



Photon Counting Toolkit (PcTK)

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Disclosure and acknowledgment

■ Disclosure

- Research support: Siemens Healthineers
- Consultant: LISIT, JOB Corporation
- Former projects: DxRay, Toshiba/Cannon, Philips

■ Acknowledgment

- Drs. Karl Stierstorfer, Christoph Polster, Steffen Kappler, Thomas G. Flohr, Matthew K. Fuld, and George S.K. Fung (Siemens)
- Okkyun Lee, Ph.D. (former JHU and current DGIST, South Korea)
- JHU-2016-CT-1-01-Taguchi_C0022
- Carl R. Crawford, Ph.D. (Csuptwo, LLC)

So What? Who Cares?

- Space: Photon counting detector (PCD)-based security systems
- Problem: Lack of good [PCD simulator](#) with realistic spectral distortion
- Solution: Developed photon counting toolkit (PcTK)^[1]
- Results:
 - *PCD model: Excellent agreements with a Monte Carlo simulator, which has good agreement with a PCD.*
 - *Simulator: A wrapper for correlated/un-correlated noisy data generator and CT workflow wrapper*
- TRL: 9
- Contact: pctk.jhu.edu and ken.pctk@gmail.com

[1] Taguchi K, *et al.*, Medical Physics 2018;45(5):1985–1998

Why simulation?

- Lower cost than building and optimizing prototype systems
- Faster time-to-market, because algorithms for correction and calibration can be developed earlier, in parallel to hardware development
- Identifies products earlier that will never achieve required performance and never reach the market



■ What's available?

- *Digital phantoms (Taly Gilat-Schmidt¹, XCAT^{2,3}, Forbild⁴)*
- *X-ray system simulator (TGS¹, ASTRA toolbox⁴, etc.)*

■ What's missing?

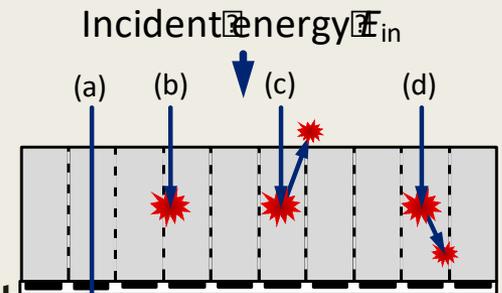
1. https://myfiles.nyu.edu/groups/ALERT/strategic_studies/ADSA12_Presentations/24_Schmidt.pdf
 2. <https://slideplayer.com/slide/9985506/>
 3. <http://deckard.csls.duke.edu/~sailabs/xcatmobymobyphantom.html>
 4. <http://www.imp.uni-erlangen.de/phantoms/>
 5. <http://www.astra-toolbox.com>
- PCD model: Computes PCD outputs from incident x-rays*

Photon counting toolkit (PcTK,

pctk.jhu.edu)

■ What are modeled?

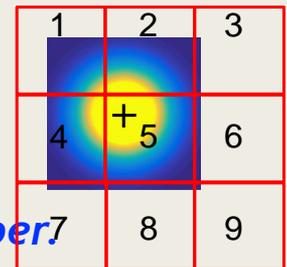
- Photoelectric effect (PE): Total absorption, fluoro emission and re-absorption
- Electronic noise
- Charge sharing up to 3x3 pixels
- Crystal: CdTe
- Energy range: 5-200 keV



■ Limitations? What are not included? → Anything but above

- Compton/Rayleigh scattering, pulse pileup, etc.
- X-ray interaction with objects (attenuation, scatter, etc.)
- Charge cloud/pixel size < 1 , K-ray travel distance/pixel < 1

PDF($E_{out} | E_{in}$)



■ Others

- How to simulate a new scanner? → It is outside PcTK. Need a [wrapper](#).
- How to access the software? → Download the application from pctk.jhu.edu, fill and send it to ken.pctk@gmail.com. We will review and provide a link to download the Matlab codes.
- Is there a cost to use it? → No. But has to be an academic site.
- Are paid consultants available to help using the software? → Yes. Myself.
- What's in it for you to develop and maintain the toolkit? → Pulse pileup effect.

Photon Counting Toolkit (PcTK,

pctk@jhu.edu)

PHOTON COUNTING TOOLKIT

Photon Counting Toolkit (PcTK) - What PcTK Can Do

PHOTON COUNTING TOOLKIT

PcTK

Welcome to the home of Photon Counting Toolkit (PcTK), a software tool to help your research on photon counting x-ray computed tomography (PCD-CT).

The PcTK is a Matlab program for a PCD model which takes into account spatio-energetic cross-talk and correlation between PCD pixels. We have developed PcTK in collaboration with

Search ...

RECENT POSTS

- Presentation at SPIE MI 2018
- First public release of PcTK!

TaguchiK_PcTK_MP2018.pdf

Spatio-energetic cross-talk in photon counting detectors: Numerical detector model (PcTK) and workflow for CT image quality assessment

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Computed Tomography, Siemens Healthineers, Forchheim, Germany

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Institute for Clinical Radiology, Ludwig-Maximilians-University Hospital, Munich, Germany

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Steffen Koppert²
Computed Tomography, Siemens Healthineers, Forchheim, Germany

(Received 23 August 2017; revised 6 February 2018; accepted for publication 25 February 2018; published 15 April 2018)

Purpose: The interpixel cross-talk of energy-sensitive photon counting x-ray detectors (PCDs) has been studied and an analytical model (version 2.1) has been developed for double-counting between neighboring pixels due to charge sharing and K-edge fluorescence x-ray emission followed by its absorption (Taguchi K, et al., Medical Physics 2016;43(12):6386–6404). While the model version 2.1 simulated the spectral degradation well, it had the following problems that has been found to be significant recently: (1) The spectra is inaccurate with smaller pixel size; (2) the charge cloud size must be smaller than the pixel size; (3) the model underestimates the spectrum/counts for 10–40 keV; and (4) the model version 2.1 cannot handle n-angle-counting with $n > 2$ (i.e., triple-counting or higher). These problems are inherent to the design of the model version 2.1; therefore, we developed a new model and addressed these problems in this study.

Methods: We propose a new PCD cross-talk model (version 3.2; PcTK for “photon counting toolkit”) that is based on a completely different design concept from the previous versions. It uses a numerical approach and starts with a 2-D model of charge sharing (as opposed to an analytical approach and a 1-D model with version 2.1) and addresses all of the four problems. The model takes the following factors into account: (1) multi-valued electron density of the charge cloud (Gaussian-distributed), (2) detection efficiency, (3) interactions between photons and PCDs via photoelectric effect, and (4) electronic noise. Correlated noisy PCD data can be generated using either a multivariate normal random number generator or a Poisson random number generator. The effect of the two parameters, the effective charge cloud diameter (d_{eff}) and pixel size (d_{pix}), was studied and results were compared with Monte Carlo simulations and the previous model version 2.1. Finally, a script for the workflow for CT image quality assessment has been developed, which started with a few material density images, generated material-specific sinograms (line integrals) data, noisy PCD data with spectral distortion using the model version 3.2, and reconstructed PCD-CT images for four energy windows.

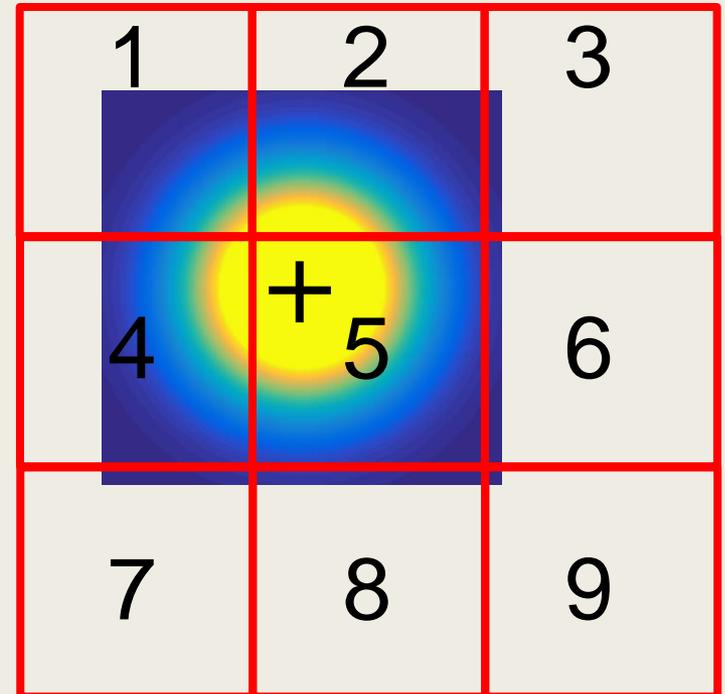
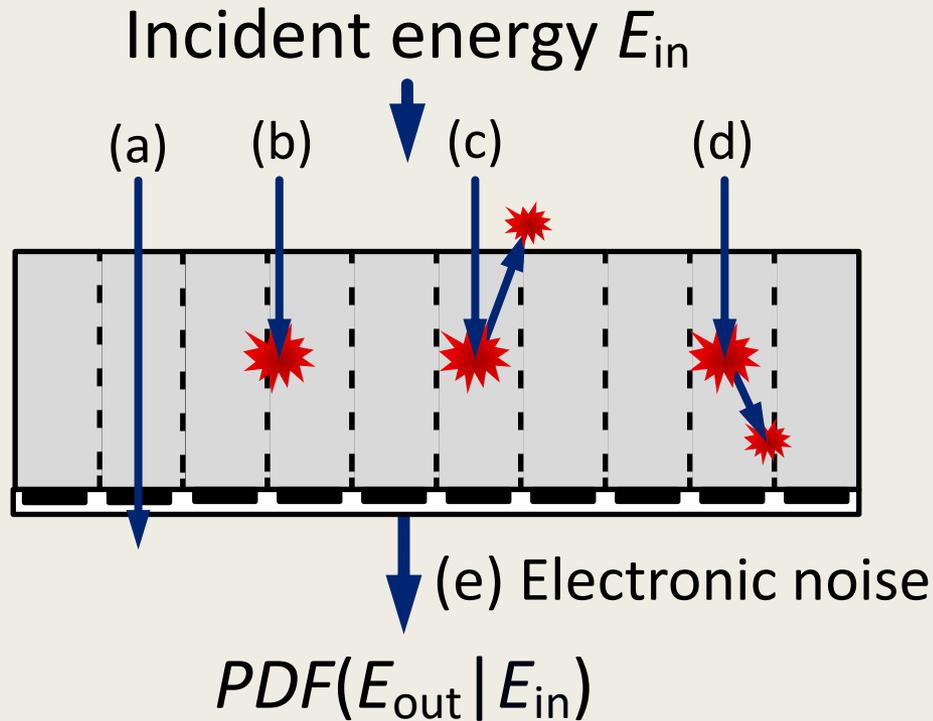
Results: The model version 3.2 addressed all of the four problems listed above. The spectra with $d_{eff} = 56\text{--}113\ \mu\text{m}$ agreed with that of Medipix3 detector with $d_{eff} = 55\text{--}110\ \mu\text{m}$ without charge sharing modeling qualitatively. The counts for 10–40 keV were larger than the previous model (version 2.1) and agreed with MC simulations very well (root-mean-square difference values with model version 3.2 were decreased to 16%–67% of the values with version 2.1). There were many non-zero off-diagonal elements with n-angle-counting with $n > 2$ in the normalized covariance matrix of 3×3 neighboring pixels. Reconstructed images showed biases and artifacts attributed to the spectral distortion due to the charge sharing and fluorescence x-rays.

