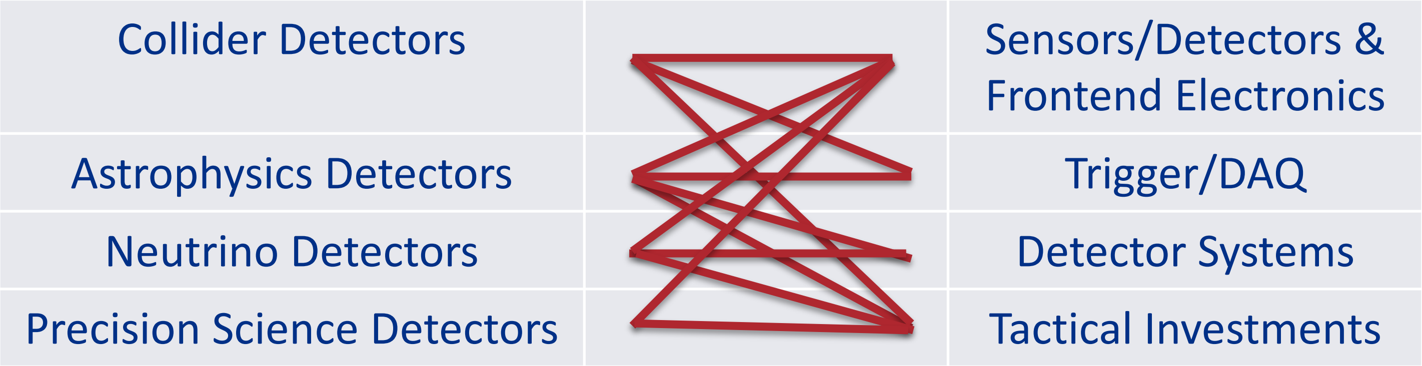
Strategy and Vision of Detector R&D at the Laboratory

Petra Merkel – Fermilab Detector R&D Coordinator

Fermilab PAC Meeting

July 18th 2019

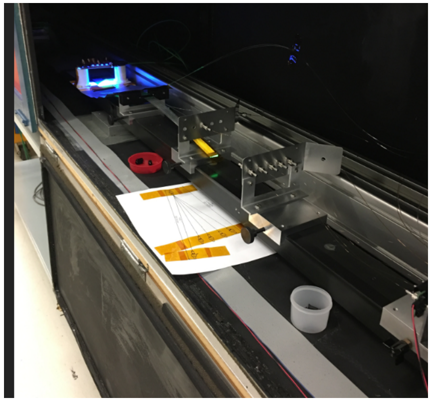
- **Organization:**
  - Detector R&D Coordinator: Petra Merkel
  - Detector Advisory Group: ~15 experts of different detector technologies across the lab, including 2 external advisors
  - Meet bi-weekly to discuss ongoing R&D efforts, new proposals, coordination issues, budget, strategic and tactical investments
  - Detector R&D [website]
- **Detector R&D Thrusts, guided by P5 and CPAD Grand Challenges**

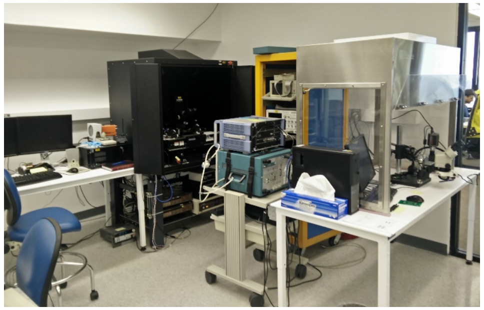


Collider Detectors		Sensors/Detectors & Frontend Electronics
Astrophysics Detectors		Trigger/DAQ
Neutrino Detectors		Detector Systems
Precision Science Detectors		Tactical Investments

- **Need to position ourselves to influence and execute next Snowmass/P5 process**
  - Fermilab Scientific Advisory Council is organizing strategic lab planning process for 2026 and beyond, also for detectors.

Detector Facilities and Infrastructure





- Common Detector Test Facility Systems
  - Silicon Detector Facility
  - Precision Metrology
  - Scintillation Detector Development Facility
  - Thin Film Facility
  - Noble Liquid Detector Development (PAB)
  - Rapid Prototyping and Special Materials
- ASIC Development Facility
- Fermilab Test Beam Facility (FTBF)

Promote and benefit from partnership with universities and other national laboratories. Previous construction projects at Fermilab either created or contributed to these facilities enabling subsequent Projects and research efforts to capitalize on these investments. Current projects and laboratory operations co-fund these facilities.

Collider Detector R&D

Collider Detector Challenges

- **Electron colliders** (e.g. ILC, CLIC, FCC-ee, CepC)
  - High granularity trackers (x20 finer than CMS), with timing stamp and/or high speed readout and ultra low mass (x10/x100 lighter than CMS barrel/endcap
  - High granularity calorimeters (x200 finer than CMS) with timing stamp and/or high speed readout; dual readout
- **Hadron colliders** (e.g. HE-LHC, FCC-hh)
  - High granularity trackers and calorimeters with timing information and fast sensors (x5 HL-LHC PU)
  - Radiation hard sensors and frontend electronics (x30 HL-LHC fluence)
  - Electronics, trigger systems and high-speed links to accommodate high particle rates (x4 HL-LHC)
- **Muon collider**
  - Huge background from muon decays from beam: requirements similar to electron machine detectors, but even smaller pixel sizes (20μm) and fast sensors (50ps) needed everywhere

R&D Needs – Collider Detectors

- CMOS silicon sensor R&D: Can provide very precise spatial and timing resolution, a low material budget as well as high radiation tolerance while maintaining a reasonable production and cost effort. CMOS Monolithic Active Pixel Sensors (MAPS) combine the sensing part and the readout circuitry in one layer. With this, the production effort, costs and material budget can be significantly reduced.
- Hybrid pixel detector R&D: For very high radiation environment, e.g. 3D sensors, active edge planar sensors, spatial and time information, e.g. deep trench electrodes: need specialized ASICs (deep-deca nanometer technologies) and need to solve interconnection issues (DBI, TSV).
- Ultra-small pixel R&D: Very small pixel size (25mm) on thick (200mm) sensors can deliver track angle within single sensor and fast timing information; needs fast, smart 3D integrated electronic.
- Ultra-fast silicon R&D: Need R&D to increase fill factor and radiation hardness of gain layer.
- Picosecond-level system design R&D: Readout ASICs, clock distribution, electronics jitter, module design, cooling.
- Alternative semiconductor material R&D: e.g. graphene for large-scale, ultra-low mass tracking systems.

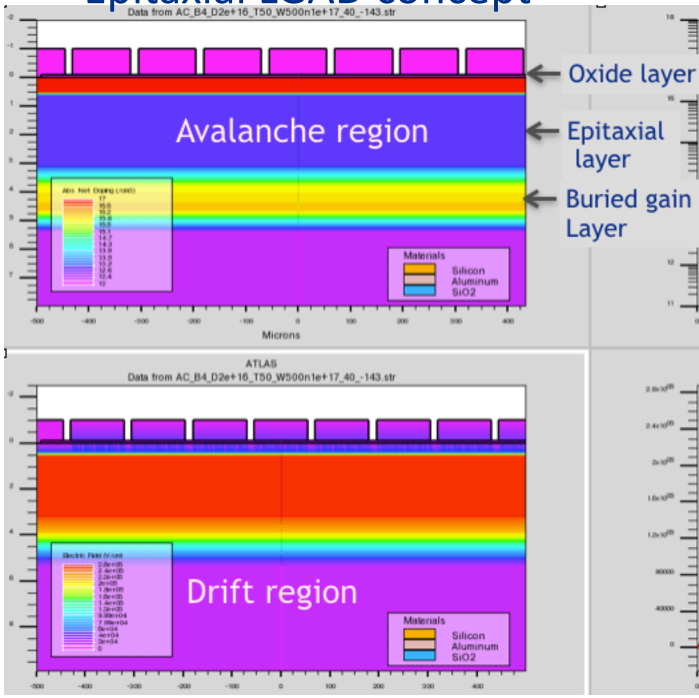
R&D Needs – Collider Detectors

- Large-area silicon arrays for calorimetry: packaging, cooling, large fill factors, radiation hardness, readout speed
- Crystal R&D for calorimetry: radiation hardness, segmentation, light yield, photo detection
- Plastic scintillator R&D for calorimetry: radiation hardness through doping (3D printed, injection molded, co-extruded); explore new materials such as polysiloxanes.
- Semiconductor scintillator R&D: e.g. quantum dots for fast light read out, low mass, radiation hardness
- SiPMs on scintillator tiles or strips: coating, wrapping, automated assembly
- Segmented gas amplification structures: e.g. MicroMegas
- High-granularity Noble Liquid calorimeter R&D: (e.g. LAr) for radiation hardness
- High-speed readout links

