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# Spatial and spectral resolution of semiconductor detectors in medical X-ray and gamma ray imaging

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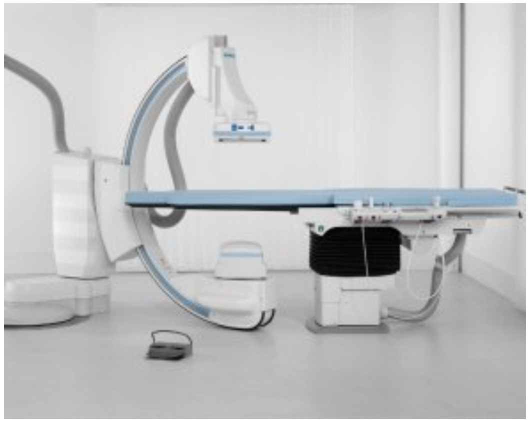
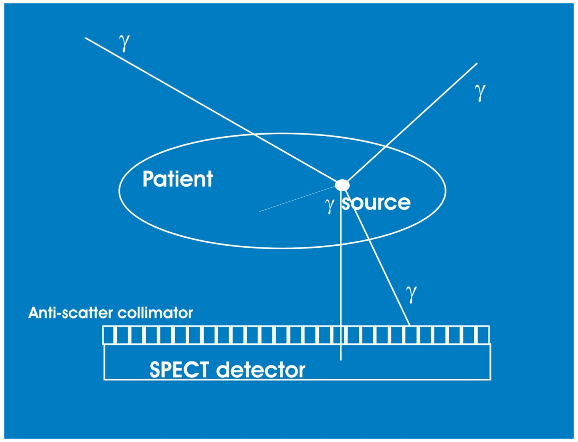
# Medical imaging devices, X- and γ-ray based

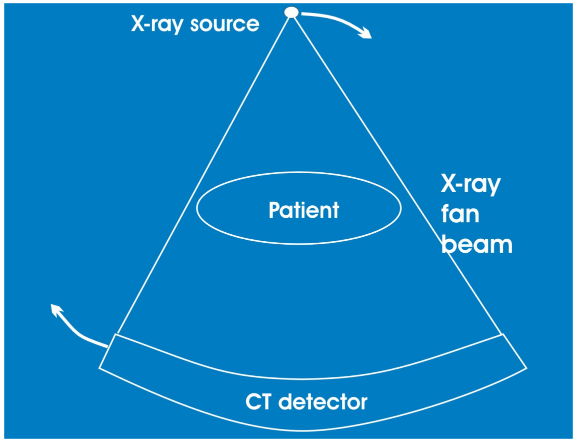
Single Photon Emission Computed Tomography

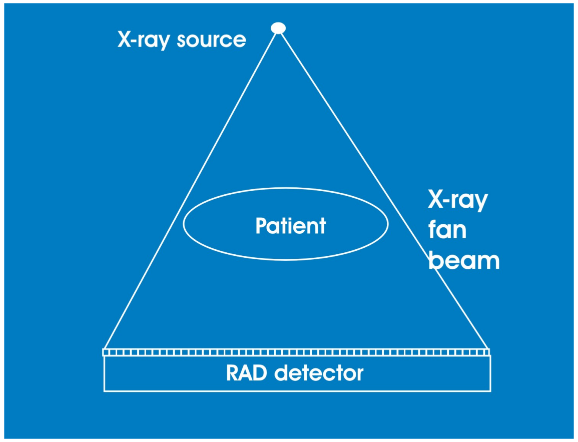
Computed Tomography



Radiography



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# Direct conversion detectors and Medical Imaging

## SPECT

- Dedicated cardiac, scintimammography and small-animal imaging prototypes exist, improved energy resolution reported

## CT

- Prototype counting systems developed
- Full CT flux rate is found to be a major challenge

## CZT material

- Defects, e.g. Te inclusions, affect the dynamic electrical field, charge trapping and resulting spectral behavior
- Polarisation occurs at high flux (>$10^7$ qt / smm$^2$)


K.B. Parnham, S. Chowdhury, J. Li, D.J. Wagenaar and B.E. Patt, „Second-Generation, Tri-Modality Pre-Clinical Imaging System", in: Bo Yu, 2007 IEEE Nuclear Science Symposium Conference Record, M06-29 (2006)

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G. S. Camarda, A. E. Bolotnikov, Y. Cui, A. Hossain, S. A. Awadalla, J. Mackenzie, and H. Chen and R. B. James, "Polarization Studies of CdZnTe Detectors using Synchrotron X-ray Radiation", in: Bo Yu, 2007 IEEE Nuclear Science Symposium Conference Record, R27-3 (2007)

L. Abbene, S. Del Sordo, F. Fauci, G. Gerardi, A. La Manna, G. Raso, A. Cola, E. Perillo, A. Raulo, V. Gostilo and S. Stumbo, "Study of the spectral response of CZT multiple-electrode detectors", in: Bo Yu, 2007 IEEE Nuclear Science Symposium Conference Record, N24-298 (2007)

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## Motivation

*Analyze and compare*

- **spatial and spectral resolution of pixelized**
  - **direct conversion** semiconductor detectors (e.g. CZT) and
  - **indirect conversion** scintillator detectors (e.g. GdOS)

