Future Prospects in Gamma-ray Astronomy

Advanced Compton Telescope

In recognition of the outstanding contributions of Prof. Rüdiger Staubert to high-energy astrophysics

Jim Kurfess
Naval Research Laboratory
Washington, DC

Outline

Brief Comments on Scientific Objectives

Advanced Compton Telescope (ACT)

- **Mission Concept Study (Vision Mission)**
- **Alternative techniques under development**
- **Solid-State Detector Development**

Alternative Techniques

- **Laue Collectors**
- **Fresnel Lens**

Summary

Scientific Objectives

- **Supernovae**
- **Novae**
- **Compact Galactic Objects**
- **Diffuse Galactic Emissions**
- **Active Galactic Nuclei**
- **Gamma Ray Bursts**
- **GRB-SN Connection**
- **Polarization**
- **Cosmic Gamma-ray Background**
- **Solar Activity**

Main goal is to achieve a dramatic improvement in sensitivity (50-100X) for broad scientific objectives relative to Compton Observatory and INTEGRAL

Science Objective	**Isotopes and Lines (MeV)**
Understand Type Ia SN explosion mechanism and dynamics	^{56}Ni (0.158, ***0.812***, …) ^{56}Co (***0.847, 1.238***, …) ^{57}Co (0.122)
Understand Core Collapse SN explosion mechanism and dynamics	^{56}Ni (0.158, ***0.812***, …) ^{56}Co (***0.847, 1.238***, …) ^{57}Co (0.122), ^{26}Al (***1.809, 0.511***)
Map the Galaxy in nucleosynthetic radioactivity	^{26}Al (***1.809, 0.511***) ^{60}Fe, ^{60}Co (***1.173, 1.332***) ^{44}Ti (0.068, 0.078, ***1.16***)
Map Galactic positron annihilation radiation	e^+–e^- annihilation (***0.511***, 3 photon continuum) SN Ia ^{56}Co positrons (***0.511***) ^{26}Al and ^{44}Ti positrons (***0.511***)
Understand the dynamics of Galactic Novae	^{13}N, ^{14,15}O, ^{18}F positrons (***0.511***) ^{7}Be (***0.478***), ^{22}Na (***1.275, 0.511***)
Cosmic Ray Interactions with the ISM	^{12}C (4.4), ^{16}O (6.1), ^{20}Ne(***1.634***), ^{24}Mg(***1.369***,2.754),^{28}Si(***1.779***), ^{56}Fe(***0.847,1.238***)
Neutron Star Mass-Radius	p-n (***2.223***)

Polarization Science

Source	Polarization	Comments
Blazars	10-15%	Need ***P*** measurements around spectral breaks (MeV). Discriminate int./ext. or disk/cloud radiation fields. Discriminate jet geometry.
GRBs	0-50%	Discriminate emission mechanisms (synchrotron/SSC/IC). Discriminate field geometry. Note: Coburn and Boggs—(80±20%) polarization in GRB021206 (Nature 243, 415 (2003)
Pulsars	10-30% (PC) weaker (OG)	Study ***P*** vs. phase. Discriminate between outer gap and polar cap models
Gal. BHs	5-10% (τ~1) ~50%(τ~0.1)	***P*** due to an-isotropic input radiation (disk model).

Advantages of Compton Telescopes

- Large Field-of-View (can be up to 2π ster. or larger)
- Broad Band (300 keV – 30 MeV)
- High Sensitivity
- Imaging (projection of Compton direction cones)
- Background reduction
- Efficiency improves rapidly with scale size (up to several γ-ray MFP: 50 g/cm^2)
- High efficiency using multiple Compton technique
- Can have good energy resolution
- Electron tracking can further restrict direction of incident gamma ray

Limitations of Compton Telescopes

Energy Threshold: (200-300 keV)

Limited angular resolution (~ degree due to Doppler broadening phenomena)

Requires event reconstruction (not unique)

- More important and difficult in high efficiency instrument

Internal backgrounds (spallation products, neutron capture, etc.)

ACT Mission Concept Study

Response to NASA solicitation for Concepts for Space Science Vision Missions

PI: Steve Boggs (UCB)

Executive Committee: Jim Ryan, Jim Kurfess, Steve Boggs, Elena Aprilc, Allen Zych, Mark Leising, Neil Gehrels

Co-I Institutions: UC Berkeley, NRL, UNH, Columbia Univ., UCR, LANL, GSFC, Clemson, SLAC, UCSC, Rice

ACT Collaborators: UCSB, MSFC, IEEE-CSIC, CESR, MPE, ISAS

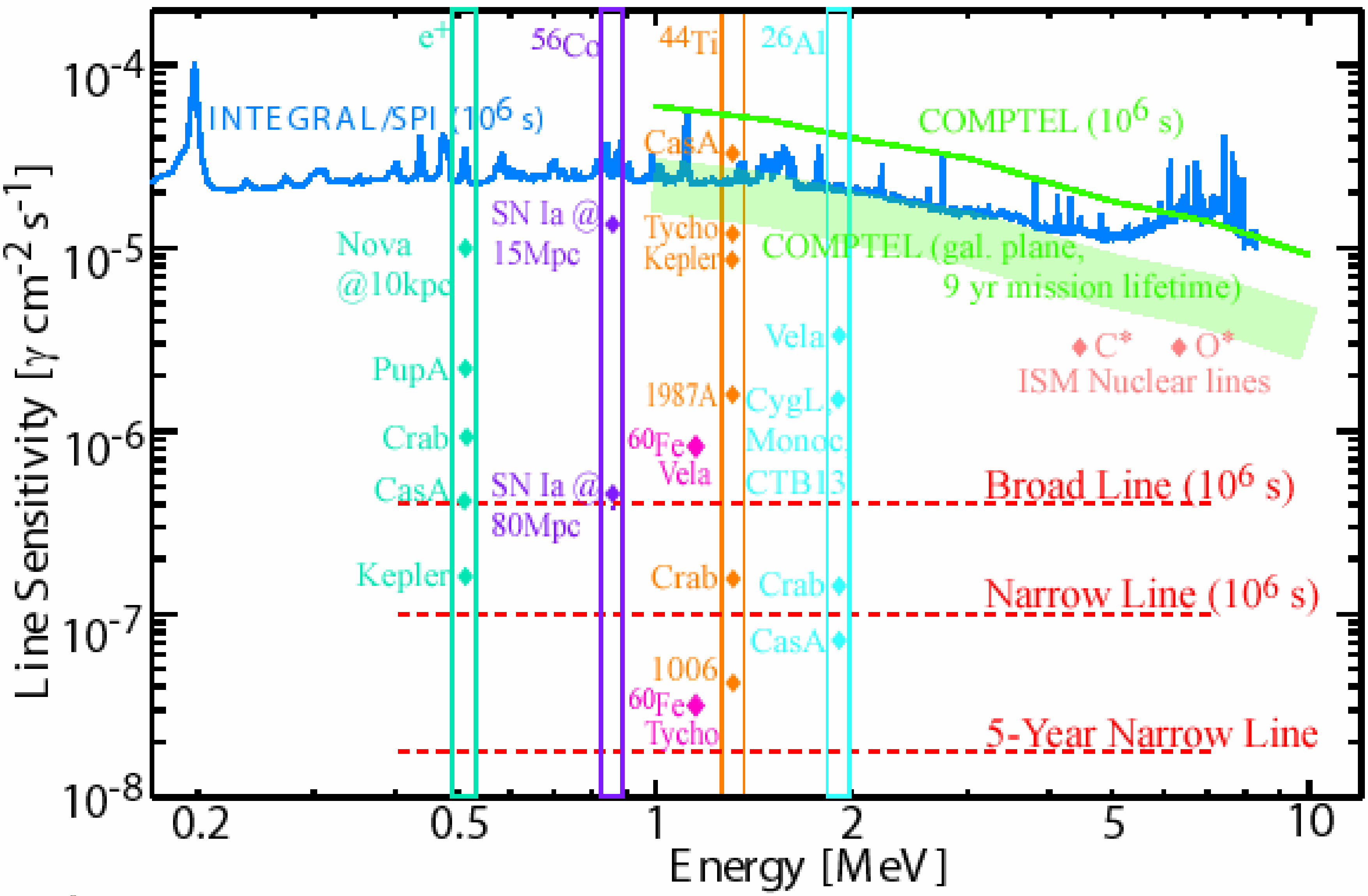
Aerospace contractor support: Ball Aerospace

