



# A Novel Total-Body PET Scanner Using Xenon-Doped Liquid Argon Scintillator for Outstanding Detection

An application in medical physics of the DarkSide collaboration

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On behalf of the 3D $\pi$  TB-TOF-PET Collaboration

ASTROCENT



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# PET Principle

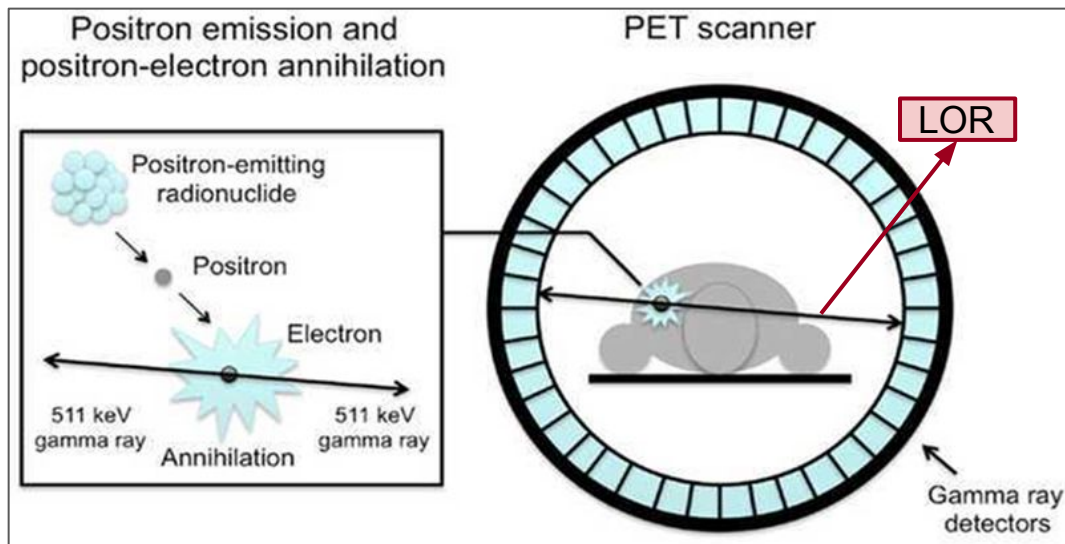
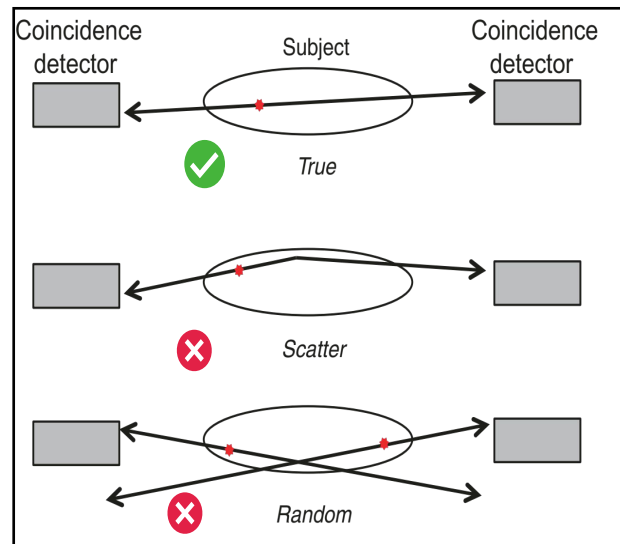


Illustration describing PET annihilations



Three types of coincident events

# Liquid Xenon vs. Liquid Argon

## And Benefit of Cryogenic

0.5%

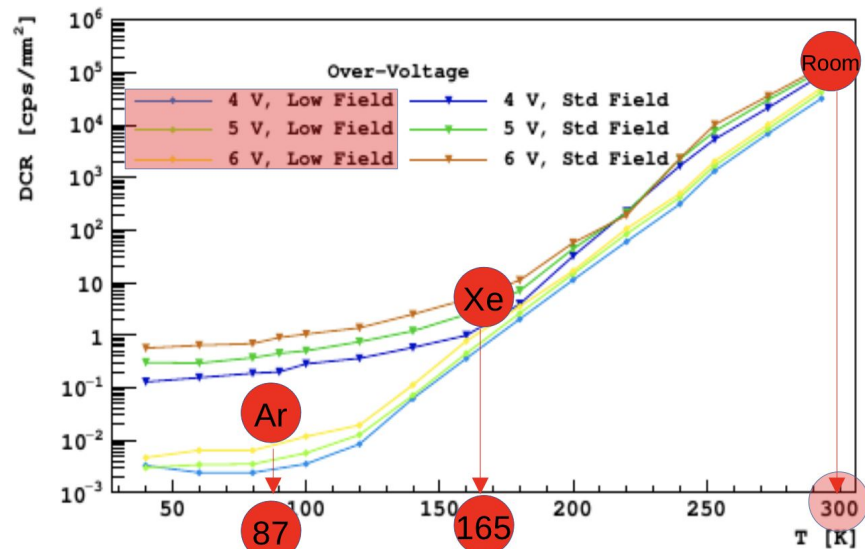
Scintillator:	LAr	LXe	LAr + Xe	LYSO
Decay F/S (ns):	7/1600	4.3/22	~6/100	41
Wavelength (nm):	128	175	~175	420
Density (g/cm <sup>3</sup> ):	1.40	2.94	~1.40	7.1
Temperature (K):	87	162	87	298
Photons/keV:	40	42	~41	28.5
Cost (US\$/kg):	~2	~2000	~2	~4

