Cameras, Detectors for Internal Diagnostic Imaging – SPECT, PET, and beyond

State-of-the-art Challenges and Emerging Technologies

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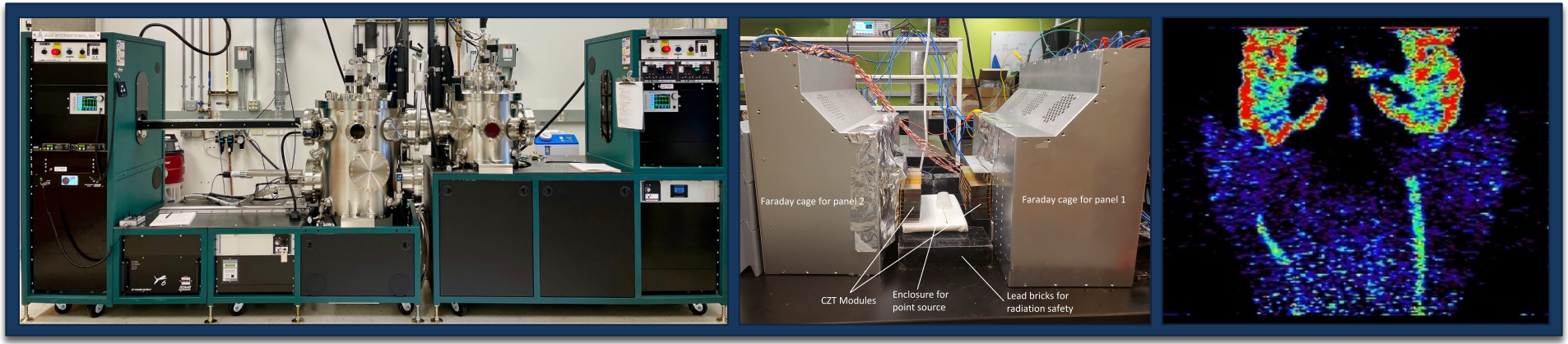
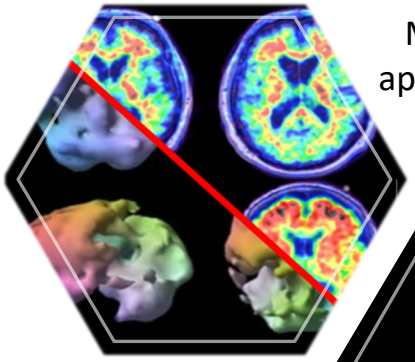
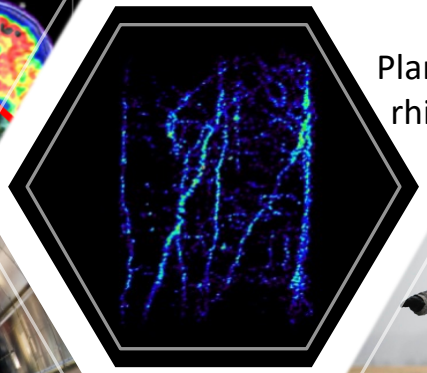


Detectors:
A tool with many applications



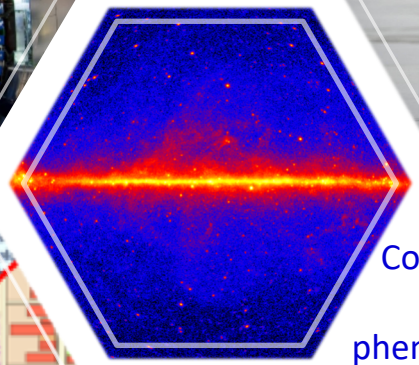
Medical imaging applications include SPECT and PET



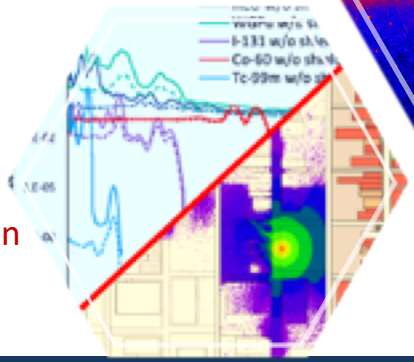
Plant and soil imaging for rhizosphere discoveries

