

This is what you should know after this lecture + own work:

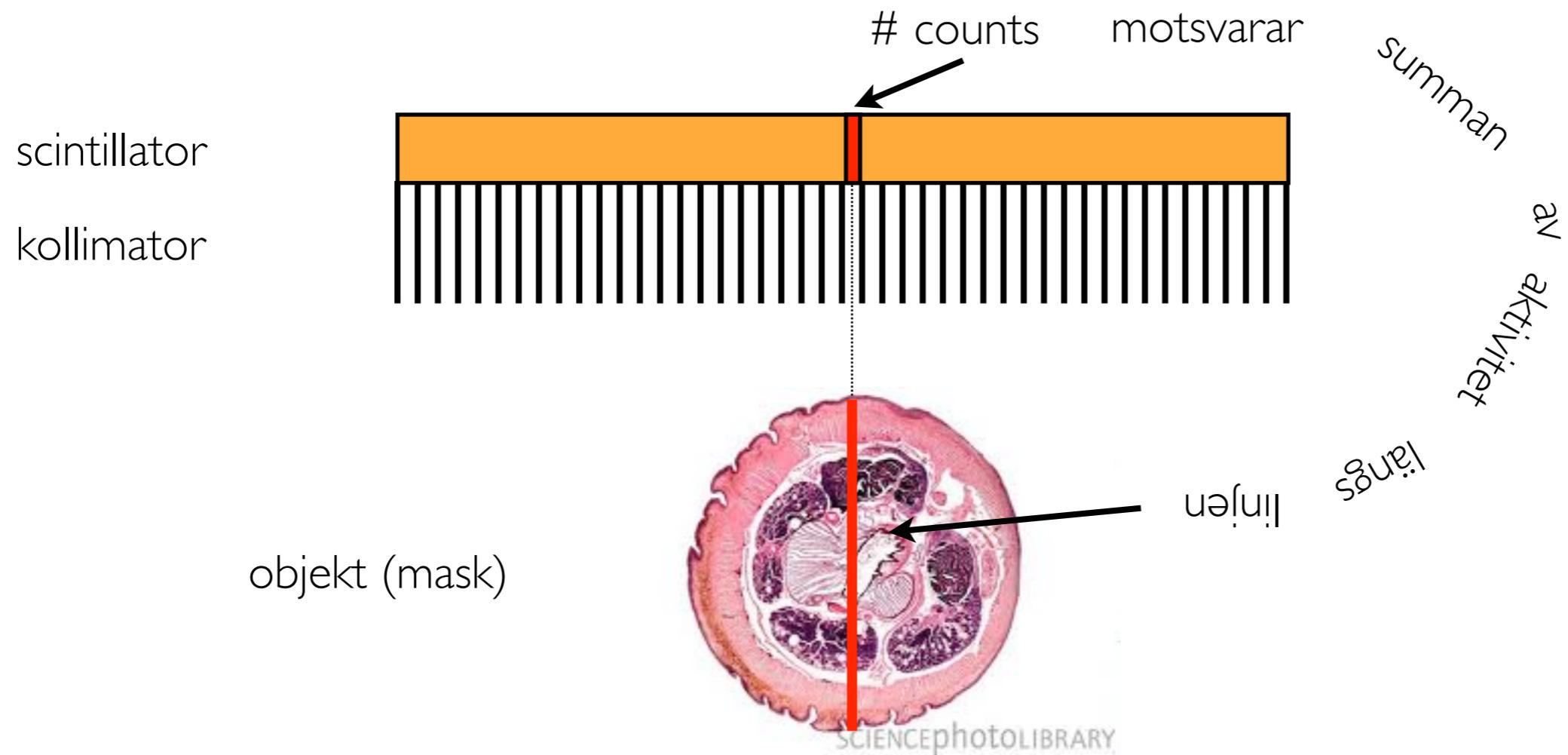
1. Explain why one needs to perform *attenuation correction* in emission imaging
2. For a gamma camera or a PET scanner estimate count rate given activity and attenuation distribution. In simple cases, from the count rate and attenuation map estimate the activity distribution.
3. Describe how SPECT imaging works
4. Describe the rationale behind PET imaging
5. List the different kinds of coincidences in PET acquisition
6. List the main components of a PET scanner and describe how different detector designs influence image quality.
7. Explain why using different isotopes in both SPE and PET influences image quality

Emission 3

(SPECT and PET)

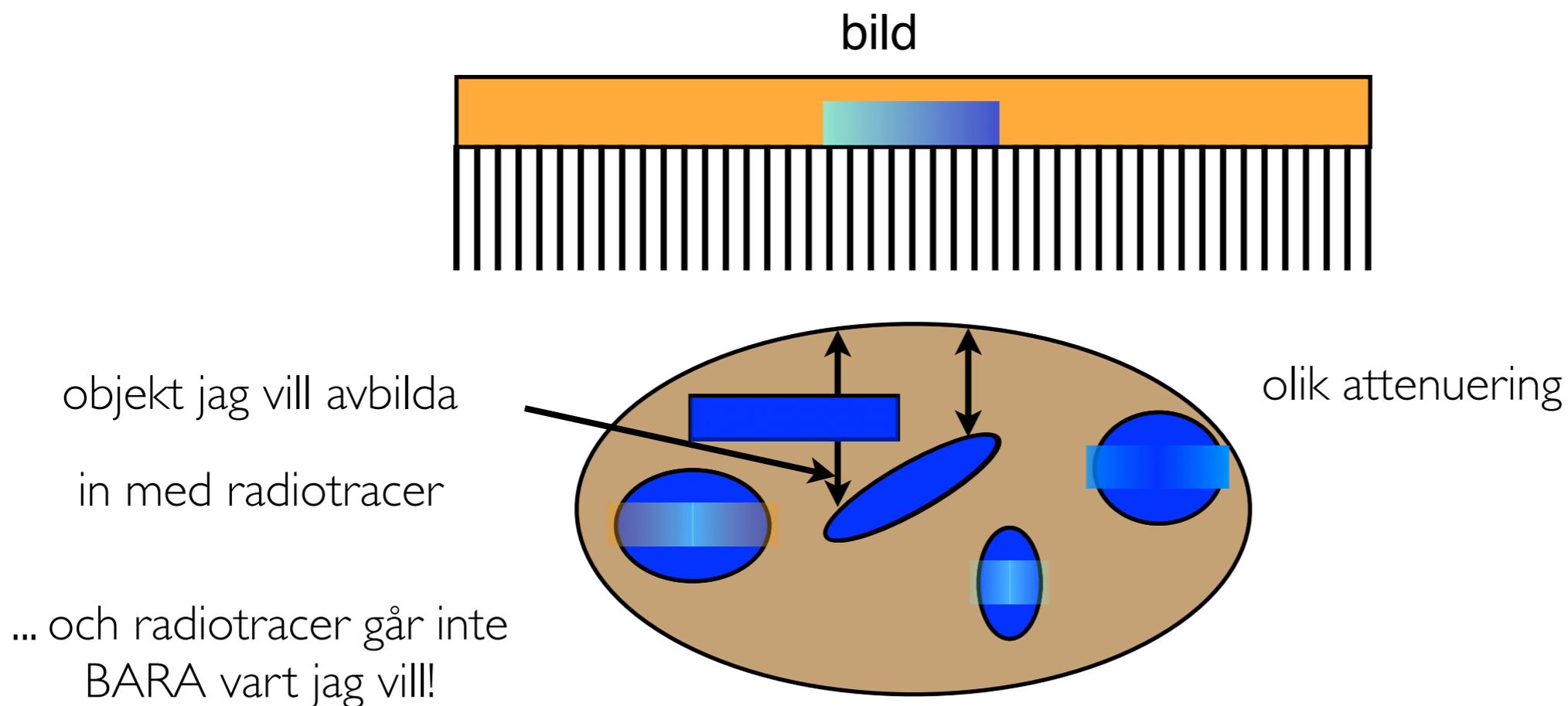
snabb sammanfattning av tidigare avsnitt

i bästa möjliga fall:



goal: aktivitetesfördelning (aktivitet och position)

Några problem



Viktigt med radiotracer som är organspecifika!

Viktigt med attenueringskorrektion (CT)

Ett enkelt exempel av: från räknehastigheten och
attenuering bestäm aktivitet

Vad är "imaging task" i emission? (och i "Single Photon Emission" avbildning i synnerhet)

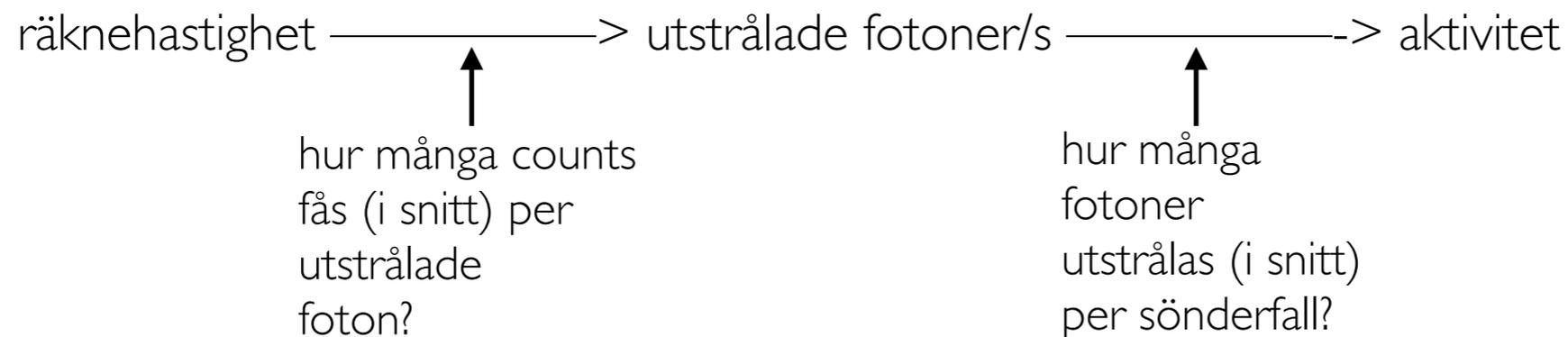
Vi startar enkelt:



Under 100 s fås 10000 counts i ett område på kameran på 50 pixels.
Uppskatta källans aktivitet och position.

I. Källans aktivitet.

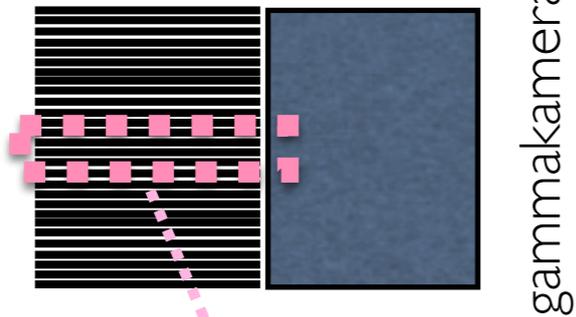
Kom ihåg de "stora" stegen i lösningen:



Att göra: effektivitet
måste mätas eller
uppskattas

Att göra: kolla
sönderfallsschemat


 ^{99m}Tc punktkälla

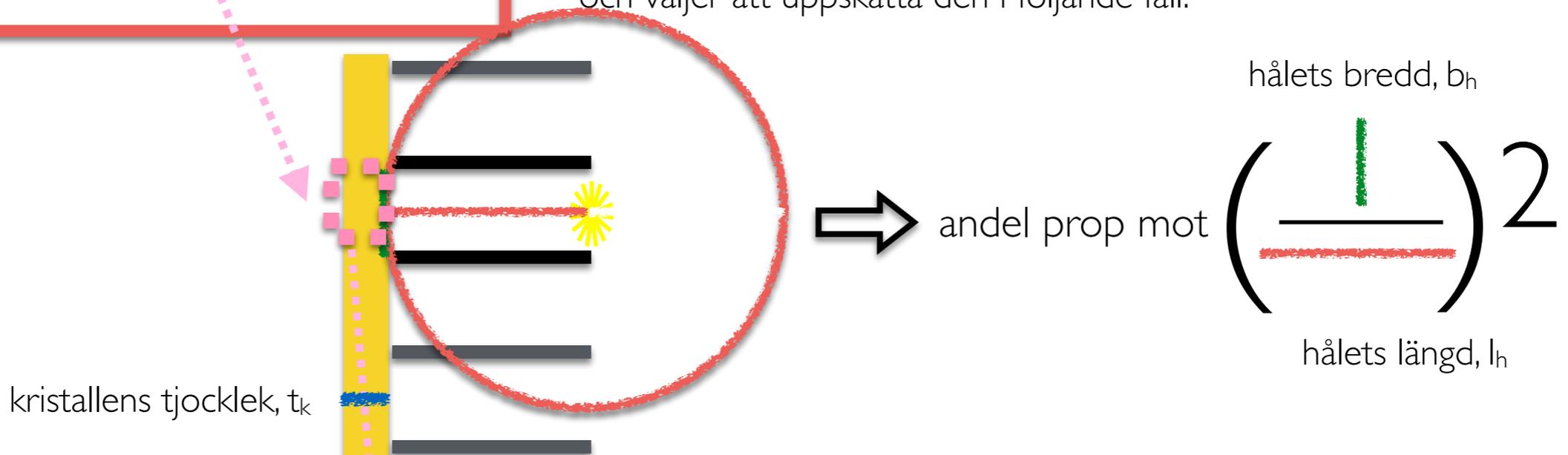


Under 100 s fås 10000 counts

Räknehastighet, r , är 100 cps (antal counts/insamlingstid)

Hur stor andel utstrålade fotoner träffar detektor?

Utnyttjar att effektivitet är oberoende av avståndet och väljer att uppskatta den i följande fall:



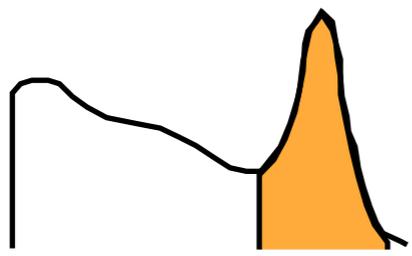
kristallens tjocklek, t_k

Låt oss antaga att hålen är fyrkantiga, vi kan uppskatta geometriska effektivitet till:

$$\eta_{\text{geo}} \approx \frac{b_h^2}{4\pi l_h^2}$$

Nu tittar vi på fotoner som har träffat kristallen. Hur stor andel detekteras? (denna andel kallas *intrinsic efficiency*)

$$\eta_{\text{int}} \approx 1 - e^{-\mu(E_\gamma)t_k}$$



Låt oss antaga att bara 50% växelverkar via PE, då är intrinsic efficiency vid photopeak:

$$\eta_{\text{int}}^{\text{PP}} \approx 0,5(1 - e^{-\mu(E_\gamma)t_k})$$

Vi kan då uppskatta antal utstrålade fotoner/s, u_{fps} , till:

$$u_{\text{fps}} \approx \frac{r}{\eta_{\text{geo}}\eta_{\text{int}}^{\text{PP}}} \approx \frac{r}{\frac{b_h^2}{4\pi l_h^2} \cdot 0,5(1 - e^{-\mu(E_\gamma)t_k})}$$

räknehastighet → utstrålade fotoner/s

→ aktivitet



^{99m}Tc punktkälla



gammakamera

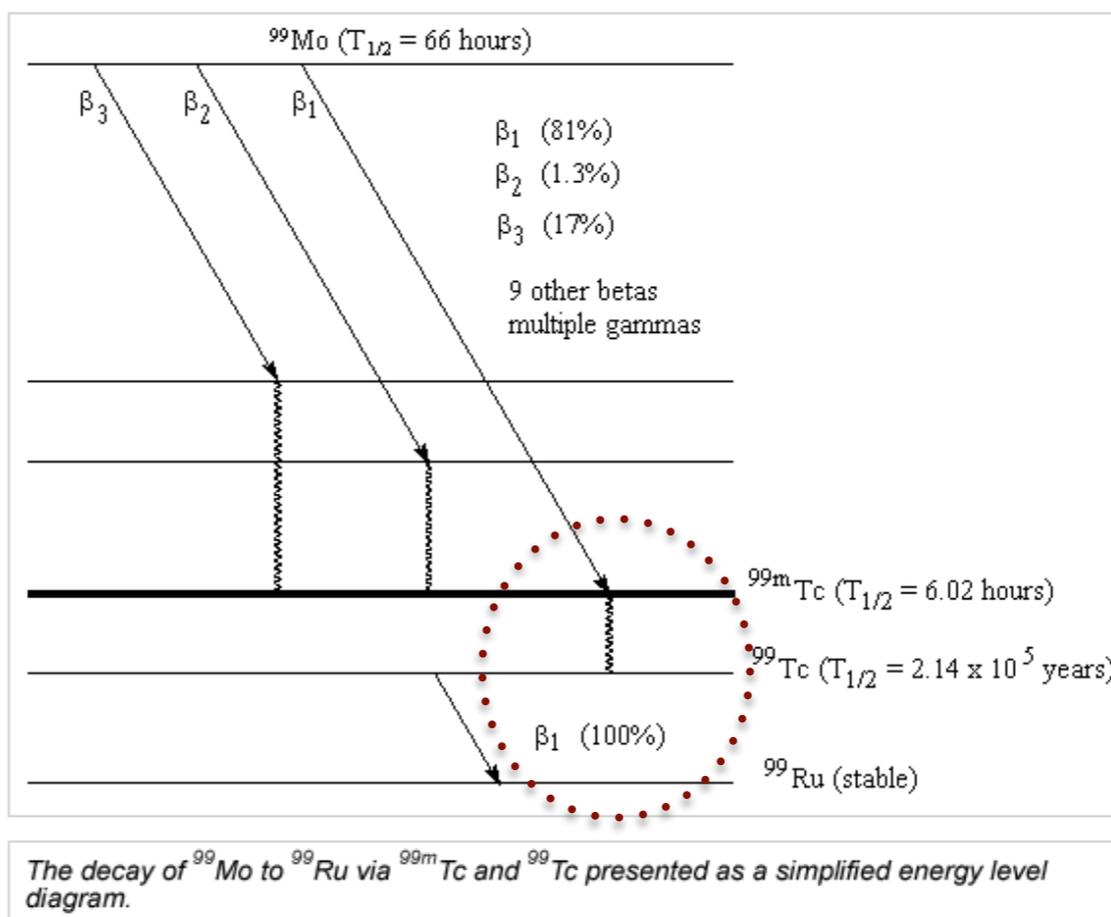
Under 100 s fås 1 Mcounts

Räknehastighet, r, är 100 cps (antal counts/insamlingstid)

Antal utstrålade fotoner/s, u_{fps}

$$u_{fps} \approx \frac{r}{\eta_{geo} \eta_{int}^{PP}} \approx \frac{r}{\frac{b_h^2}{4\pi l_h^2} \cdot 0,5(1 - e^{-\mu(E_\gamma)t_k})}$$

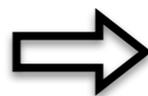
För ^{99m}Tc är antal utstrålade fotoner/s = aktivitet



Om vi tar:

Kristall: Csl, 8 mm tjock

Kollimator: hålbredd 0,8 mm, hållängd 20 mm



Källans aktivitet ≈ 1,7 MBq

räknehastighet



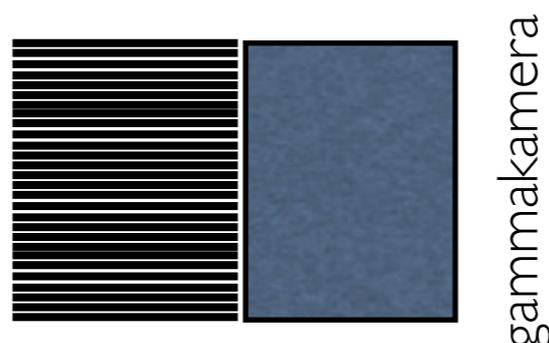
utstrålade fotoner/s



aktivitet

Vad är "imaging task" i emission? (och i "Single Photon Emission" avbildning i synnerhet)

Vi startar enkelt:

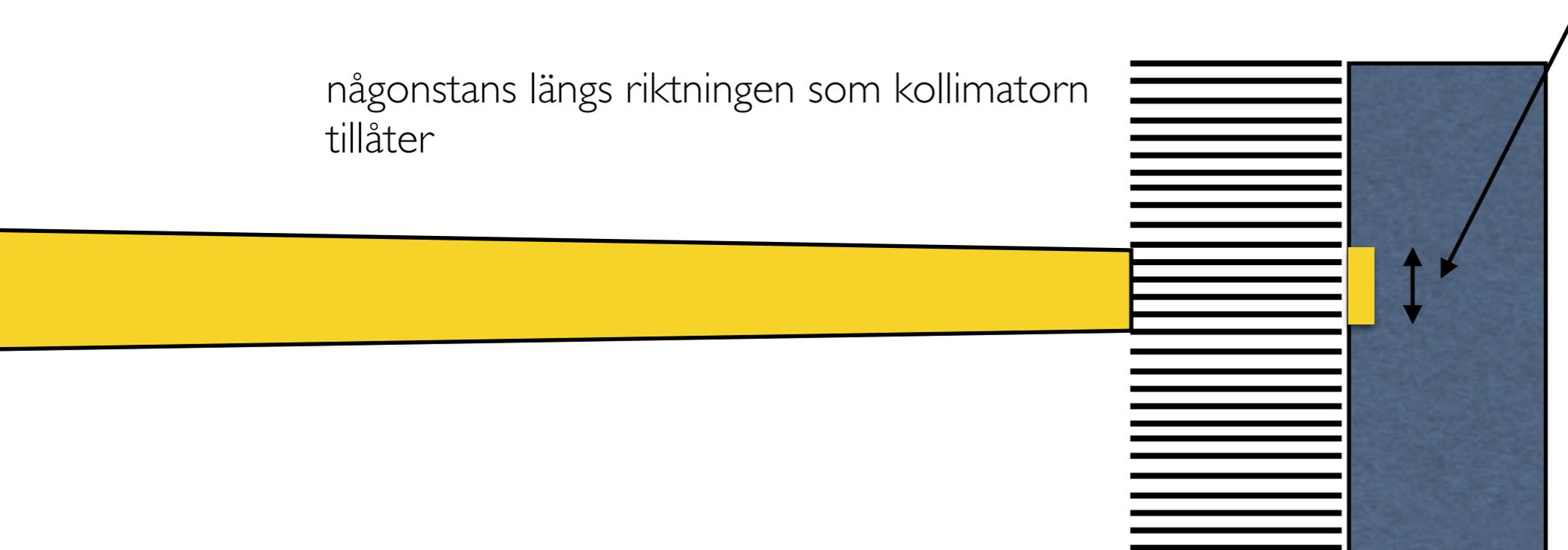


Under 100 s fås 10000 counts i ett område på kameran på 50 pixels.
Uppskatta källans aktivitet och position.

