Development of High-Z Semiconductor Detectors and Their Applications to X-ray/gamma-ray Astronomy

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9/19/2007 SLAC Advanced Instrumentation Seminar

Outline

- Introduction
- CdTe Diode Detector
- CdTe Pixel Imaging Sensor
  - Readout Analog ASIC
  - Bump Bonding
- Application to Compton Telescope

Collaboration

- ISAS/JAXA (Tadayuki Takahashi)
- SLAC (Hiro Tajima & Taka Tanaka)
- University of Tokyo
- Hiroshima University
- ACRORAD (Manufacturer of CdTe devices)
- IDEAS ASA (Readout ASICs)
- Mitsubishi Heavy Industries (Bump Bonding etc.)

Why High-Z Semiconductor?

Fine imaging is limited in the energy region below ~10 keV

e.g.) Supernova Remnants (SN1006)

Accelerator of Cosmic Rays

X-ray (< 10 keV)

Hard X-ray (> 10 keV)

?

We need hard X-ray optics & Hard X-ray Imager

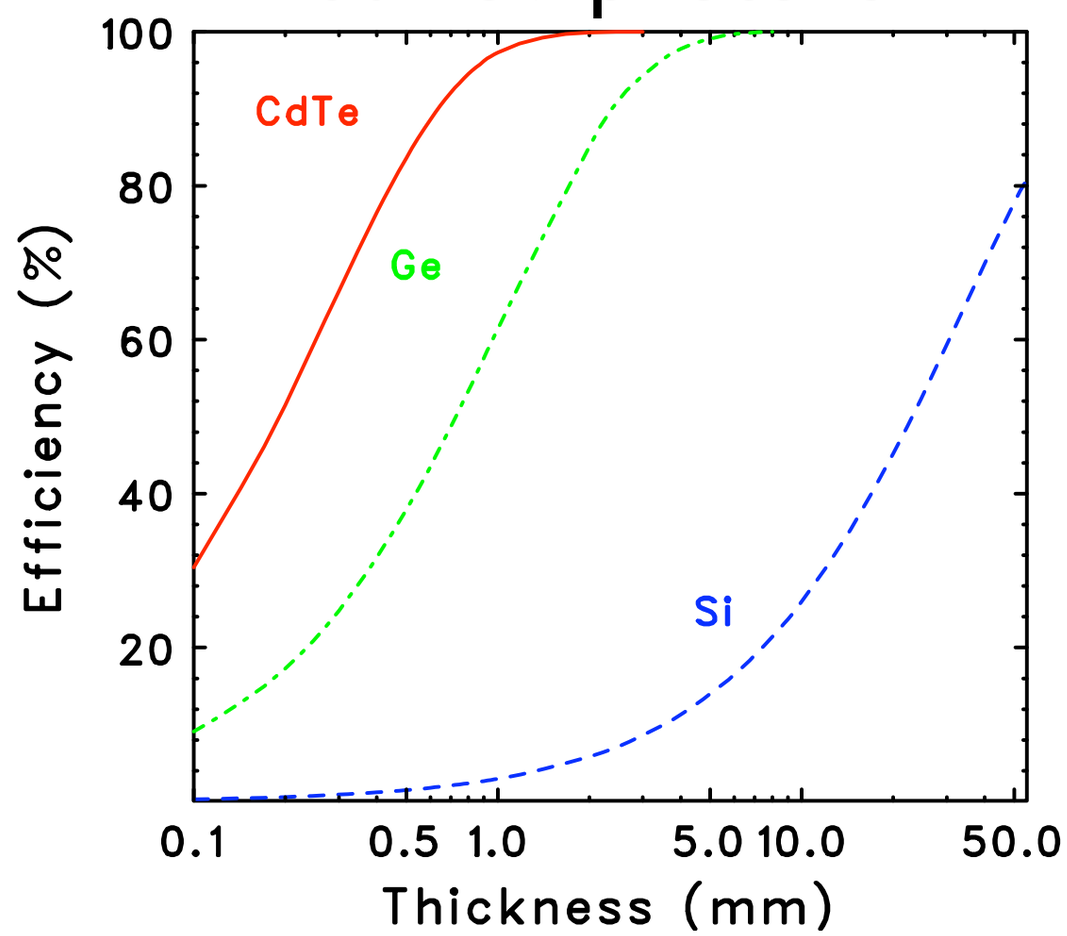
Cadmium Telluride (CdTe)

