# The Detector R&D Program at Fermilab

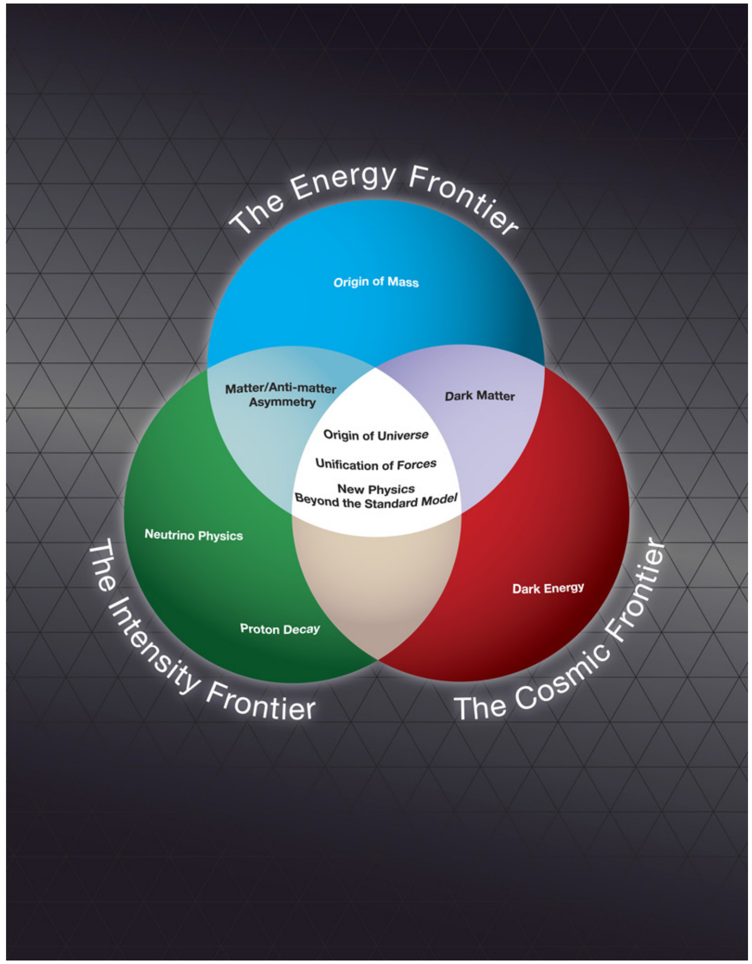
Erik Ramberg

OHEP Site Visit

23 August, 2010

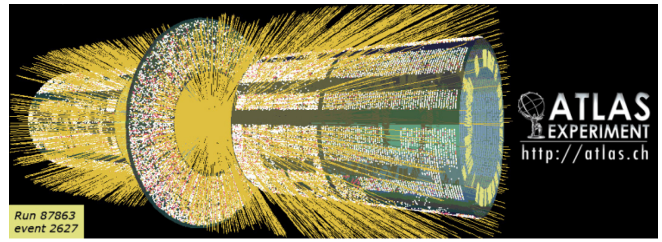
# What are the major challenges in the Frontiers of HEP?

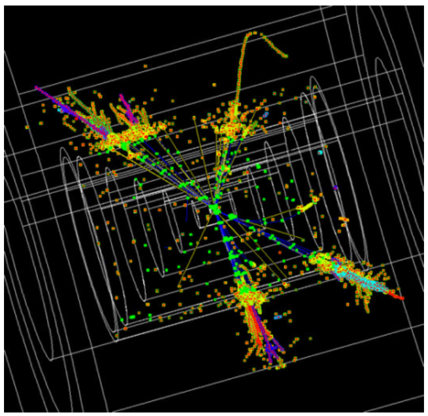
- The '3 frontiers' outline the major thrusts of high energy physics
- In each area, the physics is advancing rapidly. It is crucial that the detector technology keep pace.



# The Energy Frontier

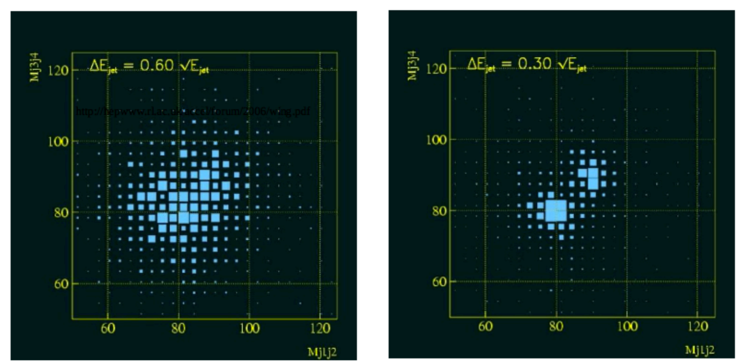
Vertex sensors that can withstand a fluence of $10^{16}$ particles/cm$^2$



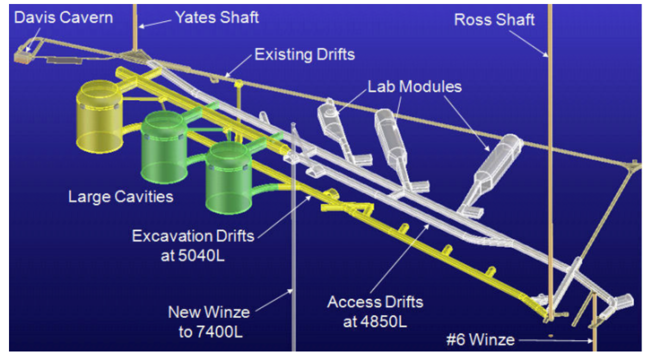
Less than 4 micron point precision tracking at a lepton collider

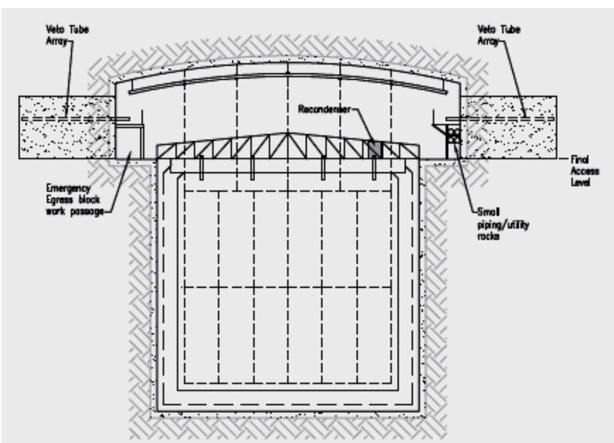
Hadronic jet energy resolutions at a lepton collider of 30%/sqrt(E)



# The Intensity Frontier

Finding a low-cost, efficient photodetector that can tile a water tank of 300 kton  (150,000 PMT's !)

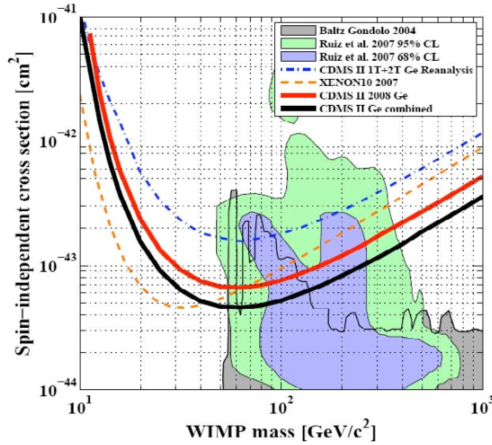


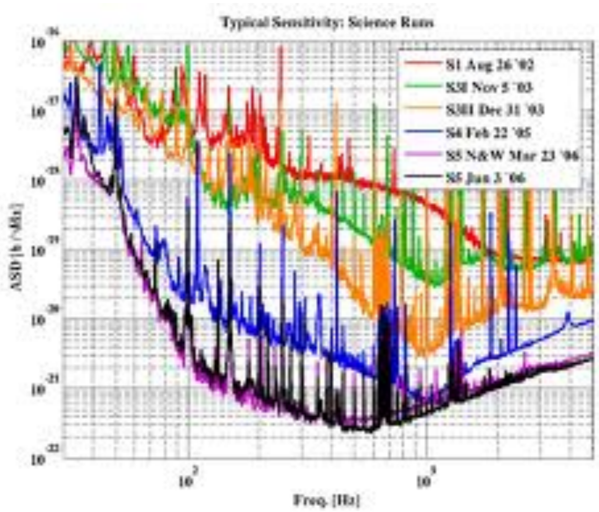




Developing a 20 kton liquid Argon TPC detector that can be filled easily, with simple electronic readout

# The Cosmic Frontier

Reducing background rates in dark matter detectors down to a level of 1 nuclear recoil per ton per year




Probing the Planck scale of space-time with holographic interferometry

# What can and should Fermilab be doing?

- Detector R&D at Fermilab is geared towards our strengths as a national lab, meaning that the lab's institutional capabilities come into play. These are
  - Presence of unique facilities like the Test Beam Facility or Silicon Detector Facility
  - Experienced, well established engineering groups, such as ASIC development and Cryogenics
  - Managing large projects that may require substantial investments of manpower, time or money

- We encourage a high degree of collaboration with the university community and other (inter)national labs.

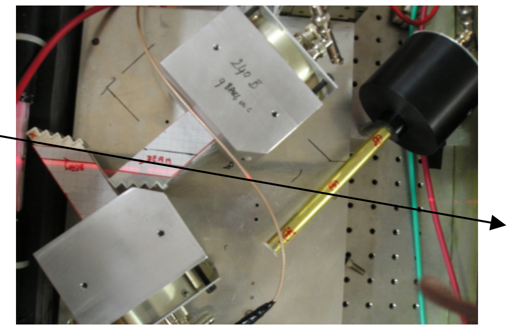
Liquid Argon purity tank

Inspection at SiDet

CALICE at the test beam

# Examples of detector R&D topics being addressed at Fermilab:

- Developing silicon readout in 3 dimensions instead of 2
- Making hadronic calorimeters out of crystals
- Smashing the 100 psec barrier in time-of-flight
- Filling liquid Argon tanks without evacuating them
- Freezing Xenon into a solid crystal, instead of using liquid
- Performing particle identification…



(15 psec resolution quartz TOF devices)

