Data acquisition and radiation detection essentials for Positron Emission Tomography

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IEEE NPSS School of Application of Radiation Instrumentation Dakar - Senegal

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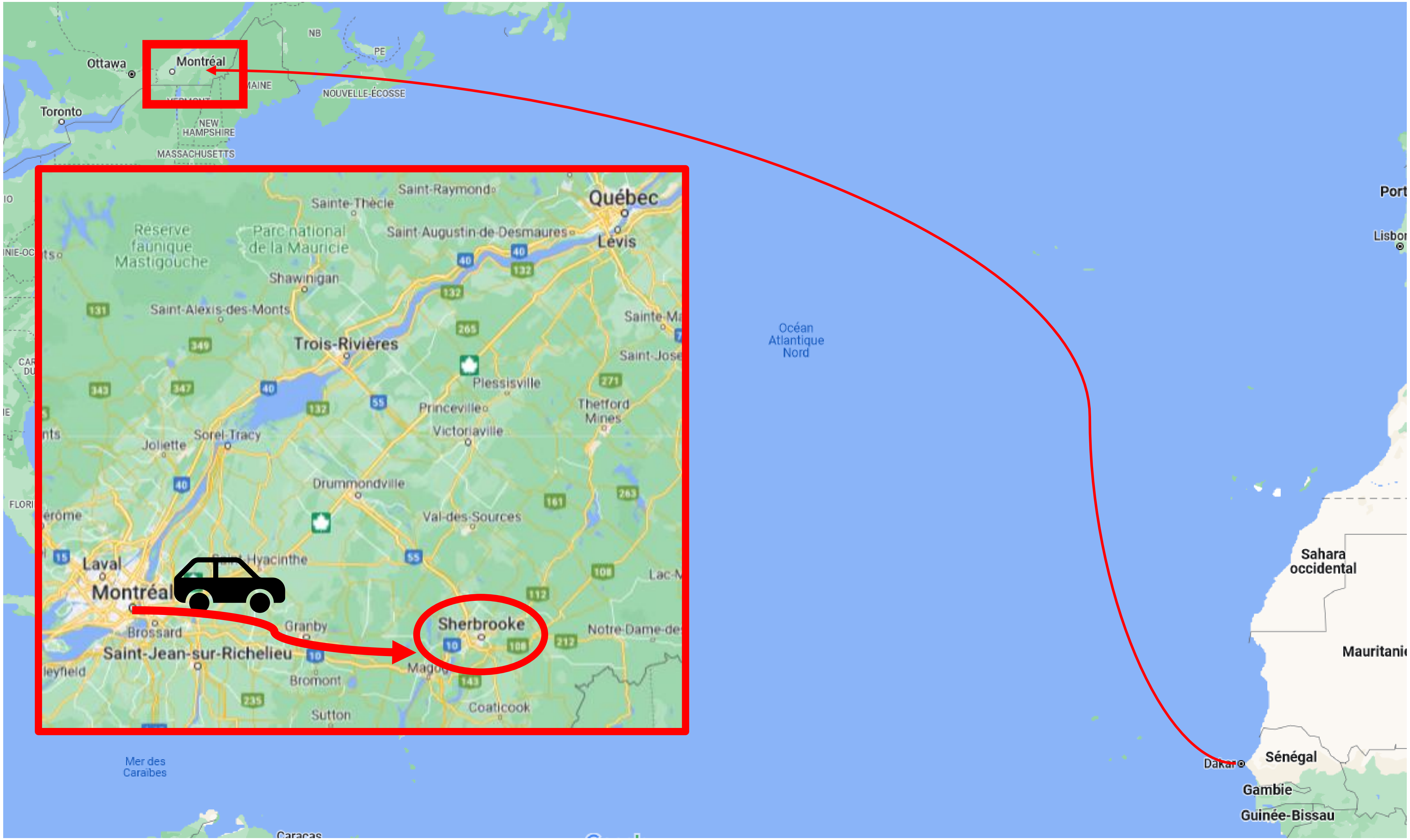
Université de Sherbrooke

Where do I come from?



Université de Sherbrooke – Main Campus

UDS

3IT : Institut Interdisciplinaire d'Innovation Technologique

UDS

A little about me

UdS

My path in research

- 2003-2015 Small animal scanner
- 2010-2017 PhD on 3D Digital SiPM
- 2017-2019 Postdoc at MGH/HMS on PET brain scanner
- 2019-Today Professor at Sherbrooke
  - Electrical and computer engineering

At IEEE

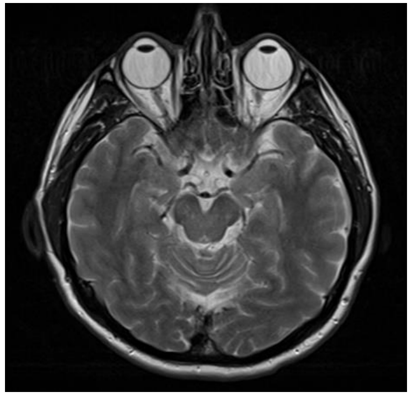
- Involved in CANPS
  - IEEE NPSS Real Time Conference
- IEEE TNS Assistant Editor
- IEEE NPSS RISC elected member
  - Contribute to the IEEE NSS/MIC Conference
- IEEE NPSS School!
  - Next week

What is Positron Emission Tomography?

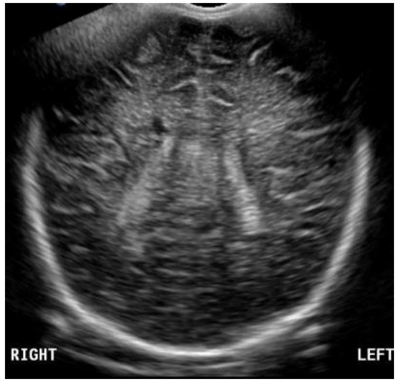
Families of medical imaging

Structural Imaging

MRI

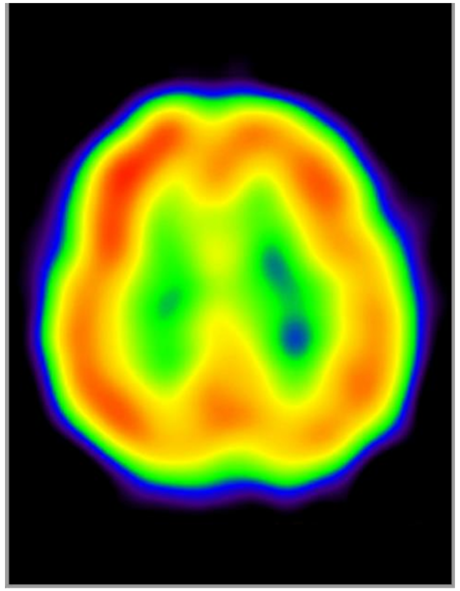


CT

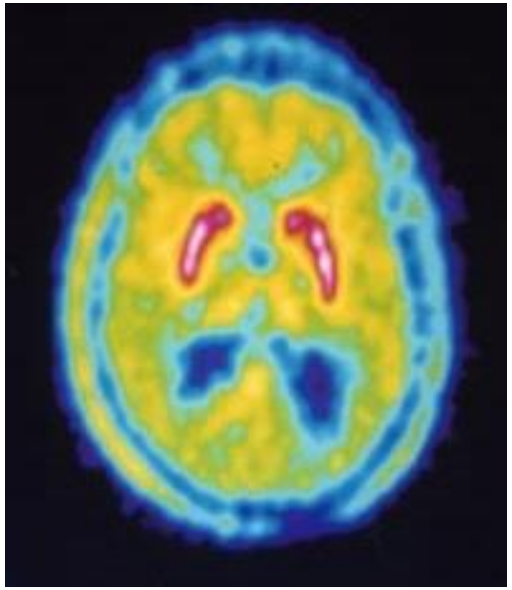


Ultrasound

Molecular Imaging (see metabolism)



SPECT



PET

Positron Emission Tomography

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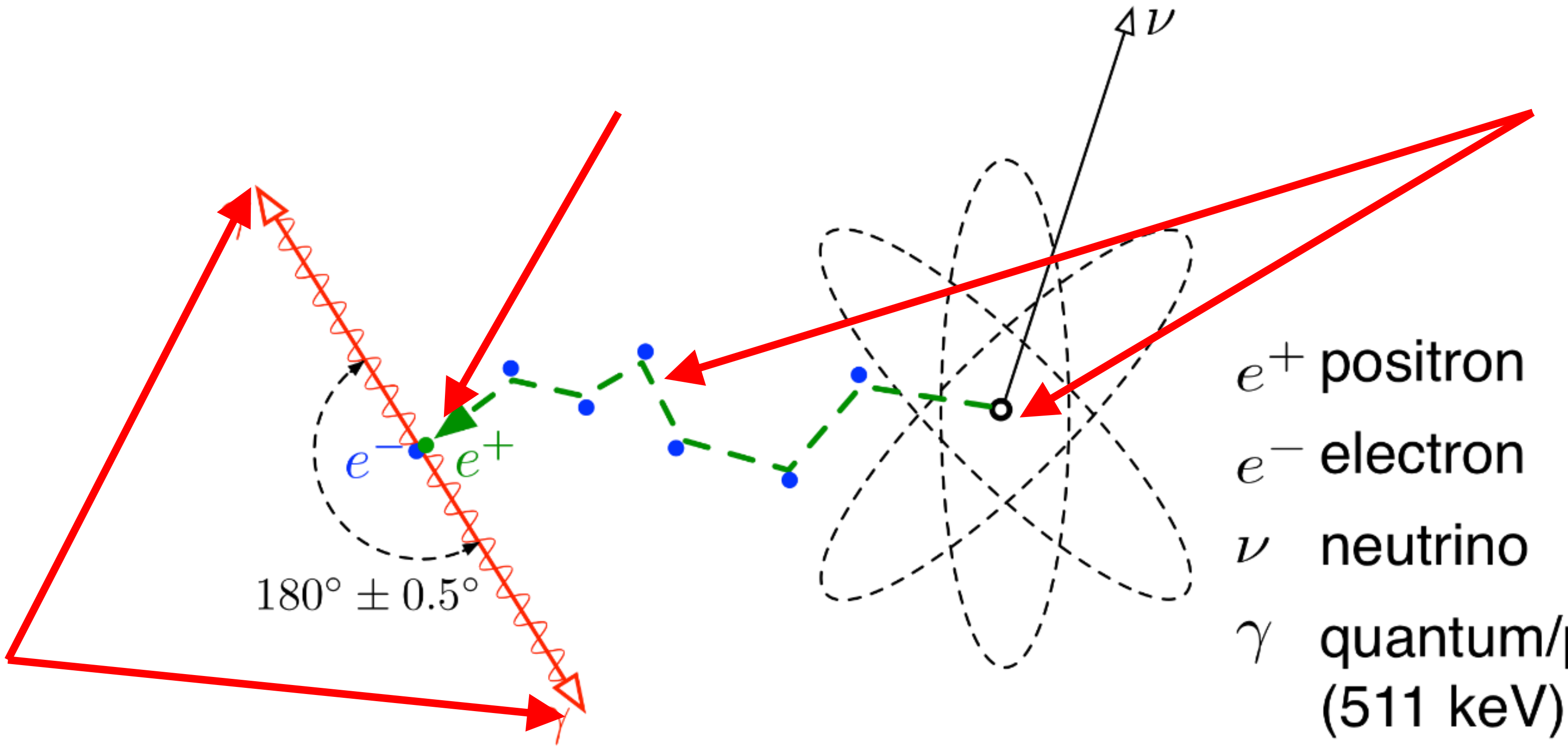


e^+ positron

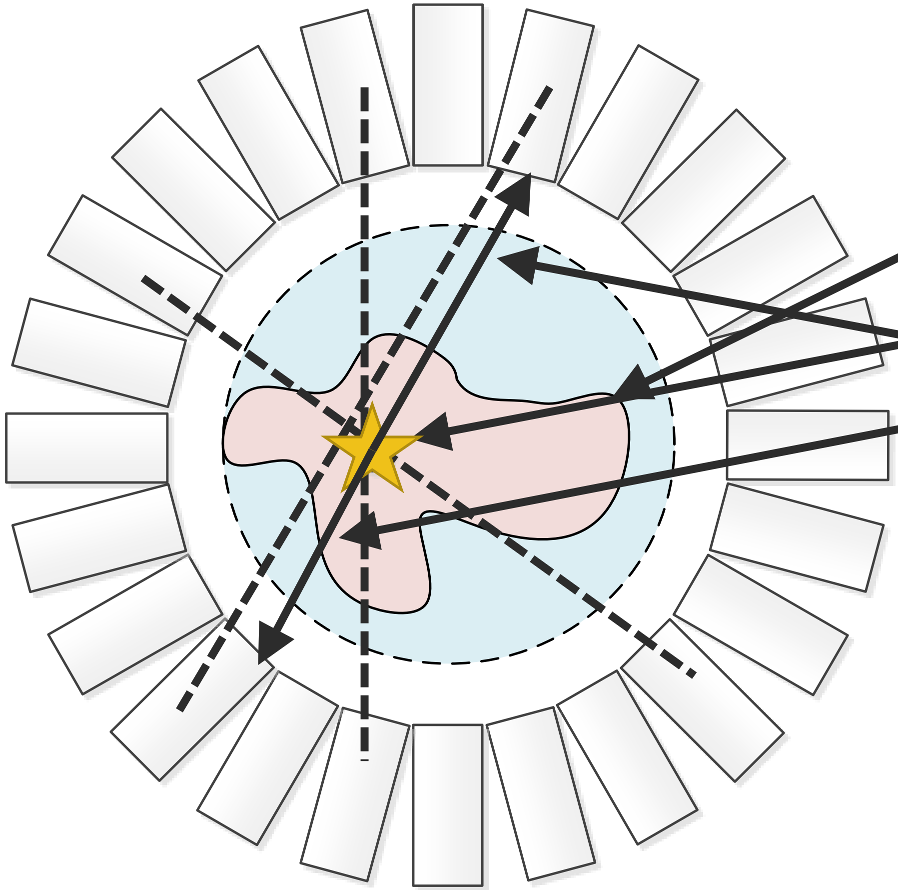
e^- electron

ν neutrino

γ quantum/photon (511 keV)

Positron Emission Tomography

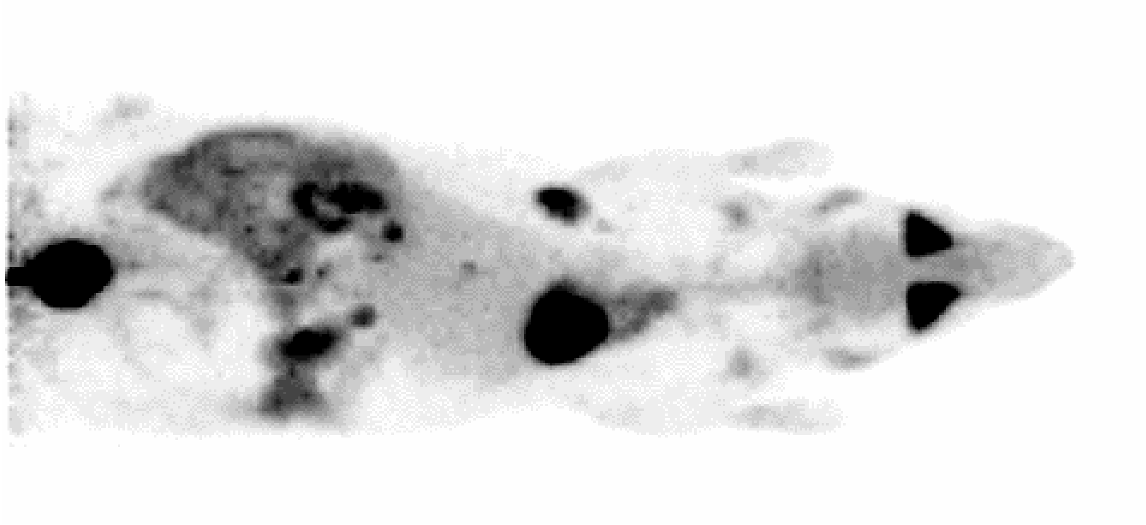
UDS



- Molecular Imaging Modality
  - Tracer distribution (positron emitter)
    - Hot spot on the left side
  - Positron Annihilation
  - Collinear 511 keV particles
  - Line of response

Examples of PET images

^{18}FDG (Glucose) tracer



Bone Tracer ([^{18}F]NaF)

What is PET used for

Clinical applications

- Oncology
  - Diagnose cancer
  - Follow treatment evolution
- Cardiology
  - Assess damage from a heart attack
  - Evaluate the blood flow
  - Assist doctors in choosing proper intervention
- Neurology
  - Epilepsy

Research

- Evaluate new treatments
- Better understand the human body
  - Alzheimer’s disease

But how does a PET scanner work?

