Precise Timing - the route to better PET images

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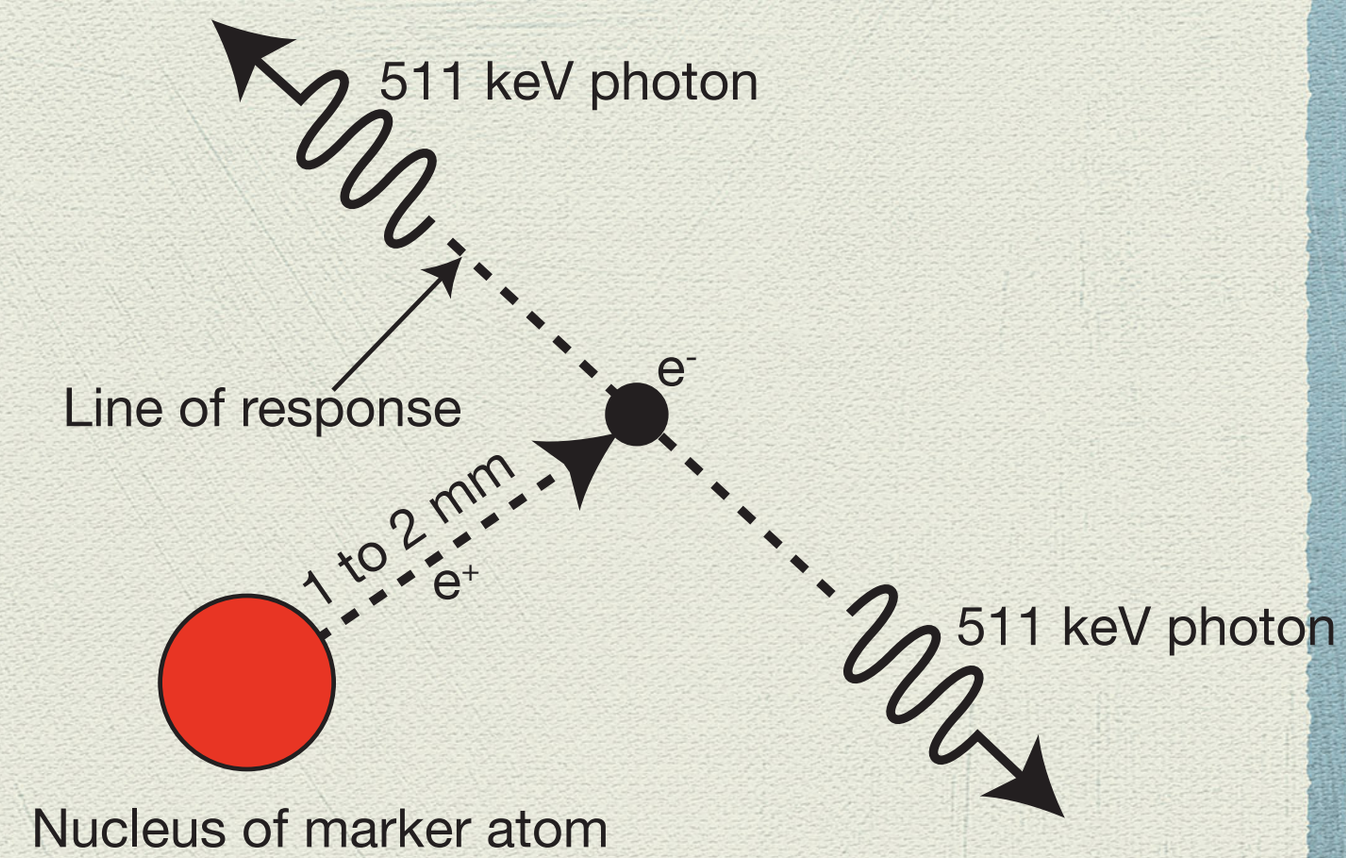
What is Positron-Emission Tomography?

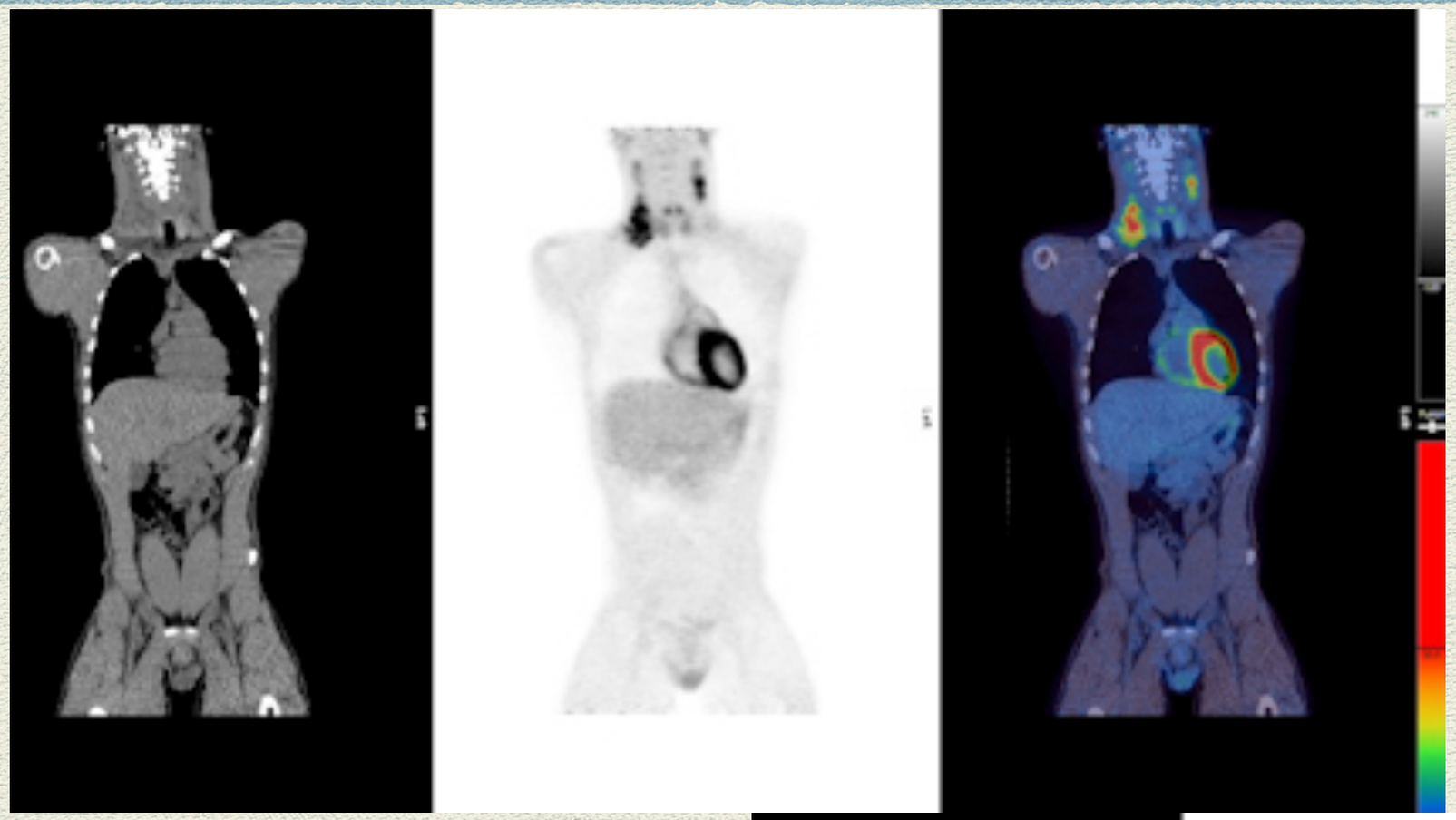
Patient to be scanned injected with substance that carries a radio-tracer

A common radiotracer: ^{18}F-FDG: Glucose with one H exchanged with ^{18}F). ^{18}F emits positron that will annihilate creating two back-to-back 511 keV gamma photons. These gamma photons are detected - and a line drawn between the two detection points (LOR = line of response)

