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 mar

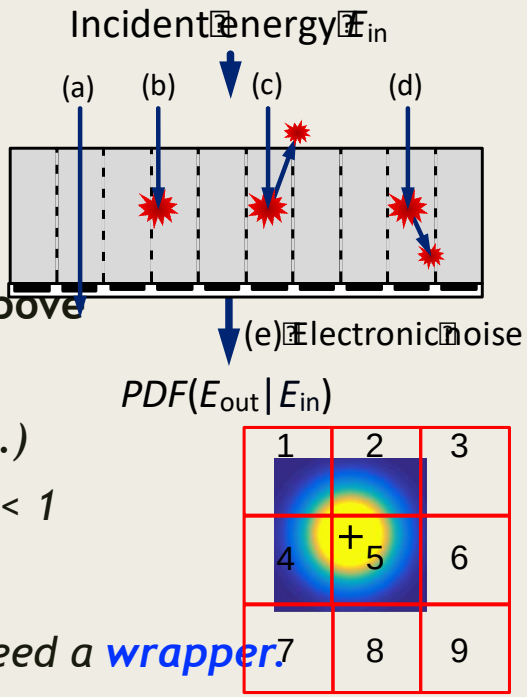
return

- What's available?
  - *Digital phantoms (Taly Gilat-Schmidt[1], XCAT[2,3], Forbild[4])*
  - *X-ray system simulator (TGS[1], ASTRA toolbox[4], etc.)*
- What's missing?
  - *PCD model: Computes PCD outputs from incident x-rays*

1. https://myfiles.neu.edu/groups/ALERT/strategic_studies/ADSA12_Presentations/24_Schmidt.pdf
2. https://slideplayer.com/slide/9985506/
3. http://deskard.duke.edu/xailabs/xcatmobydobyphantom.html
4. http://www.imp.uni-erlangen.de/phantoms/
5. http://www.astra-toolbox.com

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*

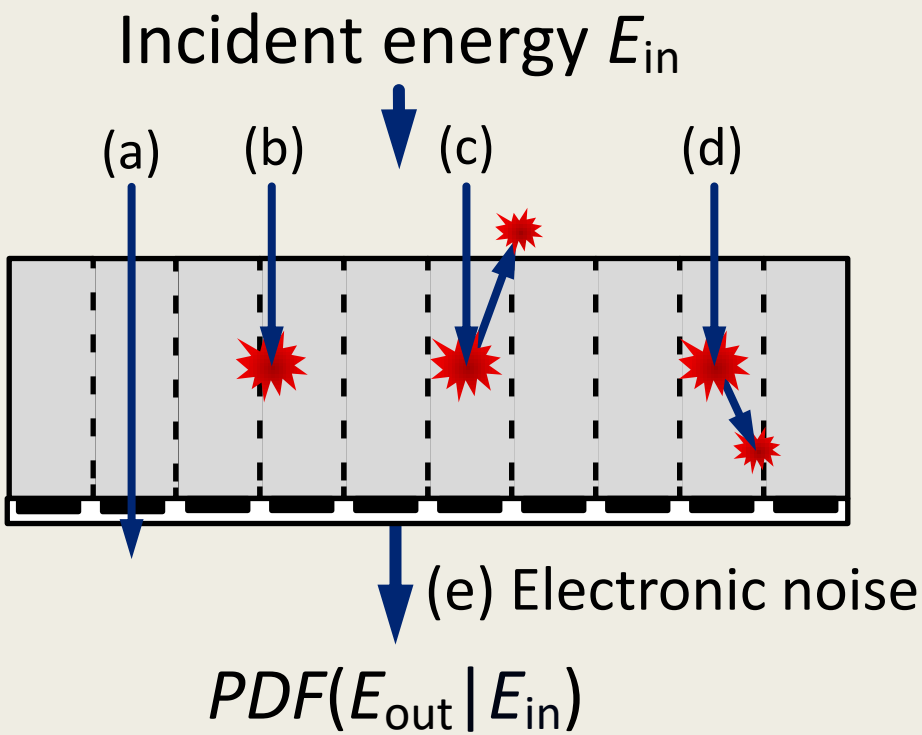


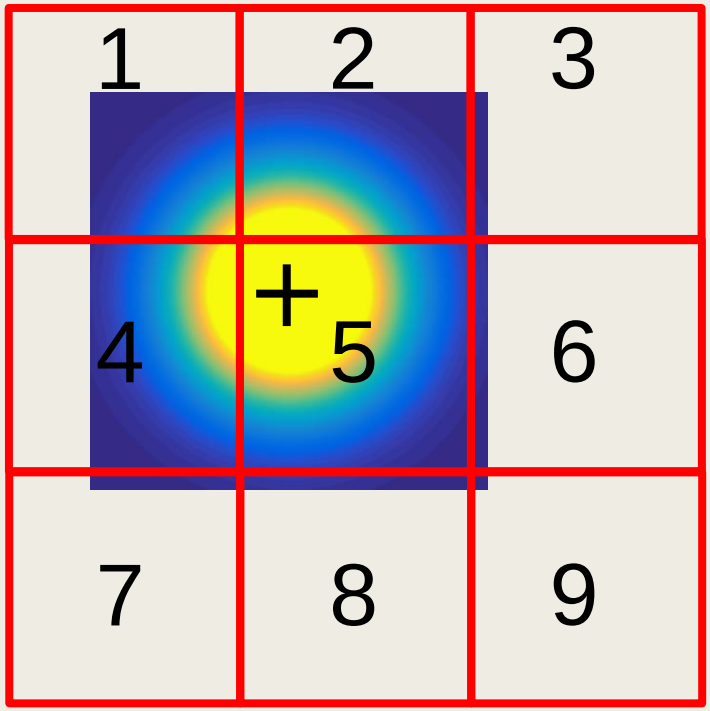
- **Limitations? What are *not* included? → Anything but above**
  - *Compton/Rayleigh scattering, pulse pileup, etc.*
  - *X-ray interaction with objects (attenuation, scatter, etc.)*
  - *Charge cloud/pixel size < 1, K-ray travel distance/pixel < 1*
- **Others**
  - *How to simulate a new scanner? → 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)

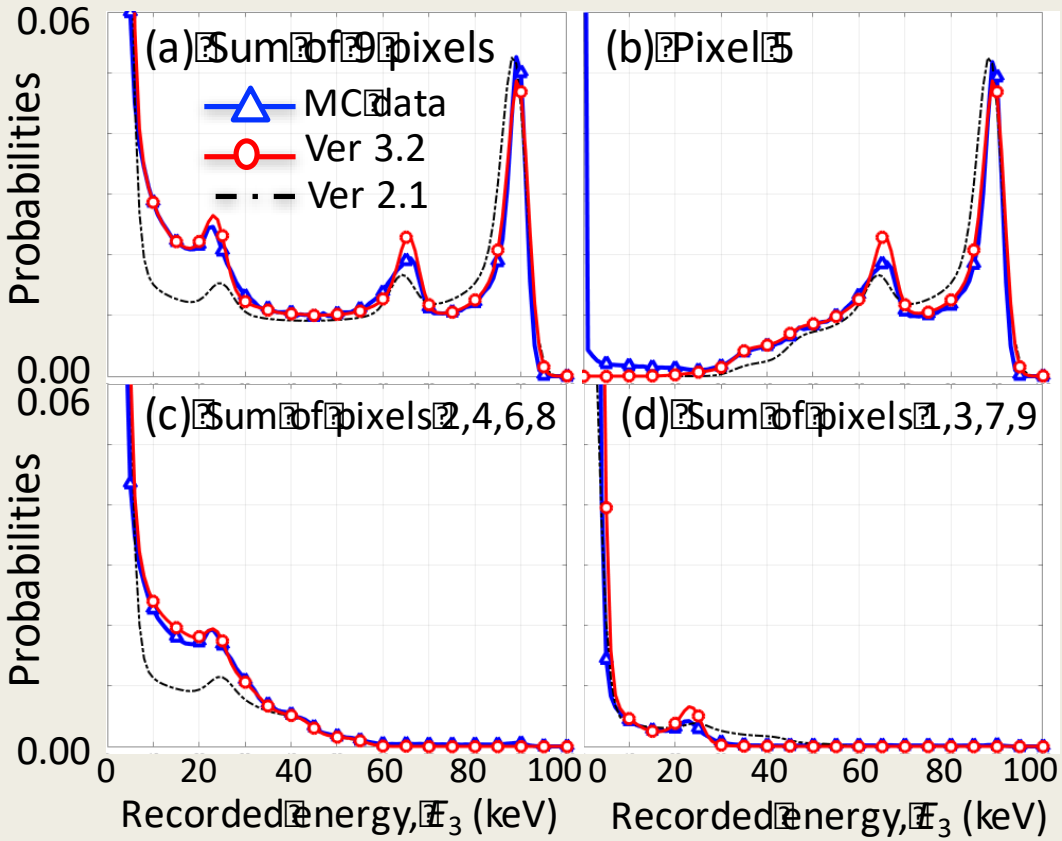
- "Spectral response" model of photon counting detectors
- Medical Physics 2018;45(5):1985–1998
- Matlab programs
- Available for academic research, free of charge
- Download the application and send to ken.pctk@gmail.com

