Applications of FAST detectors in Positron Emission Tomography

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Outline

Scatter properties at high timing resolution

- TOF data correlate strongly with position
- Scatter-based reconstruction

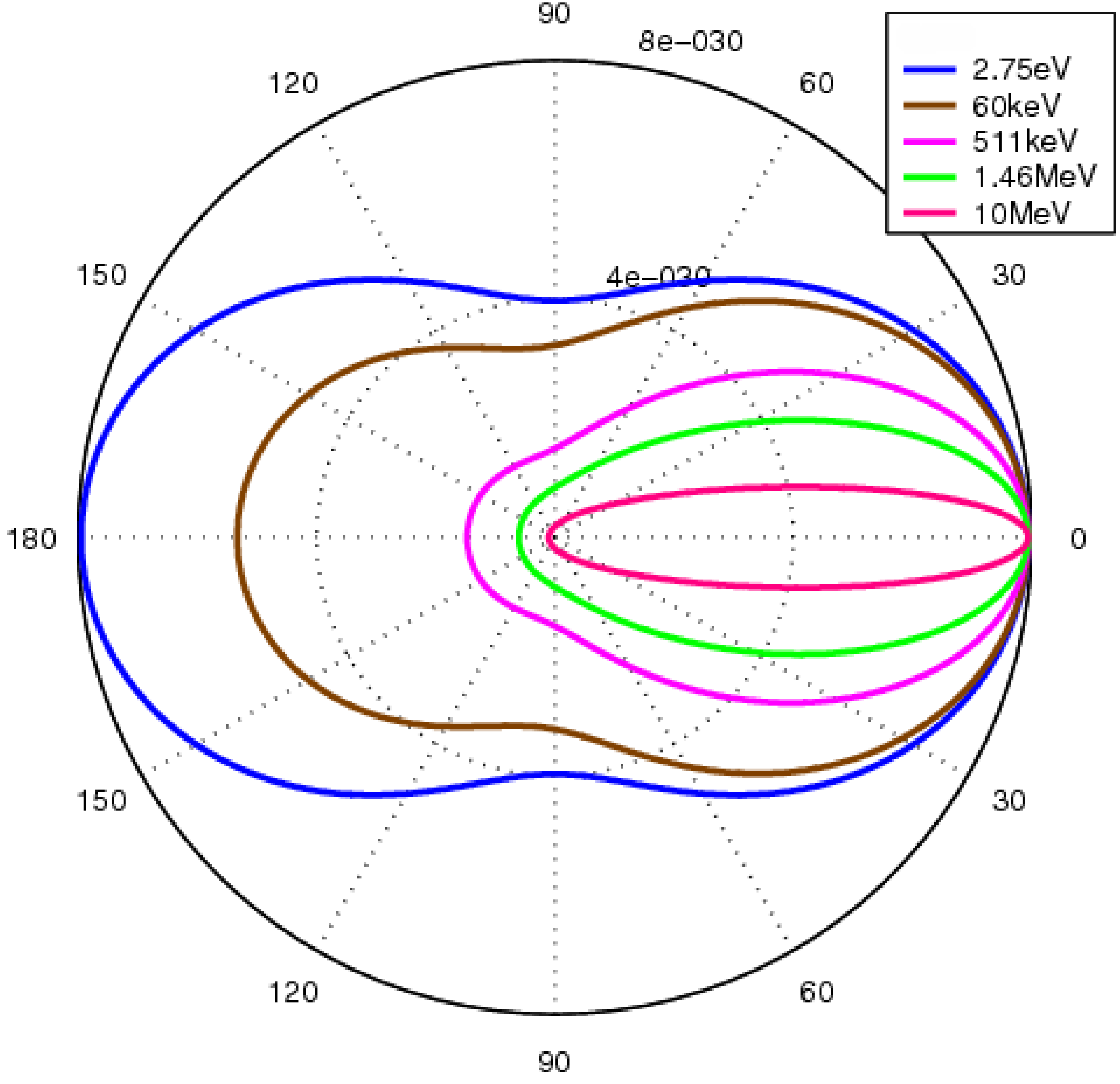
Measurements enabled by very fast reconstruction

- Inter-crystal scatter detection: Multiple emission tomography
- Single events: mid-energy single gammas theranostics
- Three gamma decay: statistics increase/positronium lifetime

Scatter and temporal resolution

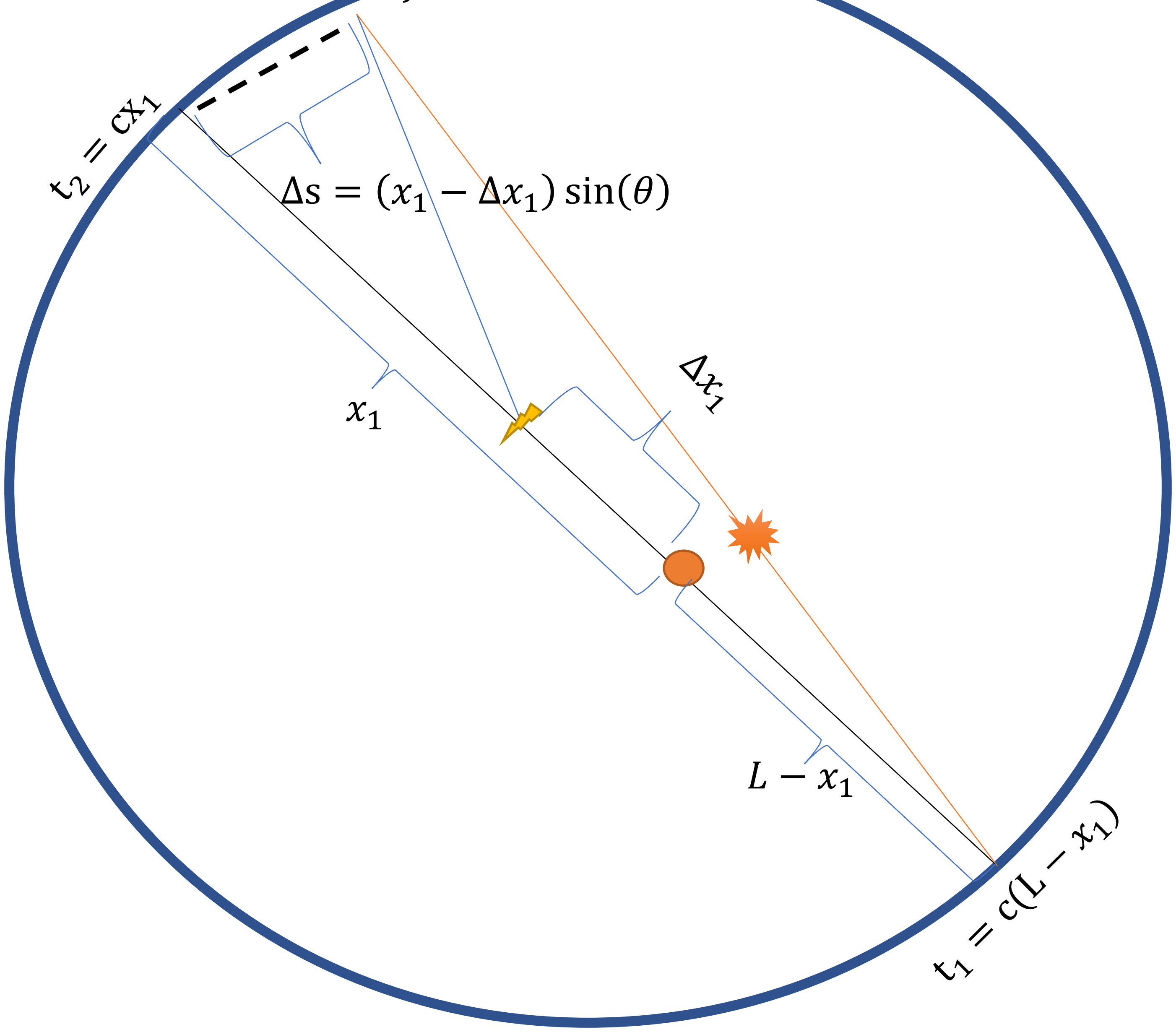
WHY FOCUS ON SCATTER?

- Mean Free Path (MFP) of a 511 keV photon in water 10.5 cm
- Major axis adult abdomen: 42 cm (4 MFP)
- Most likely scattering angle: Small <30°
- Compton cross section in water @ 511 keV : $9.6\ \ 10^{-2}cm^{-1}$
- Photoelectric cross section in water @ 511 keV :$1.8\ \ 10^{-5}cm^{-1}$
- Energy loss @ $30°$, 511 keV: 12% $- 450\ keV$
- Energy loss @ $10°$, 511 keV: 1,5% $- 503\ keV$
- Rule of thumb: ~40% of non-random coincidences in the PET energy window have at least 1 photon that underwent scattering



$$t_2^* = c\left\{(x_1 - \Delta x_1) + \sqrt{\Delta x_1^2 + \Delta s^2}\right\}$$

