Enhancing Astrophysical MeV Gamma-Ray Detection with GRAMS

Status of MicroGRAMS Detector R&D at Northeastern University

By Nabin Poudyal

Postdoc @ Northeastern University

On behalf of GRAMS Collaboration

at

11th Fermi Symposium Sept 13th Meeting

Introduction - GRAMS

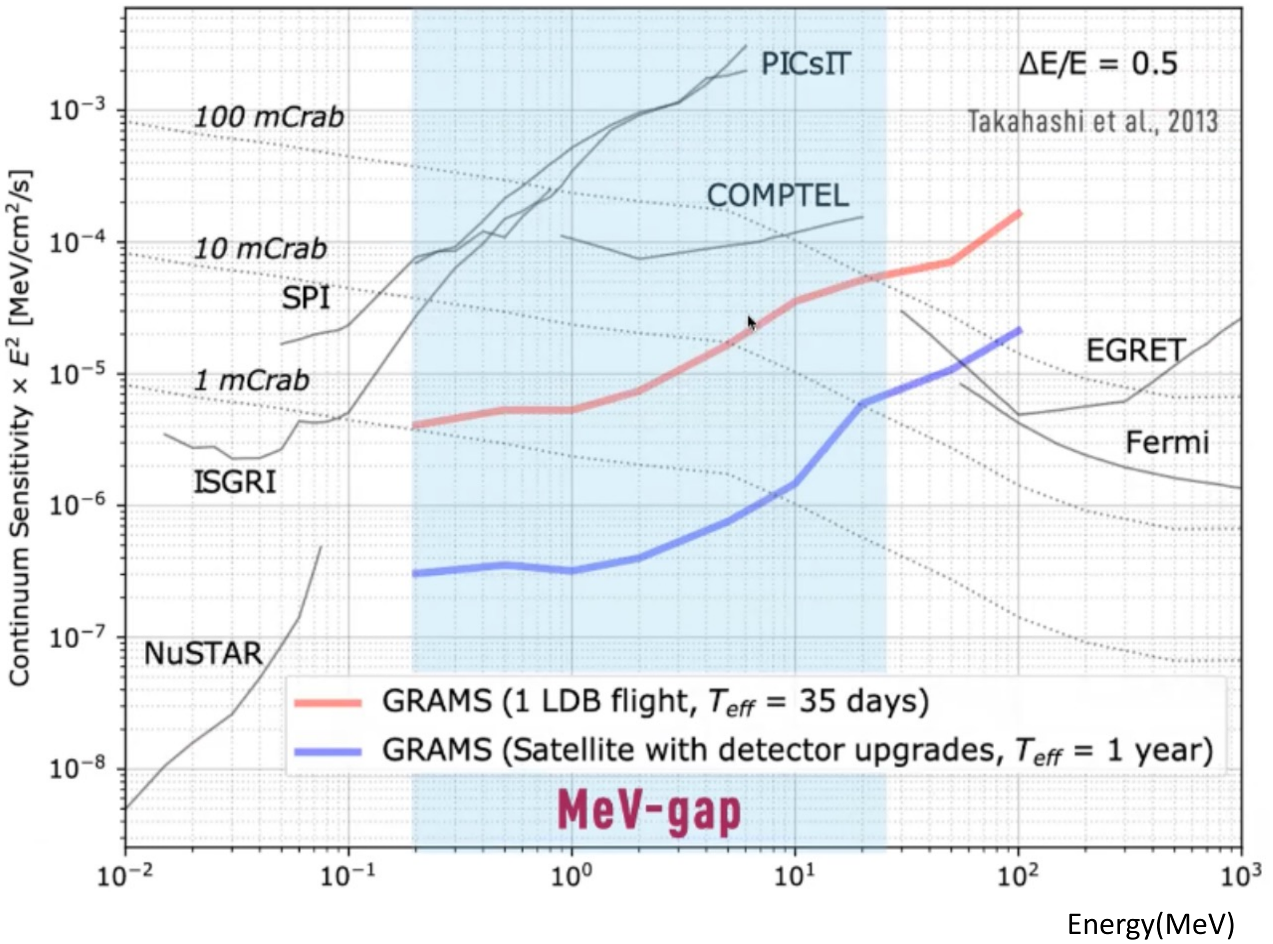
- Gamma-Ray and AntiMatter Survey.
- GRAMS is part of NASA's Physics of Cosmos mission, selected for development under NASA APRA GRANT.
- Objectives: observe both MeV gamma-rays and search for indirect dark matter.
- GRAMS, uses Liquid Argon Time Projection Chamber (LArTPC) technology, represents a novel approach with enhanced sensitivity to gamma-rays and antiparticles, offering a cost-effective and high resolution.
- pGRAMS@US is a prototype balloon flight which is scheduled to launch in 2025/2026.
    - We are developing a 30x30x20 cm LArTPC detector for the flight.
    - Goal is to detect gamma ray events and reconstruct the trajectory of charged particles.

https://pcos.gsfc.nasa.gov/projects/suborbital.php https://grams.sites.northeastern.edu/

Motivation I – MeV gamma-rays survey

- Gamma-rays in MeV energy band are under-explored, hence called MeV-gap.
- Lack of large-scale detector to provide a high sensitivity to detect gamma-rays in MeV-gap region.
- GRAMS will have an improved sensitivity by an order of magnitude for Long Duration Balloon flight and by another order for satellite mission.

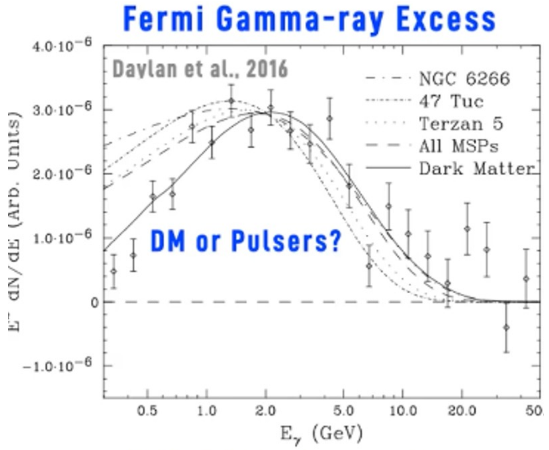
- In fact, MeV-gap survey opens to wide range of astrophysical studies.
- For example, possible existence of transitional physics processes and nuclear lines in astrophysical events.

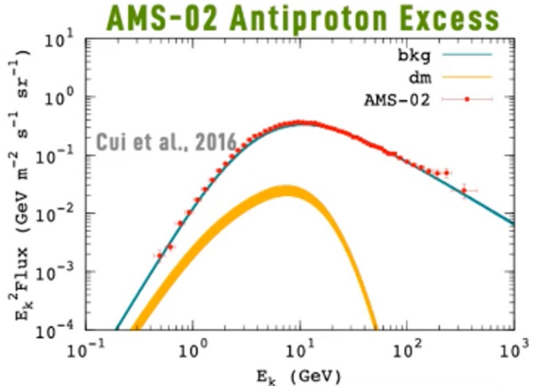


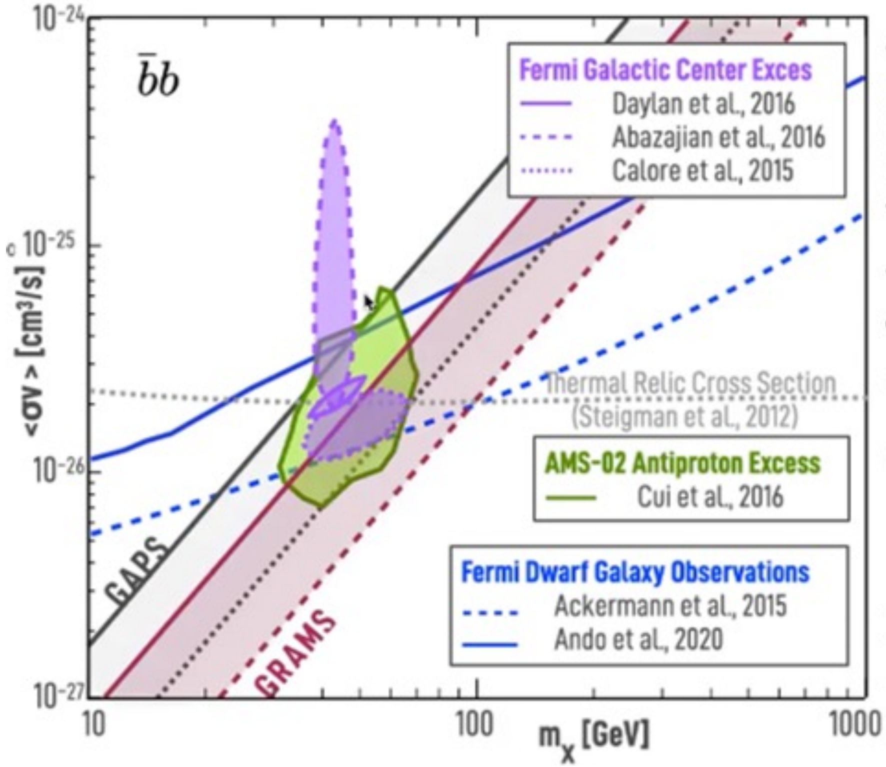
https://doi.org/10.1016/j.astropartphys.2019.07.002

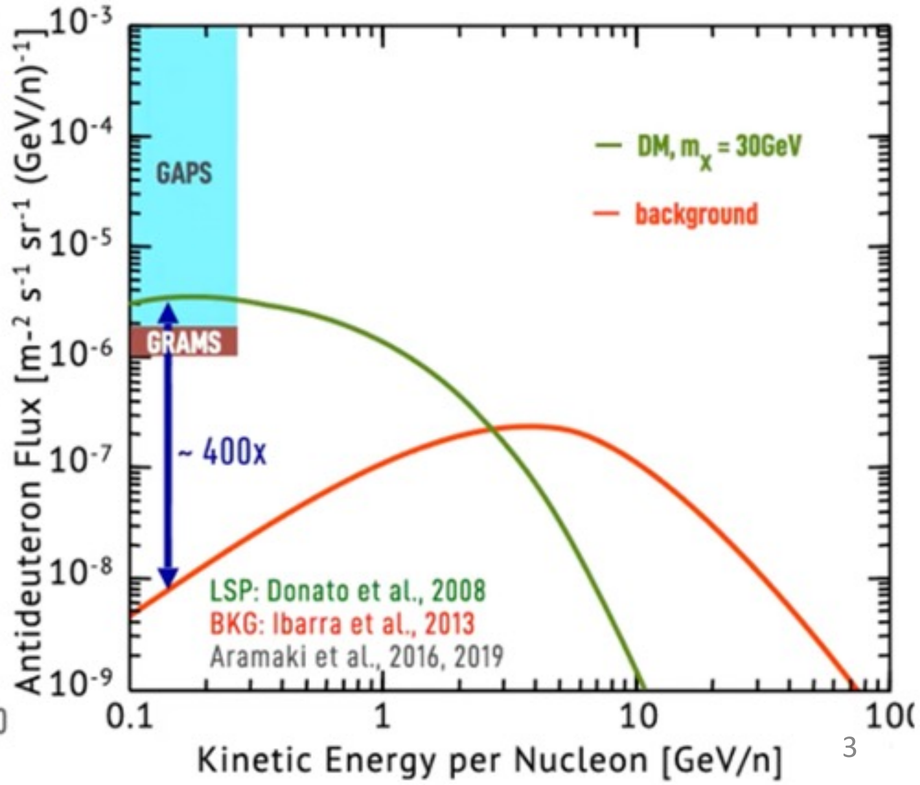
Motivation II – antimatter survey

- Fermi LAT observed surplus gamma-rays near the center of the galaxy. **Could be due to Dark matter (DM) or Millisecond pulsars. {Fermi LAT GeV excess}**
- AMS result showed an excess of antiprotons. Explanation: **DM annihilation or uncertainties in the background model. {AMS-02 Antiproton excess}**
- GRAMS will have the capability to explore this area further by measuring the flux of antideuterons/antiheliums in low mass region.
- Signal to background ratio about 400 in the low energy region provides a background free condition for DM searches.



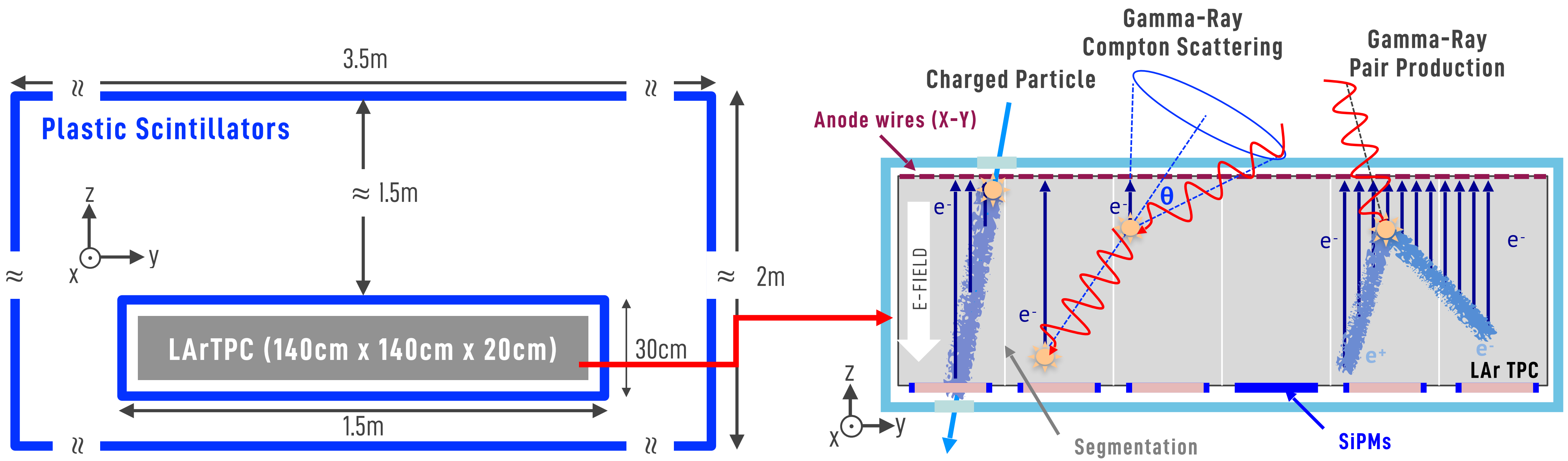






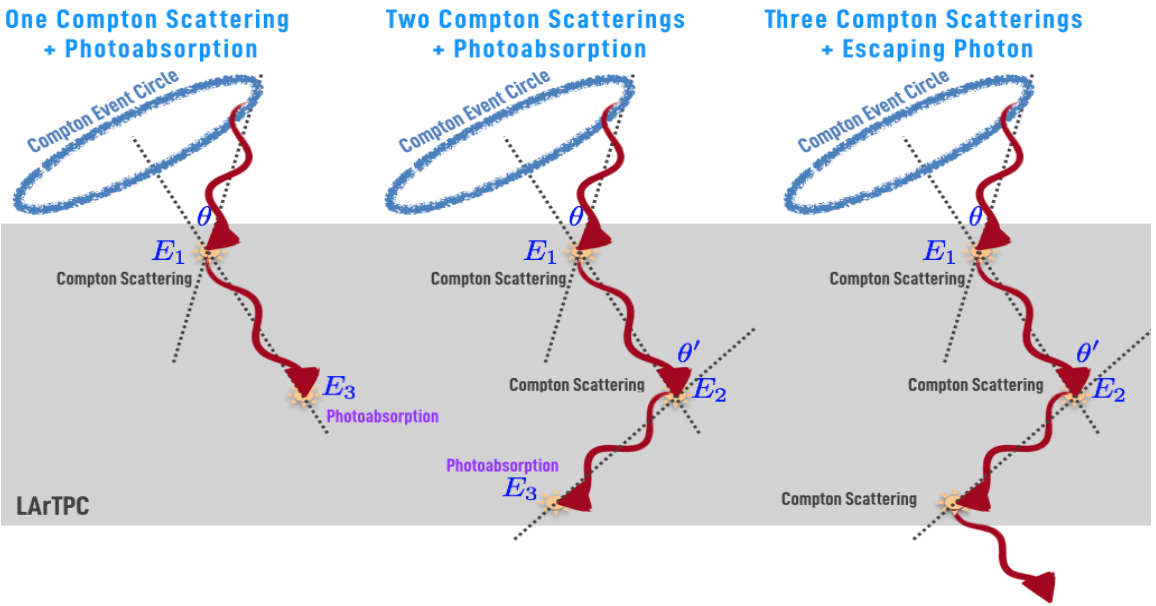
GRAMS detector design

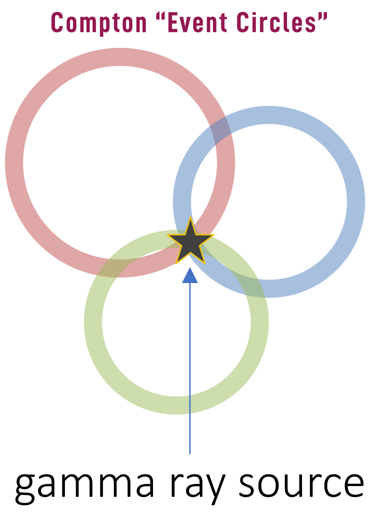
- Composed of LArTPC has a dimension of 1.4m x 1.4m x 20cm and surrounded by two layers of Plastic Scintillators.
- Primary objective of TPC is to reconstruct the 3D track and PS determines the velocity of a charge particle.
- MeV gamma-ray measurements: Plastic scintillator as veto; TPC as Compton camera and calorimeter.
- Antideuteron Detection: Plastic scintillator as Time-of-Flight (TOF); TPC as tracker and calorimeter.
- TPC reconstruct the 3D tracks by collect scintillation light and ionized electrons.

