Photon-Counting CT Technology

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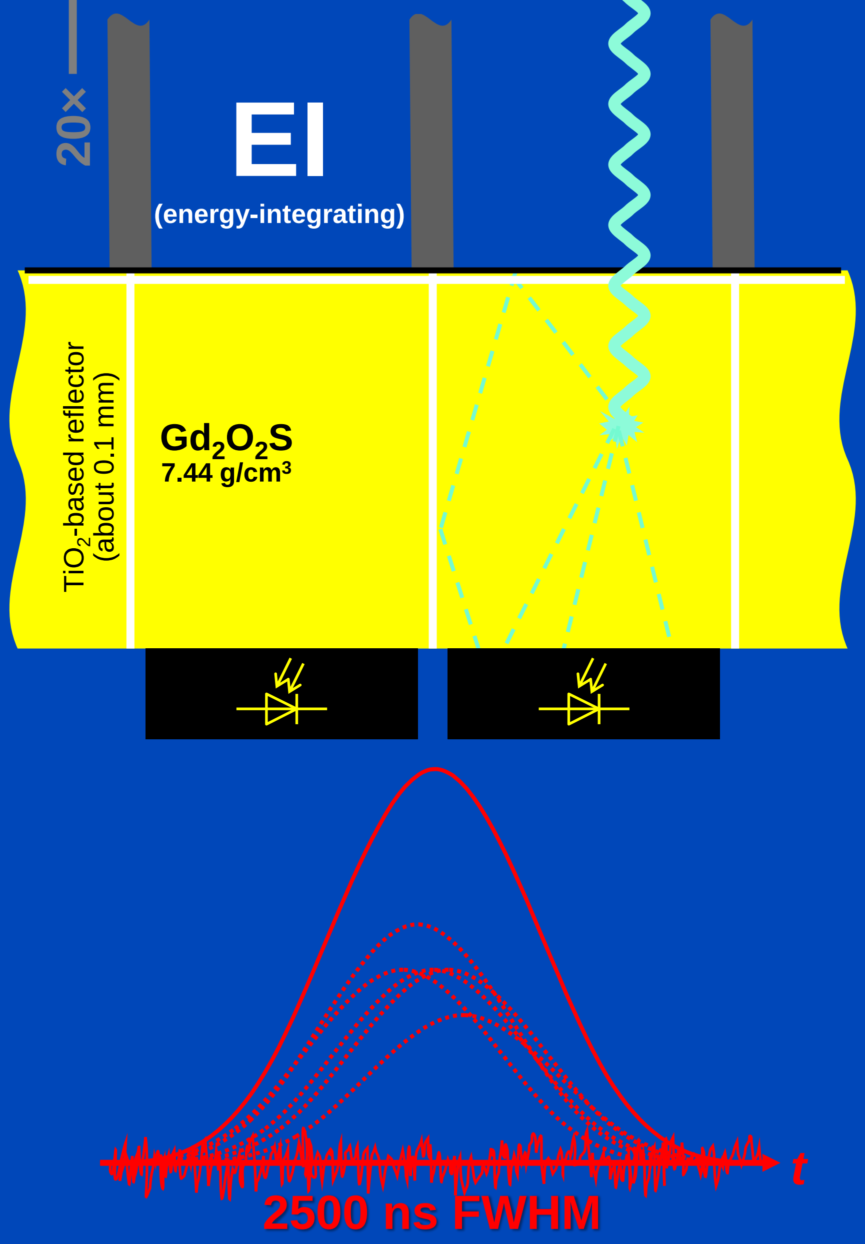
DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

CT Systems 2024/2025

H = high-end, M = mid-range

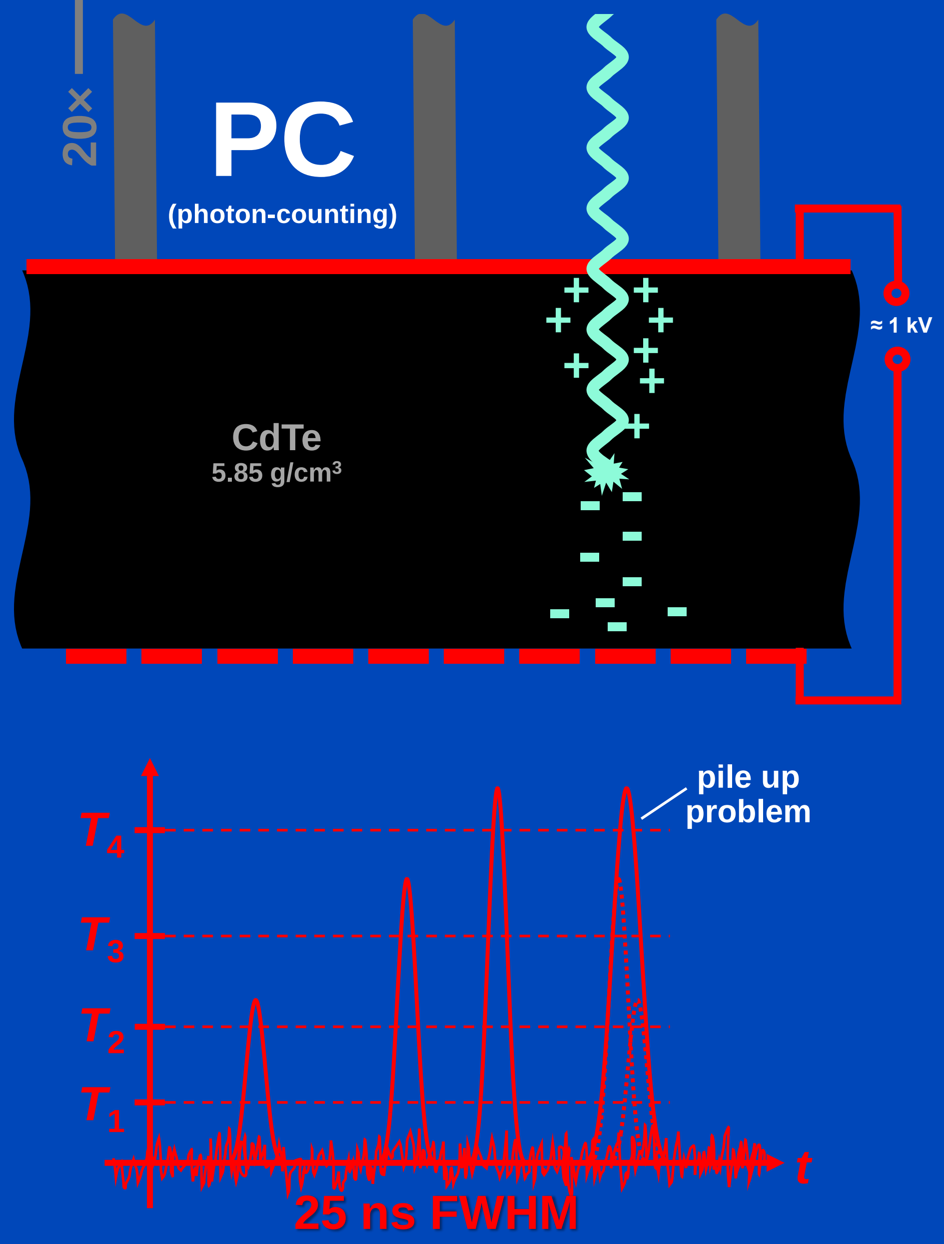
CT System	Rotation, Cone, Coll.	Max. Power, Anode Angle, Name, Max. mA @ low kV	Patient-specific prefilters	Detector Configuration, Type, Name	FOM, Reconstruction Matrix	Special Reconstruction Algorithms	Spectral	
Canon Aquilion ONE Prism Edition	0.275 s, 15°, 160 mm	100 kW, 10°, MegaCool Vi, 600 mA @ 80 kV	Ag, {0, *x*} mm	320 × 0.5 mm, EI, PUREViSION	50 cm, 512	iterative (AIDR 3D), deep (AiCE, PIQE)	fast TVS with DL	H
Canon Aquilion Precision Edition	0.35 s, 3.8°, 40 mm	72 kW, 7°, MegaCool, 600 mA @ 80 kV	none	160 × 0.25 mm, EI, PUREViSION	50 cm, 512, 1024, 2048	iterative (AIDR 3D), deep (AiCE)	2 scans	H
GE Revolution Apex Elite	0.23 s, 15°, 160 mm	108 kW, 10°, Quantix 160, 1300 mA @ 70+80 kV	none	256 × 0.625 mm, EI, GemStone Clarity	50 cm, 512		fast TVS or 2 scans	H
GE Revolution Apex Plus	0.28 s, 7.6°, 80 mm	108 kW, 10°, Quantix 160, 1300 mA @ 70 kV	none	128 × 0.625 mm, EI, GemStone Clarity	50 cm, 512	deep (TrueFidelity), SnapshotFreeze	fast TVS or 2 scans	M
Philips Spectral CT 7500	0.27 s, 7.7°, 80 mm	120 kW, 8°, iMRC, 925 mA @ 80 kV	none	2 · 128 × 0.625 mm, EI, NanoPanel Prism	50 cm, 512, 768, 1024	iterative (iDose)	sandwich	H
Philips Incisive CT	0.35 s, 3.9°, 40 mm	80 kW, vMRC	none	2 · 64 × 0.625 mm, EI	50 cm, 512, 768, 1024	iterative (iDose), deep (Precise Image&Cardiac)		M
Siemens Somatom X.ceed	0.25 s, 3.7°, 38.4 mm	120 kW, 8°, Vectron, 1300 mA @ 70+80+90 kV	Sn, {0, 0.4, 0.7} mm	2 · 64 × 0.6 mm, EI, Stellar	50 cm, 512, 768, 1024	iterative (ADMIRE)	split filter (Twin Beam) or 2 scans (Twin Spiral)	M
Siemens Somatom Force	0.25 s, 5.5°, 57.6 mm	2 · 120 kW, 8°, Vectron, 2 · 1300 mA @ 70+80+90 kV	Sn, {0, 0.6} mm	2 · 2 · 96 × 0.6 mm, EI, Stellar	50 cm/35 cm, 512, 768, 1024	iterative (ADMIRE)	DSCT	H
Siemens Naeotom Alpha.Prime	0.25 s, 3.6°, 38.4 mm	1 · 120 kW, 8°, Vectron, 2 · 1300 mA @ 70+90 kV	Sn, {0, 0.4} mm	144×0.4 or 120×0.2 mm, PC, QuantaMax	50 cm, 512, 768, 1024	iterative (QIR)	PCCT	H
Siemens Naeotom Alpha.Pro	0.25 s, 5.4°, 57.6 mm	2 · 120 kW, 8°, Vectron, 2 · 1300 mA @ 70+90 kV	Sn, {0, 0.4, 0.7} mm	2 · 96×0.4 or 2 · 120×0.2 mm, PC, QuantaMax	50 cm/36 cm, 512, 768, 1024	iterative (QIR)	DSCT, PCCT	H
Siemens Naeotom Alpha.Peak	0.25 s, 5.4°, 57.6 mm	2 · 120 kW, 8°, Vectron, 2 · 1300 mA @ 70+90 kV	Sn, {0, 0.4, 0.7} mm	2 · 144×0.4 or 2 · 120×0.2 mm, PC, QuantaMax	50 cm/36 cm, 512, 768, 1024	iterative (QIR)	DSCT, PCCT	H

