Gate Simulations of a Novel Positron Emission Tomography based on Liquid Opaque Detection

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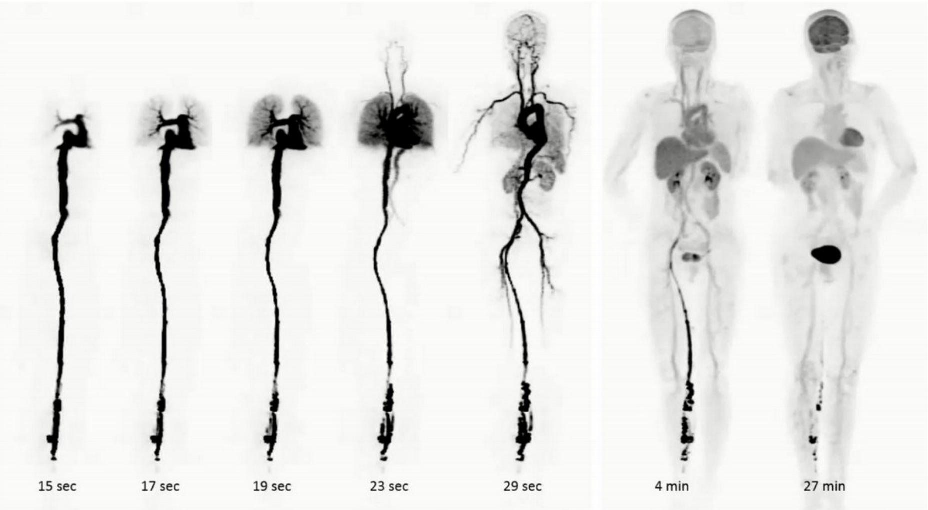
Current PET Camera Developments (1)

$$SNR \approx \sqrt{k \cdot A \cdot G \cdot \varepsilon^2 \cdot T}$$

- k: specific to patient
- A: Injected activity
- G: Geometrical efficiency
- ε: Detector efficiency
- T: Acquisition time



Dynamic True Whole Body PET Imaging following injection of FDG in the leg

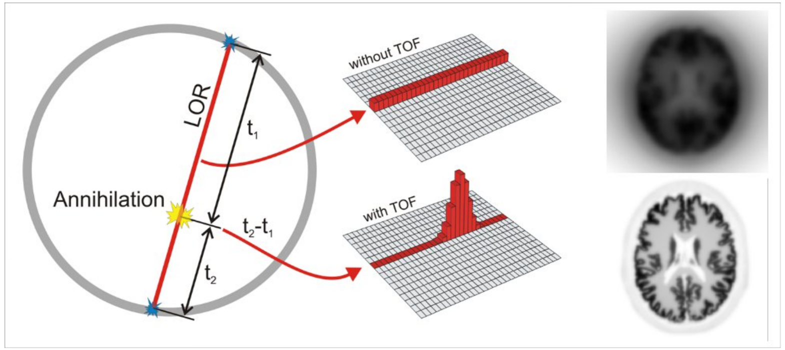
R.D. Badawi et al., Jour. of Nucl. Med. 2019, 60 (3) 299-303

- Current PET experimental development challenges: Increase sensitivity via various improvements

- Improving detector efficiency
  - Compact and faster photodetectors
  - Scintillator developments
  - Multi-layers and monolithic scintillators module for Depth of Interaction (DoI)

- Increasing geometrical acceptance
  - Full body PET :~1-2 m (Explorer (Davis), PennPET, ...)
  - Same total acquisition time : better image quality
  - Dynamical studies of full-body biodistribution

Oncovision CareMiBrain



Adapted from P. Lecoq & J. Nuyts

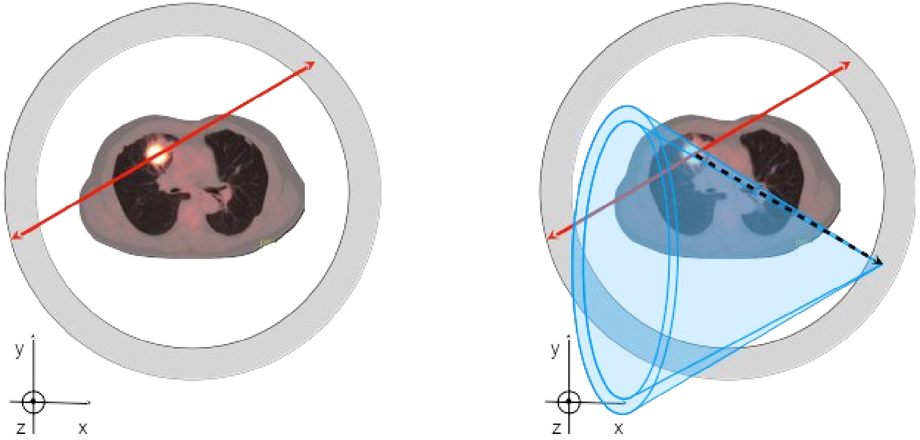
$$\frac{SNR_{Tof}}{SNR_{nonToF}} = \sqrt{\frac{2D}{c \times CTR}}$$

