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**

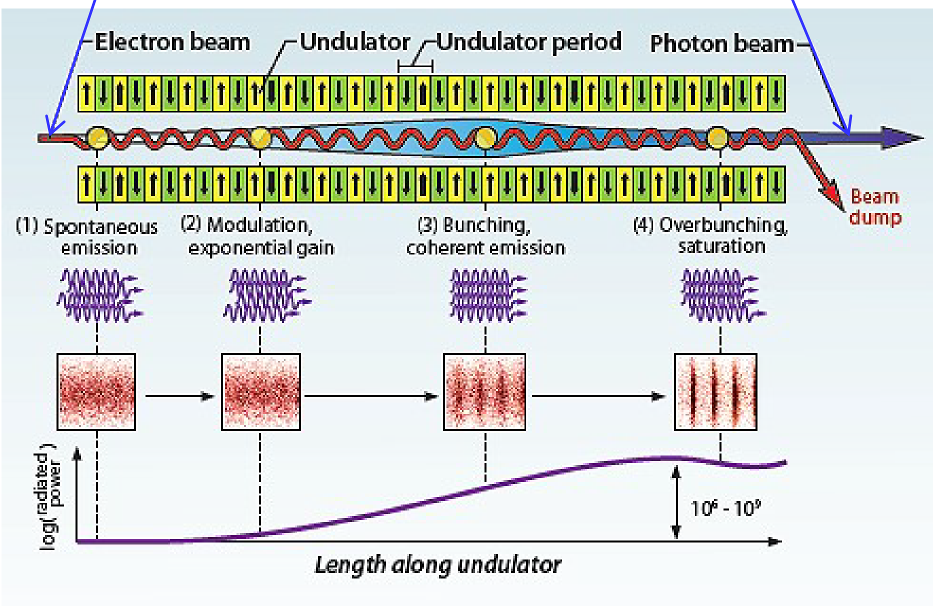
No solution exists today.

Very exciting time for detector/instrument developers

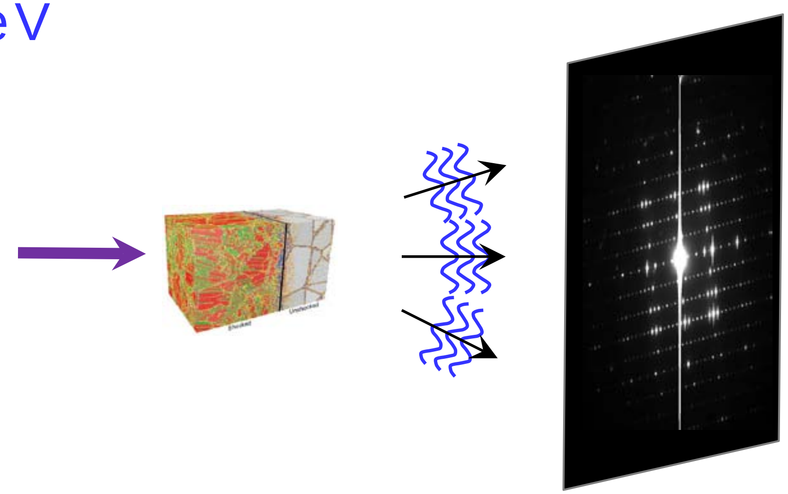
MaRIE XFEL

12 GeV

5 - 42 keV



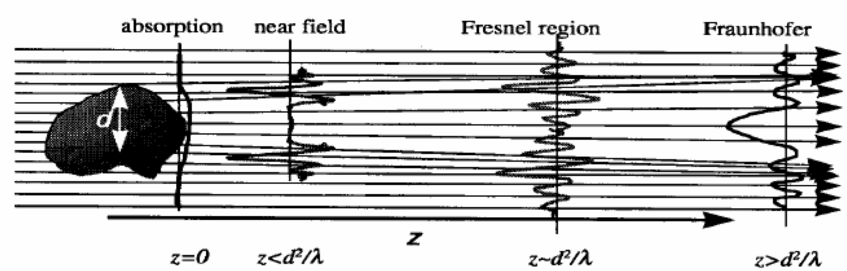
80 - 100 m



Shadow/contact imaging

Phase contrast

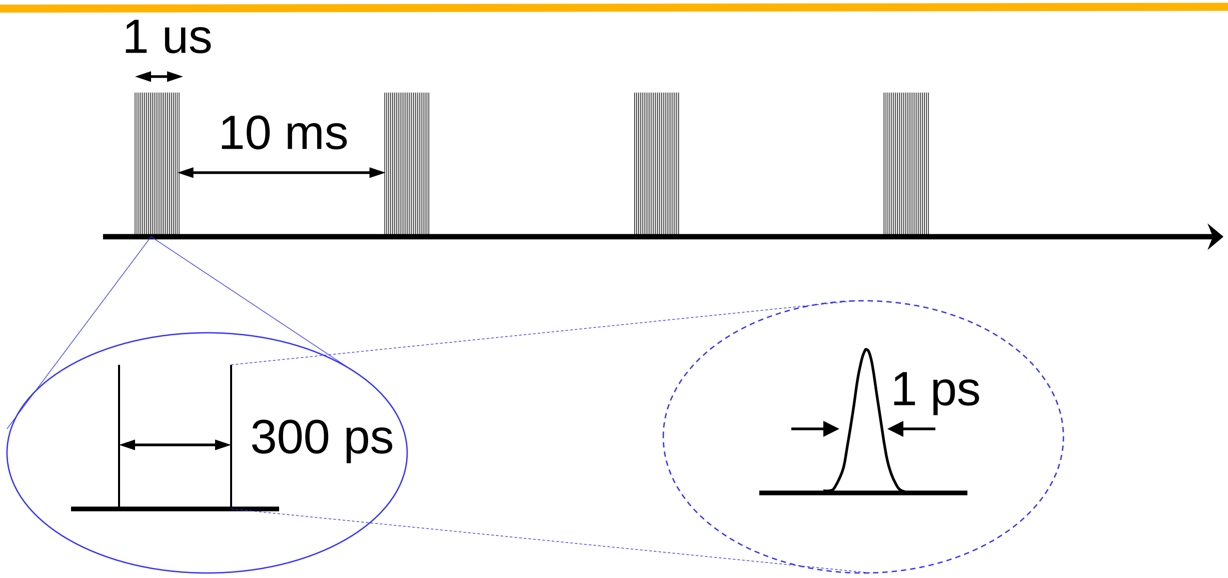
Holography/CXDI



A. Snigirev et al, RSI (1995)

Input: Rich Sheffield, Richard Sandberg

Experimental time scales for MPDH



τ_1 ~ 1 ps (laser pulse/gating)

τ_2 ~ 300 ps (3 GHz or faster)

τ_3 ~ 1 μs

τ_4 ~ 10 ms

↔

Light source

Detector Technology

Detector Technology / cost

Source/Facility cost

Input: C. W. Barnes

R&D Challenges for MPDH HX imaging

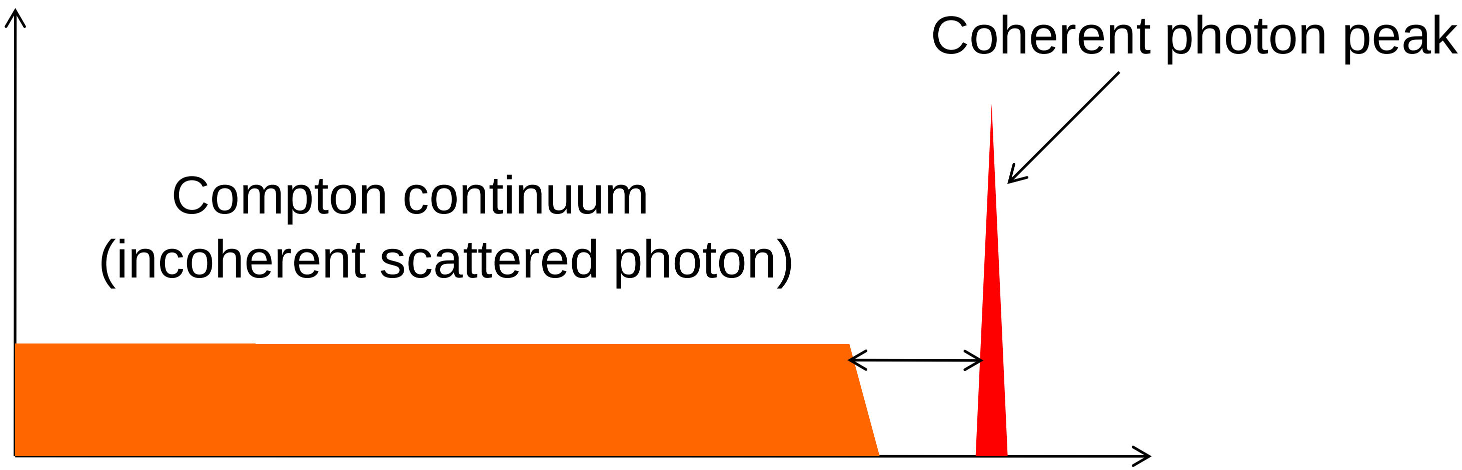
- **The "efficiency + ps challenge"**
  - High-efficiency (>50%) for 42 keV X-rays
  - fast time response (300 ps or less)