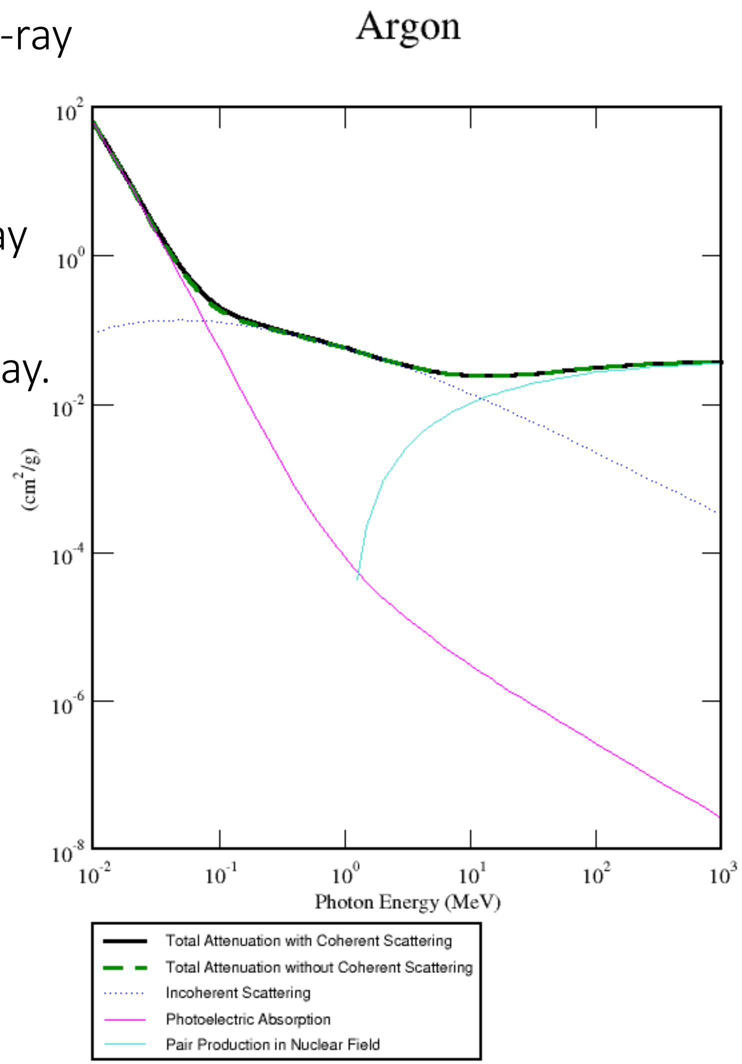


MeV gamma ray detection method

- Dominant interaction process in the LArTPC is a <u>Compton scattering</u> for MeV-gamma-ray survey.
- Consider 3 possible cases of gamma interactions inside the TPC.
- At least three Compton event circles are required to pin-point direction to gamma ray source.
- This requires determination of accurate energy and direction of an incident gamma ray.

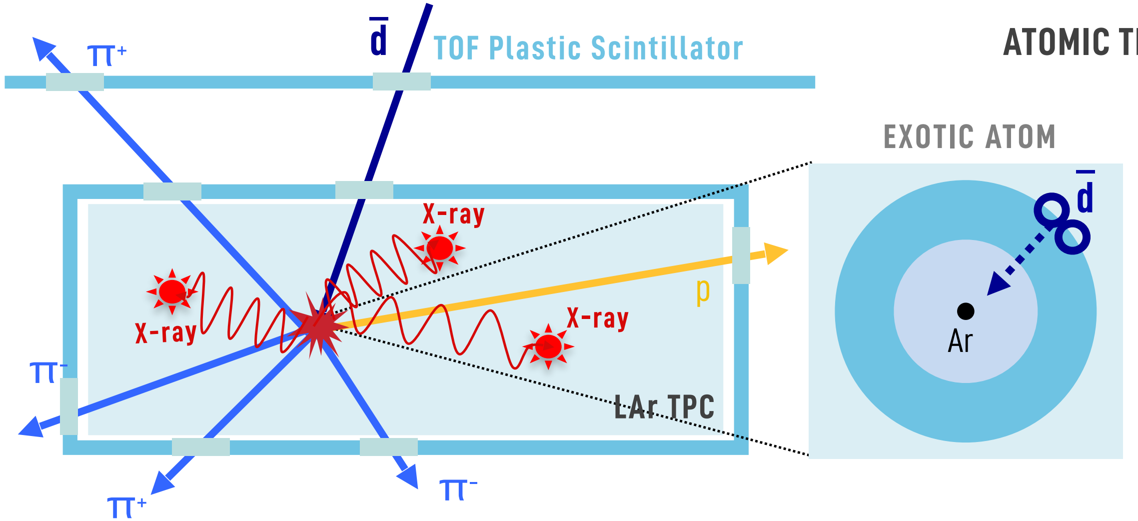






Antideuteron detection method

- Low energy antideuterons slow down in LAr and combine to form excited exotic atoms.
- Excited exotic atoms emit X-rays during de-excitation and eventually annihilates producing pions/protons.
- X-ray energy depends on type of antiparticle and target atom.
- Combining all these things together make a unique signature for detecting antideuteron with a nearly a background free condition.



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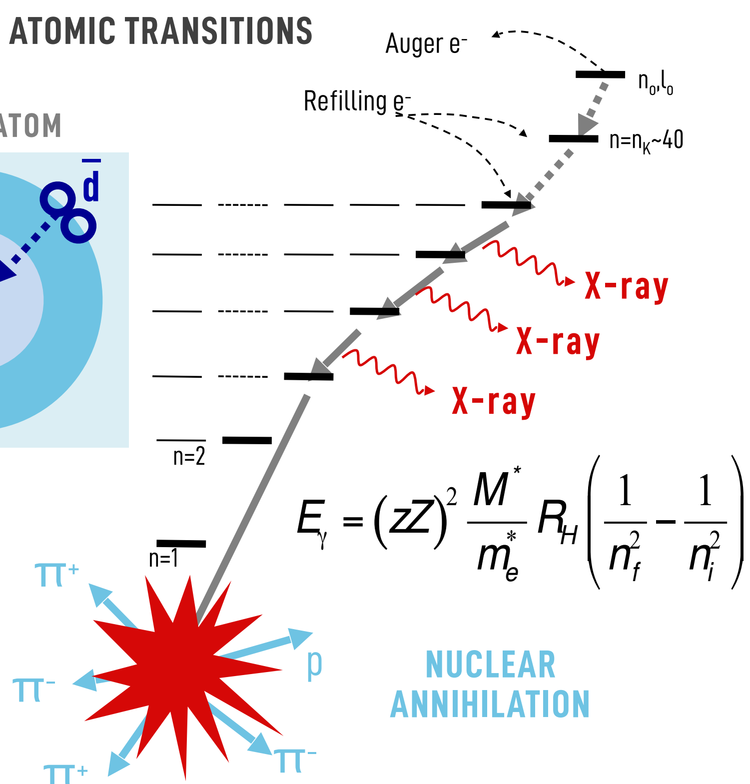
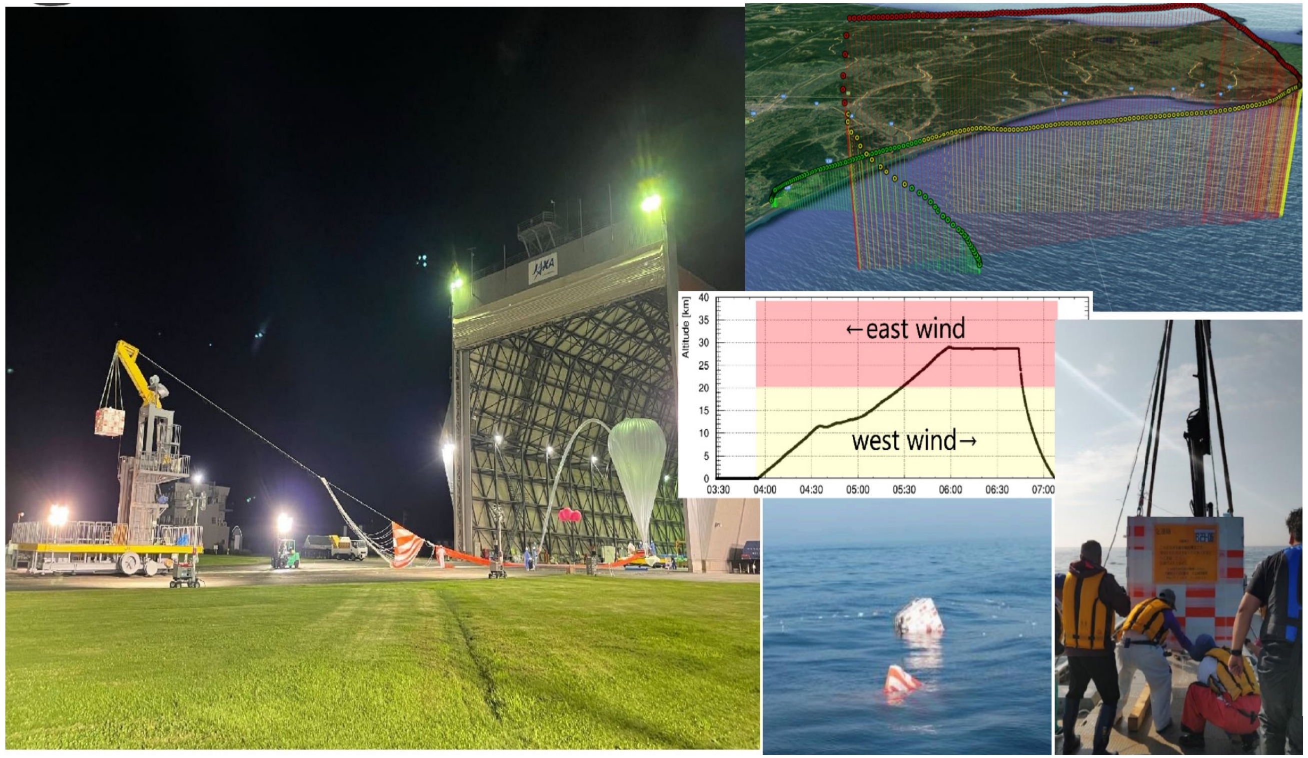
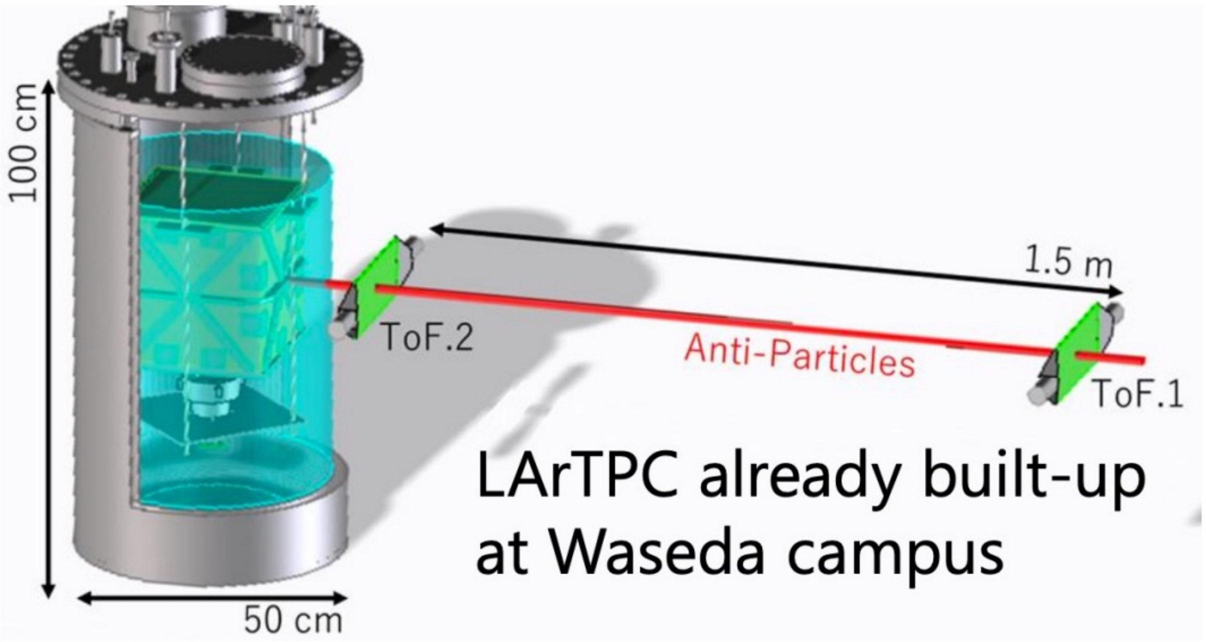


Status of GRAMS R&D

1. eGRAMS: An engineering balloon flight
   - Successfully launched in July 2023 @JAXA Taiki Aerospace Research Field in Japan
   - First LArTPC operation at stratosphere ($\leq$10 min level flight at $\geq$ 25 km)
   - TPC: (10 x 10 x 10) cm designed by Waseda University with a PMT and 3 charge channels
   - Use of pressure vessel for RPi/DAQ
2. Beam Test: An anti-proton beam test
   - Scheduled @J-PARC in 2024
   - Validate LArTPC performance as an antimatter detector by measuring atomic X-rays/annihilation products
3. pGRAMS: A prototype balloon flight
   - Scheduled to launch in 2025/2026 from Arizona USA
   - TPC (30x30x20) cm designed at Northeastern University with 180 charge and 32 SiPM light signal readout channels

Status of GRAMS R&D



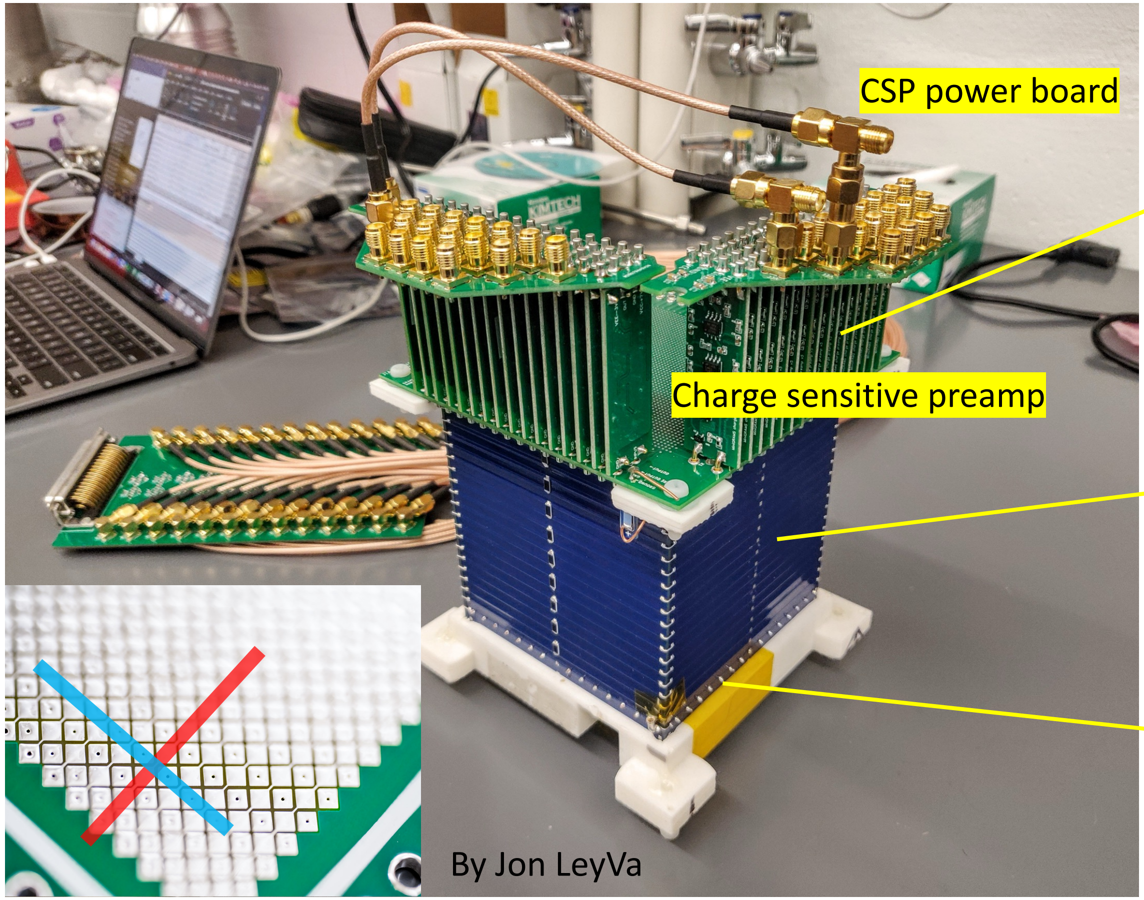


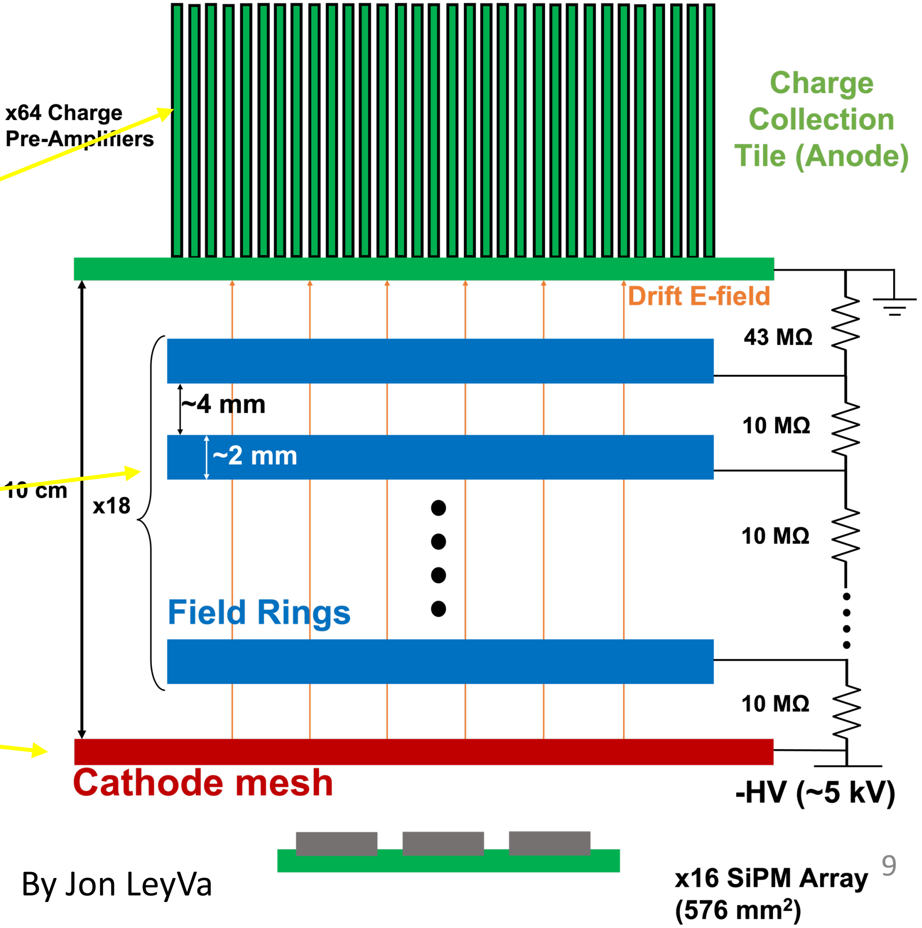
Accomplished
eGRAMS flight operation picture @ JAXA Japan

