Medical Imaging with Ionising Radiaton

- X-ray
  - Plane Radiography
  - CT
  - DEXA – Bone Desitometry etc.
- Nuclear Medicine
  - PET
  - SPECT

Detectors

- X-ray
  - Integrating detectors
    - Film, film screen; photo stimulable phosphors; image intensifiers; TFT arrays (selenium and CsI); gas detectors; crystalline ceramics
  - Good spatial resolution
  - No spectral resolution
- Nuclear Medicine
  - Counting detectors
    - Scintillators (NaI(Tl); BGO; LSO….)
    - Gas counters with converters
  - Relatively poor spatial resolution
  - Very poor spectral resolution

Detector

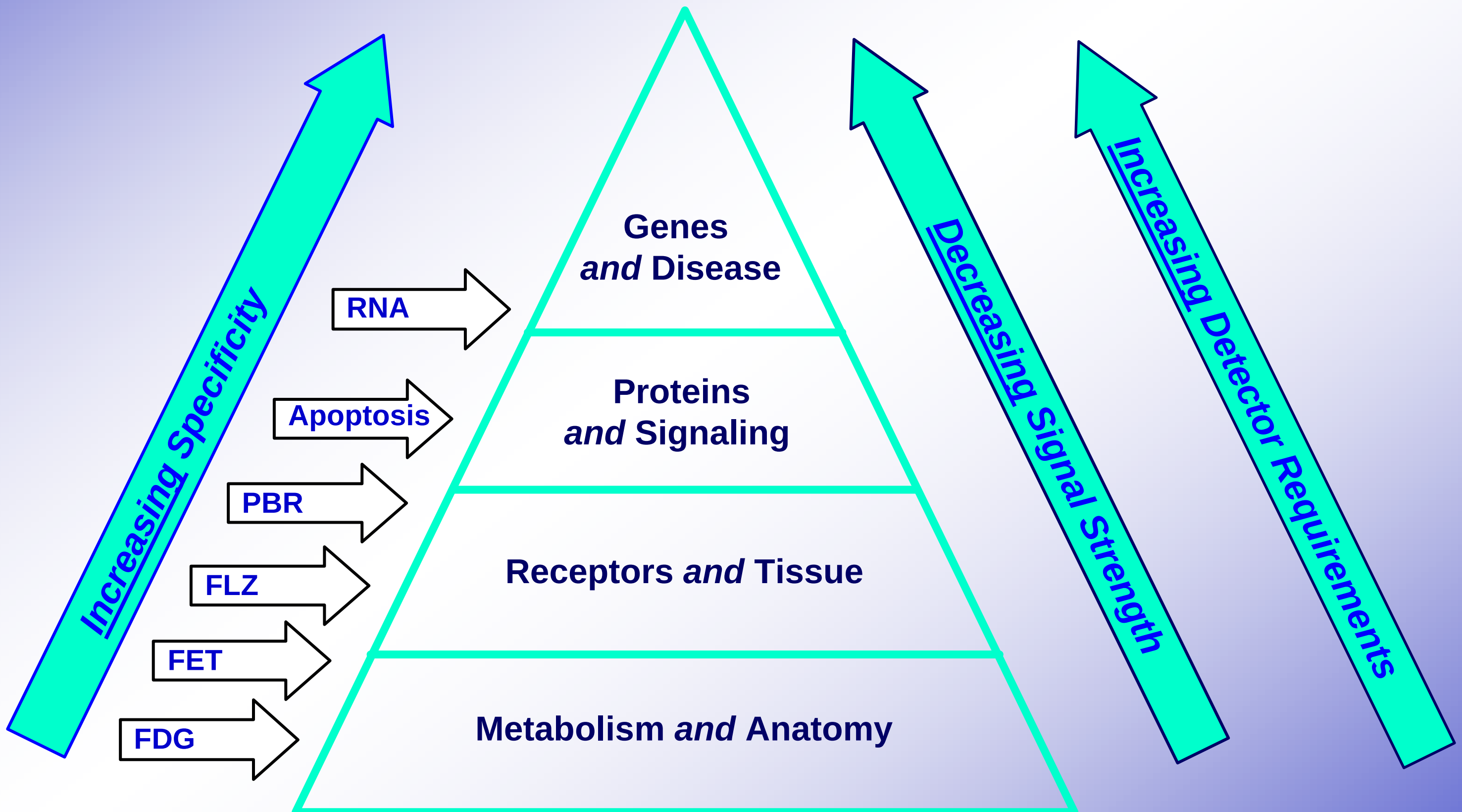
- We are on the verge of a major change in detector characteristics
- Multi-electrode HPGe detectors offer:
  - Excellent spectral resolution (<1% fwhm) and
  - 3D position resolution
- Pixel detectors potentially offer:
  - Imaging at 100μm resolution whilst photon counting
  - Spectral resolution
- Traditional spectroscopic devices have gained spatial resolution and imaging detectors have gained spectral resolution

CRC in Biomedical Imaging

- IBM
  - Access to 90nm fabrication process
- GE Healthcare
  - Medical Imaging
  - Monash Clinical Imaging Centre a Luminary Site
    - Mayo Clinic, UCSD, UCSF, University of Illinois, Tokyo University
- Cyclotek and Berthold Australia
  - Detector technology and radiation monitoring
- Monash University
  - Detector Physics
- Budget
  - More than AU$80M: Half for detectors

The Technical Challenge

Paradoxically, the better the tracer the harder it is to "see" it



Functional and Traditional (X-ray) Imaging

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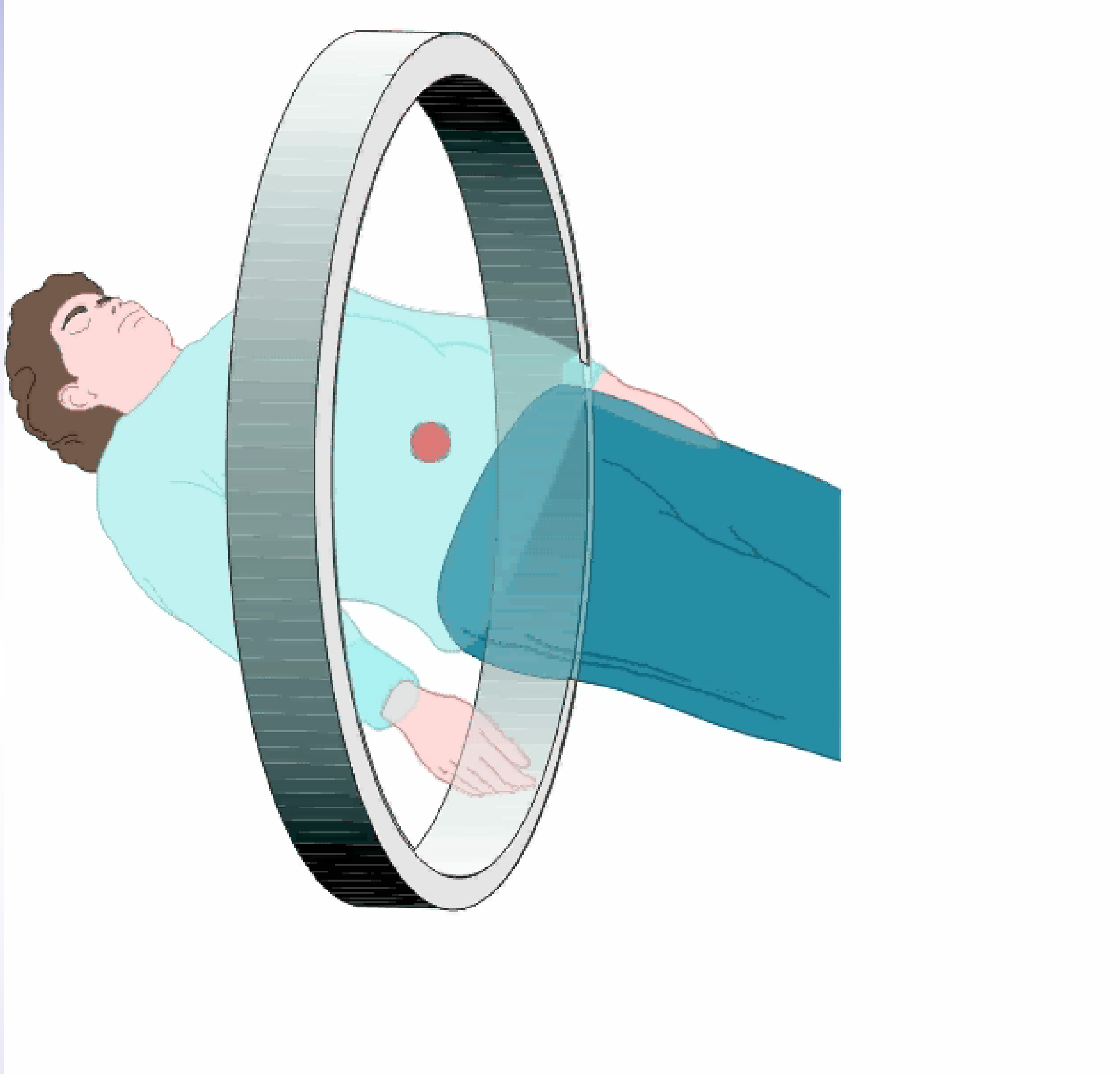
Detector Projects

- High spectral resolution detectors for PET
- Pixel devices for radiography

Positron Emission Tomography

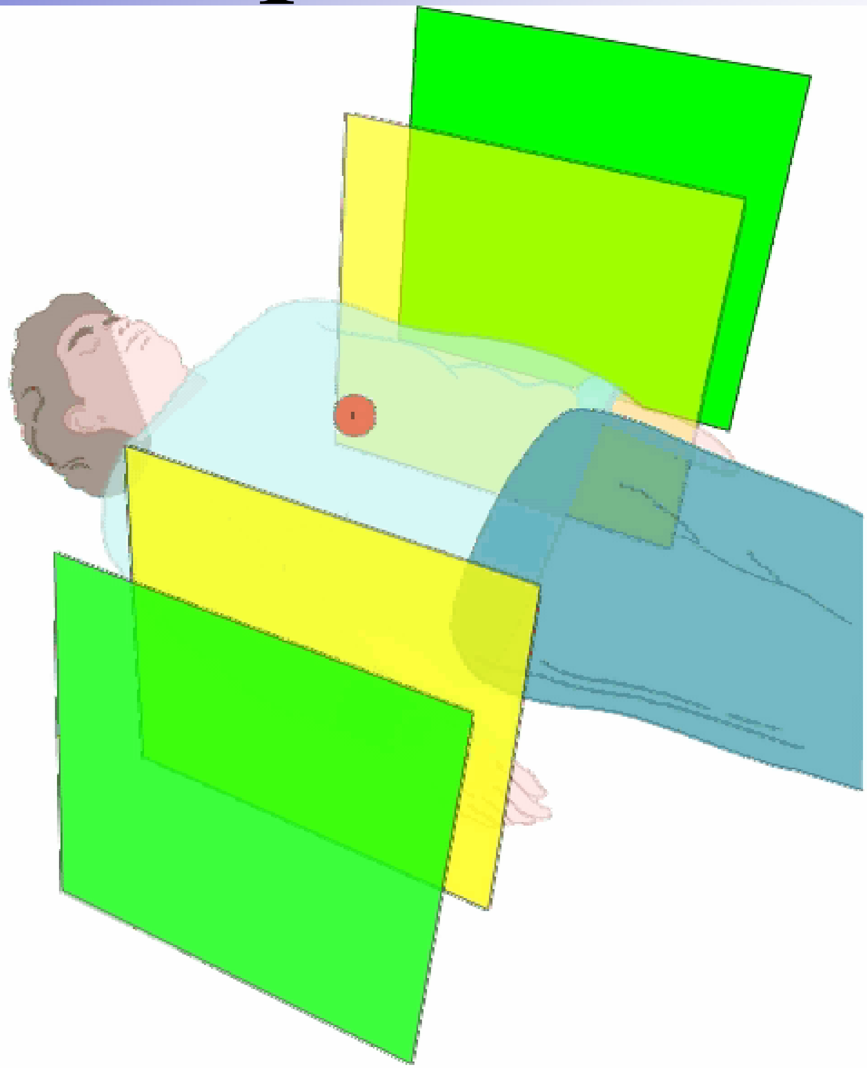
- Introduce a compound labelled with a positron emitter into body
- Positrons annihilate with electrons to produce two 511keV back to back gamma rays
- Detect both gamma rays
- Join the dots >>> inherent tomography



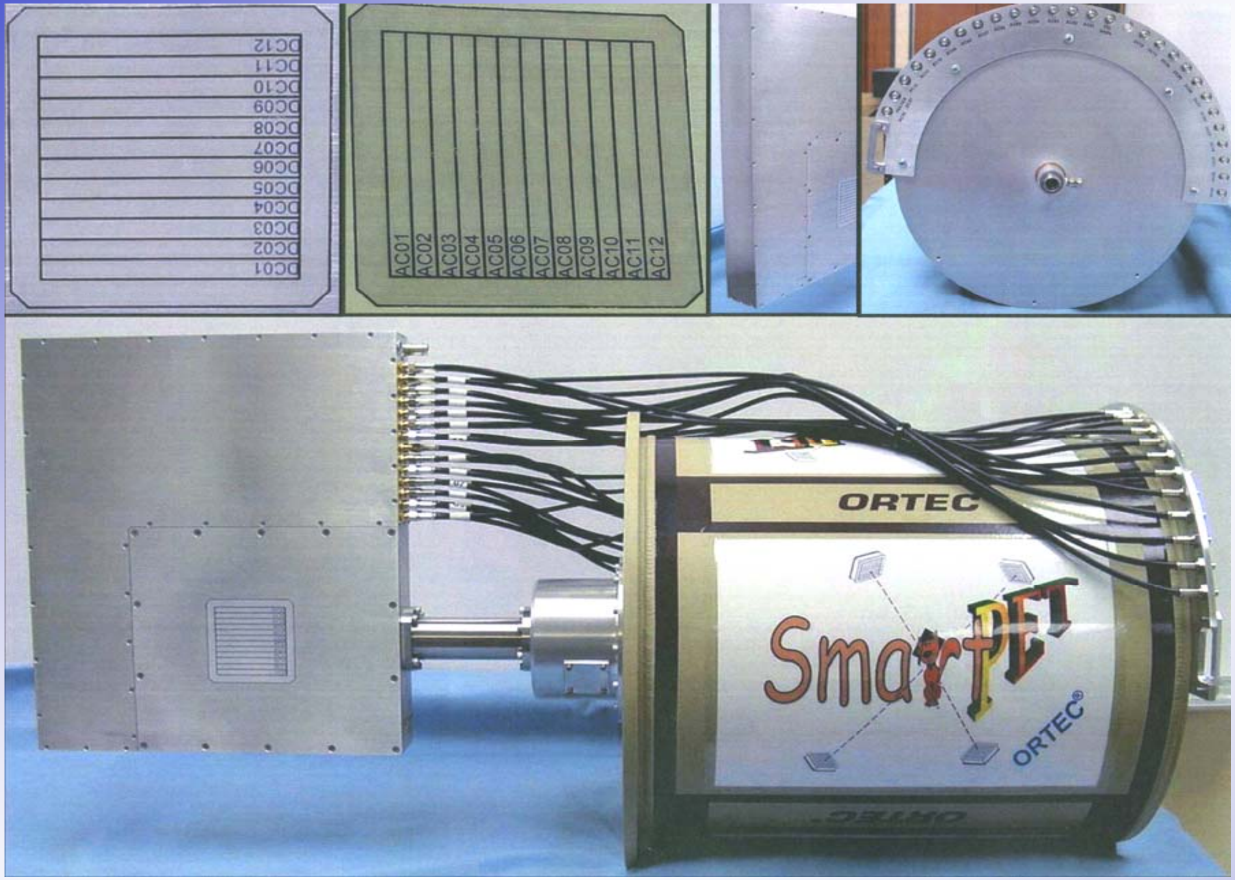
Planar HPGe

- Spatial resolution <1mm
- Spectral resolution < 1%
- Compared to existing systems
  - ✓ Spectral resolution much improved
  - ✓ Spatial resolution improved
  - ✗ Pulse Length Longer
    - Time of arrival information less accurate
    - Counting rate capability lower
  - ✗ Absorption efficiency lower
- BUT
  - ♦ Combination of position and spatial resolution allows use of Compton kinematics

