Ultrafast imaging technology

From visible light to high-energy X-ray photons

Zhehui (Jeff) Wang

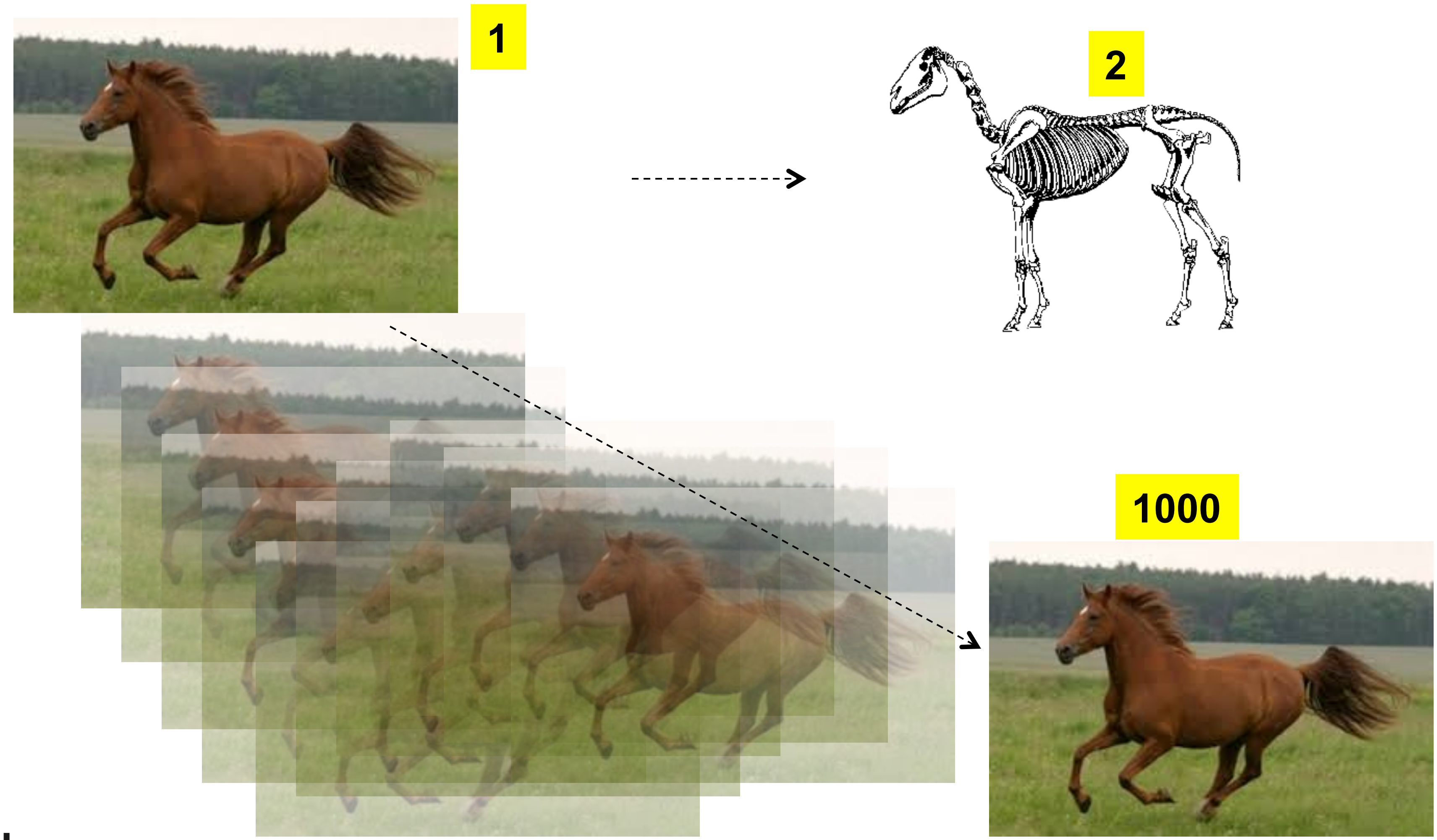
P-25, LANL

P/T colloquium, Jan. 19, 2017

Dynamic, fast & interesting

UNCLASSIFIED

How fast is ultrafast?



Outline

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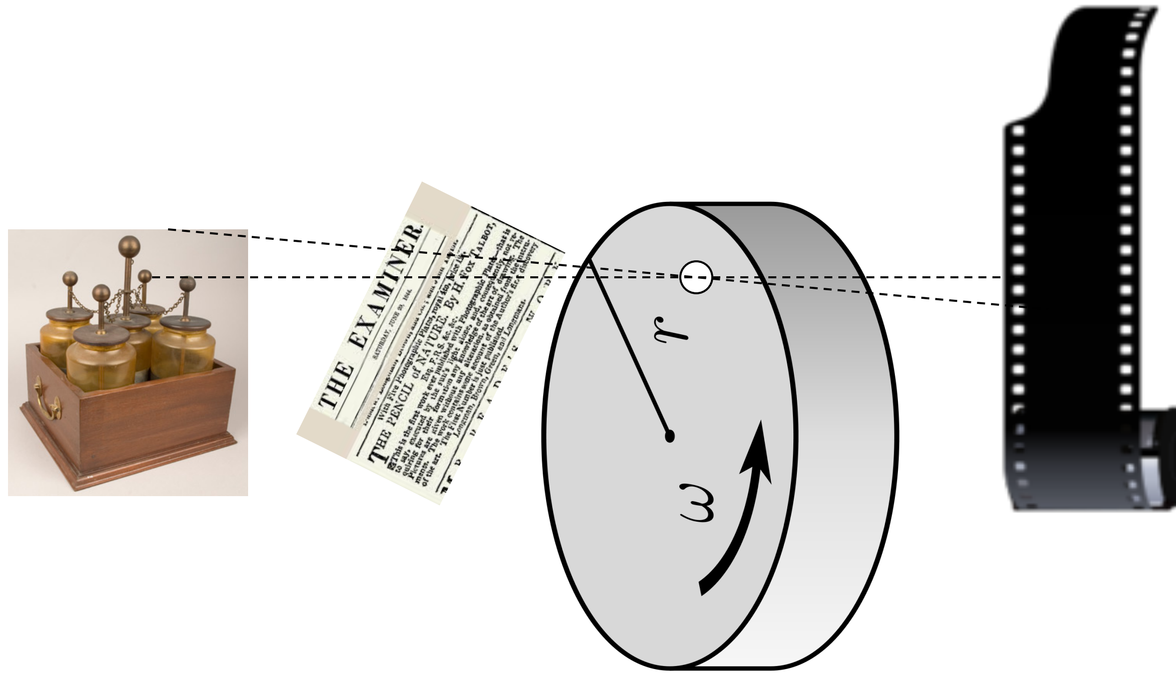
  - Hardware: Materials challenge
    - Conventional “bulk” materials → architecture innovations (near term)
    - Micro/Nano materials → Proof-of-concepts (Long term)

William Henry Fox Talbot

and the Invention of high-speed photography

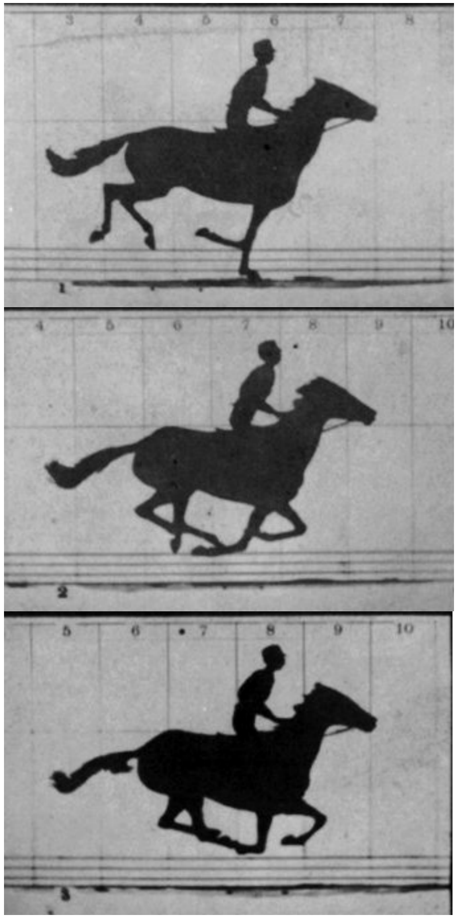


'Further progress in this direction would not be difficult'

--British J. Photography, 1864

Eadweard Muybridge

and the galloping horse photography



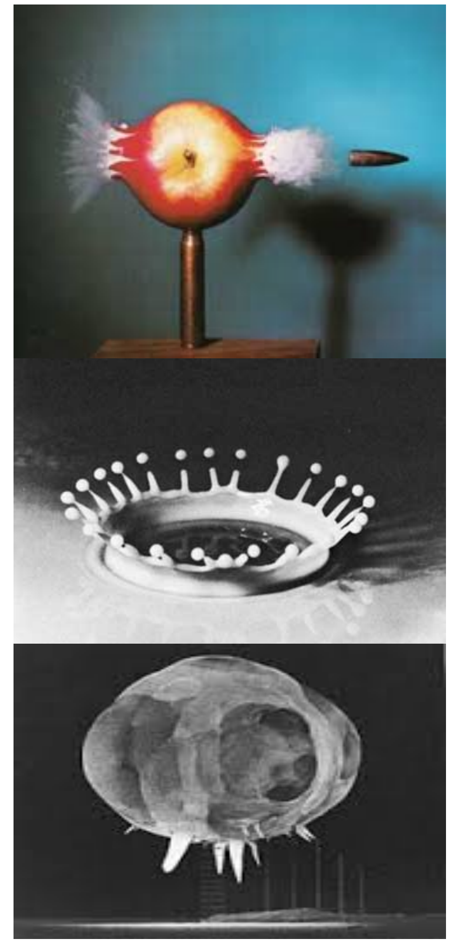
Muybridge designed his own high speed electronic shutter and electro-timer

Harold "Doc" Edgerton

and stroboscope photography

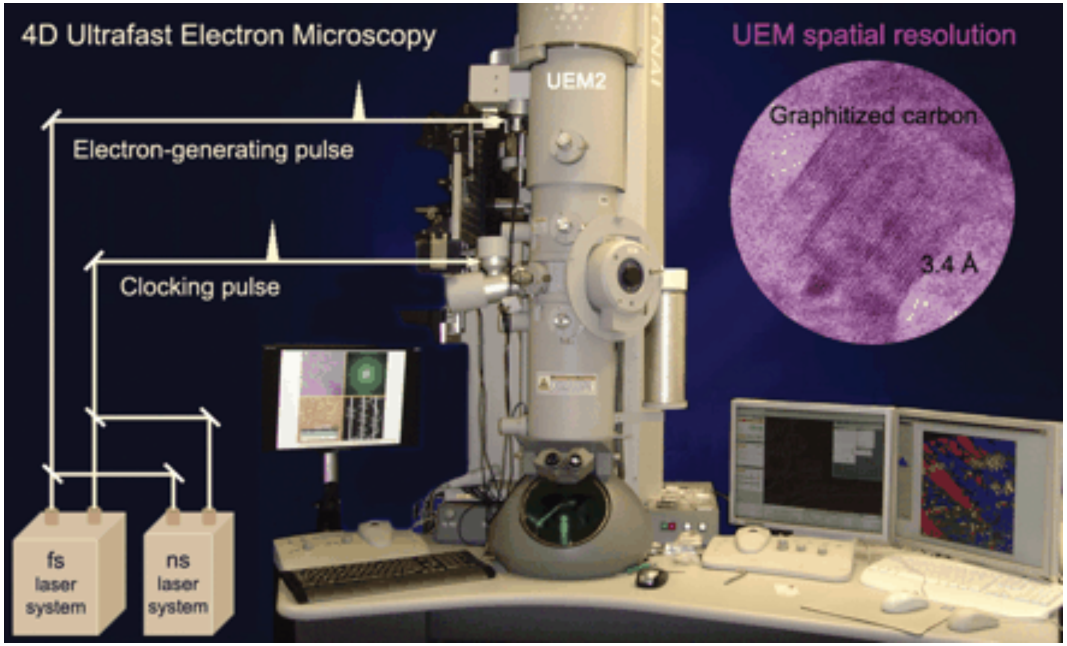
"perfected strobe lighting"

