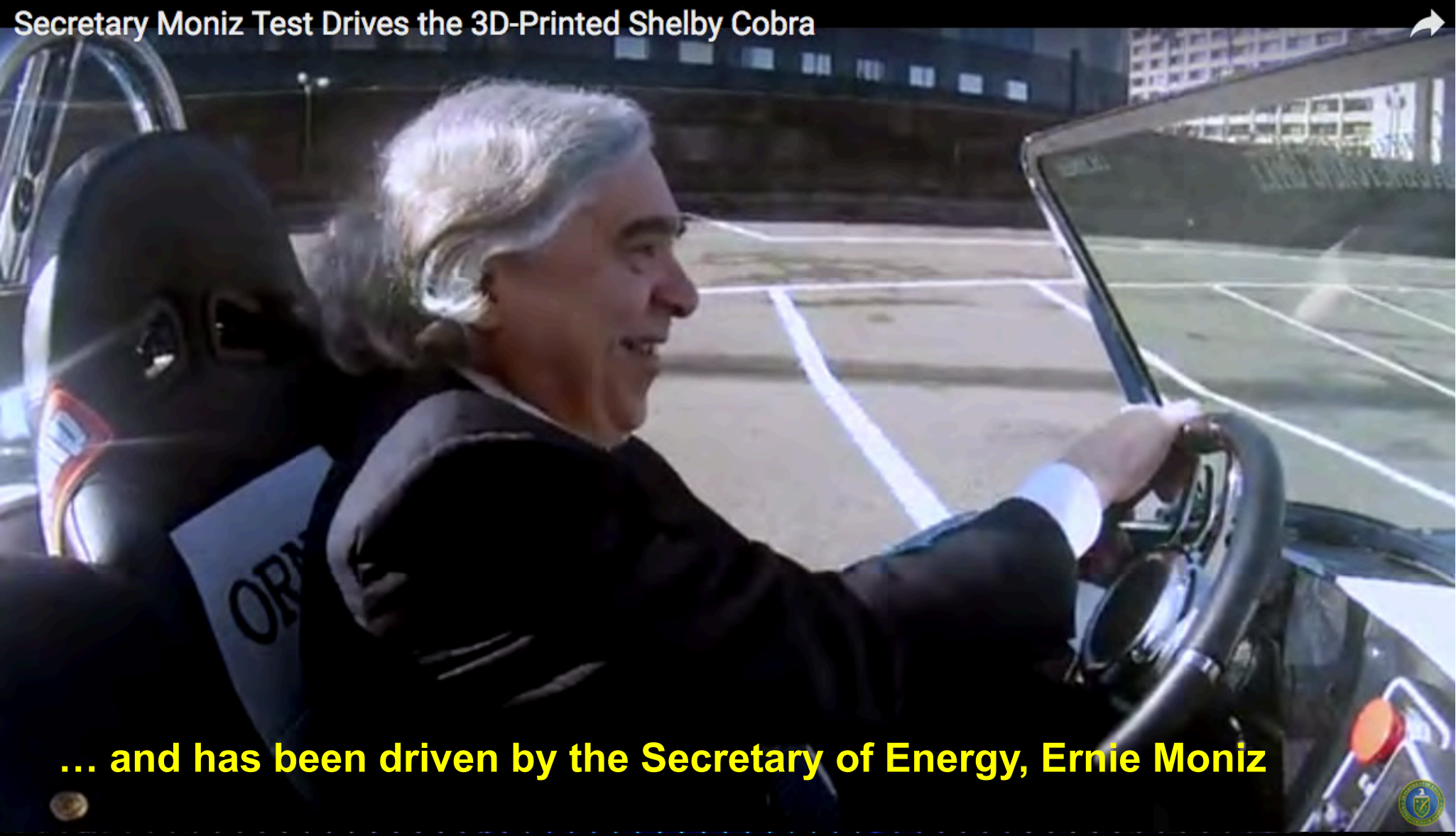
Build

Finish

Additive Manufacturing

http://web.ornl.gov/sci/manufacturing/shelby/

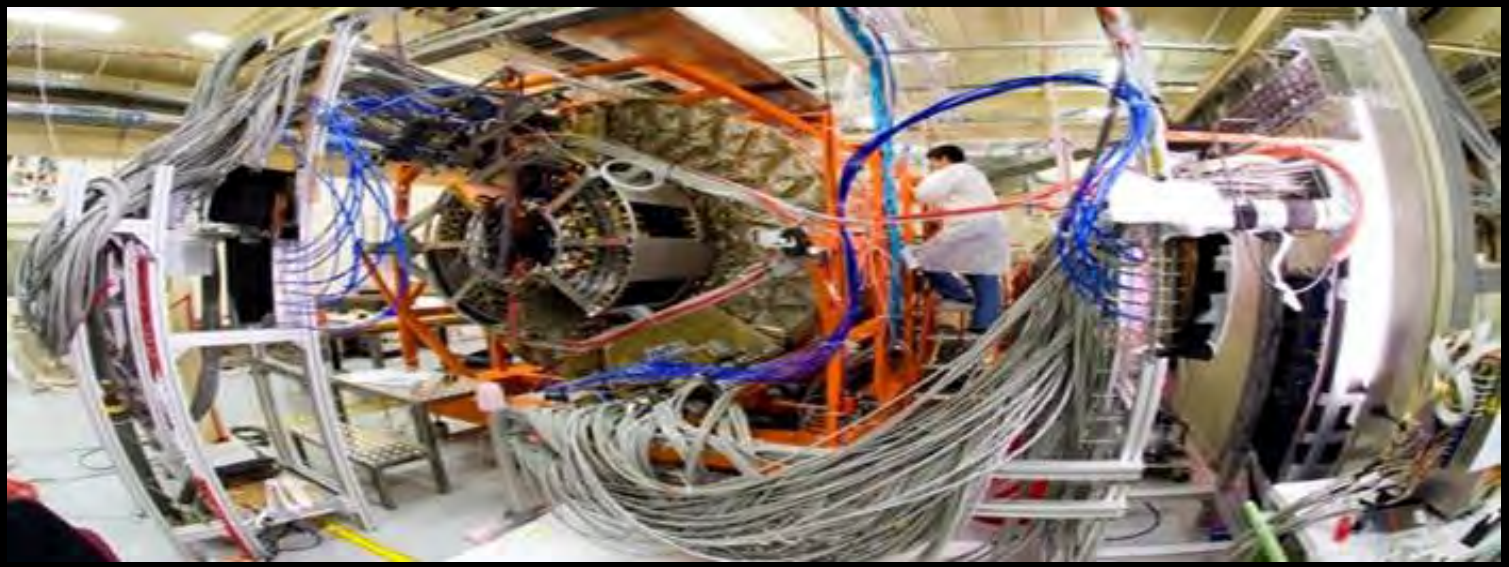
Additive Manufacturing

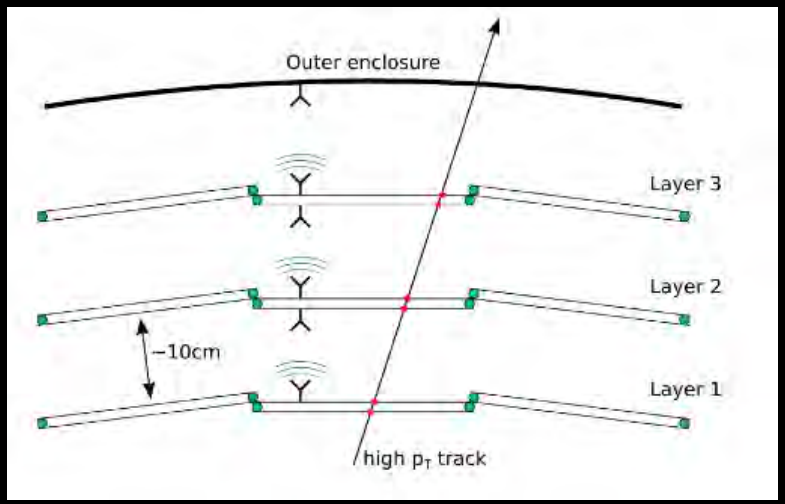


… and has been driven by the Secretary of Energy, Ernie Moniz

http://web.ornl.gov/sci/manufacturing/shelby/

Cables ?

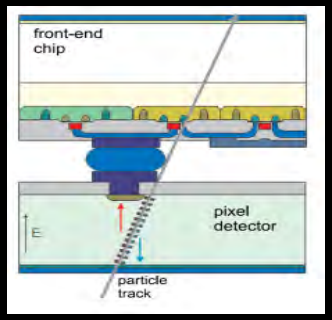




- **60 GHz wireless readout system built**
