Omnidirectional 3D Gamma-ray Imaging with a Free-moving Spherical Active Coded Aperture

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Outline

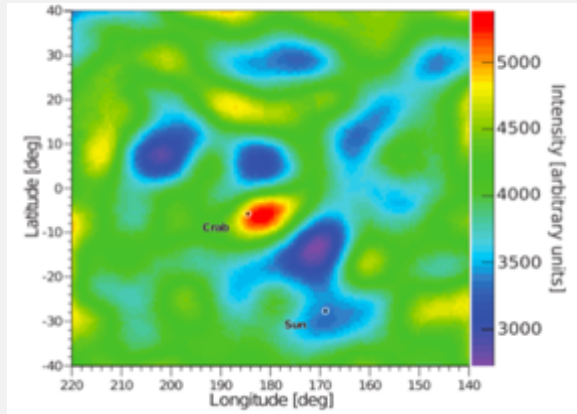
- Introduction
- Active spherical coded aperture – PRISM
- 2D imaging
- 3D imaging
- Experimental results
- GPU acceleration
- Conclusions and future work

Introduction

Motivation

Detect, locate, and identify weak radioactive sources in complex environments and efficiently map radiation fields. Applications in astrophysics, nuclear security and safeguards, nuclear contamination remediation, medical imaging

Crab nebula with NCT



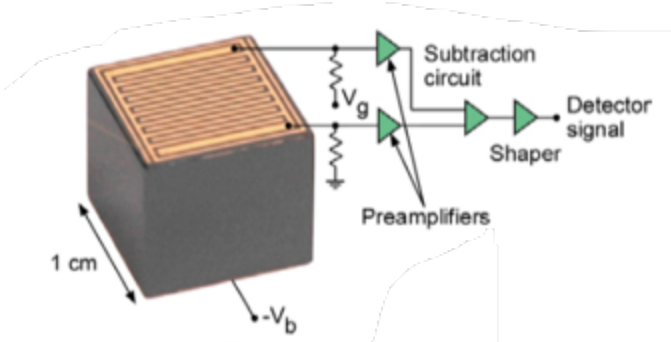
Bandstra et al, The Astrophysical Journal, 738(1), 2011

Need

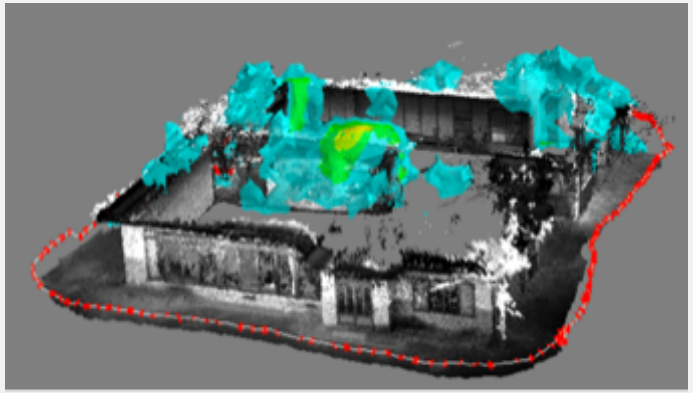
Portable (hand-held) 2D/3D imaging system with high efficiency, wide field-of-view, high energy resolution, and broad energy sensitivity

Approach

Multiple room-temperature operated cm^3 CdZnTe (CZT) coplanar gird (CPG) detectors arranged to facilitate coded aperture (40 – 400 keV) and Compton imaging (300 keV – 2 MeV) modalities



