NRC·CNRC

Modular Survey Spectrometer and Compton Imager

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Ionizing Radiation Standards
Measurement Science and Standards
National Research Council Canada

On behalf of the SCoTSS collaboration (Silicon photomultiplier-based Compton Telescope for Safety and Security) . NRC: P. Saull, A. MacLeod. NRCan: L. Sinclair, A. McCann, DRDC: P-L. Drouin, L. Erhardt, R. Ueno, D. Waller

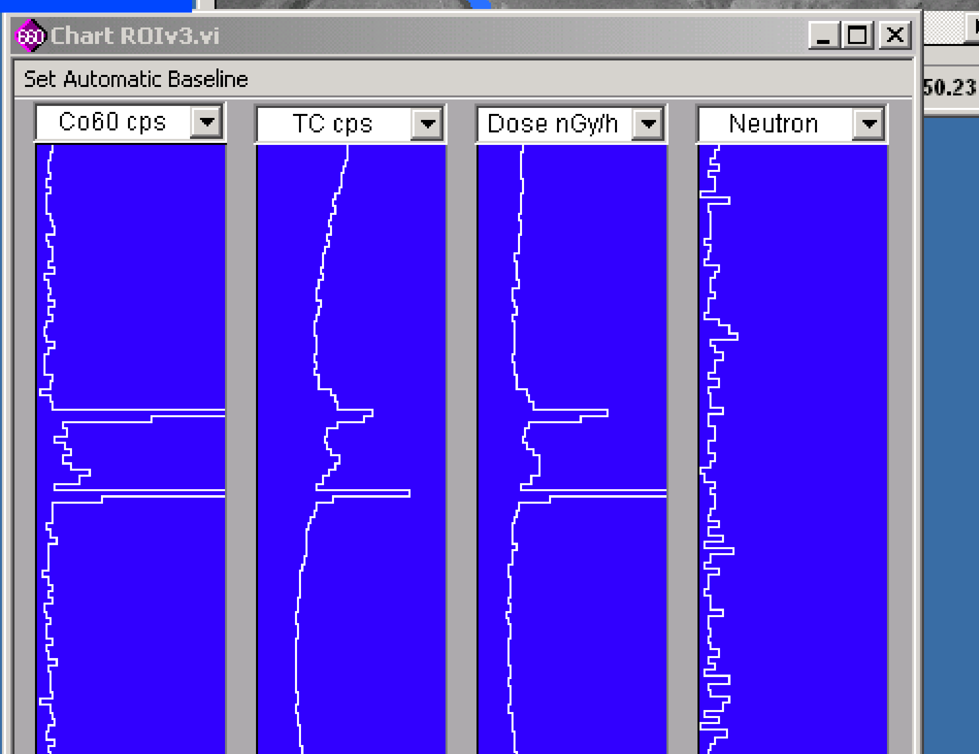
Outline

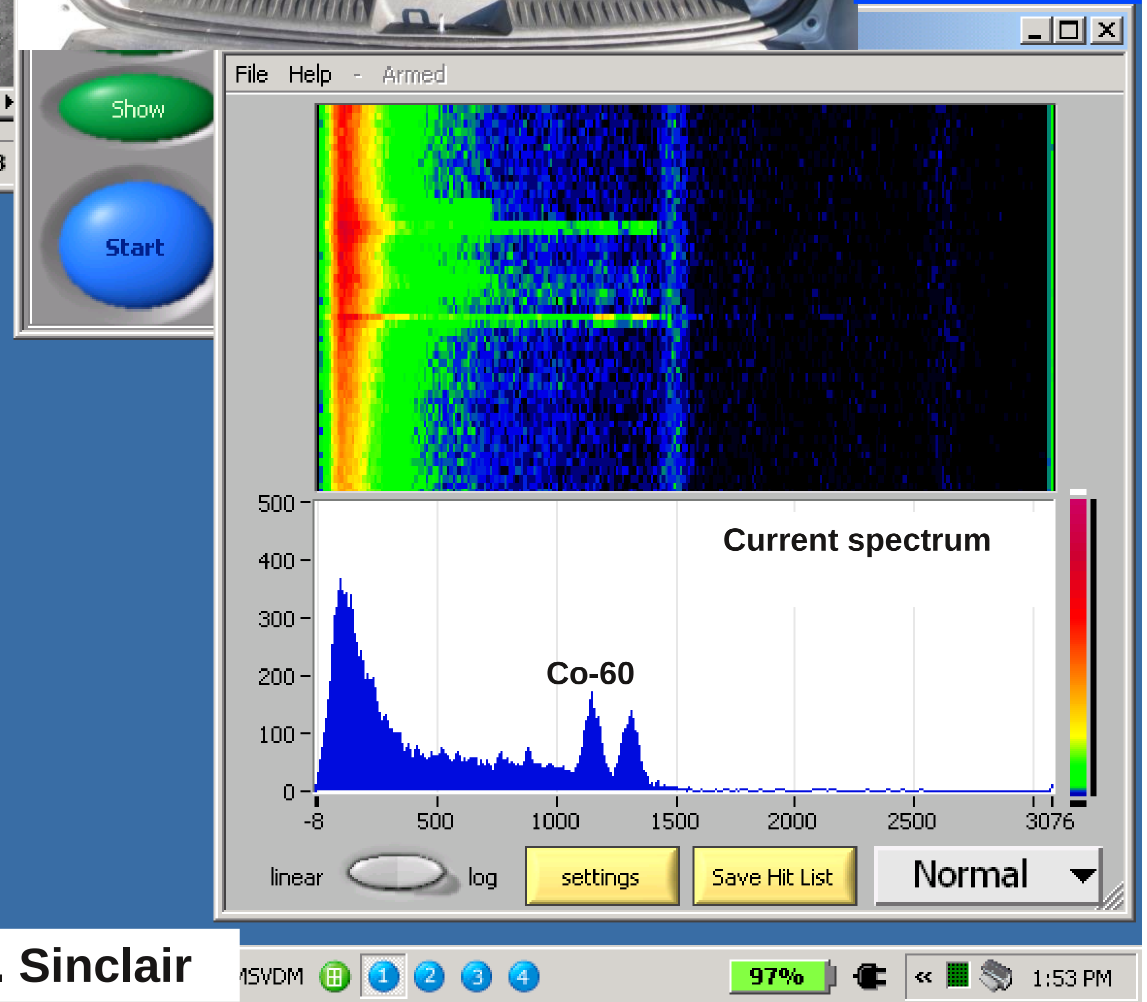
- Introduction
  - What is a Compton imager?
  - Potential applications
- History of Compton imaging at the National Research Council Canada (NRC)
- Current project to commercialize a Compton imager + spectrometer

What is a Compton imager?

- **Display location of radioactive sources (those that emit gamma rays) overlaid on a visual image of the surroundings.**
- **Aid intelligence gathering prior to or following a radiological or nuclear incident.**

Current state of surveying techniques in Canada: airborne and truck surveying with sensitive spectrometers



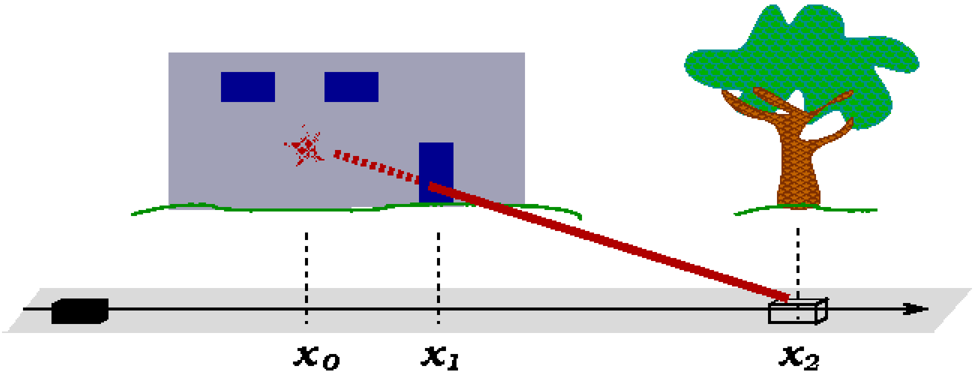


Natural Resources Canada
Ressources naturelles Canada
Canada

Courtesy of L. Sinclair

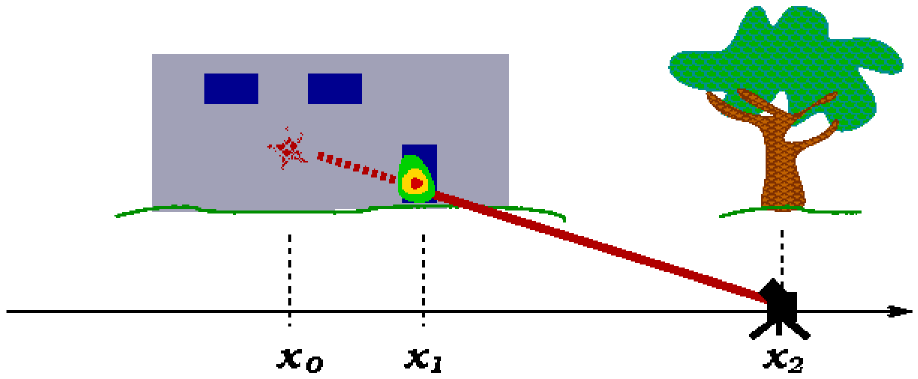
Why an imager?

Source inside building radiating through door



Phase 1: truck-borne survey identifies highest intensity location along road

$x = x_2$ → tree?



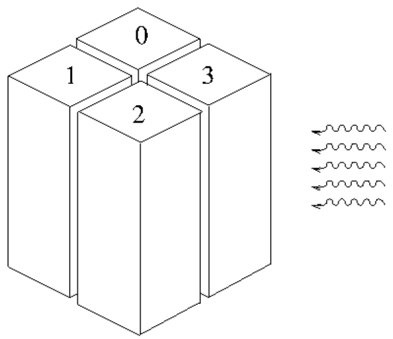
Phase 2: camera correctly locates source on line through door

$x = x_0$ or $x = x_1$ → building

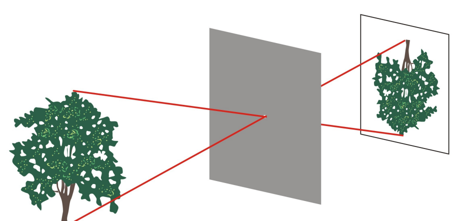
Competing imaging methods have major limitations

Methods

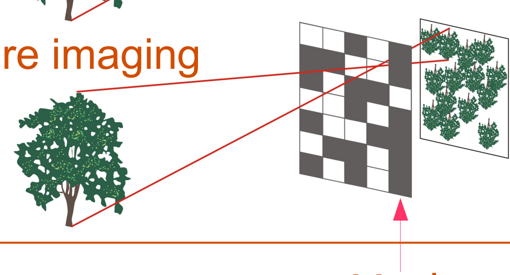
shelf-shielding – directional



pin-hole camera imaging



coded aperture imaging



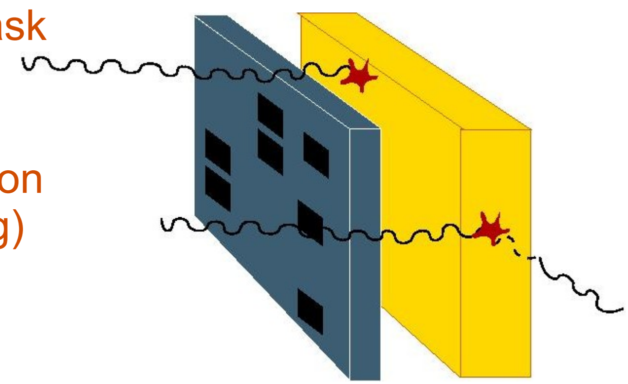
Mask

Limitations

Azimuthal information only

punch-through mask

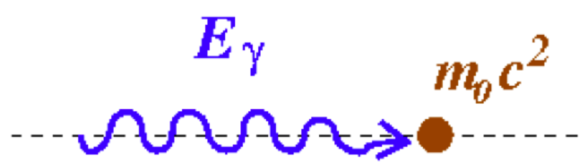
incomplete absorption
(Compton scattering)

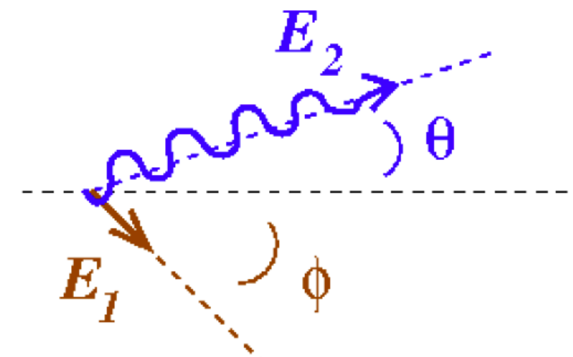


A much better approach is to use Compton imaging

Compton imaging relies on tracking the gamma ray as it scatters through your detector

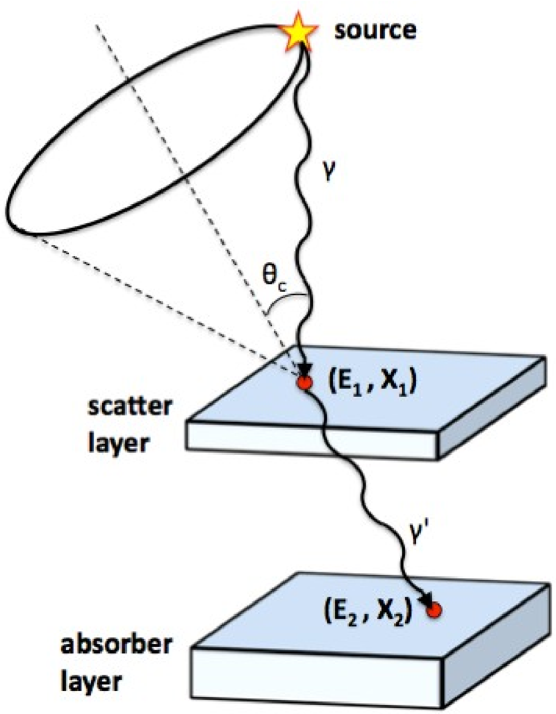
- **Incoming gamma ray Compton scatters off an electron**