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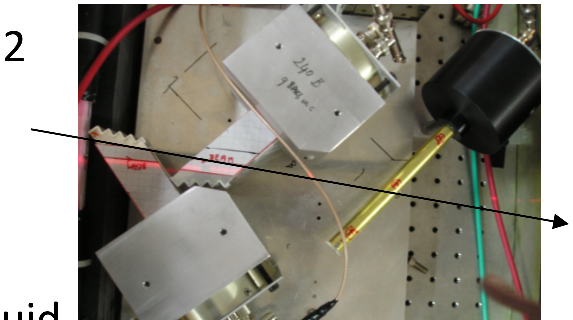
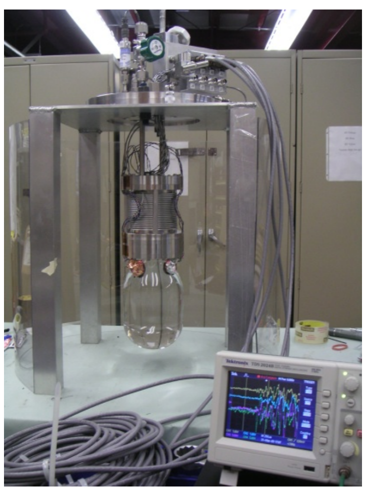
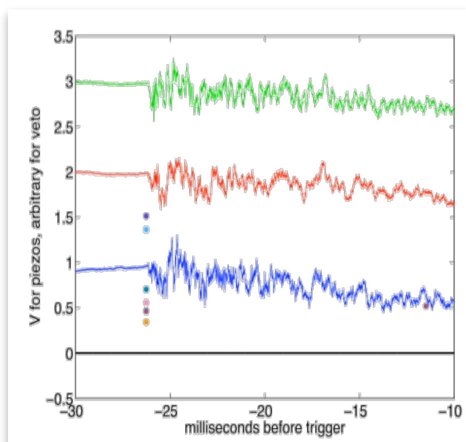


(15 psec resolution quartz TOF devices)

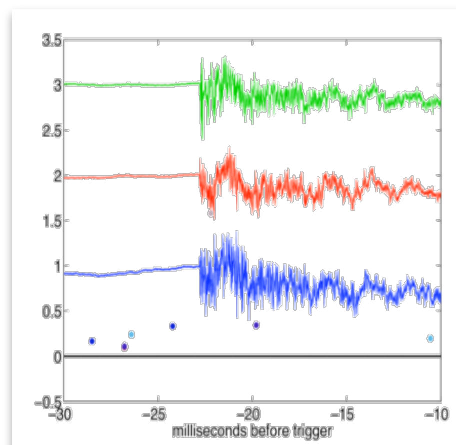
With sound waves!

COUPP
4 kg Test
Chamber






Neutron interaction

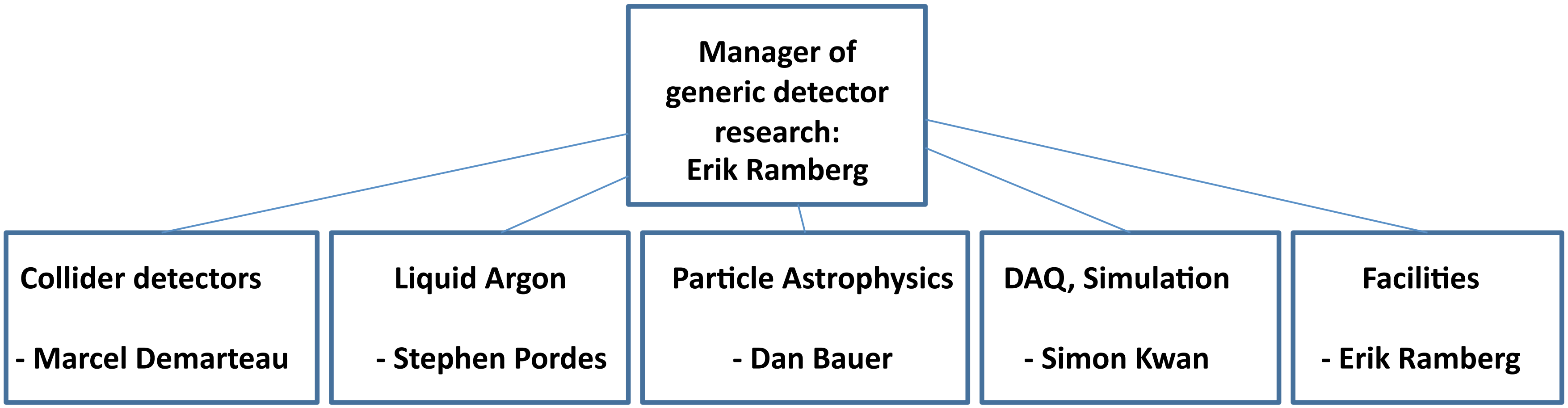



$\alpha$ Decay

# How does Fermilab manage detector R&D?

- In the last year we have renewed and strengthened our national leadership in particle detector R&D by developing a new internal management structure, and emphasizing our role in international workshops and schools.

# Generic Detector R&D Organization Structure




**The Detector R&D group assists the manager by:**

- Meeting every month
- Reporting on the status of the effort and budget under their purview
- Assisting in creation of the future fiscal year budgets
- Advising and suggesting changes in the direction of the program

**The R&D proceeds under current Divisional management structure**

# Generic Detector R&D (KA15) Funding for FY10

| Collider detectors - Marcel Demarteau | Liquid Argon - Stephen Pordes | Particle Astrophysics - Dan Bauer | DAQ, Simulation - Simon Kwan | Facilities - Erik Ramberg |
|---|---|---|---|---|
| $3.31 M | $1.61 M | $1.02 M | $0.68 M | $0.29 M |

+ overheads = $9.88 M

# Generic Detector R&D (KA15) Technical Effort

| Collider detectors<br>- Marcel Demarteau | Liquid Argon<br>- Stephen Pordes | Particle Astrophysics<br>- Dan Bauer | DAQ, Simulation<br>- Simon Kwan | Facilities<br>- Erik Ramberg |
|---|---|---|---|---|
| 18 FTE | 9 FTE | 6 FTE | 5 FTE | 1 FTE |

- Scientific involvement is about 8-10 FTE

# Connecting with the Community

- Workshop on National Coordination of HEP Detector R&D
  - At Fermilab on October 7-9, 2010
  - Goal is to understand interplay between national labs and universities in detector R&D
- Participation in new EDIT Detector School
  - "Excellence in Detectors and Instrumentation Technologies"
  - Goal is to train young researchers in detector techniques
  - At CERN, 31 January - 10 February 2011
  - At Fermilab a year later
- Hosting 2$^{nd}$ TIPP Workshop:
  - Technology and Instrumentation in Particle Physics, 9-14, June, 2011
  - A follow-on to the very successful workshop in Japan in 2009
- Significant leadership in focused workshops on individual technologies (e.g. 3-D ASICS, homogenous hadron calorimetry, optical DAQ, etc.)


Our new web site: http://detectors.fnal.gov

## Collider Detector Research:

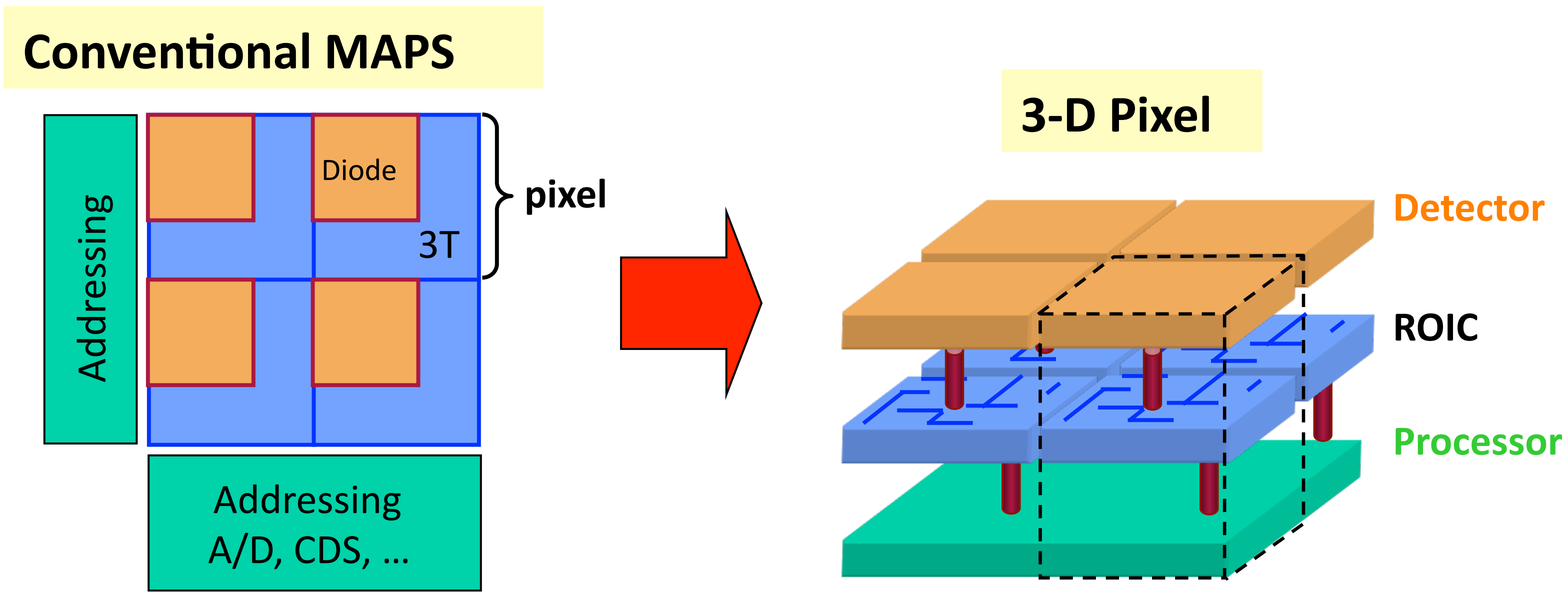
- 3D ASIC development
- Intelligent tracking systems
- Serial power distribution
- Homogenous Hadron Calorimetry
- SiPM Characterization
- Fast Timing detectors

# 3-Dimensional ASICs

The development of 3D integrated circuits has recently received much attention in trade journals, special sessions have been arranged at various IEEE meetings, and dedicated meetings such as *"3D Architectures for Semiconductor Integration and Packaging"* have taken place.

