Development of precision tracking and quantum detectors at Fermilab

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Second Annual U.S. Future Circular Collider (FCC) Workshop 2024

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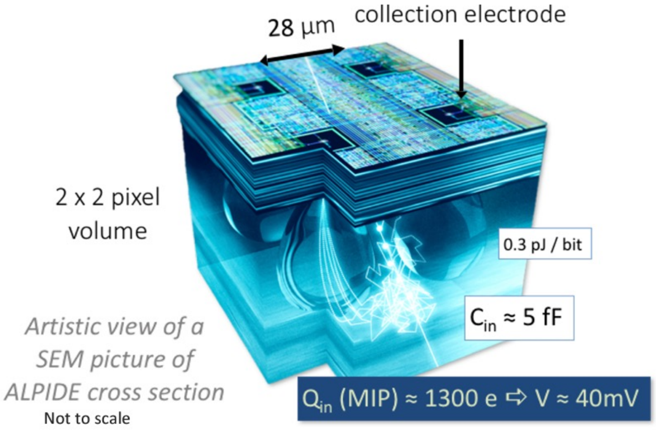
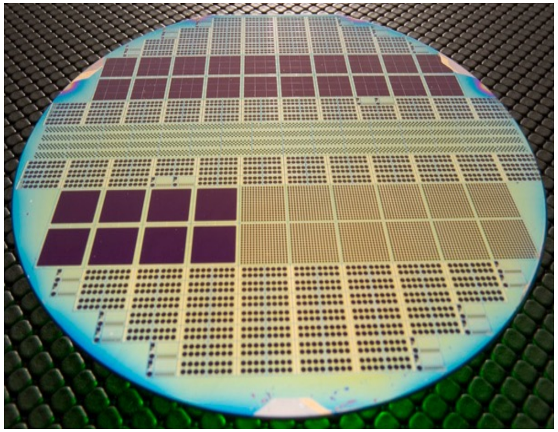
MAPS design efforts with Skywater

- **GOALS**
  - US manufactured sensor capability for HEP experiments
  - Optimize the process towards HEP sensors
  - Co-design sensor and readout electronics
  - Broad adoption of development in community



- **HOW?**
  - Partner with Skywater Technologies
  - Strong support from UC, UIC, Purdue, UIUC, Cornell, for device simulation and testing
  - Engineering run with various designs
  - Testing of sensors at Fermilab and partners



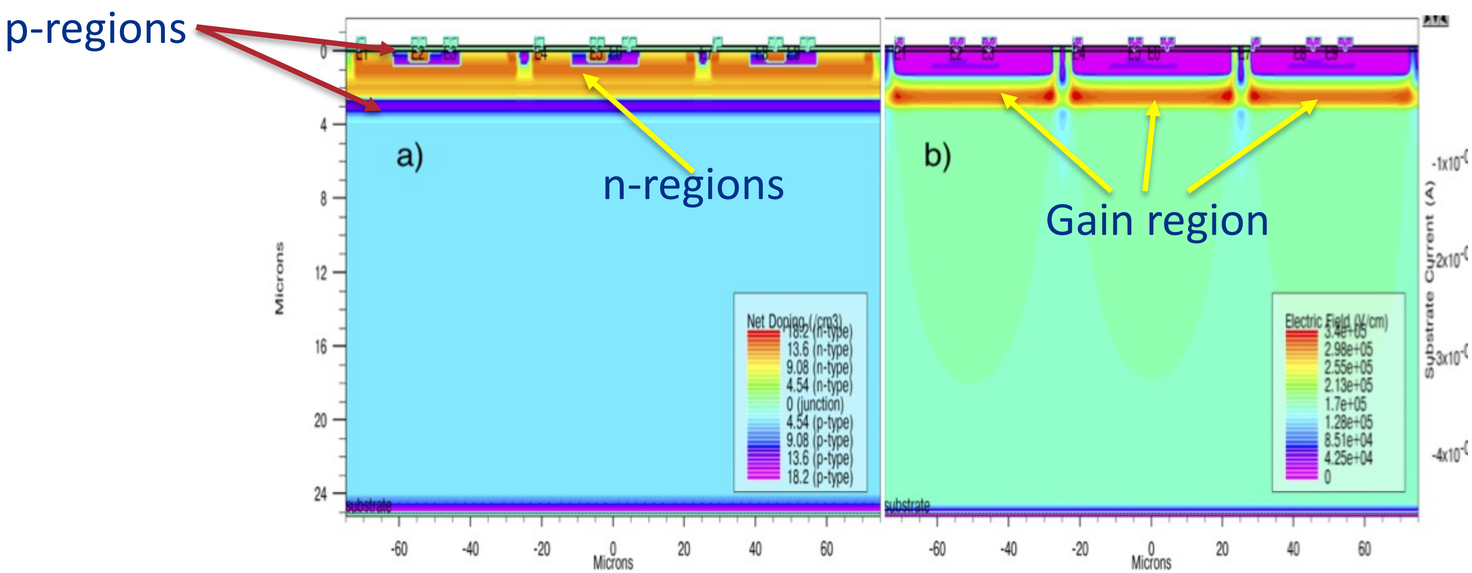
Commercial Partner

- Most **advanced process** among HEP MAPS
  - Fabricated on SkyWater's **90 nm** process
  - Demonstrate domestic production for future HEP experiments

- We will work with SkyWater to modify their standard epitaxial silicon layer
  - Adapt and optimize SkyWater process to develop particle detectors
  - Use thicker, higher-resistivity epitaxy with deep-well implants on a standard CMOS substrate
  - The standard CMOS process flow can then be used to fabricate IC resulting in a monolithic sensor with integrated signal processing

Simulations

- TCAD simulations were used to establish the feasibility of the proposed work, and we started discussions with SkyWater.
  - The initial TCAD studies for SkyWater CMOS are based on our previous work to establish designs for 8” sensor wafer production



Net doping density of the structure

Electric field profile

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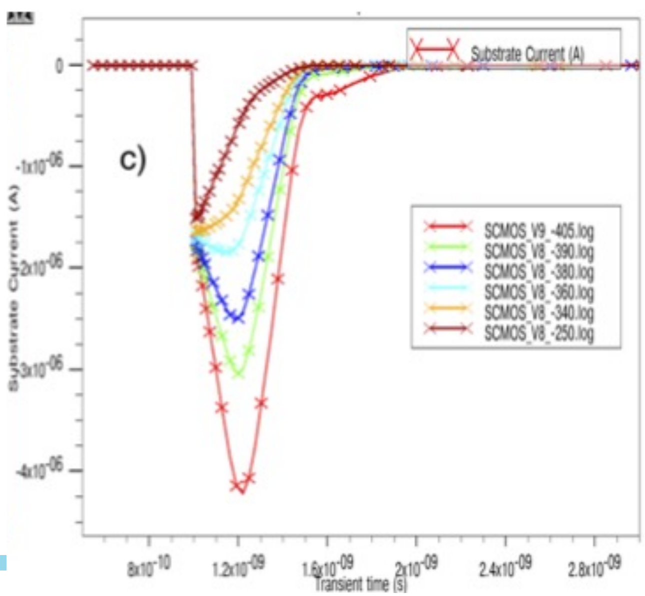
Simulations