Understanding the building blocks of matter

Personal security and surveying

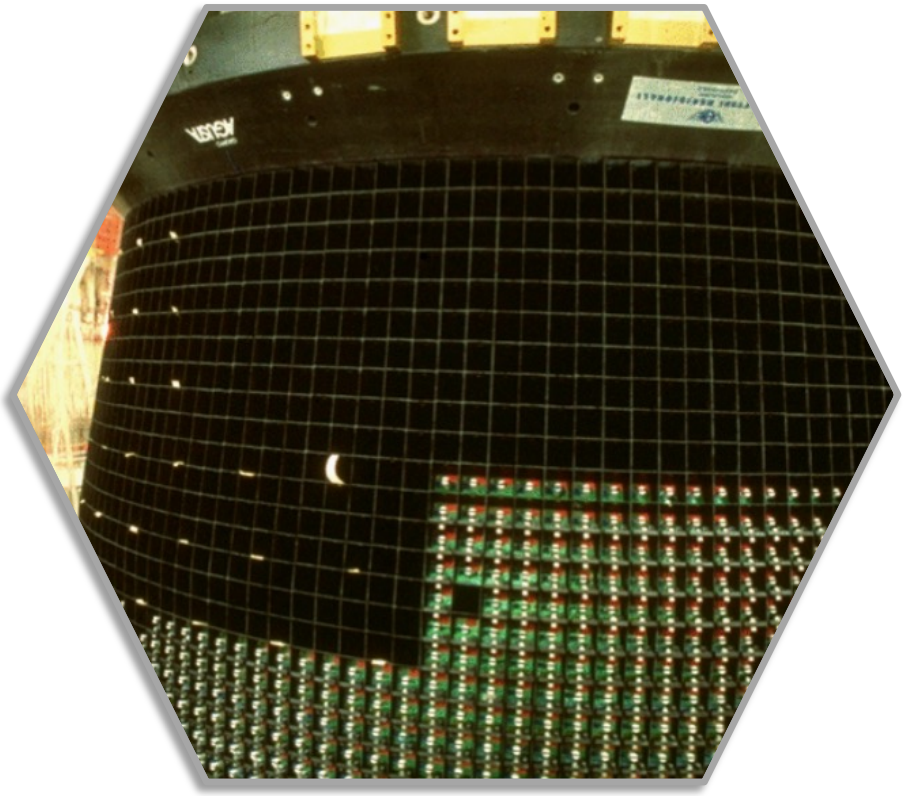


Cosmic imaging and astronomical phenomena monitoring

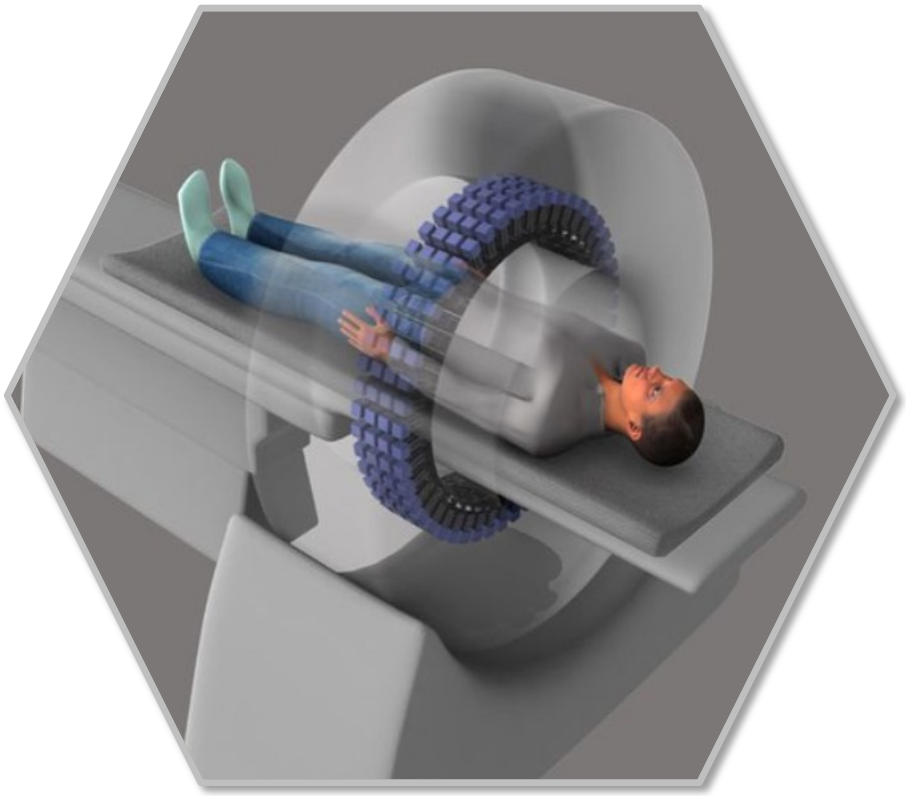


Source identification

Detectors:
From Particle Physics to Medical Imaging



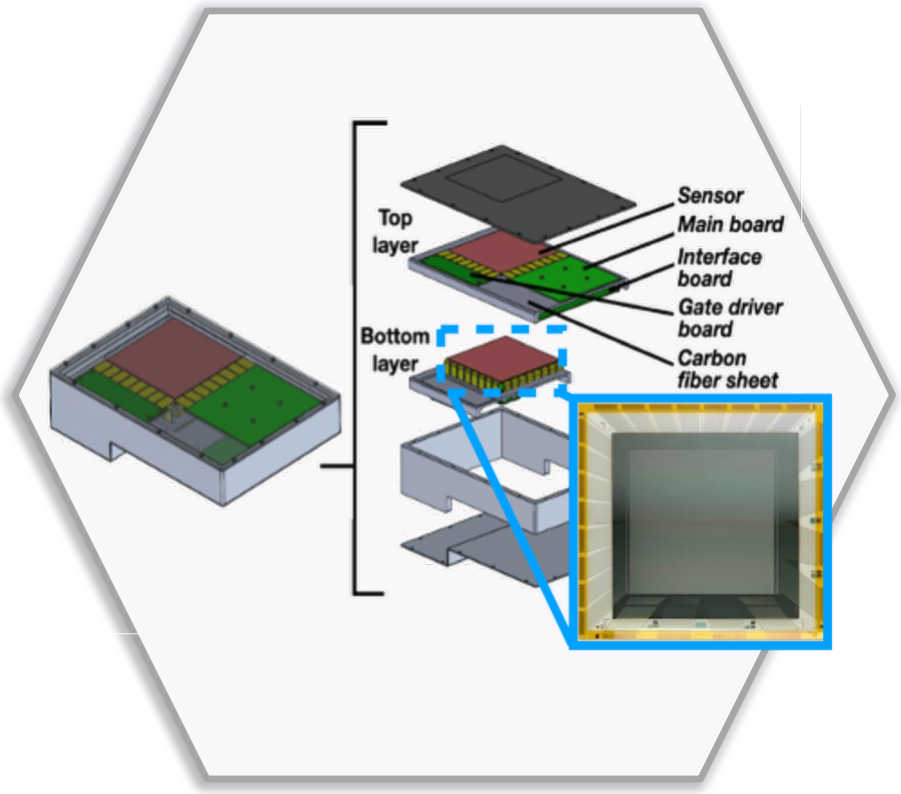
BGO crystals in calorimeter of L3 experiment at LEP collider at CERN



Advancement of PET scanners

Fleming, B., and I. Shipsey. "Basic Research Needs for High Energy Physics Detector Research & Development." (2019).

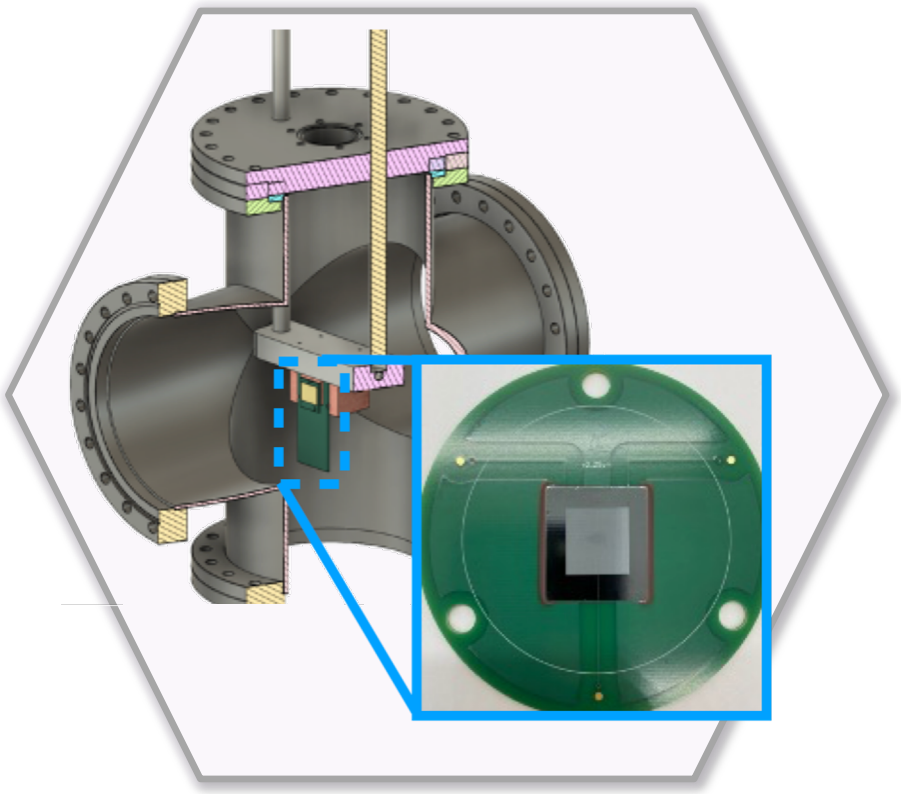
Detectors:
From Medical Imaging to Particle Physics



a-Se flat panel detector

W. Zhao et al, *Medical Physics* 30, 254-263 (2003)

Hellier et al, SPIE Medical Imaging (2023)

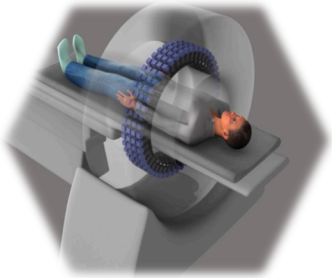


a-Se detector for use in liquid noble detector (PI: Jonathan Asaadi)

Rooks, M., et al, *Journal of Instrumentation* 18, P01029 (2023).

The collaborative approach helps to democratize access to advanced imaging technologies.

State-of-the-art: PET

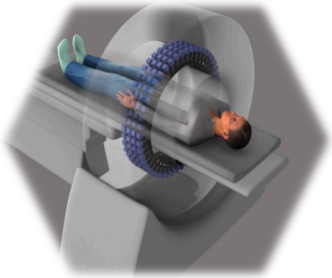


Time-of-Flight (TOF) PET hardware technology was enabled by the advancements and widespread commercial availability of SiPM photodetectors.

Product Name	Manufacturer	Diameter (cm)	Axial FOV(cm)	Scintillator/Det Dim (mm)	Energy Res (%)	Time Res (ps)	Spatial Res (mm) Trans/Axial	Sensitivity (cps/KBq)
Biograph Vision	Siemens	78	26.1	LSO/ SiPM 3.2 x 3.2 x 20	3.5/3.6	214	3.55/3.5	16.4
uMI 550 uMI 780	United Imaging	76.0	24 30	LYSO/ SiPM 2.76 x 2.76 x 16.3		372	2.95/2.97	10.2
Discovery MI PET/CT	GE	74.4	20	LYSO/. SiPM 3.95 x 5.3x 25	9.4	375.4	4.49/6.0 ring) @ 10cm	13.7
Vereos	Philips	76.4	16.4	LYSO/ SiPM 3.86 x 3.86 x 19	11	332	4.0/3.96	5.7
Cartesion Prime	Canon	78	27	LYSO/SiPM 4.1 x 4.1 x 20		258		13.5
Omni Legend	GE		32	Digital BGO				

Hsu et al, J Nucl Med, 58:1511–1518 (2017)
Sluis et. al, J Nucl Med, 60:1031–1036 (2019)

State-of-the-art: PET



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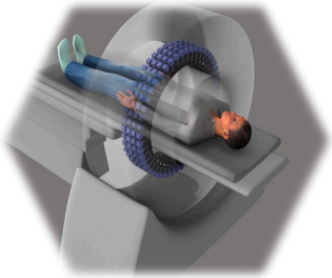

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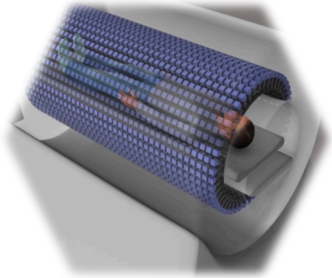

