Generic Detector R&D at Fermilab

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Fermilab

U.S. DEPARTMENT OF ENERGY

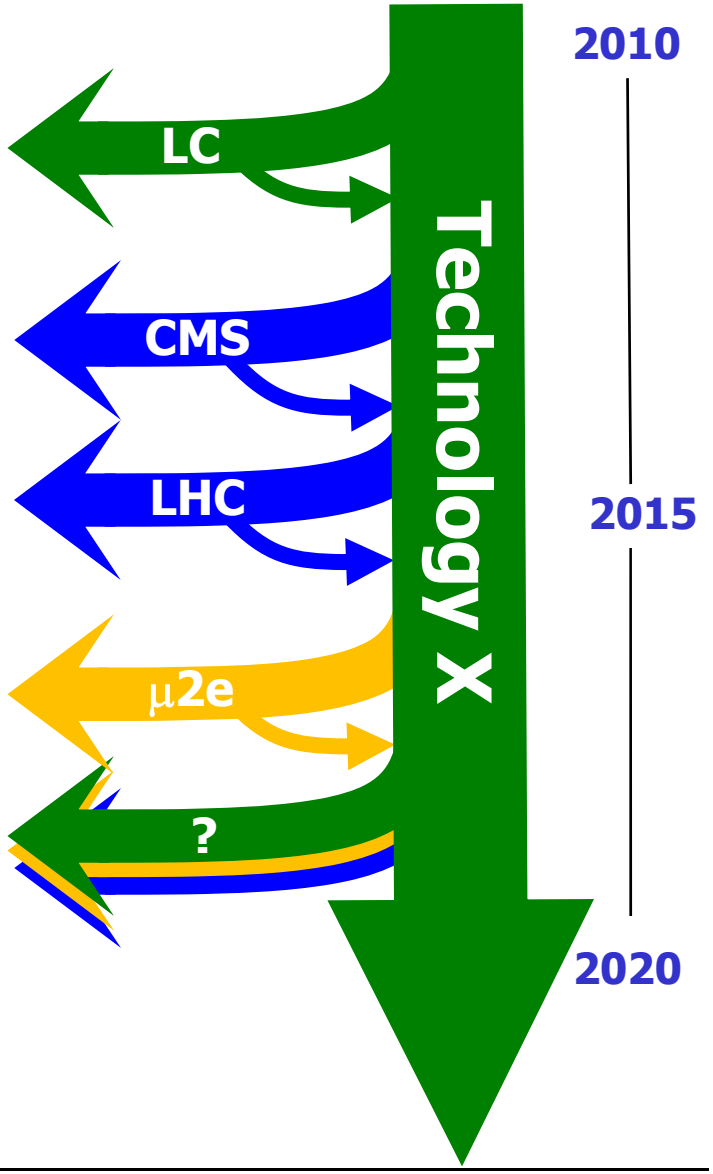
Fermilab

Outline

- **Introduction**
- **Goals, elements and priorities of detector R&D**
- **Organization**
- **Highlights of main detector R&D initiatives**

Innovation

- **Innovations in detector technology have contributed tremendously to the reach and success of experiments in particle physics.**
- **The community is working to define the next generations of (upgraded) experiments**
- **Particle detectors with unprecedented precision will be required**
- **To that end, Fermilab is establishing a well focused and balanced program of detector R&D**

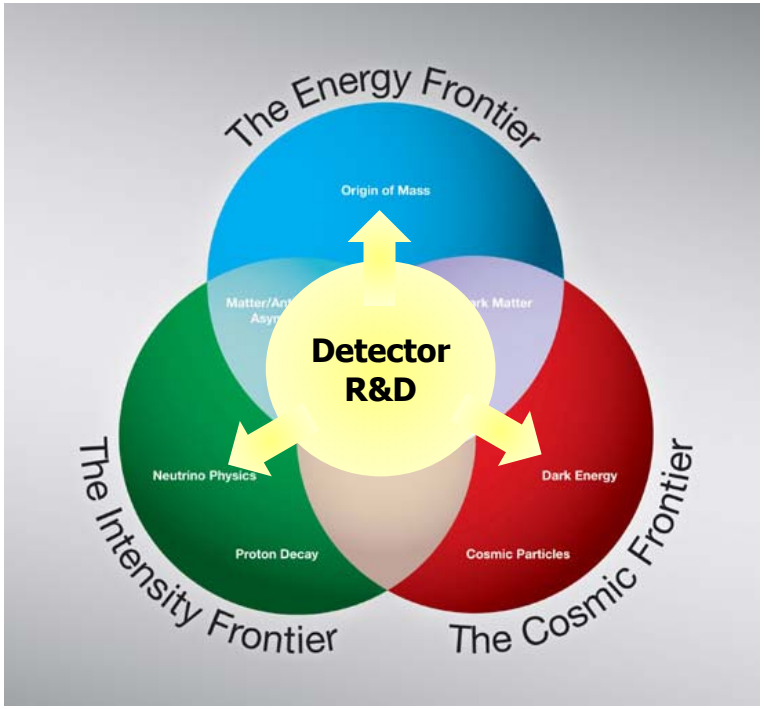


Goals of R&D Program

- **The goals of our strategic detector R&D plan are:**
  1) **Achieve a leadership role in detector R&D for intensity frontier experiments within the next five years**
  2) **Continue world-class detector R&D at the energy frontier which will enable the US community to fully exploit the LHC and prepare for the next generation lepton collider**
  3) **Create and facilitate development of new technologies to explore the cosmic frontier**

- **The detector R&D will leverage the areas of expertise of the laboratory**

- **Our goals are well-aligned with the P5 recommendations**



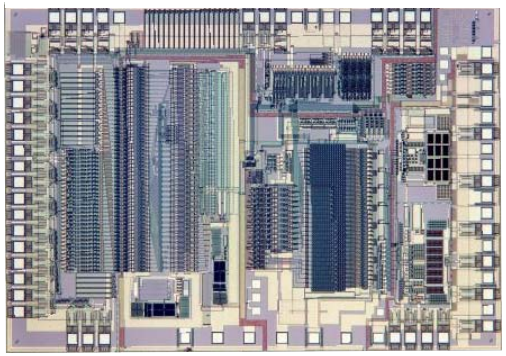
Elements of Detector R&D Program

- **Device R&D**
  - **Significantly extend or develop technologies that will enable new capabilities and experiments**
- **Core engineering**
  - **Build on core capabilities in engineering (electrical, mechanical and civil) to develop conceptual designs, prototypes, detector systems, and full experimental designs**
- **DAQ and online computing**
  - **Develop forefront high performance DAQ systems**
- **Simulation Support**
  - **Develop flexible tools for simulating experimental designs and benchmarking physics performance**
- **Detector Systems**
  - **Lay the groundwork for new HEP experiments, by establishing initial concepts and feasibility, integrating physics requirements with detector designs, identifying and defining basic technologies and required R&D**
- **Test Beams**
  - **Provide a facility with unique capabilities for beam tests of new detectors**

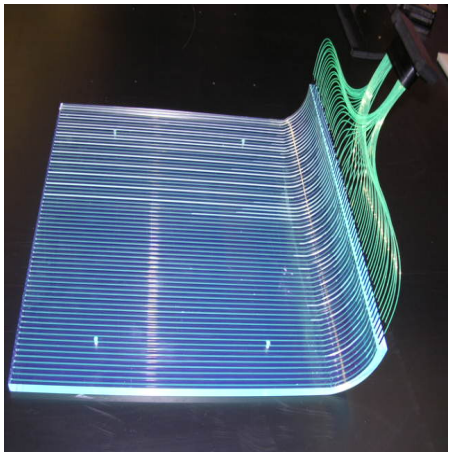
Core and Programmatic Support for R&D

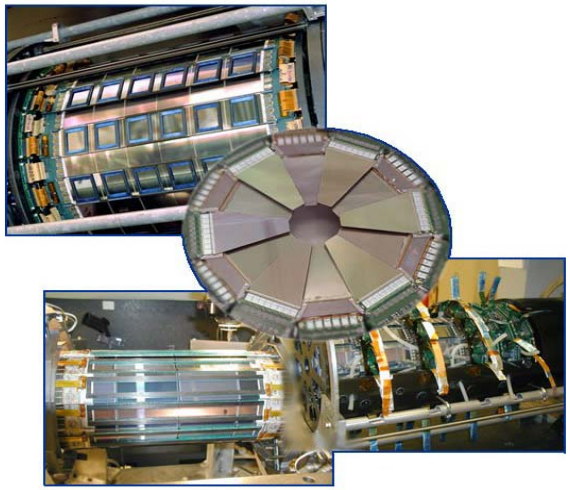
- **Engineering support with up-to-date design tools**
  - **Electronic engineering**
    - ASIC design with software support
    - Data acquisition and Trigger systems
  - **Mechanical engineering**
    - Mechanical supports
    - Cryogenic systems
  - **Civil Engineering**
    - Beamlines and Caverns

CMS HCAL QIE - 2002



- **Many unique facilities and trained technical support staff**
  - **Silicon Detector Center**
  - **Scintillator extrusion**
  - **CNC routing**
  - **Thin film deposition**
  - **Chamber stringing**
  - **LAr cryogenics**
  - **Metrology**
  - **Test beam facility**





Priorities

- **Invest in detector R&D to achieve transformational discoveries**
  - **Organize and focus on breakthrough new technologies**
  - **Develop and nurture science and engineering talent**
  - **Invest in technologies with broad range of applicability**

- **Organize targeted, coordinated detector R&D effort**
  - **Coordinate work across the laboratory and projects**
  - **Enhance Fermilab's strengths**

- **Maximize synergy and coordination among projects**
  - **Leverage investments and expertise across projects**
  - **Transfer technology to other areas when resources permit**

- **Strengthen collaboration with other national labs and universities**
  - **Leverage different strengths at each institution**

Organization

- **R&D is directed within each major physics area**
  - **Collider Detector, Dark Energy and Dark Matter, LAr TPC**
- **To align the detector R&D with the overall planning of the lab, formal reviews are being held on a bi-/tri-weekly basis to evaluate the various existing activities and new initiatives at the laboratory, organized by Bruce Baller and Marcel Demarteau**