- **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, 6×10^{16} bit of data per second = 3×10^{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



0.38 keV (10 keV)

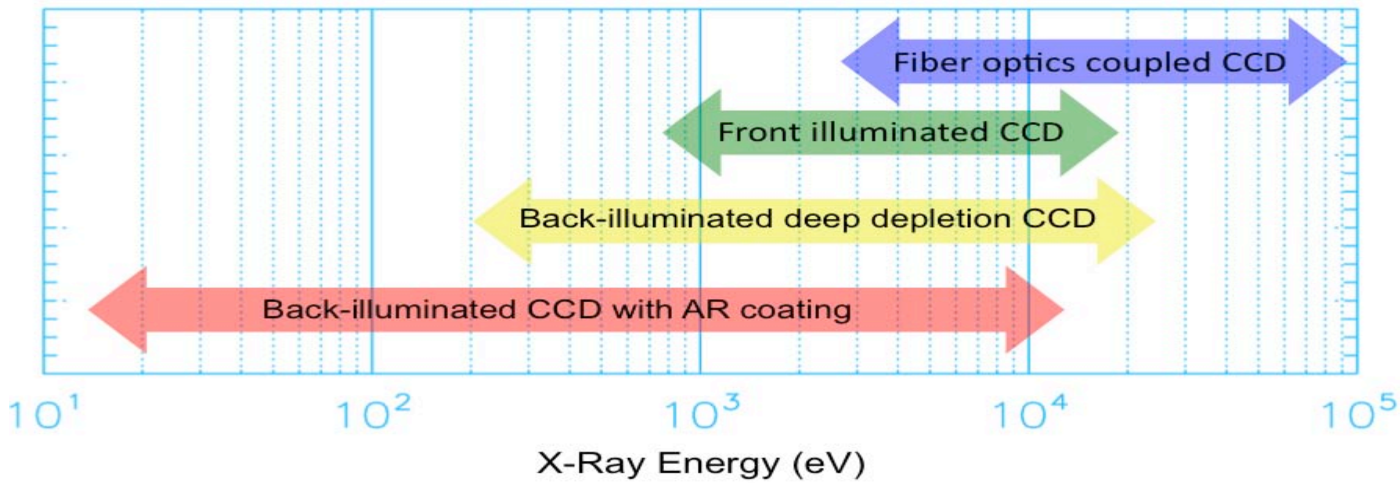
8.2 keV (50 keV)

Outline

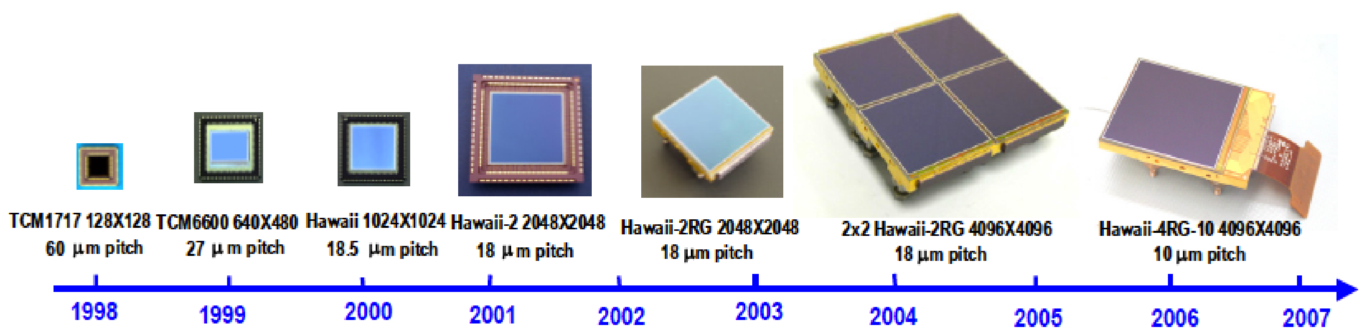
- **MPDH/MaRIE HX imaging requirements**
  - The efficiency challenge for HX (42 keV)
  - The ps (“sub-ns”) challenge
  - The GHz challenge
  - The GB challenge
- **Detectors today**
- **Paths forward**

Commercial X-ray detectors (Si dominance)

CCD



CMOS

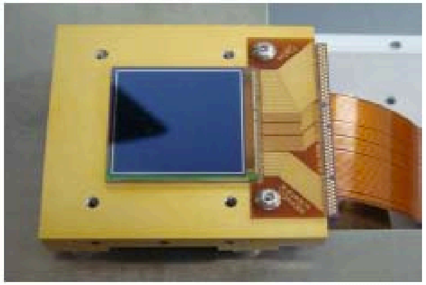


State-of-the-art hybrid CMOS-based detection (Si dominance)

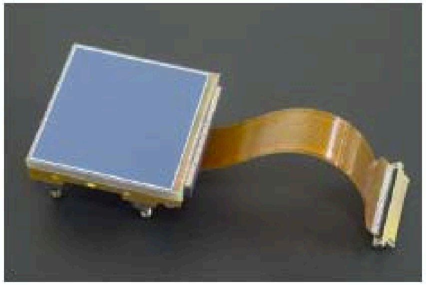
The Crab Nebula (M1)

NGC2683 Spiral Galaxy

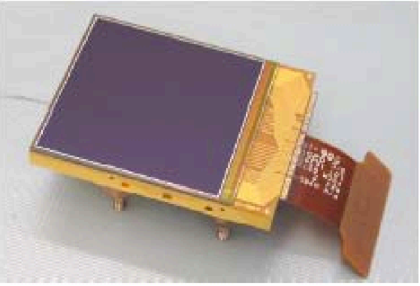
The Hercules Cluster (M13)



1Kx1K H1RG-18 HyViSI



2Kx2K H2RG-18 HyViSI



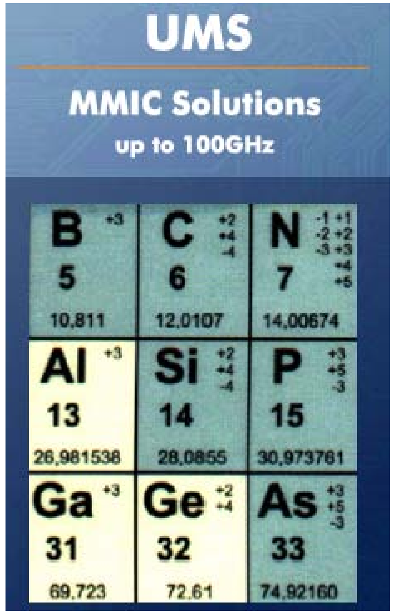
4Kx4K H4RG-10 HyViSI

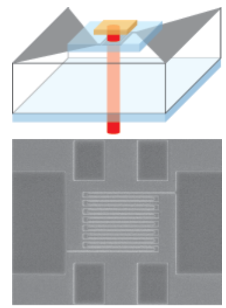
(too slow for MPDH)

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

New scintillators

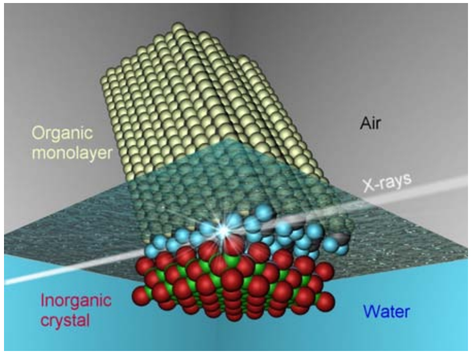
(Zhu et al.)