- Depleted CMOS sensor operation can be limited by the fields in the region of the deep wells causing breakdown or affecting transistor operation.
  - Processes designed for HV operation have been studied in RD50
  - While the SkyWater 90 nm process is not an explicit HV design, it is likely compatible with the fields in fully depleted sensors
  - Can mitigate the fields near the wells with deep n-implant



- Substrate current pulses for bias voltages from 250 (brown) to 405 (red) volts showing the onset of gain.
- Rise time of the top electrodes will be determined by the details of the CMOS well capacitance

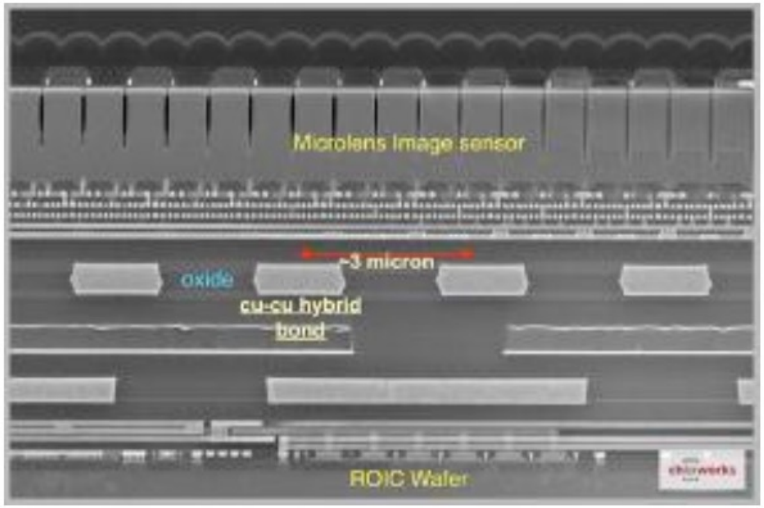
Project Deliverables

- Design and manufacture sensors using SkyWater's 90 nm CMOS process
- Create a HEP specific MPW run
  - Reticle divided into dies of varying designs: ½ wafer with only sensors and ½ wafer with sensors & readout circuits
  - Perform detailed characterization of MAPS, LGAD, and SPAD detectors, and quantify their performance for HEP

- Create a US-based silicon sensor manufacturing facility for next generation HEP/NP experiments
  - Enable US-teams to lead the design and fabrication of tracking detector(s) for a future Higgs factory
  - Enable a **broad participation of university groups** in cutting edge instrumentation

3D-integrated sensors project

- Development of low-power, highly granular detectors in ($\vec{x}$, t)
  - Required to achieve breakthroughs across HEP, NP, BES, and FES
  - Adoption of 3D-integration has been cost-prohibitive in academia
- Supported by DOE “Accelerated Innovation in Emerging Technologies”
  - Joint development effort of SLAC and FNAL teams
  - Partner with industry leaders to implement new technologies
  - Design goal is to achieve position resolution ~5 µm, timing ~ 5-10 ps

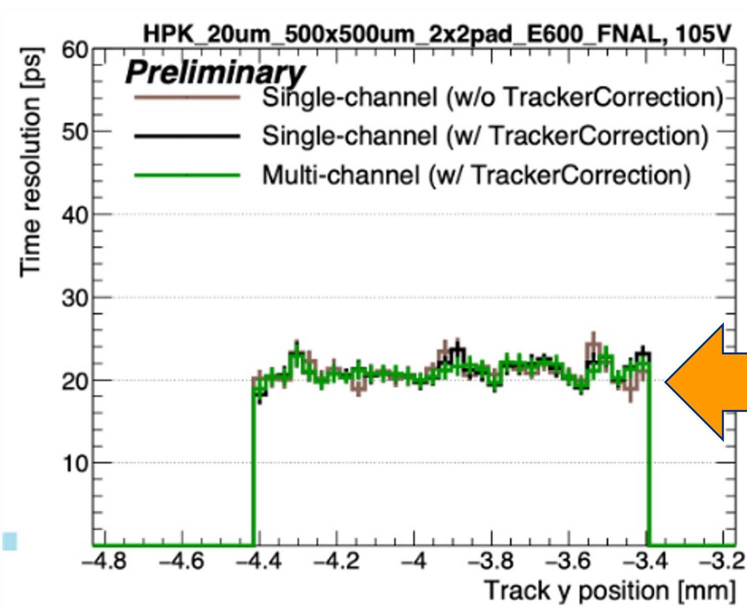


Objectives

- The research program consists of three main thrusts towards developing the proposed detector:
  - **Thrust 1:** *Design and manufacture Low-Gain Avalanche Diodes (LGADs) devices compatible with 12'' foundry processes*
  - **Thrust 2:** *Design application specific integrated circuit (ASIC) techniques to meet various application needs for granularity, precision timing, and power*.
  - **Thrust 3:** *Enable a new generation of particle detectors that utilize 3D-integration, combining state-of-the-art 12" wafers from different foundries*.

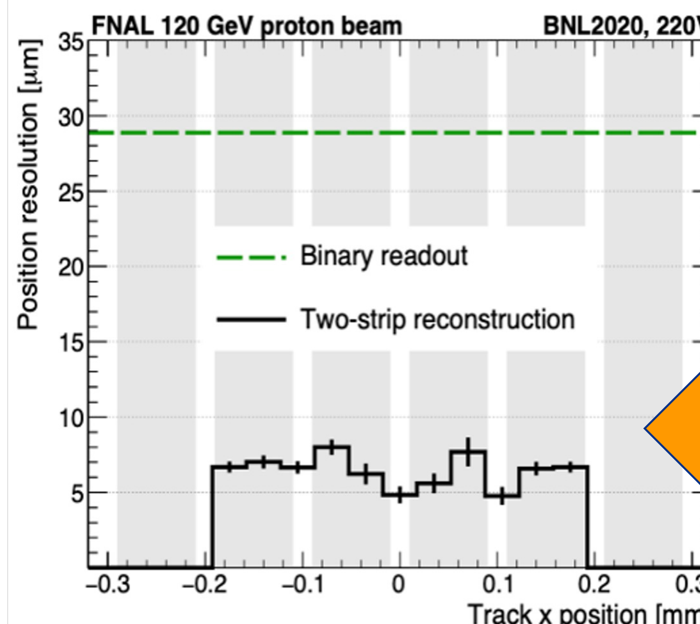
Applications in High Energy Physics (HEP)

- CMS and ATLAS are building first-generation detectors
  - Very coarse position resolution, around 30-40 ps timing
- First demonstration of simultaneous ~5 µm, ~30 ps resolutions with AC-LGADs beam: technology for 4D-trackers!



