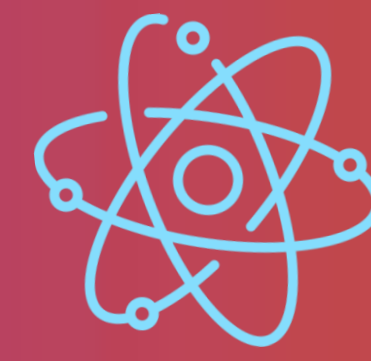# Development of a PET/CT GATE model for voxel-wise Dosimetry in Radionuclide Therapy
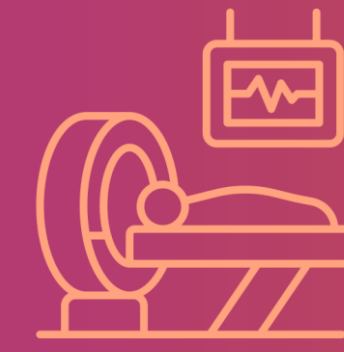
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Introduction

- **Liver Cancer** is the **6th most diagnosed cancer** and the **3rd deadliest** type globally.

- Treatment options depend on the cancer stage, which is determined by tumour's size, location, and level of cellular differentiation.

- Patients with **unresectable liver tumours** are treated with Selective Internal Radiation Therapy (SIRT), also known as **Transarterial Radioembolization** (TARE).
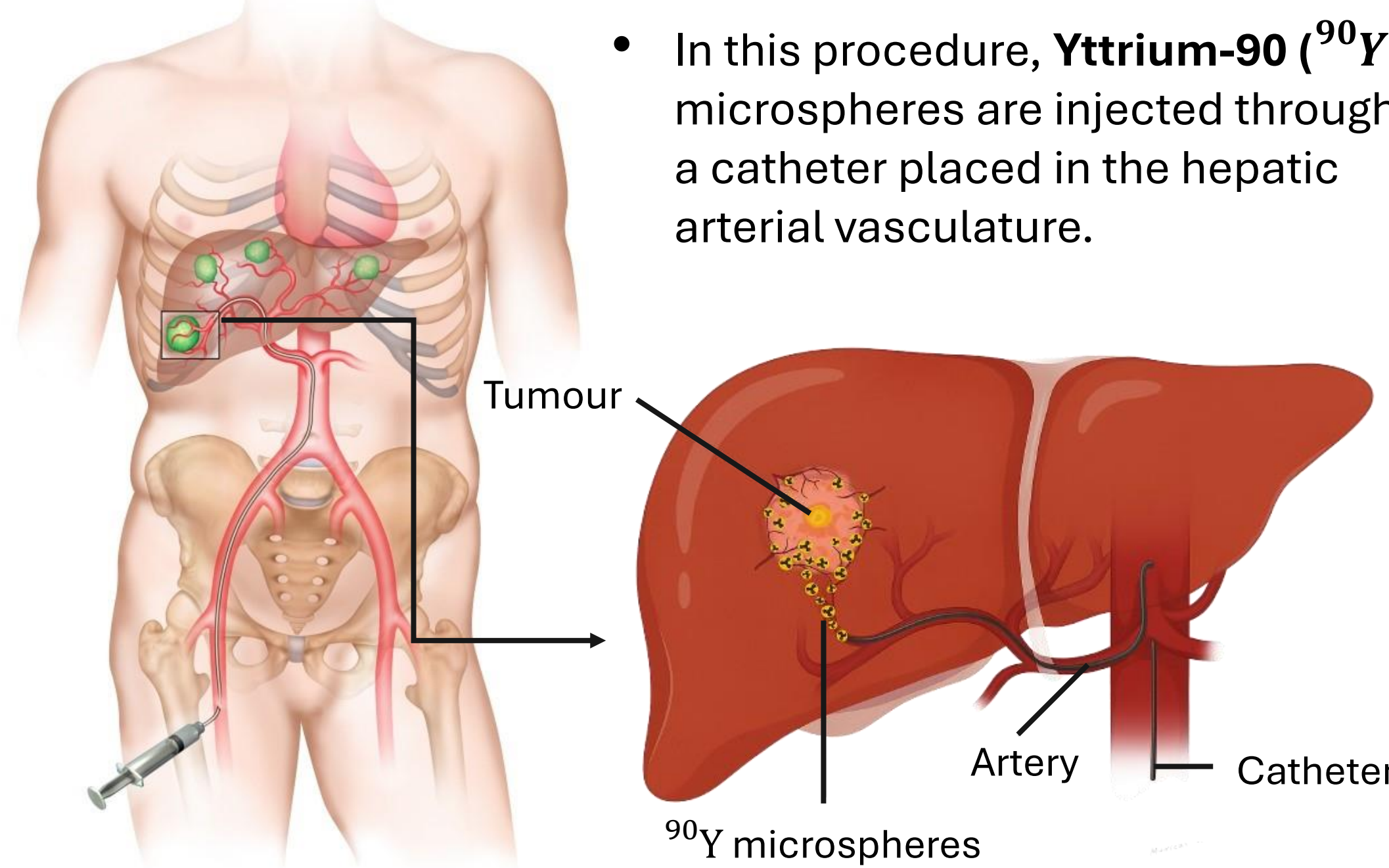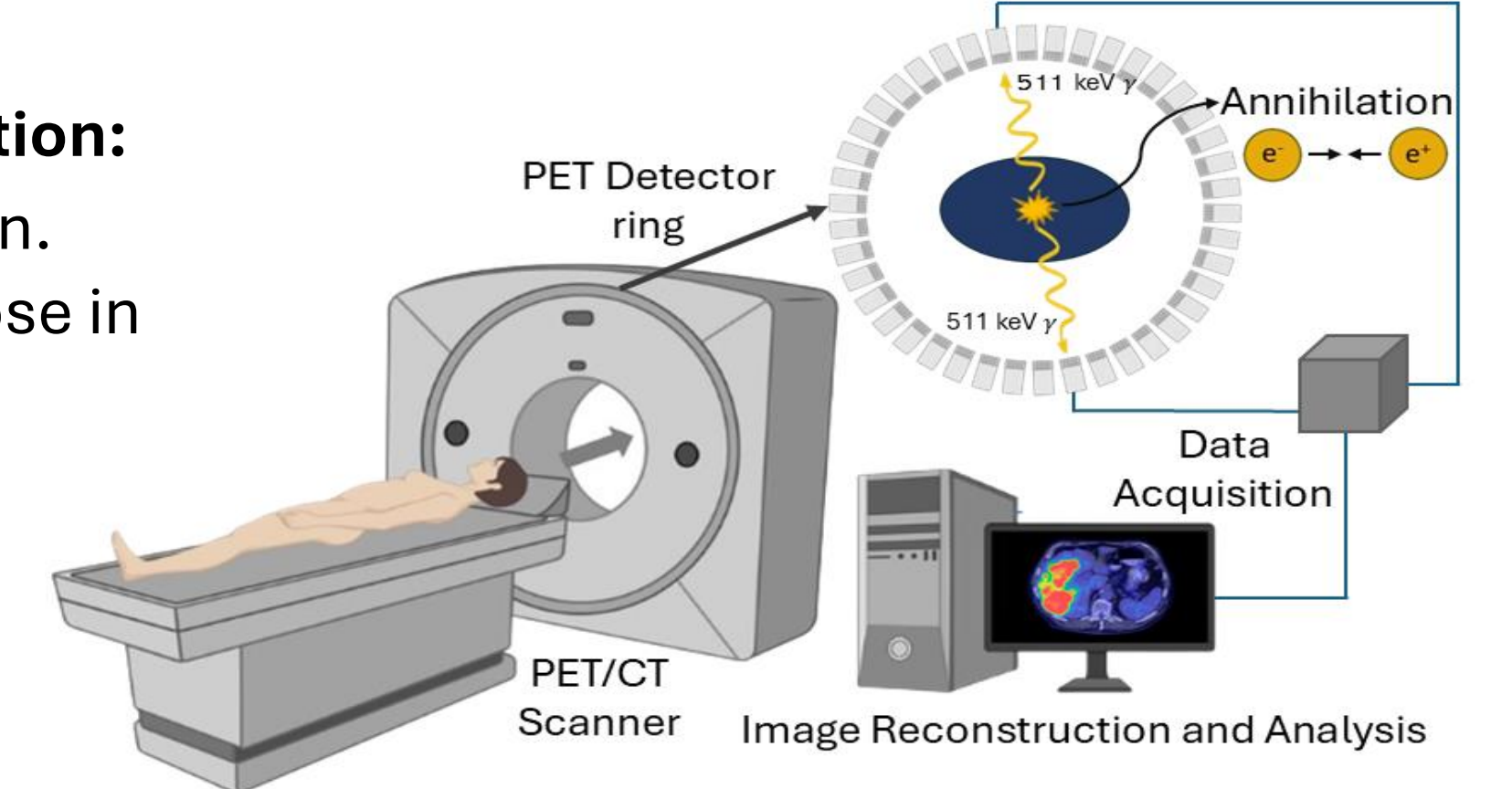
- In this procedure, Yttrium-90 (^{90}Y) microspheres are injected through a catheter placed in the hepatic arterial vasculature.

