Detector R&D Program
at
Argonne National Laboratory

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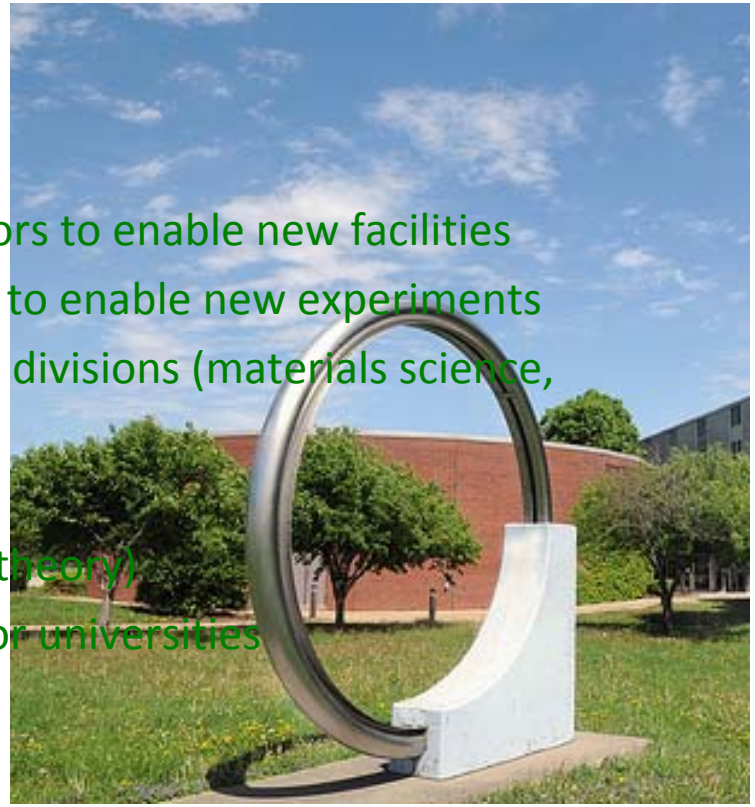
Beijing - University of Chicago Workshop
On Detector R&D
Beijing, June 1-2, 2012

Mission at Argonne HEP

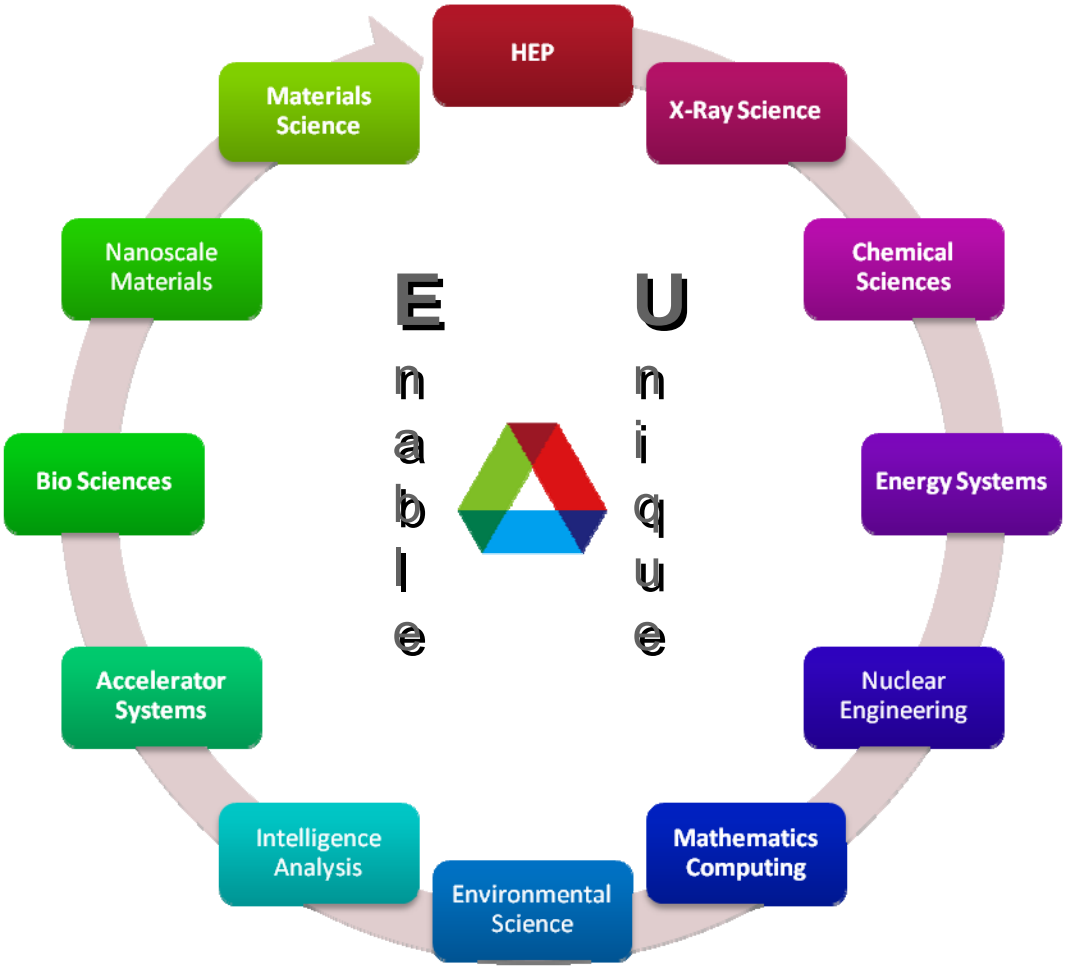
- **The mission and goal for ANL HEP is: *to enable, be unique***



- **Enable the future of High Energy Physics:**
  - Enabling participation in experiments
  - Developing new "technologies" for accelerators to enable new facilities
  - Developing new "technologies" for detectors to enable new experiments
  - Interact with & use expertise in other science divisions (materials science, computing, nano scale) to do this
  - Transfer HEP expertise to other fields
  - Enable guiding future direction of the field (theory)
  - Connections & collaboration with/resource for universities

- **Unique:**
  - Basic development of new directions, tools, sensors, detectors, acceleration methods…… driven by HEP needs & use non-HEP expertise at Argonne

Approach

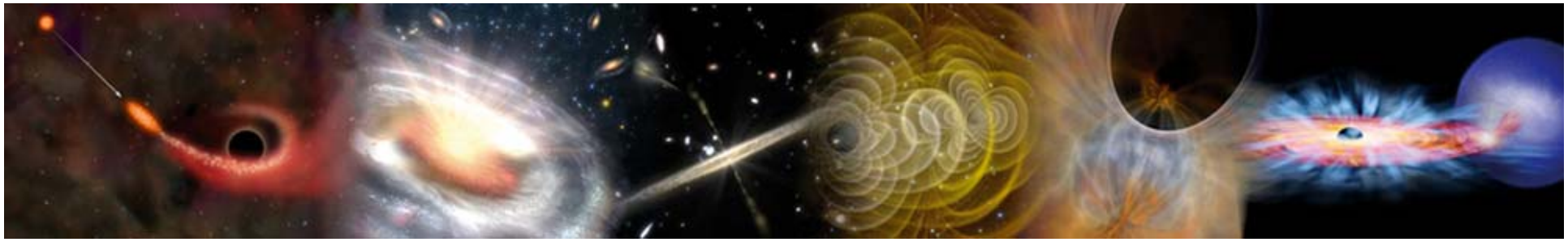


- **"Multi-disciplinary is a really key missing part of society ..... We've gotten so good at getting deep ..... but don't know how to talk, let alone build anything together."**

Interview of 'The Atlantic' with Joi Ito, director of MIT Media Lab, Sept. 13, 2011

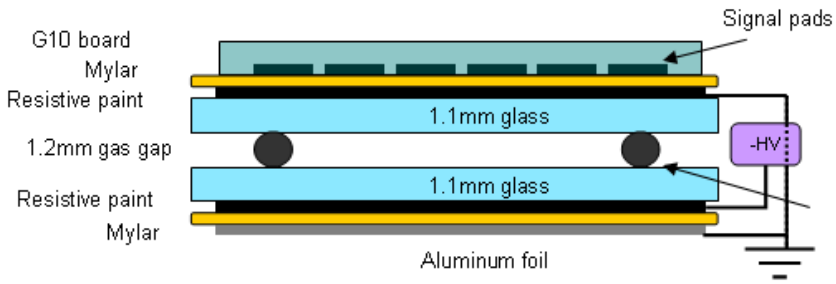
Outline

- Digital Hadron Imaging Calorimetry
- Transition Edge Sensors
- Track Trigger
- Optical Readout
- Large-Area Photo-Detector Development
- Accelerating Cavities
- Facilities
- Concluding remarks



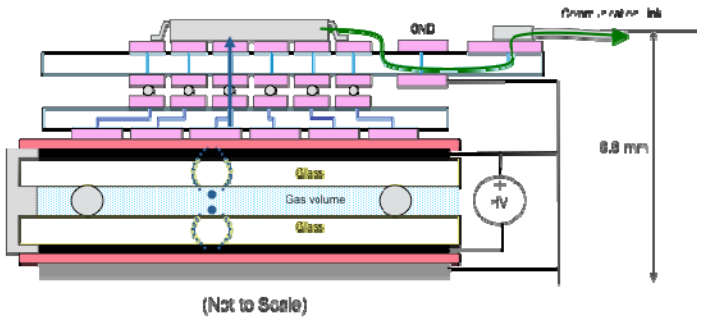
Digital Hadron Calorimetry

- Motivation: improve hadronic energy resolution through the use of imaging calorimetry
- Implementation: glass-based Resistive Plate Chambers with pixelated readout



- Fully designed and constructed at Argonne
- 1 m^3 stack; total # channels = 479,232
  - > ATLAS + CMS calorimeters combined
  - Readout of 1 x 1 cm^2 pads with one threshold (1-bit)
  - 38 + 13 layers with Fe absorber, each ~ 1 x 1 m^2
  - Each layer with 3 RPCs, each 32 x 96 cm^2

