Using Xenon-Doped Liquid Argon Scintillation for Full-Body, Time of Flight Positron Emission Tomography

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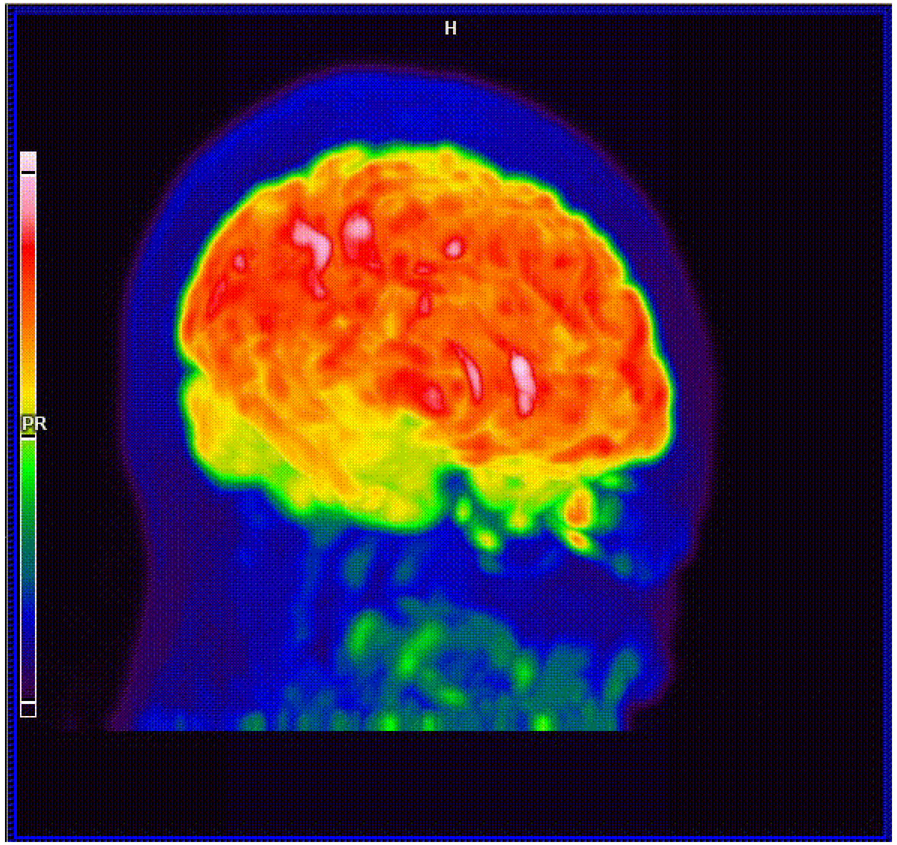
Background: What is PET?

- Positron Emission Tomography (PET) is a medical imaging technique used to observe metabolic activity in cells and tissue



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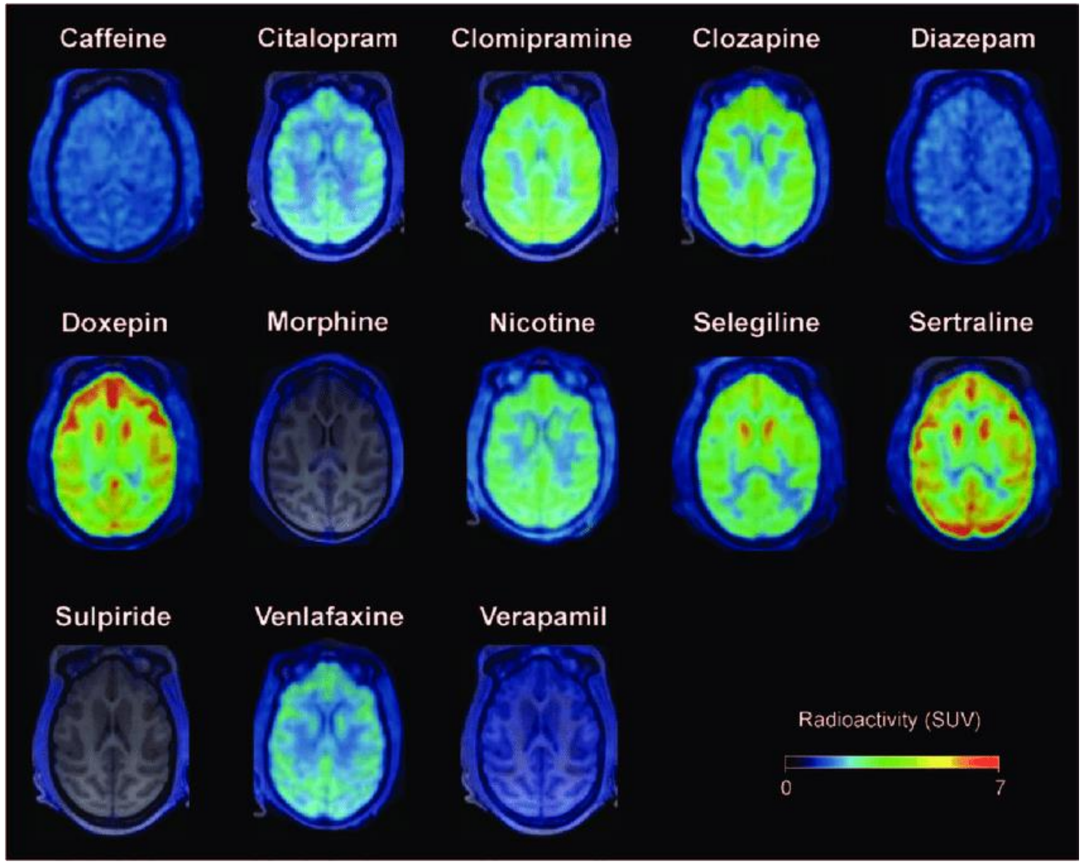
- Locate tumors and diagnose patients
- Monitor patient's response to therapy



Background: What is PET?