Scatter timing properties in PET: a geometric problem



$\Delta t_{true} = 2c\, x_1$

θ very small at 511 keV

e.g.: Shift in detected position large

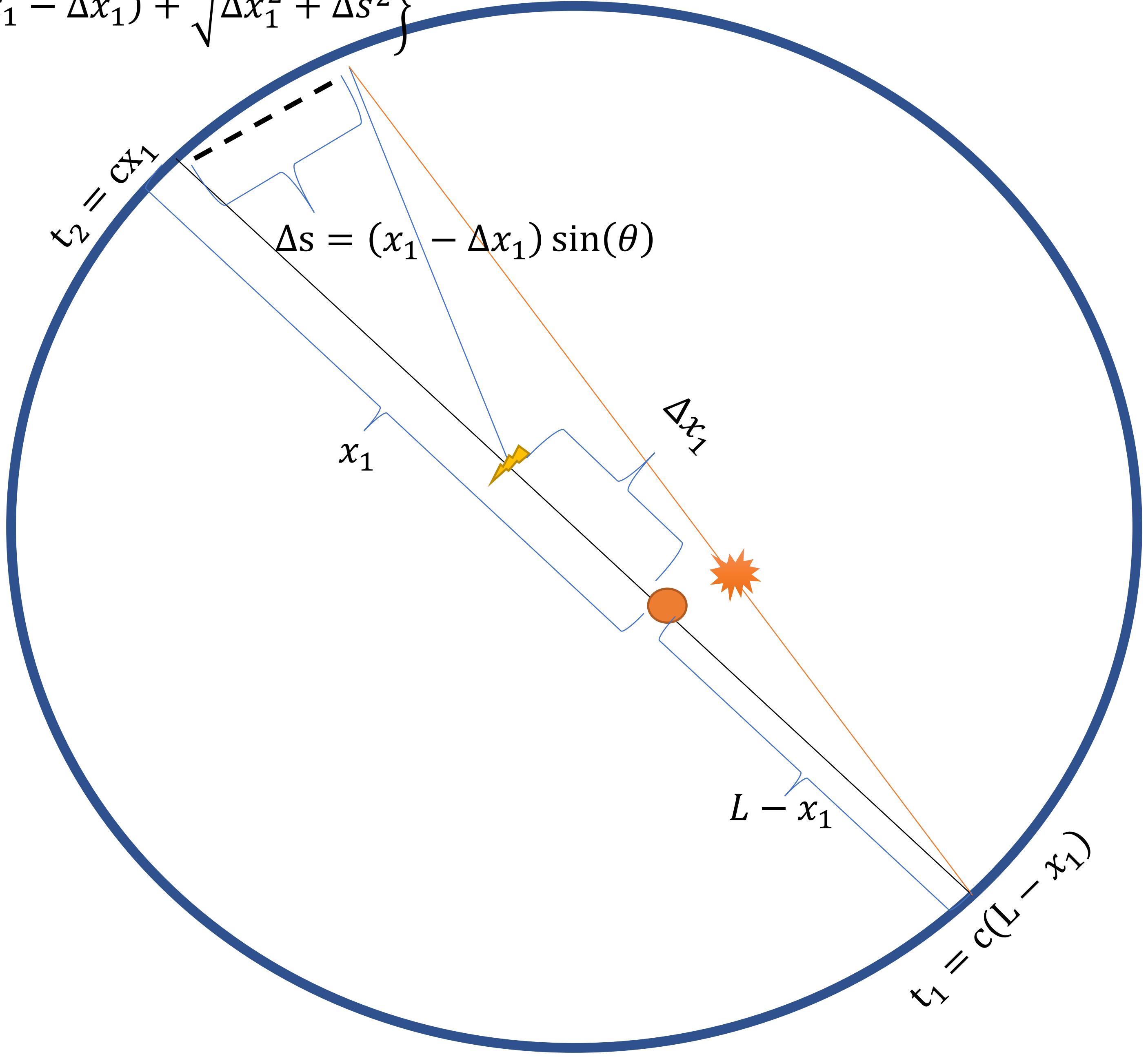
$$30\ cm \times \sin(10°) = 5.2\ cm$$

$$= \sqrt{5.2^2 + 30^2}cm = 30.4\ cm \rightarrow$$
$$\Delta\Delta t \approx 13\ ps$$

$t2^* \approx t2$ if θ “small”

$$t_2^* = c\left\{(x_1 - \Delta x_1) + \sqrt{\Delta x_1^2 + \Delta s^2}\right\}$$

Scatter timing properties in PET: a geometric problem



$\Delta t_{true} = 2c\, x_1$

θ very small at 511 keV

e.g.: Shift in detected position large

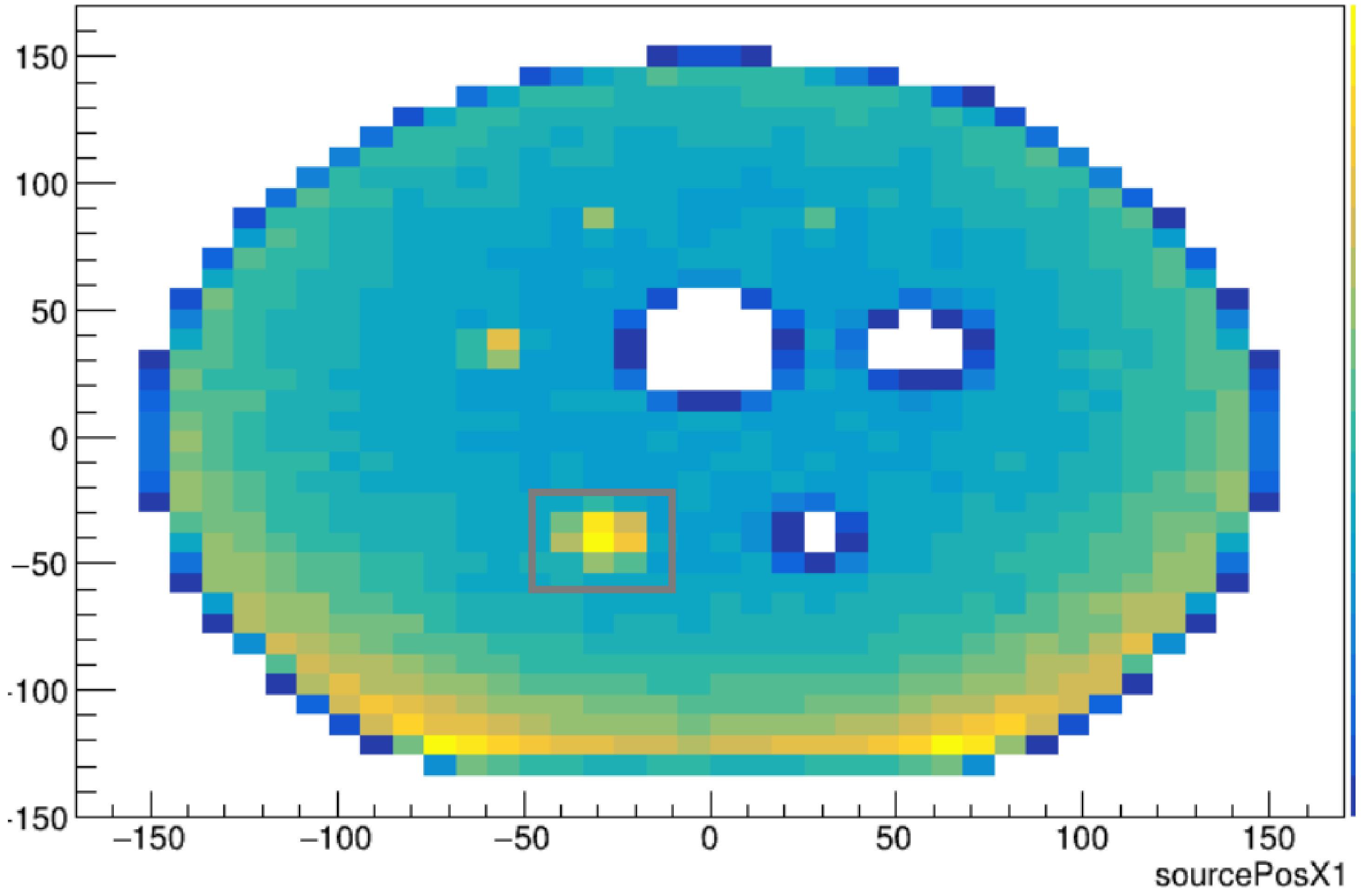
$$30\ cm \times \sin(30°) = 15\ cm$$

$$= \sqrt{15^2 + 30^2}cm = 33.5\ cm \rightarrow$$
$$\Delta\Delta t \approx 120\ ps$$

$t2^* \approx t2$ if θ "small"