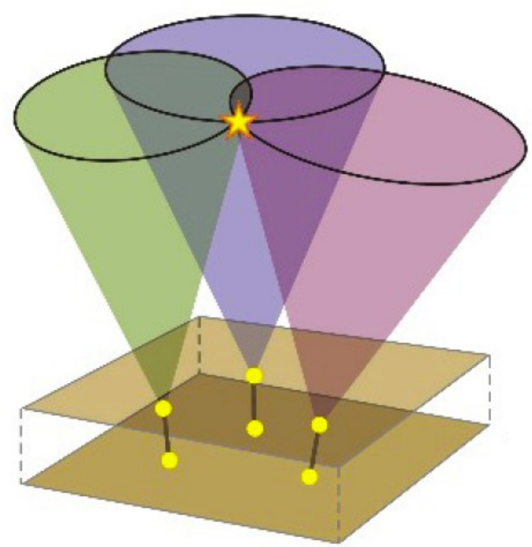


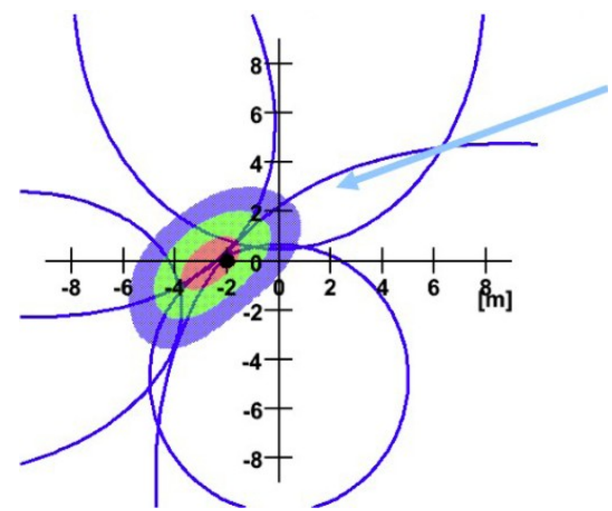


$$cos(\theta_C) = 1 + m_0c^2(\frac{1}{E_\gamma} - \frac{1}{E_2})$$

$$E_2 = E_\gamma - E_1$$





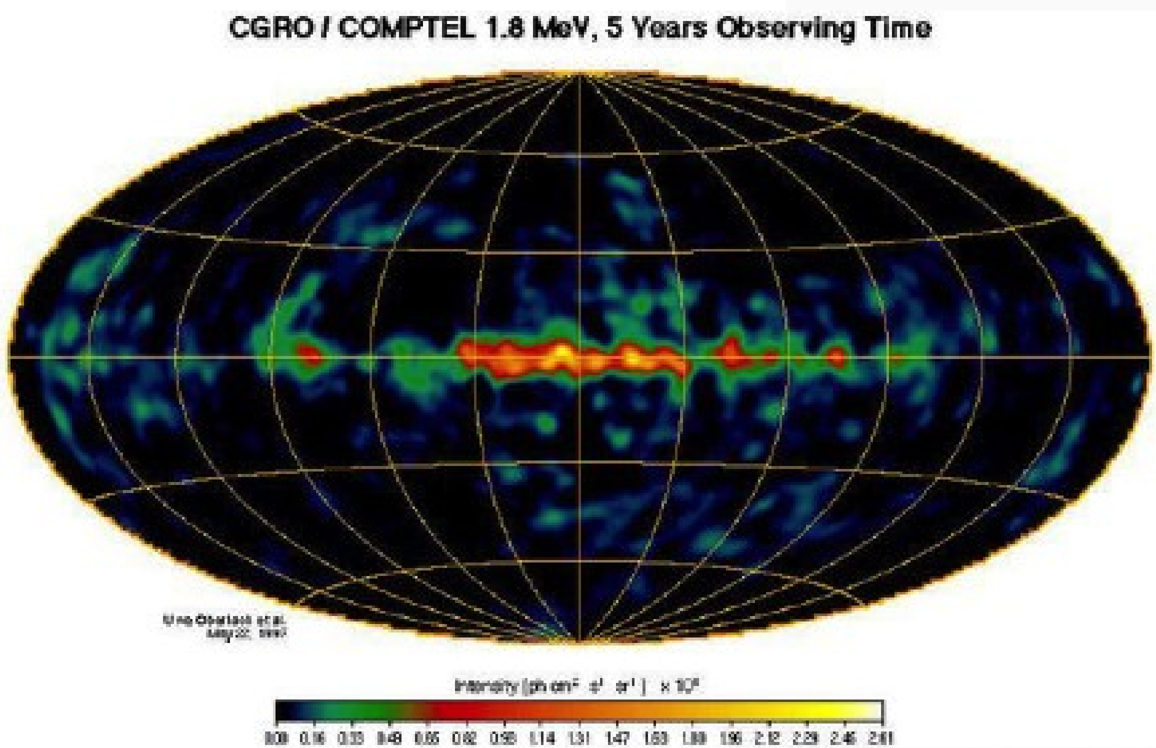


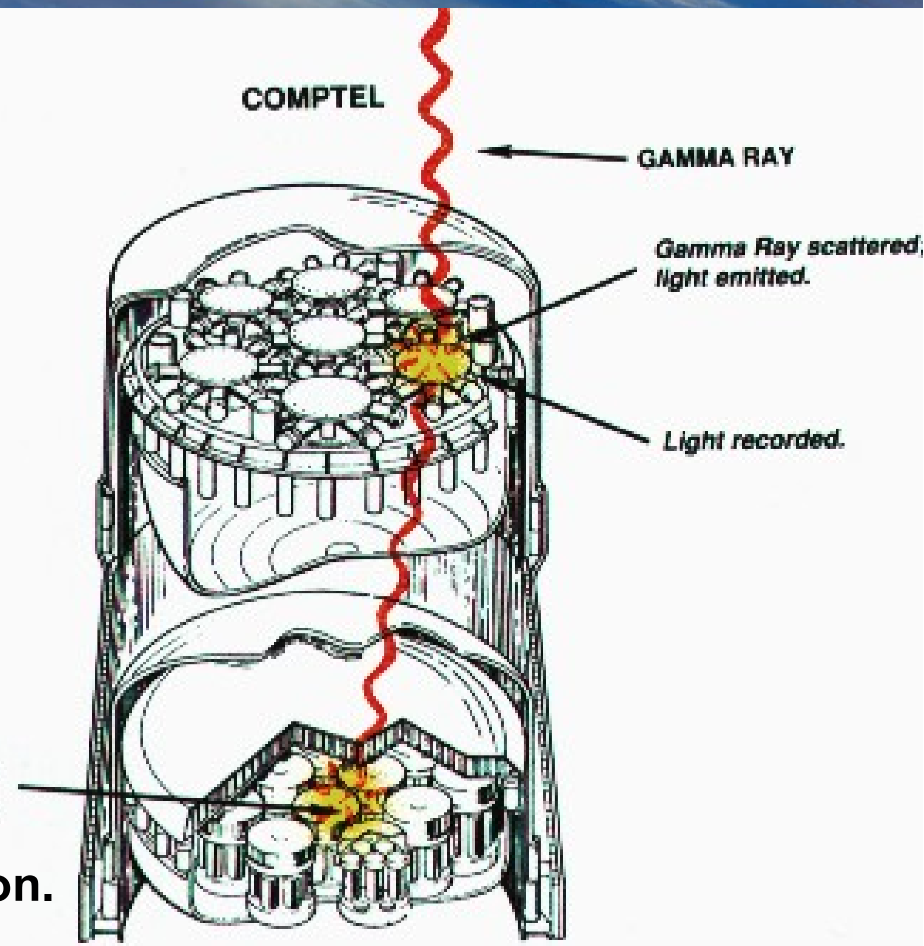
reconstructed position from five projected cones

- **Reconstruction of scattering angle from measured energies**

Comptel pioneered Compton imaging

- Flew on NASA's Gamma-Ray Observatory from 1991- 2000
- Detected gamma-ray sources (0.75 - 30 MeV)





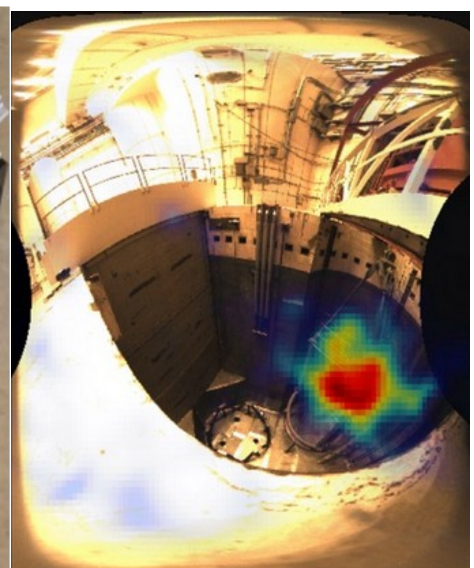
Al-26 emission at 1.8 MeV → indicates star formation.

A gap exists in the market for a mid-sized imager/spectrometer

Handhelds
Low Sensitivity:
Volume ~ < 50 cm3

GeGi: segmented HPGe detector

H3D : CZT semiconductor

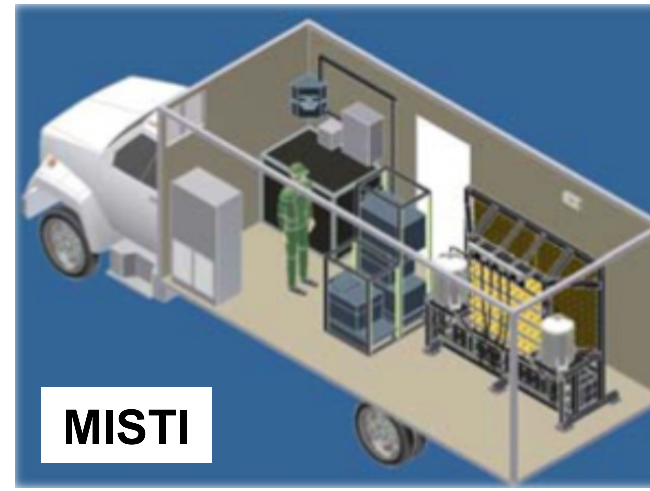


High Sensitivity:
Medium-Large Volume
Affordable

- Portable: suitable for mounting on various platforms (truck, helicopter, etc).

-Operates in survey mode: high sensitivity: spectrometer + Compton imager

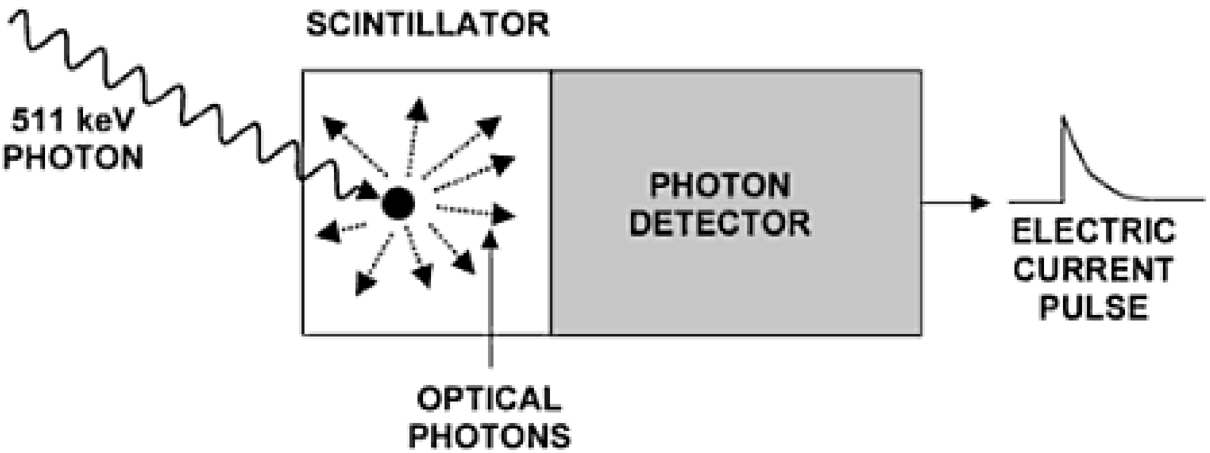
Very High Sensitivity
Ultra Large Volume
High Cost



MISTI

SORDS

Detection Medium: Inorganic scintillator

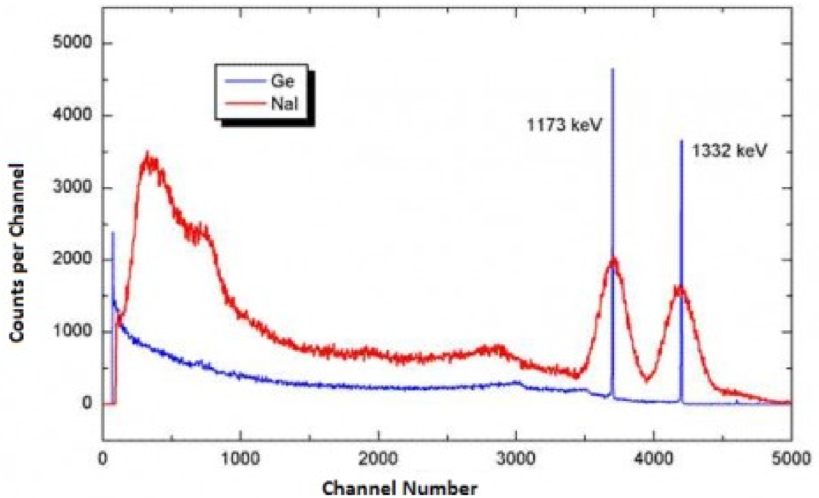


Scintillators converts high energy radiation to visible light!

Cost

- **Semiconductors (HPGe, CZT, …)**
- **Inorganic Scintillator (NaI, LaBr3,…)**
- **Organic Scintillator (PVT)**
- **Liquid Scintillator**

Resolution



https://Wiki.uio.no/mn/safe/nukwik/index.php

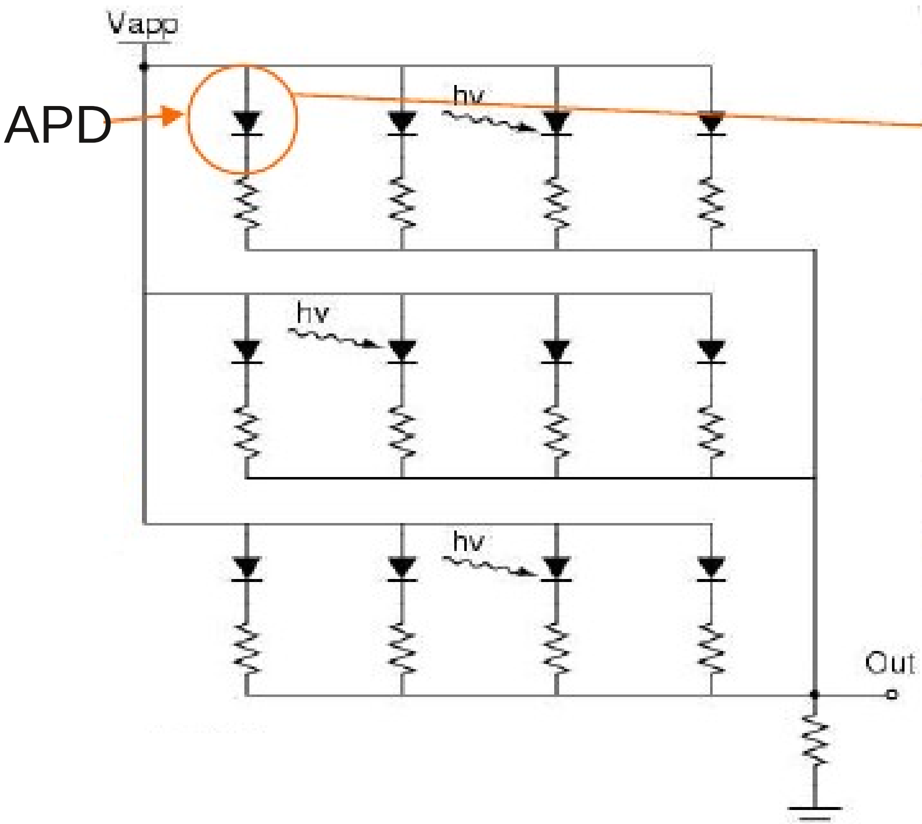
Inorganic scintillator – good choice for large-volume + low cost + decent resolution