\*Shorter slow decay time than the pure liquid argon

\*Scintillation light at a wavelength of 175 nm; Xe operates as a wavelength shifter (WLS)

\*Operating at temperatures near the boiling point of argon eliminates the need for cooling and results in lower Dark Count Rate (DCR)

### SiPM Dark Count Rate (DCR) vs. Temperature



<https://oar.princeton.edu/rt4ds/file/1663/1610.01915v1.pdf>

**Reduction in the dark count rate (DCR), improves the timing capability of the devices and Signal-to-Noise Ratio (SNR)**

# 3DPi Overview

## A **Total-body (TB)**, **Time of Flight (TOF)** PET scanner

- Xenon-doped Liquid Argon instead of Crystal scintillators
- Using Silicon Photomultipliers (SiPM)
- Double sided SiPM on scintillation
- Multiple detection layers

## Geometry:

- 9 annulus detection layers
- Each layer has the scintillator sandwiched between two layers of SiPMs
- Each detection layer has ~18 mm LAr thickness
- PTFE supporting structure
- 2 m in length
- Geant4 simulations

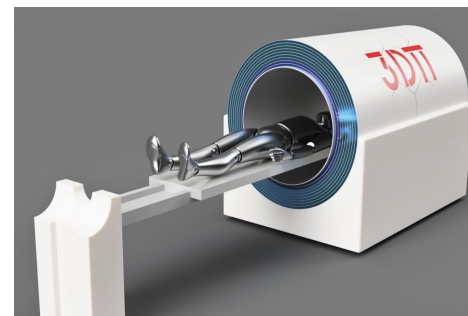
## Two configurations:

\*LAr+Xe

\*LAr+TPB (TetraPhenylButadiene: an organic WLS)

## Geant4 Geometry Parameters

Parameter	Value
Inner radius (cm)	45
Outer radius (cm)	64
Length/AFOV (cm)	200
LAr thickness (cm)	16.2
Number of LAr layers	9
SiPM size (mm x mm)	10 x 10
Number of SiPMs	$\sim 1 \times 10^6$
Cryostat Thickness (mm)	6



3DPi Geometry rendered in Fusion 360

# Fluctuation Sources in Parallel and Perpendicular to LOR

## Sources of fluctuation for construction of events parallel to the LOR:

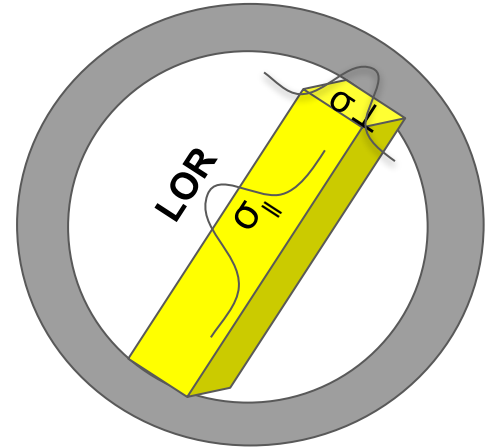
### 1- Timing fluctuations:

- The statistical nature of scintillation photon detection,
- The time resolution of the SiPMs and their associated electronics.

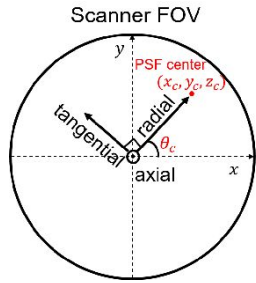
2-Uncertainty resulting from imperfect scatter depth correction within the annular cylinder.

## Sources of fluctuation for construction of events perpendicular to the LOR:

The lattice size of the SiPM layout imposes a limitation on the resolution in each of the two directions perpendicular to the LOR.