Silicon R&D

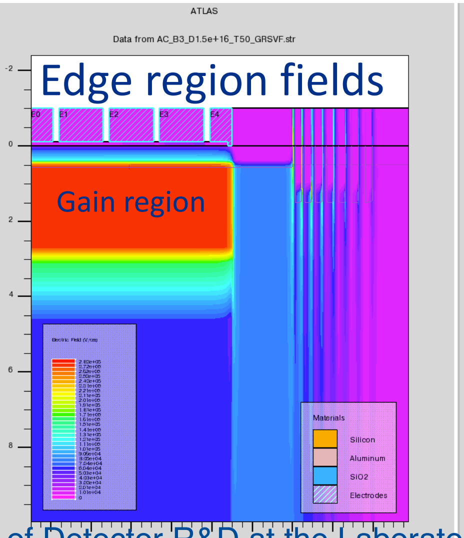
- Our work has been focused on development of sensors and sensor/electronics integration
- Working on solving problems with current LGADs by improving fill factor and increasing radiation hardness
- AC LGAD concept (UCSC and BNL) eliminates dead regions between pixels
- Buried epitaxial layer improves radiation hardness and increases design margins

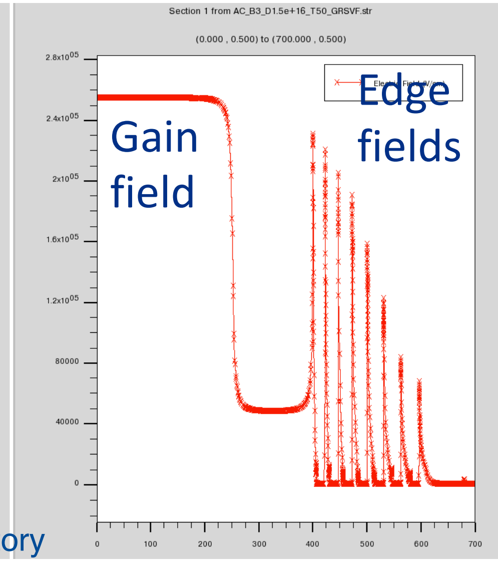
Epitaxial LGAD concept



Development Plan

- Year 1,2 - develop epitaxial engineered substrate (SBIR) and demonstrate concept
- Year 3,4 – fabricate optimized LGADS
- Year 5 – Fabricate production devices

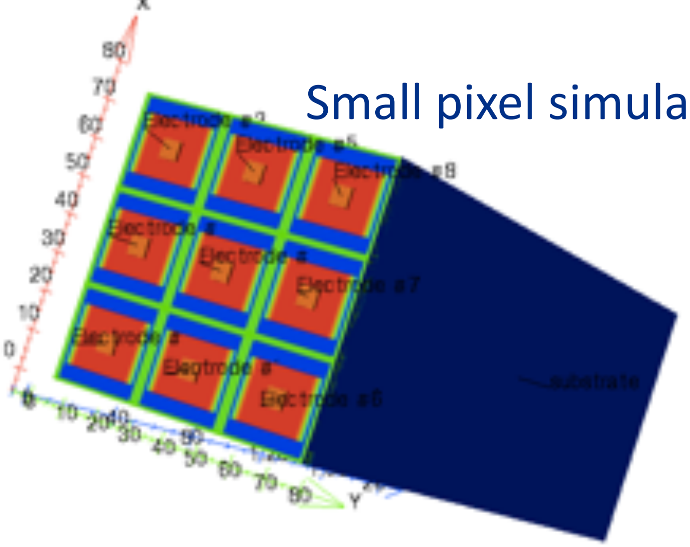




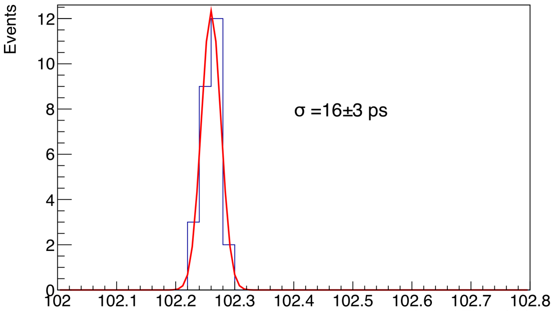
Silicon R&D

Multi-tier 3D integrated systems of readout electronics and small (<25 micron pixels)

- Can integrate ps timing, pattern recognition, and momentum reconstruction on a single detector with a sensor, analog, and digital tier
- Use full current pulse information in a highly integrated detector/readout. Digital tier combines pixel information and provides signal/background discrimination
- Builds on our pioneering work on 3D

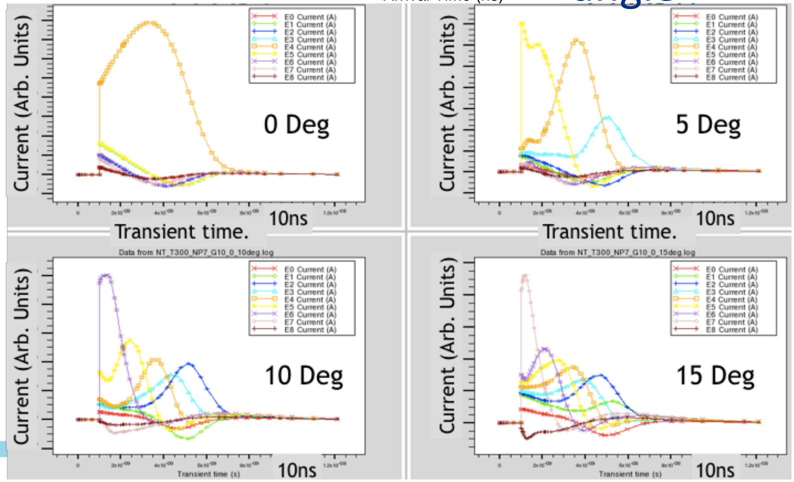


Small pixel simulation



Timing resolution

Pulse shape vs angle



Development Plan

- Years 1-2 – Develop 3D technology (with MIT-LL), simulate full analog system
- Year 3 – build two-tier prototypes
- Year 4 – Develop digital tier
- Year 5 – build demonstration chip

ASIC R&D

- **Radiation hard design:**
  - **SEE/SEU tests** in advanced process nodes 65nm and 28/22nm. Following development of SEE/SEU mitigation techniques and SPICE-type/timing-libraries for 100, 200 and 500 Mrad irradiation levels
  - **Rad-hard processors**, e.g. RISC processor for application in controlled radiation environment, e.g. magnet controls

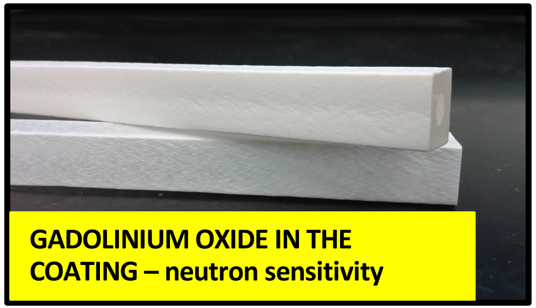
- **High density wafer-to-wafer interconnects:**
  - Enabling next generation Scientific Instruments for HEP and BES including development of process technology with MIT-LL and testing 3D-integrated test structures

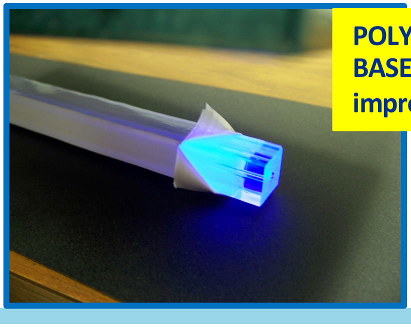
- **Deep deca-nanometer technologies:**
  - 28/22nm CMOS for future applications at room and cryogenic temperatures

Scintillator R&D

Scintillator extrusions are used for many Fermilab experiments. Minerva, Mu2e, providing large mass / cross section for detection of rare processes.

- **Important extrusion R&D issues:**
  - **Light yield studies:** Improve scintillator and wrapper, with potential to increase LY by factor two or more
  - **Timing:** How to improve timing. More light yield, faster wavelength shifter to shorten light pulse, increase photons/ns impacting photodetector.
  - **Cryogenic scintillators:** Cryogenic detectors are increasingly important for FNAL physics program. Need fundamental research of scintillators and wavelength shifters at low temperature.
- **New materials:** produce structured scintillators by 3-D printing different materials. Study possibility of use in special purpose detectors like n-detectors. Investigate nanoparticles (quantum dots) in semiconductors for potential use as specialty scintillators.