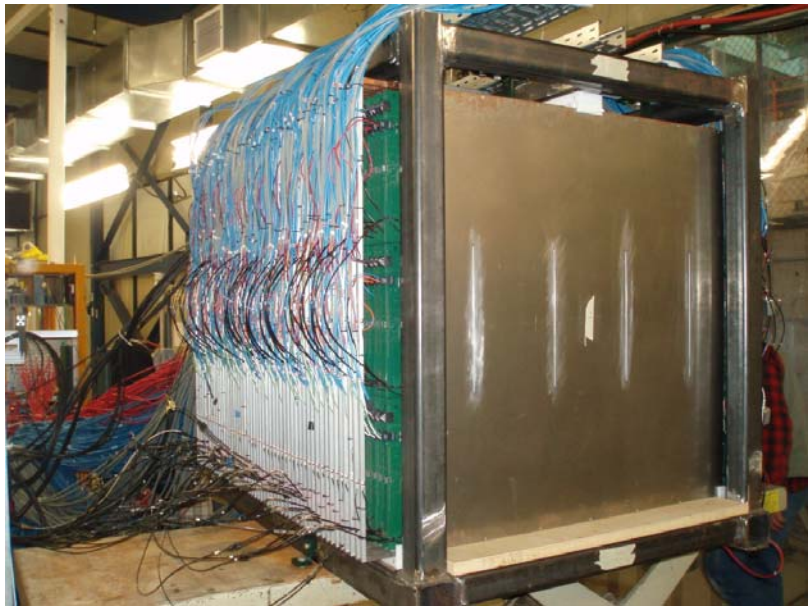
DHCAL Operation



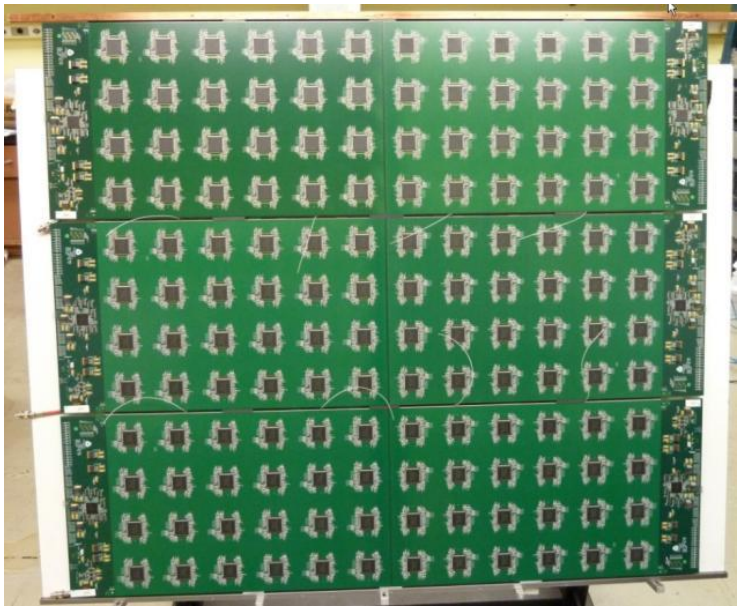
Avalanche in gap

Induced signal on pads

Digitized in Front-End



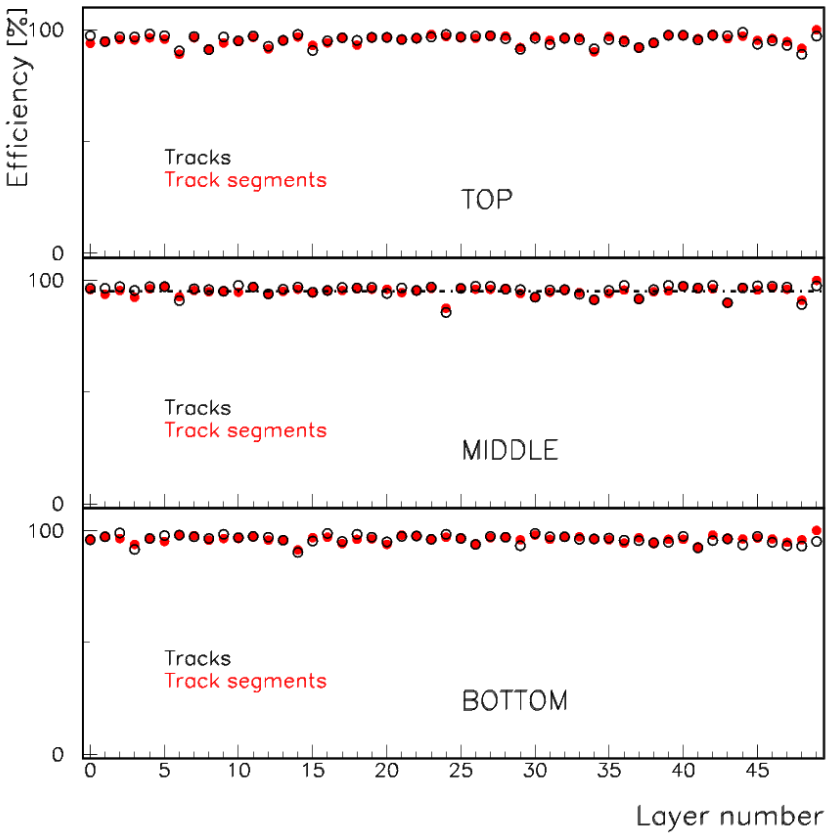
Completed stack



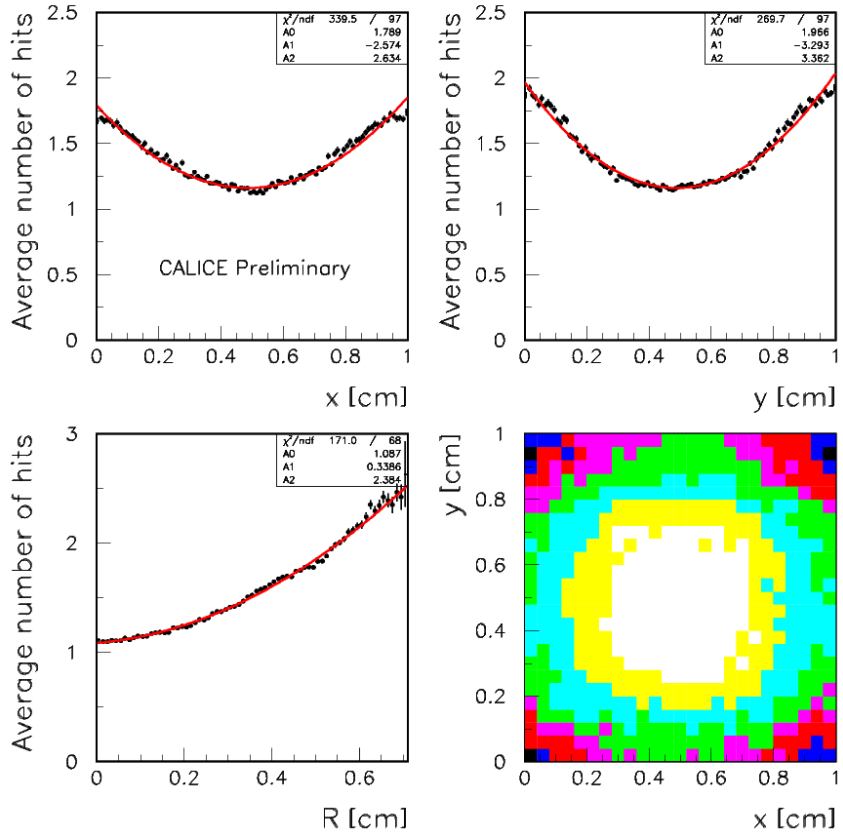
Front face of one layer

DHCAL Performance

DHCAL Run 650265



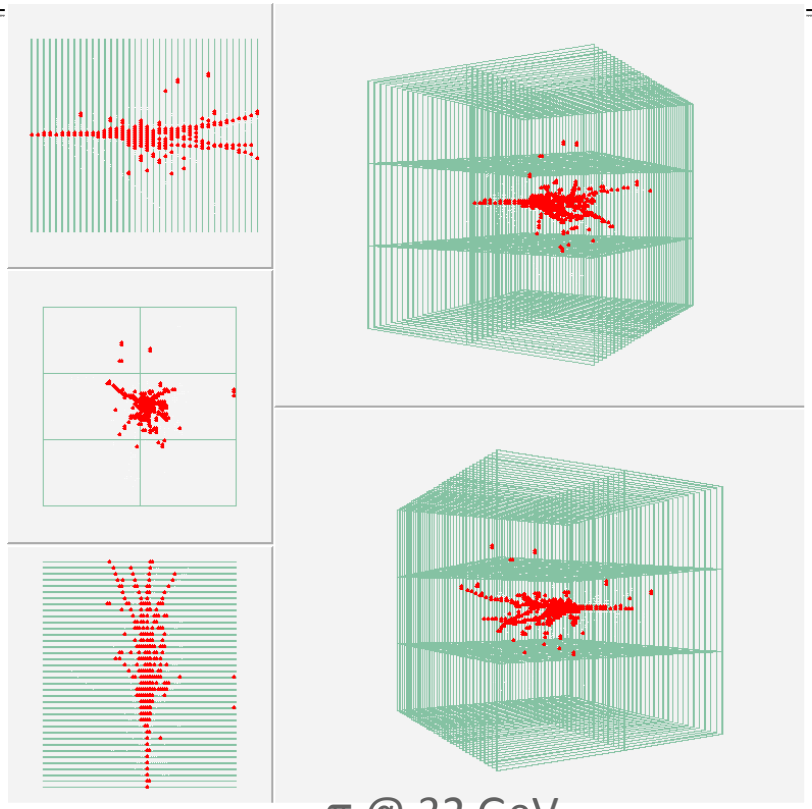
Data



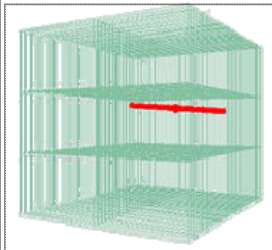
Efficiency = 93.6% in data
93.8% in MC

Multiplicity = 1.563 in data
1.538 in MC

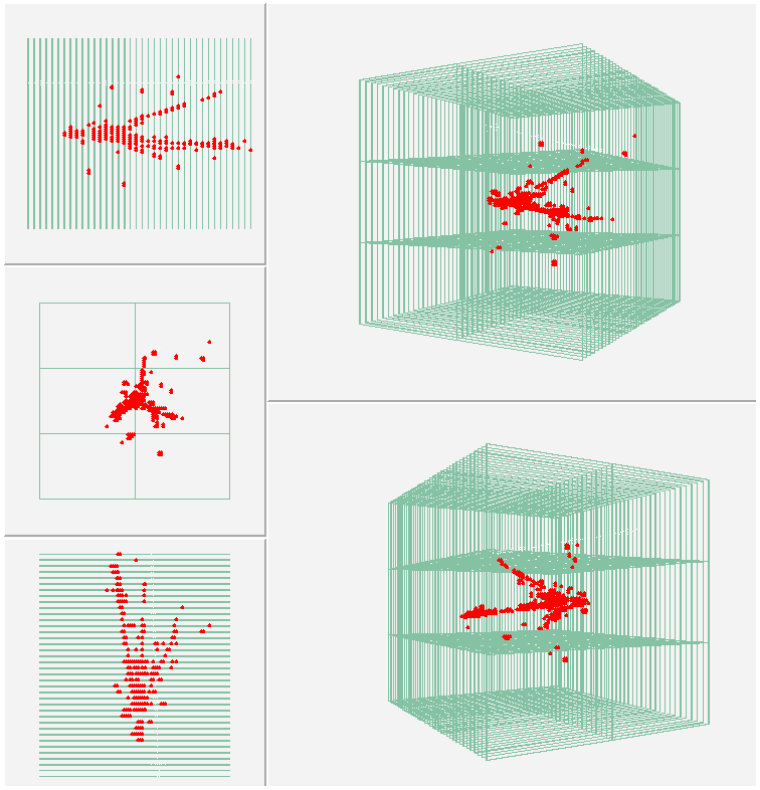
Imaging Calorimetry



π @ 32 GeV



single muon
(no noise!)



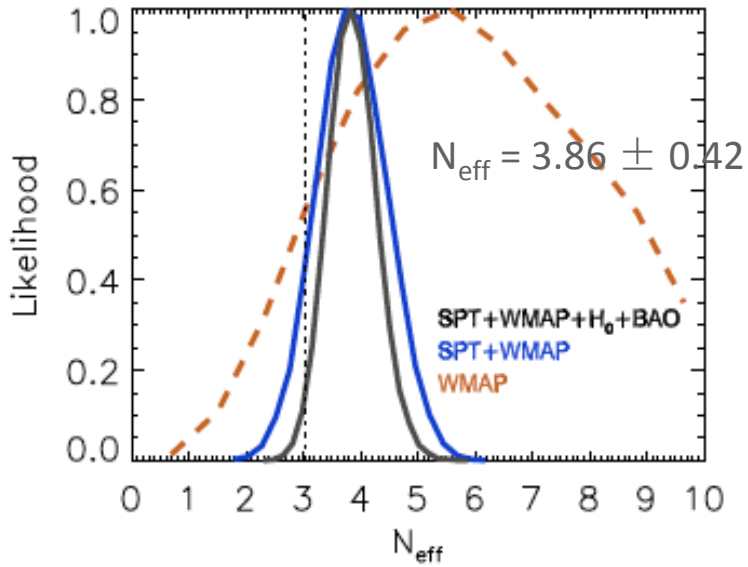
neutral hadron

Truly imaging calorimetry

Cosmic Microwave Background (CMB) Radiation

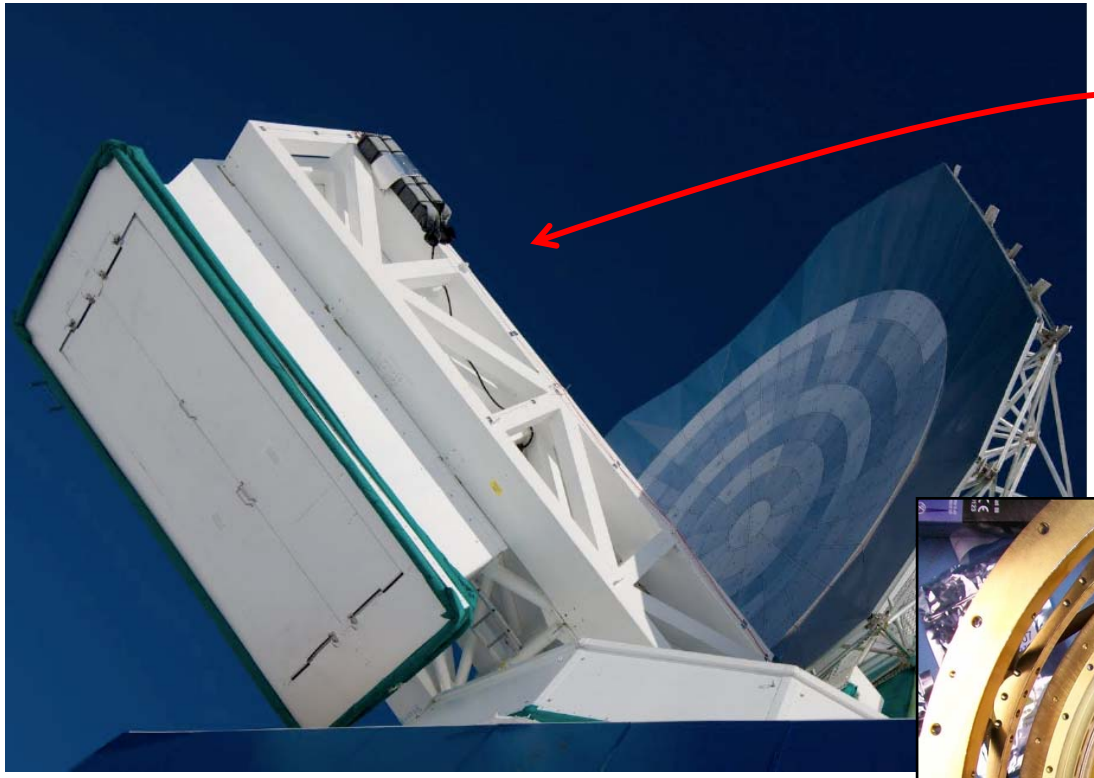
- The South Pole Telescope Polarization (SPTpol) experiments measures CMB radiation and its polarization
- Addresses fundamental physics:
  - Uniquely sensitive to Inflationary physics at GUT-scale
  - Dark Energy: Lensing of CMB polarization sensitive to early DE models
  - Neutrinos: mass and number

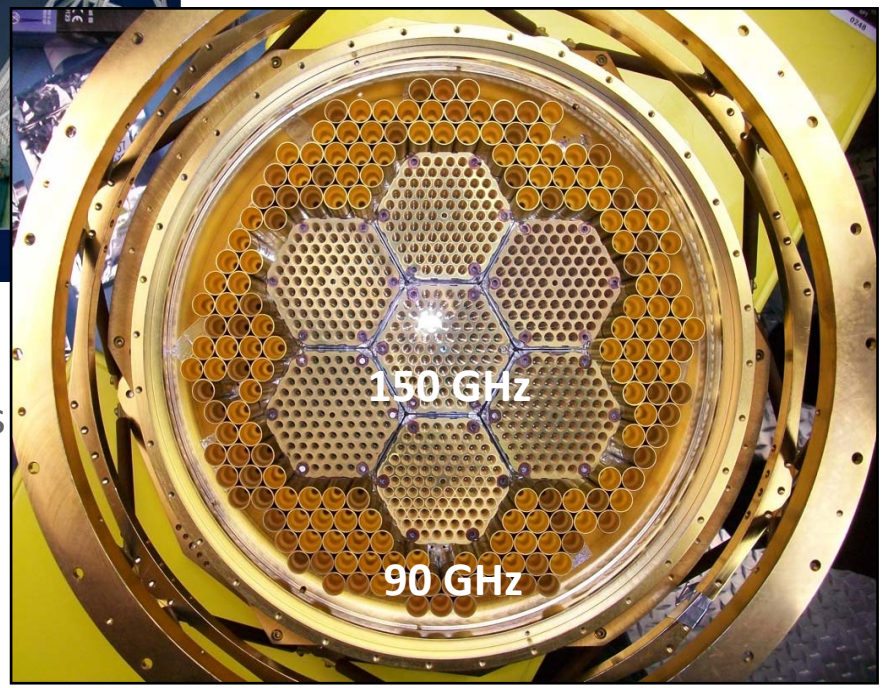
Keisler et al 2011, ApJ, 743, 28



- Measurements are sensitivity limited
- New detector architecture
  - Array fabrication and mounting
  - Increase detector optical bandwidth (more photons per pixel)
  - More pixels

South Pole Telescope

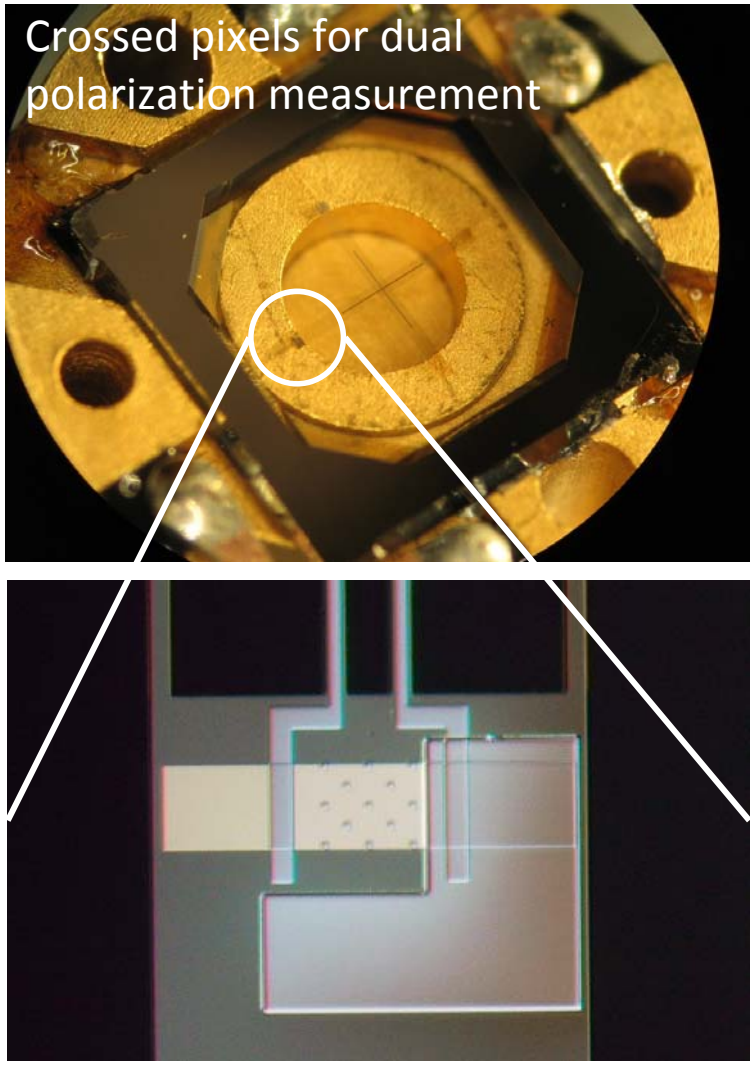




The outer ring of superconducting TES detectors with band pass centered at 90 GHz developed from scratch at Argonne (inner sensors from NIST)

Transition Edge Sensors

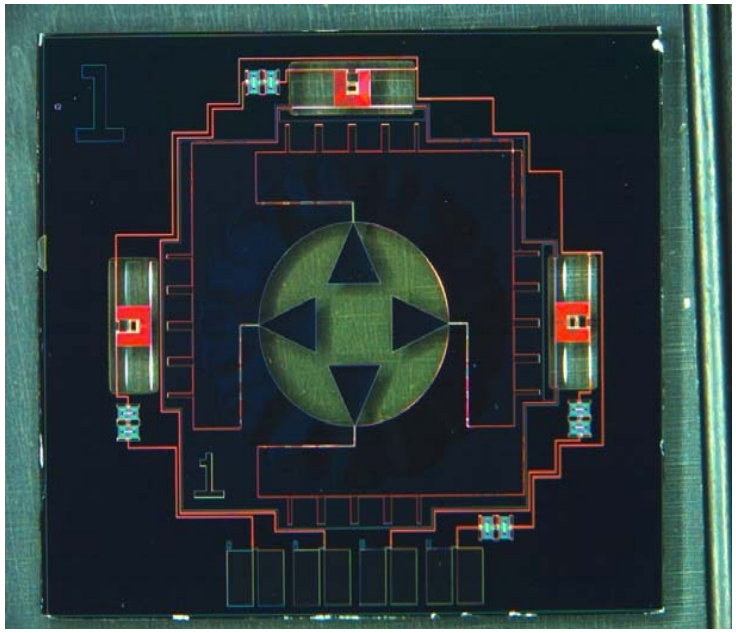
Materials Science Deposition System for superconducting detectors