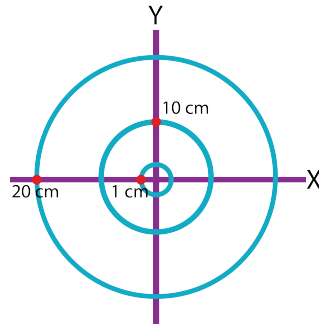


# Spatial Resolution of Single Point Sources

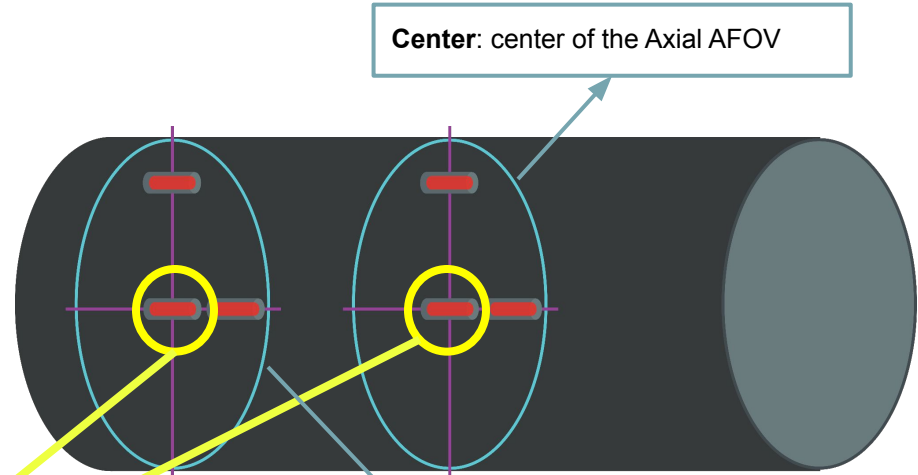


$$\theta_c = \text{atan}(y_c/x_c)$$
$$\rho = x \cos(\theta_c) + y \sin(\theta_c)$$
$$\alpha = z$$
$$\tau = y \cos(\theta_c) - x \sin(\theta_c)$$

Definition of radial, tangential, axial



Radial offsets

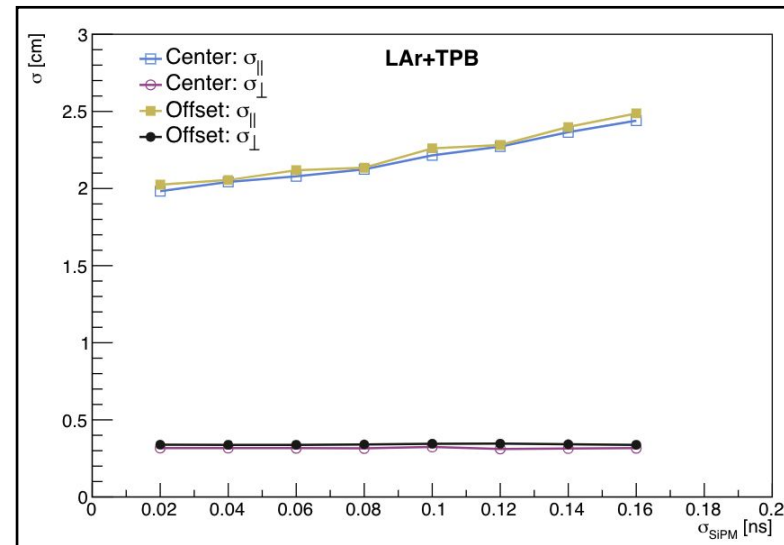
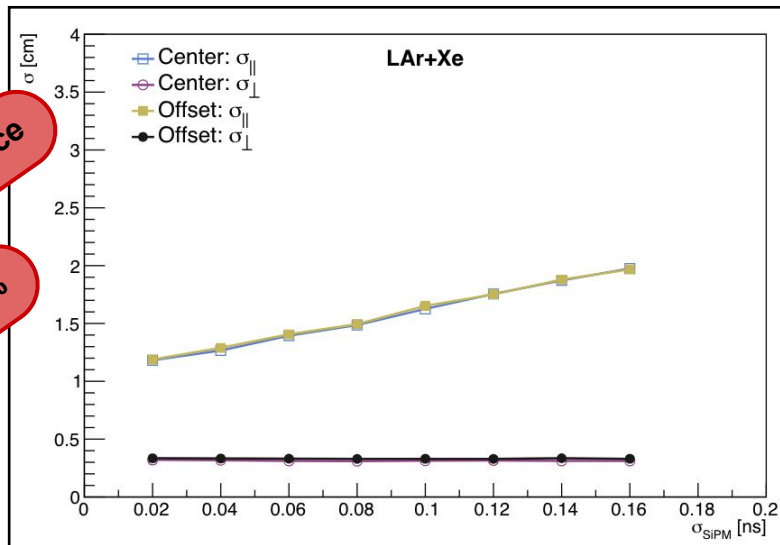


Offset: one-eighth of the AFOV from the end of the tomography device

Two point sources

# Dependence of Spatial Resolution on SiPM Parameters

Spatial resolution, in directions parallel and perpendicular to Line Of Response (LOR)



