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Simulations & ML in medical imaging

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Disclosure

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- Virtual simulations performed and presented here are part of DukeSim virtual platform developed at CVIT, Duke University, USA

- Other similar software are Victre, XCIST, …

- Experimental part was performed in Trieste, Italy

Overview

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PART I – computer simulations in medical imaging

- Virtual imaging simulations: how and why to virtual imaging?
- Simulation parts: virtual humans and virtual detectors
- Spectral CT: modeling photon-counting detectors

PART II – machine learning in medical imaging

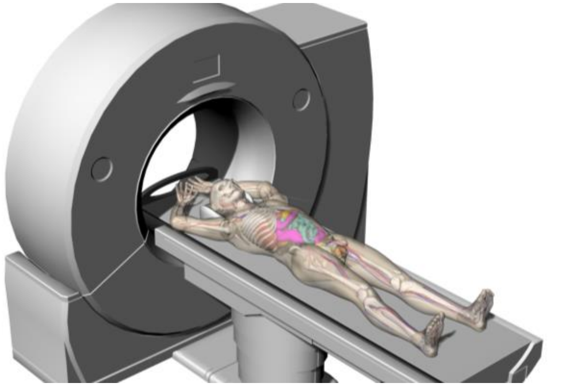
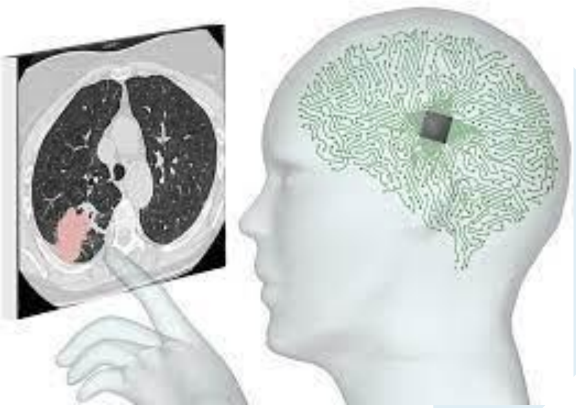
- Beyond traditional radiology: density and effective atomic number

How to virtual imaging?

Real world



Virtual world

Why to virtual imaging?

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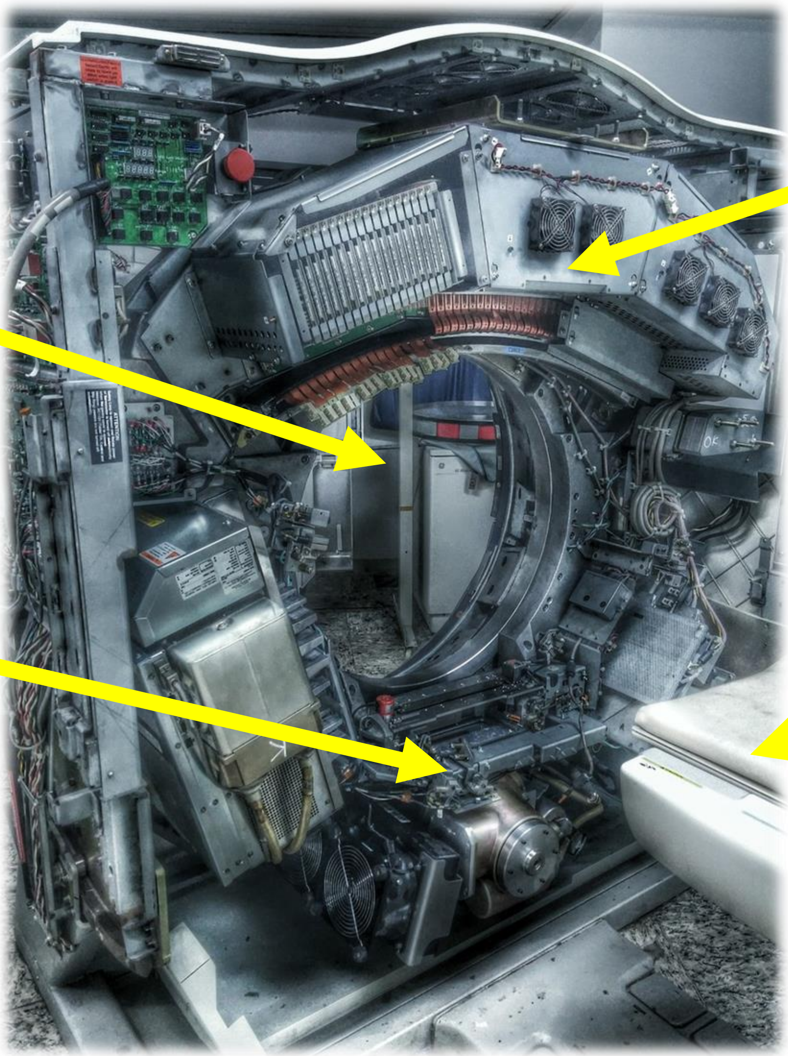
Technology development

Geometry?
Magnification?

Source type?
What power?
Size of focal spot?



Which detector?
Detector size?
Pixel size?

Couch material?

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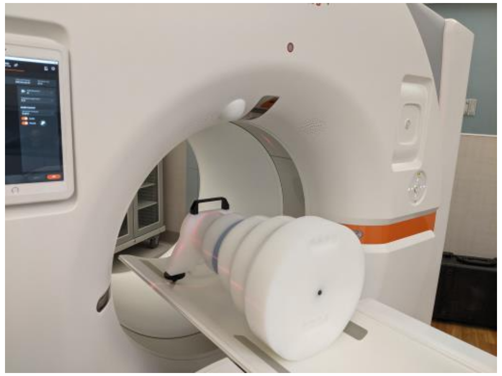
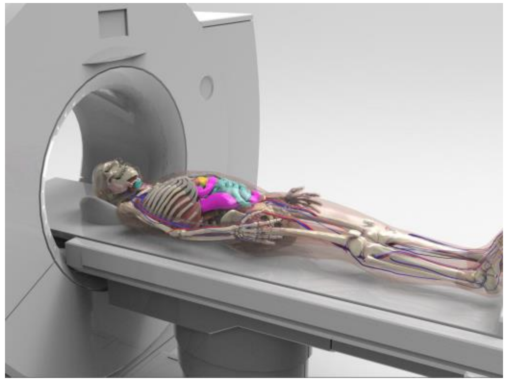
Technology evaluation – virtual imaging trials

physical phantoms | virtual | clinical

credibility



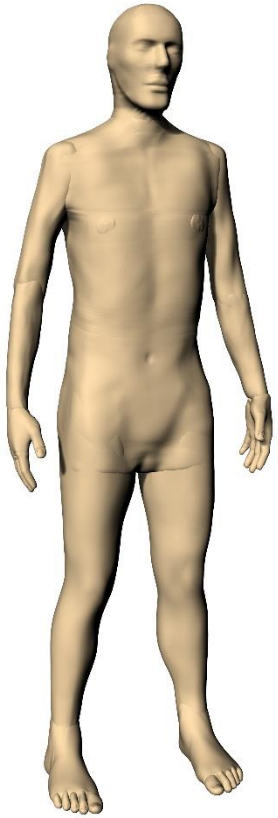


not anthropomorphic
not disease specific
not diverse
simple

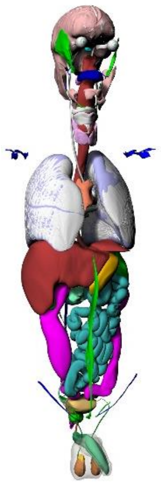
ground truth limited
expensive
dose concern
complex

