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Title: GHz Hard X-ray imaging: challenges in efficiency, timing and rate

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GHz hard X-ray imaging

Challenges in efficiency, timing and rates

Zhehui Wang

P-25, Los Alamos National Lab

(Collaboration discussion with MIT/LL, LLNL)

LANL Collaborators (growing):

C. W. Barnes, E. Guardincerri, J. Kapustinsky, K. Kiwatkowski,

A. V. Klimenko, S.-N. Luo and C. L. Morris

(May. 16, 2013)

Outline

- **LANL MPDH/MaRIE HX imaging requirements**
  - The efficiency challenge
  - The ps challenge
  - The GHz challenge
  - The GB challenge
- **Detectors today**
- **Paths forward**

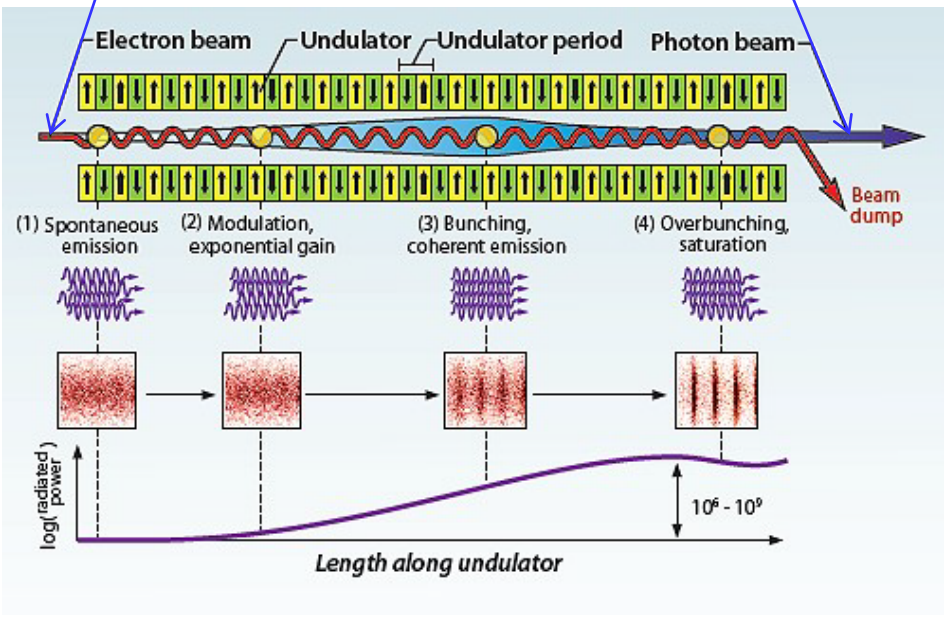
No solution exists today.

Very exciting time for detector/instrument developers

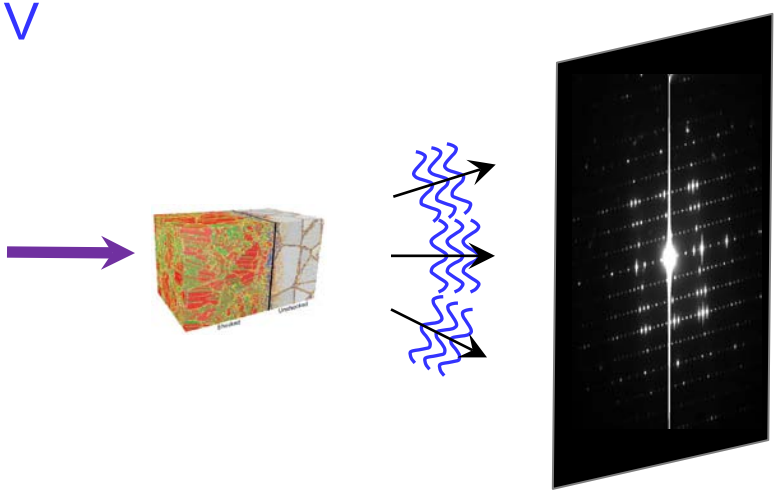
MaRIE XFEL

12 GeV

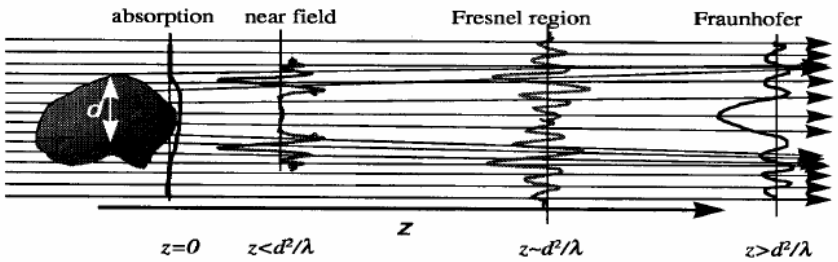
5 - 42 keV



80 - 100 m



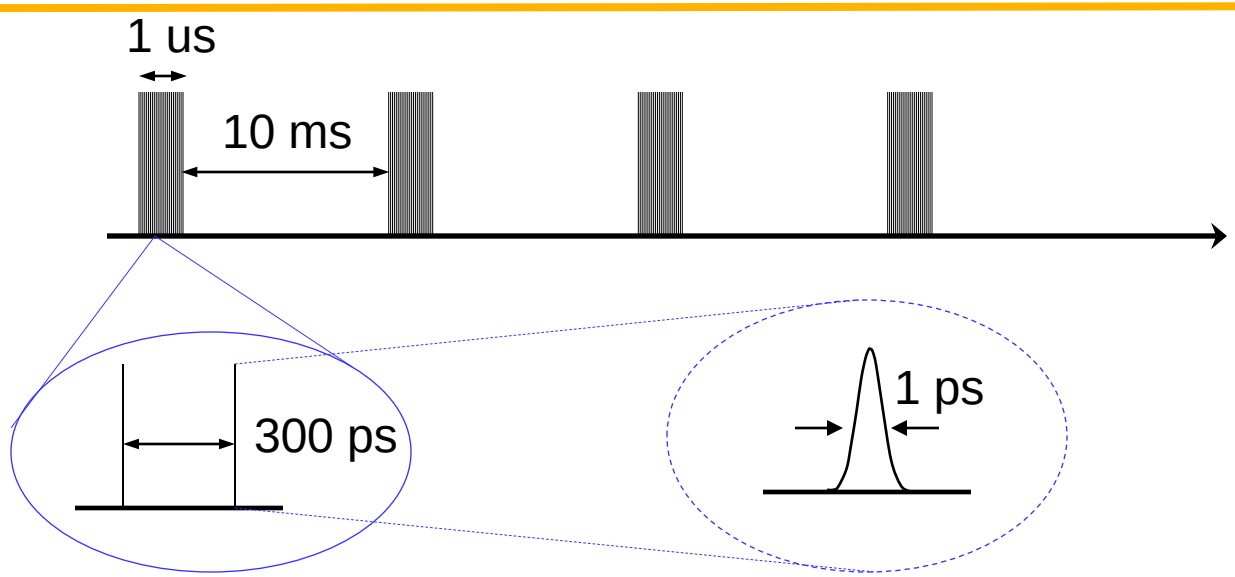
Shadow/contact imaging | Phase contrast | Holography/CXDI



