Dual Energy CT (DECT)
and beyond

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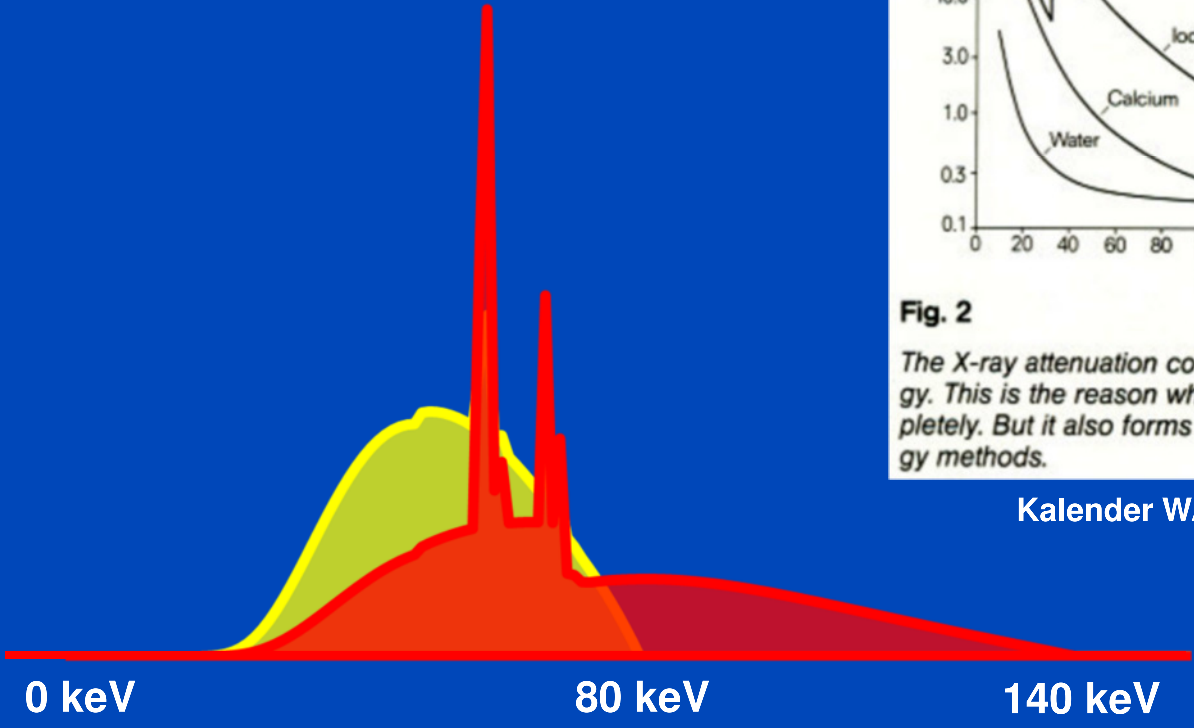
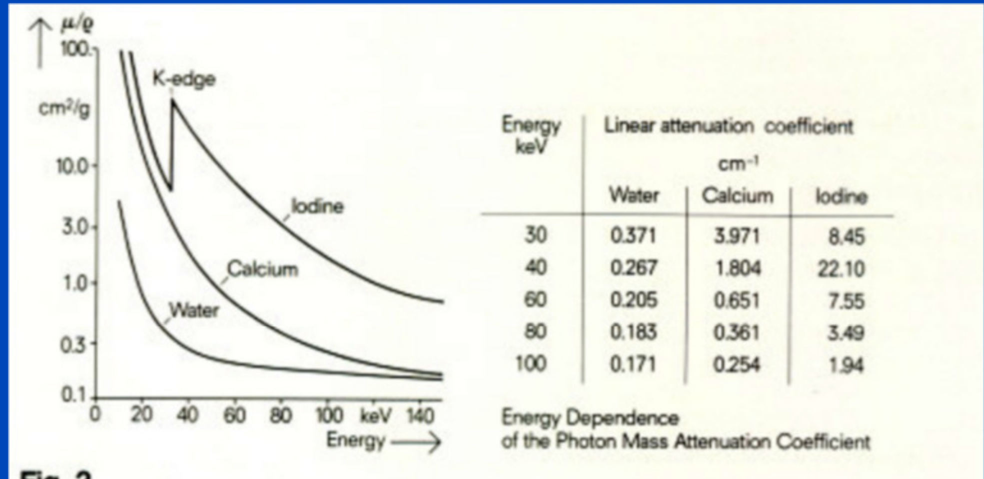
DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

DECT



$$\mu(\boldsymbol{r}, E) = f_1(\boldsymbol{r})\psi_1(E) + f_2(\boldsymbol{r})\psi_2(E)$$



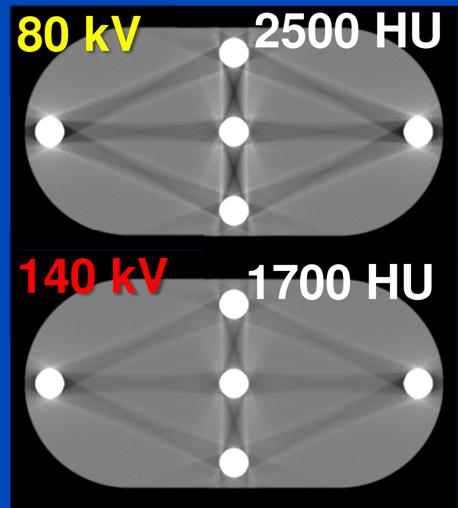
Energy keV	Linear attenuation coefficient cm⁻¹		
	Water	Calcium	Iodine
30	0.371	3.971	8.45
40	0.267	1.804	22.10
60	0.205	0.651	7.55
80	0.183	0.361	3.49
100	0.171	0.254	1.94

Energy Dependence of the Photon Mass Attenuation Coefficient

Fig. 2

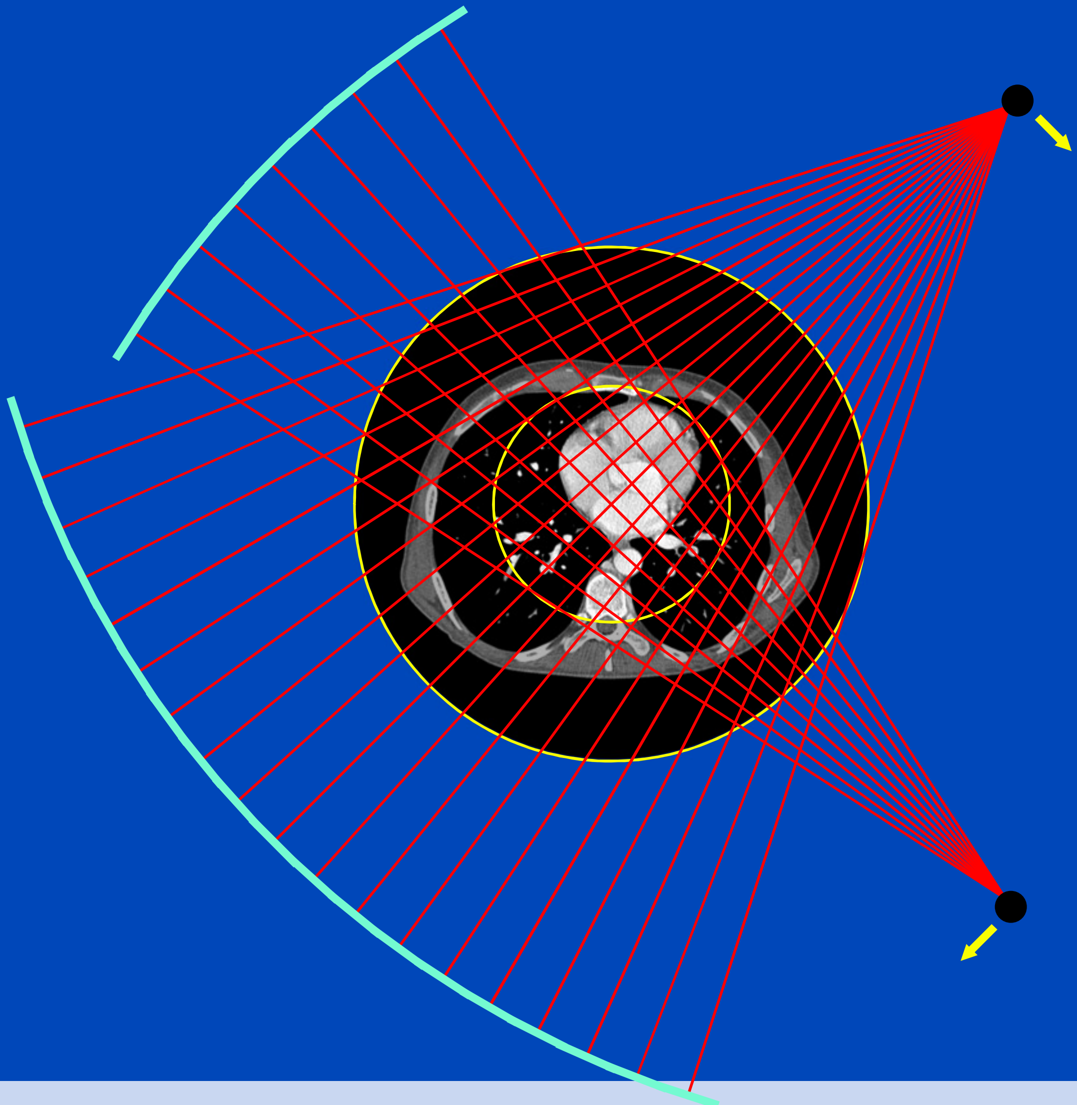
The X-ray attenuation coefficients of different materials vary widely with energy. This is the reason why beamhardening effects cannot be controlled completely. But it also forms the basis for material-selective imaging by dual energy methods.

Kalender WA et al. Radiology 164:419-423, 1987

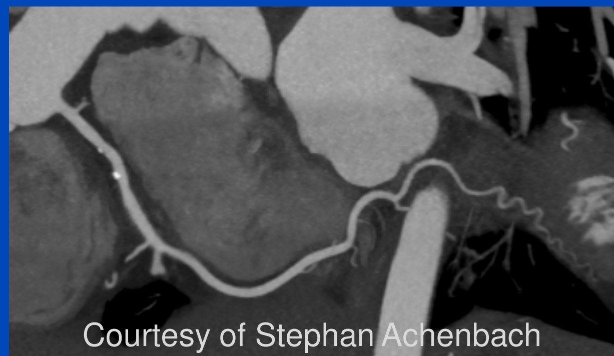


Simulation with conventional spectra (no additional prefiltration) to emphasize artifacts.

Dual-Source-CT (since 2005)



Siemens SOMATOM Force
3rd generation
dual source cone-beam spiral CT

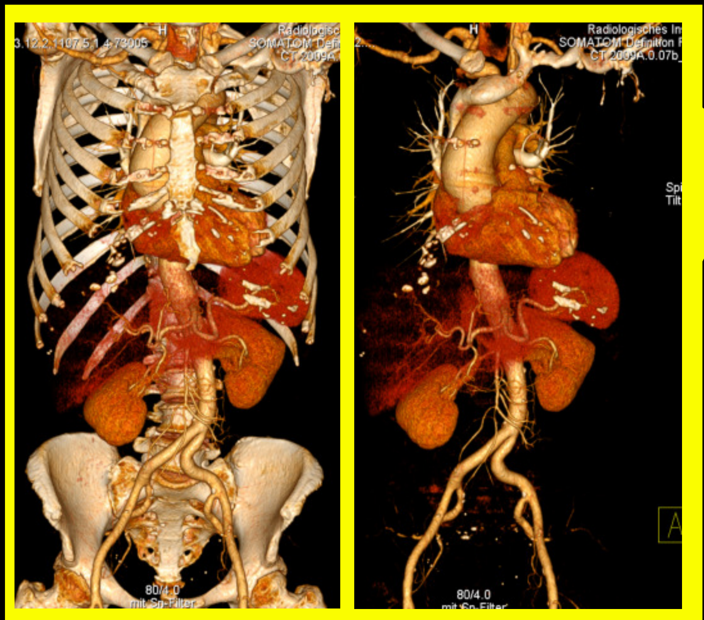


Turbo Flash, 70 kV, 0.55 mSv
63 ms temporal resolution
143 ms scan time

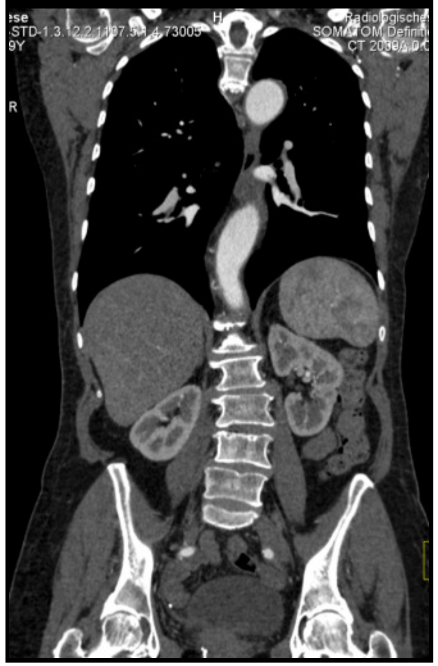
Examples

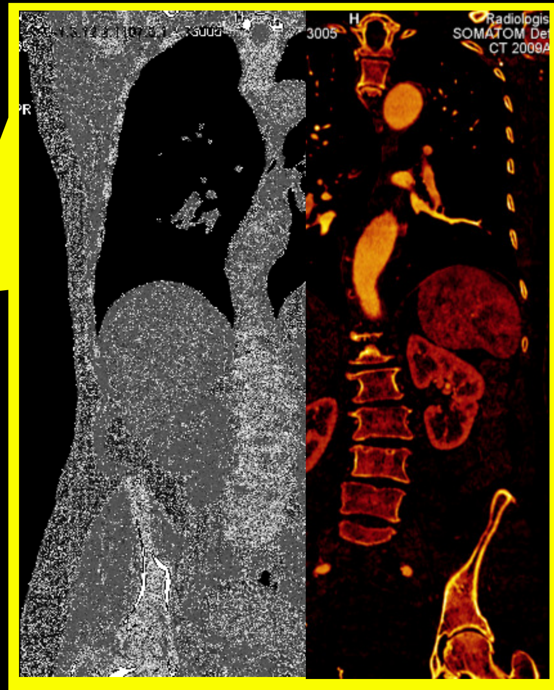
(Slide Courtesy of Siemens Healthcare)

DE bone removal



Single DECT Scan





Virtual non-contrast and Iodine image

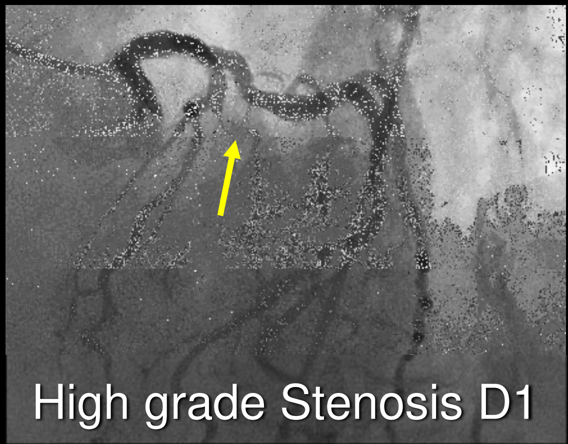
Dual Energy whole body CTA: 100/140 Sn kV @ 0.6mm

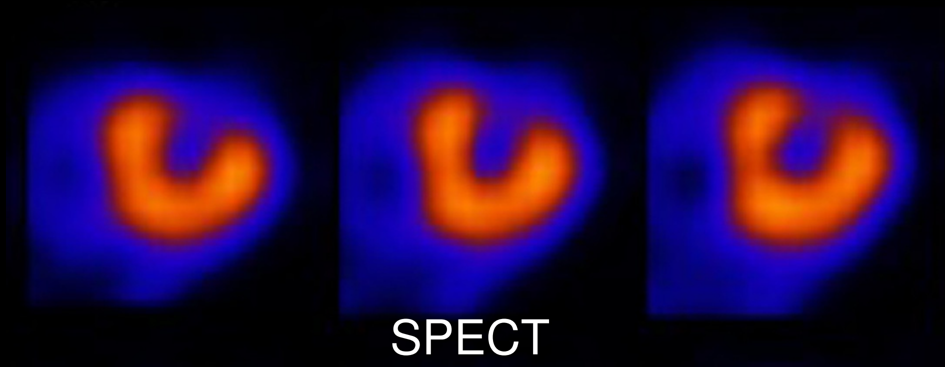
Courtesy of Friedrich-Alexander University Erlangen-Nürnberg

