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Title: Ultrafast imaging technology: from visible light to high-energy X-ray photons

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Intended for: ET CMOS conference, 2017-05-28 (Warsaw, Poland)
P/T collloquium talk

Issued: 2017-01-13 (Draft)

# Ultrafast imaging technology

## From visible light to high-energy X-ray Photons

Zhehui (Jeff) Wang

P-25, LANL

P/T colloquium, Jan. 19, 2017

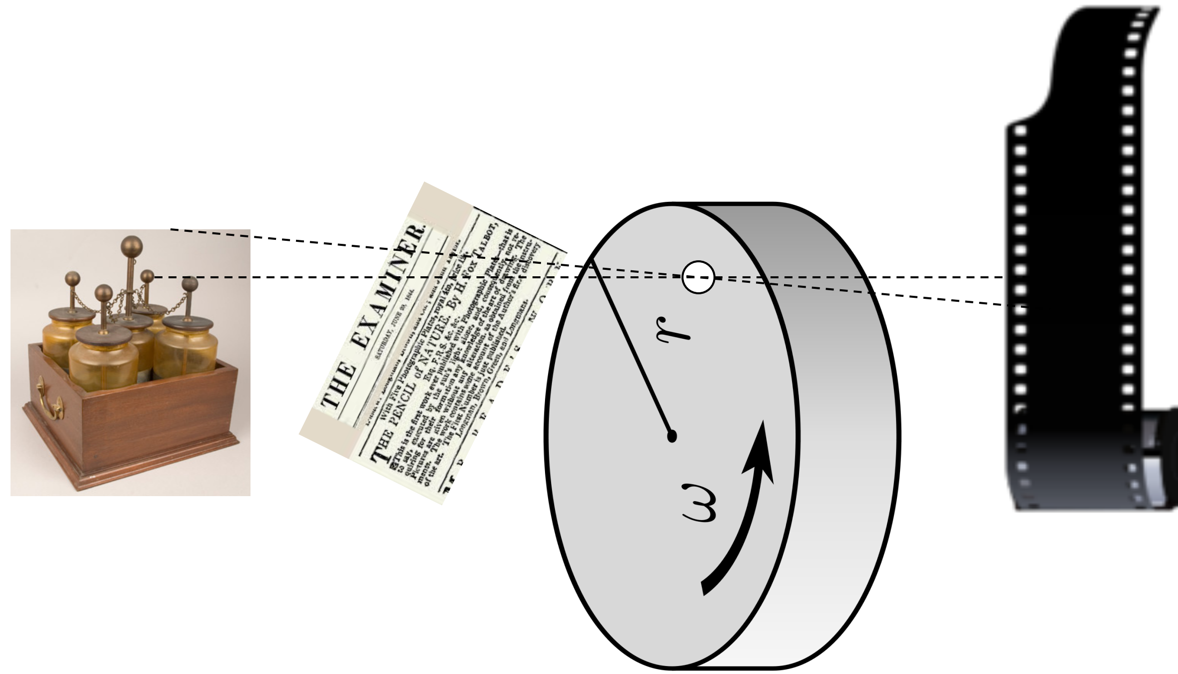
*Dynamic, fast & interesting*

# Outline

- **Introduction**
  - Historical highlights of high-speed photography/imaging
  - Recent advances in ultrafast imaging technology
- **New ingredients for ultrafast imaging**
  - photons + <u>cameras</u> + <u>data</u>
  - LANL interest → MaRIE & others (LCLS, APS, etc)
- **Towards gigahertz HE x-ray imaging**
  - *Software: Data challenge (acquisition, storage, transport, processing)*
  - Hardware: Materials challenge
    - Conventional “bulk” materials → architecture innovations (near term)
    - Micro/Nano materials → Proof-of-concepts (Long term)

# William Henry Fox Talbot

## and the Invention of high-speed photography

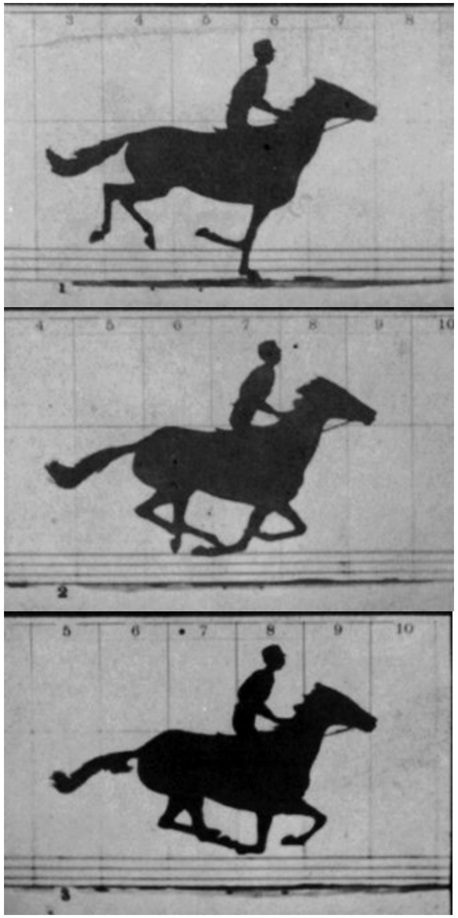



*'Further progress in this direction would not be difficult'*

--British J. Photography, 1864

# Eadweard Muybridge

## and the galloping horse photography

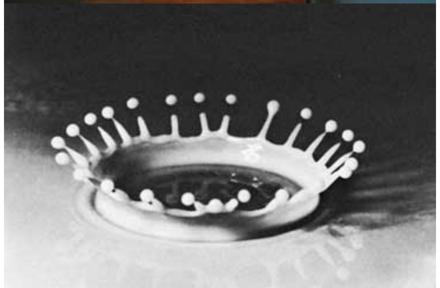



*Muybridge designed his own high speed electronic shutter and electro-timer*

# Harold "Doc" Edgerton

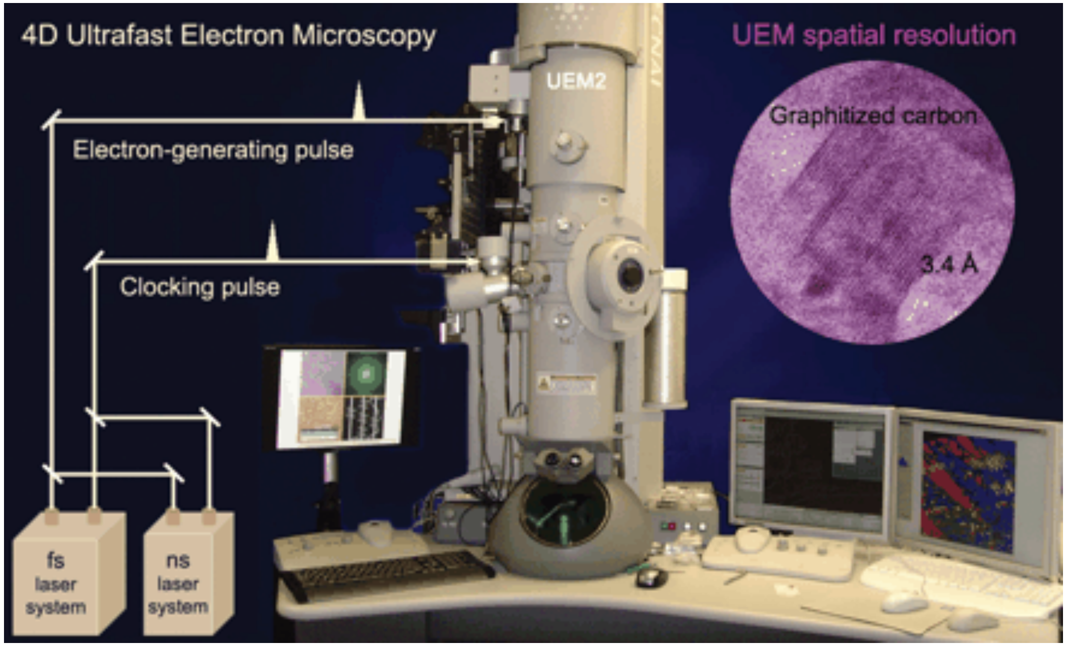
## and stroboscope photography in MIT

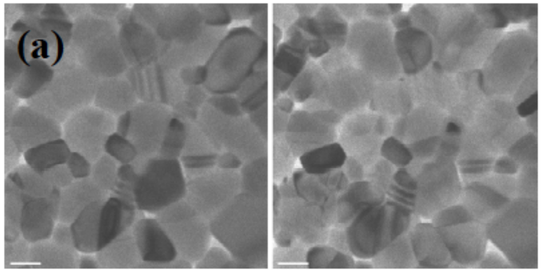
"strobe lighting"



