# The Detector Research and Development Program at Fermilab

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Chicago-IHEP Workshop
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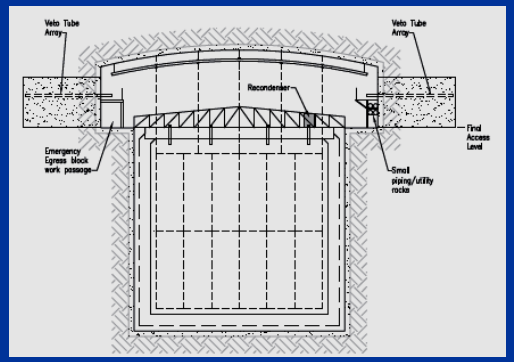
U.S. DEPARTMENT OF ENERGY

Fermilab

# Examples of challenges in the 'Frontiers' of High Energy Physics that Fermilab is addressing

'Energy Frontier' :

In an upgrade to the LHC detectors, vertex sensors and triggers will need to withstand a fluence of $10^{16}$ particles/cm$^2$

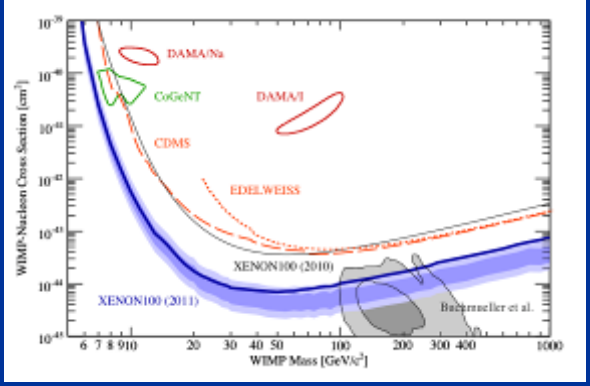



'Intensity Frontier':

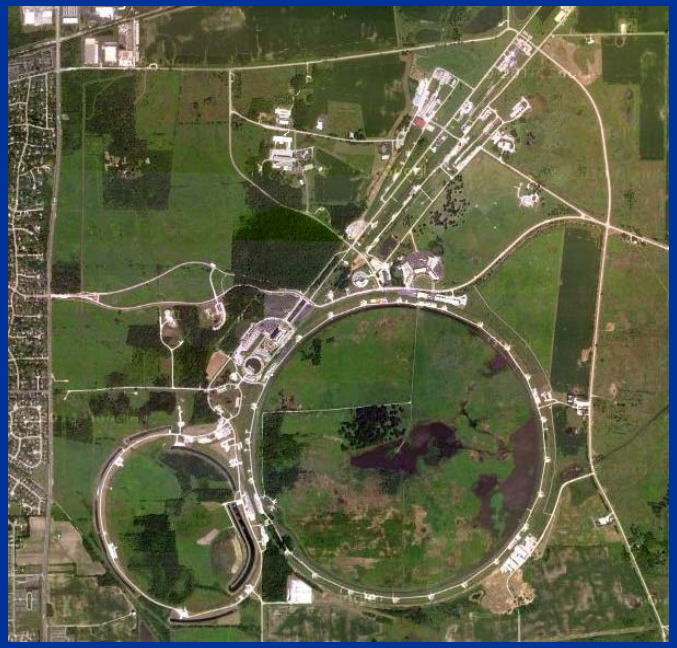
As an alternative to water Cerenkov neutrino detectors, the U.S. program is advancing neutrino detector research with large volumes of Liquid Argon

'Cosmic Frontier':

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



Fermi National Accelerator Laboratory is
25 square kilometers in Batavia, Illinois,
(about 50 kilometers west of Chicago)



Test Beam Facility

Silicon Detector Facility

Liquid Argon Test Facility

MINOS Underground Laboratory (300 mwe)

Thin Film Deposition; Scintillator fabrication; carbon fiber layup

D0 Experimental hall.

CDF Experimental Hall

# Fermilab supports engineers and technicians working on a very wide array of detector R&D projects

| PROJECT | TASK | DESCRIPTION |
|---|---|---|
| | | |
| Collider Detectors | Tracking ASIC R&D | Development of 3D ASIC's with large international collaboration |
| | Tracking Mechanical | Mechanical support and cooling designs for lepton colliders |
| | Calorimetry | Dual readout techniques, SiPM characterization, new QIE design |
| | psec Time-of-Flight | Contribution to the LAPPD phototube program at ANL |
| | Scintillators | Scintillator extrusion and testing for community |
| | | |
| Liquid Argon | 20 Ton Demonstrator | Large scale liquid Argon purification test |
| | Materials Test Stand | Testing materials for LAr TPC |
| | Cold Electronics | Cold electronics in conjunction with BNL (digital) and MSU (analog) |
| | Low backgrounds | Production of clean, low background Ar for dark matter community |
| | | |
| Astrophysics | CCD R&D | Low noise readout & dark matter & neutron imaging |
| | Bubble Chamber | Acoustic rejection of $\alpha$ background |
| | Laser interferometry | New high finesse laser lab for space-time measurements |
| | Solid Xenon | New type of dark matter/axion detector |
| | | |
| DAQ | Sensor DAQ | Radiation hardness testing in new sensors for community |
| | Optical DAQ | Large collaboration to work on multi-Gbit optical links |
| | $\mu$TCA and ATCA | Evaluation of newest data-flow architecture |
| | | |
| Facilities, Outreach | Tools | Upgrading R&D tools as needed |
| | ASIC support | Supporting software for ASIC development |
| | Test beam equipment | Pixel telescope support for FNAL Test Beam Facility |
| | Mcenter test beam | Development of second test beam line |
| | General Initiatives | New program to support University initiatives |
| | Detector School | EDIT 2012 graduate student school |

# Examples of Fermilab Tracking Detector R&D –

Sensor

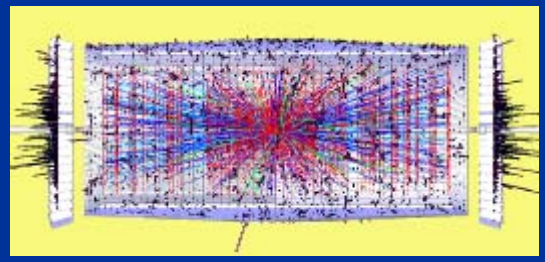
Front End

DAQ

Triggering

In the Energy Frontier, LHC upgrades will need to withstand a daunting luminosity of $10^{35}/cm^2/sec$.

Fermilab is using a comprehensive approach to this detector problem.



Sensor — Radiation hardness in new sensors (3D columnar + Diamond)

Front End — New 3D ASIC developments to give integrated track segment information

L1 Trigger — Track trigger using 3D techniques; Associative Memories

Data Transmission — Multi-wavelength optical DAQ

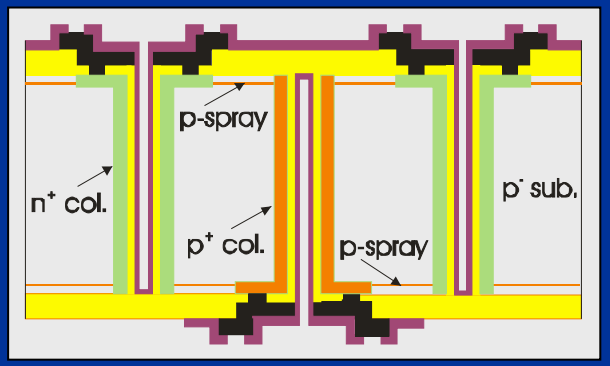
Track Fitting — GPU's; xTCA

15 US universities
19 foreign institutions
5 laboratories
8 industrial partners

# Sensor Test Beam at Fermilab

- Goal is to test detection efficiency of sensors, have them irradiated at SLHC levels, and test them again
  - Diamond sensors
  - 3D sensors
  - Magnetic Czochralski (MCz) planar silicon sensors
  - Float Zone (FZ) planar silicon, p-type silicon

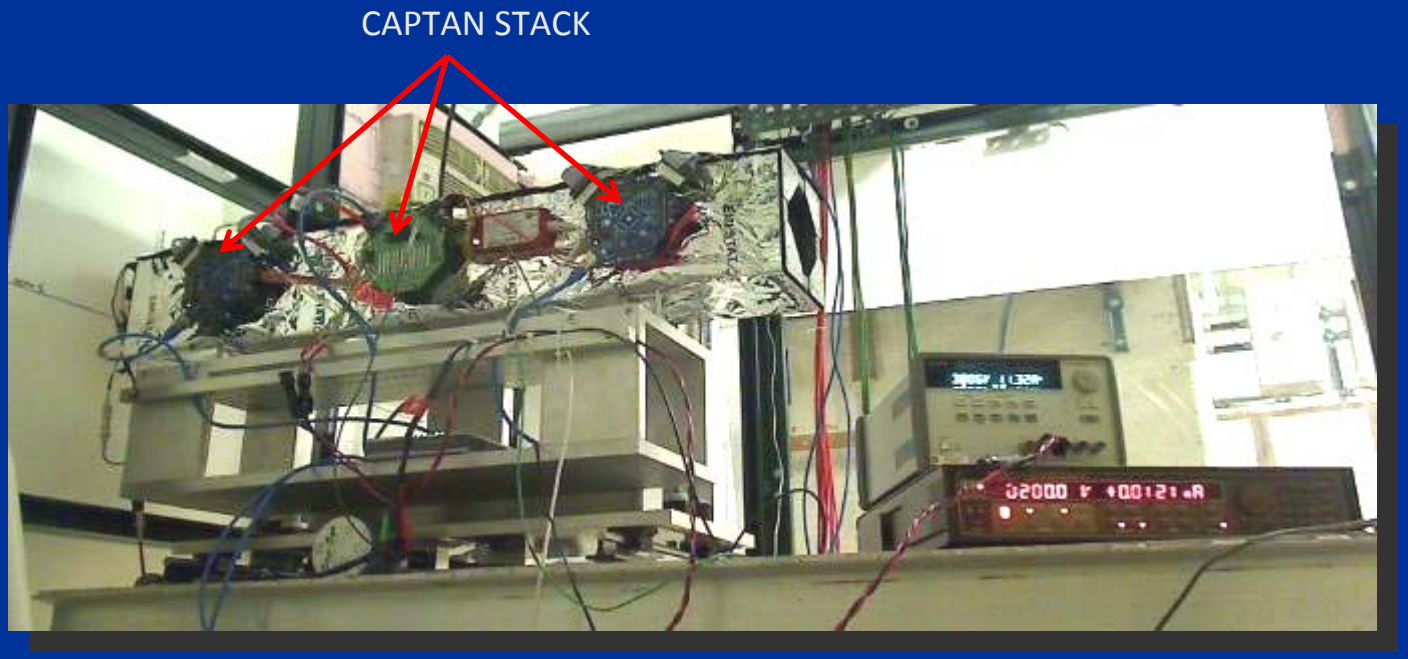
- We test all sensor materials using the same readout electronics in the same environment and apparatus
  - fair comparison of all candidates




Advanced design from FBK for ATLAS:

**3D-DDTC$^{+}$: double-sided 3D with passing through columns**

# Test Beam Pixel Telescope and DAQ



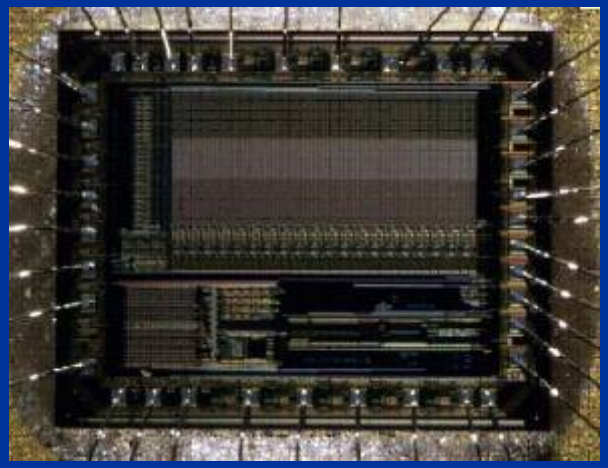

CMS pixel sensors read out by CAPTAN DAQ, developed by Fermliab Computing Division.

