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Web

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# Advanced X-ray Methods

For PMI in MFE

Zhehui (Jeph) Wang for **UDA** collaboration

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**UDA= Ultrafast Detectors & Applications**



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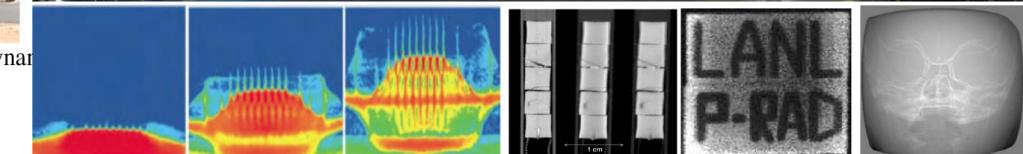
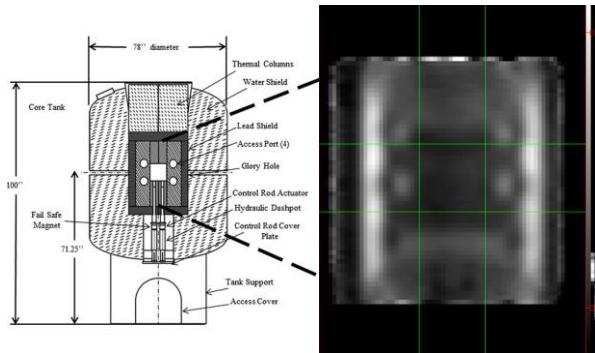


# LANL Radiographic imaging

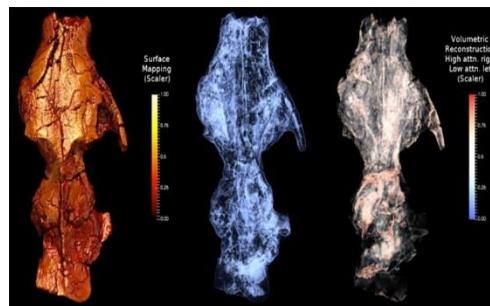
- X-rays, Gamma-rays
- Protons
- Muons
- Neutrons
- Electrons



Figure 1. Aerial view of the Dual Axis Hydrodynamic Laboratory (DAHL) facility.



Perry et al (2013)



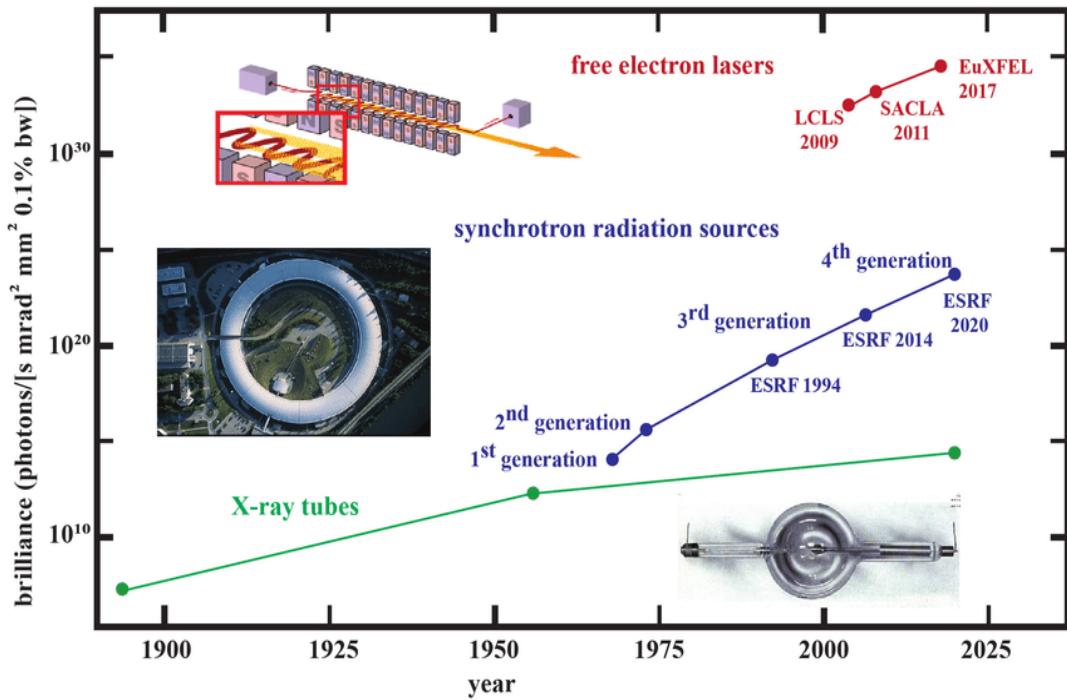
Nelson et al (2018)



Merrill et al (2018)

# Physics & Technol. of Advanced X-ray imaging

- **X-Ray Sources**
  - Coherent vs incoherent
- **X-ray Imaging methods**
  - Propagation, Geometry and Optics
- **X-ray Detector, electronics physics, Noise**
- **Data Science & Methods**
- **Theory & Interpretation**
  - X-ray-interaction physics
  - Multi-scale multi-physics Simulations



V. Cerantola et al, J. Phys. Cond. Matt. 33 (2021) 274003.



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# CMOS sensor designs down to pixels



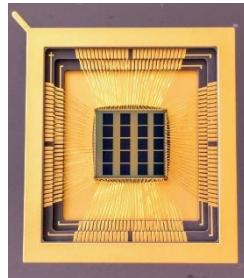
Photon-number-resolving megapixel image sensor  
at room temperature without avalanche gain

JIJU MA,\* SALEM MASOUDIAN, DAKOTA A. STARKEY, AND ERIC R. FOSSUM

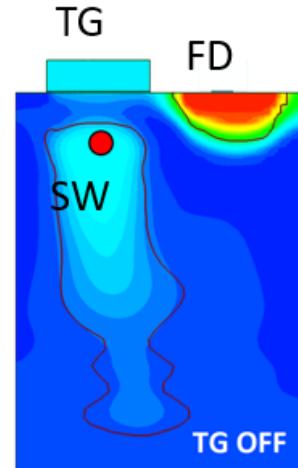
Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, USA

\*Corresponding author: jiju.ma@th.dartmouth.edu

Received 7 July 2017; revised 22 October 2017; accepted 23 October 2017 (Doc. ID 301901); published 29 November 2017