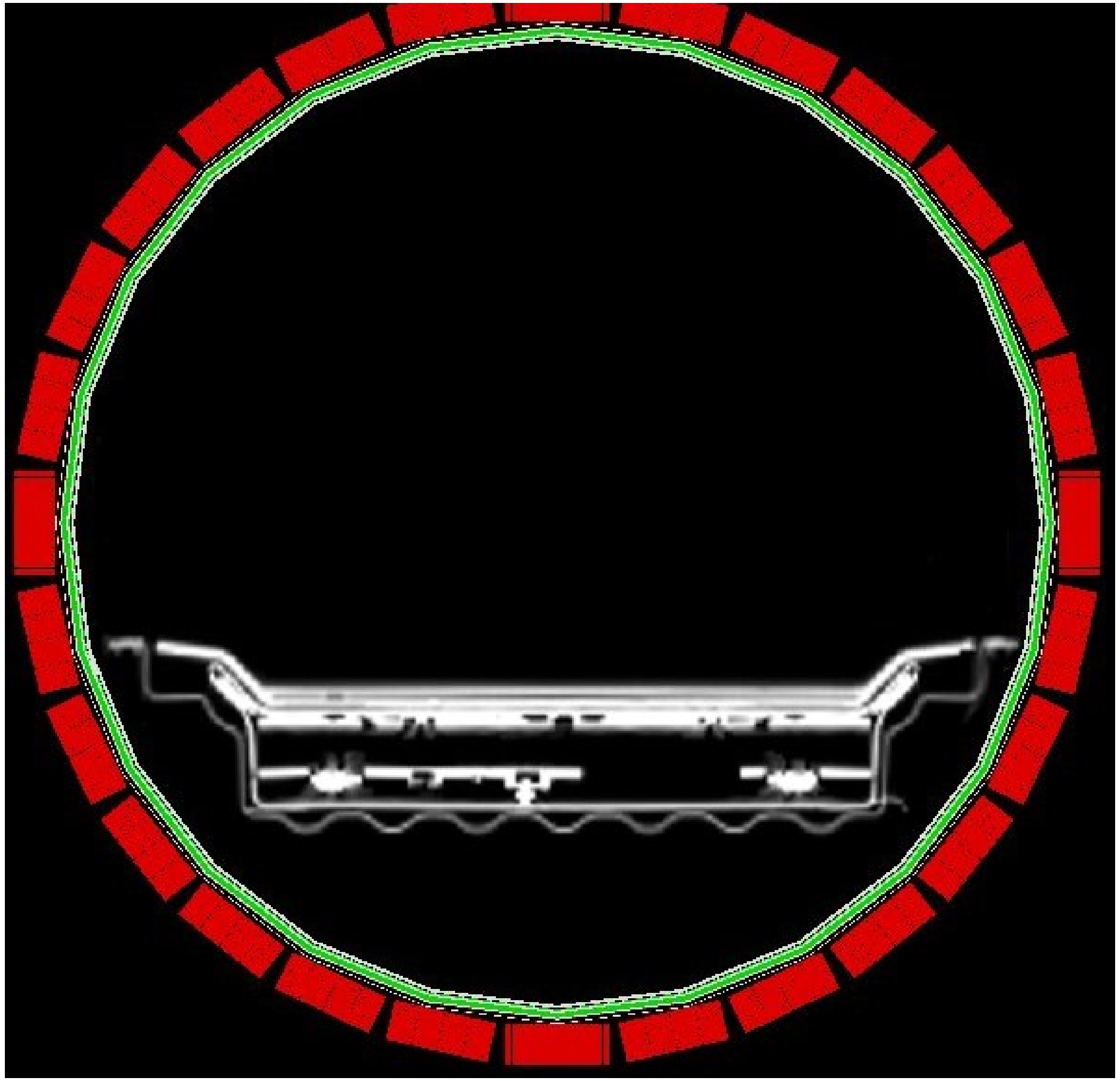
GATE simulation

- Large phantom (major axis ~ human abdomen)
- NEMA-IQ like phantom (bigger, more scatter)
- ~30 cm diameter (standard NEMA: 22 cm)
- Focus on emission from central source and compare expected with measured parameters



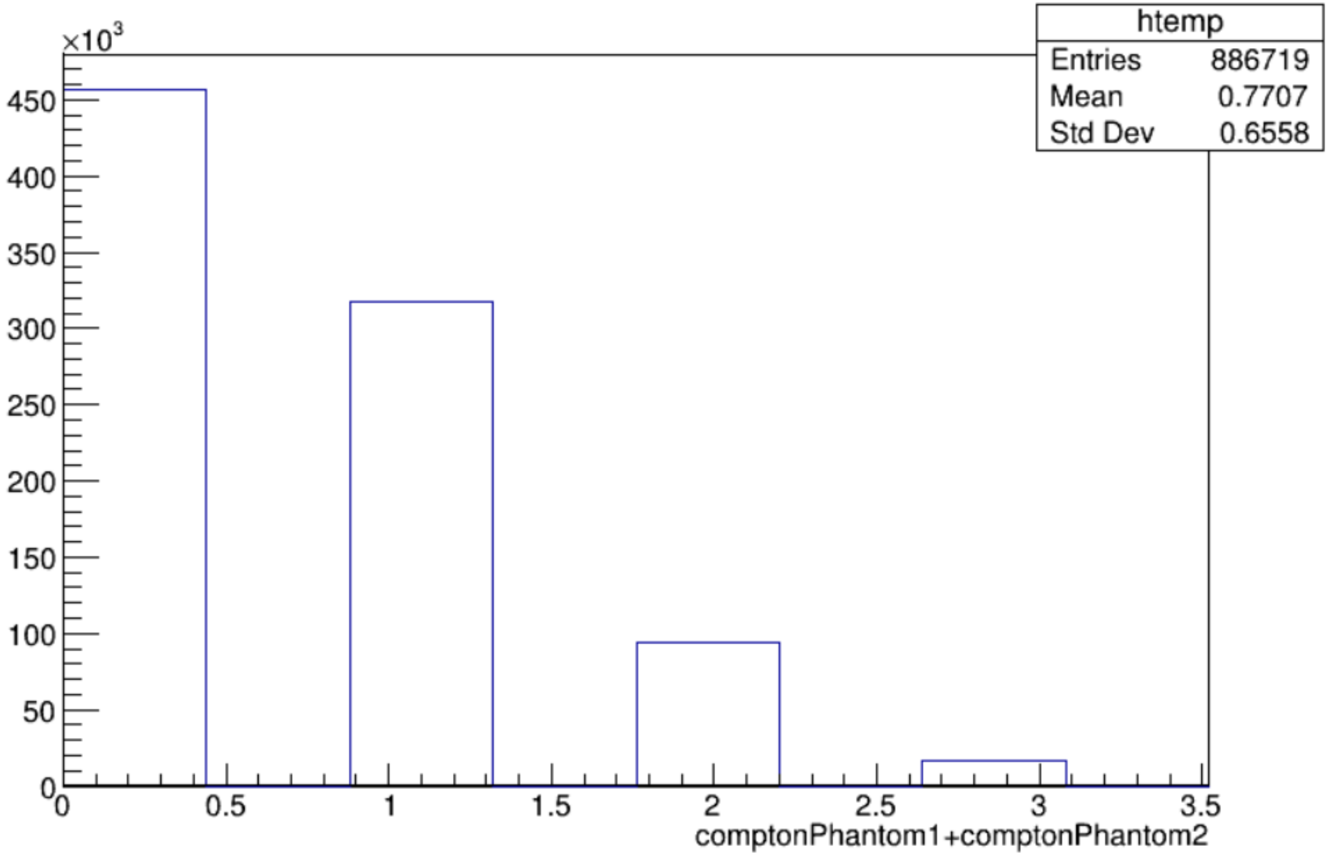
Detector: Ideal TOF PET

- «Infinite» TOF
- Perfect DOI
- 4x4x25 mm^3 LYSO-like crystals
- 75 cm ring – 25 cm length
- 10 % energy resolution
- Energy Window: 425 – 650 keV



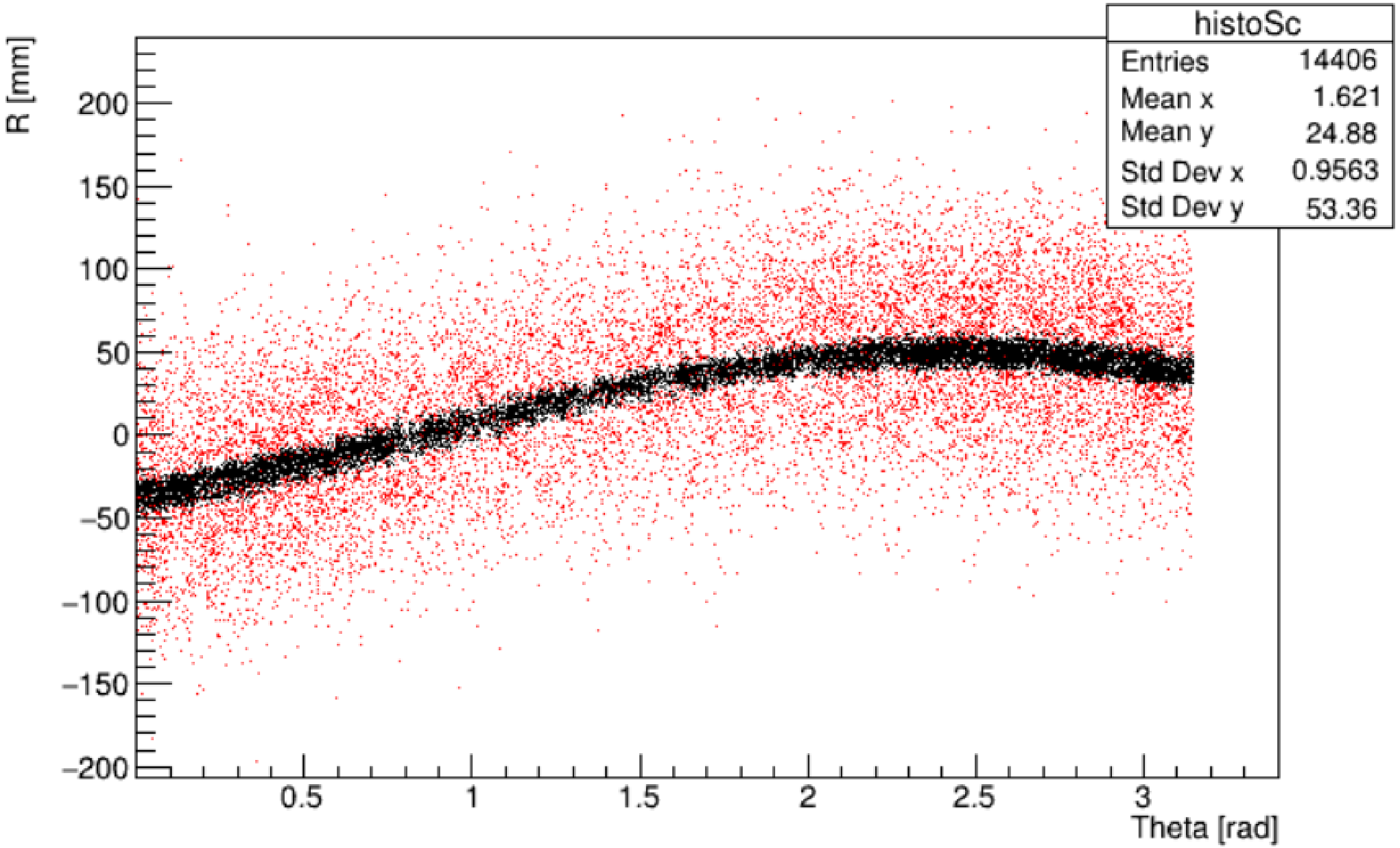
Known scatter properties

Coincidence type	% of true coincidences
Unscattered	52
Single scatter	35
Double scatter	10
3+	3