Indirect Conversion



i.e. max O(40·10³) cps

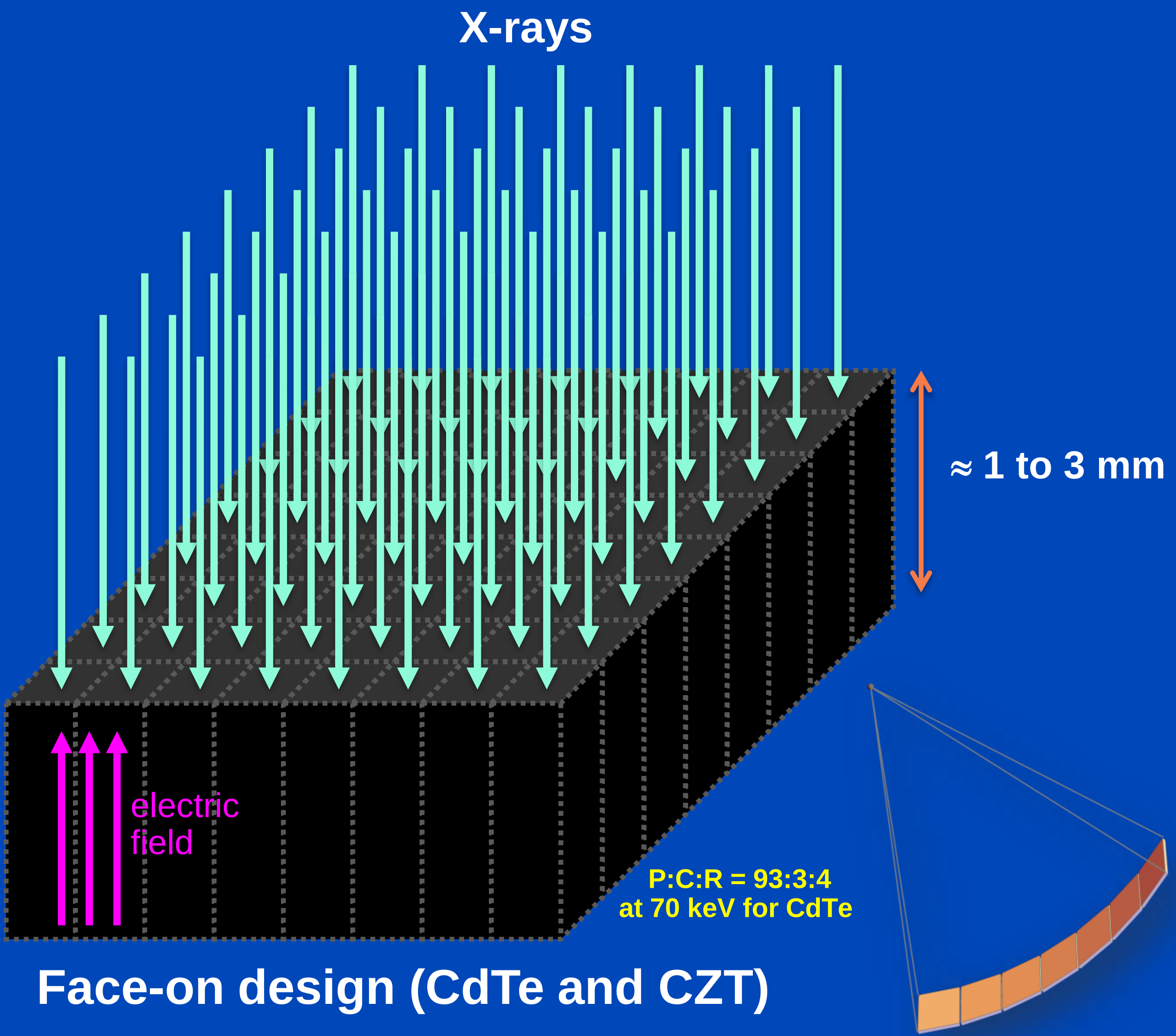
Direct Conversion

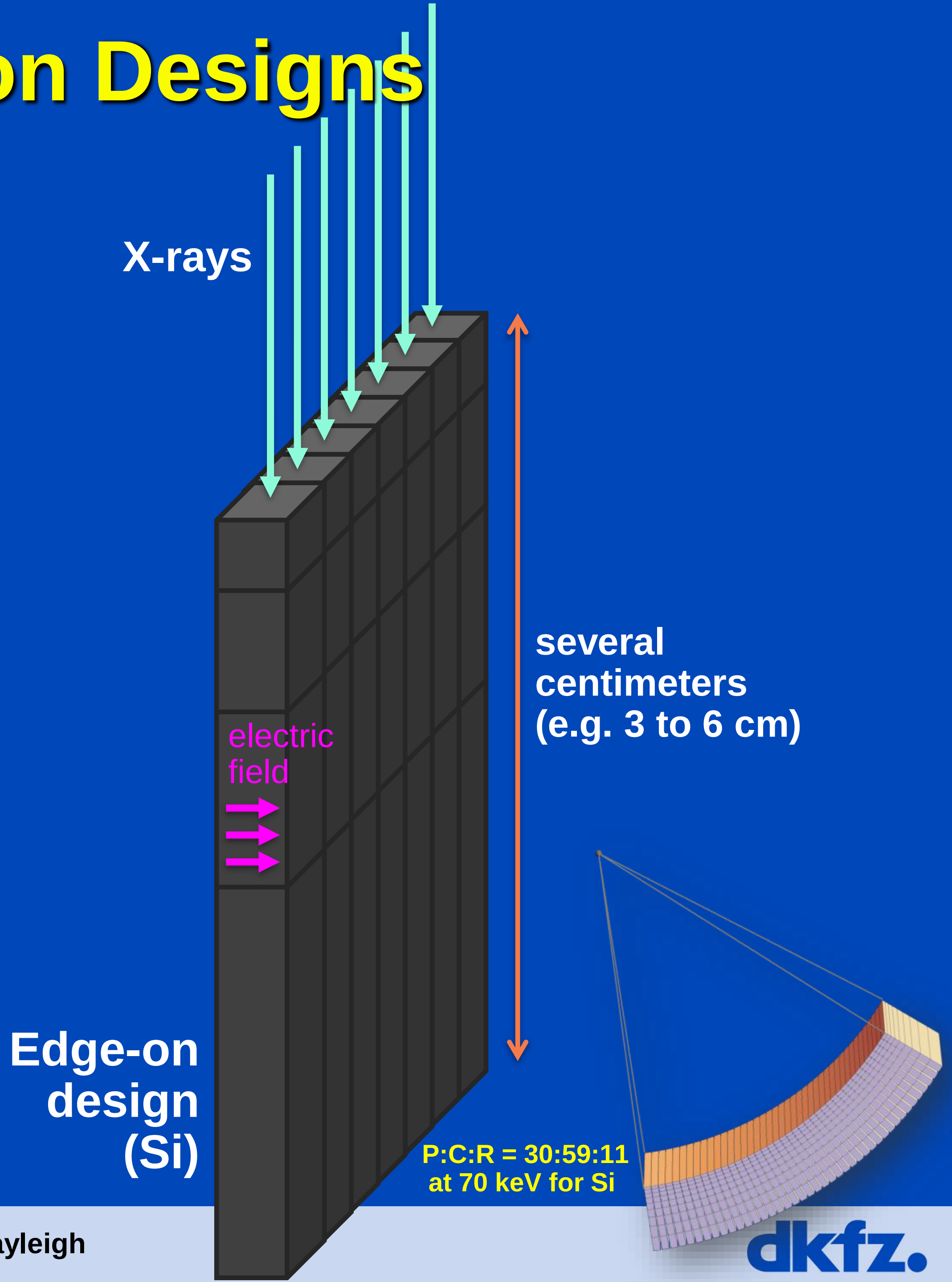


i.e. max O(40·10⁶) cps

Requirements for CT: up to 10⁹ x-ray photon counts per second per mm².
Hence, photon counting only achievable for direct converters.