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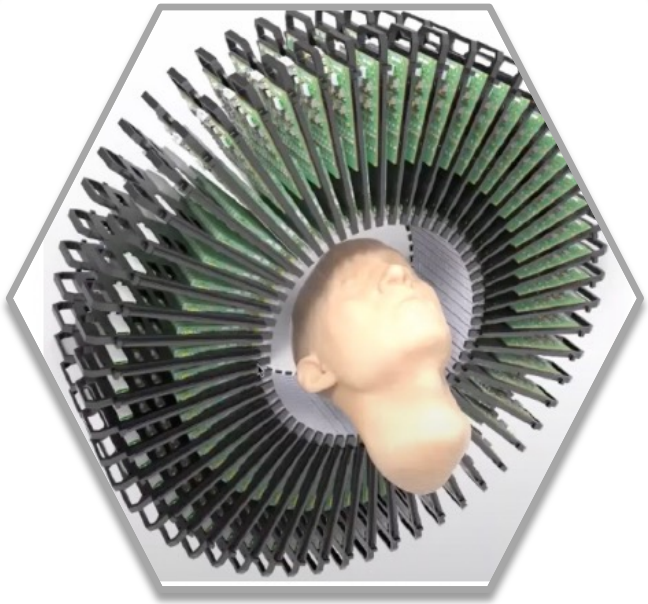
Biograph Vision Quadra	Siemens	82	106	LSO/ SiPM 3.2 x 3.2 x 20	9.8-10.1	228/230	3.4/3.8	83 (MRD 85) 176 (MRD 322)
uEXPLORER	United Imaging	68.6/78.6	194.8	LYSO/ SiPM 2.76 x 2.76 x 16.3	11.7	505	3.0/3.5	191.5@ 0cm
Penn PET Explorer	Philips Vereos	70/81	70/140	LYSO/ SiPM 3.86 x 3.86 x 19	10	250 (cooled)	4.0/4.0	55/ 83

Daube-Witherspoon et al, Br J Radiol 10.1259/bjr.20220357 (2022)
G. A. Prenosil, et al, J Nucl Med, 63:476–484 (2022)
S. R. Cherry, et. al, J Nucl Med, 59:3–12 (2018)
Vandenberghe et al, EJNMMI Physics 7:35 (2020)

State-of-the-art: Dedicated Systems

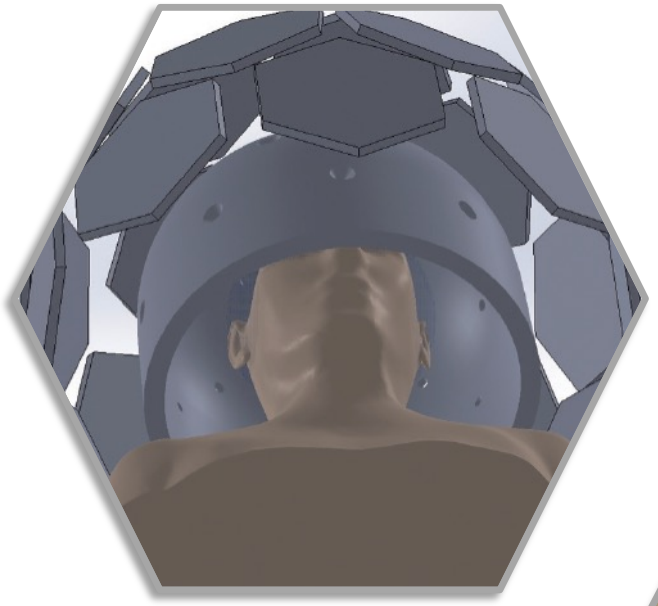
BPET_DBT
University of Pennsylvania
S. Krishnamoorthy et al , *IEEE MIC* (2021)



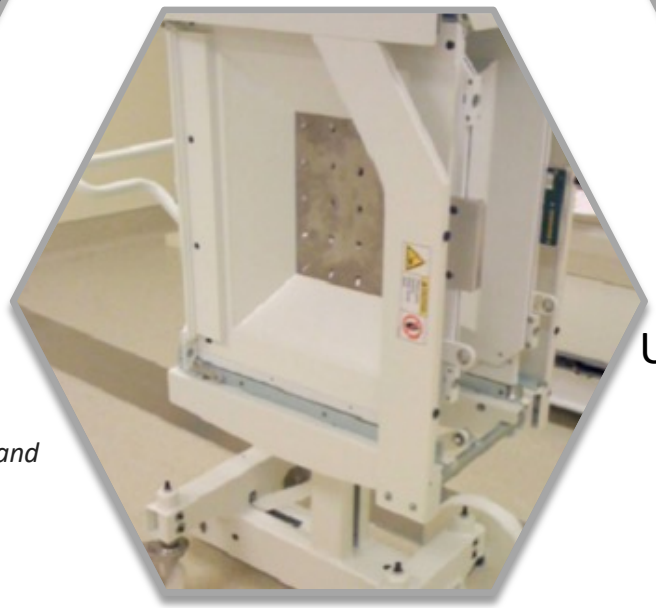
SAVANT
MGH
R. Lecomte et al, *JNM* (2022)

Prism-PET Brian Scanner
Stony Brook University
X. Zeng, *JNM* (2022)

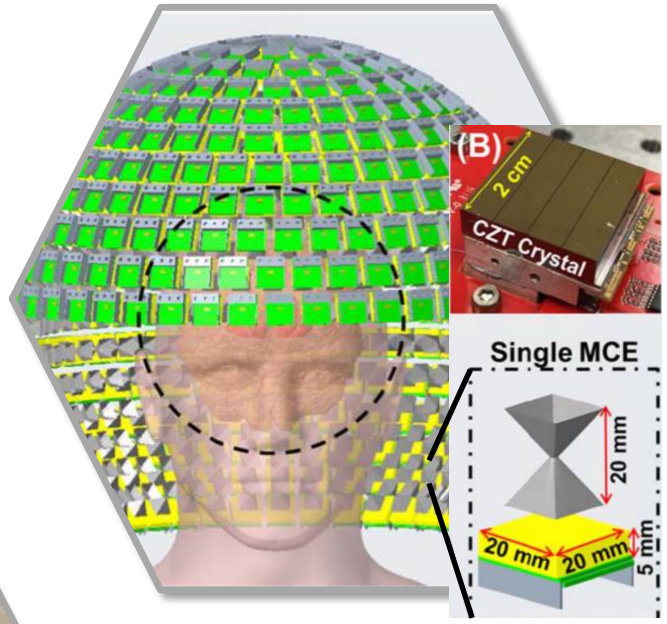
State-of-the-art: Dedicated Systems



AdaptiSPECT-C
Umass Medical School &
University of Arizona
I. Ozsahin, et al, *Quantitative Imaging in Medicine and Surgery* 10.10 (2020)



20-pinhole aperture Plate (GE Infinia Hawkeye 4)
University of California, San Francisco
TC Lee et al, *Medical Physics*, *41*, 112501 (2014)



Compound-Eye Brain SPECT
University of Illinois at Urbana-Champaign
E.M. Zannoni et al, *IEEE TMI*, 40, 3711 (2021)

Challenges

Increase sensitivity

Challenges

Increase sensitivity

Temporal resolution

Challenges

- Increase sensitivity
- Temporal resolution
- Spatial resolution

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- Workflow standardization

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- Increase sensitivity
- Temporal resolution
- Spatial resolution
- Multiple scales
- Workflow standardization
- R&D cost, commercial cost, market

High Sensitivity

Gaps & Needs

- To increase temporal resolution for dynamic imaging of body function
- To improve the tradeoffs between sensitivity and resolution gains
- To enable new therapeutic strategies (e.g., image-guided therapies for more effective treatment)

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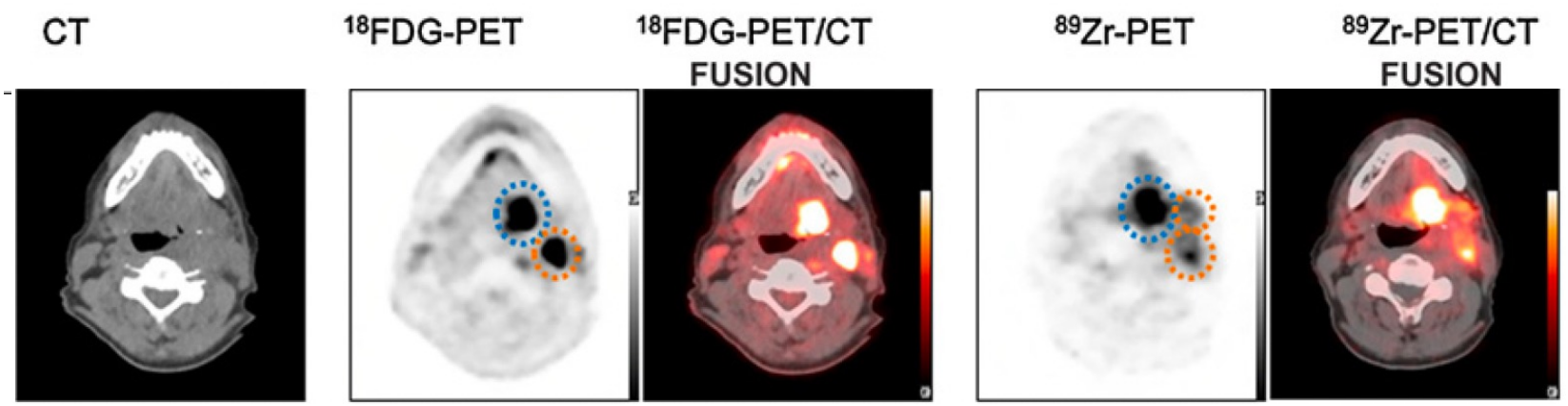
Example of high-quality images for low dose by increasing acquisition time