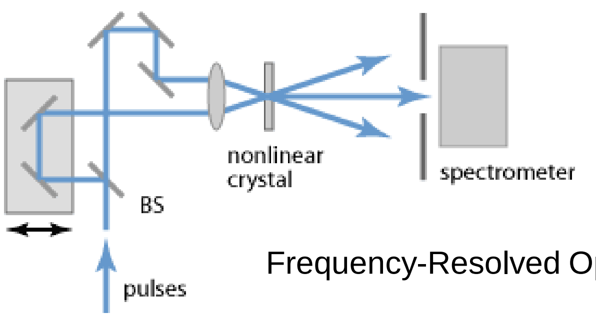
SNSPD

(Gol'tsman et al)



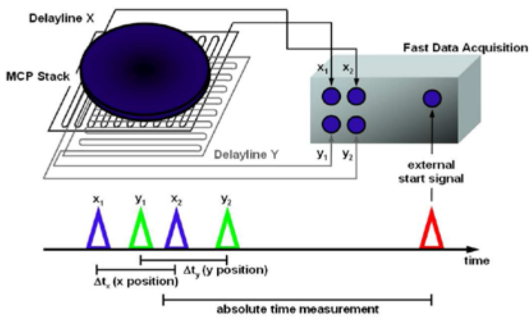
Molecular detectors

(Kemtko et al; Tahara et al)



Frequency-Resolved Optical Gating

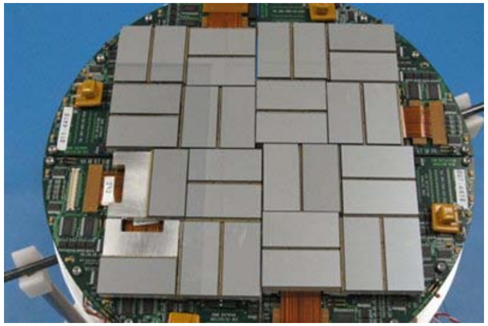
(Trebino et al.)



Delayline detectors

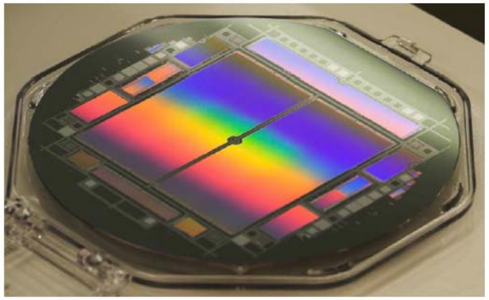
(http://www.surface-concept.de/)

Source-specific development



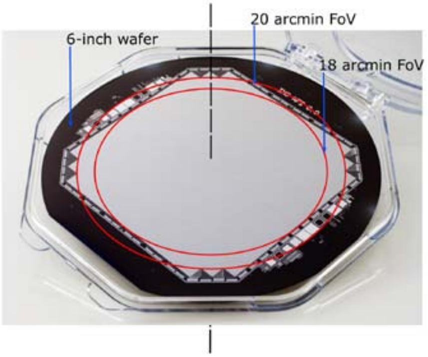
CS-PAD

Synchrotron/XFEL



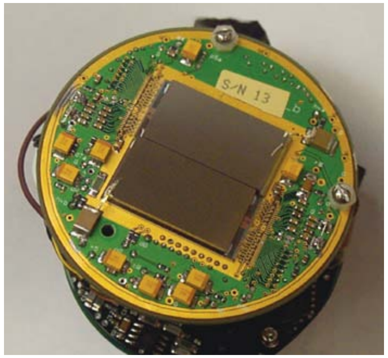
pnCCD

Synchrotron/XFEL/Astronomy



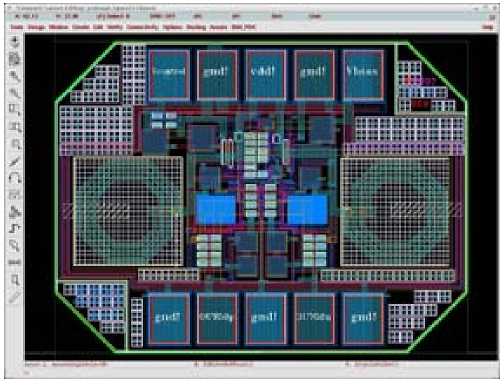
DEPFET

Astronomy/Synchrotron/XFEL



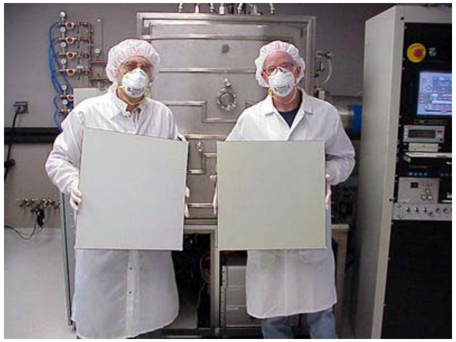
CZT detector

NIF



Large-area ps photodetector

HEP

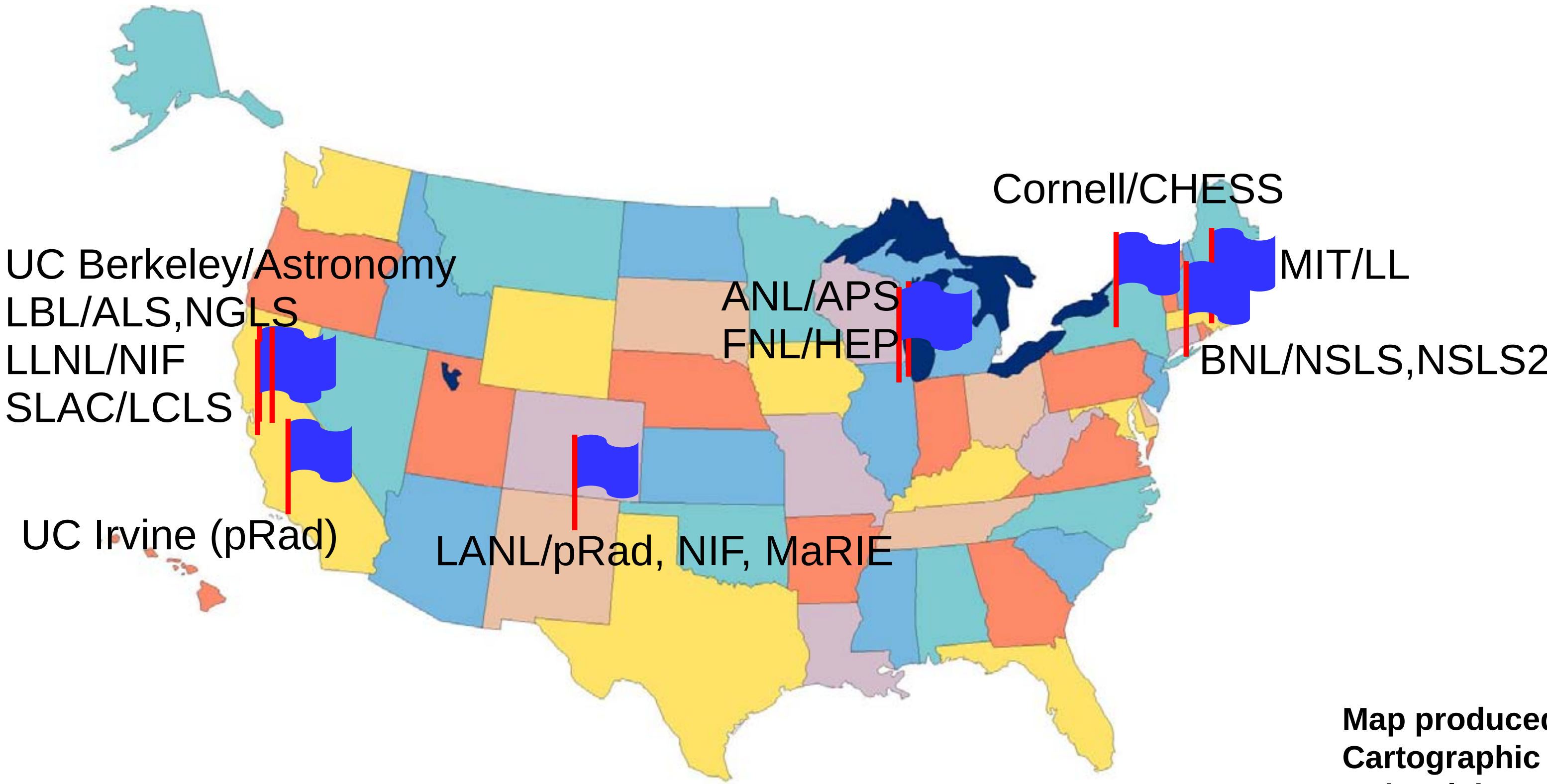


CsI(Tl) array

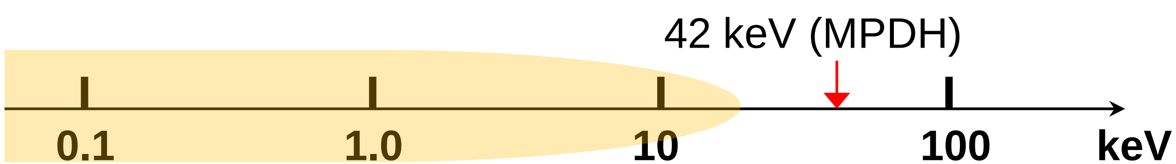
Commercial (RMD)