Uses conventional 3-dimensional architecture with potential of more than 100 Gbps along 4 buses.

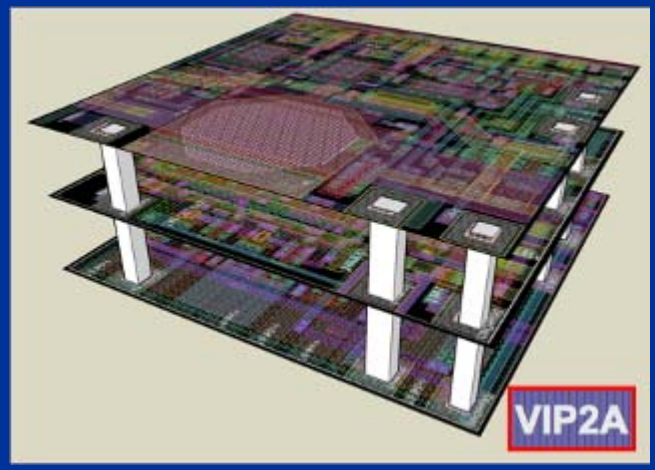
Same data acquisition system as used in IHEP silicon telescope

# 3-Dimensional ASIC program

(See Ron Lipton's Talk)



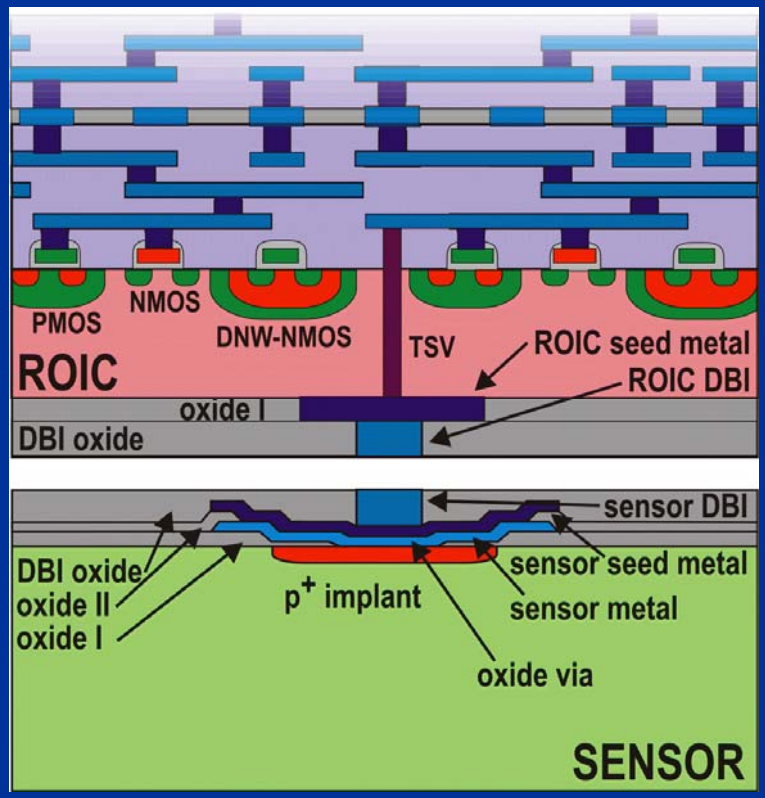
Conventional Monolithic Active Pixel Sensor




3 tier 3D stack for FNAL ILC vertex chip, fabricated by MIT-LL

- Fermilab has led the formation of a large international group (http://3dic.fnal.gov) addressing this new technology. This group of 17 members from 6 countries shared a multi-project run in 2009 and are still testing structures coming from that run. New devices are coming this year.
- A very important development has occurred in that the tools and techniques learned from this process have been adopted by the major silicon fabrication brokers: MOSIS, CMP and CMC.

# FNAL, in Cooperation with Industry, Have Established Enabling Technologies:




- Wafer bonding
- Thinning and annealing (with Cornell)
- Through-silicon interconnects
- Silicon on Insulator

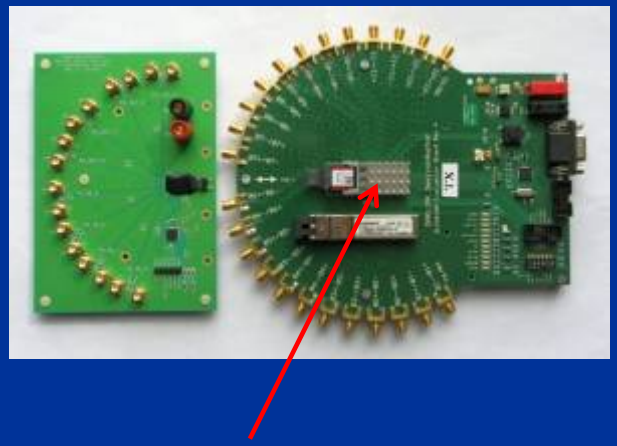
Adds capabilities to classical amplifier/discriminator:

- Time stamping (LC, CMS,…)
- Time correlations (x-ray)
- Centroid finding (x-ray, CMS)
- Triggering (CMS, ATLAS, MC)
- Fast readout (CMS)
- Region of interest readout (CMS)

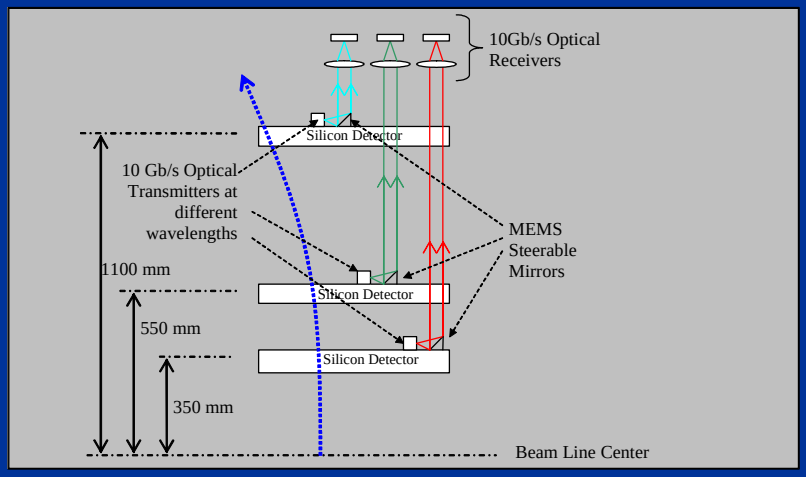
Progress has been slow due to multiple handling and fabrication problems.

# Parallel MultiWavelength and Rad-Hard Optical DAQ Device Evaluation

Collaborative Effort (CERN, ANL, industry) to Develop
Low Power/Low Mass MultiGigabit Data Readout



Testing commercial devices
(12 channel transmitter,
2.7 Gbps/channel) after irradiation




Can foresee using free space optical transmission through silicon, with multi-wavelengths centered on infrared band

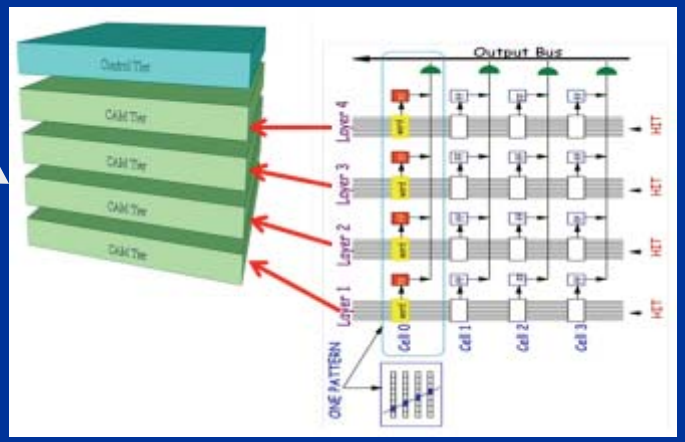
# Moving to new DAQ/Triggering methods

(See Tiehui Liu's talk)

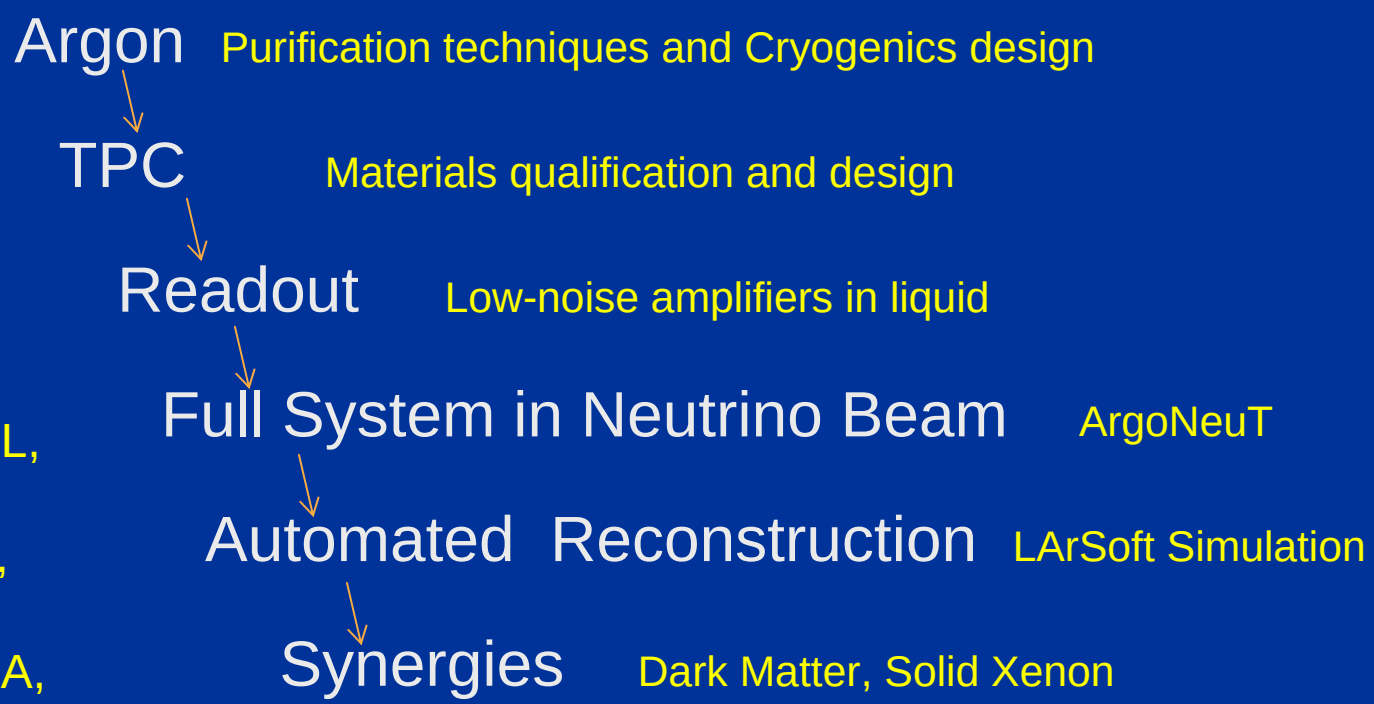
- ATCA = Advanced Telecommunications Computing Architecture.
  - Large experiments (CMS, ATLAS, LHCb, PANDA) are considering xTCA over VME.
  - Task force at Fermilab formed including engineers from CD, PPD, and AD. Collaboration with SLAC

12U 14-slot ATCA

- L1 with embedded Associative Memory
- L2 with Graphical Processing Units



Next Generation Neutrino Physics requires a detector which provides tracking, particle ID and calorimetry for unambiguous identification of rare processes => Liquid Argon TPC.




