Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab Detector R&D Program

Petra Merkel – Fermilab Detector R&D Coordinator

Fermilab Engineering Retreat

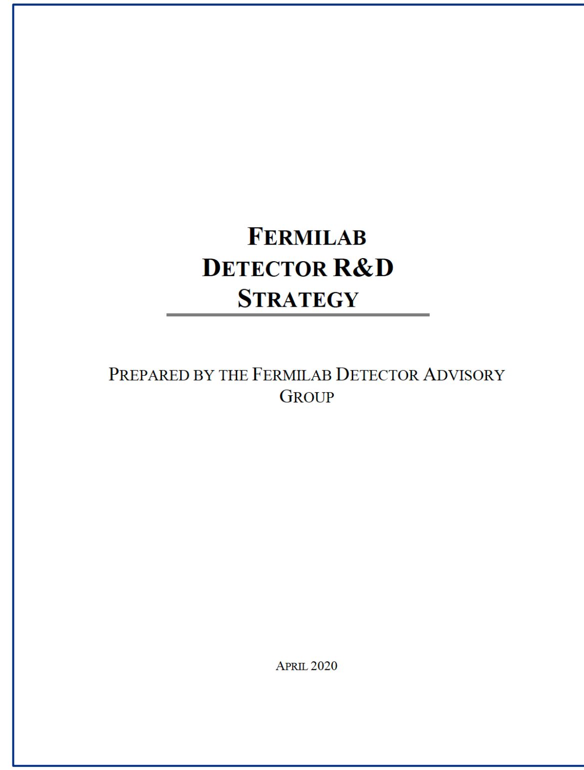
February 24th, 2021

- **KA25 Detector R&D: dedicated DOE program for detector development**
- **Fermilab organization:**
  - Detector R&D Coordinator: Petra Merkel (petra@fnal.gov)
  - 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

- **Recent Highlights:**
  - Developed 5-year strategic plan for Detector R&D
  - Defined high-priority R&D thrusts aligned with recent DOE BRN for Detectors and with Fermilab's mission, facilities and expertise
  - Integrated with annual lab planning (IPPM)
  - Initiated call for competitive start-up R&D proposals ("New Initiatives")
  - Engaging in quarterly tele-conferences with DOE program manager for detectors and with the other national labs

Detector R&D: High Priority Areas

- Developed Detector R&D Strategic Plan in April'20 in answer to PEMP notable
- Aligned with recent BRN for Detectors and with Fermilab's scientific interests and technical expertise
- Two high priority research areas identified:
  - PICOSECOND TIMING
  - NOBLE ELEMENT DETECTORS
- In addition, boost for Blue Sky R&D in view of Snowmass/next P5


FERMILAB
DETECTOR R&D
STRATEGY

PREPARED BY THE FERMILAB DETECTOR ADVISORY GROUP

APRIL 2020

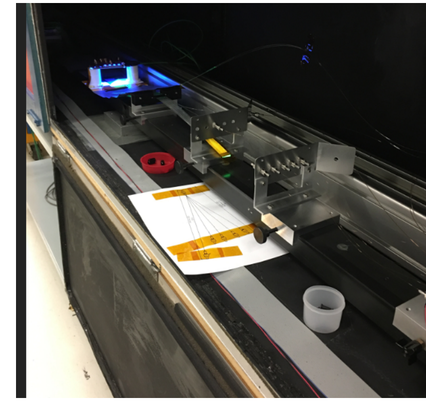
New Initiatives Program

- Initiated new competitive call for proposals, the **New Initiatives**, with the aim to attract new members and new ideas to the detector R&D community at the lab. Open to engineers as well!

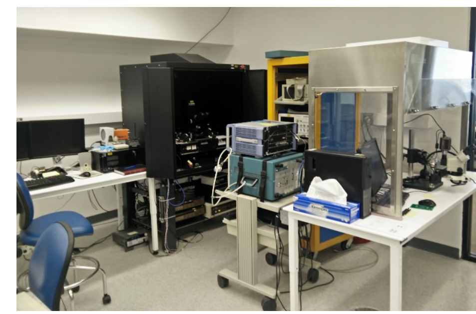
- Directed towards newly identified strategic areas

- 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.

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
  - Rapid Prototyping and Special Materials



- ASIC Development Facility
- Fermilab Test Beam Facility (FTBF)
- Irradiation Test Area (ITA)

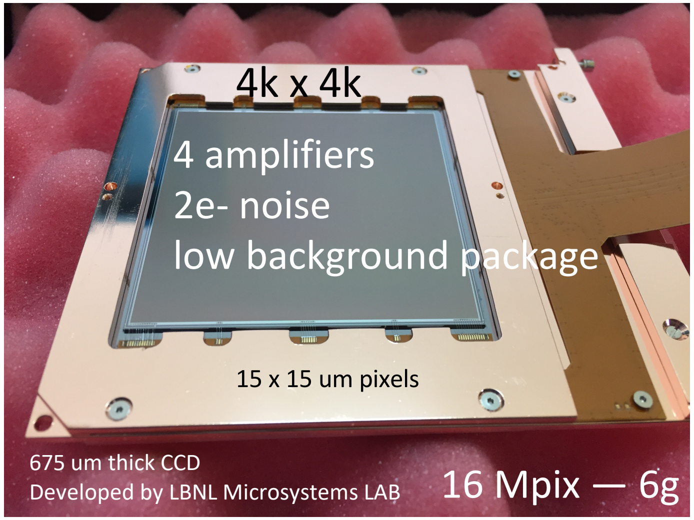
Promote and benefit from partnership with universities and other national laboratories. Facilities are supported by excellent technical workforce (specialized technicians and engineers).

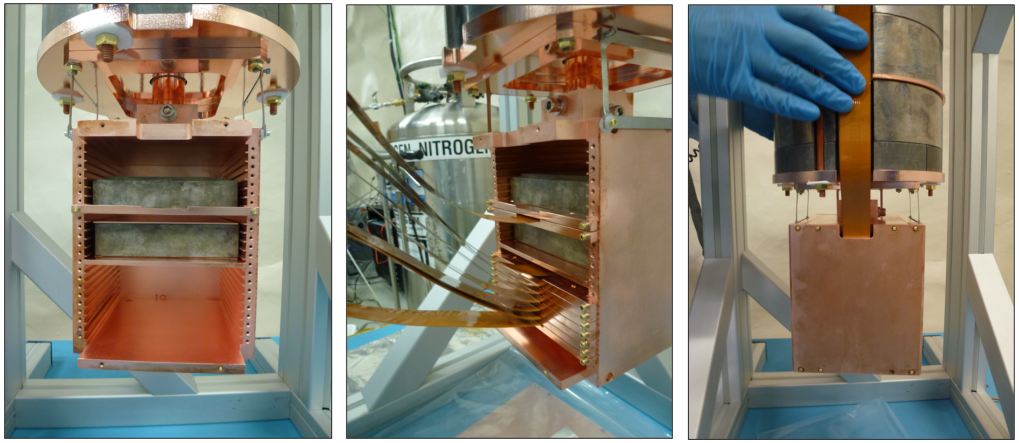
CCD R&D

Juan Estrada's group

- Over the past ~10 years mechanical engineers Greg Derylo, Hemanth Kiran Gutti, Abhishek Bakshi, and Stefanie Timpone have enabled us to produce cryogenic low background experiments for dark matter and neutrinos using CCDs.

- After developing the readout system for DECam the FNAL engineering team has supported the development of low noise readout systems for low threshold CCD experiments: Terri Shaw, Jamieson Olsen, Gustavo Cancelo, Ken Treptow, Neal Wilcer