^{137}Cs contamination in Fukushima home

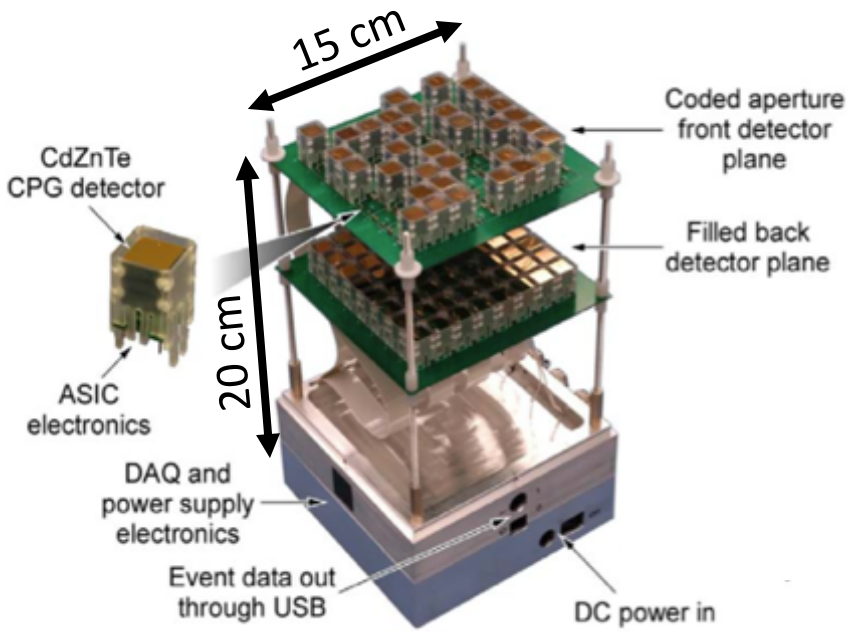


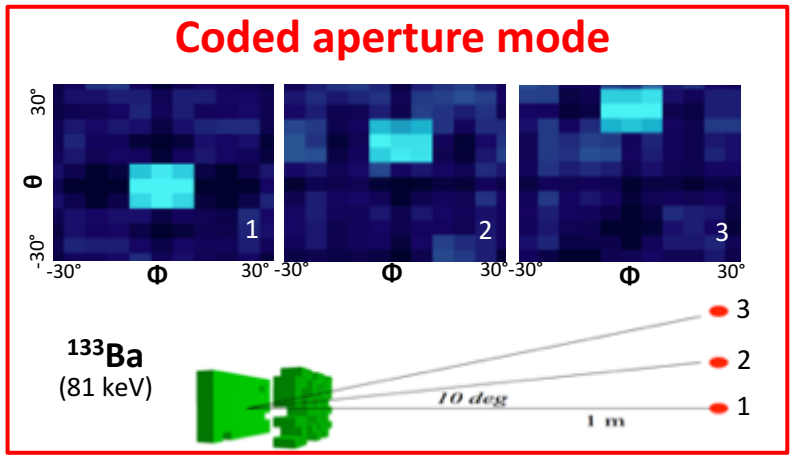
Courtesy of A. Haefner, LBNL, 2016

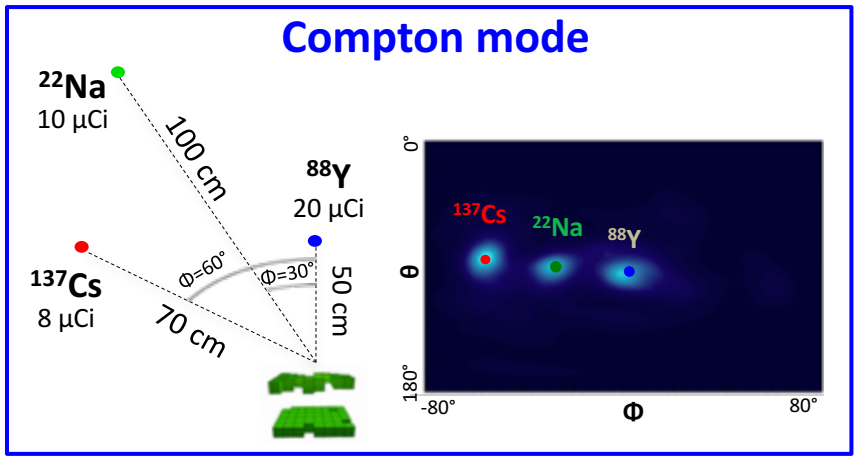
Active Planar Arrangement - HEMI

High Efficiency Multi-modal Imager (HEMI)

- 96 CZT CPG detectors (1 cm^3, <2% FWHM at 662 keV)
- 32 in **active coded** front plane, 64 in fully populated back plane
- Coded aperture (50 keV to 350 keV) and Compton imaging (300 keV to 3 MeV)
- 10° resolution at 662 keV (Compton) and 186 keV (CA)
- < 10 lbs