*Establish and verify*

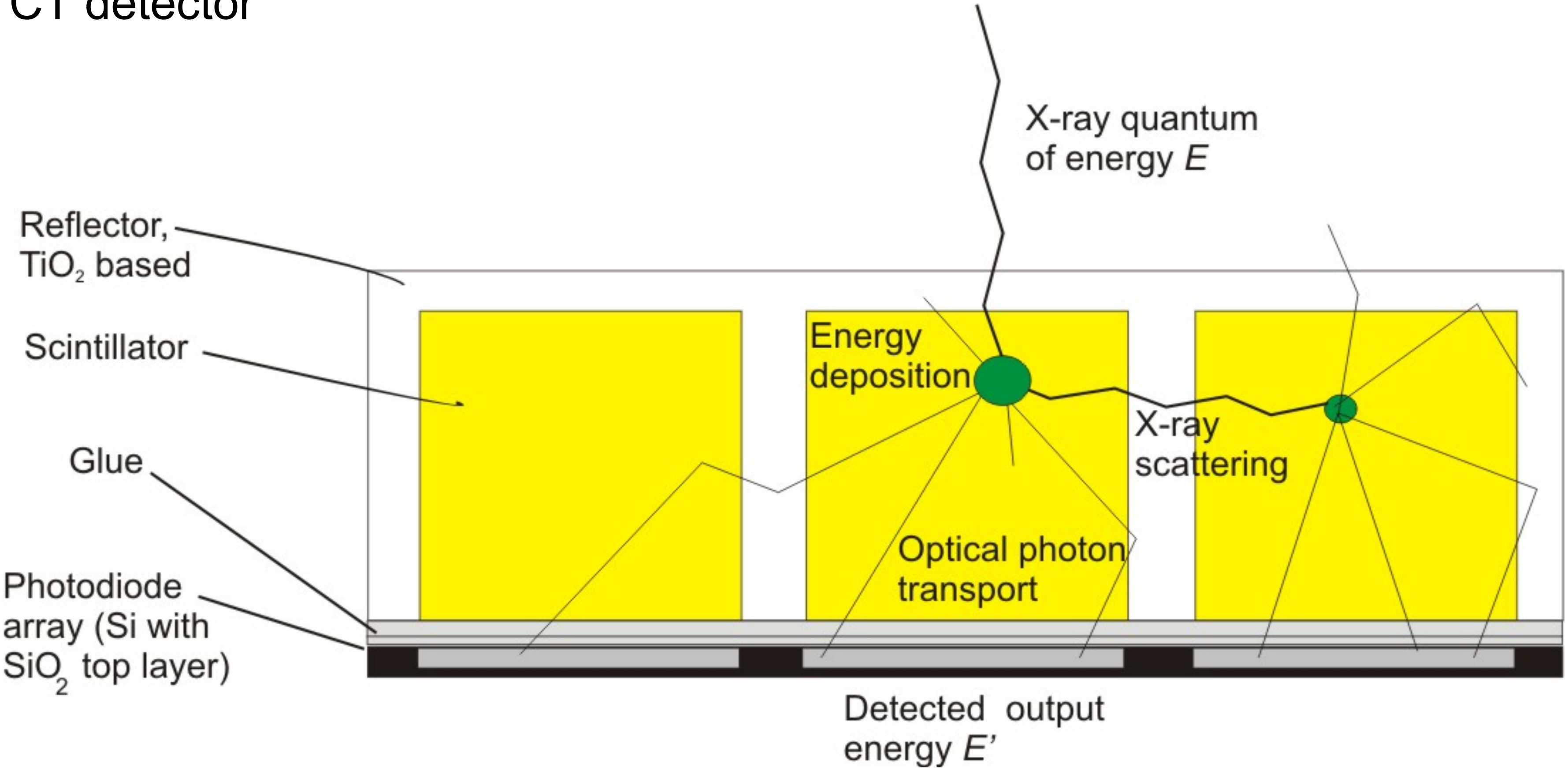
- Physical detector models

*Use figures of merit*

- Modulation transfer function MTF($f$)
- Detector response function $D(E,E')$

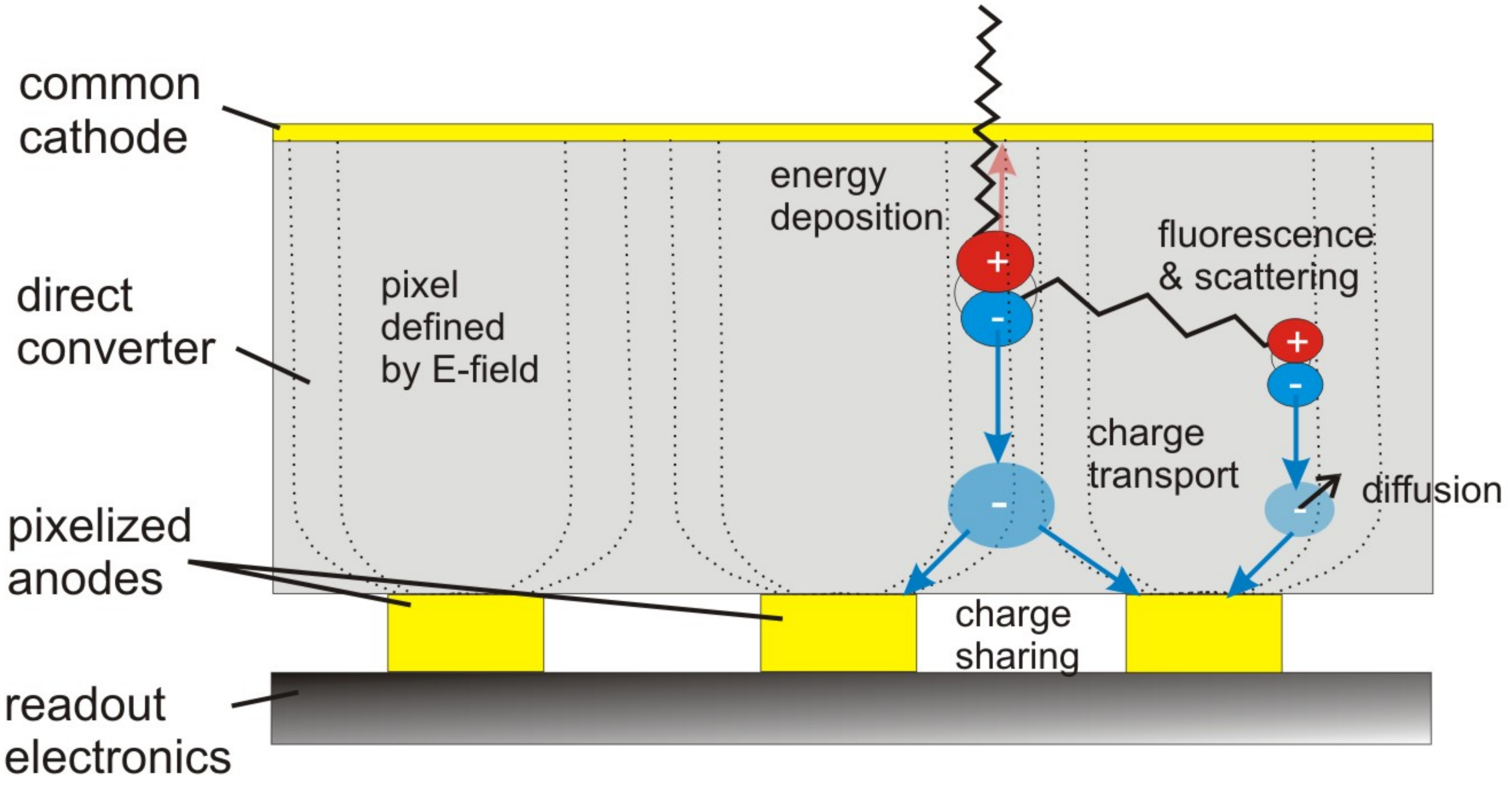
# Indirect conversion detector

CT detector



# Direct conversion detector

## Typical common cathode set-up



## Figures of merit

**Spatial resolution:**
Modulation Transfer Function

$$MTF(f) = \frac{|FT(PSF(x))|}{FT(PSF(0))}$$

**Spectral resolution:**
- Pulse height spectrum (PHS)