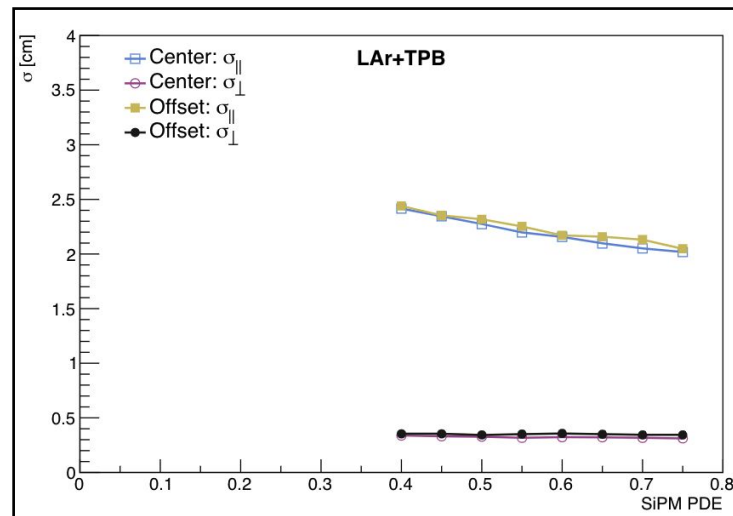
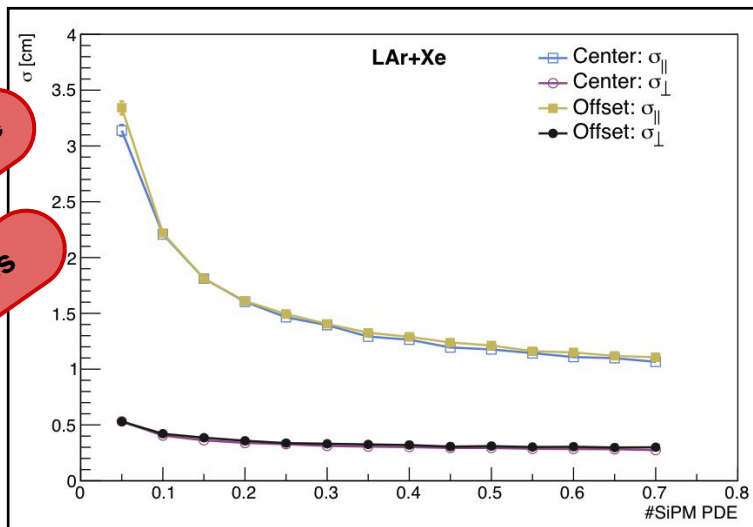
Point Source

PDE = 70%

Desirable timing resolution:  $\sigma_{\text{SiPM}} < 60 \text{ ps}$

# Dependence of Spatial Resolution on SiPM Parameters

Point Source  
 $\sigma_{\text{SiPM}} = 60 \text{ ps}$



Improved PDE (>40%) ensures acceptable resolution, independent of PDE.

In this work, we assume a  $\sigma_{\text{SiPM}} = 60 \text{ ps}$  and the PDE is based on ref [1] at an over-voltage of 4 V.

[1] FBK VUV-sensitive Silicon Photomultipliers for cryogenic temperatures, NIMB, Volume 982, 1 December 2020



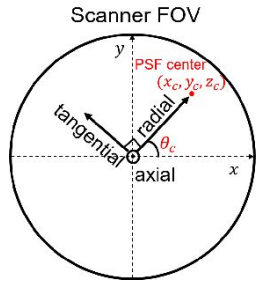
# National Electrical Manufacturers Association



NU 2-2018

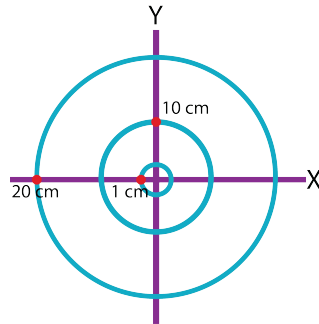
A guide to characterize PET performance

# Spatial Resolution of Single Point Sources

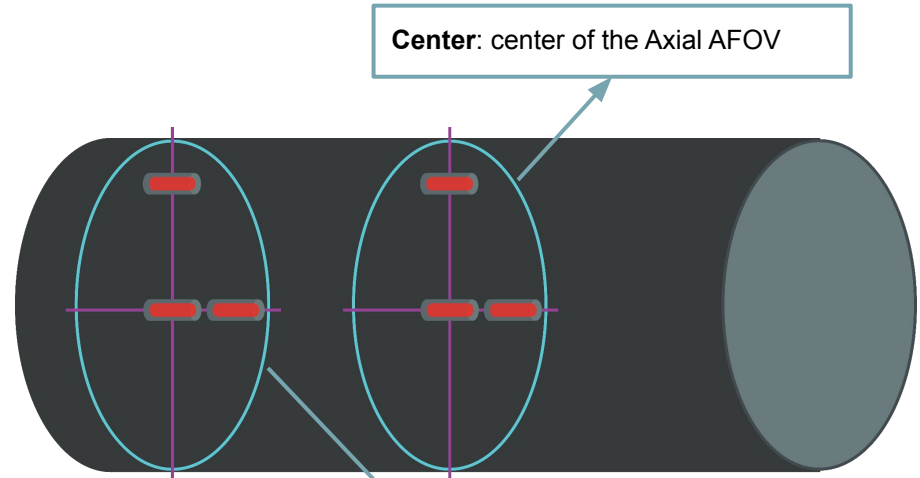


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Definition of radial, tangential, axial



