Detector R&D and Facilities at LBNL

Jim Siegrist

7 October 2010

Overview

- Facilities used for Physics Division R&D
- Energy Frontier
- Cosmic Frontier
- Synergy with other LBNL R&D

LBNL Facilities/Capabilities for R&D

- **R&D Facilities:**
  - **Composites Fabrication**
  - **IC Design**
  - **MicroSystems Lab**

More details follow

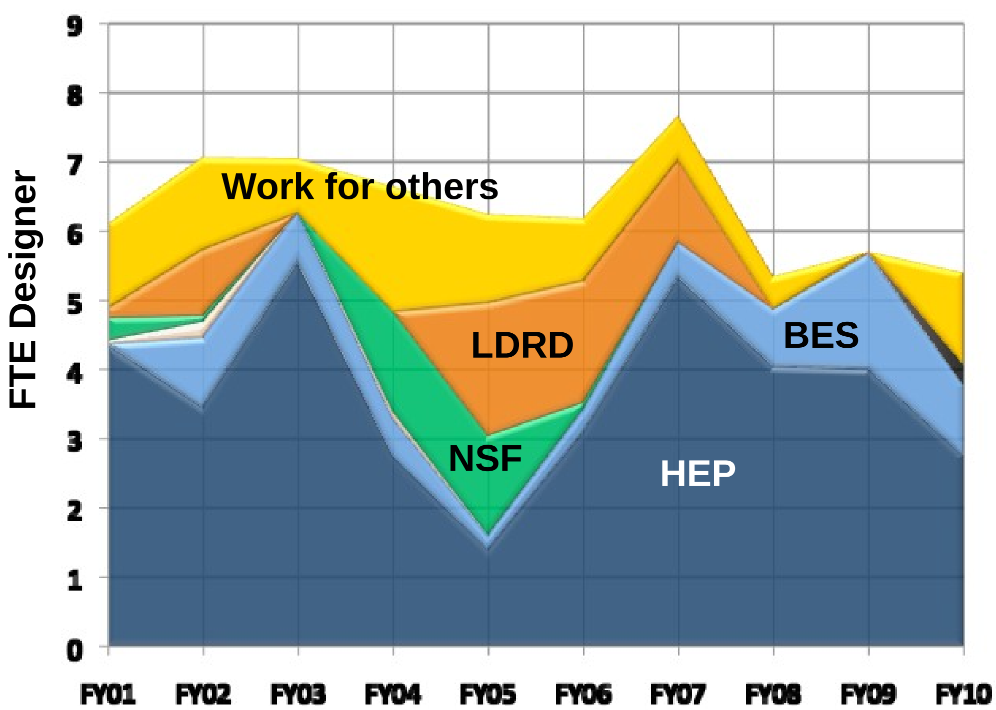
- Infrastructure:
  - Engineering: Mechanical & Electrical
  - Computing:
    - NERSC (National Energy Research Scientific Computing Center)
  - Accelerators/Testbeams/Radiation Testing
  - Low background counting capability

LBNL Composites Facility
Central to Energy Frontier R&D

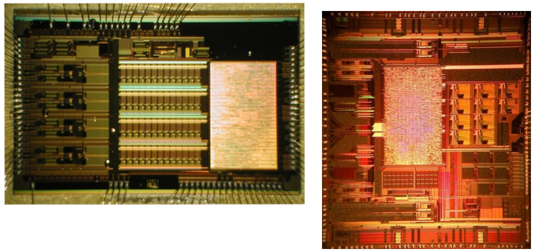
- Engineering and technical infrastructure for precision fabrication
- Expertise & collaboration with industry (SBIR)
- Used extensively in past for **ATLAS** construction and future R&D, now also **STAR**, **PHENIX** upgrades
- Experienced FT technical staff in-place
- Equipment includes large autoclave, CAD/CAM tools, fixturing, inspection and testing systems, cleaning, adjacent precision machine shop

IC Design
Critical to all R&D

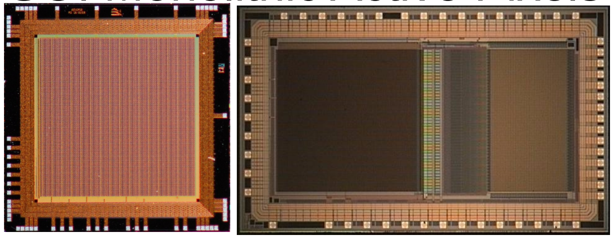
- Experienced group with 5-7 FTE leveraging different funding lines
- Exchange and sharing of ideas, concepts, tools, design elements between different projects



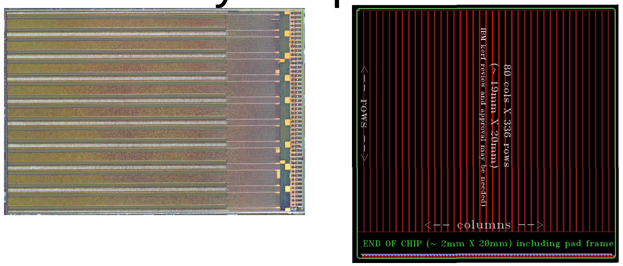
CCD control and readout



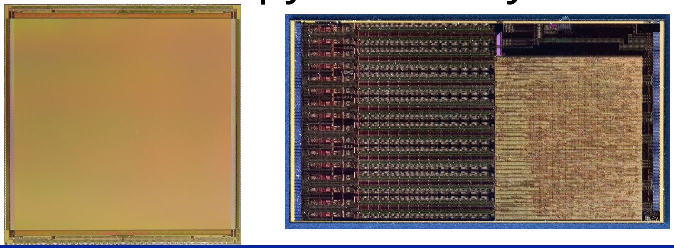
SOI Monolithic Active Pixels



Hybrid pixel readout

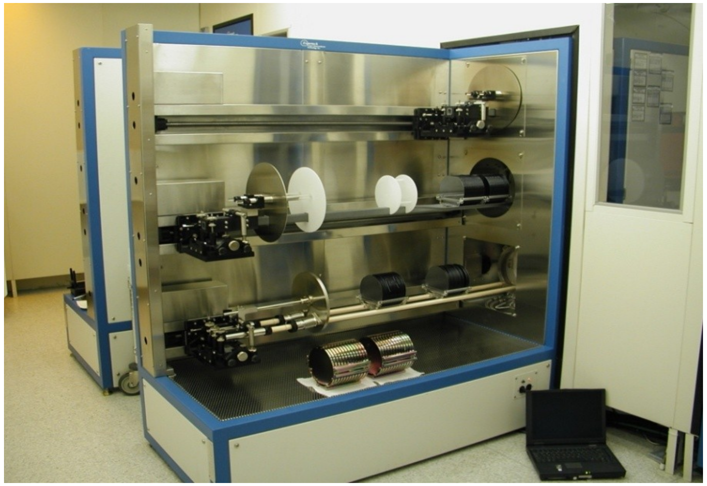


Electron microscopy and X-ray detection



Recent chips -- Pictures not to scale

LBNL MicroSystems Laboratory
Central to Cosmic Frontier R&D



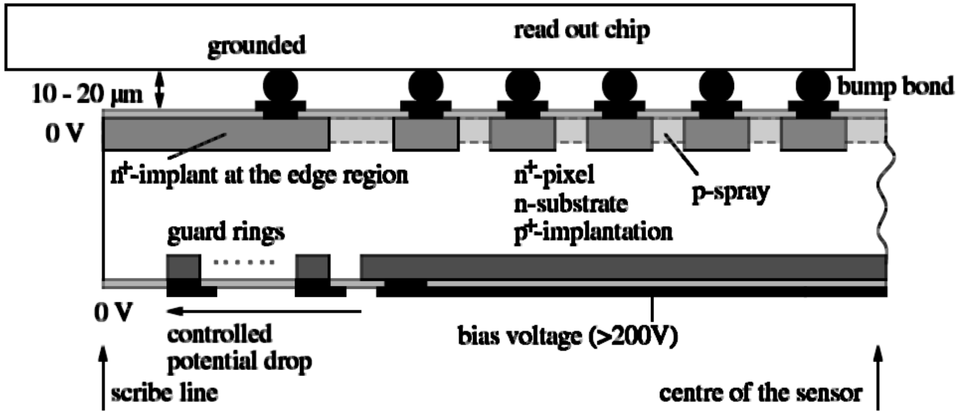
- Class 10 clean room
- CMOS processing equipment: furnaces, lithography, dry & wet etching, sputtering, wet stations, etc.
- First CCD fabricated in 1996.
- MSL also includes CCD Testing Laboratory in nearby building:
  - Cryogenic light projection systems, QE measurements, charge diffusion, wafer cold probe station, packaging and wire bonding, etc.
- N. Roe – MSL lead

R&D for Energy Frontier

- ATLAS Upgrades *(G. Gilchriese, M. Garcia-Sciveres, C. Haber)*
  - Pixel Integrated circuits
  - Mechanics and integration for silicon detectors
- New Concepts *(M. Garcia-Sciveres, C. Haber, B. Heinemann)*
  - Intelligent trackers example
- Multi-core Computing *(P. Califiura)*

