Fermilab Detector R&D Program

Zoltan Gecse – Fermilab Detector R&D Deputy Coordinator

Fermilab User's Meeting

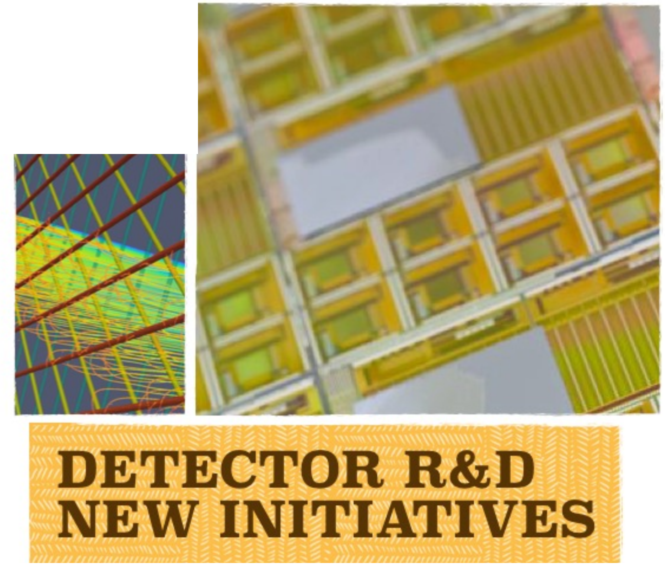
June 30th, 2023

- **Detector R&D: dedicated DOE program for detector development**
- **Fermilab organization:**
  - Detector R&D Coordinator: Petra Merkel, Deputy: Zoltan Gecse
  - Detector Advisory Group: ~15 experts of different detector technologies across the lab, including 2 external advisors
  - Meet bi-weekly to discuss ongoing R&D efforts, new proposals, coordination issues, budget, strategic and tactical investments
  - Detector R&D website
  - Coordinating with DOE program manager and other national labs

- **Selected Highlights:**
  - Maintaining 5-year strategic plan for Detector R&D, updating soon after P5
  - Defined high-priority R&D thrusts aligned with recent DOE BRN for Detectors and with Fermilab's mission, facilities and expertise
    - Current highest priorities: picosecond timing and noble element detectors
  - Annual competitive R&D proposals, "New Initiatives" program
  - Participating in national initiatives, e.g. AI/ML and Microelectronics

New Initiatives Program

- The goal of the **New Initiatives** program is to attract new members and new ideas to the detector R&D community at the lab.
- Directed towards newly identified strategic areas
- Great resonance to this new call, which will enable PIs to perform demonstrator stages of their ideas, which could subsequently enable them to successfully apply for additional funding, such as LDRD, ECA, etc.

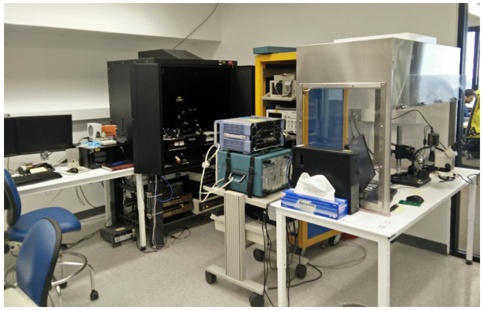


2023 Winners:

PI: Grace Cummings
Maximal Information Calorimetry – characterizing picosecond timing capabilities of total absorption dual-readout calorimeters

PI: Ana Martina Botti
Building a portable Skipper-CCD camera for quantum imaging and astronomical applications

Detector Facilities and Infrastructure



- Common Detector Test Facility Systems
  - Silicon Detector Facility
  - Precision Metrology
  - Scintillation Detector Development Facility
  - Thin Film Facility
  - Noble Liquid Test Facility (NLTF)
  - Low Background Facility (NEXUS)
  - Rapid Prototyping and Special Materials

- ASIC Development Facility
- Fermilab Test Beam Facility (FTBF)
- Irradiation Test Area (ITA)
- New Helen Edwards Integrated Engineering Research Center

Promote and benefit from partnership with universities and other national laboratories. Facilities are supported by excellent technical workforce (specialized technicians and engineers).

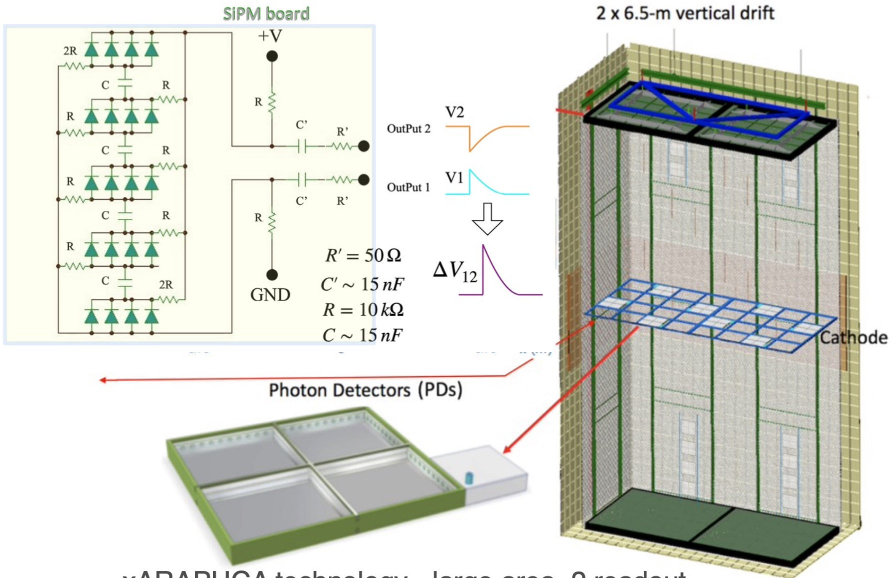
Selected R&D Topics

Noble Element Detectors

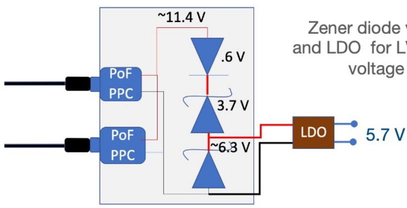
- **Fermilab continues being a key element in the development of LArTPCs worldwide**. Experience from experiments all over the world has been gathered and it has **culminated in the DUNE phase I design**. The focus of the LAr R&D is **now shifting towards what is needed for DUNE Phase II**:
  - **Optimizing light and charge collection**: doping LAr, charge amplification in liquid, combining light and charge collection, developing new technologies like power- over-fiber & signal-over-fiber SiPMs to increase the number of viable light collection surfaces, metalenses, NIR light studies, etc.
  - **Improving near detector systematics**: design and optimize high pressure gaseous argon TPC.
  - Final State Charge information: **magnetized LAr TPCs**.
    → ArCS (Argon detector with Charge Separation) is a Fermilab project with a goal to run a LArTPC inside a magnetic field around 0.7T.

Photodetectors for HV surfaces in DUNE VD

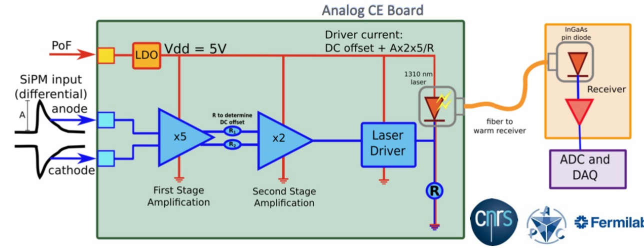
- Scintillation light readout (PDS) in LAr-TPC complementary to charge
  - PDS particularly important for detection & reconstruction of low energy underground events and background rejection
- Operating photodetectors on HV surface (300 kV) requires electrically floating Photo-sensors and r/o Electronics ⇒ Power (IN) and Signal (OUT) transmitted via optical Fibers (commercial technique)
- Successfully tested at CERN in Dec 2021

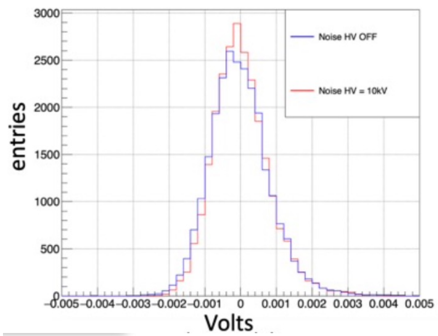


xARAPUCA technology - large area, 2 readout channels (each 4x20 SiPMs in hybrid ganging)



Zener diode voltage divider and LDO for LV-HC PoF output voltage regulator



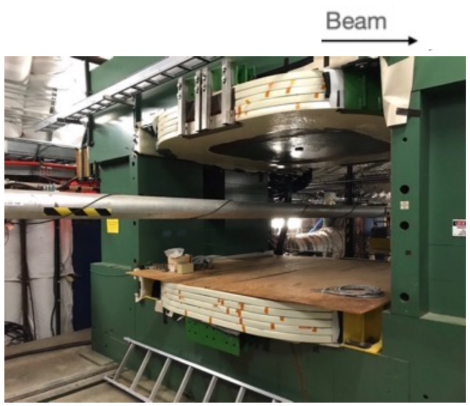


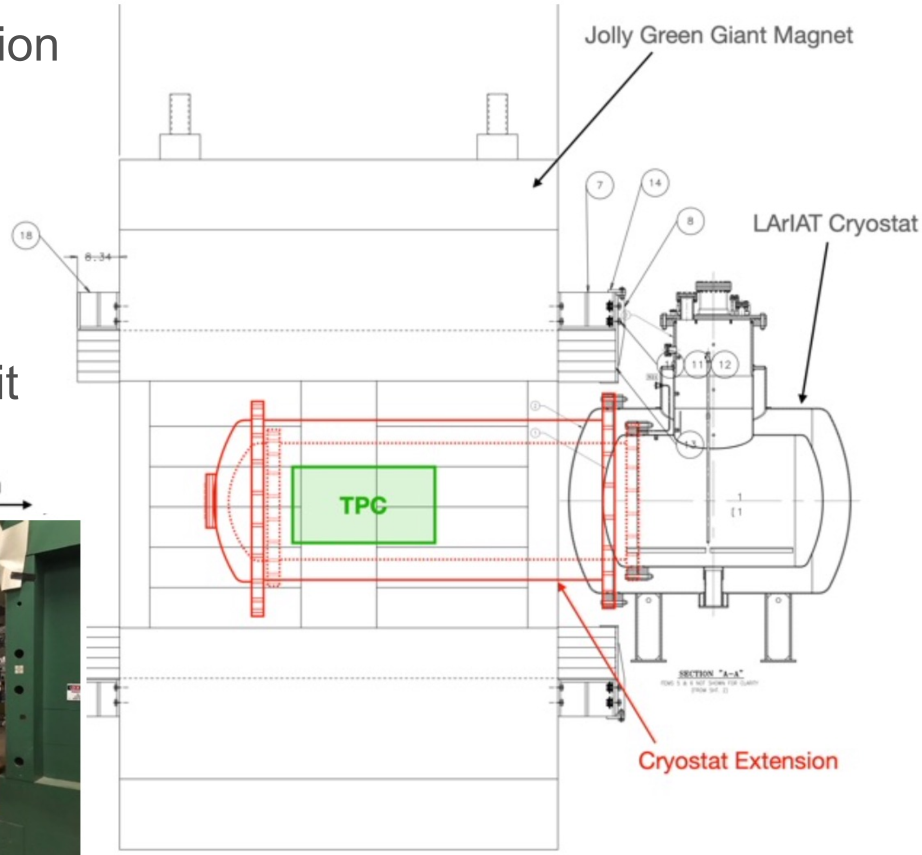
HV OFF:
Mean = -0.05 mV
Sigma =0.77 mV

HV = 10 kV
Mean =-0.02 mV
Sigma=0.71 mV

ArCS: Argon detector with Charge Separation

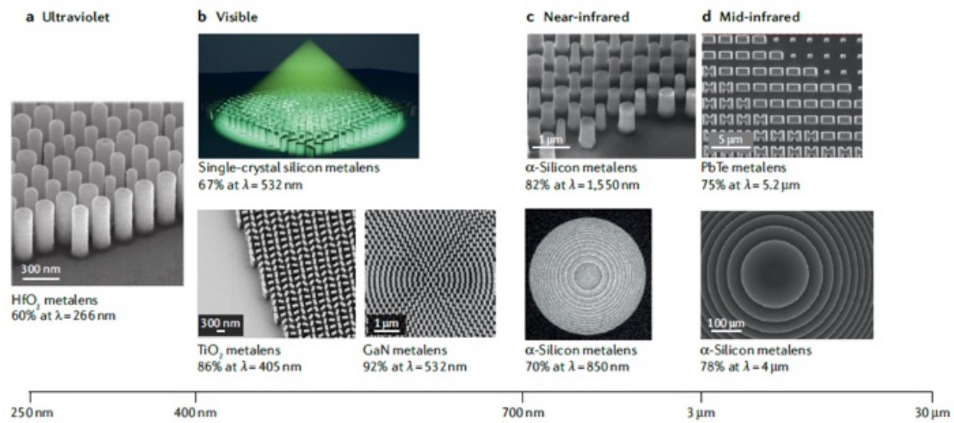
- Fermilab LDRD project with the goal to run a LArTPC inside a ~ 0.7T magnetic field to:
  - establish minimum required magnetic filed for electron-photon separation of O(100)MeV
  - demonstrate electron/photon separation
  - measure electron diffusion in the presence of a magnetic field
- Magnetic field would also allow measuring momentum via curvature
- ArCS will reuse the LArIAT TPC, placing it inside the Jolly Green Giant magnet at the Fermilab's Test Beam Facility