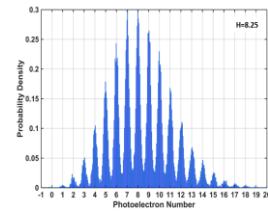


20-Mpixel SPDA

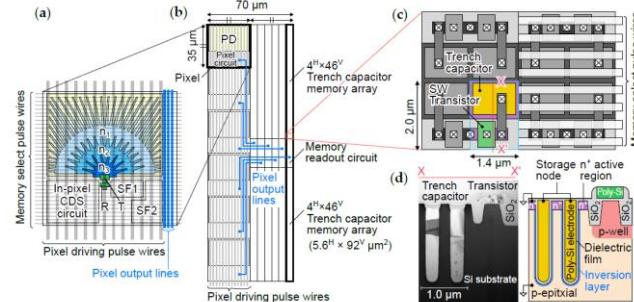


~0.2e<sup>-</sup> rms noise

Room temperature, no avalanche, 20 CMS cycles, joti:TPG PTR BC



Quantized PE



100 M fps+ capability

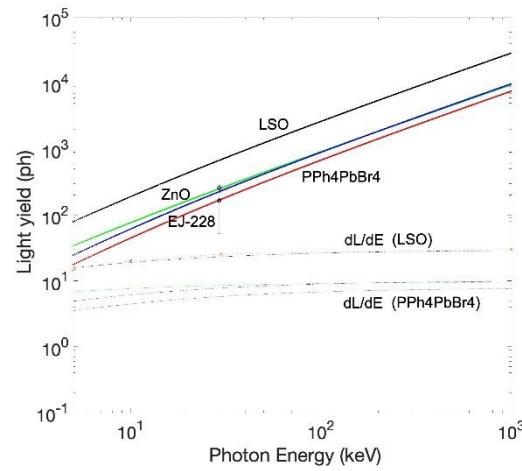
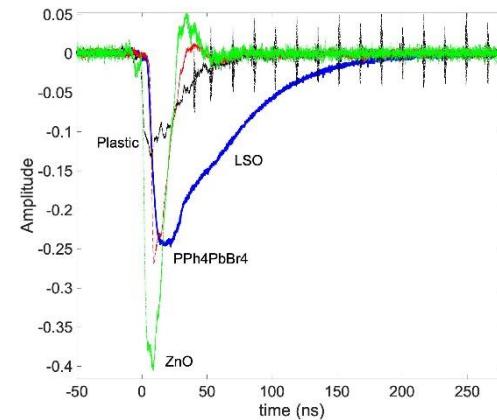
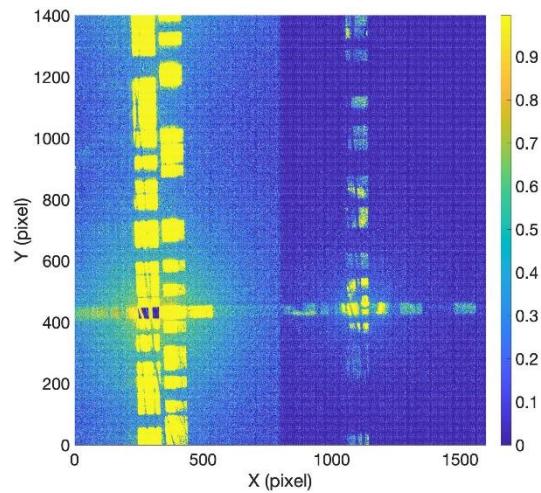
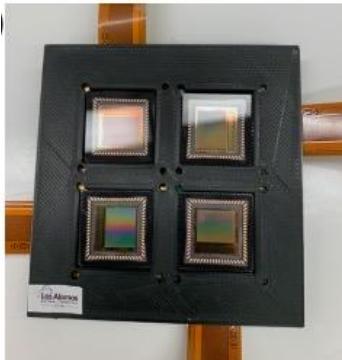
Suzuki et al, Sensor 20 (2020) 1086

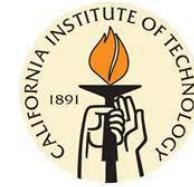
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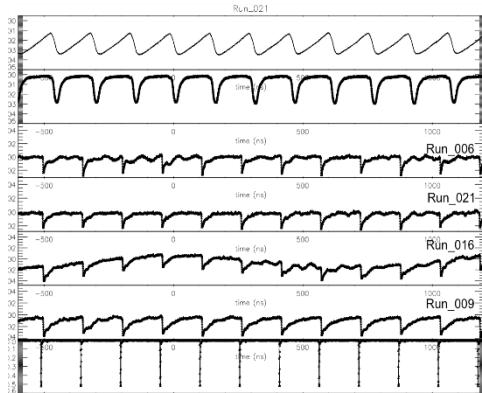
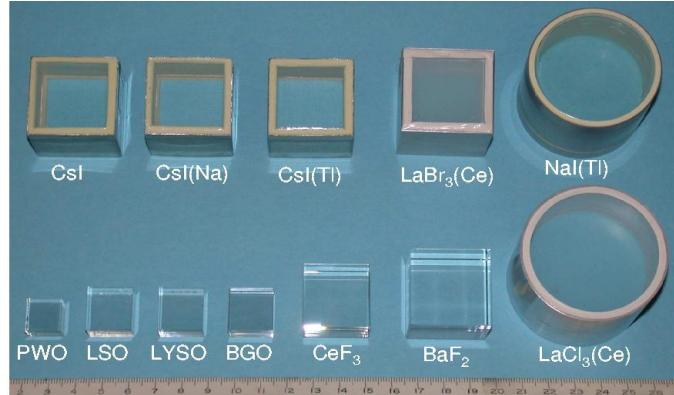
zwang@lanl.gov Slide 4

