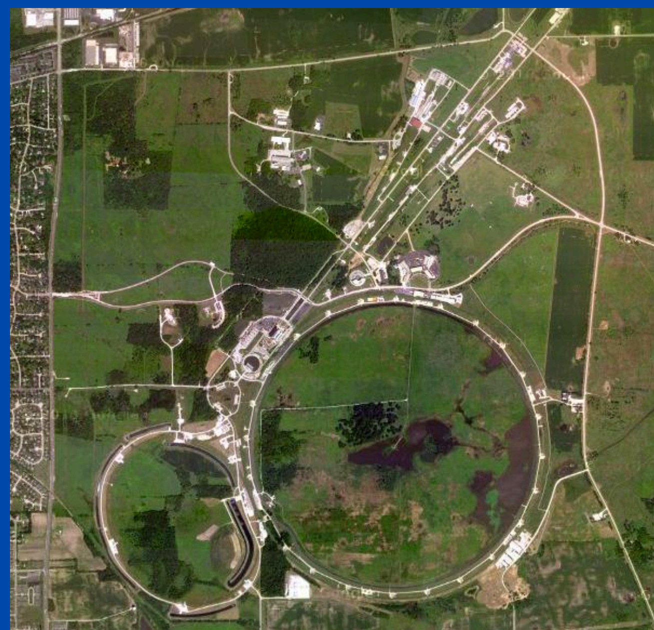
The Detector Research and Development Program at Fermilab

Erik Ramberg
Tsinghua Visit
30 May, 2012

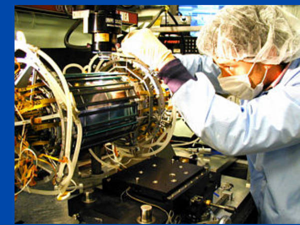
U.S. DEPARTMENT OF ENERGY

Fermilab

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



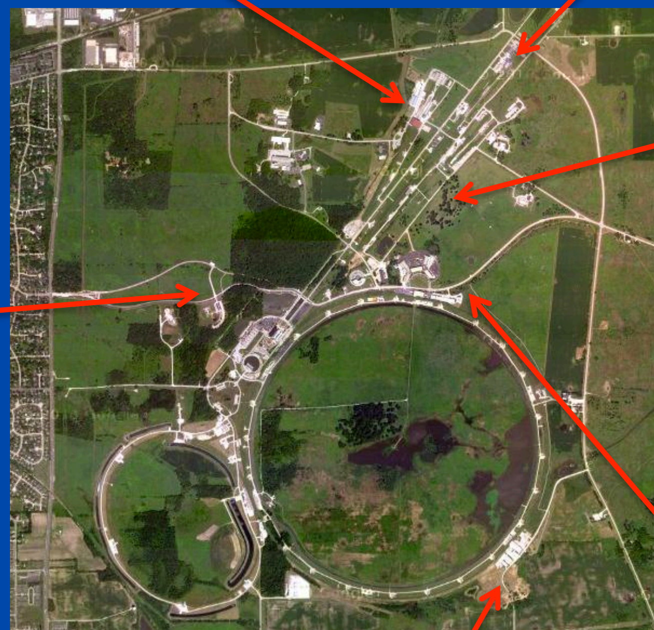
The European CALICE hadron calorimeter being installed at the Test Beam Facility

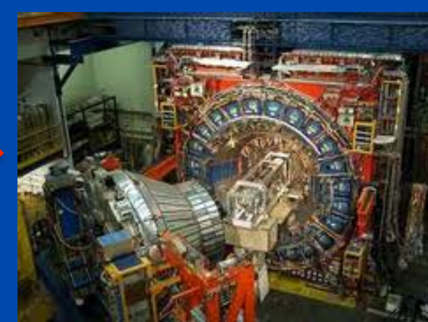


Building a silicon vertex detector at the Silicon Detector Facility

Liquid Argon Test stands at Proton Assembly Building

MINOS Underground Lab – 300 mwe depth.





CDF Experiment Hall – to be used for new kaon experiment

D0 Experiment Hall to be used for kiloton LAr detector

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

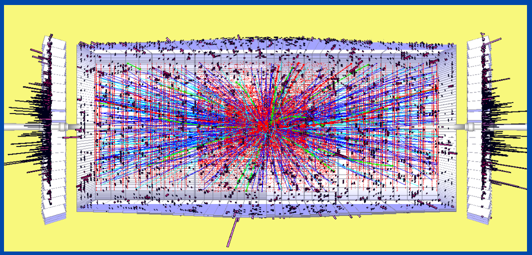
PROJECT	TASK	DESCRIPTION
Collider Detectors	Tracking ASIC R&D	Development of 3D ASIC's with large international collaboration
	Tracking Mechanical	Mechanical support and cooling designs for lepton colliders
	Calorimetry	Dual readout techniques, SiPM characterization, new QIE design
	psec Time-of-Flight	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 α 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
	μTCA 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

↓

Data Transmission — Multi-wavelength optical DAQ

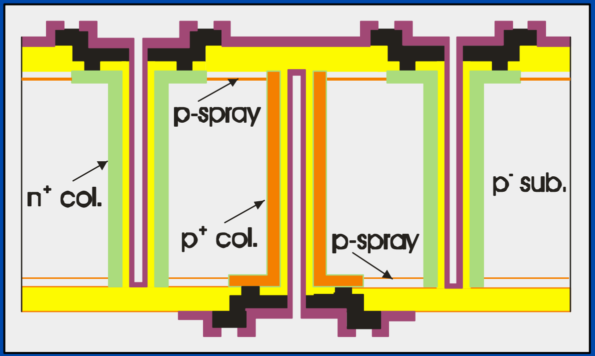
↓

Track Fitting — GPU's and Associative Memory

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

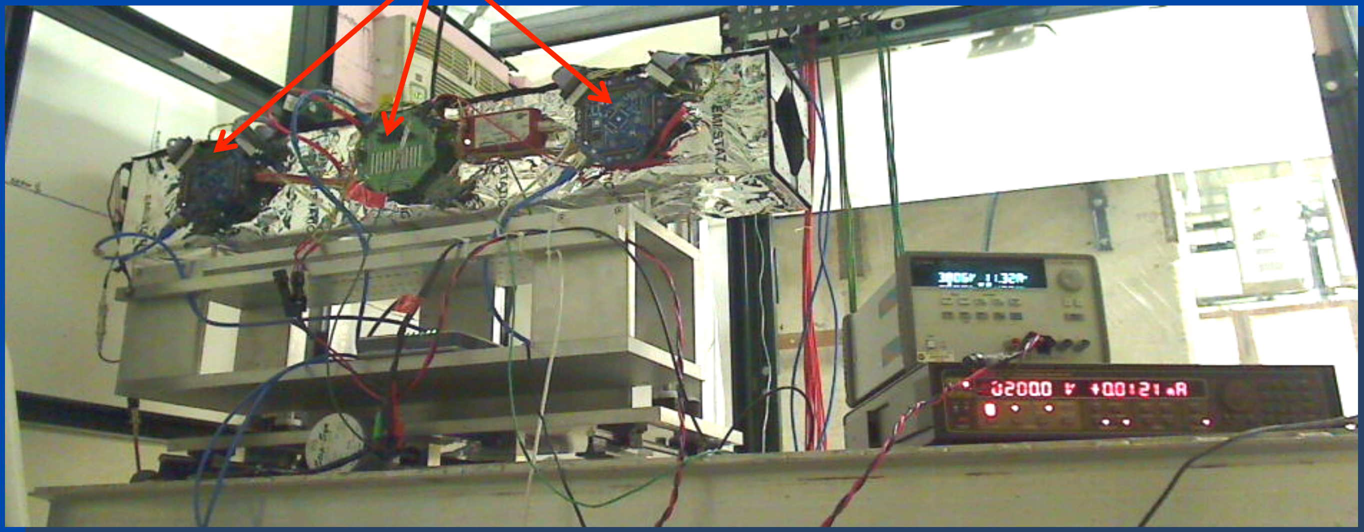


Advanced design from FBK for ATLAS:

3D-DDTC⁺: double-sided 3D with passing through columns

Test Beam Pixel Telescope and DAQ

CAPTAN STACK

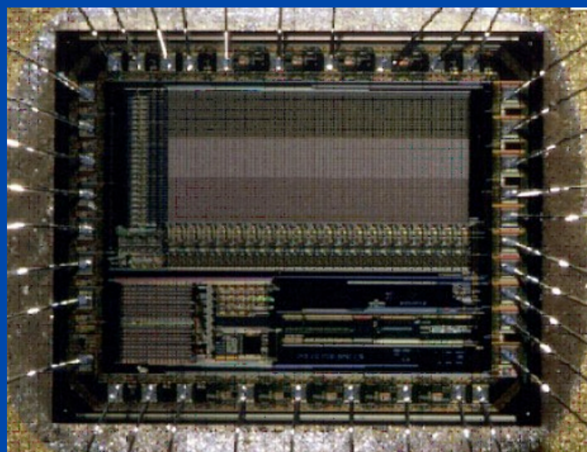


CMS pixel sensors read out by CAPTAN DAQ, developed by Fermliab Computing Division.