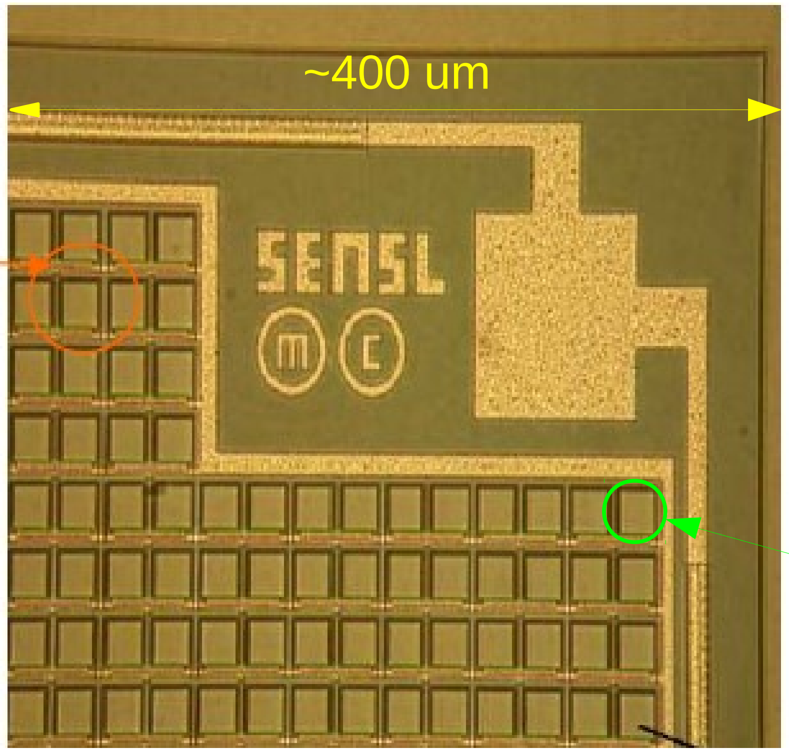
Scintillator Light Readout: SiPMs

Silicon Photomuliplier (SiPMs or SPMs): Arrays of avalanche photodiodes (APDs) operating in Geiger mode

Light-weight: Suitable choice for a portable device

All APD outputs summed





There are **76 384** of these APDs on this SPM Array

Close-up of 3x3 mm SiPM (array of APDs)

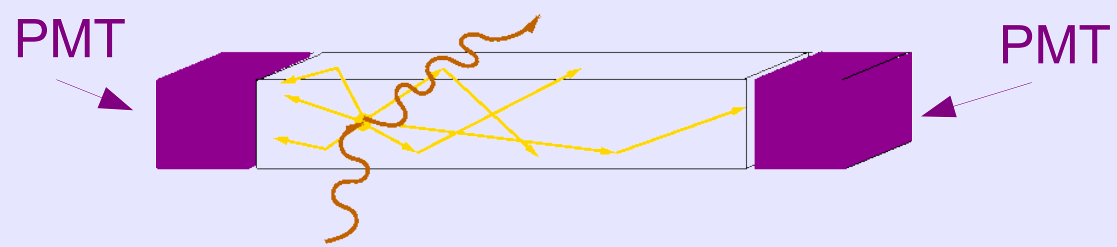
Two Compton imagers were developed (2008 – 2013)

Project funded by CRTI (chemical, biological, radiological and nuclear, CBRN, Research and Technology Initiative)

Two designs pursued

Bar design

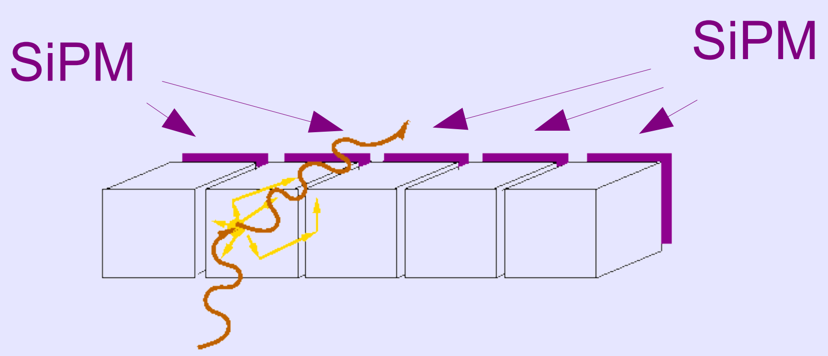
(McGill)



PMT: photomultiplier tube

Pixel design

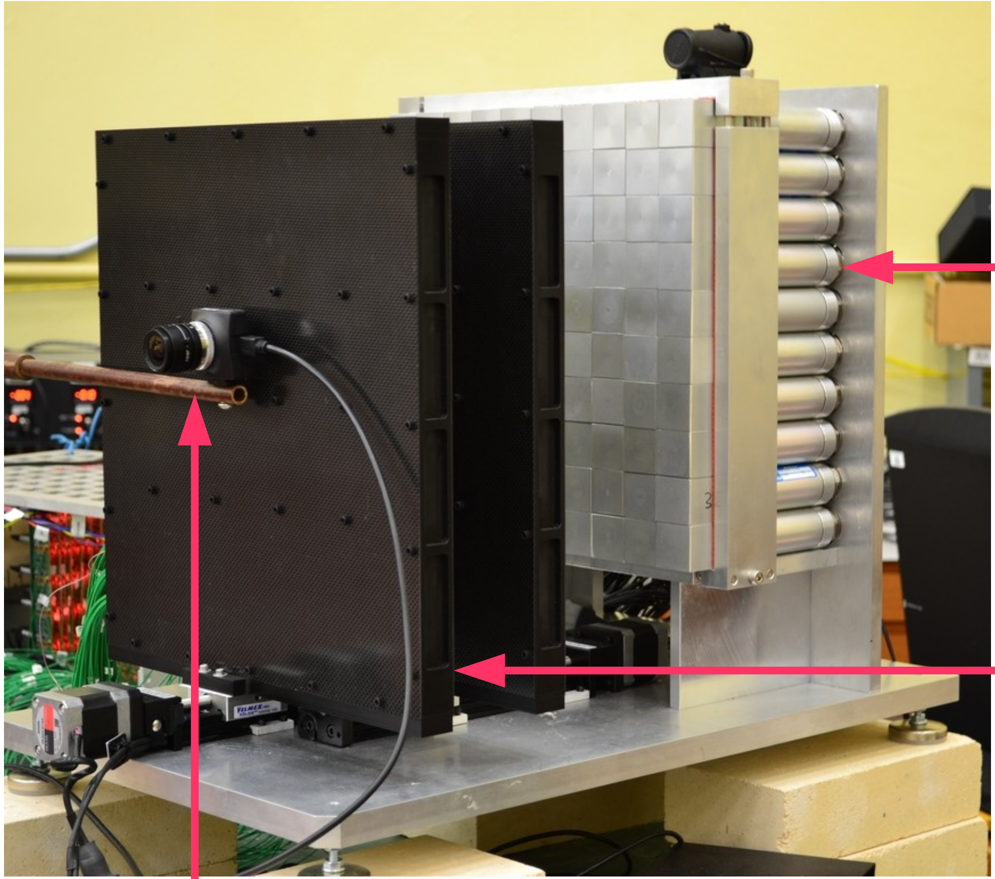
(NRC/NRCan)



SPM: silicon photomultiplier

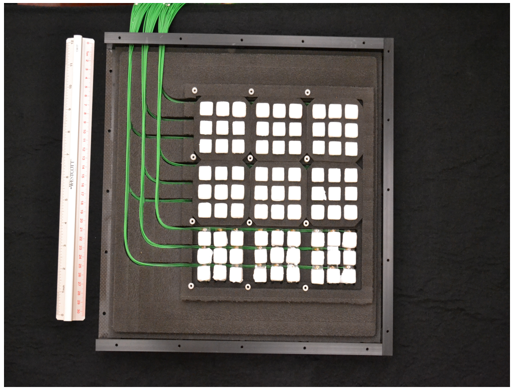
Early tests showed pixel design would be more robust in the field.

Pixel imager



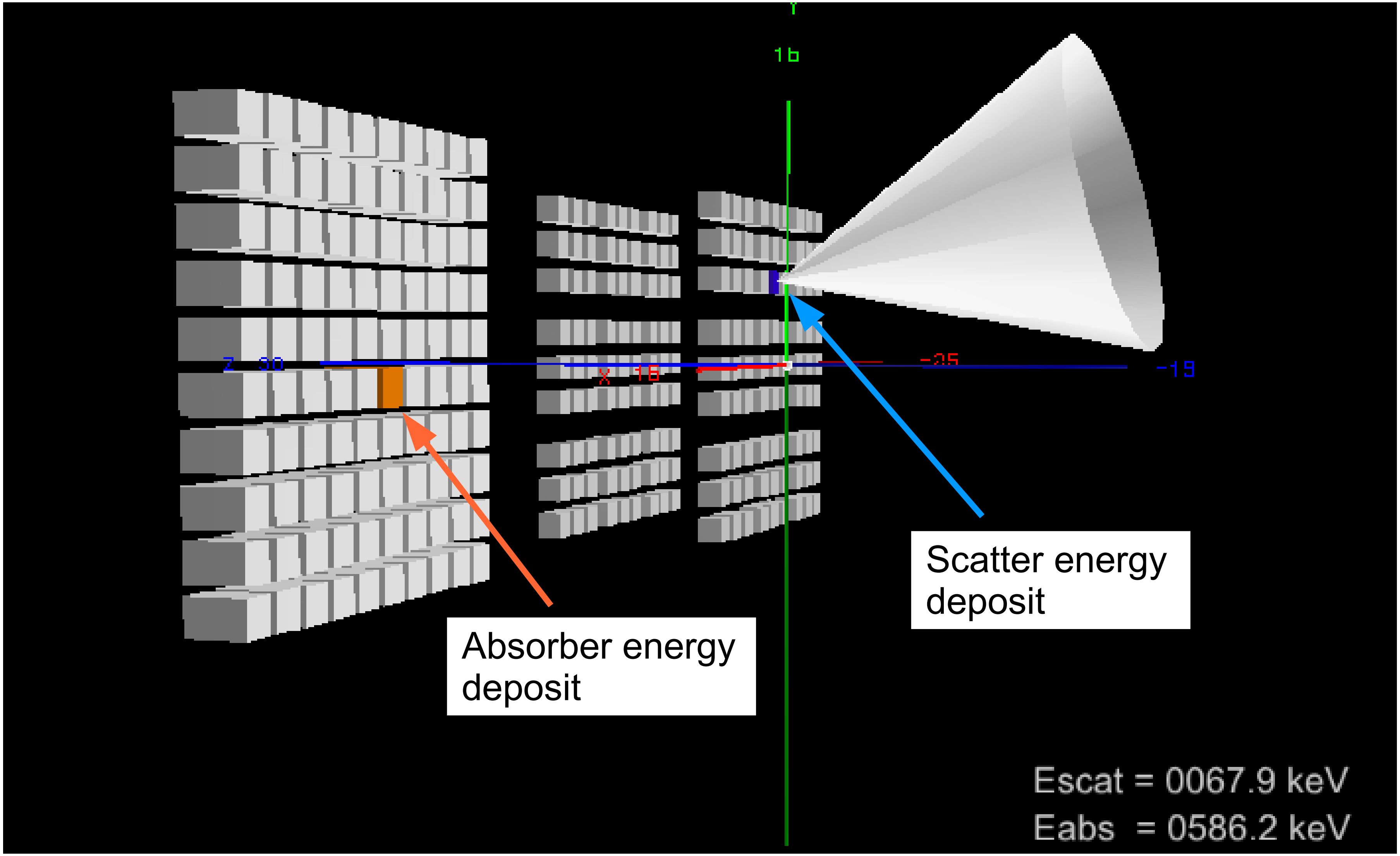
Absorber: 10 x 10 array of NaI(Tl)/PMT

Scatter: Two 9x9 arrays of 1.35 cm³ CsI(Tl)/SiPM



Optical camera

A typical event yields a single Compton cone



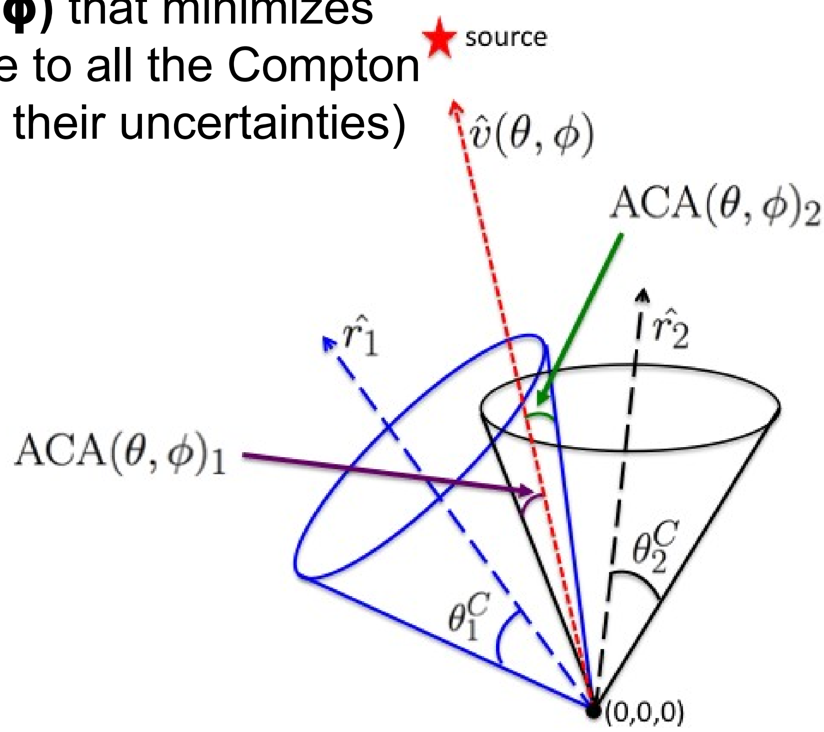
Source Localization

1) Back-projection Image

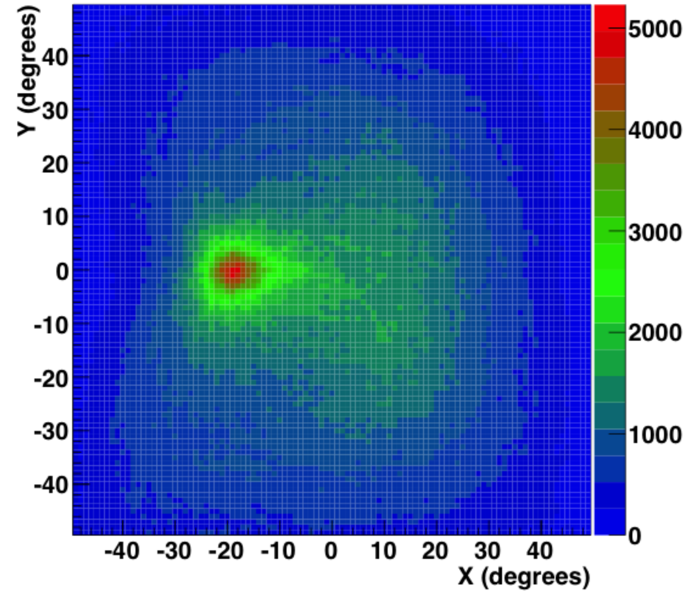
- Back-projecting Compton cones onto a plane and converting into angular units