GADOLINIUM OXIDE IN THE COATING – neutron sensitivity


POLYETHYLENE-BASED COATINGS – improve light yield

Scintillator R&D

- **Injection Molding R&D:**
  - Fermilab has had very successful program in extrusion of many 100 tons of scintillator for a number of experiments
  - Injection molding allows for different geometries. In particular pixilation.
  - With advent of SiPMs, pixelated scintillator calorimeters become possible. Suitable for high rate experiments like fixed target or collider experiments.
  - Perform studies of scintillator chemistry suitable for injection molding process.
  - Fermilab ideally suited with in-house expertise and scintillator chemistry laboratory

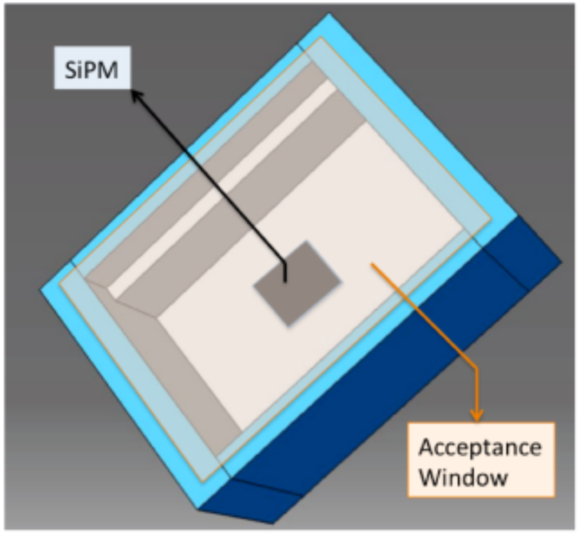
New Addition to Lab 5 Facility (with NIU): 4.6 oz Injection Molding Machine. Suitable for making scintillator tiles large enough for CMS, CALICE

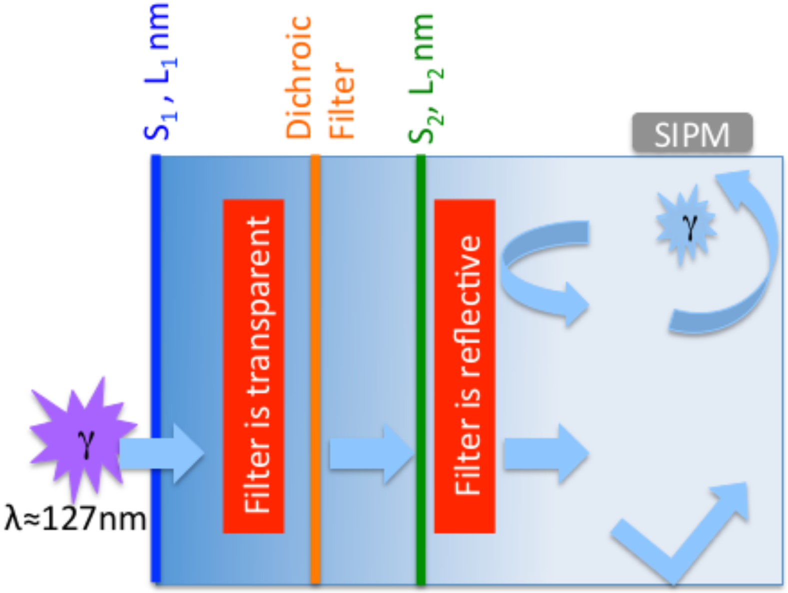

Wrapped scintillator tile

Thin Film R&D

Thin films are critical for new detector technologies (e.g. ARAPUCA, LAPPD, Ultra Cold Neutron detection)

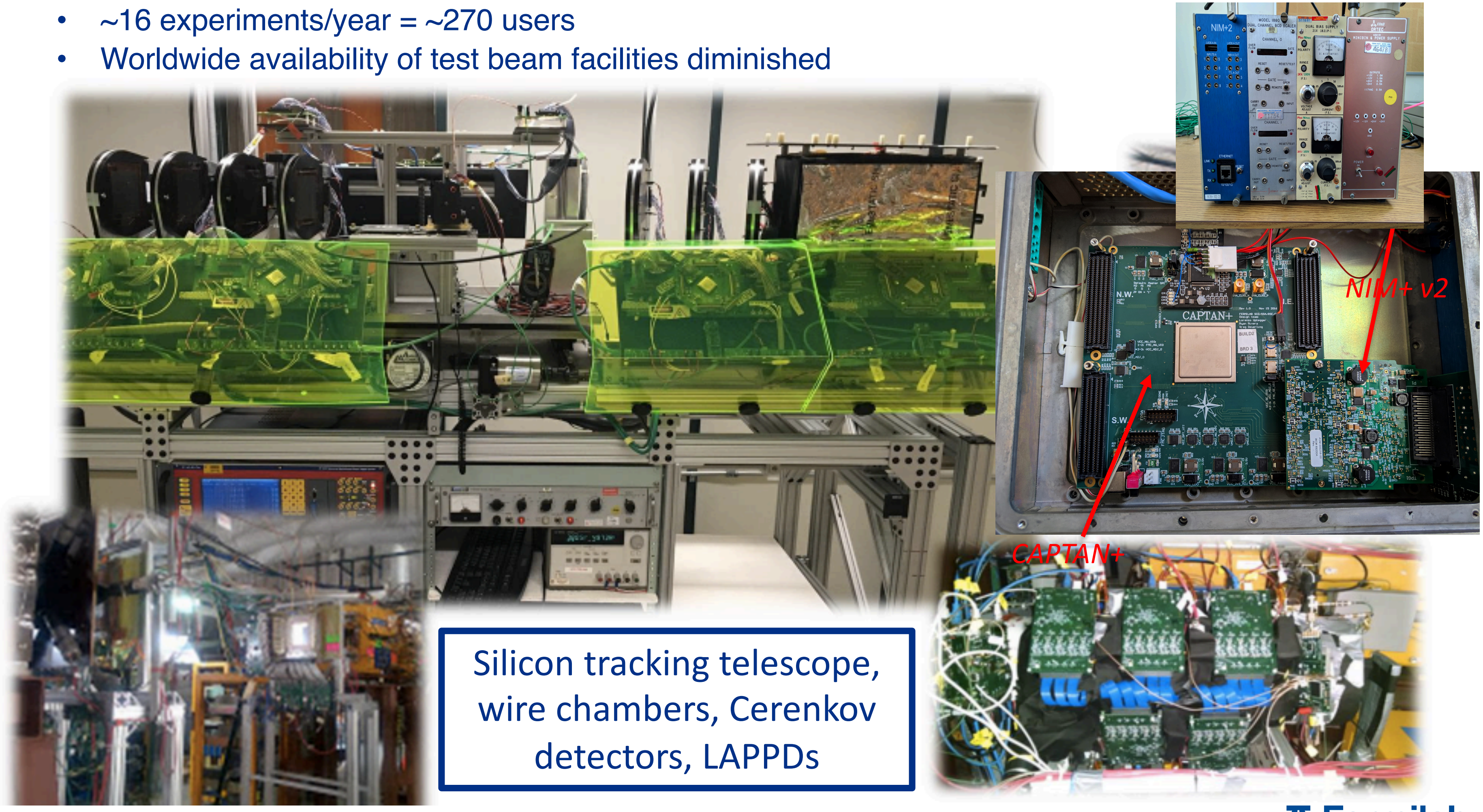
- ARAPUCA (for DUNE): improve light yield for LAr scintillation light compared to traditional WLS+PMT or lightguide bars
- Deposit organic WLS films onto substrate (Tetra-Phenyl-Butadiene, P-Terphenyl as examples)
- Issues are controlled thickness and uniformity of surface. Surface quality measurement and rapid turn-around measurements at cryogenic temperatures are important.





DAQ for Detector R&D

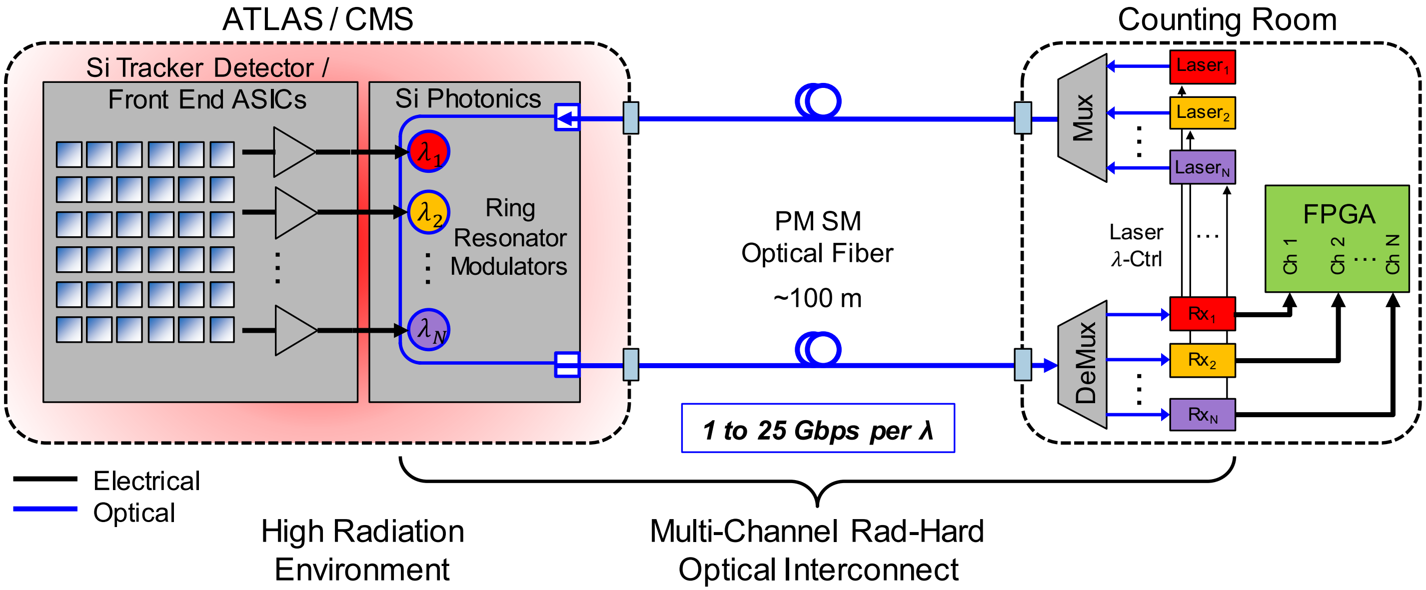
- We provide modern DAQ in support of detector R&D
- Commissioning of a standard readout solution with *otsdaq* at the Fermilab Test Beam Facility
  - FTBF at capacity over last years; crucial facility for collider and neutrino communities
  - ~16 experiments/year = ~270 users
  - Worldwide availability of test beam facilities diminished