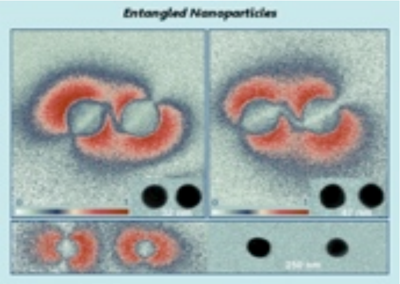
# Ahmed Zewail

## and the dancing molecule photography



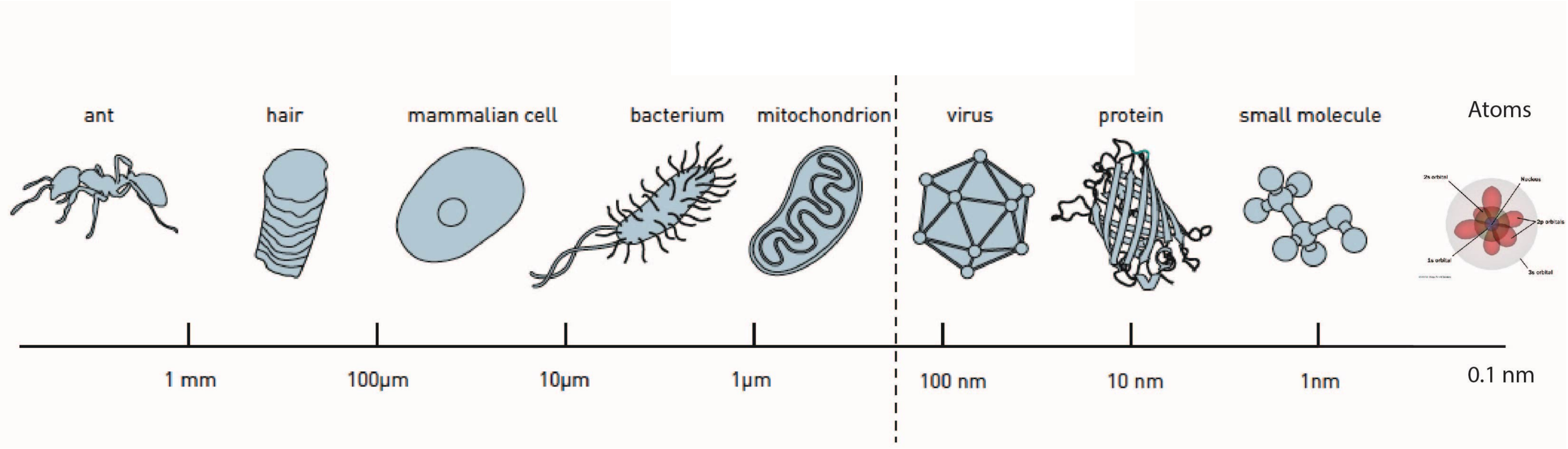




VO$_2$ phase transition

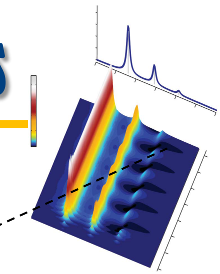


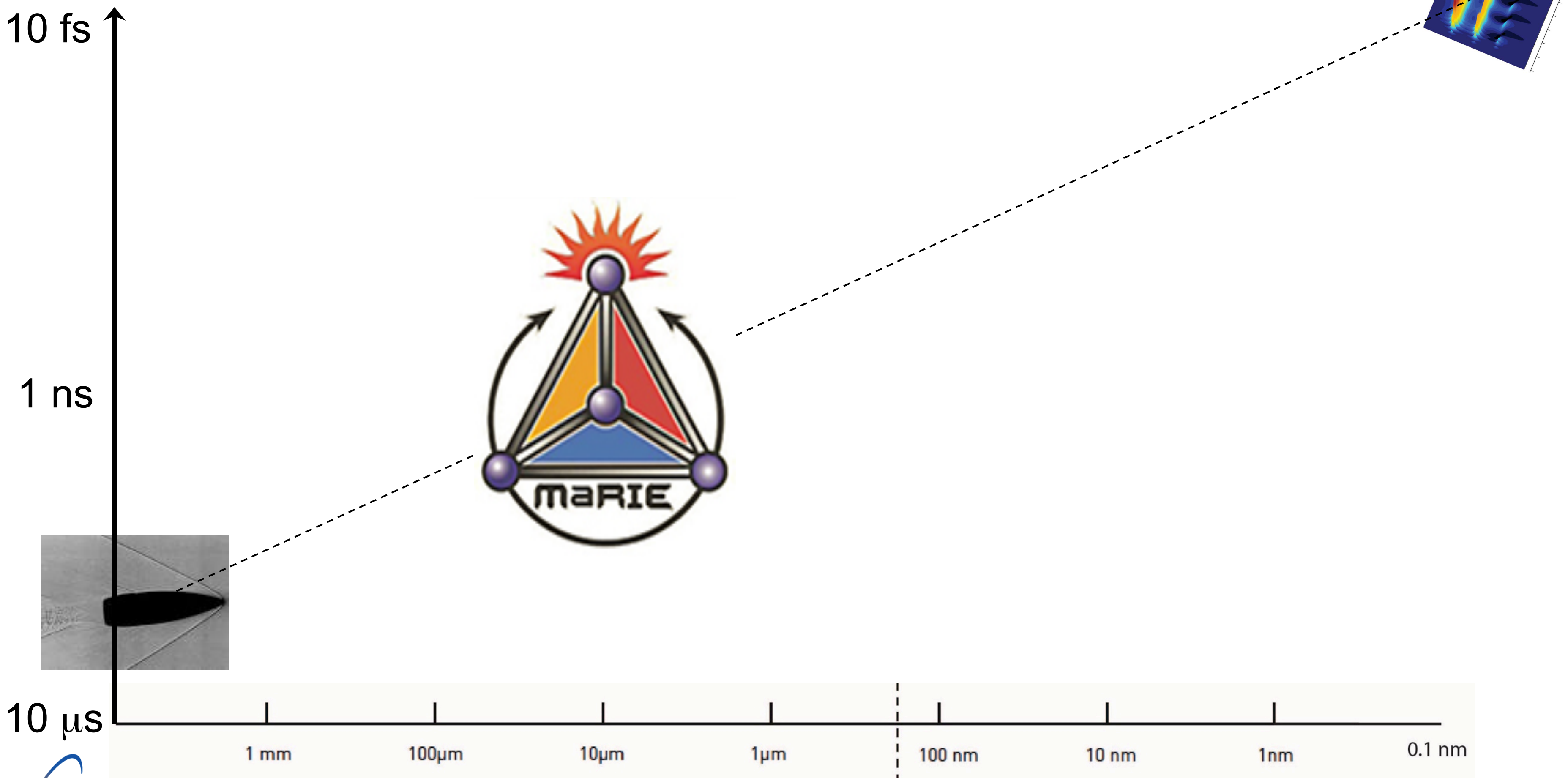

Entangled nanoparticles

# mm- & nano- horses



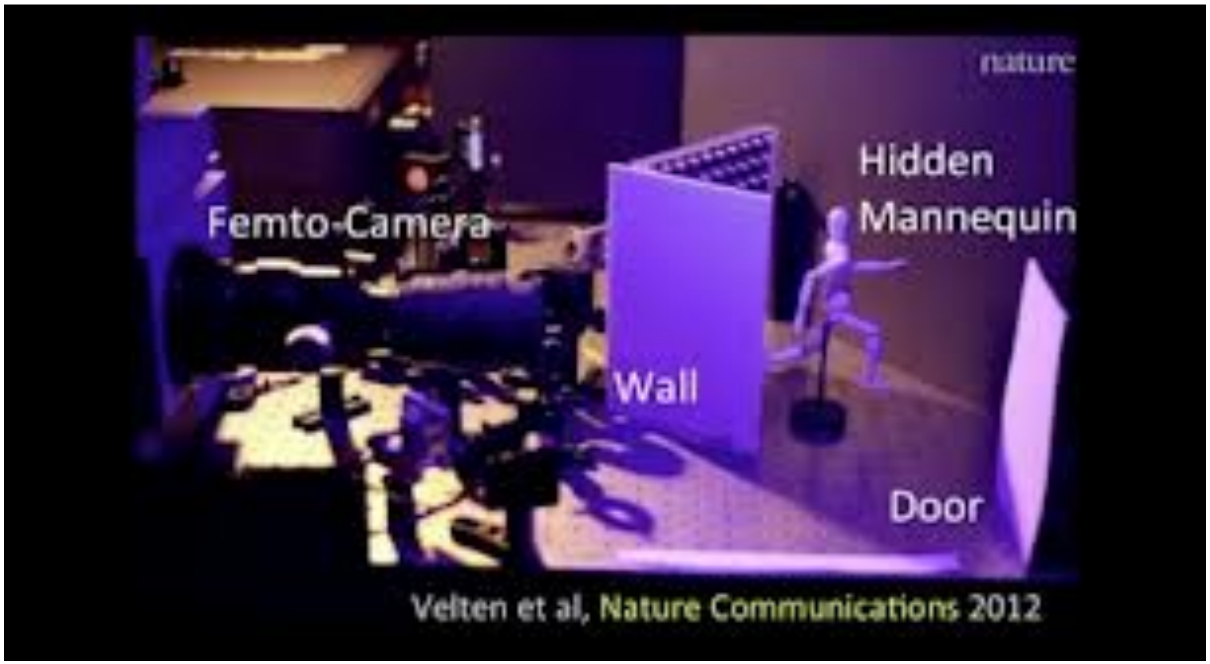
# Camera frame-rate inversely proportional to dimensions





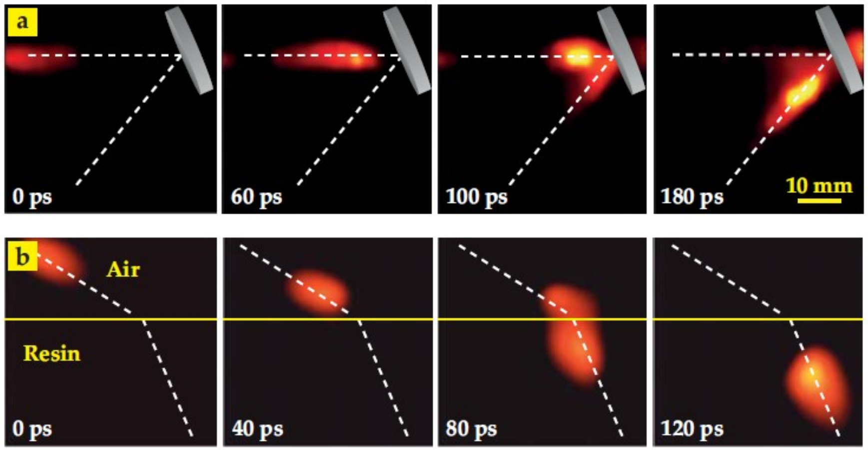
# Macroscopic applications also possible

## Seeing things around the corner



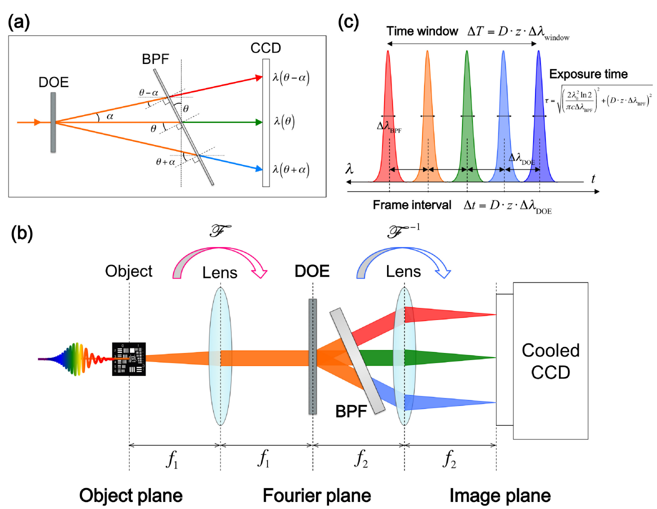

R. Raskar et al. — MIT Media Lab

# “Trillion frame cameras” for visible light




“CUP”

Gao et al (2014)




“STAMP”

Suzuki et al (2015)

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  - Recent advances in ultrafast imaging technology
- **New ingredients for ultrafast imaging**
  - 'Horses' + photons + cameras + data
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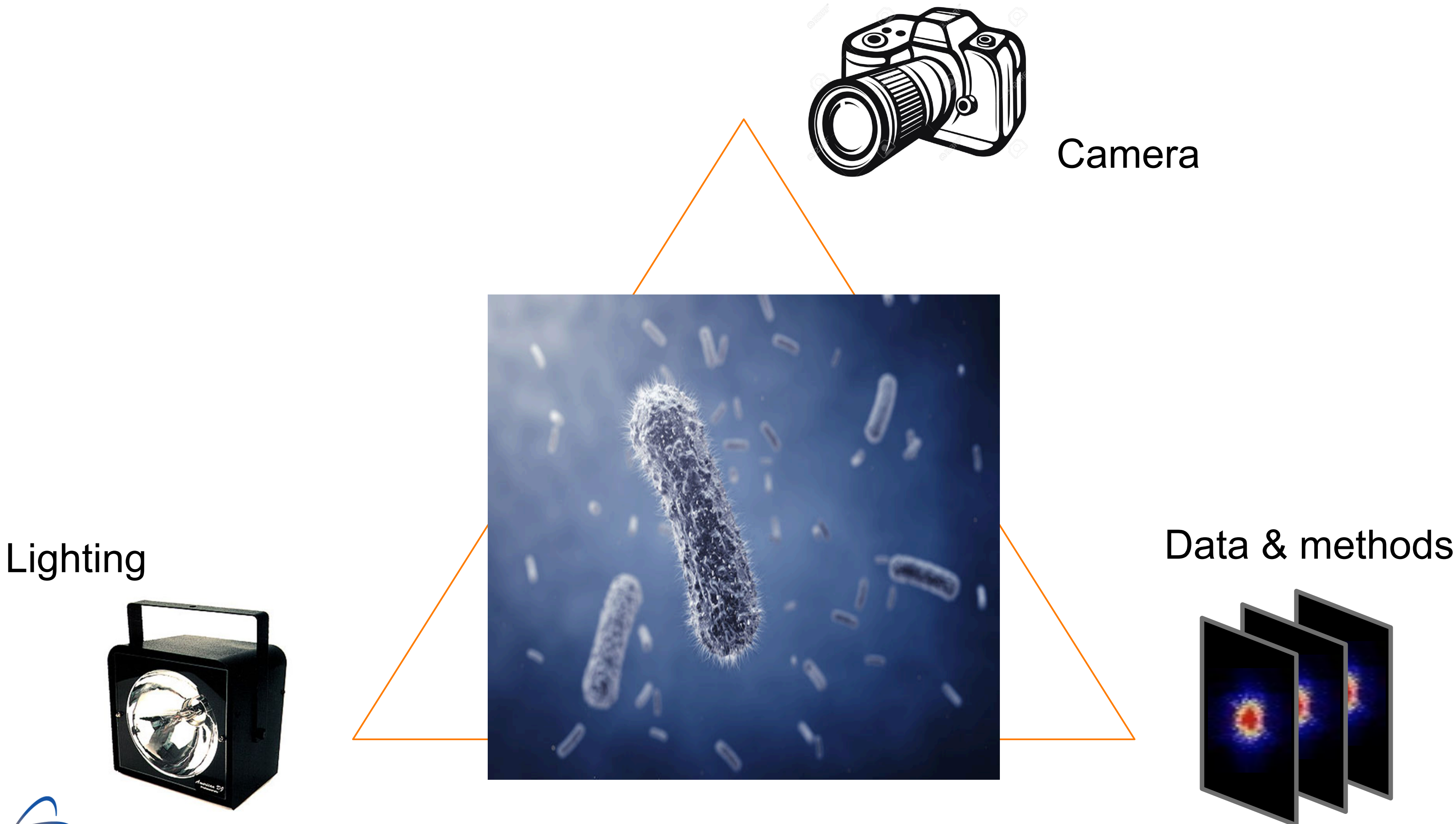
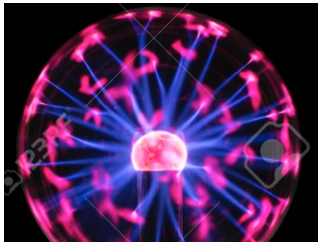
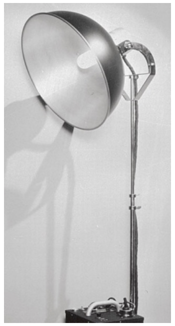
    - Conventional "bulk" materials → architecture innovations (near term)
    - Micro/Nano → Proof-of-concepts (Long term)