A. Snigirev et al, RSI (1995)

Input: Rich Sheffield, Richard Sandberg

Experimental time scales for MPDH



τ_1 ~ 1 ps (laser pulse/gating) — Light source

τ_2 ~ 300 ps (3 GHz or faster) — Detector Technology

τ_3 ~ 1 μs — Detector Technology / cost

τ_4 ~ 10 ms — Source/Facility cost

Input: C. W. Barnes

R&D Challenges for MPDH HX imaging

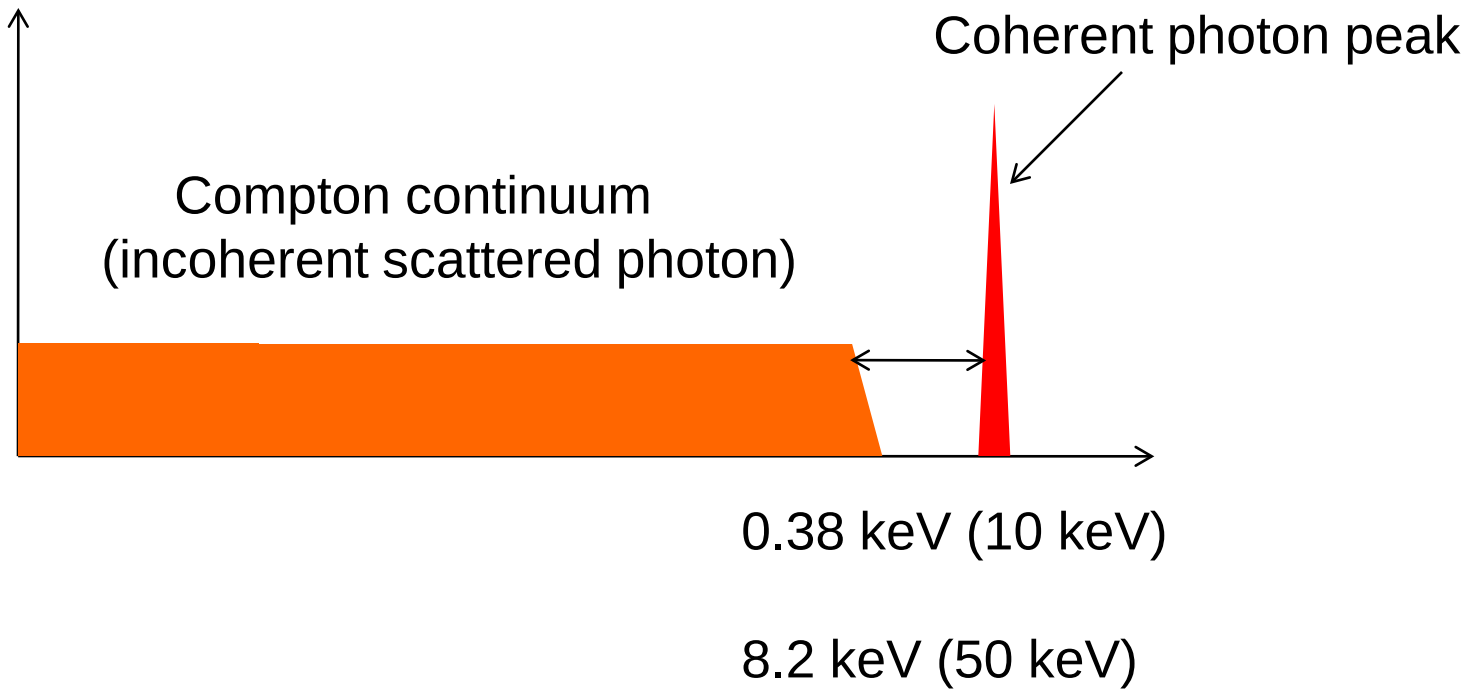
- **The "efficiency + ps challenge"**
  - High-efficiency (>50%) for 42 keV X-rays
  - fast time response (300 ps or less)

- **The "GHz challenge"**
  - Sub-ns (~ 3 GHz or faster) frame rate X-ray cameras
  - Movie length, 10 to 10,000 frames

- **The "GB challenge"**
  - High data rate, 6 x 10^{16} bit of data per second = 3 x 10^{9} (frame per second) x 10^{6} (number of pixels) x 20 bit.
  - Large amount of data, up to 10 GB per 1 μs event .

Energy resolution desirable

Separation of coherent from incoherent photons, background reduction

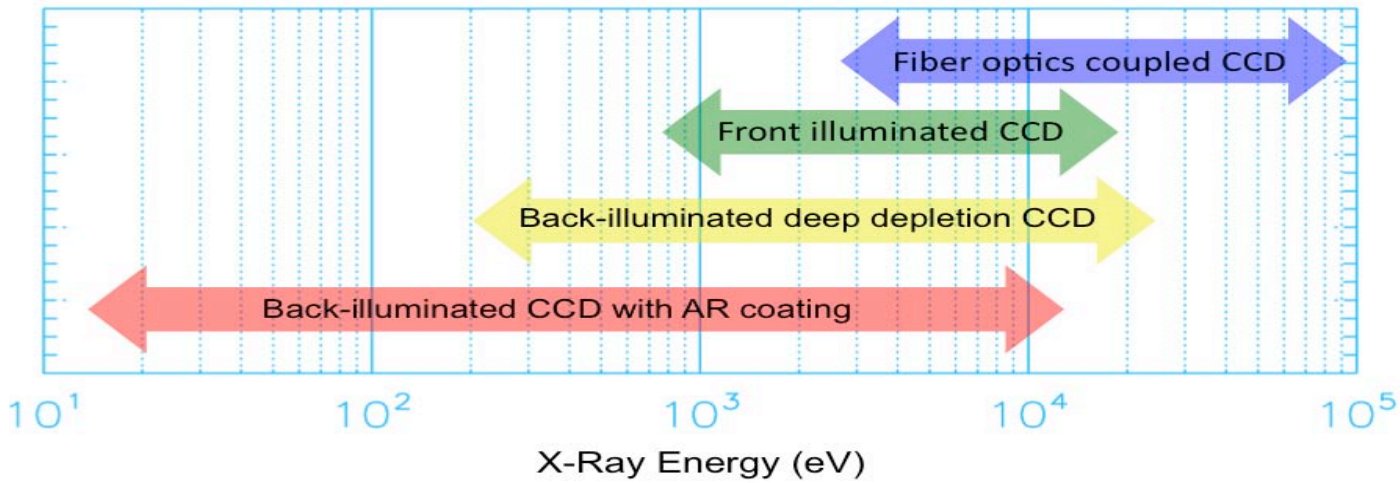


Outline

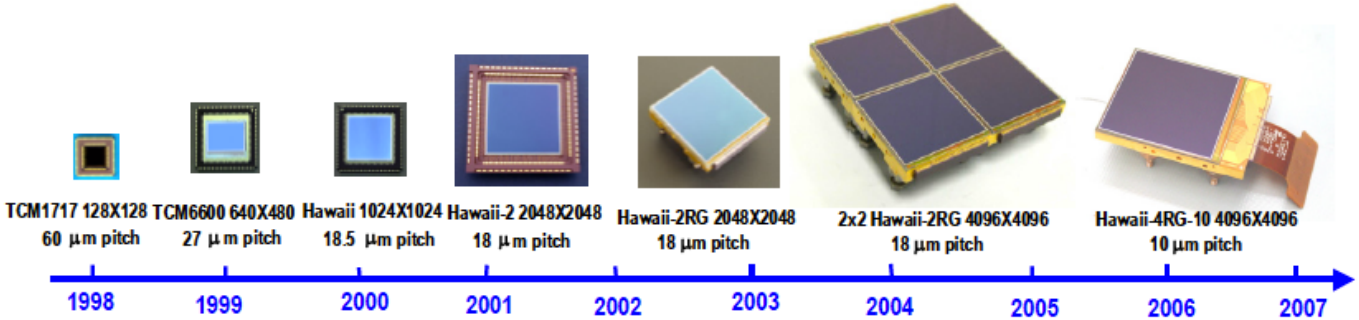
- **MPDH/MaRIE HX imaging requirements**
  - The efficiency challenge for HX (42 keV)
  - The ps (“sub-ns”) challenge
  - The GHz challenge
  - The GB challenge
- **Detectors today**
- **Paths forward**

Commercial X-ray detectors (Si dominance)

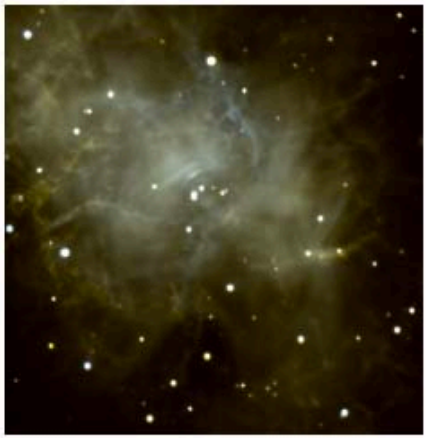
CCD



CMOS



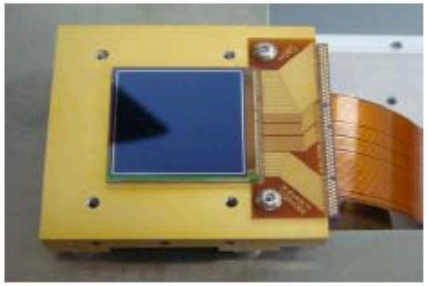
State-of-the-art hybrid CMOS-based detection (Si dominance)



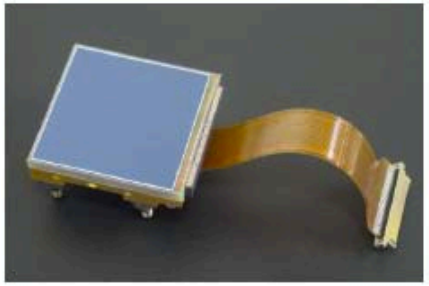
The Crab Nebula (M1)

NGC2683 Spiral Galaxy

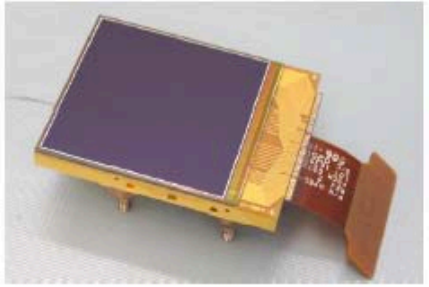
The Hercules Cluster (M13)



1Kx1K H1RG-18 HyViSI



2Kx2K H2RG-18 HyViSI



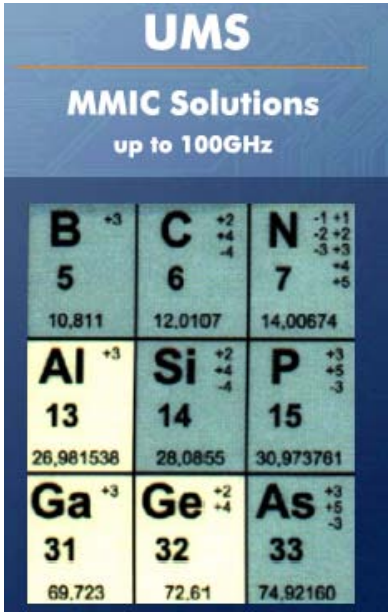
4Kx4K H4RG-10 HyViSI

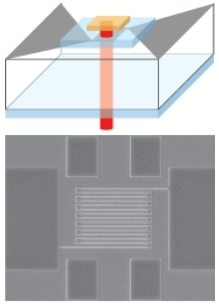
(too slow for MPDH)

Small group R&D, industrial activities *(many more)*

New scintillators

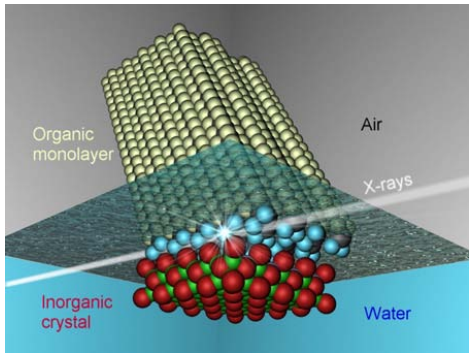
(Zhu et al.)