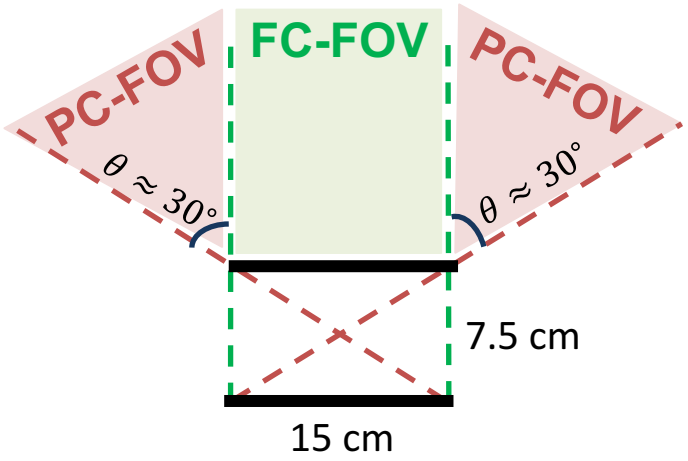


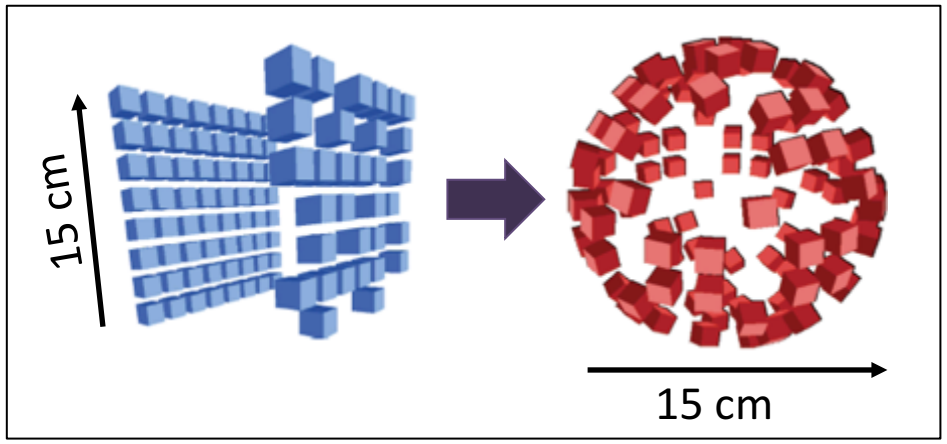


M. Galloway, Ph.D. Thesis, UC Berkeley, 2014

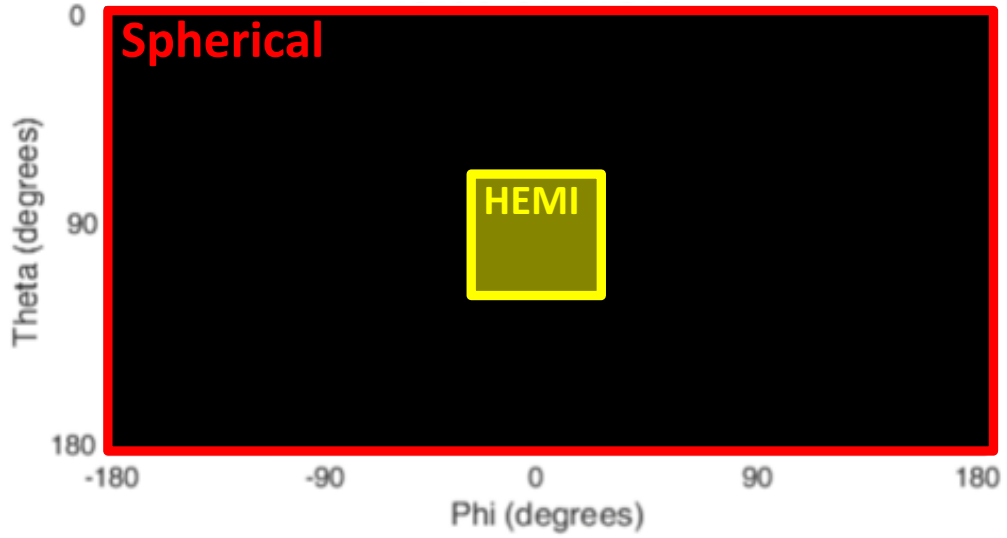
Active Spherical Coded Aperture

- Planar arrangement of HEMI suffers from a **limited and anisotropic field-of-view** in the **coded aperture** modality
- Mask-detector geometry has partial coding except on-axis
- Arrange detectors into a spherical active coded configuration to facilitate **omnidirectional imaging**





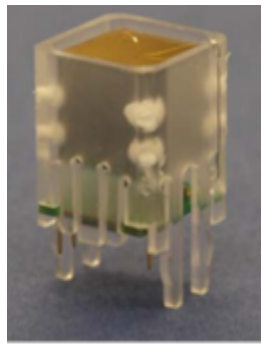
4π Coded Aperture Field of View

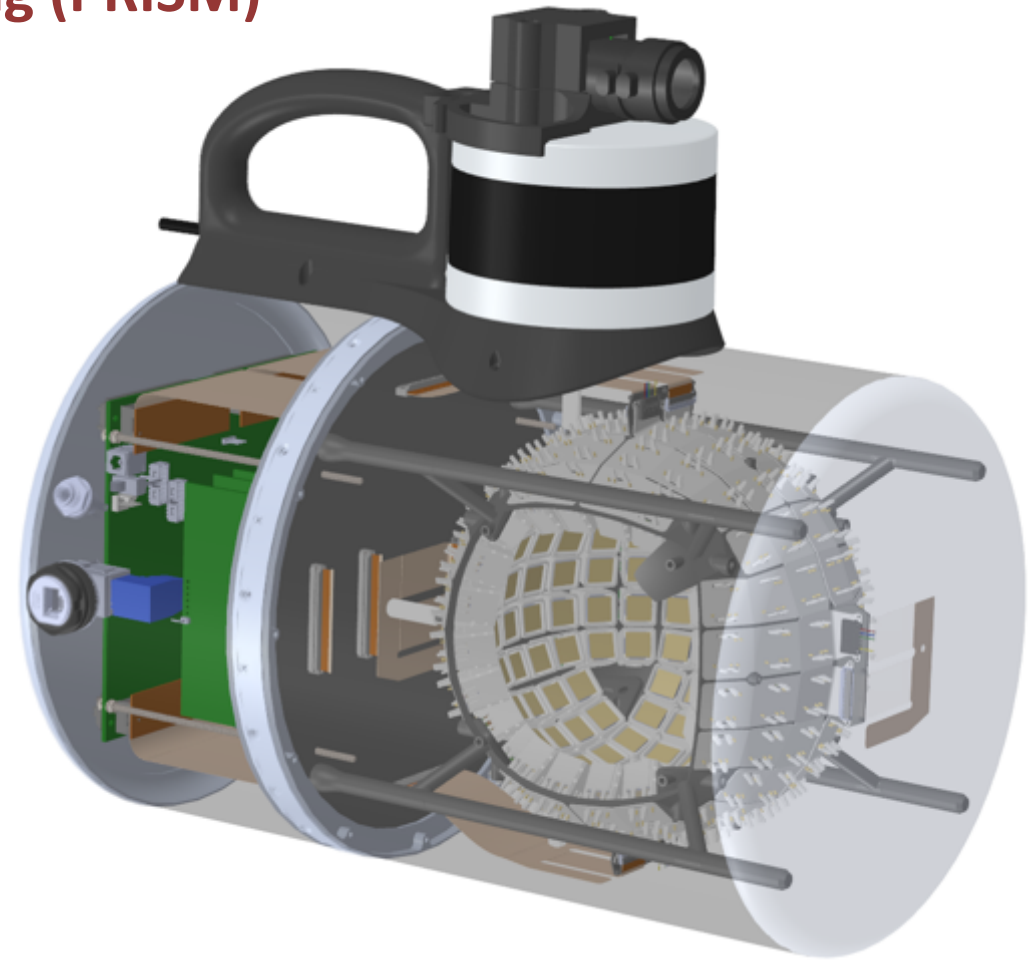


PRISM

Portable Radiation Imaging Spectroscopy and Mapping (PRISM)

- Hand-held, free-moving, CZT CPG-based, spherical active coded aperture
- 1 cm^3 crystals in modular Lexan casings
- 6 modular (identical) faces
- 192 total available detector locations
- < 2% FWHM at 662 keV
- < 10° resolution at 186 (CAI) and 662 keV (Compton)
- < 10 lbs, < 10 W power