Tumour · Artery · Catheter · ^{90}Y microspheres
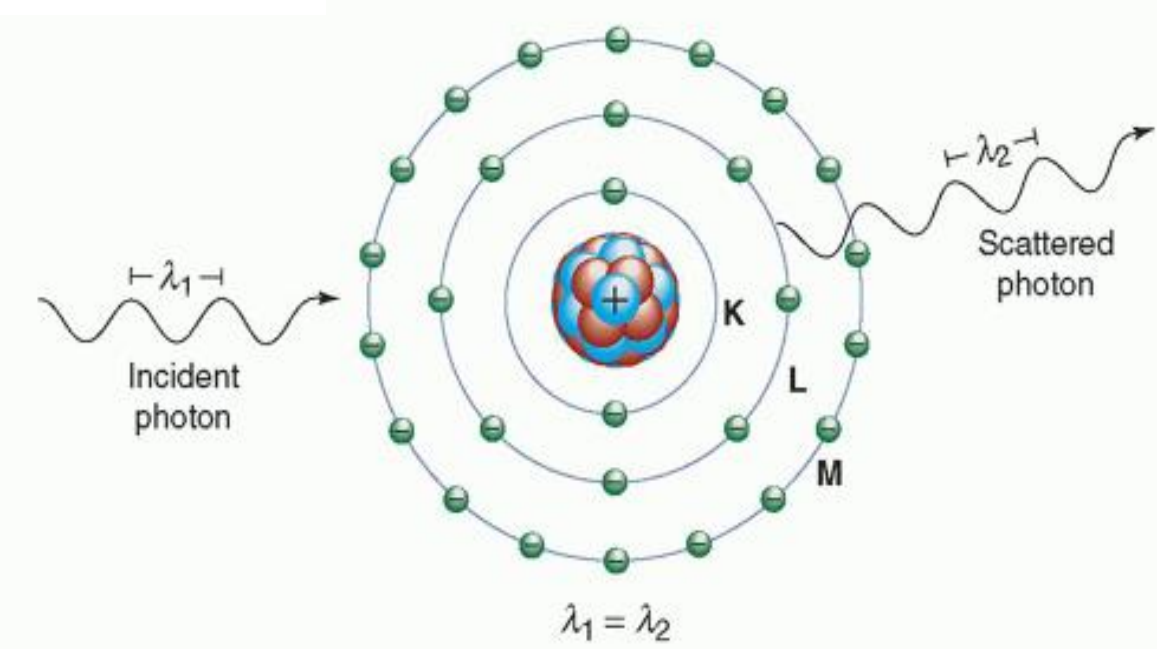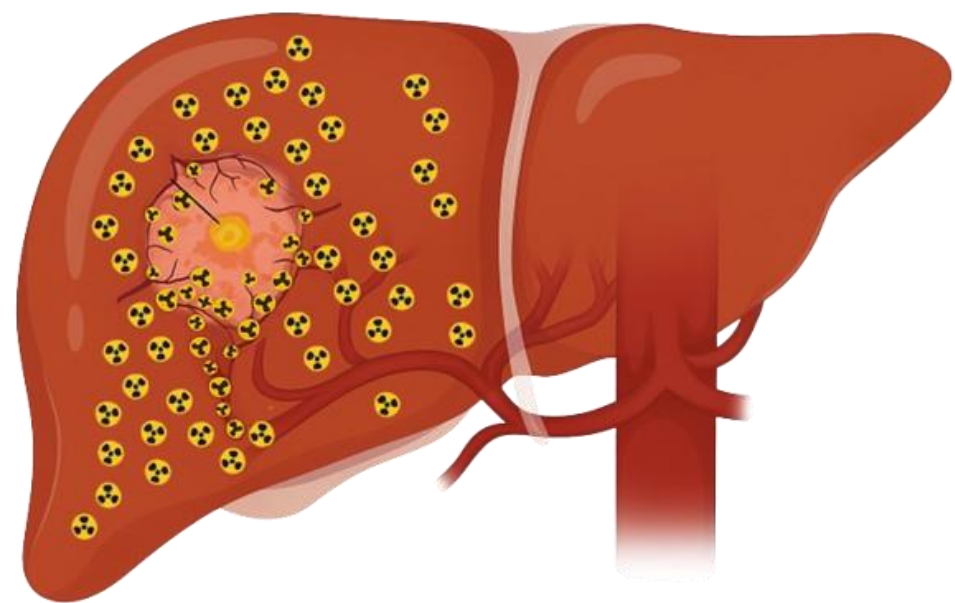
90 Y 39 Yttrium 64.2 h
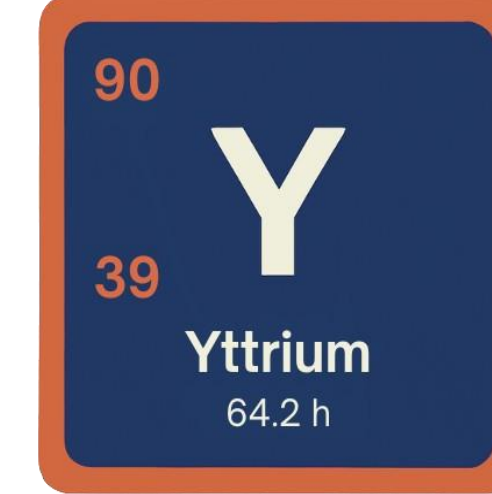
- β^- decay (99.98 %) into stable Zirconium-90 (^{90}Zr).
- Energy: maximum 2.27 MeV, average 0.937 MeV.
- Tissue penetration: ~ 2.5 - 11 mm.
- 0.0115 % decay branch that can produce e^+ via IPP.
- Produces e^+ at a rate of 3.26×10^{-5} pairs per decay.

