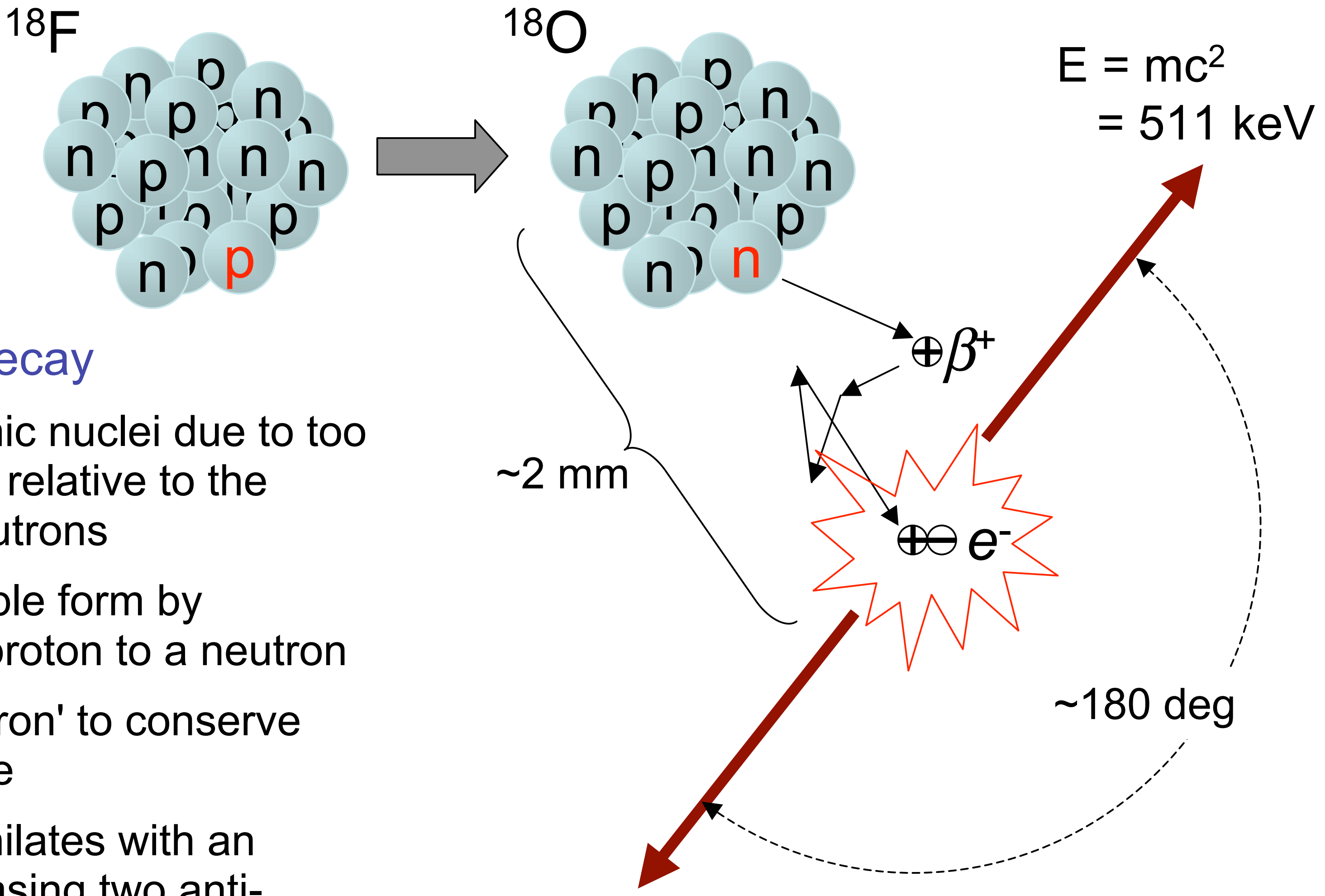
How it works: Positron Emission



Radioactive decay

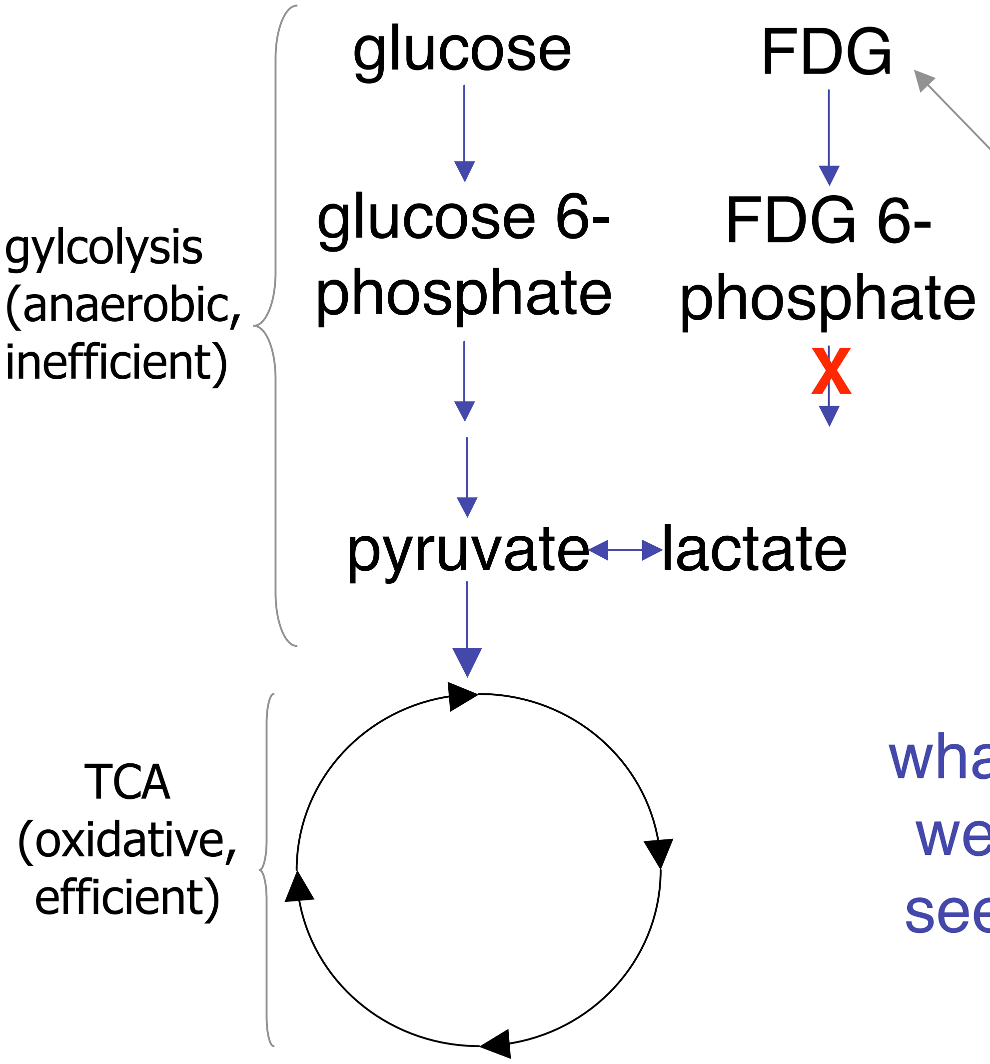
- unstable atomic nuclei due to too many protons relative to the number of neutrons
- decays to stable form by converting a proton to a neutron
- ejects a 'positron' to conserve electric charge
- positron annihilates with an electron, releasing two anti-colinear high-energy photons

Types of Photons

- X-ray photons
- gamma (γ) ray photons (Greek letters for radiation from nuclear decay processes)
- annihilation photons

all can have the same energy

Molecular Imaging: Glu Metabolism



gylcolysis (anaerobic, inefficient)

glucose

glucose 6-phosphate

pyruvate ↔ lactate

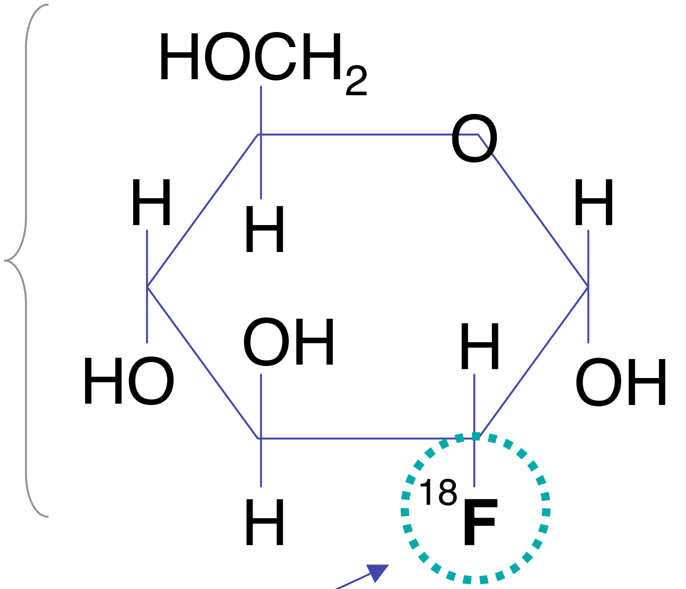
FDG

FDG 6-phosphate

X

TCA (oxidative, efficient)

[18F]fluorodeoxyglucose (FDG)