PET Compton



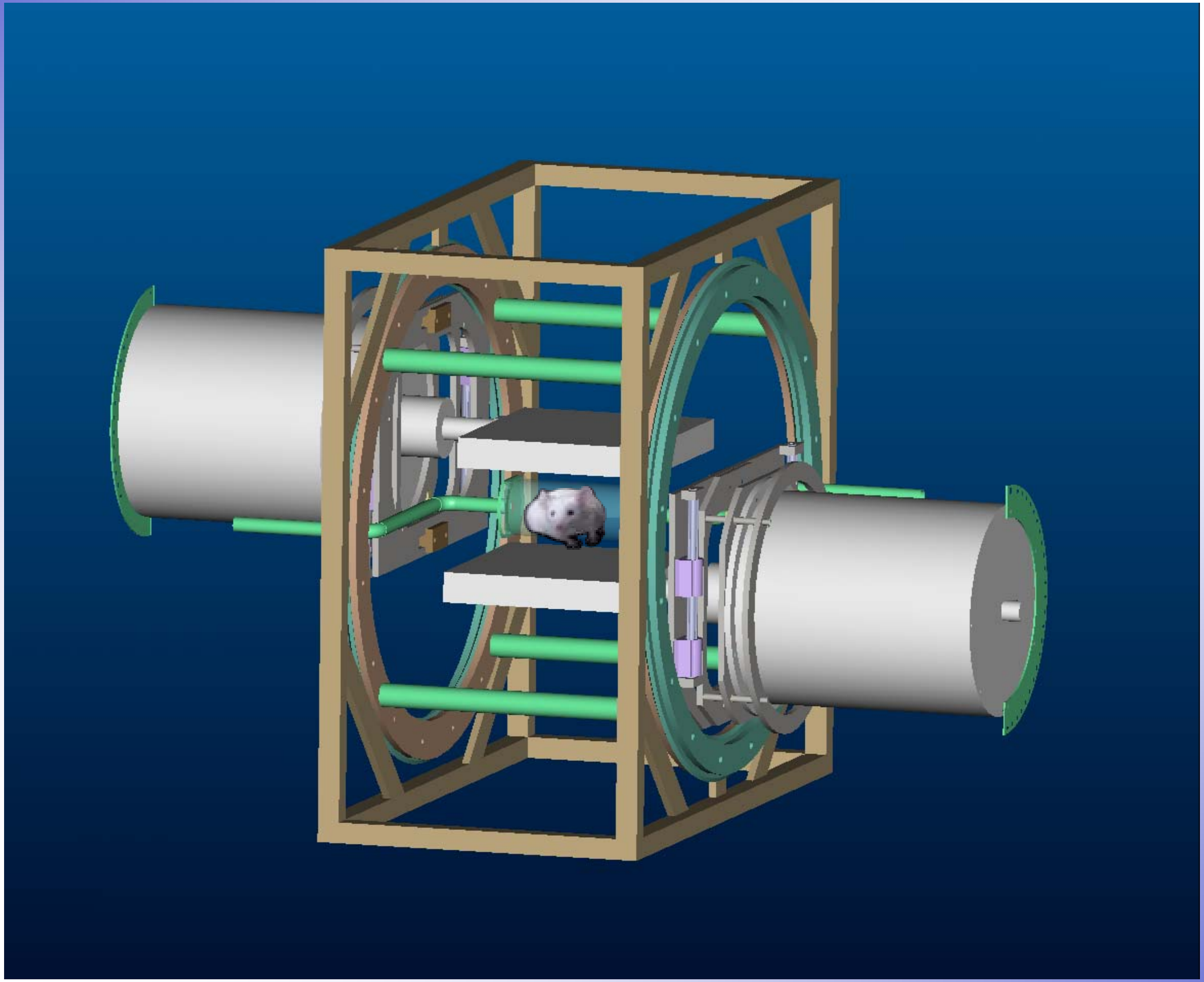
The SmartPET



- Only one detector on each side
- 60x60x20mm
- 12 strips each side
- 3D spatial resolution

University of Liverpool, Physics Department
CLRC Daresbury Laboratory
Monash University, School of Physics

SmartPET Gantry



Is Germanium technology useful in PET?

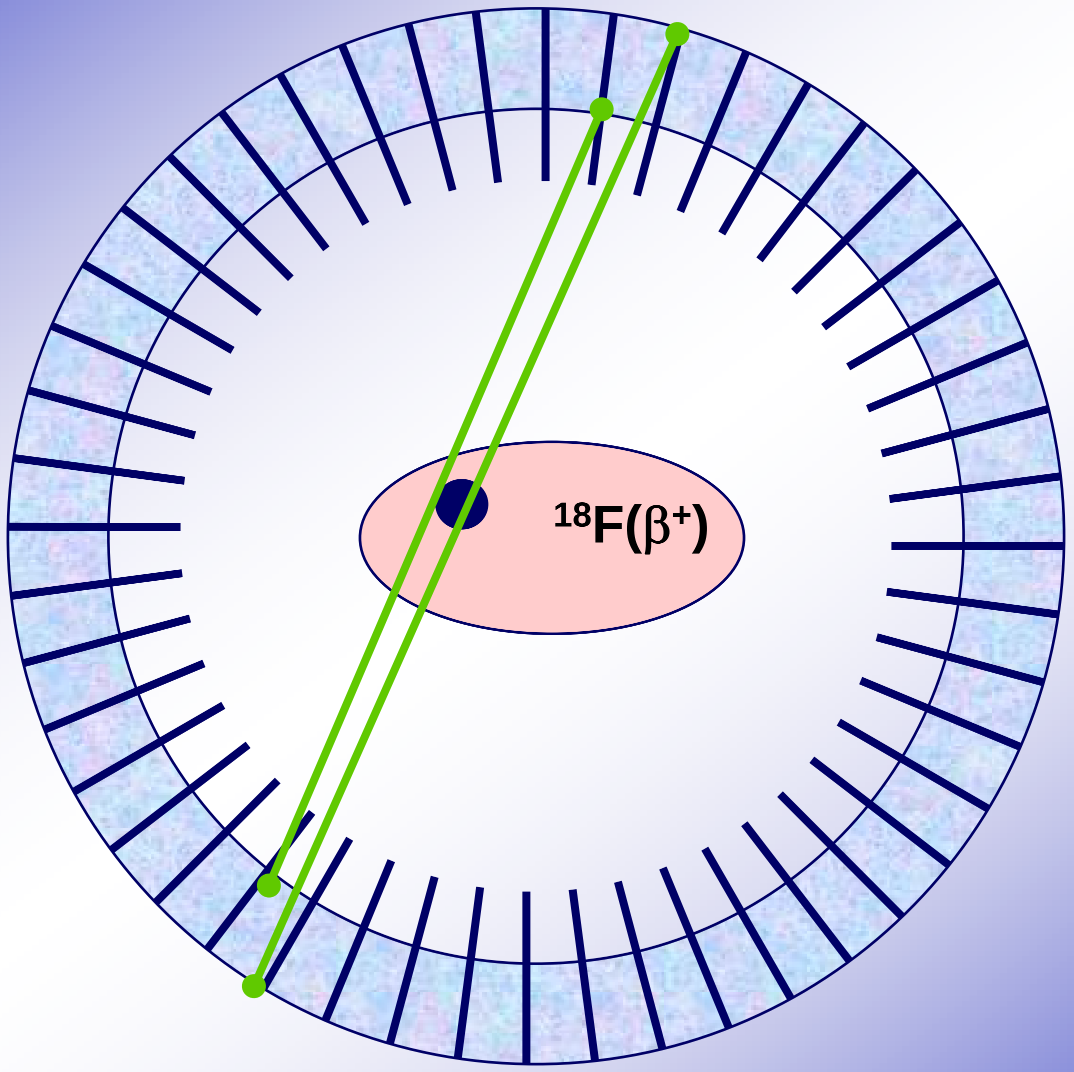
- Relationship between detector performance and system performance is not obvious

- Which parameters matter and how?

PET Problems Potentially Soluble

- Parallax Error
- Scatter in patient/animal
  - Good spectral resolution Can be detected by measuring incident energy
- Scatter in detector
  - Detected by sensitivity to multiple interactions
  - Nb. Effect on position measurement
- Random noise
  - Can be reduced by good time resolution

Parallax Error PET Camera

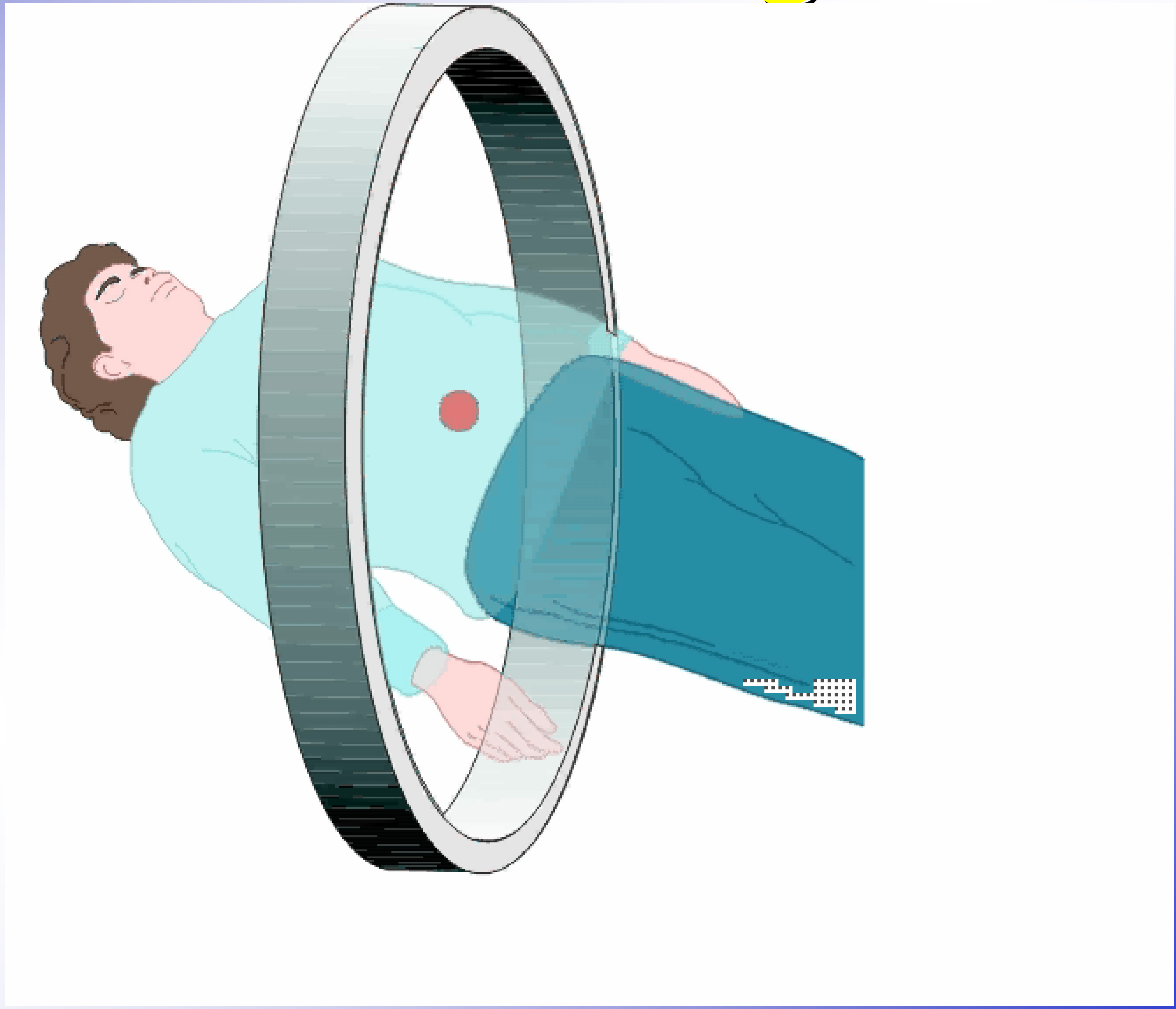


20/30mm BGO

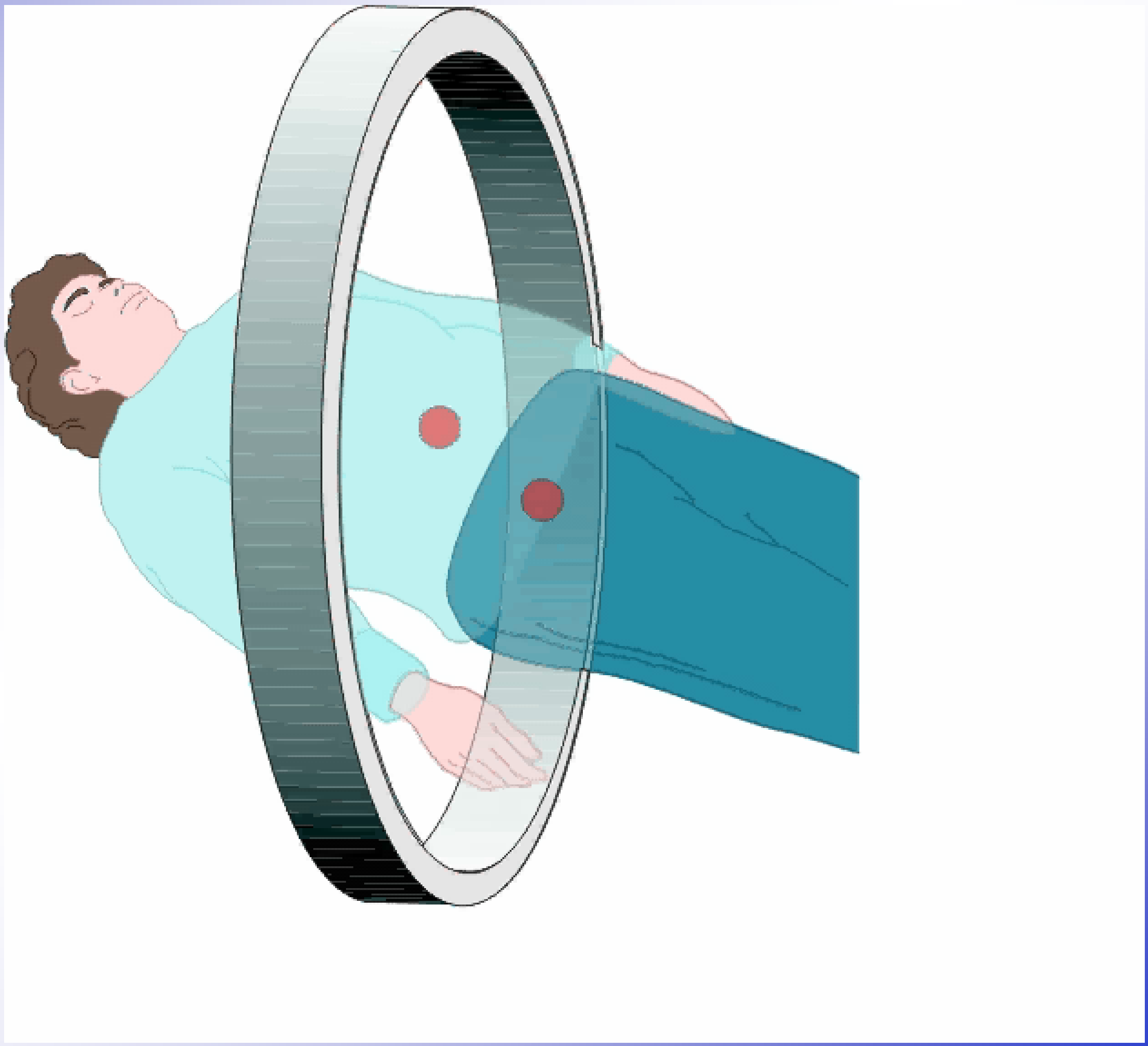
Parallax Error

- Planar HPGe devices give depth of interaction as well as x-y position
- In principle parallax error is much reduced