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

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



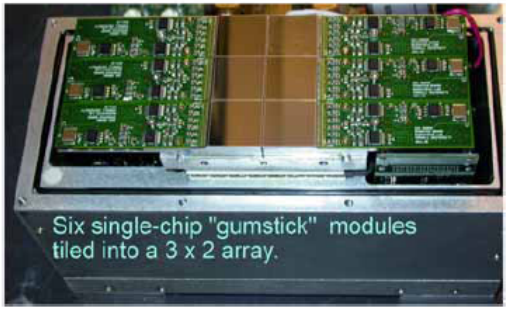
Map produced by
Cartographic Res. Lab
Univ. Alabama



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

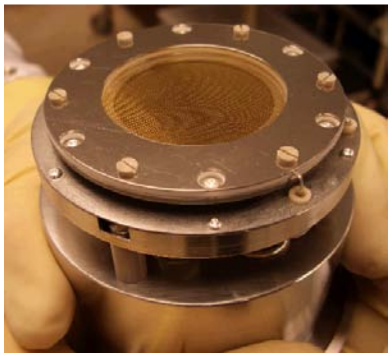


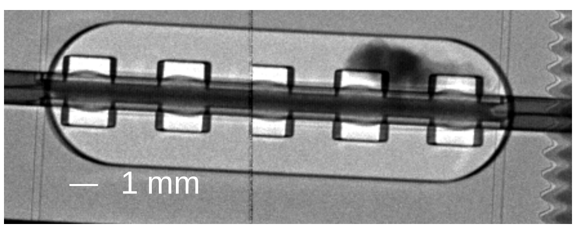
Credit: Sol M. Gruner
Cornell Univ.

*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

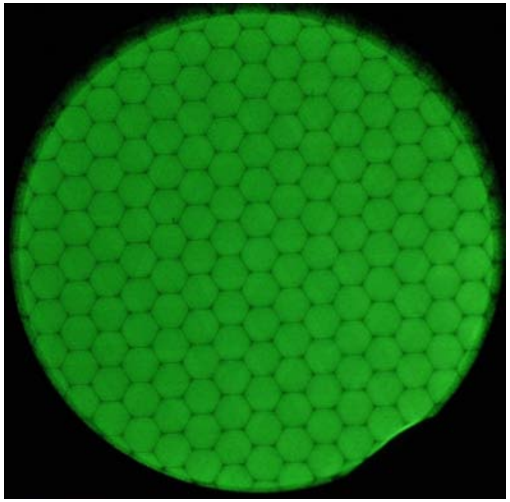




Thermal neut.
radiography

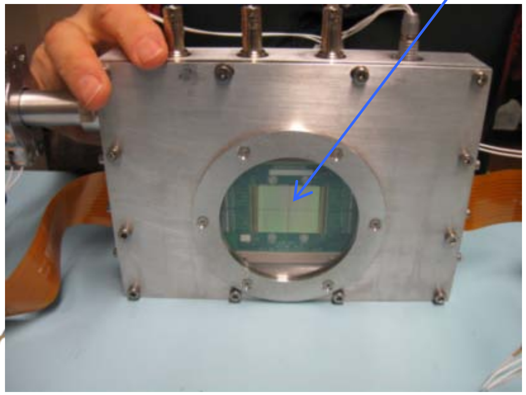
COS detector
installed on last Hubble repair mission

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	~15 × 10^{-3}ph ~50e	0.21ph (0.93ph) 700e (3100e)	~45 × 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		

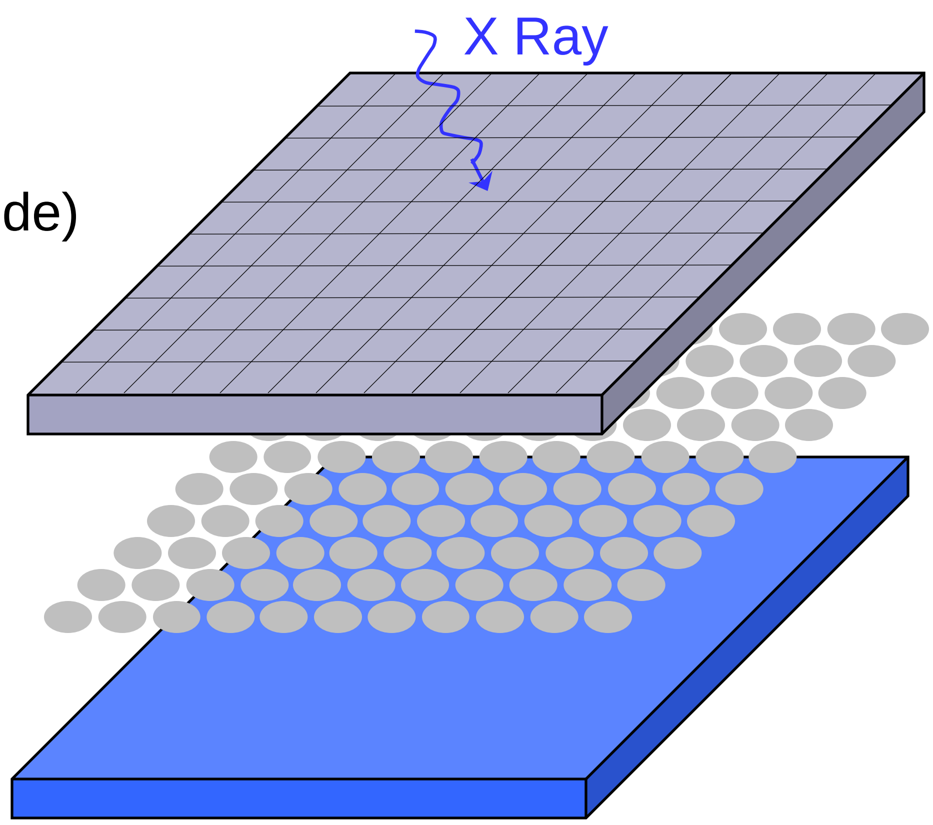
U. Trunk, ASICs for XFEL Detectors, CMOS ET Workshop (2009)

Hydrid CMOS: Flexible, Fast, bright Future

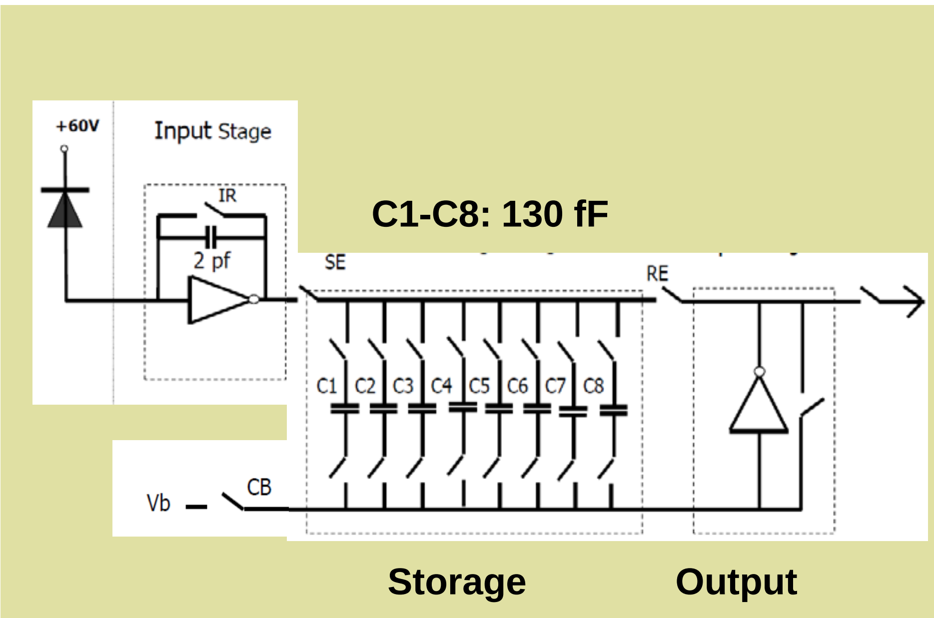
Sensor layer (diode)