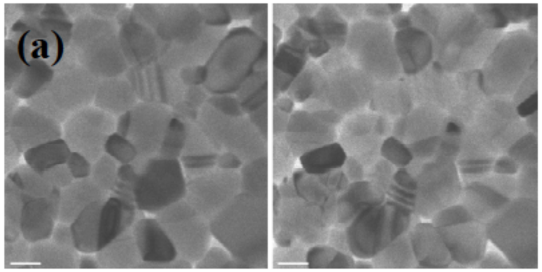
EG&G founder



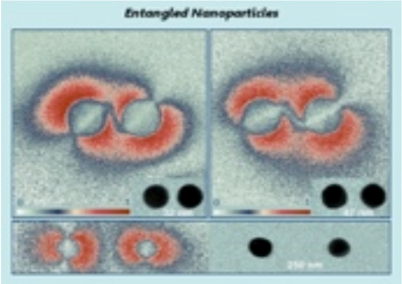
Ahmed Zewail

and the dancing molecule photography





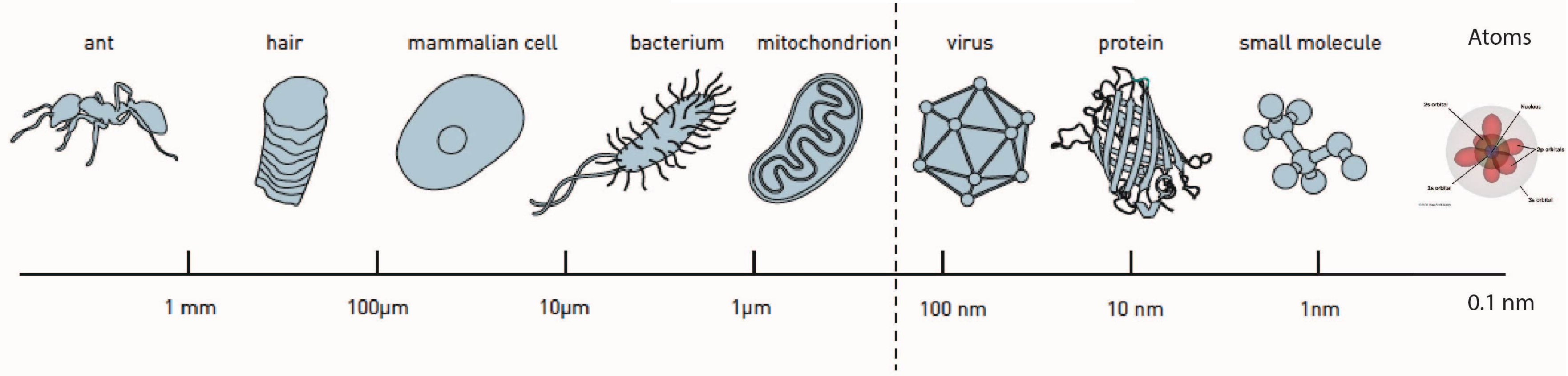
VO_2 phase transition



Entangled nanoparticles

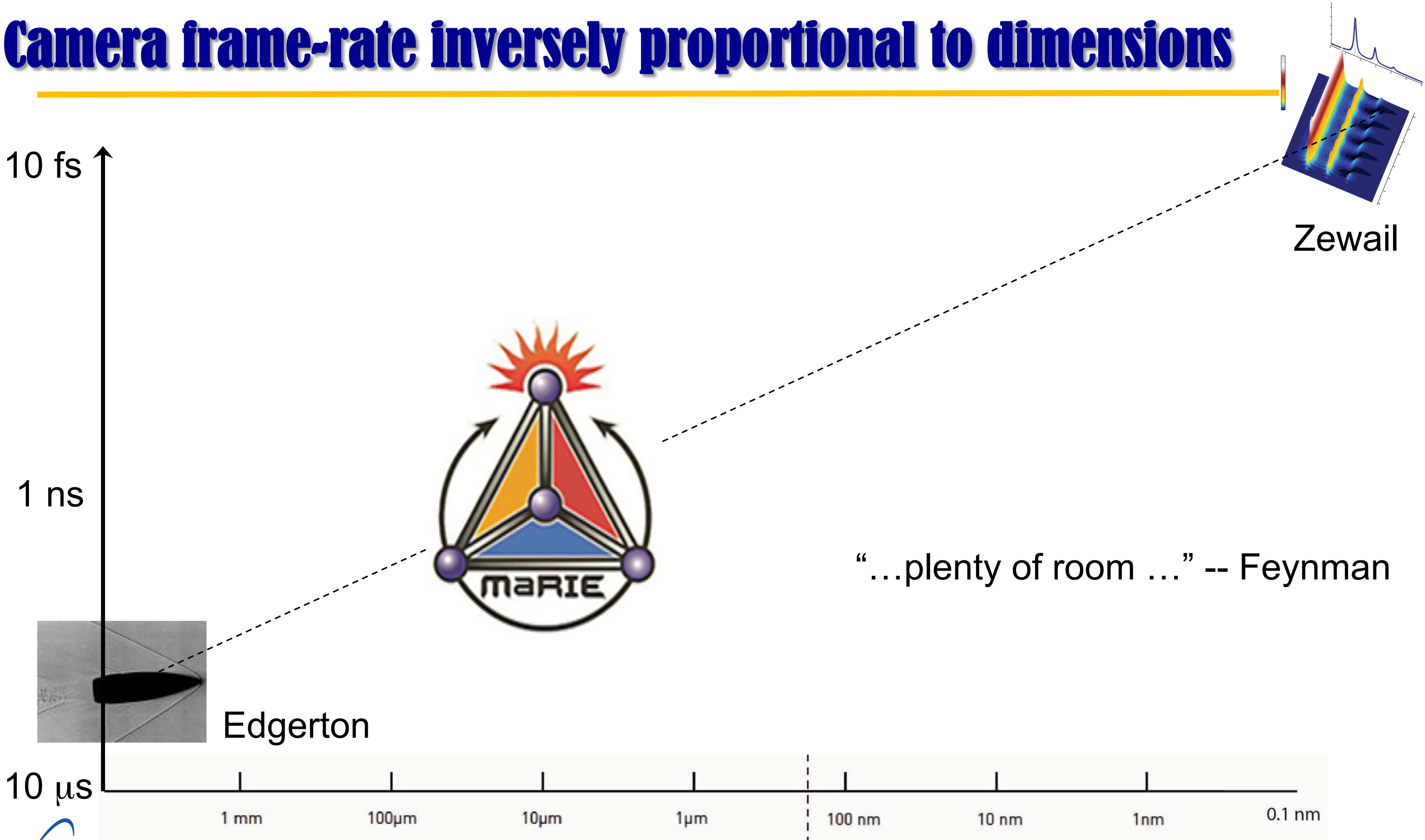
Plenty of 'horses' grazing in nature: from mm- to nano- land

Biology:



Material science, Geology, Quantum world, …

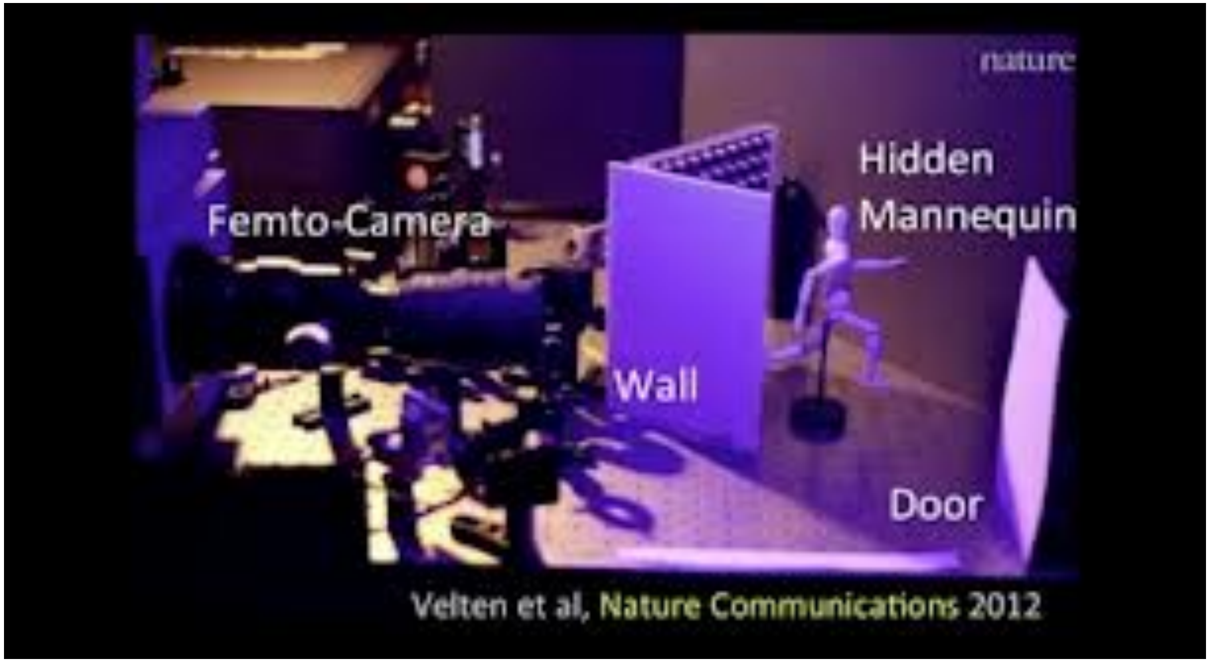
Camera frame-rate inversely proportional to dimensions



Is ultrafast imaging boring for macroscopic objects?

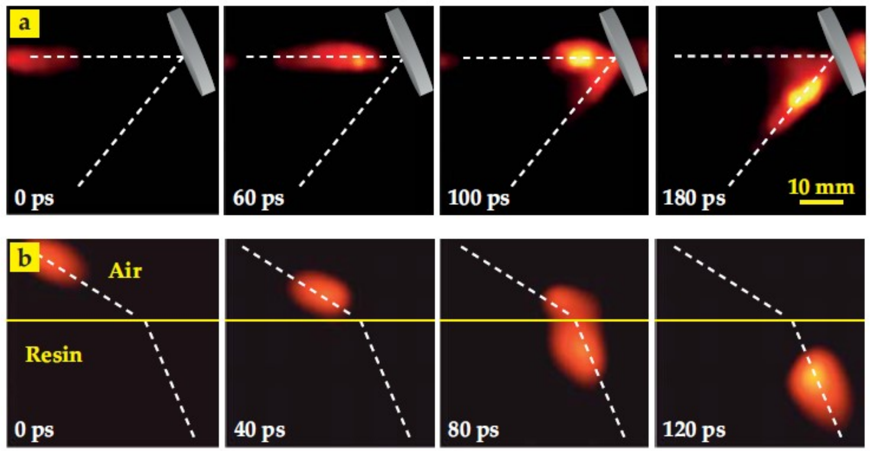
Non-trivial macroscopic applications

Seeing things around the corner



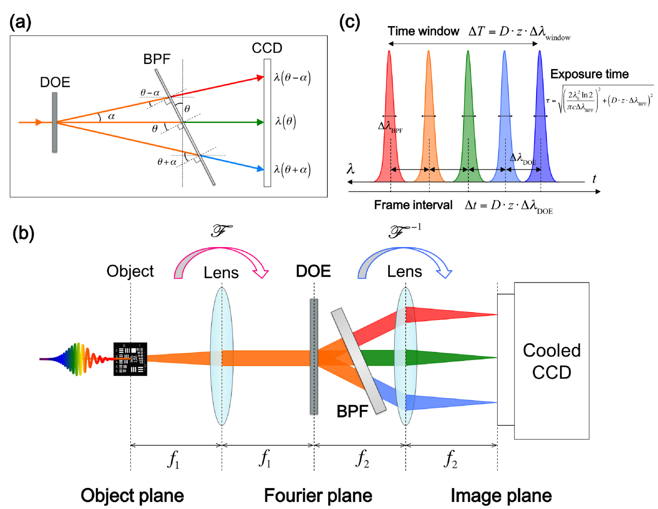
R. Raskar et al. — MIT Media Lab

"Trillion frame cameras" for visible light booming



"CUP"