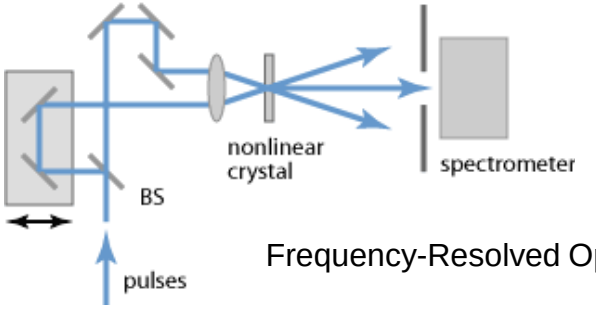
SNSPD

(Gol'tsman et al)



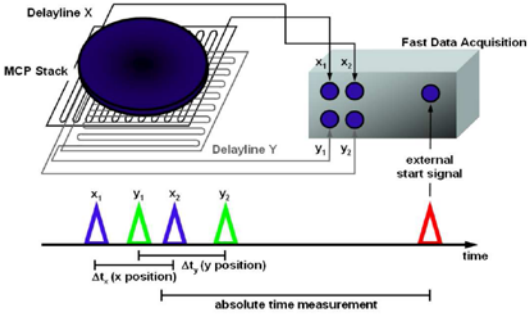
Molecular detectors

(Kemtko et al; Tahara et al)



Frequency-Resolved Optical Gating

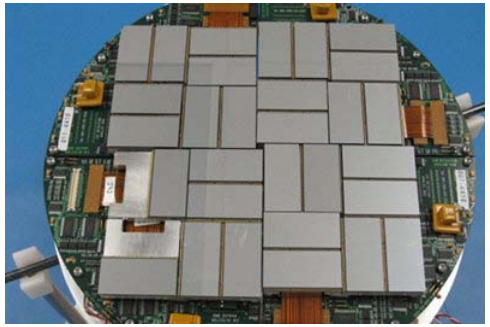
(Trebino et al.)



Delayline detectors

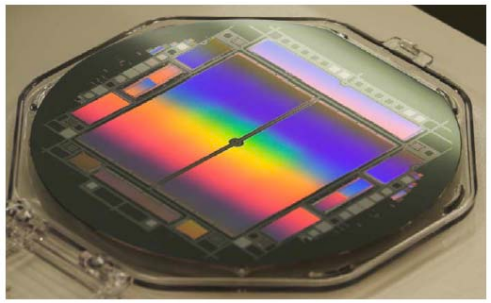
(http://www.surface-concept.de/)

Source-specific development



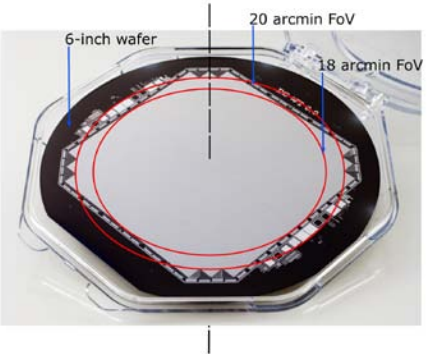
CS-PAD

Synchrotron/XFEL



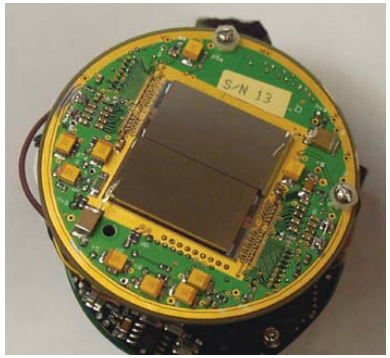
pnCCD

Synchrotron/XFEL/Astronomy



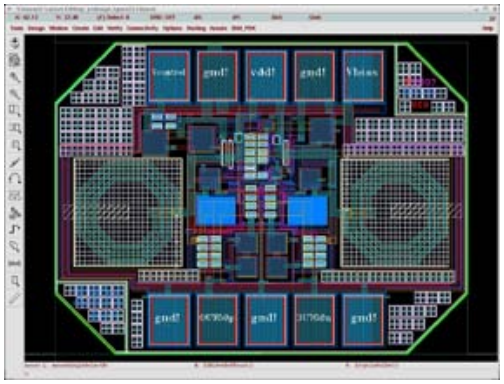
DEPFET

Astronomy/Synchrotron/XFEL



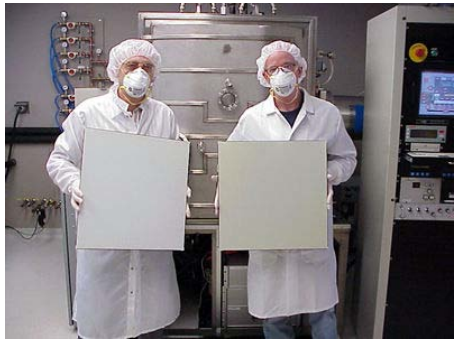
CZT detector

NIF



Large-area ps photodetector

HEP



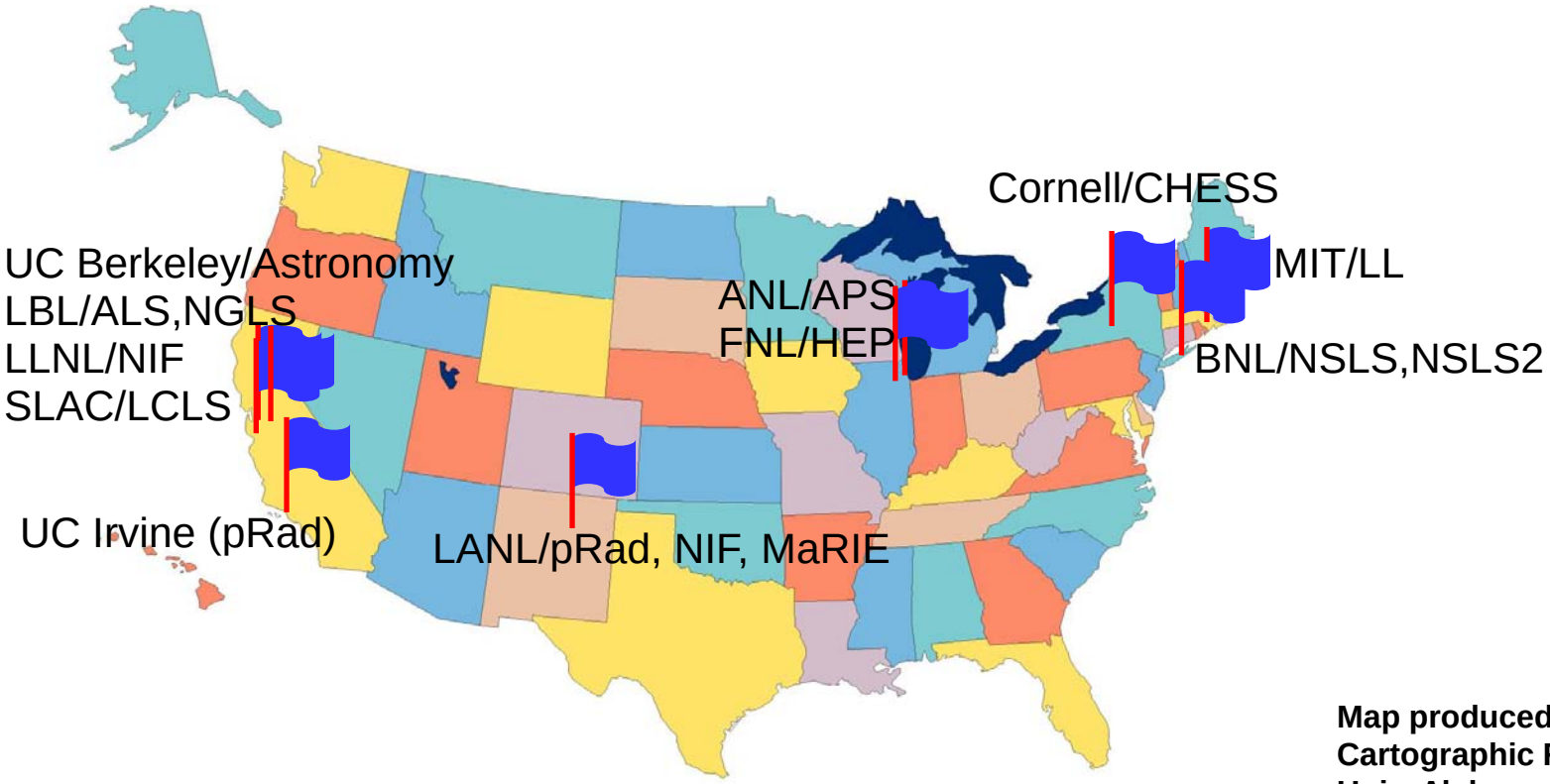
CsI(Tl) array

Commercial (RMD)