Bump bonding

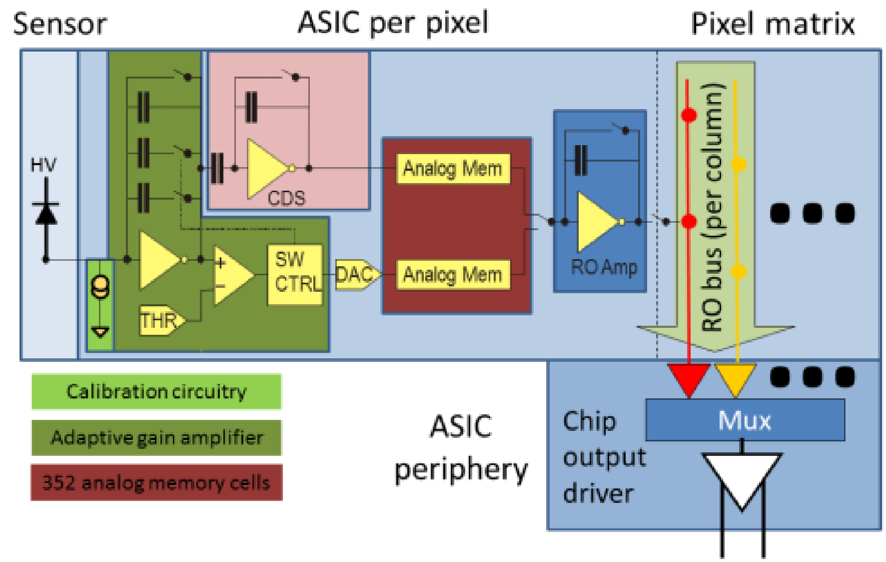
ASIC(CMOS)



ASIC architectures



G. Rossi *et al* (1999)



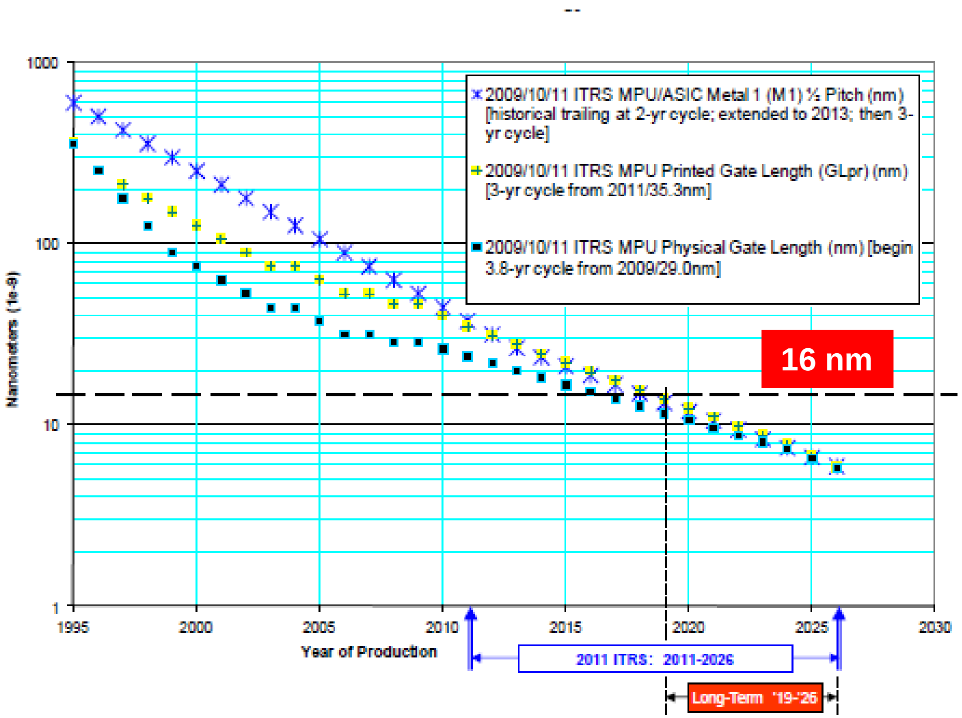
AGIPD

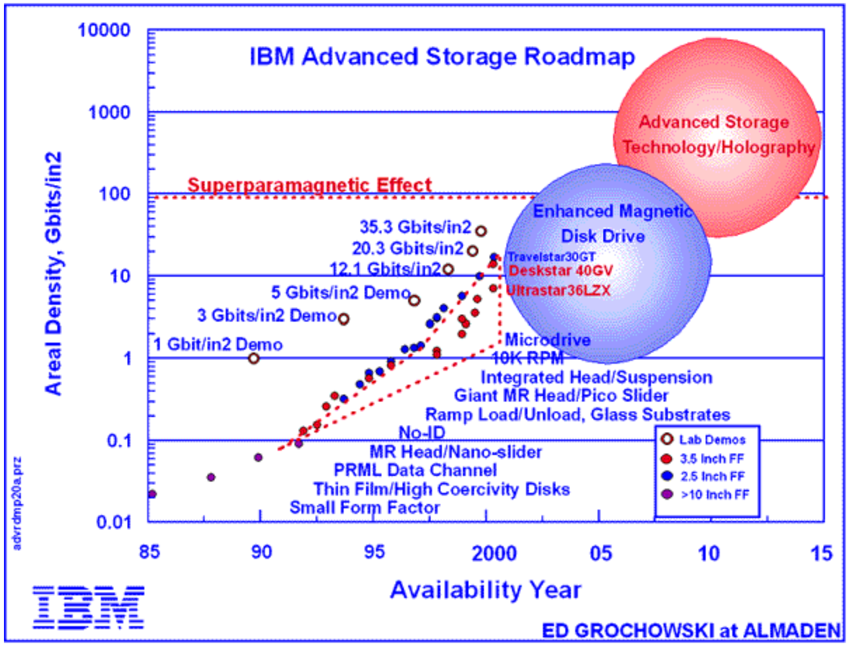
ASIC Fabrication: *shares* CMOS technology