- 4.5Gbps @1m
- 240mW power consumption
- Bit Error Rate < 4x10-15

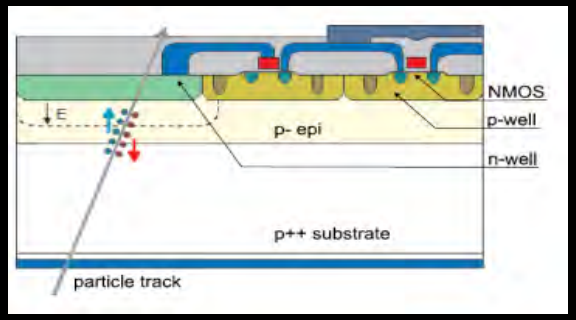
Technologies

Hybrid Pixel



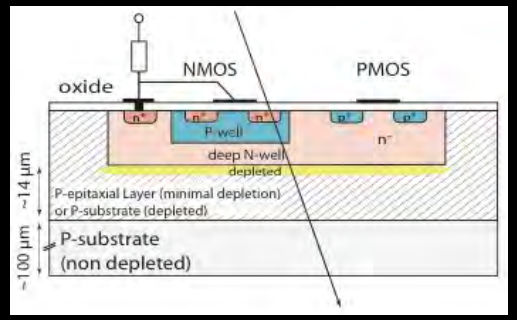
- Q collection by drift

CMOS-MAPS



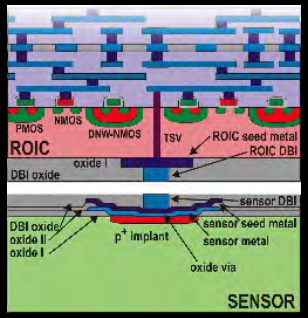
- Charge collection by diffusion

HV-CMOS



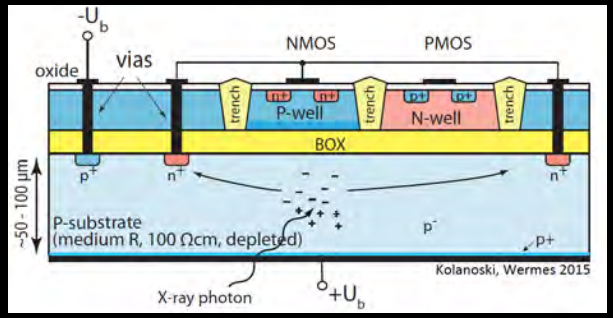
- HV process, 10 – 15 µm depletion region under deep N-well