Ongoing
Beam Test R&D for antiproton capture at J-PARC Japan

Micro-GRAMS LArTPC detector at NU

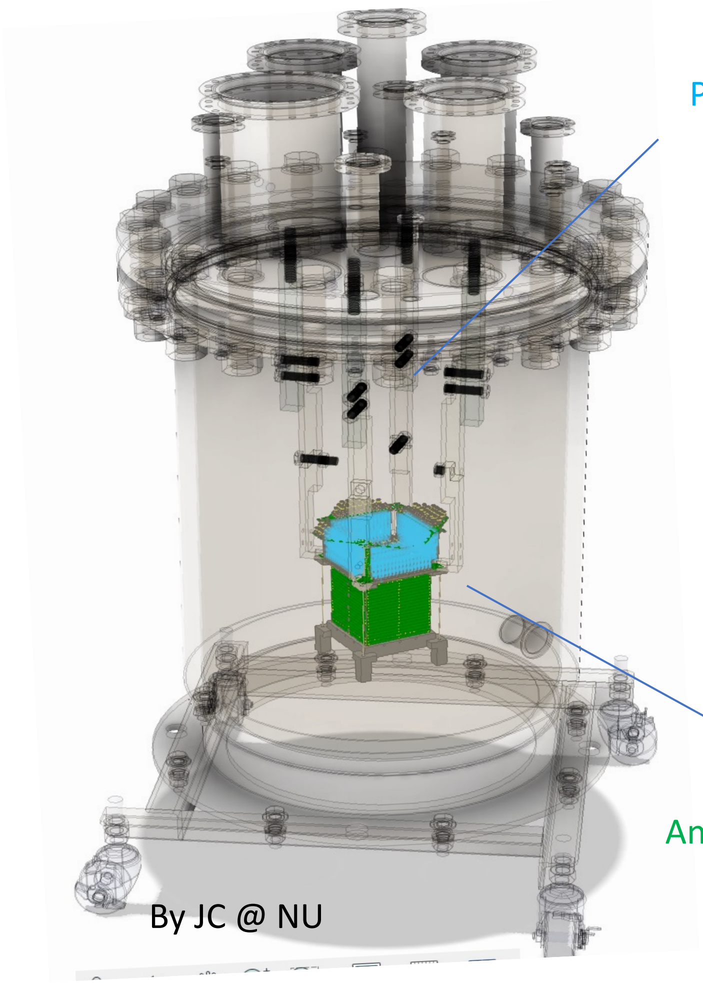
- Dimension of (10 x 10 x 10) cm with cathode mesh near the bottom and anode tile on the top.
- Anode tile consist of x and y strips separated by 3 mm and has a total of 64 strips.
- Each strip is connected to 64 charge signal channels, each of which is read out by a charge-sensitive preamp.
- We deploy an array of SiPMs at the base of the TPC to collect light read out with a total of 4 channels.



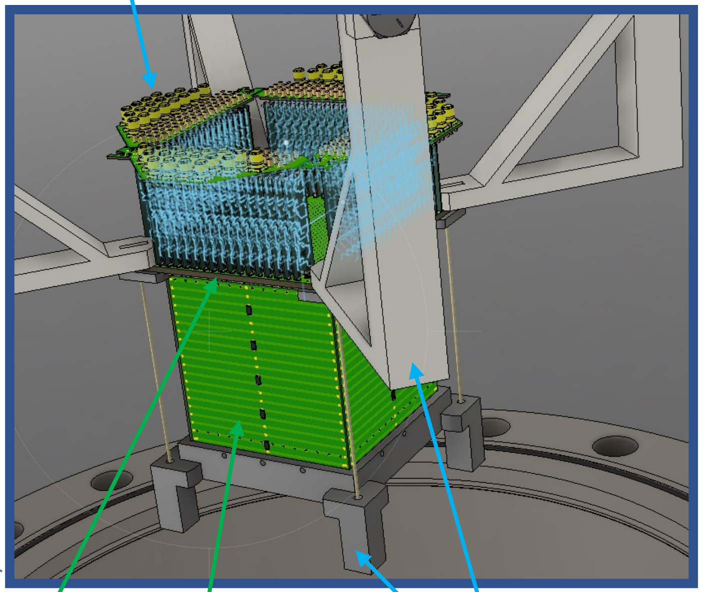


LArTPC cryostat

- Full 3D design of chamber and TPC at Northeastern University.
- During the operation, the chamber is filled with LAr till TPC is fully submerged.
- Maintain the chamber at constant pressure and temperature during the data taking.
- A CAEN digitizer to record the cosmic muon and Co-60 events.



Pre-amp power and signal distribution boards

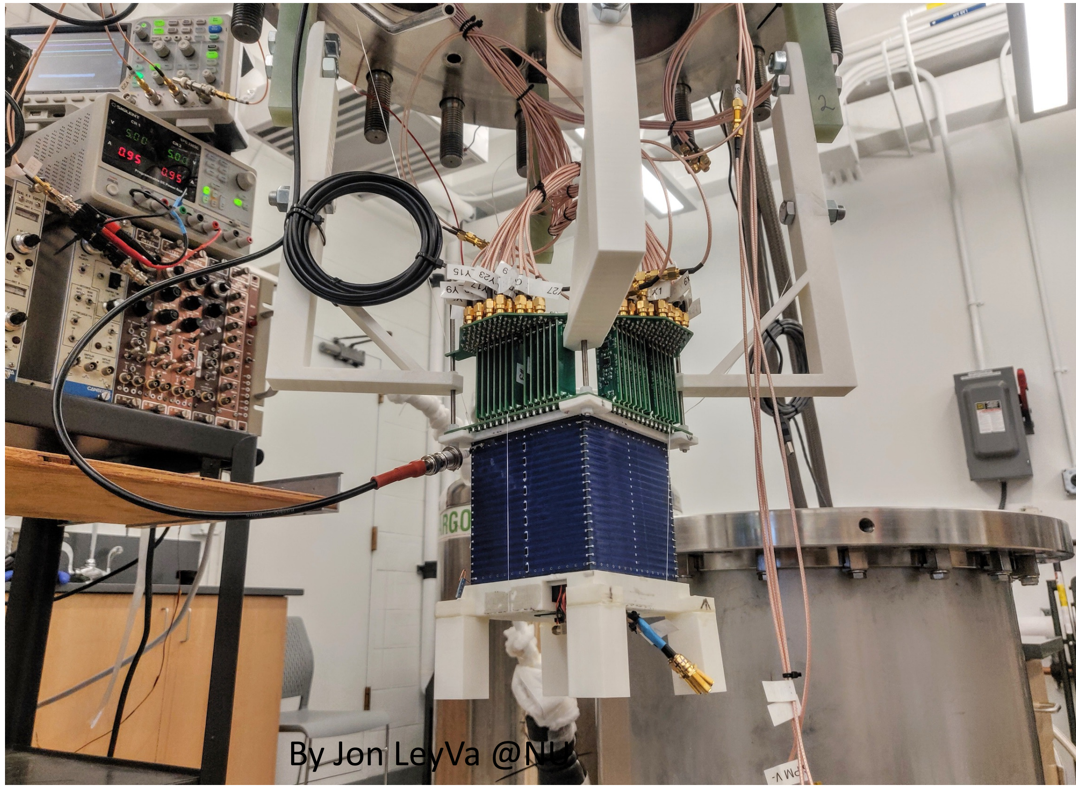


By JC @NU

Anode Tile

Field Cage

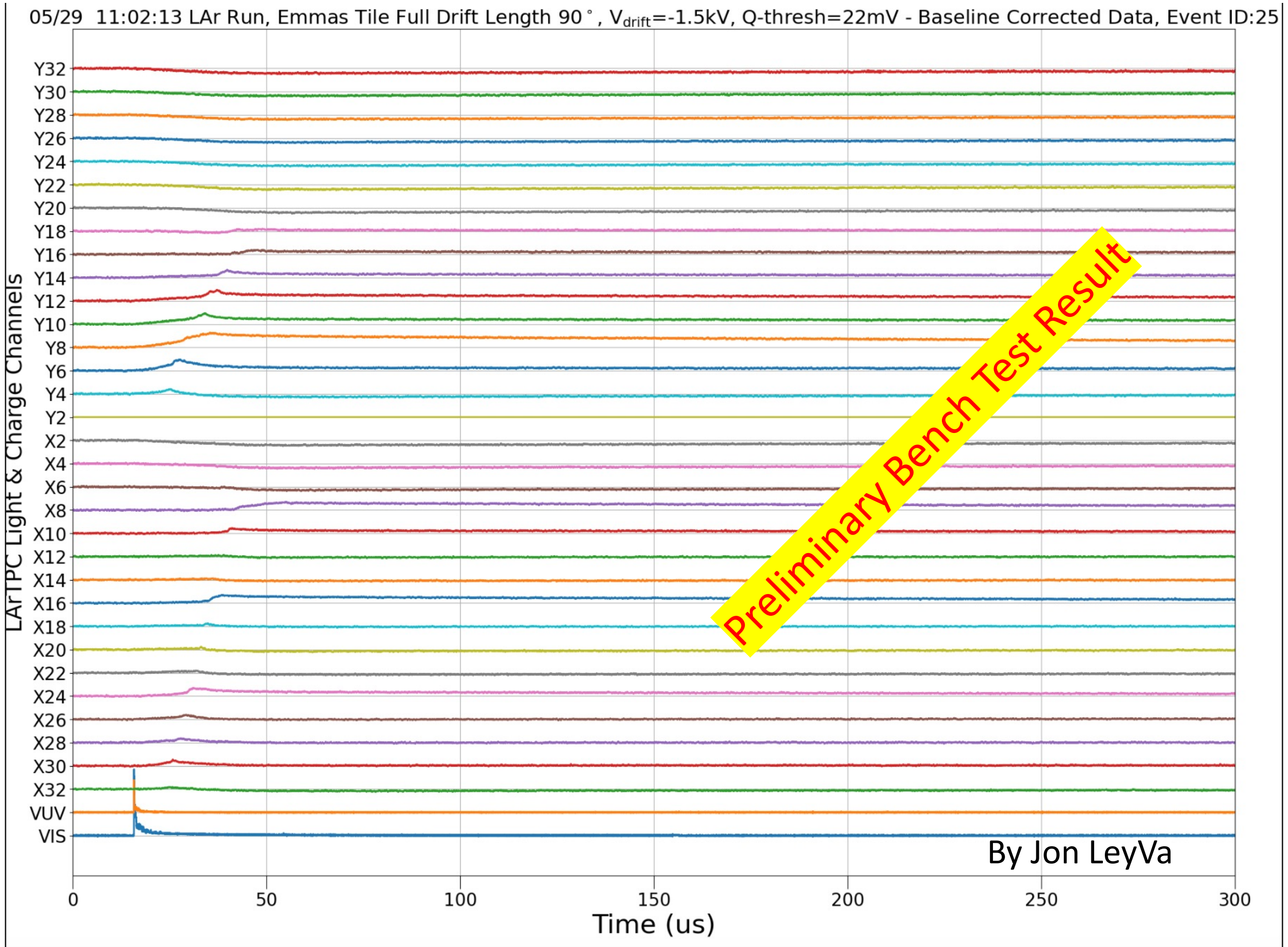
3D Printed TPC support rod



Supported TPC

Preliminary data analysis and track reconstruction

- NU Lab Achievements: Muon track reconstruction
  - Record all the charge channels immediately after SiPM hits, search for signals above a specific threshold to reconstruct a muon track.



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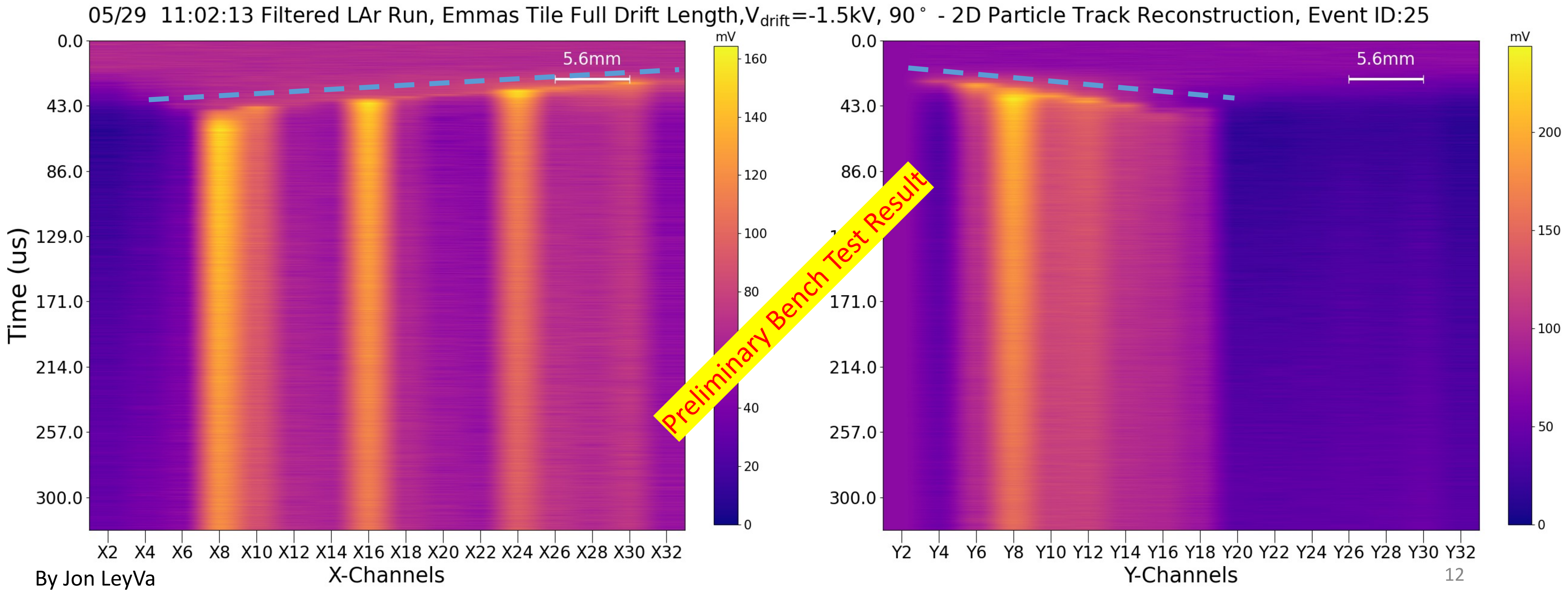
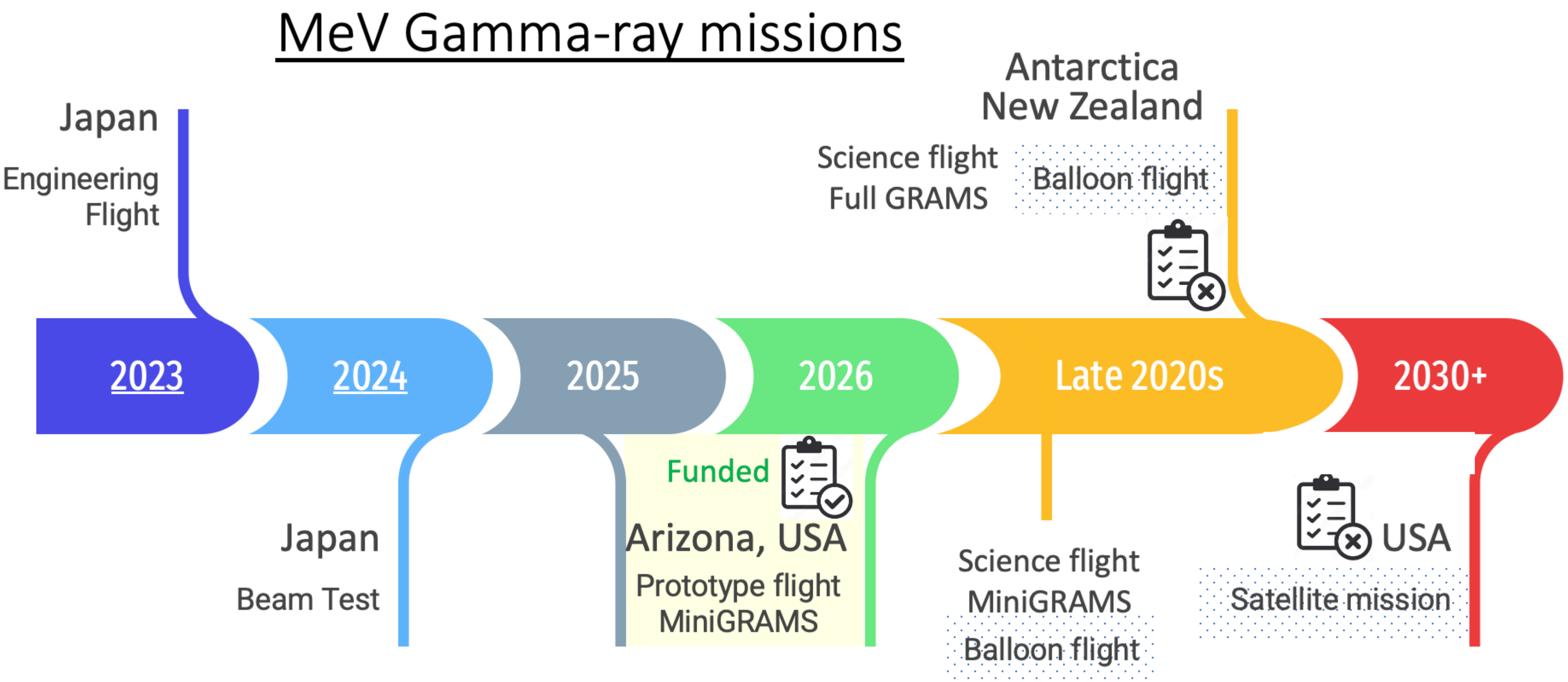


By Jon LeyVa

Conclusion and outlook

- GRAMS: Optimized for MeV gamma-ray observations and indirect dark matter searches.
- The first large-scale LArTPC detector above the ground and will have highly improved sensitivity.
- Encouraging advancements are being made with the ongoing R&D of the GRAMS prototype detector.