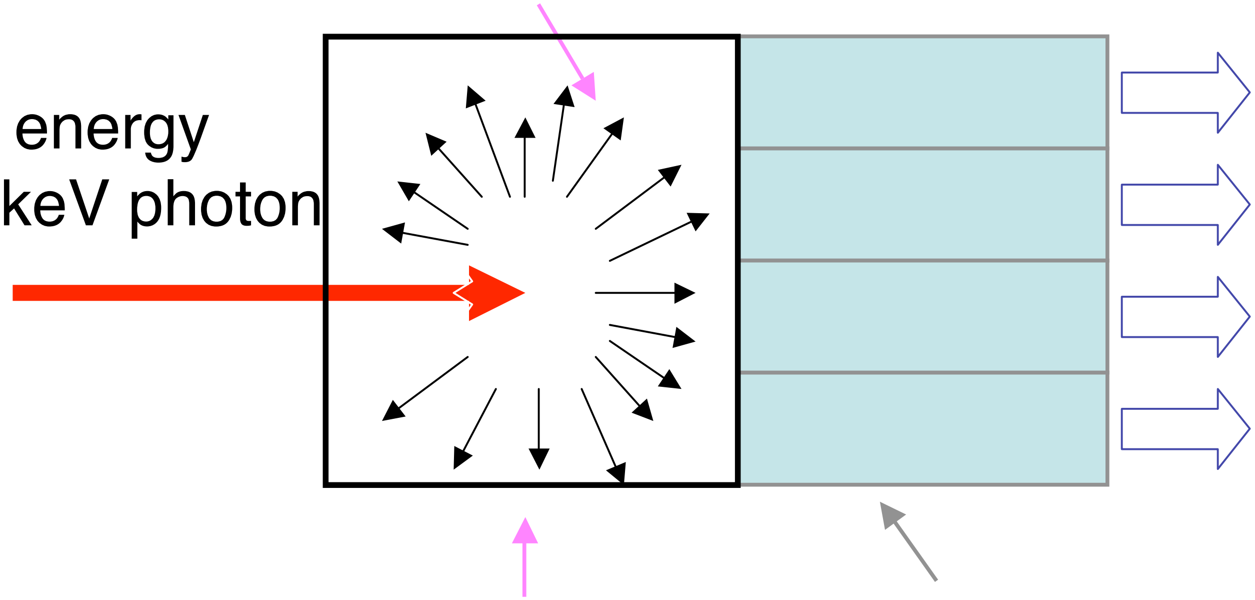


radioactive fluorine

what we see

FDG-6-PO$_4$ is ‘trapped’ and is a good marker for glucose metabolic rates*

How it works: Scintillation



optical photons (~ 1eV)

high energy
511 keV photon

current
pulse for
each UV
photon
detected

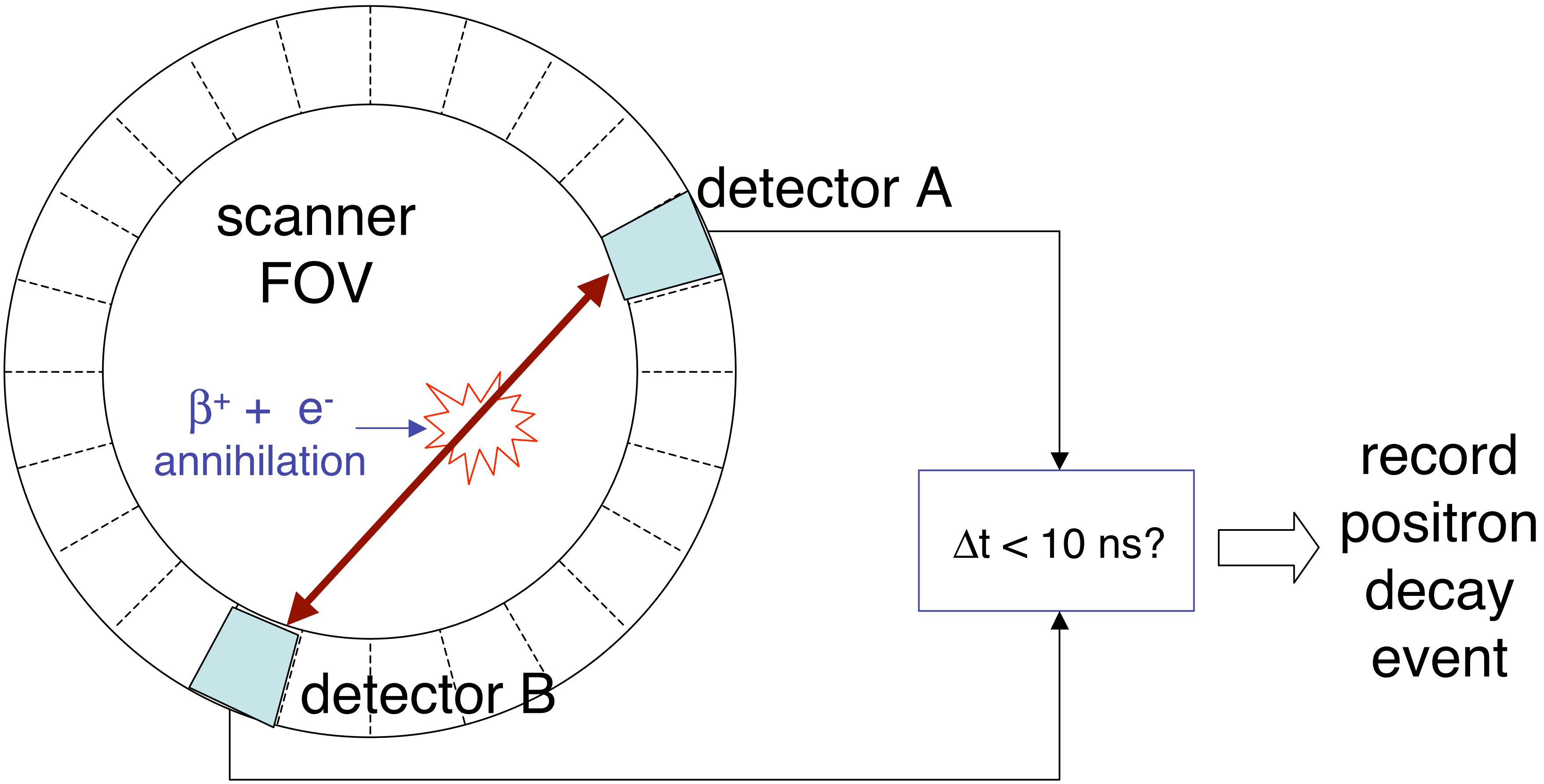
scintillator
(e.g. BGO Dense
yet transparent)

photomultiplier
tubes (PMTs)
gain of ~ 10^6

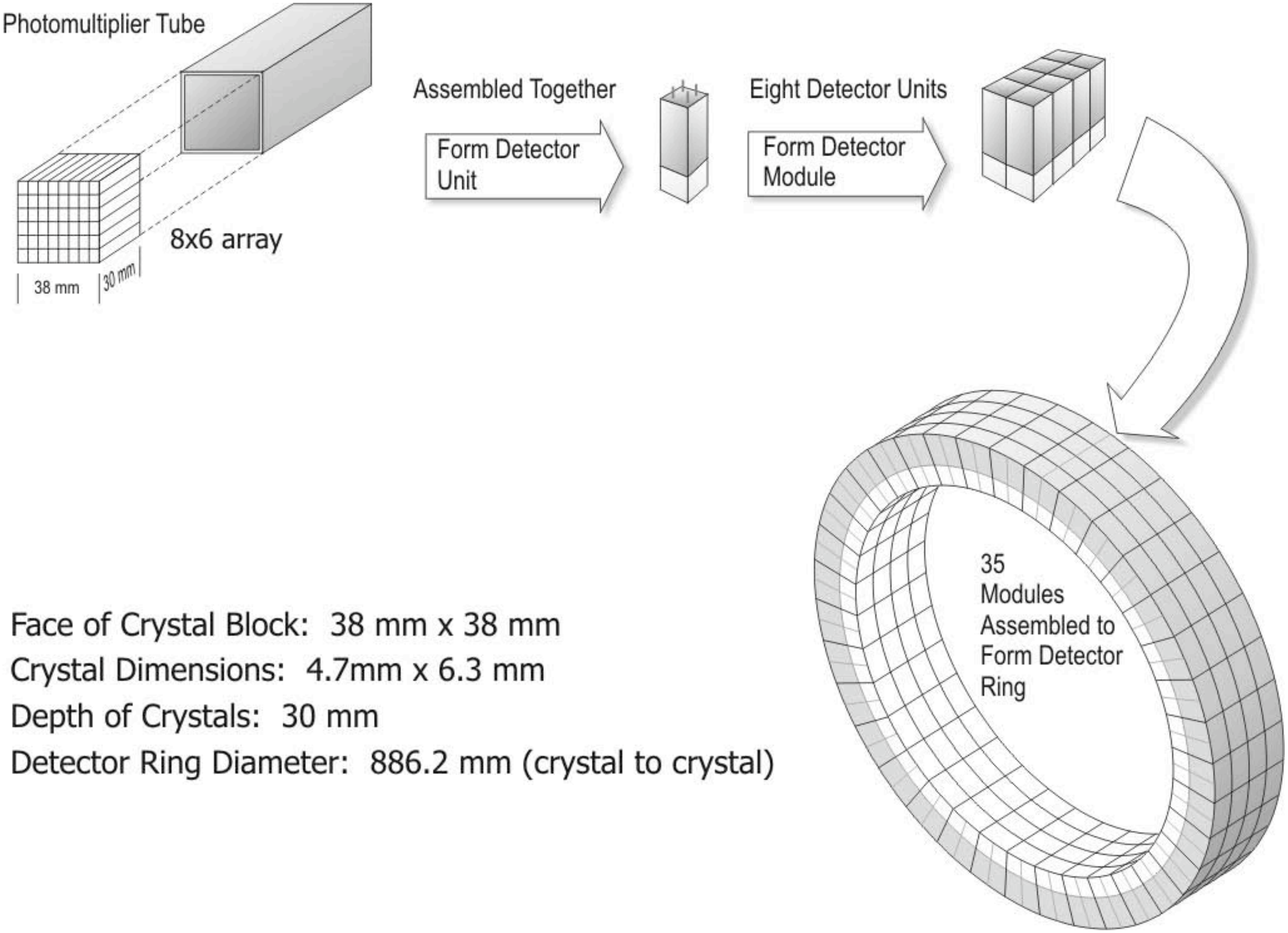
Scintillators used in PET Scanners

Material	Cost	*Effective* number of scintillation photons @ 511 keV determines energy and spatial resolution	*Effective* Density determines scanner sensitivity	Decay time (μs) determines deadtime and randoms	Comments
NaI(Tl)	cheap (relatively)	highest	lowest	long	Hygroscopic
BGO	expensive	lowest	highest	long	workhorse
LSO	more expensive	high	high	very short	new technology
GSO	more expensive	very high	somewhat lower than LSO	very short	new technology