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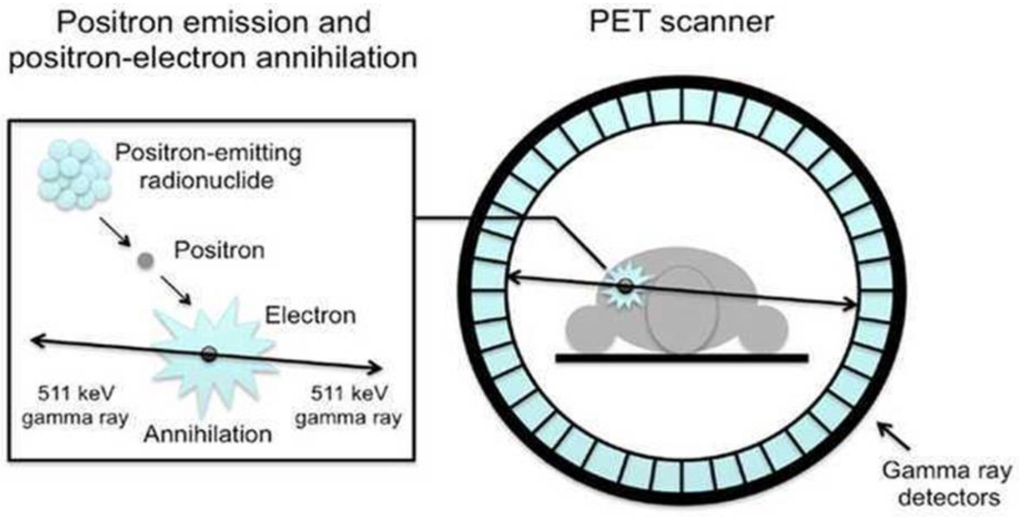
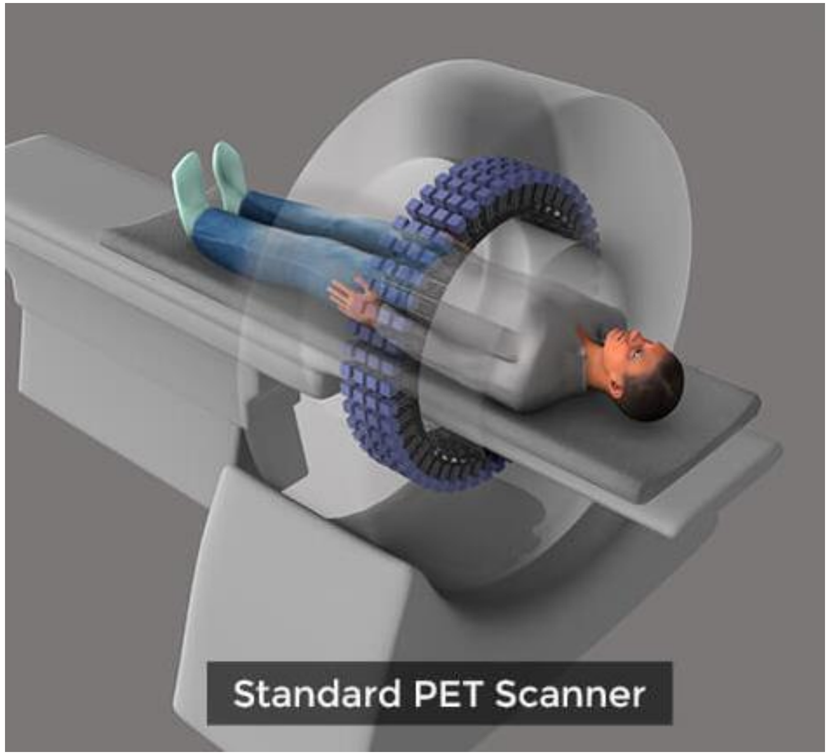
- Locate tumors and diagnose patients
- Monitor patient's response to therapy
- Patient inoculated with a radiotracer such as FDG (F-18, e+)
- e- and e+ annihilation - > two 511 keV γ
- Reconstruct the annihilation event



3-Dimensional Positron Identification (3DPi)

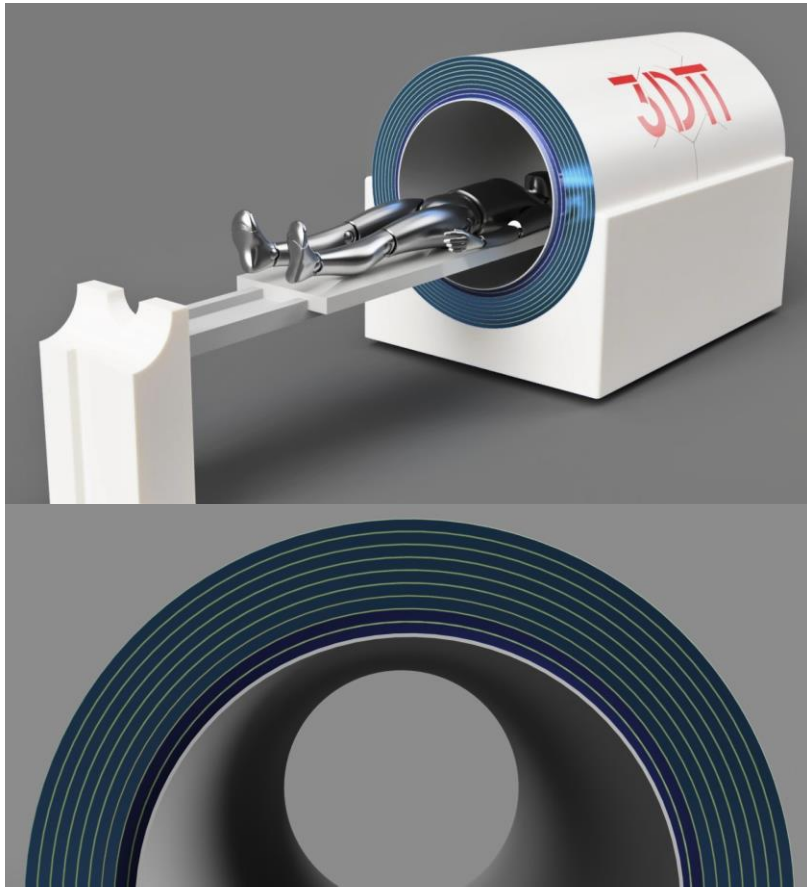
- Traditional PET:
  - 20-30 cm coverage
  - Used photomultiplier tubes as photosensors (now solid-state)
  - Crystal Scintillation: Lutetium-yttrium oxyorthosilicate (LYSO)