  - FWHM of emission line
  - Photo peak fraction

- Generalization for CT and Rad: PHS for each input energy: Detector response function $D(E,E')$

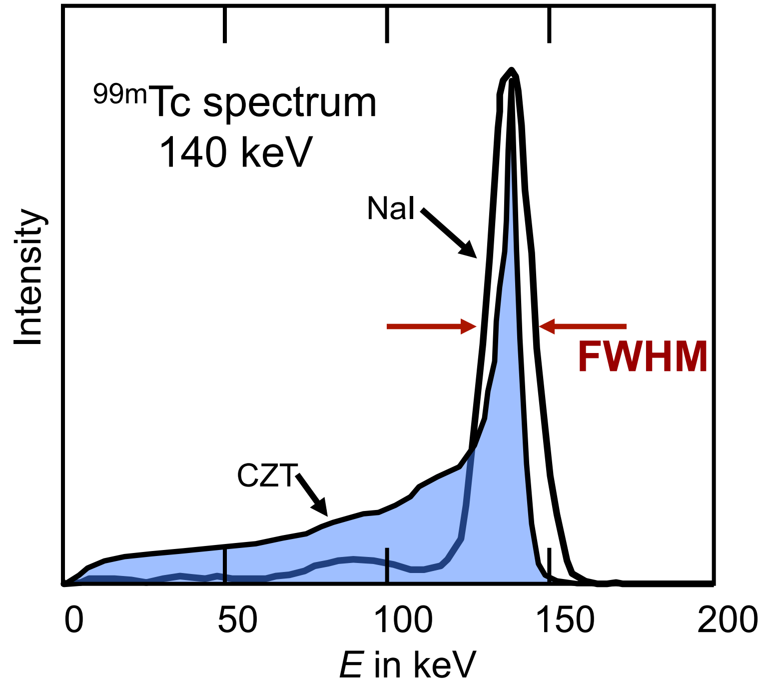
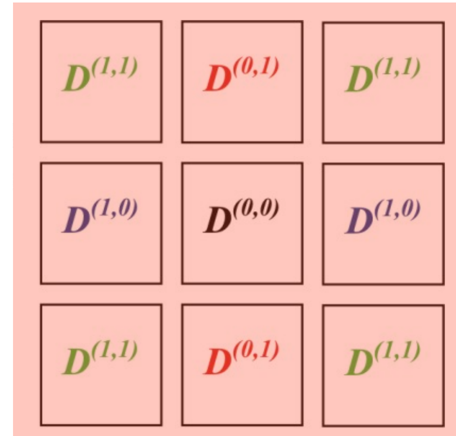



figure taken from: M. N. Wernick and J. N. Aarsvold, 'Emission Tomography', p. 275, Elsevier Academic Press, (2004)

# Detector response function

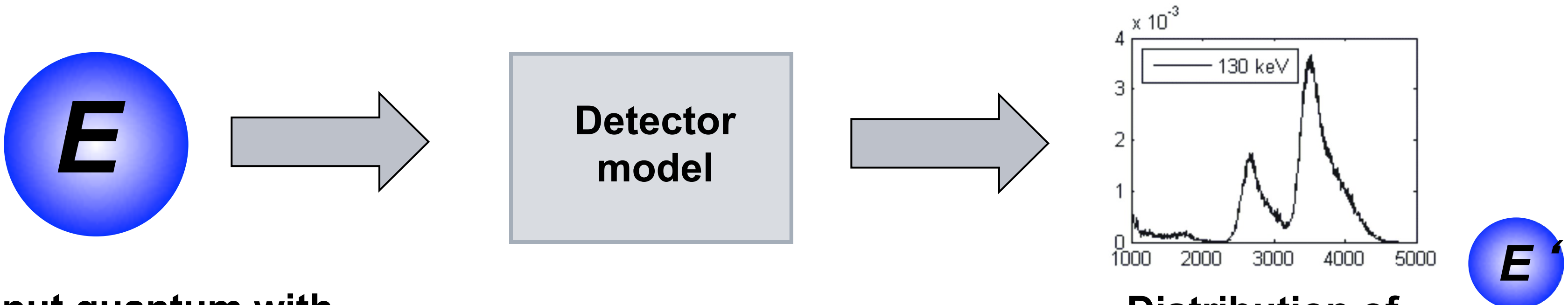
$D^{(i,k)}(E, E')$:=

Macroscopic probability density function for measuring output energy *E'* at input energy *E*