Post-treatment verification:
- Assess ^{90}Y distribution.
- Estimate absorbed dose in tumours, liver and surrounding tissues.
- Identify undertreated regions.

PET Detector ring · 511 keV · Annihilation · Data Acquisition · PET/CT Scanner · Image Reconstruction and Analysis

Problems

- ^{90}Y microspheres **are not uniformly distributed** in the Volumes of Interest (VOI's).

- **Photons interactions with tissues** affect the quality of **PET/CT imaging**.

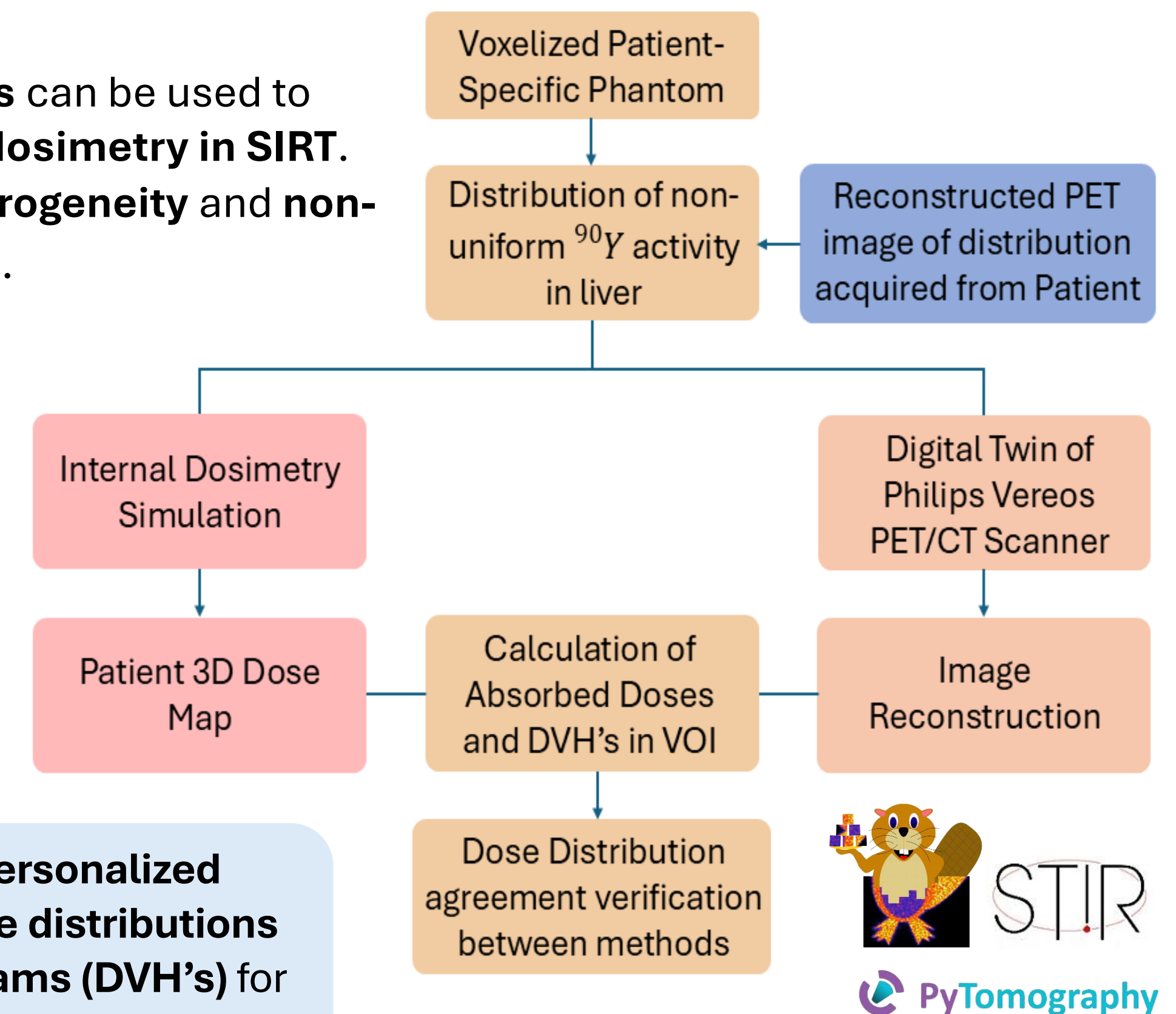*Incident photon · Scattered photon · $\lambda_1 = \lambda_2$*