- **Internal Review presentations and reports available at (internal only) http://www-ppd.fnal.gov/DivOffice/internal_rd/Reviews.htm**
  - **GammeV (Dec 3, 2008)**
    - David Christian (chair), David Harding, David McGinnis, Rick Tesarek, Jay Theilacker
  - **COUPP (Dec. 10, 2008)**
    - Bob Kephart (chair), Rich Stanek, Fritz DeJongh, Juan Estrada
  - **LAr (Jan. 26, 2009)**
    - Liz Buckley-Geer(chair), Jim Hylen, Jonathan Lewis, Ting Miao, Russ Rucinski
  - **PPD (Feb. 17, 2009)**
    - Bob Wagner (chair), Steve Hahn, Kurt Krempetz, Bob DeMaat, Ron Ray
- **To be scheduled**
  - **Scintillating Bubble Chamber**
  - **CCD**
  - **3D Silicon Technology**
  - **CMB Detector**

R&D Initiatives

- **Major R&D in the area of collider detectors, dark matter, LAr TPC**
- **Proposed activities for FY09, as submitted to DOE**

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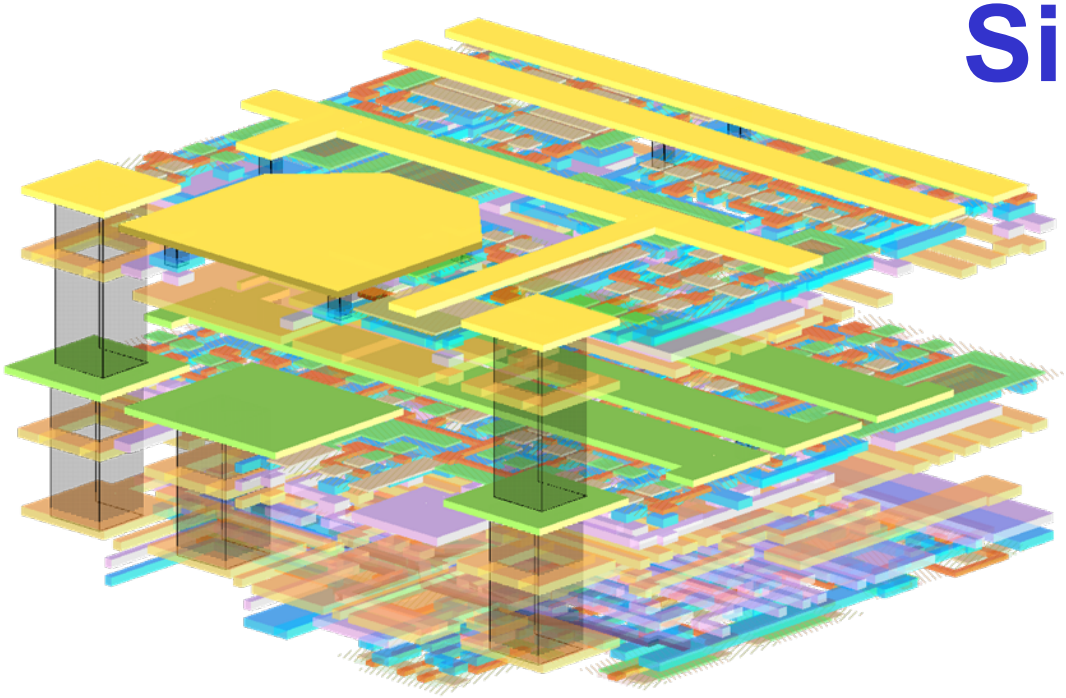
KA 15 03 02 Detector Development - Detector Systems

Est. FTE	Expenditure Descripti	Personnel	Materials & Services	Overhead	Total
2.74	Other Experimental Initiatives	255.8	229.6	186.5	671.8
9.35	Liquid Argon TPC R&D	910.0	740.0	649.2	2,299.2
14.38	Collider Detector R&D	1,542.0	486.0	976.9	3,004.8
1.15	MicroBooNE Pre-CD 0	145.0	300.0	132.6	577.6
3.32	Dark Energy R&D	427.9	52.0	283.1	763.0
7.72	COUPP	733.2	268.0	465.8	1,467.0
0.00	Other Dark Matter	0.0	68.0	10.9	78.9
38.66	**Total Detectors/Detector Systems**	**4,013.9**	**2,143.6**	**2,704.9**	**8,862.4**

- **These numbers are augmented by engineering core support (6.2 FTE, $608k M&S) and computing support (0.3 FTE, $78k M&S).**

Silicon Detectors



Issues and Goals

- **Precision vertexing/tracking/imaging requires detectors that have**
  - **zero mass**
  - **zero power**
  - **zero dead zones**
  - **zero dead time**
  - **zero effective occupancy**
  - **zero noise susceptibility**
  - **infinite precision**

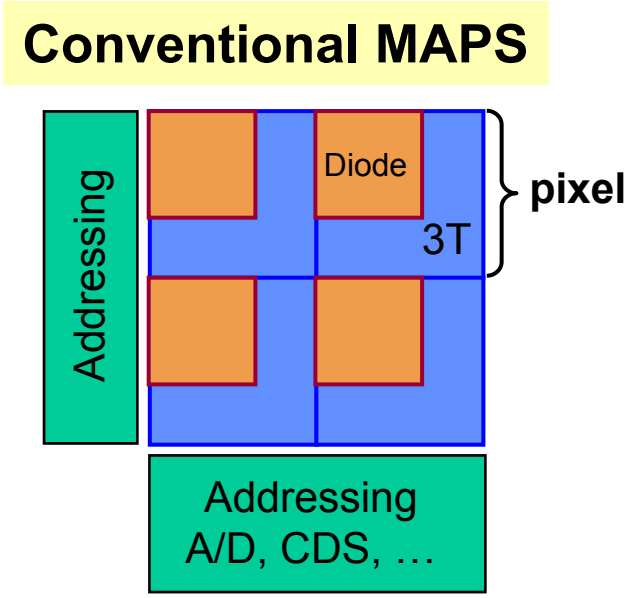
- **Establish the vertical integrated (3D) silicon technology for application in particle detectors (not limited to vertex detectors)**
- **Investigate ways to build low-mass silicon detectors through the study of**
  - **alternative powering schemes to reduce overall power budget**
  - **alternative silicon bonding technologies**
  - **alternative silicon support structures**
  - **thinning of silicon sensors**
  - **use of Silicon On Insulator (SOI) technology**

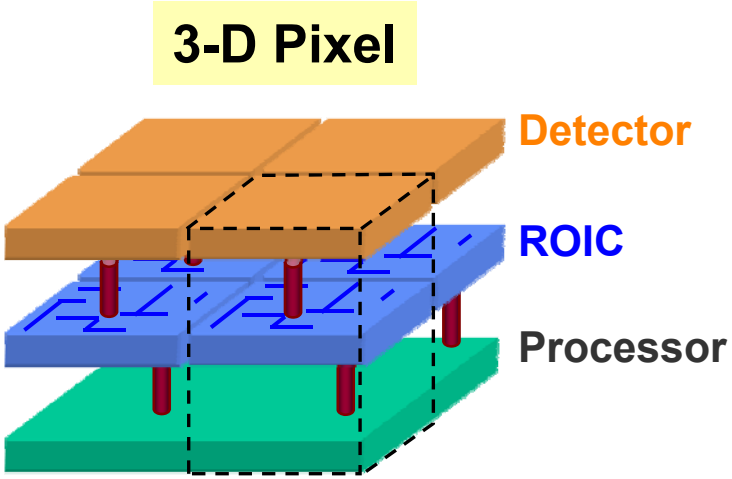
Vertical Integrated Circuits – 3D

- "Conventional MAPS"
  - Pixel electronics and detectors share area
  - Fill factor loss
  - Co-optimized fabrication
  - Control and support electronics placed outside of imaging area

- 3D Vertical Integrated System
  - Fully active sensor area
  - Independent control of substrate materials for each of the tiers
  - Fabrication optimized by layer function
  - Local data processing
  - Increased circuit density due to multiple tiers of electronics
  - 4-side abuttable

- Technology driven by industry
  - Reduce R, L, C for higher speed
  - Reduce chip I/O pads
  - Provide increased functionality
  - Reduce interconnect power, crosstalk





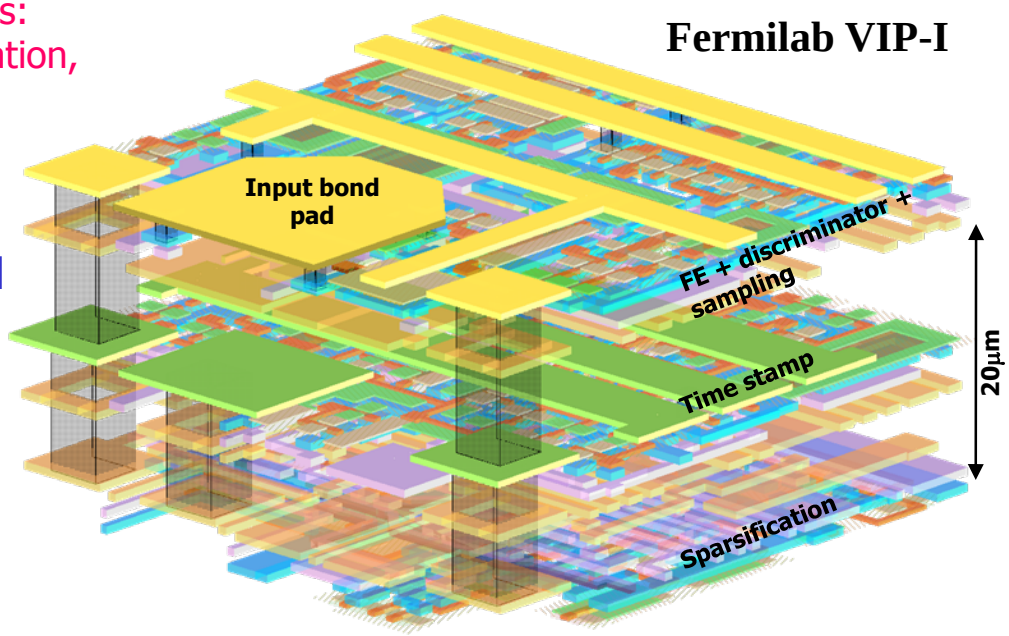
VIP-1 Chip

- **Fermilab started to actively pursue the 3D technology in early 2006**

- **MIT Lincoln Laboratories (MIT-LL) had developed the technology that enables 3D integration**
  - **Demonstrated the 3D technology through fabrication of imaging devices**
  - **Has infrastructure to allow for 3D Multi-Project Run fabrication**