Collaborating Institutions: BNL, Indiana, MIT, Michigan State, Princeton, Syracuse, UCLA, Yale

# Liquid Argon Purity Demonstration

- Most LArTPC detectors have been evacuated before filling. Not practical for multiple kiloton detectors.
- Demonstrate good life-time in an industrial vessel without evacuation.
- First multi-ton purification system designed and built at Fermilab.
- Commissioning started in October 2011
  - Stage 1 – bare tank has achieved 3 msec lifetime in 1/3 full vessel
  - Stage 2 – with 2 meter TPC


Argon Source and Materials Test System, &
Electronics Tests for TPC's - constructed 2006 - 2009

`A system to test the effects of materials on the electron drift lifetime in liquid argon and observations on the effect of water' R. Andrews *et al.*, Nucl.Instrum.Meth.A608:251-258,2009.

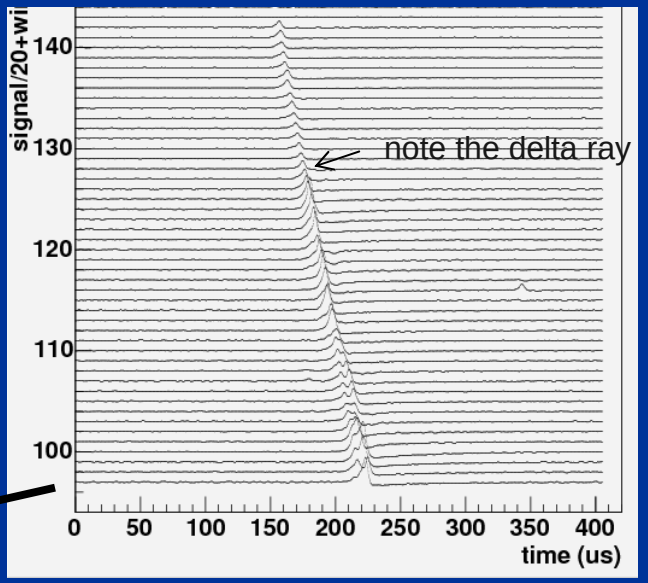
| Material | Date test started | Preparation | Tests | Water [ppb] | Lifetime [ms] | LogBook # |
|---|---|---|---|---|---|---|
| Cleaning Solution | 6/29/09 | evac. 24 h | vapor/liquid | 4 | 5 | 946 |
| Vespel | 7/9/09 | evac. overnite | liquid/vapor | 5-7 | 2-5, 4-6 | 960 |
| MasterBond glue | 7/16/09 | purged 18 h | vapor/liquid | 1.6 | 1.3- 2.9 | 974 |
| LEDs | 7/31/09 | purged 38 h | vapor | 3.5 | 5 | 993 |
| Carbon filter material | 8/12/09 | evac. 24 h | liquid/vapor | 2 | 4-9 | 1000 |
| 962 FeedTru Board V2 | 10/12/09 | evac. 24 h | vapor/warm | 85 | 1-5 | 1062 |
| Teflon cable | 1/9/10 | purged 28 h | warm/liquid/vapor | 8-20 | 2-5 | 1175 |
| 3M "Hans" connectors | 1/29/10 | purged 46 h | warm/liquid/vapor | 5-12 | 3 | 1198 |
| 962 capacitors | 3/2/10 | evac. 24 h | warm/liquid/vapor | 6-14 | 3-6 | 1228 |
| 962 polyolefin cable | 4/12/10 | evac. 16 days | warm | 25-60 | 2 | 1237 |
| Rigaku feedthrough | 4/20/10 | purged 7.5 h | warm | 15 | 3 | 1250 |
| Rogers board (Teppei) | 4/23/10 | purged 26 h | warm/liquid/vapor | 40 | 2, 6-10 | 1254 |
| Arlon Board (Teppei) | 5/14/10 | evac. 0.5 h, pur.2 days | warm/vapor | 300, 80 | 1.3, 3.5 | 1263 |
| Polyethylene tubing | 5/24/10 | evac. 6 h, pur. 66 h | warm | 300-500 | 1 | 1278 |
| Teflon tubing | 5/27/10 | evac. 1 h, pur.17 h | warm | 9-13 | 4-5 | 1283 |
| Jonghee board | 5/28/10 | evac. 6 h, pur. 1.5 h | warm/vapor | 100,28 | 1.2, 5-8 | 1285 |
| Jonghee connectors | 6/4/10 | evac. 3.5 h, pur. 16 h | warm/vapor | 50 | 2-3 | 1290 |
| PVC cable | 6/14/10 | evac. 29 h, pur.1 h | warm | 120 | 1-2 | 1296 |
| Teppei TPB samples | 8/3/10 | purged 26 h | warm | 600-1600 | 0.7 | 1342 |
| Teppei TPB samples | 9/4/10 | purged 37 h | liquid /vapor | 15, 300 | 6 | |
| PrM feed tru (baked) | 10/5/10 | purged 25 h | warm/vapor | 35, 20 | 3, 2 | 1396 |
| Copper foil on mylar film | 10/14/10 | purged 26 h | warm/liquid/vapor | 15, 10, 9 | 3, 8, 7 | 1409 |
| Teppei SHV connector | 10/25/10 | purged 25 h | warm/vapor/liquid | 35, 11, 0 | 2, 6, 6 | 1415 |
| FR4 | 11/16/10 | purged 25 h | warm/liquid/vapor | 180, 20, 65 | 1.5, 6, 2.5 | 1429 |
| Gaskets | 3/11/11 | purged 24 h | warm/liquid/vapor | 8, 10 | 2.5, 8 , 7 | 1521 |
| LBNE AP-219 Color. Developer | 4/13/11 | purged 25 h | warm/vapor | 65, 15 | 4, >6 | 1722 |
| LBNE RPUF Foam | 4/22/11 | evac. 26 h, pur.1 h. | warm | 800 | 0.2 | 1729 |
| LAPD LEDs | 5/12/11 | purged 49 h | vapor | 0.6 ppb | 10 | 1769 |

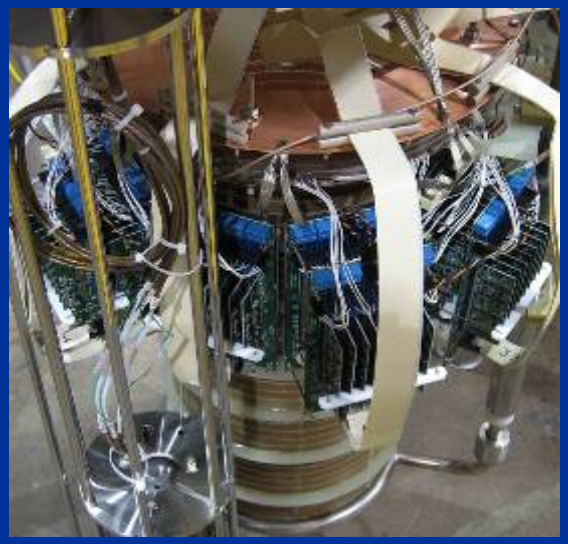
Sample data on different materials (bad, good)

# TPC Electronics Test System

with external amplifiers

(as used in ArgoNeut)



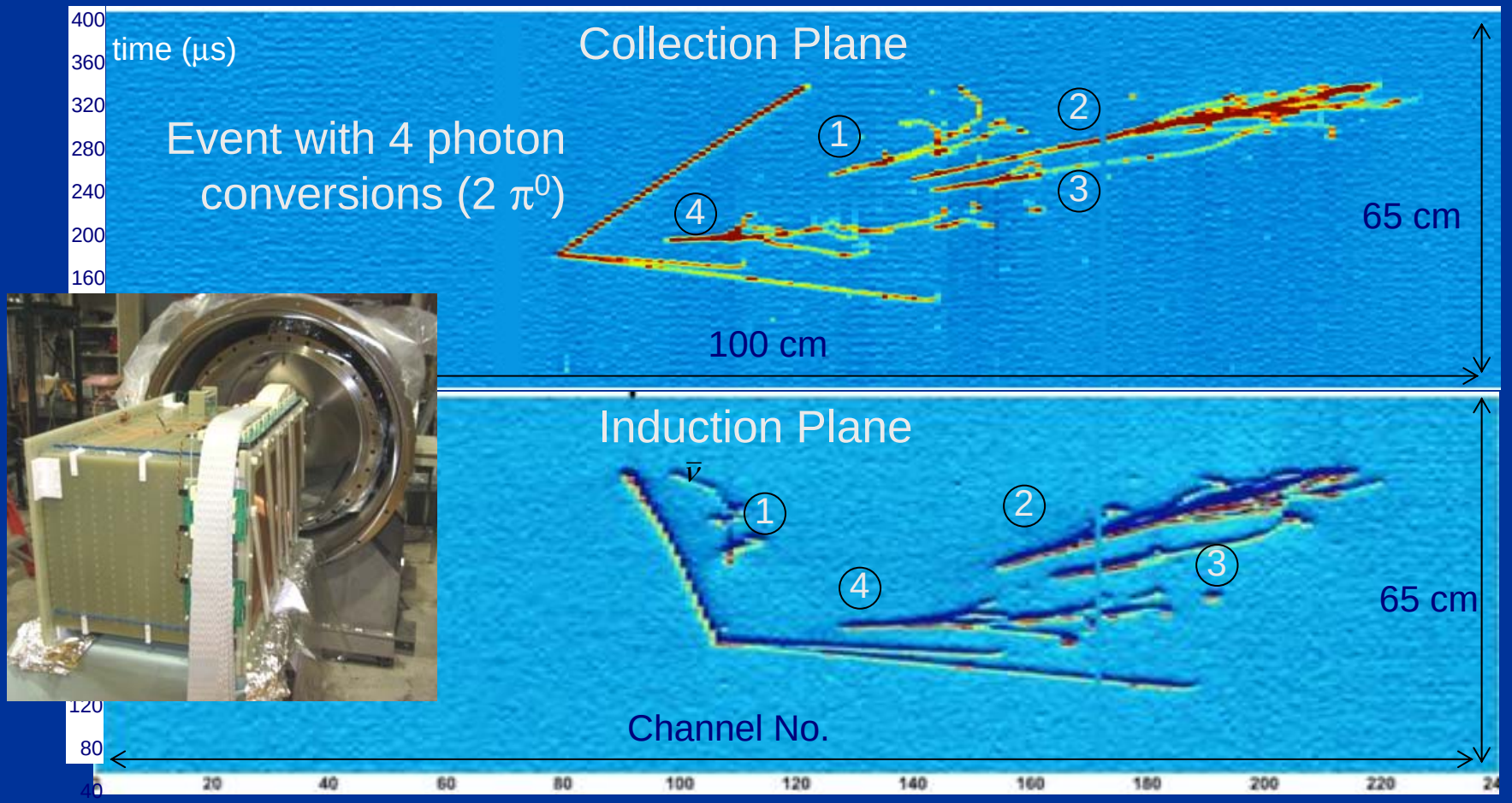



State of the Art:

in-liquid amplifiers from MSU

- PMOS based design
- Operates very well at 90K
- Improves Signal to Noise
- Multiplexing reduces cable plant
- Can be converted to ASIC

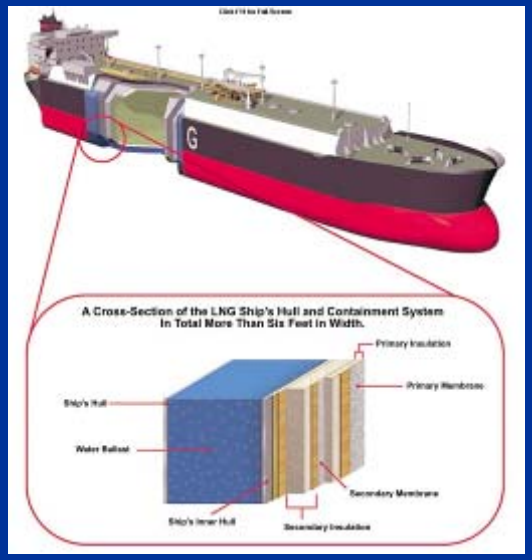
# ArgoNeuT in NuMI beam (2009 – 2010)