Credit: Simon R. Cherry, University of California, Davis

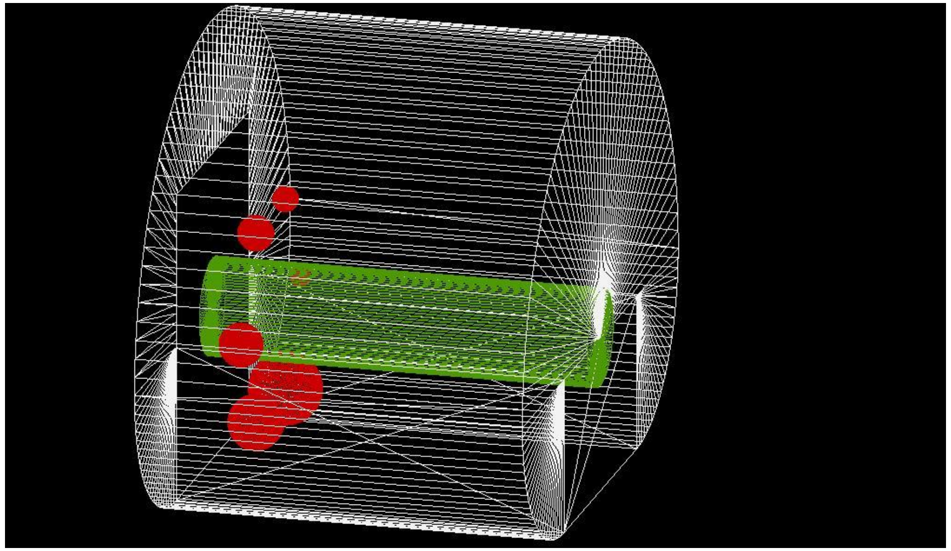
3-Dimensional Positron Identification (3DPi)

- Traditional PET:
  - 20-30 cm coverage
  - Used photomultiplier tubes as photosensors
  - Crystal Scintillation: Lutetium-yttrium oxyorthosilicate (LYSO)
- 3DPi:
  - Full body (2 m coverage)
  - Use NUV SiPMs as photosensors
  - Can use time of flight (TOF) information
  - Xenon doped Liquid Argon (LAr+ Xe)



Geant4 Simulations

- Simulations based off the Geant4 from DarkSide
  - Optical properties of LAr Scintillation light
  - Real DarkSide-50 detector data used
- 9 detection layers
  - SiPMs assumed a 40 ps intrinsic timing resolution
  - Each detection layer has ~18 mm LAr thickness
  - Titanium cryostat assumes a thickness of 6mm



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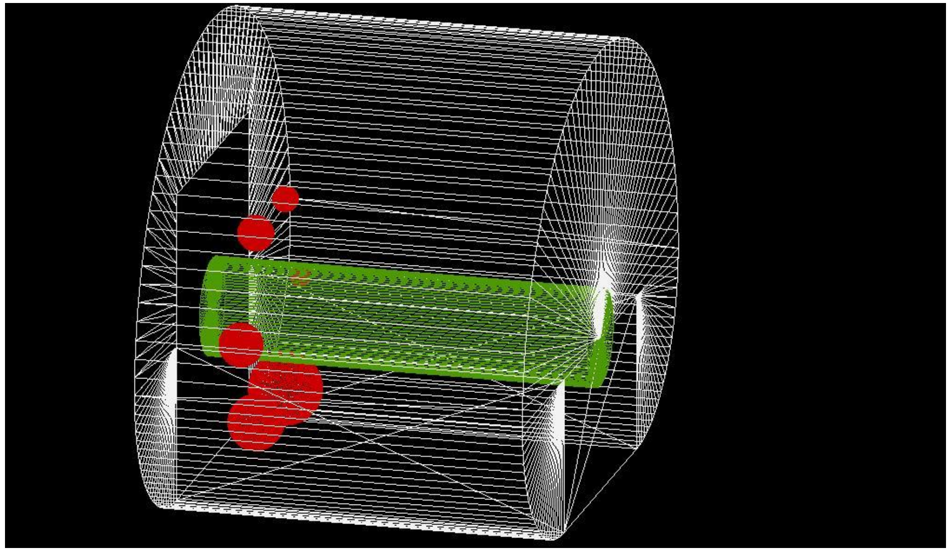


Work in progress to construct a small prototype!