Gao et al (2014)



"STAMP"

Suzuki et al (2015)

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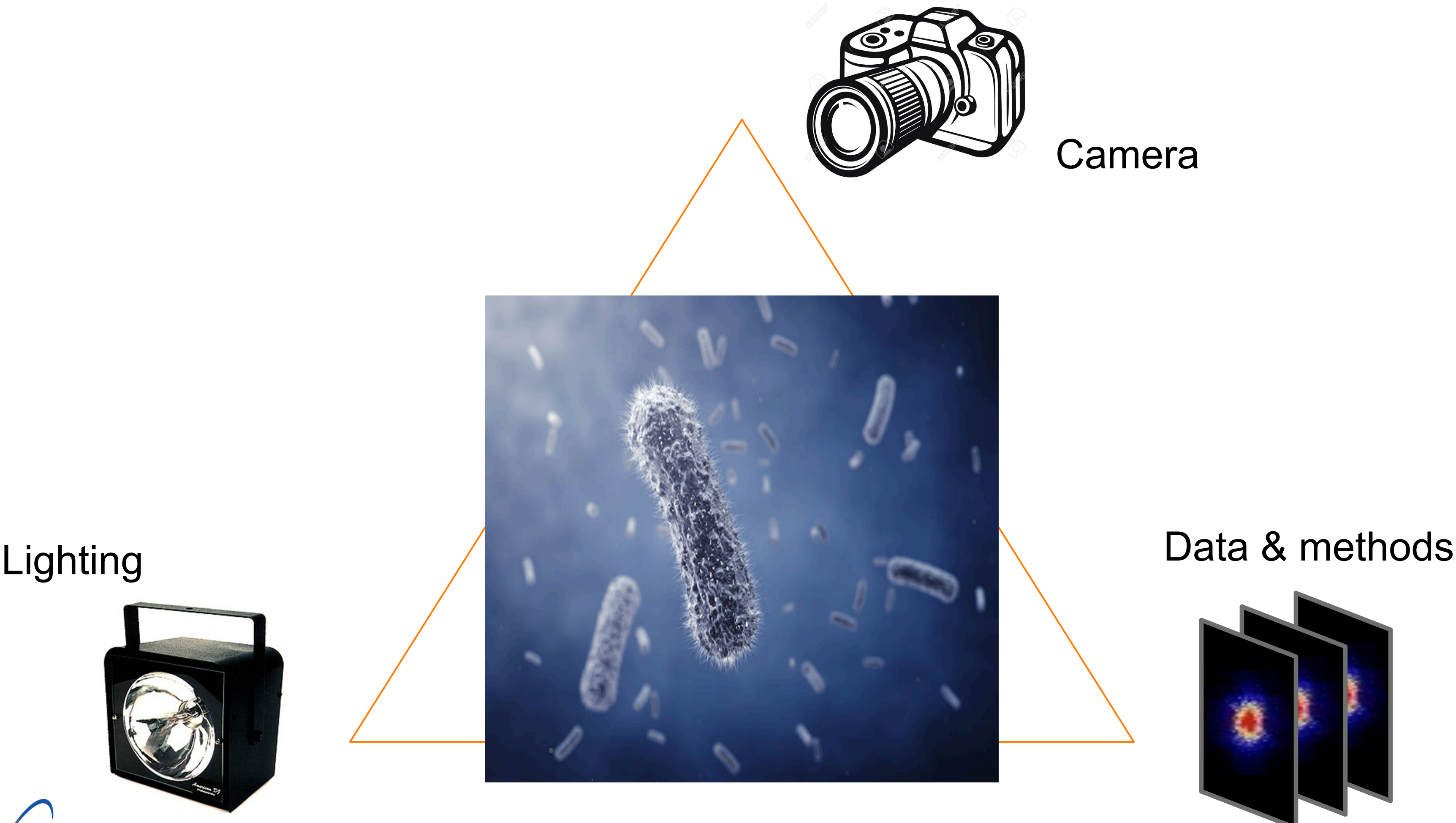
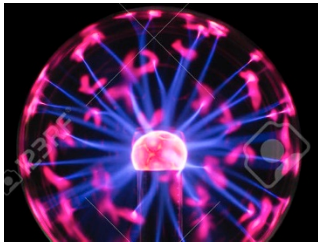
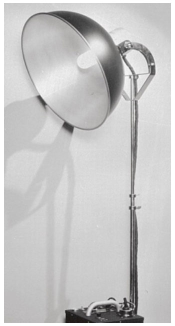
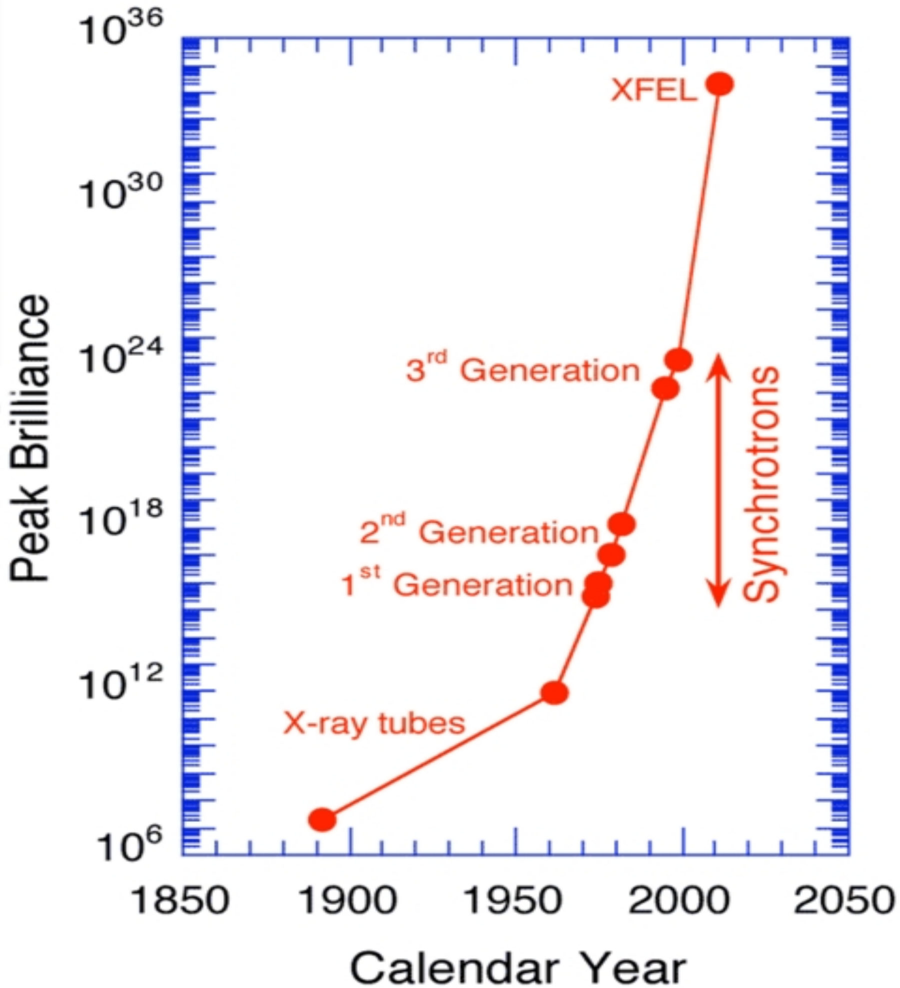
High-speed imaging technology triangle