- **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



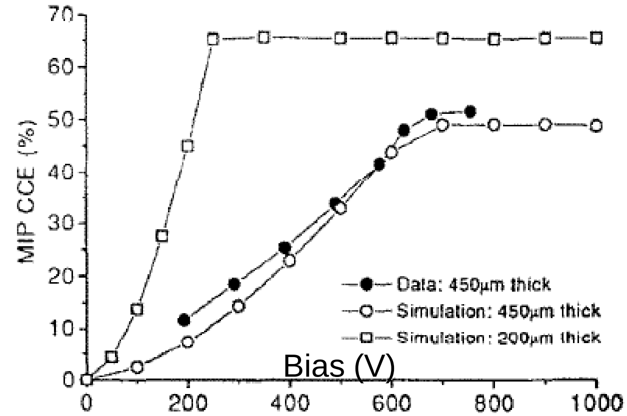


MPU/ high performance ASIC half pitch and gate length trends

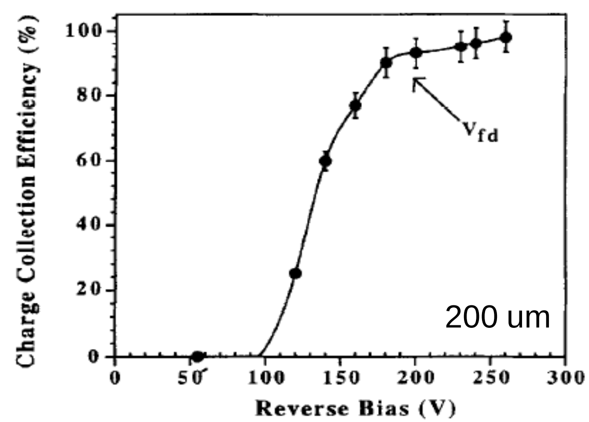
From: ITRS 2011 report

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



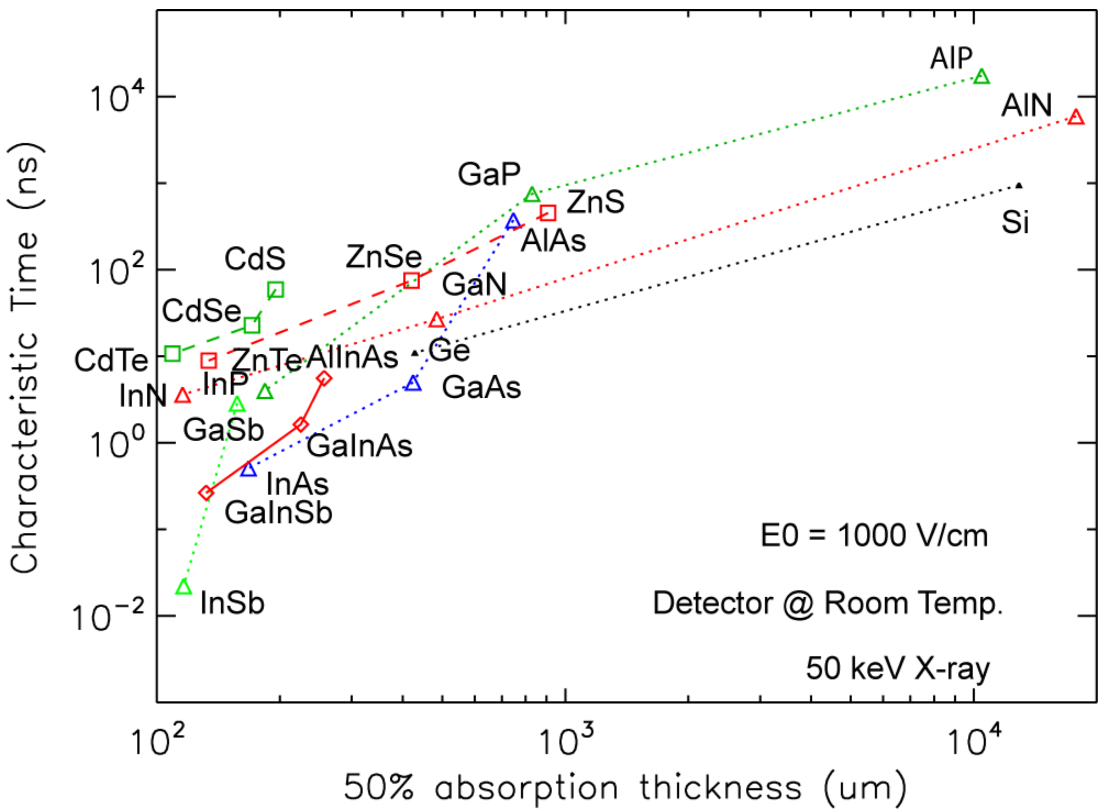
C. M. Buttar, NIM A 395 (1997) 1.