- **MIT-LL offers DARPA funded three-tier multi-project run**
  - **3D design laid out in MIT-LL 0.18 μm SOI process**
    - SOI provides additional advantages: BOX, full isolation, direct via formation, enhanced low-power operation
  - **3 levels of metal in each layer**

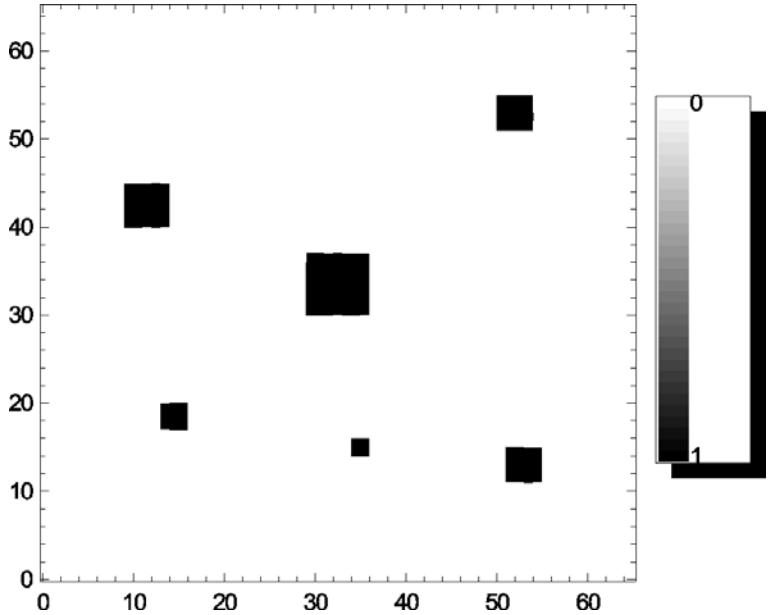
- **Designed Vertical Integrated Pixel (VIP) readout chip for ILC pixel detector**
  - **Pixel size 20 x 20 μm**
  - **64 x 64 pixel array**
  - **No integrated sensor**



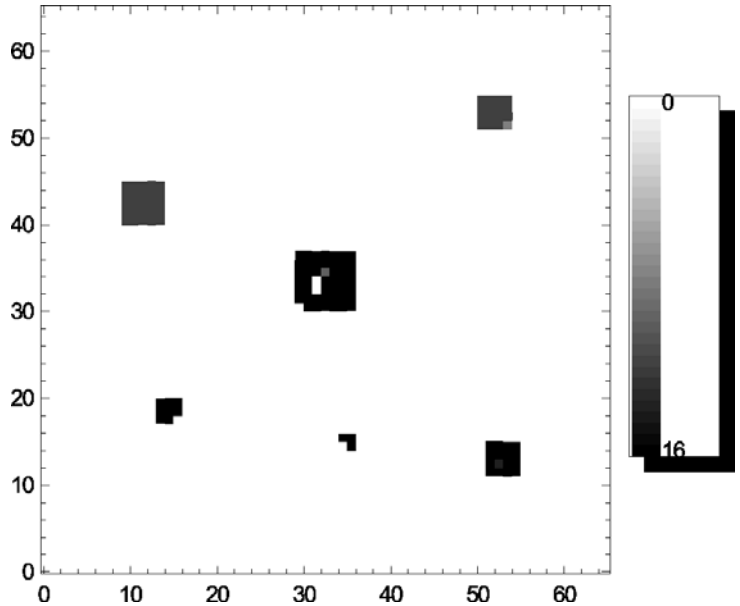
VIP-1 Chip Test Results

- VIP-1 chip submitted Oct. 2006; ~20 devices delivered late 2007
- Chip works !
- Major breakthrough in the development of advanced ASICs and integrated detector systems

- Data readout out using data sparsification scheme on full array



Preselected injection pattern of pixels to the front-end amplifiers



Readout pattern of pixels from the preselected injection pattern reported as hit

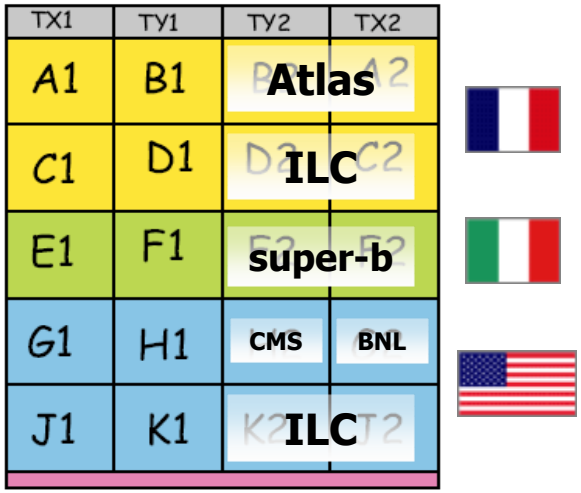
Next Steps

- MIT-LL run has been very successful and has provided a proof of principle
- An improved version of VIP1 has been submitted to MIT-LL on October 13, 2008 (150nm, SOI, 3 tiers): VIP-2a
  - Different power and grounding layout;
  - Redundant vias and larger traces in critical paths; Added diagnostics
- MIT-LL process does have some shortcomings
  - Processing and design problems; Significant chip-to-chip variations
  - Yield is poor, reasons not understood; Measurements disagree with simulations

- Fermilab started an initiative with local vendor willing to accept MPW runs: Tezzaron (Naperville and Singapore)
  - One of the leaders in developing 3D technology
  - Wafers are fabricated by Chartered in Singapore
  - 3D assembly is completed by Tezzaron in Singapore
- Advantages:
  - Existing rules for vias and bonding
  - Relatively fast turn around
  - One stop shopping for wafer fabrication, via formation, thinning, bonding
  - Low cost
  - Process is available to customers from all countries

Fermilab 3D Multi-Project Run

- **Fermilab will be hosting a 3D multi project run with Tezzaron (May 2009)**
- **There will be only 2 layers of electronics fabricated in the Chartered 130 nm process, using only one set of masks. (Useful reticle size is 16 x 24 mm)**
- **The wafers will be bonded face to face**



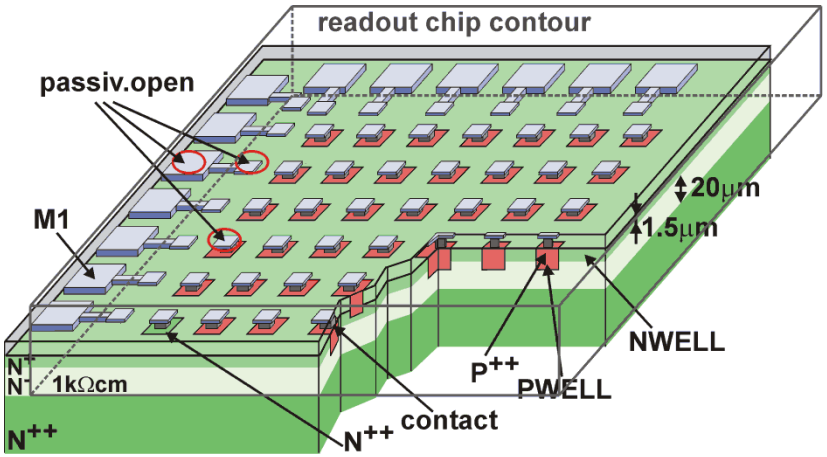
Frame layout

Yellow = France
Green = Italy
Blue = USA
Magenta = alignment
Grey = test chips

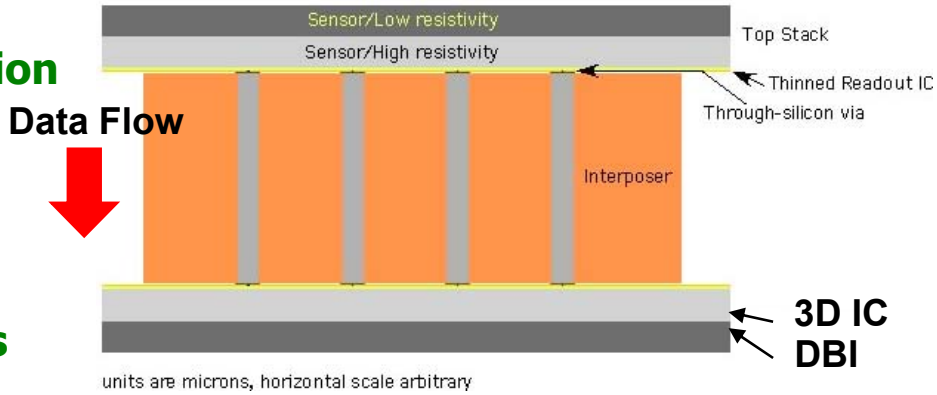
- **Participants in MPW run:**
  - **Fermilab, Batavia**
  - **University at Bergamo**
  - **University at Pavia**
  - **University at Perugia**
  - **INFN Bologna**
  - **INFN at Pisa**
  - **INFN at Rome**
  - **CPPM, Marseilles**
  - **IPHC, Strasbourg**
  - **IRFU Saclay**
  - **LAL, Orsay**
  - **LPNHE, Paris**
  - **CMP, Grenoble**
  - **BNL (NSLS)**
- **Discussions with:**
  - **SLAC (LCLS)**

Projects for 3D MPW Run

- **In collaboration with BNL, evaluating application for X-ray correlation spectroscopy: sensor developed by BNL, 3D ASIC by Fermilab**
  - **calculate autocorrelation function per pixel**
  - **100x100 μm^2 pixels**
  - **γ flux: 1000 γ/pixel/s**
  - **time stamping of ~10 μs**