Image created by analysing all these LORs

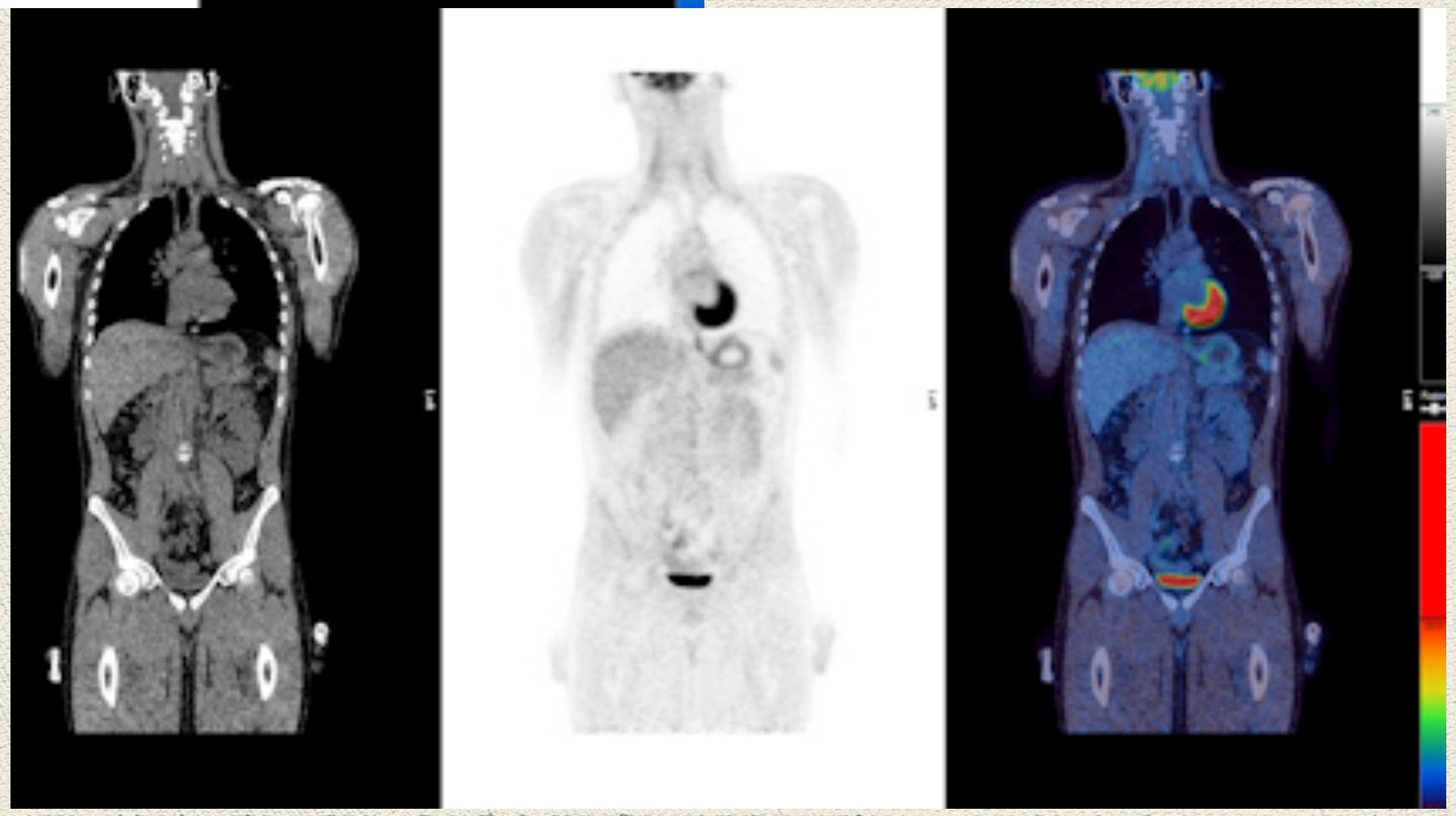


Hodgkin's lymphoma



before chemotherapy

after chemotherapy

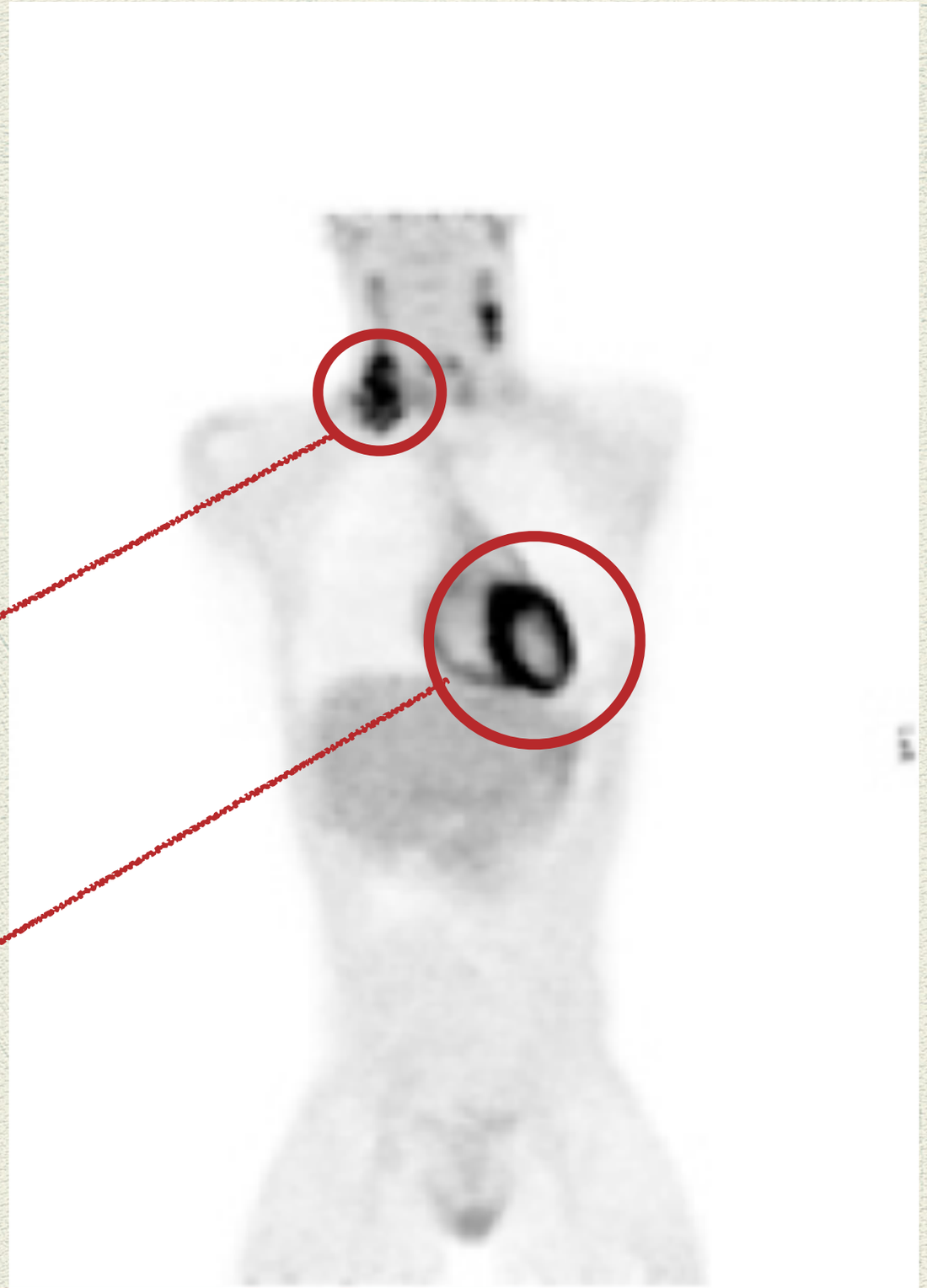


So what is non-ideal with the PET image?

Image is not so clear (fuzzy) - need CT scan for detail (and attenuation map)

Tumour needs to be some centimetres in size to be visible

Radio-tracer flows in the blood and needs to be removed from body - large dose to heart, brain, kidneys, and badder



Molecular imaging is an important technology - however we must do better concerning the imaging

Important aspects that must be improved

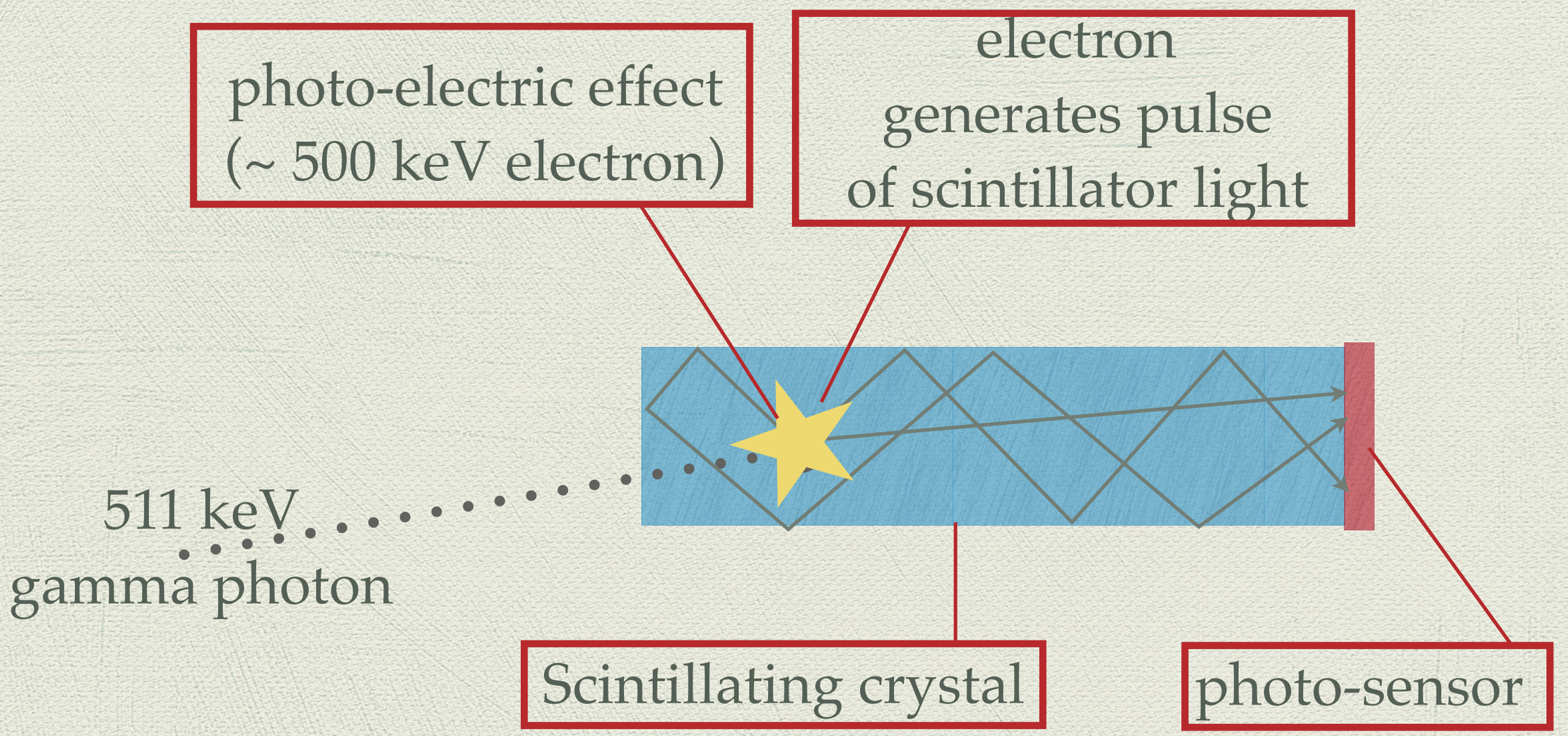
- high resolution images : (less fuzzy)
- less background - need to improve signal to noise and be sensitive to smaller tumours
- lowest possible dosage of radio-tracer (very important for paediatric use)

- Question: how can we …..
  - (a) reduce dose of radio-tracer
  - (b) improve image resolution
  - (c) reduce background?