Lee et al, Clinical Cancer Research, 28, 4425-2234 (2022)

Zr-89 Pan: 20 mins

89Zr-pan PET/CT is highly specific for HNSCC on whole body imaging

High Sensitivity

Gaps & Needs

- To provide longitudinal studies and better pediatric imaging
- To perform imaging with empathy
- To disseminate and democratize technologies for basic discoveries

High Sensitivity

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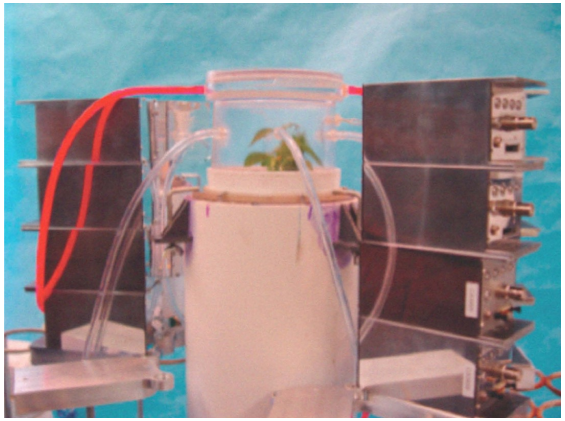
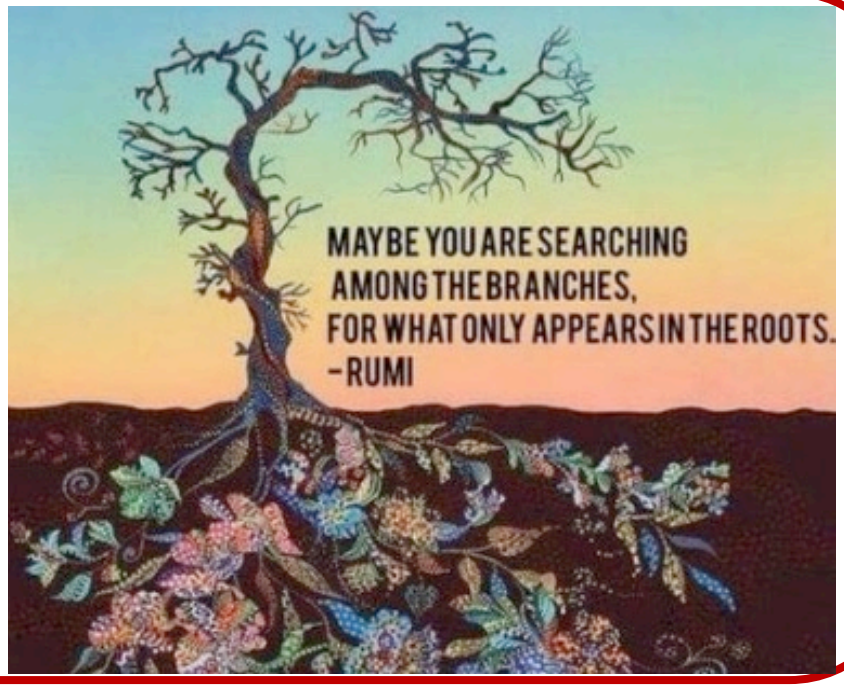
Finding clarity through imaging: Why the answer may lie in the roots



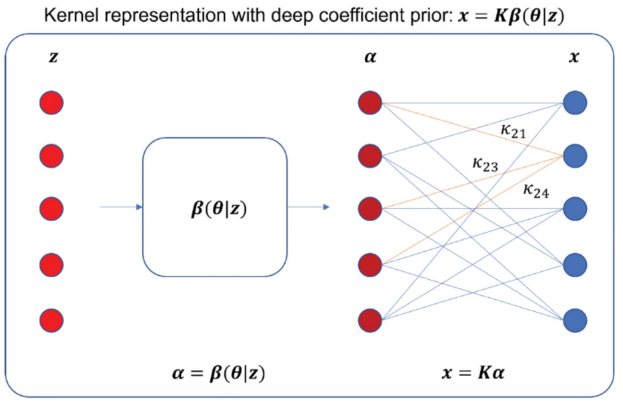
AG Weisenberger et al, *IEEE NSS-MIC* (2011)
Swaby et al, *Proceeding of SPIE*, vol. 12304, 302 (2022).
Sergey, and Tai, *High-Throughput Plant Phenotyping: Methods and Protocols*, pp. 97-118., 2022.
Ariño-Estrada, *Scientific Reports* 9, no. 1 (2019): 18626.



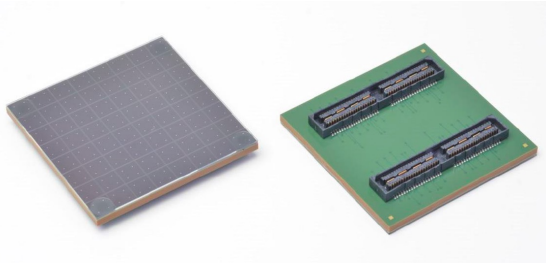
High Sensitivity

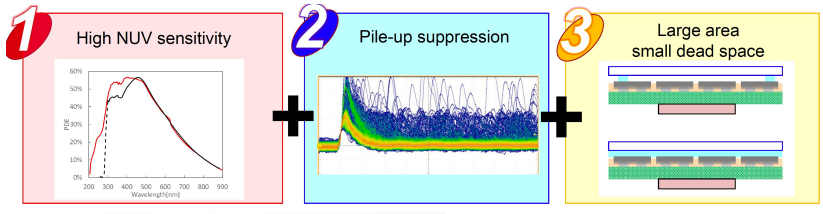
Opportunities

- Deploying machine-learning with domain knowledge (biology, physics, biochemistry) and regularized reconstruction to enhance value for the investment.
- New hardware that significantly improves signal-to-noise ratio (pushing for the timing performance and detector efficiency)
- Combining multiple approaches to maximize benefits



S. Li et al, *IEEE TMI*, V42, 785 (2022)





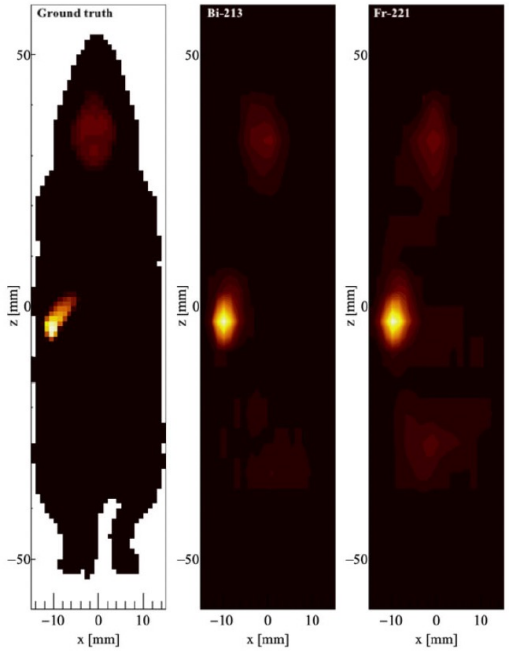
R. Yamada et al, *IEEE NSS/MIC/RSTD* (2022)

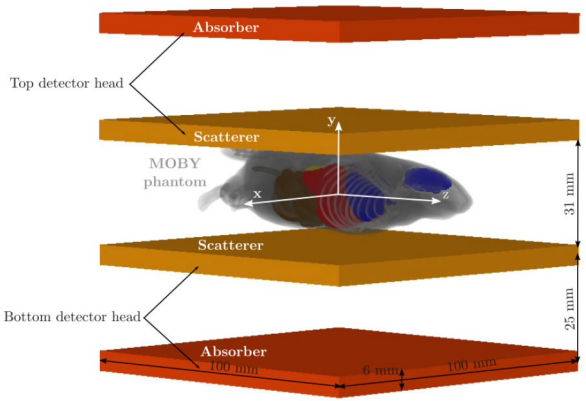
Emerging Technology

Combining multiple approaches to maximize benefits

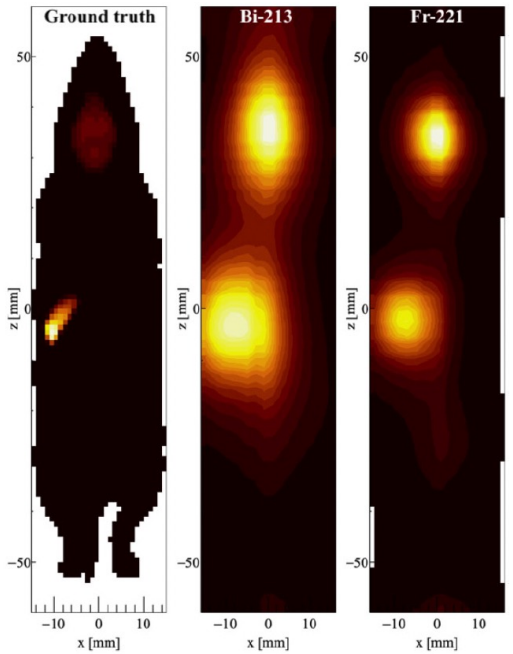
Compton Imaging and Proximity Imaging enables imaging of low activity radionuclide for alpha emitter radiopharmaceutical development.