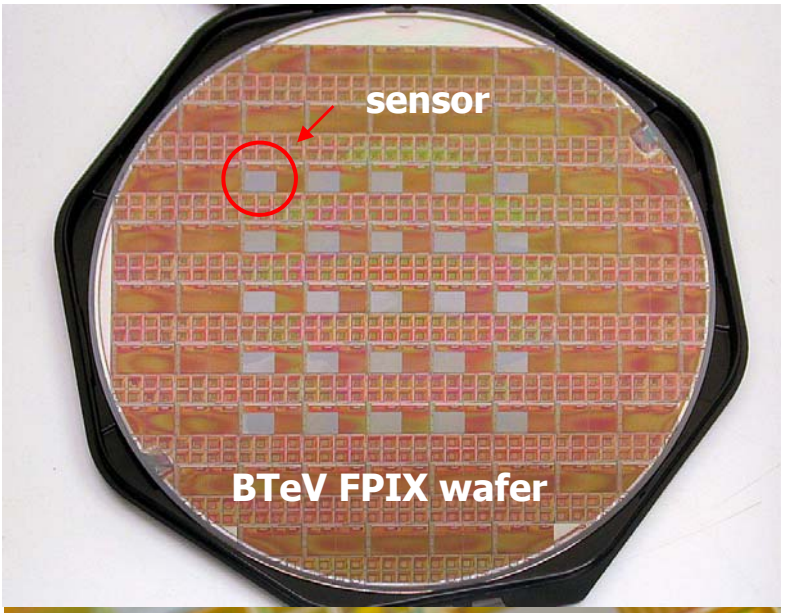


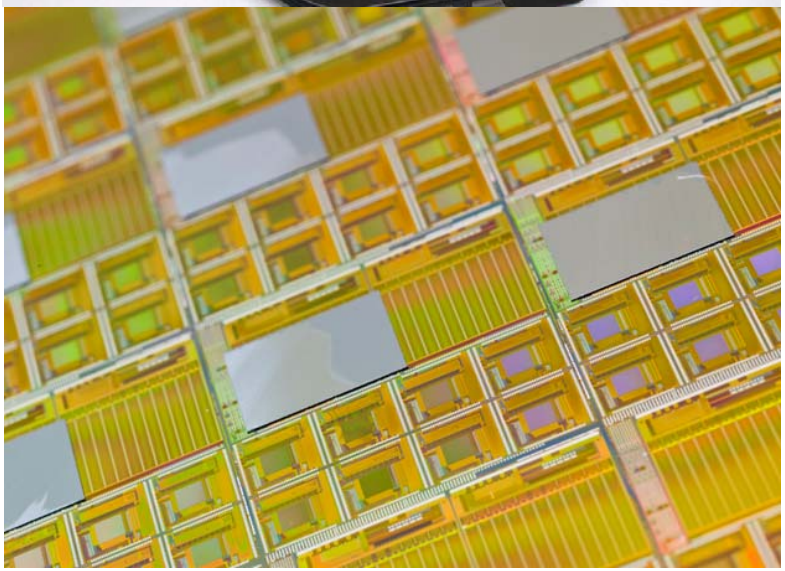
- **CMS Upgrade plan to move tracker information to first level trigger**
  - **Test high speed digital transmission across an interposer**
  - **Test digital-to-analog crosstalk using amplifiers connected to a sensor tier**
  - **Include structure to test schemes for encoding of hit position**
  - **Sensor corresponding to CMS test chip fabricated by BNL**



Integrating Detectors

- Ultimate goal is to have integrated unit of front-end electronics and thin (~50μm thick) detectors with very fine pitch
- Edgeless trenched pixel sensors:
  - p^+ diodes on n^-bulk (ρ=5kΩ·cm);
  - 50 μm deep n^{++} trench at the edge
  - Masks designed at Fermilab
  - Fabricated by MIT-Lincoln Lab
- BTeV FPIX2.1 readout chips
  - 22x128 pixel cells of 50x400 μm;
  - Designed for e-signals (3 bits ADC), can work with small hole signals
- Above two items DBI bonded (Ziptronix) and then sensor thinned to 100 μm
- Method valid for pitch down to ~ 5 μm



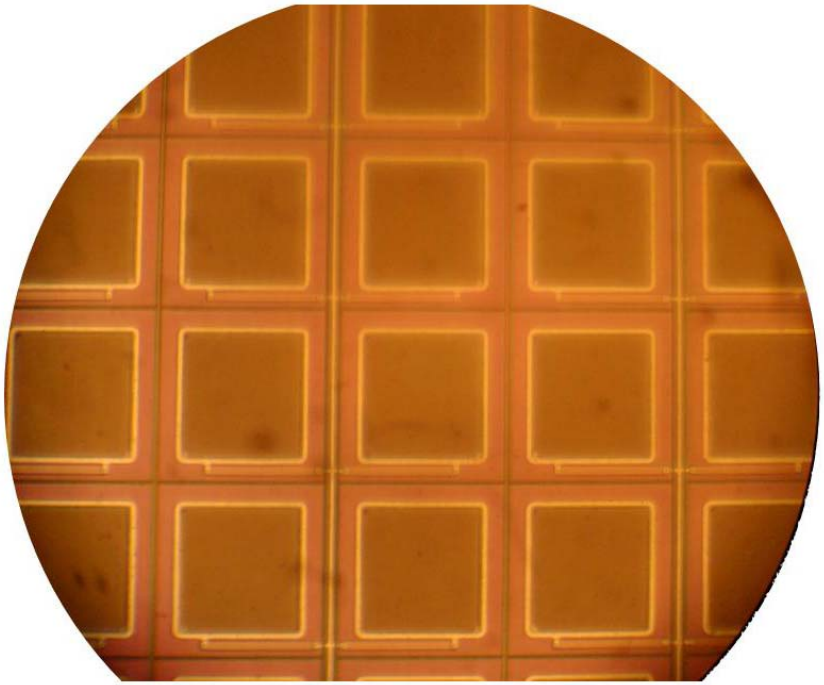


Summary Silicon

- **Fermilab has recognized the promise of the 3D technology for particle physics and is pioneering the 3D technology and its application for silicon detectors**

- **We have many "firsts":**
  - **Working 3-tier device for pixel detector readout**
  - **Established low-mass bonding technologies at 20 micron pitch with 100 micron thick sensors**
  - **Organizing a world-wide 3D Multi-Project Wafer run with 12 participating international institutions**
  - **Designed dedicated Serial Powering Interface ASIC**
  - **Demonstrated all silicon support structure**

- **Highly focused, integrated detector R&D which, if successful, could lead to transformational new detectors**



Pixelized Photon Detectors

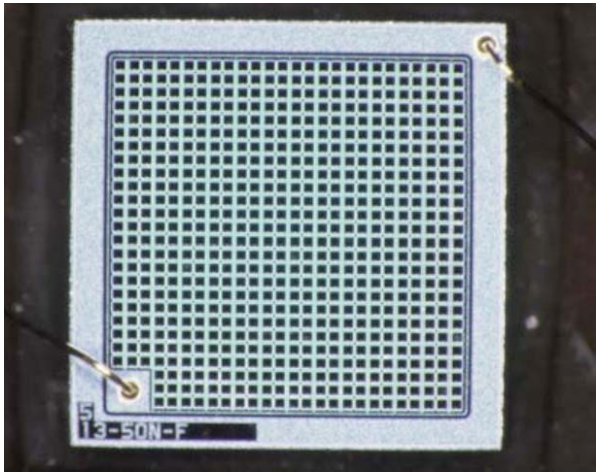
Issue and Goals

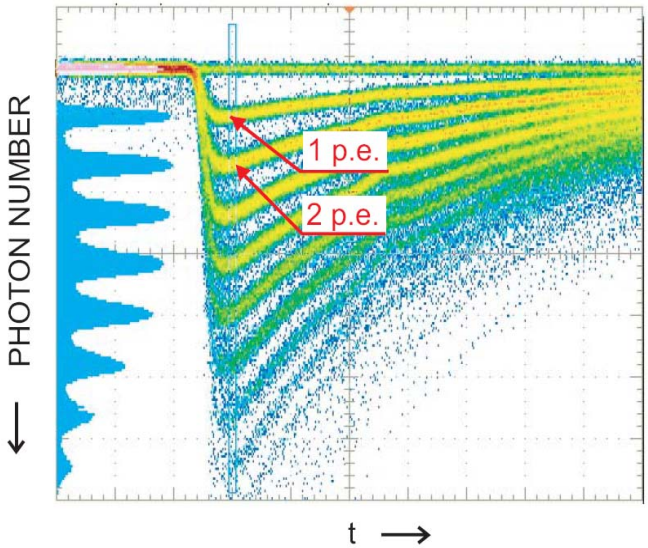
- **The availability of Pixelized Photo Detectors (PPDs) has opened many avenues in all frontiers that were heretofore closed.**

- **Investigate the feasibility and develop the technology for the application of PPDs for particle physics detectors**
  - **Develop facility for the characterization of PPDs**
  - **Detector-scale homogeneous total absorption calorimetry with dual readout with pixelized photon detectors obtaining a jet energy resolution of 20%/√E**
  - **Synergize with development of replacement of HPDs for CMS**
  - **Develop front-end electronics for large scale integrated readout**
  - **Explore potential for application at intensity frontier and integration of PPD and 3D readout**

PPD

- **Pixelized Photon Detector (PPD) is avalanche photodiode operating in Geiger-mode**
  - **Array of pixels connected to a single output**
  - **Signal = Sum of all cells fired**
    - Very compact, High PDE (15~20% for 1600 pix)
    - Low bias voltage operation
    - High thermal noise rate, x-talk and after-pulsing
    - Insensitive to magnetic field
  - **Portrayed as potential replacement of PMT**





- PPD is generic name; device also known as
  - SiPM (Silicon Photo-Multiplier)
  - MRS-APD (Metal Resistive Semiconductor APD)
  - MPGM-APD (Multi-Pixel Geiger-Mode APD)
  - AMPD (Avalanche Micro-pixel Photo-Diode)
  - SSPM (Solid State Photo-Multiplier)
  - GM-APD (Geiger-Mode APD)
  - SPAD (Single Photon Avalanche Diode)
  - MPPC (Multi-Pixel Photon Counter)