Conclusion: We have developed a new PCD model for spatio-energetic cross-talk and correlation between PCD pixels. The workflow demonstrated the utility of the model for general or task-specific image quality assessments for the PCD-CT. Note: The program (PcTK) and the workflow scripts have been made available to academic researchers. Interested readers should visit the website (pctk@jhu.edu) or contact the corresponding author. © 2018 American Association of Physicists in Medicine [https://doi.org/10.1002/mp.12863]

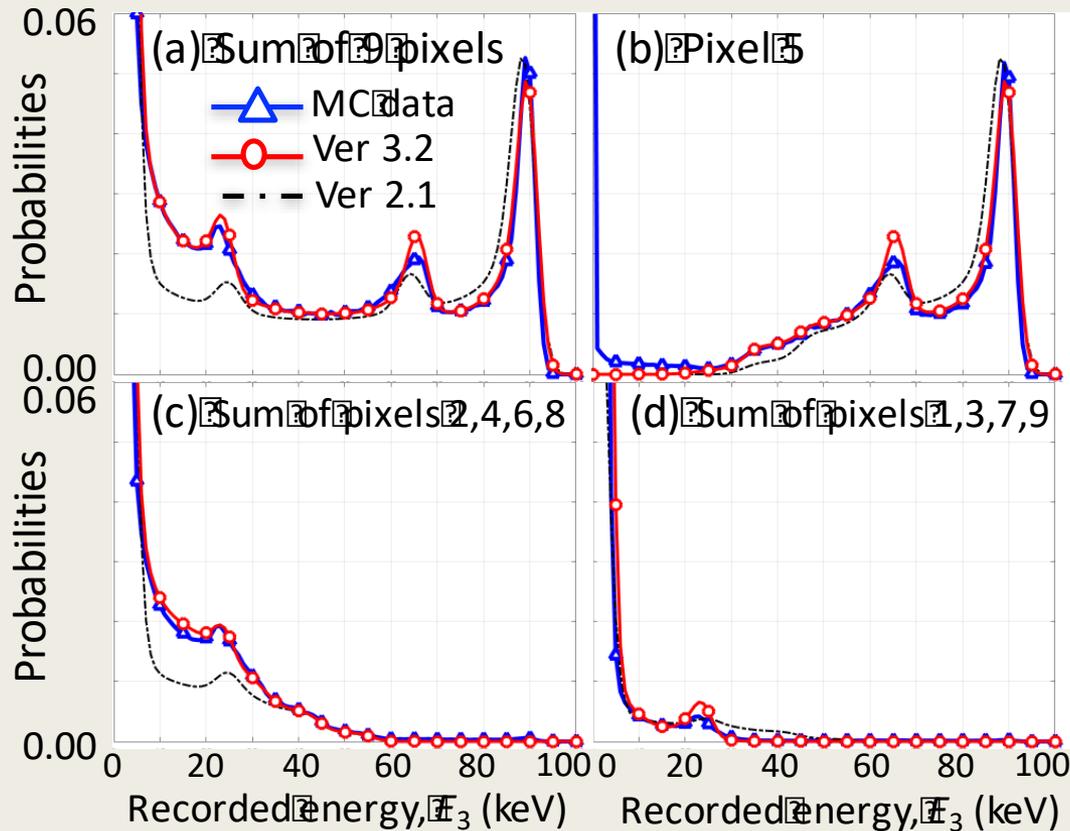
1985 Med. Phys. 45 (5), May 2018 0094-2445/2018/45(5)/1985/14 © 2018 American Association of Physicists in Medicine 1985

- “Spectral response” model of photon counting detectors
- Medical Physics 2018;45(5):1985–1998
- Matlab programs
- Available for academic research, free of charge
- Download the application and send to ken.pctk@gmail.com

Cascaded parallel systems model



Study spill-out spectra



1	2	3
4	5	6
7	8	9

Default settings

CdTe, 1.6 mm

Pixel size (d_{pix}): 225 μ m

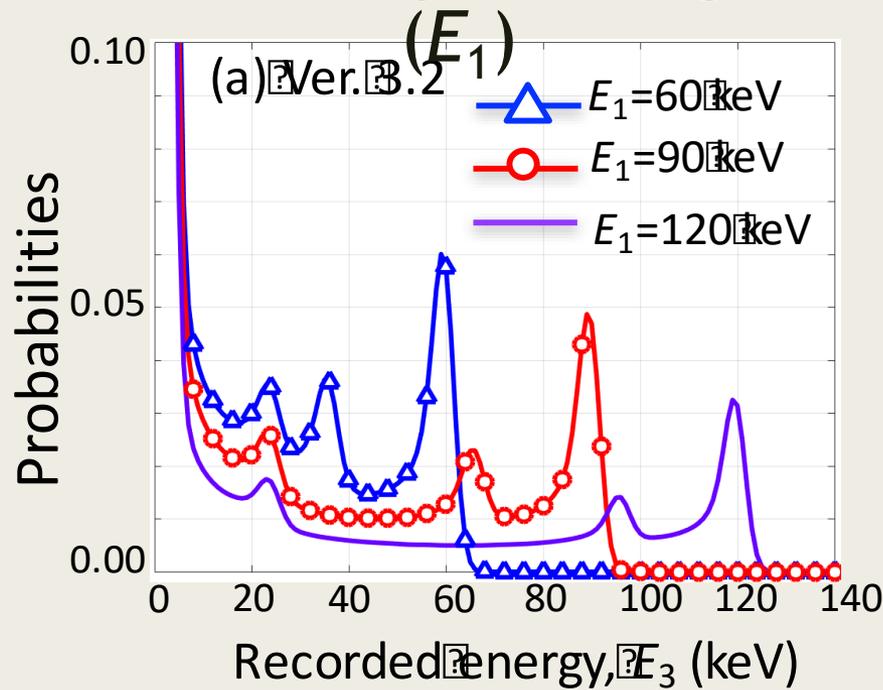
Charge cloud size (d_0):
 \varnothing 48 μ m (v3.2)
 \varnothing 96 μ m (v2.1)

Electronic noise:
 2.0 keV (v3.2)
 2.5 keV (v2.1)

Monte Carlo (MC) by Stierstorfer K, Med Phys, 2018;45(1):156-166.