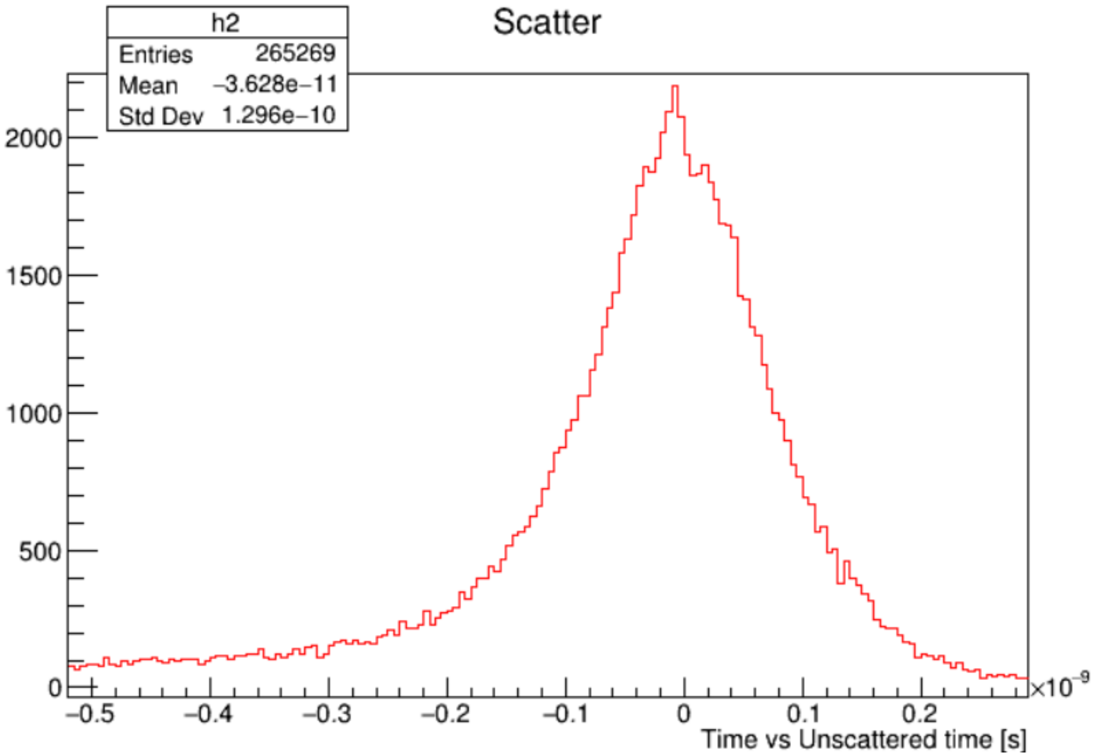
Scatter: non-TOF sinogram

- Scattered events (RED) form a band that’s ~10 cm wide per side!

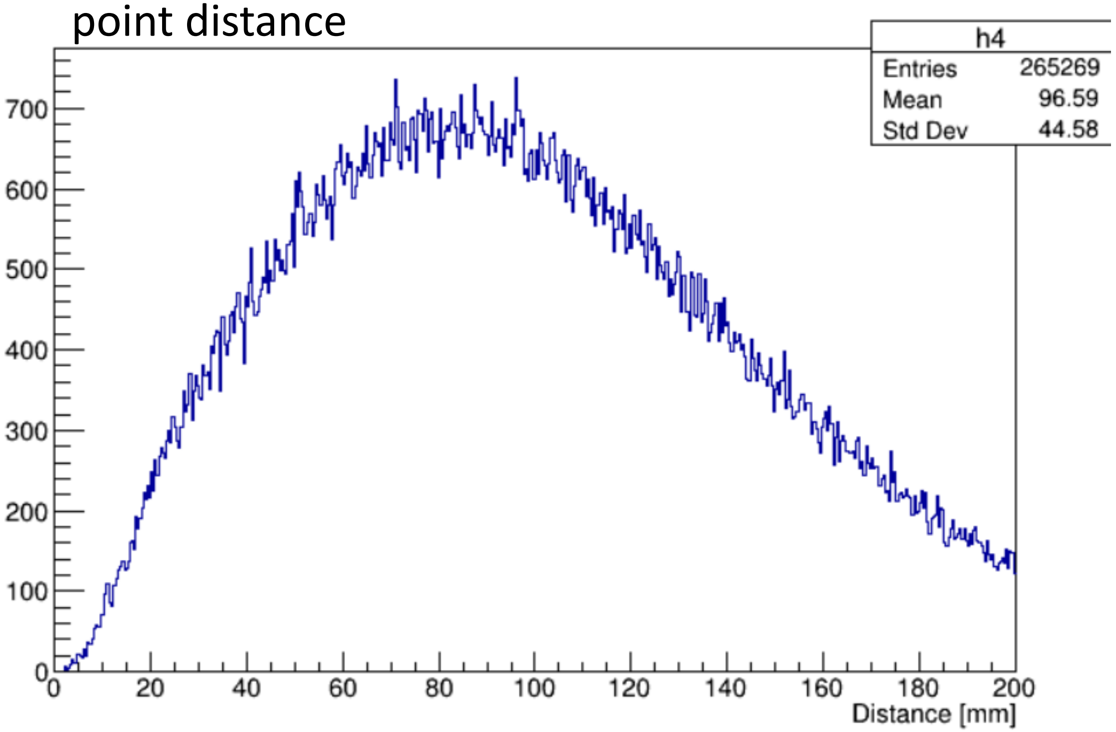


Timing spectrum

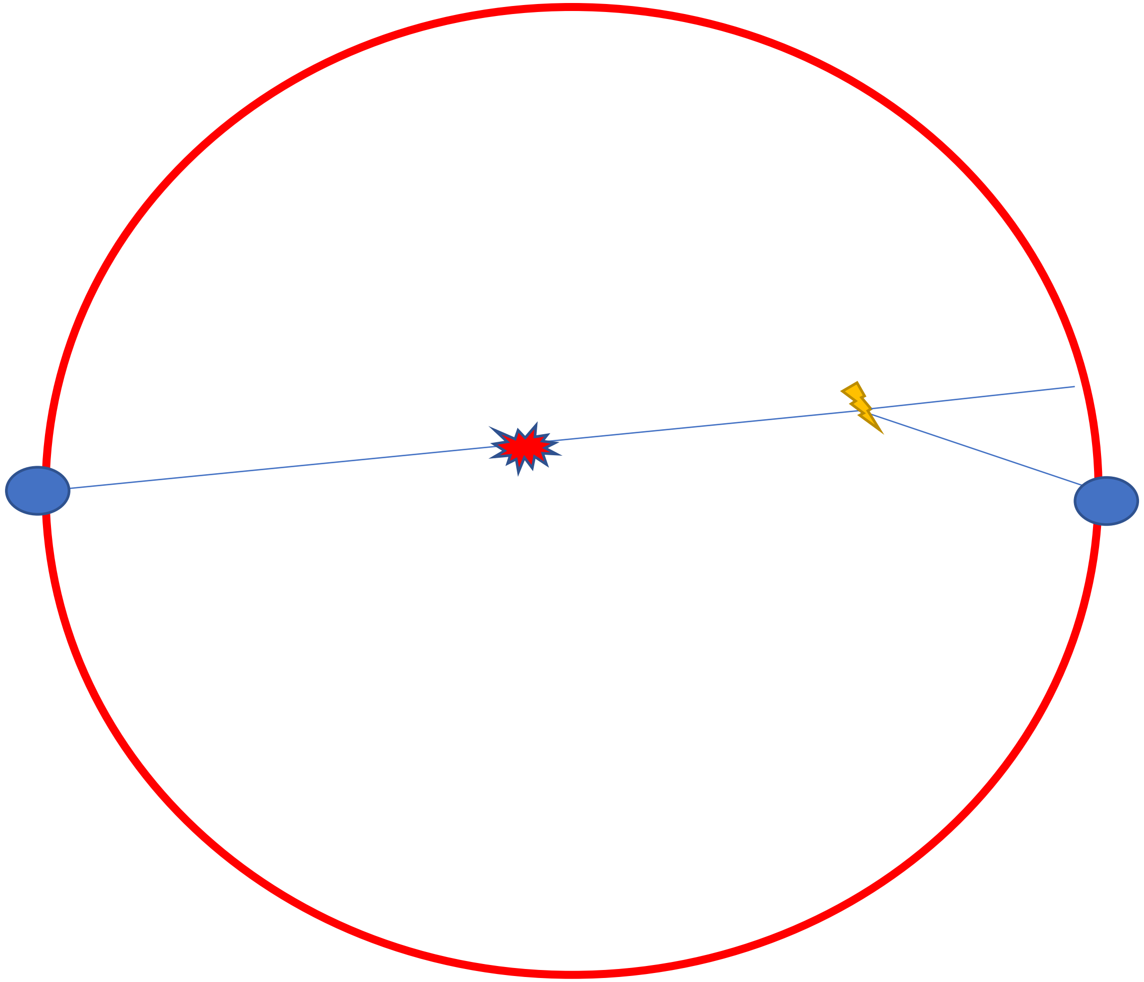
- Deflection over time is ~±100 ps (‘3 cm’)



Scattered vs unscattered hit point distance



Recon from scatter and TOF?