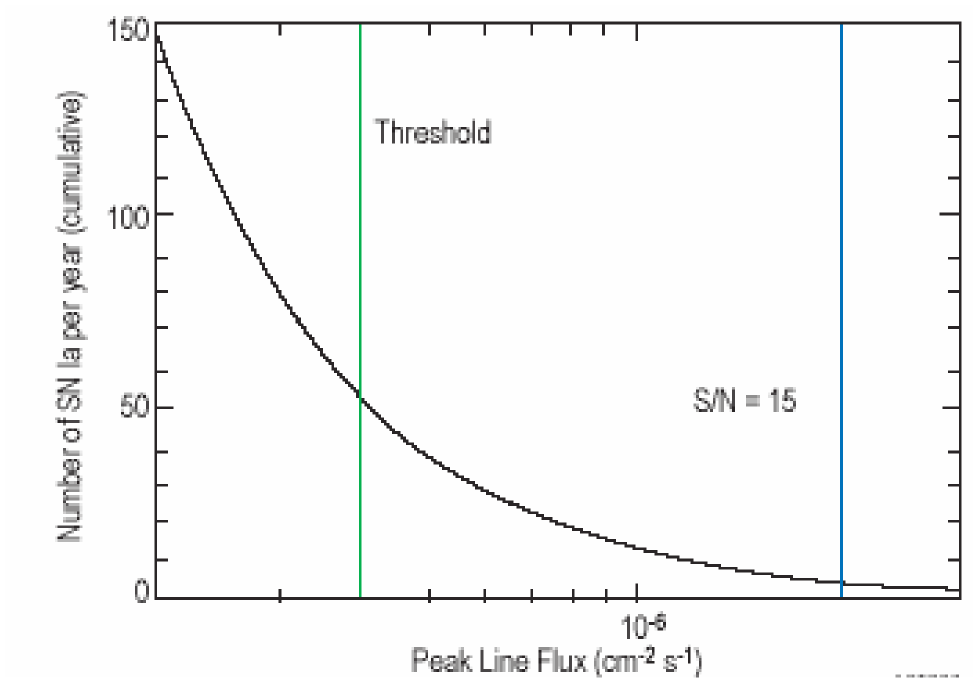
ACT Science

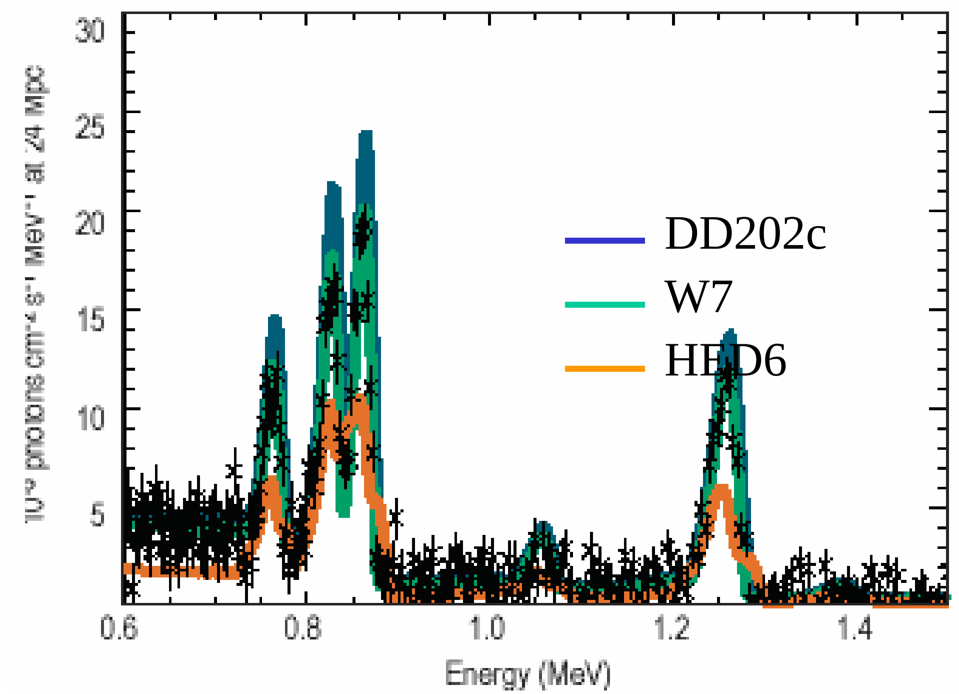
Table 2: ACT Science Requirements

Energy Range	0.2 – 30 MeV Compton mode
Energy Resolution	<10 keV FWHM @ 1 MeV
Field of View	>4 steradian
Angular Resolution	1°
Source Localization	5' bright sources
Line Sensitivity	1×10^{-7} $cm^{-2}s^{-1}$ in 10^6 s (narrow) 5×10^{-7} $cm^{-2}s^{-1}$ (broad)
Continuum Sensitivity	1×10^{-5} $cm^{-2}s^{-1}MeV^{-1}$ @ 0.5 MeV
Polarization Sensitivity	1%, 2×10^{-3} $cm^{-2}s^{-1}$ MeV^{-1} 10% 2×10^{-4} $cm^{-2}s^{-1}$ MeV^{-1}

ACT Sensitivity Goals







Cumulative number of Type Ia SN/yr as function of peak 847 keV line flux

Simulated ACT observation of Type Ia SN at 24 Mpc for alternative models

Detector Options

Table 4: Potential ACT Detector Technologies

PROPERTY	CZT STRIP	Si STRIP	Ge STRIP	LIQUID Xe	Xe μWELL
ΔE/E (1 MeV)	1%	0.2-1%	0.2%	4.5%	1.7%
Spatial Resolution	<1mm^3	<1mm^3	<1mm^3	<1mm^3	0.2 mm^3
Stopping Power (Z, density)	48 8.3 g/cm^3	14 2.3 g/cm^3	32 5.3 g/cm^3	54 3.0 g/cm^3	54 0.02 g/cm^3 (3 atm)
Volume (achieved)	4 cm^3	60 cm^3	130 cm^3	3000 cm^3	50 cm^3
Operating T	10° C	-20° C	-190° C	-100° C	20° C
Application	calorimeter	scatterer	scat/cal	scat/cal	scatterer
Institutions	UNH, UCSD	NRL, UCR	Berkeley, NRL	Columbia, Rice	GSFC
References	[34–36]	[37–40]	[41–43]	[44–46]	[47–49]

Improvements in Next Generation Compton Telescopes

Increased Efficiency
- More Compact Design
- Monolithic, Position-sensitive detectors

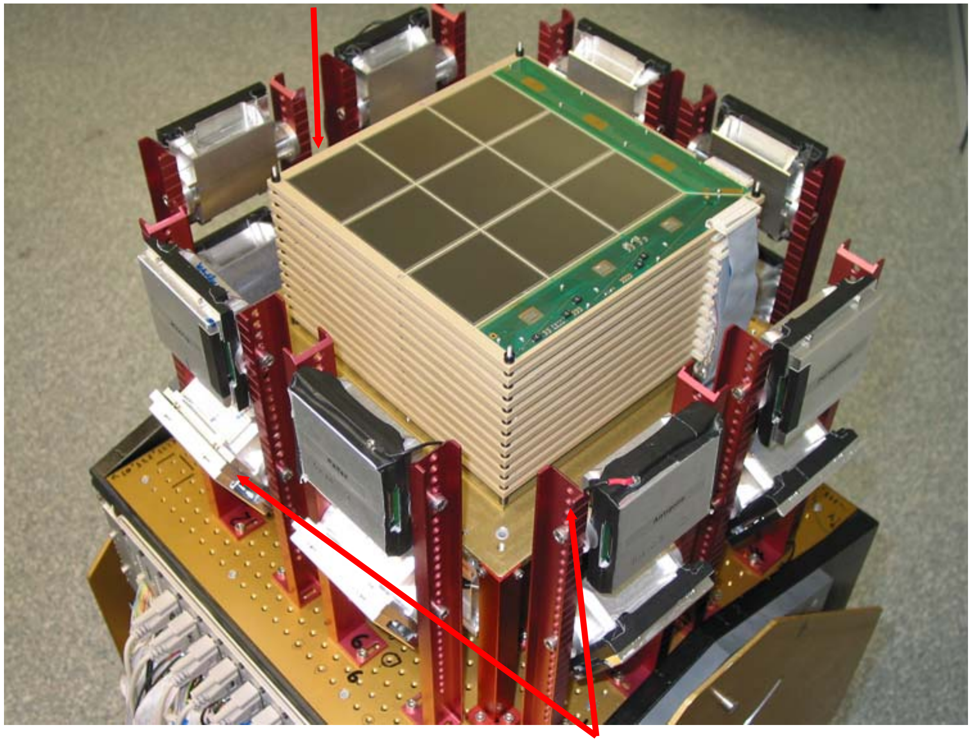
Energy Resolution
- Solid State Detectors
- Gas Detectors

Angular Resolution
- Position-sensitive detectors
- Energy resolution
- Electron tracking

Background Reduction
- Electron tracking
- Event reconstruction
- Choice of orbit

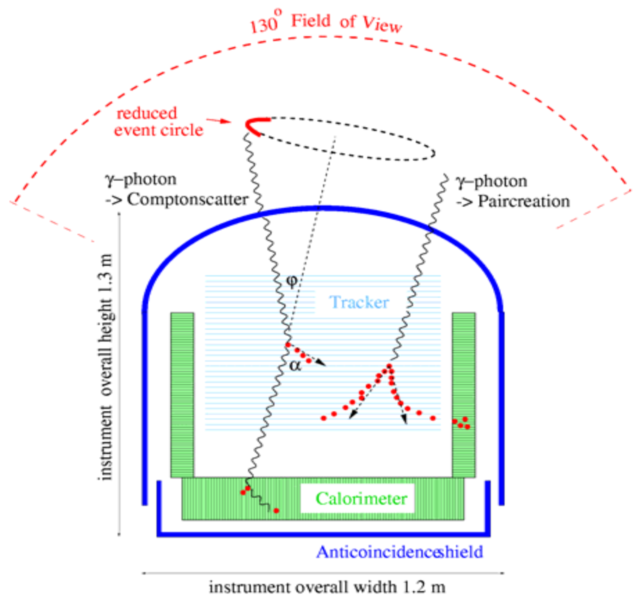
Note: No time of flight with most systems under consideration

Tracker:
10 layers of Silicon stripdetectors

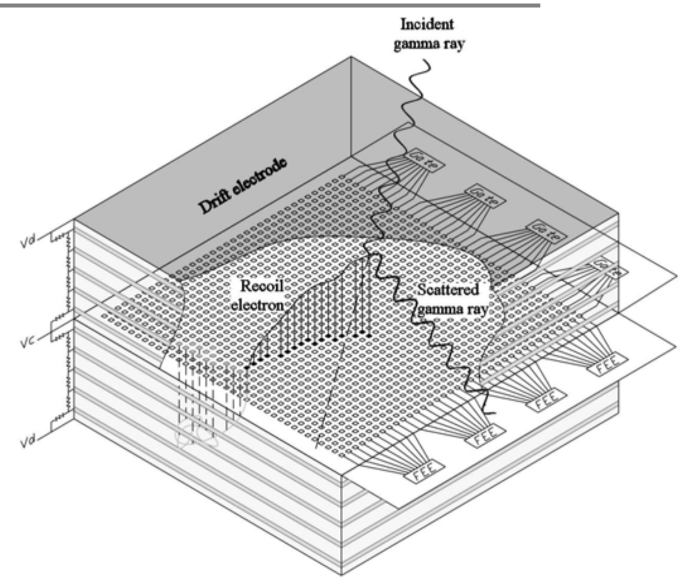


Calorimeter: modules of CsI(Tl) Scintillators

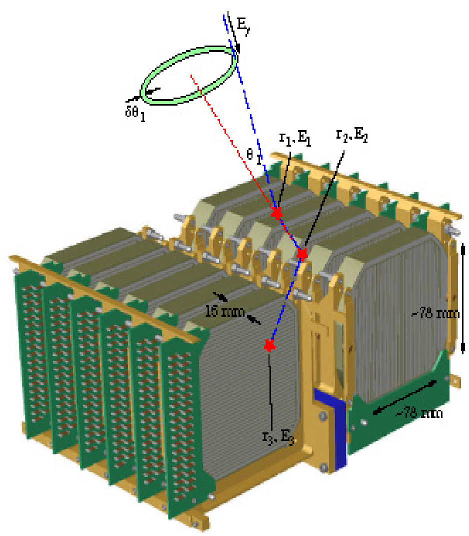
Compton Telescopes



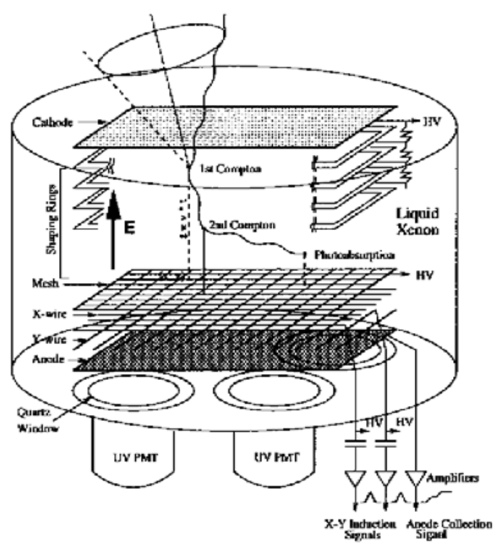
MEGA



Xe 3-dimensional track imager using pixelized gas micro-well detectors (MWDs)



Nuclear Compton Telescope (NCT)



LXeGRIT

FIGURE 1. Schematic of the liquid xenon time projection chamber

NRL Advanced Compton Telescope (ACT)