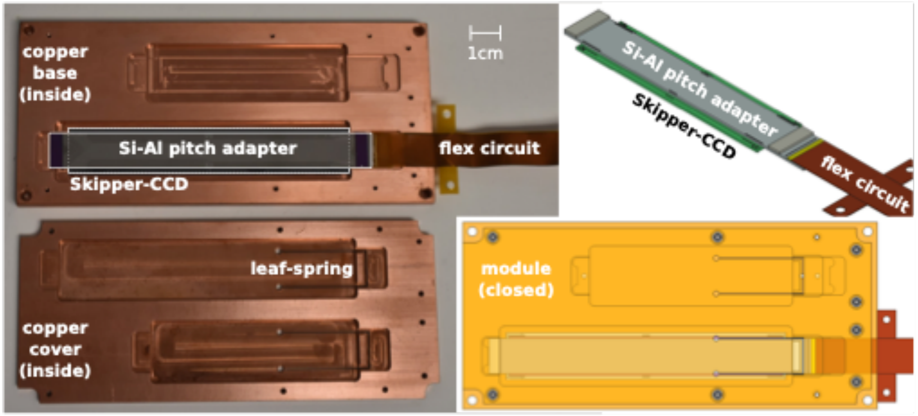


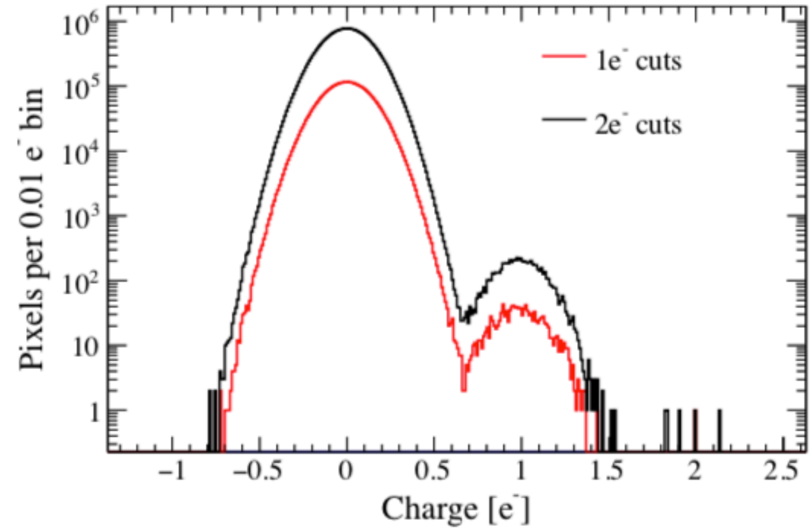


DAMIC @ SNOLAB
started in 2014

SENSEI 2020 results
arXiv:2004.11378

Juan Estrada's group

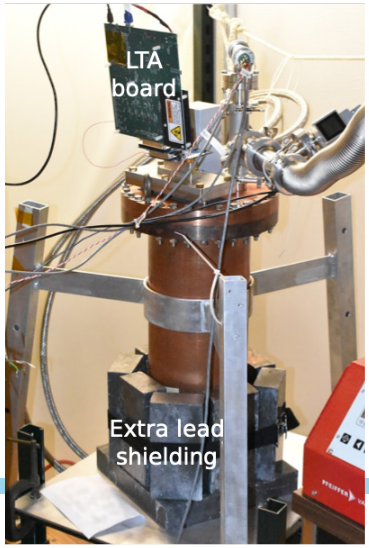


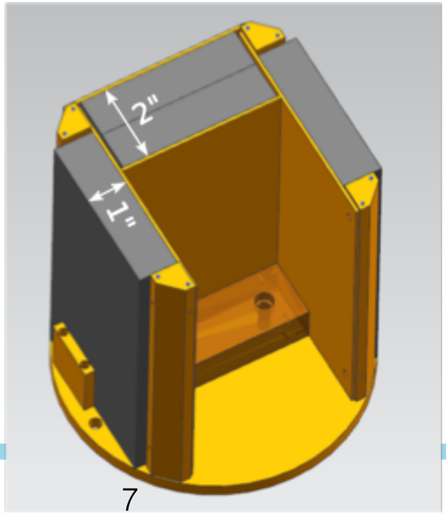


Rates:

- 1e- = 450 ev/g-day (1.6 10^{-4} e/pix/day)
- 2e- = 2.4 ev/g-day

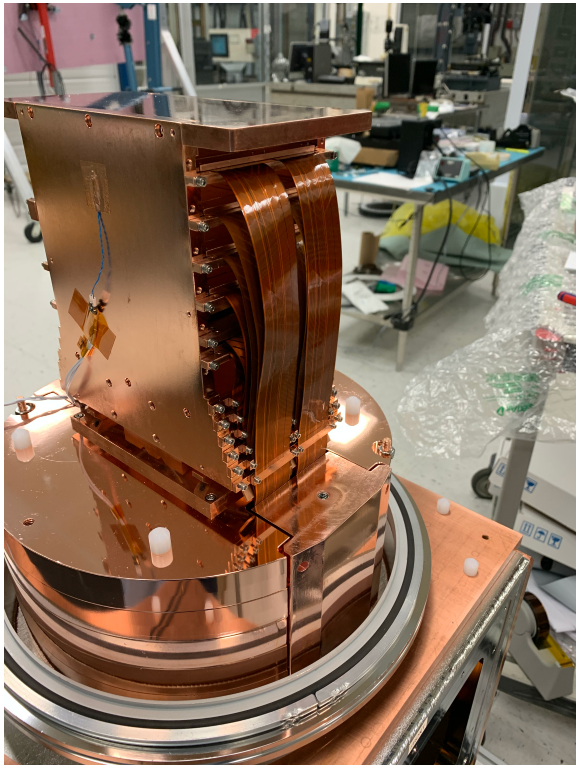
FIG. 3. The pixel charge spectra (after selection cuts) used for the $1e^-$ and $2e^-$ analyses. There are no $3e^-$ or $4e^-$ events.



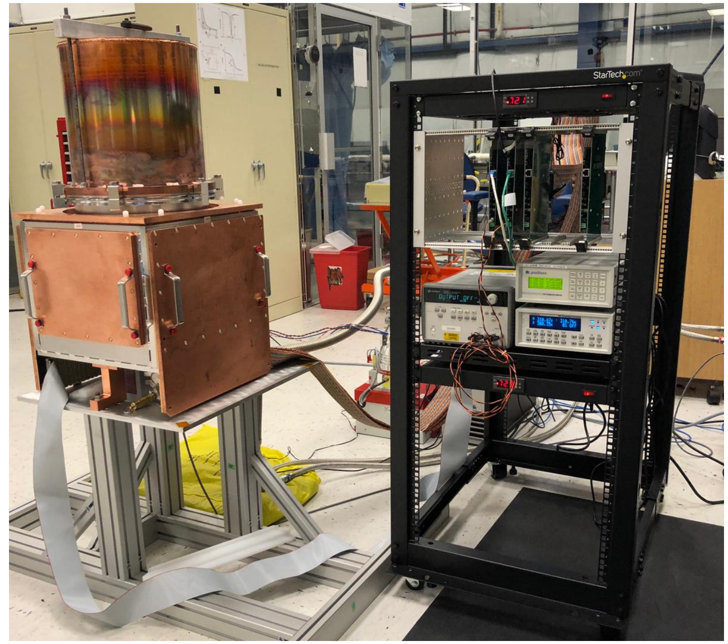


SENSEI-100 : now being built at SiDet

Juan Estrada's group

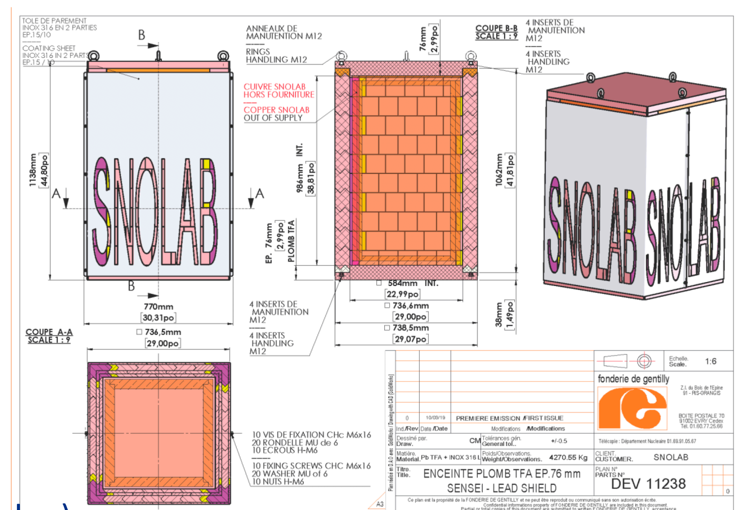


7 supermodules installed
(not all science detectors)



readout system tests going on now
(FNAL electronics)

now at SNOLAB.



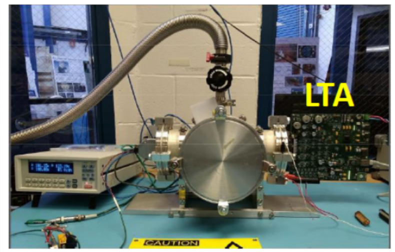
- system at SNOLAB since last week

(a couple skippers in DAMIC@snolab (5DRU) also in the plan)

RSE-CDT group electronics for CCD: LTA (Low threshold architecture)

Gustavo Cancelo's group

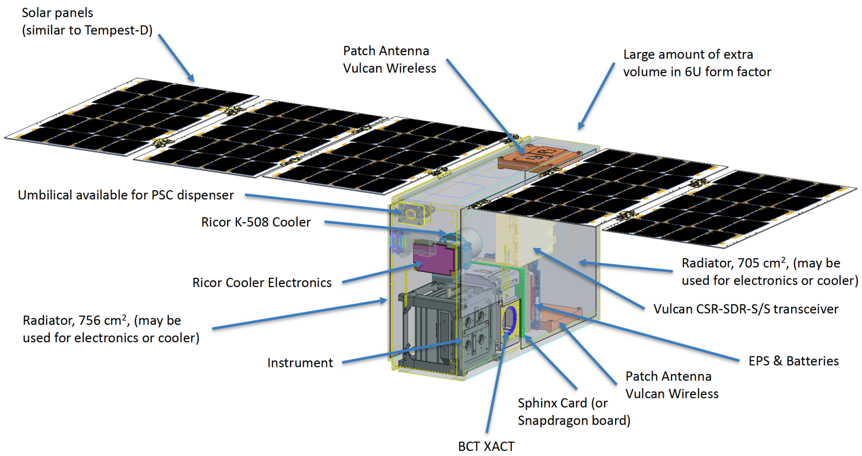
- **Science**: Dark matter (DAMIC, SENSEI, DAMIC1Kg, Oscura10Kg),
- coherent neutrino scattering (CONNIE, Violeta10Kg),
- DM from space (CubeSAT).