PET Bad Events 1: Singles



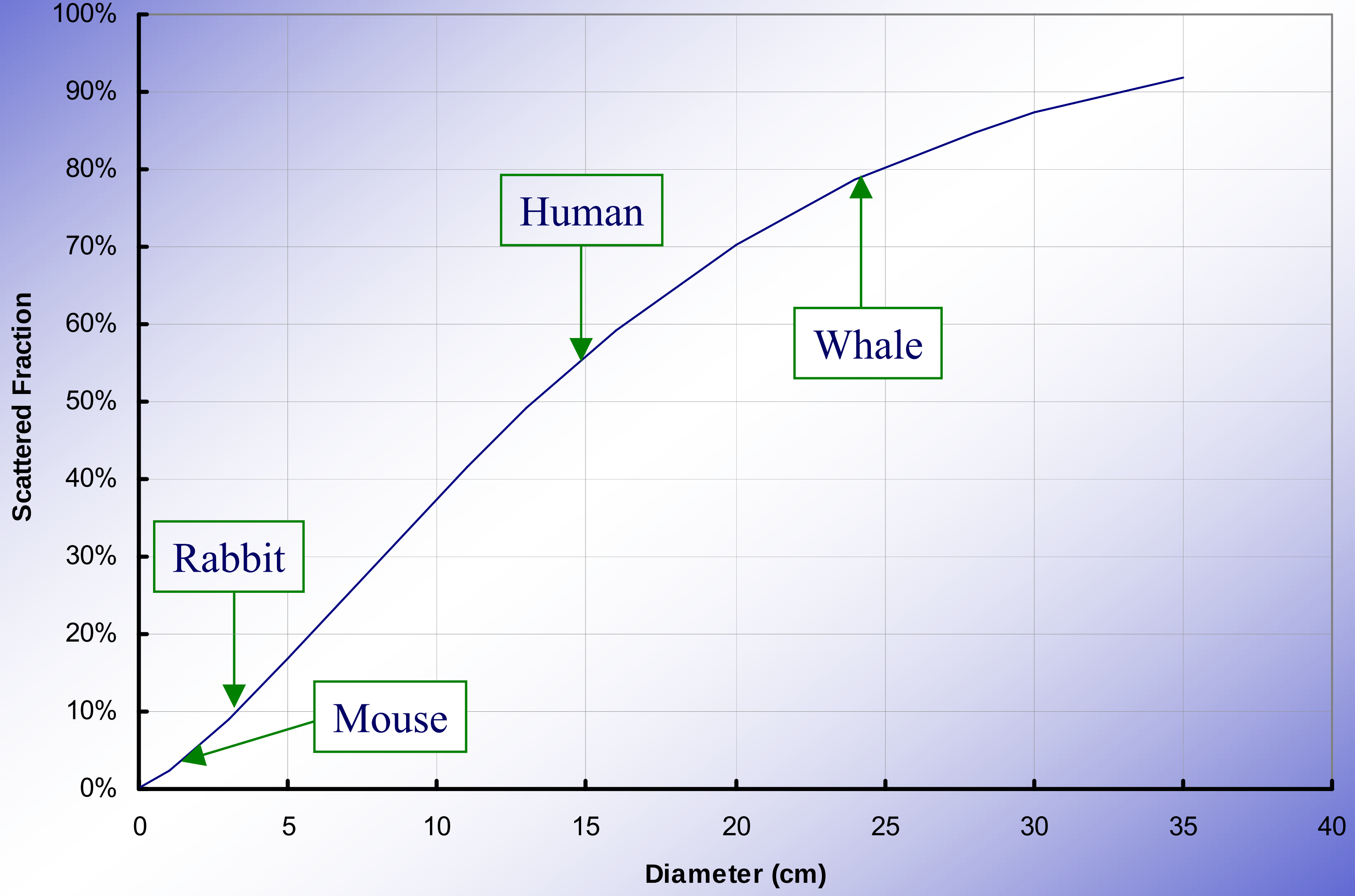
PET Bad Events 2: False LORs



Scatter in Patient or Animal

- How bad is scatter?
- Scatter fraction
  - 2D mode: 8-12%
  - 3D mode: 40-50%
- How bad is scatter?
  - Almost all PET is 2D
  - 3-4 times loss in sensitivity outweighed by improved image quality

Scatter Fraction as f(object size)



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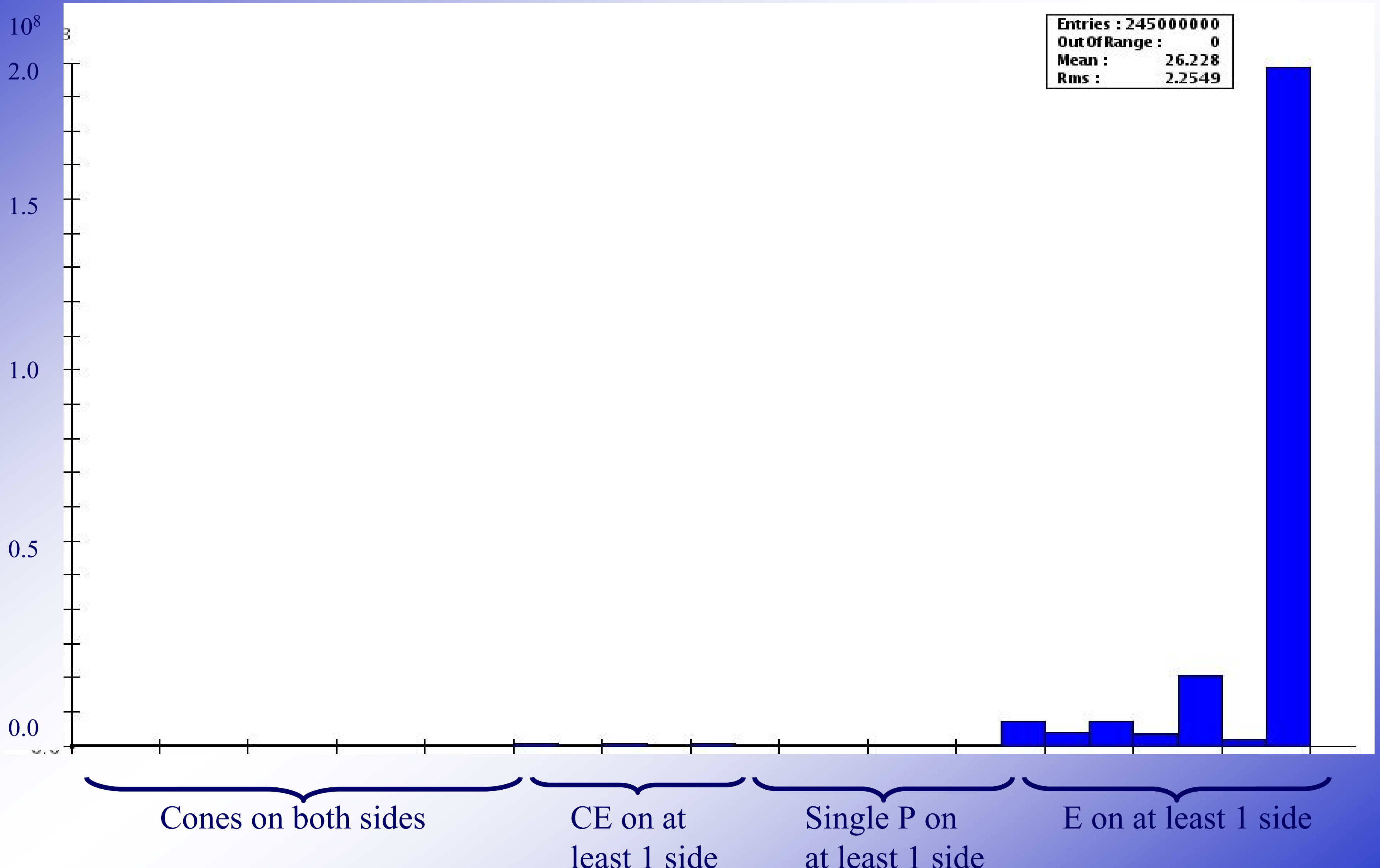
Scatter in Patient or Animal

- In small animal PET the ability to detect scatter is probably not an issue
- In human PET the ability to detect scatter is important

Scatter within Detector

- Is it a problem?
- GEANT 4 simulatons

Isotropic Source



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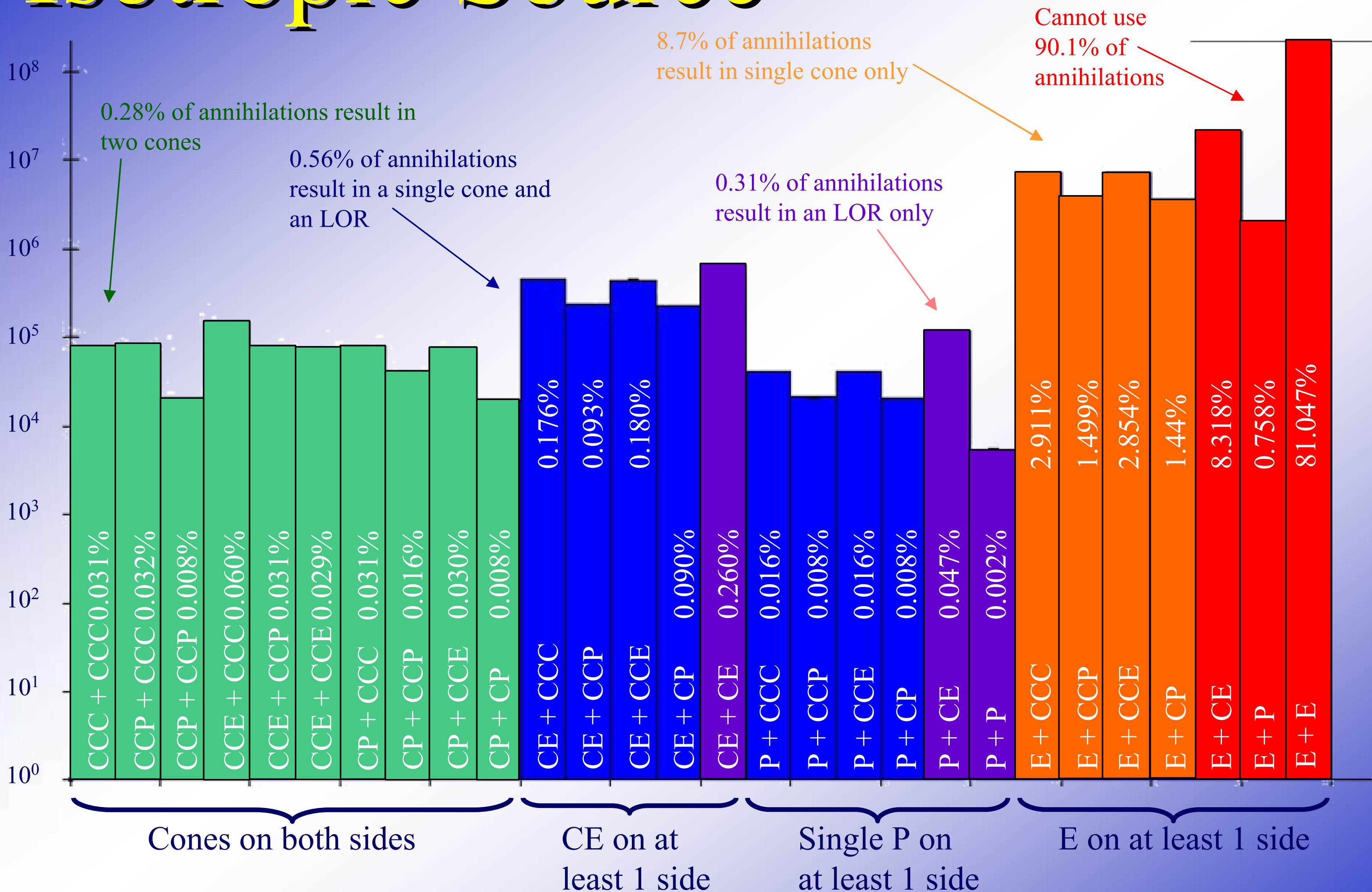
Isotropic Source



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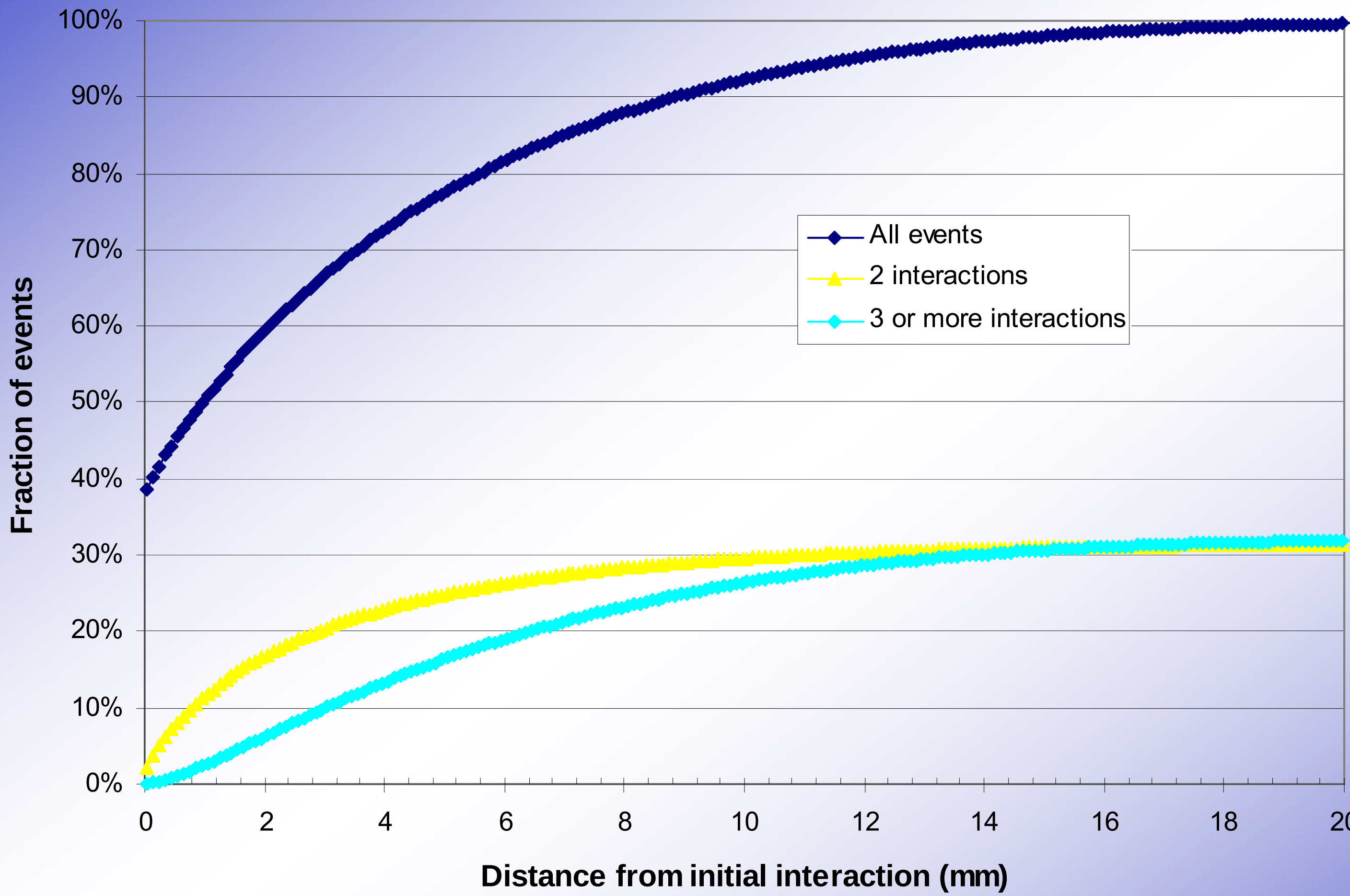
E=Escape; P=Photoelectric; C=Compton