2) Iterative χ2 Minimization

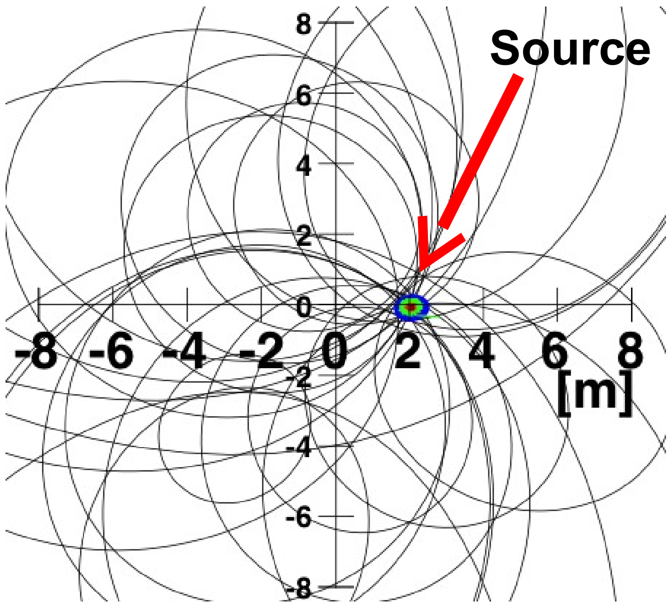
- Find the vector ***v*(θ,ϕ)** that minimizes the angular distance to all the Compton cones (weighted by their uncertainties)



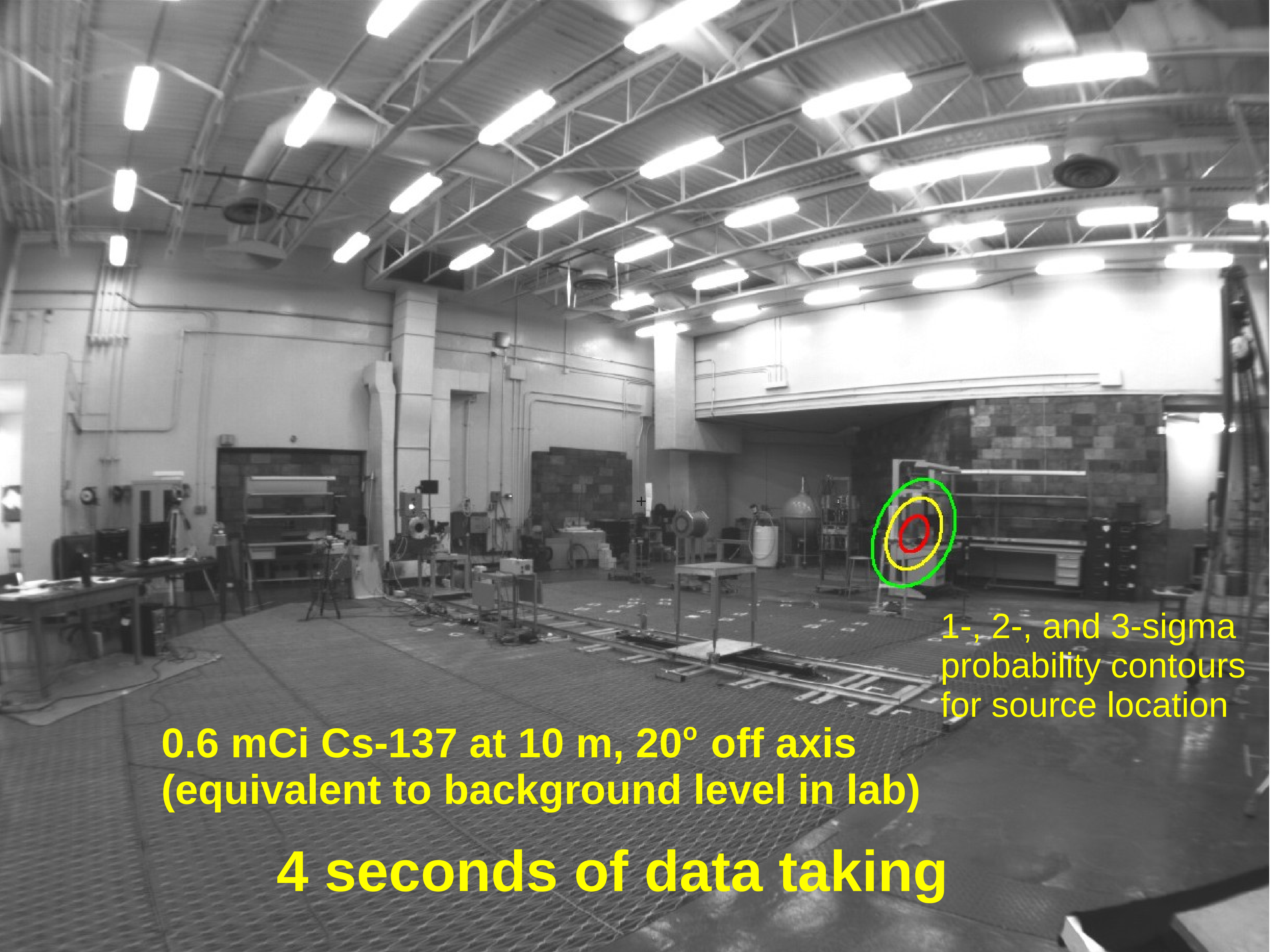
Back-projection (real data)
[2 hrs – 0.6 mCi Cs-137 at 8 m]



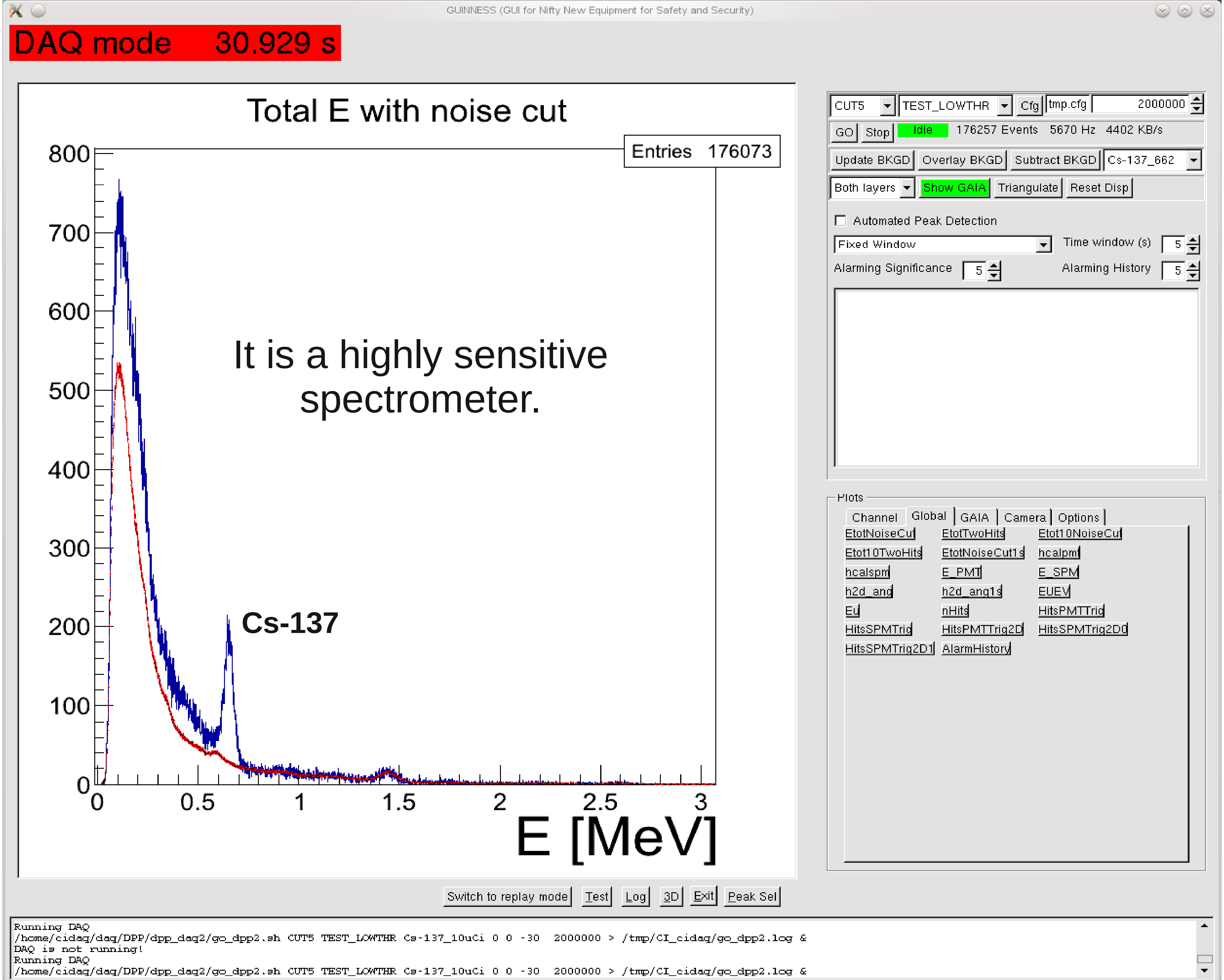
Minimization (real data) [~ 10 s]



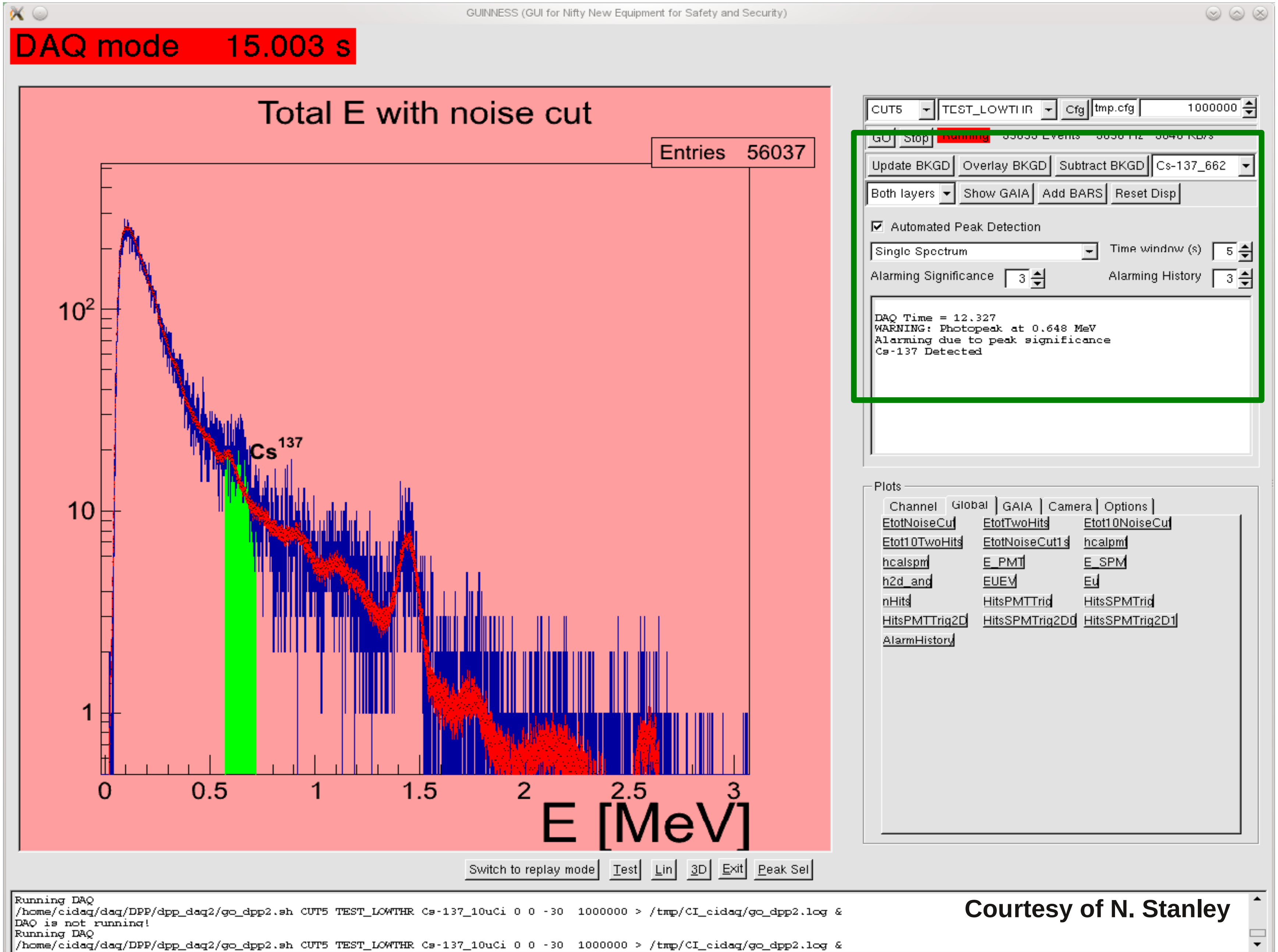
Demonstration of imager performance


1-, 2-, and 3-sigma probability contours for source location
0.6 mCi Cs-137 at 10 m, 20° off axis
(equivalent to background level in lab)
4 seconds of data taking


60 seconds of data taking


GUINNESS (GUI for Nifty New Equipment for Safety and Security)
DAQ mode 30.929 s
Total E with noise cut
Entries 176073
It is a highly sensitive spectrometer.
Cs-137
E [MeV]
0 100 200 300 400 500 600 700 800
0 0.5 1 1.5 2 2.5 3
CUT5
TEST_LOWTHR
Cfg
tmp.cfg
2000000
GO
Stop
Idle
176257 Events 5670 Hz 4402 KB/s
Update BKGD
Overlay BKGD
Subtract BKGD
Cs-137_662
Both layers
Show GAIA
Triangulate
Reset Disp
Automated Peak Detection
Fixed Window
Time window (s) 5
Alarming Significance 5
Alarming History 5
Plots
Channel
Global
GAIA
Camera
Options
EtotNoiseCut
EtotTwoHits
Etot10NoiseCut
Etot10TwoHits
EtotNoiseCut1s
hcalpmt
hcalspm
E_PMT
E_SPM
h2d_ang
h2d_ang1s
EUEV
Eu
nHits
HitsPMTTrig
HitsSPMTrig
HitsPMTTrig2D
HitsSPMTrig2D
HitsSPMTrig2D1
AlarmHistory
Switch to replay mode
Test
Log
3D
Exit
Peak Sel
Running DAQ
/home/cidaq/daq/DPP/dpp_daq2/go_dpp2.sh CUT5 TEST_LOWTHR Cs-137_10uCi 0 0 -30 2000000 > /tmp/CI_cidaq/go_dpp2.log &
DAQ is not running!
Running DAQ
/home/cidaq/daq/DPP/dpp_daq2/go_dpp2.sh CUT5 TEST_LOWTHR Cs-137_10uCi 0 0 -30 2000000 > /tmp/CI_cidaq/go_dpp2.log &