Invaluable data set: 1000's of $\nu$ interactions in Argon

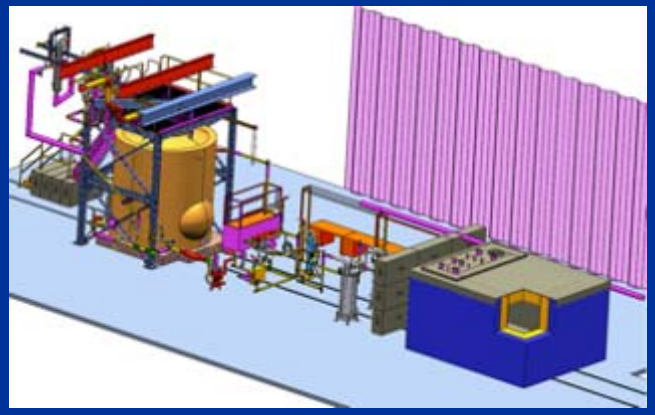
arxiv 1111.0103 : First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon – J. Spitz (Yale) Thesis (uses automated reconstruction)

# Meeting the challenges for multi-kiloton scale detectors

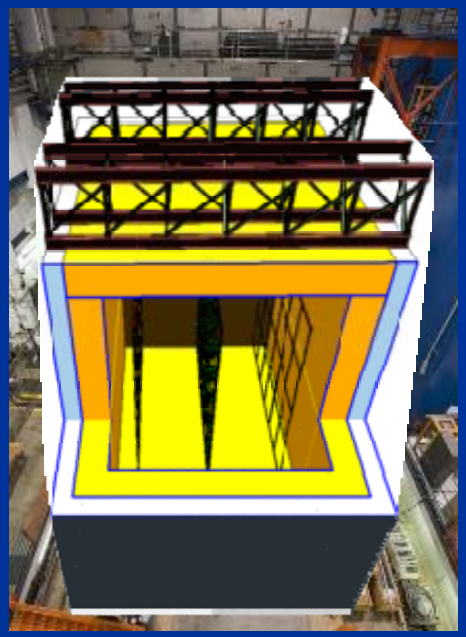



Liquid Natural Gas carriers routinely carry 120,000 cubic meters of liquid at -160° C. The key is a rippled surface that can contract without changing overall shape.

LAPD LAr35t



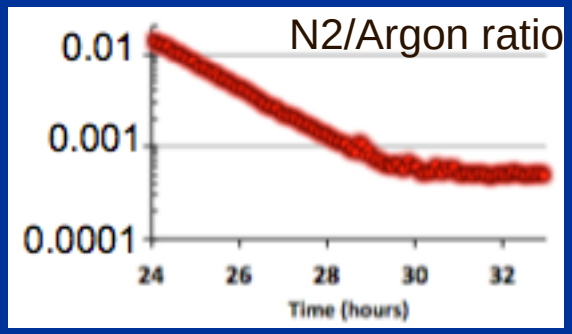
The LAr35t cryostat is our first foray into the use of membrane cryostats. It will use the same cryogenics and purification system as developed for the Liquid Argon Purity Demonstration.



The LAr1k (kton) is designed to be built in the DZero pit where there is significant liquid argon infrastructure. It is intended to validate technologies adopted for kton neutrino detectors.

# LAr Distillation Column for Dark Matter (Princeton-Fermilab)

- Atmospheric Argon: ~ 1 Bq/kg from $^{39}Ar$ - too high!
- Low background source comes from $CO_2$ wells - arrives at Fermilab as 5%Ar, 45% $N_2$, 55% He
- He escapes, $N_2$ needs to be distilled off
- Column commissioned 11/11 with atm. Argon
- Purified to >99.95% with 80% capture




Sensitivity limit of gas analyzer

Aimed at DarkSide and DEAP programs

# Other Examples of Fermilab Detector R&D –

Calorimetry

Time-of-Flight

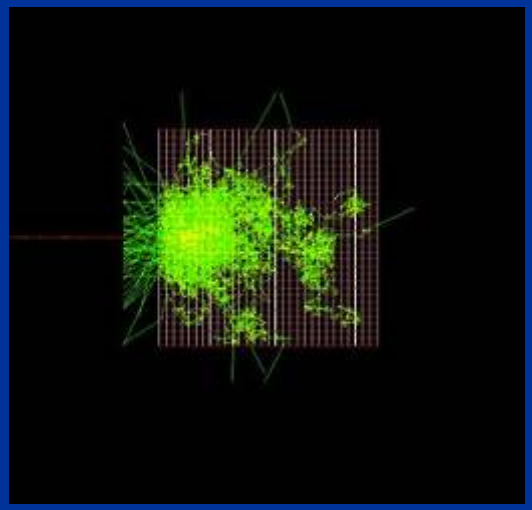
Dark Matter

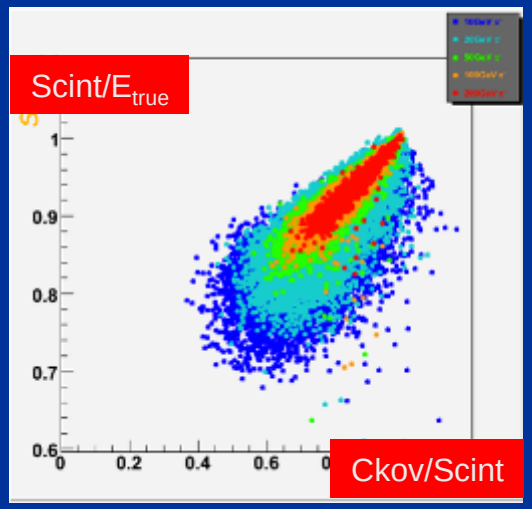
CCD's

# A Homogeneous Hadron Calorimeter

(see Adam Para's talk)

- Di-jet resolution is important for collider detectors and is currently limited by traditional hadron calorimetry techniques
- Our simulation studies of a highly segmented, pure crystal calorimeter with both Cerenkov and scintillation readout shows it is possible to achieve 15%/$\sqrt{E}$ resolution
- The thin profile of SiPM's makes a full absorption hadron calorimeter possible

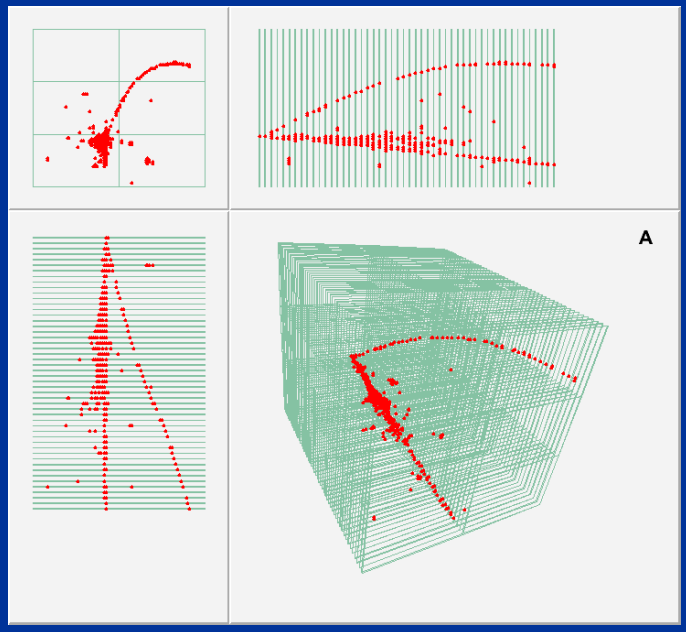





Simulation of pions interacting in a segmented, dual readout calorimeter shows how to correct for undetected binding energy losses

We (FNAL/ANL/CalTech) are working with SICCAS to search for an appropriate scintillating doped $PbF_2$

# Digital Hadron Calorimeter (ANL) at Fermilab's Test Beam Facility (see Marcel Demarteau's talk)

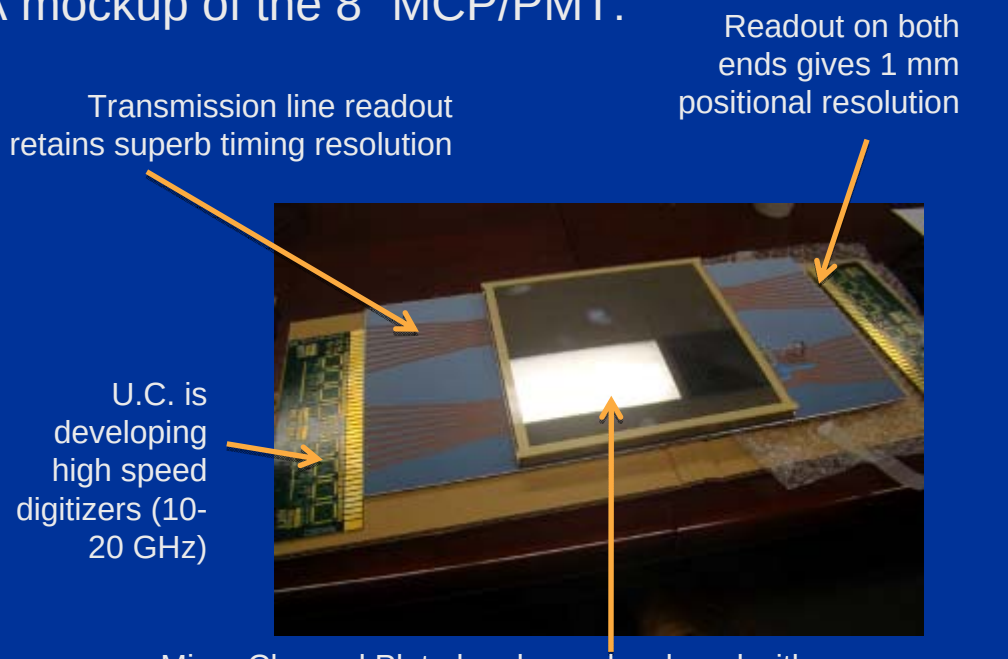


- This test device consists of RPC layers with pad readout
- Has more channels (400K) than CMS + ATLAS + LHCb calorimeters combined
- Fermilab designed the readout chip and trigger modules for this detector
- May pave the way for a pointing calorimeter for high intensity decay experiments

# Fermilab is supporting the U.Chicago/ANL led LAPPD project
(see Henry Frisch's talk)

- "Large Area Picosecond level Photo Detectors"
- FNAL provides technical and scientific help on the project
- Created new electrode coating chamber

A mockup of the 8" MCP/PMT:




Micro Channel Plate has been developed with new process
(ALD coating of drawn glass channels)

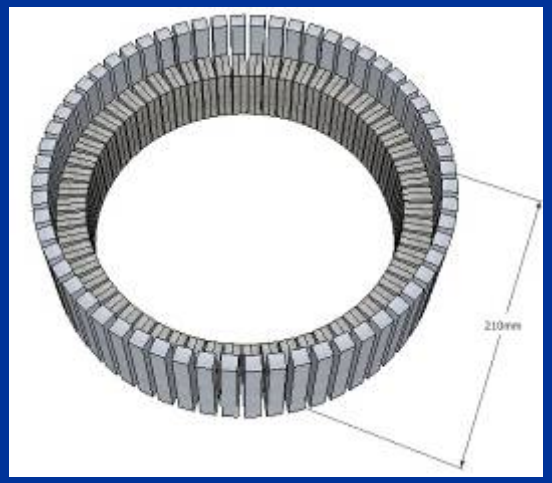
New thin film coating facility

# SiPM's for Time-of-Flight in PET Imaging

- Silicon PhotoMultipliers are multi-pixel avalanche photodiodes
- About 50 microns in size, they count individual photons
- Fermilab/U.C. have been studying their use for time-of-flight in high energy physics calorimeters and in PET imaging