3D Tiered



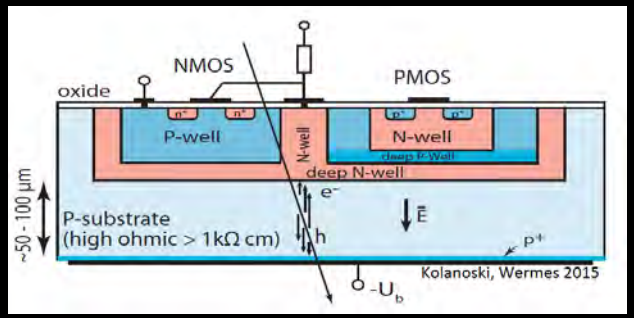
- Fully depleted

SOI-CMOS



- Fully depleted or HV process

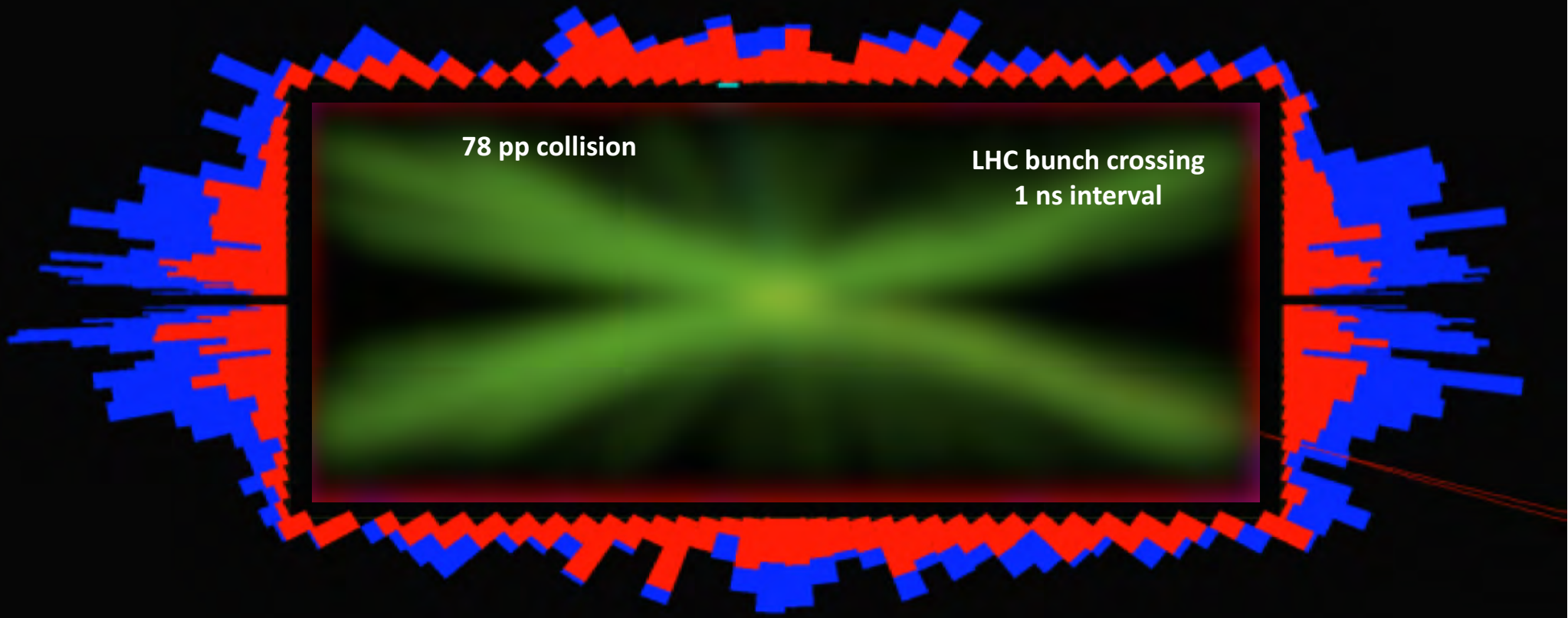
HR-CMOS



- Can be fully depleted

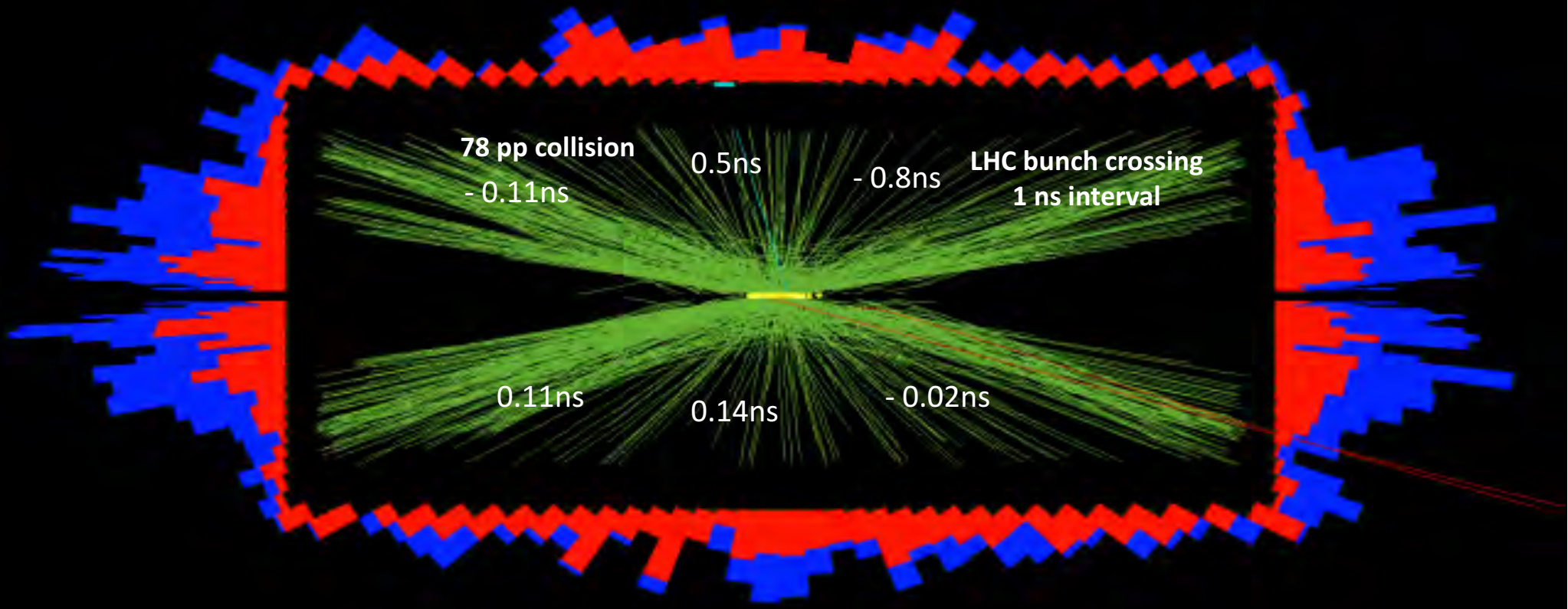
Mitigating Pile-Up

- By adding timing, as being planned for the HL-LHC upgrades



Viewing collisions in 3D

Mitigating Pile-Up



Viewing collisions in 4D

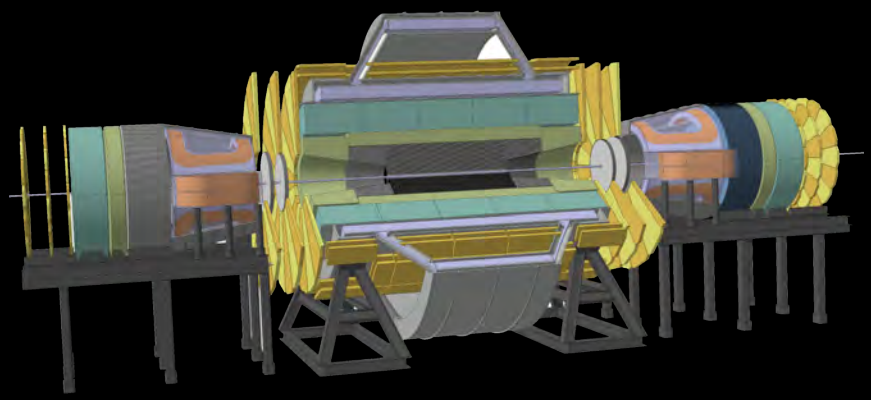
Tracking And B-Field

- Momentum Resolution:

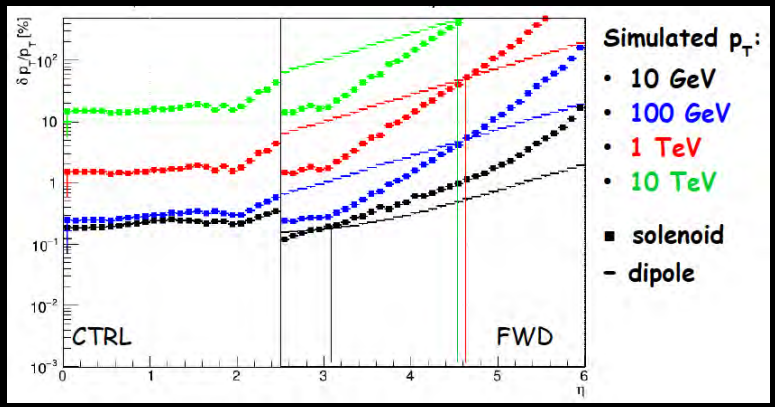
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

- Challenge:
  - A factor 7 in energy from 14 TeV → 100 TeV, requires a gain of a factor 7 in σ/BL^2 to retain LHC p_T resolution, down to $|\eta|<6$!
    - B=4T → B=6T
      L=1.1m → 2.4m
    - σ=20μm → 5μm
      L increase by $\sqrt{7}/4 \approx 30\%$

Magnet: 6T/12m bore
System: 20-30 m diameter, 30-50 m long