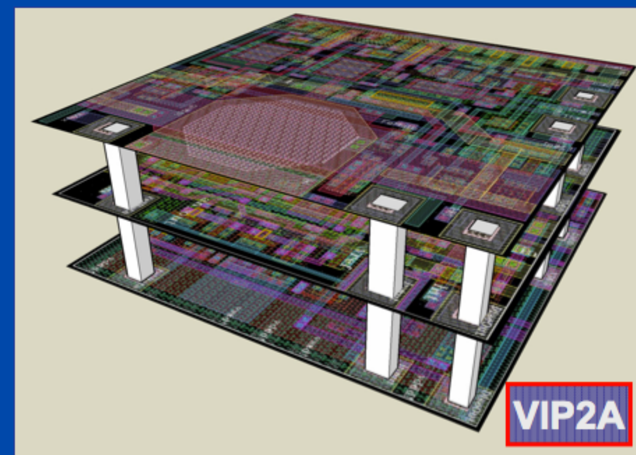
Uses conventional 3-dimensional architecture with potential of more than 100 Gbps along 4 buses.

Same data acquisition system as used in IHEP silicon telescope

3-Dimensional ASIC program



Conventional Monolithic Active Pixel Sensor

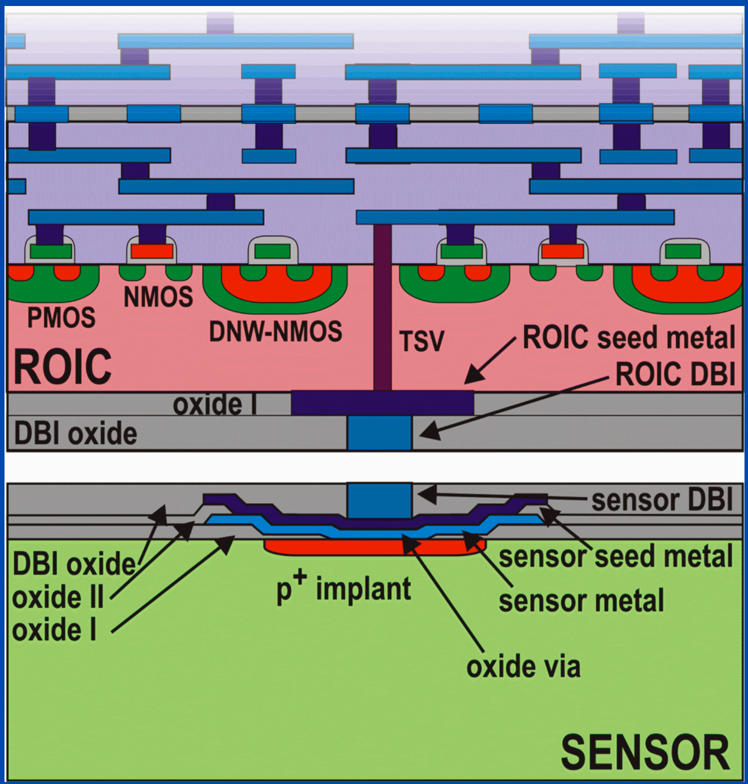


3 tier 3D stack for FNAL ILC vertex chip, fabricated by MIT-LL

-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

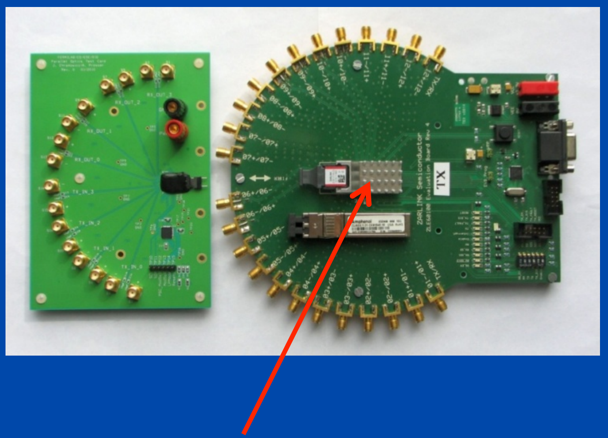
Adds capabilities to classical amplifier/ discriminator:

- 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)

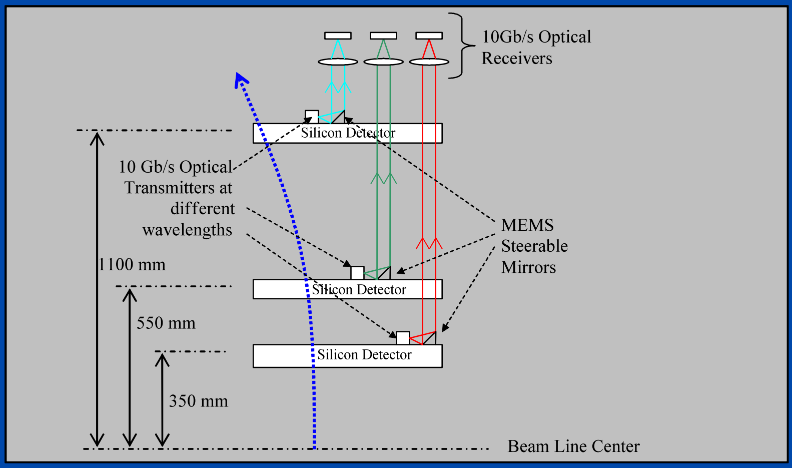
Progress has been slow due to multiple handling and fabrication problems.

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



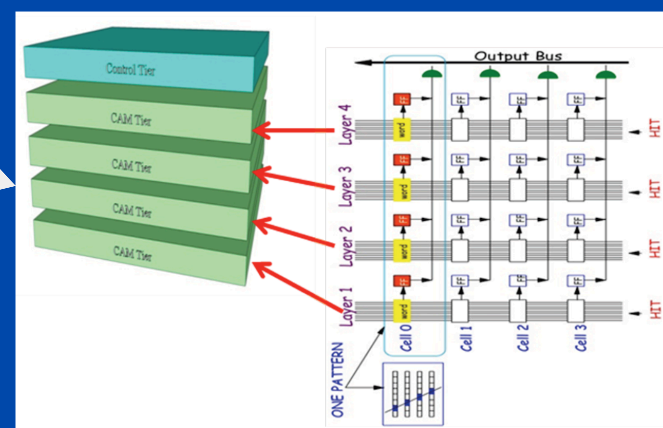
Can foresee using free space optical transmission through silicon, with multi-wavelengths centered on infrared band

Moving to xTCA (‘x’ = Advanced or Micro)

(See Tiehui Liu’s talk)

12U 14-slot ATCA

- 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
- L1.5 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.