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

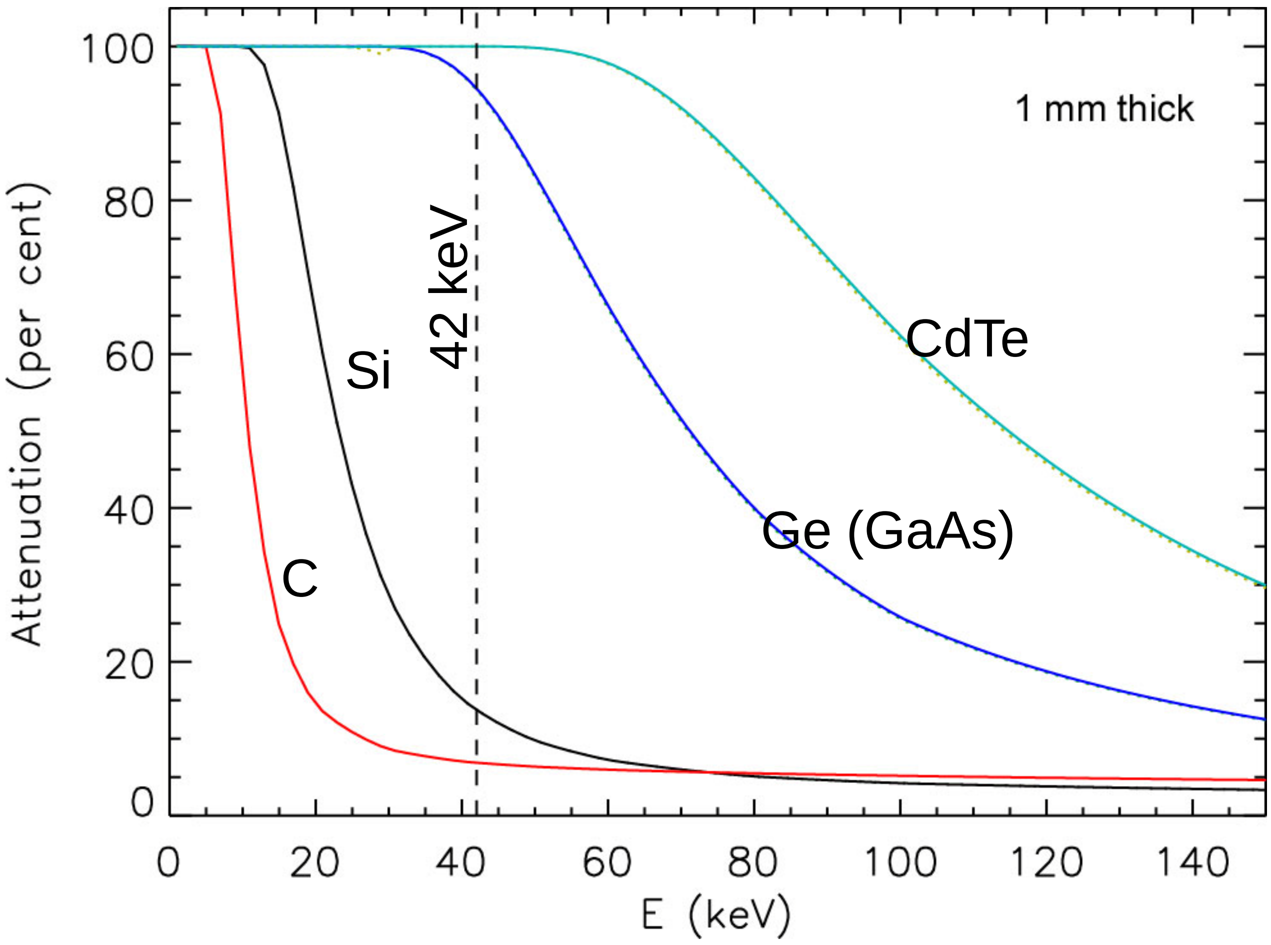
1 yr. ago…

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

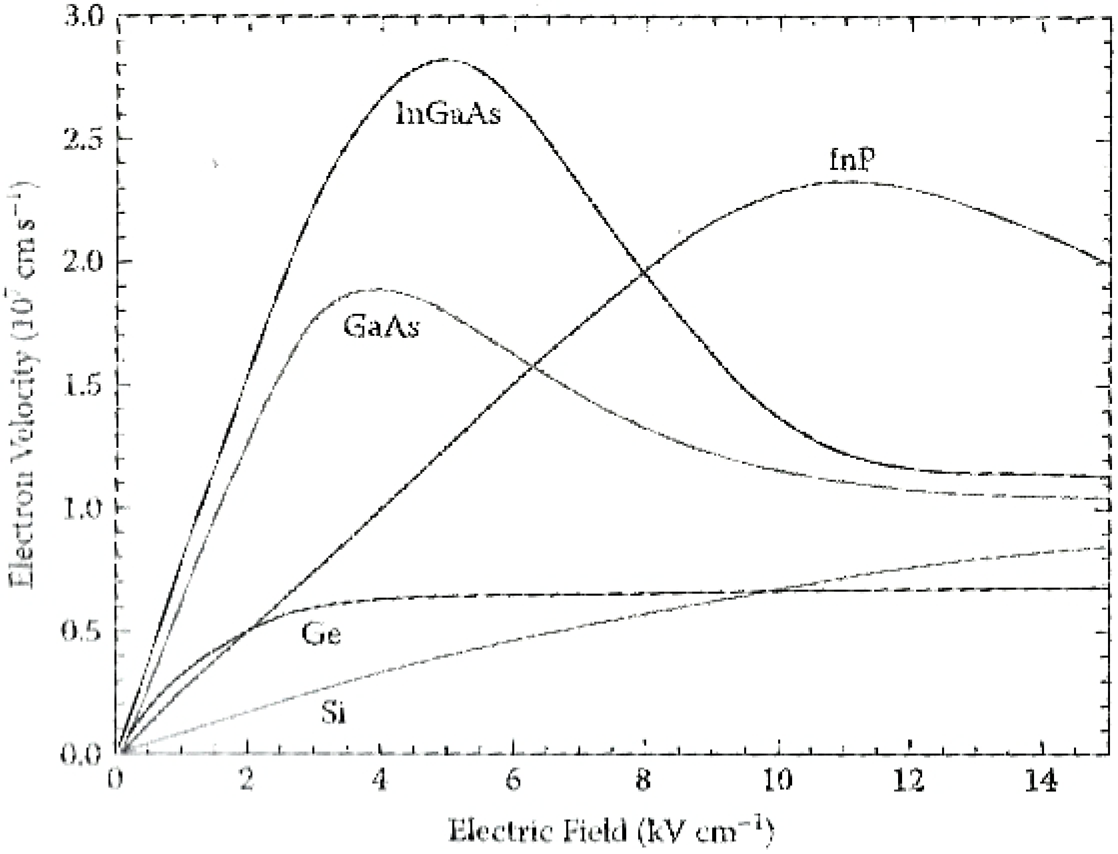


Wang et al, RSI (2012)

Efficient absorption thickness ← High Z



Response time ← electron drift time



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

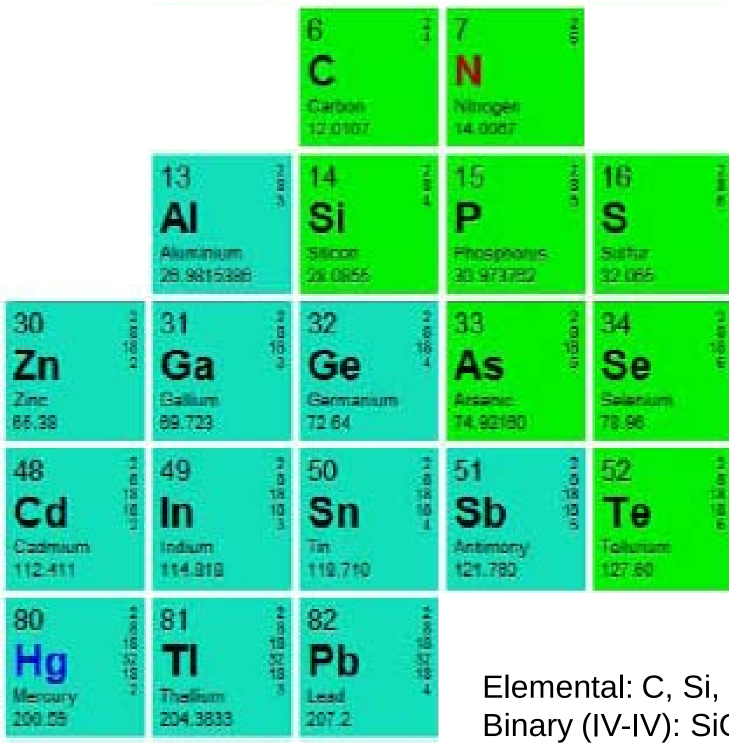
10^5 m/s x 50 ps
= 5 um

Ee = 0.03 eV

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

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

Semicondutor down-selection

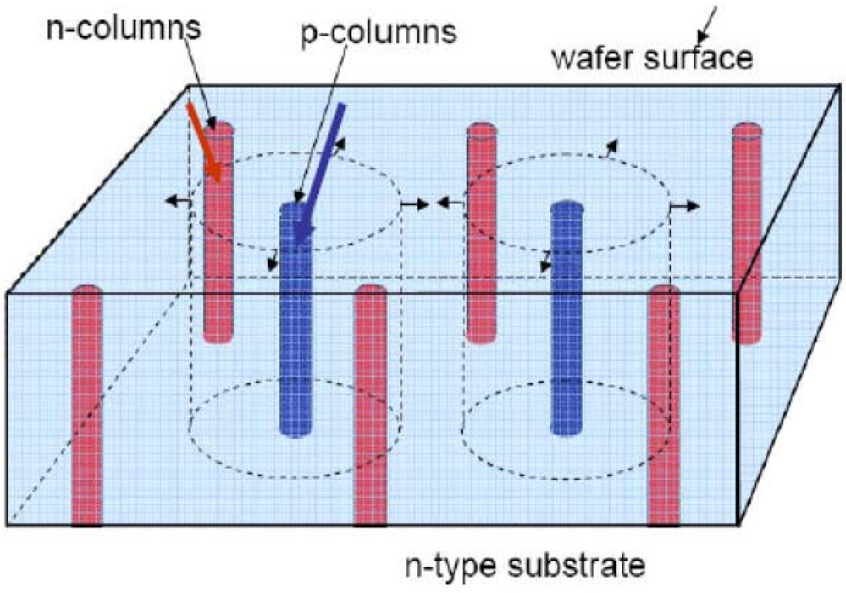


Elemental: C, Si, Ge
Binary (IV-IV): SiGe
Binary (III-V): InP, GaAs
Binary (II-VI): CdTe, HgTe
Binary (I- VII):AgCl
Ternary: HgCdTe, CZT
Quarternary: InGaAsP

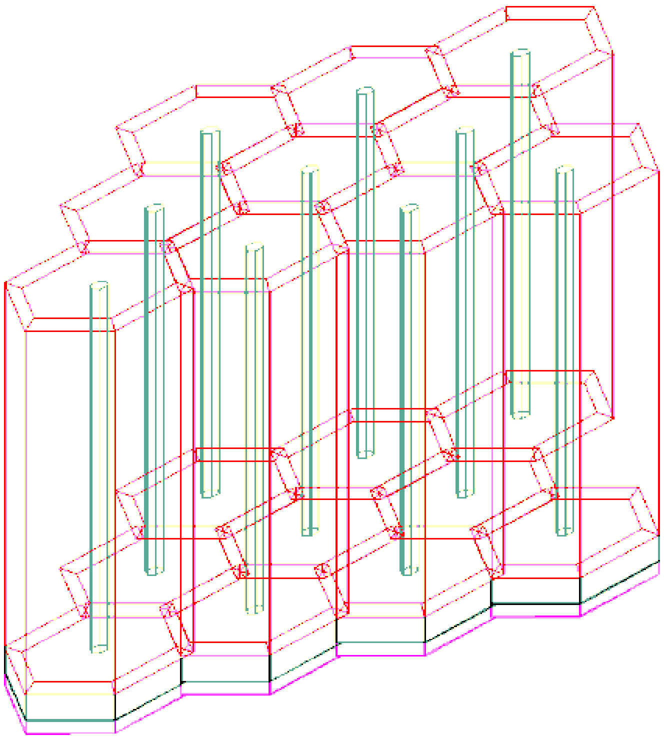
- **Si**
- **GaAs, Ge**
- **InP**

3D structures ← reducing charge collection time

150 - 300 ns → 5 - 30 ns → 300 ps



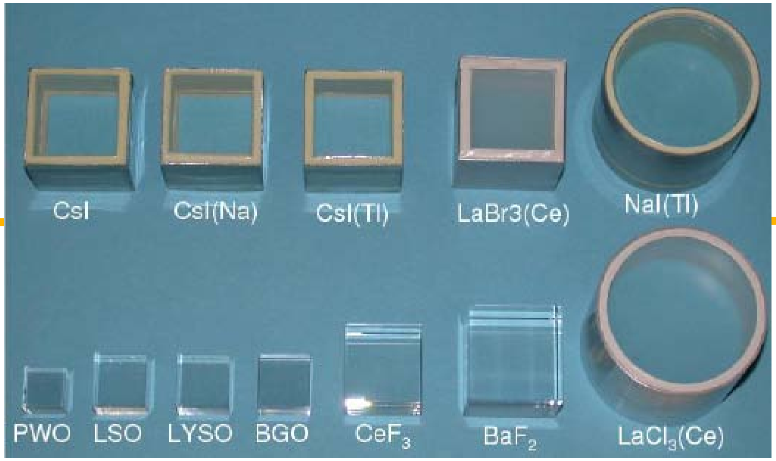
D. Eckstein , DPG spring meeting, Munich (2009).