Centroid of Energy vs Distance



511keV photons

50% of events deposit an energy centroid more than 1mm away from correct position

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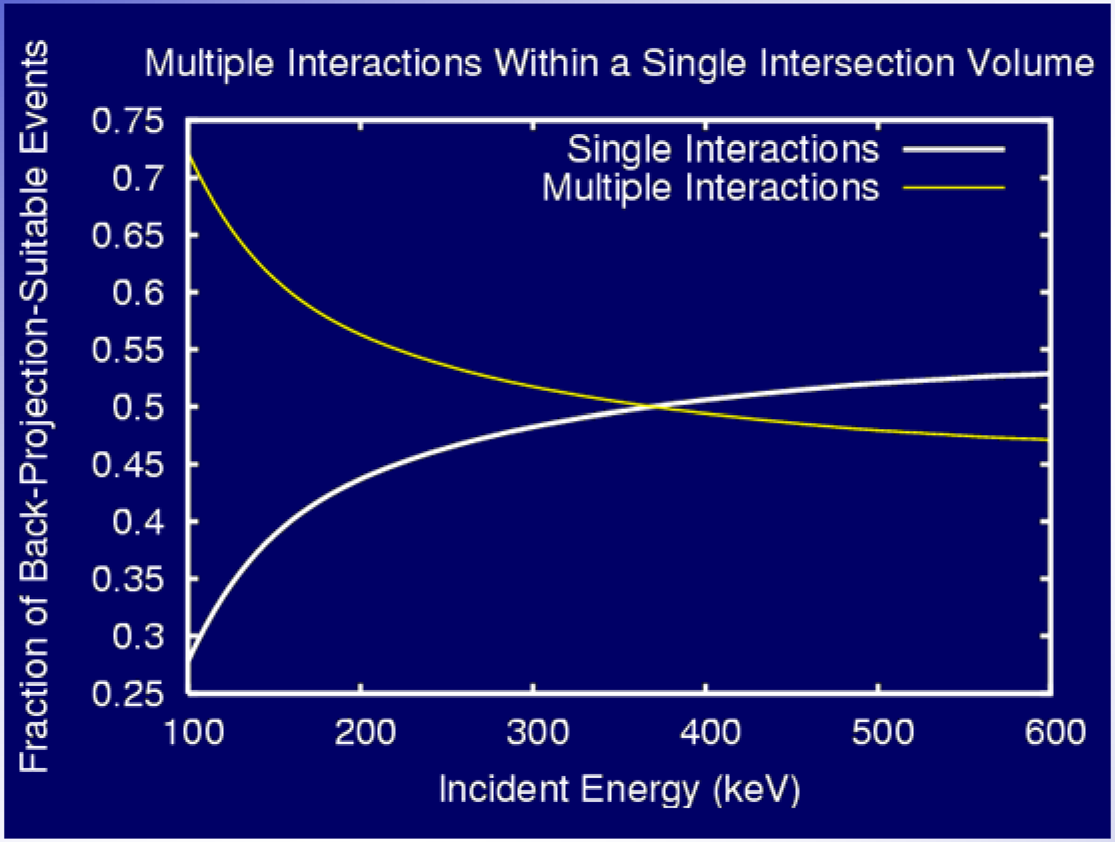
Scatter in Germanium

- 50% of events deposit an energy centroid more than 1mm away from correct position
- How can we detect this?
  - Energy resolution?

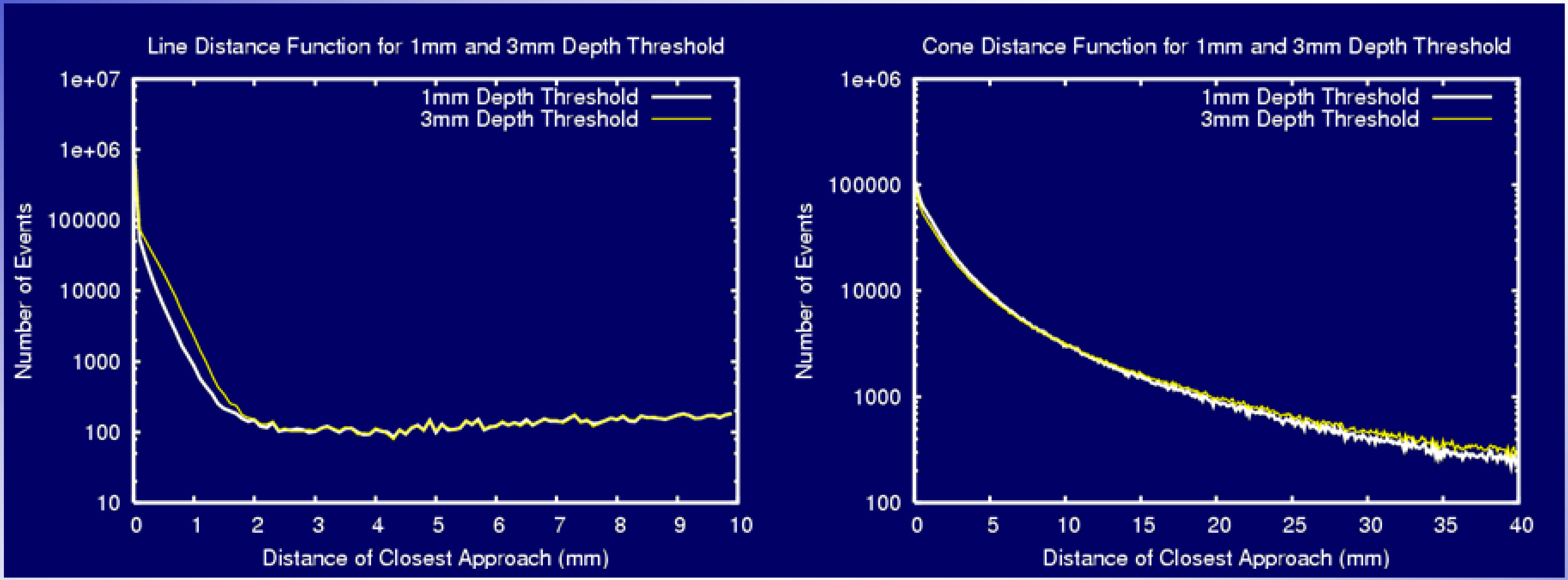
Multiple interactions



- Isotropic γ-ray source 5cm from centre of face of SmartPET detector
- At 511 keV, > 45% of back-projection-suitable events include multiple occupancy

- How bad is it?
- Can we validate?

Distance Functions as f(depth res)



- It seems that depth resolution is not very important

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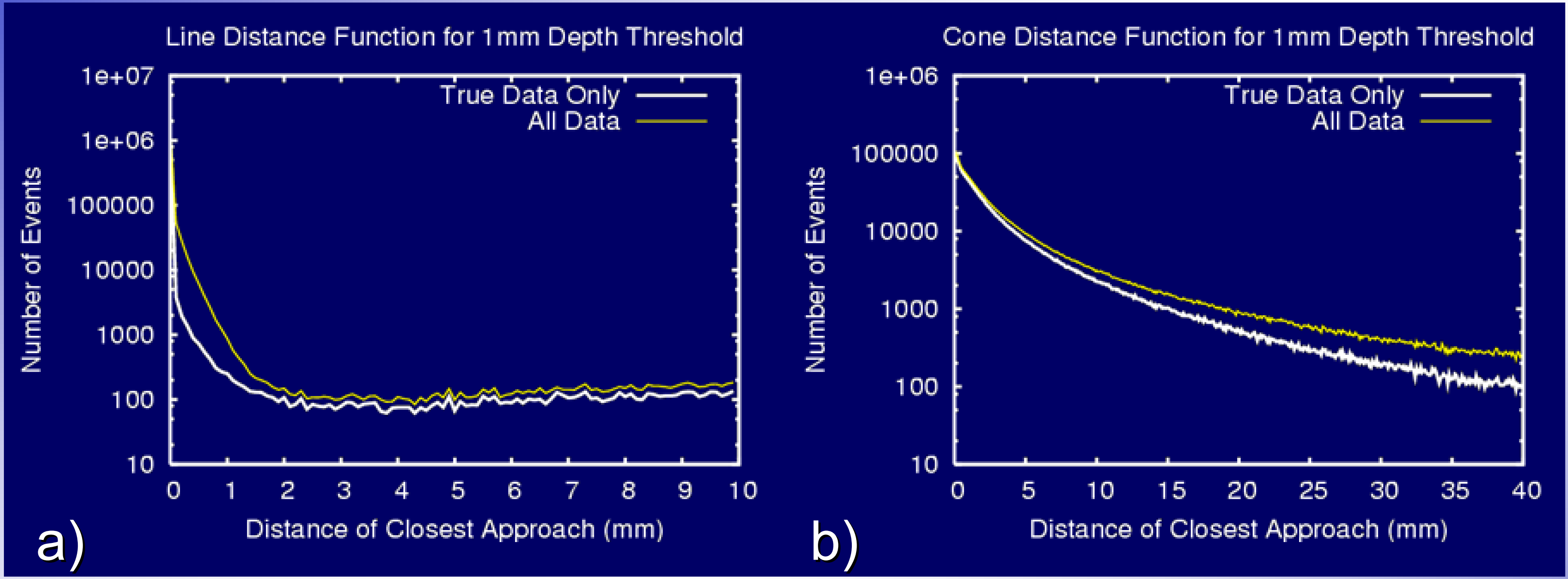
Distance Functions as f(truth)

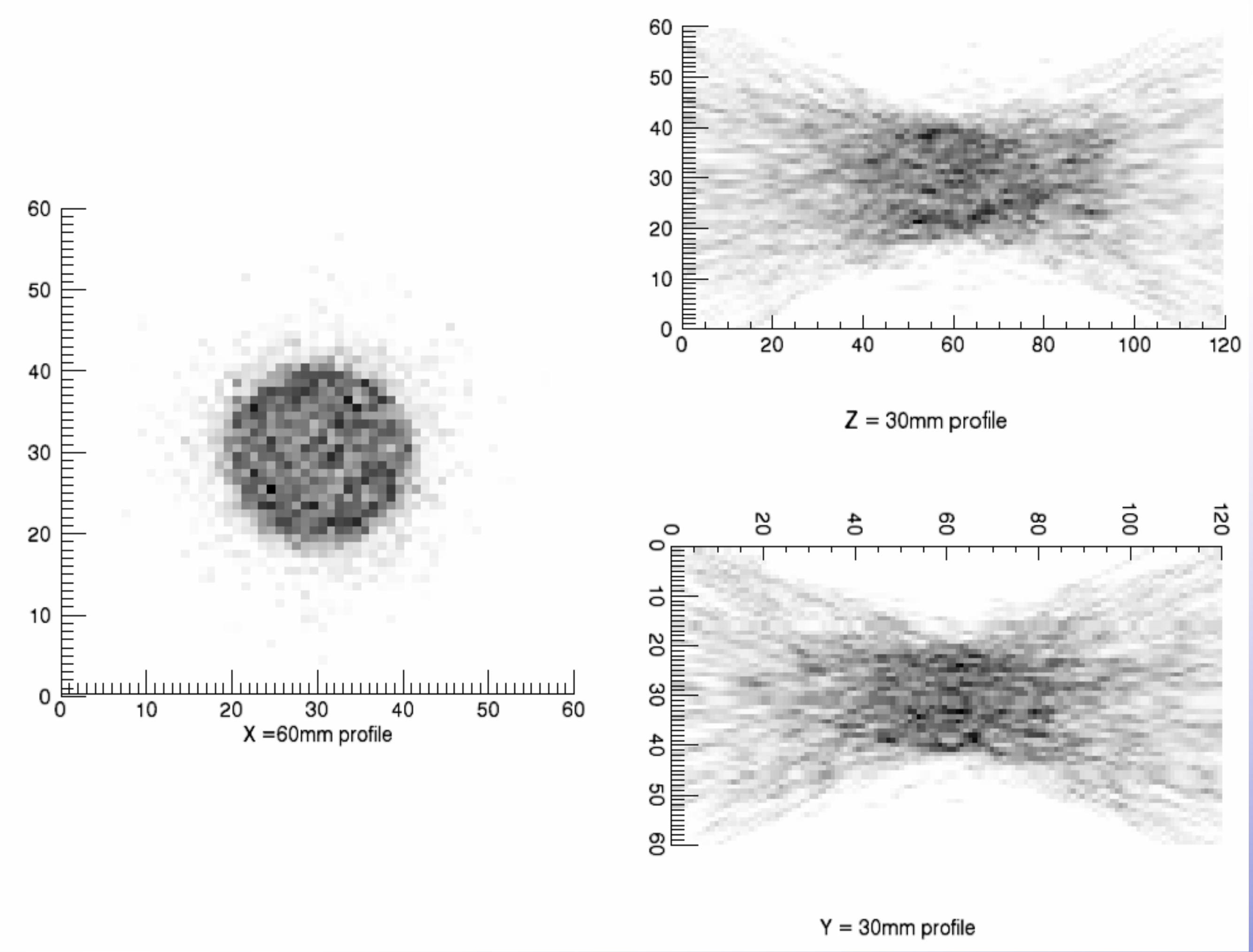


- If two interactions lie within the distance threshold, they will be considered as one
- The affect of this is the removal of many cone-surfaces from the data set, as they now appear to be a single interaction, unsuited to cone back-projection
- This accounts for the minimal affect of the false data on the distance function in figure b

Multiple Interactions

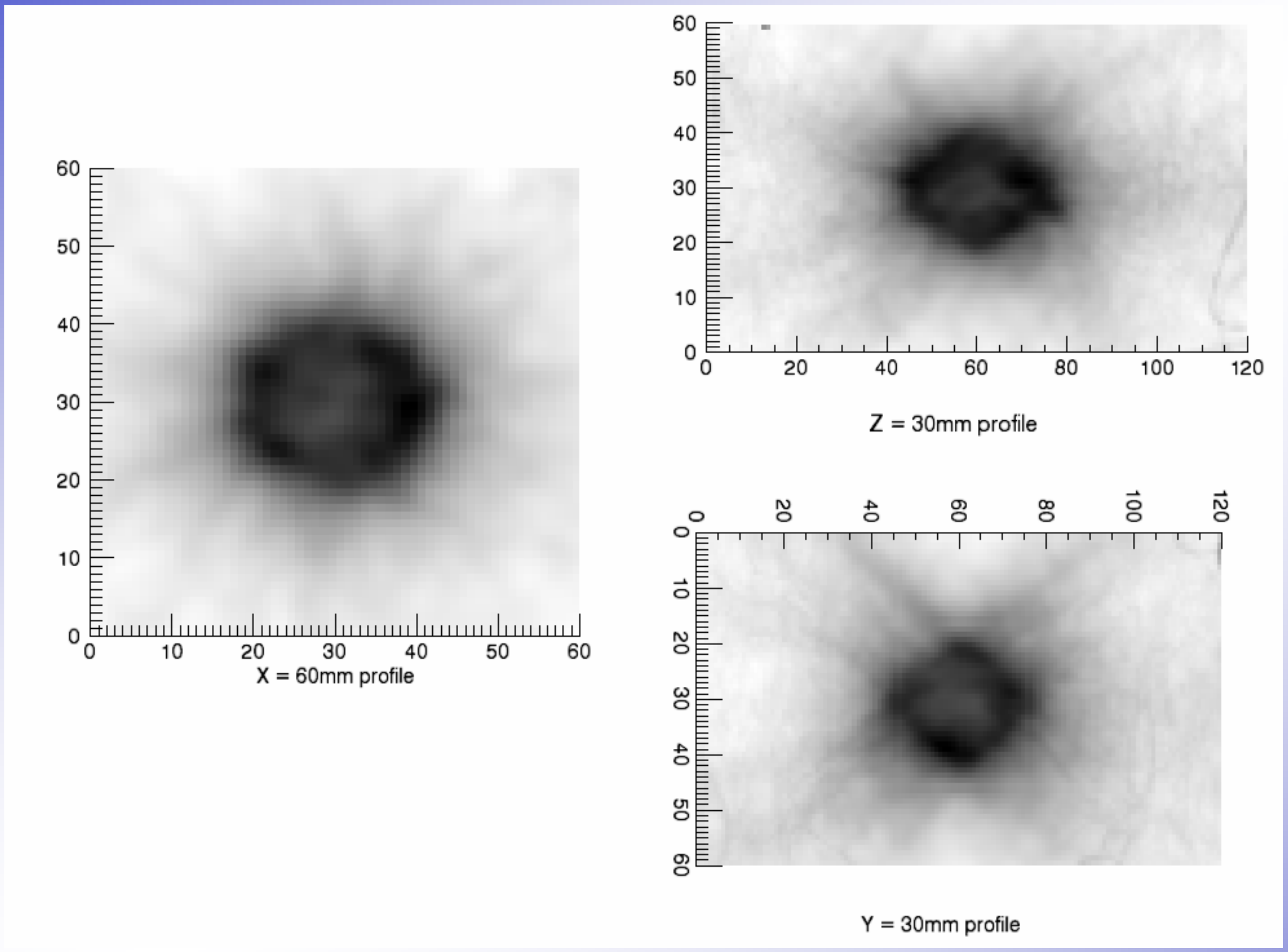
- These results were obtained without any discrimination based on scattering angle or distance between interactions.
- There is a possibility of improving the distance functions in the above plots.
- Additionally, many incorrect lines of response can be removed from the final data set using other techniques