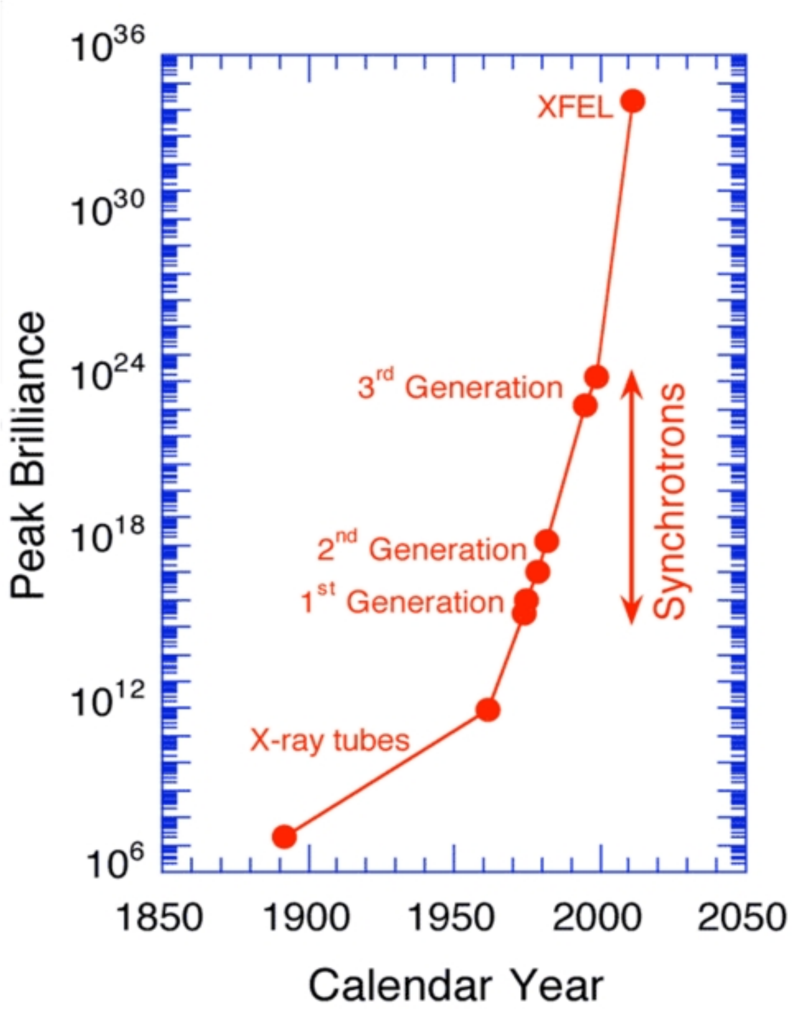
# Imaging technology triangle



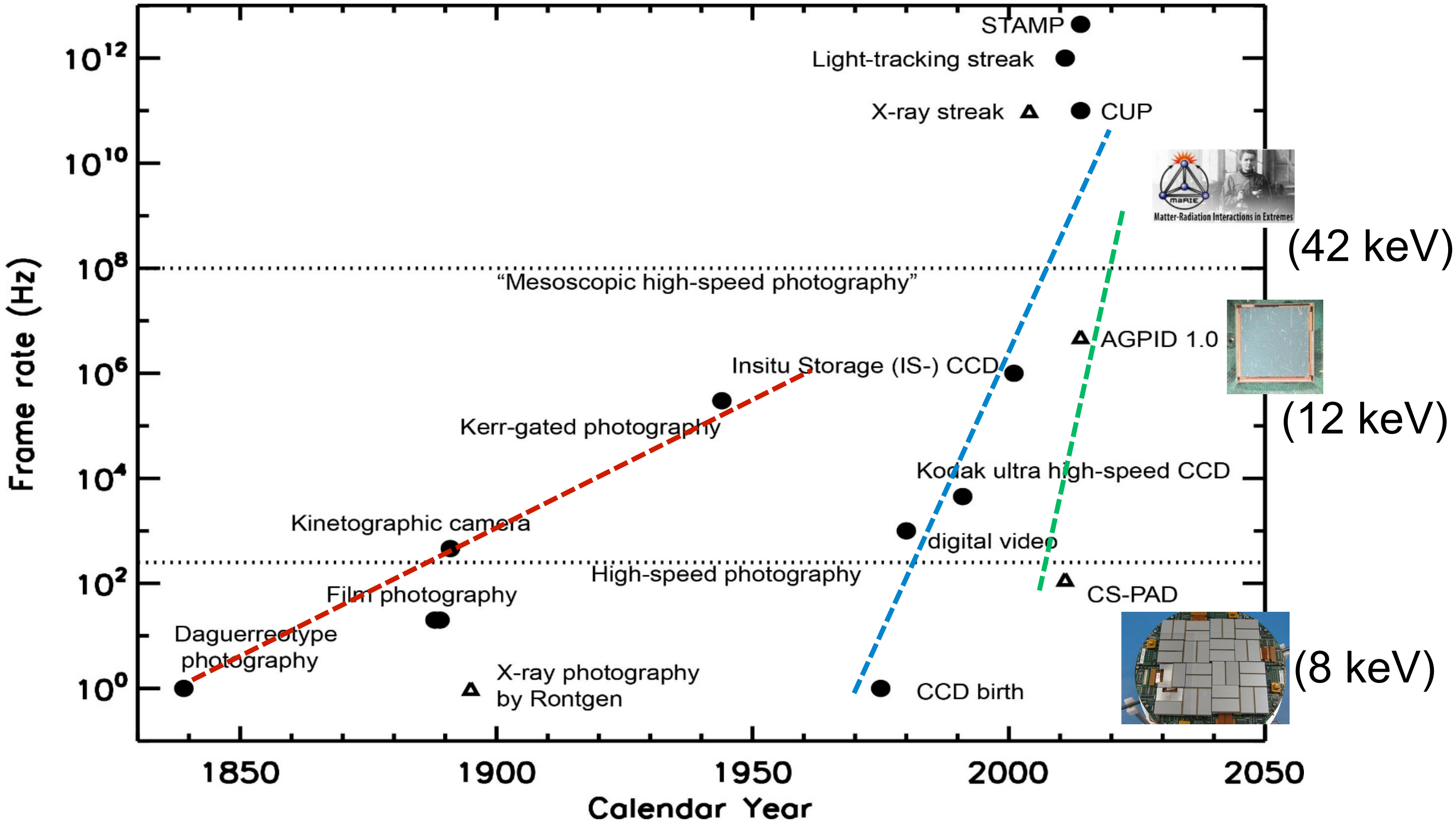
# Evolution of lighting







# Evolution of high-speed imaging technologies



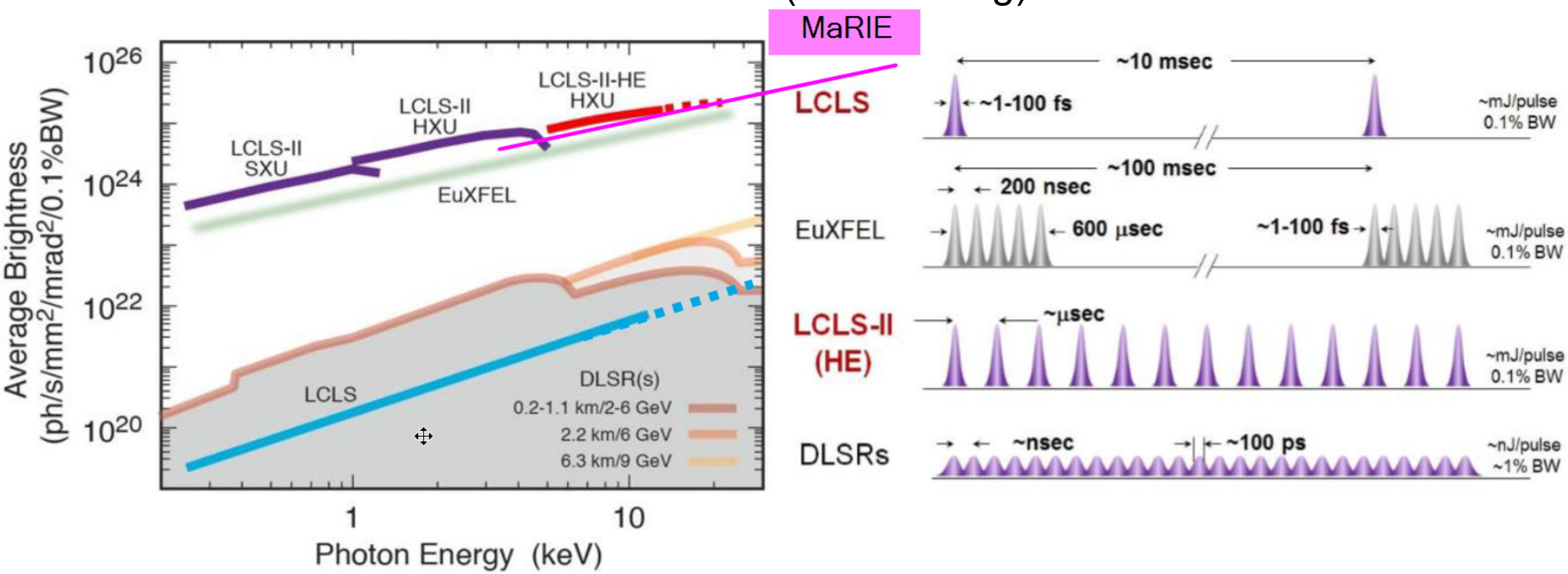
# A lot of parallel efforts…

| | Detector/ Camera | Voxel dimension | Noise | CMOS technol. | Pixel Bias | Digital clock | Frame rate |
|---|---|---|---|---|---|---|---|
| | | ($\mu m^3$) | | ($\mu m$) | (V) | (MHz) | (MHz) |
| XFEL | CSPAD | 110 ×110 × 500 | 330 $e^-$ | 0.25 (TSMC) | 190 | 25 | $1.2\times10^{-4}$ |
| | ePix100a | 50 × 50 × 500 | 50 $e^-$ | 0.25 (TSMC) | 200 | 0.1 | $1.2\times10^{-4}$ |
| sync | Keck-PAD | 150 ×150 × 500 | 1530$e^-$ (860 $\mu$V) | 0.25 (TSMC) | 200 | 50 | 6.5 |
| XFEL | AGIPD 1.0 | 200 ×200 × 500 | 265$e^-$ <14.4 | 0.13 (IBM) | 500 | 99 | 4.5 |
| XFEL | DSSC (DEPFET) | 136 (hex) × 450 | 50 $e^-$ | 0.13 (IBM) | 150 | 700 | 5 |
| XFEL | pnCCD (CAMP) | 75 ×75 × 280 | 5 $e^-$ (100 ms) | CCD | 140 (0.5V/$\mu$m) | 10 | $2.5\times10^{-4}$ (5, burst) |
| XFEL | LPD | 500 ×500 × 500 | 1000 $e^-$ | 0.13 (IBM) | ~250 | 100 | 4.5 |
| XFEL | MPCCD [HG:2015] | 50 × 50 × 50 | 200 $e^-$ | CCD | ~20 | 5 | $6\times10^{-5}$ |
| XFEL | SOPHIAS | 30 × 30 × 500 | 150 $e^-$ | 0.2 FD-SOI | ~200 | 25 | $6\times10^{-5}$ |
| XFEL | JUNGFRAU [SMS:2015] | 75 × 75 × 450 | 100 $e^-$ | 0.11 (UMC) | 220 | 40 | $2.4\times10^{-3}$ |
| HEP | ALPIDE[2] (MAPS[3]) | 28 × 28 × 50 | ~ 20 $e^-$ | 0.18 (TowerJazz) | <10 | 40 | $5.0\times10^{-2}$ |
| sync | FASPAX [ZIM:2016] | 100×100 × 500 | <1000 $e^-$ | 130nm SiGe (IBM) | 1000 | 100 | 13 (burst) |

# Ultrafast imaging technology driven by sources

Inputs: Rich Sheffield, Dinh Nguyen

MaRIE
(w/o seeding)

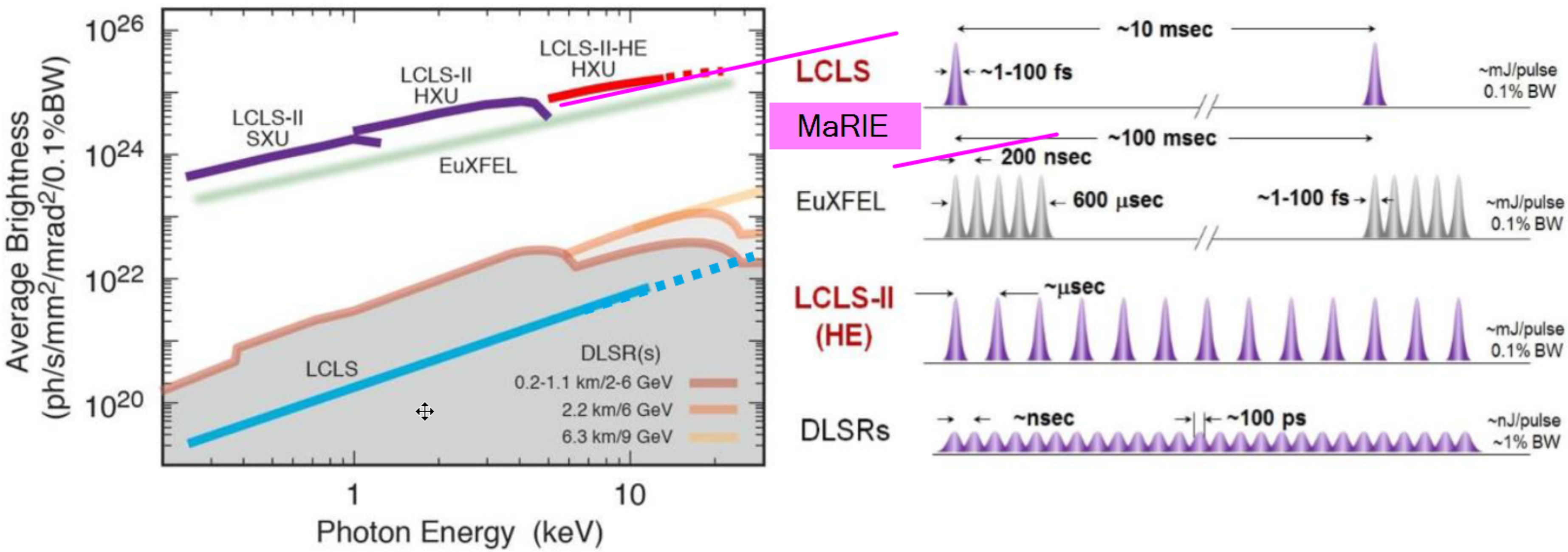



T. Raubenheimer
LCLS-II-HE Workshop, September 26-27, 2016
P. Abbamonte et al., SLAC-R-1053 (2015)

# Ultrafast imaging technology driven by sources (3rd harmonic included)

Inputs: Rich Sheffield, Dinh Nguyen