Argon — Purification techniques and Cryogenics design

↓

TPC — Materials qualification and design

↓

Readout — Low-noise amplifiers in liquid

↓

Full System in Neutrino Beam — ArgoNeuT

↓

Automated Reconstruction — LArSoft Simulation

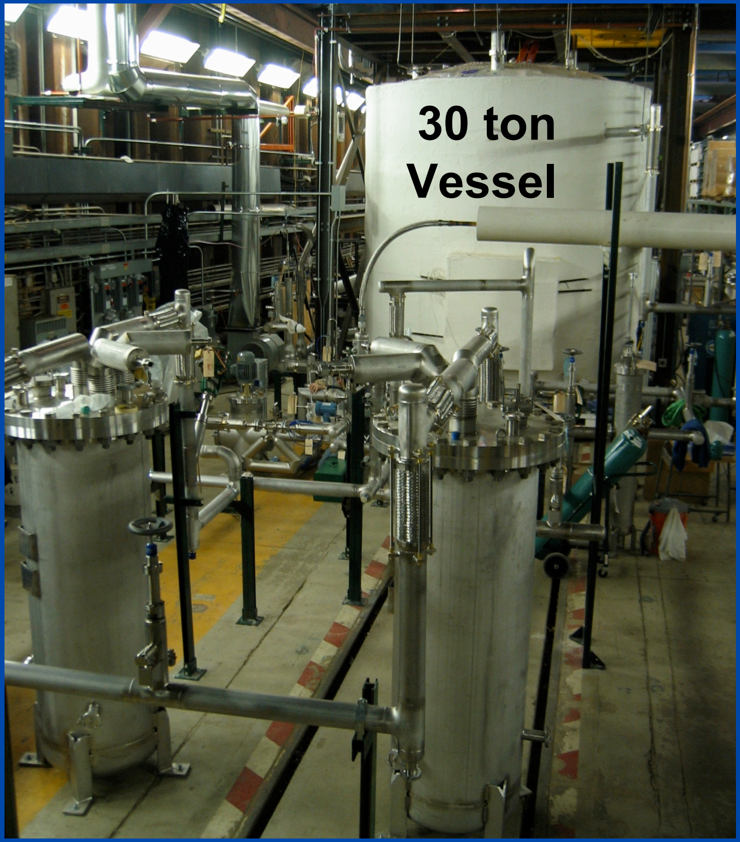
↓

Synergies — Dark Matter, Solid Xenon

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

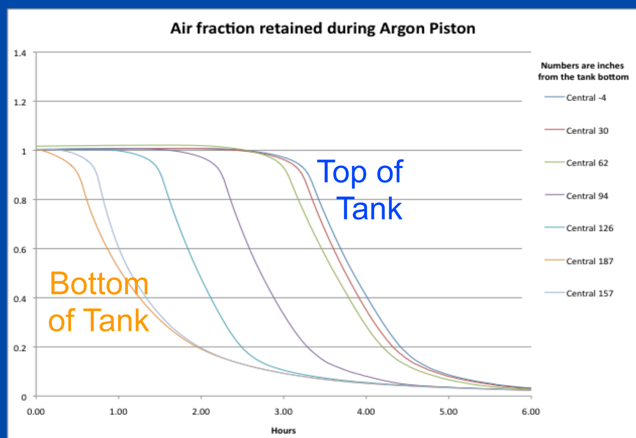
Liquid Argon Purity Demonstration

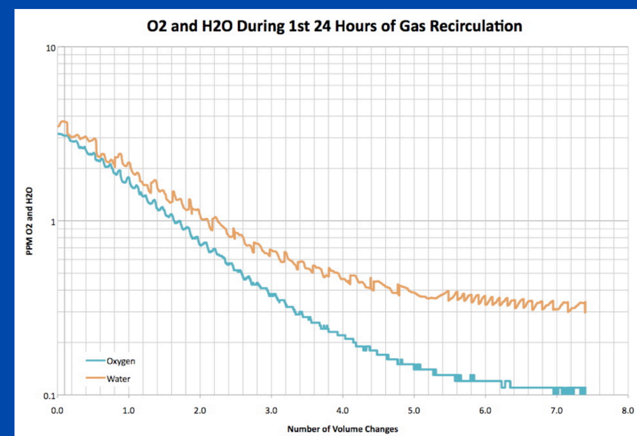
- Most LArTPC detectors have been evacuated before filling. Not practical for kiloton detectors.
- Demonstrate good life-time in an industrial vessel without evacuation.
- First multi-ton purification system designed and built at Fermilab.



- 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

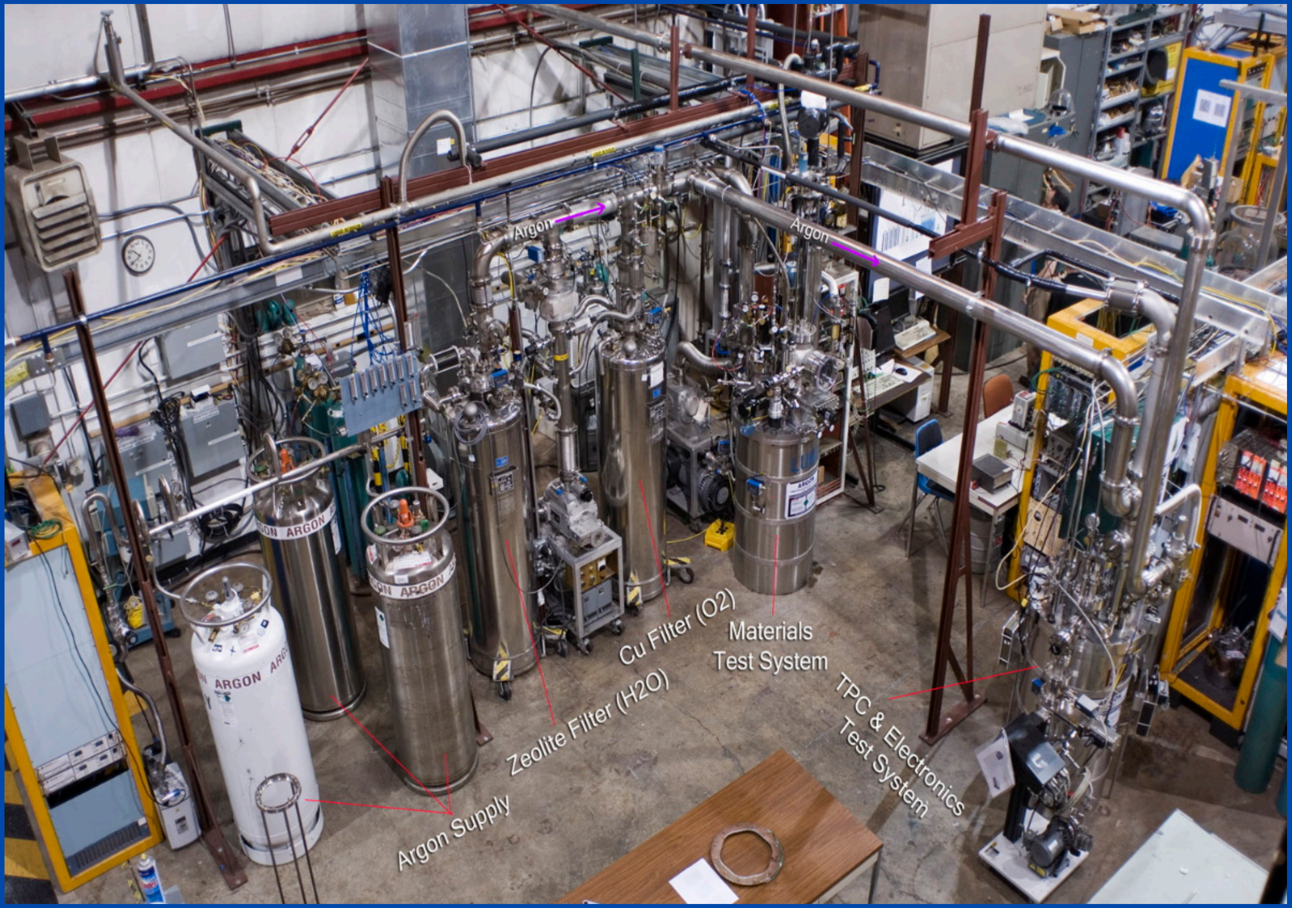
Results of Gaseous Argon Purge





- Set of sniffer tubes monitored the oxygen content of the gas inside the vessel at various depths throughout the purge
- Plots show the content relative to the pre-purge state of the tank
- 9.1 volume exchanges total before the purge was stopped

- Both O2 and H2O contamination were well below 1 ppm (delivery specification for liquid argon) after 3 volume changes
- Maintained sub-ppm levels in the gas for over 20 days
- Concentrations continued to drop after tank shell heaters were turned on



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

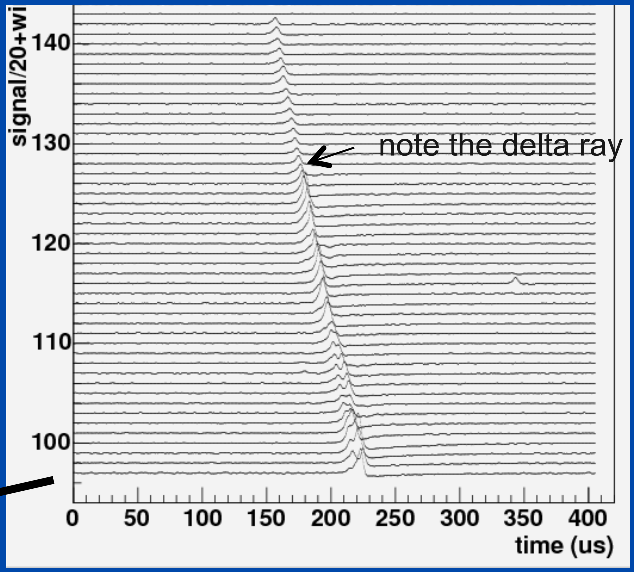
`A system to test the effects of materials on the electron drift lifetime in liquid argon and observations on the effect of water' R. Andrews *et al.*, Nucl.Instrum.Meth.A608:251-258,2009.