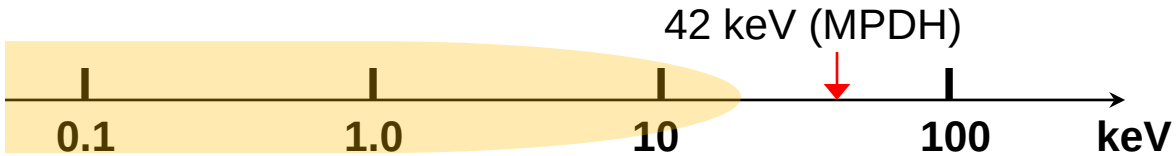
Outline

- **Paths forward**
  - Peer groups
  - Sensor development strategies
    - Si
    - High-Z semiconductors
    - Scintillators

Major US X-ray detector R&D groups ← major sources



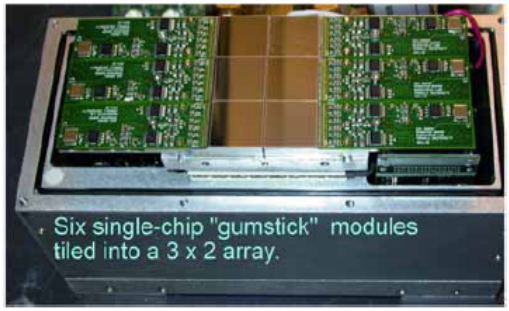
Map produced by Cartographic Res. Lab Univ. Alabama



Beyond CS-PAD: Mixed Mode PAD

PAD Tile Format	6 modules, each 128 x 128 pixels
Pixel Size	150 µm x 150 µm
Max Frame Rate	1,000 Hz
Data Rate	400 MB/s
Read Noise (rms)	0.15 X-ray [8 keV] / pix
Sensor	300 um silicon, fully depleted
Well Capacity	> 3 x 10^7 X-rays/pix/frame

Reconfigurable Tiled Array

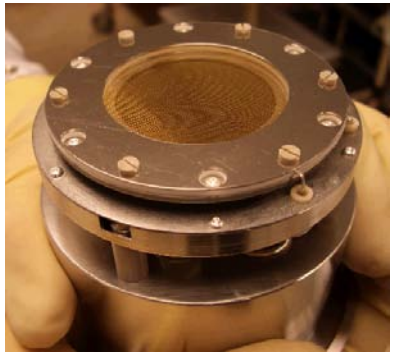


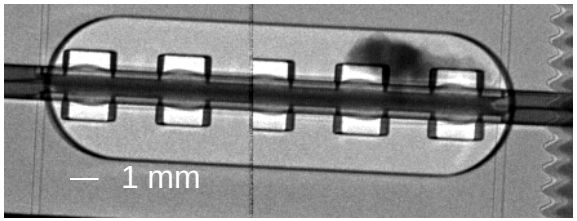
Credit: Sol M. Gruner
Cornell Univ.

***Chip development: collaboration with Area Detector Systems Corp.**

Tremsin's team (Space Sci. lab/UC Berkeley)

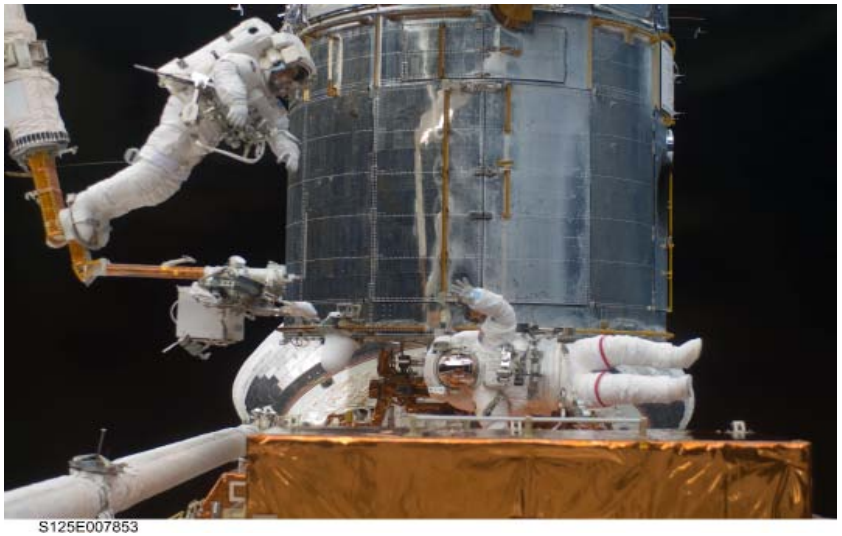
Synchrotron beamline detectors:
ARPES – angular resolved
photoelectron emission spectroscopy



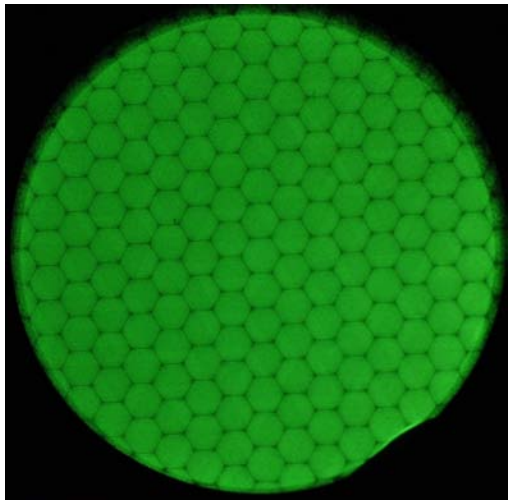


Thermal neut.
radiography

COS detector
installed on last Hubble repair mission

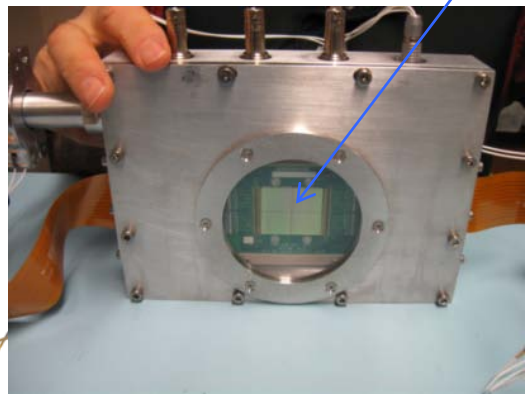


ANL and collaborators– MCP technologies



Phosphor screen image of a 33mm diameter borosilicate/ALD MCP with 20µm holes

512x512 of 55 um pixels
(2x2 Timepix ASIC)



- ✓ MCP technology
- ✓ ASIC's (Timepix, U. Hawaii)
- ✓ ALD and other processes

Credit: A. Tremsin, UC Berkeley.

European detector R&D ← ESRF, XFEL

European XFEL @ DESY

Si

- HPAD -> AGIPD (DESY)
- DEPFET-APS -> DSSC (DESY)
- LPD (UK group)
- LAMBDA (Medipix-based)

High-Z

- Germanium
- Galapad (GaAs)
- HiZPAD (CdTTe)
- XNAP

European XFEL Si imagers

	DSSC	LPD	AGIPD
# Pixels	1k × 1k	1k × 1k	1k × 1k
Pixel size	200μm × 200μm	500μm × 500μm	200μm × 200μm
Sensor	DEPFET array	Si-pixel	Si-pixel
Dynamic range	$>10^4$ ph	2×10^4 ph (10^5 ph)	2×10^4 ph
Noise	$\sim 15 \times 10^{-3}$ph ~50e	0.21ph (0.93ph) 700e (3100e)	$\sim 45 \times 10^{-3}$ph ~150e
Concept	DEPFET nonlinear gain compression Per-pixel ADC	Multiple gain paths On-chip ADC	Adaptive gain switching (preset gain option)
Storage	8bit DRAM	3-fold analogue	2bit digital + analogue
Storage depth	≥256	512	>200
Challenges	Linearity & calibration In-pixel ADC DRAM refresh Power budget Pixel area	Preamplifier: noise, dynamic range & PSRR Feedback discharge Analogue storage	Dynamic gain switching Charge injection Analogue storage Pixel area
	Radiation hardness		

