SAND2018-1616PE

Defense Nuclear Nonproliferation Research & Development

Nuclear Security Applications Research & Development Portfolio Review

NSARD 2018

Directional Spectrometer Software

Dean J. Mitchell

Sandia National Laboratories

2018

SAND2018-XXXX PE

Directional Spectrometer Software

Project title:	**Directional Spectrometer Software**
Project number:	**SL15-V-DirectSoftware-PD2Jc**
Participating laboratories:	**SNL, ORNL, NSTec**
Participating contractors:	**H3D, University of Michigan**
Status:	**Final Year (year 4 with no-cost extension)**

- **Participants**
  - Sandia National Laboratories
    - Dean Mitchell (PI)
    - Steve Horne
    - Lee Harding
    - Greg Thoreson
    - Lisa Theisen
  - Oak Ridge National Laboratory
    - Klaus Ziock
  - NSTec
    - Rusty Trainham
  - H3D, Inc.
    - Willy Kaye
    - Jason Jaworski
    - Chris Wahl
  - University of Michigan
    - Zhong He
    - Jiyang Chu

Supporting Technology

- **Polaris**
  - Developed by H3D and UM
  - CZT segmented detector system
  - Both Compton Camera (CC) and Coded Aperture (CA) imaging modes
    - Ability to synthesize directional spectra for both methods developed for this project
- **Germanium Gamma-ray Imager (GeGI)**
  - Commercial imager by PHDS, software by ORNL
  - CA imager using tantalum mask
  - More sensitive to low energy photons (< 400 keV)
- **Compton Crosstalk / Occlusion Methods / Baby Janus**
  - Imaging software developed by NSTec applicable to multi-element sensors
  - Compton crosstalk demonstrated for Baby Janus detector
  - Evaluating occlusion method for application to Polaris
- **Gamma Detector Response and Analysis Software (GADRAS)**
  - Extensive capabilities for forward calculations and analysis of gamma-ray and neutron measurements

Project Goals (all accomplished)

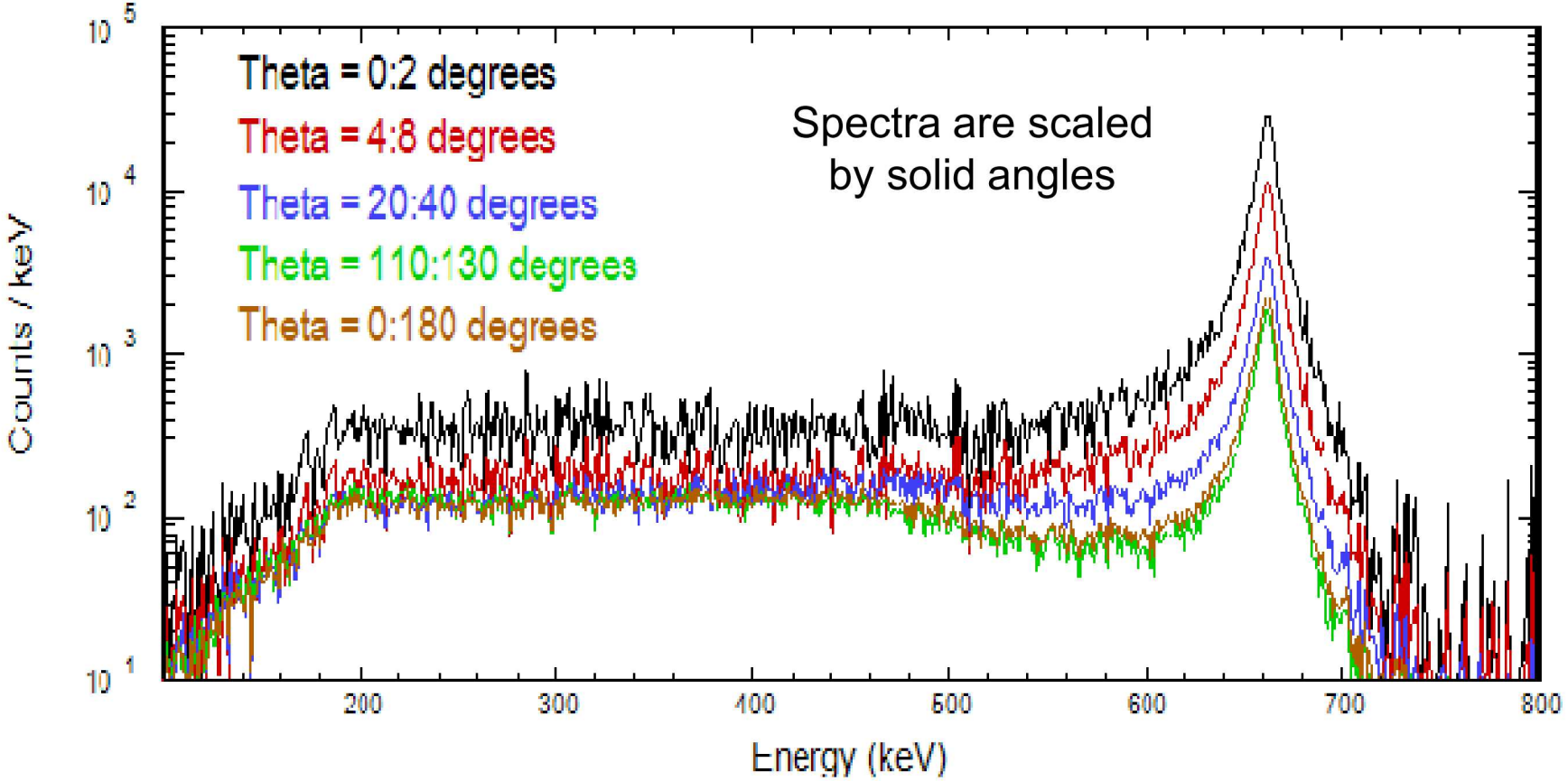
- **Utilize spectroscopic information collected by directional sensors**
  - Utilize directional spectra for analysis (normal focus is imaging)
  - Develop DRF for use in forward calculations and analysis
- **Explore alternative directional processing methods**
  - Assess Compton crosstalk and occlusion methods developed by NSTec
- **Develop common interface for data processing and analysis**
  - Application Programming Interface (API) developed and used by GADRAS to display and process data collected by Polaris and GeGI
  - Common GUI for CA and CC, analysis tools enabled for directional spectra
- **Evaluate Limitations and Compare Performance**
  - Non-imaging sensors (best statistics by using all data)
  - Coded Aperture (best for low-E gamma rays)
  - Compton Camera (best for high-E gamma rays)
    - Simple Back Projection (SBP)
    - Filtered Back-Projection (FBP)
    - Energy-Image Integrated Deconvolution (EIID)
    - Directional Unfolded Source Term (DUST)

Accomplishments in FY17-18

- **Evaluation of Imagers and Processing Algorithms**
  - Coded Aperture Mask/Anti-mask (**GeImager**) by ORNL
    - Automatic background rejection, HPGe energy resolution
    - DLL developed FY16, refined in FY17
  - Simple Back Projection (**SBP**) by H3D
    - DLL developed in FY15-16 to transform list-mode file into binary data cube (probability spectrum as function of location), callable by other applications (GADRAS specifically)
  - Filtered Back-Projection (**FBP**) by UM
    - Uses spherical harmonics transform to improve spatial resolution
    - DLL developed FY16, refined FY17 for robustness and accelerated by using SBP data cubes rather than list-mode files
  - Energy-Image Integrated Deconvolution (**EIID**) by UM
    - Uses Maximum Likelihood Estimation Maximization (MLEM) to tracks every interaction
    - DLL developed FY16, refined in FY17
    - Hours of computation time for 1-hour measurement
  - Directional Unfolded Source Term (**DUST**) by SNL
    - Improve spectral accuracy so data are compatible with GADRAS analysis algorithms
    - Developed FY16, extensive refinements in FY17

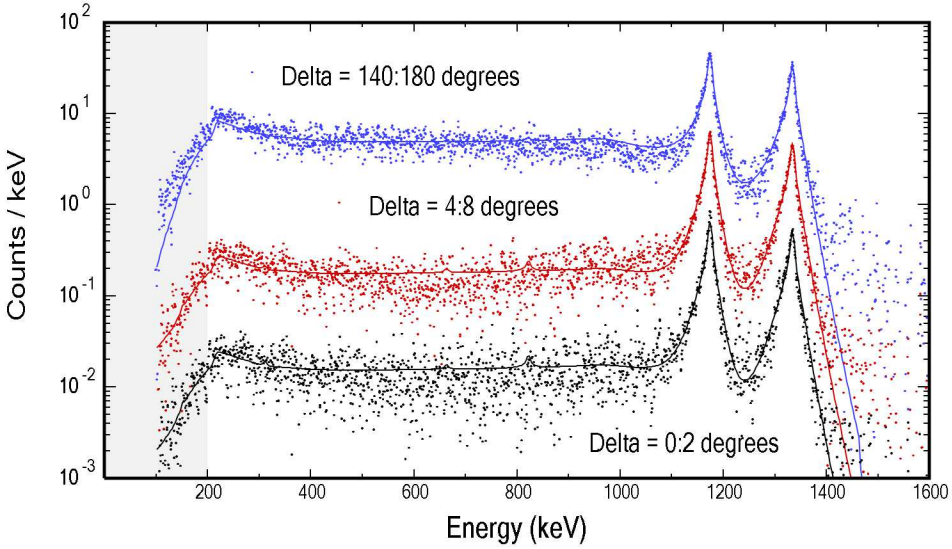
Compton Camera Challenge

- Probability cones render peaks in all spatial regions
- Plot below shows SBP spectra at various angles relative to the actual location of a ^{137}Cs source



DUST Approach

- **Detector Response Function**
  - Ability to characterized energy and spatial dependence of spectra developed and integrated into GADRAS
    - Fundamental response accurate to within about 50%
    - Empirical compensation yields accuracy to within 10%