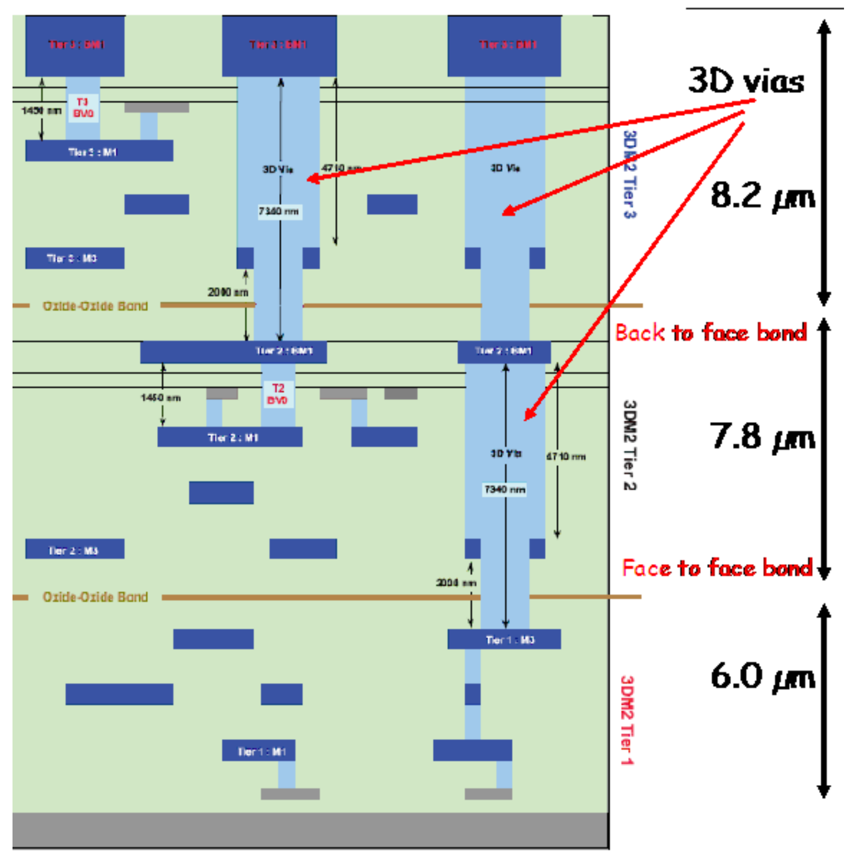
The 3D technology is being driven entirely by industry. However, the time has come when HEP can begin to benefit from work in progress.

Fermilab began exploring 3D technology for HEP several years ago and submitted the first 3D IC (VIP1) for HEP to MIT Lincoln Labs in October 2006.



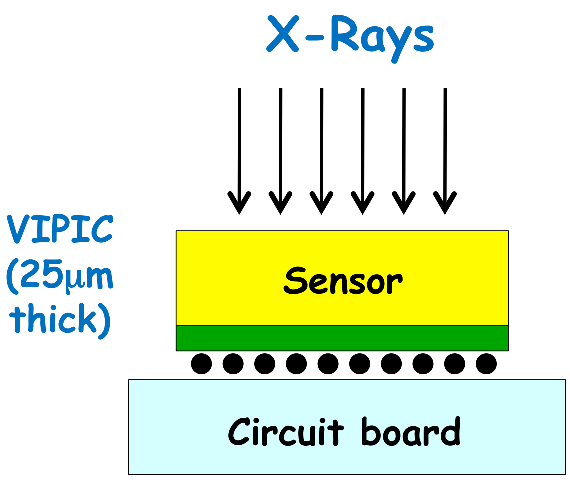
# Milestones Achieved in First HEP 3D Circuit called VIP1

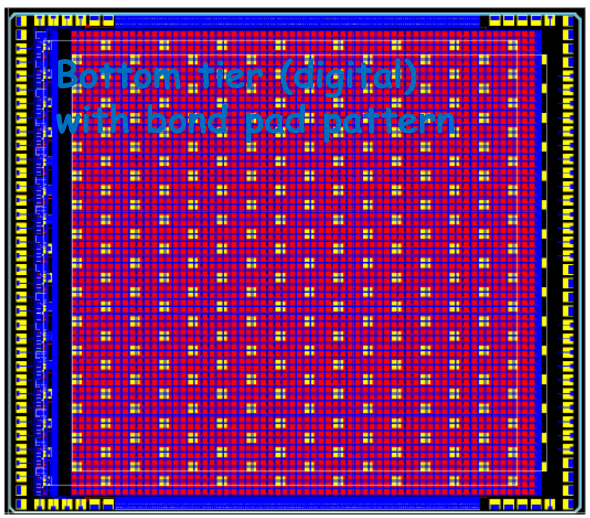
- Demonstrated increased circuit density by integrating 3 circuit tiers
- Showed that extreme circuit thinning (7um) was possible
- Showed that small vias (~1.5 um) were possible thus allowing for small pixel sizes.
- Showed that 3D vias and bonding were reliable




MIT LL 3 Tier Assembly

# 3D Project: VIPIC




- Vertical Integrating Pixel Imaging Chip (VIPIC)
  - Evaluating application for X-ray photon correlation spectroscopy (XPCS) in collaboration with BNL to calculate autocorrelation function per pixel
- Functionality
  - 64x64 array of 80x80 $\mu m^2$ pixels
  - $\gamma$ flux: 1000 $\gamma$/pixel/s
  - Deadtimeless, triggerless operation
  - Sparsified data readout
  - Binary readout (no energy information)
  - High speed frame readout time
  - 16 serial high speed LVDS output lines
- Pads for backside bump bonding allows for 4-side buttable arrays

# Exceedingly Fast TOF in Test Beam Facility

**Microchannel Plate Photomultipliers have proven themselves as exquisite TOF detectors, with <8 psec intrinsic timing resolution!**

**Fermilab has proven almost as good timing resolution (13 psec) for SiPM – best in the business!**

ULTRA FAST PHOTOMULTIPLIERS Photek

*Ultra Fast Photomultipliers*

**FEATURES**

- Our photon counting tubes have sharply peaked pulse height distribution and low jitter.
- Our tubes are well matched via SMA or N-Type connectors to 50 Ohm systems
- All tubes are gateable
- 10 mm to 40 mm diameter

**APPLICATIONS**

- Single photon counting fluorescence
- Lidar
- Time correlated photon counting
- Nuclear Physics
- Analysis of fast optical pulses

**THE PMT FAMILY**

Photek offers a range of ultra-fast MCP Photomultiplier detectors for the scientific community. Each detector is customised and may be supplied with a choice of input window, photocathode, MCP configuration, pulse rise time and gating options.

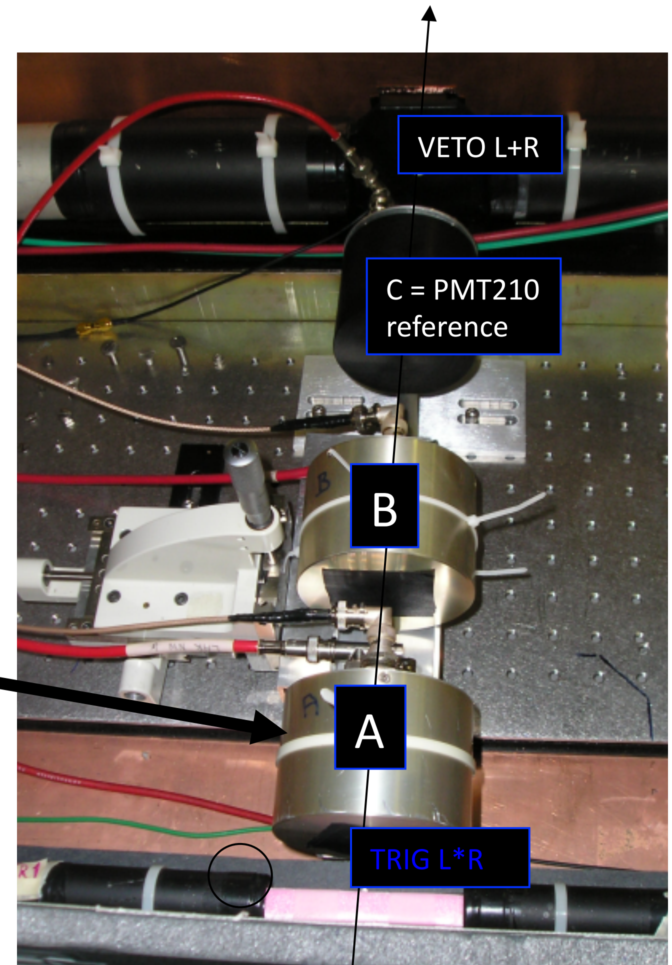
The current PMT family includes the following detectors:

PMT X10 PMT X13 PMT X18
PMT X25 PMT X40

Where X defines the MCP configuration and may be 0, 1, 2 or 3 gain stages and the number following this corresponds to the active diameter of the detector. For example a PMT213 is a two stage 13 mm detector.

Each MCP gain stage broadens the electron pulse time spread as well as increasing the gain. Small pore MCPs have faster time response than standard MCPs. Our PMT X10 and PMT X13 use small pore MCPs and have the fastest time response in our product range. Time response is improved in small detectors, because of reduced capacitance and hence smaller CR time constant.

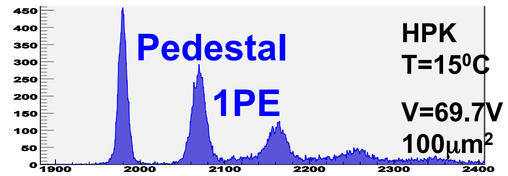
All tubes have metal-ceramic construction, with remotely processed cathodes to minimise noise and maximise QE at the customers chosen wavelength. All tubes use a mesh to electrically screen the anode and improve the rise time.

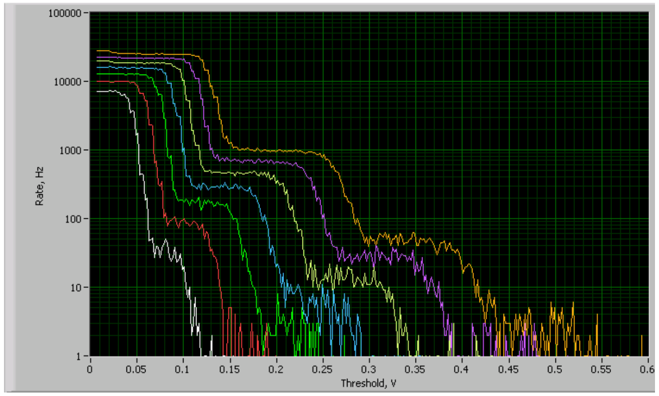


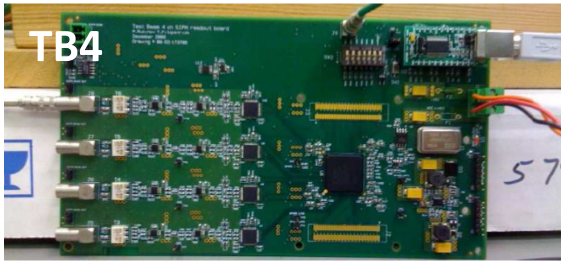

120 GeV/c proton

# SiPM Characterization and Readout

- Fermilab has developed a general facility for characterization of SiPMs
  - Dark current and photo response
  - Cross talk
  - Temperature dependence
  - Four channel readout board with waveform digitization
    - 12 bit, 250MSPS ADC
    - Large FPGA
    - USB interface
    - On-board bias control
- Developing plans for dedicated ASIC for SiPM readout. With 3D readout, you can conceive of reading out each pixel separately, and realize a truly digital photon detector.