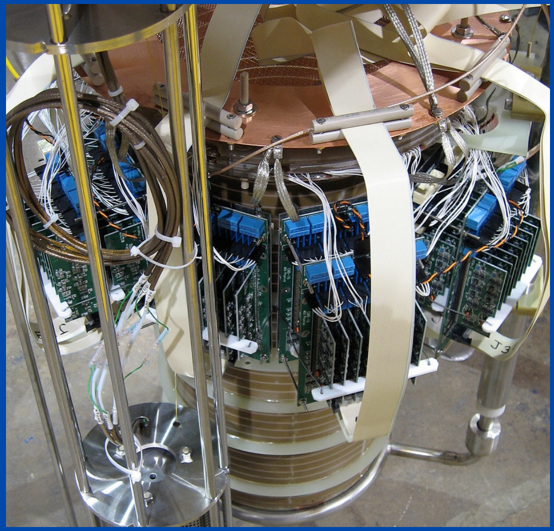
Material	Date test started	Preparation	Tests	Water [ppb]	Lifetime [ms]	LogBook #
Cleaning Solution	6/29/09	evac. 24 h	vapor/liquid	4	5	946
Vespel	7/9/09	evac. overnite	liquid/vapor	5-7	2-5, 4-6	960
MasterBond glue	7/16/09	purged 18 h	vapor/liquid	1.6	1.3- 2.9	974
LEDs	7/31/09	purged 38 h	vapor	3.5	5	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)



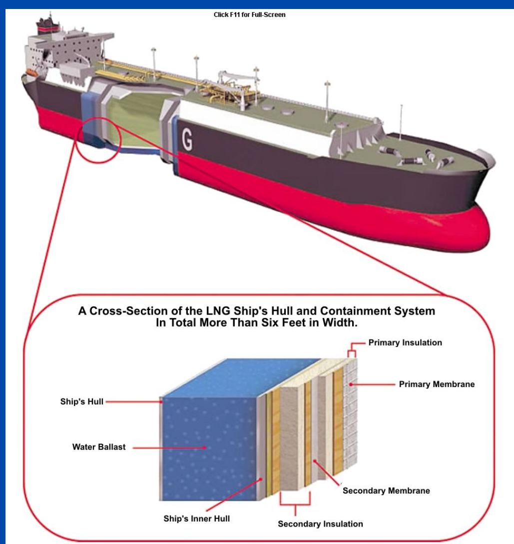


State of the Art:

in-liquid amplifiers from MSU

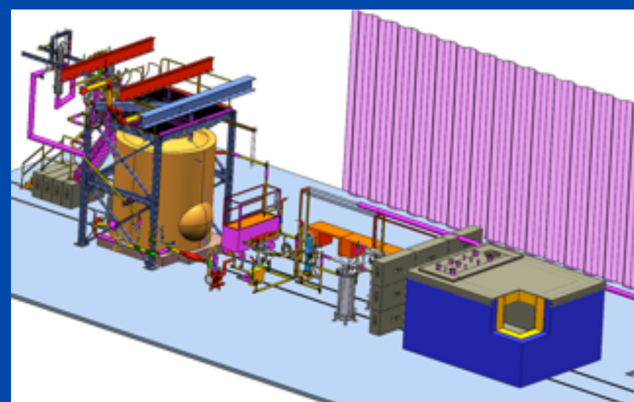
- PMOS based design
- Operates very well at 90K
- Improves Signal to Noise
- Multiplexing reduces cable plant
- Can be converted to ASIC

Meeting the challenges for multi-kiloton scale detectors

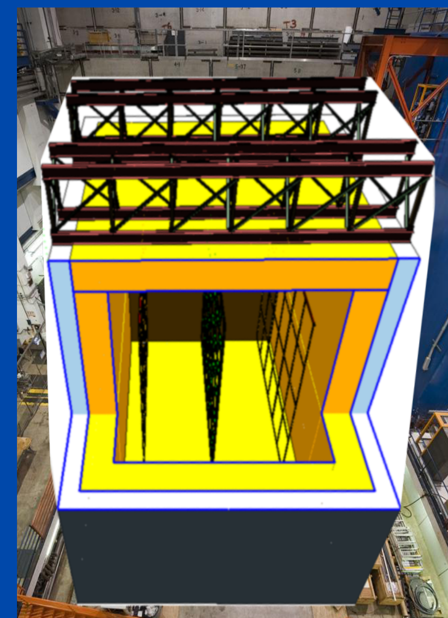


Liquid Natural Gas carriers routinely carry 120,000 cubic meters of liquid at -160º C. The key is a rippled surface that can contract without changing overall shape.

LAPD LAr35t



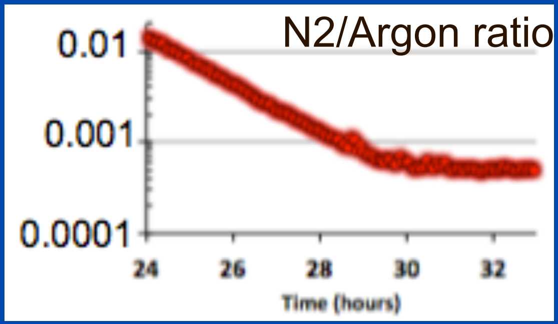
The LAr35t cryostat is our first foray into the use of membrane cryostats. It will use the same cryogenics and purification system as developed for the Liquid Argon Purity Demonstration.



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



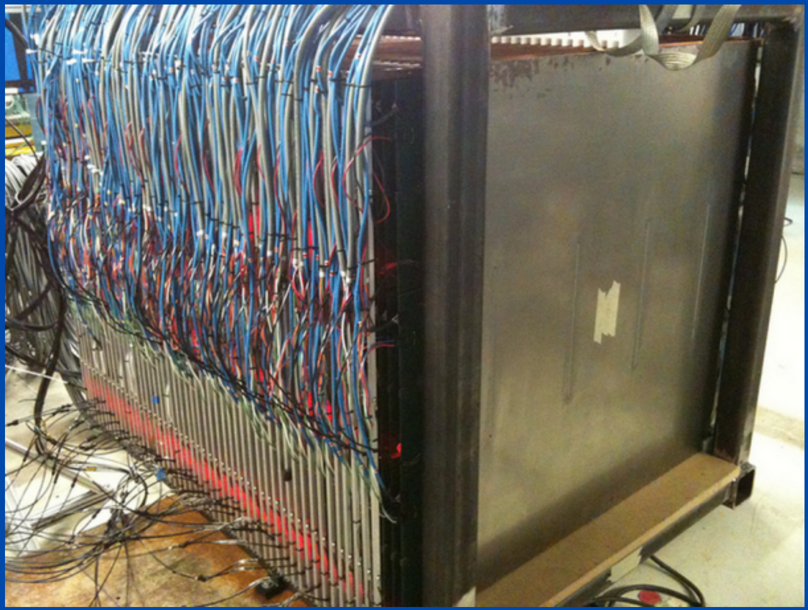
Sensitivity limit of gas analyzer

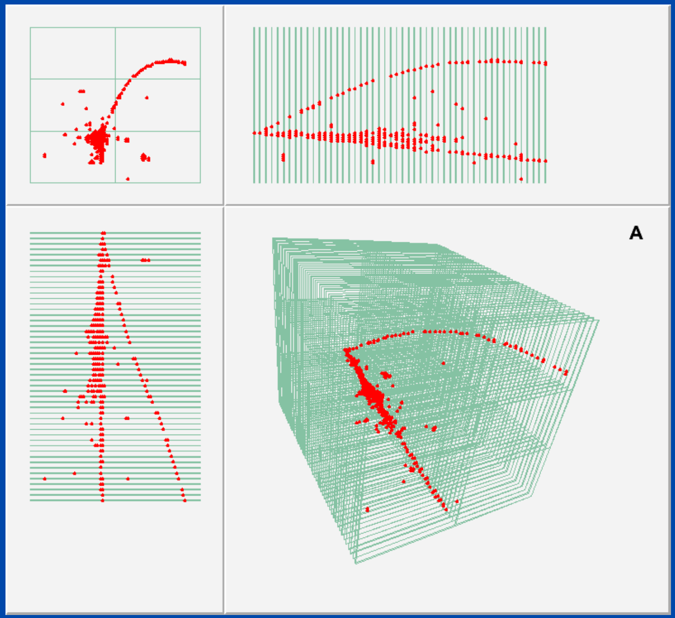
Aimed at DarkSide and DEAP programs

Other Examples of Fermilab Detector R&D –

Calorimetry
Time-of-Flight
Dark Matter
CCD's

Digital Hadron Calorimeter (ANL) at Fermilab's Test Beam Facility





- This test device has more channels (400K) than CMS + ATLAS + LHCb calorimeters combined. (Each 'channel' is only 1 bit, however!)
- 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