MaRIE
(w/o seeding)

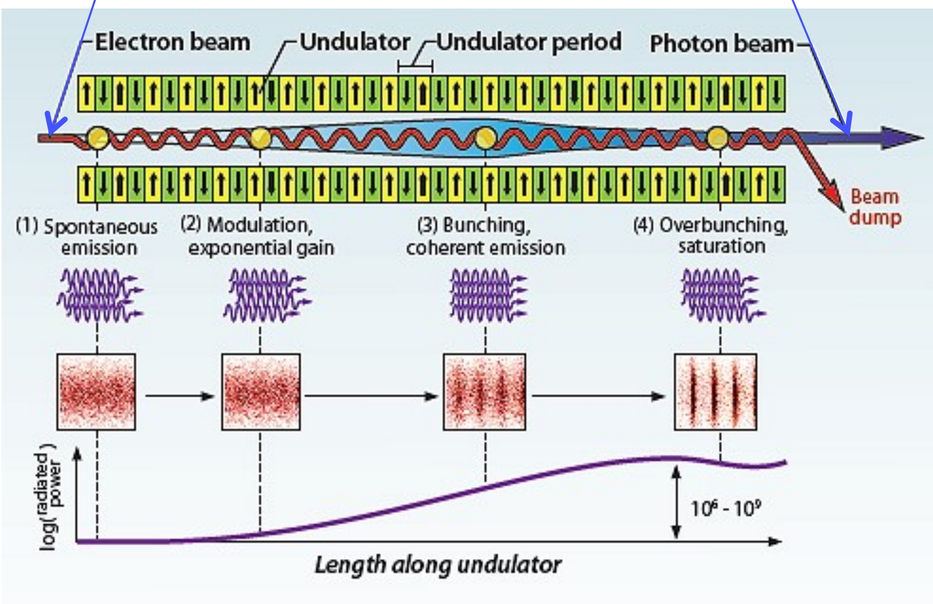



T. Raubenheimer
LCLS-II-HE Workshop, September 26-27, 2016

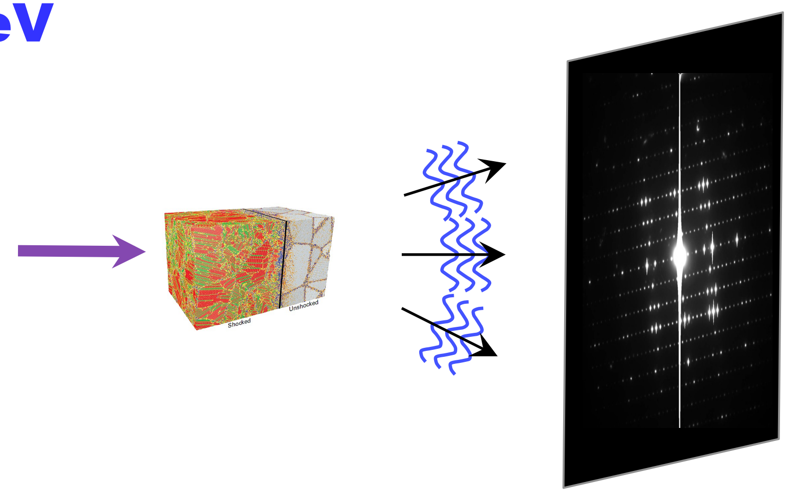
P. Abbamonte et al., SLAC-R-1053 (2015)

# MaRIE XFEL & Experiments

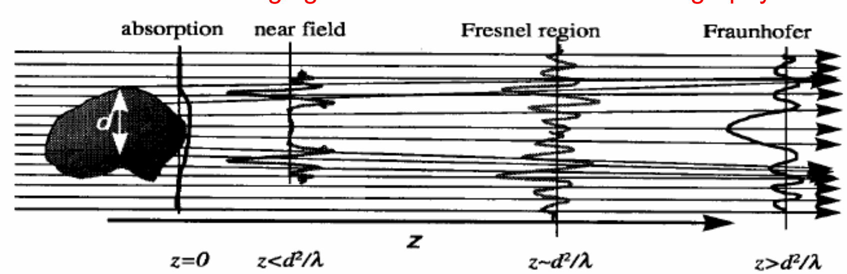
**12 GeV** **5 - 42 keV**




**80 - 100 m**



Shadow/contact imaging Phase contrast Holography/CXDI




A. Snigirev et al, RSI (1995)

Input: Rich Sheffield, Richard Sandberg

# MaRIE-camera: Performance summary

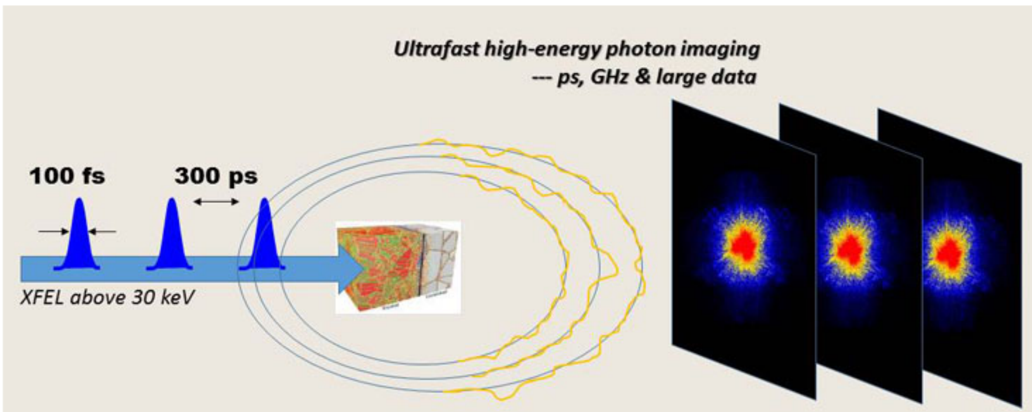
- **PicoSecond sensor <-> Materials challenge**
  - highly efficient (>50%) x-ray detection at 40-keV and above energies.
  - Sub-ns ( <100-ps ) X-ray sensor and storage response.
- **GigaHertz frame-rate <-> Fabrication/scaling challenge**
  - Many pixels, interframe time, 300 ps ( 3 GHz)
  - Multiple frames per experiment/ framing for acoustic velocities across grains
  - Single line-of-sight
- **Large data <-> Computing challenge**
  - 3 MB per image (20 bit, 1 Mpix)
  - Up to $10^6$ images per experiment
  - big data sets transmission and processing driven by scientific "co-design"

# The August 2016 workshop

## High-energy and Ultrafast X-Ray Imaging Technologies and Applications

*A MaRIE workshop shining a light on the future of ultrafast high-energy photon technology*

ACCOMMODATIONS | ABSTRACTS | REGISTRATION | PROGRAM | TRAVEL




### High-energy and Ultrafast X-Ray Imaging Technologies and Applications

**Date : August 2-3, 2016**
**Hotel venue: Hilton Santa Fe at Buffalo Thunder**

The goal of this workshop is to gather leading experts in the fields related to ultrafast high-energy photon imaging and prioritize the path forward for ultrafast hard x-ray imaging technology development, identify important applications in the next 5-10 years, and establish foundations for near-term R&D collaboration.