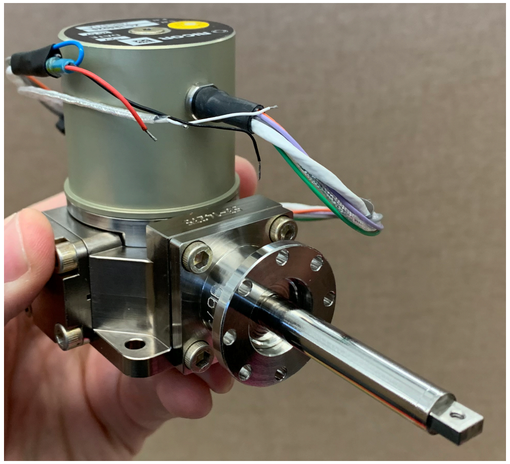


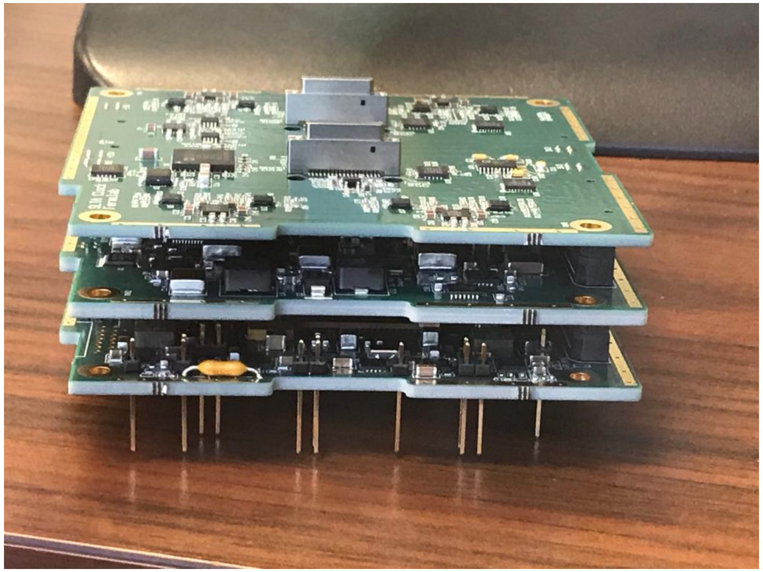
- LTA helps SENSEI scientists win New Horizons 2020. (Tiffenberg (FNAL), et. al.)
  - SENSEI PRL paper chosen "editor's pick" (2nd time for SENSEI)
  - SENSEI at SNOLAB: 200 channels in 2021. Being built at SiDet.
- CONNIE (Coherent Neutrino Nucleus Interaction Experiment) at Angra2 (Brazil) 2015-2020: New result W&C of Dec 4th (F. Moroni).
  - G.F.Moroni URA Tollerstrup award.
- CubeSat LTA: 3 board space hard LTA for cube sat dark matter experiment. In collaboration with PPD, UIUC, NASA.
- Future 1Kg and 10 Kg experiments (DAMIC, Oscura and Violeta will use LTA or a newer version of LTA.
- The RSE-CDT group participates in the science and some are authors of all the papers from SENSEI, DAMIC, CONNIE, and LTA.

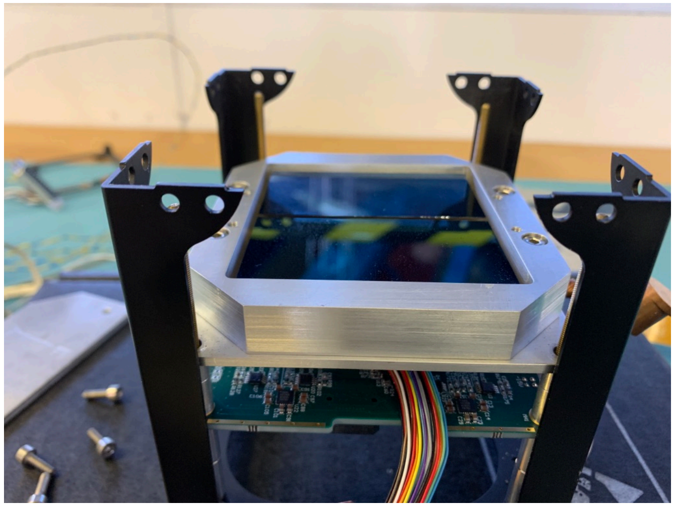
CubeSat: lead by FNAL engineering physicist (S.Timpone) combining mechanical and electronics developments for first small satellite payload by FNAL.

Juan Estrada's group



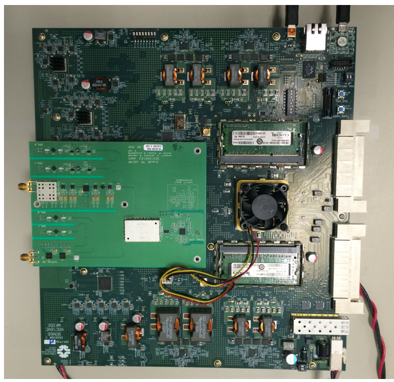




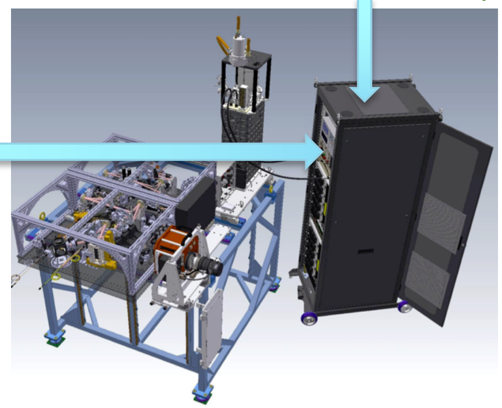


Readout and controls for superconducting detectors, Gen2 (fMESSI)

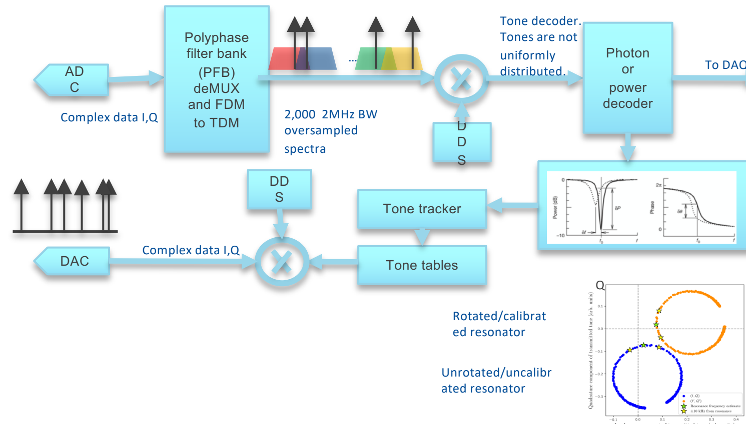
fMESSI 2016-2020



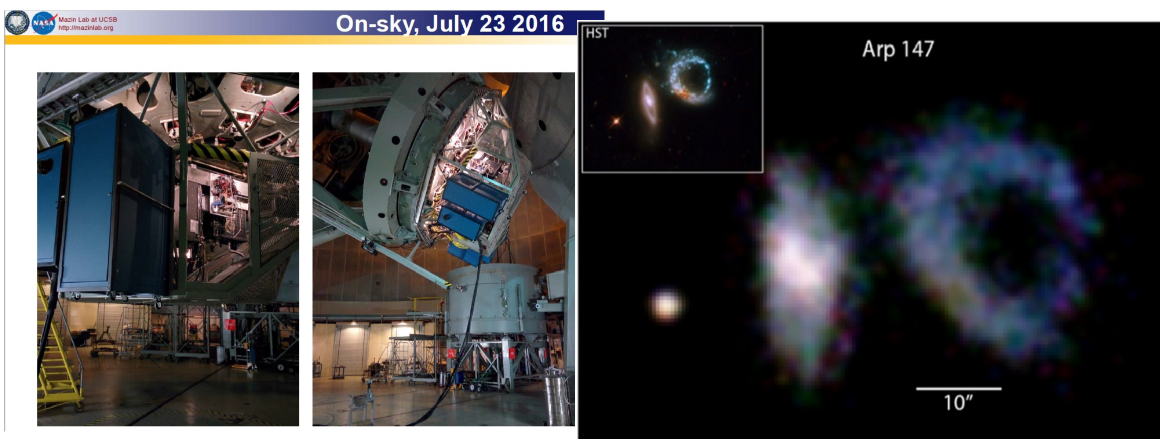
MEC: 20K MKID system operating at 8m telescope at Subaru since 2018 using FNAL Gen2 fMESSI electronics (20 boards)



fMESSI readout and control block diagram



DARKNESS at Palomar 2016



Papers:

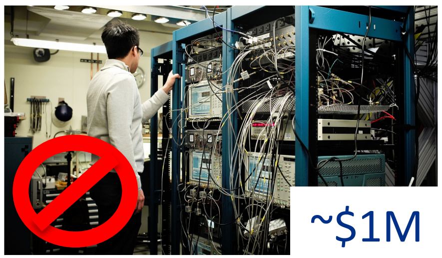
arXiv:2011.06685
Second Generation Readout For Large Format Photon Counting Microwave Kinetic Inductance Detectors
Authors: Neelay Fruitwala, Paschal Strader, Gustavo Cancelo, Ted Zmuda, Ken Treptow, Neal Wilcer, Chris Stoughton, Alex B. Walter, Nicholas Zobrist, Giulia Collura, Isabel Lipartito, John I. Bailey III, Benjamin A. Mazin.

arXiv:1803.10420, doi 10.1088/1538-3873/aab5e7
DARKNESS: A Microwave Kinetic Inductance Detector Integral Field Spectrograph for High-Contrast Astronomy
Authors: Seth R. Meeker, Benjamin A. Mazin, Alex B. Walter, Paschal Strader, Neelay Fruitwala, Clint Bockstiegel, Paul Szypryt, Gerhard Ulbricht, Gregoire Coiffard, Bruce Bumble, Gustavo Cancelo, Ted Zmuda, Ken Treptow, Neal Wilcer, Giulia Collura, Rupert Dodkins, Isabel Lipartito, Nicholas Zobrist, Michael Bottom, J. Chris Shelton, Dimitri Mawet, Julian C. van Eyken, Gautam Vasisht, Eugene Serabyn

Fermilab control and readout replaces expensive commercial equipment and messy cabling and discrete RF components.

Gustavo Cancelo's group

Currently at IBM and most QIS big labs

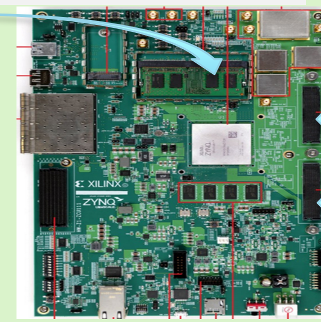


~$1M

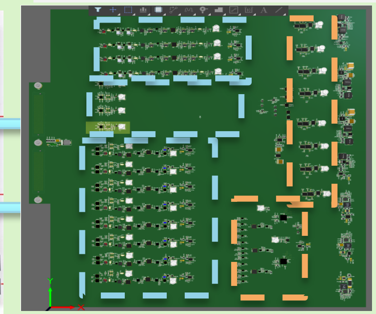
No Missed Connections
Jerry M. Chow, PhD, manager of theory of quantum computing and information at IBM Research, inspects the cables connecting a vast array of microwave equipment powering quantum computing processors in the lab.

Gen3 (RFSoC) : FNAL Readout and Control: Up to ~80 qubits/module (if FMUXed) >1000 qubits/system

FPGA+ADC+DAC+memory+interfaces

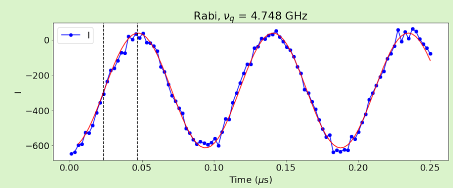


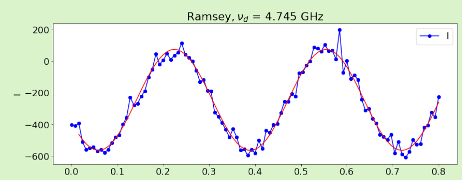
RF inputs, outputs, LO, fast flux contr high precision bias,



FNAL Gen3 electronics stakeholders:

- U. Chicago: Davis Schuster lab.
- U Princeton: Andrew Hock lab.
- Fermilab: SQMS (A. Grassellino)
- Fermilab: QSC Thrust 3 (A. Chou)
- UCSB: Ben Mazin Lab.
- U. Perdue: Alex Ruichao Ma.
- IIT-FNAL: Rakshya Khatiwada.
- Fermilab CMB MKIDs (B. Benson).
- Fermilab DM MKIDs: Noah Kurimsky.
- Fermilab DE MKIDs: Juan Estrada.





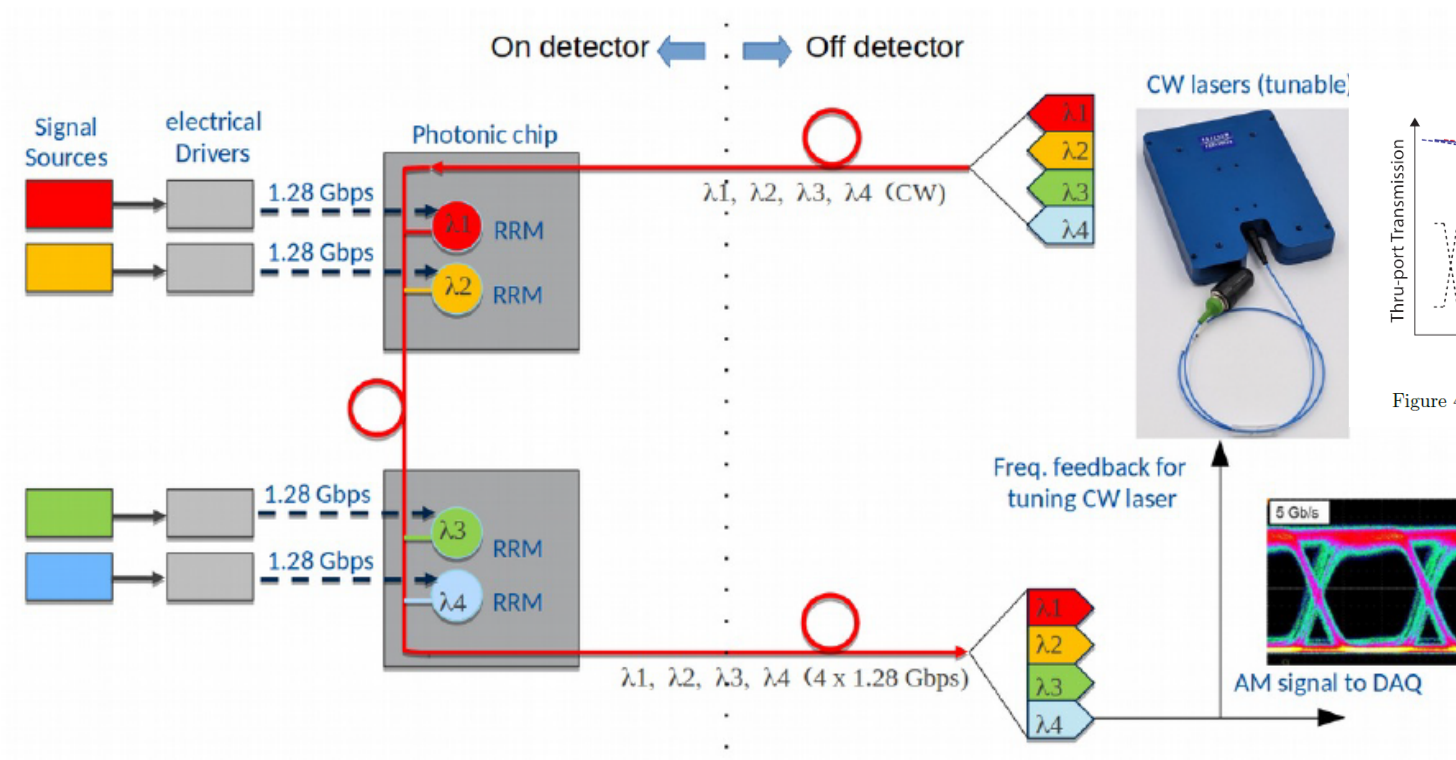
Qubit measurements at U. Chicago. D. Schuster lab

Silicon Photonics Ring Resonator Modulators for Rad Hard Optical Links

Alan Prosser's group

Important for future collider experiments

SBIR with Freedom Photonics, UCSB, LBNL



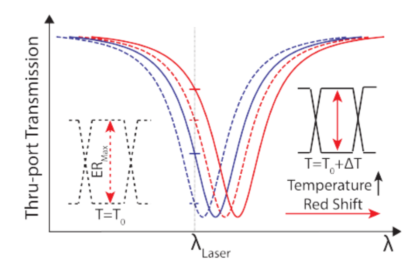
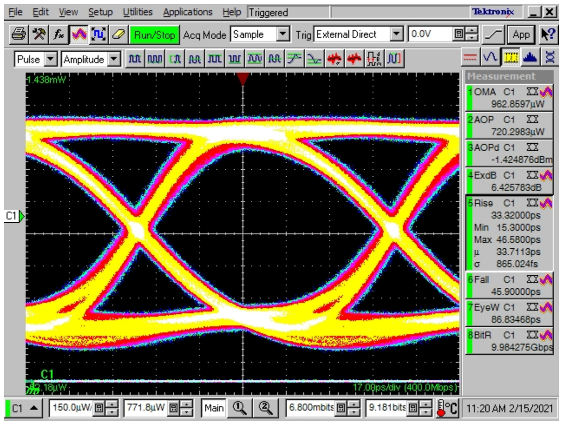


Figure 4.2: Thermal effects on ring-modulators.