How it works: Timing coincidence

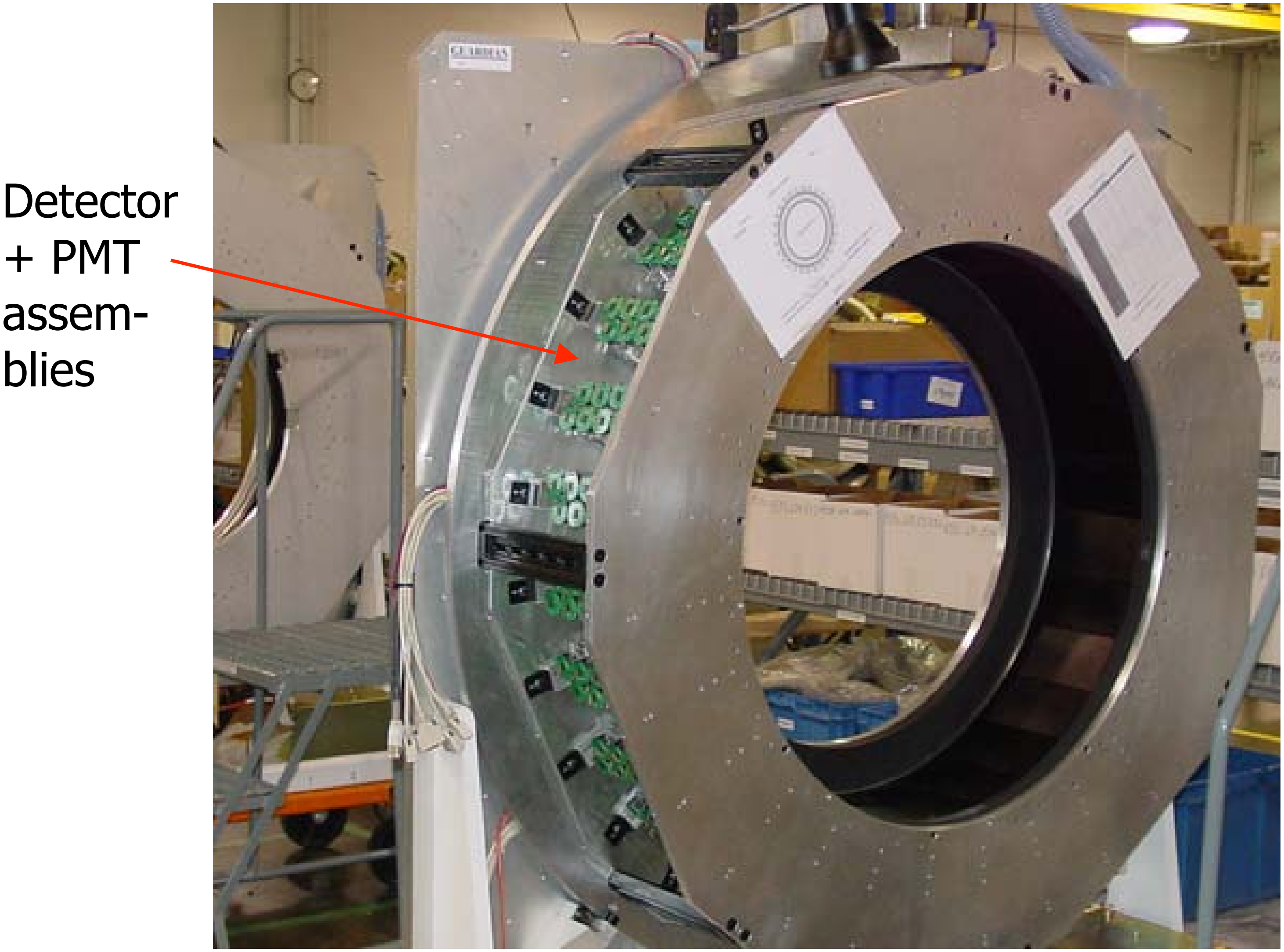


Typical PET Scanner Detector Ring



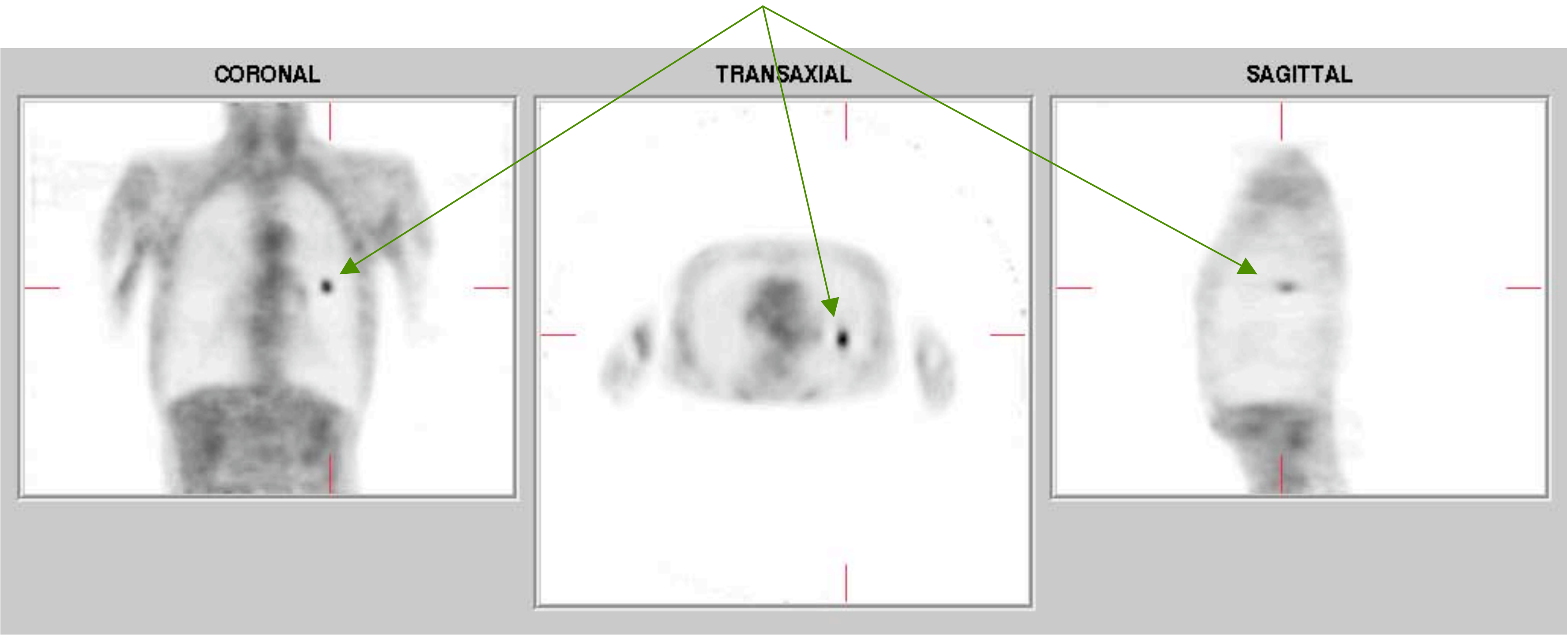
Face of Crystal Block: 38 mm x 38 mm
Crystal Dimensions: 4.7mm x 6.3 mm
Depth of Crystals: 30 mm
Detector Ring Diameter: 886.2 mm (crystal to crystal)

Anatomy: PET gantry



Detector + PMT assem-blies

Typical PET Image



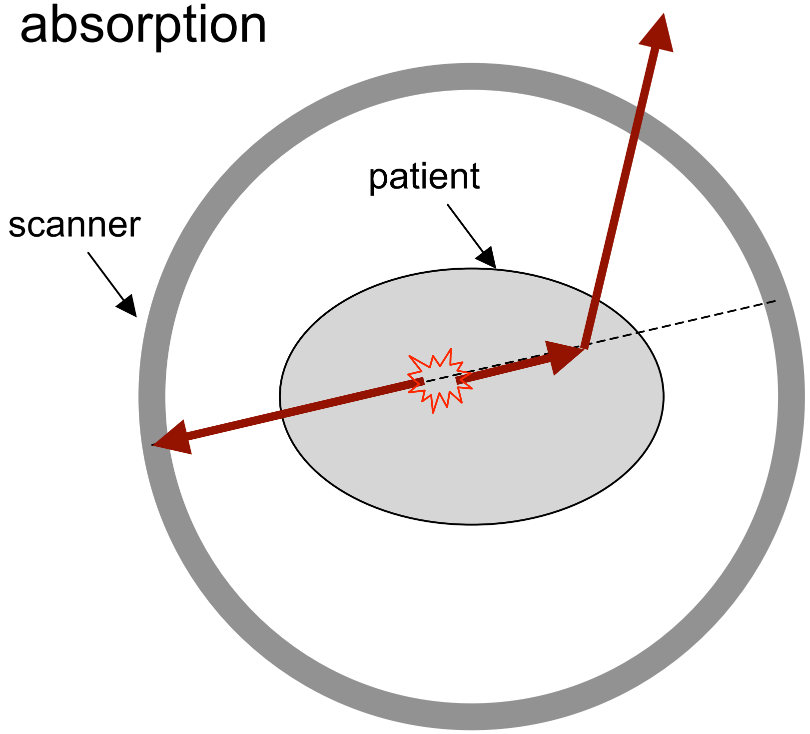
Elevated uptake of FDG (related to metabolism)

Lung cancer example: Very obvious!