- **It is an enabling technology for many applications**

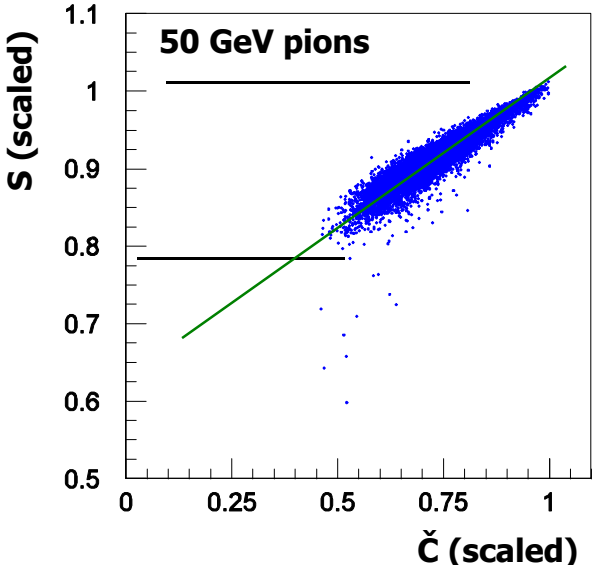
Dual Readout Calorimetry

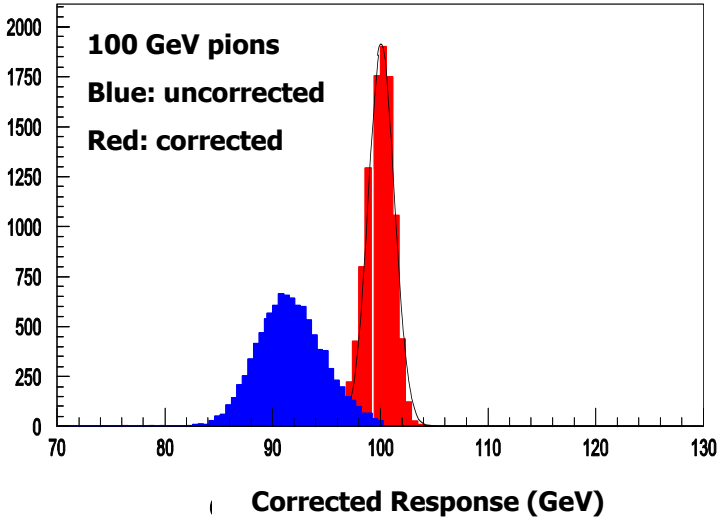
- **Dual-readout calorimetry: measure every shower twice**
  - **Scintillation light: from all charged particles**
  - **Čerenkov light: β=1 particles, mainly EM**

- **Correct on a shower-by-shower basis using the correlation of the total observed ionization (S) and Cherenkov (Č) light**

- **Monte Carlo shows:**
  - **Gaussian response**
  - **Energy resolution (0.2-0.25)/√E**
  - **No constant term up to 200 GeV**

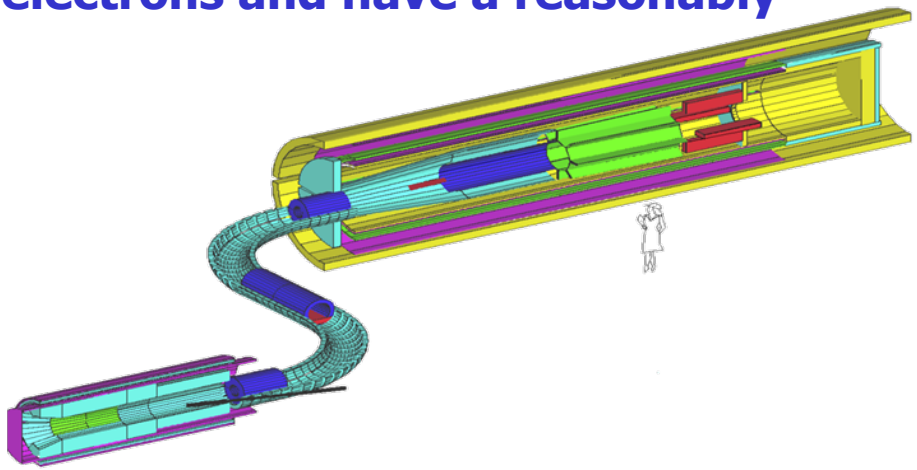
- **The enabling technology is pixelized photon detectors**
  - **Separation Č-light and scintillation light**
  - **Yield, wavelength,**
  - **uniformity, # SiPM**
  - **Simulation of scintillation and Č-light**





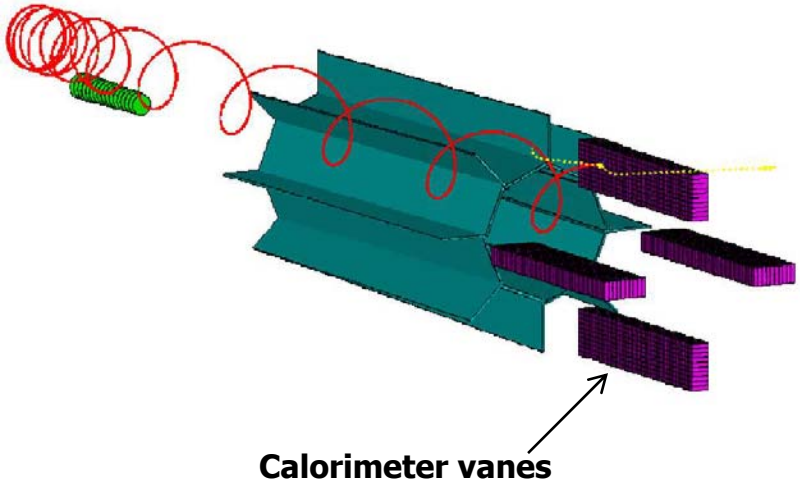
μ2e Calorimetry

- Calorimeter in μ2e must measure energy (~5%), position (1-2 mm) and timing (10 ns) of 100 MeV/c electrons and have a reasonably fast pulse



- Differentiate between electrons, muons and protons at these momenta.

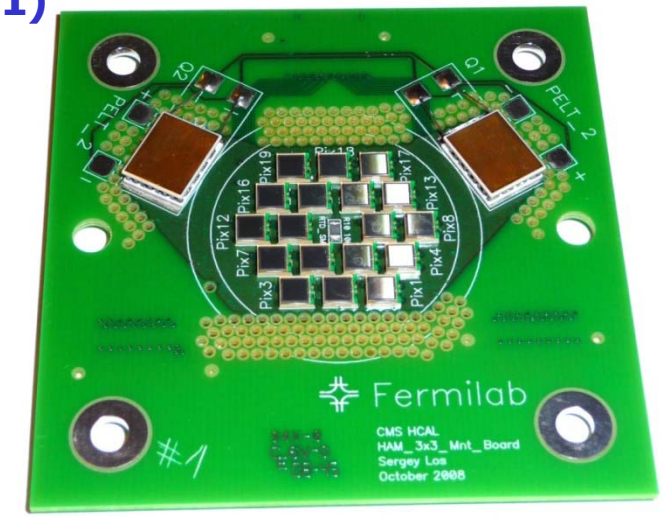
- 1800 lead-tungstate crystals, each 3x3x12 cm^3, 0.2 m^3 total operating in a 1 Tesla magnetic field
  - APD readout is the baseline.
  - Possible application for SiPMs



- Another application is for extinction factor between beam bunches of 10^{-9}

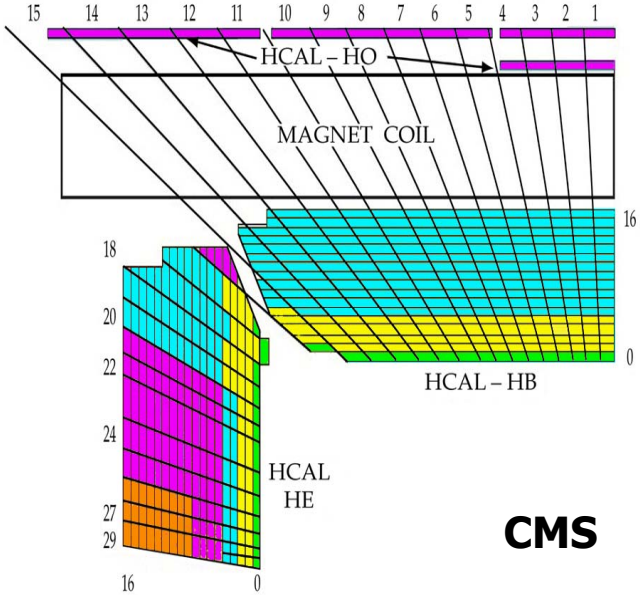
CMS Synergy: HCAL

- **CMS HPD replacement: Outer Calorimeter (~2011)**
  - **~3,000 PPDs**
  - **Each fiber in bundle (18) guided to its own SiPM**
  - **Readout by QIE ASIC (Fermilab)**
  - **Control board supplies SiPMs with individual bias voltage, measures leakage currents, and provides attenuation to match QIE resolution and dynamic range (Fermilab)**



- **CMS HPD replacement: whole calorimeter (Phase I)**
  - **~110,000 PPDs**
  - **Allows for longitudinal segmentation**
  - **SIPM tailored to HCAL**
  - **New ADC = new ASIC (QIE10)**
  - **Temperature Regulation for SiPMs**

- **Strong overlaps**



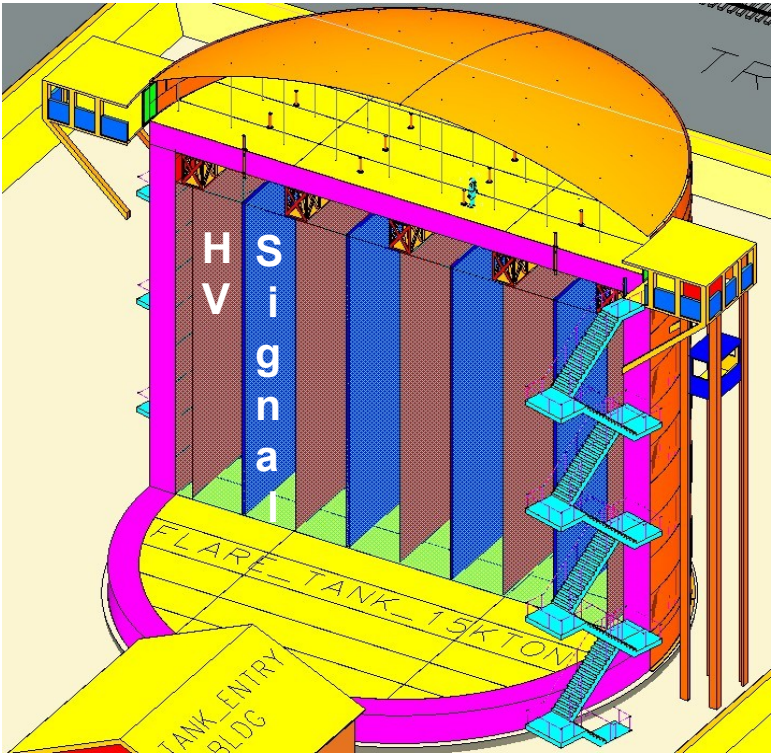
Summary PPD

- **Program for application of Pixelized Photo Detectors is very broad with wonderful synergies**

- **Fermilab has a good entrée in this area, but program is rather ambitious :**
  - **Characterization of PPDs**
  - **Proof viability of dual-readout calorimetry for large scale experiments**
  - **Detector-scale homogeneous total absorption calorimetry with dual readout with pixelized photon detectors obtaining a jet energy resolution of 20%/√E in test beam**
  - **Develop front-end electronics for large scale integrated readout**
  - **Explore potential for application at intensity frontier and integration of PPD and 3D readout**