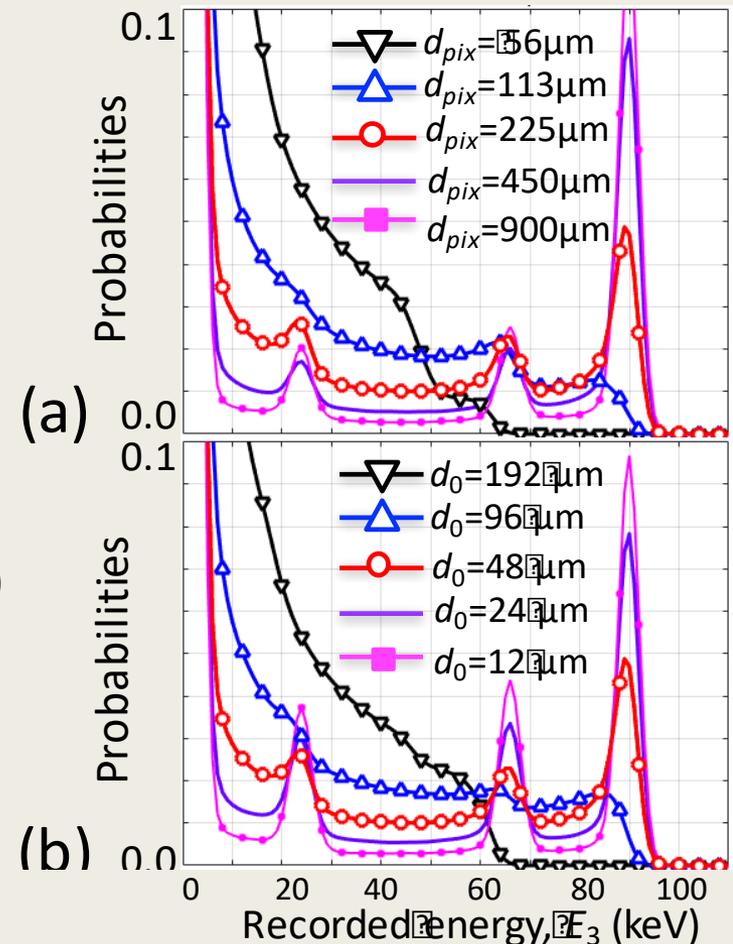
Study recorded spectra

Various input energies

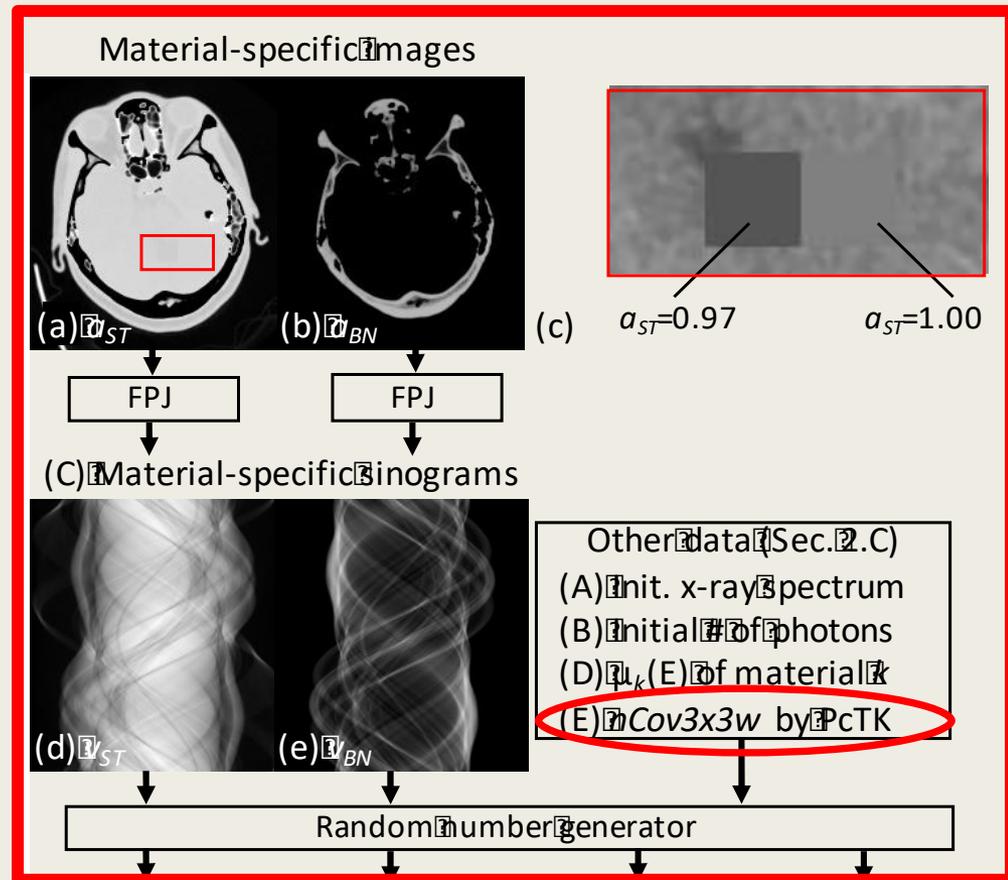
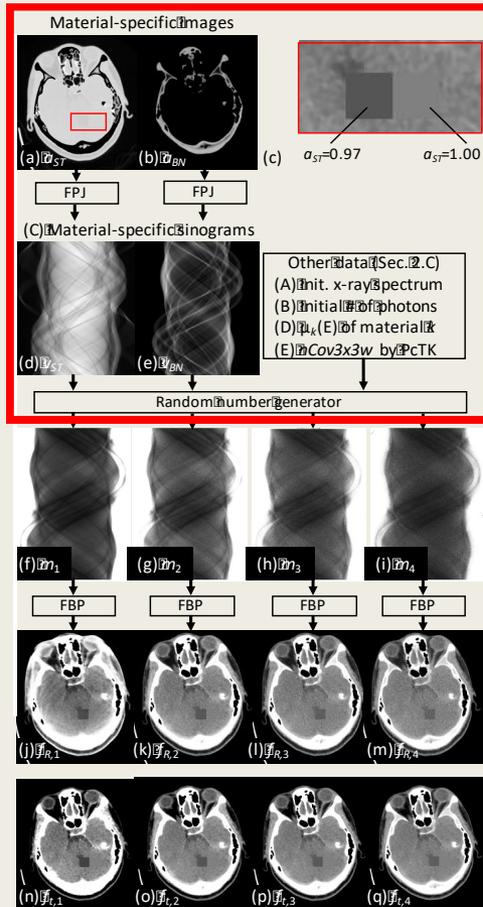


CdTe, $(225 \mu\text{m})^2 \times 1.6 \text{ mm}$
 FWHM of charge cloud size = $\phi 48 \mu\text{m}$
 Electronic noise = 2.0 keV

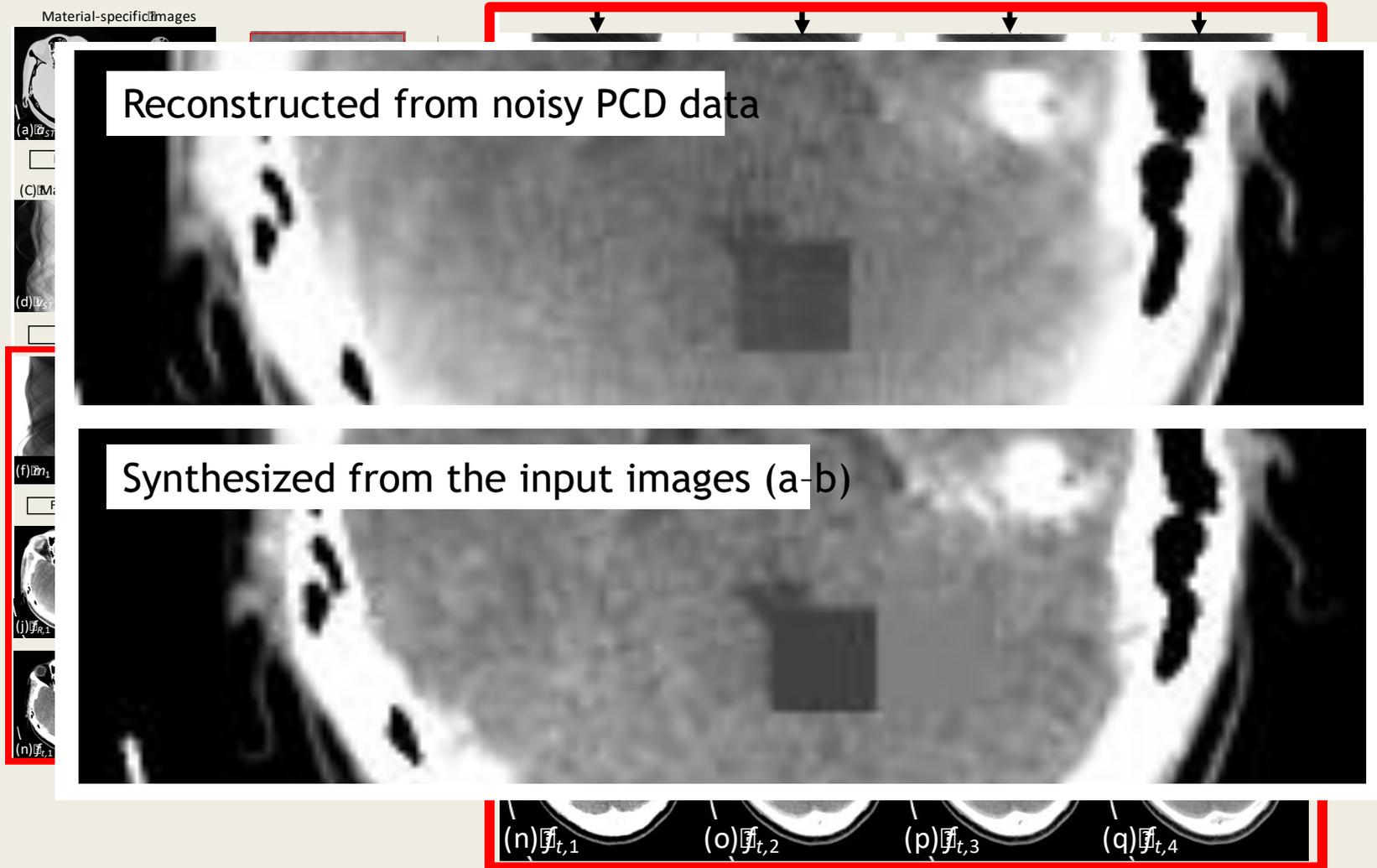
Various PCD parameters



Simulate correlated noisy CT data



Simulate correlated noisy CT data



Photon counting toolkit (PcTK,

pctk.jhu.edu)

■ What are modeled?

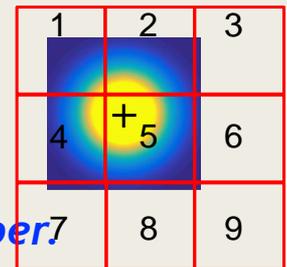
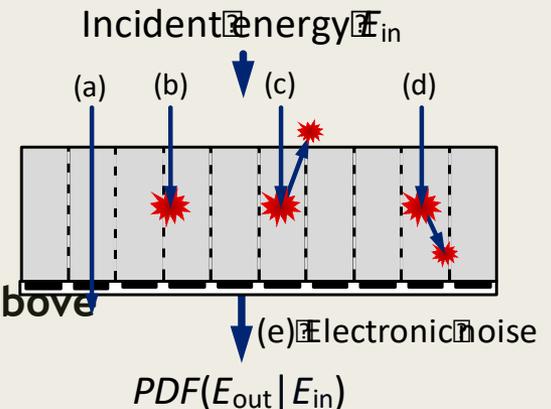
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- Electronic noise
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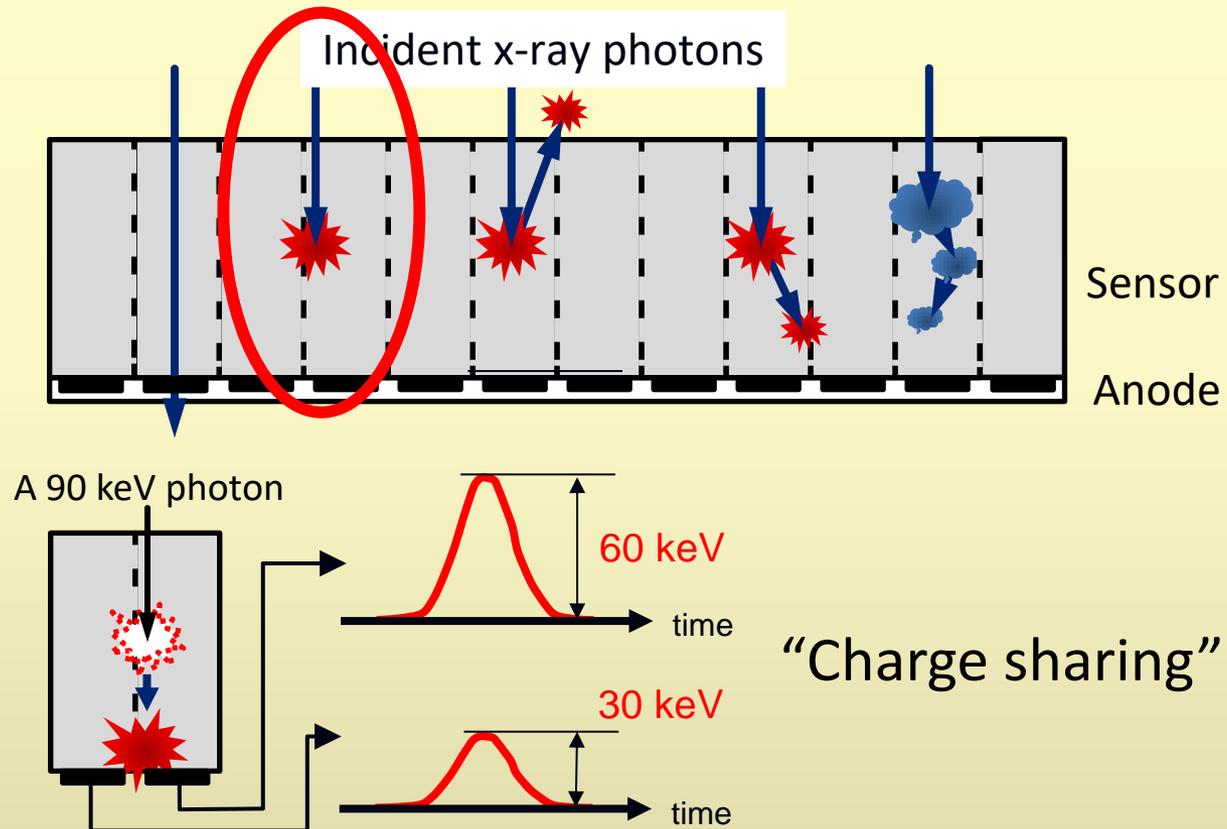
■ Others