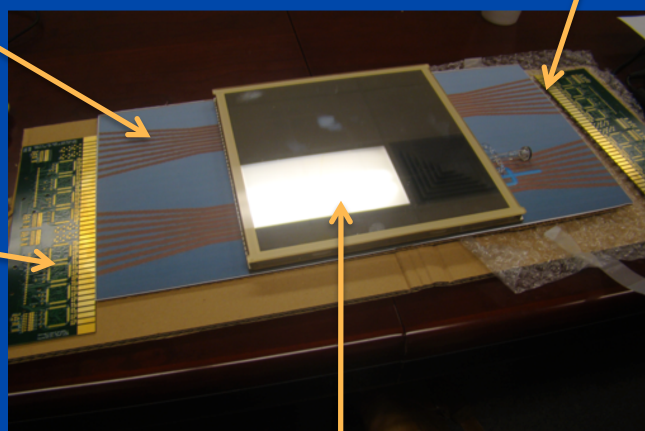
- LAPPD = "Large Area Picosecond level Photo Detectors"
- FNAL provides technical and scientific help on the project
- Created new electrode coating chamber

A mockup of the 8" MCP/PMT:

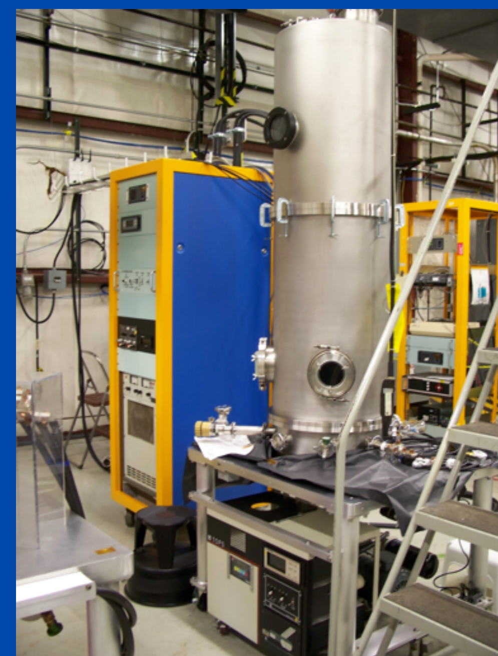
Transmission line readout retains superb timing resolution

Readout on both ends gives 1 mm positional resolution

U.C. is developing high speed digitizers (10-20 GHz)



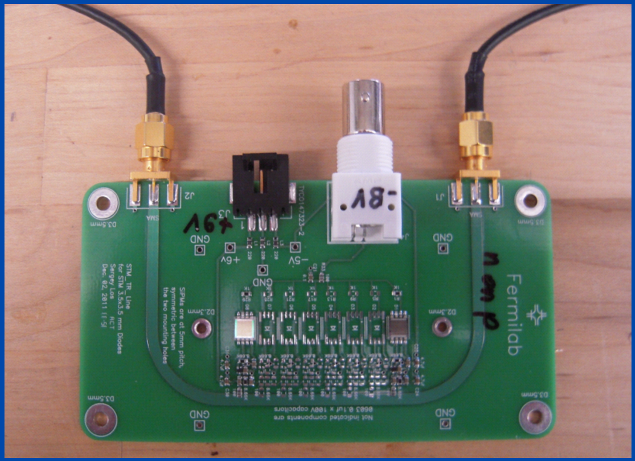
Micro Channel Plate has been developed with new process (ALD coating of drawn glass channels)



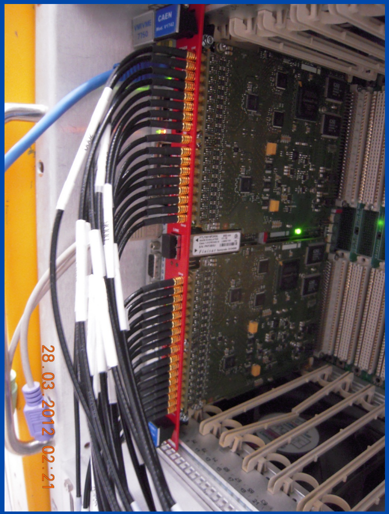
New thin film coating facility

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

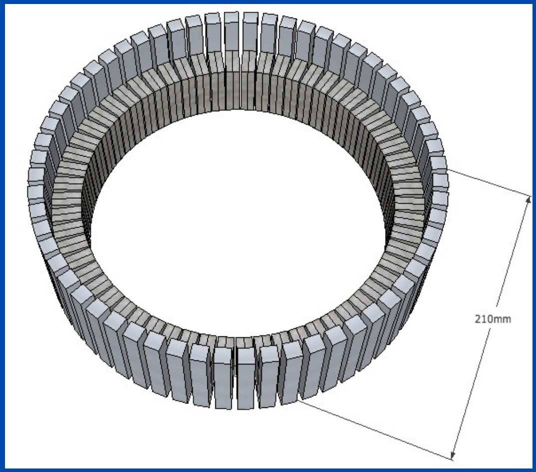
- Silicon PhotoMultipliers are multi-pixel avalanche photodiodes
- About 50 microns in size, they count individual photons
- Fermilab/U.C. have been studying their use for time-of-flight in high energy physics calorimeters and in PET imaging



Transmission line readout suitable for reading 8 separate SiPM's



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

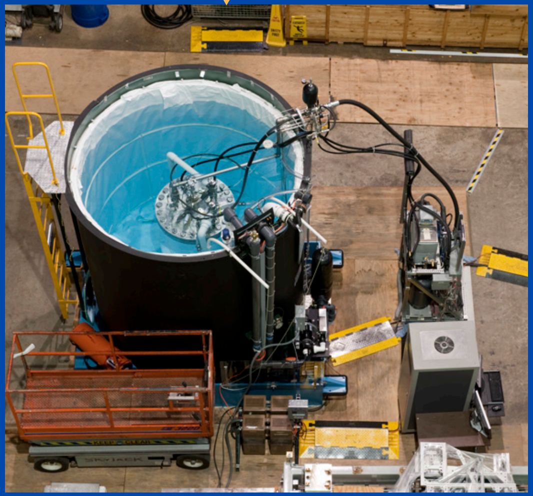


Ring of transmission line readouts can make up new PET-TOF detector

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

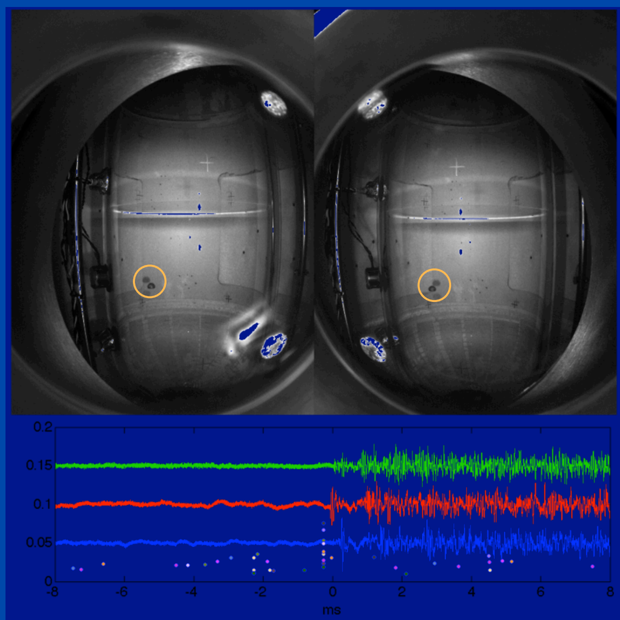
- Superheated CF_3I target near room temperature and pressure
- Can tune chamber so it is sensitive ONLY to nuclear and not electron recoils
- Started out as an R&D test beam experiment
- Now a full-fledged dark matter experiment; the 60 kg detector is moving soon to SNOLAB
- ANL is now using our technology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