Goal of PET Scanner

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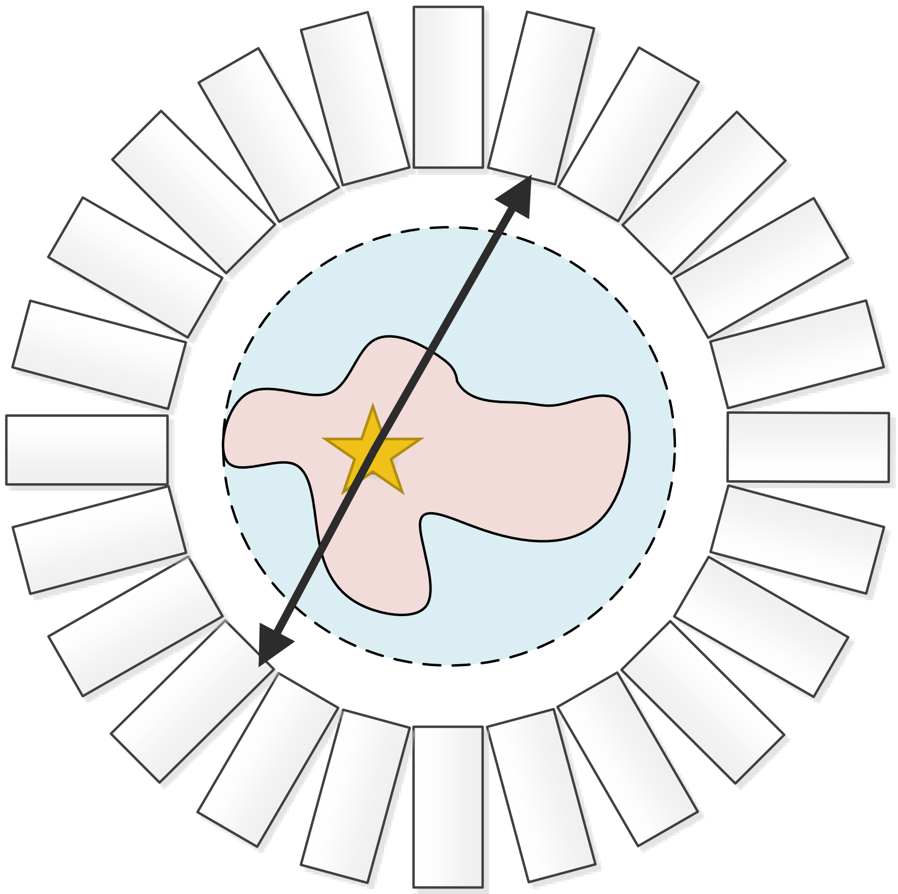
- Get images to help doctors and biologists do their work
- To build an image, the scanner needs to collect as many lines of response (LOR) as possible
  - How do we find them?



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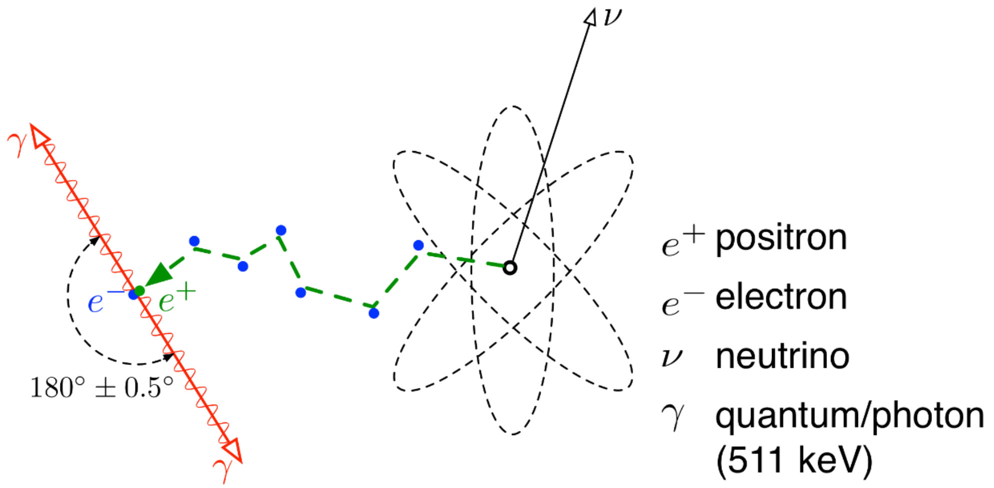
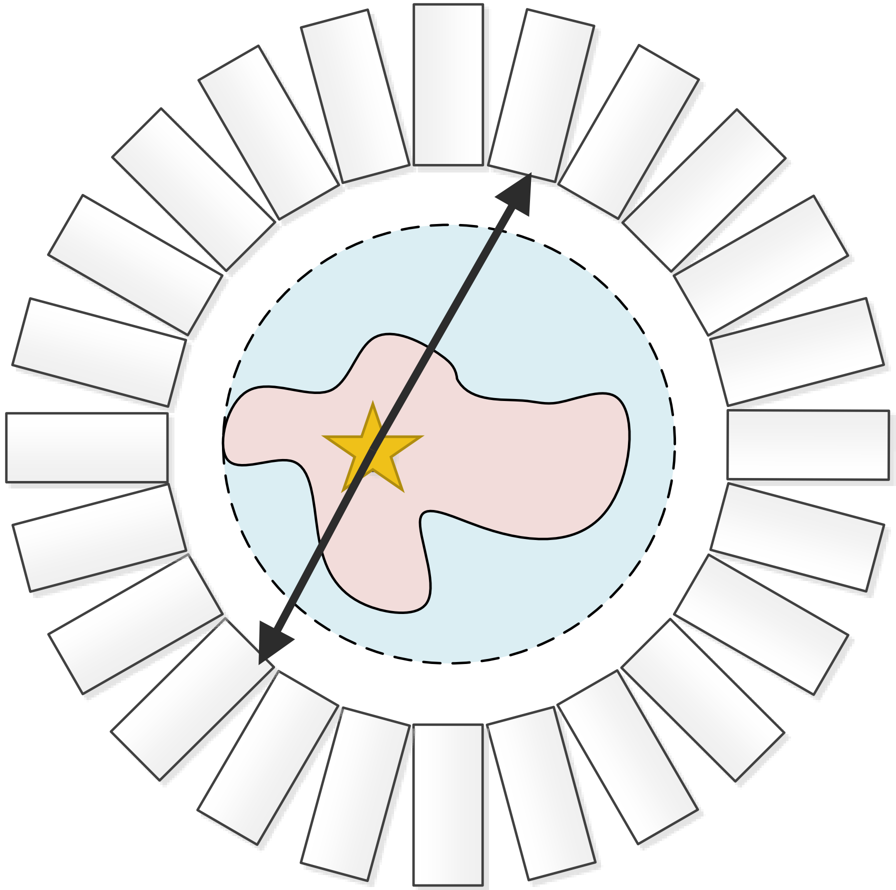
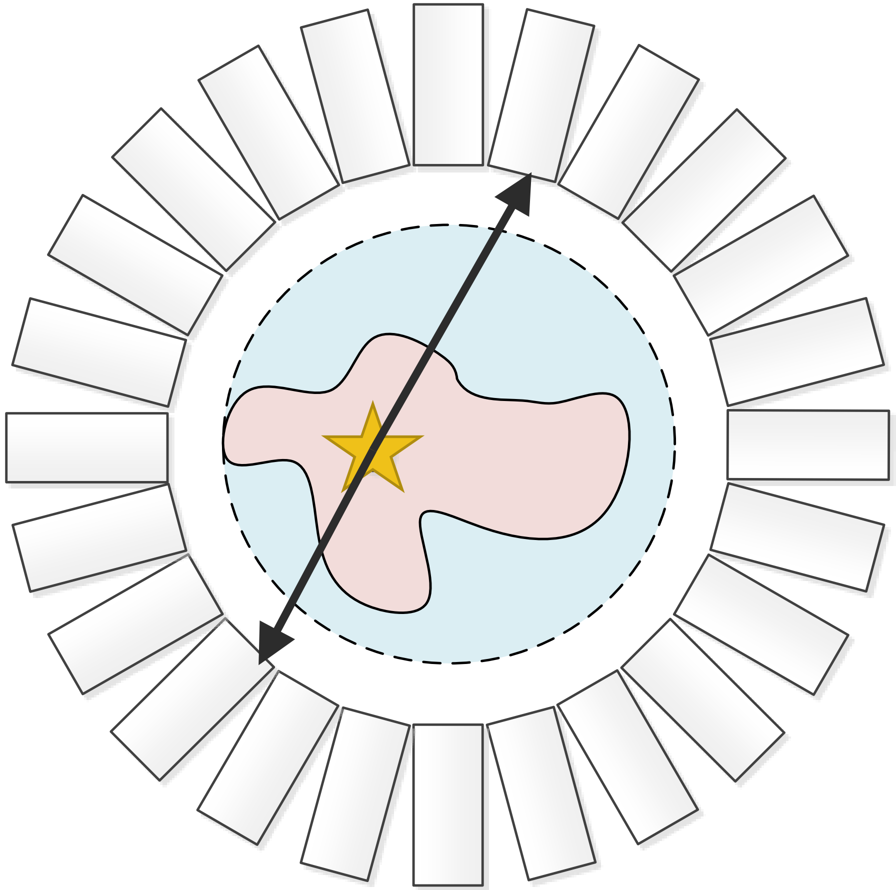




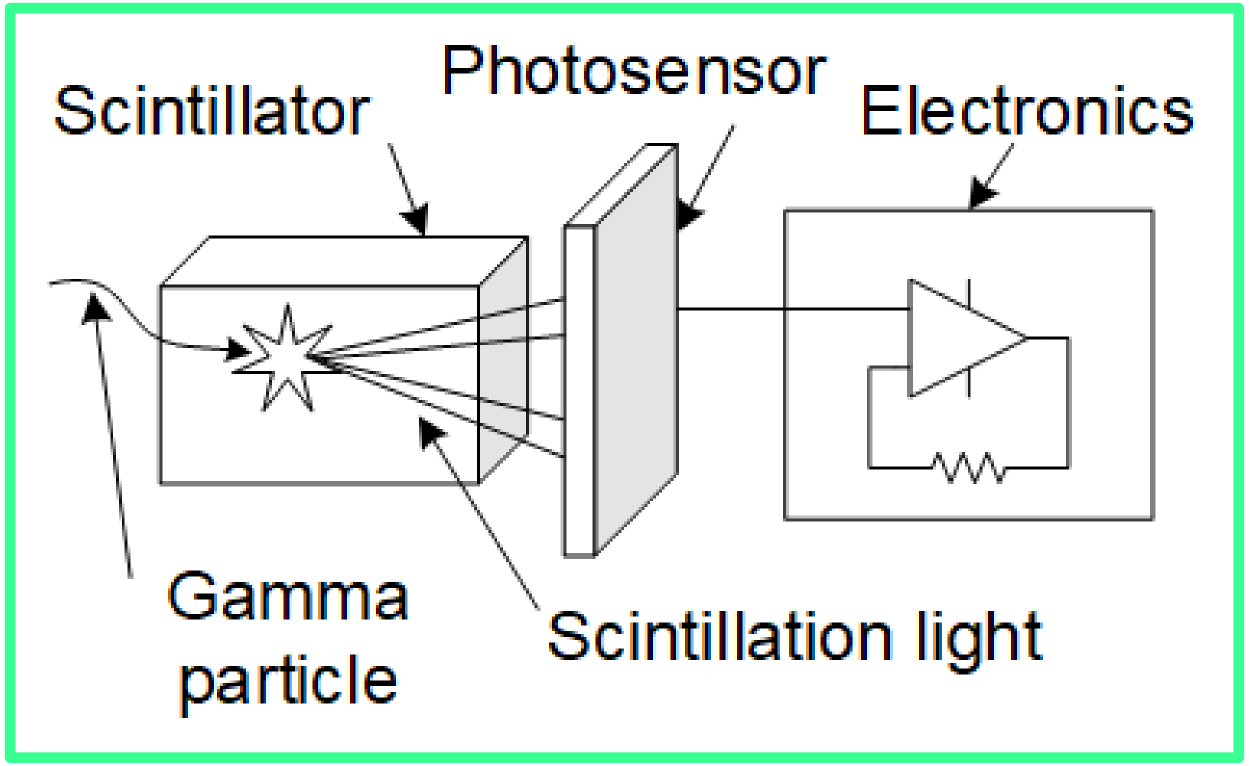
- The gamma energy is known (511 keV)
- They always come in pairs
  - Found at the same time
  - On opposite sides of the scanner

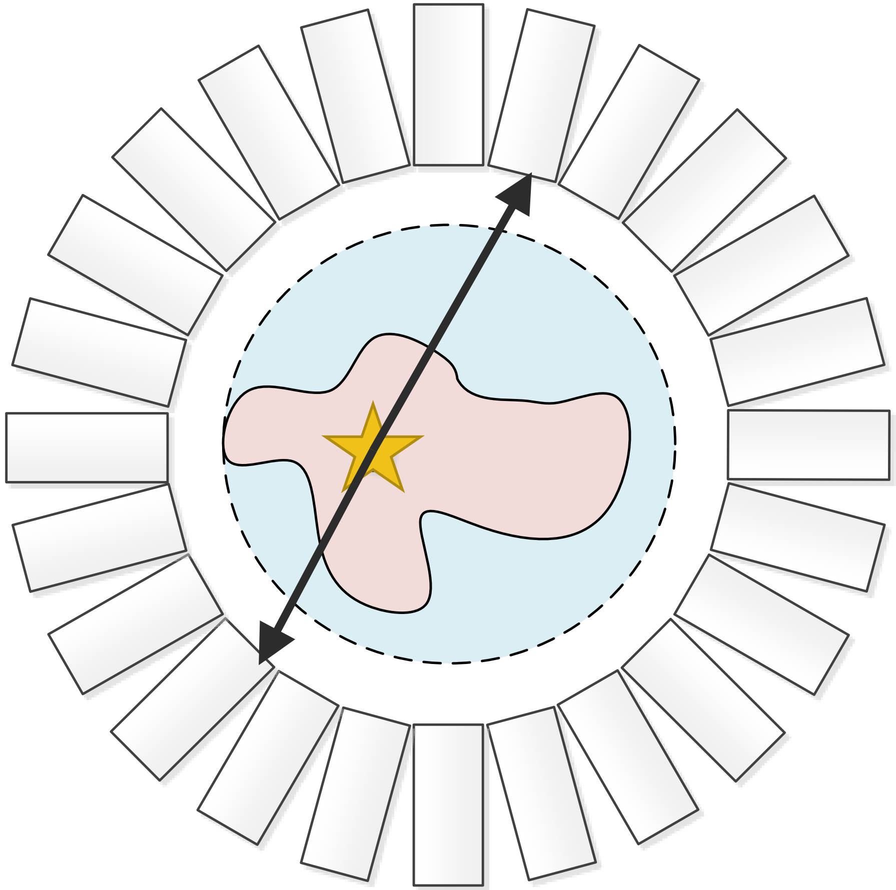
Unique properties of PET radiation

- We need to find events with the correct
  - Energy
  - Timing
  - Position (in the ring)