2. Källans position.

någonstans längs riktningen som kollimatoren tillåter

projektion på detektor motsvarar
50 px => längden är cirka 7 px



Vad är "imaging task" i emission? (och i "Single Photon Emission" avbildning i synnerhet)

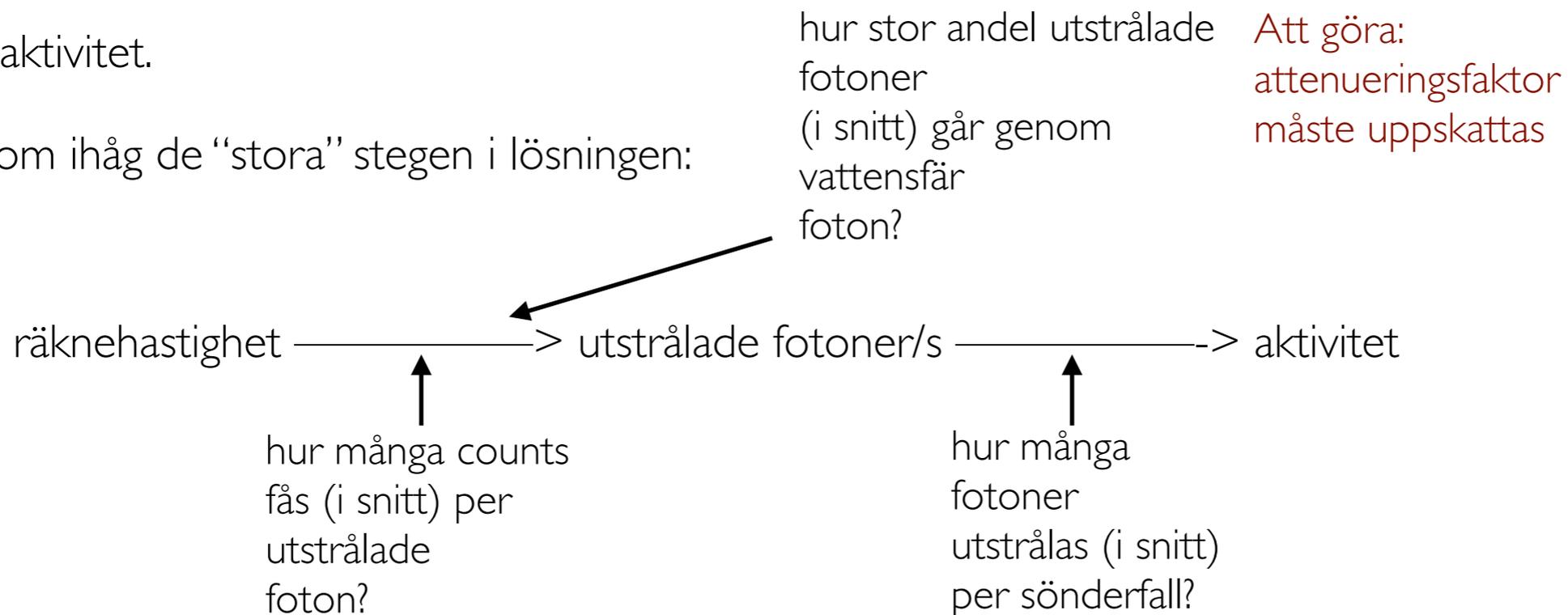
Vi fortsätter med mindre enkelt:



Under 100 s fås 10000 counts i ett område på kameran på 50 pixels.
Uppskatta källans aktivitet och position.

I. Källans aktivitet.

Kom ihåg de "stora" stegen i lösningen:



hur stor andel utstrålade fotoner (i snitt) går genom vattensfär foton?

Att göra: attenueringsfaktor måste uppskattas

Att göra: effektivitet måste mätas eller uppskattas

Att göra: kolla sönderfallsschemat

Vad är "imaging task" i emission? (och i "Single Photon Emission" avbildning i synnerhet)

Vi fortsätter med mindre enkelt:



Under 100 s fås 10000 counts i ett område på kameran på 50 pixels.
Uppskatta källans aktivitet och position.

I. Källans aktivitet.

Kom ihåg de "stora" stegen i lösningen:

hur stor andel utstrålade
fotoner
(i snitt) går genom
vattensfär
foton?

räknehastighet $\xrightarrow{\hspace{10em}}$ utstrålade fotoner/s $\xrightarrow{\hspace{10em}}$ aktivitet

↑
hur många counts
fås (i snitt) per utstrålade
foton som har gått genom
vattensfär?

↑
hur många
fotoner
utstrålas (i snitt)
per sönderfall?

Att göra: effektivitet
måste mätas eller
uppskattas

Att göra: kolla
sönderfallsschemat

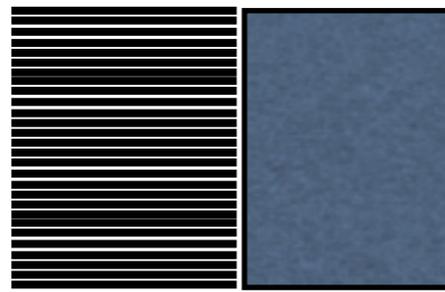
Vi fortsätter med mindre enkelt:



Utan att ta hänsyn till att källan var i en vattensfär hade vi uppskattat dess aktivitet till 1,7 MBq. Men källan var i en vattensfär och därför är det riktiga aktivitet:

1. Lägre än 1,7 MBq
2. 1,7 MBq, vi har ju precis räknat ut det!
3. Högre än 1,7 MBq
4. Det går inte att säga något

Vi fortsätter med mindre enkelt:



gammakamera

NIST-tabell
för vatten

Energy (MeV)	μ/ρ (cm ² /g)
1.00000E-03	4.078E+03
1.50000E-03	1.376E+03
2.00000E-03	6.173E+02
3.00000E-03	1.929E+02
4.00000E-03	8.278E+01
5.00000E-03	4.258E+01
6.00000E-03	2.464E+01
8.00000E-03	1.037E+01
1.00000E-02	5.329E+00
1.50000E-02	1.673E+00
2.00000E-02	8.096E-01
3.00000E-02	3.756E-01
4.00000E-02	2.683E-01
5.00000E-02	2.269E-01
6.00000E-02	2.059E-01
8.00000E-02	1.837E-01
1.00000E-01	1.707E-01
1.50000E-01	1.505E-01
2.00000E-01	1.370E-01
3.00000E-01	1.186E-01
4.00000E-01	1.061E-01
5.00000E-01	9.687E-02
6.00000E-01	8.956E-02
8.00000E-01	7.865E-02
1.00000E+00	7.072E-02
1.25000E+00	6.323E-02
1.50000E+00	5.754E-02
2.00000E+00	4.942E-02
3.00000E+00	3.969E-02
4.00000E+00	3.403E-02
5.00000E+00	3.031E-02

Låt oss säga att vattensfär har en radie på 5 cm. Uppskatta källans aktivitet som, utan attenueringskorrektion, uppskattades till 1,7 MBq.

Antal fotoner som når detektor har attenuerats med:

$$e^{-0,146 \frac{\text{cm}^2}{\text{g}} \cdot 1 \frac{\text{g}}{\text{cm}^3} \cdot 5\text{cm}} \approx 0,48$$

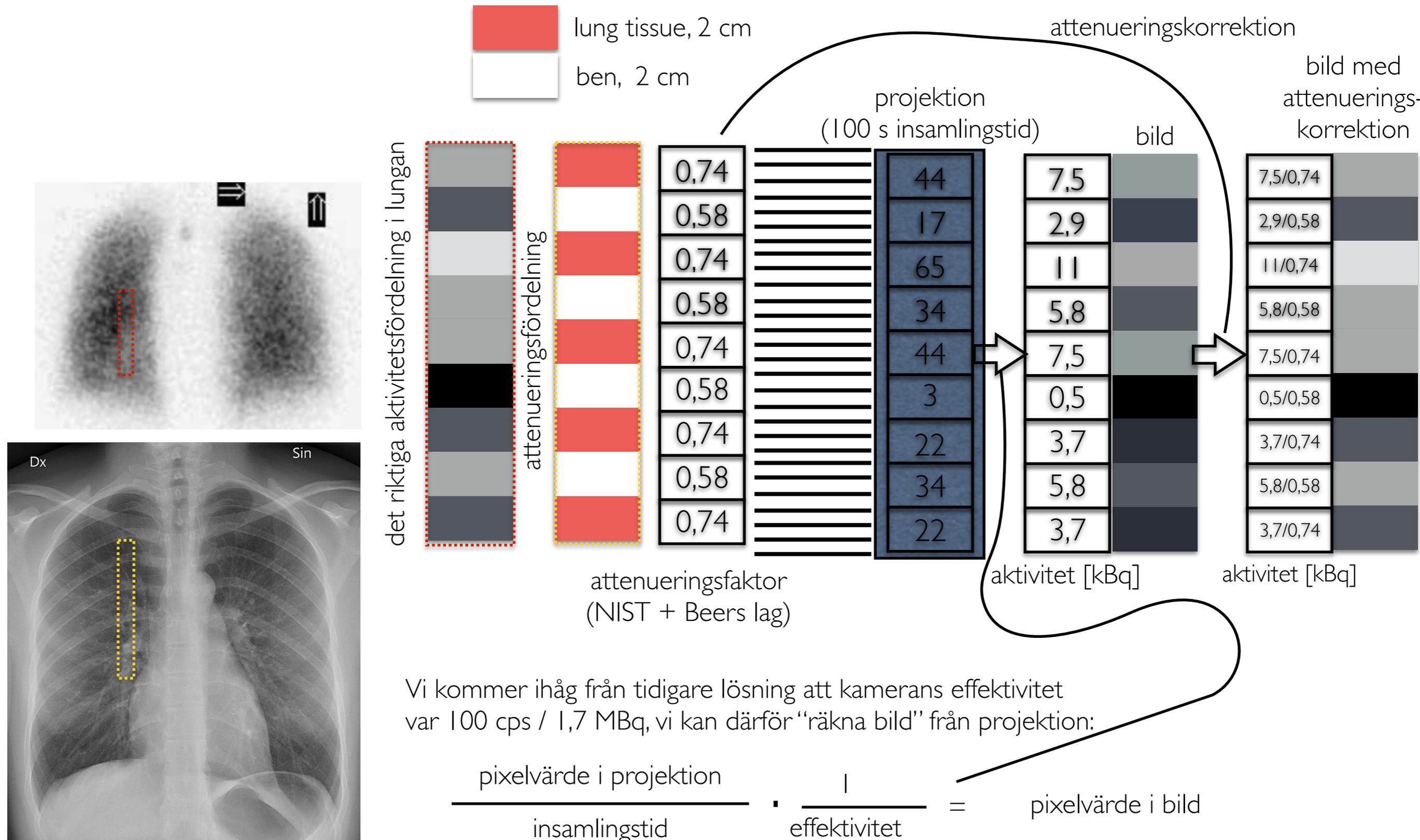
Aktivitet uppskattas då till:

$$\frac{1,7 \text{ MBq}}{0,48} \approx 3,5 \text{ MBq}$$

Ett mindre enkelt exempel av: från räknehastigheten och attenuering bestäm aktivitet

OK mammo, jättekul med punktkällor men, please, ge oss någon form av klinisk relevans!!!!!!!

(jag skall göra mitt bästa, men måste ändå förenkla så att det går att enkelt räkna på, OK?)

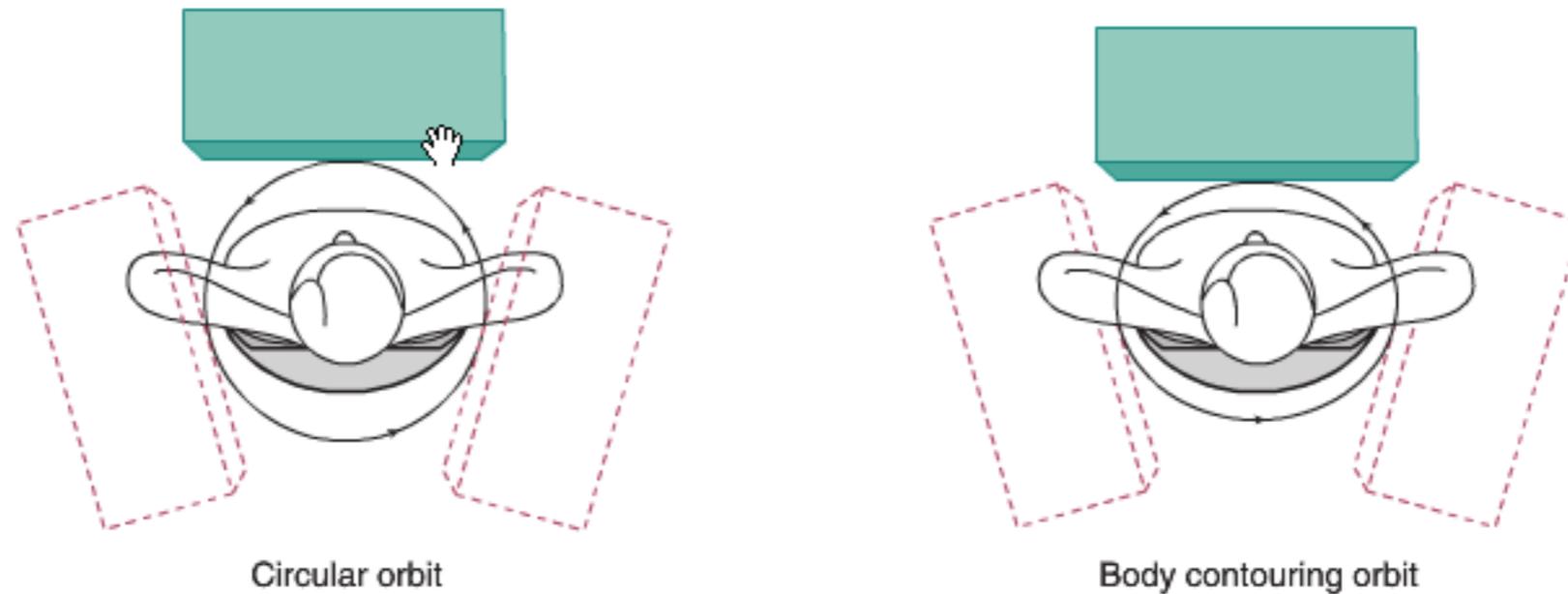


Vi kommer ihåg från tidigare lösning att kamerans effektivitet var 100 cps / 1,7 MBq, vi kan därför "räkna bild" från projektion:

Single Photon Emission Computed Tomography

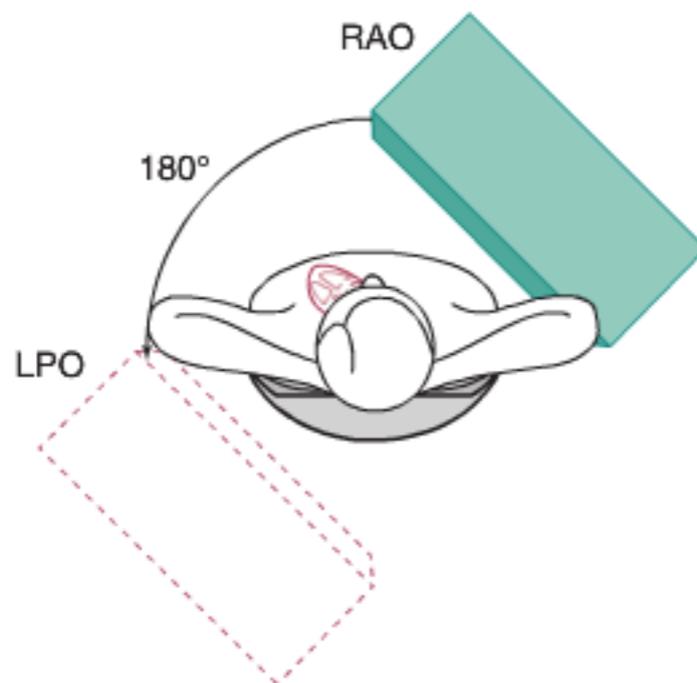
Single Emission Computed Tomography

(ofta gör man också en CT för attenuation korrektion)

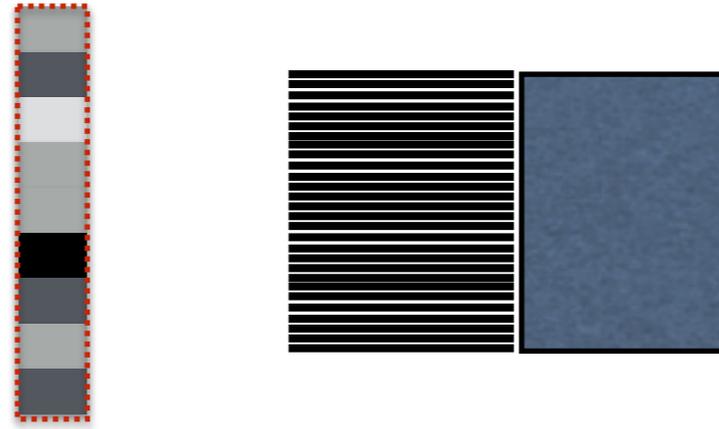


■ FIGURE 19-3 Circular (A) and body-contouring (B) orbits.

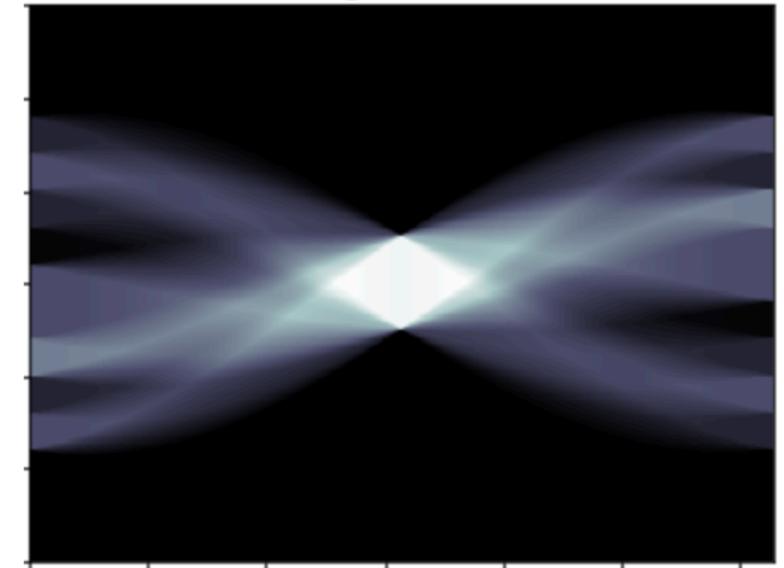
180-degree cardiac orbit.