High Z semiconductor
(Z_{Cd} = 48, Z_{Te} = 52)

High Density
(ρ = 5.9 g/cm^3)

semi-conductor	density [g/cm^3]	Z	E_{gap} [eV]	ϵ [eV]	X_0 [cm]
Si	2.33	14	1.12	3.6	9.37
Ge	5.33	32	0.67	2.9	2.30
CdTe	5.85	48,52	1.44	4.43	1.52
CdZnTe	5.81		1.6	4.6	
HgI_2	6.40	80,53	2.13	4.2	1.16
GaAs	5.32	31, 33	1.42	4.3	2.29

Efficiency for
60 keV photons



- Mildly Wide Band Gap (Eg:1.4 eV, 4.4 eV/e-h pair)

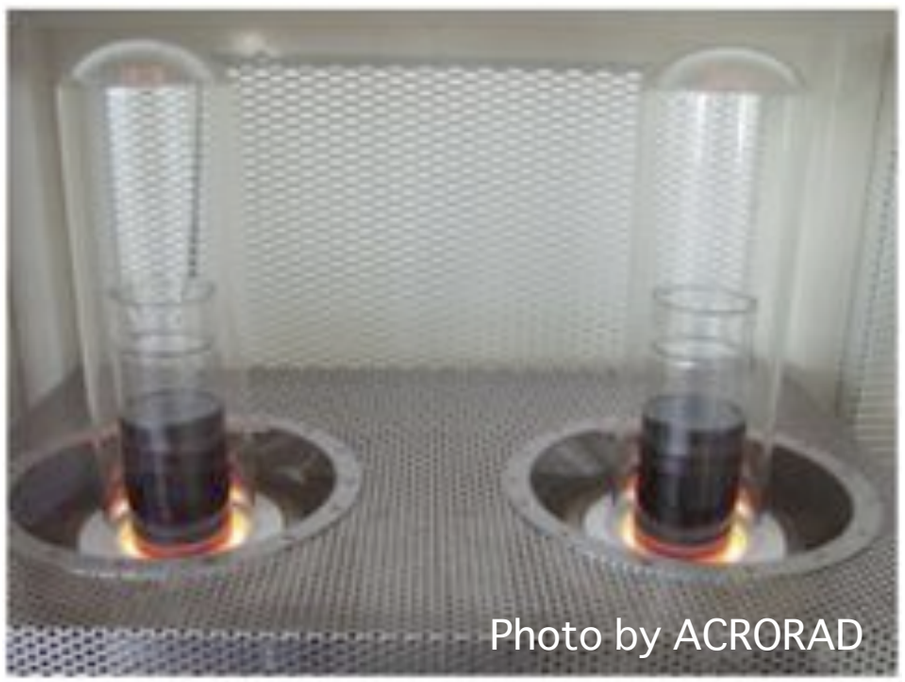
⇒ Allows room temperature operation or
the operation under moderate cooling (> –20 ℃)