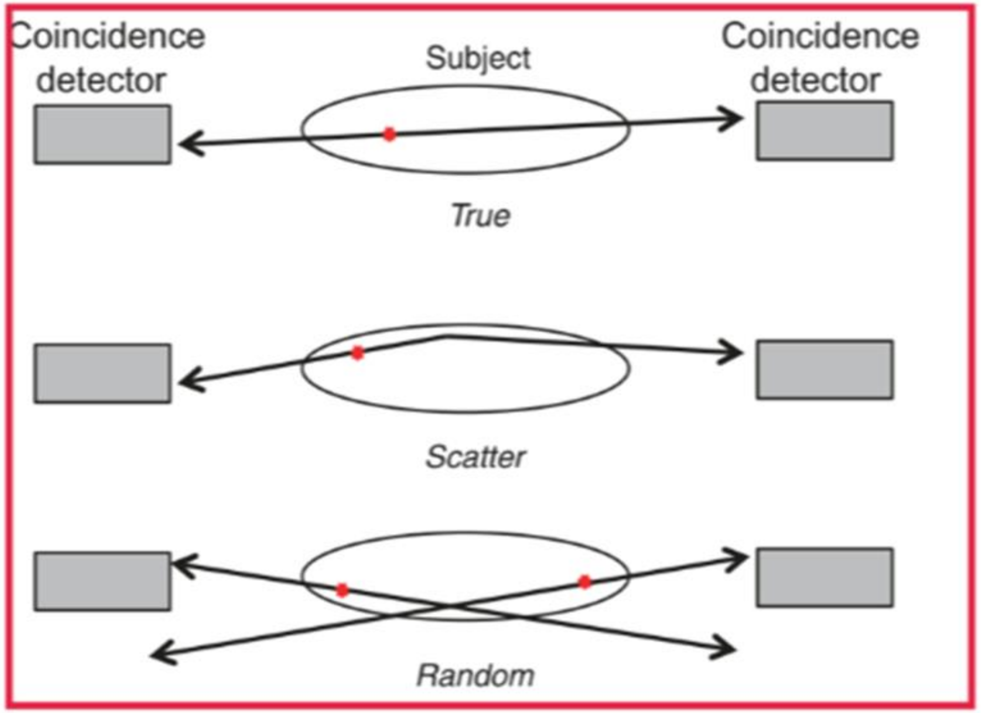
3DPi Performance: NEMA Tests

- The National Electrical Manufacturers Association (NEMA) has a guide to characterize PET performance
- Use these tests to benchmark scanner and compare with others
- Used the guide NEMA NU 2-2018
- Conducted the tests
  - Scatter Fraction
  - Spatial Resolution
  - Sensitivity

National Electrical Manufacturers Association

3DPi Performance: Scatter Fraction

- Measure of the system's sensitivity to scattered radiation
- $SF = \frac{\sum_i C_{r+s,i,j} - \sum_i C_{r,i,j}}{\sum_i C_{TOT,i,j} - \sum_i C_{r,i,j}}$
- $NECR = \frac{T^2}{T+R+S}$



Three types of coincident events

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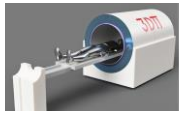
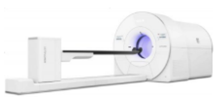
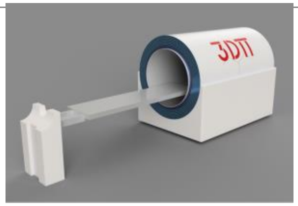
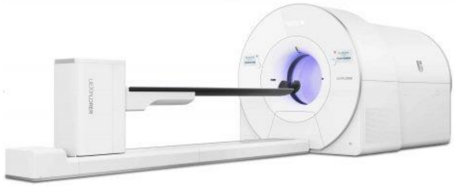




Scanner	Peak NECR (~good true counts) [Mcps]	Activity concentration at peak [kBq/mL]	Scatter Fraction [kcps/MBq]
3Dπ (MC) (Preliminary)	~8.75	~8	35.2%
uEXPLORER TB-PET/CT	~1.5	17.3	36.3%
J-PET-TB (MC)	0.63	30	36.2%

3DPi Performance: Spatial and Sensitivity





	Values	LAr + Xe	GE Signa PET/MR	GE Discovery 710 PET/CT	uExplorer (Full body TOF-PET)
Center Position (1 cm)	$\sigma_{tangential}$ (mm)	5.3	4.7	4.7	2.9
	σ_{radial} (mm)	5.0	4.4	4.9	3.2
Off-center Position (20 cm)	σ_{radial} (mm)	5.0	8.4	5.3	4.8
	$\sigma_{tangential}$ (mm)	5.4	5.2	4.8	4.6
	σ_{axial} (mm)	3.9	7.3	5.6	3.4
	Sensitivity (cps/kBq)	505	21.8	5.5	~174
	Timing Res. (ps)	~163	~ 386	NA	~412

3DPi Performance: Sources of Noise for 3DPi

- Noble liquid detectors (such as DarkSide) usually encounter these backgrounds
  - Argon-39
  - Krypton-85
  - Radon Decay chain
  - Cosmic Muons

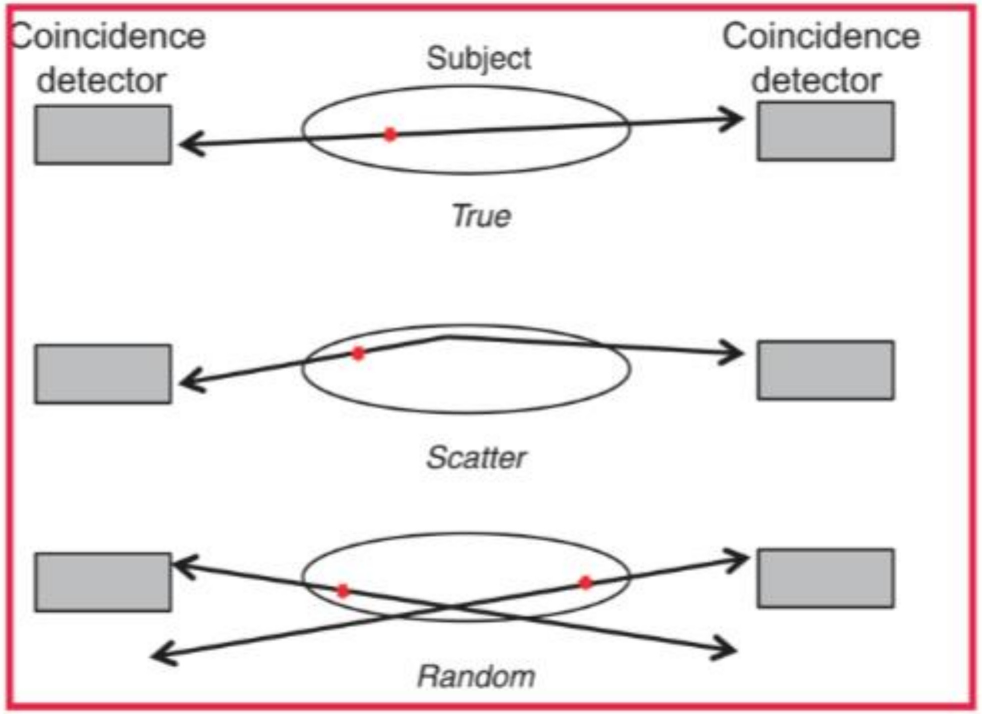
3DPi Performance: Sources of Noise for 3DPi