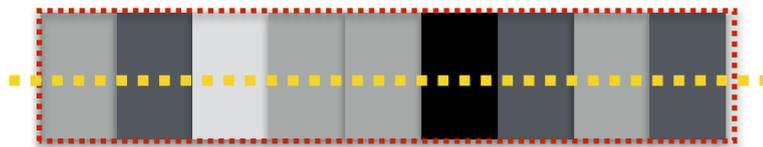
Låt oss säga att vi vill göra SPECT



Sinogram / data



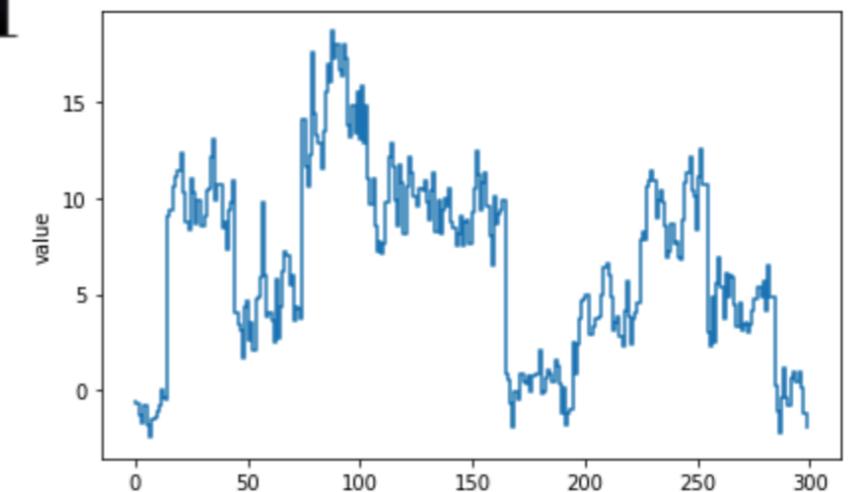
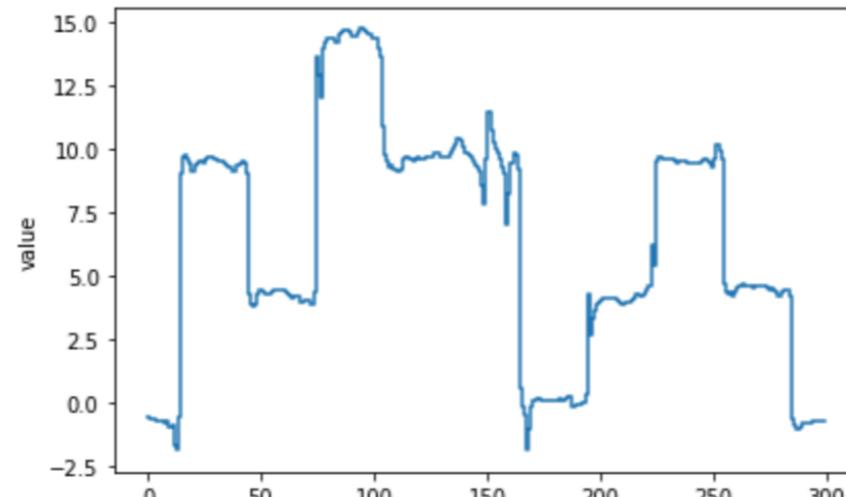
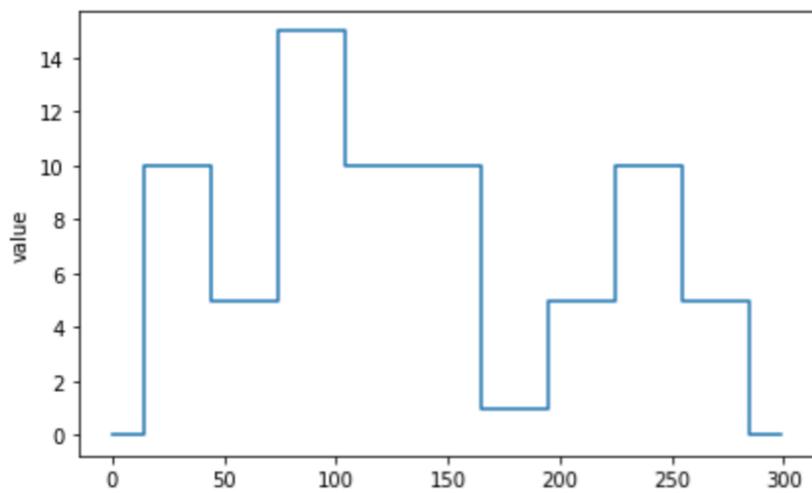
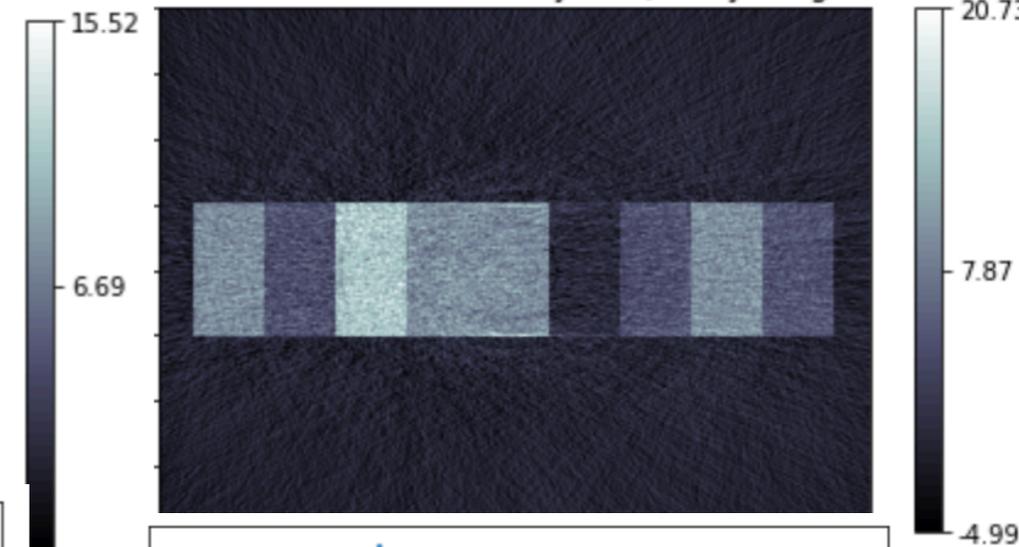
objekt



Reconstruction from noise free data / image



Reconstruction from noisy data/ noisy image

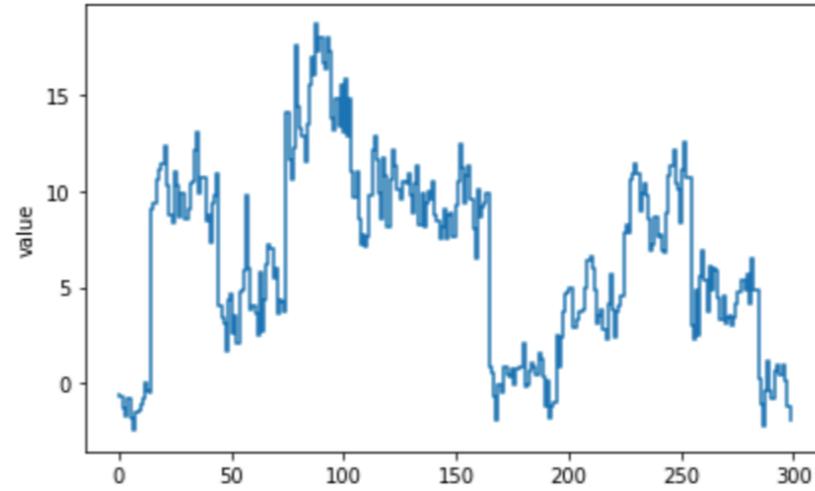
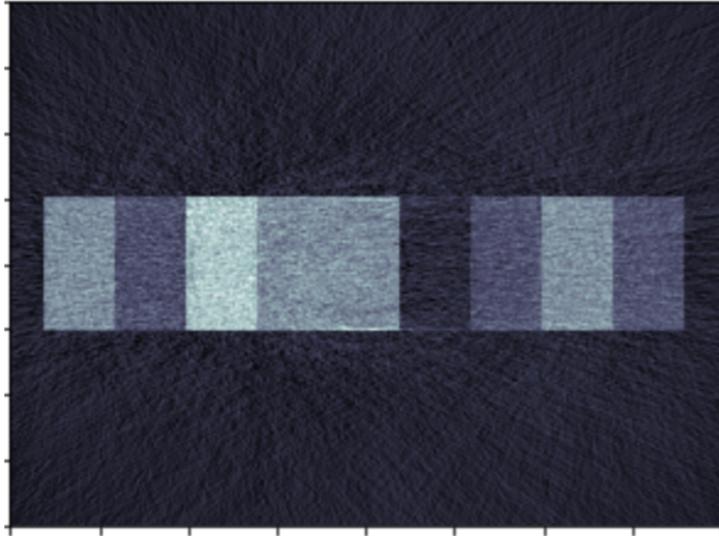


(bildsupplösning -bredd- 300 px)

Vad händer om jag gör upplösning 2 ggr bättre?
(detektor pixellisering 1/2 så stor, bilpixellisering 1/2 stor => 600 px)

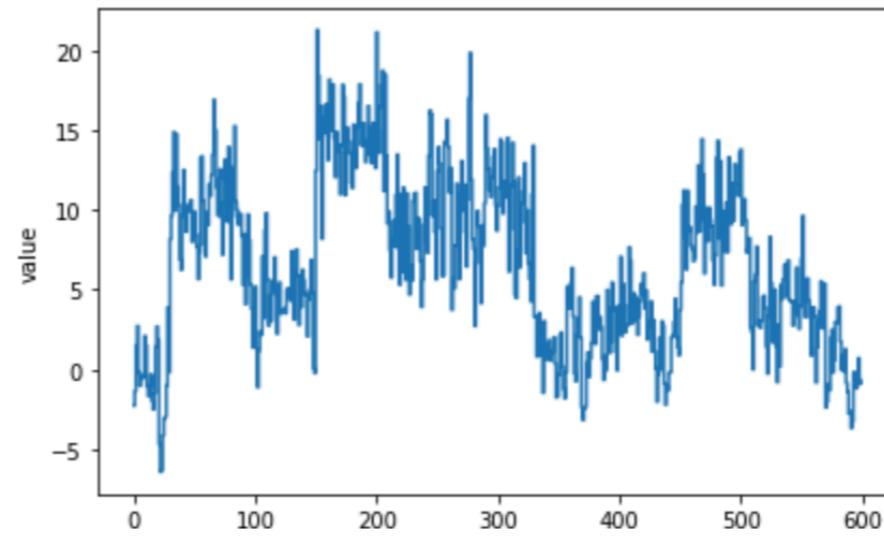
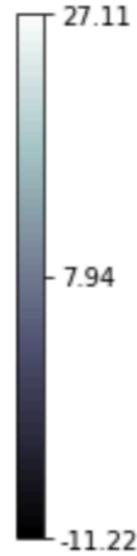
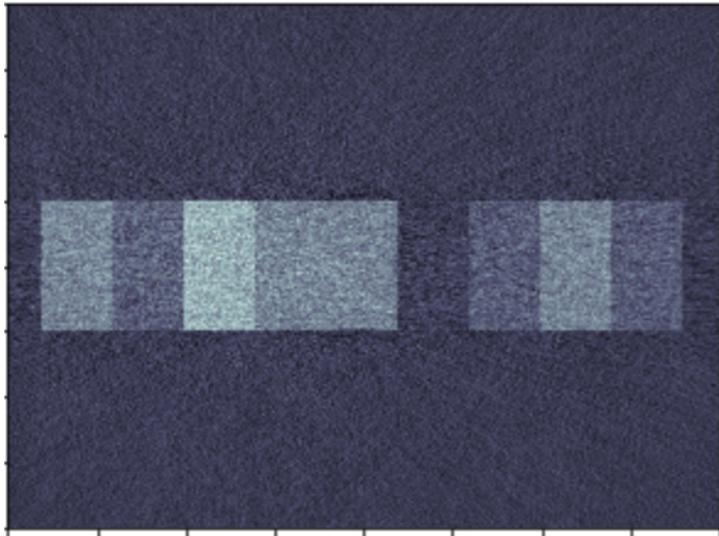
baseline

Reconstruction from noisy data/ noisy image



dubbelt så bra
Spatiell upplösning

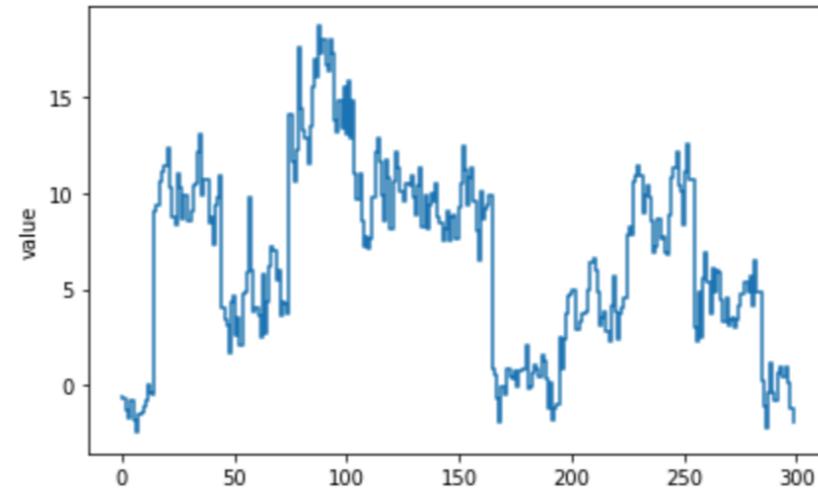
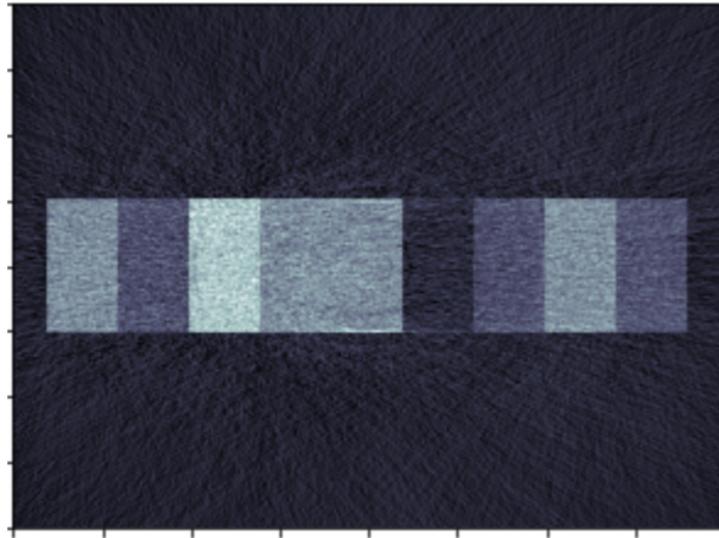
Reconstruction from noisy data/ noisy image



Vad händer om jag halverar insamlingstid?

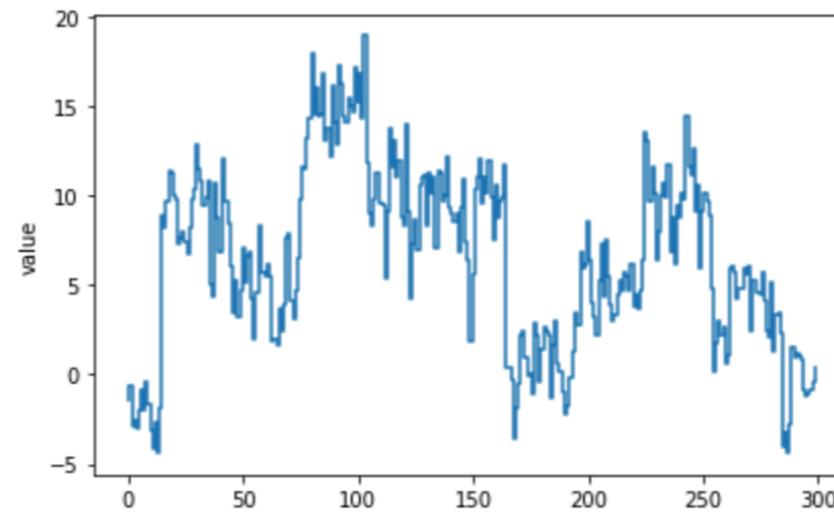
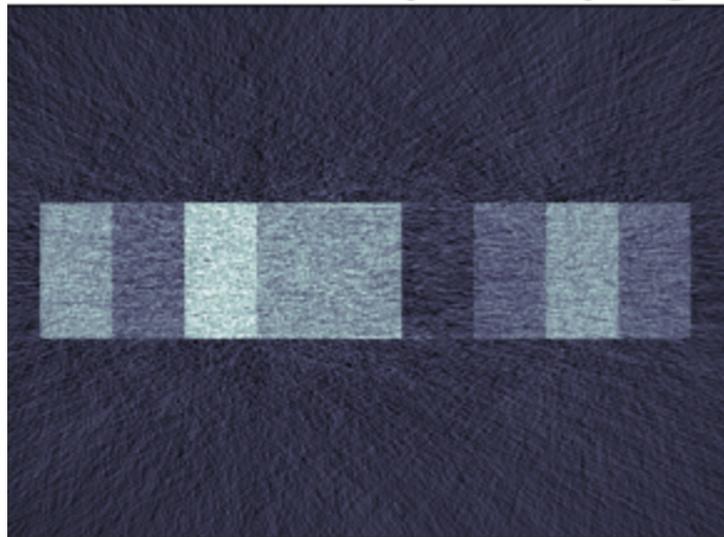
baseline

Reconstruction from noisy data/ noisy image

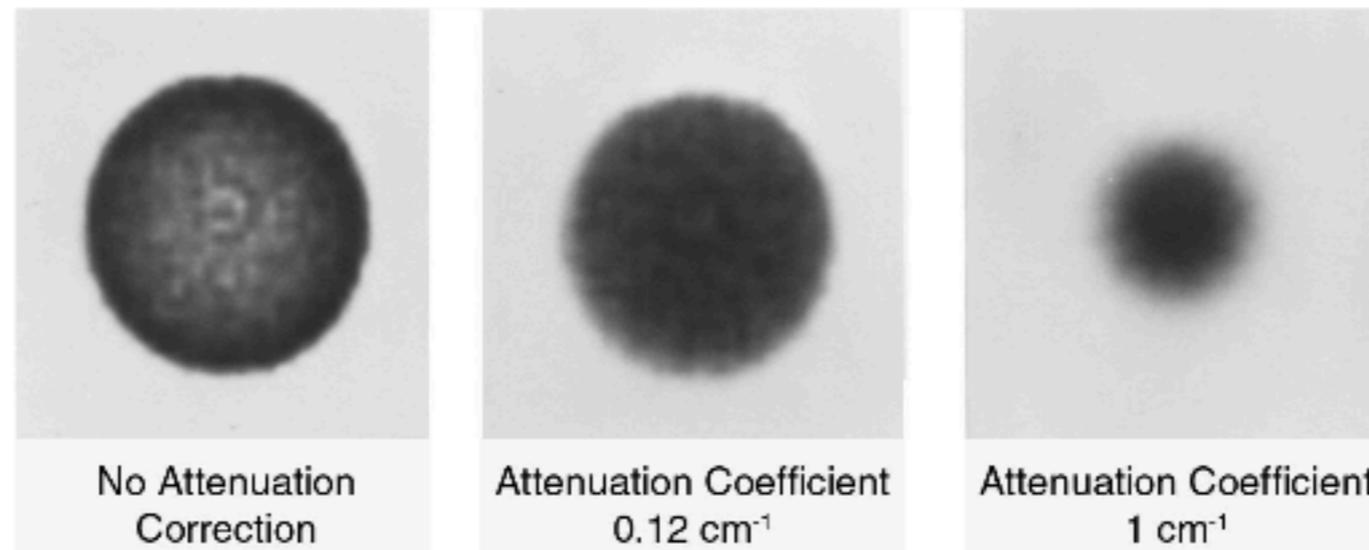


dubbelt så bra
temporal upplösning

Reconstruction from noisy data/ noisy image



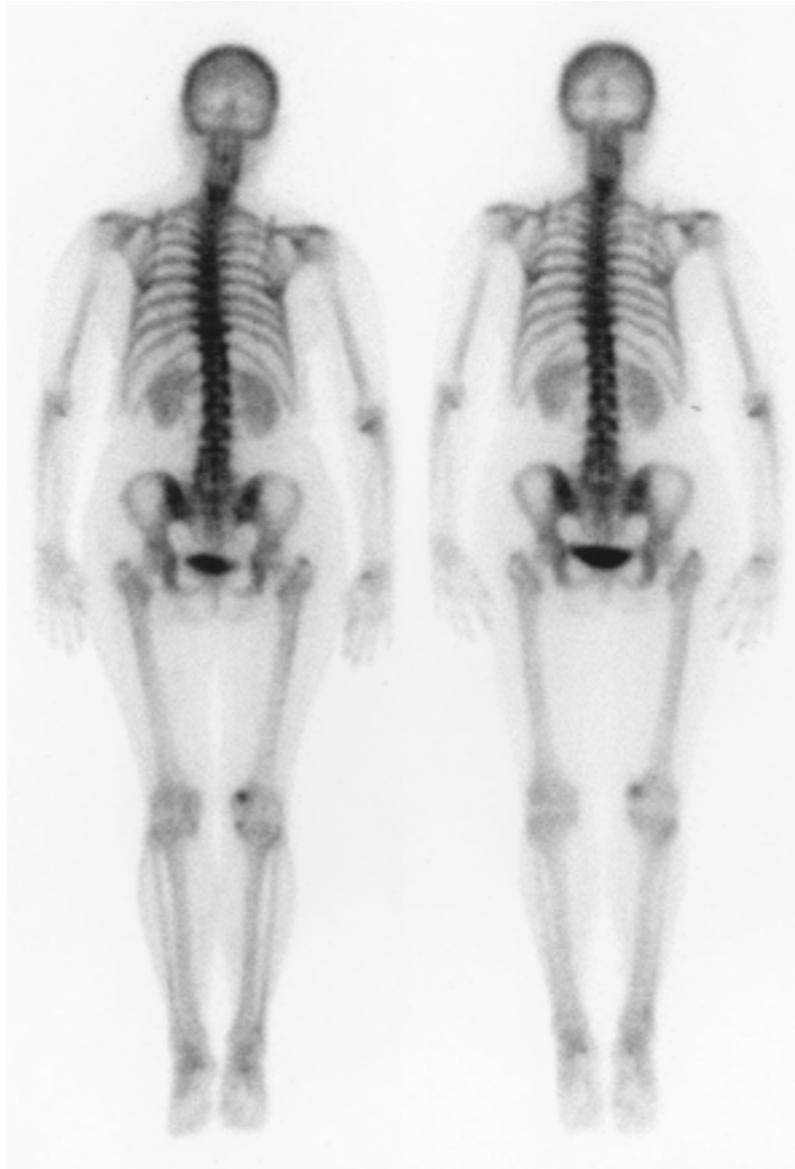
Attenuation correction in SPECT



■ **FIGURE 19-7** Attenuation correction. On the left is a reconstructed transverse image slice of a cylindrical phantom containing a well-mixed radionuclide solution. This image shows a decrease in activity toward the center due to attenuation. (A small ring artifact, unrelated to the attenuation, is also visible in the center of the image.) In the center is the same image corrected by the Chang method, using a linear attenuation coefficient of 0.12 cm^{-1} , demonstrating proper attenuation correction. On the right is the same image, corrected by the Chang method using an excessively large attenuation coefficient.

