Living at the K-Edge: Is it Iodine Forever?

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DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Disclaimer

- This talk is about physics.
- This talk is not about chemistry.
- Contrast agent in this talk refers to the atom that generates the contrast and not to the molecule into which the atom is integrated.
- Other atoms in such molecules typically are H, C, N, O and have atomic numbers as 1, 6, 7, and 8 and thus are x-ray interaction-wise not much different from water or soft tissue.
- Contrast is generated by high Z materials, and by high densities.

Can CT do Molecular Imaging?

- To obtain an enhancement of 100 HU, in the order of 10^{19} atoms iodine (or gadolinium) per mL are required.[1]
- A human cell approximately occupies a sphere of 25 µm diameter.
- Thus, in the order of 10^{11} iodine (or gadolinium) need to be populated within or on the surface of a cell.

- The answer is: No ☹

- Why not?
  - PET requires only about 10^8 tracer atoms per mL and thus about 1 per cell[2].
  - PET tracer atoms shout “We are here!”.
  - CT iodine atoms are quiet and need to be probed by an x-ray photon.
  - There are not more than 10^5 x-ray photons probing a mm^2. Many iodine atoms are needed to increase the likelihood of having some of the x-ray photons hit an iodine atom.

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[1] About $2.3\cdot10^{22}$ iodine atoms fit into a mL and make about 128 kHU. Scaling linearly down to 100 HU yields about $1.8\cdot10^{19}$ iodine atoms per mL.

[2] C.S. Levin. New Imaging Technologies to Enhance the Molecular Sensitivity of Positron Emission Tomography. IEEE Proc., vol. 96(3):439-467, 2008.

Element	Z	K-edge	HVL	HVL×ρ	Hygrosc.	Cost (2025)	Machinability
Silicon	14	1.8 keV	13.213 mm	3.08 g/cm^2	Low	1.70 $/kg	Moderate
Calcium	20	4.0 keV	11.862 mm	2.05 g/cm^2	High	2.28 $/kg	Low
Copper	29	9.0 keV	1.001 mm	0.89 g/cm^2	Low	6.00 $/kg	High
Silver	47	25.5 keV	0.251 mm	0.26 g/cm^2	Low	521.00 $/kg	High
Cadmium	48	26.7 keV	0.293 mm	0.25 g/cm^2	Low	4.10 $/kg	Low
Tin	50	29.2 keV	0.315 mm	0.23 g/cm^2	Low	18.70 $/kg	High
Iodine	53	33.2 keV	0.404 mm	0.20 g/cm^2	Moderate	35.00 $/kg	Low
Barium	56	37.4 keV	0.505 mm	0.18 g/cm^2	High	0.26 $/kg	Low
Cerium	58	40.4 keV	0.239 mm	0.16 g/cm^2	Moderate	4.64 $/kg	Moderate
Gadolinium	64	50.2 keV	0.169 mm	0.13 g/cm^2	Moderate	28.60 $/kg	Moderate
Holmium	67	55.6 keV	0.164 mm	0.14 g/cm^2	Moderate	57.10 $/kg	Moderate
Ytterbium	70	61.3 keV	0.190 mm	0.13 g/cm^2	Moderate	17.10 $/kg	Moderate
Hafnium	72	65.4 keV	0.098 mm	0.13 g/cm^2	Low	900.00 $/kg	Moderate
Tantalum	73	67.4 keV	0.079 mm	0.13 g/cm^2	Low	305.00 $/kg	Low
Tungsten	74	69.5 keV	0.071 mm	0.14 g/cm^2	Low	35.30 $/kg	Low
Gold	79	80.7 keV	0.076 mm	0.15 g/cm^2	Low	44800.00 $/kg	Moderate
Bismuth	83	90.5 keV	0.170 mm	0.16 g/cm^2	Low	6.61 $/kg	Moderate

Used or proposed as prefilter

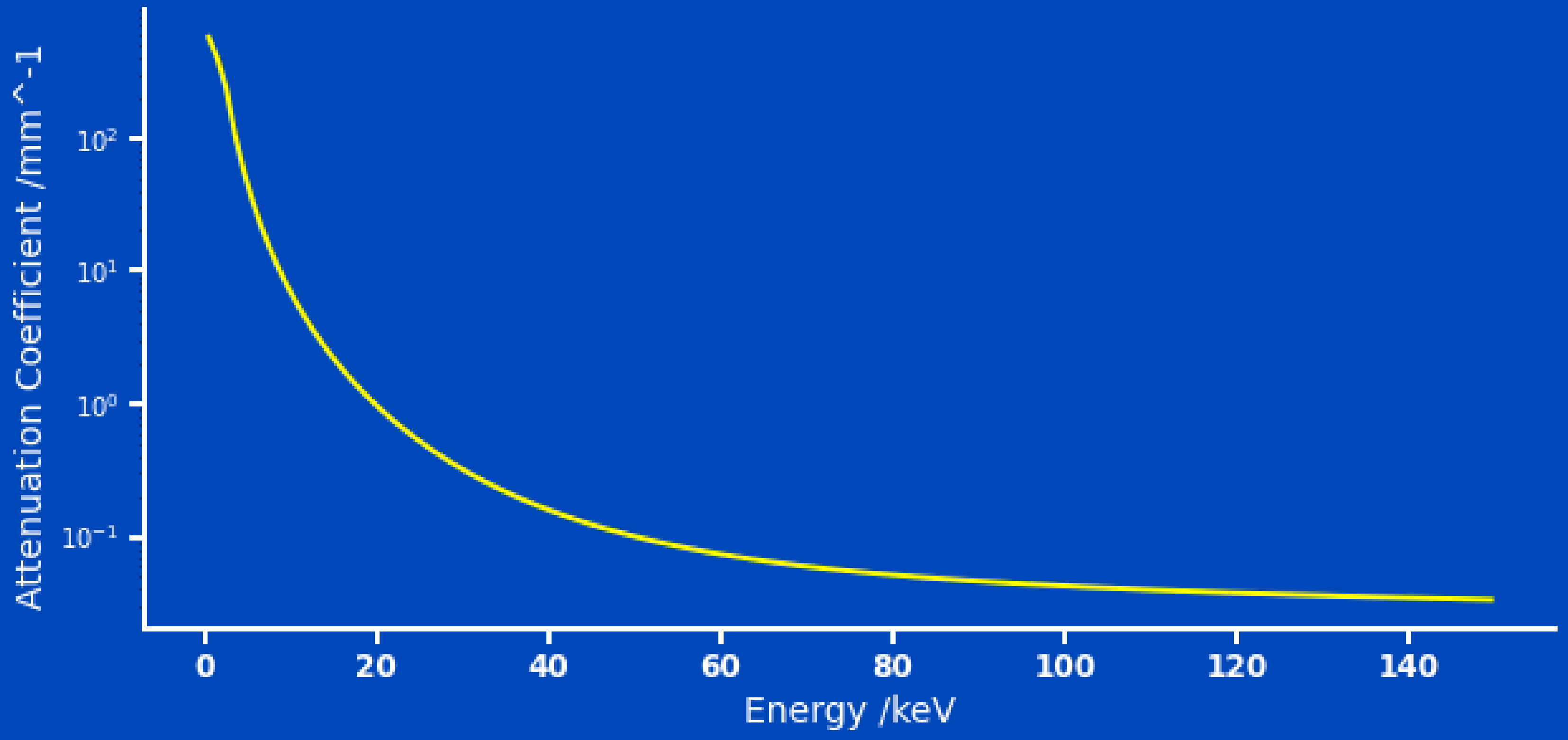
K-edges quite low to discriminate Ca and CA.

K-edges covered by most kV

HVLs are calculated for the 120 kV Tucker spectrum with intrinsic + 32 cm water prefiltration as seen for a 1.6 mm CdTe sensor above 20 keV.