Unique properties of PET radiation





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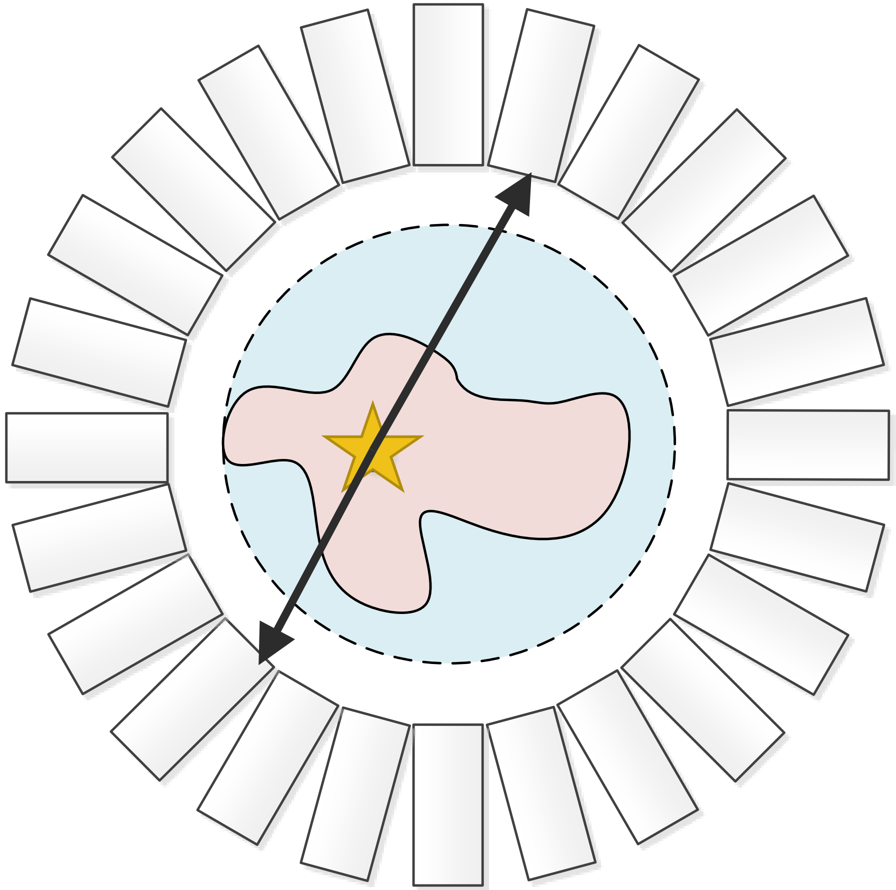
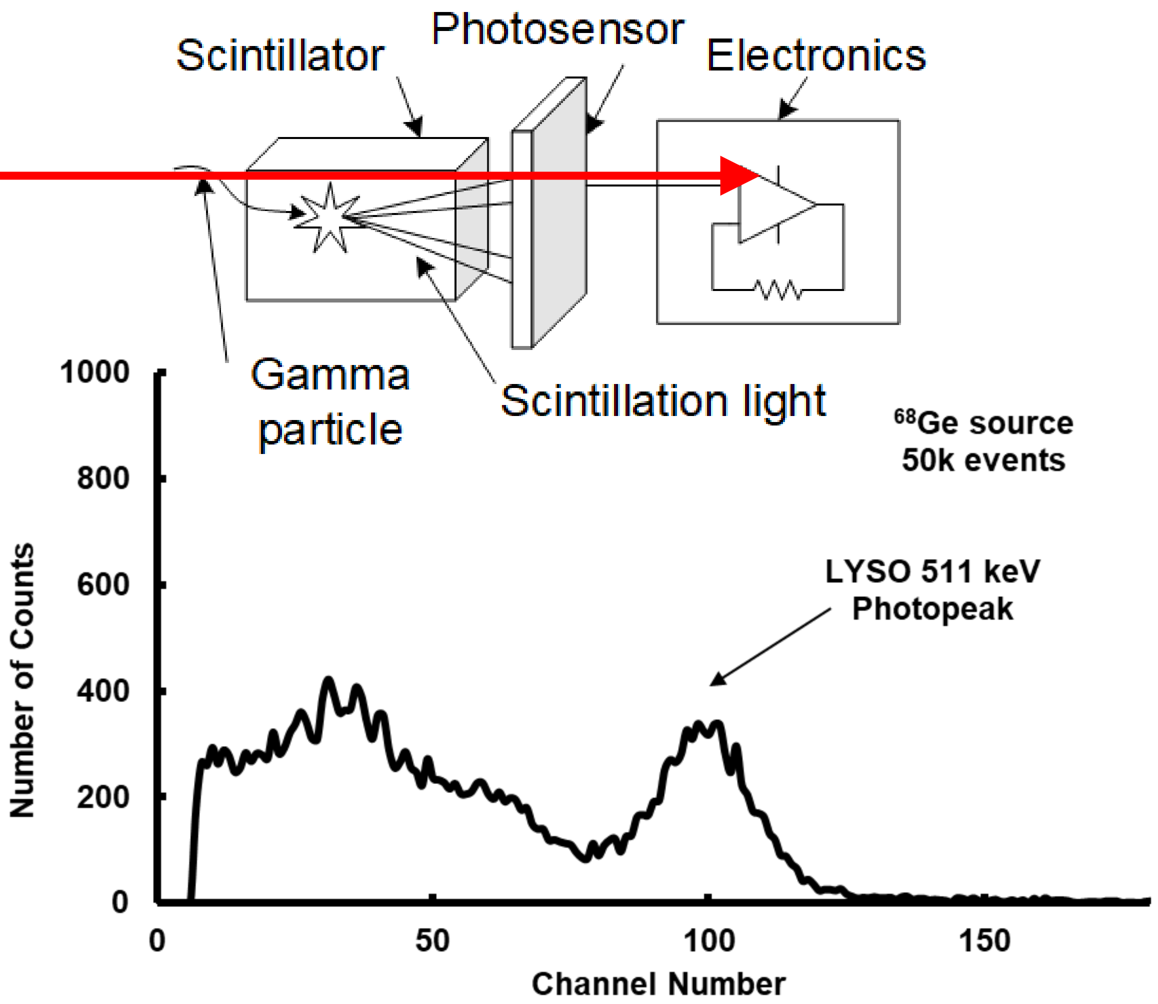


How to find 511 keV events?

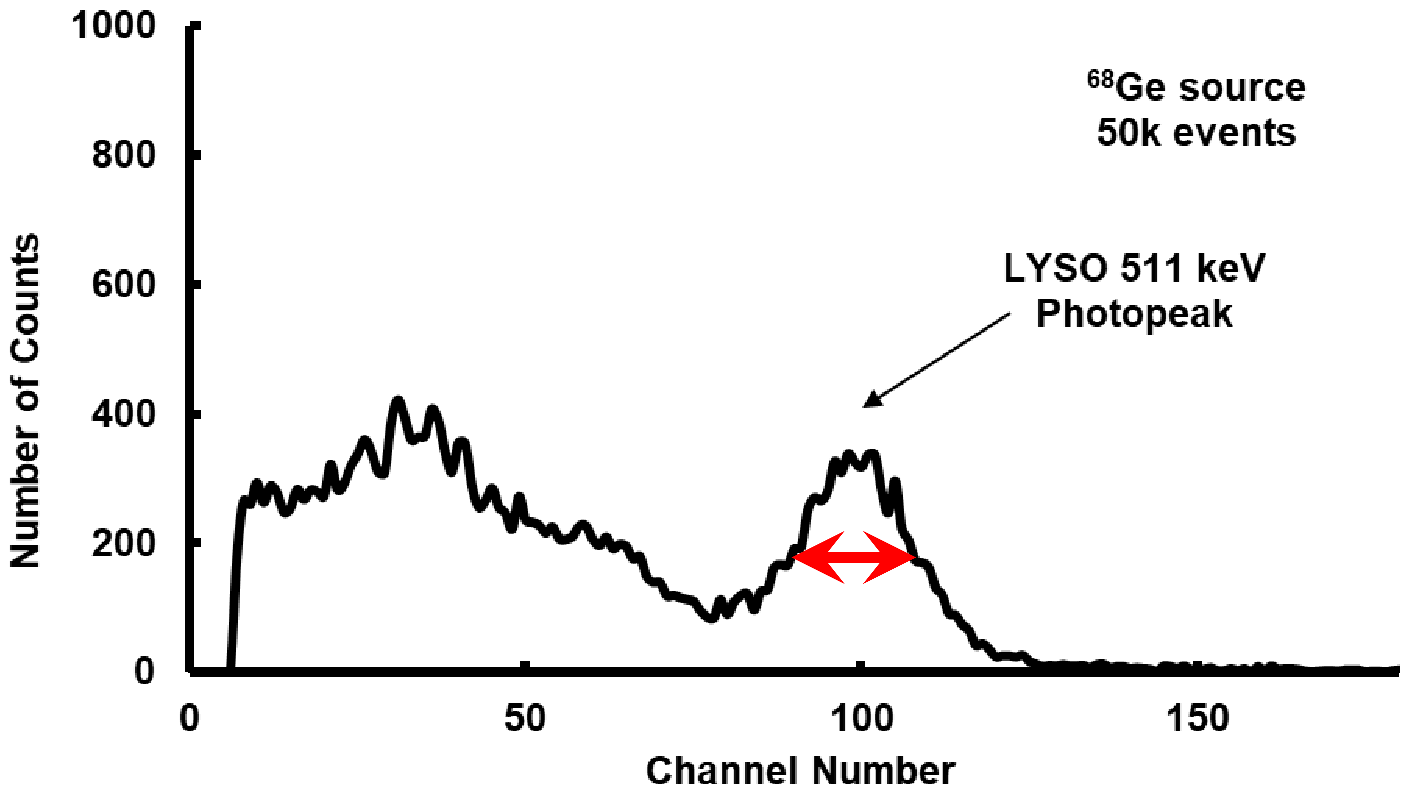
- Energy ≡ Number of Scint. Photons
  - Equivalent to electrical charge measurement
- How to determine energy?
  - Collect many events with known source
  - Build histogram (+1 for each event at amplitude number)
  - Find peak
  - Scale axis
  - Compare new events to scale



How good is an energy measurement?

- Energy resolution depends on
  - Crystal
  - Photosensor
  - Electronics

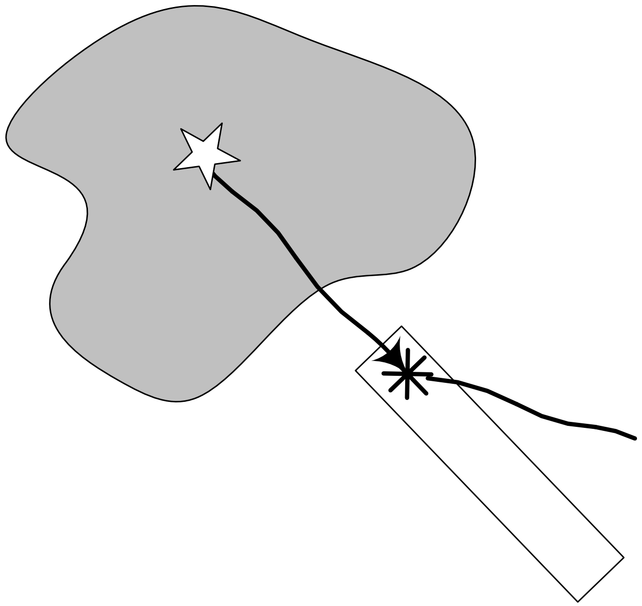
- Width of peak divided by position on histogram
  - $\frac{FWHM}{E}$
  - For SiPM-LYSO, typically 10-12% FWHM

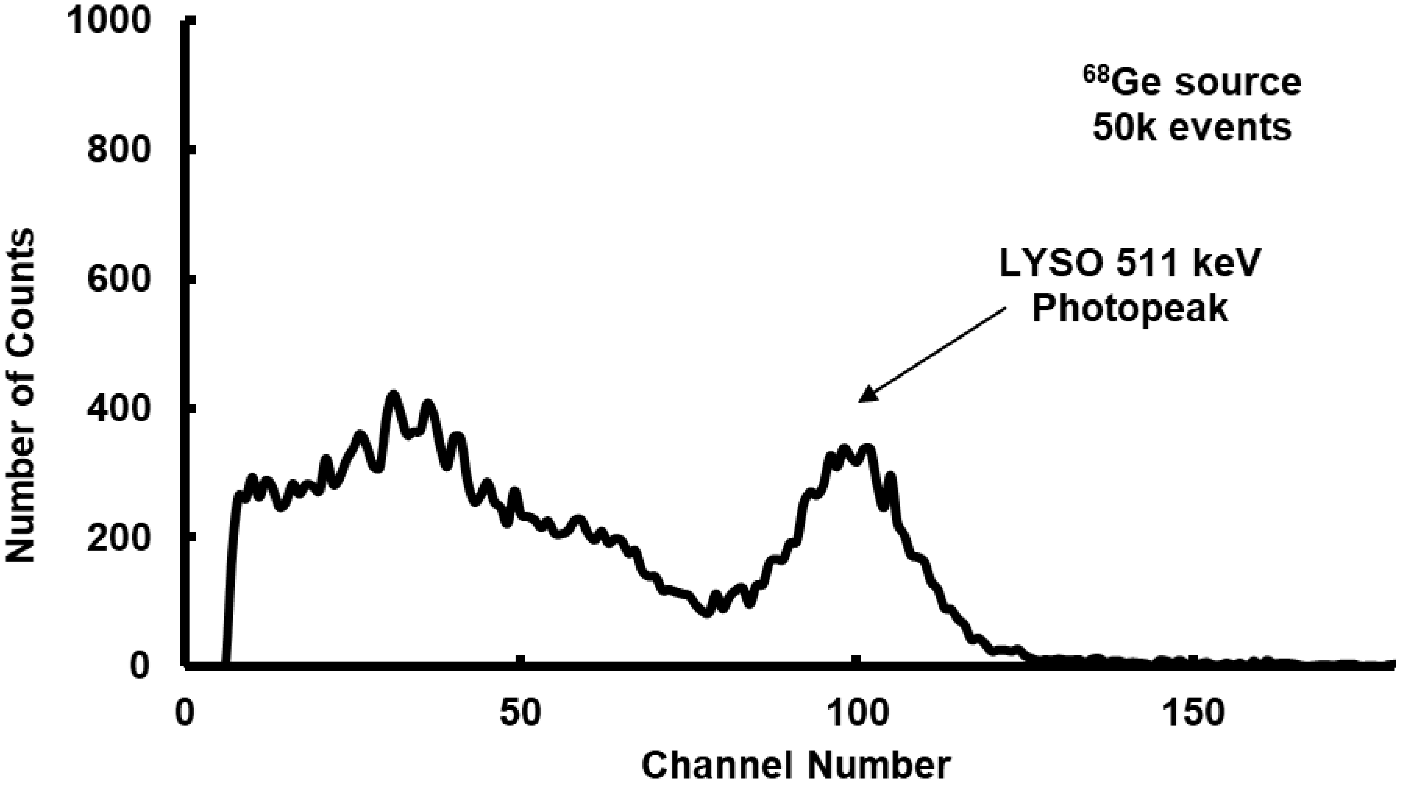


*FWHM → Full Width at Half Maximum

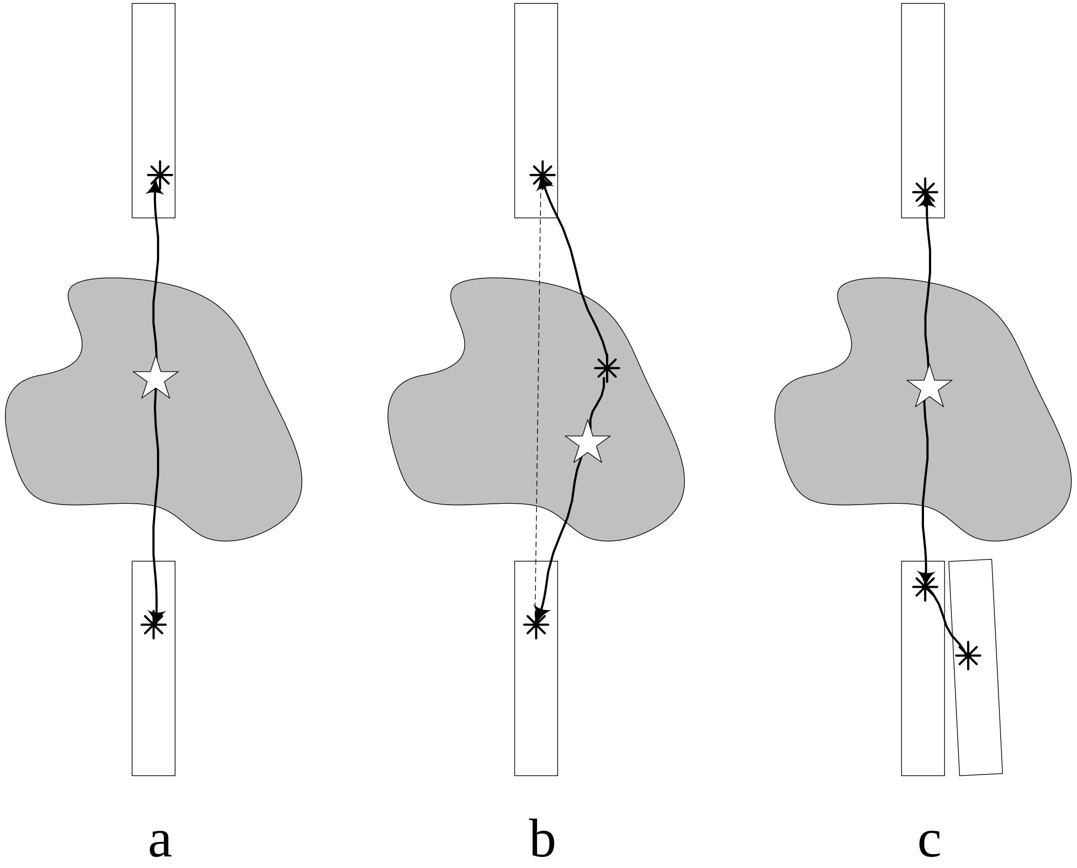
What's that bump before the peak?