Face-on and Edge-on Designs





Only sensor material is shown. The electrodes are not shown. P:C:R = Photo:Compton:Rayleigh

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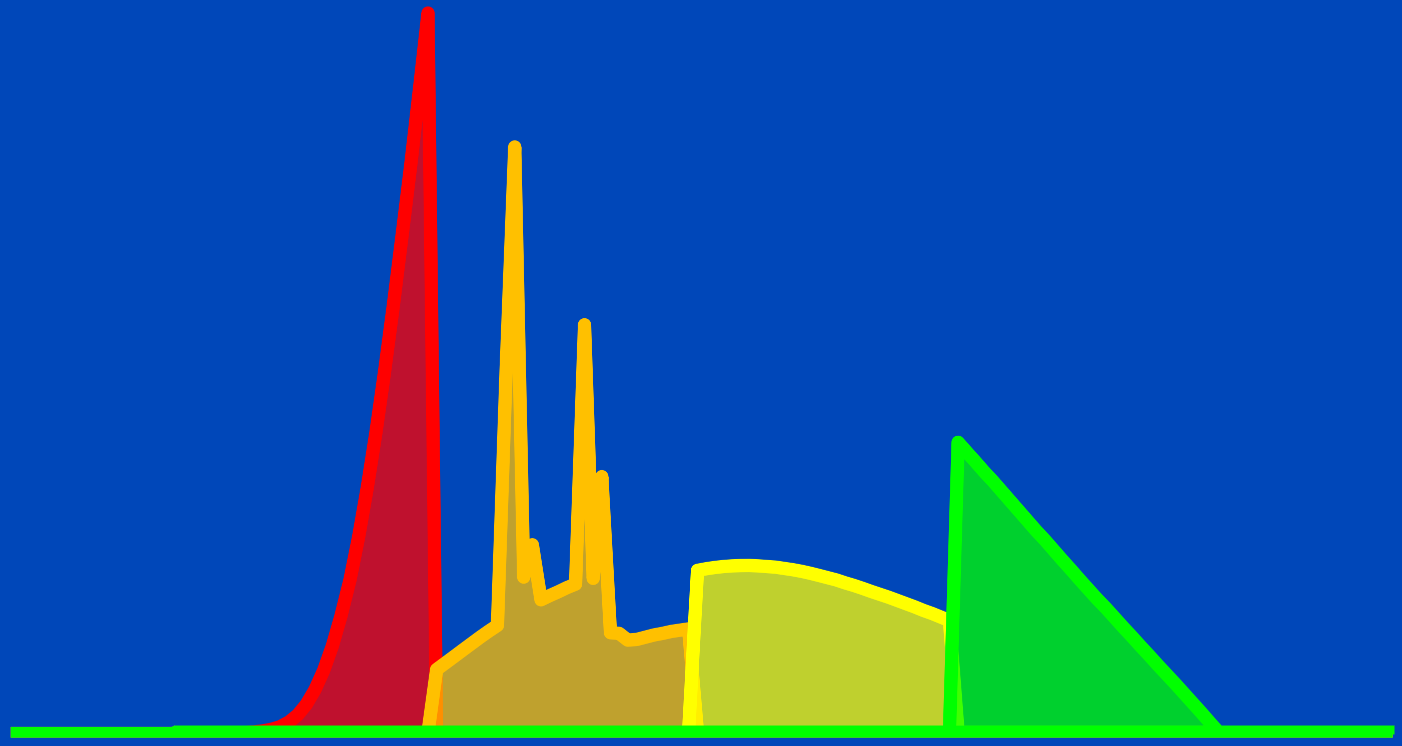
Energy-Selective Detectors: Improved Spectroscopy, Reduced Dose?

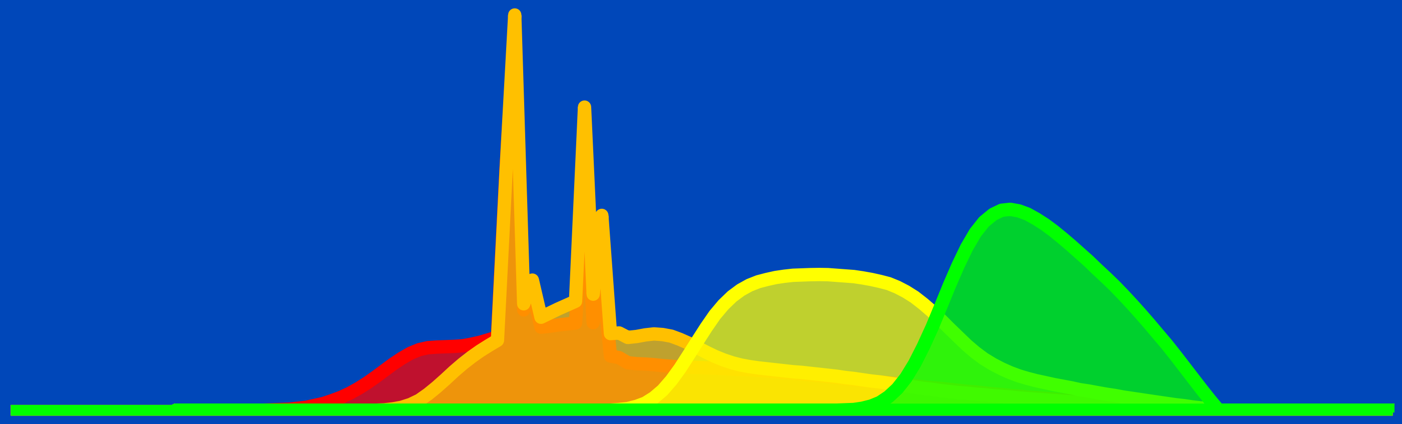
Ideally, bin spectra do not overlap, …



Spectra as seen with 4 bins after having passed a 32 cm water layer.

Energy-Selective Detectors: Improved Spectroscopy, Reduced Dose?

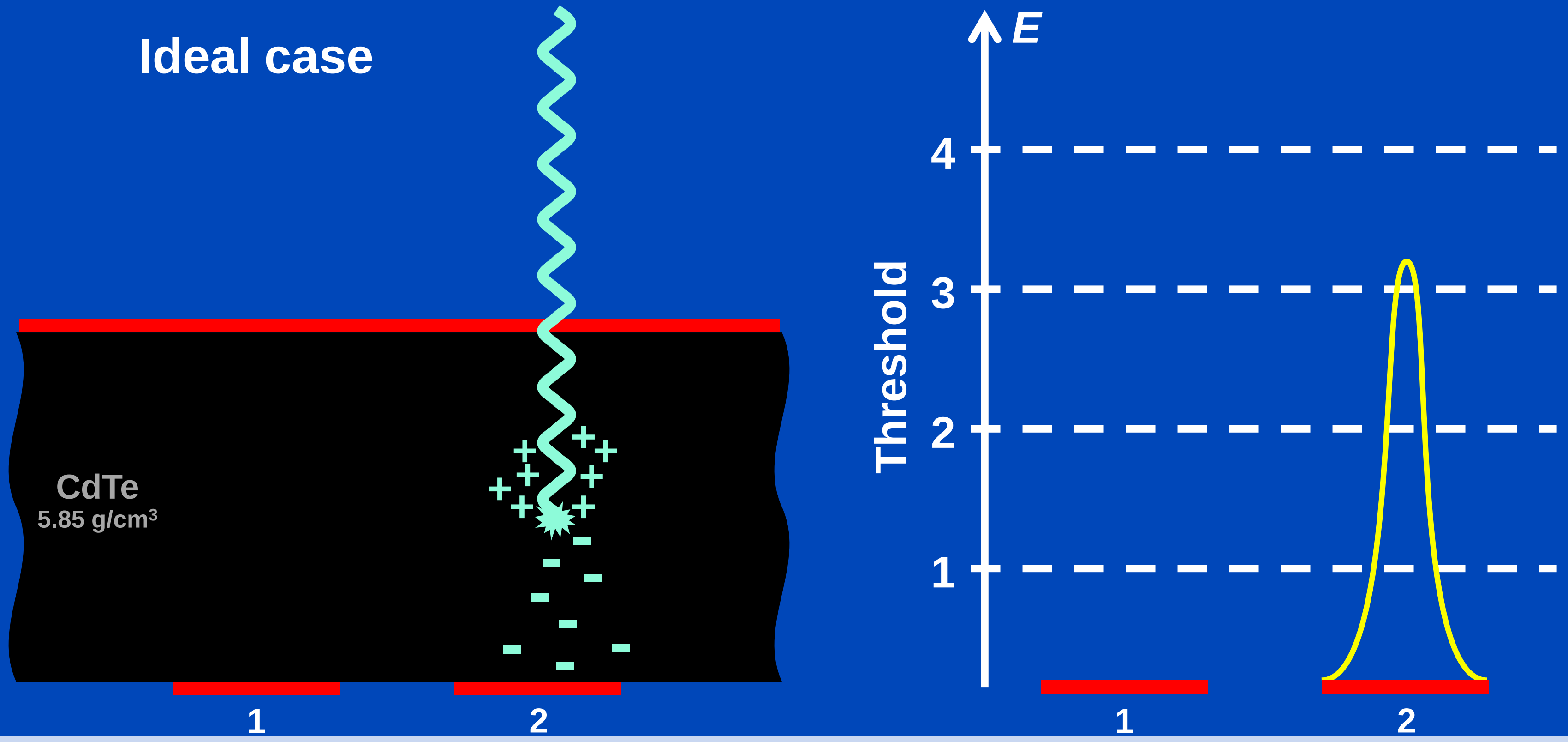
… realistically, however, they do!



Spectra as seen with 4 bins after having passed a 32 cm water layer.