Alarms when a source is present

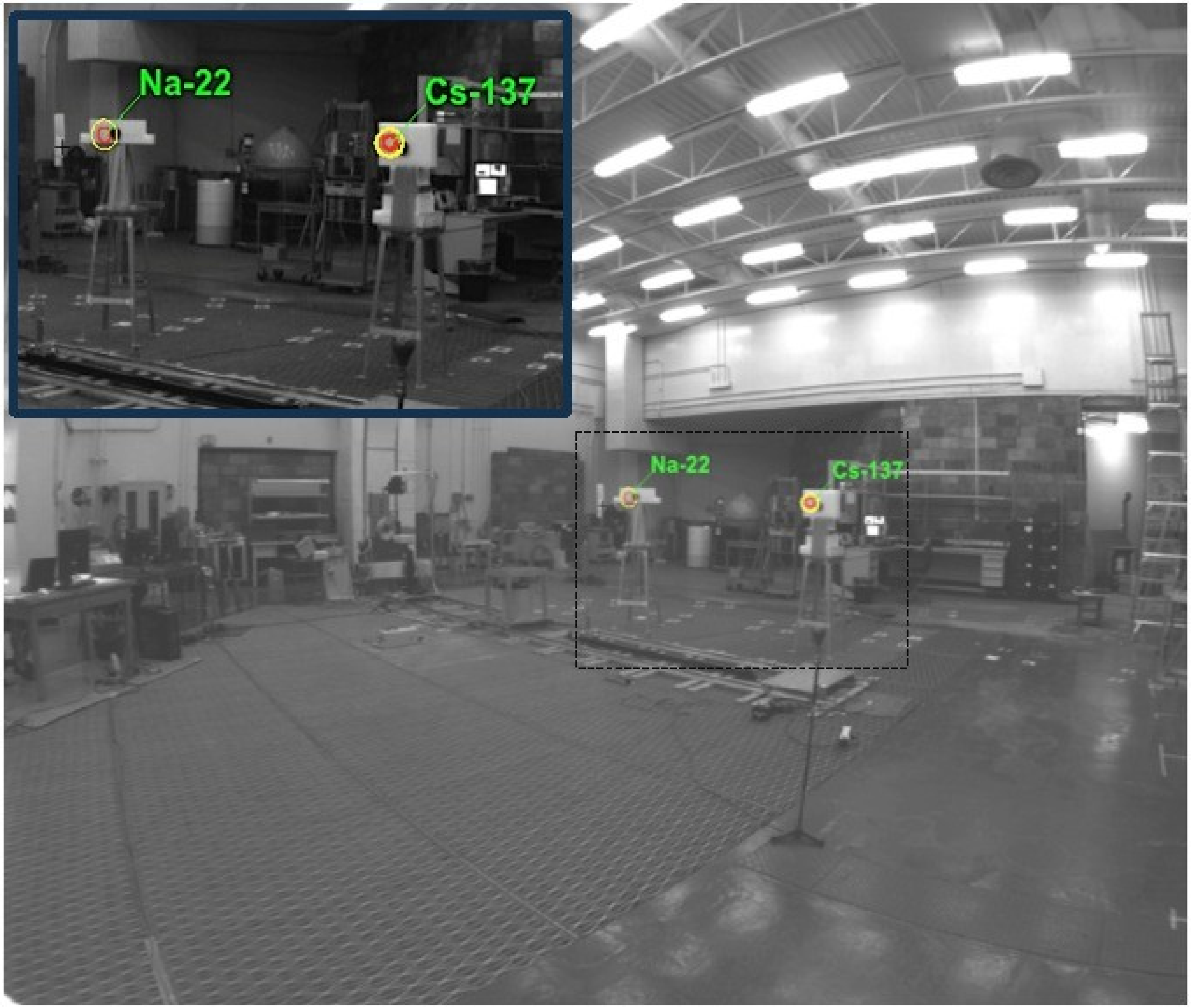


Courtesy of N. Stanley

Imaging Multiple Isotopes

0.6 mCi Na-22,
0.6 mCi Cs-137
placed at 7m

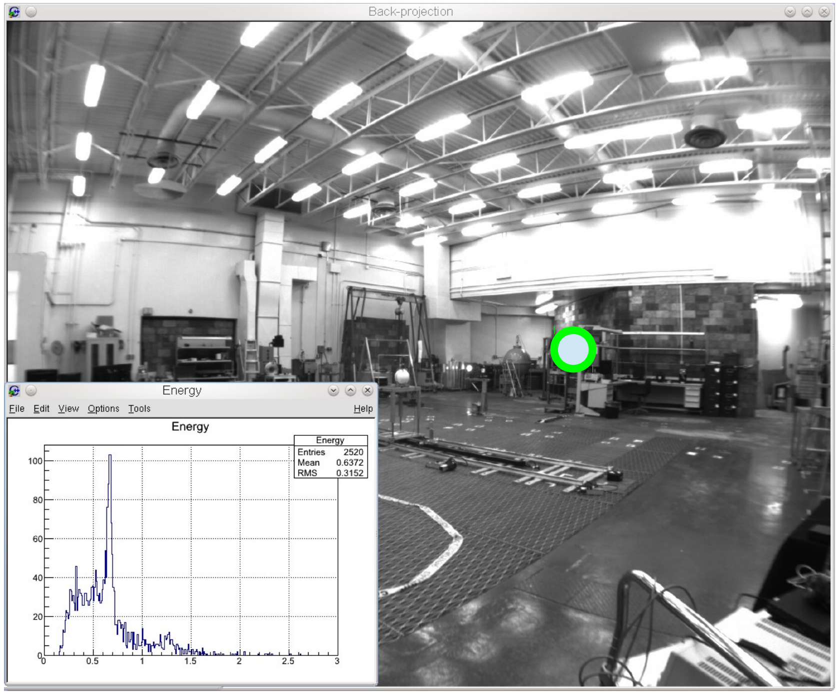
Reconstructed in 30 s

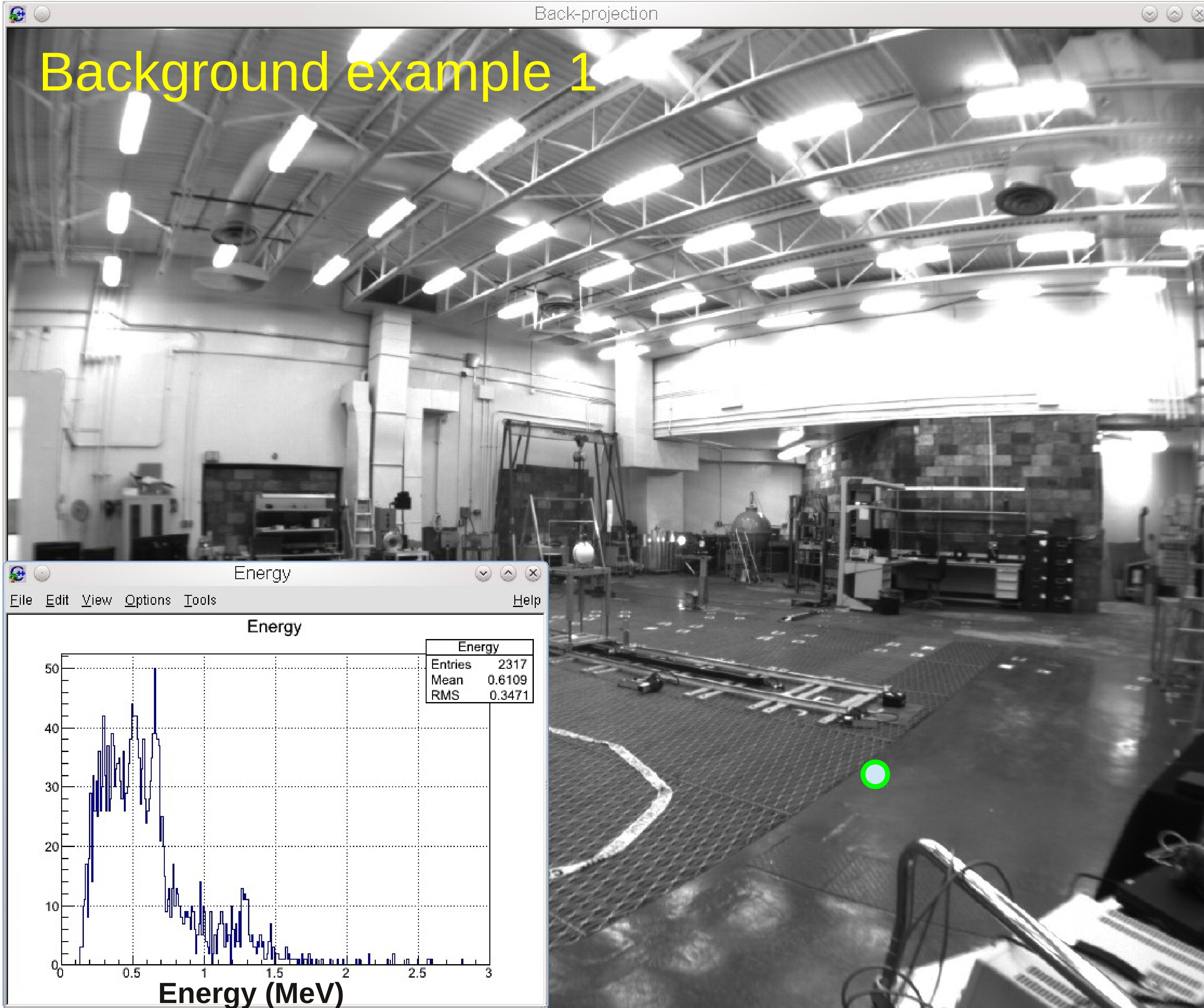


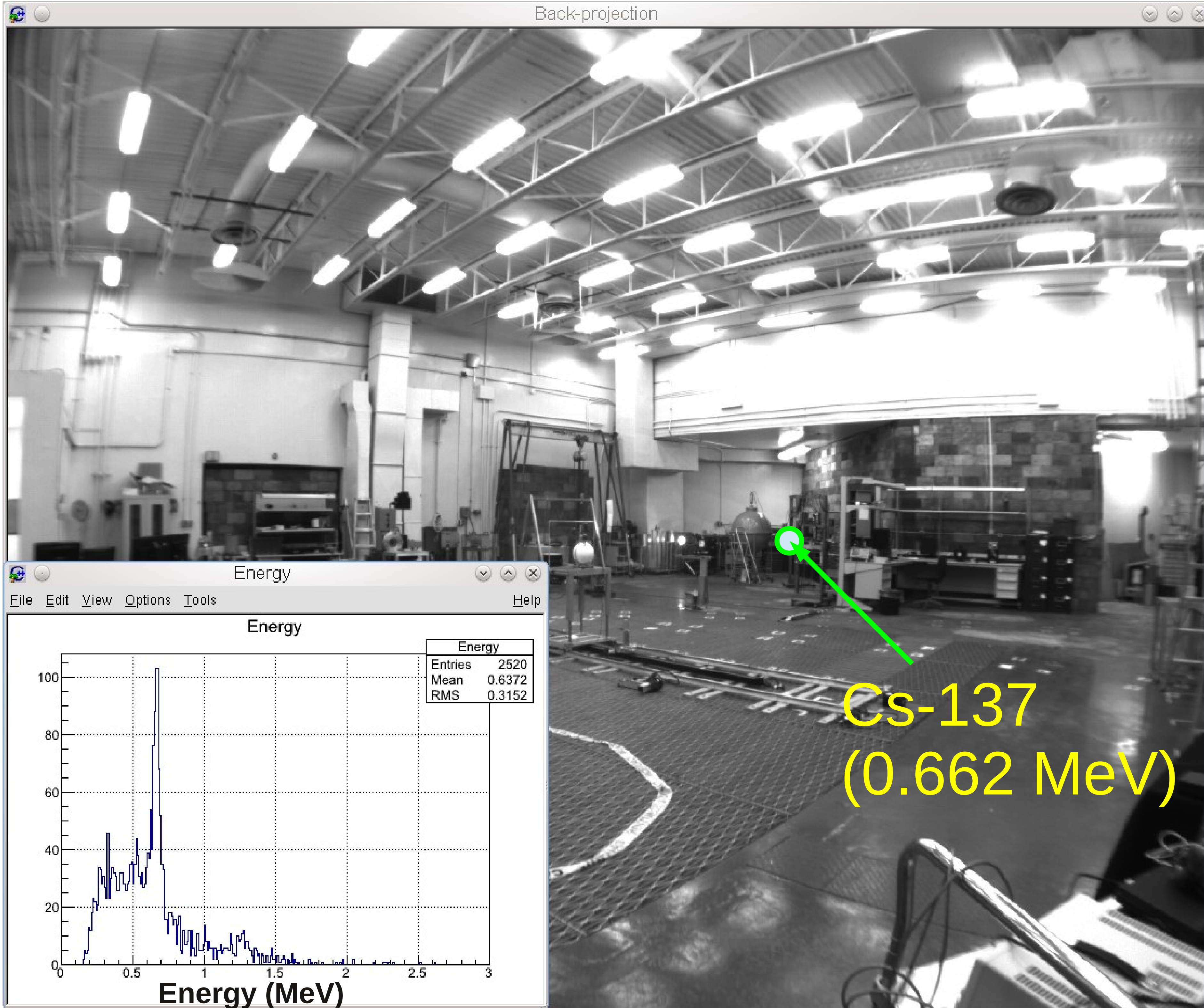
Spectral photo-querying

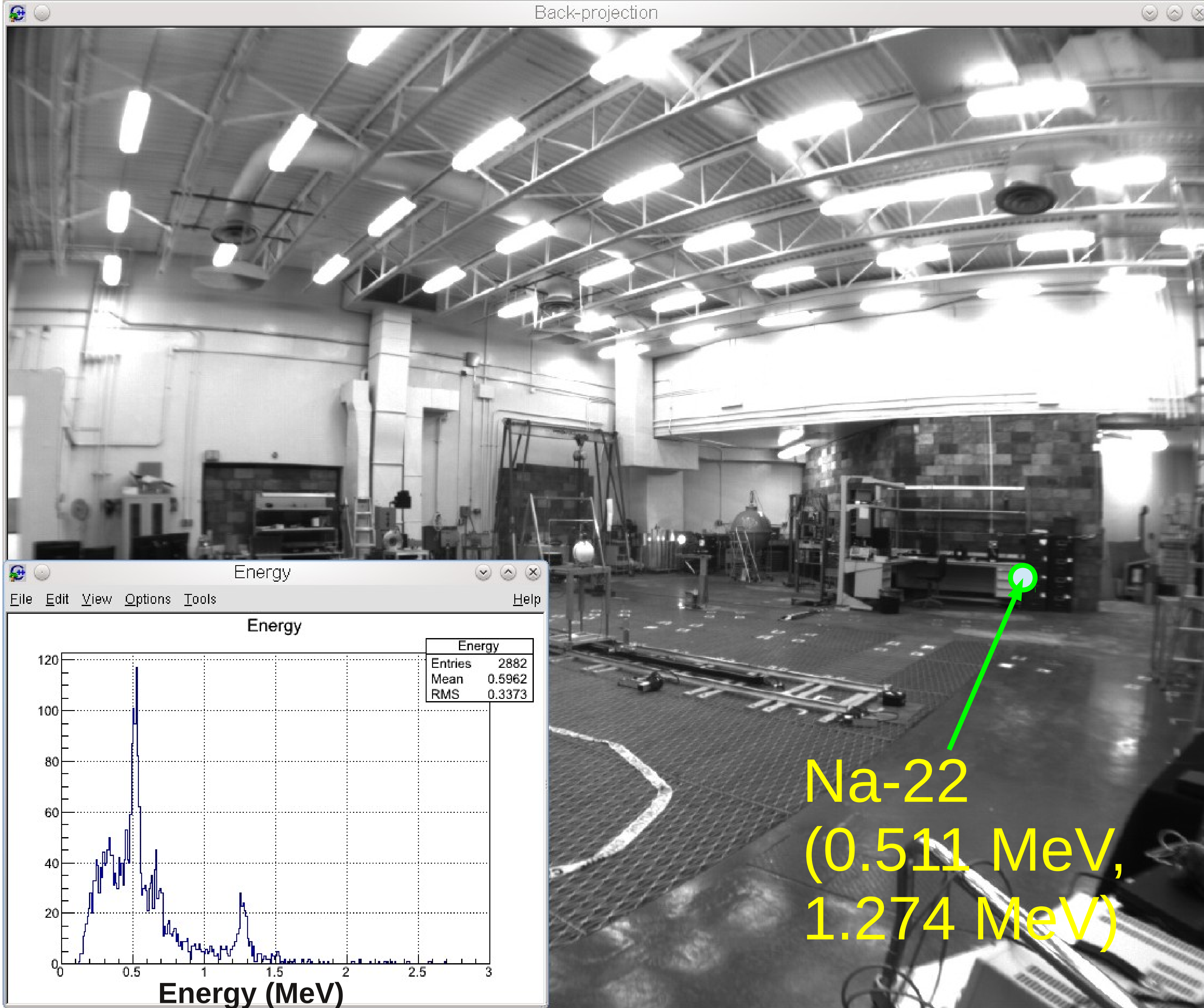
- Move cursor over room photo
- Plot energy of all Compton cones which have an angle of closest approach to cursor direction to within ~ 3 degrees
- Can improve signal-to-background
  - Useful for detecting shielded sources (ie. shielded special nuclear material (SNM)).

- Example: 1 to 2 minutes with 0.6 mCi Cs-137 and Na-22 sources present at ~ 9 m

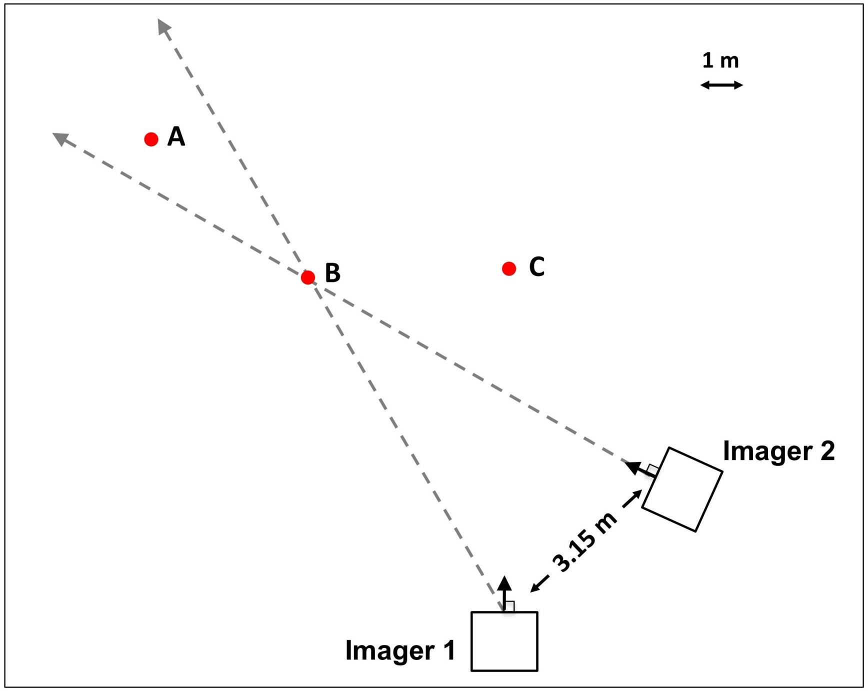


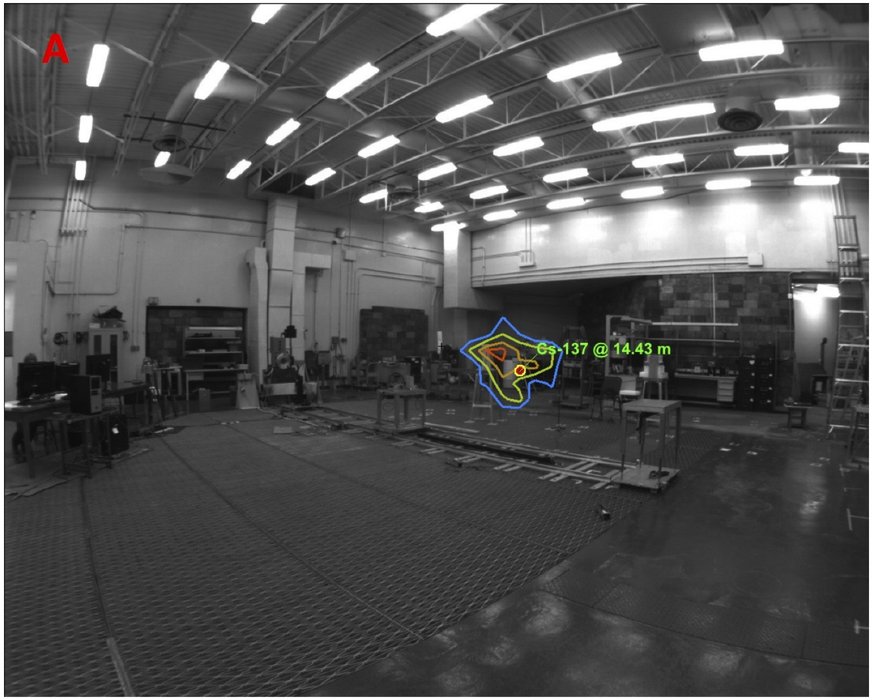

Back-projection
Background example 1
Energy
File Edit View Options Tools Help
Energy
Energy
Entries 2317
Mean 0.6109
RMS 0.3471
0
10
20
30
40
50
0
0.5
1
1.5
2
2.5
3
Energy (MeV)


Back-projection
Energy
File Edit View Options Tools Help
Energy
Energy
Entries 2520
Mean 0.6372
RMS 0.3152
0 20 40 60 80 100
0 0.5 1 1.5 2 2.5 3
Energy (MeV)
Cs-137
(0.662 MeV)


Back-projection
Energy
File Edit View Options Tools Help
Energy
Energy
Entries 2882
Mean 0.5962
RMS 0.3373
120
100
80
60
40
20
0
0 0.5 1 1.5 2 2.5 3
Energy (MeV)
Na-22
(0.511 MeV,
1.274 MeV)

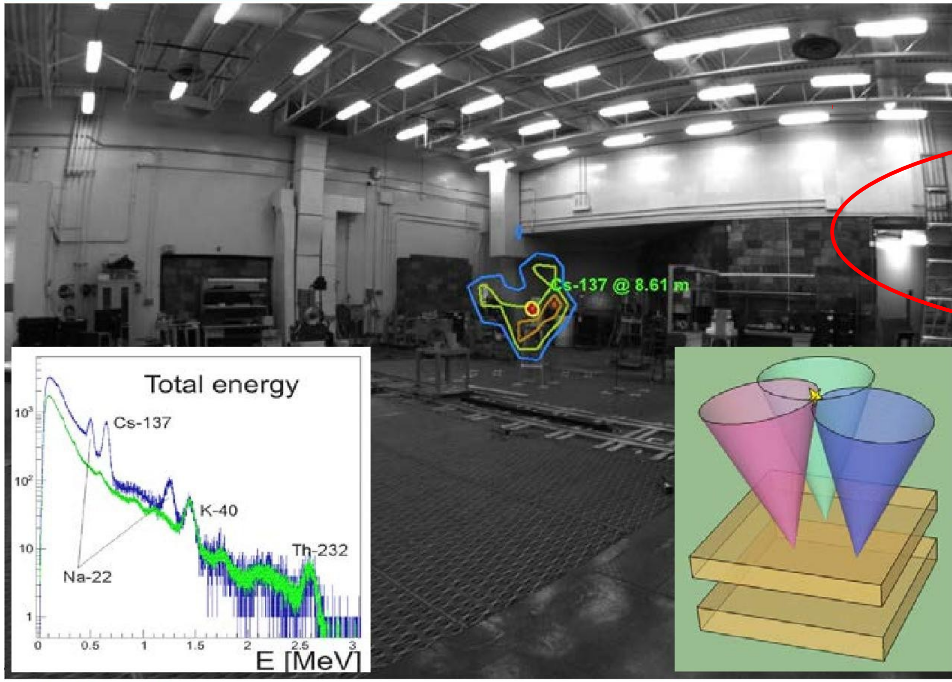
Triangulation





All reconstructed to within 0.5 m in less than 2 minutes (0.6 mCi Cs-137 source)

A MISSION-READY COMPTON GAMMA IMAGER FOR SAFETY AND SECURITY



Lead : National Research Council

Partnership: **Radiation Solutions Inc., Natural Resources Canada, Canada Border Services Agency, Royal Canadian Mounted Police, Defence Research and Development Canada, Department of National Defence CANSOFCOM**

Start-End: July 2015 to December 2017

Funds:

CSSP Funds	Co-Investment Funds In-Kind	Co-Investment Funds Cash	Total Funds