Exact scattering angle known
Exact TOF known:
Emission Point is known!

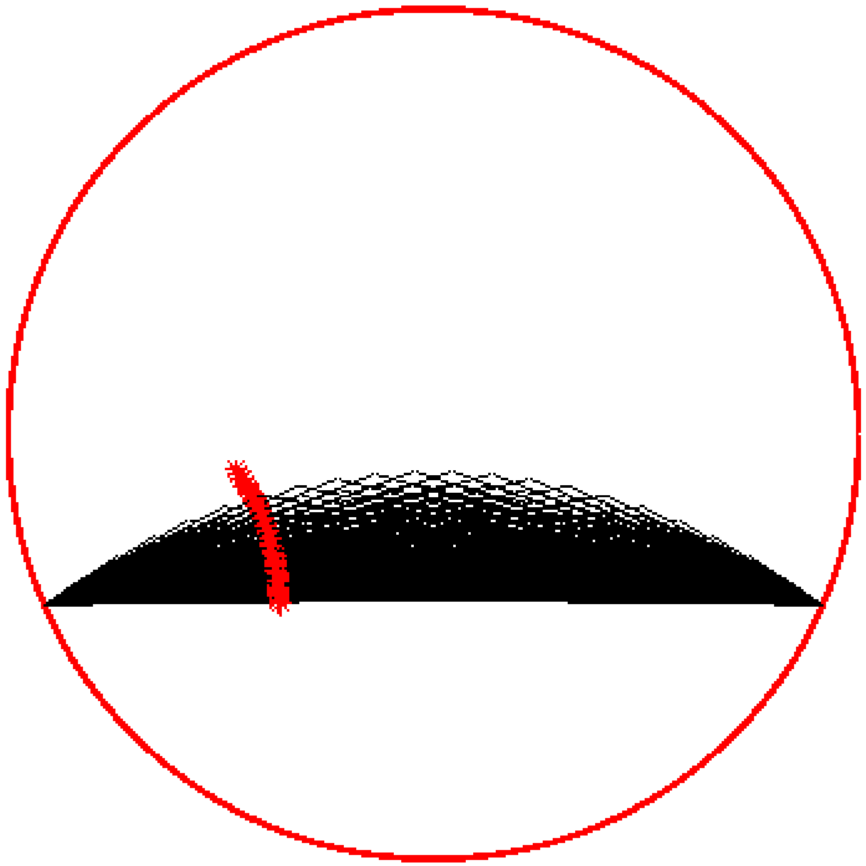
Angle is unknown unless
energy resolution<<1%!

M. Conti, I. Hong, and C. Michel, "Reconstruction of scattered and unscattered PET coincidences using TOF and energy information," *Phys. Med. Biol.*, vol. 57, no. 15, pp. N307–N317, Aug. 2012.

Angle unknown but TOF is?

- Angle unknown (smaller <~ 40°). Exact TOF.

- Event happened along the red curve. It is a (easy?) tomographic problem!



M. Conti, I. Hong, and C. Michel, “Reconstruction of scattered and unscattered PET coincidences using TOF and energy information,” *Phys. Med. Biol.*, vol. 57, no. 15, pp. N307–N317, Aug. 2012.

Takeaway

Scatter is a prevalent problem in human PET scanner (Special care is needed if Energy res. under ~12% is used to improve TOF!)

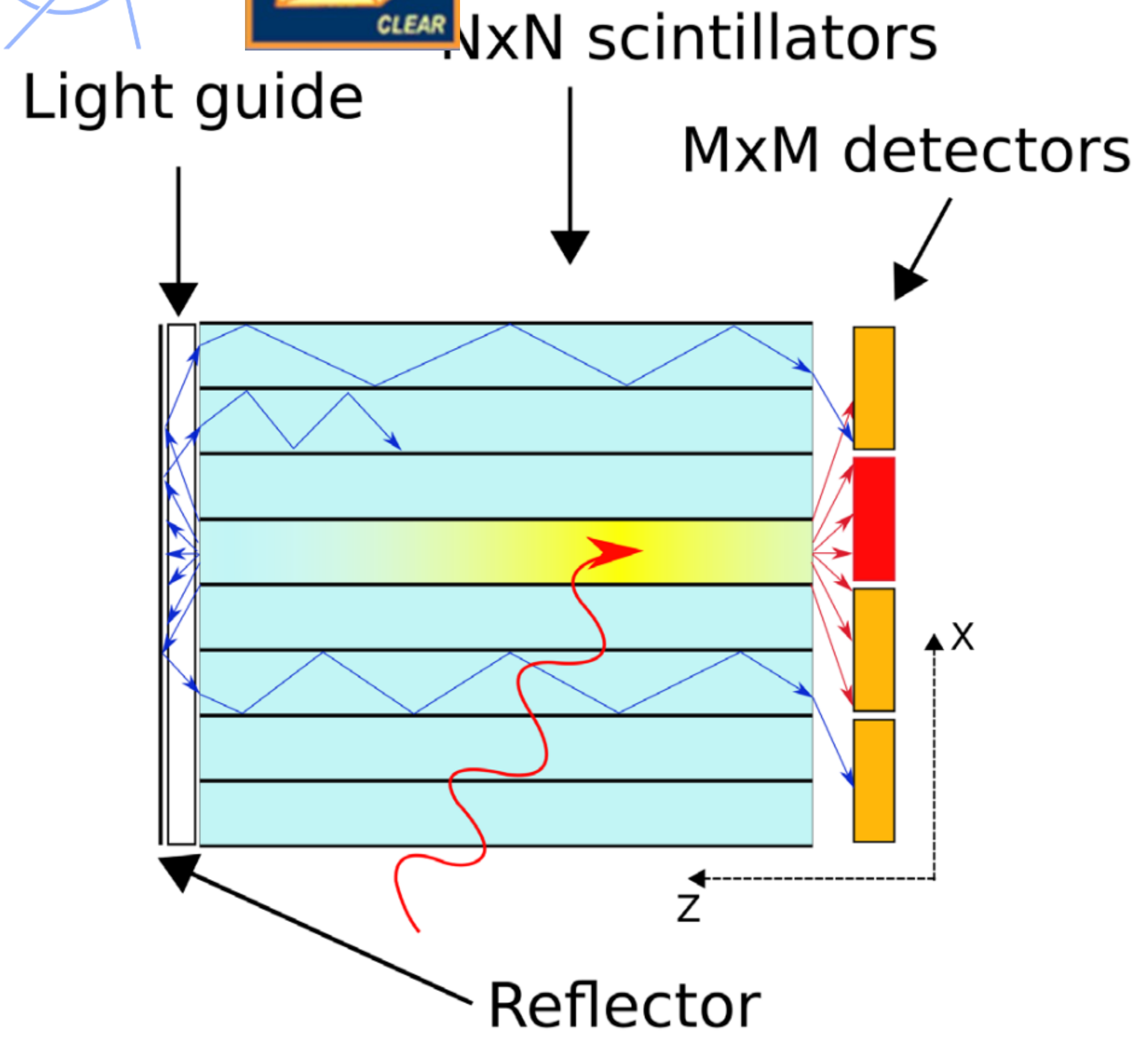
Increasing TOF resolution (<~150 ps) require thinking about extremely accurate scatter correction to achieve unbiased image reconstruction

TOF resolution ~<40 ps (6 mm) allows reconstruction from trues+scattered coincidences!

Exact algorithm to be implemented and optimized

The MET project

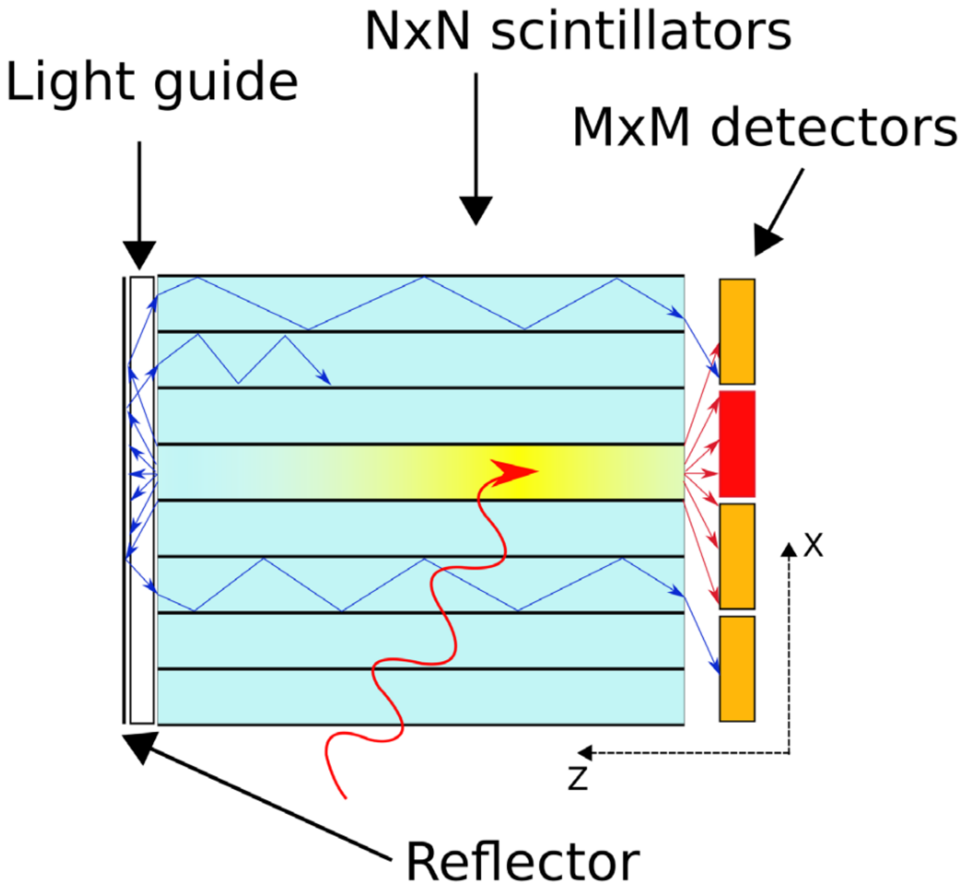
“Multiple emission Tomography”