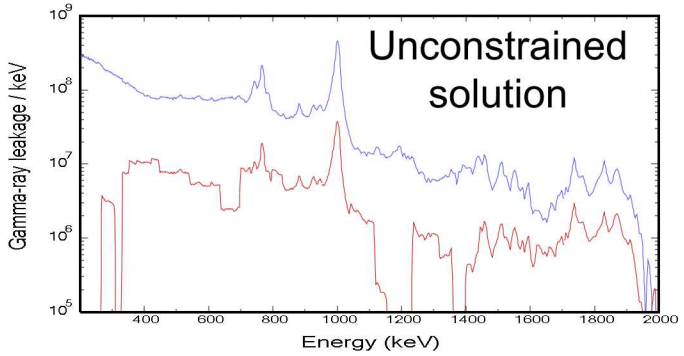
- **DUST Concept**
  - Solve by linear regression for source terms $S_{i,j}$ by fitting directional SBP spectra $Y_{i,j}$ using response function $R_{i,\delta(j,k)}$
  - Progress from high to low energy, stripping the continuum response at lower energies

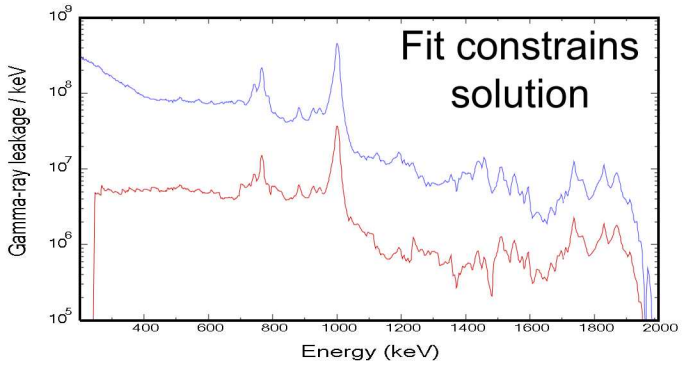
$$Y_{i,j} = \sum_{k=1}^{nAngles} R_{i,\delta(j,k)} S_{i,j}$$

$$Y_{1:i-1,j} = Y_{1:i-1,j} - \sum_{k=1}^{nAngles} R_{1:i-1,\delta(j,k)} S_{i,k}$$

DUST Implementation

- **Flaw in brute force approach**
  - 10^7 degrees of freedom if 1000 energy groups and 100×100 spatial elements
    - Poor statistical confidence and inability to resolve features with spatial overlap
- **Multi-step process solves for source terms progressively**
  - A. Generate several contours that cluster regions with similar spectral signatures
  - B. Solve for foreground versus background only to obtain best foreground source term
  - C. Solve for source terms in each contour region using foreground/background solution to constrain spectrum from sum of contour regions
  - D. Fit the source terms using linear combination of over 300 computed templates
  - E. Repeat (C) using fit from (D) as weak constraint to suppress impossible solutions



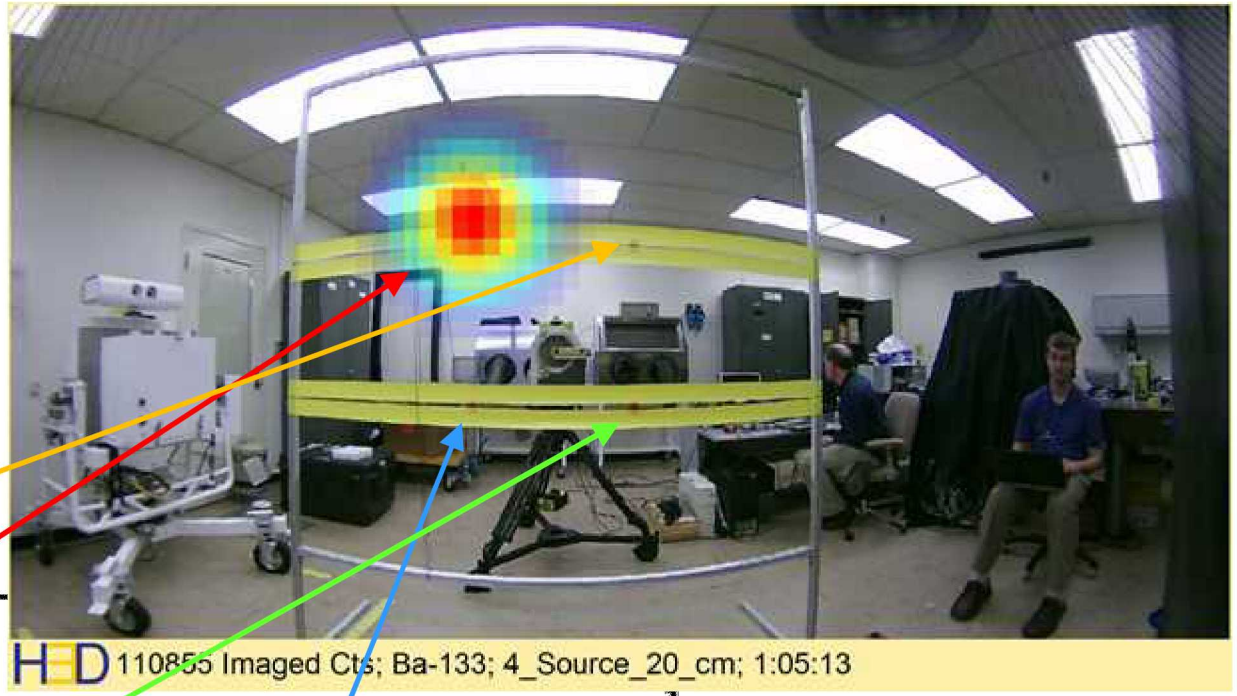


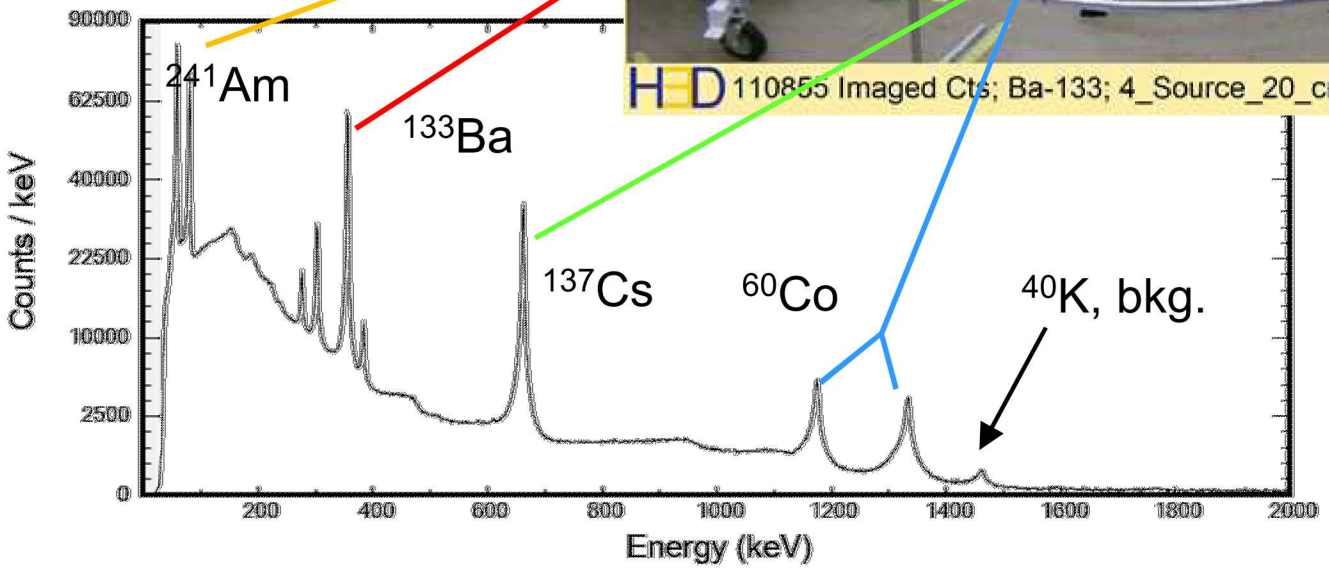
  - F. Fit spatial distributions within contours using sum spectra for contours from Step E

ORNL Experiment / Evaluation

Measurements with Polaris and GeGI:

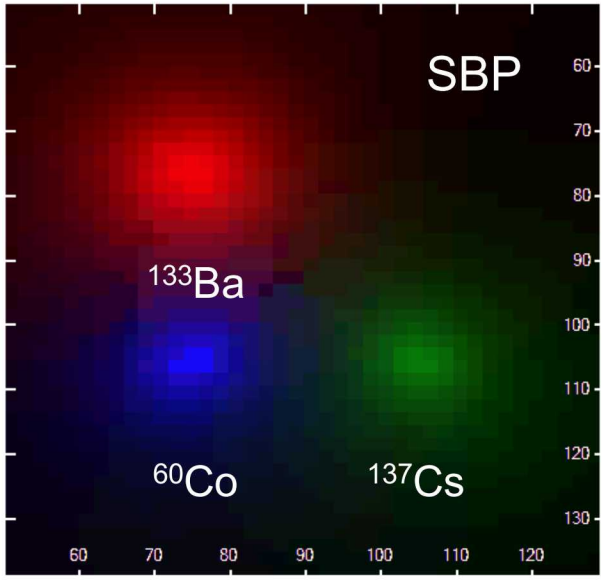
- Calibration sources at series of separations (1, 2, 5, 10, 15, 20, 30, 50 cm)
- DU cylinders
- Thorium plate