Cascaded parallel systems model





Study spill-out spectra



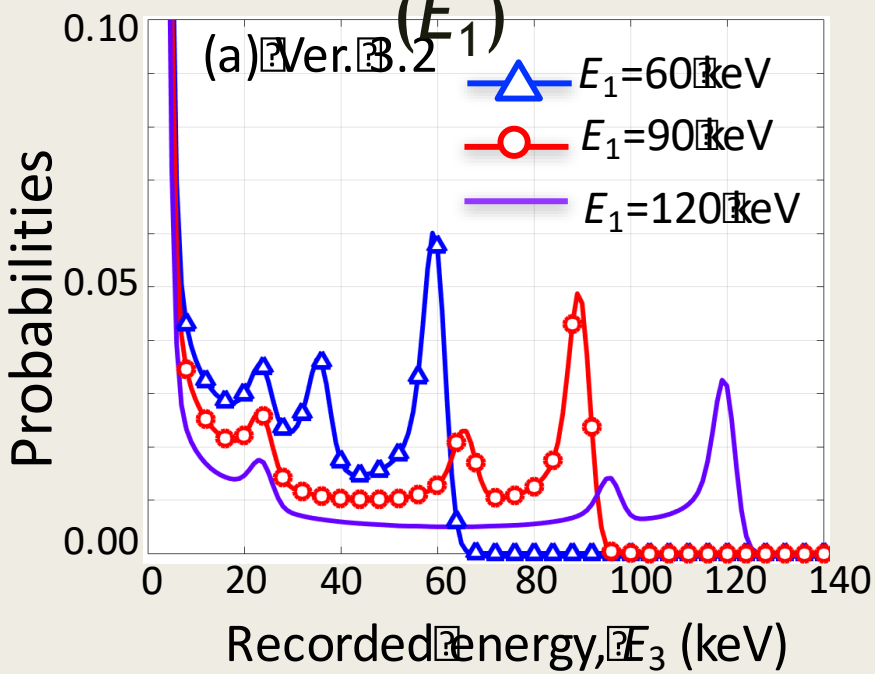
1	2	3
4	5	6
7	8	9

<u>Default settings</u>
CdTe, 1.6 mm
Pixel size (d_{pix}): 225 μm
Charge cloud size (d_0):
Ø48 μm (v3.2)
Ø96 μm (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.

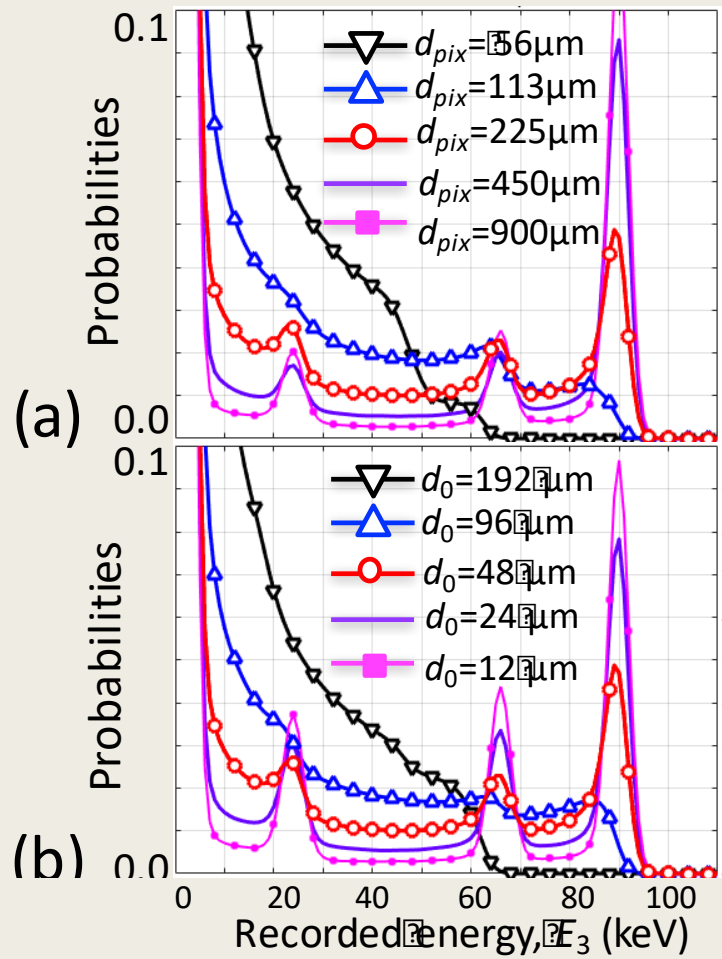
Study recorded spectra

Various input energies (E_1)

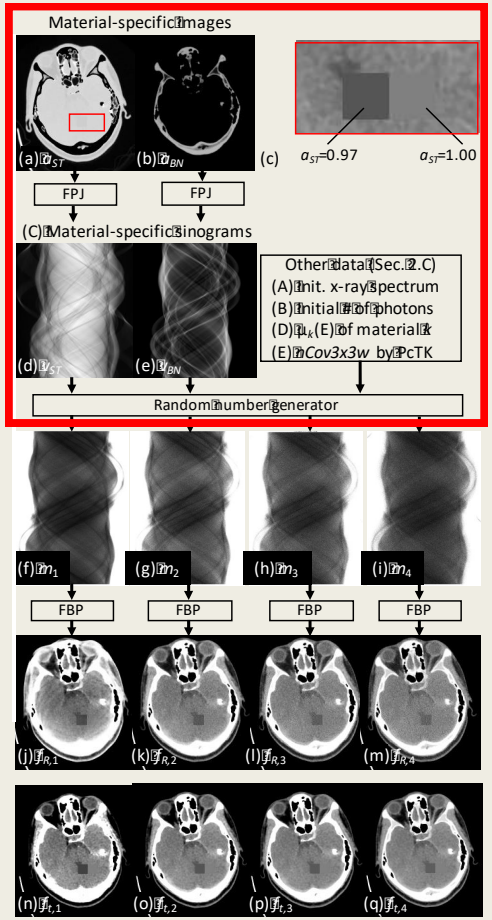


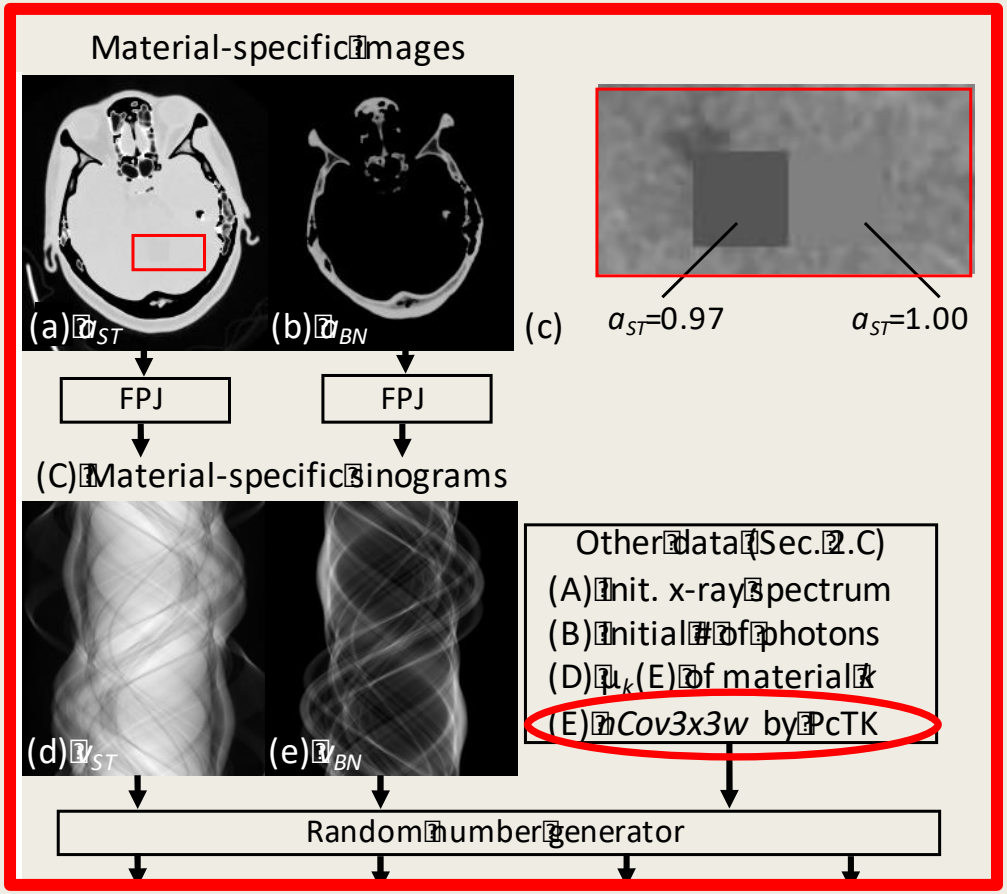
CdTe, (225 μm)^2 x 1.6 mm
FWHM of charge cloud size=Ø48 μm
Electronic noise = 2.0 keV