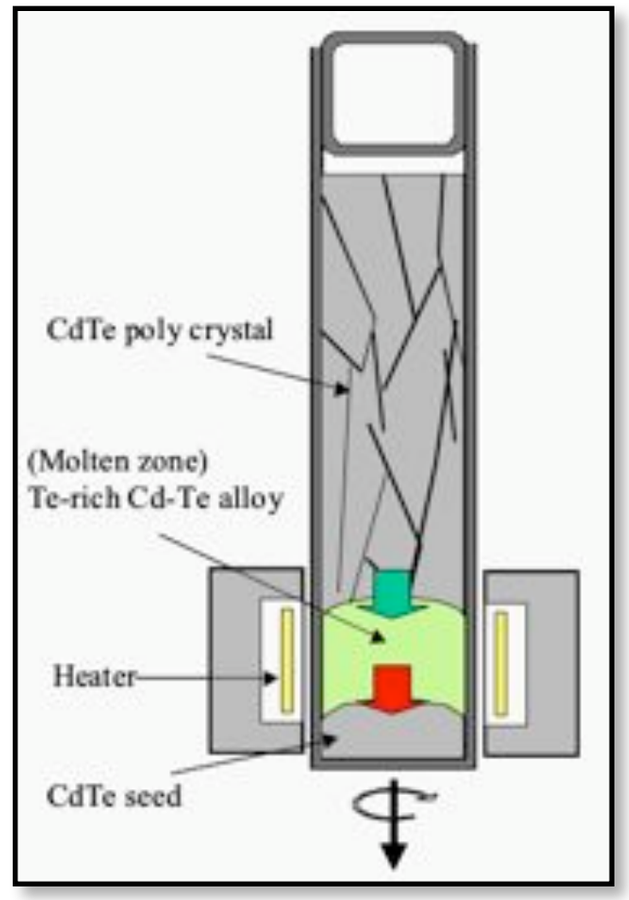
- High Resistivity ~ 10^9 Ωcm

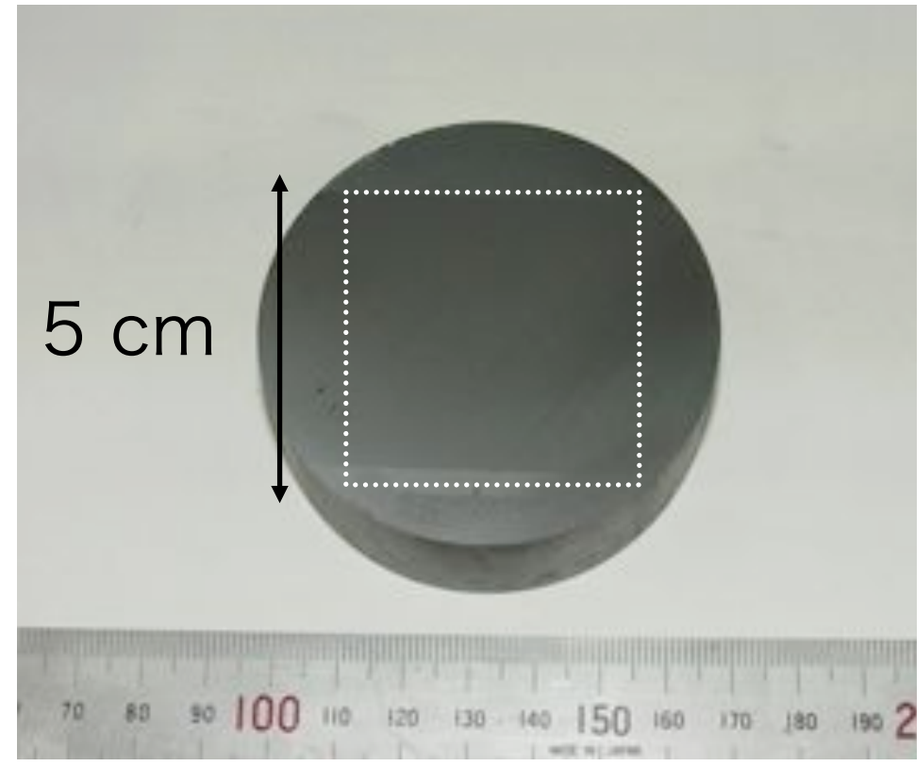
Promising for Hard X-ray Imagers for Astrophysics or Medicine