Silicon tracking telescope, wire chambers, Cerenkov detectors, LAPPDs

High Speed Optical Links R&D

- Need fast (Gbps), rad-hard, low mass data links
- Use electrical links in highest radiation areas
- Optical links outside
- Need large multiplexing



ATLAS / CMS

Si Tracker Detector / Front End ASICs

Si Photonics

Ring Resonator Modulators

λ_1 λ_2 λ_N

PM SM Optical Fiber

~100 m

1 to 25 Gbps per λ

Counting Room

Mux

DeMux

Laser_1 Laser_2 Laser_N

Laser λ-Ctrl

Rx_1 Rx_2 Rx_N

FPGA

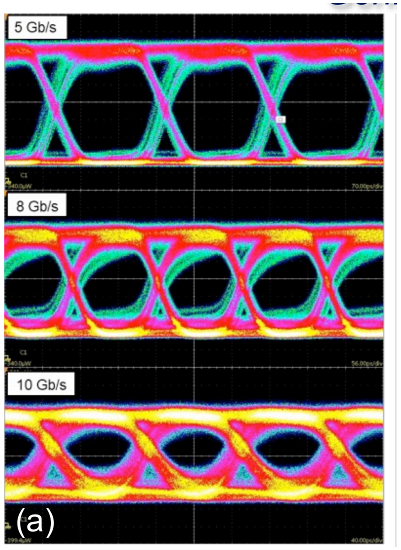
Ch 1 Ch 2 … Ch N

Electrical

Optical

High Radiation Environment

Multi-Channel Rad-Hard Optical Interconnect



Schematic of proposed multi-channel, rad-hard, optical interconnect, utilizing serially coupled Si RRMs on a single chip to interface with HEP detectors, while lasers, receivers and corresponding electronic circuitry remain in the counting room.

Astrophysics Detector R&D

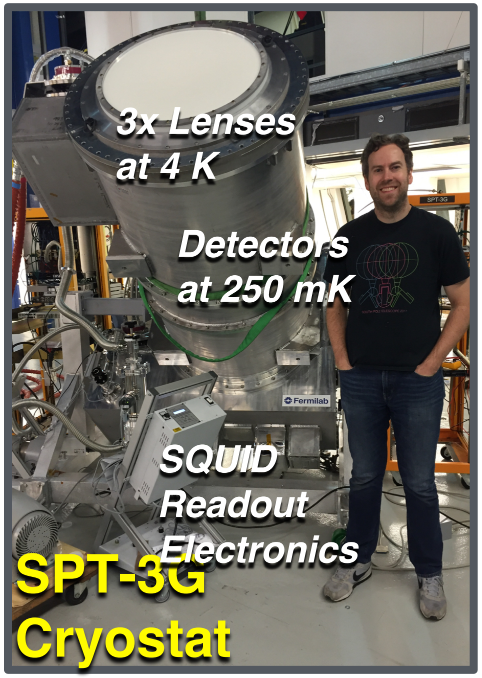
Astrophysics Detector Challenges

- **CMB** (e.g. CMB-S4 and beyond)
  - Scale by more than order of magnitude the number of detectors in receiver.
  - Improve receivers and packaging.
  - New sensors.
- **Dark matter** (e.g. axions, sub-GeV DM)
  - Axions will create a photon in magnetic field, and these need to be collected, detected and readout.
  - Lower threshold sensors and readout.
- **Cosmic surveys** (e.g Stage V Dark Energy spectroscopic survey).
  - More channels than DESI, more efficiency (higher signal to noise).
  - New sensors with lower noise, going further into the IR.
  - Higher density fiber positioners.

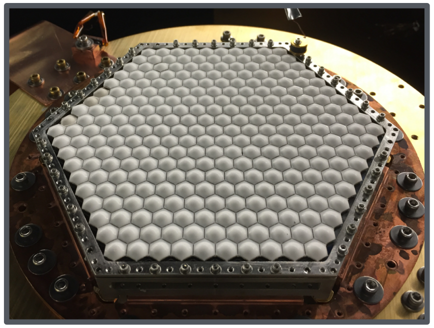
R&D Needs – Astrophysics Detectors

- CMB sensor packaging and characterization
- Readout electronics for superconducting detectors
- Single-photon detectors, e.g. TES, KIDs, SNSPDs (below IR)
- Photon concentrators for axions
- Cryogenic bolometers
- Low-noise silicon detectors (CCD-in-CMOS skipper)
- Multi-fiber positioner
- Ge-CCD

CMB Experiments



SPT-3G Cryostat



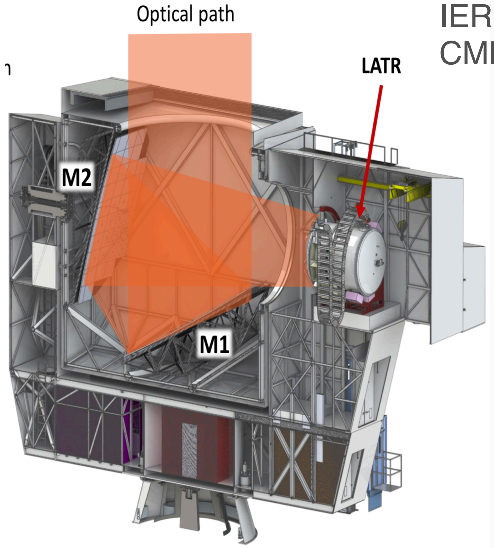
SPT-3G Detector Module

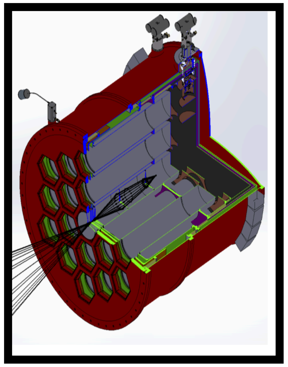
SPT-3G Focal Plane Assembly

Future: CMB-S4.

~500,000 detectors

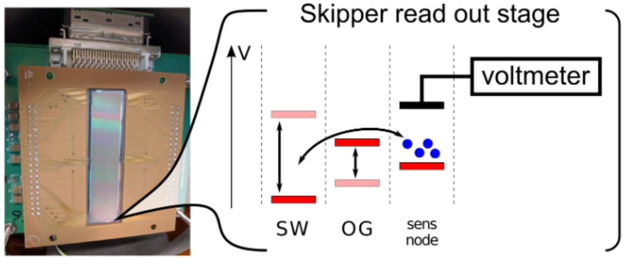
- **Detector module packaging**:
  - Experience from CDF, D0, CMS, DES, DESI, SPT-3G.
- **Detector testing and characterization**:
  - Experience from DES, SPT-3G, DESI. Leverage sub-Kelvin test-beds built for SPT-3G detector & readout development; cryo facilities in IERC; synergy with Quantum (similar technology and infrastructure).
- **Cryostat Integration:**
  - Experience with DES, SuperCDMS, SPT-3G. IERC will include lab for integration of largest CMB-S4 cryostats.