M Pizzichemi *et al* 2019 *Phys. Med. Biol.* 64 155008, doi: 10.1088/1361-6560/ab2cb0

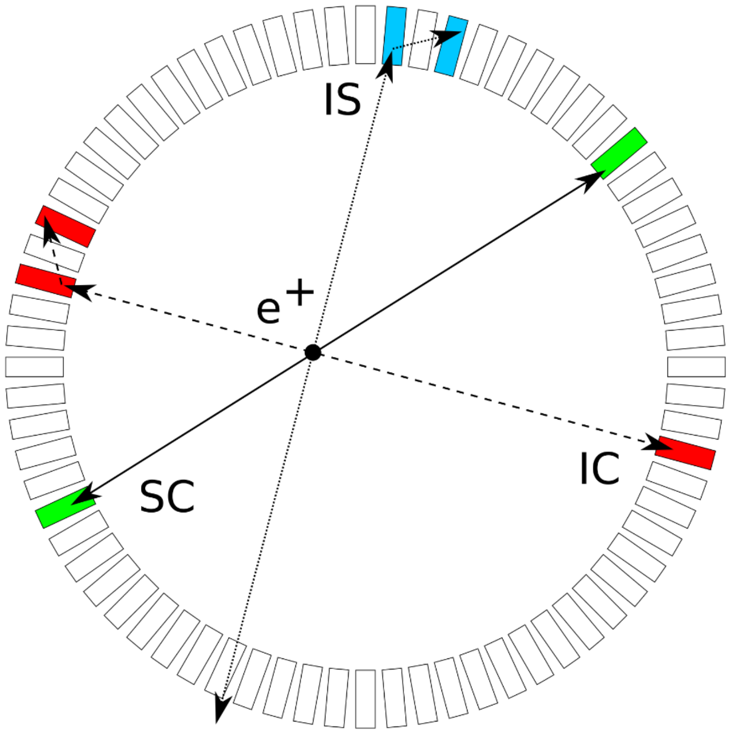
Depth of interaction and timing

- x-y position with Anger logic
- DOI from fraction of signal in most intense pixel vs overall
- Timing from weighted timestamps of all pixels accounting for DOI-dependent delay
- Readout timing resolution: 16 ps
- DOI resolution: 3.0 mm FWHM
- Energy resolution 9%
- CTR of 157 ps



Detected events in a crystal system

- IC probability: ~60% @ 511 keV with LYSO (single), 84% coinc.
- Mean Absolute error small (<0.5 mm), large contribution to FWTM



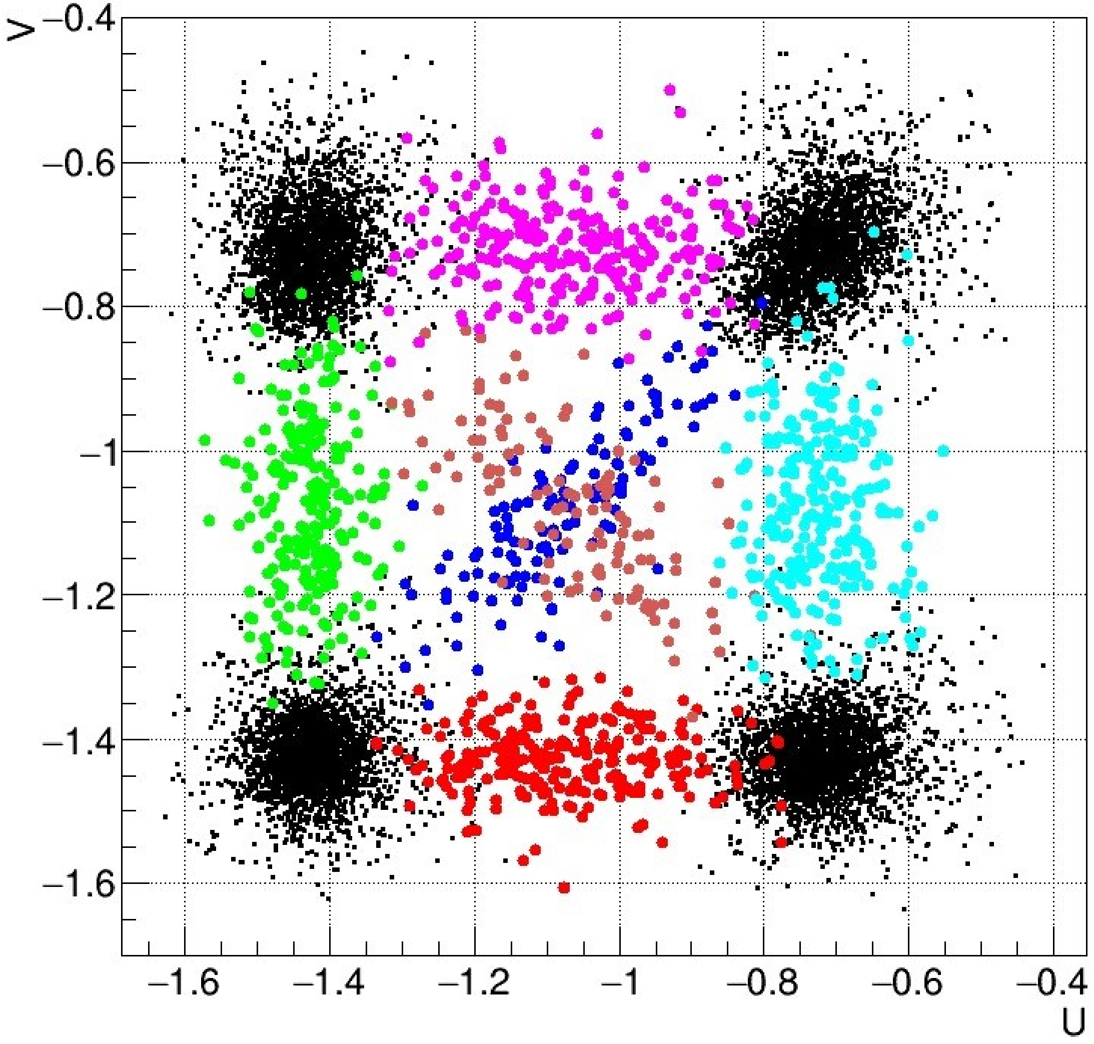
Standard Coincidences (SC): both gamma rays deposit all their energy in the detector, each one in an individual crystal

Inter-crystal Coincidences (IC): one gamma ray deposits all its energy in one crystal, and the other deposits all its energy in two crystals

Inter-crystal Singles (IS): one gamma ray deposits all its energy in two crystals, while the other gamma escapes from the detector