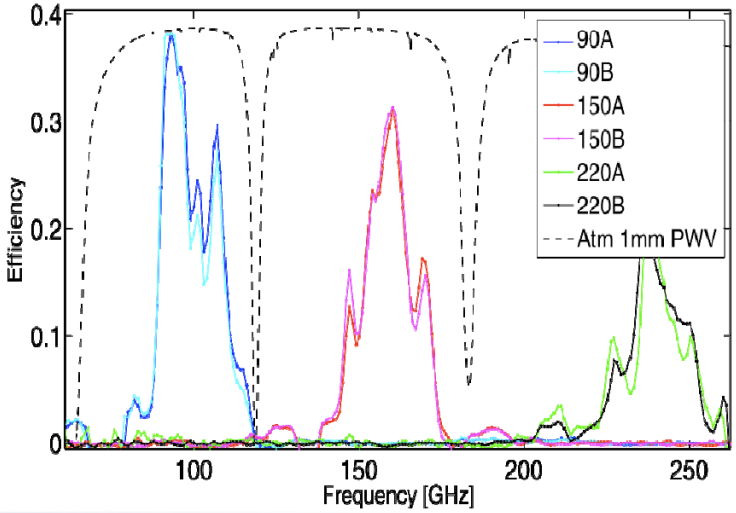


- Measure change in resistance of TES due to absorbed photon flux
- Superconducting structures engineer the transition shape
  - 8 μm × 1186 μm PdAu dipole on 200 μm × 2100 μm SiN
- Magnetic materials to regulate the thermal bandwidth

Next Generation Transition Edge Sensors

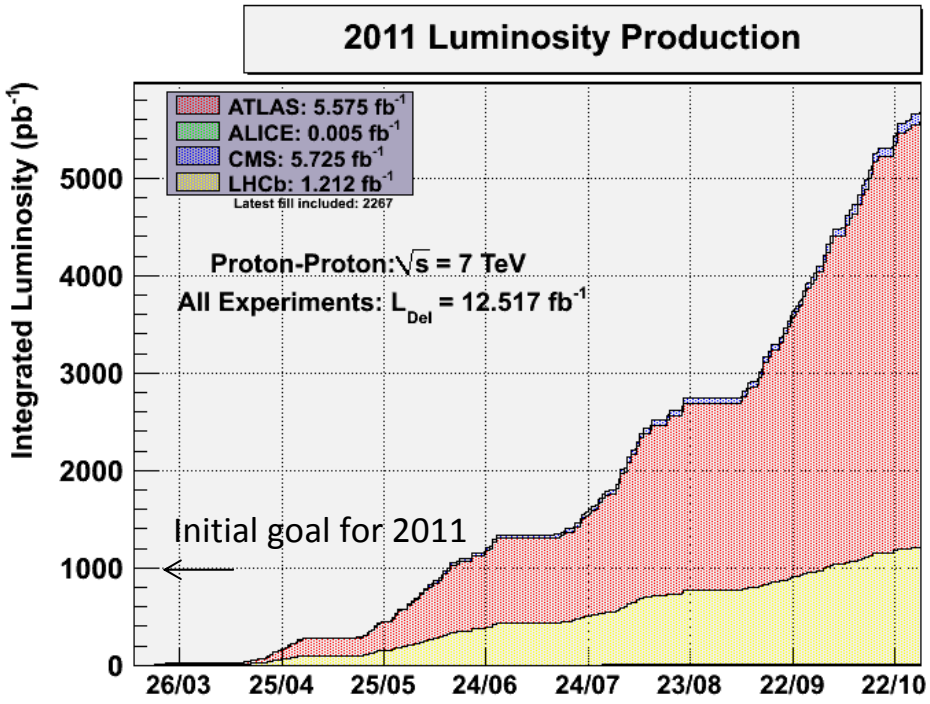
- Development of multi-chroic pixels
- Superconducting microstrips offer the potential to utilize in-line filters to define the detector optical band pass which enables building multi-chroic pixels.
- Current multi-chroic devices have very non-uniform frequency response
- Use Atomic Layer Deposition of super-conducting microstrip lines to improve uniformity
- Trade-off between optical throughput and superconducting microstrip loss.



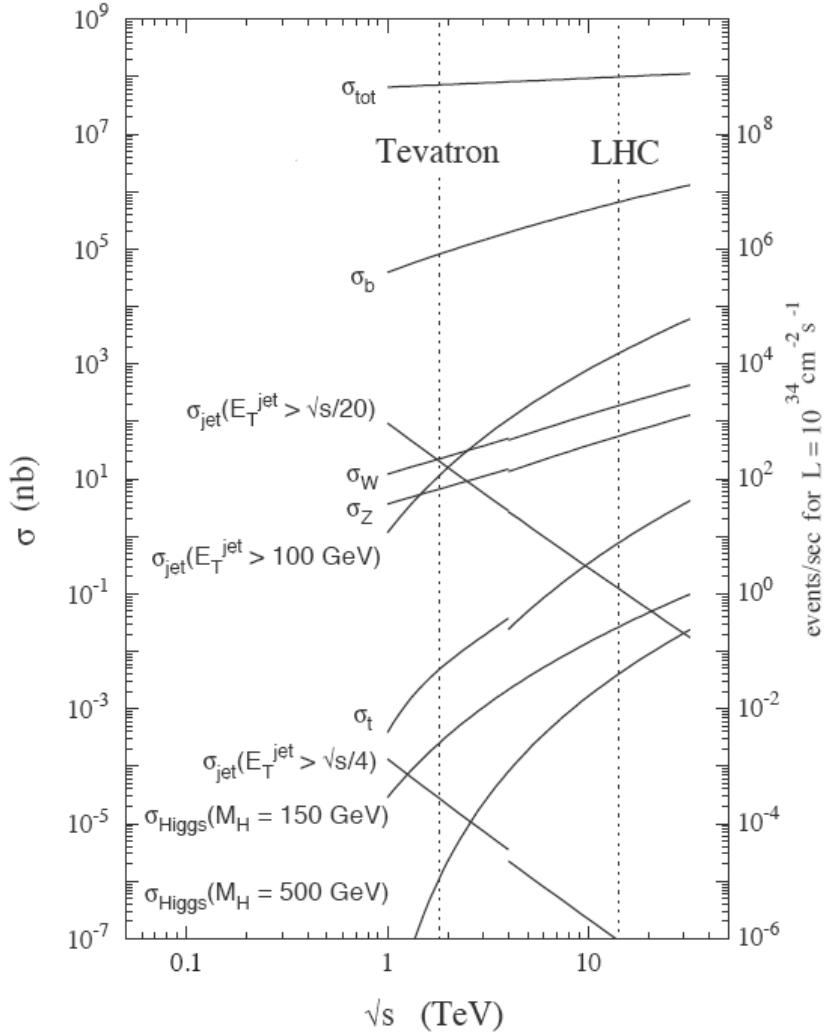


Large Hadron Collider (LHC)

- The challenge:



LHCC Meeting, Dec. 7, 2011

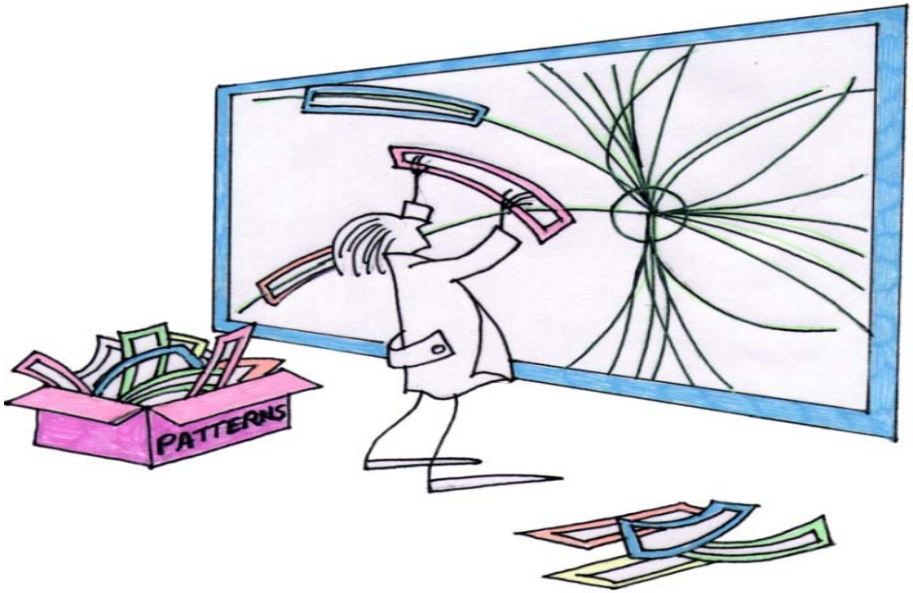


- The answer: Trigger !

ATLAS Fast TracK Trigger

See talk by Ted Liu

- Fast TracK Trigger (FTK): hardware processor that completes GLOBAL track reconstruction by the beginning of level-2 processing
  - Rapid rejection of the background that dominates the level-1 trigger rate.
  - Frees up the L2 farm to carry out the needed sophisticated event selection algorithms.
- FTK based on fast pattern recognition
  - Patterns of events of interest stored in Associative Memory
  - Compare hits of events to stored data bank



The problem:

- Current generation of experiments using Associative Memory (AM) for Pattern Recognition
  - 6M patterns stored, 5000 patterns per AM Chip (180 nm)
  - About 100 bits / pattern
- Need 1B patterns for sLHC
  - Event hit pattern evaluated every 25 ns !

Vertically Integrated Silicon Devices (3d-Si)

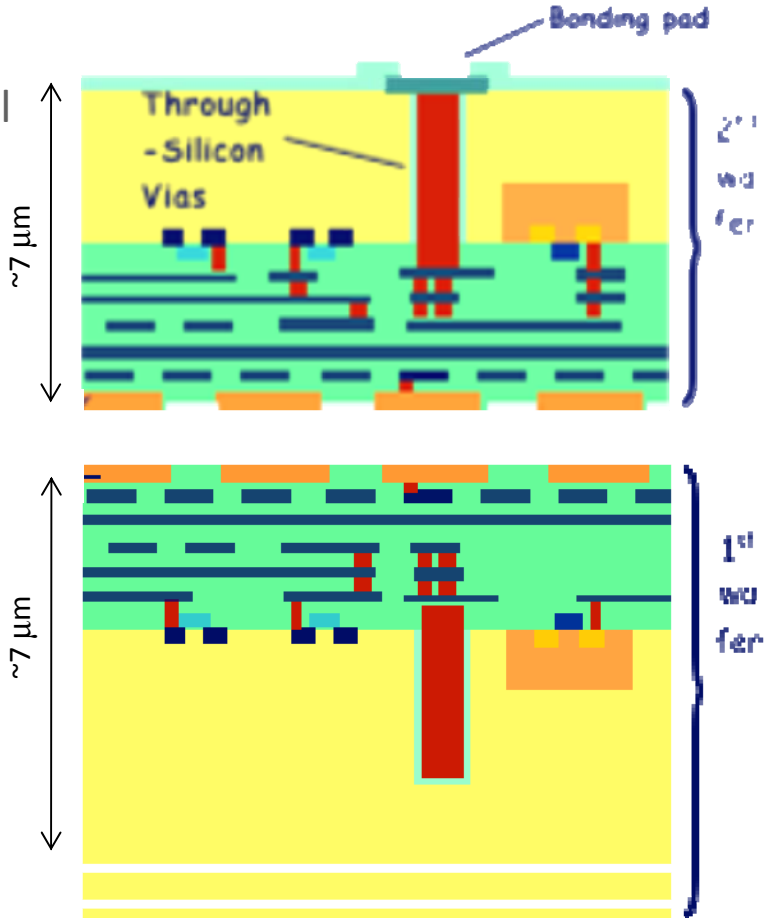
- Vertical integration of thinned and bonded silicon layers with vertical interconnects – Through Silicon Via (TSV) – between the IC layers

- Individually processed wafers, each optimized for its function, thinned and bonded. Electrical contacts provided by TSVs.

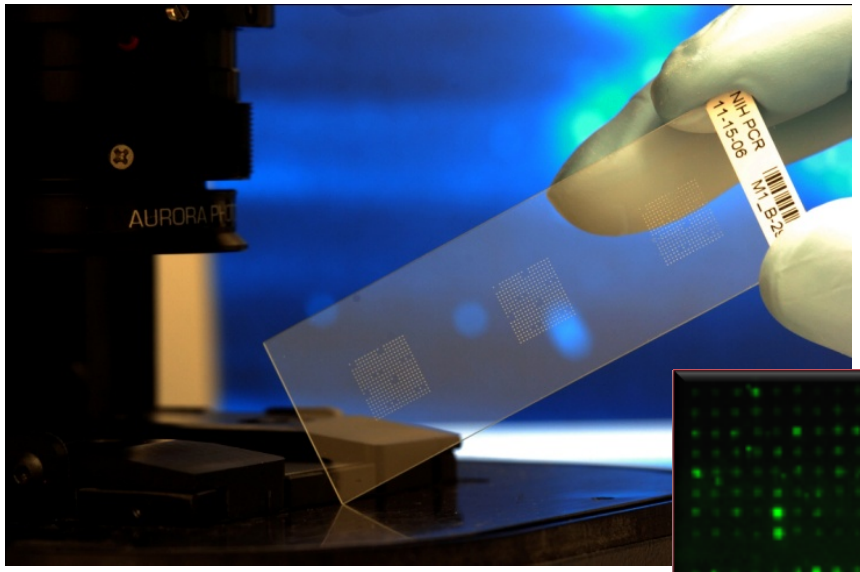
- Diameter of TSV ~1.5 µm
  Pitch of TSV ~ 4 µm

- Advantages
  - Fully active sensor area
  - Increased circuit density due to multiple tiers of electronics
  - Local data processing
  - Reduce Power, R, L, C for higher speed

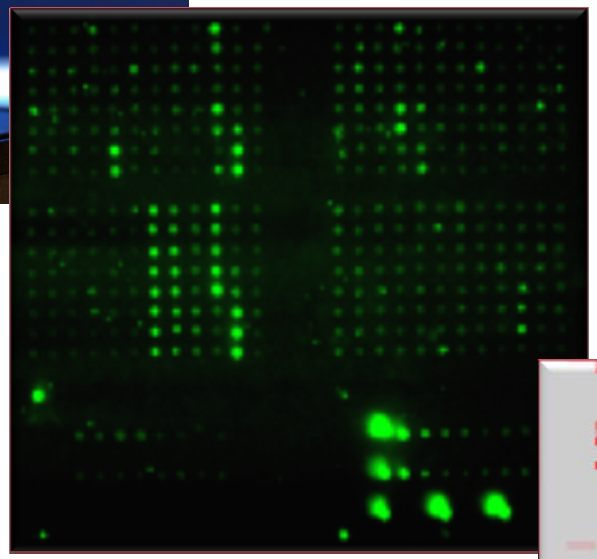
- Made strategic decision to explore 3D-SI, with Fermilab, for LHC upgrades and pattern recognition in general