multi vs single head spect

bättre sensitivity vs
resolution trade off



bättre uniformity
enklare mekanik

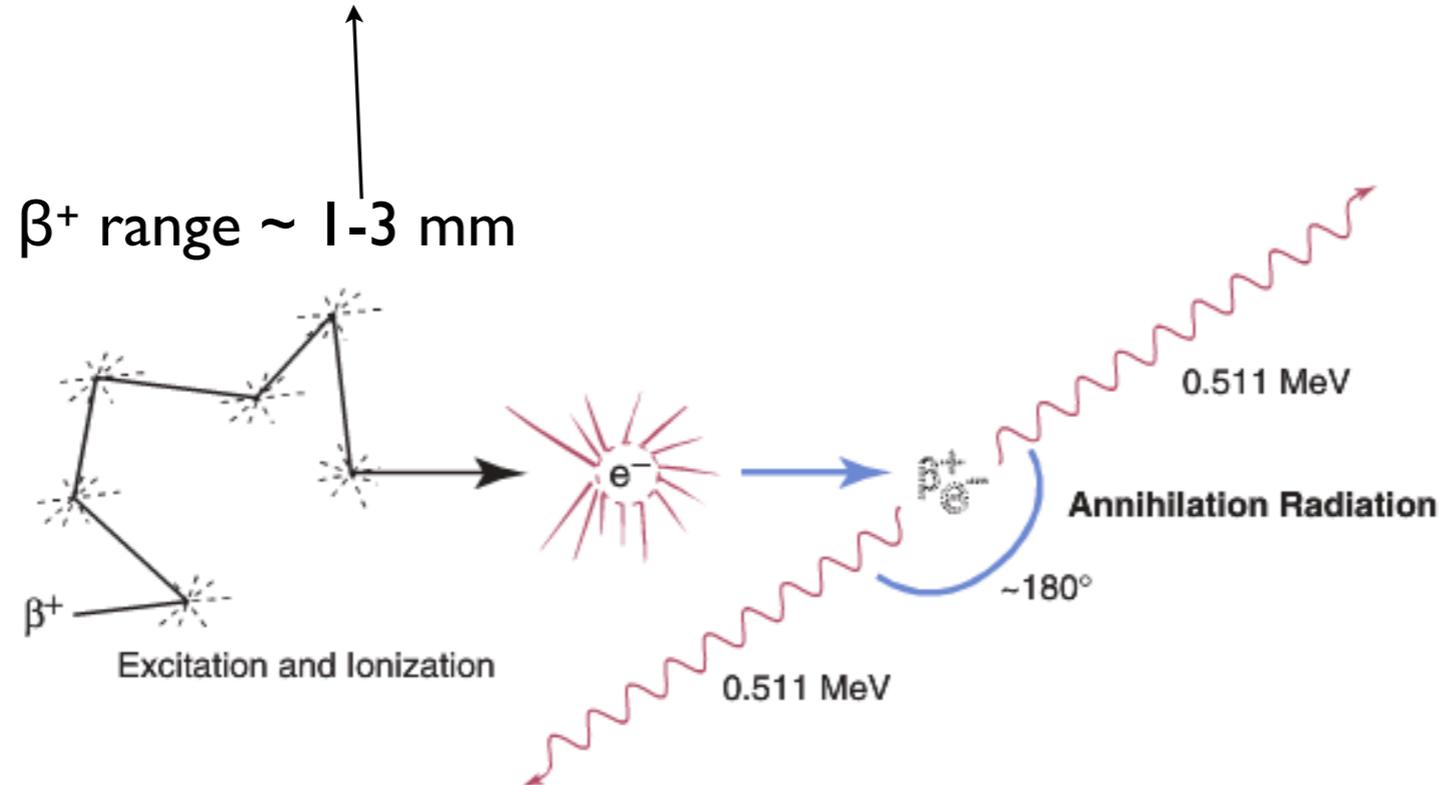
Positron Emission Tomography

Outline

1. PET basic idea
2. “electronic” collimation
3. sensitivity (vs resolution)
4. cyclotron (production of isotopes for PET)
5. comparison emission vs transmission

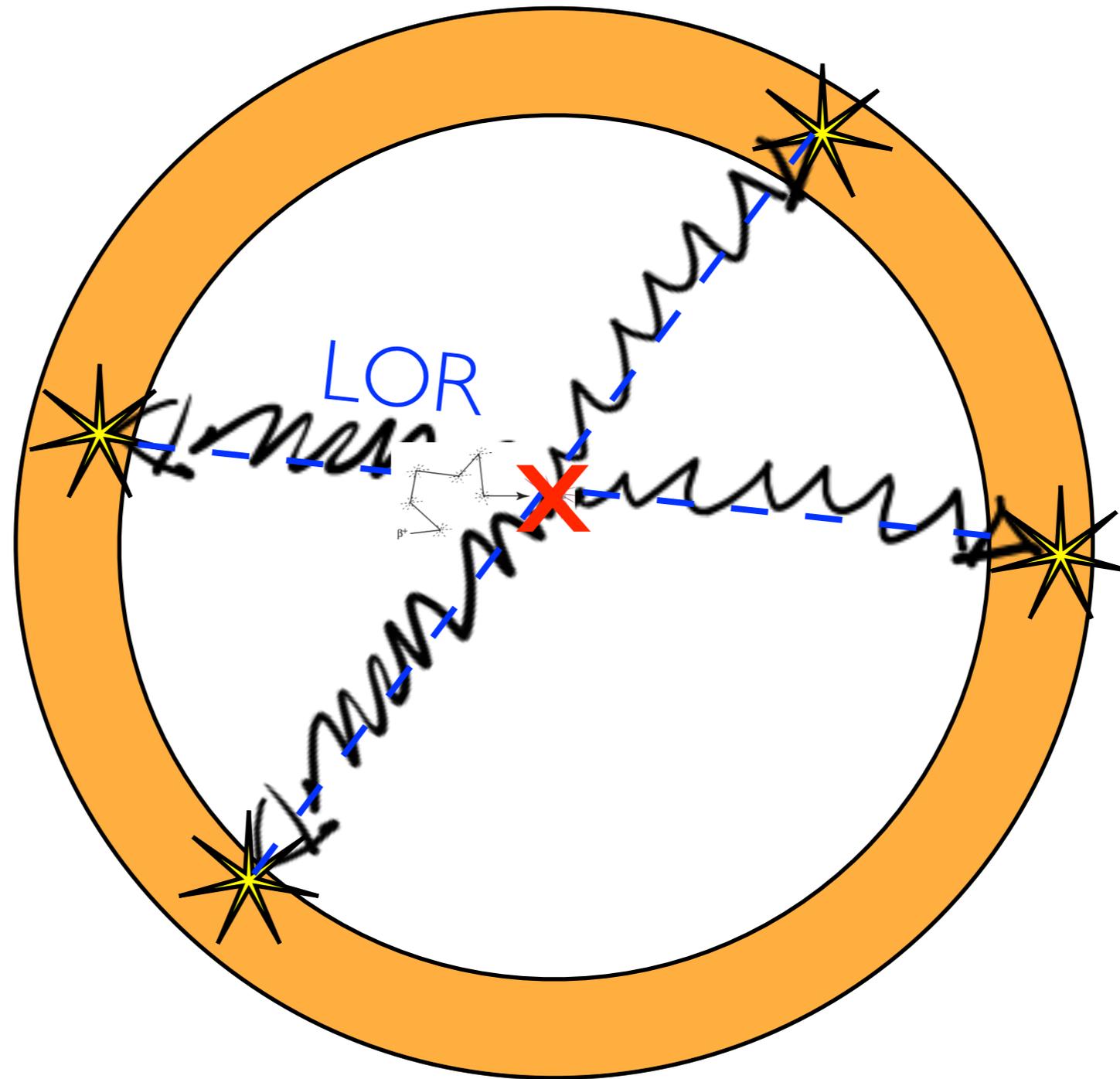
Positron Emission Tomography

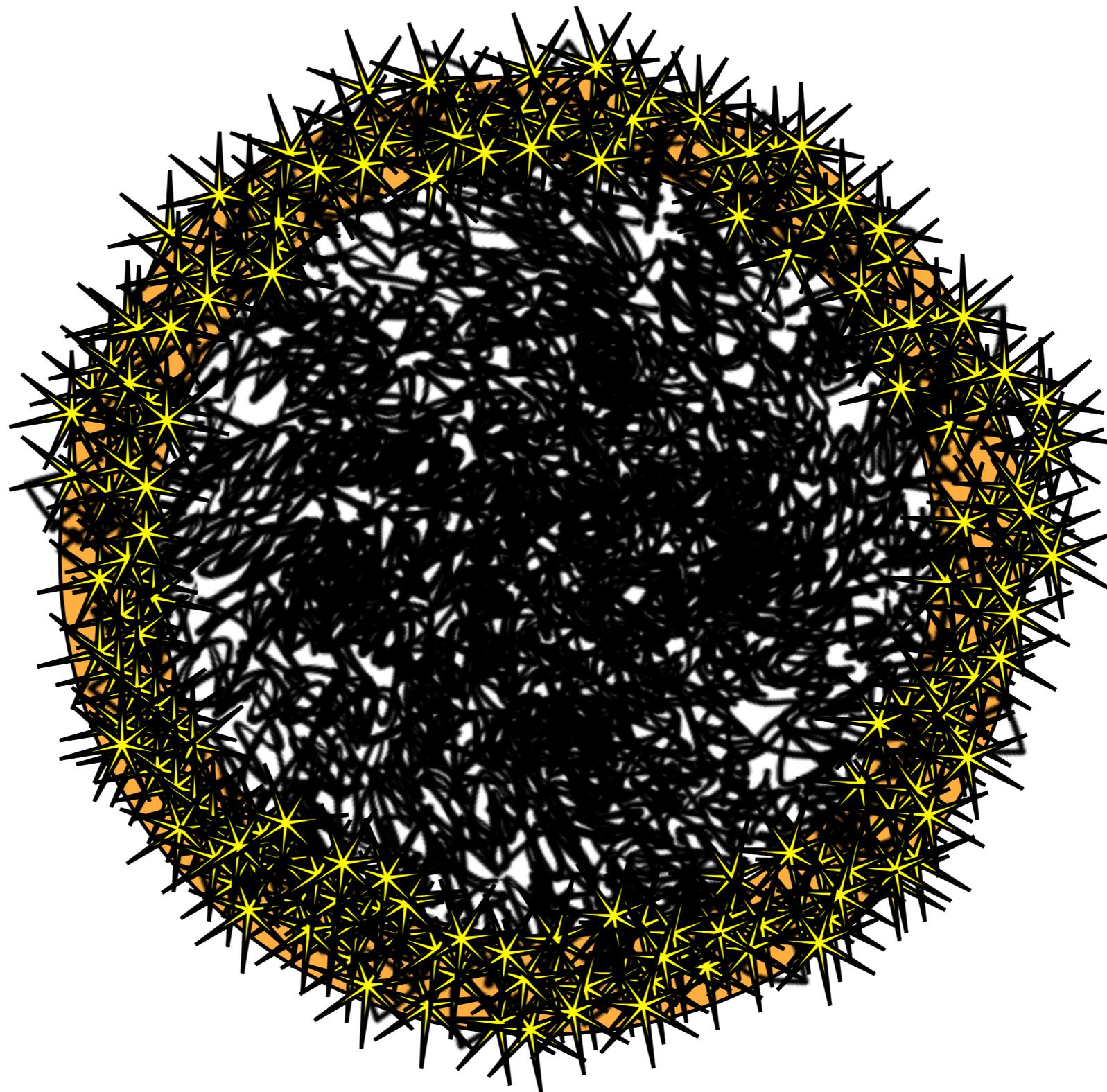
depends on β^+ energy and "material"
1-3 mm for ^{18}F in tissue



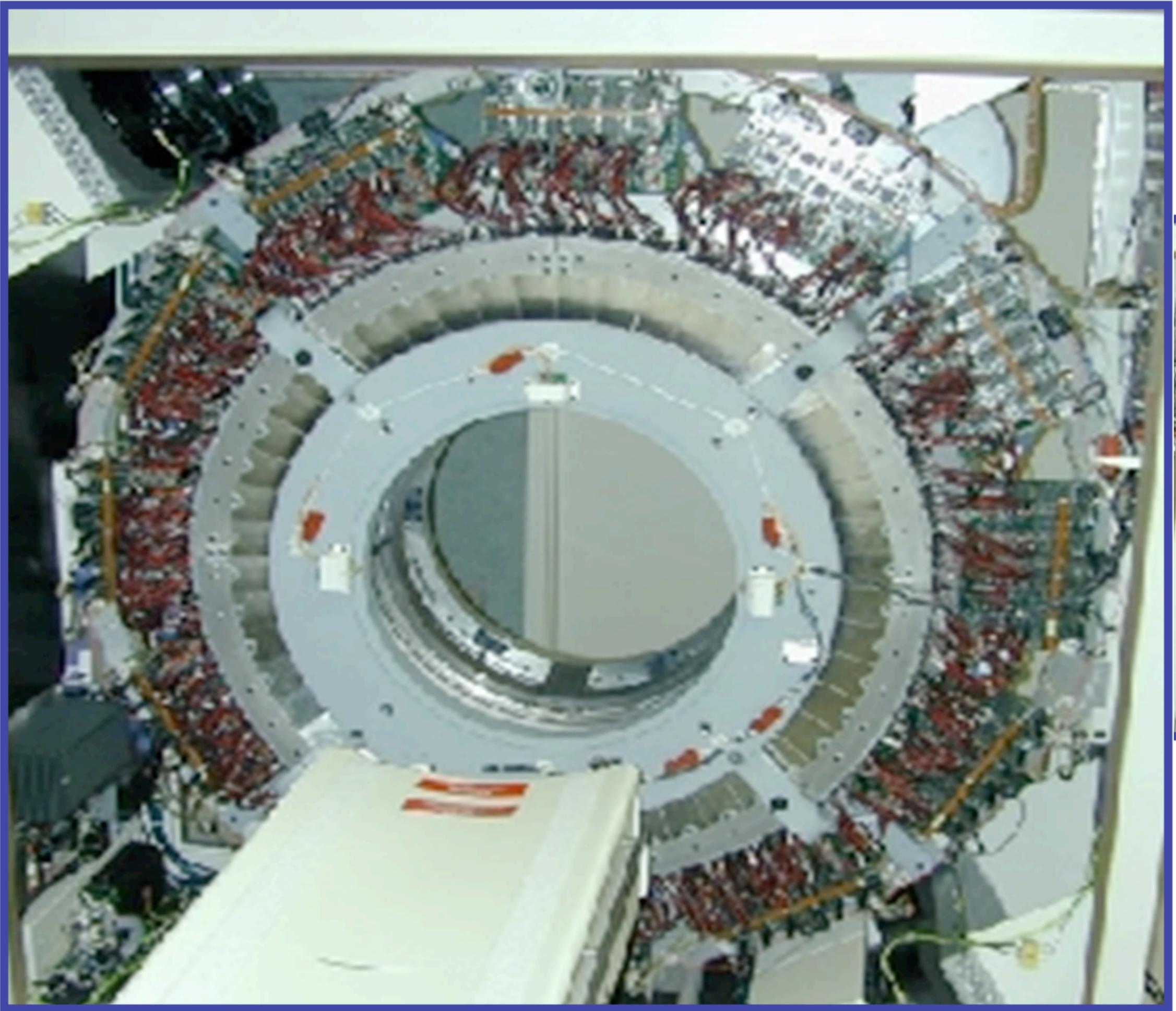
■ FIGURE 15-7 Annihilation radiation.

Basic idea



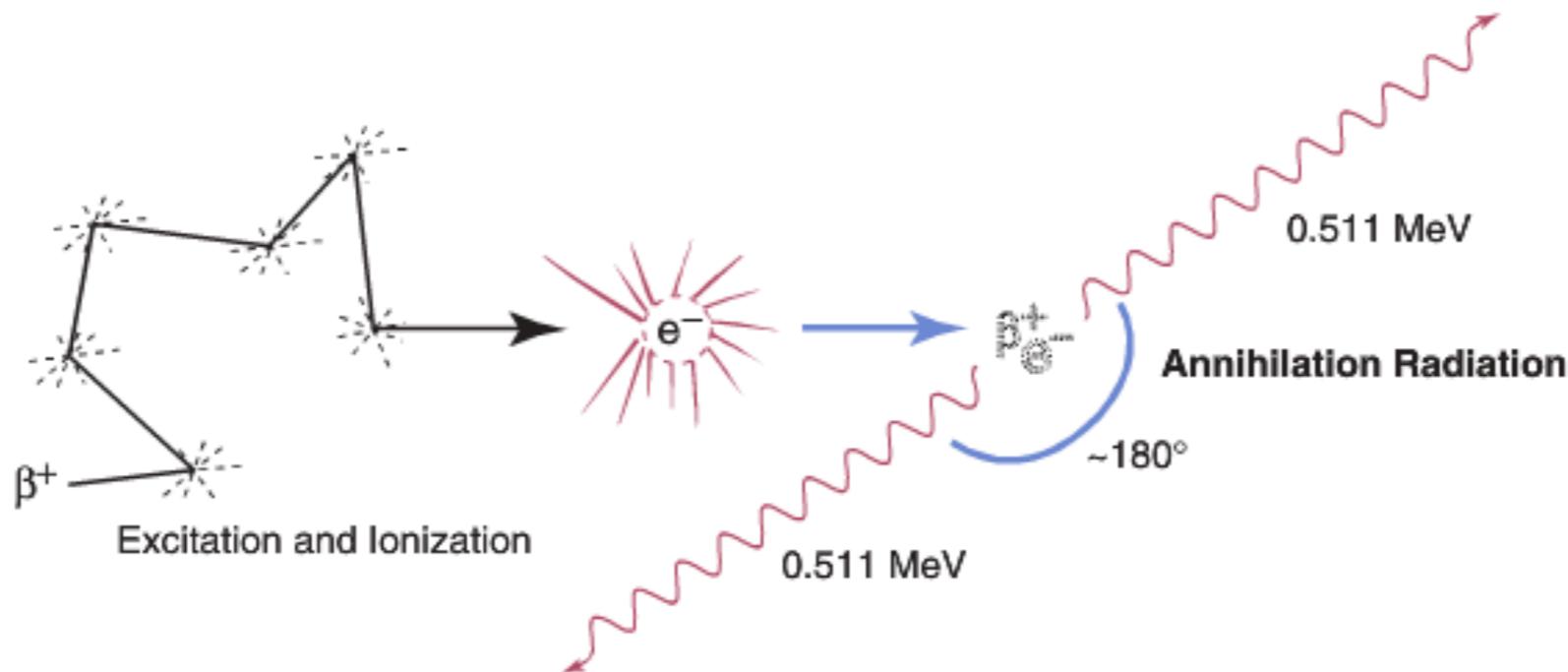


many counts/s!!!!!!