$762,000	$949,000	$144,000	$1,855,000

Project Summary:

Objective(s):

The objective of the project is to improve safety and security for Canadians from RN threats by providing national border/security, military, and consequence-management teams with a Compton gamma imager designed for their use. Specifically, we aim to transition the high-performance imaging prototypes developed during project CRTI 07-0193RD from TRL 5 to TRL 8, producing a commercially-available, optimized, fieldable, cost-effective, mission-ready imager, thus improving Canada's operational preparedness in the event of an RN incident. The deliverable will provide an image of radiation-emitting objects, superimposed on an optical photograph of the surroundings to aid in detecting and localizing sources in an intuitive manner. It will be modular in nature to suit a wide variety of end users, and include data outputs in the forms of energy spectra, GPS location and direction, and photographic image with radiation map overlay for easy integration of information across sectors.

Outcome(s):

Deliverable(s):

- One TRL 8 single-module Compton gamma imager and one large-array 3x3 Compton gamma imager ready for deployment in the field
- Availability of further imagers of arbitrary array size for purchase from Radiation Solutions Inc.

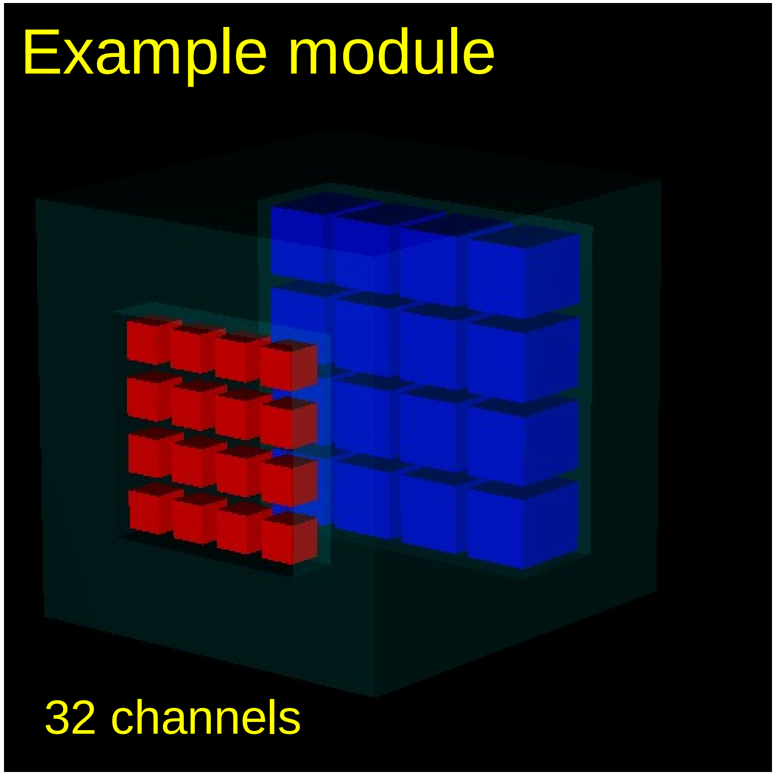
Impact(s):

Secure and open borders; connected and protected practitioners.

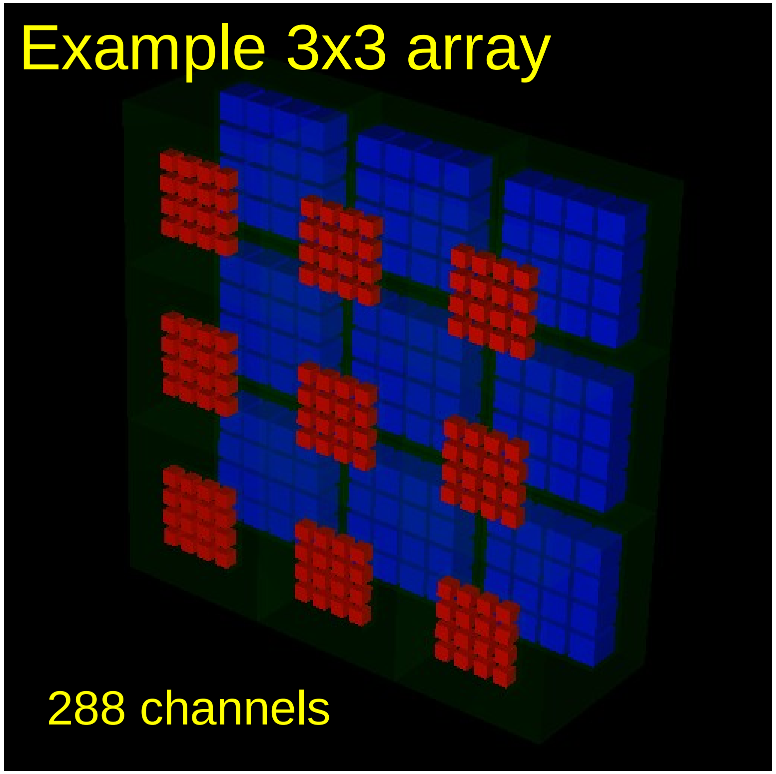
- Qualitatively new product enables visualization of radiation for the first time, with an order-of-magnitude improvement in source localization over direction-blind instruments
- Stand-off nature of device significantly reduces first-responder risk
- Long-range capability enables rapid screening of stacked containers
- Dual-mode operation as imager and sensitive spectrometer for isotope ID and threat attribution.