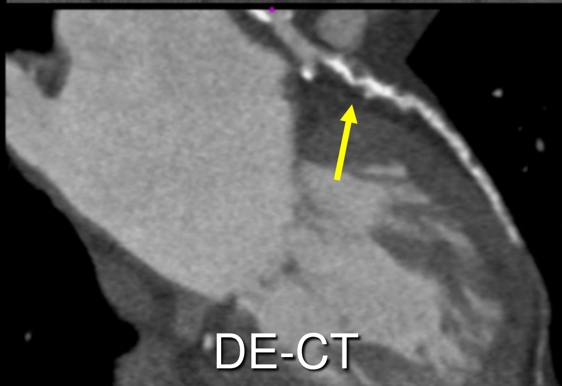
DECT Today: Widely Available via DSCT

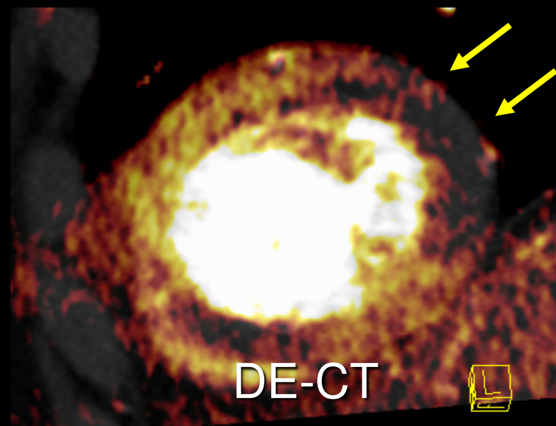
(Slide Courtesy of Siemens Healthcare)

- **New approach: Detection, visualization and quantification of iodine**
  → Characterization of perfusion defects in the myocardium
  → Hemodynamic relevance of coronary artery stenosis:
  Coronary CTA = morphology, local blood volume = function









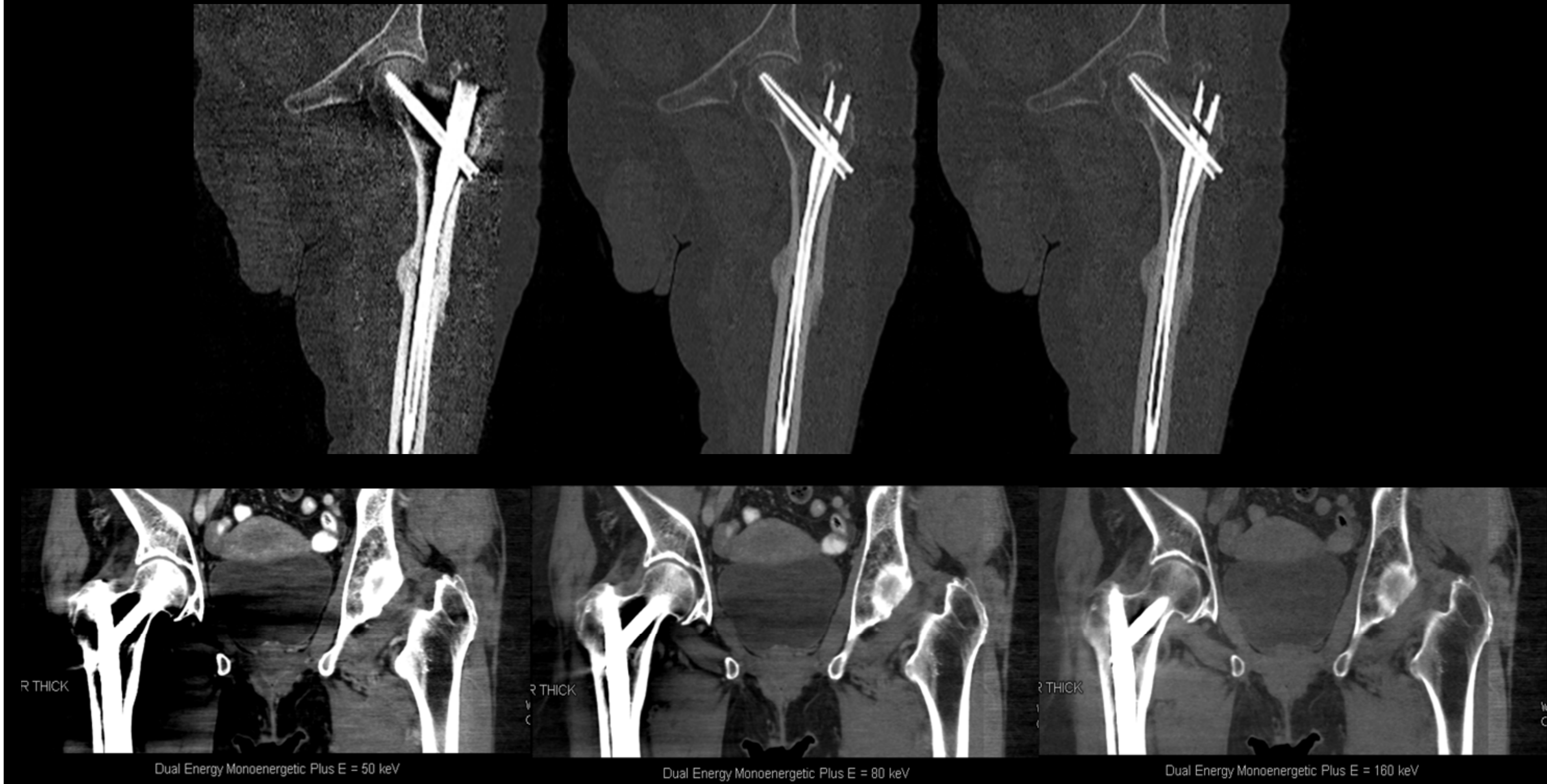
Courtesy of MUSC, Charleston, USA

Monoenergetic Imaging
(mono+ = noise reduction with frequency split)

Courtesy of Prof. Michael Lell, Friedrich-Alexander University Erlangen-Nürnberg

Dual Energy Metal Artifact Reduction

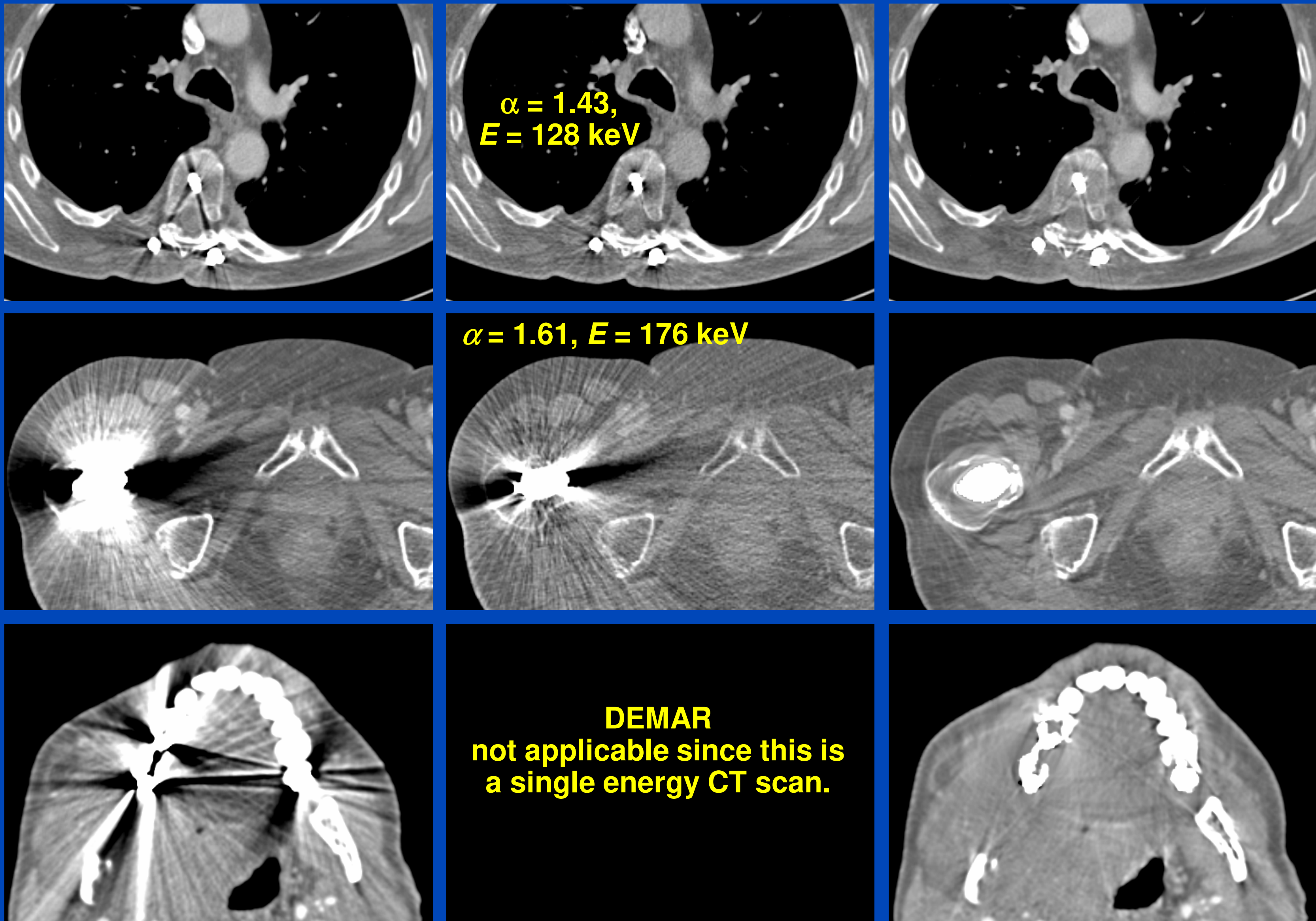
(linear combination plus noise reduction with mono+)



50 keV **80 keV** **160 keV**

Courtesy of Prof. Michael Lell, Friedrich-Alexander University Erlangen-Nürnberg

	Original	DEMAR	iMAR[1] (FSNMAR[2])
Patient 1 100 kV 140 kV Sn			
Patient 2 100 kV 140 kV Sn			
Patient 3 100 kV			



[1]Iterative metal artifact reduction (iMAR) is the Siemens product implementation of FSNMAR.
[2]Frequency split normalized metal artifact reduction: Meyer, Kachelrieß. MedPhys 39(4), 2012.

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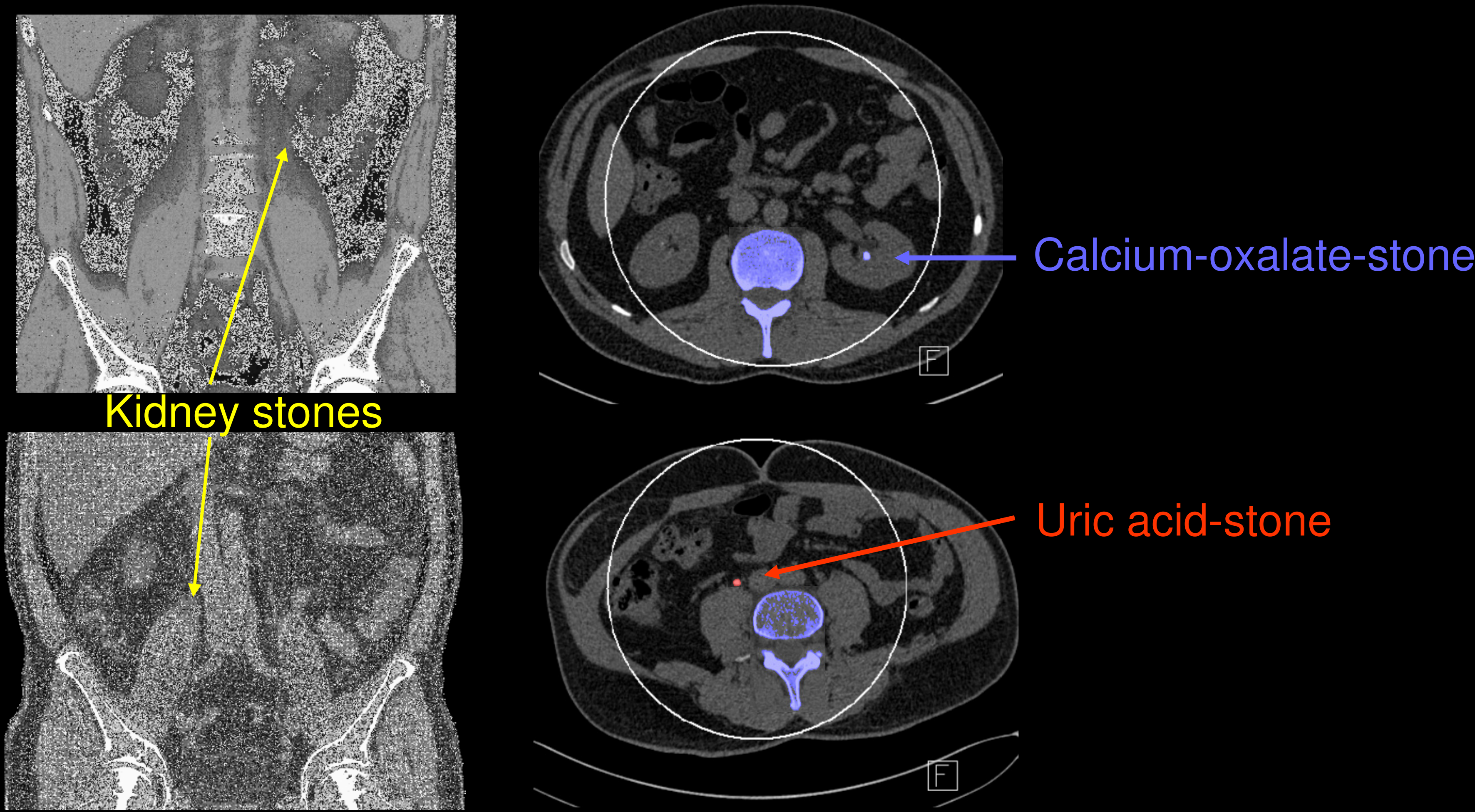
DECT Today: Widely Available via DSCT

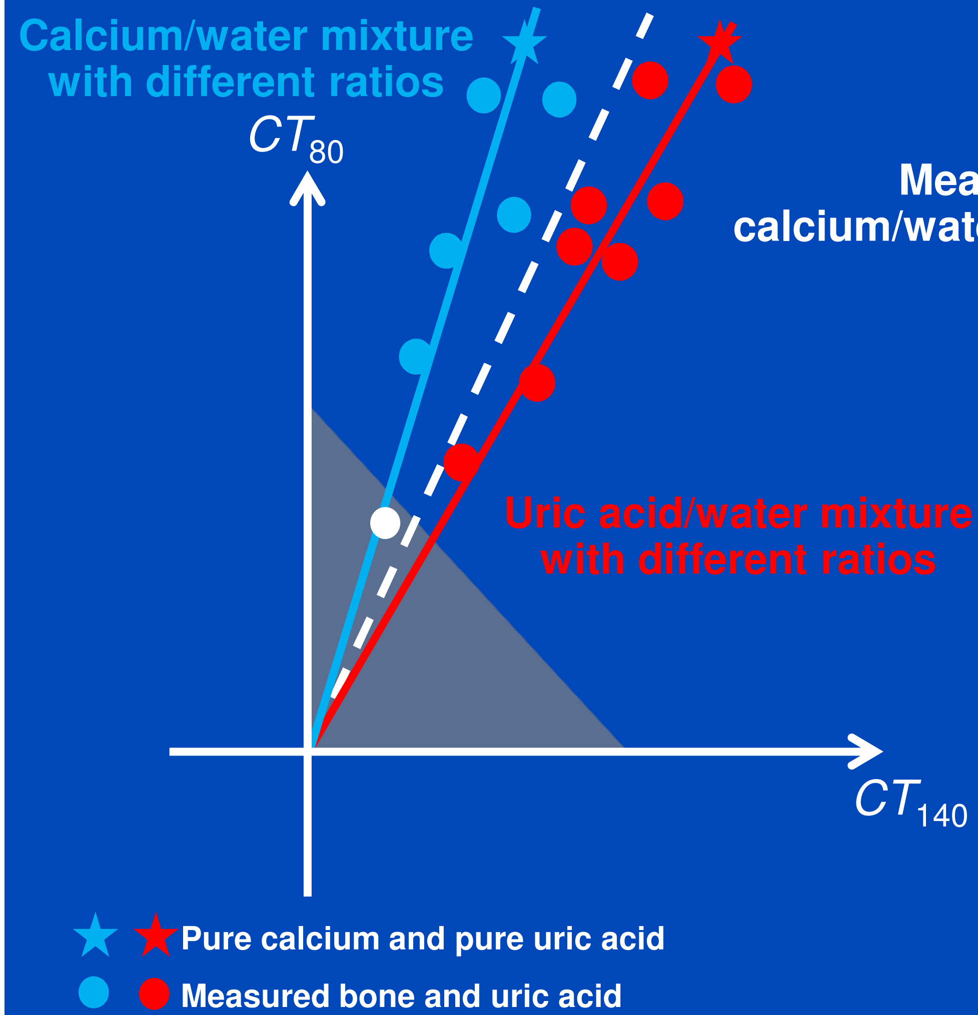
(Slide Courtesy of Siemens Healthcare)

- **“Spectroscopy“: more specific tissue characterization**
  → Detection and visualization of calcium, iron, uric acid, …..