Resolution

- limited by range of positron before annihilation i.e. 1-2 mm
- smeared by ‘depth-of-interaction’ uncertainties

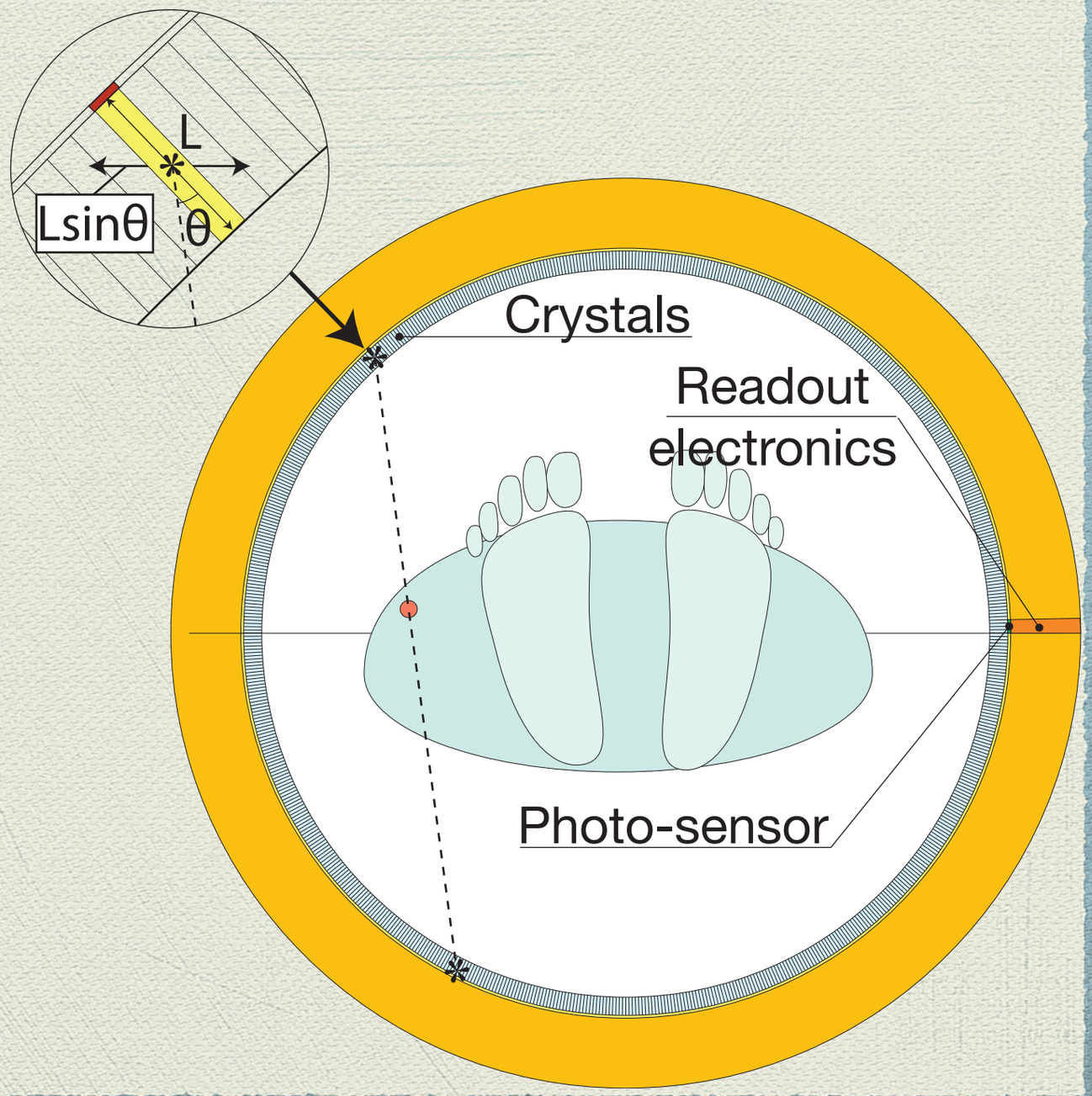
First: necessary to detect 511 keV gamma photon



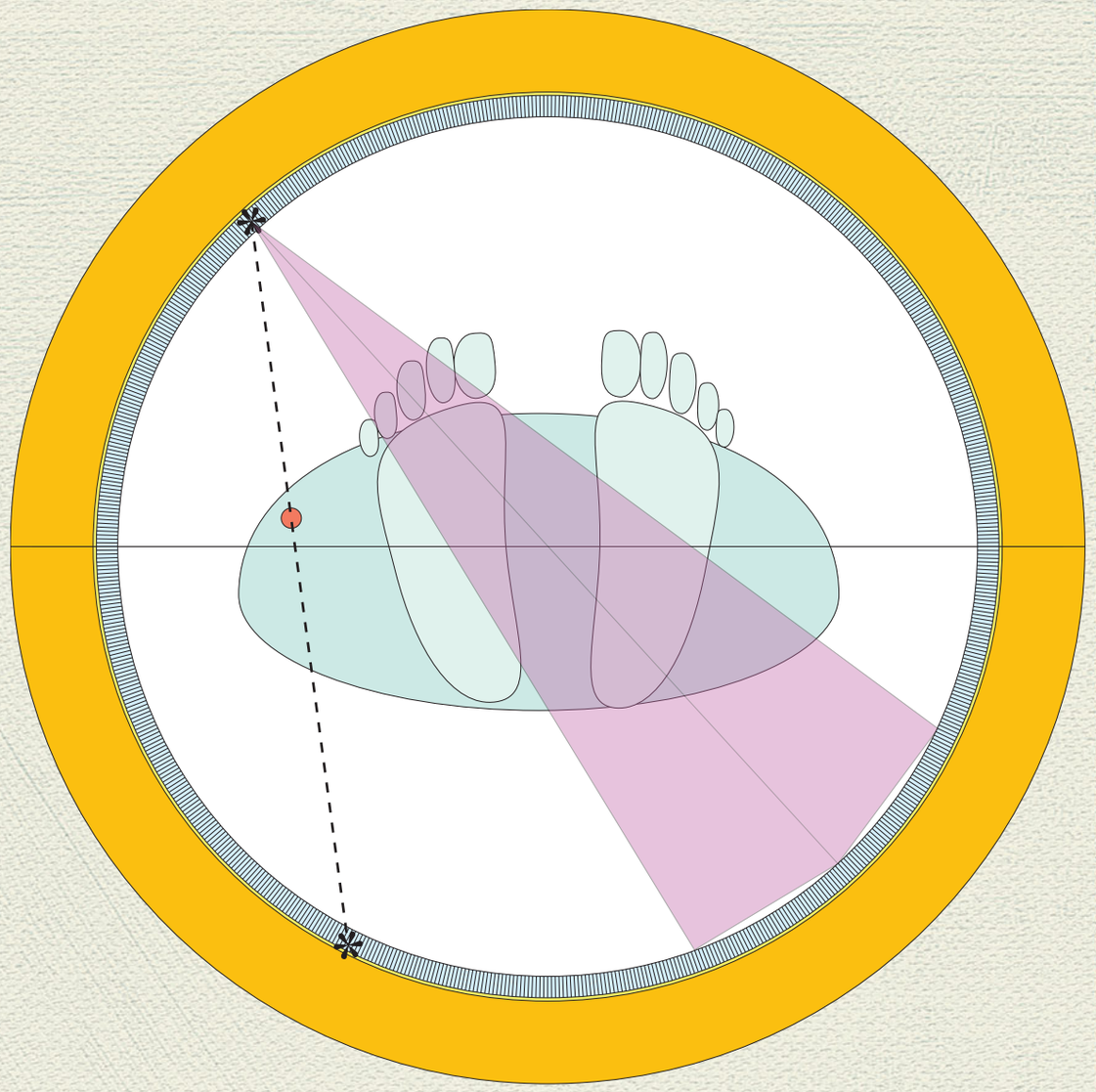
parallax error - depth of interaction

- 511 keV gamma photon can interact anywhere along crystal length - introduces error of Lsinθ (L is the crystal length)

- Current solutions:
  (1) make L short (13 mm for a commercial breast scanner)
  (2) Limit θ with large ring (90 cm for GE PET scanner)