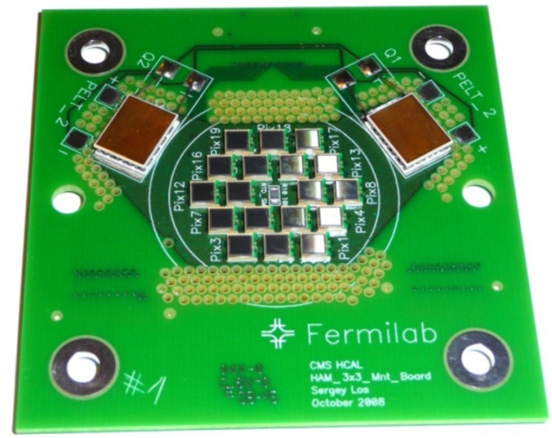



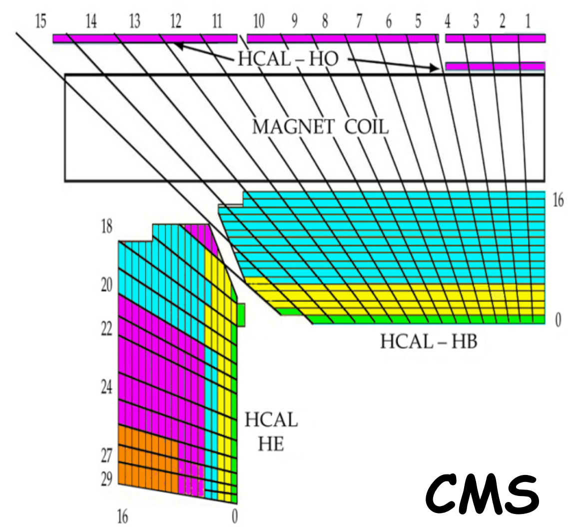



# CMS Synergy: HCAL

- CMS HPD replacement step 1:
  Outer Calorimeter (~2011)
  - ~3,000 PPDs
  - Each fiber in bundle (18) guided to its own SiPM
  - Readout by QIE ASIC (Fermilab)

- CMS HPD replacement step 2:
  Whole calorimeter (Phase I)
  - ~110,000 PPDs
  - Allows for longitudinal segmentation
  - SIPM tailored to HCAL
  - New ADC = new ASIC (QIE10)



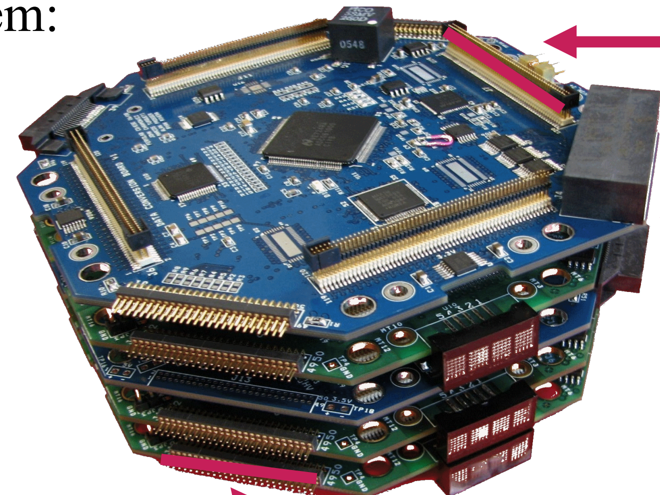



## DAQ Development and Simulation:

- Versatile, high speed DAQ for detector R&D
- Sensor characterization
- Optical DAQ
- Simulation for dual readout calorimetry

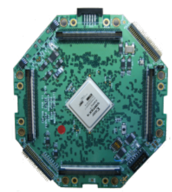
# The CAPTAN DAQ system

- The CAPTAN DAQ system has been developed by the DIG (Detector Instrumentation Group) of CD/ESE. There are 3 basic concepts behind the system:



1)Vertical standard bus

2)A set of core boards:

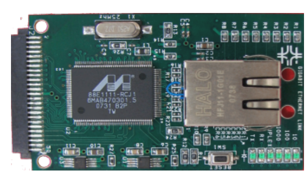


**NPCB – Node Processing and Control Board**

**DCB – Data Conversion Board**

3)Horizontal connectivity

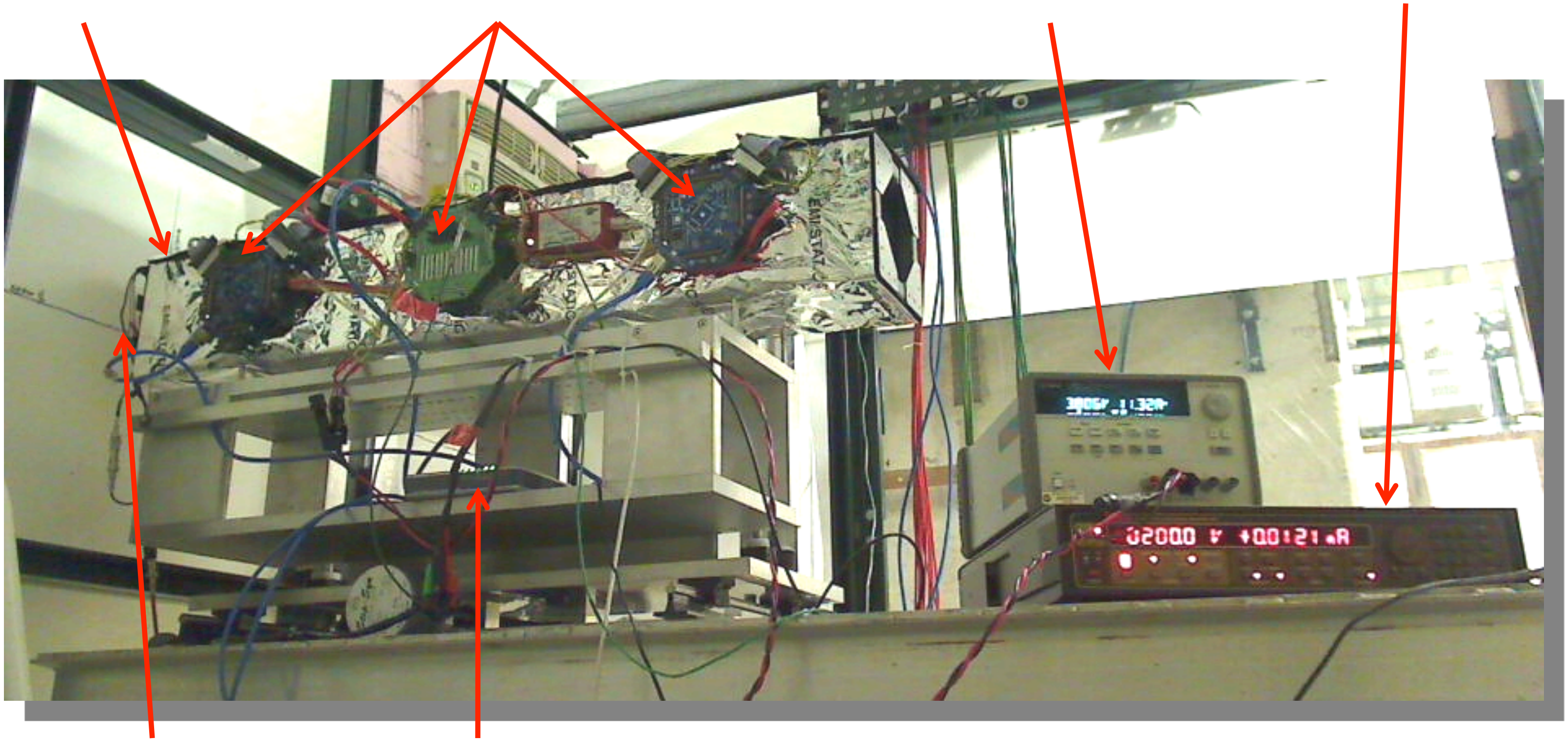
- **Gigabit Ethernet Link**
- **Interface Boards**
- **Level Translator**
- **USB**



- The software is a multithreaded application running on windows

# Test Beam Pixel Telescope Overview

TELESCOPE BOX CAPTAN STACK POWER SUPPLY DUT SENSOR BIAS

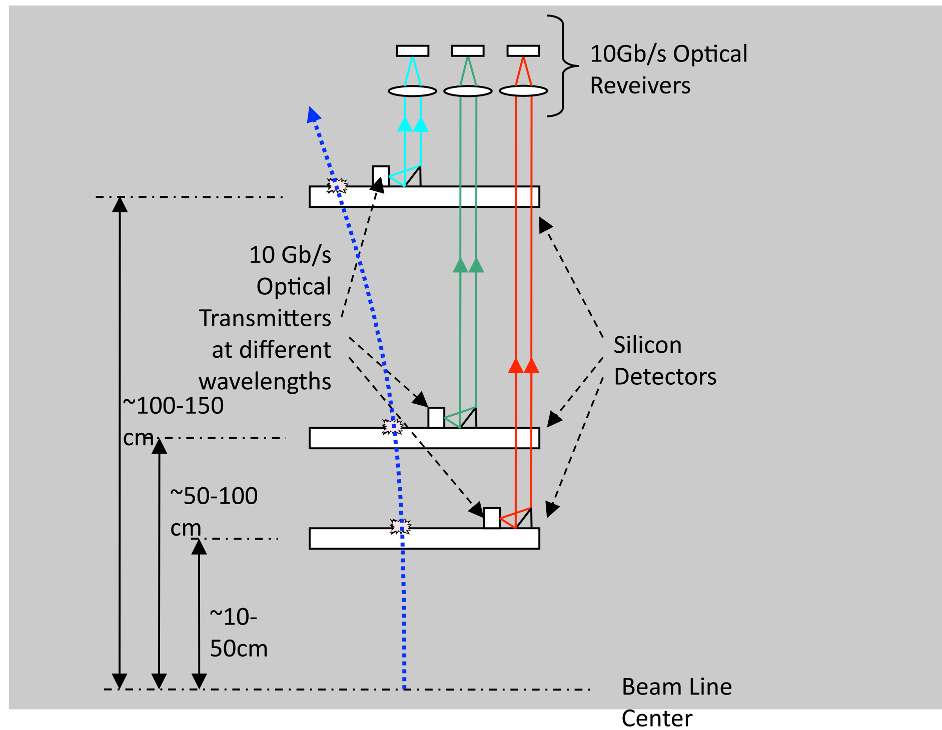


SCINTILLATOR ROUTER

A great example of the synergy between detector development, Fermilab's unique facilities (test beam, in this case) and the User community, which now benefits from this added capability.