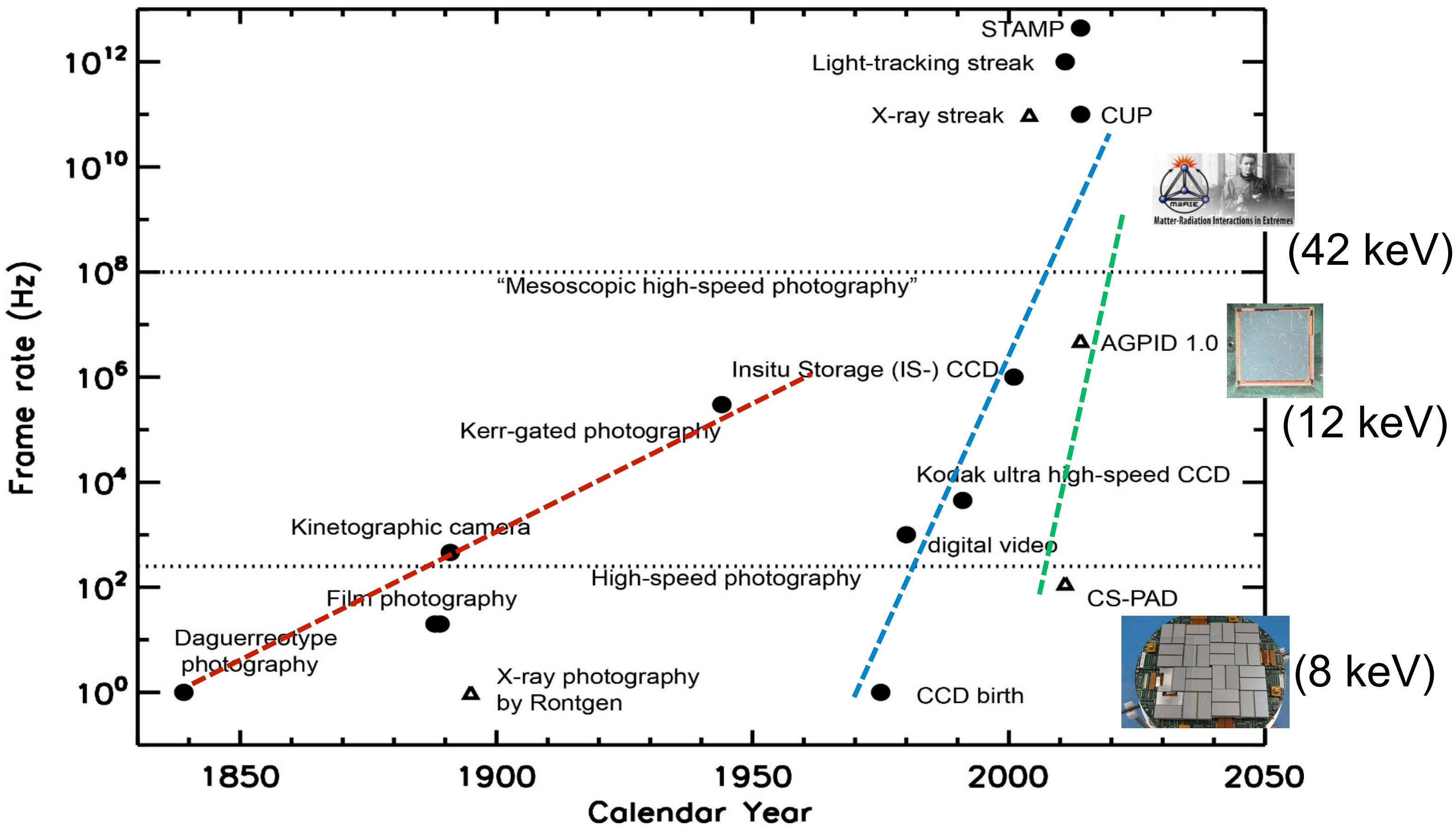
Evolution of lighting







Evolution of high-speed imaging technologies



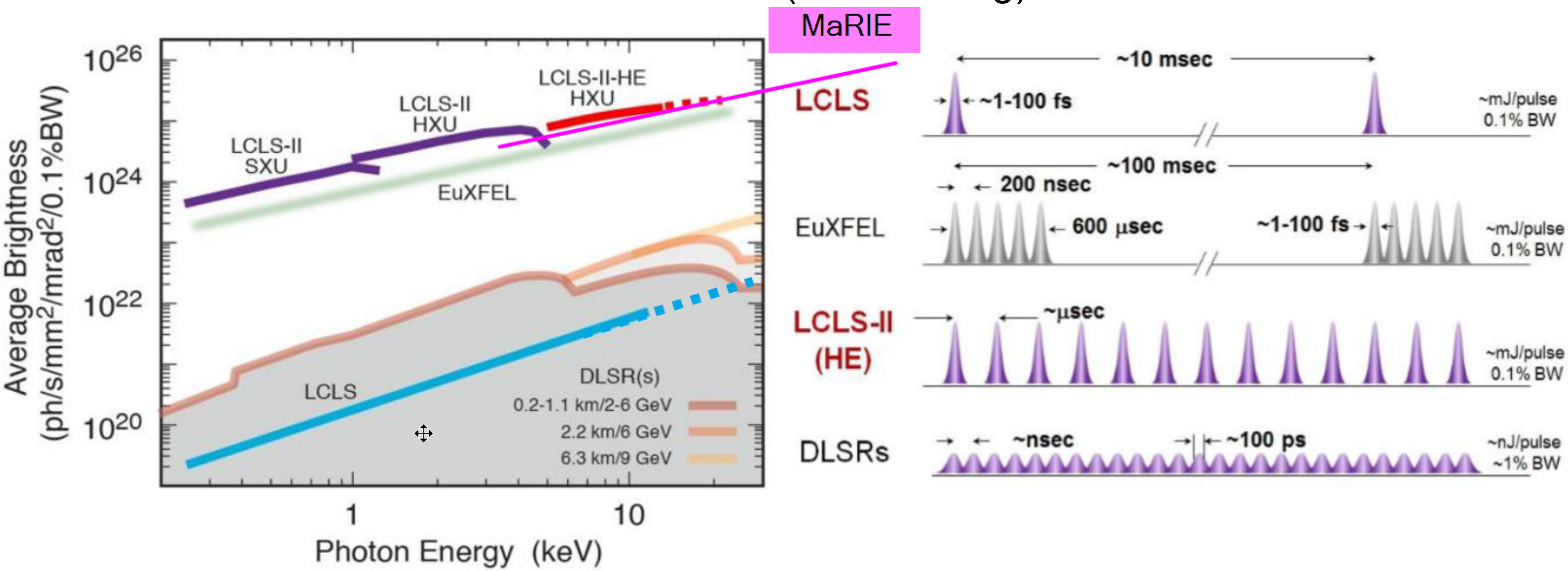
A lot of parallel efforts…

	Detector/ Camera	Voxel dimension	Noise	CMOS technol.	Pixel Bias	Digital clock	Frame rate
		(μm^3)		(μm)	(V)	(MHz)	(MHz)
XFEL	CSPAD	110 ×110 × 500	330 e^-	0.25 (TSMC)	190	25	1.2×10^{-4}
	ePix100a	50 × 50 × 500	50 e^-	0.25 (TSMC)	200	0.1	1.2×10^{-4}
sync	Keck-PAD	150 ×150 × 500	1530e^- (860 μV)	0.25 (TSMC)	200	50	6.5
XFEL	AGIPD 1.0	200 ×200 × 500	265e^- <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/μm)	10	2.5×10^{-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	6×10^{-5}
XFEL	SOPHIAS	30 × 30 × 500	150 e^-	0.2 FD-SOI	~200	25	6×10^{-5}
XFEL	JUNGFRAU [SMS:2015]	75 × 75 × 450	100 e^-	0.11 (UMC)	220	40	2.4×10^{-3}
HEP	ALPIDE[2] (MAPS[3])	28 × 28 × 50	~ 20 e^-	0.18 (TowerJazz)	<10	40	5.0×10^{-2}
sync	FASPAX [ZIM:2016]	100×100 × 500	<1000 e^-	130nm SiGe (IBM)	1000	100	13 (burst)

MaRIE driven ultrafast imaging technology

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-camera: Performance summary

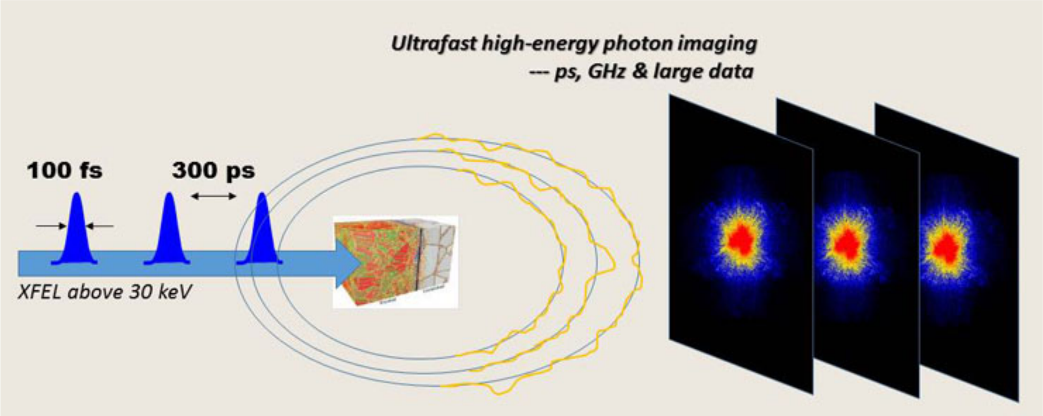
- **PicoSecond sensor <-> Materials challenge**
  - highly efficient (>50%) x-ray detection at 30-keV and above energies.
  - Sub-ns (<100-ps) X-ray sensor and storage response.
- **GigaHertz frame-rate <-> Fabrication/scaling challenge**
  - Many pixels, interframe time, 300 ps (3 GHz)
  - Multiple frames per experiment/ framing for acoustic velocities across grains
  - Single line-of-sight
- **Large data <-> Data 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

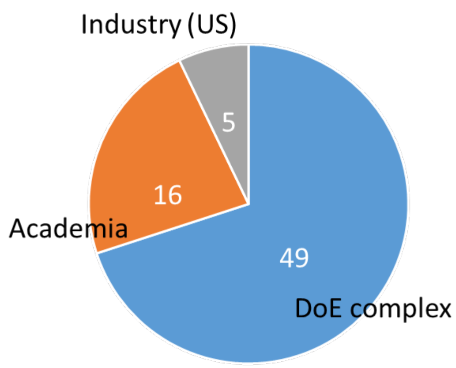
Meeting Planner

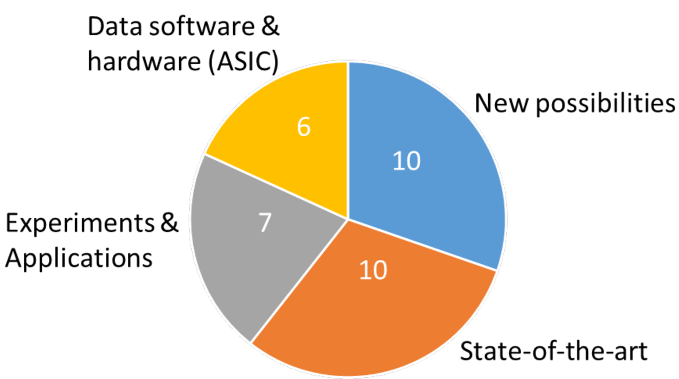
- Peggy Vigil
  (505) 667-8448
  For logistical purposes and questions

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-pronged development process: (Low & High Risk)

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

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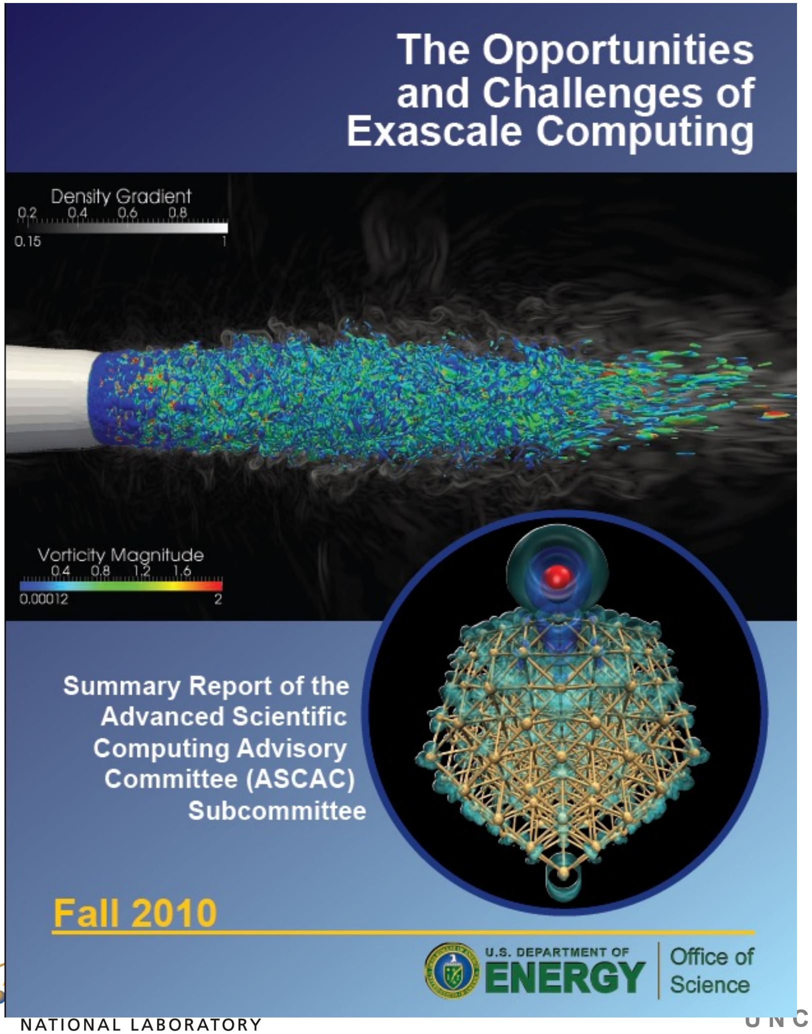
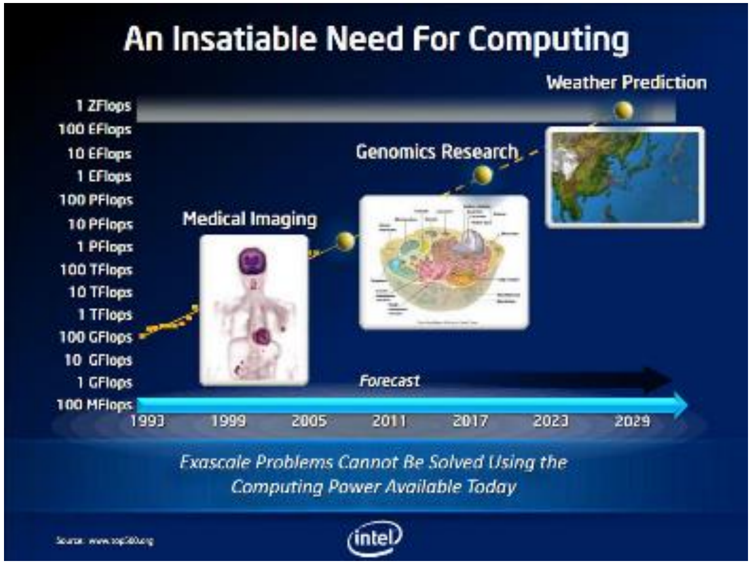
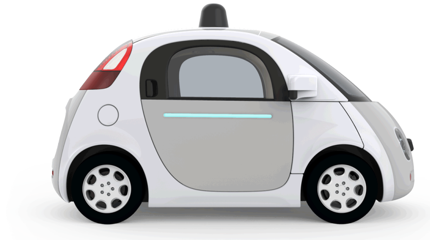
Data challenge: Exascale computing & Data analytics