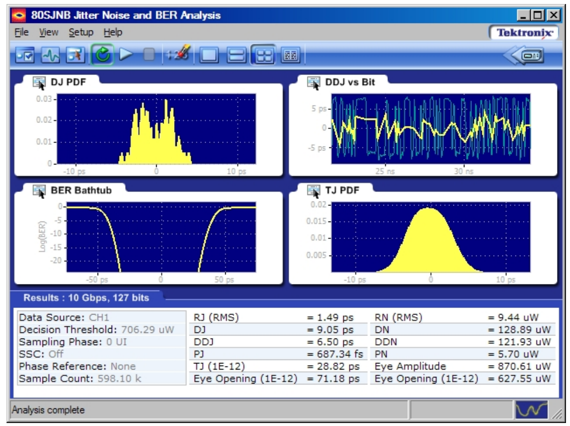
Figure 1: WDM readout system proposed architecture. RRM stands for Ring Resonator Modulator.

Cryogenic Optical Links for HEP

SFP+ Optical Eye

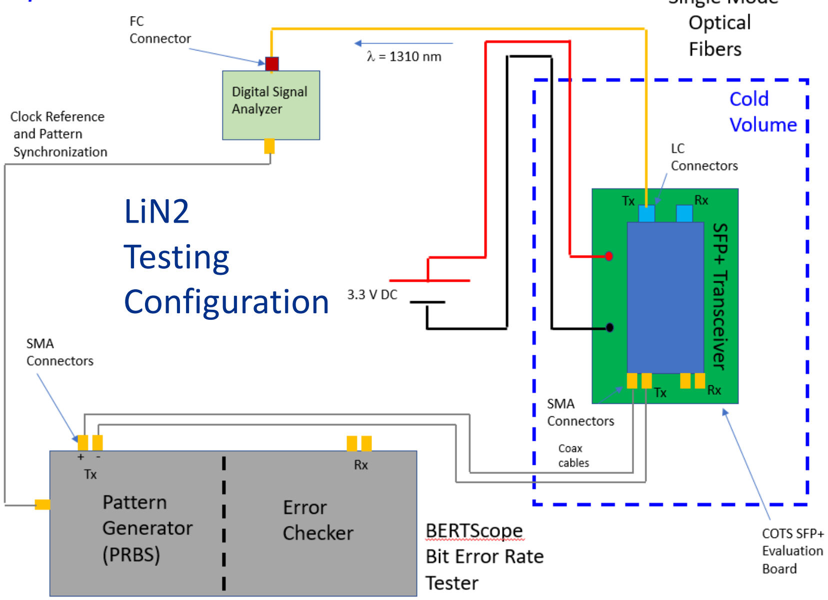


SFP+ Optical Jitter

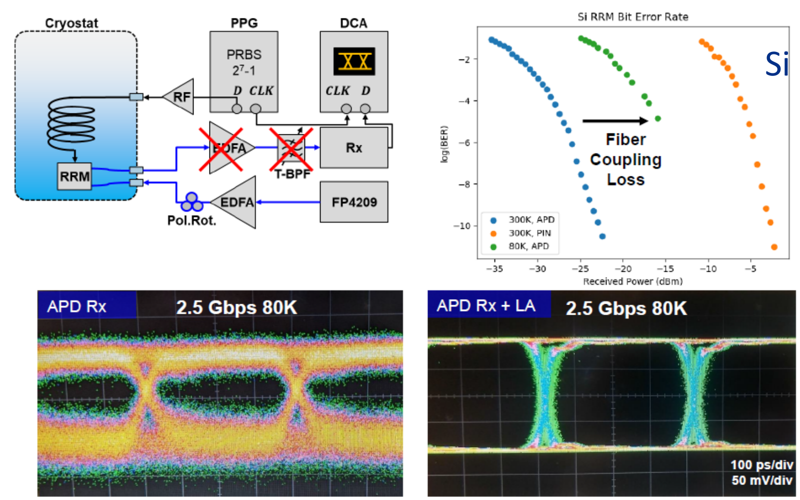


Applications in DUNE: digital optical data communications in LAr temperatures. Testing of COTS Small Form Factor Pluggable footprint EELs (SFP+)

Complete Tx Characterization



Recent Cryogenic Optical Link Tests



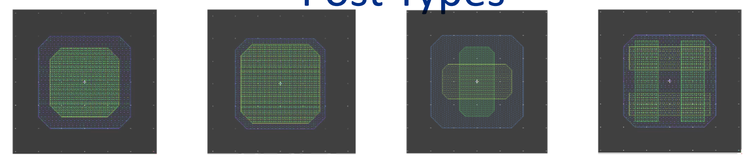
Si RRM at 80 K

ASIC group

High-Density Interconnects with MIT-LL

- Wafer to wafer connection R&D for 3D devices
  - Next-generation vertex or pixel detectors for HEP and BES
- Fermilab, Brookhaven, and MIT-LL
  - Funds from Fermilab and Brookhaven
  - MIT-LL Microelectronics Lab
    - 90 nm fab
    - Engineering expertise in 3D
    - Licensed Ziptronix Direct Bond Interconnect (DBI) process
- First production run ongoing:
  - Four lots of wafers with different post types
    - Two types of wafers per lot
    - Tier 1 – bottom wafer with test chains
    - Tier 2 – top wafer with test pads for probing
  - Deliberately misaligned posts
  - Four different chain type
- Expect to complete first run April 2021 and test
  - 2nd run with best post geometry
  - Possibly other Tier 1 or Tier 2 top metals

Post Types

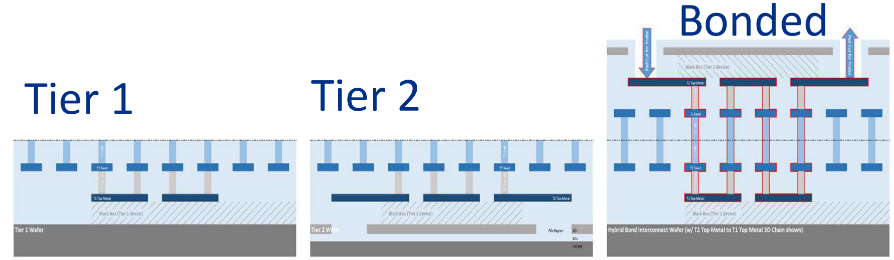


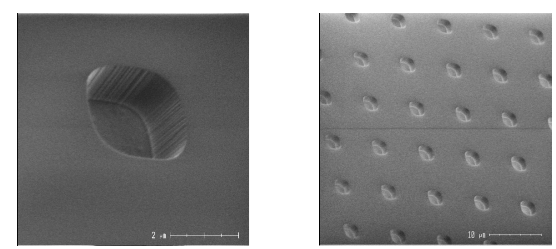
double slot

3um (standard) | 3.5um | 1.5x3um slot | 1.5x3.5um

(Slots: Tier 1 Horizontal, Tier 2 Vertical)

Tier 1 | Tier 2 | Bonded





Courtesy of: Renée Lambert
Lead Engineer, MIT-LL

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
- Many ways for engineers to contribute!
  - Also had very good experience working with engineering students from surrounding universities

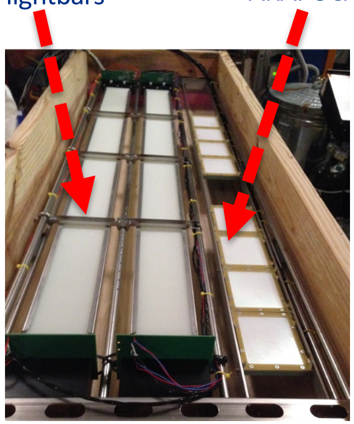
BACKUP

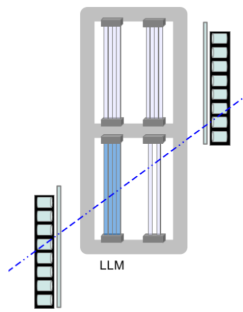
DUNE photon detector: ARAPUCA and active ganging of SIPMs