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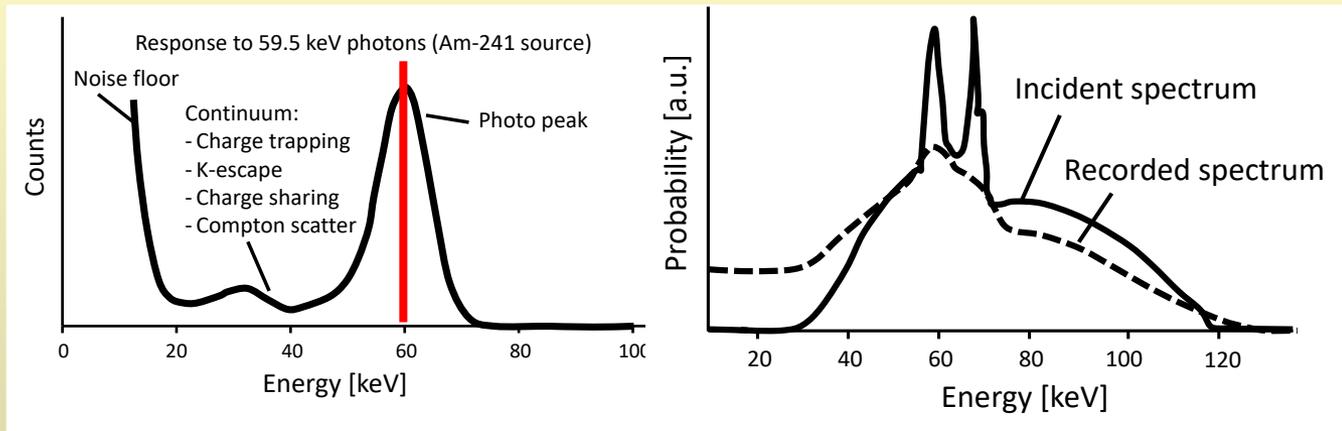
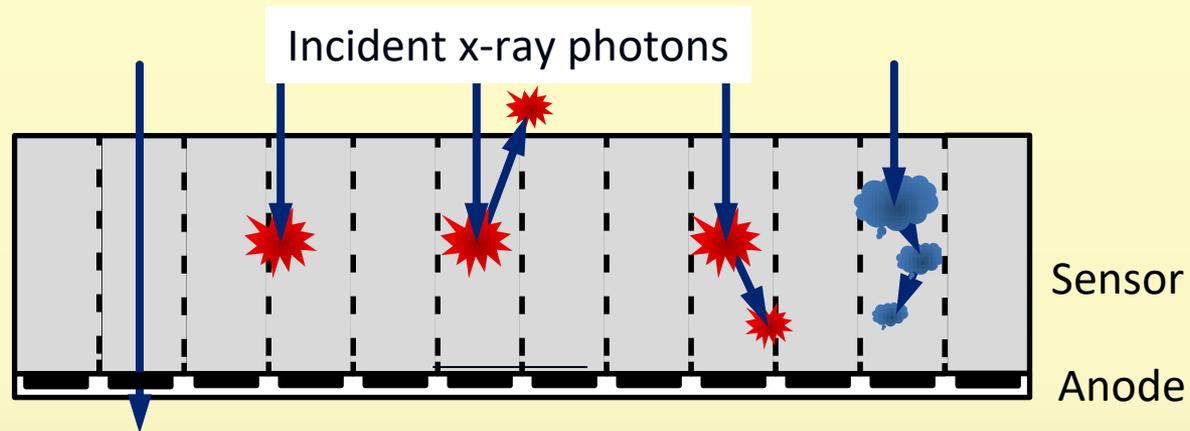


Backup slides

Spatio-energetic cross-talk

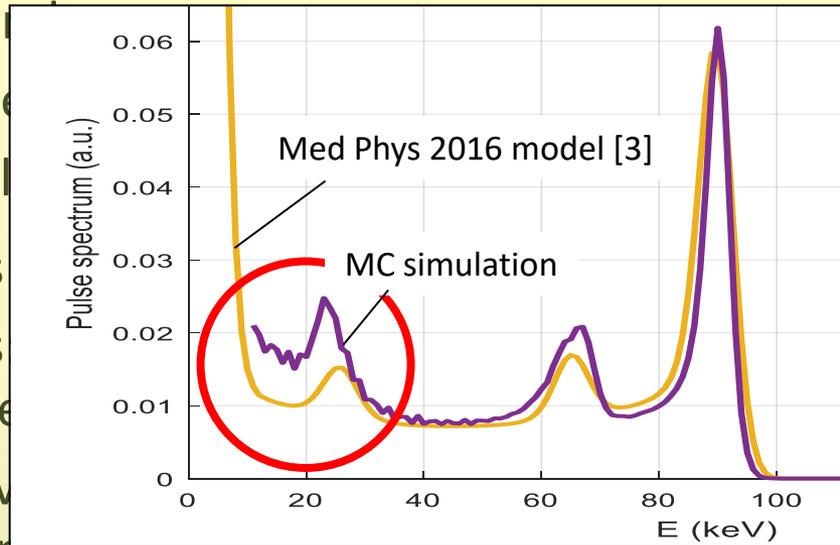


Spectral distortion



Problems and study aims

- Background
 - PCD model
 - Analytical
- Problems
 - Problems
 - (2) Charge
 - Aims: Dev
 - restriction on a_0



is [1,2]

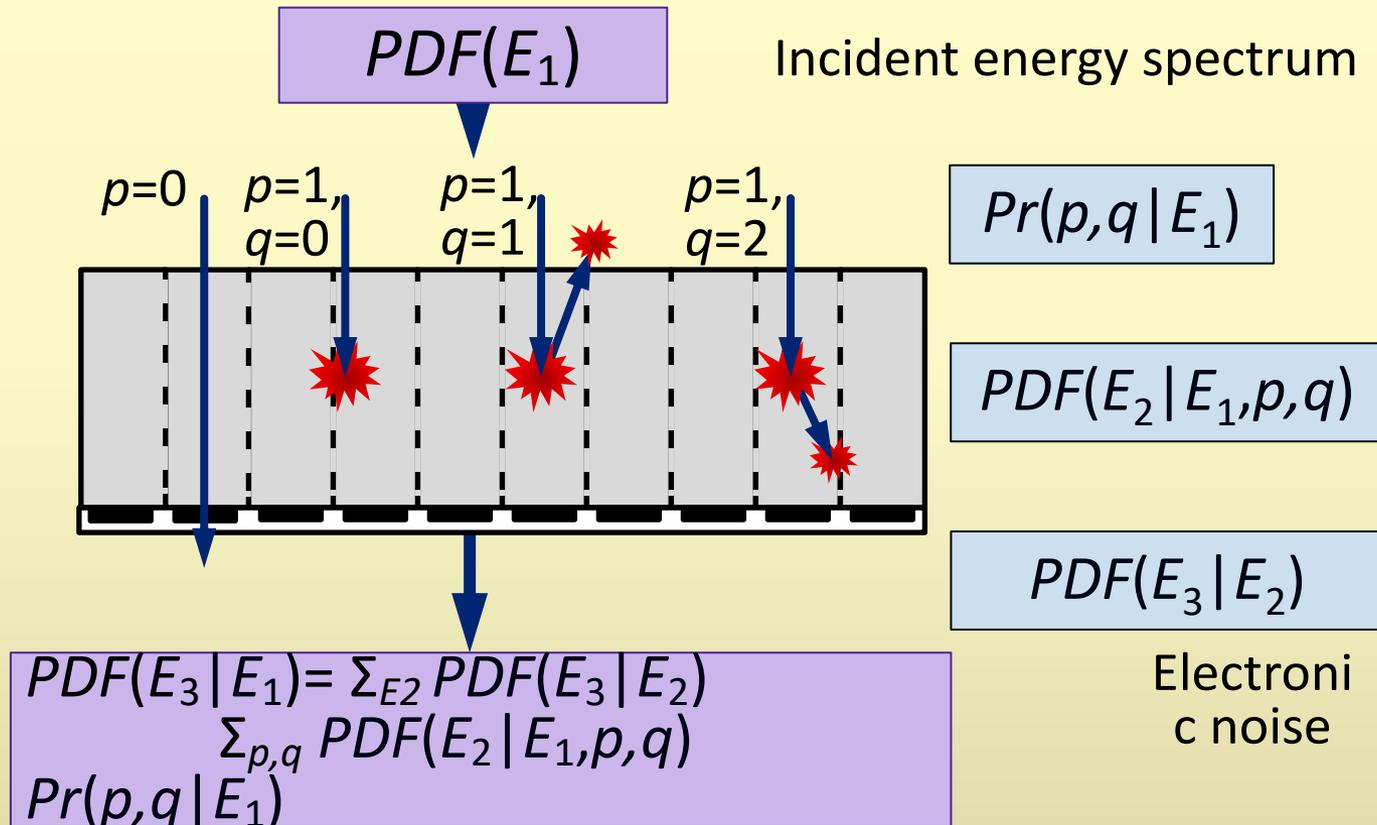
counts at low energies
 ing (with $n>2$) and no