Solutions in the making

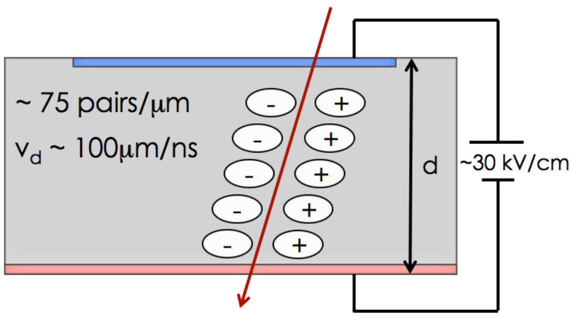




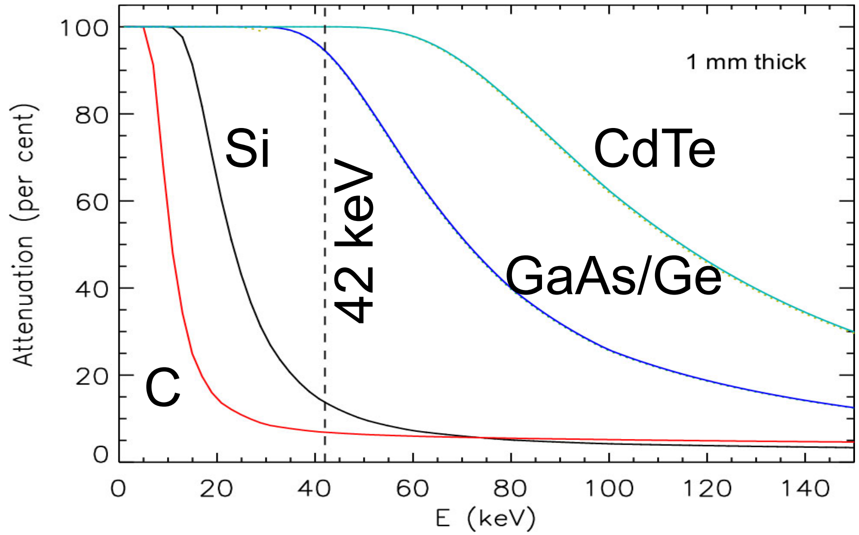
Google AlphaGo

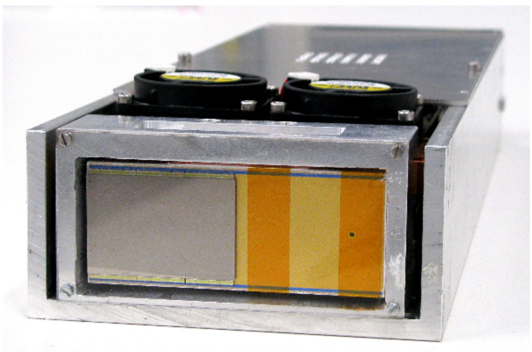


Efiiciency (1): High-Z semiconductor sensors

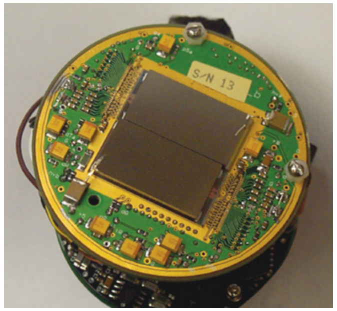


Direct detection



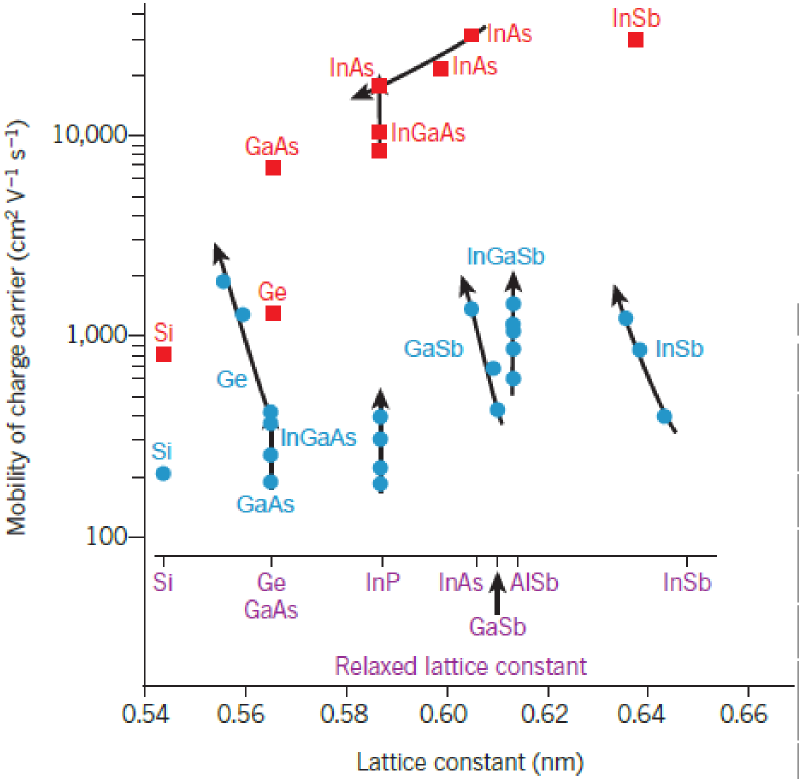


GaAs (DESY)



CZT (LLNL)

Speed limited by e-/h mobilities, *bandgap also important*



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

Material	Mobility, μ, $cm^2/V.s$	Dielectric Constant, ε	Bandgap, Eg, eV	Break down field, Eb 10^6V/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 (cm^2/Vs)	1500	8500	500	1000	1250	2200
Hole mobility (cm^2/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).

Thick sensors → insufficient speed for GHz imaging

- Cons: required sensor thickness

	42 keV		126 keV	
	Λ_{tot} (cm)	3 Λ_{tot} (cm)	Λ_{tot} (cm)	3 Λ_{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

- charge collection length for 1 ns, ≤ 200 μm

(saturated drift $2x10^7$ cm/s)

- aspect ratio, 10 to > 1000.

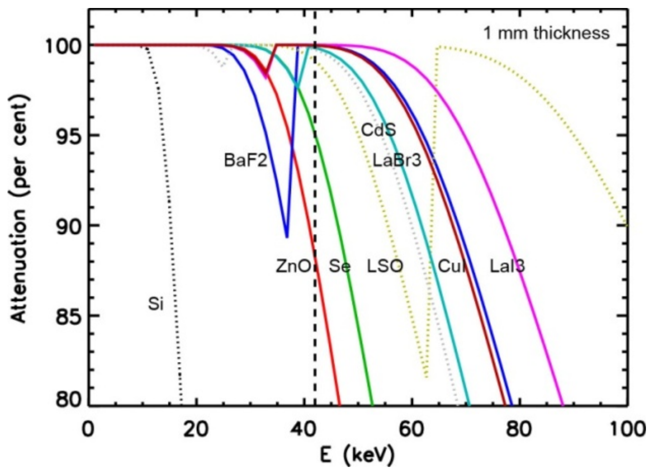
→ 100 MHz (Type I technology OK), Type II (GHz difficult)

Dragone et al (2016)

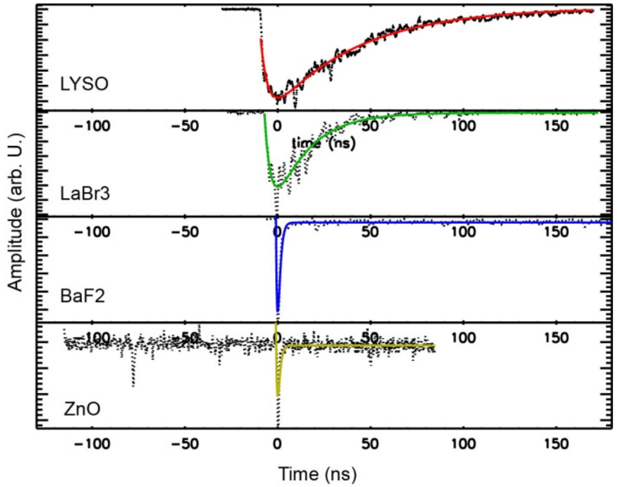
Efficiency (2): Scintillators also have significant problems at GHz

- Pros
  - Light moves x1000 faster than e-.
  - Thin scintillators sufficient

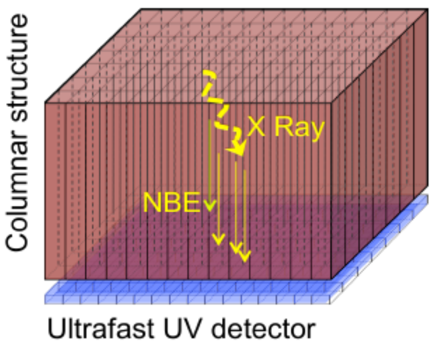
- Cons
  - Light yield & decay time constants.
  - Needs ultrafast photodetectors (semiconductors)
  - Material supply issues
  - Spatial resolution limited due to internal reflection

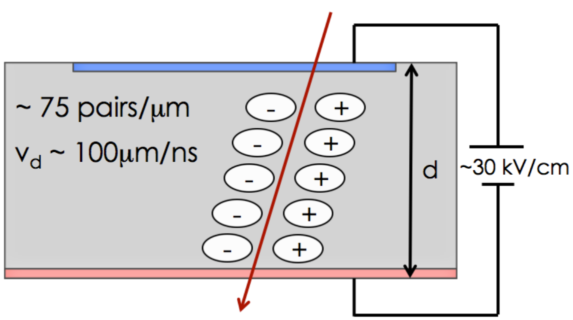


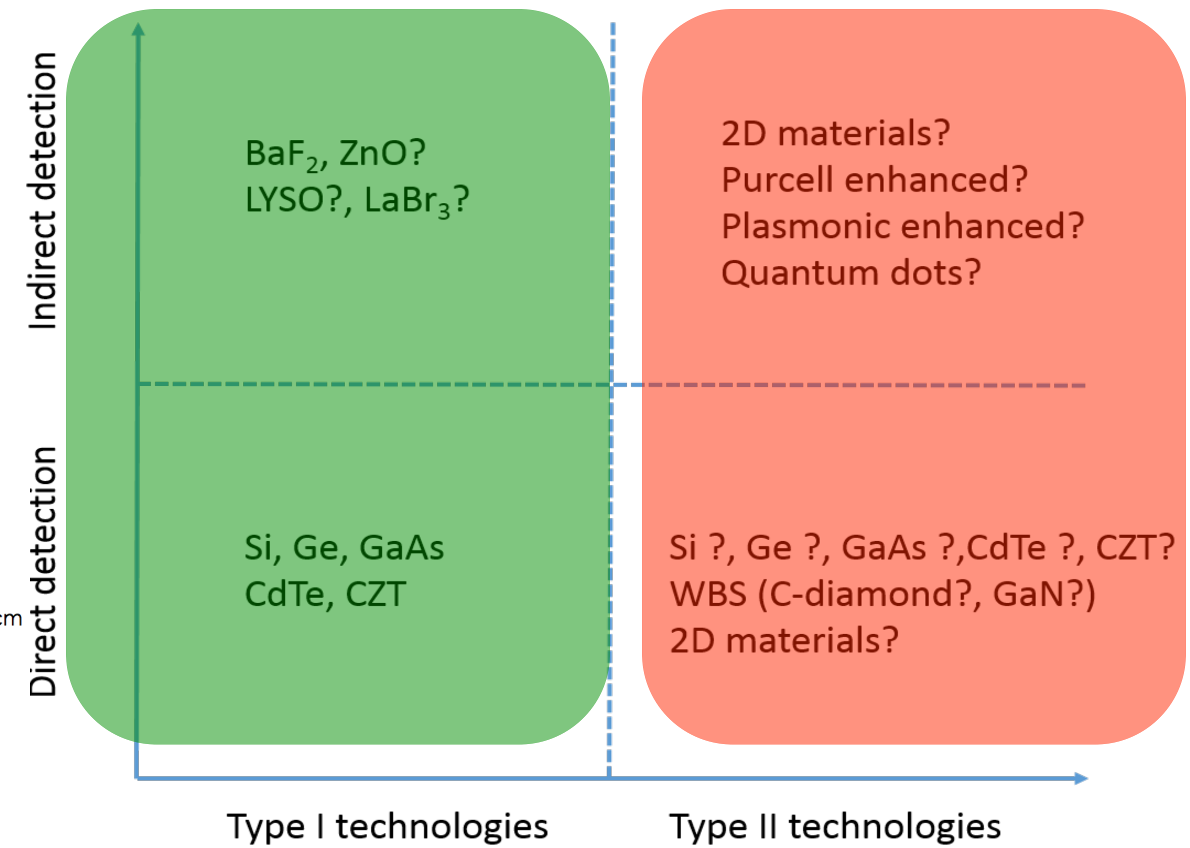
(ZnO)