1 m^2 frontal area

43 g/cm^2 thick

6-mm thick Si(Li) <ρ>=0.8
-or-
1 cm thick Ge <ρ>=2.7

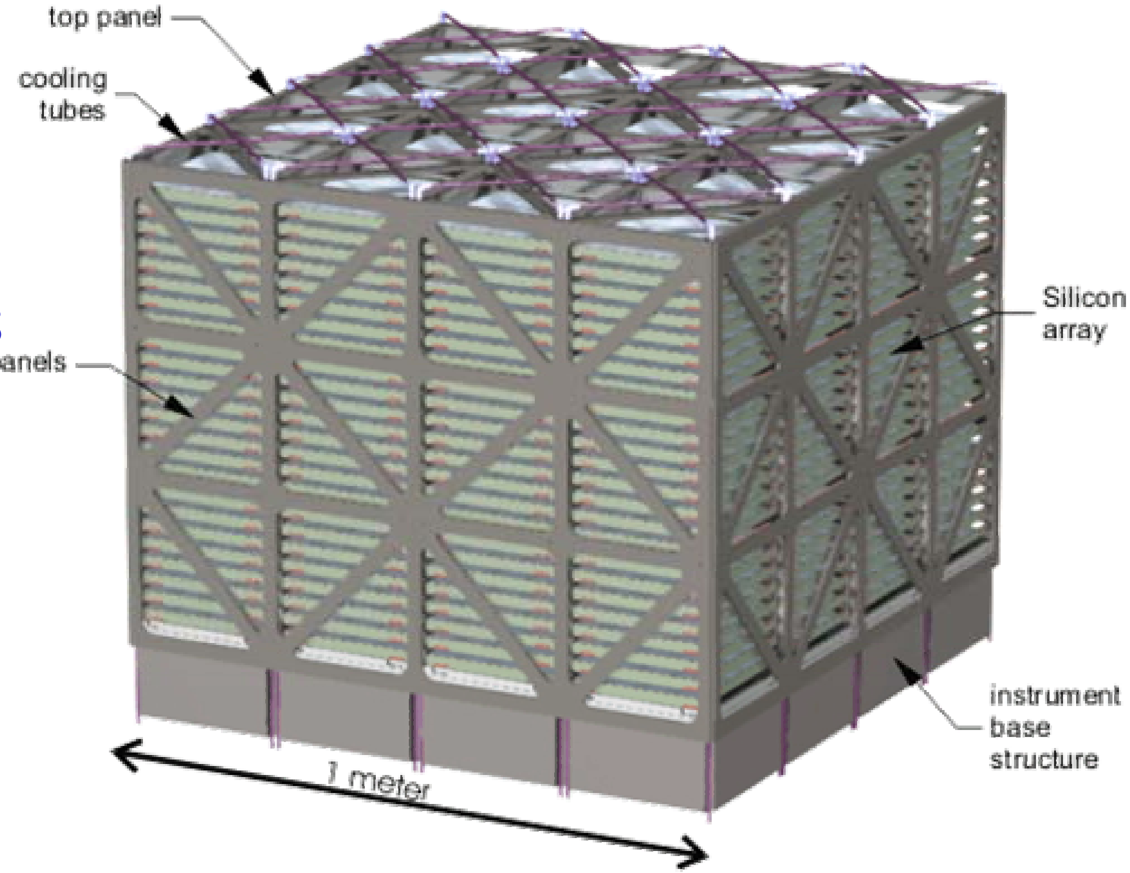
430 kg active volume

Fluid loop cooling

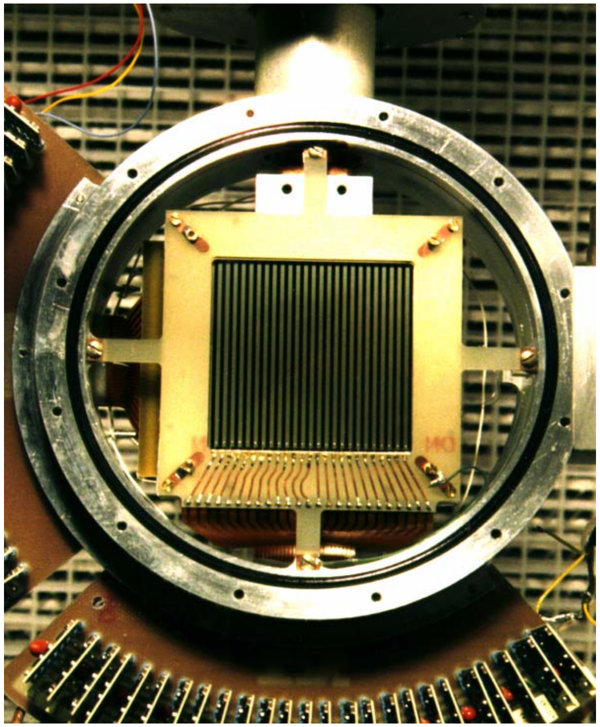
CMOS electronics

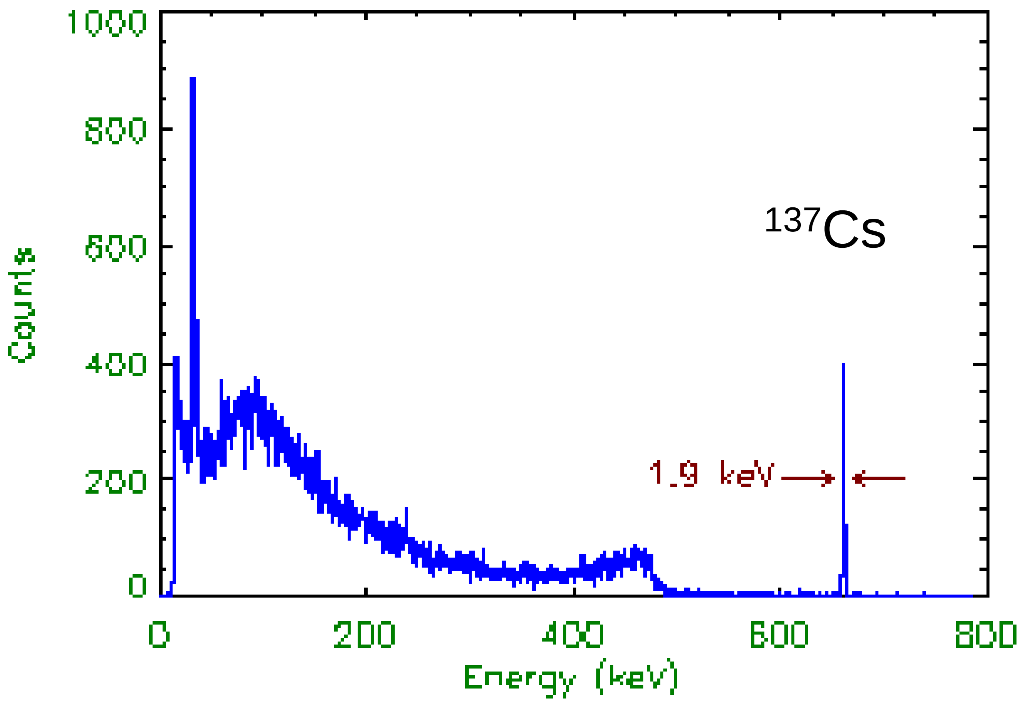
Passive mass <10%

Broad FoV (± 60-75 deg)



Position-sensitive Germanium Detectors

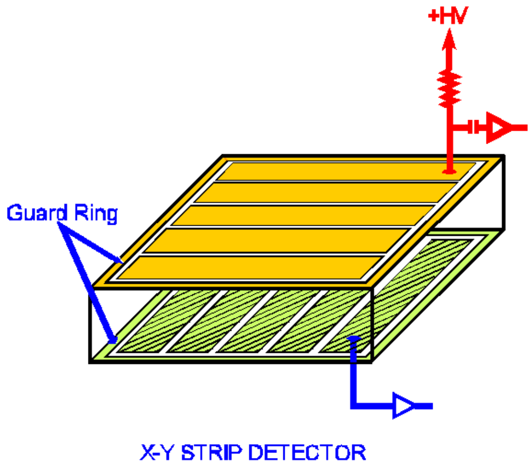




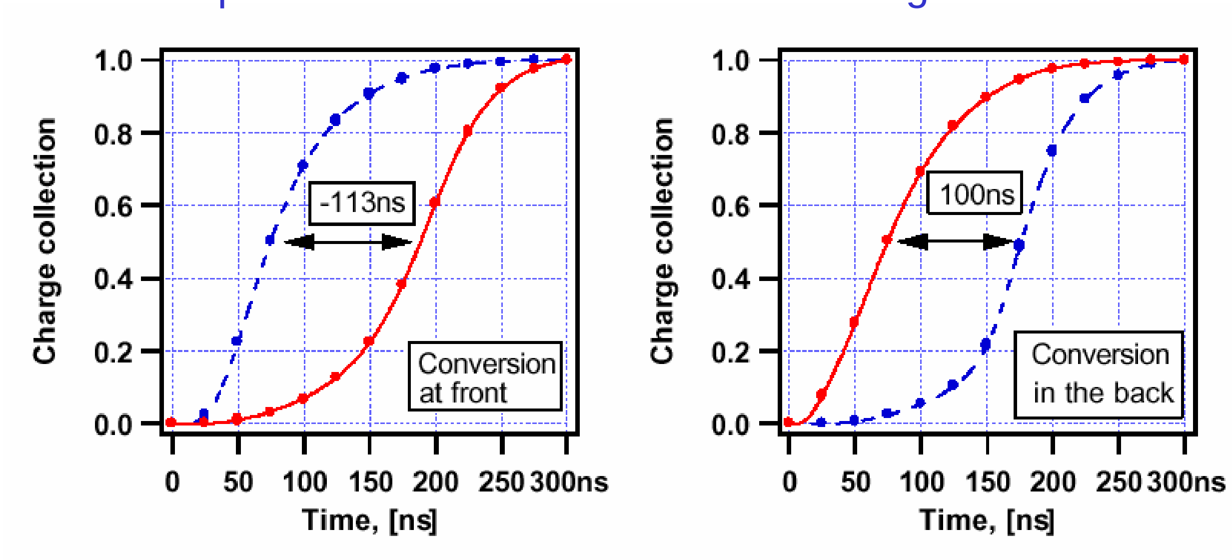
- Orthogonal Strip Planar Germanium Detector
- 5 × 5 × 1 cm detector; 2mm strip width
- Detector cooled to 80K in cryostat
- Room temperature electronics

Note: currently testing 80mm x 80mm x 2mm LBNL detector with amGe contacts

Depth Measurement



Depth of interaction affects time of charge collection



Depth is proportional to the time difference between charge collection on the front and back face of the detector.