Project Overview

- Deliverable (late-2017): commercial sensitive spectrometer suitable for radiation surveying, with precision imaging capability
- Industry partner (RSI) has wealth of experience fielding rugged radiation detectors for use in the field
- Modular Design: imagers of different size and therefore price point

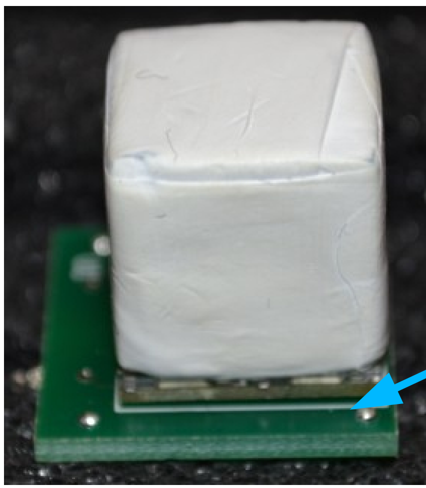


Build up arrays of various sizes

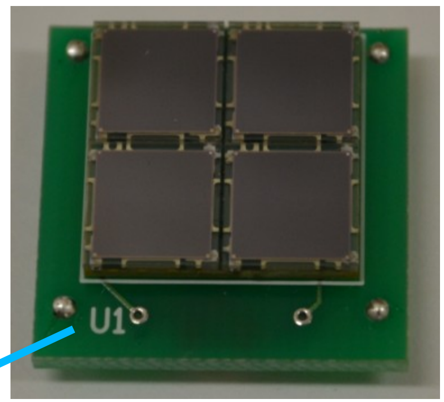


Scatter pixels

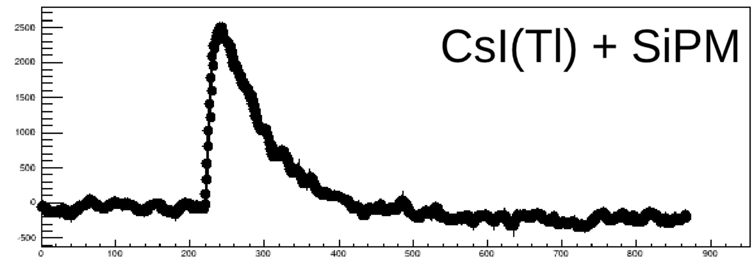
Scatter pixel:
- SiPM: 2 x 2 array of ArrayC-60035-4Ps
- Scintillator: 1.35 cm^3 CsI(Tl) crystal



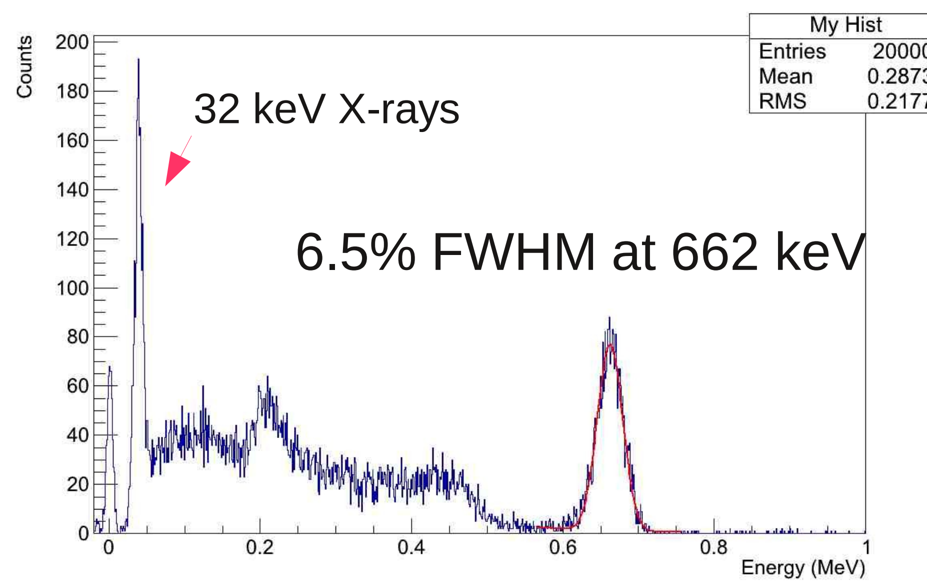
Scatter pixel



Custom SiPM array board



Sample trace



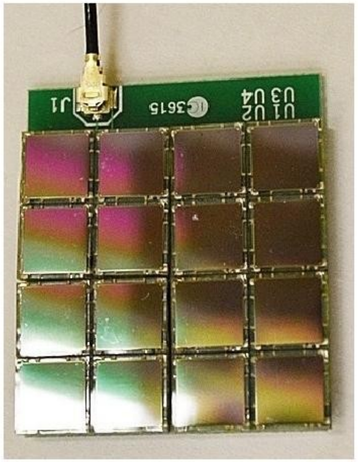
Typical performance:
- Energy Resolution ~ 6.5 % at 662 keV
- Noise (energy-equivalent) ~ 1.6 keV

Low Noise → record lower energy deposits → image low energy sources

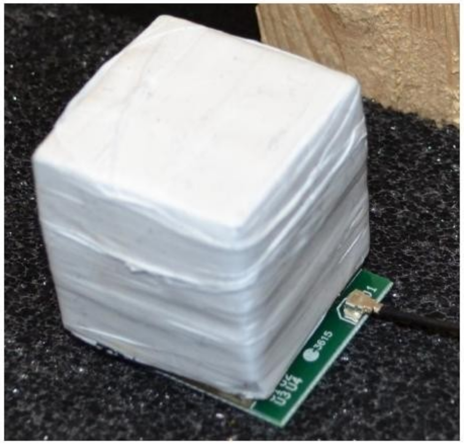
Absorber pixels

Absorber crystal:
- form a 2 x 2 array of ArrayC-60035-4Ps
- mate to 2.8 cm^3 CsI(Tl) crystal

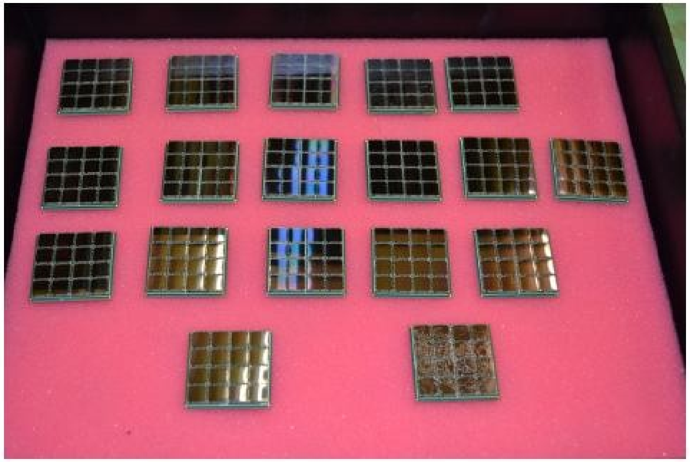
Typical performance:
- Energy Resolution ~ 6.5 % at 662 keV
- Noise ~ 4.6 keV



Sipm

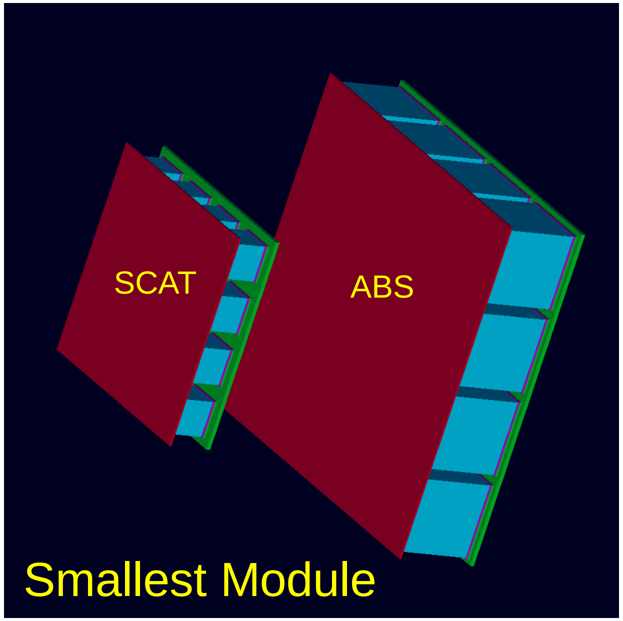


Absorber pixel

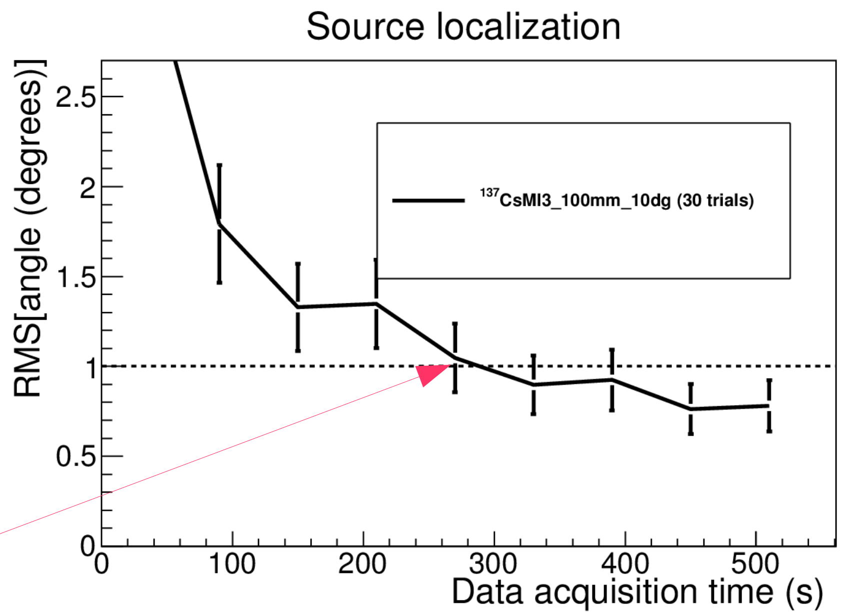


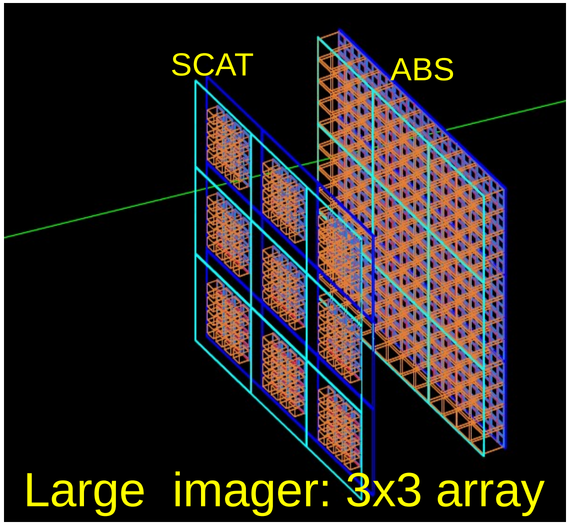
Lot of sensors (Cancino)