- **Risk of radiation damage** to healthy liver tissues.

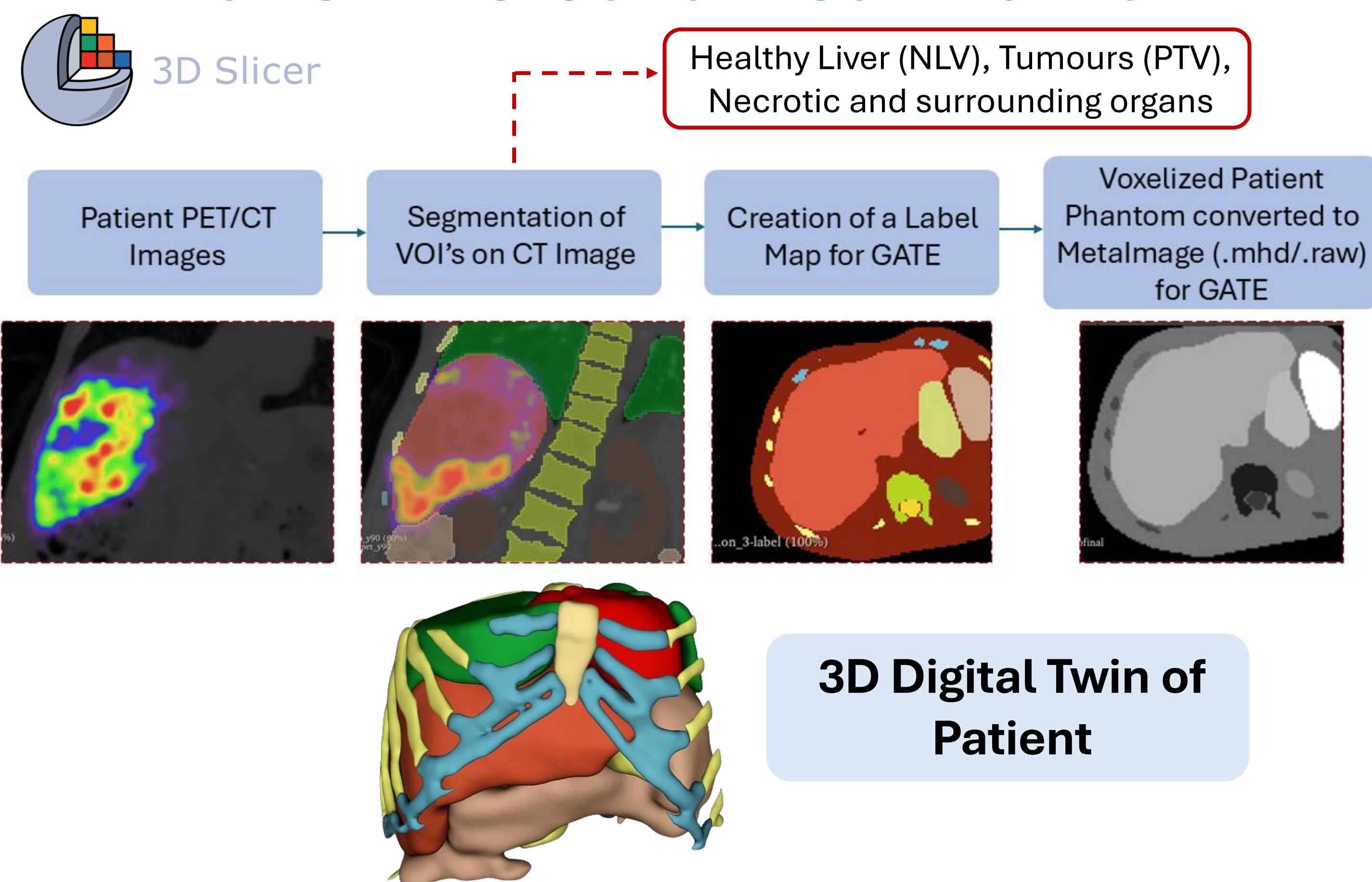$$D(r_T, T_D) = \sum_{r_S} \int_0^{T_D} \tilde{A}(r_S, t) S(r_T \leftarrow r_S) dt$$