- Organ Dedicated PET
  - Brain, breast, …
  - Closer to the region of interest ➡ increased detection efficiency
  - Dedicated segmentation ➡ improved spatial resolution
  - Less background from other organs ➡ improved contrast

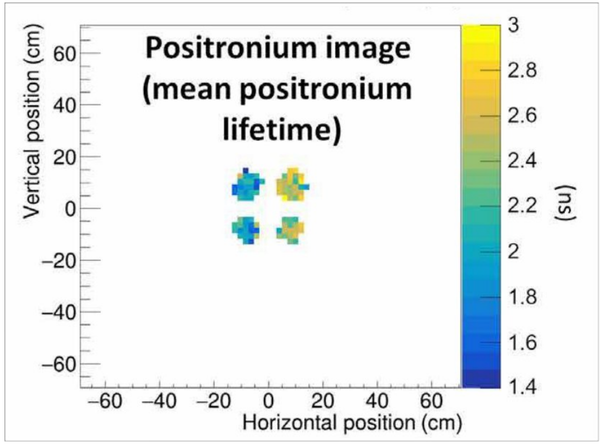
- Toward 10 ps ToF
  - Best CTR in commercial PET : ~214 ps (Siemens Biograph Vision) ➡ Resolution of 6 cm along the LoR
  - CTR <10 ps would reduce resolution to 1.5 mm along the LoR
  - Gain x16 in SNR
  - No more tomographic inversion for reconstruction

➡ Difficult to achieve with traditionnal PET
➡ Using 3γ imaging ?

Current PET Camera Developments (3)



D. Giovagnoli et al., 2021, doi: 10.1109/TRPMS.2020.3046409.



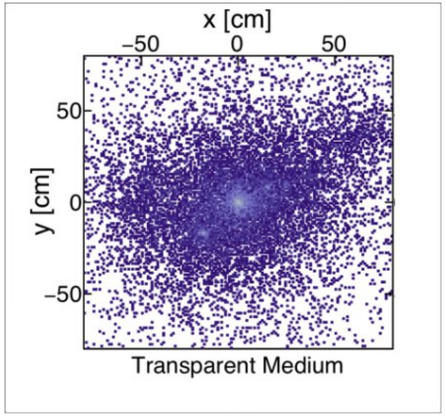
Moskal et al., Sci. Adv. 2021; 7 : eabh4394

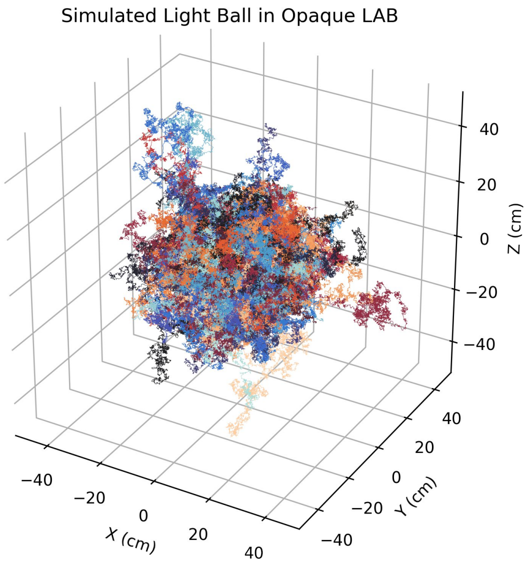
- 3 γ Imaging (beta-gamma isotope)
  - Pseudo-ToF:
    - Compton cone from the prompt γ
    - Intersection between the cone and the LoR to constrain the localization of the decay
  - Ortho-Positronium lifetime studies
    - delay between the prompt 1.16 MeV γ and the two 511 keV photons
    - impact of the biological tissue