- Events with less than 511 keV?
- Compton Scatter
  - Partial energy transfer





Photoelectric Compton Scatter Compton Scatter



Unique properties of PET radiation

- We need to find events with the correct
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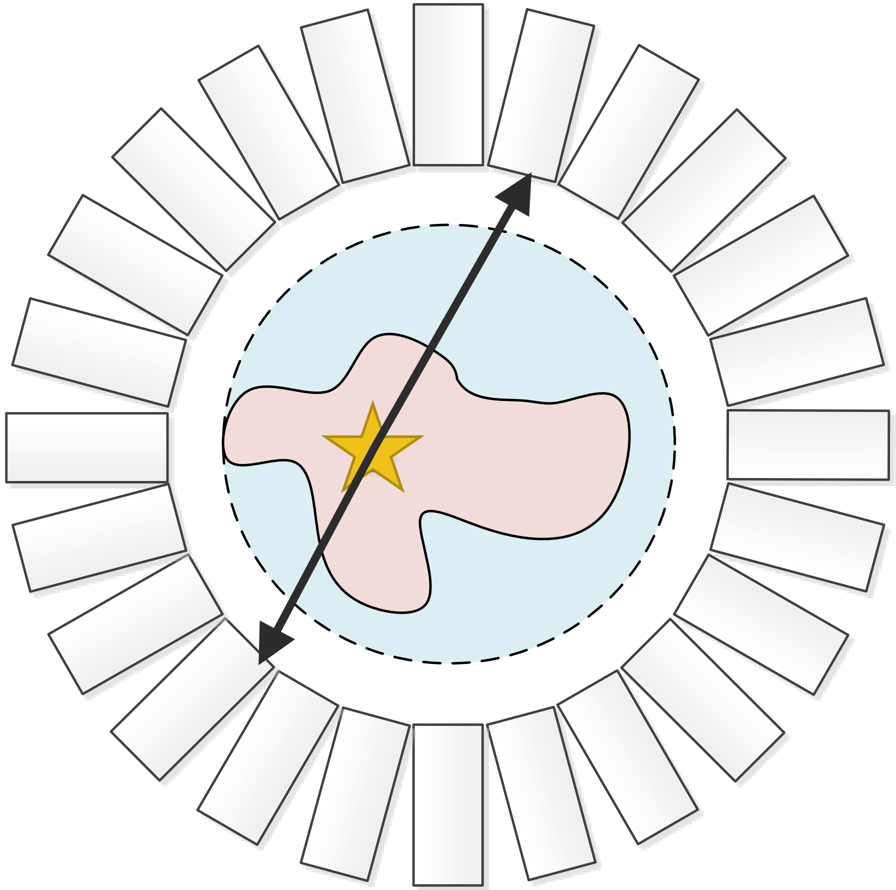
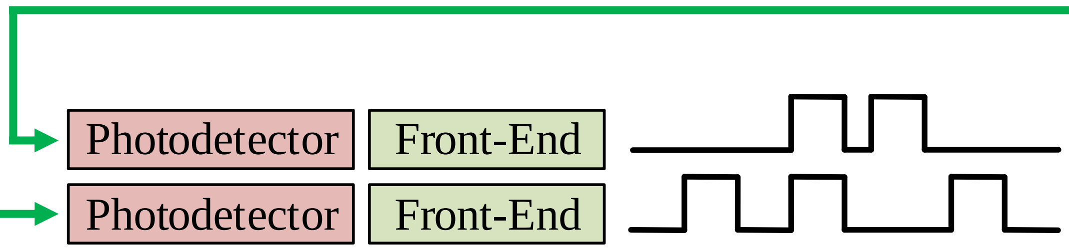
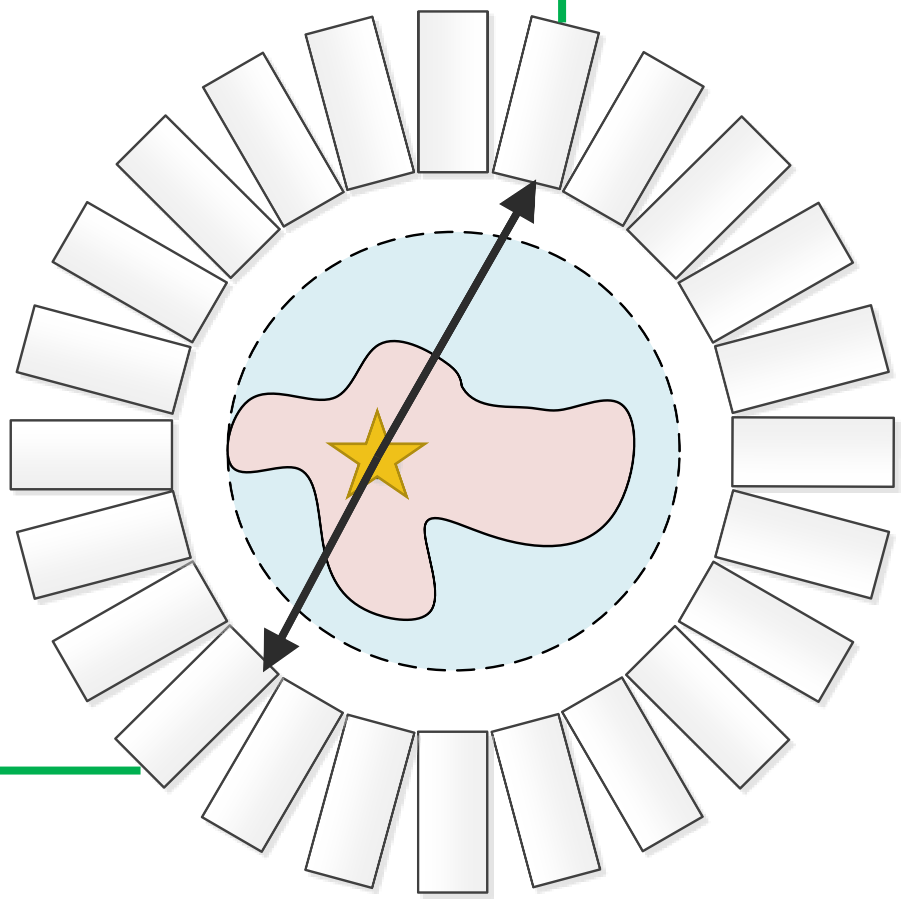




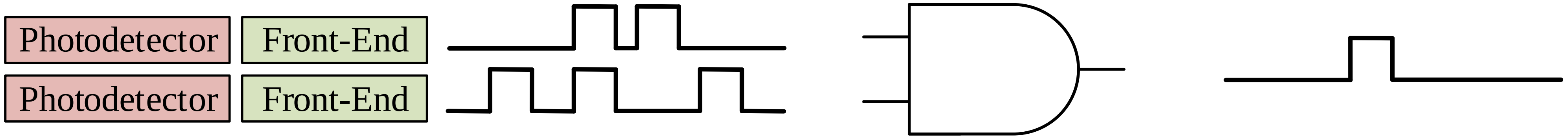
- Pulse is generated when gamma is found
  - But save data only for pair



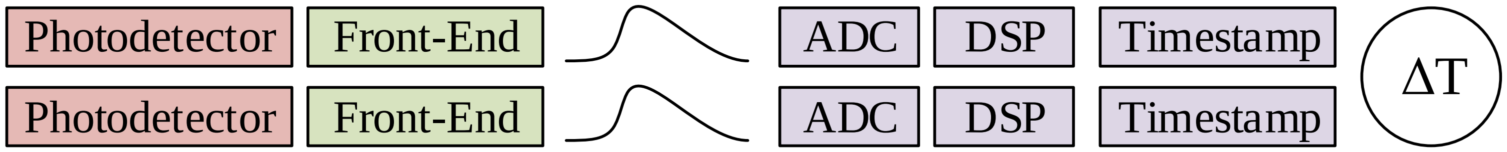
Time and Position Electronic Collimation

UdS

- Pulsed systems (before 2004)

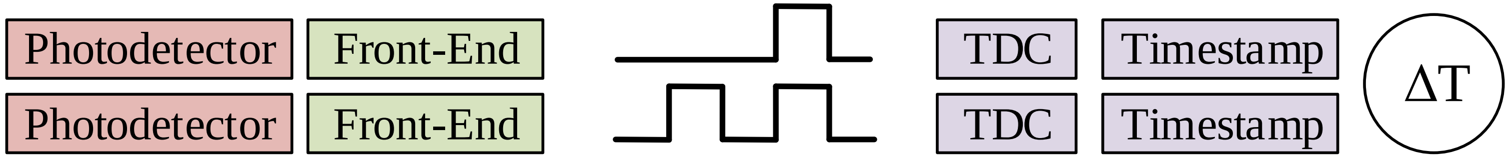


- Waveform sampling systems (2003-)

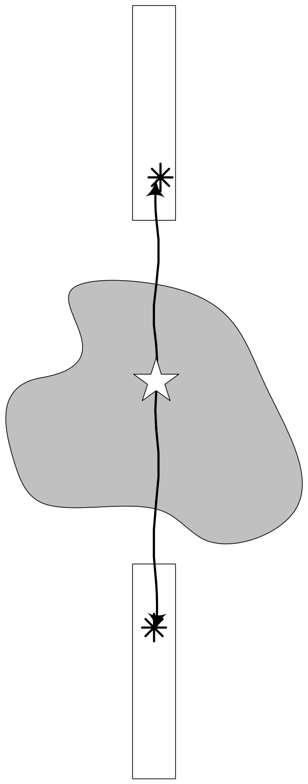


event 1: Time, Position, Energy
event 2: Time, Position, Energy
…

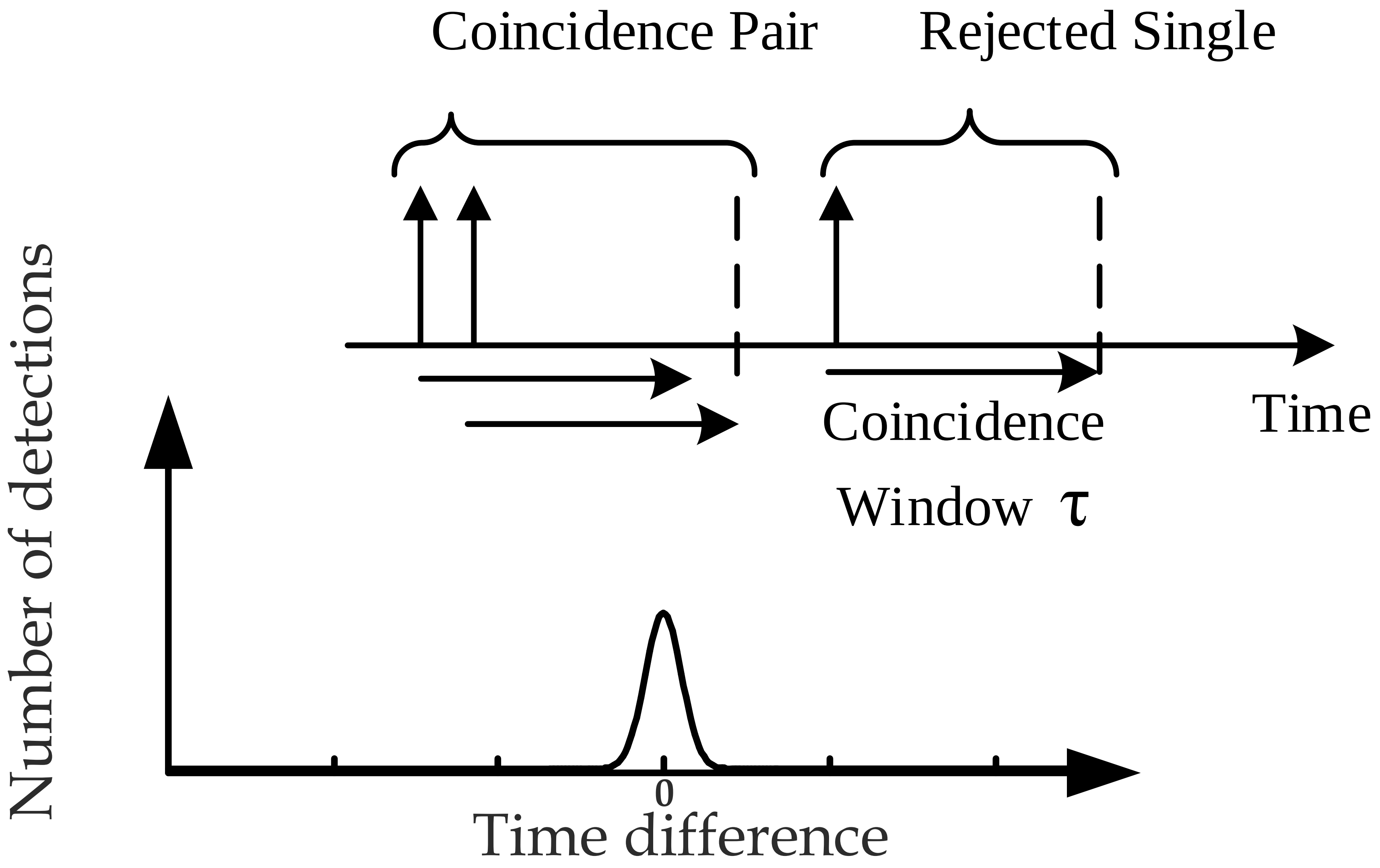
- Triggered systems (many variations)