[1] Tanguay J, Med Phys, 2015;42(1):491–509

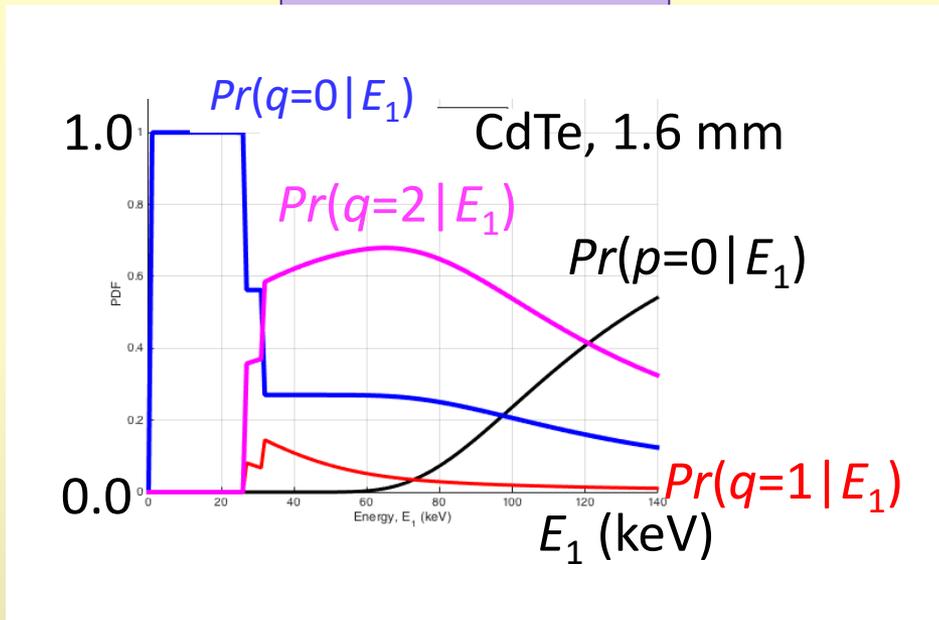
[2] Xu J, Med Phys, 2014;41(10):101907

[3] Taguchi K, Med Phys, 2016;43(12):6386–6404 and SPIE MI 2016

Cascaded parallel systems model



Cascaded parallel systems model



t energy spectrum

$$Pr(p, q | E_1)$$

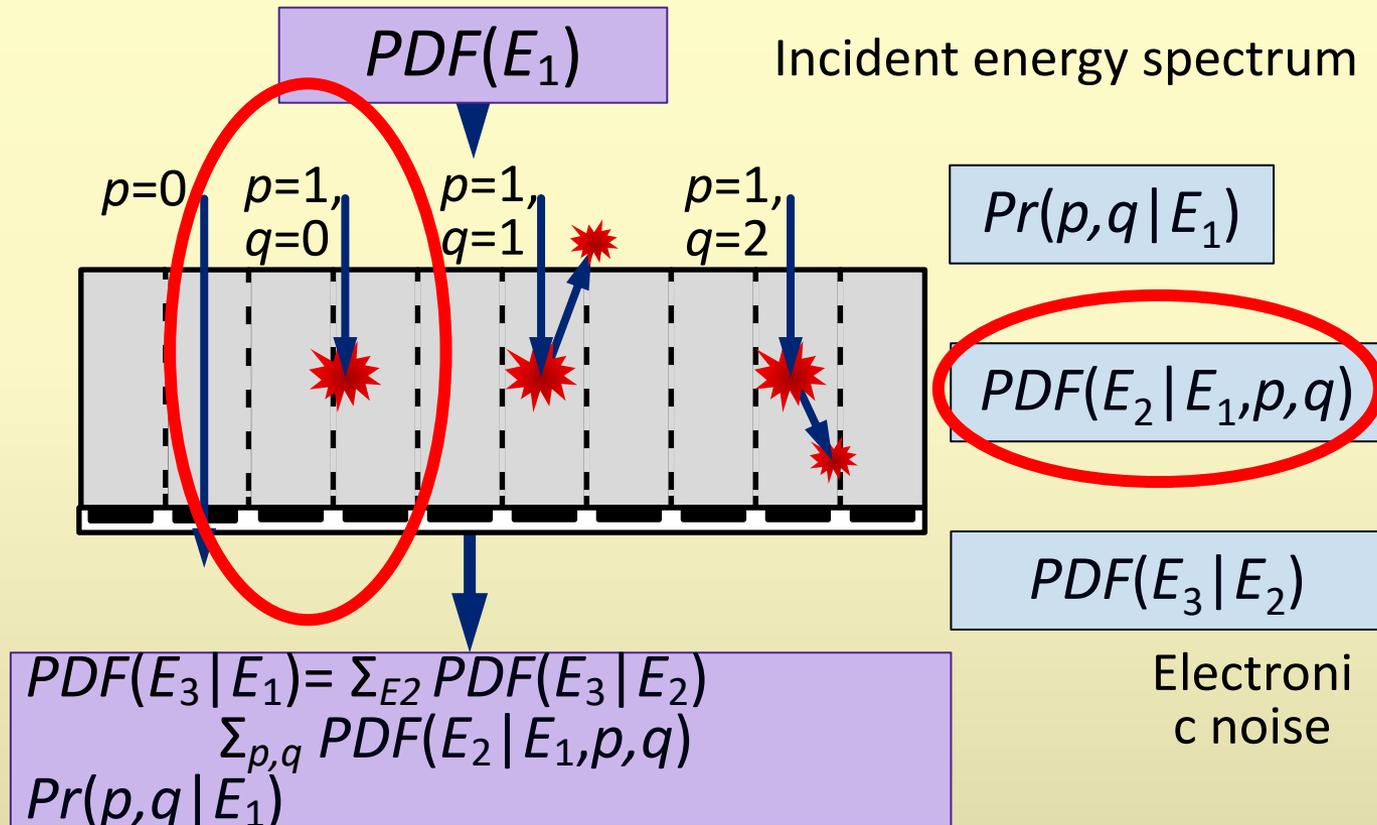
$$PDF(E_2 | E_1, p, q)$$

$$PDF(E_3 | E_2)$$

Electroni
c noise

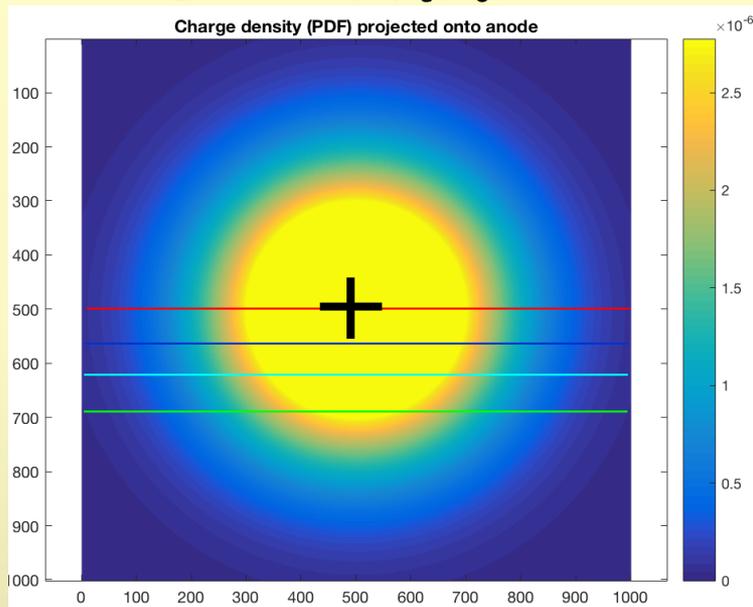
$$PDF(E_3 | E_1) = \sum_{E_2} PDF(E_3 | E_2) \sum_{p, q} Pr(p, q | E_1) PDF(E_2 | E_1, p, q)$$

Cascaded parallel systems model



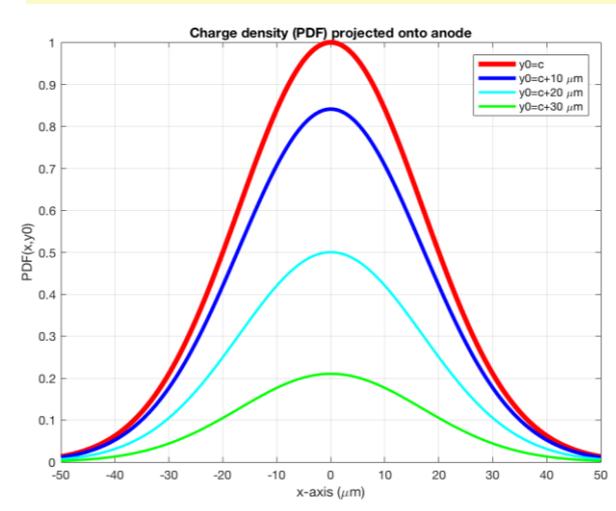
Charge density: 3D Gaussian

Charge density: $\rho_e(d_0)$

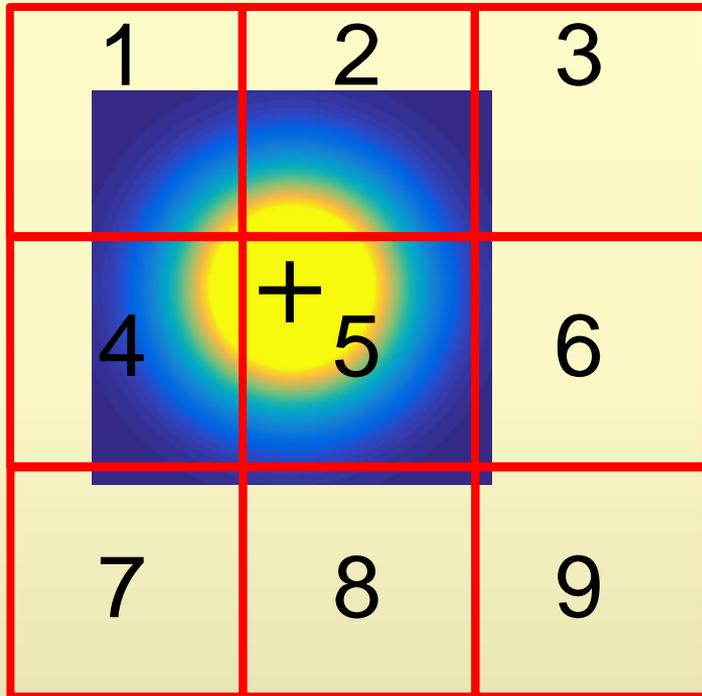


FWHM= d_0 (μm)