This workshop is one in a series being organized by Los Alamos National Laboratory to engage broader scientific community in the MaRIE (Matter-Radiation Interactions in Extremes) development process. MaRIE is the proposed

MaRIE

**Local Organizers**

- Michael Stevens
- Zhehui (Jeff) Wang
  (505) 665-5353

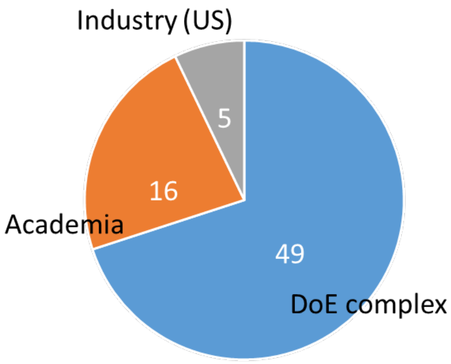
**Meeting Planner**

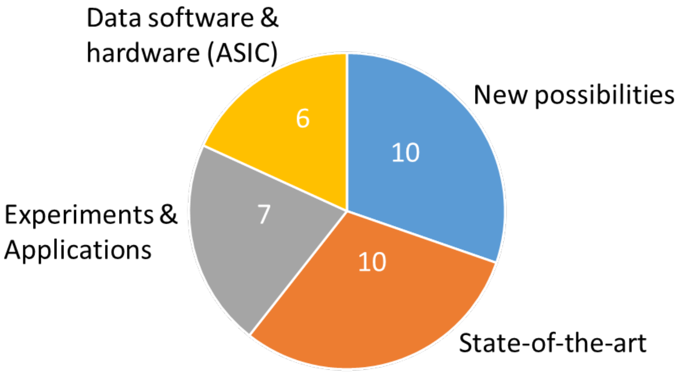
- Peggy Vigil
  (505) 667-8448
  For logistical purposes and questions

**External Co-Organizers**

- Peter Denes (LBL)
- Sol Gruner (Cornell Univ.)

# The August 2016 workshop summary




**Ultrafast and High-Energy X-Ray Imaging Technologies & Applications**

*(August 2-3, 2016; Santa Fe, NM 87506, USA)*

**Table of Contents**

# Two-step development process

| Performance | Type I imager | Type II imager |
|---|---|---|
| X-ray energy | 30 keV | 42-126 keV |
| Frame-rate/inter-frame time | 0.5 GHz/2 ns | 3 GHz / 300 ps |
| Number of frames | 10 | 10 - 30 |
| X-ray detection efficiency | above 50% | above 80% |
| Pixel size/pitch | ≤ 300 mm | < 300 mm |
| Dynamic range | $10^3$ X-ray photons | ≥ $10^4$ X-ray photons |
| Pixel format | 64 x 64 (scalable to 1 Mpix) | 1 Mpix |

MaRIE KPP requirements

| ASIC/Data | No. Chan. | Analog bandwidth (GHz) | digital sampling (GHz) | S/N (dB) | Bit Res. | CMOS technol. |
|---|---|---|---|---|---|---|
| PSEC4 | 6 | 1.5 | 15 | | 10.5 | IBM 130 nm |
| "Hawaii chip" | 128? | 3 | 20 | 58 dB/ 1Vpp | 9.4 | (TSMC 130 nm) |
| "Cornell Keck GHz" | 384 x 256 | 0.5 | | | | |
| epixΔ | 1M | 3 | | | >= 8 | TSMC 250 nm |

UNCLASSIFIED

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  - *Software: Data challenge (acquisition, storage, transport, processing)*
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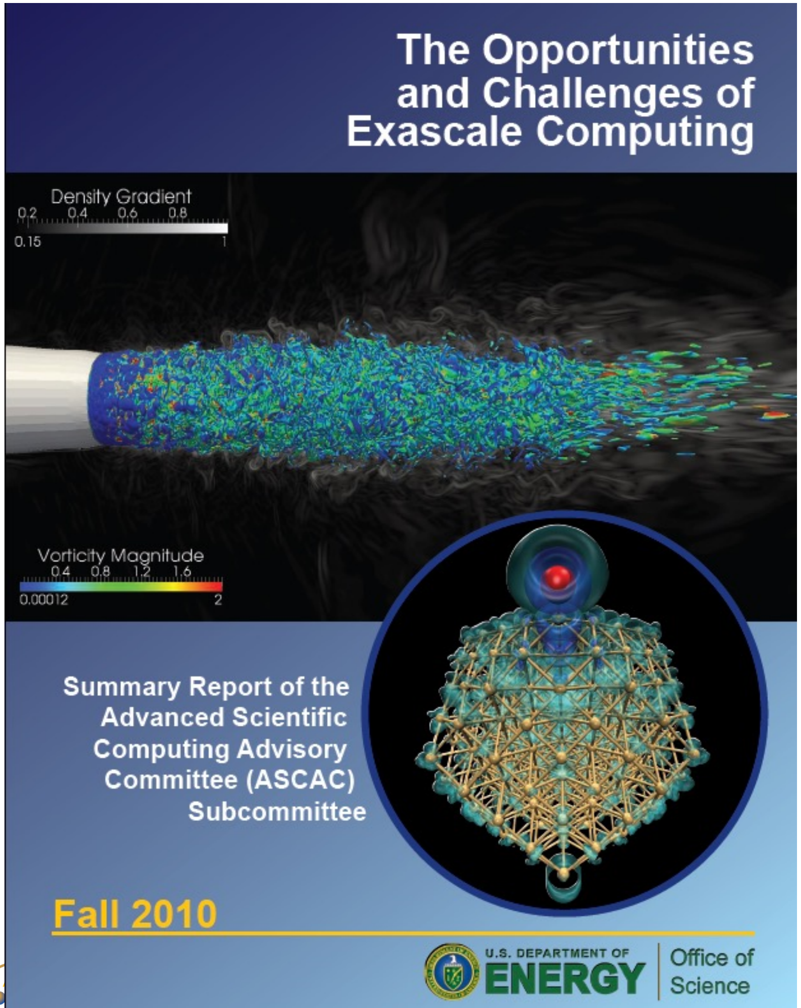
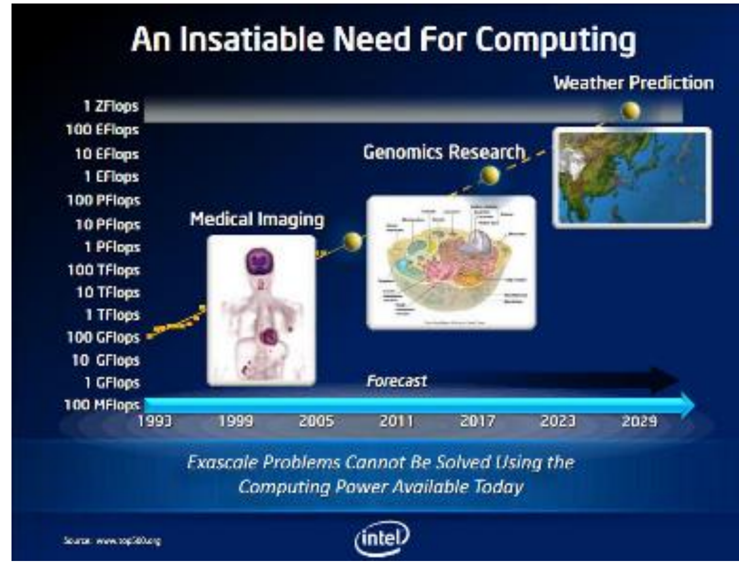
    - Micro/Nano → Proof-of-concepts (Long term)

# Data challenge: Exascale computing & machine learning

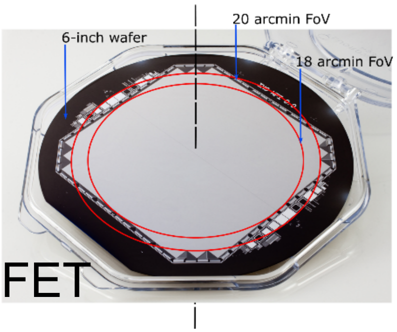



*Solutions in the making*

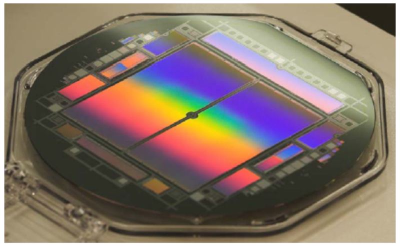



Google AlphaGo

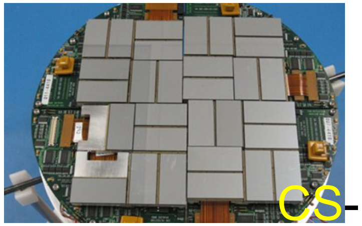
# The materials challenge: Silicon is the chosen one so far