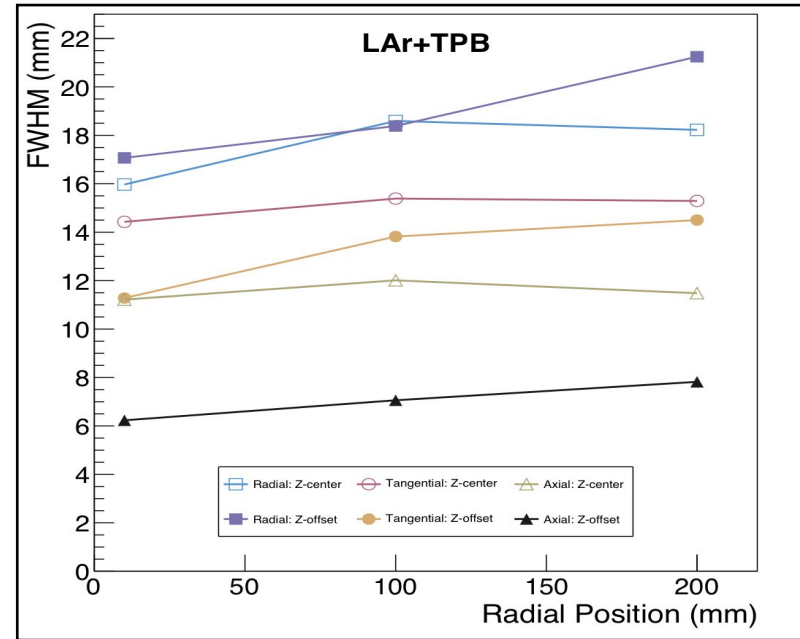
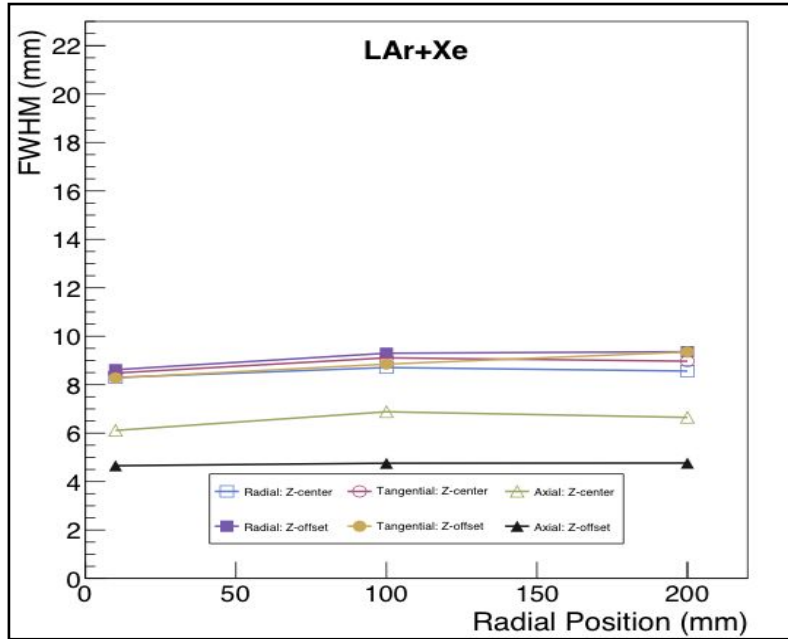
Radial offsets



Offset: one-eighth of the AFOV from the end of the tomography device

# Spatial Resolution of Single Point Sources

Raw data (before image reconstruction stage)



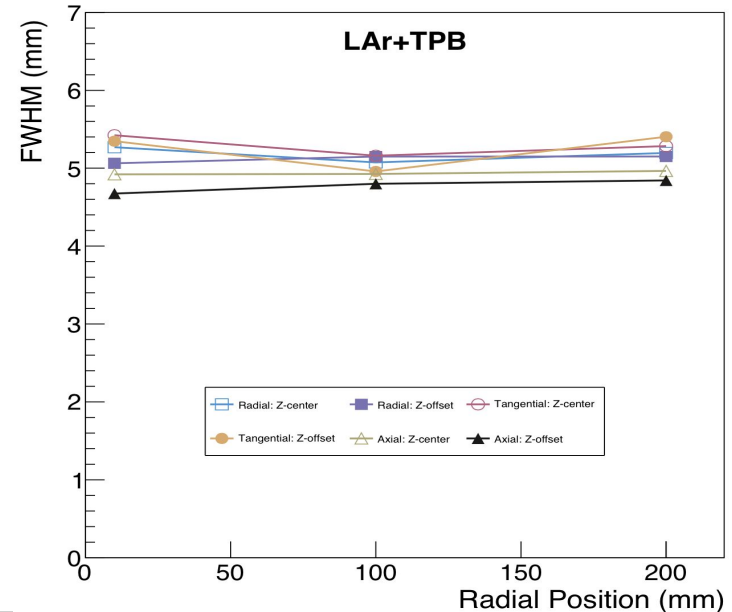
LAr+Xe improves spatial resolution by more than a factor of 2.