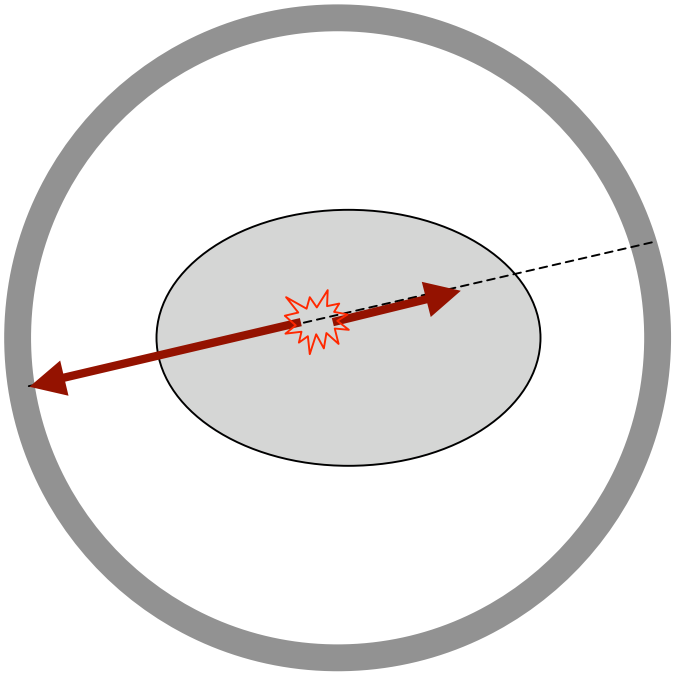
What is Attenuation?

The single most important physical effect in PET imaging:

- The number of detected photons is significantly reduced compared to the number of positron decays in a spatially-dependent manner
- For PET it is due to Compton scatter out of the detector ring
- For CT it is a combination of Compton scatter and photoelectric absorption

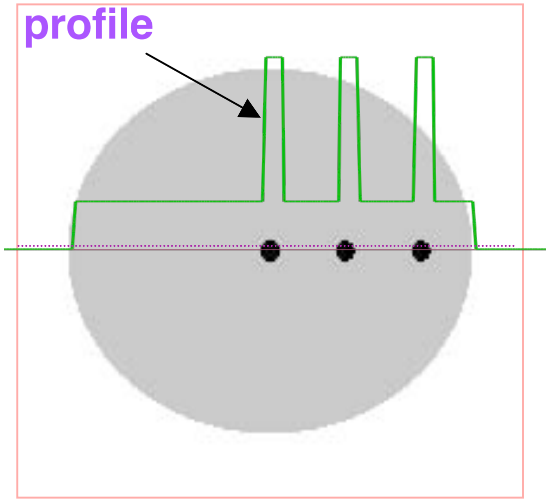


one 511 keV photon
scattered out of scanner

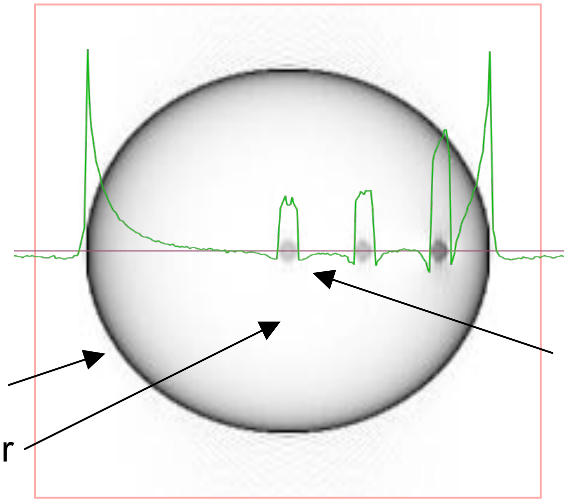


one 511 keV photon absorbed

Simulation of the Effects of *not* Performing Attenuation Correction of PET Emission Image



True PET image
(simulation of abdomen)



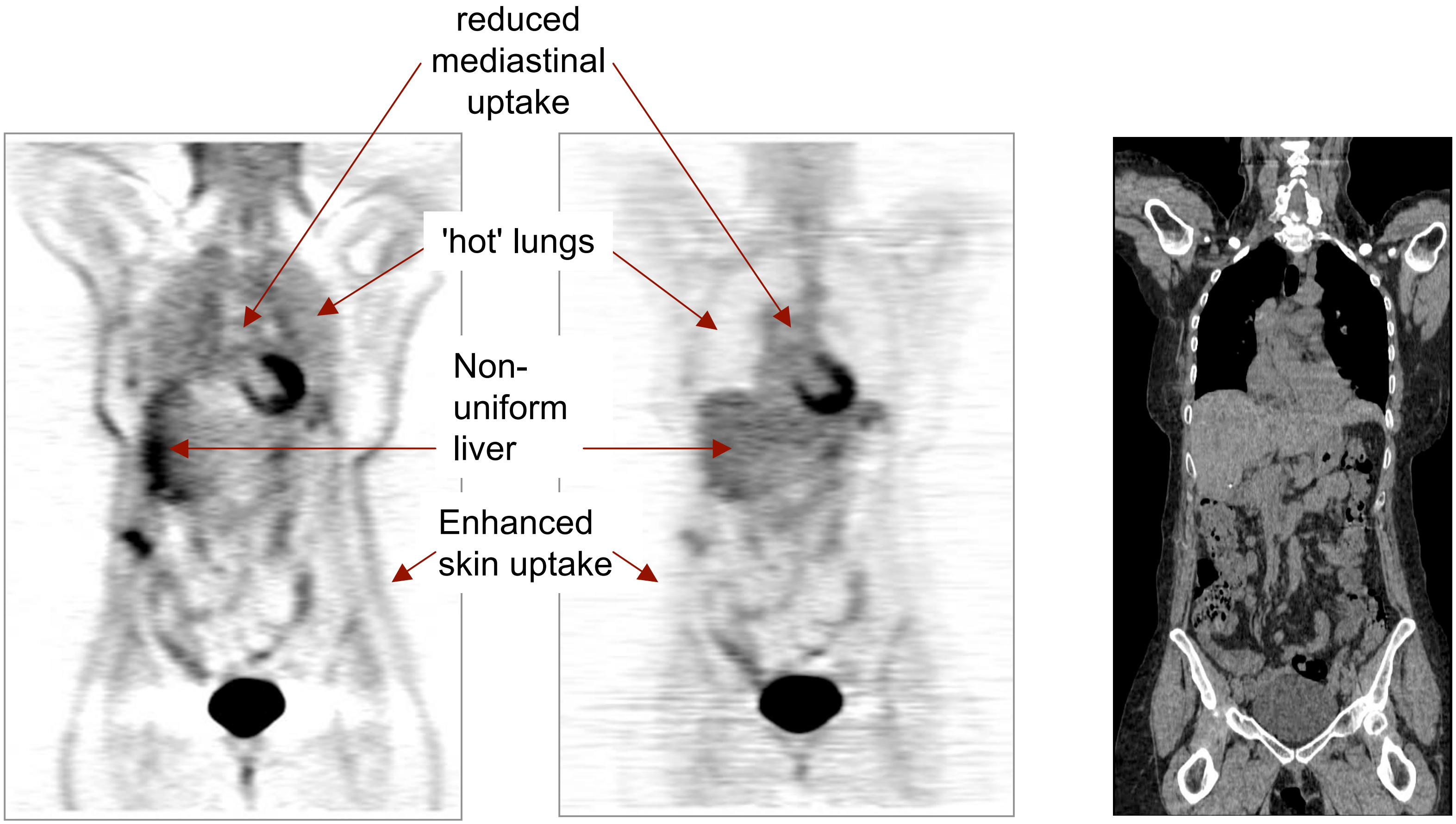
Enhanced 'skin'

Reduced interior
(even neg.!)

Locally
increased
contrast

PET image without
attenuation correction

Effects of Attenuation: Patient Study



reduced mediastinal uptake

'hot' lungs

Non-uniform liver

Enhanced skin uptake

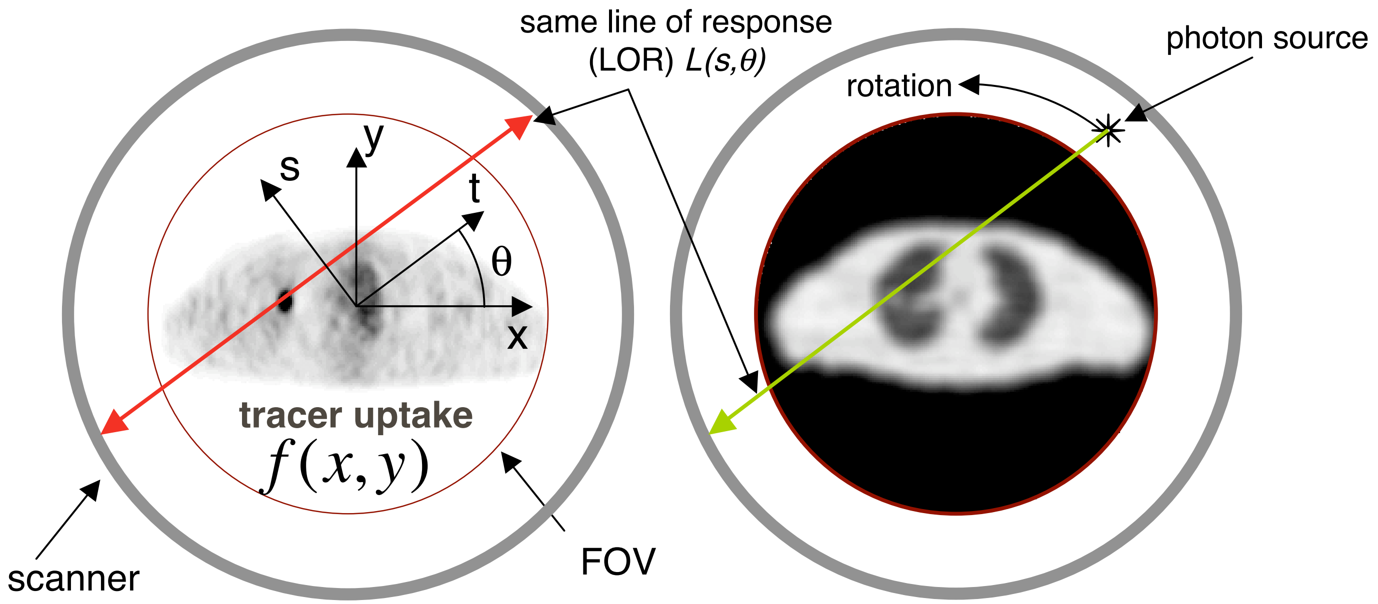
PET: without attenuation correction

PET: with attenuation correction (accurate)