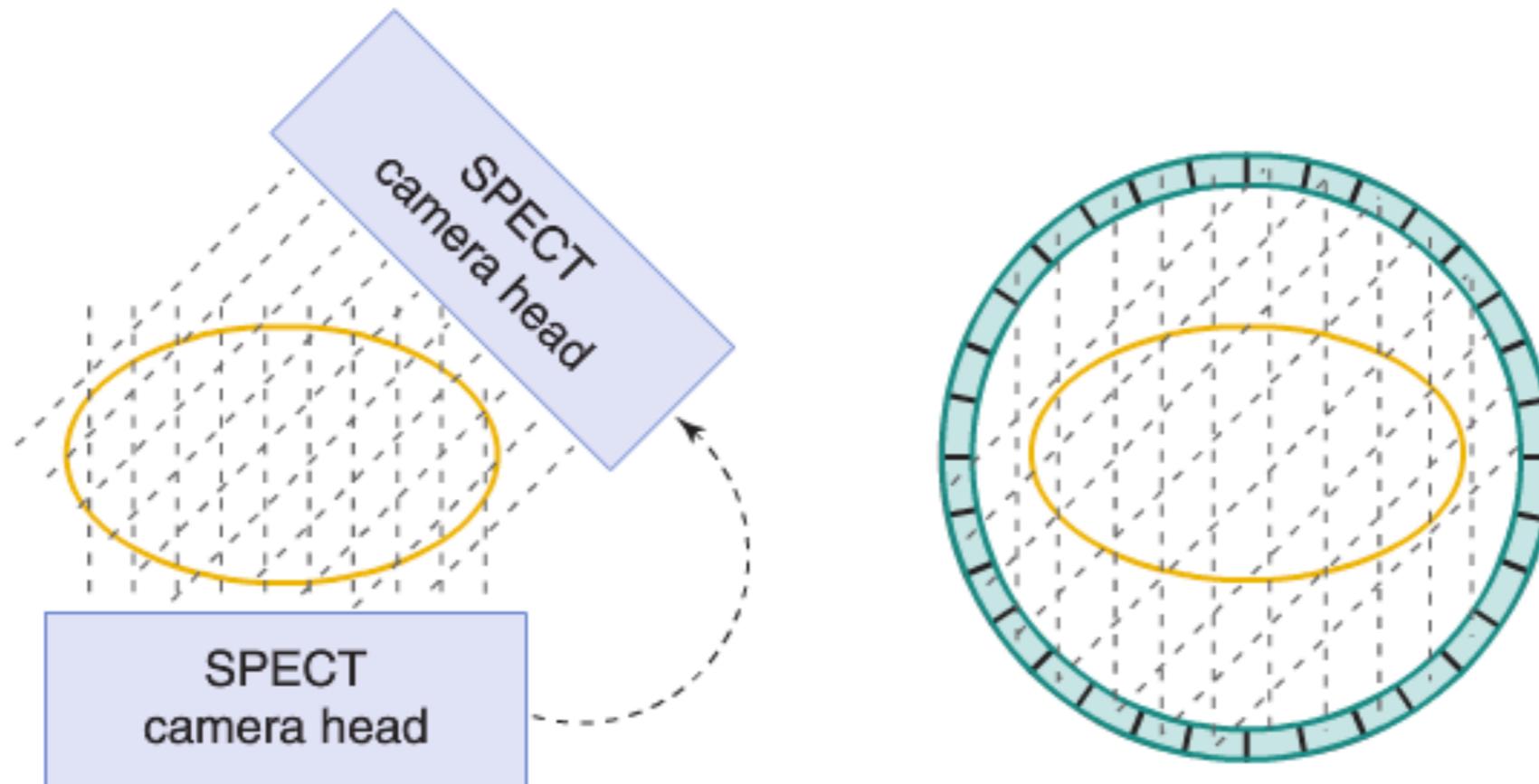
I PET kan ett sönderfall som bäst placeras:

1. med en precision som beror bara på detektorn
2. med en precision som beror på fotonernas energi.
3. med en precision som beror på positron range



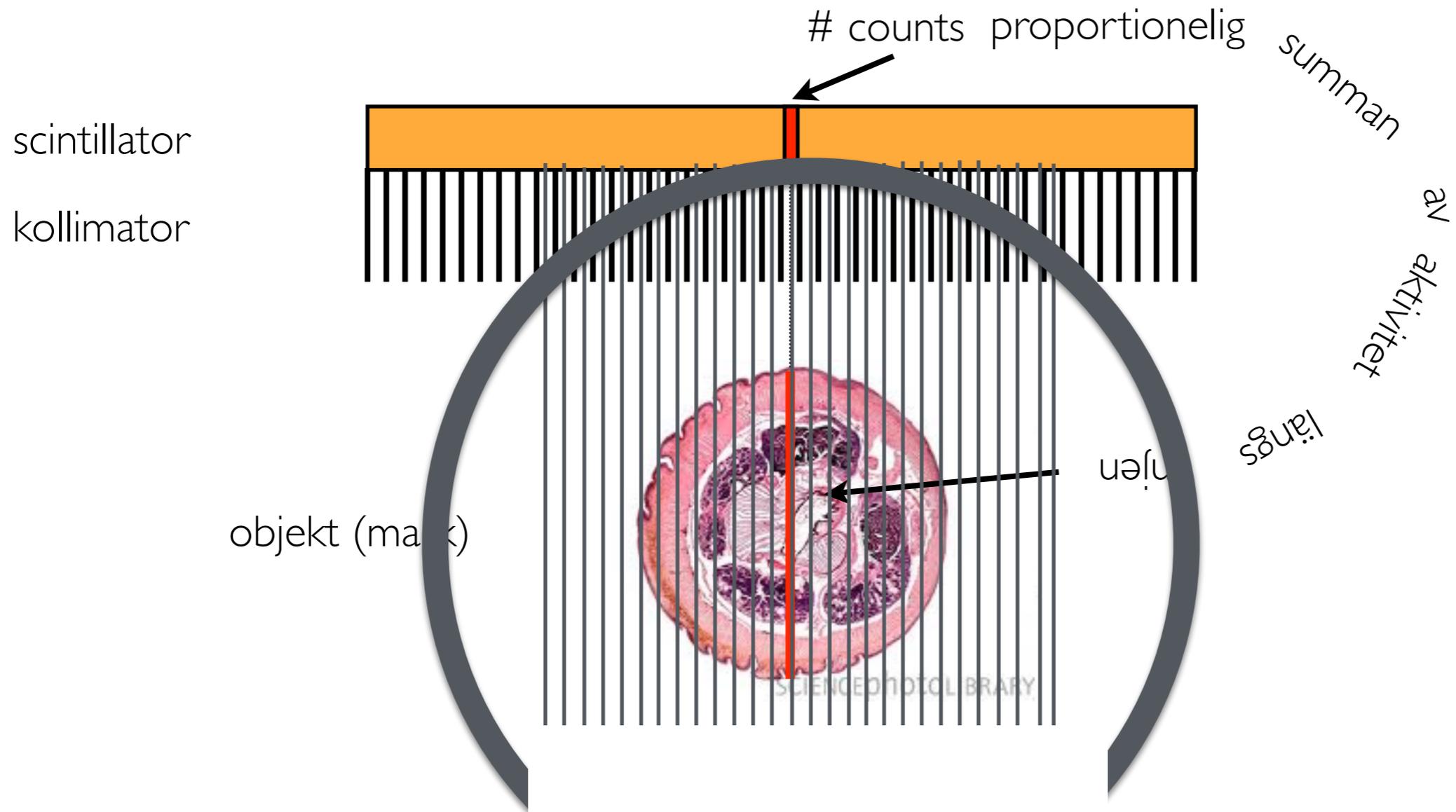
■ FIGURE 15-7 Annihilation radiation.

All projections at the same time!

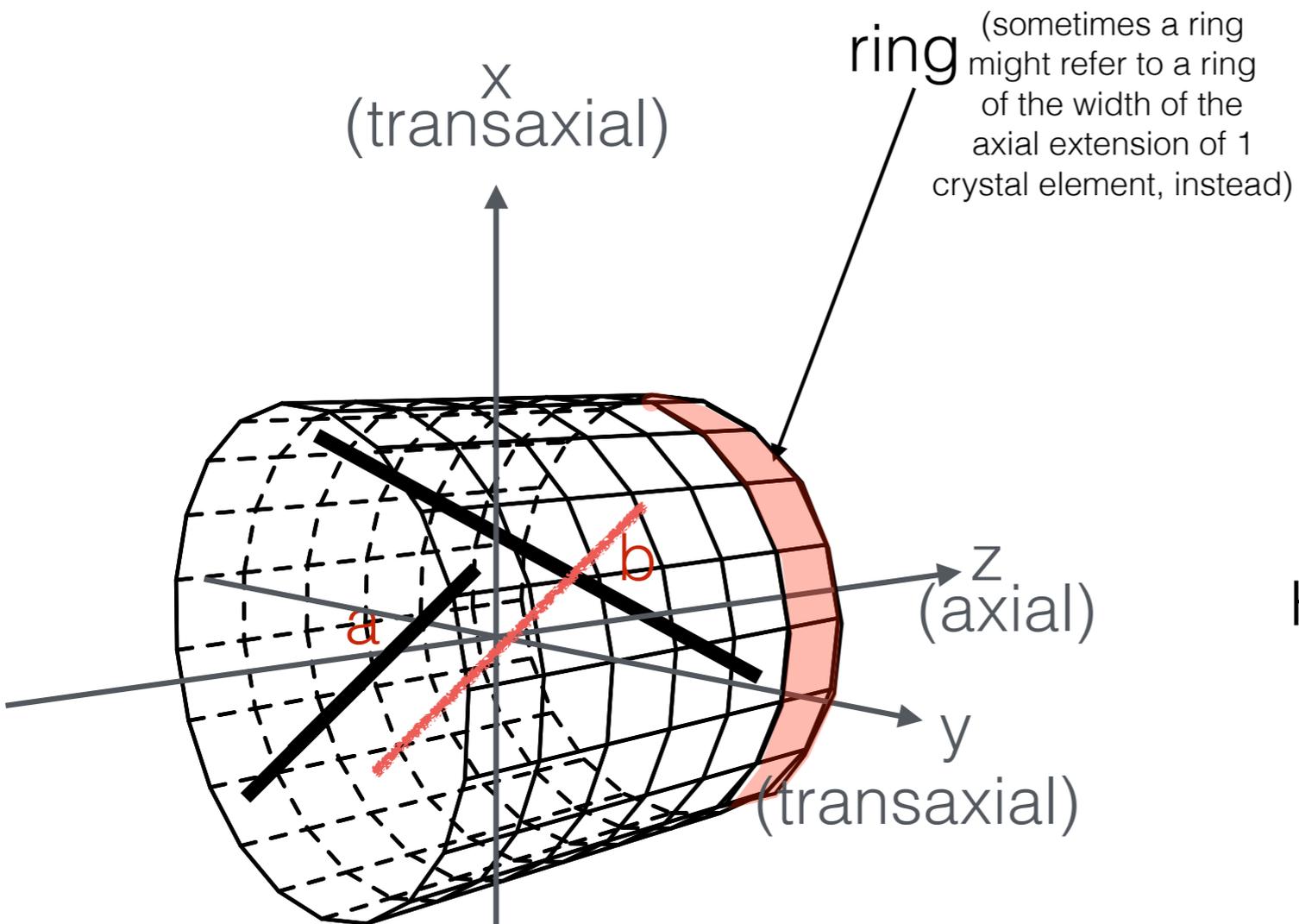


+ no rotation gantry
- risk for paralysis!

i bästa möjliga fall:

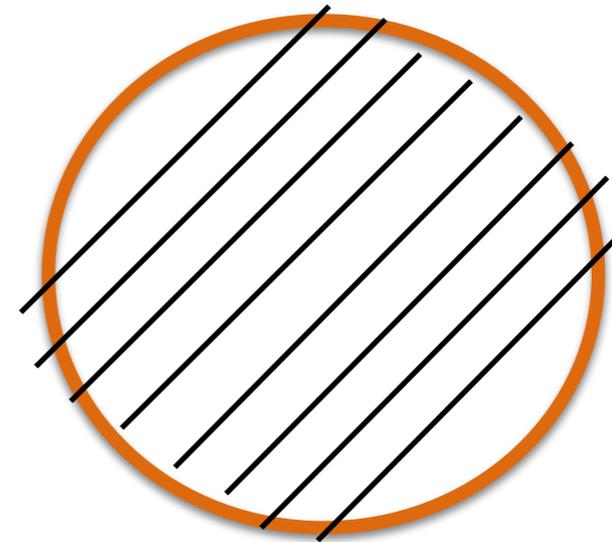


PET geometri och data



LOR a mellan kristaller inom samma ring

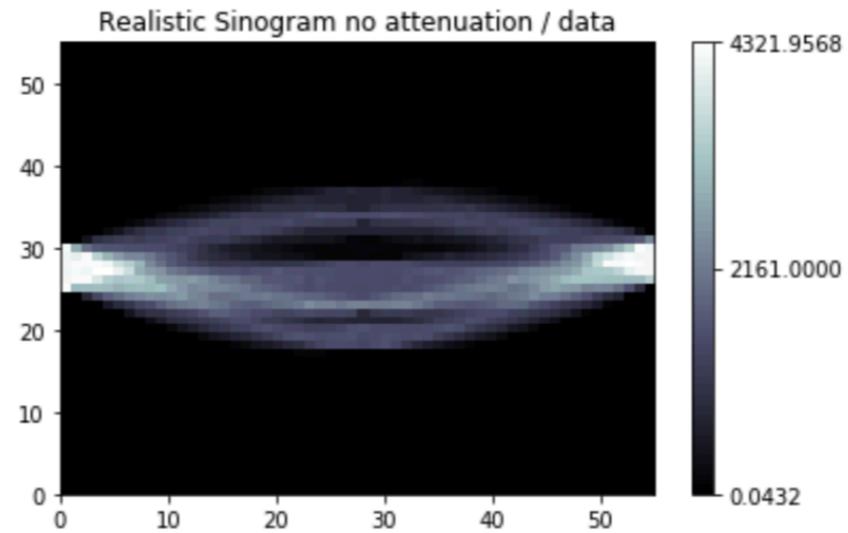
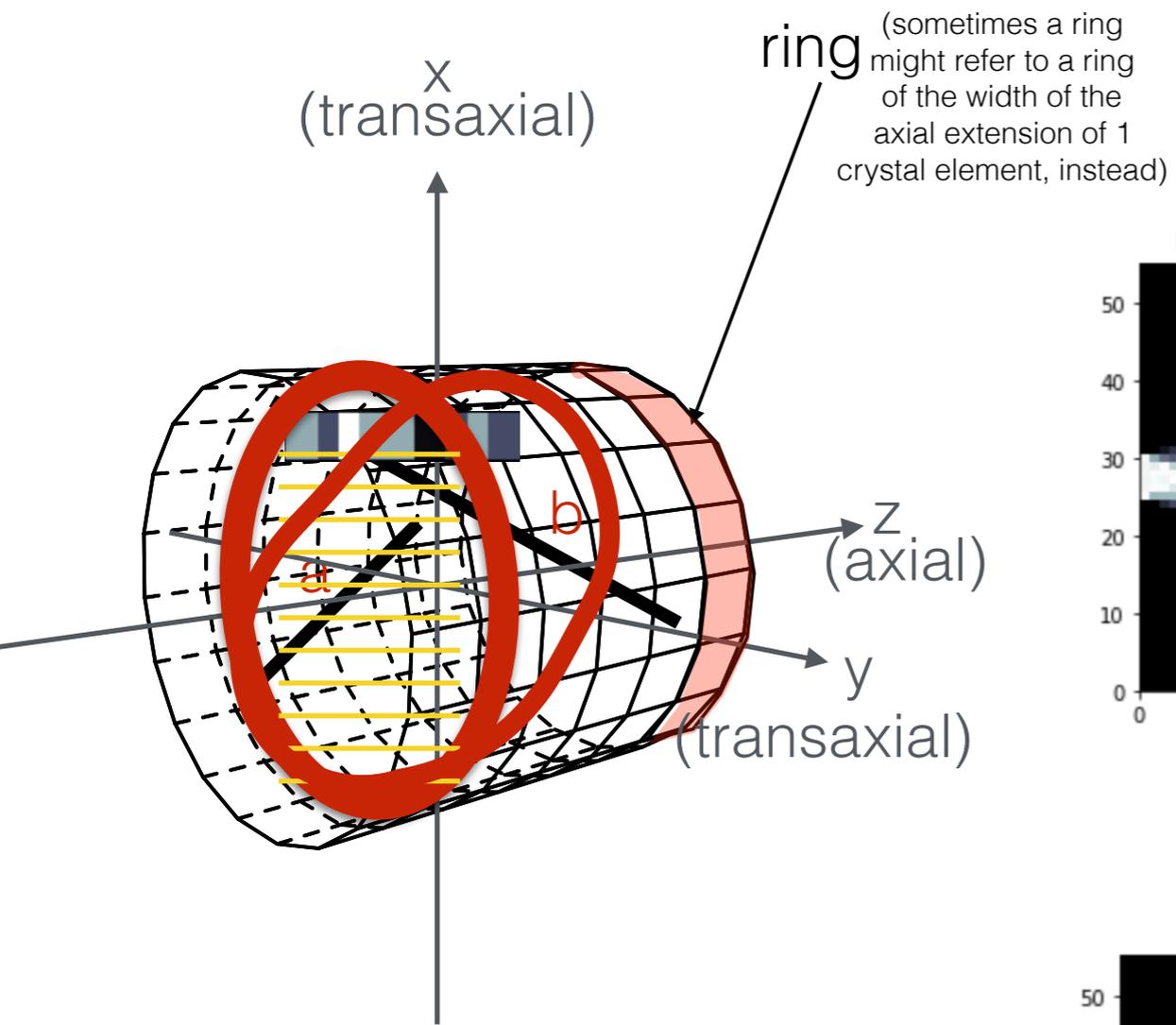
LOR b mellan kristaller i olika ringar



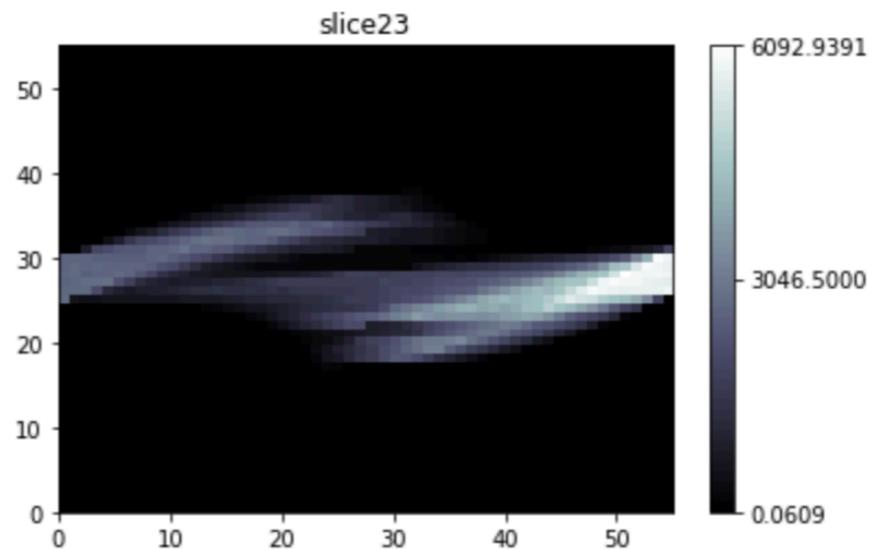
Hur många parametrar behövs för att bestämma en linje i rummet?

1. axial coordinate
2. vinkel i xy-plan
3. avstånd från centrum av FOV
4. vinkel i xz-plan (ringskillnad)

PET data är 4D! 1-3 ger sinogram(er)



direct sinogram
 LOR:s inom samma ring



oblique sinogram
 LOR:s mellan olika ringar

x
(transaxial)

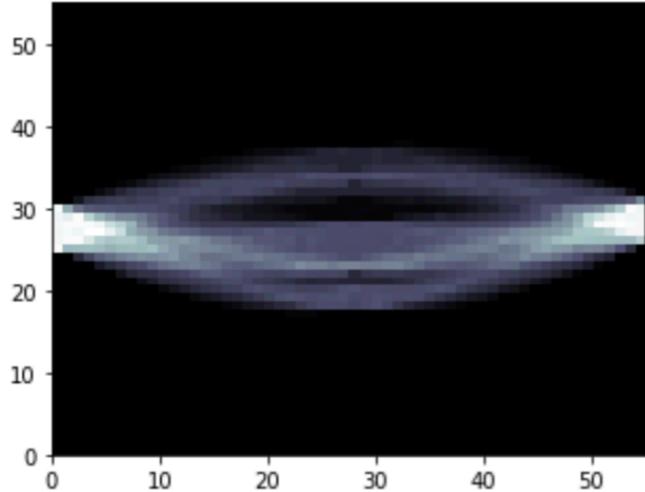
ring (sometimes a ring might refer to a ring of the width of the axial extension of 1 crystal element, instead)

z
(axial)

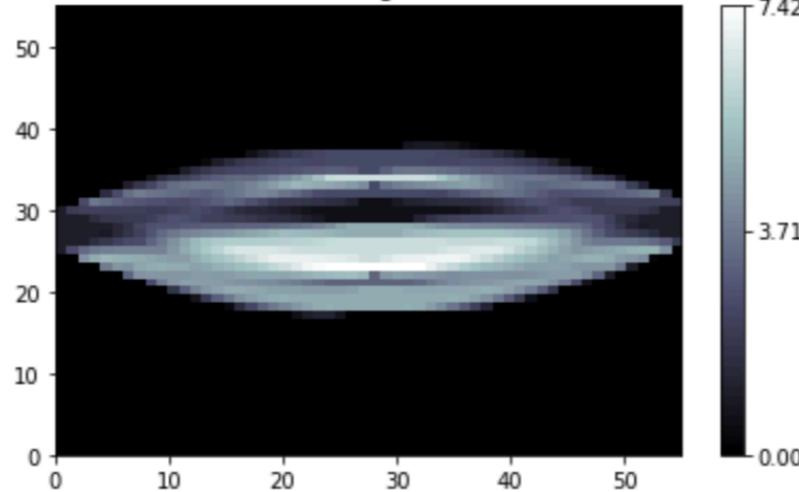
Attenueringskorrektions för PET är (relativt) enkelt om man har attenuation map (dvs CT)

(tra

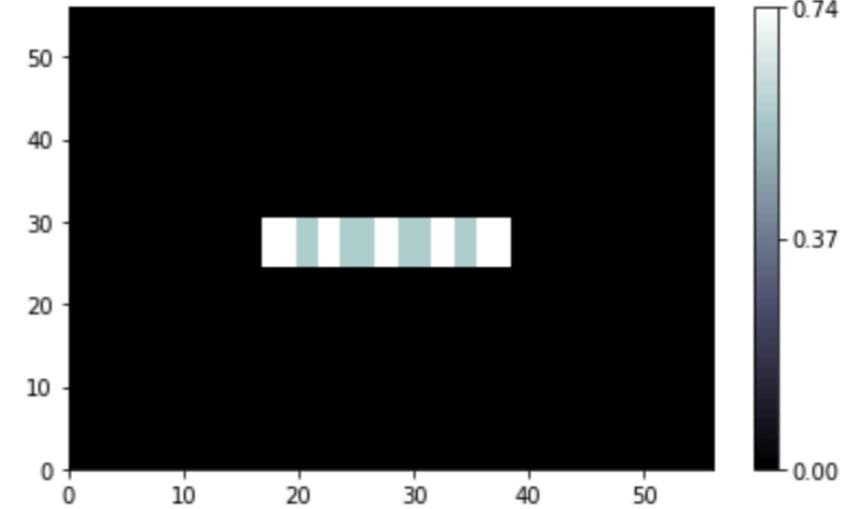
Realistic Sinogram no attenuation / data