- Noble liquid detectors (such as DarkSide) usually encounter these backgrounds
  - Argon-39 ($T_{1/2}$ = 230 yr, 10 $\frac{mBq}{m^3}$, e-)
  - Krypton-85 ($T_{1/2}$ = 10.5 yr, 1 $\frac{Bq}{m^3}$, e-)
  - Radon Decay chain (50 $\frac{Bq}{m^3}$, decay (α,β-) products energy > 511 keV)
  - Cosmic Muons (1 $\frac{\mu}{min*cm^2}$ yr @ 16 ft & 100 $\frac{\mu}{min*cm^2}$ yr @ 4200 ft)

Backgrounds too low or high of energy to be of great significance. PET activity concentrations on the order of $\frac{kBq}{mL}$

3DPi Performance: Sources of Noise for 3DPi

- Typical PET noise
  - Scatters (Compton and Rayleigh)
  - Randoms (two gammas from two separate annihilations tagged as one)



Three types of coincident events

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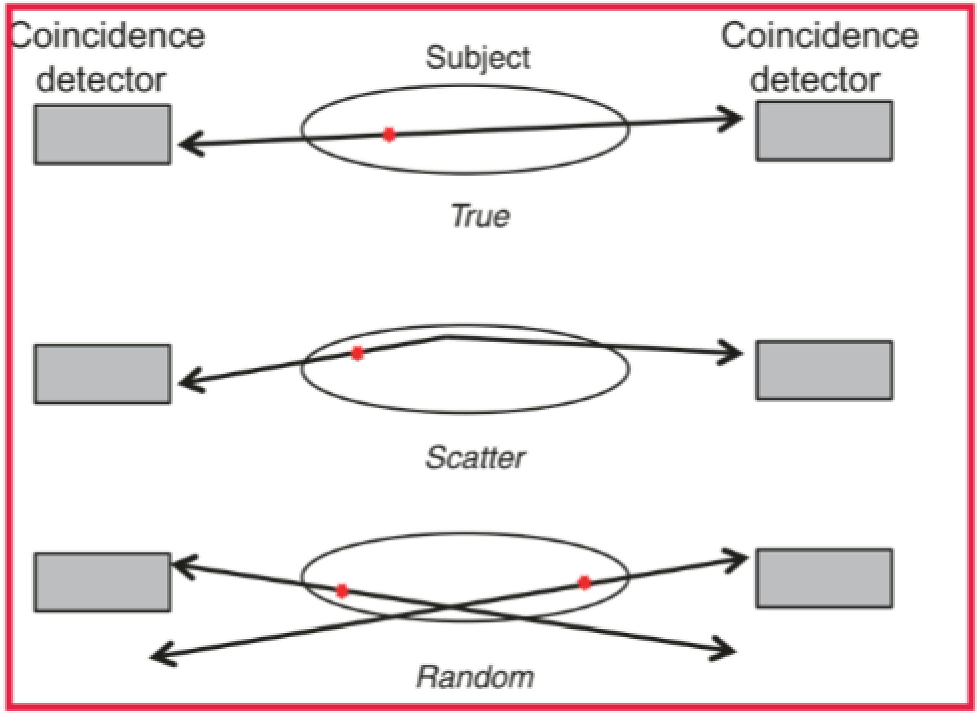
Ongoing work to characterize these types of noise for this cryogenic scintillation in this use case



Three types of coincident events

Last remarks

- Increase in detector size yields large increase in sensitivity but more data
- Total-body PET will open up new avenues of research and clinical studies
- Results from simulations are very promising, especially for low dose PET
- Scanner can reduce scan durations or radioactive tracer dosage given to patients
- Still a lot of work to be done (newer image reconstruction, noise profile, prototype)

Thank You

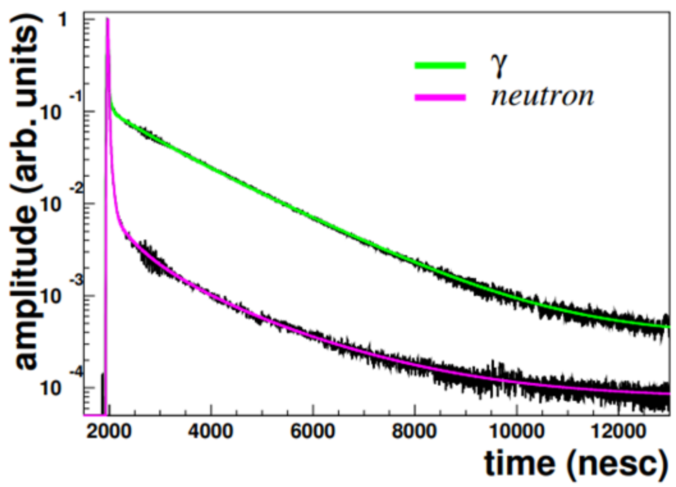
Backup

Xenon Doped Liquid Argon (LAr+Xe)