# Large FOV: Billion-pixel X-ray cameras (BiPC-X)





# Multiple Fast Scintillator Candidates

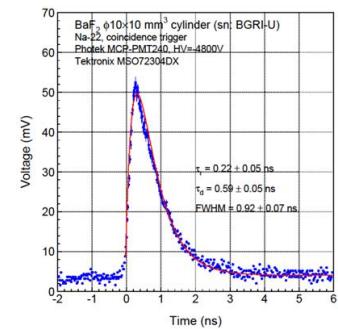


Xie et al, NIMA 927 (2019) 287

	LYSO:Ce,C <sub>a</sub>	ZnO:Ga	BaF <sub>2</sub> :Y	YAP:Yb	LuAG:Ce	LaBr <sub>3</sub> :Ce
Density (g/cm <sup>3</sup> )	<b>7.4</b>	<b>5.67</b>	<b>4.89</b>	<b>5.35</b>	<b>6.76</b>	<b>5.29</b>
Melting Points (°C)	<b>2050</b>	<b>1975</b>	<b>1280</b>	<b>1870</b>	<b>2060</b>	<b>783</b>
X <sub>0</sub> (cm)	<b>1.14</b>	<b>2.51</b>	<b>2.03</b>	2.77	1.45	1.88
R <sub>M</sub> (cm)	<b>2.07</b>	<b>2.28</b>	<b>3.1</b>	2.4	2.15	2.85
λ <sub>1</sub> (cm)	<b>20.9</b>	<b>22.2</b>	<b>30.7</b>	22.4	20.6	30.4
Z <sub>eff</sub>	<b>64.8</b>	<b>27.7</b>	<b>51.6</b>	31.9	60.3	45.6
dE/dX (MeV/cm)	<b>9.55</b>	<b>8.42</b>	<b>6.52</b>	8.05	9.22	6.9
λ <sub>peak</sub> <sup>a</sup> (nm)	<b>420</b>	<b>380</b>	<b>300</b> 220	350	520	360
Refractive Index <sup>b</sup>	<b>1.82</b>	<b>2.1</b>	<b>1.5</b>	1.96	1.84	1.9
Normalized Light Yield <sup>a,c</sup>	<b>100</b>	<b>6.6<sup>e</sup></b>	<b>1.7</b> 4.8	0.19 <sup>e</sup>	35 <sup>f</sup> 48 <sup>f</sup>	153
Total Light Yield (ph/MeV)	<b>30,000</b>	<b>2,000<sup>e</sup></b>	<b>2,000</b>	57 <sup>e</sup>	25,000 <sup>f</sup>	46,000
Decay Time <sup>a</sup> (ns)	<b>40</b>	<b>&lt;1</b>	<b>600</b> 0.5	1.5	820 50	16
Light Yield in 1 <sup>st</sup> ns (photons/MeV)	<b>740</b>	<b>610<sup>e</sup></b>	<b>1200</b>	28 <sup>e</sup>	240	2,200
40 keV Att. Length (1/e, mm)	<b>0.185</b>	<b>0.407</b>	<b>0.106</b>	0.314	0.251	0.131

LYSO + PMT 1  
Fast plastic + PMT 2  
Diamond (Quadrant A)  
Diamond (Quadrant B)  
Diamond (Quadrant C)  
Diamond (Quadrant D)

APS timing pulses

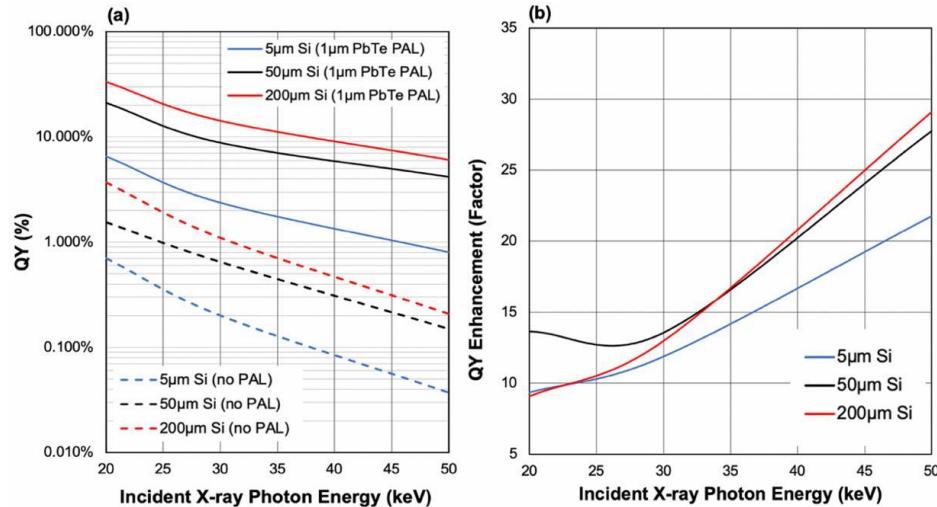


Hu et al, NIMA 950 (2020) 162767



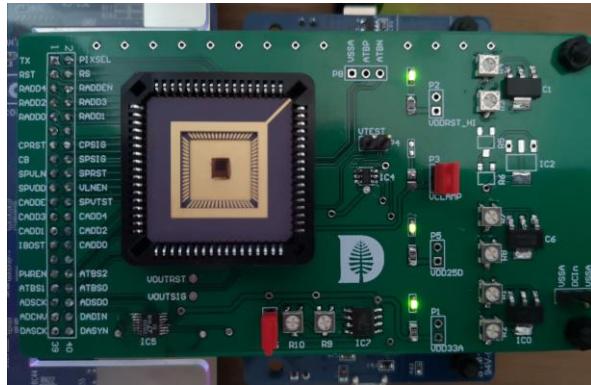
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# PAL layer integration with CMOS sensor