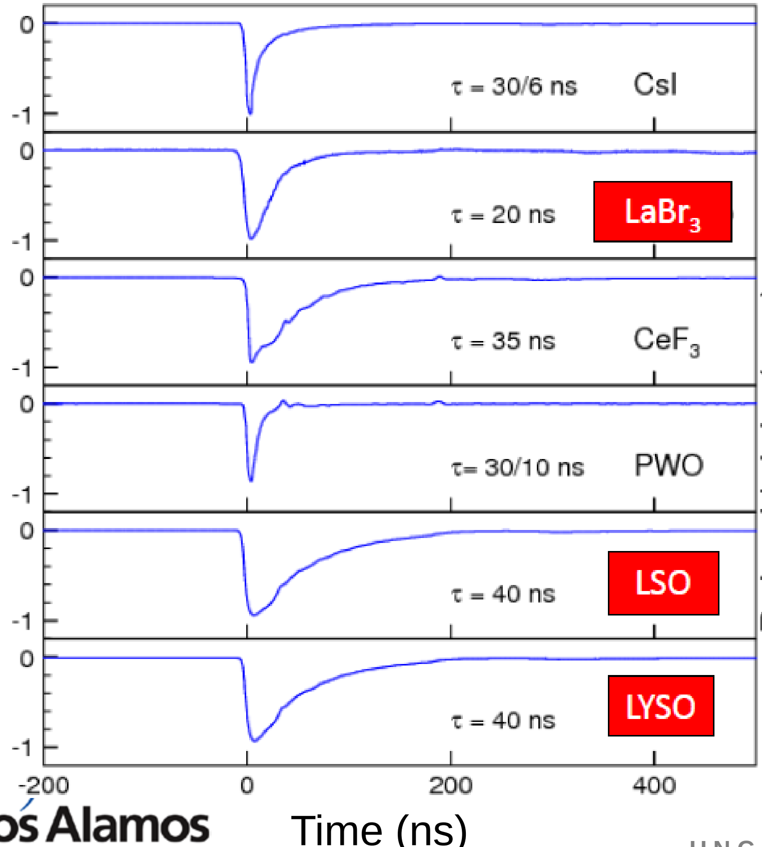


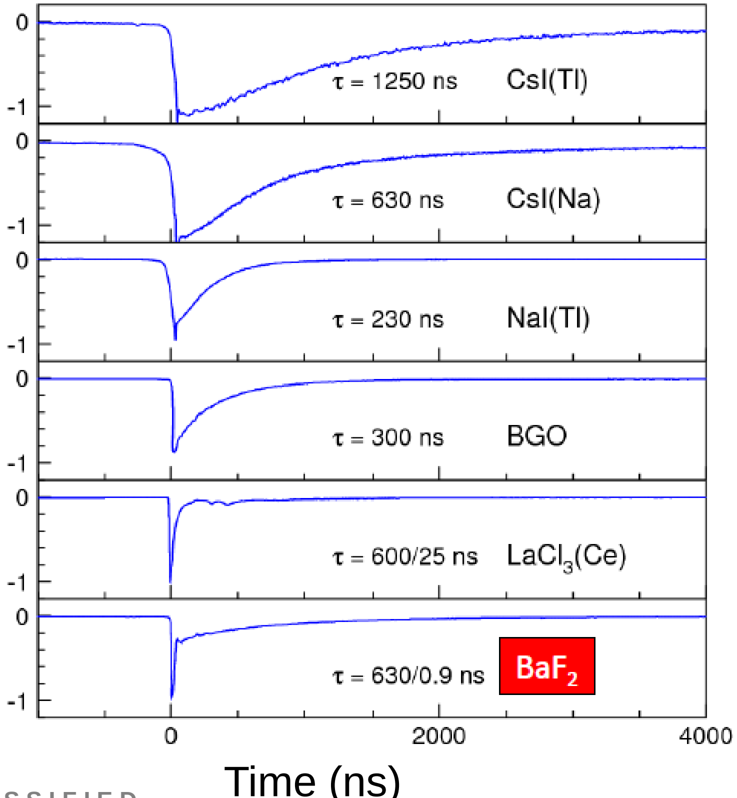
Z. Li , BNL Seminar, Apr. 20 (2011).

Scintillators … the list is growing

Credit: R-Y Zhu, Caltech

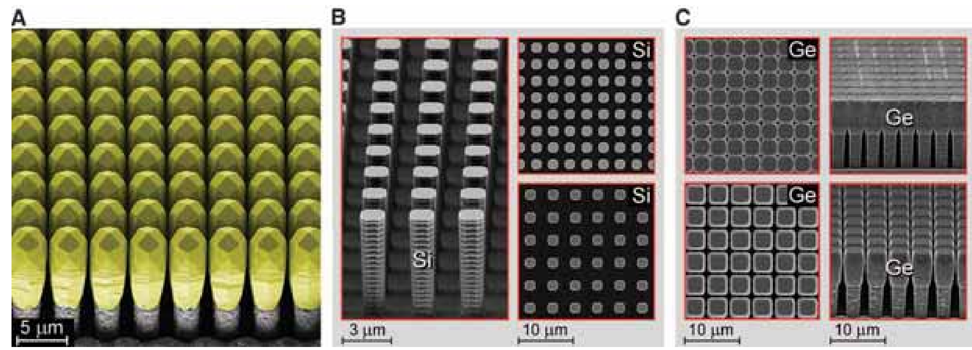




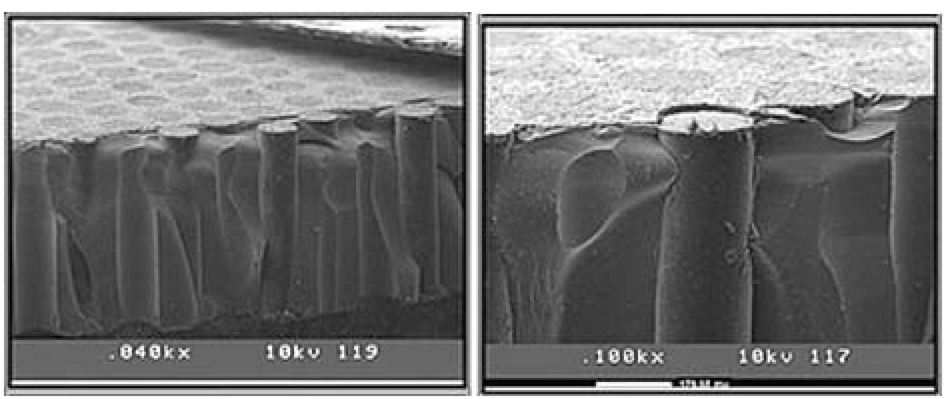


Columnar structures for efficient light guide

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

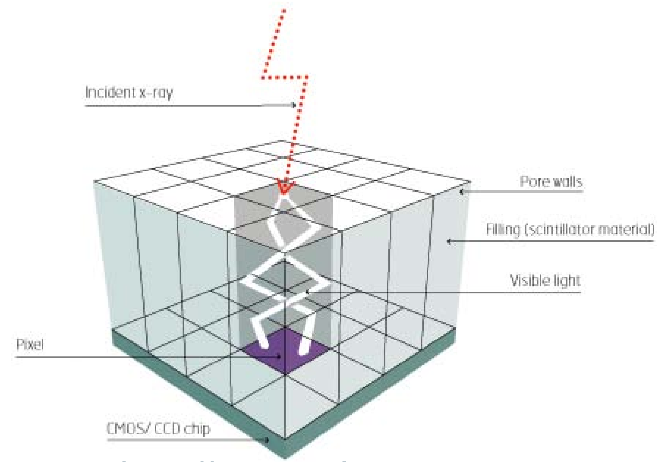


C. V. Falub et al, *Science* **335** (2012) 1330.



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