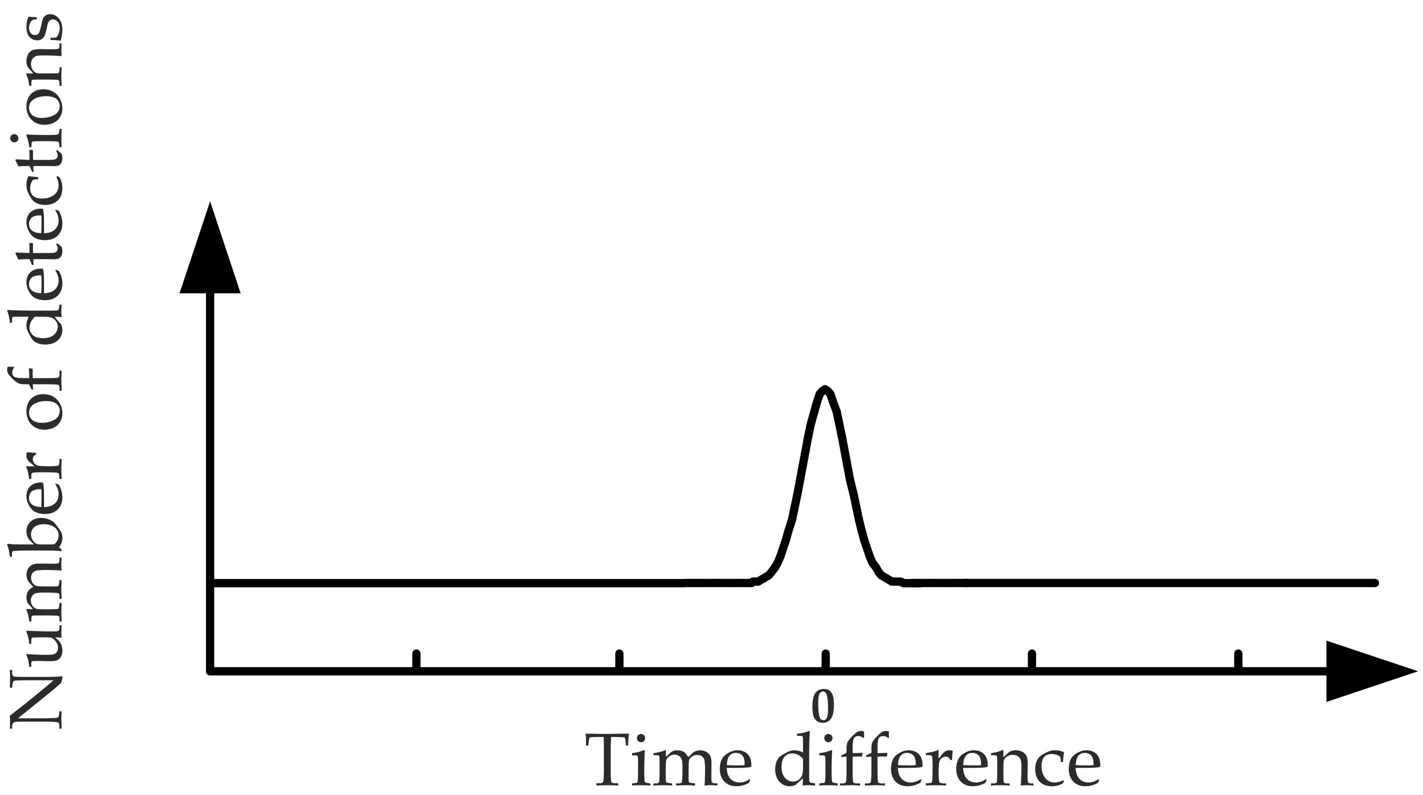
Building the timing histogram



a

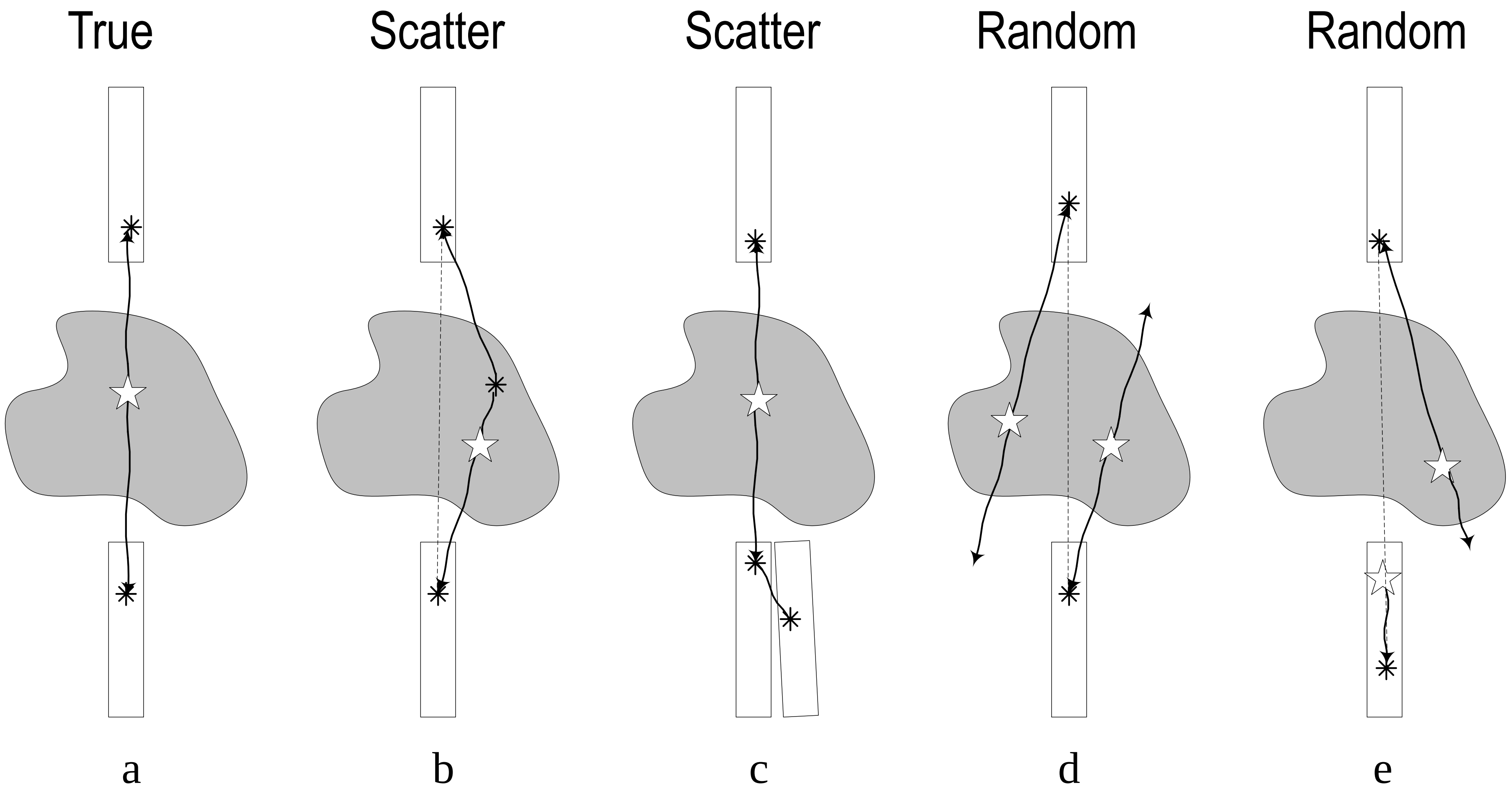


Actual Timing Spectrum

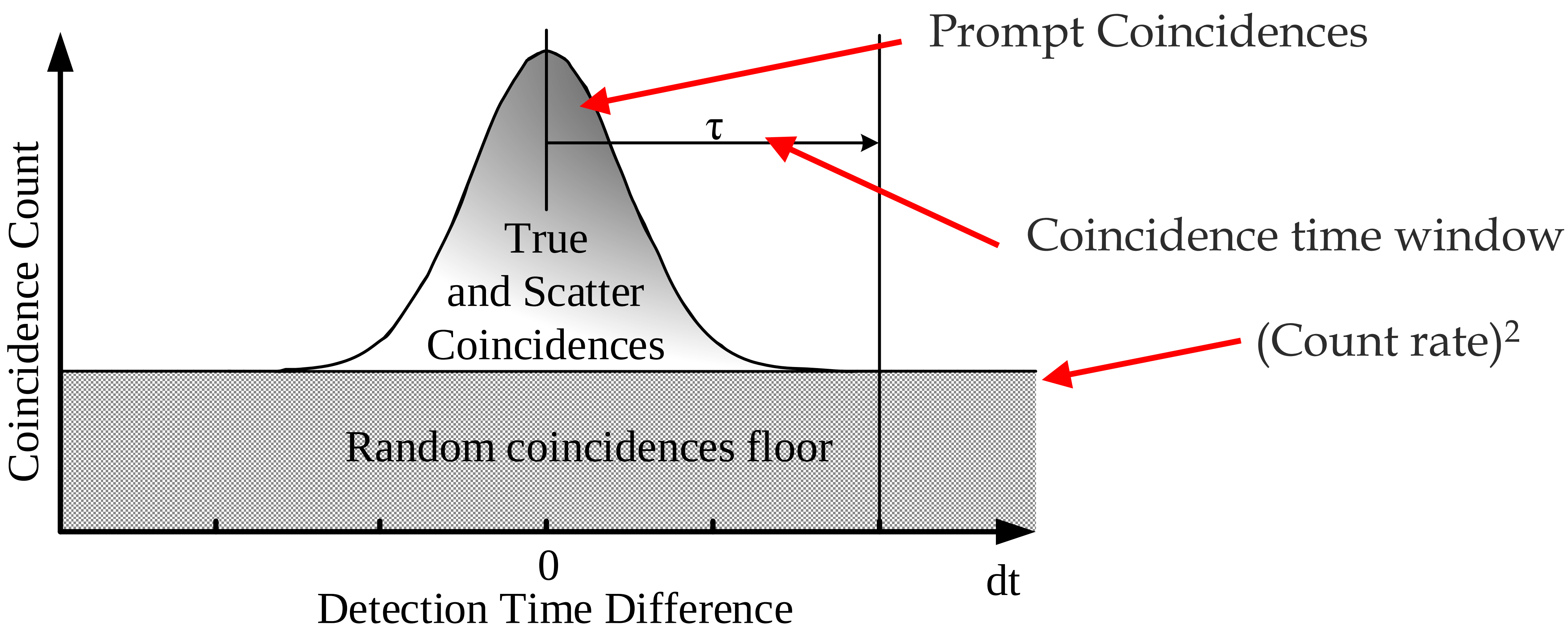


Types of coincidence

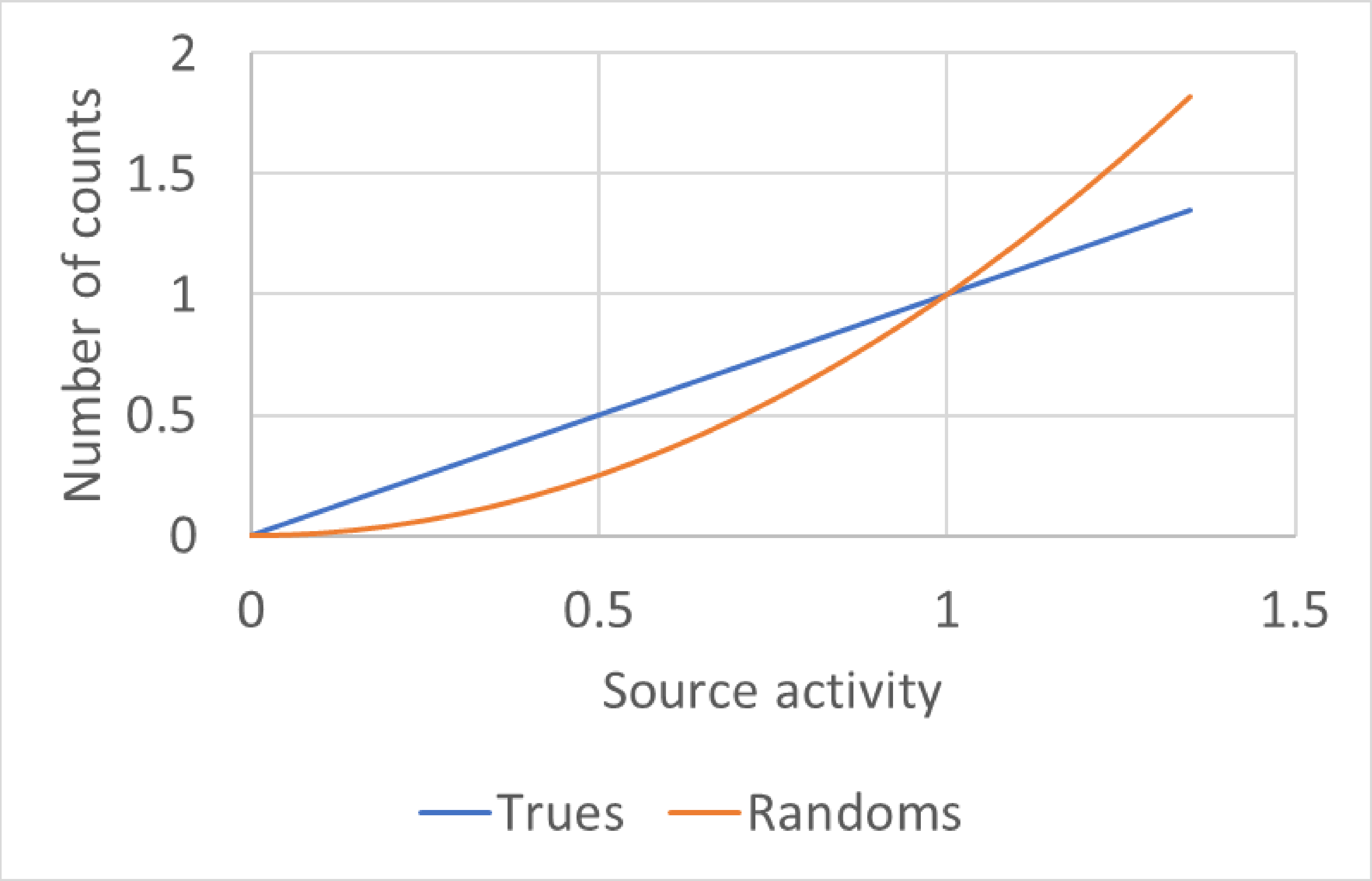
UDS



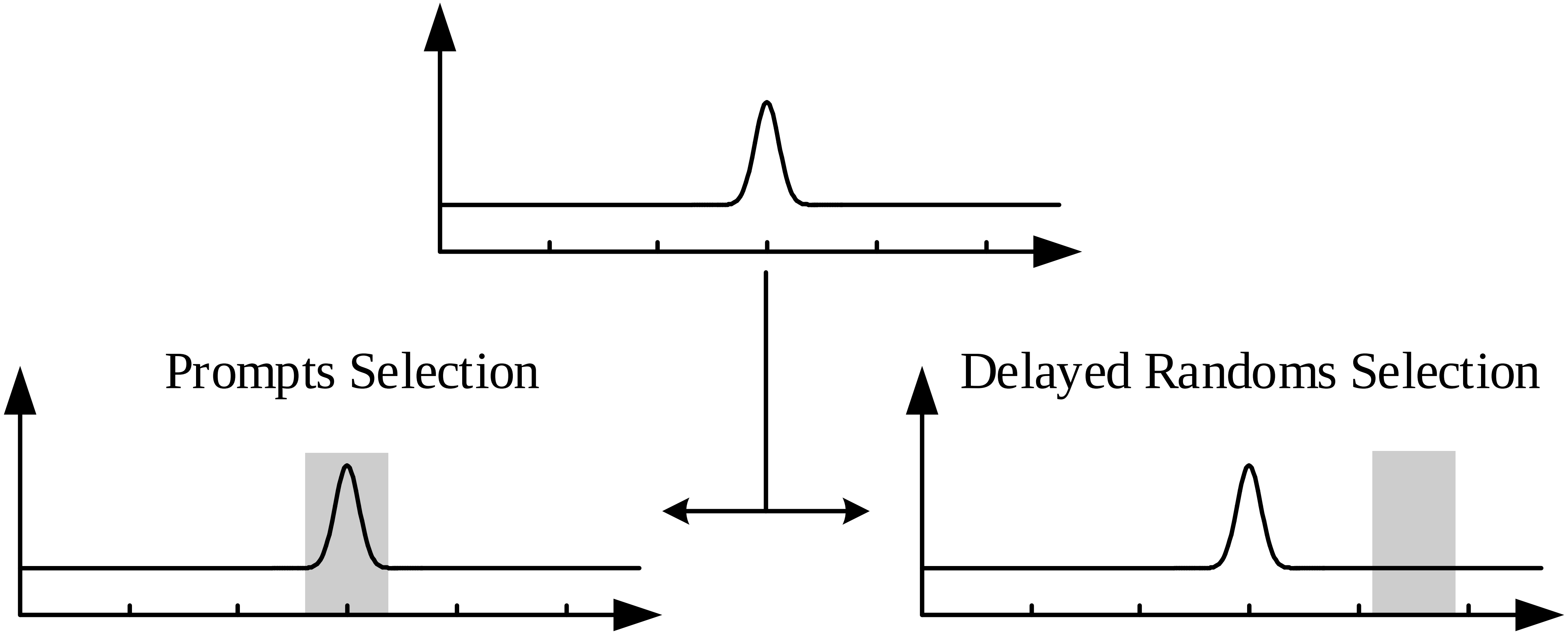
The coincidence timing spectrum



Coincidences vs Relative Activity

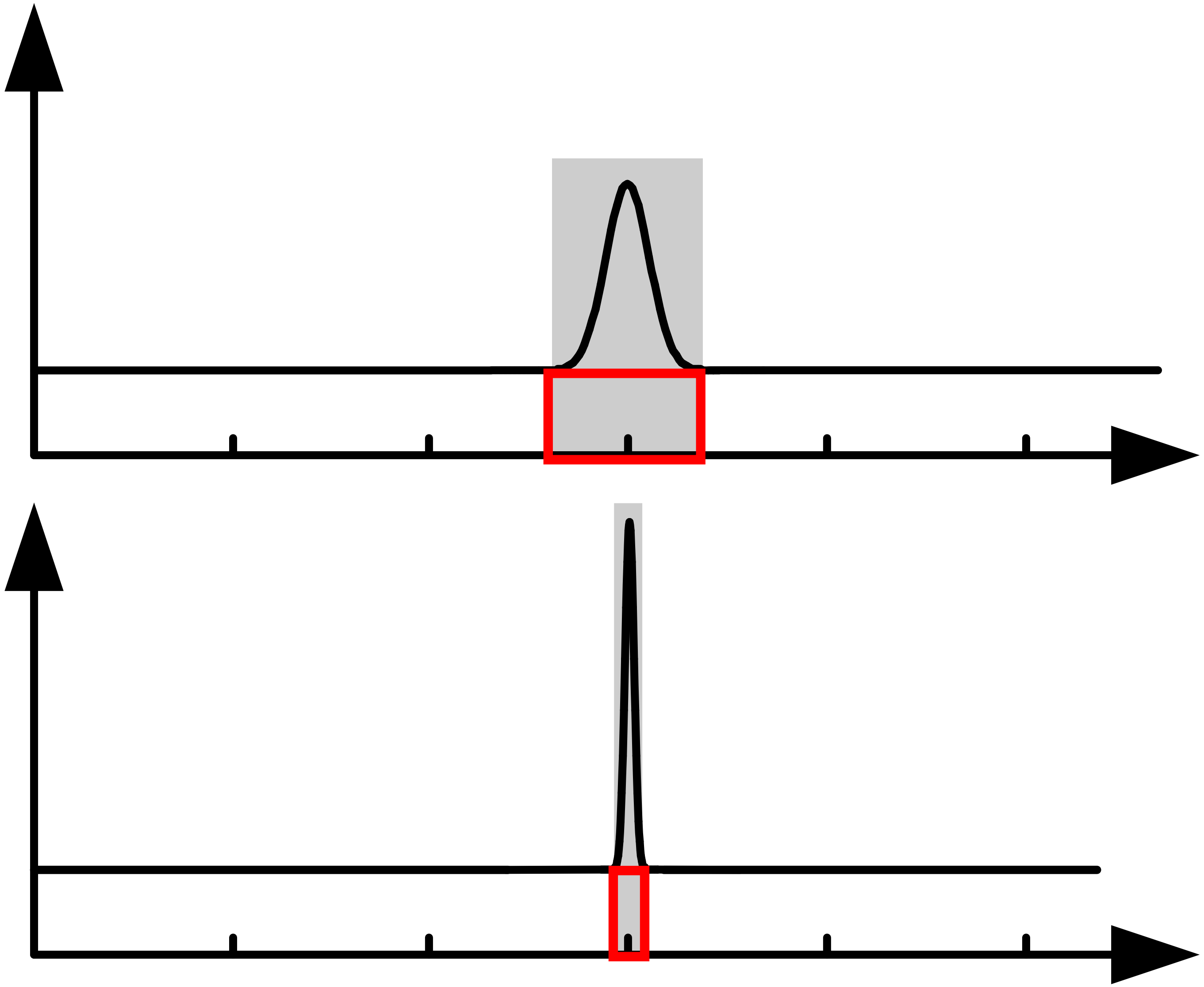


Solution 1: Estimate Random Coincidences



Solution 2: better timing measurement

UDS



Why is PET so interesting?

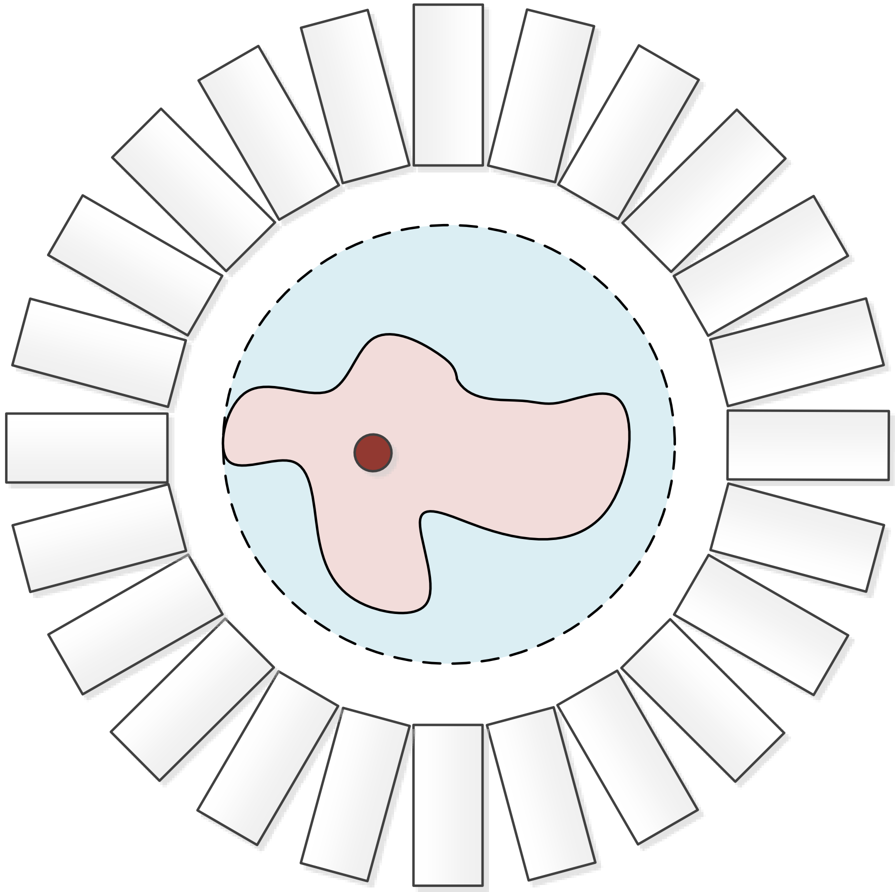
SPECT

- Single Photon Emission Computed Tomography
- Broad selection of short-lived isotopes
  - ^{99m}Tc is about 6-hour half-life
- Radiation has known energy value
  - Use energy reading to reject events
- Further rejection requires a physical collimator
  - Reduces sensitivity
- Small-sized generators provide the material
- …

PET

- Positron Emission Tomography
- Broad selection of short-lived isotopes
  - 18F is about 2-hour half-life
- Radiation has known energy value
  - Use energy reading to reject events
- Further event selection is electronic