Stored Energy: 50-60 GJ.

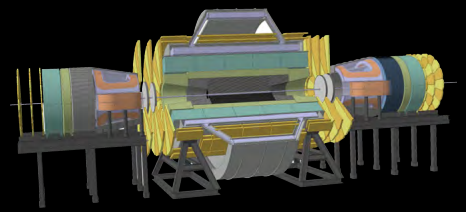


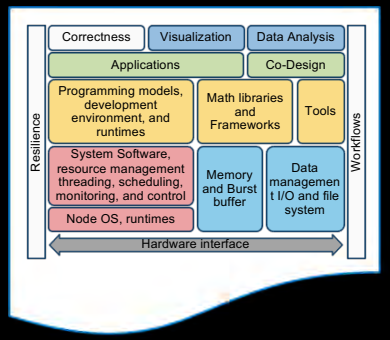
Dipole or solenoid in forward region



Software And Computing

Detector Parameters	Software Technology	Hardware Technology	Infrastructure
Science and mission application	Scalable and productive software stack	Hardware technology elements	Integrated exascale supercomputers and networks



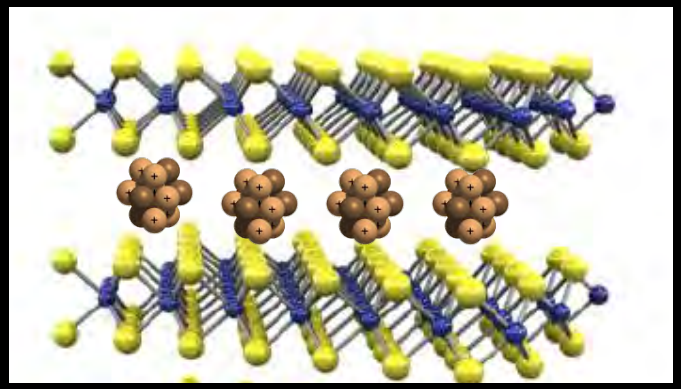


- Computing challenges are already with us
- HL-LHC will require more revolutionary than evolutionary thinking
- **Future Collider experiments will require truly revolutionary thinking**

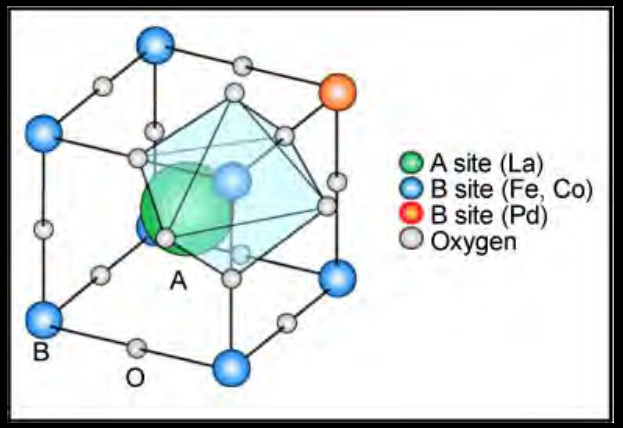
New Developments in Other Fields

- Develop a plan to establish and maintain a repository of new developments in other fields that might benefit the development of new sensors or instrumentation in HEP