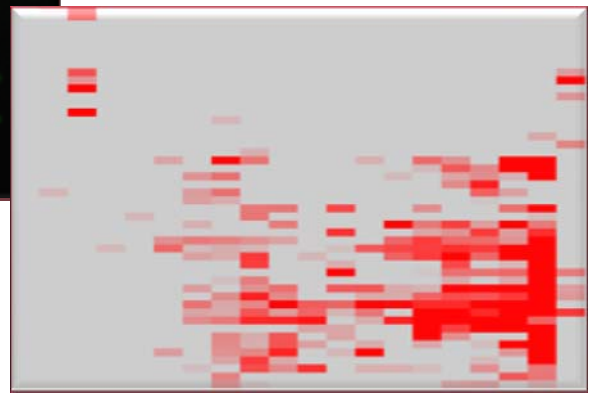
Identifying Signatures in Biosciences



Sample



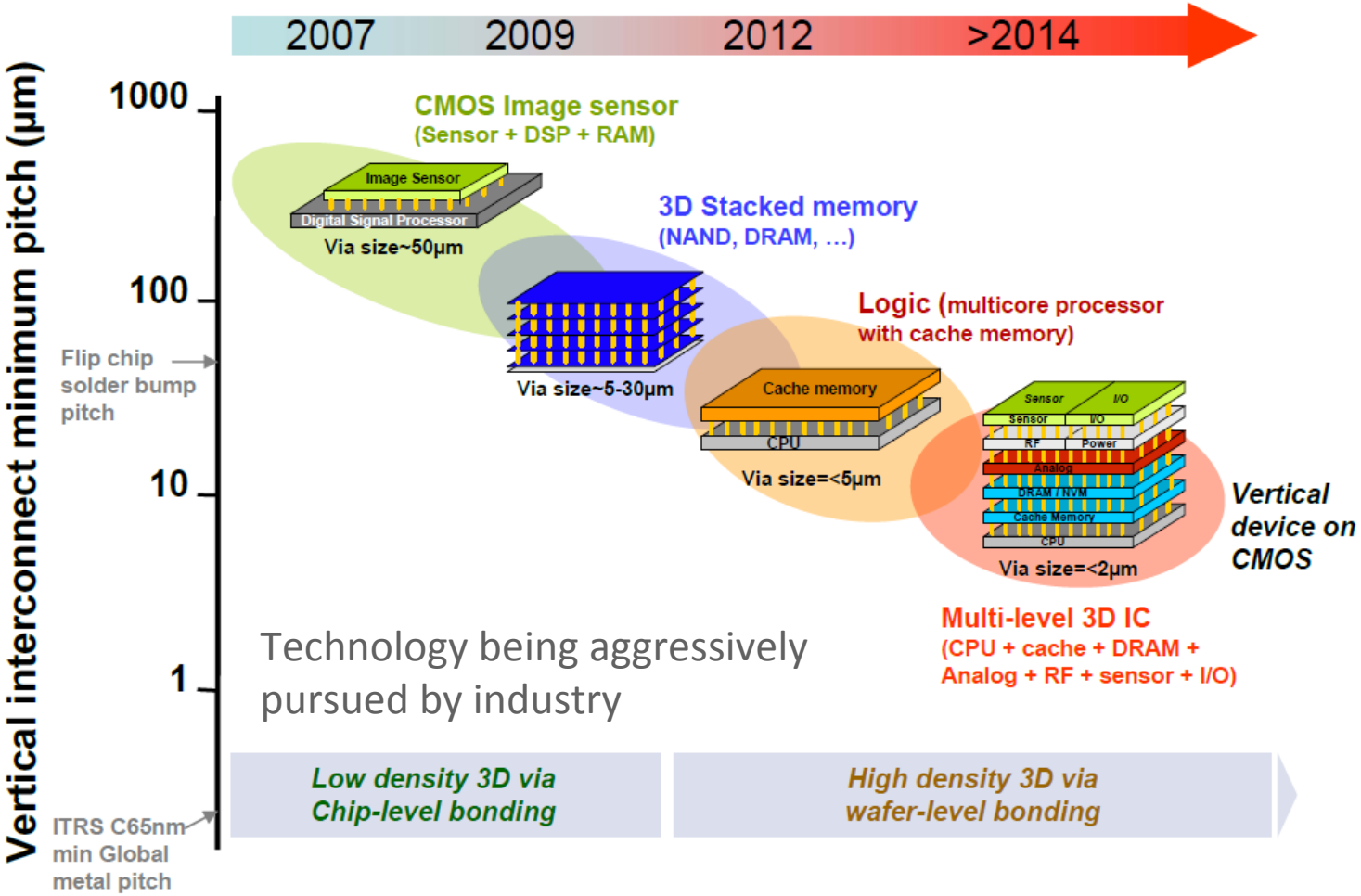
Interrogation



Pattern

Pattern Recognition is a universal problem

Industry Roadmap

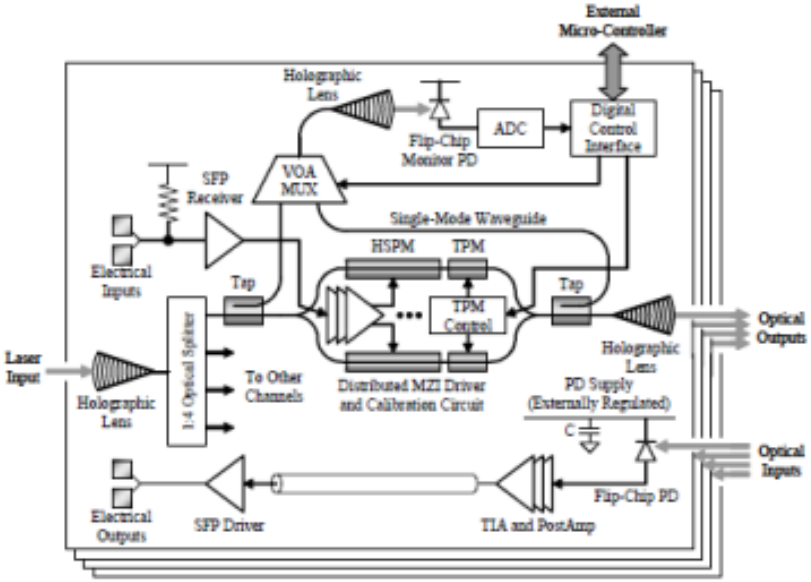


EMC-3D European Technical Symposium
Minatec June 29th, 2007

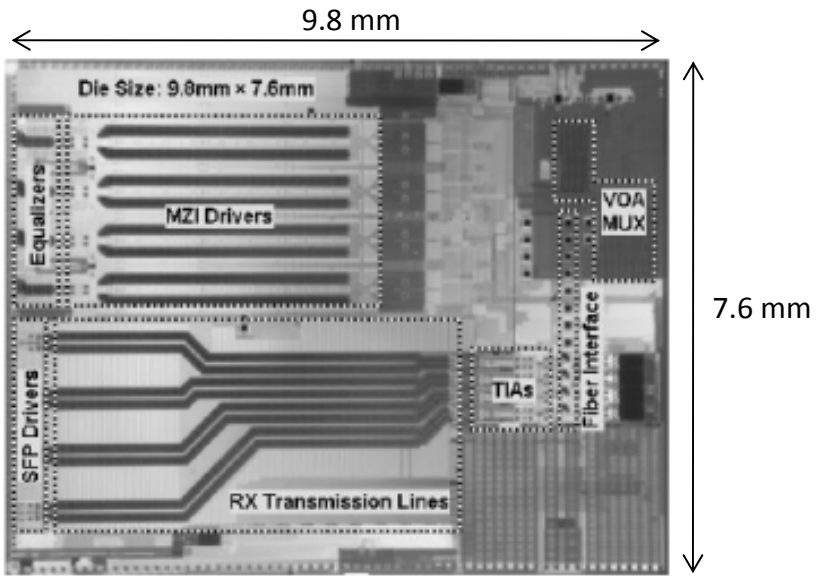
Optical Data Acquisition

- The data volume of experiments will increase by an order of magnitude !

- Current experiments use modulated lasers (including VCSEL) to output the data
- Initiated an R&D program on using CMOS Photonics:
  - Hybrid devices in which the optical and electronic components are integrated onto a single silicon microchip; Many electrical/optical blocks are available



Block diagram



Picture of actual device

Commercial 130nm CMOS SOI integrated 4x10 Gb/s single chip MZI modulator-based transceiver

Technology Comparison

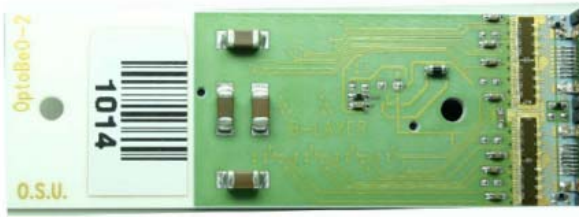
	Versatile Links (target)	SNAP 12	SOI based 40 G	InP Modulators	LiNbO3 Modulator
Technology	Modulated laser based (eg. VCSEL)		Modulator based		
Bandwidth (Gb/s)	5	5	14	80	40
Bit Error Rate (BER)	?	10^{-12}	10^{-18}	10^{-18}	10^{-18}
Rad-hardness at		Some SEU at ~10^{10} p/cm^2	No SEU at ~10^{12} p/cm^2 Theoretically LiNbO3 & InP should be very rad-hard		
Fiber Type	Multi Mode		Single Mode		
Reach (m)	100	100	4000	10000	10000
Power (mW/Gb/s)	100	53	8	<50*	<50*
Density (mm^2/Gb/s)	100	33	4	<50*	>1000*
Cost ($/Gb/s)		37	10	~100*	~100*
Reliability	VCSELS have many failure mechanisms, complex, all the parameters on the edge		No known failure mechanisms, very simple, 300M accumulated hours of operation without a single internal failure		

- For single mode fiber the limit is ~80Tb/s/km for BER 10^{-18}; most common fiber type in the world (@1490-1560 nm, single-mode, > 4 km, 28 Gb/s with BER of 10^{-18})

HEP Implementation

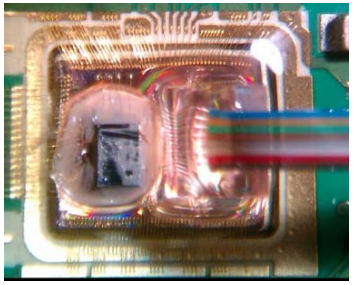
- Goals are to adapt the commercial off-the-shelf electronics to particle physics applications and extend the current technology

Atlas TileCal

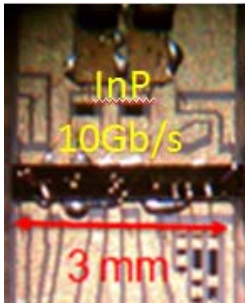


7.2 x 2 cm^2
12 x 80 Mb/s

Existing



9.8 x 7.6 mm^2
4 x 10 Gb/s

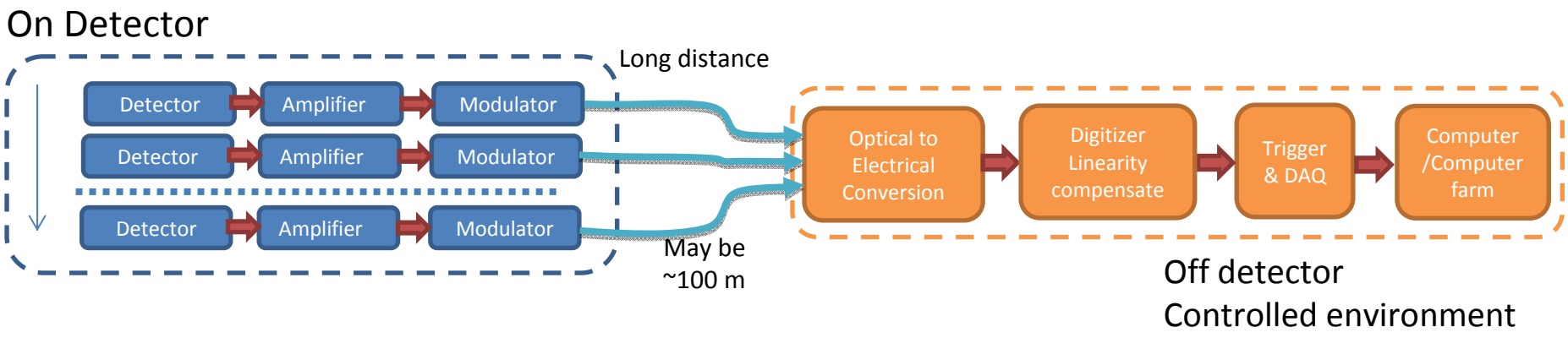


3 x .25 mm^2
10-60 Gb/s

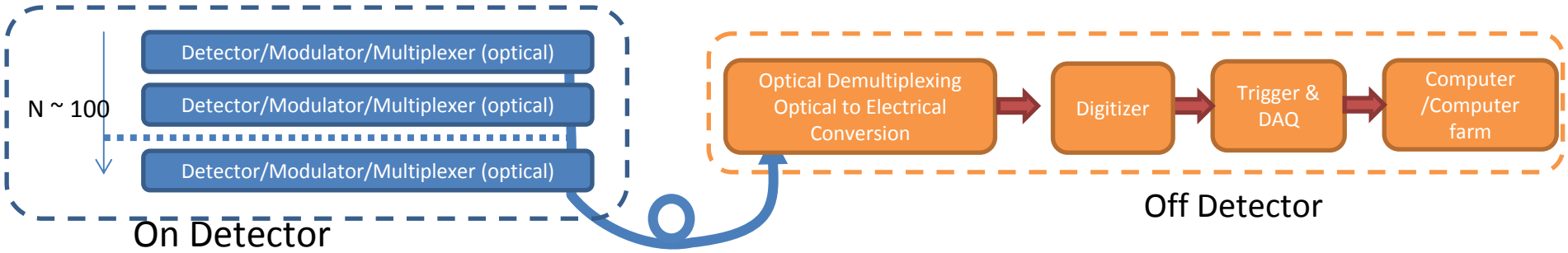
Bandwidth	Studied devices up to 10 Gb/s
Reliability	Measured BER <10^{-16} (with jitter analysis prediction <10^{-18})
Radiation hardness	Tested SEE at 10Gb/s for ~10^{12} protons/cm^2 and TID of ~64 kRad

Long-term HEP Implementation

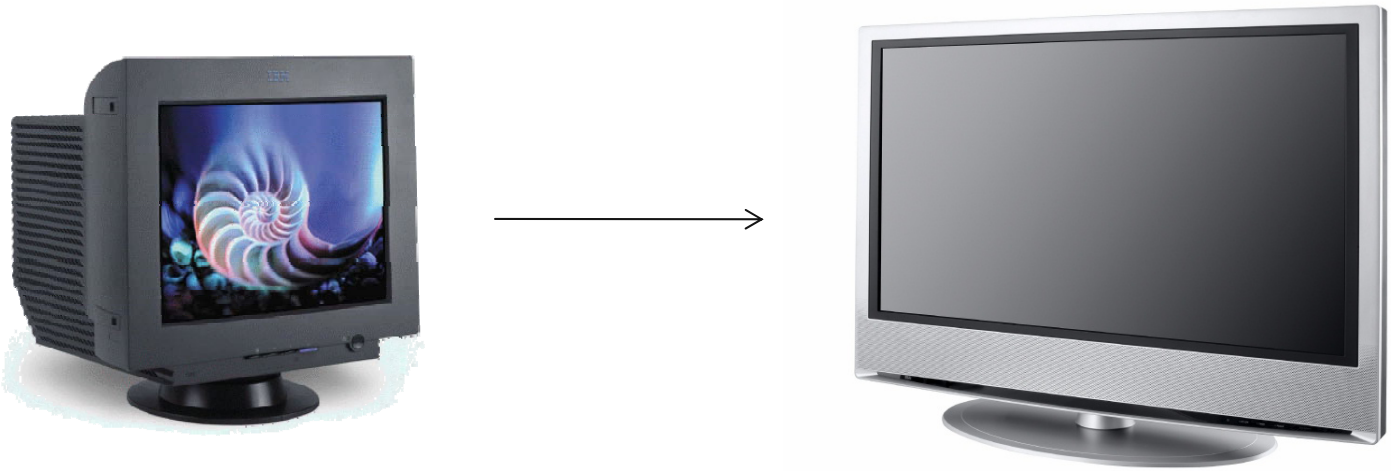
- Integration of modulators directly into the front-end electronics



- With very high data transfer modulators, multiplex data



Large Area Picosecond Photo-Detectors



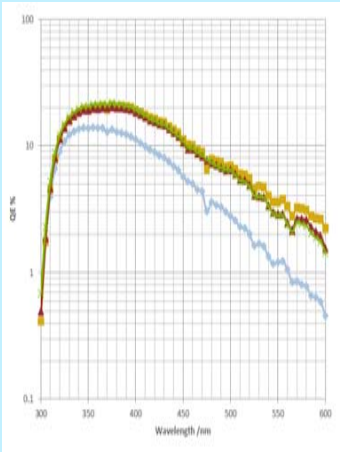
- Develop cost-effective large-area compact photodetectors by bringing new technologies from other science disciplines into the development of the detector, while improving its performance