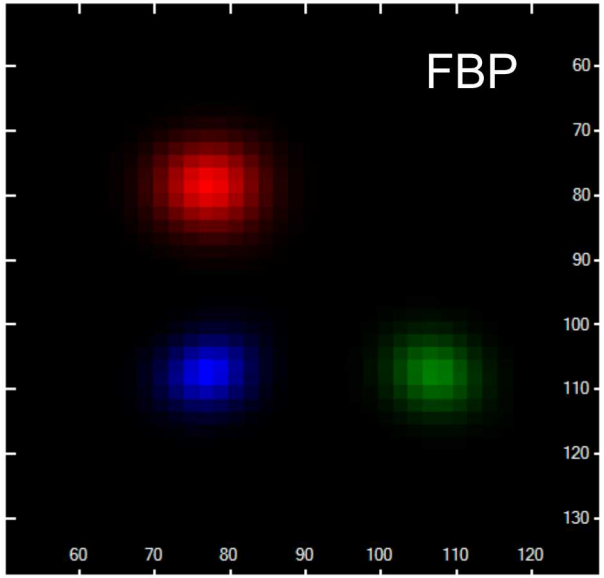


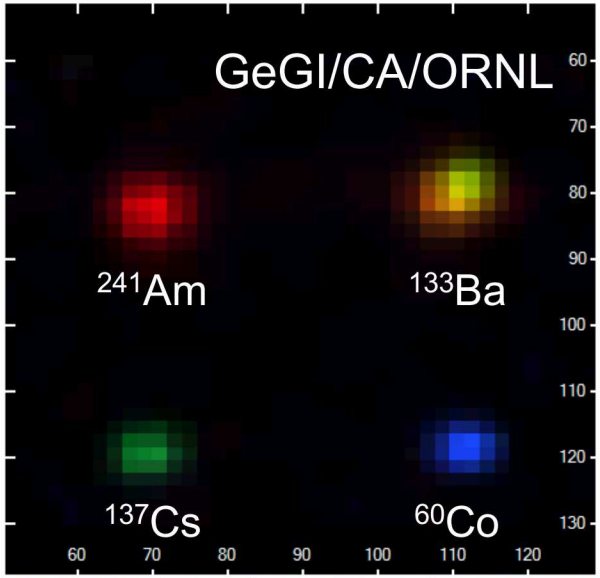


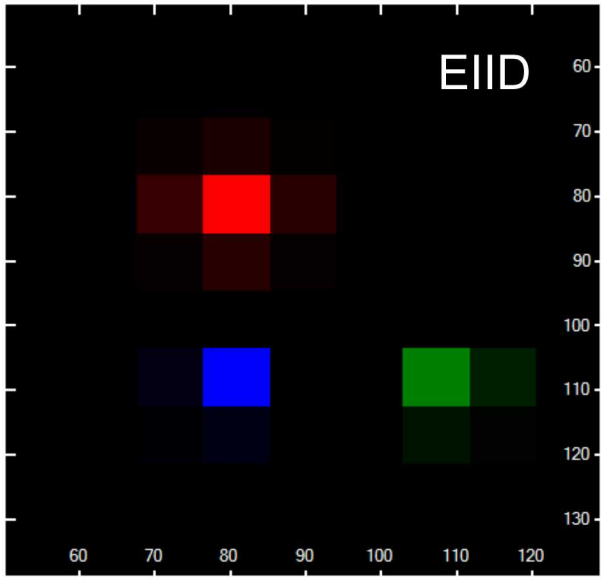
Gross spectrum recorded by Polaris shows all sources, but no location information