Transmission line readout suitable for reading 8 separate SiPM's

CAEN 1742 module digitizes at 5 Gs/s. Good for timing and energy measurement



Ring of transmission line readouts can make up new PET-TOF detector

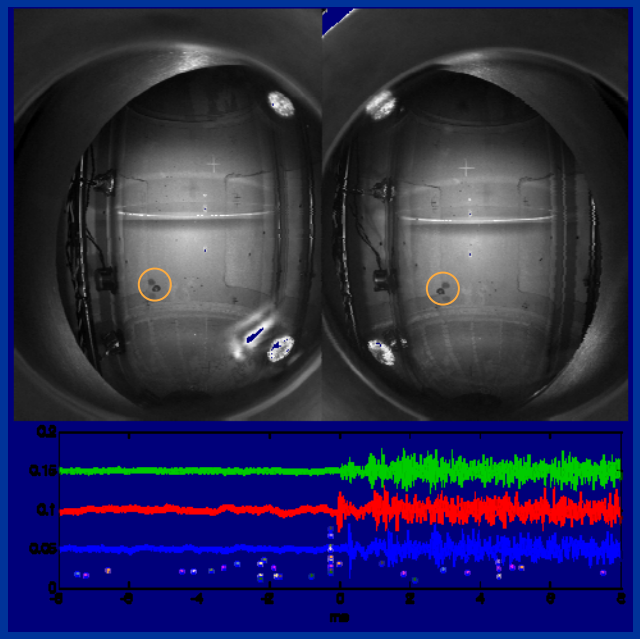
# COUPP Bubble Chamber – How Detector R&D Evolves into an Experimental Program

- Superheated $CF_3I$ target near room temperature and pressure
- Can tune chamber so it is sensitive ONLY to nuclear and not electron recoils
- Started out as an R&D test beam experiment
- Now a full-fledged dark matter experiment; the 60 kg detector is moving soon to SNOLAB
- ANL is now using our technology for nuclear astrophysics studies

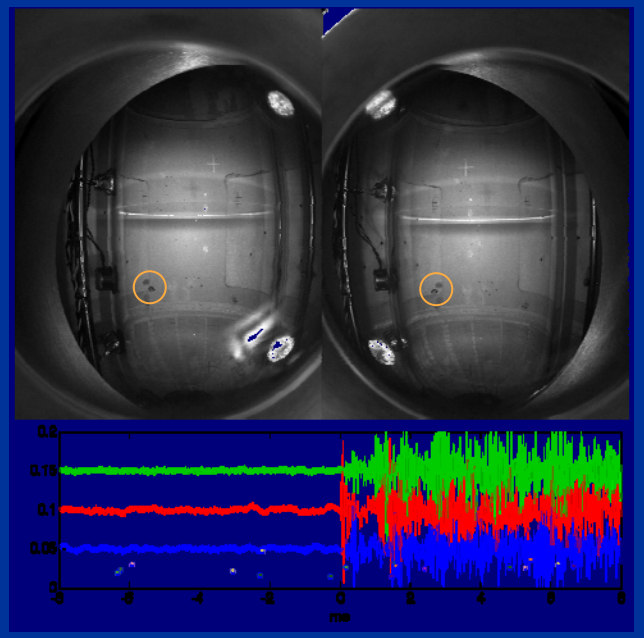
COUPP-4 at SNOLAB

COUPP-60 at FERMILAB

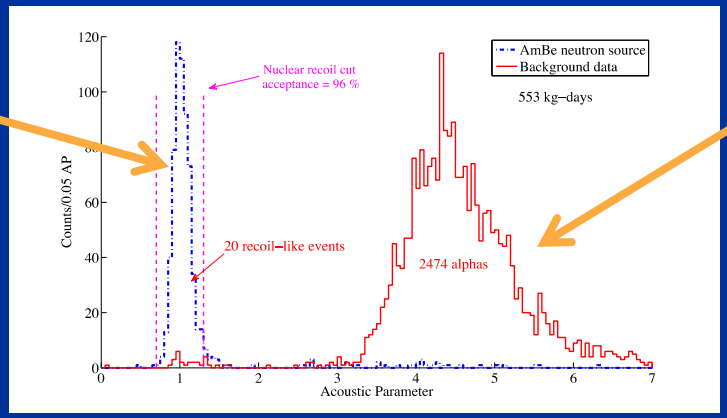
# Major advance on PICASSO discovery of acoustic rejection



Particle I.D.
by Sound !



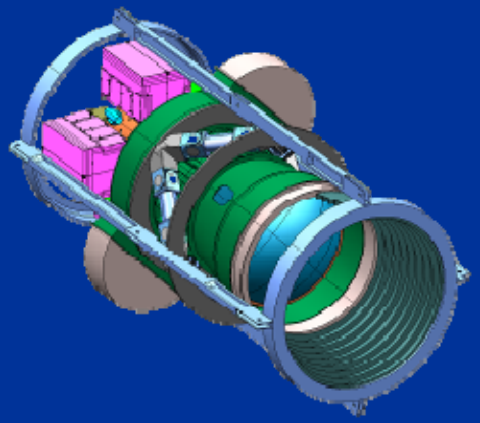
Cosmic-induced neutron

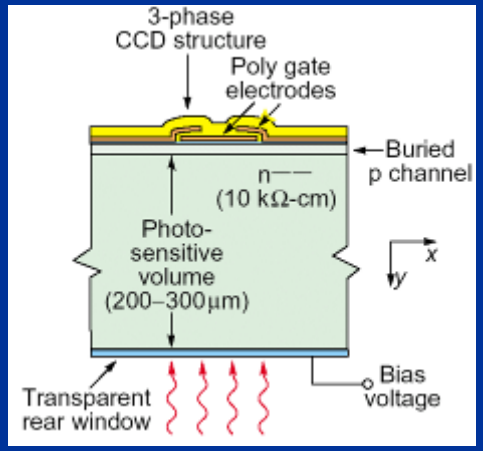



Alpha decay in same region

# Dark Matter Search with CCD's (DAMIC)

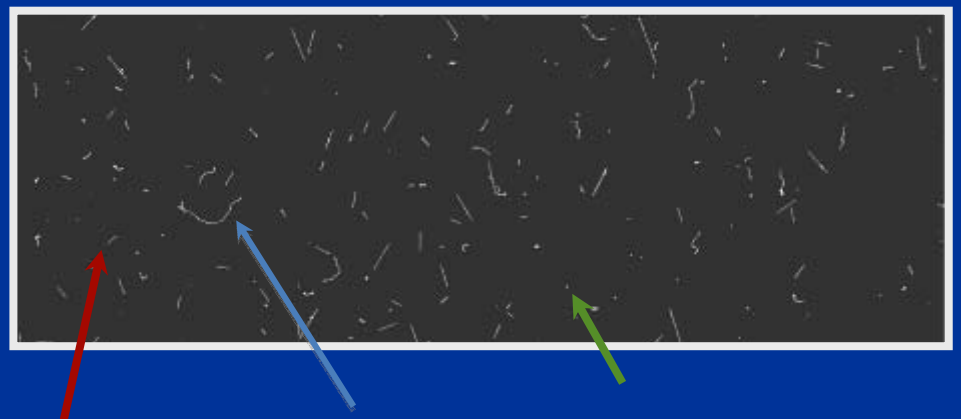
DECam: wide field imager





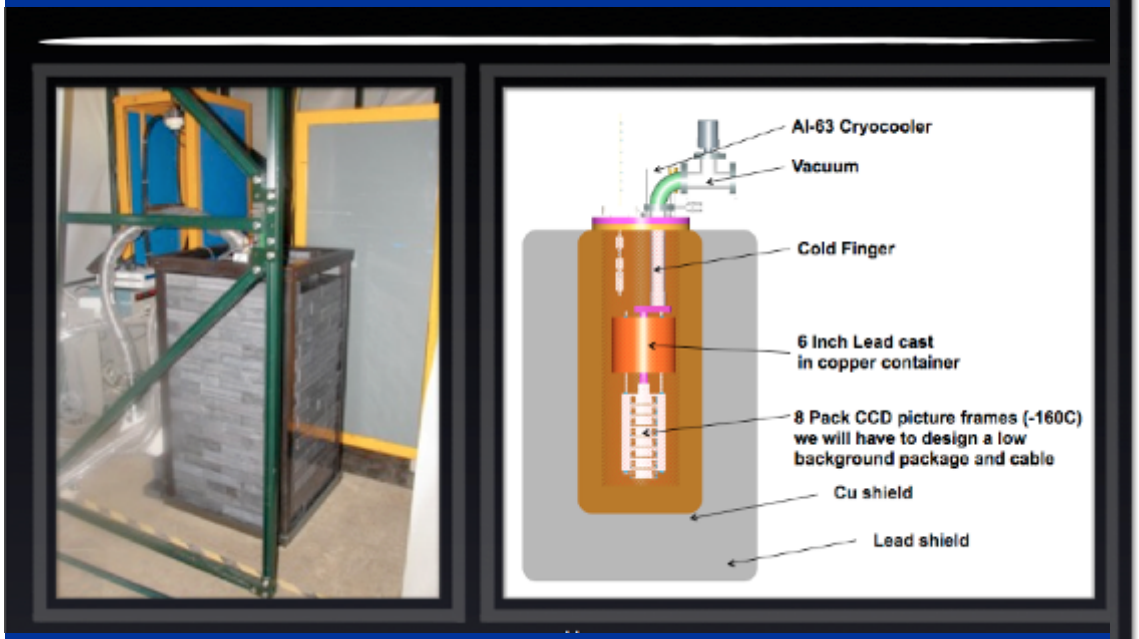

To improve the efficiency in the near-IR, the DECAM detectors are extraordinarily thick: 250um instead of the typical 30 um for astronomical CCDs.

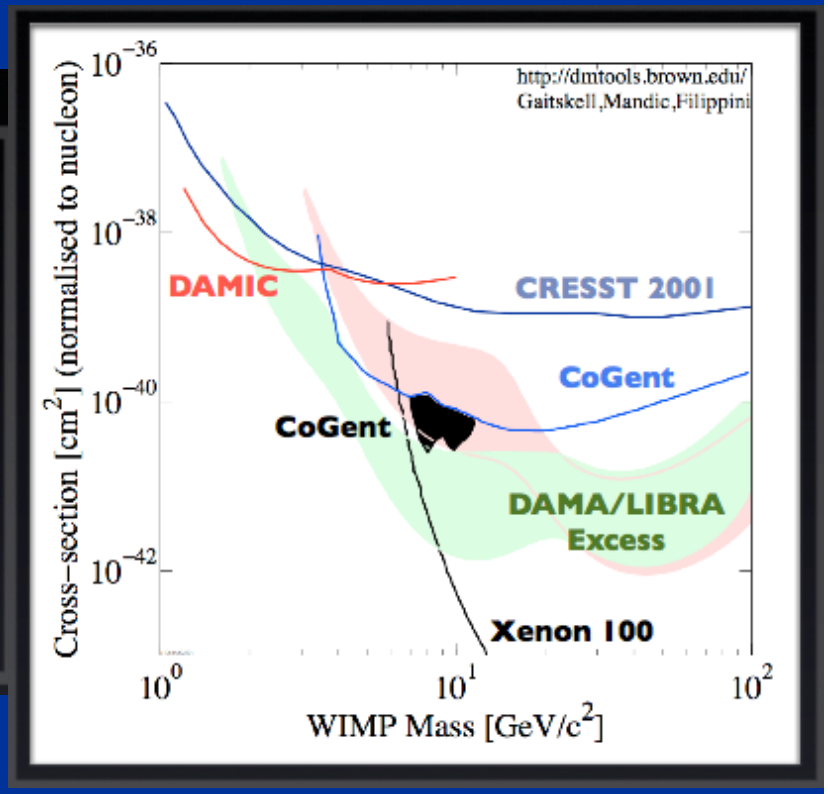
Very low noise: 2e- (RMS) !