Attenuation Coefficients

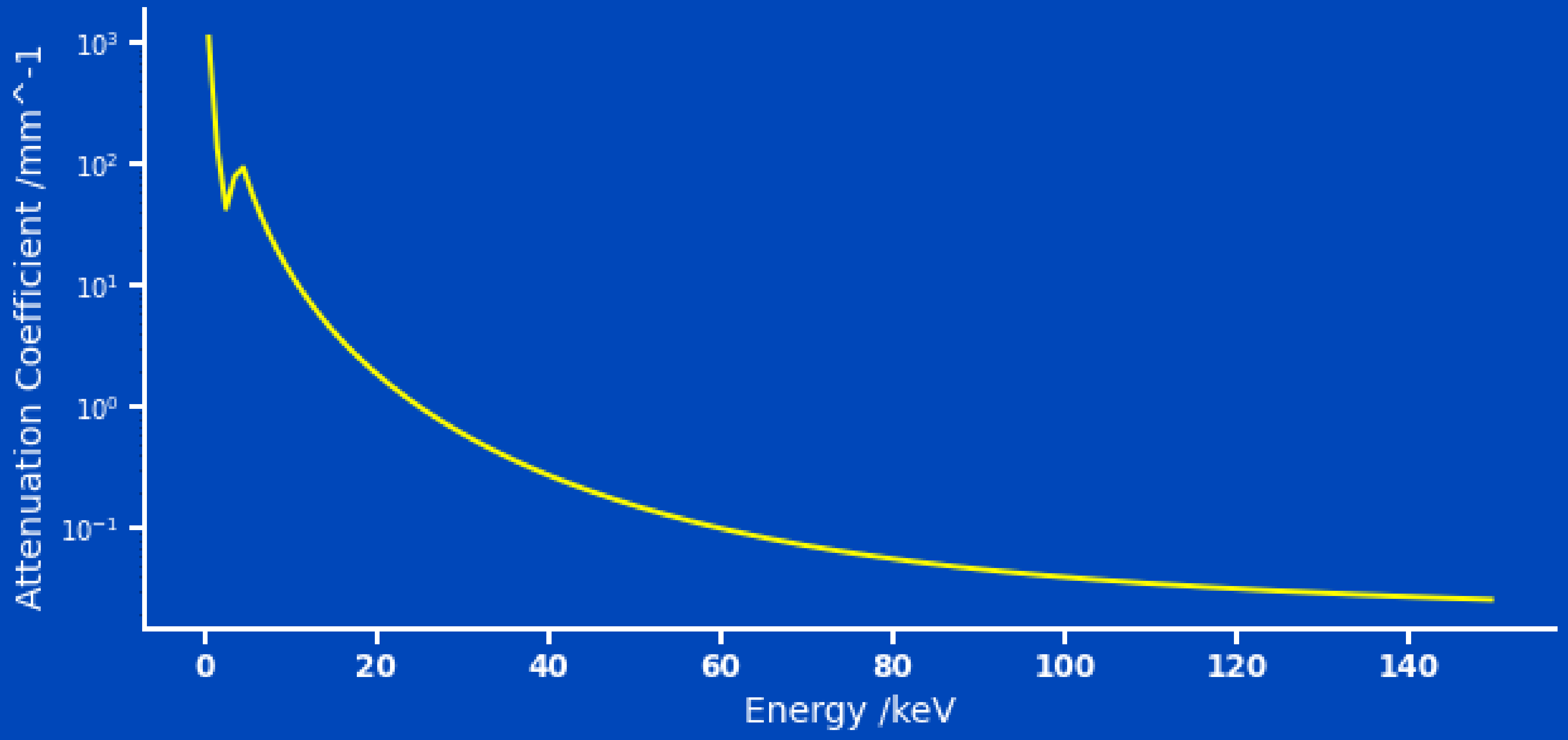
Attenuation coefficient of silicon



energy range “visible” to the detector

Attenuation Coefficients

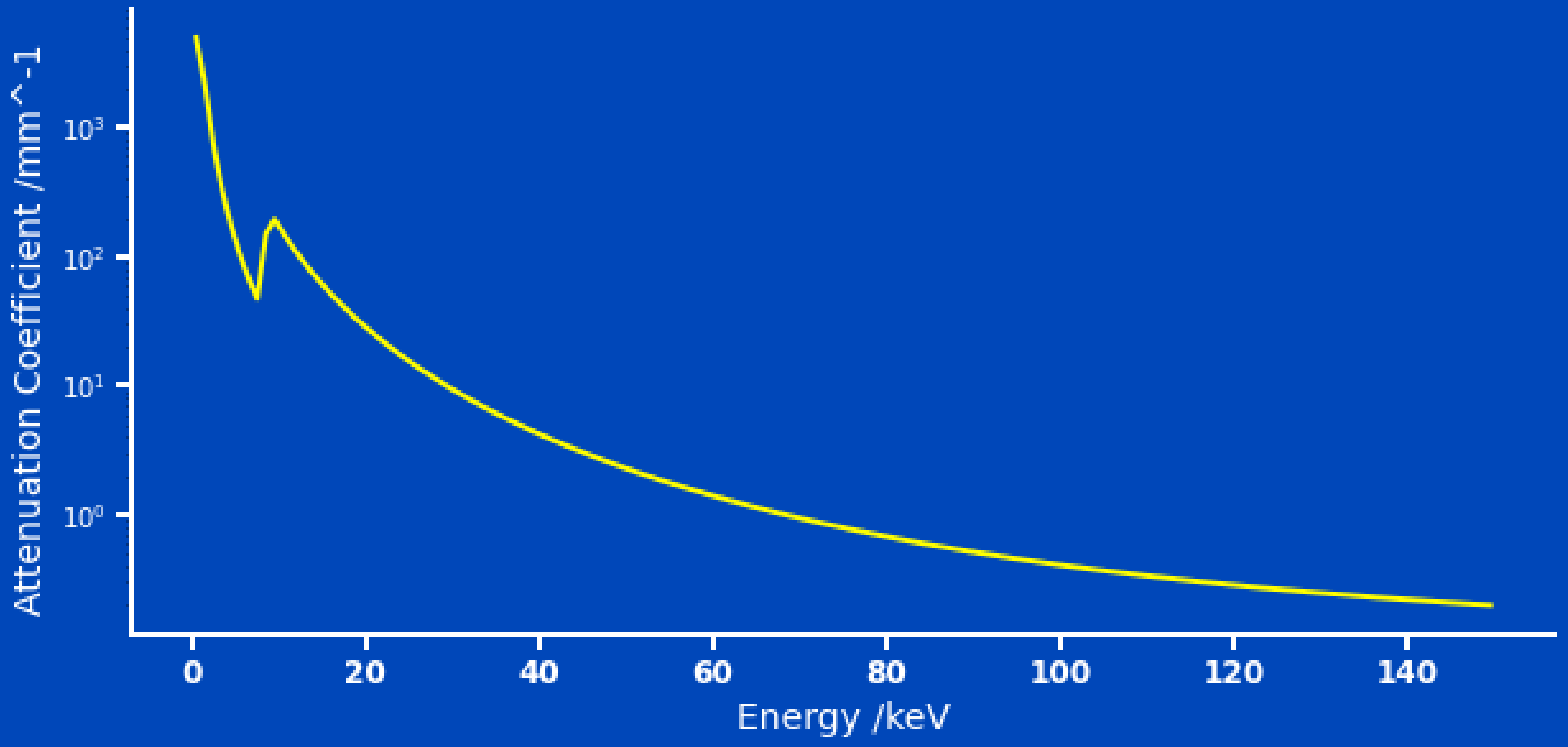
Attenuation coefficient of calcium



energy range “visible” to the detector

Attenuation Coefficients

Attenuation coefficient of copper



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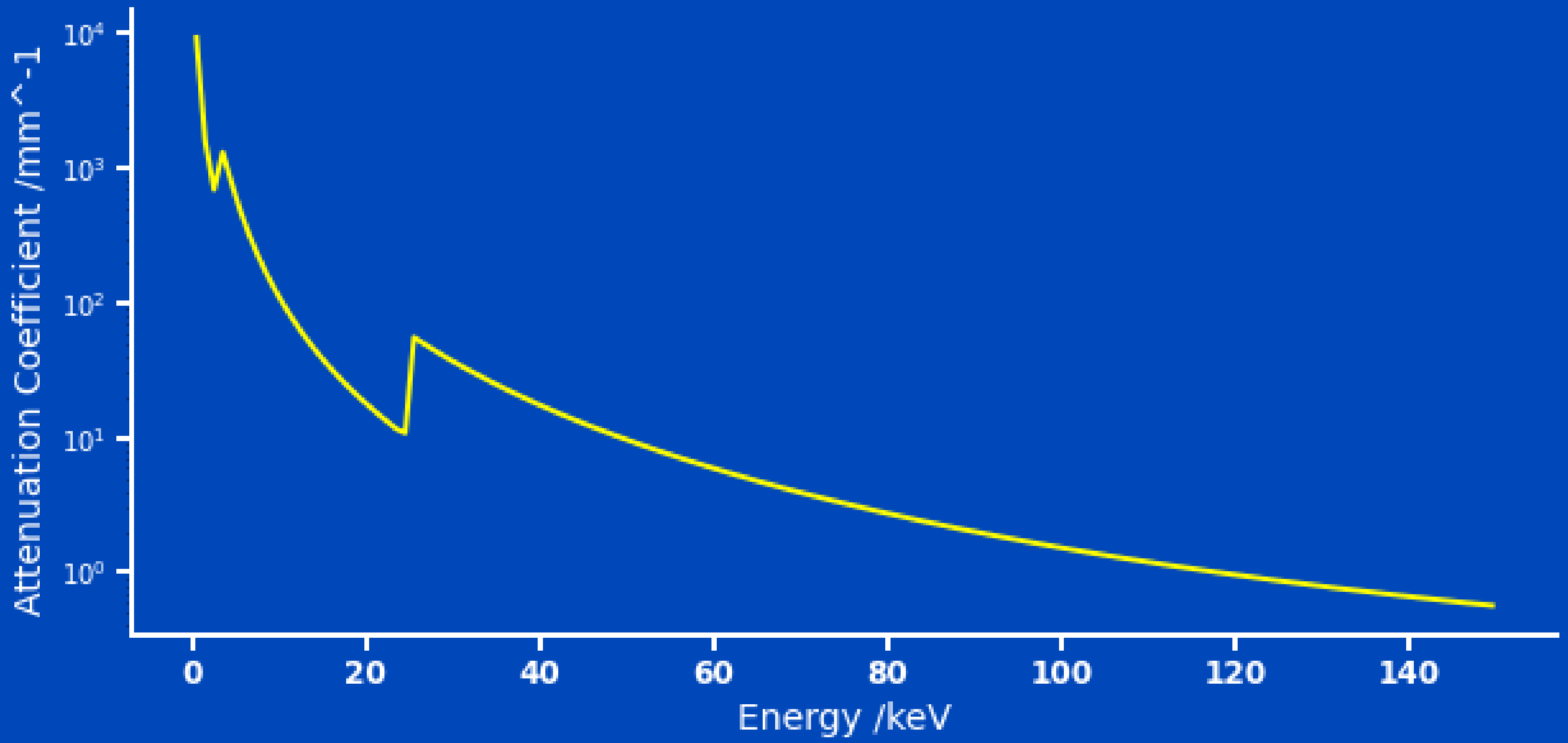

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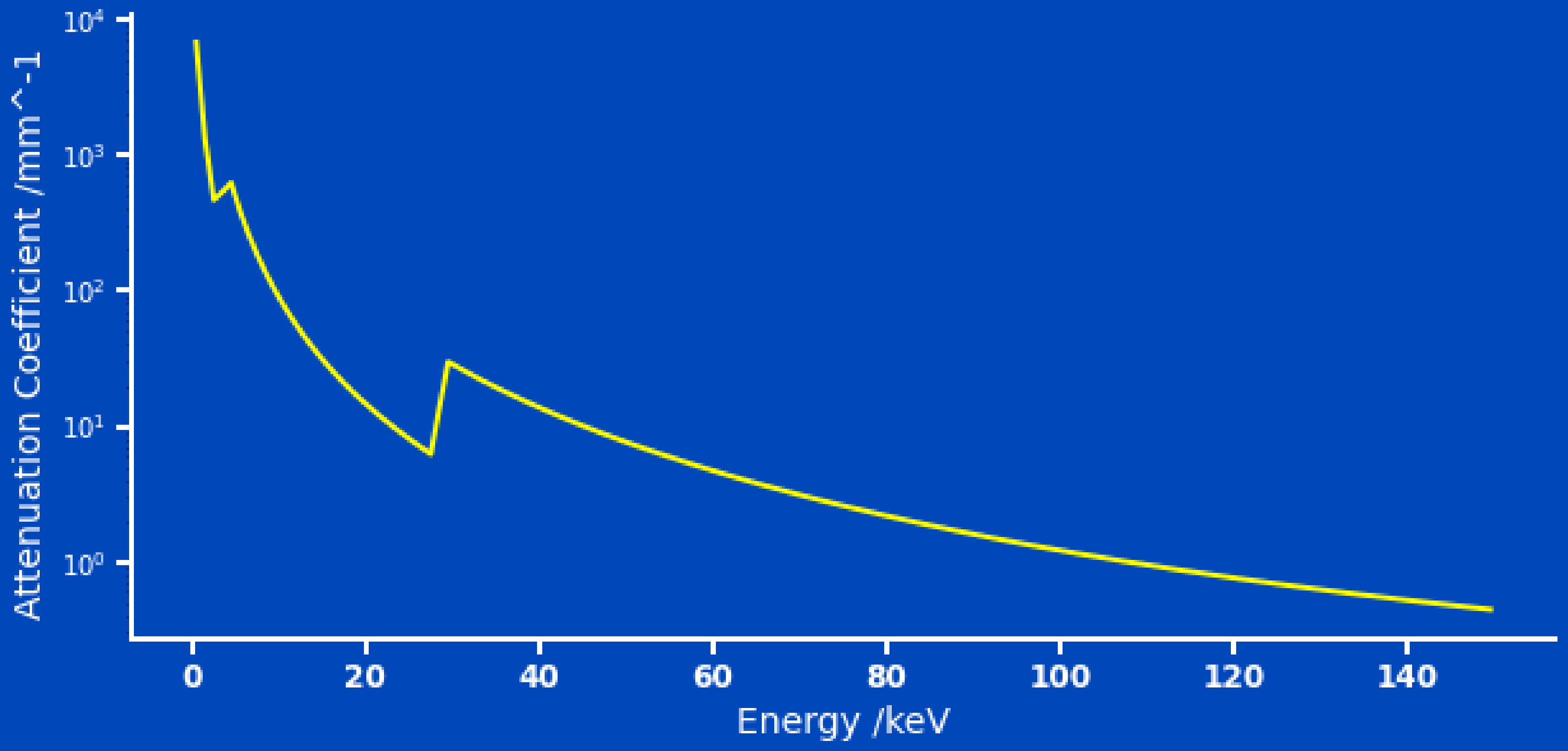
Attenuation Coefficients

Attenuation coefficient of tin



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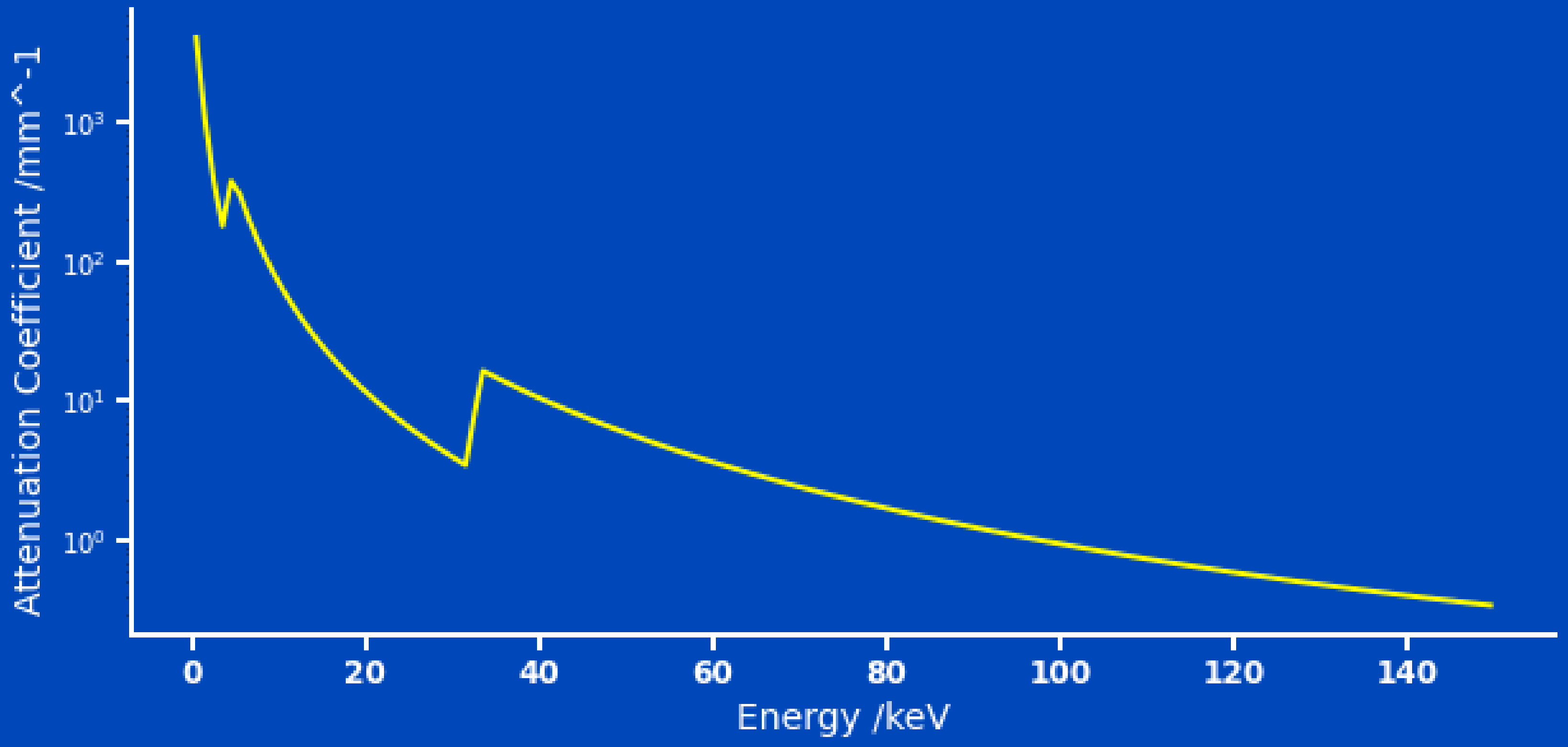

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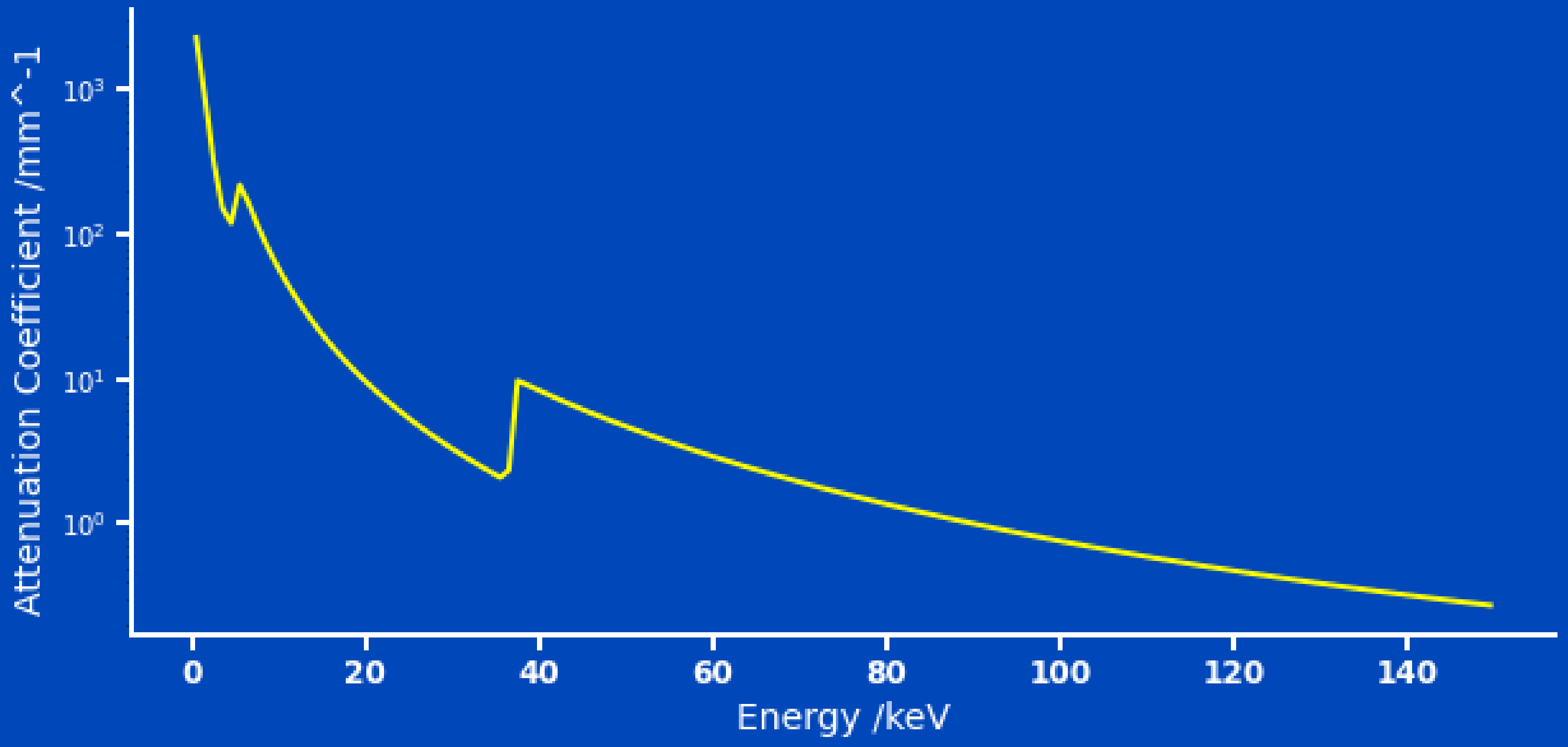
Attenuation Coefficients