This talk:

- Central pixel $D^{(0,0)}(E,E')$ only
- Flat-field irradiation



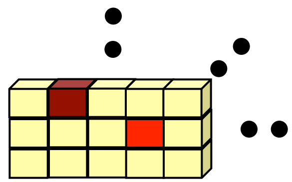

**Input quantum with energy *E*, e.g. 130 keV**

**Distribution of output energies**

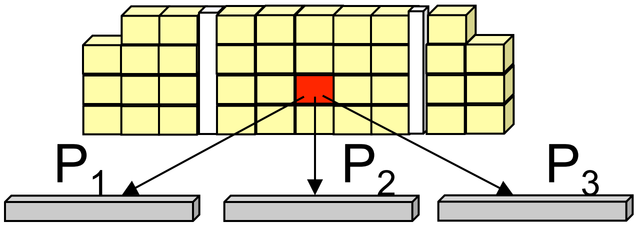
# Detector modeling

# Model for indirect conversion detector*

1. X-ray energy deposition
   (Monte Carlo look-up table)

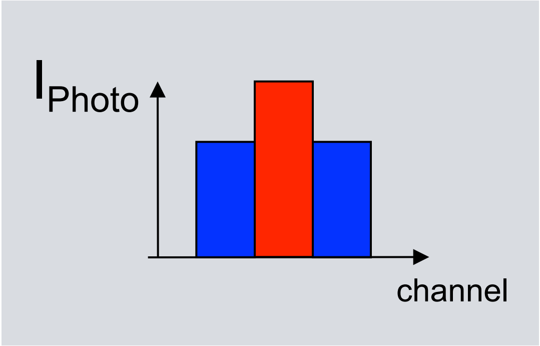


2. Light transport probabilities




3. Electronics (noise, linearity, ...)

→ Photo-electrons detected in pixel




*Heismann B.J., Pham-Gia K., Metzger W., Niederlöhner D., Wirth S., "Signal transport in Computed Tomography detectors", Nucl. Inst. and Meth. in Phys. Res., A, 591, pp. 28–33 (2008

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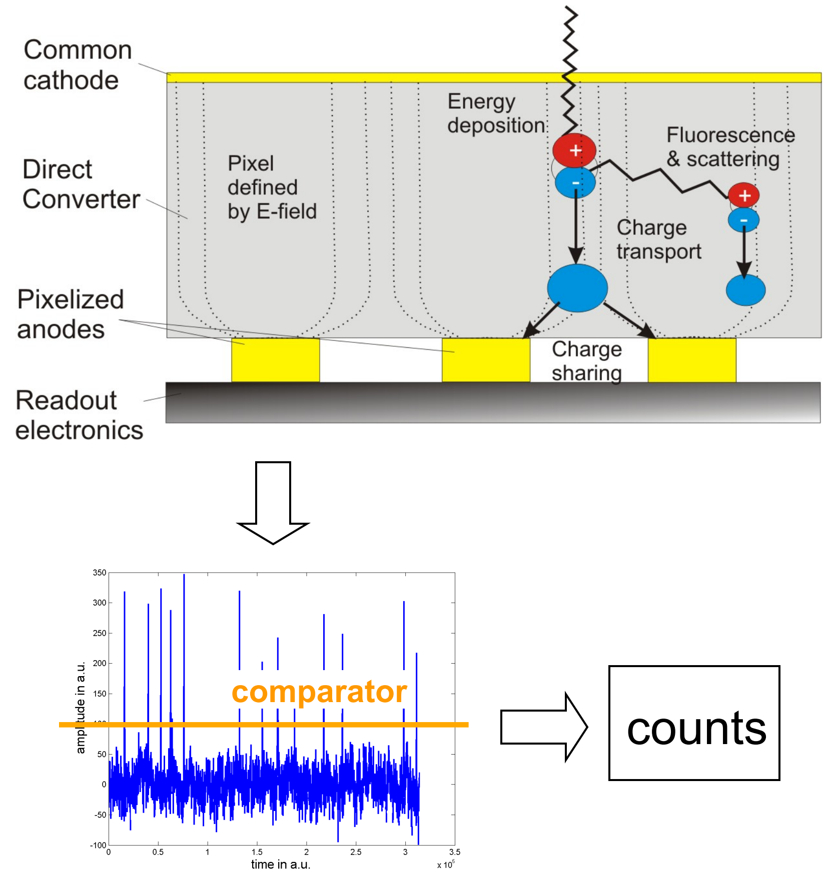
# Model for direct conversion detector (I)

1. X-ray energy deposition (Monte Carlo look-up table)*

2. FEM modeling of charge transport**, ***

3. Pulse train signals on electrodes

4. Electronics (noise, shaping, comparator, ...)




→ Pixel count readings

* J. Giersch and J. Durst, Monte Carlo simulations in X-ray imaging, NIM A, Vol. 591, pp. 300 (2008)
** J. D. Eskin et.al., Signals induced in semiconductor gamma-ray imaging detectors, J. Appl. Phys., Vol.85, pp.647 (1999)
*** B. Kreisler et.al., Generalised Adjoint Simulation of Induced Signals in Semiconductor X-Ray Pixel Detectors, submitted to J. of Instrumentation, (2008)