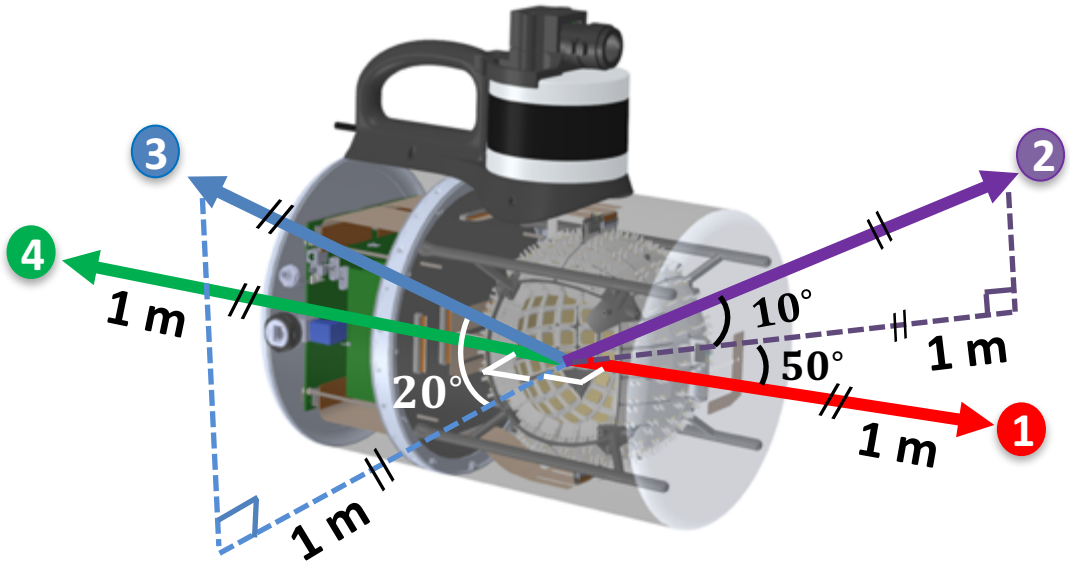




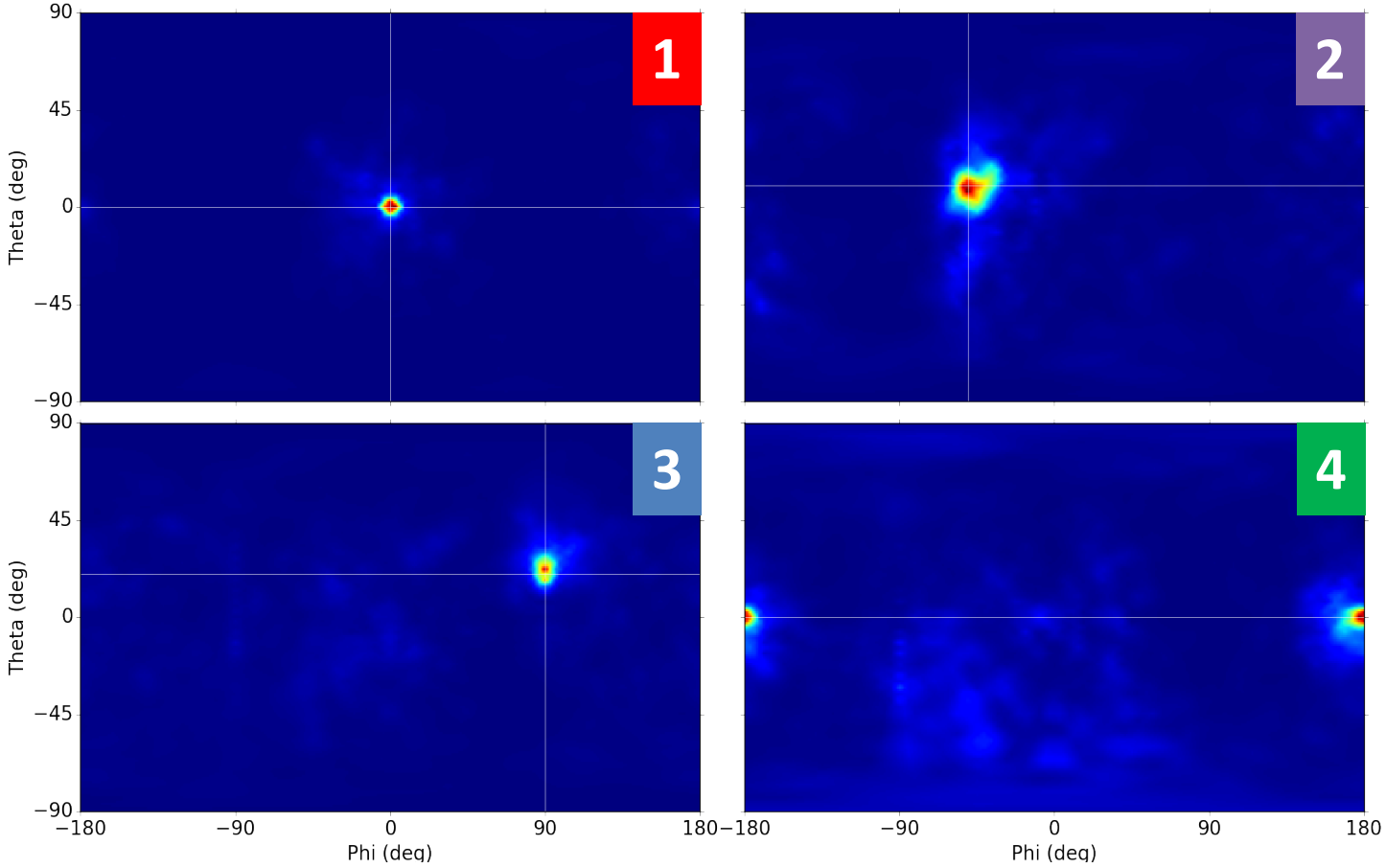
➔ **Hardware specific talk in the NSS/RTSD joint session (next) in Centennial II by Paul Barton**