Reconstruction - LORs



- 5000 LORs
- Single Projection
- 1mm Pixel size
- No Iterations

Reconstruction - Cones



- 5000 Cone-Surfaces
- 5 degree fwhm
- Single Projection
- 1mm Pixel size
- No Iterations

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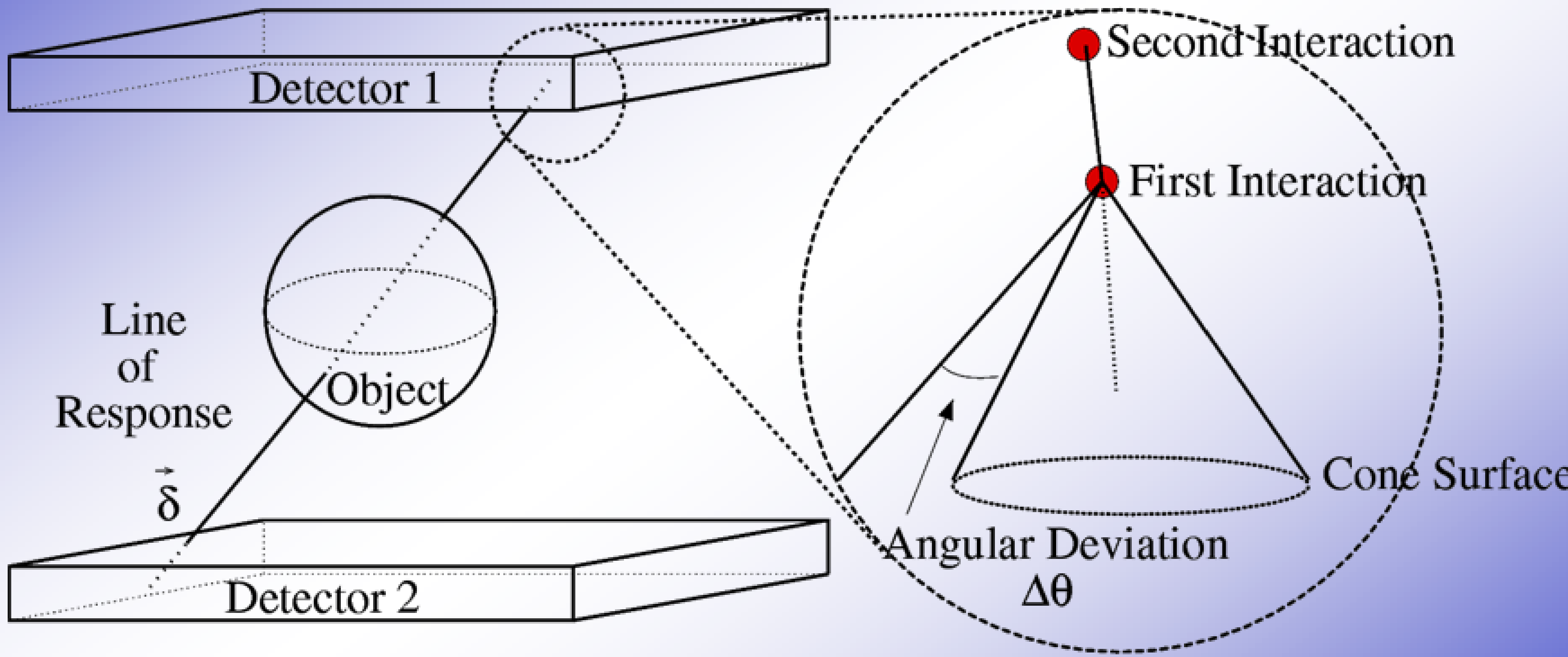
Validation of Data



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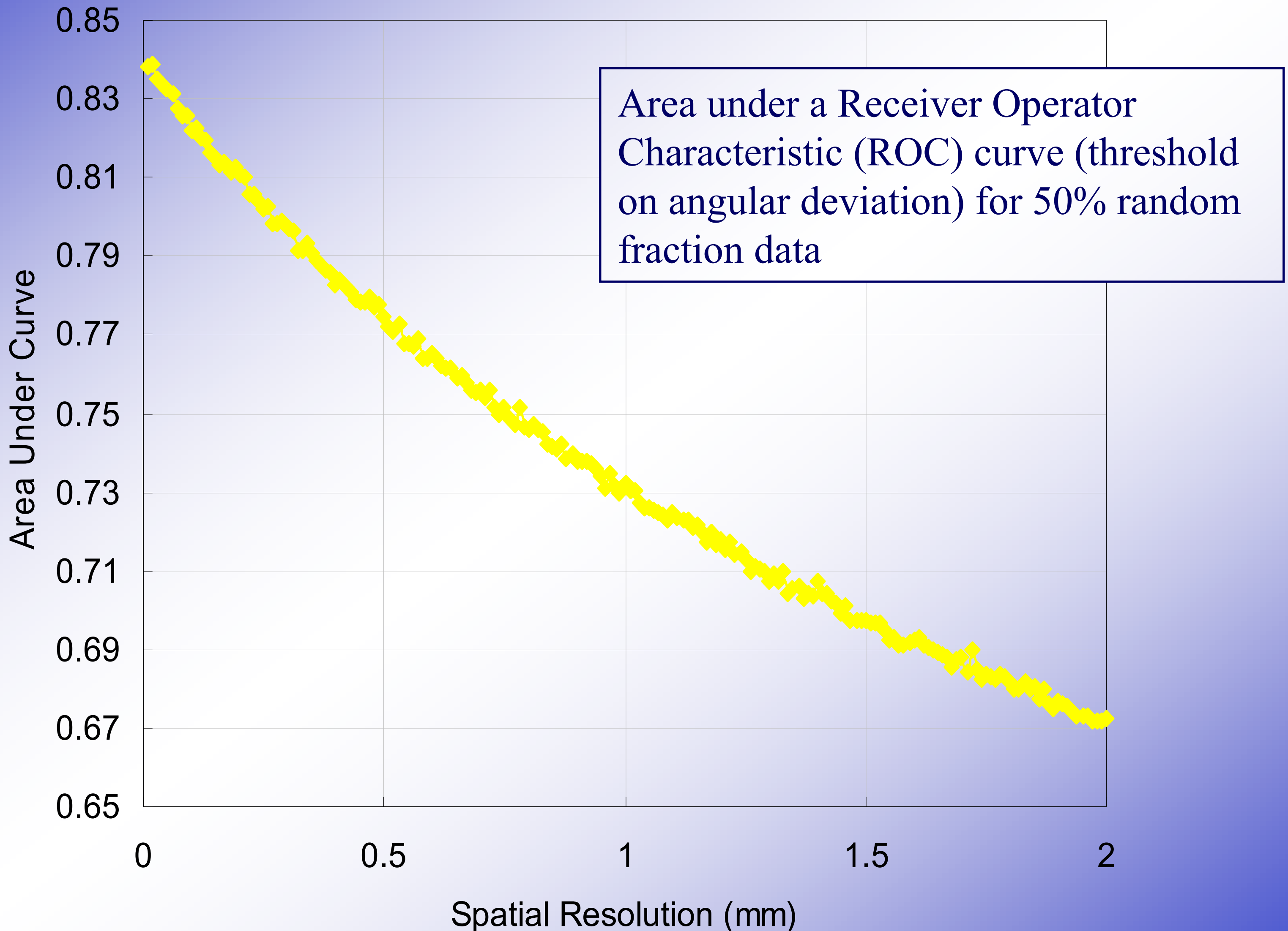
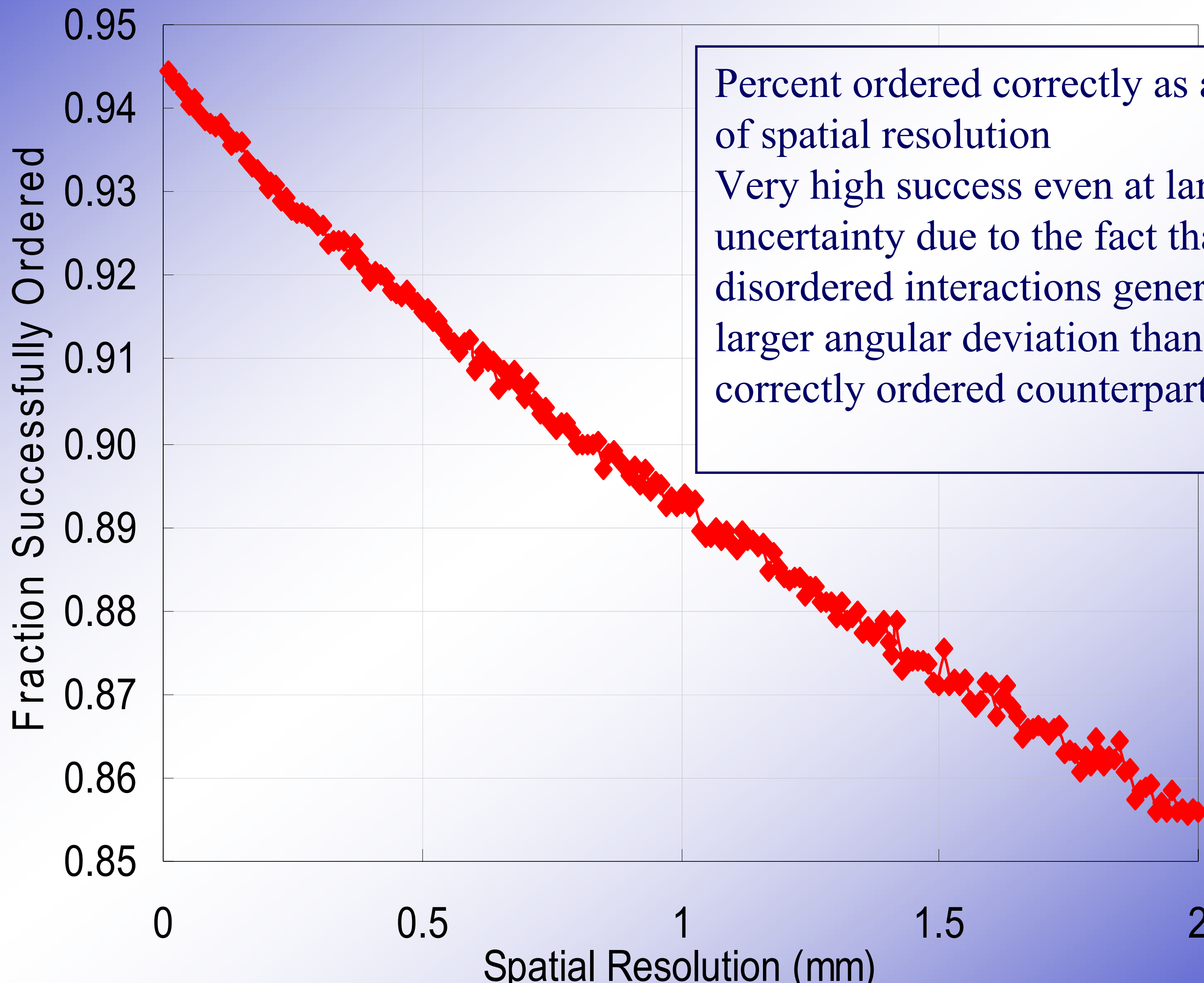
Random Coincidences



The non-unity value for perfect spatial resolution derives from Doppler-broadening

Interaction Ordering



Percent ordered correctly as a function of spatial resolution
Very high success even at large spatial uncertainty due to the fact that disordered interactions generally have a larger angular deviation than their correctly ordered counterparts.

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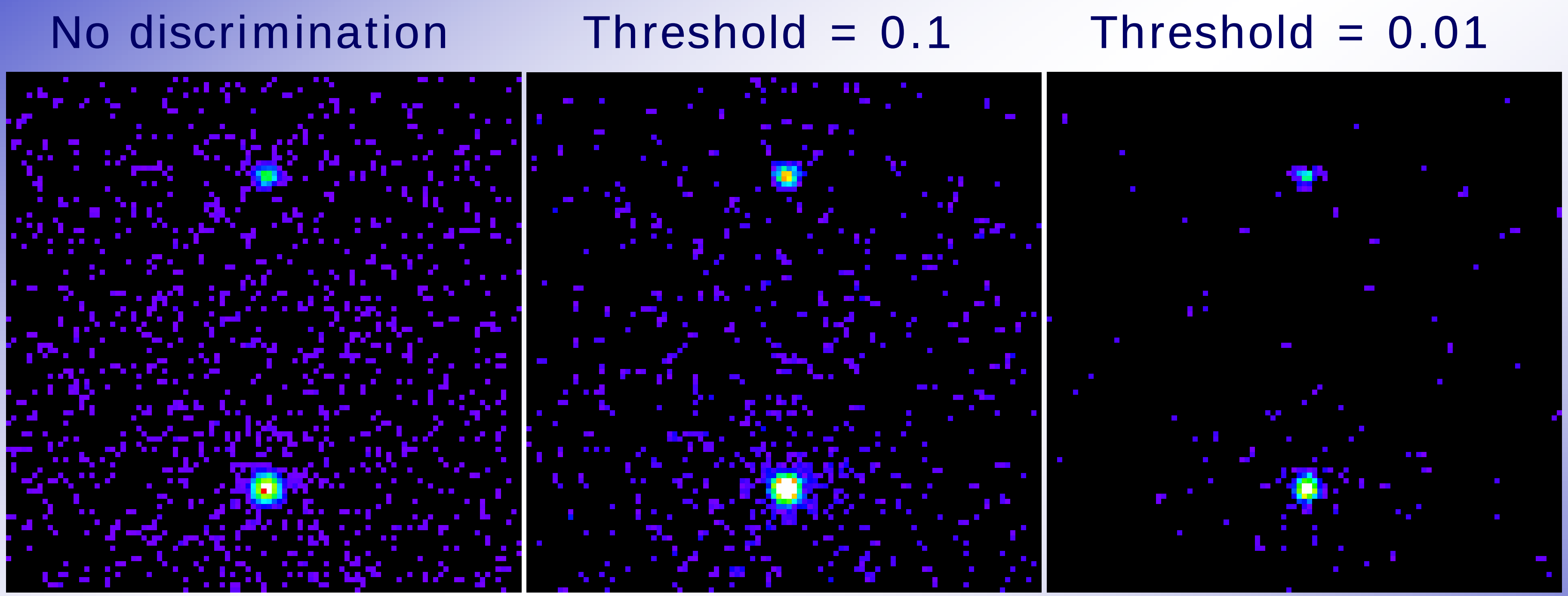
LOR Validation

- The area under a Receiver Operator Characteristic (ROC) curve gives an overall indication of the success of the test at a given spatial resolution.
- Because a threshold value is used, the SNR may be dynamically adjusted to suit the particular source distribution and situation.