# Spatial Resolution of Single Point Sources

*after image reconstruction*

The spatial resolution of a system represents its ability to distinguish between two points *after image reconstruction* (*Filtered backprojection*)

3DPi is able to produce consistent and accurate images regardless of the location of the source.



<b>Central Phantoms:</b>	<b>1 cm radial position</b>			<b>10 cm radial position</b>			<b>20 cm radial position</b>		
<b>Scanner</b>	Radial [mm]	Tangent [mm]	Axial [mm]	Radial [mm]	Tangent [mm]	Axial [mm]	Radial [mm]	Tangent [mm]	Axial [mm]
3DPi (LAR+Xe)	4.8	4.9	4.5	4.9	4.9	4.5	4.8	5.0	4.6
uExplorer (LYSO)	3.0	3.0	2.8	3.4	3.1	3.2	4.7	4.0	3.2

# Sensitivity

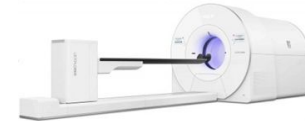
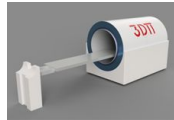
The sensitivity test measures the counts per second that the scanner measures for every unit of activity present in a source.

$$S_{\text{tot}} = \frac{R_{\text{CORR},0}}{A_{\text{cal}}}$$

$S_{\text{tot}}$ : System Sensitivity

$R_{\text{CORR},0}$ : The true coincidences count rate with no attenuation

$A_{\text{cal}}$ : Line source radioactivity



Line source radial position in transaxial field of view	3DPi LAr+Xe (200 cm AFOV) [kcps/MBq]	GE SIGNA PET/MR (25 cm AFOV) [kcps/MBq]	uExplorer PET/CT (192 cm AFOV) [kcps/MBq]
<b>Center</b>	564.0	21.8	174.0
<b>10 cm radial offset</b>	501.1	21.2	177.0

A higher system sensitivity indicates that the scanner can detect a larger fraction of the emitted photons, which allows for shorter scan times or lower radiotracer doses.

# Noise Equivalent Count Rate (NECR)

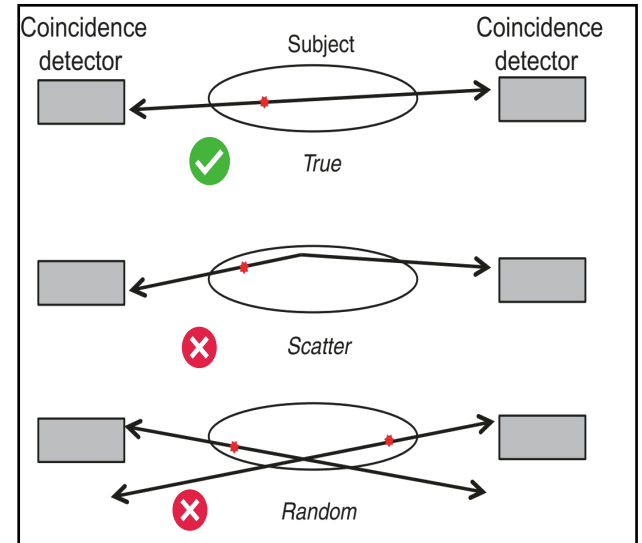
$$NECR = \frac{T^2}{T + R + S}$$

Noise Equivalent Count Rate: ability to detect and accurately quantify true coincident counts while minimizing the impact of noise, (random, and scatter events.)