Photon Events

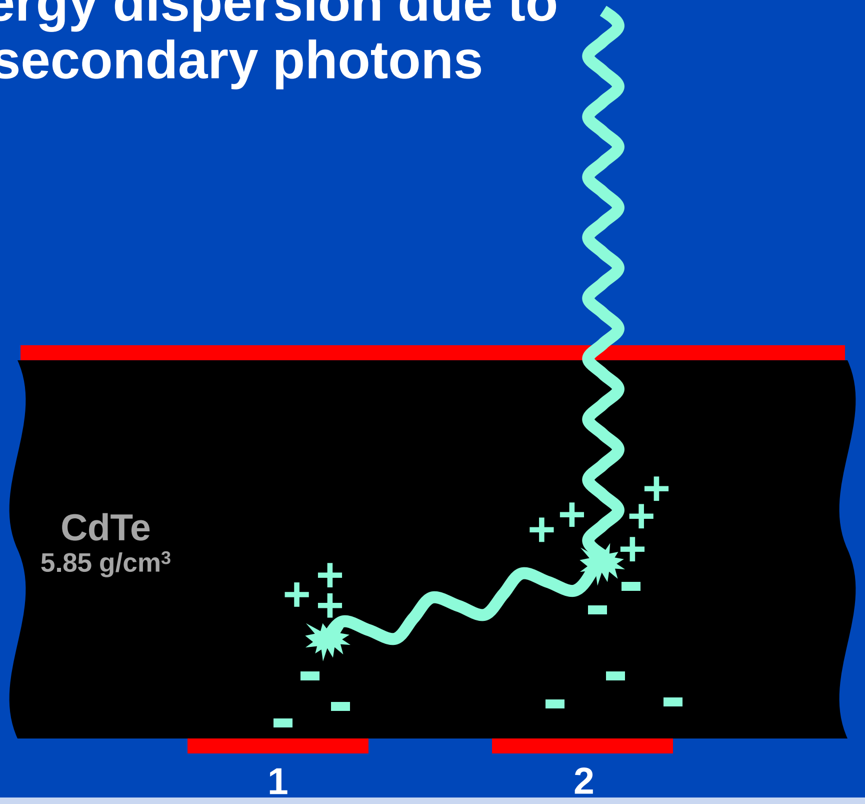
- Detection process in the sensor
- Photoelectric effect (e.g. 80 keV)

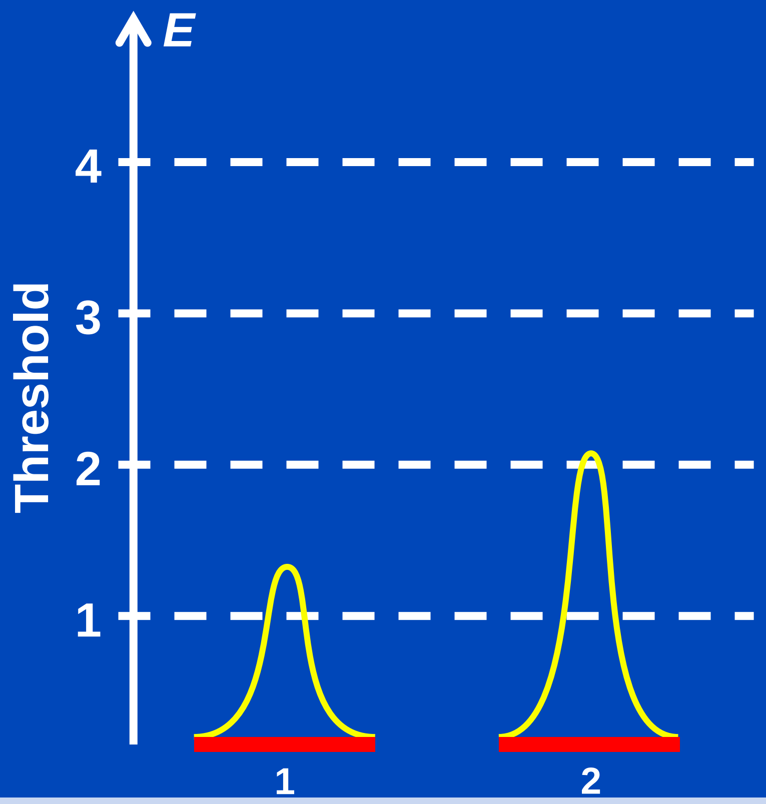


Photon Events

- Detection process in the sensor
- Compton scattering or K-fluorescence (e.g. 80 keV)

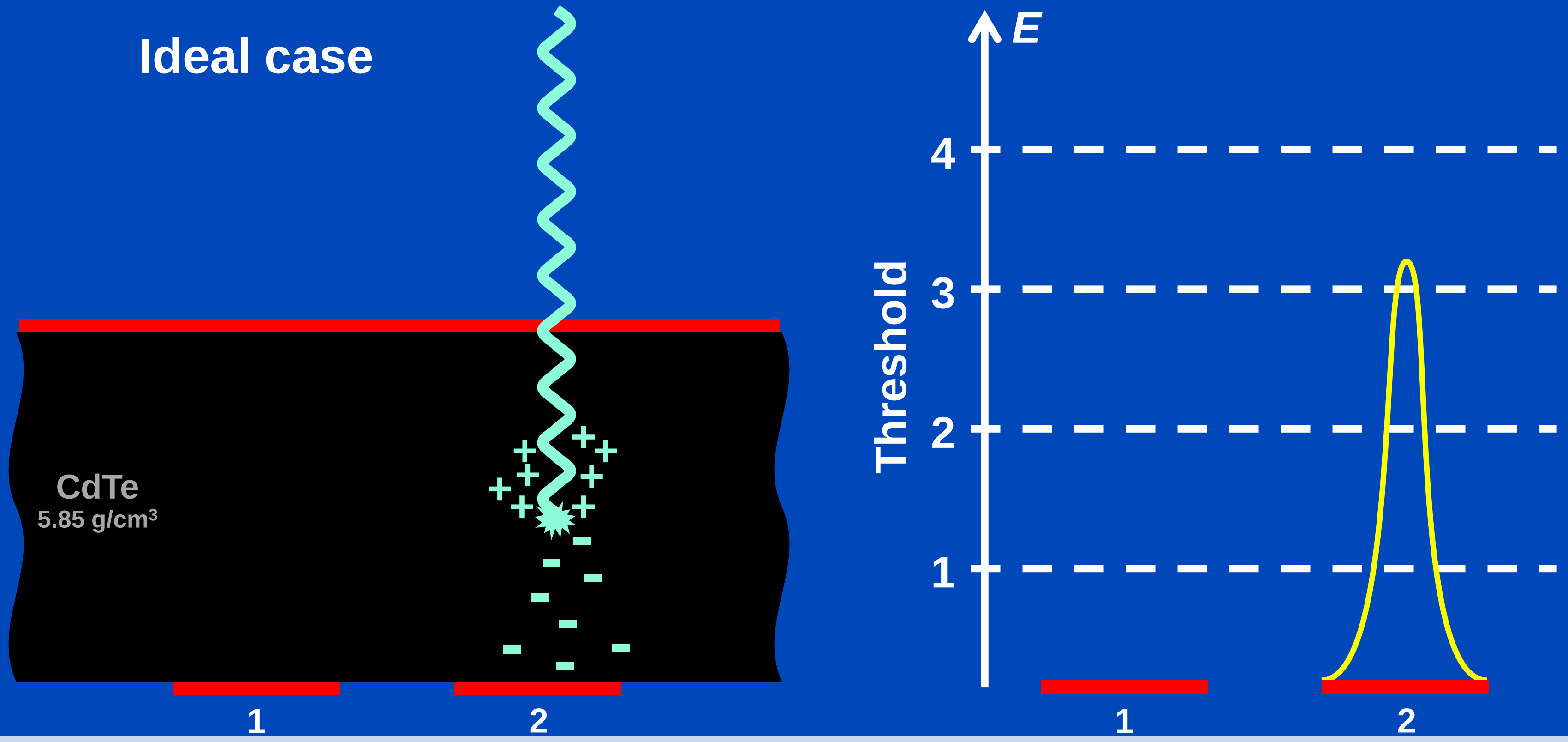
Energy dispersion due to secondary photons





Photon Events

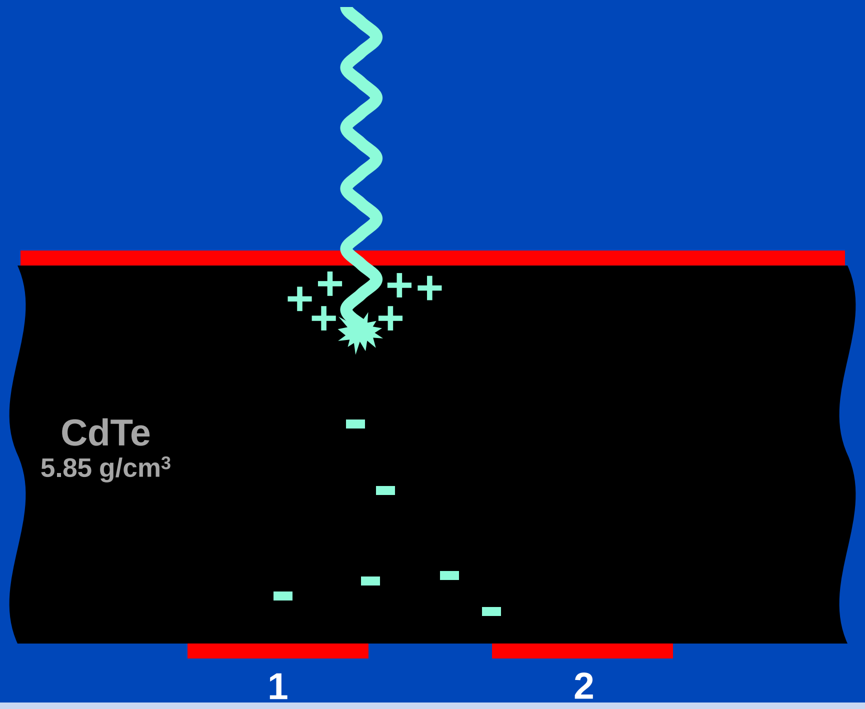
- Detection process in the sensor
- Photoelectric effect (e.g. 80 keV)