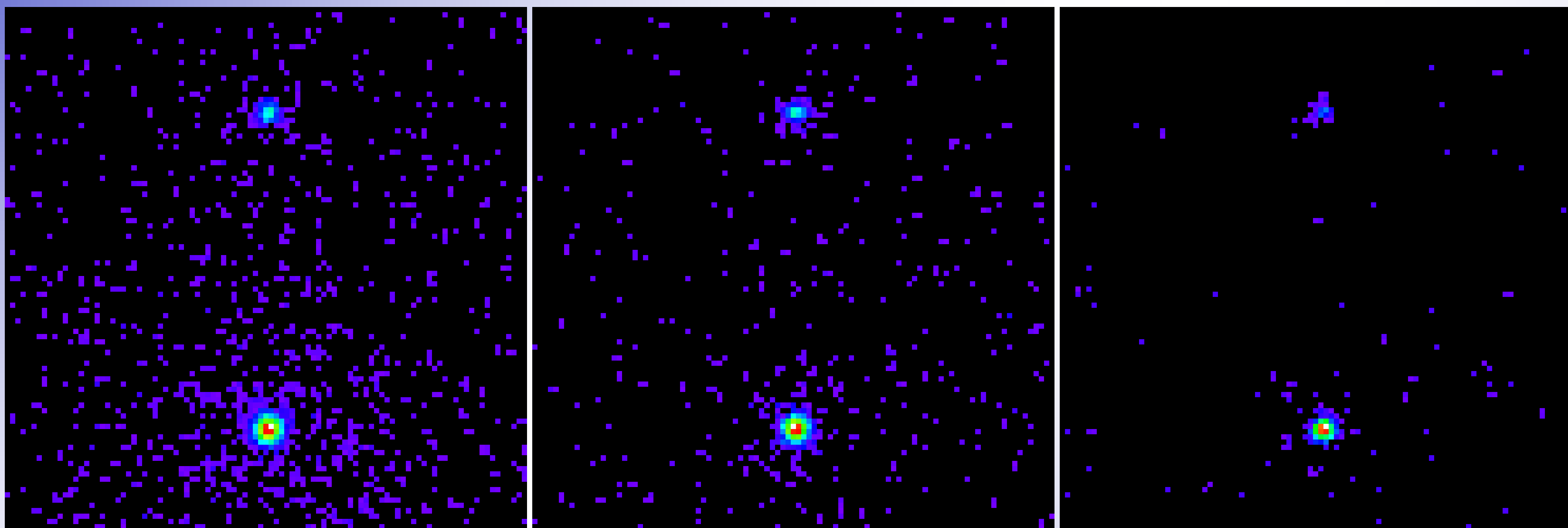
Elimination of Incorrect Ordering



The effect on image reconstruction using LoR discrimination techniques with a spatial resolution of 0.5 mm in the case of a highly scattering environment.

Elimination of Random Coincidences

No discrimination | Threshold = 0.1 | Threshold = 0.01



The effect on image reconstruction using LoR discrimination techniques with a spatial resolution of 0.5 mm in the case of randomly assigned coincidence events

Other improvements

- Efficiency improvement for ^{123}I
  - 20% 511keV anhilation
  - 80% γ emission

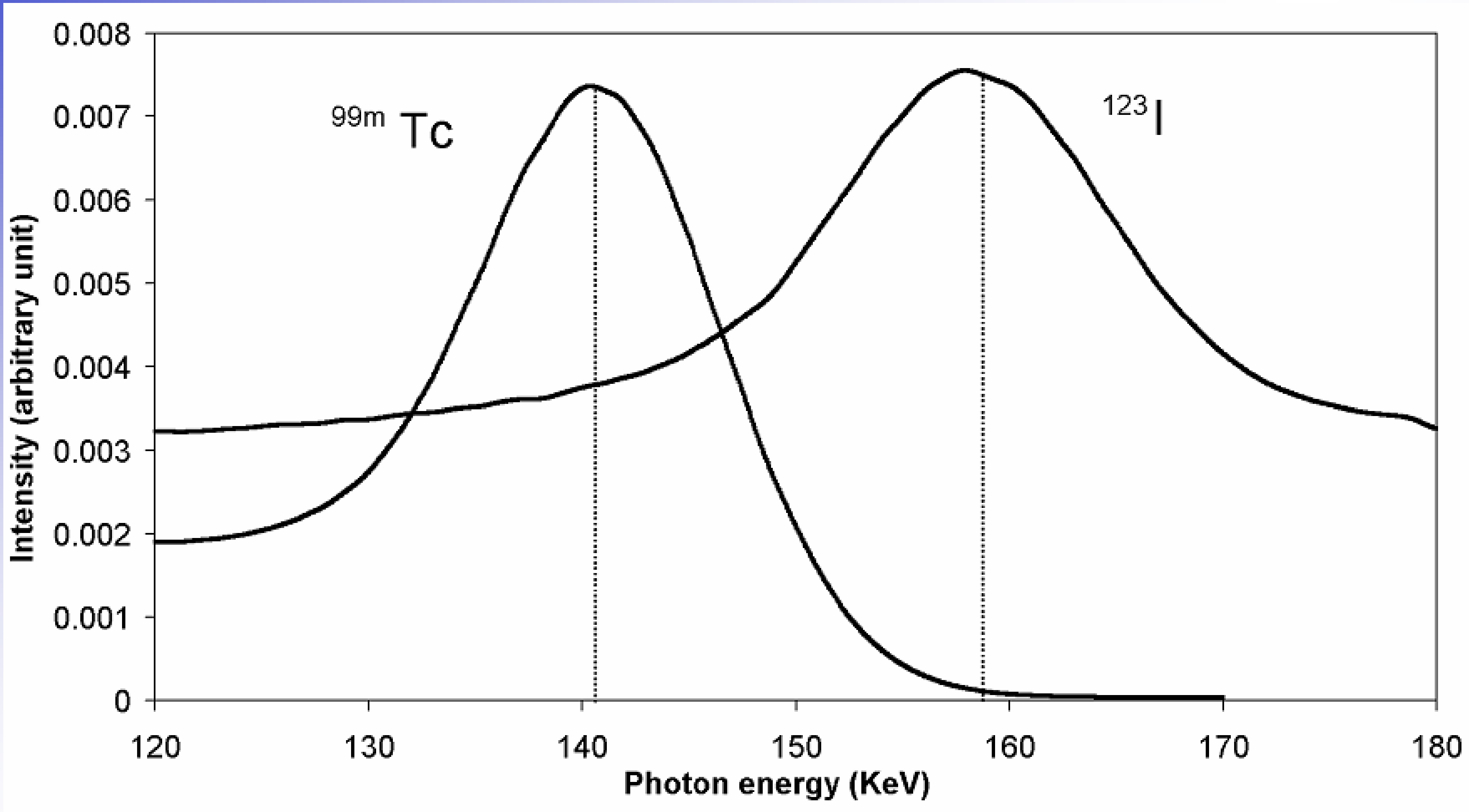
Multiple Tracer Studies

- Pet Problem
  - All photons are 511keV and so multiple tracer studies are impossible
- Compton Camera
  - Can handle multiple energies over range 50 to 511keV with high sensitivity
  - Energy resolution better than 2%
  - => Simultaneous PET and SPECT possible

Multiple Tracer Studies

- Multiple tracer studies for simultaneous imaging of two or more agents
- Applications
  - Neurodegenerative diseases, e.g. Parkinson's, Huntington's, and Alzheimer's.
    - Use a ^{99m}Tc-labeled perfusion agent and a ^{123}I labeled neurotransmitter
  - Myocardial ischemia using
    - ^{201}Tl and ^{99m}Tc-sestamibi
- Advantages
  - Reduced acquisition time
  - Perfect registration of the images from both isotopes in time and space
- Drawback
  - Crosstalk of images from different isotopes

Multiple Tracer Studies



Measured spectrum of ^{99m}Tc and ^{123}I from separate acquisition of a hot sphere embedded in a water-filled cylindrical phantom.

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Y. Du, E. C. Frey, W. T. Wang, and B. M. W. Tsui, IEEE Transactions on Nuclear Science, 50(5), 1556 (2003)

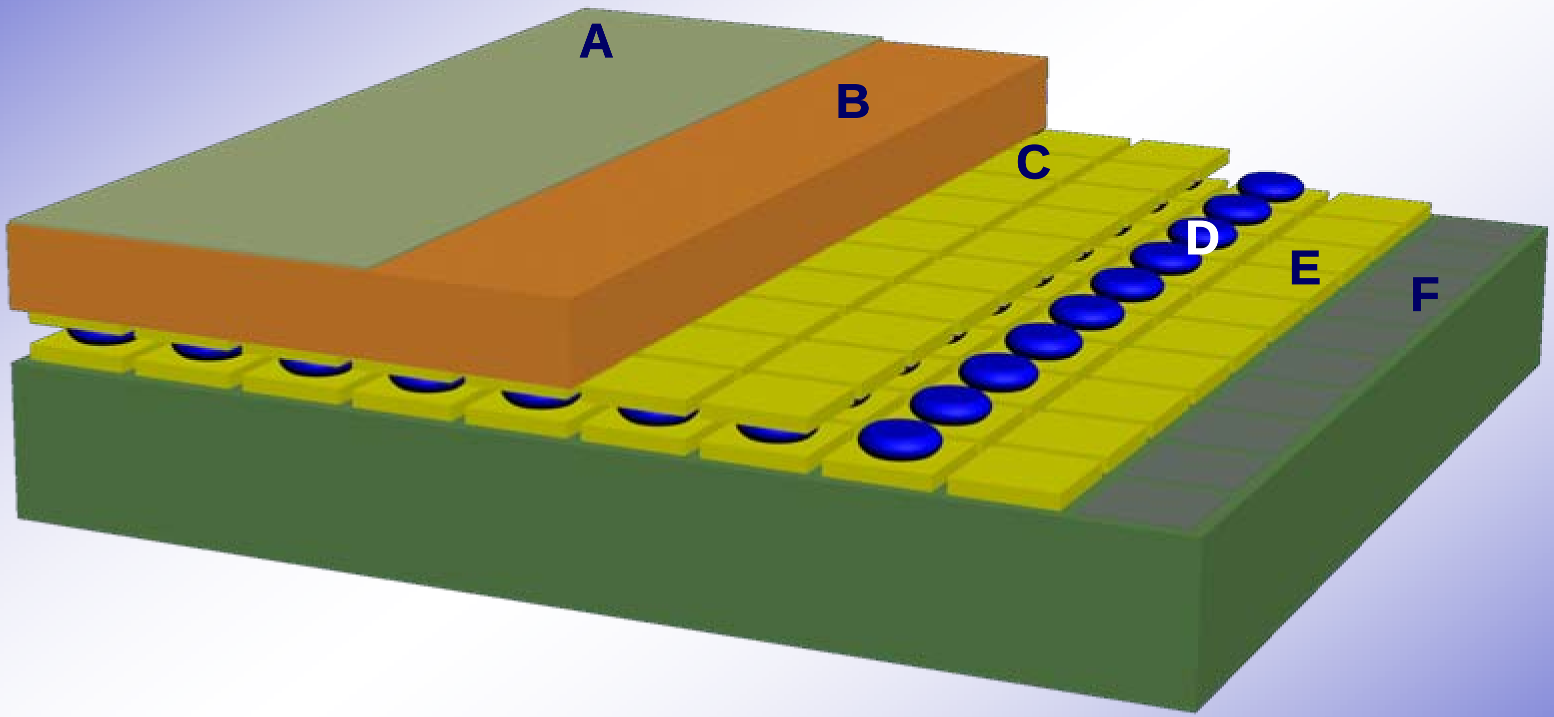
Summary

- High spectral and spatial resolution will improve nuclear medicine imaging
  - Reduction of scatter
  - Reduction of random coincidences
  - Simultaneous PET and SPECT
  - Reduction of crosstalk in multiple isotope imaging
- SmartPET
  - Poor Compton camera
  - Good PET camera

Radiography

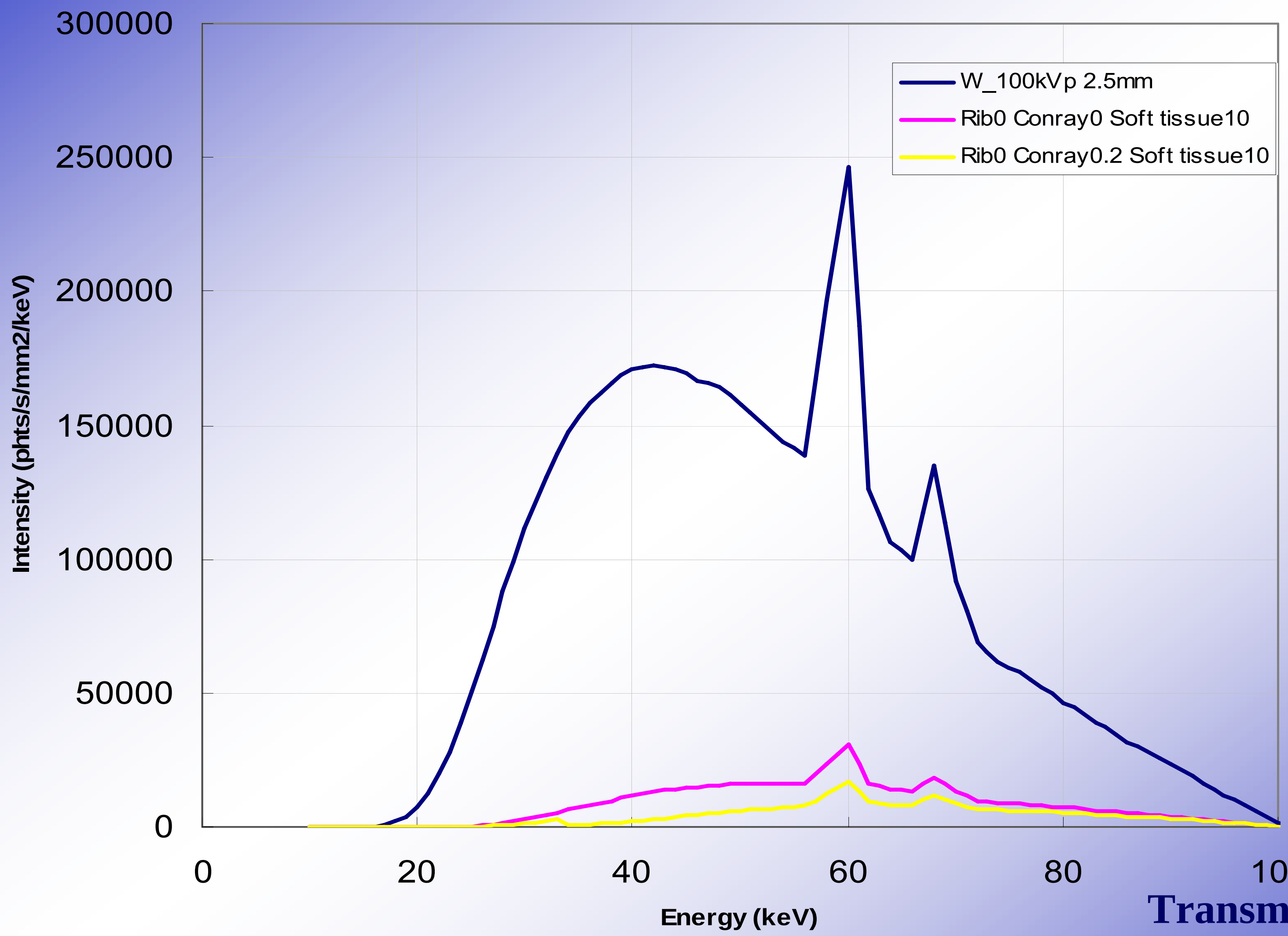
- All X-ray medical imaging uses a polychromatic source
- A small fraction of photons incident on the patient contribute (usefully) to the image
  - Higher than necessary patient dose
  - Scatter to primary ratios can be 3:1 or worse
- Ideal source would be tunable and monochromatic
- Can energy resolving pixel detectors help approach monochromatic performance with polychromatic source?