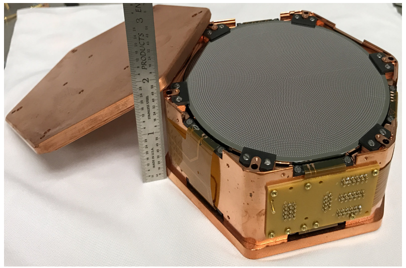




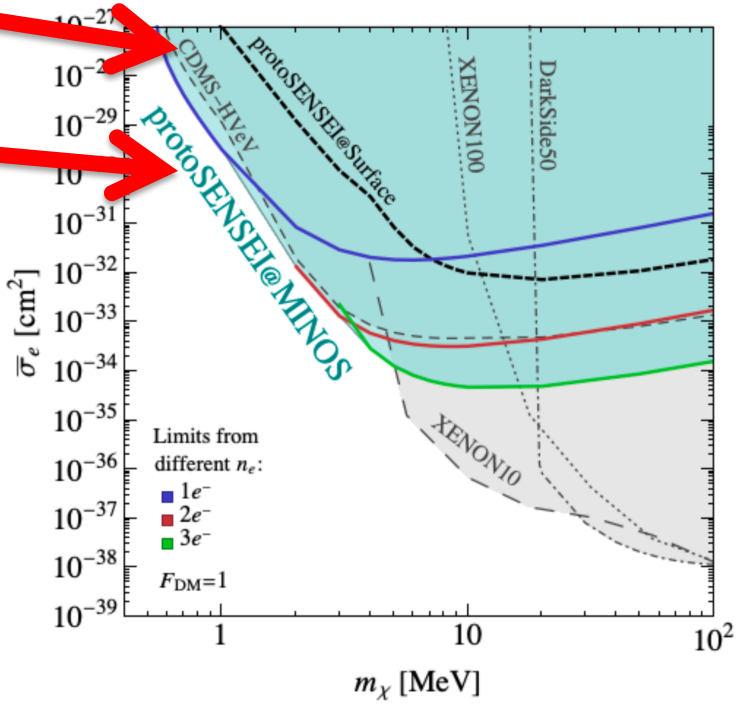
Sub-GeV Dark Matter R&D

- SuperCDMS: R&D on HVeV detectors with NEXUS (underground cryogenic cleanroom in NuMI tunnel).
- Skipper-CCD technology R&D for DM (SENSEI) and neutrinos; strong collaboration with LBNL Microsystems Lab; supported by Heising-Simons, ECA, LDRD, QuantiSED.
- Skipper and HVeV detectors have potential for factor of ~10^7 sensitivity improvement at SNOLAB with 1 kg-year background-free





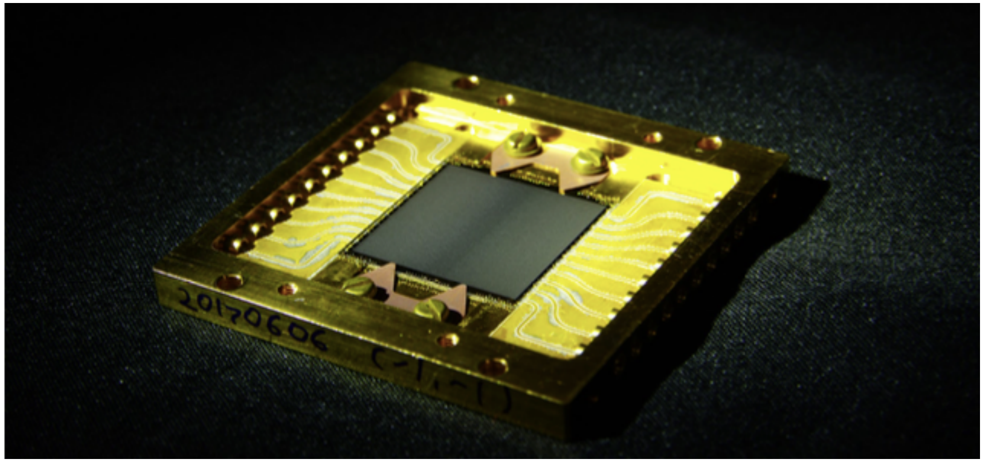
arXiv:1901.10478

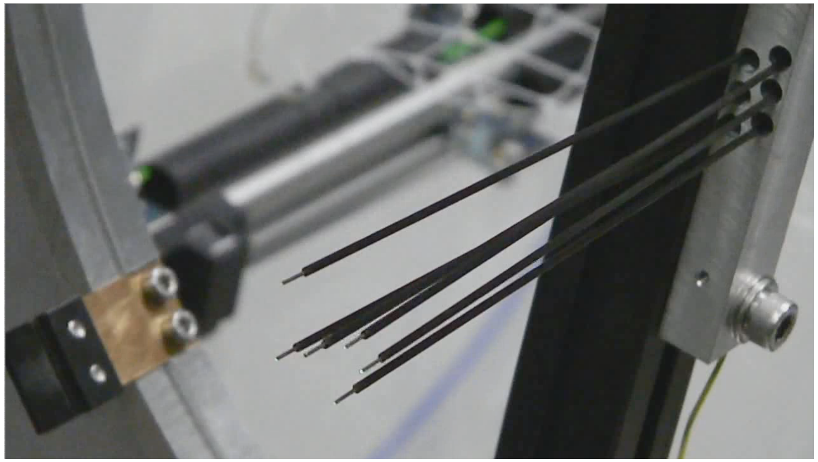


New SENSEI result - world's best limit for dark matter scattering on electrons. These experiments making rapid progress.

Cosmic Survey R&D

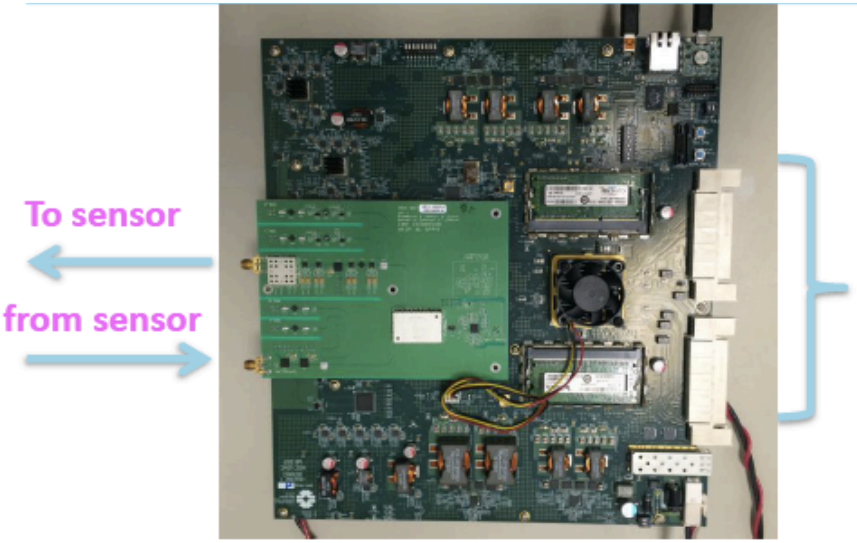
- R&D targeting next-generation, wide-area spectroscopic survey to enhance dark energy science reach of LSST (LDRD)
  - MKIDs – Low-resolution, time-resolved spectroscopy over the entire sky
  - Skipper CCDs – Low readout noise to increase sensitivity to faint systems
  - Fiber positioners – Decrease fiber separation (~5mm) to achieve dense packing & large multiplexing
- P5 and Cosmic Visions - Dark Energy reports called out need for such R&D





Readout Electronics: fMESSI

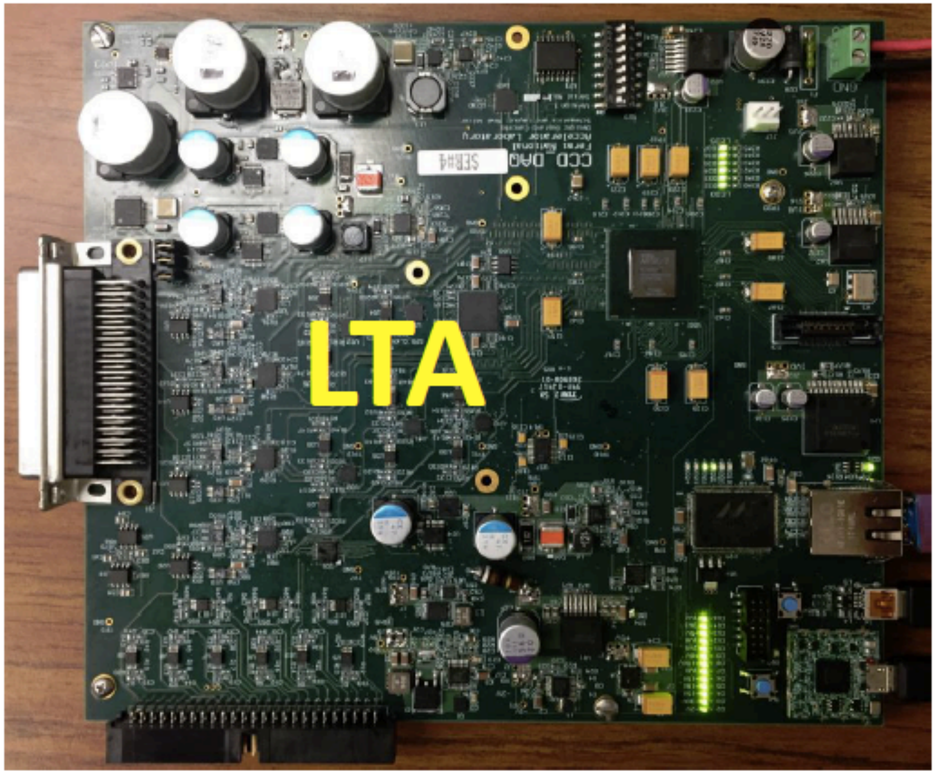
(Frequency Multiplexed Electronics for Superconducting Sensor Instrumentation)