Compton images of a simulated mouse phantom with 0.5 uCi of Actinium (^{225}Ac) for 15 min.





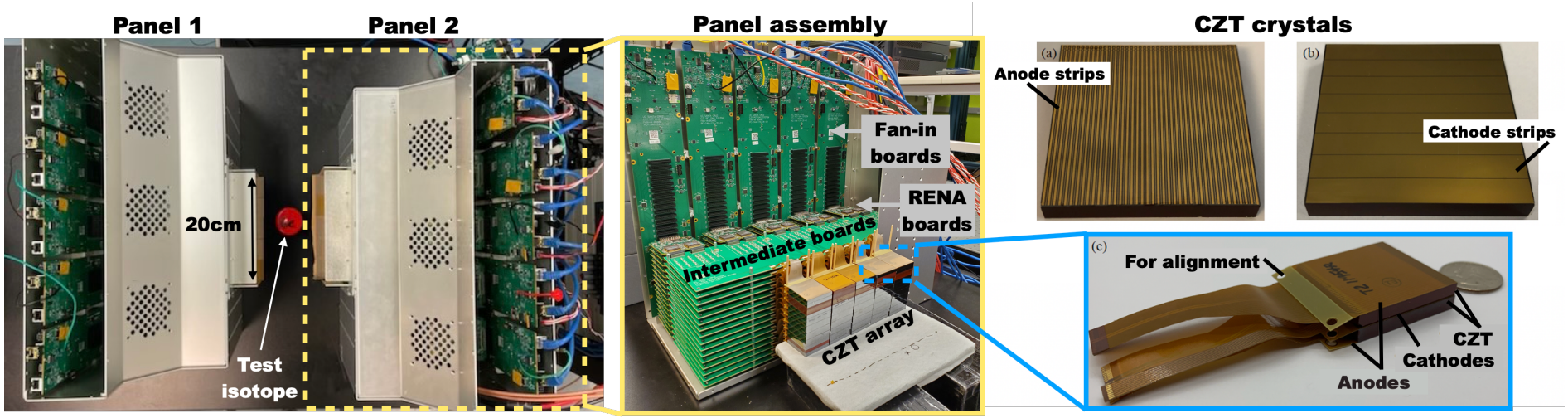
Proximity images of a simulated mouse phantom with 0.5 uCi of ^{225}Ac for 5 min.



Caravaca et al, *IEEE Trans Rad Plasma Med Sci* 6; 904 (2022)

Emerging Technology

- Combining multiple approaches to maximize benefits
- Harnessing the properties of annihilation photons



Abbaszadeh et al, *Phys Med Biol* 63: 025012 (2018)
Wang et al, *IEEE Trans Rad Plasma Med Sci,* 6; 517 (2021)
Enlow et al, *IEEE Trans Rad Plasma Med Sci*, in press.

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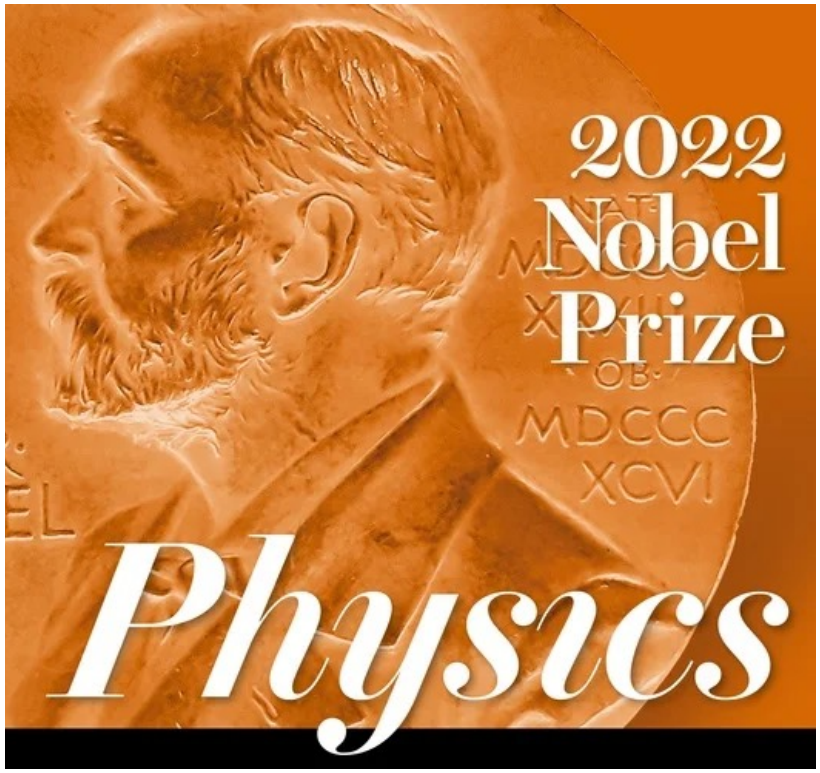
New Physics-based Approaches for Random and Scatter Rejection

The two positron-electron annihilation photons are predicted to be produced in a quantum-entangled state.

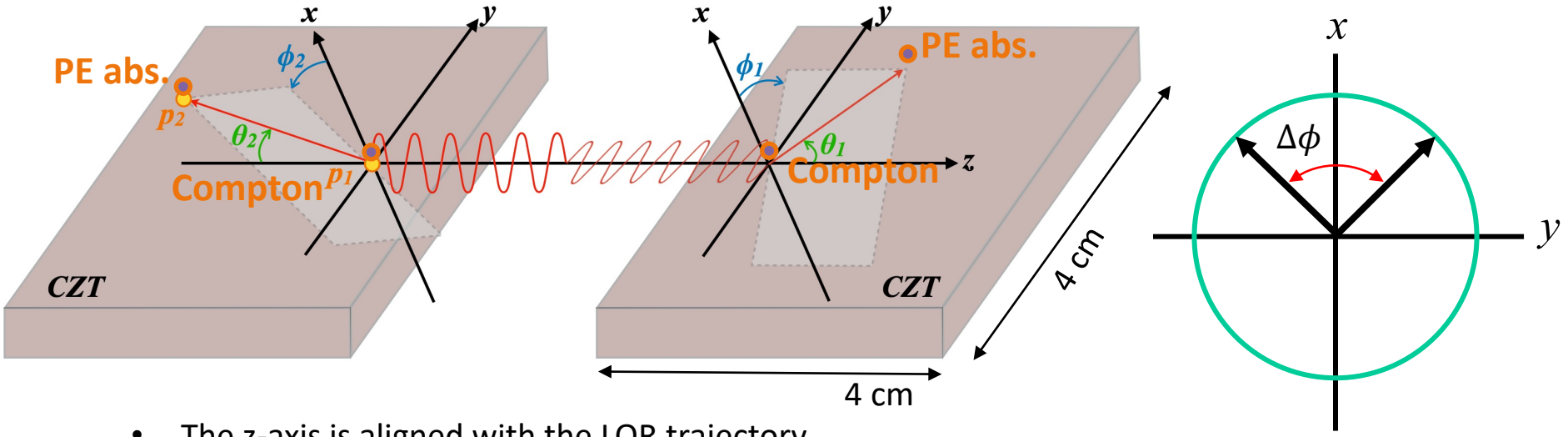
“Entanglement” implies correlations in the photon properties:

- Polarization
- Spatial/momentum
- Time/Frequency



Billings, Lee. “Explorers of Quantum Entanglement Win 2022 Nobel Prize in Physics.” Scientific American. Oct. 4, 2022

Emerging Technology



- The z-axis is aligned with the LOR trajectory
- θ is the classical polar scattering angle off the z-axis
- ϕ is the azimuthal scattering angle in the x-y plane
- Δϕ favors 90° for entangled gammas

