CT Images: What Do These Values Mean and How Can We Use Them?

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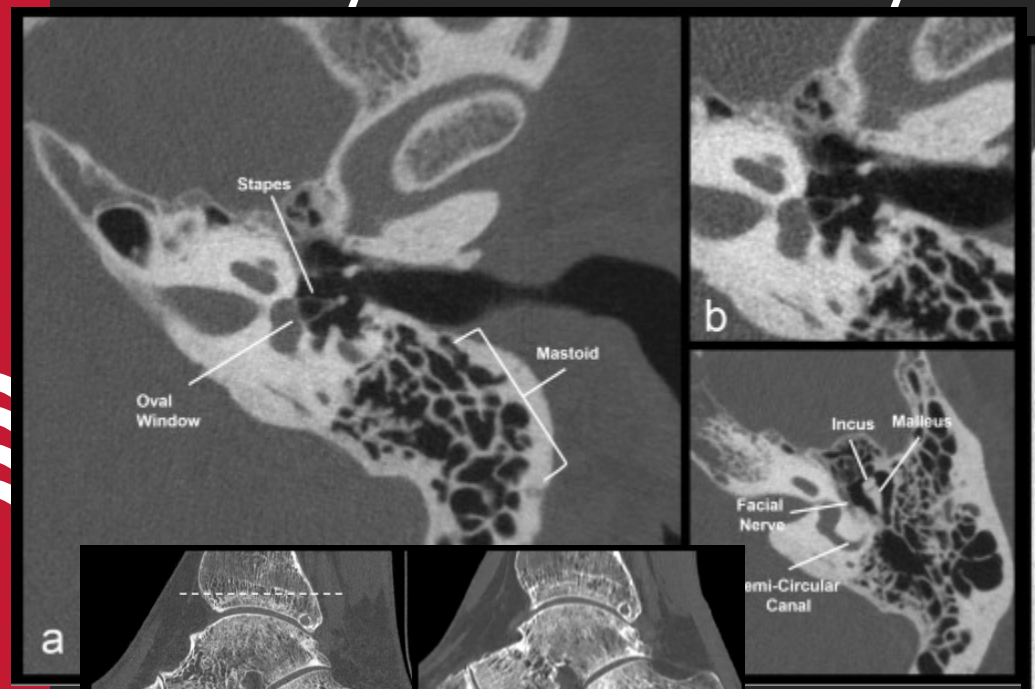
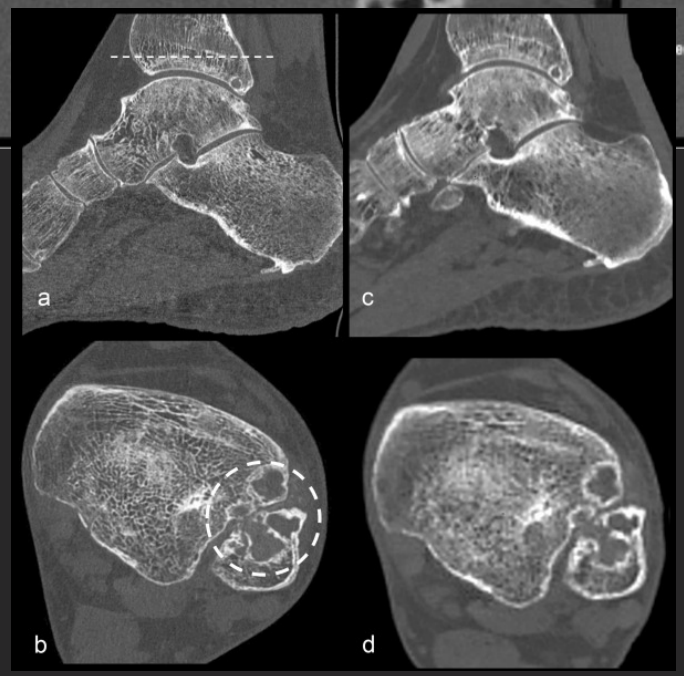
SCHOOL OF MEDICINE AND PUBLIC HEALTH

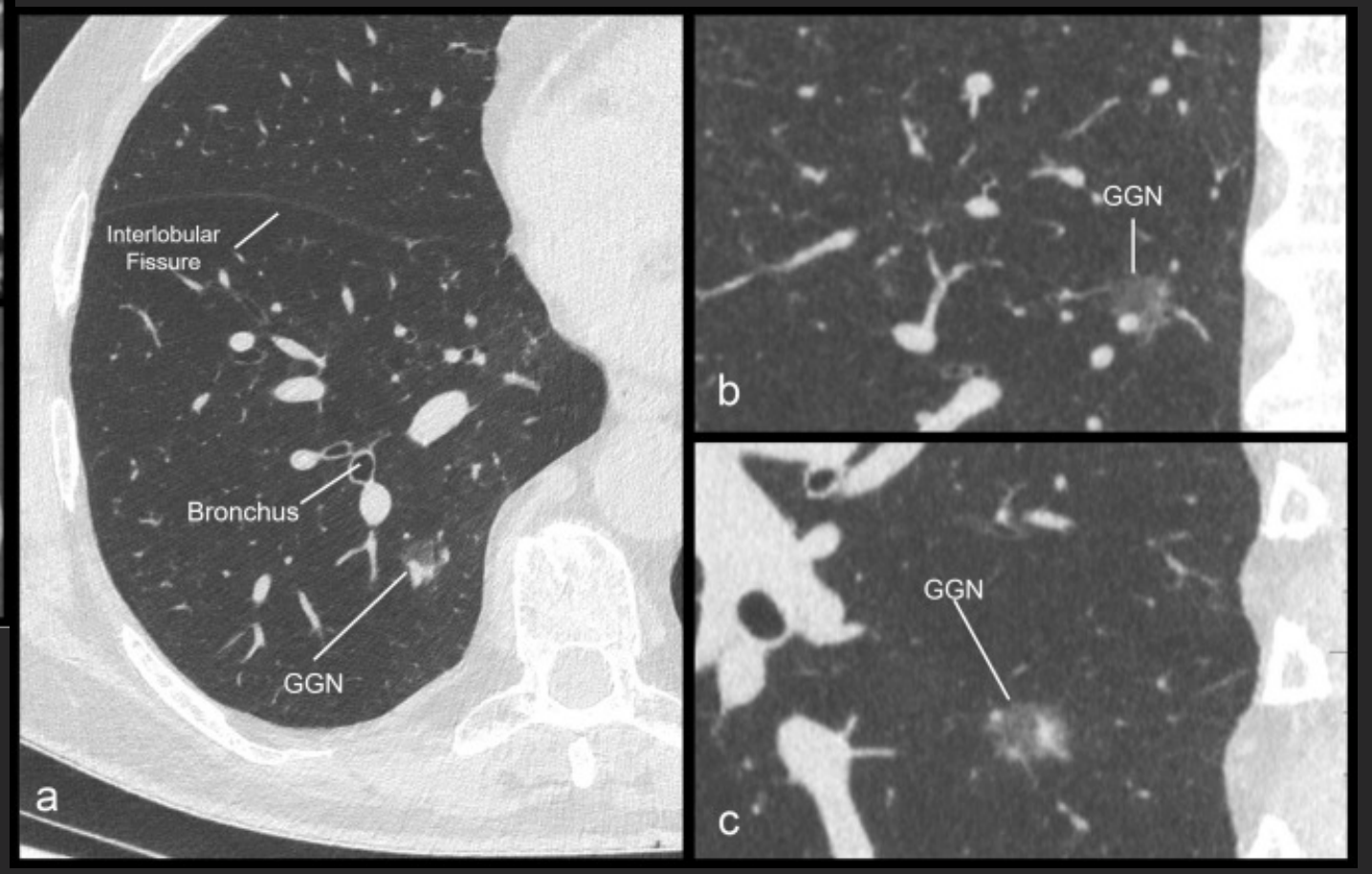
Overview

1. Motivation
2. CT numbers:
    1. What is linear attenuation?
    2. How are CT numbers affected by energy?
3. Spectral CT:
    1. How do we obtain spectral CT data?
    2. How do we use spectral CT data?
4. Issues with units:
    1. Beam hardening
    2. Issues with material quantification

- Why do we care beyond pretty pictures?

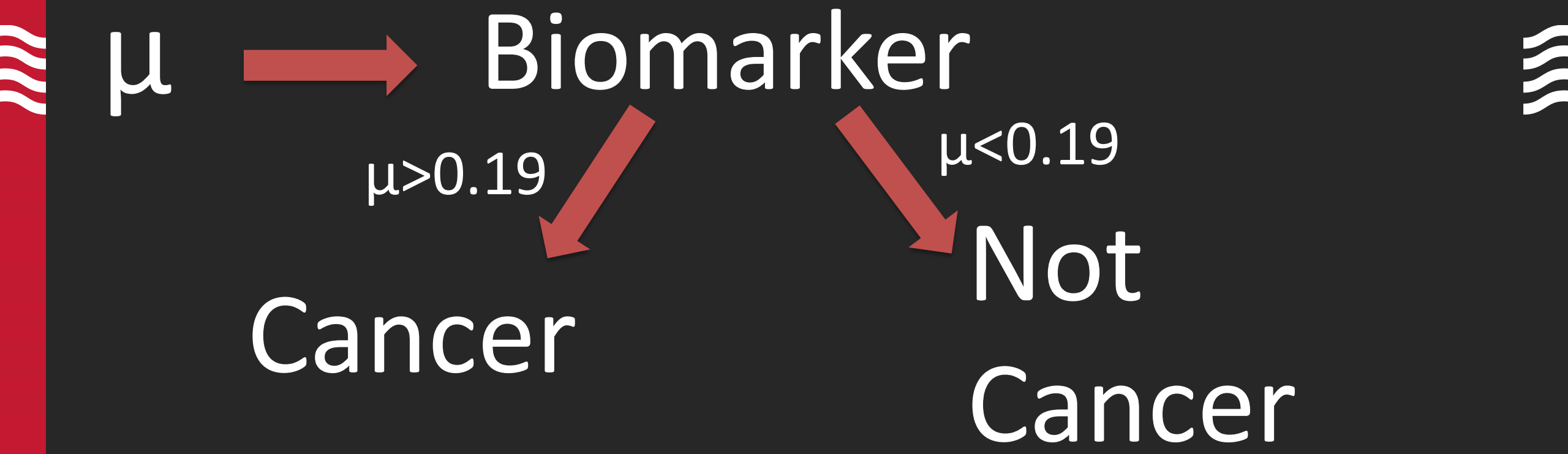


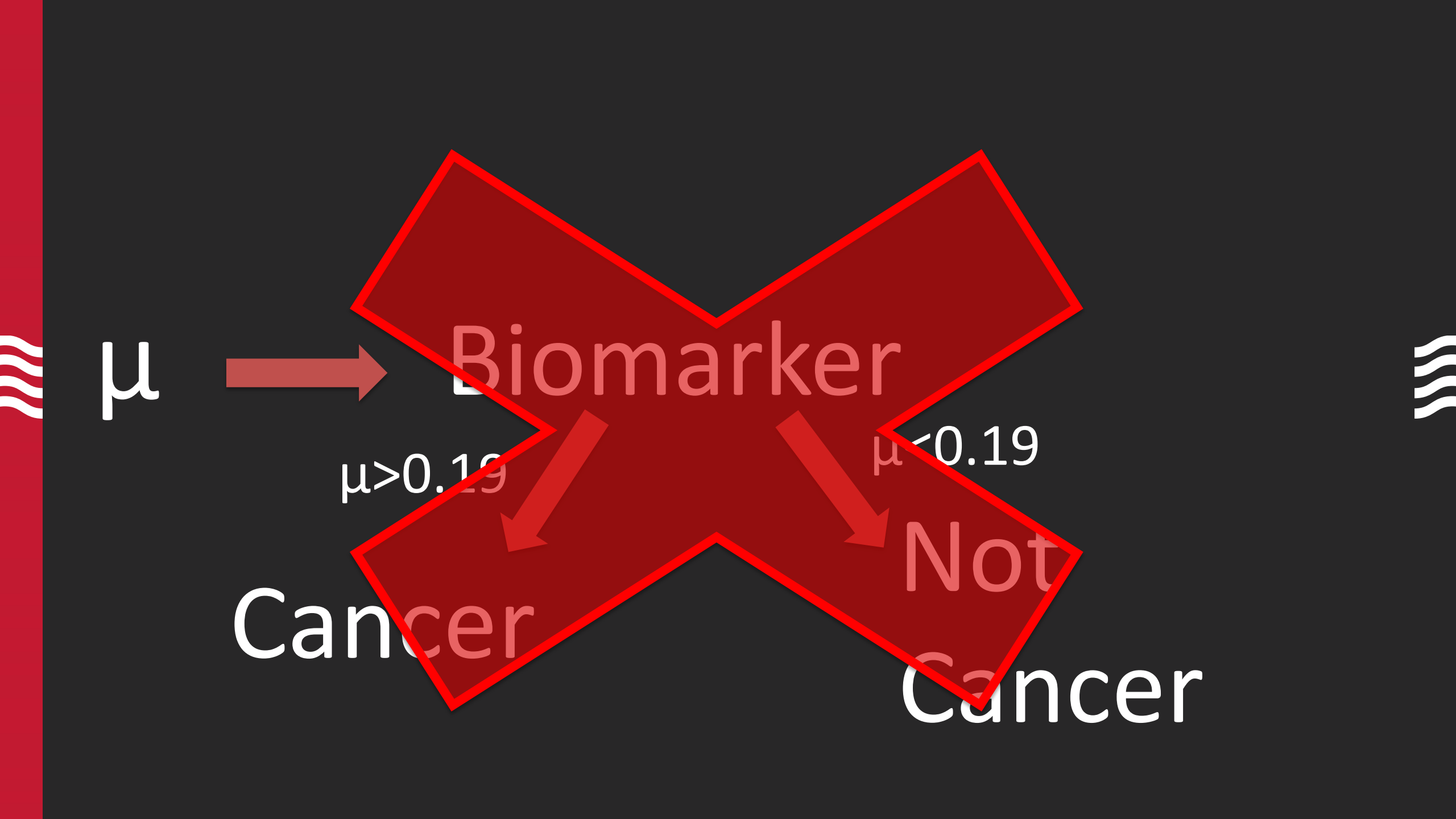




Almqvist H, Crotty D, Nyren S, Yu J, Arnberg-Sandor F, Brismar T, Tovatt C, Linder H, Dagotto J, Fredenberg E, Tamm MY. Initial clinical images from a second-generation prototype silicon-based photon-counting computed tomography system. Academic radiology. 2024 Feb 1;31(2):572-81.

- Want to answer questions about what we're looking at:
  - Is this cancer?
  - Is this a new brain bleed or an old one?
  - How old is this bone break?
  - Does this person have osteoporosis?
  - What is this kidney stone made of?
  - Is that a coronary plaque or iodine contrast?
  - What grade of NAFLD is this liver?
- Need CT-based biomarkers
  - Based on image values


μ
Biomarker
μ>0.19
μ<0.19
Cancer
Not Cancer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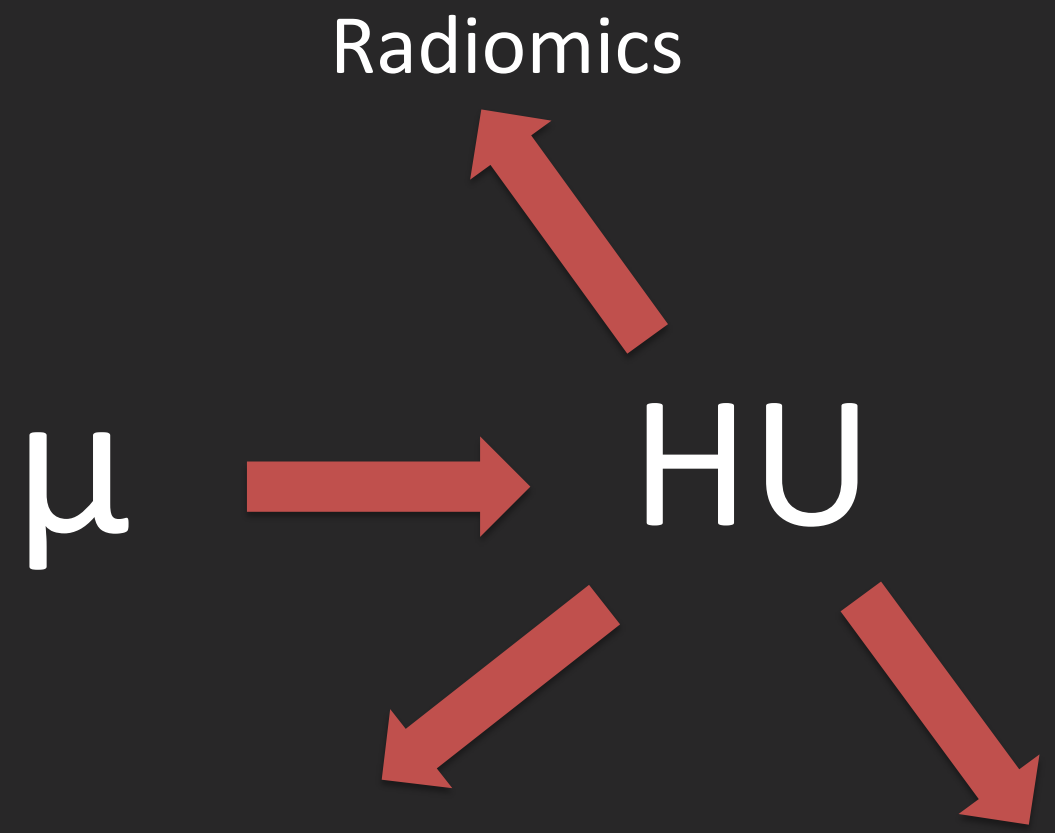


Look up tables:

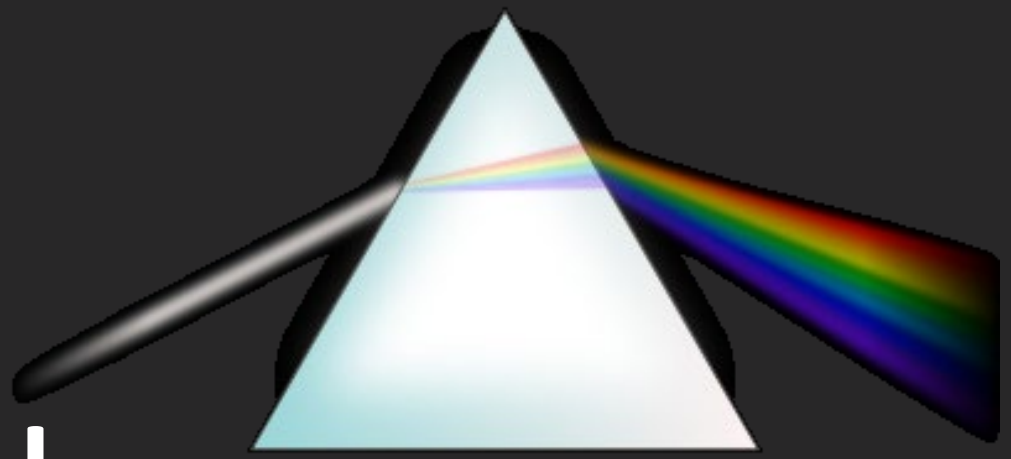
- Bone mineral density
- Nodule classification
- Calcium score
- Stopping power ratios