Various PCD parameters



Simulate correlated noisy CT data





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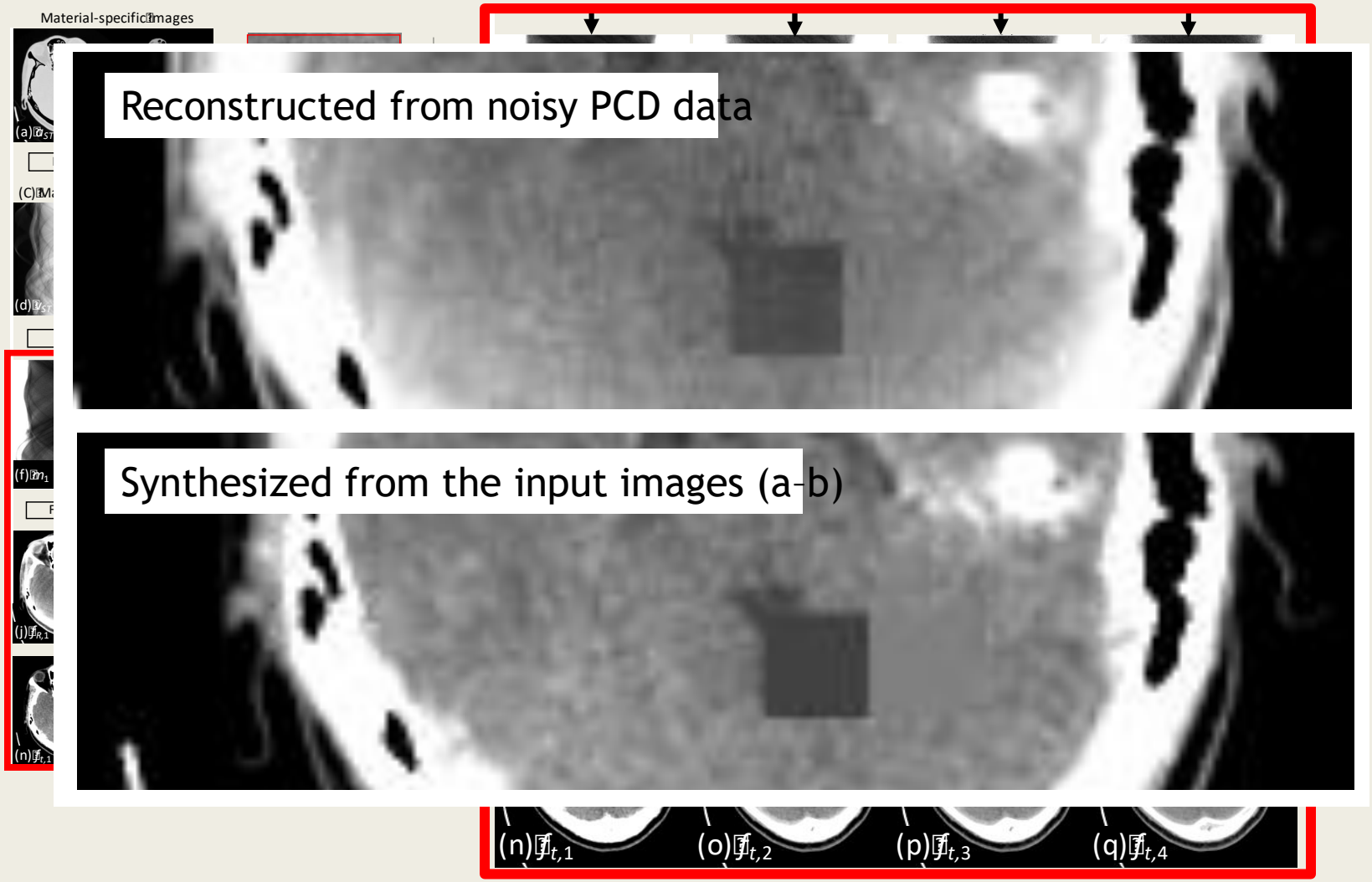

Photon counting toolkit (PcTK, pctk.jhu.edu)

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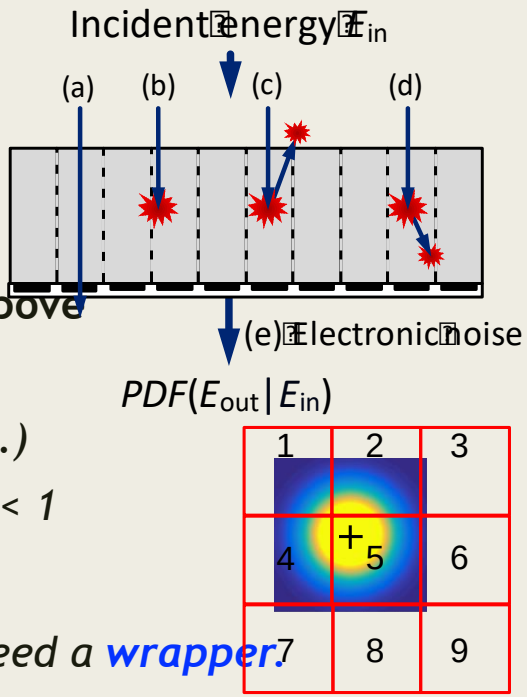

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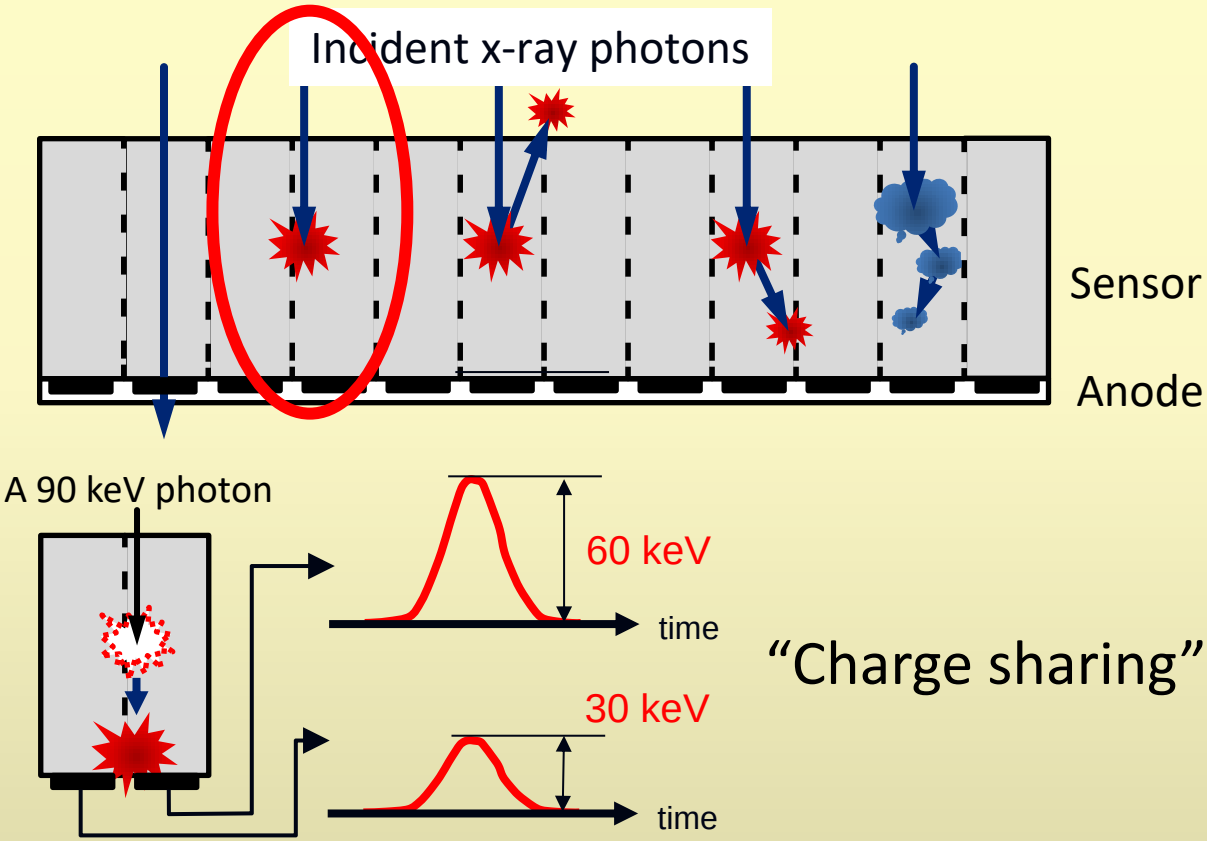
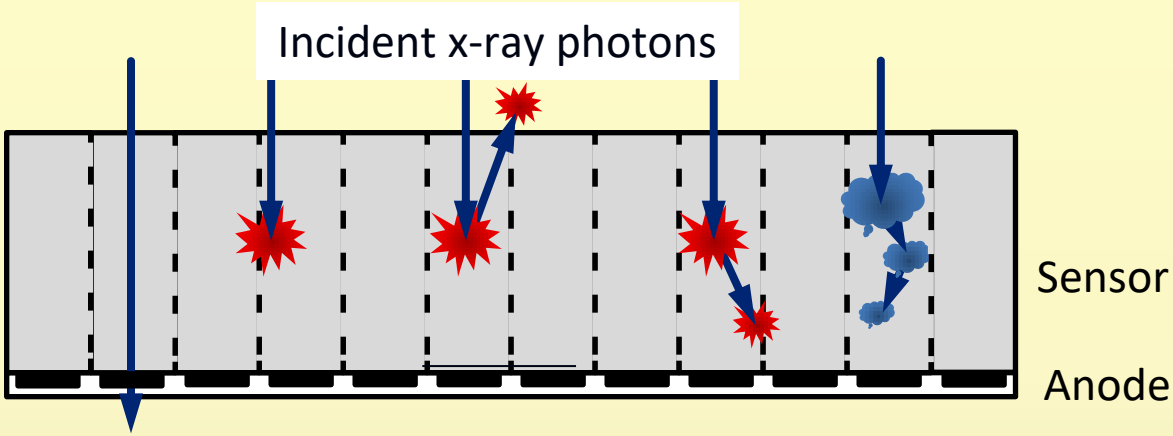
Backup slides

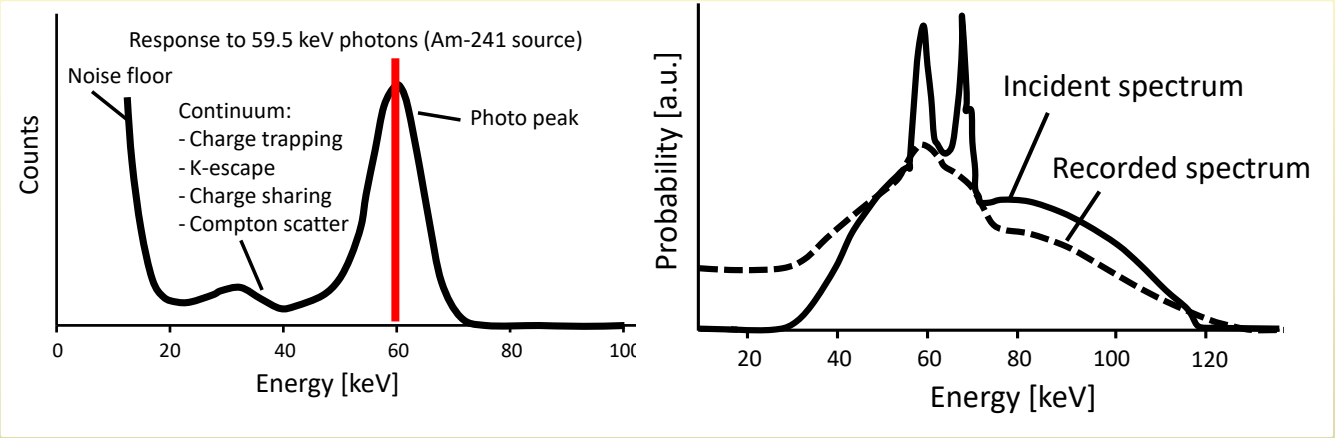
Spatio-energetic cross-talk



"Charge sharing"