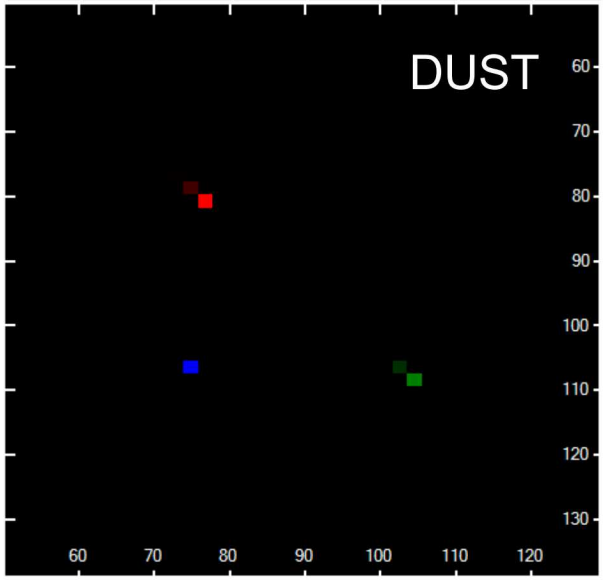
Images at 30-cm Separation

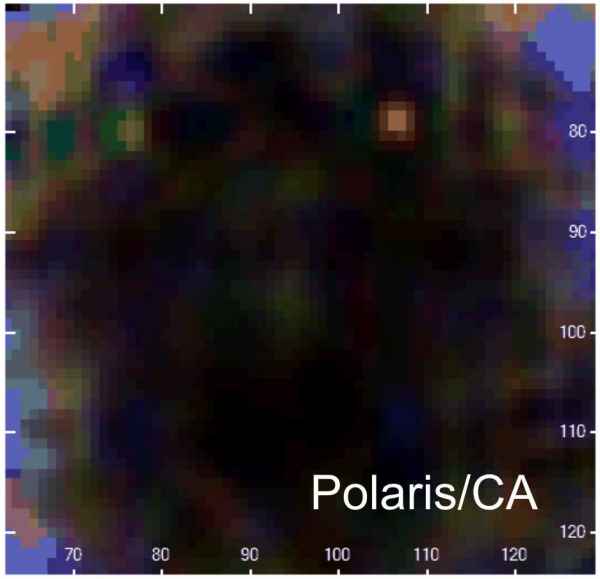




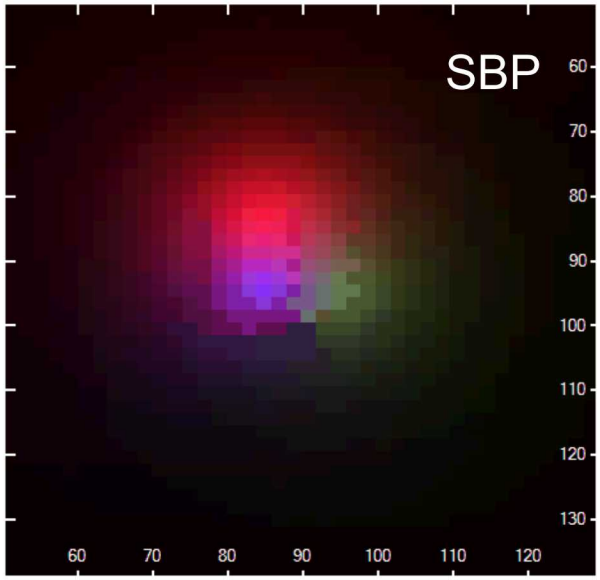


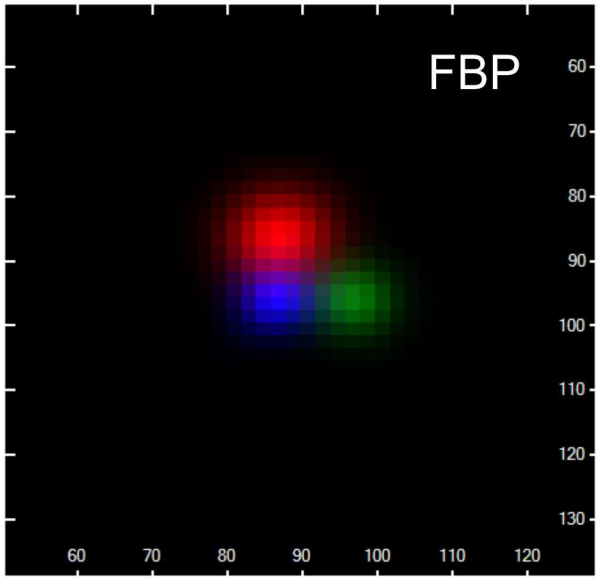


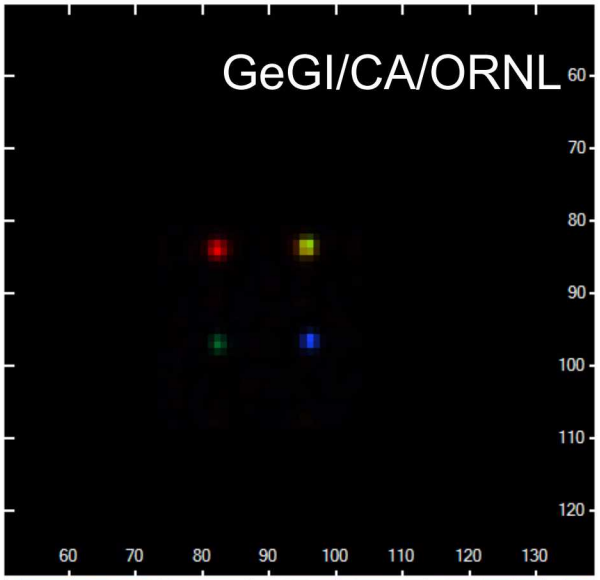


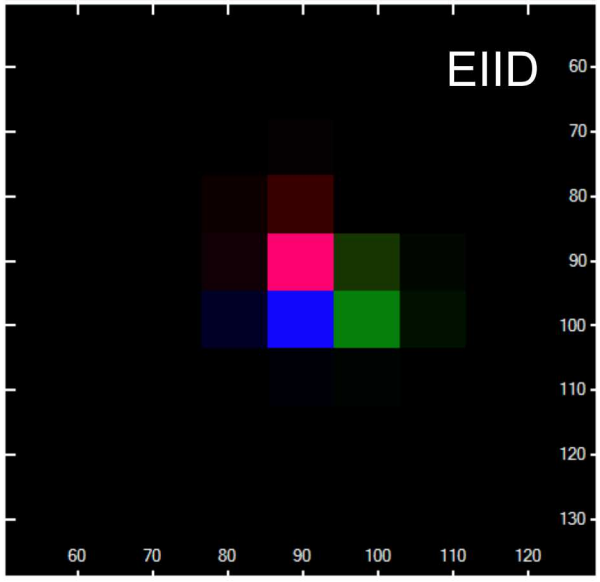


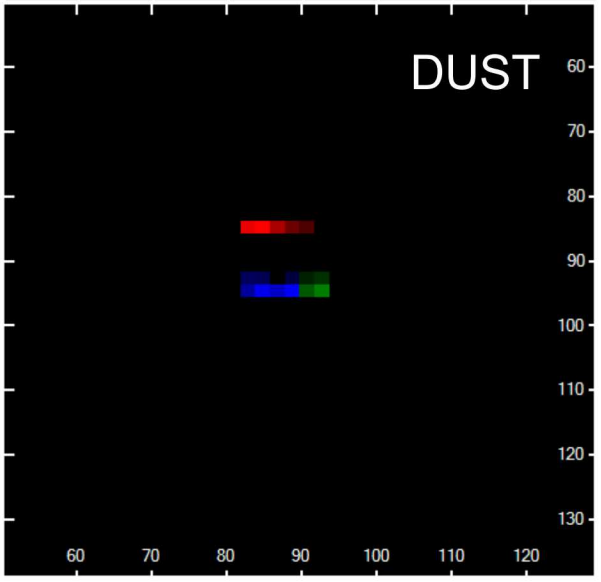
Images at 10-cm Separation

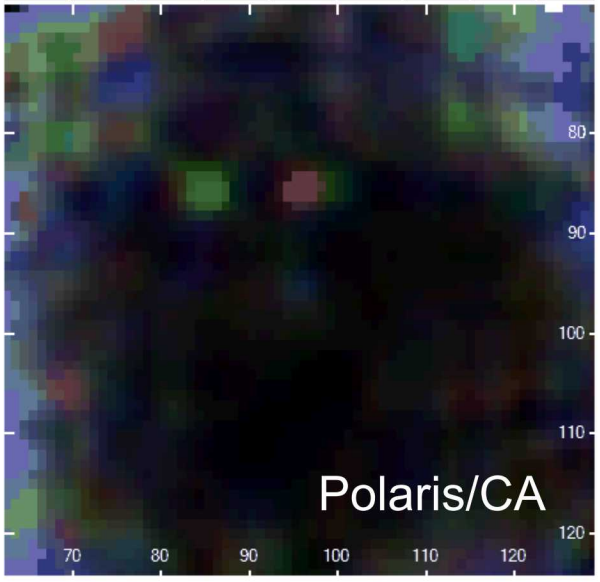




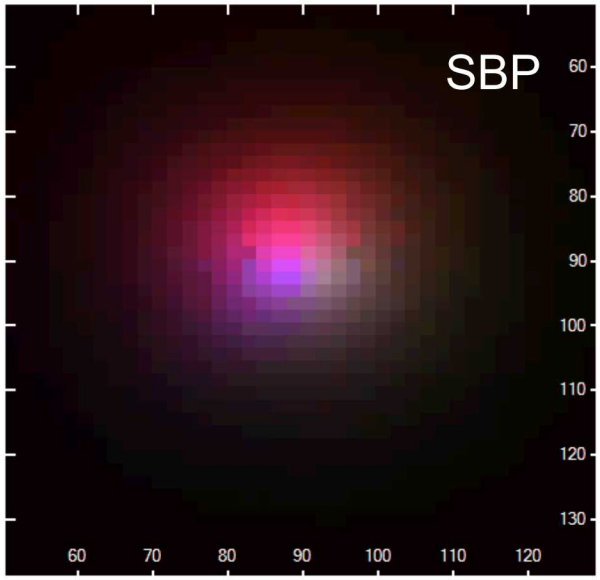


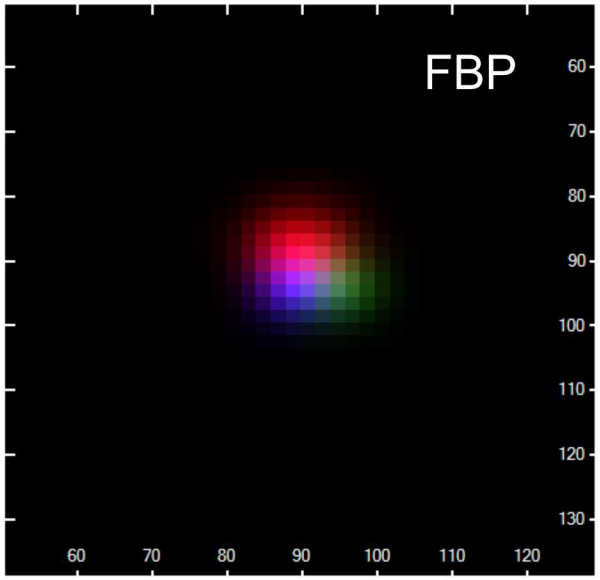


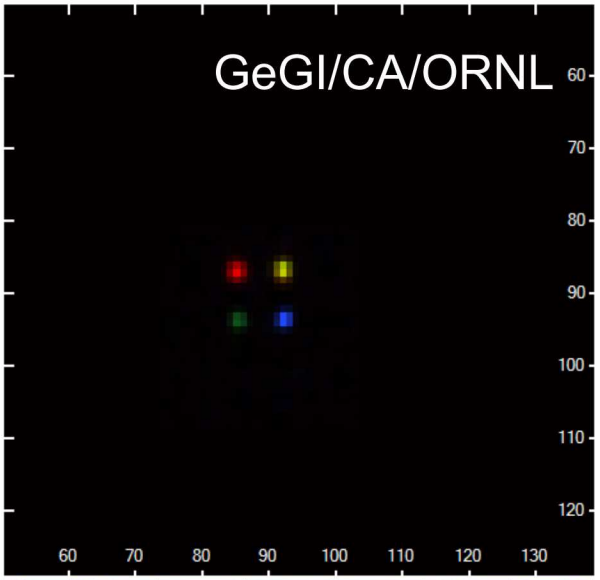


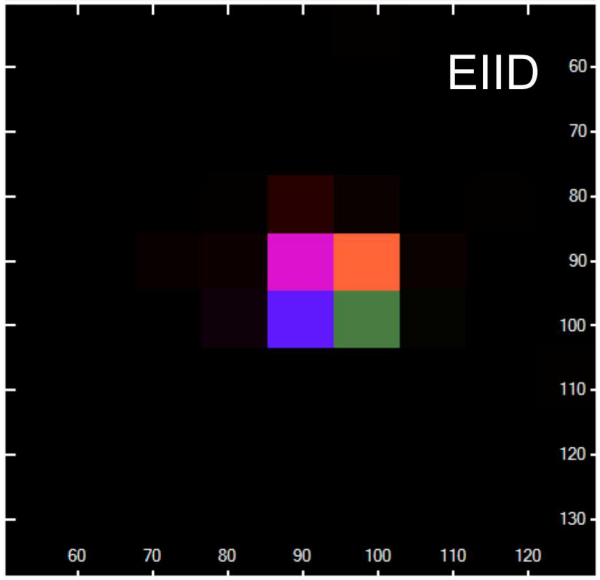


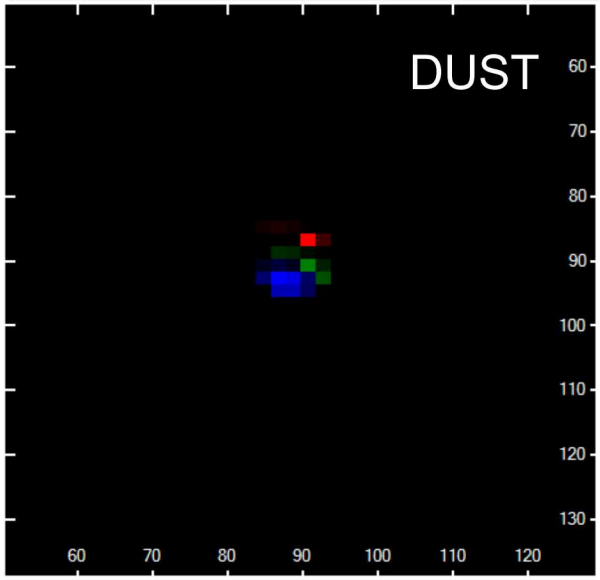
Images at 5-cm Separation

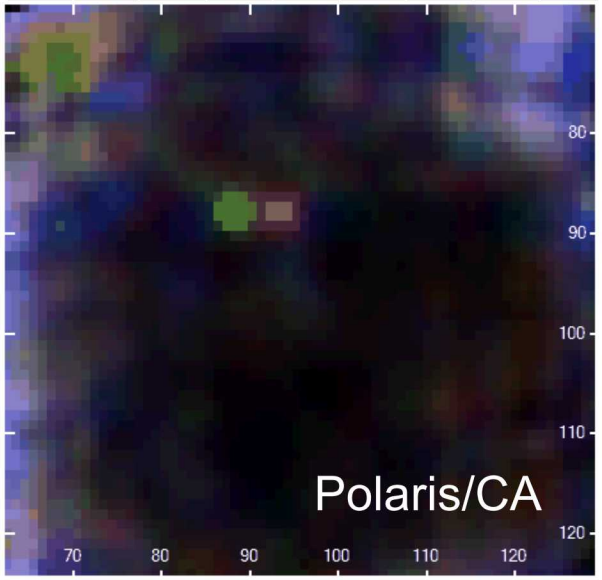




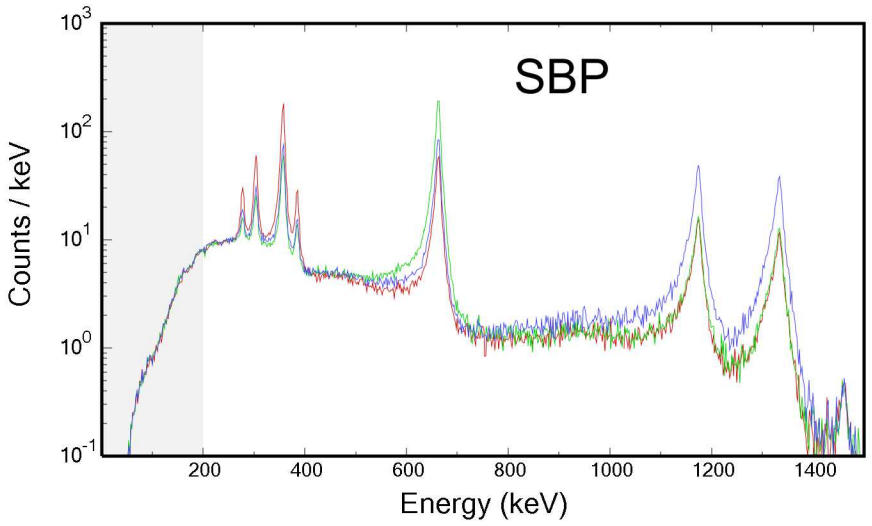