20 ps time resolution

Hamamatsu 20 µm AC-LGAD sensor



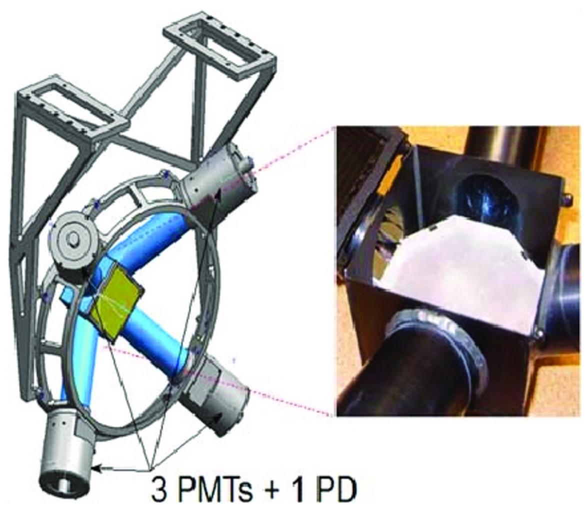
~5 µm positi resolution

BNL AC-LGAD sensor

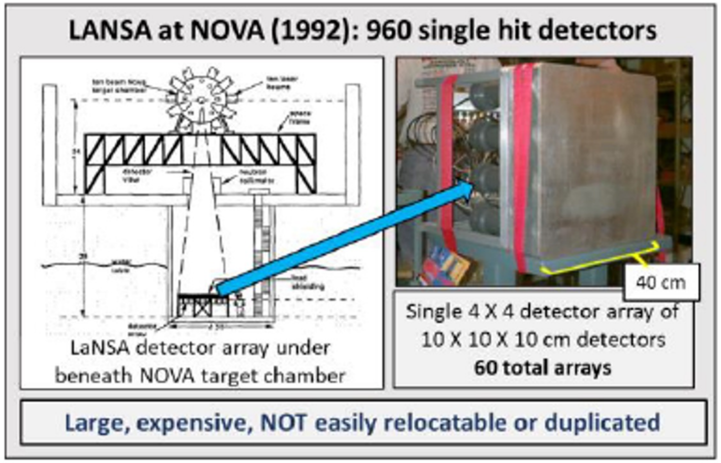
Applications in Nuclear Fusion Energy Research

- Exciting results recently at LLNL Ignition Facility
  - Net energy gain fusion reaction achieved
- Neutron spectrometers and low signal high speed imaging
  - Neutron spectrometer using time stamping single hit detector
  - Neutron TOF detectors need wider dynamic range

Current nTOF uses 4-PMTs

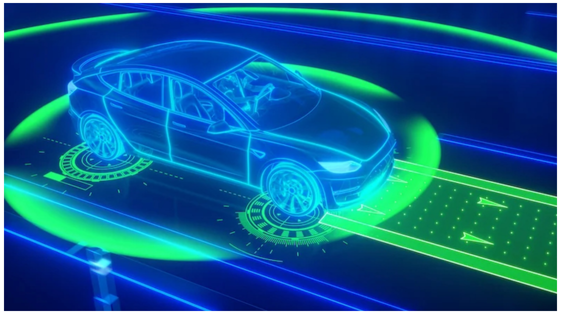


PMT based TDC system was built in the 90s

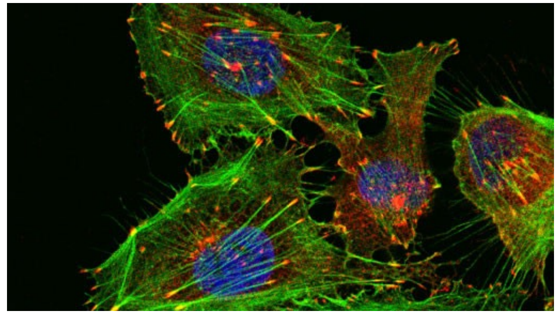


M. B. Nelson, M. D. Cable; LaNSA: A large neutron scintillator array for neutron spectroscopy at Nova. Rev. Sci. Instrum. 1 October 1992; 63 (10): 4874–4876. https://doi.org/10.1063/1.1143536