- Work supported by LDRD 2018-2020 (P.I. G. Cancelo) and Director's International fellow (D. Totani, U. L'Acquila)

Eigen lightbars

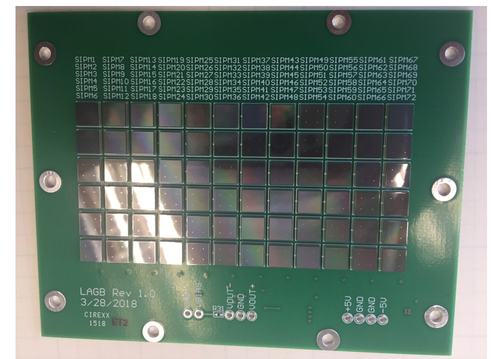
ARAPUCA module





TallBo experiment at PAB-Fermilab 2019

72 SIPM active array (largest in the world)



- During a 3-year period, ARAPUCAs and active gangs of SIPMs were designed, built and characterized. They outperformed previous DUNE photon detector candidates (e.g. Eigen light bars) by x50. Tests were also validated at ProtoDUNE (CERN).
- Both ARAPUCAs and active ganging designed from our group have been adopted and baselined for DUNE.
- Future: more R&D for DUNE module 2.

- Papers:
- A measurement of absolute efficiency of the ARAPUCA photon detector in Liquid Argon, Dante Totani, Gustavo Cancelo, Flavio Cavanna, Carlos O. Escobar, Ernesto Kemp, Franciole Marinho, Laura Paulucci, Dung D. Phan, Stuart Mufson, Chris Macias, David Warner, arXiv:2008.05371 doi 10.1088/1748-0221/15/06/T06003.
- Differences in the response of two light guide technologies and two readout technologies after an exchange of liquid argon in the dewar, S. Mufson, B. Adams, B. Baugh, B. Howard, C. Macias, G. Cancelo, E. Niner, D. Totani, arXiv:1912.05987 doi 10.1016/j.nima.2020.164240
- Increasing the efficiency of photon collection in LArTPCs: the ARAPUCA light trap G. Cancelo, F. Cavanna, C. O. Escobar, E. Kemp, A. A. Machado, A. Para, E. Segreto, D. Totani, D. Warner , arXiv:1802.09726 doi 10.1088/1748-0221/13/03/C03040

Alan Prosser's group

Ring Resonator Modulators for Rad Hard Optical Links

Demonstrator

Inspired from SIPHOSPACE (ATTRACT) and PHOS4BRAIN (INFN) R&D projects

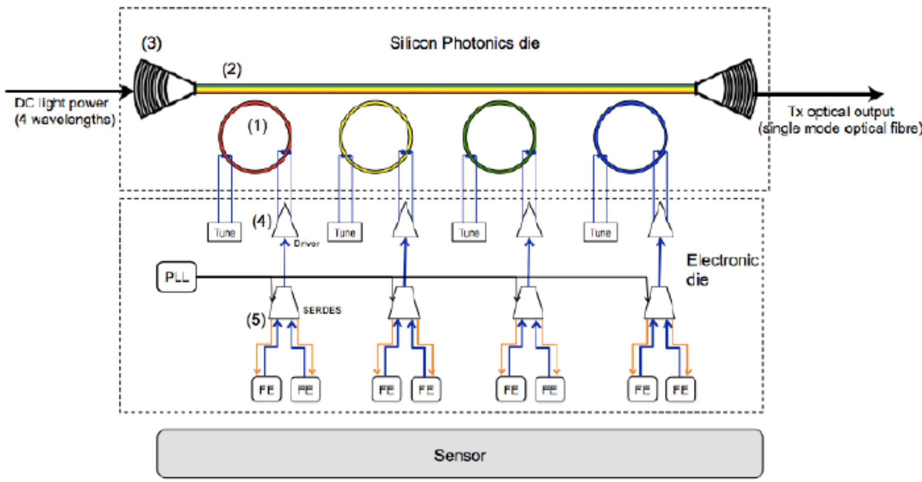


Fig. 2. Schematics of proposed demonstrator. Ring resonators (1) with different and tunable resonator wavelengths are located along horizontally drawn bus waveguides (2) which are connected to optical glass fibres by efficient and robust focusing grating couplers (3). Data from the front-ends (FE) and serializers (5) are sent to the drivers (4). The Front-End (FE) is embedded in the demonstrator but it can be bypassed. The sensor is not part of the demonstrator.

Test Parameters

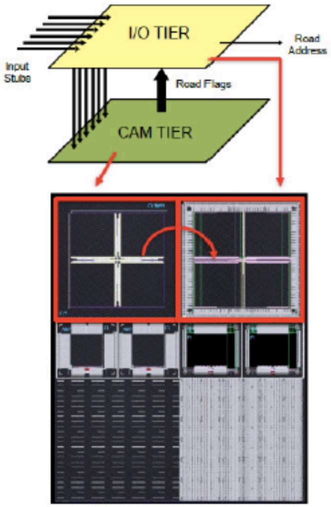
FREEDOM PHOTONICS

- Suggested TID:
  - Based on simulations done in Sentaurus TCAD, we anticipate significant degradation in performance at around 5 Mrad. The following TID points should provide a good resolution around this point:
    - 250 krad, 500 krad, 1 Mrad, 5 Mrad, 10 Mrad
- During Irradiation:
  - Constant -3V DC bias
  - All devices can be biased by the same switch PCB by stacking the connectors. Alternatively, we may provide 4 D-Sub plugs to act as closed switches, but this requires 4 separate power supplies to be used.
- After Irradiation:
  - I-Vs on each device using a Keithley 7001 switch system (24 devices/board * 4 boards = 96 devices total)
    - -5V (1mA max), up to 1.5V (10mA max), 400 points

Selected R&D Updates: ASIC Group

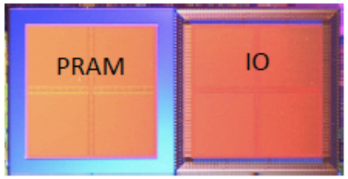
VIPRAM L1CMS Bump Bonding

- **Research Goal:**
  - Development of High-Density Wafer-to-Wafer Interconnects for 3D Circuits
  - Technology required for next-generation of on-detector pattern recognition for high-rate experiments → ***Critical Technology Development***
- **VIPRAM (Vertically Integrated Pattern Recognition Associative Memory)**
  - Develop 3D vertical integration technology to build faster and denser Associative Memory devices
  - Goal: 3D bond CAM (Content Addressable Memory) chip to I/O tier
  - Original intent: use wafer-to-wafer DBI through Tezzaron, but were not successful
  - Back-up plan: Dice wafer, and bond together face-to-face using bump bonding → Done

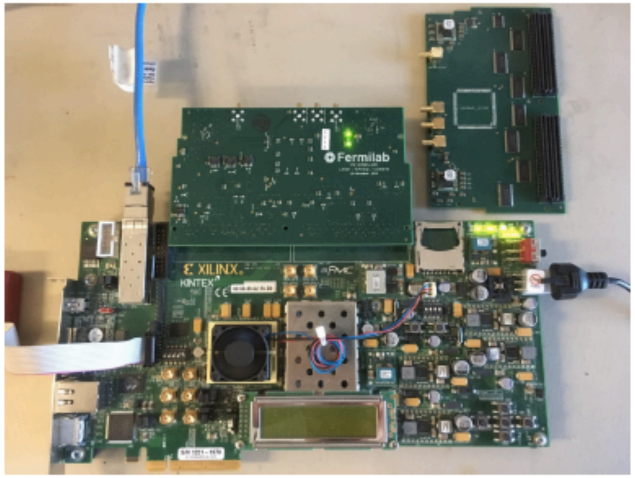


VIPRAM Concept

VIPRAM Dies

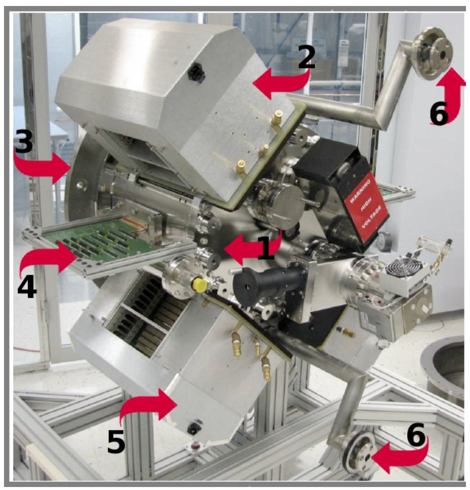


Bump Bonded VIPRAM with PRAM on top

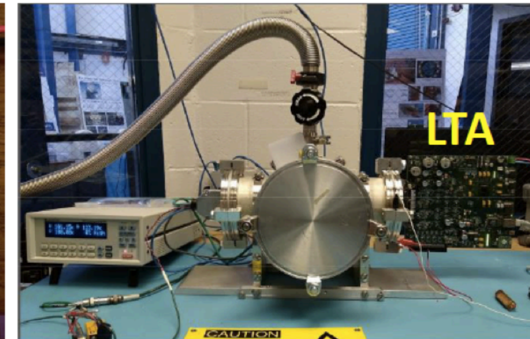


- **Status:**
  - Wafers have been fabricated → Done
  - Attempts to do DBI wafer-to-wafer bonding through Tezzaron failed
  - Have contracted with CVInc to dice chips and bond face-to-face → Done
    - Produced 9 bonded dies
    - Sent for packaging → Done
    - Have produced test board → Done
    - Testing at Fermilab is imminent
    - Several pairs remaining to be completed at CVInc
- **Outlook**
  - Chips in hand
  - Test board built; software & firmware complete
  - ~2-3 person-months of effort
  - Goal is to try to complete in FY20