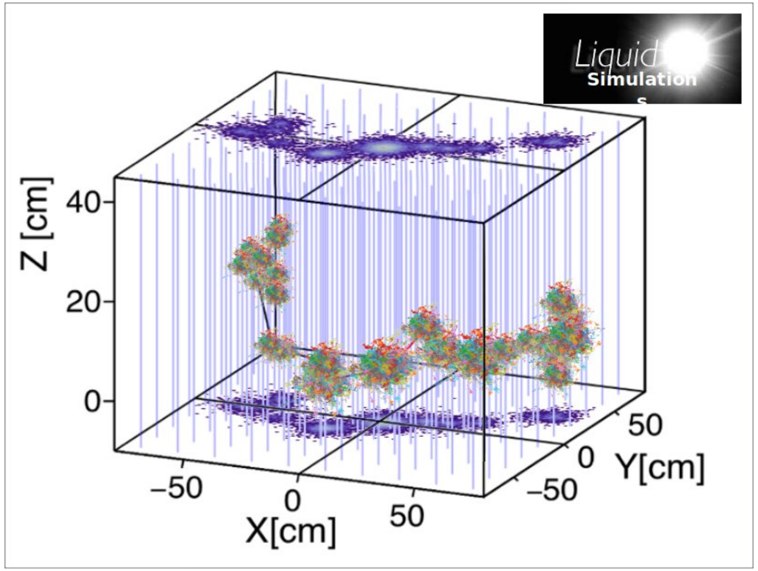
Opaque Scintillation – LiquidO Technology

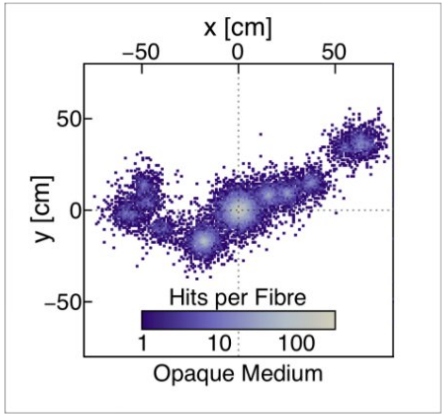
- Objective: Identify and localize each interaction of γ
  - Move away from segmented scintillator crystals
  - LiquidO*technology: Liquid opaque scintillator
    - Light is stochastically confined into light balls due to scattering (Mie, Rayleigh)
    - Large detection volume achievable
    - Light is readout via a dense lattice of wavelength shifting fibers (WLS)

*LiquidO Consortium. Neutrino physics with an opaque detector. *Commun Phys* **4**, 273 (2021)