Current solutions: only use diagonally opposite hits in ring to limit angle: this will reduce sensitivity



Naviscan breast scanner - crystals length = 13 mm lower sensitivity

Less background

- Use Time-of-Flight

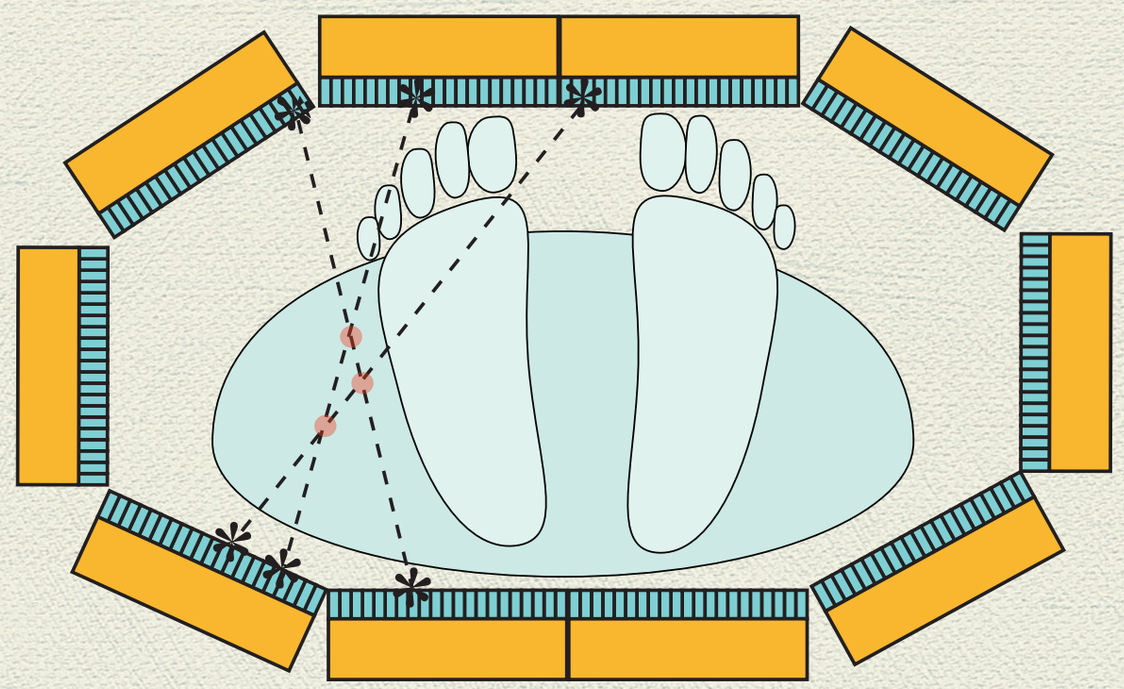
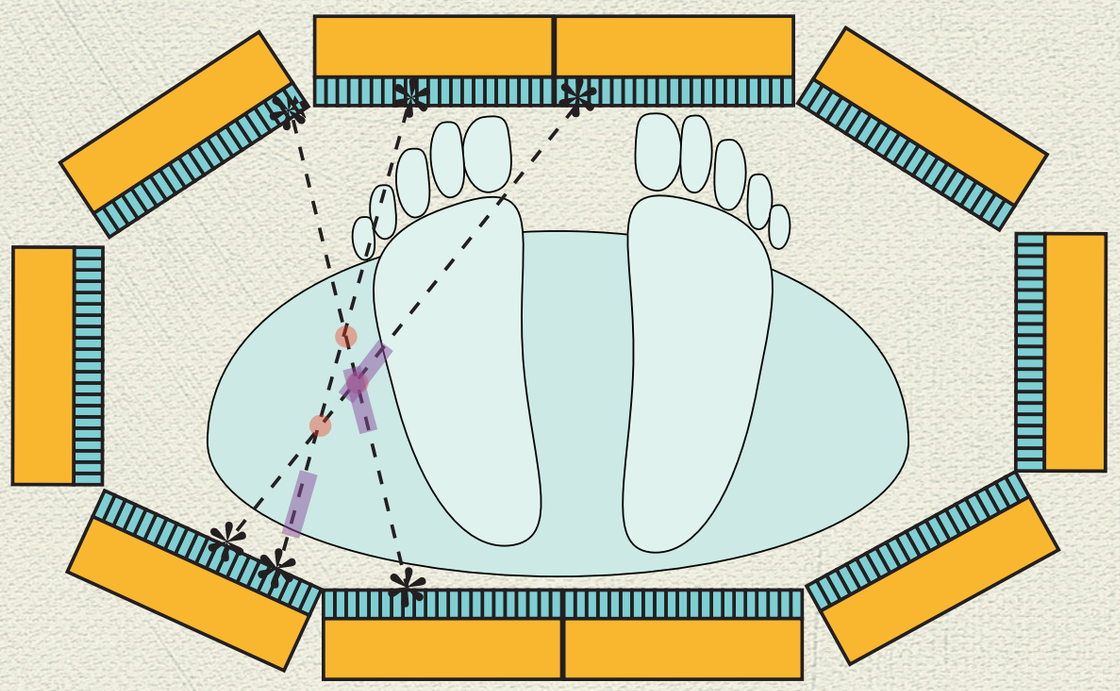


Image reconstructed from lines of response (LOR); however we do not know location along line.

TIME-OF-FLIGHT: locate position of positron along the line of response



Coincidence Time resolution (CTR)

CTR of 400 ps : segment 6.5 cm

CTR of 100 ps : segment 1.6 cm

speeds up image reconstruction

Can we reduce dose of radio tracer? (i.e. how to improve sensitivity)

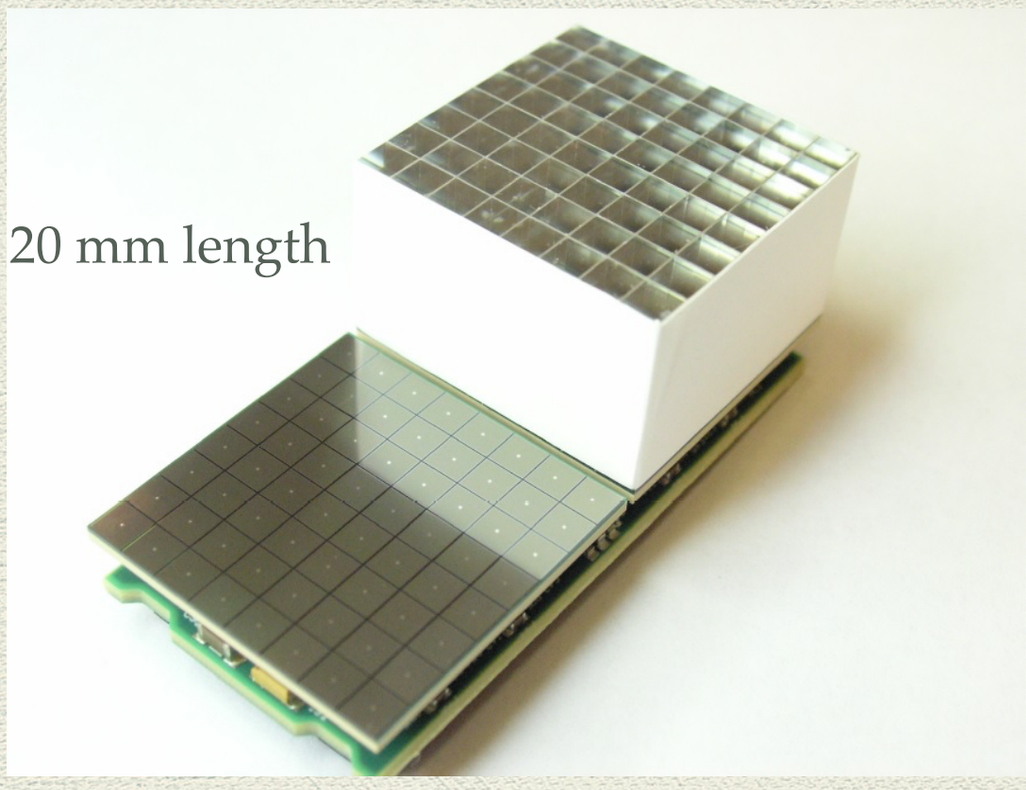
- Long crystals
- Mount detectors close to subject (large solid angle)