Abbaszadeh et al, *SNMMI* (2023)

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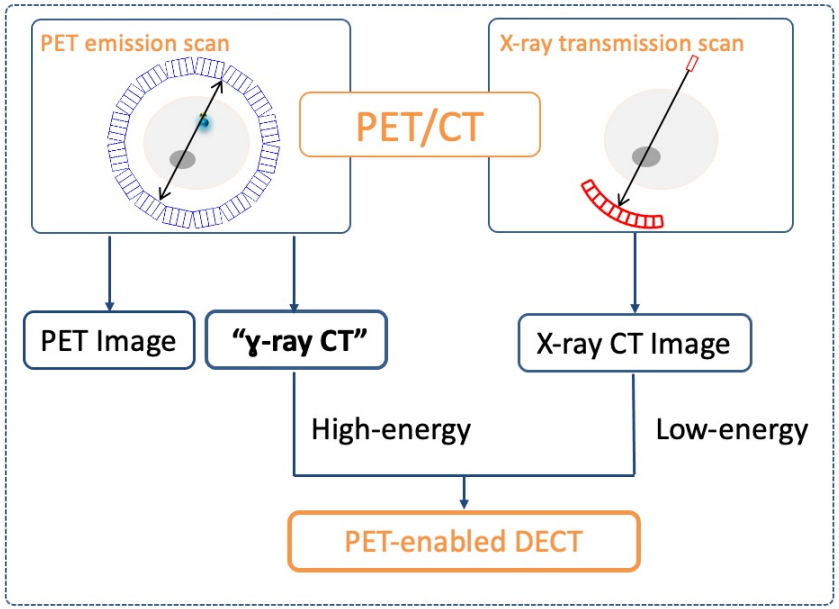
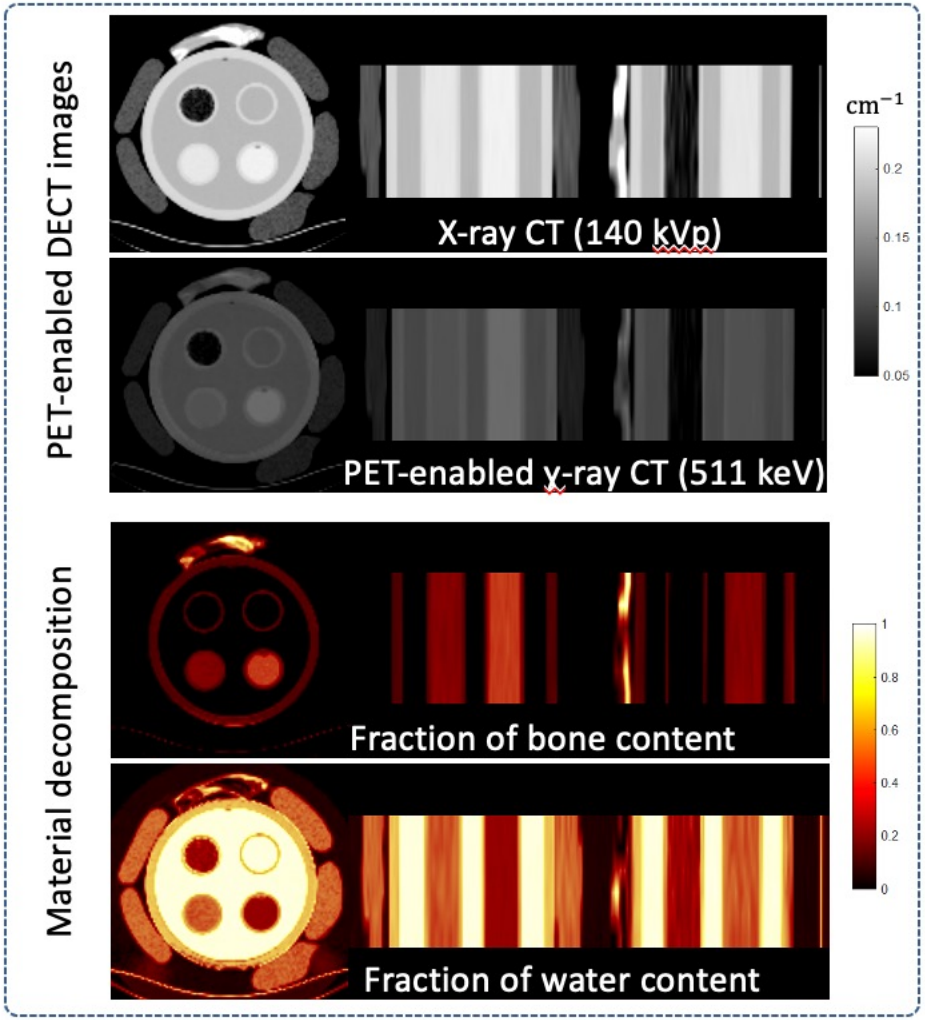
Emerging Technology

PET-enabled dual-energy CT Imaging

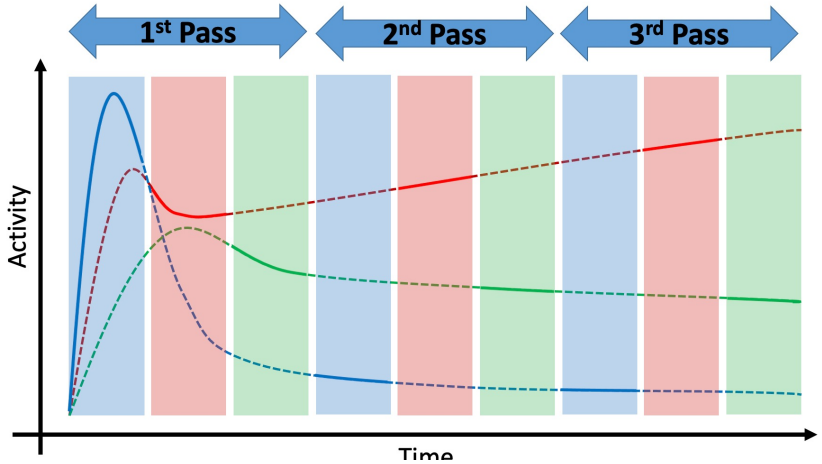


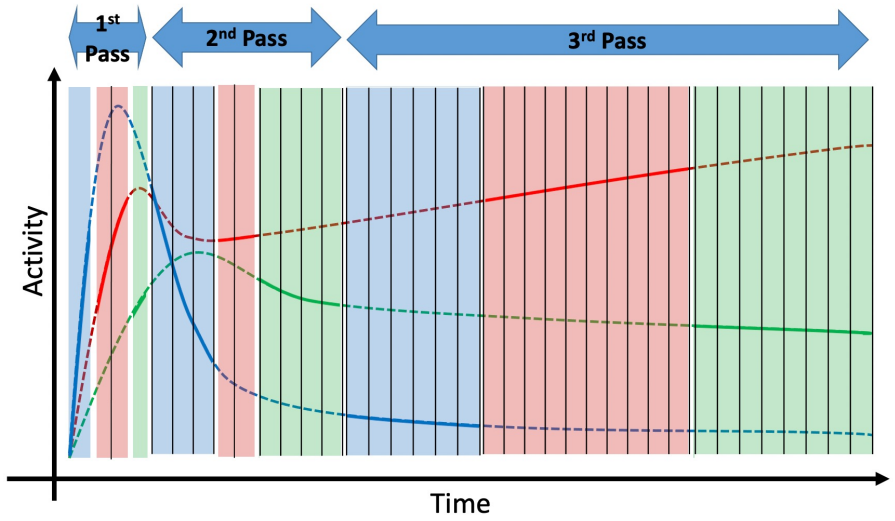


Wang GB, *Phys. Med. Biol.* 2020.