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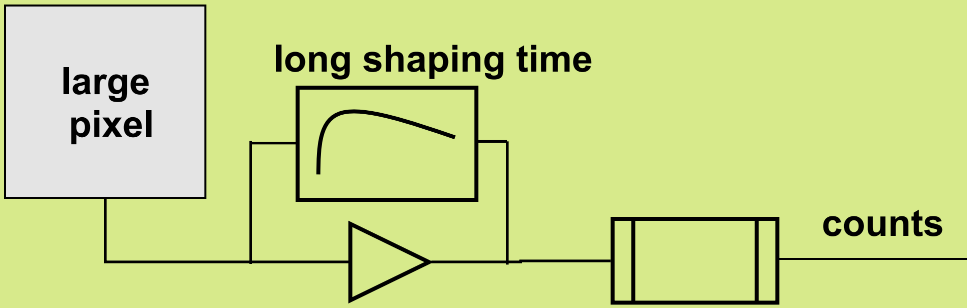
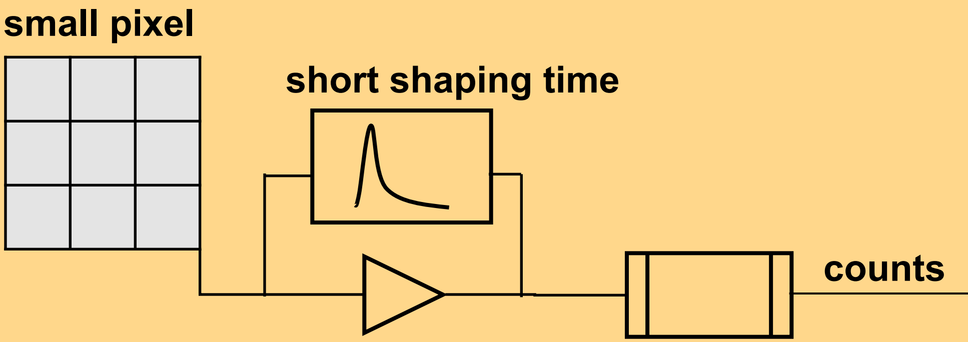
# Model for direct conversion detector (II)

## Configuration for…

… good energy resolution
… low spatial resolution




… high spatial resolution
… low energy resolution
… *good* high flux performance




**Parameters for simulation study:**
CZT with 2mm thickness and 700V bias
- small pixel area (pitch = 450µm)
- short shaping time ($\tau$ = 50ns)
- electronic noise equivalent to 3 keV

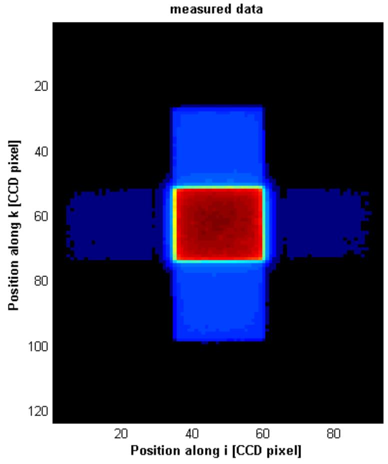
# Results

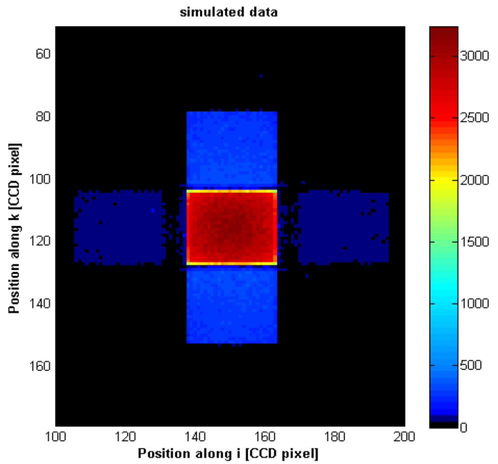
# Results indirect conversion CT detector

CT detector model reproduces experimental results on

- Light output and sensitivity profile*
- MTF**
- DQE

with small deviations in the percent range.

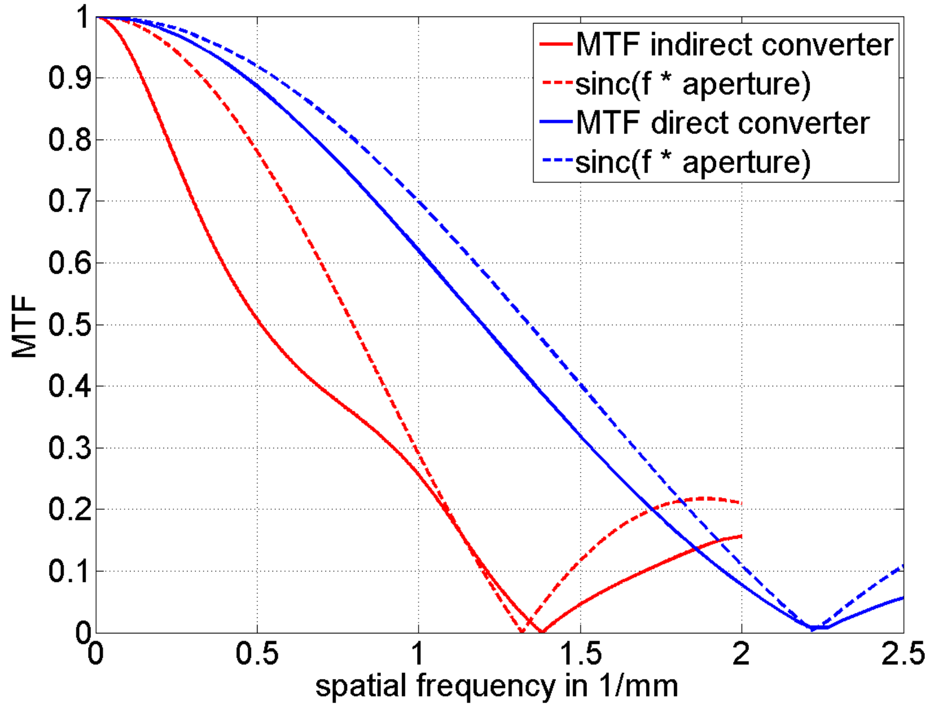



*Heismann B.J., Pham-Gia K., Metzger W., Niederlöhner D., Wirth S., "Signal transport in Computed Tomography detectors", Nucl. Inst. and Meth. in Phys. Res., A, 591, pp. 28–33 (2008)