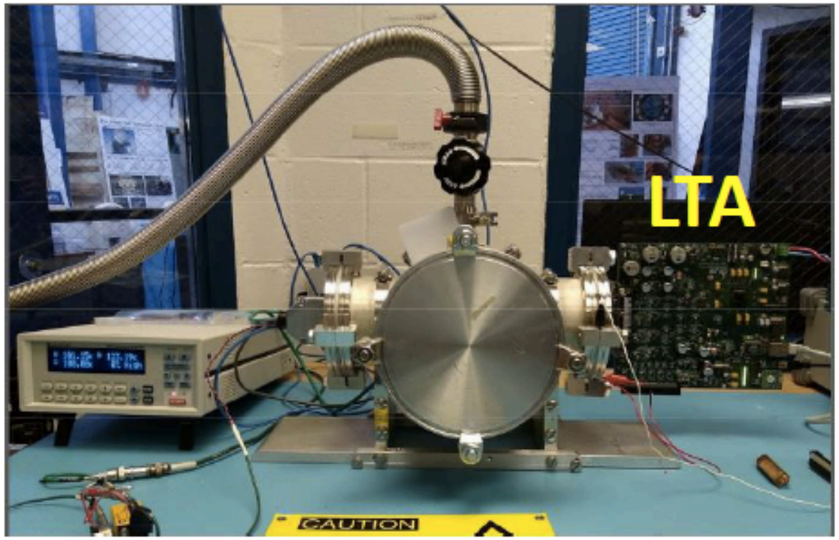



On-sky, July 23 2016

fMESSI has been on the sky since 2016.
10k and 20k resonator instruments at Palomar and 8m-Subaru telescopes taking science images.

Readout Electronics:
Low Threshold Architecture (LTA) for Skipper CCD Readout





- Single sample 1.3 e-1 noise achieved (lowest for any CCD readout system at Fermilab)
- LTA has replaced all previous CCD readout systems at SiDet
- It has been officially adopted for all current and new experiments using skipper CCDs
- New version LTA-QSM being fabricated

Neutrino Detector R&D

Neutrino Detector Challenges

- **DUNE**
  - Measurement of hadrons in the decay pipe through transition radiation requires pure X-ray detectors and rad hard magnets.
  - Pile-up of ν interactions at the near site with long drift times in LAr-TPC's.
  - Charge separation and momentum measurement requires very intense magnetic field (> 1 T) on large volumes.
  - Increase photo-coverage and scintillation light yield.
  - High-speed data links to increase throughput and allow for continuous readout (for example for Supernova neutrino applications)

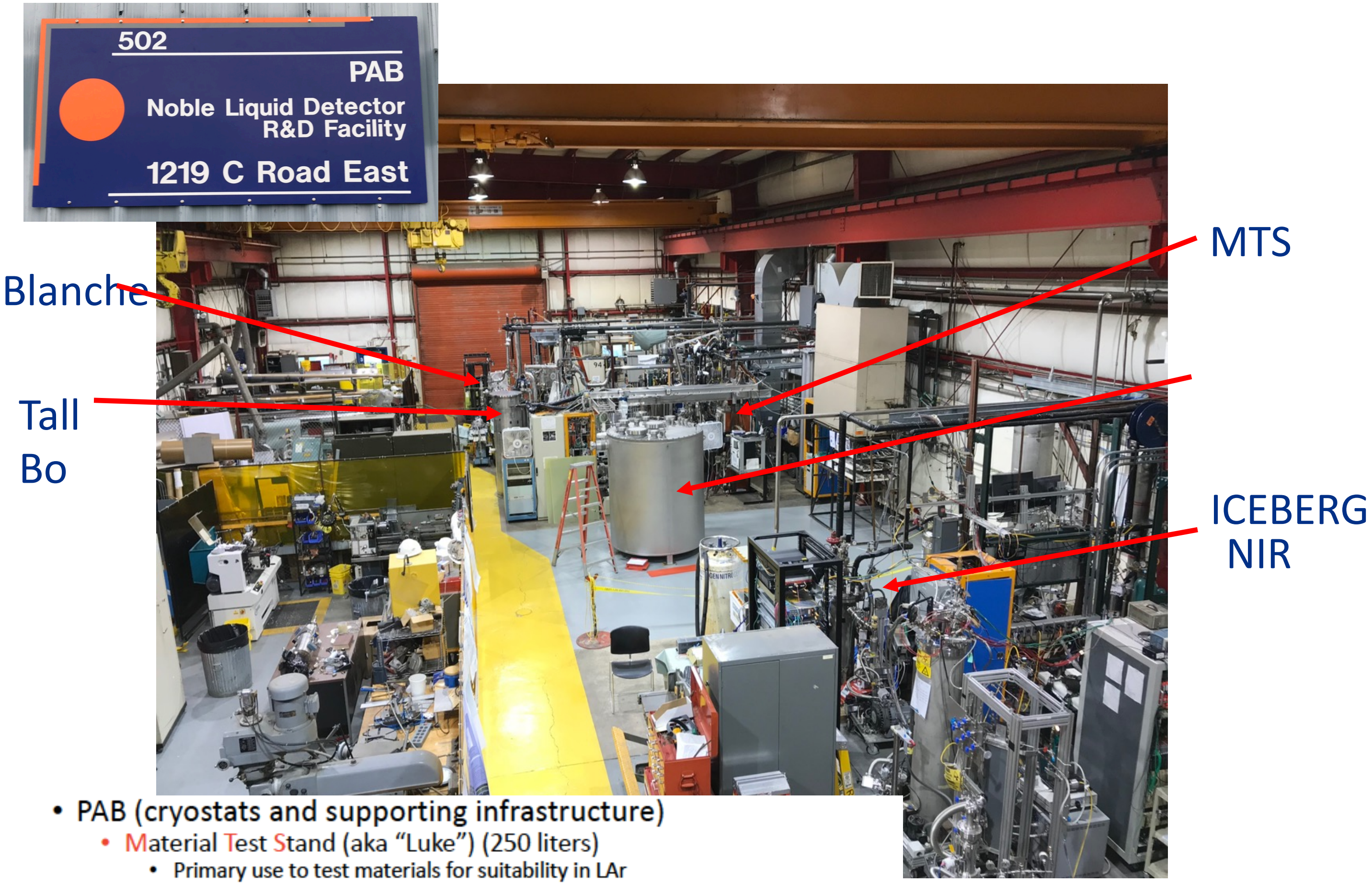
- **ν_τ oscillation experiment**
  - Tracker with 10's of microns resolution and automated readout.
  - Large mass totally active.

- **Low energy neutrino interaction** (e.g coherent scattering).
  - In order to detect nuclear recoils in liquid noble TPC through ionization charge, signal to noise needs improvement by 2 orders of magnitude.

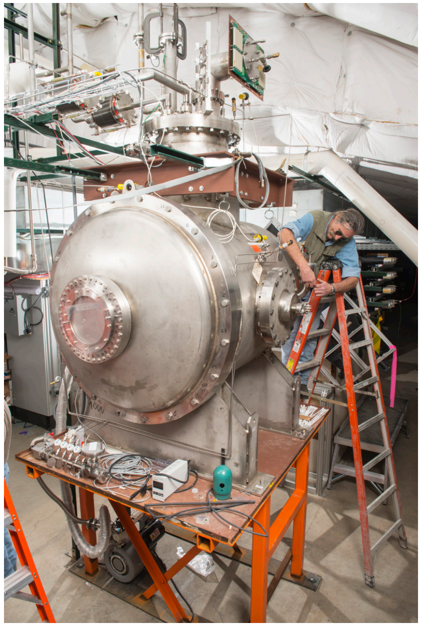
R&D Needs – Neutrino Detectors

- Transition radiation detectors
- High pressure gas argon TPC
- Magnetization of LAr detectors
- Improve scintillation light detection in liquid argon (e.g: IR, Xe doping)
- HV feedthroughs for LAr
- Totally active large mass high resolution tracker
- Amplification of ionization electrons in liquid argon

Existing Infrastructure for LAr R&D



LAriAT Cryostat at FTBF



- PAB (cryostats and supporting infrastructure)
  - Material Test Stand (aka “Luke”) (250 liters)
    - Primary use to test materials for suitability in LAr
  - Tall Bo (450 liters)
    - Primary PD studies
  - Blanche (500 liters)
    - Primary HV studies
  - ICEBERG (3000 liters - 4.2 tons LAr)
    - Primary Cold Electronics
  - NIR (Near Infra Red)—Photon Detector
  - Some modest infrastructure & space for Dark Matter R&D (not funds)