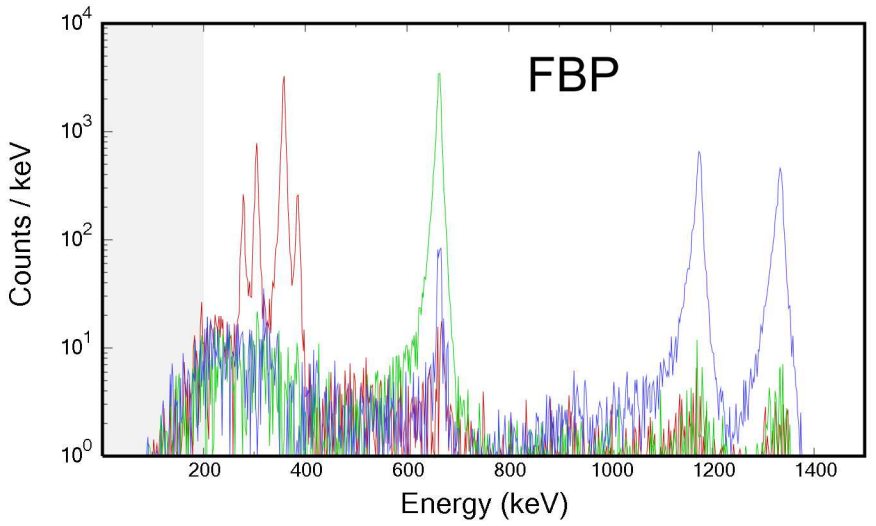


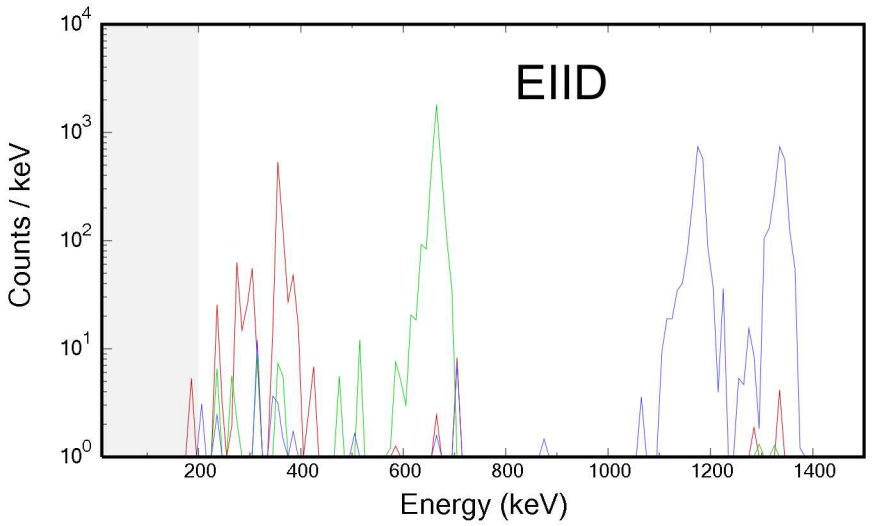


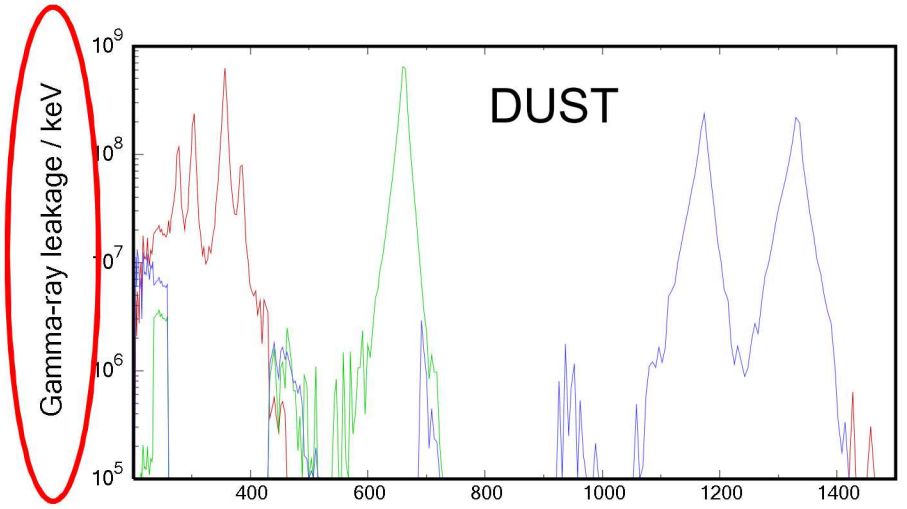


Spectra at 30-cm Separation

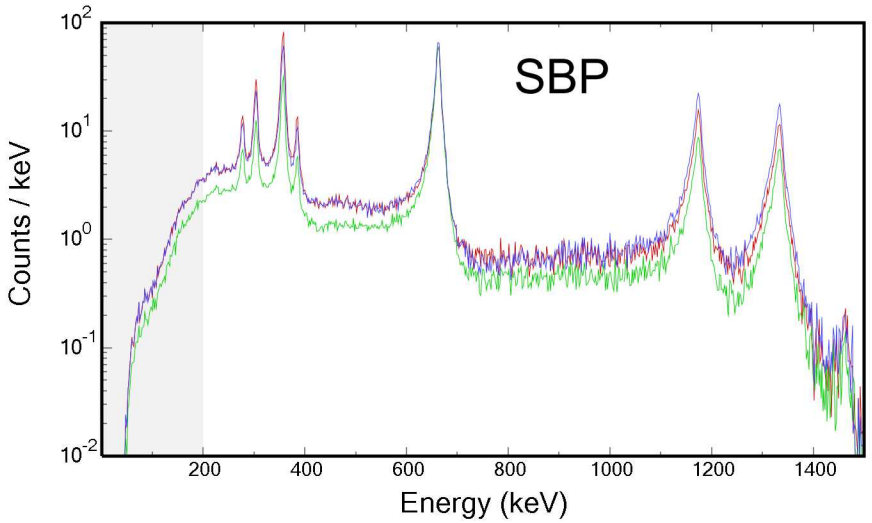


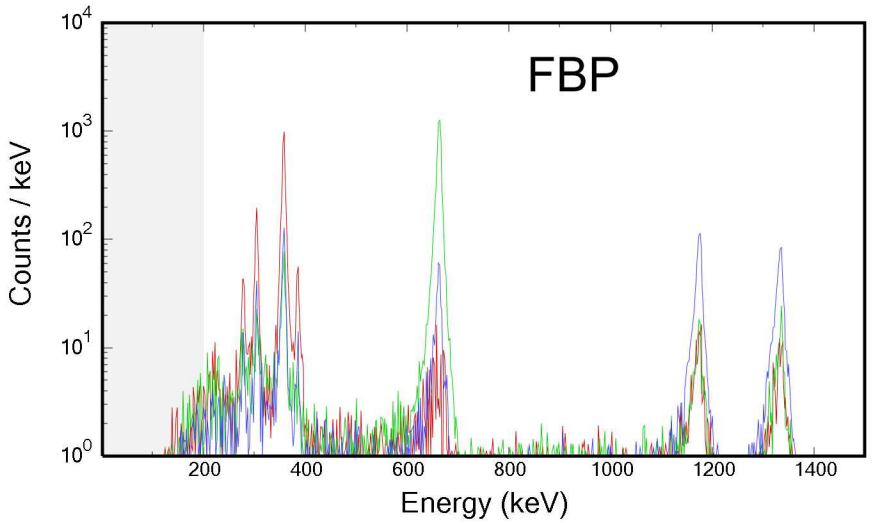


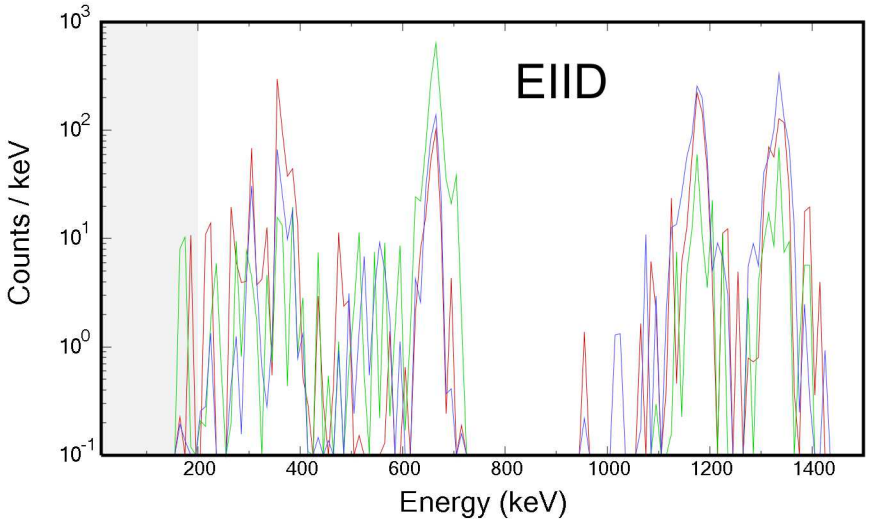


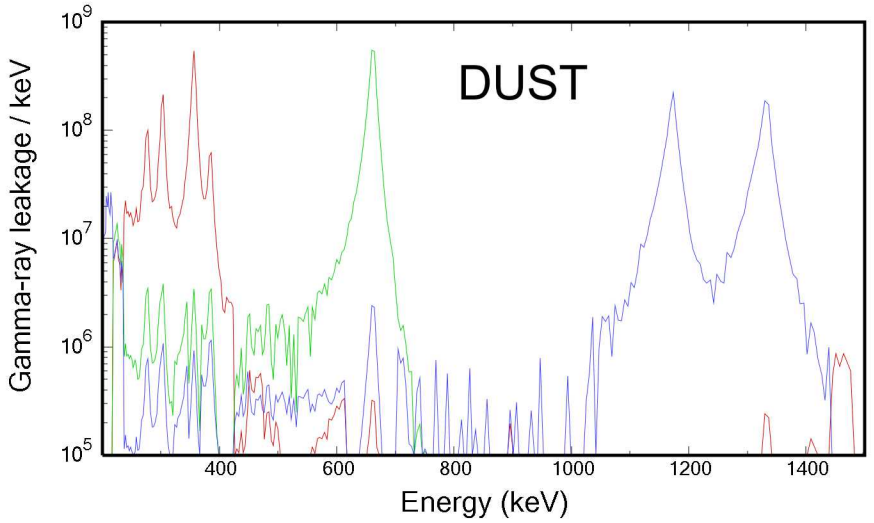


Spectra at 10-cm Separation

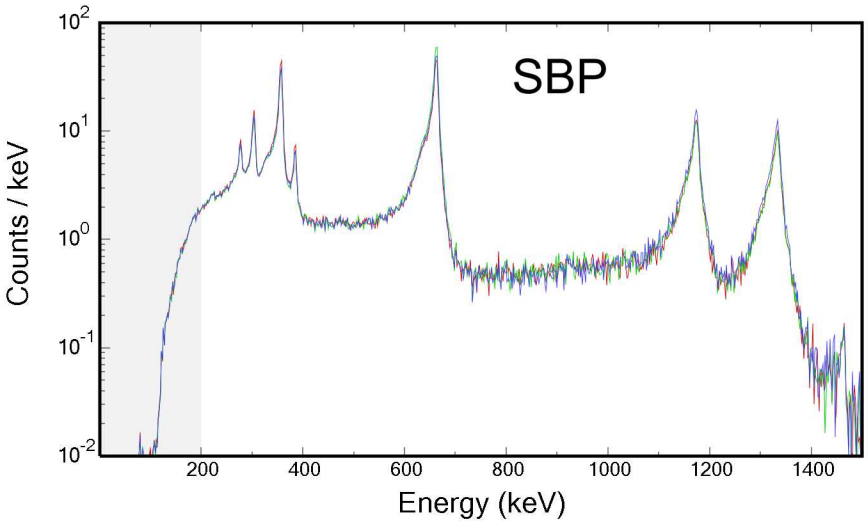


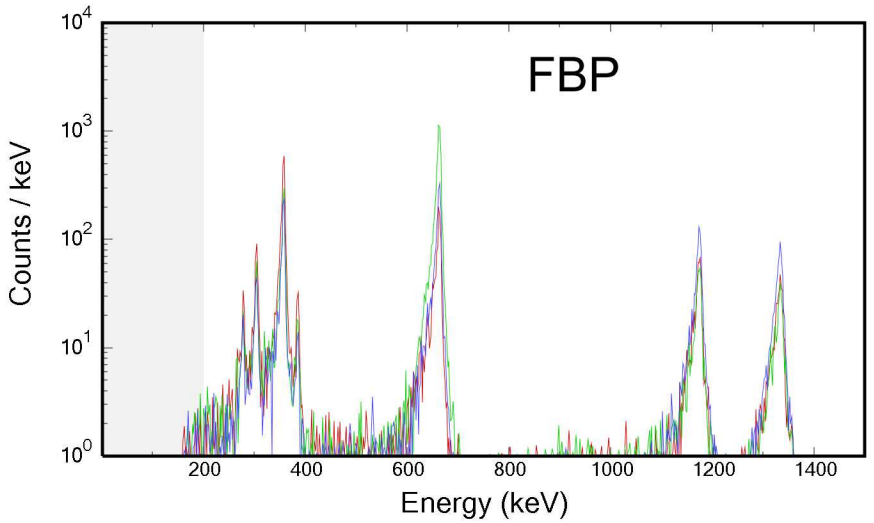


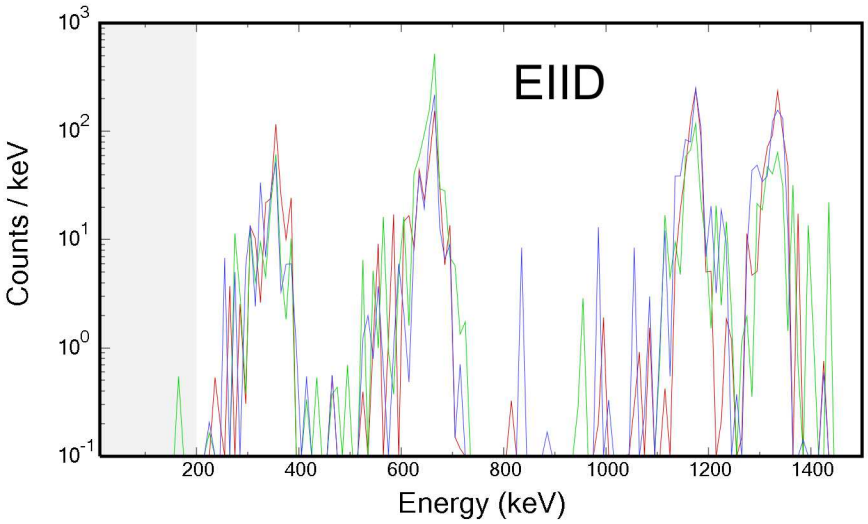


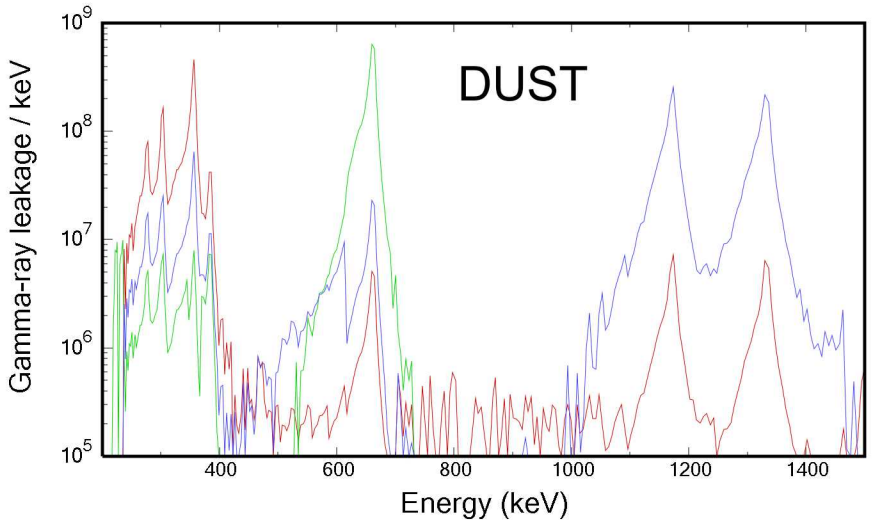


Spectra at 5-cm Separation

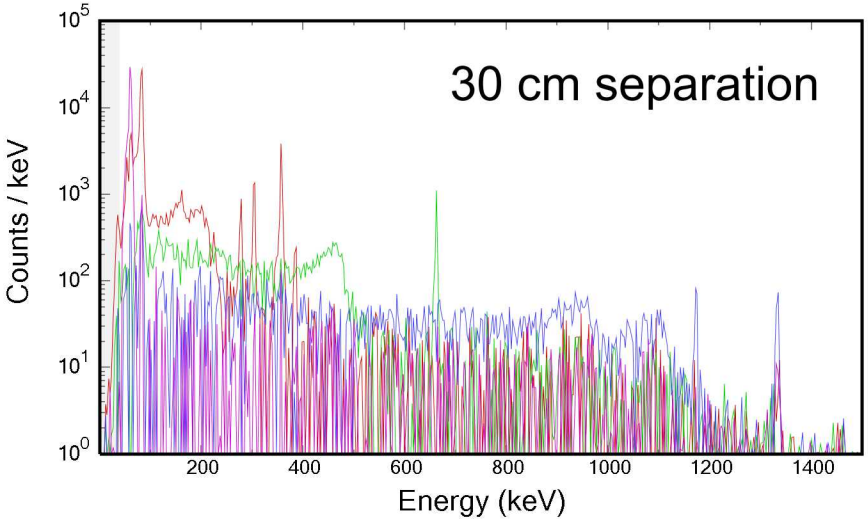


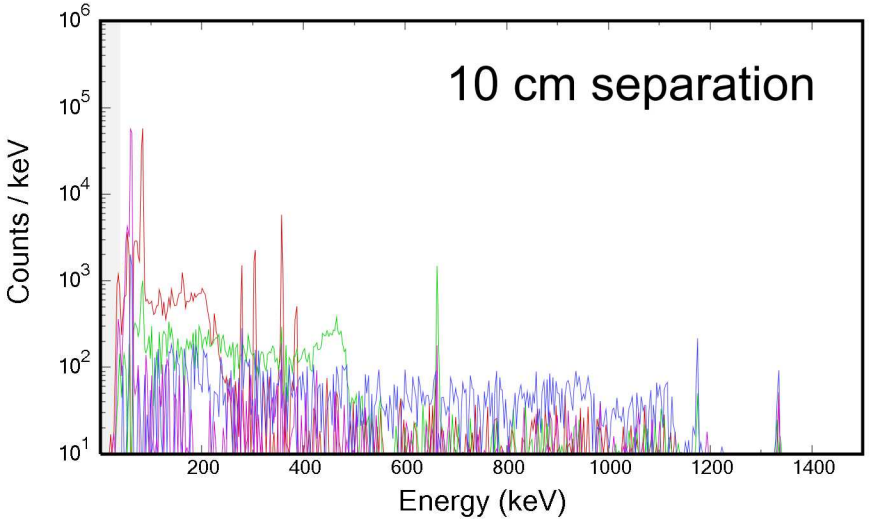


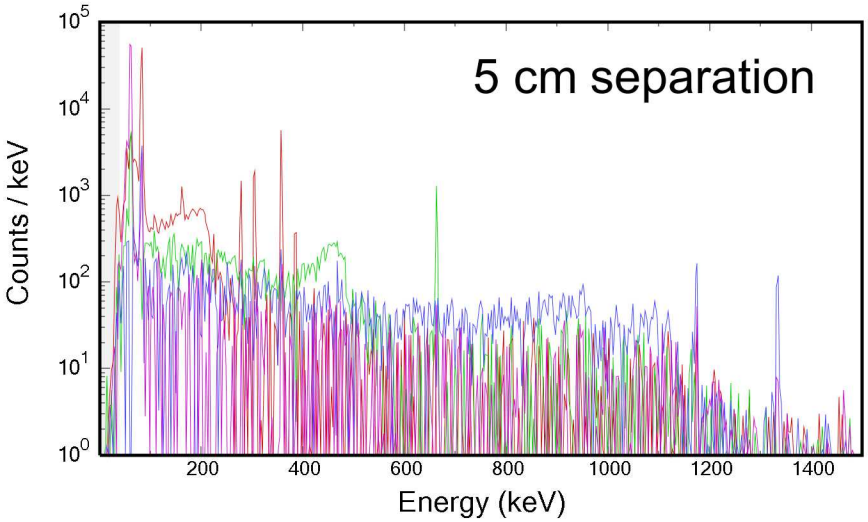