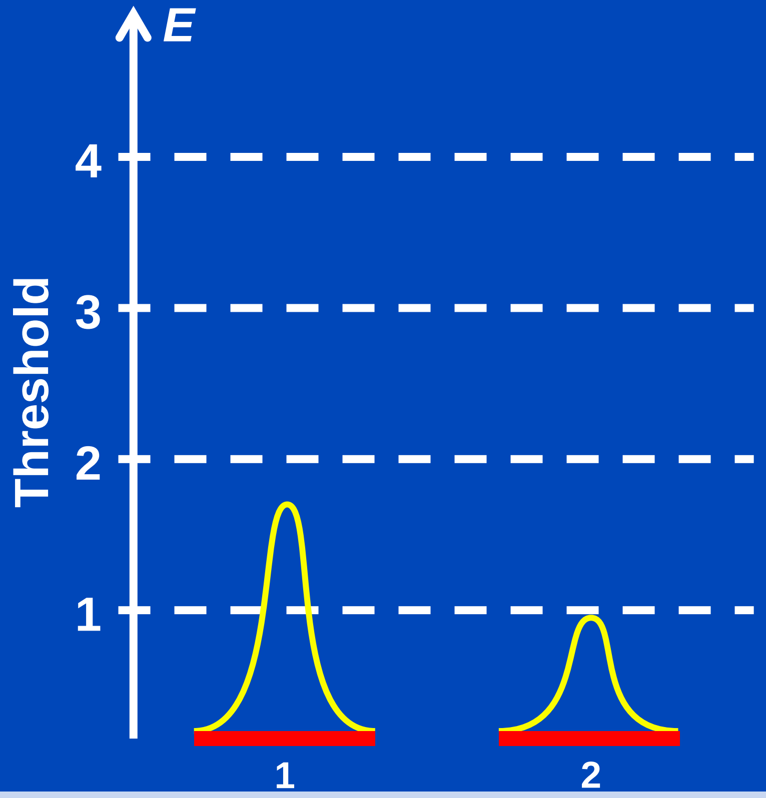


Photon Events

- **Detection process in the sensor**
- **Photoelectric effect (e.g. 30 keV), charge sharing**

Energy dispersion due to charge diffusion

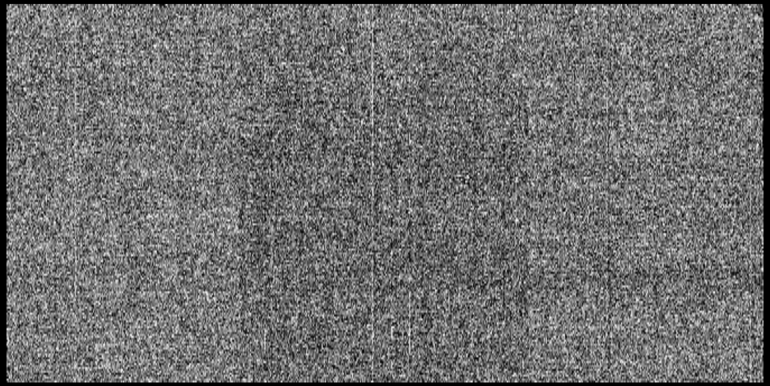




Advantages of Photon-Counting CT

- No reflective gaps between detector pixels
  - Higher geometrical efficiency
  - Less dose
- No electronic noise (every photon counts)
  - Less dose for infants
  - Less noise for obese patients
- Counting
  - Swank factor = 1 = maximal
  - “Iodine effect“ due to higher weights on low energies
- Energy bin weighting
  - Lower dose/noise
  - Improved iodine CNR
- Smaller pixels (to avoid pileup)
  - Higher spatial resolution
  - “Small pixel effect” i.e. lower dose/noise at conventional resolution
- Spectral information on demand
  - Dual Energy CT (DECT), Multi Energy CT (MECT)
  - Standardization (e.g. VMI)

EI (Dexela)



Readout noise only. Single events hidden!

PC (Dectris)

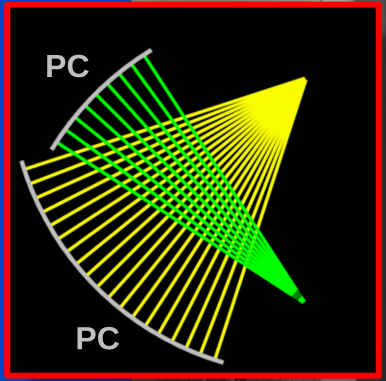
No readout noise. Single events visible!

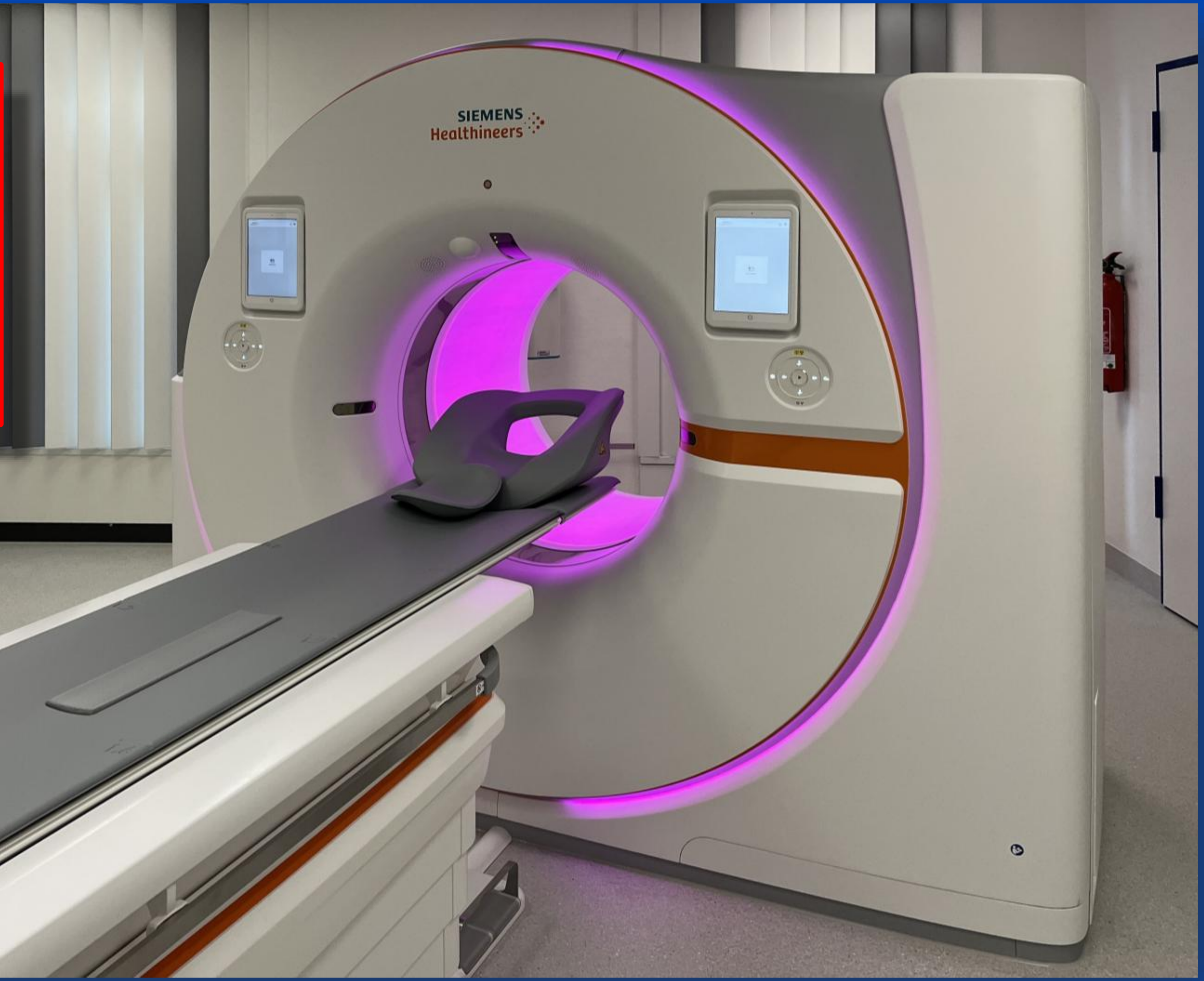
18 frames, 5 min integration time per frame, x-ray off

Siemens Naeotom Alpha.Peak
The World's First Photon-Counting CT

- **Tubes**
  - tube A: 120 kW
  - tube B: 120 kW
  - Focal spot size down to 181 µm

  ≈ ¼ MW
- **Detectors**
  - pixel size down to 150 µm
  - 288 detector rows
  - 2752 detector columns
- **Speed**
  - up to 4 rotations per second
  - up to 737 mm/s scan speed
  - down to 66 ms native temporal resolution
- **50 cm FOM**
- **Spectral**
  - VNC, VNCa (pure lumen), VMI
  - Z_{eff}, electron density, …