Integrated circuits for hybrid pixels

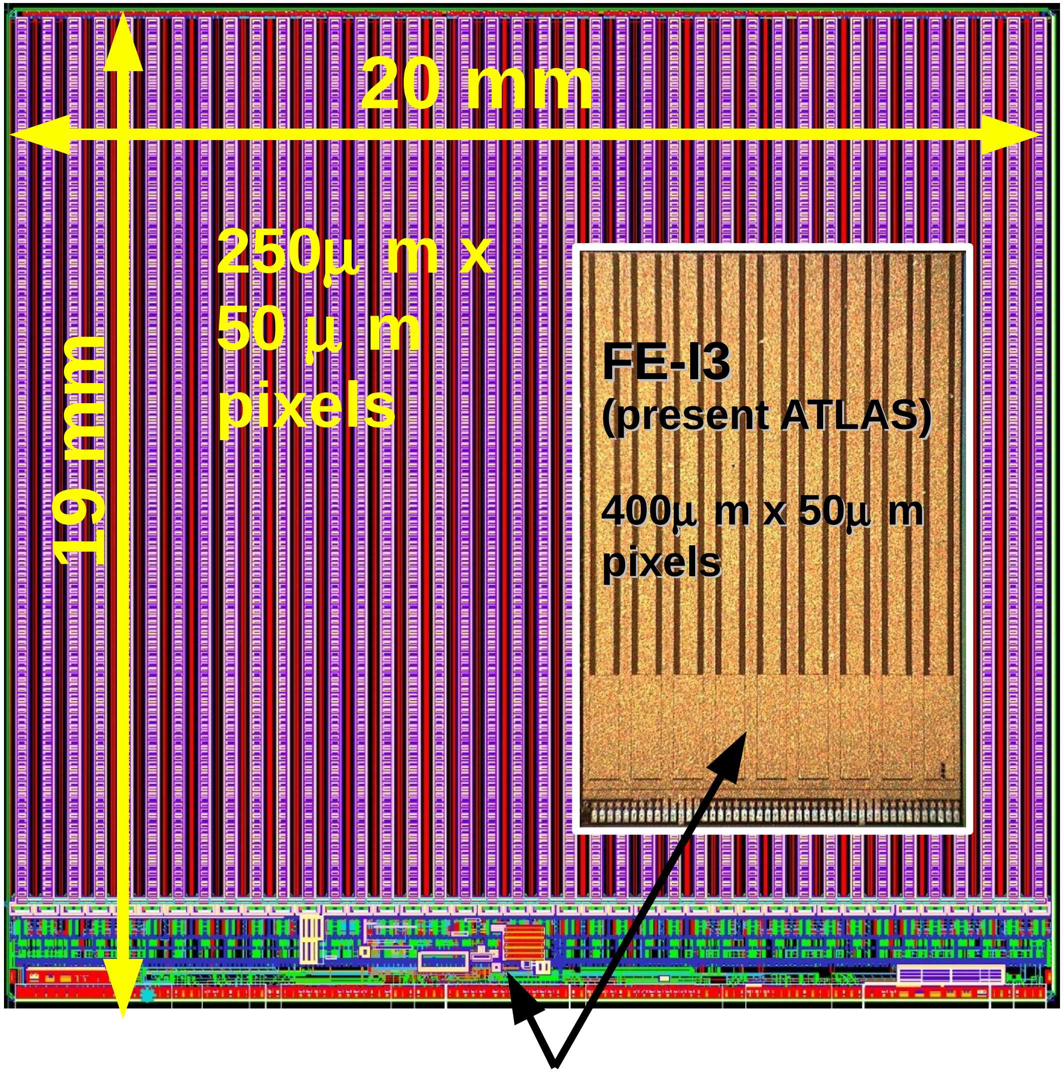
- Critical to reduce the cost and power of pixel systems
- Push the limits of rate and radiation tolerance
- LBNL is leading the ATLAS collaboration in this area
- Brand new FE-I4 chip is largest in HEP to date: see poster
- Now working on generation after FE-I4 to reach highest possible data rates
- Power reduction includes on-chip DC-DC conversion: FE-I4 is first HEP chip to have one.



Hybrid pixel technology:
Each pixel is a parallel channel
Ultimate frame rate capability

R&D on Hybrid Pixel Chips

- **FE-I4:** Ambitious step towards system-on-chip
  - Full custom layout and synthesized logic tightly integrated down to pixel level
  - (see poster)



More functionality yet less "dead" space

Hybrid Pixel Chips Beyond FE-I4

- Further reduce pixel size and at the same time increase rate capability
- Further reduce power
- LBNL leading effort to achieve goals using smaller feature size.
  - This is “The devil we know”
  - Working towards 65nm feature size CMOS submission end of yr.
  - Combined effort of 3 projects: Energy frontier (this one), Intensity Frontier (for Mu2e), and Cosmic frontier (fast ADCs for CCD).
- LBNL is also involved in European-led ATLAS parallel effort using 3D integrated circuits in Multi-Project Run organized by Fermilab.
  - This is a promising, but very challenging approach.
  - This is “The devil we don't know”

Integrated Macro-Assemblies
(called staves and petals)

- GOALS: Faster construction and reduced material
- Expand the size of silicon detectors to the entire tracking volume
- Integrate electrical functions, mechanics, and power distribution
- LBNL led the ATLAS strip collaboration in this direction
- Now leading the application of these concepts to ATLAS pixels
- Exploit new carbon foam materials developed in collaboration with industry (SBIR)

Stave concept:
CDF --> Generic --> ATLAS --> Generic

CDF

Generic

ATLAS

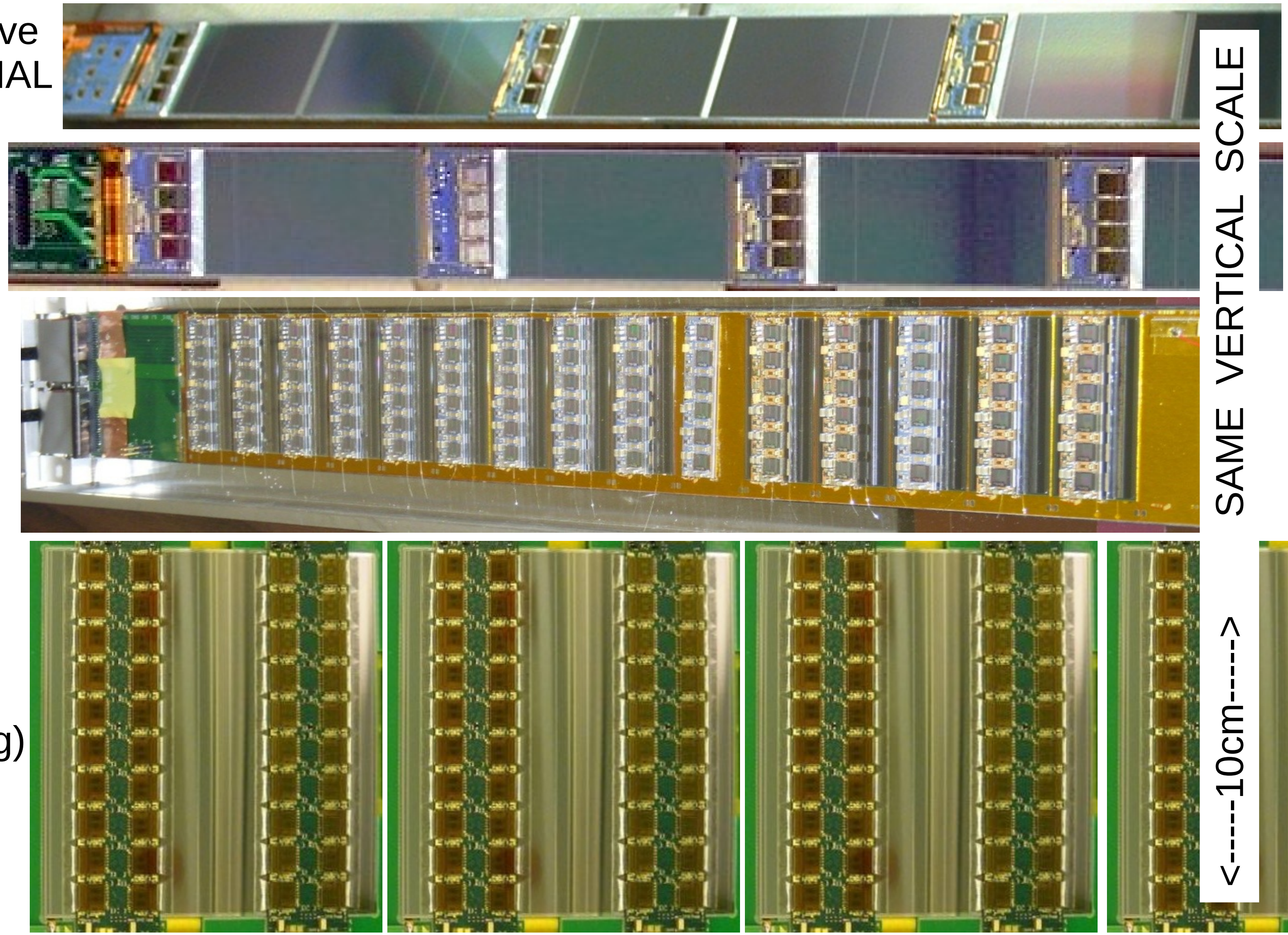
Generic

CDF Run2B stave
2004, LBNL+FNAL

Stave 06
(60cm long)
LBNL

Stave 07
(1m long)
LBNL+ RAL

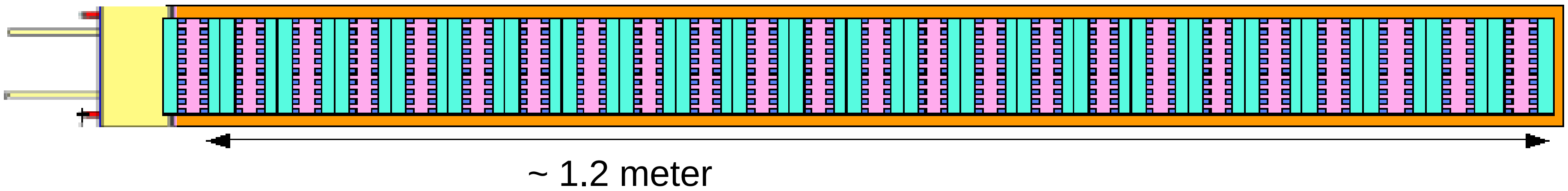
Stave 09
(stave 1.2m long)
International
Collaboration

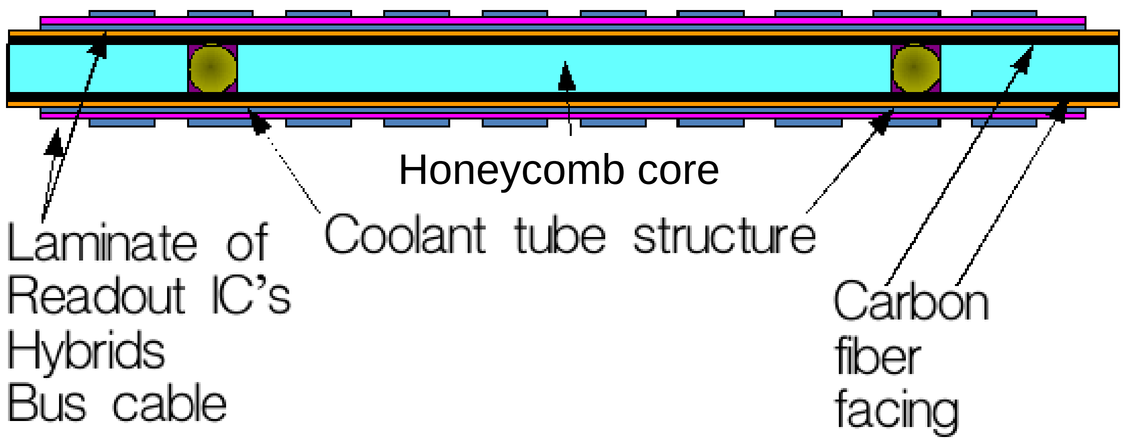


FY11: Coupled doublet stave for direction measurement & trigger.