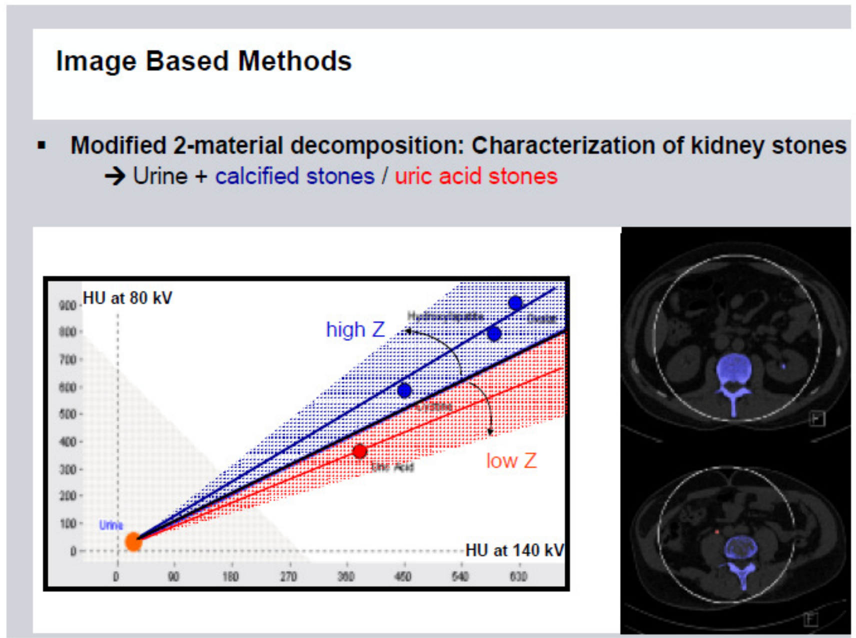


Courtesy of Klinikum Großhadern, LMU München

Image-Based Classification of Materials



Measured data can be classified into calcium/water mixtures and uric acid/water mixtures.



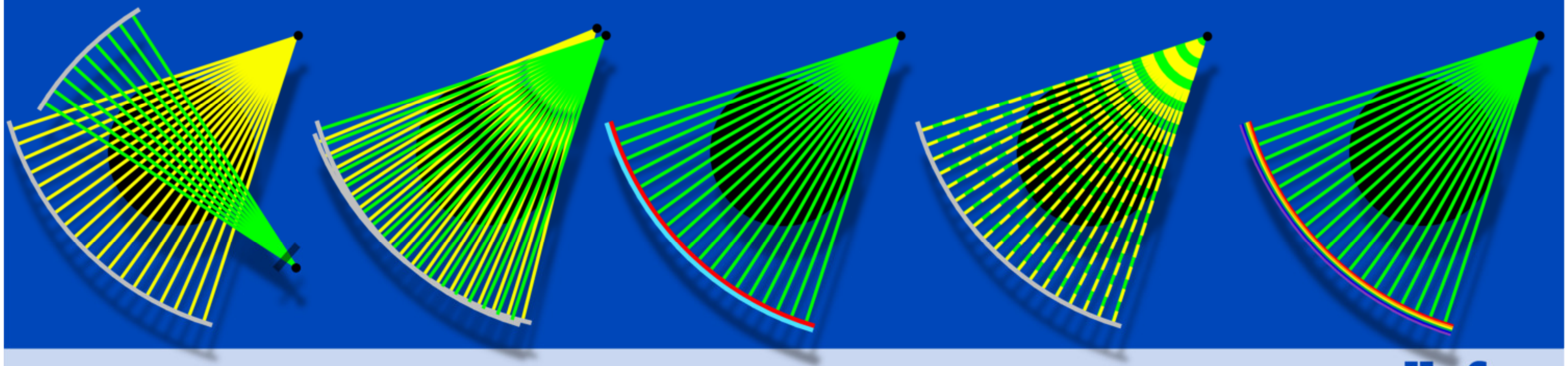
DECT Technology

- In the clinic:

– Multiple scans at different spectra	mid-range
– Dual source CT (DSCT), generations 2, and 3	high-end
– Fast tube voltage switching	high-end
– Dual layer sandwich detectors	high-end
– Split filter	mid-range

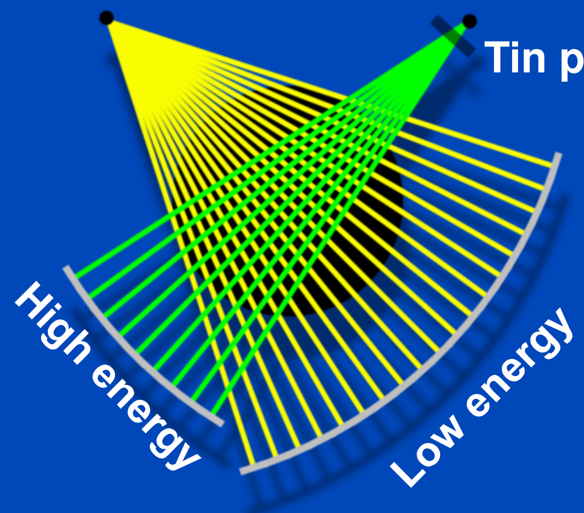
- First prototypes:

– Photon counting detectors (two or more energy bins)	high-end?



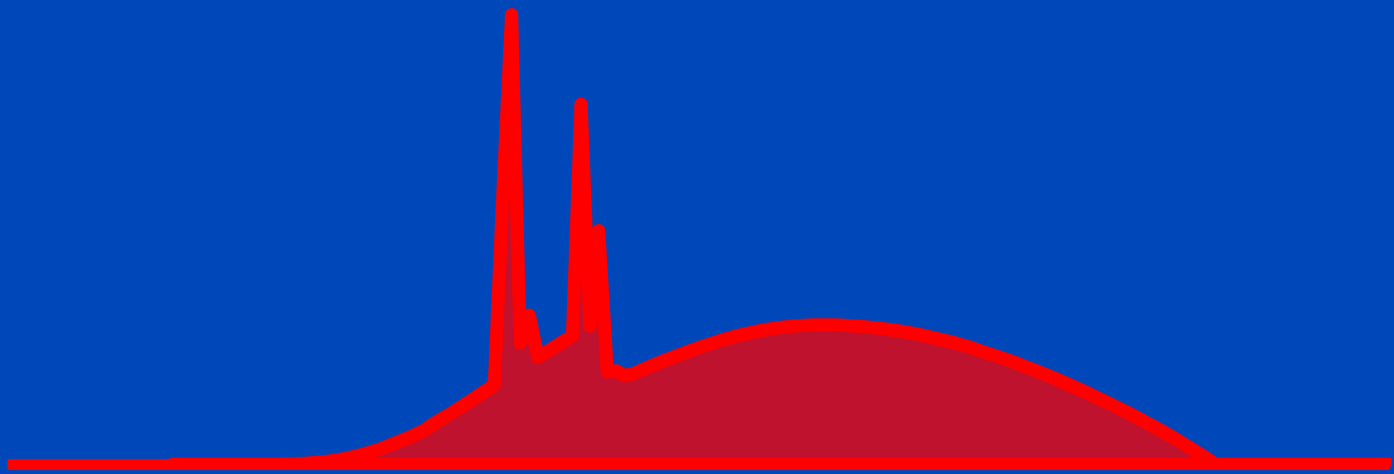
DECT Technology

- **DECT approaches in the clinic:**
  - Dual source DECT (Siemens)



Siemens Somatom Force

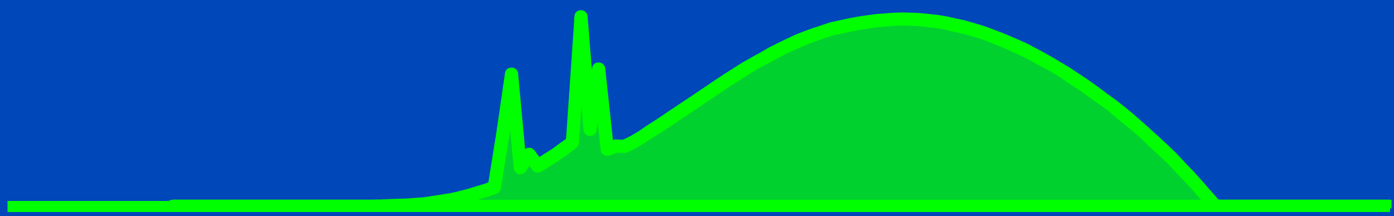
Effect of the Prefilter: Without Sn



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

dkfz.

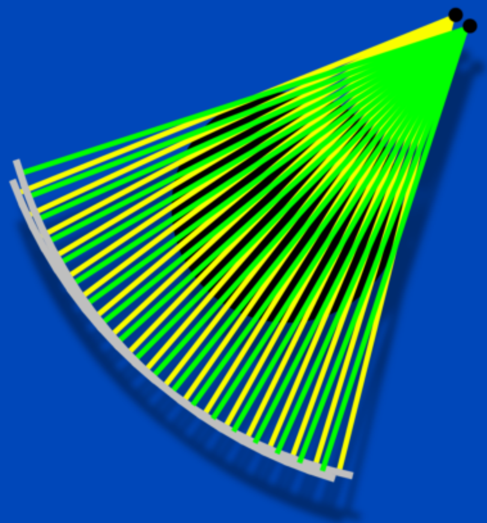
Effect of the Prefilter: With 0.4 mm Sn

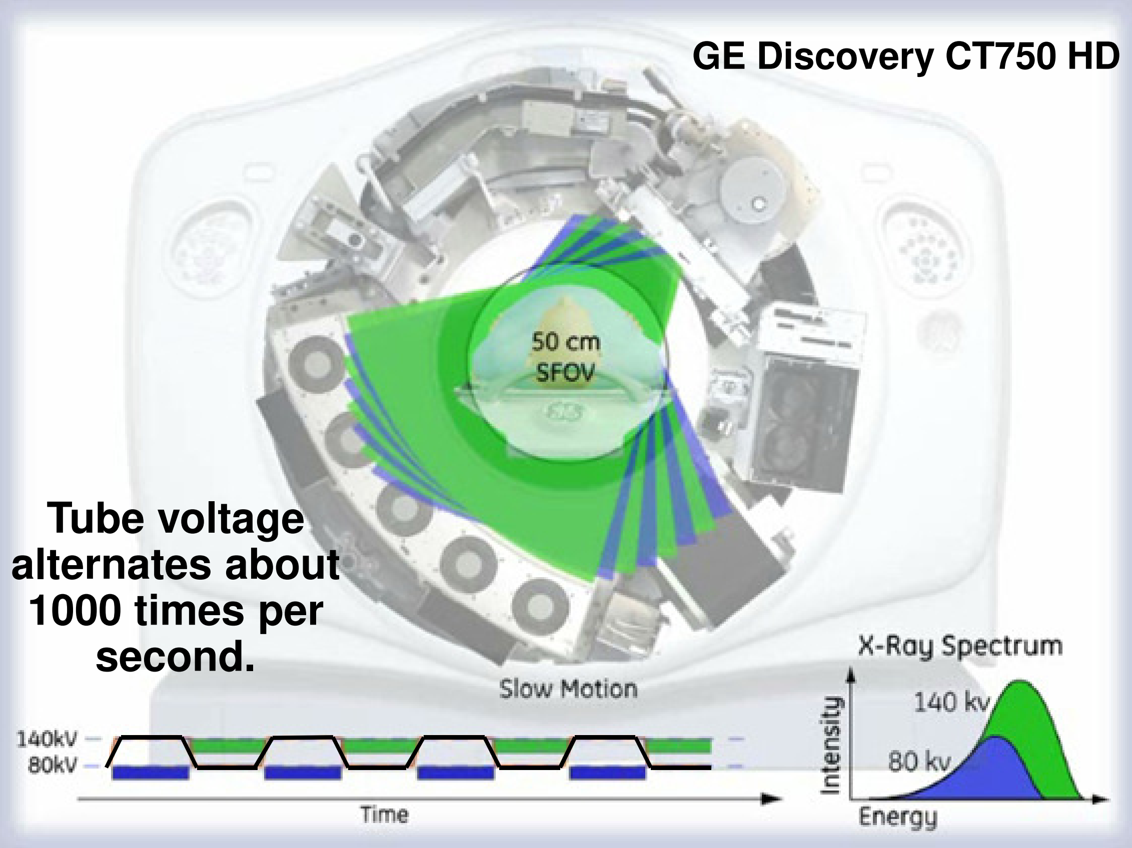


Spectra as seen after having passed a 32 cm water layer.

DECT Technology

- DECT approaches in the clinic:
  - Dual source DECT (Siemens)
  - Fast tube voltage switching (GE)





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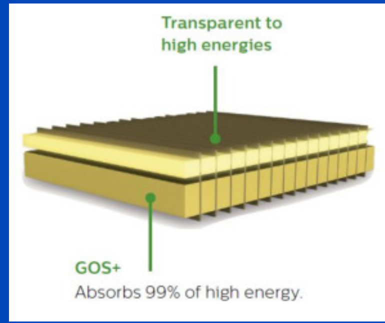
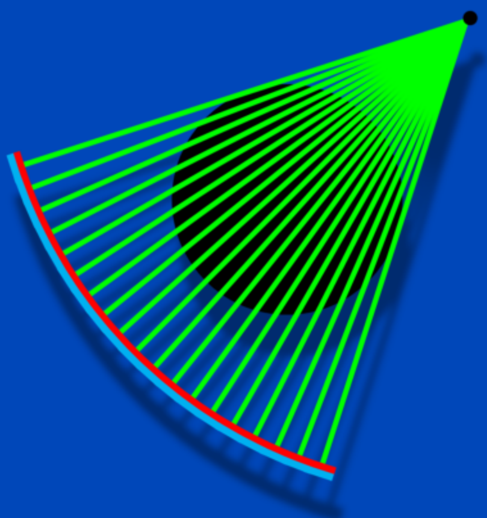
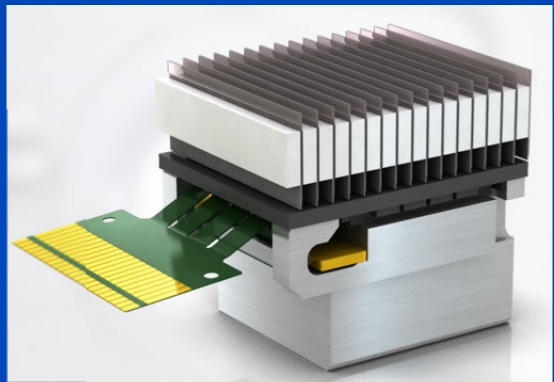
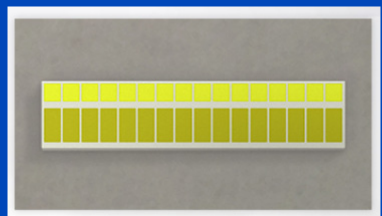
DECT Technology



- DECT approaches in the clinic:
  - Dual source DECT (Siemens)
  - Fast tube voltage switching (GE)
  - Dual layer (sandwich) detector (Philips)



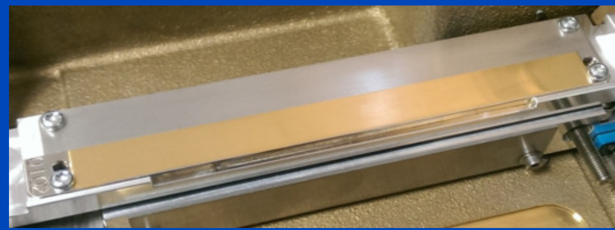


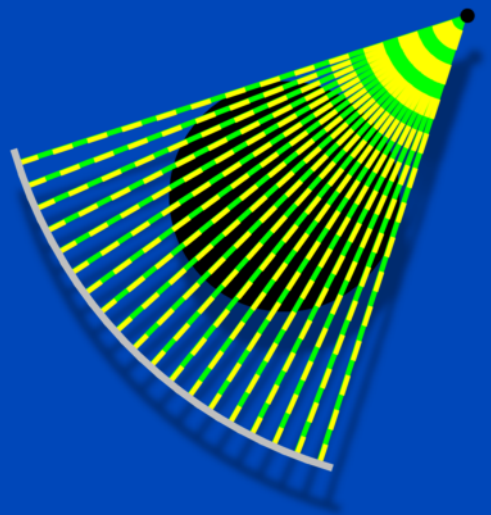


Philips IQon

DECT Technology

- DECT approaches in the clinic:
  - Dual source DECT (Siemens)
  - Fast tube voltage switching (GE)
  - Dual layer (sandwich) detector (Philips)
  - Split filter (Siemens)

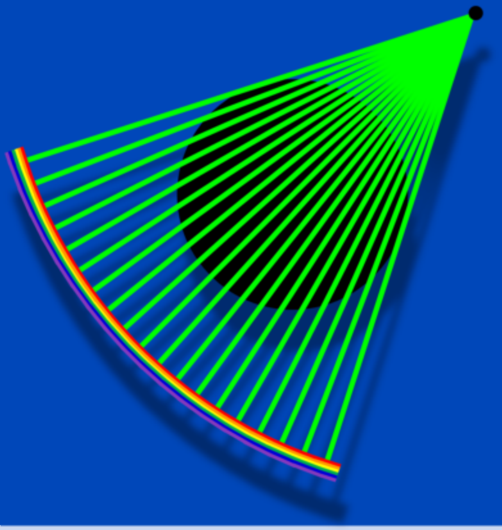




Siemens Definition Edge TwinBeam

DECT Technology

- DECT approaches in the clinic:
  - Dual source DECT (Siemens)
  - Fast tube voltage switching (GE)
  - Dual layer (sandwich) detector (Philips)
  - Split filter (Siemens)
- First prototype systems
  - Photon counting detector, multiple energy bins