**Paper M06-257 : S. Wirth, B.J. Heismann, D. Niederlöhner, L. Bätz, W. Metzger, K. Pham Gia, Simulations and Measurements of the Modulation Transfer Function of Scintillator Arrays, IEEE Conference, Dresden (2008)

# MTF



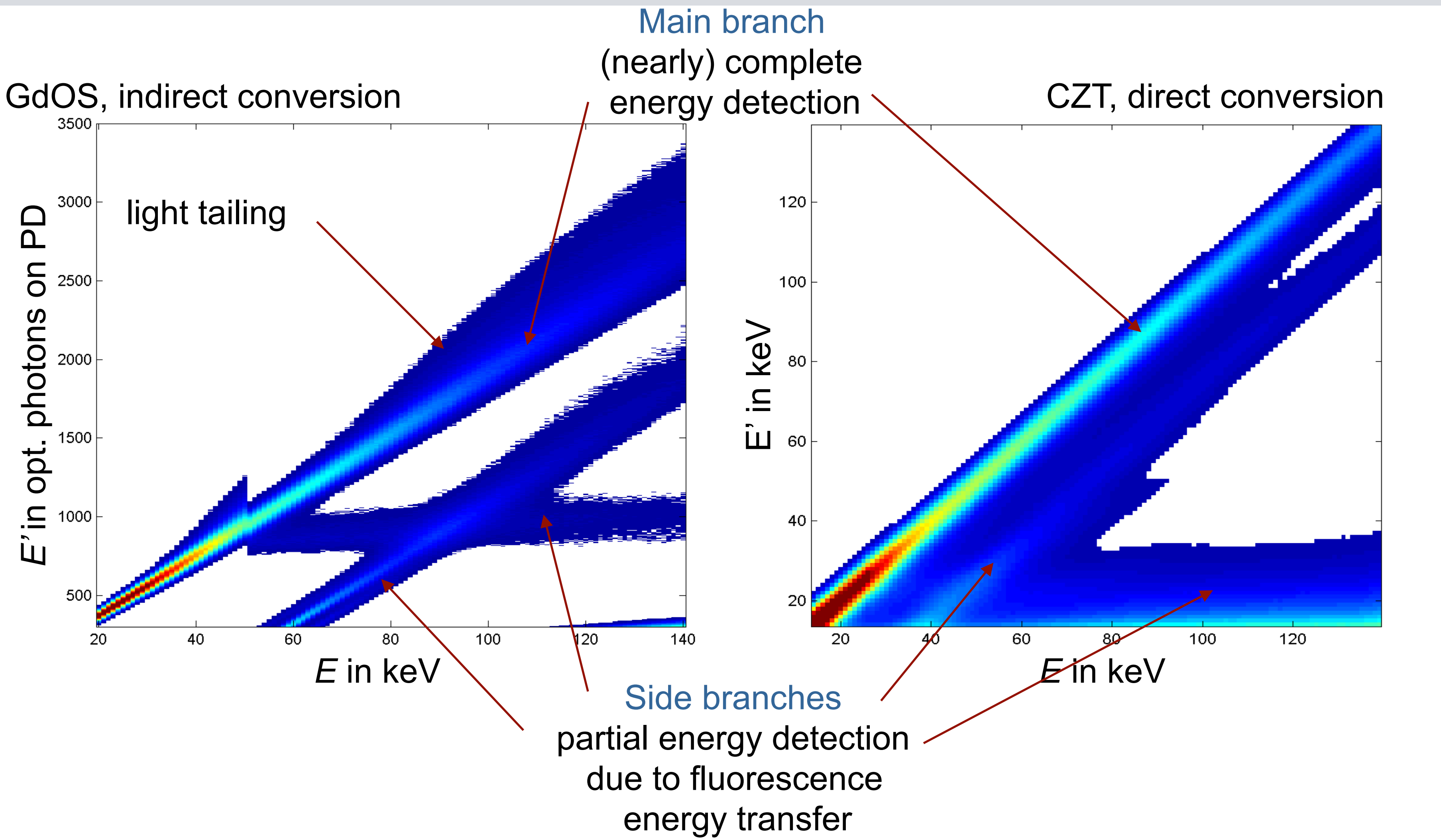

**Indirect** conversion detector

- mid-frequency drop due to optical crosstalk
- almost lossless recovery possible