Recent Achievements of Crystal Growth

Traveling Heater Method (THM) by ACRORAD







Large Wafer of Single Crystal

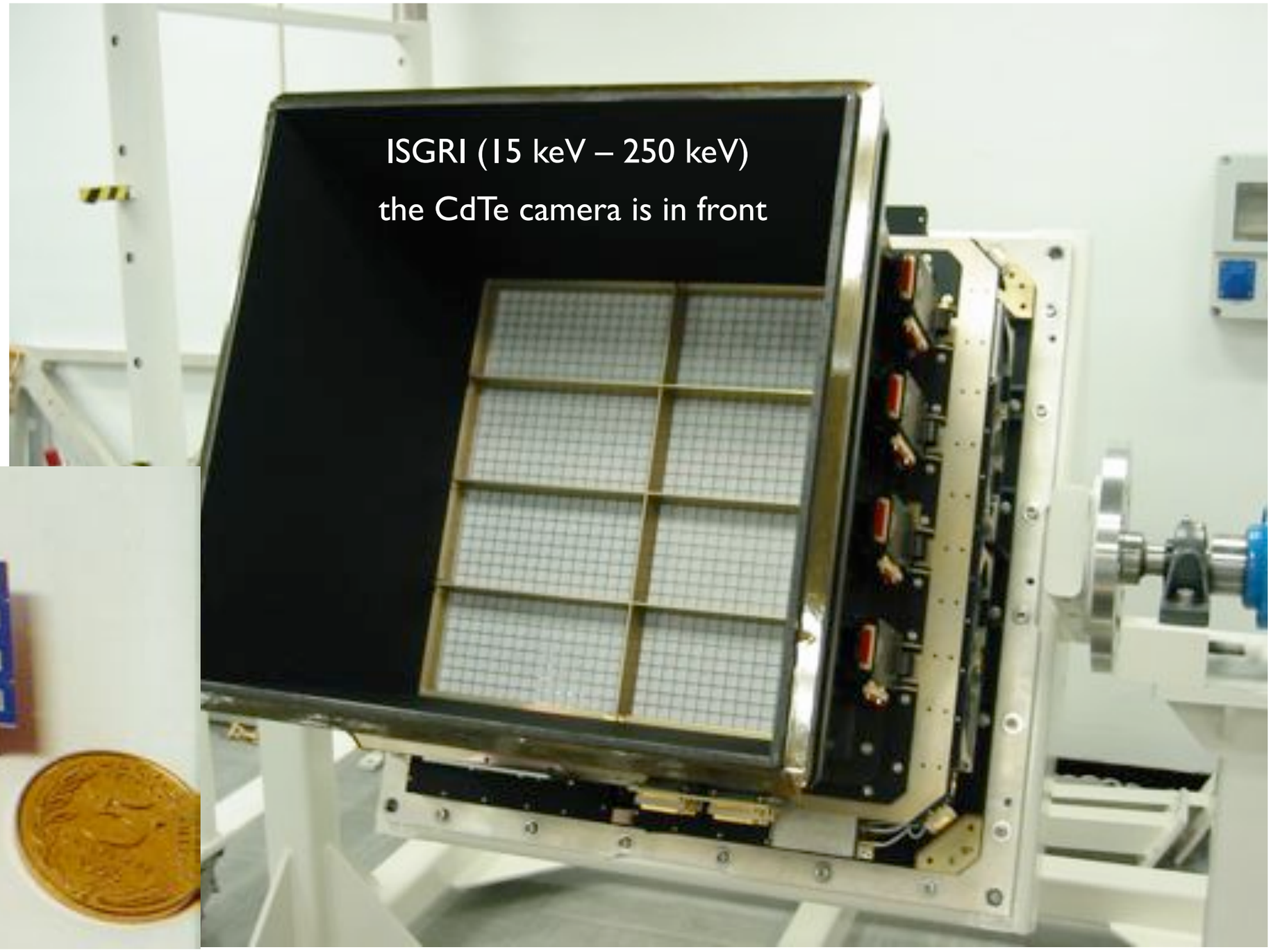
High Uniformity !! (Important Feature for Imagers)