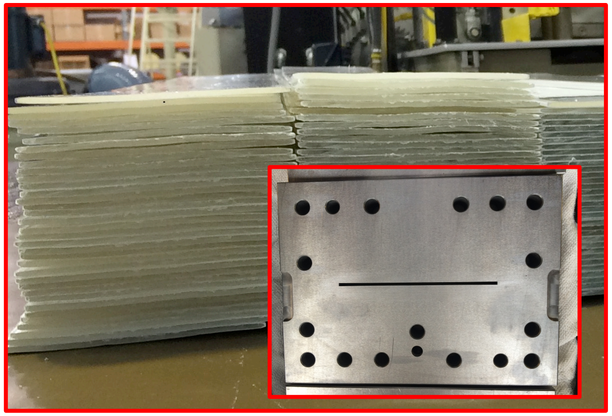
- LArIAT
  - 200 liter Cryostat in MC7 in FTBF
- PC4
  - Liquid Argon Purity Demonstrator (LAPD) (21k liters--~ 30 tons)
  - 35 Ton Prototype (25k liters)

Photo Detection R&D

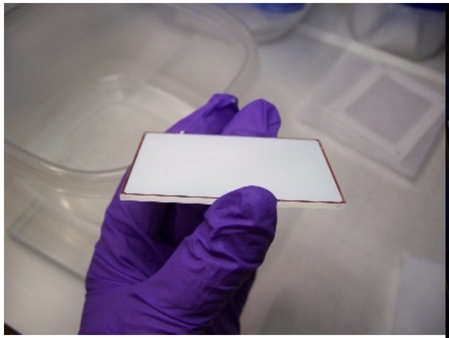
- Photo detection in LAr: big ongoing area of R&D; very low efficiencies at LAr scintillation wavelenegth
- Various technologies still being investigated
- Leveraging Fermilab’s extrusion and thin film capabilities

Use UV-transmitting acrylic pellets to test extrusion into plates as replacement for wavelength shifting plates currently used in ProtoDUNE.

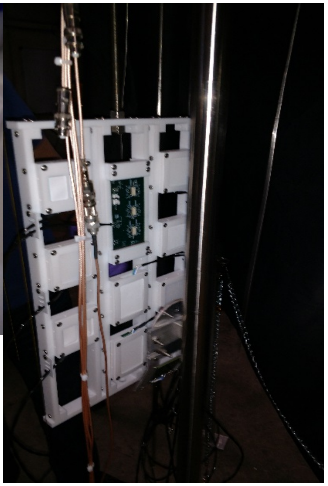
Arapuca: R&D on WLS vacuum coatings and cleaning/baking procedures on dichroic filters. This has led to other WLS coating requests for DUNE R&D-on SIPM arrays, on specialty liquid argon PMTs, on resistive acrylics.



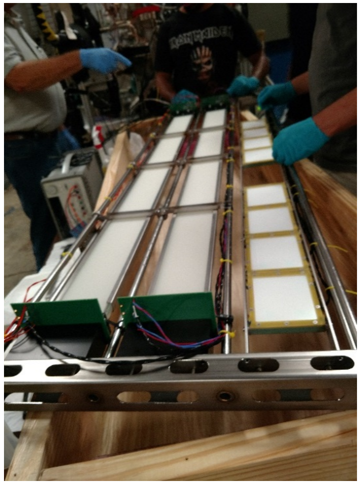
Wavelength shifting plates



WLS coated dichroic filter



Array of coated dichroic filters at Tallbo



CERN test of dipped acrylic bars and dichroic filters (all made at FNAL)

Neutrino Detector R&D: next 3-5 years

- LAr Scintillation: increasing photon yield to enable low energy event detection—especially for very large LAr Detectors with increasingly long drift regions.
    - Wavelength shifting: Infrared photons (900 nm < λ < 1300 nm) do not suffer from Rayleigh scattering.
    - Xenon doping of LAr to down-convert the 128 nm LAr Scintillation photons to 174 nm photons.
        - Does Xenon persist long term as a solute in LAr, or does it freeze out on cold surfaces?
    - Various light collection techniques will continue to be tested.
    - Might impact the third or fourth DUNE Detector designs.

- High Voltage Stability studies: Higher voltages to support the standard 500 V/cm electric field are pushing both power supply capabilities as well as potential HV instabilities around the cathode as drift regions are increased to longer distances.

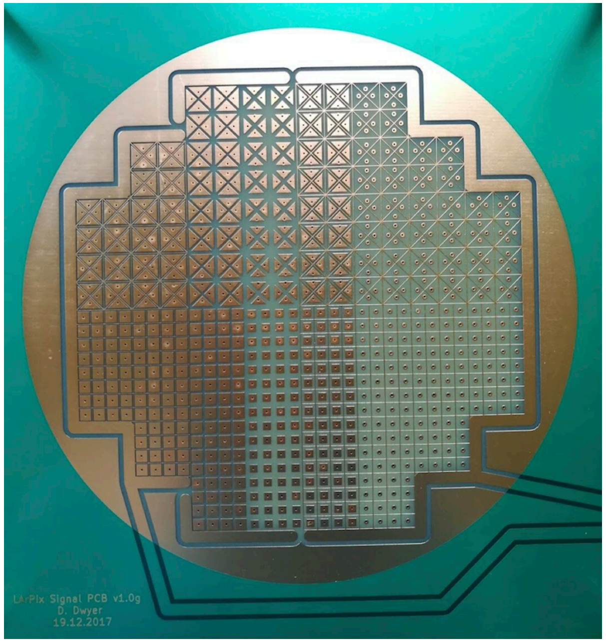
- Electron multiplication in LAr to allow very low energy event detection with large detectors. The multiplication could either be in the LAr itself, or in the electronics (similar to gain in an Avalanche Photodiode) in the LAr.

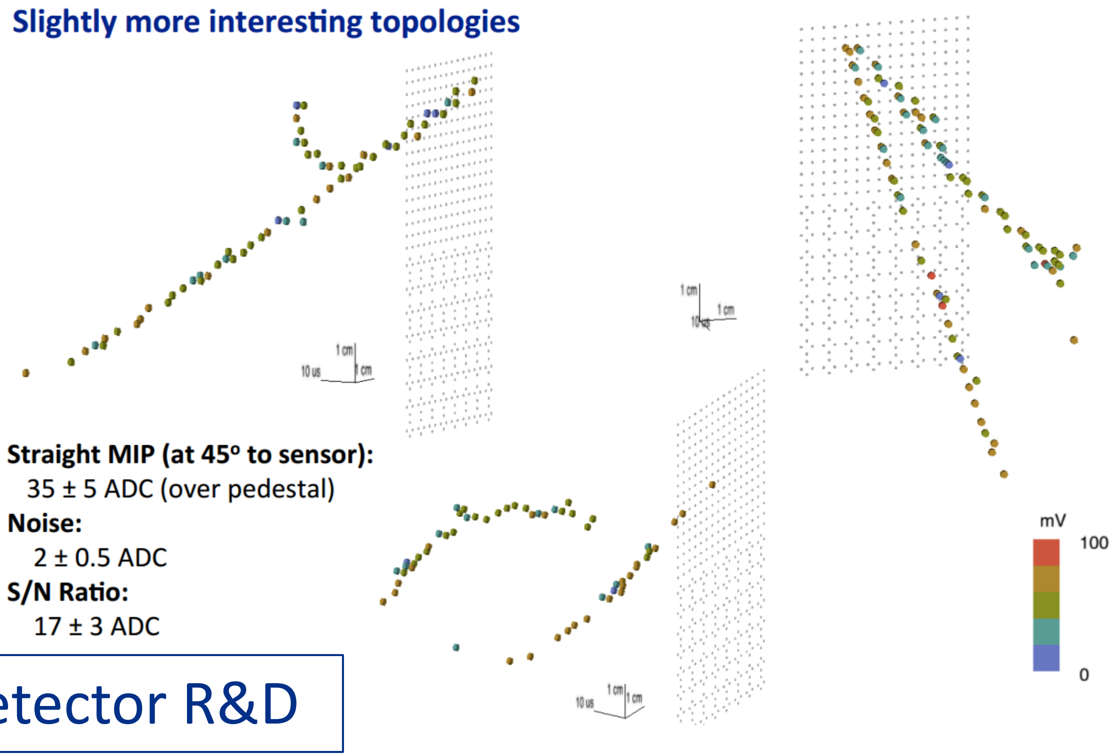
- Magnetized LAr detectors: LAr-temperature superconductors to place magnet in the LAr.

- Pixel Electronics: small-scale infrastructure for testing available—e.g. ICEBERG, LArIAT.

ASIC R&D

- **High-granularity pixelated TPC electronics:**
  - Targeting R&D for a far detector (not baseline) and development of high granularity readout. Probably would resemble MAPS and might need 3-D interconnect technology.