GRAMS Collaboration

May 2024 Collaboration meeting

Washington University in St.Louis
KANAGAWA UNIVERSITY
YNU
Berkeley UNIVERSITY OF CALIFORNIA
JAXA
Julius-Maximilians-UNIVERSITÄT WÜRZBURG
OAK RIDGE National Laboratory
UNIVERSITY OF TEXAS ARLINGTON
HOWARD UNIVERSITY
Northeastern University
立教大学 RIKKYO UNIVERSITY
COLUMBIA UNIVERSITY
BARNARD COLLEGE COLUMBIA UNIVERSITY
TOKYO UNIVERSITY OF SCIENCE since 1881
WASEDA University 早稲田大学

Back up

Reference

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7. https://doi.org/10.1016/j.astropartphys.2013.08.003

Acknowledgment

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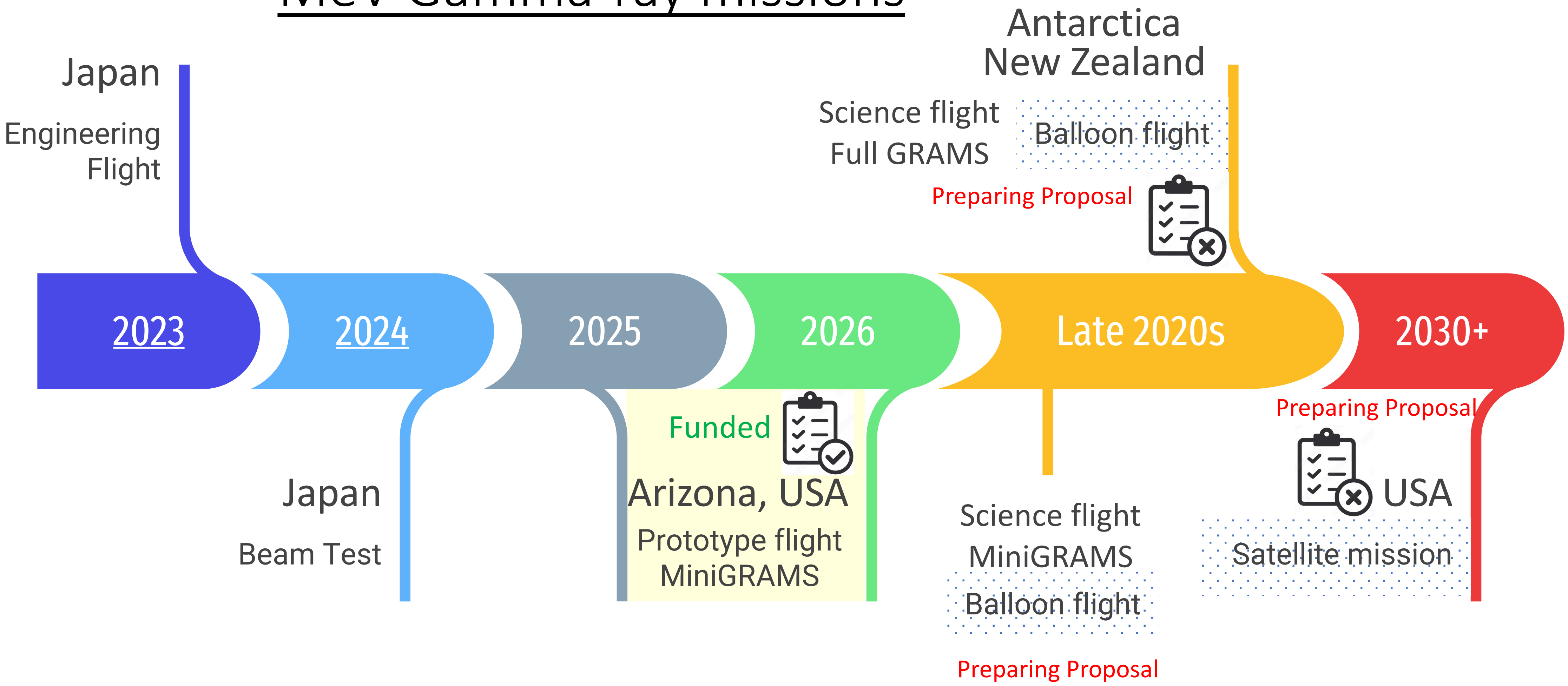
MeV Gamma-ray missions



Outline

- Introduction GRAMS experiment
- Project motivations and objectives
- Design concept of the GRAMS Detector
- MeV gamma-ray and antideuteron detection methods
- Status of MicroGRAMS detector R&D at Northeastern University
- Detector hardware and data analysis

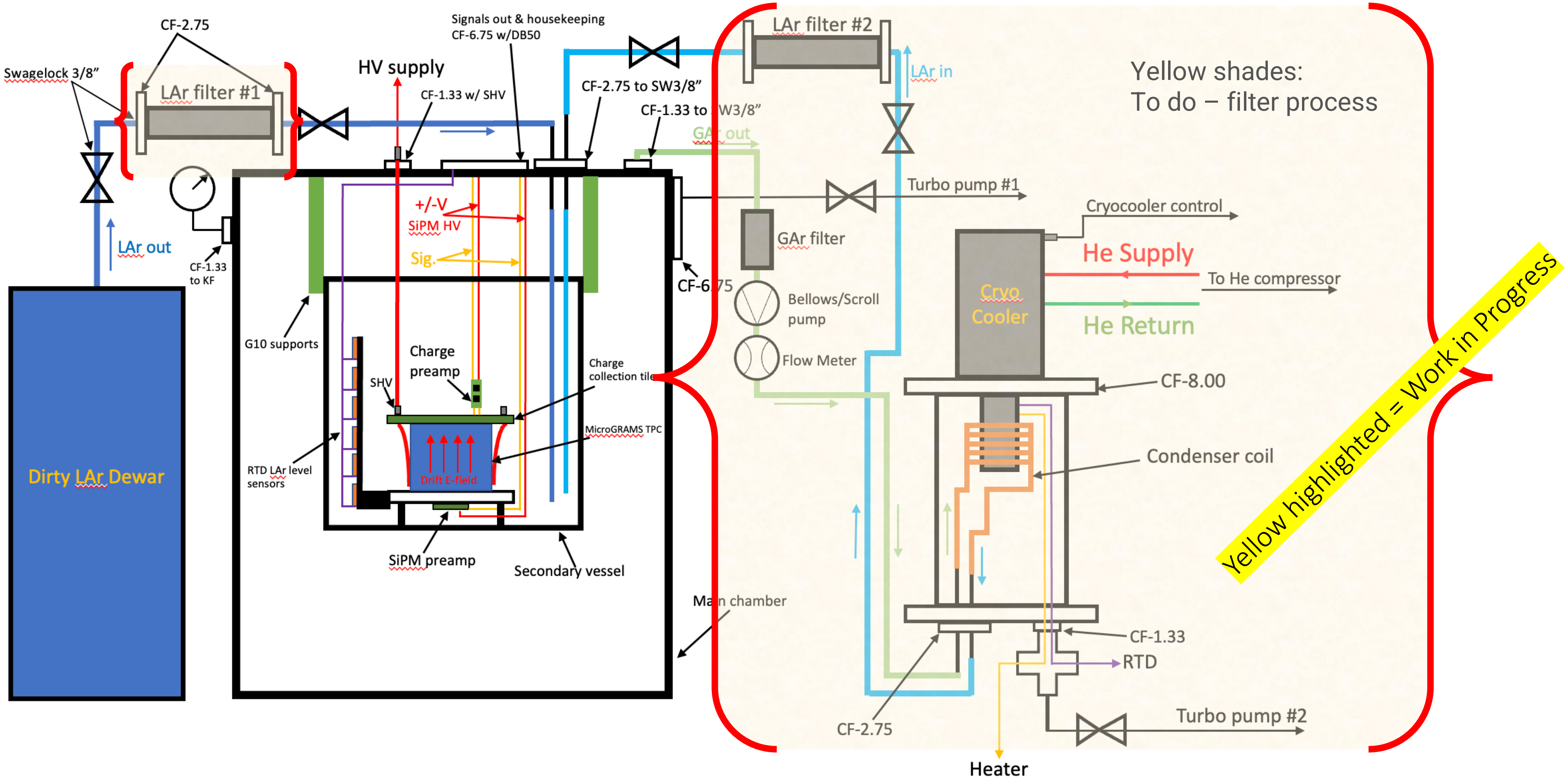
Details

Conservative design: To improve the angular resolution, a set of event selections was also applied; Compton scatterings must be spatially separated by ≥ 10 (2) cm, and pair-produced electrons and positrons must stop inside the sensitive volume and leave tracks ≥ 2 (0.4) cm long (with detector upgrades).

Energy resolution are adopted”: The energy resolution of LArTPC is estimated from measurements by other experiments deploying similar detectors; DarkSide-50 and nEXO measured σ E ∼ 5% at 41.5 keV and ∼ 1% at 2.5 MeV, respectively

Schematics of current TPC detector at NU

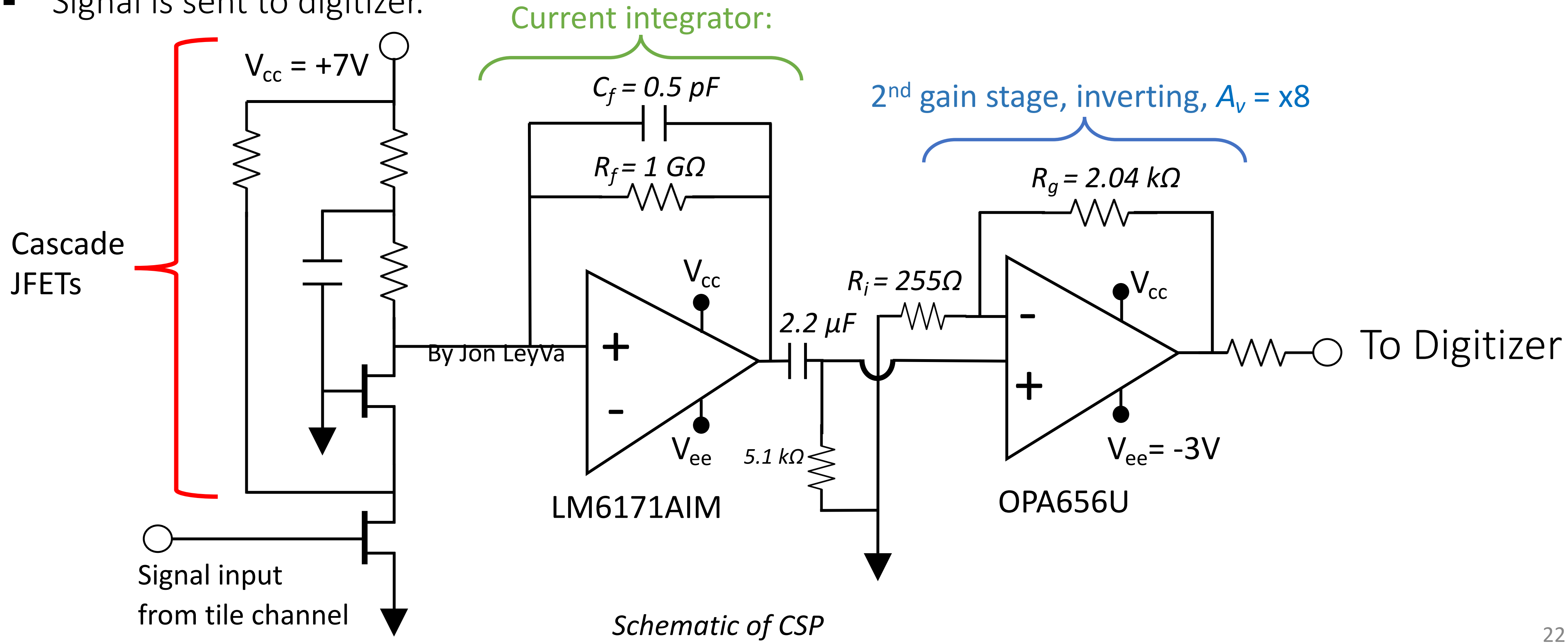
- Pump out the chamber using roughing pump and turbo pump tilll we reach about 10^-5 torr pressure.
- Liquid argon is directly filled via ullage pipe.
- Through the filling procedure, we cool down the chamber by running cold head.
- Monitor the temperatures and pressures inside the chamber using House keeping software.



By Jon LeyVa

Current pulse processing - conditioning

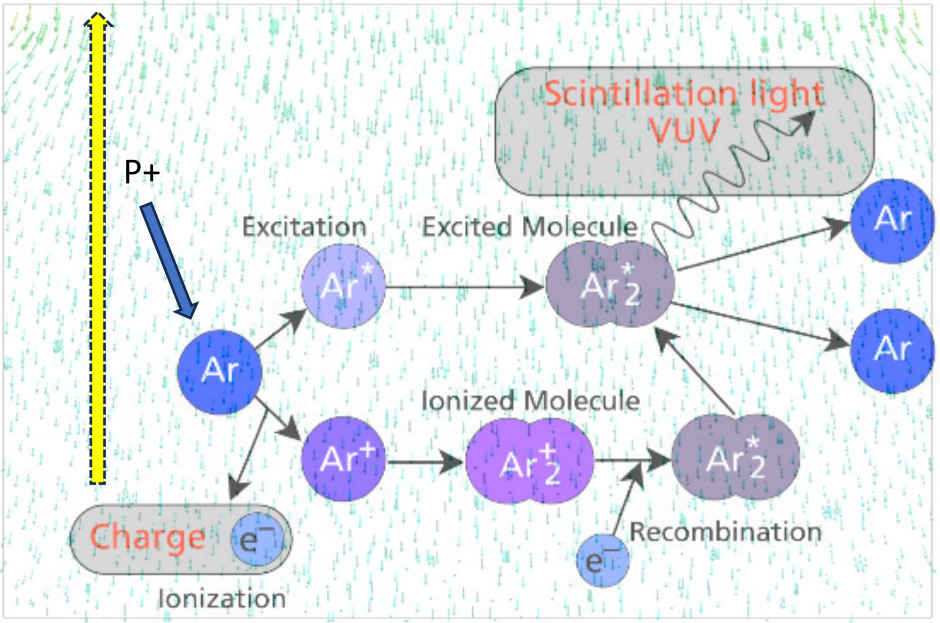
- Cascade JFETs: Reduce the impedance imposed by the Cf and increase the signal bandwidth
- CM = Cf (1 + Av)
- Current pulse is integrated using op-amp LM6171 using CSP configuration with Cf, Rf.
- Output voltage is amplified in second stage
- Signal is sent to digitizer.



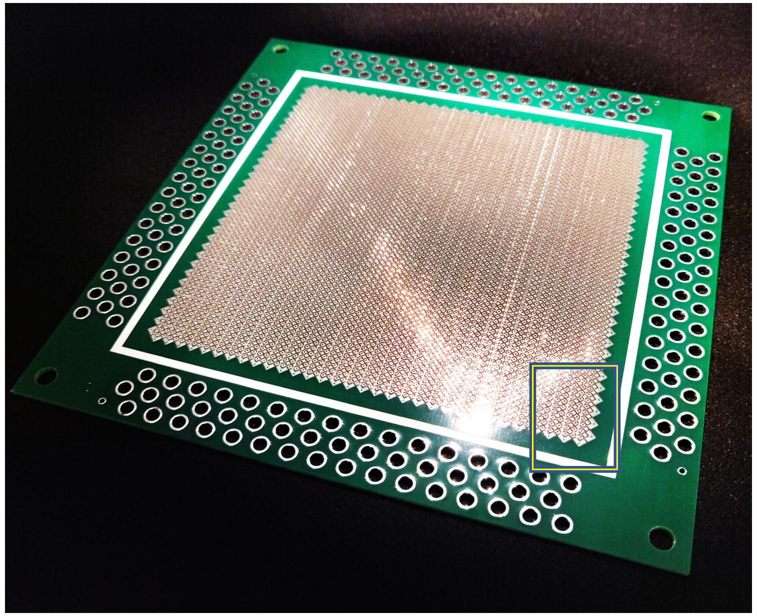
Schematic of CSP

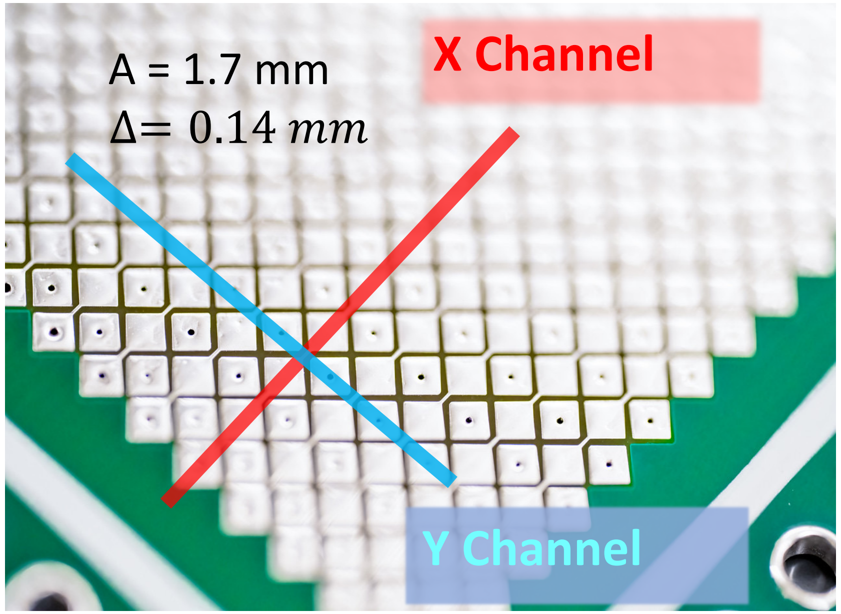
LArTPC: determination of interaction position

- When a charged particle interacts with Ar, there will be a generation of ionization electrons and scintillation VUV light.
- The electrons drift towards the anode tile due to e-field setup.
- Anode tile is arranged with X & Y strips → a hit → x,y coordinates of an interaction point.
- The VUV light produced is collected by an array of SiPMs at the base of TPC.