- **Work is progressing on forming collaborative efforts with universities and research institutions in dual readout calorimetry**

- **More coordination and resource matching will be required**



Liquid Argon

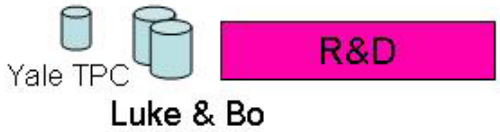
Issue and Goals

- **Fermilab's long term strategic term plan calls for the development of new neutrino and dark matter detectors with far reach. What is the road to technical feasibility for the construction of large scale LAr detectors?**

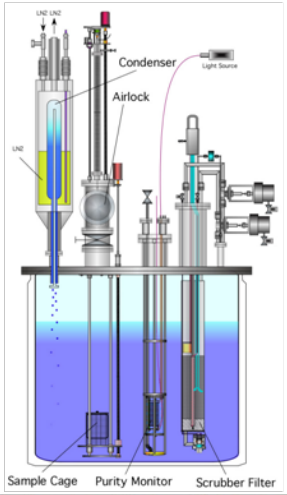
- **Develop a scalable Liquid Argon technology leading to the construction of a large scale Liquid Argon TPC experiment**
  - **Argon purity (without evacuation): achieving, measuring, maintaining**
  - **Large volume TPC design: many meters of drift**
  - **Electronics**
  - **DAQ reconstruction, analysis**
  - **Ultimate R&D goal is a large scale (5kTon) system test**
- **Develop confidence in the construction technology**
- **Develop confidence in the cost estimate (derive scaling laws)**
- **Develop a reasonable cost device**
- **(And do interesting and relevant physics on the way)**

LAr Neutrino Detectors

- **Neutrino physics and underground facilities will be a major emphasis of US experimental program**
- **Development phase I:**
  - **Ar purity: achieving, measuring and maintaining**



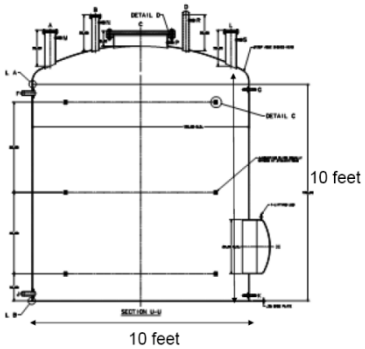
Purity, electronics development



- **Development phase II:**
  - **Prototype TPC: ArgoNeuT, 550(175) vessel(active)**

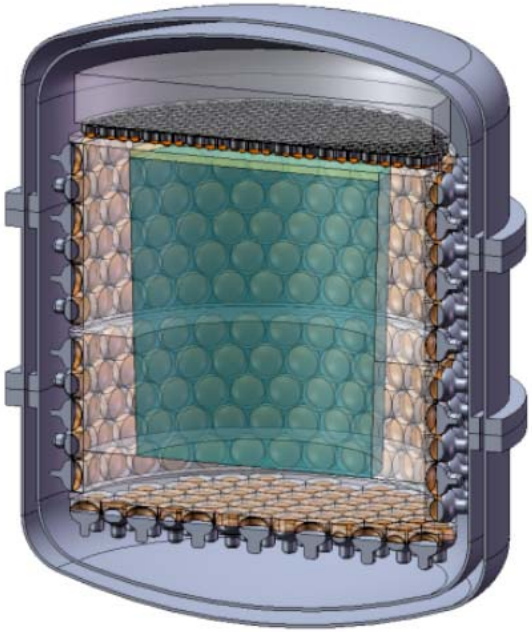
Underground safety, cryo operation, TPC performance, reconstruction

- **Development phase III:**
  - **LAPD (nanoBoone): 20 ton**
  - **Non-evacuated fill**
  - **Very targeted R&D which benefits worldwide LAr projects, which are all coping with the same issues of scalability**



LAr Dark Matter Detectors

- **NSF S4 proposal for MAX detector:**
  - **Liquid noble 2-phase TPC dark matter detector**
  - **For background suppression, the scintillation pulse shape and ionization/scintillation ratio combine to provide the highest discrimination between nuclear recoils and β / γ events**
- **Possible limit to the size and sensitivity of argon dark matter detectors comes from ^{39}Ar, a β-emitter**
- **R&D goals:**
  - **Obtain argon gas with low Ar-39**
  - **Measure light yield**
    - Preserve >4 p.e./keV with scaling up?
    - Validation of optical Monte Carlo
  - **Test position reconstruction vs. Monte Carlo**
  - **Electric field and shaping**
  - **Argon handling**
  - **Acrylic vessel cryogenics**