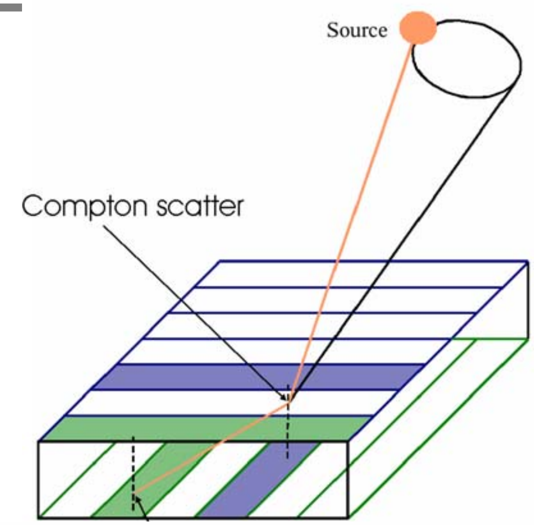
An interaction occurring at the front face will have the charge on that face collected ~100ns before the other face of the detector.

Achieve 0.5mm depth resolution

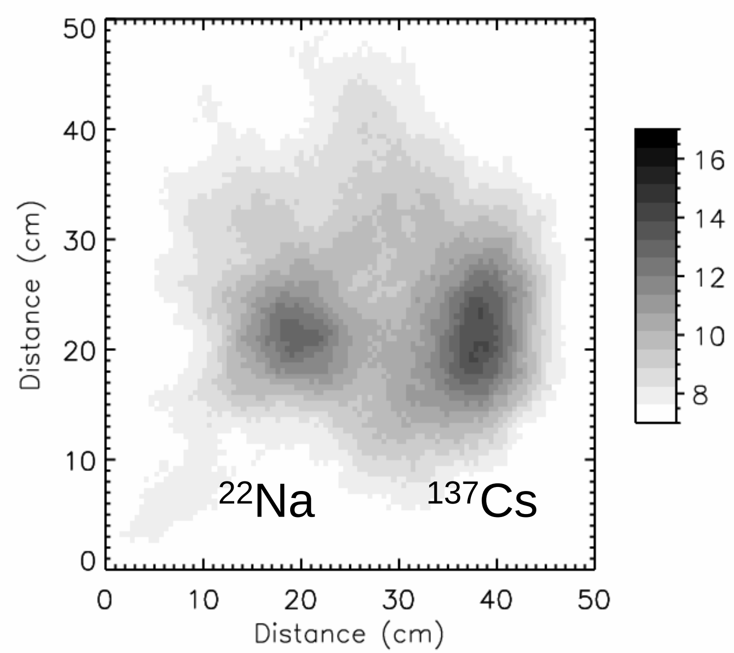
From Momayezi, Warburton and Kroeger (SPIE, 1999)

Single Detector Imaging

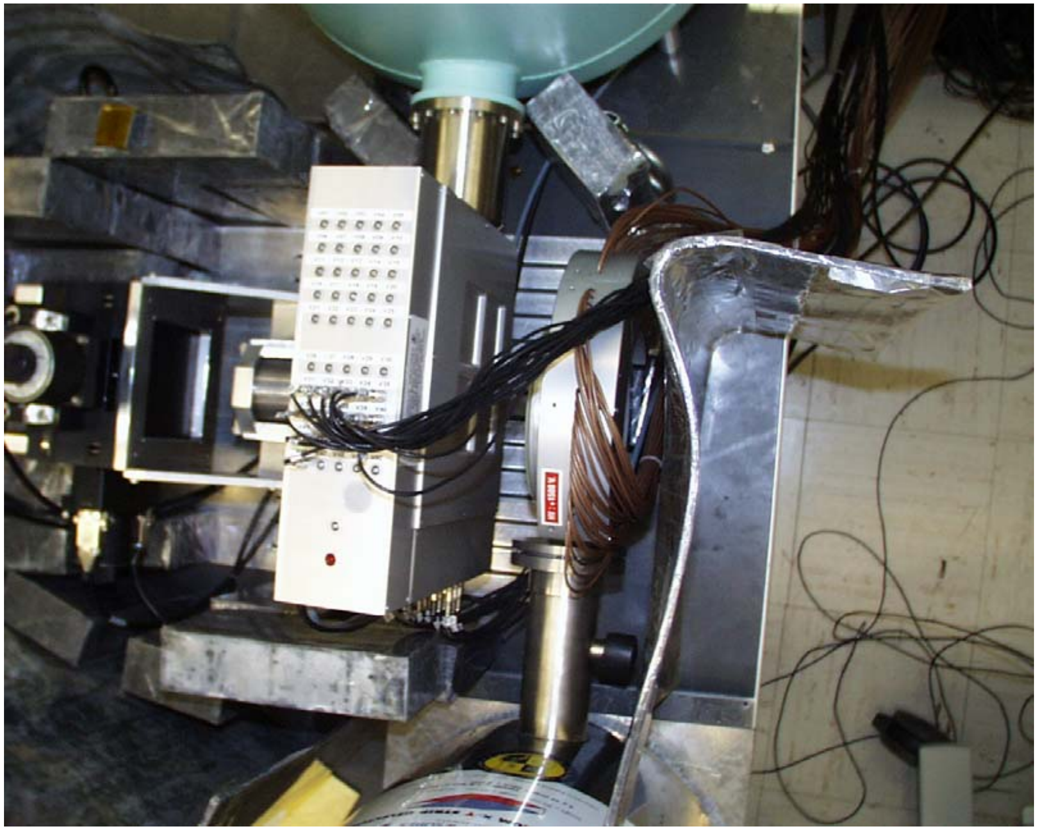
$$\cos\varphi_1 = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right)$$



- **First Demonstration of Compton Imaging in a single position-sensitive solid-state detector**
- **Use 50mm x 50mm x 10mm Ge detector**
- **Na-22 and Cs-137 at 40 cm from detector**
- **Point Spread Function at 662 keV is ~5 cm or 7º angular resolution**
- **Impossible in a single detector without depth information**



3-Compton Imaging with two Germanium detectors



Experiment set-up with two orthogonal Ge strip detectors---2mm position resolution with depth sensing (0.5mm)

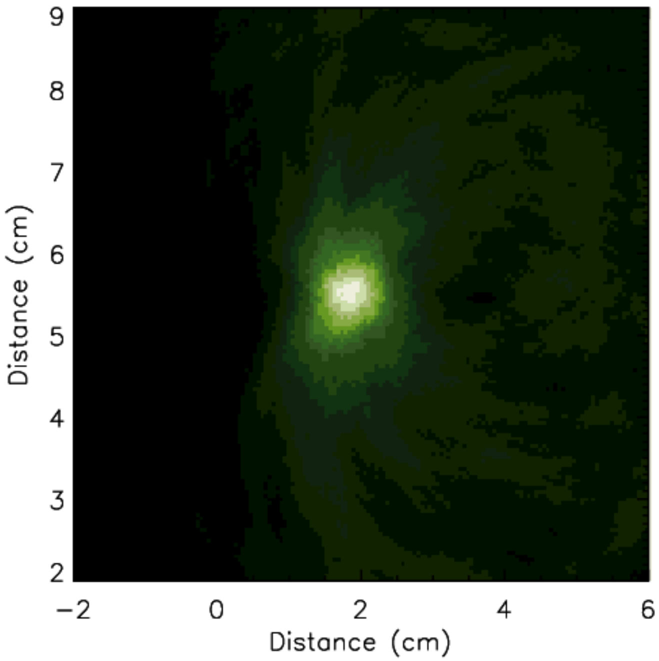
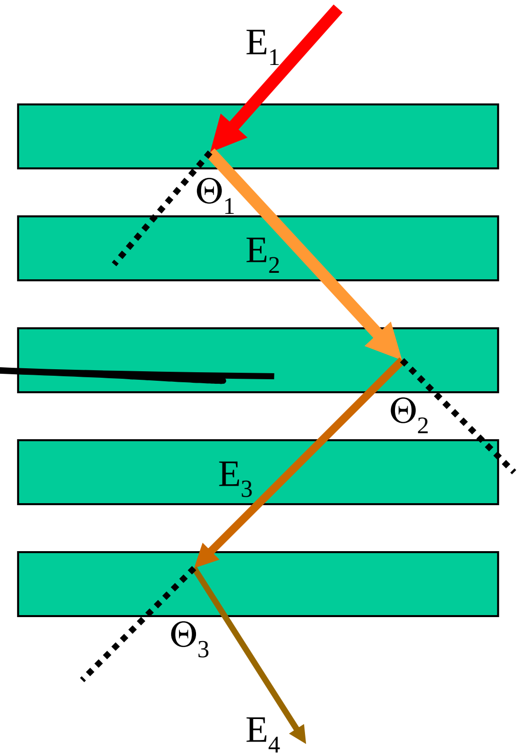


Image of ^{22}Na source in 511 keV positron annihilation gamma rays.

Three Gamma Interaction Technique

$$\cos\Theta_2 = 1 - m_e c^2\left(\frac{1}{E_3} - \frac{1}{E_2}\right); \quad L_2 = E_2 - E_3$$

$$E_1 = L_1 + \frac{L_2 + \left[L_2^2 + \frac{4 m_e c^2 L_2}{1-\cos\Theta_2}\right]^{\frac{1}{2}}}{2}$$



- **Unknown source: 3 interactions required to determine energy, E_1**
- **Known source: 2 interactions required to determine energy, E_1**
- **Does not require total energy absorption**
- **Efficient Compton telescope, even if using *silicon* detectors**

Thick Silicon Detectors

<u>Advantages of silicon detectors</u>

Operating Temperature: -20 to –50 C

Reduced cost

Lower Doppler Broadening effects on angular and energy resolutions compared to Ge, CZT

<u>Silicon detectors</u>

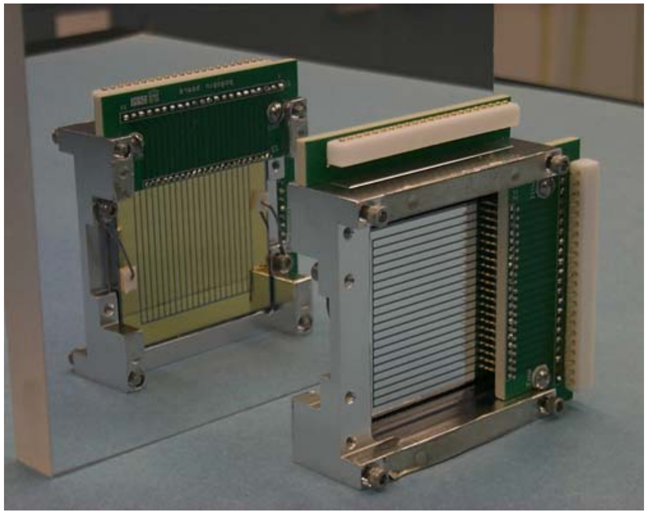
Lithium-drifted silicon

- Can drift to 6-10mm thick
- 125mm dia. wafers available

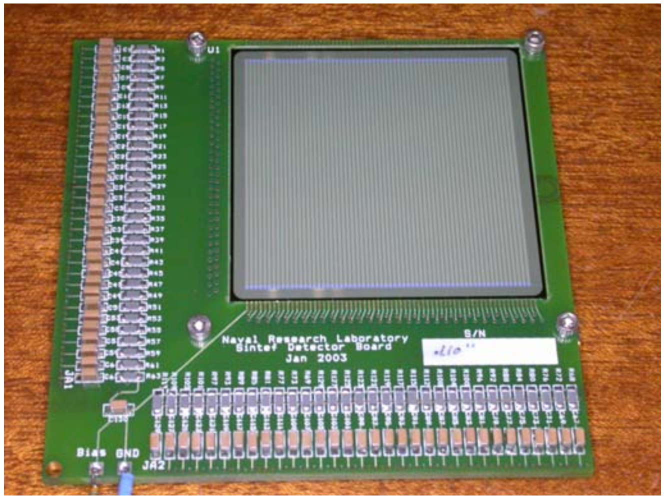
High Resistivity Silicon

- 2-3mm thickness
- 150mm wafers available

ASICs for many analog channels (Power)