Attenuation coefficient of barium



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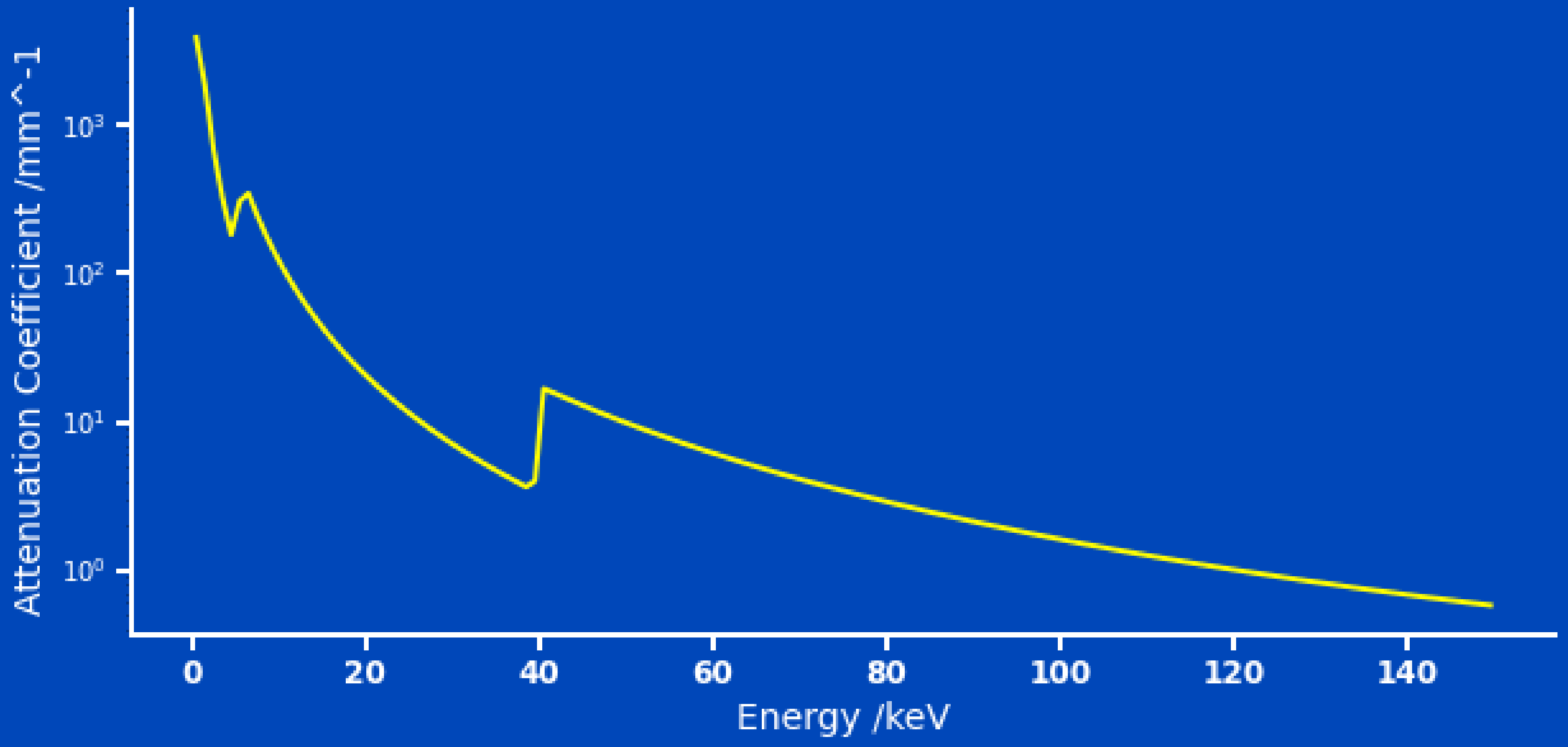
Attenuation Coefficients

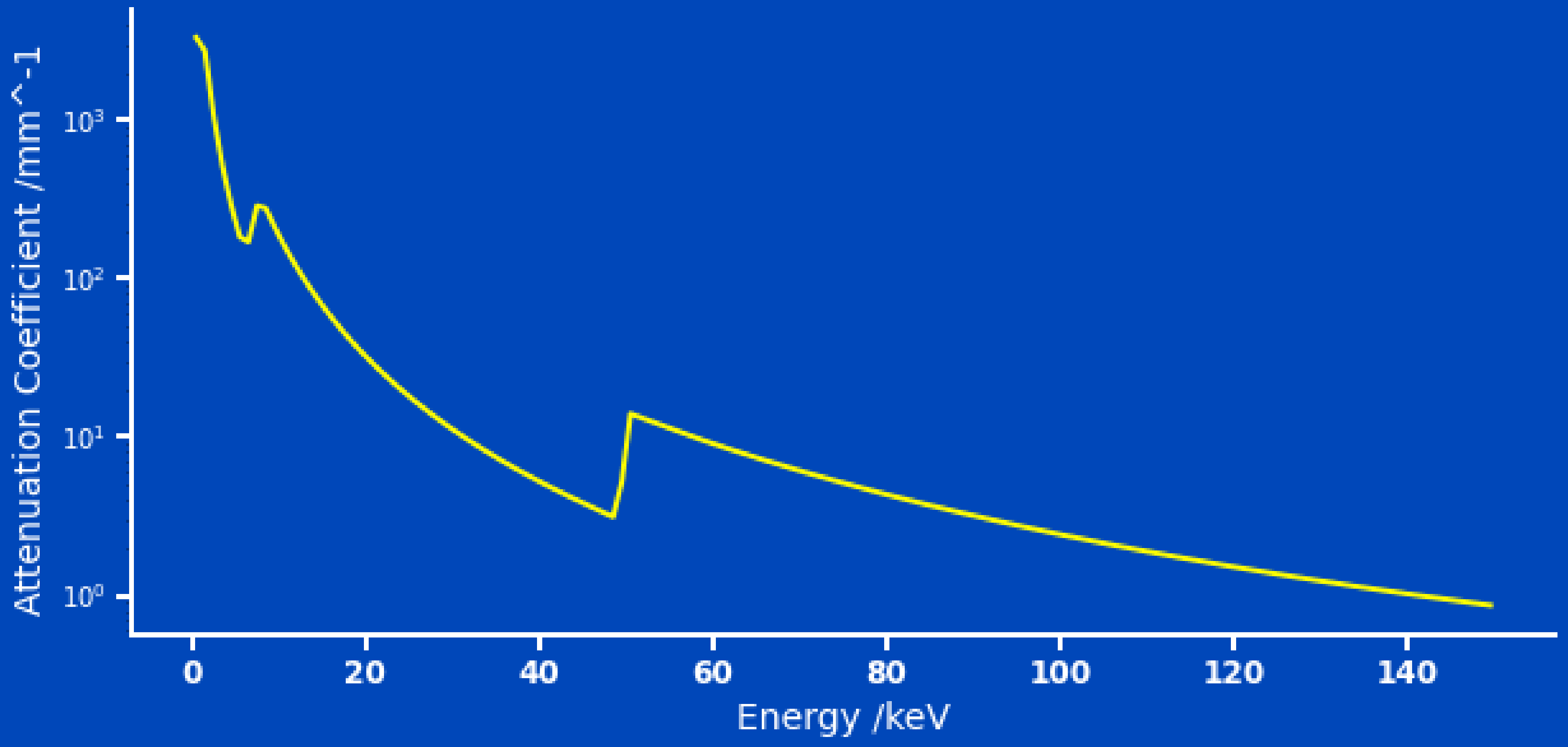
Attenuation coefficient of cerium



energy range “visible” to the detector

Attenuation Coefficients

Attenuation coefficient of gadolinium



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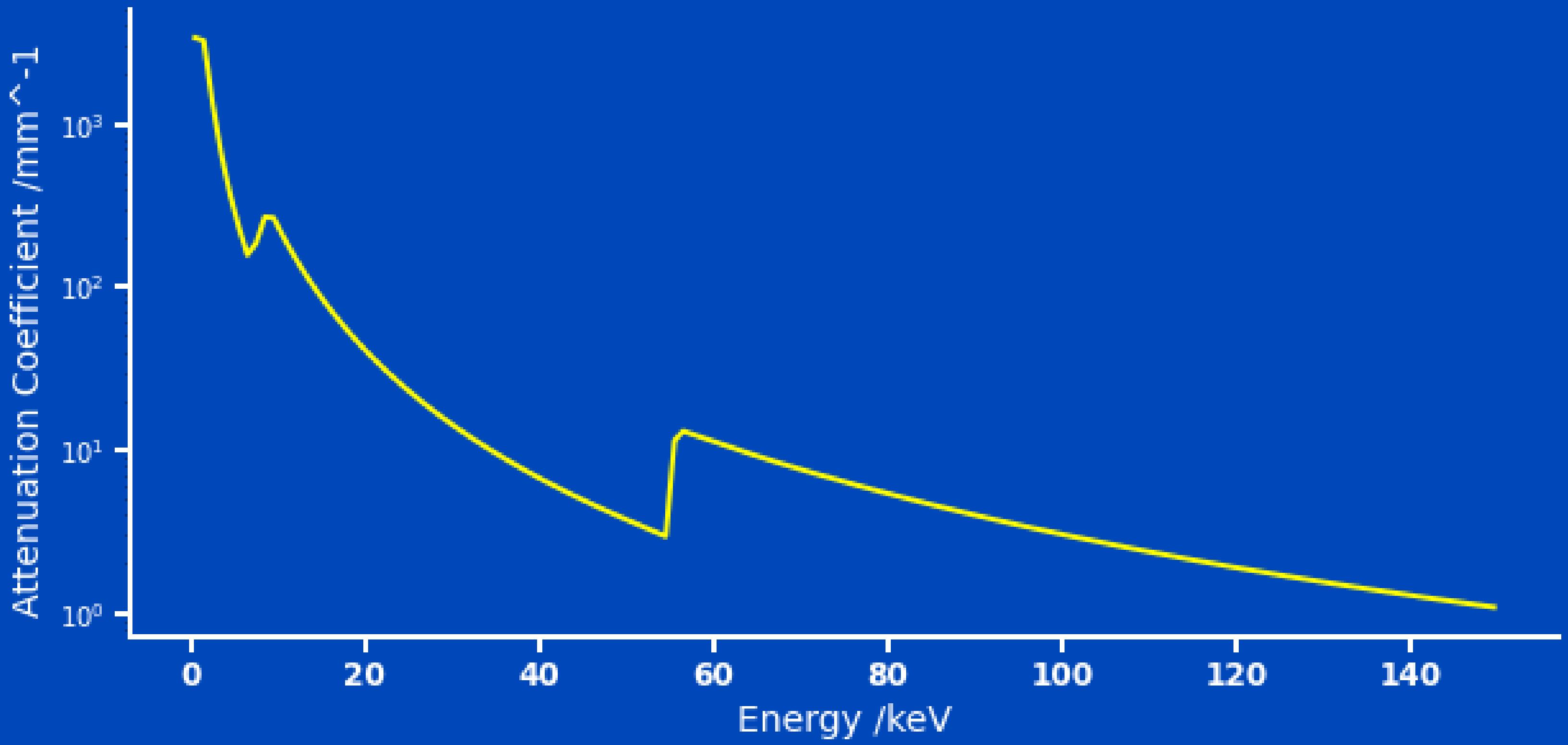
Attenuation Coefficients

Attenuation coefficient of holmium



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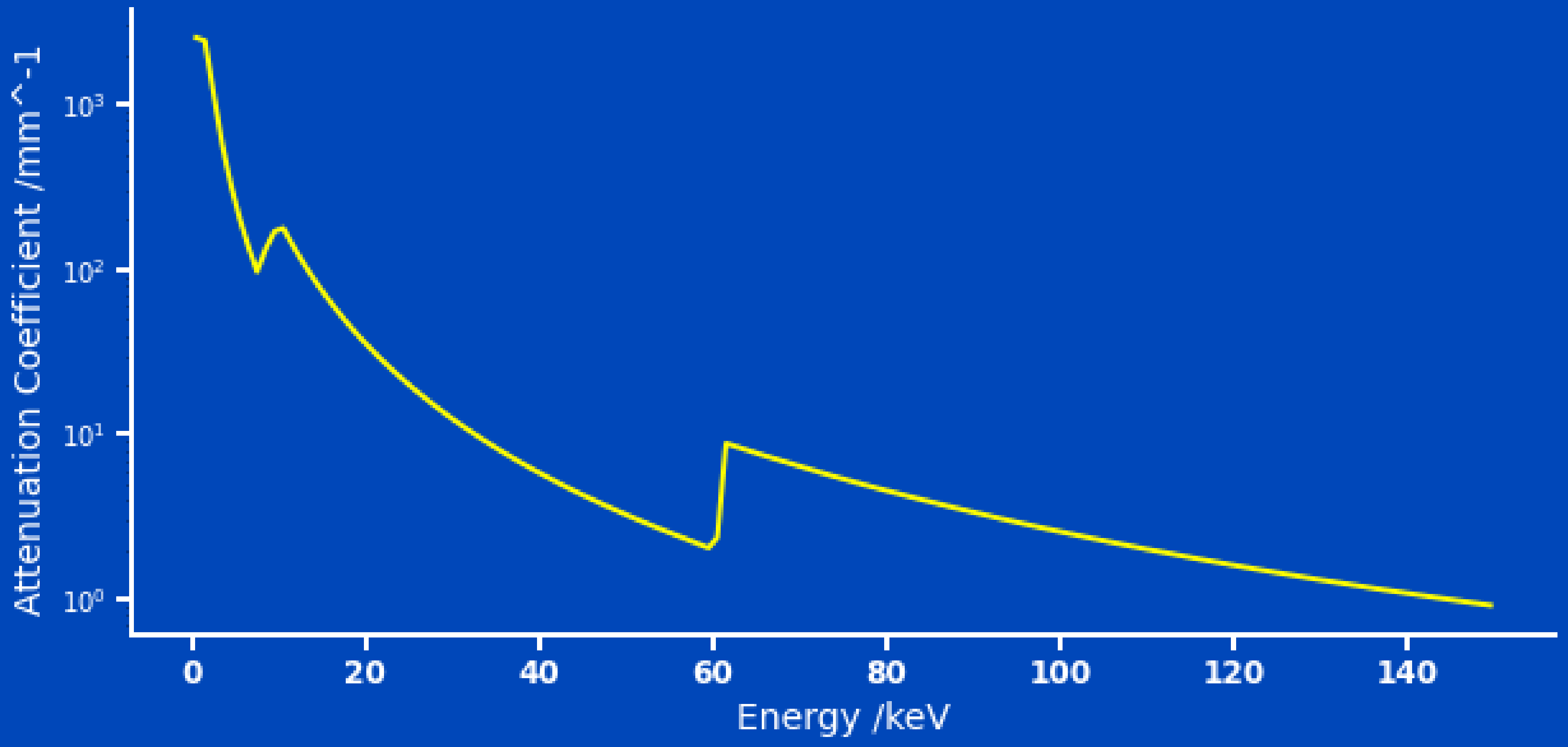