- Liquid Argon is cheap, monolithic and cryogenic (87 K)
- Although, it has a long scintillation component which degrades TOF resolution
- Xenon has better scintillation but is expensive

Property	Argon	Xenon
Fast decay time (ns)	7	4.3
Slow decay time (ns)	1600	22
Light yield (photons/keV)	40	42
Wavelength (nm)	128	175
Density at boiling temperature at 1 atm (g/cm^3)	1.40	2.94
Cost (US$/kg)	~2	~2000

Credit Wahl et al (2014): arXiv:1403.0525



Credit Akimov et al (2019) : arXiv:1906.00836

Xenon Doped Liquid Argon (LAr+Xe)

- Dope small amounts of Xenon into Lar
- Concentrations up to 1000 ppm.
- Combine perks of both scintillators
- Suppresses long decay component from 1 µs to ~90 ns around 100 ppm and beyond.
- Increase in light yield from xenon doping.

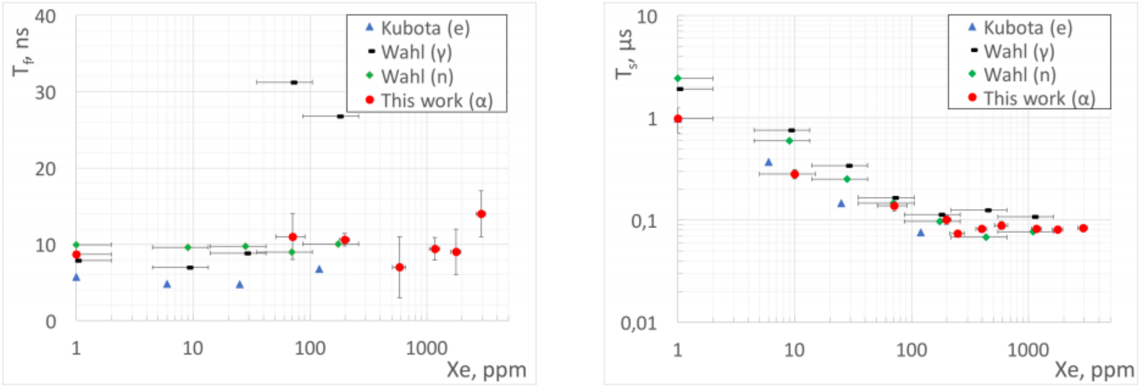
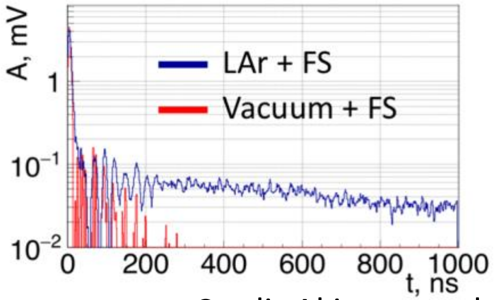


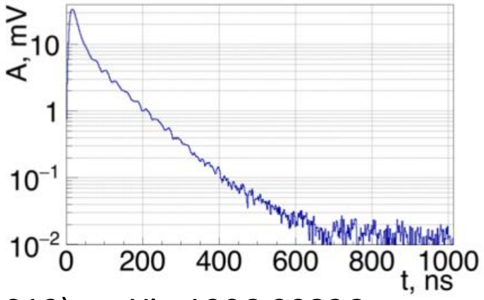
Figure 7. Fast (left) and slow (right) decay times for different Xe concentrations.

Credit Akimov et al (2019) : arXiv:1906.00836

<u>Pure Argon</u>



<u>Xe concen: 1170 ppm</u>



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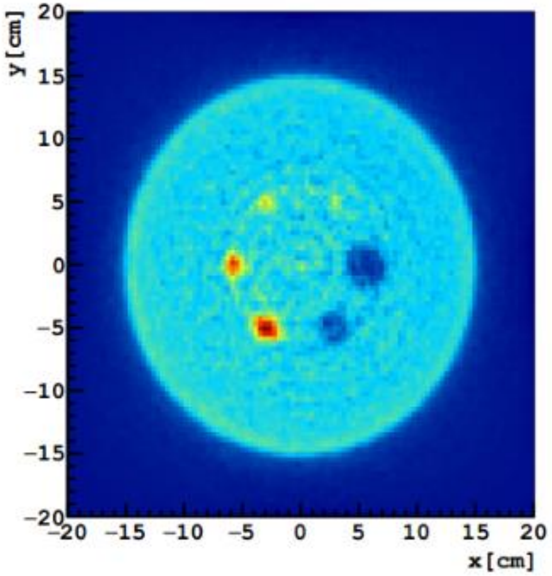
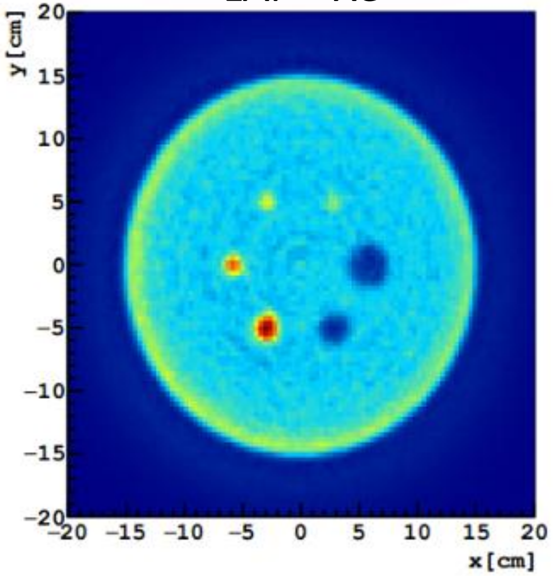
3DPi Performance: Image Quality