Strip Stave 09

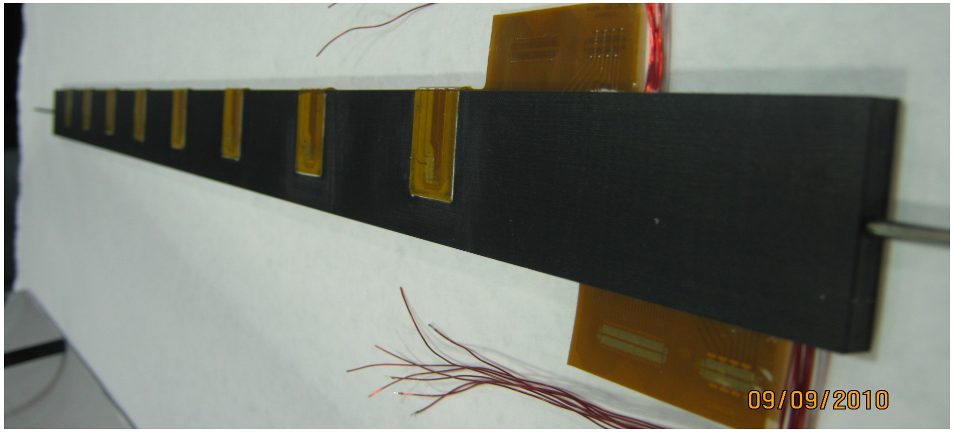
- Prototyping effort being carried by large collaboration:
- LBNL, BNL, UCSC, Yale, NYU, Duke, RAL, Liverpool, Oxford, Cambridge, Sheffield, UCL, Valencia, CERN.
- 1 Stave has up to 120k channels- compare to 46k of original CDF SVX



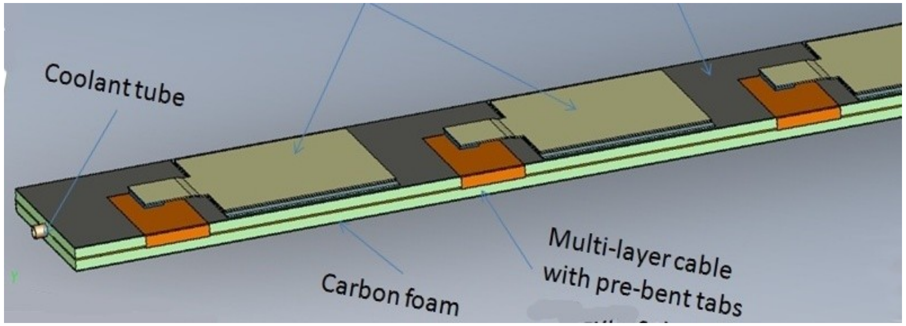


(C. Haber)

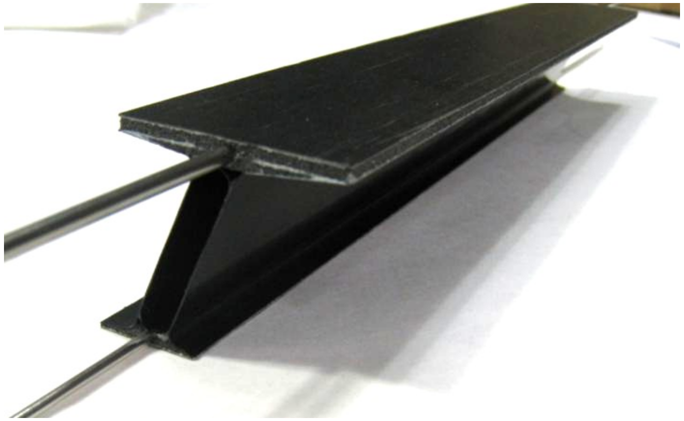
Pixel Staves 2010



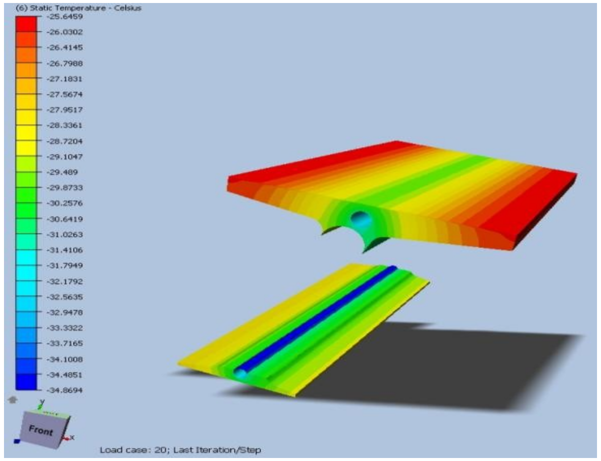
Stave2010 prototype with embedded cable, LBNL Sept. 2010



Model of electrical stave with functional modules using FE-I4 chip. Goal for April 2011

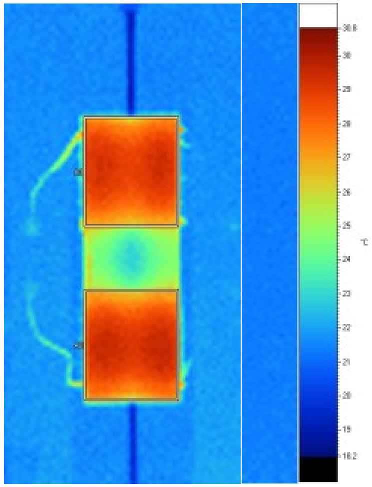


I-beam prototype (after STAR), LBNL Apr. 2010



Thermal simulations

IR image of stave segment

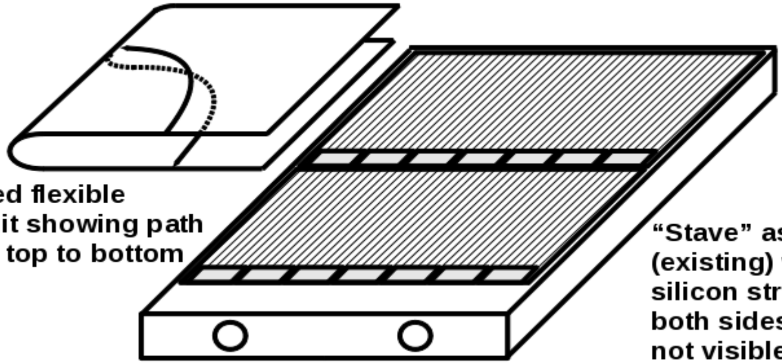


Lots of measurements to tune simulation parameters

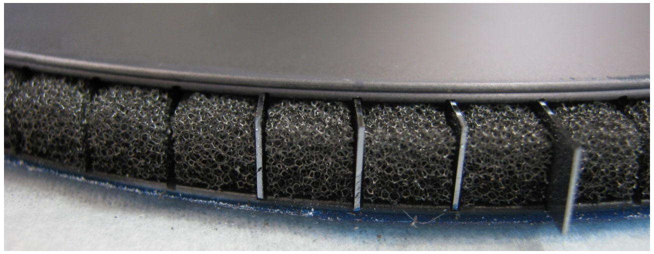
All based on new material – low density thermally conducting carbon foam – developed with industry (SBIR)

Intelligent Trackers

- Community wide interest in increased functionality tracking layers for improving triggers in very dense high rate events.
- "Workshop on Intelligent Trackers" held at LBNL in Feb. 2010.
- 50 participants from LHC experiments and beyond
- Proceedings published in JINST
- LBNL Plans: continue work on coupled layer design. Add collaborators: (Uppsala, US groups...)