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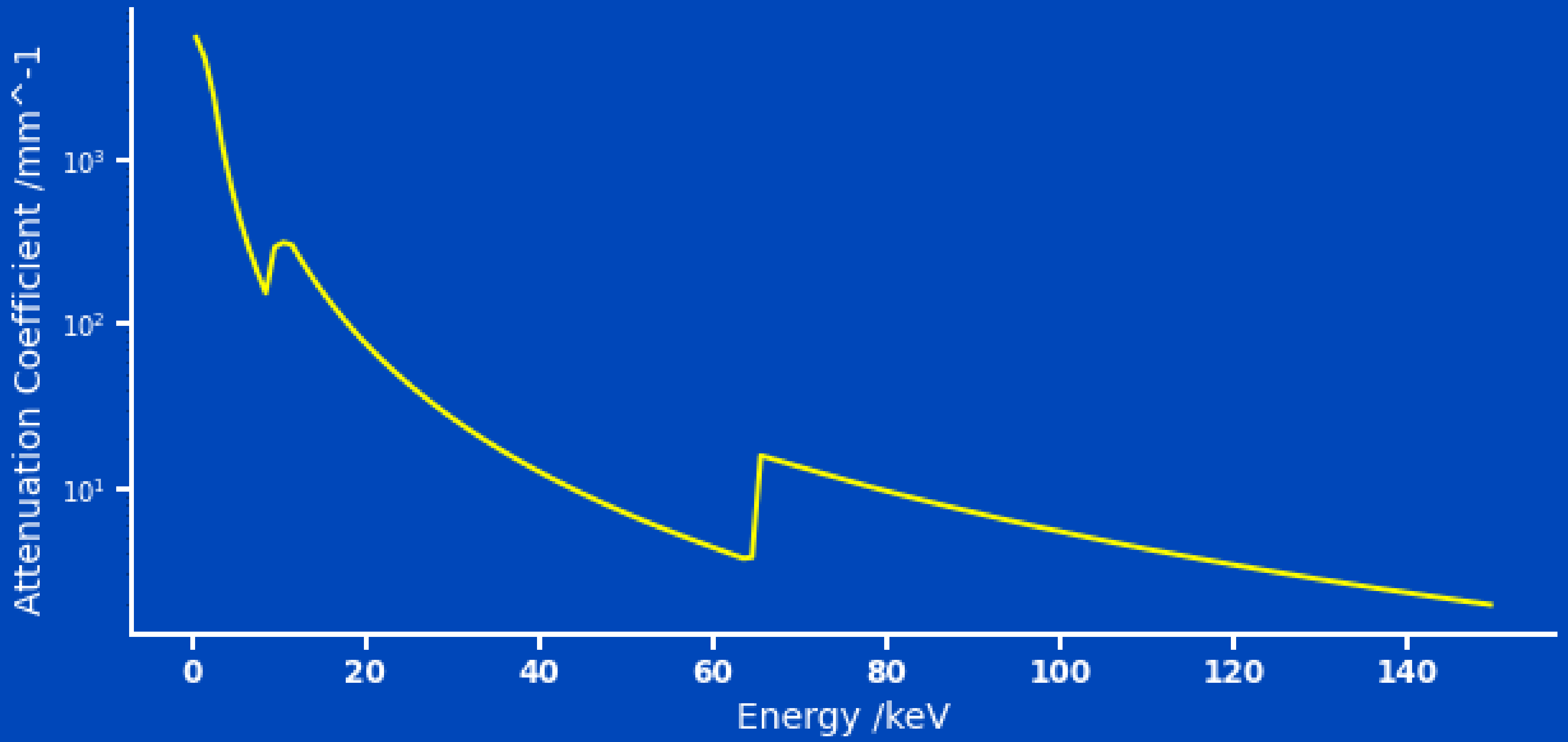
Attenuation Coefficients

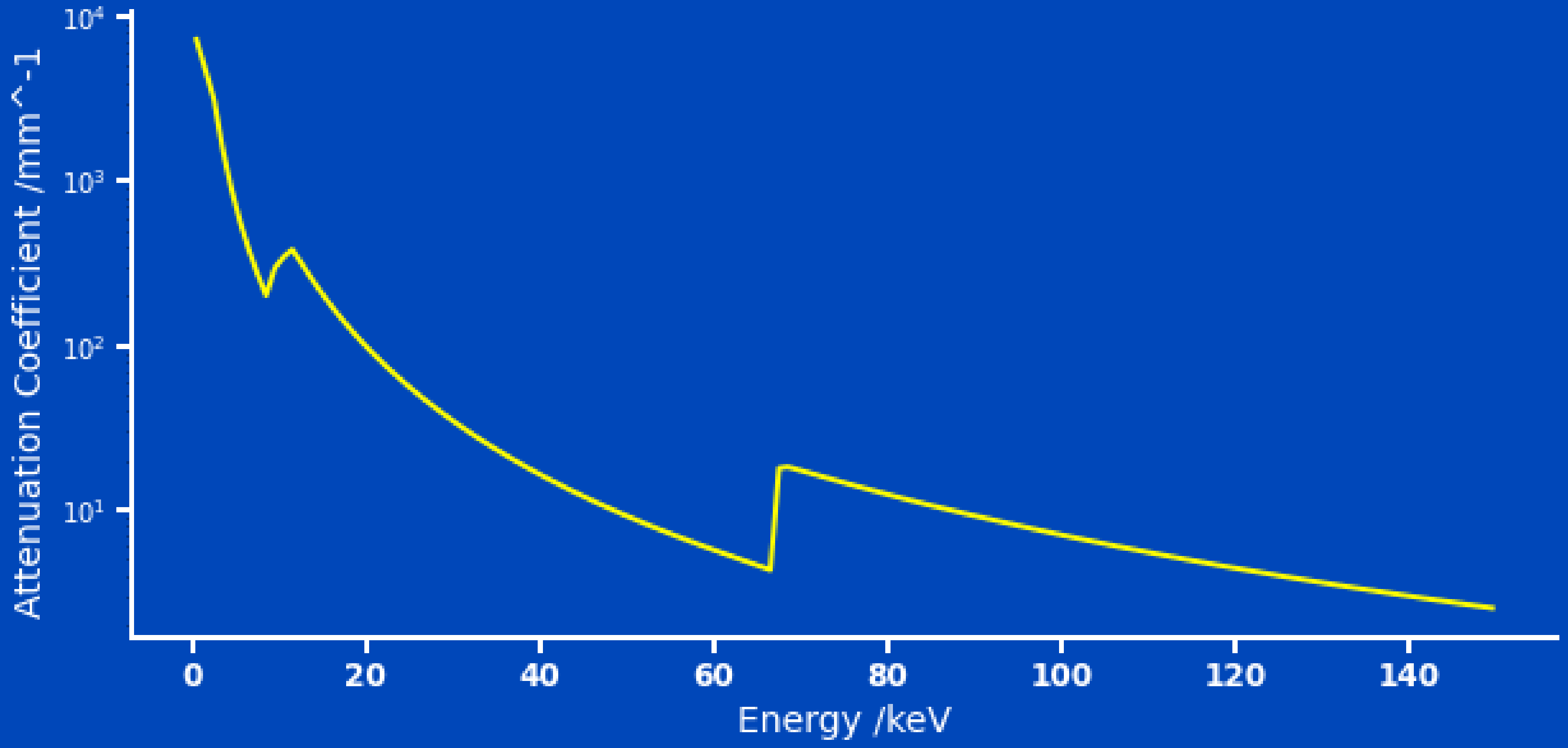
Attenuation coefficient of hafnium



energy range “visible” to the detector

Attenuation Coefficients

Attenuation coefficient of tantalum



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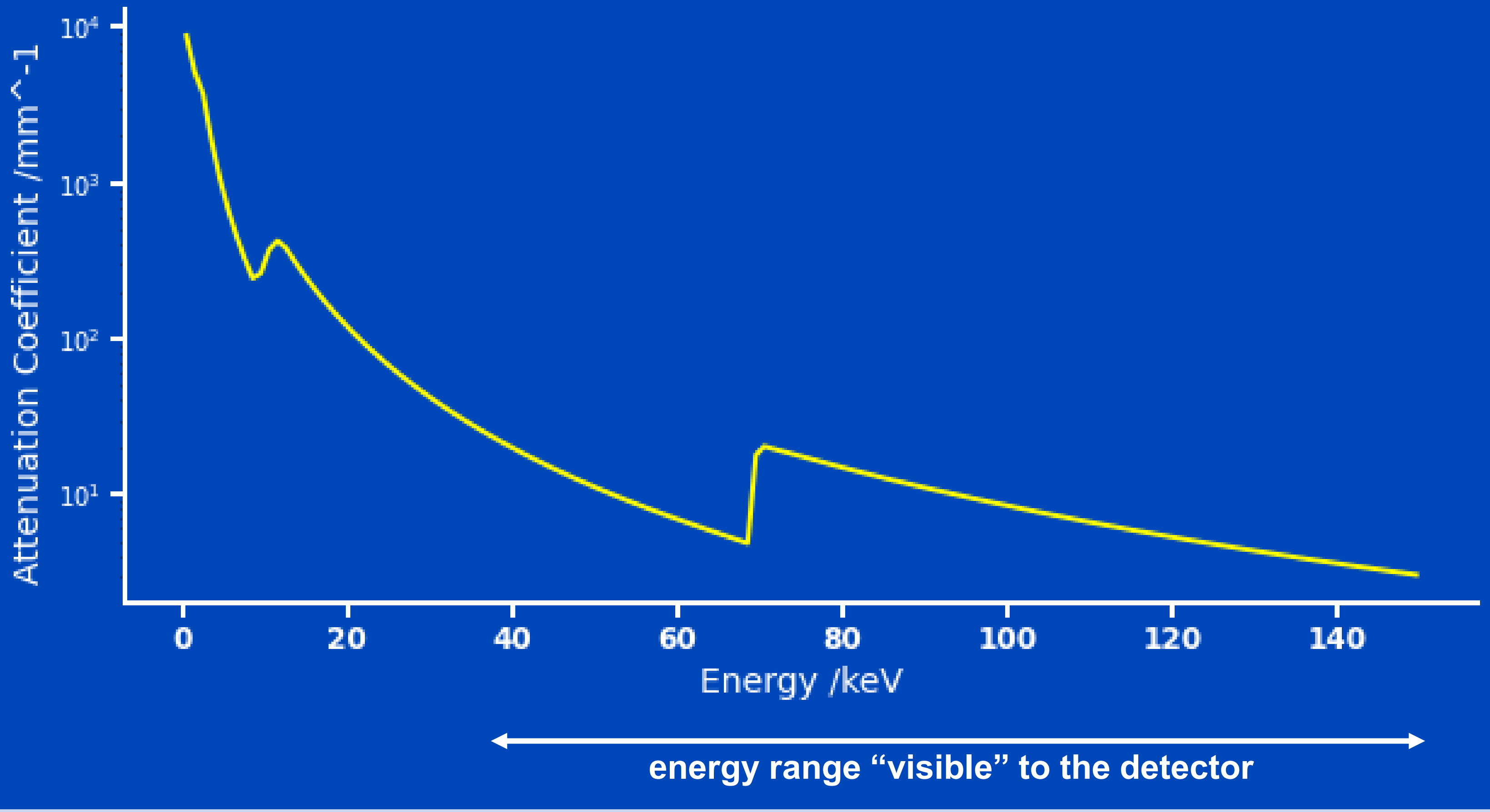
Attenuation Coefficients

Attenuation coefficient of tungsten



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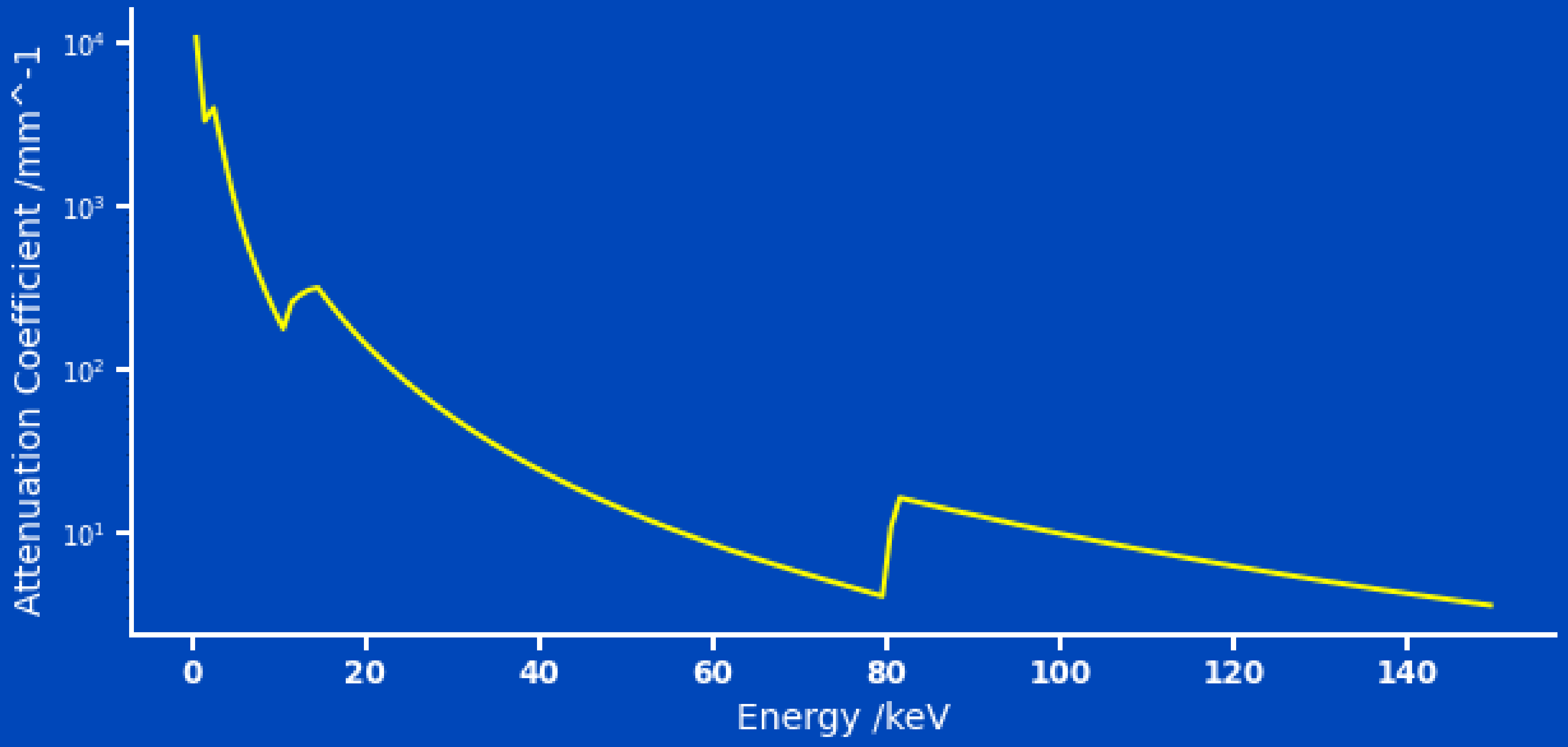
Attenuation Coefficients