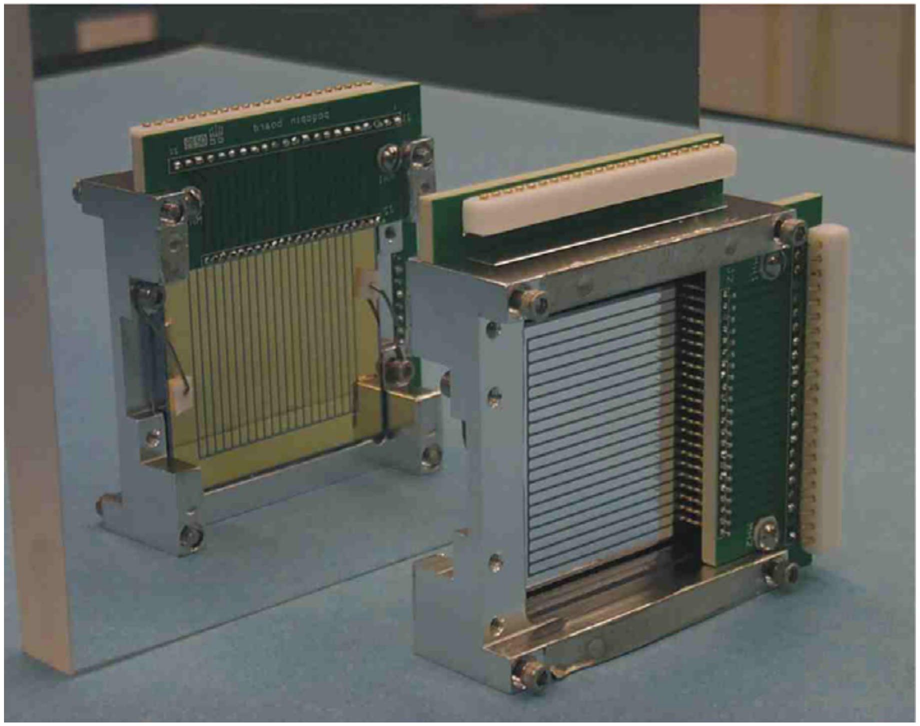


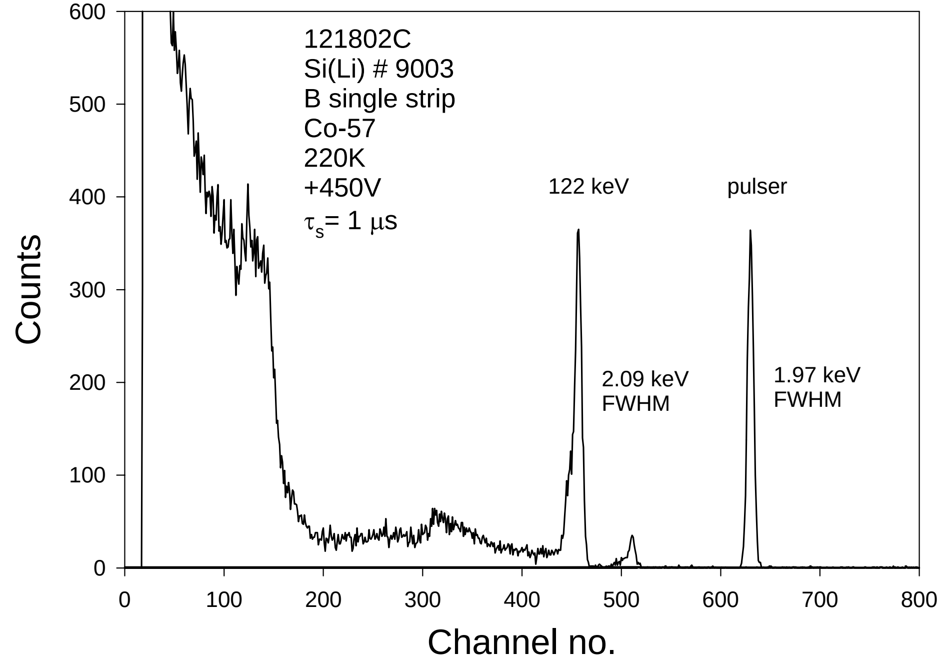
LBNL 54mmx54mm Si(Li) Detector



SINTEF 63mm x 63mm double sided intrinsic silicon detector

LBNL Si(Li) Detector (54mm x 54mm x 3.5mm thick





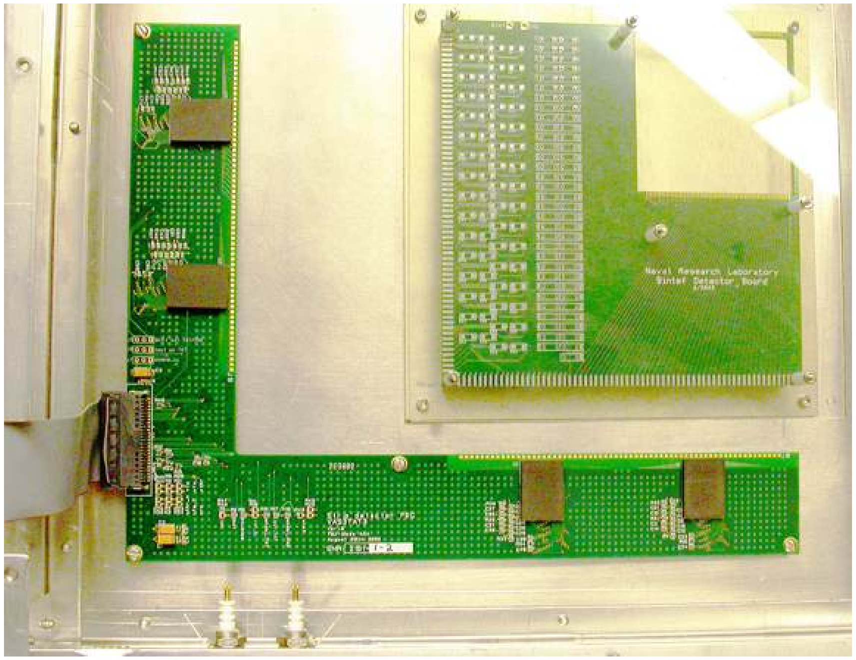
N-contacts: am-silicon

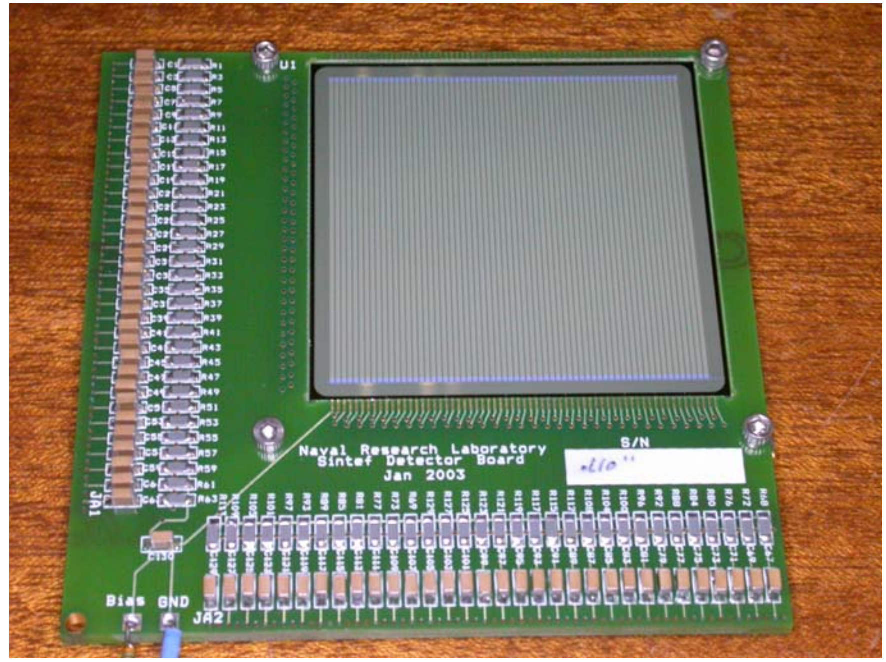
P-contacts: boron implants

Strip pitch: 2mm

^{57}Co spectrum from the α-Si contact side of the LBNL orthogonal strip detector.

SINTEF intrnisic Si detectors/ ASICs



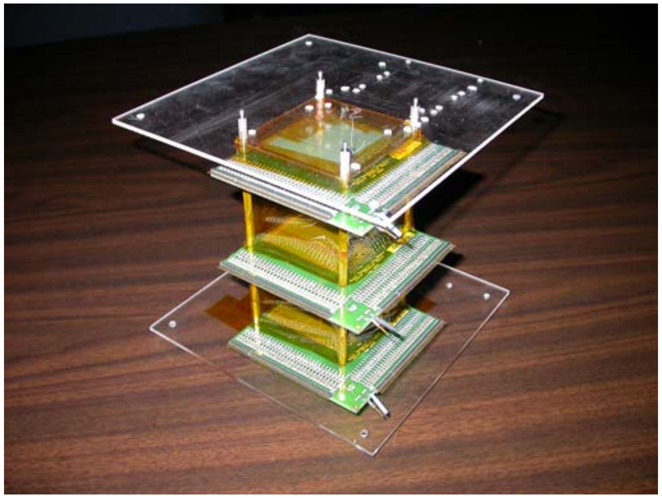


Four VAS3/TAT3 chip sets mounted on an "L" shaped test board. A silicon detector is shown in relation to the board.