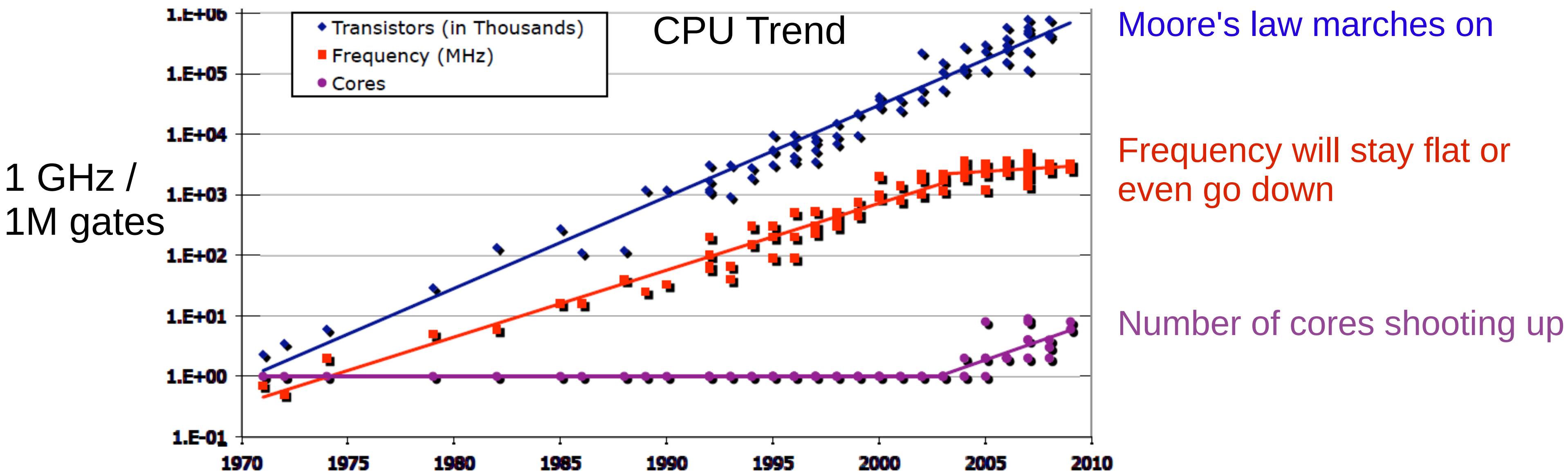


Continue development of Si + C-foam interposer wafers

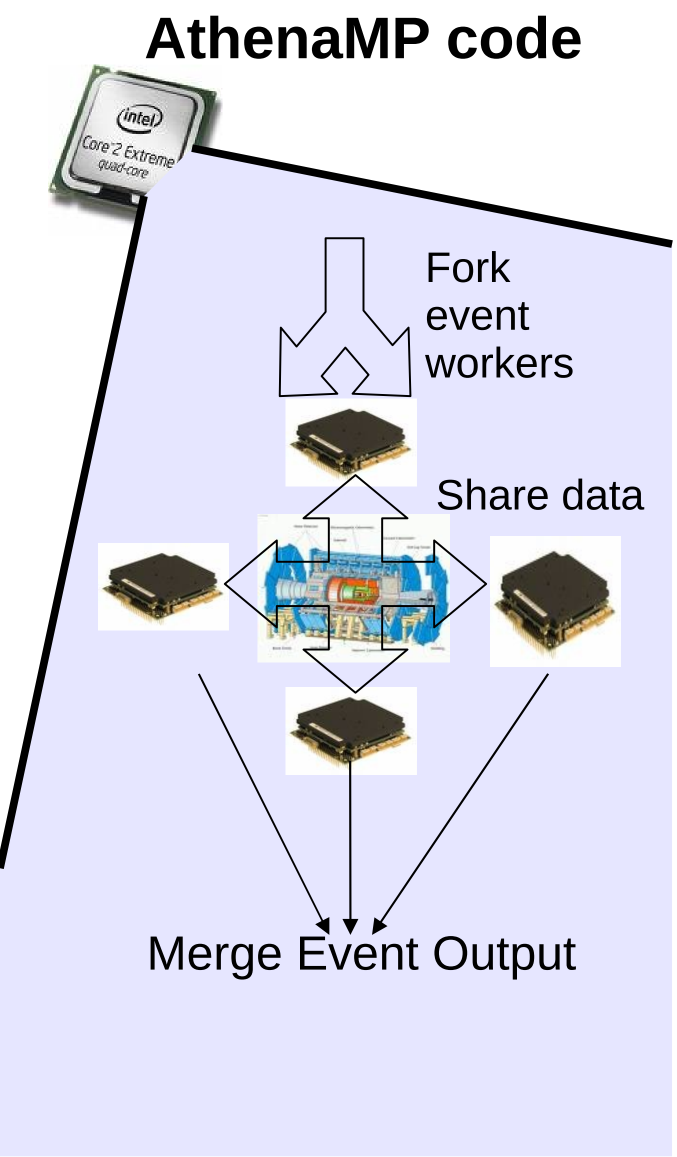


Multi-core computing

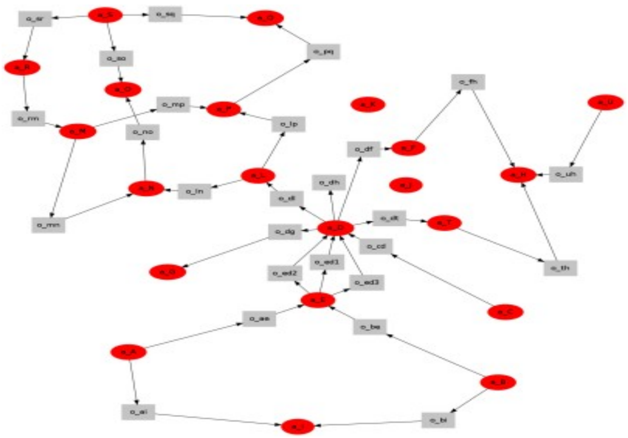
- Computers are changing
- The traditional CPU is a thing of the past
- From now on it's all Multi-Core, rapidly increasing 8, 32, 64.... (supercomputers have been this way for a long time, but now ALL computers are this way)
- This is a challenge, but also a big opportunity for physics software
- LBNL R&D aims at the next generation physics software, taking full advantage of parallel processing



Multi-core development for ATLAS



- AthenaMP code (2-8 cores)
  - Lightweight, process-based, event parallelism
  - Use Linux fork() to share memory automatically
- Many-core (>32) code challenges
  - Reduce memory footprint, maximize data and code locality
  - Group modules according to their code and data “closeness”



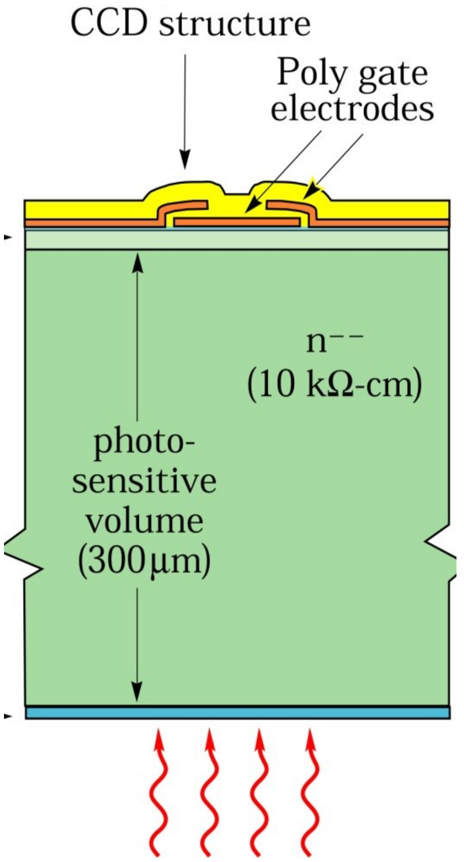
Representation of module grouping algorithm

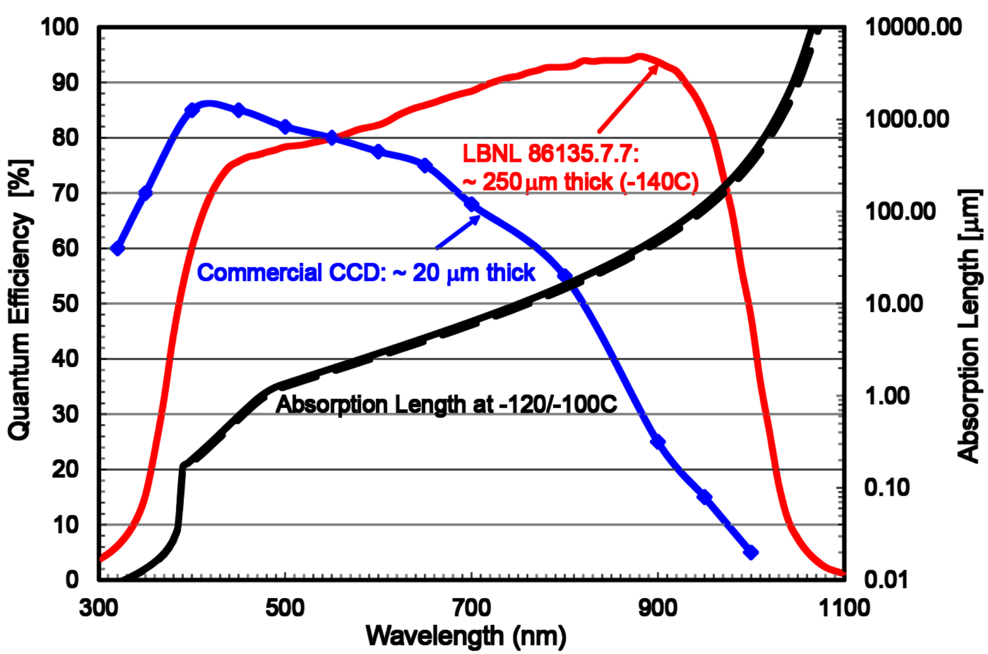
R&D for Cosmic Frontier

- CCDs for Space and Ground *(S. Holland, N.Roe)*
  - MicroSystems Lab (MSL) is devoted to this
  - MSL is both an R&D and a fabrication facility
- IR Detectors *(C. Bebek)*
- WFIRST *(M. Levi)*
- CMB detectors *(A. Lee, H. Spieler)*
- Direct Detection of Dark Matter *(D. Nygren, S. Loken)*
  - Low-Threshold/High-Resolution/Imaging/Directionality
  - Germanium cost reduction strategies
- DUSEL planning *(G. Gilchriese)*

LBNL CCDs

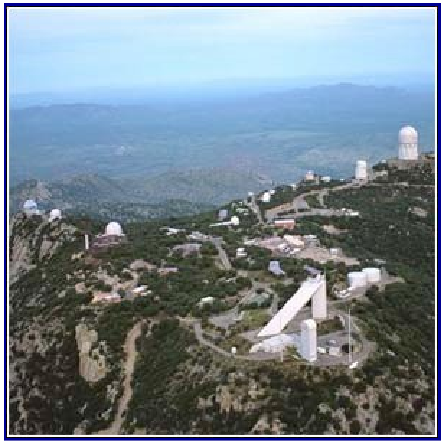
- Thick, fully-depleted CCDs were invented and first fabricated at the LBNL MicroSystems Lab (MSL) in the mid 1990's
- More sensitive at red wavelengths (=high redshifts)
- Very radiation tolerant for space
- HV-compatible design has very good point resolution
- Partnership with DALSA semi. enables large scale production for projects such as Dark Energy Survey (over 160 wafers processed)