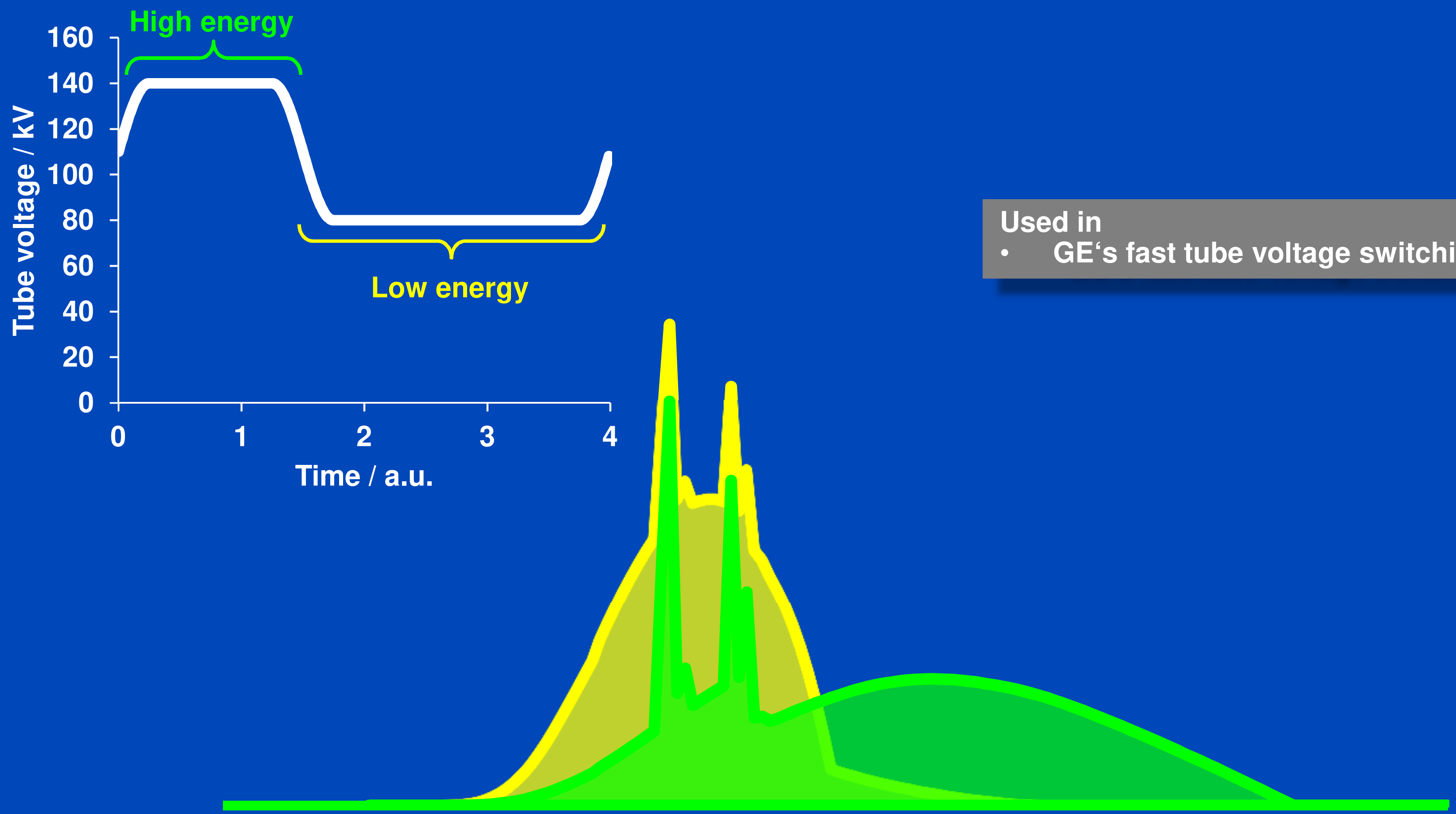
2014-2016	Configuration	Collimation	Rotation	DECT
GE Revolution	256 × 0.625 mm	160 mm	0.28 s	fast TVS
Philips Brilliance iCT	2·128 × 0.625 mm	80 mm	0.27 s	2 scans
Philips IQon	2·64 × 0.625 mm	40 mm	0.27 s	sandwich
Siemens Definition Edge	2·64 × 0.6 mm	38.4 mm	0.28 s	split filter
Siemens Definition Flash	2·2·64 × 0.6 mm	38.4 mm	0.28 s	DSCT
Siemens Force	2·2·96 × 0.6 mm	57.6 mm	0.25 s	DSCT
Siemens PC Prototype	28 × 0.5 mm	14 mm	1.00 s	PC
Toshiba Acquil. ONE Vision	320 × 0.5 mm	160 mm	0.275 s	2 scans

Folie 34

MK3

Siemens: 2*1160 in 0.5 s
Philips iCT: (2400 readings / rotation) / (0.27 seconds / rotation) = 8.889 kHz
Thoshiba: "Sampling rate is 2.6 KHz. ", Mike Silver, Mail of 20.5.2012
Prof. Dr. Marc Kachelrieß; 21.05.2012

80 kV / 140 kV Sinrect kV-Switching



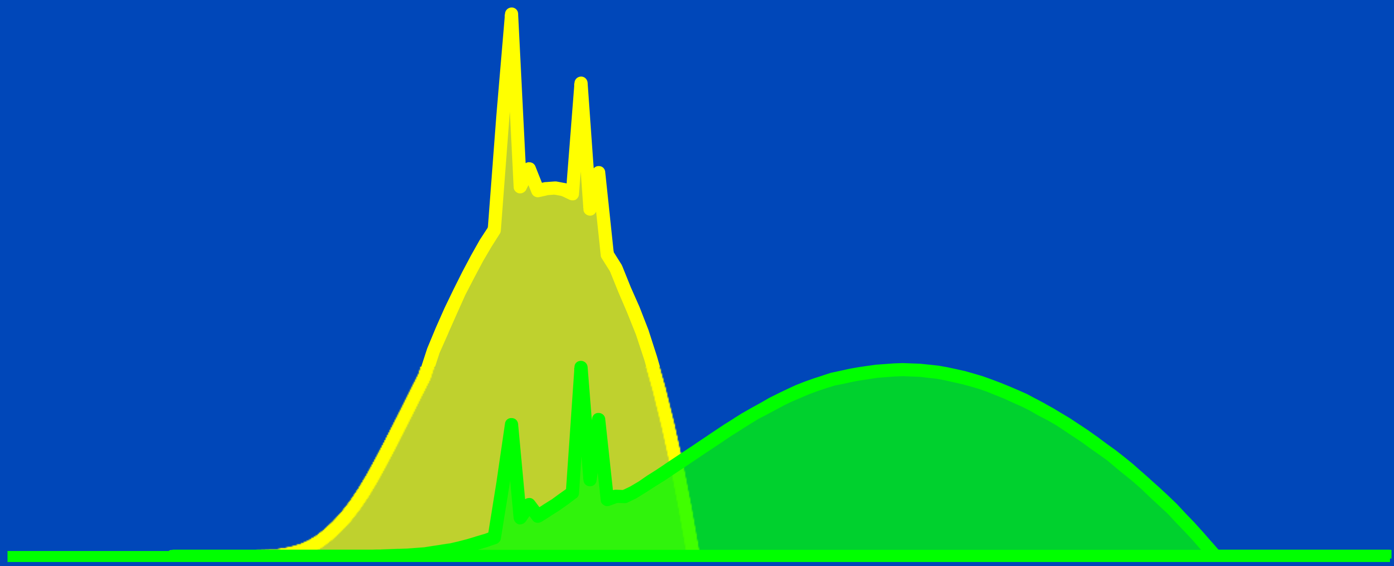
Used in
- GE's fast tube voltage switching CT

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

dkfz.

80 kV / 140 kV $Sn_{0.4\ mm}$

Used in
- Siemens‘ 2nd generation DSCT

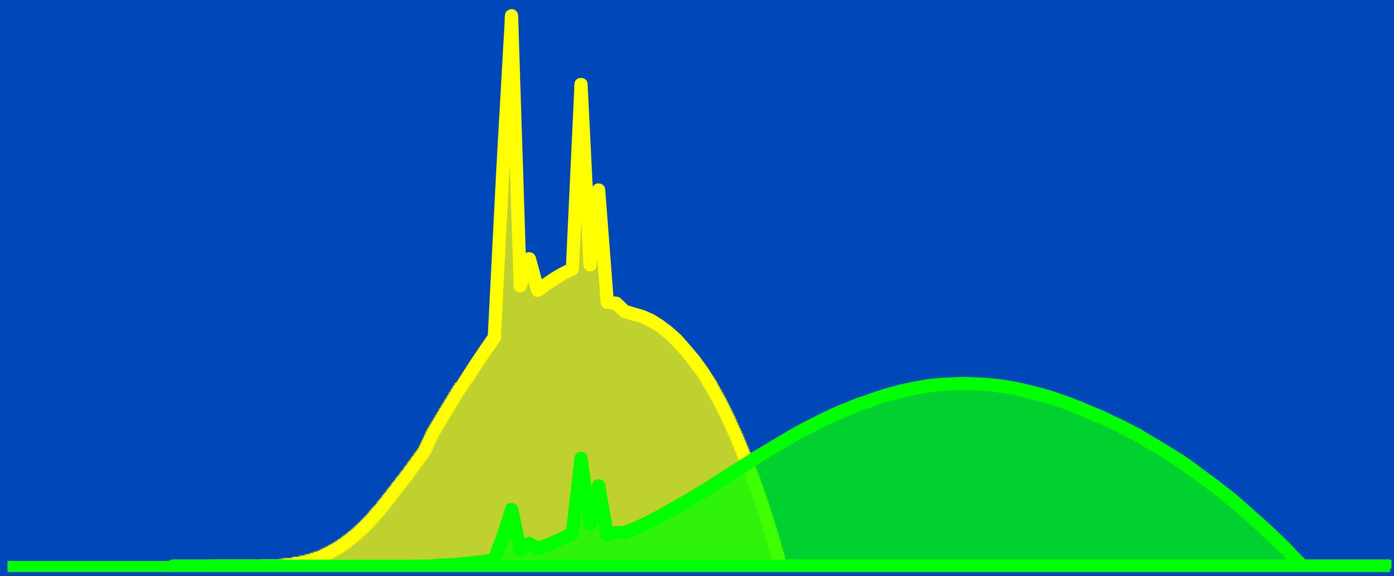


Spectra as seen after having passed a 32 cm water layer.

dkfz.

90 kV / 150 kV $Sn_{0.6\ mm}$

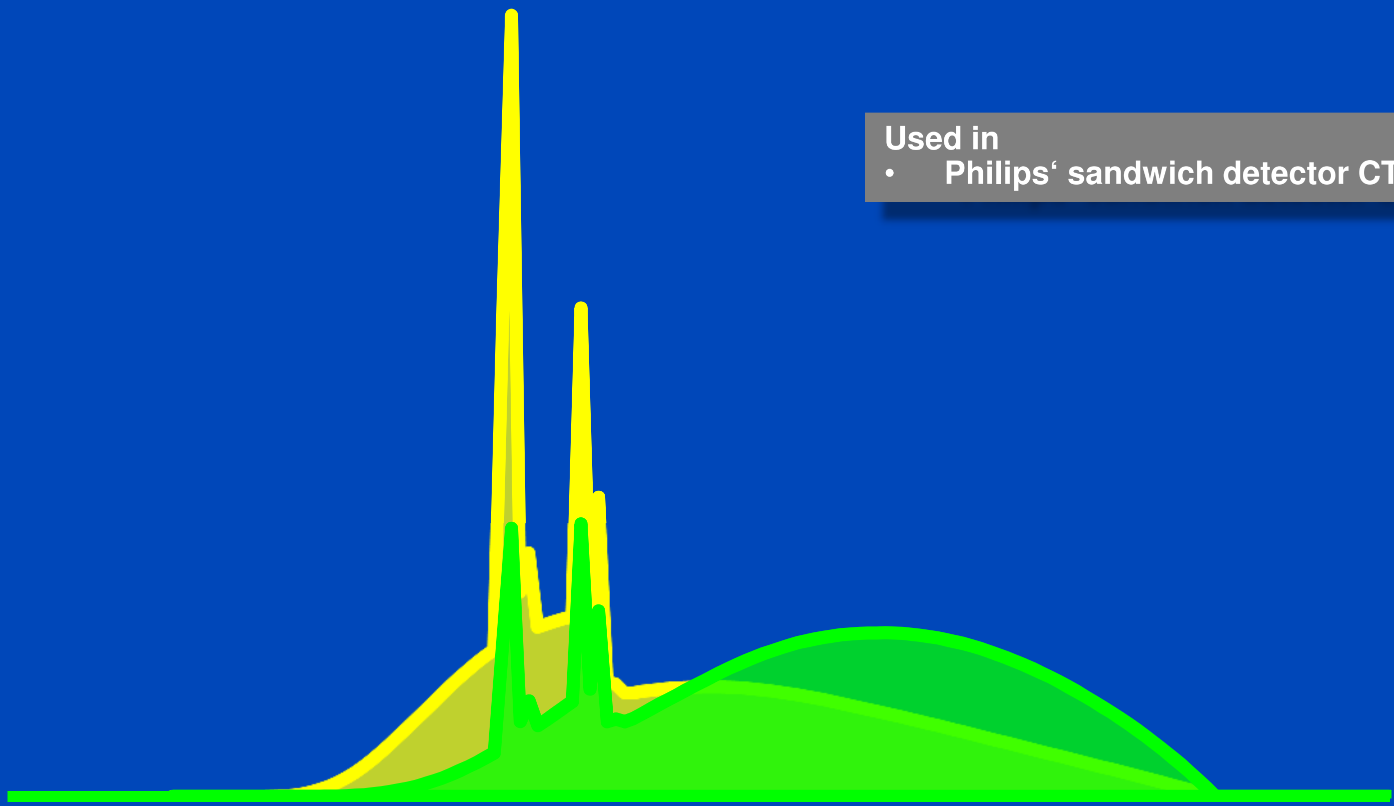
Used in
- Siemens‘ 3rd generation DSCT



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

dkfz.