Large-Area Photodetectors

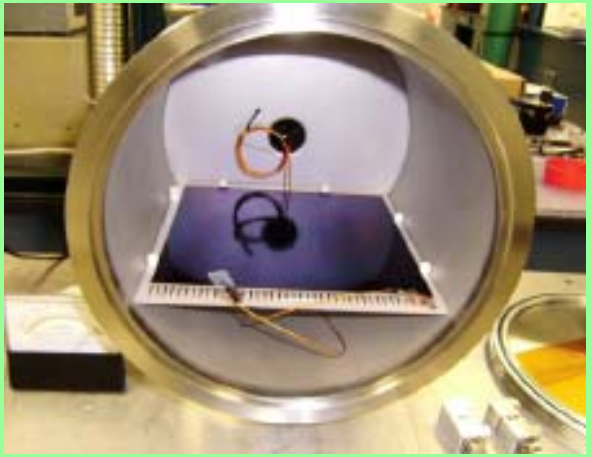
See talk by Henry Frisch

Four Main Areas of LAPPD

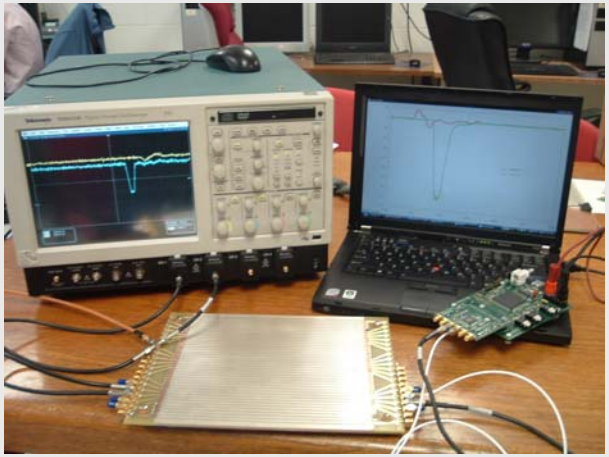
Photocathode



Multi-Channel Plate



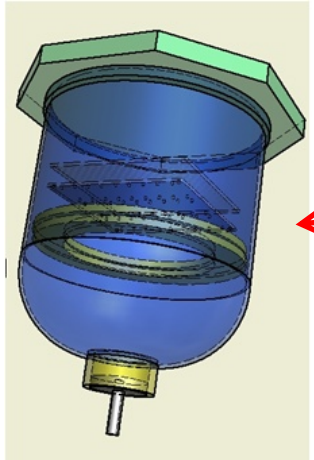
Readout

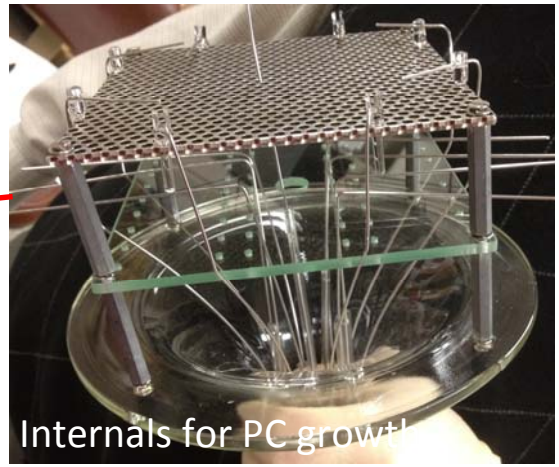


Hermetic Package

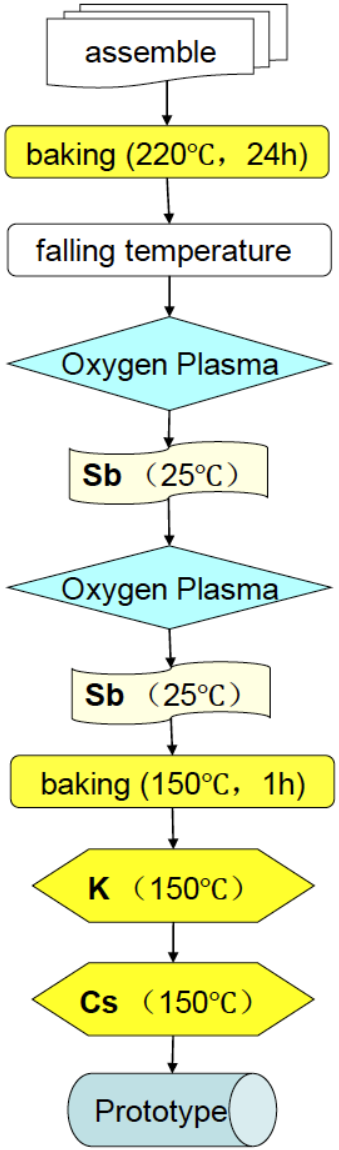
LAPPD Deconstructed: Photocathode

- Glass vessel design for photocathode growth





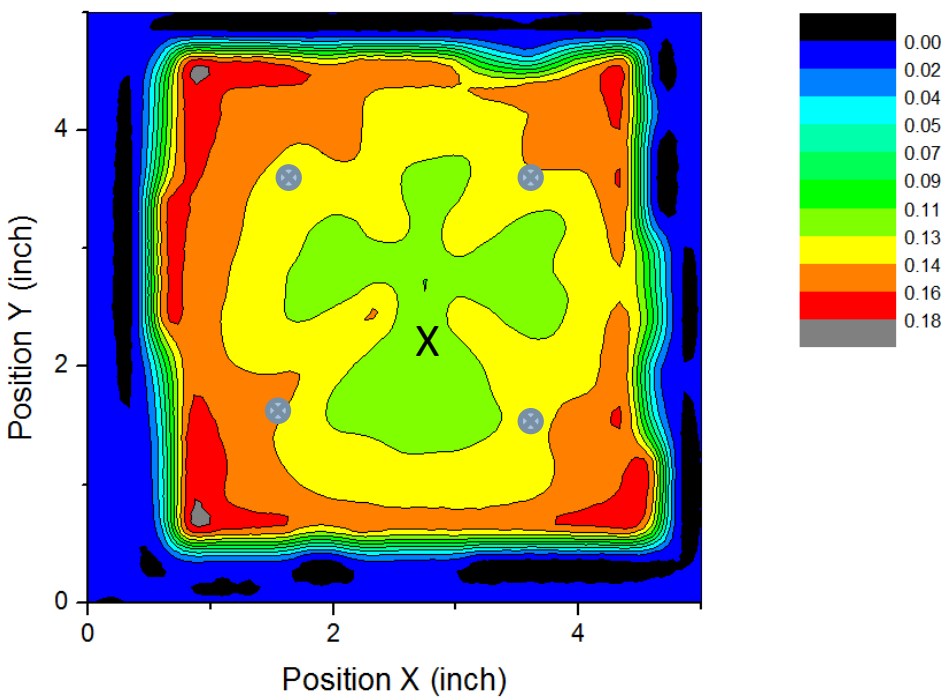
- Grown 6 4”x4” bi-alkali photocathodes following recipe as indicated

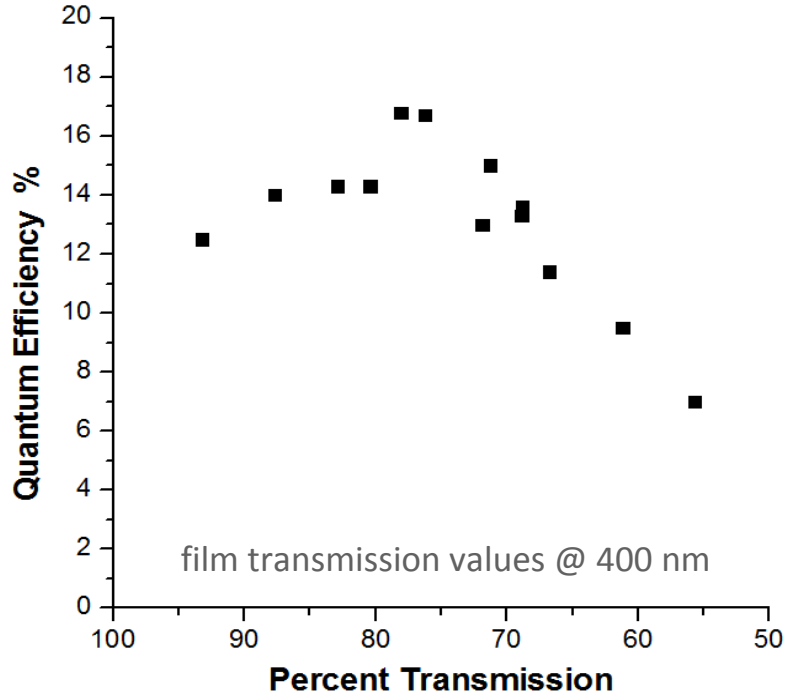


LAPPD Deconstructed: Photocathode

- Correlation between QE and Sb thickness

  4 Sb beads

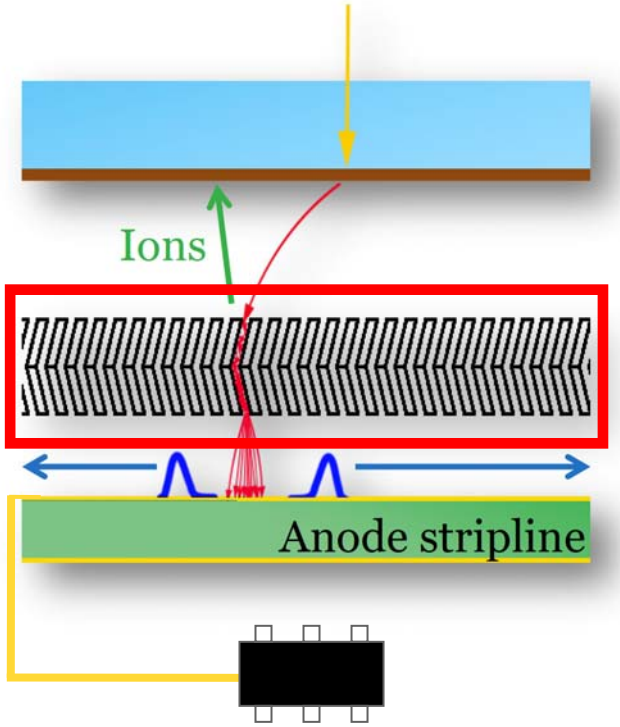


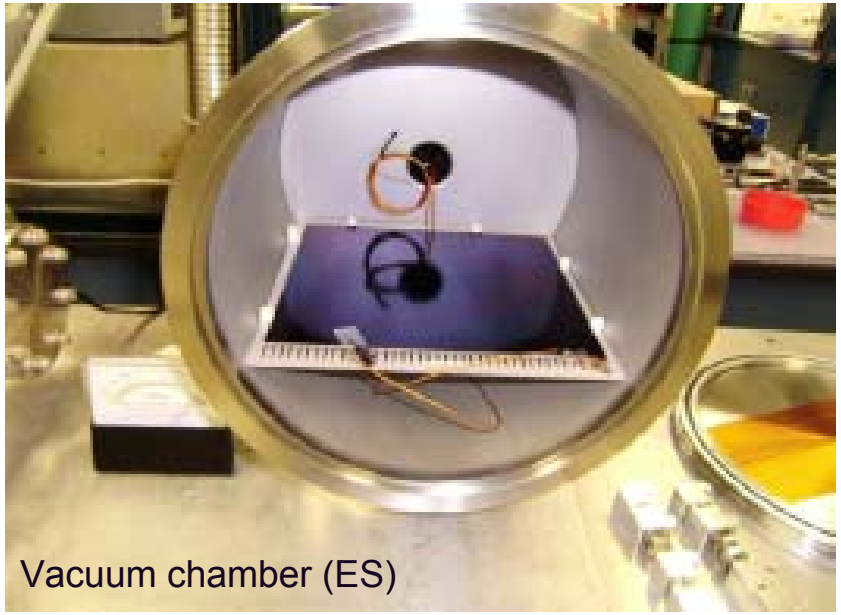


- Relation between film transmission (@400 nm) and KCs-Sb cathode QE
- The highest QE is around 78% Sb transmission (400nm beam)
- Start of understanding of the fundamentals of photocathode QE

LAPPD Deconstructed

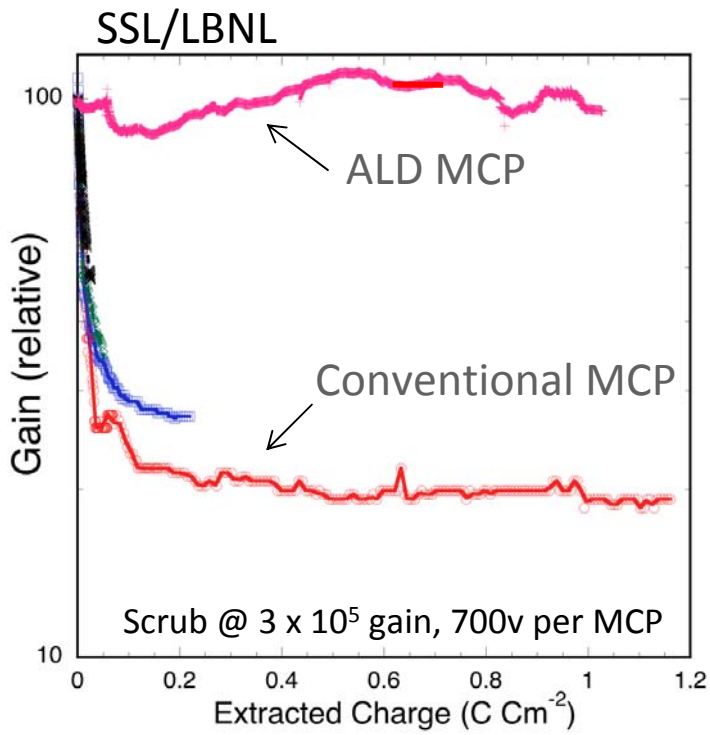
2. Micro-Channel Plates
   - Amplification of signal: two plates with tiny pores, held at high potential difference. Use Atomic Layer Deposition for emissive material on inert substrates to create avalanche

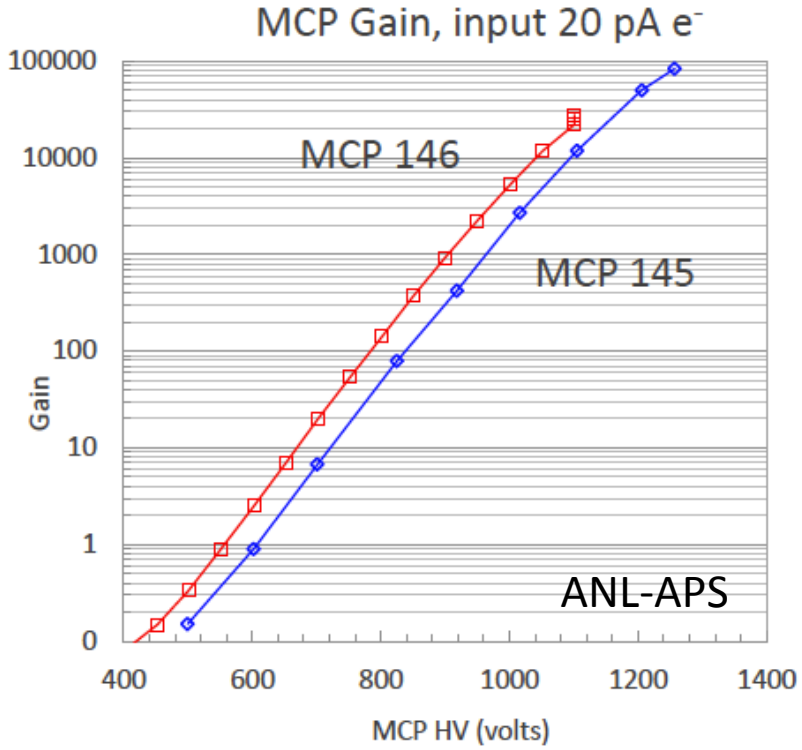




Successful Atomic Layer Deposition of 8”x8” glass substrates
ALD process proven to be very successful!