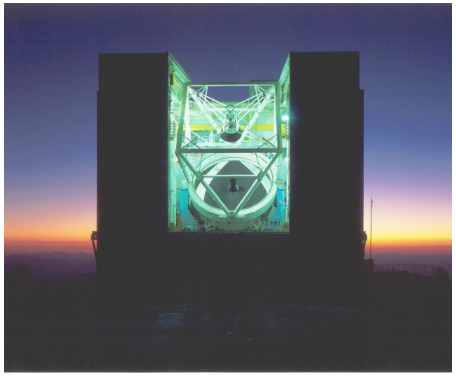


CCDs produced and deployed

Keck 10m telescope
LRIS spectrograph



Kitt Peak/Mayall 4m
MARS and RC spectrographs



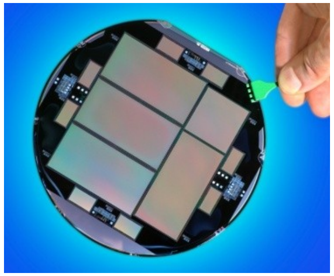
MMT 6.5m/Mt. Hopkins
Red Channel spectrograph

Lick Observatory/Mt Hamilton
Hamilton Echelle spectrograph

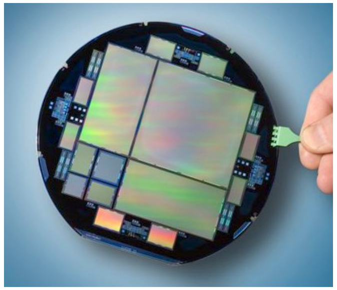
Palomar Hale 200"telescope
SWIFT spectrograph

2.5m SDSS telescope
BOSS spectrographs

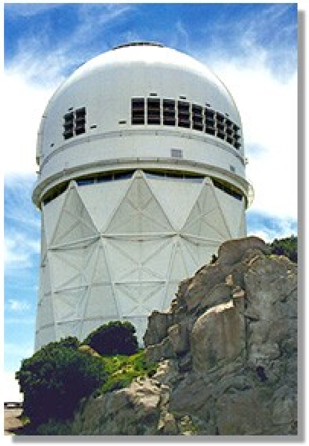
Future CCDs



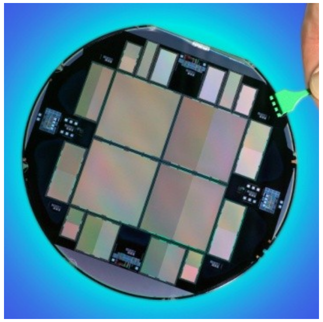
Dark Energy Survey 2011
CTIO Blanco 4m Telescope



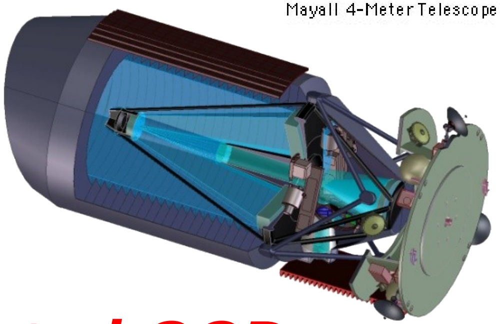
BigBOSS 2015 - proposed
KPNO Mayall 4m Telescope



Mayall 4-Meter Telescope



Joint Dark Energy Mission/
WFIRST ?



LSST has also baselined fully depleted CCDs

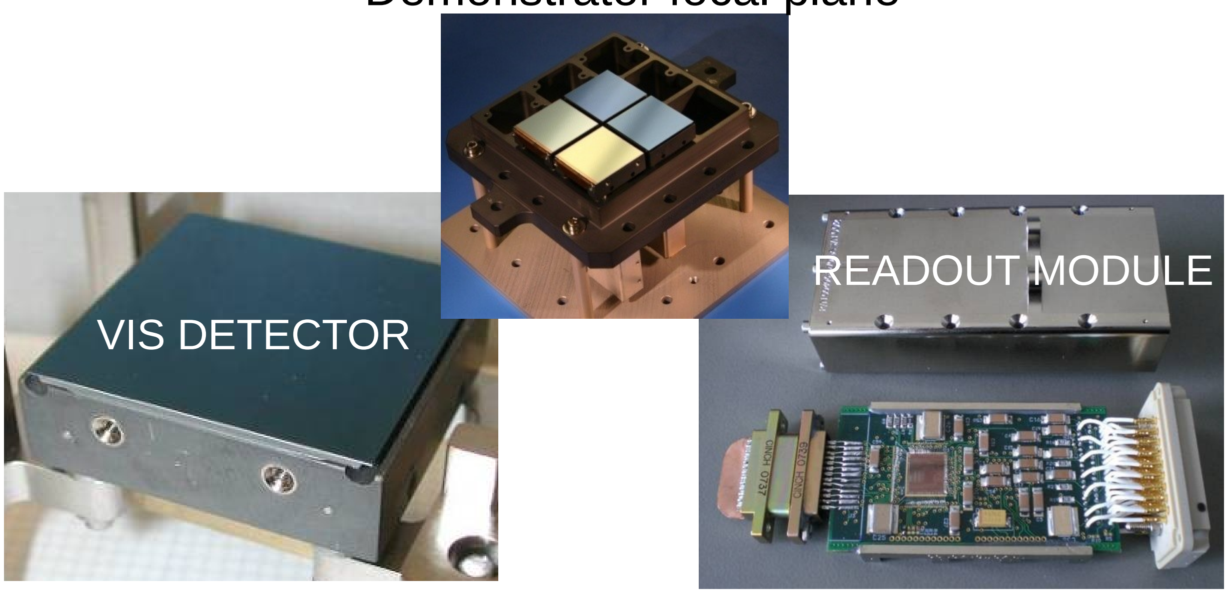
CCD R&D directions

- Thinner CCDs using TiN metal for reduced diffusion, improved yields
- Charge multiplying CCD for single photon sensitivity
- Lower noise output transistors
- Higher speed output transistors
- Combination of the above in a single device, e.g. an LSST prototype with multiple readouts, low noise and thin substrate using TiN.
- Fast CCD with multiple outputs for soft x-ray detection at ALS

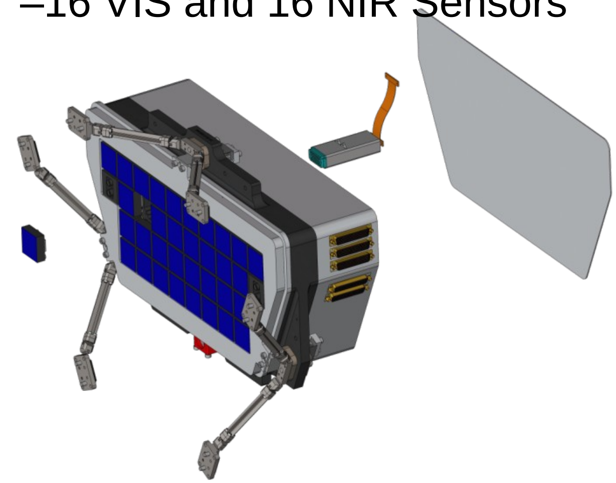
R&D done for JDEM (now for WFIRST)

- HV-compatible architecture to reduce Point Spread Function
  - Achieved 4 μm rms with 100V bias voltage
- Irradiation studies at LBNL 88” cyclotron
  - Demonstrated robustness for 6 yr space mission
- Buttable package with space qualified components and compact readout module

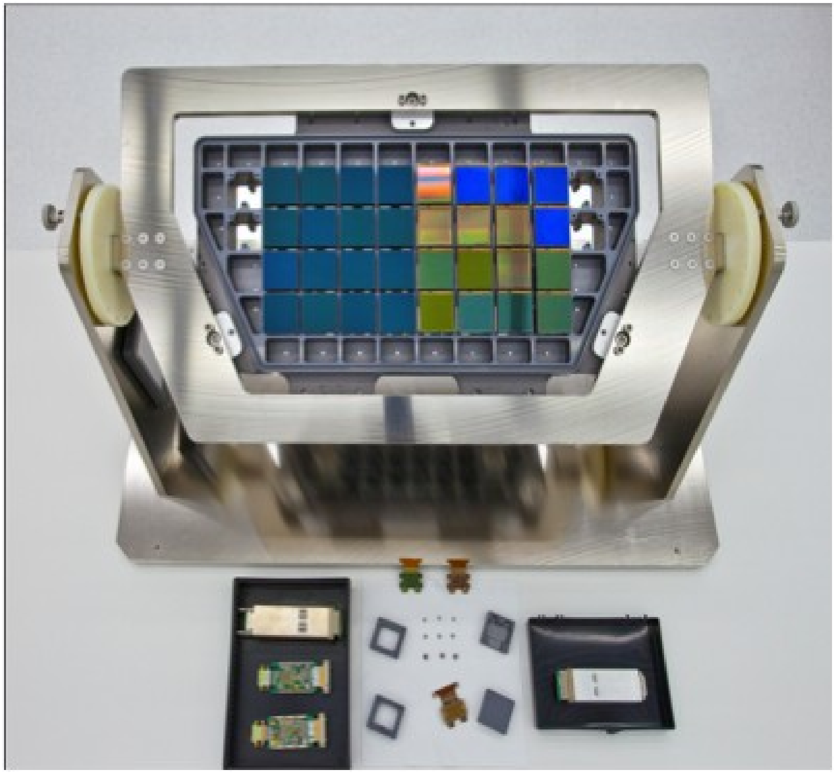
Demonstrator focal plane



JDEM Demonstrator Focal Plane
–16 VIS and 16 NIR Sensors



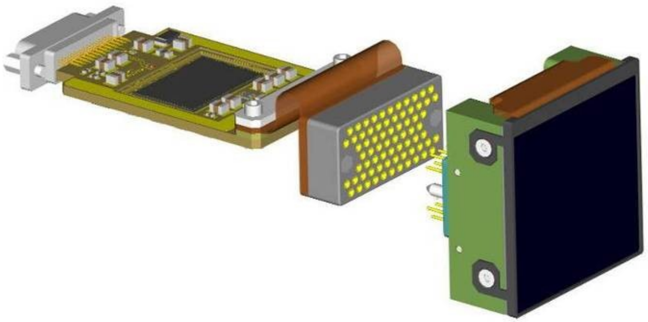
JDEM / WFIRST heterogeneous focal plane prototype