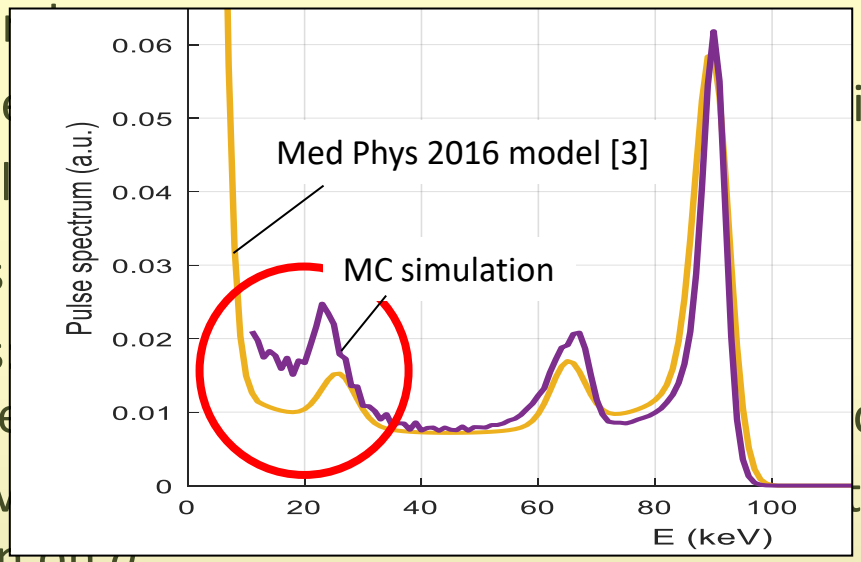
Spectral distortion





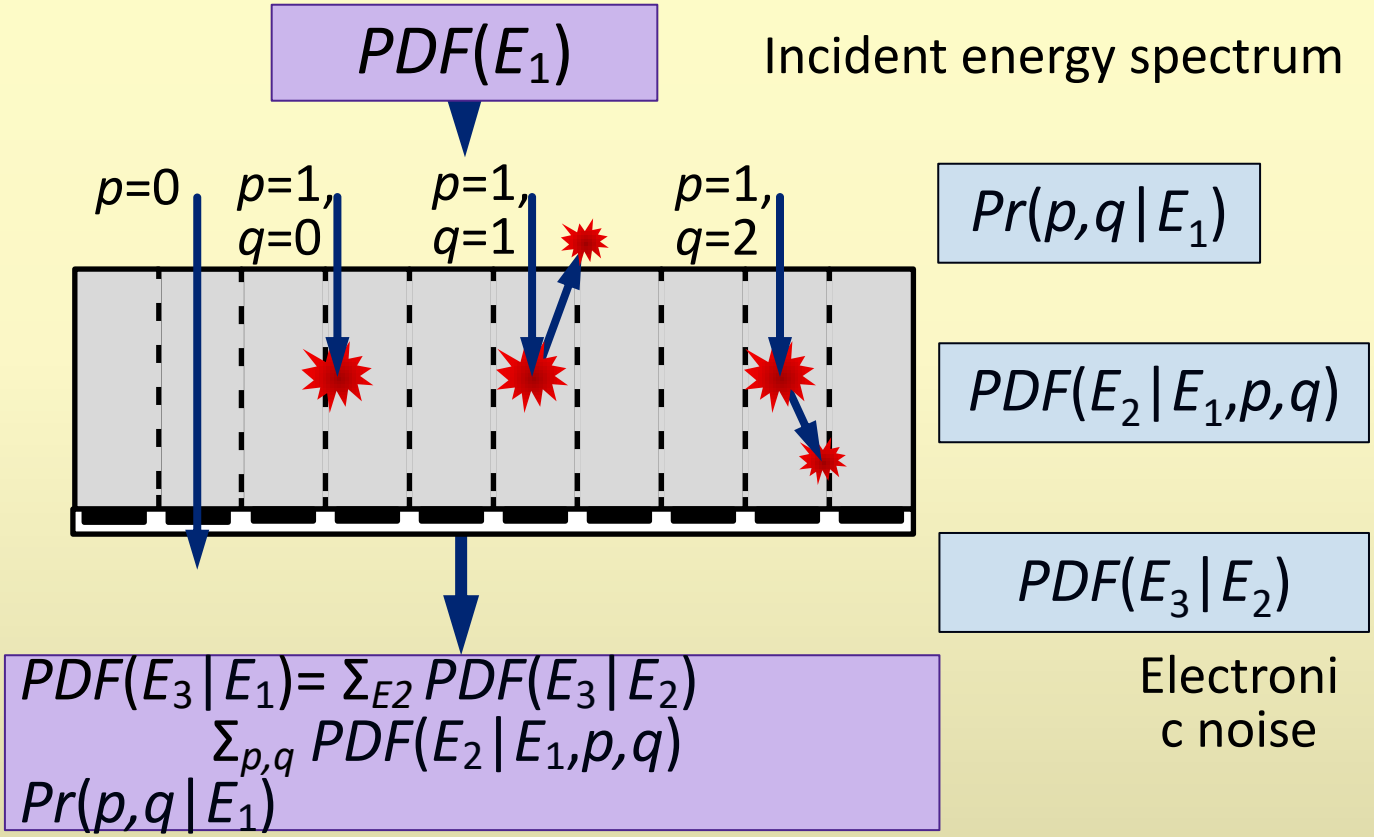
Problems and study aims

- Backgrou
- PCD mod is [1,2]
- Analytical
- Problems
- Problems
  (2) Charge counts at low energies
- Aims: Dev ting (with n>2) and no restriction on a_0



[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



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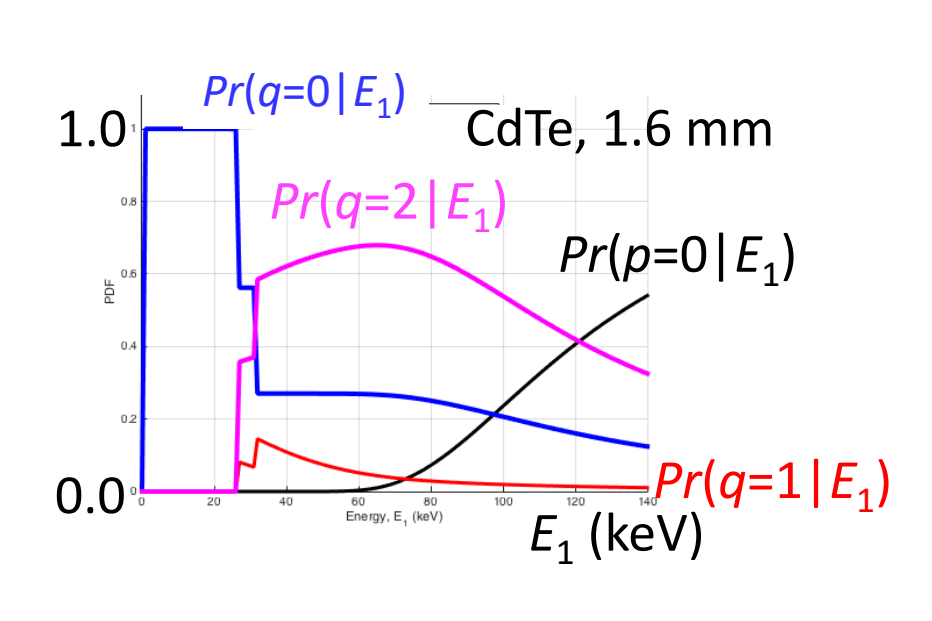