DOI:10.13140/RG.2.2.22656.79360



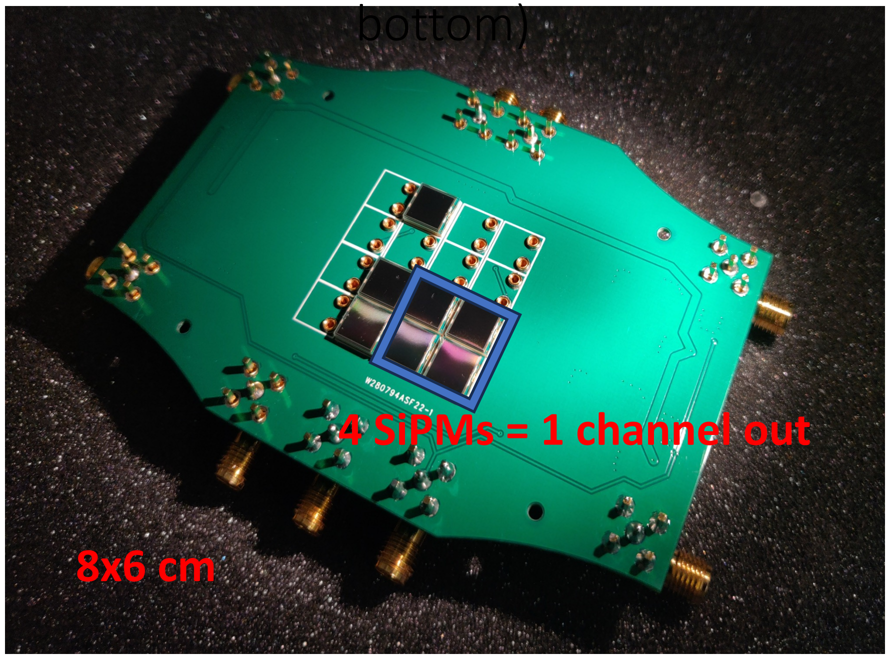


By Jon LeyVa

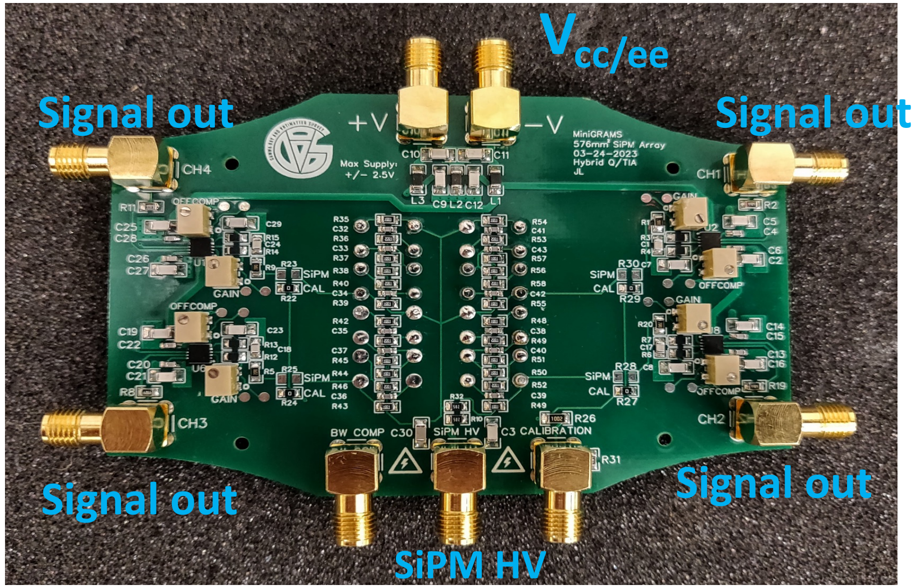
Analog signal processing board

- The TPC has a SiPM board at bottom, measuring approximately 8x6 cm.
- 16 SiPMs are grouped into sets of 4, collectively producing one light output.
- Signal amplification for the SiPMs is done by a circuit with adjustable gain, utilizing an operational amplifier configured in a transimpedance setup.
- Additionally, there's a charge-sensitive preamplifier circuit for the detector tiles, followed by a second-stage amplifier.

SiPM configuration (TPC bottom)

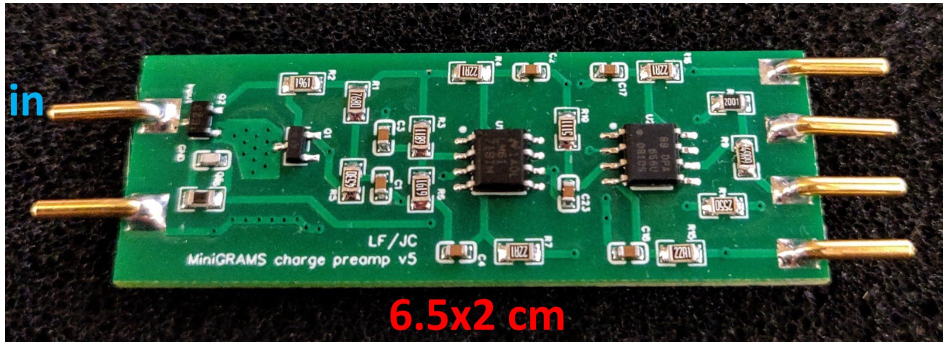


SiPM signal amplifier - TIA configuration



Charge sensitive preamp

Signal in



V_{cc}

Signal out

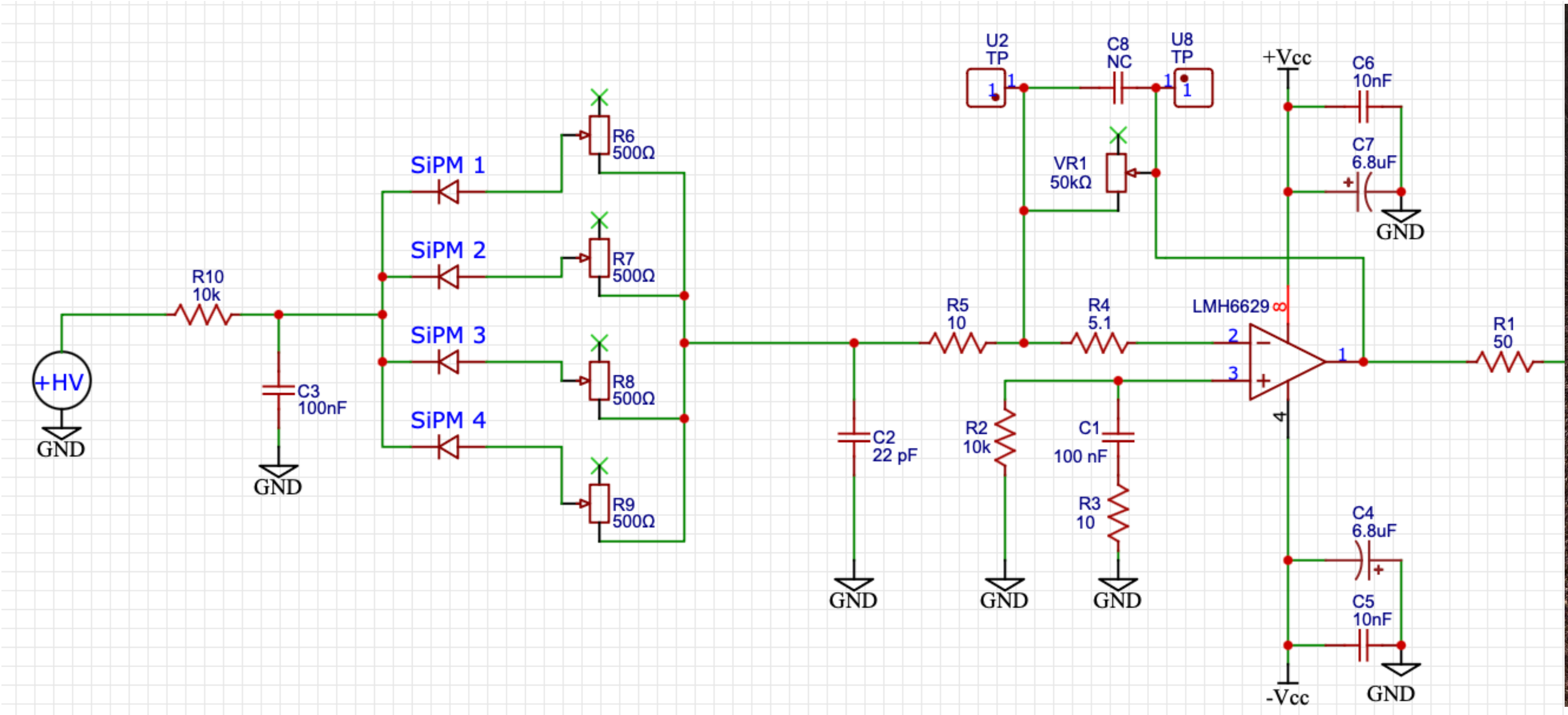
V_{ee}

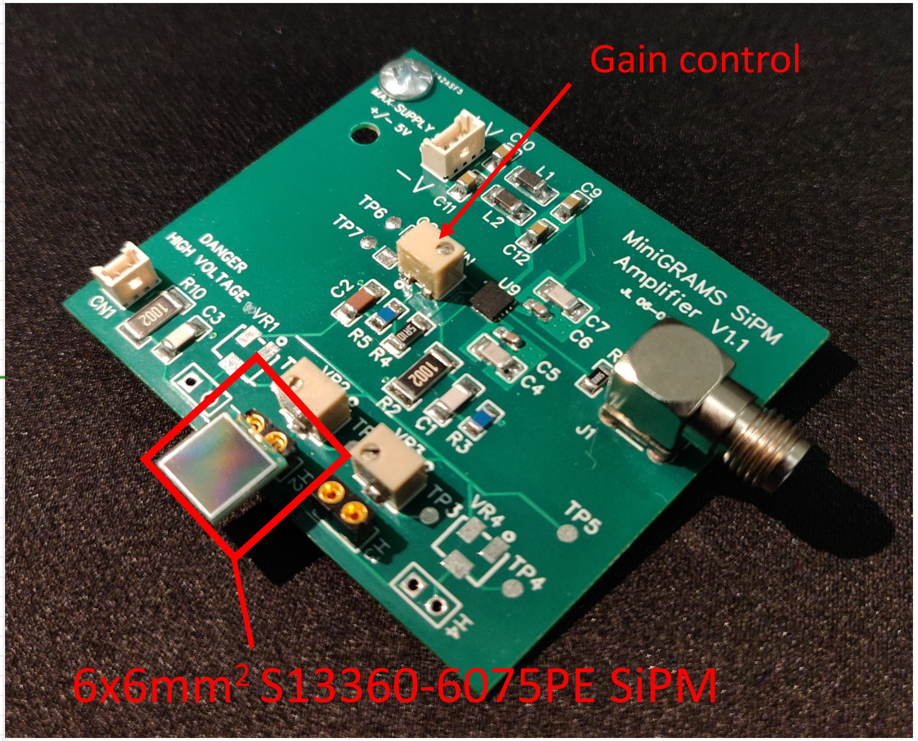
By Jiancheng Zeng

By Jon LeyVa

Light signal processing - conditioning

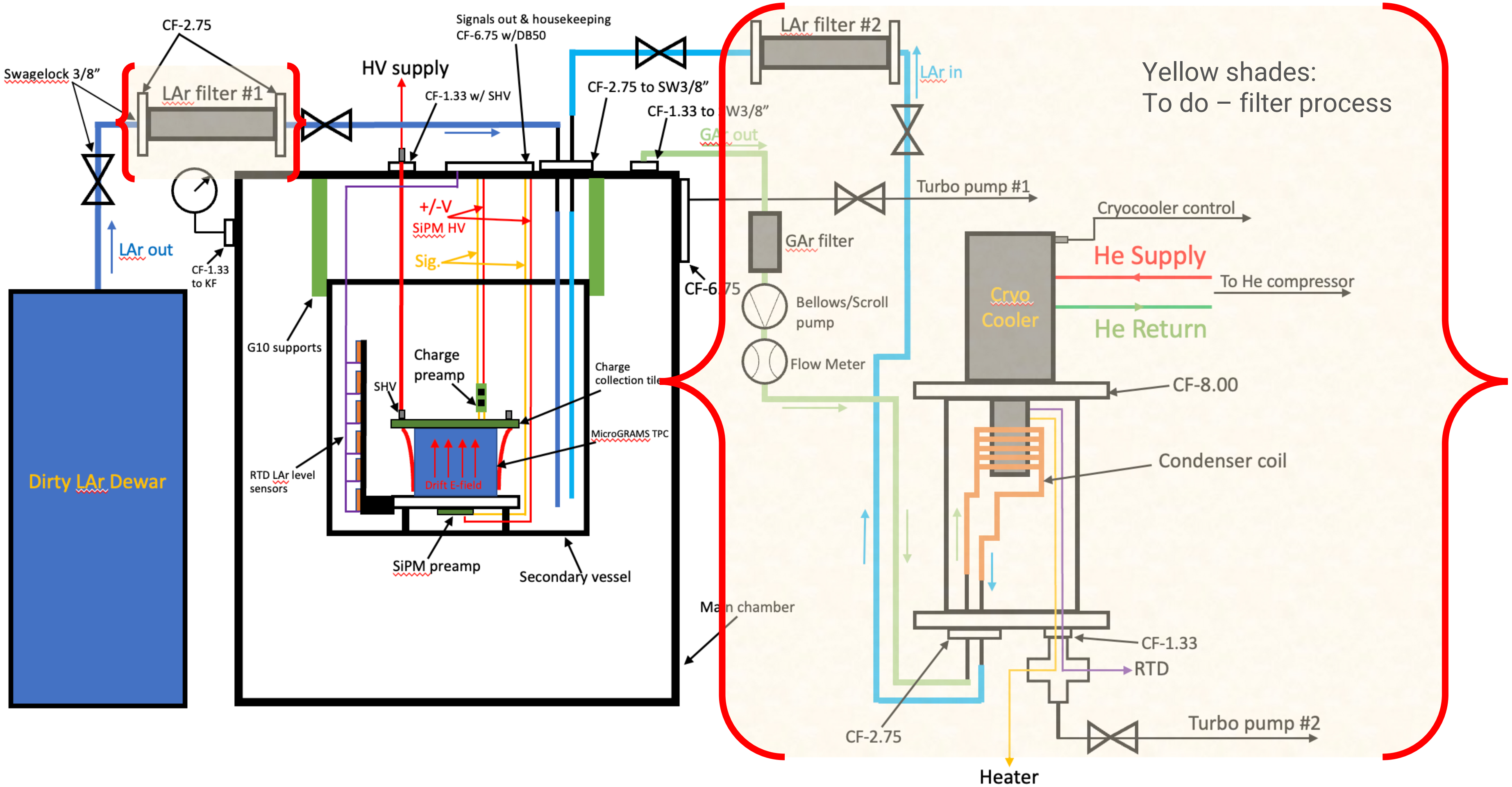
- First, Digitizer usually have limited resolution for a dynamic range.
- The current from SiPM is very weak and may seem absent due to accumulate in the first bin.
- To amplify the weak signal, we combine four SIPMs (Silicon Photomultipliers) in parallel and output is amplified using an op-amp in a transimpedance configuration.