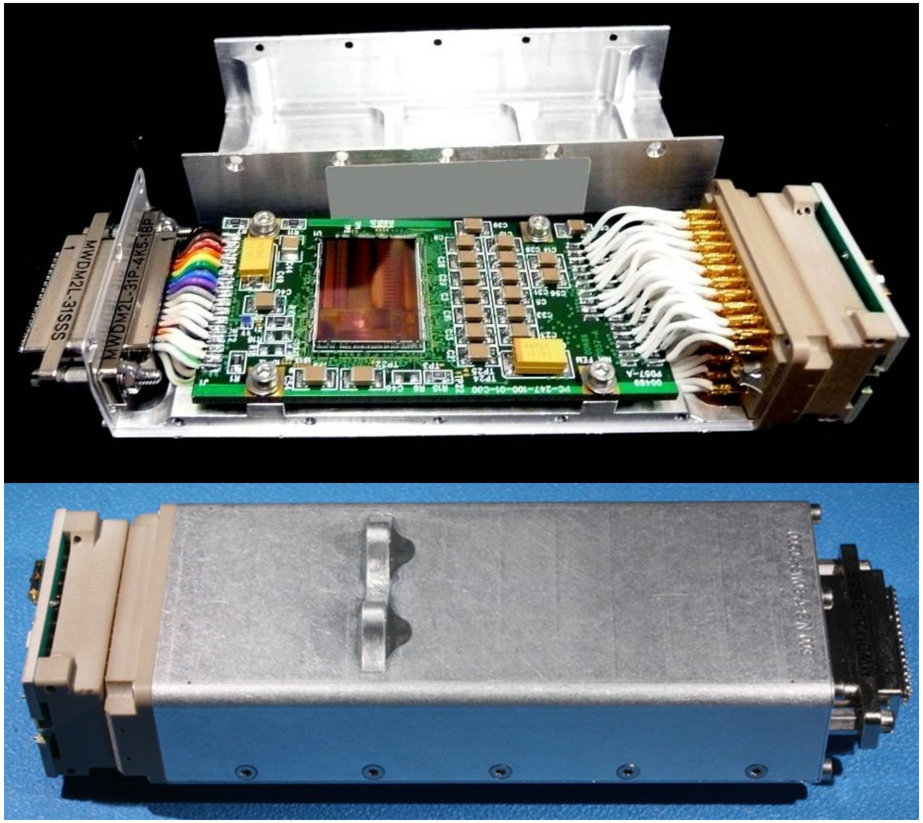


- 32-detector silicon carbide focal plane prototype
- Space qualified Near Infrared (NIR) detectors
- Space qualified fully-depleted CCDs from MSL
- Instrument now assembled and undergoing electrical tests.

NIR modules for focal plane

- Commercial components
  - Teledyne SIDECAR ASIC
  - Hg(x)Cd(1-x) 2kx2k photo diode arrays
- LBNL electro-mechanical packaging
  - Supports direct connect to detector
  - Supports 36-channel mode
  - LVDS digital interface
  - Four science data links
  - Temperature monitoring
  - Two delivered; four more in assembly

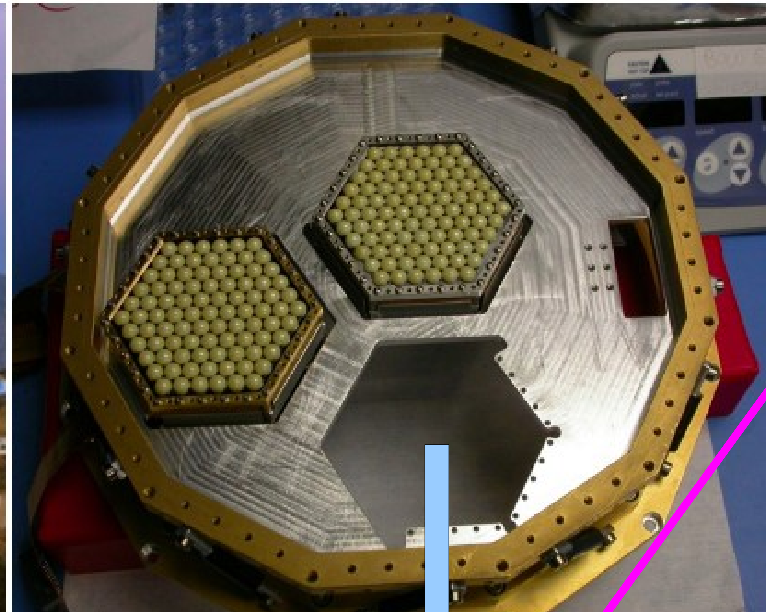


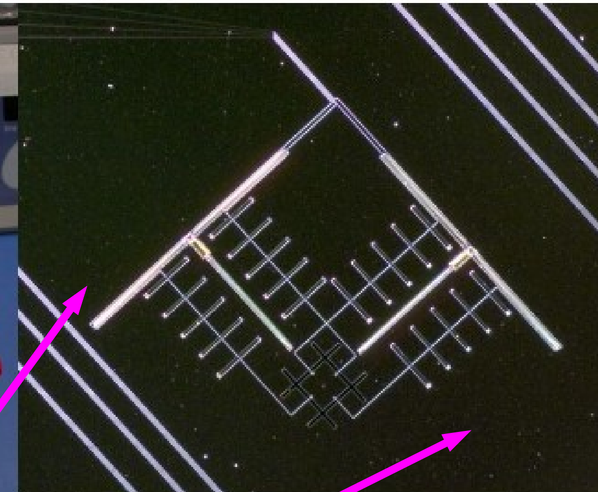


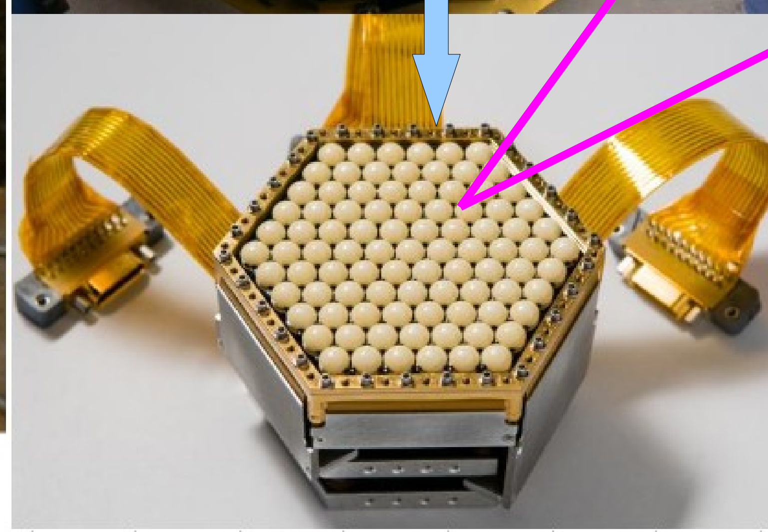
CMB detectors (LBNL & UCB)

- Superconducting Transition Edge Sensor bolometer arrays
- New technology yields unprecedented sensitivity and systematic error control for mm wavelength radiation
- To be used in several detectors:
  - Galaxy Clusters
    - **APEX-SZ**
      - First science from new generation TES arrays
    - **South Pole Telescope (SPT-SZ)**
      - Discovery of first clusters via SZ effect
  - CMB Polarization
    - **POLARBEAR**
      - First science data is 2010/2011 with 1274 bolometer array
- Use LBNL-developed frequency-domain mux
- Pixel design in cooperation with UCB
- Future: Array integration and high-speed low-power readout

POLARBEAR: CMB Polarization







Dipole antennas coupled to TES on silicon nitride film.

(A. Lee)

High Pressure Xenon for Dark Matter and Double Beta Decay

- Excellent intrinsic energy resolution:
    - (only 3 times worse than Ge)
- TPC + Electroluminescence =
  3D tracking (background suppression by event topology) +
  excellent E resolution
- Low background
- 1 kg prototype nearly completed at LBNL, to demonstrate ~0.5% FWHM @ 511 keV gammas
- Optimizing design towards a 100 kg enriched ^{136}Xe for $0\nu\ \beta\beta$ search @ Canfranc underground lab

(D. Nygren)

