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Title:	"6H" X-Ray Imaging Frontiers & Some Recent Highlights
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"6H" X-Ray Imaging Frontiers

& Some Recent Highlights

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Ultrafast Detectors & Applications (**UDA**) institutions

UNCLASSIFIED

DARTMOUTH

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

NNSA

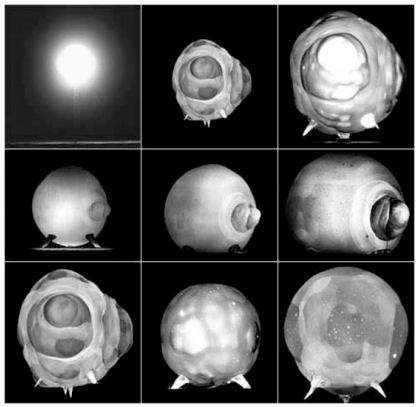
Outline

- **Motivations**
  - Flash radiography
  - High-speed imaging for dynamic experiments
  - ‘6H’ frontiers
- **Recent progress & highlights**
  - Electronics-driven: CMOS sensors
  - (Photonics-driven)
  - Materials-driven: Scintillators (primarily)
  - X-Ray Applications
  - (Neutron demo) work in progress
- **Summary**

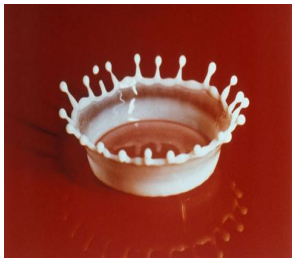
Flash Optical photography

Flash X-ray/proton radiography

Harold Edgerton



Nuclear explosion



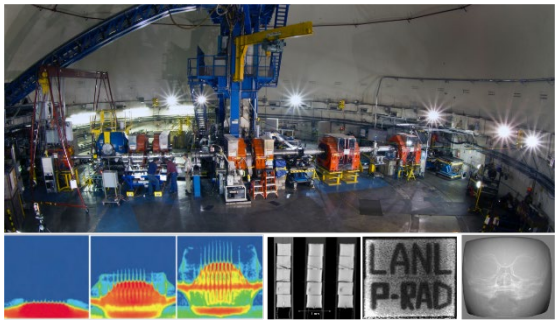
(1935)

(1964)

(1970)

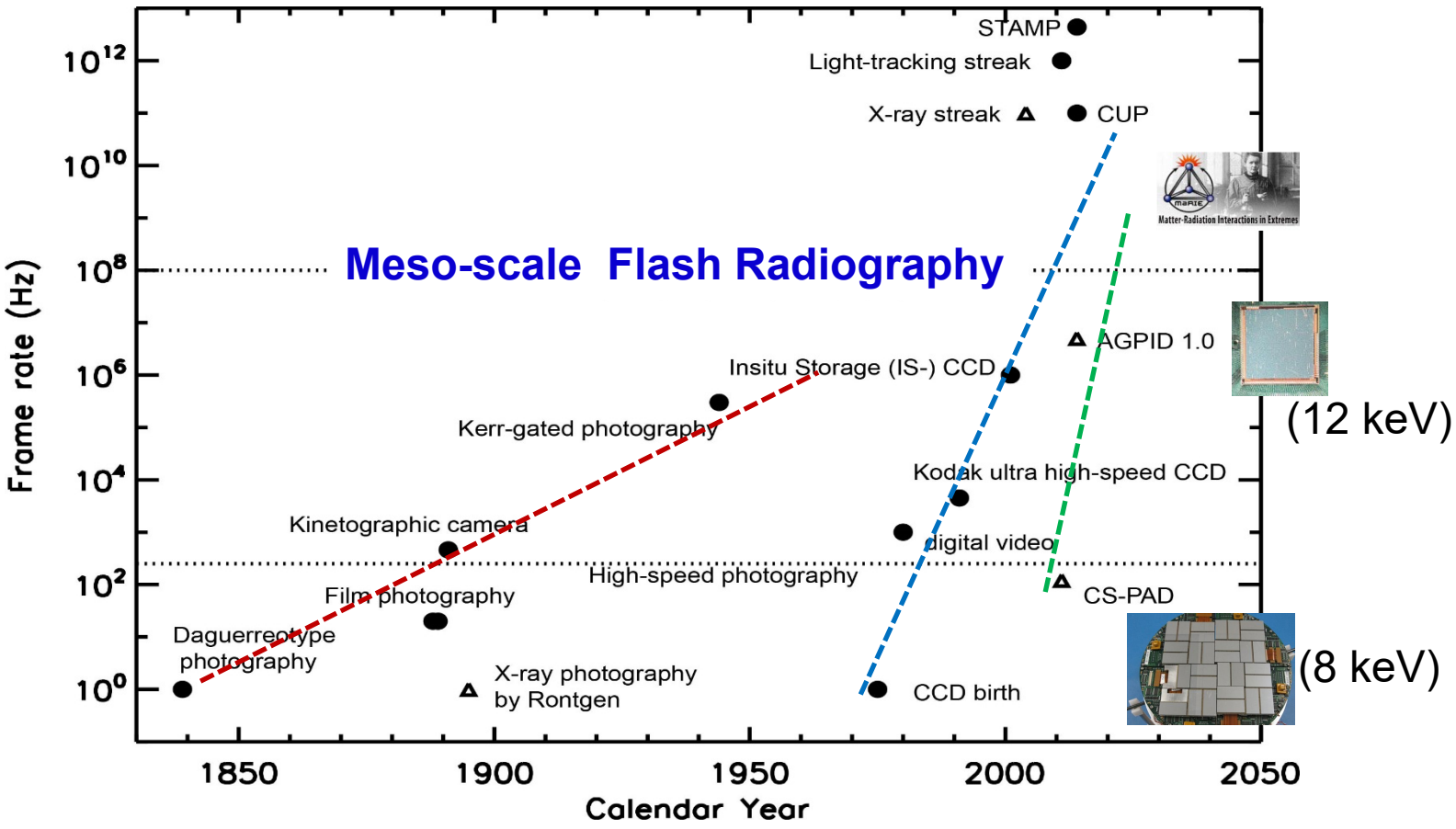
DARHT

P-Rad

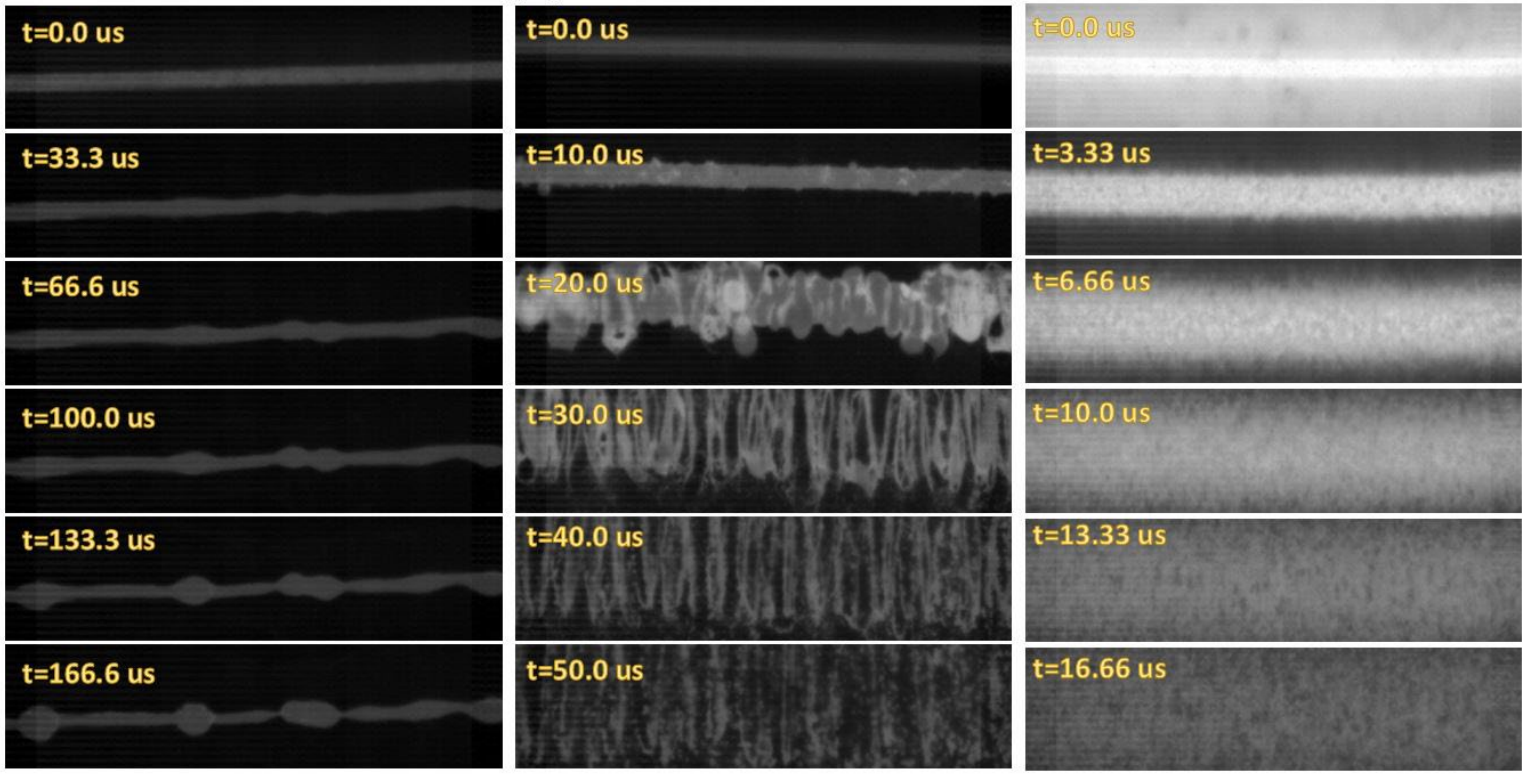


APS

Evolution of high-speed imaging as of ~ 2017



In need of better temporal resolution

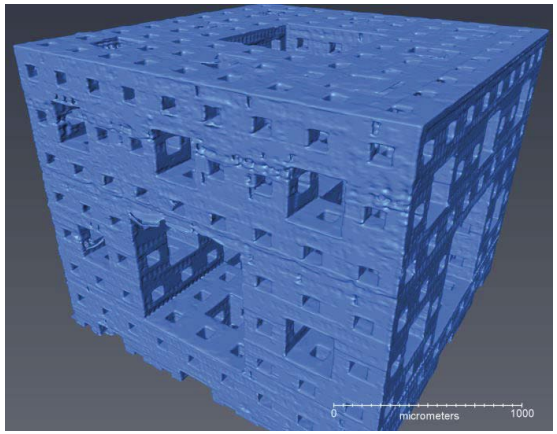


Fluid phase — "Phase explosion"