Setting up the particle detector

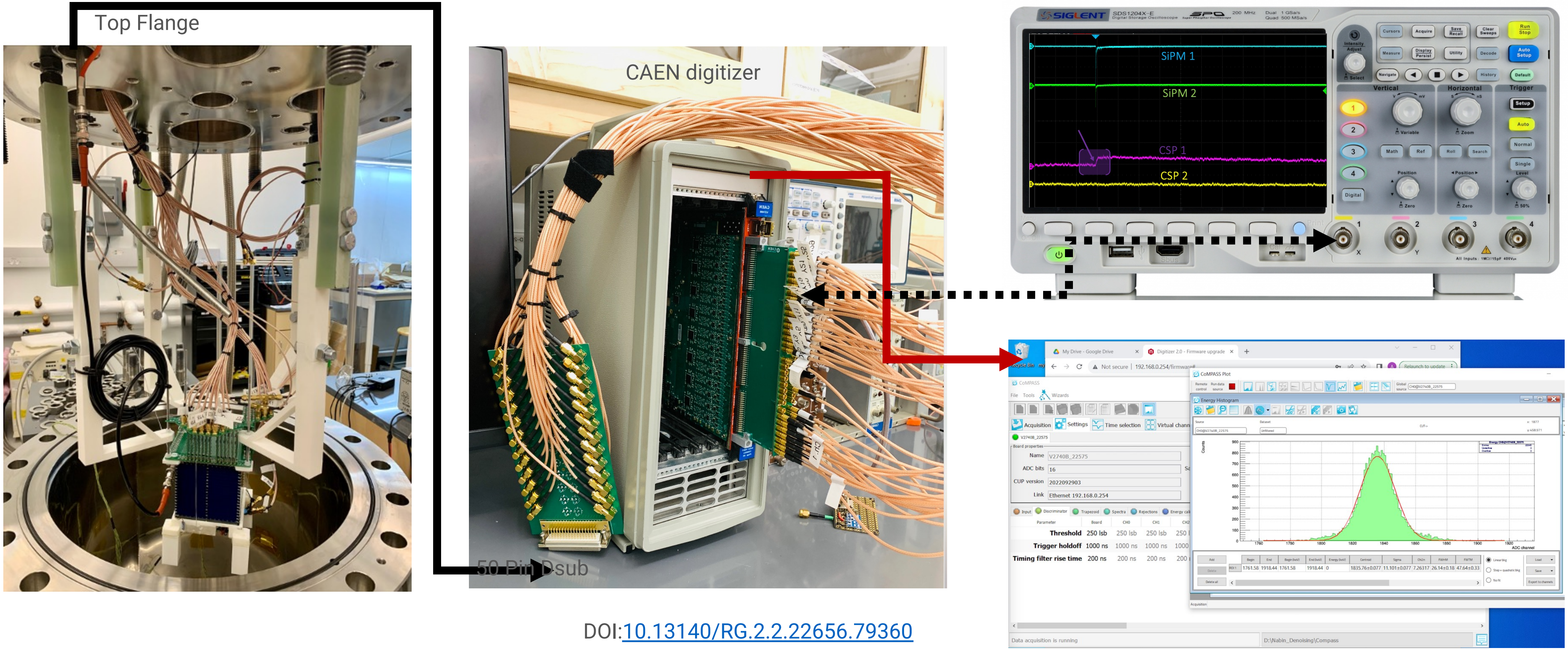
- Pump out the chamber using roughing pump and turbo pump tilll we reach about 10^-4 torr pressure.
- Liquid argon is directly filled via ullage pipe.
- Through the filling procedure, we cool down the chamber by running cold head.
- Monitor the temperatures and pressures inside the chamber using House keeping software.



By Jon LeyVa

Tested with scope and setup the DAQ system

- Once the TPC is fully submerged into LAr and system is stable and ready, we record the data .
- Signal channels are transmitted via 50 pin D-sub with co-ax cable to digitizer.
- We can directly feed the signal to scope and do waveform analysis.
- Do signal processing with CAEN digitizer and see the output in computer.



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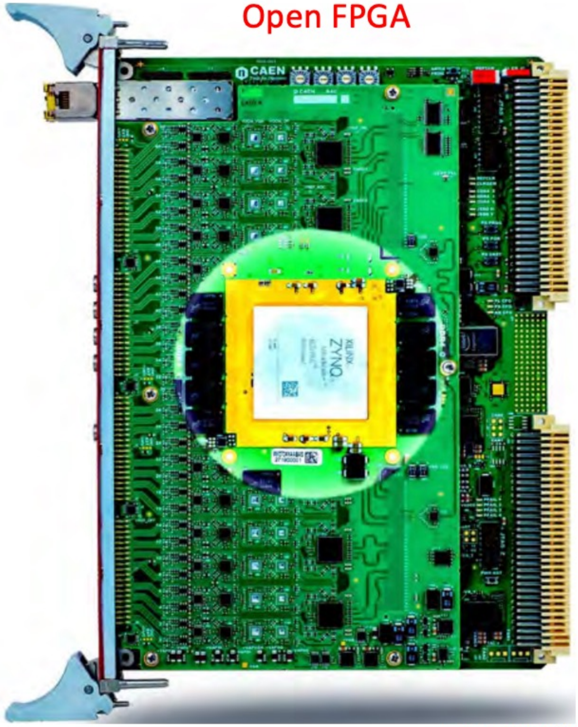
CAEN digitizers V2740B (Vx2730)

- In experiment, we have many channels and may events to readout.
- We need system with high sampling rate, faster response, configurable, etc.
- V2740 digitizers: 64-Channel Digital Signal Processor (waveform digitization, digital pulse processing)
- Almost any logic can be implemented that is required for signal processing such as Coincidence/veto, Complex Trigger Logic, Gate and Delay generator, etc.
- Can be controlled and programmed via inbuilt USB or ethernet cable.

Open FPGA



www.caen.it

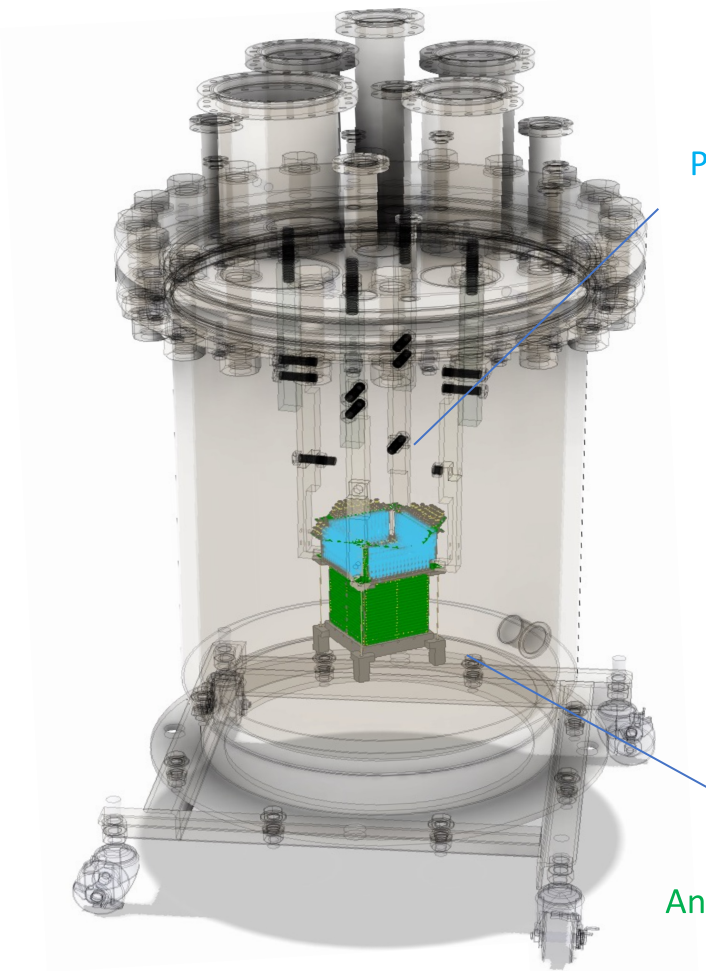
V2740B

Features of V2740B

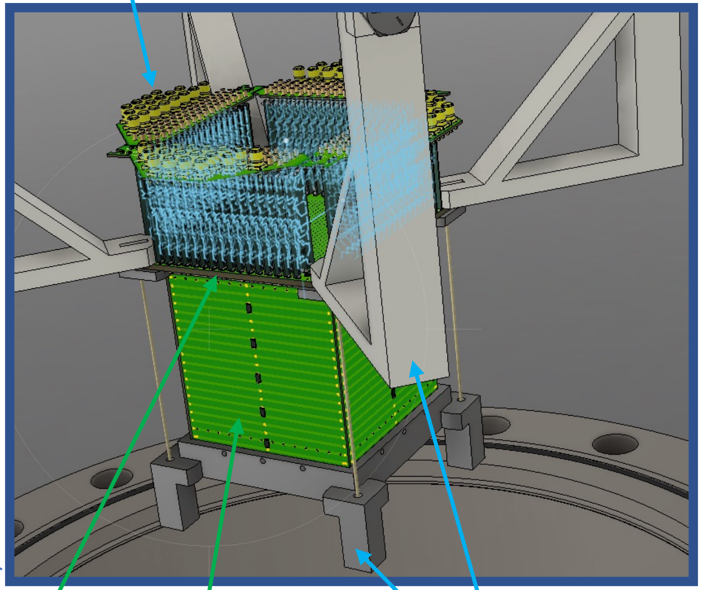
- Dynamic range: 2Vpp
- 64 Channels, bandwidth of 50MHz at -3dB
- 125MS/s rate with 16 bits resolution
- RMS noise is about 120uV.
- Common and individual trigger
- Timestamp resolution of 8ns (fine timestamp in ps range)
- 2.5 GB of total acquisition memory (DDR4)
- Multiple boards can be synced at 62.5MHz clock frequency.

LArTPC cryostat

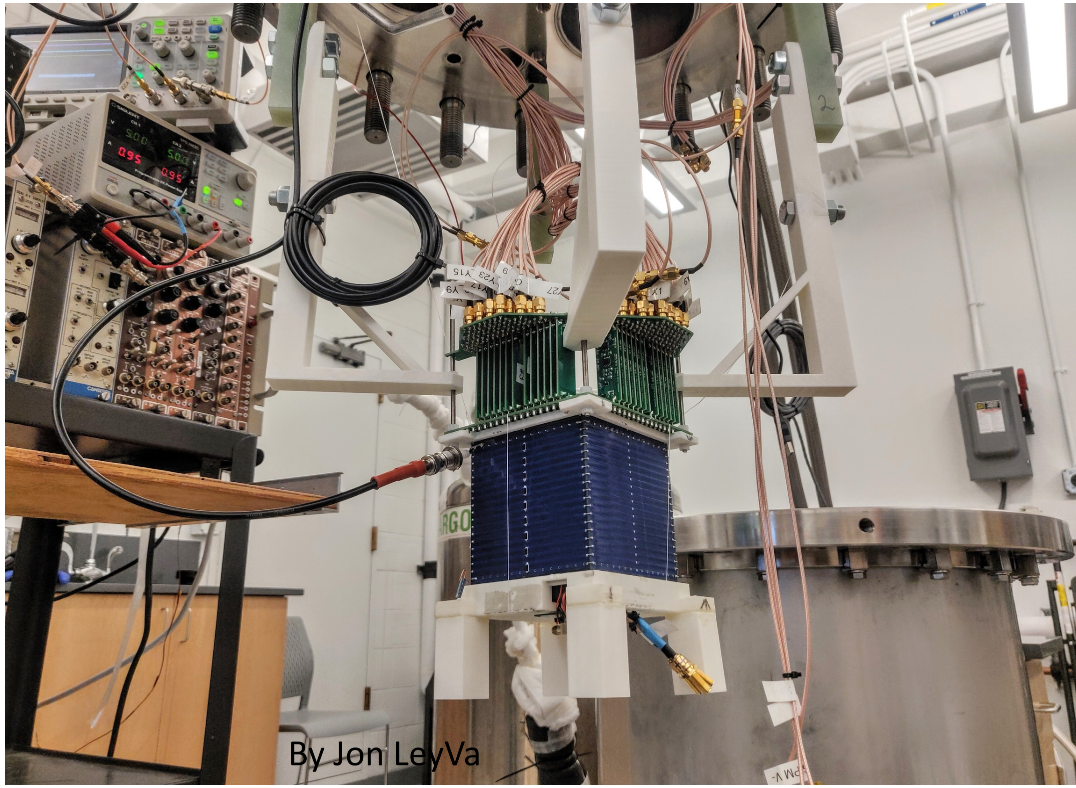
- Full 3D design of chamber and TPC done by JC. TPC is supported by 3D printed rods.
- During the operation, the chamber is filled with LAr till TPC is fully submerged.
- Maintained at constant pressure and temperature during the data taking.



By JC



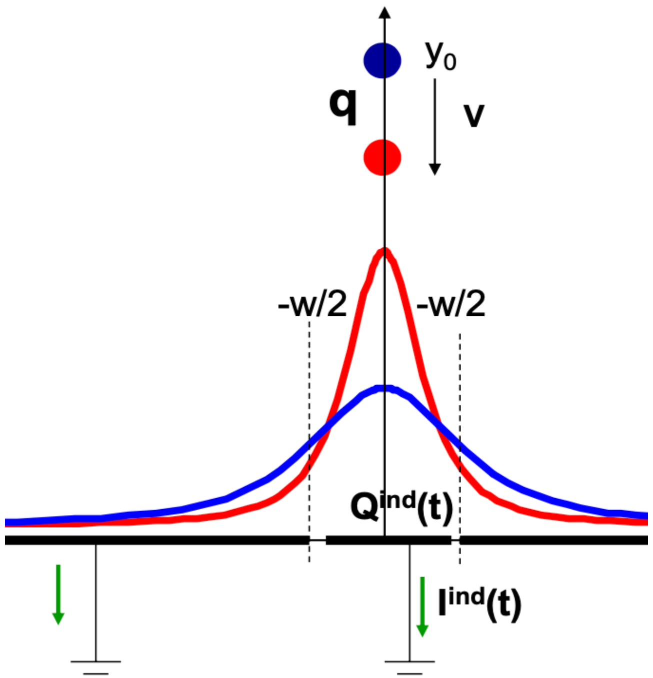
By JC

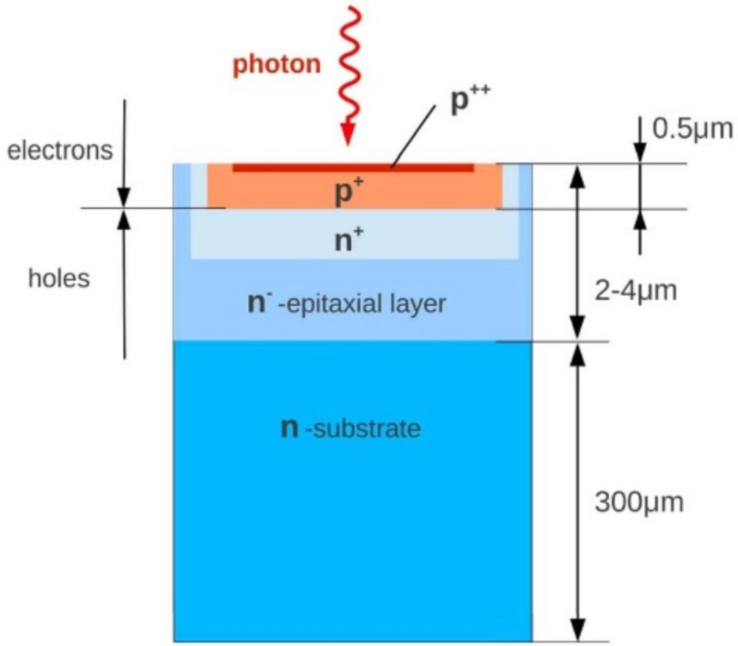


Supported TPC

Charge and light signals production in Sensors

- When a free charge q moves towards the metal strip, it induces rate of change of the charge → current(I) at anode strip.
- If the light is captured by SiPM via photoelectric effect, it produce electron and hole pair.
- If it happens in avalanche region, then each photoelectron get amplified which in turn produce a short pulse of current.
- In both cases, signals are quite small ~ 1mV.
- These require conditioning before we digitize them.





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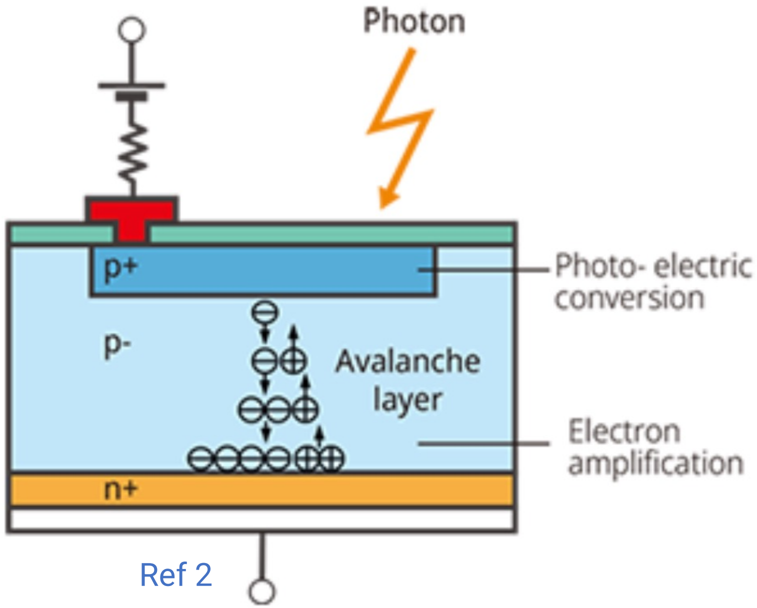
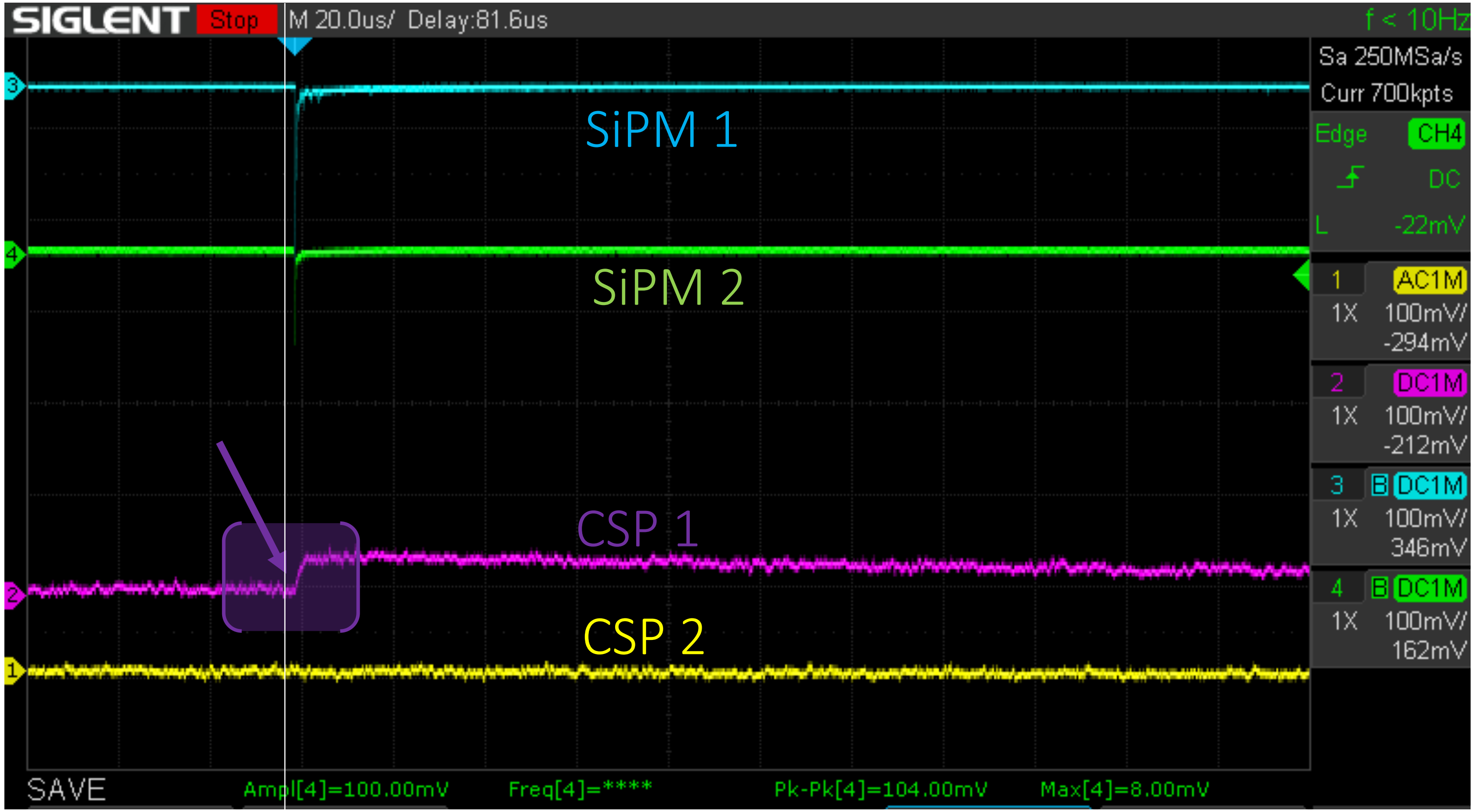