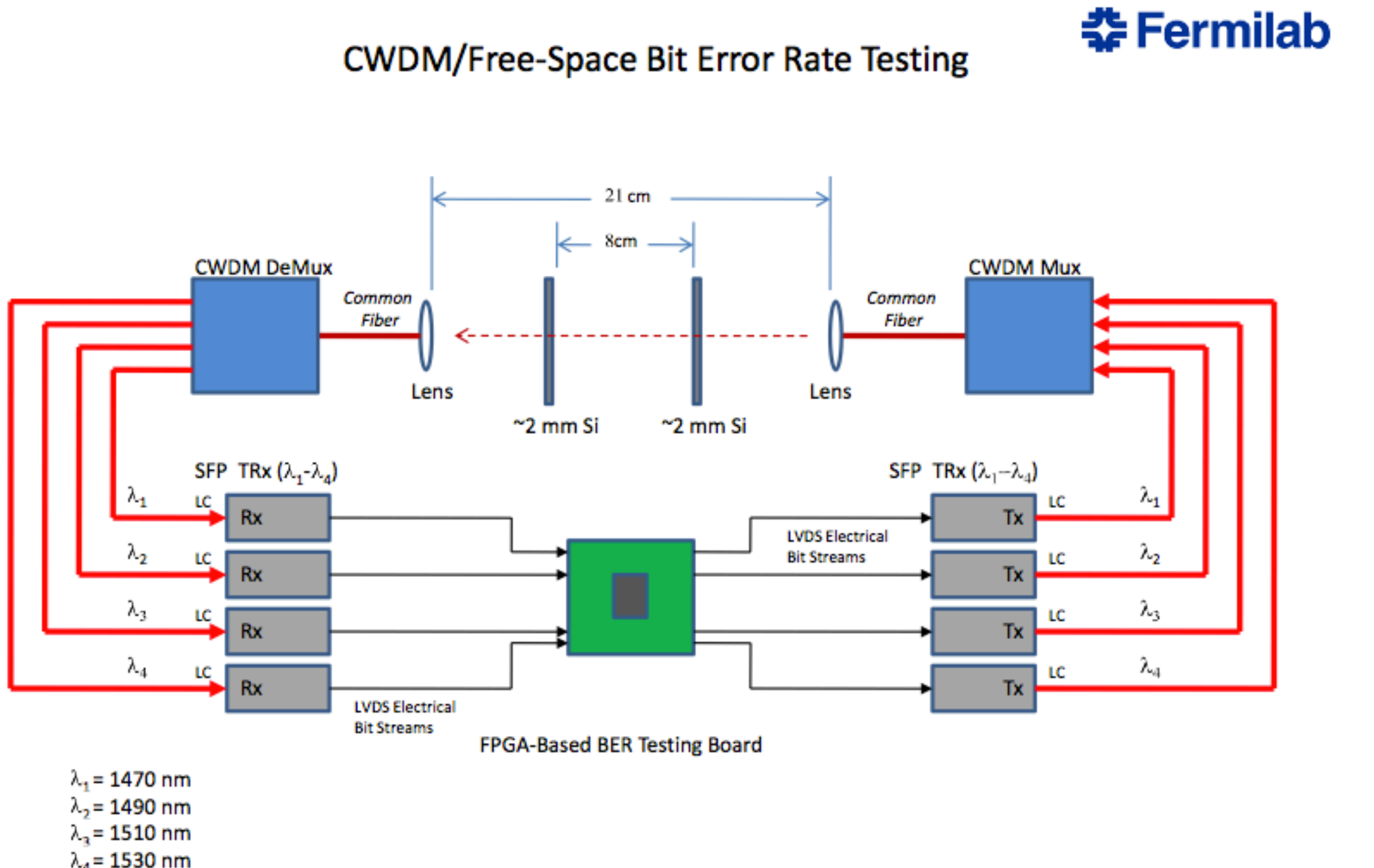
# Free-Space Optical DAQ Interconnects

- **The Problem:** Future particle physics experiments at the high energy frontier will all require large arrays of silicon detectors making data transmission cumbersome.
- **A Solution:** Vega Wave Systems proposes to design and develop a free-space optical link for trigger and data extraction.
- The novelty and feasibility of this system is based upon the fact that silicon detectors are transparent to the infrared wavelengths (1.4 micron) of the optical data link.
- Two Phase 1 SBIR proposals submitted with Fermilab as partner

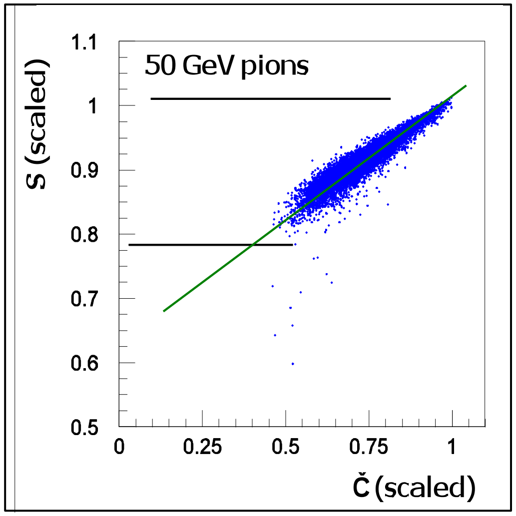


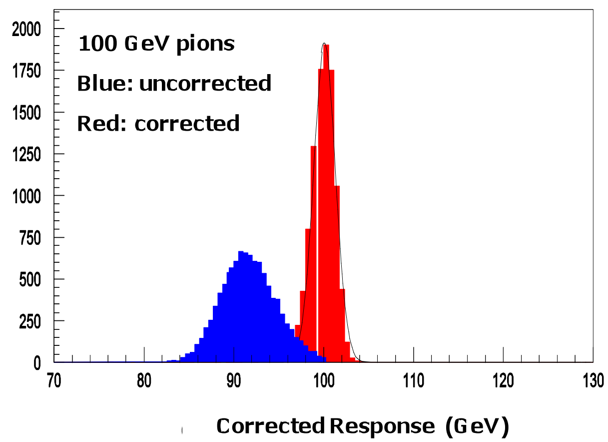

*A conceptual sketch of a free-space optical link for data extraction and trigger functions in a vertex detector.*

# Multi-wavelength Free Space Data Transmission Results Shown at Optical DAQ Workshop at Fermilab



# Dual Readout Calorimetry



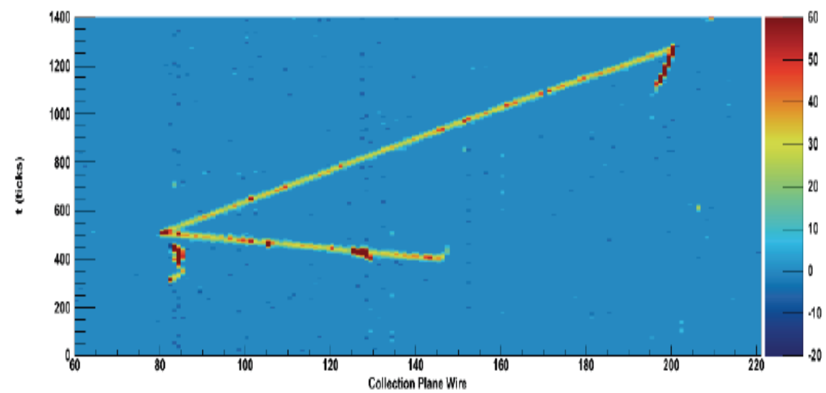

- Dual-readout calorimetry: measure every shower twice
  - Scintillation light: from all charged particles
  - Čerenkov light: b=1 particles, mainly EM
- Correct on a shower-by-shower basis using the correlation of the total observed ionization (S) and Čerenkov (Č) ligh
- From Monte Carlo studies:
  - Energy resolution (0.2-0.25)/√E (Gaussian)
  - No constant term up to 200 GeV
- The enabling technology is thin profile pixelated photon detectors. This would not be possible with normal phototubes
- We need to compare simulation with data – especially in a large crystal array

## Liquid Argon R&D:

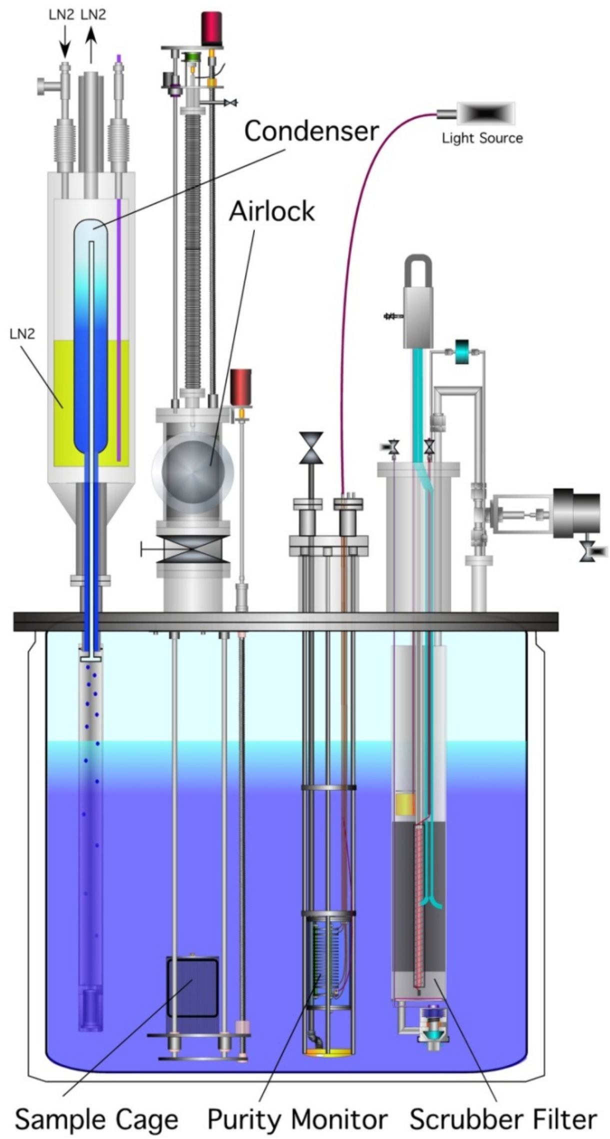
- Successful operation of a LAr TPC - ArgoNeut
- Test stands for purity investigations
- 20 ton LAr demonstrator
- Distillation column for low background Ar
- CMOS Processes for long-term operation in LAr
- Digital electronics for TPC readout.

# A Working Liquid Argon TPC in a neutrino beam

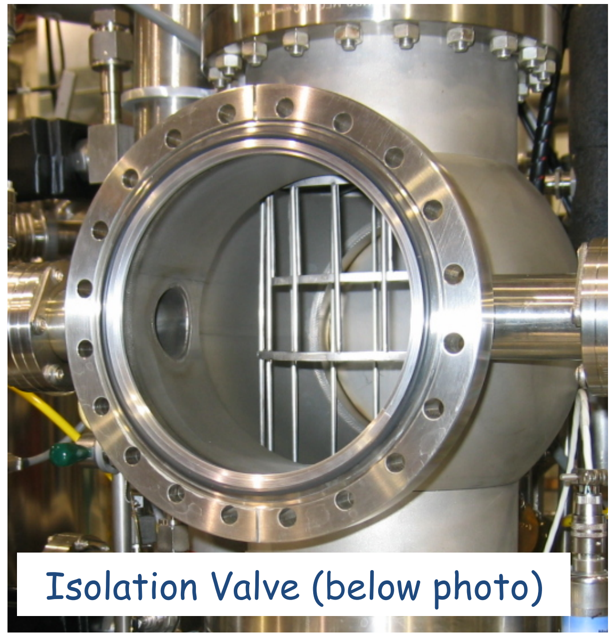
ArgoNeut succeeds in capturing and analyzing the first low energy neutrinos (<10 GeV) seen in a liquid Argon TPC.