Time resolved measurements:

- Cerebral blood flow
- Cerebral blood volume
- Mean transit time

Radiomics

μ → HU



Spectral enabled "measurands"

- Virtual Monoenergetic Images
- Material Density
- Effective Atomic Number
- Electron Density
- Material suppression

Look up tables:

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- Nodule classification
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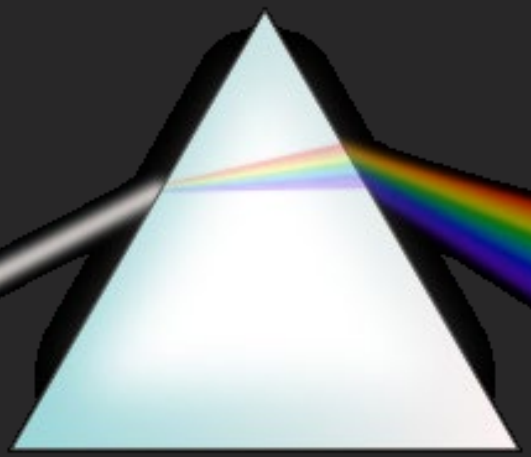
μ

HU



Spectral enabled "measurands"

Virtual Monoenergetic Images

Material Density

Effective Atomic Number

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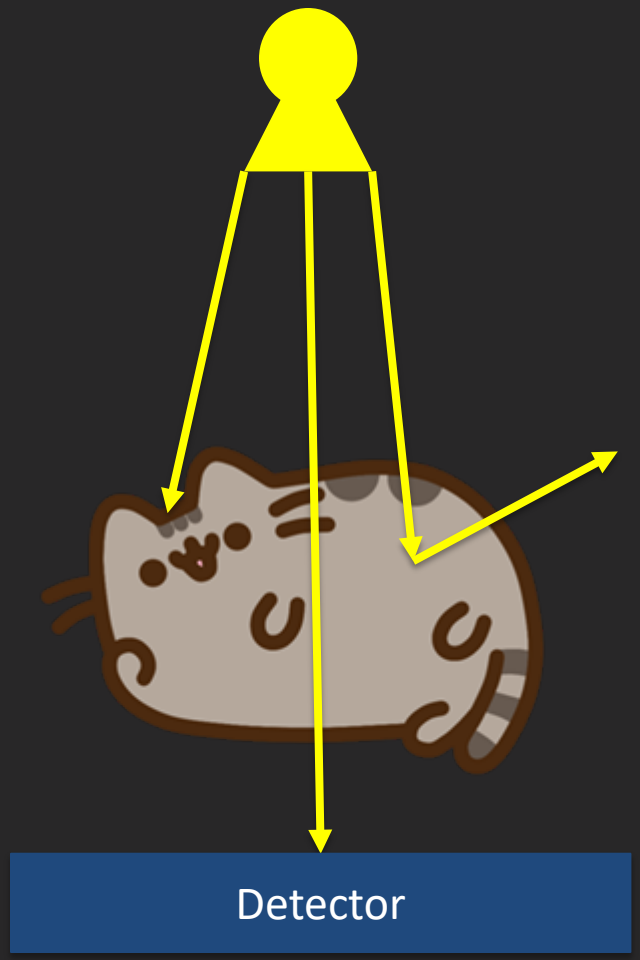
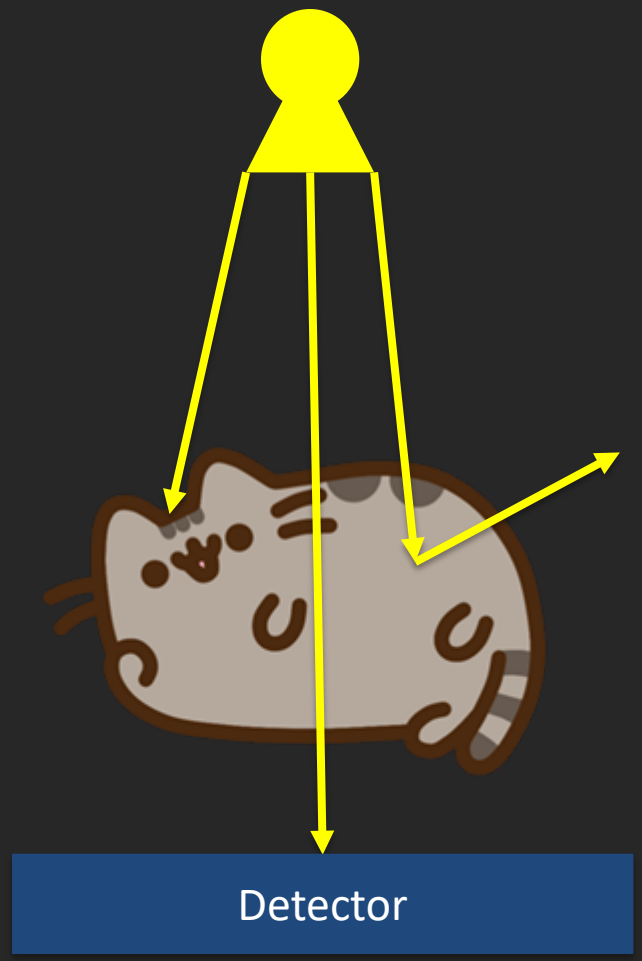
CT Numbers

Basics of CT Numbers





What we put in

Patient thickness

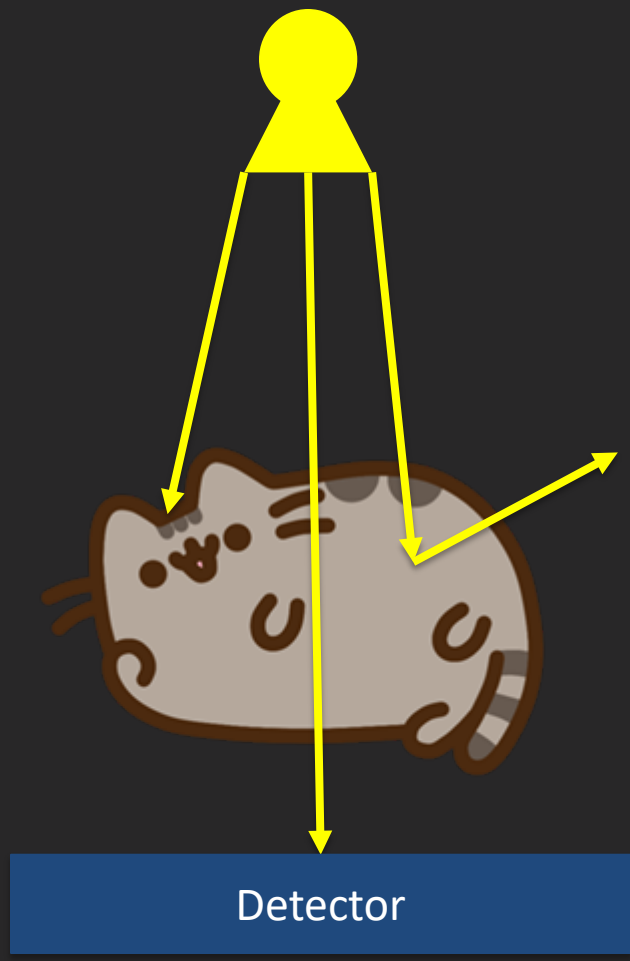
$$I = I_o e^{-\mu \cdot t}$$

What we get out

Attenuation coefficient

Beer-Lambert Law

Basics of CT Numbers



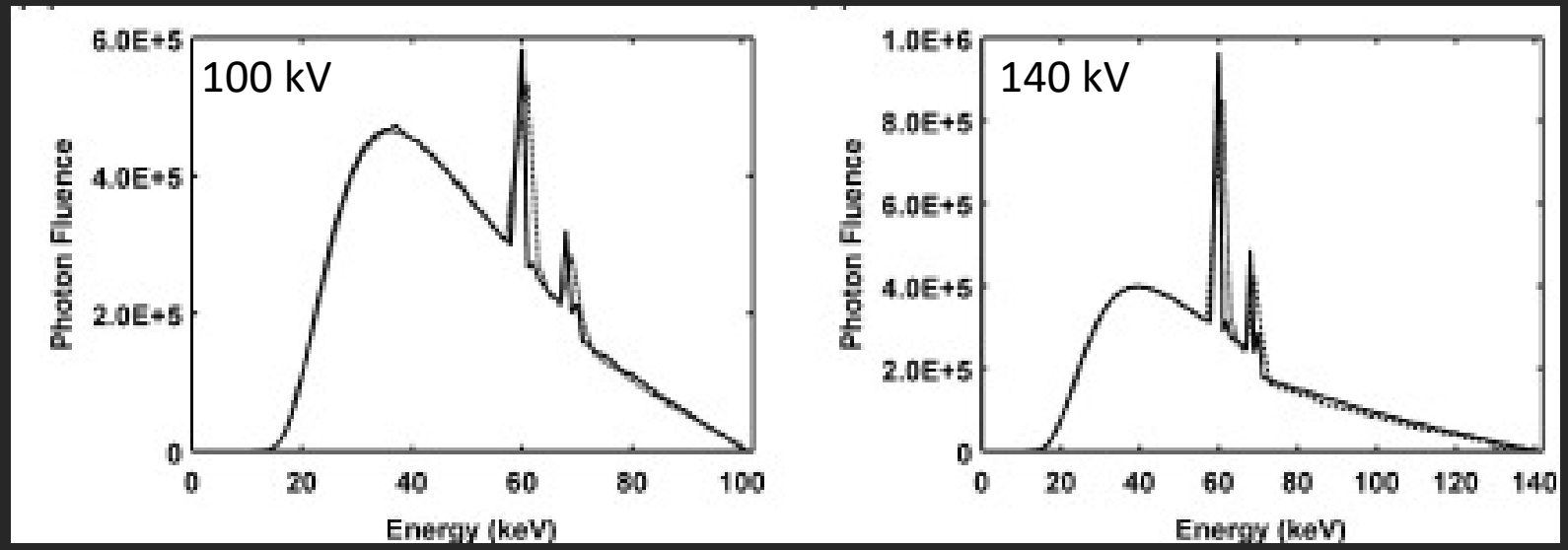
Attenuation coefficient of patient's tissues

$$CT_{\#} = \frac{\mu_{tissue} - \mu_{water}}{\mu_{water}} \cdot 1000$$

Attenuation coefficient of water

- CT uses tube voltages between 80-140 kV
  - X-rays produced with max energy = tube current

$$E_{eff} = \frac{1}{2}E_{max} \text{ or } E_{eff} = \frac{2}{3}E_{max}$$



Hernandez AM, Boone JM. Tungsten anode spectral model using interpolating cubic splines: unfiltered x-ray spectra from 20 kV to 640 kV. Med Phys. 2014 Apr;41(4):042101. doi: 10.1118/1.4866216. PMID: 24694149; PMCID: PMC3985923.

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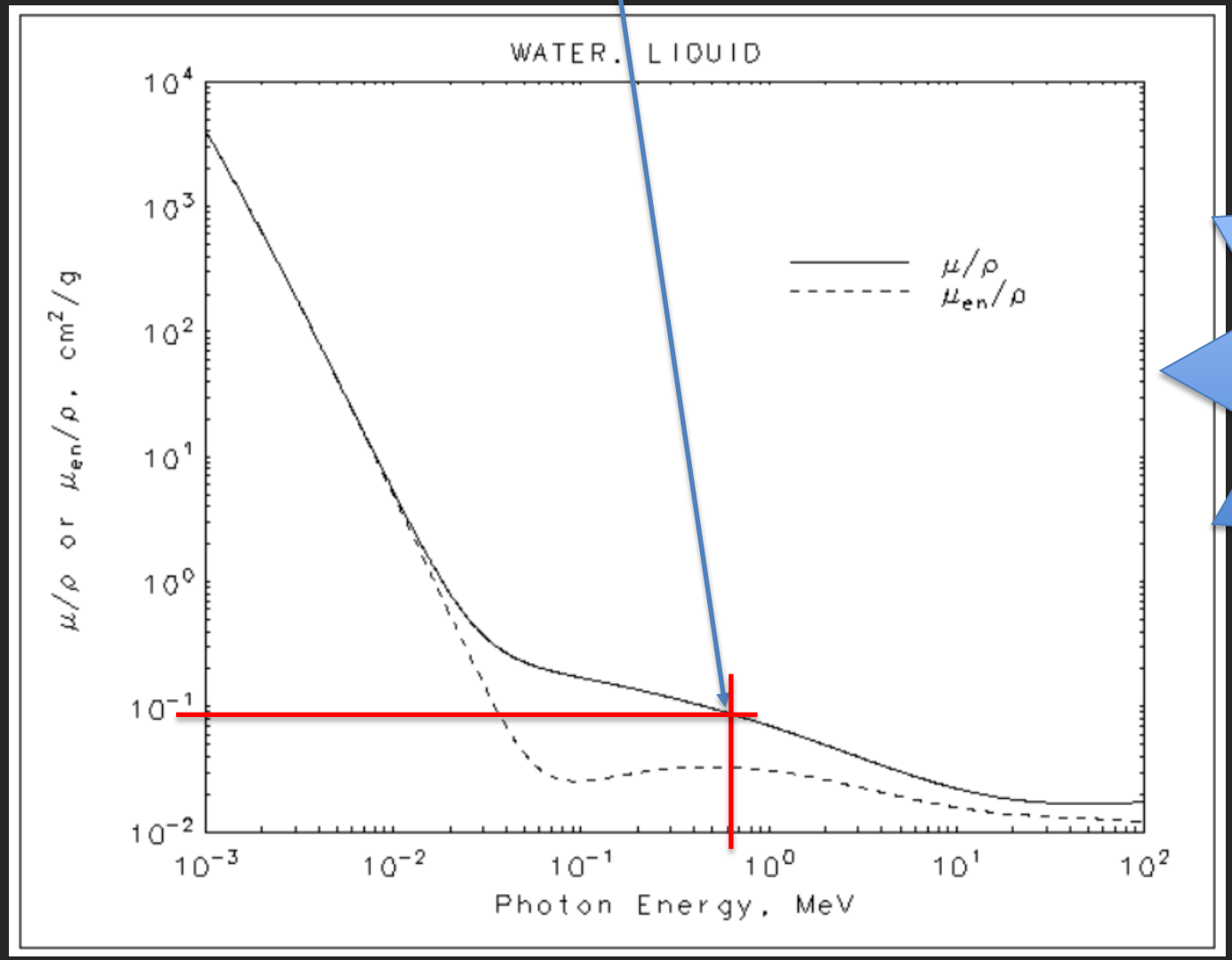
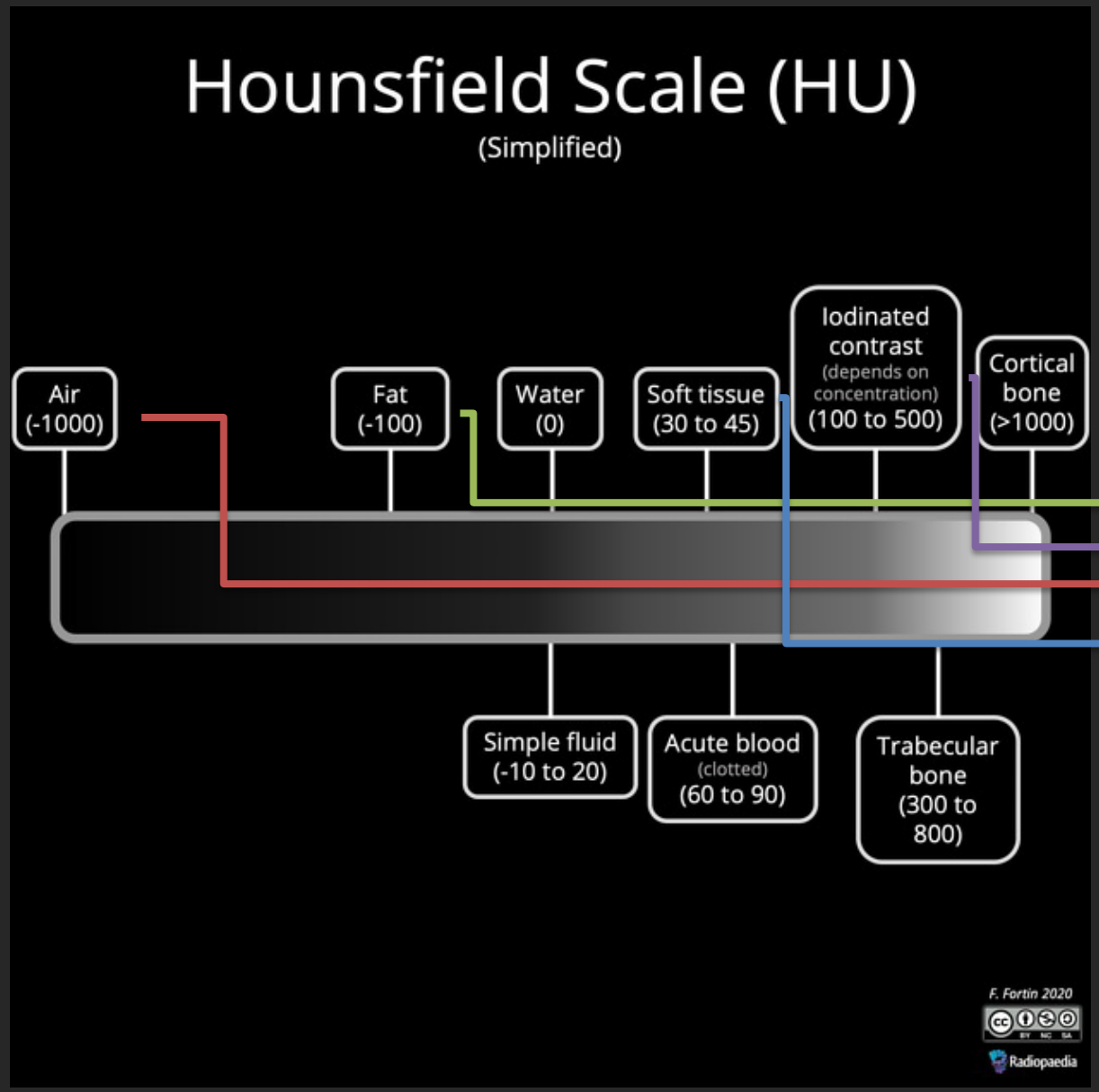
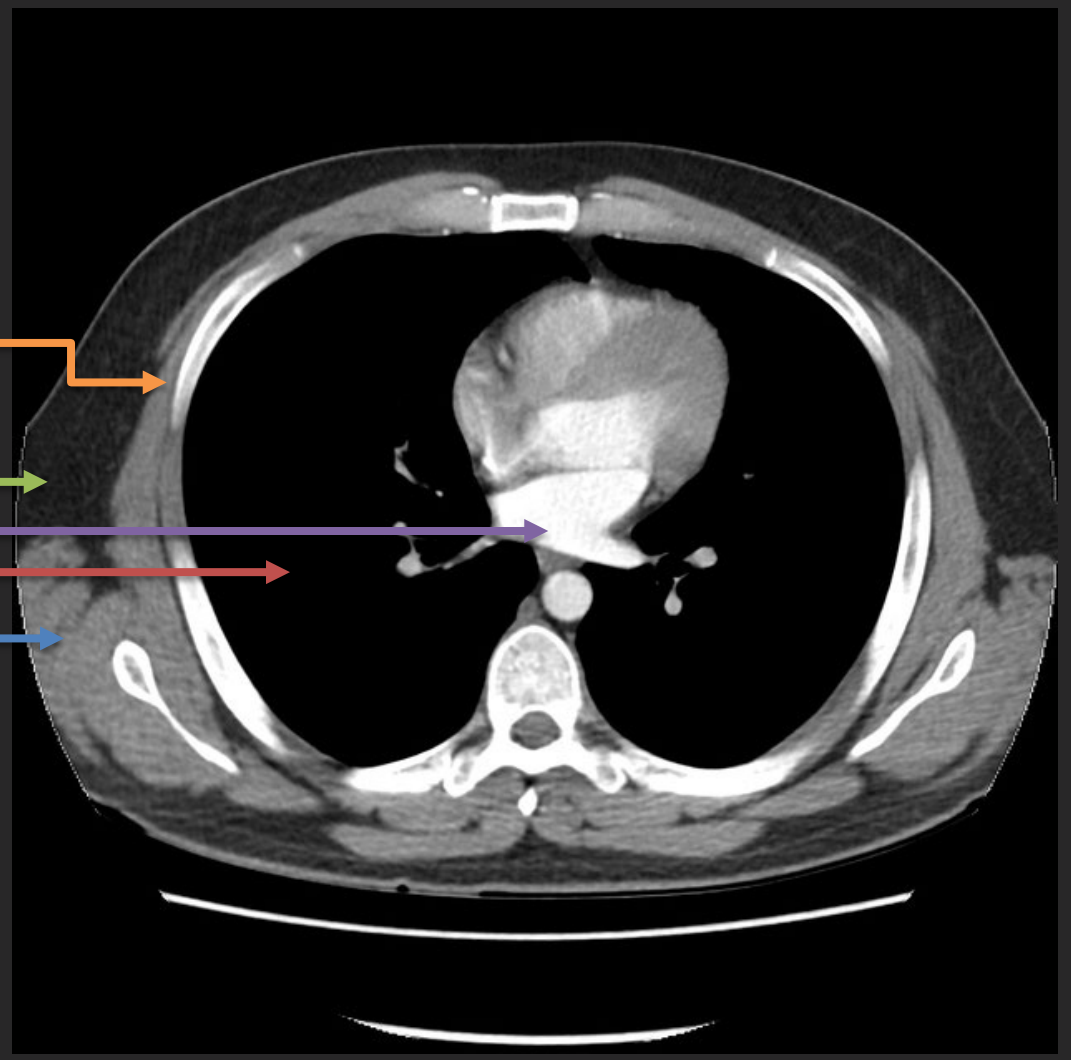