CT image (accurate)

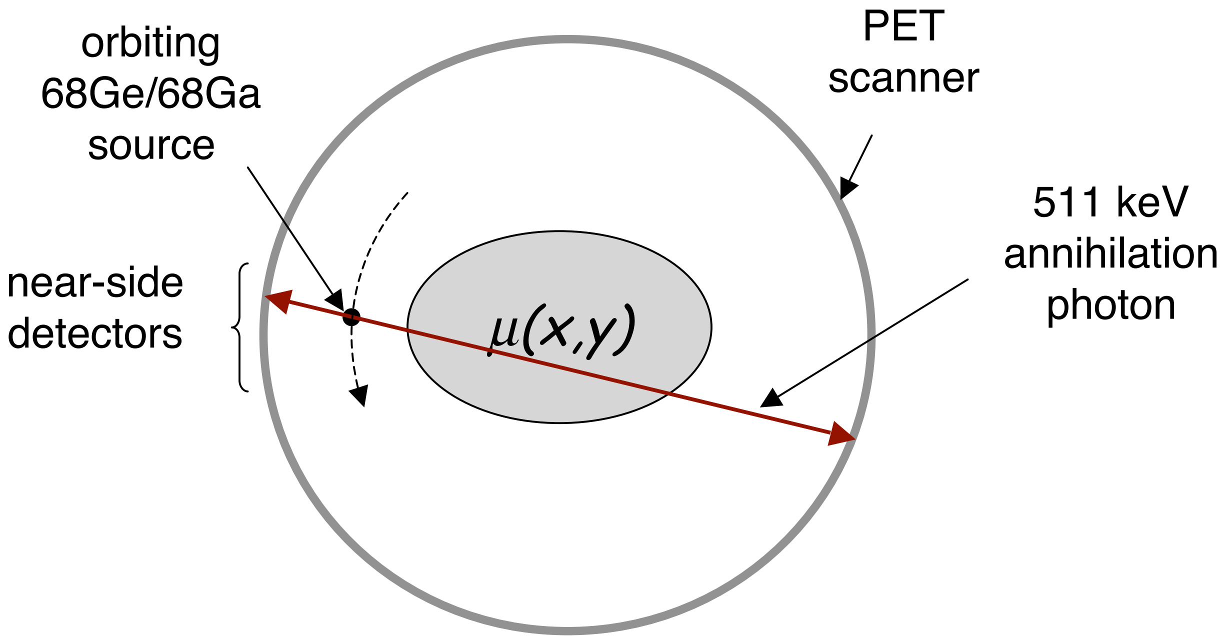
Attenuation Correction

- Transmission scanning with an external photon source is used for attenuation correction of the emission scan
- The fraction absorbed in a transmission scan, along the same line of response (LOR) can be used to correct the emission scan data
- The transmission scan can also be used to form a 'transmission' or 'attenuation' image



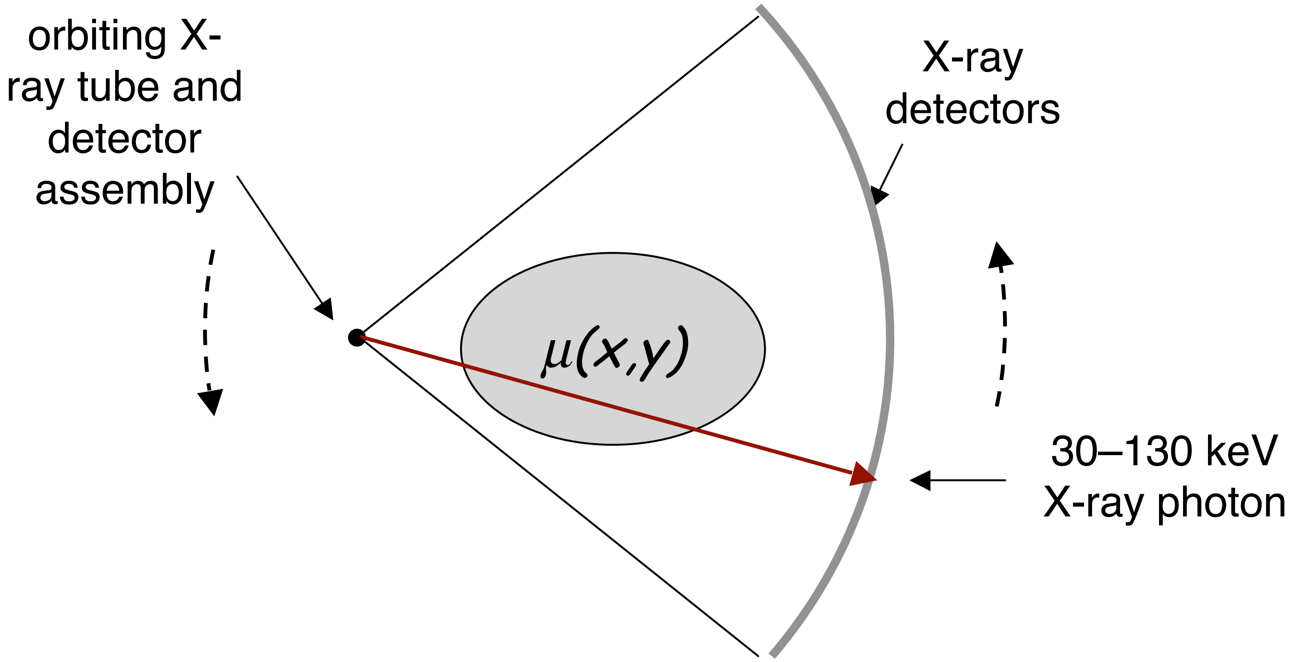
Emission scan (EM) Transmission (TX)

PET Transmission imaging (annihilation photon imaging)



- Using 3-point coincidences, we can reject TX scatter
- $\mu(x,y)$ is measured at needed value of 511 keV
- near-side detectors, however, suffer from deadtime due to high countrates, so we have to limit the source strength (particularly in 3D)

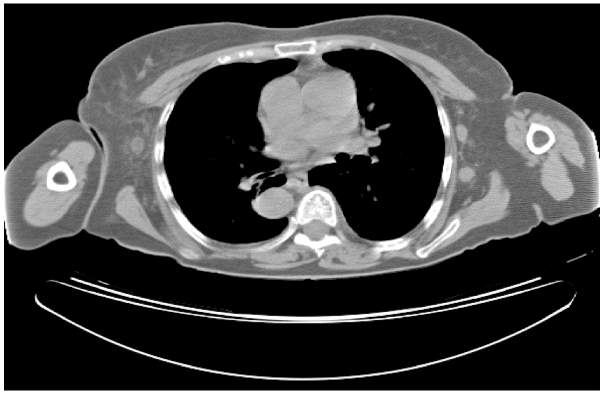
And, if you have PET/CT scanner: X-ray TX

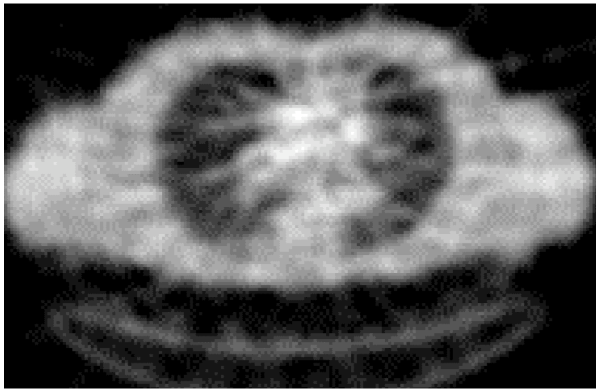


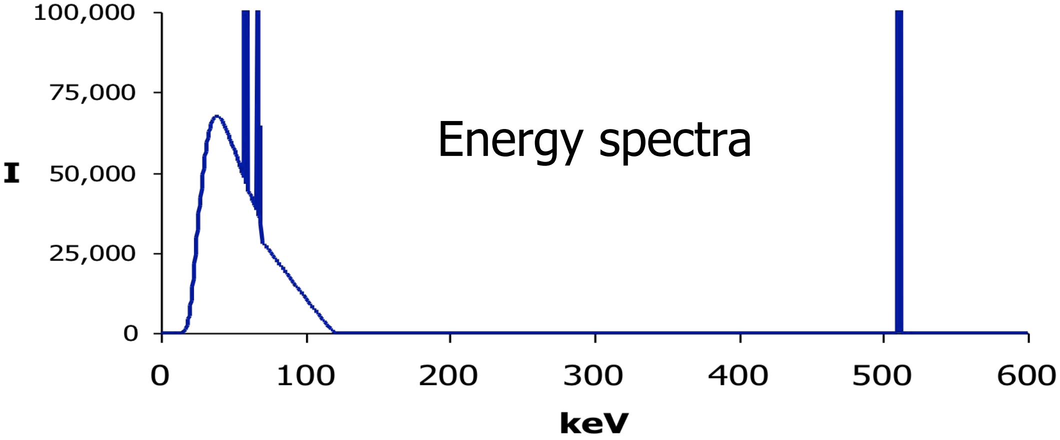
- Photon flux is <u>very</u> high, so very low noise
- Greatly improved contrast at lower photon energies.
- Scatter and beam-hardening can introduce bias.
- $\mu(x,y,E)$ is measured as an weighted average from ~30-120 keV, so $\mu(x,y,511\text{keV})$ must be calculated, potentially introducing bias