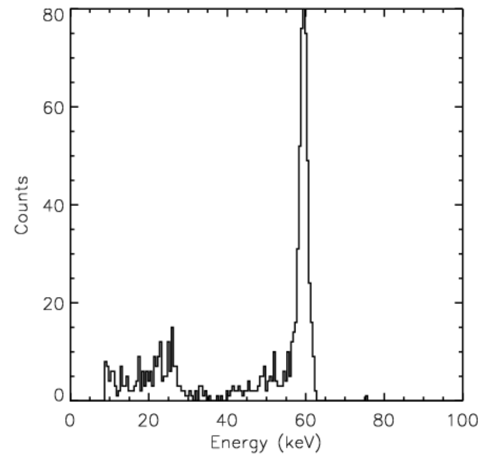
63mm x 63mmx 2mm inSilicon detector

We plan to pursue 95mm x 95mm x 2-3mm thick detectors

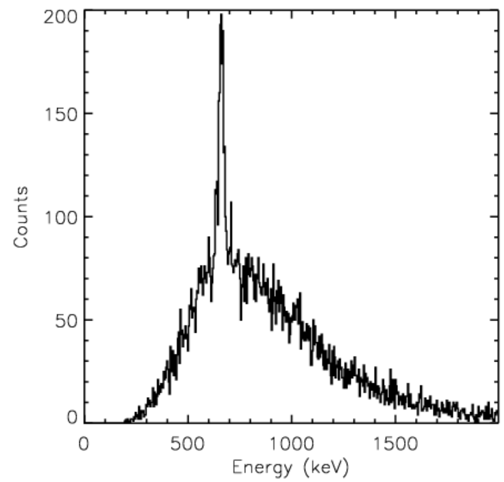
Compton Imaging with 3-layer silicon stack



3-Layer silicon stack. Each detector is 63mm x 63mm x 2mm thick with 64x64 strips. Strip pitch is 890 microns.



Room temperature spectrum with ^{241}Am source. FWHM=2.8 keV



Room temperature spectrum with ^{137}Cs source FWHM ~25 keV. Most events are accidental coincidences.

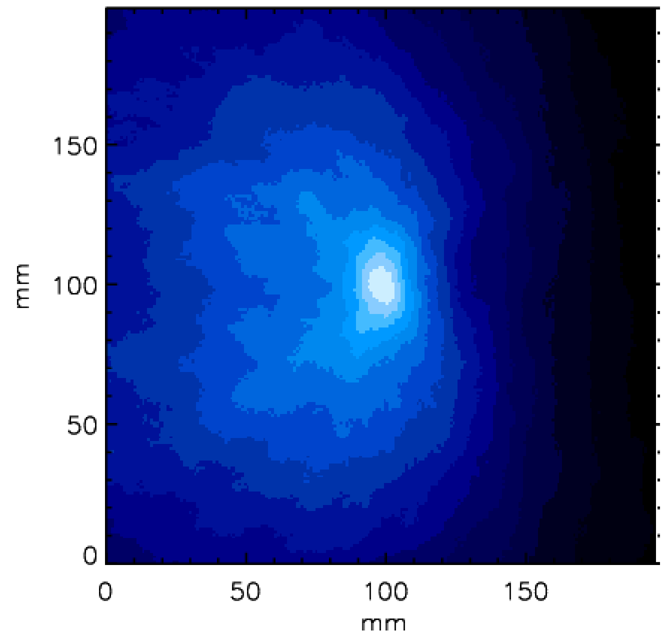
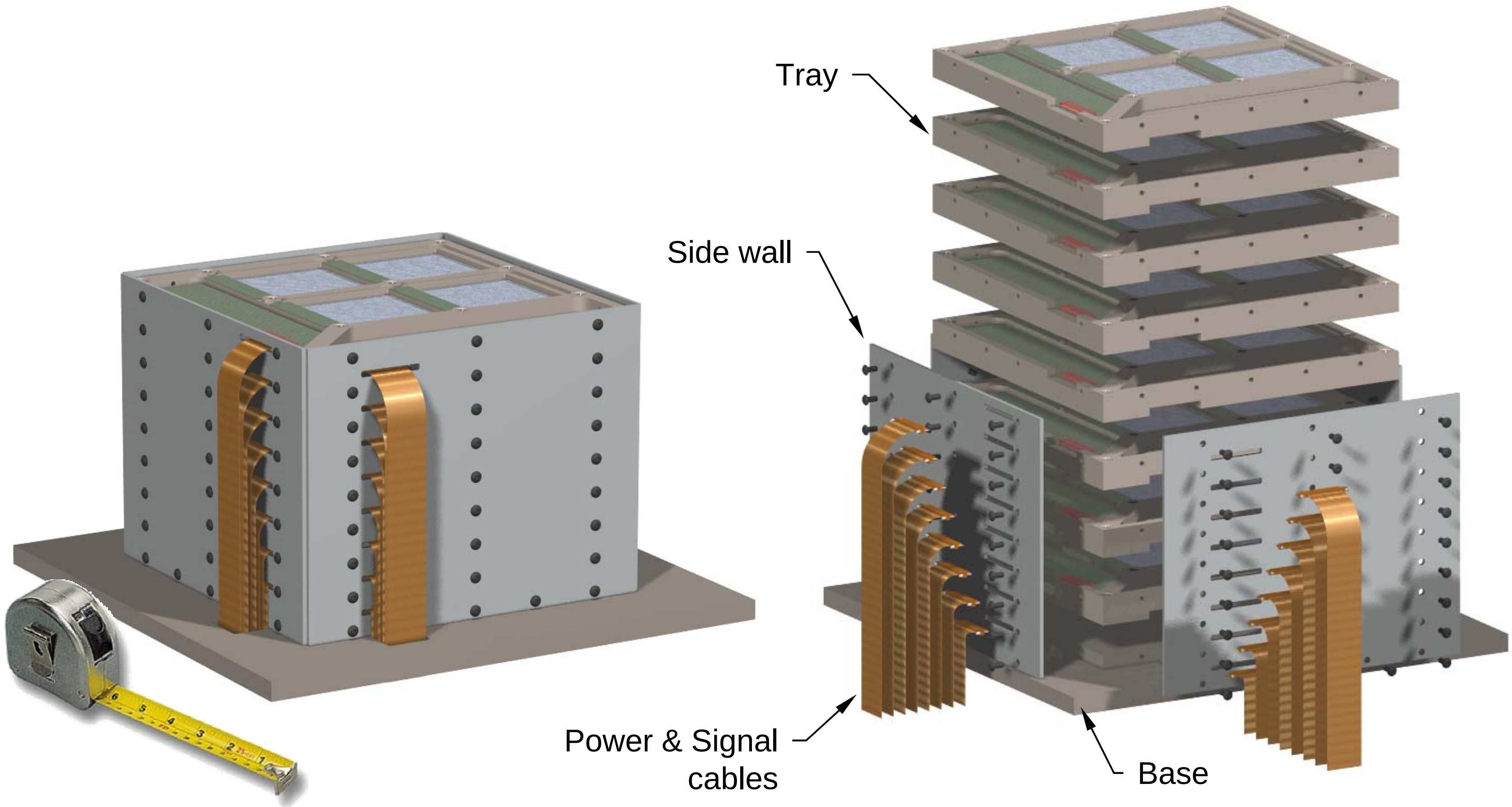


Image of a 662 keV source using 3-layer intrinsic Si detector stack. Angular resolution of approx. 5° limited by energy resolution and detector separations.

Prototype Unit

- 8 identical trays held in a stack by side-walls
- Side-walls provide structural support and cooling



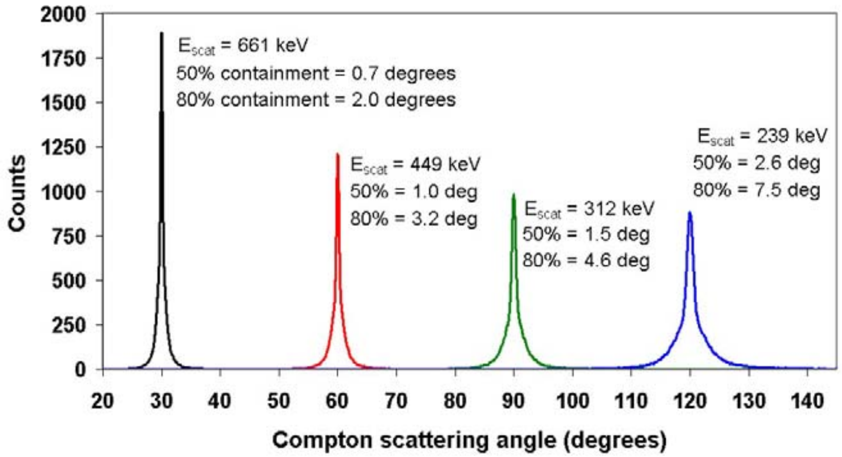
Compton Telescope Issues

- Orbit: equatorial vs. 30° inclination vs. high altitude
- Preferred detectors (Ge, Si, CZT, CdTe, Xe, others) (or some combination of the above)
- Use of active shield/scattered gamma ray detector
- Scientific Emphasis (lines/continuum/large FOV for transients/polarization)
- Importance of tracking scattered electrons
- Event reconstruction efficiencies and accuracies
- Background rejection efficiencies
- Relative costs and capabilities

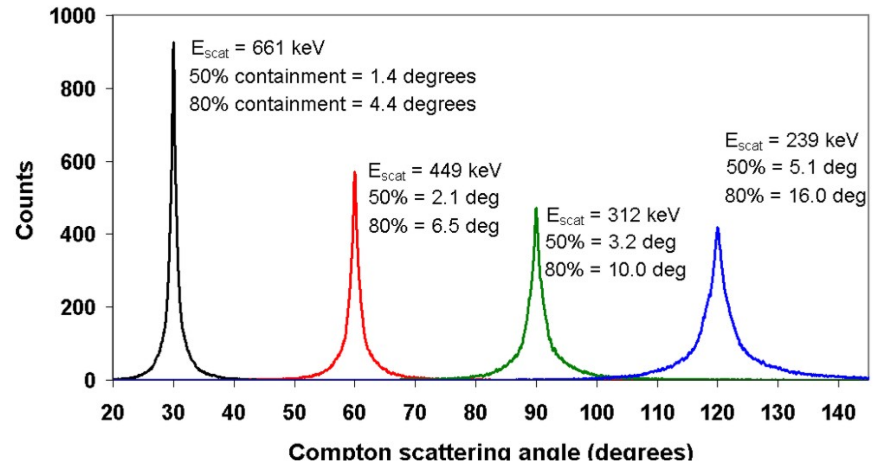
ALL OF ABOVE REQUIRE EXTENSIVE SIMULATIONS!!!