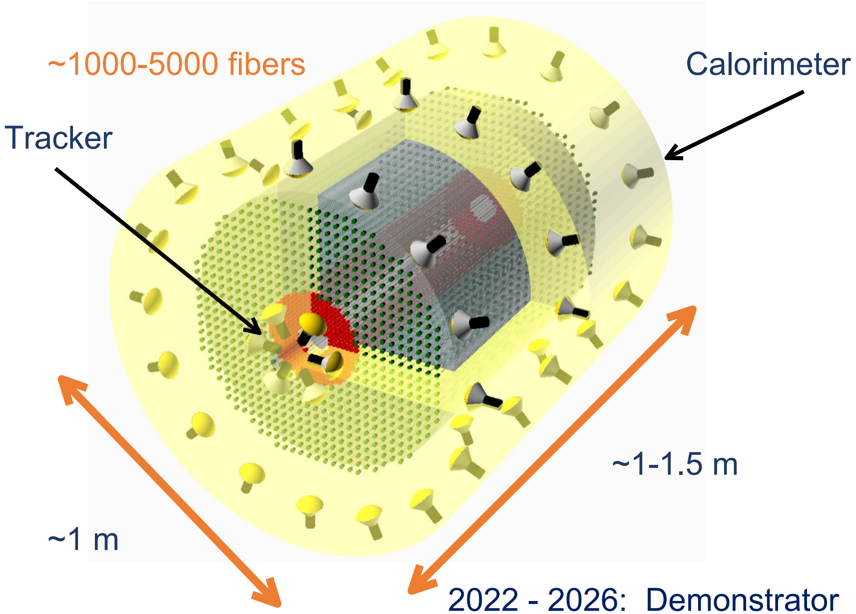




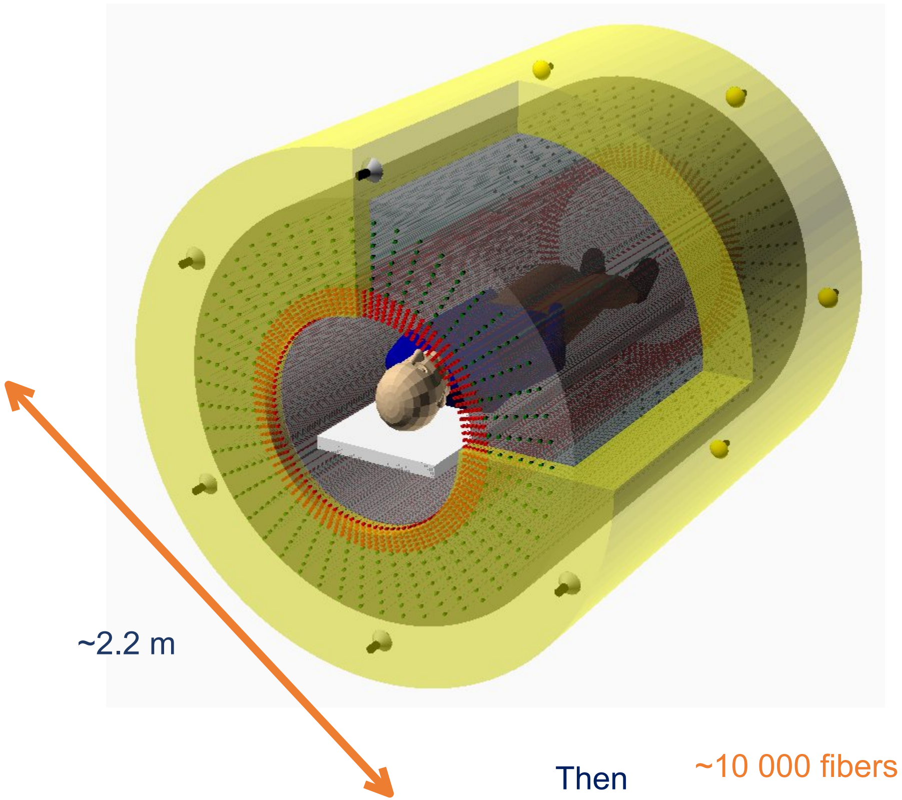




- Objectives
  - Validation of the capabilities of LiquidO technology for PET:
    - Spatial resolution
    - Energy resolution
    - Sensitivity
    - 2 and 3 γ tracking capabilities



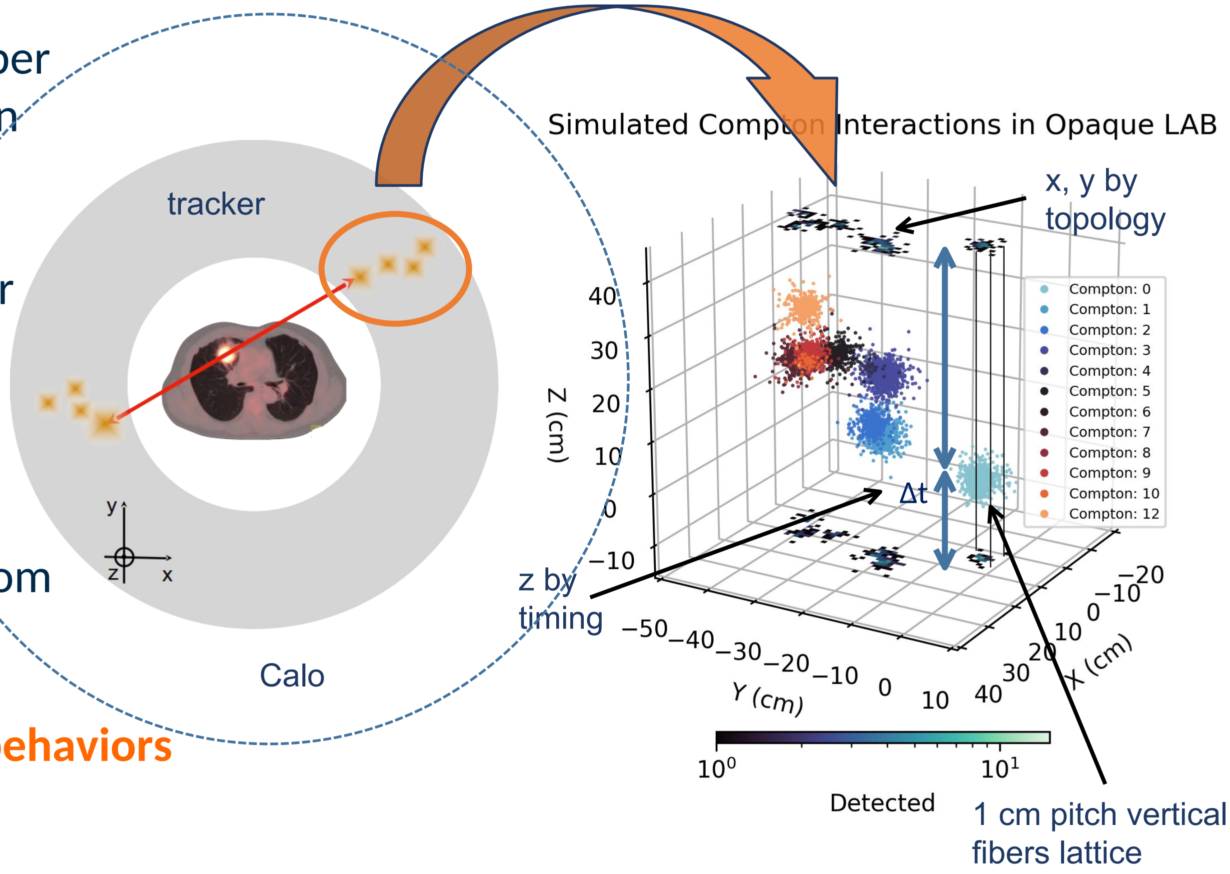
2022 - 2026: Demonstrator
(French ANR funded: ANR-21-CE19-0036-04 TEP-OTech)