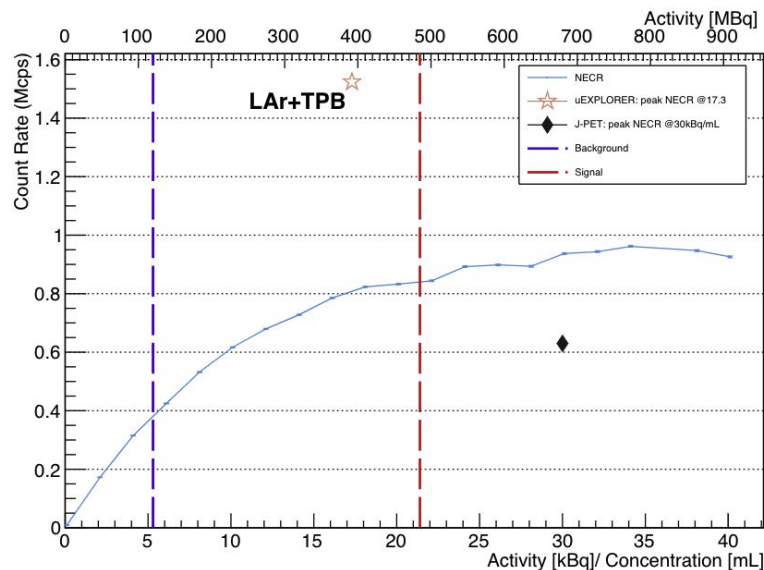
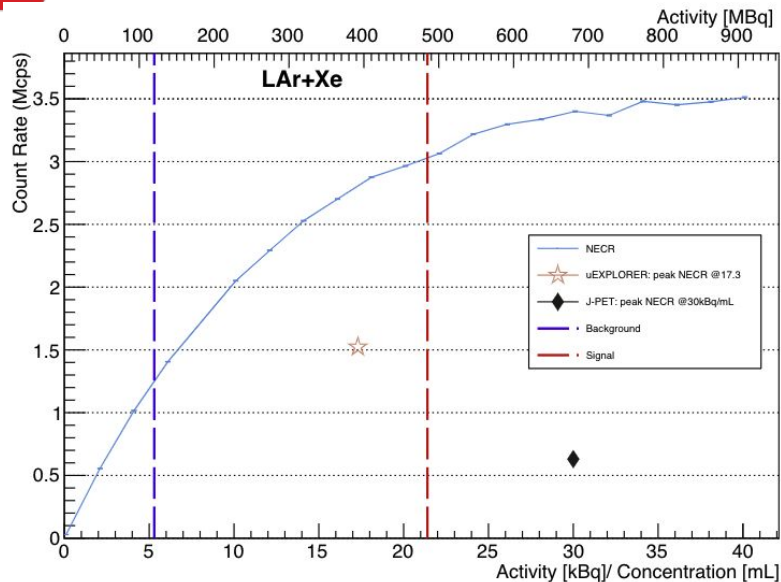
## Source Distribution:

A solid right circular high density polyethylene cylinder with a line source.



Three types of coincident events

# Noise Equivalent Count Rate (NECR)



**Background:** Activity concentration used as the background in the Image Quality test

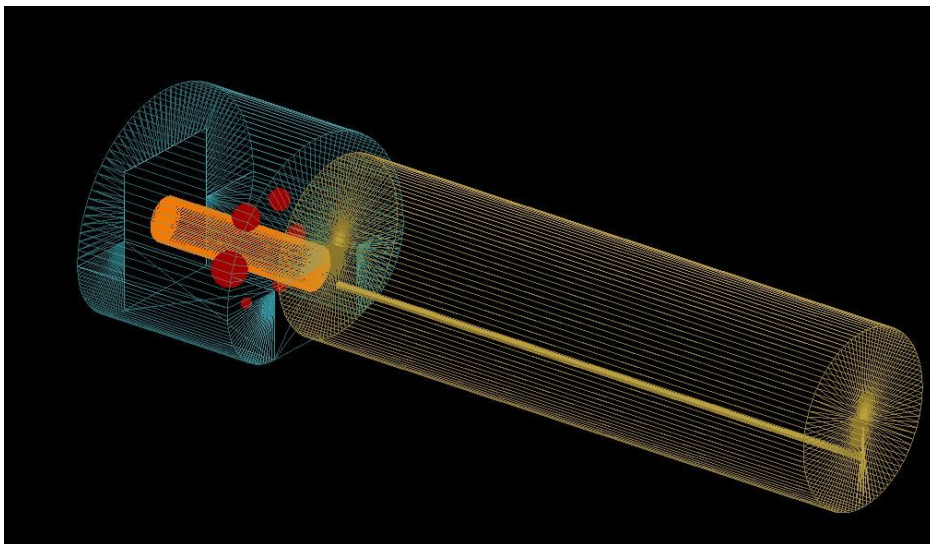
**Signal:** Activity concentration used as the signal in the Image Quality test

$$NECR = \frac{T^2}{T + R + S}$$

**Higher NECR at lower activity decay rate means extremely reduction radiopharmaceutical dose**

# Image Quality

- Measure **image contrast** and **background variability** using “hot” spheres in a uniform background
- Data generation and process **still ongoing**



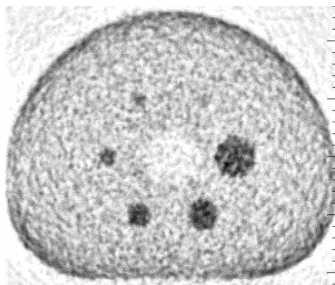
Spheres (Red) phantom geometries  
Activity concentration:  $4 \times 5.3 \text{ kBq/mL} = 21.2 \text{ kBq/mL}$