COUPP-4 at SNOLAB

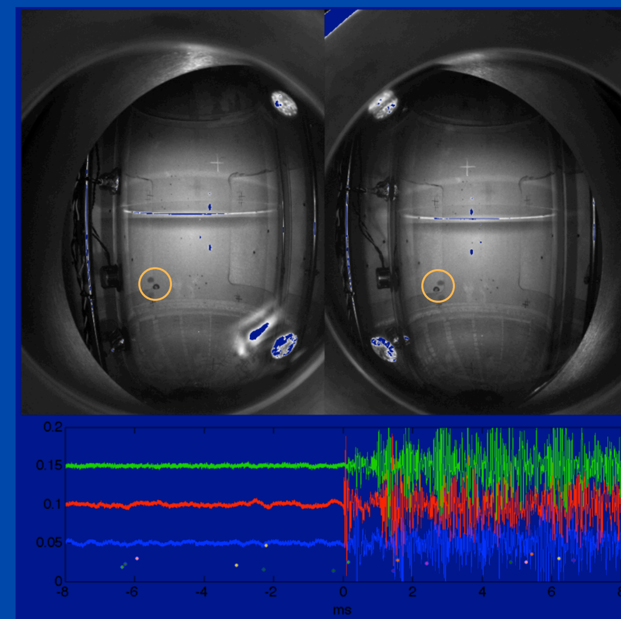


COUPP-60 at FERMILAB

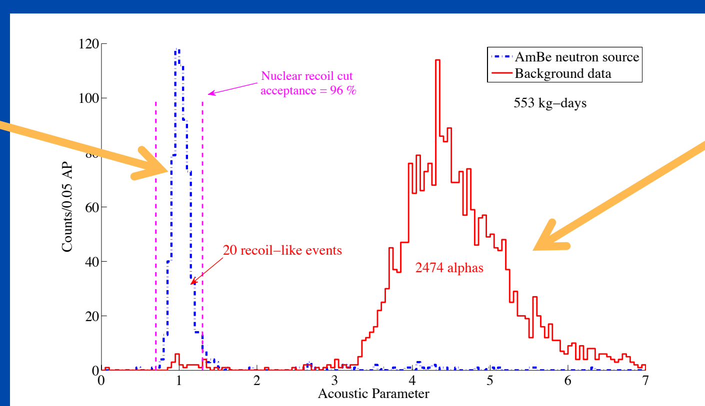
Major advance on PICASSO discovery of acoustic rejection



Particle I.D.
by Sound !



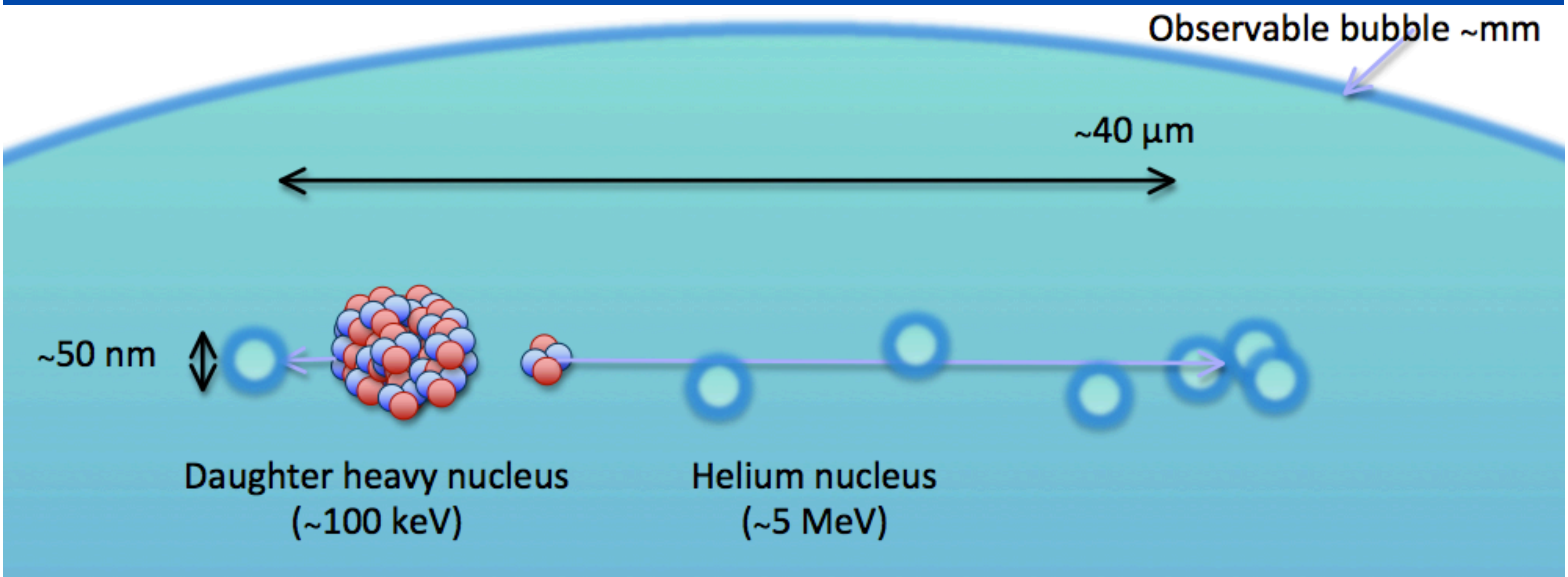
Cosmic-induced neutron



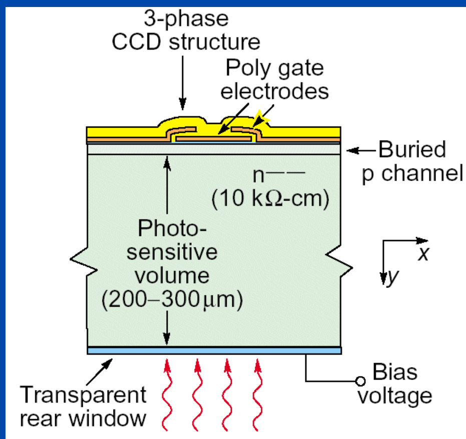
Alpha decay in same region

Heuristic View of Acoustic Discrimination

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

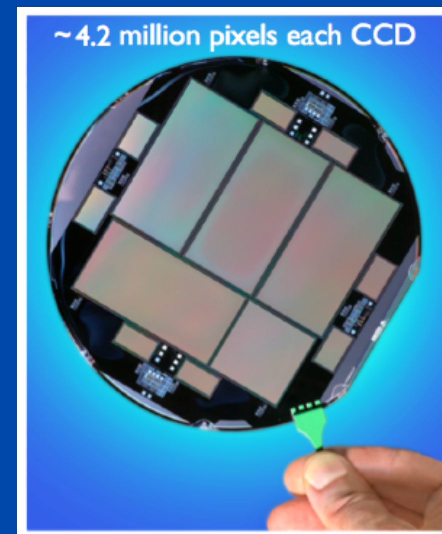


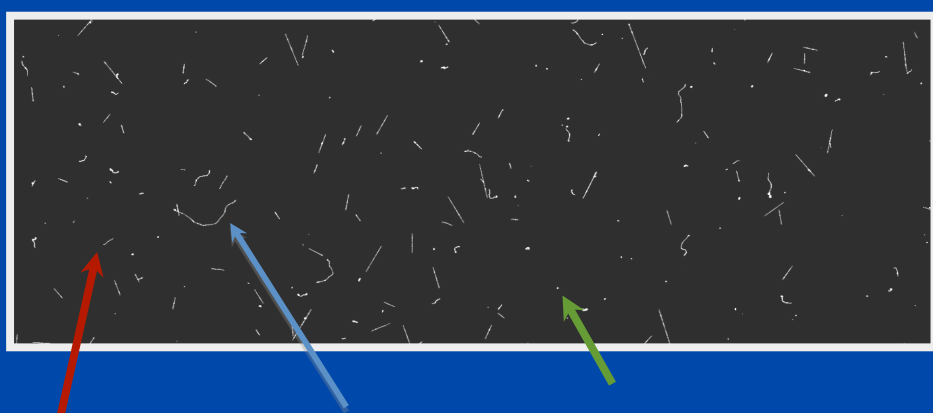
Dark Matter Search with CCD's (DAMIC)



To improve the efficiency in the near-IR, the DECAM CCD detectors (from Lawrence Berkeley lab) are extraordinarily thick: 250um instead of the typical 30 um for astronomical CCDs.