Can this be scaled up so that it competes with water Cerenkov detectors for long baseline neutrino detectors?




*insertion of materials without exposure to vacuum*




**A unique system for testing Argon purity**

- Put materials in Sample Cage in the Argon Lock
- Seal the Argon Lock (open in photograph).
- [Evacuate the Argon Lock (or not).]
- Purge with pure argon gas (available from the cryostat).

**An additional system is used for testing electronic systems at liquid Argon temperatures**

# "LAPD" = Liquid Argon Purity Demonstrator

• Primary goal is to show that required electron lifetimes can be achieved without evacuation in an empty (20 ton) vessel - Phase I

• Will also monitor temperature gradients, concentrations of water, O2, and N2

• Phase II will place materials that would be used in a TPC into the volume and show that the lifetime can still be achieved

• Possible Phase III upgrade could place an actual TPC in the volume to provide a test bed for electronics, light collection, etc

# World's largest research distillation column

Atmospheric Argon has activity of 1 Bq/kg from $^{39}Ar$, which is a source of background and pile-up in multi-ton Argon based Dark Matter detectors. Underground Argon has been shown to be depleted in $^{39}Ar$ by at least a factor of 25.

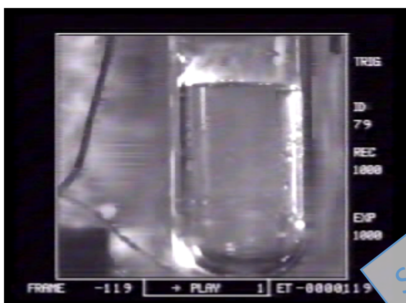
Distillation Column at the PAB was designed at Princeton and assembled at Fermilab, for the separation of underground Argon from the accompanying Nitrogen and Helium.

## Astrophysics R&D:

- Particle identification in a bubble chamber
- Solid Xenon research
- CCD's used as dark matter detectors
- Planck structure of space-time to be tested

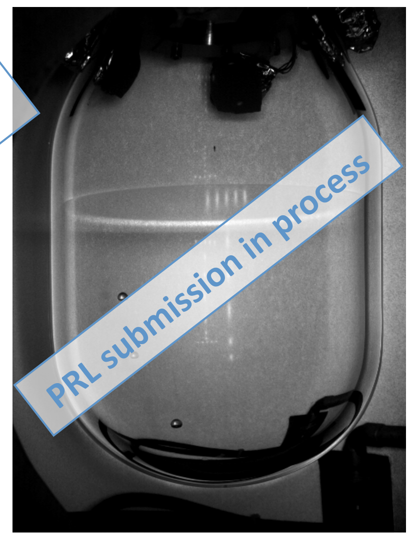
# Dark Matter Bubble Chamber Program

- Strategy is to take long runs with smaller chambers to understand backgrounds, operations, and for research and development while developing and commissioning an order of magnitude larger chamber
- Bubble chamber R&D will continue with KA15 funding.  Operations of COUPP-60 will be funded through KA13.



Test tube
(U Chicago)