- **Standard dosimetry** assumes uniform ^{90}Y distribution and homogeneous tissues, ignoring patient-specific variations and resulting in suboptimal prescribed activity.
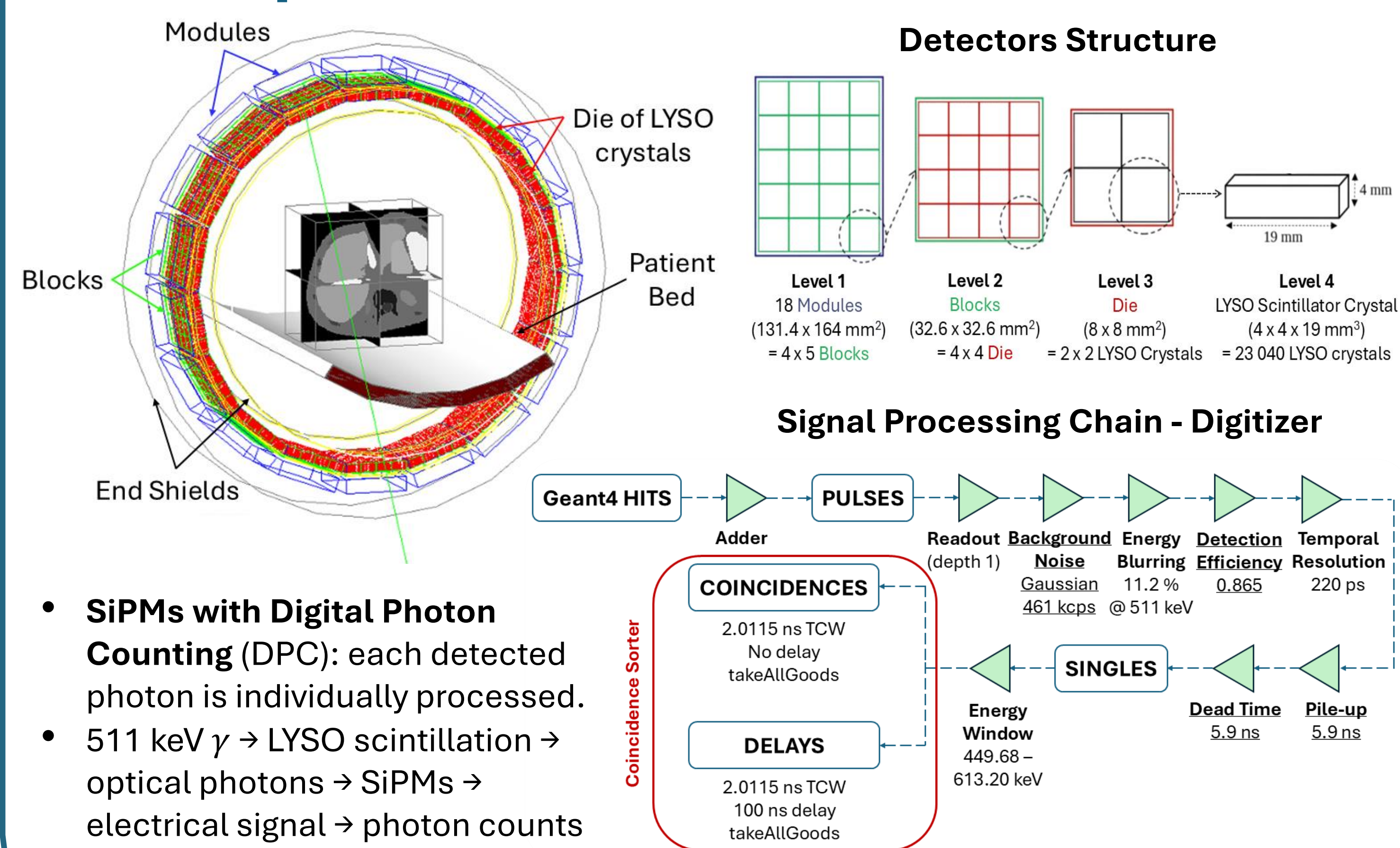
Solution

- **Monte Carlo simulations** can be used to achieve **more accurate dosimetry in SIRT**.
- Accounts for **tissue heterogeneity** and **non-uniform ^{90}Y distribution**.