Micro Channel Plate Performance



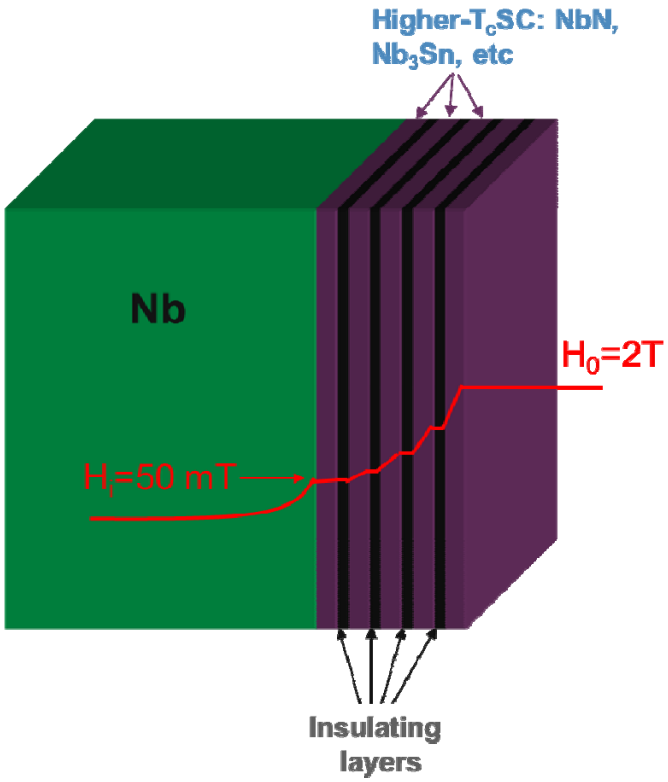


- **Incredibly stable performance at very large integrated charges**
  - Scrub carried out at Space Science Lab (LBNL)
  - Background rate of 0.0845 events cm^{-2} sec^{-1} at 7×10^6 gain, 1050 V bias on each MCP
- **MCP pair gain of > 10^7 with > 10^5 in a single plate**
  - Attractive for cost/simplicity

Superconductor Research

- Goal is to develop SRF cavities E_{max} ~ 70 MV/m and Q > 10^{10} at T > 4.2 K

- Lower Q and E_{max} caused by magnetic impurities
  - Cause residual surface resistance and are correlated with cavity "hot spots"
  - Increase both by getting rid of the oxides => cleaner surface



- ALD coating and post UHV annealing creates a clean interface and suppresses impurities as tested on Nb coupons

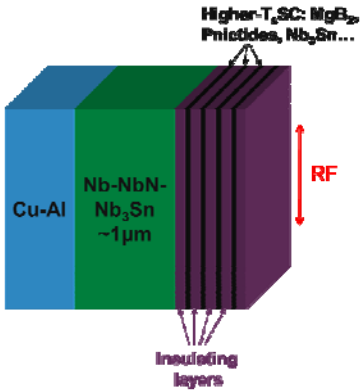
- Established the basis for building new cavity layered structures that allow transformationally higher gradients

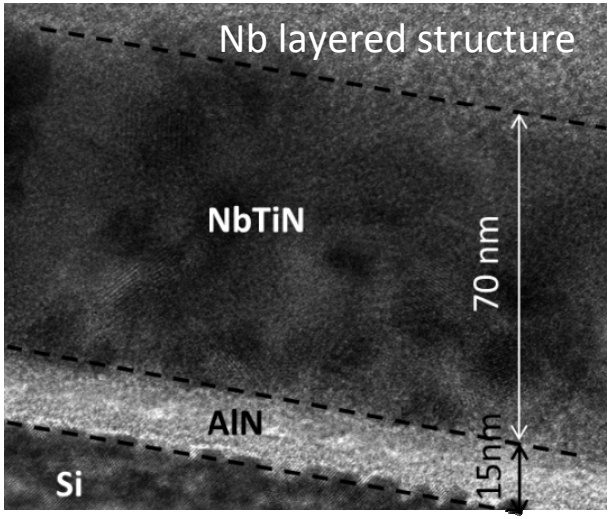
M. Kharitonov, Th. Proslier, accepted to PRB (2012)
Th. Proslier, J. Zasadzinski accepted to PRB (2012)
J. Zasadzinski, Th. Proslier accepted to APL (2012)
Th. Proslier, M. Kharitonov, submitted to PRL (2012)

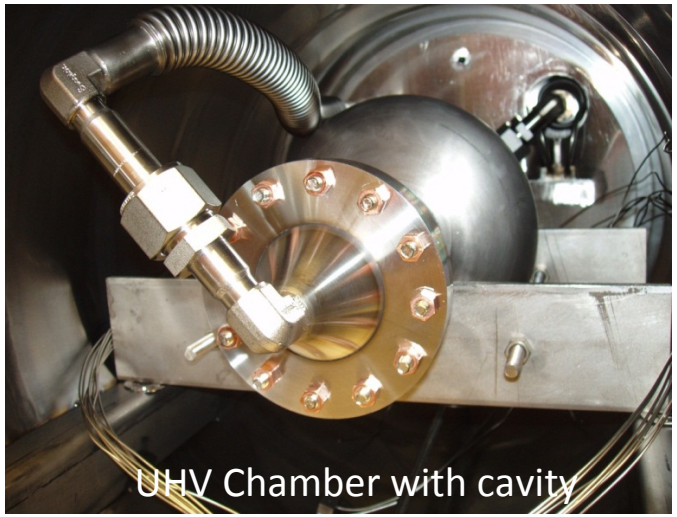
Superconductors through ALD

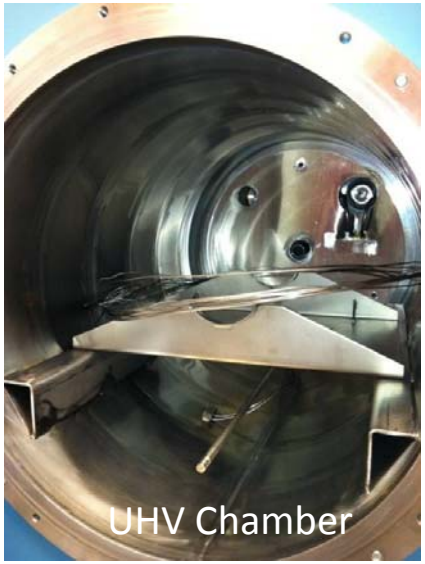
- Able to synthesize better superconductors than Niobium:
  - NbTiN with new ALD chemistry is very pure (<0.05%)
  - NbTiN Tc= 14K for 60 nm thick film (bulk=16K)

- Multilayer structure:
  Aluminum Nitride (AlN) + NbTiN
  works perfectly:
  (15 nm AlN/ 70 nm NbTiN) x n



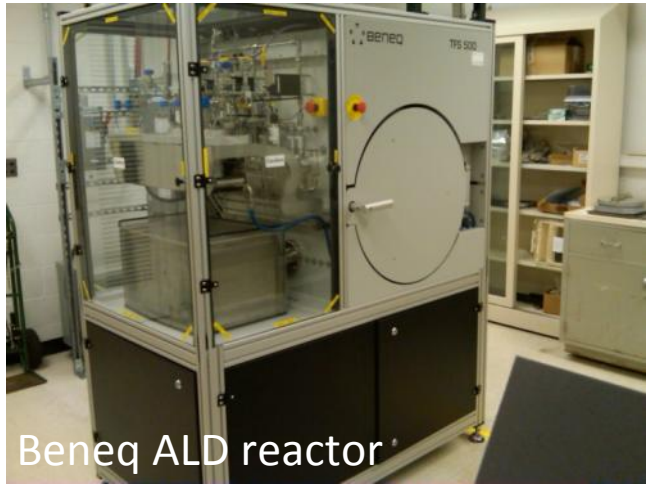






Facilities at Argonne

- Atomic Layer Deposition Reactor
  - MCP functionalization for LAPPD
- Plasma enhanced Atomic Layer Deposition System
- Large Assembly Facilities
- Photocathode Growth Facility



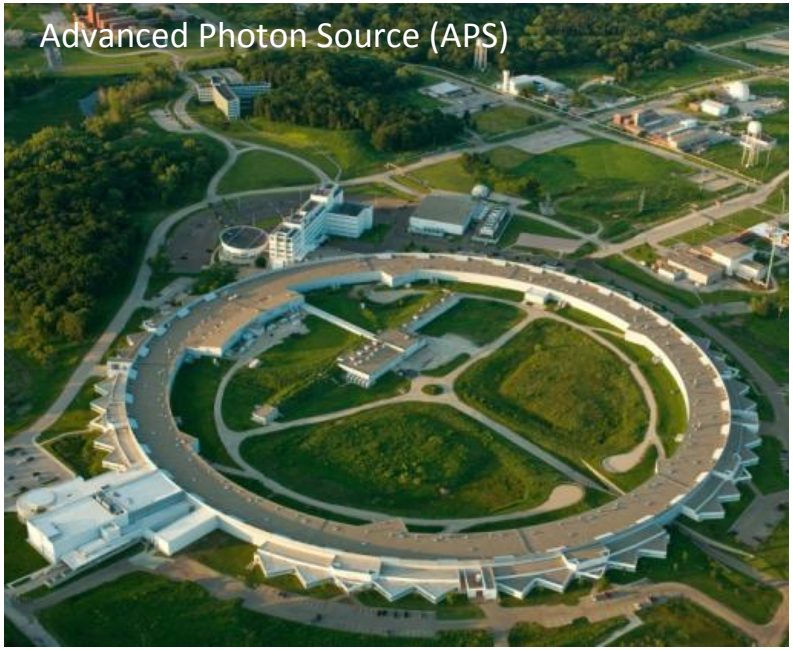
Beneq ALD reactor

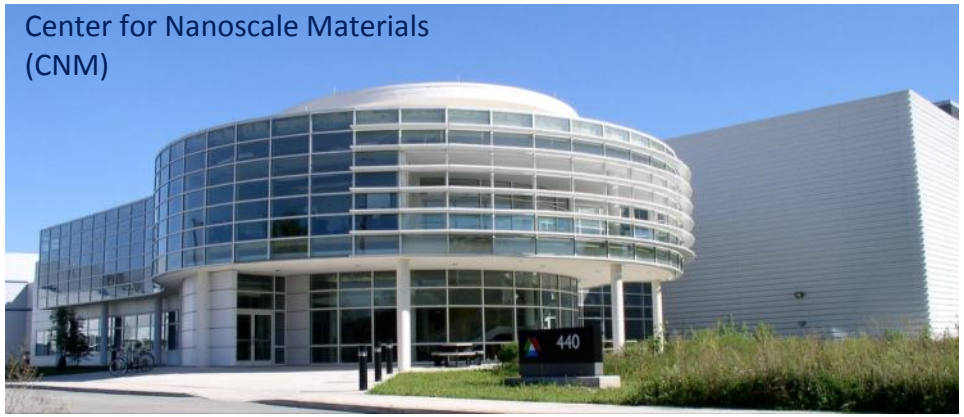
Large construction facility

Photocathode growth

Facilities at Argonne

- Advanced Photon Source (APS)
  - 35 sectors, 3-100 keV photons
- Center for Nanoscale Materials (CNM)
  - Nano-scale lithography
  - Etching
  - …
- Deposition of superconducting materials in Materials Science Division





Summary

Project	Impact	Motivation
LAPPD	Transformational in HEP, medical imaging, security ...	Non-cryogenic, large volume tracking neutrino detectors, sub-psec timing for colliders, low-dose PET, security scanners, ...
ATLAS FTK	Crucial for physics	At the heart of the physics program Exploring involvement in Phase II
TES/MK ID	Understanding the dawn of time	Move towards monolithic arrays Addresses a most fundamental science question
DHCAL	True imaging calorimetry	Furthest advanced of all ILC calorimetry Continued R&D; Possible applications for LHC upgrades
Optical DAQ	Required for upgrades	Addresses data volume, integrity and mass budget; Applying advances from other fields

- Development projects that bring technologies from different science disciplines together to target fundamental physics questions.

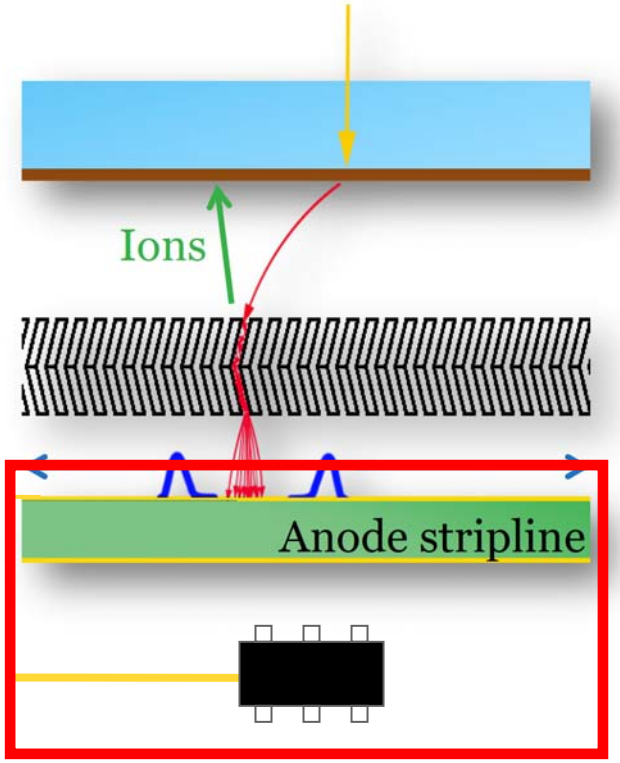
Conclusion

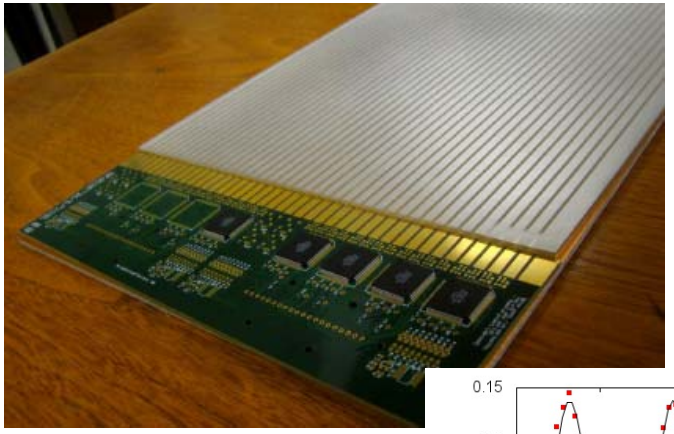
- After yesterday's visit to the IHEP laboratories can only conclude that there is a lot of room for strong collaborative efforts !

谢 谢 !