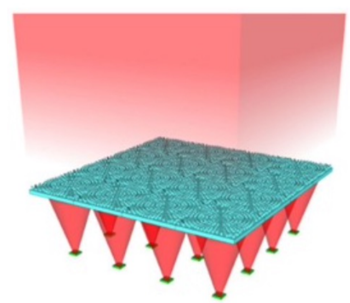


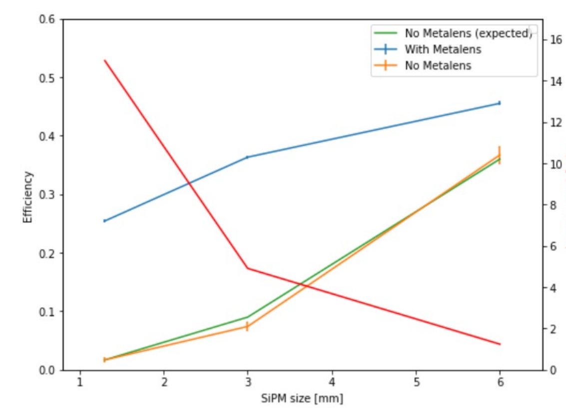
Metalenses as Light Concentrators

- Metalenses: flat optics achieved through controlling the wave front of light (amplitude and phase) by way of subwavelength-spaced nanostructures
- R&D at FNAL, Harvard and Manchester to use them as light concentrators instead of imaging devices
- Estimated increase in light collection of up to a factor of 15 if used in combination with small area (1.3 mm x 1.3 mm) SiPMs [AA.Loya Villalpando et al. arXiv: 2007.06678]
- Many challenges:
    - Cryogenic environment
    - VUV part of the spectrum



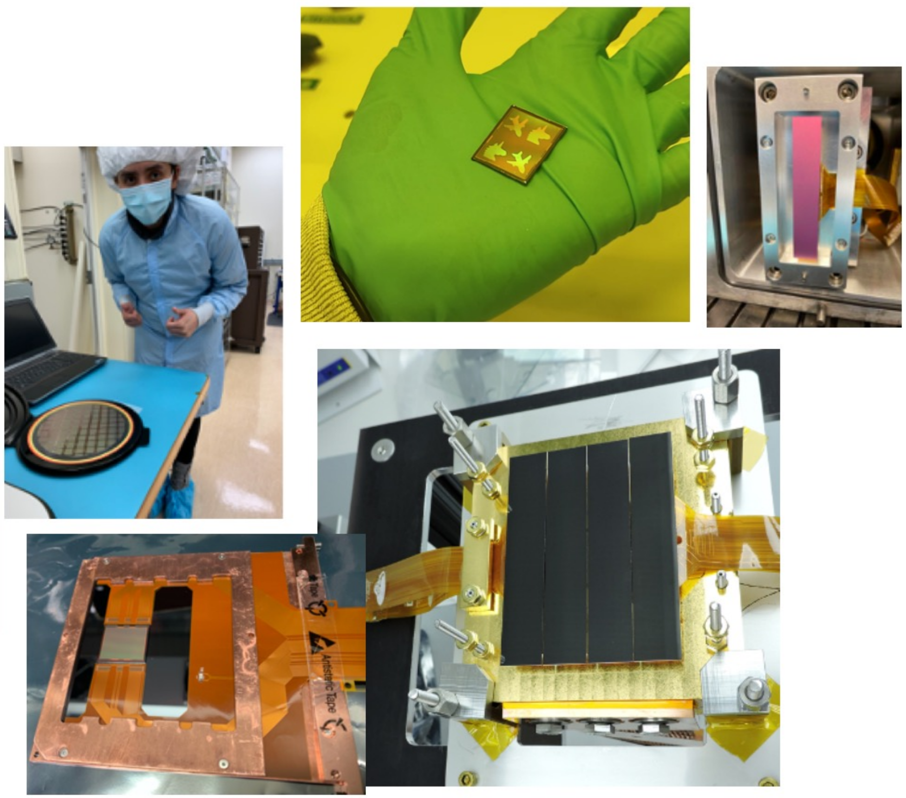
Chen, Zhu, Capasso: Nature Reviews Materials 5, 604–620(2020)



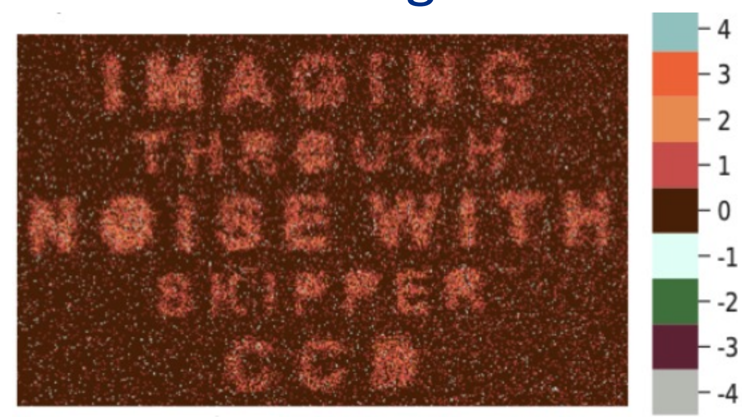


Skipper-CCDs for Astro Physics and Beyond

- Skipper-CCDs: single photon sensors for dark matter, cosmic surveys, quantum imaging
- Completed R&D demonstrations, targeting large experiments: Oscura, DESI2, Spec-5, outside HEP