2D Far-field Coded Aperture Imaging in 4π

- 93/192 detectors populated
  - Pseudo-random (not optimized[†])
  - 74/93 detectors functional
- 10-min dwell, 20 μCi ^{241}Am (60 keV)



MLEM reconstruction (50 iterations)

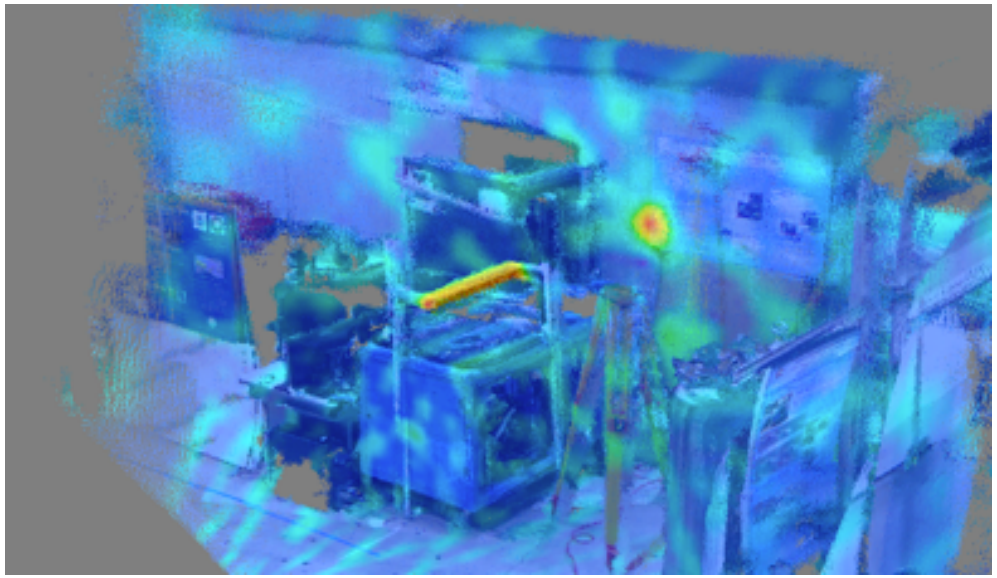


[†] For optimization, see *D. Hellfeld et al, IEEE TNS, 2017*. DOI: 10.1109/TNS.2017.2755982

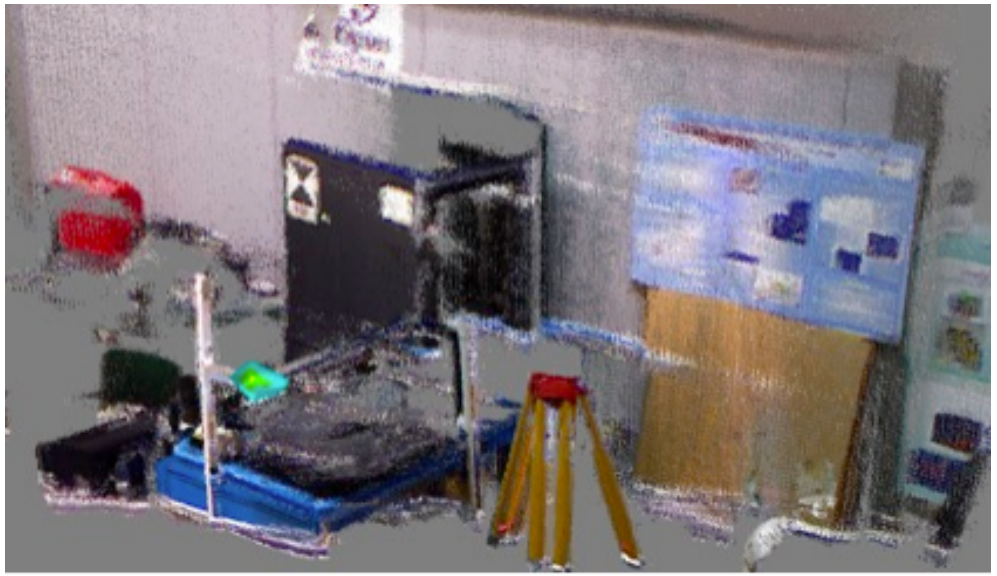
2D to 3D Imaging

- 2D imaging provides accurate reconstructions of the source direction in space, though **position along direction is ambiguous**
- Data from different perspectives can be combined to create 3D images