Ref 2

Signal analysis by waveform visualization

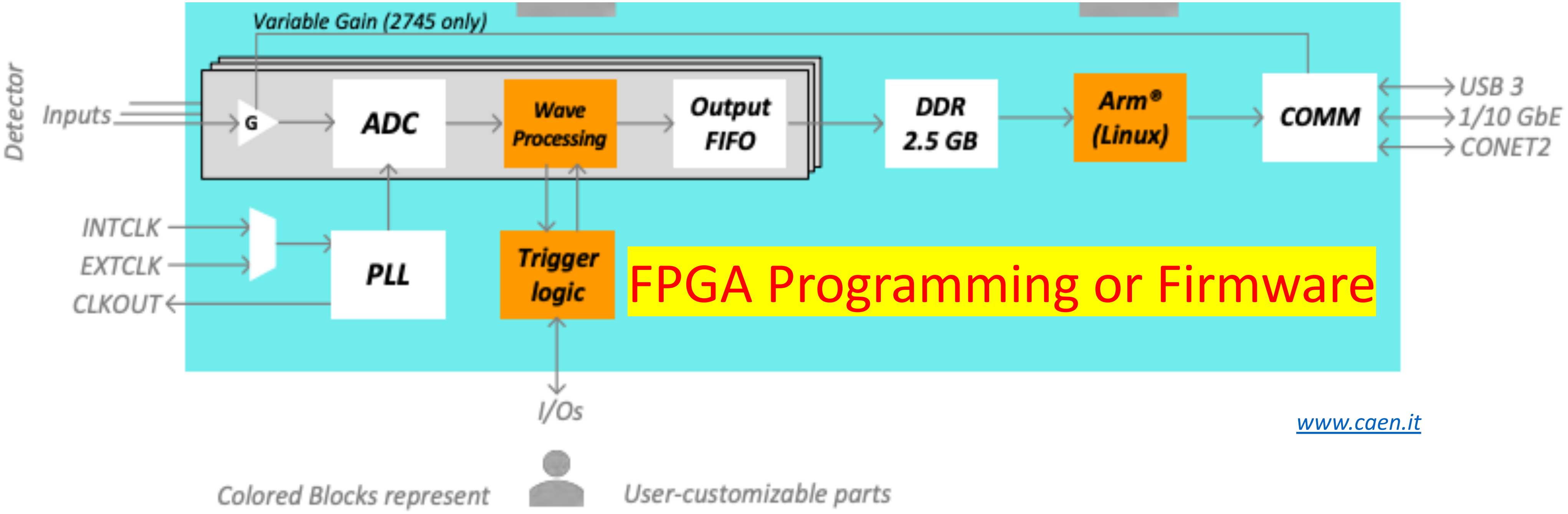
- When interaction happens in the TPC, it produces flash of light which are instantly detected by SiPM1 and SiPM2.
- Immediately after that, we can see CSP 1 collecting the ionized electrons for about 4us.
- Such events are called coincident events.



V2740B (Vx2730) digitizer architecture

- The system continuously samples analog input at a rate of 125MS/s using its built-in ADC and stored in a circular buffer memory by the FPGA.
- When a trigger signal is received, the buffer is frozen for readout.

- Users have a flexibility to customize the trigger logic and wave processing.
- Users also have an option to develop their own custom data acquisition software on an embedded Linux system using the scisdk library provided by CAEN.



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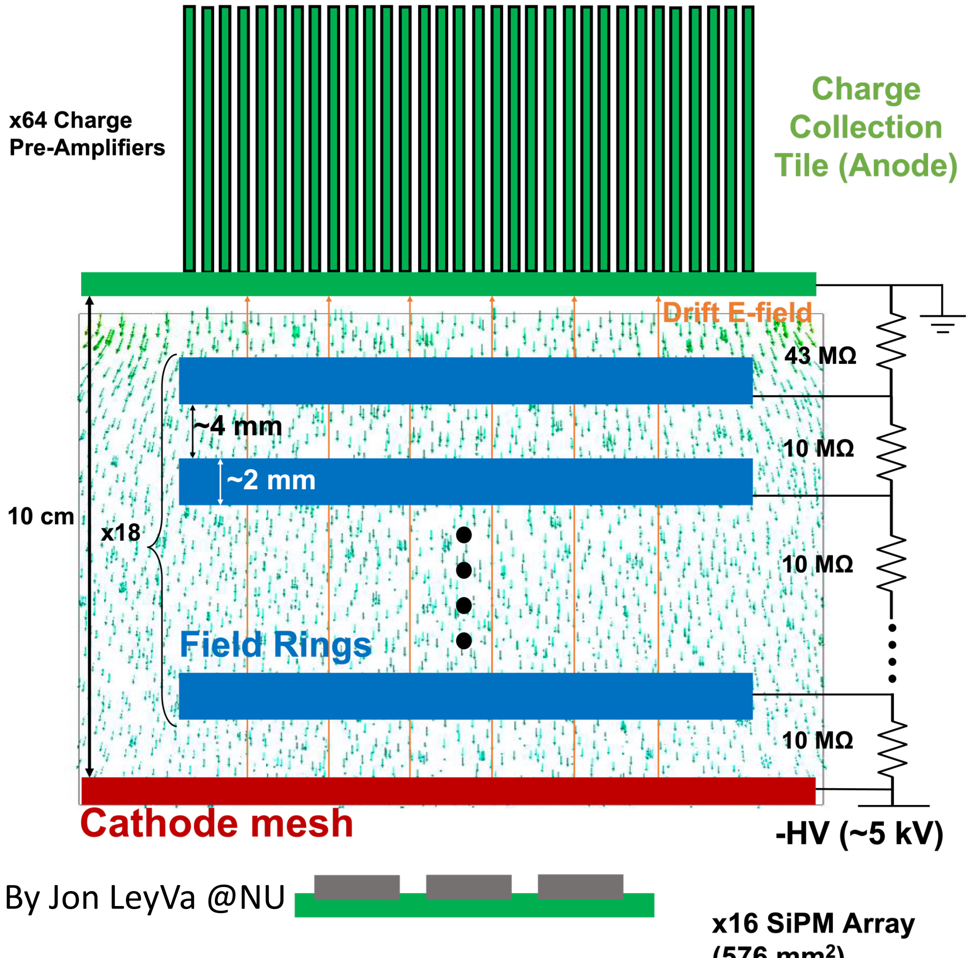
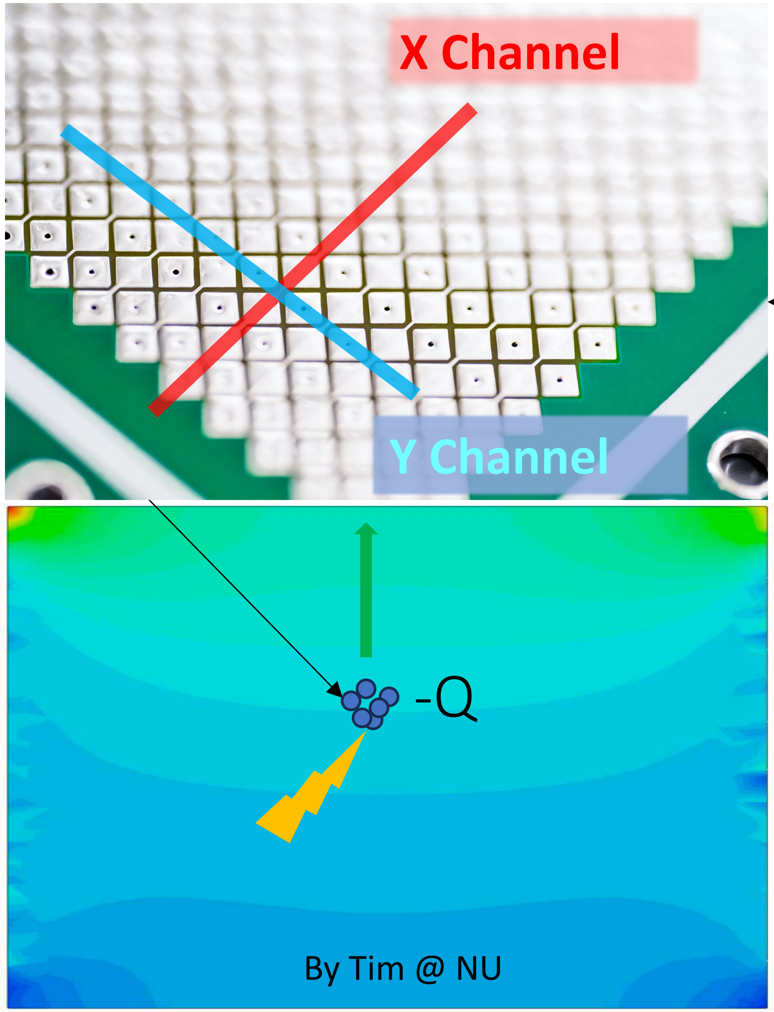
LArTPC: E-field setup and tile design (x,y,z,t,E)

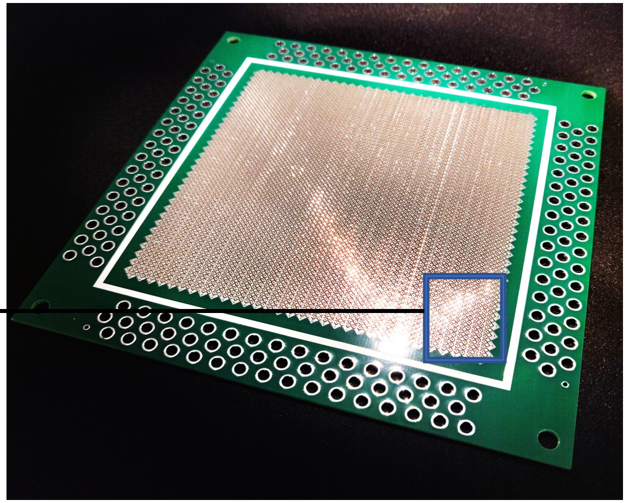
- Supply the –ve HV to setup a uniform e-field inside the TPC.
- If there exist free charge (-Q), drift towards the anode tile due to e-field.
- Anode tile is arranged with X & Y strips → hits → x,y coordinates of –Q
- Energy (E) ∝ charge amplitude.



By Jon LeyVa @NU



By Tim @ NU

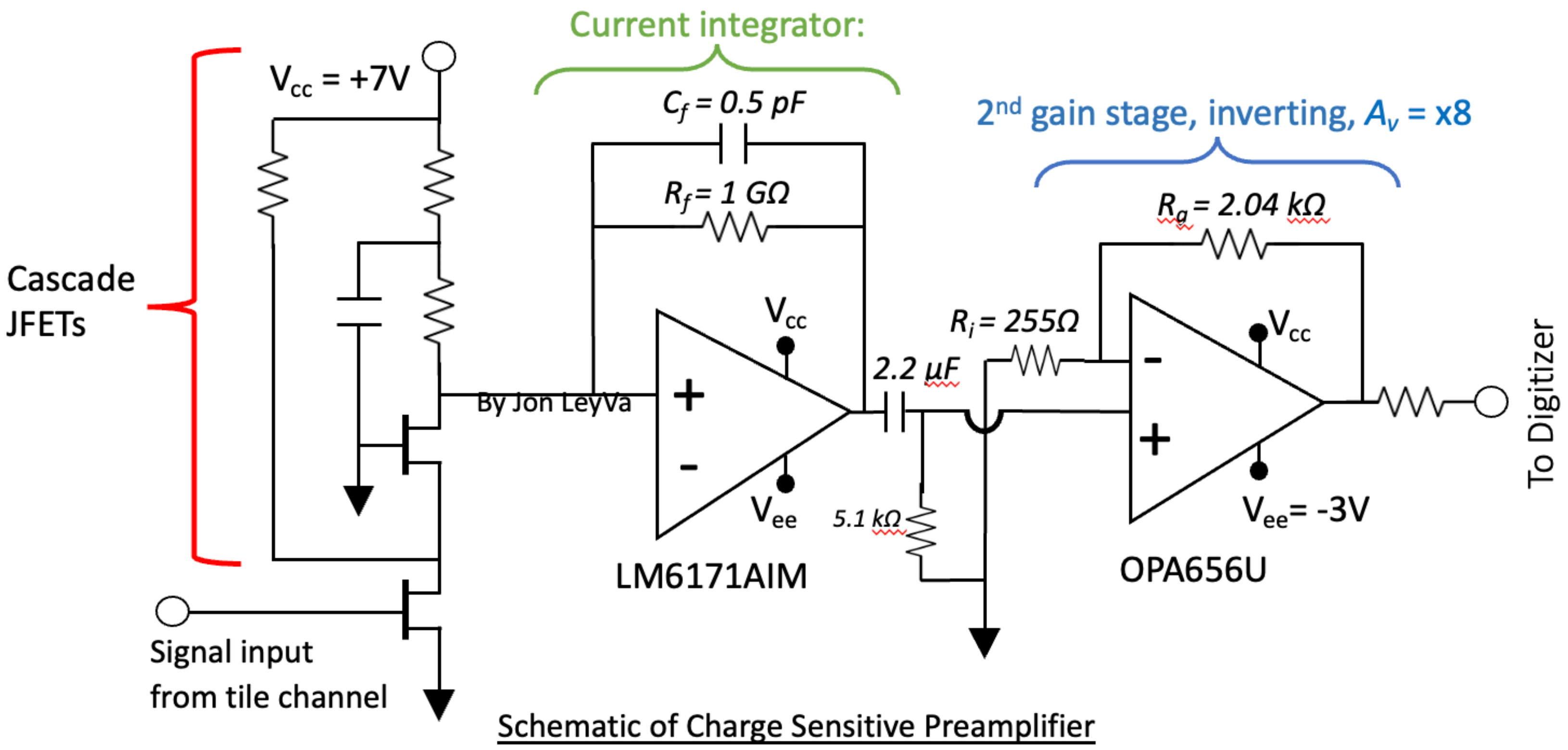


By Jon LeyVa @ NU

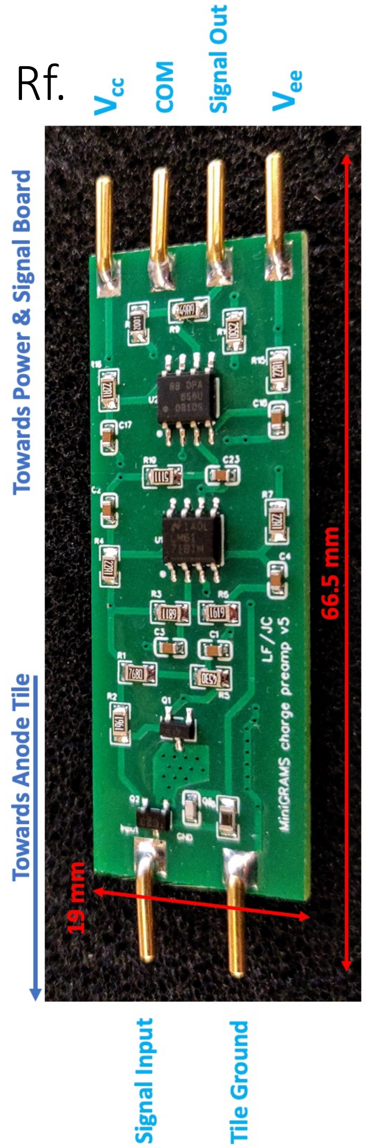
Z = f(v, t)
where v = f(-HV)

Current pulse processing - conditioning

- Cascade JFETs: Reduce the impedance imposed by the Cf and increase the signal bandwidth
- CM = Cf (1 + Av)
- Current pulse is integrated using op-amp LM6171 using CSP configuration with Cf, Rf.
- Output voltage is amplified in second stage.
- Signal is sent to digitizer.