monsoon readout
system 2012



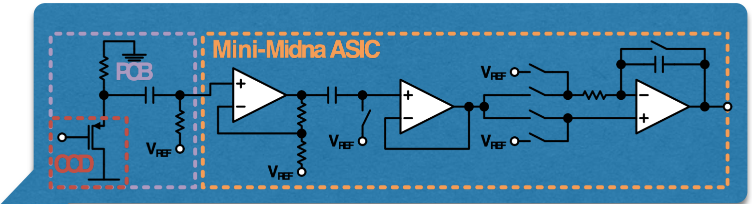
LTA readout 2018
lower cost, optimize for skipper-CCD

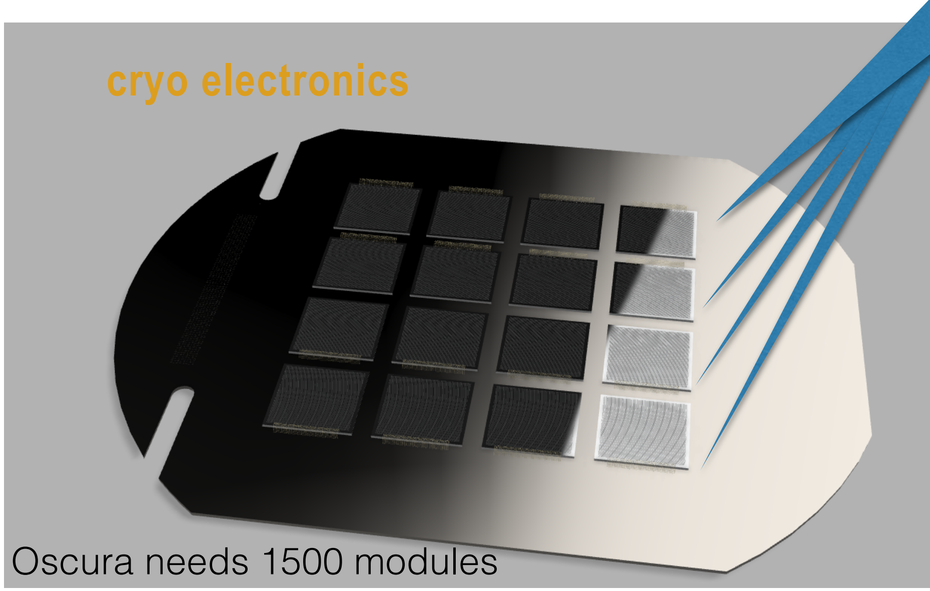


spaceLTA readout 2020
optimize for cubesat

synergy between large and big projects builds
expertise, and strong collaboration with engineering
schools facilitates progress in R&D

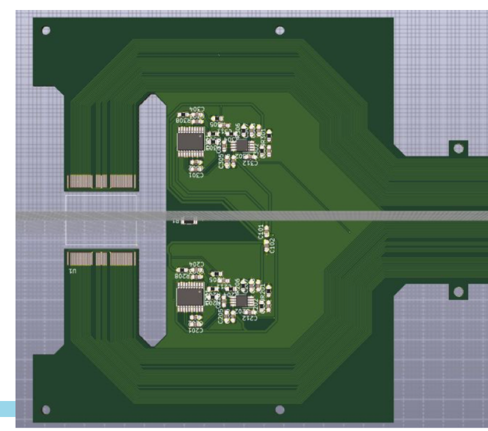
16 module CCD on silicon substrate





ASIC for cold analog signal processing on the silicon substrate. (Discrete solution being considered, bare die)

currently testing discrete solution in in CCD package



Now we are building Oscura, need to push all our engineering developments to the limit. **Oscura is a very significant engineering R&D problem in cryogenics, electronics and several integration aspects.**

Oscura : 10-kg skipper-CCD experiment

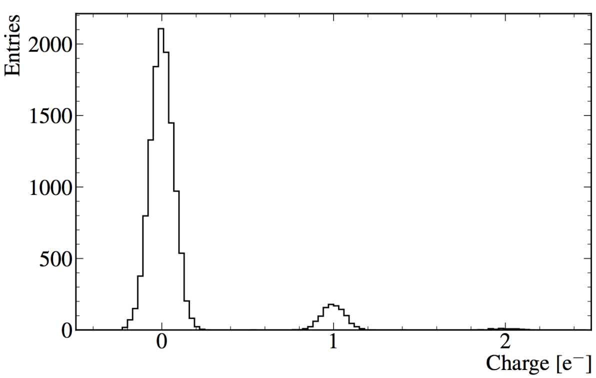
https://astro.fnal.gov/science/dark-matter/oscura/

- <u>**Observatory of Skipper CCDs Using Recoiling Atoms**</u>
- **Science goal : e-recoil low mass direct dark matter search (1 MeV → 1 GeV)**
- **Technology : skipper-CCD array (sub-electron noise) at underground lab (SNOLAB, SURF, other).**
- **R&D: scale the existing technology towards a 10kg experiment**
- **Schedule : small project execution plan completed in 2023**

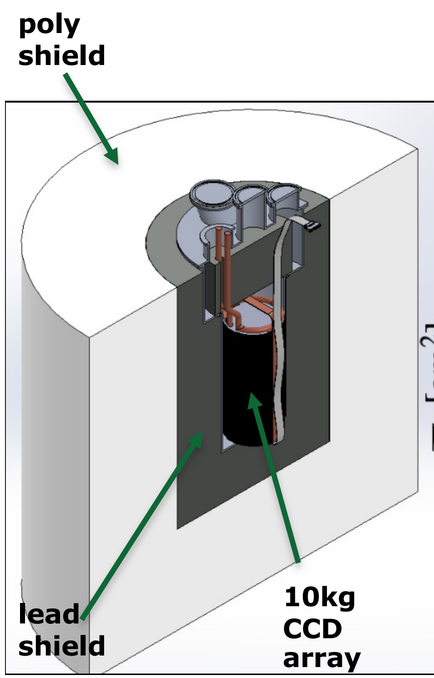
R&D: FY19,FY20,FY21

Design: FY22,FY23

Execution : FY24-27

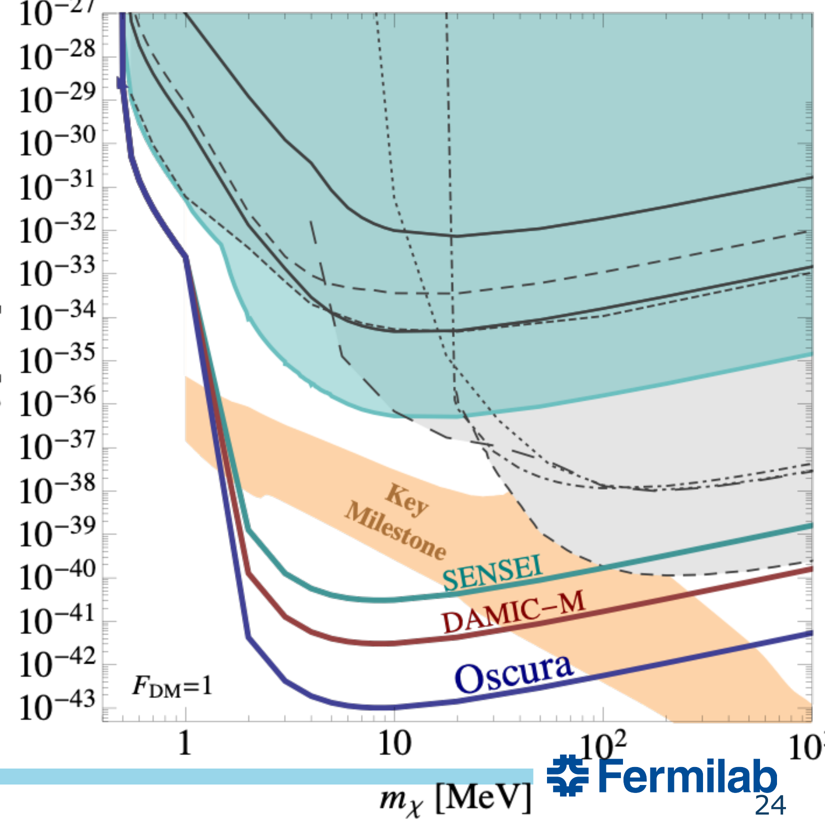


demonstrated performance of skipper-CCD



detector concept

scientific reach



Oscura R&D priorities

Sensors : transfer to new fab technology.