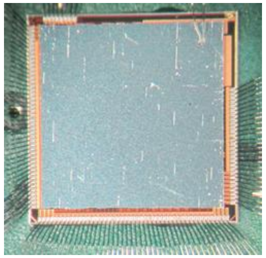

DEPFET



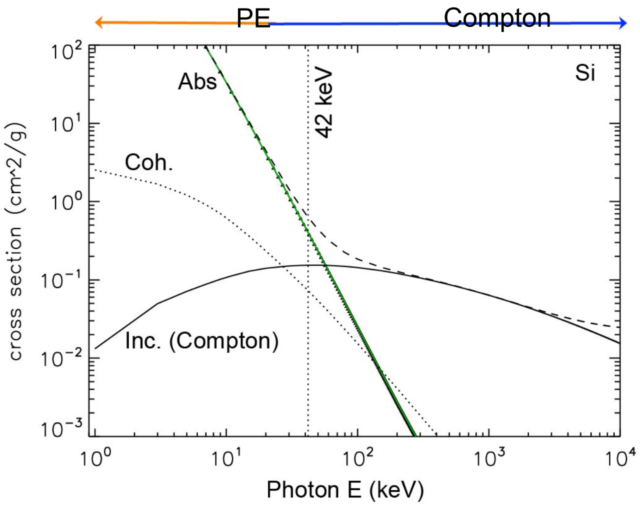
pnCCD

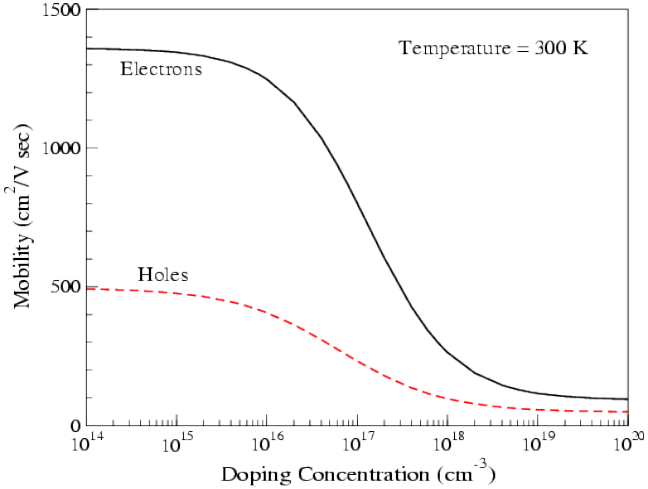


CS-PAD

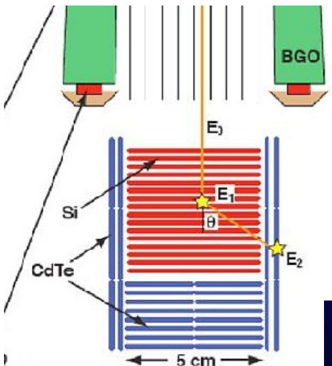


AGPID

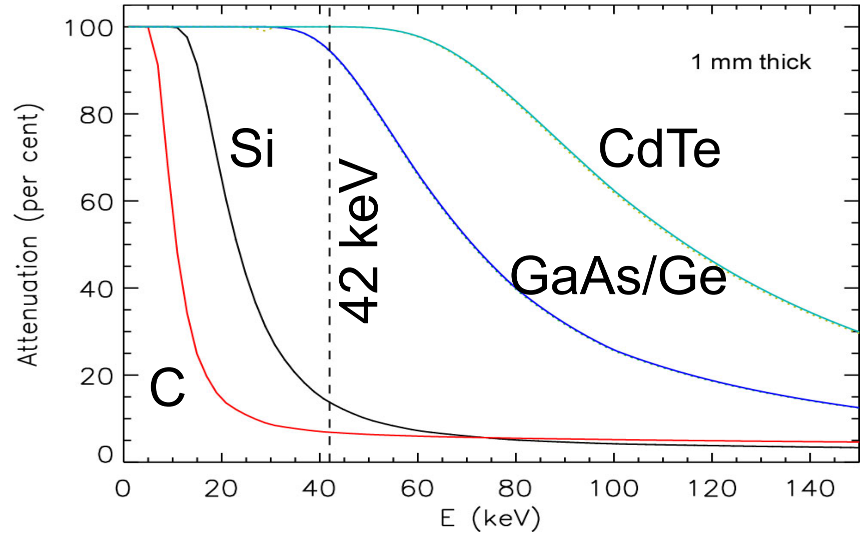


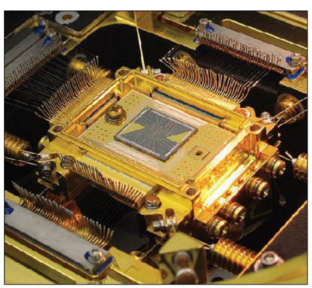



# Emerging Materials: High-Z Sensors

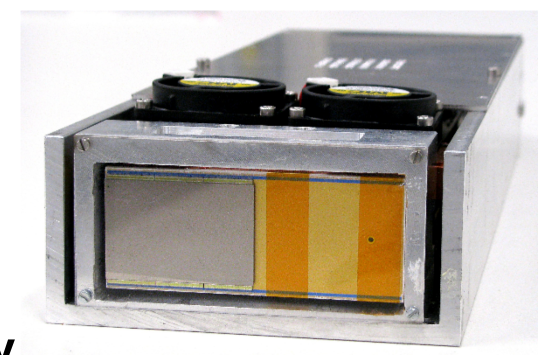




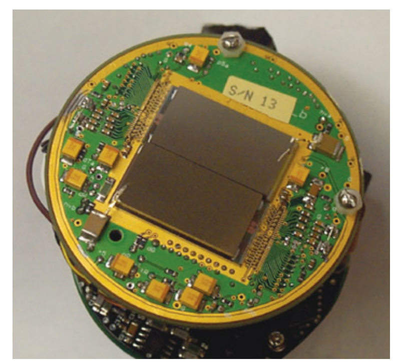


**microcalorimeter array**

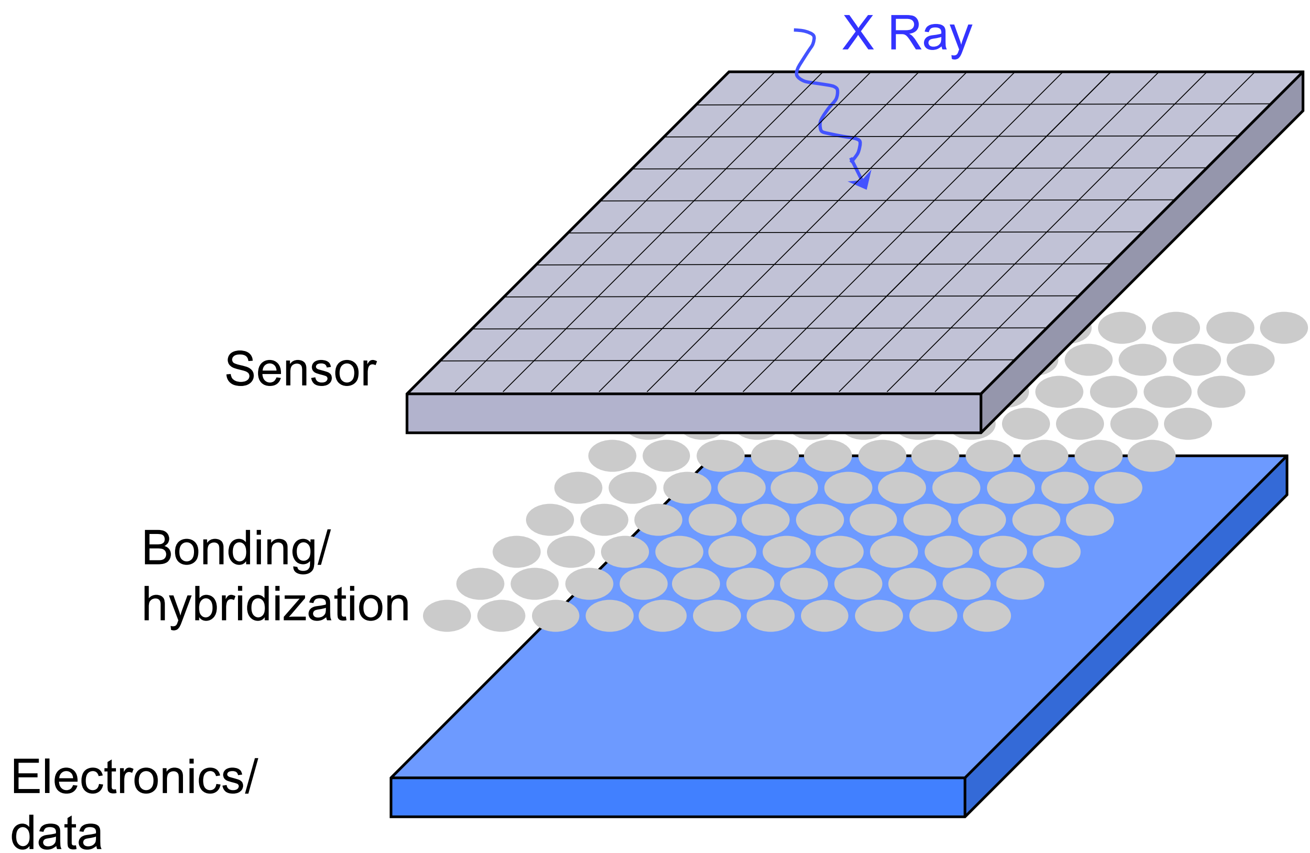


GaAs (DESY)




CZT (LLNL)

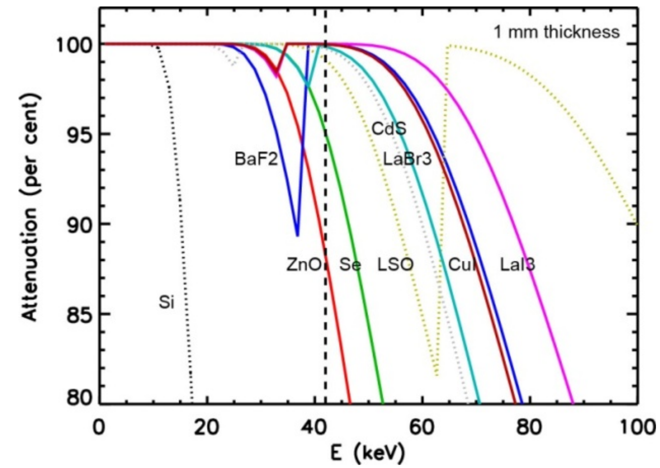
# Existing camera architecture: 2D hybrid



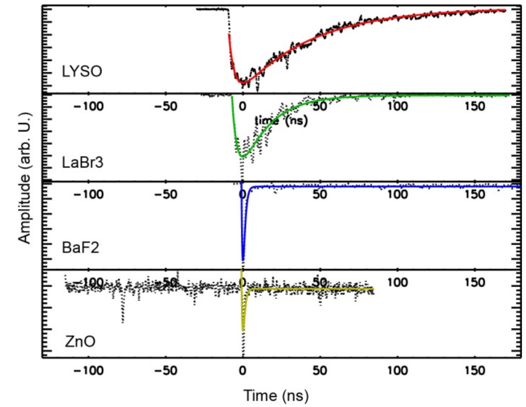
# The need for "3D" architecture: speed & efficiency

- Efficiency driven total sensor thickness

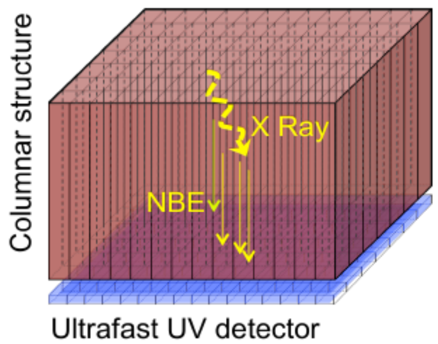
| | 42 keV | | 126 keV | |
|---|---|---|---|---|
| | $\Lambda_{tot}$ (cm) | $3\,\Lambda_{tot}$ (cm) | $\Lambda_{tot}$ (cm) | $3\,\Lambda_{tot}$ (cm) |
| C (Diamond) | 1.4 | 4.2 | 2.0 | 6.0 |
| Si | 0.7 | 2.0 | 2.7 | 8.1 |
| Ge | 3.3e-2 | 0.1 | 0.52 | 1.55 |
| GaAs | 3.4e-2 | 0.1 | 0.52 | 1.55 |
| CdTe | 9.5e-3 | 0.028 | 0.17 | 0.51 |

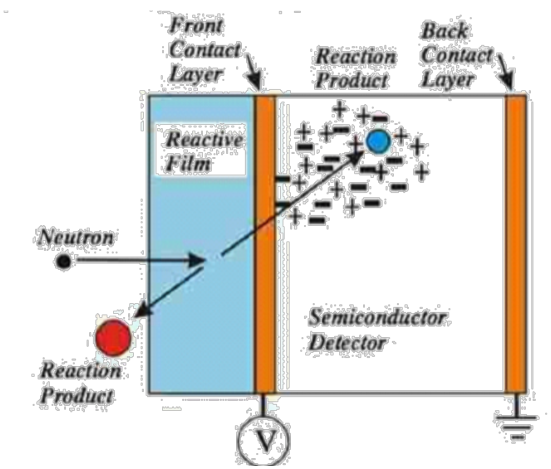



- Speed driven pixel thickness
  - charge collection length for 1 ns, ≤ 200 μm (saturated drift $2\times10^{7}$ cm/s)
  - aspect ratio, 10 to > 1000.