140 kV YAG / GOS

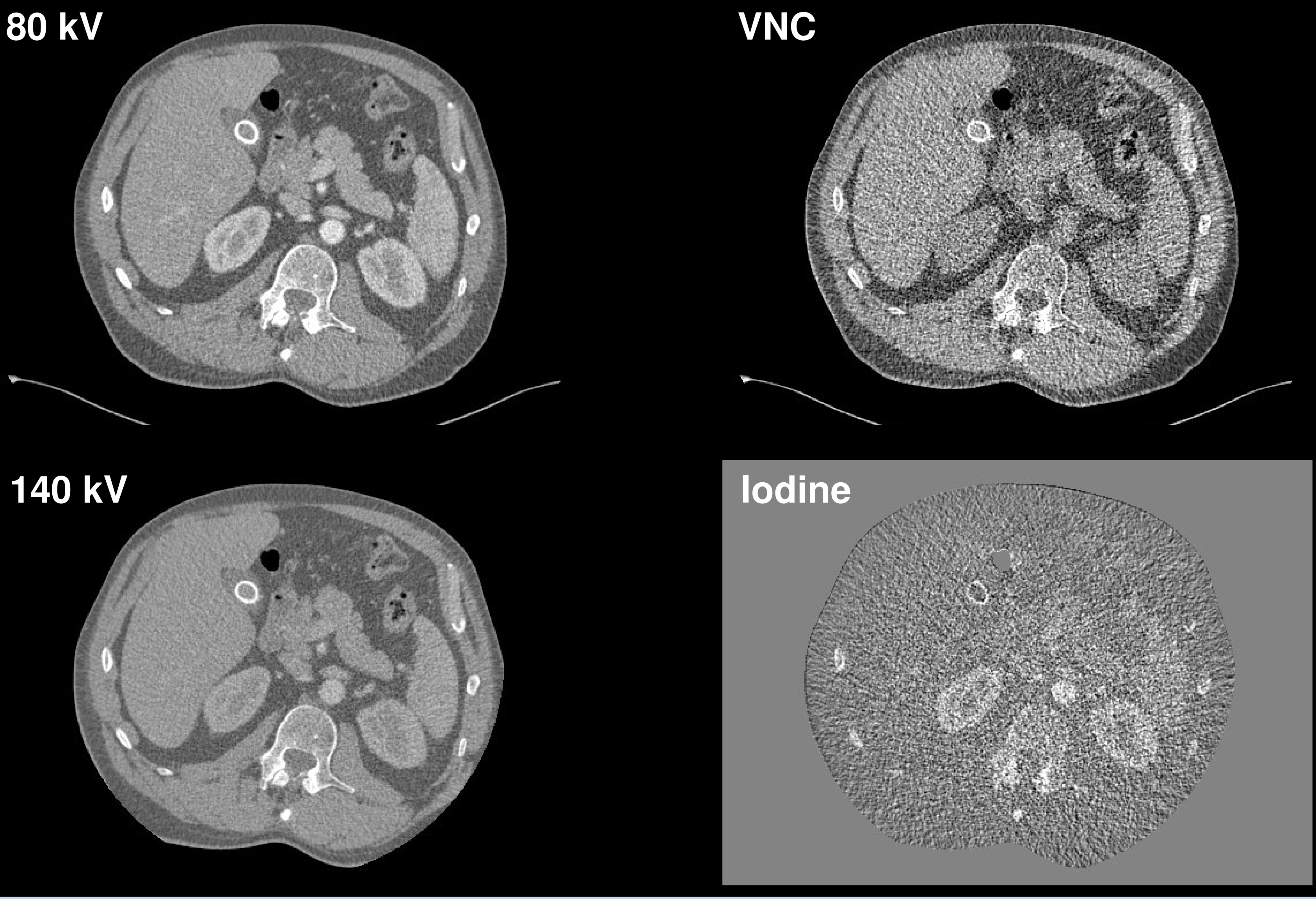


Used in
- Philips‘ sandwich detector CT

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

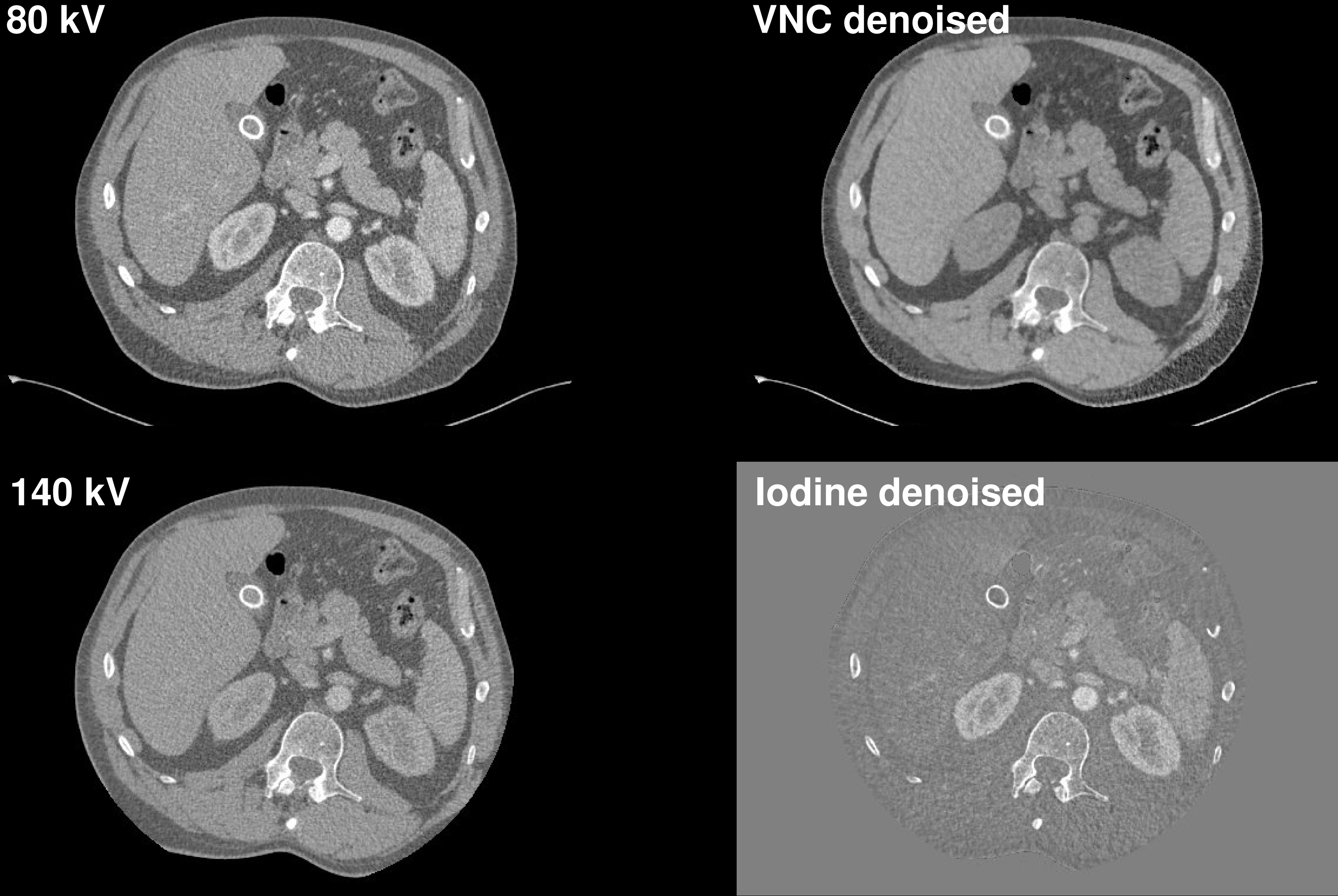
dkfz.

Decomposition Increases Noise



C = 0 HU, W = 700 HU

Denoising is Mandatory!



C = 0 HU, W = 700 HU

More than Dual Energy?

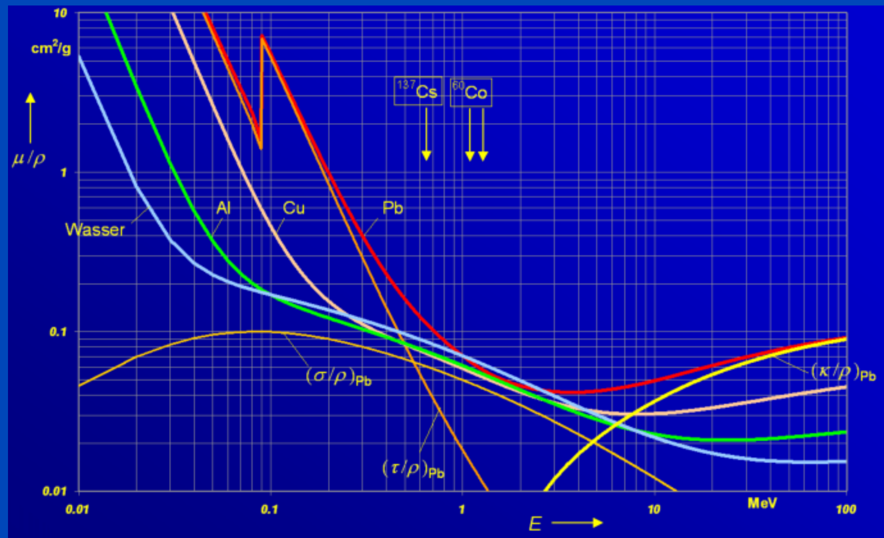
- Ways to remove the spectral overlap?
- Lower noise, less dose?
- Improve contrast-to-noise ratio at unit dose?
- Distinguish more than three materials?

$$\mu(E) = \cancel{\eta(E)} + \tau(E) + \sigma(E) + \cancel{\kappa(E)}$$

Rayleigh Photo Compton Pair

$$\tau(E) \propto \rho \frac{Z^3}{E^3}$$

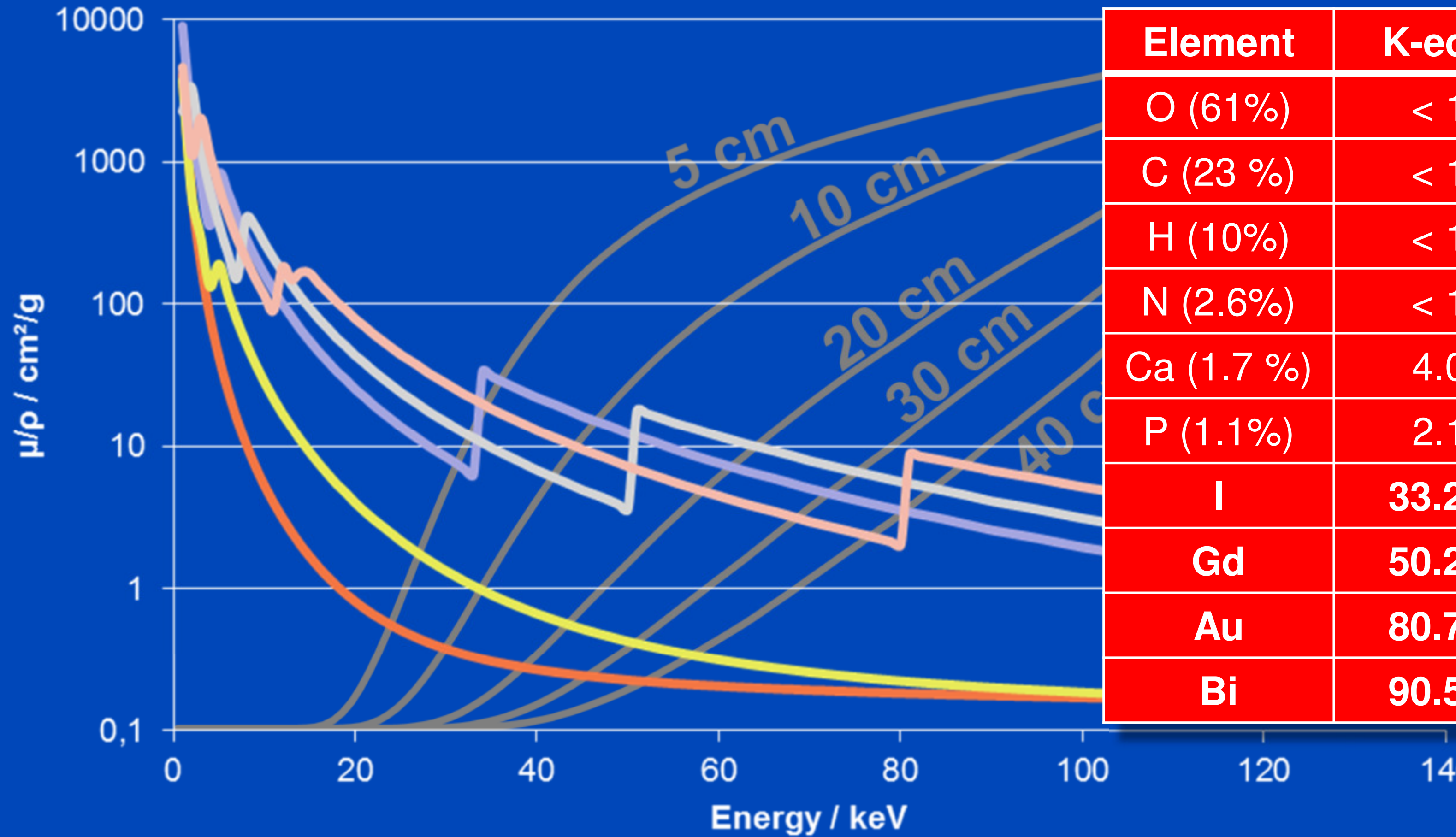
$$\sigma(E) \propto \rho \frac{Z}{A} f(E)$$



K-Edges: More than Dual Energy CT?

$$\mu(\boldsymbol{r},E) = f_1(\boldsymbol{r})\psi_1(E) + f_2(\boldsymbol{r})\psi_2(E) + f_3(\boldsymbol{r})\psi_3(E) + \ldots$$

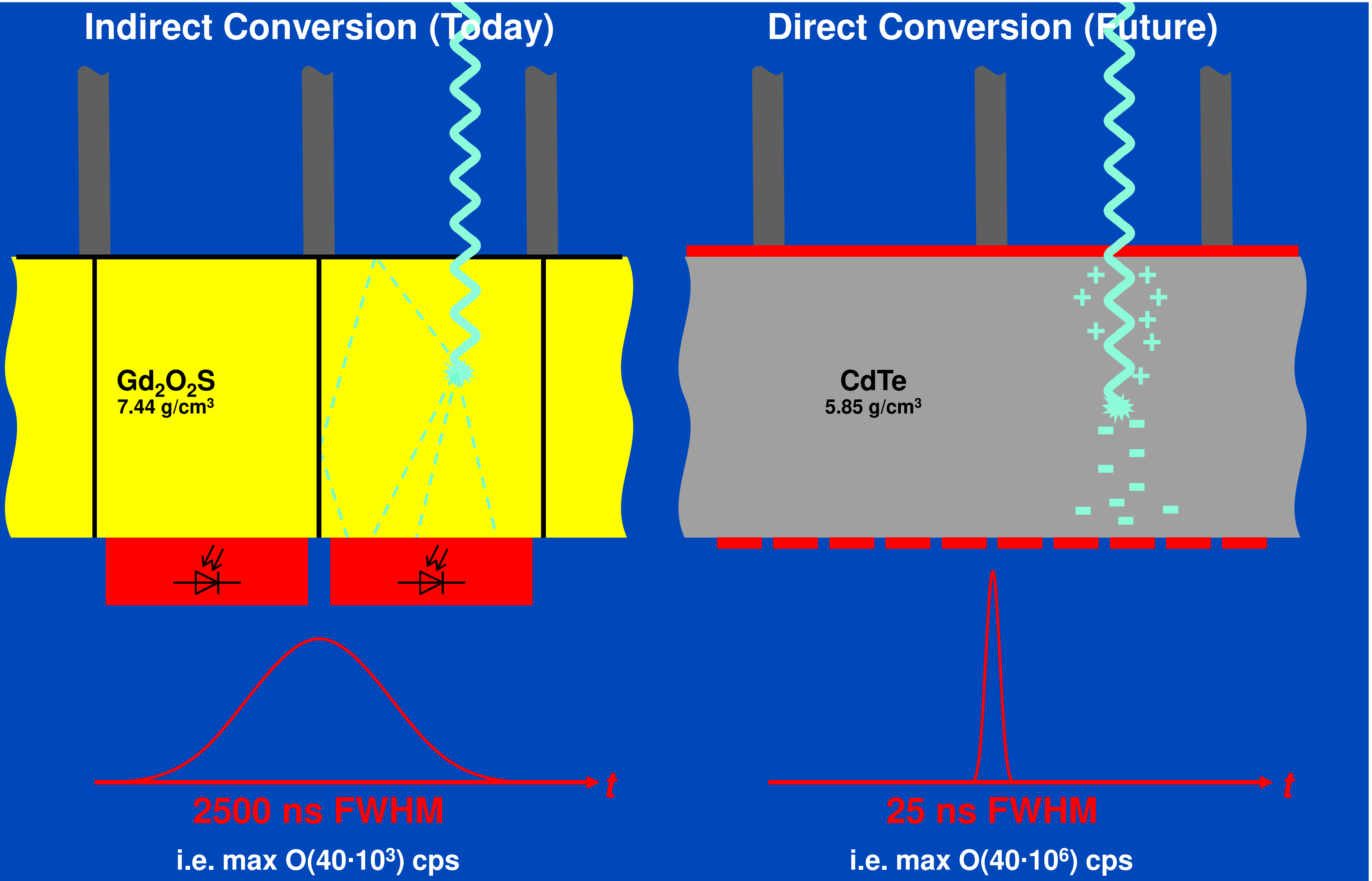
Apart from special applications, e.g.
Iodine k-edge imaging of the breast



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**
Au	**80.7 keV**
Bi	**90.5 keV**

120 kV water transmission curves (gray) given in relative units on a non-logarithmic ordinate.

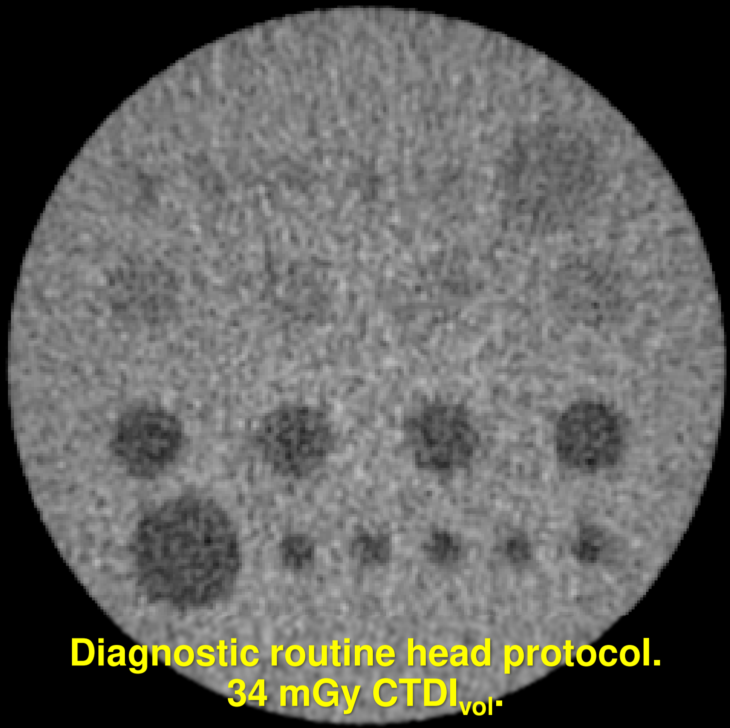
dkfz.