Trans Metal Di-chalcogenides



Perovskites



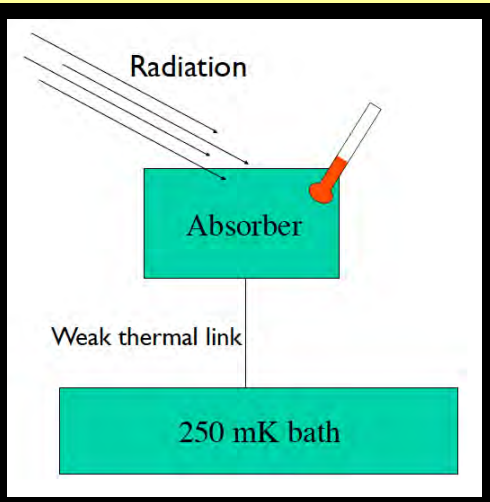
Wavelength shifting through Quantum Dots

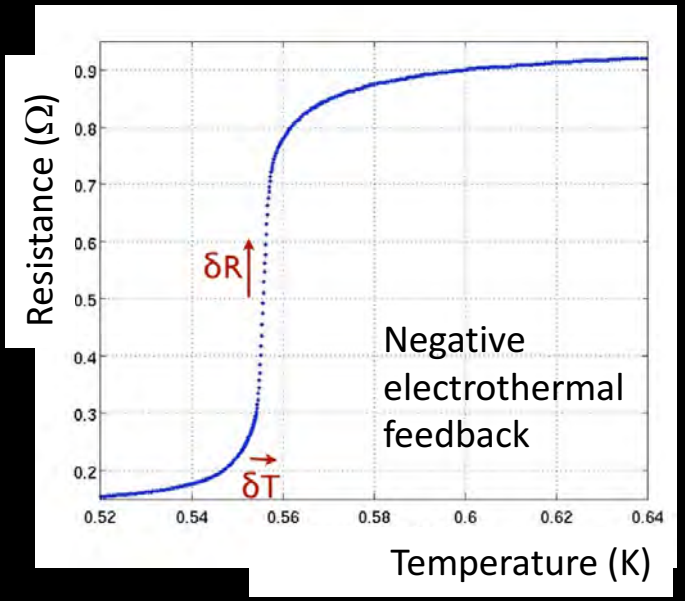
Additive manufacturing

.....

Quantum Sensors

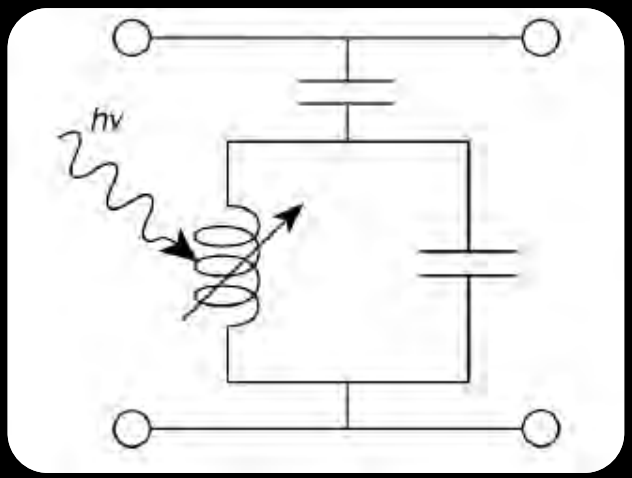
Transition Edge Sensors

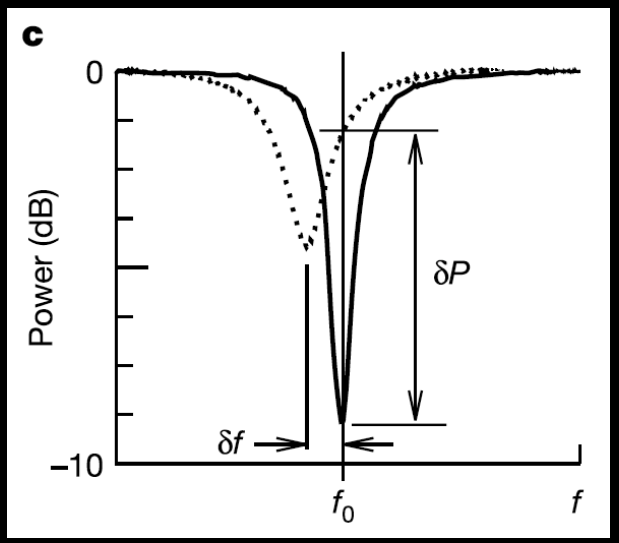




- Thermometer; held at transition between normal and superconducting
- Measures pW incident power