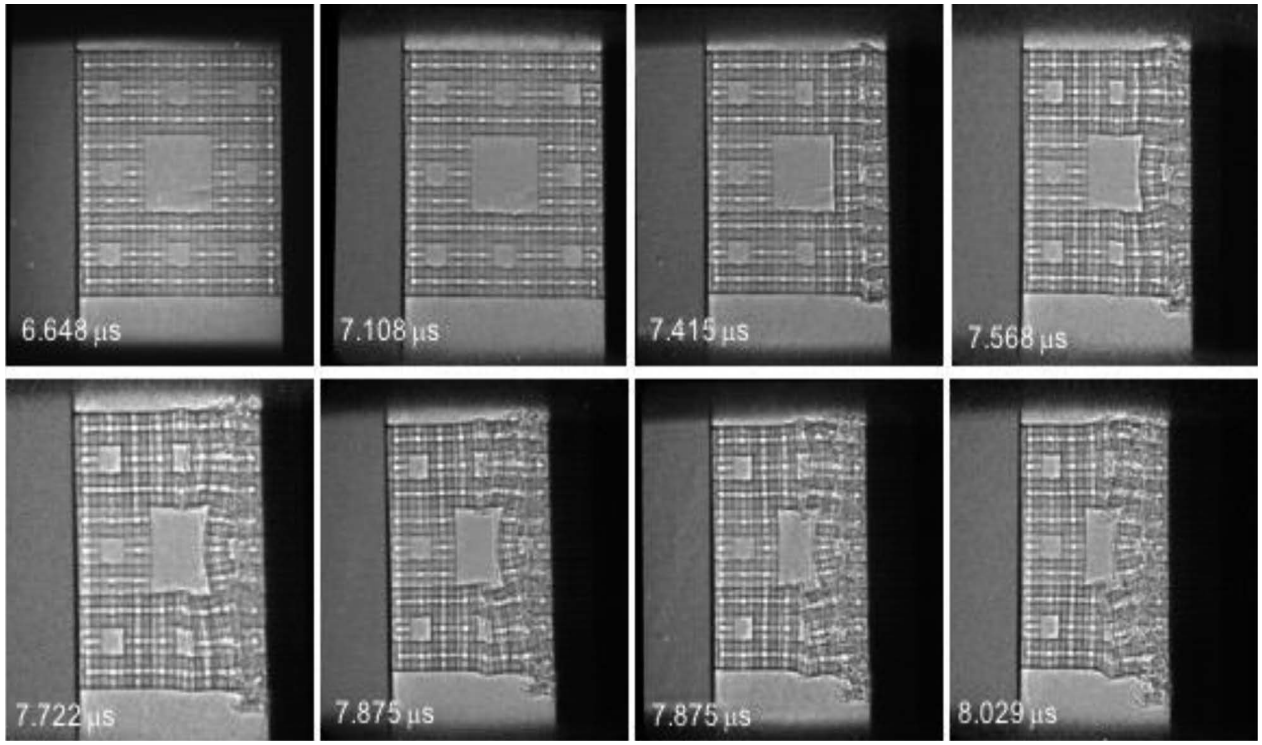
$T \sim T_0$ $T > T_0$

Sechrest *et al*, Appl. Phys. Lett. **117** (2020) 124102.

In need of better spatial resolution: X-ray experiment @ APS

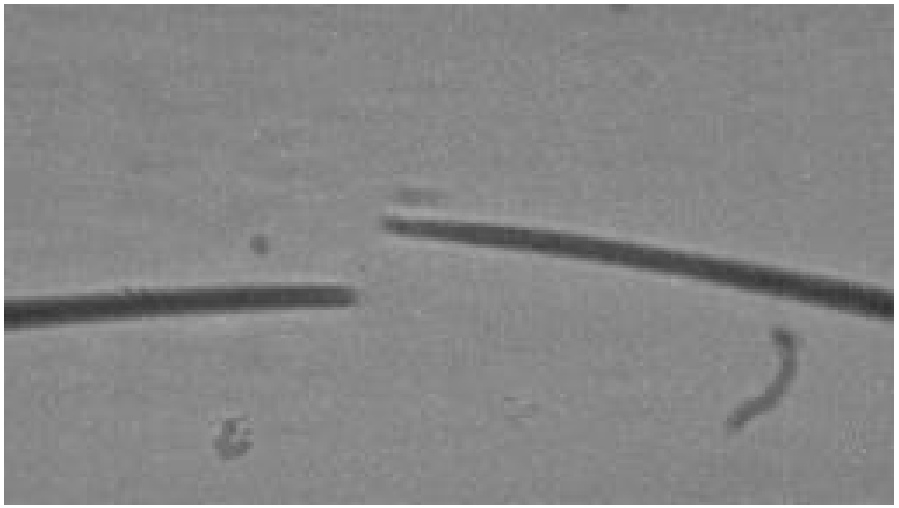


2PP-printed Menger sponge. The dimension of the cube is 1.7^3 mm^3

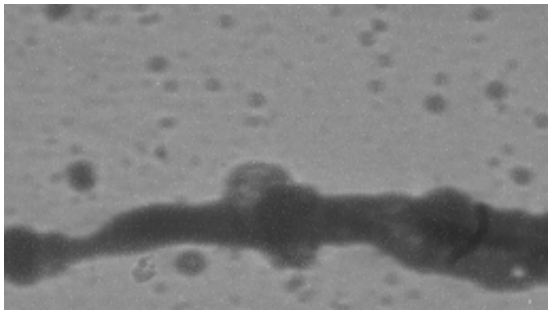


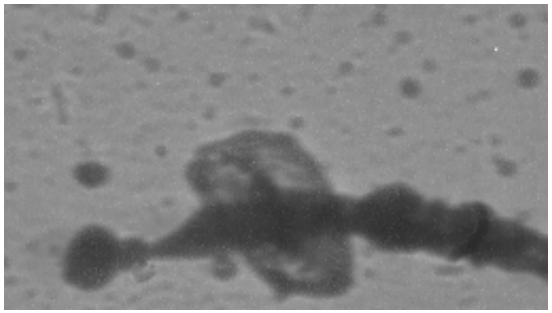
Dattelbaum *et al*, AIP Advances **10** (2020) 075016; AIP Conf. Proc. 2272 (2020) 040002.

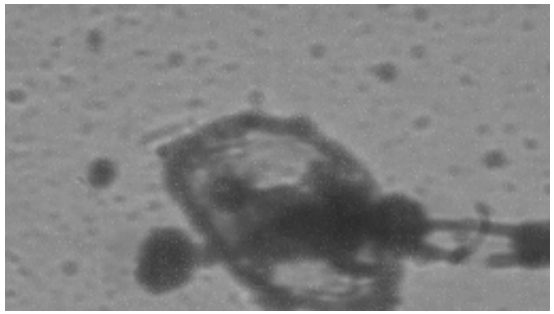
In need of 3D information: X-ray experiment @ APS



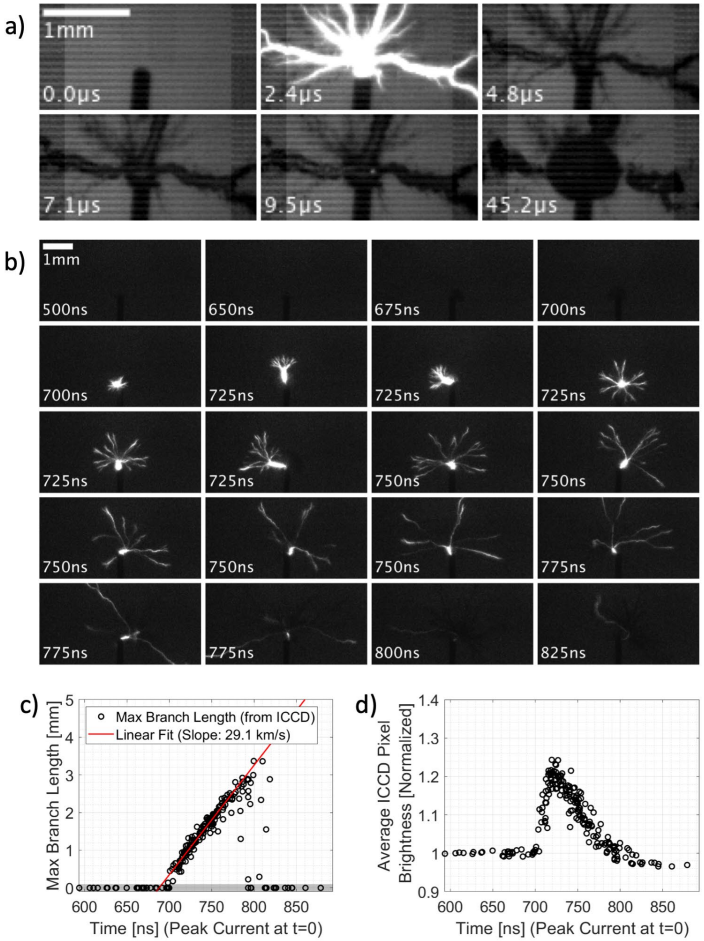
~ 100 kfps

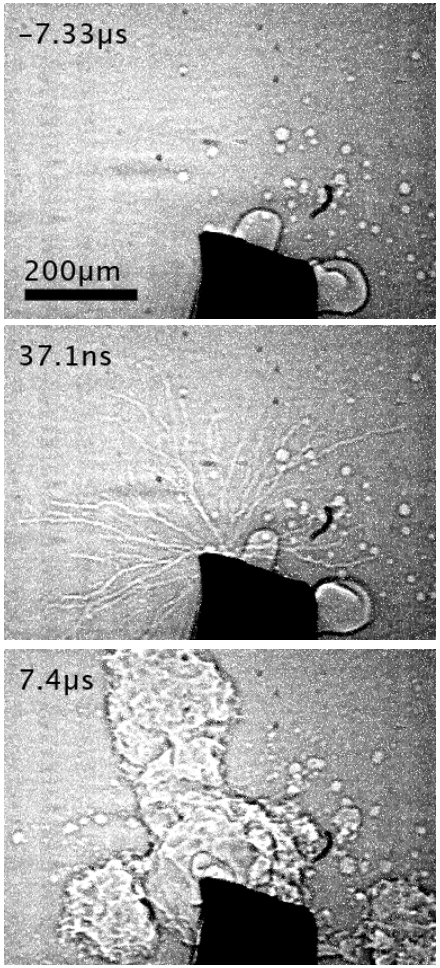






In need of Large FoV: X-ray experiment @ APS

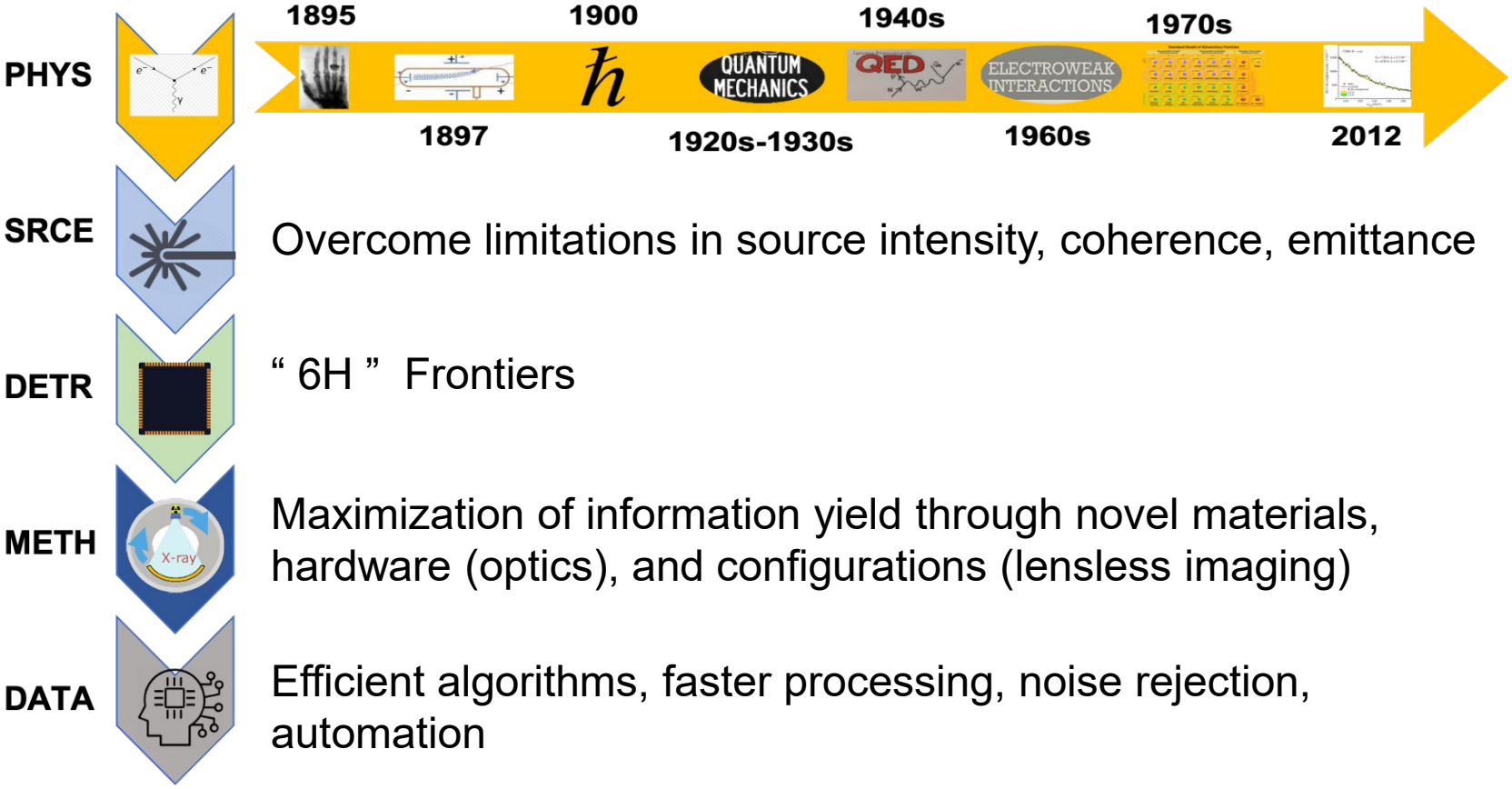




'Lightening in water'