Then
Full body L-PET

LPET: Paradigm Shift

- Cylindrical geometry with two regions:
  - Inner (~40 cm): **tracker** region and axial fiber readout for first Compton events detection
    ➡ ~90% detection efficiency
  - Outer: **calorimeter** with “standard” transparent liquid scintillator and PMTs for energy measurement
- Reconstruction of Compton interactions by topological and timing informations:
  - x, y: barycenter of light
  - z: Δt of detected photons on top and bottom



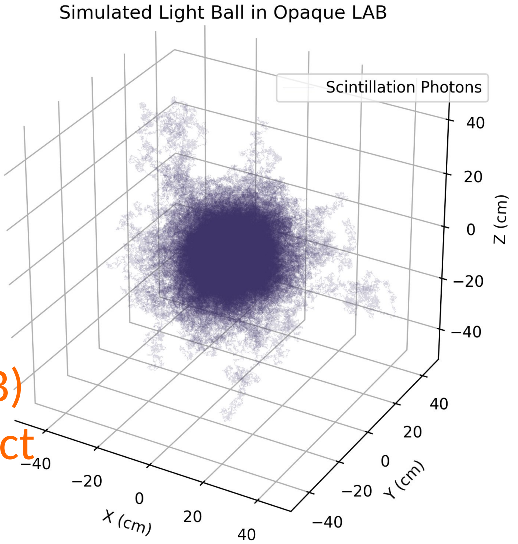
➡ Ongoing GATE simulations:
- **Understanding opaque scintillation behaviors**
- **Optimizing detector design**

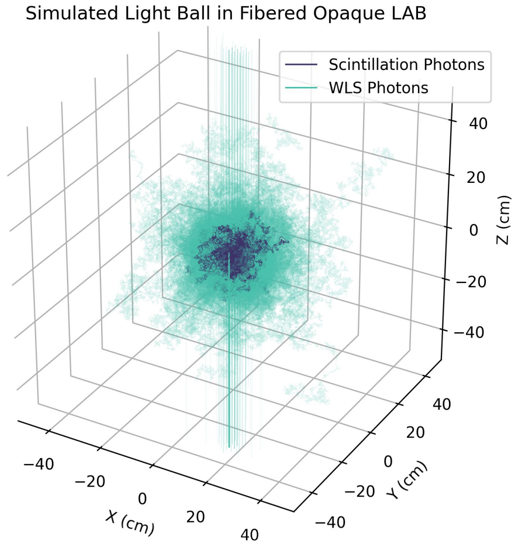
GATE Optical Simulation Setup

- Volume of liquid scintillator: opaque linear alkylbenzene (LAB):
  - Light yield
  - Scintillation time constants
  - Emission spectrum (UV)
  - Mie scattering parameters
  - Absorption spectrum
  - Refractive indices
- Lattice of WLS fibers (Kuraray B3 double cladding) + SiPM:
  - Repeating pattern:
  - UV absorption length spectrum
  - WLS emission spectrum
  - Shifted light absorption spectrum
  - Refractive indices
  - SiPM PDE

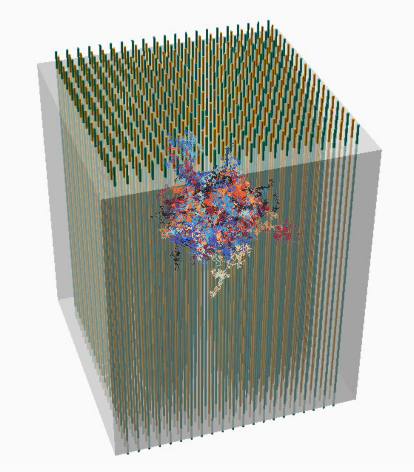
- Some optical parameters not fully known (guesstimated)
- Ongoing R&D on opaque scintillator development