Static 2D image with 3D overlay



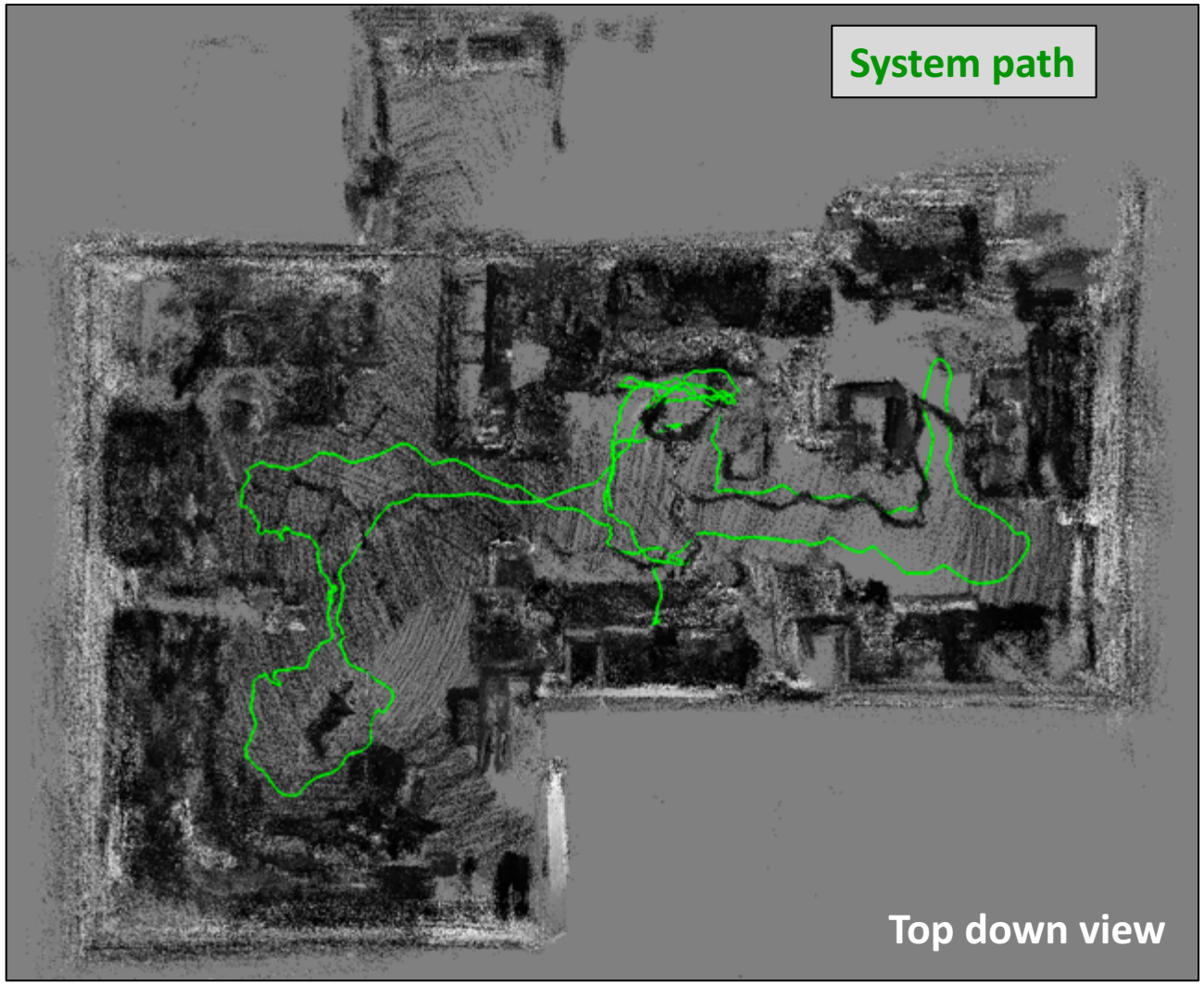
Multi-location 3D reconstruction



Barnowski, Ph.D. Thesis, UC Berkeley, 2016

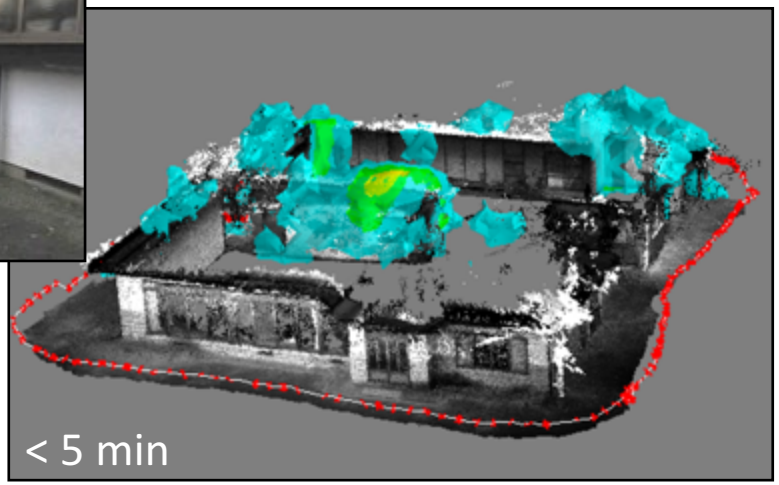
Free-moving Tracking and Scene Data Fusion

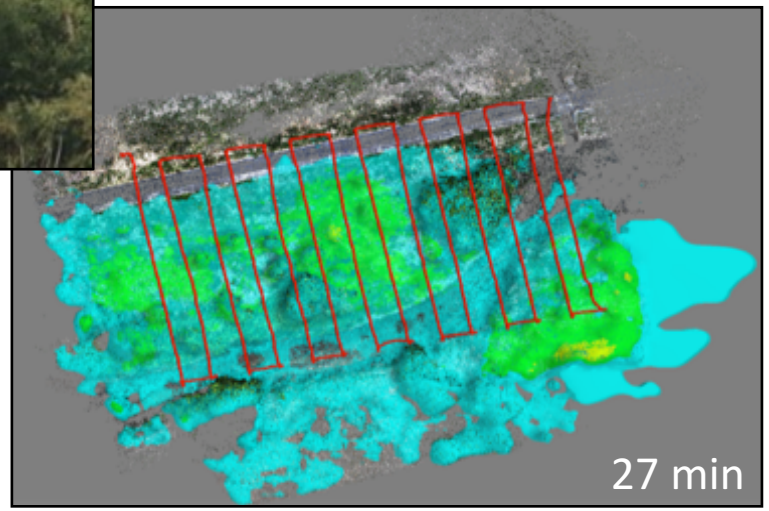
- Auxiliary **contextual sensors** (visual camera, LiDAR, IMU) used with **Simultaneously Localization and Mapping (SLAM)** algorithms to track the **position and orientation** of the system as it moves freely through an environment
- 3D scene data fused with 3D radiation image to provide **visual context, increase image accuracy, reduce noise,** and **decrease reconstruction computational time**