n.b. coincidence ~ (detector sensitivity)^2

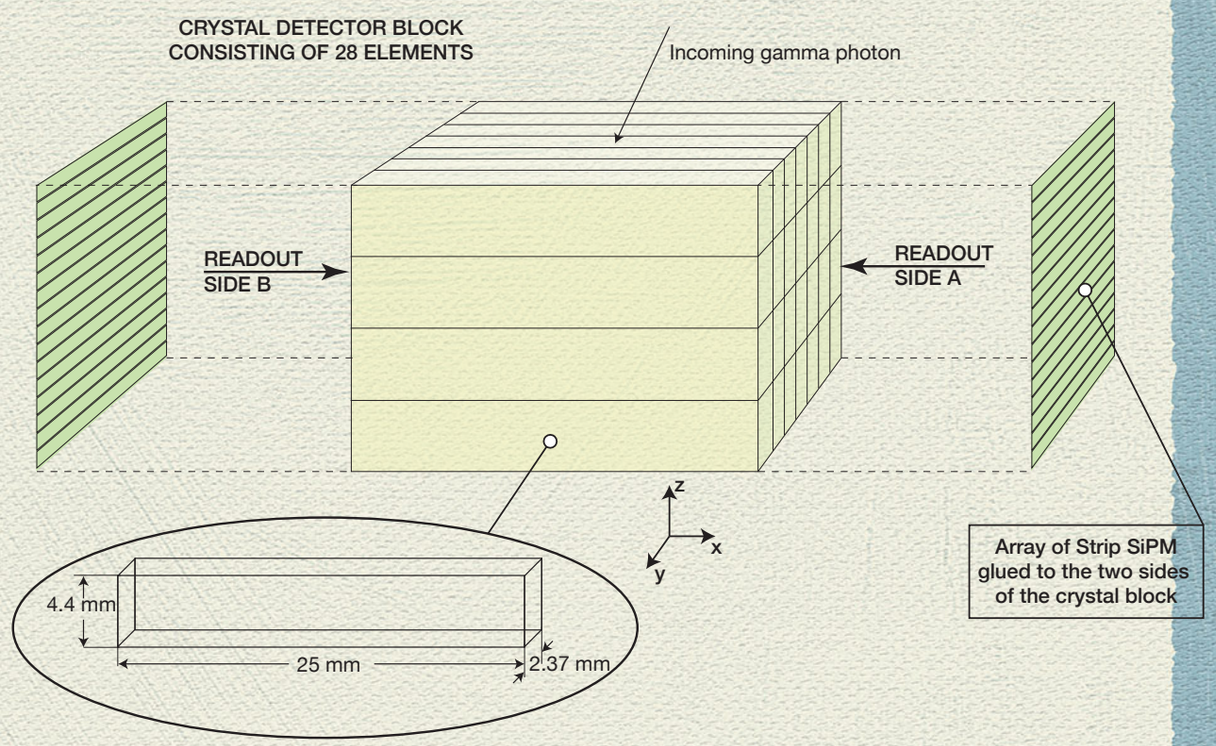
However improving sensitive makes smearing caused by the 'unknown' depth of interaction worse

- Solution: imperative to measure the depth of interaction

Comments on timing:
Why is our solution superior to ‘standard’ setup?

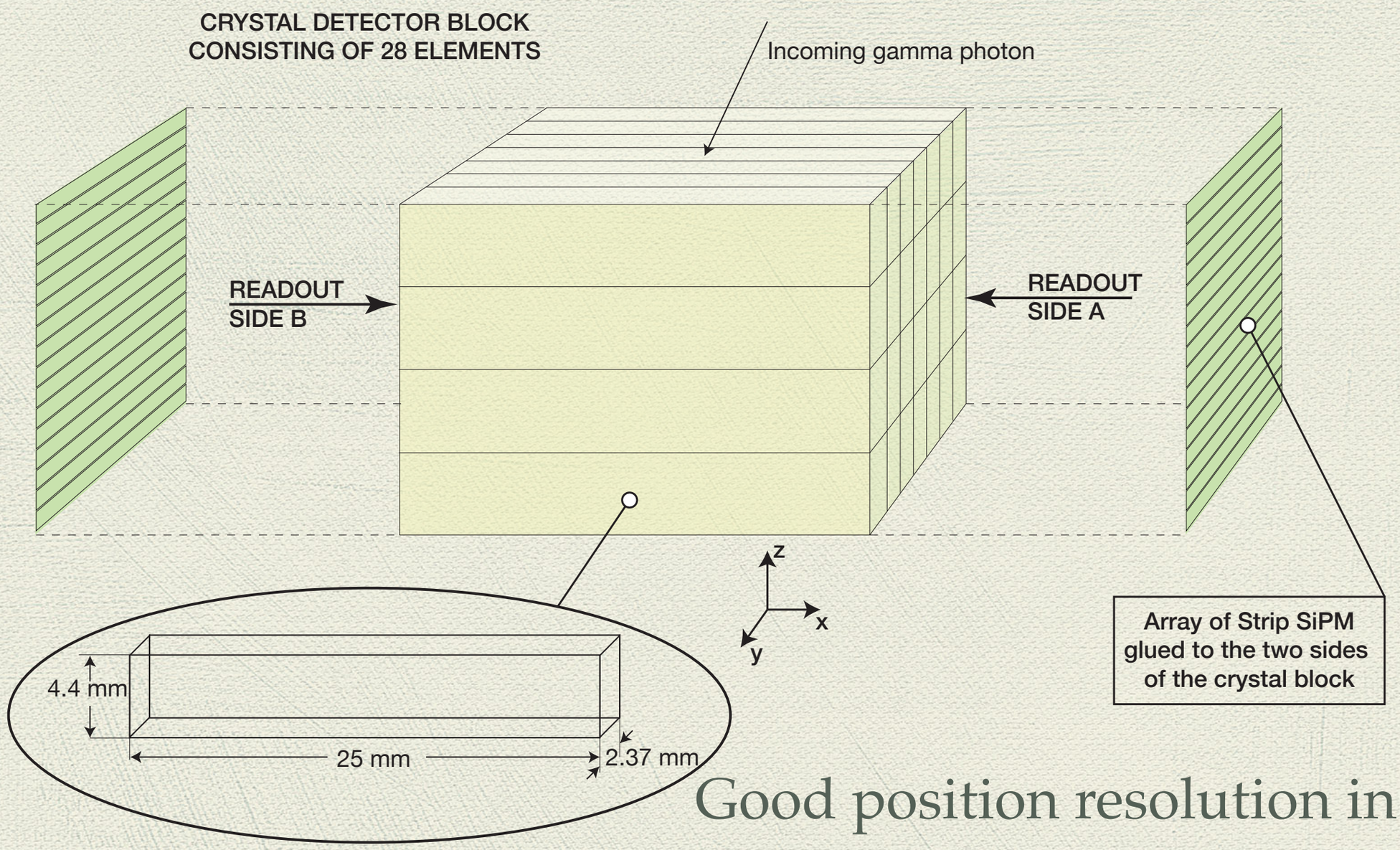


length of crystal 20 mm - so time difference if 511 keV gamma interacts at the top or bottom of the crystal CTR is > 200 ps just due to crystal length



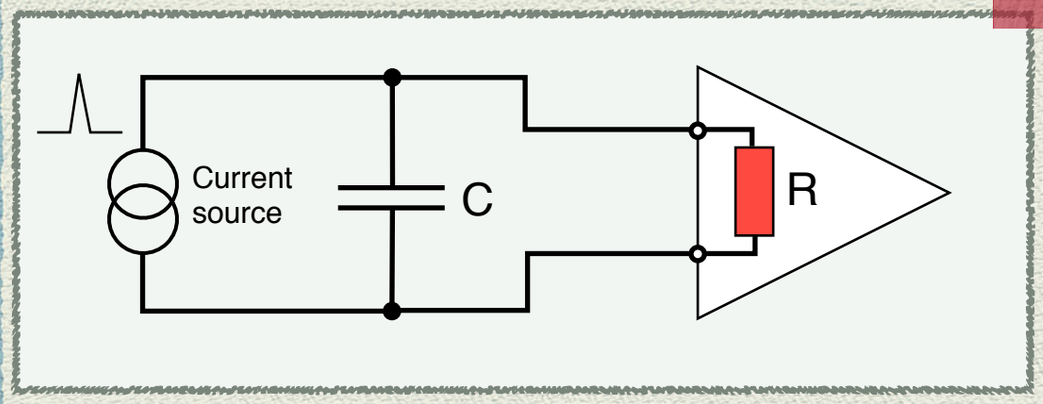
time measured on both sides: time difference gives position : average of times used for time stamp independent of position of interaction
Also: 4 independent strips on each side: algorithm for ‘best’ timing

Design of crystal block with strip SiPMs (protected by patent held by CERN/INFN)



Good position resolution in 3D
no parallax smearing

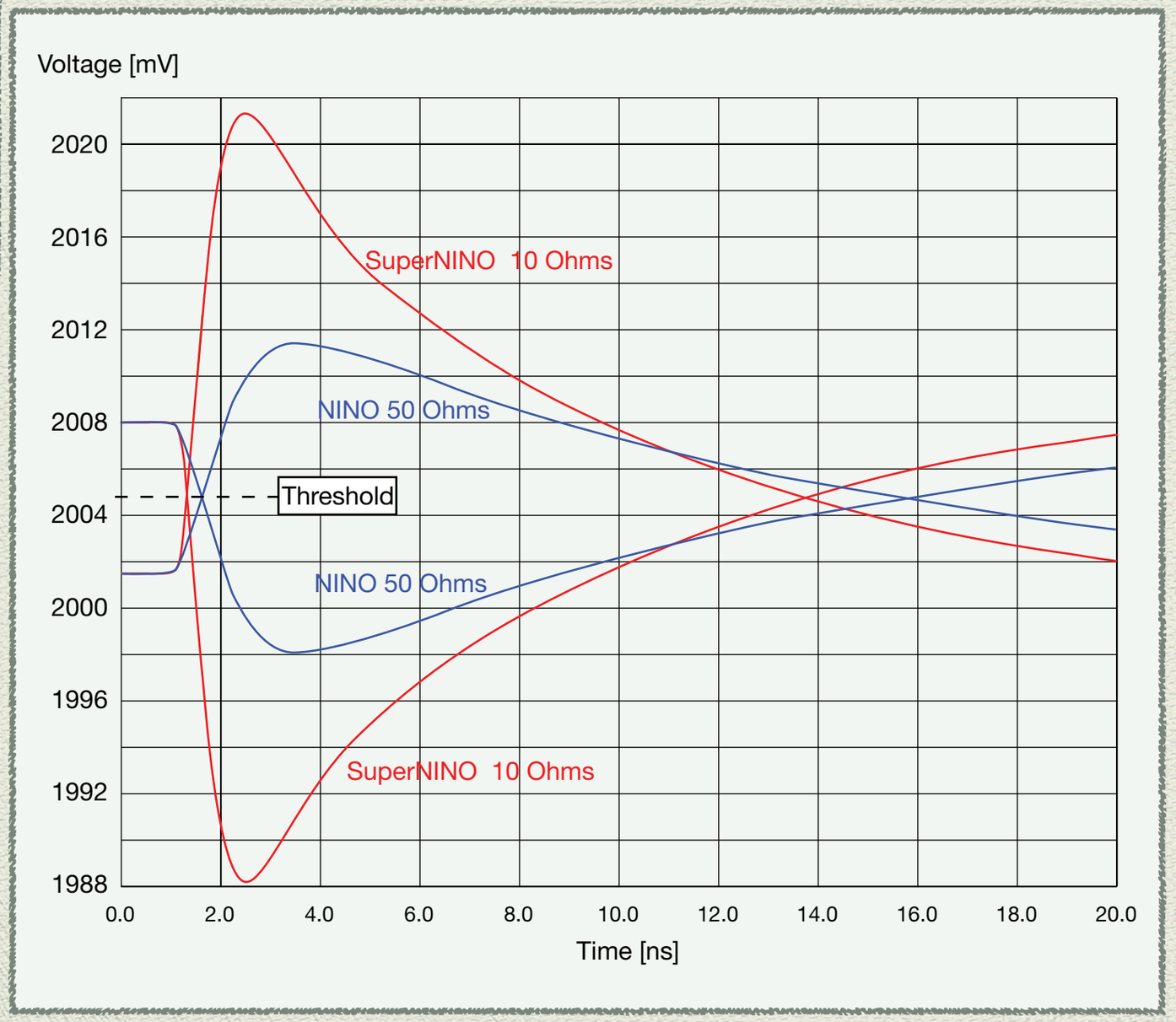
Just one slide on electronics



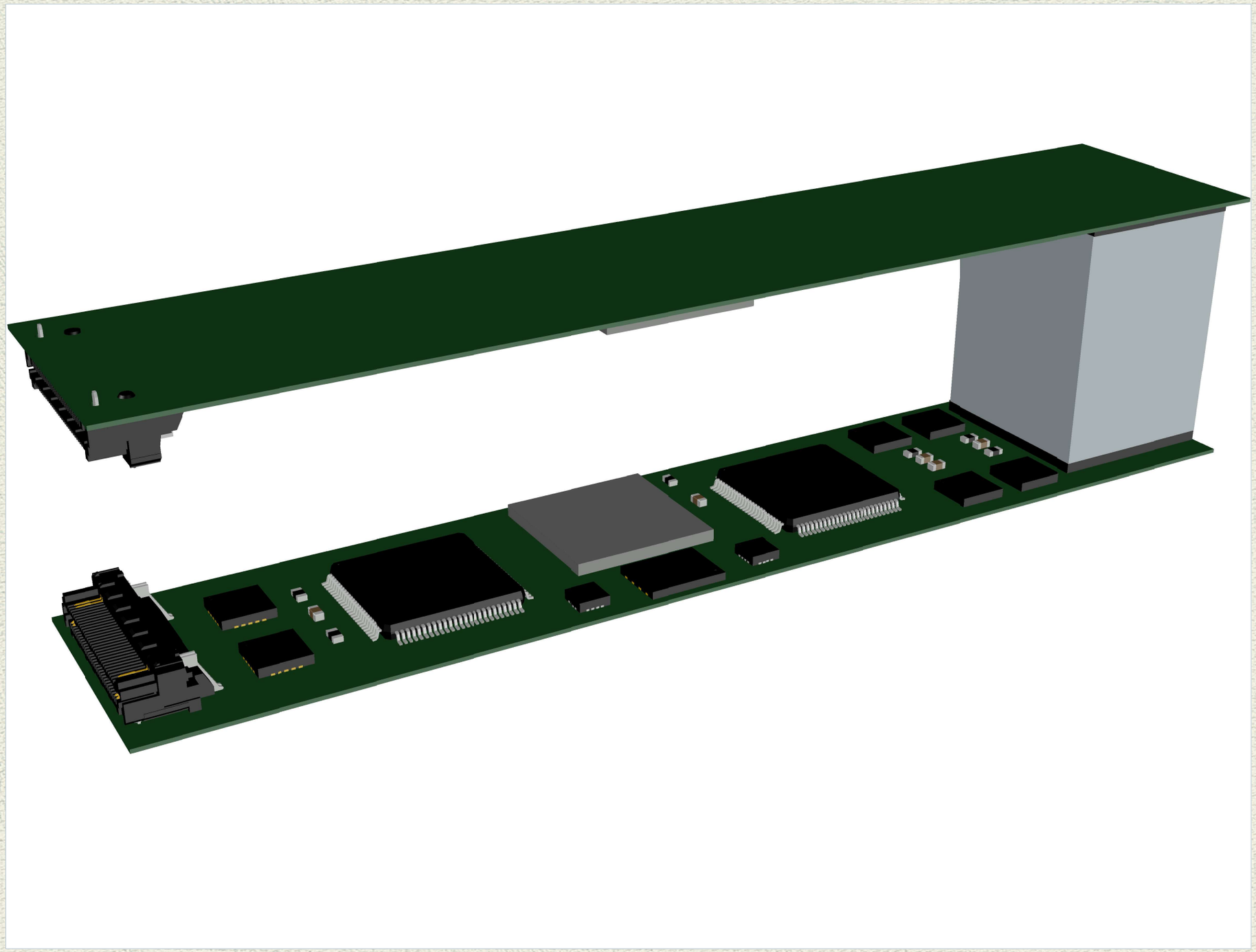
Silicon photomultiplier is a high capacity detector

Need to move charge from capacitor into the front-end electronics as quick as possible (i.e. R must be small)

Differential readout important



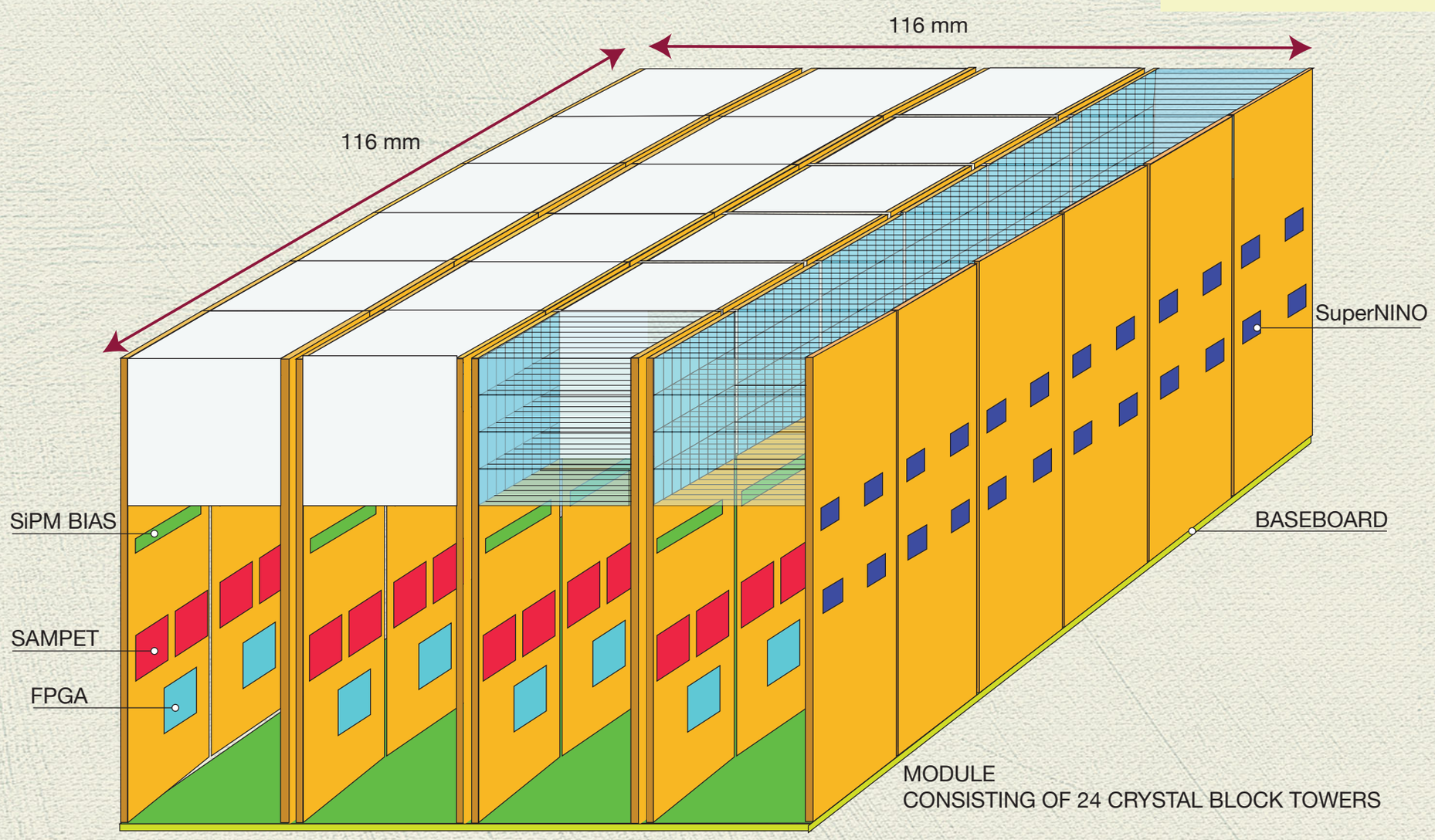
TOF PET device will be a matrix of ‘towers’
Each tower will consist of the crystal array, 2 Strip SiPM arrays
8 SuperNINOs, and 4 SAMPET asics

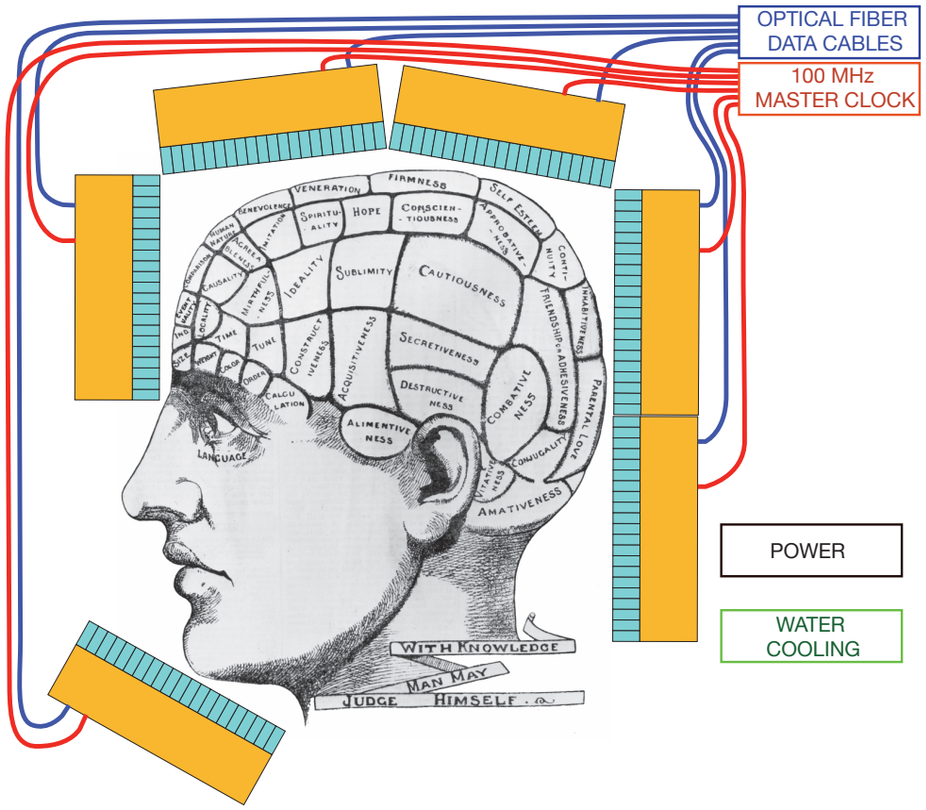


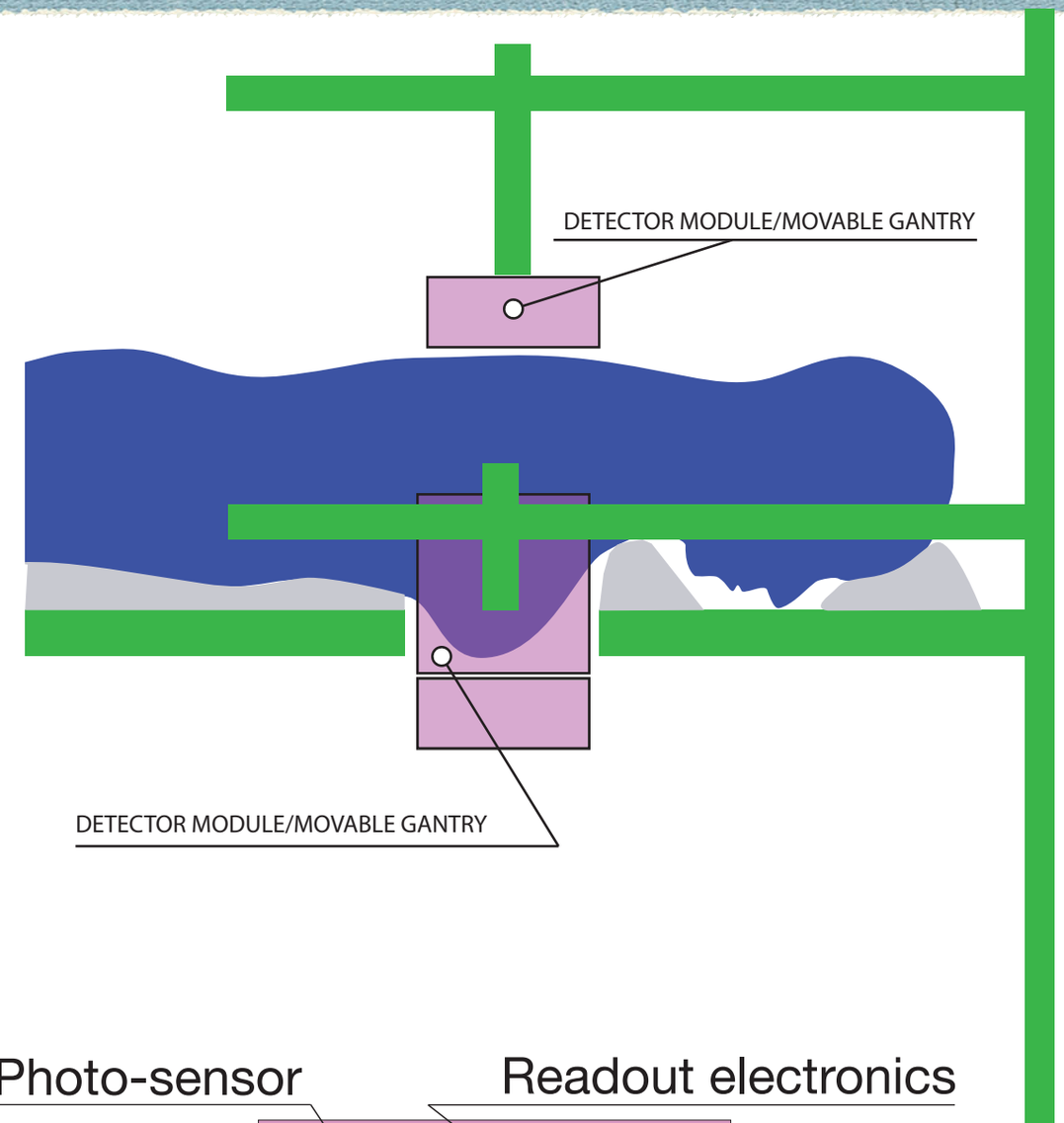
24 ‘towers’ collected together to form a module
The ‘time-stamp” and ‘energy deposit’ information processed on-module - and 5 data words produced and sent out via optical fibre.

5 word description of game interaction

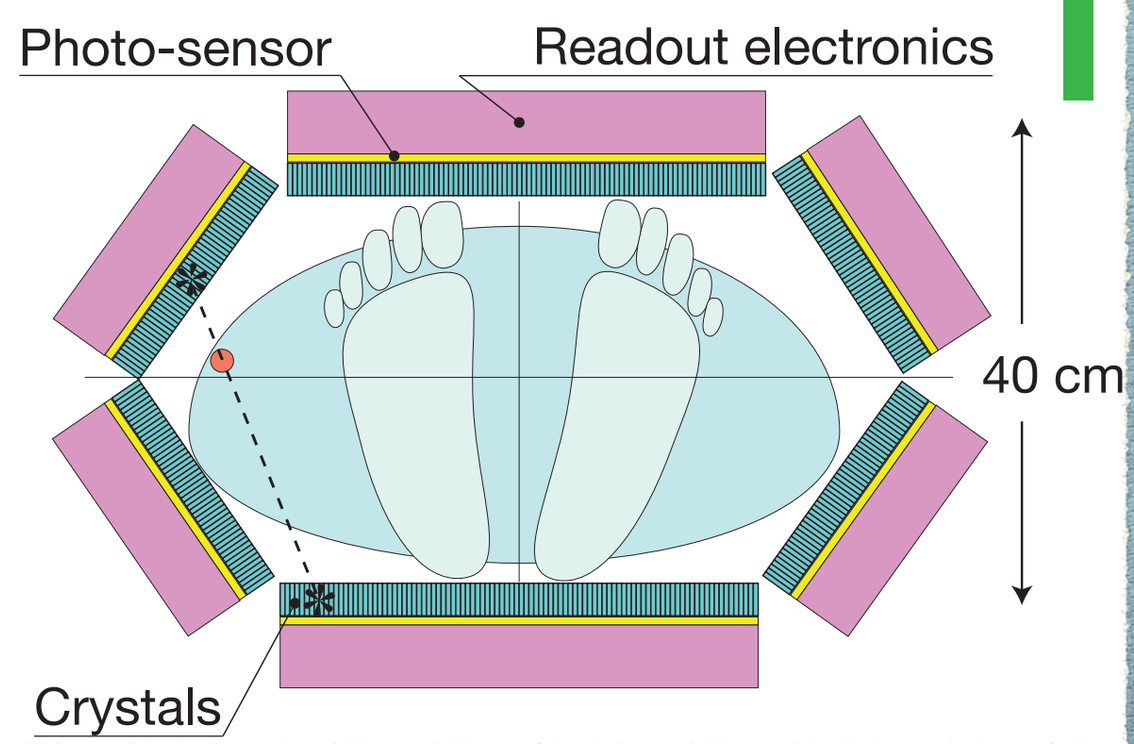
energy deposit,
3 D position
time-stamps

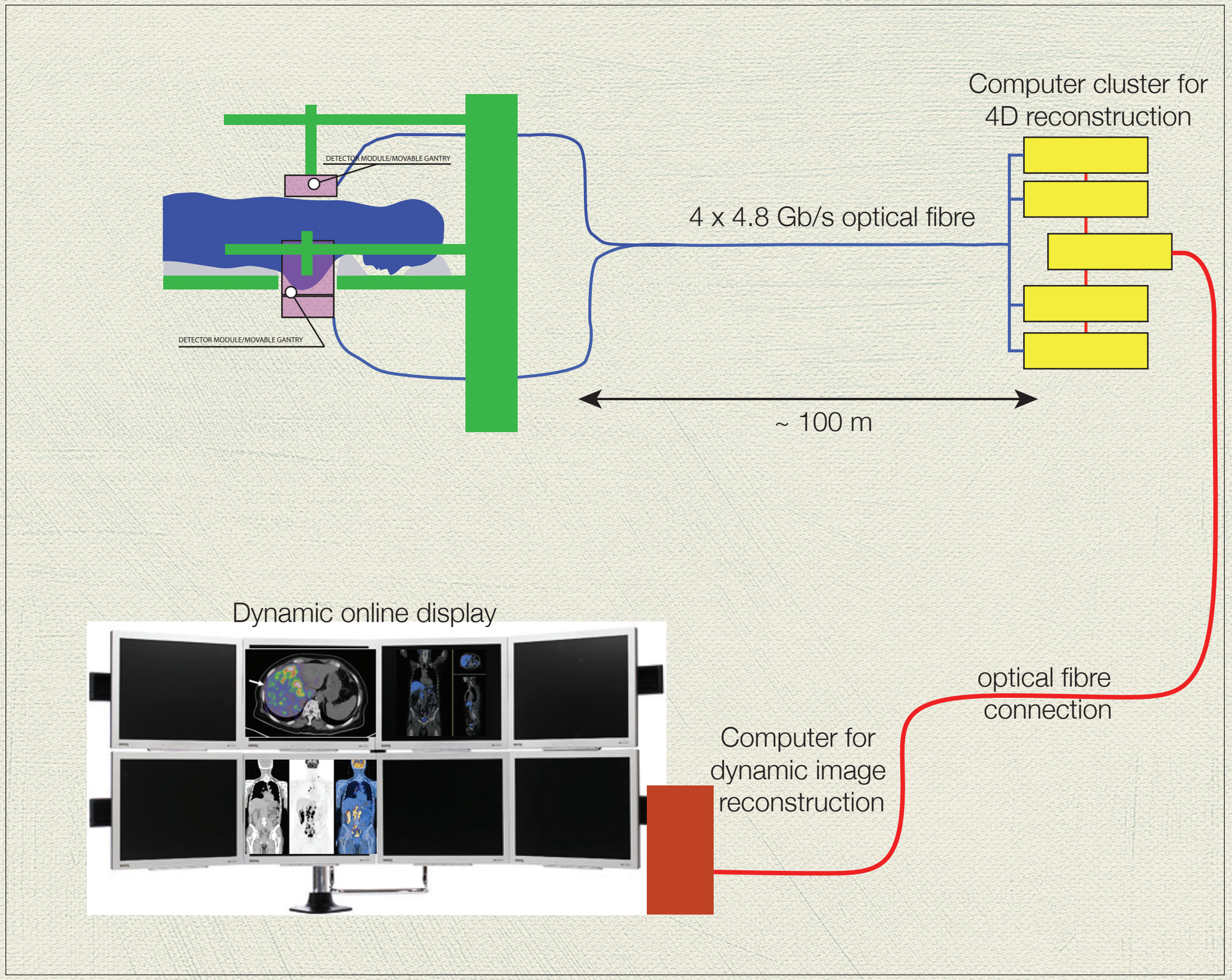






Note: the sensor modules are movable and will be positioned as close to the subject as possible; each module equipped with position sensor: reconstruction software will take care of relative positions.

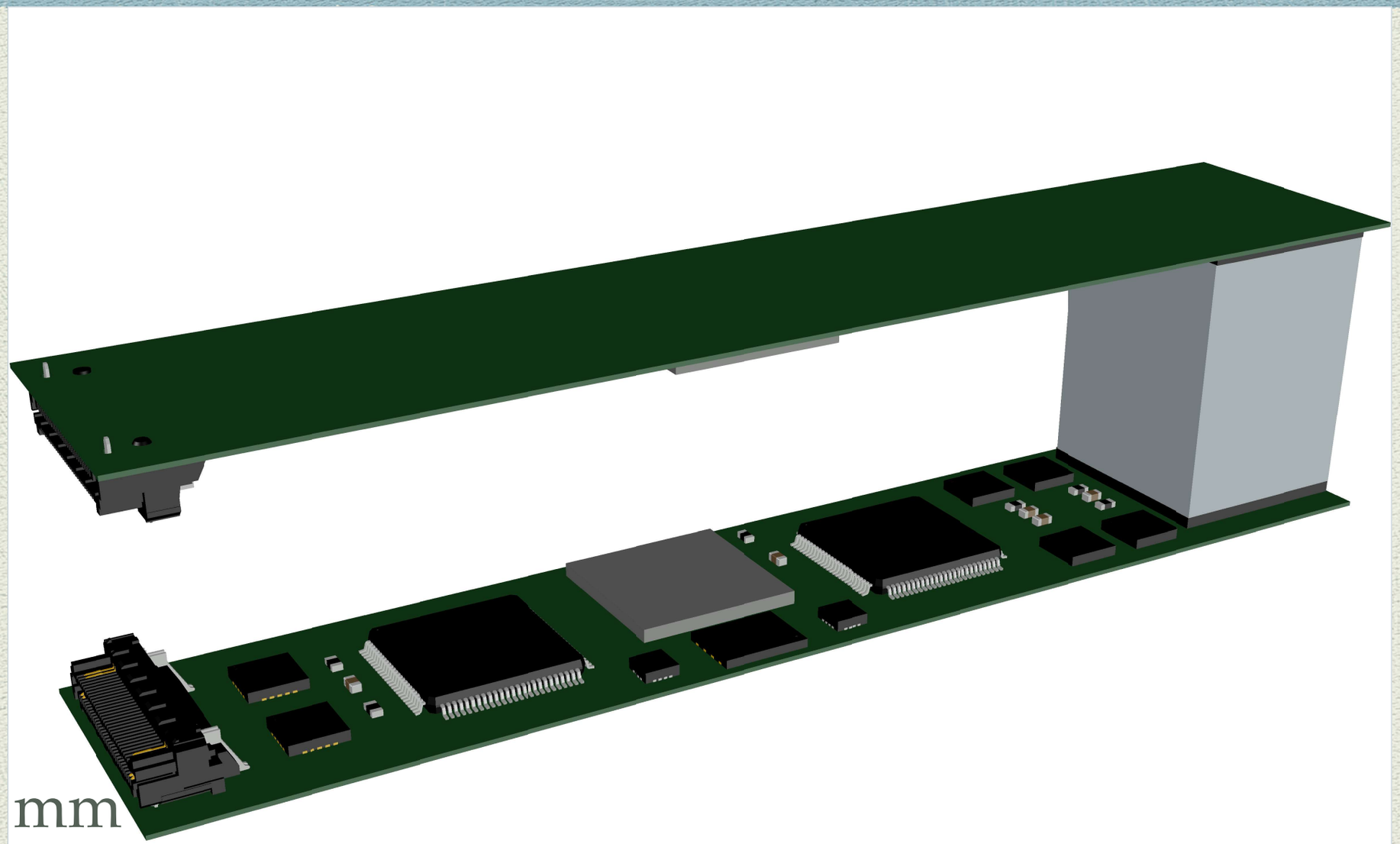



Computer cluster for
4D reconstruction
DETECTOR MODULE/MOVABLE GANTRY
DETECTOR MODULE/MOVABLE GANTRY
4 x 4.8 Gb/s optical fibre
~ 100 m
Dynamic online display
optical fibre
connection
Computer for
dynamic image
reconstruction

Disruptive technology

- This is not an incremental improvement.
- Will allow us to reach a Coincidence Time Resolution of 100 ps - there is no other proposal that could reach this limit.

Need highly compact TDC system



Each board has 32 channels of SuperNINO
and 32 channels of SAMPET

Critical parameters

- SiPMs have relatives high noise - singe SPAD firing (Dark Count Rate (DCR))
- For precise timing - need lowest possible threshold - best timing from 1st detected photoelectron
- Need TDC that is not busy all the time processing DCR (development of TOT filter for the **SAMPET** asic)
- Need TDC that can trigger on energy deposits (long time over threshold) (original SAMPIC needed two channels, 1 for leading edge, the next channel for the trailing edge) - Width measurement incorporated into single channel for the **SAMPET**.
- Need many channels - differential inputs (64 channels/asic ?)zz
- Ideally would like to incorporate time stamping within SAMPET (no external FPGA)
- Low power : is it possible to move to 65 nm technology?

Thank you for you attention