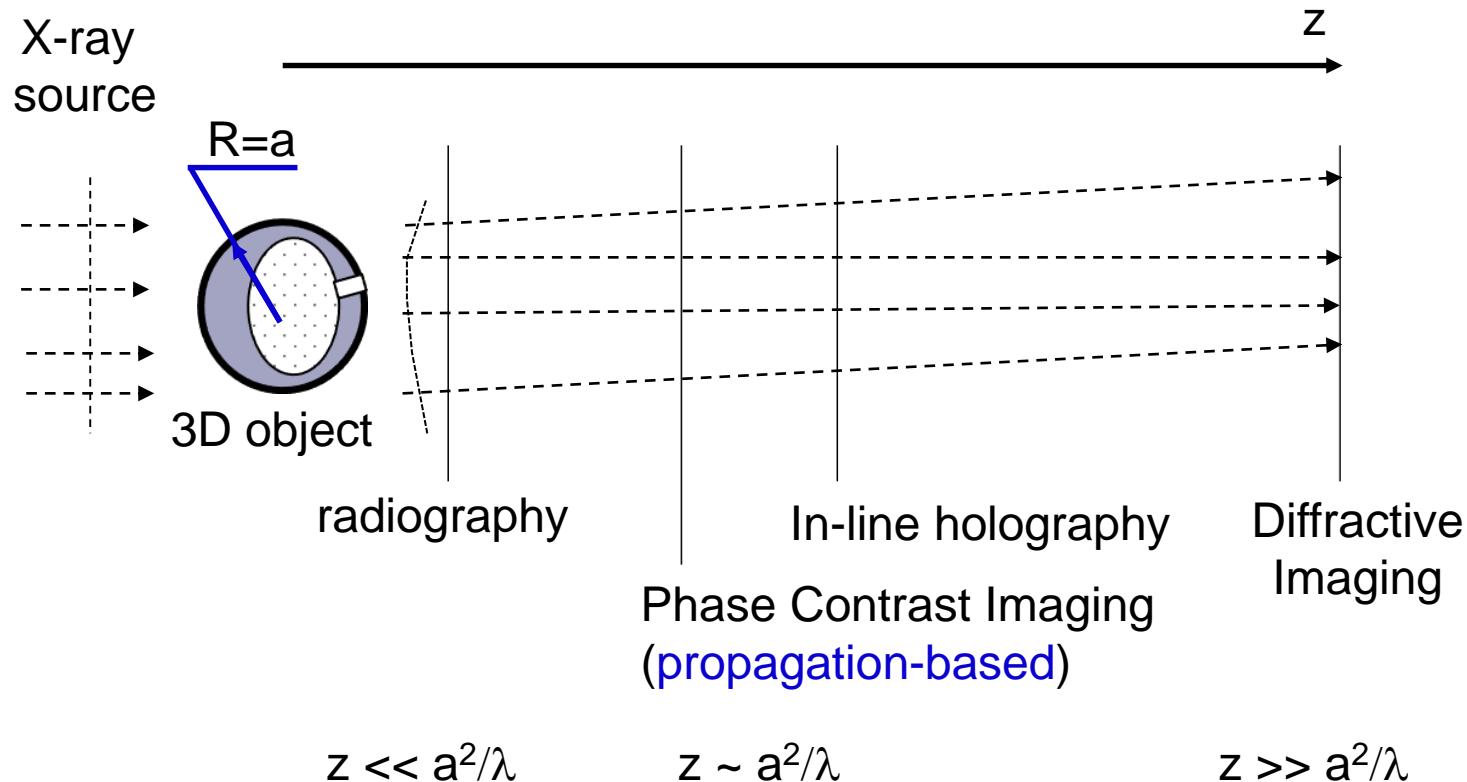
## Pixel-level hybridization

Lee *et al*, Instruments 5 (2021) 17



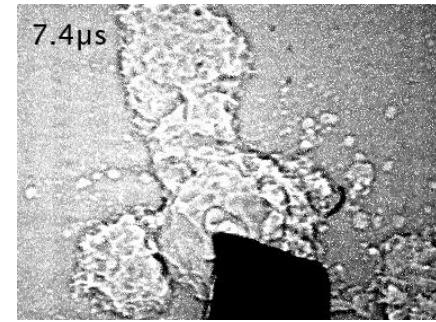
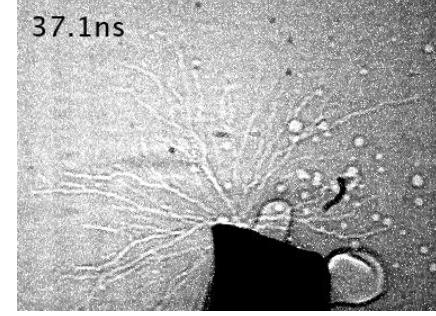
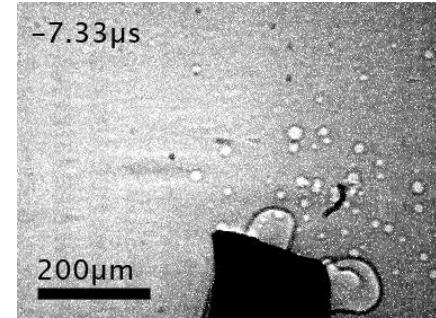
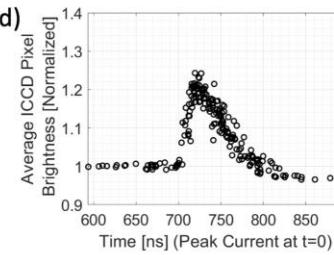
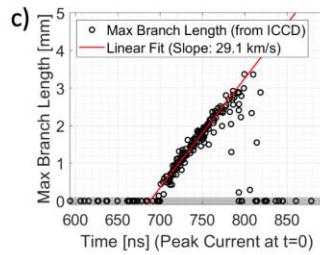
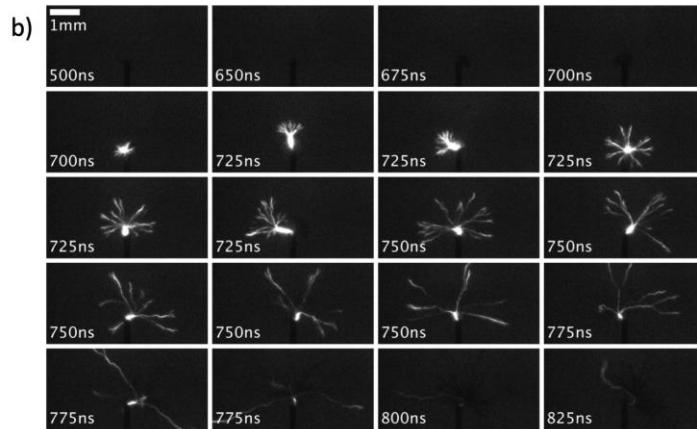
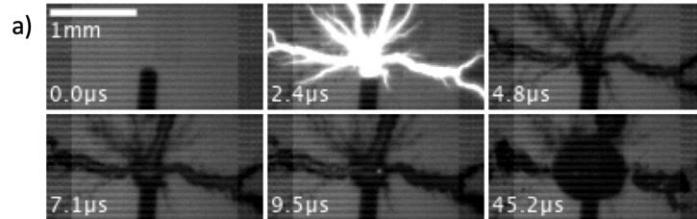
Yue *et al*, (2021)