Anthropomorphic phantoms: virtual humans

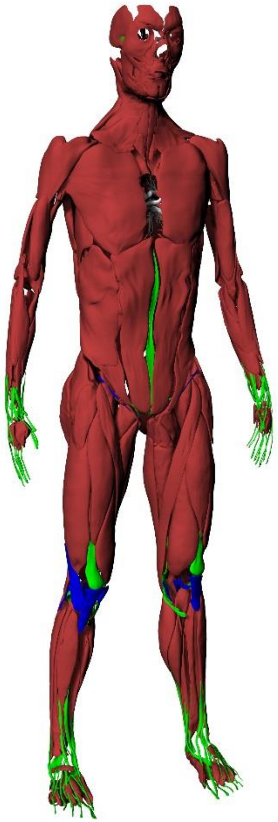
body surface



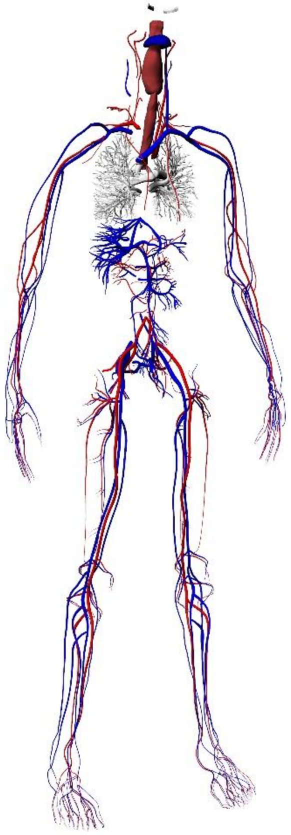
organs



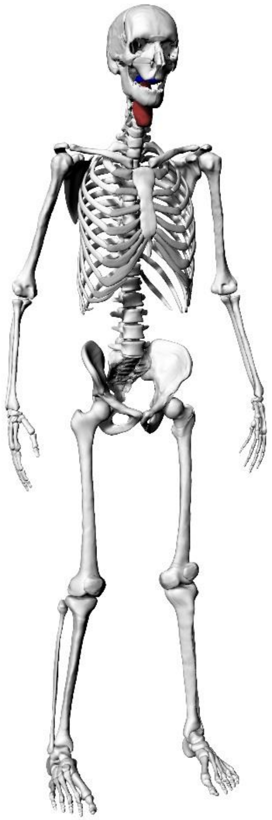
muscles



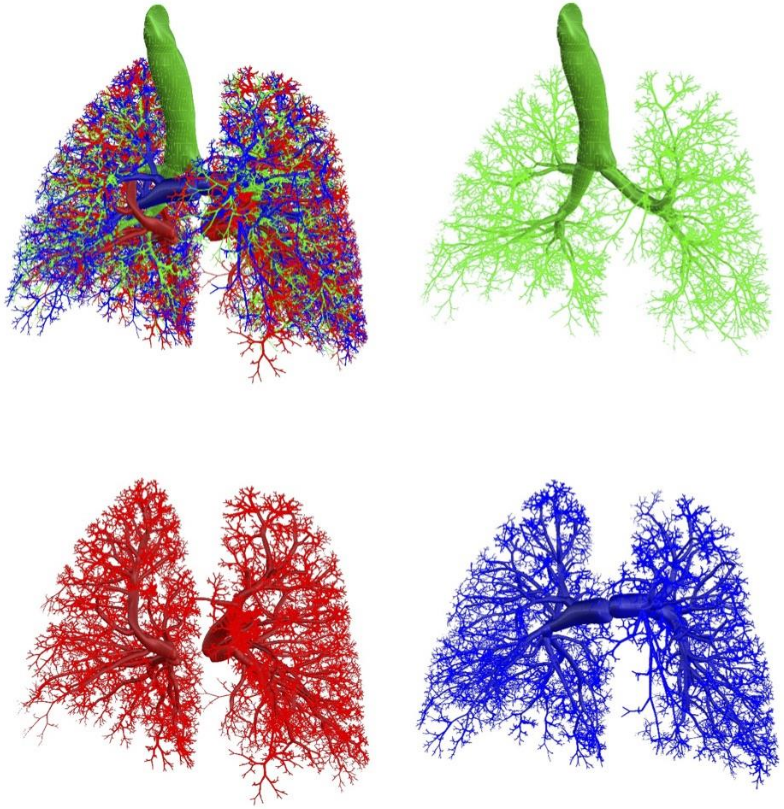
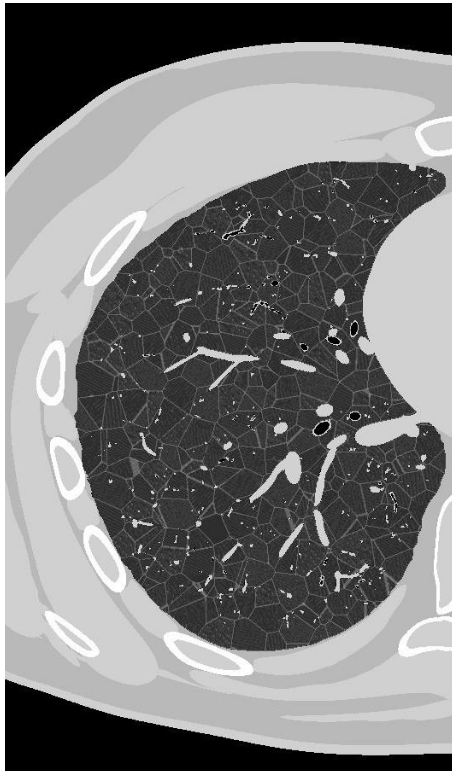
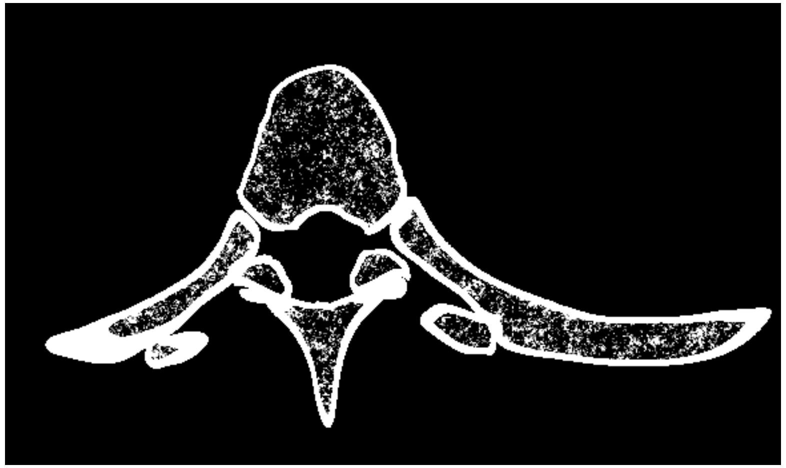
vasculature