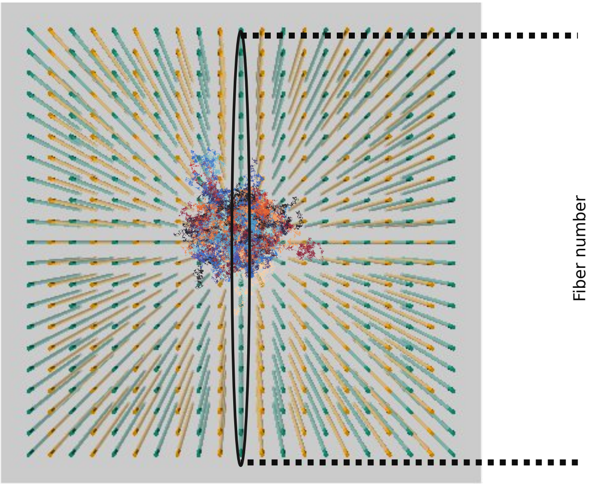
- Only guided WLS photons can be measured (~10-20%)
- WSL photons escaping fibers are lost (absorbed in the LAB)
- Both optical properties and the fiber lattice structure affect the light balls

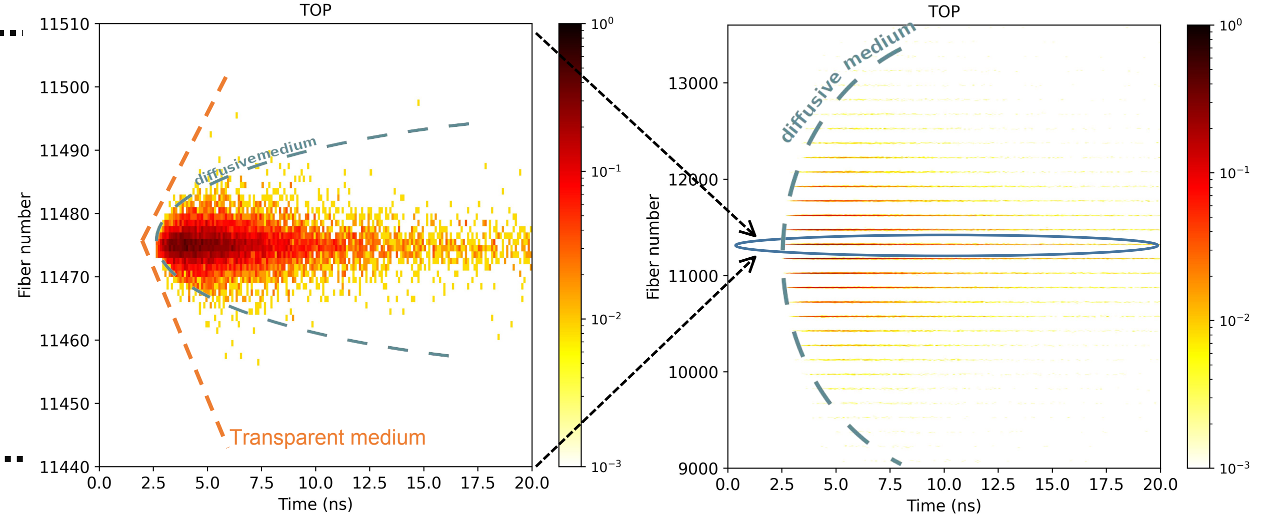




Preliminary Monte-Carlo Results (1)

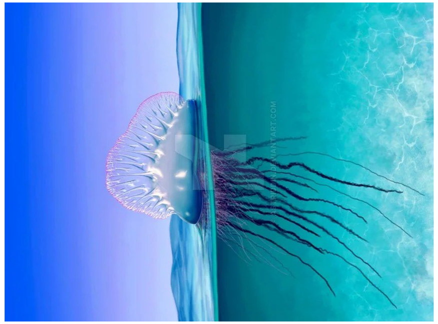






200 GATE light ball simulation, 5000 photons / event

- GATE Monte Carlo simulation:
  - 1.5 m cube of opaque linear alkylbenzene (LAB)
  - Vertical WLS fibers lattice with various pitches
  - Light balls of UV optical photons
  - Perfect SiPM on each fiber side (100% PDE)