Campbell *et al*, Phys. Rev. Res. 3 (2021) L022021

Open problems in Flash Radiography



Overcome limitations in source intensity, coherence, emittance

“ 6H ” Frontiers

Maximization of information yield through novel materials, hardware (optics), and configurations (lensless imaging)

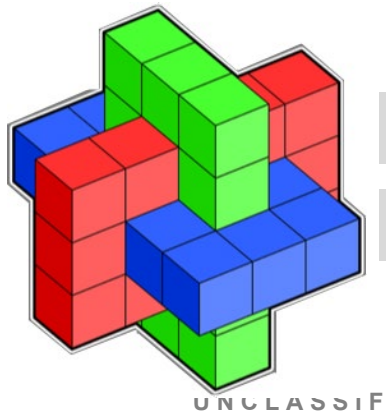
Efficient algorithms, faster processing, noise rejection, automation

Appl. Opt. 16 (2022) RDS1-RDS4

'6H' frontiers

High dimensional space optimization

- High-energy photons (20 keV +)
- High photon flux (10^7 + per pulse, sub-ns duration)
- **High-efficiency /sensitivity (50% +)**
- **High temporal resolution (< 75 ns -)**
- **High spatial/pixel resolution (1-100 um -)**
- **High Data Volume**



X-ray source

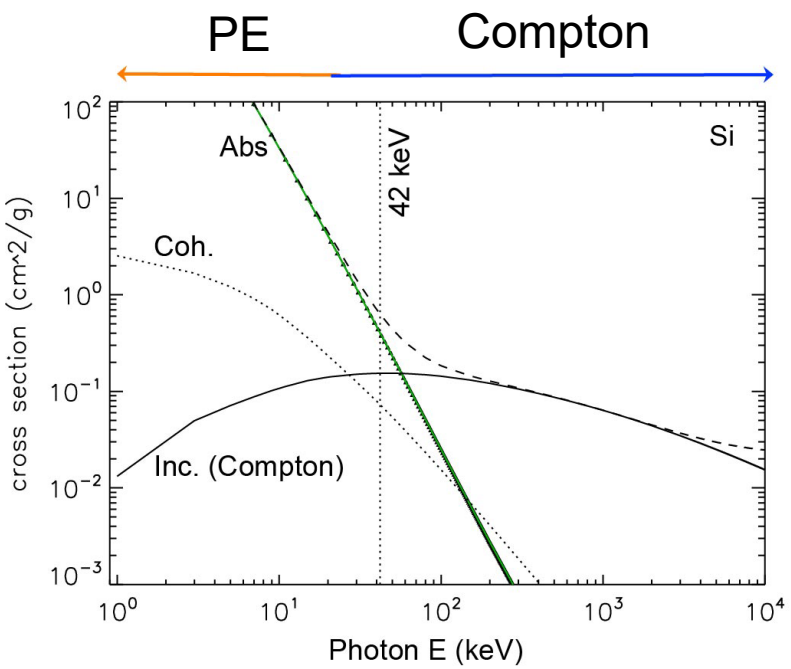
architecture

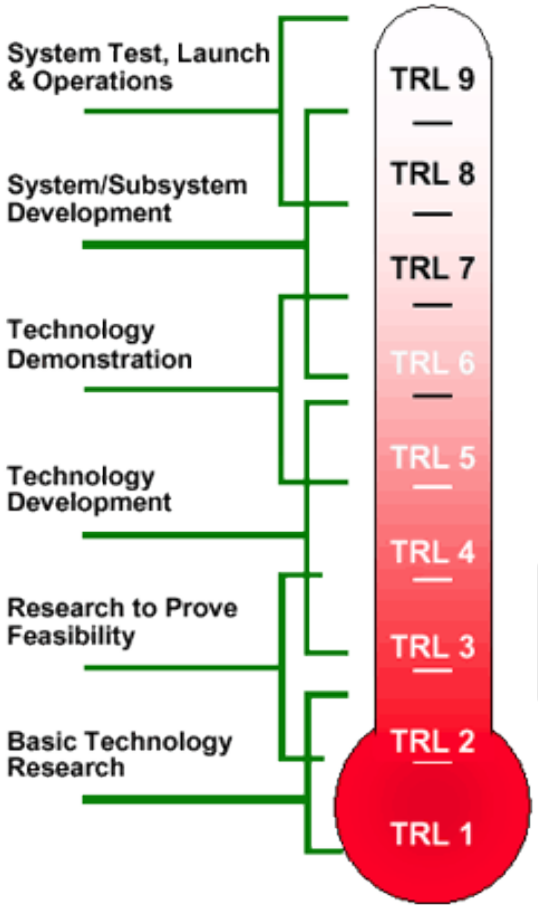
Sensor materials

Data

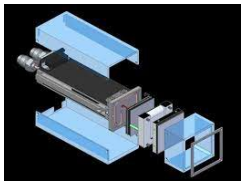
High-speed X-ray Cameras & prototypes

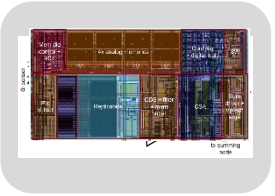
- **Hybrid CMOS**
- **Highest TRL Driven by near-term needs /light sources**





ePix (SLAC)





SparkPix (SLAC)

CMOS sensor designs down to pixels

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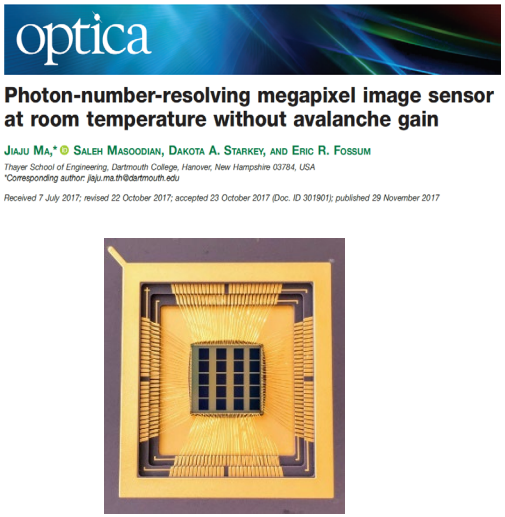
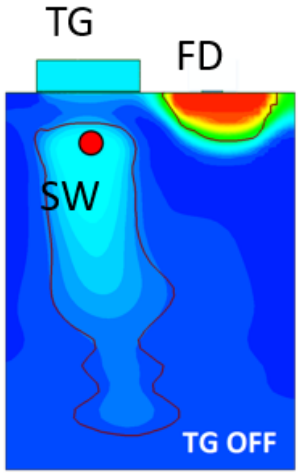
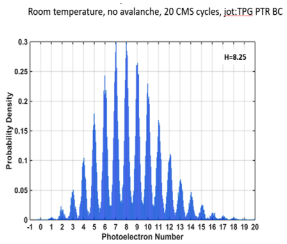


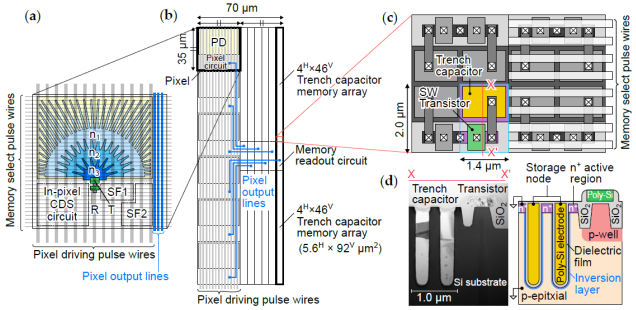
20-Mpixel SPDA



~0.2e$^-$ rms noise



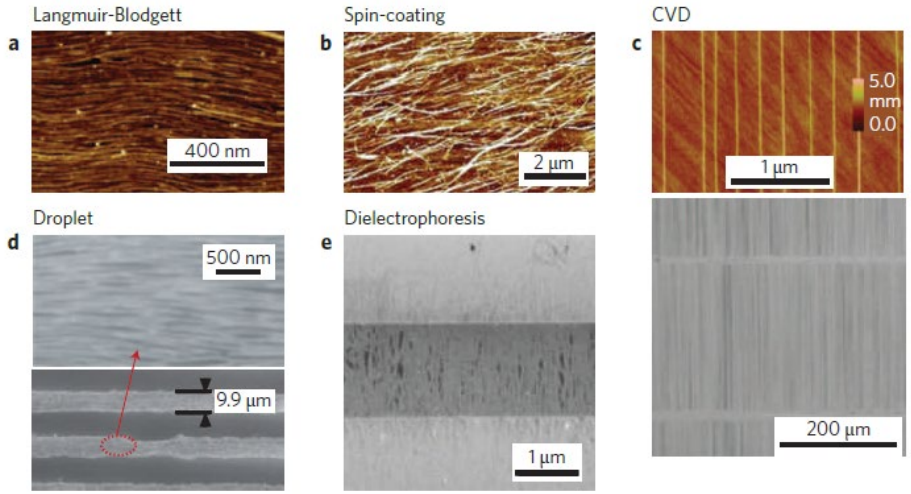
Quantized PE

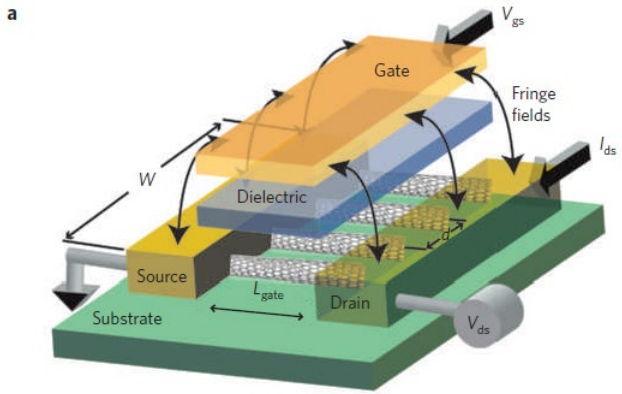


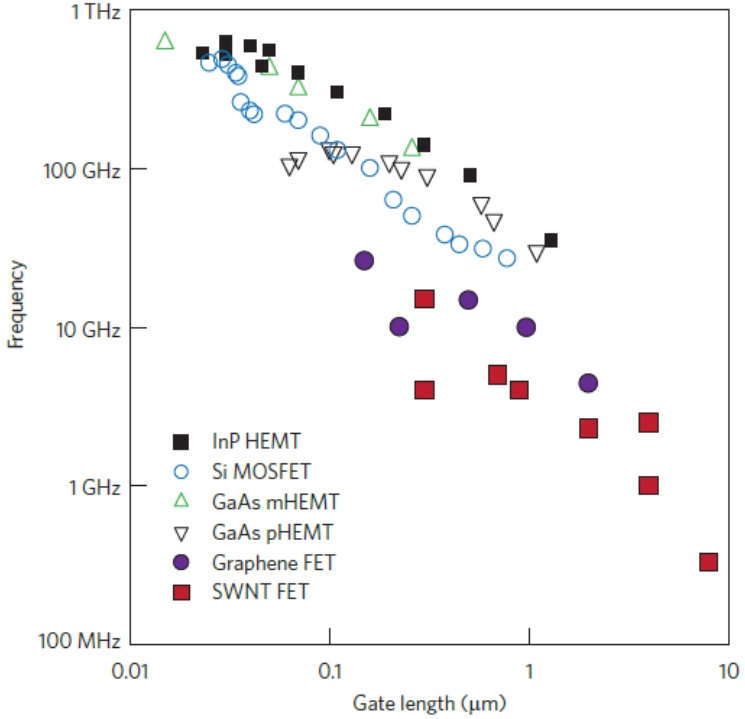
100 M fps+ capability

Suzuki et al, Sensor 20 (2020) 1086

Components: GHz FETs based on nanotubes → Extremely long development path & high cost …