Emerging Technology

Temporally optimized dynamic step and shoot protocol using limited field of view enable quantitative multi-organ PET imaging to support systems biology imaging research



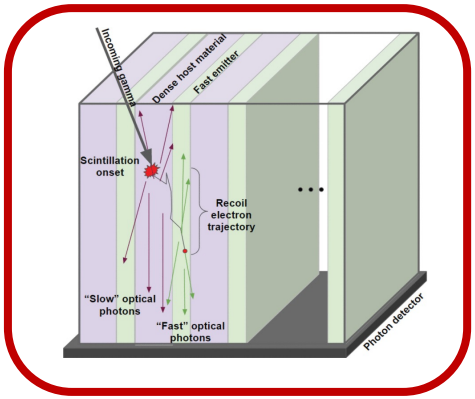


Li et al, *SPIE Medical Imaging* (2023)

Emerging Technology

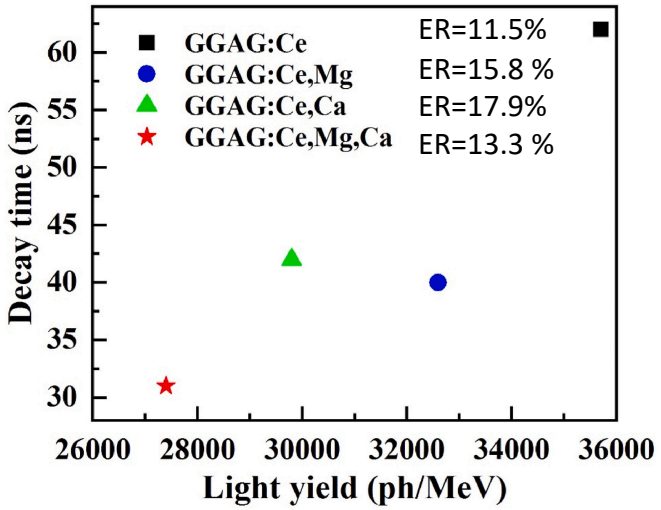
Indirect conversion:

- Materials engineering
- Photonic crystal cavities

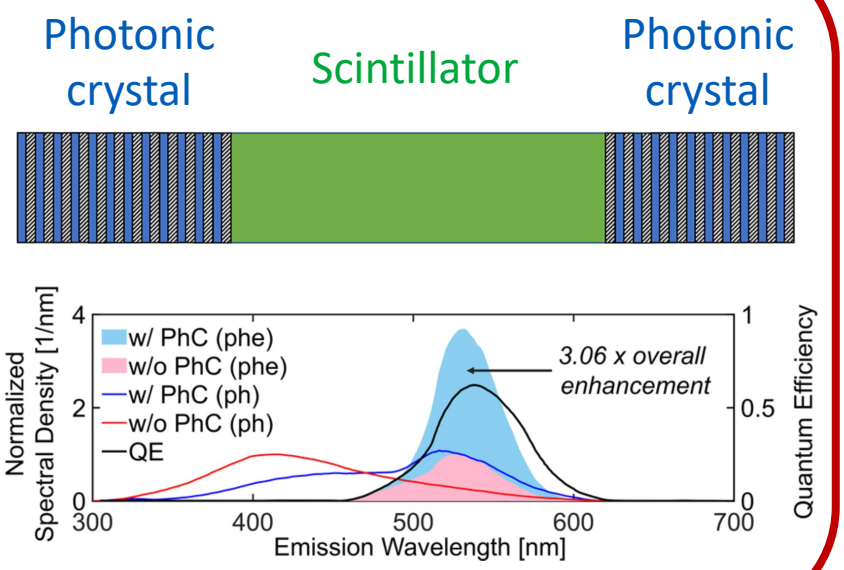


Konstantinou G. *IEEE Transactions on Radiation and Plasma Medical Sciences*. 6(1):5-15, (2021).

Co-doping of Ca^{2+}& Mg^{2+} maintain good energy resolution (137 Cs) and decay time



X. Huang st al, *Ceramics International* 48, 23571 (2022)



W. Ye, et al, *ACS Photonics*, 9 (12), 3917 (2022)

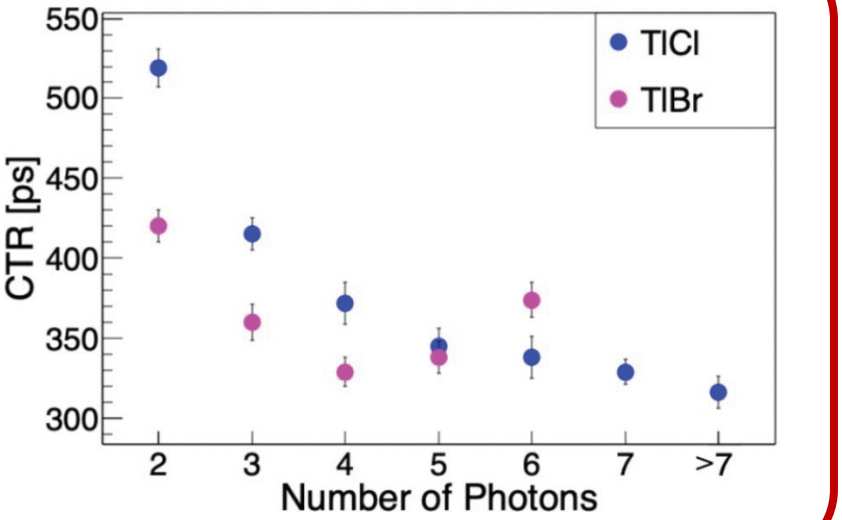
Emerging Technology

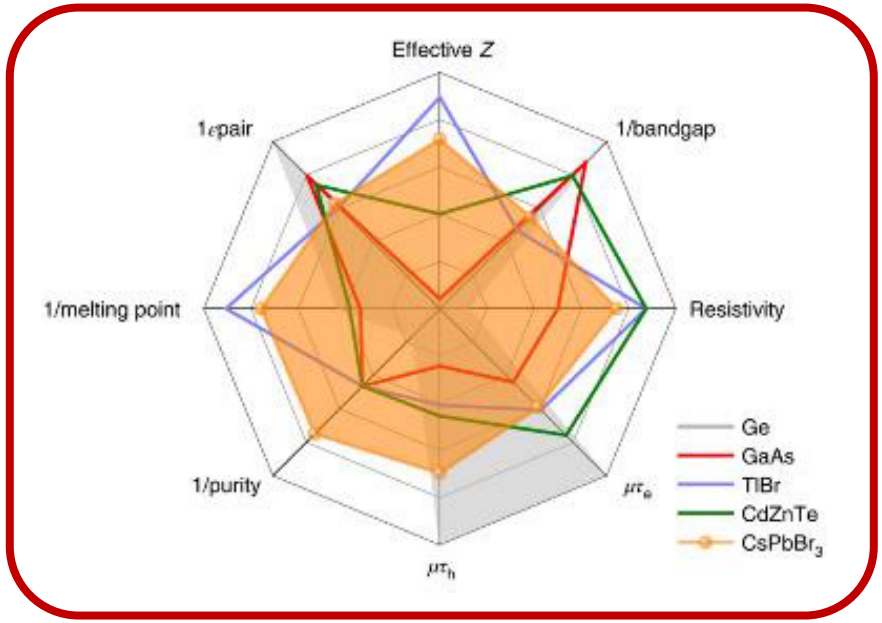
Indirect conversion:

- Crystal engineering
- Photonic crystal cavities

Direct conversion:

- Improved growth yield (e.g., CZTS)
- Improved mobility-lifetime product (e.g., TlBr)
- Emerging metal halide perovskite (e.g., $CsPbBr_3$)





Ariño-Estrada G. *IEEE Transactions on Radiation and Plasma Medical Sciences*. 5(5):630 (2020).

He Y. *Nature Photonics*. 16(1):14 (2022).

Summary

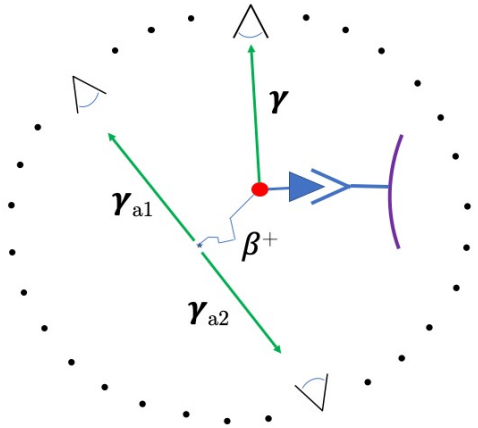
Every single photon with accurate energy/time of interaction and position matters!