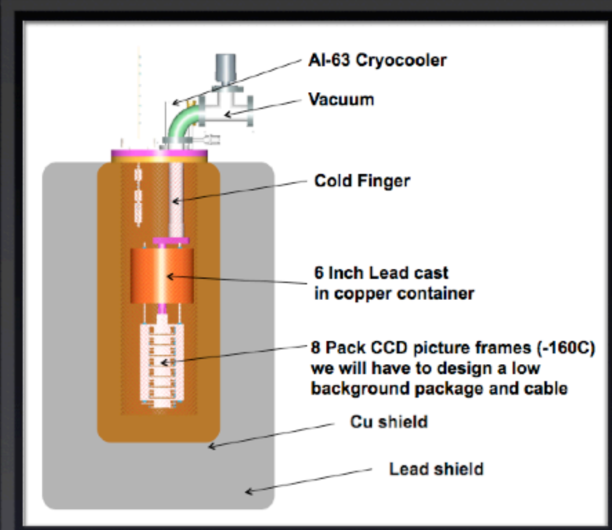
Very low noise: 2e- (RMS) !

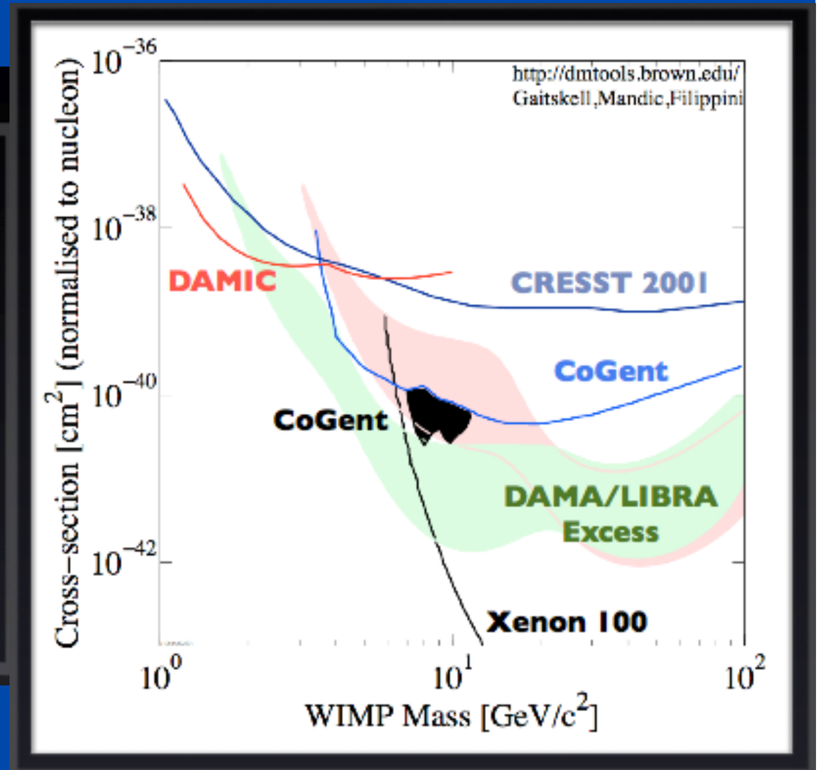




Muons electrons diffusion limited hits.

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

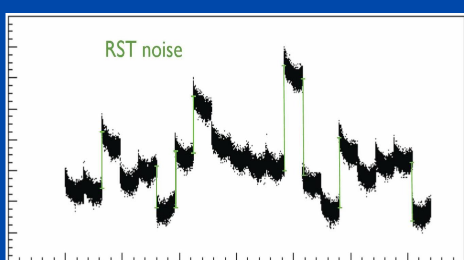




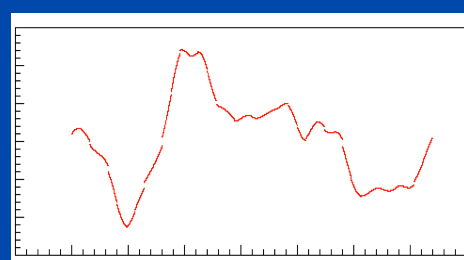
Obtained competitive dark matter limit with a run in Fermilab's Underground Lab. Now moving to SNOLAB.

Also Developing New Ultra Low Noise CCD Readout

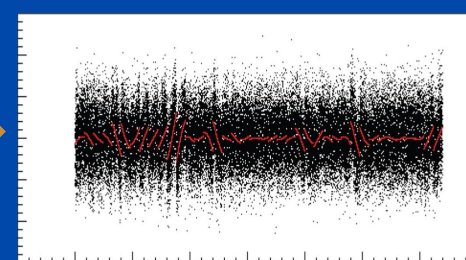
- Digital sample the video output rather than just record the individual pixel charge.
- Estimate the correlated noise of a string of pixels.
- Subtract the correlated noise from the original video.
- This technique can be performed on any CCD. It does require longer integration times per pixel (~ 120 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

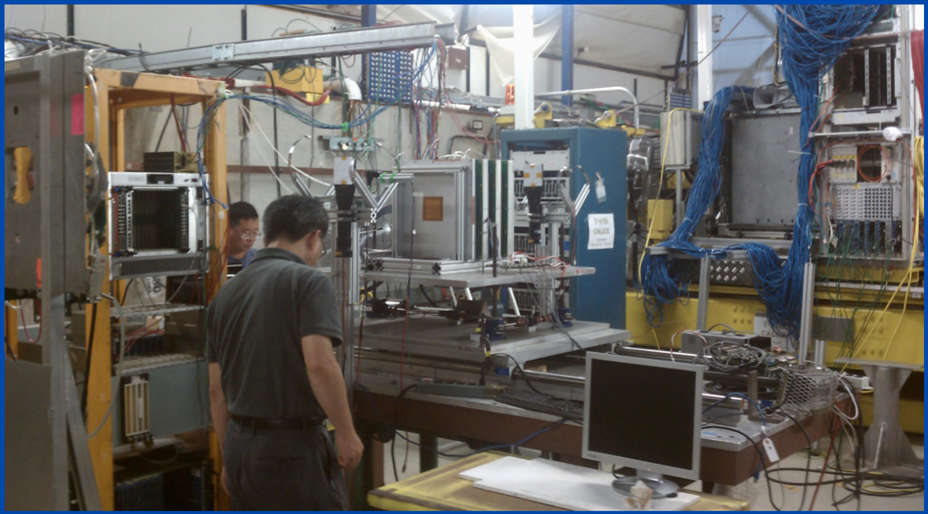


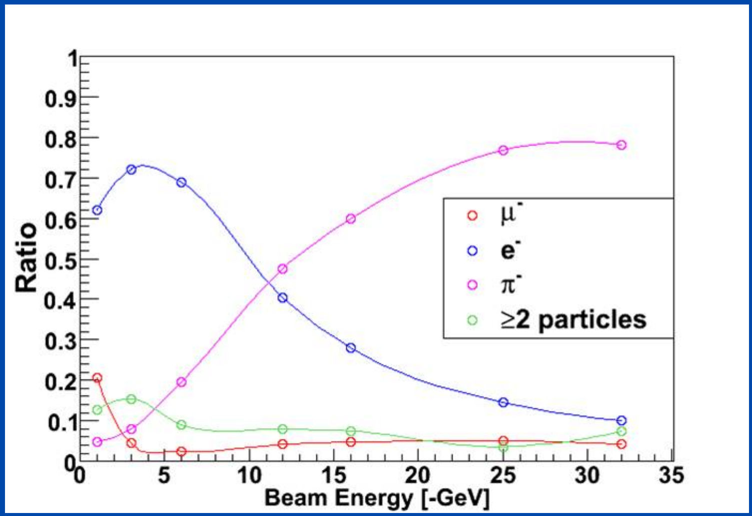
Subtracting low frequency noise

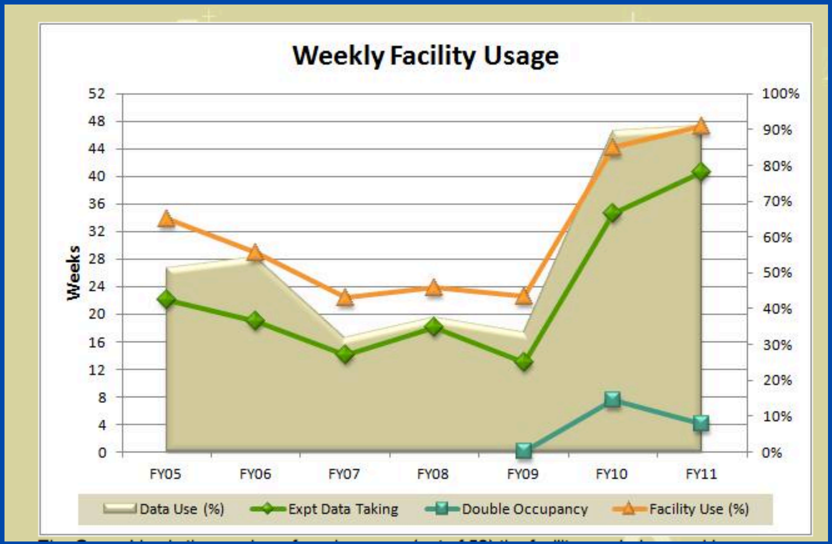
Future support of the HEP Detector Community–
Test Beam Facility
Silicon Detector Facility
Future Detector Development