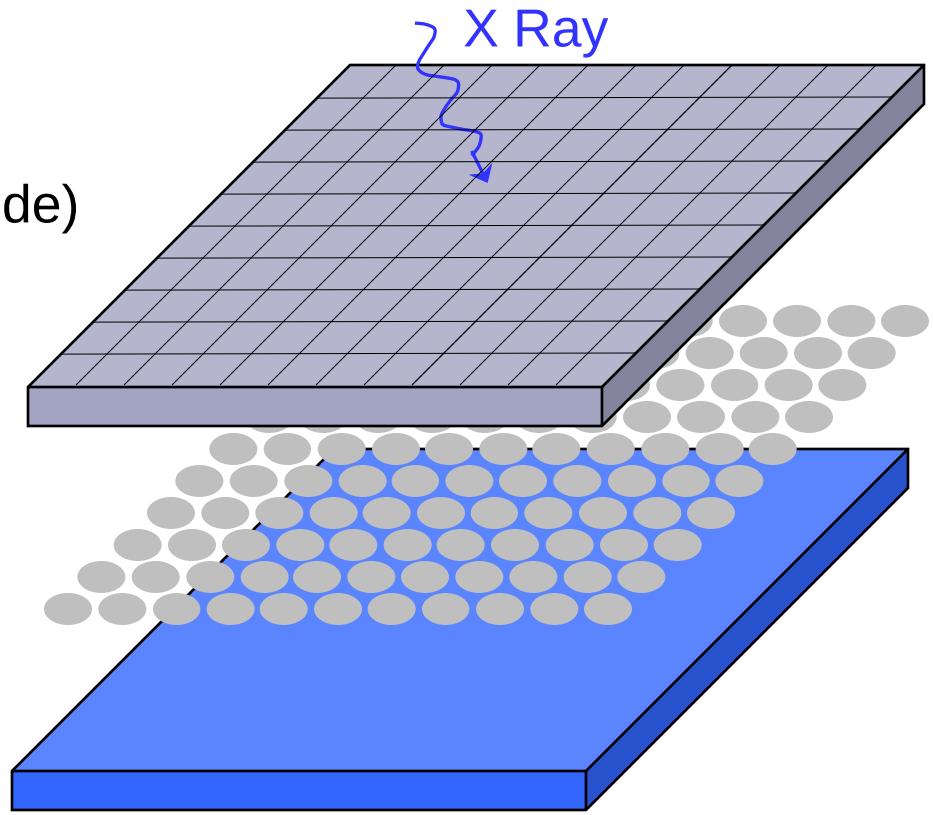
U. Trunk, ASICs for XFEL Detectors, CMOS ET Workshop (2009)

Hydrid CMOS: Flexible, Fast, bright Future

Sensor layer (diode)

Bump bonding

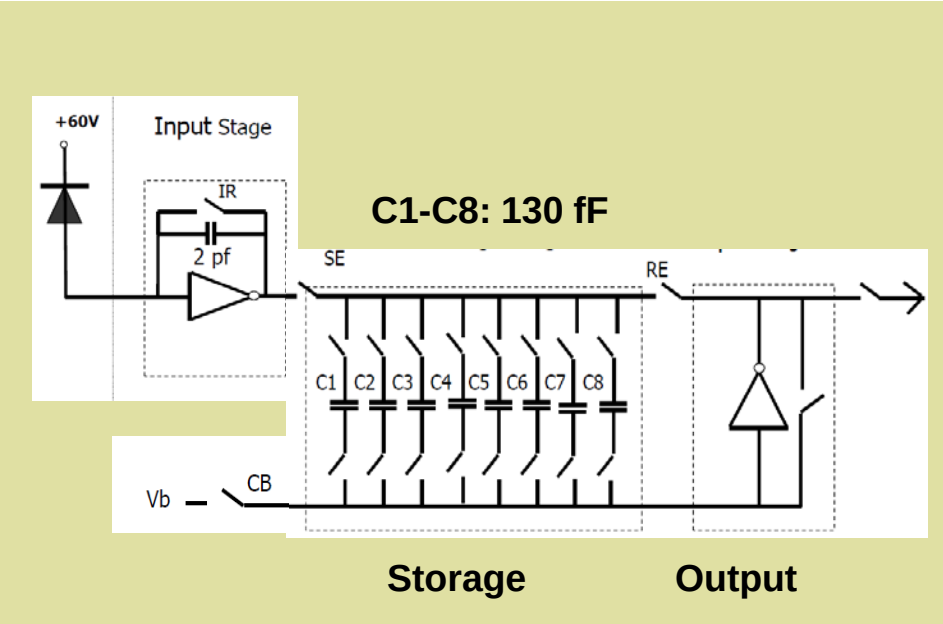
ASIC(CMOS)



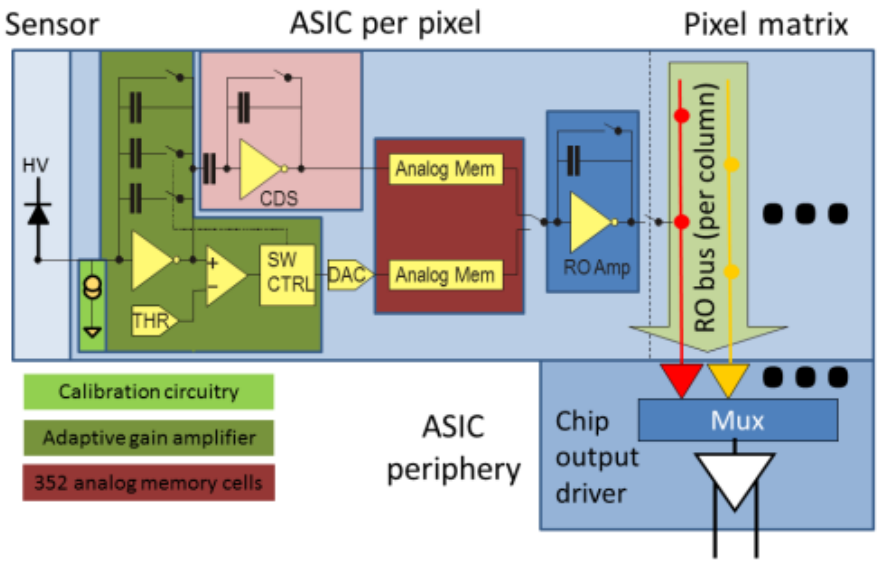
Los Alamos NATIONAL LABORATORY EST. 1943

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

ASIC architectures



G. Rossi *et al* (1999)



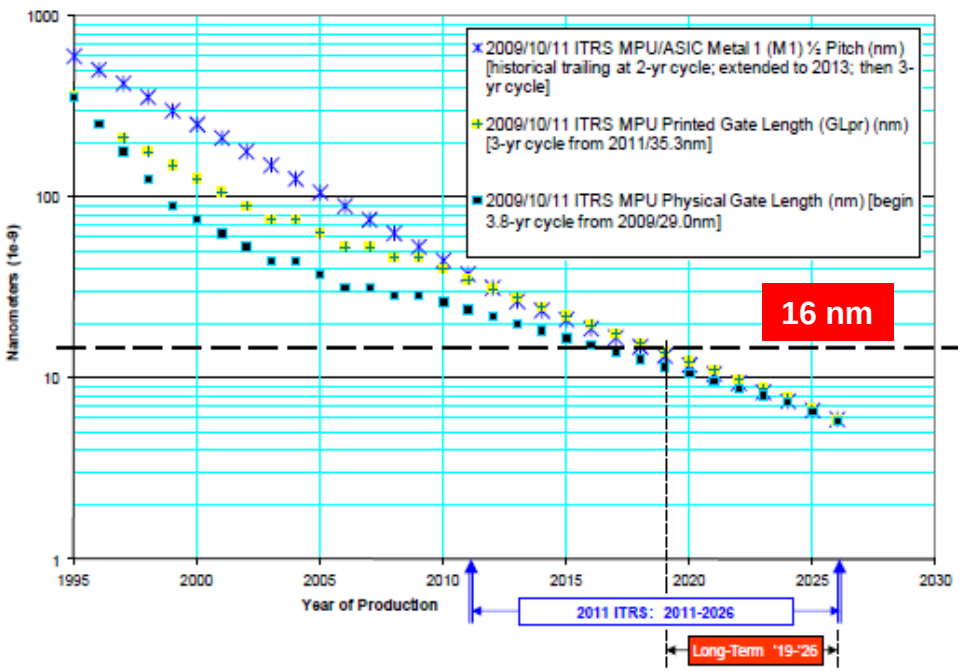
AGIPD

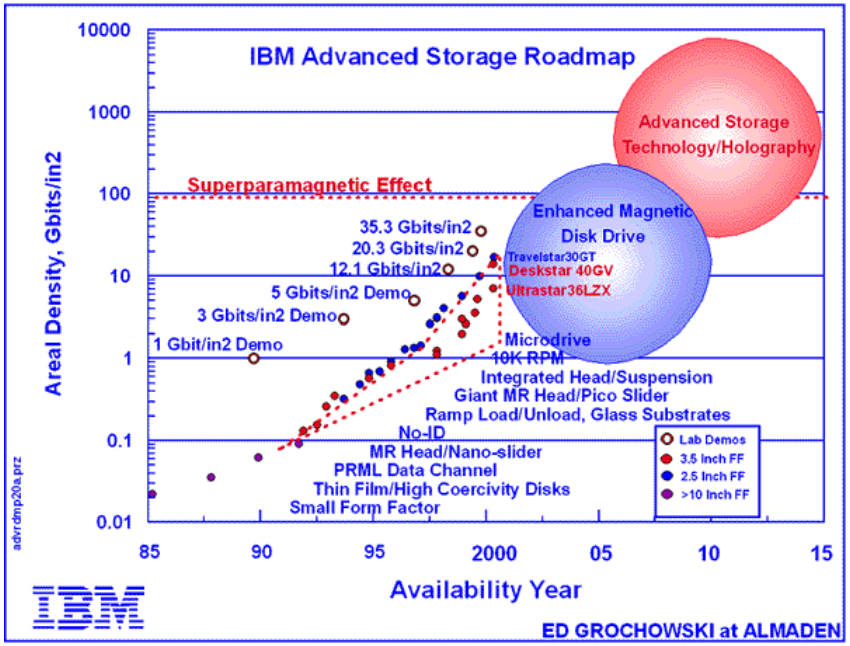
ASIC Fabrication: *shares* CMOS technology