Photon counting in near IR



$N = 150 \quad \sigma = 0.24\ e^-$

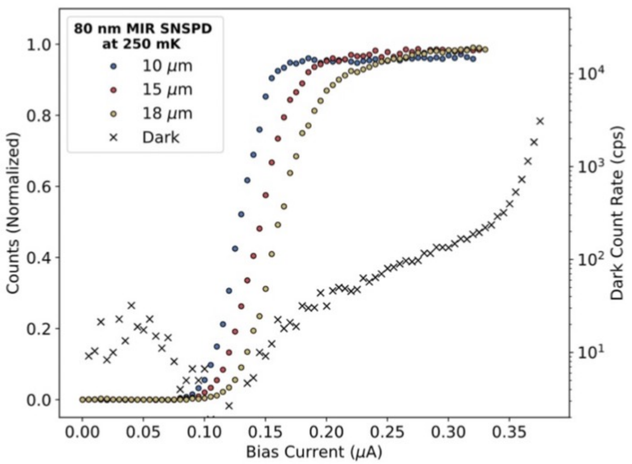
arxiv:2301.10891

Next step: use photon counter for imaging entangled photons (QIS)

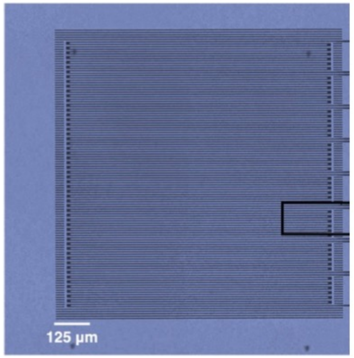
SNSPDs

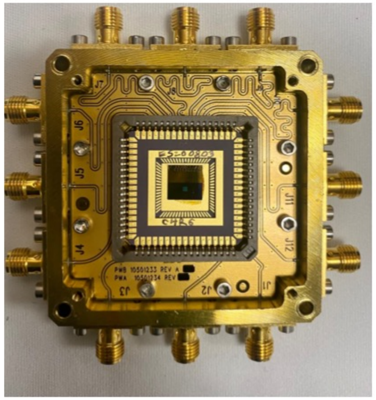
- Three main challenges:
  - Reducing energy threshold down to ~ 40 meV (30 um photons)
  - Scaling up sensitive area and channel count – micron wide wires and readout schemes
  - Exhaustive characterization of background sources, dark count
- HEP applications include searches for bosonic and fermionic DM searches and quantum gravity probes

low-thresholds

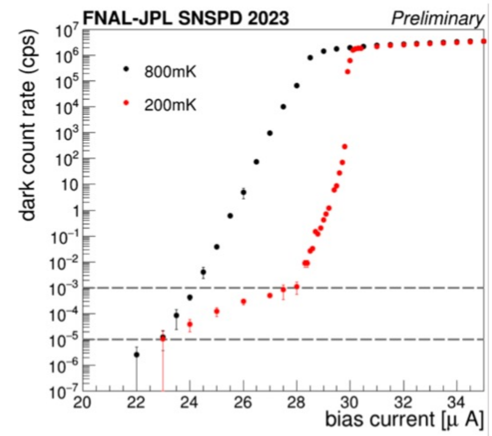


8 channel 1x1 mm SNSPD



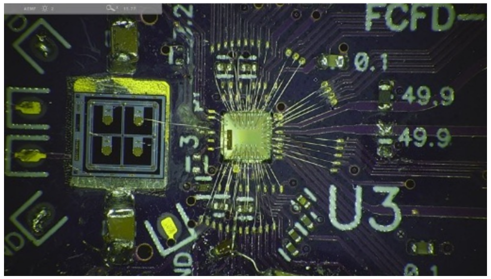


DCR @ FNAL



Silicon Sensors and Tracking

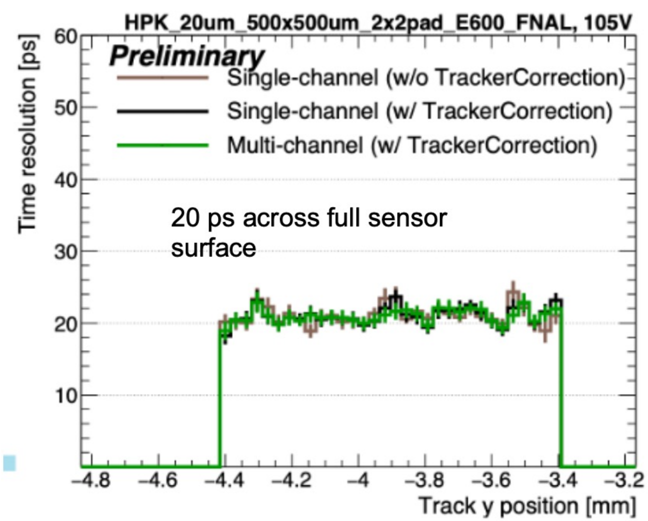
- Key challenges:
  - Trackers with position and time resolution of 10um and 10ps
  - Depending on machine (lepton vs hadron): ultralight, low power, radiation hardness up to 10^{18} n/cm^2
- **Ongoing work:**
  - Design, manufacture and test sensor and ASICs, full systems integrations and readout electronics
  - **Experience in development and assembly of trackers for original CMS and upgrades**
  - ASIC developments: ETROC timing chip for CMS
  - Developments towards integrated sensors for future with smart on-detector processing (Smart Pixels, MAPS)
  - **FCFD (Fermilab Constant Fraction Discriminator ASIC)**
    - Next generation timing ASIC FCFD for future applications with ~6-8 ps intrinsic time resolution