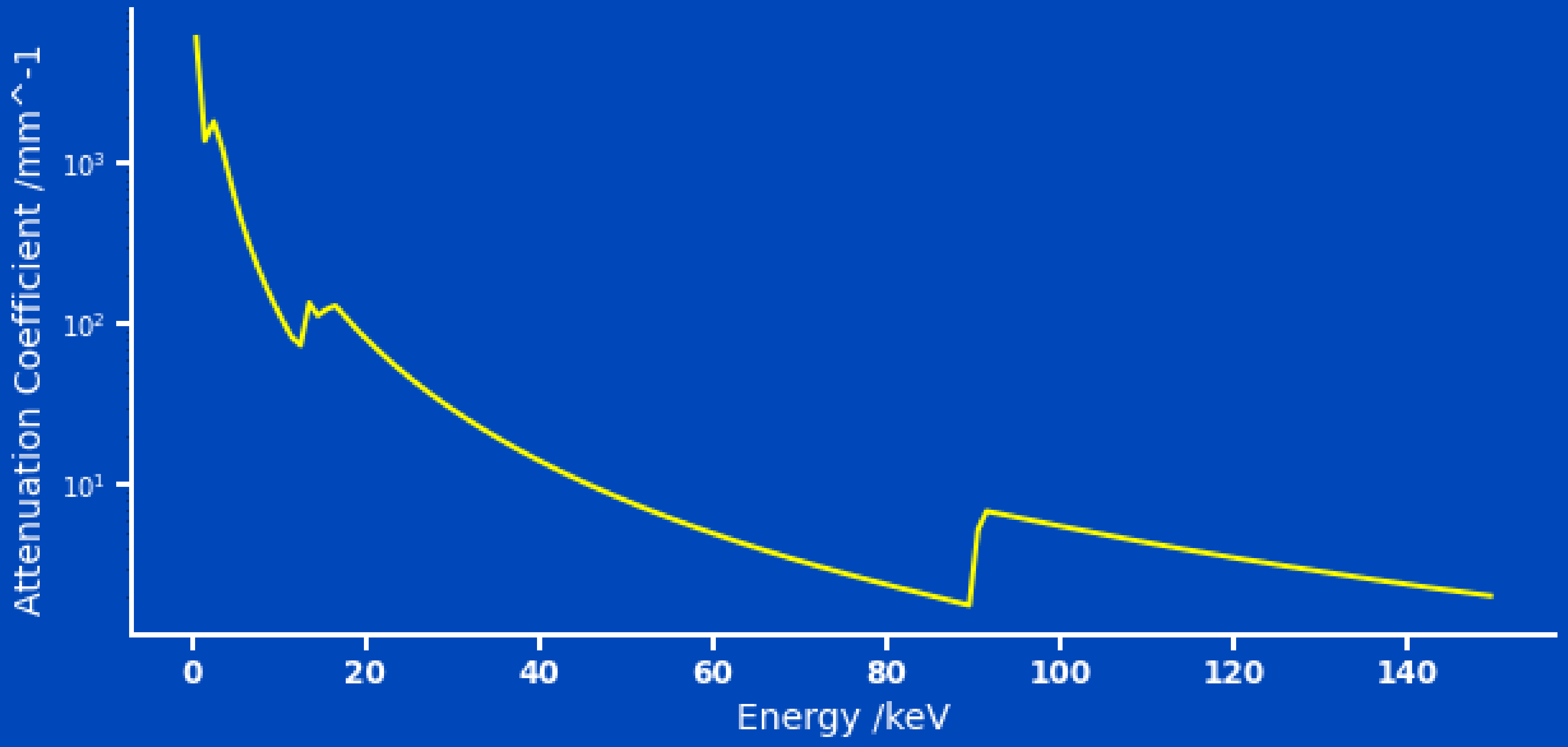
Attenuation coefficient of gold



energy range “visible” to the detector

Attenuation Coefficients

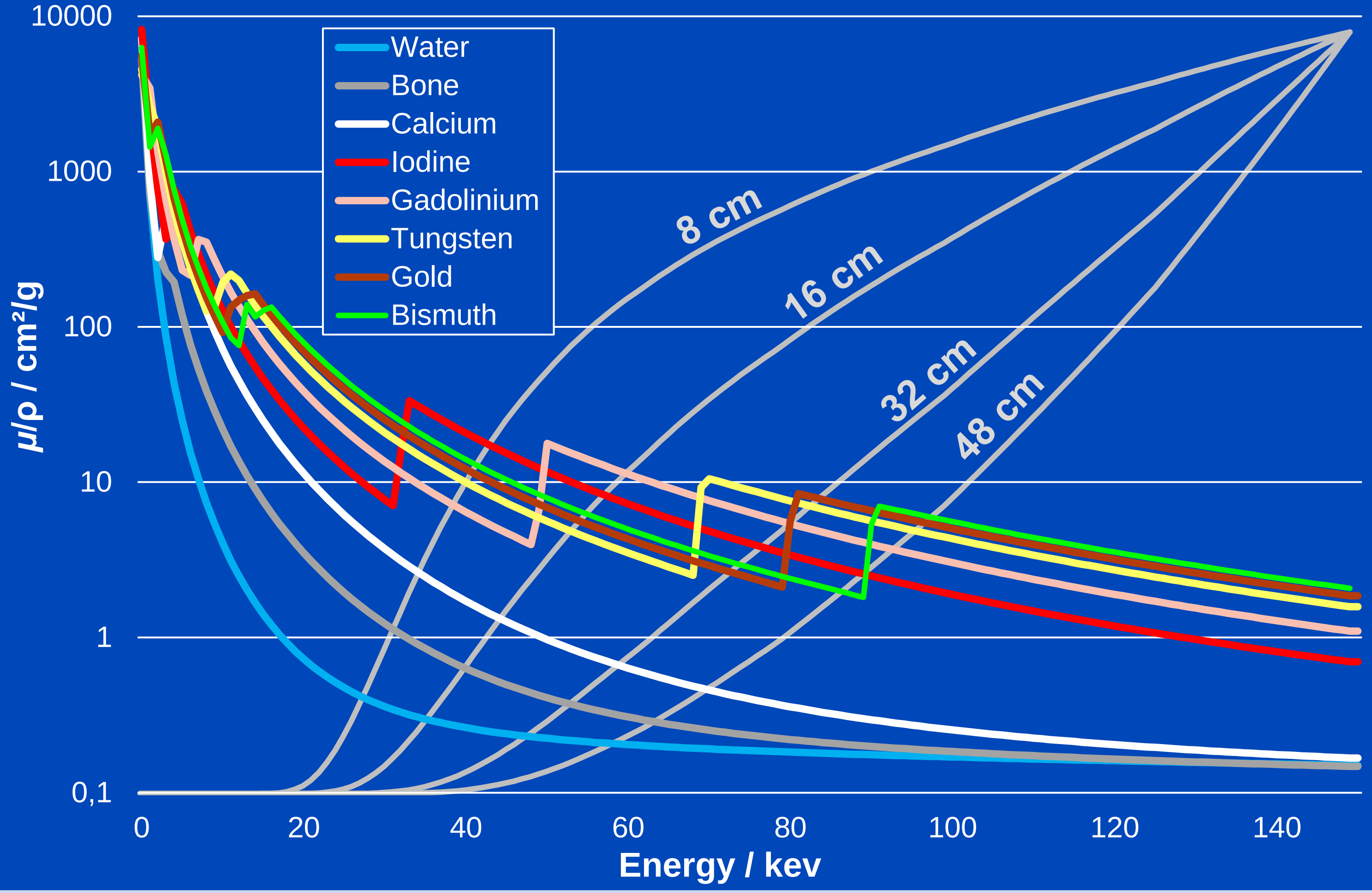
Attenuation coefficient of bismuth



energy range “visible” to the detector

More than Two Materials?

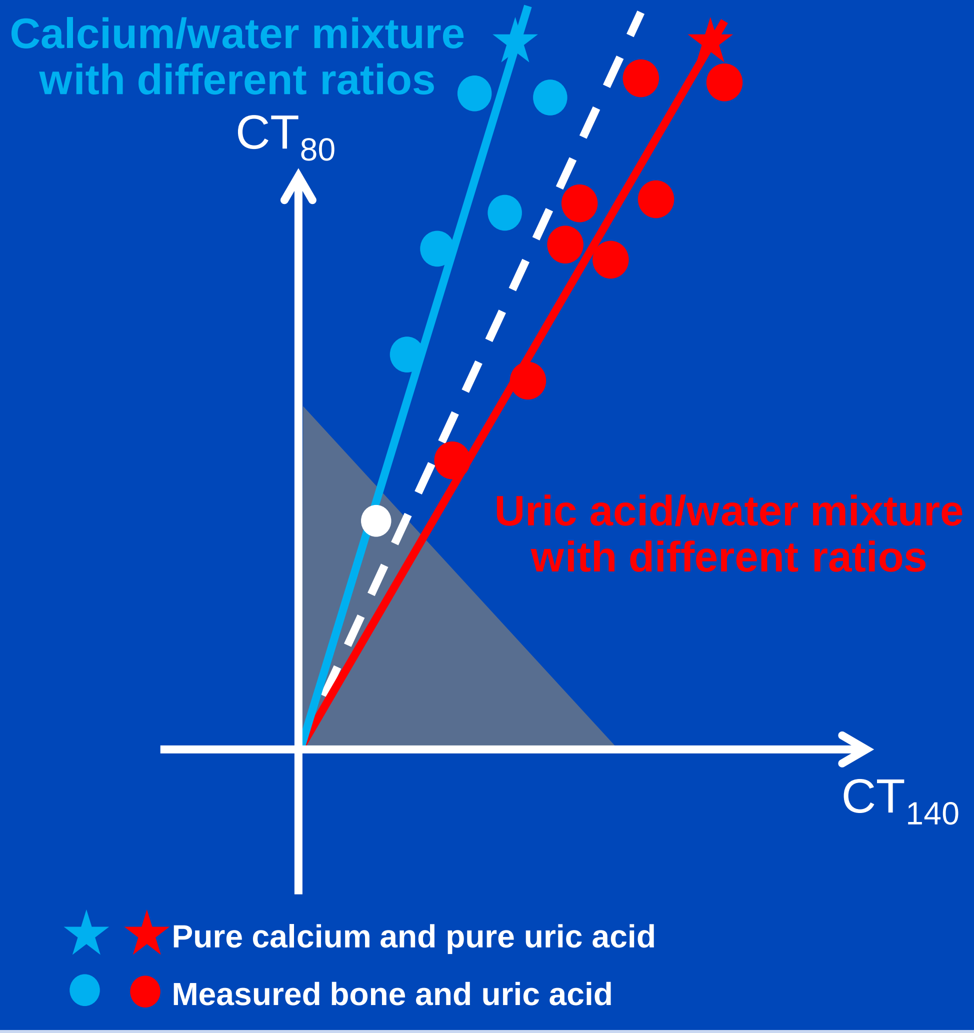
$$\mu(\boldsymbol{r},E) = f_1(\boldsymbol{r})\psi_1(E) + f_2(\boldsymbol{r})\psi_2(E) + \underbrace{f_3(\boldsymbol{r})\psi_3(E) + \ldots}_{\text{Only, if we inject high } Z \text{ materials!}}$$

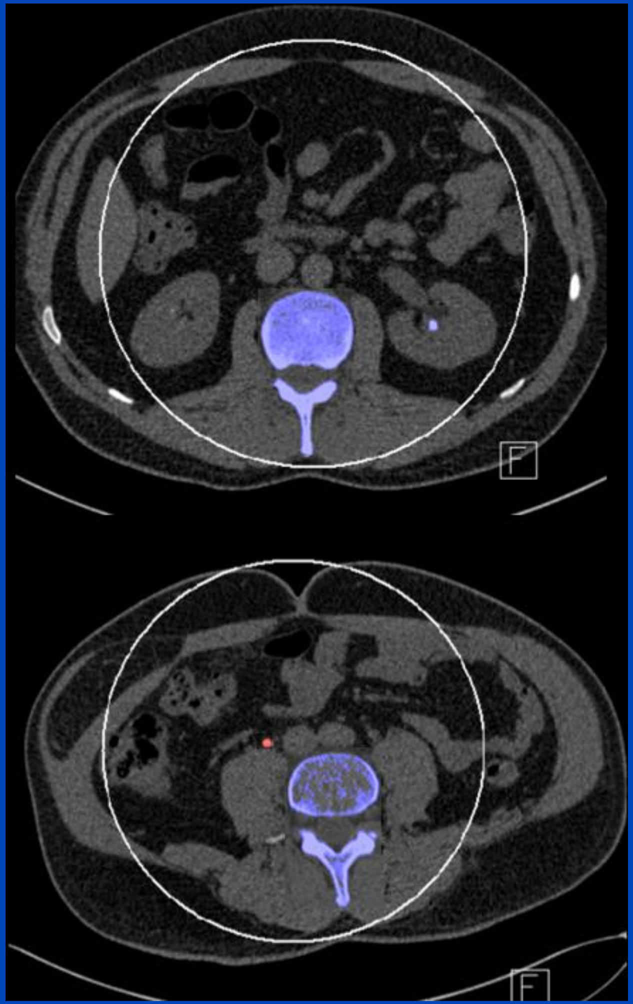


Element	K-edge
O (61%)	< 1 keV
C (23 %)	< 1 keV
H (10%)	< 1 keV
N (2.6%)	< 1 keV
Ca (1.7 %)	4.0 keV
P (1.1%)	2.1 keV
I	**33.2 keV**
Gd	**50.2 keV**
W	**69.5 keV**
Au	**80.7 keV**
Bi	**90.5 keV**

Gray curves: 120 kV water transmission on a non-logarithmic ordinate individually normalized to 1 at 140 keV.

What? Only if we inject high *Z* materials?

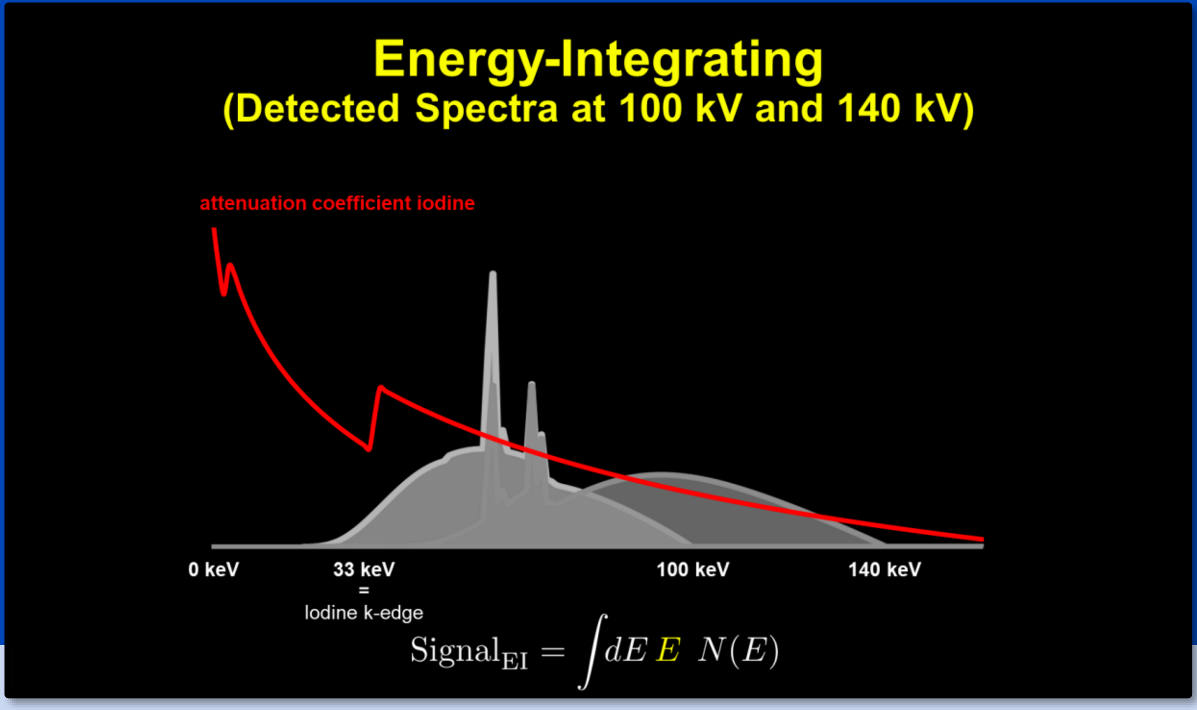




Courtesy of Klinikum Großhadern, LMU
München and of Siemens Healthineers

Iodine in Conventional (Non-Spectral CT)

- Is used successfully for decades as the CT contrast agent.
- However:
  - Iodine‘s k-edge is at 33 keV and forces us to scan with low kV, e.g. 70 kV.
  - Iodine contrast decreases at higher kV, and thus for thicker patients.
- Contrast agents (CAs) with higher k-edges may thus have an advantage
  - Unclear, how great this advantage is. We are doing very well with iodine for decades!