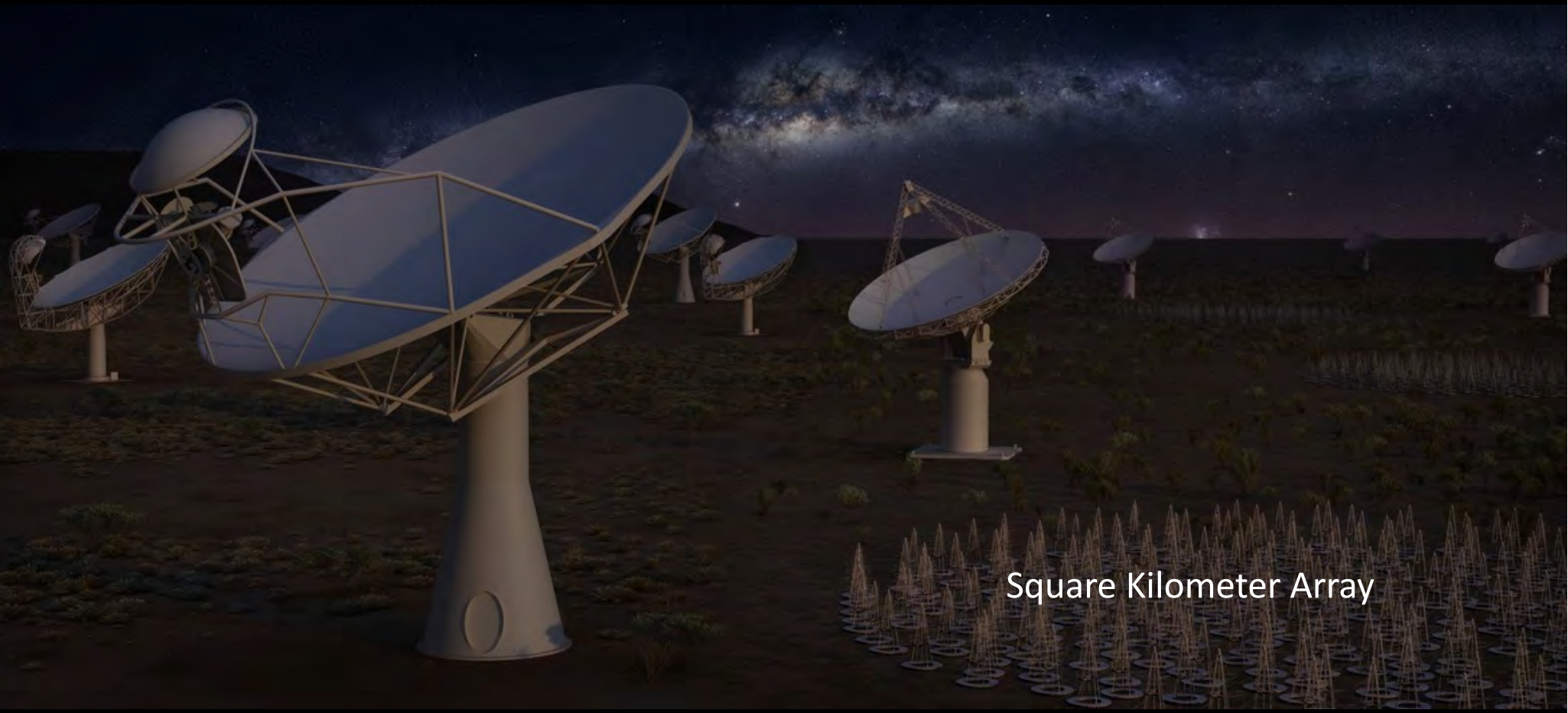
Kinetic Inductance Detectors





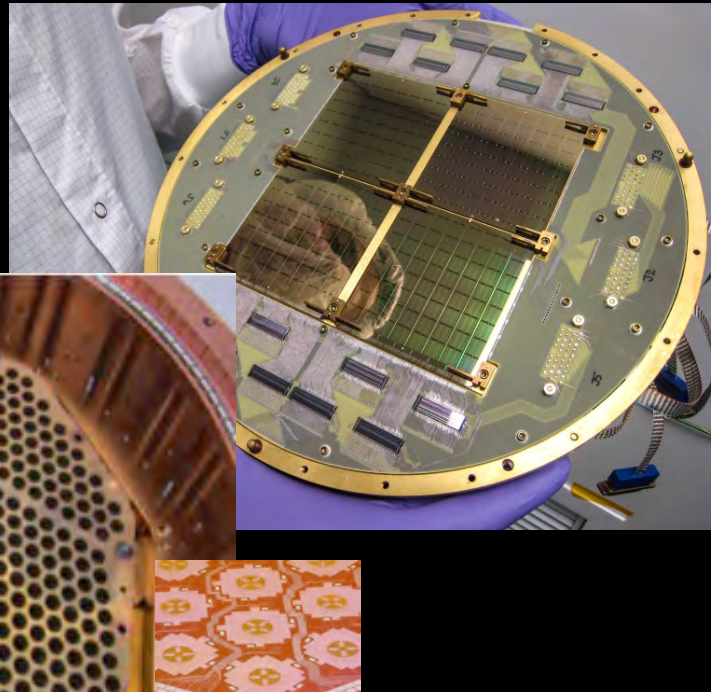
- Superconducting resonator
- Breakup of Cooper pairs changes inductance and resonant frequency

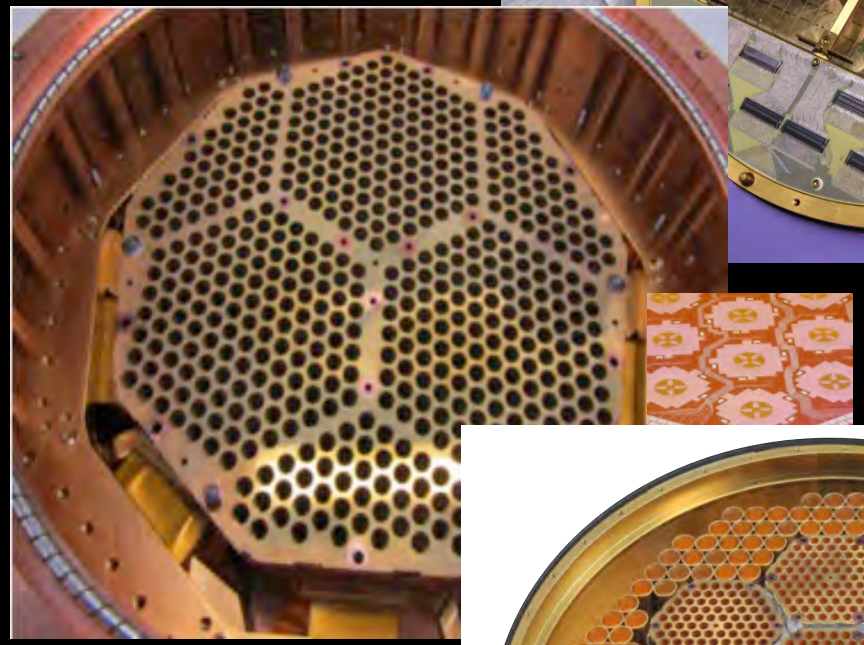
#3 Future Instrumentation Direction: 21 cm cosmology