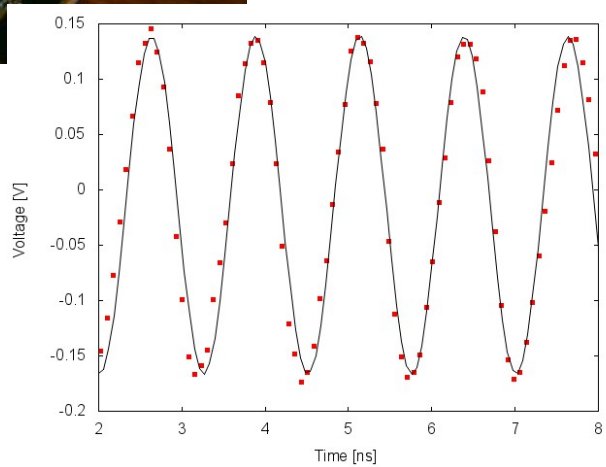
LAPPD Deconstructed

3. Electronics
   - Transmission line readout: 50 Ω scalable strip line, silk-screen printed on glass ground plane
   - Readout at both ends with fast custom CMOS SCA chip with 17 GHz waveform digitization





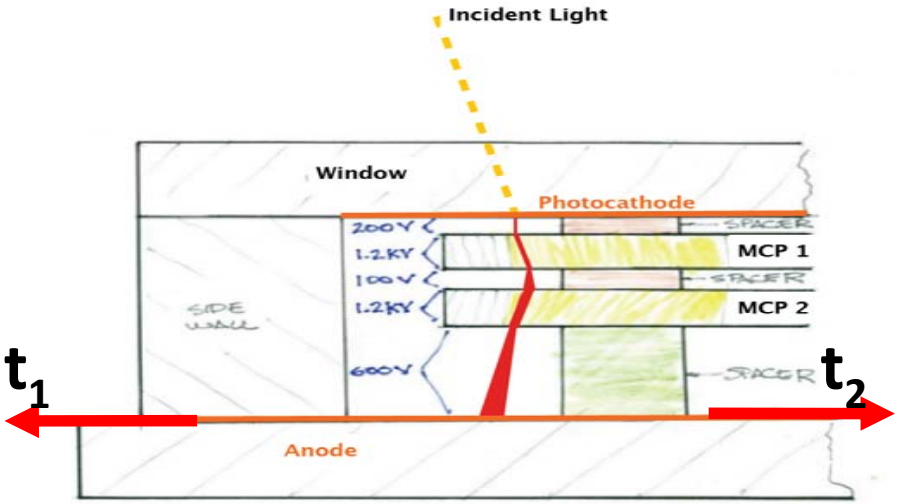
UofC



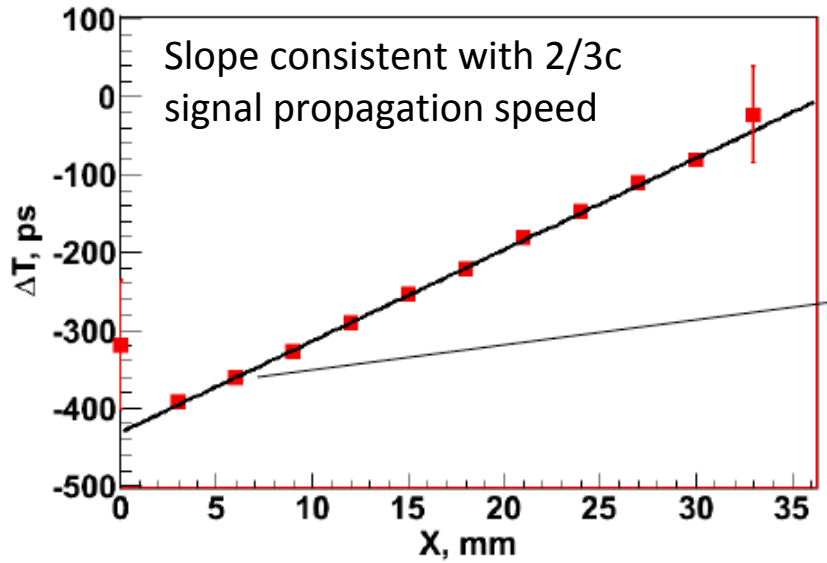
Currently the world's fastest waveform digitizer
Outside original scope of project

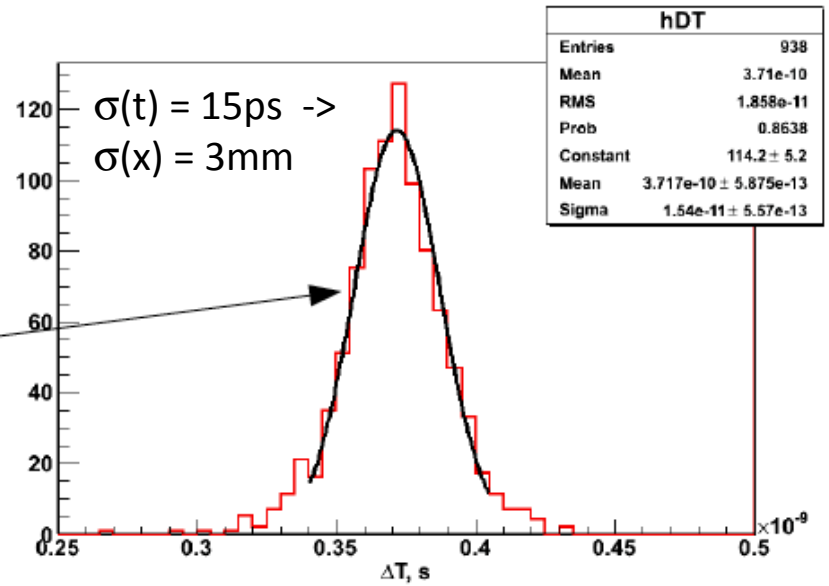
Sampling rate : 13.3 GSa/s

Performance



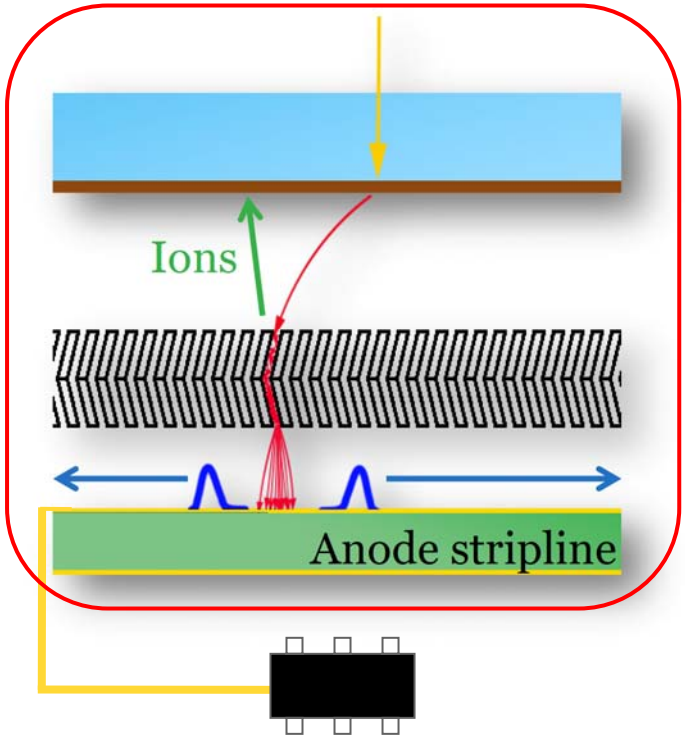
- Laser test at APS of dual 20x20 cm^2 MCP with Al photocathode
- Anode read out from both ends $\Delta t = t2 - t1$

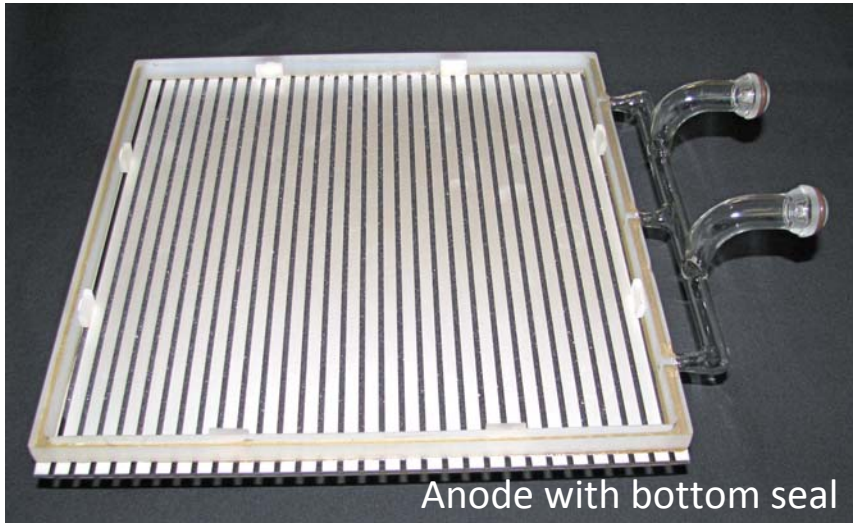




LAPPD Deconstructed

4. Hermetic Packaging
   - Maintain vacuum and provide support. No internal connections; no penetrations



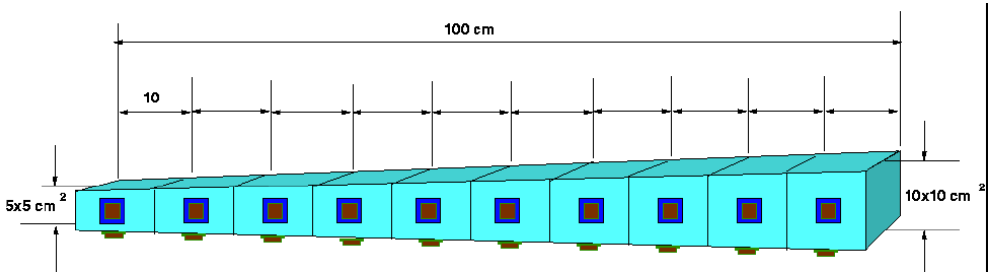


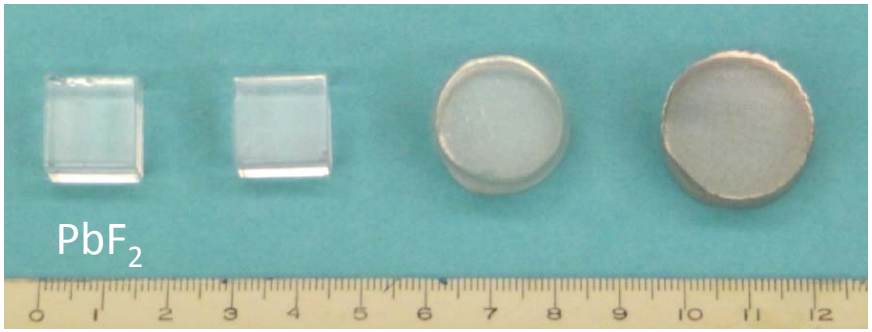
Top seal of photocathode to base (under vacuum) to form complete hermetic package being studied on small samples; Ceramic package developed at SSL LBNL

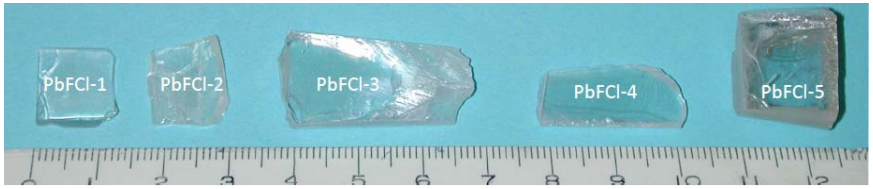
Total Absorption Calorimetry

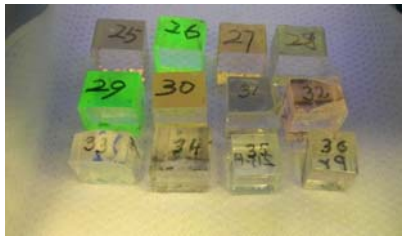
See talk by Adam Para

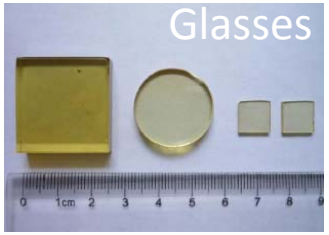
- Homogeneous total absorption calorimetry holds promise to extend EM energy resolution to hadronic jets
  - Simulations indicate ~20%/ √ E, better than PFA
- Requires dense, transparent medium with Cherenkov and scintillation light (dual readout)
- R&D program with SICCAS and Scintibow
  - 116 PbF_2 Crystals grown
  - PbFCl doped crystals
  - Scintillating Ceramics
  - Scintillating BSO glasses

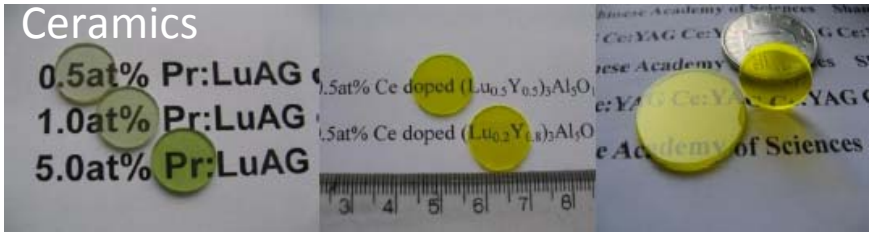








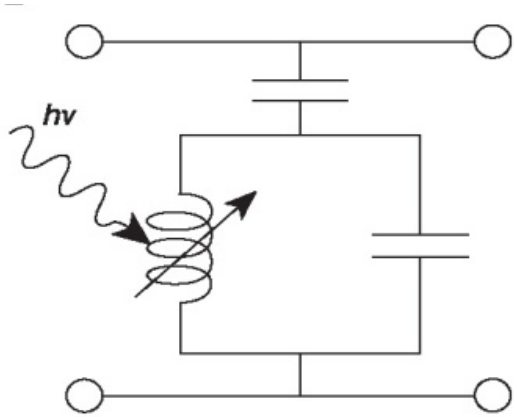




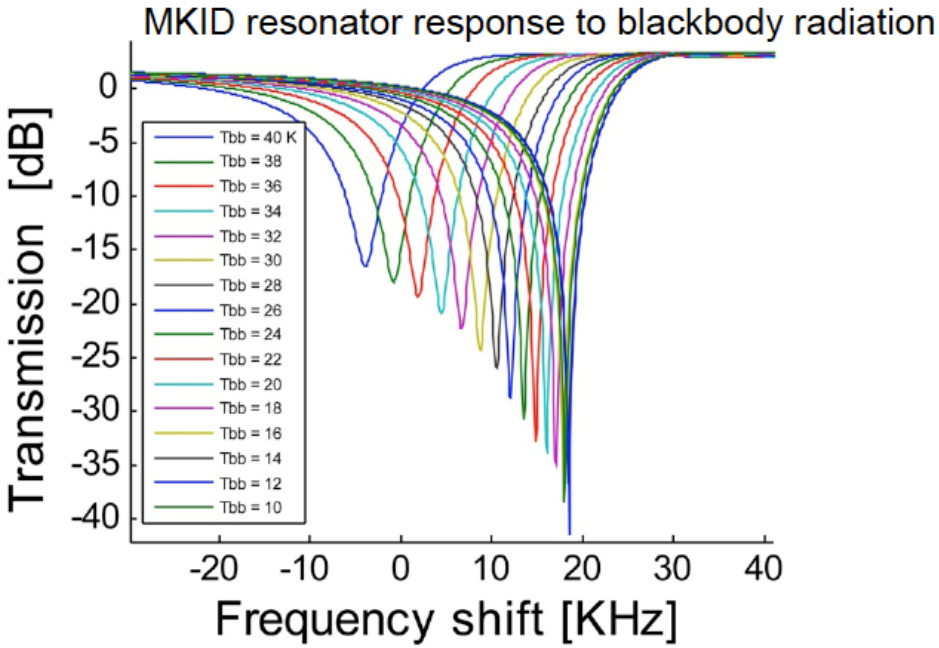
Microwave Kinetic Inductance Detectors

- Next generation more sensitive CMB detectors: MKIDs
- Superconducting resonator-based photon detectors
  - Sub-millimeter to X-ray detection
  - Each pixel at different resonant frequency
  - Potentially simple multiplexing

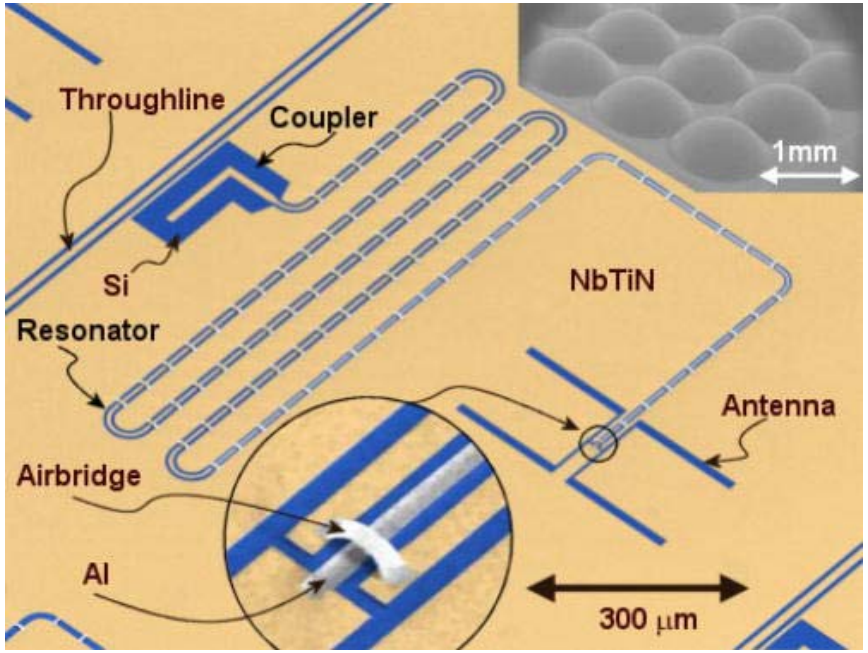
- Measure incident power (pW) by change in resonator frequency and quality factor (Q)