NEED material innovations/discoveries for GHz imaging

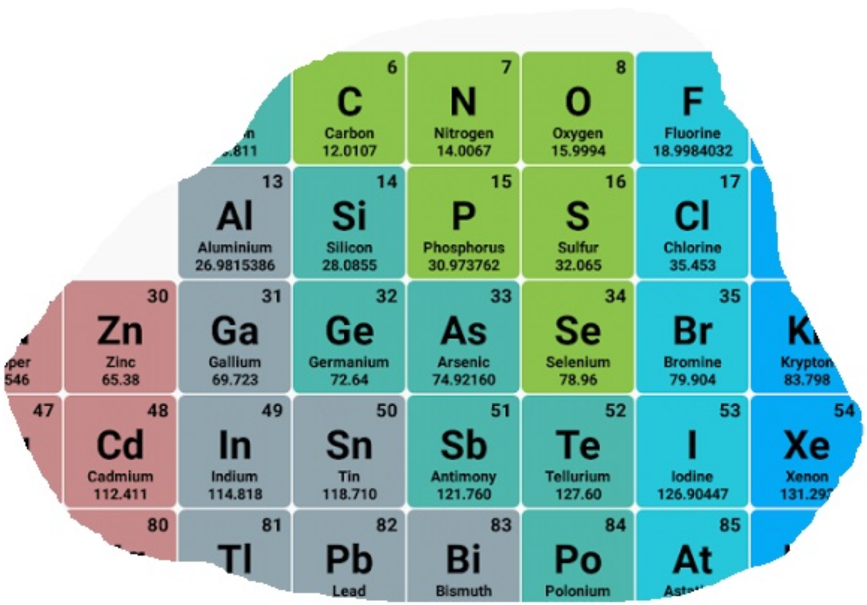






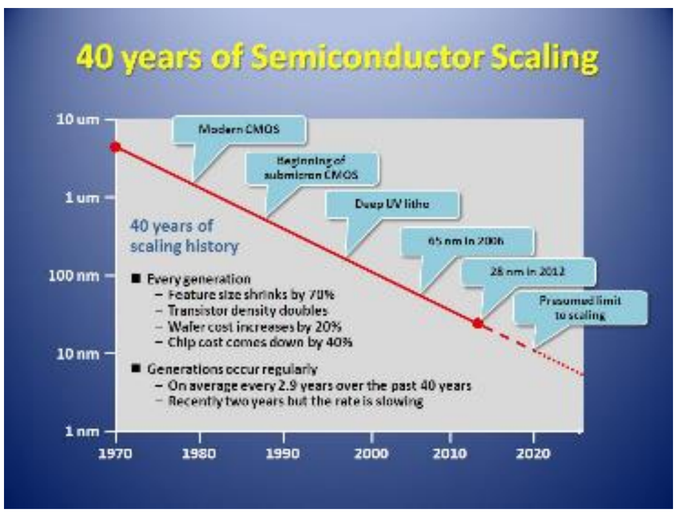
Silicon revisited

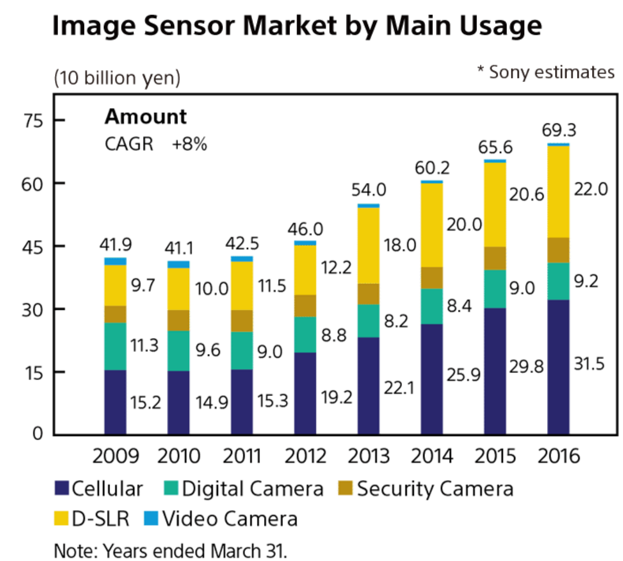
Is Silicon /CMOS out for GHz HE X-ray imaging?



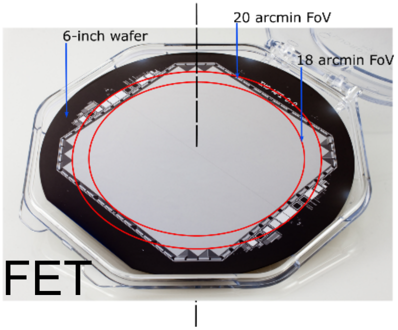
The fabrication/scaling advantages: CMOS is the best practice

- **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

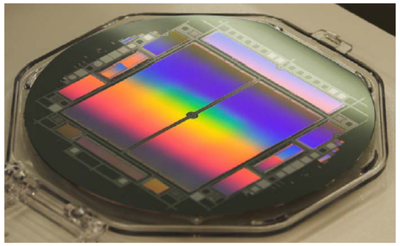




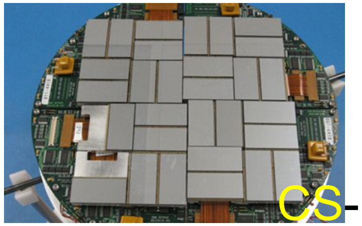
Sound community knowledge base in imaging and other uses