# Geometries of Advanced X-ray imaging



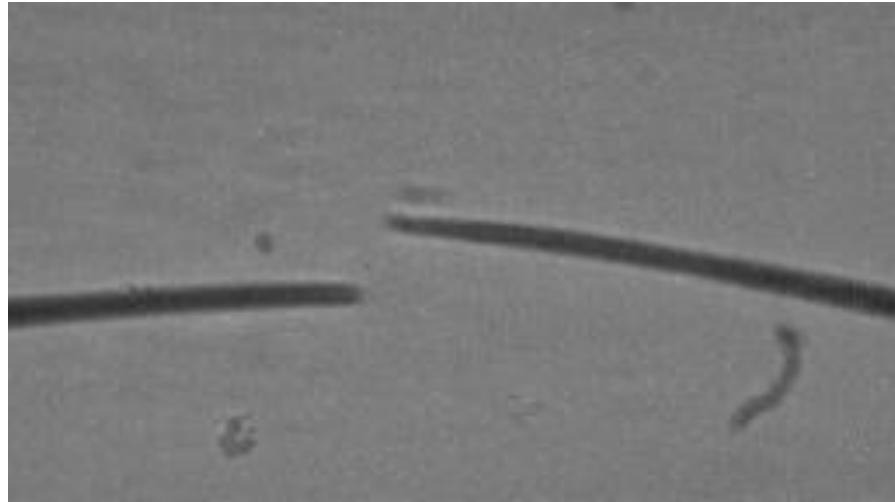
# Ultrafast lightning in water

ATM

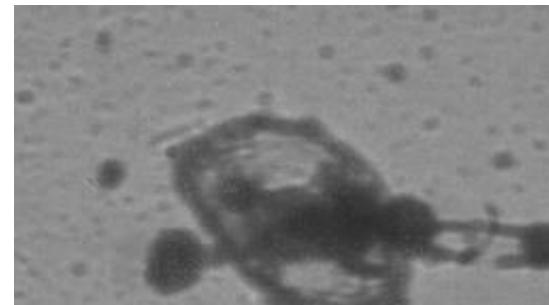
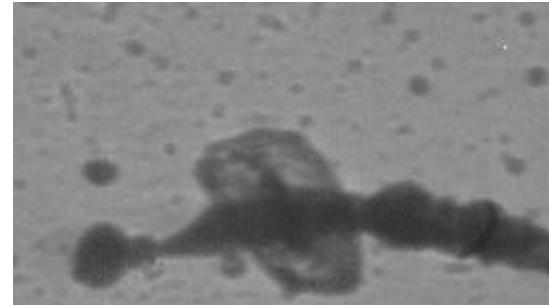
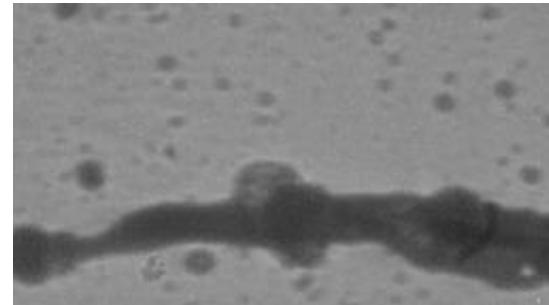


ultrafast  
lightning  
in  $\text{H}_2\text{O}$

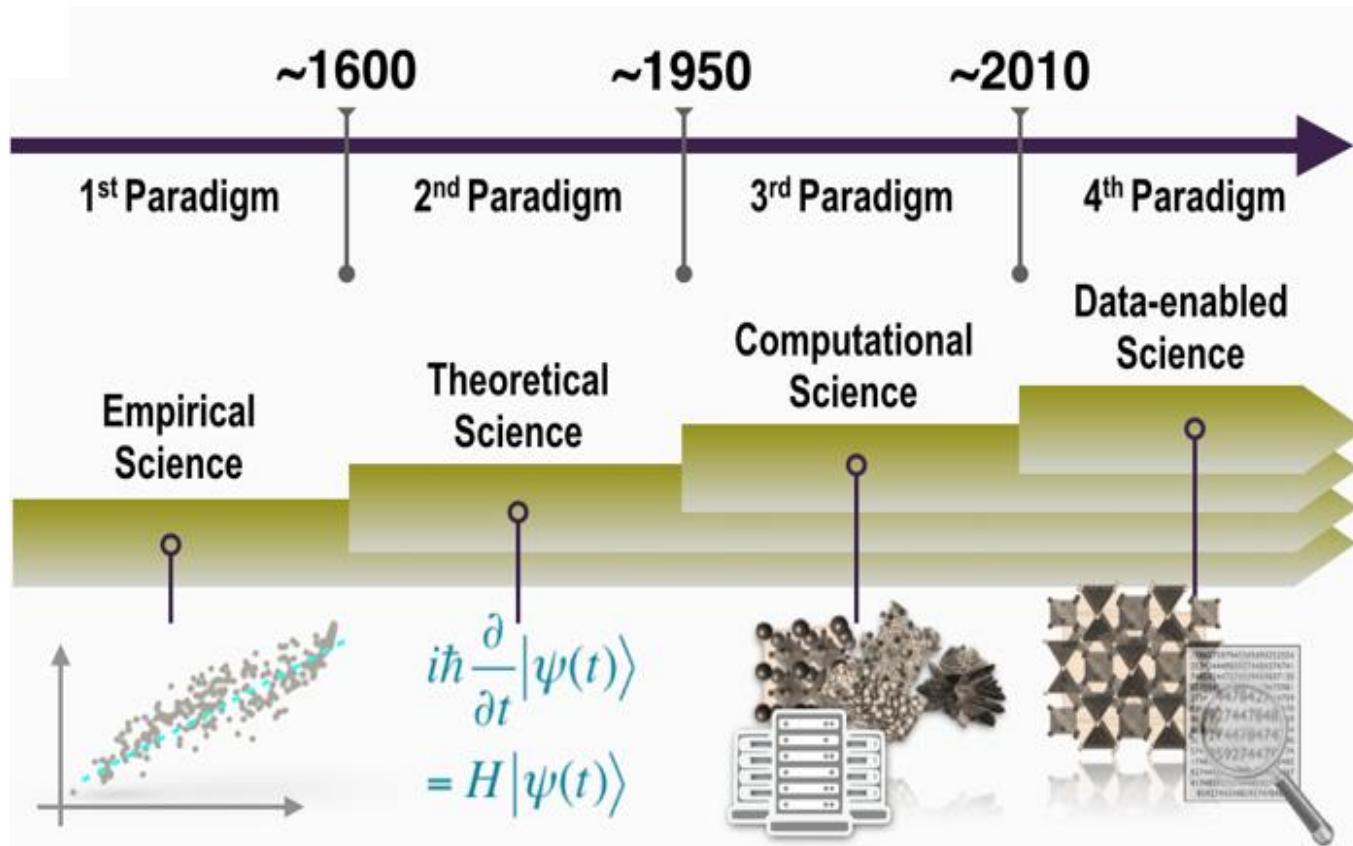
# In need of 3D information: X-ray experiment @ APS