Pixel Detector



Hybrid pixel detector comprising top electrode (A), pixellated semiconductor (B), collection electrodes (C), bump bonded (D) via input electrode (E) to the pixellated ASIC (F)

Spectrum in X-ray Imaging

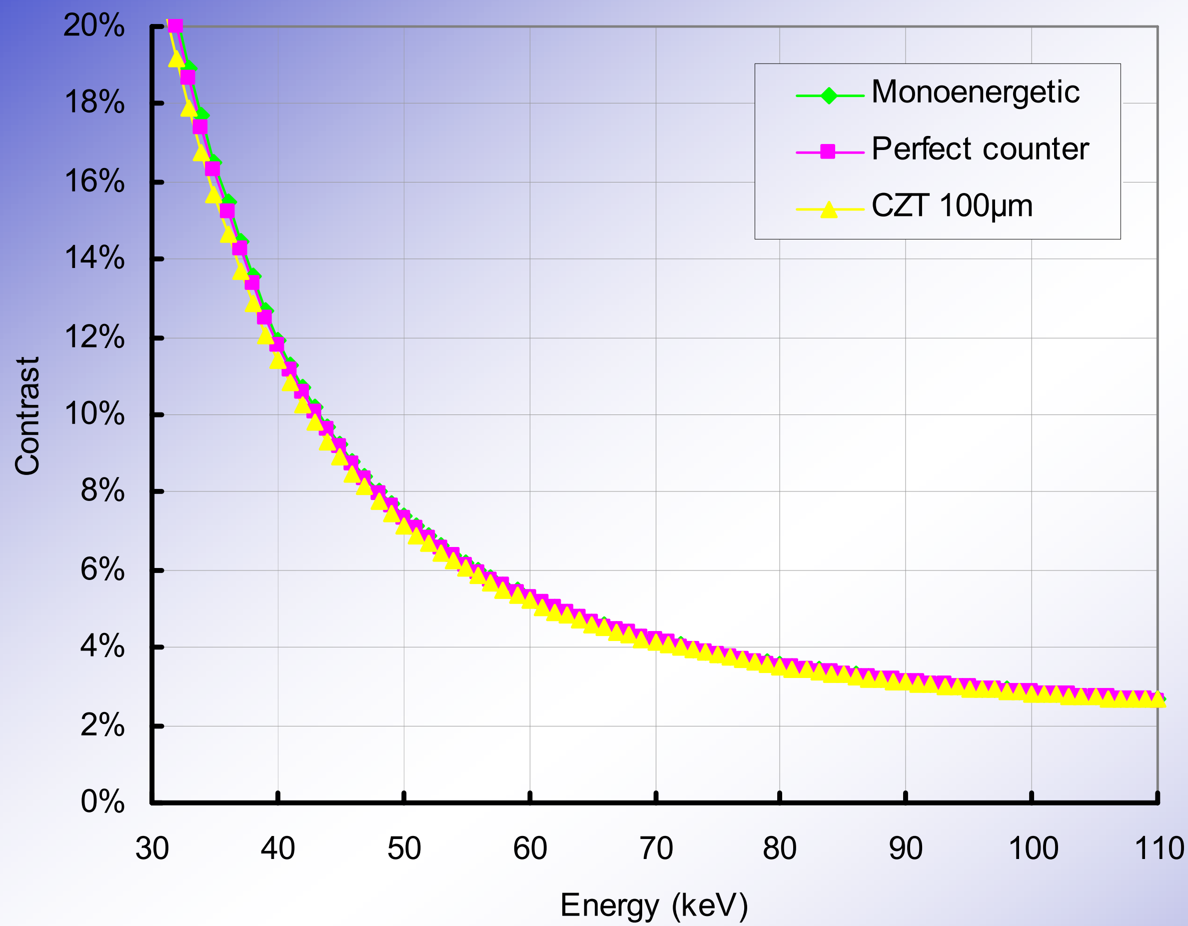


Transmission

10cm soft tissue 10%

With 2mm contrast 5%

Photon Counting

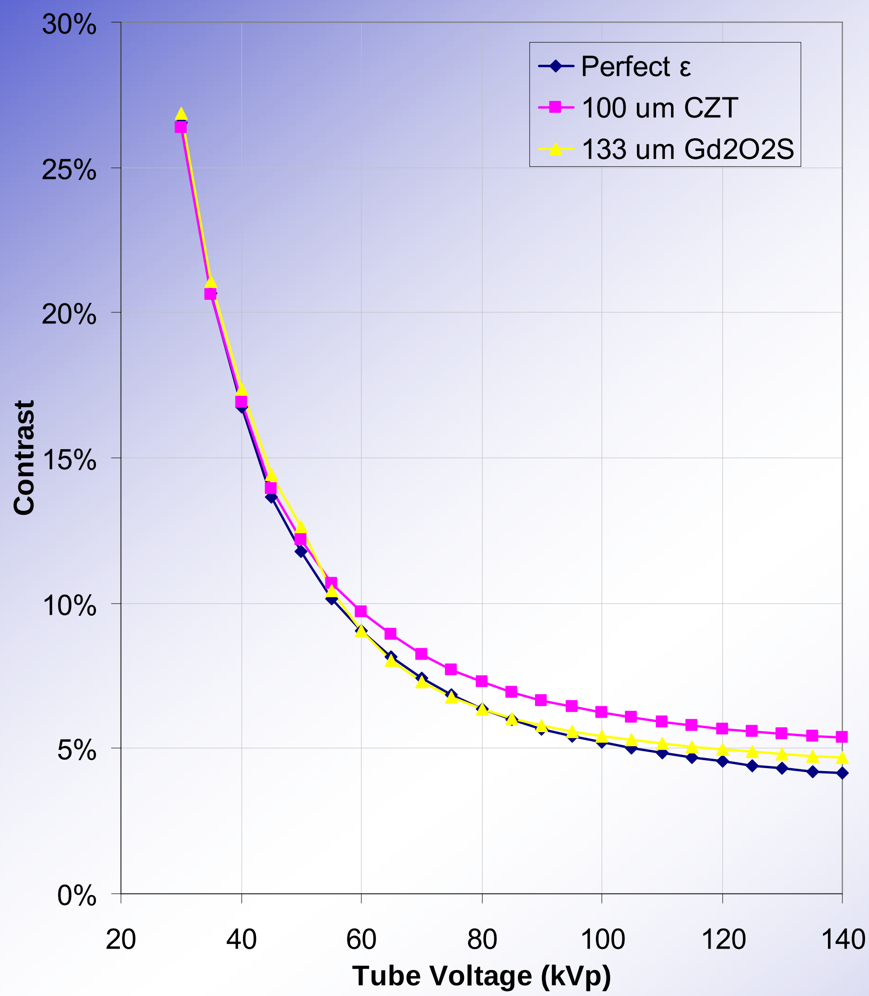


Target is 1mm Al disc in 20cm water

Real counting detectors ε(E)<1 with moderate energy resolution (b=0.2-0.4)

Contrast is similar to that from a tuneable mono-energetic X-ray source

The 'Perfect' Detector

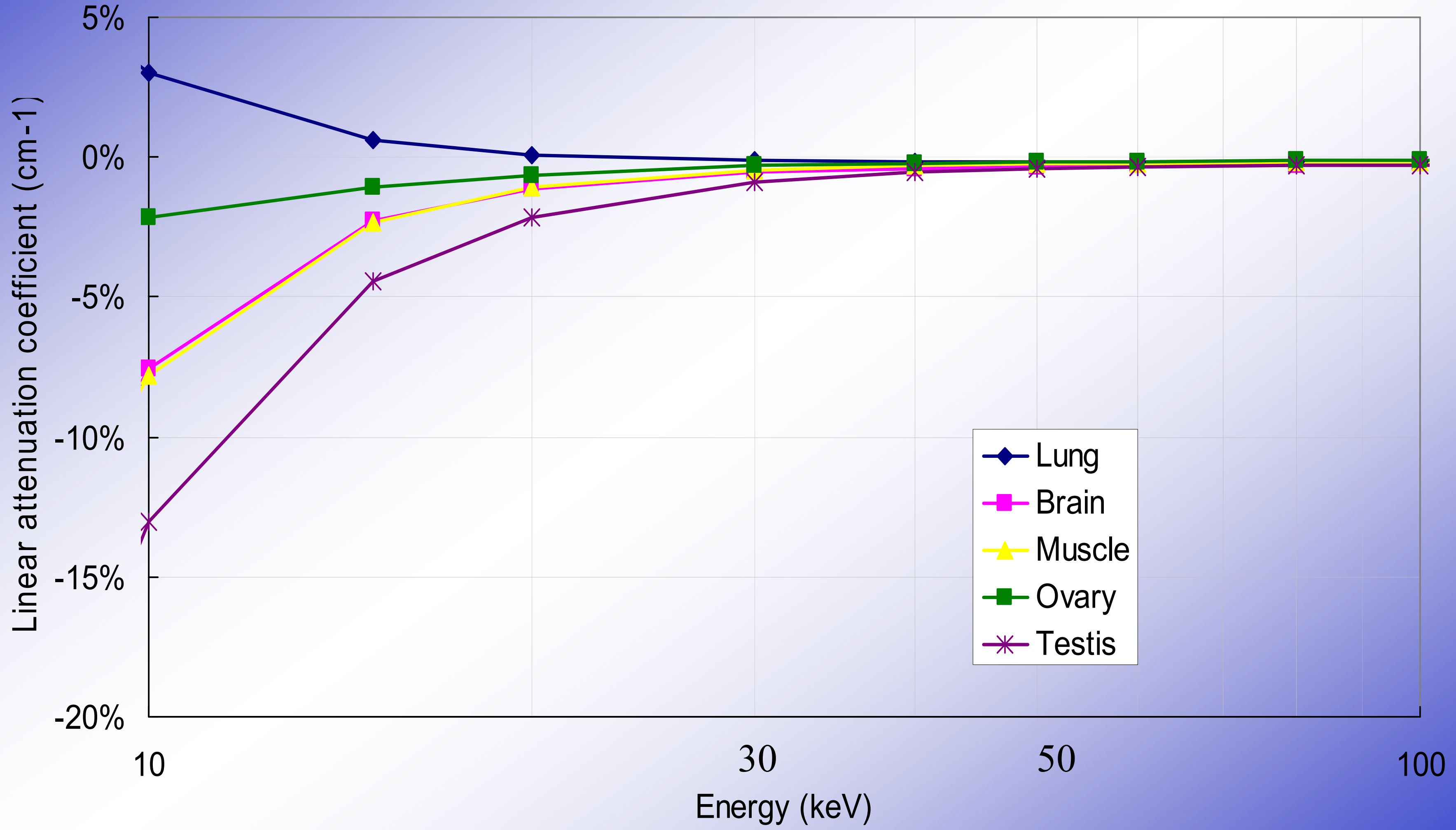


- The graph is clearly wrong
- or is it?

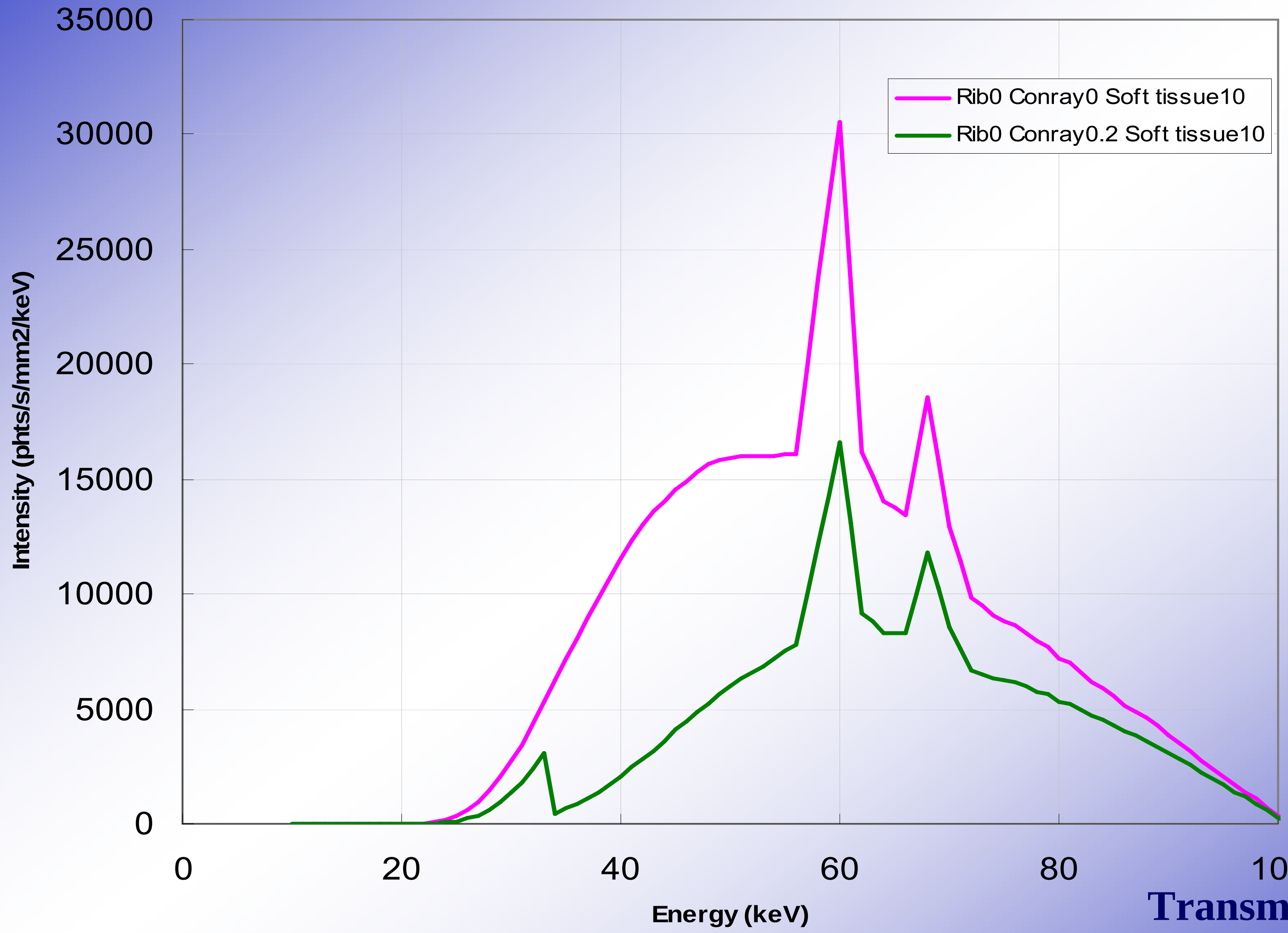
Soft Tissue Contrast

- Higher energy photons interact weakly with object
- Lower energy photons interact strongly with object
- Contrast is at carried by low energy photons

Soft Tissue Contrast



Spectrum in X-ray Imaging



Transmission

10cm soft tissue 10%

With 2mm contrast 5%

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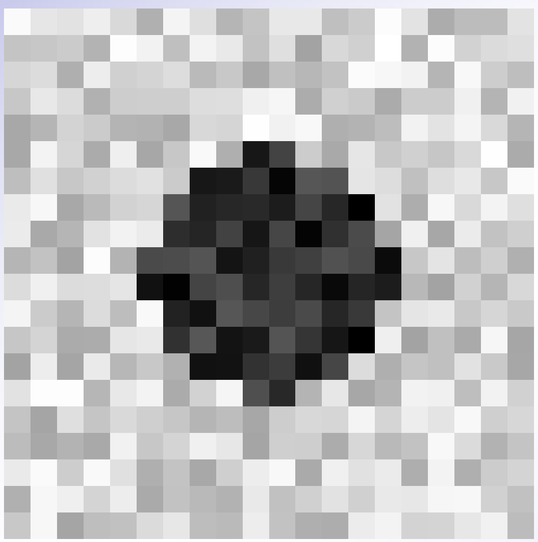
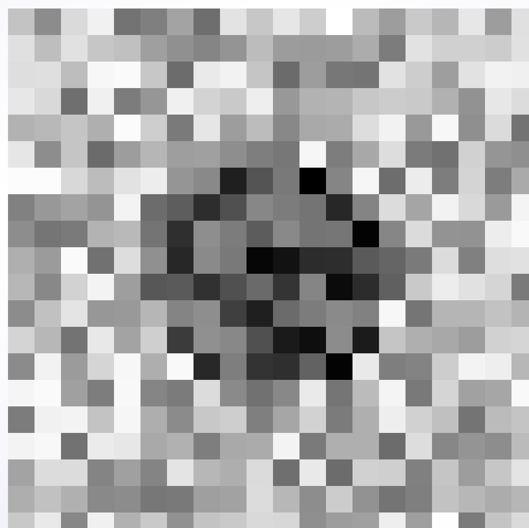
Contrast