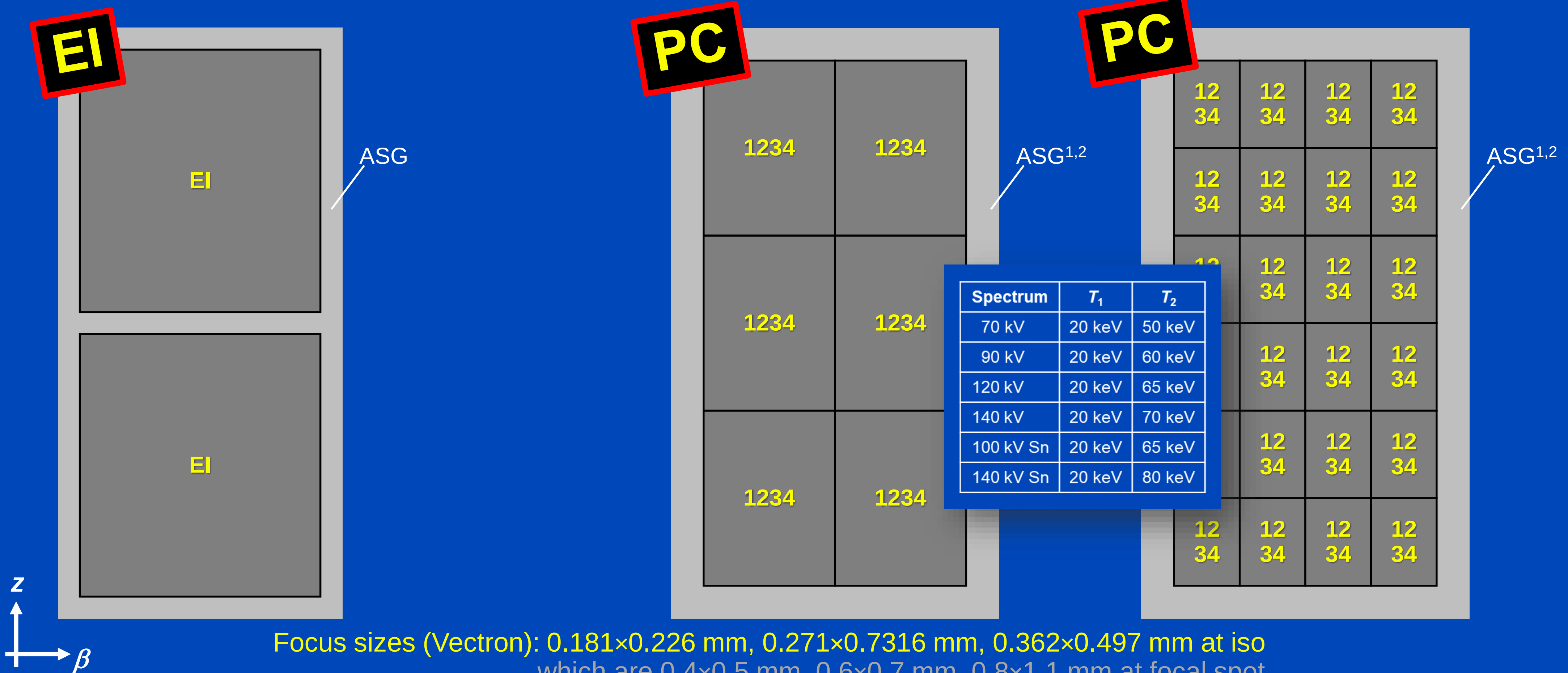


Detector Pixel Force vs. Alpha

Force
920 × 96 detector pixels
pixel size 0.52 × 0.56 mm at iso
avg. sampling 0.56 × 0.6 mm at iso
57.6 mm z-coverage

Alpha (Std, Quantum Plus)
1376 × 144 macro pixels
pixel size 0.3 × 0.352 mm at iso
avg. sampling 0.344 × 0.4 mm at iso
57.6 mm z-coverage

Alpha (UHR, QuantumHD)
2752 × 120 pixels
pixel size 0.151 × 0.176 mm at iso
avg. sampling 0.172 × 0.2 mm at iso
24 mm z-coverage



Spectrum	T_1	T_2
70 kV	20 keV	50 keV
90 kV	20 keV	60 keV
120 kV	20 keV	65 keV
140 kV	20 keV	70 keV
100 kV Sn	20 keV	65 keV
140 kV Sn	20 keV	80 keV

Focus sizes (Vectron): 0.181×0.226 mm, 0.271×0.7316 mm, 0.362×0.497 mm at iso
which are 0.4×0.5 mm, 0.6×0.7 mm, 0.8×1.1 mm at focal spot

[1]J. Ferda et al. Computed tomography with a full FOV photon-counting detector in a clinical setting, the first experience. European Journal of Radiology 137:109614, 2021
[2]Rajendran et al. Full field-of-view, high-resolution, photon-counting detector CT: technical assessment and initial patient experience. Phys. Med. Biol. 66:205019, 2021

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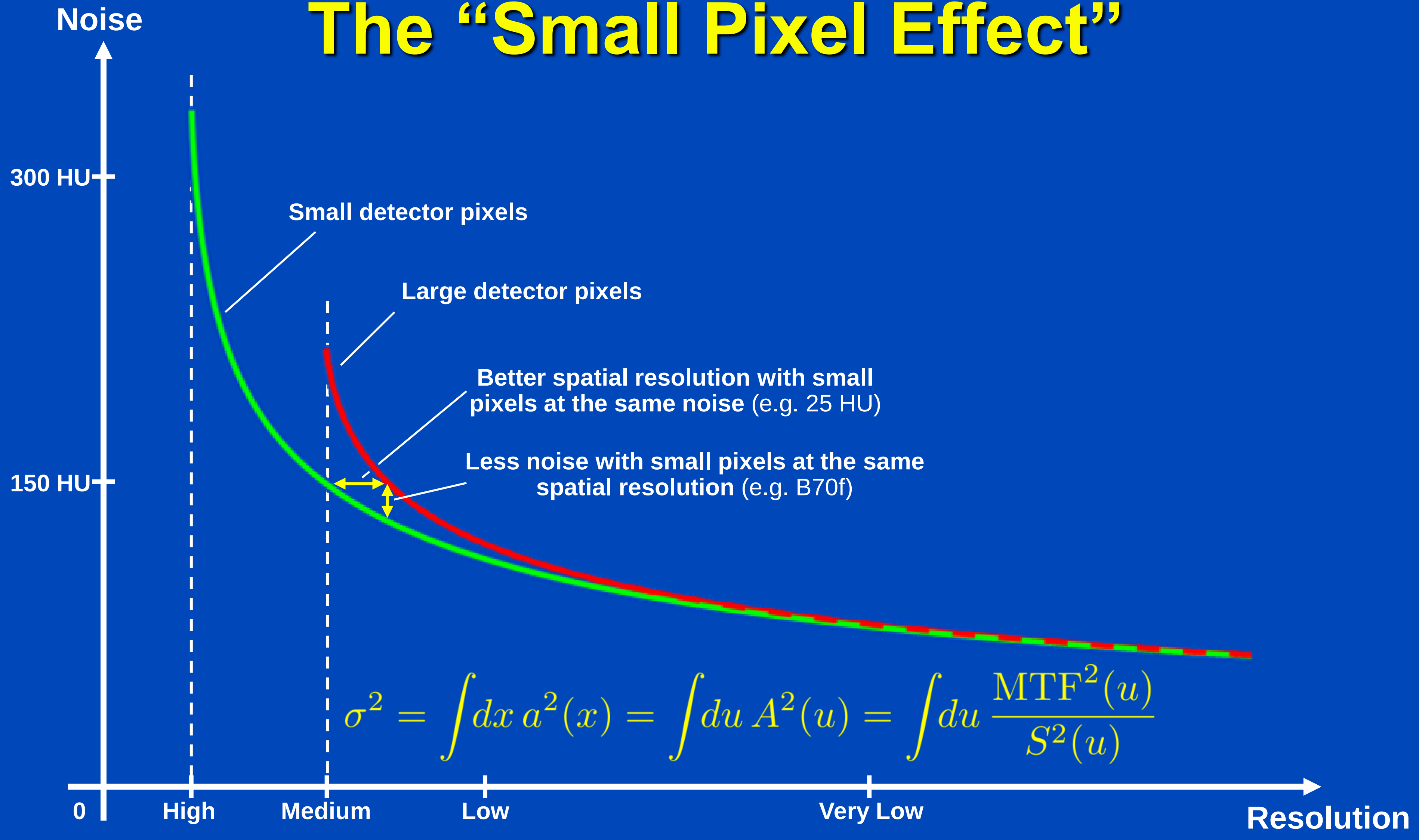
The "Small Pixel Effect"

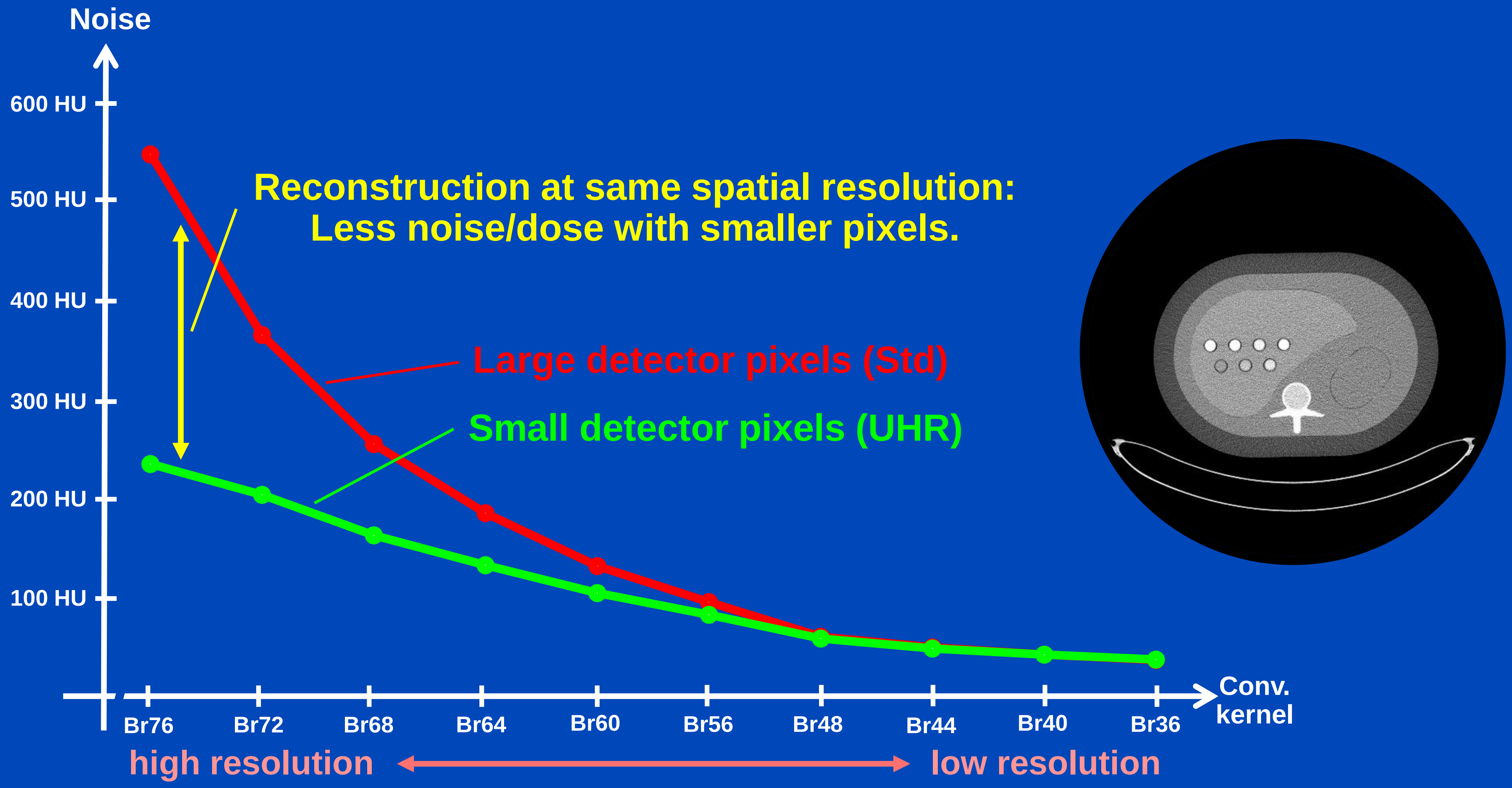


$$\sigma^2 = \int dx\, a^2(x) = \int du\, A^2(u) = \int du\, \frac{\mathrm{MTF}^2(u)}{S^2(u)}$$