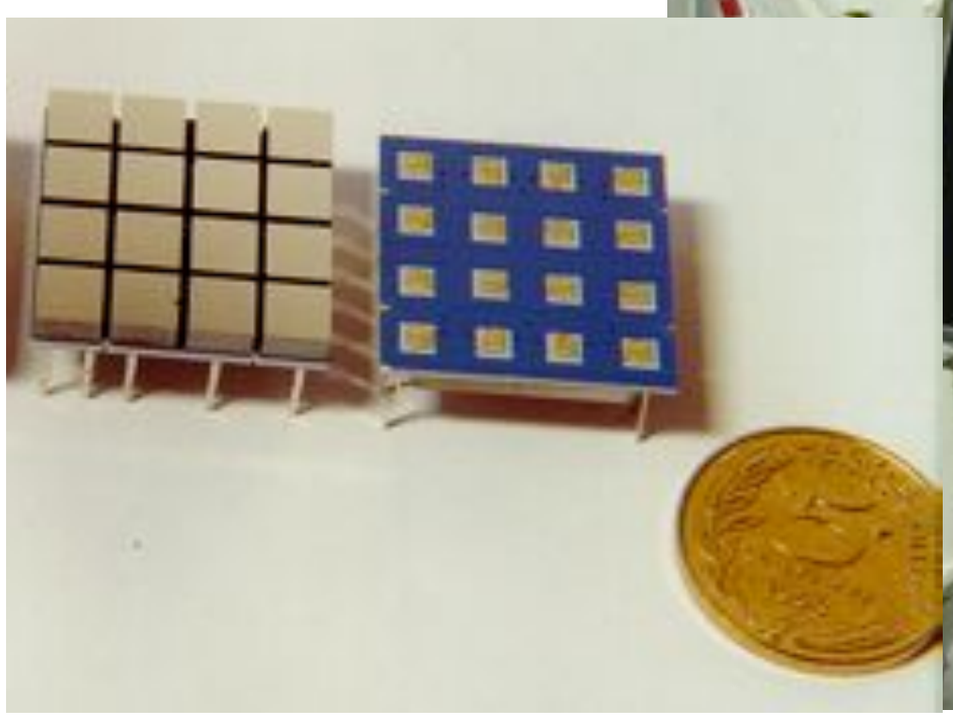
Example of Astrophysical Use

INTEGRAL IBIS
(Launched in 2004)

First large (60×60 cm) CdTe gamma camera
(16384 planar CdTe THM detectors 4×4×2 mm)