Change Energy spectrum → Change CT Number

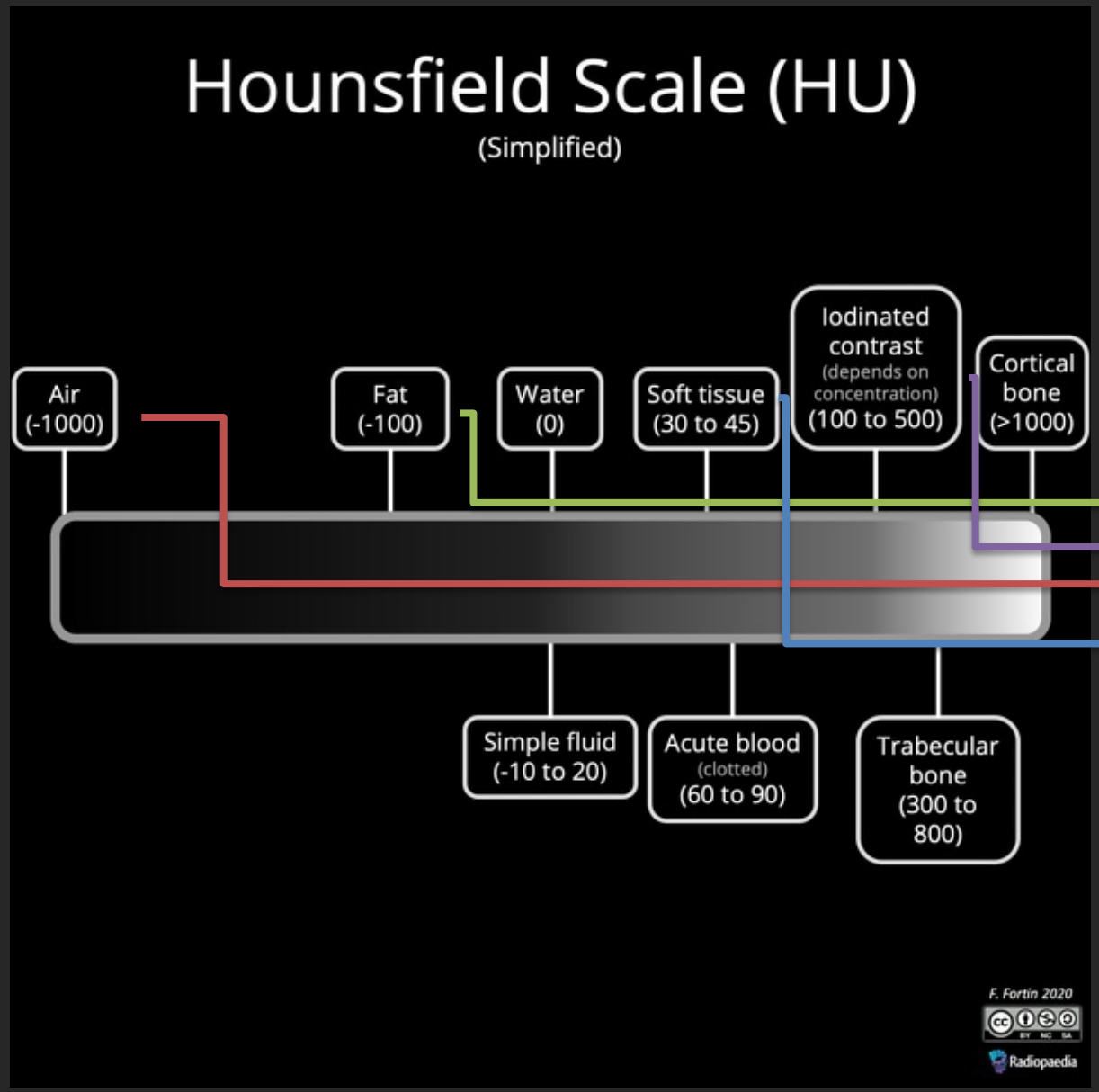
Berger MJ, Hubbell JH, Seltzer SM, Chang J, Coursey JS, Sukumar R, Zucker DS, Olsen K. XCOM: Photon Cross Sections Database. NIST Standard Reference Database 8 (XGAM). 1998

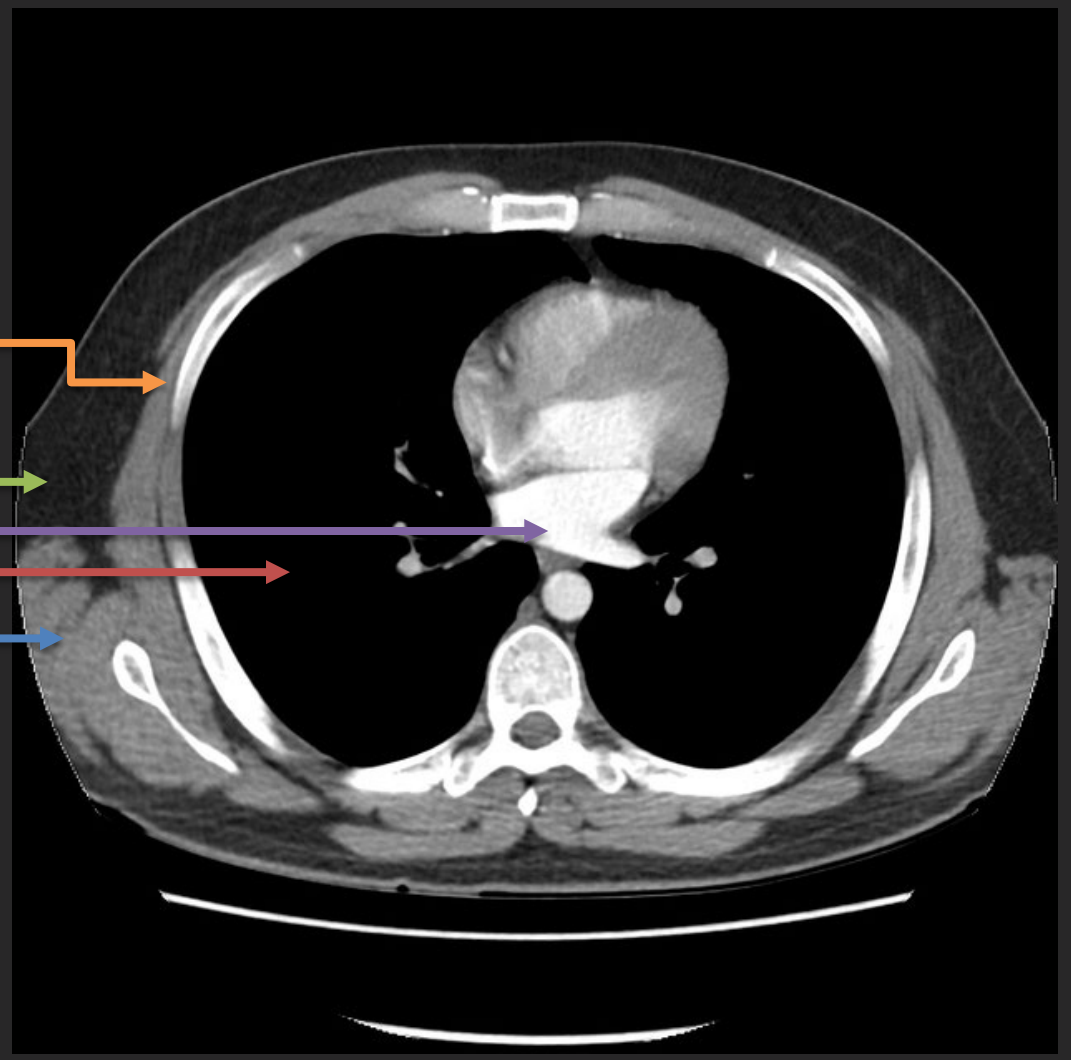
CT Numbers in Use



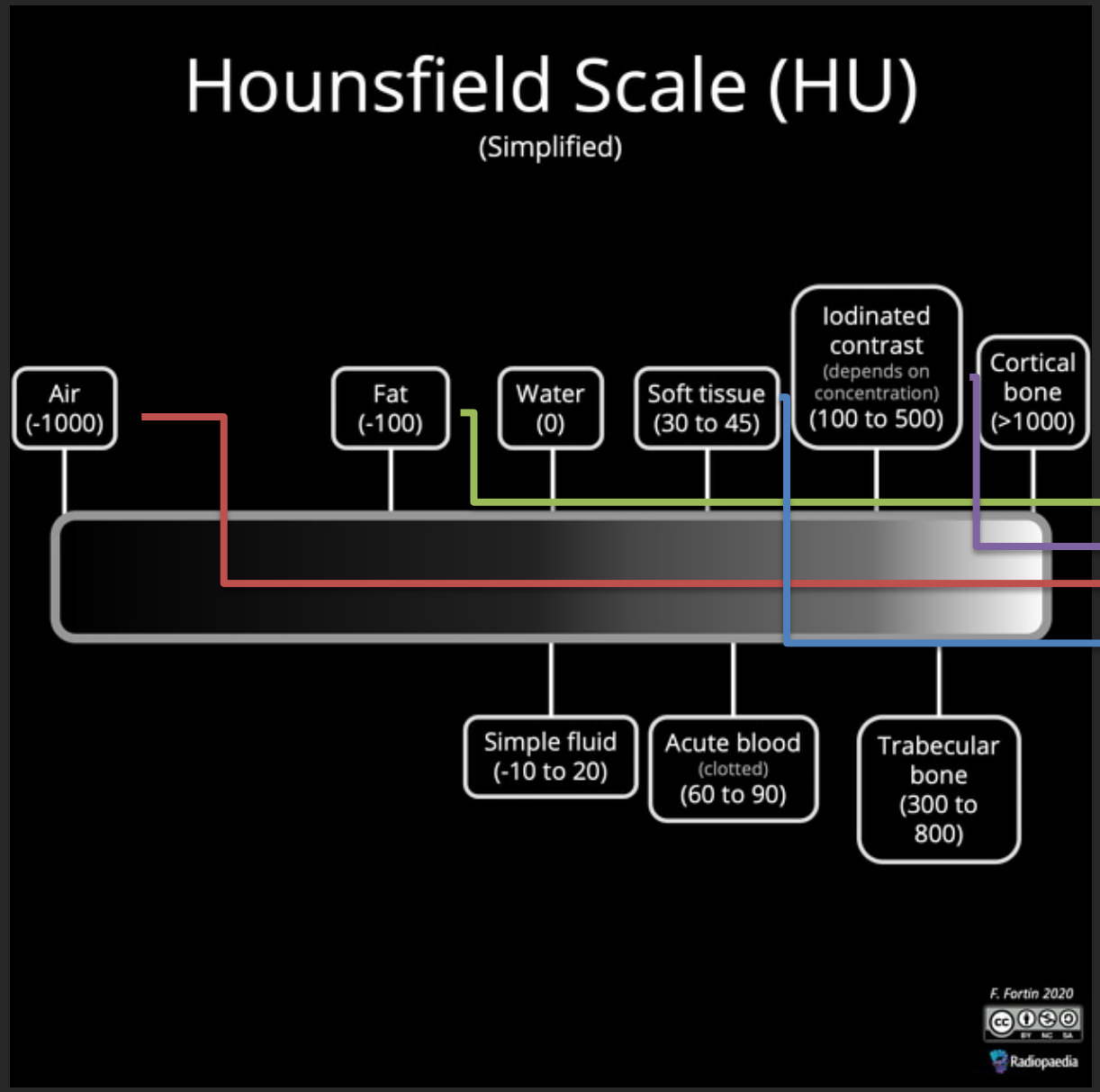


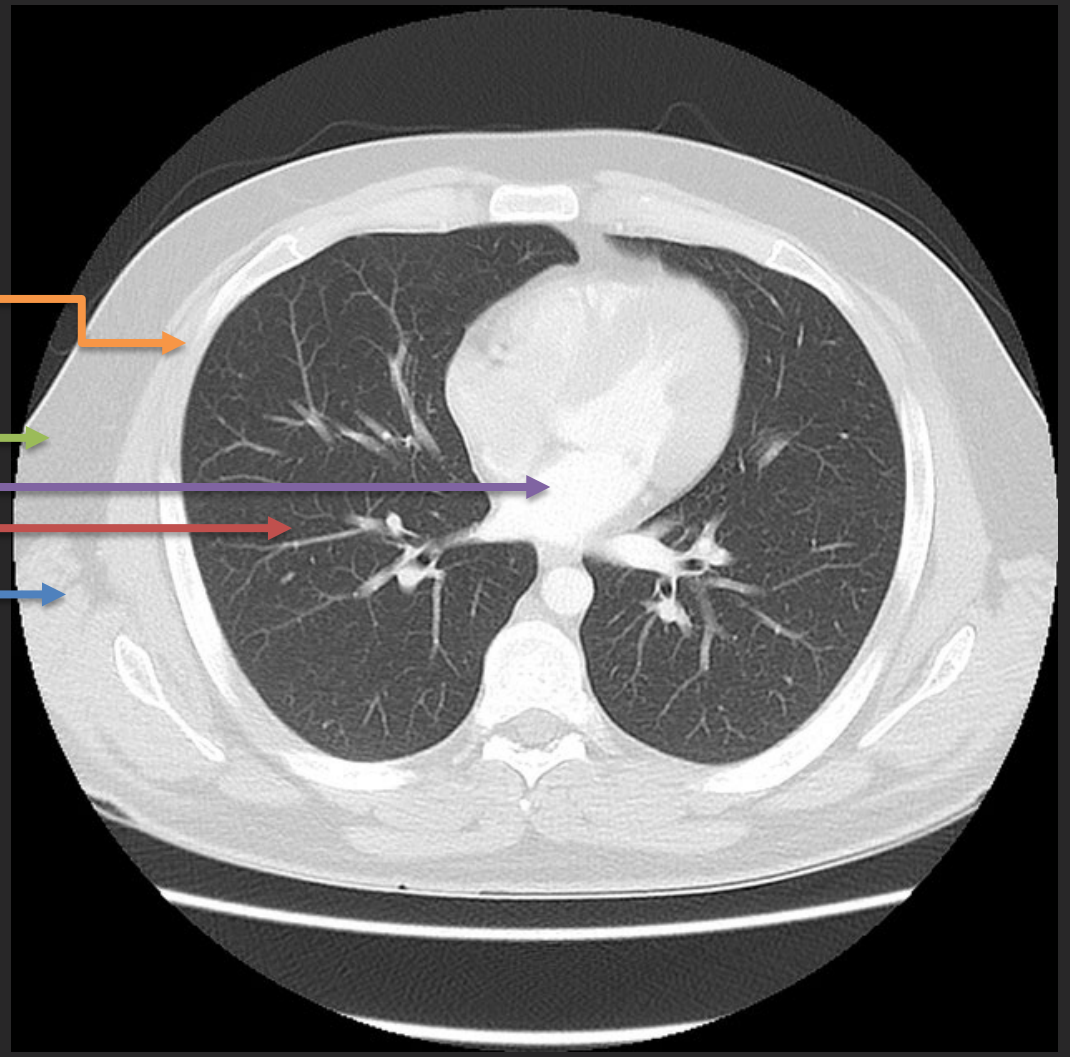
CT Numbers in Use





CT Numbers in Use





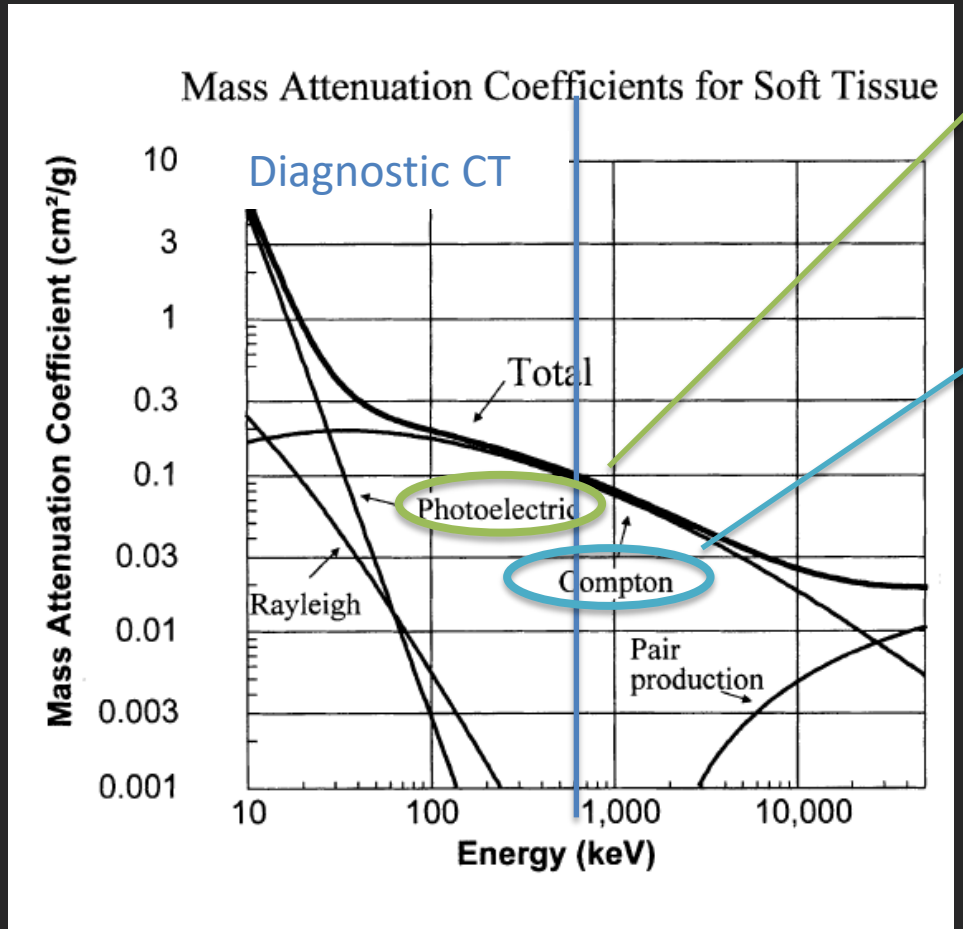
Spectral Data

What is spectral imaging in CT?

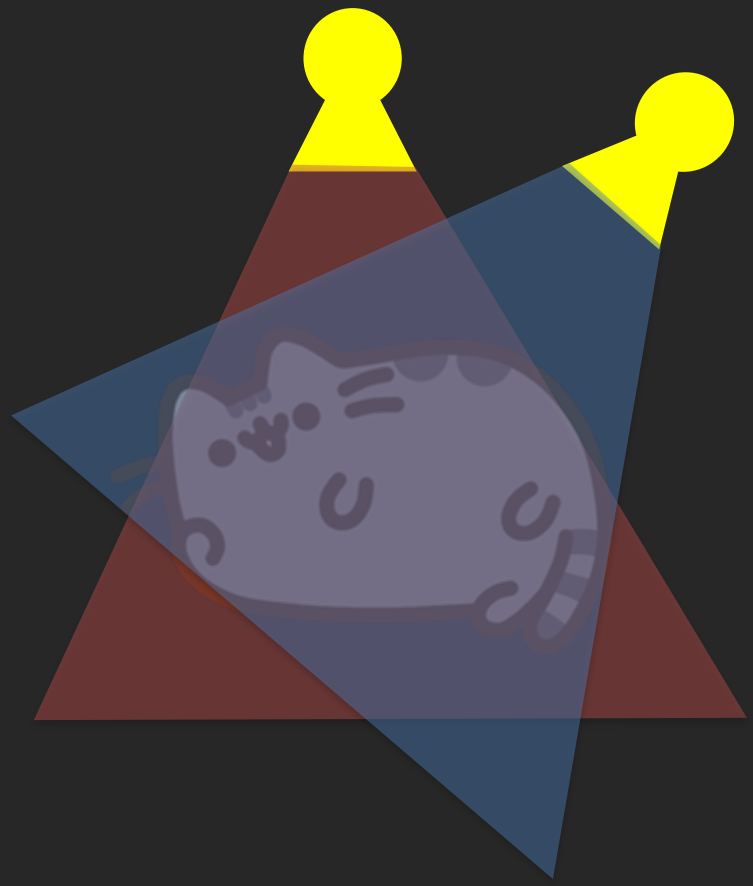
- Non-spectral values depend on beam energy:
  - Increase tube potential, CTA of the aorta is going to decrease in CT number (CT number changes with energy)
- Spectral CT values have no energy dependence
- How do we get spectral data?

Obtaining Spectral Data

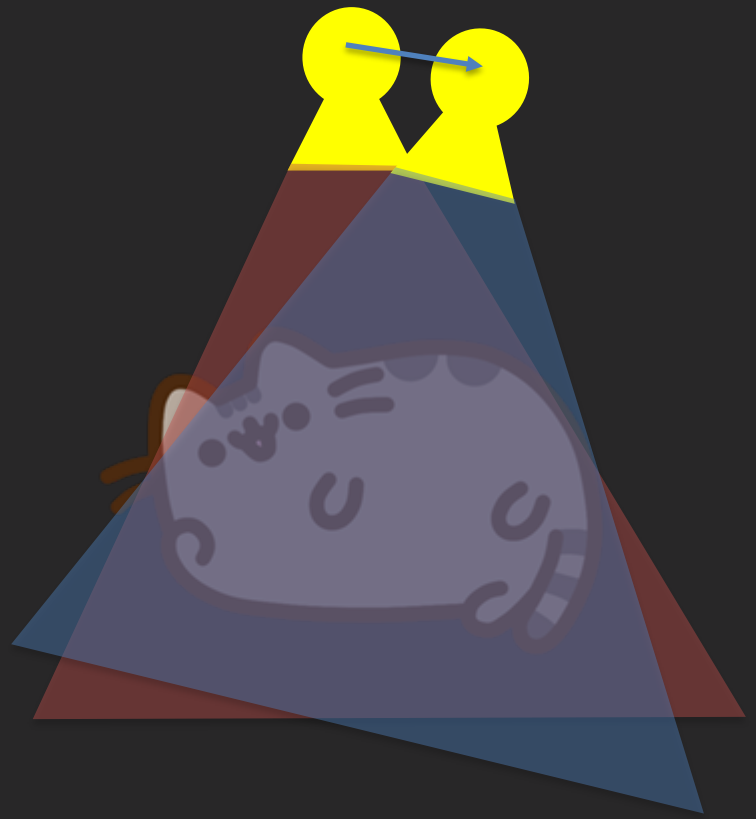
$$\ln\left(\frac{I_o}{I}\right)\cdot\frac{1}{t}=\mu \quad \Longleftrightarrow \quad \mu = a\cdot PE(E) + b\cdot CS(E)$$



- Energy-integrating detectors
  - Dual source



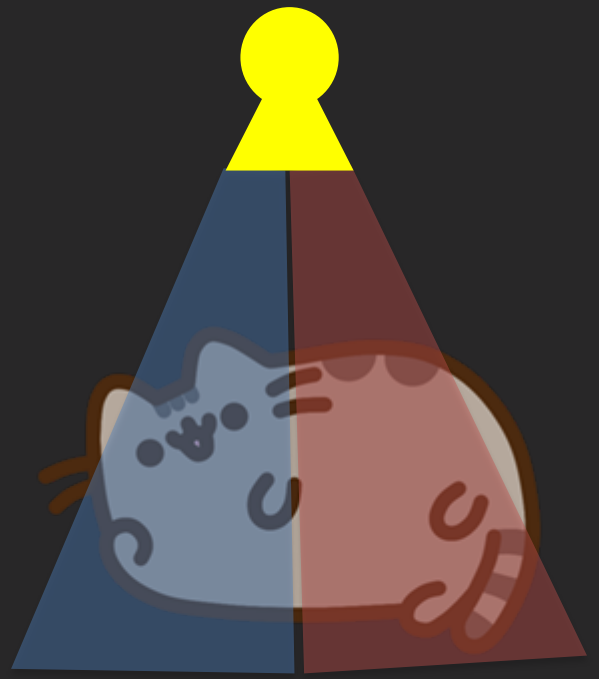
- Energy-integrating detectors
  - Dual source
  - Fast kV switching



Obtaining Spectral Data

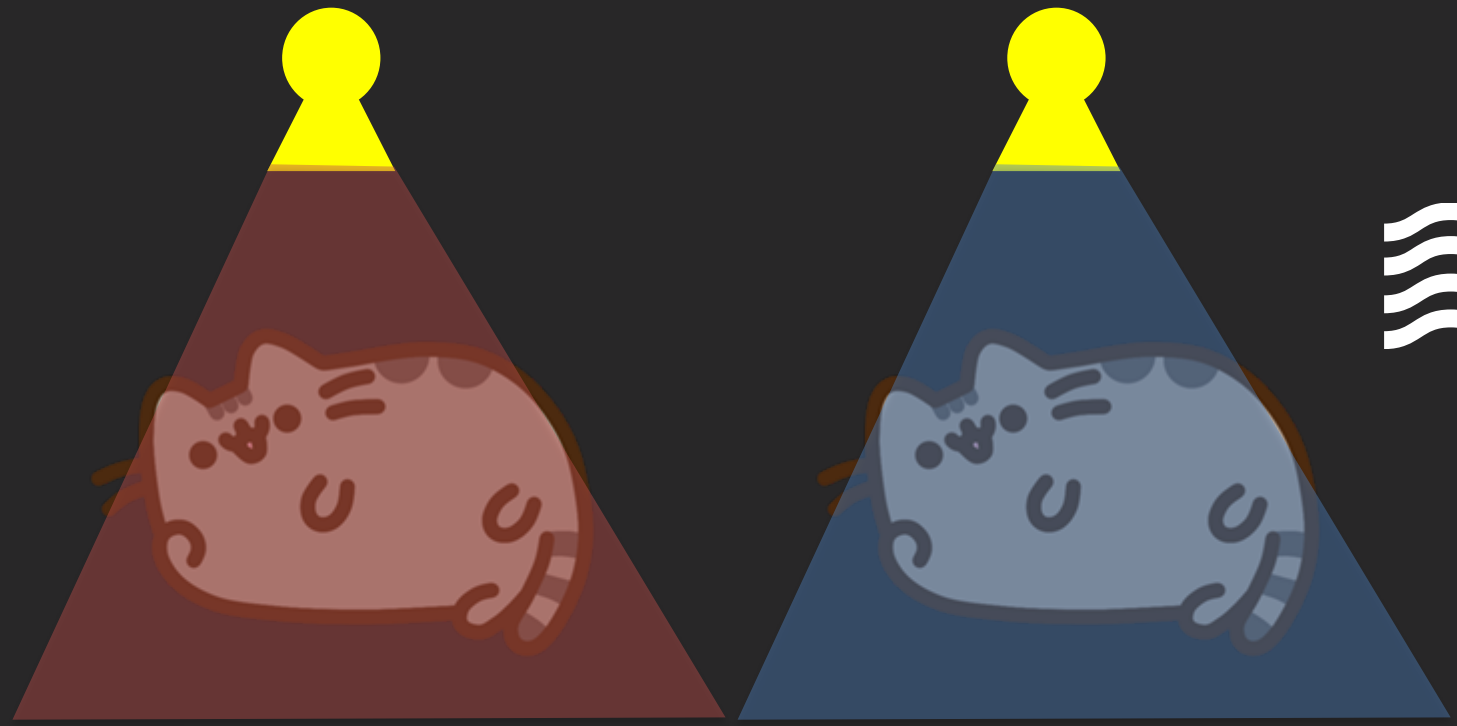
- Energy-integrating detectors
  - Dual source
  - Fast kV switching
  - Dual layer

- Energy-integrating detectors
  - Dual source
  - Fast kV switching
  - Dual layer
  - Split beam



Obtaining Spectral Data

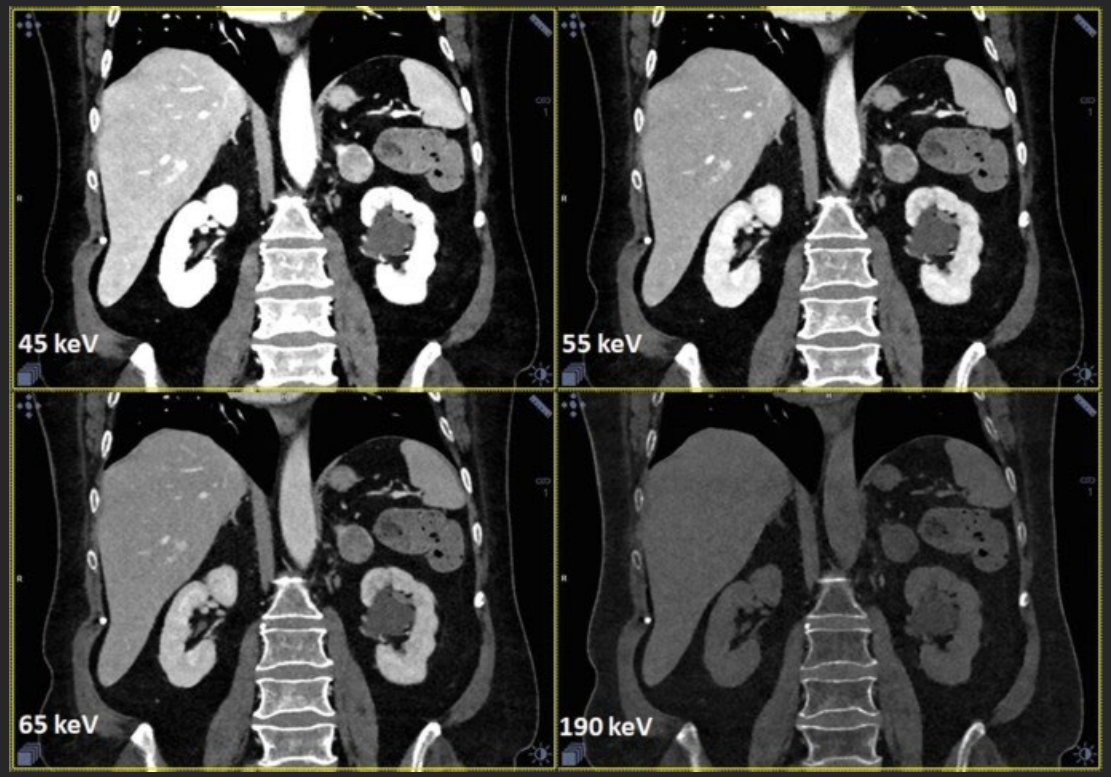
- Energy-integrating detectors
  - Dual source
  - Fast kV switching
  - Dual layer
  - Split beam
  - Rotate - rotate



Obtaining Spectral Data

- Energy-integrating detectors
  - Dual source
  - Fast kV switching
  - Dual layer
  - Split beam
  - Rotate - rotate
- Photon-counting detectors

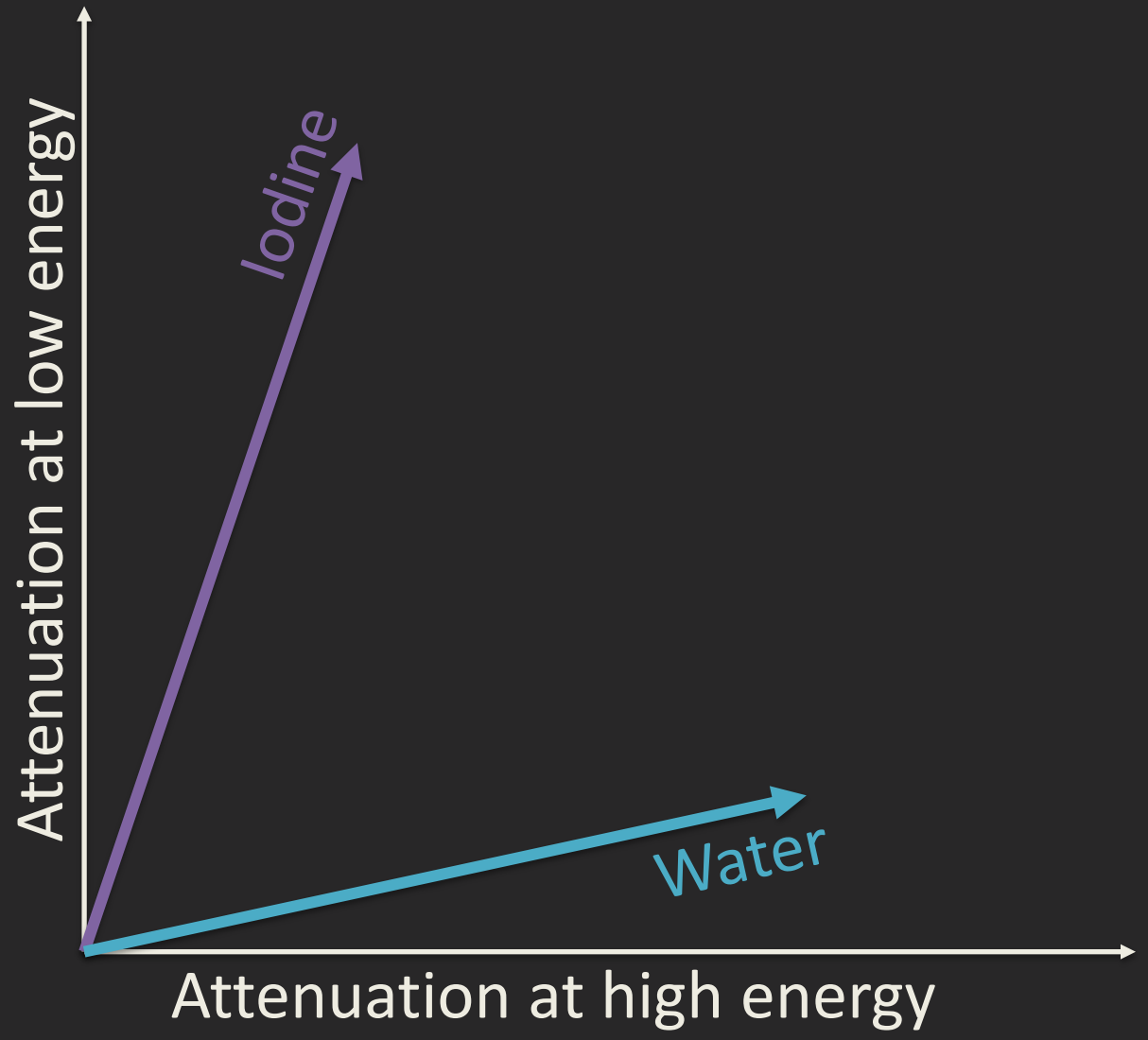
- Virtual monoenergetic images
  - Simulates monoenergetic beam images
  - Can change energy



Flohr, T., Petersilka, M., Henning, A., Ulzheimer, S., Schmidt, B. (2023). Medical Photon-Counting CT: Status and Clinical Applications Review. In: Hsieh, S., Iniewski, K.(. (eds) Photon Counting Computed Tomography. Springer, Cham. https://doi-org.ezproxy.library.wisc.edu/10.1007/978-3-031-26062-9_1

Layer YC, Mesropyan N, Kupczyk PA, Luetkens JA, Isaak A, Dell T, Ernst BP, Attenberger UI, Kuetting D. Use of virtual monoenergetic images for reduction of extensive dental implant associated artifacts in photon-counting detector CT. Scientific Reports. 2024 Jan 4;14(1):497.

Uses of Spectral Data



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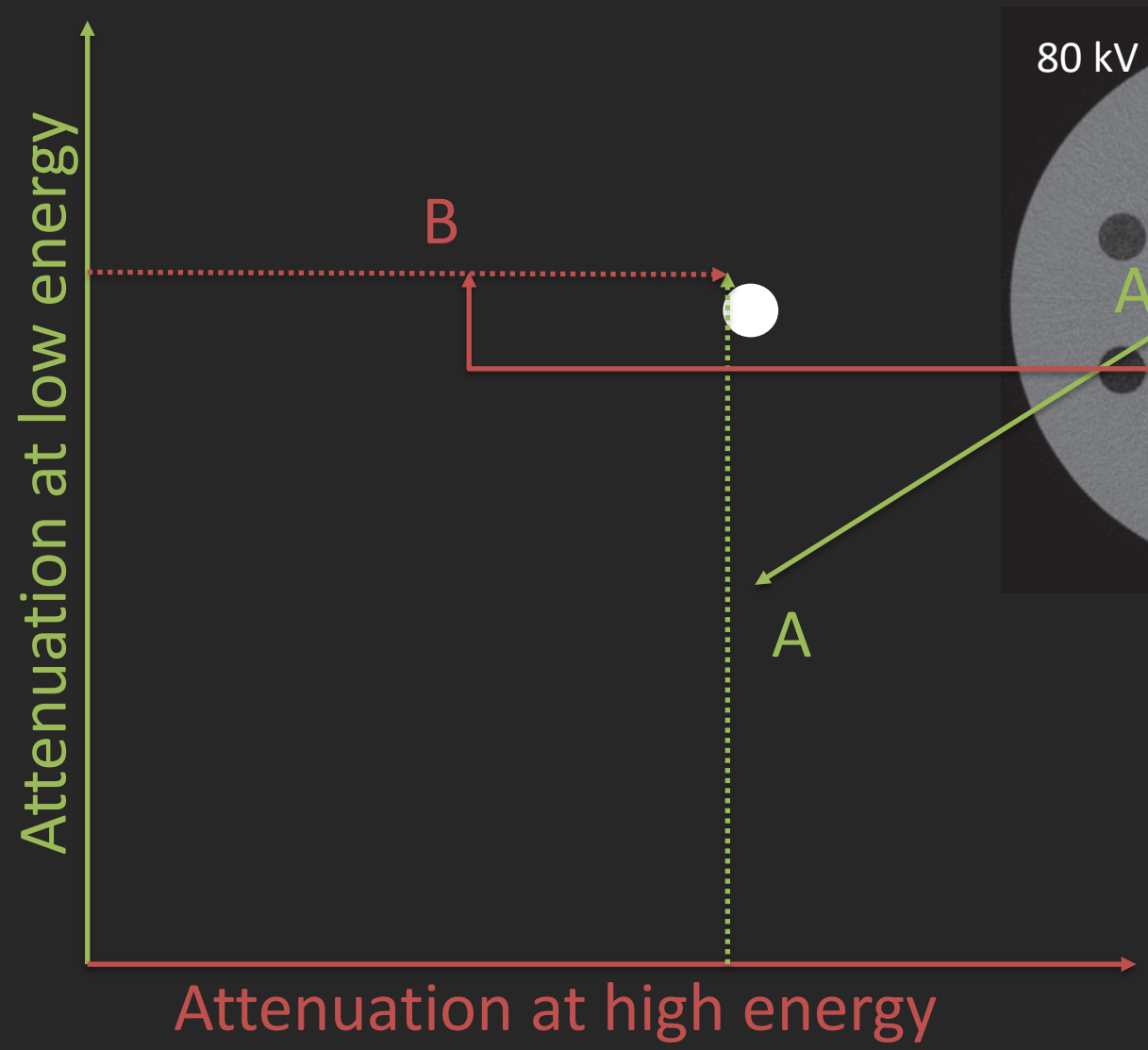

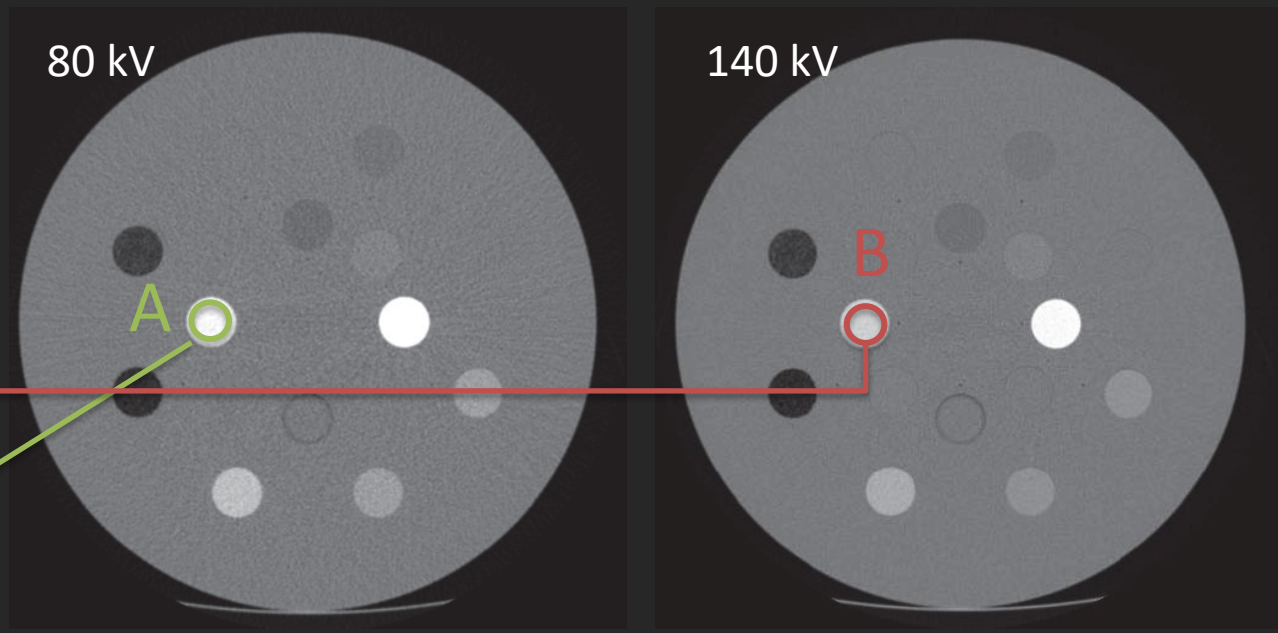

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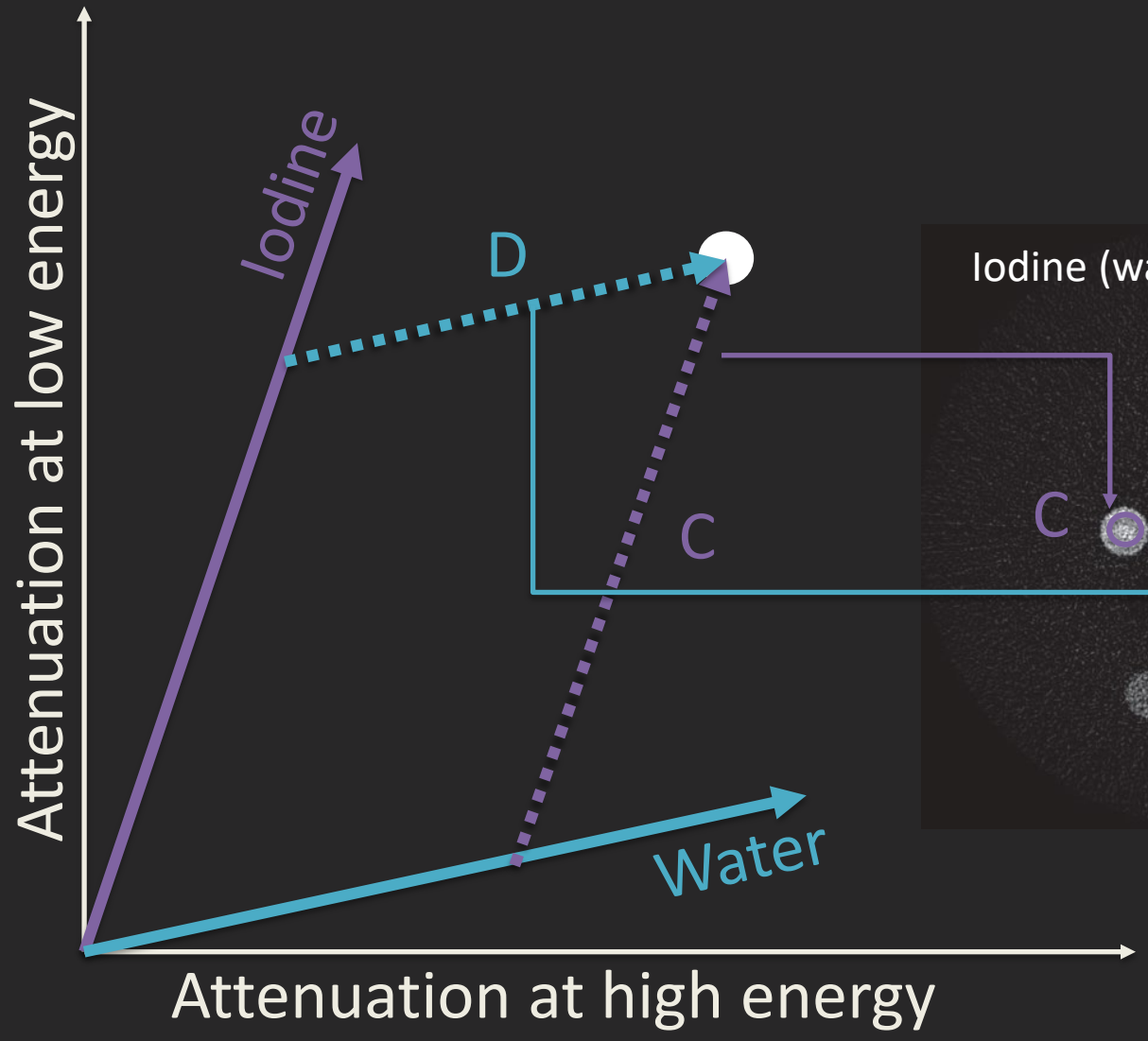
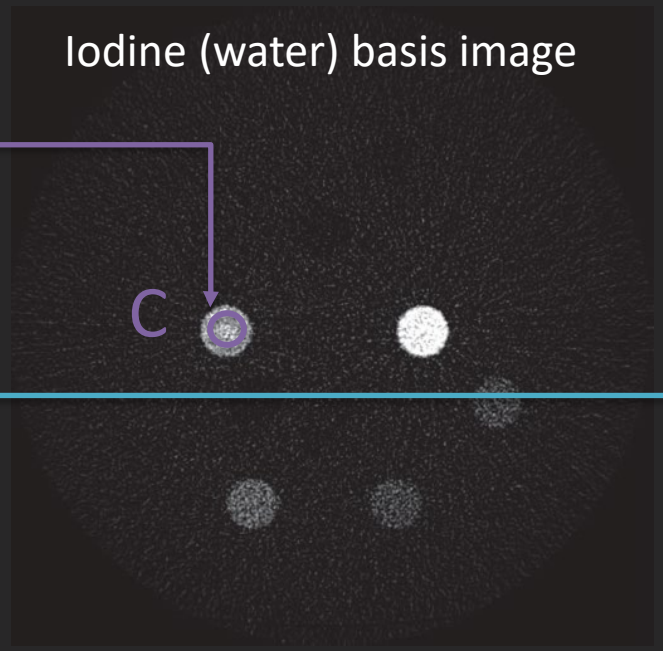
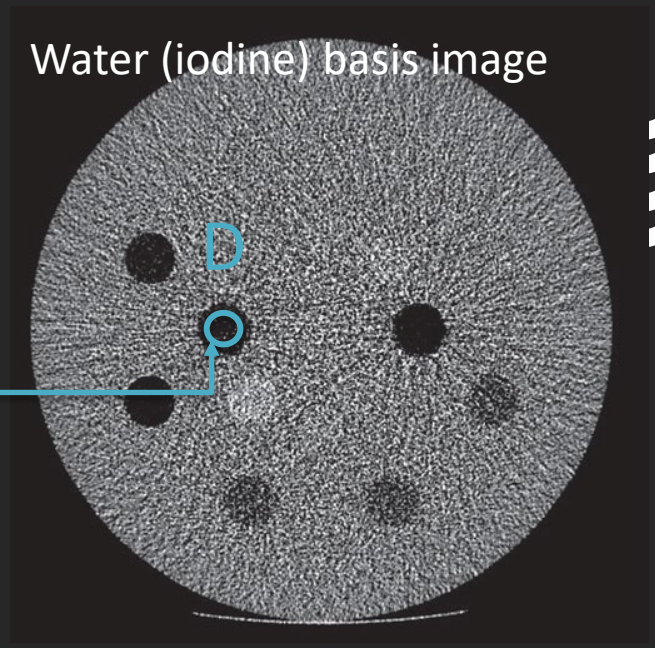
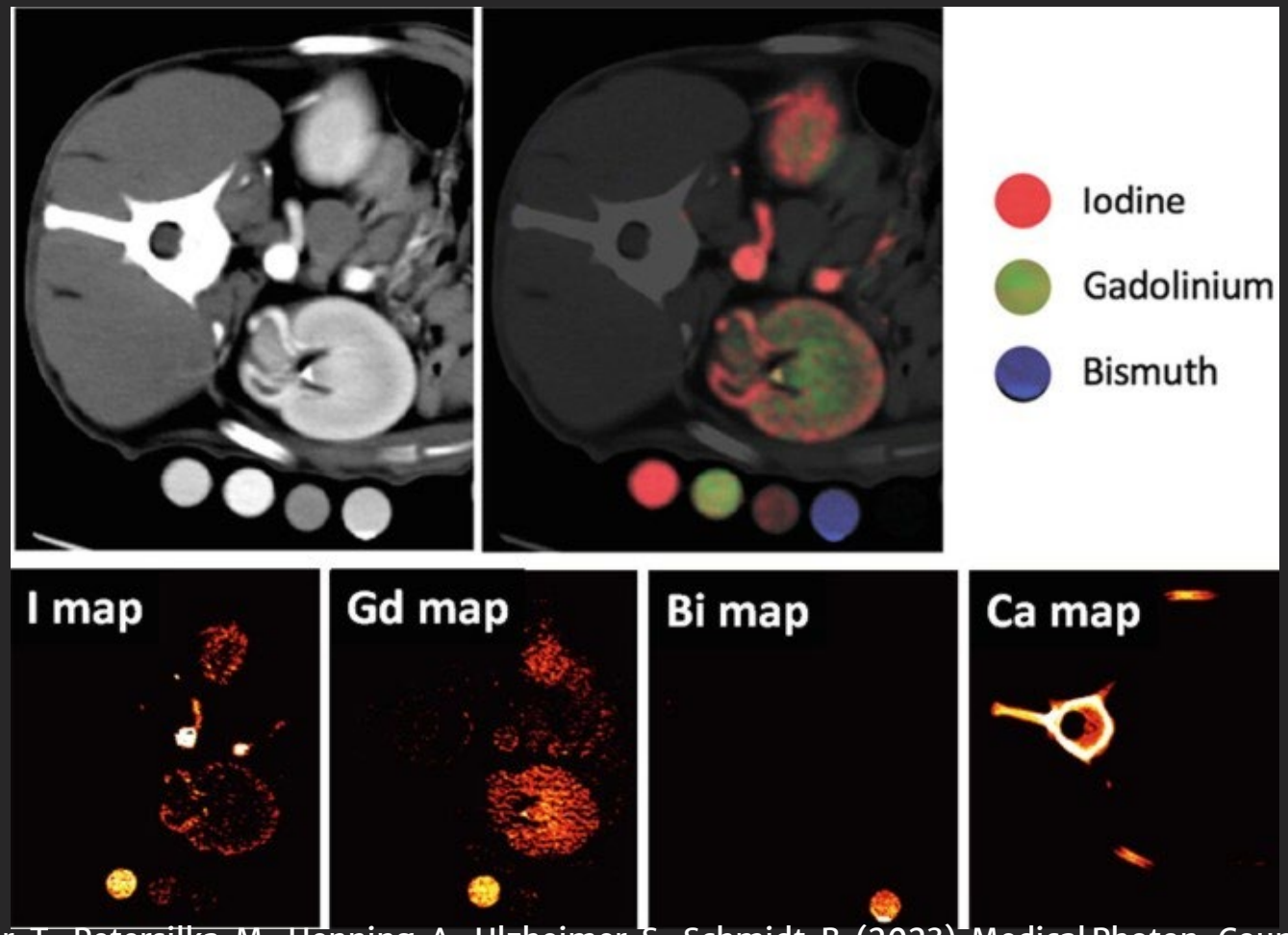
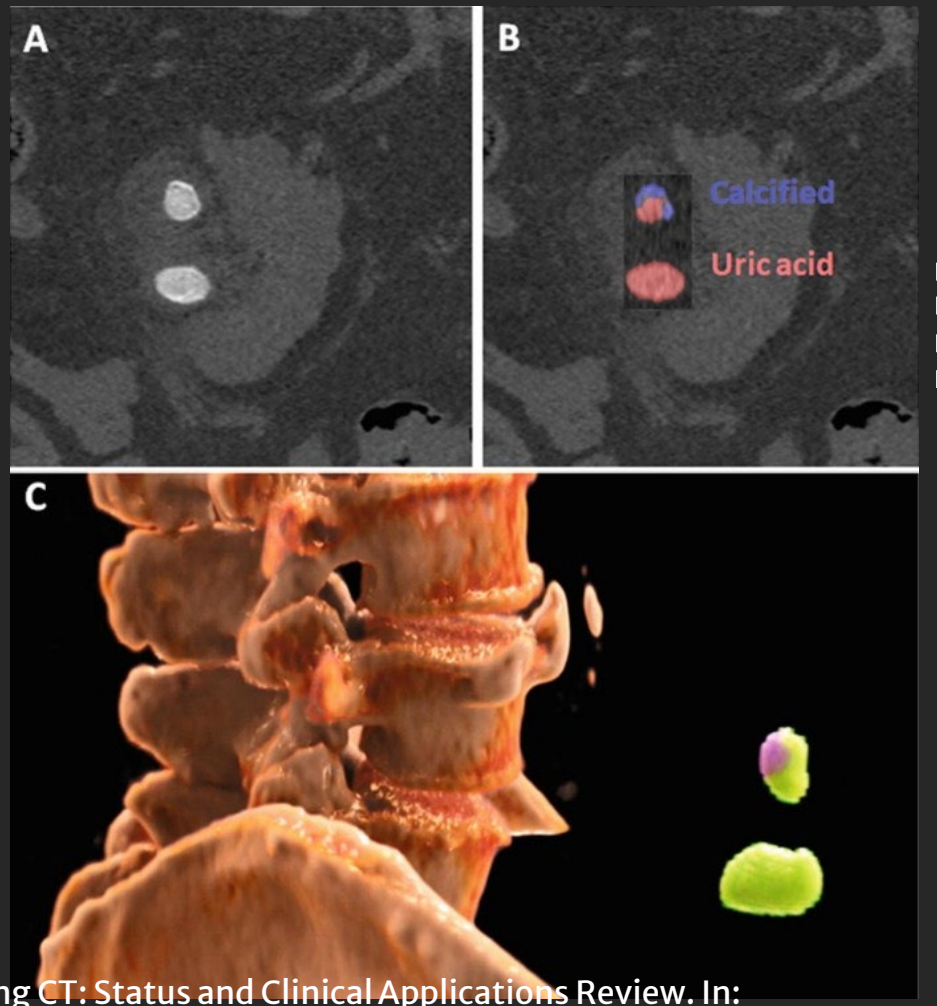






- Material quantification can be used to differentiate materials





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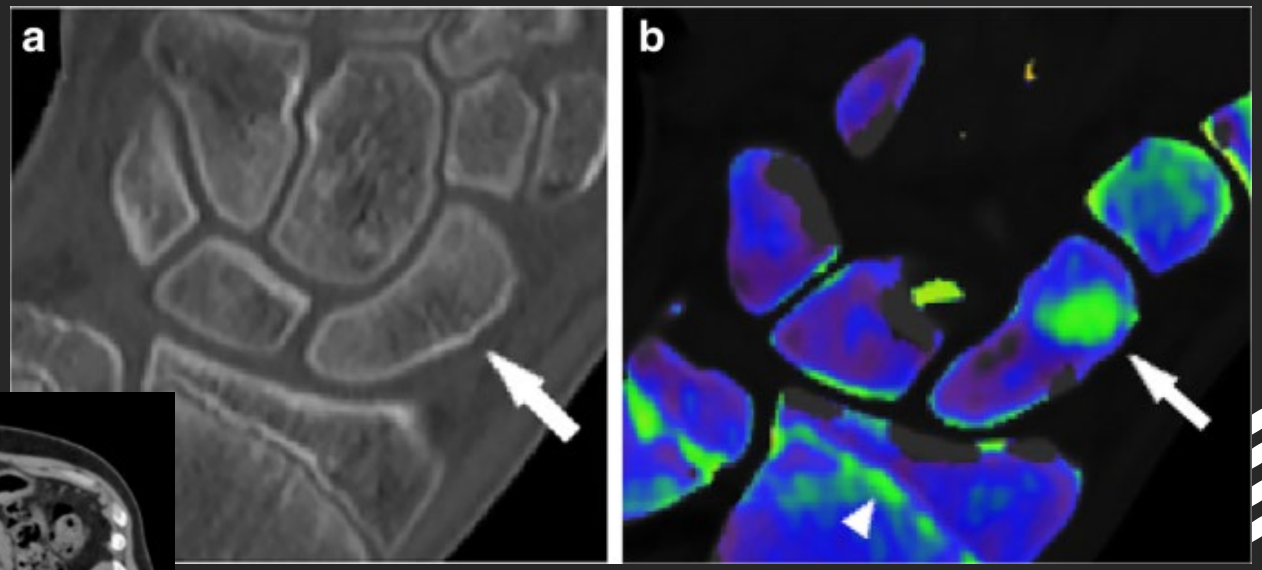
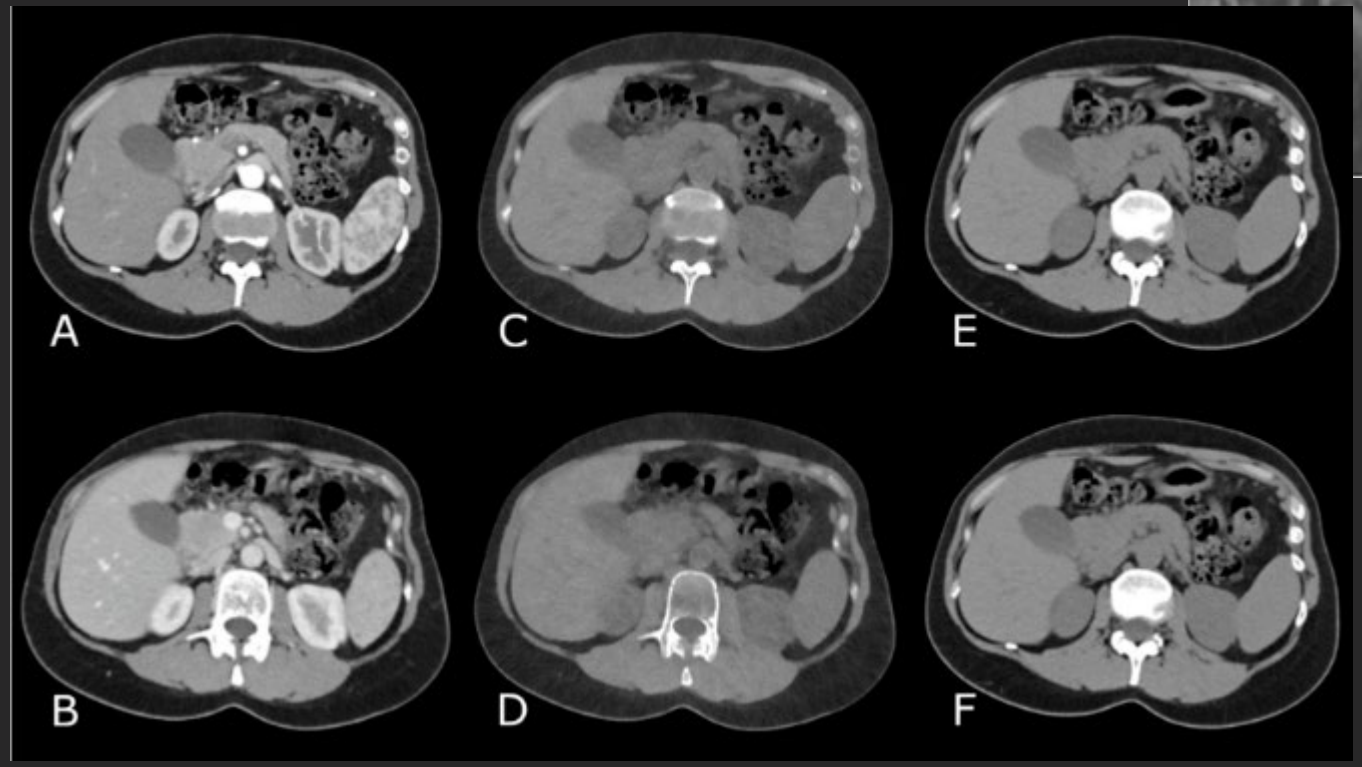
Uses of Spectral Data

- Removal of signal:
  - Iodine
  - Calcium



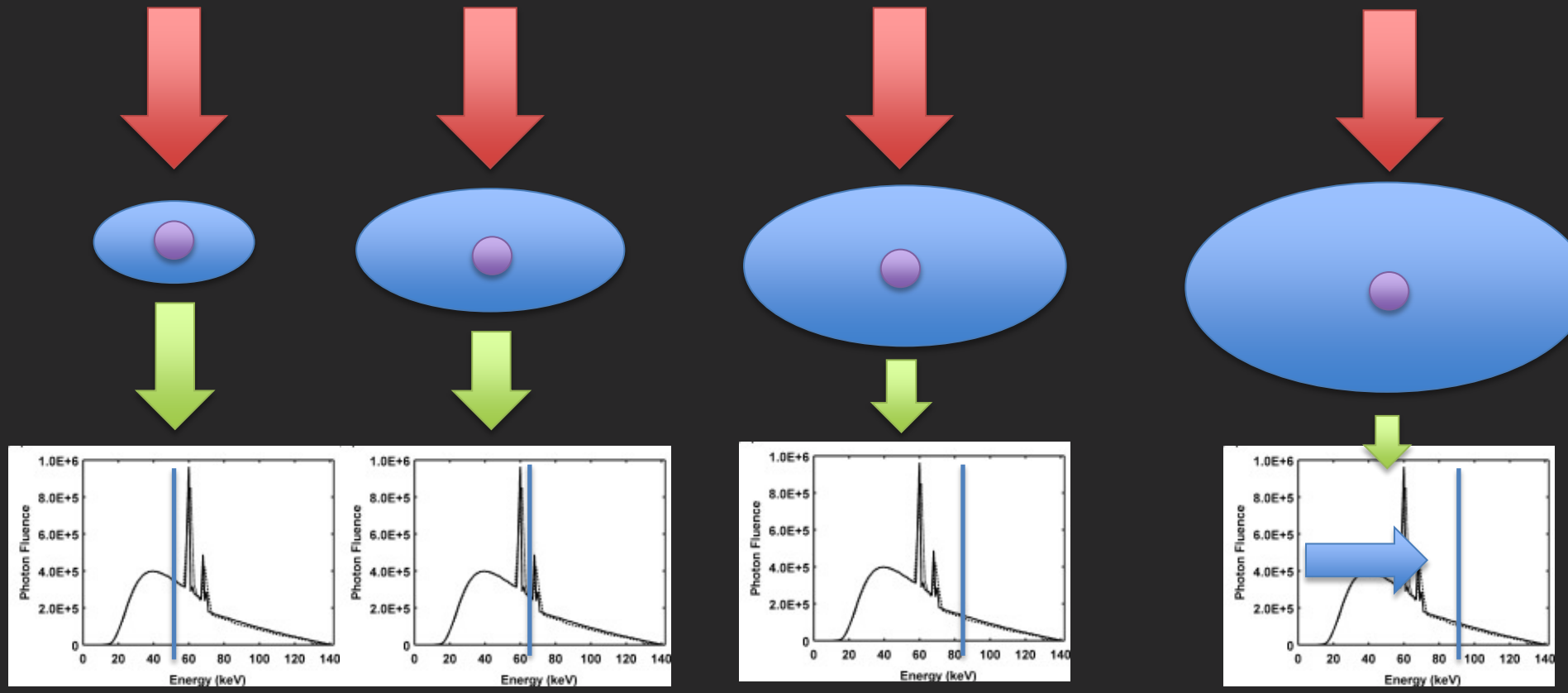
D'Angelo T, Albrecht MH, Caudo D, Mazziotti S, Vogl TJ, Wichmann JL, Martin S, Yel I, Ascenti G, Koch V, Cicero G. Virtual non-calcium dual-energy CT: clinical applications. European radiology experimental. 2021 Sep 3;5(1):38.



Niehoff JH, Woeltjen MM, Laukamp KR, Borggrefe J, Kroeger JR. Virtual non-contrast versus true non-contrast computed tomography: initial experiences with a photon counting scanner approved for clinical use. Diagnostics. 2021 Dec 16;11(12):2377.

Issues with Units

Beam Hardening



X-ray input is identical

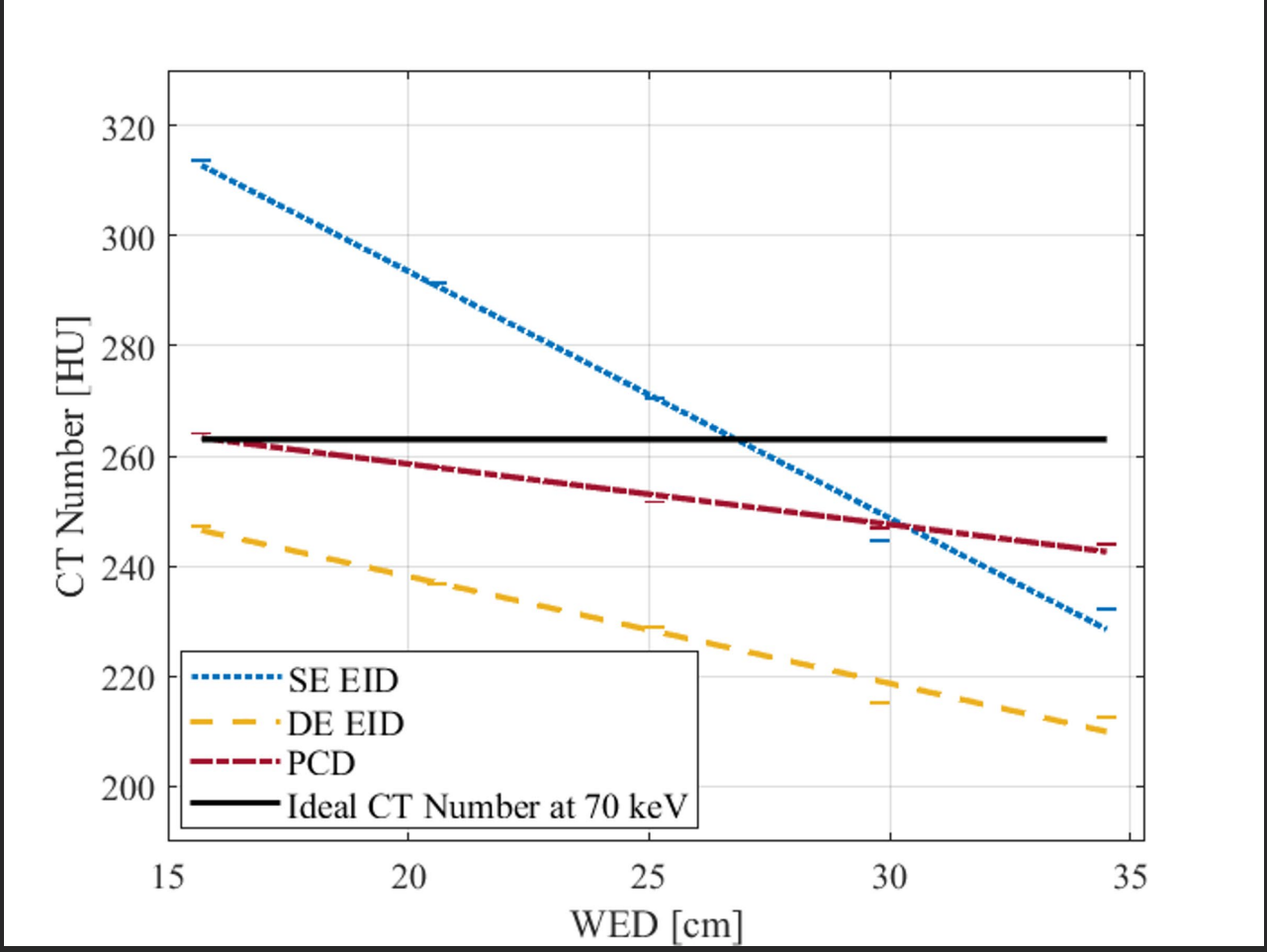
Material of interest (purple circle) is identical, size of object increases

Low energy X-rays are more attenuated

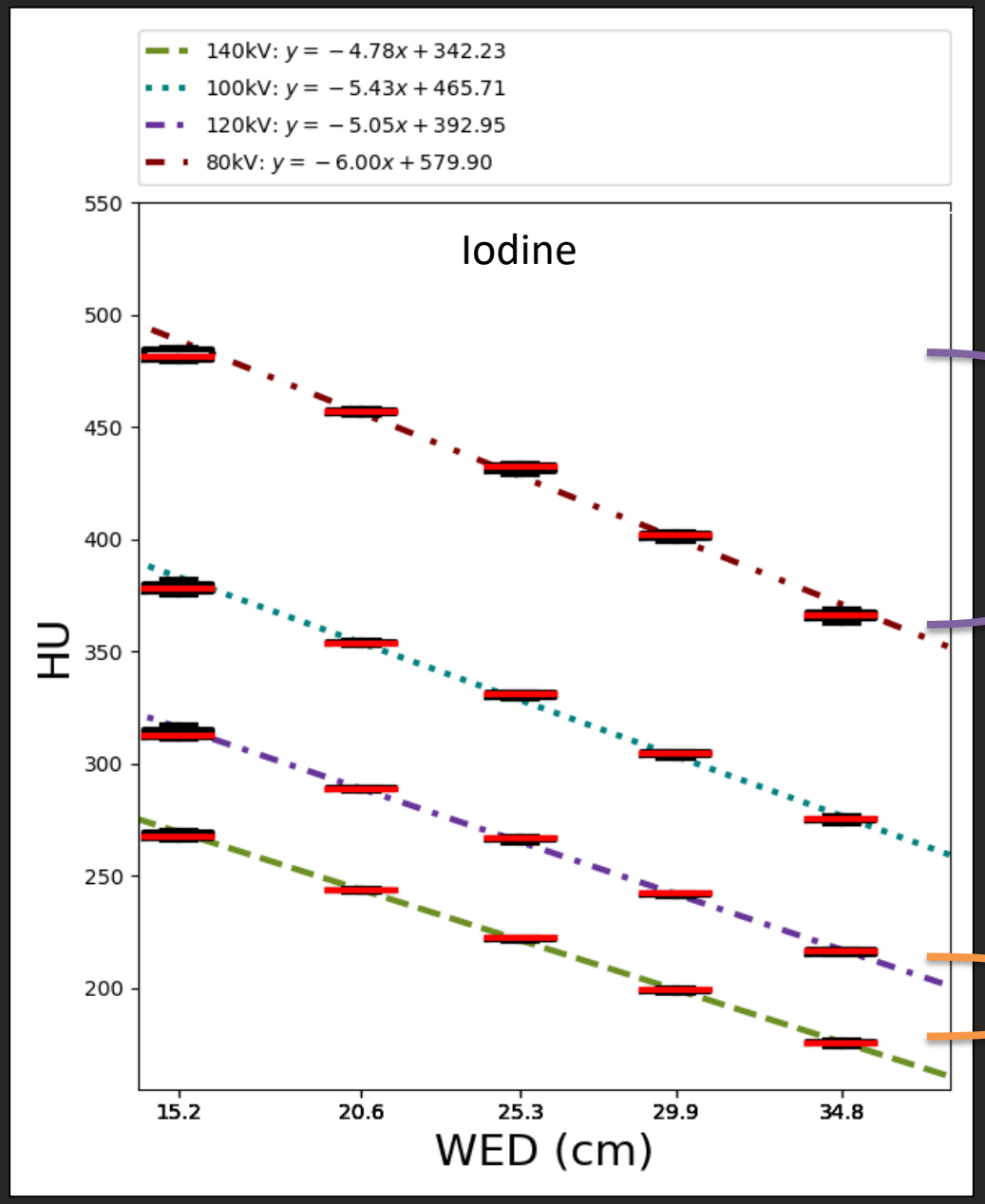
Higher effective energy

Same material + Different amounts of "patient" = Different CT numbers

- Effects of beam hardening on iodine



Salyapongse AM, Rose SD, Pickhardt PJ, Lubner MG, Toia GV, Bujila R, Yin Z, Slavic S, Szczykutowicz TP. CT number accuracy and association with object size: a phantom study comparing energy-integrating detector CT and deep silicon photon-counting detector CT. American Journal of Roentgenology. 2023 Oct 31;221(4):539-47.



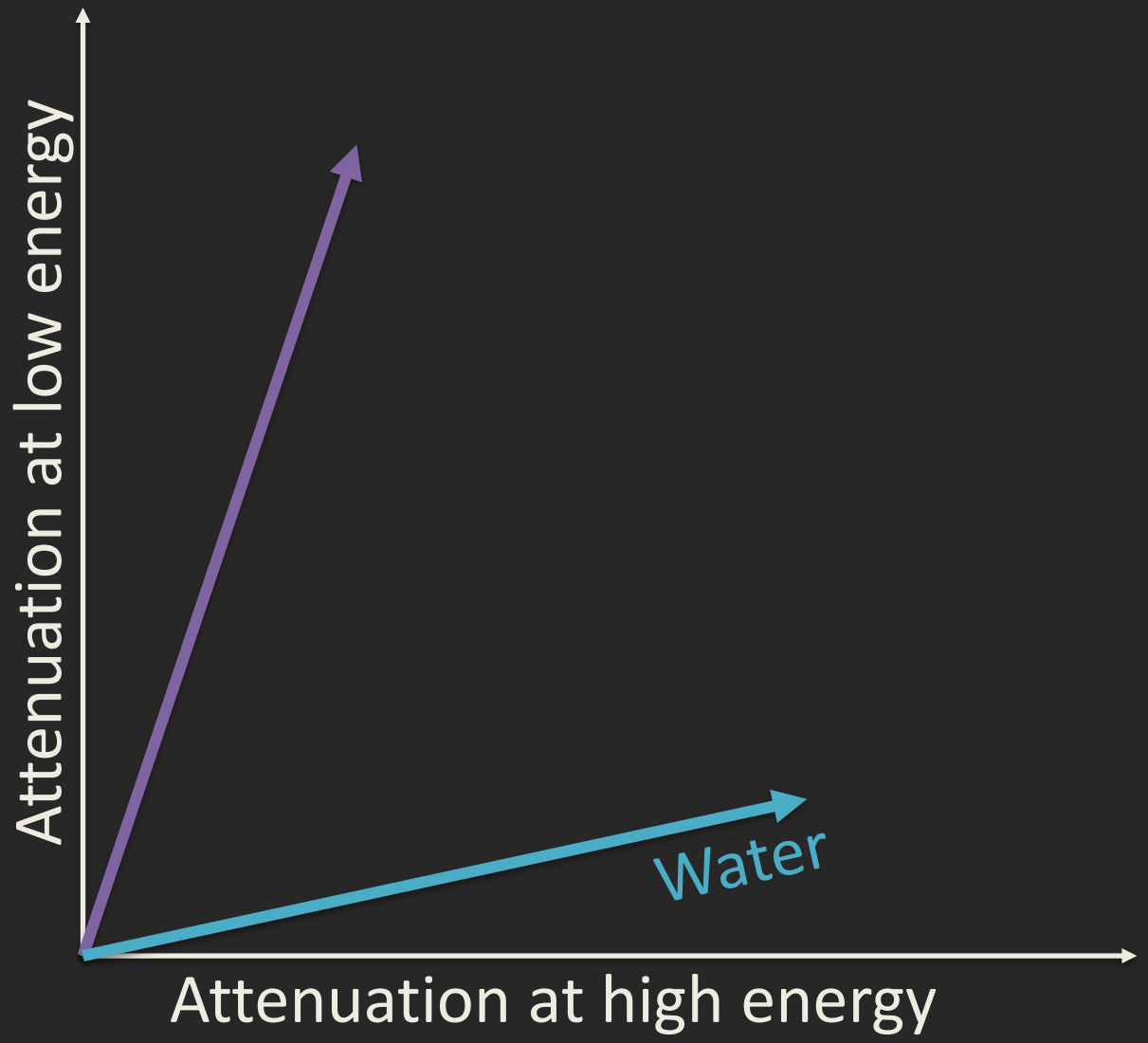
Change

CT number based biomarker? Unreliable

Change in kV: ~25 HU

Rose S, Ruyle J, Szczykutowicz T. Parameterizing Size-Based Variations in CT Number. In MEDICAL PHYSICS 2020 Jun 1 (Vol. 47, No. 6, pp. E397-E398). 111 RIVER ST, HOBOKEN 07030-5774, NJ USA: WILEY.

Issues with Material Quantification



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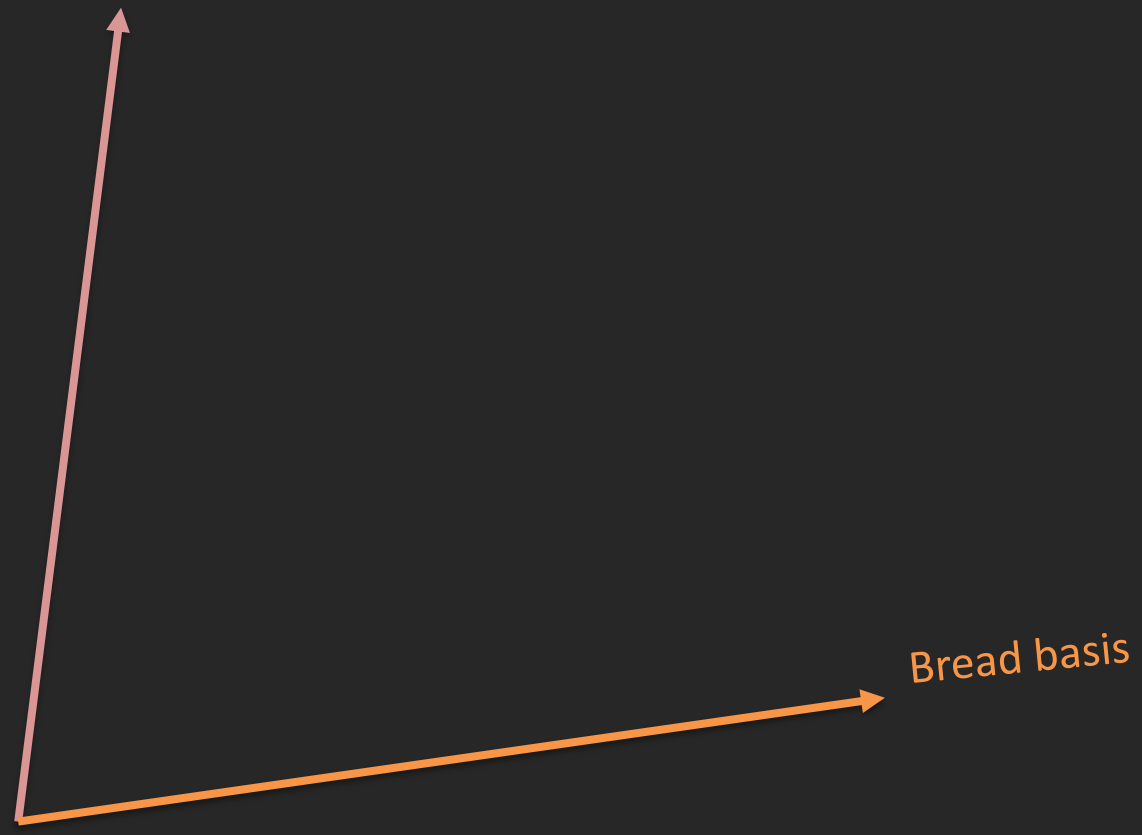


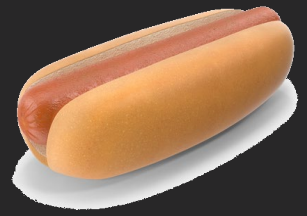
Meatball (only beef)

Toast (only bread)

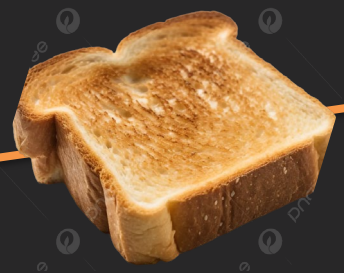
Beef hotdog (equal parts bread and beef)