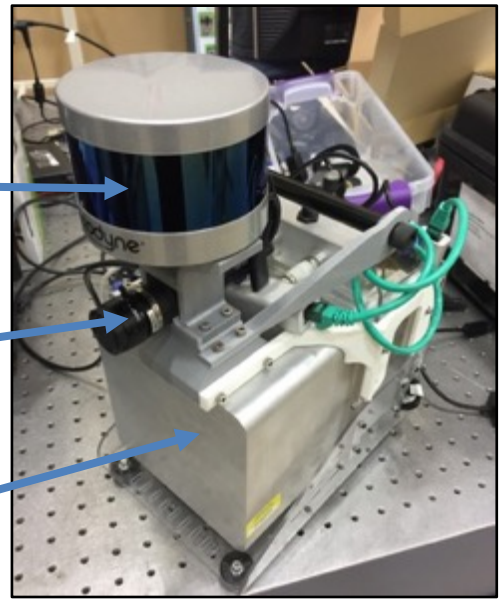


Free-moving 3D Compton Imaging with HEMI

- Equipped with auxiliary contextual sensors (visual camera, LiDAR, and IMU)
- Demonstrated ^{137}Cs mapping in Fukushima with Compton imaging
  - Hand-held and UAV operation







PRISM System Setup

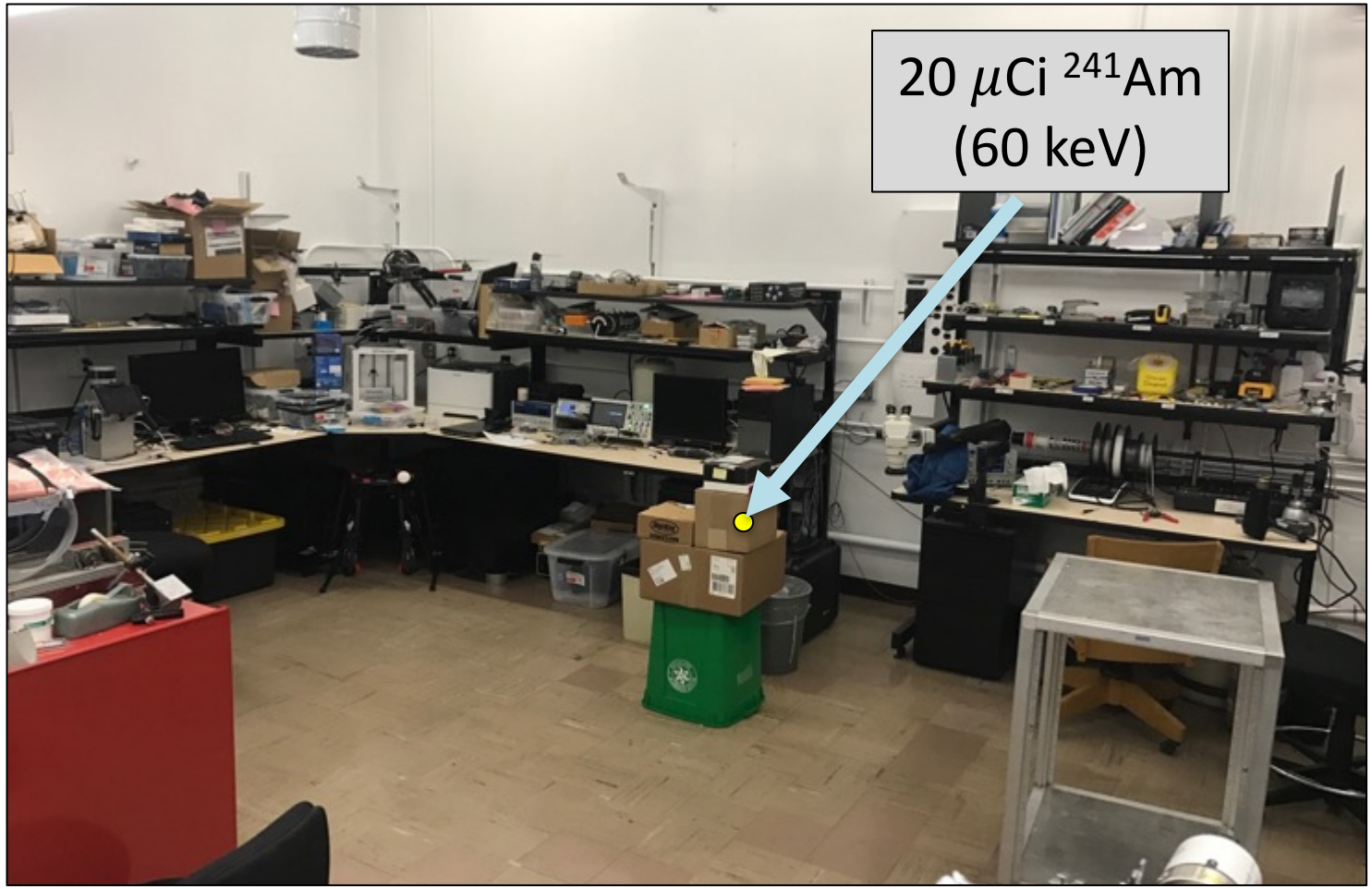
LiDAR and IMU

PRISM

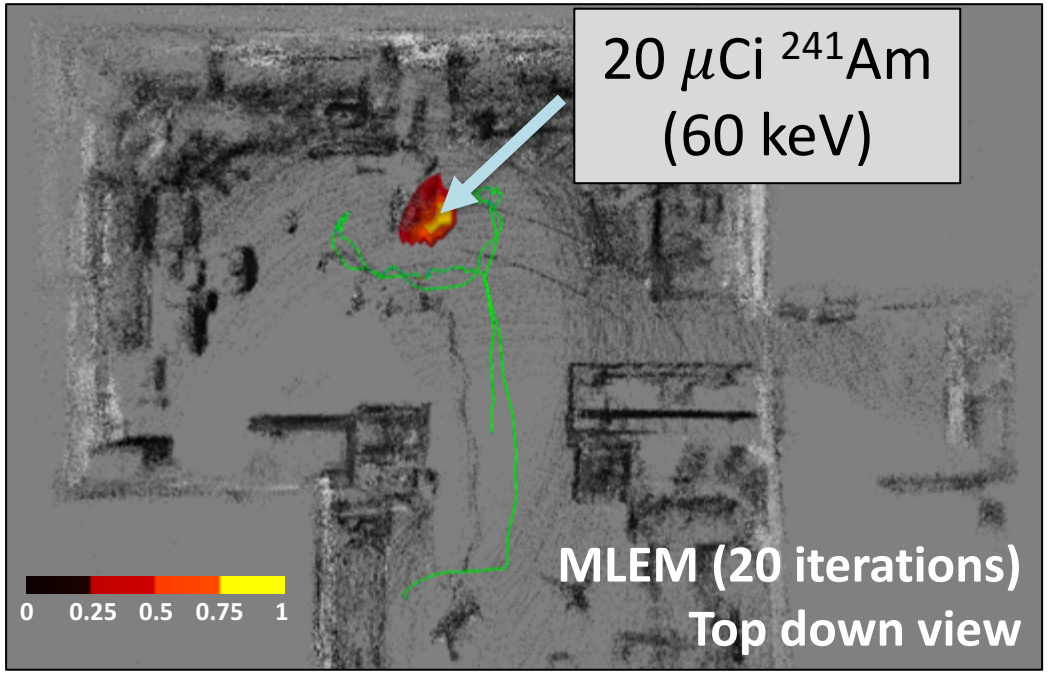
Hand-held tablet for gamma-ray reconstruction and visualization

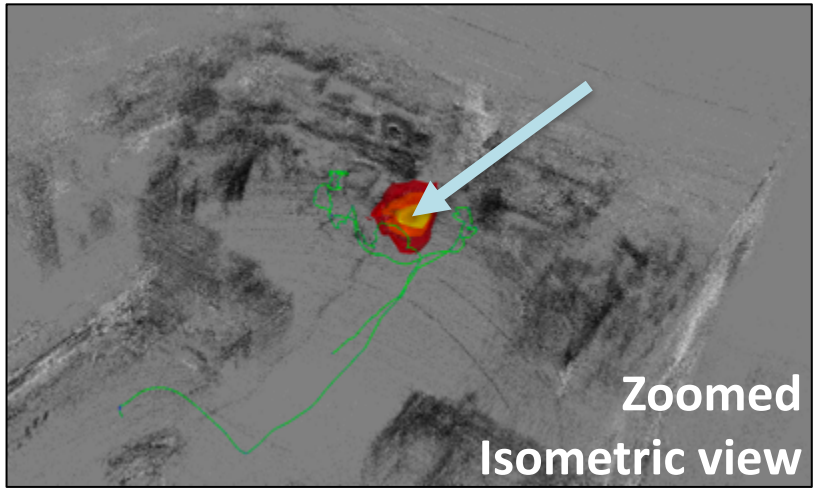
Backpack contains batteries and laptop for contextual data processing

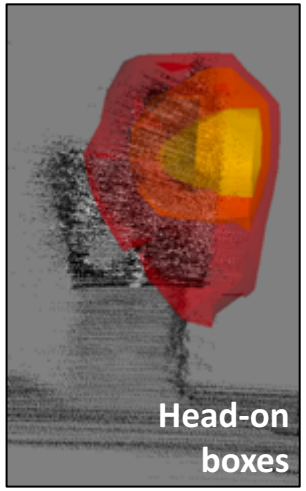
Experimental Measurement Setup



Results







Measurement time: **120 s**
Total counts (60 keV ROI): **7982**
Occupied voxels: **33340** (14% of total)
Voxel size: **10 cm**
Poses: **927**
Operating detectors: **74**

GPU Acceleration

- As the voxelized space grows larger, image reconstruction can become very computationally expensive
- Significant speedups when computation **parallelized on GPU** vs. CPU using *OpenCL*

Hardware	Sensitivity (s)	MLEM iteration (s)	Total (20 iterations) (s)	
2.7 GHz Intel quad-core i7-6820HQ	6.1	29.0	**586**	-
Intel HD Graphics 530 *(integrated)*	4.4	9.5	**173**	**3.4x**
AMD Radeon Pro 455 *(dedicated)*	2.6	4.3	**89**	**6.6x**

- Further work is necessary to improve efficiency and overcome memory management issues
- However, results are promising towards a real-time on-board image reconstruction

Conclusions

- Developing a spherical active coded aperture gamma-ray imaging system to overcome the limited and anisotropic field-of-view issues in traditional planar systems
- First experimental demonstration of spherical coded aperture omnidirectional 2D imaging
- First successful free-moving 3D coded aperture image reconstruction
- Significant speedups observed in reconstruction time with GPU parallelization

Future work

- Continue exploring the 3D coded aperture imaging capabilities/limitations of PRISM
- Real-time imaging
- 3D imaging improvements with depth-of-interaction readout
- Near-field 3D imaging

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Thank you for your attention

Questions?