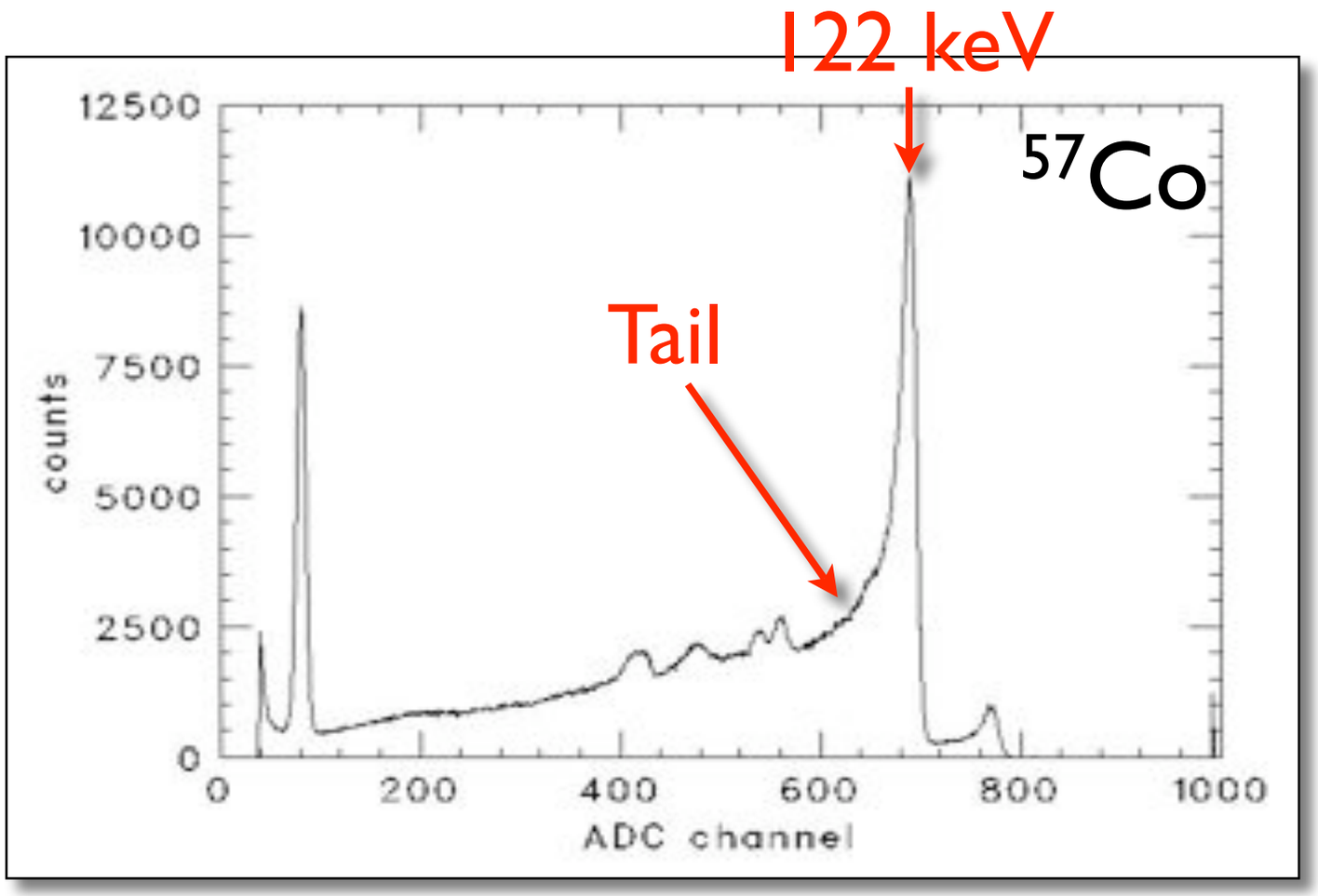
Field of view : 19° FWHM
Angular resolution : 12'
Energy range : 15 keV- 250 keV
Energy resolution : 9 % (60 keV)
Time resolution : 100 µsec