Energy-Integrating

(Detected Spectra at 100 kV and 140 kV)

$$\text{Signal}_{\text{EI}} = \int dE\, E\ N(E)$$

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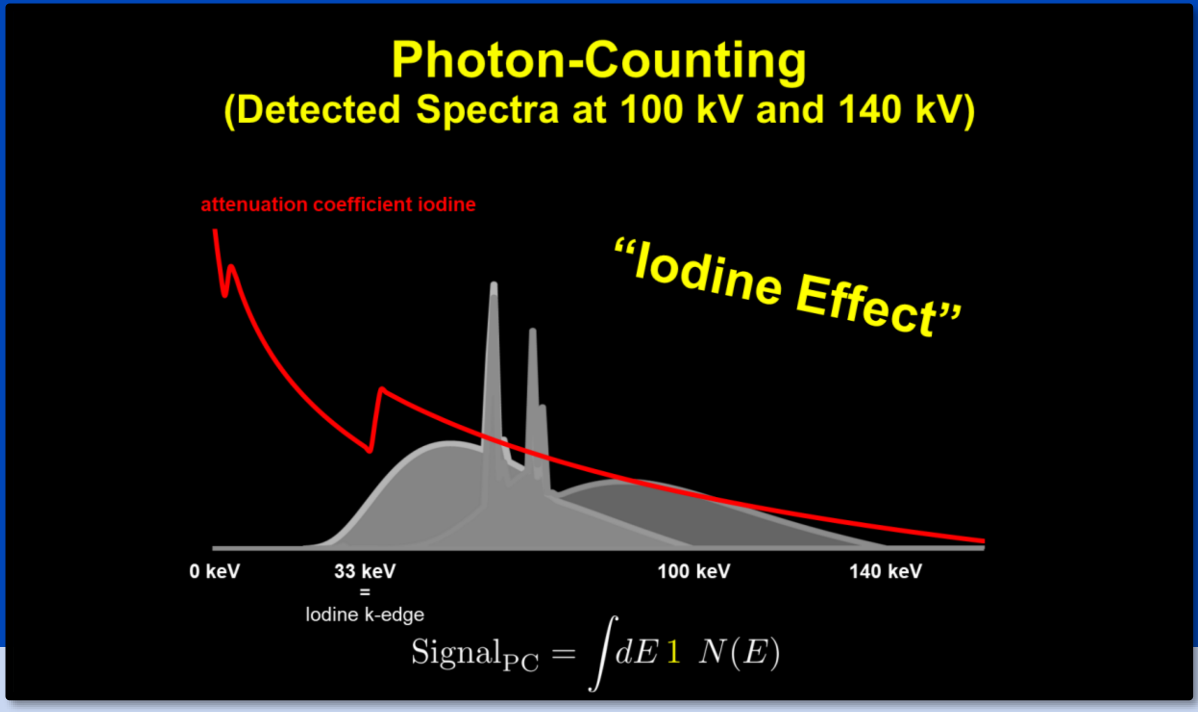


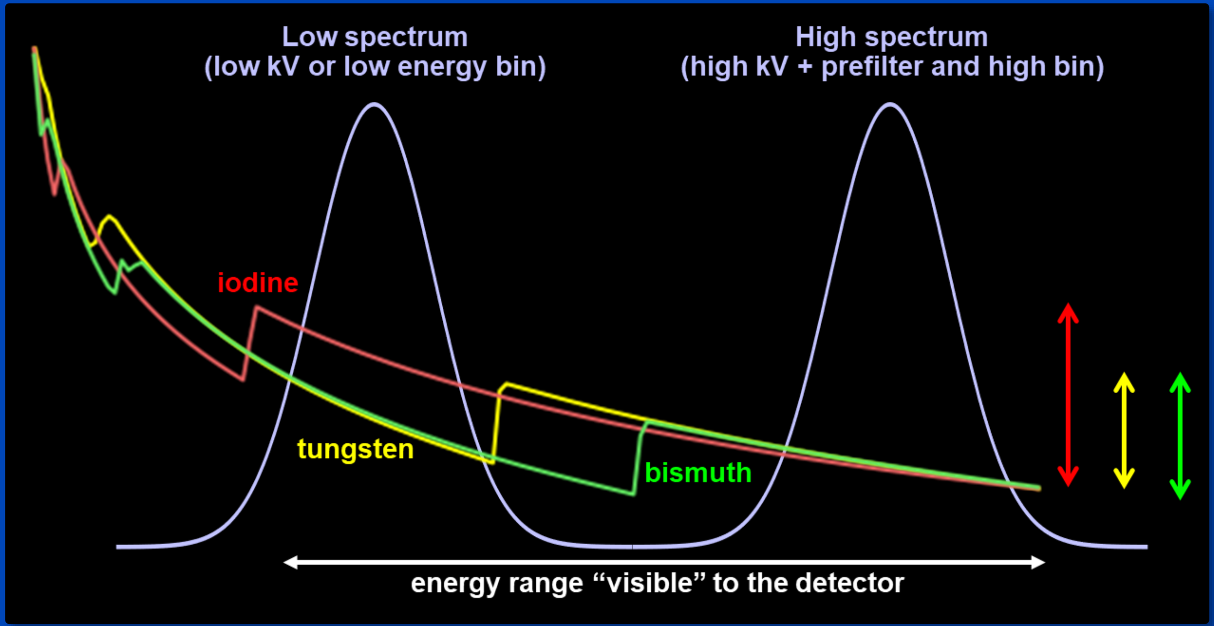
Photon-Counting

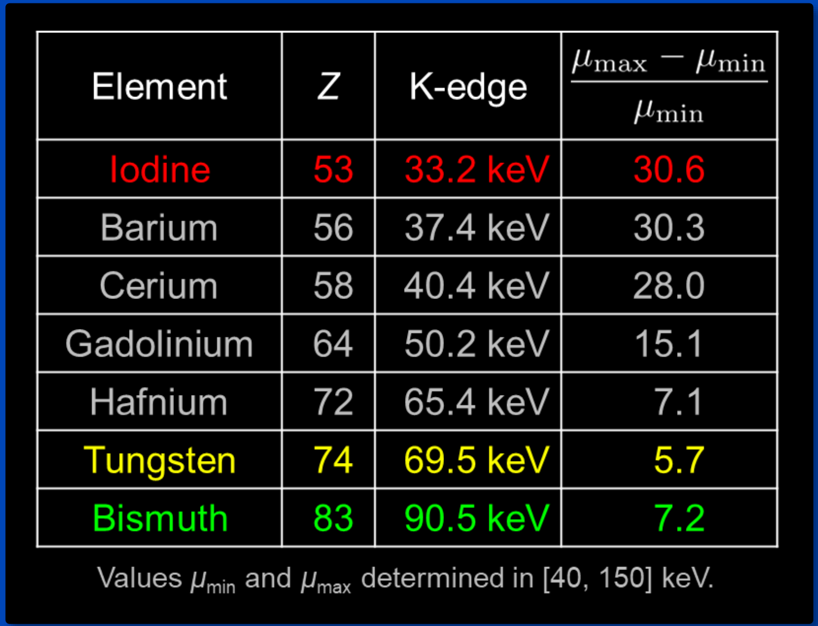
(Detected Spectra at 100 kV and 140 kV)

$$\mathrm{Signal}_{\mathrm{PC}} = \int dE\, 1\; N(E)$$

Iodine in Spectral CT

- Is the best contrast for VNC + CA map material decomposition
  - High contrast at the low end and low contrast at the high end of the photon energies.
  - Spectra (incl. PCCT thresholds) can be best selected to probe those extremes.





Element	Z	K-edge	$\frac{\mu_{\max}-\mu_{\min}}{\mu_{\min}}$
Iodine	53	33.2 keV	30.6
Barium	56	37.4 keV	30.3
Cerium	58	40.4 keV	28.0
Gadolinium	64	50.2 keV	15.1
Hafnium	72	65.4 keV	7.1
Tungsten	74	69.5 keV	5.7
Bismuth	83	90.5 keV	7.2

Values $\mu_{\min}$ and $\mu_{\max}$ determined in [40, 150] keV.

- Scanning with two different contrast agents, X and Y, say, simultaneously, does this make sense?

Proposals to Simultaneously use More than One Contrast Agent, X and Y

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11. R. Symons, B. Krauss, P. Sahbaee, T. E. Cork, M. N. Lakshmanan, D. A. Bluemke, and A. Pourmorteza. Photon-Counting CT for Simultaneous Imaging of Multiple Contrast Agents in the Abdomen: An in Vivo Study, Med. Phys. 44, 5120-5127 (2017).
12. R. Symons, B. Krauss, P. Sahbaee, T. E. Cork, M. N. Lakshmanan, D. A. Bluemke, and A. Pourmorteza. Photon-Counting CT for Simultaneous Imaging of Multiple Contrast Agents in the Abdomen: An in Vivo Study. Med. Phys. 44, 5120-5127 (2017).
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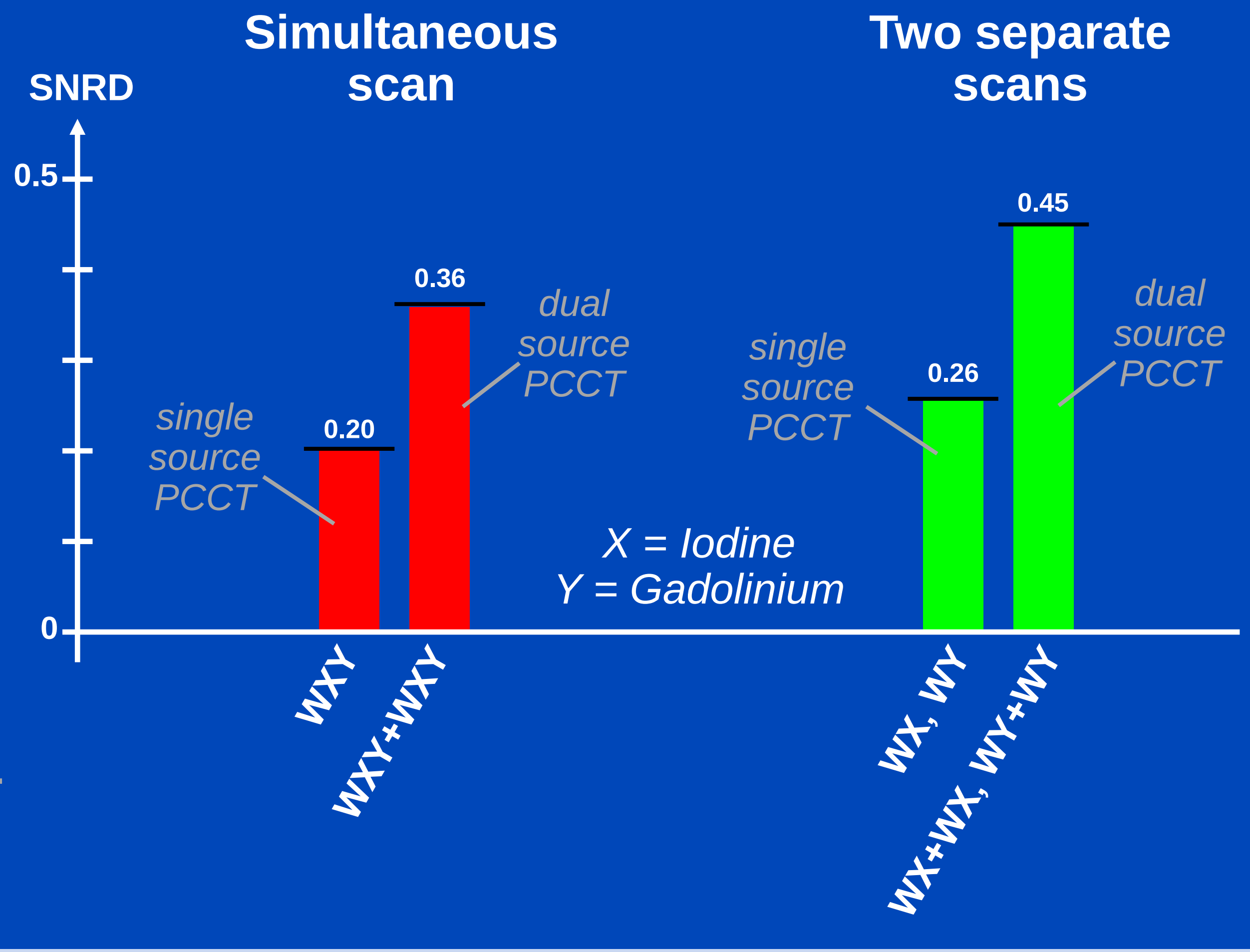
20. … many many more since 2020 …

Two Contrast Agents X and Y in the Same Region

- Must have X ≠ Y if scanned simultaneously.
- Can have X = Y if scanned separately.
- Separate scans require less dose!

- Good old liver protocols are optimal:
  - X = Y = iodine (today)
  - Two separate scans
  - Only one CA injection required
  - Unenhanced scan not necessary with PCCT



Sawall, Kachelrieß et al. CT material decomposition with contrast agents: Single or multiple spectral photon–counting CT scans? Med. Phys. 52, 2025.

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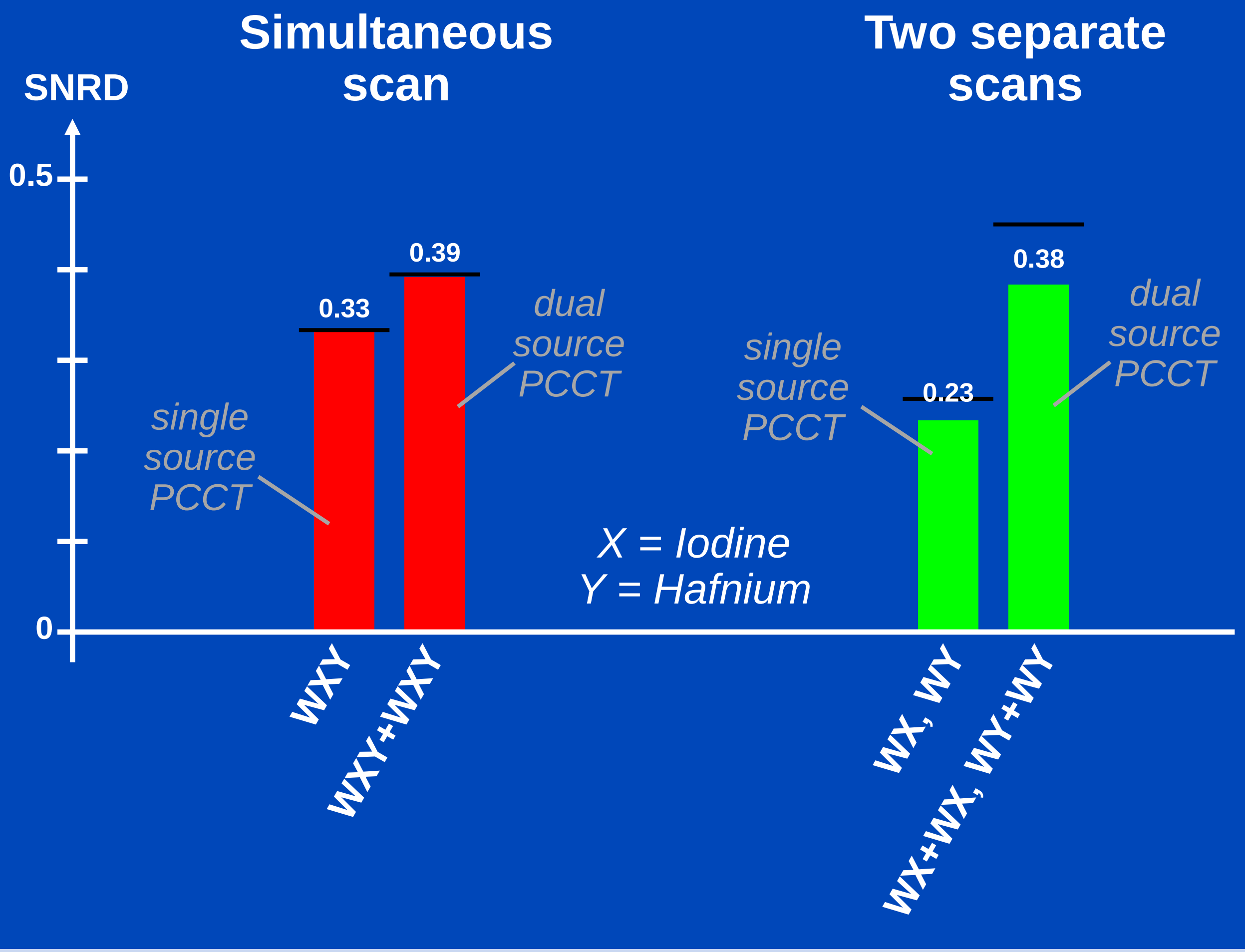