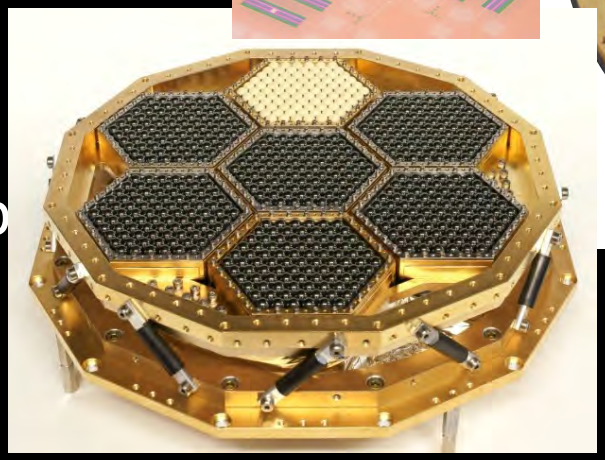


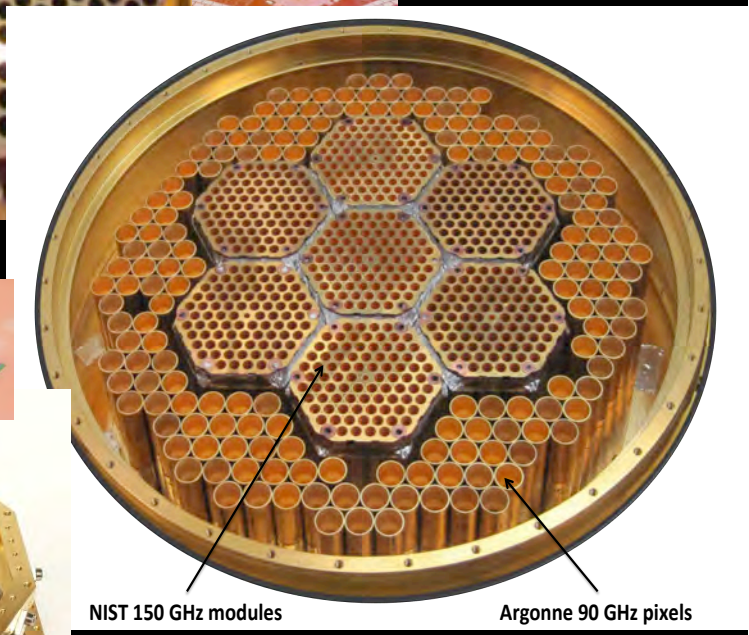
Bolometers

- Demonstrated background-limited noise performance
- Requires a ~10 layer superconducting microfabrication process
- Cost still >$100/detector
- Natural technology?
  - Microfabrication has provided scale-up to Stage 3
  - Need further scale up invest in process engineering & management





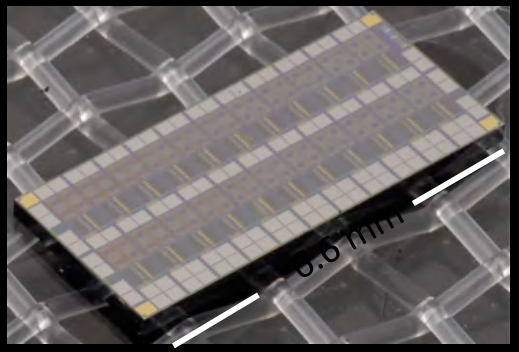




Bolometer readout using SQUIDs

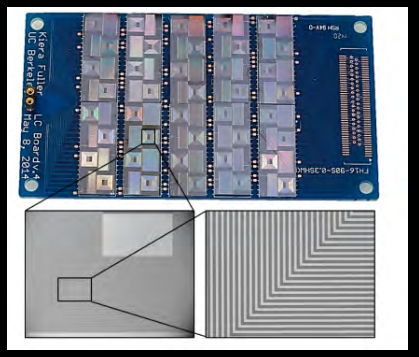
MHz carrier SQUID multiplexing
30,000 deployed pixels

Time division multiplexing



ABS, ACT, ACTPol, AdvACT, BICEP2, BICEP3, CLASS, KECK Array, MUSTANG, SPIDER, ZEUS, HAWK+, PIPER, SCUBA2

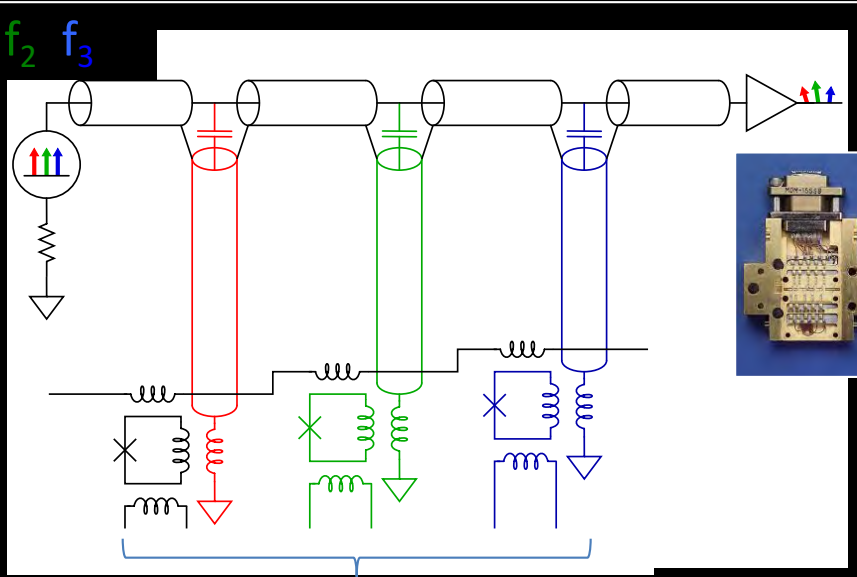
MHz frequency division multiplexing



APEX-SZ, EBEX, POLARBEAR, Simons Array, SPT, SPTpol, SPT3G

Microwave carrier SQUID multiplexing

A scalable architecture for the readout of large TES arrays. On-sky demo with MUSTANG2