Slightly more interesting topologies

Straight MIP (at 45° to sensor):
35 ± 5 ADC (over pedestal)
Noise:
2 ± 0.5 ADC
S/N Ratio:
17 ± 3 ADC

PixLAr/ArgonCube, near detector R&D

Precision Science Detector R&D

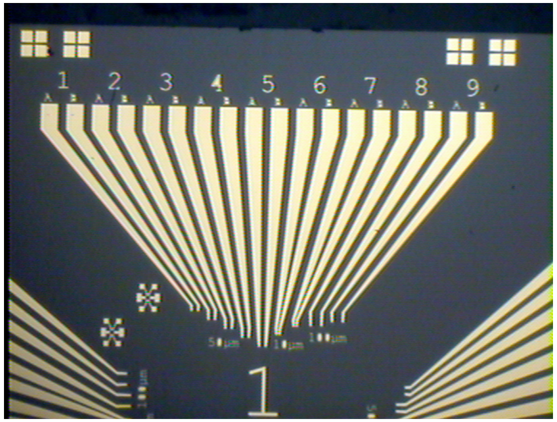
Precision Science Detector Challenges

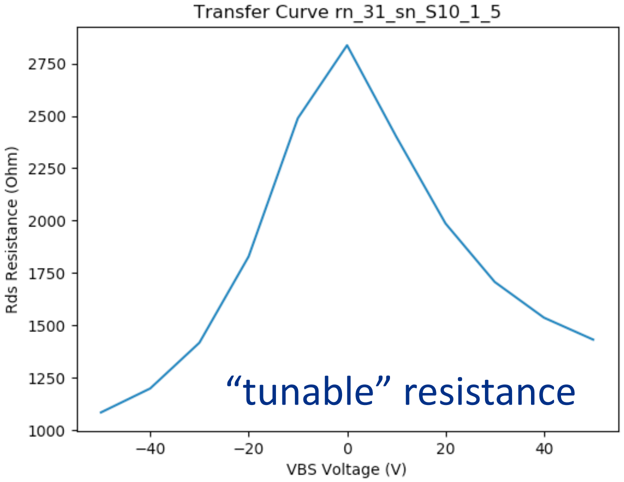
- **CLFV** (e.g. Mu2e-II), **rare eta decays** (e.g. REDTOP), **proton electric dipole moment, dark sector** (e.g. DarkQuest, LDMX)
  - High resolution tracking at low momentum (~100MeV)
  - Fast (sub-ns) electronics
  - High efficiency cosmic ray veto system
  - Medium range (~1MRad) radiation hardness for detector and electronics
  - High power delivery in radiation and magnetic fields

R&D Needs – Precision Detectors

- Radiation-hard electronics
  - Medium high radiation levels; component qualification needed
- Fast radiation-hard calorimeter
  - <10% energy resolution and 500ps timing
  - ~1MRad and 10^{13} n_1MeV/cm^2
  - Including photo sensors
- Ultra-low mass tracker
  - <0.1% X_0 with <100ps TOF tracking for PID
  - R&D of new materials, e.g. graphene
- High-efficiency cosmic ray veto system
  - >99.99% efficiency, neutron fluence issue on SiPM/scintillator
- High power, radiation-hard POL delivery
  - Radiation- and B-field-hard DC/DC converters

Graphene




Transfer Curve rn_31_sn_S10_1_5

“tunable” resistance

Facilities for Detector R&D

Facility Modernization

- IERC will house new clean rooms
- Lab 3 to move into SiDet
- D0 Assembly Building needs modernization
- Proposed D0 addition to relocate village labs
- Test beam facility under constant maintenance/modernization strain
- Irradiation Test Area (ITA):
  - Proposed proton irradiation facility at Fermilab
  - Cleanup of test area proceeding/completed
  - Hoping for construction funds from DOE in early FY20
  - Most crucial for HL-LHC Upgrades
  - Wide support from community

Summary

Fermilab has a broad and deep Detector R&D program

Closely guided by P5 priorities and CPAD grand challenges

Vibrant combination of facilities, technical personnel and instrumentation scientists as well as long culture of Detector R&D allows for very productive collaboration between divisions and with other laboratories and universities

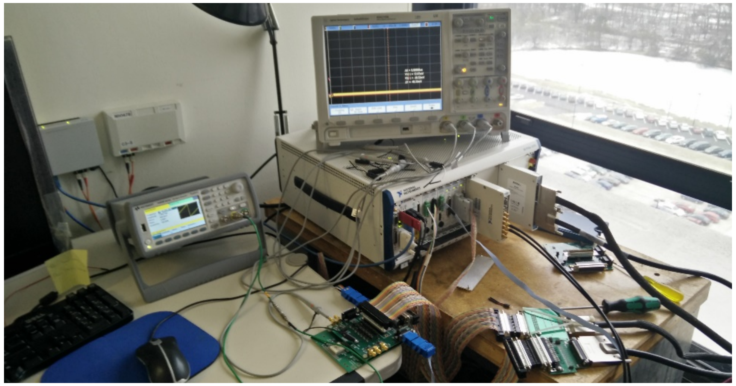
Fermilab scientists are in the process of defining future R&D strategies with the aim to be positioned to support the HEP community in the US (and abroad) for years to come

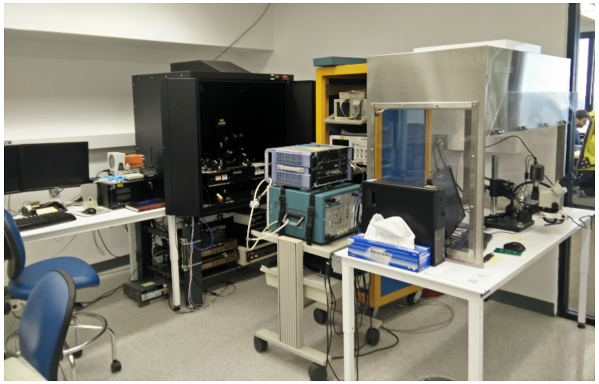
BACKUP

ASIC R&D

Resources & Infrastructure

- 10 ASIC designers and team of 6 for technical support
  - full mixed-mode flow with experience in modern digital-on-top approach,
  - state-of-the art testing infrastructure for IC and deployment of test setups,
  - areas of operation are primarily in instrumentation for HEP and where synergies, time and skills are present
- Extensive collaborations: CERN and CERN network, Geneva Switzerland,
  - other *domestic:* ANL, BNL, SLAC, MIT-LL, SMU, UPenn, NWU
  international: AGH-UST Krakow Poland, U. of Bergamo Italy and others





Current ASIC Activities and Expertise

- High speed data transceivers from 1Gbps to 10Gbps with built-in data selection for extreme total ionizing dose radiation environment (HEP - LHC upgrades),
- Multichannel, pixelated deca-picosecond timing readout integrated circuits with time-to-digital conversion for high total ionizing dose radiation environment for low gain avalanche diode (LGAD) sensors (HEP - LHC upgrades),
- Multichannel cryogenically (80K) operated readout integrated chain with analog-to-digital conversion and transmission on long Cu links at 1-2.5Gbps transmission links (HEP - DUNE),
- Pixel detectors for (soft) X-rays detection, where the technologies range from a nanosecond time resolution photon counters, through very high-dynamic range photon integrators to extremely low-noise with high-resolution per-pixel analog-to-digital conversion front-end concepts and all using three-dimension (3D) integration technology (BES, NP, HEP - Photon Science)
- High-speed (at 40MHz or higher), massively parallel pattern recognition at multi-mega pattern scale and high-speed, high reliability sparse matrix readout strategies and architectures (BES, NP, HEP – LHC upgrades, Photon Science and towards AI)

Technologies: TSMC 65nm CMOS (CERN-IMEC), GF 130nm CMOS, GF 130nm BiCMOS SiGe (MOSIS), 3D-IC (Nhanced/Tezzaron, MIT-LL)

Longer Term Impact R&D

- **Machine Learning/Artificial Intelligence and Quantum Information Science** are the two domains, where advances are likely to achieve a transformational impact and where ASIC design is well suited.
- **Deep cryogenic**, 4K and below, integrated electronics for quantum information science and quantum sensors (e.g. quantum dots aka SETs and ion traps, superconducting interconnects, spintronics, photonics and superconducting circuits)
- Smart sensors and **in-hardware processing with training for artificial intelligence** (developing integrated solutions in two areas of Machine Learning / Artificial Intelligence applicability)
- **Technology of smart sensors** is based on embedding of high-level of abstraction in-situ processing, leading to reduction of data but providing the required information
- Development of **RF integrated circuits** that will be allowing selective frequency multiplexed coupling to qubits, while operating at sub-K temperature regime
- **Glass and silicon interposers with through vias** and several metal routing layers for building edgeless and gap-less pixel detectors and light supports for integrated detector systems,
- Pixel detectors for environments requiring high **40 MHz per pixel event registration rates** with a few bit, per pixel analog-to-digital conversion for high total ionizing dose radiation environments,
- Development and characterization of standard cell libraries based on up to **500 Mrad of total ionizing dose** of radiation and for **cryogenic conditions** spice-type device models,
- Estimation of failure rates and techniques of prevention and mitigation of **single-event-effects** in integrated circuits developed for usage in radiation environments for high energy physics experiments,
- **Monolithic Active Pixel Sensors** technology (MAPS) on high resistivity, thick substrate with full CMOS capability and built-in charge processing steps