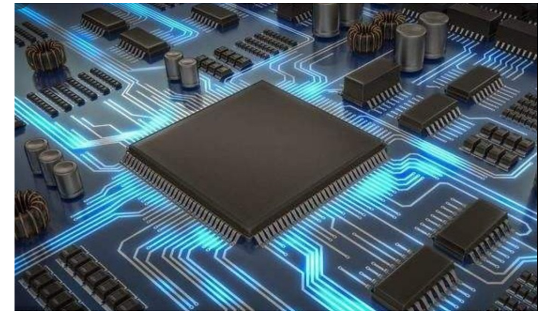
Other applications



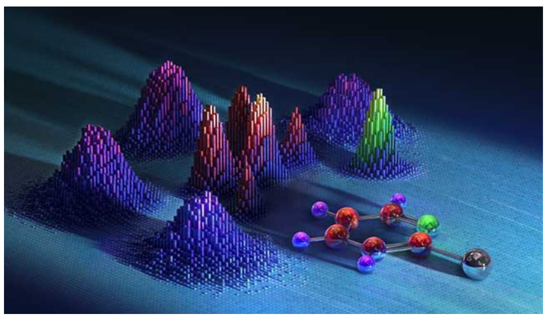
Lidars and Automotive



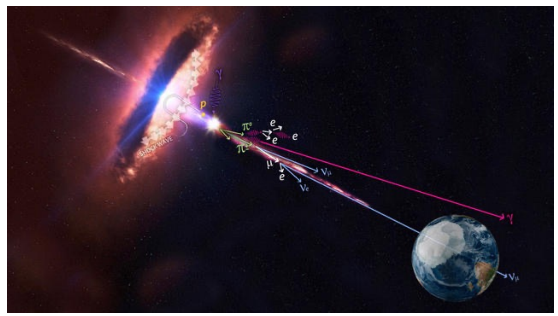
Bio Imaging and Life Science



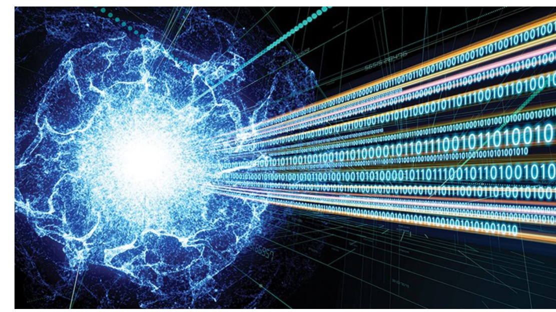
Fast timing applications



Coulomb explosion imaging



Astro-particle physics

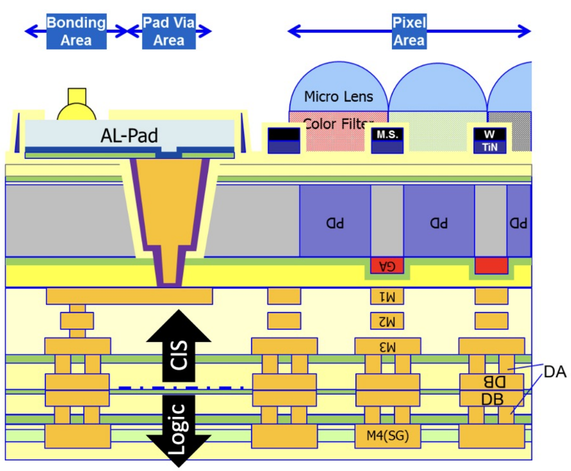


Quantum science and cryptography

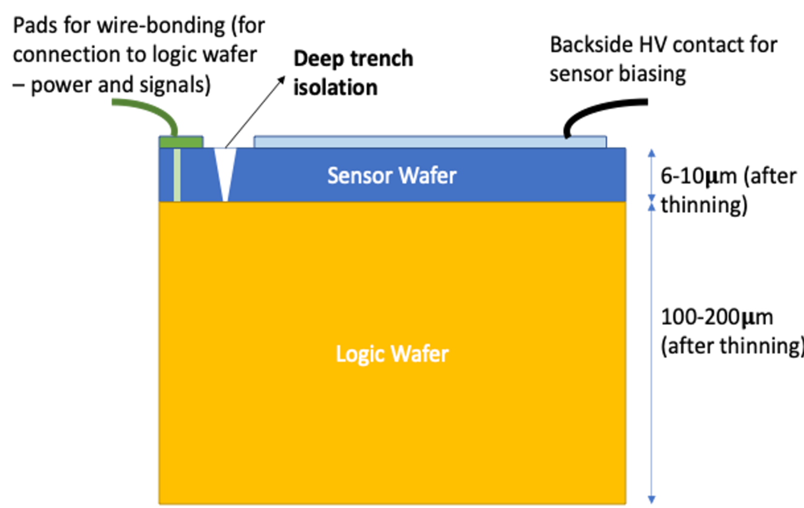
Advanced manufacturing

Development of sensors

- Produce sensors on 12” wafers with a commercial partner
  - Process is a 10 µm epi; 130-150 Ohm-cm resistivity
- We performed simulations to study the feasibility of both gain and timing performance using vendor’s parameters



Our DRM supports down to 2.5um pitch



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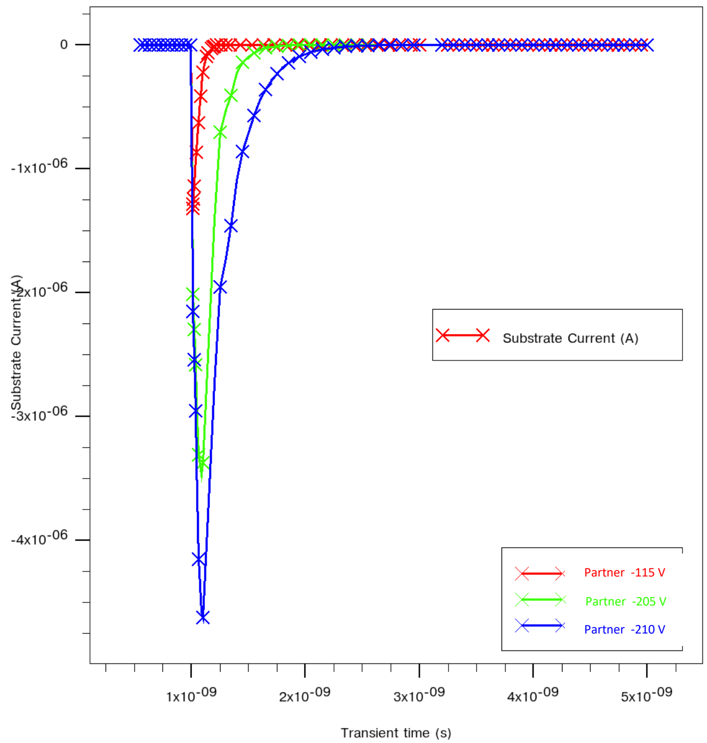
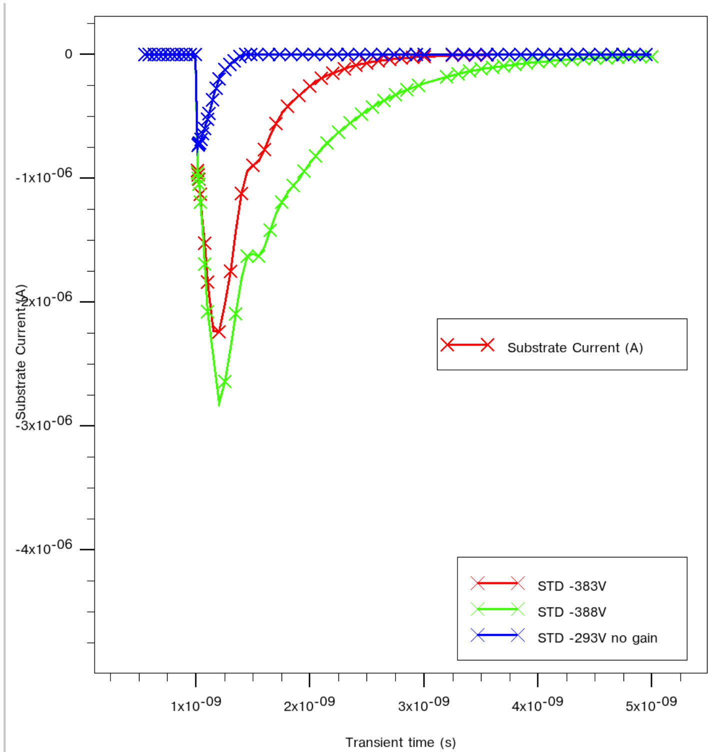
Pulse simulations





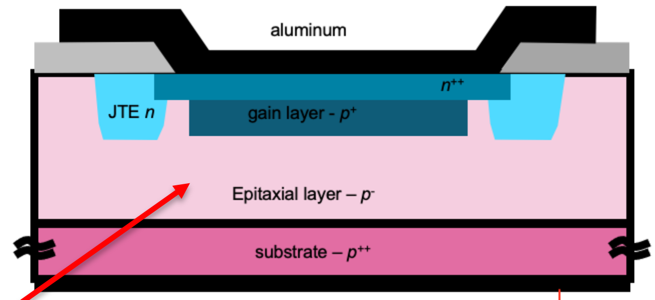
- Simulations of a “standard” LGAD and partner’s 65 nm process.
  - ”Standard” process - 20 µm thick high resistivity
  - “Partner” process - 10 µm thick, moderate resistivity
- Signals from “partner” process are narrower and faster rise time

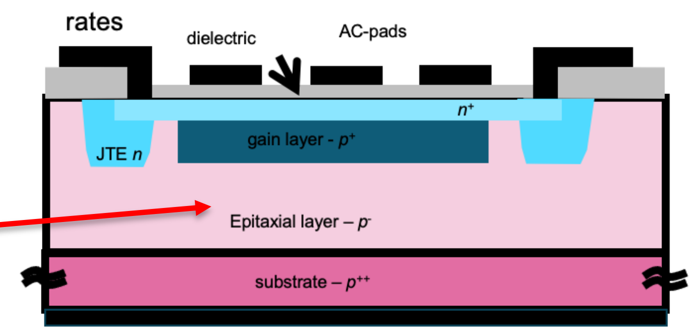
Additional processing

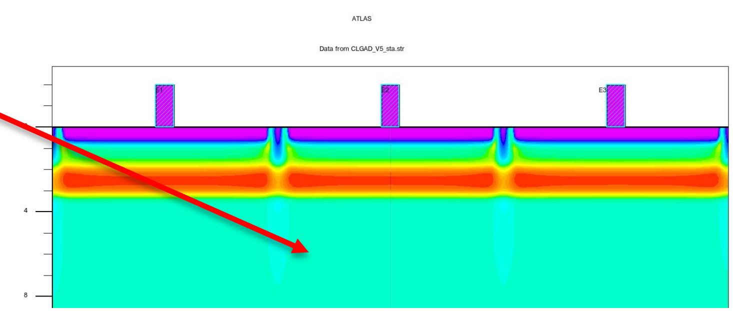
- The basic functionality of the device looks good with 10 µm epitaxy.