Kachelrieß, Kalender. Med. Phys. 32(5):1321-1334, May 2005

Small Pixel Effect at Naeotom Alpha

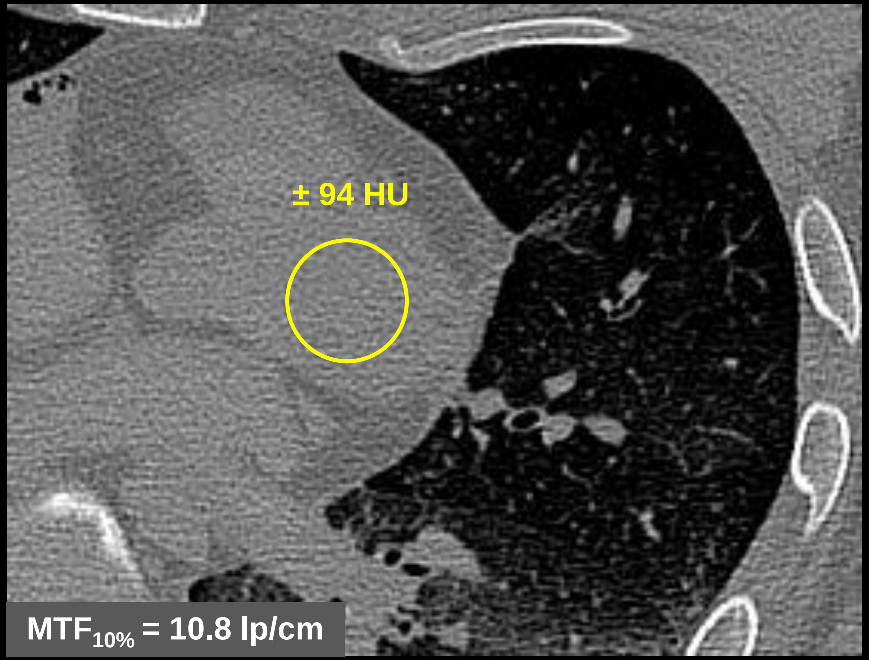
Medium Phantom, 4 mGy $CTDI_{32}$



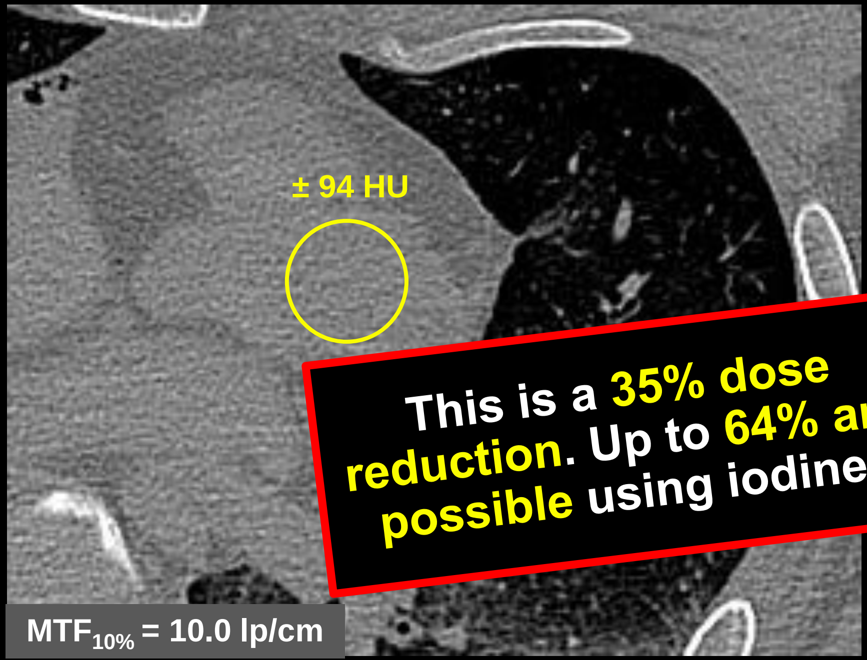
To disable the longitudinal small pixel effect, we reconstructed rather thick slices (1 mm thickness).

L. Klein, C. Amato, S. Heinze, M. Uhrig, H.-P. Schlemmer, M. Kachelrieß, and S. Sawall. **Effects of Detector Sampling on Noise Reduction in a Clinical Photon-Counting Whole-Body CT**. Investigative Radiology, vol. 55(2):111-119, February 2020.

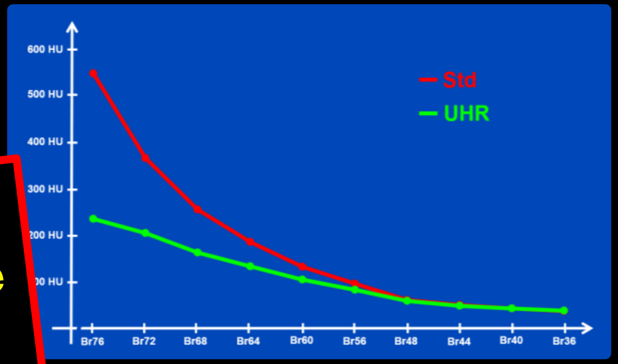
Energy Integrating Detector (B70f)



Photon Counting Detector (B70f)



This is a 35% dose reduction. Up to 64% are possible using iodine.



Acquisition with EI:

- **Tube voltage of 120 kV**
- **Tube current of 300 mAs**
- **Resulting dose of $CTDI_{vol\ 32\ cm}$ = 22.6 mGy**

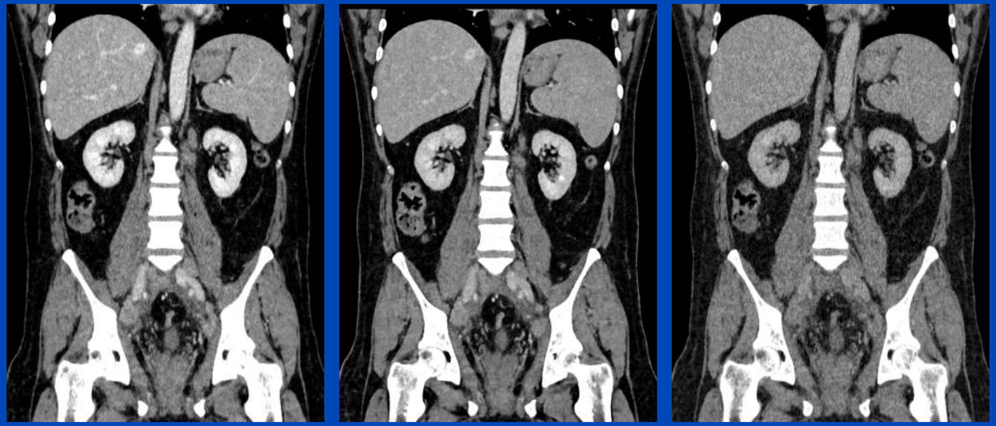
Acquisition with UHR:

- **Tube voltage of 120 kV**
- **Tube current of 180 mAs**
- **Resulting dose of $CTDI_{vol\ 32\ cm}$ = 14.6 mGy**

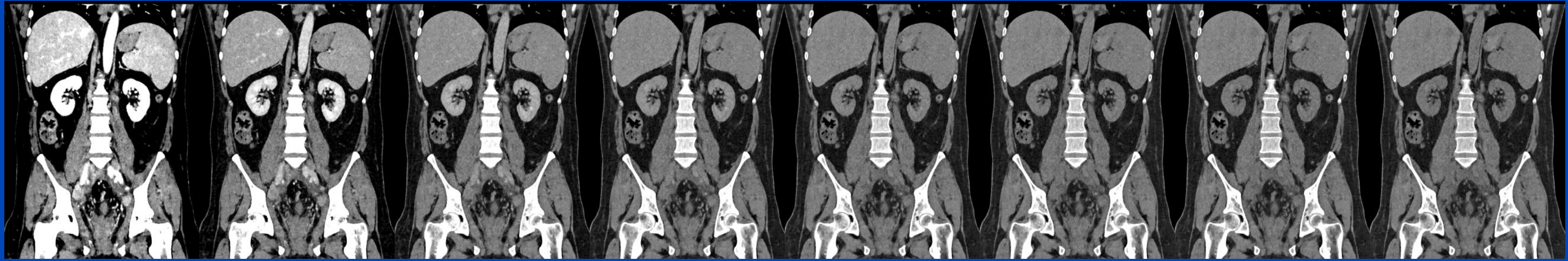
C = 50 HU, *W* = 1500 HU

Virtual Monochromatic Imaging (VMI)

- Linear image combination with noise reduction (e.g. Siemens` Mono+)
- Standardizes gray values regardless of tube voltage
  - not only for water or soft tissue
  - but also for other materials (e.g. bone, iodine, …)
- Energy or “keV level”
  - optimum value depends on task (non-contrast, bone, contrast-enhanced, vasular …)
  - can be freely adjusted
- VMI images displayed by default.