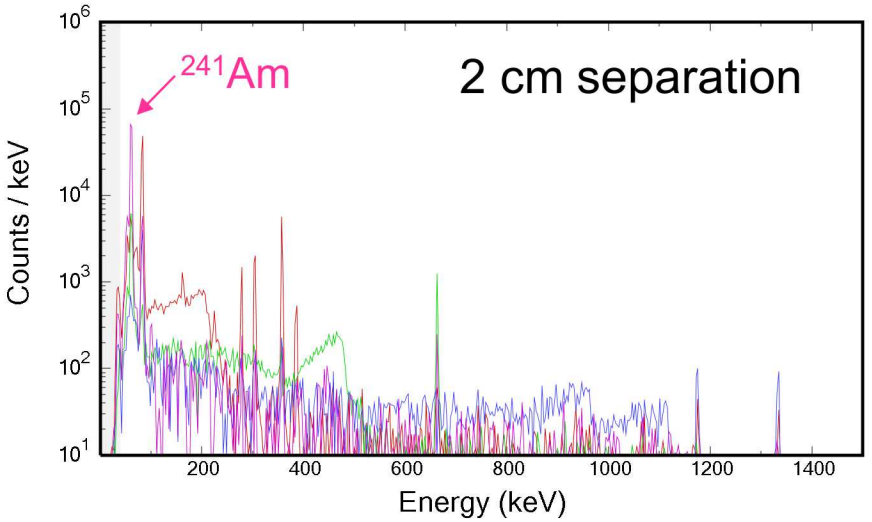


GeGI, Mask/Anti-mask, ORNL

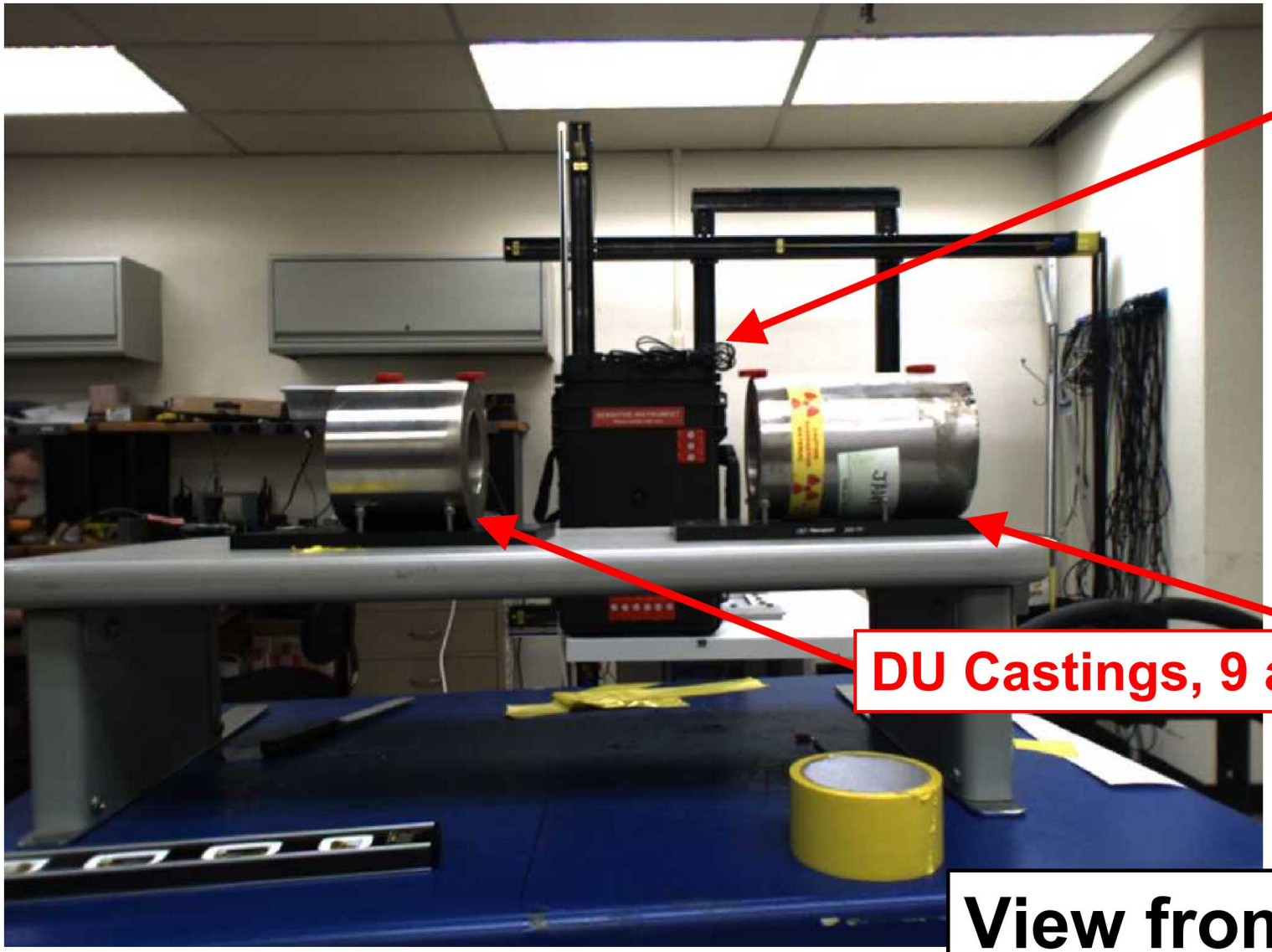




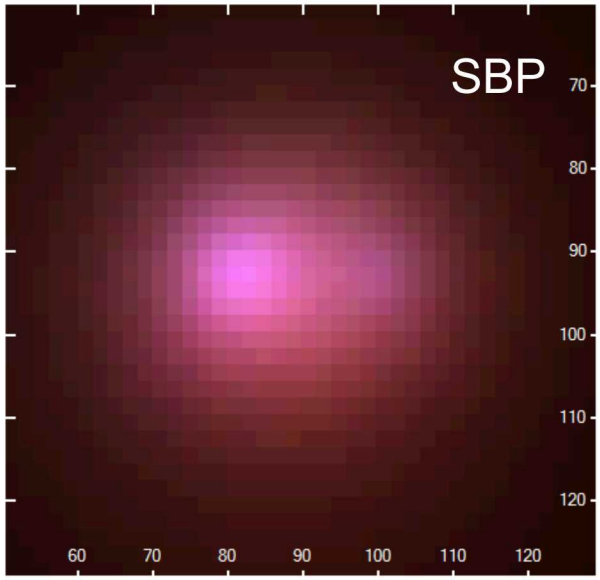


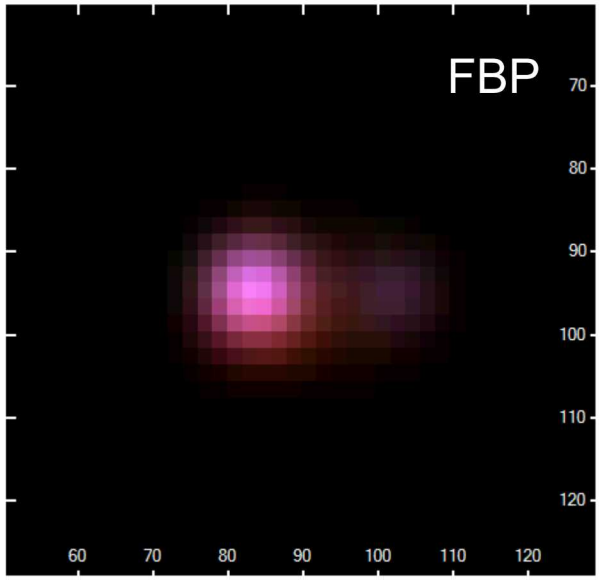


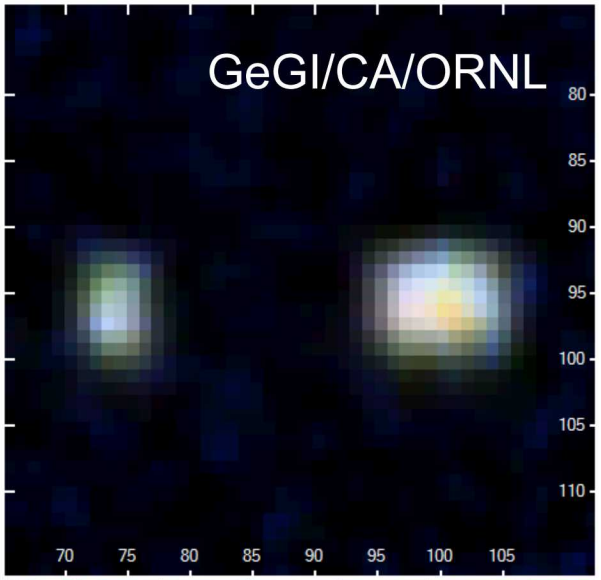
DU Castings 25 cm Separation

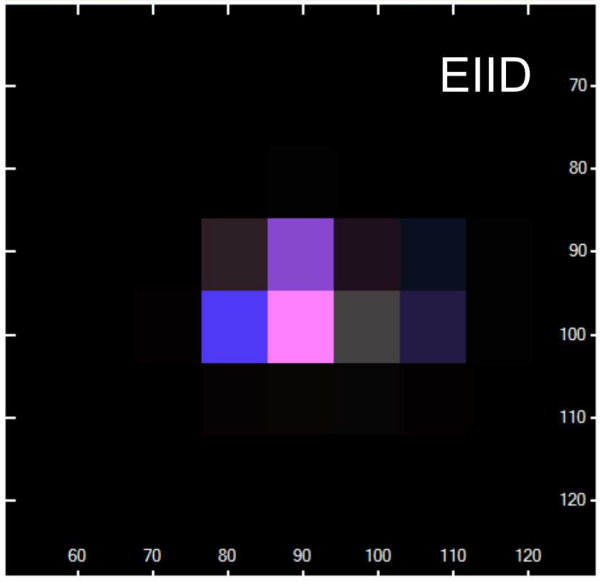


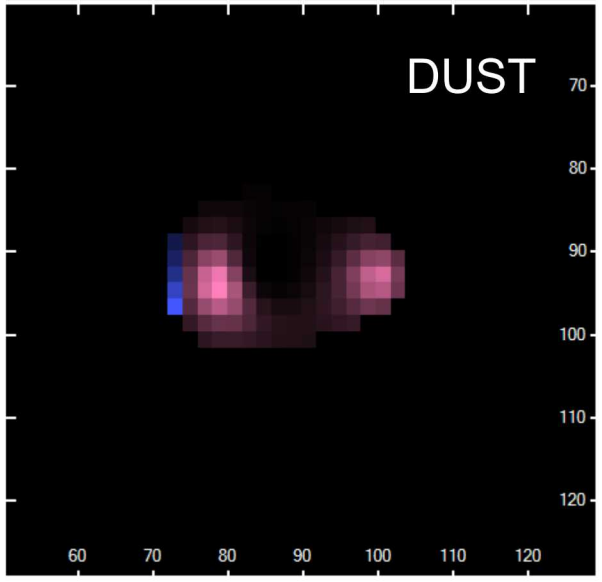
DU Castings at δ = 25 cm

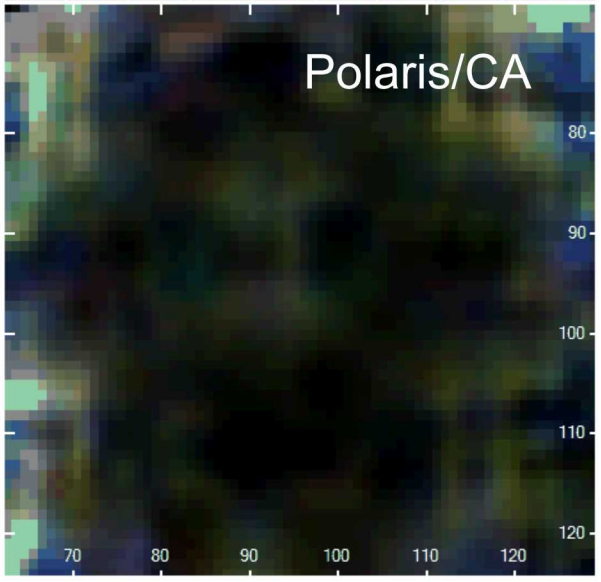




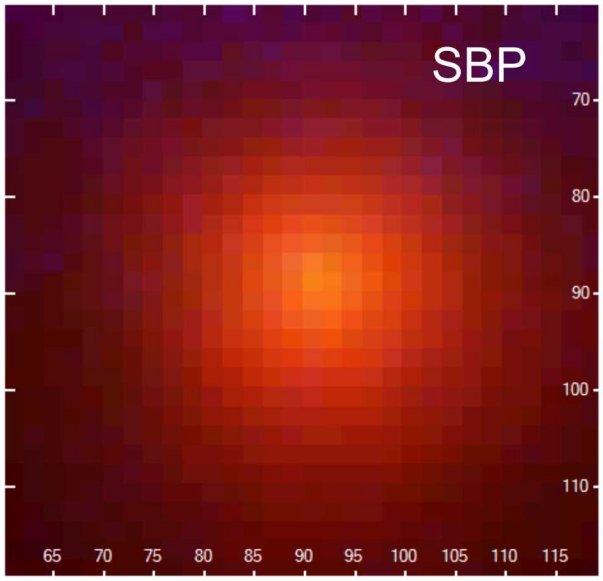


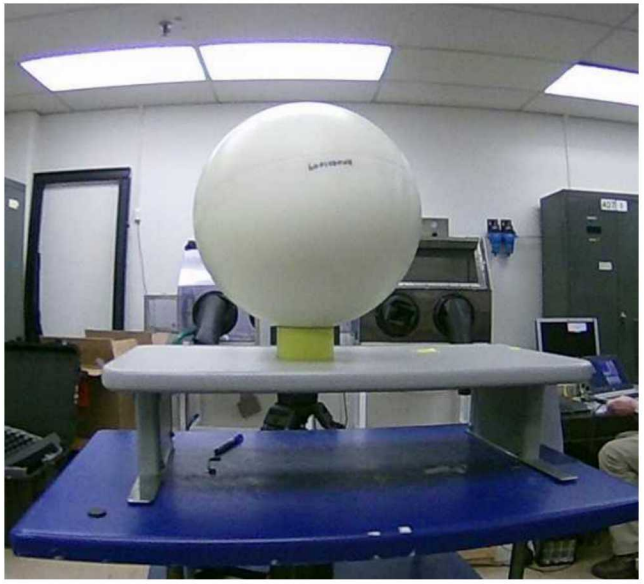


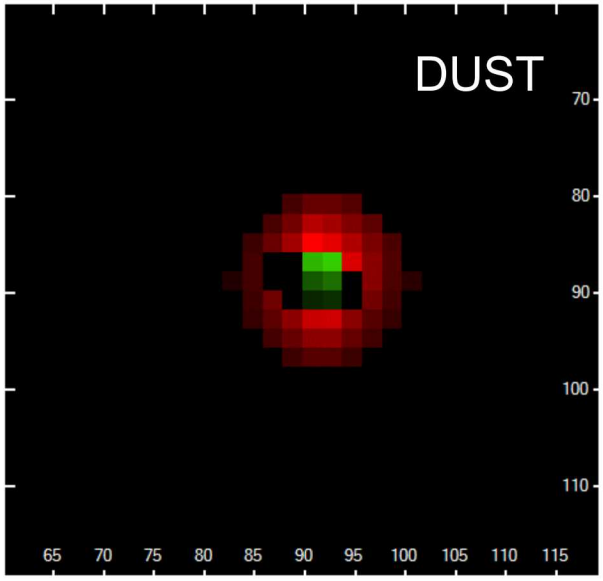


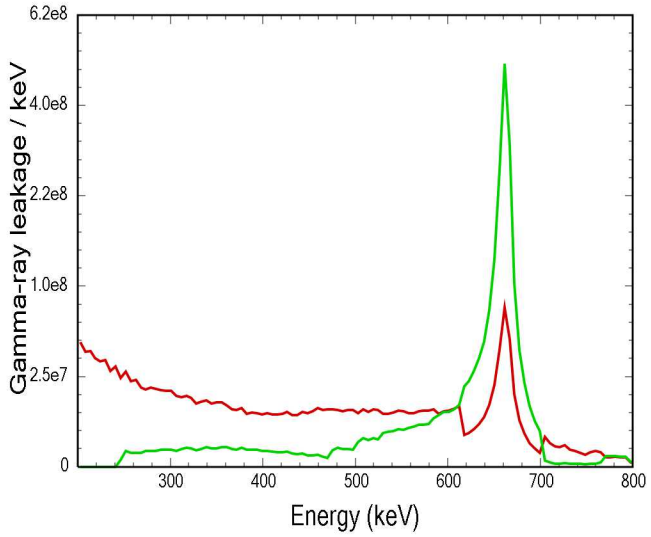


137Cs in Polyethylene Sphere









Analysis Example

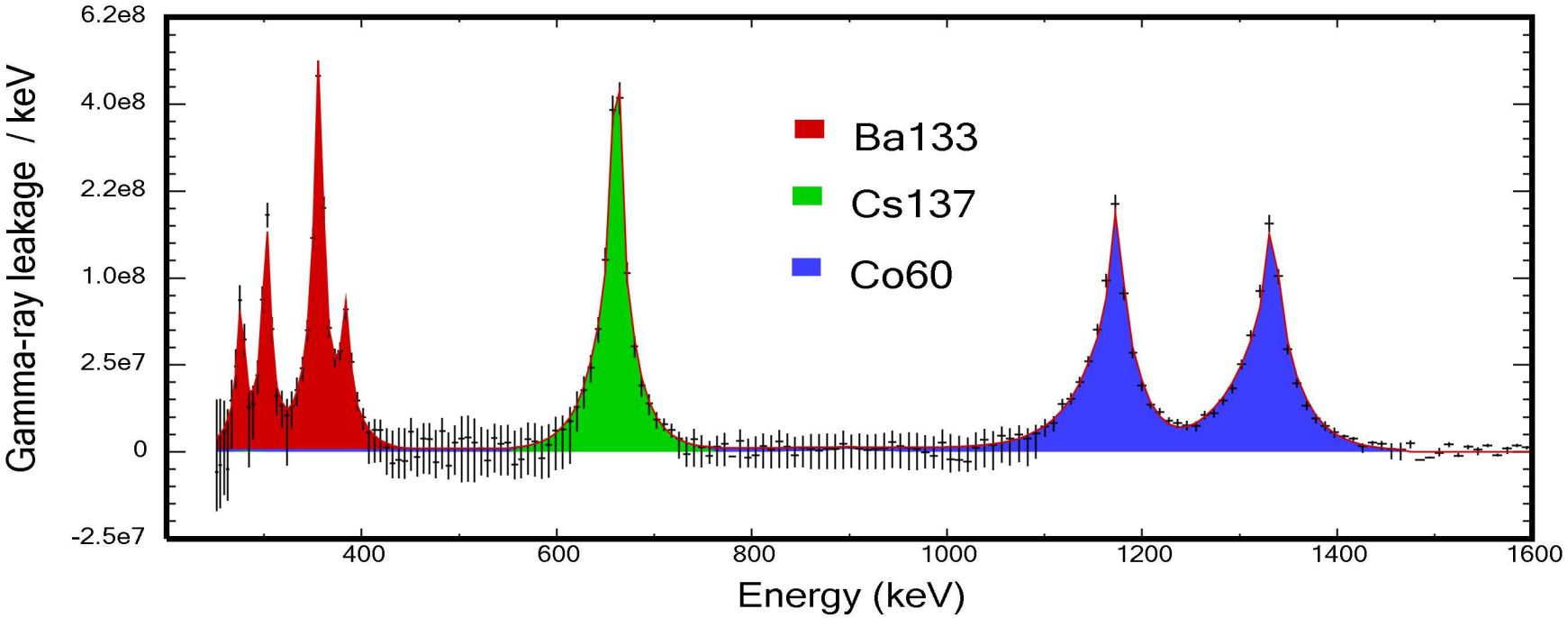