  - Use time and position instead
- Cyclotron ($$$$) typically provides isotopes
- …

Review



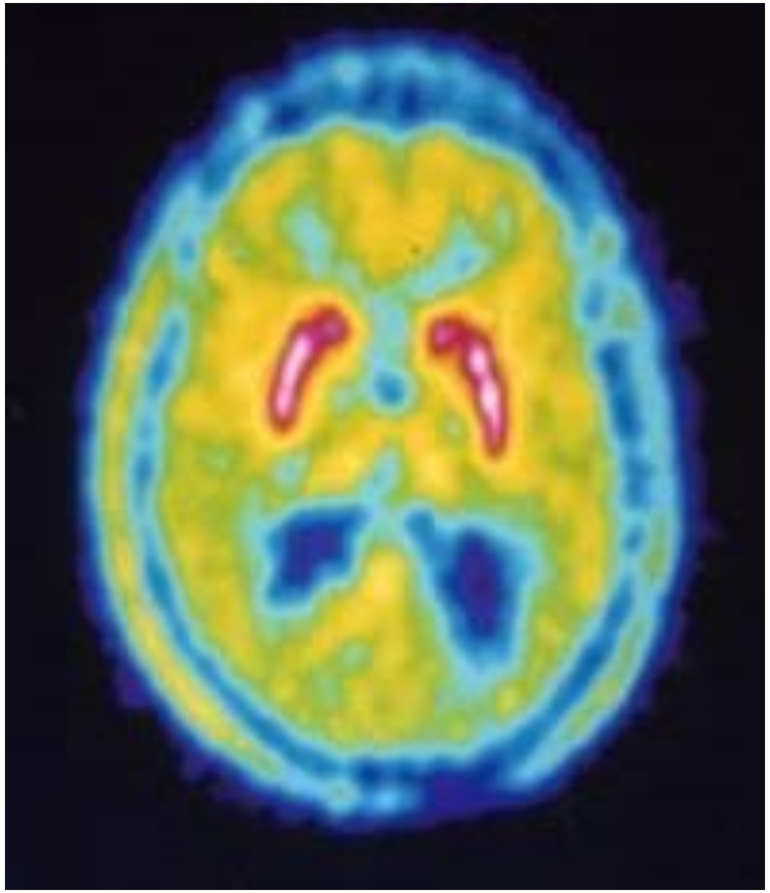
- Find lines of response (LOR) using
  - Energy
  - Timing
  - Position
- Use image reconstruction program
- Goal: Support doctors and scientists in medicine and biology

How can we improve PET scanners?

Improve image quality - spatial resolution

UDS

Better images with finer pixels



Improve image quality - spatial resolution

UDS

- We need to find events with the correct
  - Energy
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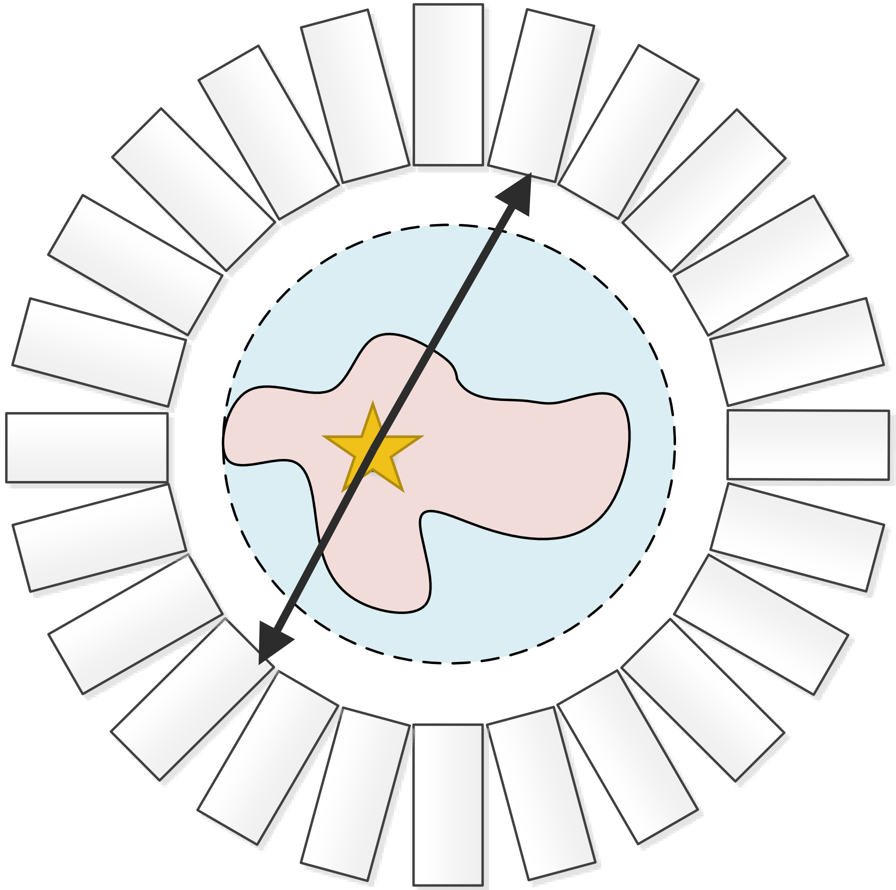
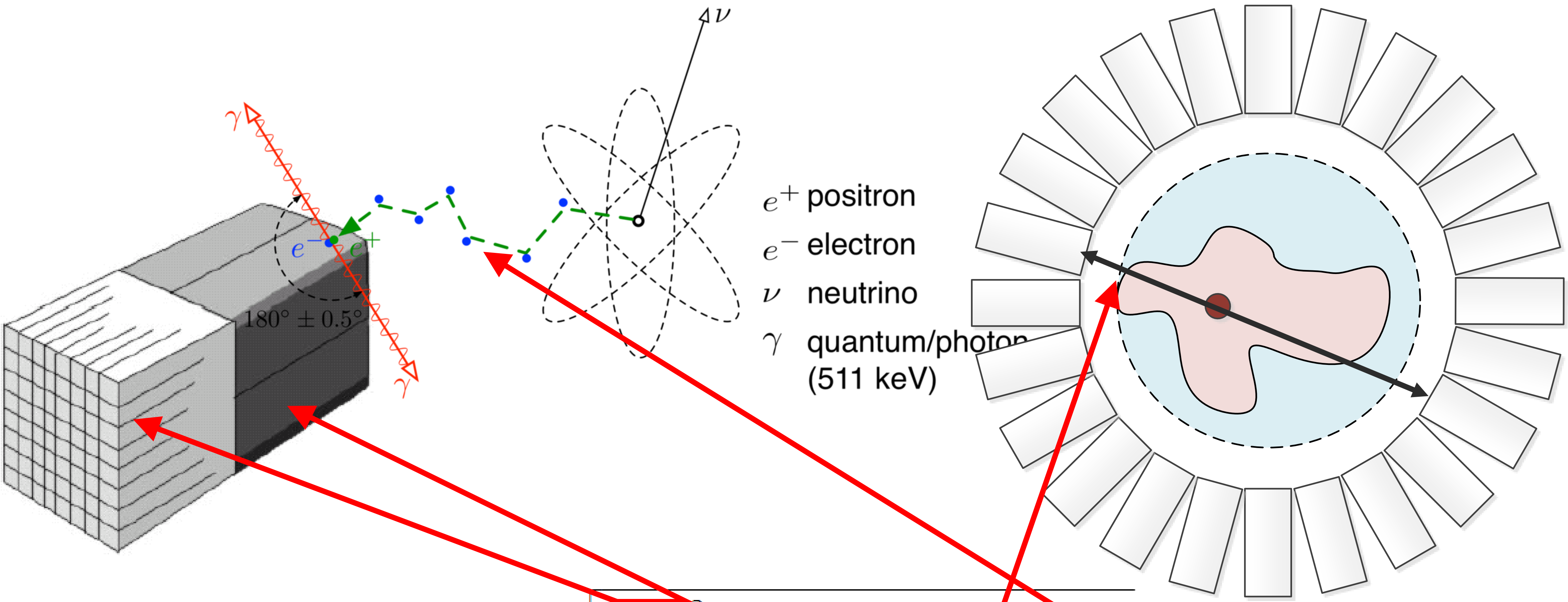


Spatial resolution – fundamental limitations



$$R_{sys} = a\sqrt{\left(\frac{d}{2}\right)^2 + b^2 + (0.0022D)^2 + r^2}$$

Spatial resolution – solutions to improve

UdS

Make crystals smaller

- Pixels will be finer
  - Until the positron range becomes dominant
- Increases visible inter-crystal scatter
- Light is harder to extract
  - Affects timing and energy resolution
- More difficult to manufacture
  - Smaller crystals break more easily
  - Increases scanner cost