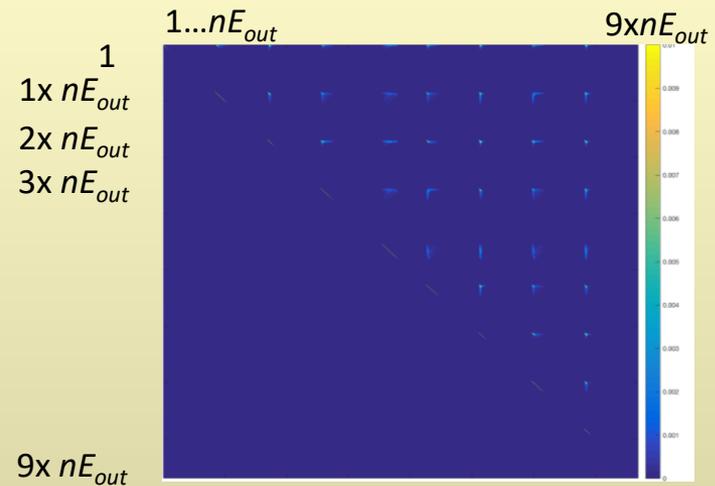
Independent of energy



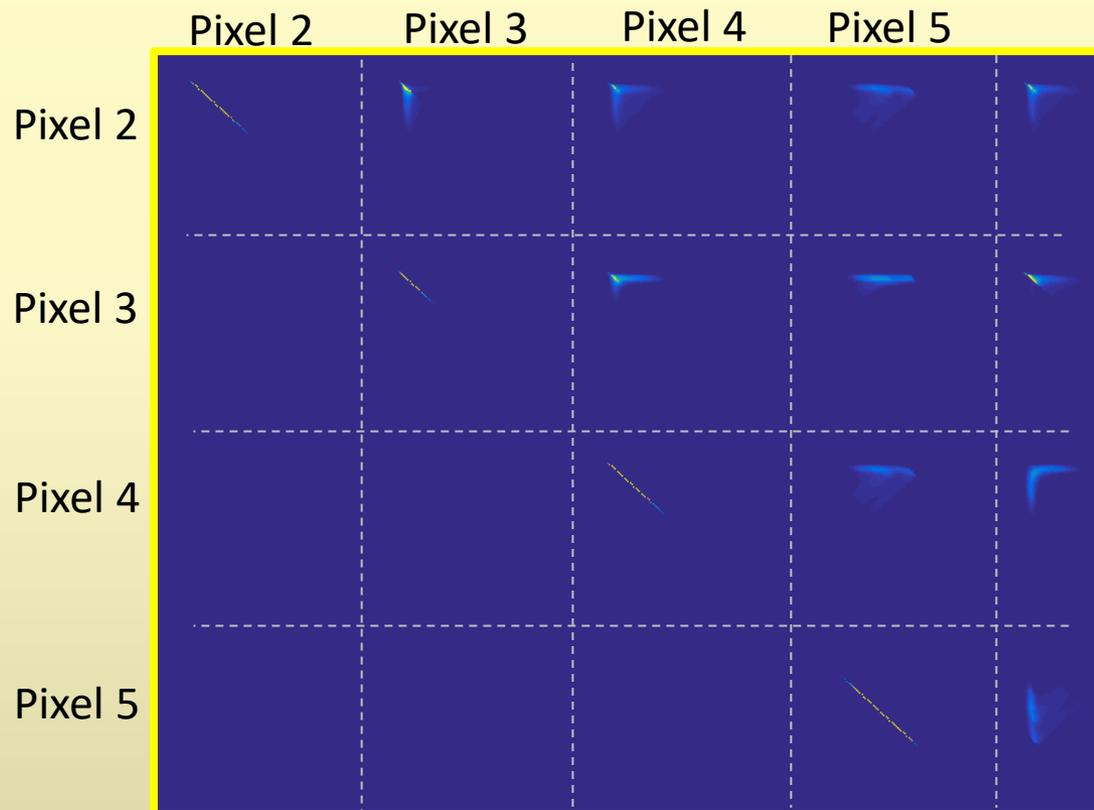
Charge sharing by 3x3 pixels



for energy $E_1=1:150$ keV
 energy density: $E_1\rho_e$
 for incident location i at pixel 5
 $E_j = \text{integ}[E_1\rho_e]$ for each pixel j
 add $PMF(i)$ to covariance element
 $nCovE(k_j(E_j), k_{j'}(E_{j'}), E_1)$
 next location i
 next energy E_1

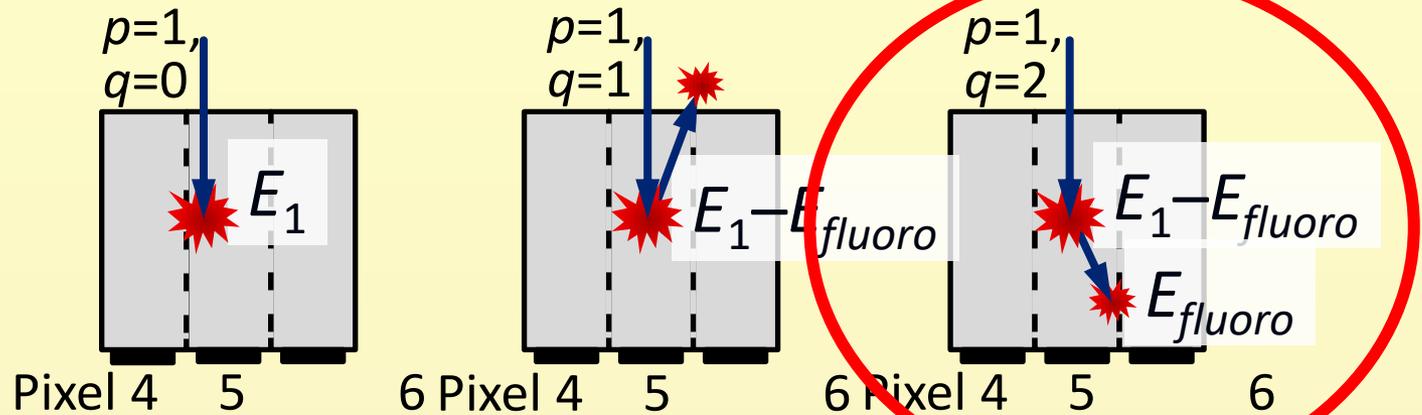


nCovE 3D matrix for recorded energy $E_j=0\dots190$ keV, $j=1\dots9$ pix, for incident energy $E_1=0\dots150$ keV



1	2	3
4	5	6
7	8	9

Various q 's (0=no fluoro, 1=K-escape, 2=re-absorption)

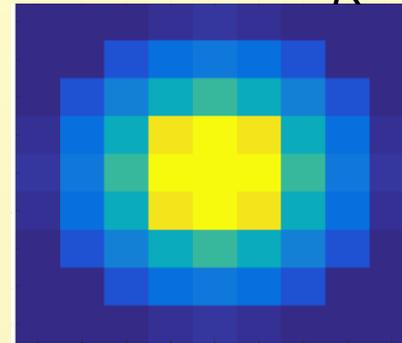
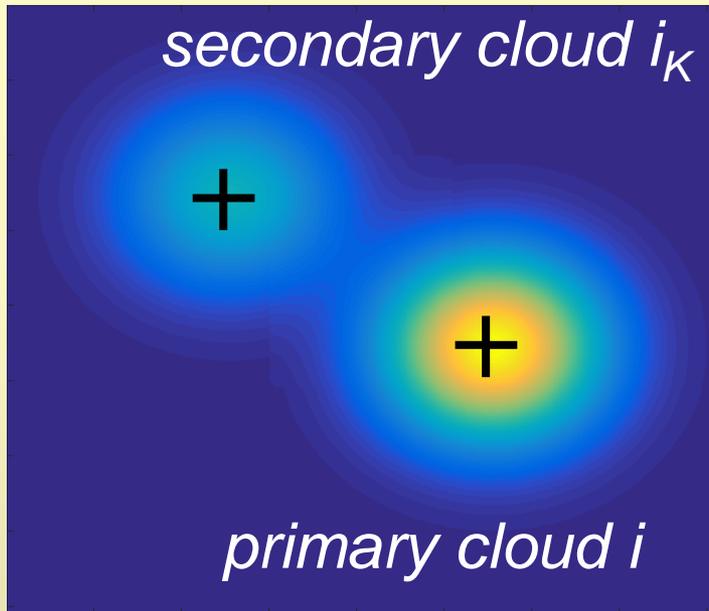


If $q=0$ (no fluoro)
 for energy $E_1=1:150$ keV
 energy density: $E_1 \rho_e$
 for incident location i at pixel 5
 $E_j = \text{integ}[E_1 \rho_e]$ for each pixel j
 add $PMF(i)$ to covariance element
 $nCovE(k_j(E_j), k_{j'}(E_{j'}), E_1)$
 next location i
 next energy E_1

If $q=1$ (K-escape)
 for energy $E_1=1:150$ keV
 energy density: $(E_1 - E_{fluoro}) \rho_e$
 for incident location i at pixel 5
 $E_j = \text{integ}[E_1 \rho_e]$ for each pixel j
 add $PMF(i)$ to covariance element
 $nCovE(k_j(E_j), k_{j'}(E_{j'}), E_1)$
 next location i
 next energy E_1

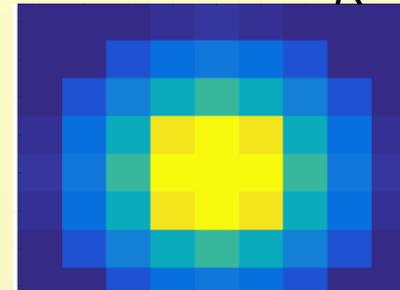
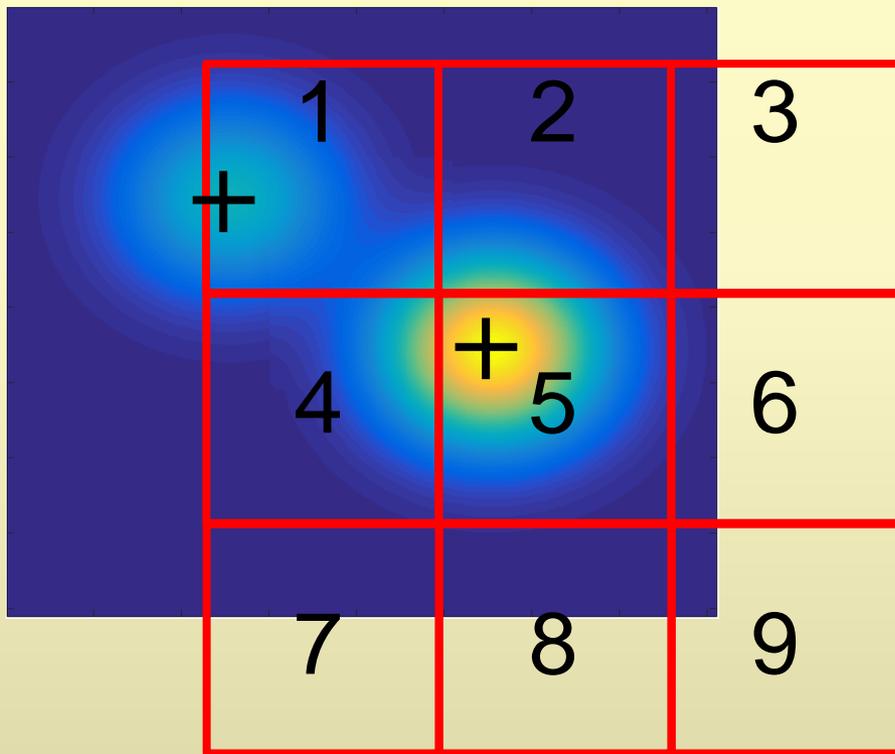
Charge sharing with 2 charge clouds