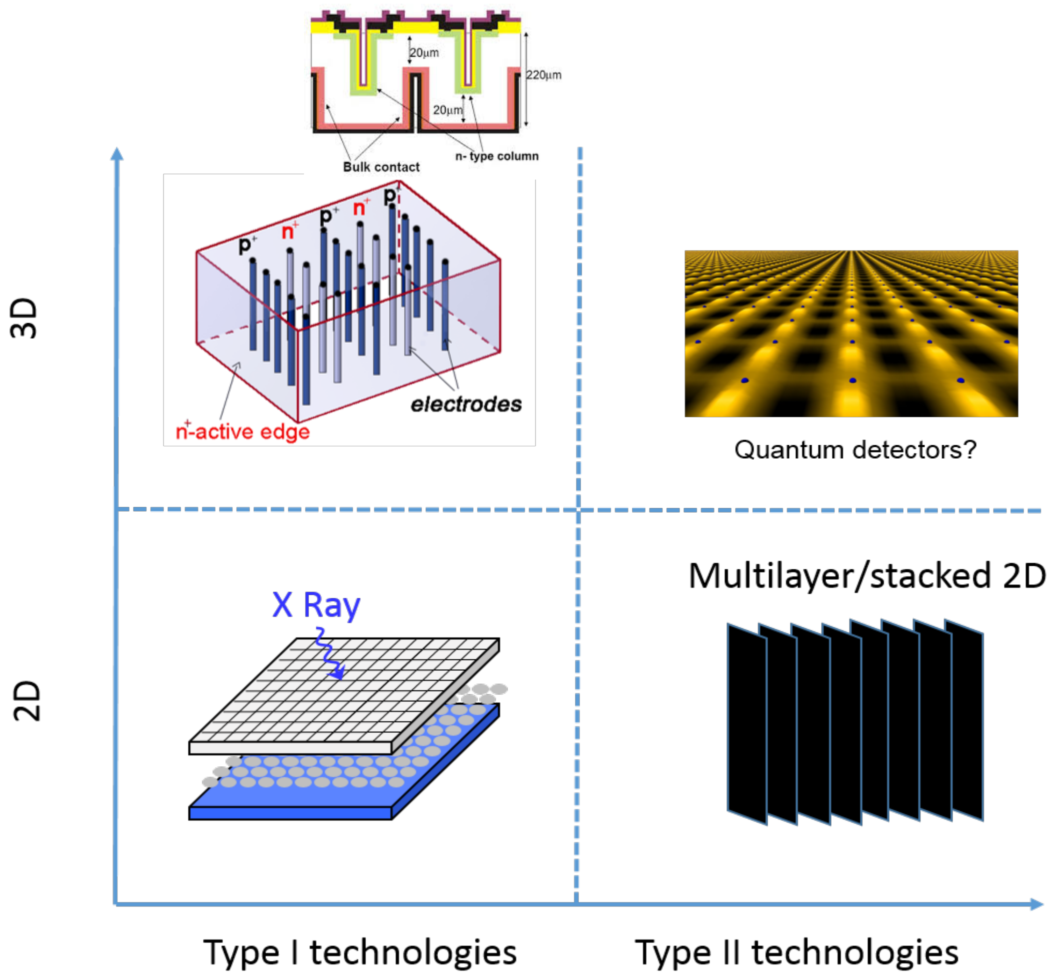
# Material innovations



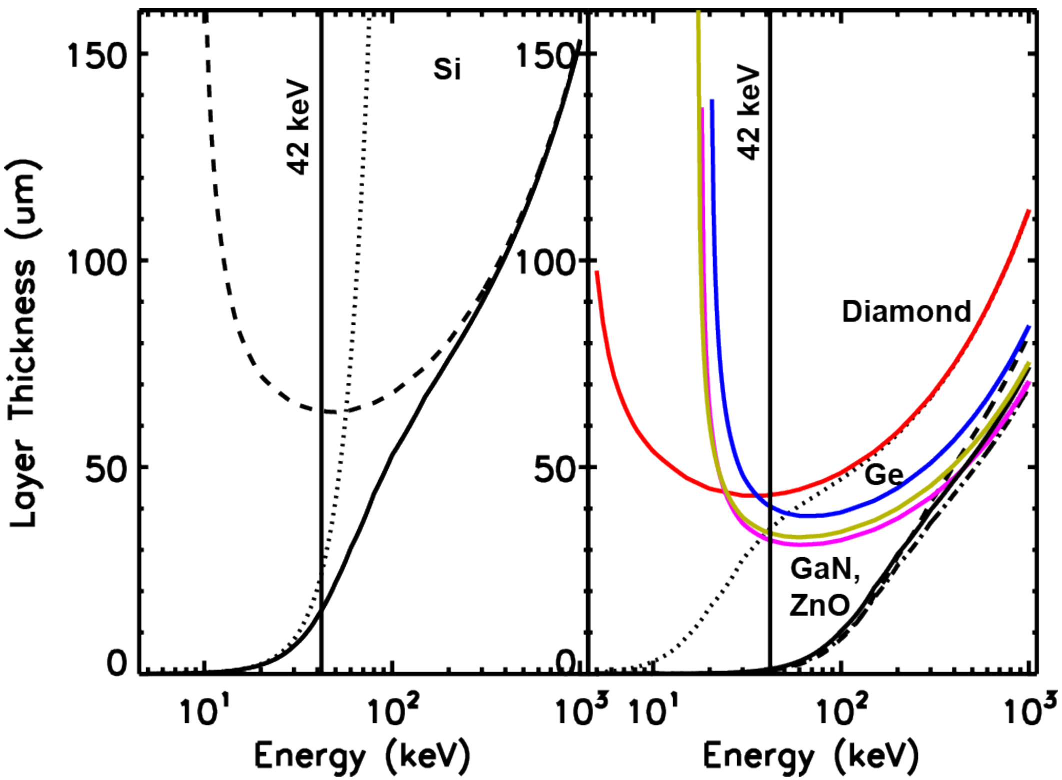

| | Type I technologies | Type II technologies |
|---|---|---|
| Indirect detection | $BaF_2$, ZnO?<br>LYSO?, $LaBr_3$? | 2D materials?<br>Purcell enhanced?<br>Plasmonic enhanced?<br>Quantum dots? |
| Direct detection | Si, Ge, GaAs<br>CdTe, CZT | Si ?, Ge ?, GaAs ?,CdTe ?, CZT?<br>WBS (C-diamond?, GaN?)<br>2D materials? |

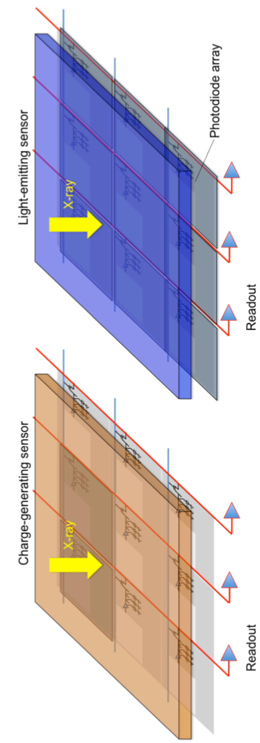
# Architectural innovations based on semiconductors

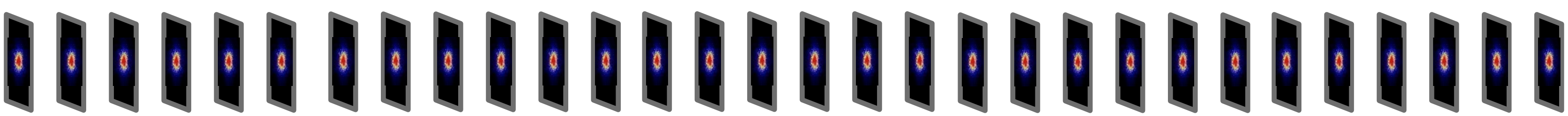


# Can we keep 2D? Thin-Film Concepts

More details: Z. *Wang* (2015) *JINST* 10 C12013



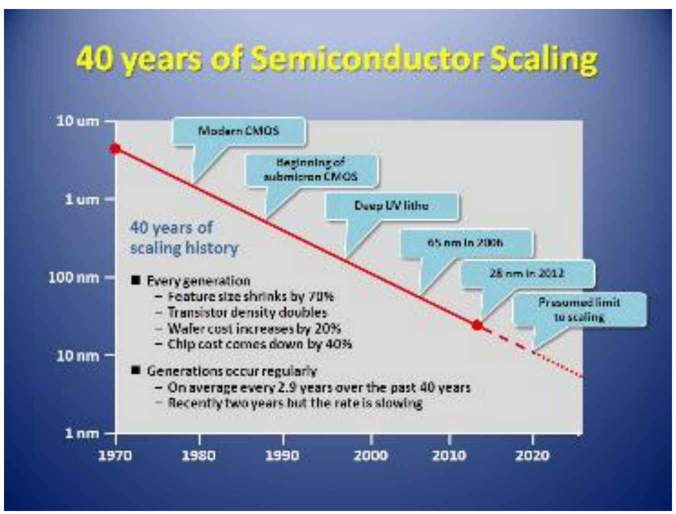



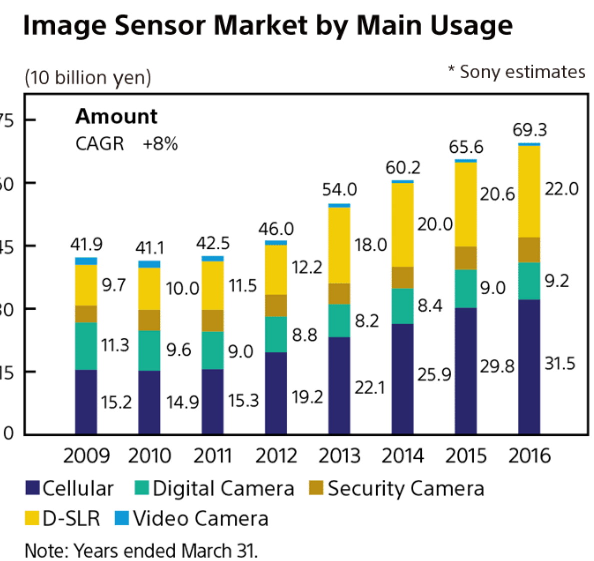



# The fabrication/scaling challenge: CMOS is the best known process

- **Driven by**
  - material selection (Si, $SiO_2$)
  - Economics / user (consumer) base

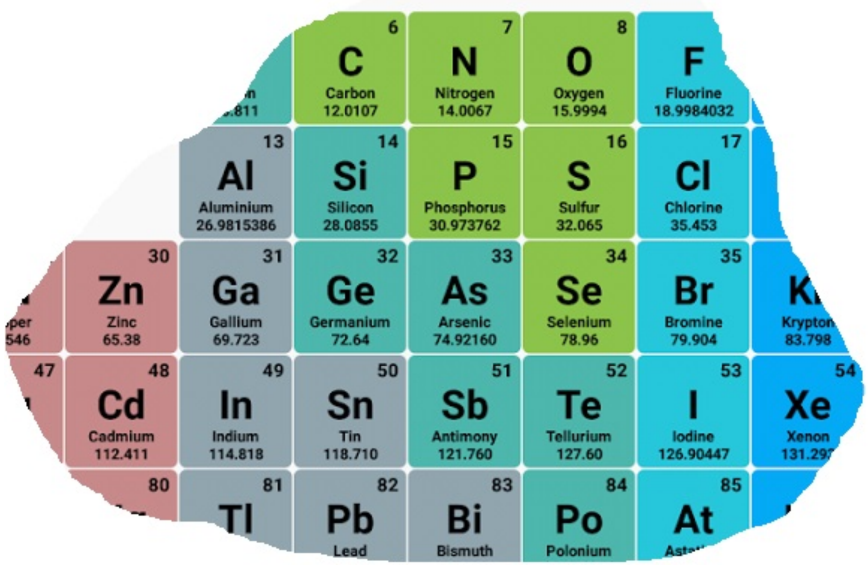
- **Leveraging prior development/investment**
  - High-energy physics community (CERN, Fermilab and others)
  - Semiconductor industry