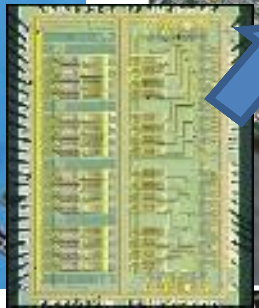
Eliminate the decoding factor

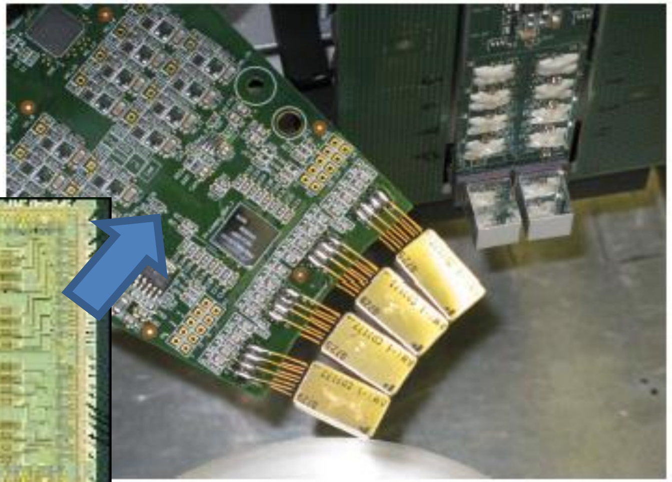
- One electronic channel per crystal
  - Very high count rate becomes possible
- Distinguish inter-crystal scatter
- High density electronics
- Higher cost

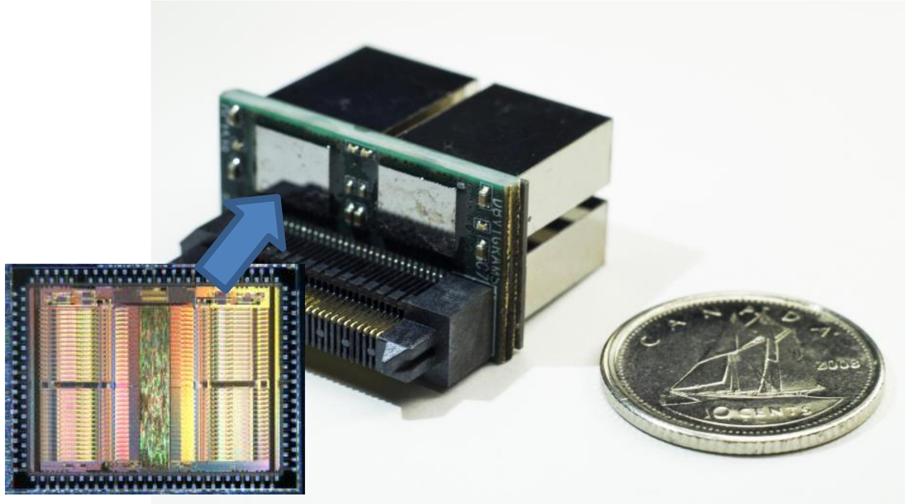
Solutions highly used in Sherbrooke

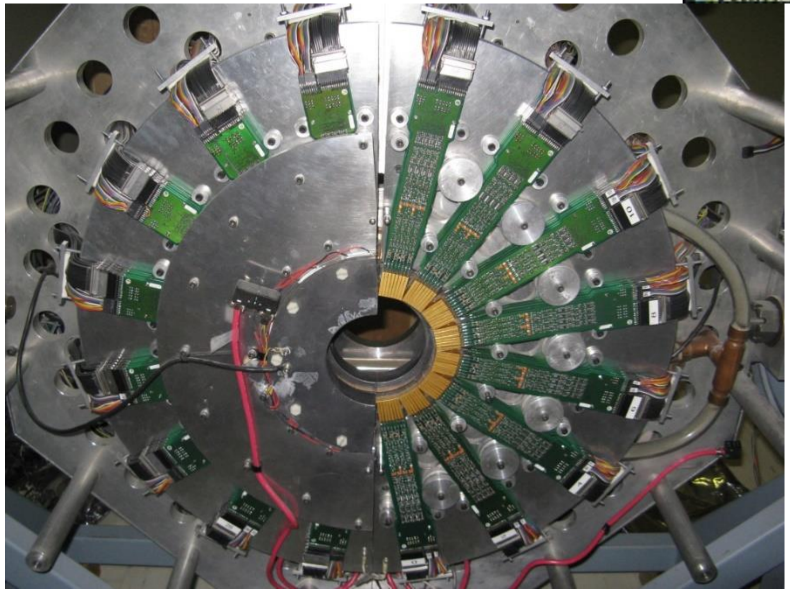
High resolution PET in Sherbrooke

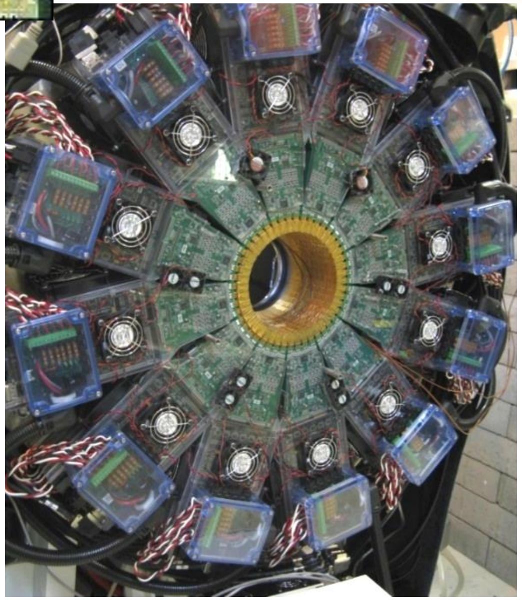
- From 1985 onto today; Small animal imaging

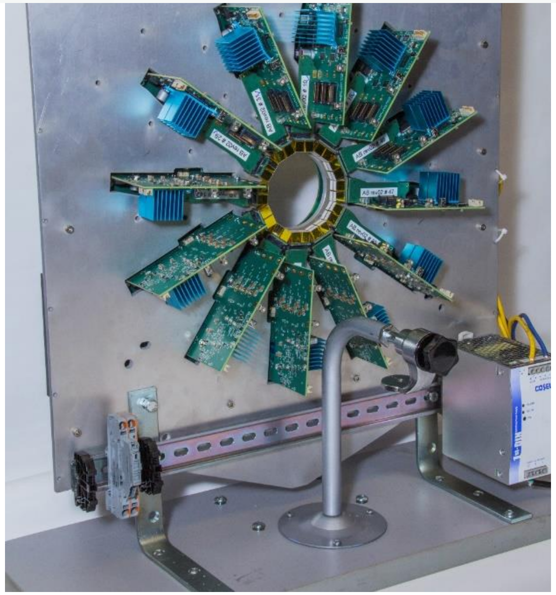










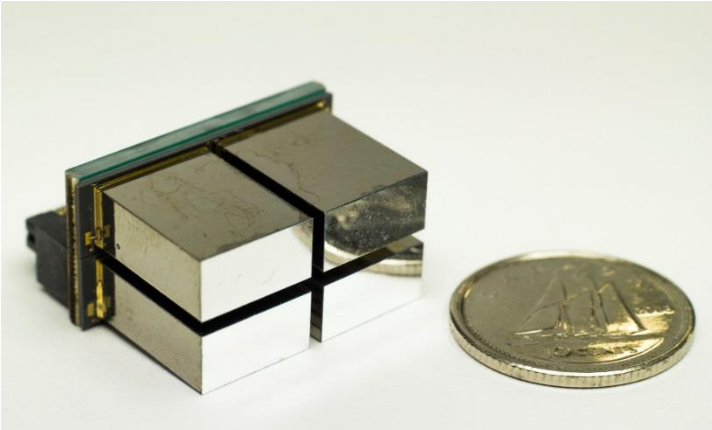


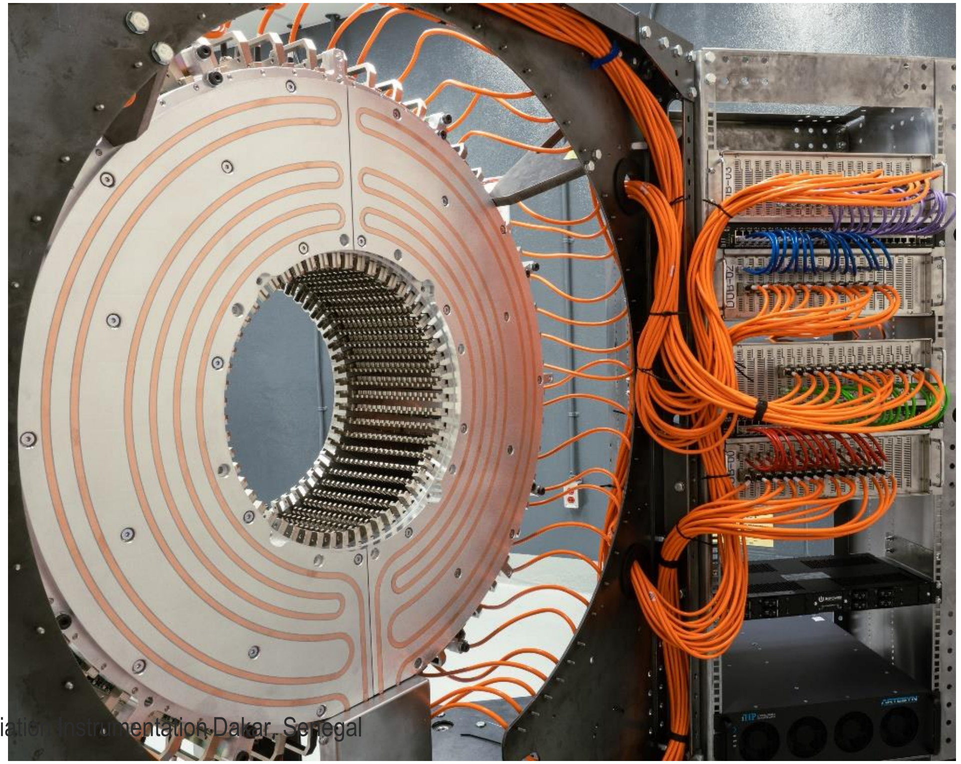
Sherbrooke PET
(1995-2009)

LabPET mouse scanner
(2007 - today)

LabPET-II mouse scanner
(2016 – today)

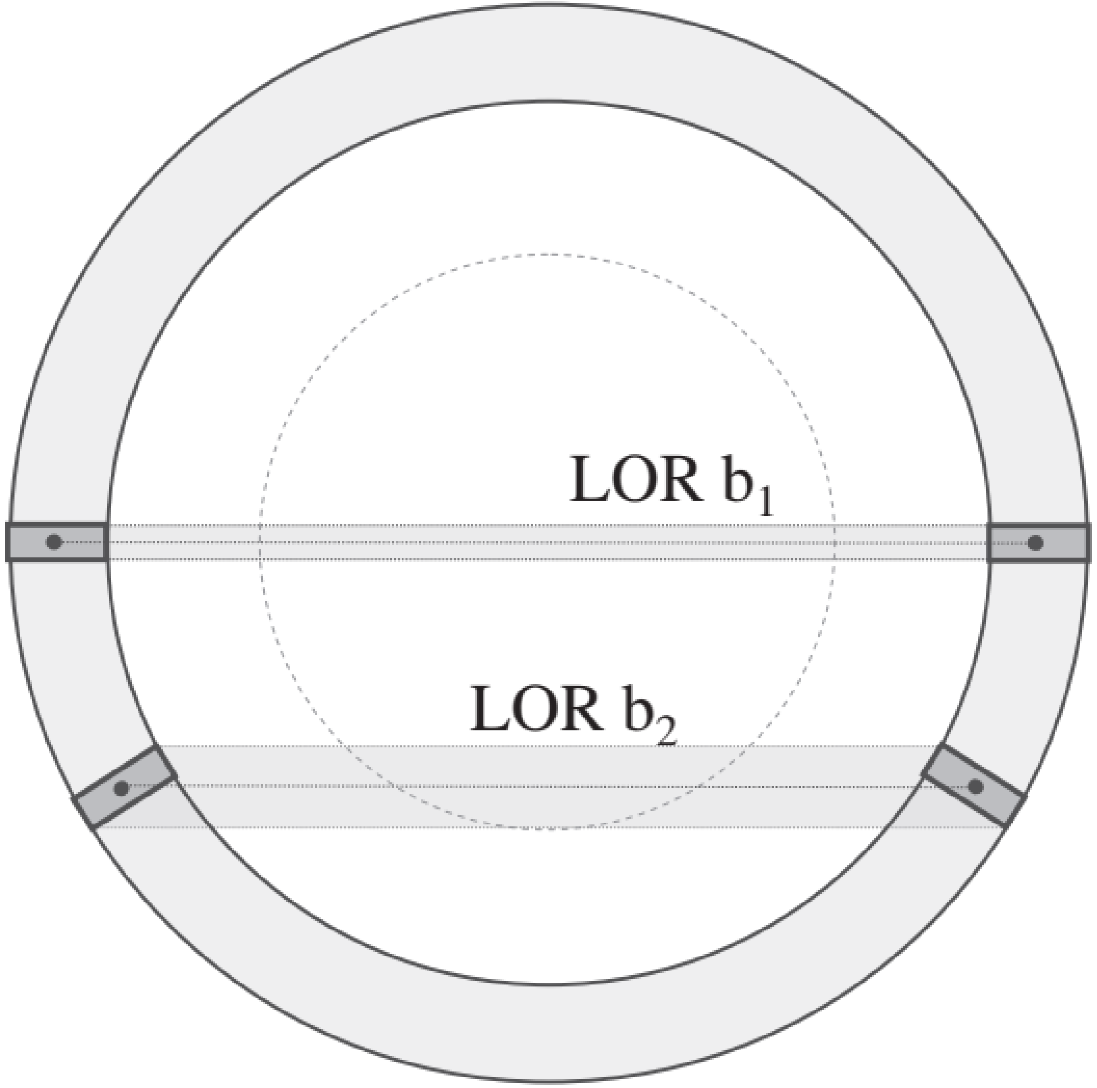
Scaling up for the human brain





Parallax error

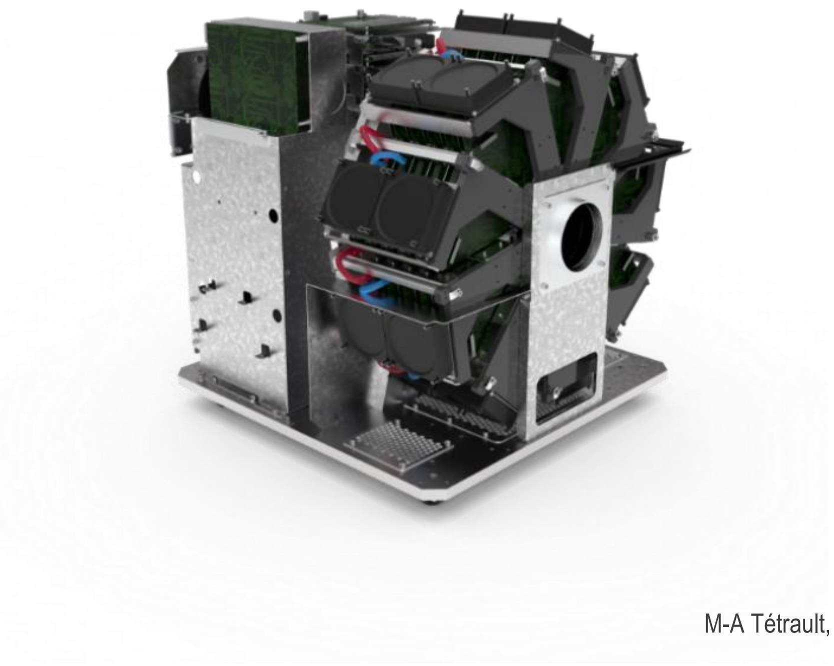
- Long crystals create widening of response tube on scanner periphery
  - Long crystals « see » more events
- To mitigate,
  - Stack two or more crytals and discriminate
  - Use light sharing techniques to find position
    - Dual sided readout
    - Light sharing between neighbouring crystals