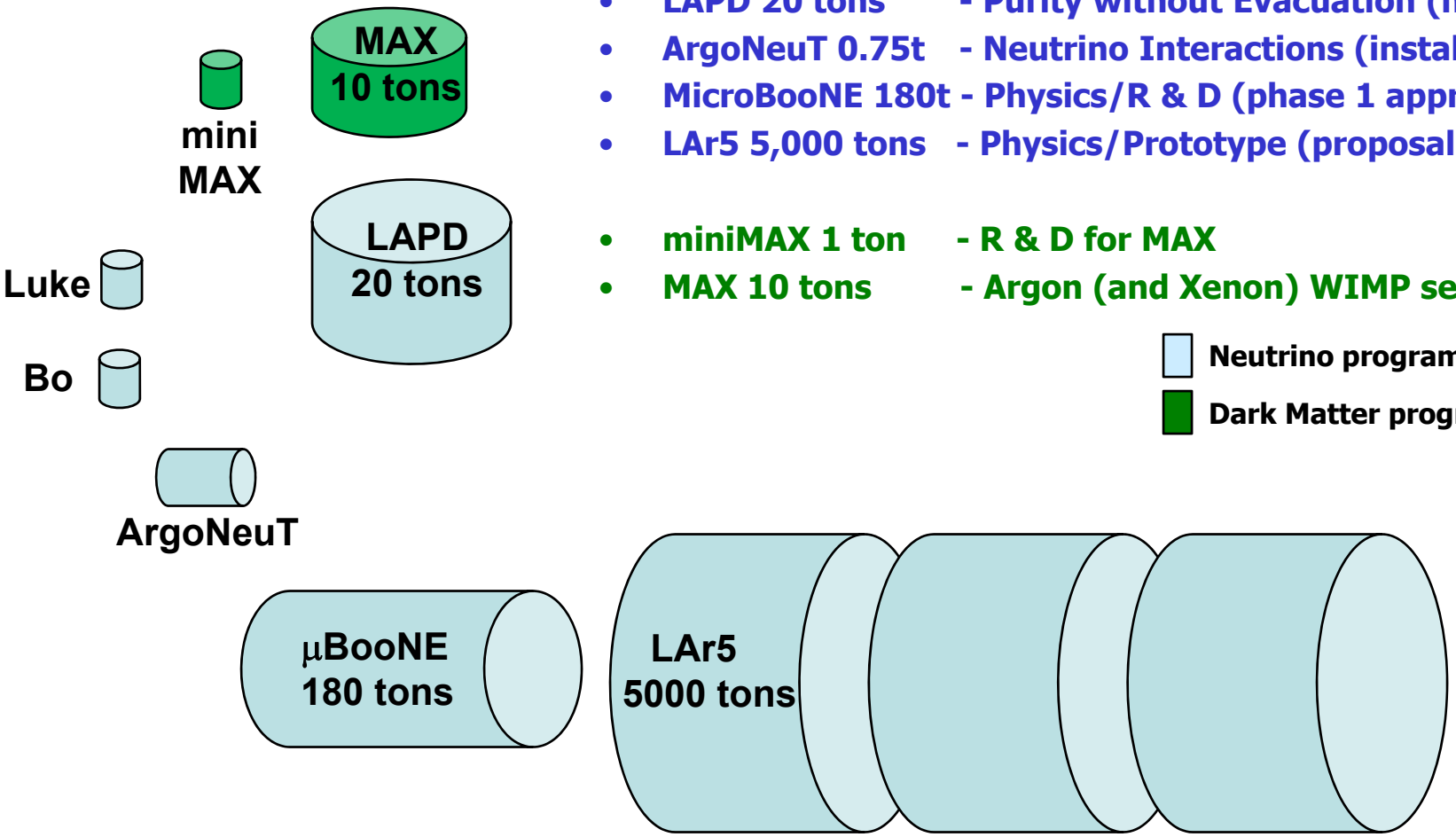


- **Facing many of the same issues as LAr neutrino detectors**

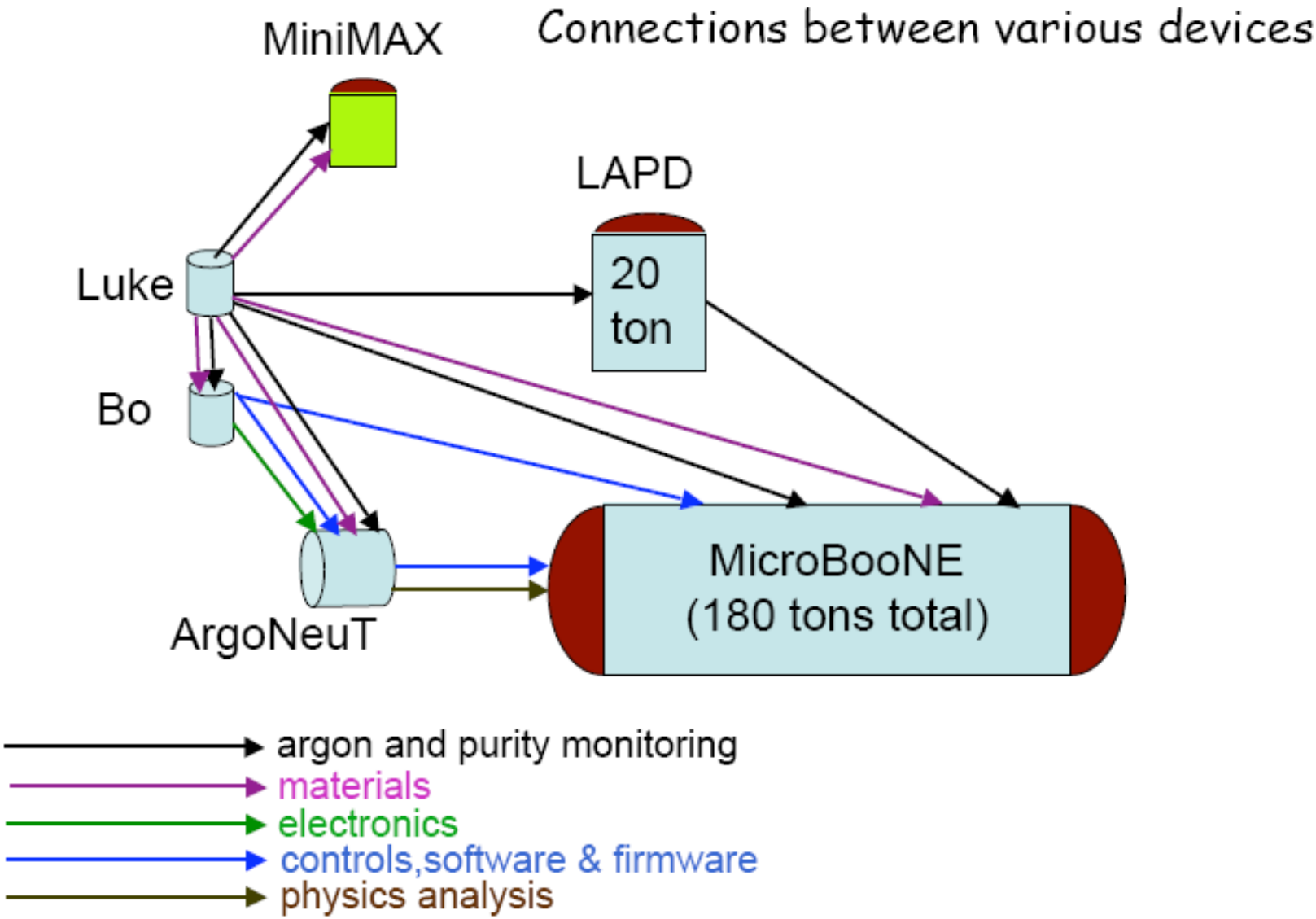
LAr Context

- Luke 280 kg - Materials Test System (operating)
- Bo 280 kg - Electronics Test System (operating)
- LAPD 20 tons - Purity without Evacuation (new)
- ArgoNeuT 0.75t - Neutrino Interactions (installed)
- MicroBooNE 180t - Physics/R & D (phase 1 apprvd.)
- LAr5 5,000 tons - Physics/Prototype (proposal)

- miniMAX 1 ton - R & D for MAX
- MAX 10 tons - Argon (and Xenon) WIMP search



LAr Synergies

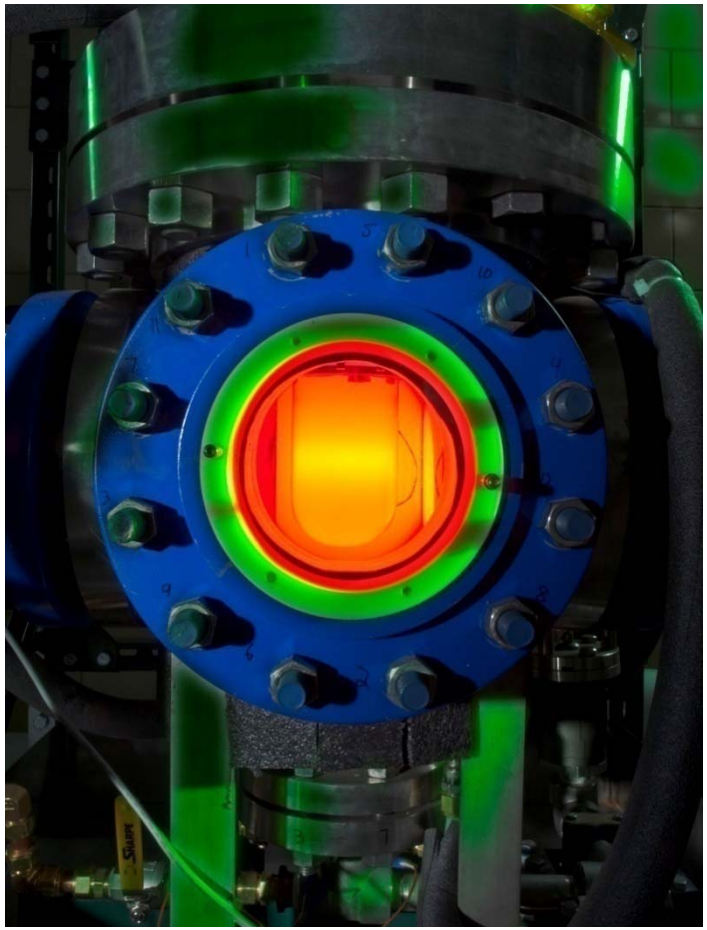


S. Pordes

Summary and Challenge

- **The challenge is to**
  - **Develop a scalable Liquid Argon technology**
  - **Determine the scaling laws**
  - **Bring down the reducible costs to a reasonable level per kTon**
    - Irreducible costs are LAr (~$1M/kTon), tank ($0.5M/kTon)

- **The R&D carried out is generic R&D**
- **However, the projects are reaching a size that they significantly impact the laboratory via resources and schedule**
- **Schedules of these projects will be resource-limited**



Bubble Chamber Detectors

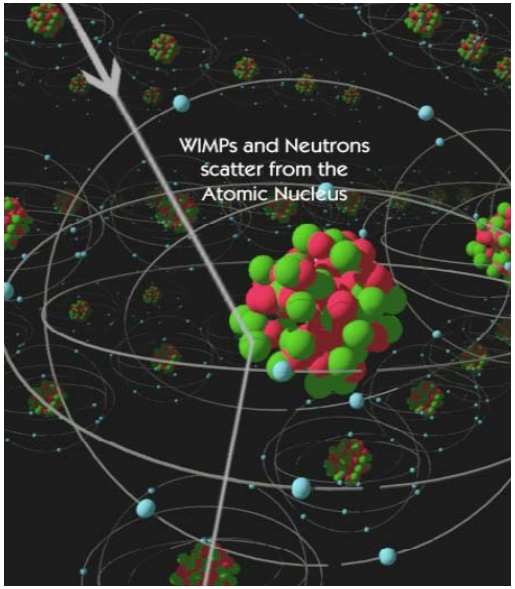
Issues and Goals

- **Bubble chambers have proven to be a very cost-effective way to search for Dark Matter and are expected to have significant larger reach through further development and application of new techniques.**

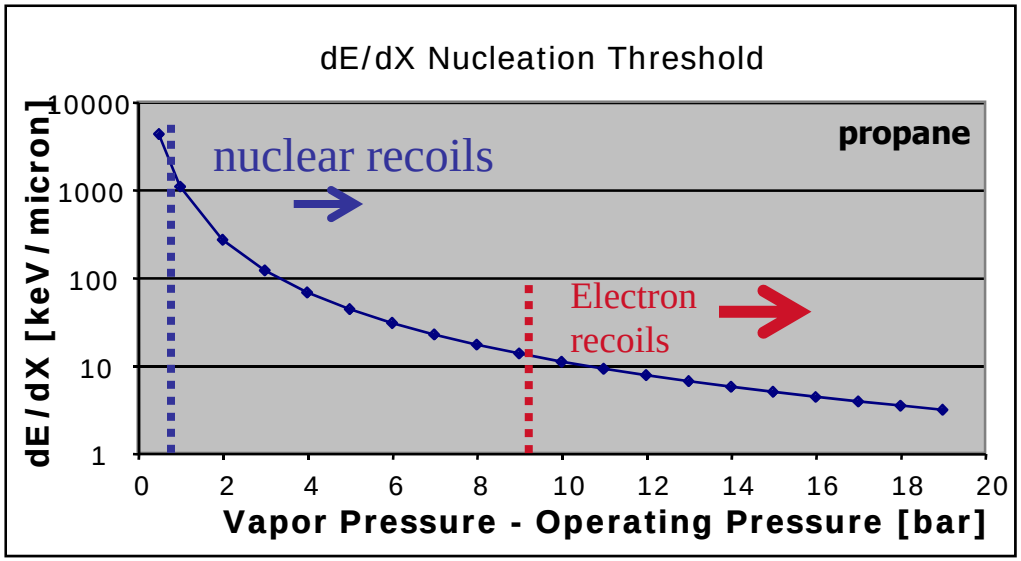
- **Extend the reach of the bubble chamber technology in the search for dark matter through scaling and the application of new techniques**
  - **Demonstrate maintaining superheated state for long periods without spontaneous nucleation and develop calibration chambers**
  - **Improve radiopurity in CF_3I, H_2O and quartz**
  - **Study scintillating superheated liquids**
  - **Study background discrimination through acoustic techniques**

Dark Matter Detectors

- **WIMPs interact directly with the nucleus**
- **Nuclear scattering can efficiently transfer energy to a nucleus, since $M_{nucl} \sim M_{wimp}$**
- **The signal will be a nuclear recoil, with energy ~10 keV**



- **Chosen technology: bubble chamber. Why ?**
  - **Large target mass achievable**
  - **Low energy thresholds (< 10 keV) for bubble nucleation easy to achieve**
  - **Backgrounds due to environmental gamma and beta activity can be suppressed by running at low pressure.**