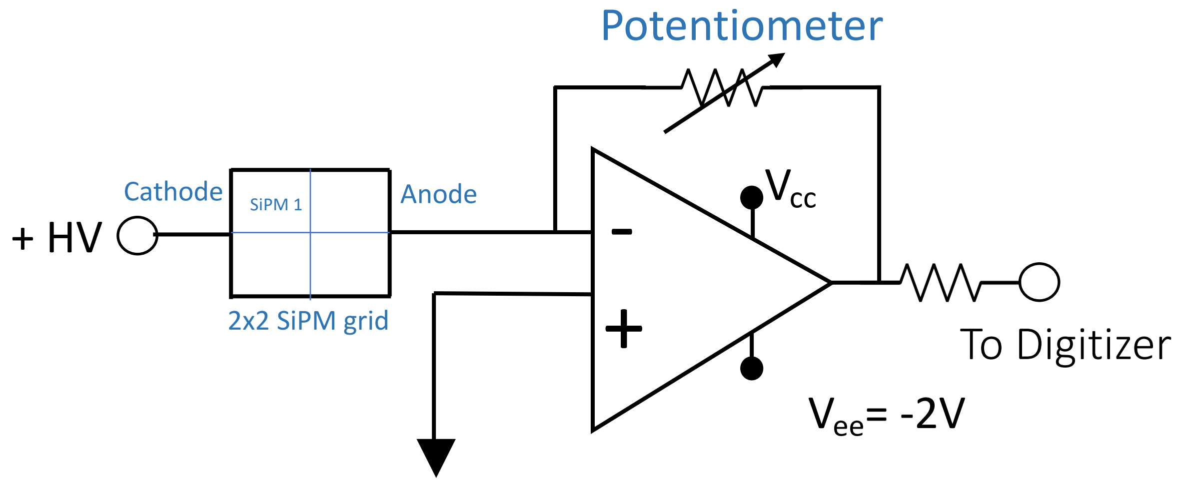


Schematic of Charge Sensitive Preamplifier

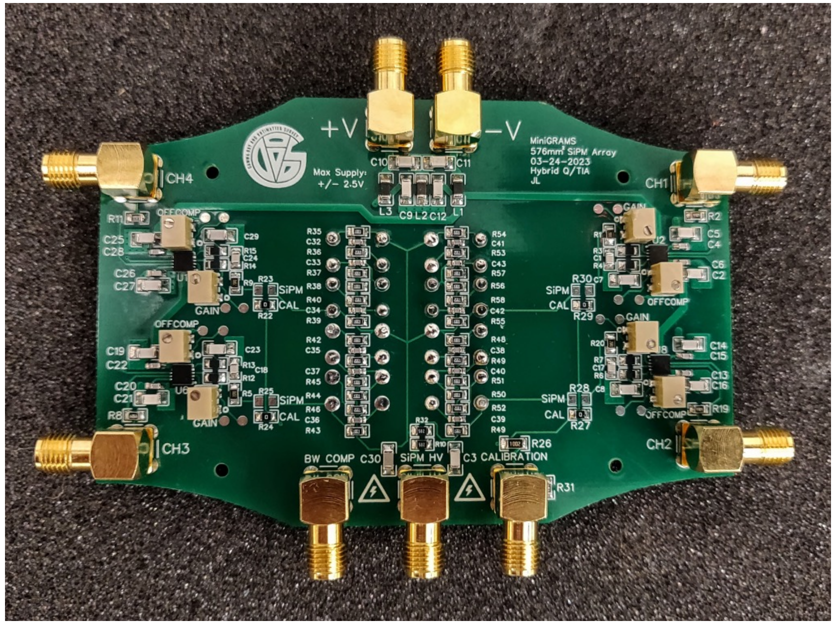


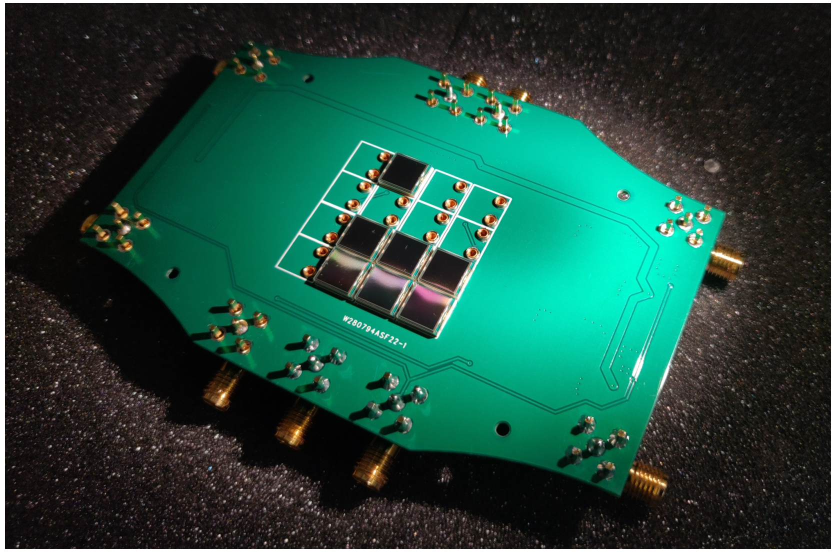
Silicon Photomultipliers (SiPM) pulse amplification

- Digitizer usually have limited resolution for a dynamic range.
- SiPM (VUV&VIS) pulse amplification is necessary before digitizing it.
- Combine four SIPMs in parallel and output is amplified using an op-amp in a transimpedance configuration.



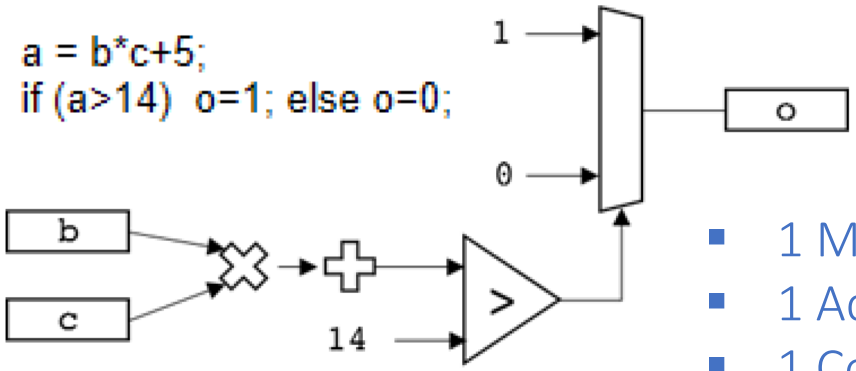
SiPM amplification schematic diagram



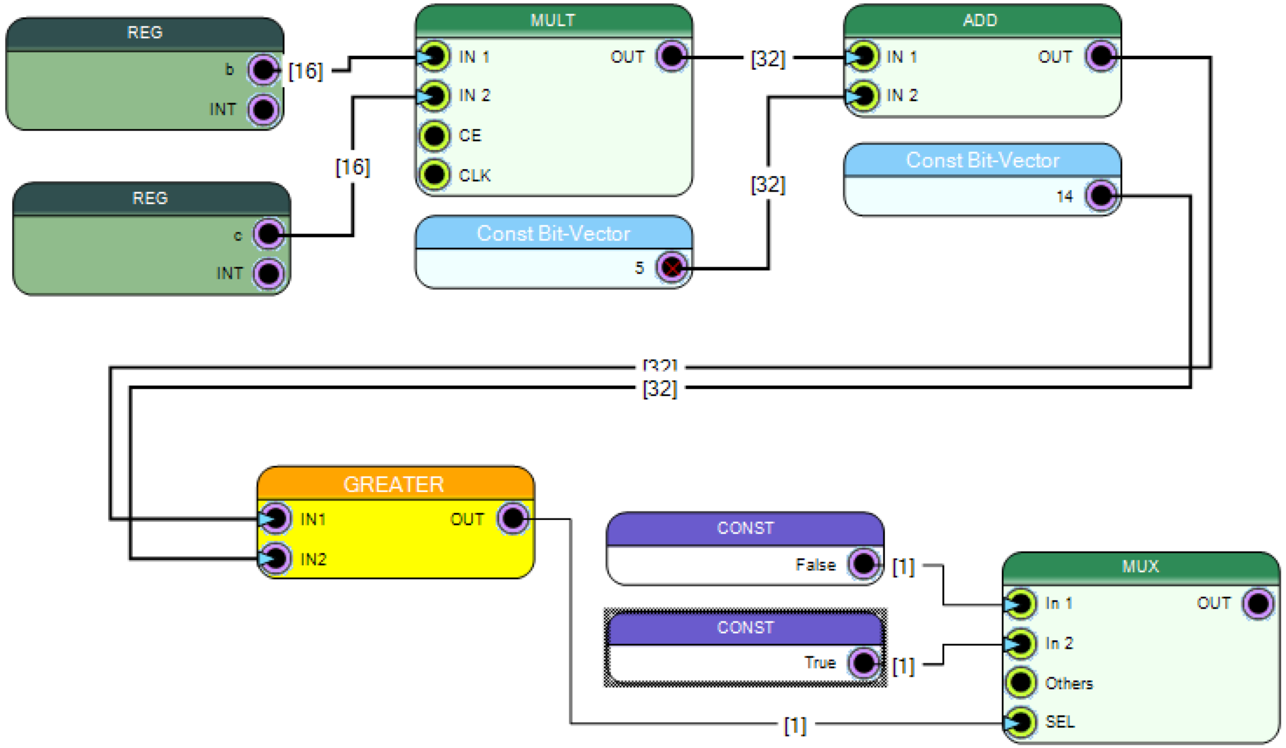


How does Sci-Compiler work?

- It uses a prebuild library set containing IP blocks with complex functionalities and can be connected with other IP blocks.
- Generates the VHDL code starting from the user design.
- Executes Xilinx Vivado in background to compile the firmware and generate the bitstream.
- Converts the bitstream in the proper configuration file compatible with one of the supported platforms.
- For example: Design a simple digital circuit.



- 1 Multiplier
- 1 Adder
- 1 Comparator
- 1 Multiplexer



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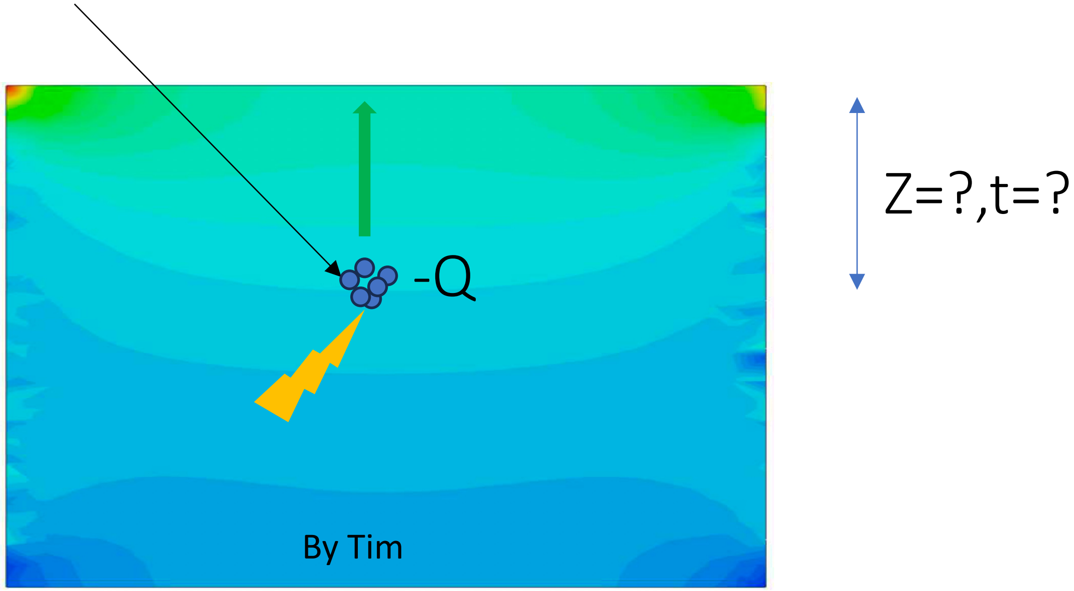
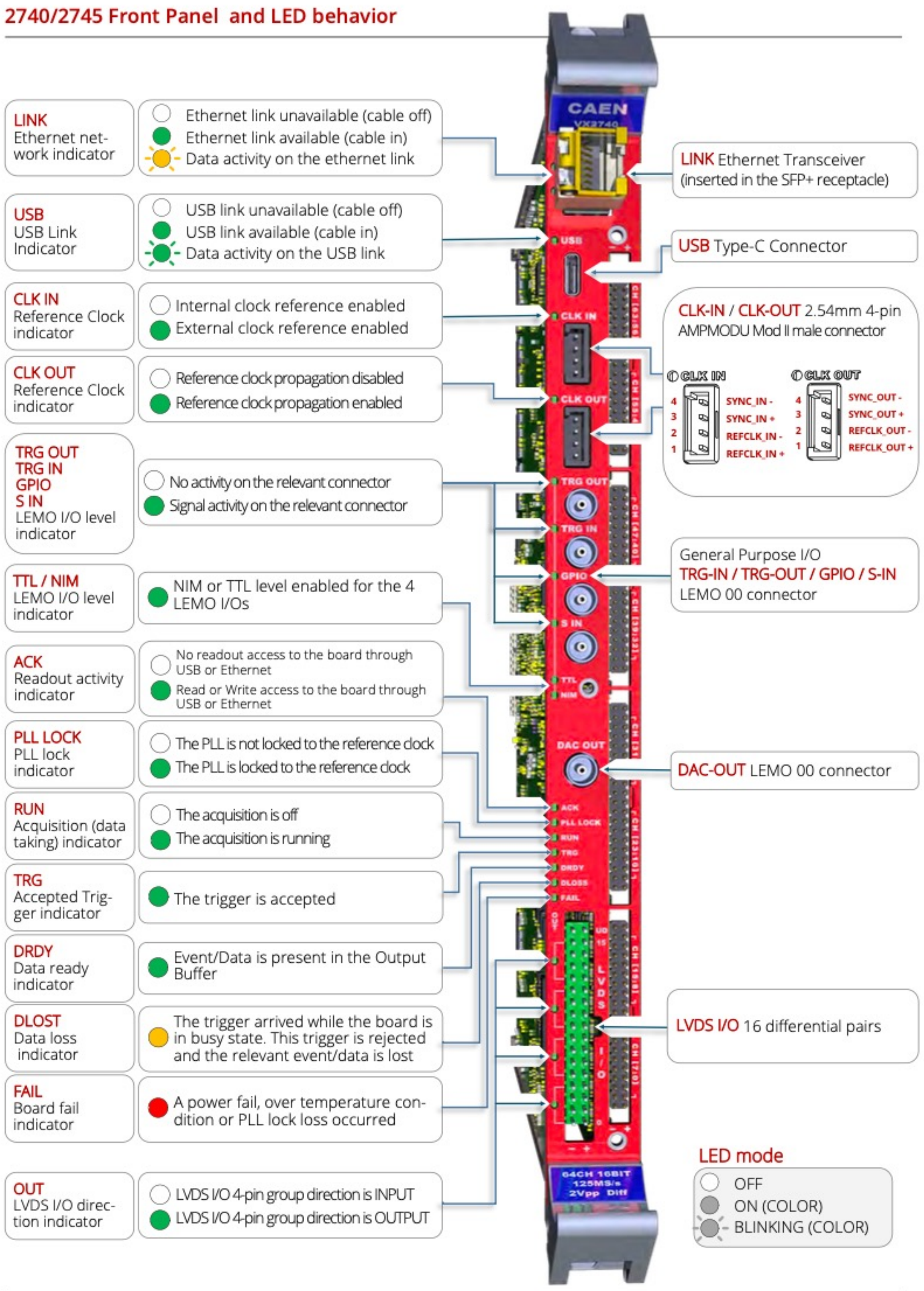

-Q
By Tim
Z=?,t=?


2740/2745 Front Panel and LED behavior
LINK Ethernet network indicator
Ethernet link unavailable (cable off)
Ethernet link available (cable in)
Data activity on the ethernet link
USB USB Link Indicator
USB link unavailable (cable off)
USB link available (cable in)
Data activity on the USB link
CLK IN Reference Clock indicator
Internal clock reference enabled
External clock reference enabled
CLK OUT Reference Clock indicator
Reference clock propagation disabled
Reference clock propagation enabled
TRG OUT TRG IN GPIO S IN LEMO I/O level indicator
No activity on the relevant connector
Signal activity on the relevant connector
TTL / NIM LEMO I/O level indicator
NIM or TTL level enabled for the 4 LEMO I/Os
ACK Readout activity indicator
No readout access to the board through USB or Ethernet
Read or Write access to the board through USB or Ethernet
PLL LOCK PLL lock indicator
The PLL is not locked to the reference clock
The PLL is locked to the reference clock
RUN Acquisition (data taking) indicator
The acquisition is off
The acquisition is running
TRG Accepted Trigger indicator
The trigger is accepted
DRDY Data ready indicator
Event/Data is present in the Output Buffer
DLOST Data loss indicator
The trigger arrived while the board is in busy state. This trigger is rejected and the relevant event/data is lost
FAIL Board fail indicator
A power fail, over temperature condition or PLL lock loss occurred
OUT LVDS I/O direction indicator
LVDS I/O 4-pin group direction is INPUT
LVDS I/O 4-pin group direction is OUTPUT
CAEN
LINK Ethernet Transceiver (inserted in the SFP+ receptacle)
USB Type-C Connector
CLK-IN / CLK-OUT 2.54mm 4-pin AMPMODU Mod II male connector
CLK IN
CLK OUT
SYNC_IN -
SYNC_IN +
REFCLK_IN -
REFCLK_IN +
SYNC_OUT -
SYNC_OUT +
REFCLK_OUT -
REFCLK_OUT +
General Purpose I/O TRG-IN / TRG-OUT / GPIO / S-IN LEMO 00 connector
DAC-OUT LEMO 00 connector
LVDS I/O 16 differential pairs
LED mode
OFF
ON (COLOR)
BLINKING (COLOR)

LArTPC: E-field setup and tile design (x,y,z,t,E)

- R&D for next generation LAr-TPC for astrophysical survey and dark matter detection.
- Purpose: design, construct and develop the detector including optimizing the geometry, electronics and DAQ, testing & calibration, and software development for data analysis.