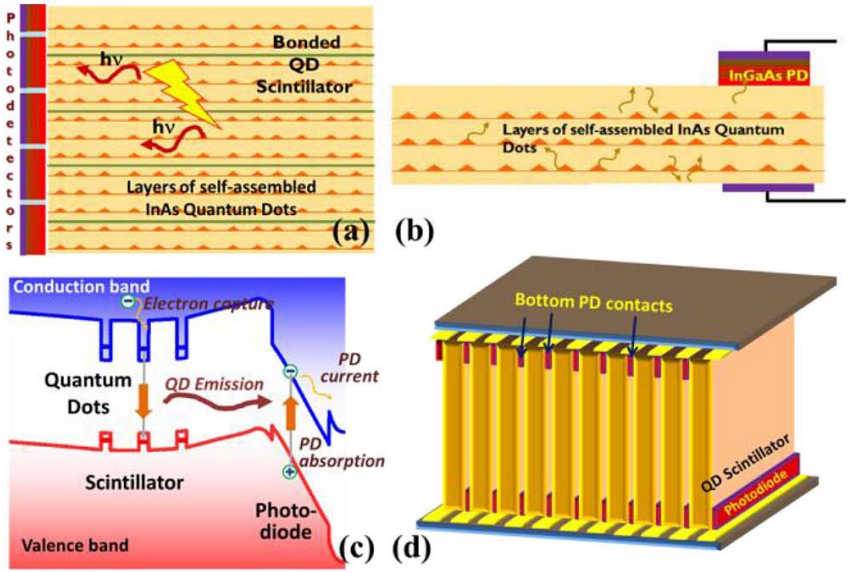


Rutherglen, Jain & Burke, *Nature Nanotech* 4 (2009) 811- 819

QD Device Concepts

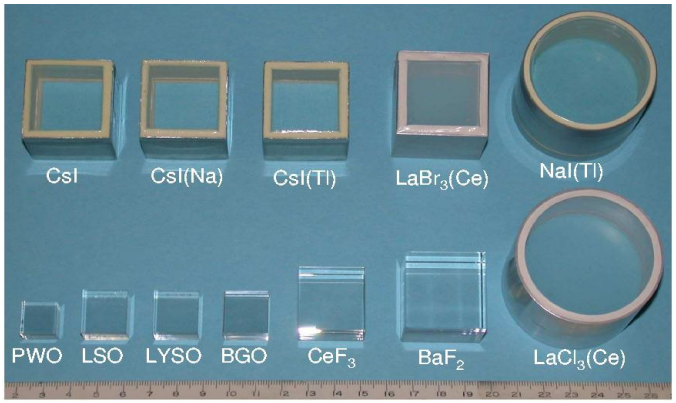
Parameter	BaF_2	LYSO	GaAs/InAs QDs
Density (g/cm^3)	4.89	7.1	5.32
Radiation length, cm	2.03	1.1	2.3
Decay constant, ns	0.8 ns	40	1
Peak emission, nm	195; 220	428	1050
Photon Yield (photons/MeV)	1,400	34,000	240,000
Time between first photons, for 1MeV	0.57ps	1.2 ps	2 fs
Poisson-limited energy resolution at 1MeV (keV) *	62	13	4.8
Radiation hardness, Gy	10^4-10^5	10^4-10^5	$>10^4$
Coupling efficiency	<50%	<50%	~100%

*Assuming collection efficiency = 1

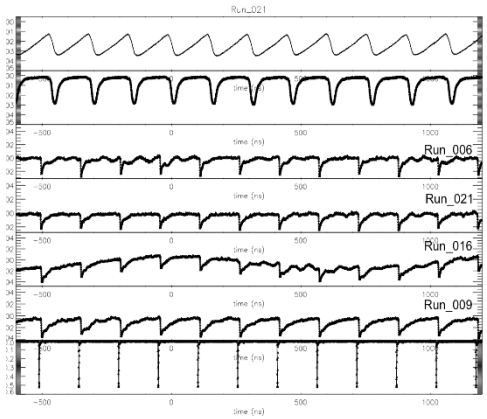


Oktyabrsky, Yakimov, Tokranov & Murat (2016)

Multiple Fast Scintillator Candidates



	LYSO:Ce,Ca	ZnO:Ga	BaF_2:Y	YAP:Yb	LuAG:Ce	$LaBr_3$:Ce
Density (g/cm^3)	7.4	5.67	4.89	5.35	6.76	5.29
Melting Points (^oC)	2050	1975	1280	1870	2060	783
X_0 (cm)	1.14	2.51	2.03	2.77	1.45	1.88
R_M (cm)	2.07	2.28	3.1	2.4	2.15	2.85
λ_I (cm)	20.9	22.2	30.7	22.4	20.6	30.4
Z_{eff}	64.8	27.7	51.6	31.9	60.3	45.6
dE/dX (MeV/cm)	9.55	8.42	6.52	8.05	9.22	6.9
λ_{peak} [a] (nm)	420	380	300 220	350	520	360
Refractive Index[b]	1.82	2.1	1.5	1.96	1.84	1.9
Normalized Light Yield[a,c]	100	6.6[e]	1.7 4.8	0.19[e]	35[f] 48[f]	153
Total Light Yield (ph/MeV)	30,000	2,000[e]	2,000	57[e]	25,000[f]	46,000
Decay Time[a] (ns)	40	<1	600 0.5	1.5	820 50	16
Light Yield in 1st ns (photons/MeV)	740	610[e]	1200	28[e]	240	2,200
40 keV Att. Length (1/e, mm)	0.185	0.407	0.106	0.314	0.251	0.131



LYSO + PMT 1

Fast plastic + PMT 2

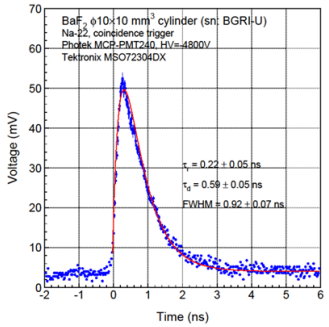
Diamond (Quadrant A)

Diamond (Quadrant B)

Diamond (Quadrant C)

Diamond (Quadrant D)

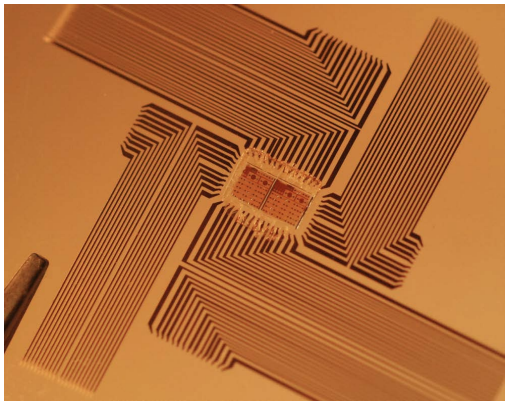
APS timing pulses

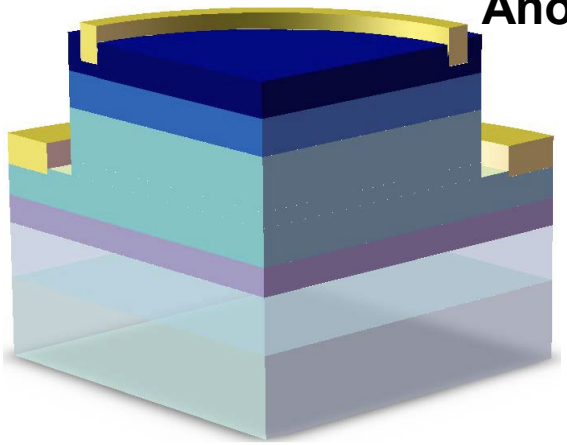


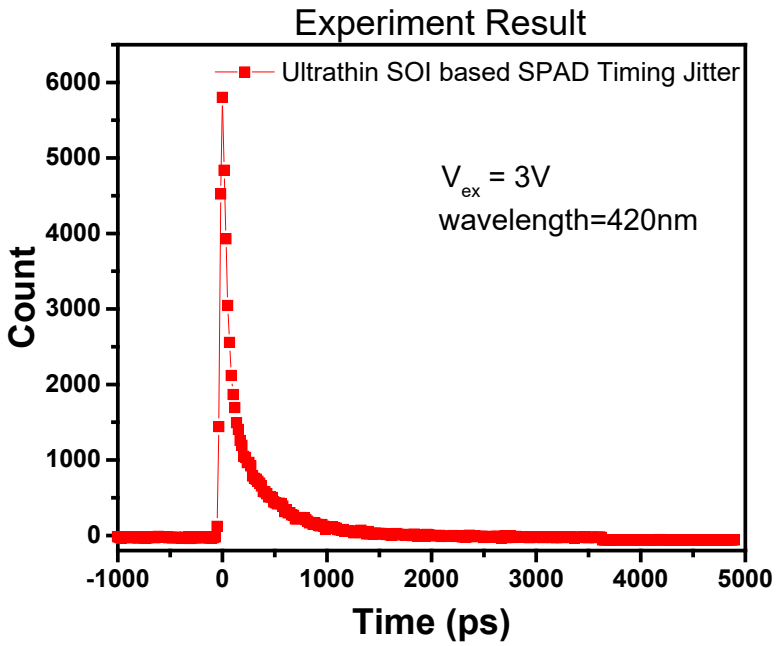
Xie *et al*, NIMA 927 (2019) 287

Hu *et al*, NIMA 950 (2020) 162767

SSAP collaboration –Univ. Wisconsin Madison

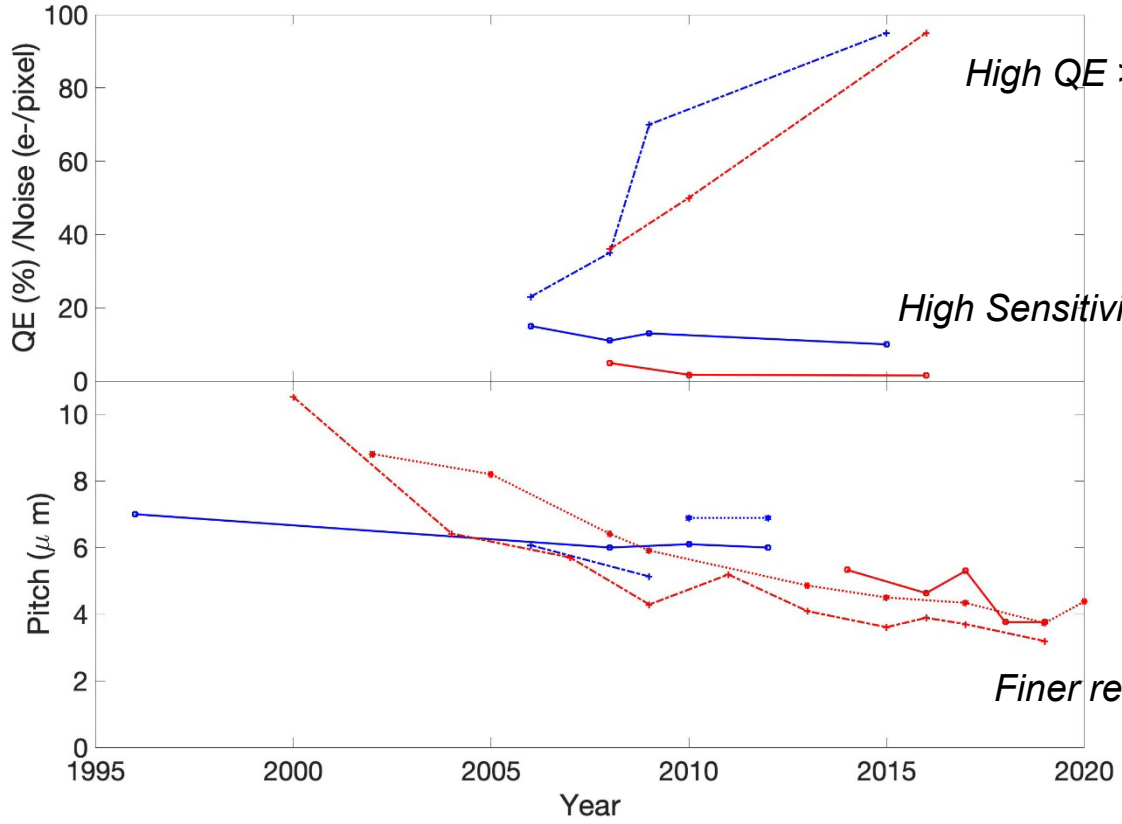






Xia et al, Appl. Phys. Lett. 111 (2017) 081109

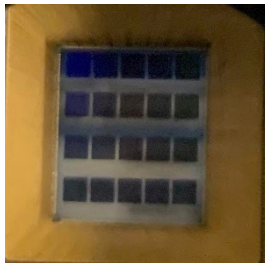
Commercial CMOS



High QE > 90%

High Sensitivity ~ low noise

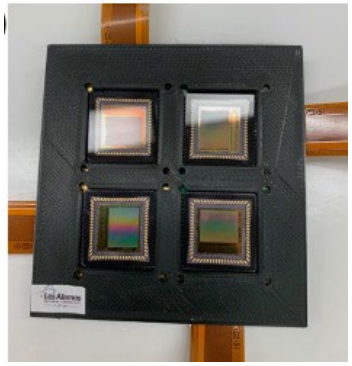
Finer resolution

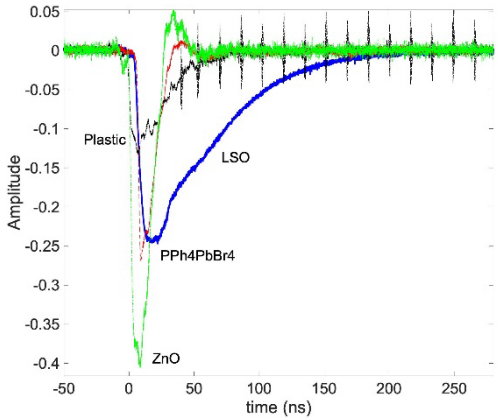


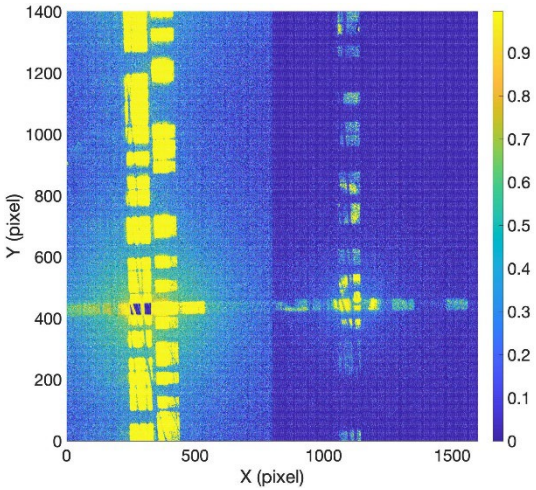
Gigajot pathfinder sensor

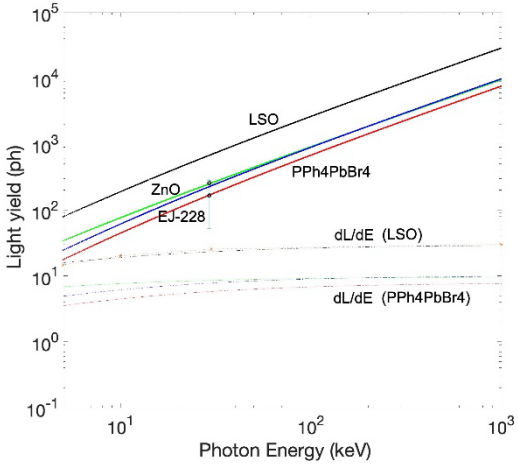
Wang *et al*, Rev. Sci. Instrum. 92 (2021) 043708

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





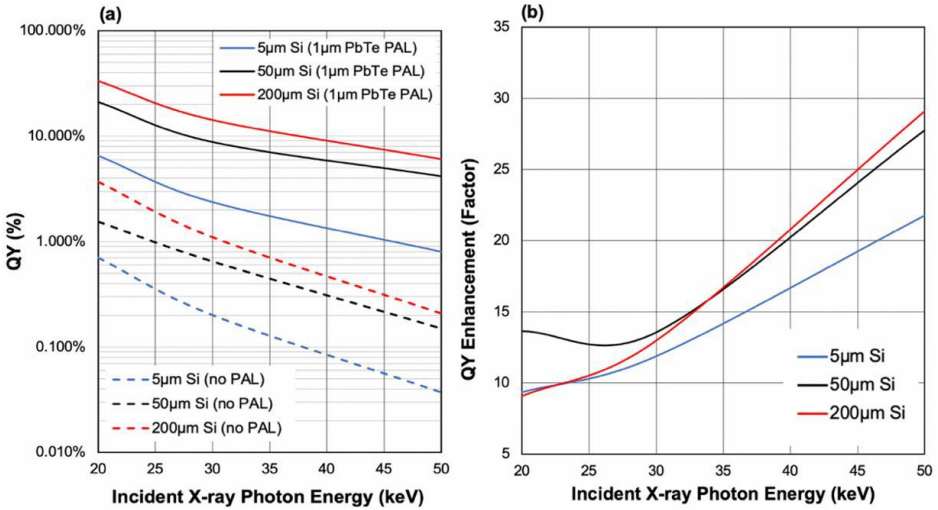




Wang *et al*, Rev. Sci. Instrum. 92 (2021) 043708

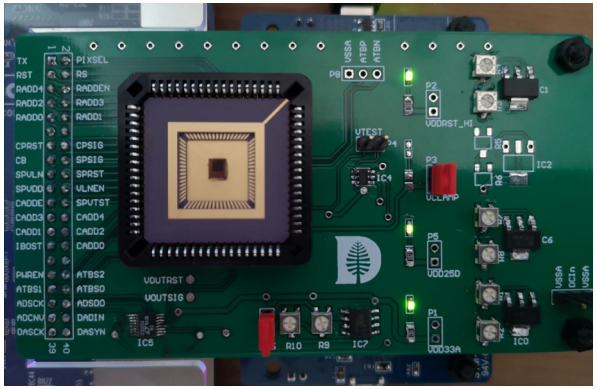
PAL layer integration with CMOS sensor

DARTMOUTH



Pixel-level hybridization

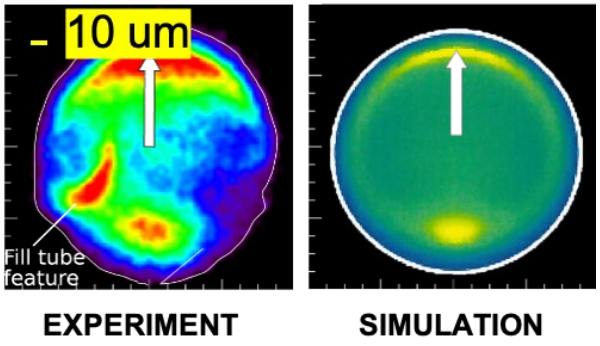
Lee *et al*, Instruments 5 (2021) 17



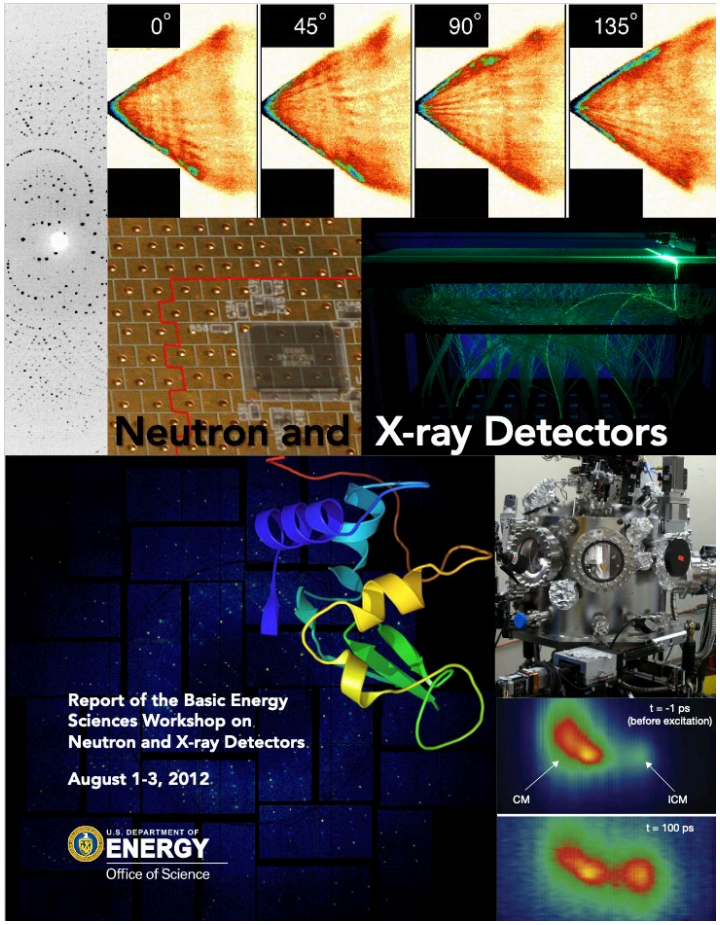
Yue et al, (2021)

Some issues with hardware centric approach

- **Long development cycle**
- **High cost**
- **Imperfect results**



D. J. Schlossberg et al, PRL (2021)



Open problems in Flash Radiography

Overcome limitations in source intensity, coherence, emittance

“ 6H ” Frontiers

Maximization of information yield through novel materials, hardware (optics), and configurations (lensless imaging)

DATA

Efficient algorithms, faster processing, noise rejection, automation

Appl. Opt. 16 (2022) RDS1-RDS4

High data volume ~ large dynamic range

- Single photon sensitivity and > 10^5 photons per pixel within the same image
- Large FOV and resolution in a single device
- Image interpretation using theory or simulations
- Calibration data depend on a number of control parameters
- Noise
- …

Algorithmic driven Data Processing

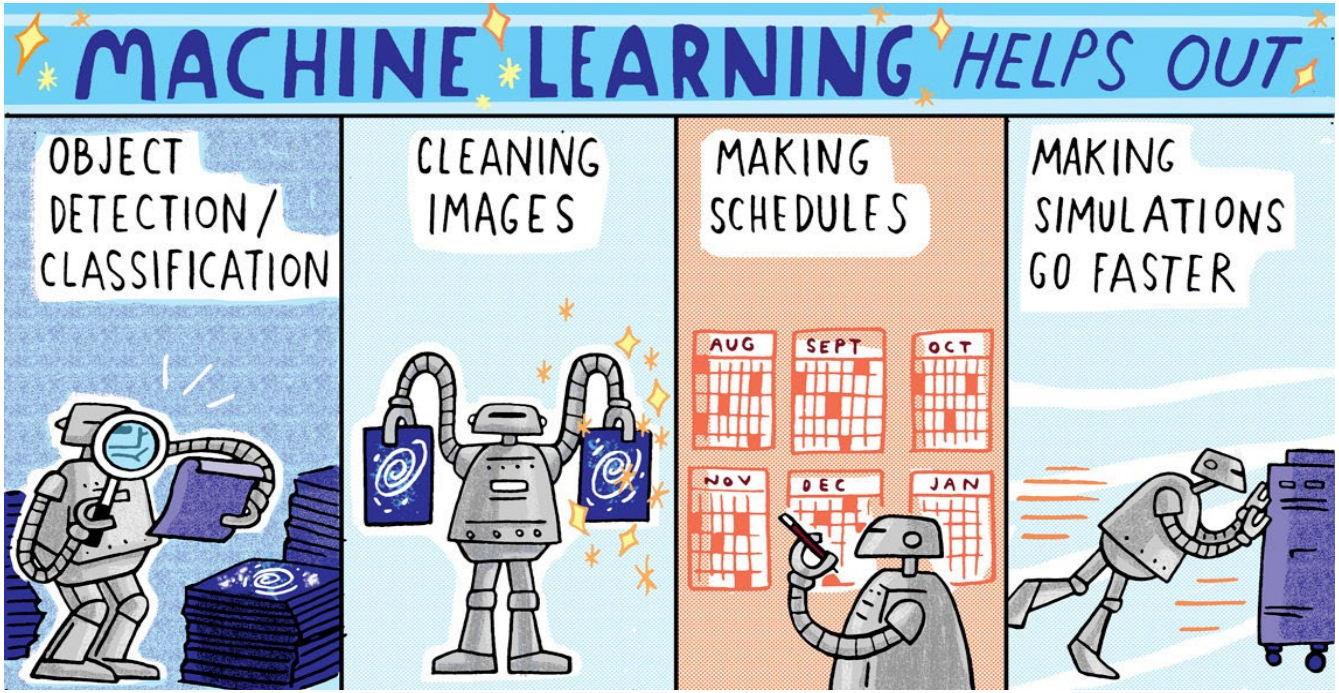
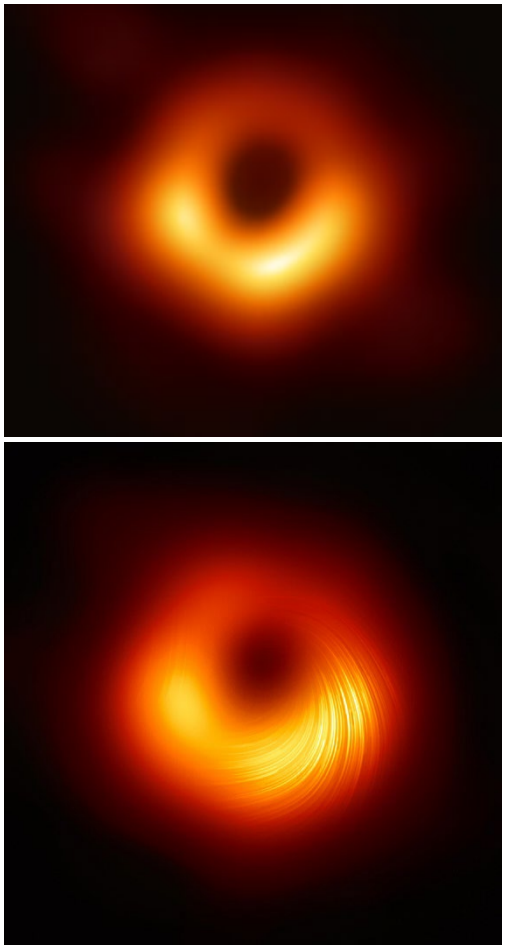
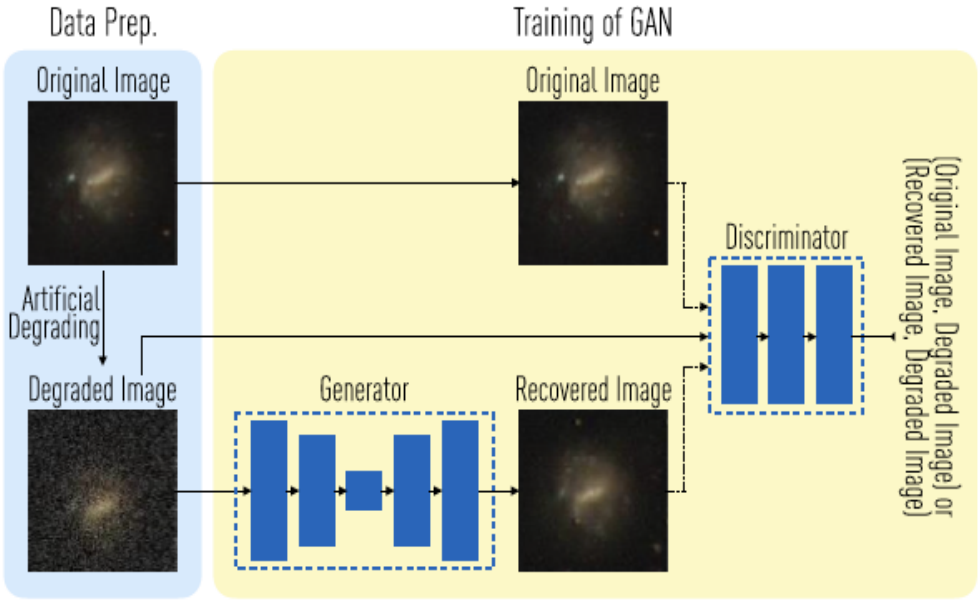


Illustration by Sandbox Studio, Chicago with Corinne Mucha

Super – resolution in astronomy

M87

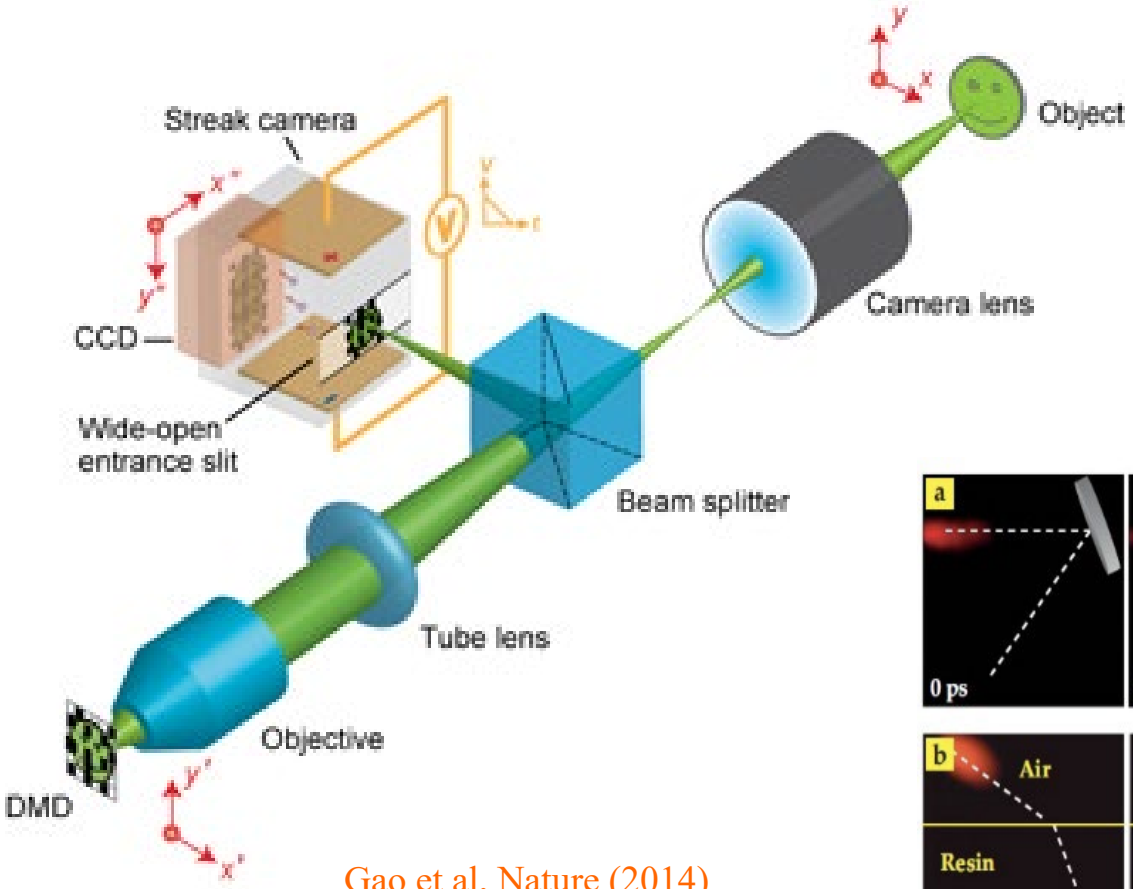


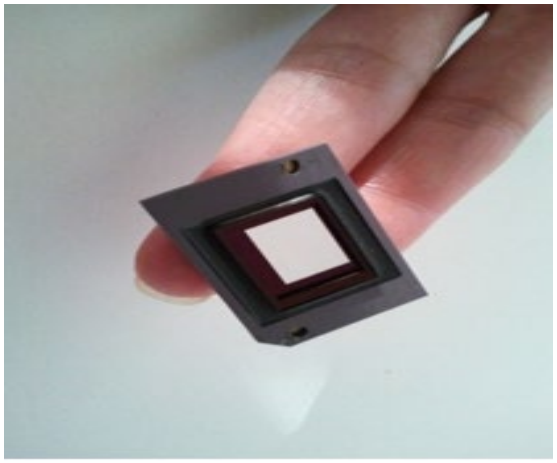


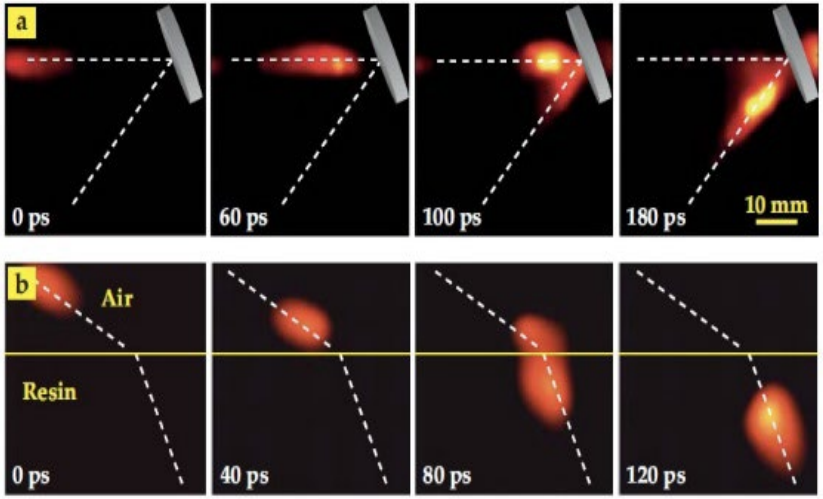
Schawinski et al, MNRAS 467 (2017) L110

The Event Horizon Telescope Collaboration *et al. Astrophys. J. Lett.* **875**, L1 – L4 (2019).

Compressed ultrafast photography (CUP)







Gao et al, Nature (2014)

Super-temporal resolution from ps to ms+

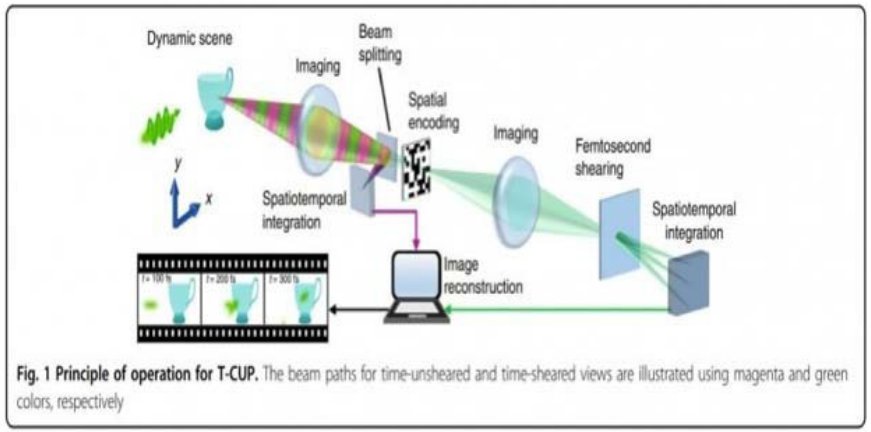
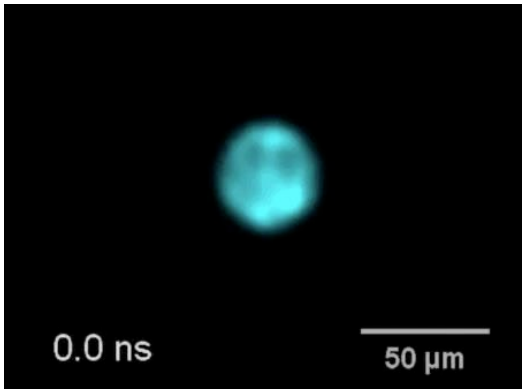


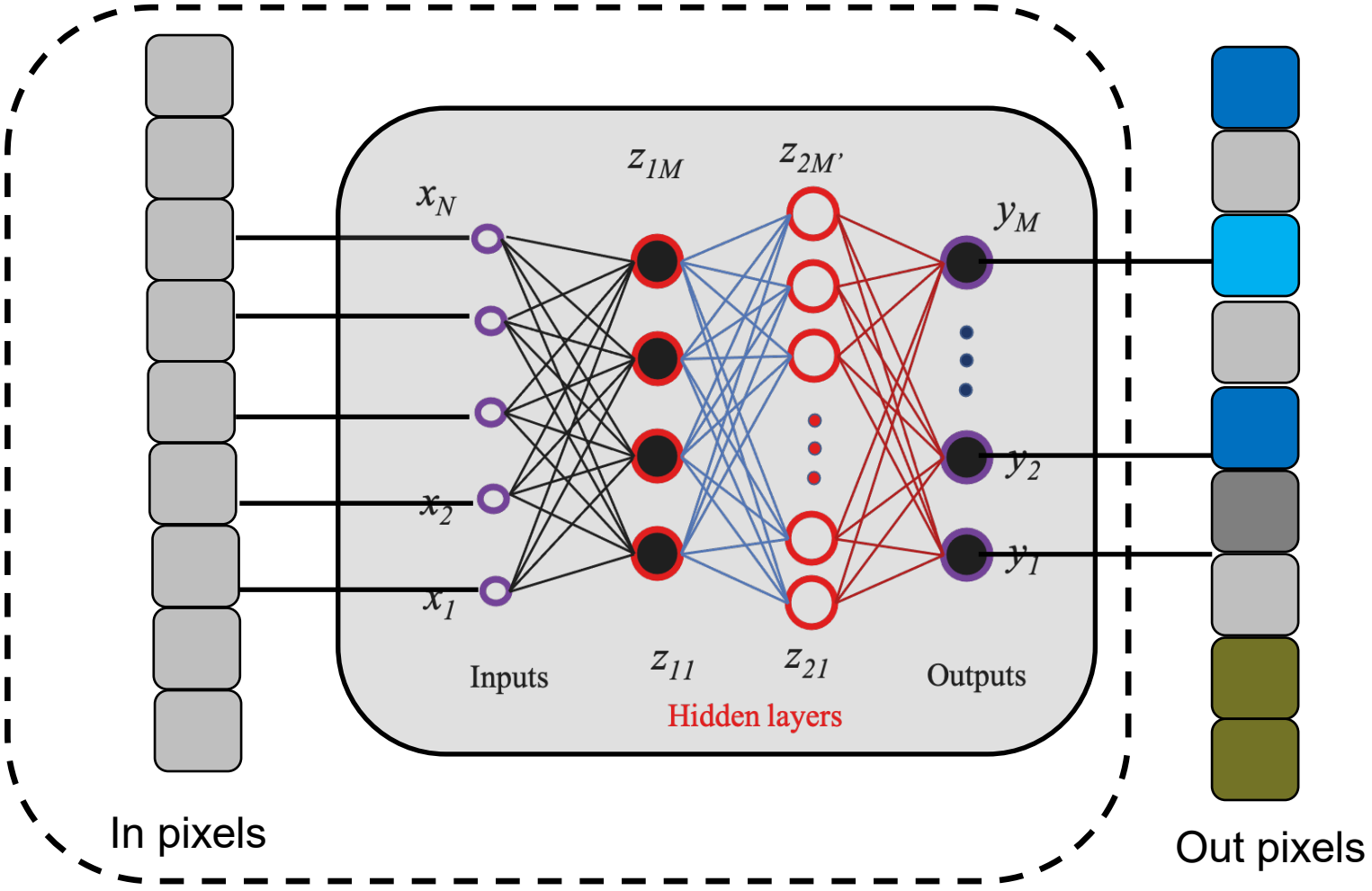
Fig. 1 Principle of operation for T-CUP. The beam paths for time-unsheared and time-sheared views are illustrated using magenta and green colors, respectively



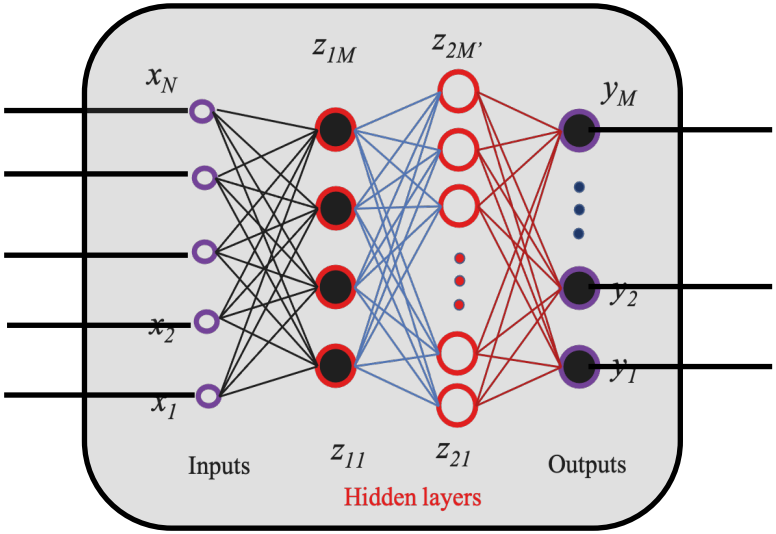
Lihong Wang (Caltech)

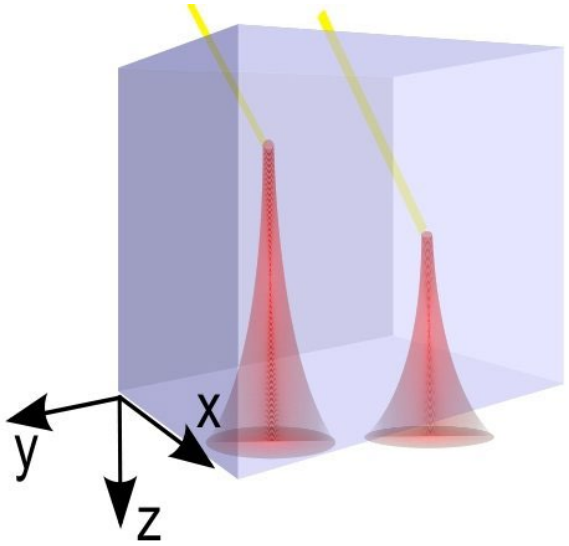
- (2014) CUP
- (2015) ToF CUP
- (2018) T-CUP
- (2020) compressed ultrafast spectral photography (CUSP)
- (2020) phase-sensitive compressed ultrafast photography (pCUP)
- (2020) 70 trillion fps

Φ–Cam Architecture based on Neural Network



Neural Network Tuning in high-dimensional space

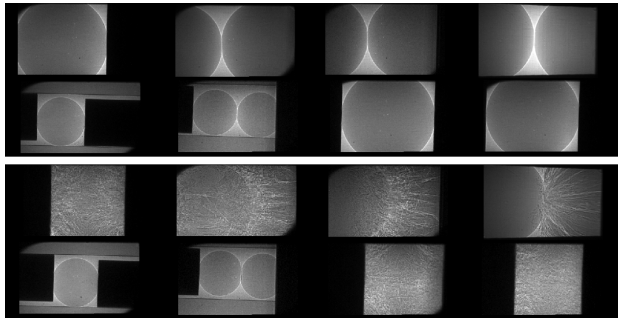




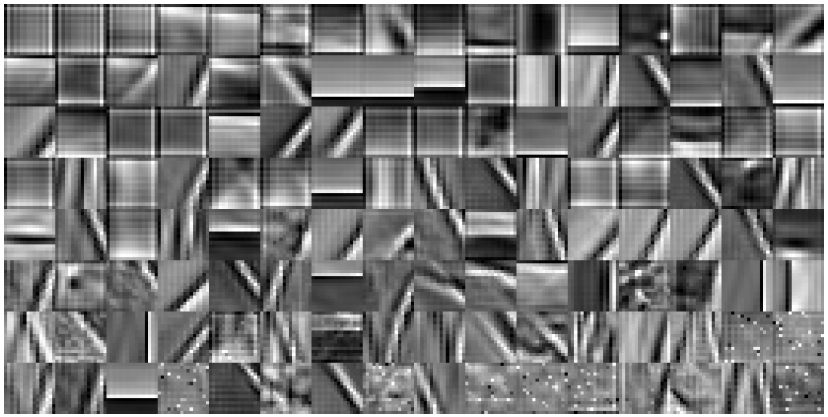
Potdevin et al 2009 JINST 4 P09010

- Sensor data
- Electronics (calibration, gain, noise, leakage) data
- Environmental parameters (temperature, age, dose)
- Scene information (object)
- Device simulation data

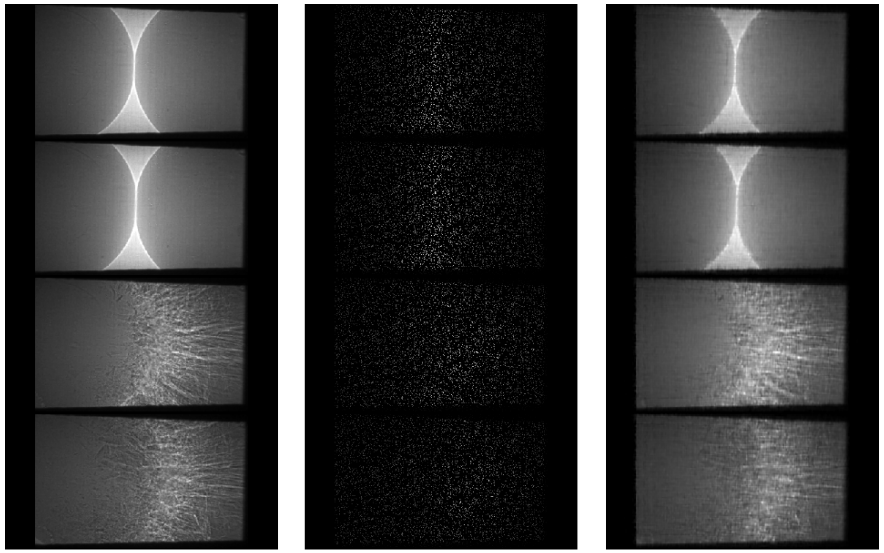
Implementation of Sparse imaging principle



Experiments



Feature extraction

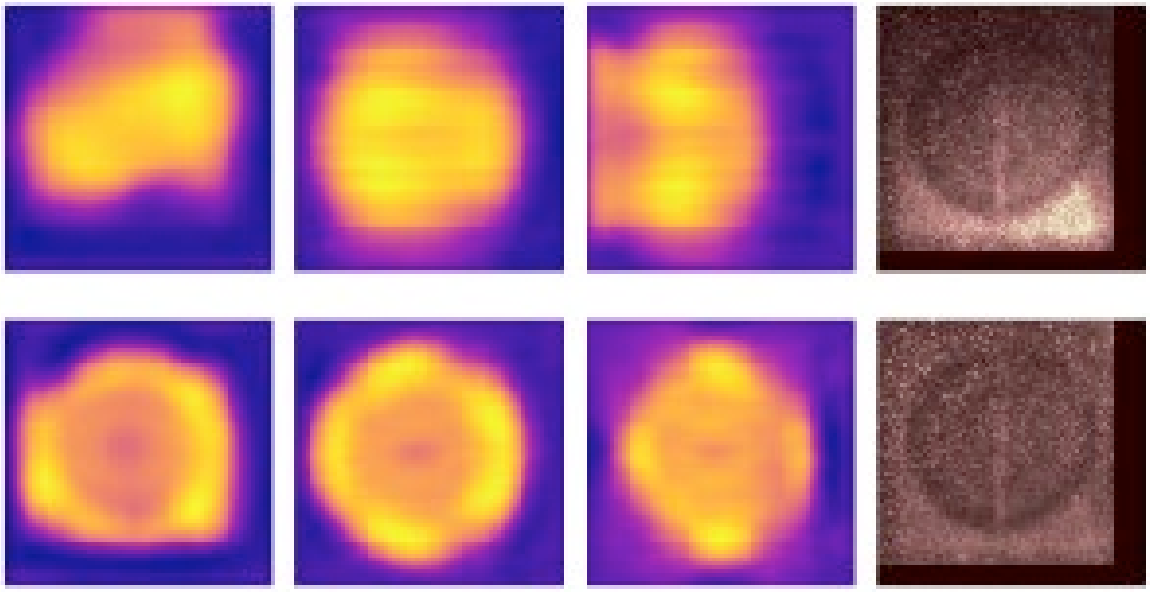


(a) (b) (c)