- 4 radioactive sources with 2 water sources arranged in a ring
- Each source varies in size an activity

LAr + TPB

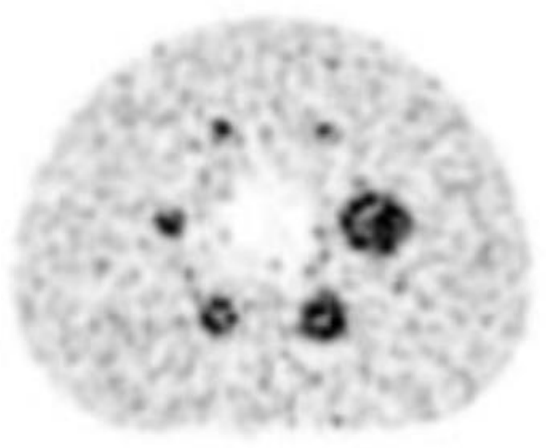


LAr + Xe



10^9 Positron Annihilations. 15 – 30 second scans

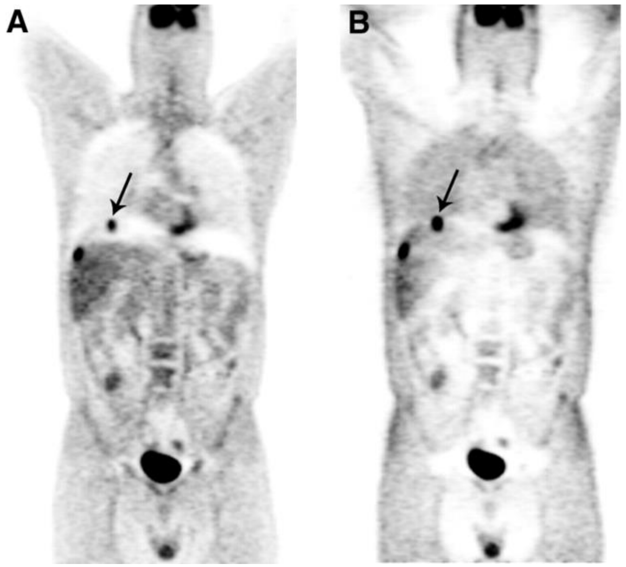
Crystal Scintillator (EXPLORER)

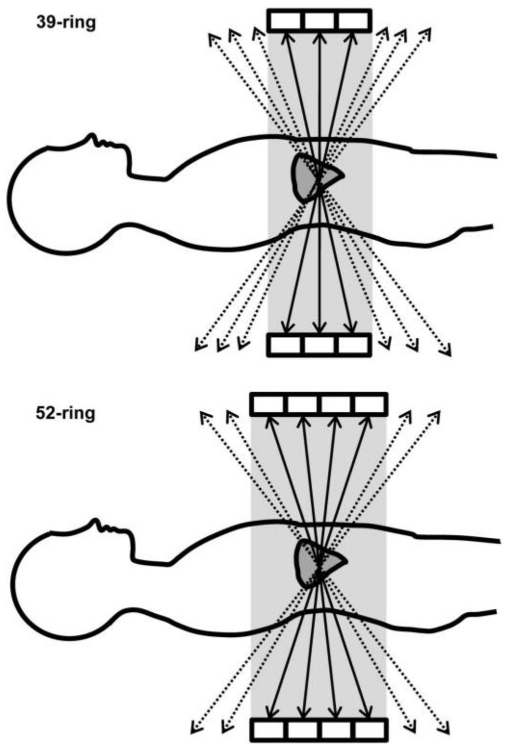


$\sim 1\ x\ 10^9$ Positron Annihilations. 10-minute scan

Limitations of current PET Scanners

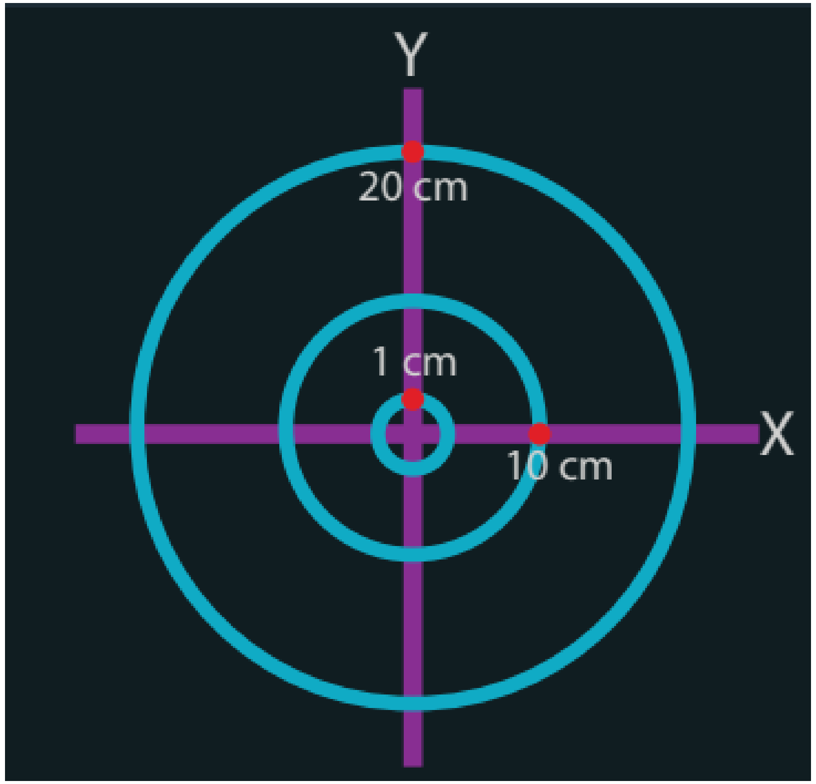
- Scanner's coverage low (~20-30 cm).
- Small sensitivity for gammas.
- Difficult full body scanning.
- Increasing dosage raises sensitivity, gamma scattering. Leads to false coincidences.
- Typical imaging scan is 30 -35 minutes.
- Motion image artifacts, distortions.