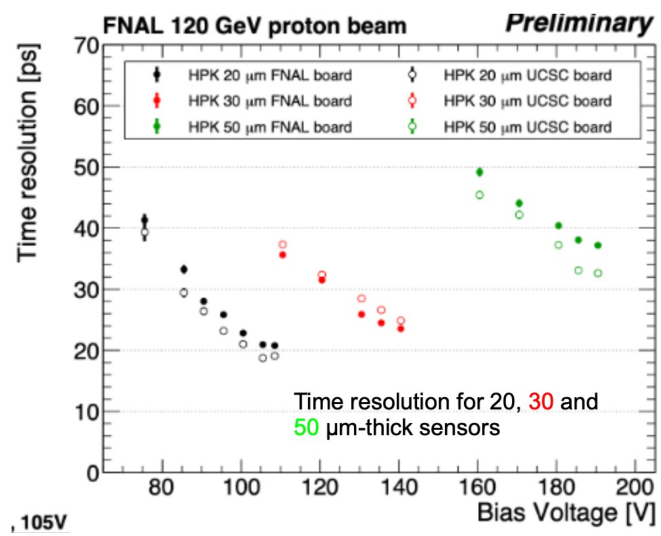


- **Permanent setup in FNAL test beam facility (FTBF) for 4D trackers**

Low-Gain Avalanche Detectors

- **New technologies applied to HL-LHC (DC-LGADs) and EIC (AC-LGADs)**
- **First demonstration of 4D-trackers with 100% fill factor,** and simultaneous ~5 μm, ~20 ps resolutions
  - Thinner sensors to decrease Landau contribution: achieve 20 ps for 20 μm thick sensor!
  - Collaboration with BNL, UCSC, KEK on AC-LGAD developments

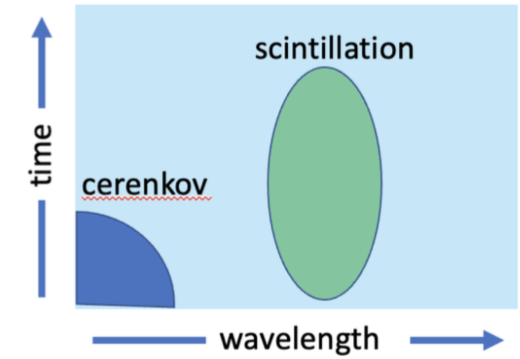




, 105V

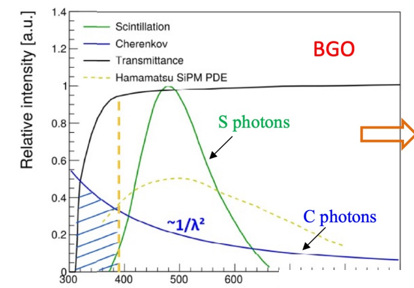
Calorimetry

- Key challenges
  - Future calorimetry at fixed target and colliding beam experiments should be fundamentally multidimensional, providing shower position, time and energy
  - Provide **detailed look at shower constituents** through the exploitation of an application-specific combination of PF techniques, materials with intrinsically **good time or energy resolution**, or DR techniques
- Dual Readout Calorimetry
  Improves jet/hadron energy resolution with Cherenkov and scintillation light measurements
  - Crystal calorimeter (CALVISION)
  - Discrimination based on wavelength and pulse shape
  - Sampling calorimeter with dedicated measurements of Cherenkov light only and scintillation light only (US-JAPAN)
- Working with industry to develop new WLS materials (Kuraray)