t energy spectrum

$Pr(p,q|E_1)$

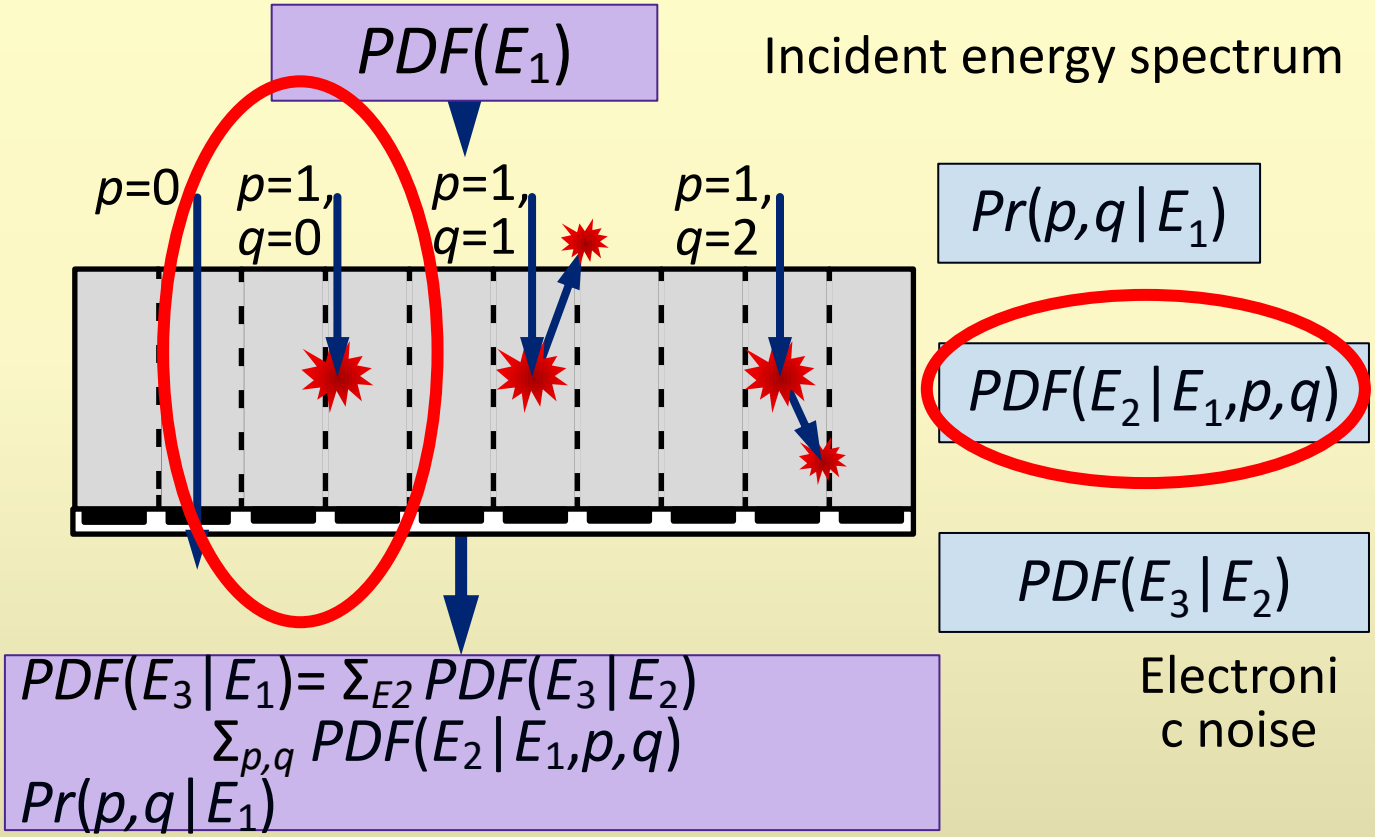
$PDF(E_2|E_1,p,q)$

$PDF(E_3|E_2)$

Electroni
c noise

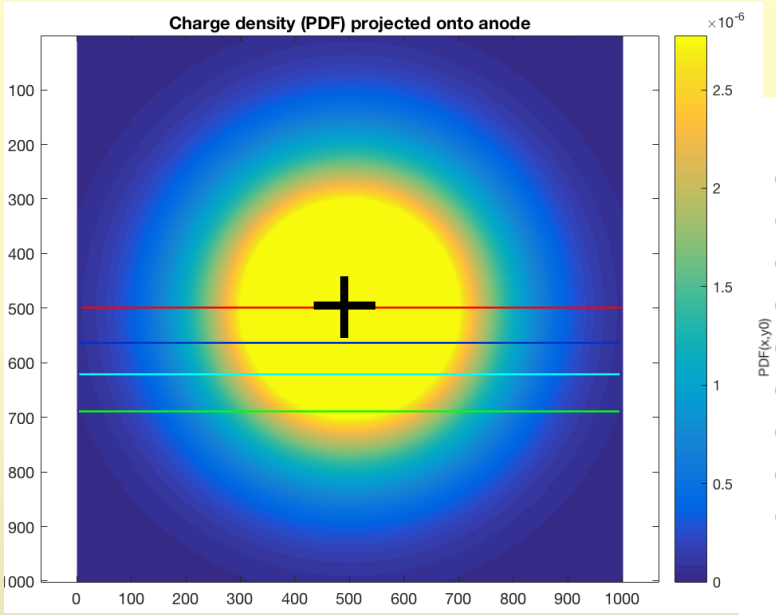
$PDF(E_3|E_1) = \Sigma_{E2}\, PDF(E_3|E_2)$
$\Sigma_{p,q}\, PDF(E_2|E_1,p,q)$
$Pr(p,q|E_1)$

Cascaded parallel systems model



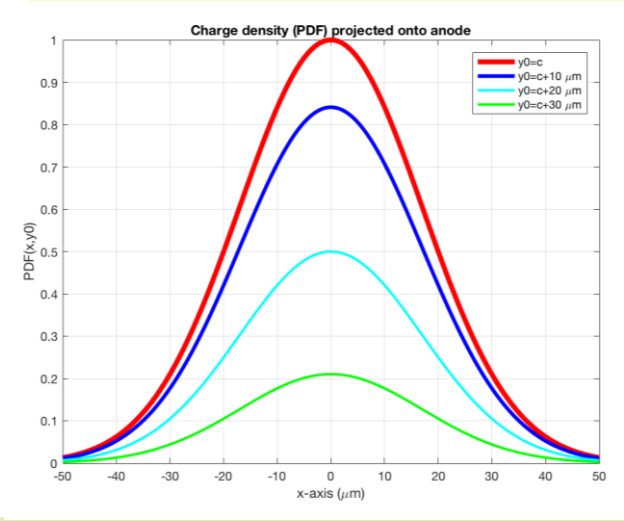
Charge density: 3D Gaussian

Charge density: $\rho_e(d_0)$

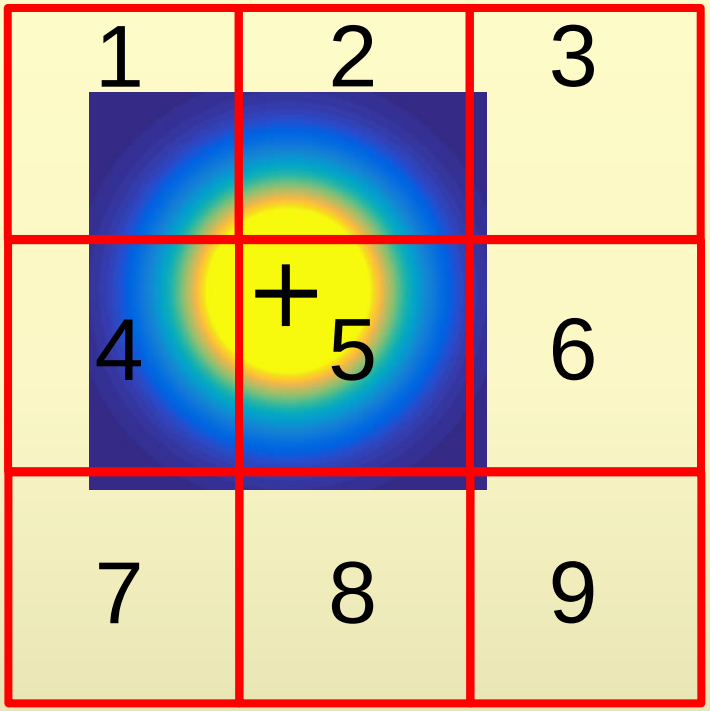


FWHM=d_0 (μm)

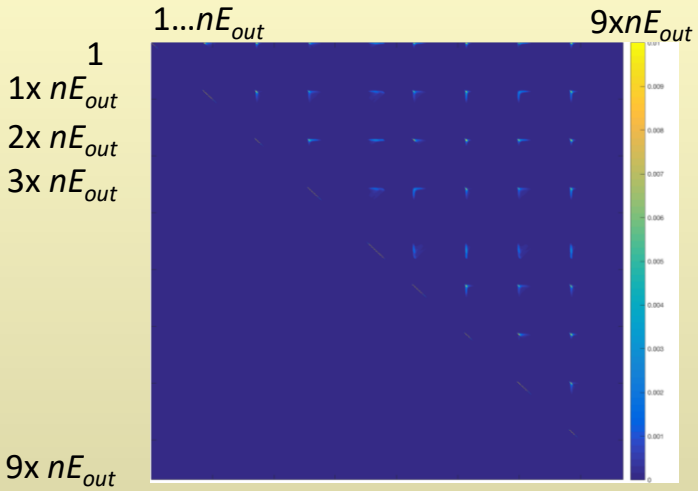
Independent of energy



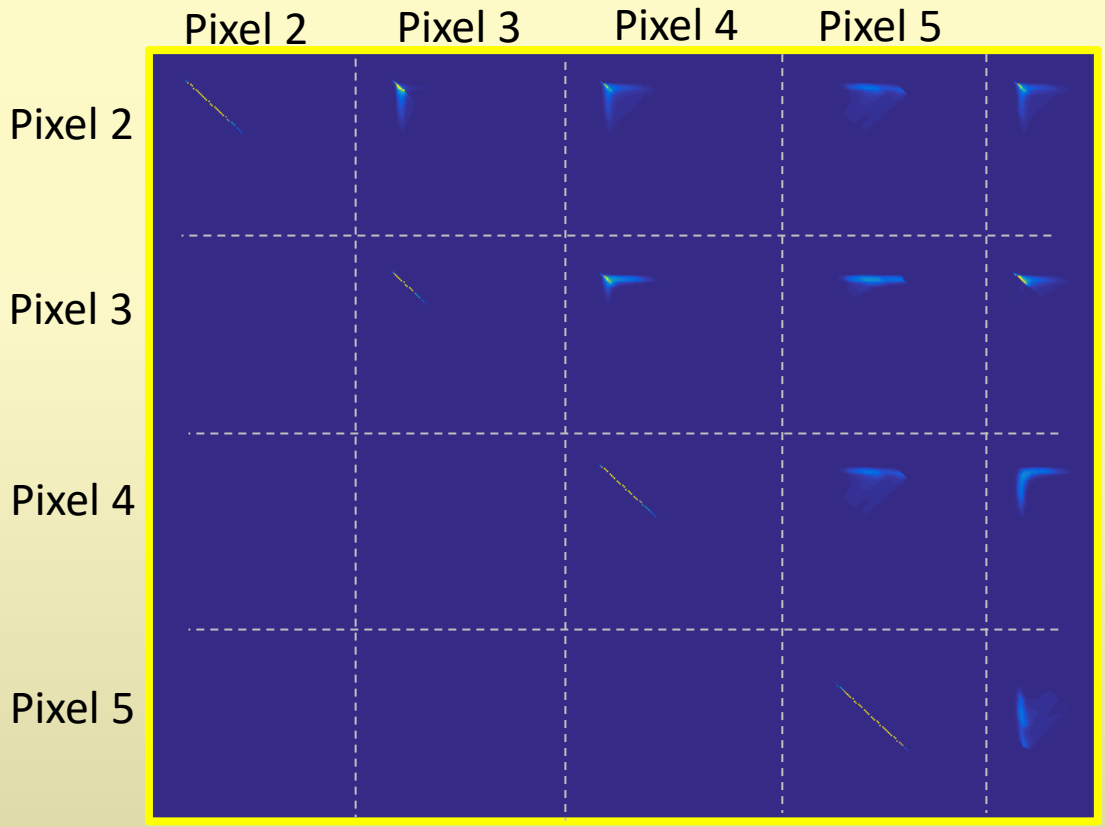
Charge sharing by 3x3 pixels



for energy E_1=1:150 keV
  energy density: $E_1 \rho_e$
  for incident location *i* at pixel 5
    E_j=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