- Is ^{137}Cs distributed within poly or concentrated within?
- Region at center of sphere shows full energy peak; annular region exhibits primarily scattered continuum
- DUST image even suggest void within poly

Summary/Milestones

- **FY15**
  - Calibration data for Polaris and GeGI collected and DRF developed
  - Analysis algorithms modified to process Polaris data
  - API developed that specifies common interface for imaging sensors
  - DLLs conforming to API developed for Polaris and GeGI
- **FY16**
  - Compton crosstalk method evaluated
  - DUST algorithm developed to unfold CC data for Polaris
  - Polaris and GeGI DLLs integrated into GADRAS and GUI developed
  - Numerous software refinements
- **FY17**
  - DUST algorithm revised to automate analysis, CA analysis in progress
  - DLL developed by UM for filtered back-projection (FBP) method
  - DUST vs. FBP vs. EIID (Polaris) vs. GeGI to be evaluated
- **FY18: Software Consolidation and Reports**
  - Complete EIID, FBP integration and CA processing for Polaris
  - Process data for complex 3-D objects (DAF and INL measurements)

Extras

Isotope ID Example



- Example for four sources at ±10 cm separation
- Black error bars: total foreground source term computed by DUST
- Colored regions: components for 3 radionuclides derived by analyzing the spectrum with GADRAS isotope identification algorithm
- Accurate spectra and uncertainty estimates required for post-analysis