- **IBM cmrf8sf DM (130nm CMOS)**
- **Chosen by DSSC, AGIPD, LPD**
- **De-facto standard for LHC upgrades**
- **Advanced over cmos6sf (0.24 um)**
- **Well established for layout based radiation hardening**
- **Permits sufficiently high integration density**
- **(dual) MIMCAPS can be employed as a (fallback) solution for storage caps.**
- **Long-term availability**
- **Uncertainties do exist (*IBM, threshold $50 M*)**

U. Trunk, ASICs for XFEL Detectors, CMOS ET Workshop (2009)

Fast electronics & data storage challenges: it takes time



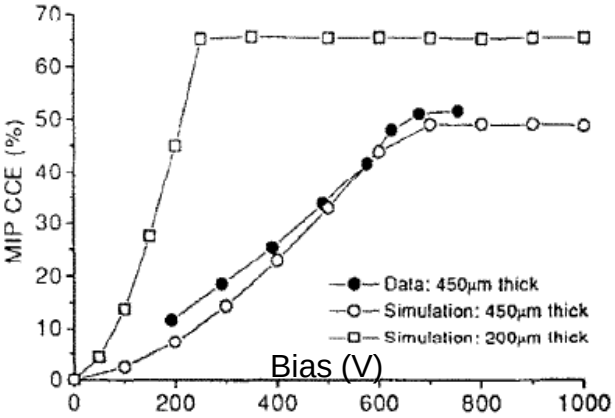


MPU/ high performance ASIC half pitch and gate length trends

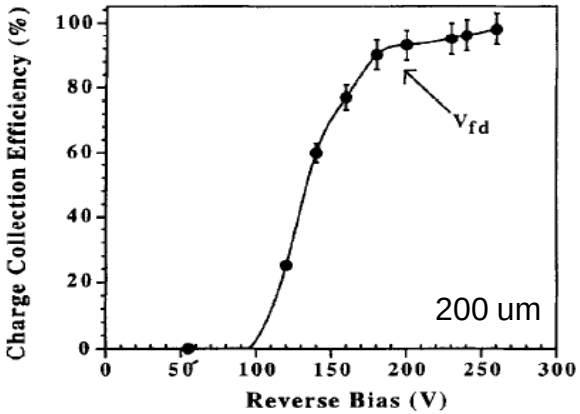
From: ITRS 2011 report

Sensor challenges

- **Materials**
  - *Standard (Si, Ge)*
  - High impurities (charge trapping)
  - Defect densities
  - Stoichiometric imbalances
  - Radiation damage
- **Structures**
  - Natural
    - Crystalline
    - Amorphous
  - Fabrication technologies
  - Signal transport
  - Integration
  - Testing



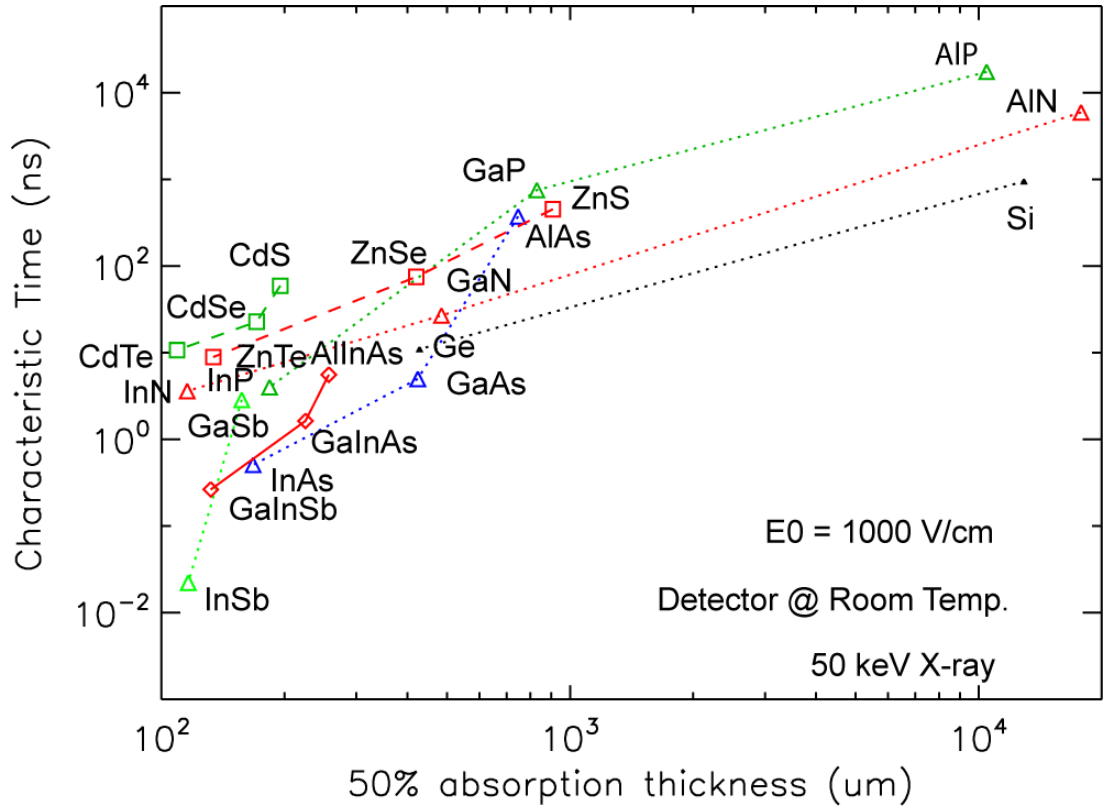
C. M. Buttar, NIM A 395 (1997) 1.



R. L. Bates et al, NIM A 392 (1997) 269.

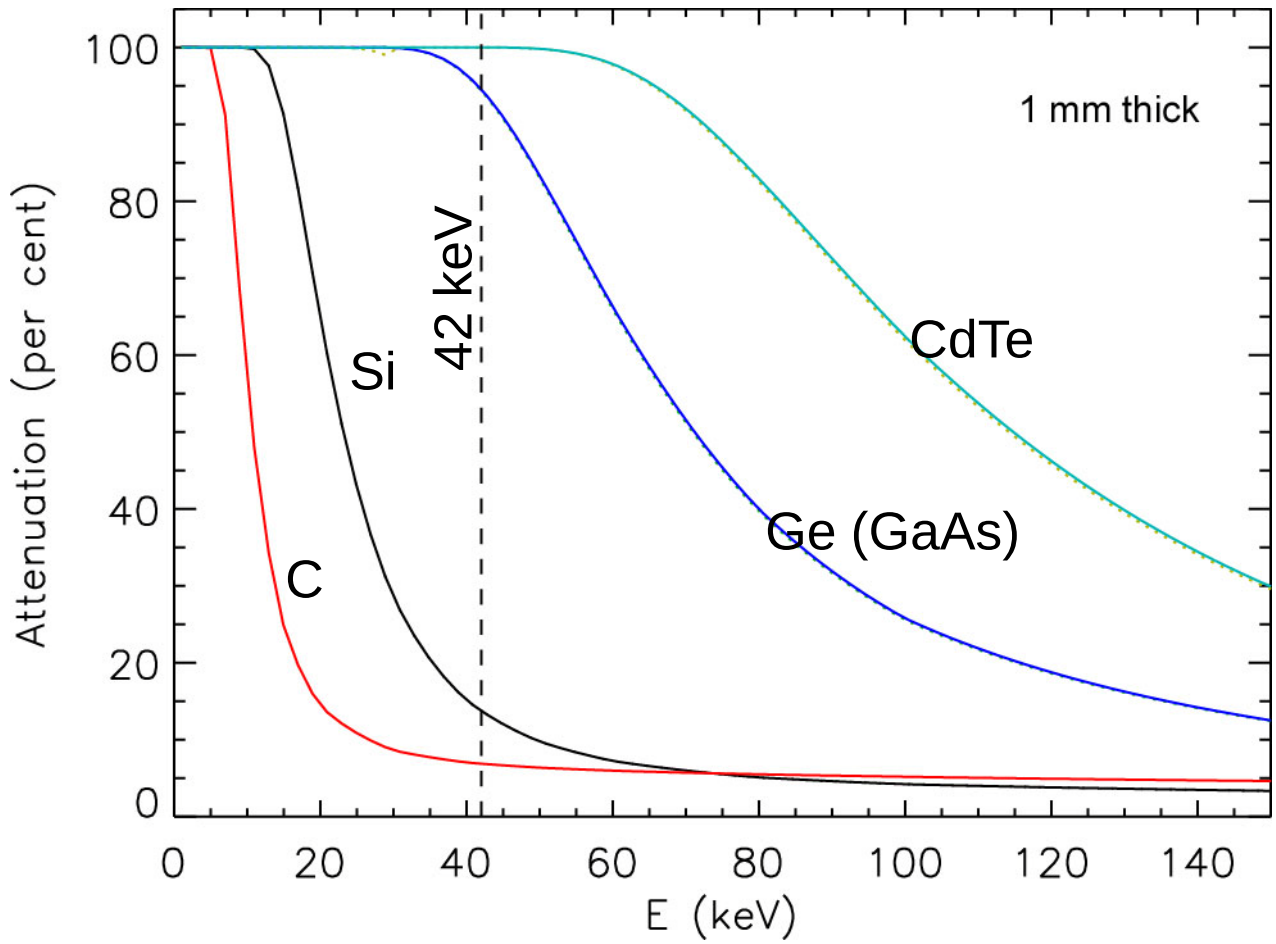
1 yr. ago…

- Maximizing electron mobility
- Lower temperature
- Higher electrical bias
- Ultimate "drift" limit ~10^8 cm/s?