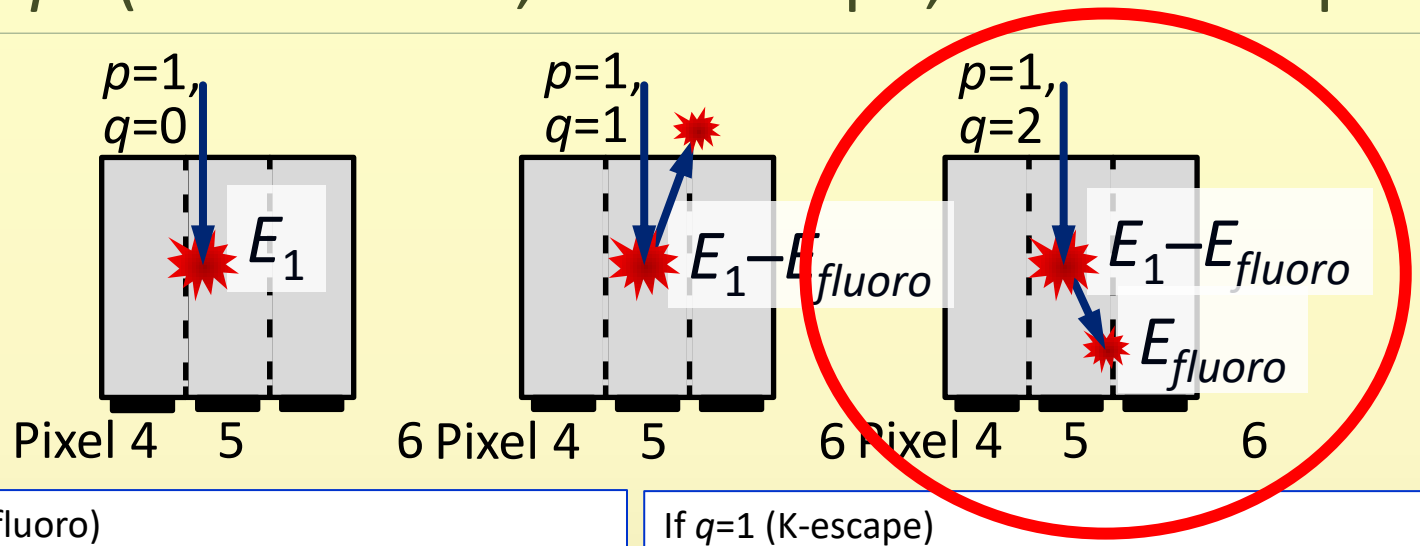


nCovE 3D matrix for recorded energy Ej=0…190 keV, j=1…9 pix, for incident energy E1=0…150 keV



1	2	3
4	5	6
7	8	9

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

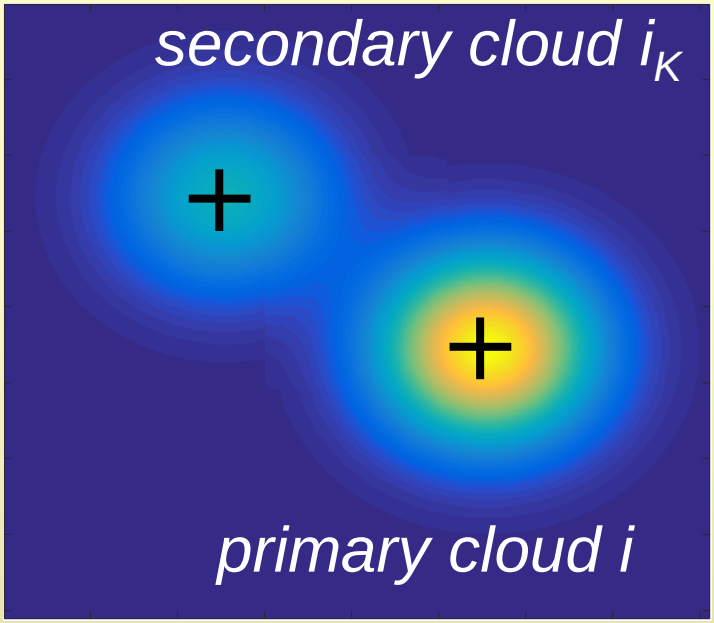


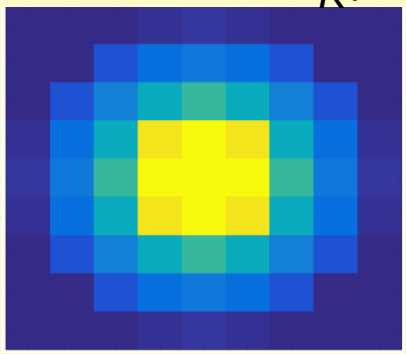
If q=0 (no fluoro)
for energy E_1=1:150 keV
  energy density: $E_1\ \rho_e$
  for incident location i at pixel 5
    E_j=integ[$E_1\rho_e$] for each pixel j
    add PMF(i) to covariance element
      $nCovE(k_j(E_j),k_{j'}(E_{j'}),\ E_1)$
  next location i
next energy E_1

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=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