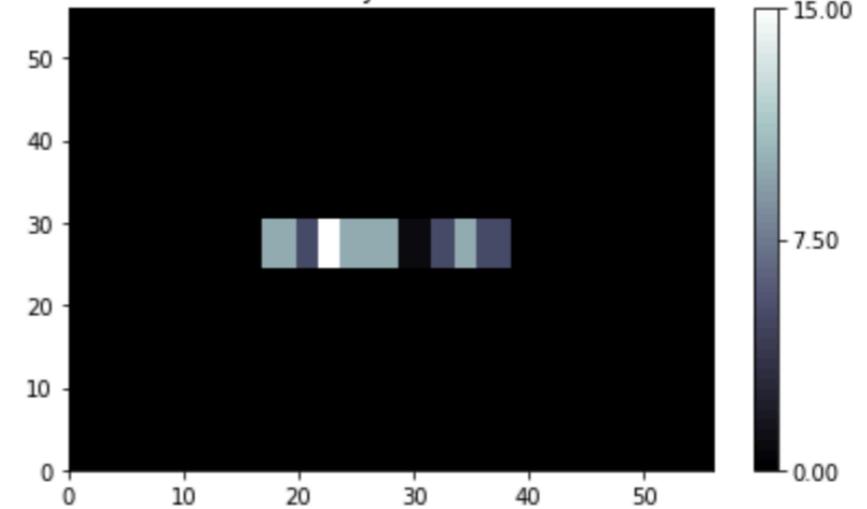
Realistic Sinogram / data



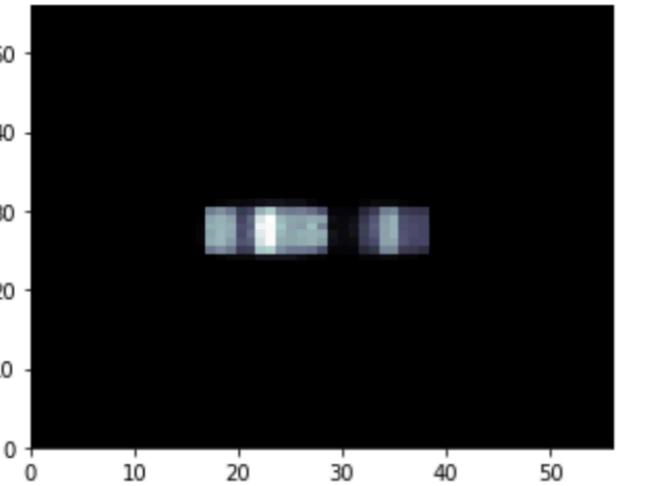
Attenuation Phantom



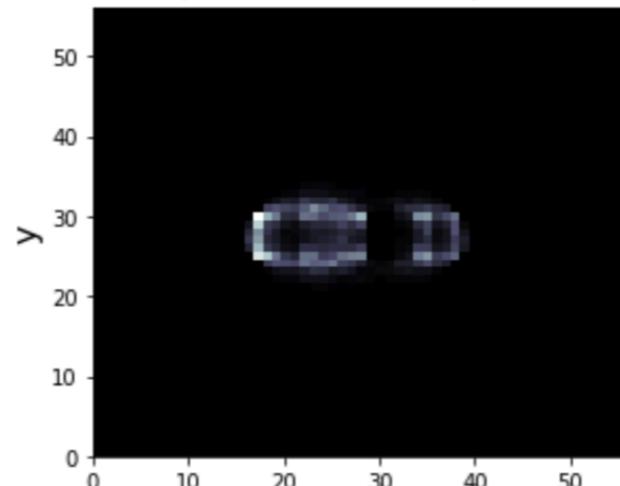
Activity Phantom



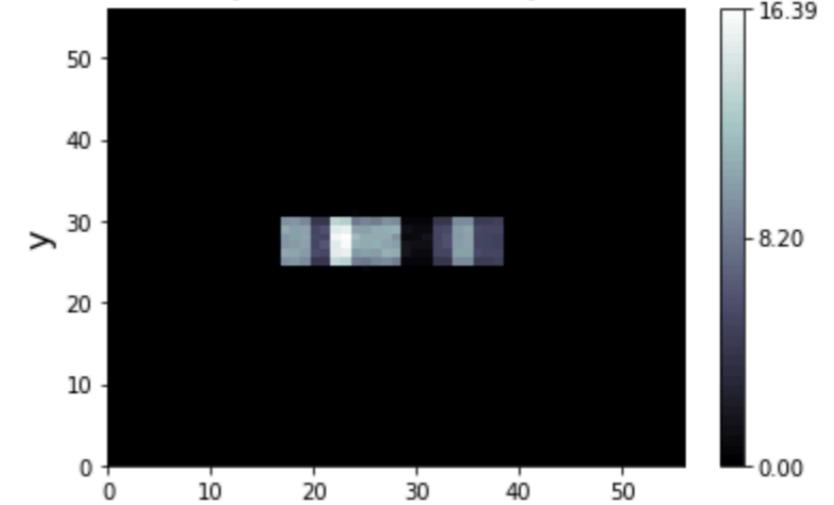
Reconstruction MLEM, from non attenuated data



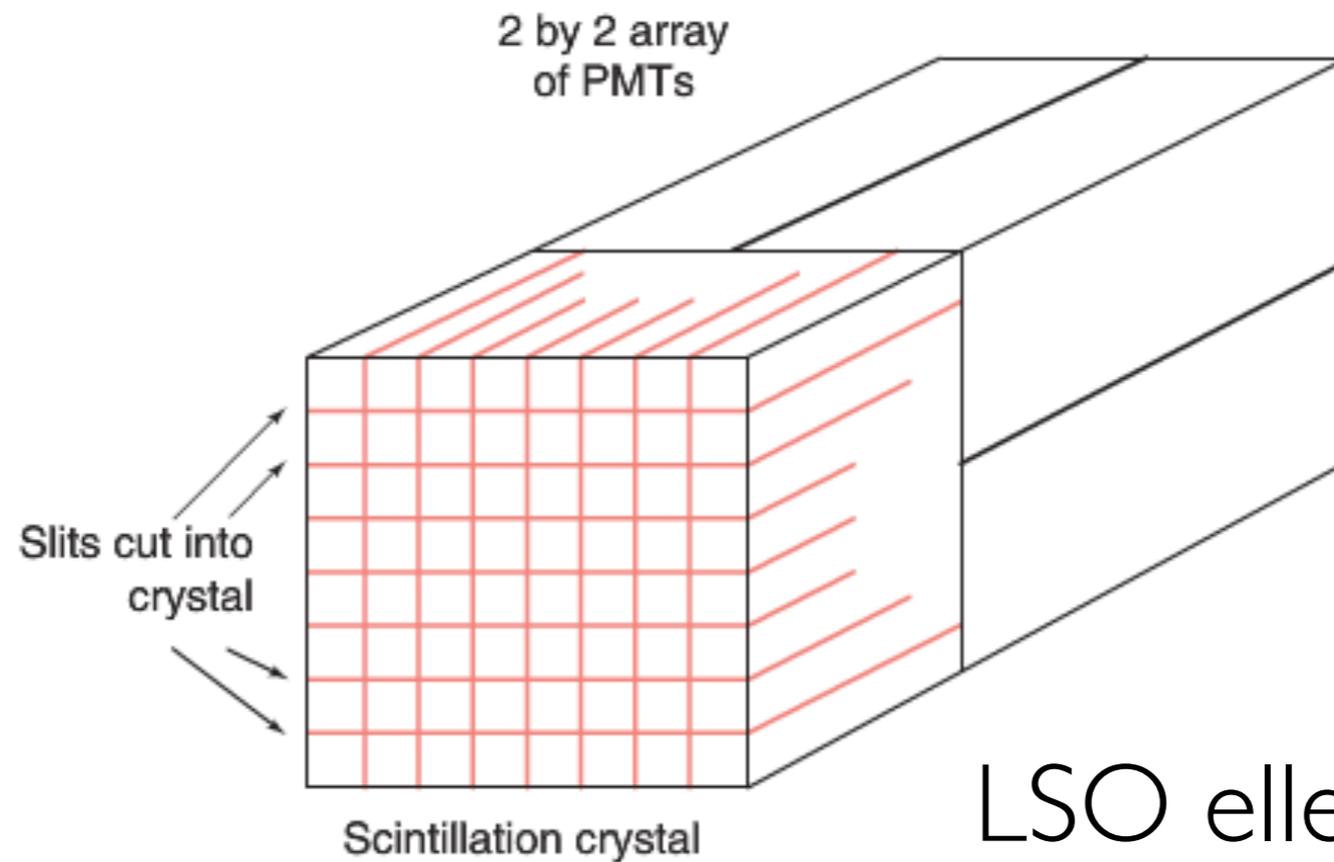
Reconstruction MLEM, from attenuated data, no attenuation correction



Reconstruction MLEM, from attenuated data, attenuation correction



Common modern detector design



LSO eller BGO
men CsF for special cases

Many of this “detector blocks” are used to form a ring.

Scintillation and Optical Properties of Some Common Scintillator Crystals

Crystal	Primary decay constant (ns)	Secondary decay constant (ns)	Relative emission intensity	Emission wavelength (nm)	Index of refraction
BaF ₂	0.8	600	12	220 and 310	1.49
CsF	4		5	390	1.48
Lu ₂ SiO ₅ (Ce) (LSO)	40		75	420	1.82
Gd ₂ SiO ₅ (Ce) (GSO)	60	600	30	430	1.85
NaI(Tl)	230	~10,000	100	410	1.85
Bi ₄ Ge ₃ O ₁₂ (BGO)	300		15	480	2.15
CsI(Na)	630		75	420	1.84
CaF ₂ (Eu)	900		40	435	1.44
CsI(Tl)	1000		45	565	1.80
CdWO ₄	5000	~20,000	20	480	2.20

Physical Properties of Some Common Scintillator Crystals

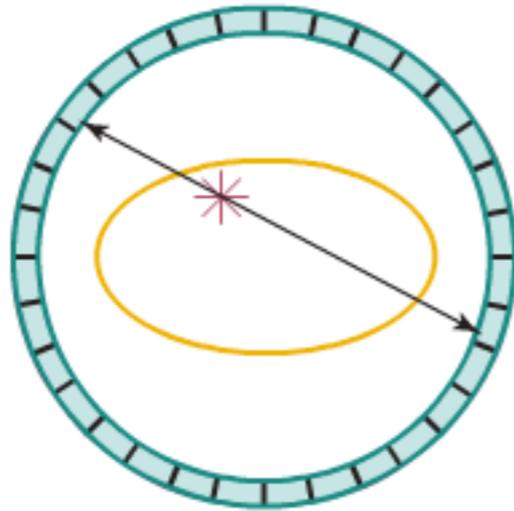
Crystal	Density (g/cm ³)	Effective atomic number	Hygroscopic	Rugged
CdWO ₄	7.90	64	No	No (cleaves easily)
Lu ₂ SiO ₅ (Ce) (LSO)	7.40	65	No	Yes
Bi ₄ Ge ₃ O ₁₂ (BGO)	7.13	75	No	Yes
Gd ₂ SiO ₅ (Ce) (GSO)	6.71	59	No	No (cleaves easily)
BaF ₂	4.88	53	No	Yes
CsF	4.64	53	Very	No
CsI(Na)	4.51	54	Yes	Yes
CsI(Tl)	4.51	54	Slightly	Yes
NaI(Tl)	3.67	51	Yes	No
CaF ₂ (Eu)	3.18	17	No	No

High Z, high density (5 | | keV)
Quick! (coincidence)

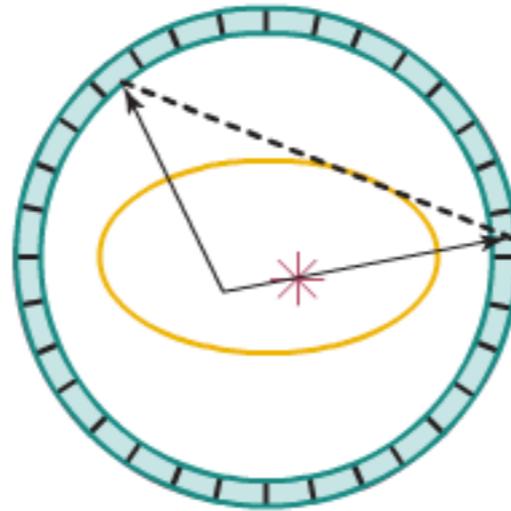
Properties of the Ideal Scintillation Crystal for PET

Crystal property	Purpose
High density	High γ -ray detection efficiency
High atomic number	High γ -ray detection efficiency
Short decay time	Good coincidence timing
High light output	Allows large number of crystal elements per photodetector
Good energy resolution	Clear identification of full energy events
Emission wavelength near 400 nm	Good match to photomultiplier tube response
Transparent at emission wavelength	Allows light to travel unimpeded to photomultiplier tube
Index of refraction near 1.5	Good transmission of light from crystal to photomultiplier tube
Radiation hard	Stable crystal performance
Nonhygroscopic	Simplifies packaging
Rugged	Allows fabrication of smaller crystal elements
Economic growth process	Reasonable cost

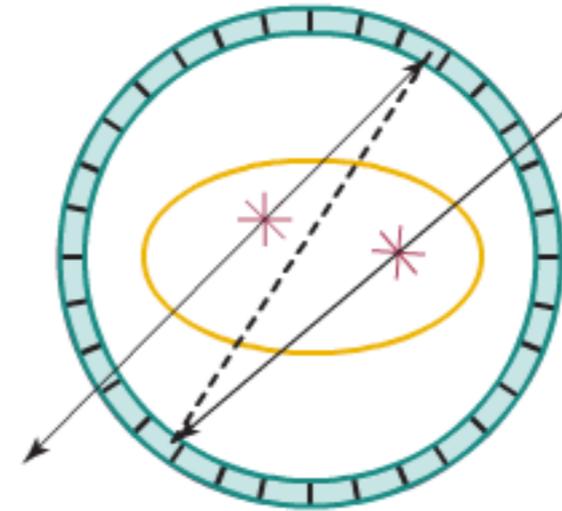
possible outcomes:



true coincidence



scatter coincidence



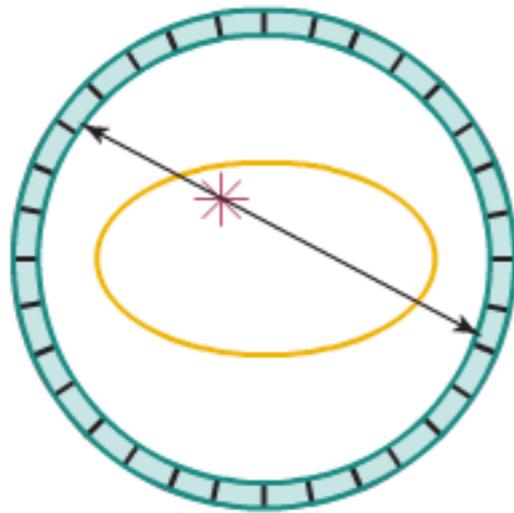
random coincidence

true = the detected gammas
come from same decay
=> true

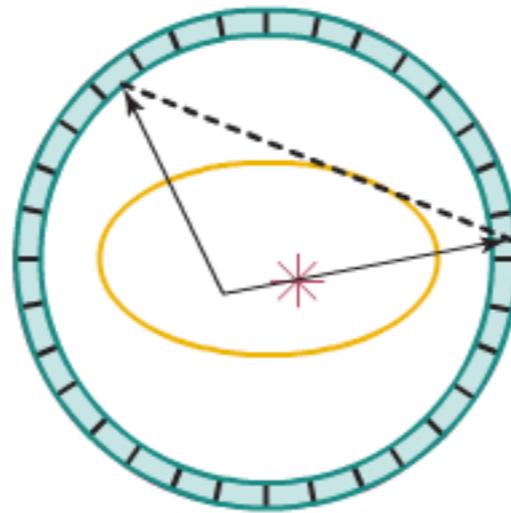
not true!
(different decays)

which can be eliminated?

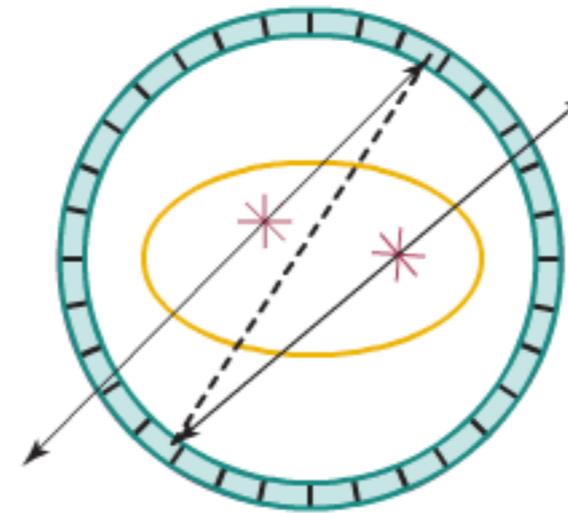
possible outcomes:



true coincidence



scatter coincidence



random coincidence

true = the detected gammas
come from same decay
=> true

not true!
(different decays)

are random coincidences many?