Relative location of i_K , $PMF(i_K)$



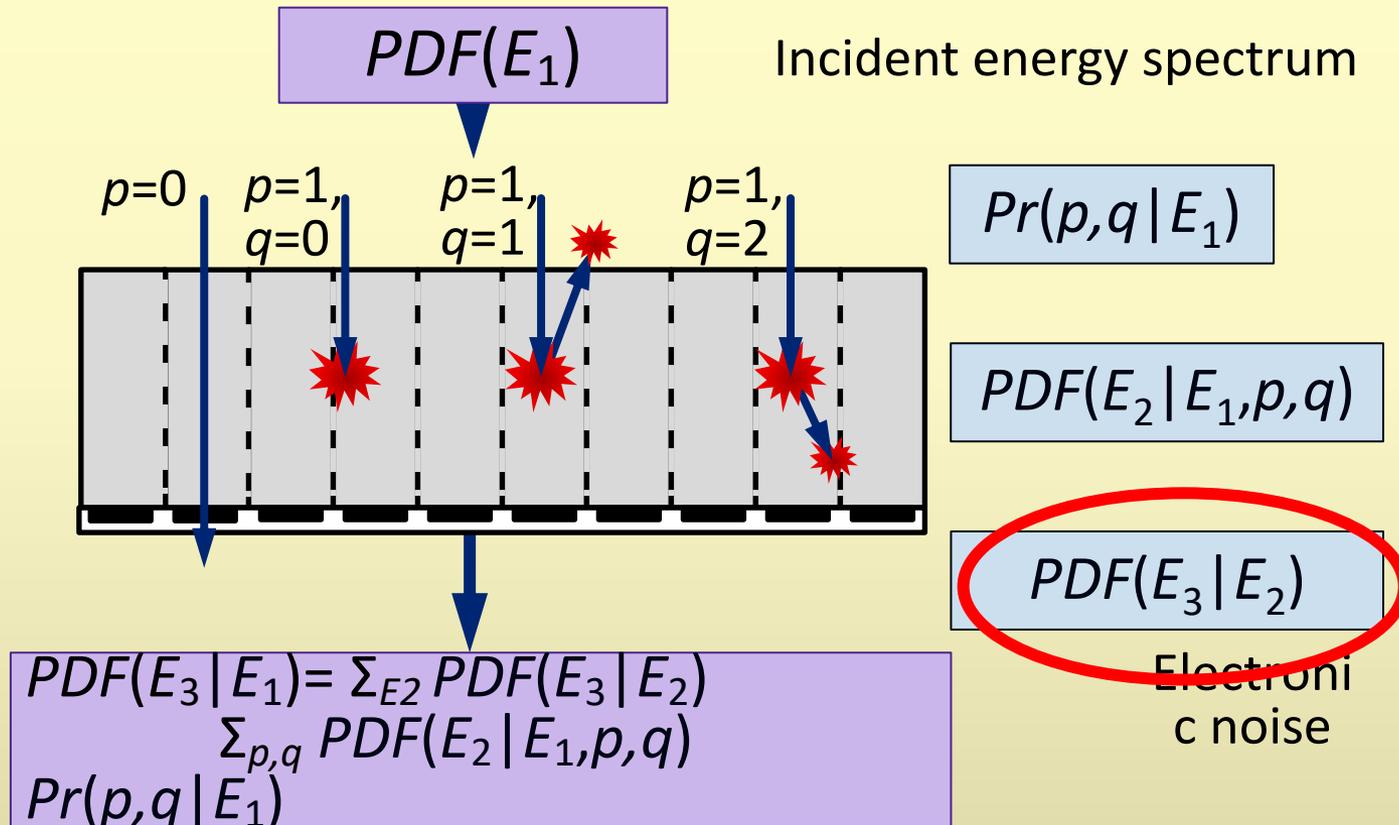
Charge sharing with 2 charge clouds

Relative location of i_K , $PMF(i_K)$



If $q=2$ (Re-absorption)
 for energy $E_1=1:150$ keV
 energy: $(E_1 - E_{fluoro})\rho_e$ and $E_{fluoro}\rho_e$
 for incident location i at pixel 5
 for incident location $i+i_K$
 $E_j = \text{integ}[E_1\rho_e]$ for each pixel j
 add $PMF(i)PMF(i_K)$ to covariance
 element $nCovE(k_j(E_j), k_{j'}(E_{j'}), E_1)$
 next location i_K
 next location i
 next energy E_1

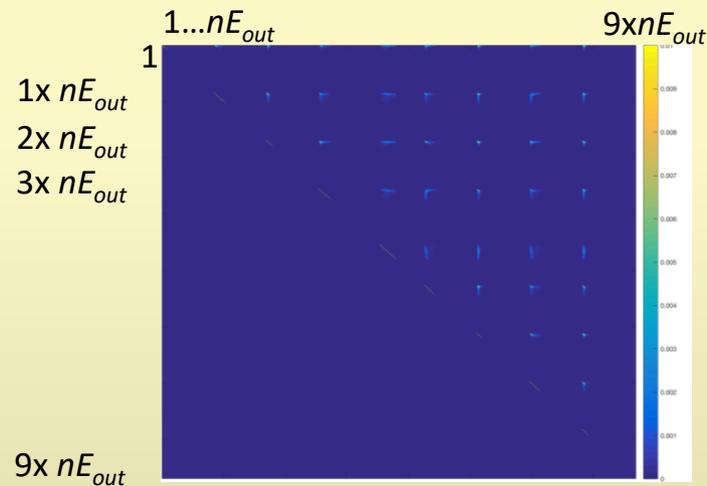
Cascaded parallel systems model



Correlated noisy PCD data generator

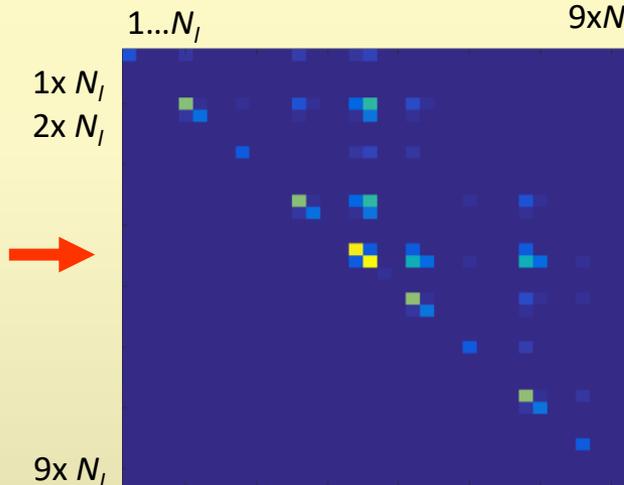
Normalized covariance matrix
for 1-keV bins, 3x3 pixels

$$nCovE(9 \times nE_{out}, 9 \times nE_{out}, nE_{in})$$



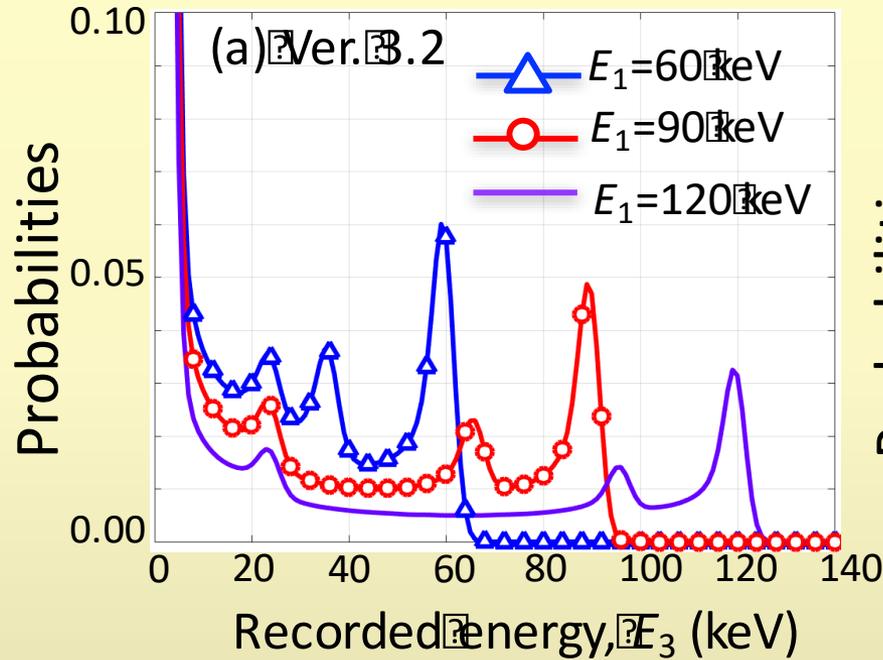
Normalized covariance matrix
for N_I bins, 3x3 pixels

$$nCovBin(9 \times N_I, 9 \times N_I, nE_{in})$$

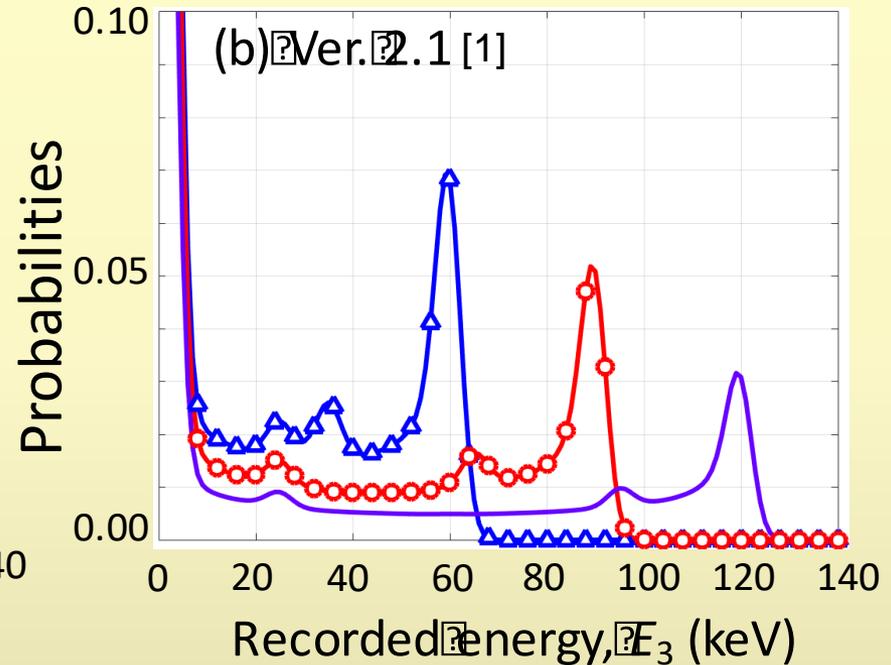


1	2	3
4	5	6
7	8	9

Results (1): Various input energies (E_1)



CdTe, $(225 \mu\text{m})^2 \times 1.6 \text{ mm}$
 FWHM of charge cloud size = $\varnothing 48 \mu\text{m}$
 Electronic noise = 2.0 keV