Test Beam SiDet Project X

Fermilab Test Beam Facility

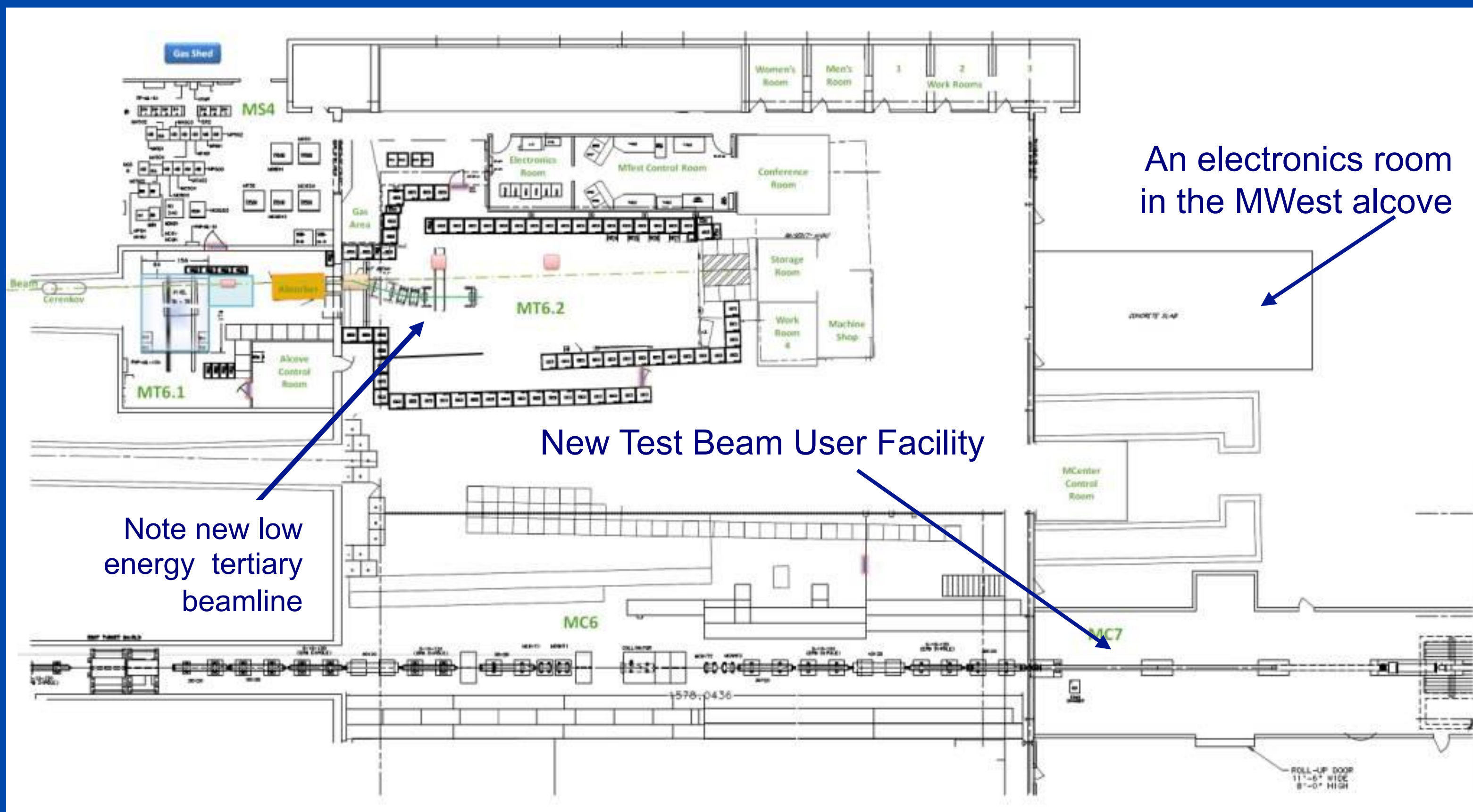






This facility is now typically booked 6 months in advance

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:

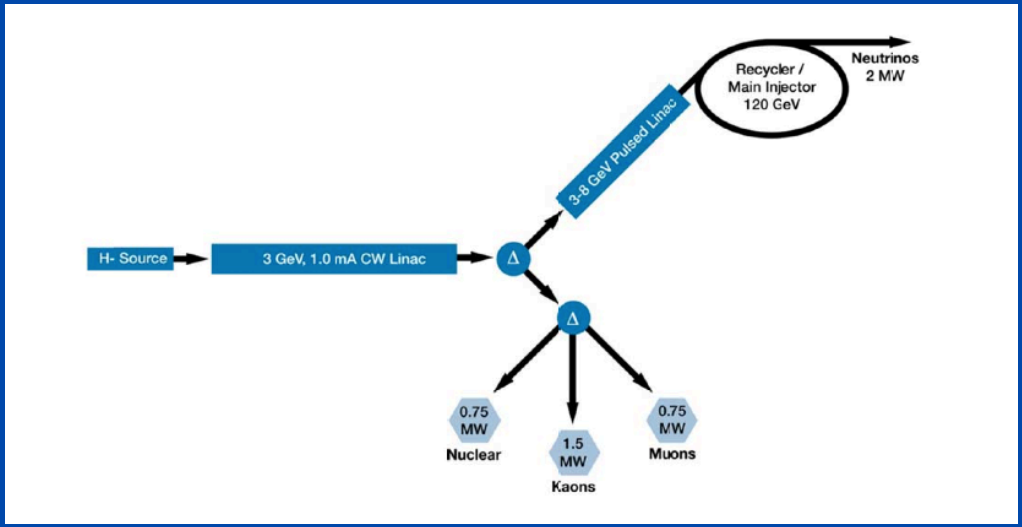
CCD Testing Infrastructure

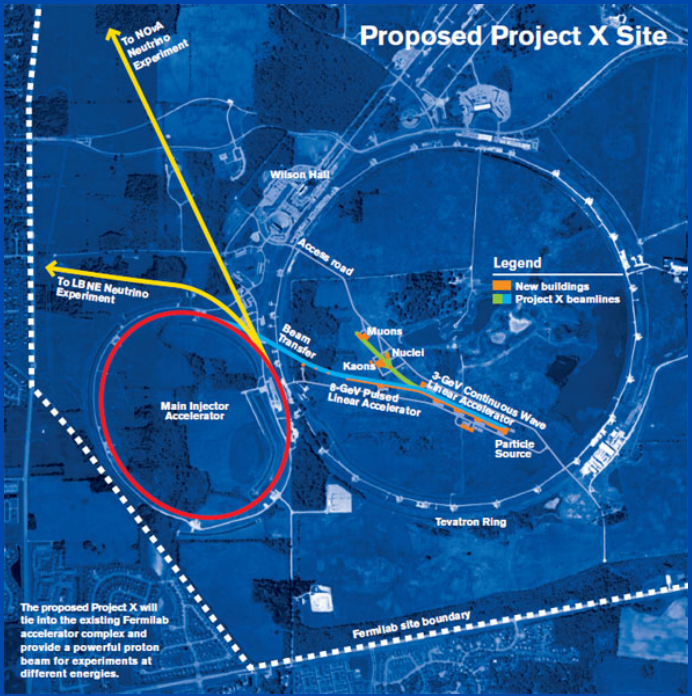
Wire bonding capability

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 potential efforts in Fermilab's future:

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 !!