GATE opengatecollaboration.org
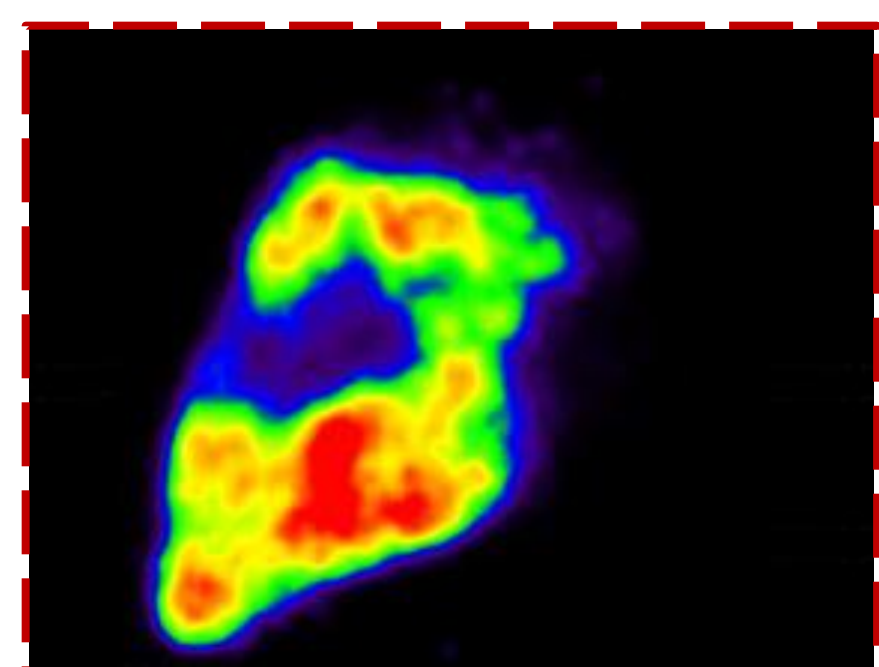
Our **goal** is to perform **personalized treatment** using **voxel-wise distributions and Dose-Volume Histograms (DVH's)** for **greater accuracy**.

Voxelized Patient-Specific Phantom → Distribution of non-uniform ^{90}Y activity in liver → Reconstructed PET image of distribution acquired from Patient → Internal Dosimetry Simulation → Patient 3D Dose Map → Calculation of Absorbed Doses and DVH's in VOI → Digital Twin of Philips Vereos PET/CT Scanner → Image Reconstruction → Dose Distribution agreement verification between methods · STIR · PyTomography

Patient Personalized Phantom

3D Slicer

Healthy Liver (NLV), Tumours (PTV), Necrotic and surrounding organs

Patient PET/CT Images → Segmentation of VOI's on CT Image → Creation of a Label Map for GATE → Voxelized Patient Phantom converted to MetaImage (.mhd/.raw) for GATE

3D Digital Twin of Patient

Philips Vereos PET/CT GATE Model

Modules · Die of LYSO crystals · Patient Bed · Blocks · End Shields

Detectors Structure

Level 1 18 Modules (131.4 x 164 mm²) = 4 x 5 Blocks
Level 2 Blocks (32.6 x 32.6 mm²) = 4 x 4 Die
Level 3 Die (8 x 8 mm²) = 2 x 2 LYSO Crystals
Level 4 LYSO Scintillator Crystal (4 x 4 x 19 mm³) = 23 040 LYSO crystals

Signal Processing Chain - Digitizer

Geant4 HITS → Adder → PULSES → Readout (depth 1) → Background Noise Gaussian 461 kcps → Energy Blurring 11.2 % @ 511 keV → Detection Efficiency 0.865 → Temporal Resolution 220 ps

Coincidence Sorter: COINCIDENCES 2.0115 ns TCW No delay takeAllGoods · DELAYS 2.0115 ns TCW 100 ns delay takeAllGoods