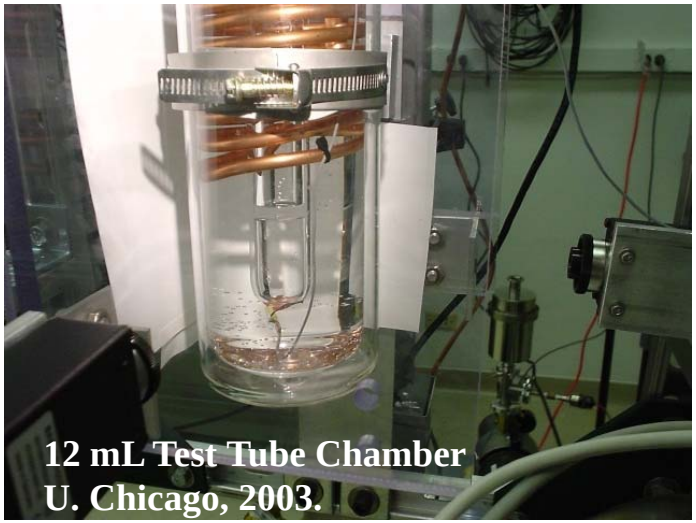


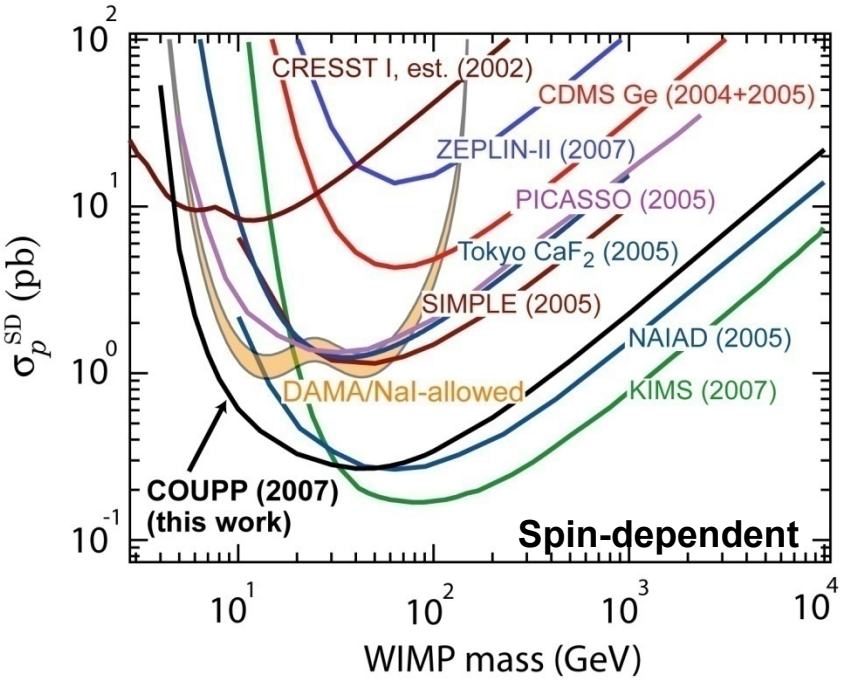
- **Environmental radioactivity limits sensitivity**

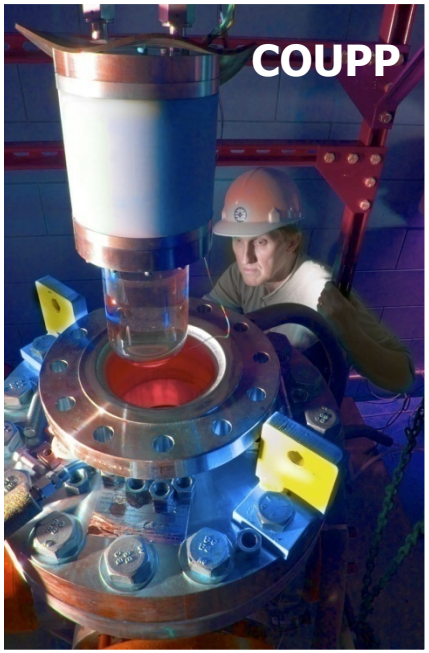
Bubble Chamber Detectors

- **COUPP started as test tube with ~ 20 grams of CF_3Br, collecting ~ 5000 events/kg day background (mostly neutrons)**
- **Brought to experimental stage with 2 kg chamber at Fermilab**

- **In the past all these activities have been funded on generic R&D**

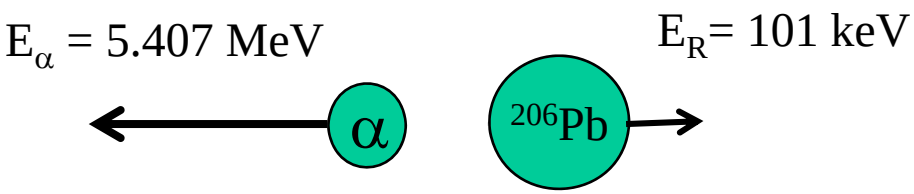


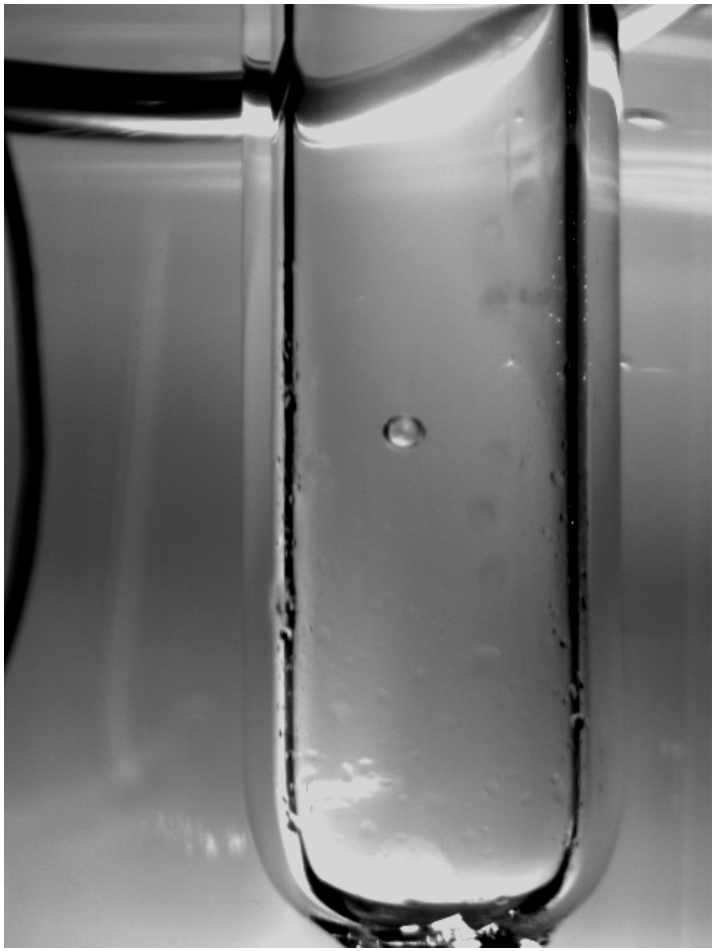




Backgrounds

- **Environmental radioactivity dominant source of background**
- **Alpha decays produce mono-energetic, energy recoils**
- **Radium decay chain is the dominant source of environmental α's**
- **Example: $^{210}Po \rightarrow {}^{206}Pb + \alpha$**



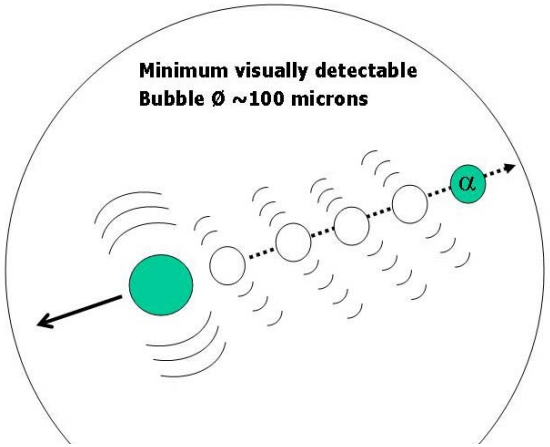


- **The recoiling nucleus will nucleate a bubble in any chamber that is sensitive to the lower energy (~10 keV) recoils expected from WIMP scattering.**

- **$^{226}Ra \rightarrow {}^{222}Rn + \alpha \rightarrow {}^{218}Po + \alpha \rightarrow {}^{214}Pb + \alpha \rightarrow {}^{214}Bi + \beta \rightarrow {}^{214}Po + \beta \rightarrow {}^{210}Pb + \alpha$**
- **Radon is highly soluble in bubble chamber liquids.**

Acoustic Detection

- **The liquid-to-vapor transition in the bubble nucleation process is explosive in nature and is accompanied by a shock wave that can be recorded using piezo-electric transducers**
  - **Fast expansion of the liquid droplet to a gas bubble: factor ~500 increase in volume within about 100 nsec**

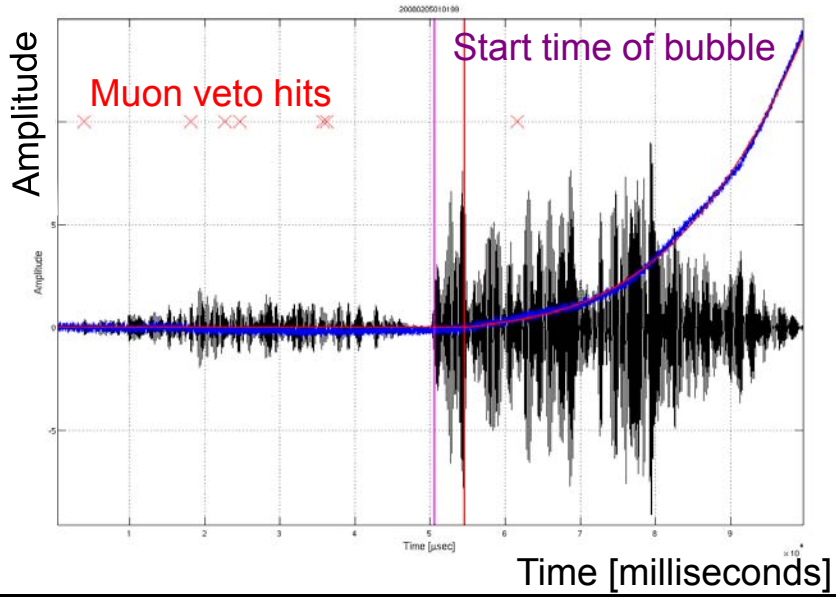


- **Background from α's also create nucleation sites**

- **Time scale of nucleation site creation smaller than time scale of visual detection of the bubble**

- **Using an acoustic technique to pinpoint time at which bubbles occur and compare with muon veto hits**

- **Future possibility for background discrimination from amplitude and frequency content of acoustic signal**



Summary and Challenge

- **Powerful Dark Matter detectors are being developed**

- **The challenge is background rejection for scalable technology through novel cost-effective techniques**

Final Remarks

- Our future program is to carry out physics at the three frontiers
- To maximize the physics potential, we are investing in promising device R&D and the development of detector systems:
  - 3D vertical integrated silicon technology
  - Enabling the pixelized photon detector technology for dual readout calorimetry and scintillator readout
  - Enabling the scaling of the Liquid Argon technology for neutrino and dark matter experiments
  - Enabling the scaling of the bubble chamber technology
  - Pursuing highly promising smaller scale activities
- All of our efforts are carried out with university partners
- The direction, scope, and cost is controlled through a series of internal reviews that follow the priorities of the lab and the field
- We are in the process of reviewing our R&D program for the DOE briefing in July 2009