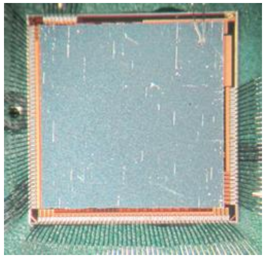
DEPFET



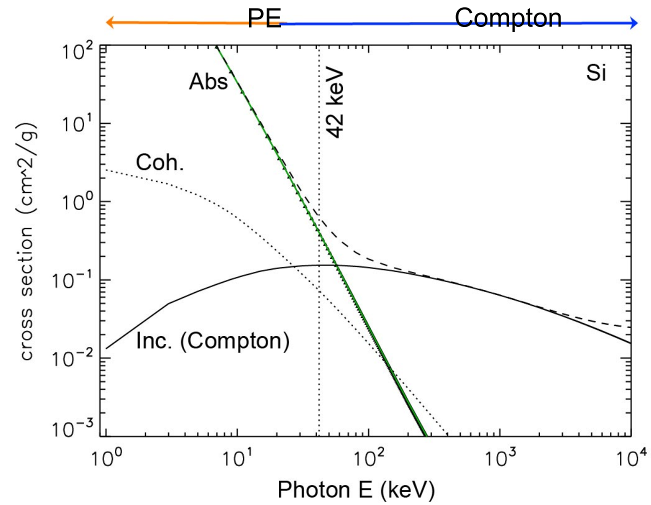
pnCCD

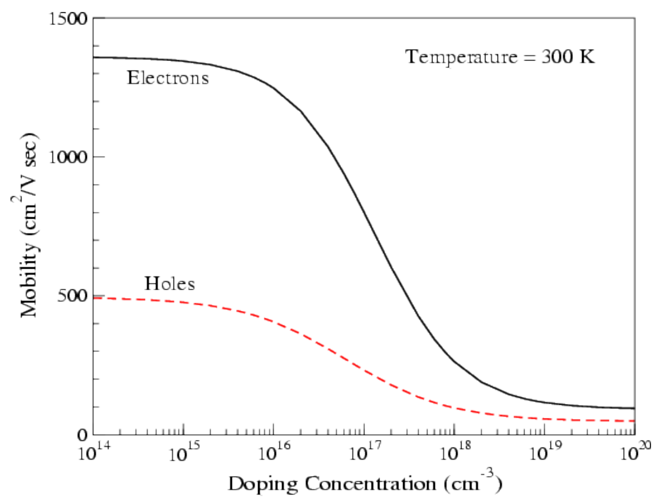


CS-PAD

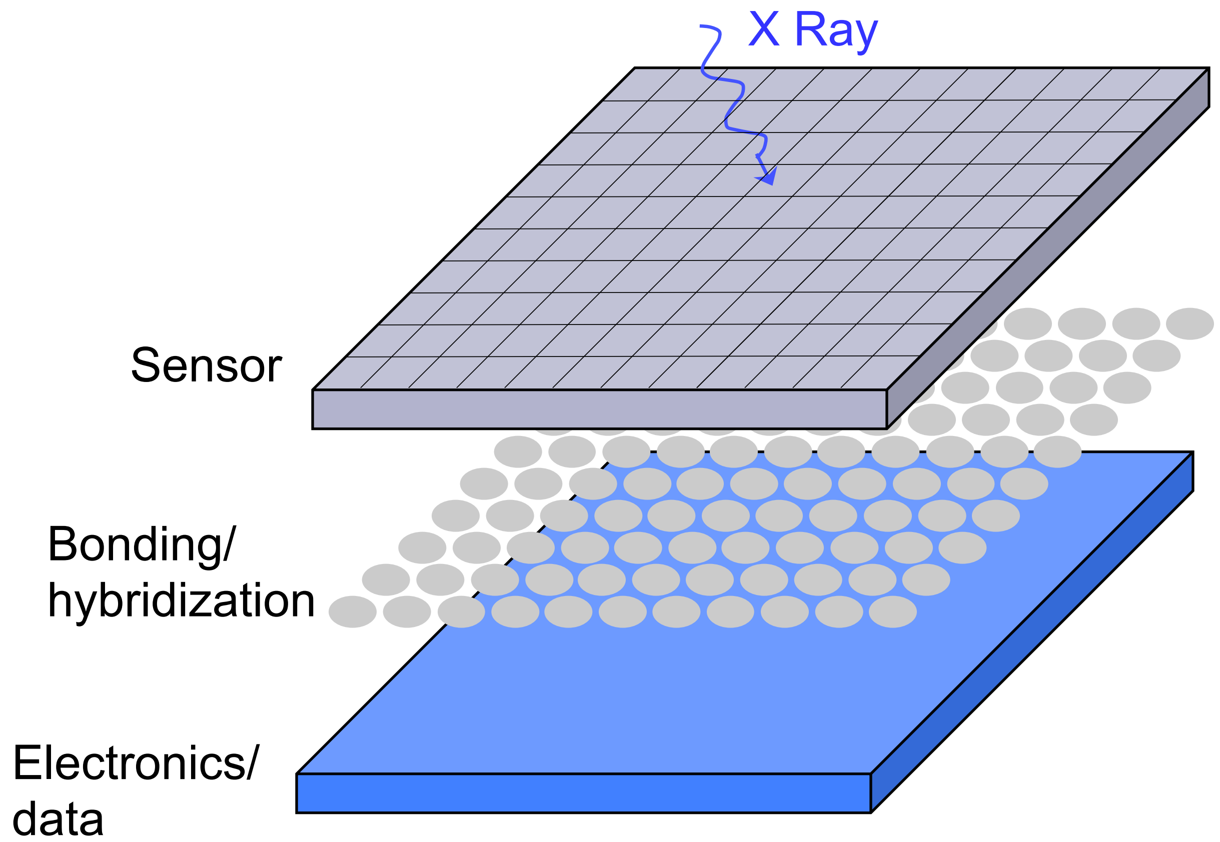


AGPID

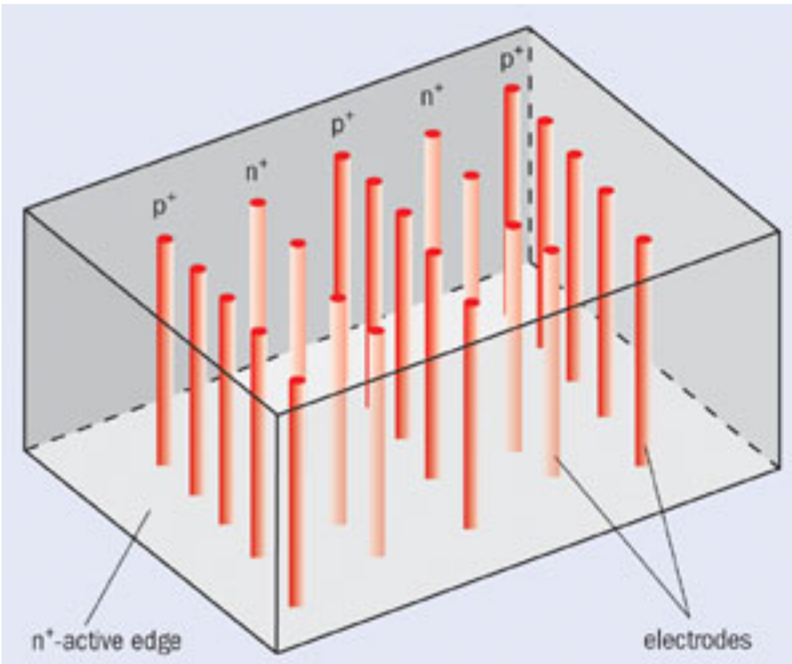




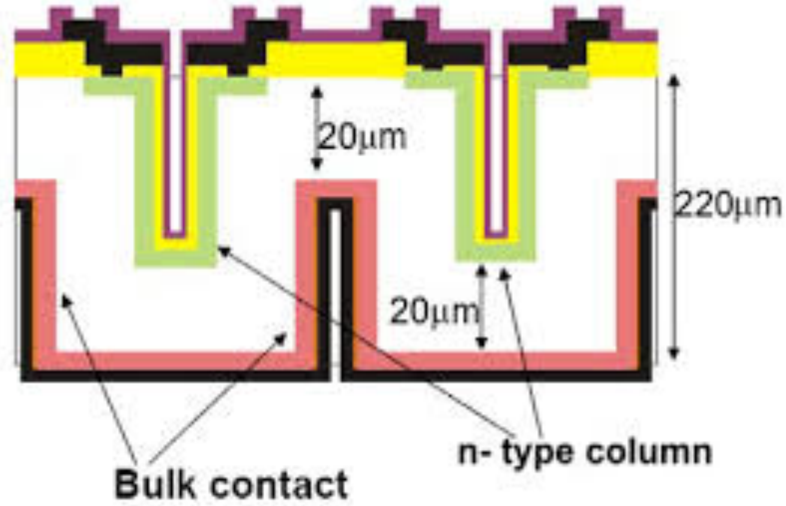
The Problem: 2D hybrid structure can not accommodate speed & efficiency simultaneously



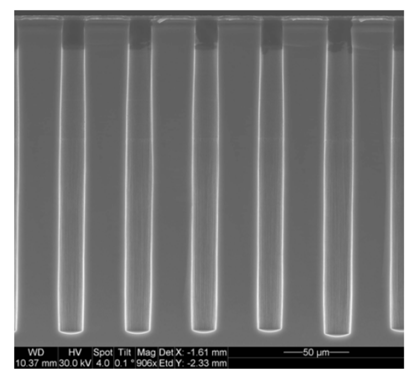
3D Architectural innovations have been proposed before



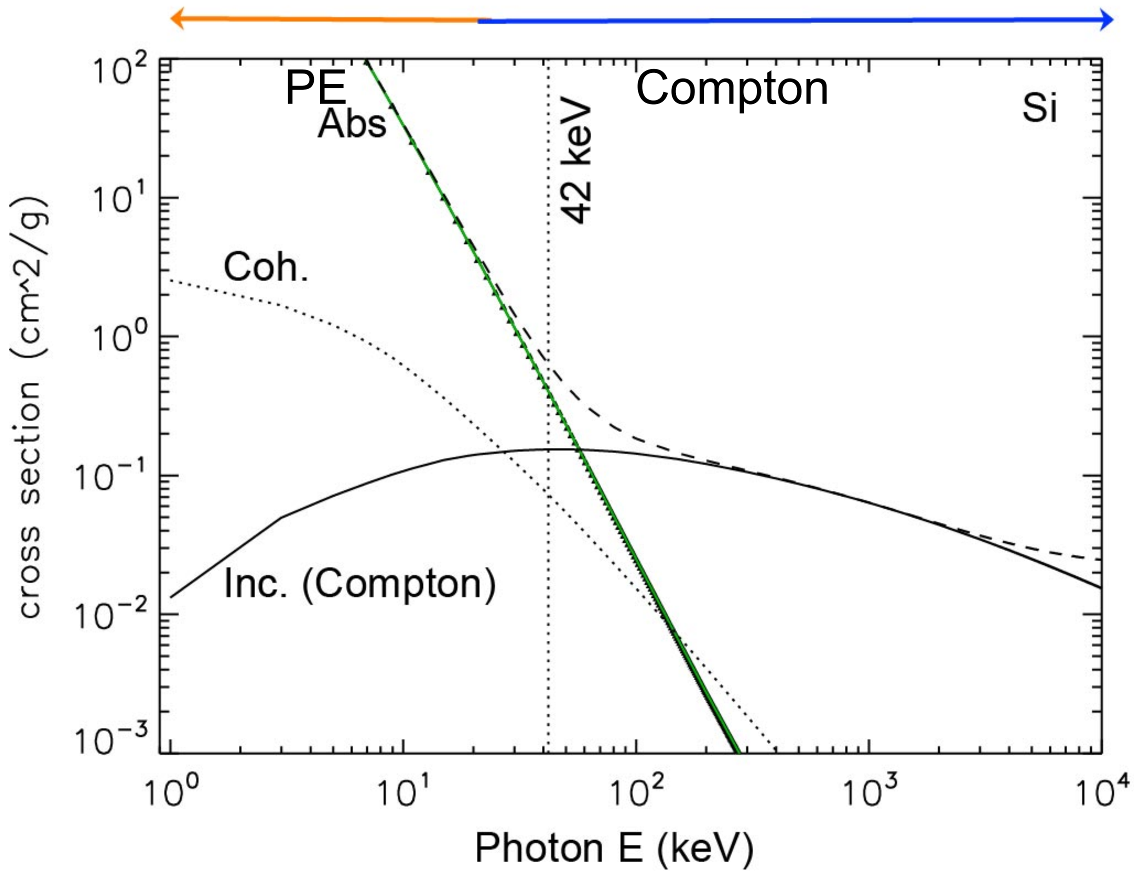
Parker et al (1997)



(2010)



Compton scattering poses a new problem for HE X-rays

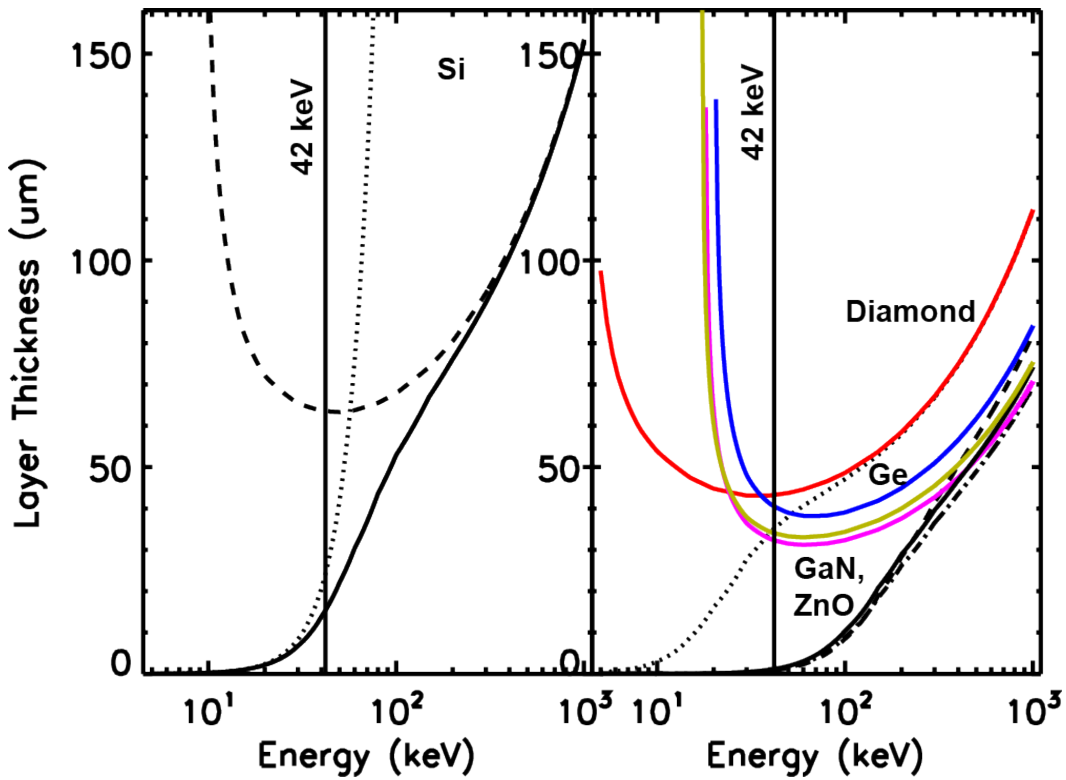


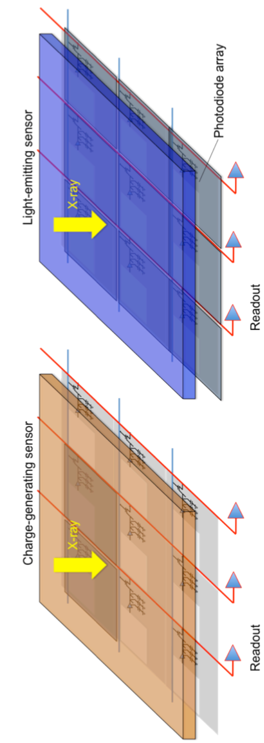
→ Spectroscopy imaging

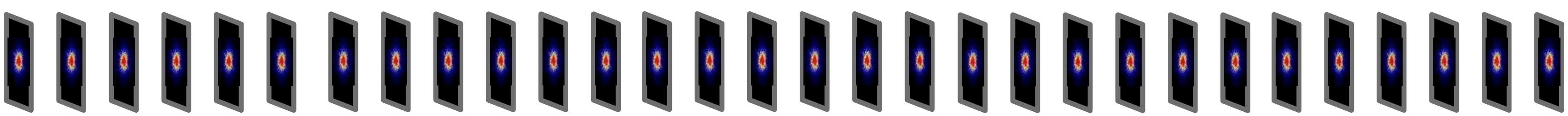
Single-photon counting

Our proposal: Thin-Film Cameras (TFC) using silicon (broader applications than MaRIE)