X-ray and Annihilation Photon Transmission Imaging

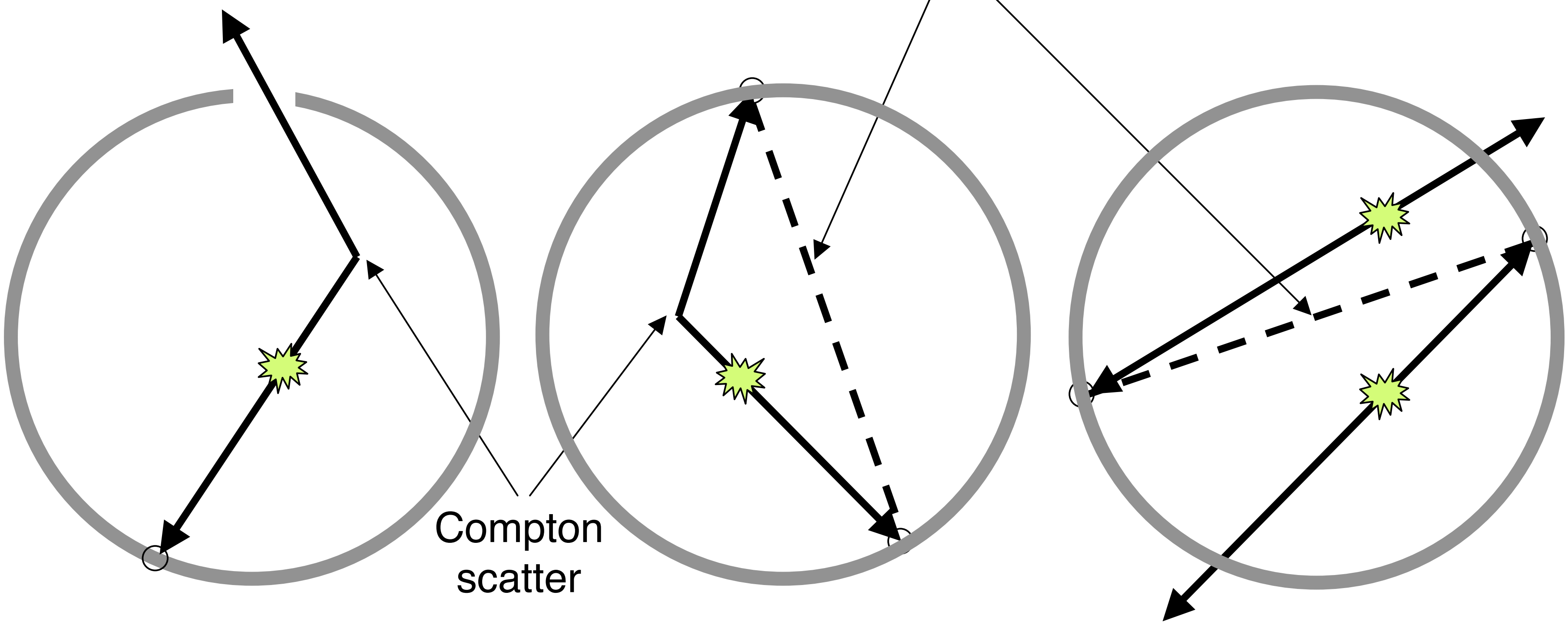
X-ray (~30-120 keV)	**PET Transmission** (511 keV)
Low noise	Noisy
Fast	Slow
Not a physical quantity	Linear attenuation coeffcient at 511 keV







Quantitative errors in measurement



no LOR

incorrectly determined LORs

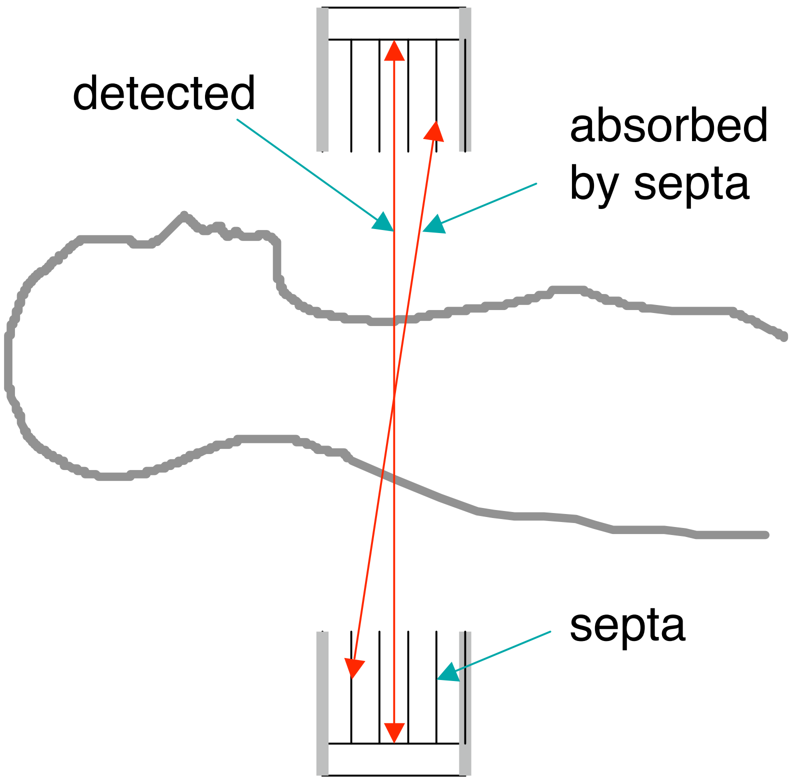
Compton scatter

Lost (attenuated) event

Scattered coincidence event

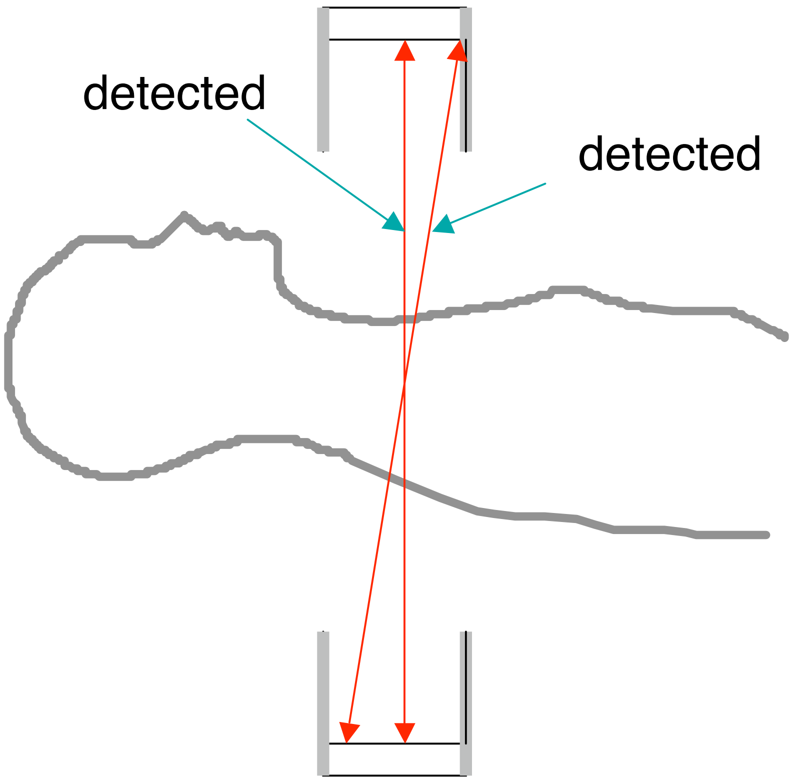
Random coincidence event

3D versus 2D PET imaging



2D Emission Scan

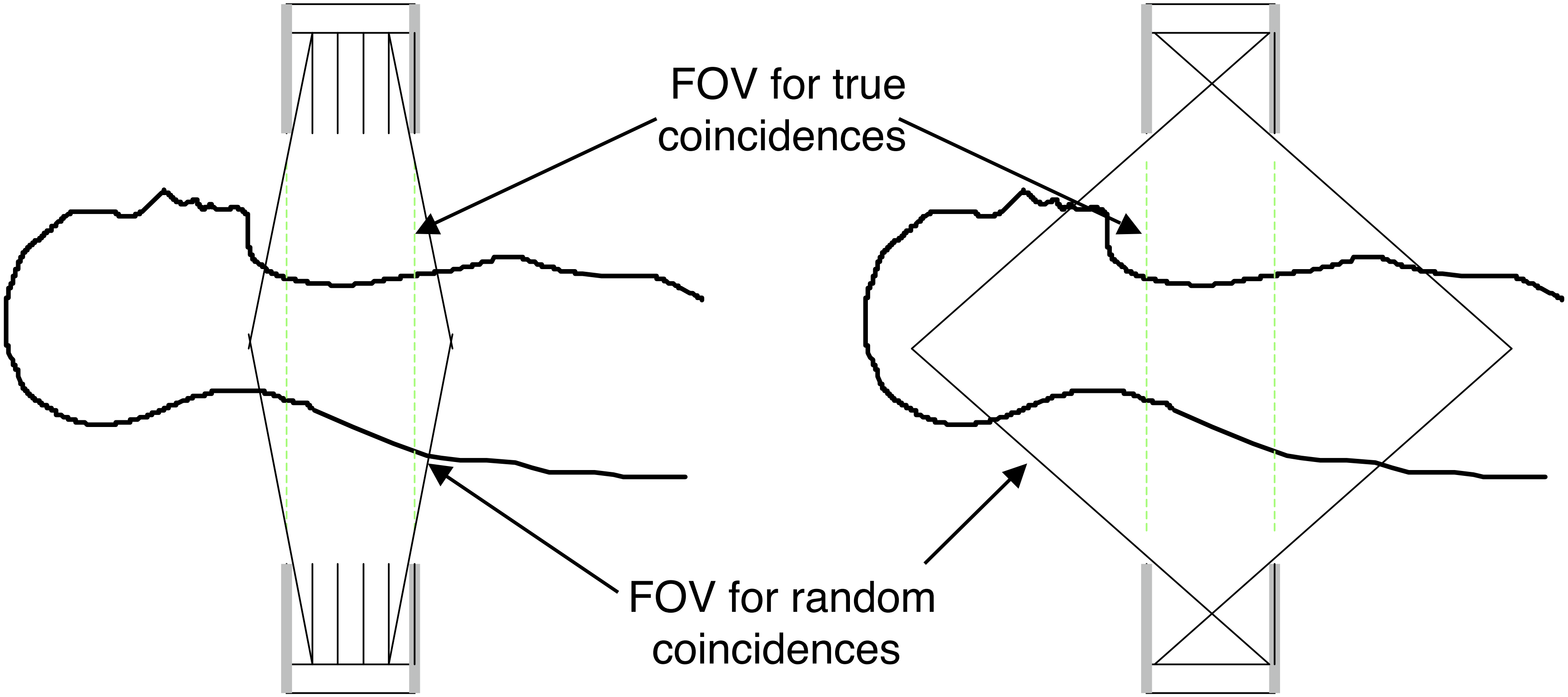
✓ fewer true, scattered, and random coincidences



3D Emission Scan

✓ more true, scattered, and random coincidences

Effect of random coincidence corrections in 2D and 3D



FOV for true coincidences

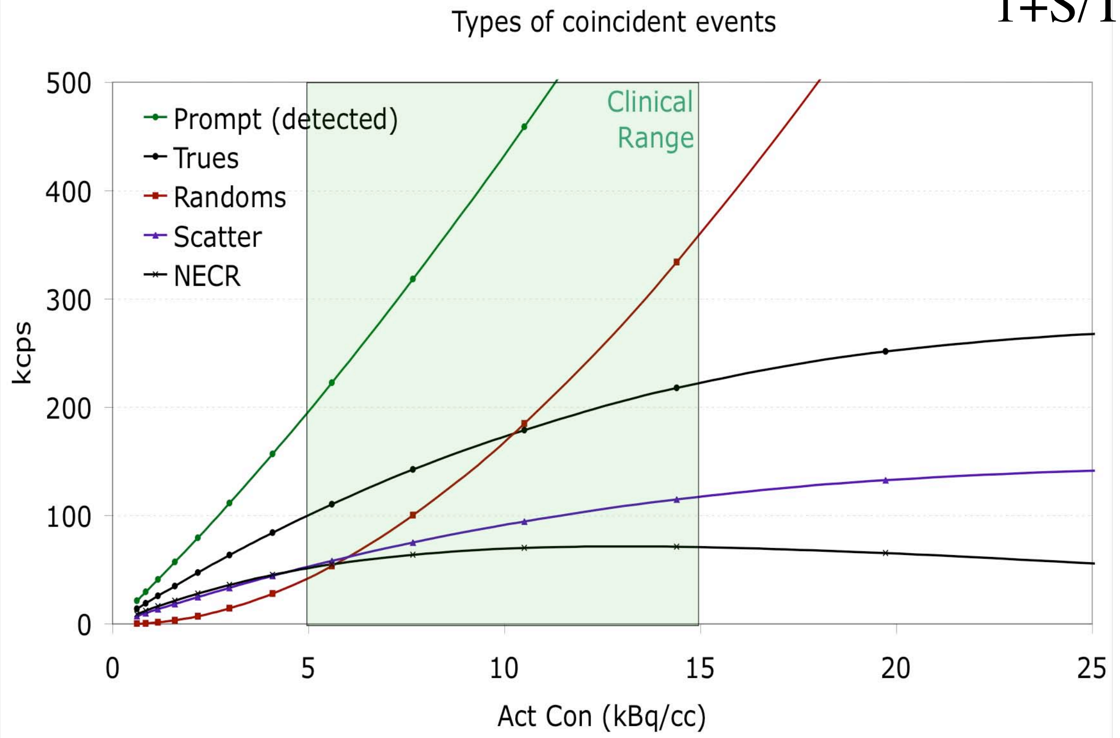
FOV for random coincidences

2D Emission Scan

3D Emission Scan

Noise Equivalent Counts or NEC

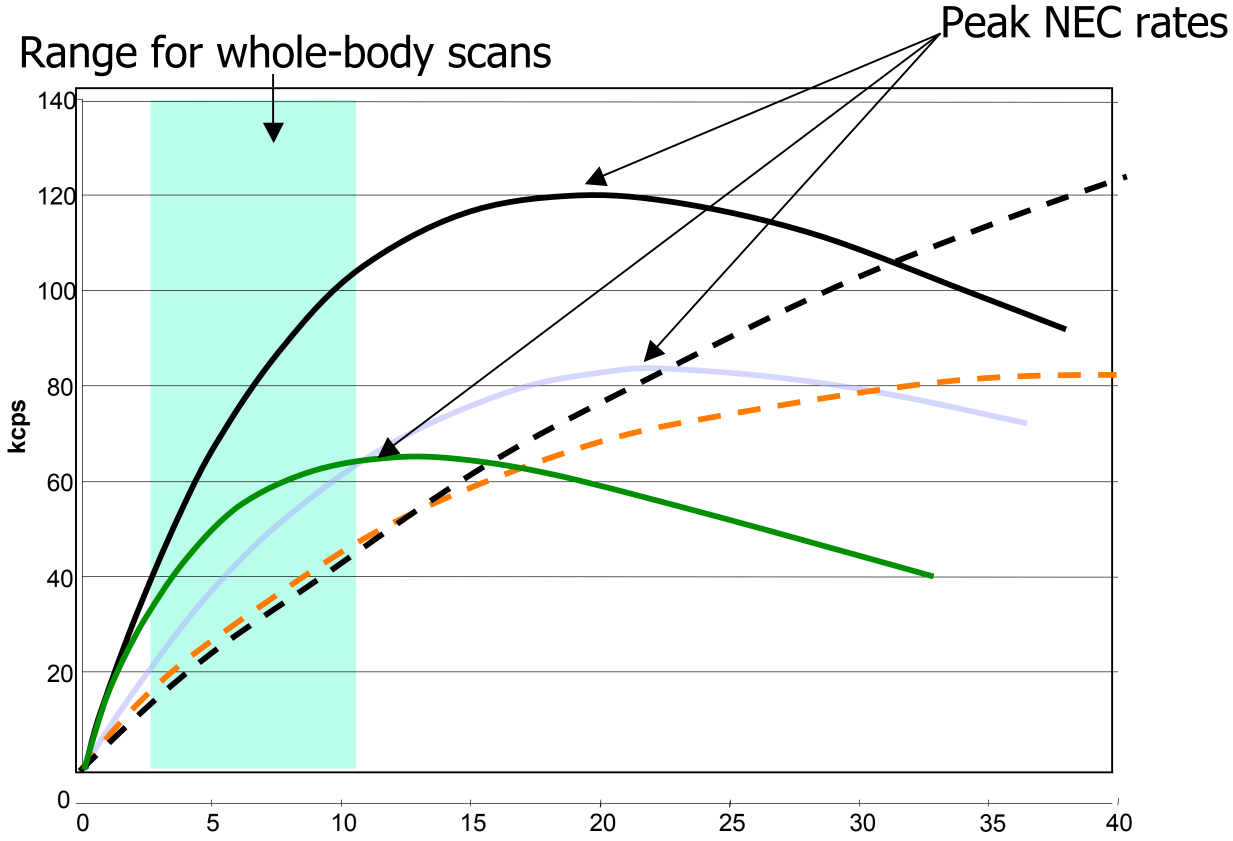
- NEC ~ 'Effective' count rate
- Prompt coincidences are what the scanner sees: P=T+S+R
- but true coincidences are what we want: T=P-S-R, which adds noise
- $$\mathrm{SNR}^2 \propto \mathrm{NEC} = \frac{\mathrm{T}}{1+\mathrm{S/T}+\mathrm{R/T}}$$



In this measured example, at 10 kBq/cc (about 6 mCi) the scanner's count rate for coincidences will be ~450 kcps, but the effective count rate (aka NEC) will be only ~75 kcps

NEC comparisons

- Major arguing point for some vendors
- Determined partly by detector type, detector and scanner geometry, acquisition mode, and front-end electronics
- Important, but not sole factor for image quality

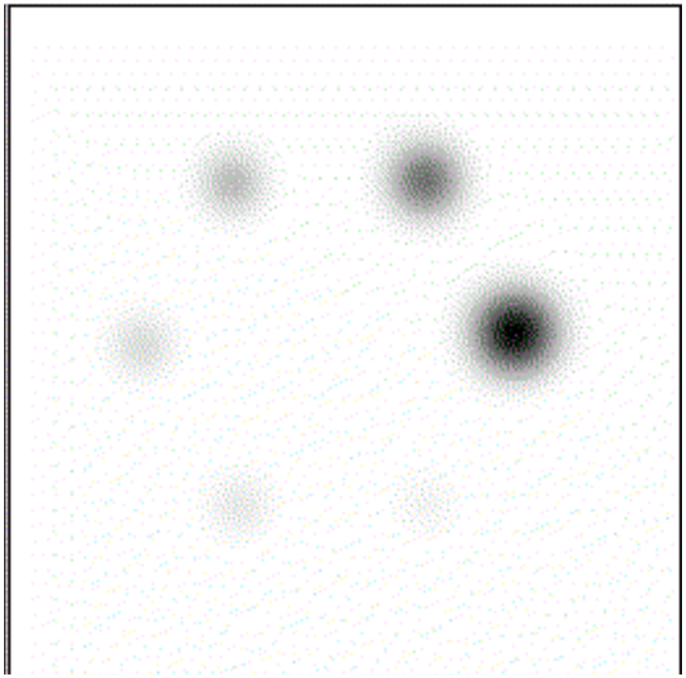

Range for whole-body scans

Peak NEC rates

Partial Volume Effect

- <u>Apparent</u> SUV drops with volume
- Also effected by image smoothing

Fillable spheres



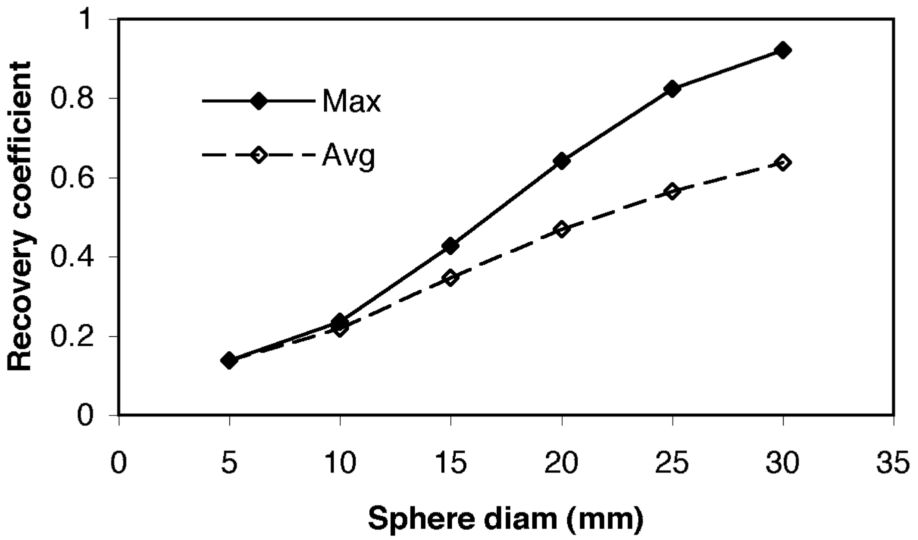
Final Image

PET Resolution Losses

true tracer uptake

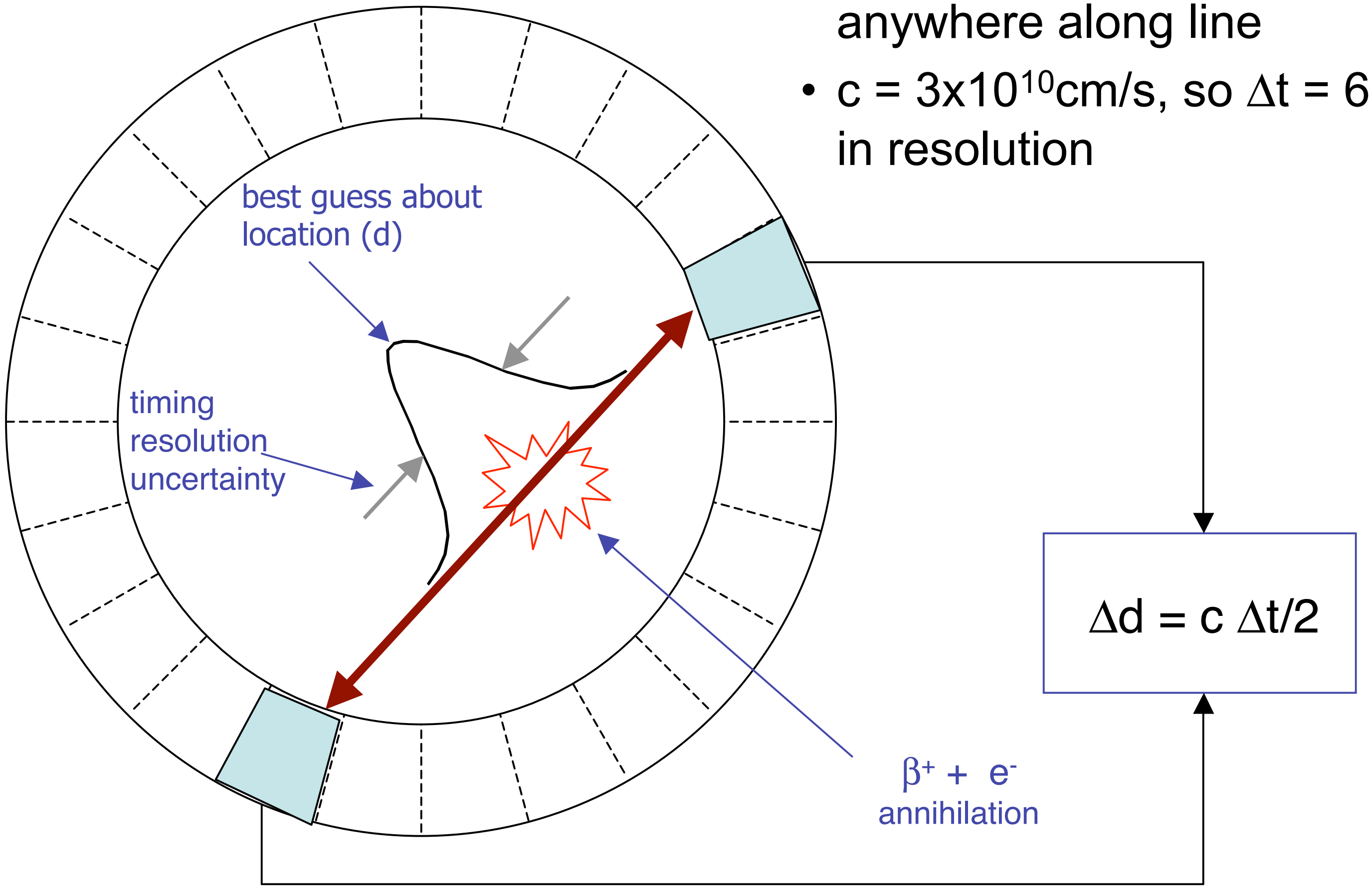
reconstructed values
(scanner resolution + smoothing of noisy data)

- Simulation study with typical imaging protocols
- Limits quantitation in oncology imaging, important for following therapy if size changes



Time of Flight (TOF) PET/CT

- Uses difference in photon detection times to guess at tracer emission point
- without timing info, emission point could be anywhere along line
- c = 3x10^{10}cm/s, so Δt = 600 ps ~ Δd = 10 cm in resolution



Philips Gemini TF

PET scanner

LYSO : 4 x 4 x 22 mm^3

28,338 crystals, 420 PMTs

70-cm bore, 18-cm axial FOV

CT scanner

Brilliance 16-slice

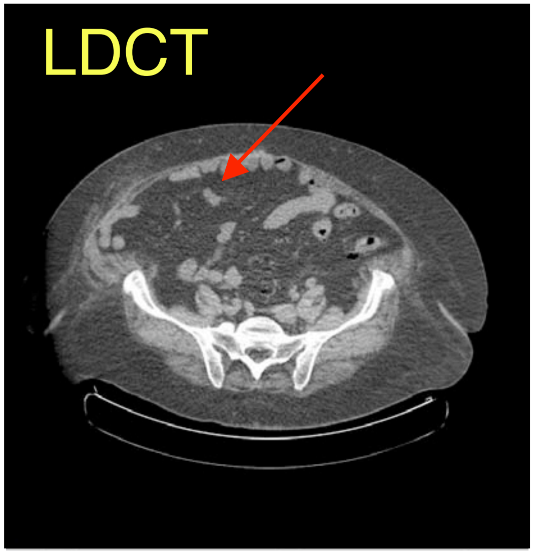
Installation at U.Penn	Nov ’05	
Validation and research patient imaging		
	Nov ’05 – Apr ’06	*50 patients*
Beta testing and upgrade to production release software		
	May ’06 – Jun ’06	*40 patients (to date)*

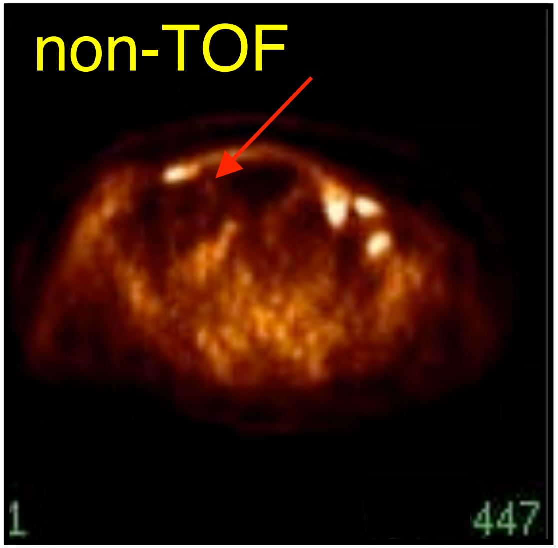
Heavy-weight patient study

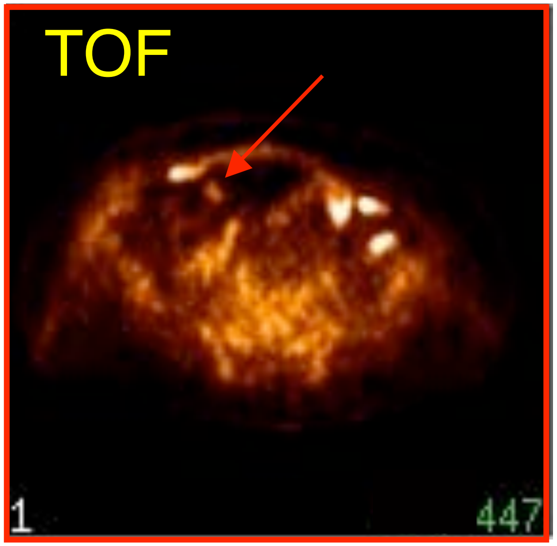
Colon cancer

119 kg
BMI = 46.5

13 mCi
2 hr post-inj
3 min/bed







Improvement in lesion detectability with TOF