EGSnrc + GEANT4 Simulations: 1 mCi Cs-137 at 10 m

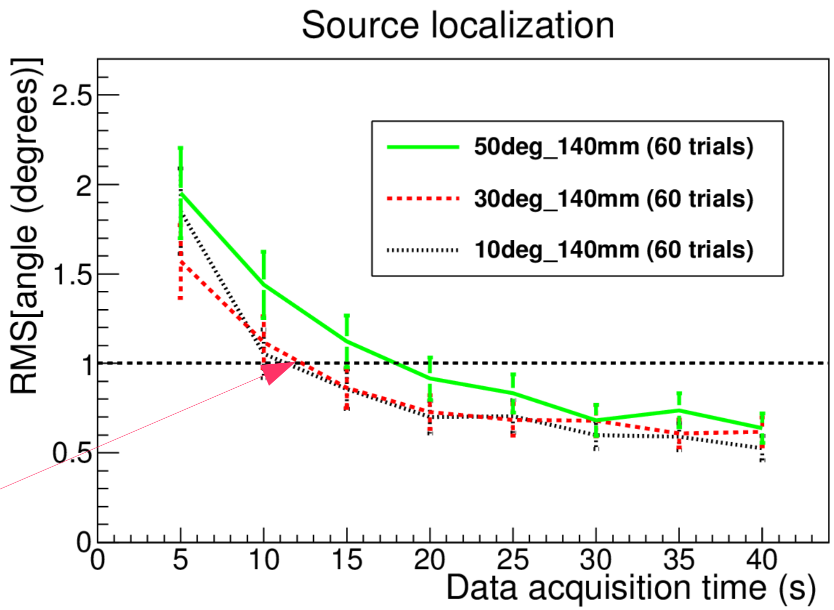


1° precision achieved in minutes



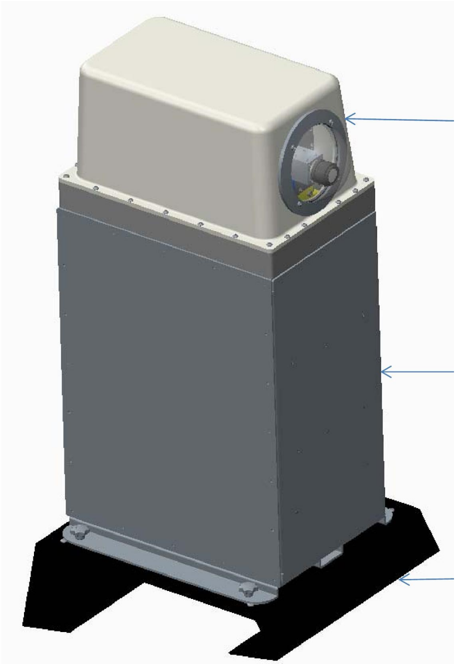


1° precision achieved in seconds



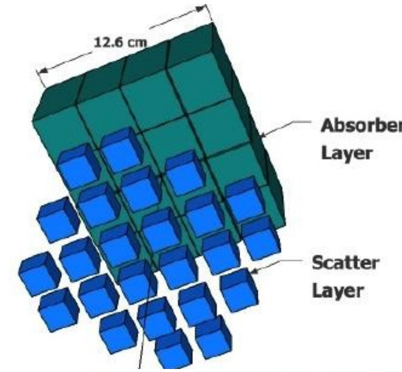
The imager will be highly sensitive

32-channel interim fieldable imager

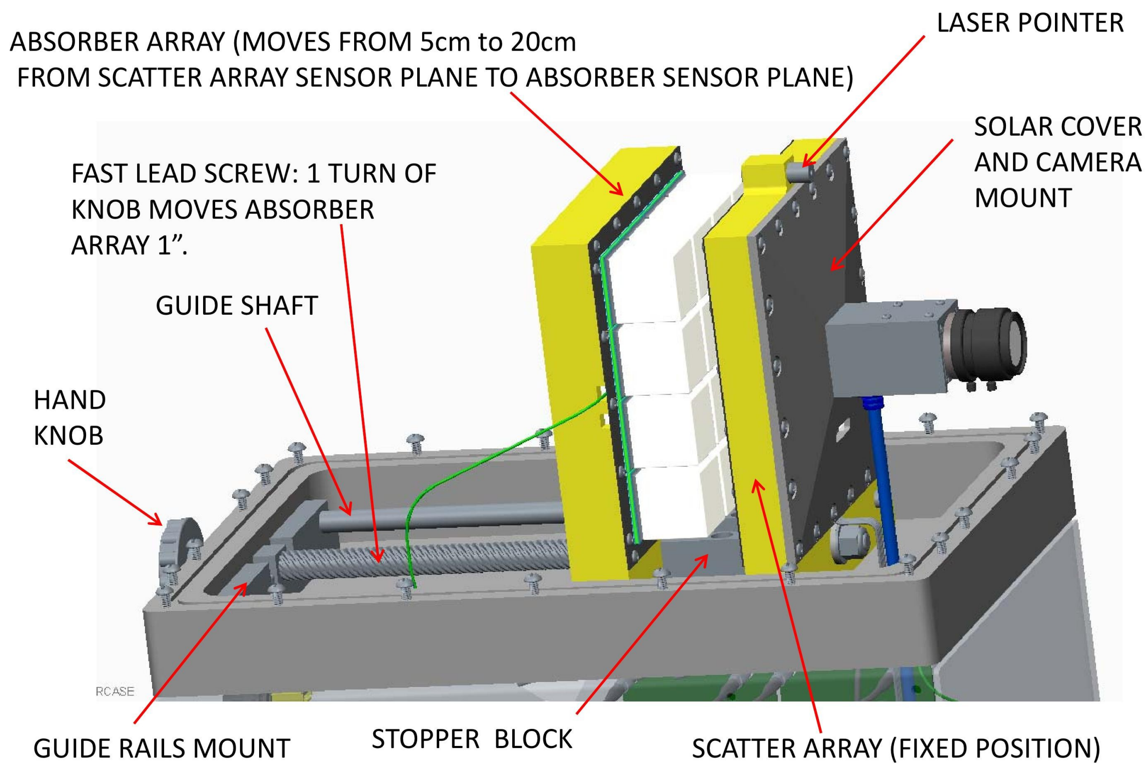


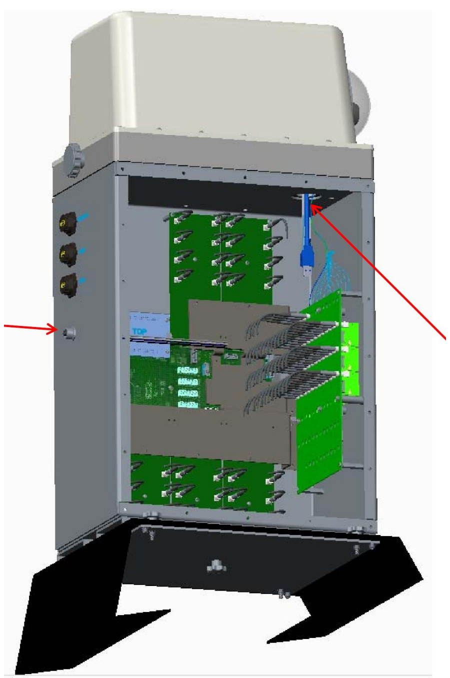
- Allows us to gain invaluable field experience for feedback into mission-ready imager design
- Currently being assembled

Absorber: 4 x 4 array of 2.8 cm^3 CsI(Tl)/SiPM
Scatter: 4 x 6 array of 1.35 cm^3 CsI(Tl)/SiPM



SENSOR ASSEMBLY





RSI digitizer board

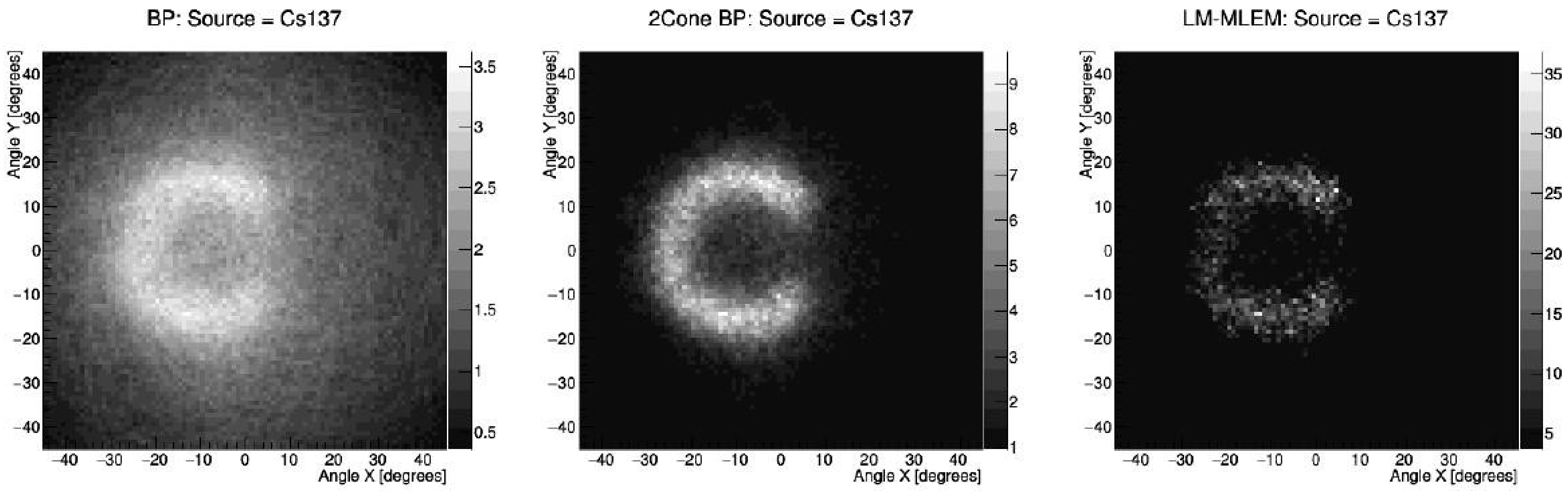
Summary

- Compton imaging has a wide range of applications
- Project to commercialize a Compton imager for first responders is underway
  - A highly sensitive spectrometer with imaging capabilities
  - Portable: suitable for different surveying platforms (truck, helicopter etc.)

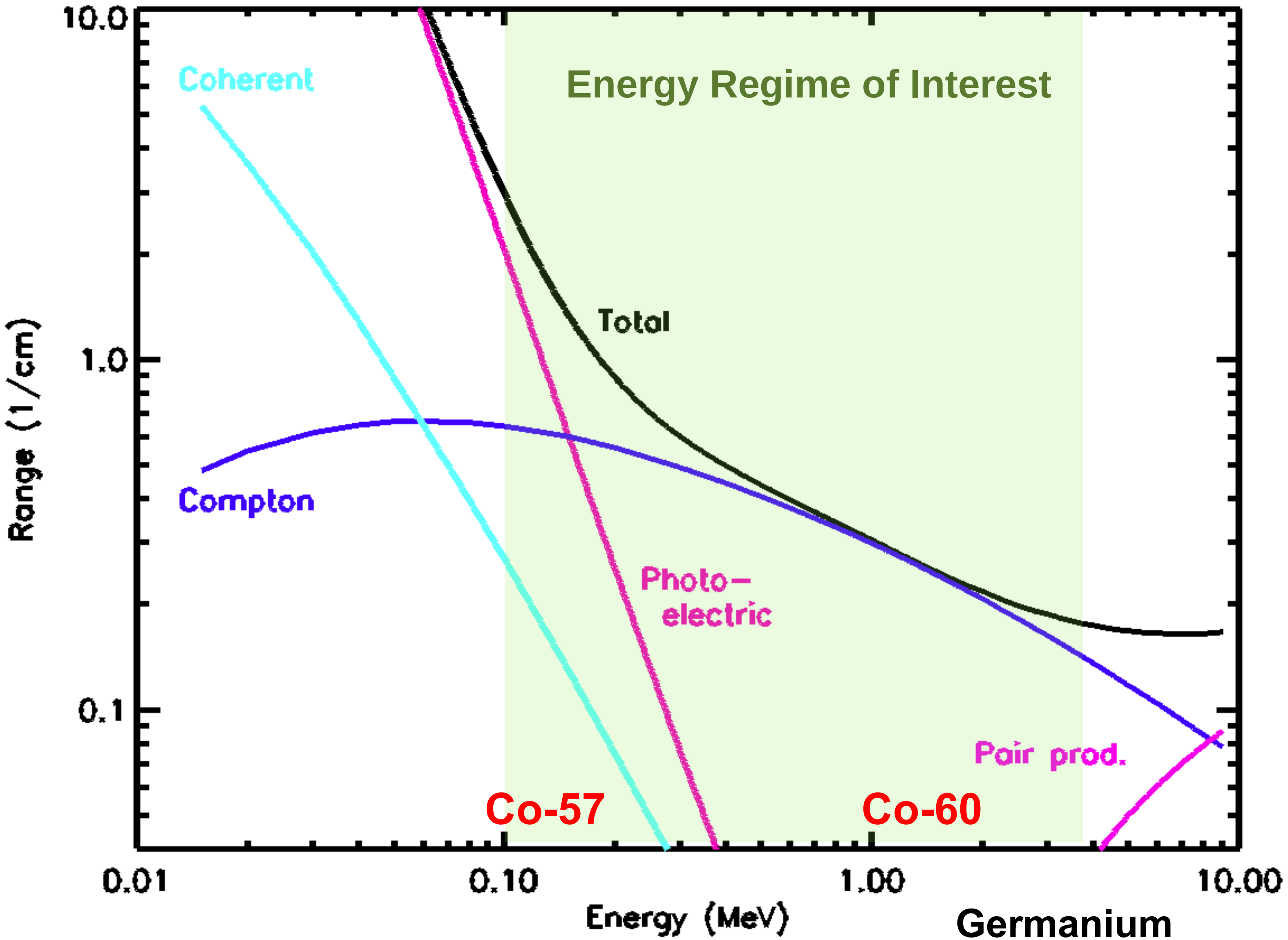
Extra Slides

Simulation: Extended source imaging

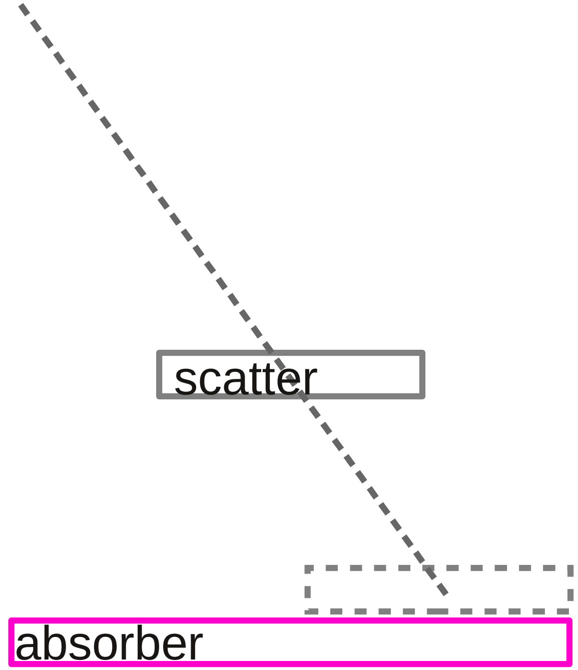
A Cs-137 line source in the shape of a 'C'



Compton scattering is the dominant interaction process from several hundred keV – several MeV



Self-shielding imaging

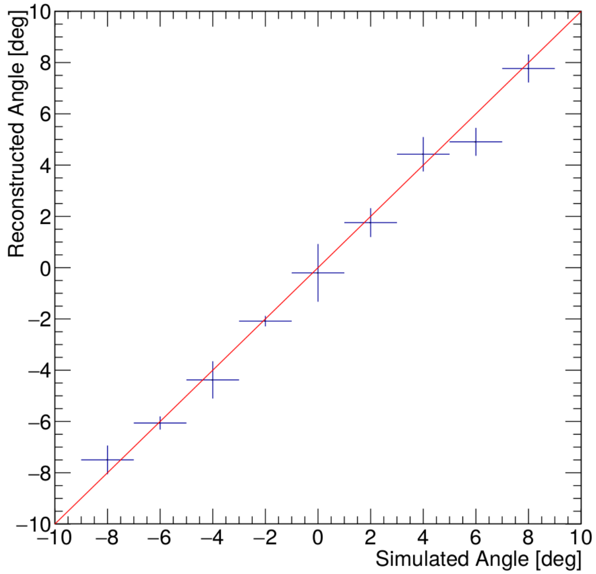


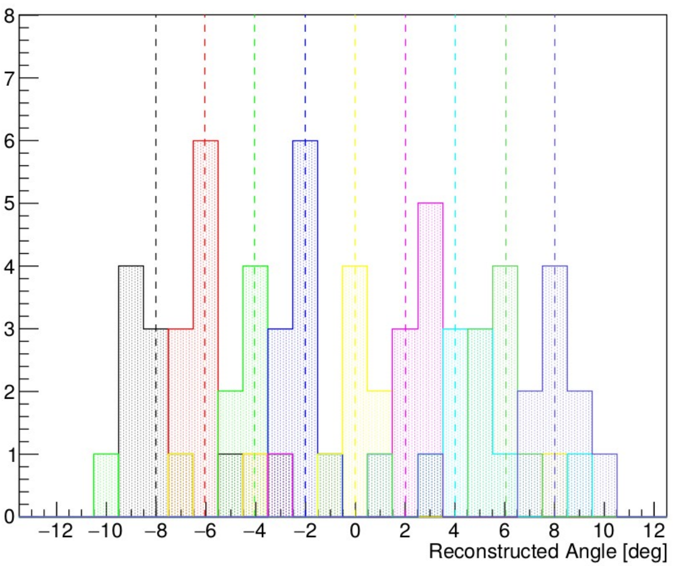
Use shadow of scatter plane on absorber plane to localize point source

Simulate source and fieldable imager (4 x 4 arrays in scatter and absorber) with Geant4

Step 0.6 mCi Cs-137 at 10 m from detector every 2^o from -10^o to +10^o

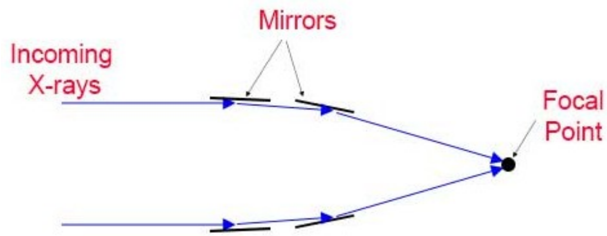
Will work best for low-energy sources



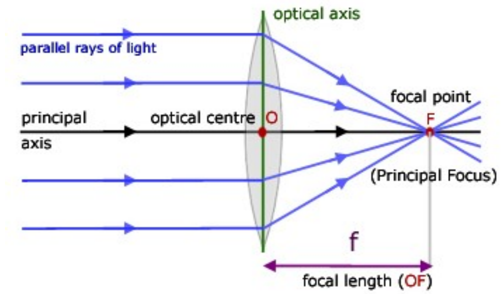


~ 1-degree angular resolution in 1 minute

Gamma ray:
Coded aperture
Compton imaging
Pinhole



X ray:
Glancing incidence mirrors
diffraction



Visible:
Mirrors/lenses

The electromagnetic spectrum