The foundry we have been using for our thick CCD (DM, dark energy, neutrinos) experiments is not going to continue with this technology. Need to find a new way of making the sensors. We also see this an as opportunity to take advantage of more modern technologies "CMOS-compatible"
This is where we starting to work with MIT-LL

Electronics: large channel number/cold electronics.

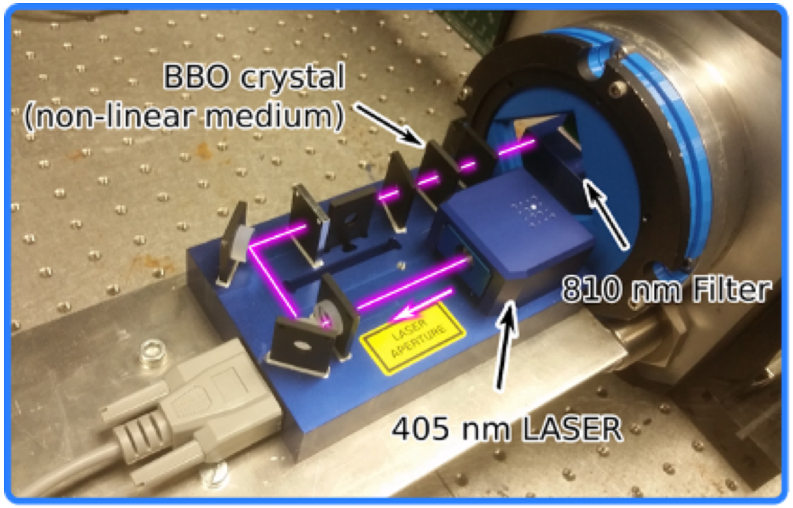
10 kg means a lot of CCD… and a lot of readout channels.

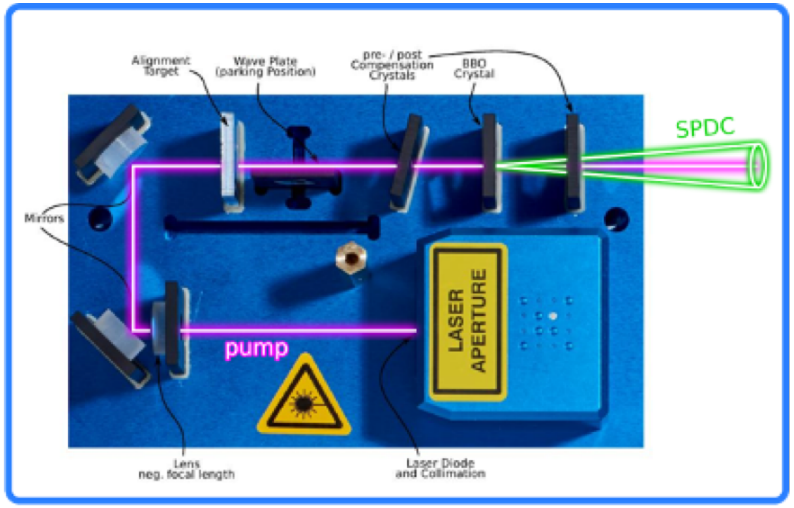
Background

The experiments need to have 0.01 events/kg/day/keV !

Donna Kubik (EP) enabled the construction of entangled photon source at SiDet

Juan Estrada's group





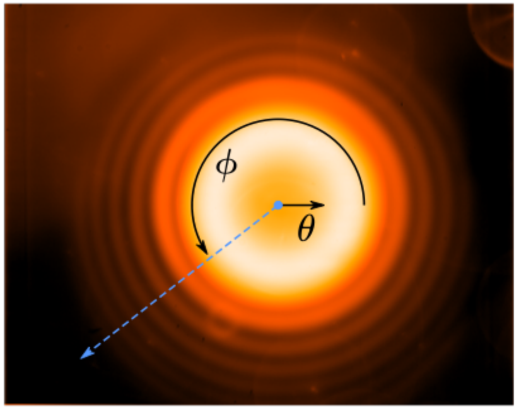
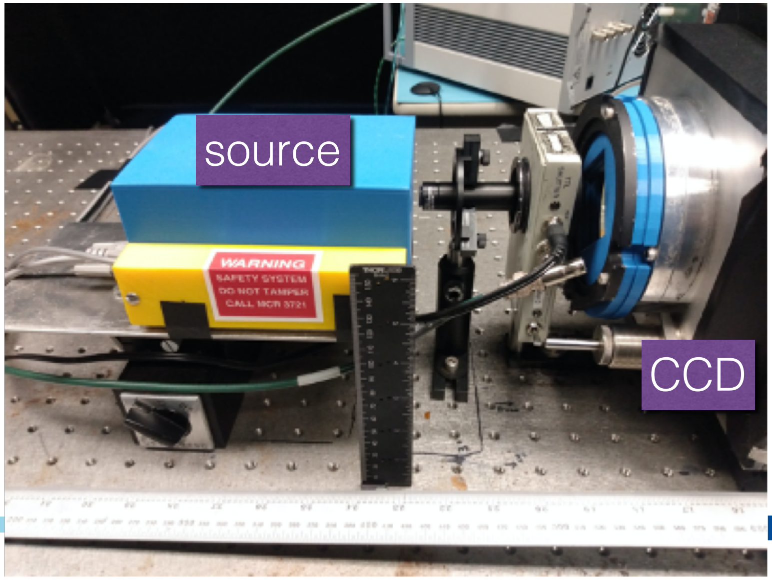


Figure 12: Average of 400 images with 200 s exposure each to the SPDC photons each using the setup depicted in Fig. 10. The angular coordinates θ and ϕ are indicated in the figure. The blue dashed line was used to extract the data profile shown in Fig. 13.

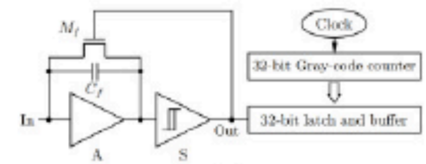


milab

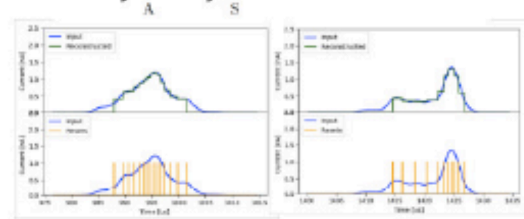
QPIX

ASIC group

Pixelated Lar Detector Readout (QPIX)



From DOE Proposal, "QPix: Achieving kiloton scale pixelated readout for Liquid Argon Time Projection Chambers"



- **Opportunity**
  - Work is in progress to define a 4th detector for DUNE → "Module of Opportunity"
  - Highly pixelated TPC is being proposed
  - Requires a readout ASIC → QPIX
  - Requirements a good match for FNAL ASIC design
- **Chip Requirements**
  - Amplifier+Discrim+Latch+Counter
  - Amplifier is self-resetting – requires very low leakage current, or current-cancelling techniques
  - Clock Distribution Counter are complex
  - Requires high-reliability, low-power
  - Final system will have ~millions of channels
  - Must operate at Lar temperatures

⇨ ***Good match for FNAL Expertise & Experience***

Primary Task	Lead Institution	Partner University Group(s)	Partner Lab(s)
Physics Sensitivity Studies	Harvard	UTA, Texas A&M	Oak Ridge, Argonne
Readout and Detector Simulation	Texas A&M	UTA, Penn, Harvard	LBNL
Front End Development	Penn	UTA, Hawaii	Fermilab, LBNL
Oscillator / Network / Readout	Hawaii	Penn	Fermilab
Photon Detection	UTA	Harvard	Argonne, Fermilab, Oak Ridge
Teststands / Mechanics	UTA	Harvard, Penn	Argonne, Fermilab, Oak Ridge

- **Outlook**
  - Simulation work is in progress now by collaborators
  - Opportunity now for R&D to develop "proof-of-principle" chip
  - Experience with DUNE Cold ASICs, 65 nm, leakage current cancellation, and discriminators could be leveraged to help develop this concept