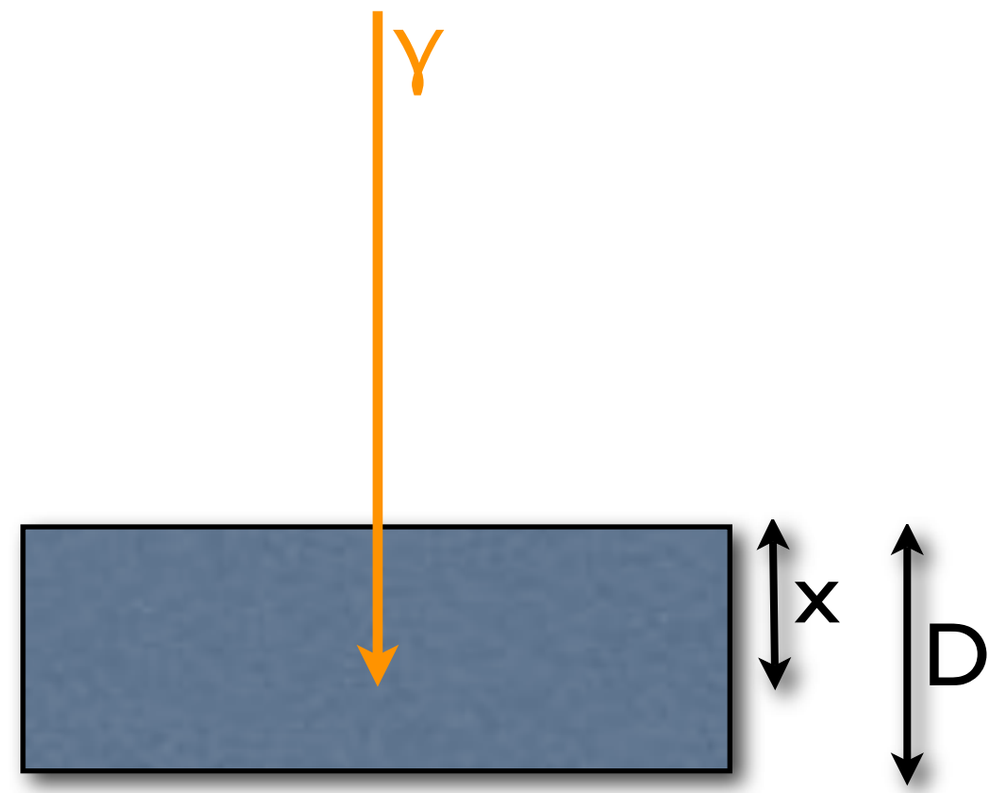




Development of CdTe Diode Detectors

Poor Charge Collection Efficiency





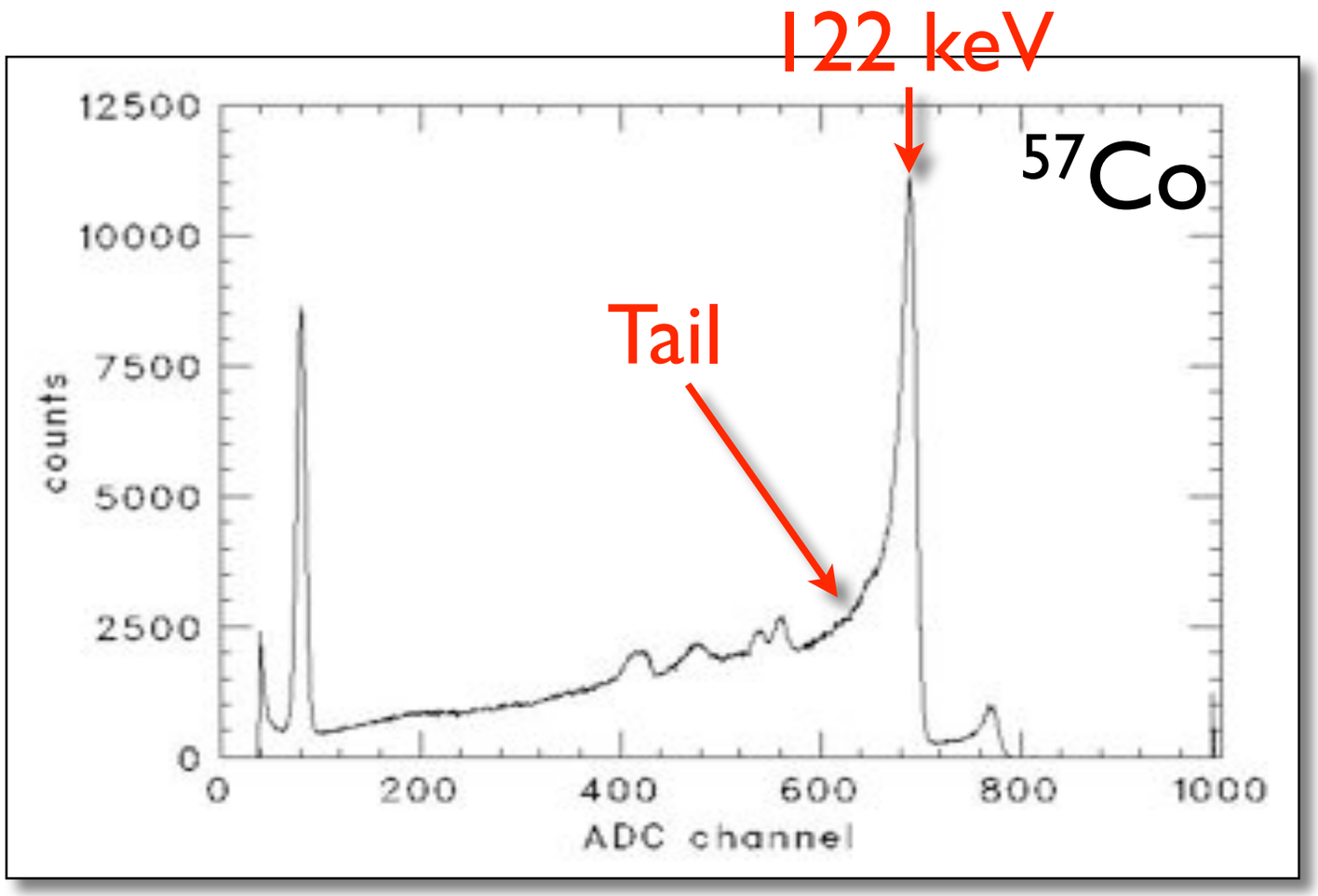
$$PH \propto (\mu\tau)_e E \left\{1 - \exp\left(-\frac{D-x}{(\mu\tau)_e E}\right)\right\} + (\mu\tau)_h E \left\{1 - \exp\left(-\frac{x}{(\mu\tau)_h E}\right)\right\}$$