- Additional structures to be produced:
  - DC LGAD: ”standard” devices
  - AC LGAD: 100% fill factor, good position resolution
  - Deep junction LGAD: for higher radiation hardness

- Working closely with our partner on the design of sensors

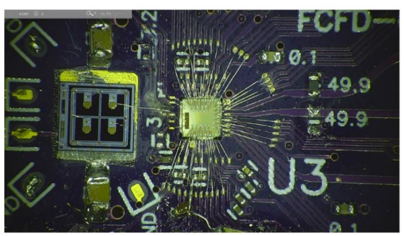






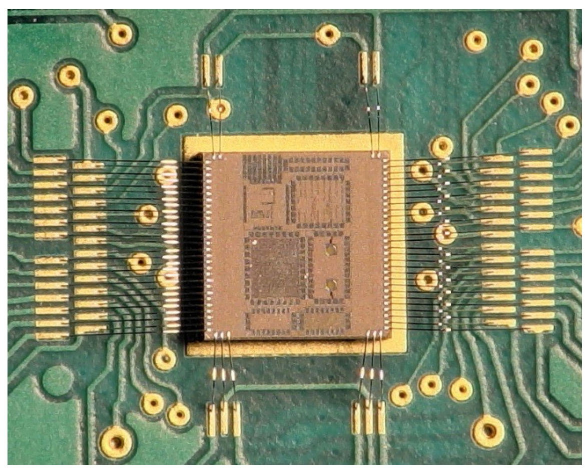
Development of ICs

- During the 1st stage we are working to optimize and produce ASIC prototypes on MPW runs to identify the best solutions
  - **Technology**: the HEP community's choice for the future 28 nm
  - **Low Noise Amplifier**: tuned for capacitances of smaller pixels
  - **Discriminator:** Design simple and robust discriminator for low-power
  - **TDC**: dominant consumer for devices with many small pixels, need innovative solutions

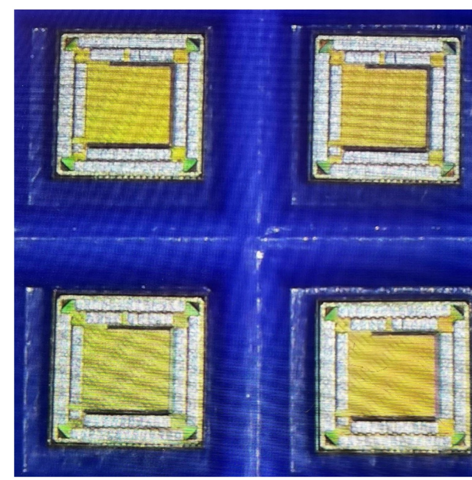


FCFDv0 pre-amp + discriminatorFCFDv0

Multi-channel FCFCv1



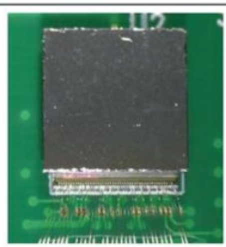
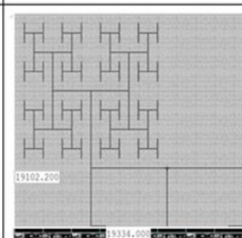
FNAL TDC



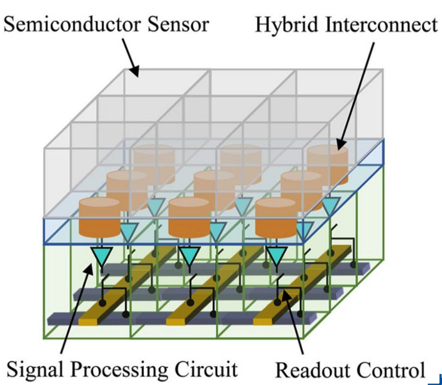
SLAC TDC

Development of ICs

- **Designs for BES applications**
  - The principal difference of applications is a requirement to also measure the deposited energy for soft X-ray imaging
- **Designs for FES applications**
  - Inertial Confinement Fusion (ICF) experiments measure peak plasma burn durations below 100 ps: need to sample with precision ~10 ps
  - X-ray imaging requires full 2D image samples over this burn history

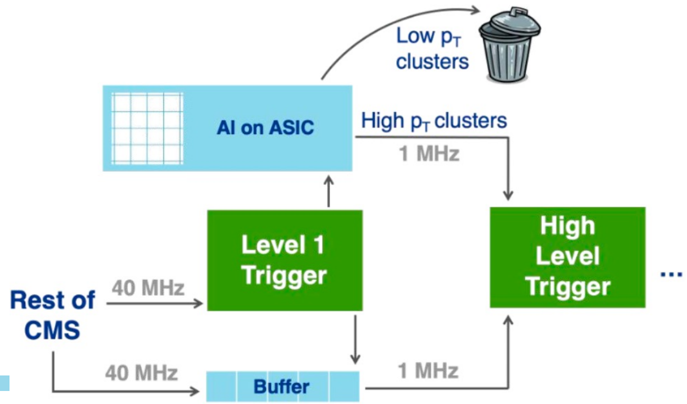
	SparkPix-ED	SparkPix-RT	SparkPix-T	SparkPix-S
Front-end	energy	energy	timing	energy
Information extraction	triggering	data compression	sparse readout	sparse readout
Frame-rate	1 MHz / 100 kHz CW	100 kHz	1 MHz	1 MHz
Picture / Layout				

hCMOS UXI Sensors coupled with LGADs could open up many low energy/low signal high speed imaging applications



Smart Pixels project

- AI embedded on a chip to:
  - Filter data at the source to enable data reduction
  - Take advantage of pixel information to enable new physics measurements and searches
- Data reduction through
  - Filtering through removing low p_T clusters
  - Featurization through converting raw data to physics information
- Combination of approaches can reduce data rate enough to use pixel information at Level 1