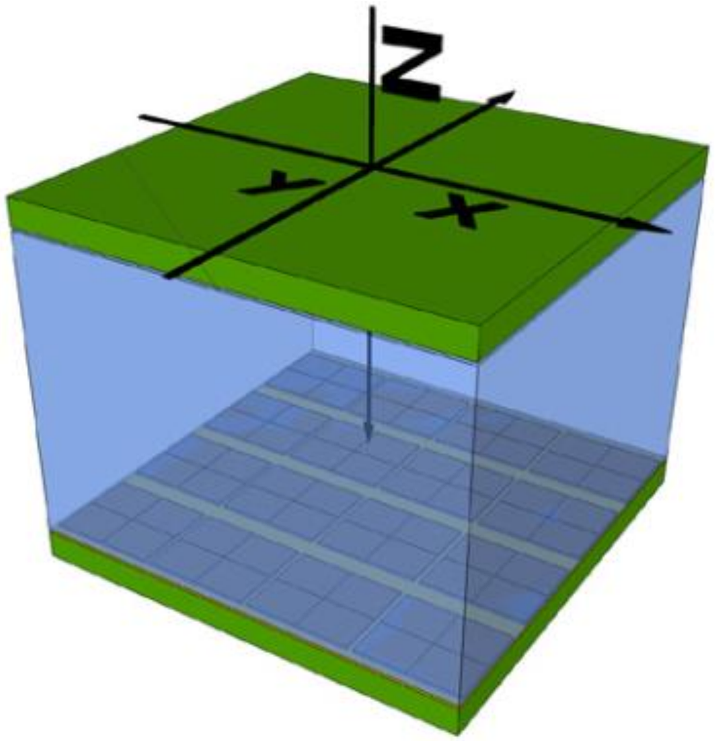


From J E Ortuno, PMB, 2010

Alternative – Monolithic crystals

- Many photosensors; one crystal
- Signal processing to find point of interaction
- Small animal scanner: Molecubes
  - https://www.molecubes.com/

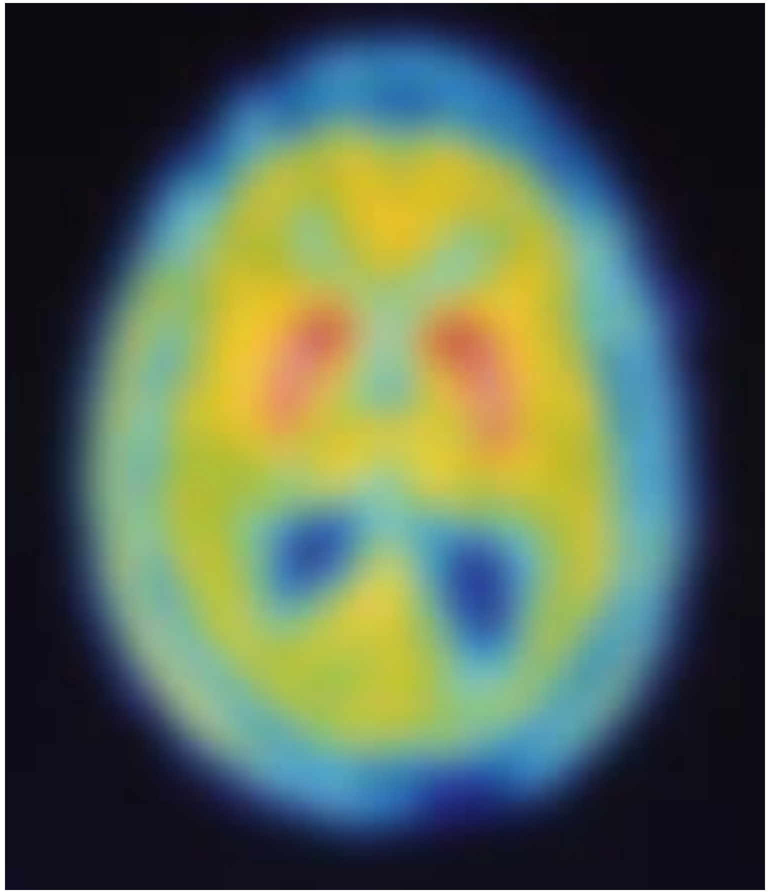


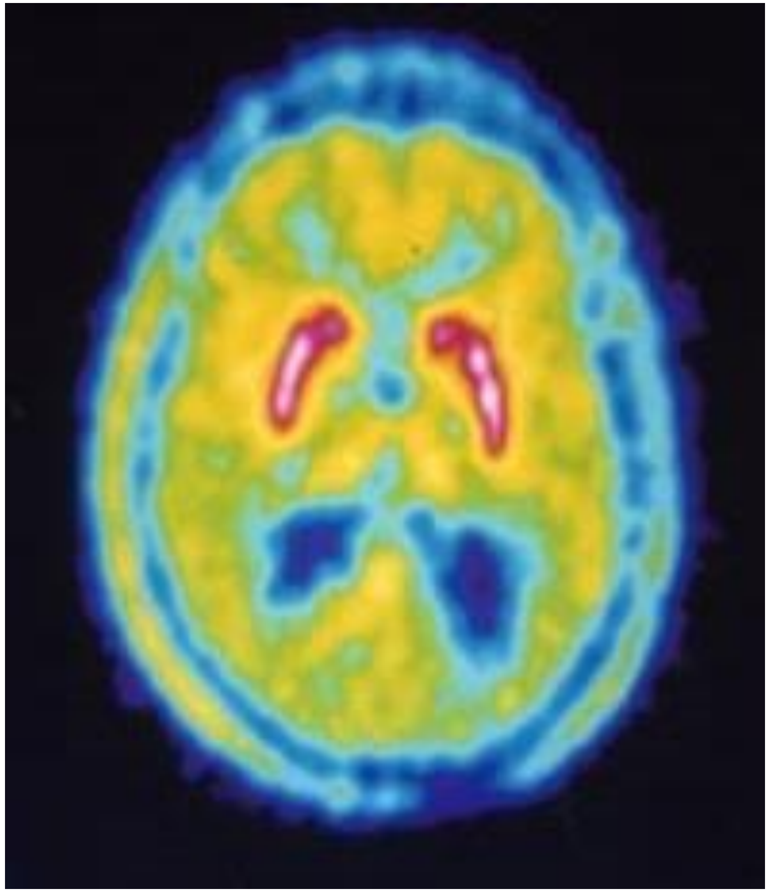


From Borghi et al, PMB 61;13, 2016

$$R_{sys} = a\sqrt{\left(\frac{d}{2}\right)^2 + b^2 + (0.0022D)^2 + r^2}$$??

Improve image quality - contrast



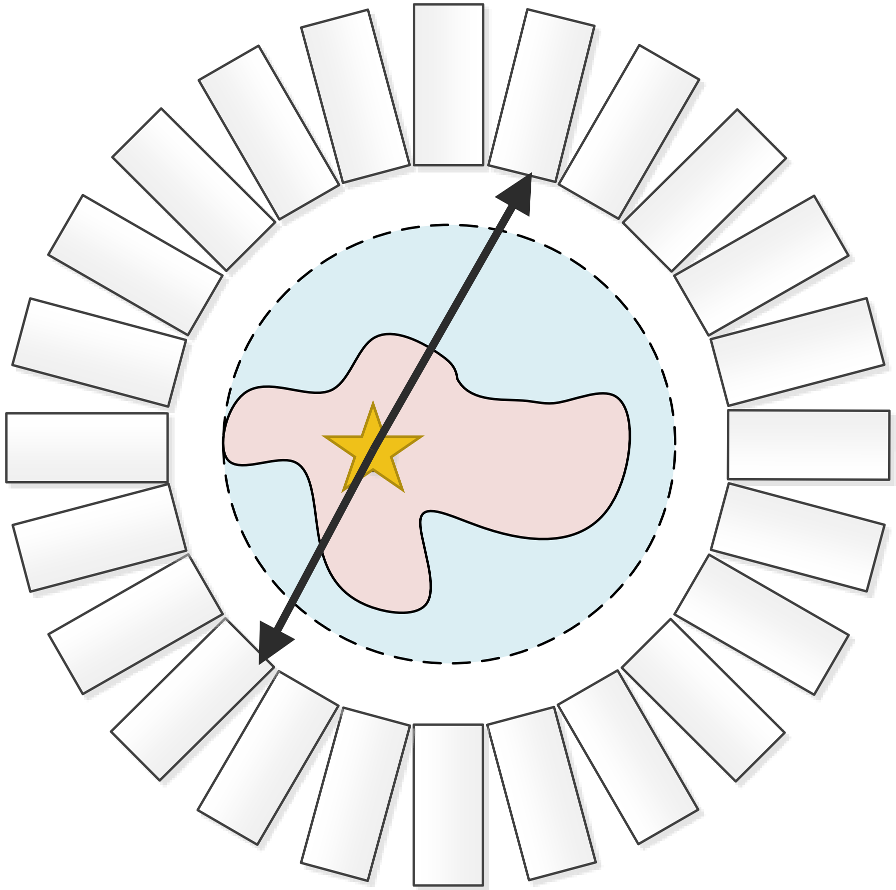


Goal : sharpen the difference between individual pixels

Improve image quality - sensitivity

UDS

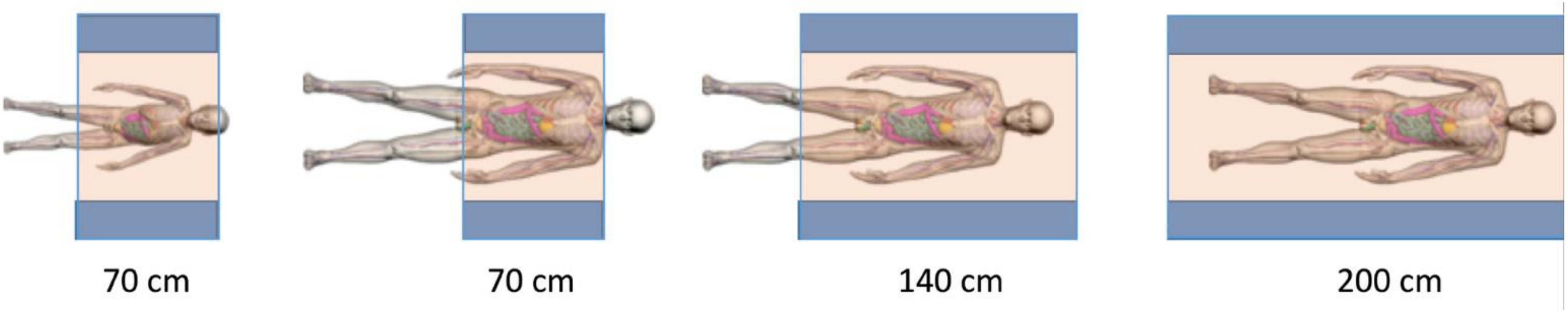
- We need to find **(all)** events with the correct
  - Energy
  - Timing
  - Position (in the ring)



UDS

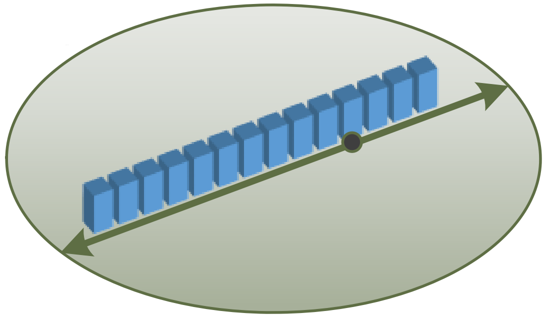
- Eliminate or minimize detector dead time or dead area
  - Maximize the effective event count rate
    - 1:1 coupling vs [Monolithic / Shared arrays]

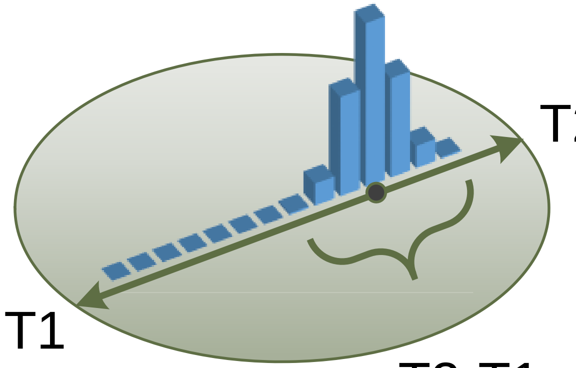
- Increase solid angle coverage



Surti et al, TRPMS, 2020

Time of Flight – Concept and expected benefits





$$G = \frac{D}{\Delta x} = \frac{2D}{c\Delta t} \approx \frac{\text{Object size}}{\text{ToF precision}}$$

40 cm object
Δt = 600 ps

$$\frac{SNR_{ToF}}{SNR_{TEP}} = \sqrt{\frac{40\text{ cm}}{9\text{ cm}}} = 2.1 \quad \Rightarrow \quad G = 4.4$$

4 cm object
Δt = 60 ps

$$\frac{SNR_{ToF}}{SNR_{TEP}} = \sqrt{\frac{4\text{ cm}}{0.9\text{ cm}}} = 2.1 \quad \Rightarrow \quad G = 4.4$$

Budinger TF., *J Nucl Med* 24(1):73-78, 1983.

More to come next week!

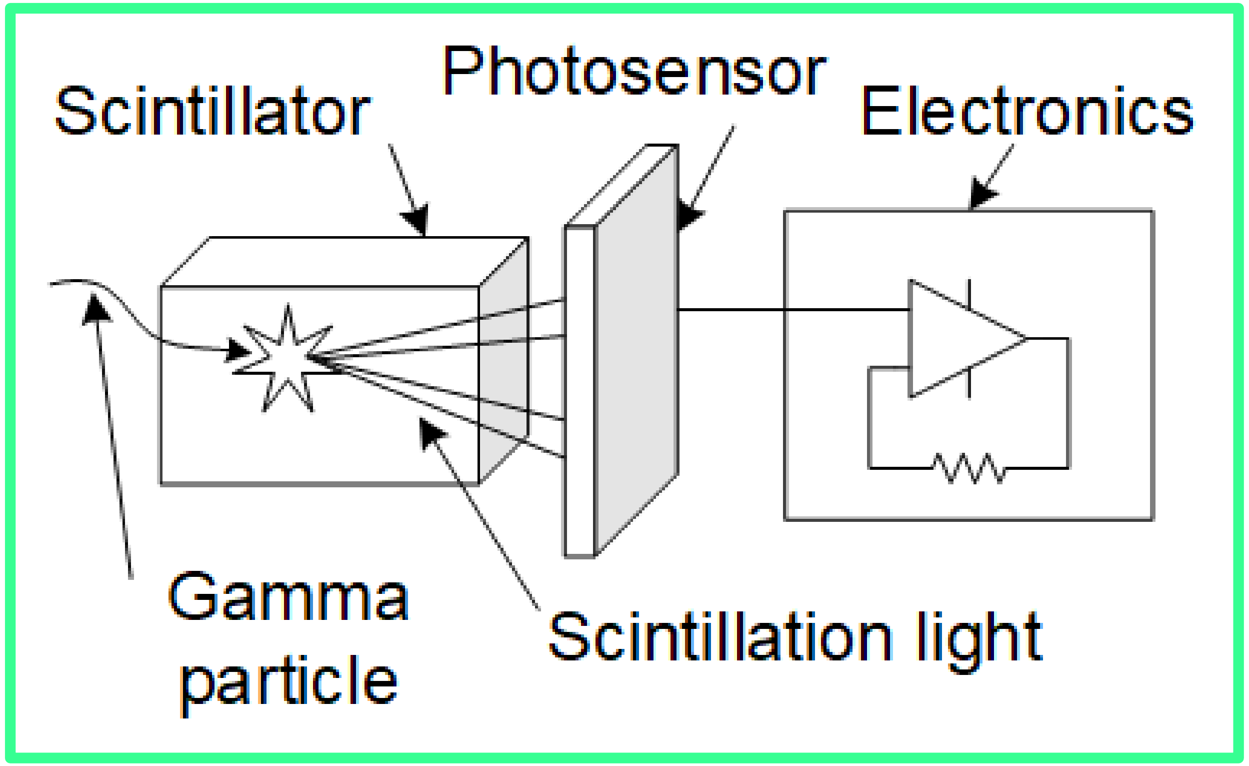
UDS

- EasyPET exercice next week!

*Next week setup is slightly different

V. Arosio et al., 2016 IEEE NSS/MIC Conference Record, DOI: 10.1109/NSSMIC.2016.8069360

ToF – Challenges in the whole acquisition chain



Very hot topic in the field!

https://the10ps-challenge.org/

Where to get involved?

- Scintillators
- Photosensors
- Front end electronics
- Data acquisition
- Image reconstruction
- Artificial intelligence (data and images)
- Small animal imaging (biology)

Thank you for your attention!

Université de Sherbrooke