A. JA

B. NEJ

time window

τ

count rate

R

a

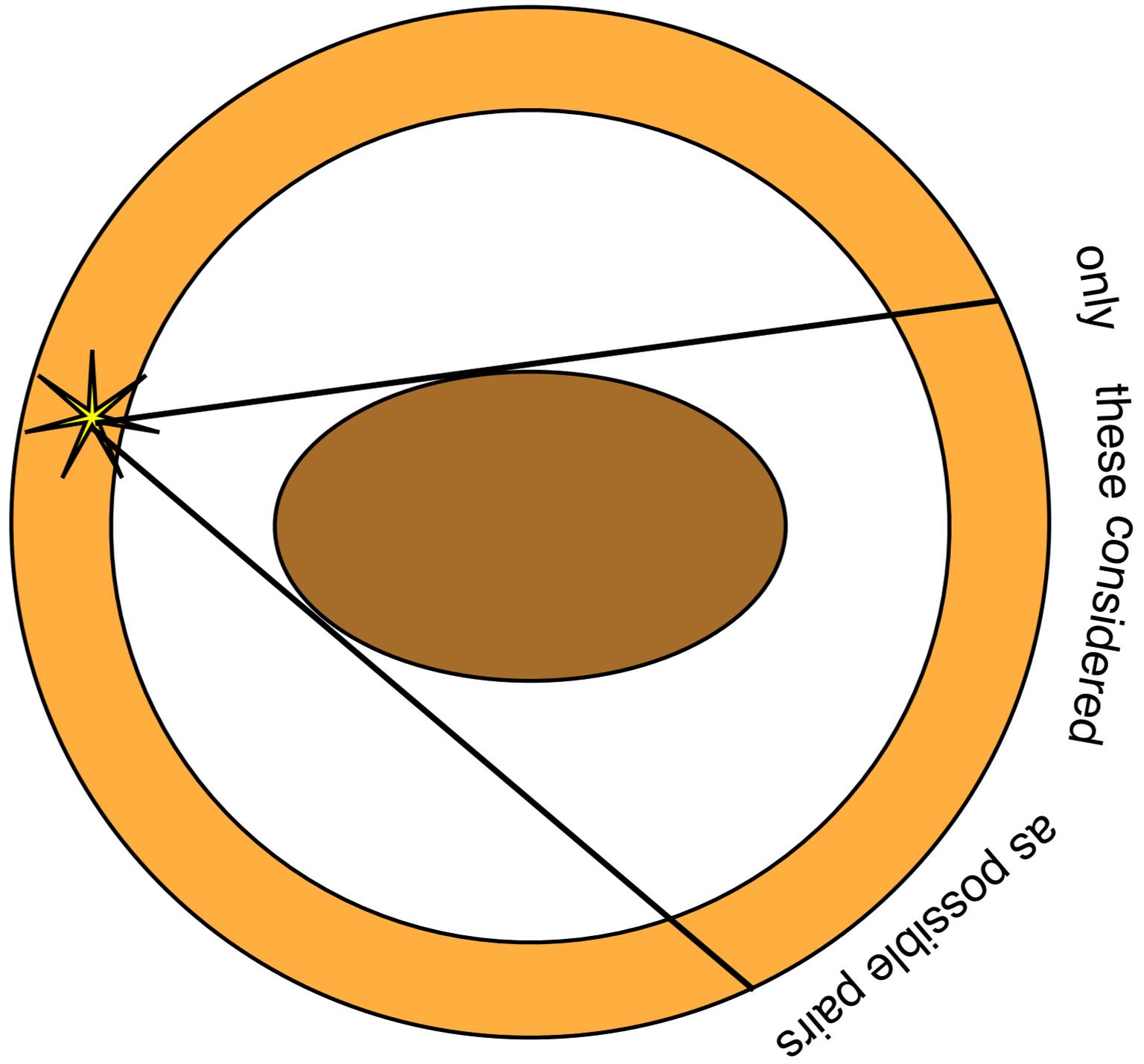


event counted in a: under τ there will be $R\tau$ counts somewhere on detector

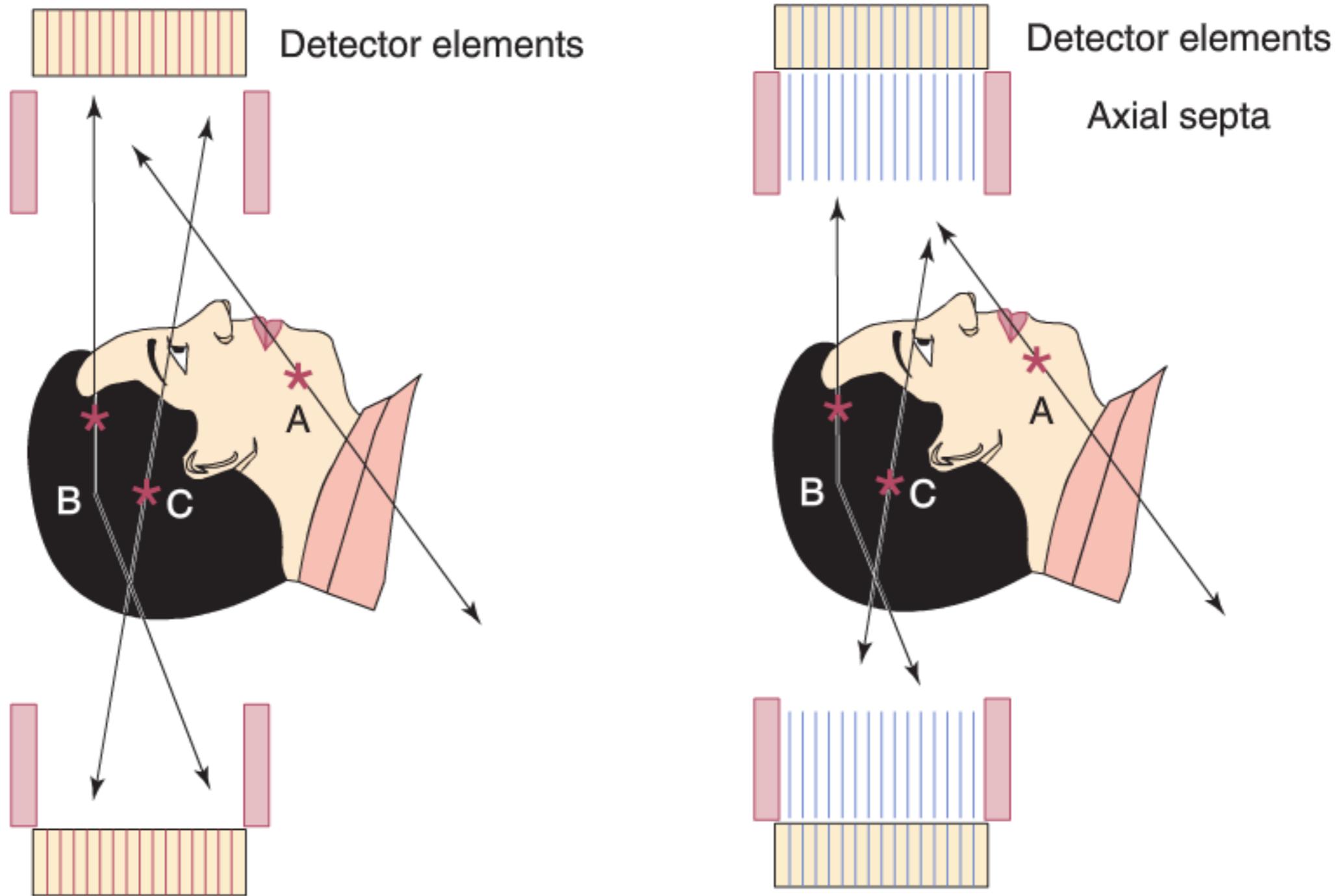
→ for every count $\rightarrow R\tau$ possible pairs (one true(?) all other untrue)

Count rate random coincidences: $R^2\tau$

minimising random coincidences

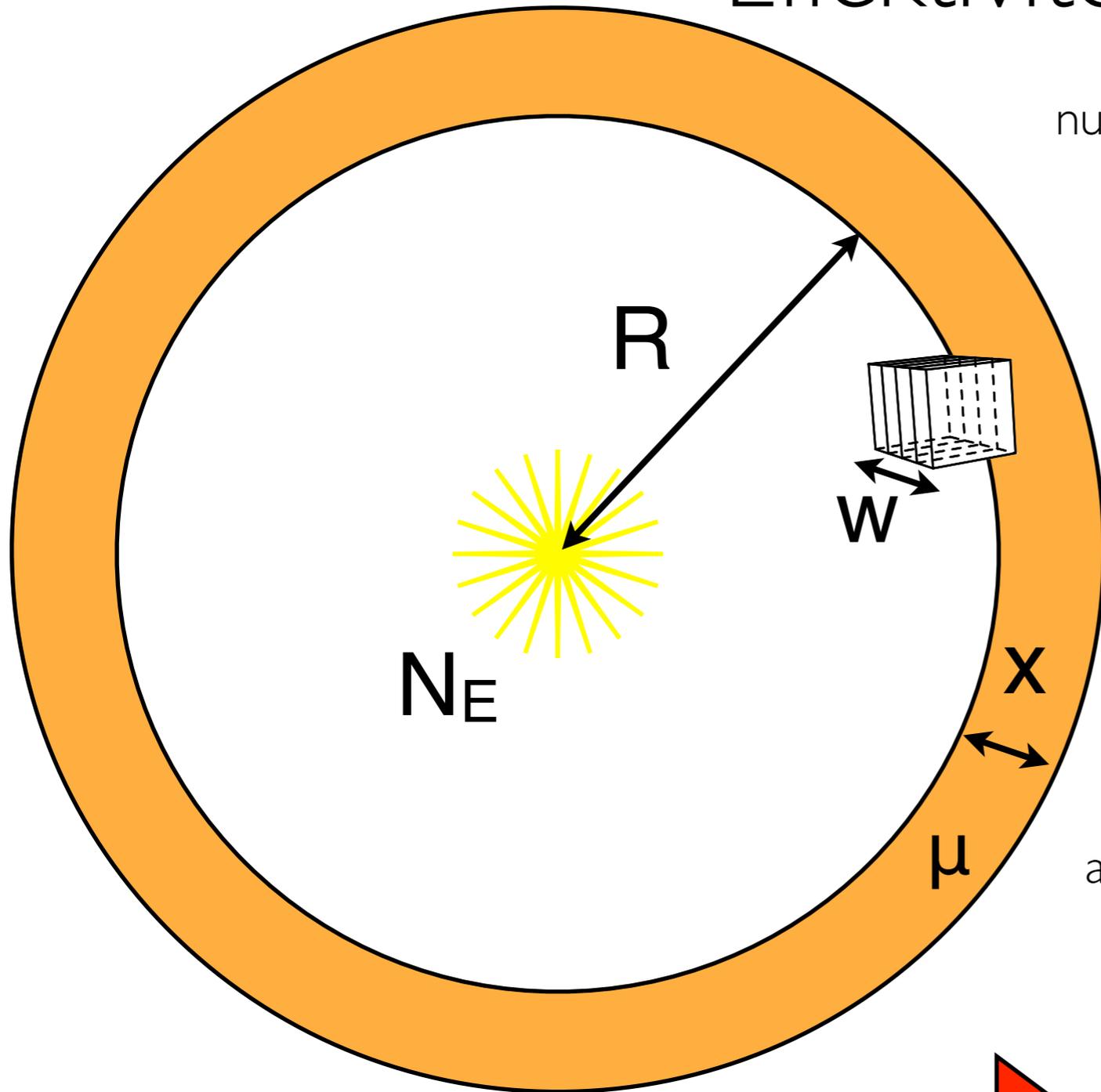


Other sources of image noise



Lower noise but lower efficiency!

Effektivitet i PET



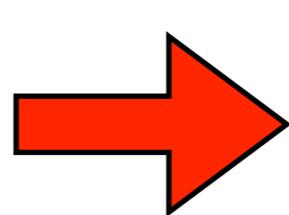
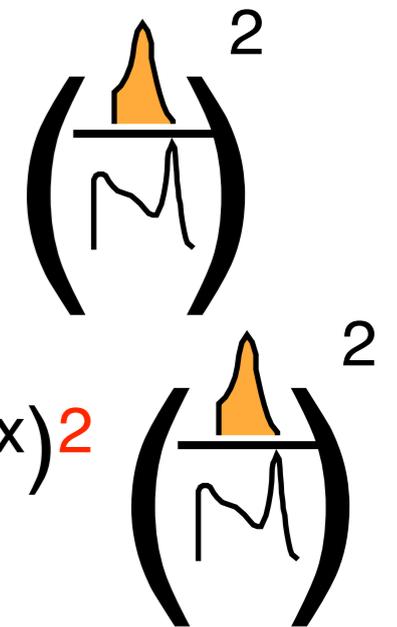
number of detected coincidences?

hit detector: $\frac{2\pi R w}{4\pi R^2} = w/2R$

attenuated: hit detector $(1 - e^{-\mu x})^2$
(both must be attenuated!)

accepted:

attenuated



$$\frac{N_E}{2} \frac{w}{2R} (1 - e^{-\mu x})^2 \left(\text{graph} \right)^2$$

Since $N_E \propto$ activity \Rightarrow CCR \propto activity

vanliga tidsfönster för PET med BGO 12 ns,
med LSO 4,5 ns



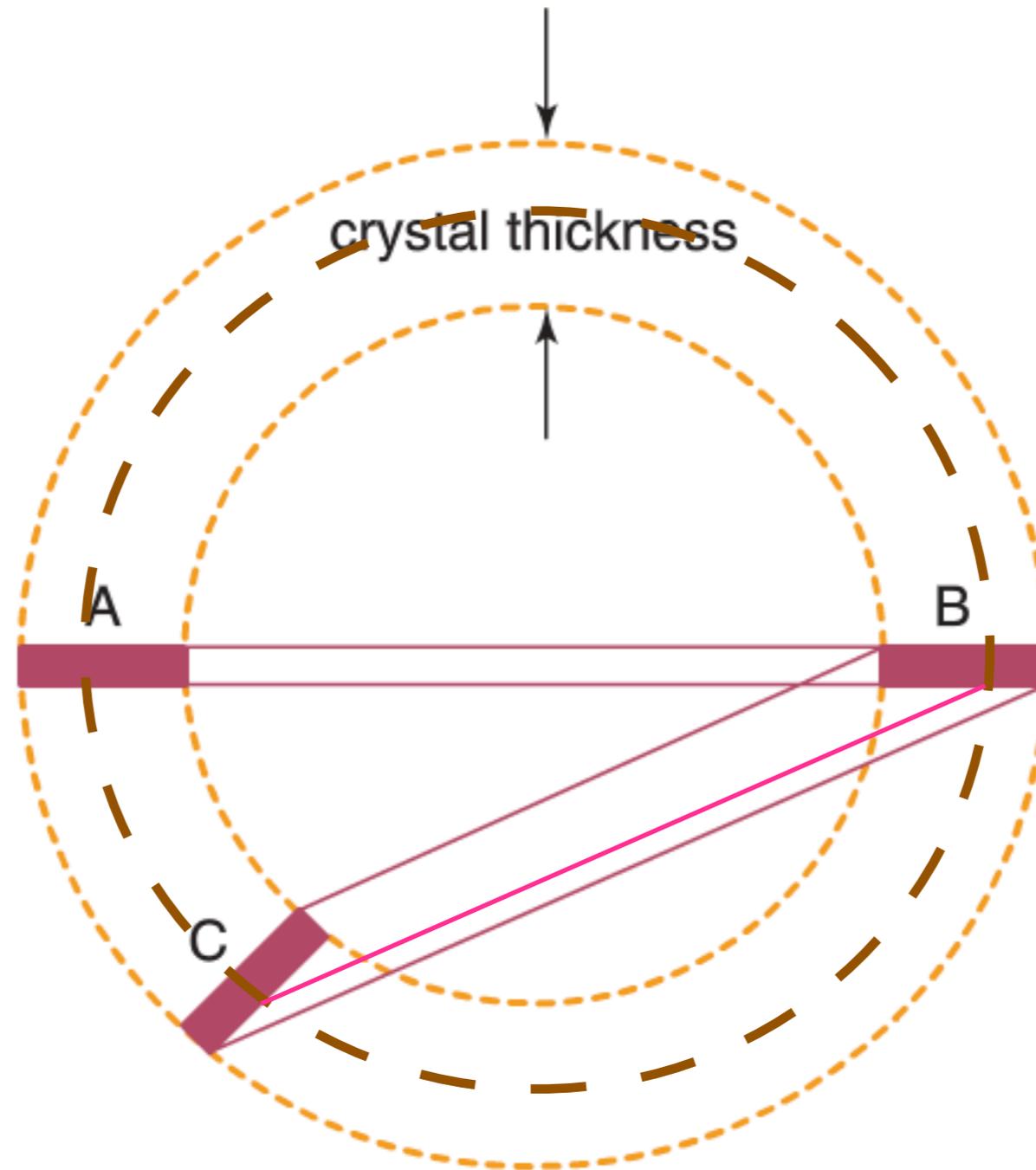
For Time Of Flight
PET one needs
time resolution
of order 100 ps

Is this a problem for coincidence timing?

A. JA

B. NEJ

resolution center vs periferi
sensitivity vs resolution



→ spatial resolution is not the same
in periphery as in middle of FOV

resolution at different positions in FOV

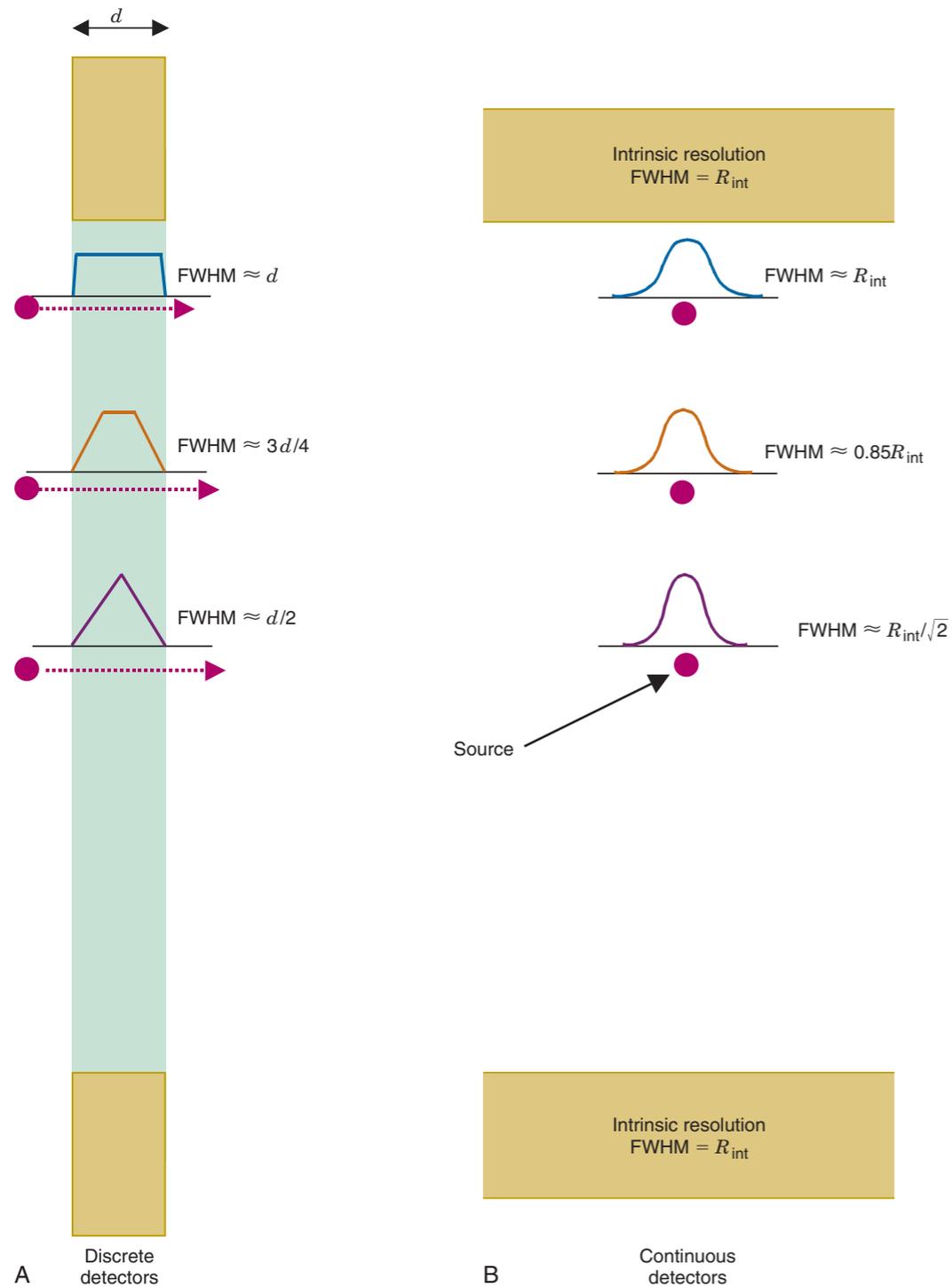
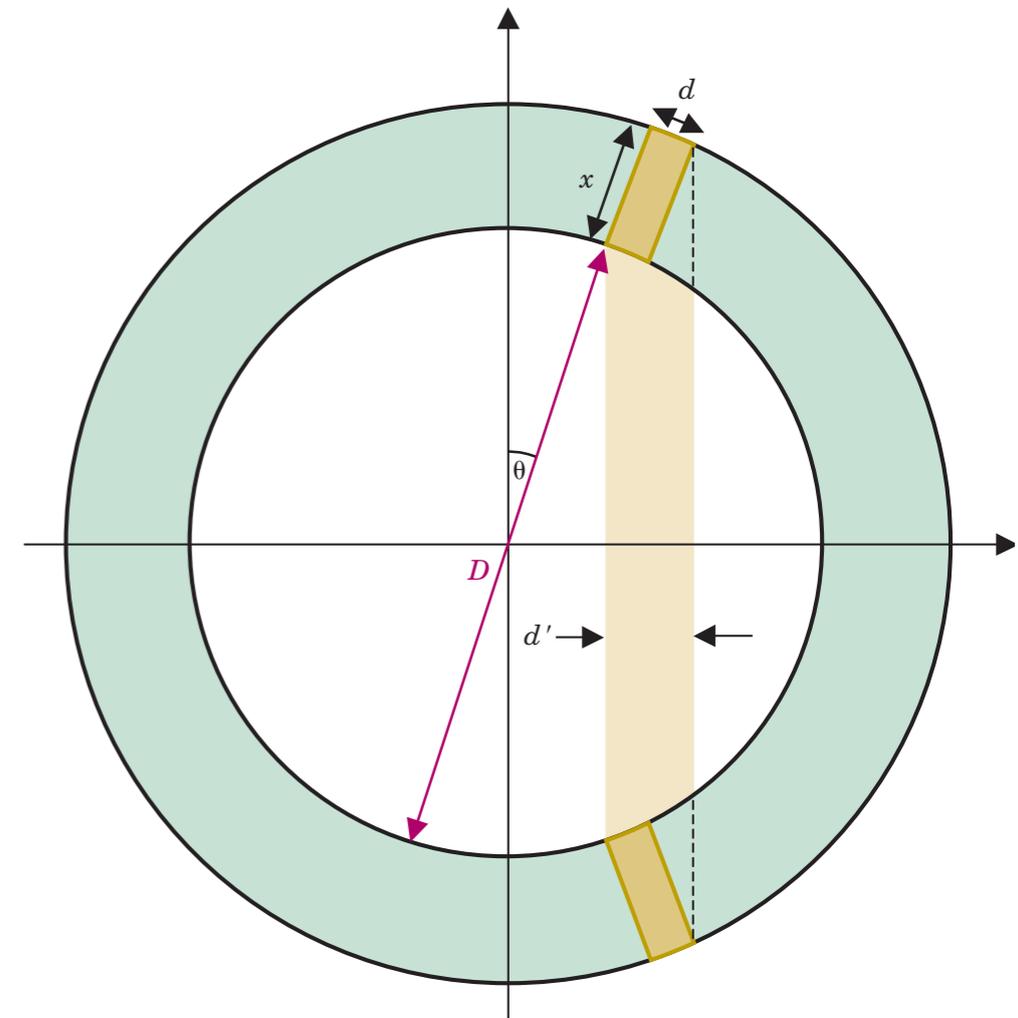


FIGURE 18-10 Apparent width of a detector element, d' , increases with increasing radial offset in a PET scanner consisting of a circular array of detector elements. Because the depths at which the γ rays interact within the scintillation crystal are unknown, the annihilation event for a pair of photons recorded in coincidence could have occurred anywhere within the shaded volume. The magnitude of the effect depends on the source location, the diameter of the scanner, D , the length of the crystal elements, x , and the width of the detector elements, d .