skeleton



Intra-organ structures

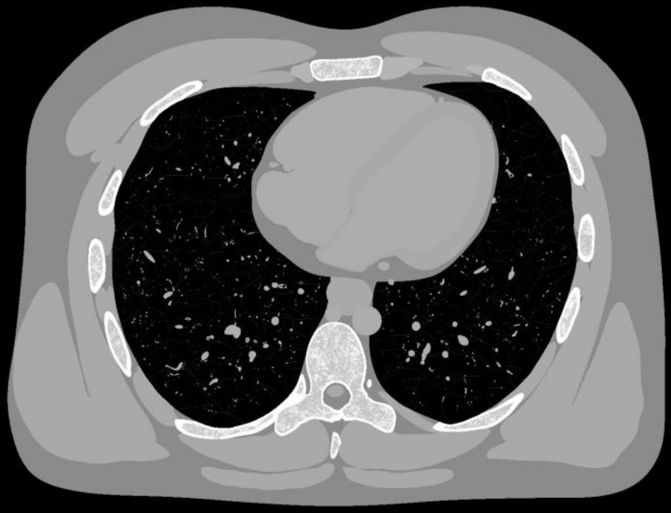
Non-parenchyma	Parenchyma	Bone
		
Abadi et al, IEEE TMI 2018	Abadi et al, SPIE 2017	Abadi et al, IEEE TRPMS, 2018

4D high-resolution voxelized phantoms:

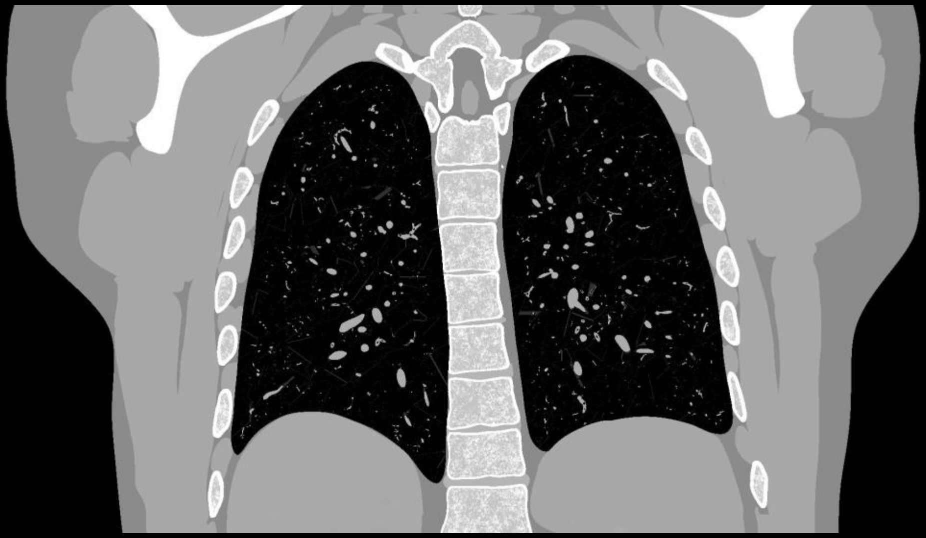
t = 5 sec

t = 0 sec

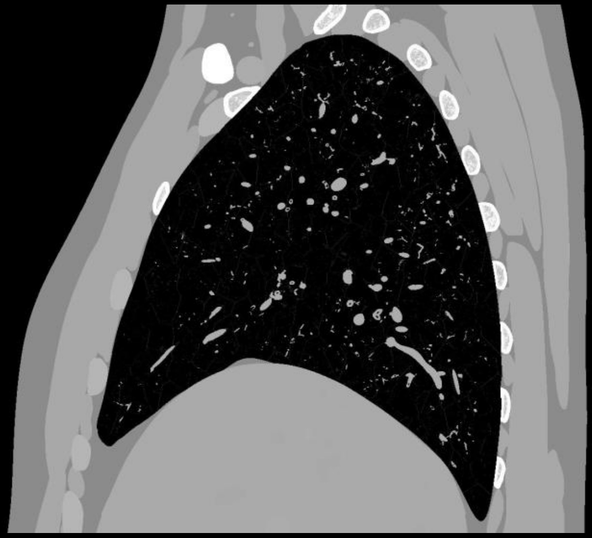
Axial



Coronal



Sagittal



Abadi et al., *JMI* 2020

X-ray detection: Photon-counting

Low imaging noise

Uniform energy response

Inherent spectral imaging

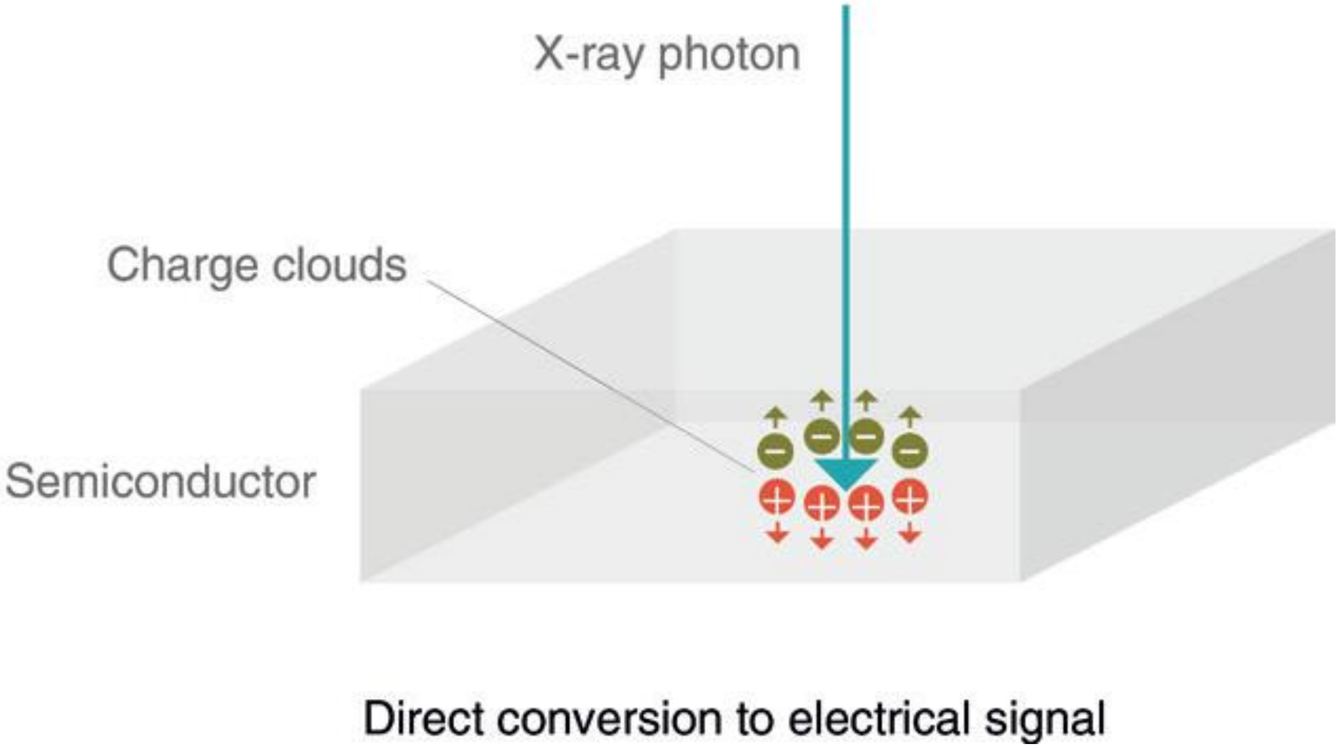
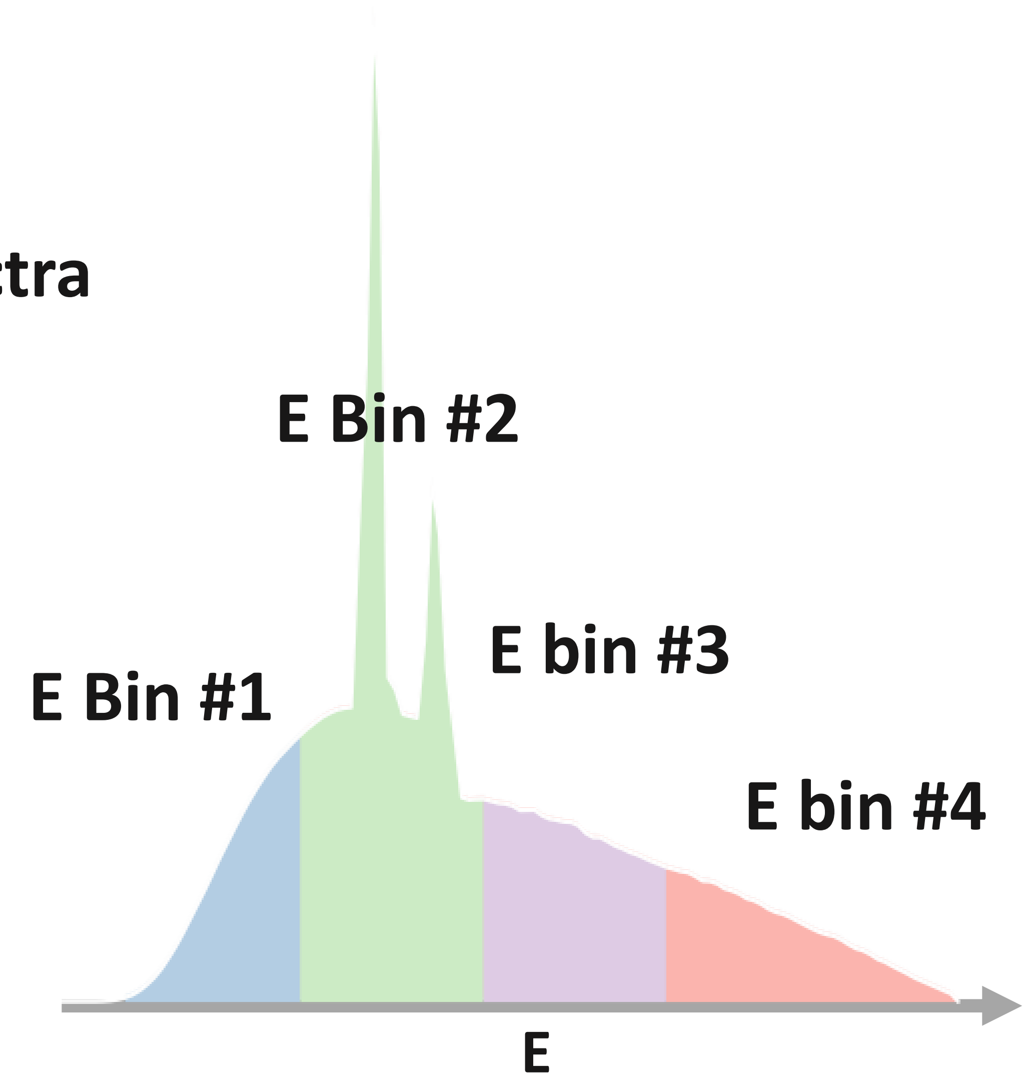


Image from Willemink et al, *Radiology* 2018

Inherent spectral separation

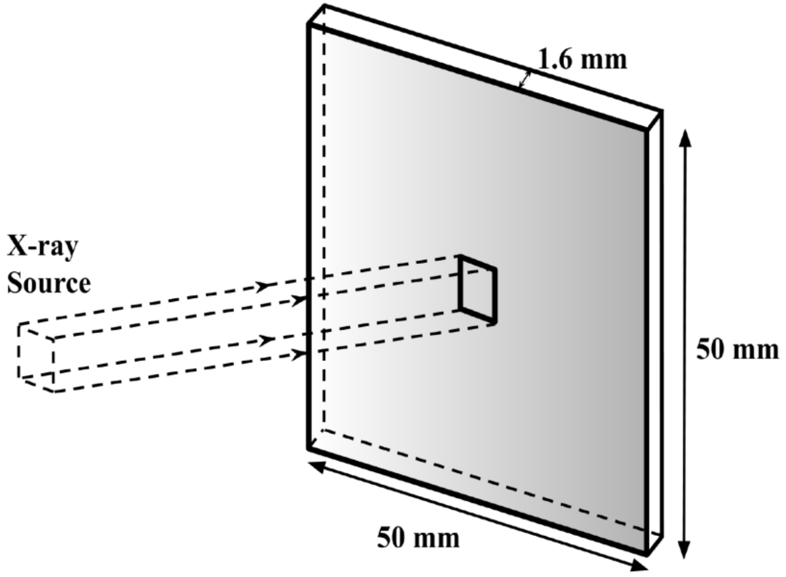
Polychromatic spectra from X-ray tube



Virtual photon-counting detectors

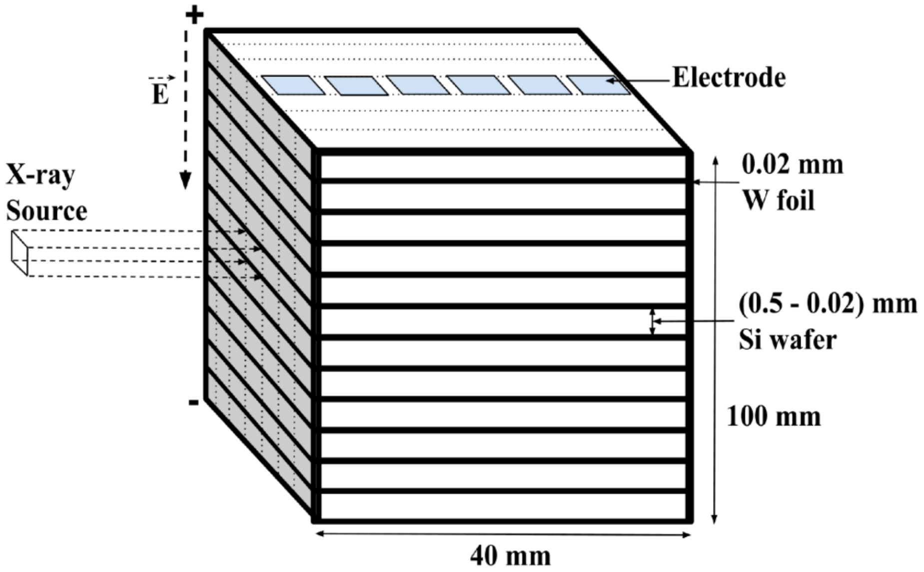
Face-on geometry

(high Z materials: CdTe, CdZnTe)



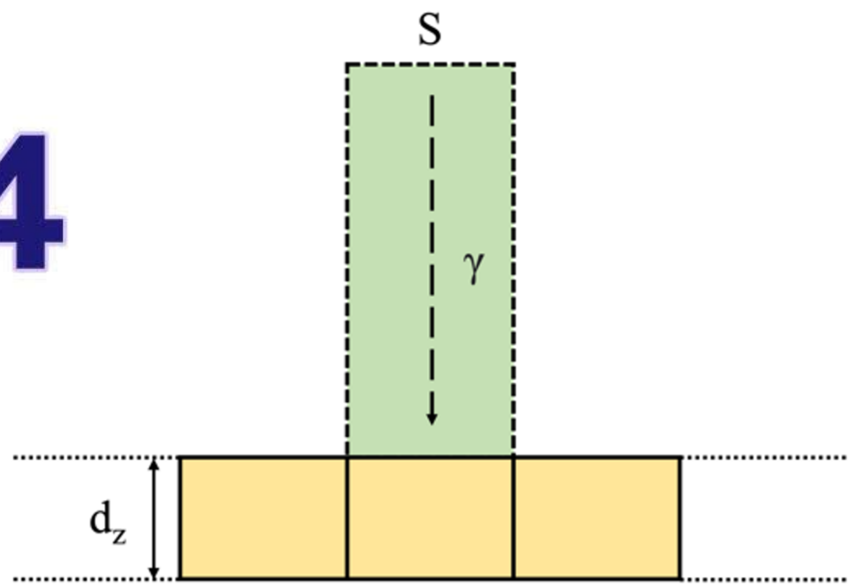
Edge-on geometry

(low Z materials: Si)



- Stochastic X-ray interaction with detector bulk
  - an array of 100x100 pixels
  - the Livermore physics list
  - range cutoff 10 µm for CdTe and 1 µm for Si
  - 100 000 histories (or events) per run

  - Energy and location of all interactions leading to energy depositions were saved in .txt file



Edep_keV	PositionX_	PositionY_mm	PositionZ_mm	DirectionX	DirectionY	DirectionZ	ParticleID	trackID	parentID	eventID	runID	processID
0.8093	-1.84707	-12.321	0.325	0	0	-1	0	1	0	274	0	1
0.75537	-1.84707	-12.321	0.305251	-0.227387	-0.383017	-0.895317	0	3	1	274	0	1
1.06706	-1.9216	-12.4465	0.0118099	-0.804098	-0.450616	-0.387779	-1	4	3	274	0	7
29.1733	-1.92188	-12.4467	0.01162	-0.583075	-0.677499	-0.44835	-1	4	3	274	0	6
1.195	-1.84707	-12.321	0.305252	-0.946756	0.260114	0.189719	-1	2	1	274	0	6
3.5354	-10.048	-5.83849	0.325	0	0	-1	0	1	0	346	0	1
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Modeling non-idealities

- Modeling statistical and electronic noise
- Photon-counting (PC) detectors suffer from **charge sharing** between pixels and **pulse pileup** within the pixel.

Charge sharing model

$$\sigma = \sqrt{2\frac{d_{iz}dkT}{eV} + \left(\frac{d_{iz}dNe}{10\pi\varepsilon V}\right)\frac{1}{\sqrt{5}\sigma_i} + \sigma_i{}^2}$$

Charge diffusion in the direction of electric field

Charge repulsion perpendicular to electric field

Initial charge cloud

Pulse pile-up model

True count rate

Probability of m-th order pulse pile-up

$$N_{PPE}(E) = a \times \frac{1}{1 + a\tau} \times \sum_{m=0}^{\infty} (a\tau)^m \frac{e^{-a\tau}}{m!} \times \Pr(E|m)$$

Approach from Taguchi et al, *Med Phys* 2010

Probability of photons being recorded

Validation – charge sharing

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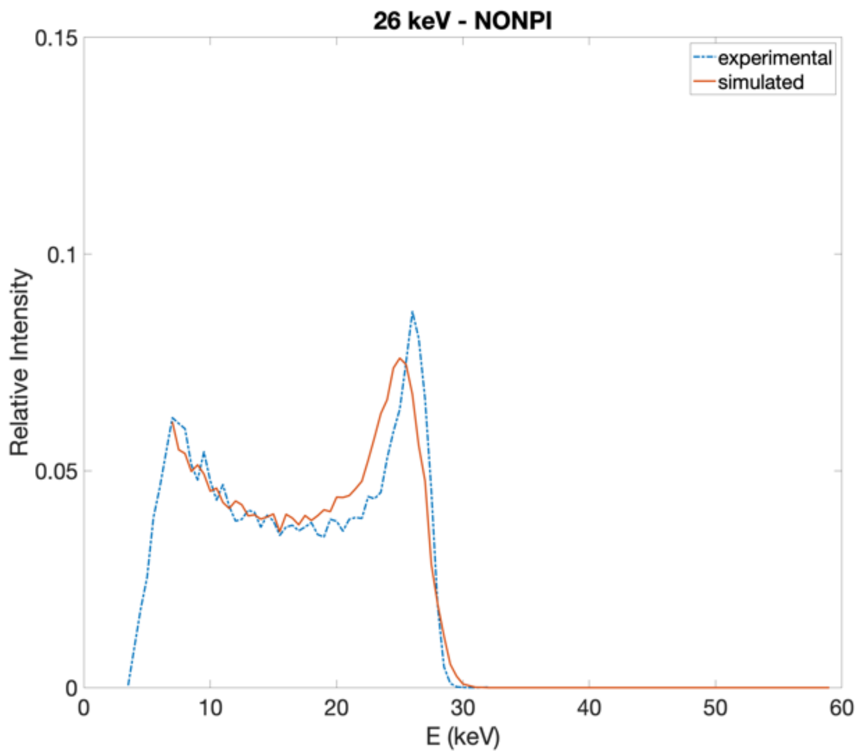
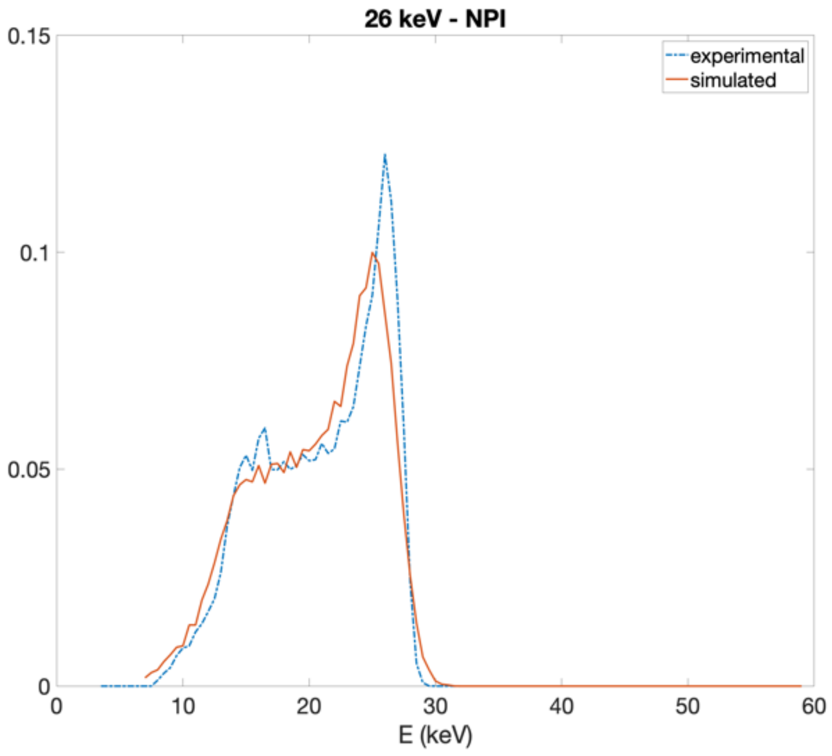
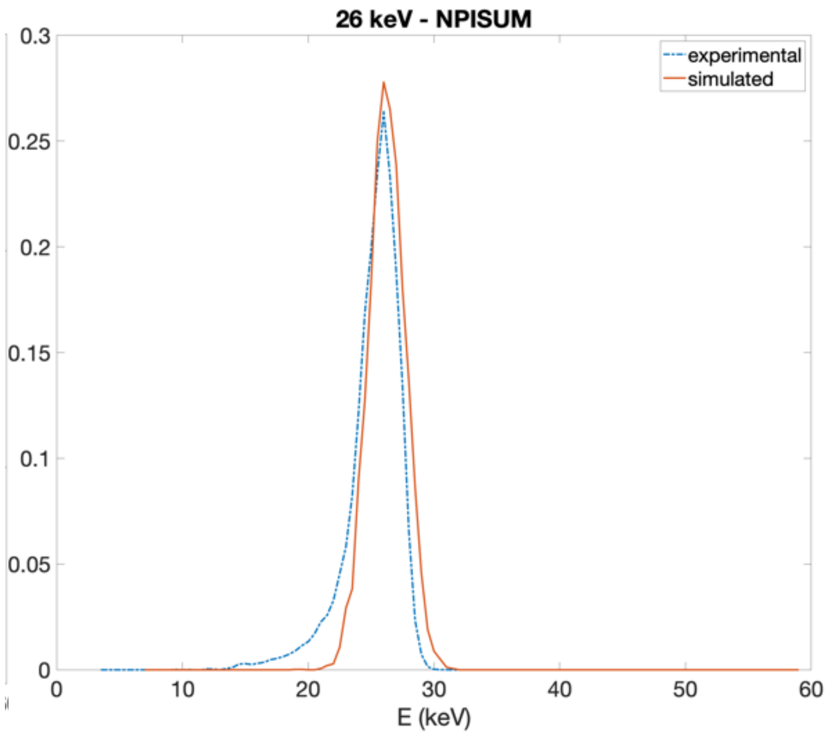
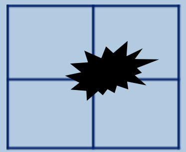
Charge sharing model was validated against experimental data obtained with monochromatic beam and CdTe PC detector in three different analog charge sharing (ACS) modes (62 x 62 x 650 μm).