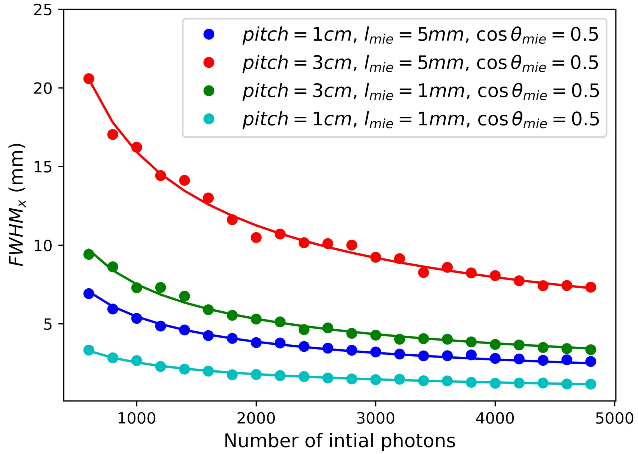


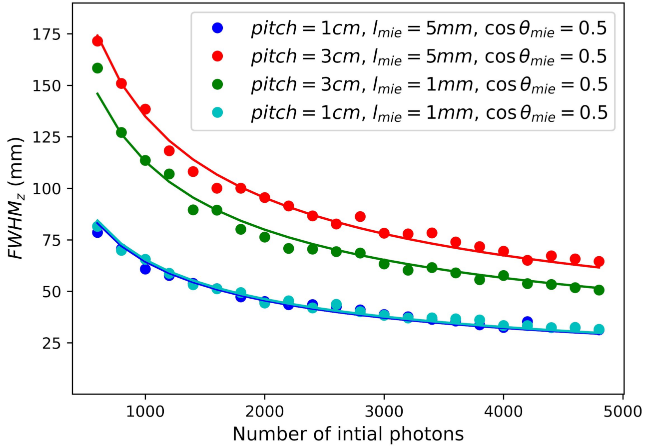
➡ Correlation between neighboring fibers waveforms

➡ Diffusive medium slower than transparent medium

➡ Pulse shape in each waveform is Z-dependent

Preliminary Monte-Carlo Results (2)

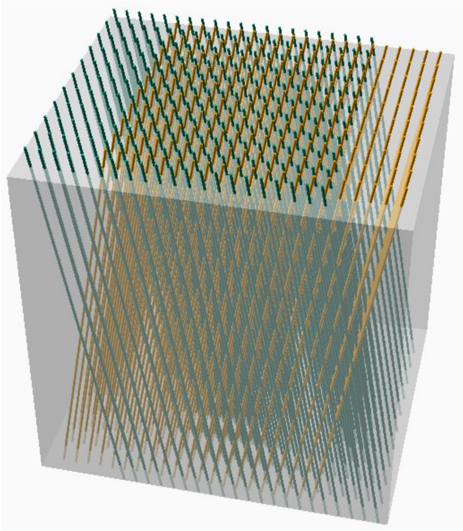


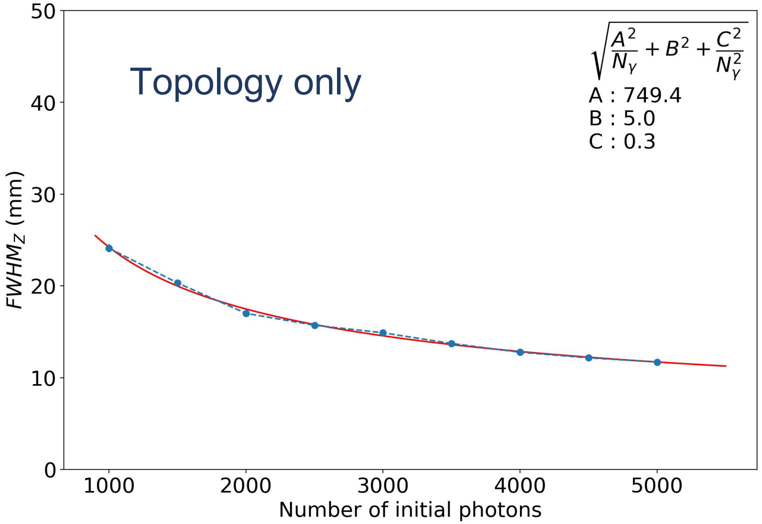


Timing only

- x, y spatial resolution: ~1-10 mm (FWHM)
- z spatial resolution: ~5-10 cm with timing only based on first top and bottom detected photons
- Alternative readout patterns with tilted fibers are under study

→ z spatial resolution reduced to 1.5 cm w/o timing (topology only)