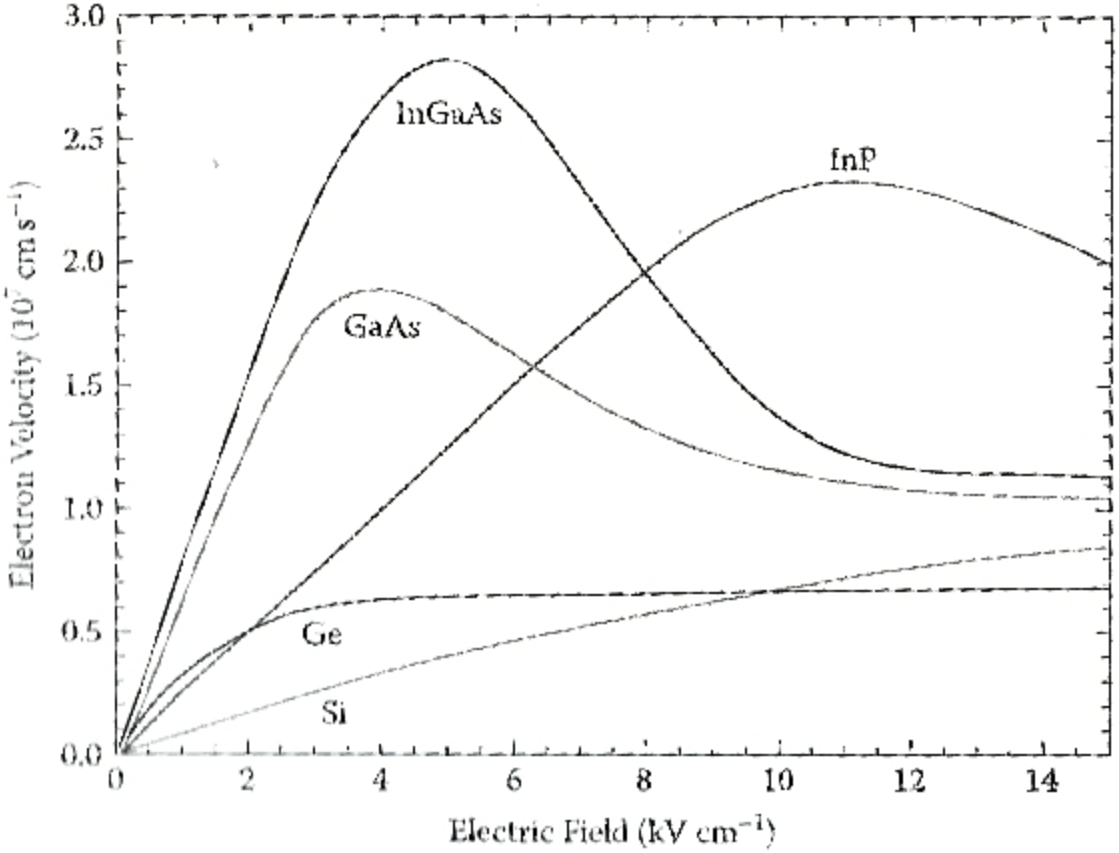


Wang et al, RSI (2012)

Efficient absorption thickness ← High Z



Response time ← electron drift time



10^5 m/s x 1 ns
= 100 um

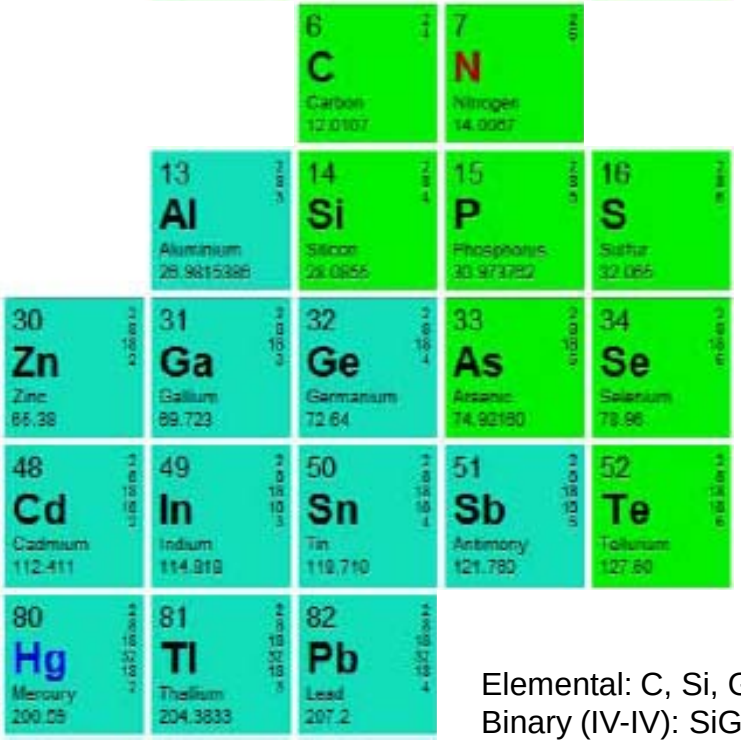
10^5 m/s x 50 ps
= 5 um

Ee = 0.03 eV

3 x10^8 m/s x 1 ns
= 300 mm

A. Owens, *Compound Semiconductor Radiation Detectors (2012).*

Semicondutor down-selection

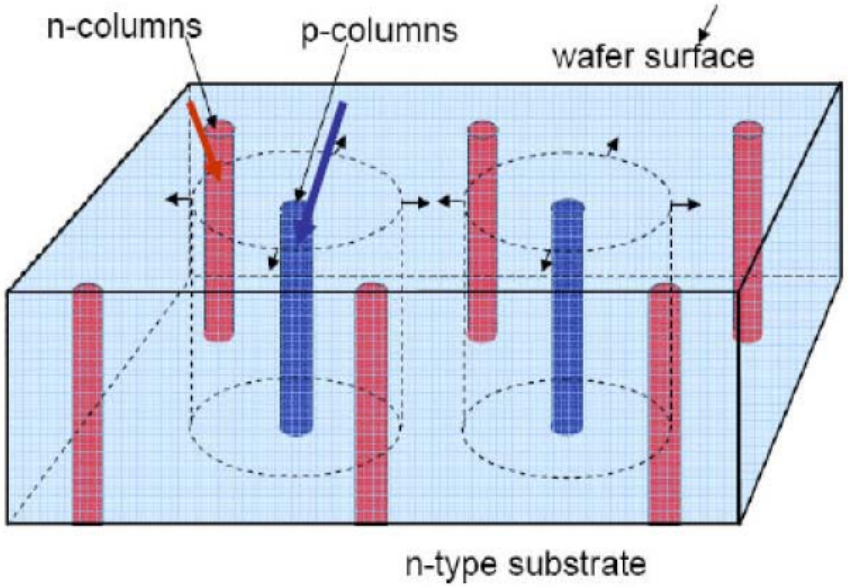


Elemental: C, Si, Ge
Binary (IV-IV): SiGe
Binary (III-V): InP, GaAs
Binary (II-VI): CdTe, HgTe
Binary (I- VII):AgCl
Ternary: HgCdTe, CZT
Quarternary: InGaAsP