- Most soft tissue contrast is at low energy
- There are few photons at low energy

23-26 keV bin



100-110 keV bin



140kVp 5mAs
2mm tumour
5cm soft tissue

Contrast

- Most soft tissue contrast is at low energy
- There are few photons at low energy
- Energy integrating detectors over-emphasize this signal

- Integrating detector signal $\propto E$

BUT

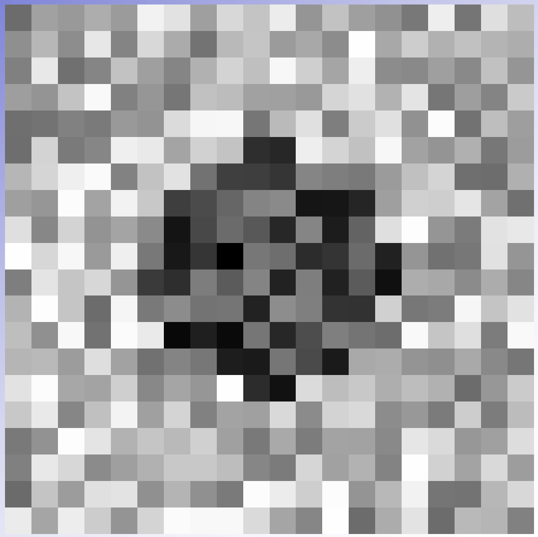
- Photoelectric cross section $\propto E^{-3}$

- Weight each photon by E^{-3}

R.N. Cahn et al., *Med. Phys.* **26** (1999) 2680

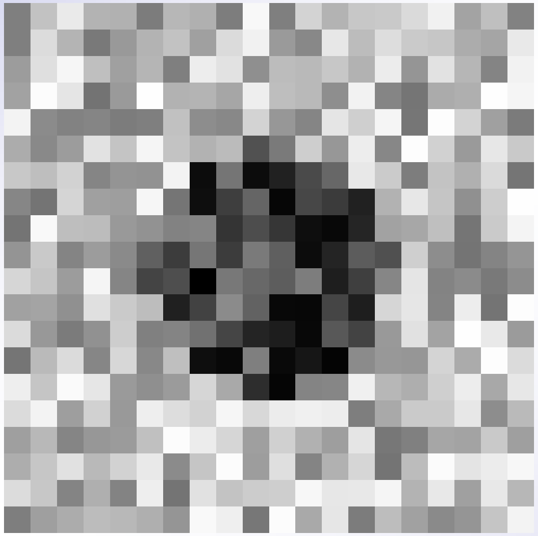
Contrast

Integrating



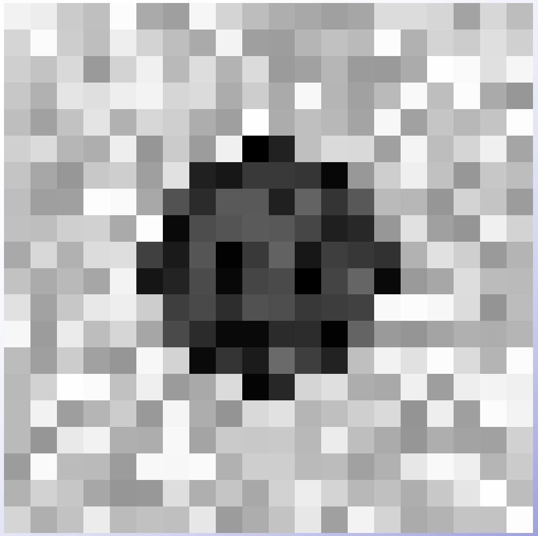
Contrast 1.1%

Counting



Contrast 1.2%

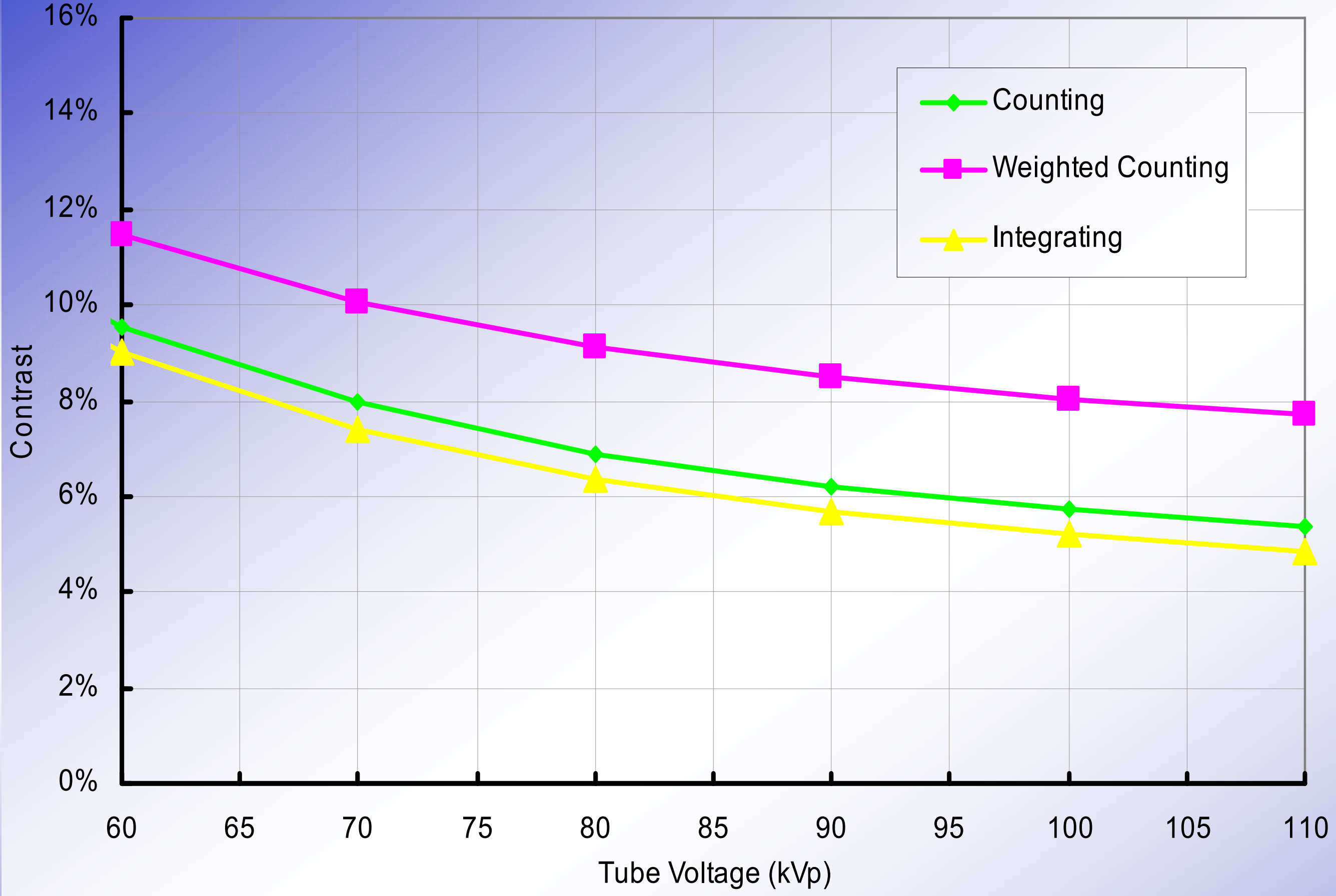
Weighted Counting



Contrast 1. 5%

100kVp 1mAs
0.5mm tumour in 5cm soft tissue

Radiographic Contrast



Target 1mm Al in 20cm of water

- Weighting data by E-3 is similar to effect of not detecting high energy photons
- i.e. use a real detector with ε=f(E)

Quantitative X-ray Analysis

- Energy dispersive detection enables multi-energy data acquisition from a single exposure
- This opens the possibility for QXRA, which delivers information about material density and composition
- How will the energy resolution affect the accuracy of QXRA?

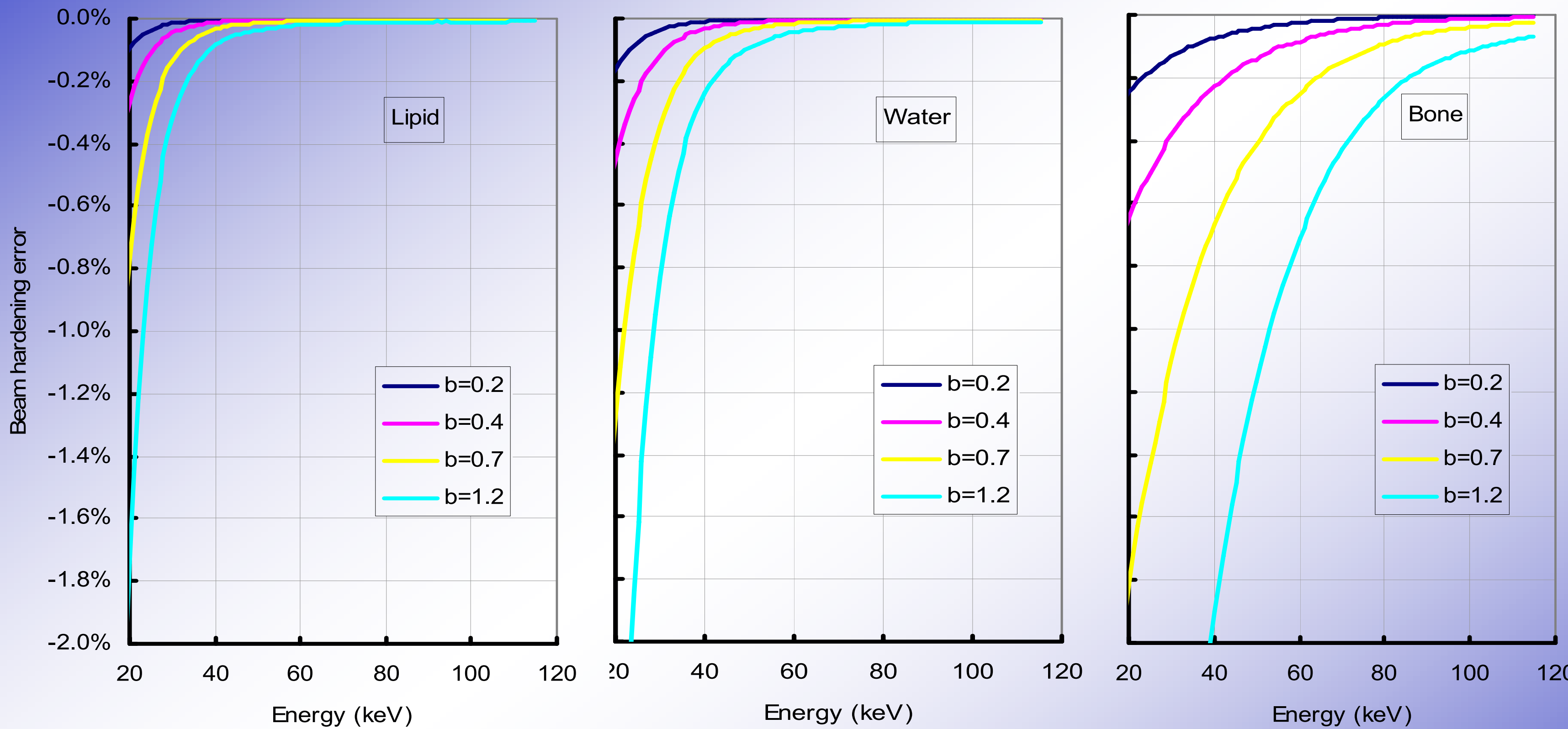
- With polychromatic source lower energies are preferentially attenuated by the object and the beam is "hardened“
- Note that this also happens within each energy bin.
- Measured attenuation coefficients,

$$\mu_{\exp t} = \frac{1}{t} \ln \left[\frac{\sum_E I_0(E) e^{-\mu(E)t}}{\sum_E I_0(E)} \right]$$

- have a unique value μ_0, for zero thickness of absorber, and decrease with sample thickness t.

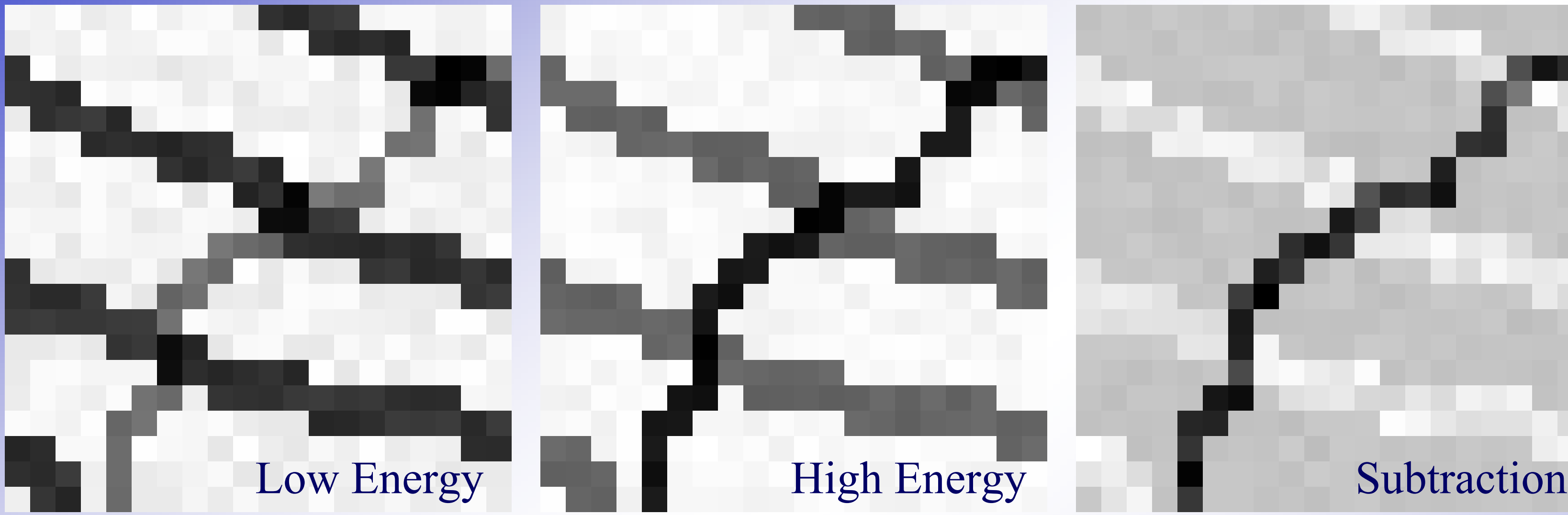
- [2] and deliver accurate measurement.
- Low energies require higher resolution (e.g., Si and Ge where b≈0.1), whilst energies above 100 keV may be studied with coarse resolution detectors (such as NaI where b≥1.0). The width of the energy integration window also introduces errors and should be no larger than ΔE.

Beam Hardening Errors



- CZT and CdTe have b≈0.2-0.4 and are accurate above ~30keV and 50keV respectively
- Low energies require higher resolution (e.g., Si and Ge where b≈0.1)
- Above 100 keV OK with coarse resolution detectors (such as NaI where b≥1.0)
- The width of the energy integration window also introduces errors and should be no larger than ΔE.

K Edge Subtraction



Source
100kVp 5mAs 2.5mm Al @1m

Object

Rib	1.0cm
Soft Tissue	10cm
Iodine contrast (Conray)	0.2mm

Summary

- Adding good spectral resolution to medical imaging will allow better images
- Exactly how to take best advantage is not obvious