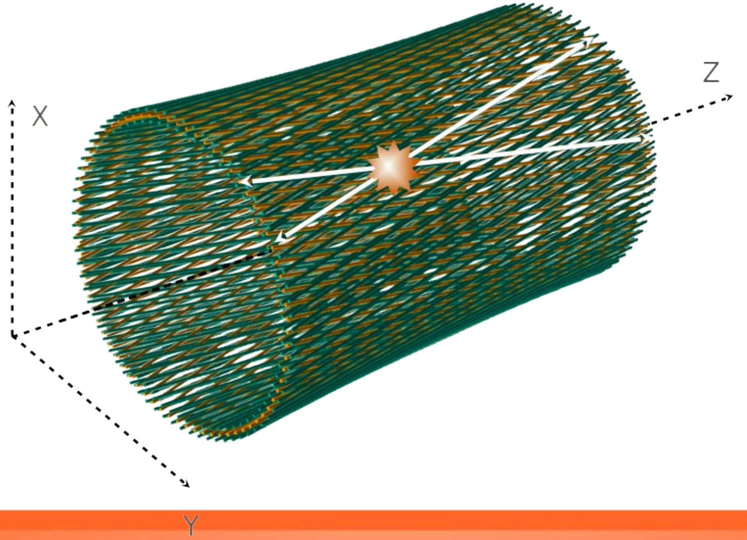


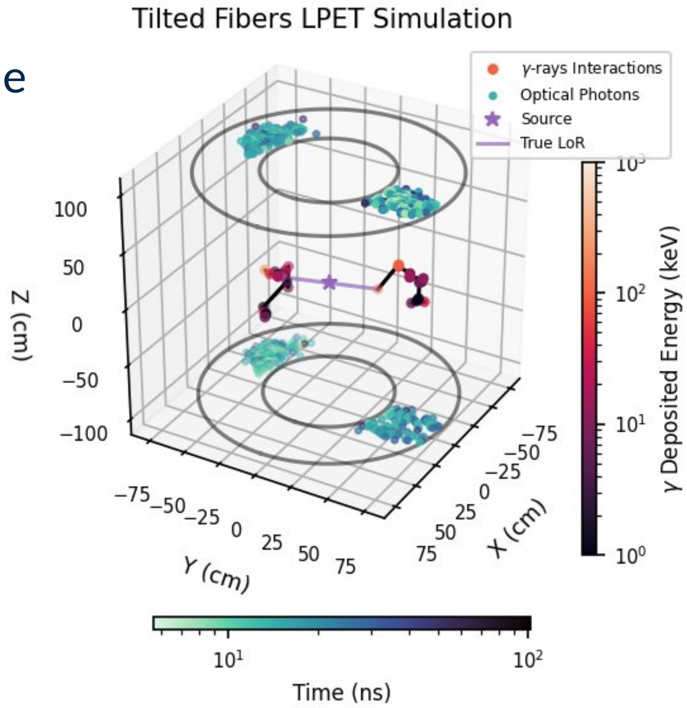
⇒ Need a lot of improvement !

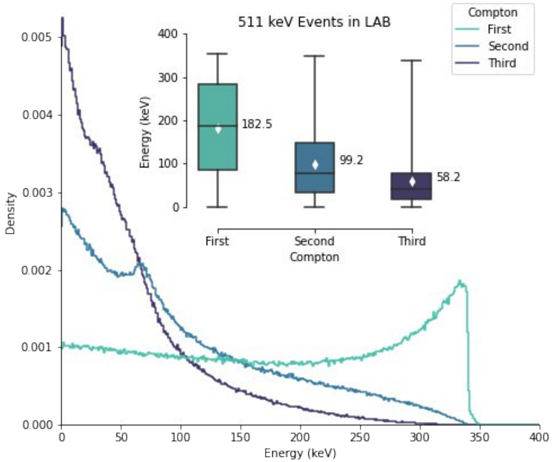
⇒ Combining topology and timing: Analytical model, ML approaches, etc

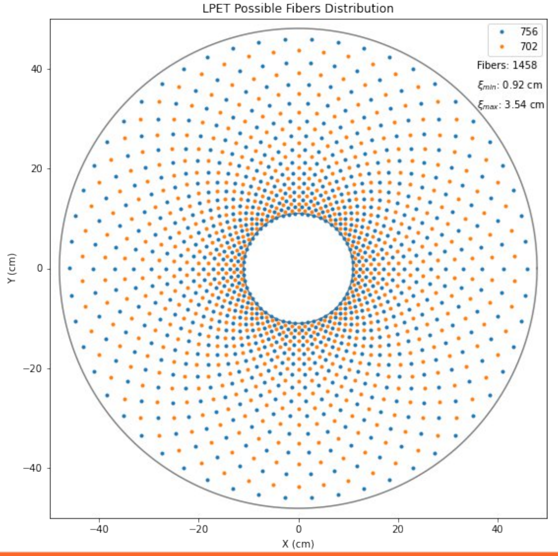
Detector Design and LPET Challenges

- Many of challenges to overcome
  - Low energy deposition (100-200 keV)
  - First Compton events identification
  - Spatial resolution in Z: ➡ reduced to 5 mm
  - Fiber pattern and tilting optimization
  - Event rate: ~1-10 MHz
  - Event reconstruction time: compatible with clinical application (~ 1µs)
  - Tomographic reconstruction









Acknowledgments

LPET-OTech Consortium

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