COUPP 2kg

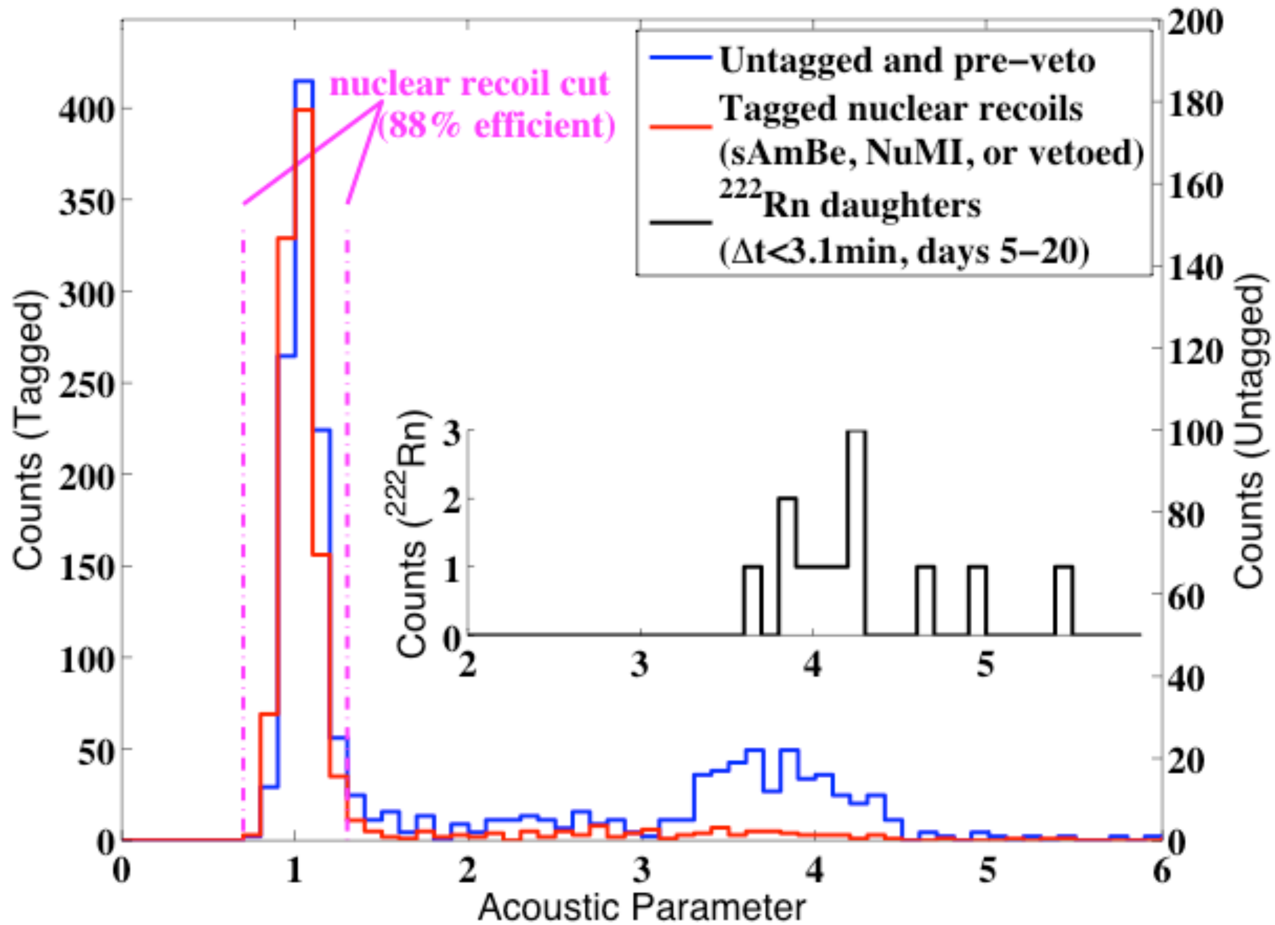


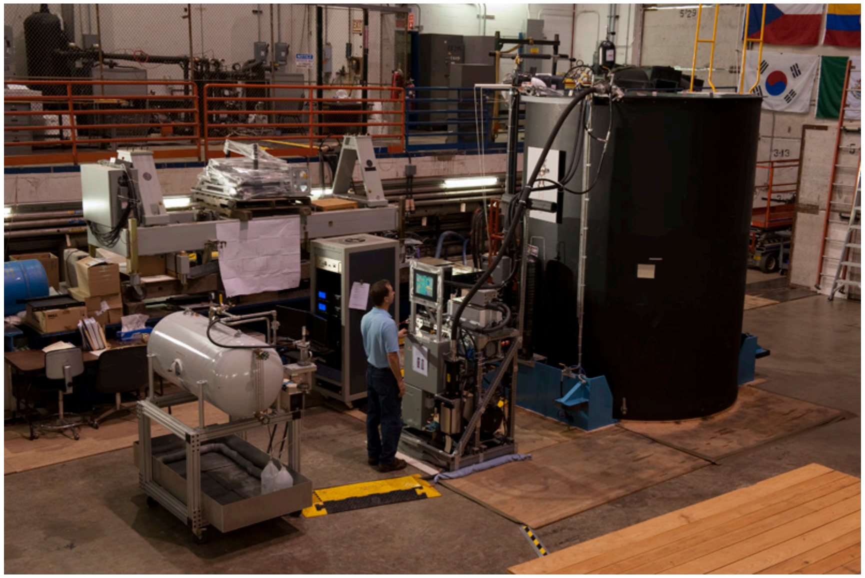

COUPP 4kg

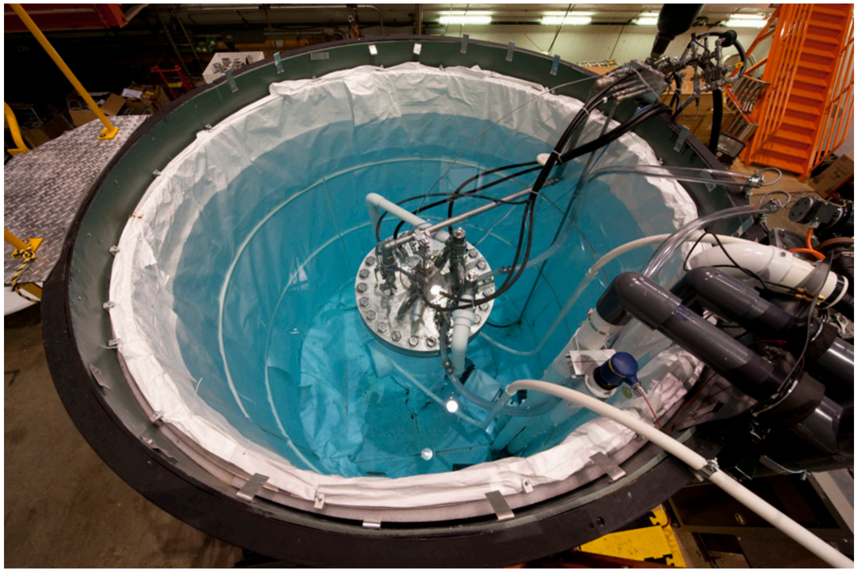

COUPP 60kg

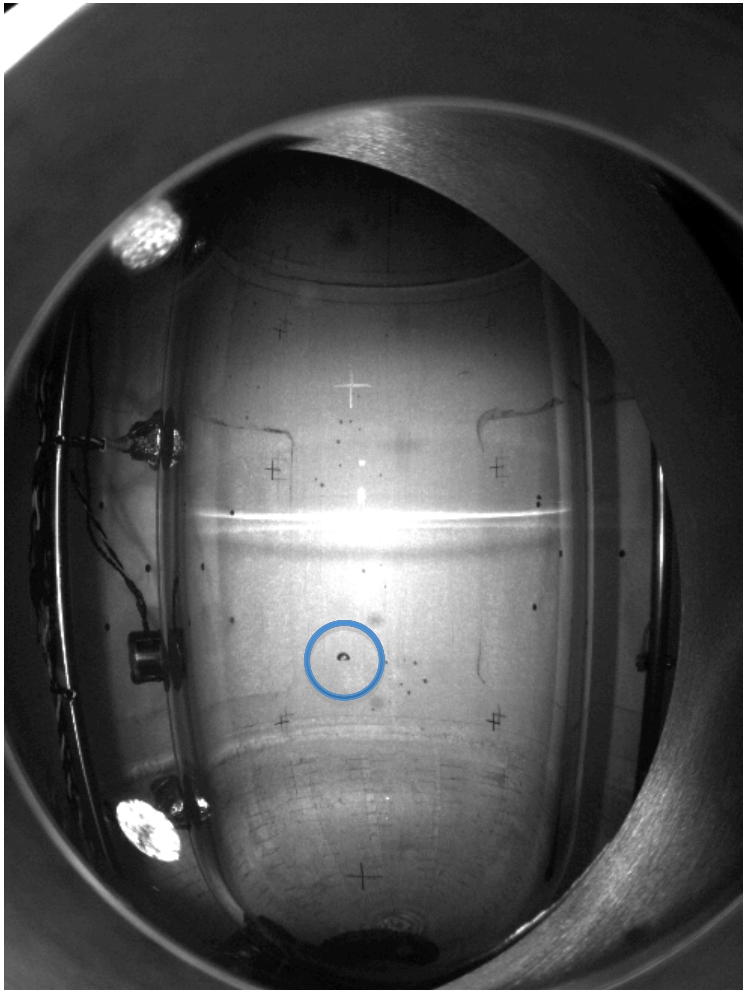
# Acoustic Parameter Discrimination

- Technique is based on observations in PICASSO detector
- (Amp • $\omega$)$^2$ (Normalized and position-corrected for each freq-bin)
- Measure of acoustic energy deposited in chamber
- Alphas are louder than neutrons
- ~200 well separated alpha events, confirming and extending PICASSO's result





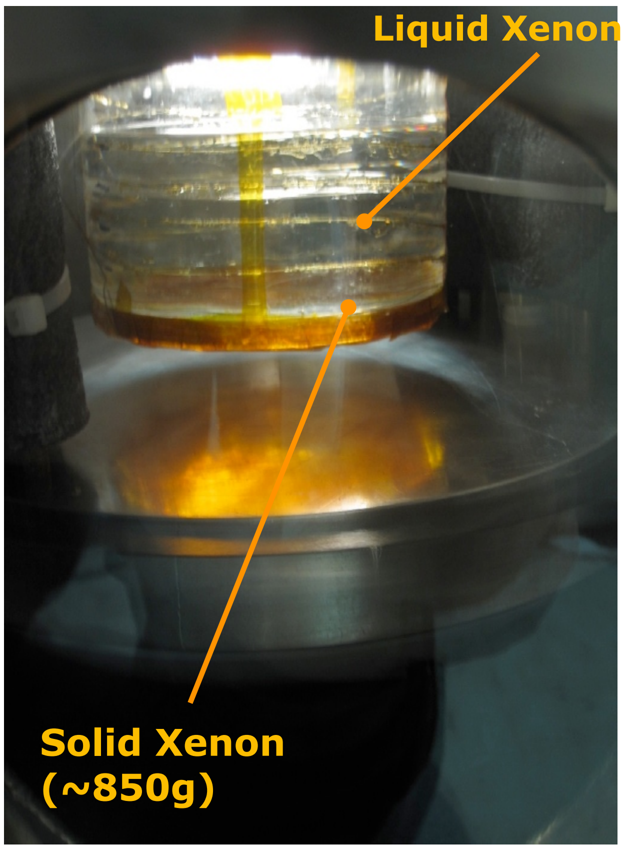




COUPP 60 kg detector has seen its first bubble underground!

# Solid Xenon Detector R&D Project

### Low Background Science
- Solar axion search
- Dark matter search
- Neutrinoless double beta decay




### Why Xenon?
- No long-lived Xe radio isotope
- High yield of scintillation light
- Easy purification (distillation, etc)
- Self shielding : Z=54

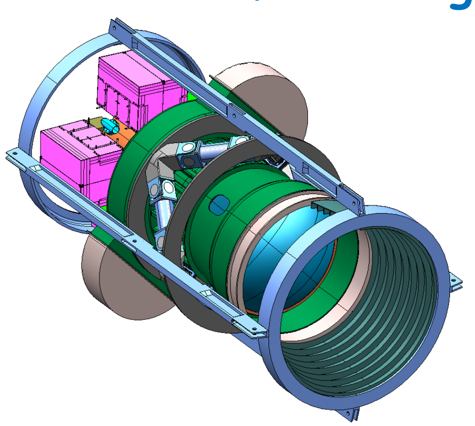
### Why Solid Xenon?
- Bragg scattering
- Simple crystal structure : fcc
- More scintillation light (solid > liquid)
- Drifting electrons faster
- No further background contamination through circulation loop

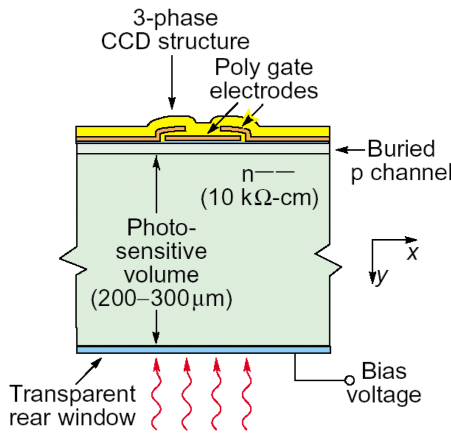
### R&D Phase-1 Completed
- Collaboration with U.Florida and TAMU
- Build optically transparent solid xenon
- Detailed recipes ready

**R&D Phase-2: Scintillation Light Readout (Now)**

# Dark Matter Search with CCD's (DAMIC)

**DECam: wide field imager**



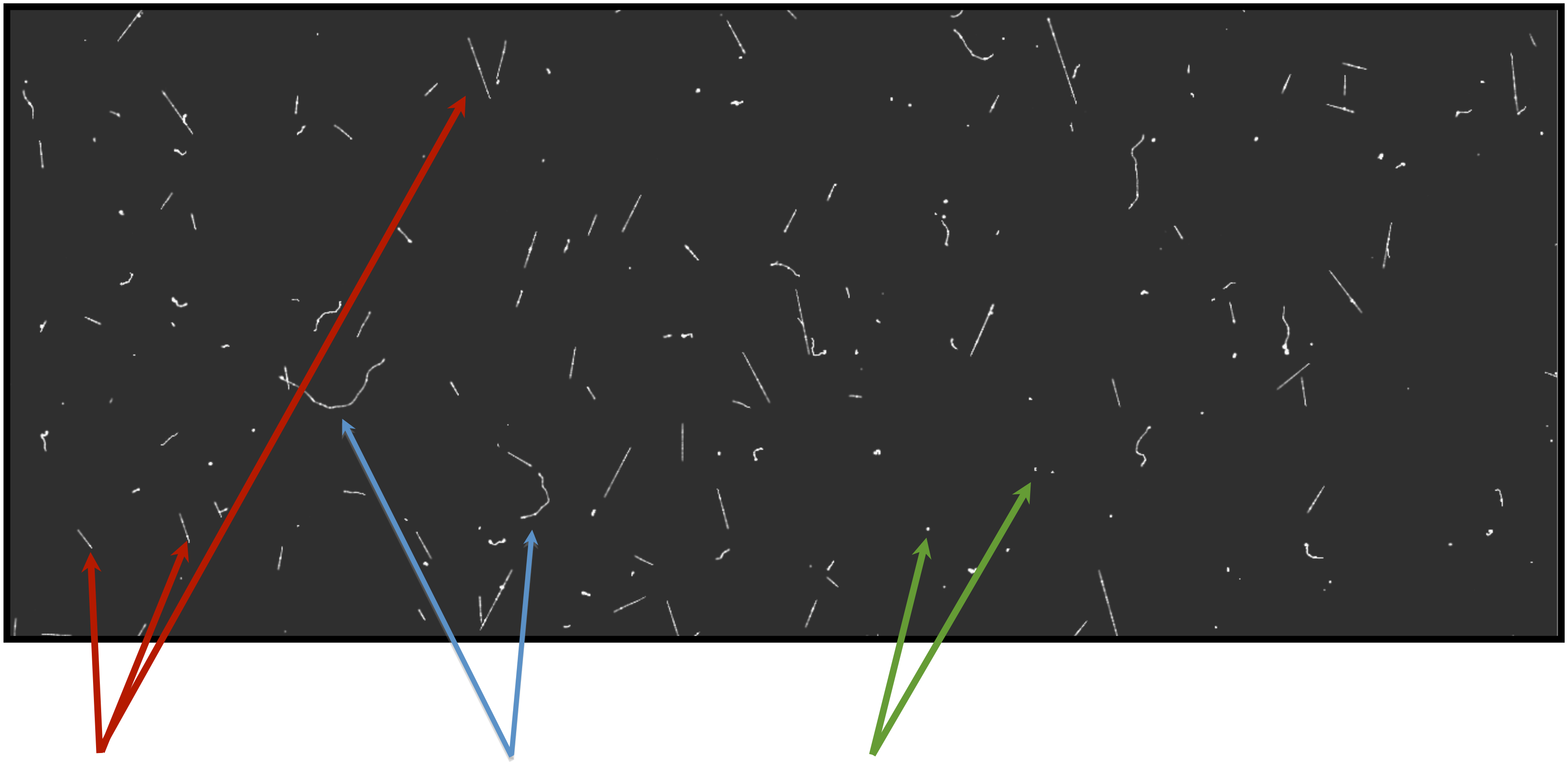



To improve the efficiency in the near-IR, the detectors extraordinarily thick. They are 250um instead of the typical 30 um for astronomical CCDs.

## Two features:

CCDs are readout serially (2 outputs for 8 million pixels). When readout slow, these detectors have a noise below 2e- (RMS). This means an RMS noise of 7.2 eV in ionization energy!

The devices are "massive",1 gram per CCD. Which means you could easily build ~10 g detector.



muons, electrons and diffusion limited hits.