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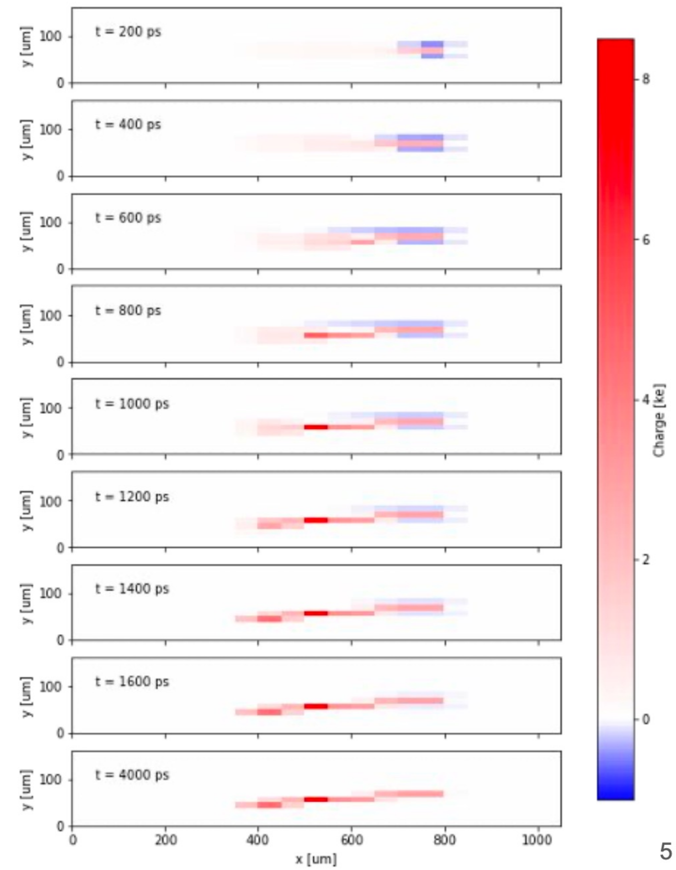
Simulation

- Simulated charge deposition from pions
- Assume a futuristic pixel detector
  - 21x13 array of pixels
  - 50x12.5 µm pitch, 100 µm thickness
  - Located at radius of 30 mm
  - 3.8 T magnetic field
  - Time steps of 200 picoseconds
- Use ML due to complicated pulse shapes, and drift & induced currents
  - y-profile is sensitive particle's p_T
  - x-profile uncorrelated with p_T



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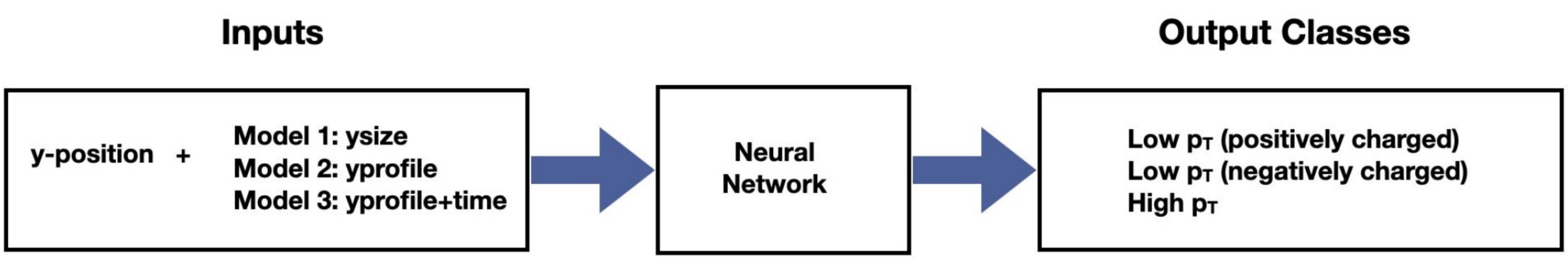
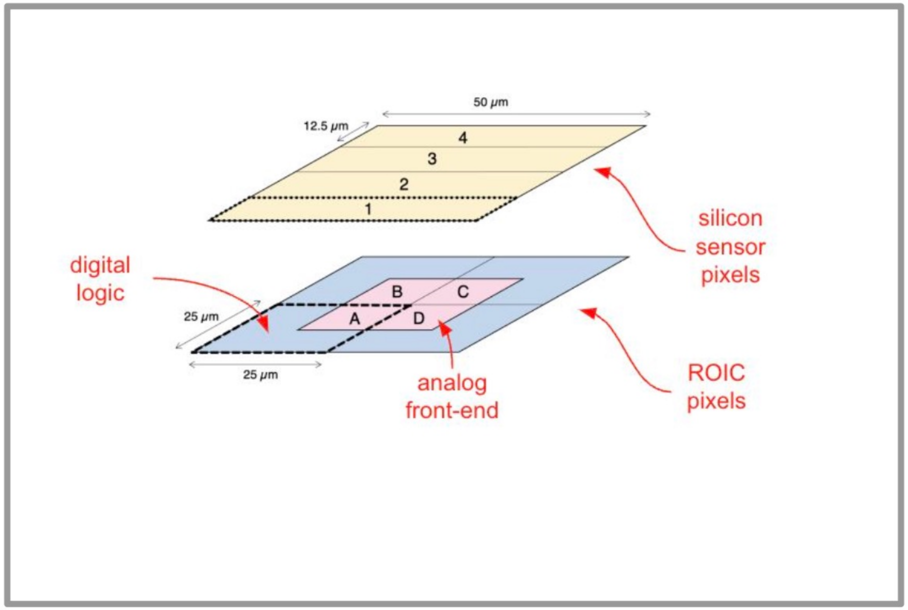
Classification

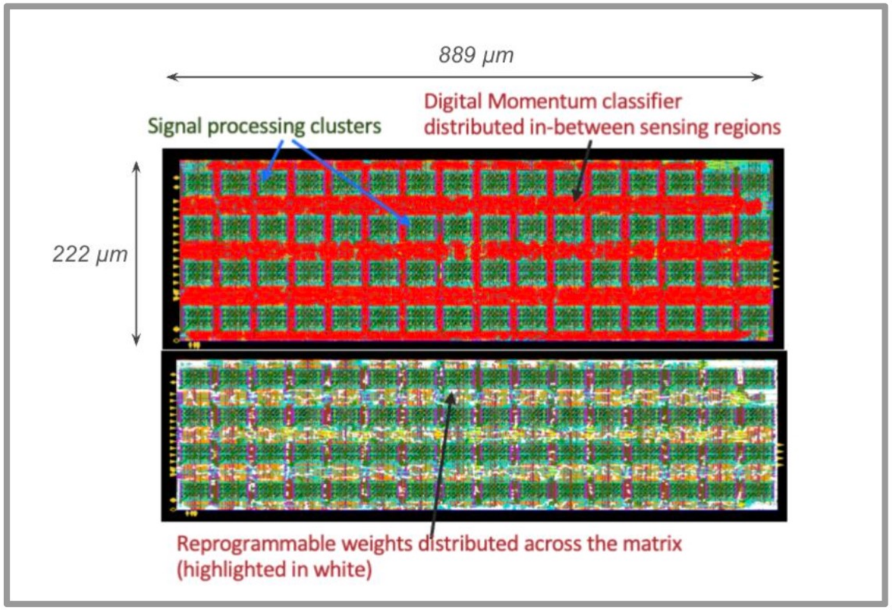
- Classification goals
  - Keep as many high p_T clusters as possible for physics
  - Decrease data bandwidth