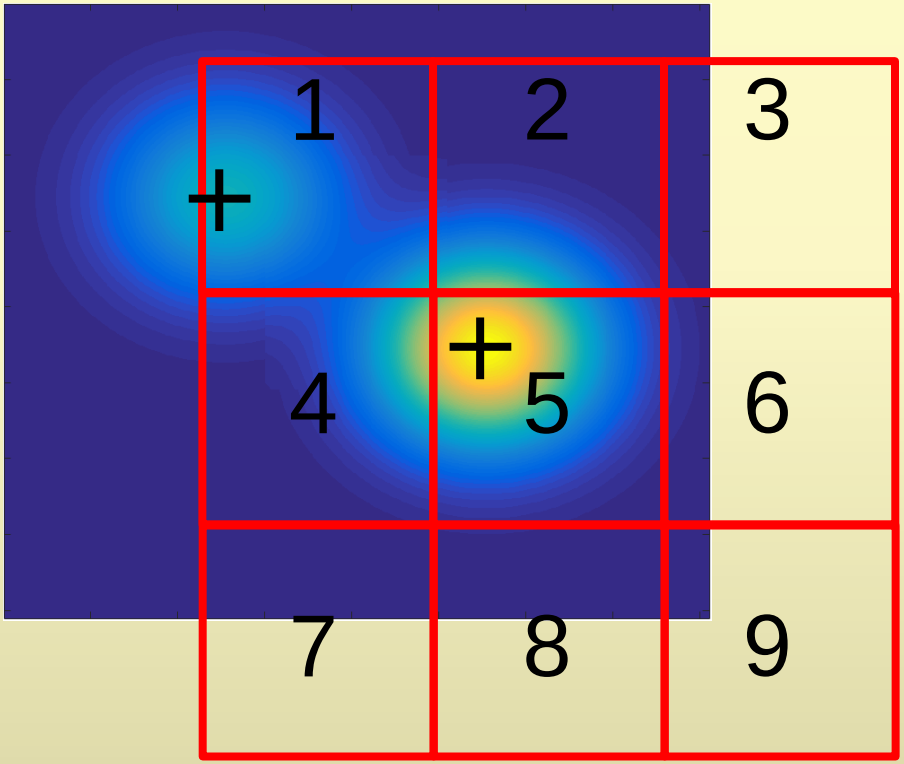
Relative location of i_K, $PMF(i_K)$

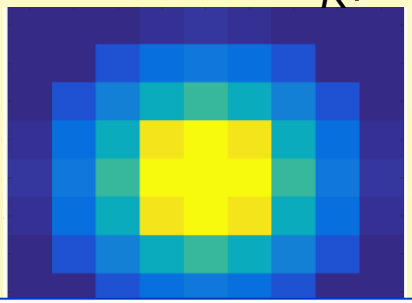




Charge sharing with 2 charge clouds

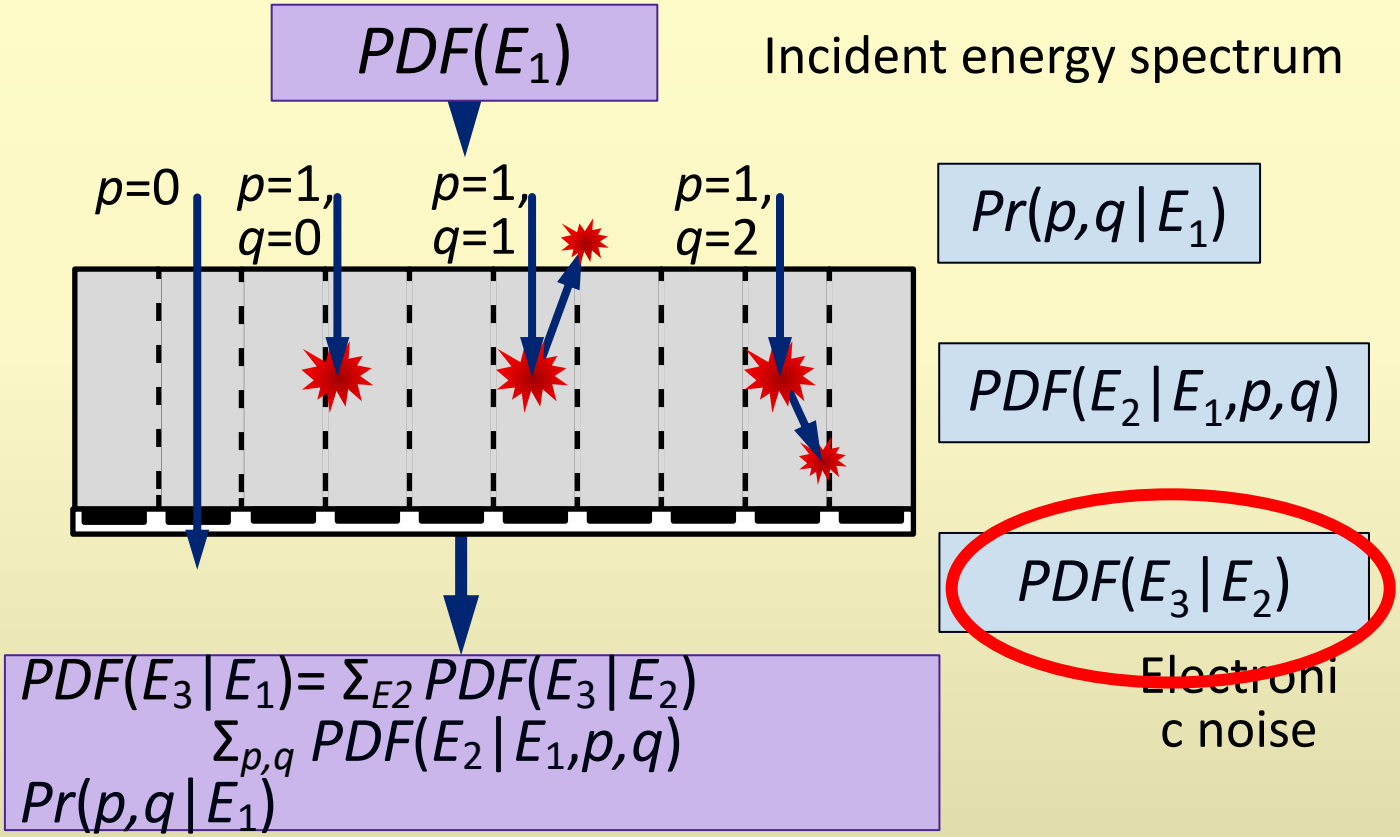
Relative location of i_K, $PMF(i_K)$





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=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

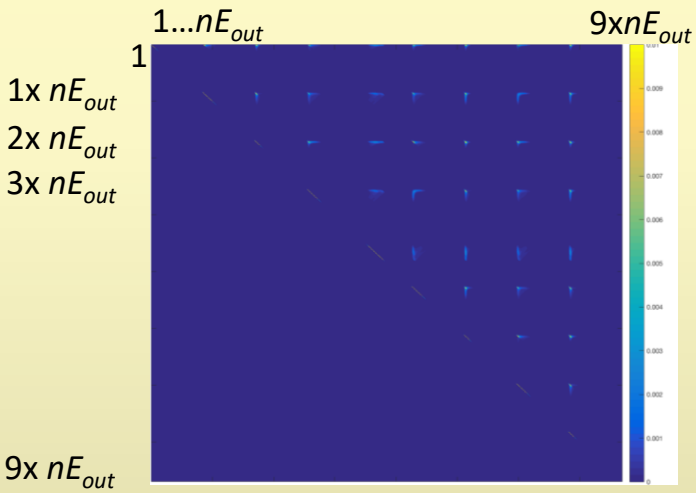
Cascaded parallel systems model



Correlated noisy PCD data generator

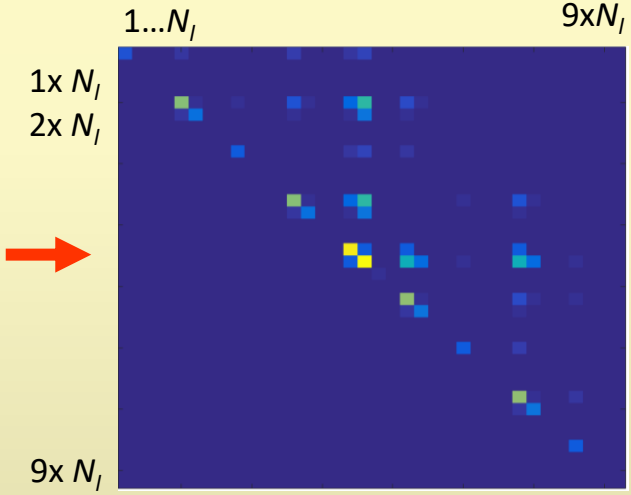
Normalized covariance matrix for 1-keV bins, 3x3 pixels

nCovE(9xnE_{out}, 9xnE_{out}, nE_{in})



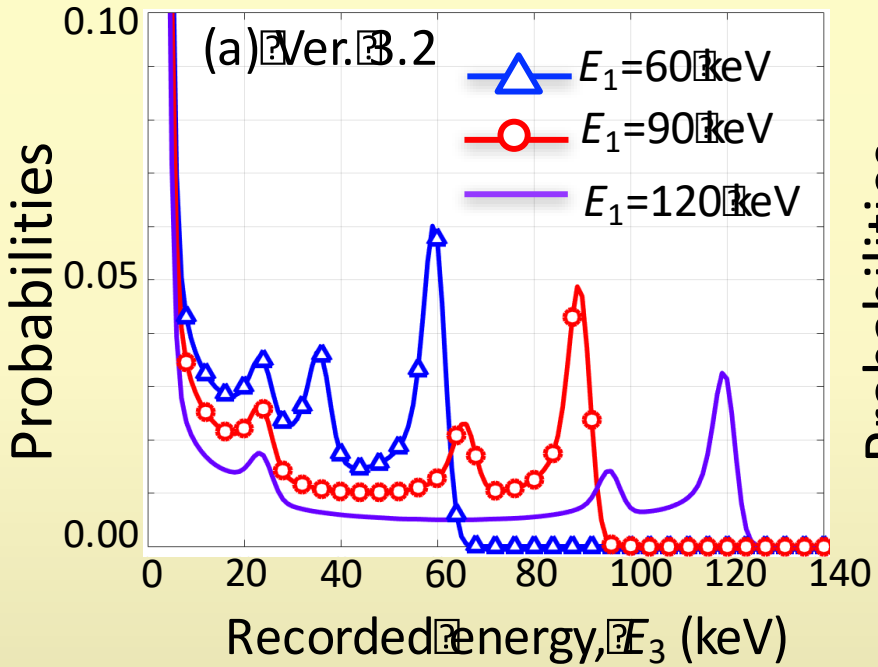
Normalized covariance matrix for N_I bins, 3x3 pixels

nCovBin(9xN_I, 9xN_I, nE_{in})

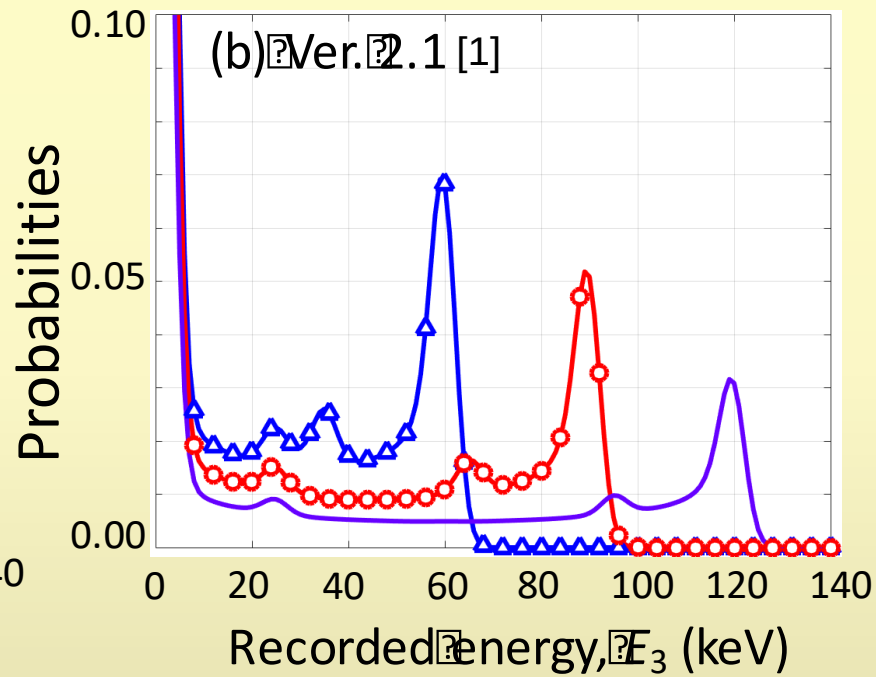


1	2	3
4	5	6
7	8	9

Results (1): Various input energies (E_1)