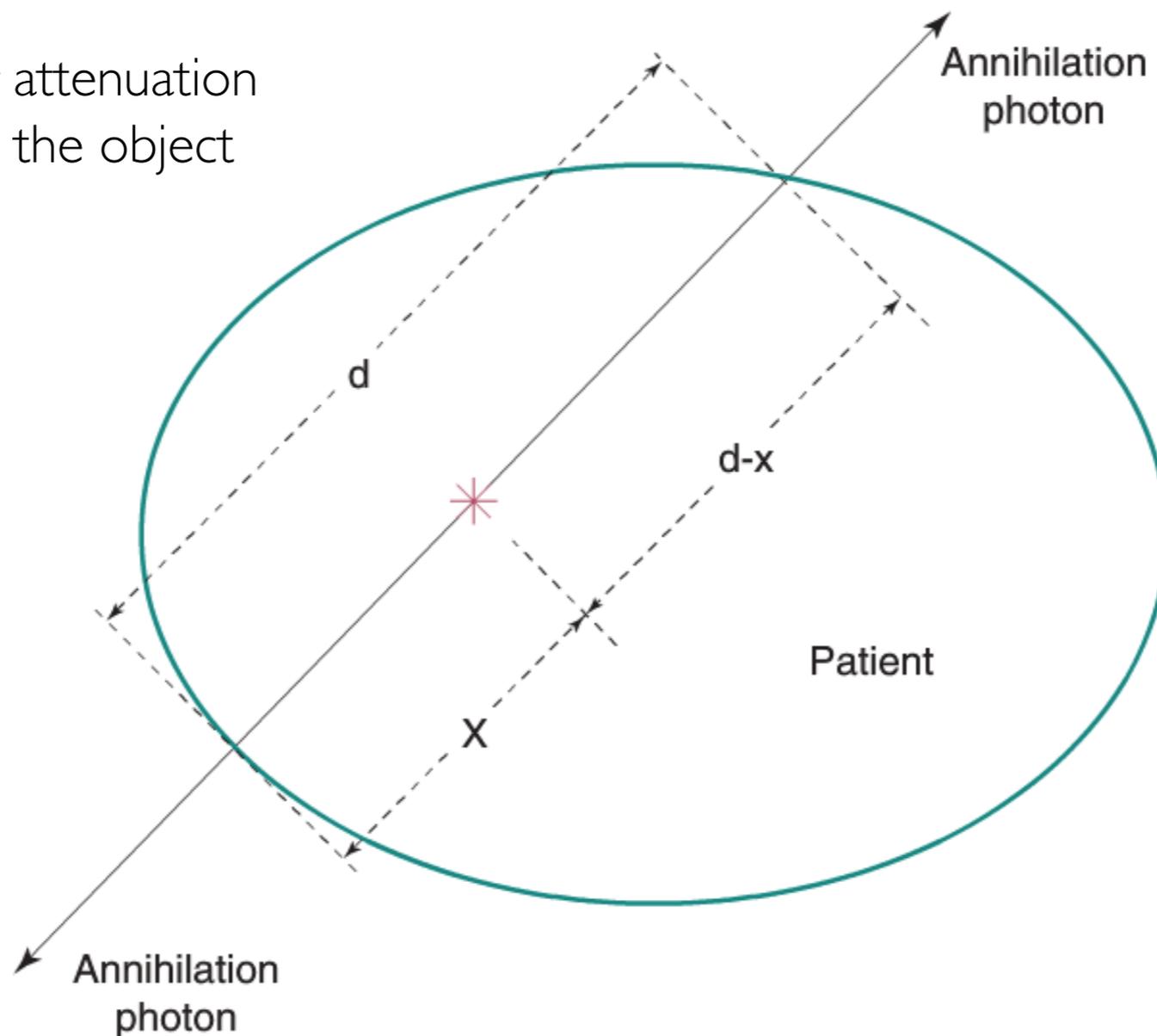


$$d' = d \cos \theta + x \sin \theta$$

Increasing crystal thickness:

- 1 improves spatial resolution
- 2 does not influence spatial resolution
- 3 worsen spatial resolution
- 4 improves efficiency
- 5 does not influence efficiency
- 6 worsen efficiency
- 7 does not influence spatial resolution in the exact centre of FOV

Assume a uniform linear attenuation coefficient μ throughout the object



Attenuation factor for coincidences is:

A. $(e^{-\mu x})^2$

B. $e^{-\mu x}$

C. $e^{-\mu(d-x)}$

D. $e^{-\mu d}$

More attenuation in PET or SPECT? Does attenuation disturb more in PET or SPECT?

SPECT

PET

collimator
(mechanical)

no collimator
("electronic collimation")

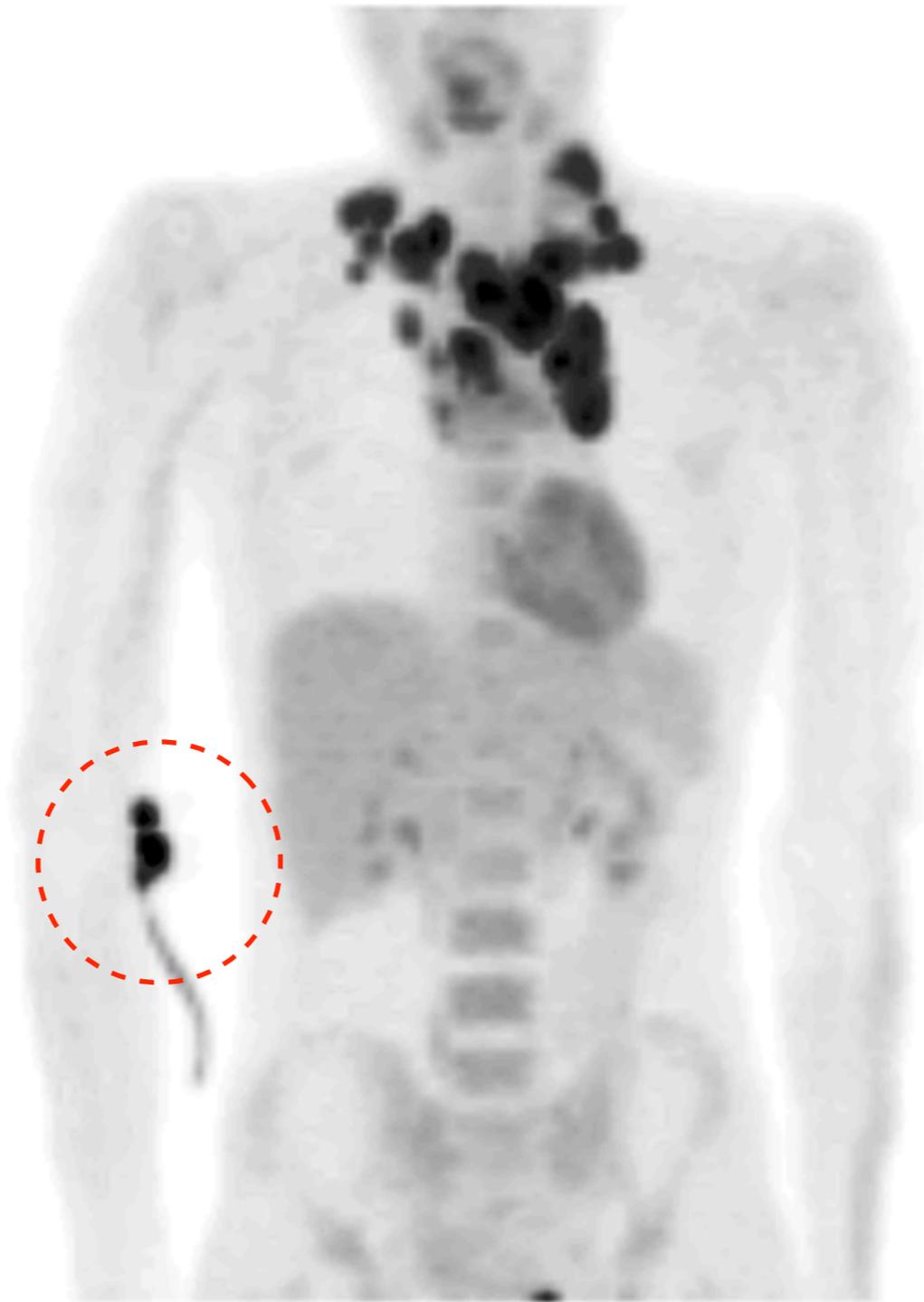
efficiency $10^{-3}\%$

efficiency up to 10%

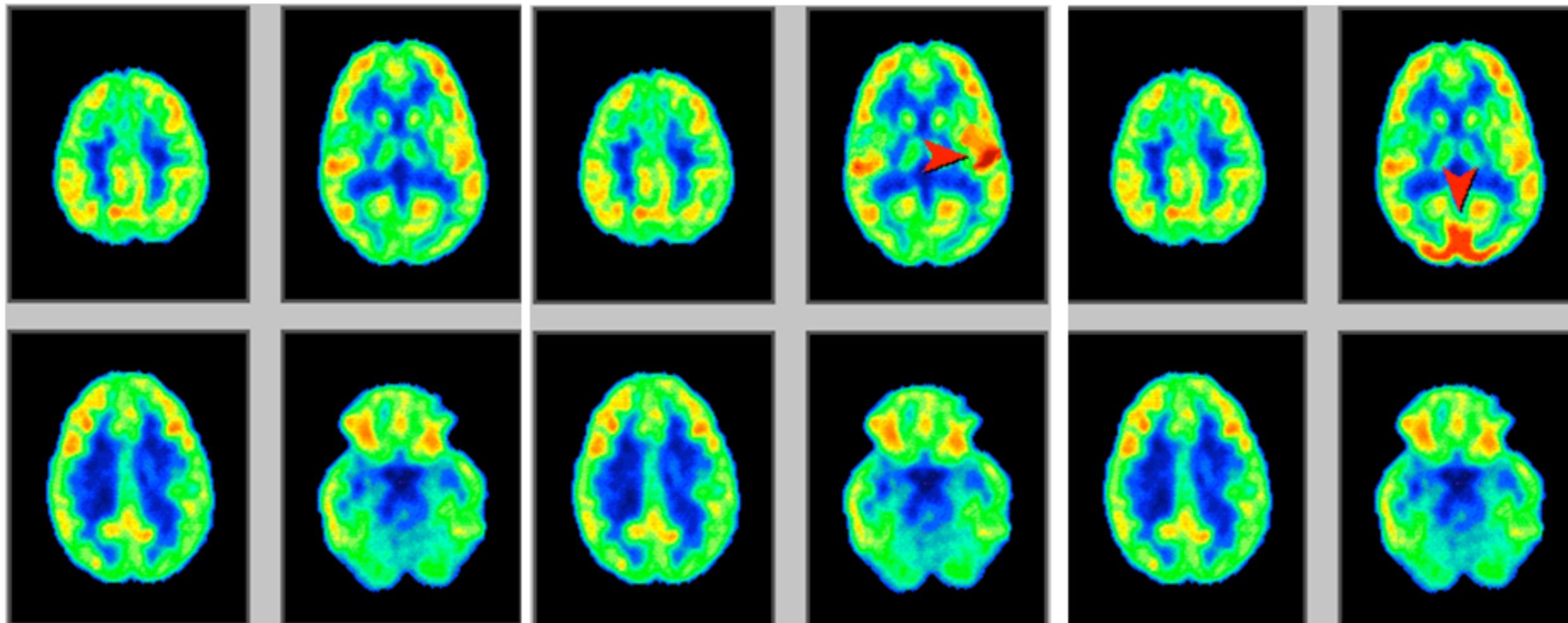
gammas $E \sim 100-200$ keV

gammas $E = 511$ keV

F-18-FDG oncology



brain activity imaging

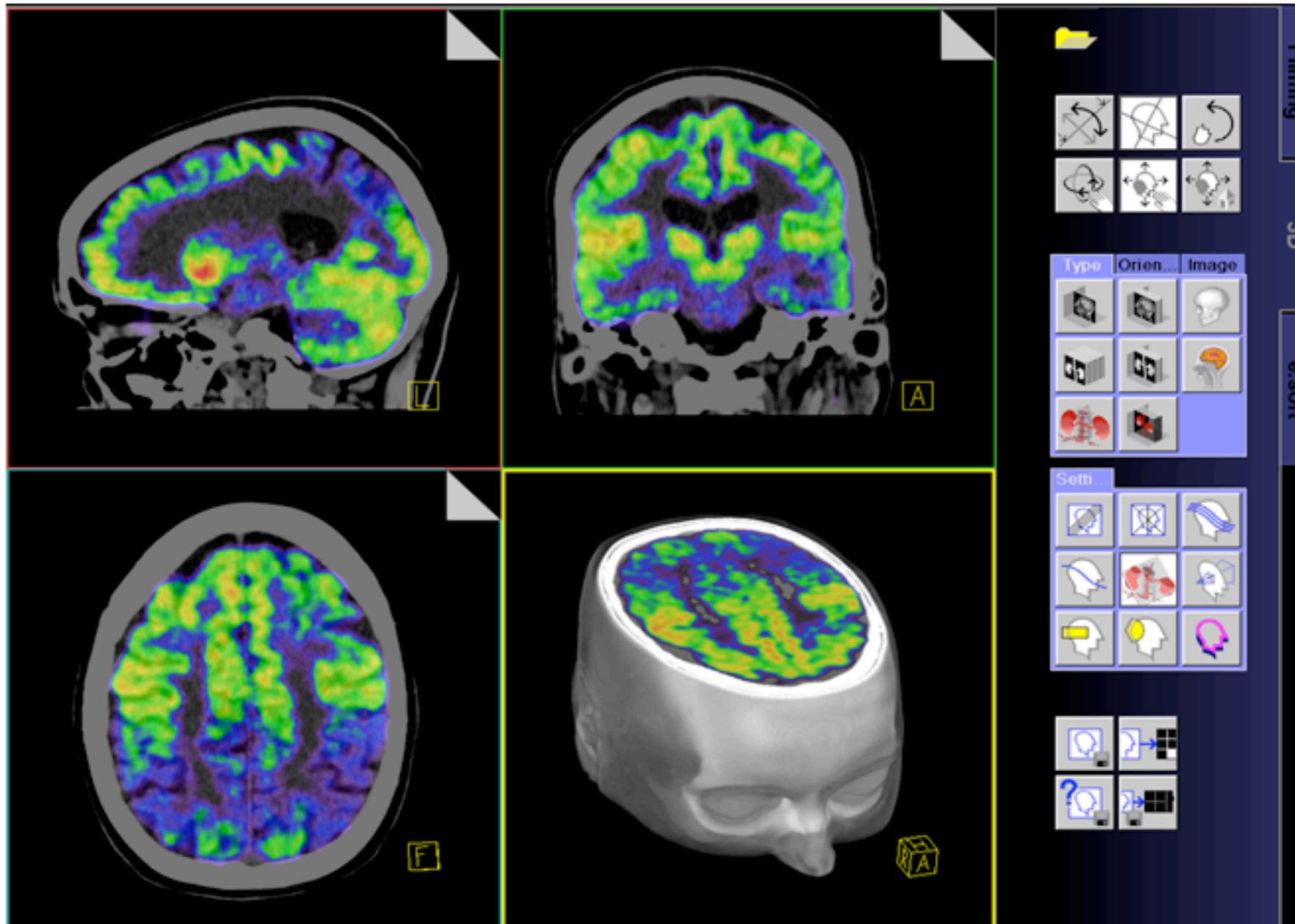


rest

music

images

alzheimer's disease



54 year old female, 68.2 kg (150 lbs)

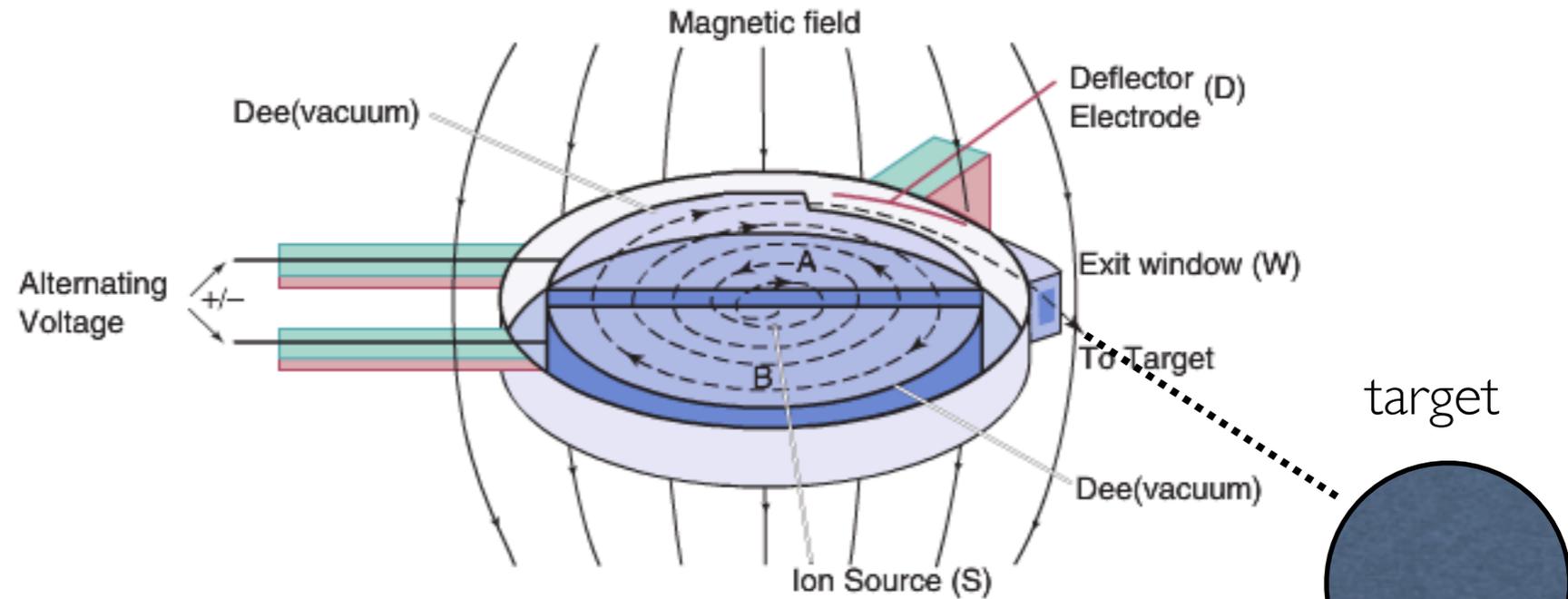
Decreased glucose metabolism in posterior parietal association cortex in patient with memory problems.

isotopes for PET

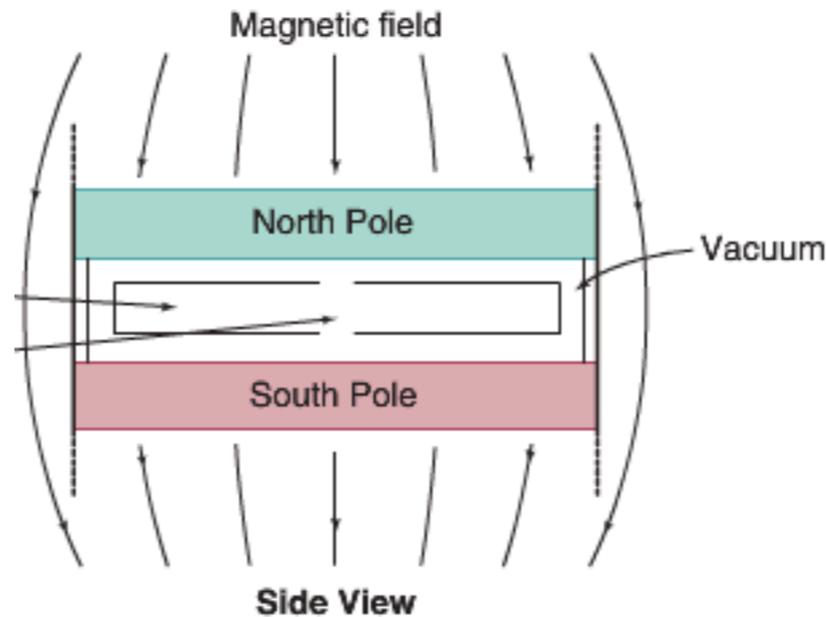
Radio-isotopes	T_{1/2}	β⁺ Max Energy (MeV)	% Ratio	Resolution (mm rms)
¹¹ C	20 min	0.96	100	0.92
¹³ N	10 min	1.2	100	1.35
¹⁵ O	122 sec	1.7	100	2.4
¹⁸ F	110 min	0.64	97	0.54
⁶⁴ Cu	12.8 h	0.65	18	0.55
⁶⁸ Ga	68 min	1.9	89	2.8
⁸² Rb	76 sec	3.4	95	6.1

Isotope	Tracer	Physiological Process	Main Application
¹¹ C	Methionine	Protein Synthesis	Oncology
¹¹ C	Raclopride	D2 Receptor	Movement Disorder
¹³ N	Ammonia	Blood Perfusion	Myocardial Perfusion
¹⁵ O	Water/Dioxise	Blood Perfusion	Brain Activation
¹⁸ F	Fluorine Ion	Bone Metabolism	Oncology
¹⁸ F	Fluorine deoxyglucose	Glucose Metabolism	Oncology
			Neurology
			Cardiology

Activity for PET: cyclotron

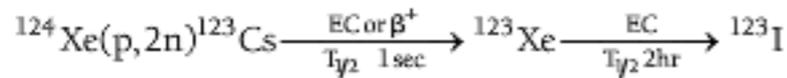
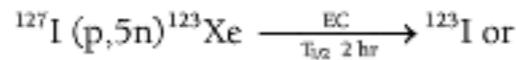


Top and bottom magnet removed



target
nuclear reaction

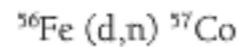
Iodine-123 production:



Indium-111 production:



Cobalt-57 production:



Thallium-201 production:

