Simulating the 100μPET Scanner

Jihad Saidi

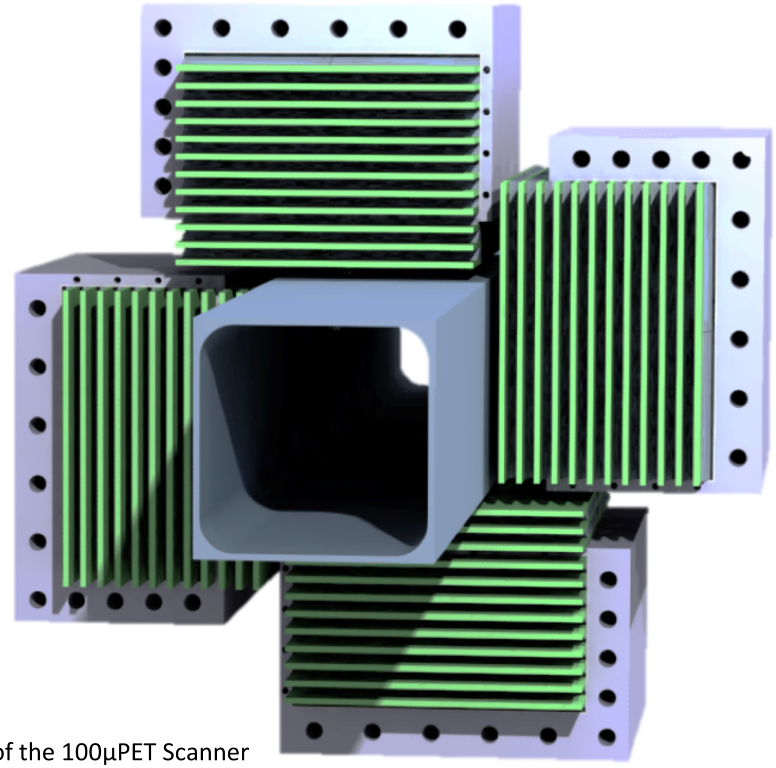
Mateus Vicente Barreto Pinto, Stefano Zambito, Giuseppe Iacobucci

3rd Allpix Squared User Workshop

10/05/2022

The 100μPET Project

- SNSF SINERGIA Funded Project with 3 institutes collaborating to deliver ultra-high resolution PET imaging
  - UNIGE, Construction of PET Scanner
  - EPFL, Development of novel imaging reconstruction algorithms
  - HUG, Clinical study of mice atherosclerosis evolution



3D Render of the 100μPET Scanner

Figure from Duclos,V et Al in Clinical Oncology. *Int. J. Mol.Sci.***2021**,*22*,4159. https://doi.org/10.3390/ijms22084159

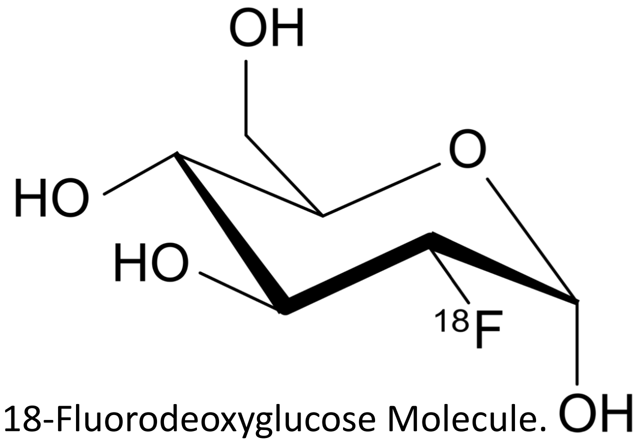
How does PET work ?

Positron
Emission
Tomography

3D reconstruction enabled by photon detection of Radioactive nuclides products

The Choice of the Radiotracer depends on the clinical focus.
^{18}F-FDG is the “GOLD STANDARD” for glucose metabolism (Oncology).

$$ {}^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + {}_{1}e^{+} + \nu_e $$



18-Fluorodeoxyglucose Molecule.
Functional analogue to classic glucose

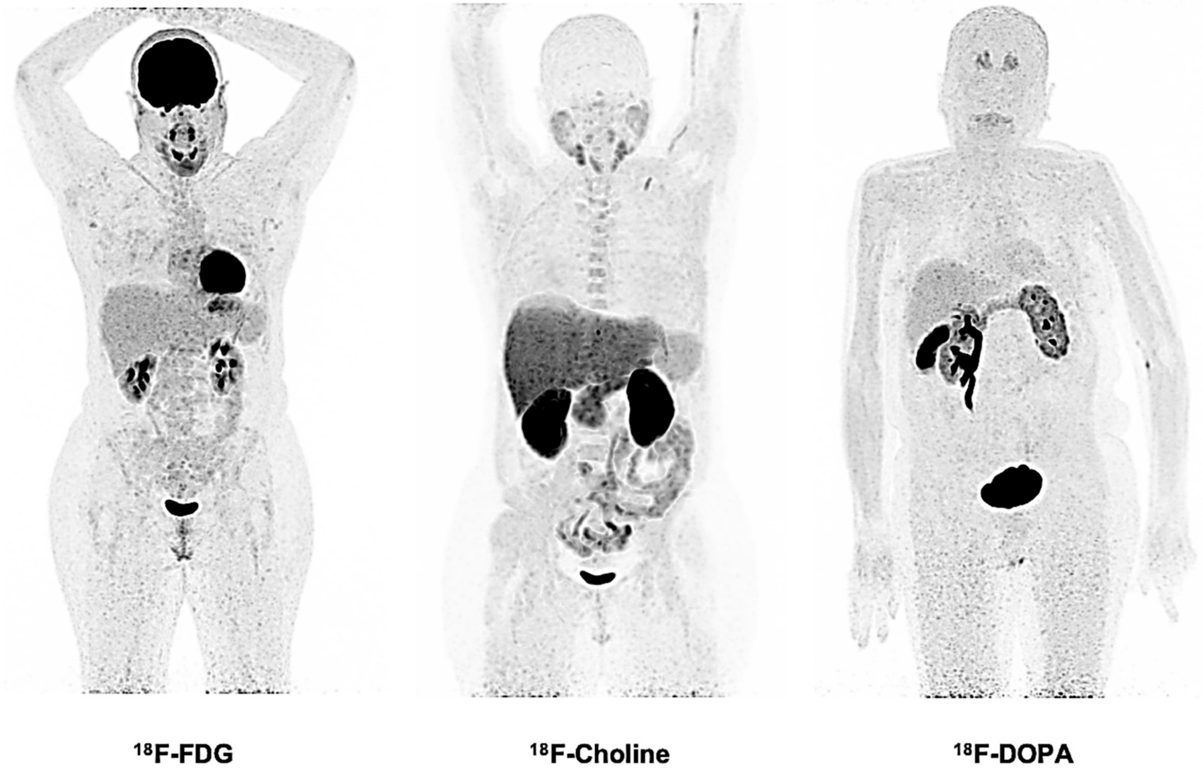


Figure from Craig S Levin and Edward J Hoffman 1999 Phys. Med. Biol. **44** 781

How does PET work ?

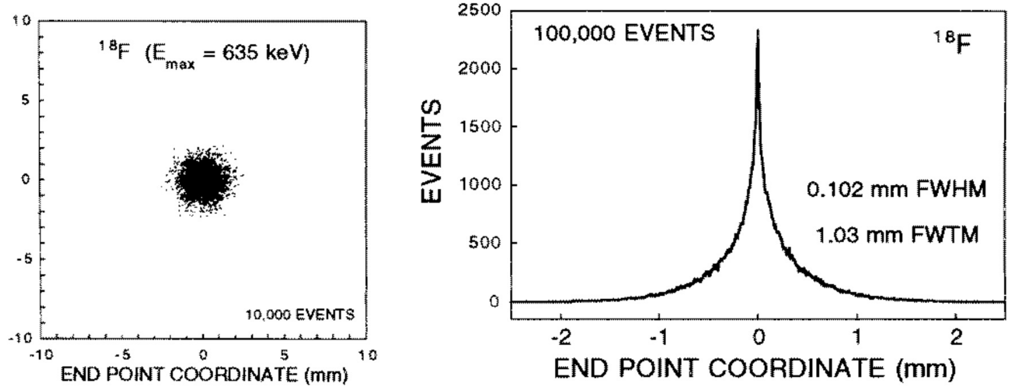
$$e^{+} + e^{-} \rightarrow \gamma + \gamma$$

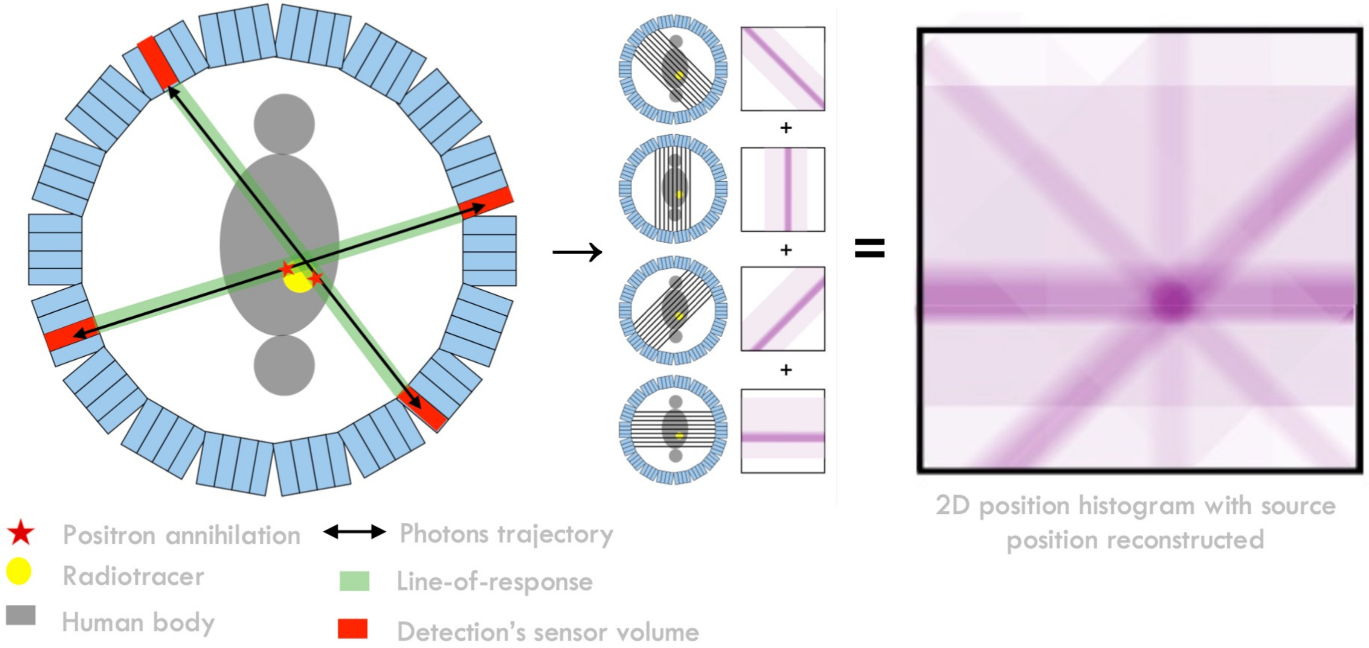
The positron travels inside the body with a given MFP before decaying with an electron.

The Pair of 511 keV photons is eventually detected, and a LOR is established.

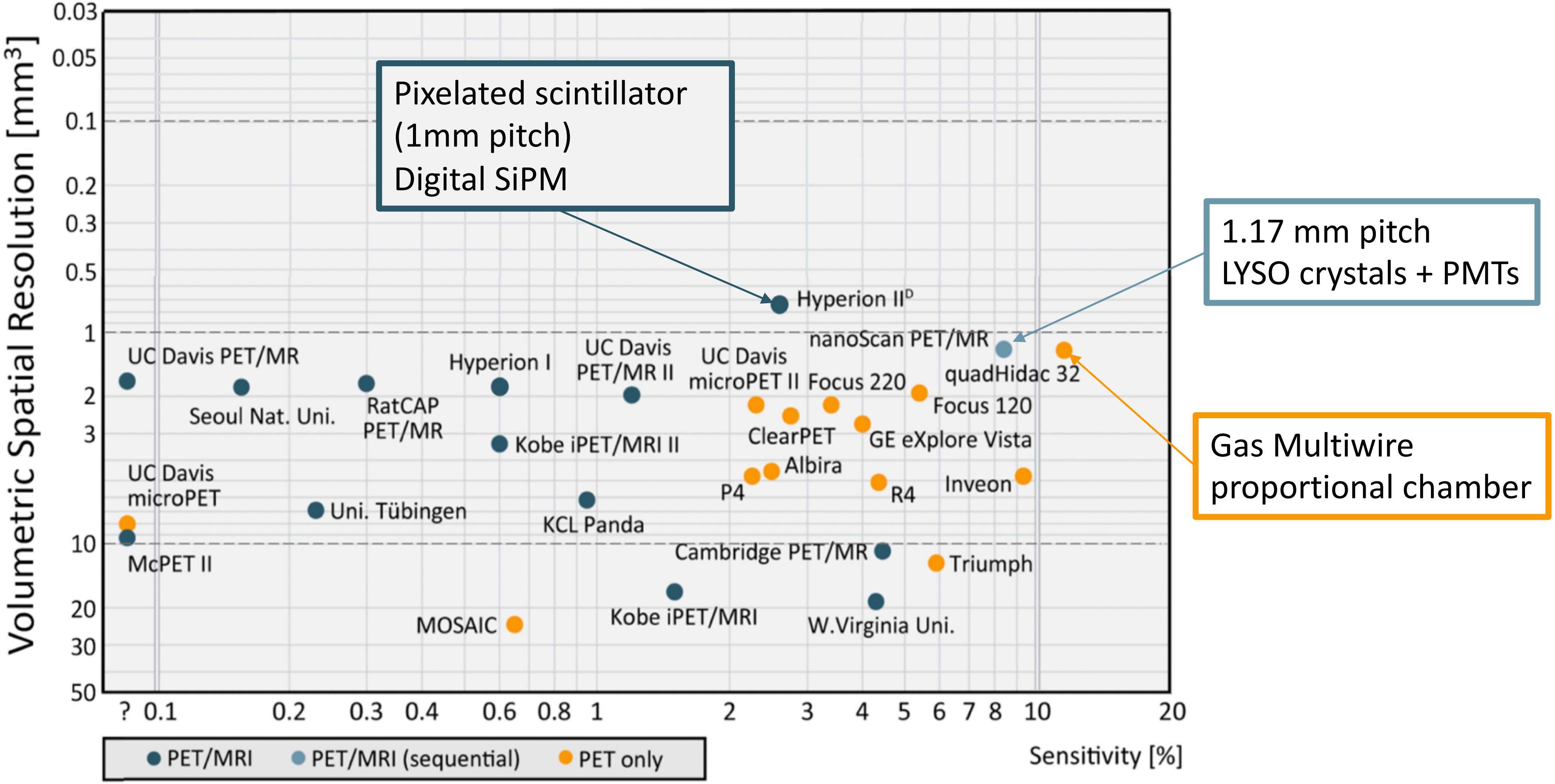
The combination of multiple detections allows to locate and quantify radiotracer's depositions.

Further Processing of coincidences data allows reconstruction. (e.g. Sinograms)





Current PET scanner landscape



100μPET simulations with Allpix Squared

Allpix Squared makes it easier to change specific parameters in simulation.

- Scanned Parameters in Allpix Squared Simulations:
  - Material Budget (Bi/Pb effect on efficiency)
  - Pixel Pitch (100μm vs 200μm or more?)
  - Active silicon thickness (are 250μm enough?)

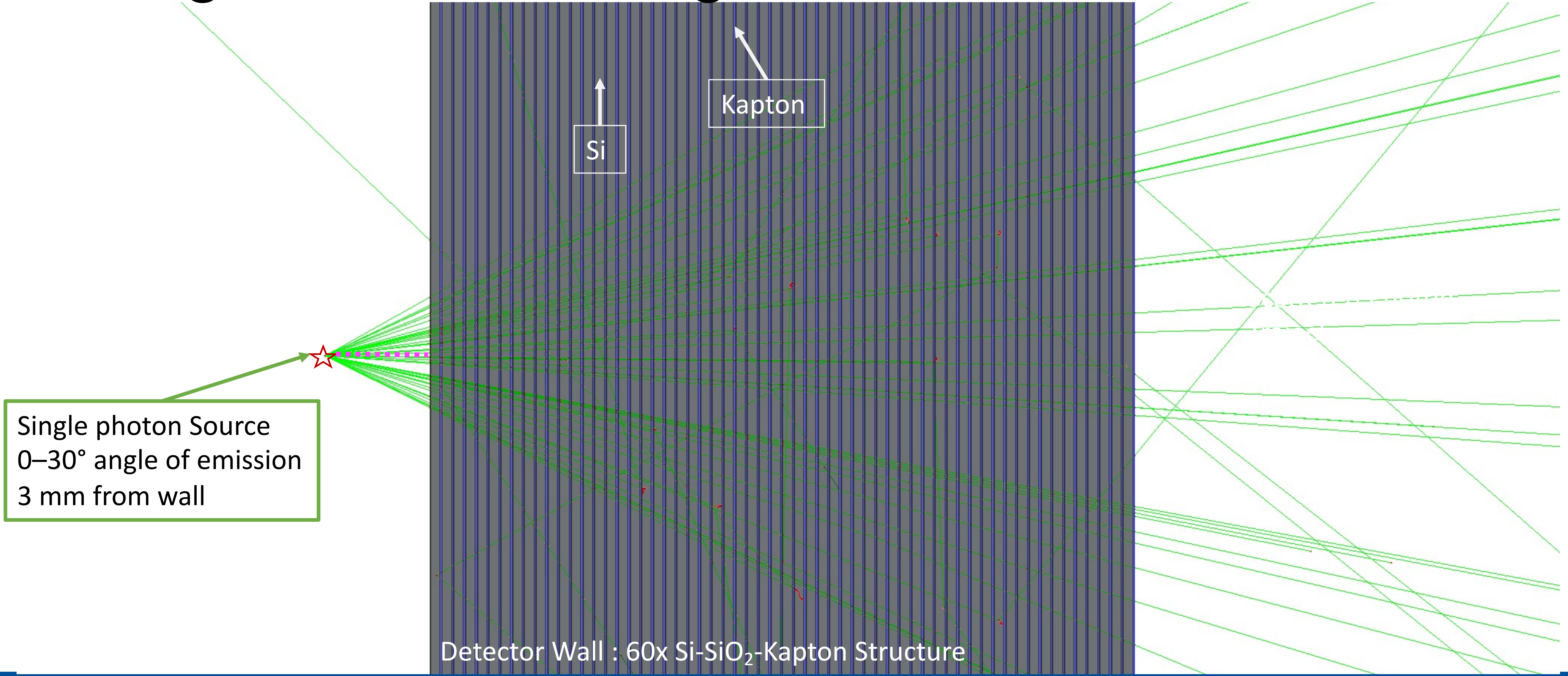
- Figure of Merit evaluated:
  - Detection Efficiency
  - "Reconstructed LOR" resolution

AP2 Team enabled us to get two new features :

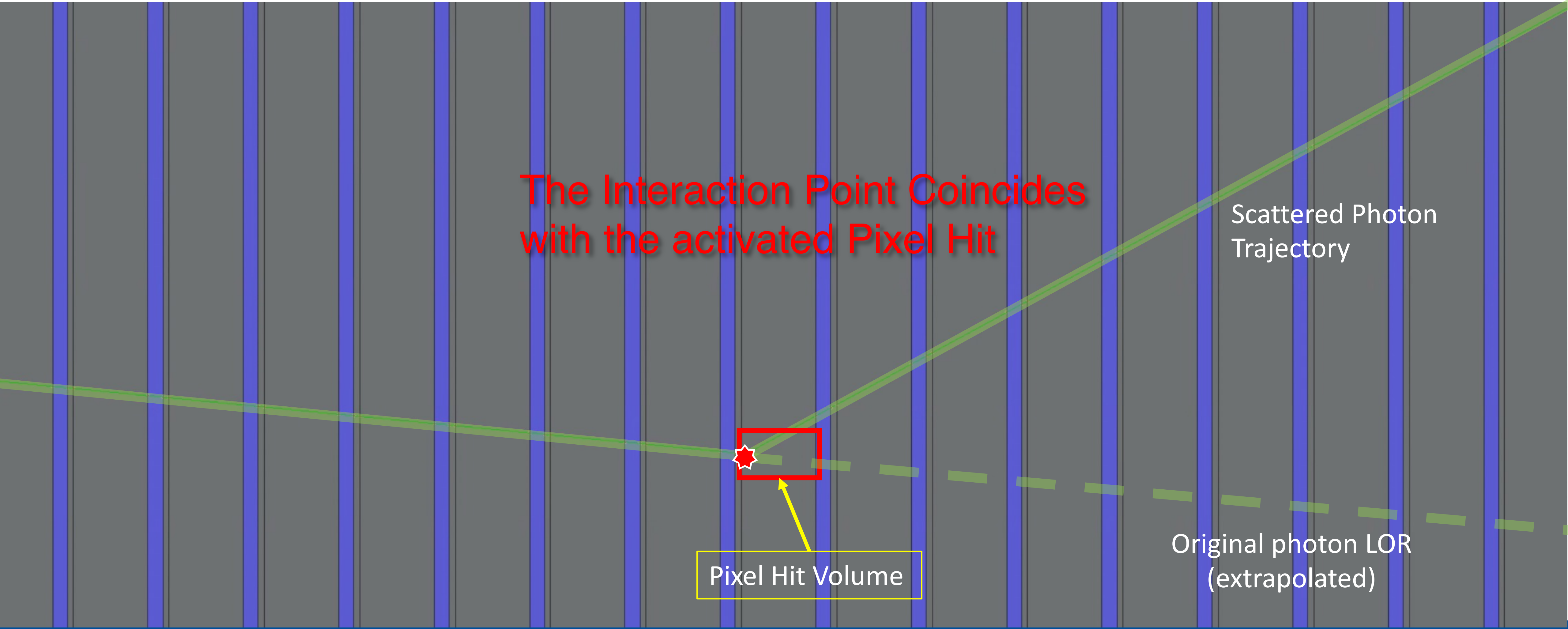
-Tracking of particles within passive world elements

-End Volume Name and Timing information for MC Tracks

Single Wall Tracking resolution – Definitions



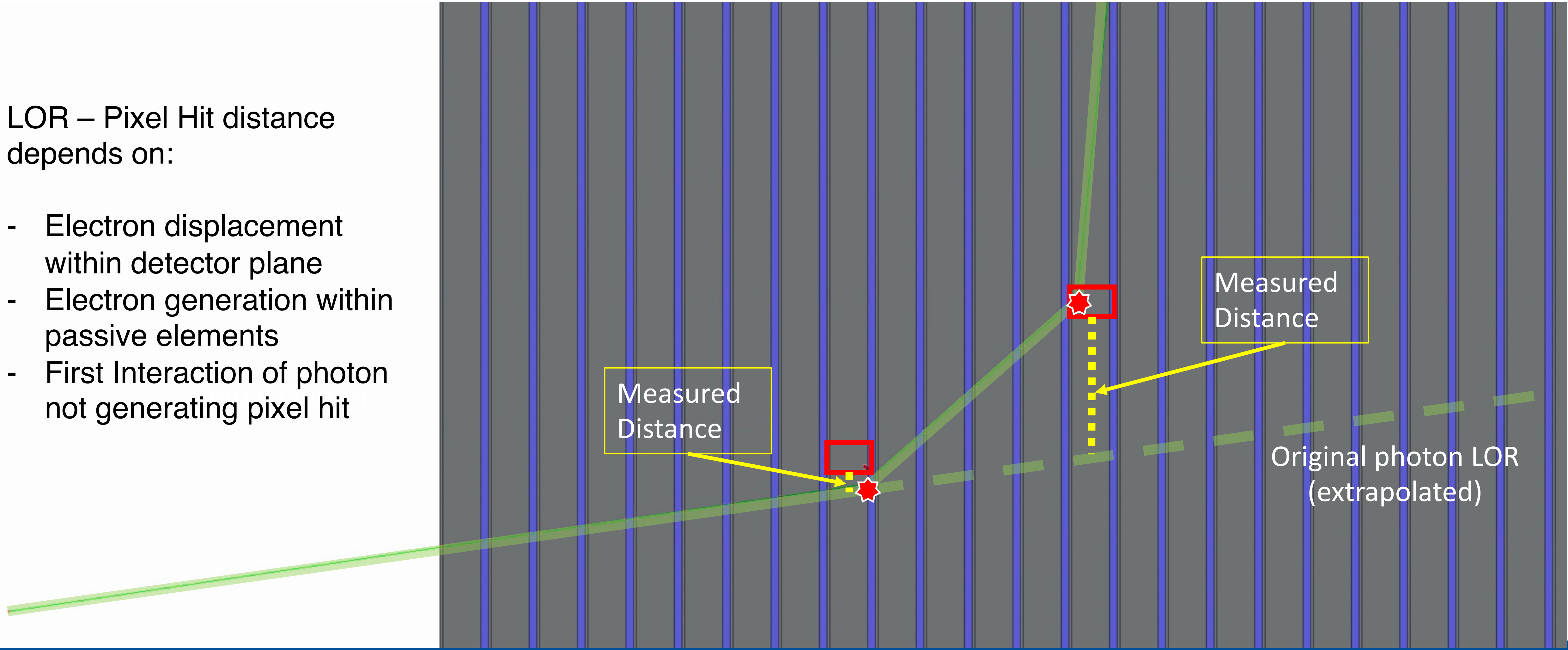
Single Wall Reconstructed LOR resolution – Definitions



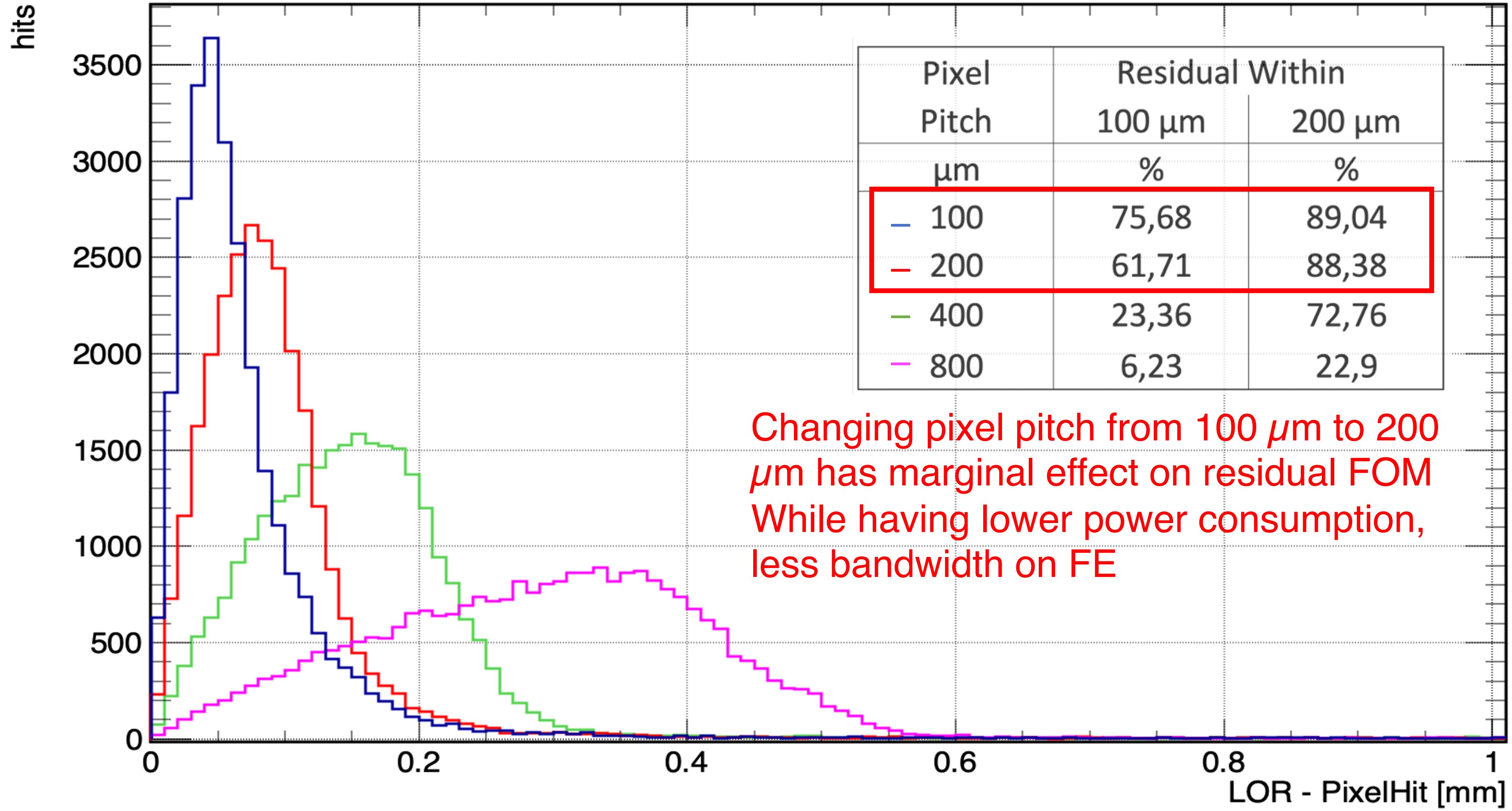
Single Wall Reconstructed LOR resolution – Definitions

LOR – Pixel Hit distance depends on:

- Electron displacement within detector plane
- Electron generation within passive elements
- First Interaction of photon not generating pixel hit



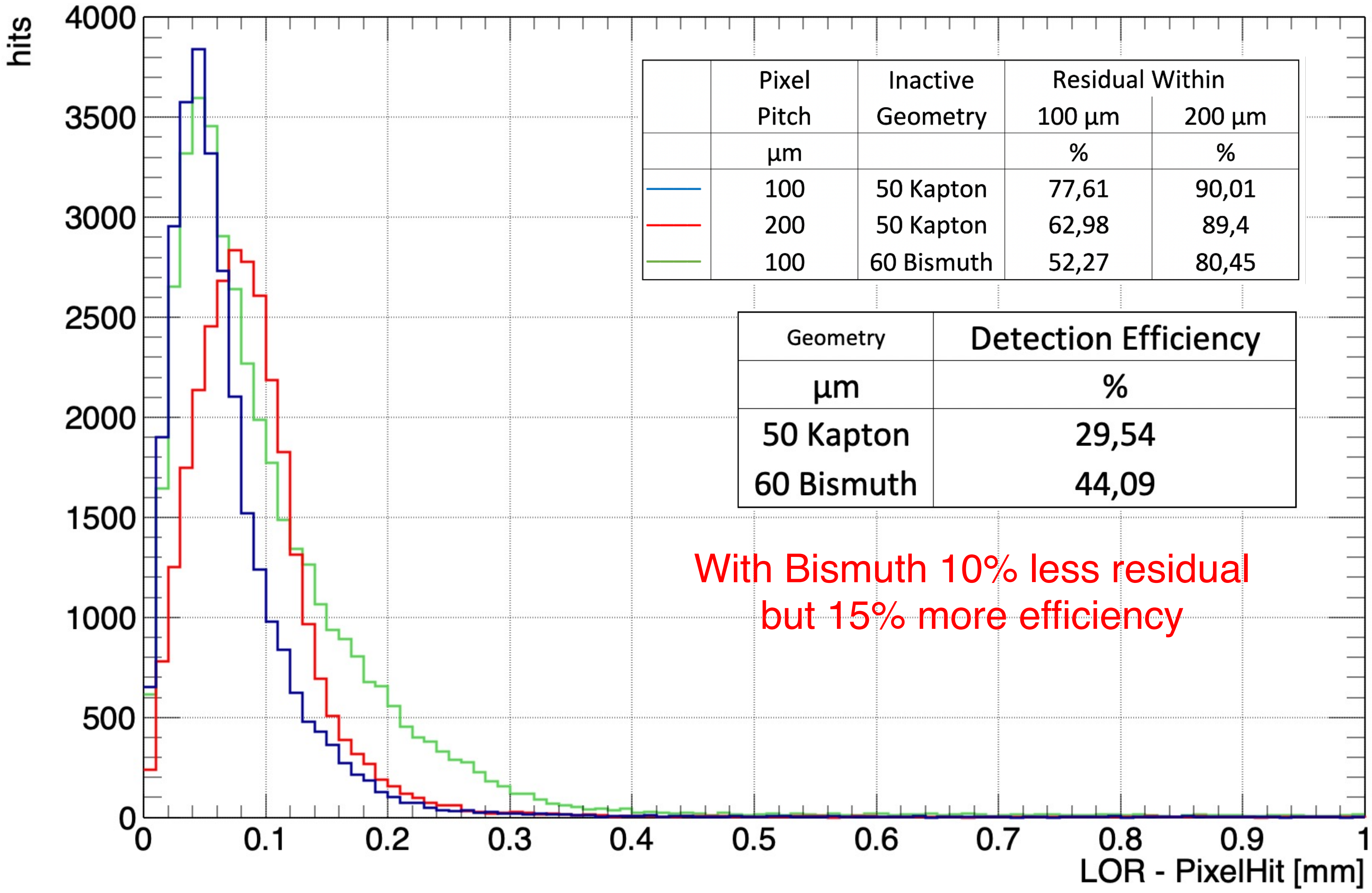
Effect of Pixel Pitch on Reconstructed LOR Resolution



Pixel Pitch µm	Residual Within 100 µm %	Residual Within 200 µm %
100	75,68	89,04
200	61,71	88,38
400	23,36	72,76
800	6,23	22,9

Changing pixel pitch from 100 μm to 200 μm has marginal effect on residual FOM While having lower power consumption, less bandwidth on FE

Effect of photon absorber



	Pixel Pitch	Inactive Geometry	Residual Within 100 µm	Residual Within 200 µm
	µm		%	%
(blue)	100	50 Kapton	77,61	90,01
(red)	200	50 Kapton	62,98	89,4
(green)	100	60 Bismuth	52,27	80,45

Geometry	Detection Efficiency
µm	%
50 Kapton	29,54
60 Bismuth	44,09

With Bismuth 10% less residual but 15% more efficiency

Is the trade off in reconstructed LOR resolution compensated with higher efficiency ?

These FOM might not be enough to characterize full detector performance.

We build up from this with full detector simulation!

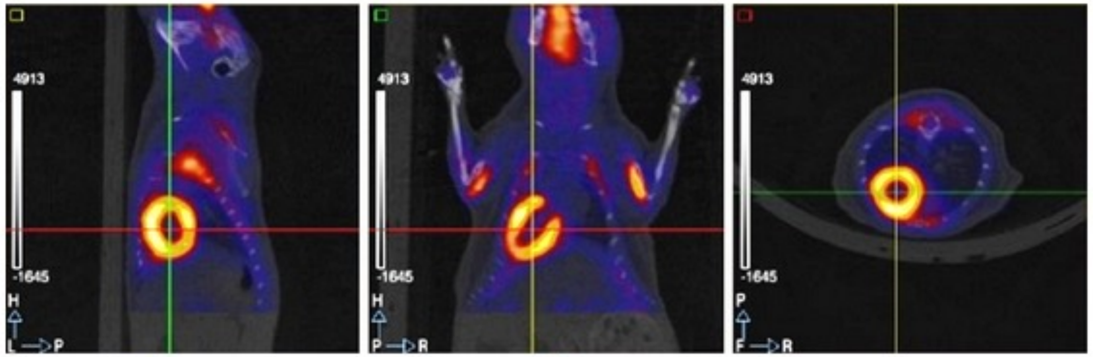
Figure from Gargiulo, Sara et al. In Journal of biomedicine & biotechnology vol. 2012 (2012): 541872. doi:10.1155/2012/541872

Initial full detector simulation

Simulating the full scanner and physics is challenging, we start from simplified case of the full detector

Simplified conditions:

- Positron generated with no kinetic energy
- Generated at fixed position (Detector's center)



FDG cardiac PET/CT in a normal mouse that highlight the distribution of radiotracer on an irregular volume

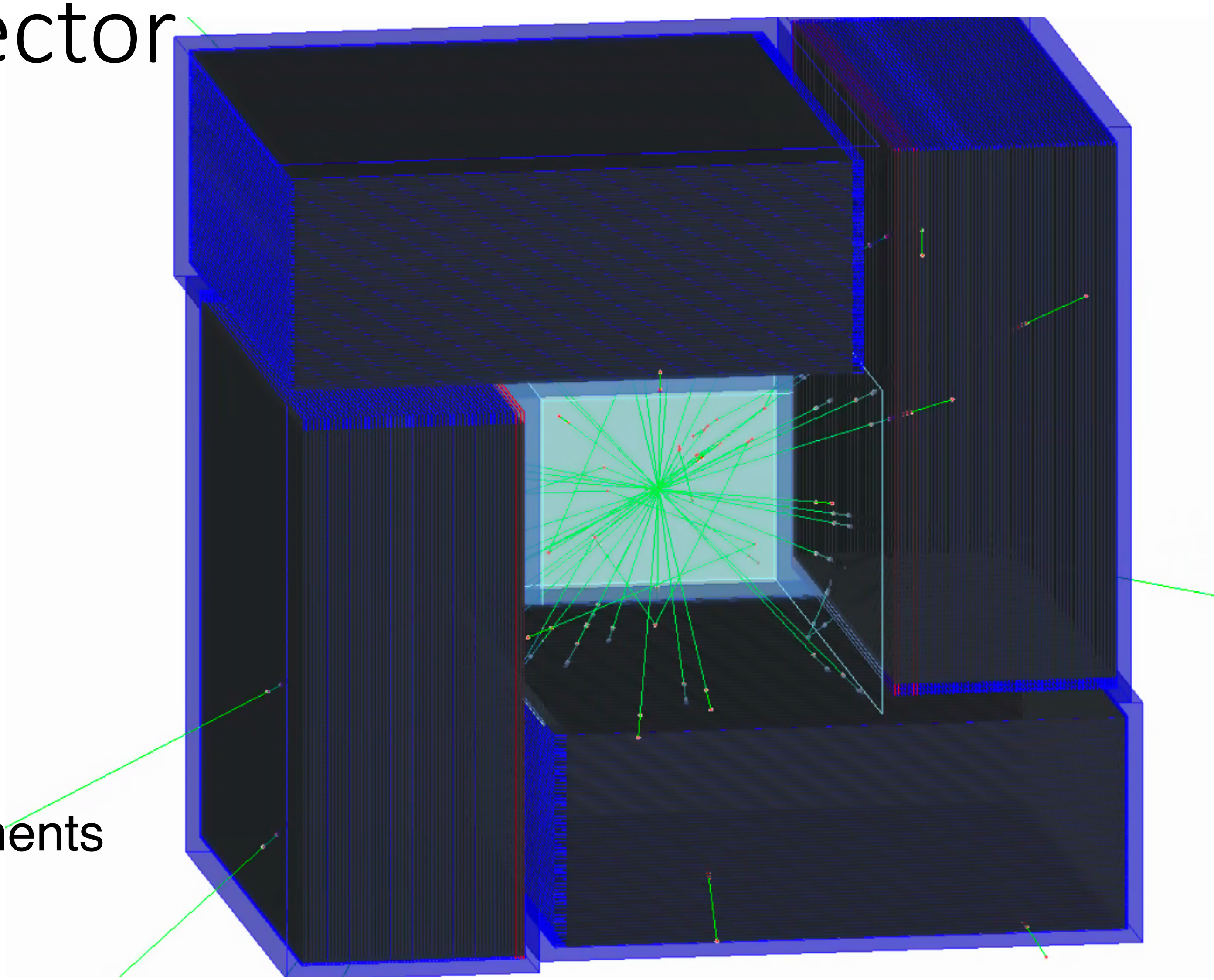
→ Gain knowledge on simplified simulation

→ find efficient strategies to apply on complex situations (no information on source's distribution)

Simulated 100µPET Detector

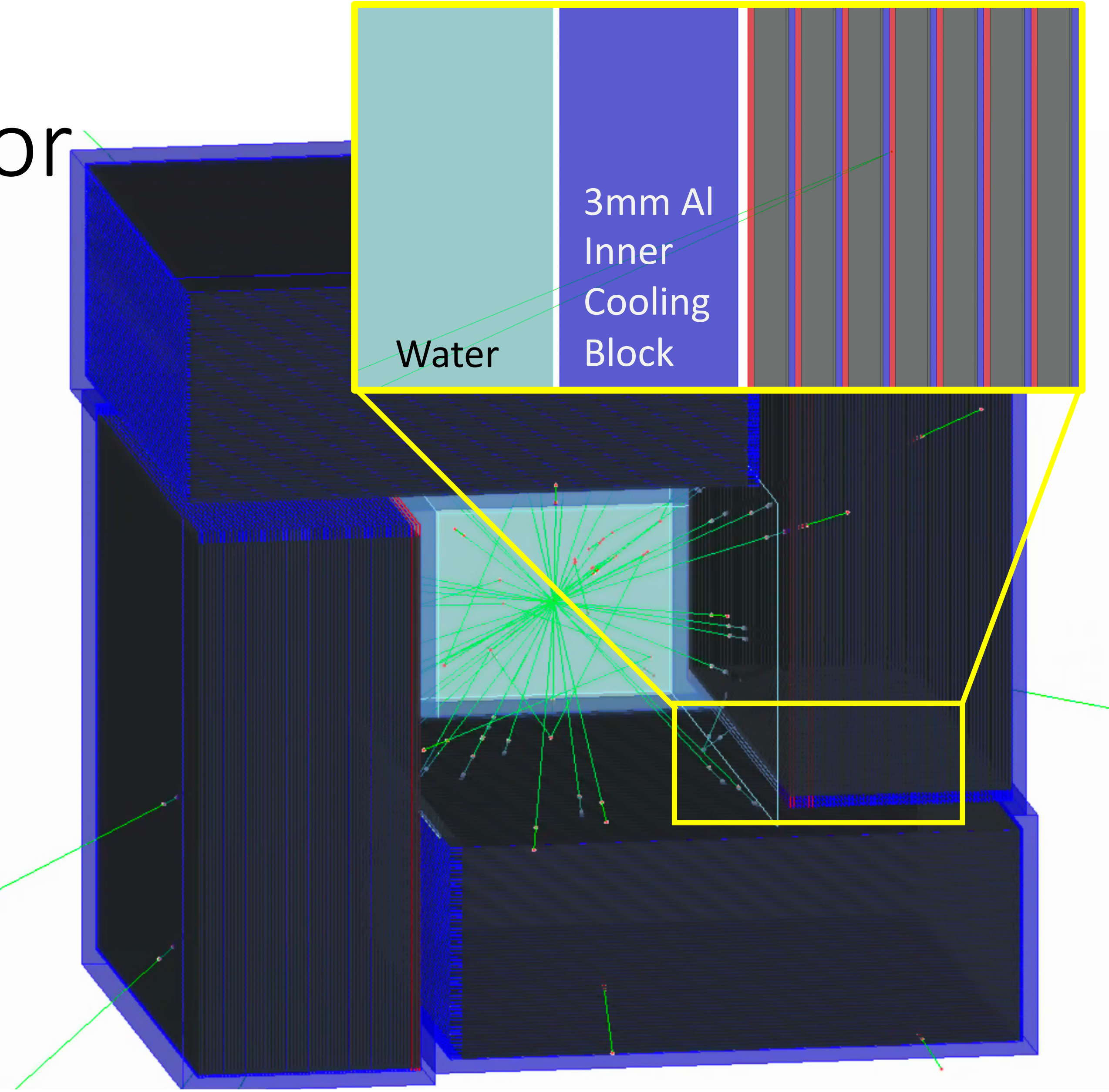
- 34 mm side detector's inner cavity
- 4 Sectors
- 60 Detection layers per sector
- 1 Chip per layer (50 x 60 mm)
- 250 μm Active Silicon, 20 μm SiO_2, 50 μm Kapton, 60 μm Bi
- 34 mm side Inner cavity filled with Vacuum/Air/Water

- Geometry Built with C++ Macro, Output made of 2900+ Lines Available on GIT for review and improvements

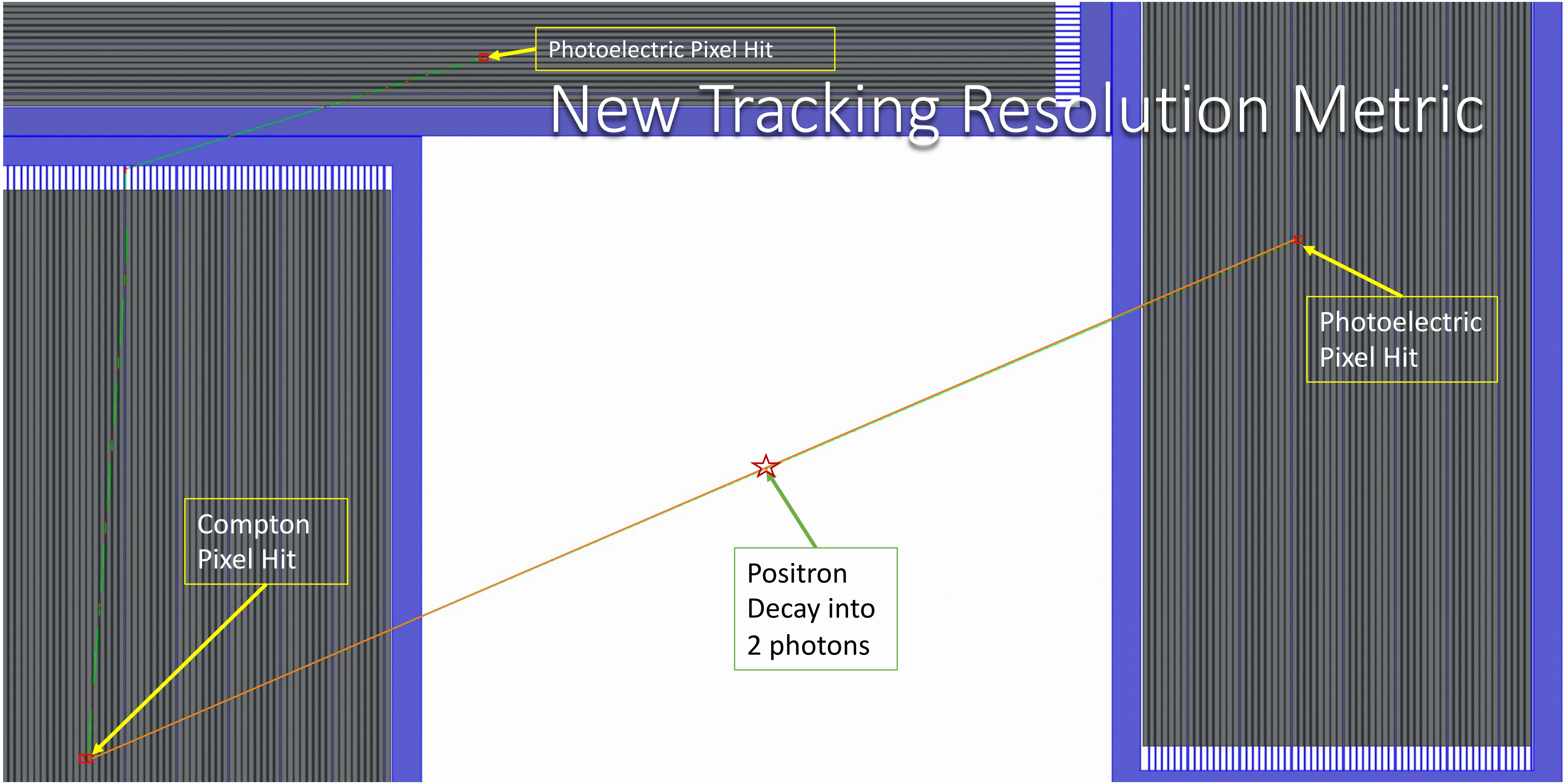


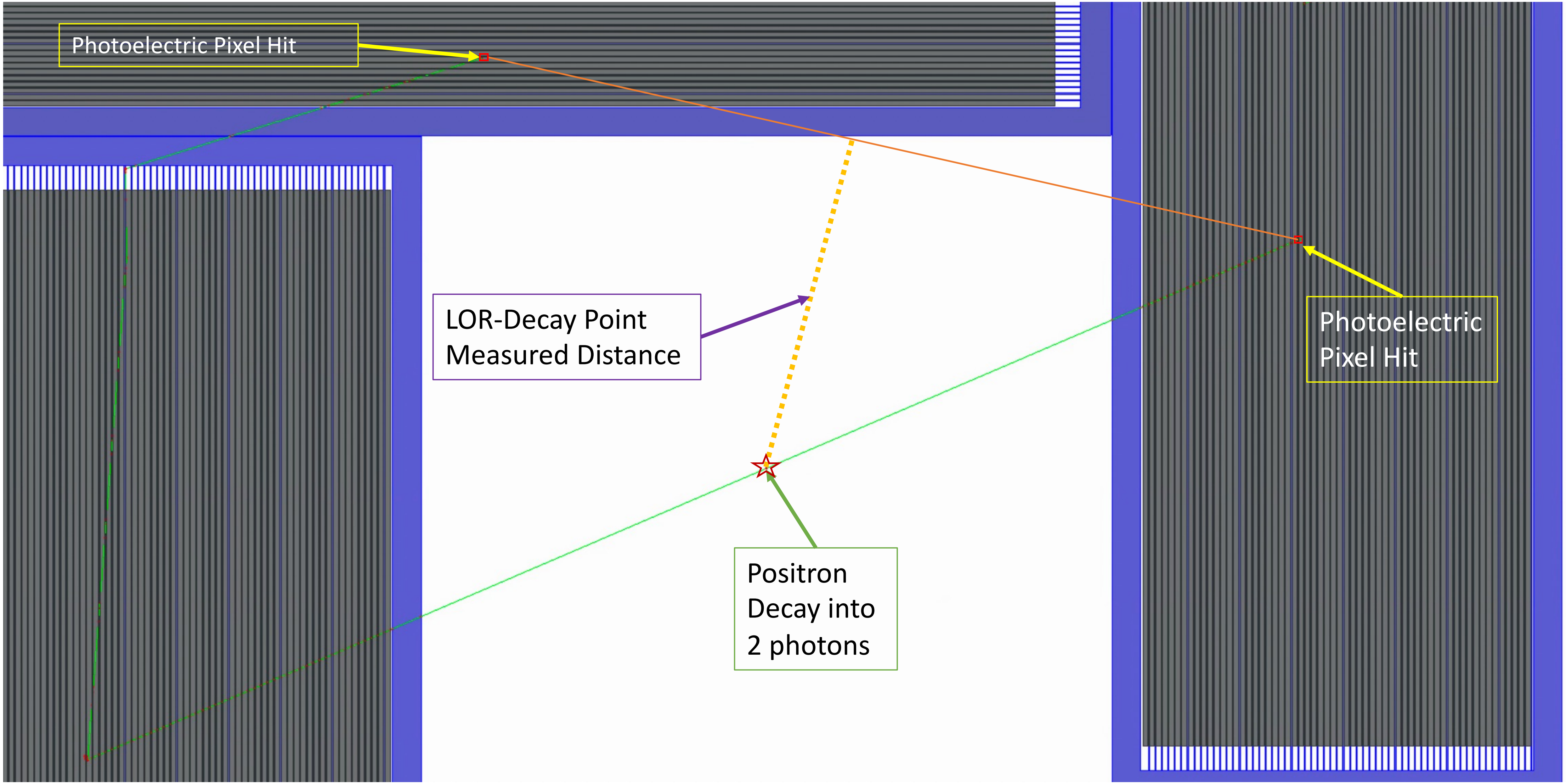
Simulated 100µPET Detector

- 34 mm side detector's inner cavity
- 4 Sectors
- 60 Detection layers per sector
- 1 Chip per layer (50 x 60 mm)
- 250 μm Active Silicon, 20 μm SiO_2, 50 μm Kapton, 60 μm Bi
- 34 mm side Inner cavity filled with Vacuum/Air/Water
- Geometry Built with C++ Macro, Output made of 2900+ Lines Available on GIT for review and improvements

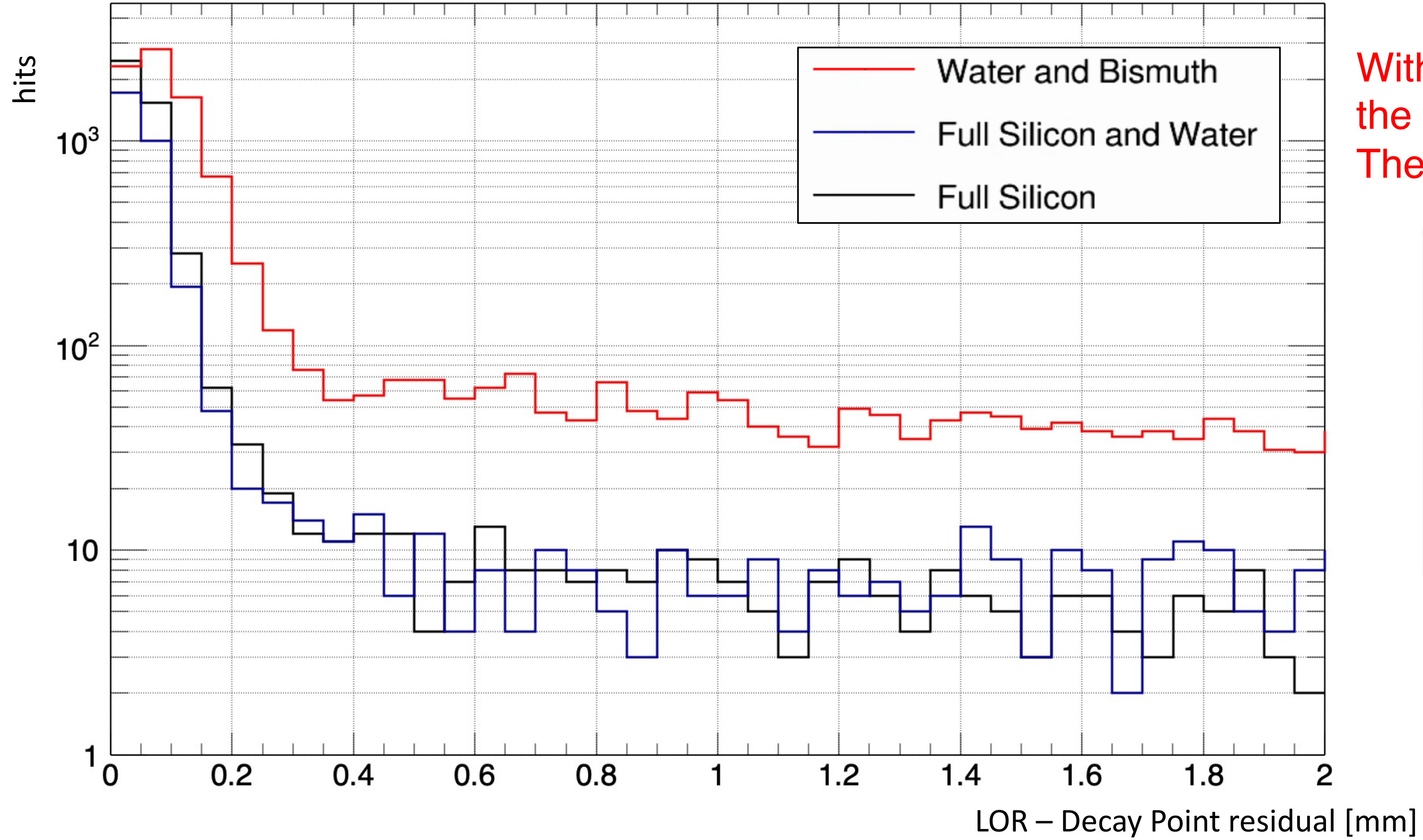


New Tracking Resolution Metric




Photoelectric Pixel Hit
LOR-Decay Point
Measured Distance
Photoelectric
Pixel Hit
Positron
Decay into
2 photons

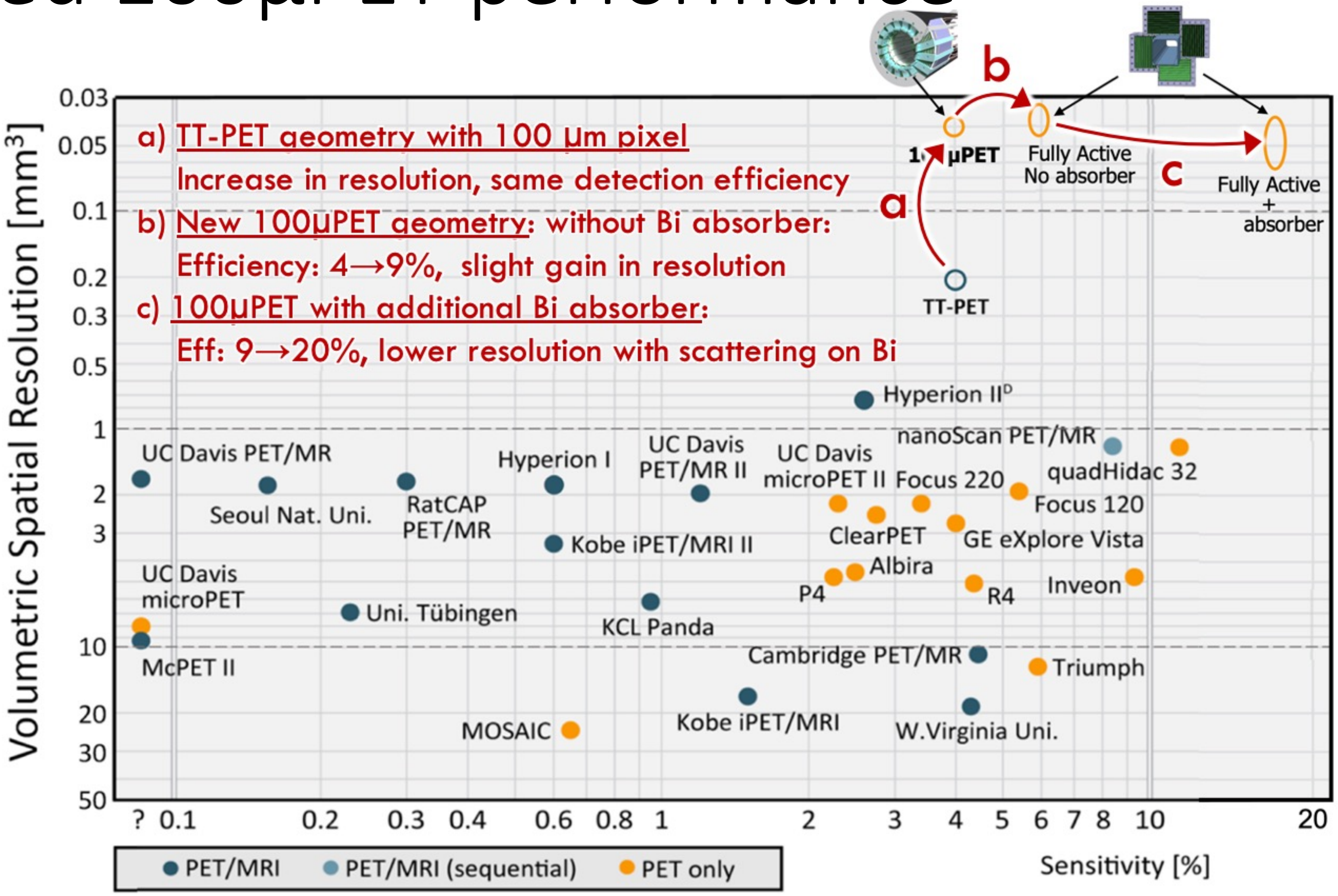
LOR – Decay point Residual



With Bismuth added
the loss in residual is only 7%
The gain in 2-photon efficiency is 11%

Configuration	Residual within 200 µm
	%
Si	78,78
Si + H2O	61,05
Si + H2O + Bi	54,34

Expected 100μPET performance

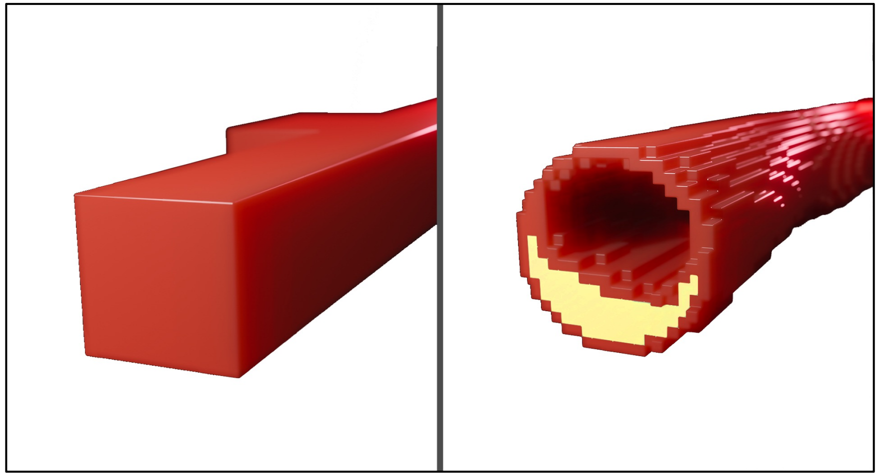


Conclusion

With Allpix team we were able to assess detector performance

100μPET scanner is expected to reach:

- Up to 9% (20% with Bi) Sensitivity
- Down to 0.07 mm^3 Volumetric spatial resolution



With today's PET technology, small blood vessels can only be visualized in their entirety (A).
The new 100µPET performance will allow the study of changes in the lining of small blood vessels, such as atherosclerotic plaques (B).
Images: © Xavier Ravinet - UNIGE

Next steps

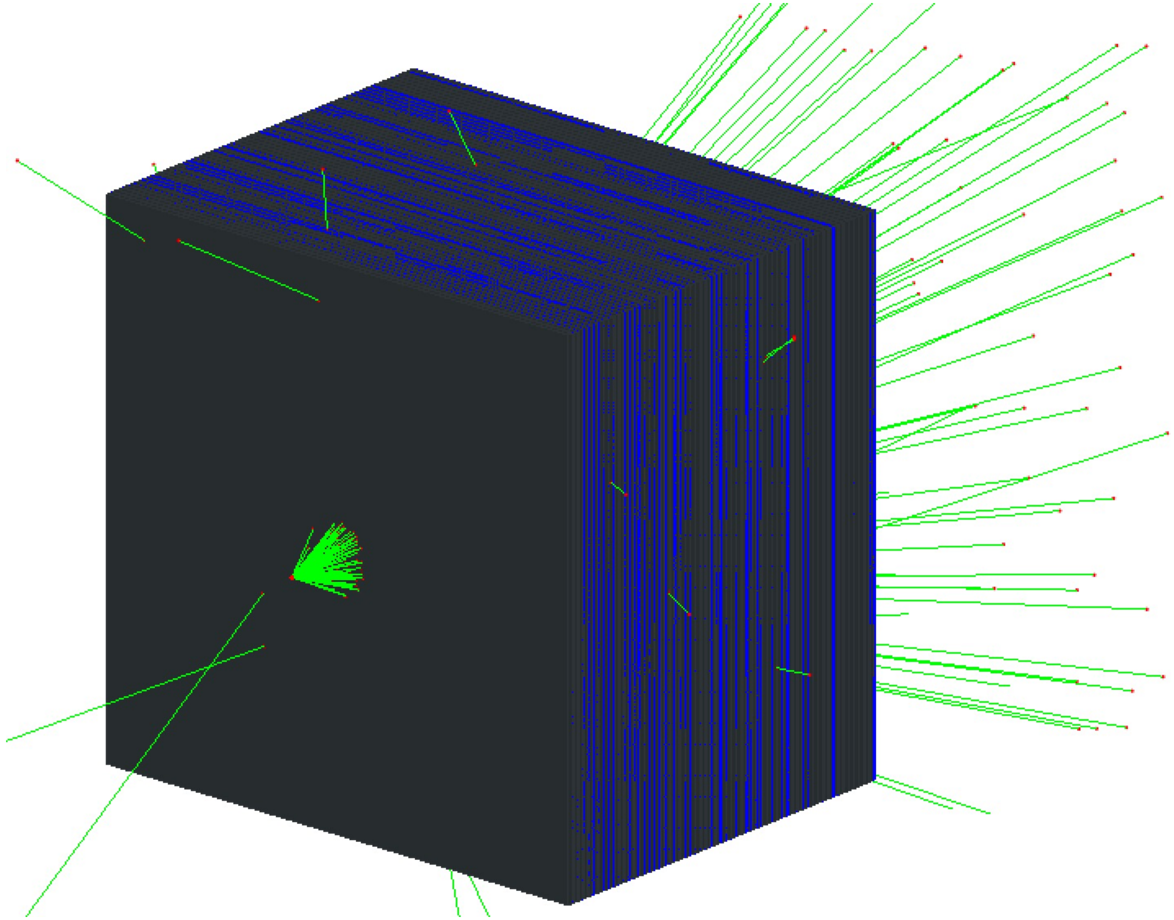
Study effect of decay position within scanner volume.
Introduce positrons' mean free path and investigate filtering strategies
Add Volumetric source (Derenzo phantoms)
Produce Monte Carlo's data for Imaging reconstruction.

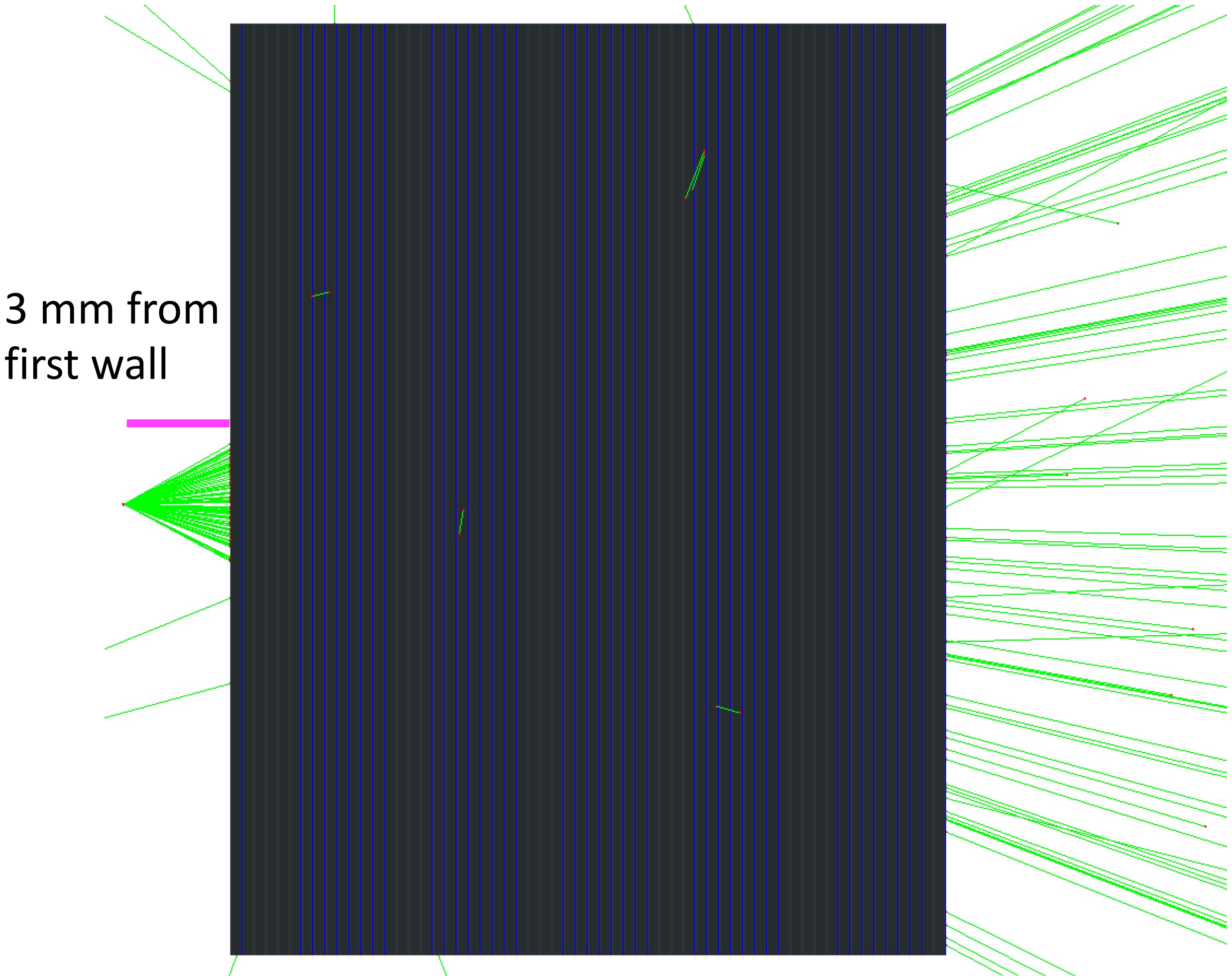
Thank you for the attention

Questions ?

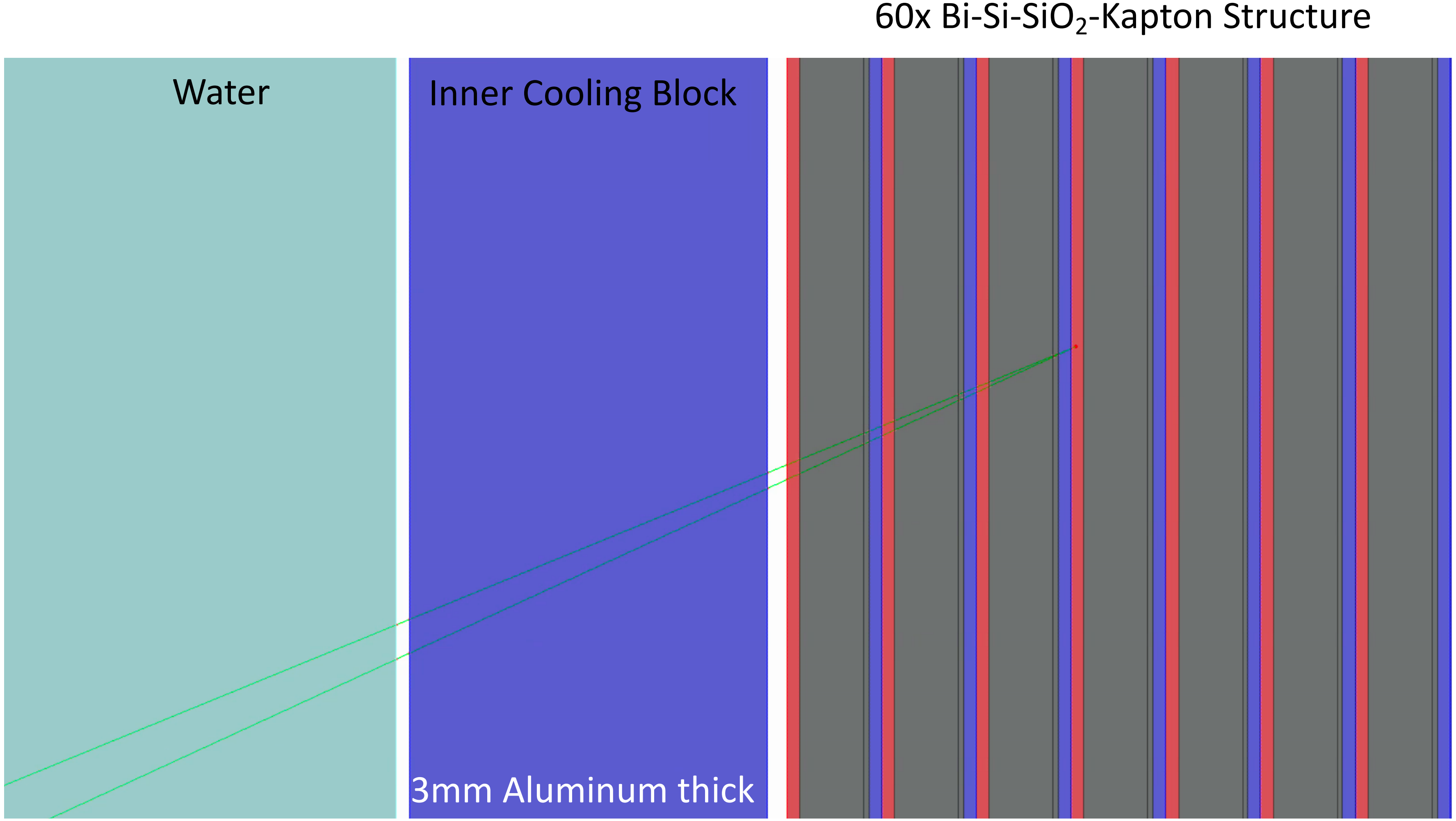
Backup

Single wall detector simulation





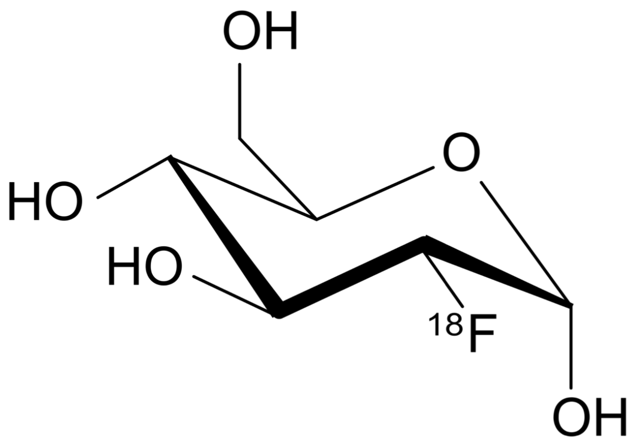
100µPET Detector – Side View



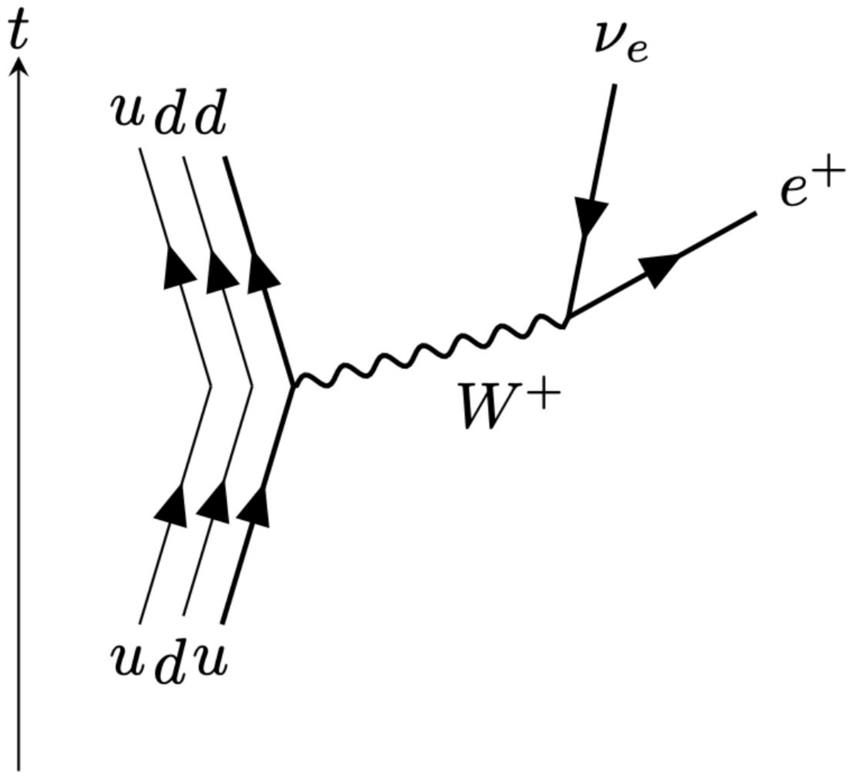
How does PET work ? Beta Decay

$$^{18}_{9}\mathrm{F} \rightarrow \, ^{18}_{8}\mathrm{O} + \, _{1}e^{+} + \nu_e$$

$$e^{+} + e^{-} \rightarrow \gamma + \gamma$$



Fluorine inside FDG decays and as a result a positron is emitted



FDG emitted photons energy distribution

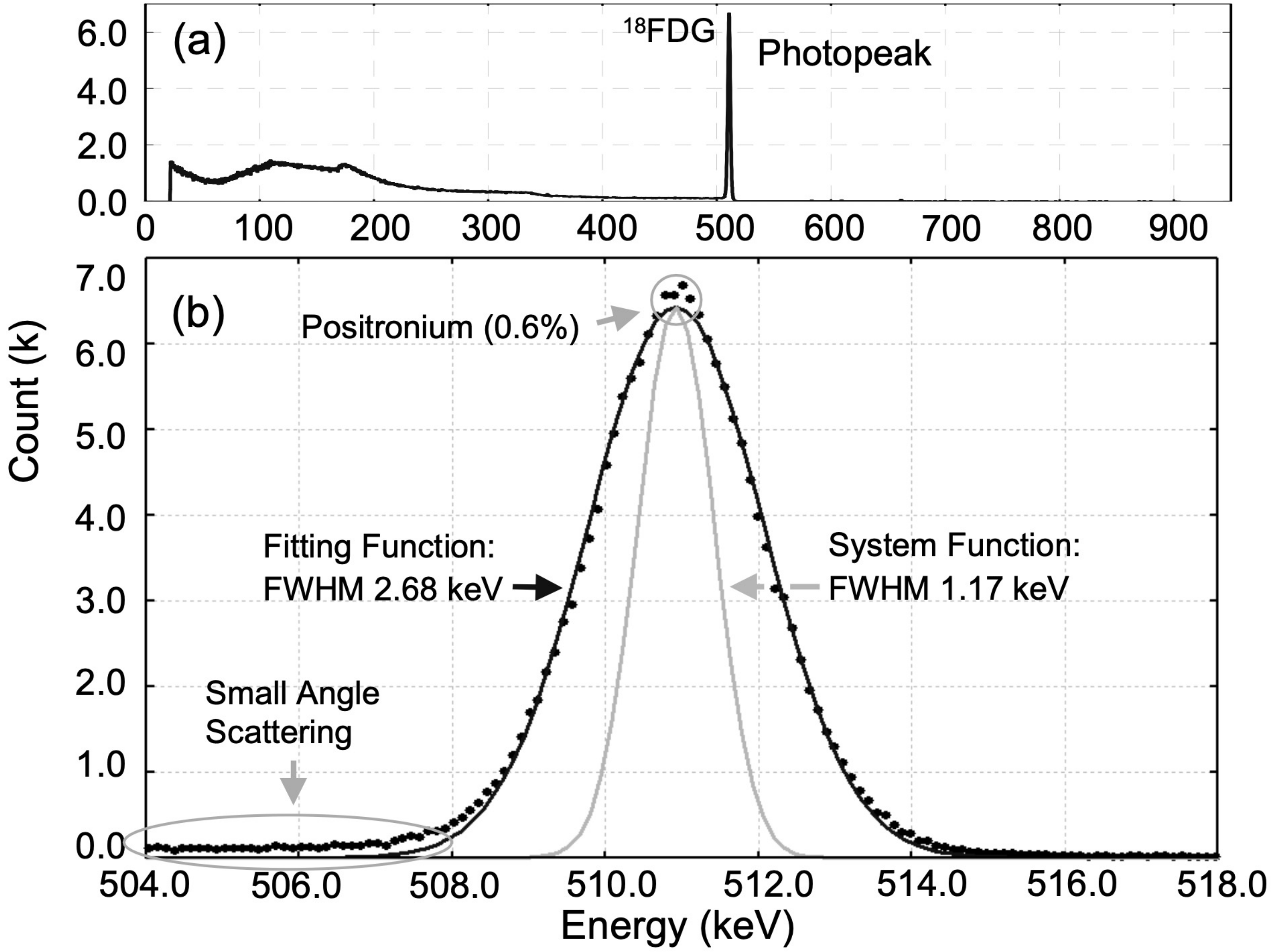
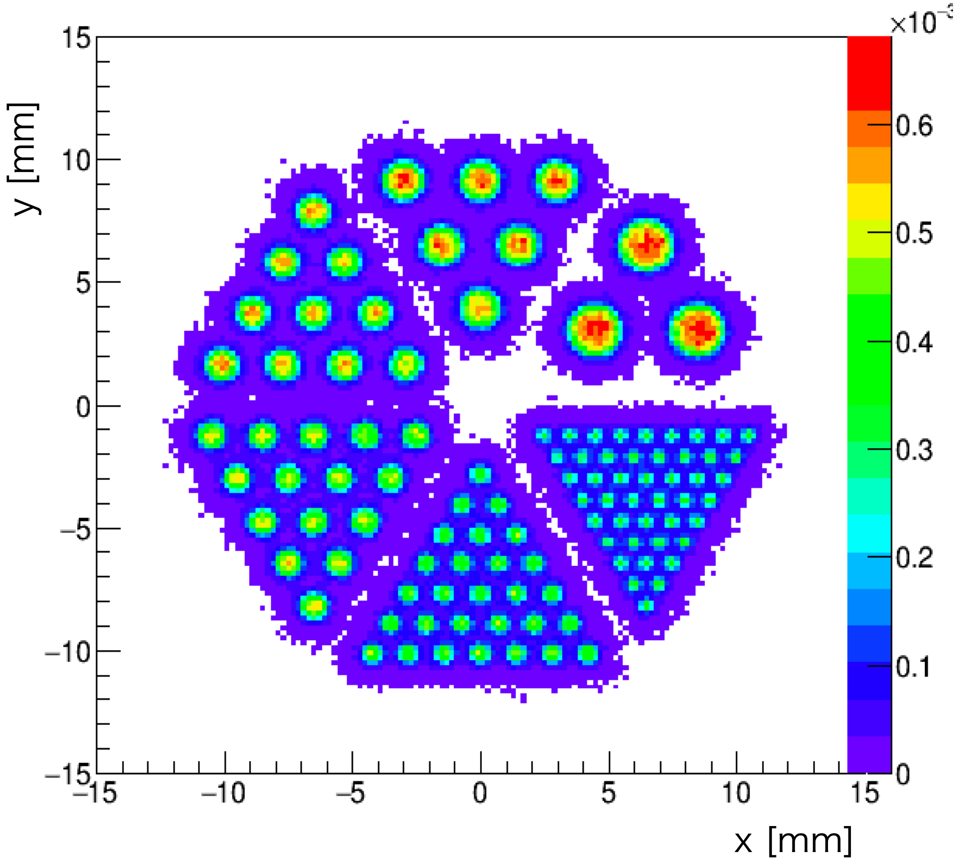


Fig.3 (a) Spectrum of *in vivo* ^{18}FDG and (b) the magnified photopeak fitted by a Gaussian function (black line). The gray line is the estimated system function of the Ge semiconductor detector at 511 keV.

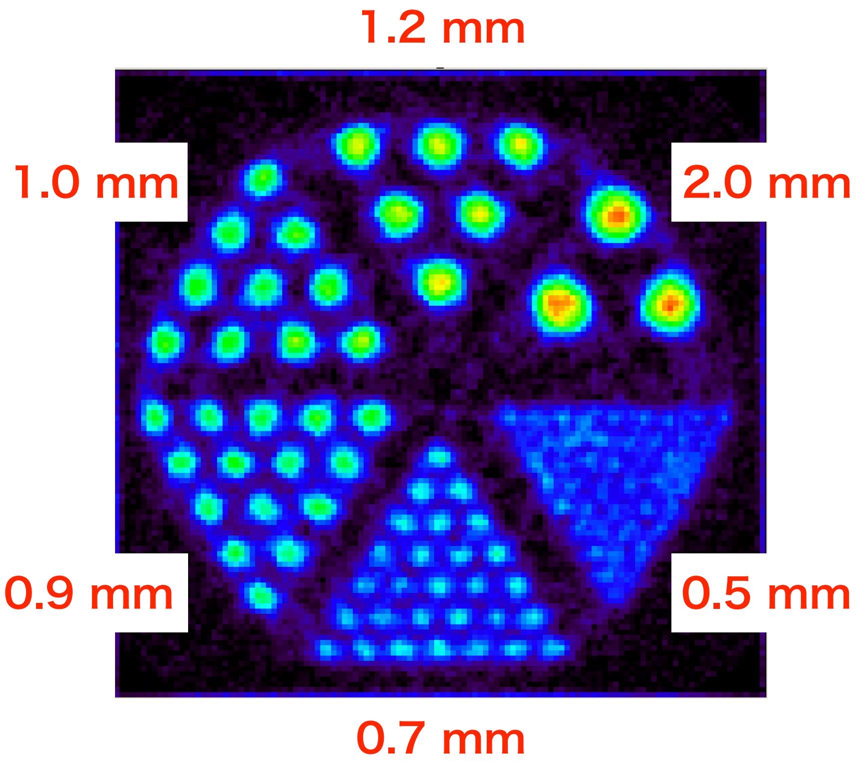
From
K. Shibuya1 et al., Limit of Spatial Resolution in FDG-PET due to Annihilation Photon Non-Collinearity

Derenzo Phantoms

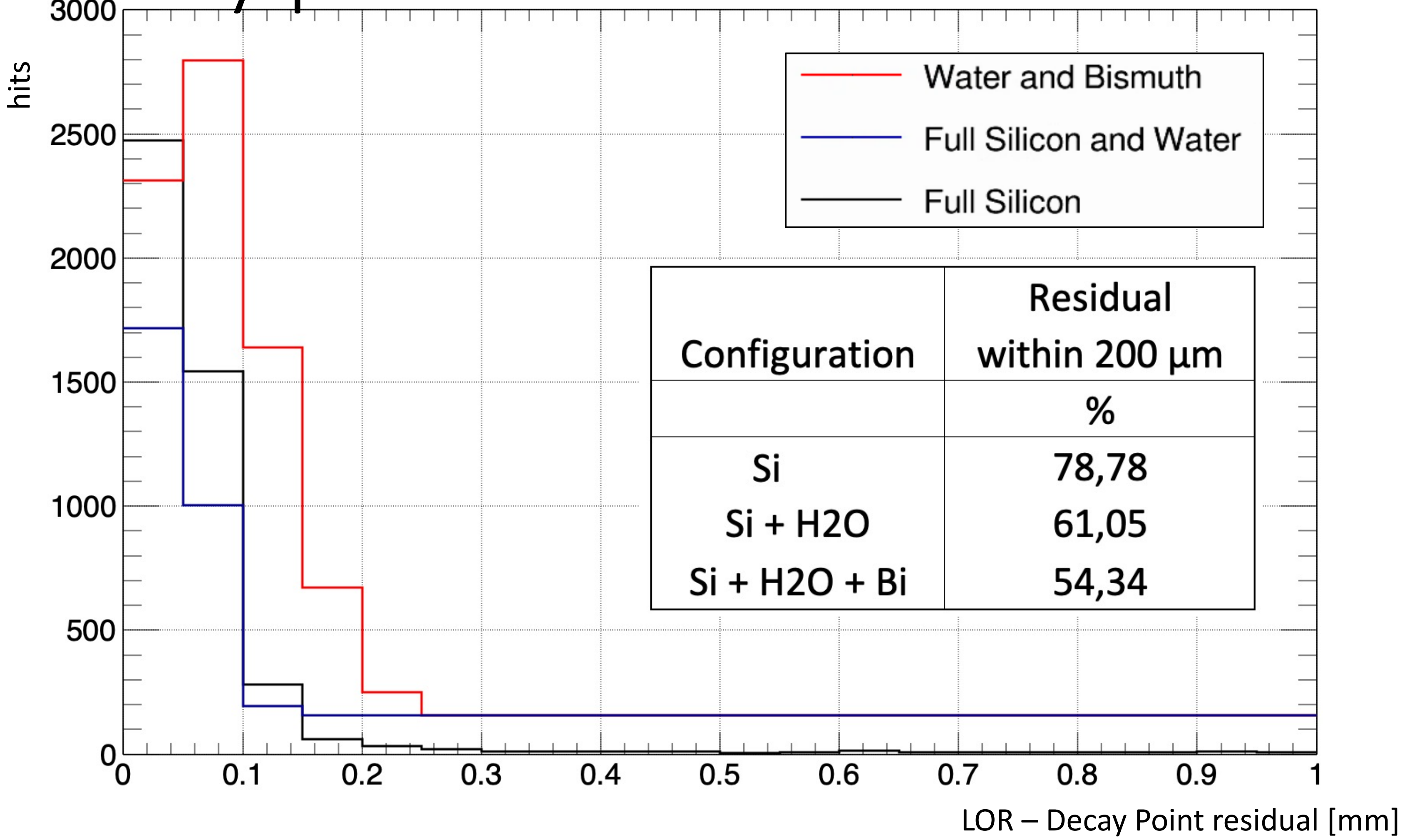
Monte-Carlo Truth



Iterative Reconstruction



LOR – Decay point Residual



Configuration	Residual within 200 µm %
Si	78,78
Si + H2O	61,05
Si + H2O + Bi	54,34

The Thin Time-of-Flight (TT-PET) project

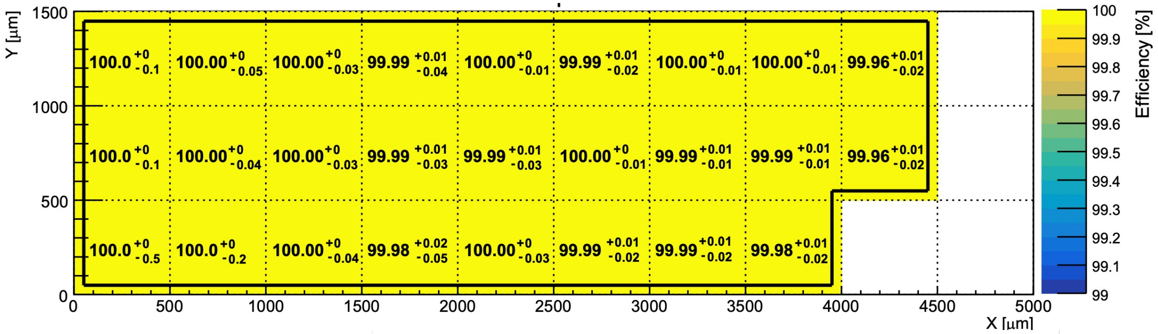
- TT-PET project: from 2016 to 2019
  - Demostrator chip achieved target **performance**,

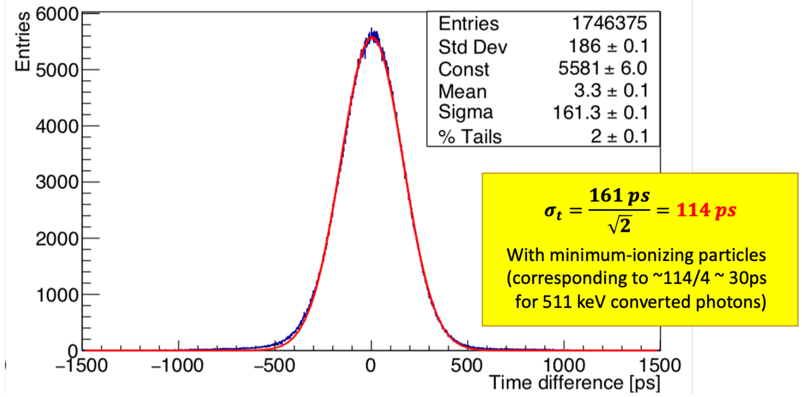
  P. Valerio et al., JINST 14 (P07013) (2018),
  L. Paolozzi et al., JINST 13 (P04015) (2018),
  L. Paolozzi et al., JINST 14 (P02009) (2018)
  - Scanner completely **engineered**,

  D. Ferrere et al., arXiv:1812.00788
  - Performance **simulated**

  E. Ripiccini et al., arXiv:1811.12381
  - Iterative imaging reconstruction **produced**

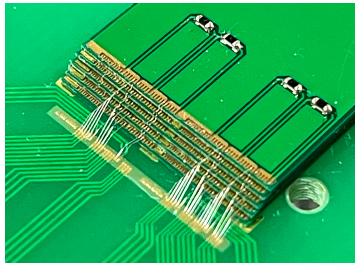
  D. Hayakawa PhD thesis, http://dpnc.unige.ch/THESES/THESE_HAYAKAWA.pdf

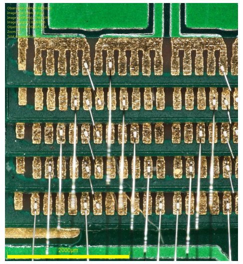




<u>Change of paradigm in PET imaging is possible with monolithic pixel detectors</u>

- Can we do even better? Must reduce even further the “LoR volume”
  - by having better **spatial resolution**, pushing the position measurement down to the **intrinsic limits** given by the **positron mean free path** in body





References for PET scanner landscape

1. Hallen, Patrick & Schug, David & Weißler, Björn & Gebhardt, Pierre & Salomon, André & Kiessling, Fabian & Schulz, Volkmar. (2018). PET performance evaluation of the small-animal Hyperion II PET/MRI insert based on the NEMA NU-4 standard. Biomedical Physics & Engineering Express. 4. 10.1088/2057-1976/aae6c2.
2. Schäfers KP, Reader AJ, Kriens M, Knoess C, Schober O, Schäfers M. Performance evaluation of the 32-module quadHIDAC small-animal PET scanner. J Nucl Med. 2005 Jun;46(6):996-1004. PMID: 15937311.
3. Performance Evaluation of the Small-Animal nanoScan PET/MRI System,
Kálmán Nagy, Miklós Tóth, Péter Major, Gergely Patay, Győző Egri, Jenny Häggkvist, Andrea Varrone, LarsFarde, Christer Halldin, Balázs Gulyás, Journal of Nuclear Medicine Oct 2013, 54 (10) 1825-1832; DOI: 10.2967/jnumed.112.119065

```
=== 2 ===
--- <global> ---

--- Printing MCTrack information for track (0x7fbf40460510) ---------------------
Particle type (PDG ID):      22
Production process:         none (G4 process type: -1)
Production in G4Volume:    World
Termination in G4Volume:   World
Initial position:                  0 mm |       12.8 mm |      -15.7 mm
Final position:              7.06933 mm |  -4.92501 mm |    -55.253 mm
Initial time:                      0 ns
Final time:                 0.154158 ns
Initial kinetic energy:        0.511 MeV | Final kinetic energy:      0.416295 MeV
Initial total energy:          0.511 MeV | Final total energy:        0.416295 MeV
Linked parent: <nullptr>
----------------------------------------------------------------------------------


--- Printing MCTrack information for track (0x7fbf40460618) ---------------------
Particle type (PDG ID):      11
Production process:        compt (G4 process type: 2)
Production in G4Volume:   chip_Plane_33_1_a_phys
Termination in G4Volume: sensor_Plane_33_1_a_phys
Initial position:           -4.16773 mm |   9.08692 mm |  -28.8135 mm
Final position:             -4.16218 mm |   9.06478 mm |   -28.838 mm
Initial time:              0.0475397 ns
Final time:                 0.047943 ns
Initial kinetic energy:   0.0947053 MeV | Final kinetic energy:            0 MeV
Initial total energy:      0.605704 MeV | Final total energy:        0.510999 MeV
Linked parent: 0x7fbf40460510
----------------------------------------------------------------------------------
```

```
--- Plane_33_1_a ---

--- Printing MCParticle information (0x7fbf4045bdc0) --------------------
Particle type (PDG ID):      22
Local start point:           8.2829  mm |   8.33613  mm |     0.125 mm
Global start point:         -4.1671  mm |   9.08613  mm |   -28.815 mm
Local end point:            8.38916  mm |   8.20364  mm |    -0.125 mm
Global end point:          -4.06084  mm |   8.95364  mm |   -29.065 mm
Local time:             0.000985107  ns
Global time:              0.0485539  ns
Linked parent:          <nullptr>
Linked track:           0x7fbf40460510
----------------------------------------------------------------------------


--- Printing MCParticle information (0x7fbf4045bea8) --------------------
Particle type (PDG ID):      11
Local start point:           8.2793  mm |   8.33774  mm |     0.125 mm
Global start point:         -4.1707  mm |   9.08774  mm |   -28.815 mm
Local end point:            8.28782  mm |   8.31478  mm |  0.101962 mm
Global end point:          -4.16218  mm |   9.06478  mm |   -28.838 mm
Local time:                       0  ns
Global time:              0.0475688  ns
Linked parent:          0x7fbf4045bdc0
Linked track:           0x7fbf40460618
----------------------------------------------------------------------------


--- Plane_34_1_a ---


--- Plane_33_1_a ---
PixelHit 83, 83, 25735, 0, 0
```