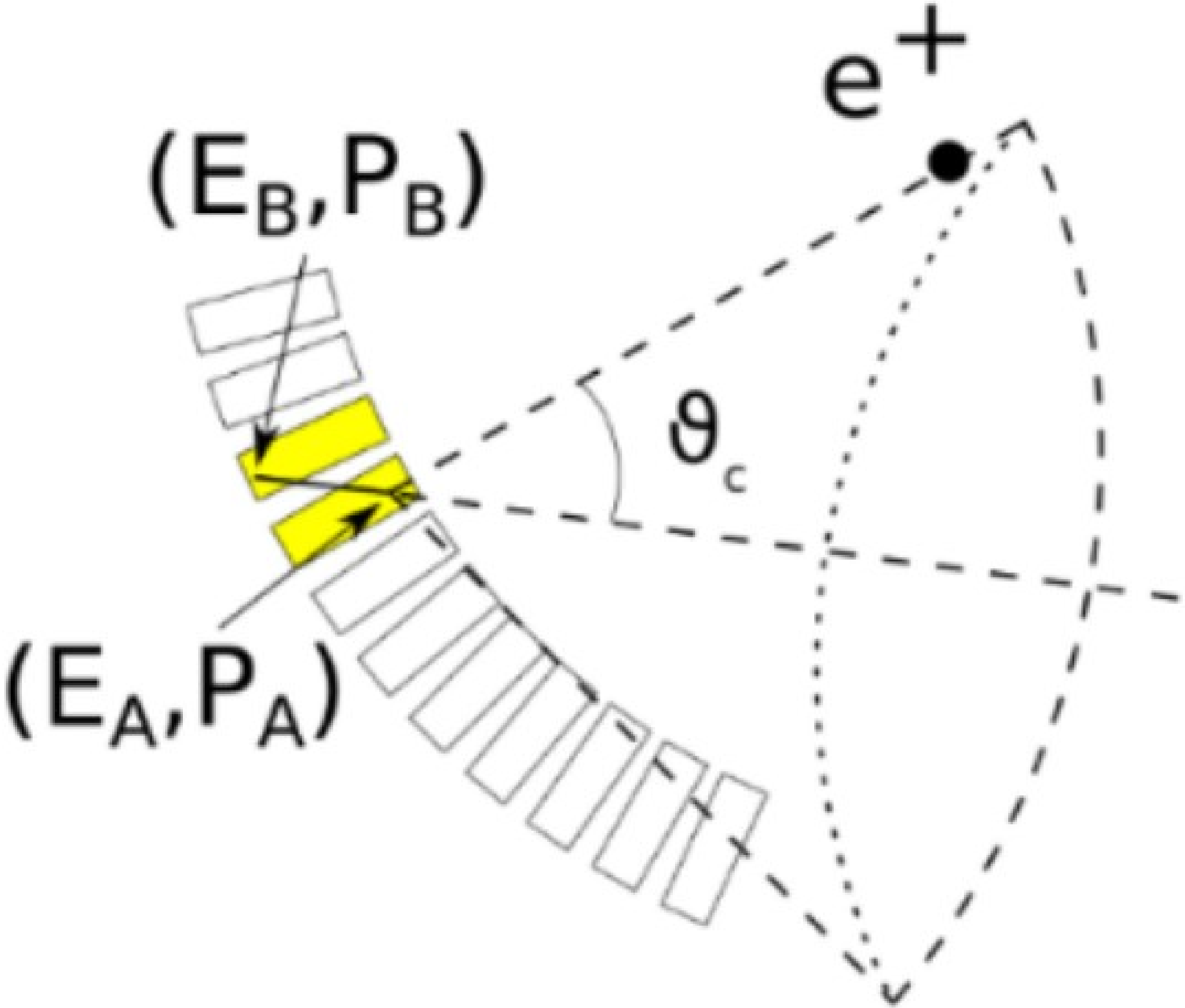
Inter-crystal scatter detection

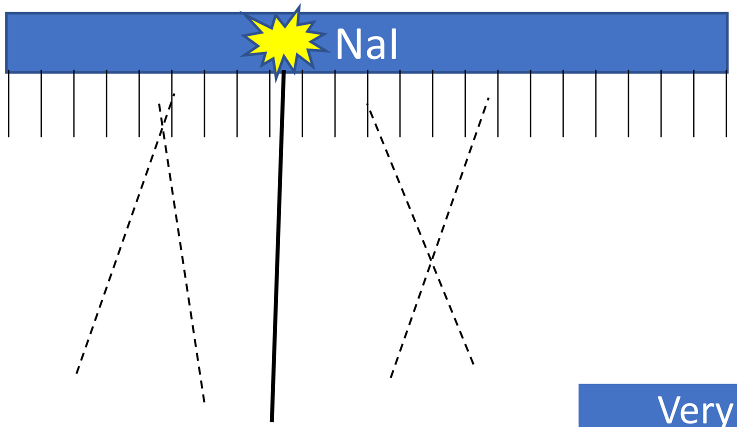
- Analysis of the light distribution to detect the kinematics of the event
- Current analysis: linear model of energy deposited in each crystal



Compton camera

- Estimate from energy and position the scattering angle
- There is a cone of probability of emission direction

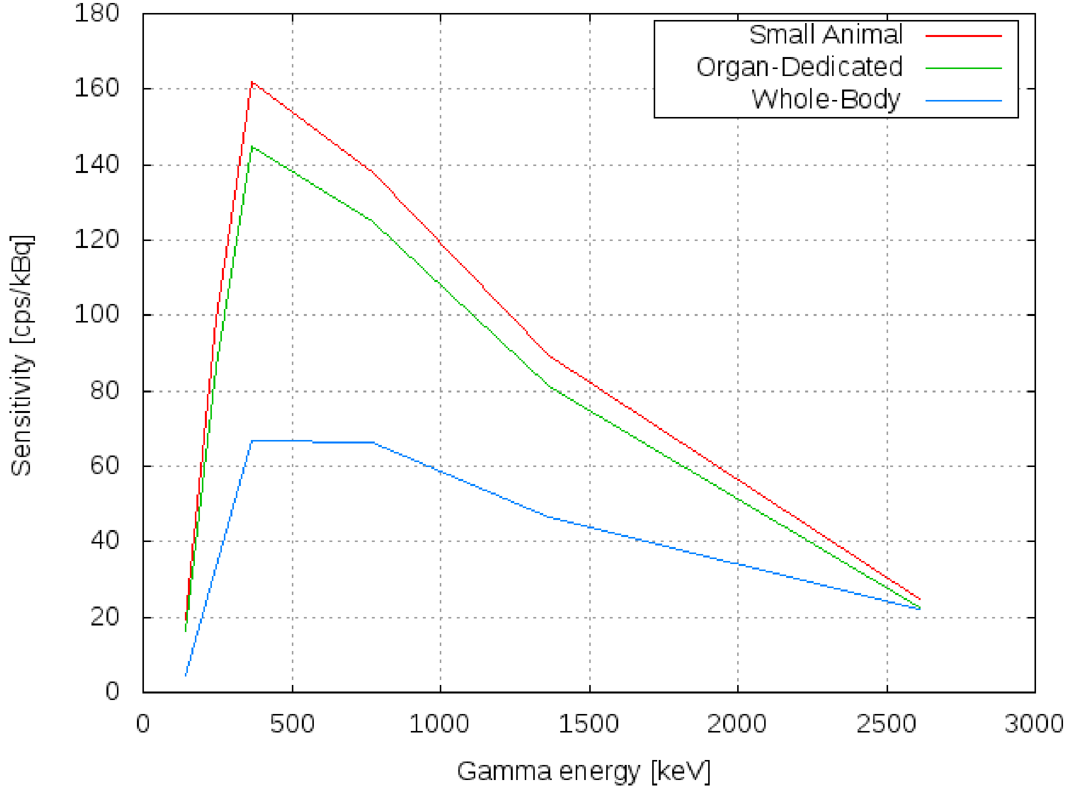




SPECT:

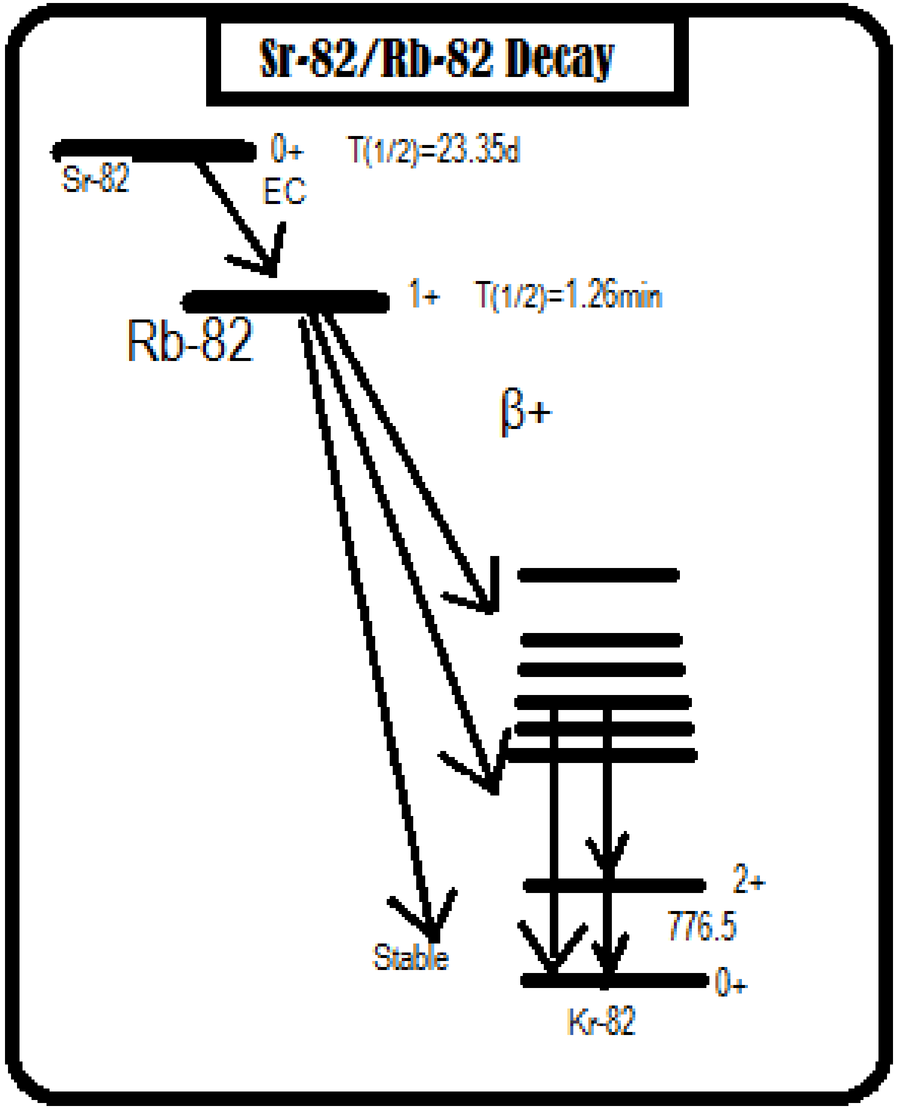
- Very low geometric efficiency (10^-4 @ 140 keV)
- Efficiency must drop with increasing energy
- Efficiency / spat. Resolution tradeoff (1e-4/9 mm @ 140 keV; 5e-5/ 13 mm @ 300 keV)

MET



PET image improvement

- IC-scatter now localized exactly
- Single events can be used for imaging
- Dirty nuclides (e.g.: 82Rb,β^++777 keV γ; 68 Ga: β^++1100 MeV γ) can exploit the third γ instead of treating it as background