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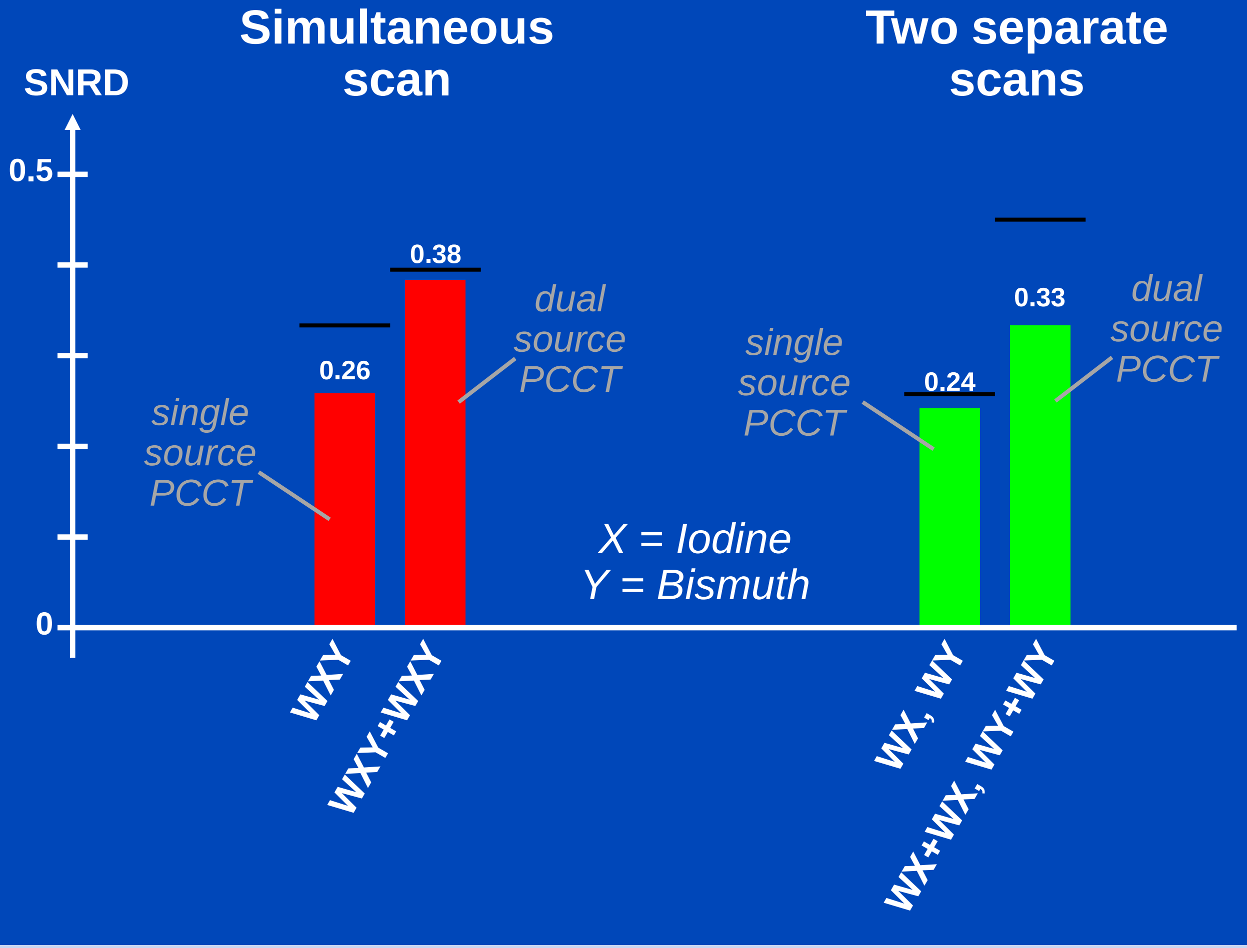

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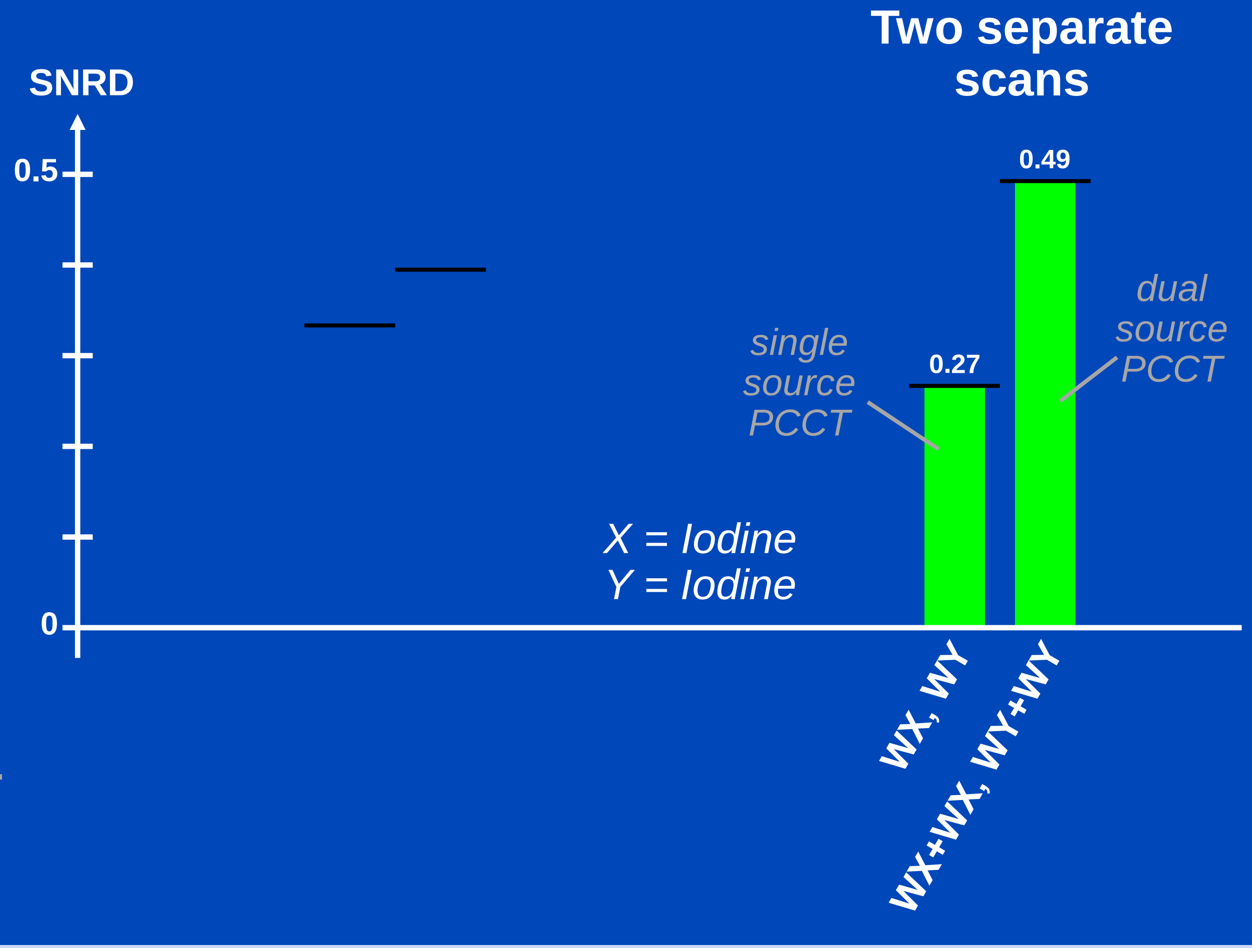

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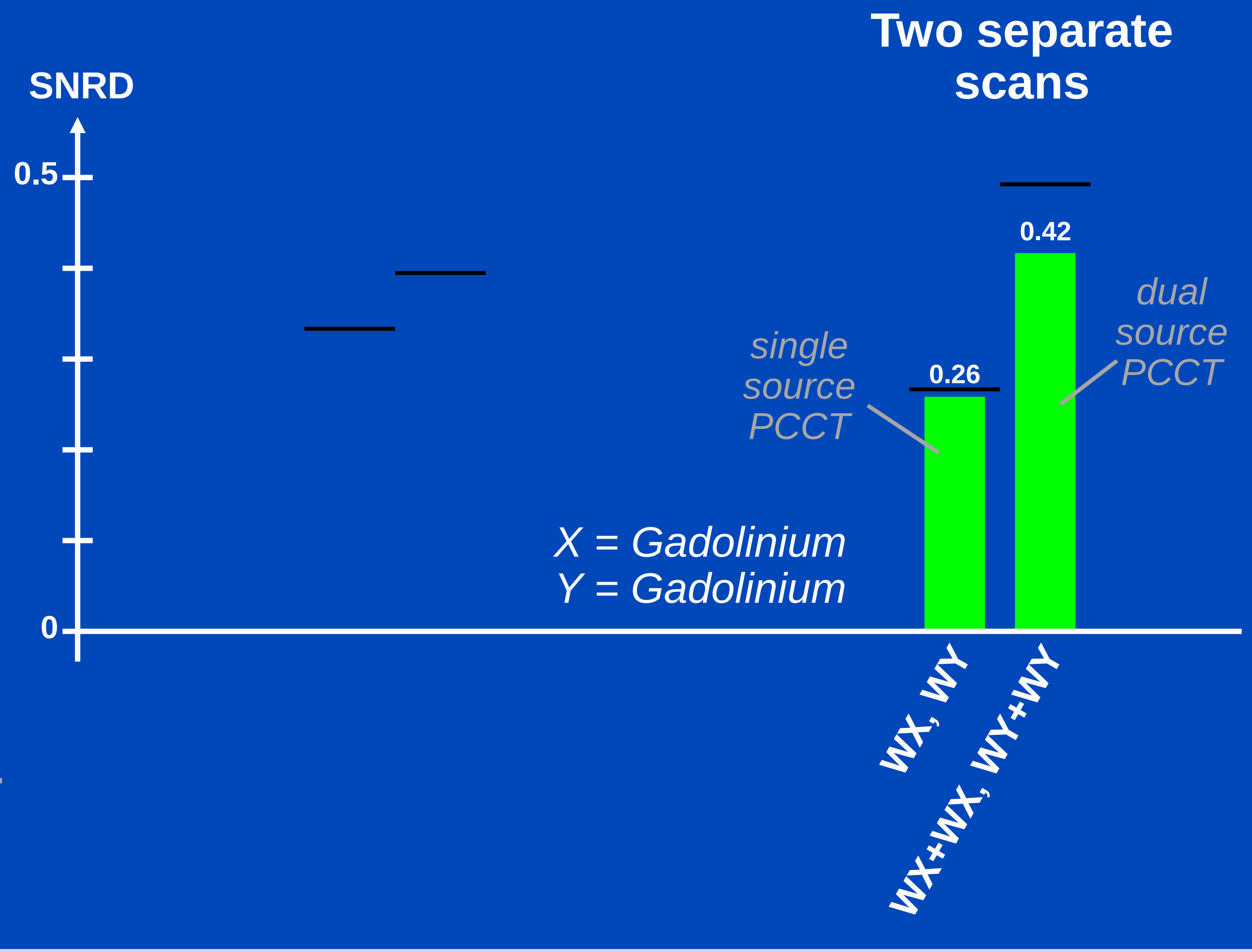

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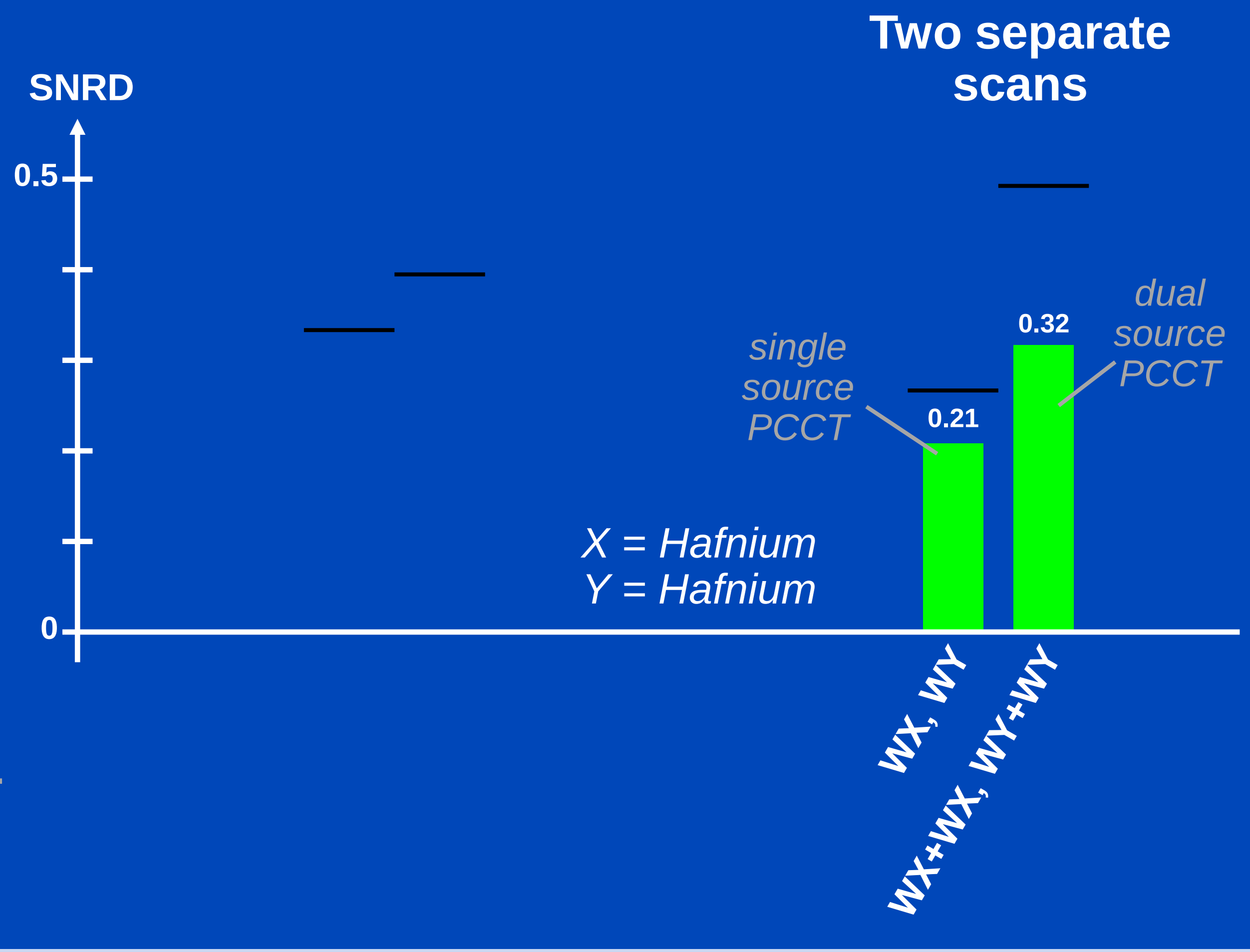
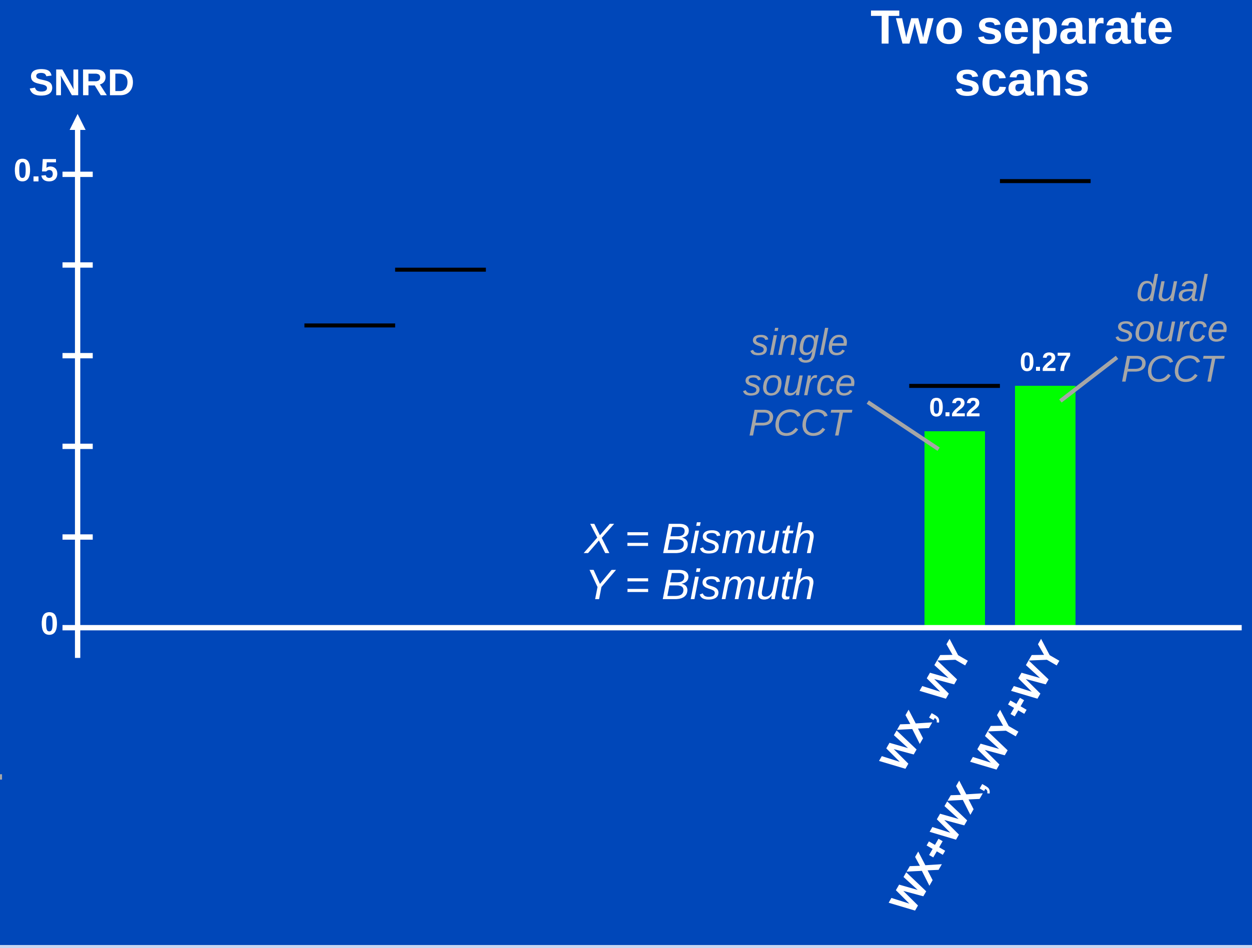