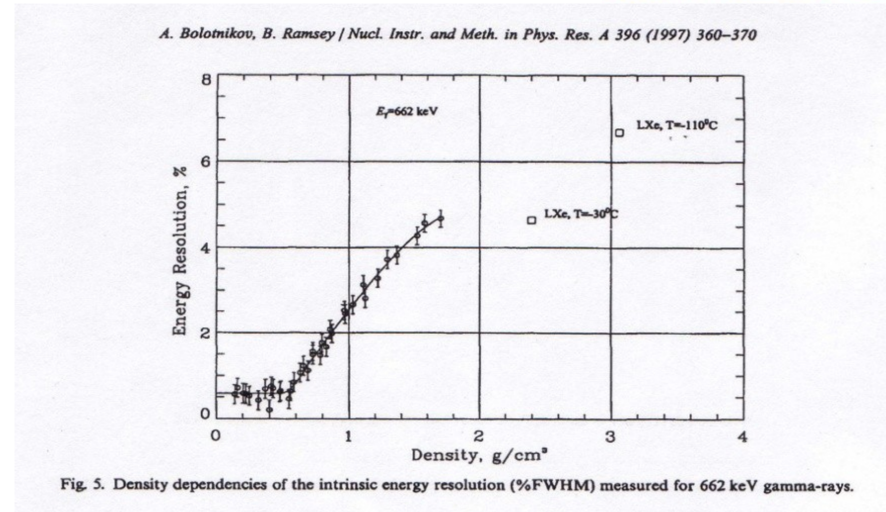
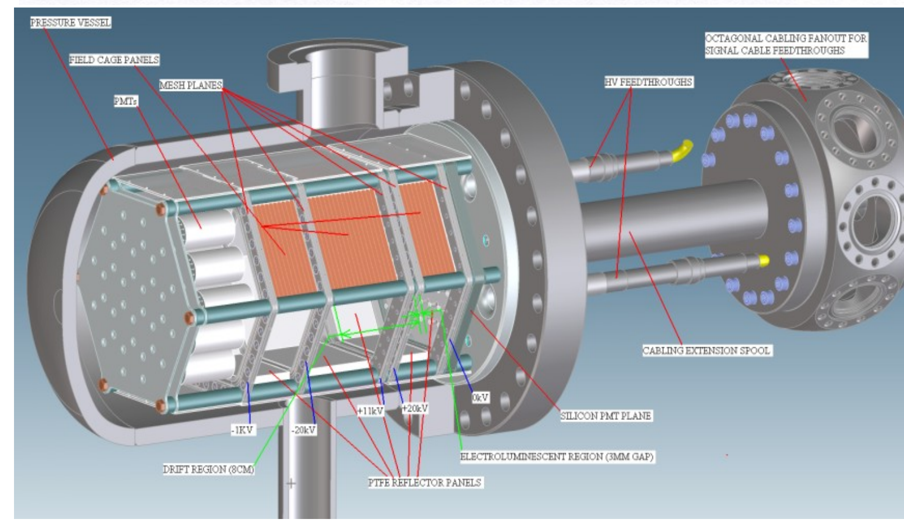
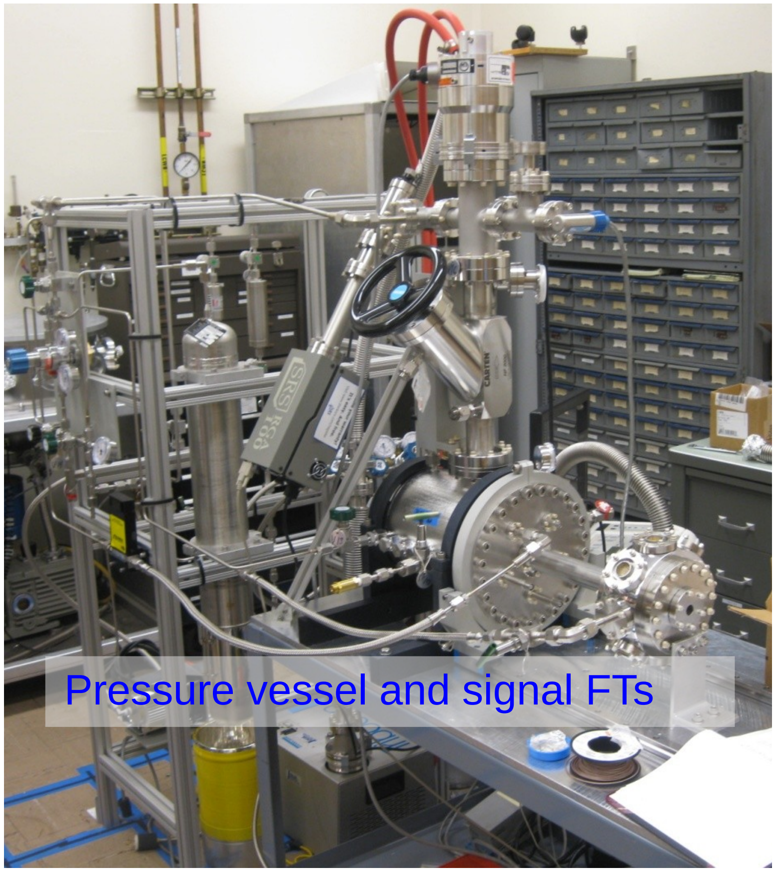


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

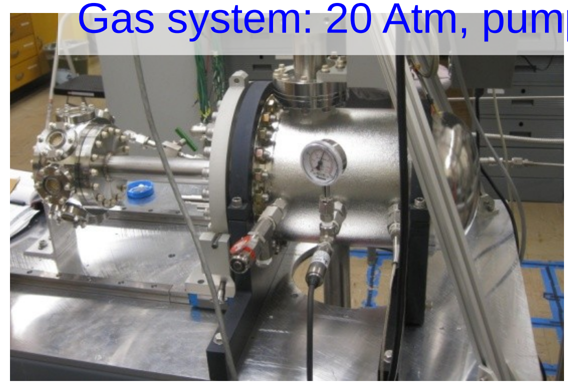


High Pressure Xe prototyping



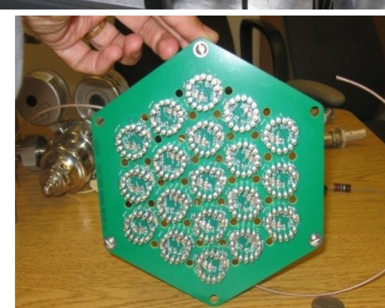
Pressure vessel and signal FTs

Gas system: 20 Atm, pump out, fill, purify, circulate



Field/Light cage panels

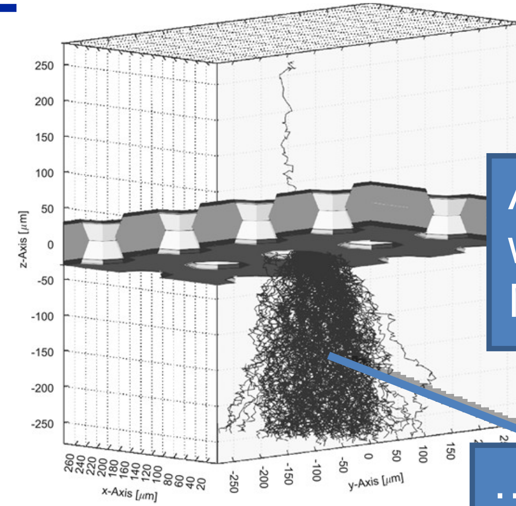
PMT plane, bases
for 19 1” tubes



TPC Mesh planes and support

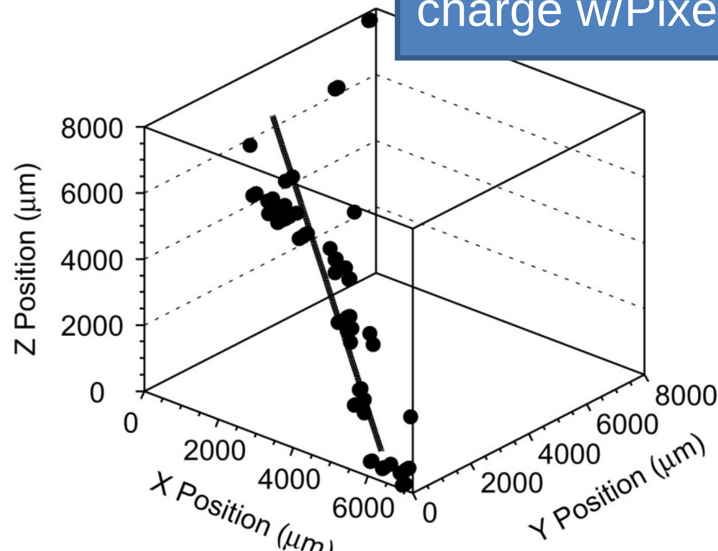
TPC with GEMs & Pixels: Collaboration with a university group

- New collaboration with U. of Hawaii
- Spinoff of pixel chip technology
- Full 3D tracking in large gas volumes
- Multiple applications
    - **Directional Dark Matter Detection**
    - Directional Neutron Detection (Homeland security)
- Current UH Work funded by NSF-ARI
- Only possible with LBNL help:
    - Initial proof-of-concept (for ILC) part of detector R&D at LBNL
    - UH PI (Vahsen) is former LBNL postdoc
    - Employs ATLAS pixel electronics developed at LBNL
    - Gas setup expertise provided by LBNL



Amplify drift charge with Gas Electron Multipliers (GEM)

… & detect avalanche charge w/Pixel chip



Tracking of cosmic ray at LBNL

Lower Cost Germanium

- Needed to meet growing R&D demand

Application	Detector Requirements	Total mass desired (next ~10 years)
Nuclear Physics (GRETA, AGATA)	n-type tapered hexagonal segmented detectors	~500 kg
$0\nu\beta\beta$ Decay, Dark Matter (MAJORANA, GERDA, 1TGe, CDEX)	p-type point-contact detectors Large volume desired	Tonnes
Space Applications (GRIPS, NCT)	Planar n-type Large area desired	~100 kg
Medical Imaging	Large area desired	Hundreds+ kg/yr
Nuclear Safeguards, Homeland Security, Environmental Monitoring, Emergency Response	Depends on success of current-generation systems	Hundreds+ kg/yr

- Must work with industry to increase yield and reduce cost of detector grade material (HPGe)

Development of a low cost production process for HPGe

Zone refining

Goal:

Equipment improvement for maximum yield (large scale at low cost)

Approach:

Numerical model of existing process (thermal fields and segregation behavior).
Engineering of improvements.

Cost analysis

Crystal growth

Goal:

Equipment design for optimized control and reproducible growth at low cost

Approach:

Global heat transfer and dislocation formation models toward puller engineering for precise controls.

Growth in clean-controlled environment

Optimization of crystal size for application (diameter and length)

Cost analysis

Organization:

Analysis and design: ***LBNL lead with selected experts and in collaboration with HPGe producer***
Equipment fabrication: ***subcontract***
Equipment testing: ***LBNL in collaboration with HPGe producer***

Synergy and collaboration

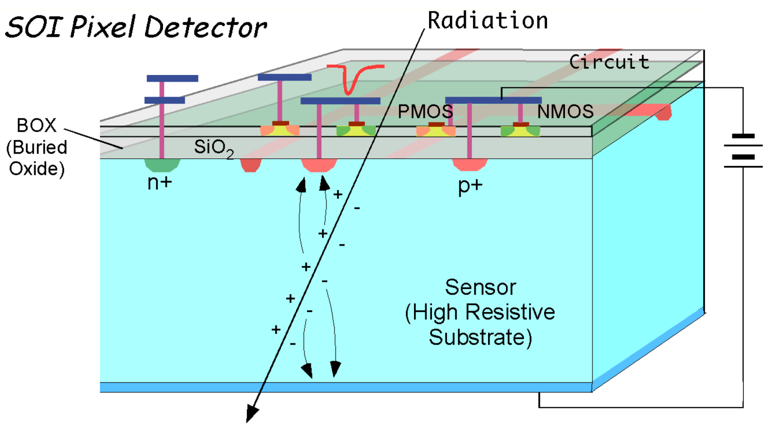
- Physics Division is one of several at LBNL
- There is a great deal of instrumentation R&D outside of physics
  - Many ideas, resources, and advances are shared
  - Will give a few examples to illustrate.
- Much of the R&D described involves collaborations of many labs and universities in the US and abroad
- In many cases LBNL has initiated the R&D and then expanded to involve collaborators.
  - Example: FE-I4 chip, 11 designers from 5 institutes outside LBNL and many more for testing
  - Example: Stave R&D, now 13 outside institutions
  - Example: WFIRST, now 5 outside institutions