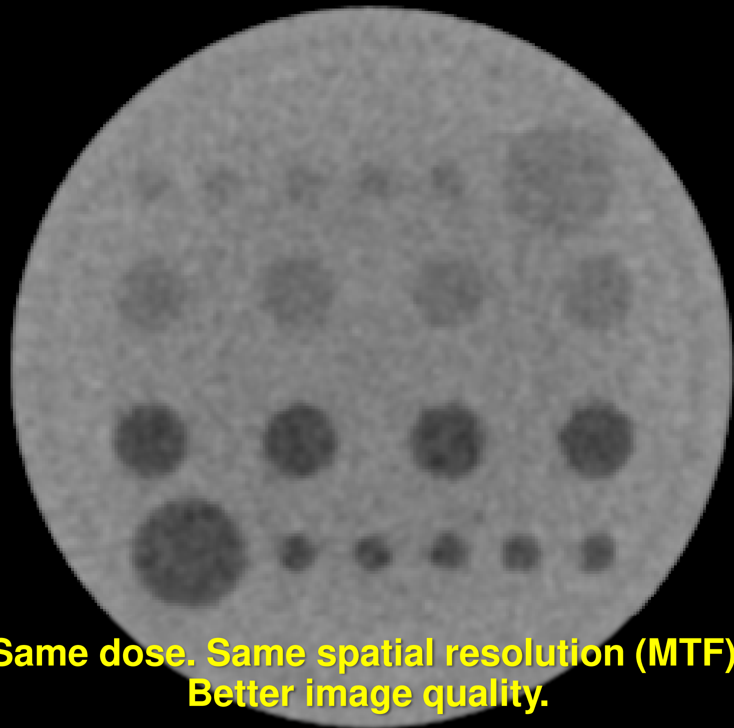
Requirements for CT: up to 10^9 x-ray photon counts per second per mm^2. Hence, photon counting only achievable for direct converters.

Diagnostic CT (Conventional Detector) of a Low Contrast Phantom

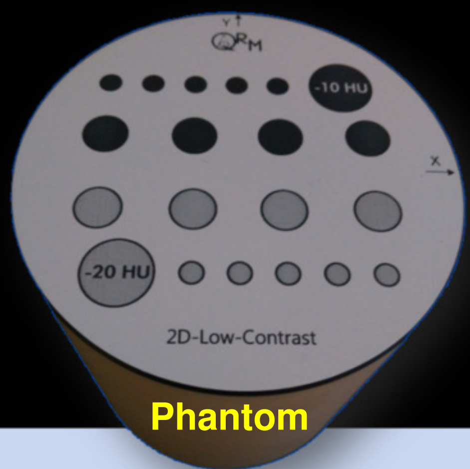
Photon Counting Detector CT of a Low Contrast Phantom

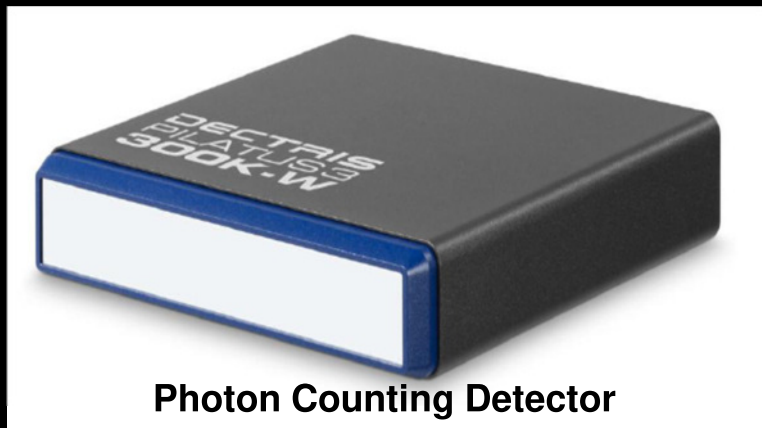


Diagnostic routine head protocol.
34 mGy $CTDI_{vol}$.



Same dose. Same spatial resolution (MTF).
Better image quality.





C = 0 HU, *W* = 80 HU

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Future, Photon Counting (≥ 2020)?

Macro Mode
1×2 readouts
16 mm z-coverage

12	12	12	12
12	12	12	12
12	12	12	12
12	12	12	12

Chess Mode
2×2 readouts
16 mm z-coverage

12	34	12	34
34	12	34	12
12	34	12	34
34	12	34	12

Sharp Mode
5×1 readouts
12 mm z-coverage

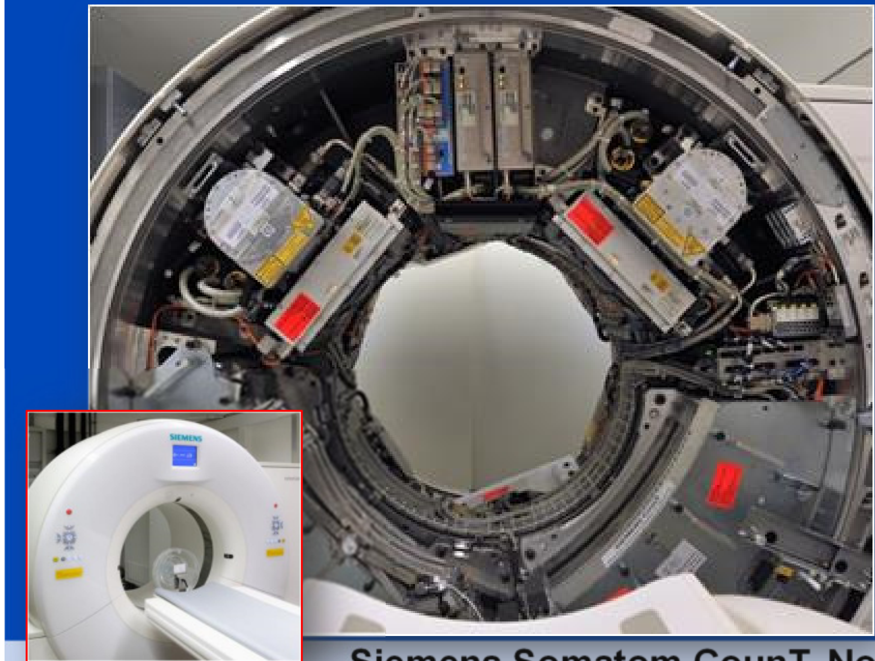
1	1	1	1
1	1	1	1
1	1	1	1
1	1	1	1

2	2	2	2
2	2	2	2
2	2	2	2
2	2	2	2

UHR Mode
4×2 readouts
8 mm z-coverage

12	12	12	12
12	12	12	12
12	12	12	12
12	12	12	12

- 4×4 225 µm subpixels
- 0.9 mm macro pixels
- Configurations:
  - Macro (0.5 mm iso)
  - Chess (0.5 mm iso)
  - Sharp (0.25 mm iso)
  - UHR (0.25 mm iso)



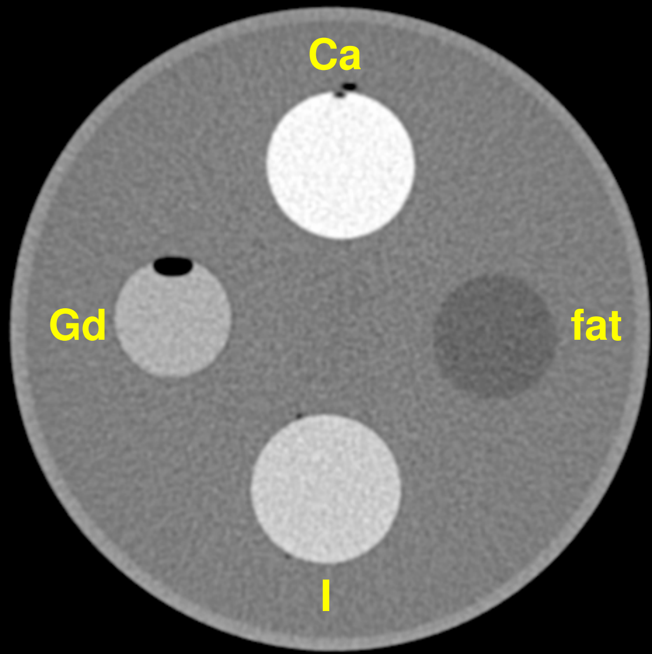
Siemens Somatom CounT. No FFS on thread B (photon counting detector).
The whole detector consists of 128×1920 subpixels = 32×480 macro pixels.

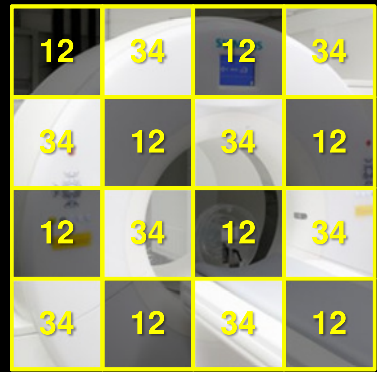
dkfz.

MECT

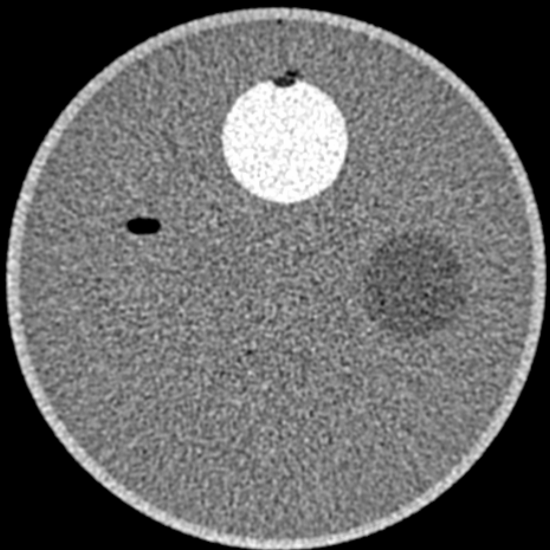
Ca-Gd-I Decomposition

Chess pattern mode
140 kV, 20/35/50/65 keV
***C* = 0 HU, *W* = 1200 HU**

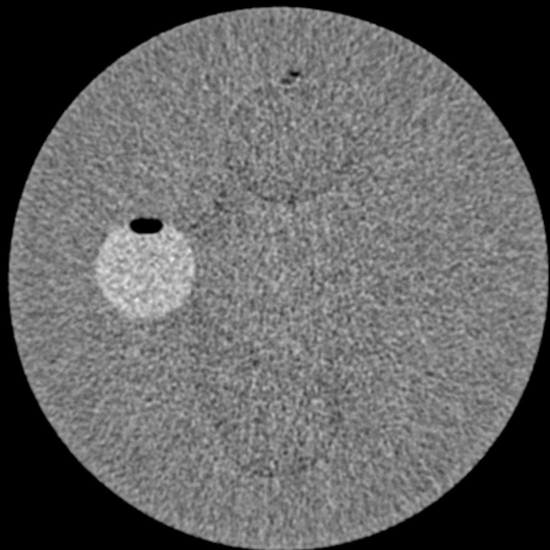




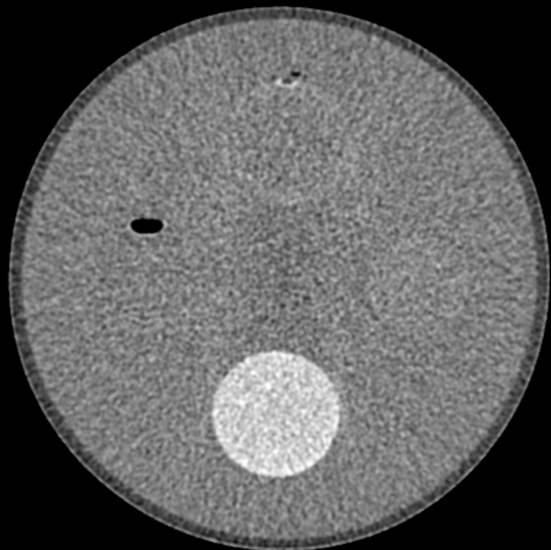
Calcium image



Gadolinium image



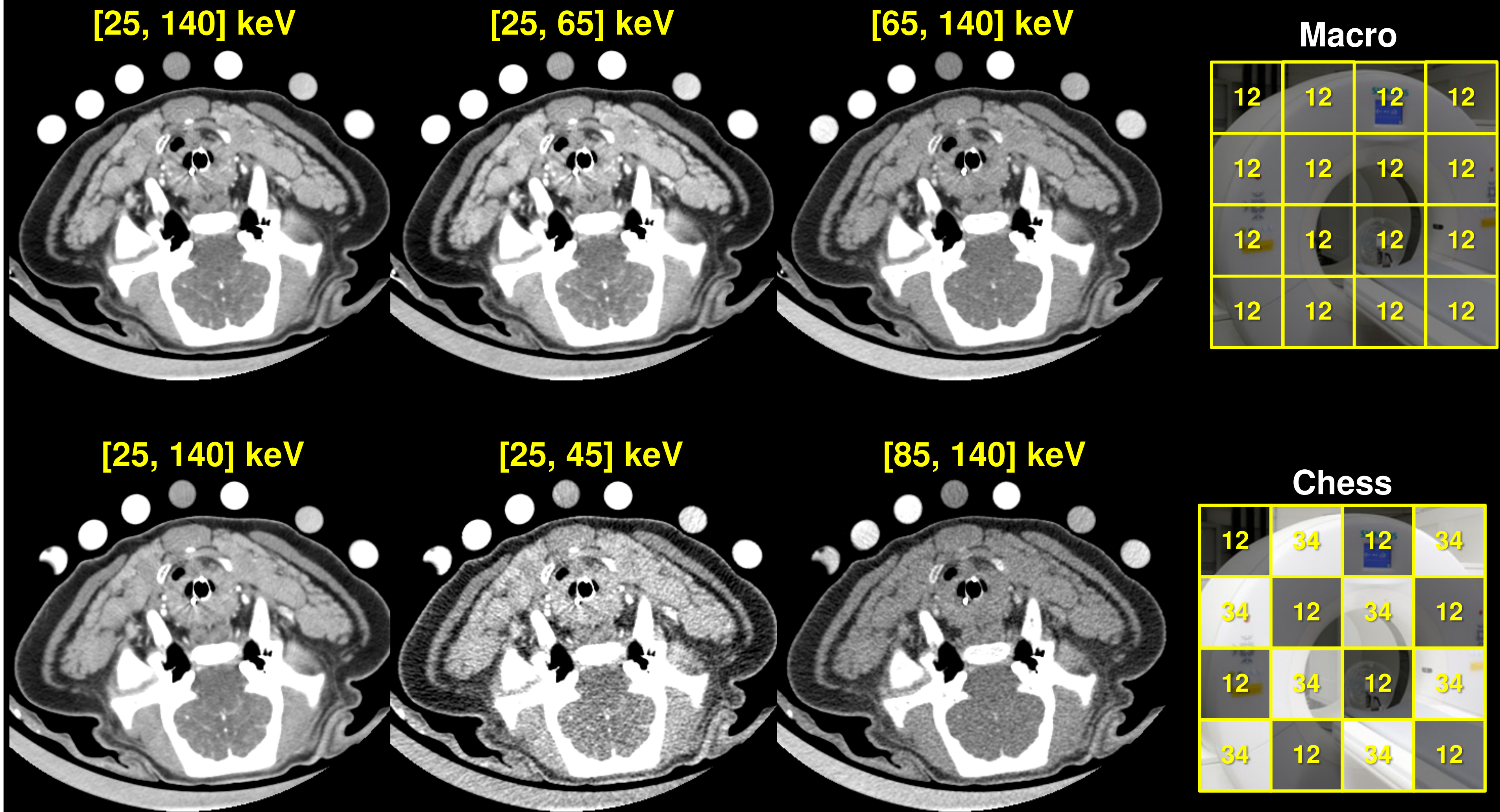
Iodine image



Courtesy of Siemens Healthcare

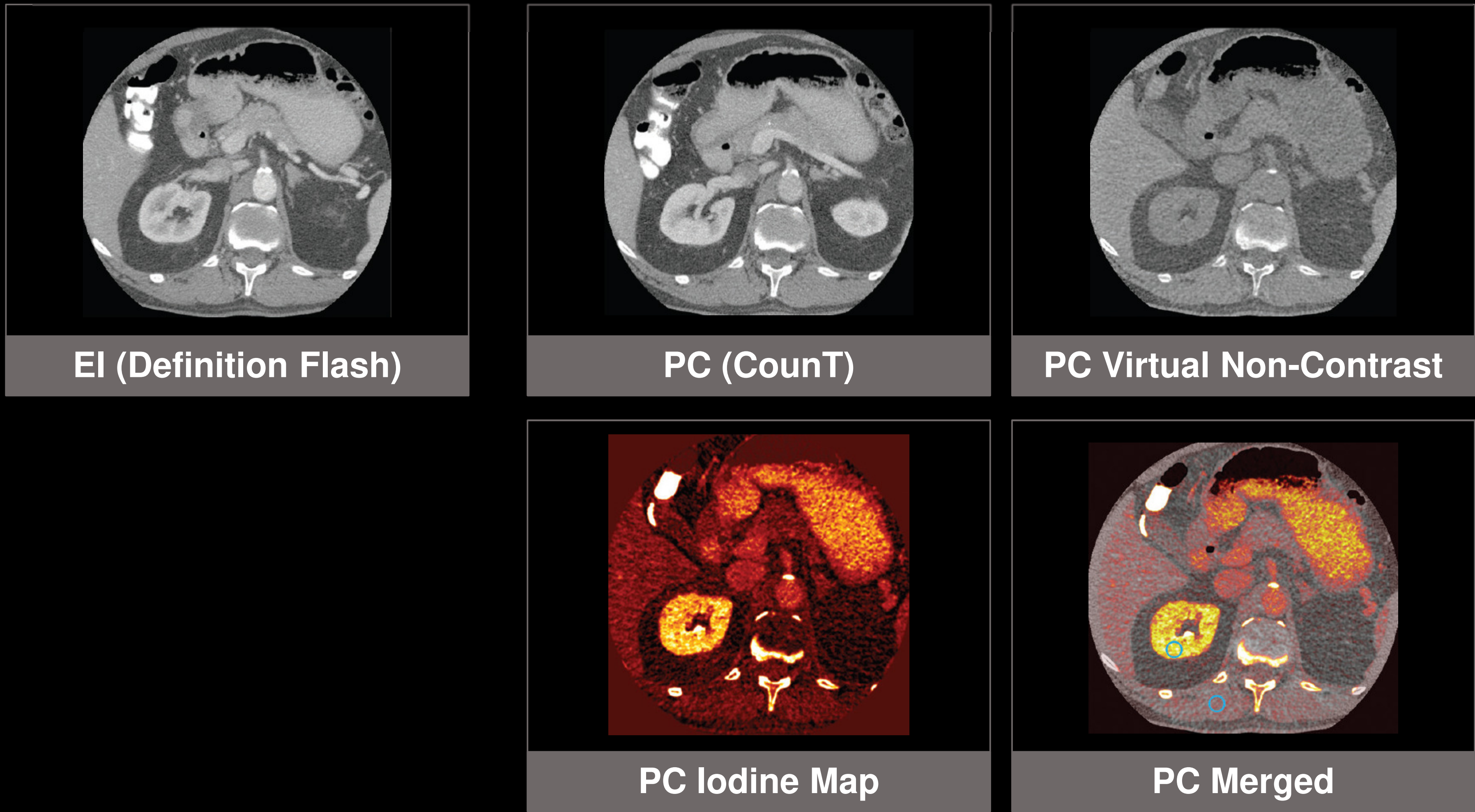
Preclinical Study

(40 kg swine, iodine contrast)