- Region specific implementation
  - 13 locally customizable (reprogrammable weights) neural networks implemented directly in the front-end
  - Reconfigurable weights so we can adapt to changing detector conditions



ROIC implementation



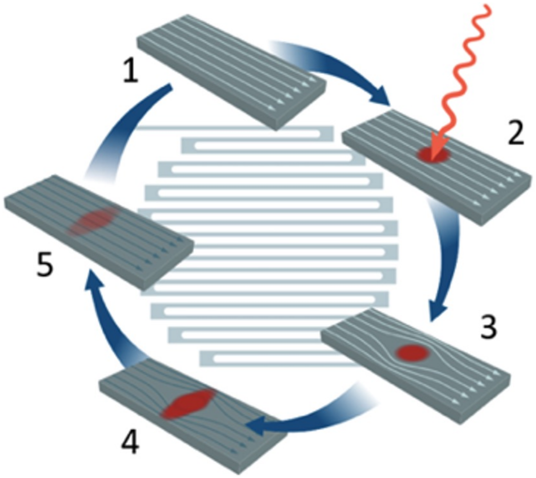


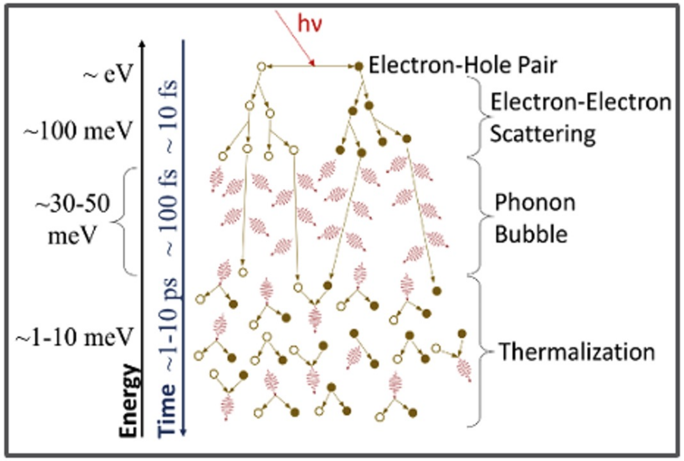
- 4 analog frontends, surrounded by a digital region
- Simulation: 13 x 21; Chip: 16 x 16

- Design expected to operate at < 300 μW
- Area < 0.2mm^2

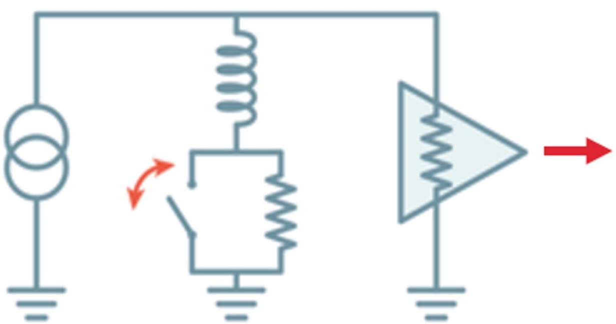
- The second chip has been submitted for tape out and we should get it back around May 20th.

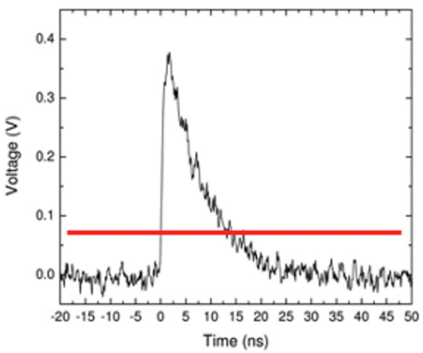
Superconducting Nanowire Single Particle Detector

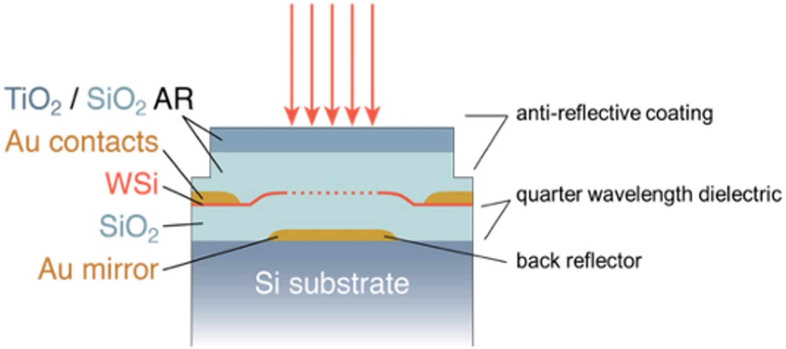




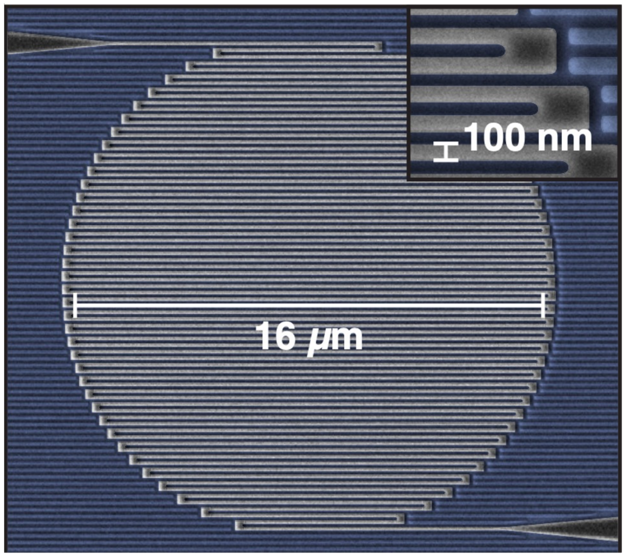
- Time-resolved single photon counting from UV to mid-IR
- Truly digital detection mechanism – reduced drift and zero read noise
- World-leading detector performance
- Operating temperature 1-4 K in most cases





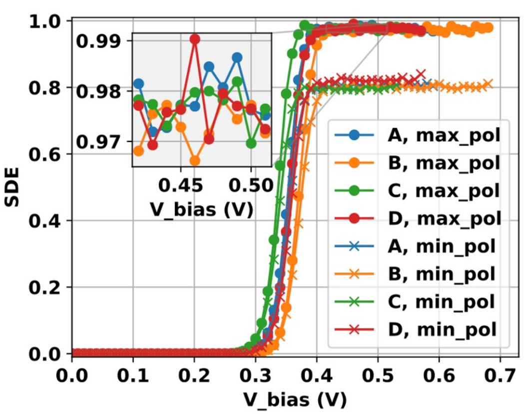


SNSPD Performance Metrics

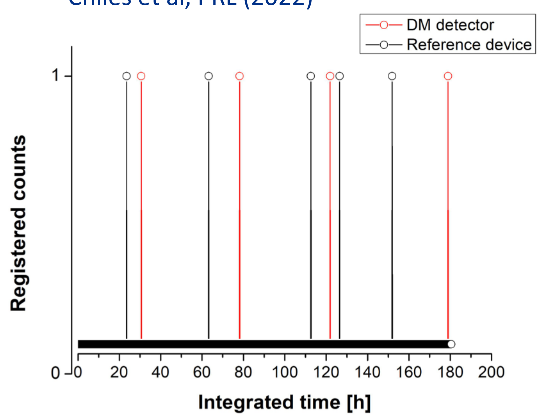


- **[For 1 eV energy deposits]()**
- >90% system efficiency
- Low dark count rate 1e-5Hz
- Record time resolution ~3ps