Angular Resolution Limits due to Doppler Broadening

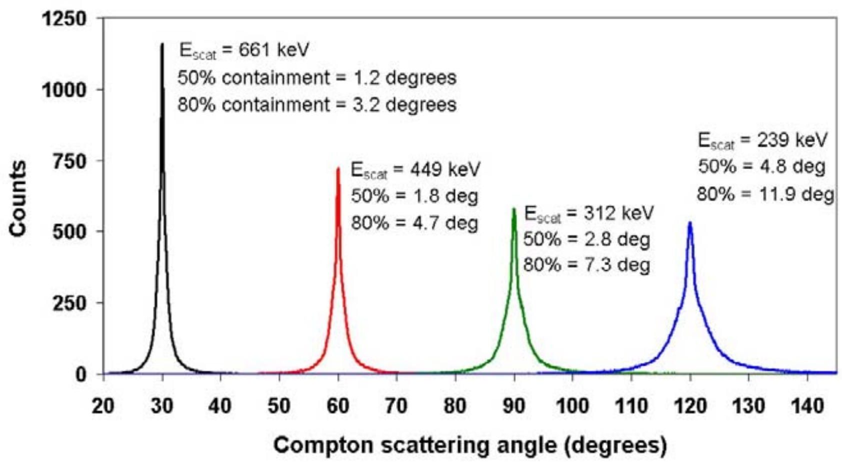
Silicon: E_{inc} = 800 keV



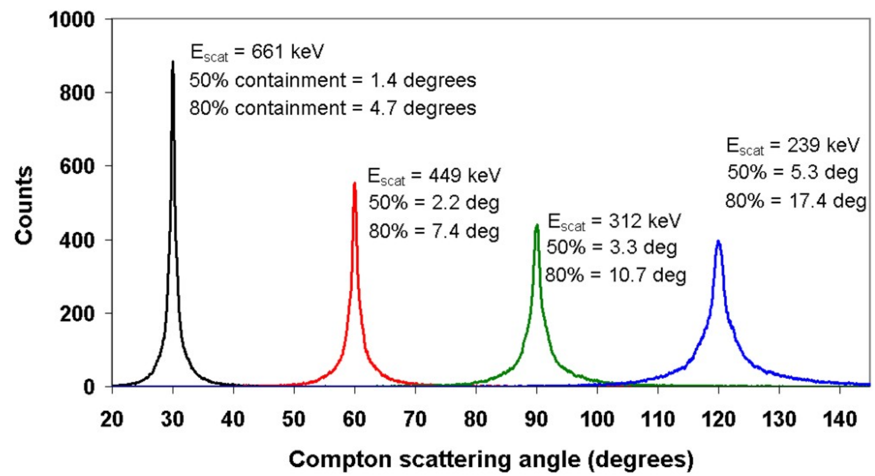
CZT: E_{inc} = 800 keV



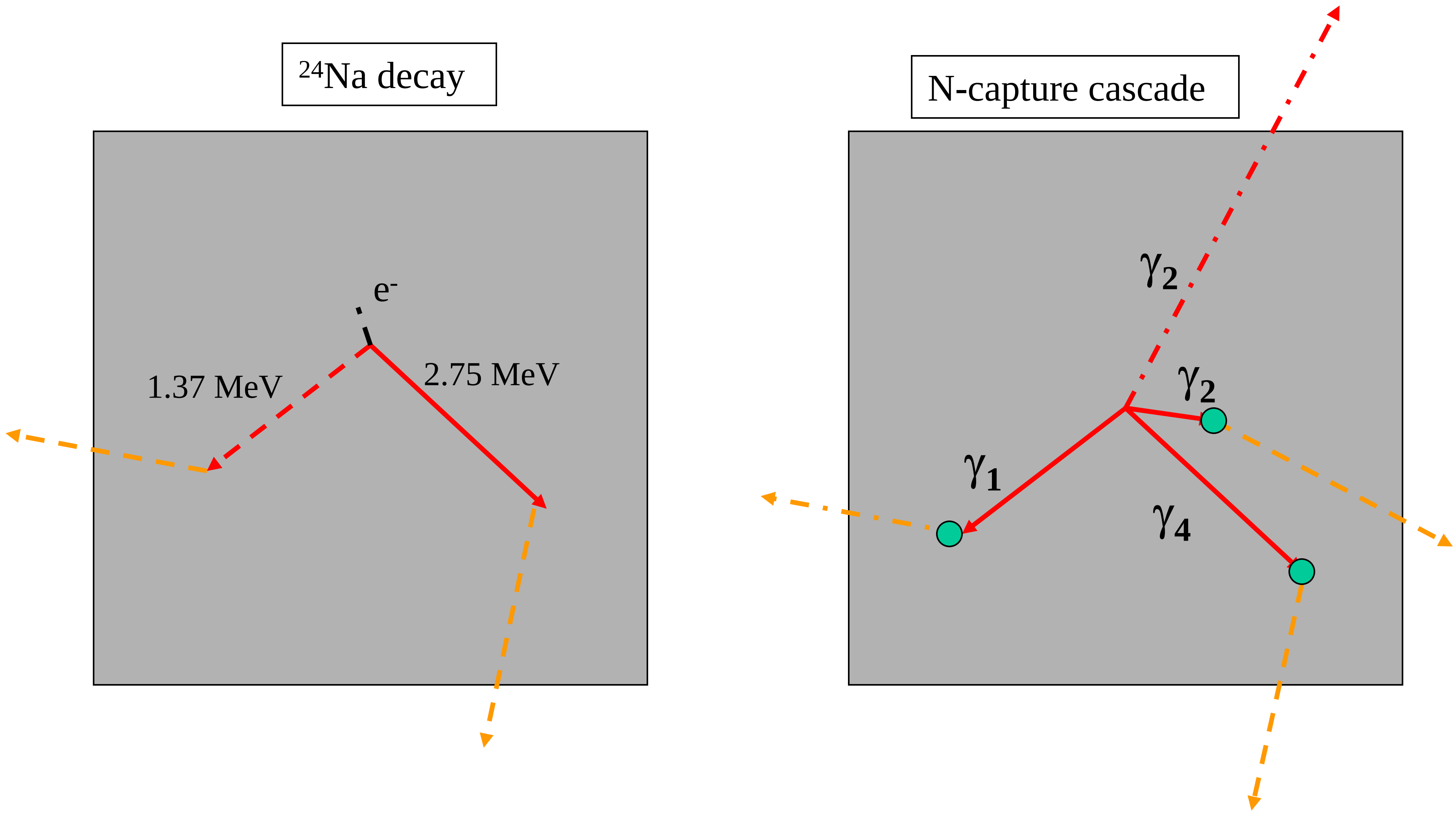
Germanium: E_{inc} = 800 keV



Xenon: E_{inc} = 800 keV

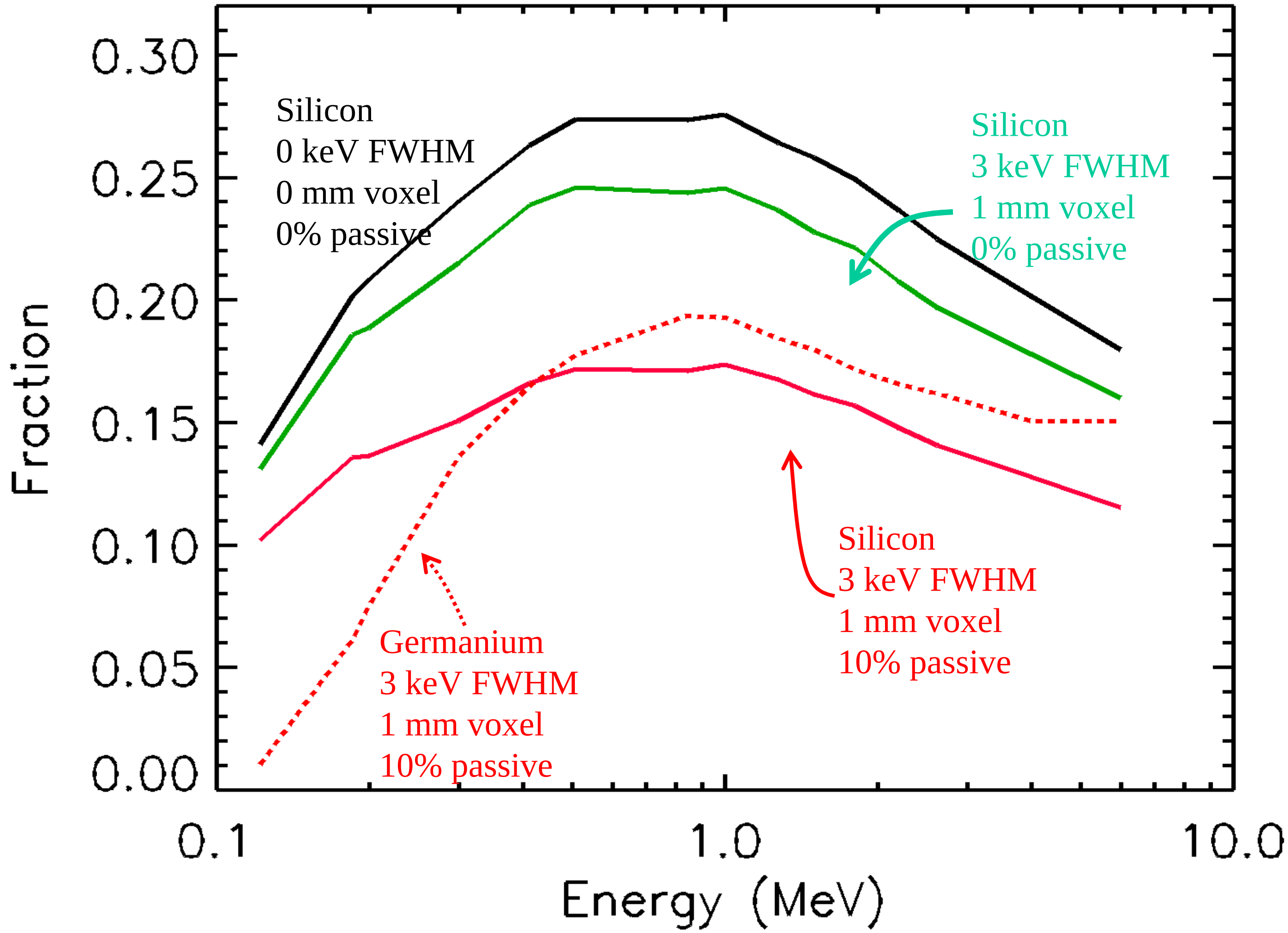


Rejection of Internal Background



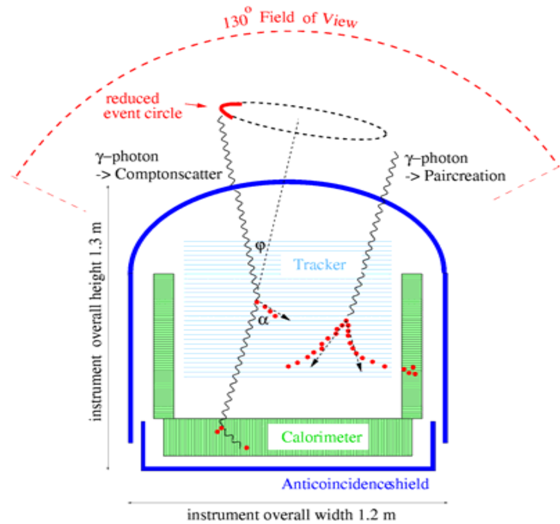
How does rejection efficiency depend on energy and position resolution?