Positronium lifetime

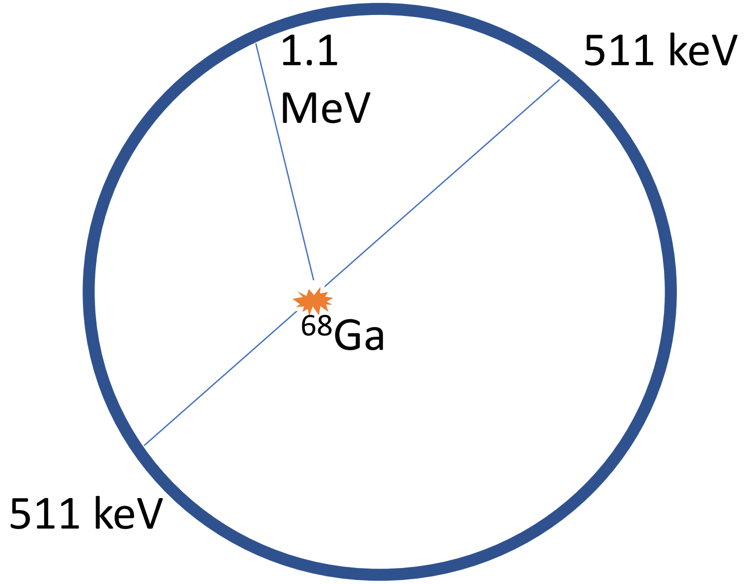
p-positronium vacuum: 125 *ps*

o-positronium vacuum: 142 *ns*

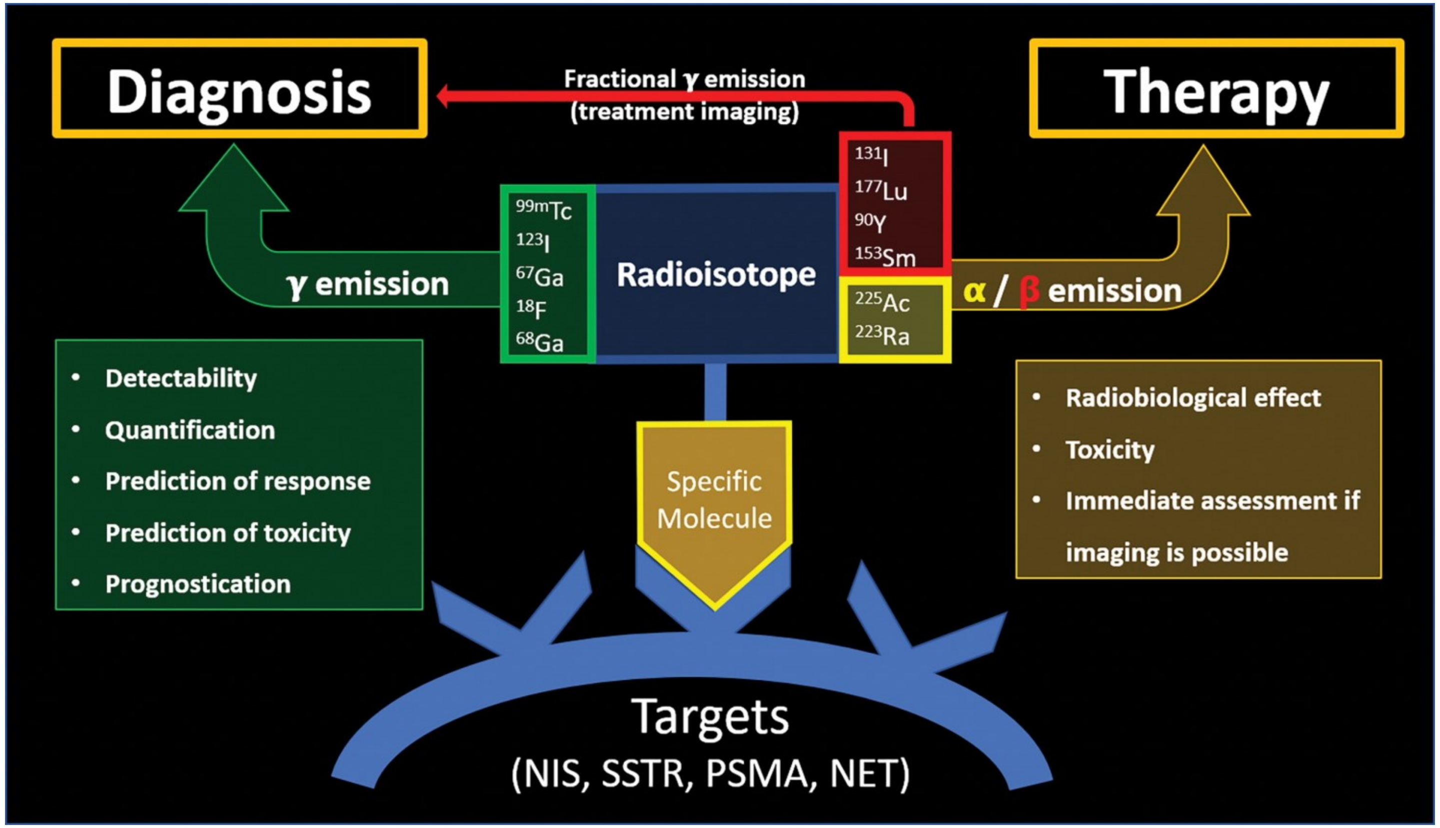
o-p Lifetime depends on prob. Of picking up an electron of opposite spin. Down to 1-10 ns

In water linearly dependent on oxygen partial pressure (hypoxic tumors)

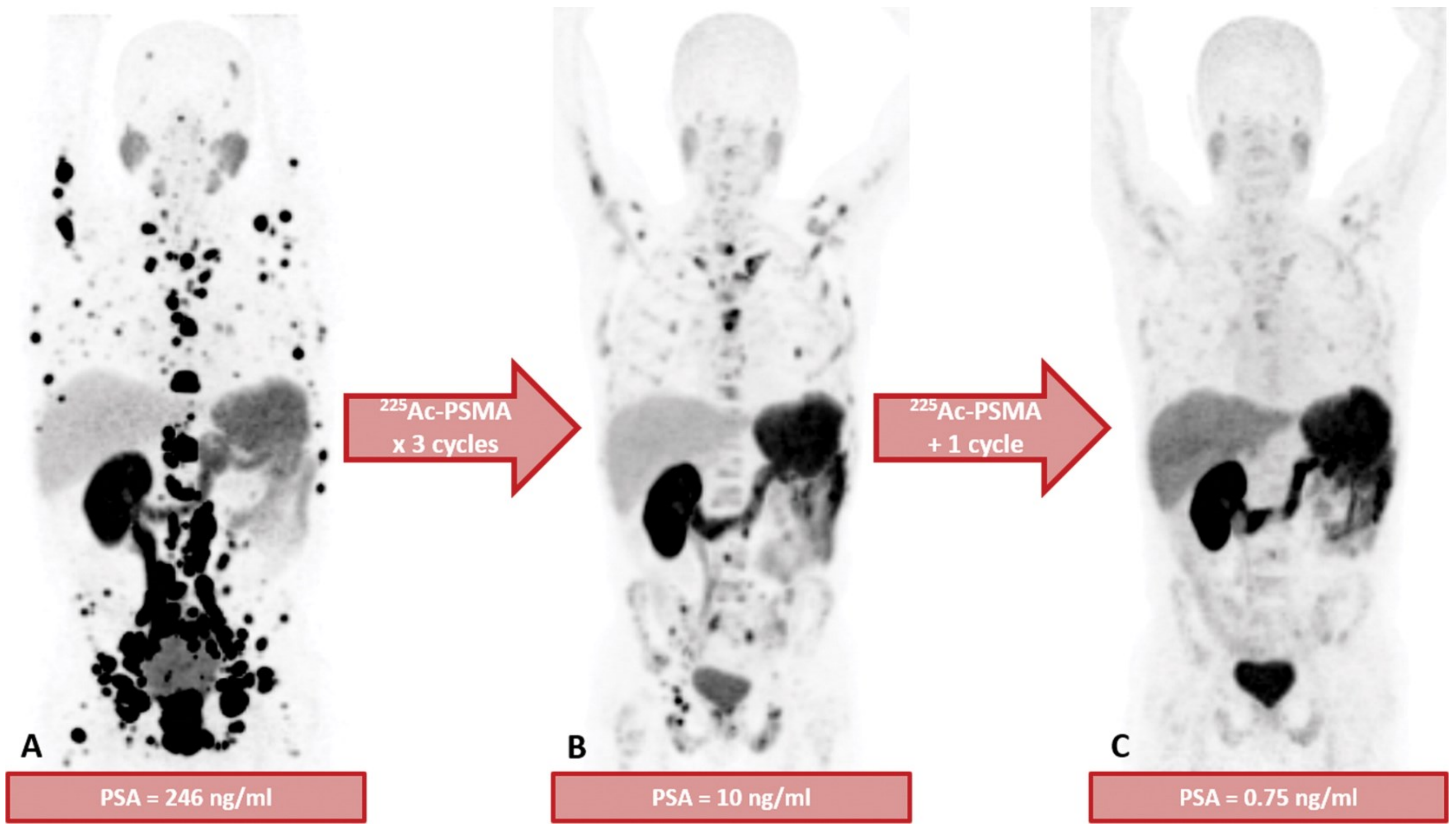
- Lifetime estimation can be performed using an isotope with a 3° gamma.
- Probability of detecting all 3 is low (both geometry and efficiency)
- With «MET» we can detect only 1 511 keV



Theranostics



- Need post-treatment imaging for dose verification
- Most nuclides have residual gamma emissions!



Castration resistant prostatic carcinoma

225Ac-PSMA (prostate specific antigen)

Conclusions

- Very fast detectors have great potential for nuclear medicine
- Research concerning how to deal with scattering events needs to start now
- Very fast timing electronics can be used to turn conventional PET detectors in PET + Compton cameras
- If such projects is successful, multiple applications in nuclear medicine are already awaiting!