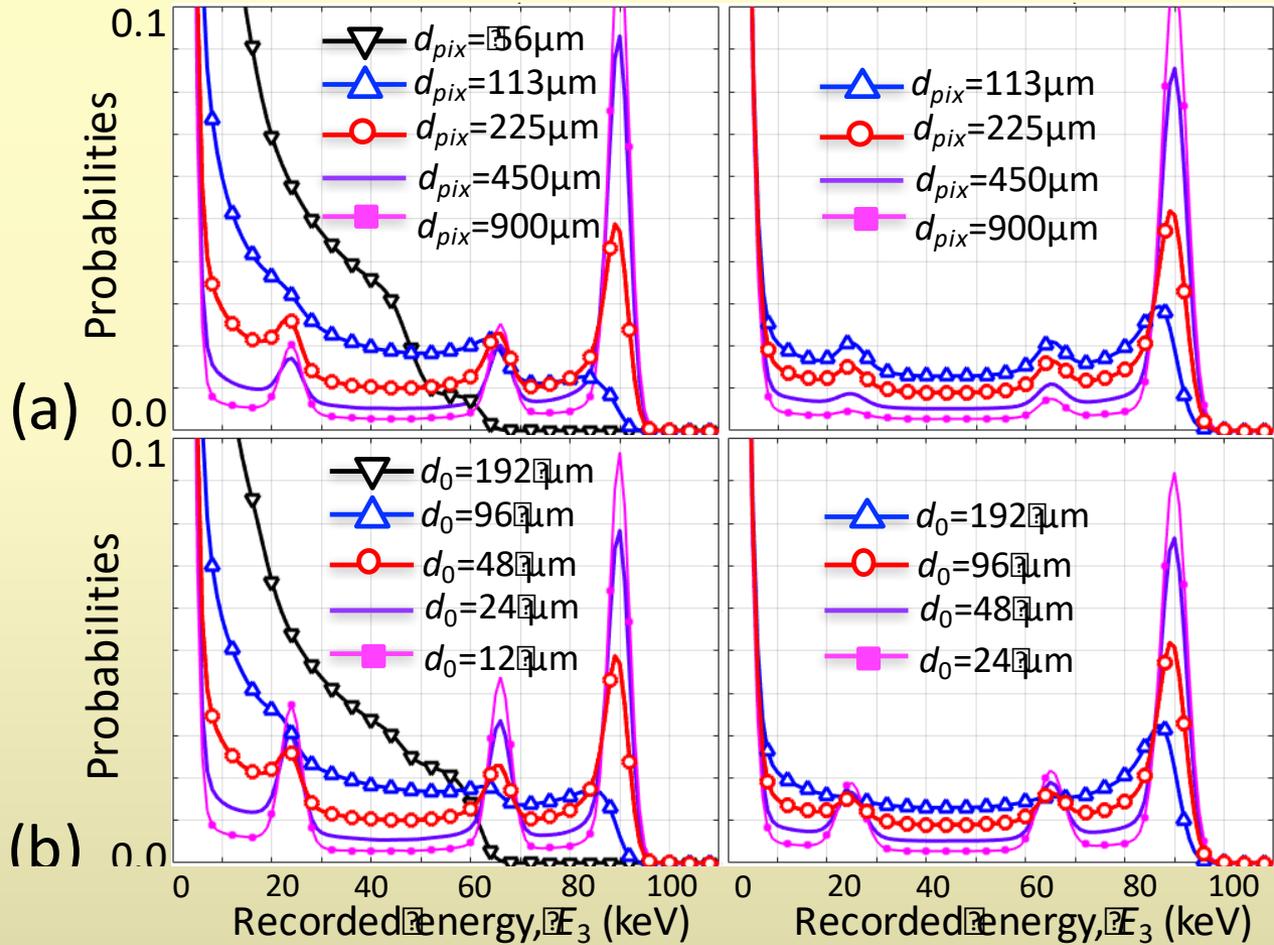


CdTe, $(225 \mu\text{m})^2 \times 1.6 \text{ mm}$
 FWHM of charge cloud size = $\varnothing 96 \mu\text{m}$
 Electronic noise = 2.5 keV

[1] Taguchi K, Med Phys, 2016;43(12):6386–6404

Model ver. 3.2

Model ver. 2.1



Default settings

CdTe, 1.6 mm

Pixel size (d_{pix}): 225 μm

Charge cloud size (d_0):

$\varnothing 48 \mu\text{m}$ (v3.2)

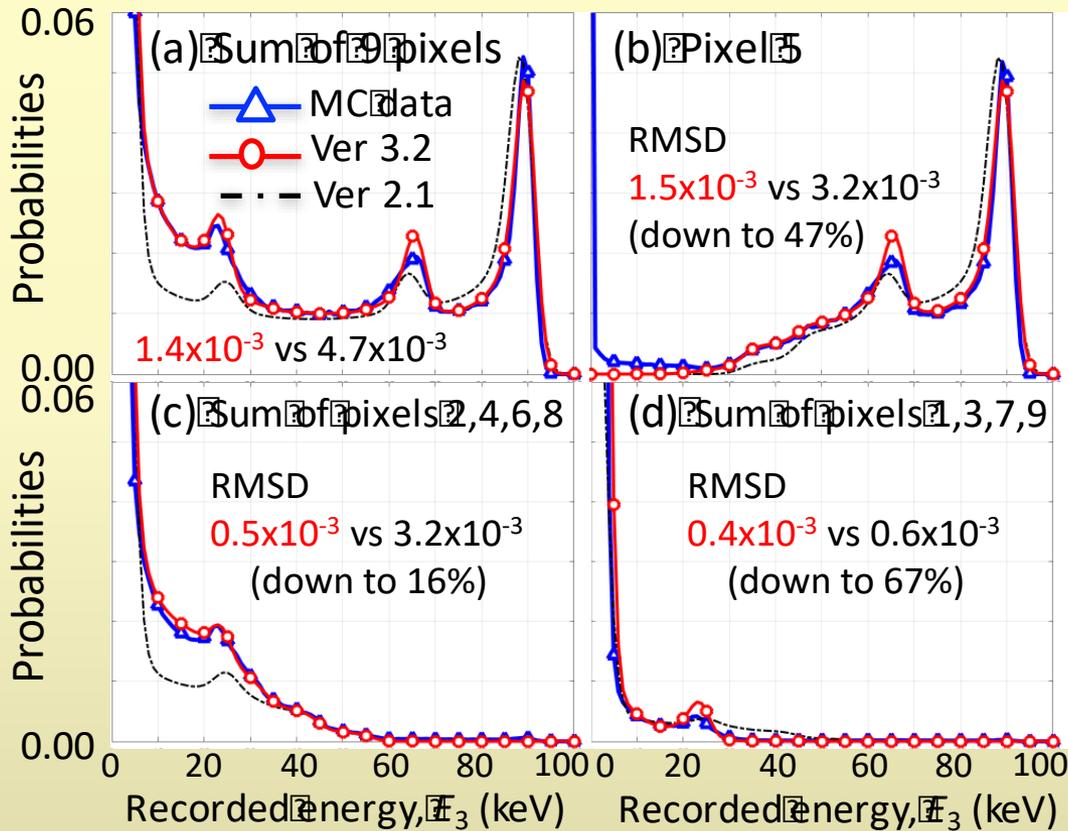
$\varnothing 96 \mu\text{m}$ (v2.1)

Electronic noise:

2.0 keV (v3.2)

2.5 keV (v2.1)

Results (3): Spill-out spectra vs MC sim.[1]



1	2	3
4	5	6
7	8	9

Default settings

CdTe, 1.6 mm

Pixel size (d_{pix}): 225 μm

Charge cloud size (d_0):

$\varnothing 48 \mu\text{m}$ (v3.2)

$\varnothing 96 \mu\text{m}$ (v2.1)

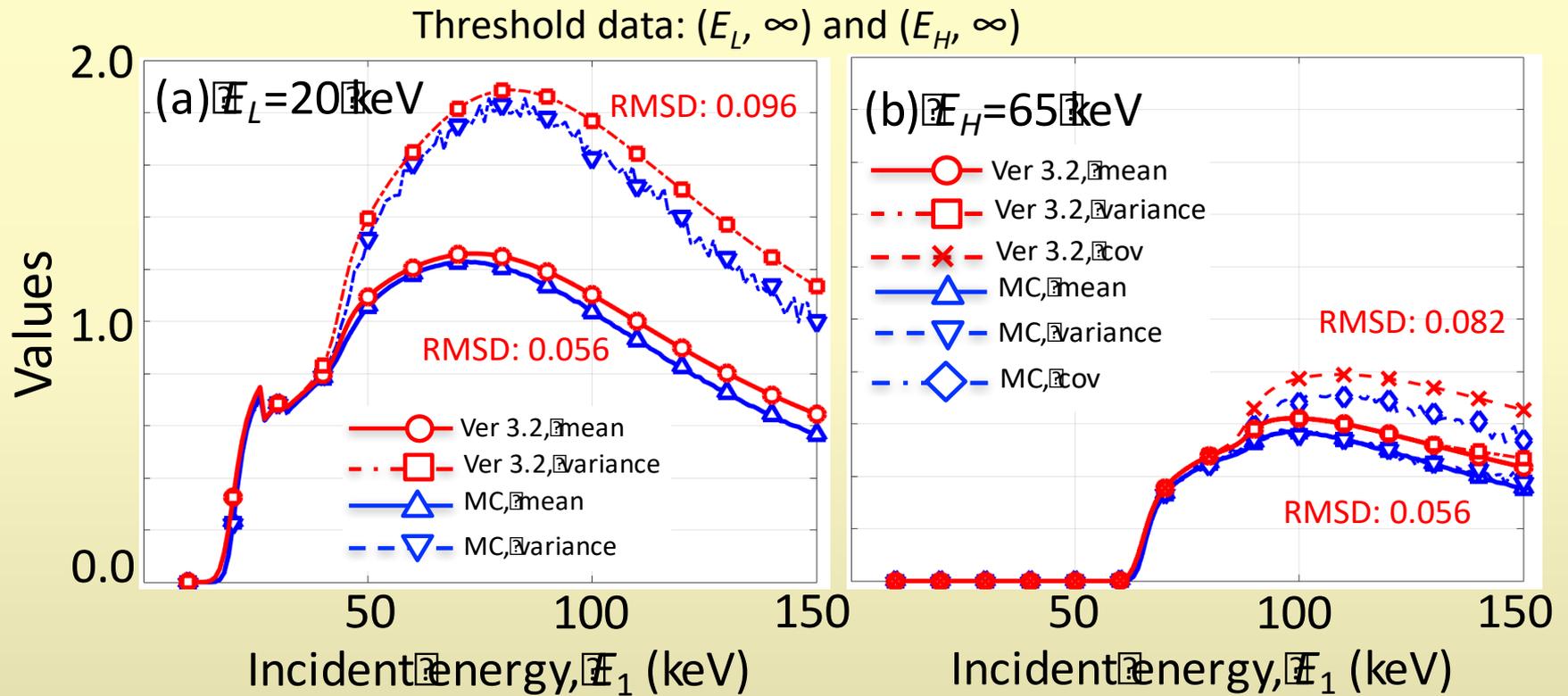
Electronic noise:

2.0 keV (v3.2)

2.5 keV (v2.1)

[1] Stierstorfer K, Med Phys, 2018;45(1):156–166.

Results (4): Mean/var/cov vs MC sim.[1]



[1] Stierstorfer K, Med Phys, 2018;45(1):156–166.