Courtesy of Mayo Clinic Rochester, USA, and of Siemens Healthcare, Forchheim, Germany

First Peer Reviewed Publication on CounT from NIH February 2016



Courtesy of National Institutes of Health, Berthesda, USA

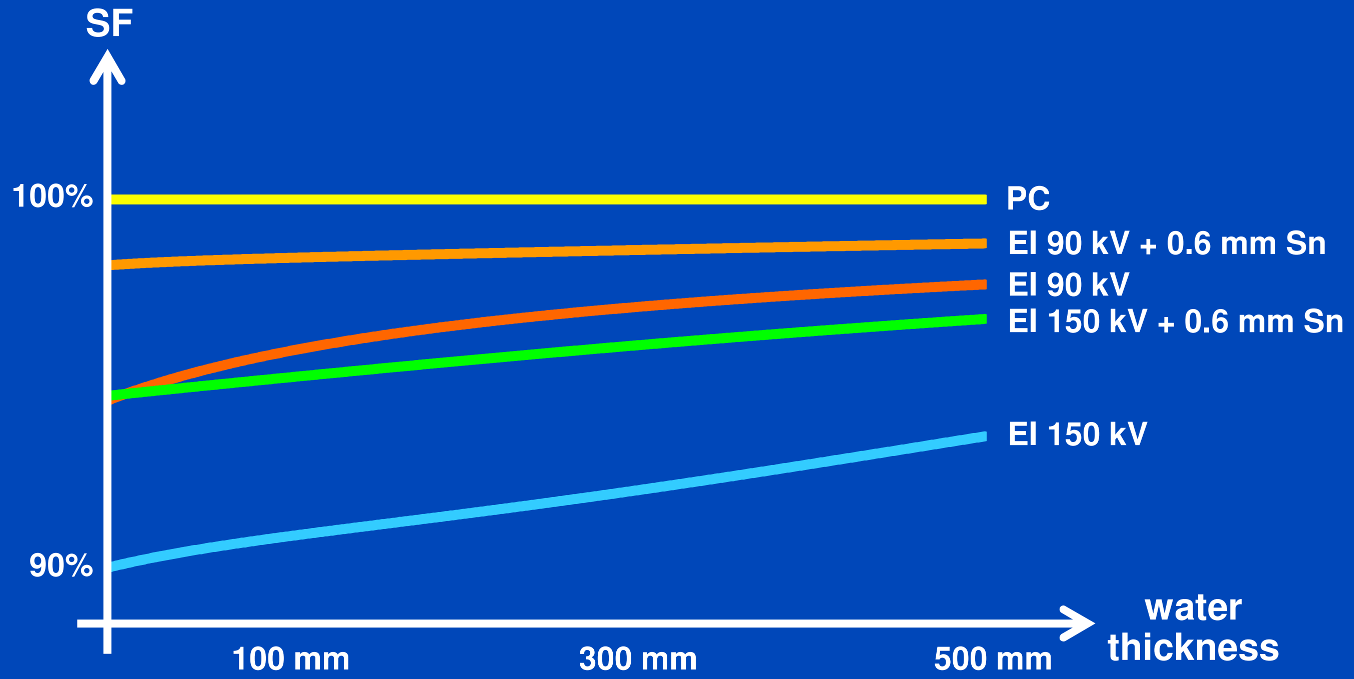
Pourmorteza A et al., Abdominal Imaging with Contrast-enhanced Photon-counting CT: First Human Experience. Radiology. 2016 Apr;279(1):239-45

Electronic Noise

- Photon counting detectors have no electronic noise.
- Extreme low dose situations will benefit
  - Pediadric scans at even lower dose
  - Obese patients with less noise
  - …

Swank Factor

- The Swank factor measures the relative SNR^2, and thus the relative dose efficiency between photon counting (PC) and energy integrating (EI).
- EI always has the lower SNR.

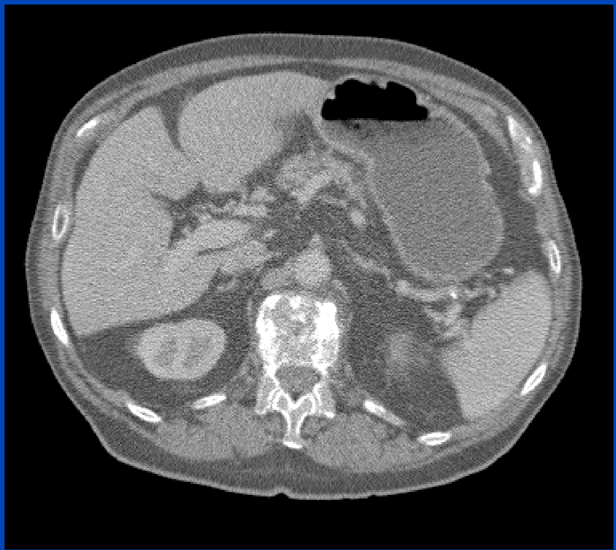


$$\mathrm{SF} = \frac{\mathrm{SNR}^2_{\mathrm{EI}}}{\mathrm{SNR}^2_{\mathrm{PC}}} = \frac{\left(\int dE\, s(E)\mathrm{E}N(E)\right)^2}{\left(\int dE\, \mathrm{E}N(E)\right)\left(\int dE\, s^2(E)\mathrm{E}N(E)\right)} = \frac{M_1^2}{M_0 M_2} \le 1$$

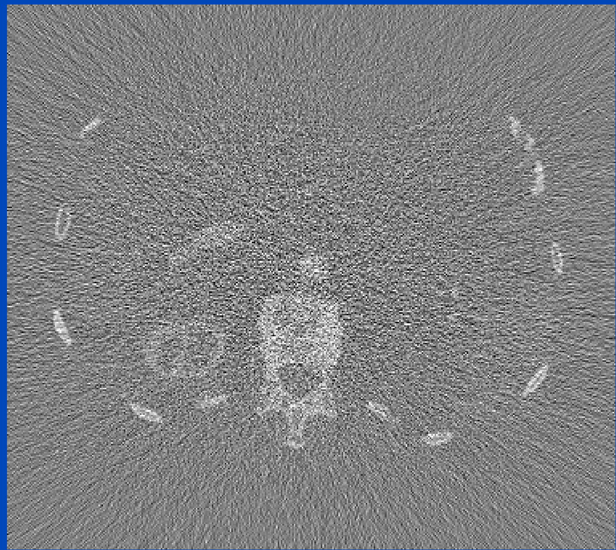
dkfz.

Photon Counting used to Maximize CNR
with 1 bin from 20 to 140 keV

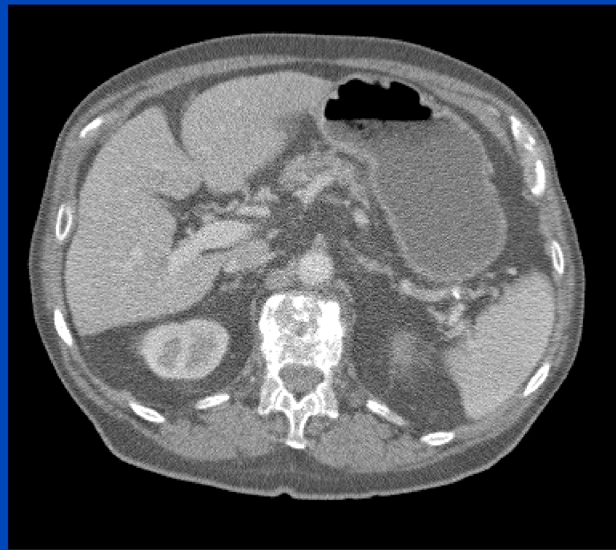
Energy Integrating



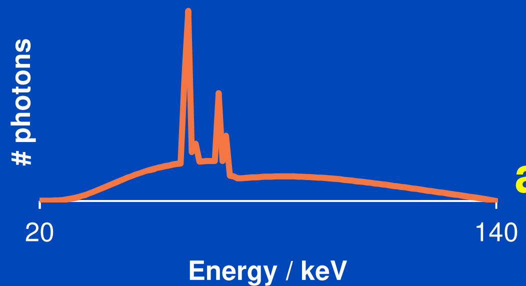
PC minus EI



Photon Counting

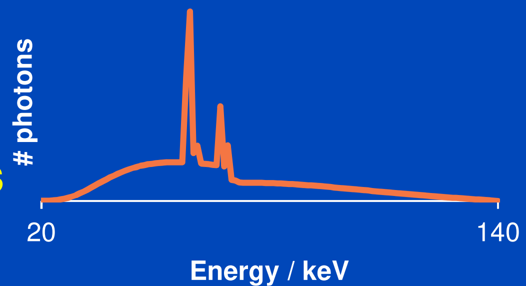


CNR = 2.11



40% CNR improvement or 49% dose reduction achievable due to improved Swank factor and more weight on low energies (iodine contrast benefits).

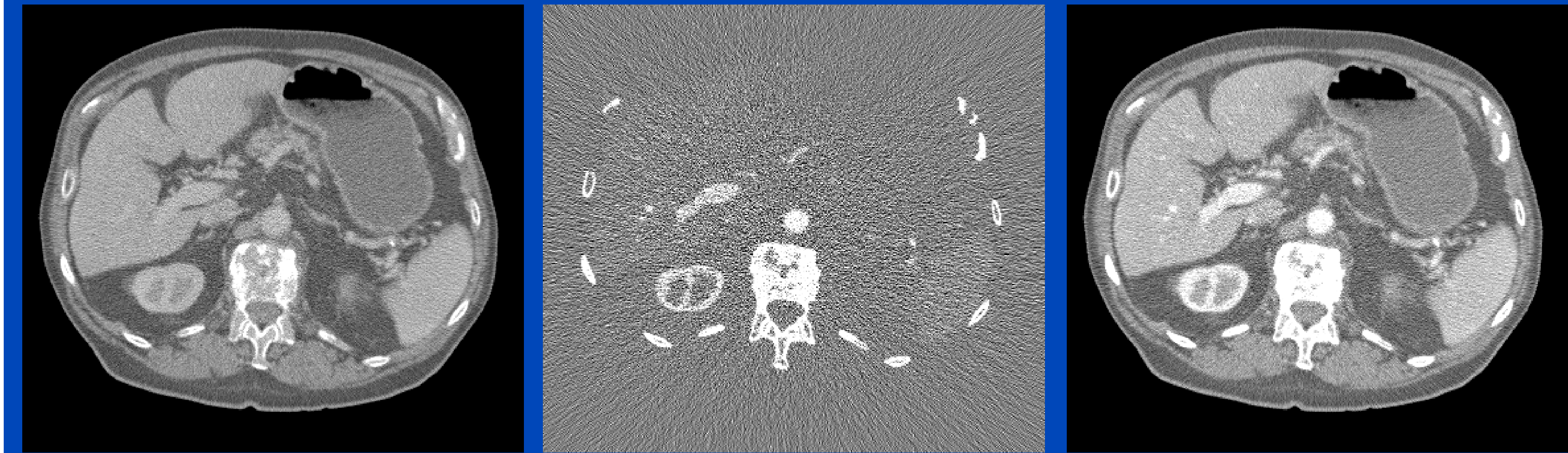
CNR = 2.95



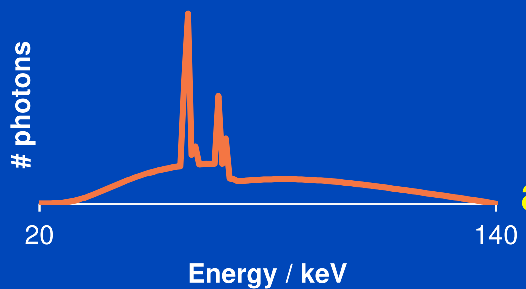
Images: *C* = 0 HU, *W* = 700 HU, difference image: *C* = 0 HU *W* = 350 HU, bins start at 20 keV

Photon Counting used to Maximize CNR with 4 bins from 20 to 140 keV

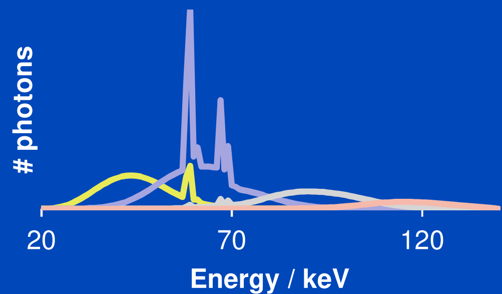
Energy Integrating | **PC minus EI** | **Photon Counting**



CNR = 2.11 | **CNR = 4.19**

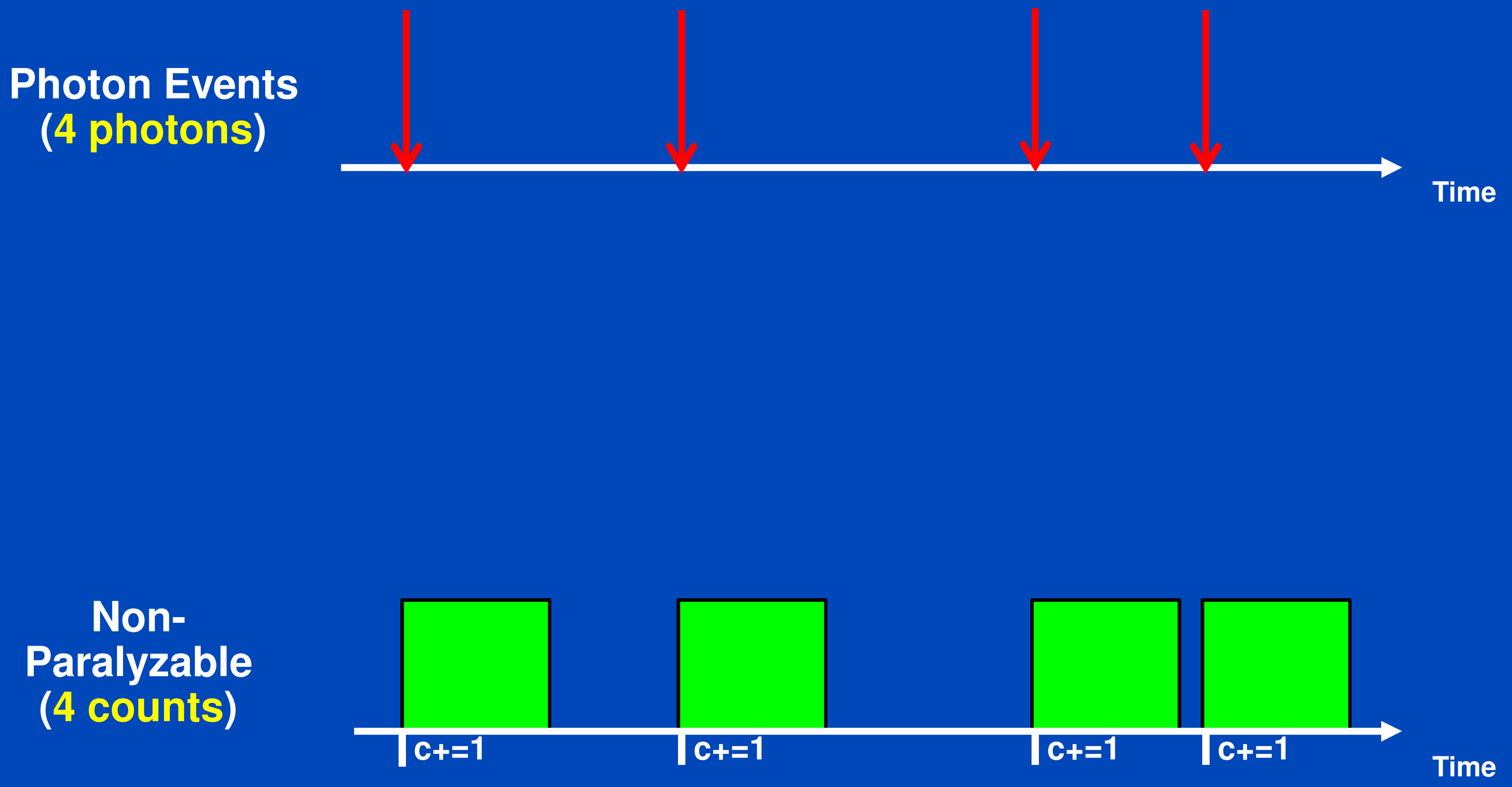


99% CNR improvement or
75% dose reduction achievable
due to improved Swank factor
and optimized energy weighting.



Images: *C* = 0 HU, *W* = 700 HU, difference image: *C* = 0 HU *W* = 350 HU, bins start at 20 keV

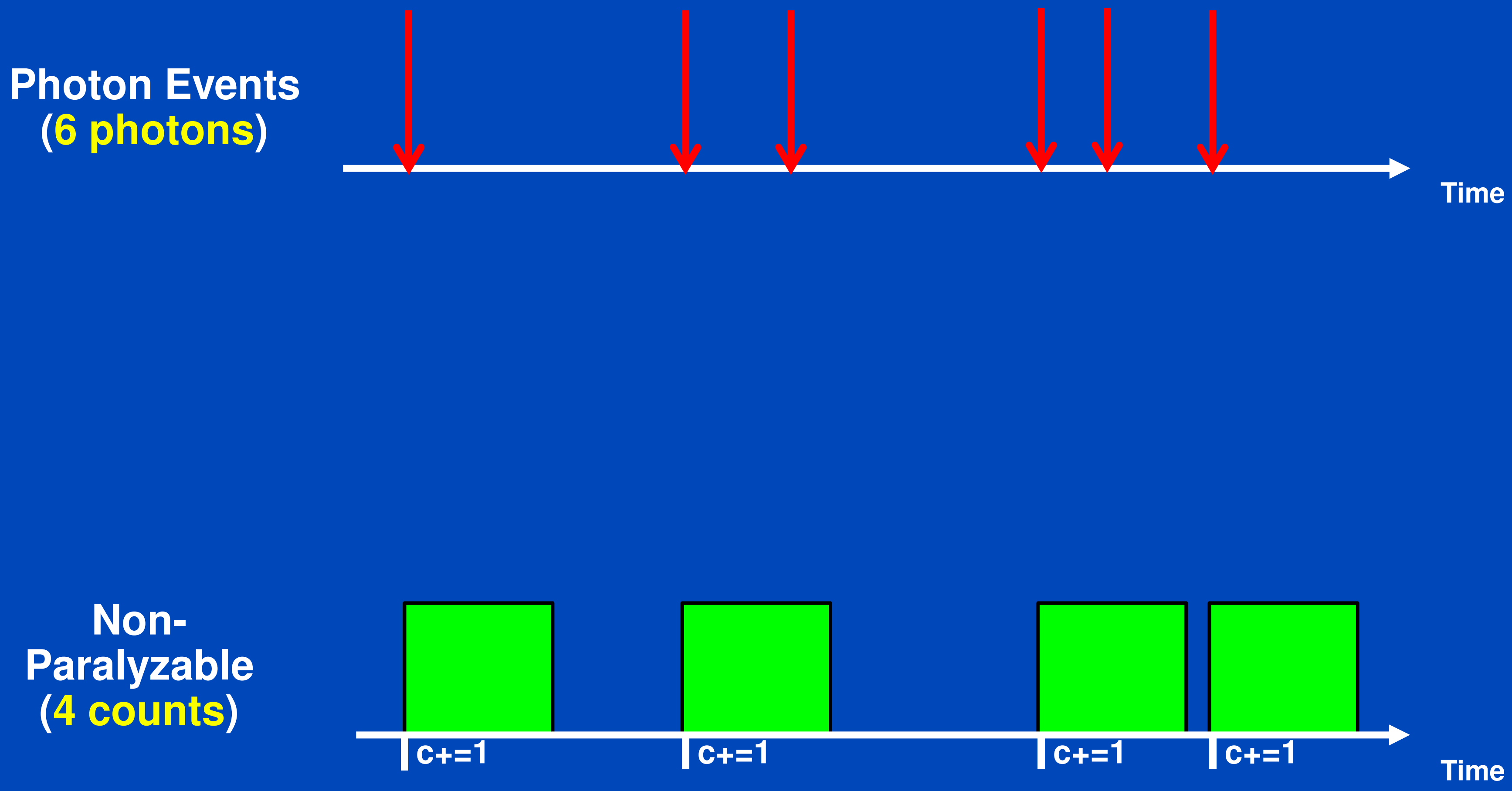
Pulse Pile-Up: Low Flux Rate



Boxes illustrate deadtime

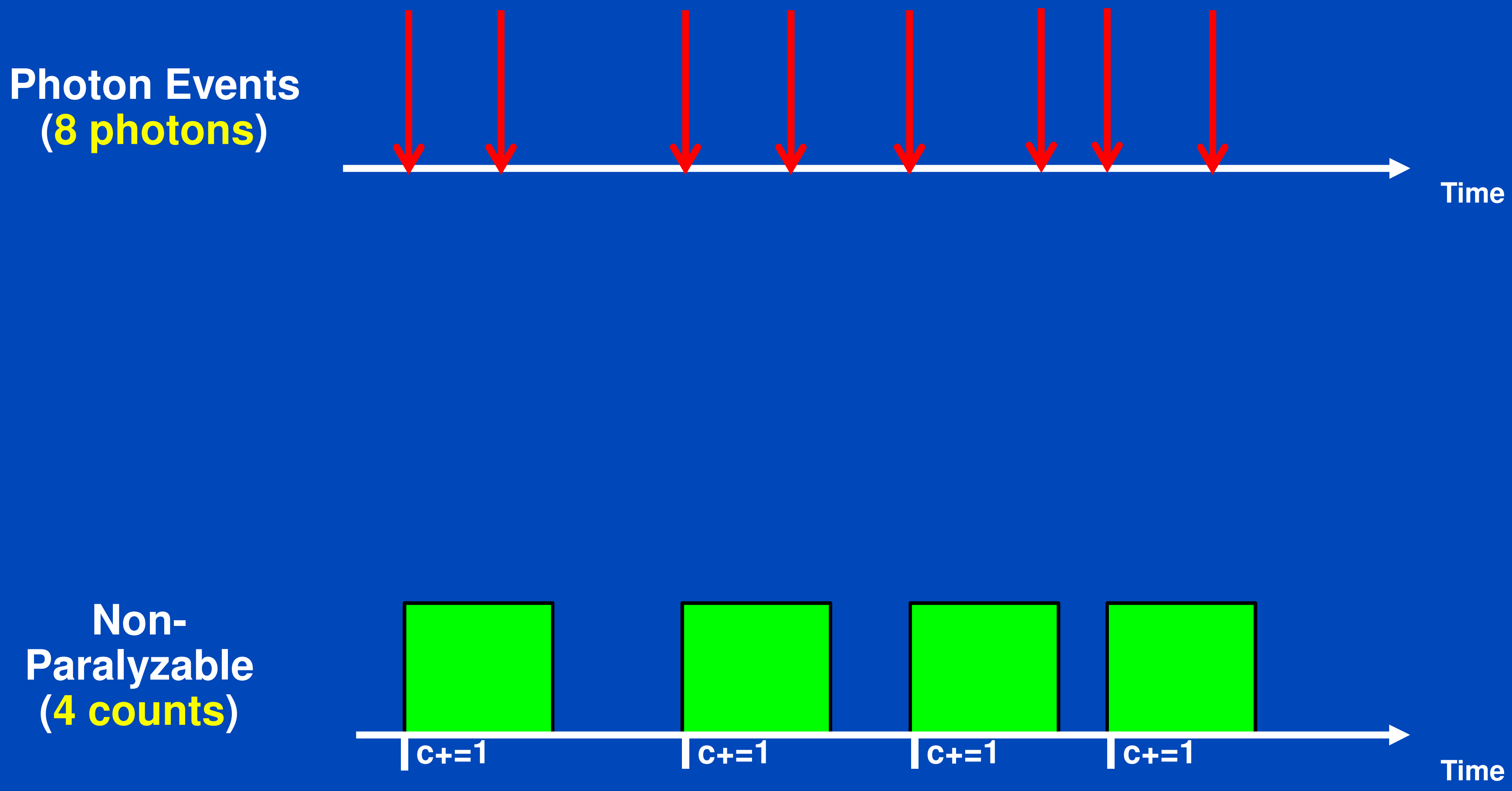
dkfz.

Pulse Pile-Up: Medium Flux Rate



Boxes illustrate deadtime

Pulse Pile-Up: High Flux Rate

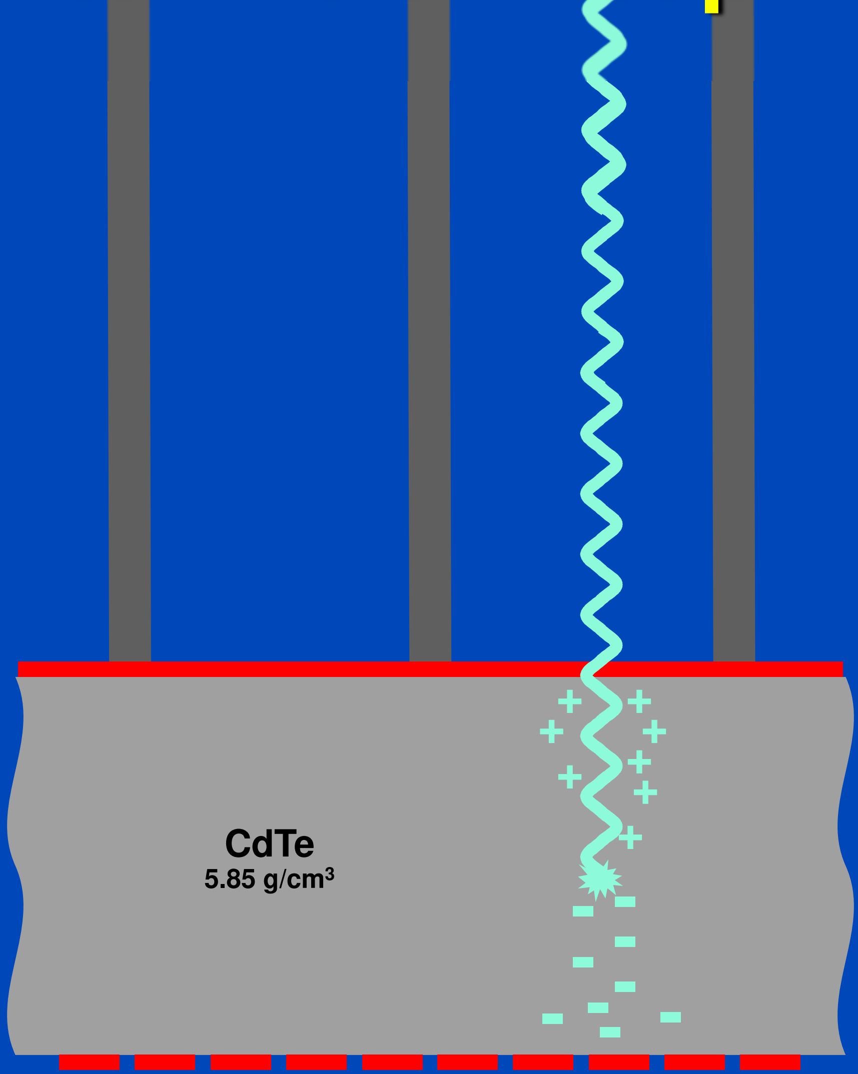


Boxes illustrate deadtime

dkfz.

Spatial Resolution to Avoid Pileup

- Small electrodes are necessary to avoid pile-up.
- High bias voltages (around 300 V) limit charge diffusion and thus blurring in the non-structured semiconductor layer.
- Thus, higher spatial resolution is achievable.



Ultra-High Resolution on Demand

Energy Integrating CT
(Somatom Flash)

Photon Counting CT
(Somatom Count. UHR-Mode)

MAYO
CLINIC

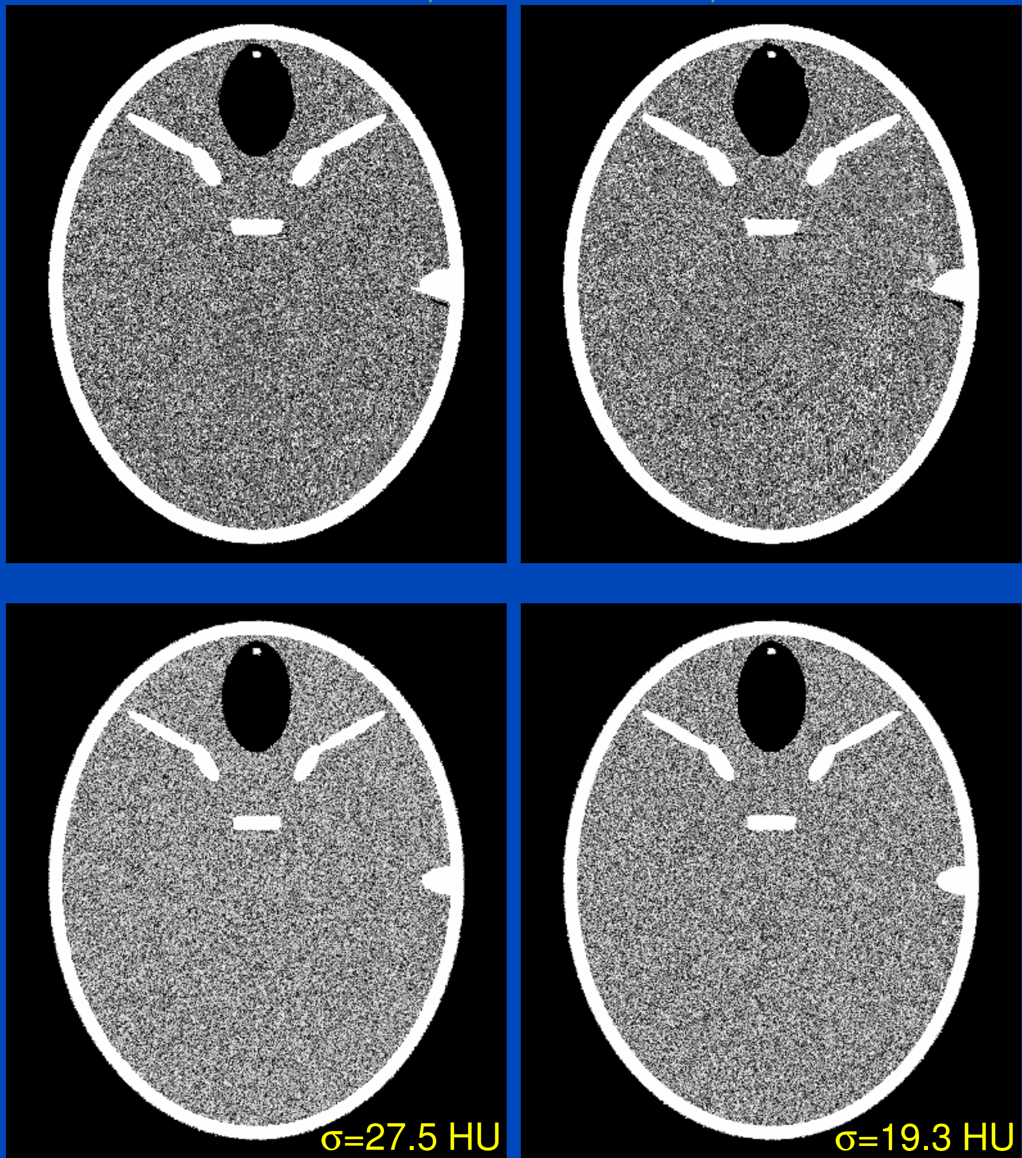
Courtesy of Cynthia McCollough, Mayo Clinic, Rochester, USA.

32×0.6 mm $s(z) = \mathrm{II}^*_S(z), a(z) = \mathrm{II}^*_{S/2}(z)$

64×0.3 mm $s(z) = \mathrm{II}^*_{S/2}(z), a(z) = \mathrm{II}^*_S(z)$

noise-free
C = 50 HU
W = 50 HU

with noise
C = 50 HU
W = 200 HU



- To bin or not to bin?
- Simulated data
- $\mathrm{SSP}(z) = \mathrm{II}^{**}_{S,S/2}(z)$
- S_{eff} = 0.6 mm
- 1.78-fold dose usage with highres detector:

$$\left(\frac{27.5}{19.3}\right)^2 \frac{1+0.1/0.6}{1+0.1/0.3} \approx 1.78$$

2.0 — 0.1 mm septa

- **44% dose reduction with highres detector**
- **Do not bin!**

Potential Advantages of Photon Counting Detectors in CT

- Higher spatial resolution due to
  - smaller pixels
  - lower cross-talk between pixels
- Lower dose/noise due to
  - energy bin weighting
  - no electronic noise
  - Swank factor = 1
  - smaller pixels
- Spectral information on demand
  - single energy
  - dual energy
  - multiple energy
  - virtual monochromatic
  - K-edge imaging
  - …

Potential clinical impact


Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs www.dkfz.de, or through Marc Kachelrieß marc.kachelriess@dkfz.de.
Parts of the simulation and reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany, www.rayconstruct.de.
This presentation will soon be available at www.dkfz.de/ct.
Thank You!