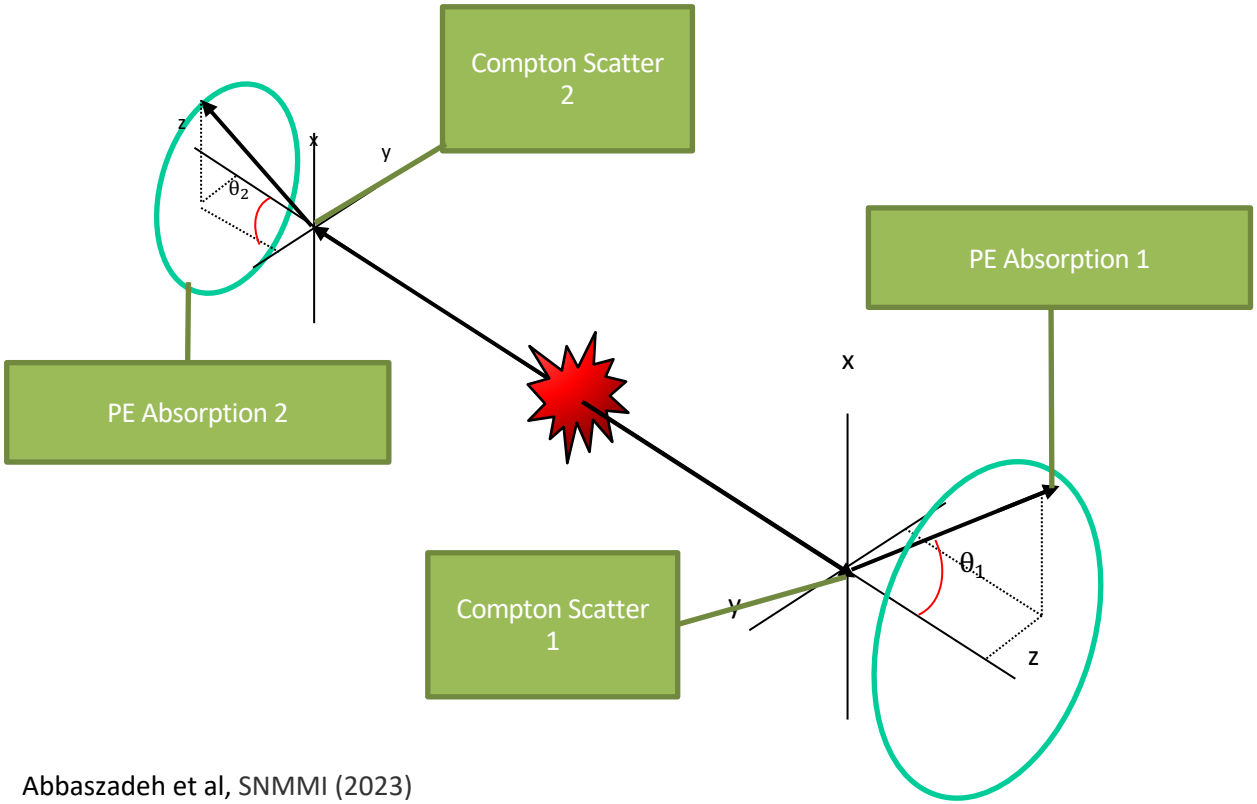
- Challenges:
  - Improving SPECT, PET, etc. to support wide range of application needs
- Ongoing research and solutions:
  - Advances in the application of machine learning, hardware development, and combining modalities/approaches to leverage their complementary benefits
  - Quantum entanglement route to improved timing & resolution
  - PET-enabled dual energy, dynamic step and shoot
  - Improvements in detectors & new materials leading to higher temporal and spatial resolution, lower cost
  - … and many more

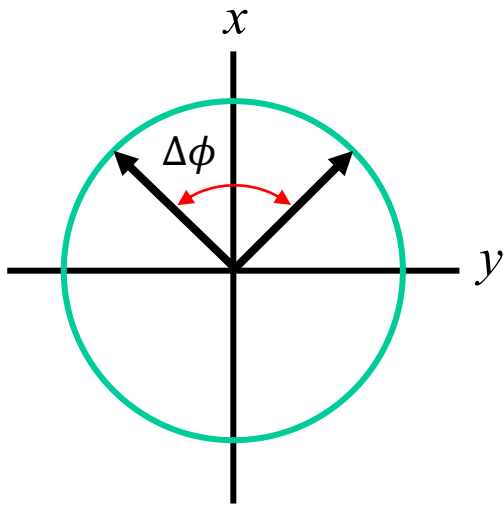
Emerging Technology

Gamma-positron Imaging promises to overcome:

- Increase sensitivity of single gamma-photon imaging
- Distinguishing between two positron-emitting isotopes
- The positron-range spatial resolution limit







Abbaszadeh et al, SNMMI (2023)

THE UNIVERSITY OF ARIZONA
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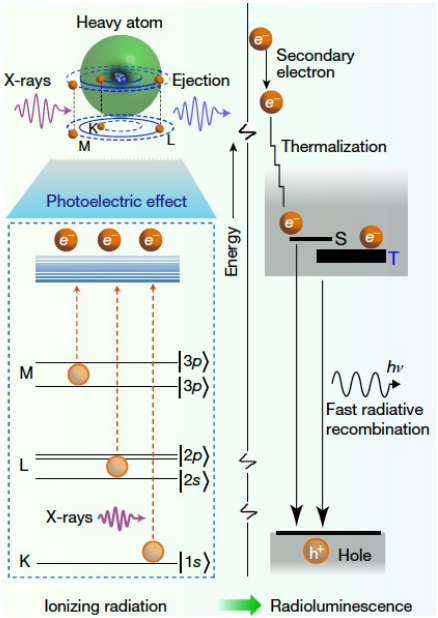
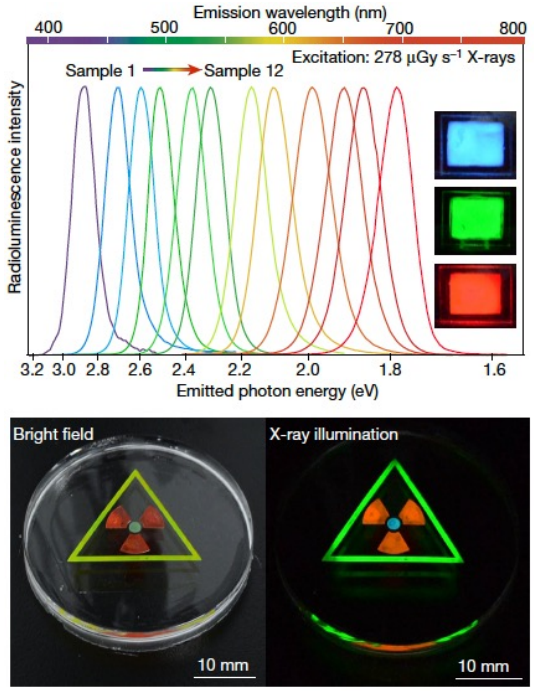
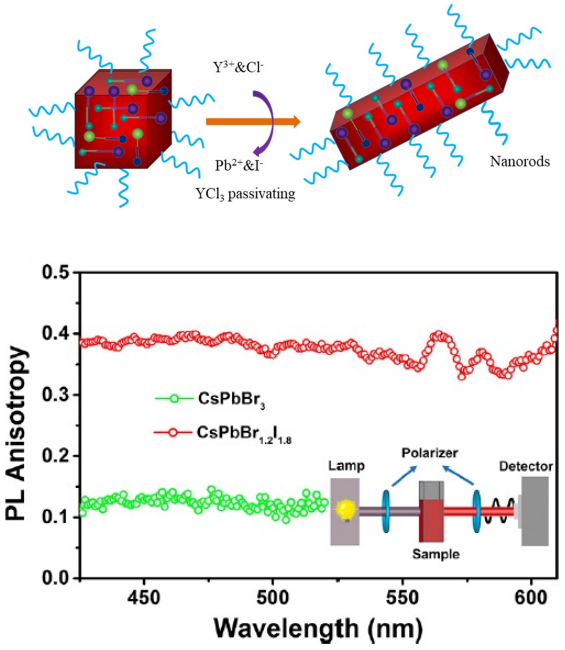
Emerging Technology

Perovskite crystals for higher emission, increased resolution, low cost gamma & X-ray scintillation

Inorganic, low cost materials	High emission, tunable wavelength	High resolution, anisotropic emission







Chen et al, Nature 561: 88 (2018)

Pan et al, Nano Energy 81: 105615 (2021)

State-of-the-art: SPECT

Product Name	Manufacturer	FOV (cm)	Scintillator/Det Dim (mm)	Energy Res (%) UFOV FWHM	Max Count (Kcps)	Spatial Res (mm) UFOV FWHM	Sensitivity (cpm/µCi) @100 mm
BrightView XCT	Philips	40.6 x 53.9	9.5/19.1 mm thick NaI crystal 59 PMT	9.6/9.8 Range: 56 - 920 keV	350	3.2/4.0	277/311 (LEGP)
Symbia Evo Excel	Siemens	53.3 x 38.7	9.5/15.9 mm thick 59.1 x 44.5 NaI crystal 59 PMT	9.9 Range: 35 - 588 keV	460	3.9/4.6	202/225 (LEHR)
NM 830	GE	54 x 40	9.5/15.9 mm thick NaI crystal 59 circular PMT	9.5 Range: 40 - 620 keV	460	3.8/4.6	160/165 (LEHR)
NM/CT 870 CZT	GE	51.17 x 39.36	39.36 x 39.36 x 7.25 module CZT crystals 130 CZT modules	6.3 Range: 40 - 250 keV	650	2.46	190 (WEHR)

LEGP = Low Energy General Purpose
LEHR = Low Energy High Resolution
WEHR = Wide Energy High Resolution
www.gehealthcare.com
www.siemens-healthineers.com
www.philips.ie