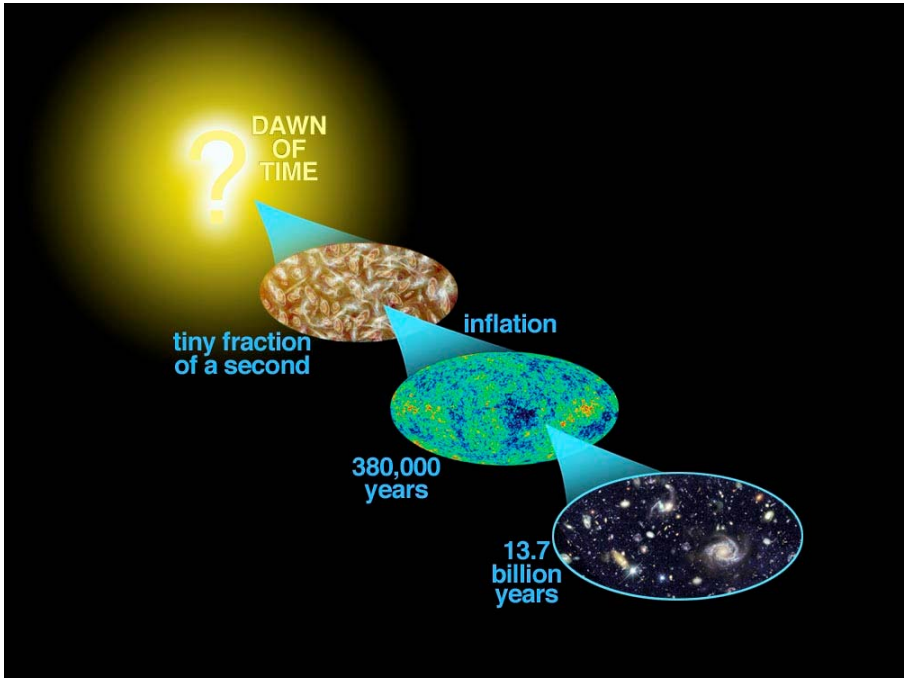
MKID - Microwave Kinetic Inductance Detector



MKIDs for CMB

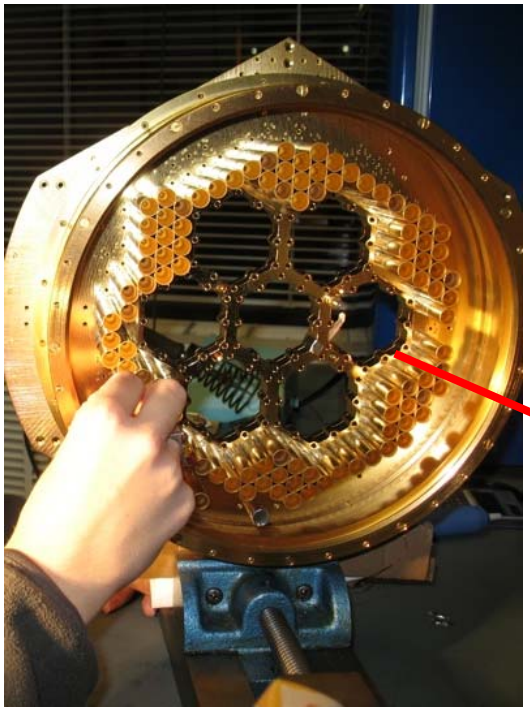


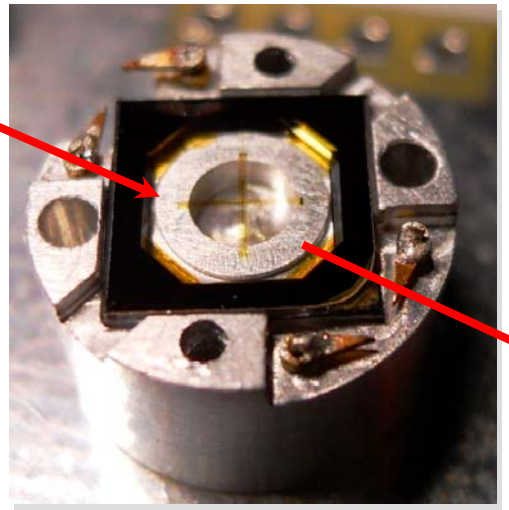
- Sensors and technology being developed: CNM – MSD – HEP – XSD



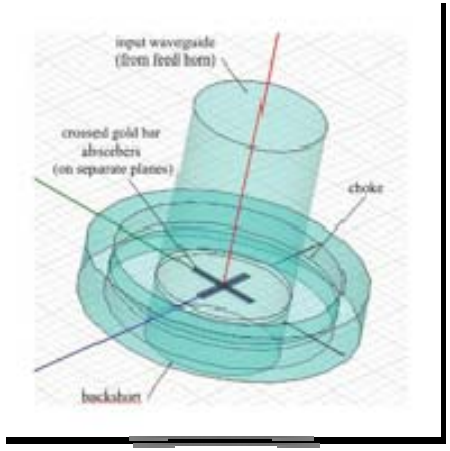
- These CMB measurements address some of the most profound science questions:
  - Tests of cryogenic dark matter
  - Tests of dark energy
  - Neutrino masses from CMB polarization
  - Test inflation with CMB polarization

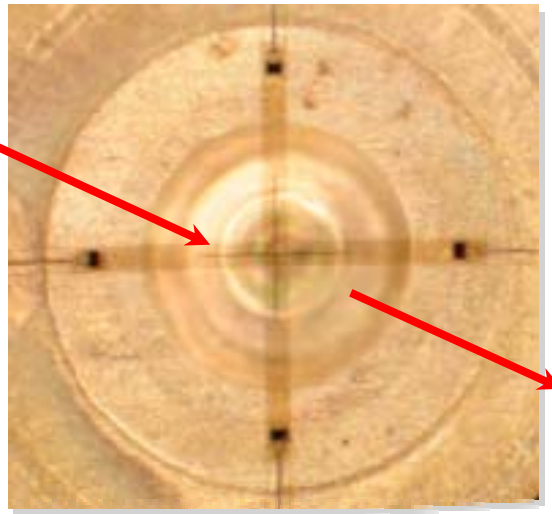
Argonne SPTpol 90 GHz TES Detectors

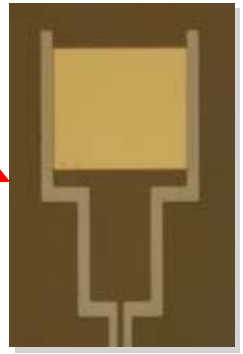




Detector in 2.5 mm waveguide mount







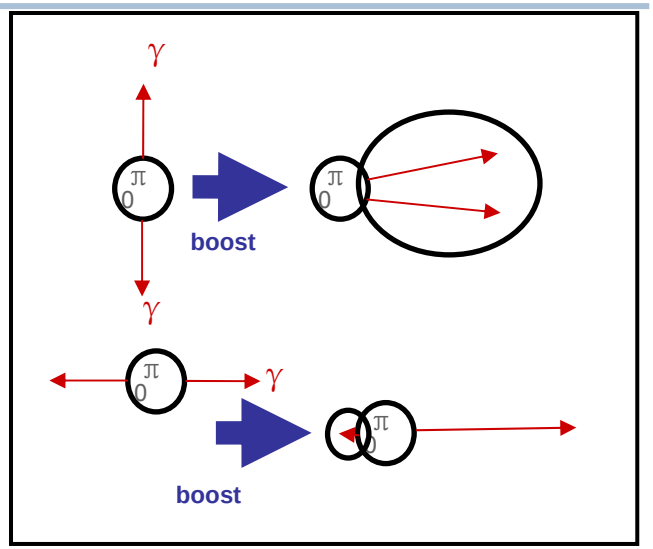
Mo/Au proximity effect
500mK T_C bilayer TES

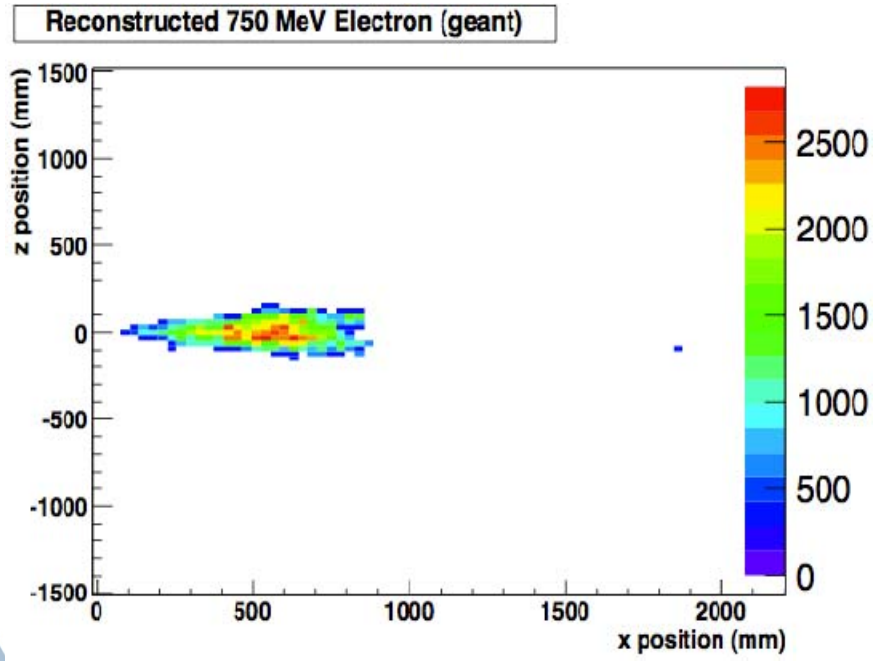
Developed from scratch at ANL
Now deployed to South Pole
This is a major milestone

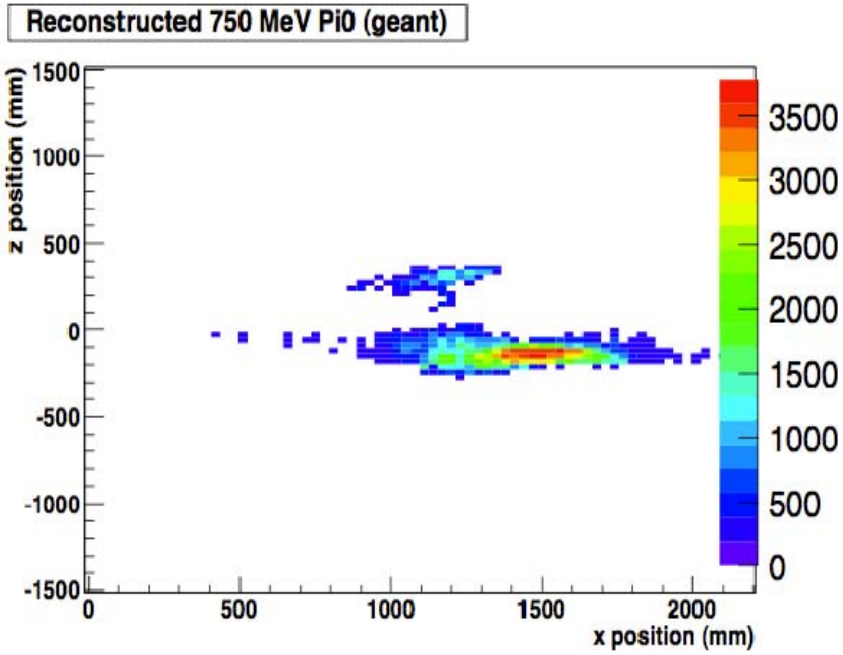
Physics Reach

- Pizero background in WC detectors:
  - For a pure electron sample (~1% π^0), harsh quality cuts required that bring signal efficiency down to 16% (28%) at 1 GeV (0.8 MeV).

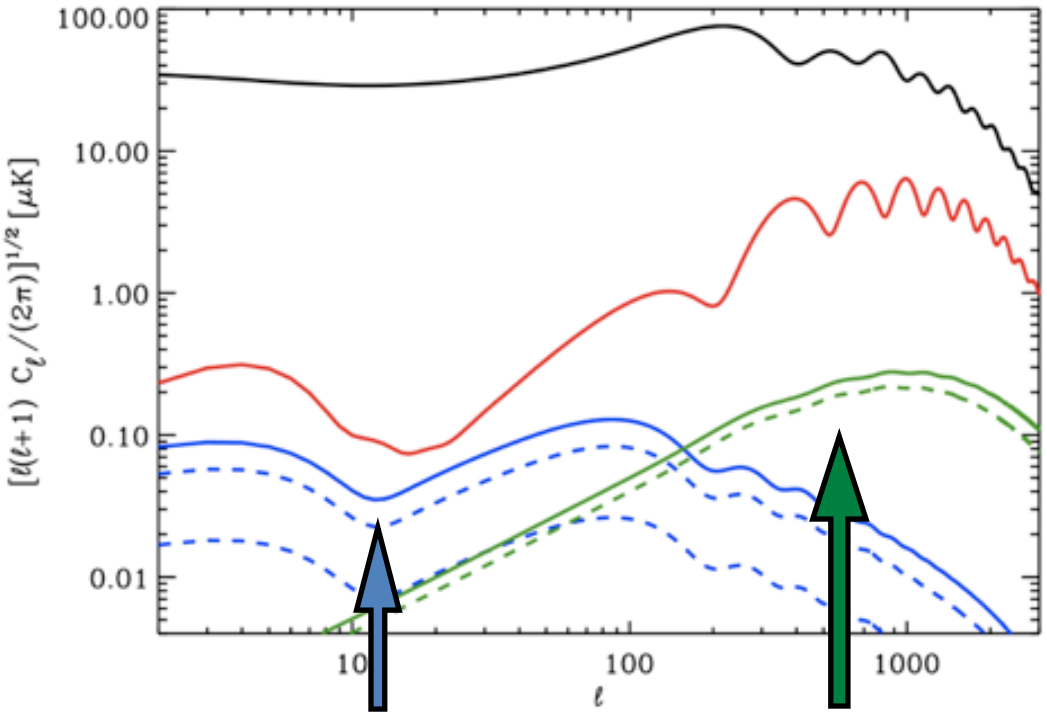
- Photons can be resolved with LAPPD detector performance





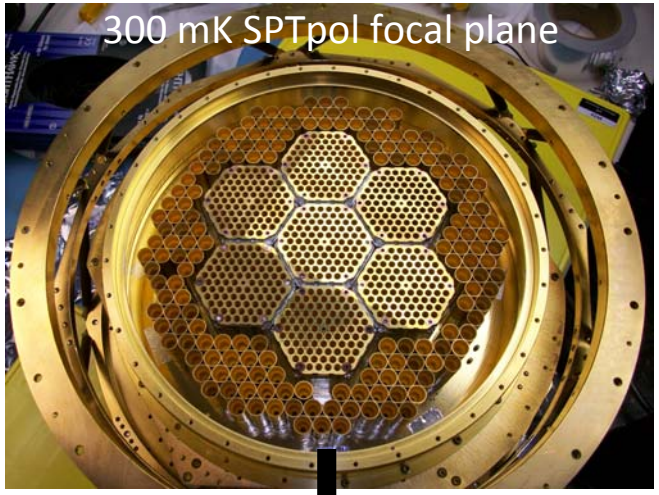


Transition Edge Sensors



Inflation B-modes (probes physics at 10^{16} GeV)

Lensing B-modes (constrains neutrino mass $\sum m_\nu = 1.5$ eV)



Superconducting Detectors for Next Generation Cosmic Microwave Background Polarization Measurements

Challenges Met

Bandwidth	• Investigated commercial optical modulators for 10 Gb/s optical links
Power Budget	• Intent to incorporate external laser light into modulators
Reliability	• Measured BER $<10^{-16}$ (with jitter analysis prediction $<10^{-18}$)
Radiation Hardness	• Tested SEE at 10Gb/s for ~10^{12} protons/cm^2 and TID of ~64 kRad
Photonic Front End	• End goal modulators and drivers monolithically integrated to the front end

- **In many parameters already achieved more than factor 5 improvement over existing readout**