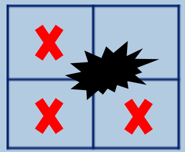




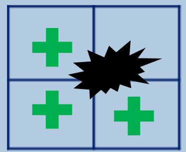




No ACS correction applied

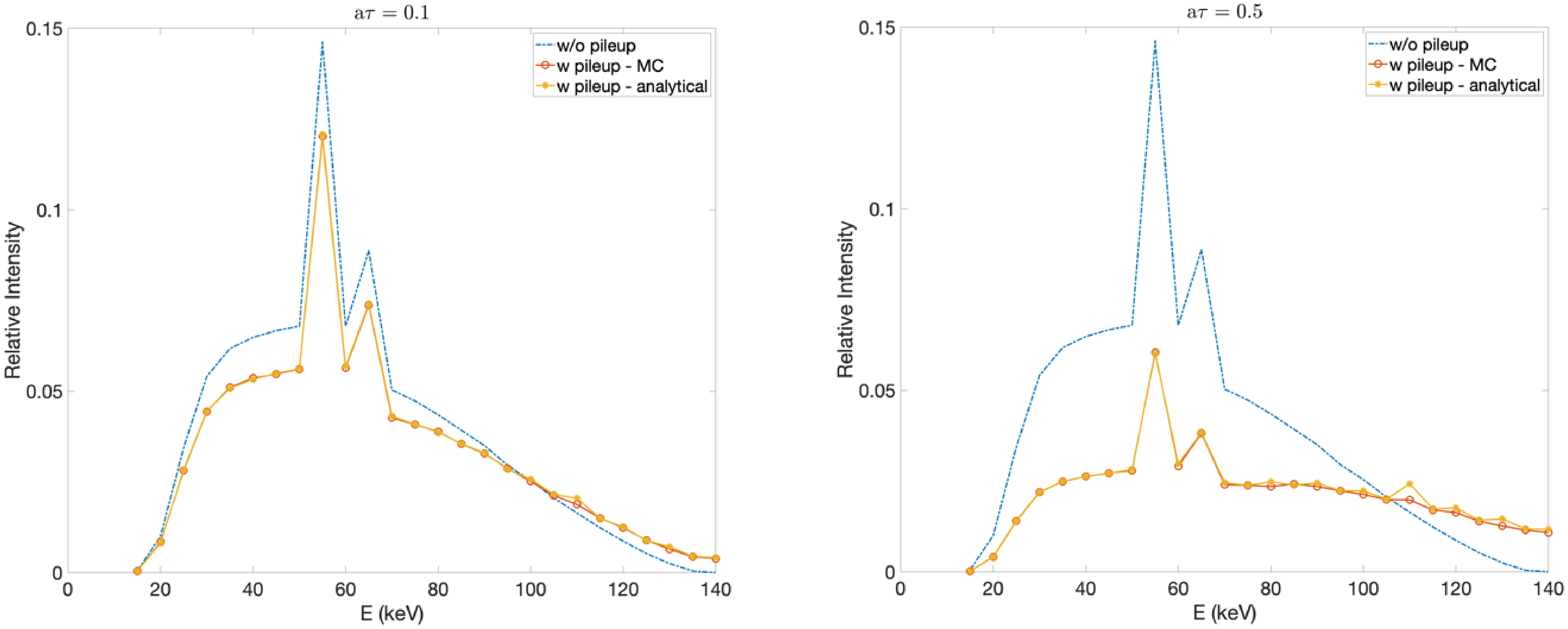


Neighbor Pixel Inhibit (NPI)
- removes multiple counts



Neighbor Pixel Inhibit and summing mode (NPISUM)
- recovers the charge spread

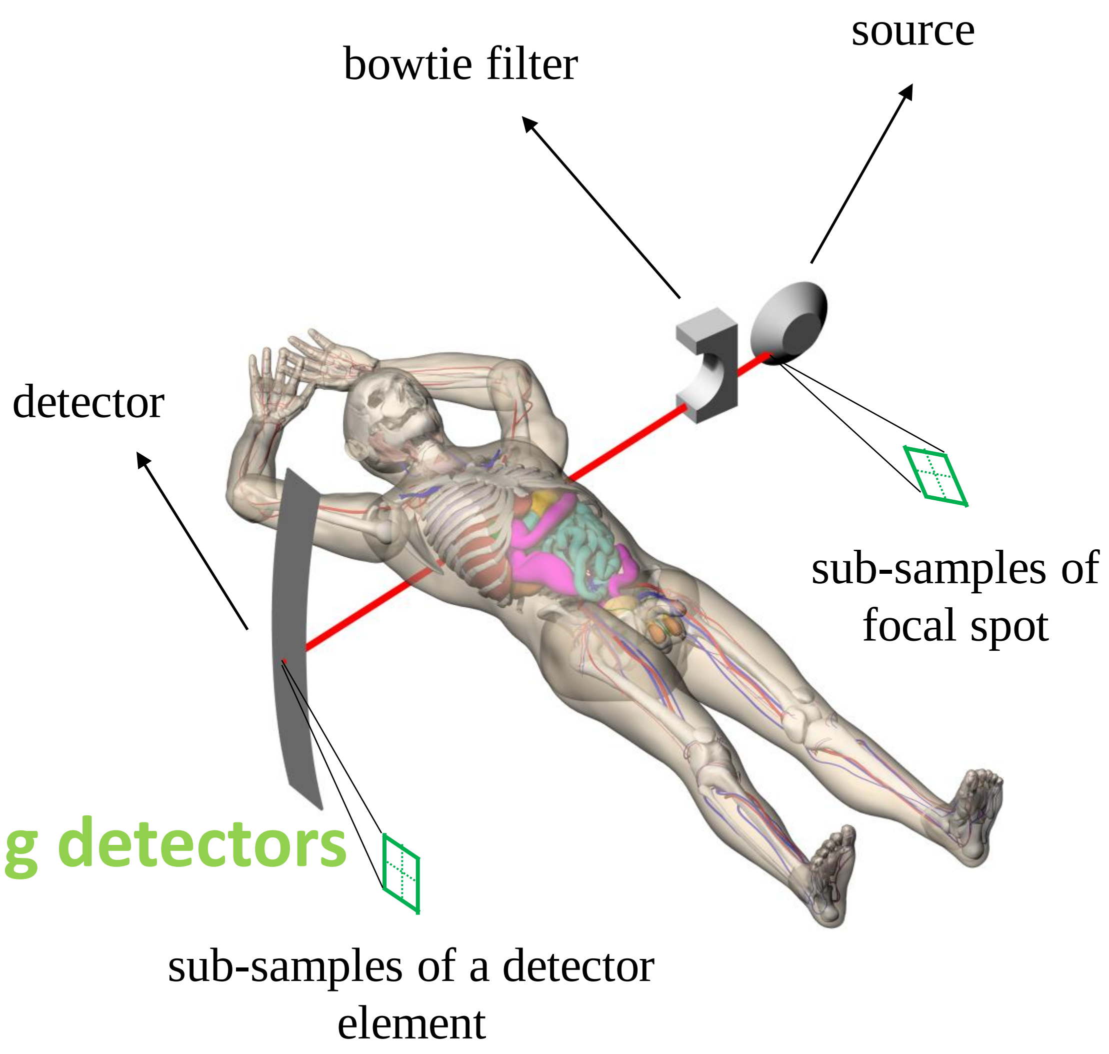
Validation – pulse pileup



Piled up photons registered as higher energy photon!

DukeSim: CT simulator

- **Scanner-specific or -generic**:
  geometry, spectrum, bowtie filter, detector
- **Hybrid**
  Ray-tracing and Monte Carlo modules
- **Tube current modulation**
- **Several tube voltage options**
- **Energy-integrating and photon-counting detectors**



XCAT: anthropomorphic chest phantom

Simulation output – CT scan

Primary signal | Primary + scatter signal | Primary + scatter signal + noise

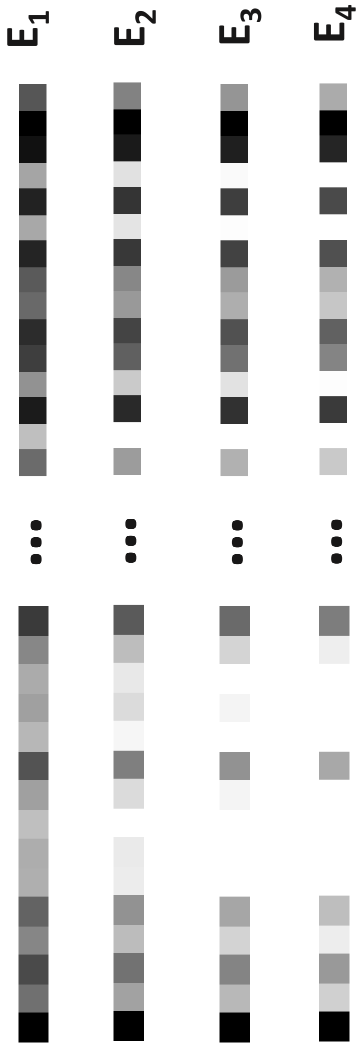
https://cvit.duke.edu/resource/dukesim-v1-1/

PART II

Machine learning in medical imaging - examples

Unsupervised model – SVD (PCA)

What is the main contribution to image formation?