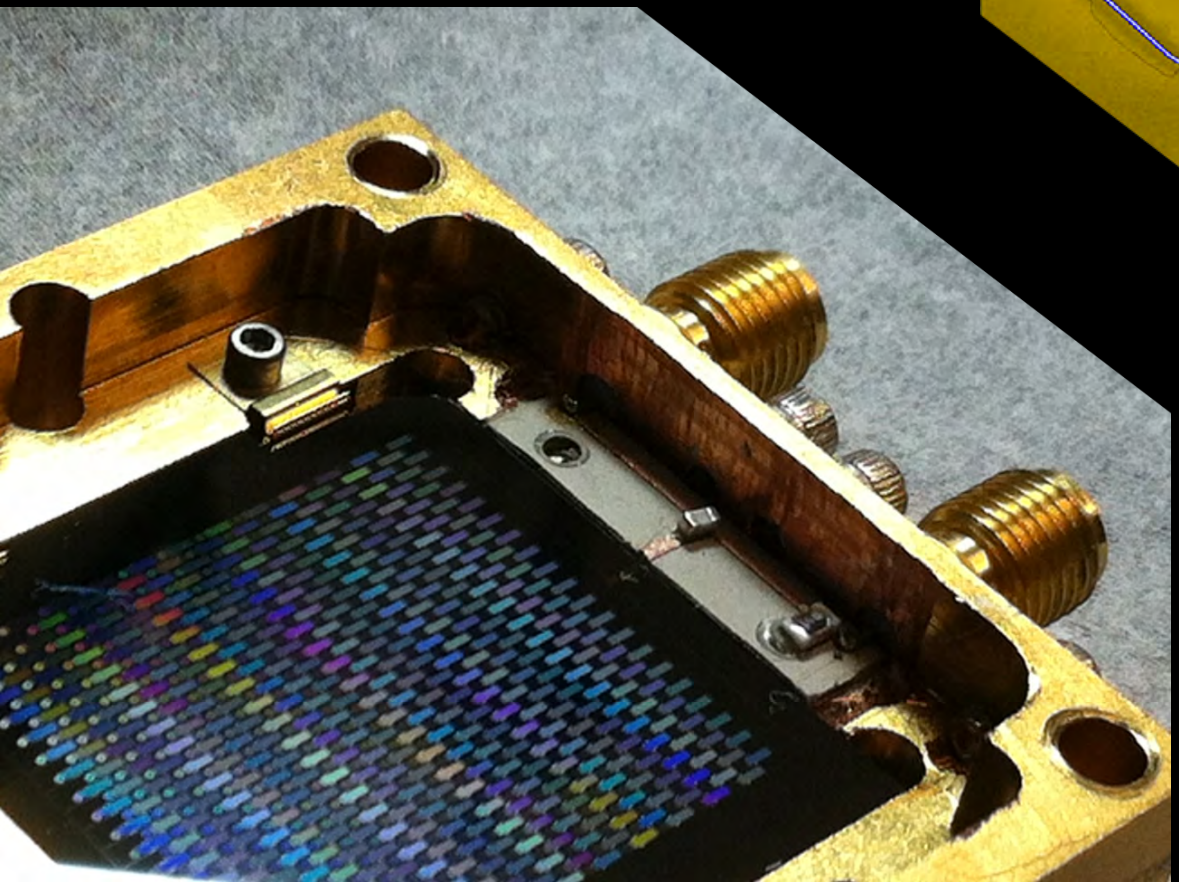


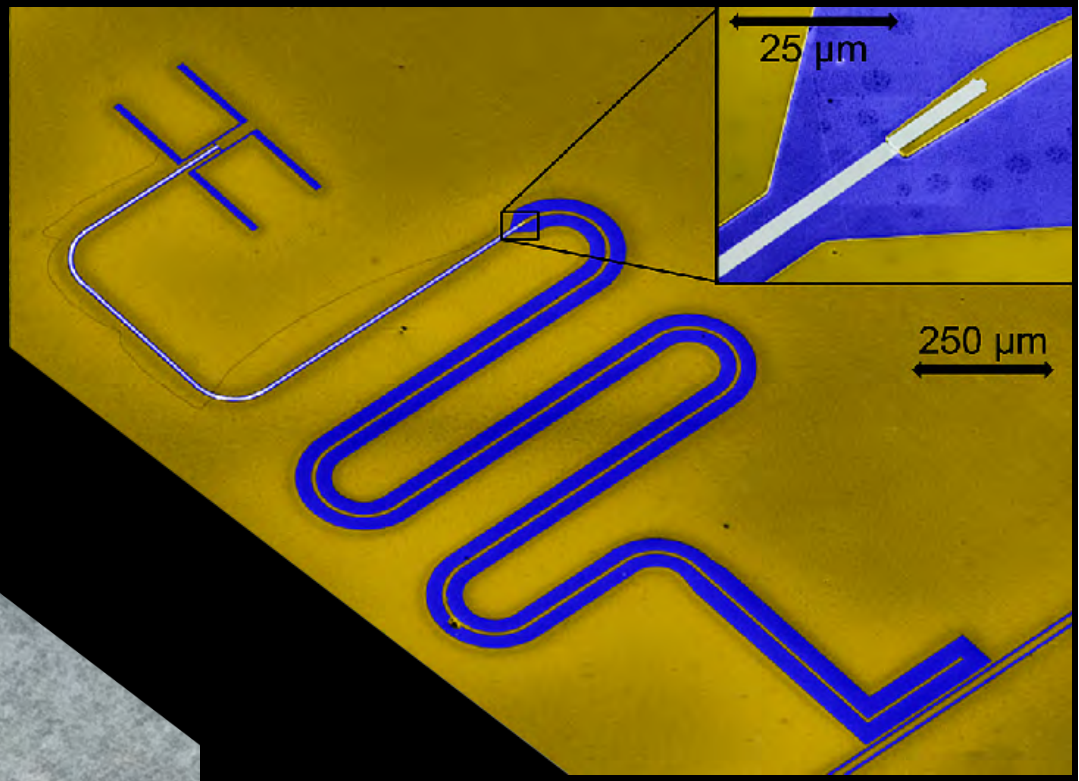
See talk by Joel Ullom

Kinetic Inductance Detectors (KIDs)

KIDs offer:

Kilopixel-per-cable on-chip multiplexing
Simple, robust fabrication
Low cost readout electronics





Demonstrated performance:

NEP required for background-limited ground-based CMB instruments
Operation from 70 GHz through THz
Fielded sub-mm science instruments

DPF Instrumentation Prize

2015 Prize: Nygren and Radeka

2016 Prize: Holland and Varner

CPAD Workshop @ Caltech