Activity concentration:  $5.3 \text{ kBq/mL}$   
Body (Cyan) and Test (Gold) phantom geometries

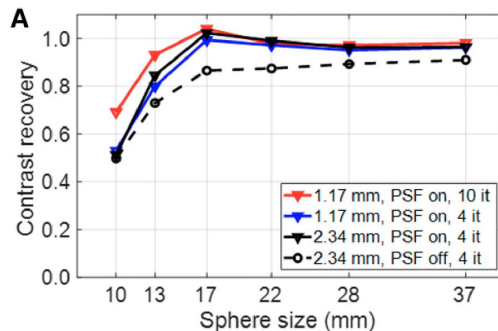
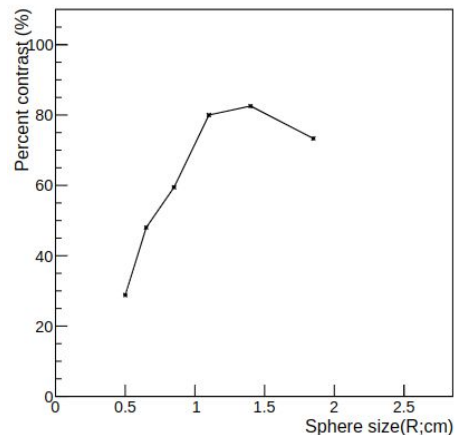
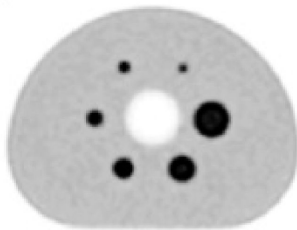


# Image Quality

3DPI  
scanned for 5 s.



uEXPLORER  
scanned for 30 min.

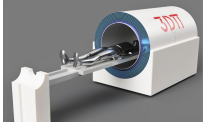






Percent contrast=

$$\frac{\left( \frac{C_{H,j}}{C_{B,j}} \right) - 1}{\left( \frac{a_H}{a_B} \right) - 1} \times 100\%$$

$a_B$ : the activity concentration in the background; 5.3 kBq/mL  
 $a_H$ : The activity concentration in the hot spheres; 4\*5.3 kBq/mL

# Comparison of NEMA Test Results

Scanner	Peak NECR [Mcps]	Activity concentration at peak [kBq/mL]	Sensitivity [kcps/MBq]	Timing resolution [ps]
 <b>3Dπ (MC) (Preliminary)</b>	~3	17.3*	560	163
	~3.5	30**		
 <b>uEXPLORER TB-PET/CT</b>	~1.5	17.3	174	412
 <b>J-PET-TB (MC)</b>	0.63	30	38	500
 <b>GE SIGNA PET/CT</b>	0.22	20.8	21.8	386
 <b>VRain PET</b>	0.14	9.8	25	229

The preliminary results demonstrate that our scanner system performance is comparable to commercial scanners.

\*Activity concentration at peak NECR, uEXPLORER

\*\*Activity concentration at peak NECR, J-PET

# Ongoing activities: Cryogenics and Hardware

- Developing a hardware prototype of a LAr+Xe PET ring at Cagliari, Sardinia
  - ❖ A dedicated laboratory is being set up in Sardinia for conducting tests and commissioning the cryostat.
- INFN Torino developed a front end ASIC board
- Testing the ALCOR board at Princeton University

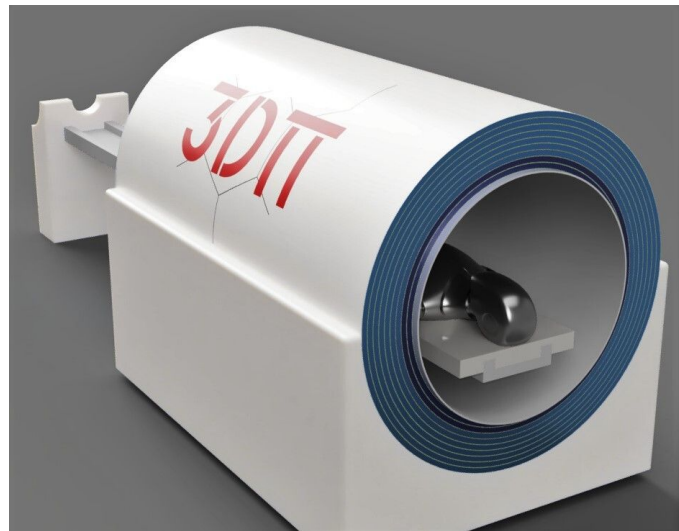
## Next steps

### Simulation/Software

- Experiment with newer reconstruction algorithms
- Improve Geant4 simulation
- Optimize detection layer geometry

### Hardware

- Testing ALCOR board with LAr+Xe
- Ensuring stability and homogeneity of LAr+Xe
- Set up cryogenic infrastructure at Sardinia
- Develop the PET scanner prototype





# Thank you

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