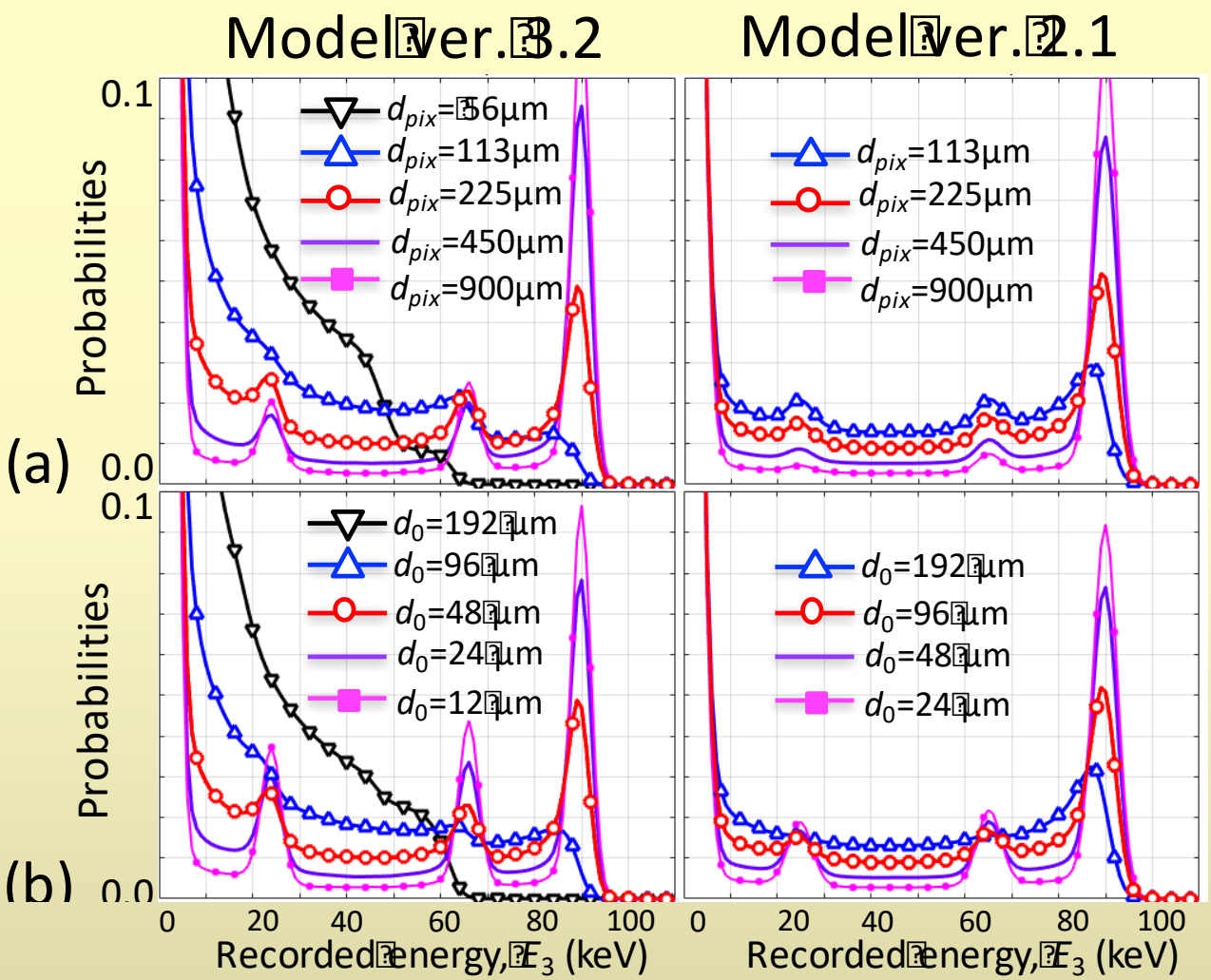


CdTe, (225 μm)^2 x 1.6 mm
FWHM of charge cloud size=Ø48 μm
Electronic noise = 2.0 keV



CdTe, (225 μm)^2 x 1.6 mm
FWHM of charge cloud size=Ø96 μm
Electronic noise = 2.5 keV

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



<u>Default settings</u>

CdTe, 1.6 mm

Pixel size (d_{pix}): 225 µm

Charge cloud size (d_0):

Ø48 µm (v3.2)

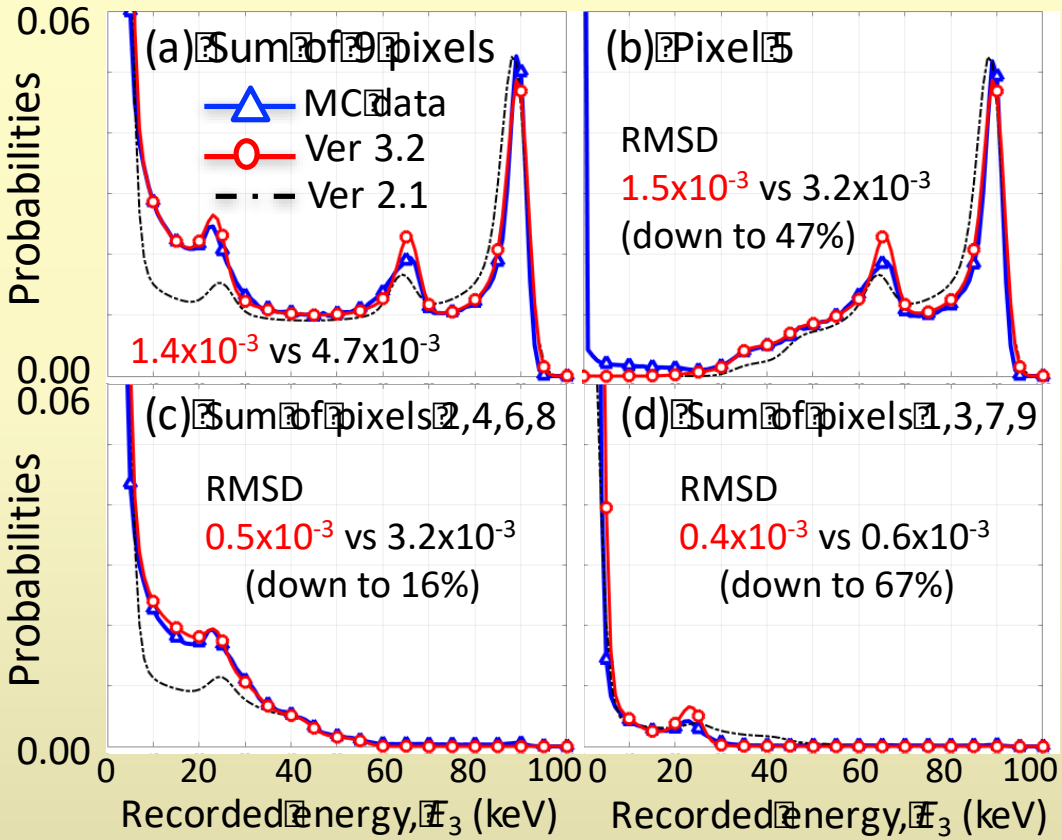
Ø96 µm (v2.1)

Electronic noise:

2.0 keV (v3.2)

2.5 keV (v2.1)

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



1	2	3
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<u>Default settings</u>

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2.5 keV (v2.1)

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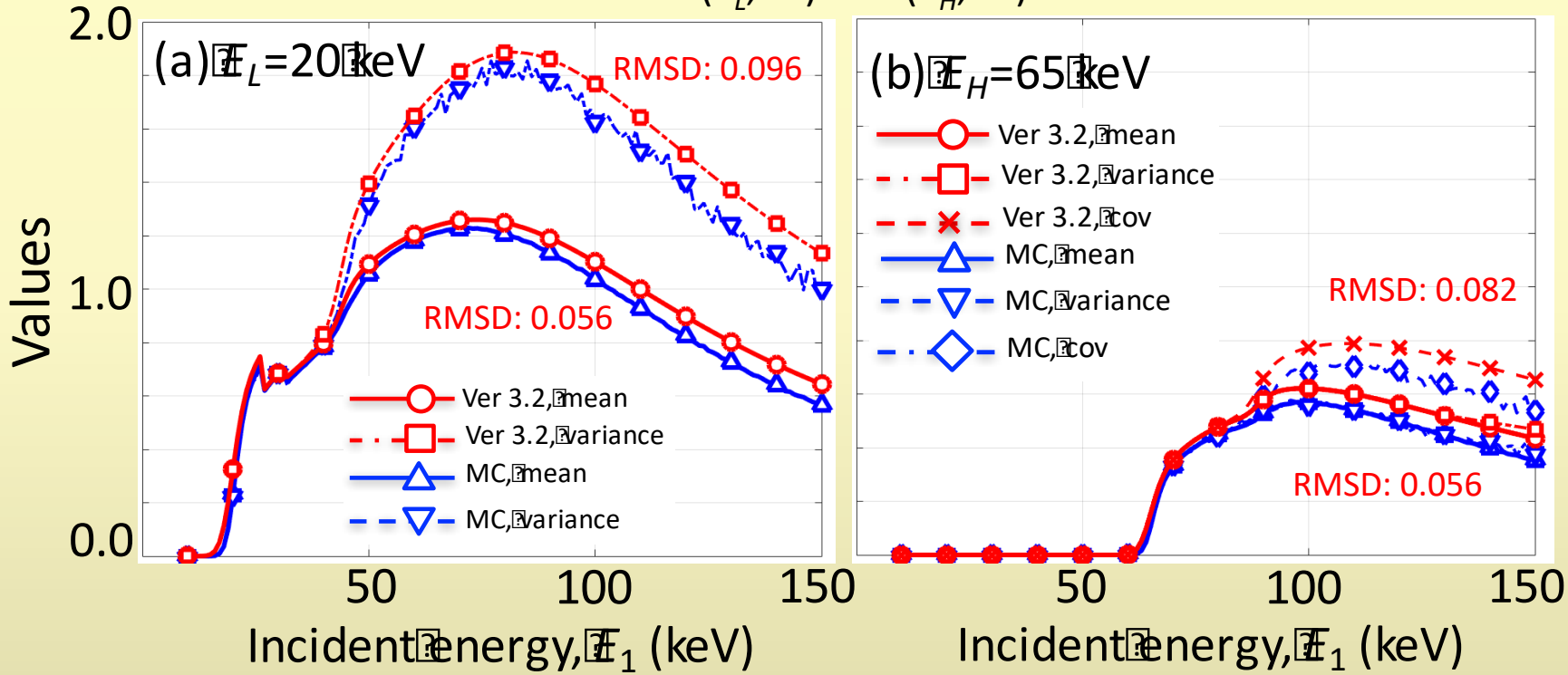
Results (4): Mean/var/cov vs MC sim.[1]

Threshold data: (E_L, ∞) and (E_H, ∞)



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