Spatial Resolution

- It is the FWHM of the point source response function in all three directions
- Axial, Radial and Tangential Resolutions
- 1 Source in 6 different positions
- Source is small cylinders , radius: 1 mm , length: 1 mm (Source encapsulated by water)
- For each simulation you only choose one position
- Events per simulation: 100K
- Filtered Backprojection reconstruction

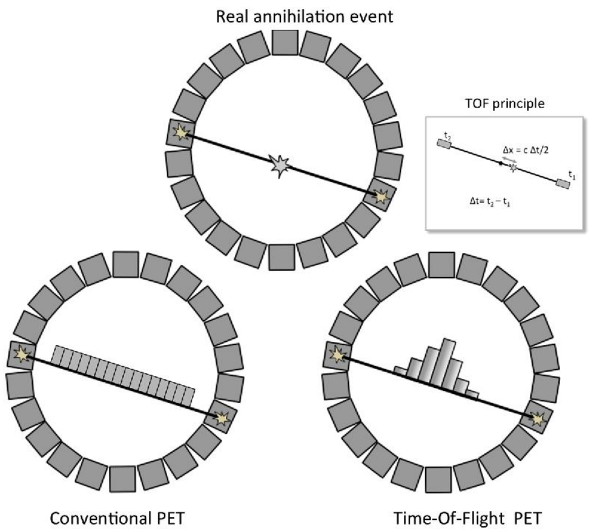


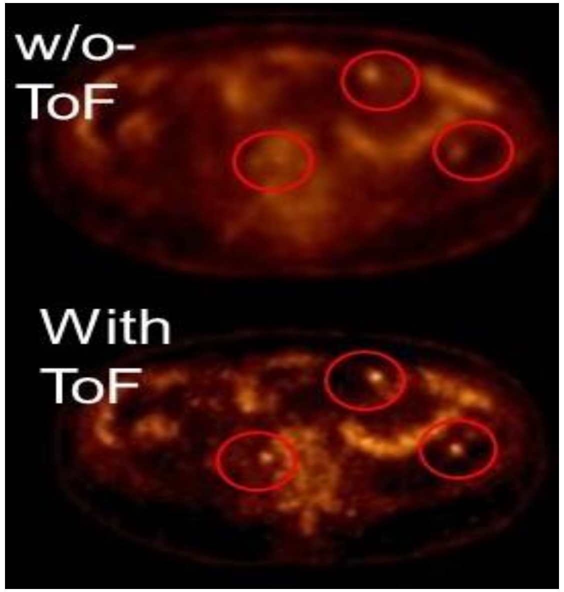
Using Time of Flight (TOF)

- Using TOF info of annihilation photons to improve image quality
- Use Silicon Photomultipliers (SiPM)
- Improves signal to noise ratio (SNR)

$$\Delta x = c\frac{\Delta t}{2} \qquad \Delta t = t_2 - t_1$$

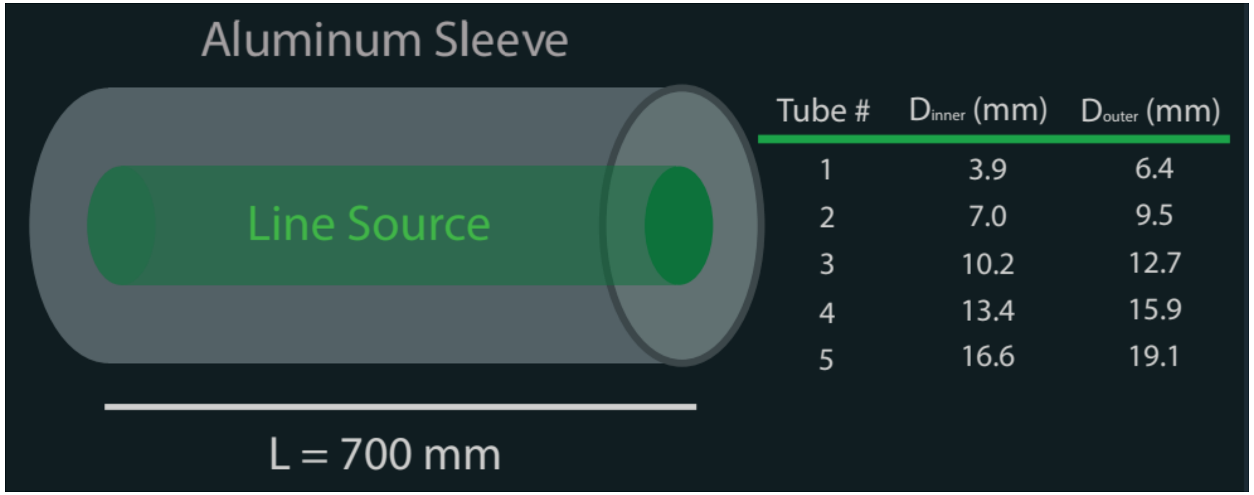
Delta x is the distance from the center of the rings to annihilation vertex





Sensitivity test

- Number of detected counts per unit time for each unit of activity within the source (cps/kBq)
- Line source encapsulated by an aluminum sleeve(s)
- For each simulation, add an additional sleeve.
- 10k events per simulation
- Extract the corrected count rate and divide by the corrected initial activity of the source



Why is sensitivity a big deal?

Explorer Scanner (UC Davis Health)

https://www.youtube.com/watch?v=JaszDkmgfMY&feature=emb_title