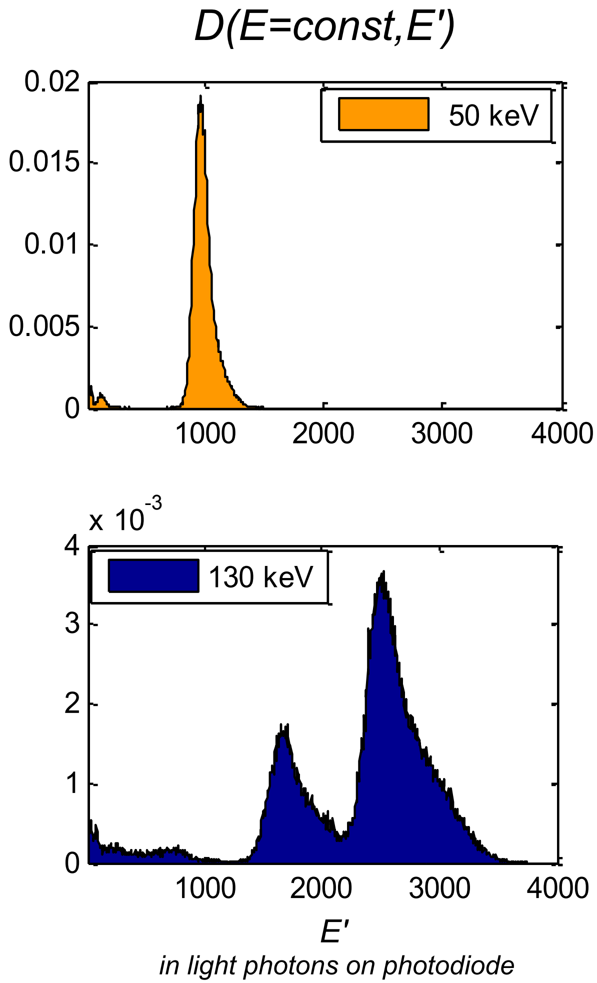
**Direct** conversion detector

- close to ideal sinc behavior
- charge sharing affects spectral behavior

# Central pixel response $D^{(0,0)}(E,E')$



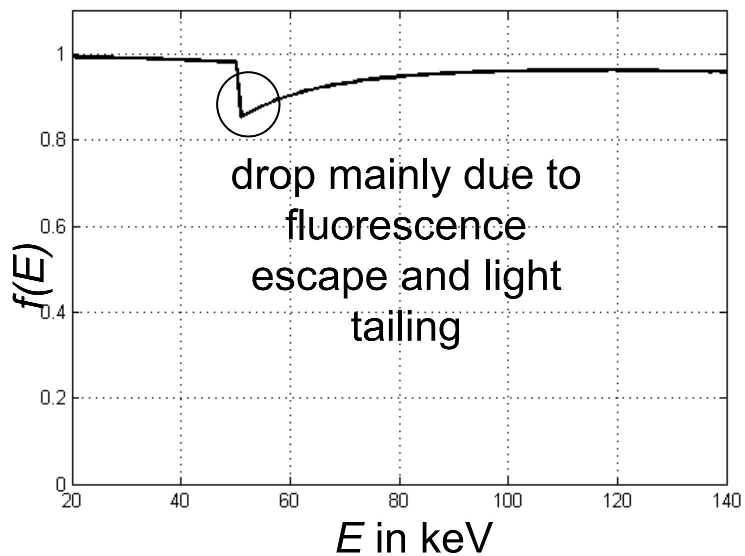
# Integrating scintillator detector: Generalized Swank factor




SNR decrease by signal transport variance*,**

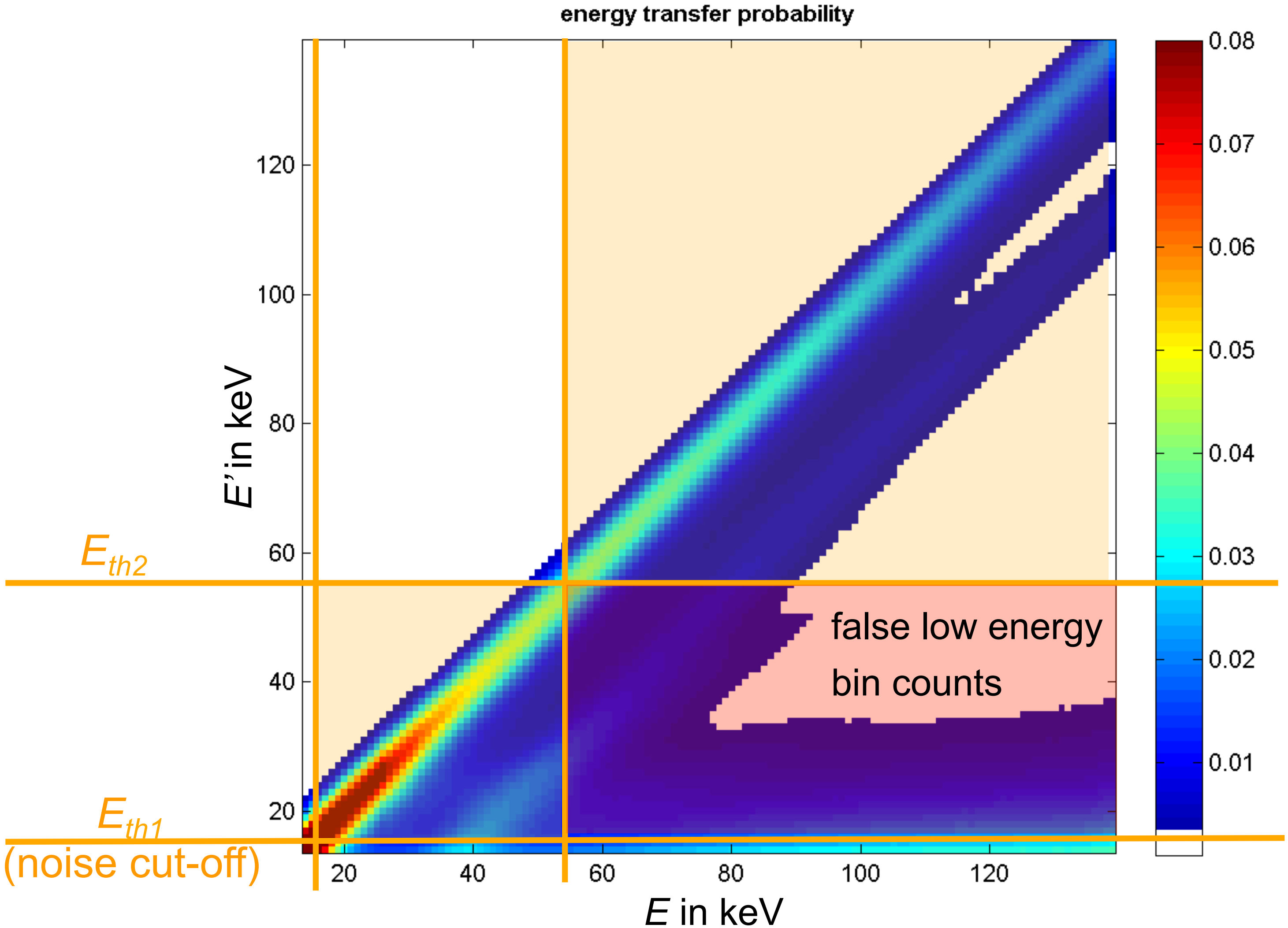
$$f(E) = \frac{1}{\sqrt{\alpha(E)}} \frac{SNR_{out}}{SNR_{in}} = \frac{\langle E' \rangle}{\sqrt{\left(\langle E' \rangle^2 + \sigma^2(E')\right)}}$$