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



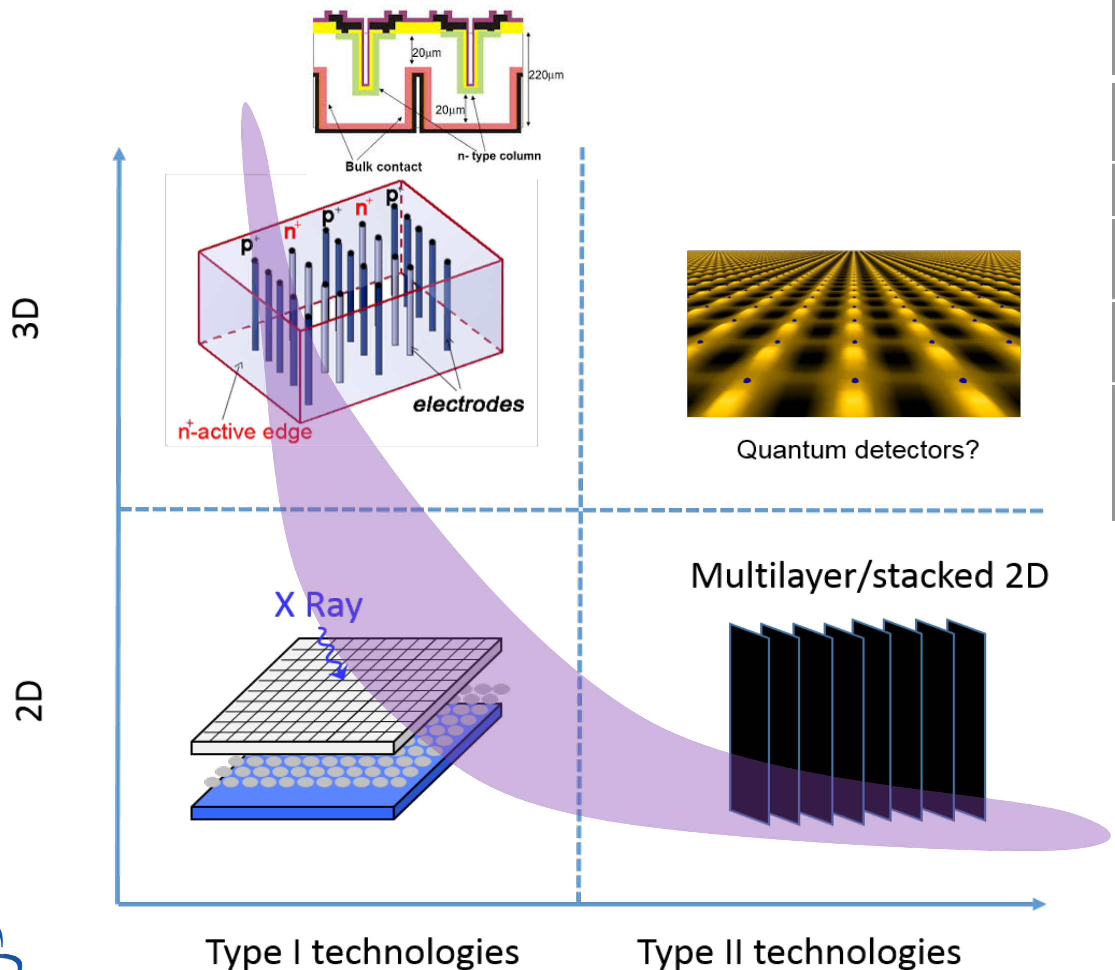




Los Alamos NATIONAL LABORATORY EST. 1943

UNCLASSIFIED

Other 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.

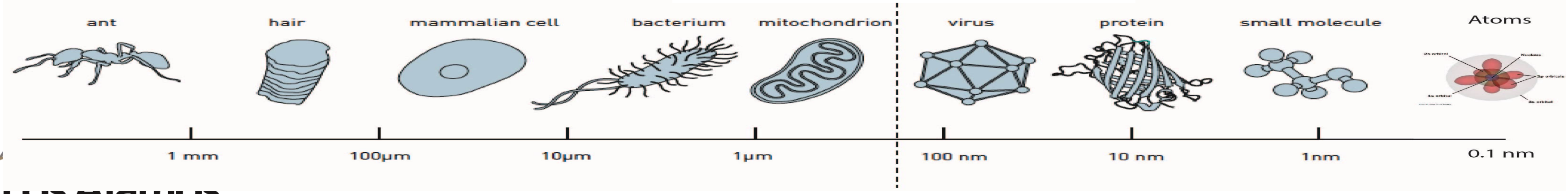
Summary

- **Ultrafast imaging technology development requires inter-disciplinary approach**

→ '*global optimization*' --- Cris W. Barnes

- Material discoveries, device physics, data science, light source experiments
- Parallel development paths (multiple concepts, low+high risk).

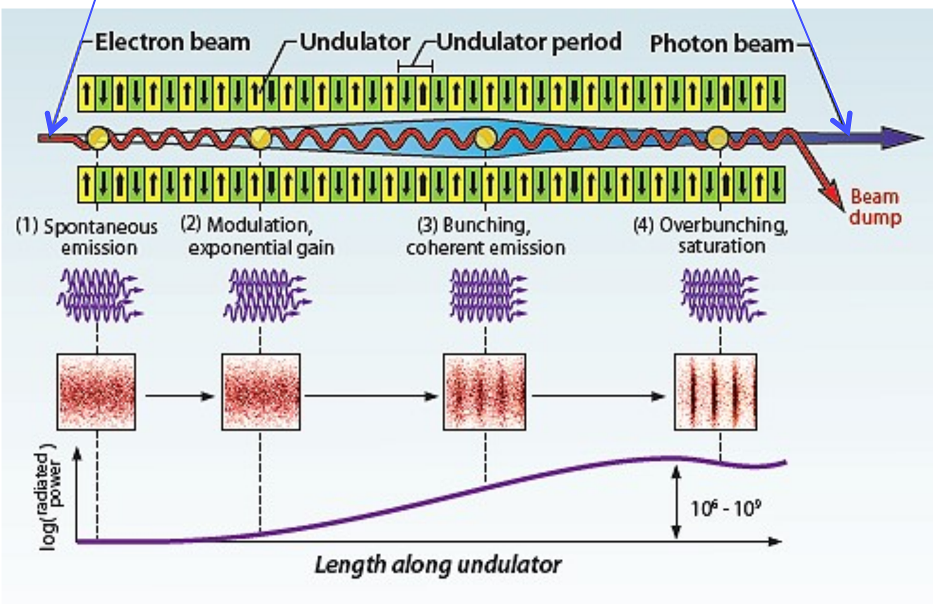
→ ***~ Dawn to photograph μ- & nano-horses feeding on atoms and molecules***



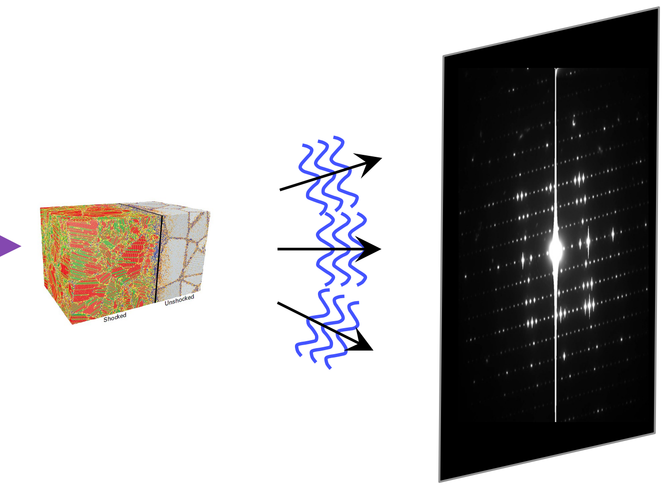
Backups

MaRIE XFEL & Experiments

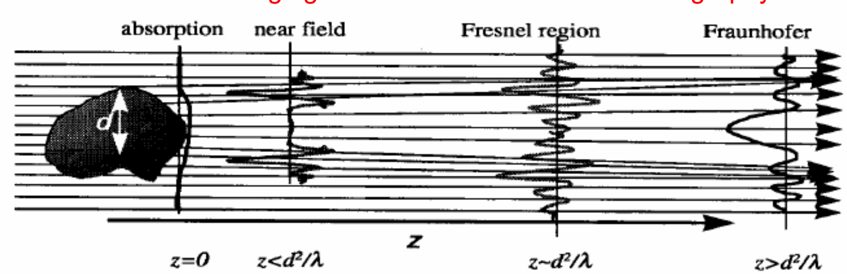
12 GeV **5 - 42 keV**



80 - 100 m



Shadow/contact imaging Phase contrast Holography/CXDI



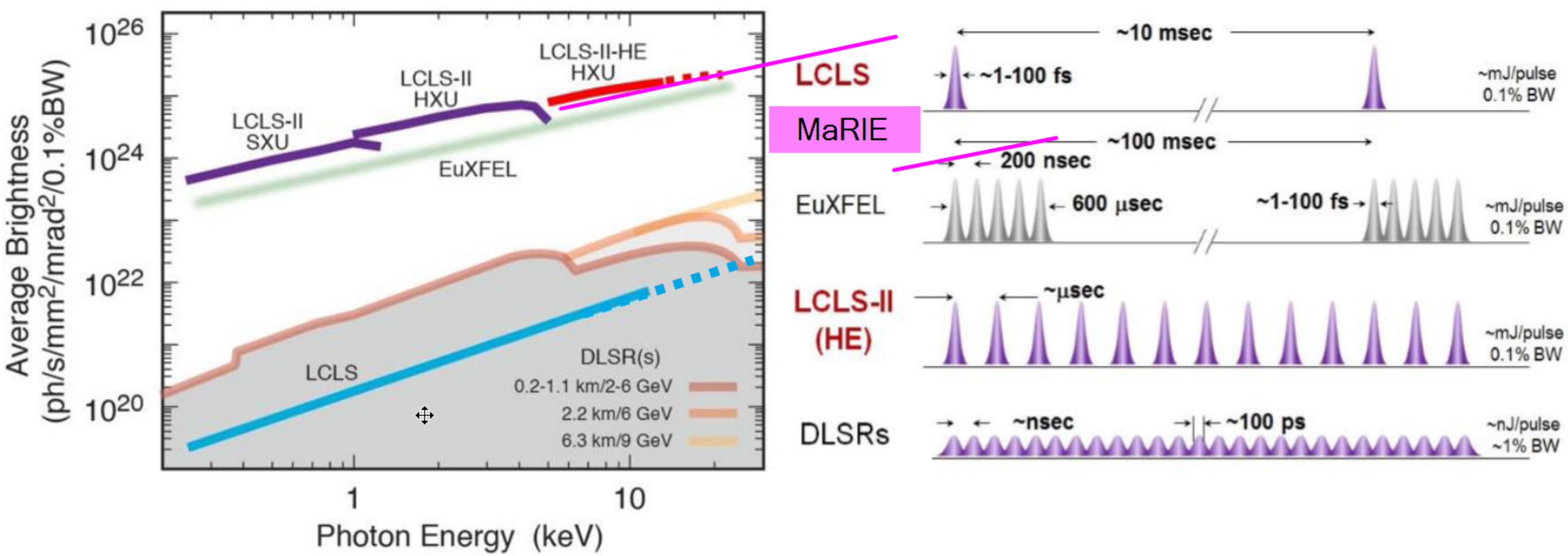
A. Snigirev et al, RSI (1995)

Input: Rich Sheffield, Richard Sandberg

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)