Sawall, Kachelrieß et al. CT material decomposition with contrast agents: Single or multiple spectral photon–counting CT scans? Med. Phys. 52, 2025.

Two Contrast Agents X and Y in the Same Region

- Must have X ≠ Y if scanned simultaneously.
- Can have X = Y if scanned separately.
- Separate scans require less dose!

- Good old liver protocols are optimal:
  - X = Y = iodine (today)
  - Two separate scans
  - Only one CA injection required
  - Unenhanced scan not necessary with PCCT



Sawall, Kachelrieß et al. CT material decomposition with contrast agents: Single or multiple spectral photon–counting CT scans? Med. Phys. 52, 2025.

Two Contrast Agents X and Y in Different Regions

- That‘s trivial, it‘s different regions
- Any reason for not using X=Y?

Is Iodine Good (or even God)?

- PCCT simulation with tube voltage, prefilter and energy threshold position optimization and optimized linear reconstruction[1].
- CAs diluted to have 200 HU in the center of a 32 cm water phantom when scanned at 120 kV spectrum with only intrinsic filtration.
- Patient sizes 20 cm, 30 cm, 40 cm.
- Scan parameters maximizing SNRD of W and X yield:

200 mm, $B = 3$, real	X=Iodine	X=Gadolinium	X=Hafnium	X=Bismuth
	SNRDs of W, X, tot	SNRDs of W, X, tot	SNRDs of W, X, tot	SNRDs of W, X, tot
WX	14.7, 3.16, 3.39	12.4, 2.55, 2.74	10.1, 2.30, 2.47	9.91, 2.33, 2.51
WX+WX	21.5, 6.08, 6.45	17.6, 3.89, 4.17	13.2, 2.87, 3.08	17.1, 4.05, 4.35

400 mm, $B = 3$, real	X=Iodine	X=Gadolinium	X=Hafnium	X=Bismuth
	SNRDs of W, X, tot	SNRDs of W, X, tot	SNRDs of W, X, tot	SNRDs of W, X, tot
WX	2.28, 0.38, 0.41	2.03, 0.36, 0.39	1.62, 0.29, 0.31	1.63, 0.31, 0.34
WX+WX	3.12, 0.69, 0.74	3.00, 0.60, 0.64	2.02, 0.45, 0.48	1.93, 0.38, 0.40

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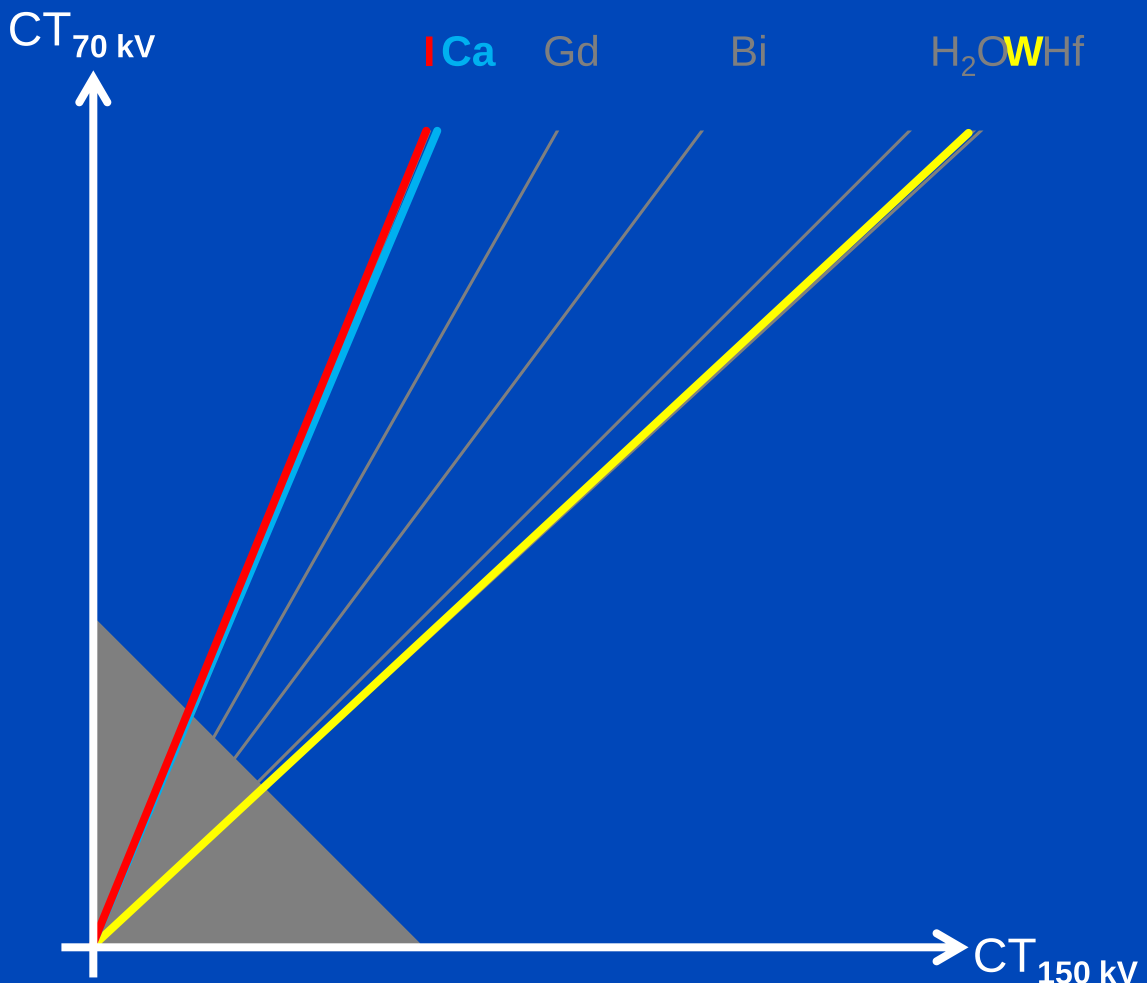
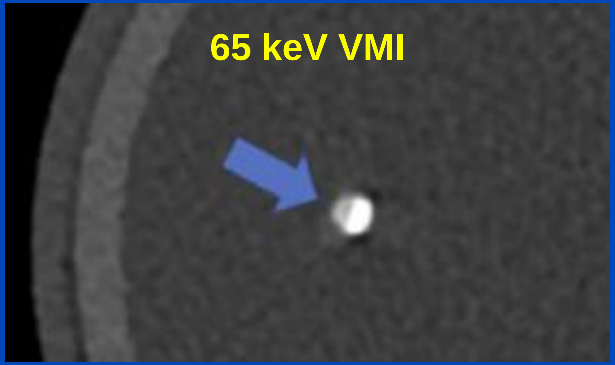
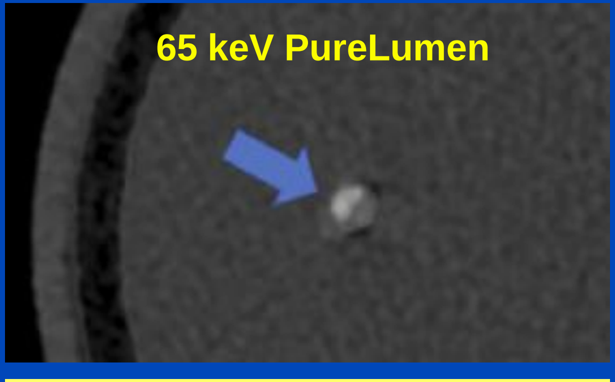
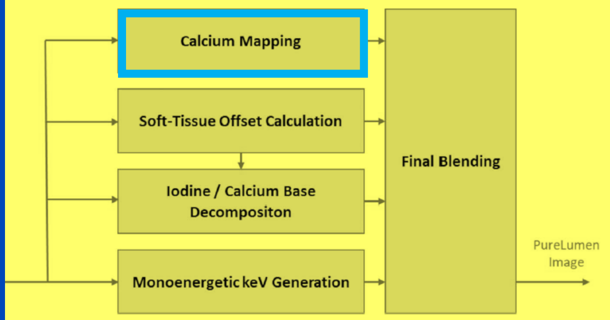
[1] Sawall, Kachelrieß et al. CT material decomposition with contrast agents: Single or multiple spectral photon–counting CT scans? Med. Phys. 52, 2025.

What if We Want to Discriminate Ca from CA?









Calcium Mapping

Soft-Tissue Offset Calculation

Iodine / Calcium Base Decompositon

Monoenergetic keV Generation

Final Blending

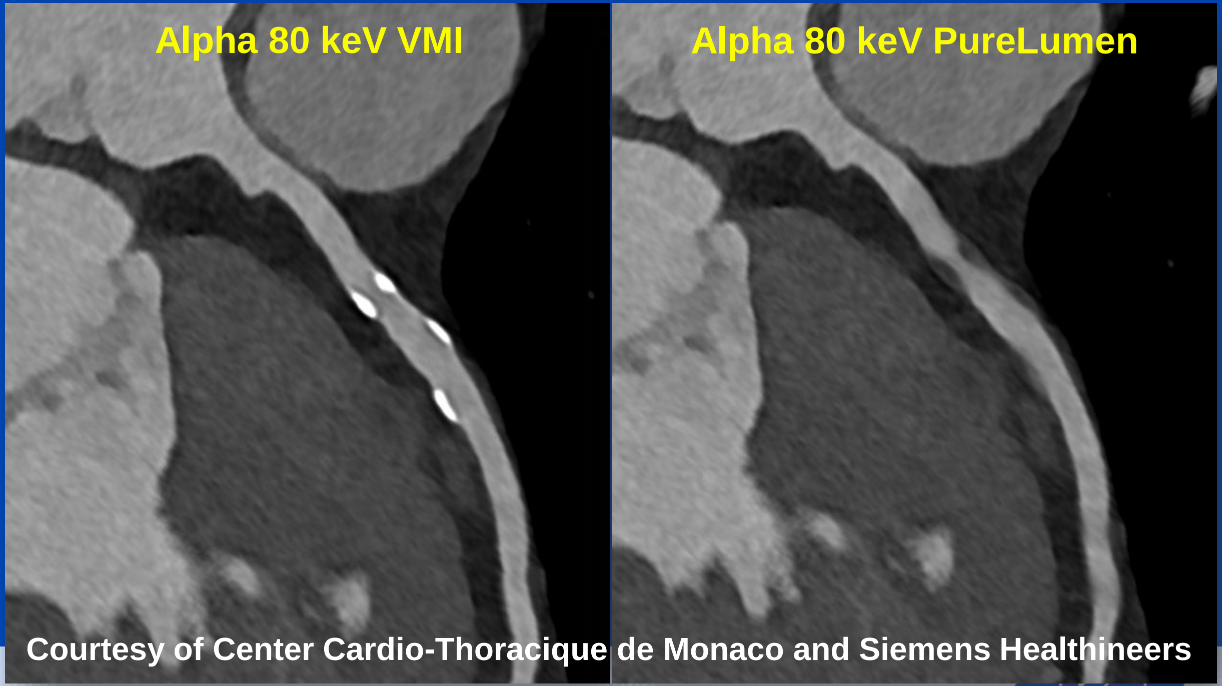
PureLumen Image

Allmendinger et al., Invest Radiol 57(6), 2022

In the energy range of clinical CT and with objects similar to patients we find that 0.5 mm Ag ≈ 0.6 mm Sn ≈ 2.0 mm Cu.

Conclusions

- Dual contrast may not make sense. Scan separately and save dose.
- Iodine is great!
- Higher *Z* may help to better discriminate Ca from CA.
  - In particular a tungsten CA (*Z* = 74) seems good to tell Ca from CA.
  - However, tungsten is not easy to discriminate from soft tissue by spectral means.
  - This means, potential tungsten maps will be of low quality. Adding prior knowledge may help.
  - Special application in coronary arteries?
  - Tungsten could be mixed with iodine!
- It is iodine forever!
- Maybe it will have a little sister.



Courtesy of Center Cardio-Thoracique de Monaco and Siemens Healthineers

Thank You!

- This presentation will soon be available at www.dkfz.de/ct.
- Job opportunities through marc.kachelriess@dkfz.de or through DKFZ’s PhD program.
- Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.

EuroSafe Imaging Session EU 13

Assessment of
AI-based image reconstruction

Friday, 9:30 to 11:00
Room M1

Low dose CT benchmark:

github.com/eeulig/ldct-benchmark

E. Eulig, B. Ommer, and M. Kachelrieß. Benchmarking deep learning-based low-dose CT image denoising algorithms. Med. Phys. 51(12):8776-8788, December 2024.

Thank You!

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