Low bin | Standard (T3D) | High bin



40 keV | 60 keV | 80 keV | 100 keV | 120 keV | 140 keV | 160 keV | 180 keV

C = 60 HU, *W* = 360 HU

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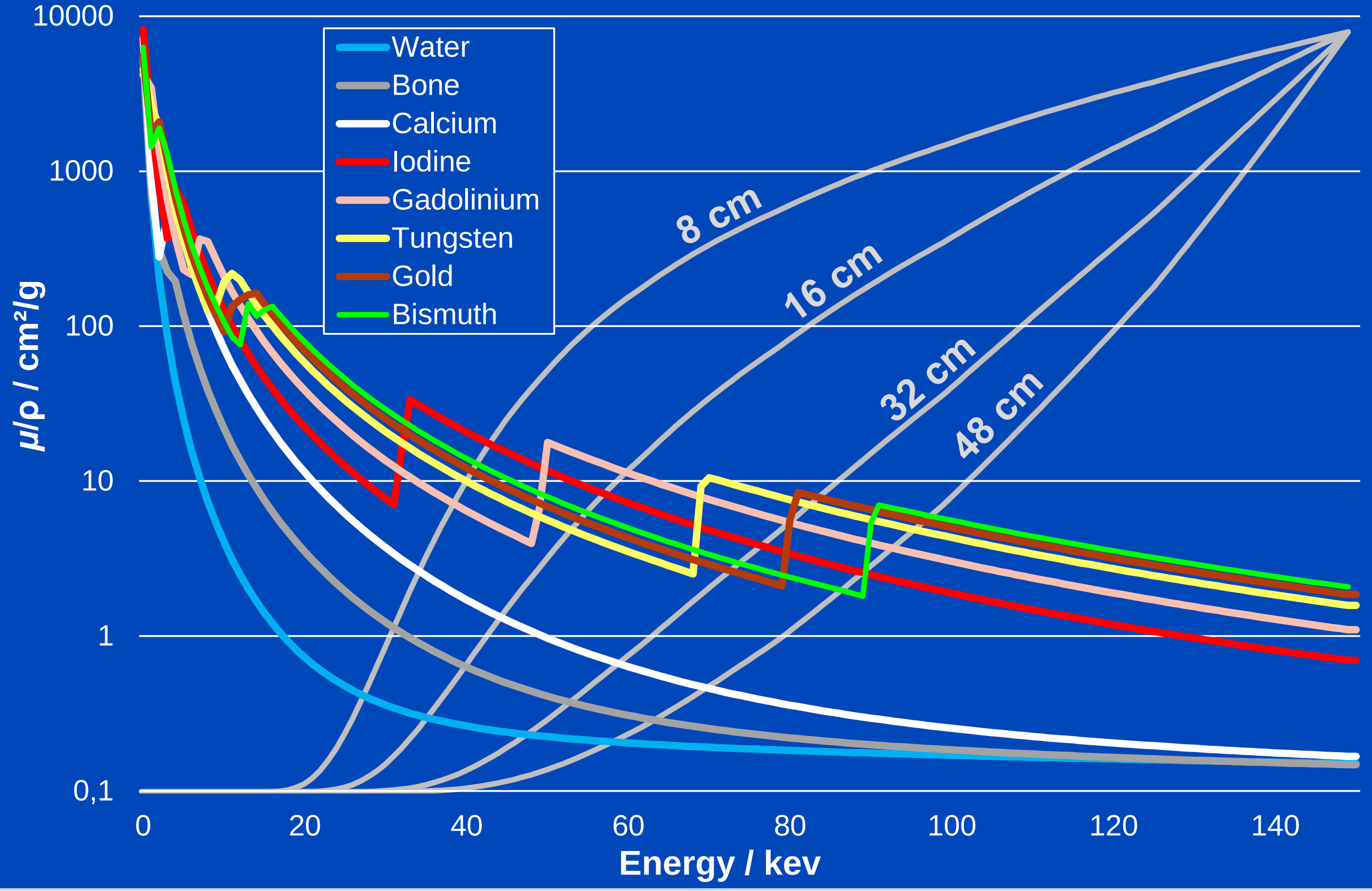
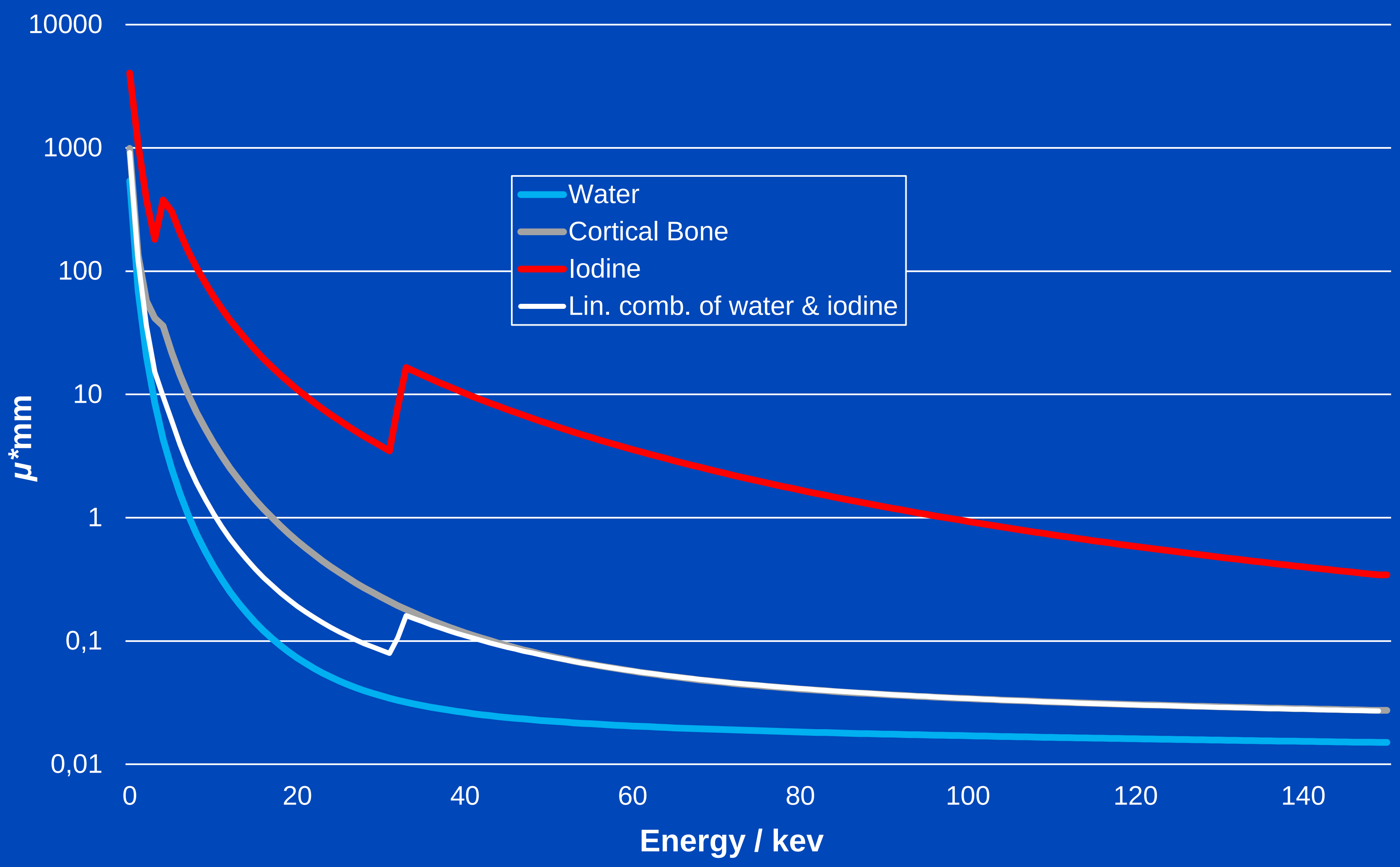
More than Two Materials?

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



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**



a = 1.6461
b = 0.0066
√RSS = 0.0031 / mm

$$(a,b) = \arg\min_{a,b} \int_{50\ \text{kev}}^{150\ \text{keV}} dE \left(a\,\mu_{\text{W}}(E) + b\,\mu_{\text{I}}(E) - \mu_{\text{B}}(E)\right)^2$$

VMI ≠ VMI

- VMI is an important tool for standardization.
- VMI makes CT even more quantitative.
- However, one needs to be aware of what type of VMI is used. E.g.
  - Two material VMI based on water and iodine

$$f_{\mathrm{VMI}}(E,\boldsymbol{r}) = \mu_{\mathrm{W}}(E) f_{\mathrm{W}}(\boldsymbol{r}) + \mu_{\mathrm{I}}(E) f_{\mathrm{I}}(\boldsymbol{r})$$

  - Two material VMI based on water and bone

$$f_{\mathrm{VMI}}(E,\boldsymbol{r}) = \mu_{\mathrm{W}}(E) f_{\mathrm{W}}(\boldsymbol{r}) + \mu_{\mathrm{B}}(E) f_{\mathrm{B}}(\boldsymbol{r})$$

  - Three material VMI

$$f_{\mathrm{VMI}}(E,\boldsymbol{r}) = \mu_{\mathrm{W}}(E) f_{\mathrm{W}}(\boldsymbol{r}) + \mu_{\mathrm{B}}(E) f_{\mathrm{B}}(\boldsymbol{r}) + \mu_{\mathrm{Gd}}(E) f_{\mathrm{Gd}}(\boldsymbol{r}) + \ldots$$

- As long as no high *Z* contrast agent exists, two material VMIs are perfectly fine (since water, bone and iodine are linearly dependent).

Conclusions

- Higher dose efficiency, also due to the small pixel effect.
- Two energy bins are sufficient, since only two materials exist
- More than two energy bins may slightly decrease noise
- VMI standardizes CT values also across bone tissue
- Radiation therapy may most benefit from the spectral information and from the VMI-based standardization of the CT values.

Thank You!

This presentation will soon be available at www.dkfz.de/ct.

Job opportunities through marc.kachelriess@dkfz.de or through DKFZ’s international PhD or Postdoctoral Fellowship programs.

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.