with $\alpha$(E): detection efficiency




* M. Rabbani, R. Shaw, and R. Van Metter, 'Detective quantum efficiency of imaging sytems with amplifying and scattering mechanisms,' *J. Opt. Soc. Am. A*, vol. 4, pp. 895-901, (1987)
**Heismann B.J., Pham-Gia K., Metzger W., Niederlöhner D., Wirth S., "Signal transport in Computed Tomography detectors", Nucl. Inst. and Meth. in Phys. Res., A, 591, pp. 28–33, (2008)

# Direct conversion: Energy binning



# Dual-energy binning

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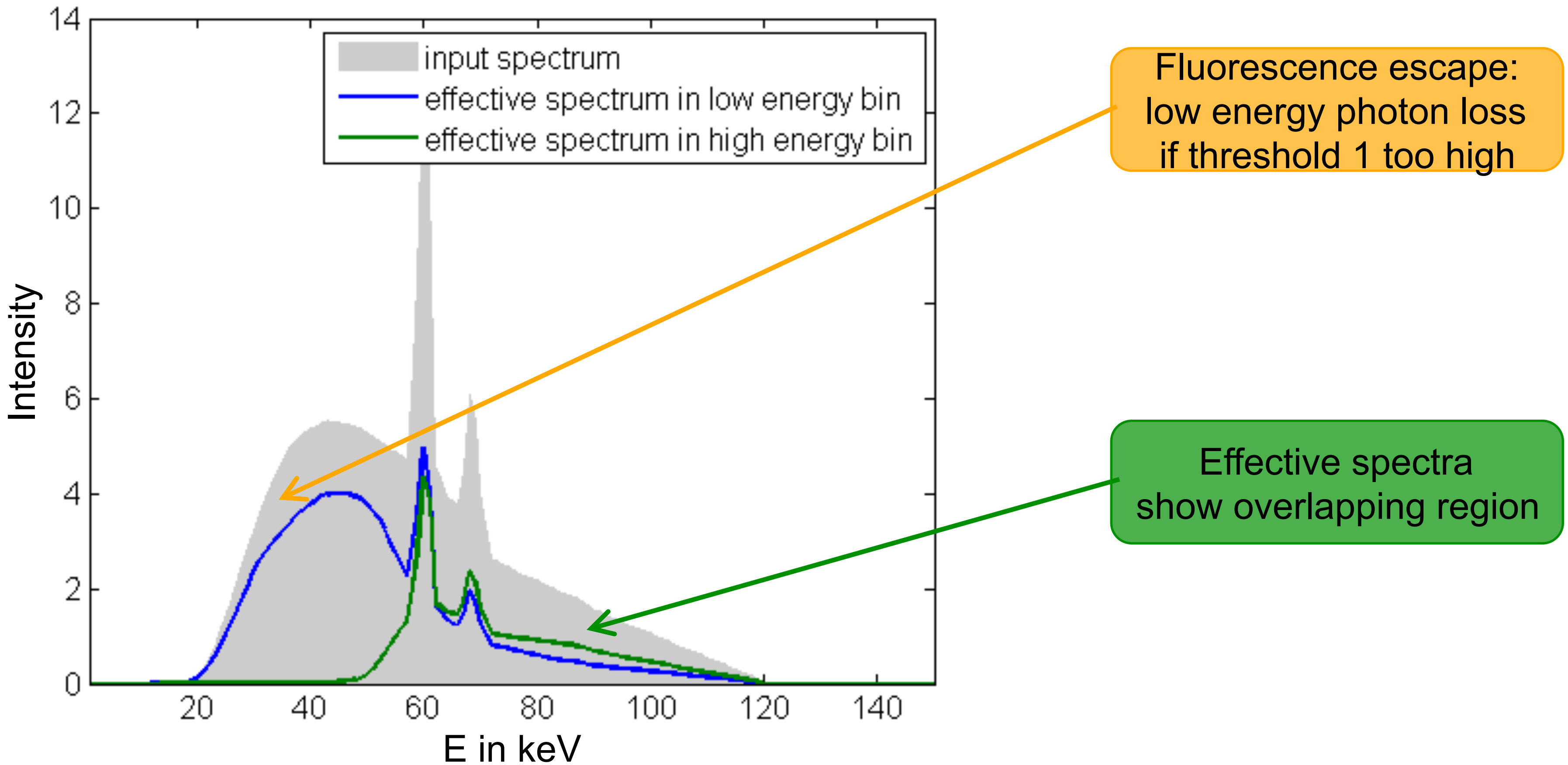
- 120kV tungsten spectrum
- $E_{th1}$ = 15 keV, $E_{th2}$ = 55 keV



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# Conclusion

- Indirect and direct conversion (e.g. CZT) detector models established
- Figures of merit for comparison: MTF and detector response $D(E,E')$

## Spatial resolution MTF

- Indirect conversion: Mid-frequency drop due to optical crosstalk
- Direct conversion: Close to ideal sinc function

## Spectral resolution $D(E,E')$

- Main linear, fluorescence and differential branches visible
- Indirect conversion scintillator detector:
  - Additional light tailing and optical cross-talk
  - Integrating: Energy-dependent Poisson excess noise
- Direct conversion semiconductor detector:
  - Counting yields energy information (full or binned)
  - Binned: Significant spectral overlap by low energy shift

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# Thank you!

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**Contact**

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