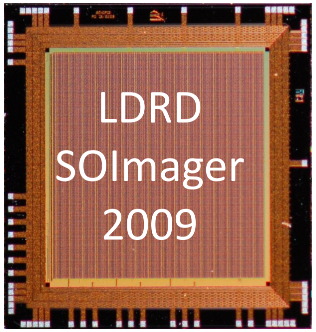
Synergy example: STAR and Phenix upgrades

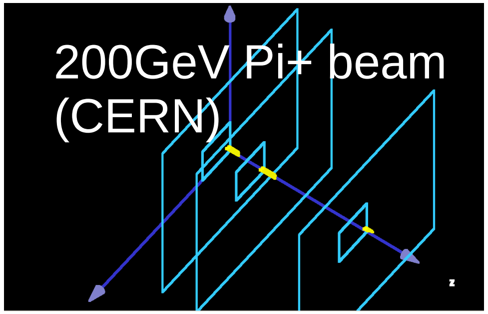
- Composites facility producing mechanics for BOTH detectors.
- STAR HFT upgrade is a major LBNL project using engineering resources and composites.
- Know-how from ATLAS construction being applied, and new concepts from STAR HFT seeding development for ATLAS upgrades

Synergy example: SOI & bulk active pixels
(silicon on insulator)

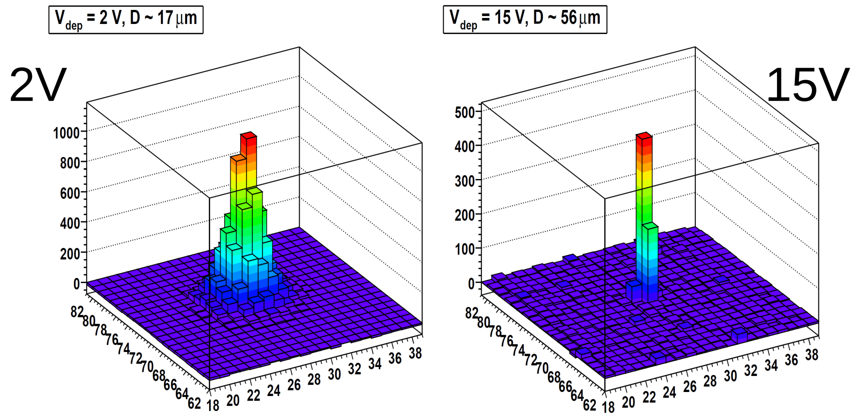
Started as ILC R&D. Now fully supported outside HEP for Electron Microscopy and Photon science *(P. Denes)*



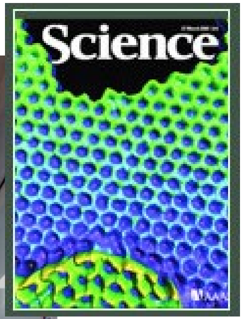




OKI SOI process in collaboration with KEK



Improved point resolution with LBNL back-side processing for reverse bias bulk depletion



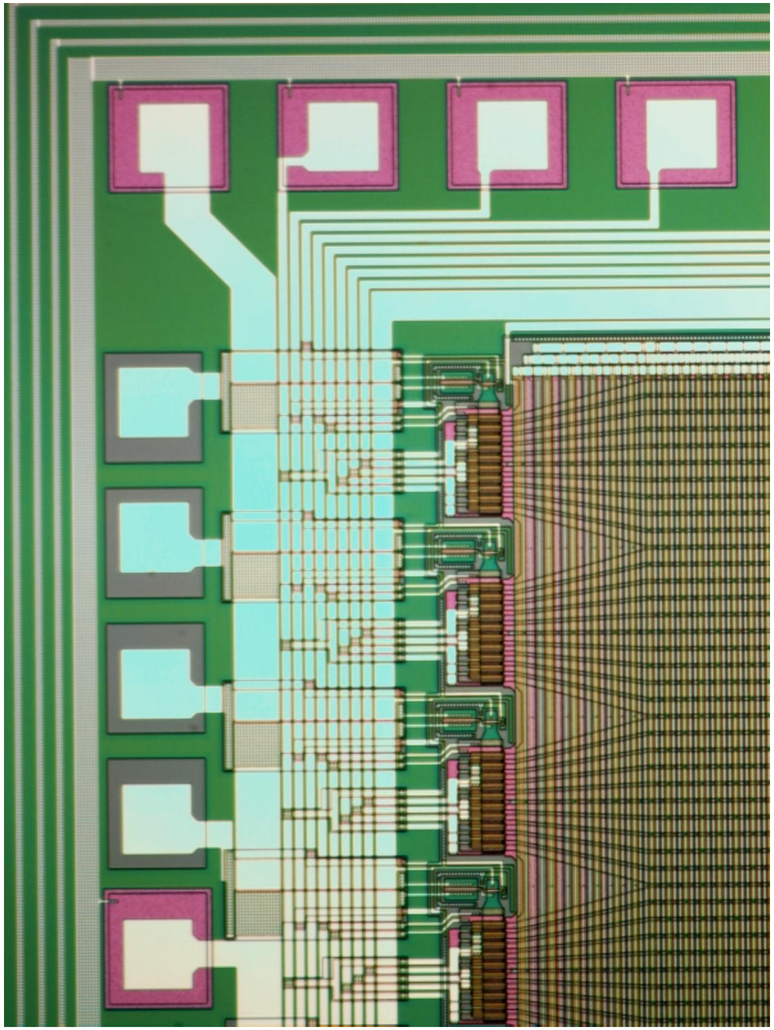
Record-breaking electron microscope (bulk CMOS)

SOI

X-Ray detection with femtosecond timing

Synergy example: parallel CCDs for photon science

- Parallel readout CCDs can greatly increase acquisition speed of light source experiments.
- This is a different solution than SOI active pixels. Each solution has different advantages.
- Next step is to use 65nm technology to fit one ADC per CCD column
- Combined 65nm submission with pixel readout for Energy Frontier and digitizer for Intensity frontier



Parallel readout CCD detail

Outlook

R&D challenges driven by physics

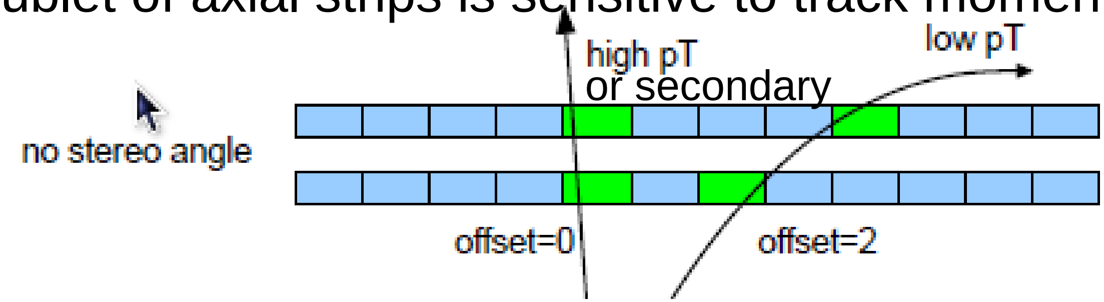
- Energy Frontier detectors:
  - LHC upgrades and Lepton Colliders detectors:
    Low mass, low power, high rates, rad hard, new ICs, etc.
- Cosmic Frontier detectors:
  - Branching out from HEP detectors to photon sensors: CCDs, IR, CMB
    - Future work: single photon counting, high rates, wide wavelength coverage
  - Dark matter, $0\nu\ \beta\beta$, neutron detection
    - Future work: new applications of TPCs, lower the cost of GE to enable large scale detectors

- **Continued support for R&D facilities and infrastructure critical for development of advanced detectors**
- **Continued collaboration with university groups is an essential part of the LBNL program**

Backup

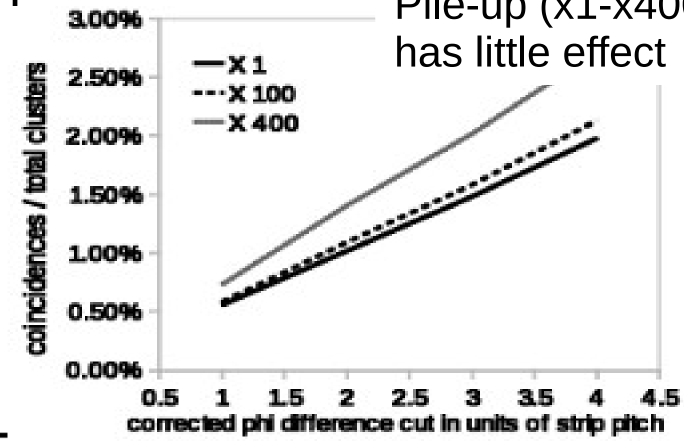
Turning staves into track trigger staves

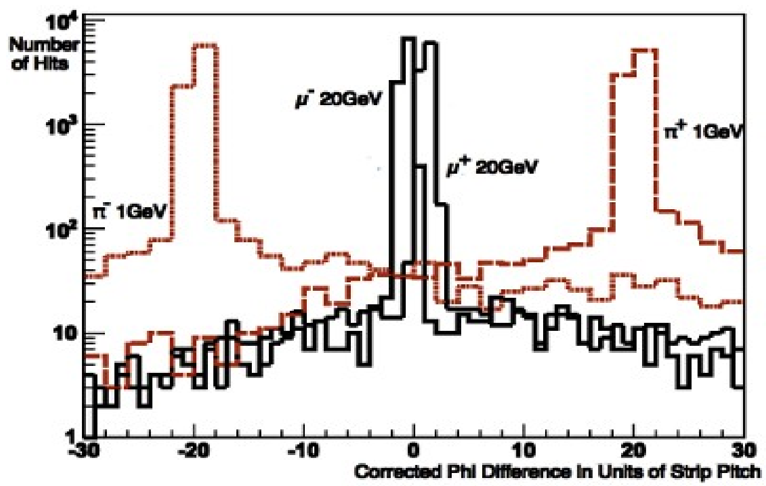
- Redundant doublet of axial strips is sensitive to track momentum



- Simulations show data reduction factor of 100 is possible
(T. Mueller, B. Heinemann, M. Garcia-Sciveres)

Data reduction vs cut offset. Pile-up (x1-x400) has little effect





offset

- Implementation concept :
(C. Haber, M.Garcia-Sciveres)