Muons electrons diffusion limited hits.

Particle Interaction Identification in DAMIC CCDs gives Dark Matter Limit in the Low Mass Region

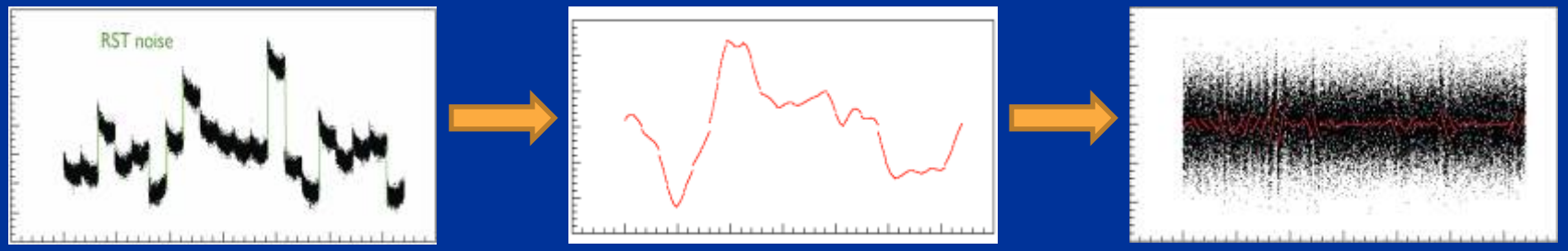



Obtained competitive dark matter limit with a run in Fermilab's Underground Lab. Now moving to SNOLAB.

# Low Noise CCD Readout

- Digital sample the video output rather than just record the individual pixel charge.
- Estimate the correlated noise of a string of pixels.
- Subtract the correlated noise from the original video.
- This technique can be performed on any CCD. It does require longer integration times per pixel (~ 120 microsec), but gives an amazing 0.4 e- noise.
- Goal is to implement the estimator and the digital CDS in an FPGA to provide real-time low-noise CCD images.




Digitized video signal | Stitching together parts | Subtracting low frequency noise

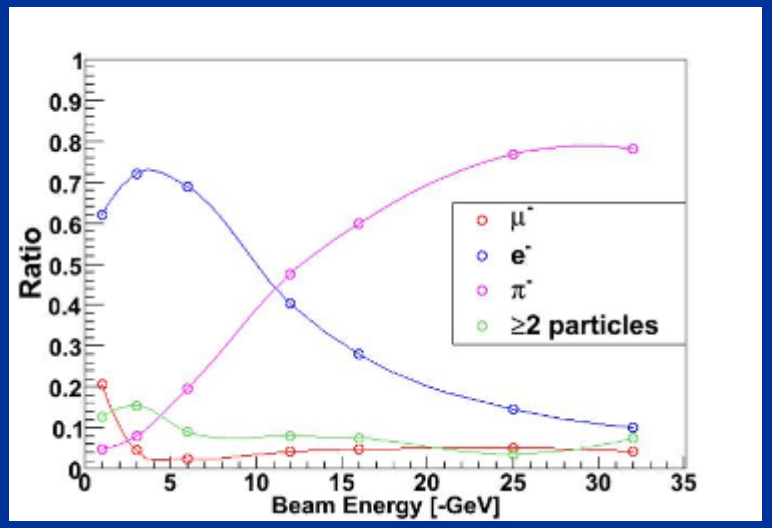
# Future support of the HEP Detector Community–

## Test Beam Facility

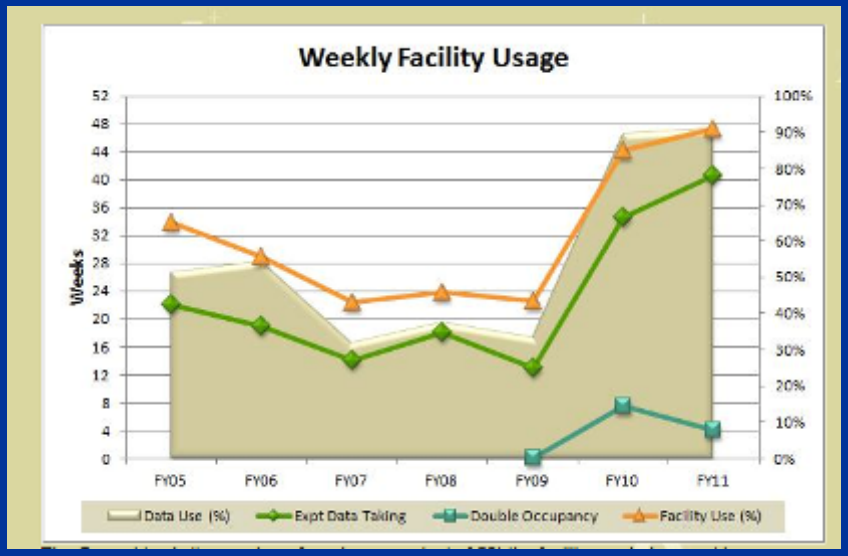
## Silicon Detector Facility

## Future Detector Development

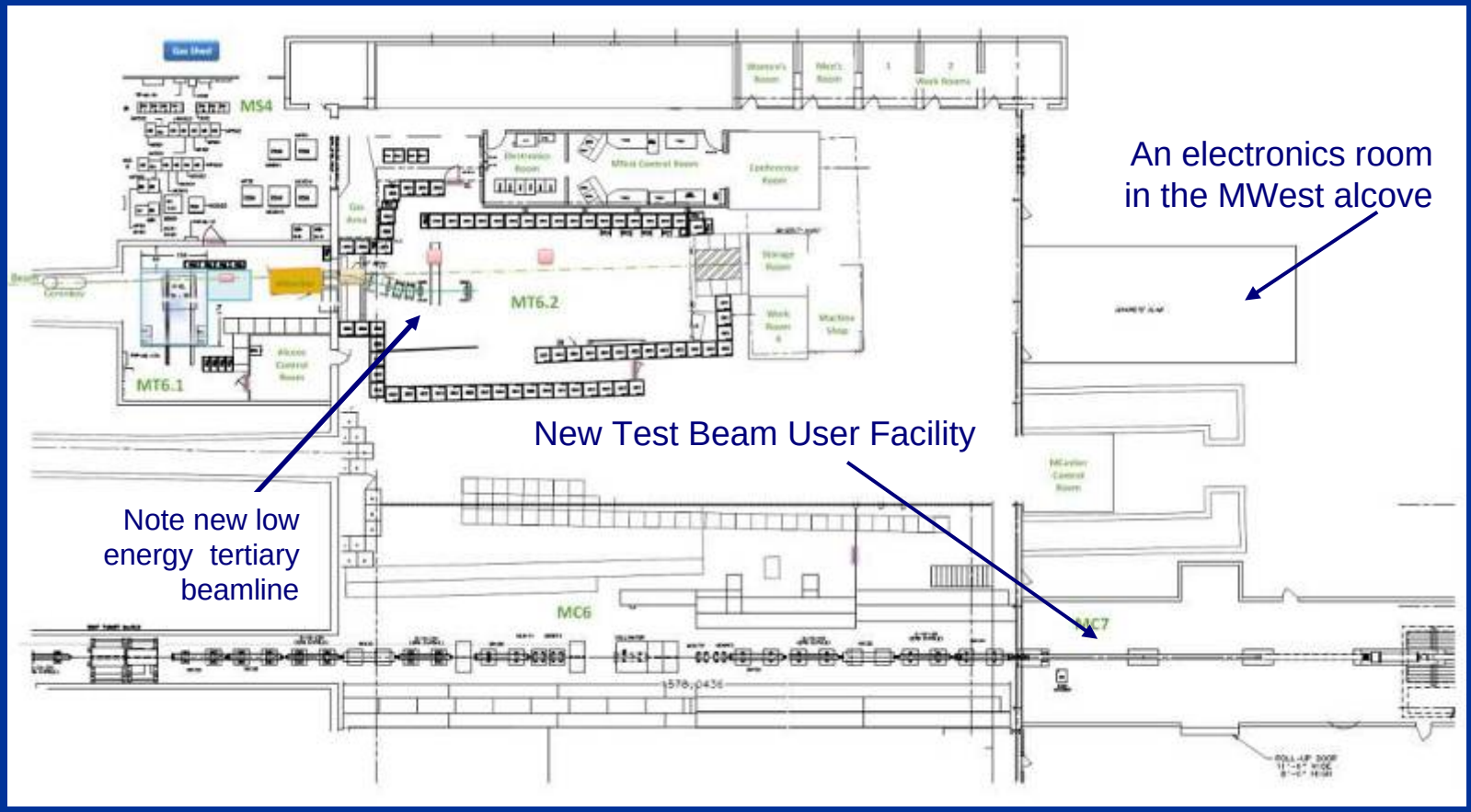
# Fermilab Test Beam Facility




This facility is now typically booked 6 months in advance



In response to this international demand, we are constructing a second test beam line in a coordinated location



# Silicon Detector Facility at Fermilab is a huge potential resource for detector development:

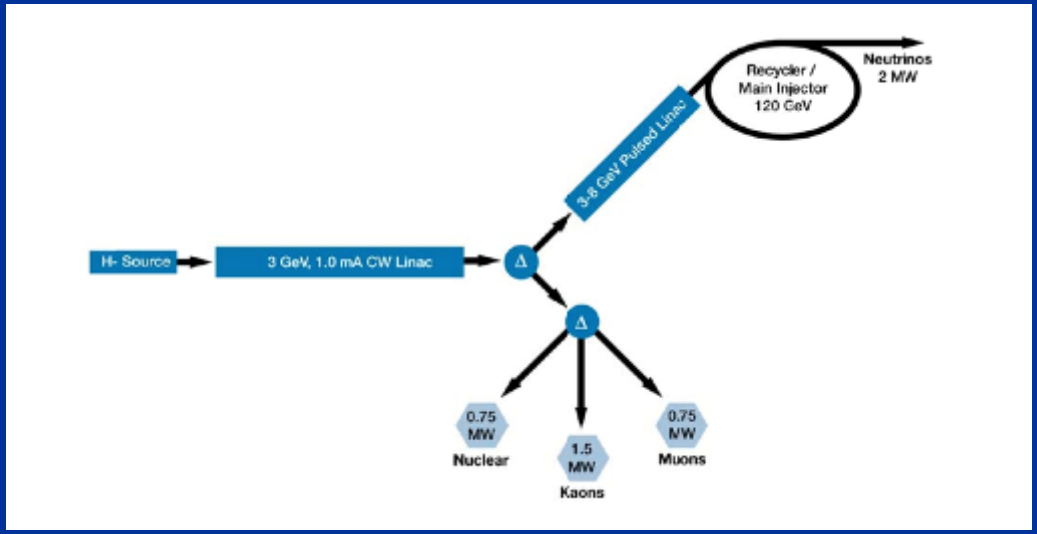
CCD Testing Infrastructure

Wire bonding capability

5000 ft$^2$ of class 10,000 clean rooms

Metrology and probe stations

# ‘Project X’ is Fermilab’s Proposed new High-Intensity, Low-Energy Proton Accelerator




- There will be a Project X physics forum in a few weeks (June 14-23, 2012) where new detector techniques will be studied. Here are some of the forums:
  - High power target experiments – neutrino systematics and exotica
  - Rare and Forbidden Muon decays
  - Rare Kaon Decays
  - Electron Dipole moments
  - Next generation fast timing and high resolution calorimeters
  - Ultra-low-mass and high rate tracking
  - 10 ps level time-of-flight systems
  - Large area, cost-effective detectors for Neutron-antineutron oscillations

# Future efforts on the frontier:

Focus on these challenges:

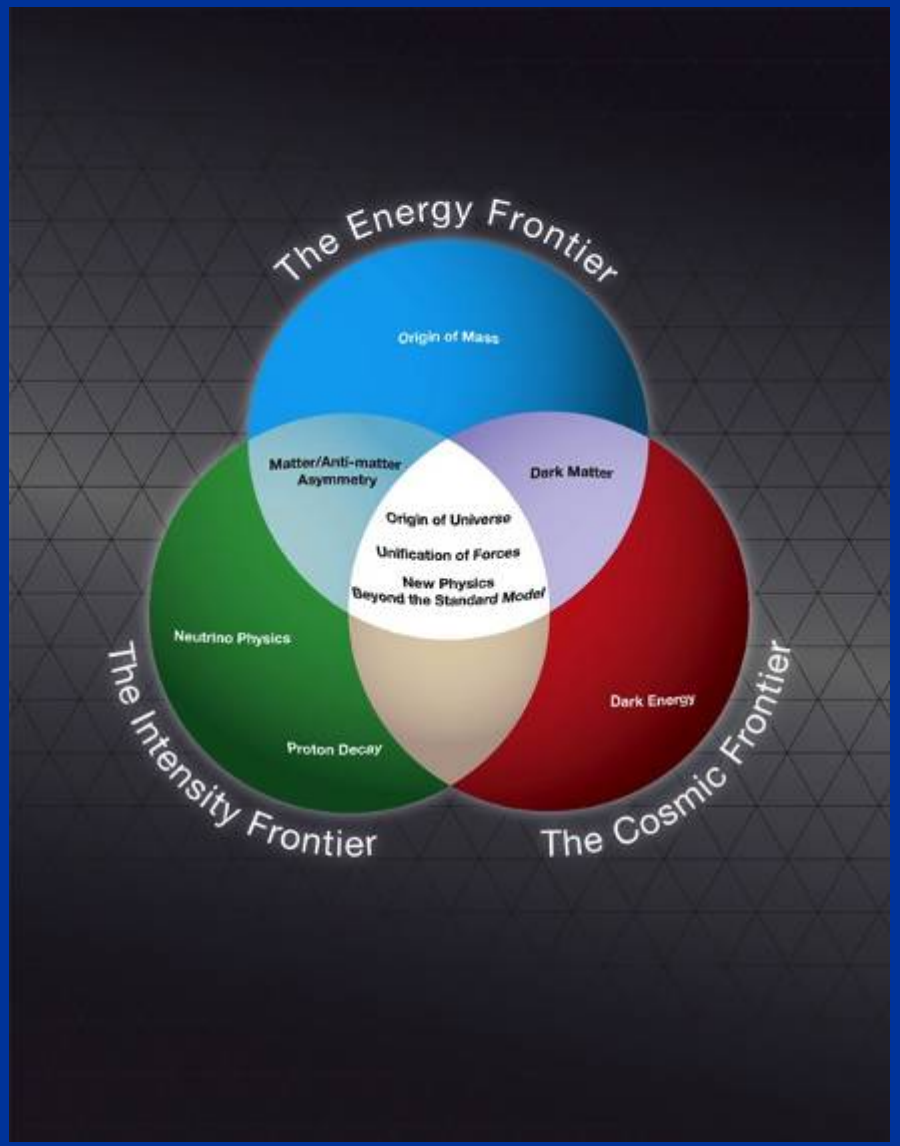
- Use our comprehensive tracking detector R&D collaboration to engineer collider detector upgrades
- Prove Liquid Argon TPC as a cost-effective, high-efficiency detector for neutrino and dark matter detection
- Develop high-rate, ultra-low-mass tracking, and high rate, high efficiency photon detection for the Intensity Frontier rare decay program
- Fully streaming DAQ technologies: GHz front-ends to Peta-Byte data stores.
- Move into MKID research ('Microwave Kinetic Inductance Detector'
- Continue outreach efforts. Detector R&D Summer Study immediately following Fermilab Users Meeting, focused on Intensity Frontier future detector challenges.

Xie Xie !!

# Extra Slides

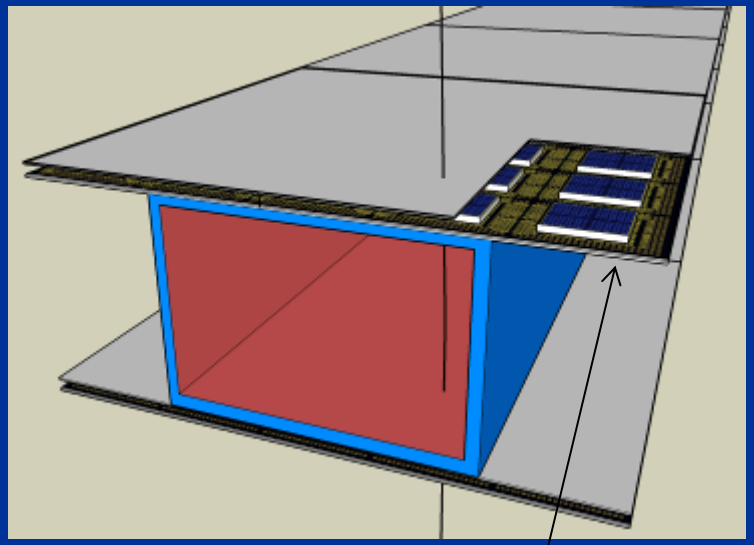
# Detectors on the Frontiers of High Energy Physics

- The '3 frontiers' describe major themes in the U.S. high energy physics research program:
  - 'Energy Frontier' is the search for beyond the Standard Model physics that can be performed at the high energy colliders – LHC, SLHC, ILC, CLIC
  - 'Intensity Frontier' is the use of intense beams to either search for rare kaon or muon decays, or to produce high statistics neutrino beams
  - 'Cosmic Frontier' includes the search for dark matter, dark energy or space-time measurements
- In each area, the physics is advancing rapidly. It is crucial that the detector technology keep pace.
- Fermilab has an organized detector R&D effort with leading projects in each frontier.



# L1 Track Trigger for CMS

- Track stubs are formed in each sensor pair by using 3D ASIC technology – 20x reduction in data flow
- Track stubs then associated with each other off-detector to form tracks.

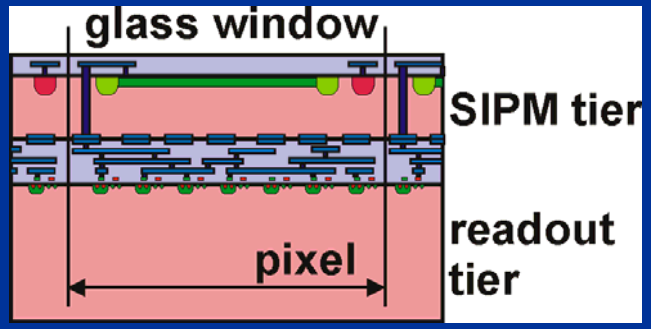


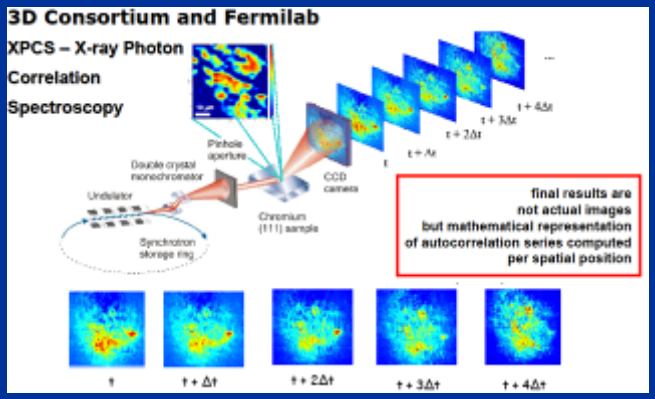
CMS Track Trigger doublet 3D modules supported by carbon fiber box beam. Doublets can be connected with 3D architecture.

CMS track trigger module box beam support for carbon fiber EMI testing

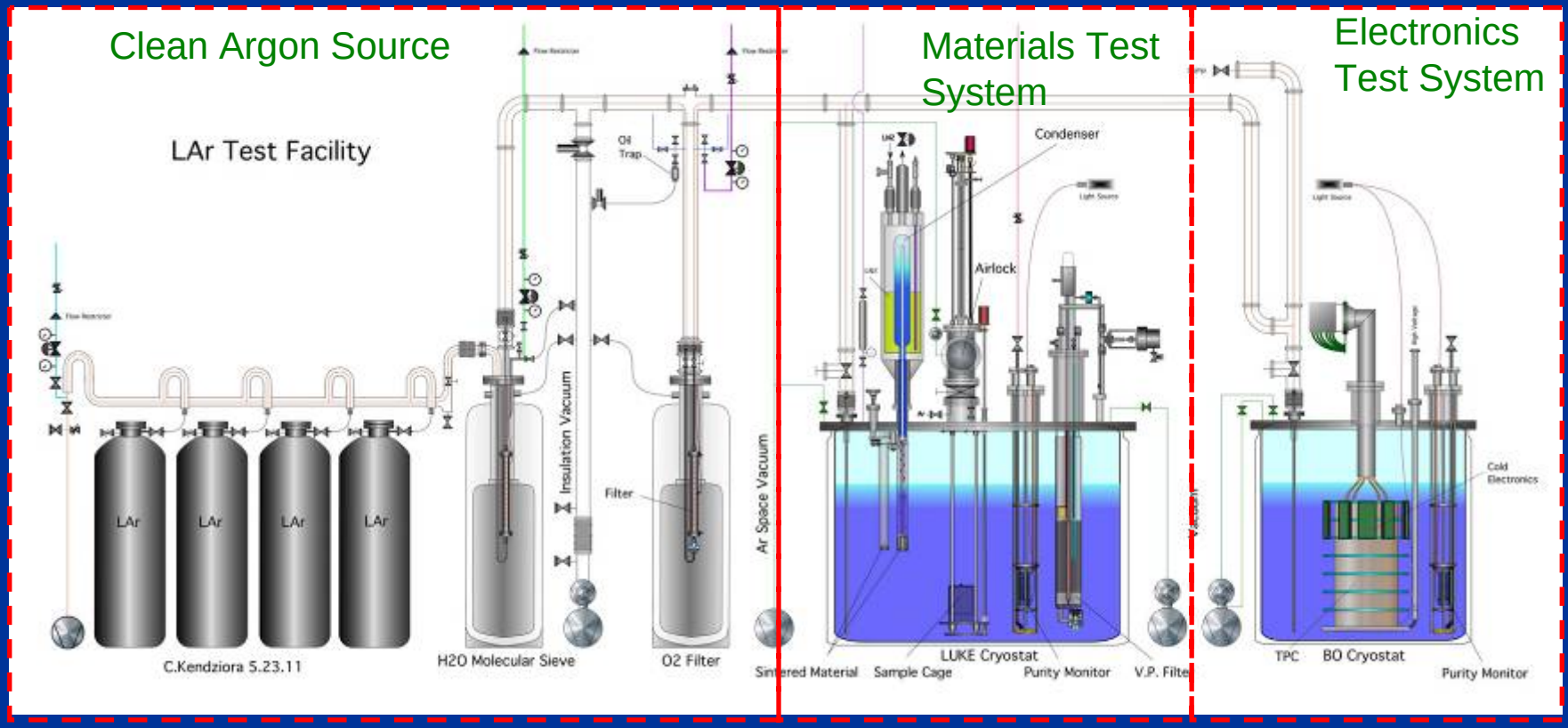
# Future 3D ASIC Activities

- 3D SiPM with active quenching and addressable subpixels (many possible collaborators)
- Collaboration with NSF/Northwestern University Imaging Center proposal
- Thinned sensors and readout for g-2
- X-ray imaging
- SBIR Collaborations with American Semiconductor, Vega Wave, Voxtel