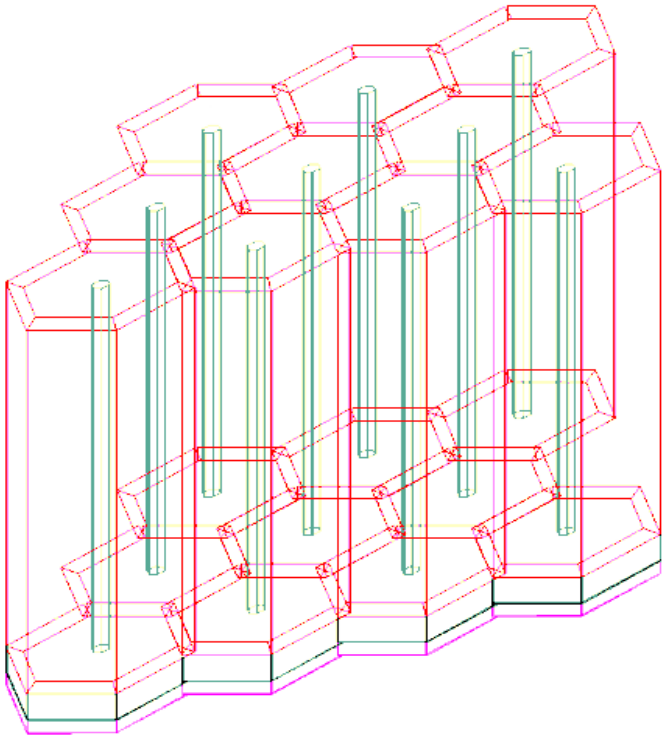
- **Si**
- **GaAs, Ge**
- **InP**

3D structures ← reducing charge collection time

150 - 300 ns → 5 - 30 ns → 300 ps

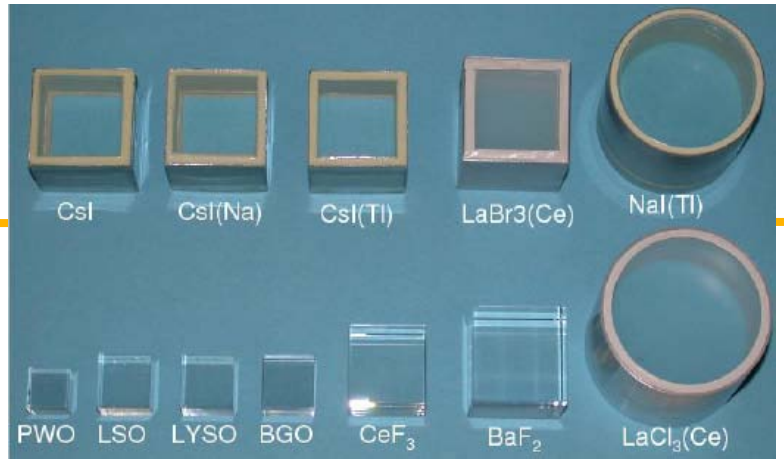


D. Eckstein , DPG spring meeting, Munich (2009).

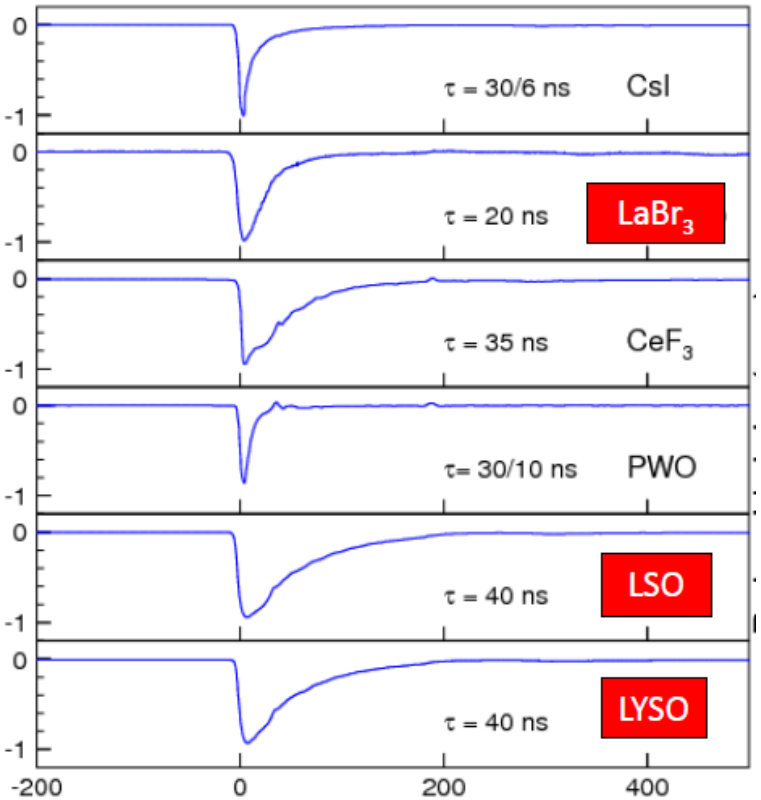


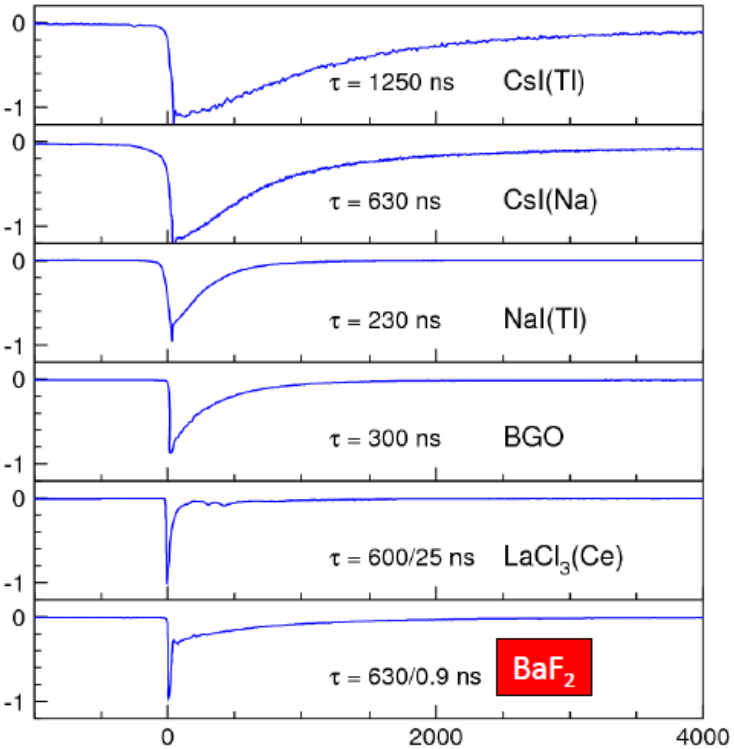
Z. Li , BNL Seminar, Apr. 20 (2011).

Scintillators … the list is growing



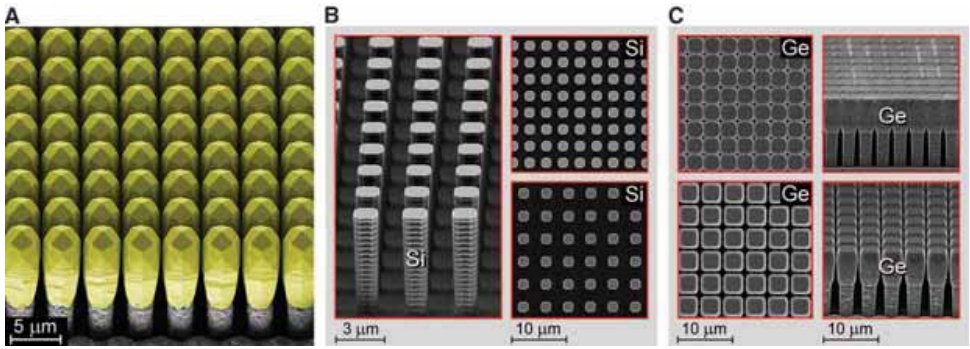
Credit: R-Y Zhu, Caltech



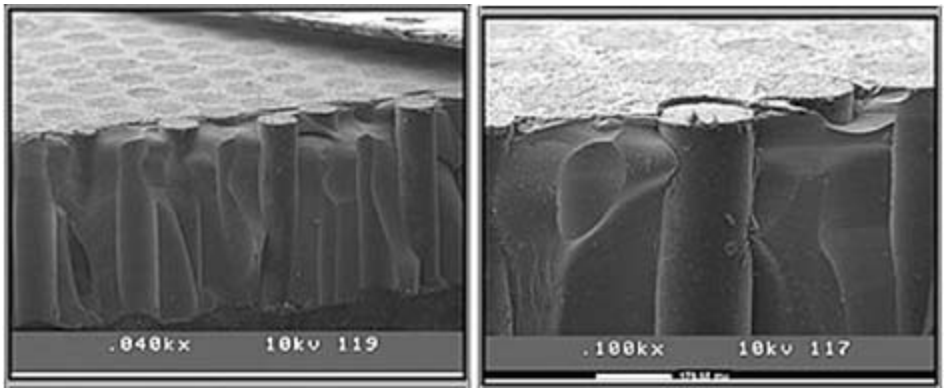


Columnar structures for efficient light guide

- **R & D**
- **Reduction to practice**

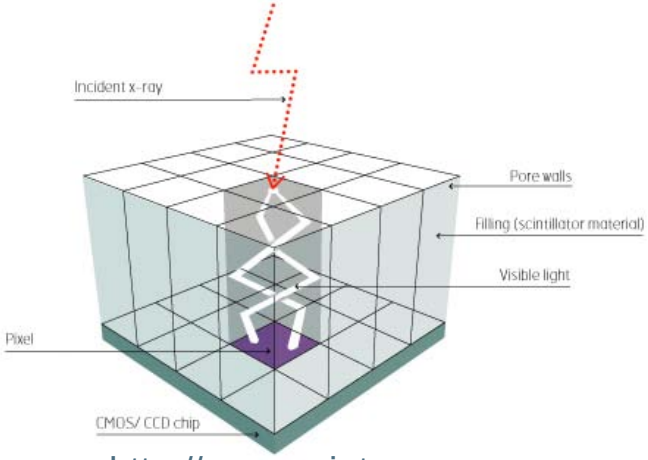


C. V. Falub et al, *Science* **335** (2012) 1330.



RMD (Scintillator injection technology)

Capillary diameter: 25 – 2000 um



http://www.scint-x.com

Summary

- **Requirements of MPDH HX imaging unprecedented**
  - Efficiency, ps, GHz, GB
- **No technology comes close in overall performance**
  - Efficiency < 10% for HX @ 42 keV
  - Time/frame rate off by ~ x 300
- **Phased development approach**
  - ~ 100 ns (today) → 5 - 30 ns → 300 ps
- **Multi-pronged approach for sensor material & 3D structure**
  - Si
  - High-Z semiconductors
  - Fast scintillators

Very exciting time for detector/instrument developers