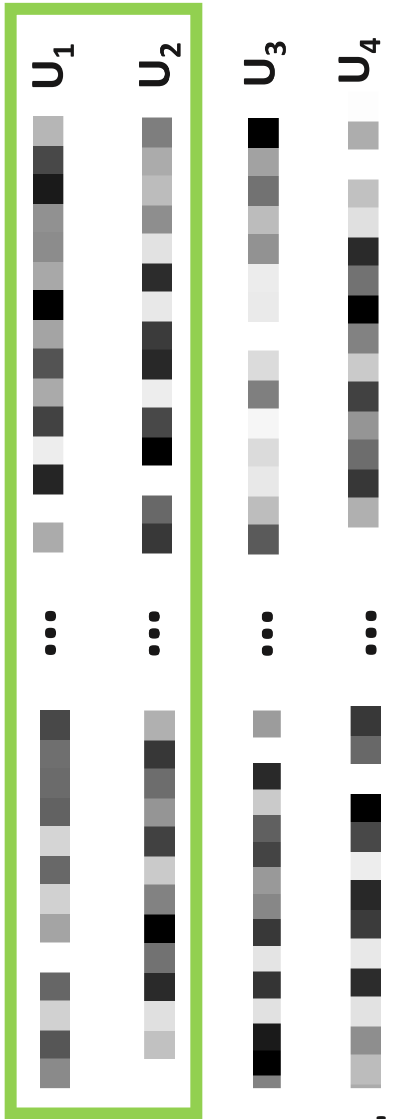


Spectral data

$$\mathrm{SVD}\,(\boxed{X}) = \boxed{U}\,\boxed{\Sigma}\,\boxed{V^*}$$

Singular values

Right singular vectors



Left singular vectors

Beyond traditional radiology: ρ and effective Z

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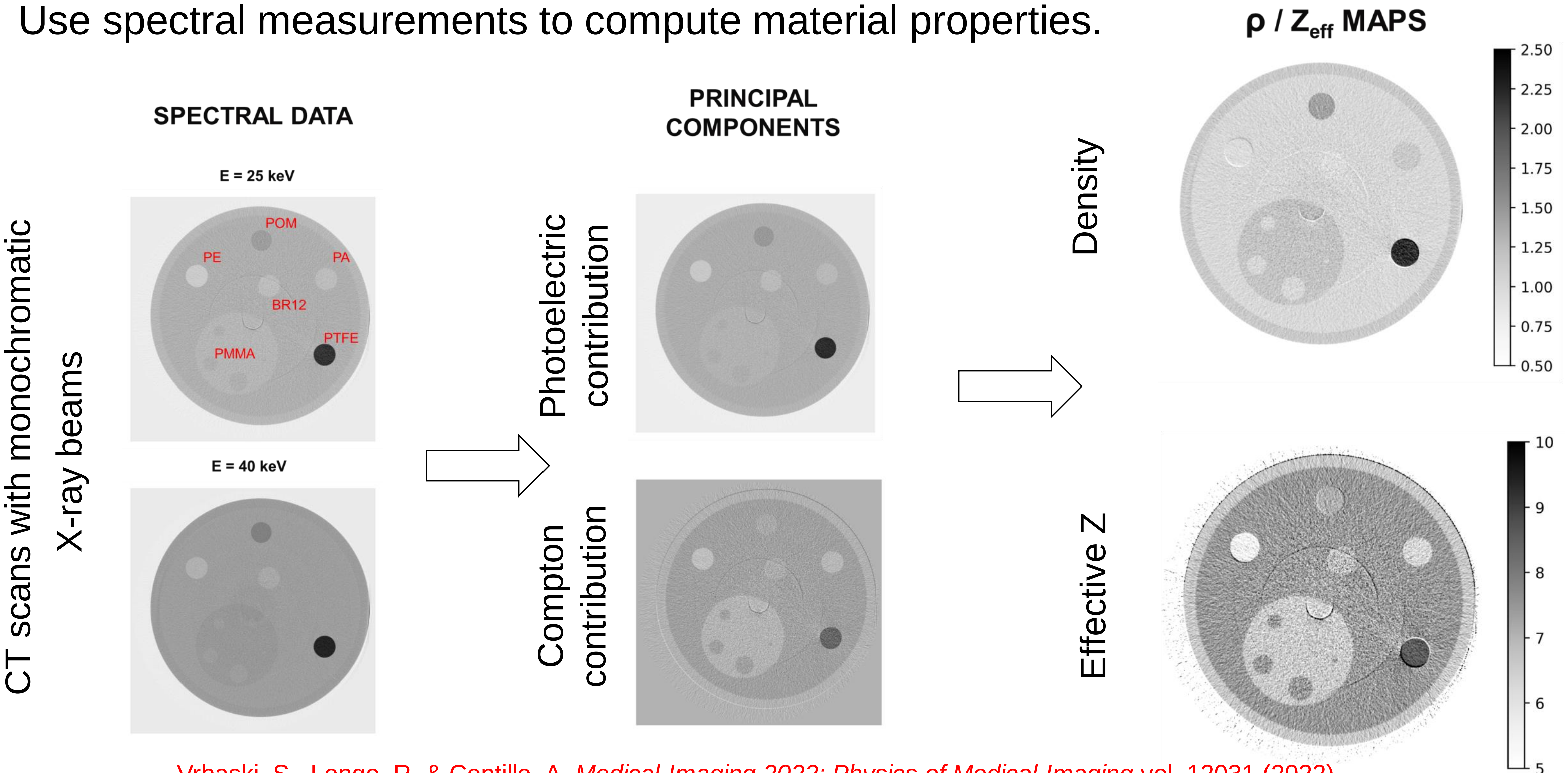
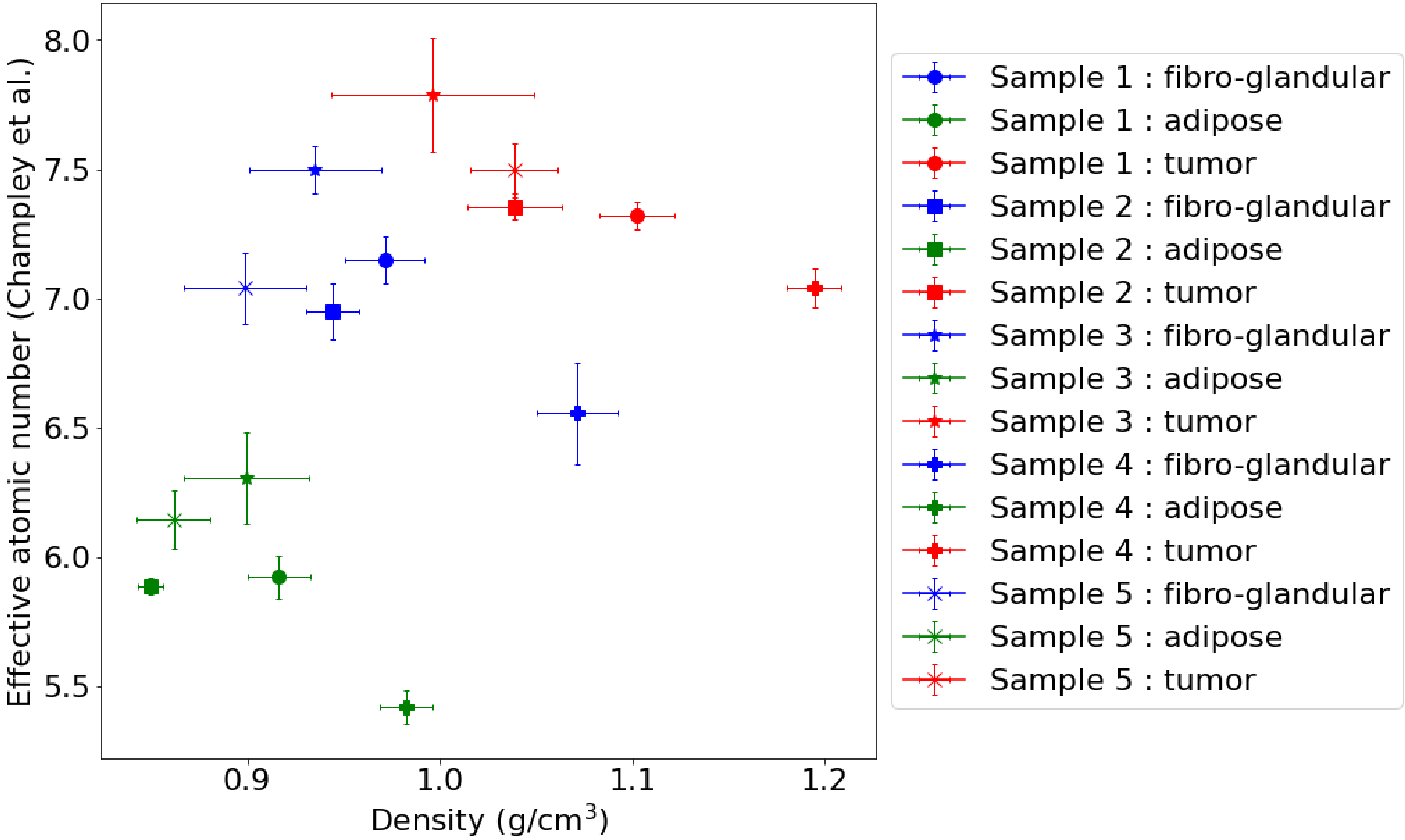
- Use spectral measurements to compute material properties.



Vrbaski, S., Longo, R. & Contillo, A. *Medical Imaging 2022: Physics of Medical Imaging* vol. 12031 (2022).

Why ρ/Zeff?

- Breast tissues can be better differentiated based on their density and effective Z, rather than using just gray levels.



Vrbaški, S. *et al. Phys. Med. Biol.* (2023) doi:10.1088/1361-6560/acdbb6.

Thank you!

Contact: stevan.vrbaski@phd.units.it