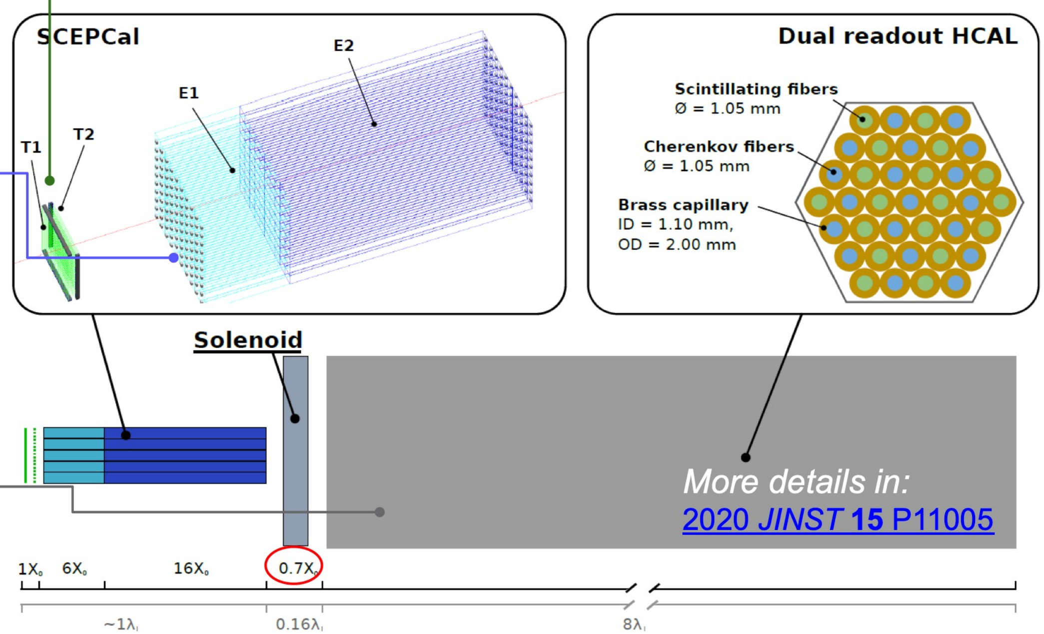


CALVISION, Dual Read-out Crystal Calorimetry

- Segmented crystal calorimeter read-out with wave-length sensitive SiPMs
  - Tuned to separate Cherenkov and Scintillation light
- Exploring timing properties with SiPMs
  - Supported by the New Initiative program



- **Two Timing layers**
  - $\sigma_t \sim 20$ ps
  - LYSO:Ce scintillating crystals ($\sim 1\ X_0$)
  - $3\times3\times60\ mm^3$ thin crystal bar
  - $3\times3\ mm^2$ SiPM (15-20 µm cell size)
- **Two ECAL layers**
  - $\sigma_{EM}/E \sim 3\%/\sqrt{E}$
  - $PbWO_4$ crystals
  - Crystal cross-section: $10\times10\ mm^2$
  - $5\times5\ mm^2$ SiPM (10-15 µm cell size)
- **Ultra-thin IDEA solenoid**
  - $\sim 0.7X_0$
- **HCAL layer**
  - $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers inserted inside brass capillaries

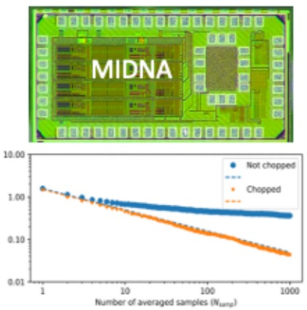


Readout ASICs

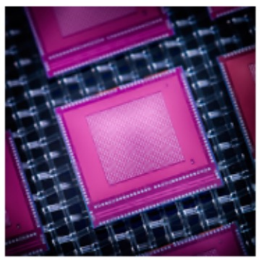
- **Key challenges: shared access to advanced technology / easy access to design tools**
- **Community Support and Coordination**
  - Consolidate CAD tool licensing, IP and foundry access across the DOE complex
  - Develop extreme environment PDKs and foundational IP blocks
  - Organize MPWs for 3DICs
- **Integrated Sensing-Computing-Communication**
  - Novel CMOS sensors (e.g. MAPS, MAPS with timing, Skipper in CMOS, CMOS LGADs)
  - Low power, low noise, ultra-sensitive analog for sensor signals
  - Advanced digital architectures and verification methods
  - Integrated high speed communication between modules and off-detector
- **Industry engagement**
  - Impactful hardware beyond HEP: AI-on-chip, Quantum cryo-electronics, 6G and more
  - Work with US fabs to enable production scale state-of-the-art chips for extreme environments
  - Leverage and advance transformative heterogeneous integration and advance packaging solutions

Innovation in Chips

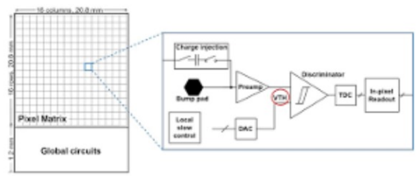
Ultra-Low Noise Sensing (Dark matter detectors)



Ultra-High Frame rates (Xray detectors)

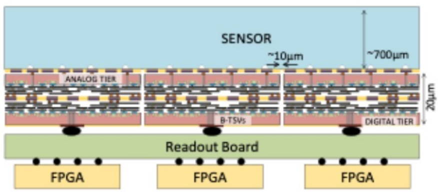


Picosecond timing (HL LHC detectors)

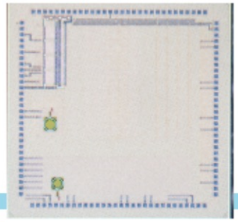


Operation in extreme radiation/ cryogenic (HL LHC/ DUNE)

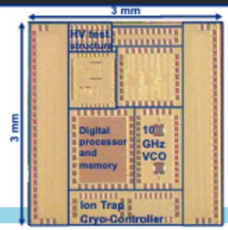
3D ICs (HEP / BES light sources)



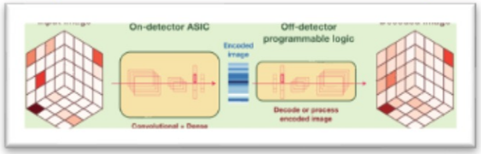
High speed cryogenic Data converters (with Microsoft)