Validation

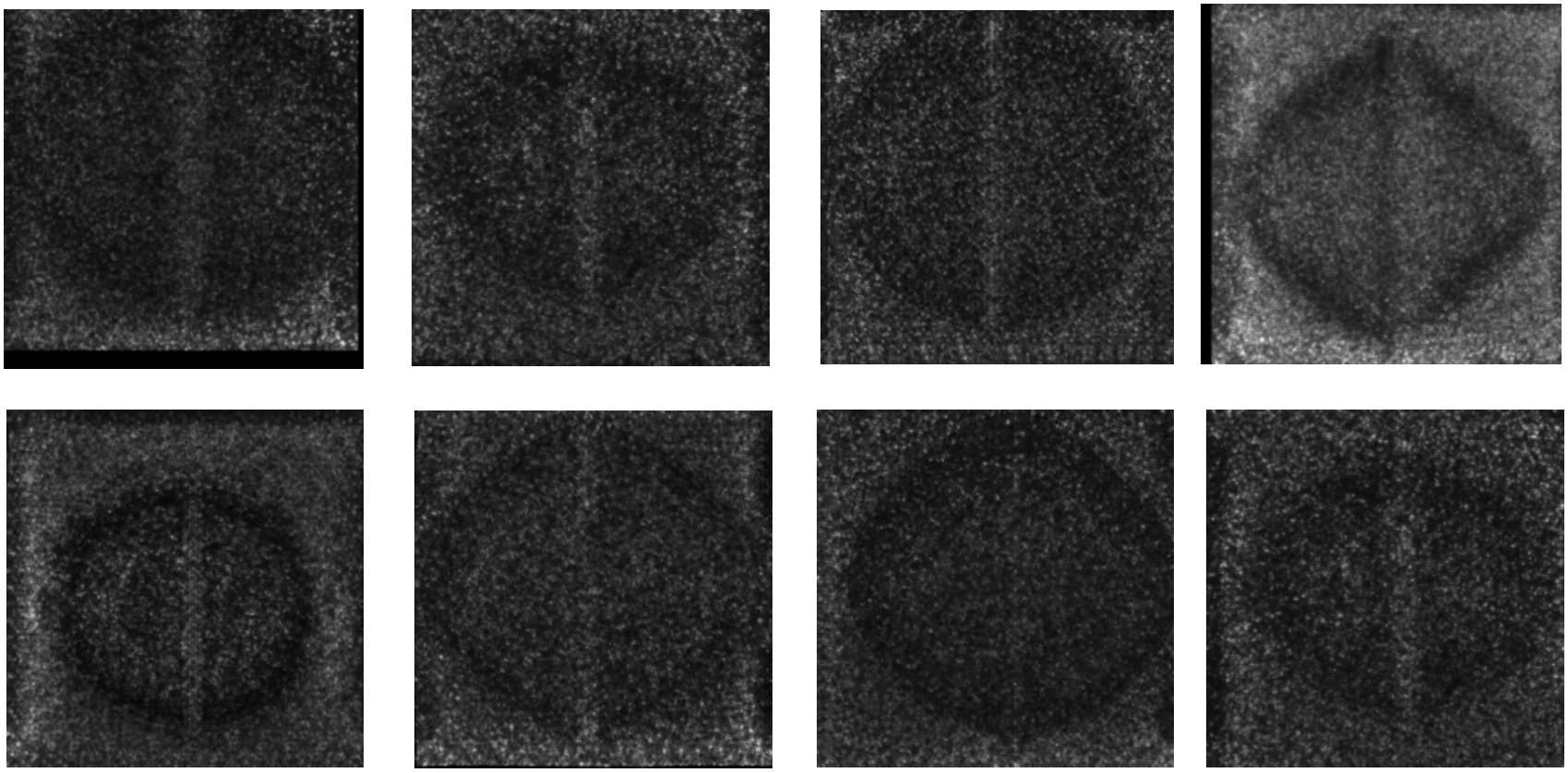
Wang, Iaroshenko, *et al*, JINST 13 (2018) C01035

3D reconstructions of X-ray images sensitive to noise

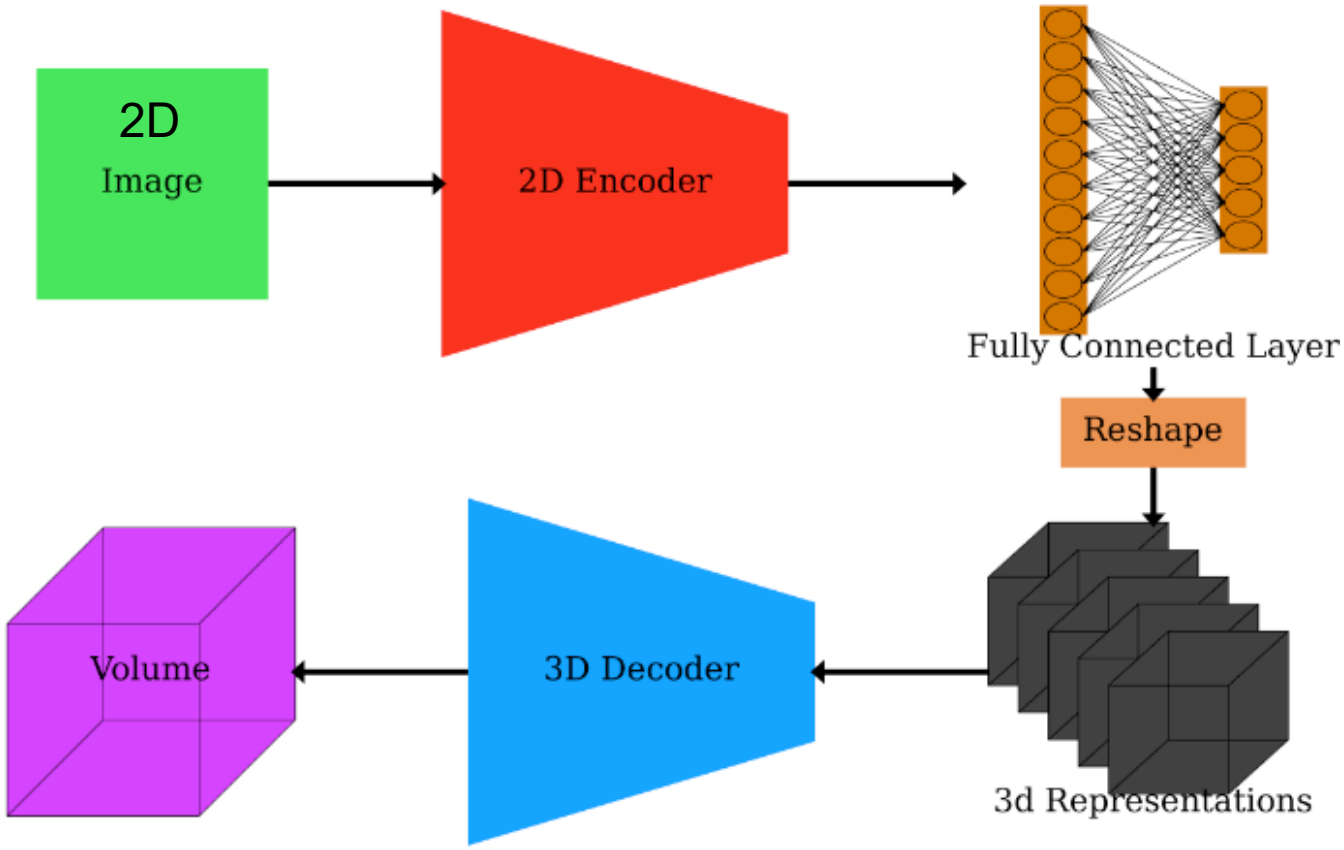


B. T. Wolfe et al, RSI (2021)

Noise models through Generative NN



An example of improved 3D NN architecture



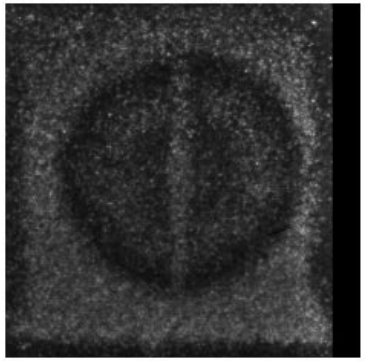
Wolfe et al, https://arxiv.org/abs/2206.02564

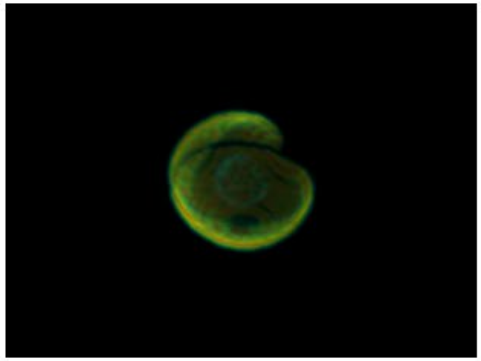
Model sensitivity studies

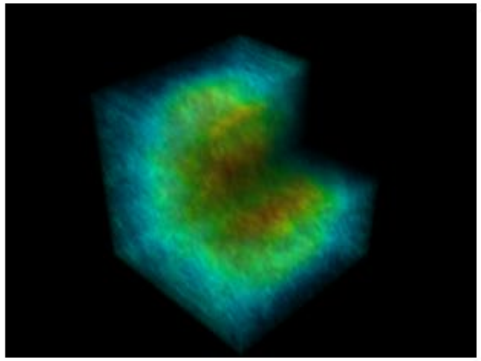
AttSets

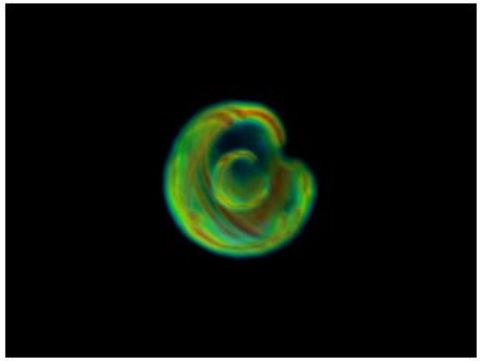
Transformable Bottleneck Networks(TBN)

Multiview Decomposition Network(MVD)



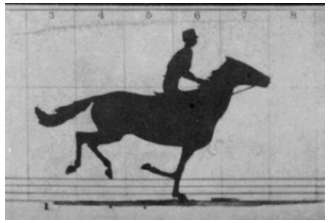




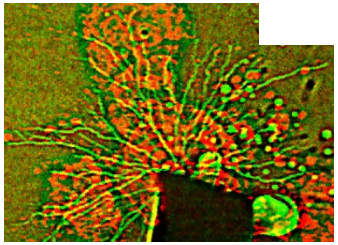


Wolfe et al, https://arxiv.org/abs/2206.02564

Summary



- **Flash X-ray radiography**
  - With roots in Flash photography
- **Recent trends** (hard-ware driven)
  - CMOS technology & device physics (legacy of the Moore's law)
  - Material discoveries (scintillators, nanomaterials),
- **Emergent opportunities** (data-driven)
  - data science, machine learning
  - Experimental validation
  - Broad application potentials



Acknowledgement

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