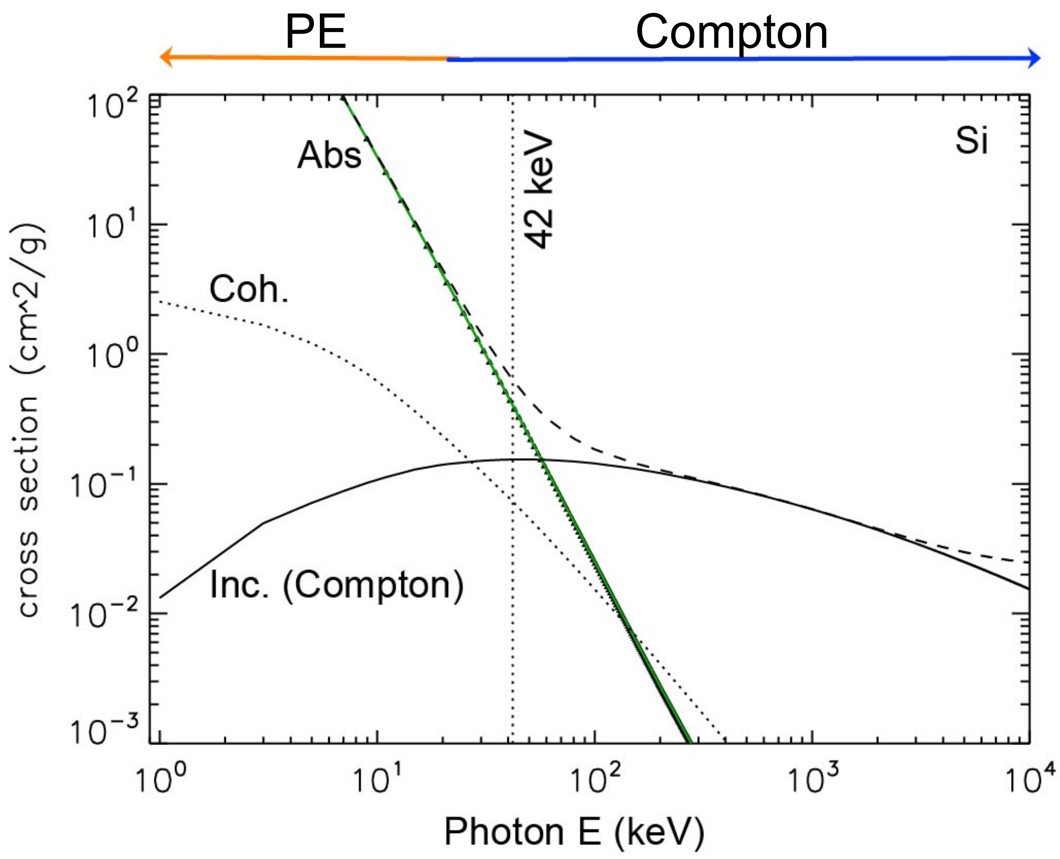



# Five materials questions for ultrafast HEXI

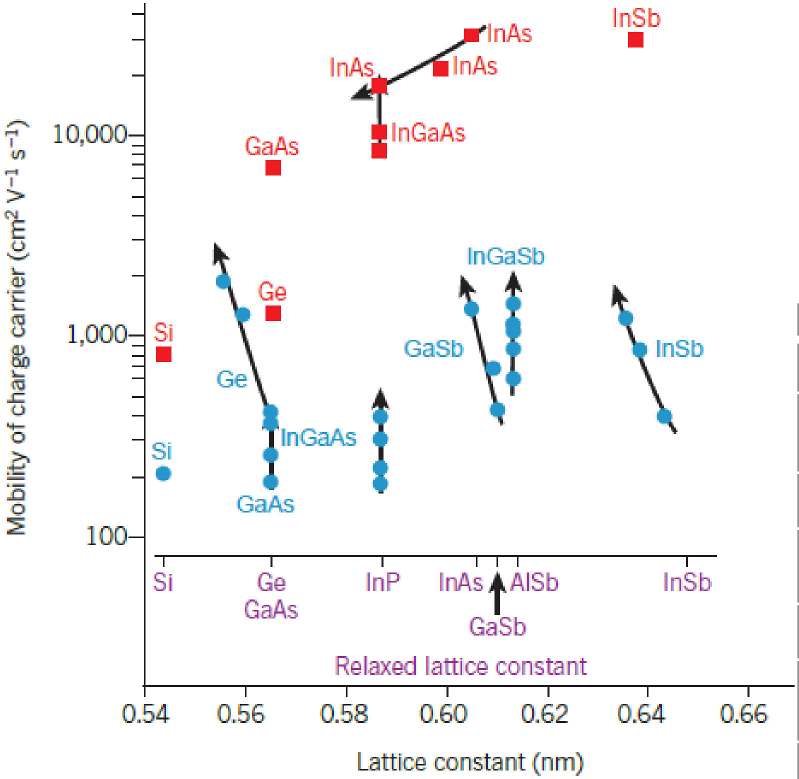
- Will silicon continue to dominate as ultrafast HEXI sensors?
- Will CMOS continue to be used for ASICs & fabrication?
- Will 3D structures replace 2D hybrid structures?
- Can quantum properties of materials be used?
- Can we speed up material discovery to device applications?



# HEX changes the physics in silicon



# Speed is still limited by charge collection, *bandgap also important*




del Alamo, *Nature 479*, 317 (2011)

| Material | Mobility, μ, cm²/V.s | Dielectric Constant, ε | Bandgap, Eg, eV | Break down field, Eb $10^6$V/cm | BFOM Ratio | Tmax, °C |
|---|---|---|---|---|---|---|
| Si | 1300 | 11.9 | 1.12 | 0.3 | 1.0 | 300 |
| GaAs | 5000 | 12.5 | 1.42 | 0.4 | 9.6 | 300 |
| 4H-SiC | 260 | 10 | 3.2 | 3.5 | 3.1 | 600 |
| GaN | 1500 | 9.5 | 3.4 | 2 | 24.6 | 700 |

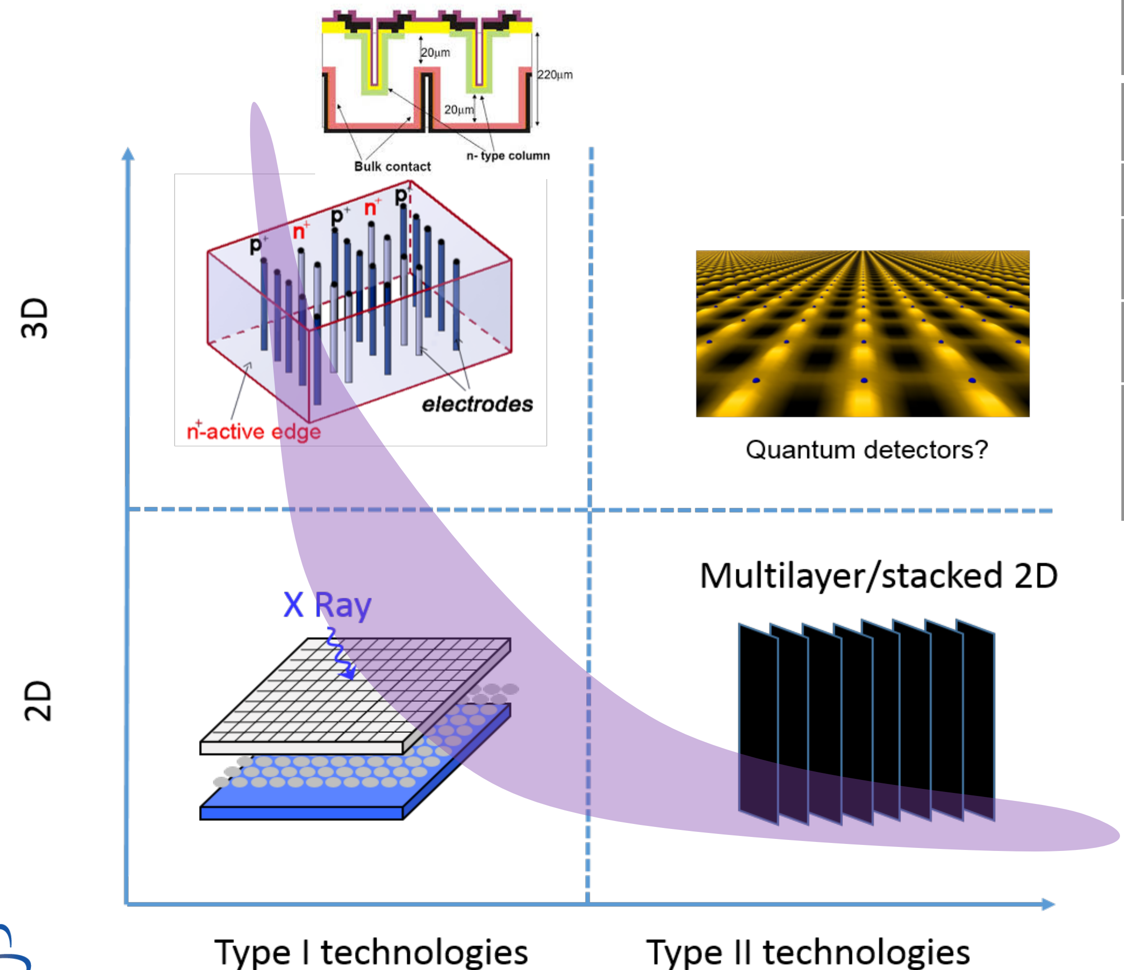
BFOM is Baliga's figure of merit for power transistor performance ($\mu * \varepsilon * Eg^3$)

B. J. Baliga, *IEEE Electron Dev. Lett.* **10**, 455 (1989).

| | Si | GaAs | 6H-SiC | 4H-SiC | GaN | Diamond |
|---|---|---|---|---|---|---|
| Bandgap (eV) | 1.12 | 1.43 | 3.03 | 3.26 | 3.45 | 5.45 |
| Relative dielectric constant | 11.9 | 13.1 | 9.66 | 10.1 | 9 | 5.5 |
| Breakdown field (kV/cm) | 300 | 400 | 2500 | 2200 | 2000 | 10000 |
| E mobility (cm²/Vs) | 1500 | 8500 | 500 | 1000 | 1250 | 2200 |
| Hole mobility (cm²/Vs) | 600 | 400 | 101 | 115 | 850 | 850 |
| Thermal conductivity (W/cmK) | 1.5 | 0.46 | 4.9 | 4.9 | 1.3 | 22 |
| Saturated electron drift velocity (100 μm/ns) | 1 | 1 | 2 | 2 | 2.2 | 2.7 |

L. M. Tolbert, *et al.*, *Proc. IASTED Mult. Conf. Pwr En. Syst.* **7**, 317 (2003).

# Structural & processing innovations




| Material Processes | Features |
|---|---|
| Thin film process | novel thin-film properties |
| Additive process | Micro-, nano-grains |
| Microfluidic process | Versatile nano-particle assembly |
| Polymer-assisted fabrication | Versatile nano-particle assembly |
| Self-assembly/ biological assisted processes | Autonomous |

Existing processes:
CMOS,
SOI,
SiGe.

# Summary

- **Ultrafast imaging technology development requires a inter-disciplinary approach – '*global optimization*'—Cris Barnes.**
  - Parallel development paths
  - Selections of specific concepts for prototype development should be based on peer-reviewed proposal rankings.
- **Opportunities exist to develop revolutionary (type II) technologies**
  - Collaborations with broad community will be the key to success
  - Integration of material, fabrication, data handling & application

***Exciting time for instrumentation & experimental science***