~ 100 kfps



# Why ML?



Pilania *et al*, J Mat. Sci 54 (2019) 8361

# What ML can do?

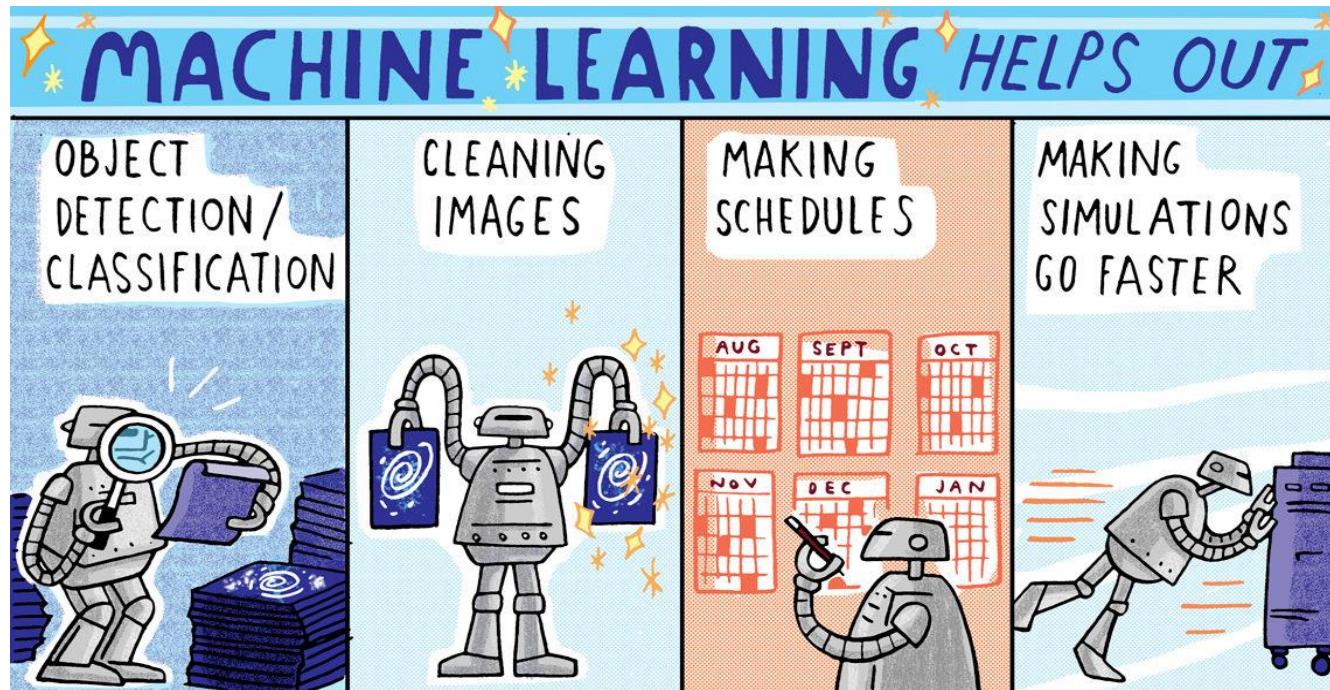
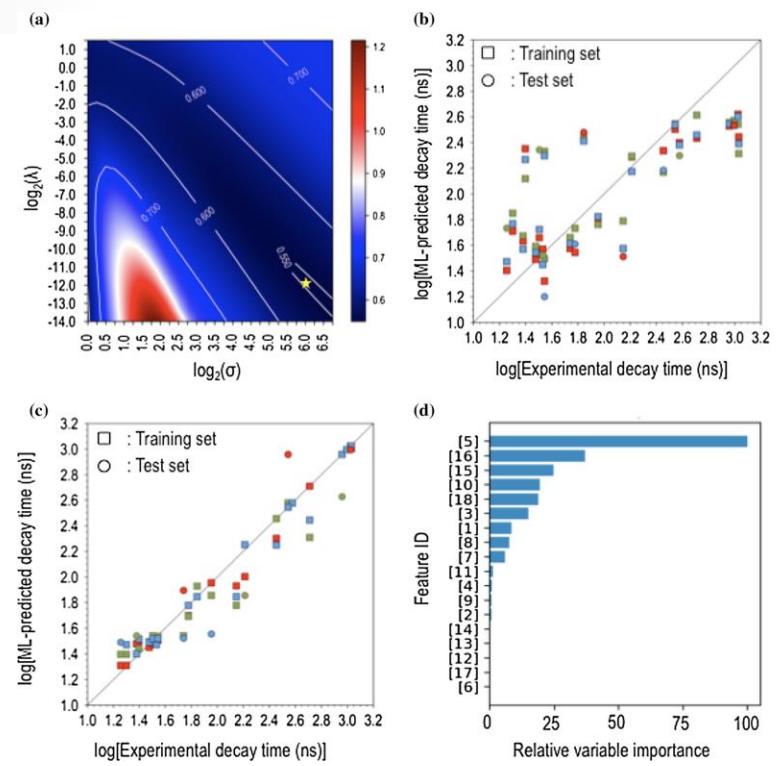
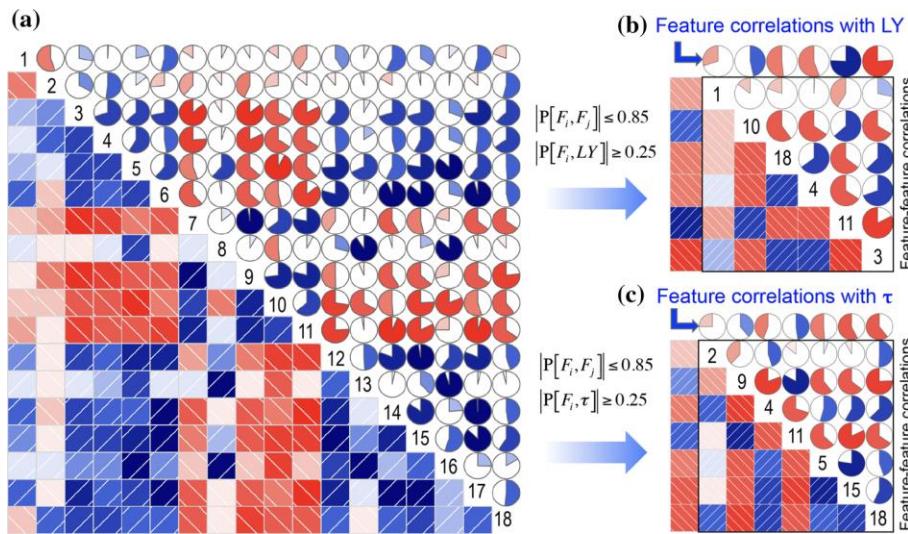