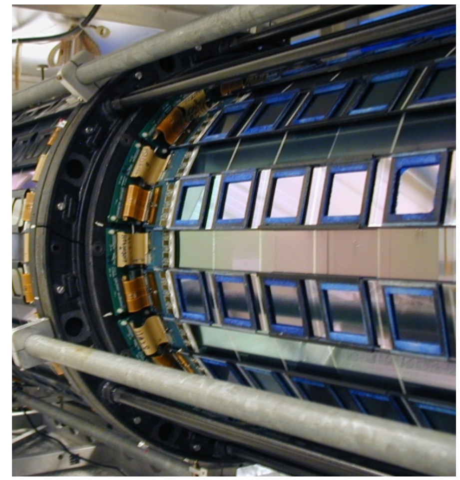
Nuclear recoils will produce diffusion limited hits

# Facilities:

- Technical Centers:
  - > Silicon Detector Facility
  - > Vacuum Deposition
  - > Detector Support
  - > PMT and SiPM Test Benches
- New high power laser laboratory
- MINOS Underground laboratory
- Particle test beam facilities

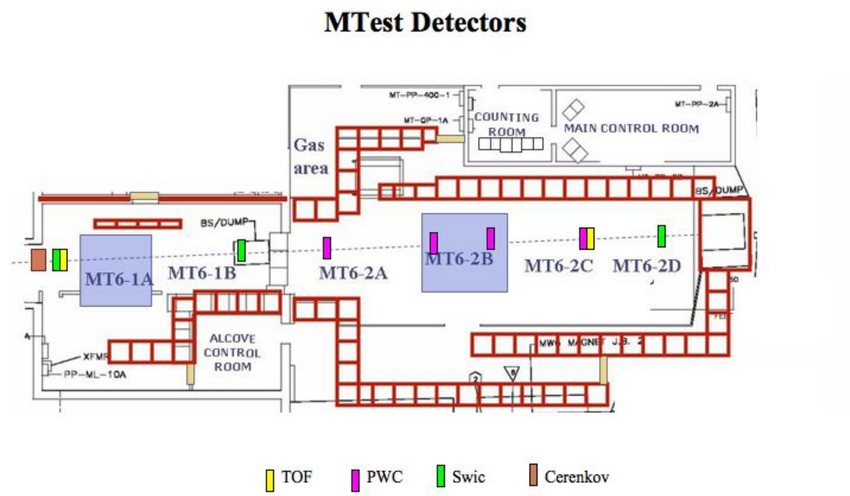
# SiDet has:

- Team of talented, experienced engineers, designers and technicians
- Extensive experience with:
  - Micron precision assembly
  - Engineering of low-mass, stiff structures
  - Thermal management issues

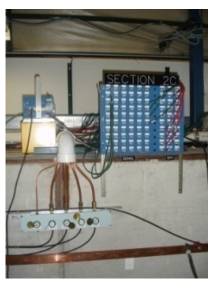


- Extensive equipment and resources
  - >7000 $ft^2$ of high-quality clean room space
    - 6000 $ft^2$ operated as class 10000
    - 1000 $ft^2$ operated as class 5000
  - 17 CMMs of various accuracies and measurement ranges
  - 1 automated optical measurement system (OGP)
  - 2600 $ft^2$ of burn-in space
  - 6 Kulicke & Soffa wire bonding machines

# Fermilab's Test Beam Facilities



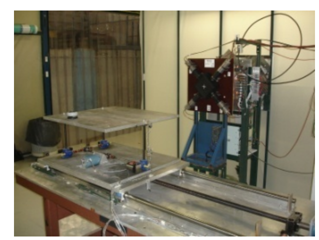

Spacious control room



Signal and HV cables

Gas delivery to 6 locations

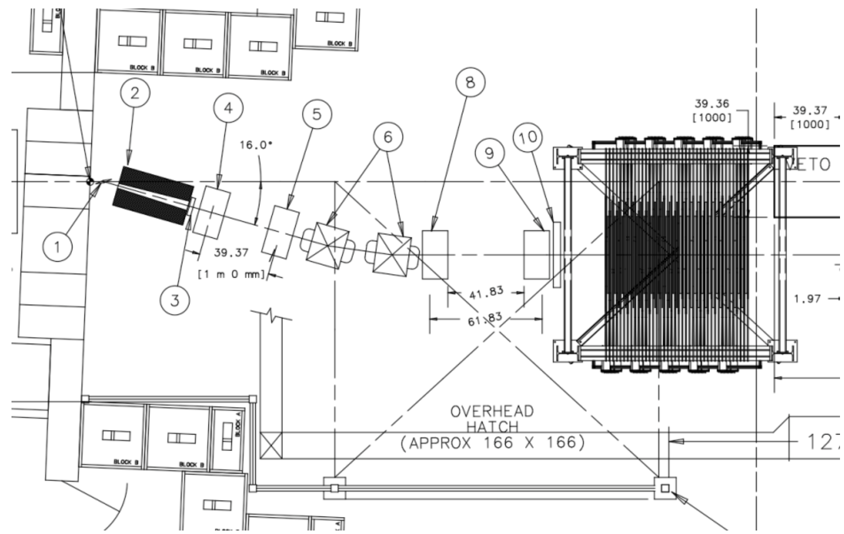
4 station MWPC spectrometer



Two motion tables

# New Tertiary 400 MeV/c Beamline

- The MINERVA experiment requested space to create a new tertiary beamline that could deliver particles down to 400 MeV/c momentum.
- The Particle Physics Division and Accelerator Division cooperated on delivering this beamline.
- Full tracking and TOF allows for momentum measurement and particle i.d.
- This new facility is now open for users.



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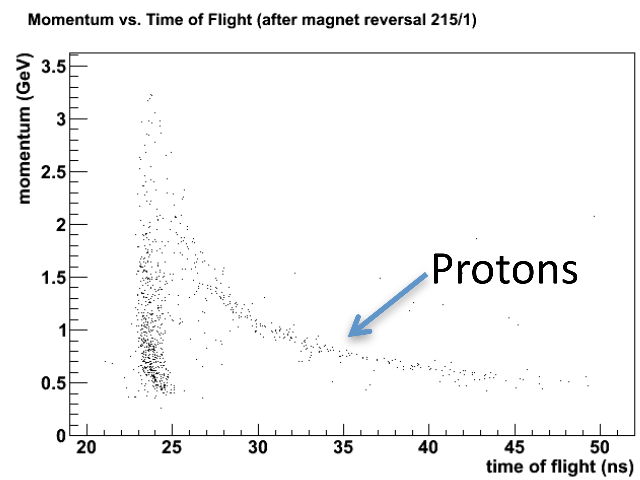
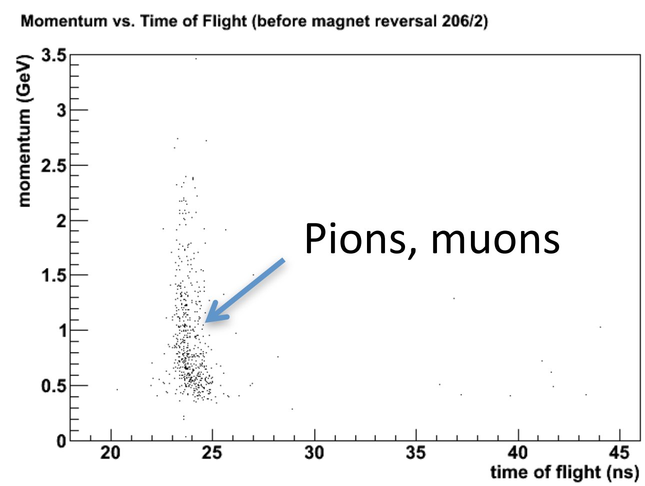


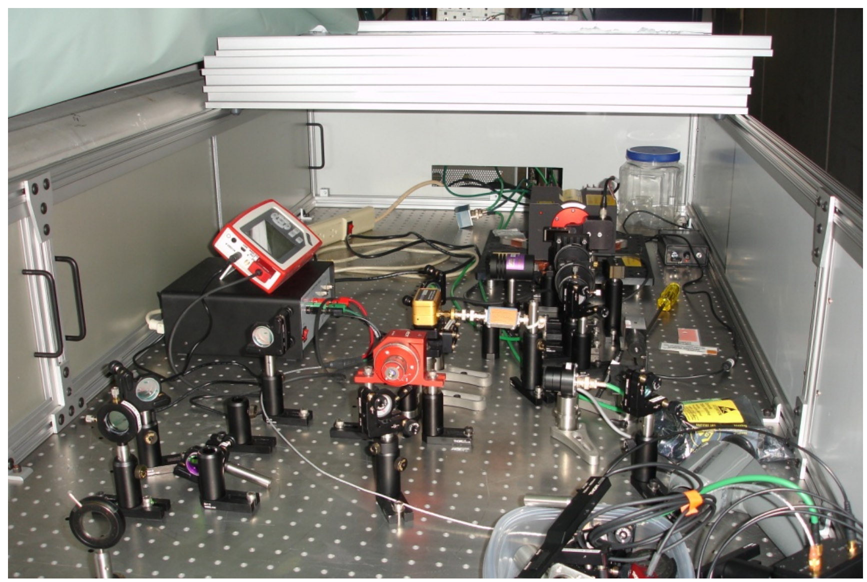



# A Second Test Beamline in MCenter


This section of beam pipe will be modified to have flanges and a bellows, so as to make it easily removable, thus allowing use of both this upstream area, and the full downstream spectrometer of the MIPP apparatus.

# A New High Power Laser Lab

- Developed in an empty beamline (MEast) to support Holometer and Axion research
- Will contain a 2 watt laser with cavity finesse of 1000.
- A baseline of 3 meters to start, with a goal of 40 m



# Where are we going?

- **In the Energy frontier:**
  - Advance silicon devices into a new 3D realm.
  - Continue work on understanding how to build a dual readout calorimeter
  - Establish a comprehensive center for SiPM characterization
  - Investigate optical data transmission for vertex detectors
- **In the Intensity frontier:**
  - Finalize construction and begin testing of a 20 ton Liquid Argon prototype detector
  - Operate new distillation apparatus to create radiopure liquid Argon for dark matter detectors
  - Develop ASIC readout for SiPM's in a time-of-flight system that can potentially be used for medical applications.
- **In the Cosmic frontier:**
  - Calibrate acoustic response to various backgrounds in a bubble chamber, for dark matter detection
  - Look for scintillation and ionization signals in solid Xenon crystals for axion and rare neutrino interactions.
  - Probe Planck scale physics in a high finesse, high power holographic interferometer
- **Improve our facilities:**
  - New MCenter test beam facility

*Fermilab is continuing its significant and focused program on detector R&D, backed up by a stronger management structure and increased involvement in national level planning.*

# What do we need?

- **We appreciate the level of detector R&D funding that has been granted to us and we strive to give good value for this investment. We can continue our current program with the level of funding in the President's budget**

- **There are holes in our program, however, that need specific attention:**
  - For ASIC and sensor development, our equipment is woefully out of date. For instance, we cannot conveniently handle wafers larger than 6", nor can we test structures in a variable temperature environment.
  - We do not have an irradiation facility for testing radiation damage in ASICs or sensors.
  - For FY12 we will not be able to operate ArgoNeut in either the Meson Test Beam Facility or in the SciBoone hall, as hoped.
  - We cannot increase our level of involvement in dual readout calorimetry, as will be required if a test beam size module is to be developed.
  - Progress on the Holometer will be in fits and starts without a commitment to proceed on the experiment.
  - We would need a significant investment to develop a large area photodetector factory onsite at Fermilab.