3-Compton Efficiency

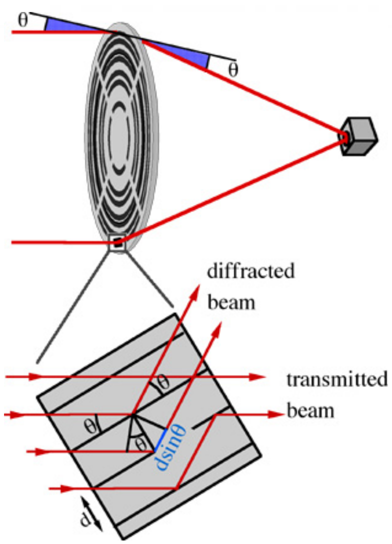


Mission Options

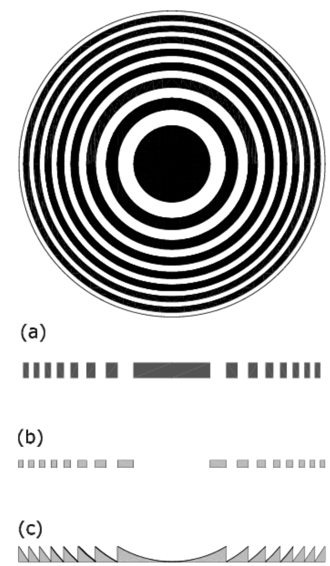
Large Area Coded Aperture--EXIST



Compton Telescopes



Laue gamma ray collector (Claire)



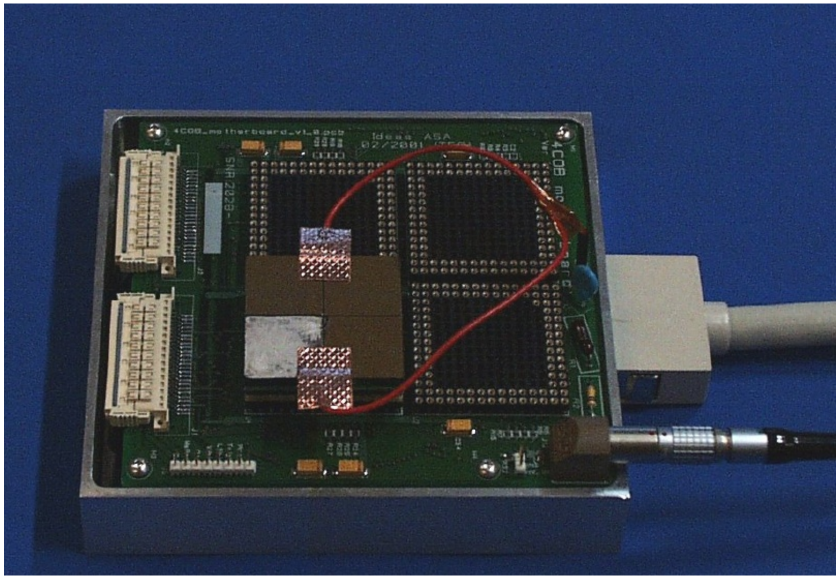
Gamma Ray Lens

EXIST

Large Area Coded Aperture--EXIST

- **CZT tiled arrays: 8m² total area**
- **10 keV – 600 keV**
- **Passive and active shielding; 25º x 20º collimation/module**
- **Mass, power, telemetry: 8500kg, 1200W, 1.2mbs (X-band)**

Mission Parameters



Technology

Active EXIST team planning mission

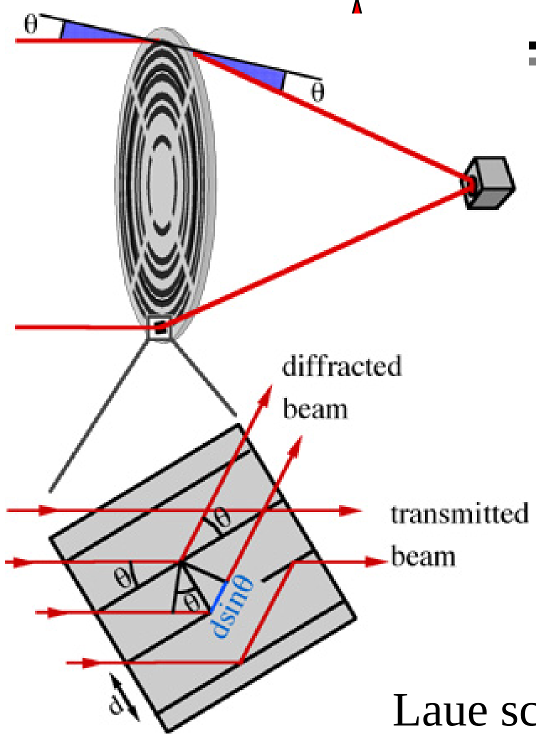
Will be proposed as Black Hole Probe mission

In NASA SEUS Roadmap as Einstein Probe.

Launch 2010-2015

Status

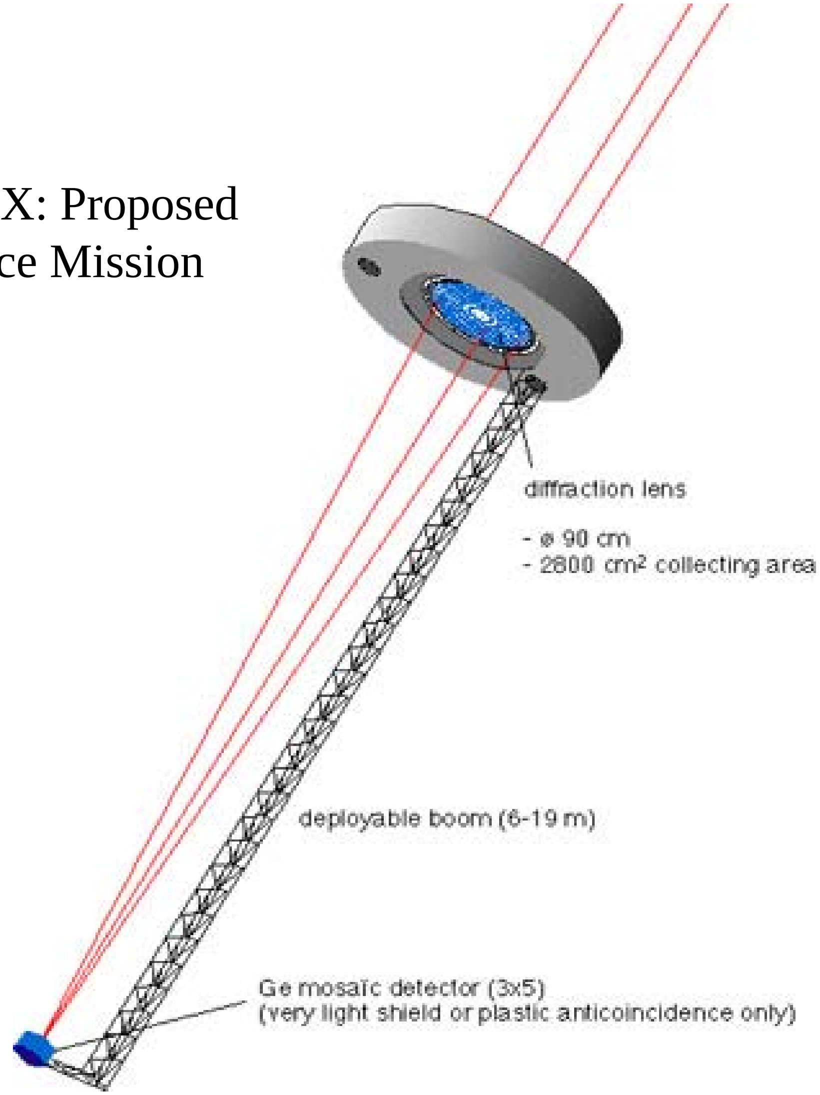
MAX: Laue Gamma Ray Lens



Laue scattering principle

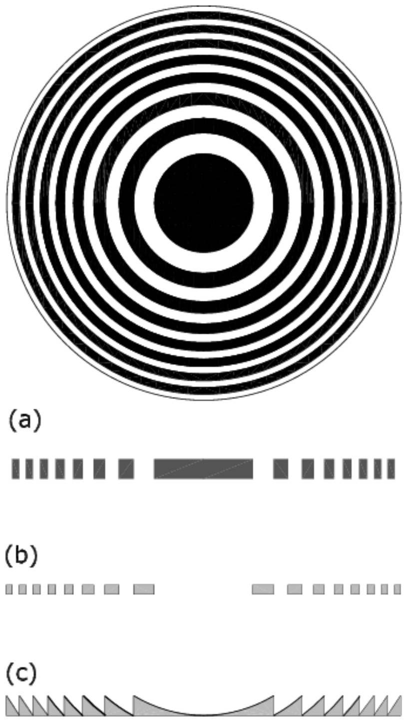
Laboratory Prototype

MAX: Proposed Space Mission

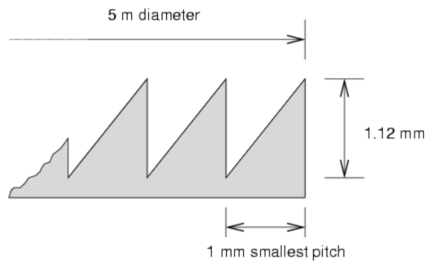


Status: Proposed new mission in France

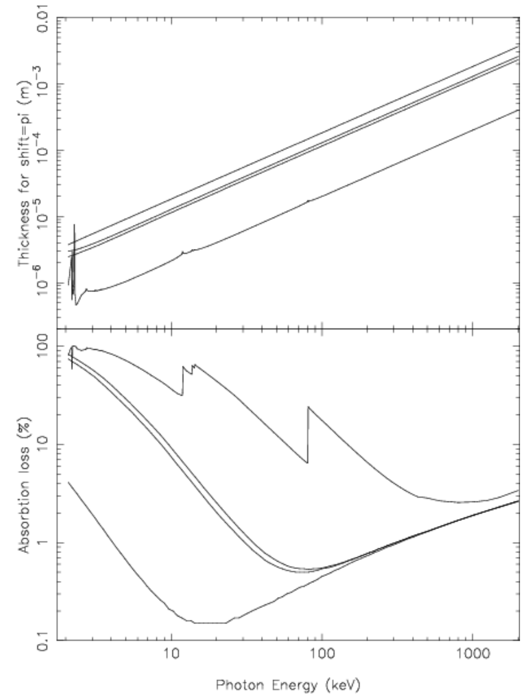
Gamma Ray Lens



$$n^* = (1-\delta) - i\beta$$



Various Fresnel Lens Configurations



Phase Fresnel Lens Thickness and Absorption Loss

$$f = 0.403 \times 10^6 \left(\frac{p}{1mm}\right)\left(\frac{d}{1m}\right)\left(\frac{E}{1MeV}\right) km$$

For ***p***=1mm; ***d***=5m; ***E***=1 MeV: ***f*** ~10^6 km!

Focal Length

E_γ = 847 ± 1.0 keV (^{57}Co line from SN)

Lens effective area: 4.4 m^2

Focal Length = 10^9 m

Sensitivity ~ 2 x 10^{-9} γ/cm^2-s in 10^6 s

Sensitivity

SUMMARY

- **Several alternative instrument options are under development that promise very significant improvements in performance/sensitivity.**
- **Many unrealized objectives in low/medium energy gamma ray astronomy can be met with an Advanced Compton Telescope that provides 50-100 times better sensitivity than CGRO and INTEGRAL.**
- **3-Compton scatter concept is attractive for a high efficiency, high sensitivity instrument.**
- **Potential for dramatic background reduction using event re-construction. Places premium on energy and position resolution.**
- **Aggressive simulation program essential to validate performance capabilities/guide technology development.**