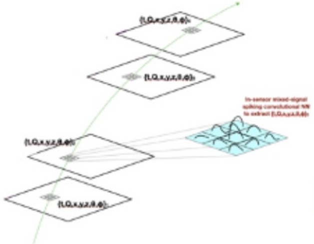
Quantum Support Chips



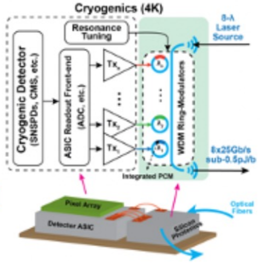
AI-on-chip (ultra-fast data processing)



AI-in-pixel (minimizing data movement)



High-speed Photonic links (low power communications)

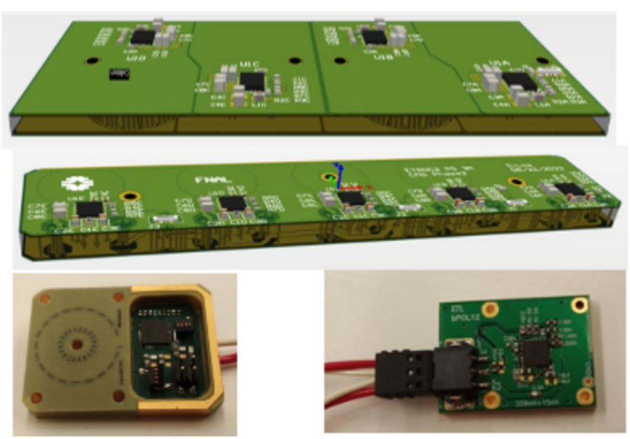


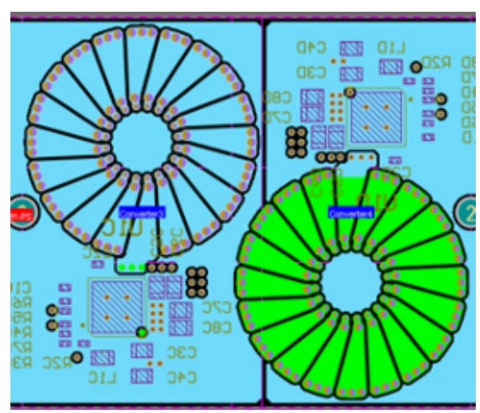
Quantum Instrumentation Control Kit (QICK)

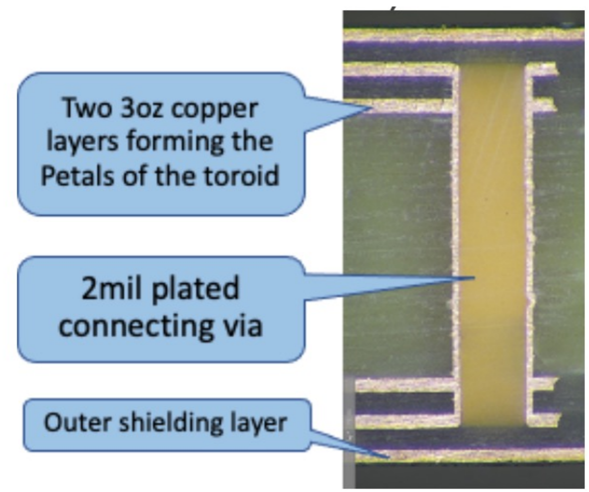
- Complete control and readout for QIS applications
- **Example of unique engineering enabling access to the most advanced FPGA technology in the HEP and QIS community**
  - Xilinx-RFSoc board for communications + custom HW, FM and SW by Fermilab
  - **Reduces cost** $50K/qubit to $1K/qubit. Scales up to ~1K qubits.
  - $1/channel for highly MUXed sensors (e.g. MKIDs, SNSPDs, QCD)
  - **Functionality outperforms other control systems,** allows new ways of doing QC experiments
  - **Tools are made immediately available to everyone interested**, and are adopted by world leading groups in every area (~20 papers using this in 2022/2023)
  - Builds a **worldwide community**: >150 people attended a QICK workshop at Fermilab (Jan, 2023) attended by academia and industry (including IBM, AWS, Rigetti, ColdQuanta, AMD, etc)
  - **Industry partnership** allows access for even a larger community

Technology for Operations in Extreme Environments

- Fermilab is involved in R&D for
  - power distribution systems in extreme environments (cold and radiation)
  - clock distribution
  - and working with companies on bringing innovative developments into HEP (packaging, PCB manufacturing, etc.)
- Example: DCDC power converter inside a PCB
  - Large magnetic field and radiation tolerant, low profile







Summary

- Strong detector R&D program at Fermilab
- World-class facilities and specialized technical staff are crucial
- Often small R&D seed efforts bring new, larger projects and funding to the lab
- Always open to establishing new collaborations with the user community!