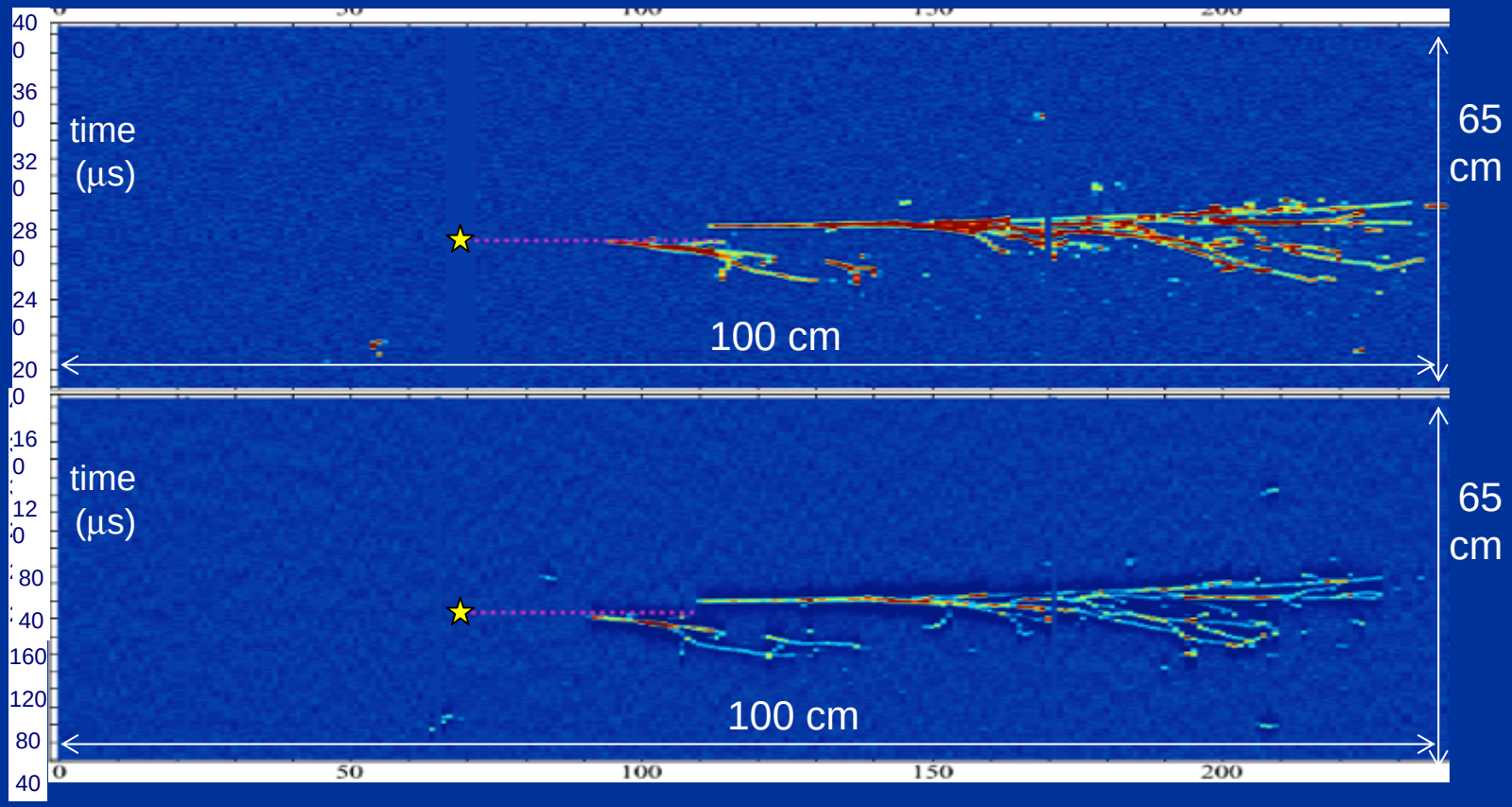



# Schematic of Materials and Electronics Test Systems



# Simulation and automated reconstruction essential for future detectors

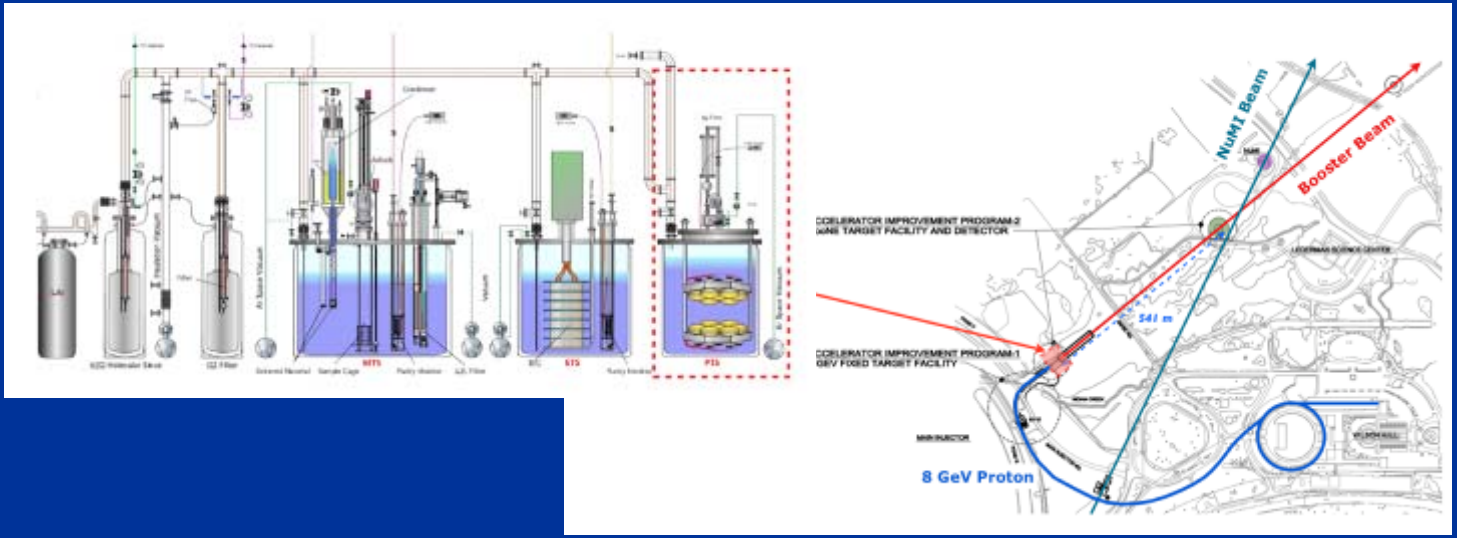
## LArSoft Simulation of a $\pi^0$ in ArgoNeut :




LArSoft: Bern, Fermilab, LNGS, Michigan State, Syracuse, Yale

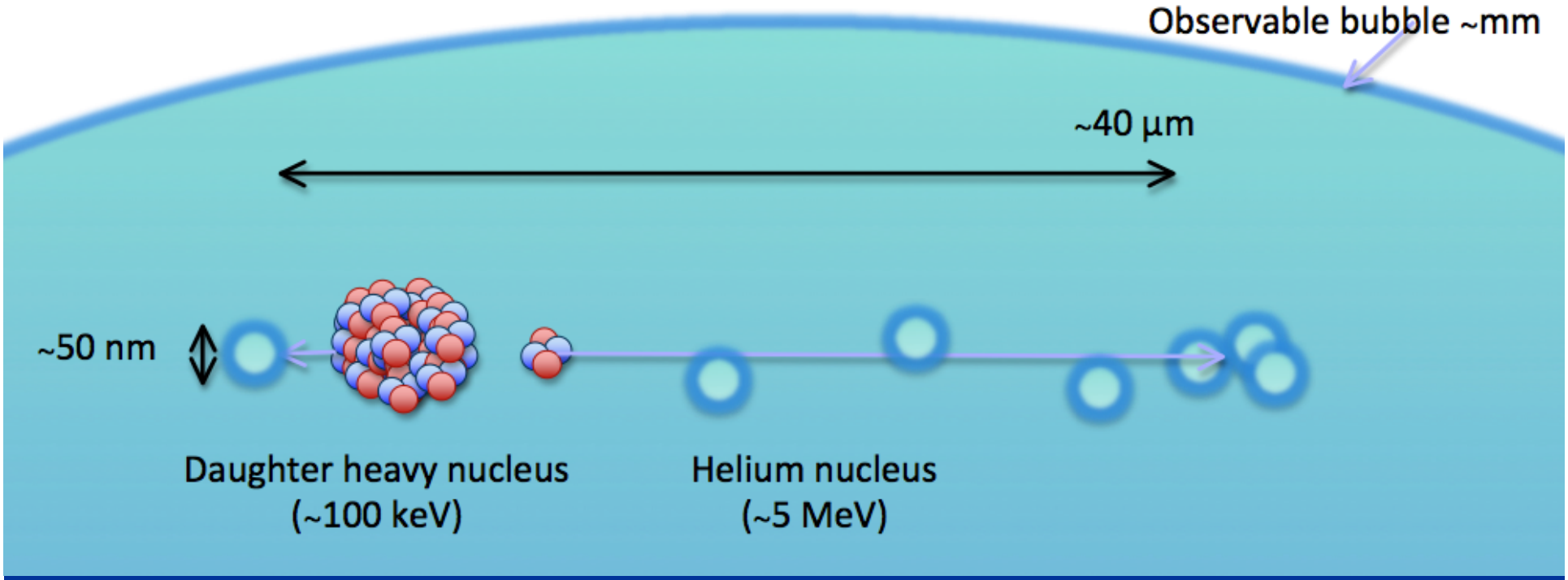
# Weak scale measurements – Dark Matter and Coherent Neutrino Scattering

- Test light collection efficiency with a 100 kg mass/14 PMT addition to our test stand
- See how nitrogen degrades UV light collection for single phase LAr detector
- Install it at the Booster Neutrino target and perhaps measure coherent neutrino scattering from the neutrinos coming off at right angles. (very low energy recoils, just like dark matter)



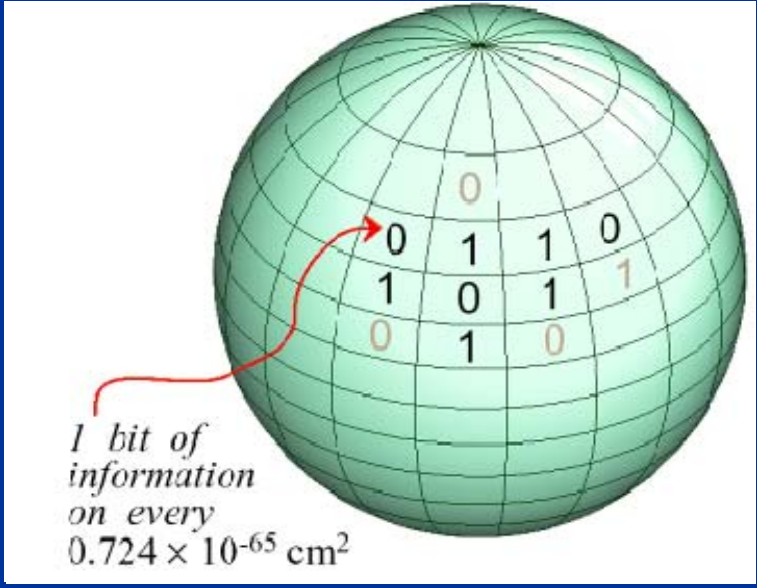
# Heuristic View of Acoustic Discrimination

- Alpha louder when probing length scales <40 μm
- Acoustic emission peaks at ~10 μm



*We are developing a machine specifically to probe the Planck scale:*

*"Holographic Interferometer"*
*or*
*"Holometer"*




*Theories suggest that all of physics emerges from 2+1 D null surfaces with a Planck scale areal bound*

*But there is no agreement on what it means for experiments*

**1696** PHILLIPS (ed. 5), *Holometer*, a Mathematical Instrument for the easie measuring of any thing whatever, invented by Abel Tull. **1727-41** CHAMBERS

# A New High Power Laser Lab

- Developed in an empty beamline (MEast) to support Holometer and Axion research
- Contains a 2 watt laser with cavity finesse of 1000, and thus 2 kW of stored power
- A baseline of 40 meters – looking for MHz signals
- Developed PZT controlled cavity mirrors