Illustration by Sandbox Studio, Chicago with Corinne Mucha

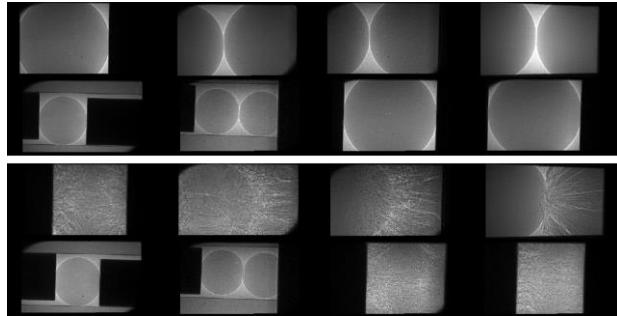
# Using Physics-informed ML for scintillator discovery

## DFT Computations: Costly and slow

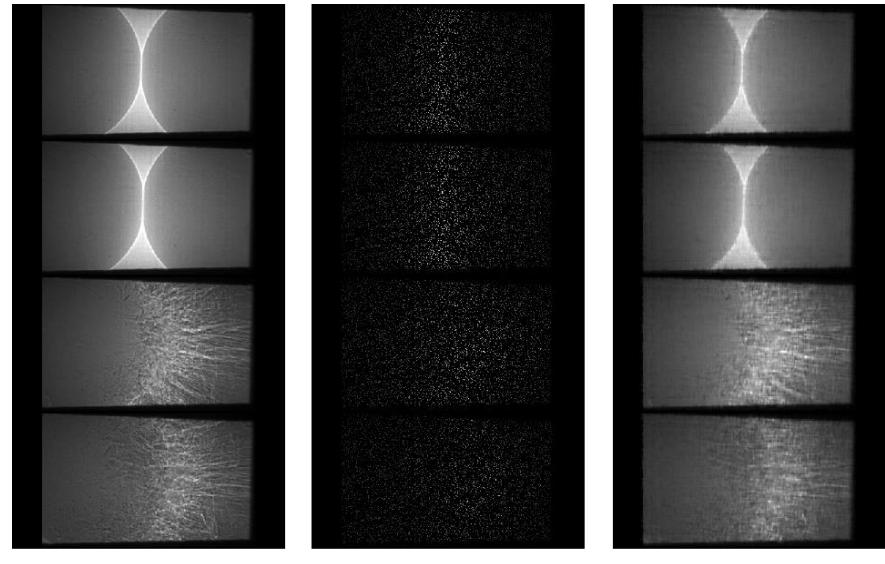


Pilania et al, J Mat. Sci 54 (2019) 8361

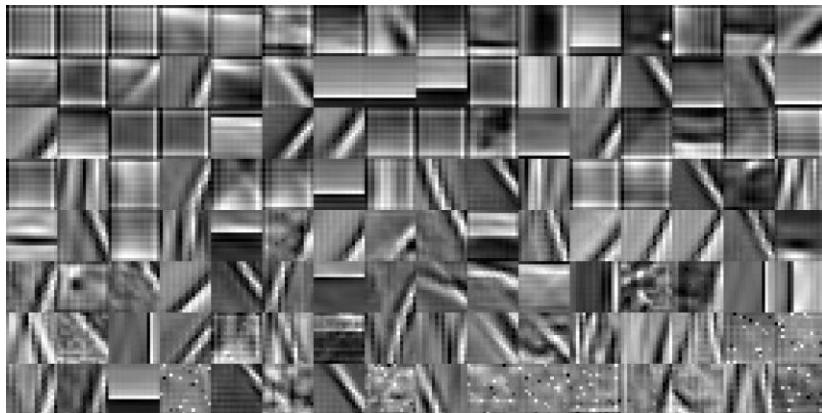
# Implementation of Sparse imaging principle



Experiments



Validation



Feature extraction

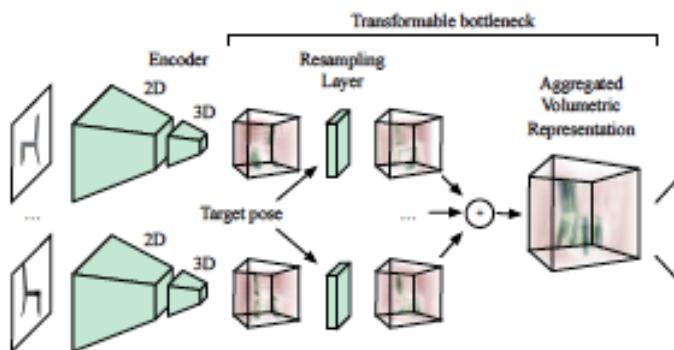
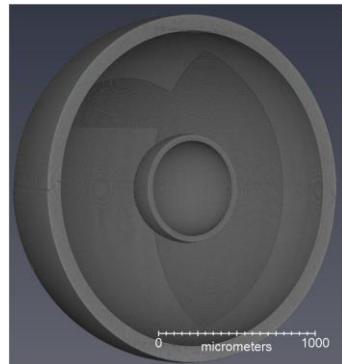
Wang, Iaroshenko, *et al*, JINST 13 (2018) C01035