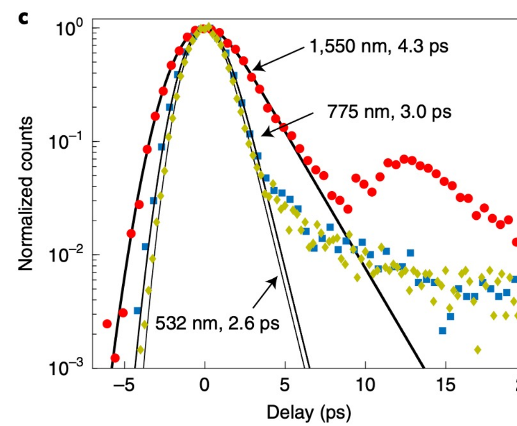
Reddy et al, Optica (2018)



Chiles et al, PRL (2022)

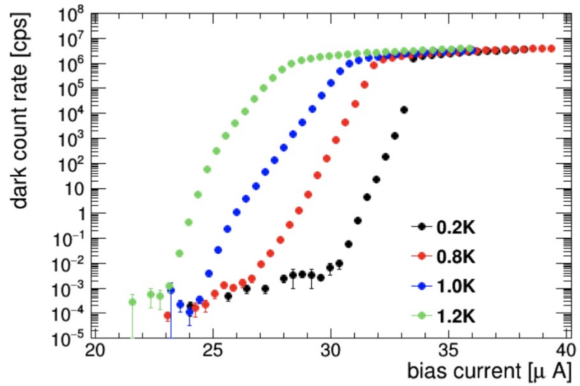


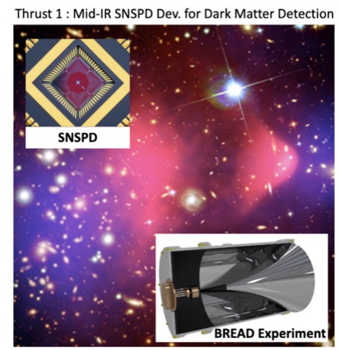
Korzh et al, Nature Photonics (2020)

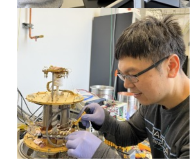


SNSPD Technology for HEP @ Fermilab

- Fermilab has developed and deployed SNSPD sensors for quantum networking and axion experiments (BREAD)







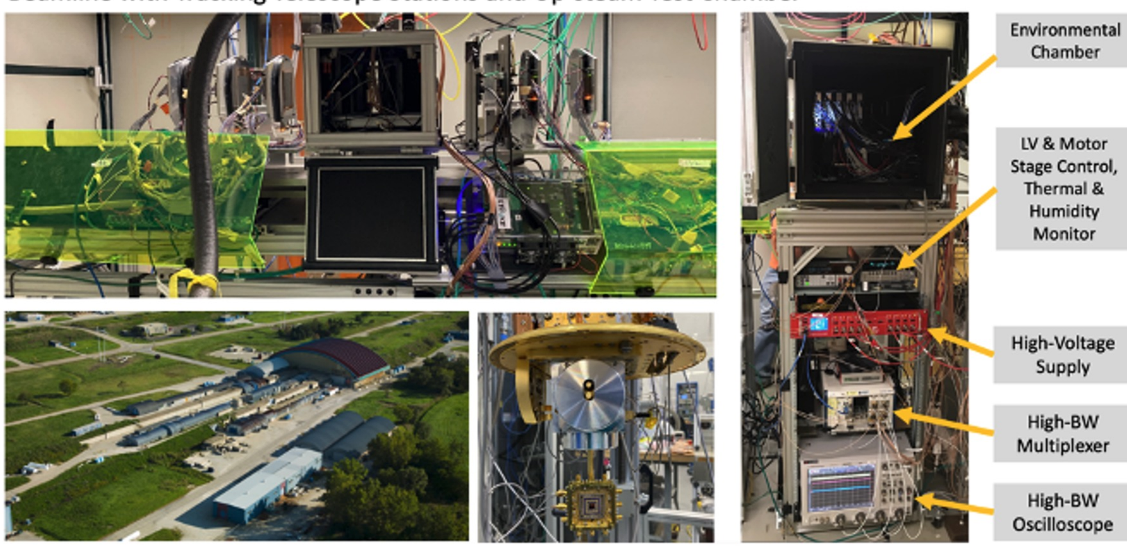
- The unique expertise in SNSPD and test beam operations provide unique platform to push SNSPD R&D for particle detection
- Strong partnership (since 2017) with JPL/MIT/NIST SNSPD group prepares us for fast sensor design-fabrication-deployment cycles

SNSPD for High-Energy Particle Detection

- Overarching goal: be at the forefront of R&D for ultra-low threshold space-time (4D) resolved particle detection

Aspirational Goal : sub-eV threshold, sub-micron spatial resolution, picosecond time resolution

Beamline with Tracking Telescope Stations and Up-steam Test Chamber

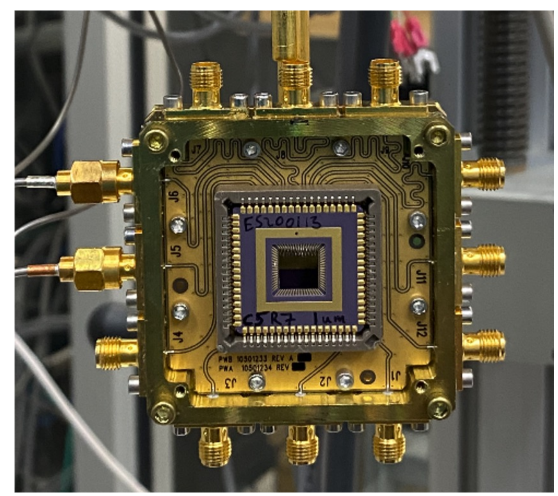


Fermilab Testbeam Facility (FTBF)

SNSPD Testing Station

Down-stream Test Chamber

SNSPD



Summary

- Many exciting R&D areas that promise to enable and enrich the physics potential of the FCC-ee experiments
  - New, disruptive technologies are emerging
- Developments of new technologies that will enable sensitivity to extremely small energy deposits from BSM physics
- Collaborative efforts are a key for the progress in many challenging directions
  - Integration with the ongoing international efforts within DRD and RDC efforts are crucial!