Issues with Material Quantification

Beef basis

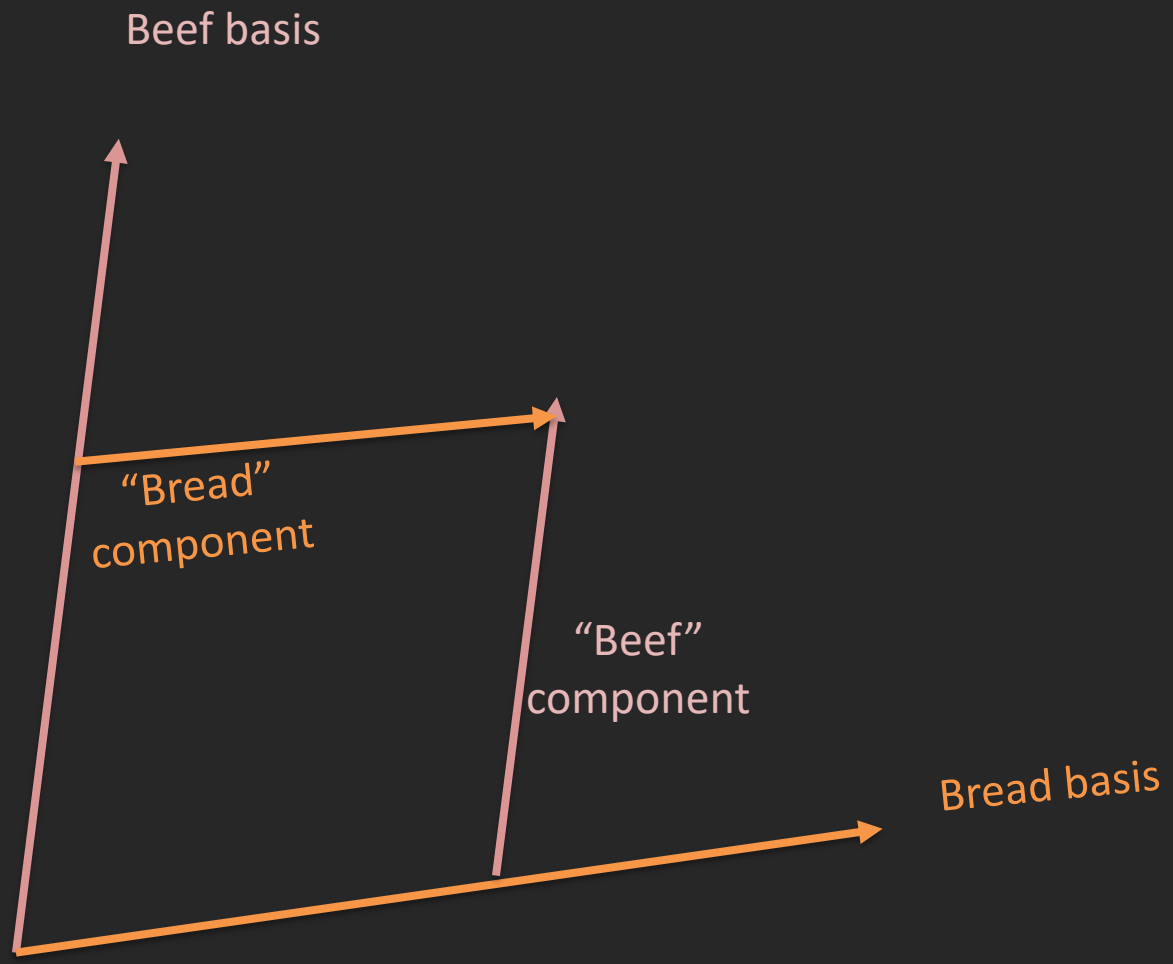


Salmon sashimi



Bread basis

Issues with Material Quantification



Salmon sashimi

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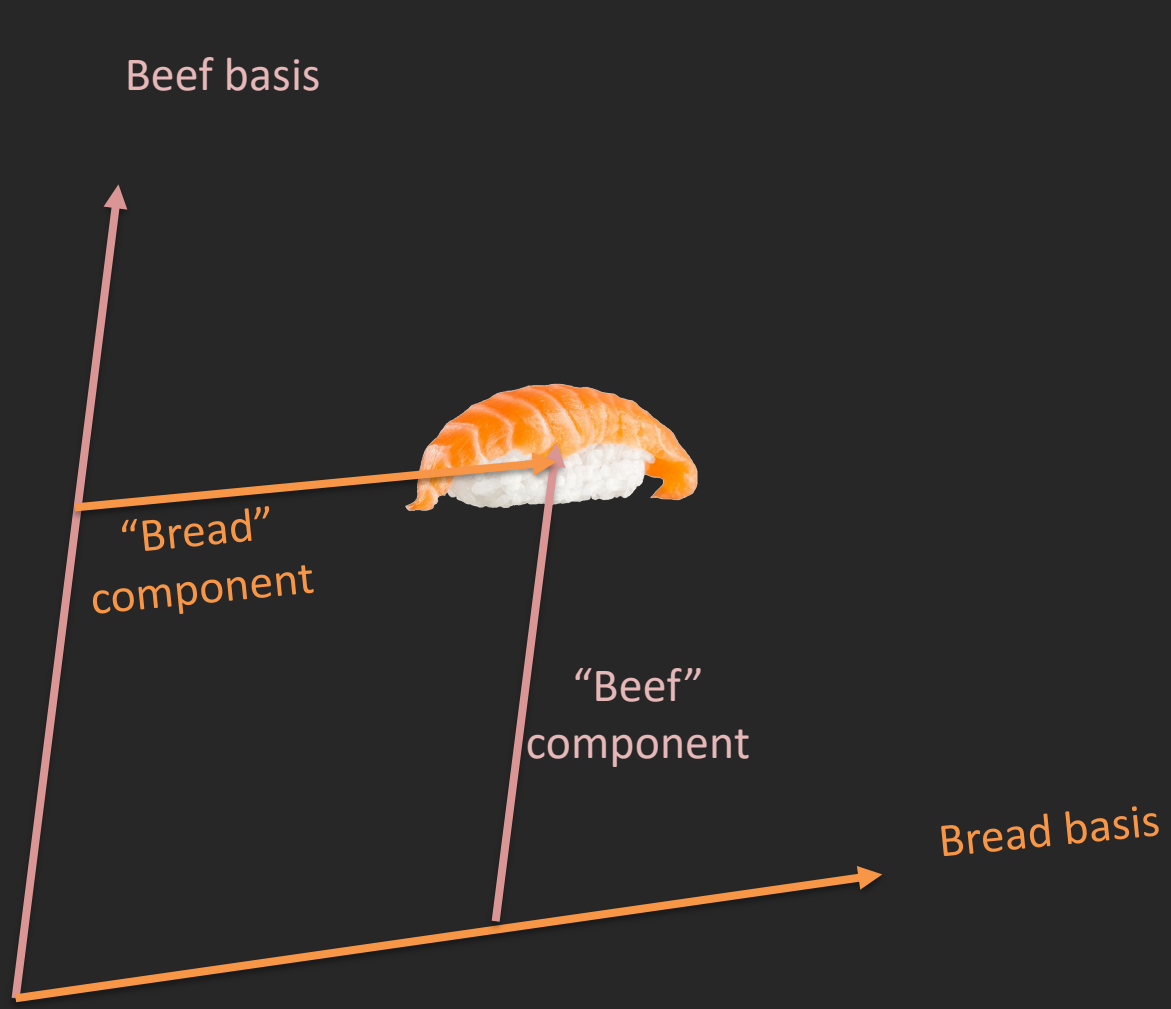
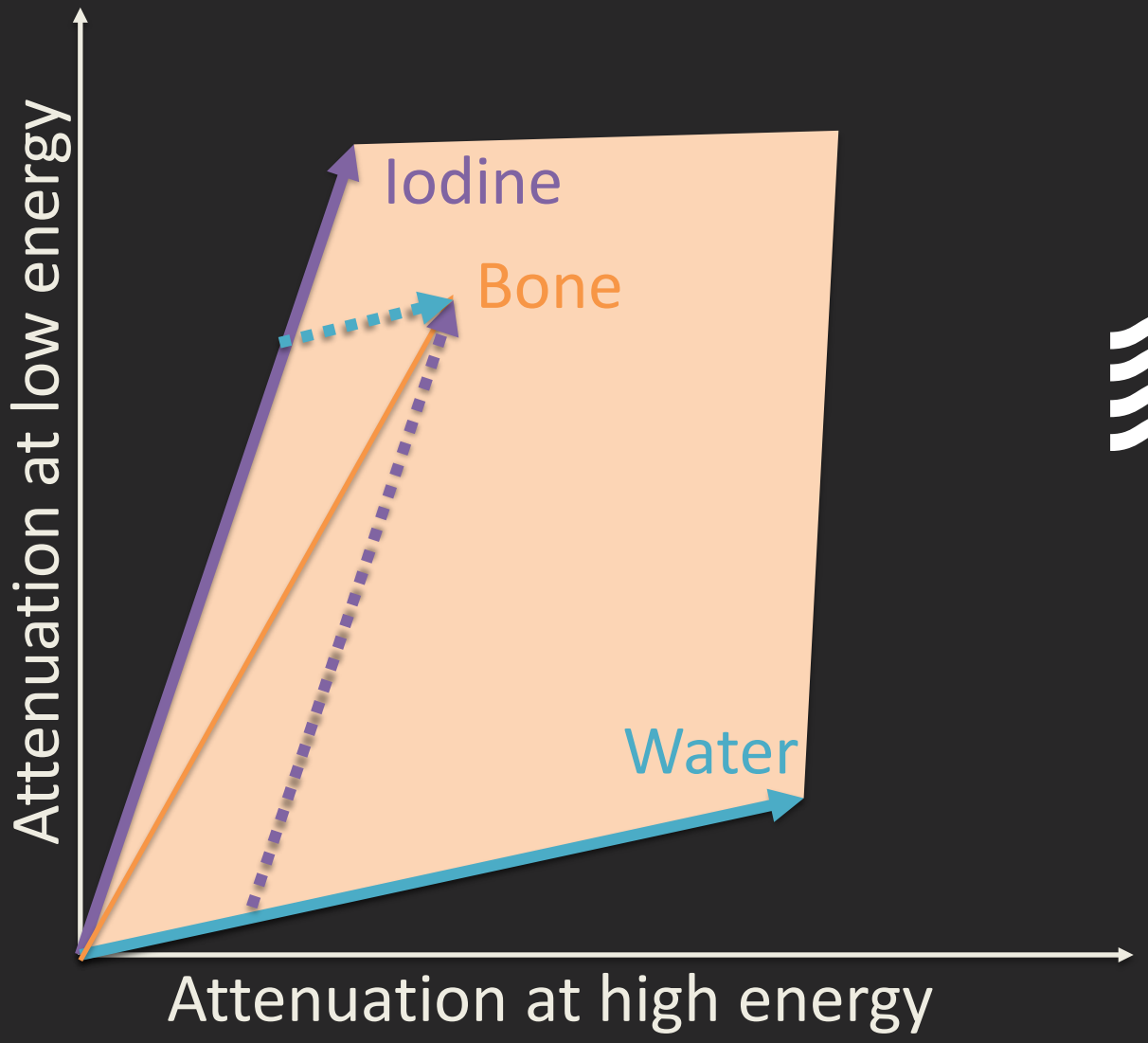
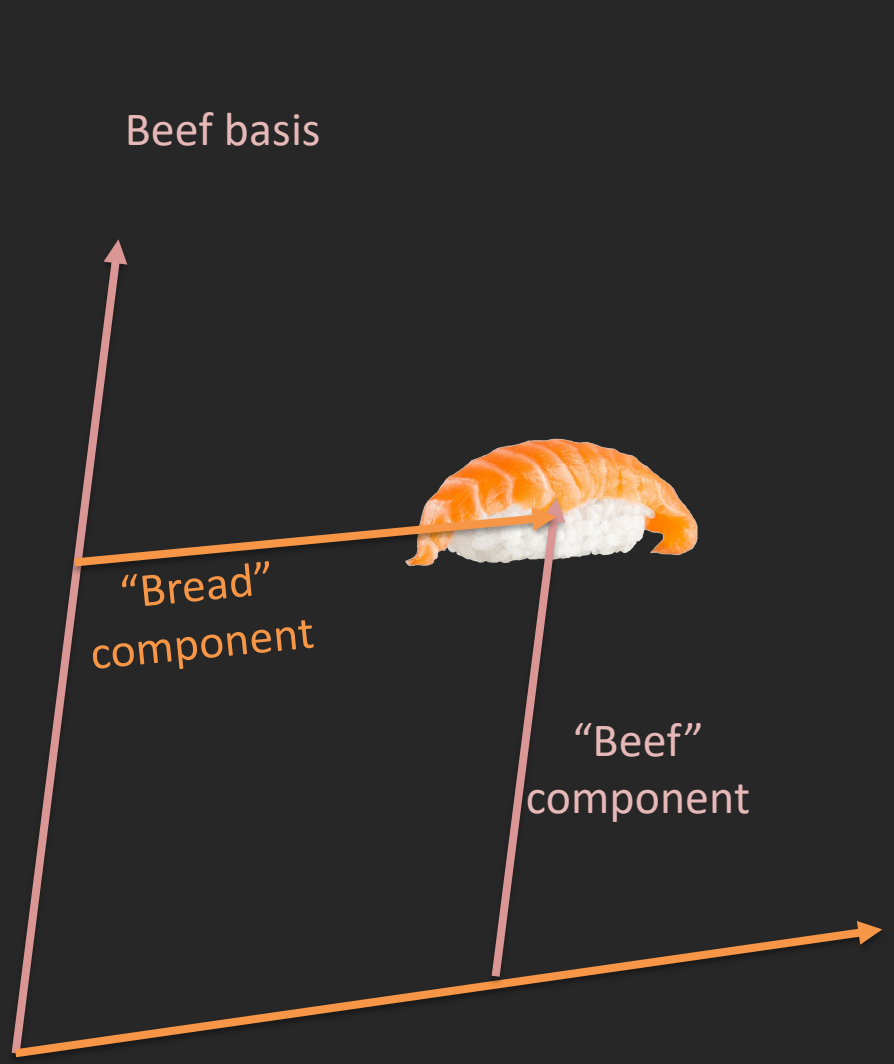
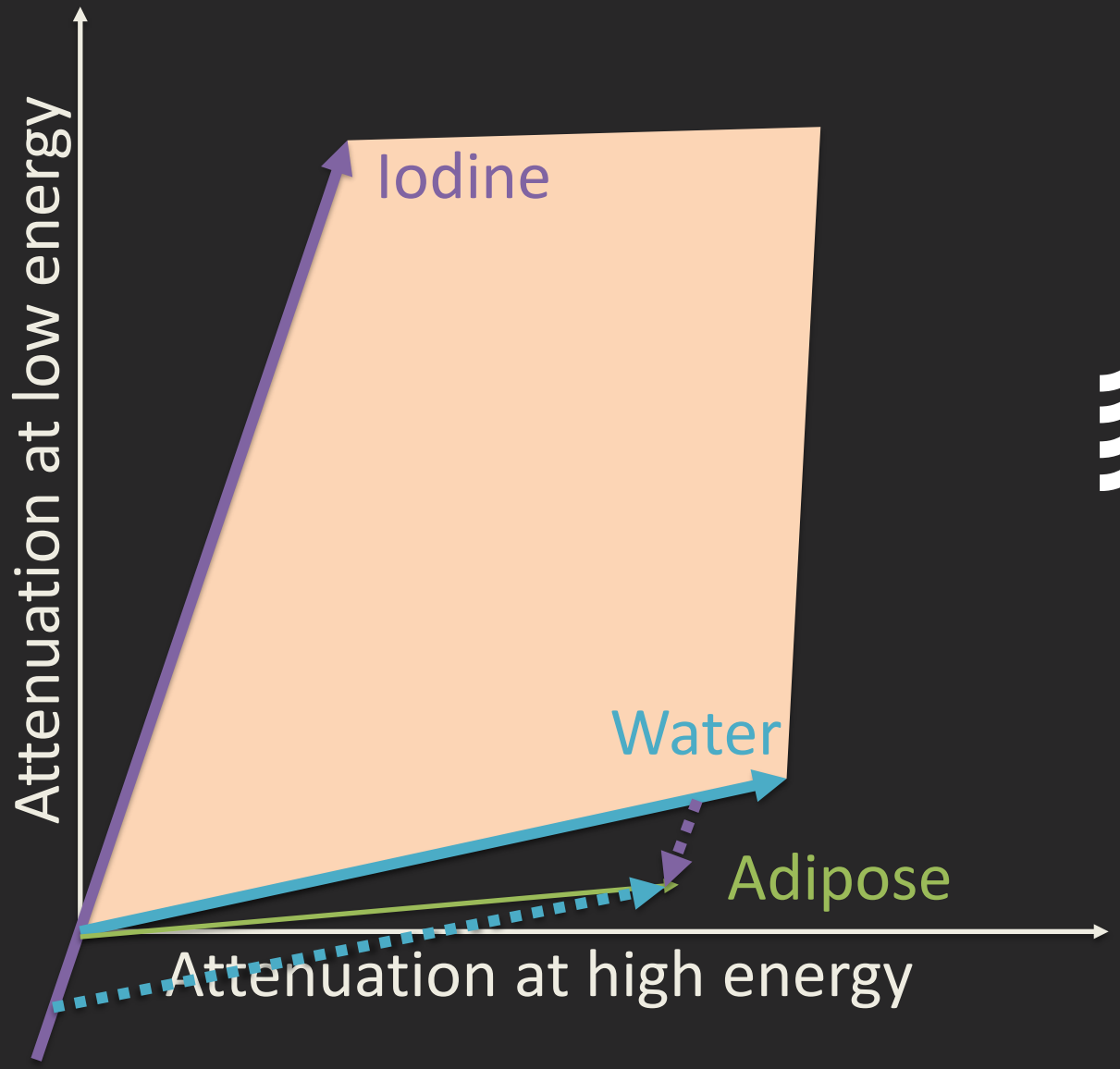


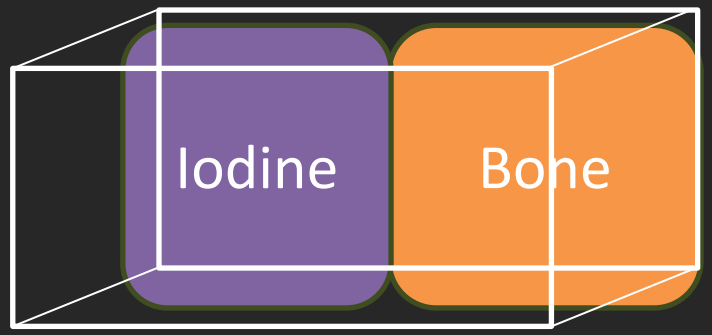


Issues with Material Quantification

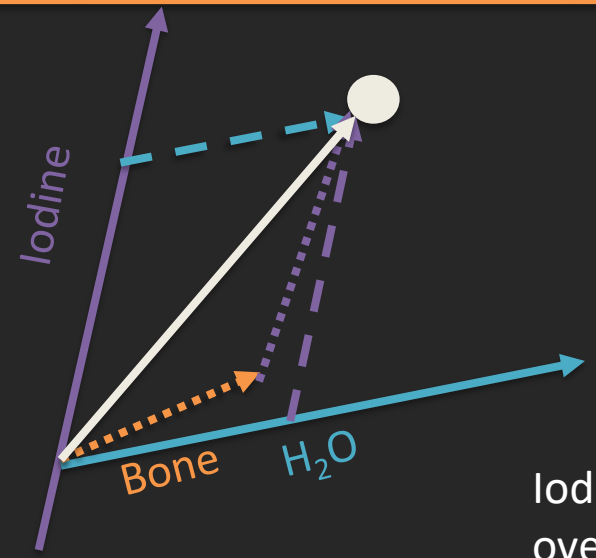




Issues with Material Quantification

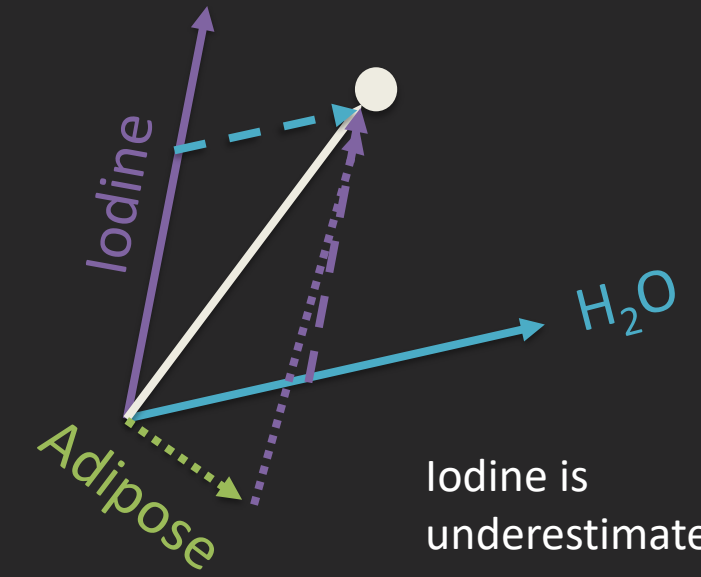


A common *in vivo* condition causing error: iodine + bone (not iodine + water)



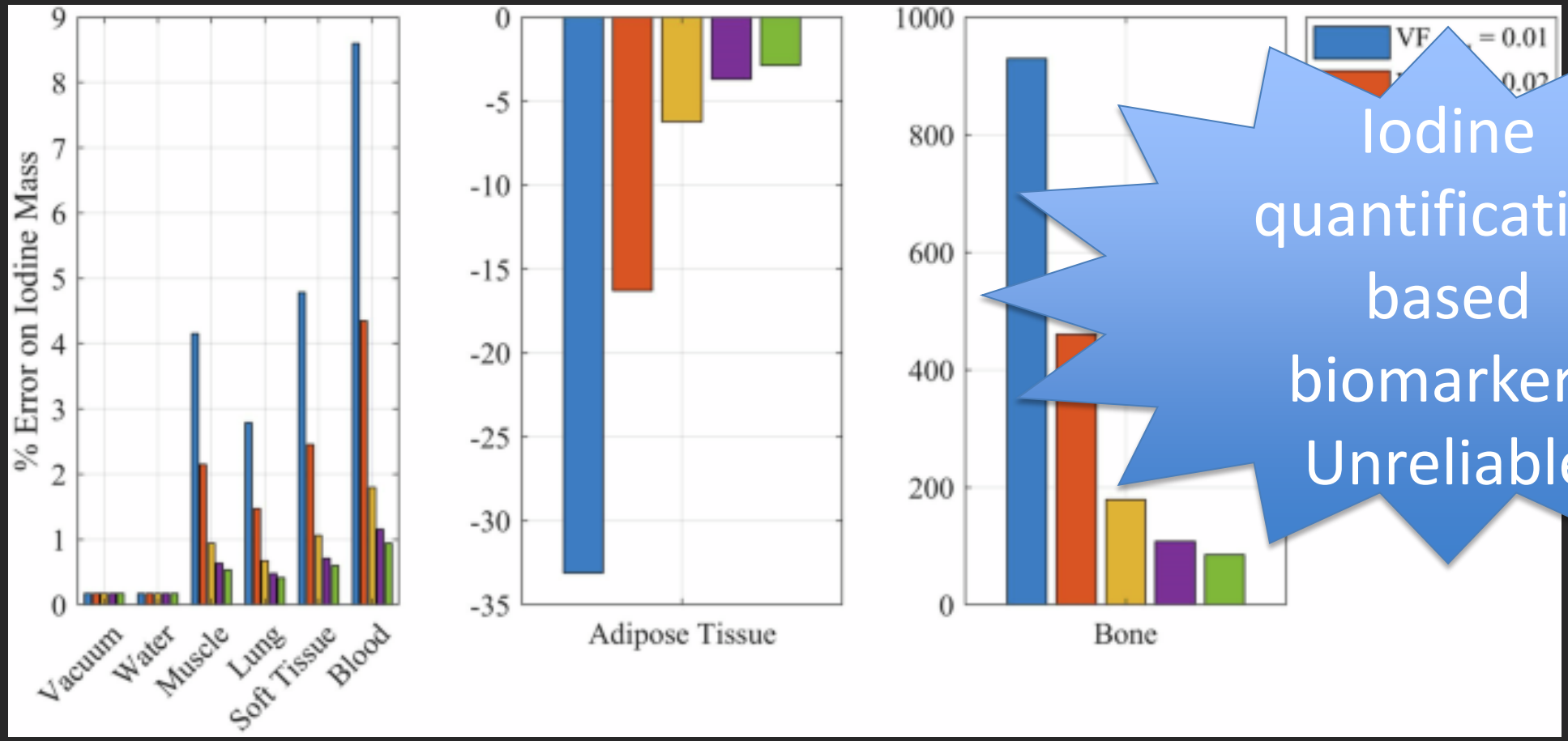
Iodine is overestimated

A common *in vivo* condition causing error: iodine + adipose (not iodine + water)



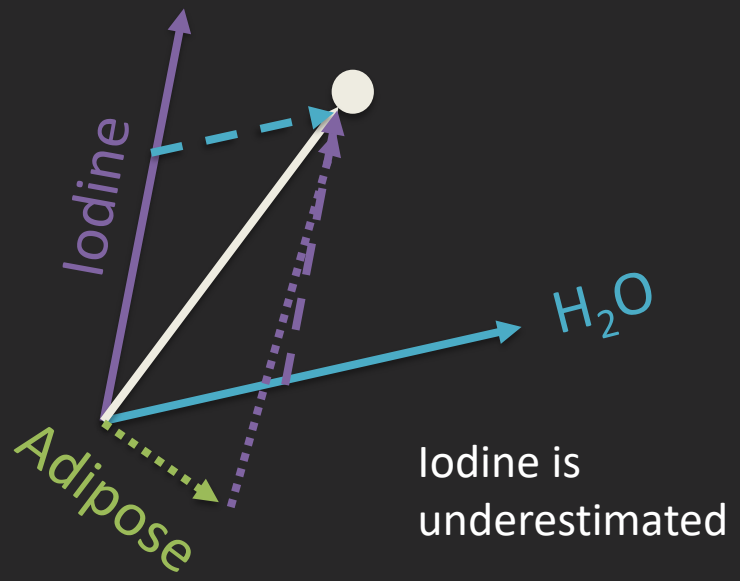
Iodine is underestimated

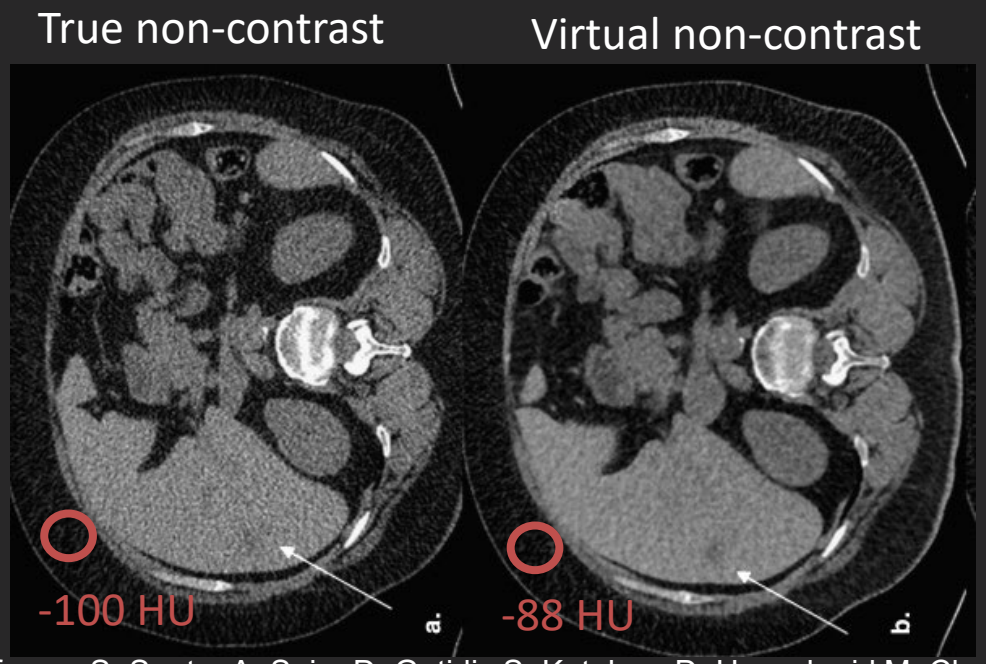
- Expected errors on iodine quantification



Salyapongse AM, Szczykutowicz TP. Misinterpretations about CT numbers, material decomposition, and elemental quantification. European Radiology. 2025 Feb;35(2):862-70.

- The most accurate material quantification occurs when the decomposition pair matches the materials in the voxel
  - Example: Virtual non-contrast scans of fat show increased CT numbers than true non-contrast scans of fat





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Summary

1. CT numbers:
    1. CT numbers are the fundamental units of CT and come from the attenuation of x-rays by patient tissues
    2. CT numbers depend on effective beam energy because of the change in attenuation coefficients
2. Spectral CT:
    1. There are many ways to obtain spectral CT data (dual source, fast kV-switching, dual layer, split beams, photon-counting detectors)
    2. Spectral CT data can be used to make VMIs, VUE/VNCs, and material density maps
3. Quantification issues:
    1. Beam hardening, caused by patient thickness changing effective beam energy, leads to a suppression of CT numbers
    2. Due to assumed water background, material quantification and suppression can be inaccurate

Thank you! Questions?

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