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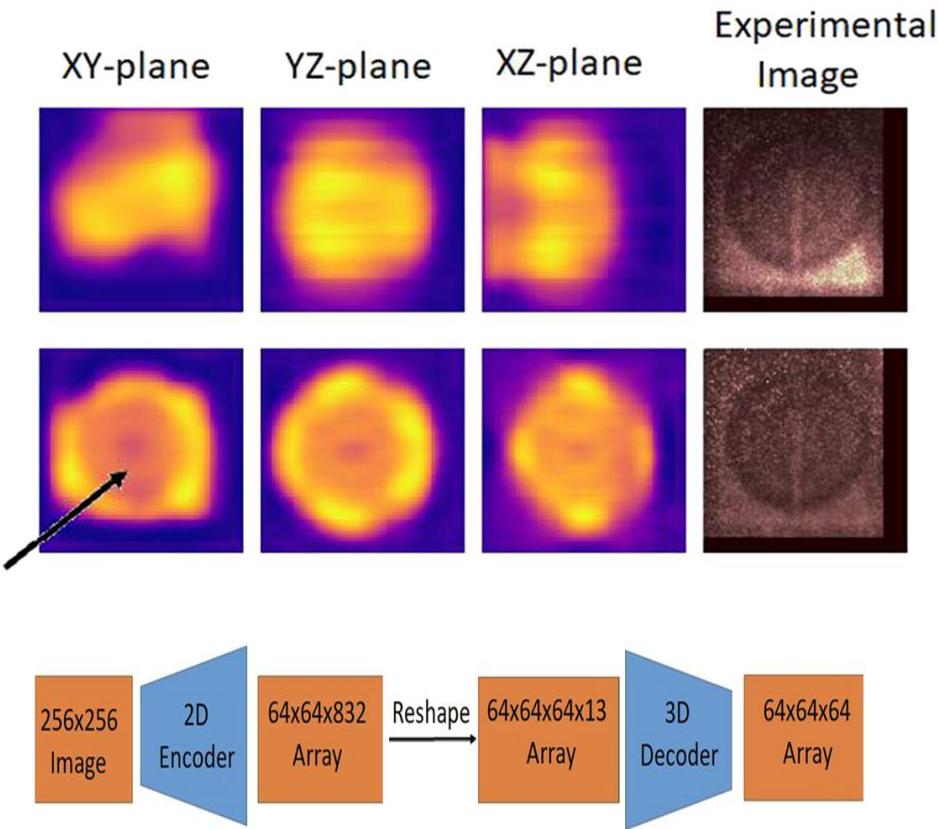
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# 3D reconstruction example

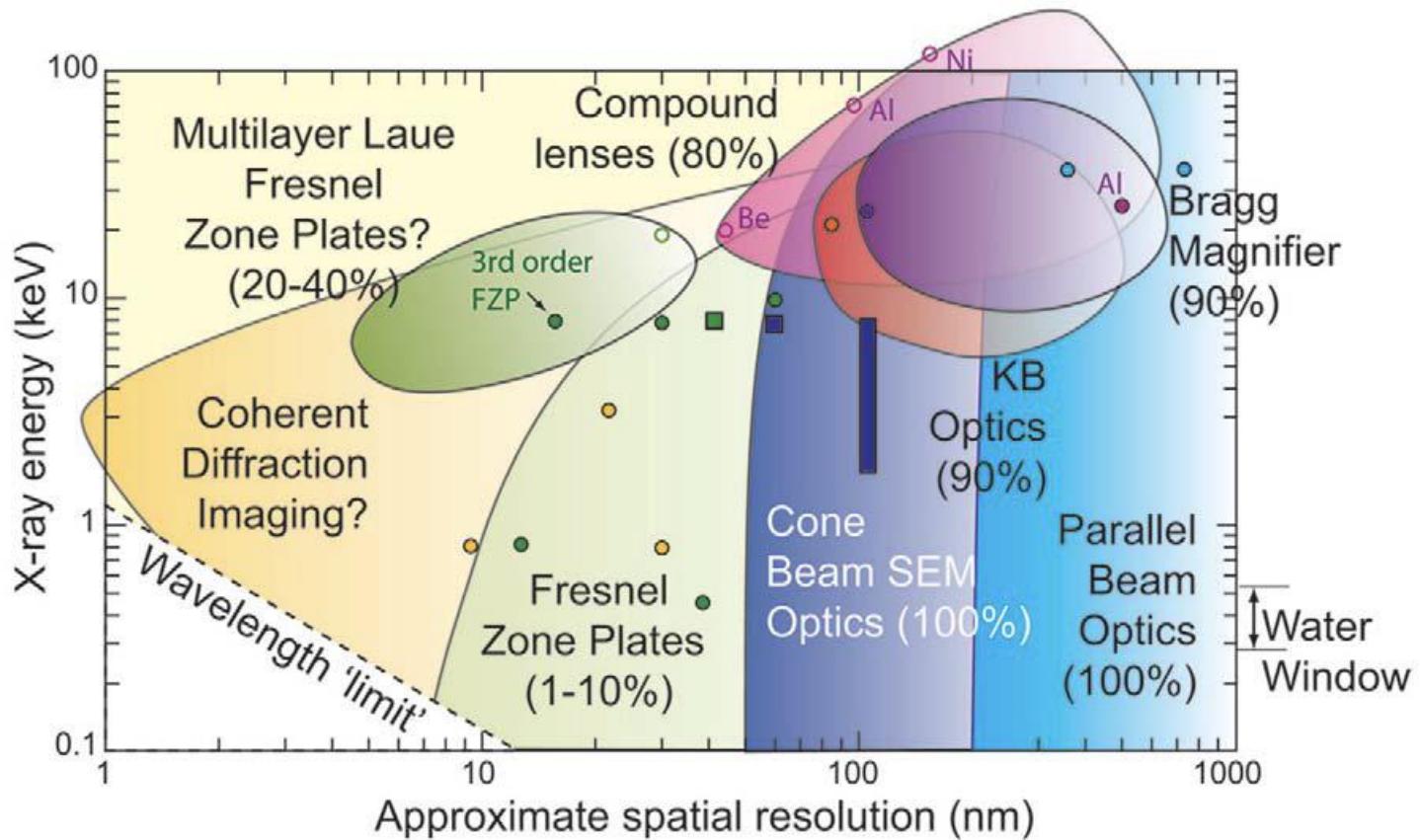


Olszewski *et al*, (2019)



Wolfe *et al*, Rev. Sci. Instrum 92 (2021) 033547

# Sub-micron resolutions



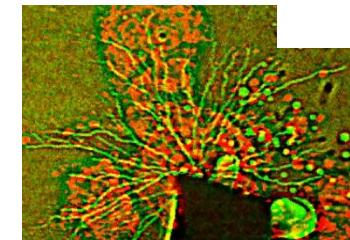
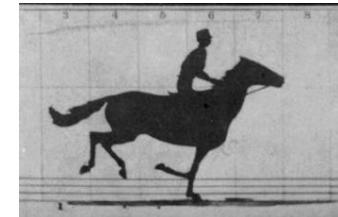
Withers (2007)

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Oct 2021 Z. Wang Slide 16

# Summary

- **Flash X-ray radiography (WWII)**
  - With Roots in Flash photography
- **Recent trends** (hard-ware driven)
  - Increasing number of probes (protons, neutrons, muons, ...)
  - CMOS technology & device physics (legacy of the Moore's law)
  - Material discoveries (scintillators)
  - Hybrid approach (PAL concept)
- **Emergent opportunities** (data-driven)
  - data science, machine learning
  - New applications for PMI





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