SINGLES → Energy Window 449.68 – 613.20 keV → Dead Time 5.9 ns → Pile-up 5.9 ns

- **SiPMs with Digital Photon Counting** (DPC): each detected photon is individually processed.
- 511 keV γ → LYSO scintillation → optical photons → SiPMs → electrical signal → photon counts
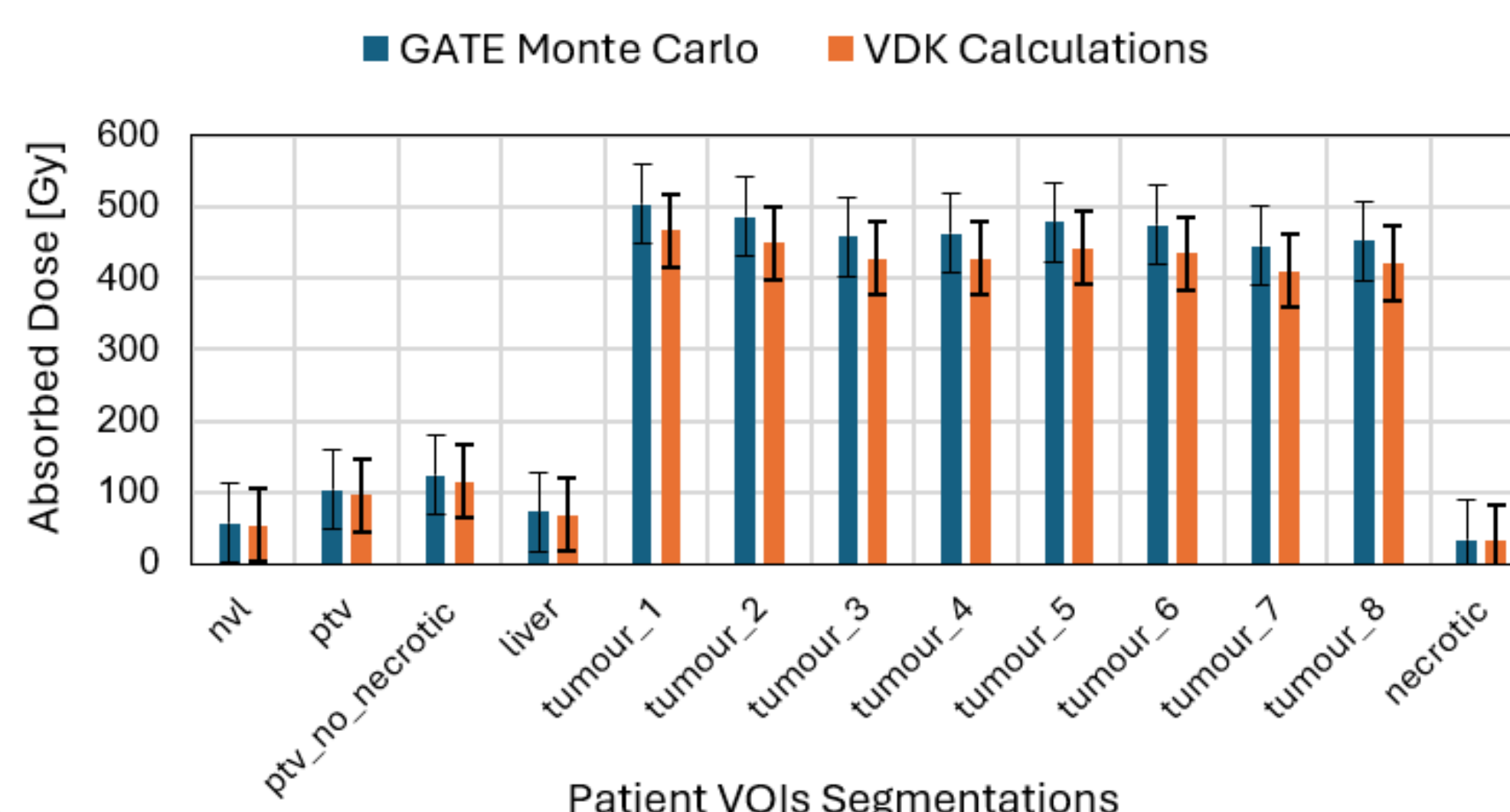
Preliminary Results

Image Reconstruction on CASToR

Administration of 3.46 GBq ^{90}Y activity

Internal Dosimetry Simulation Analysis

OSEM algorithm (4 iterations, 12 subsets) with **attenuation, scatter and randoms correction**, incremental Siddon projection and **4 mm FWHM Gaussian post-filter**

Absorbed Dose [Gy] vs Patient VOIs Segmentations — GATE Monte Carlo / VDK Calculations — nvl, ptv, ptv_no_necrotic, liver, tumour_1, tumour_2, tumour_3, tumour_4, tumour_5, tumour_6, tumour_7, tumour_8, necrotic

DVH's GATE Monte Carlo result vs. VDK Calculations

Volume [%] vs Absorbed Dose [Gy]