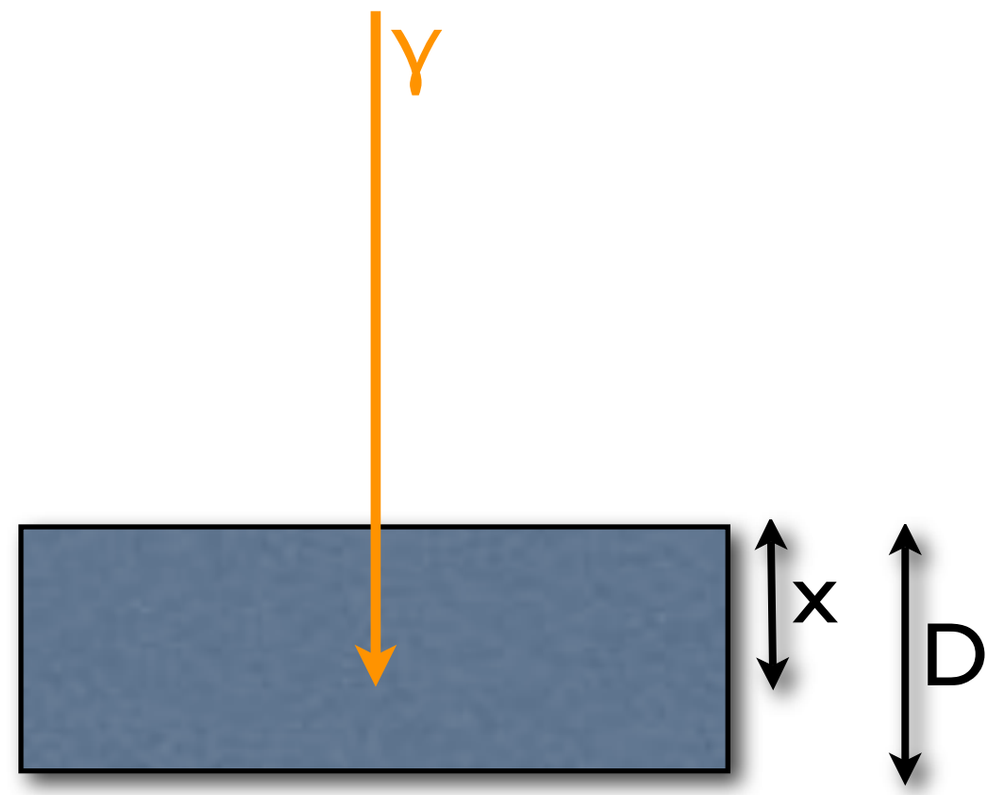
CdTe: $(\mu\tau)_e = 2\times10^{-3}$ cm^2/V, $(\mu\tau)_h = 1\times10^{-4}$ cm^2/V

cf.) Si: $(\mu\tau)_e = 0.42$ cm^2/V, $(\mu\tau)_h = 0.22$ cm^2/V

The exponential terms are not negligible → Tail Structures

To Improve Energy Resolution...





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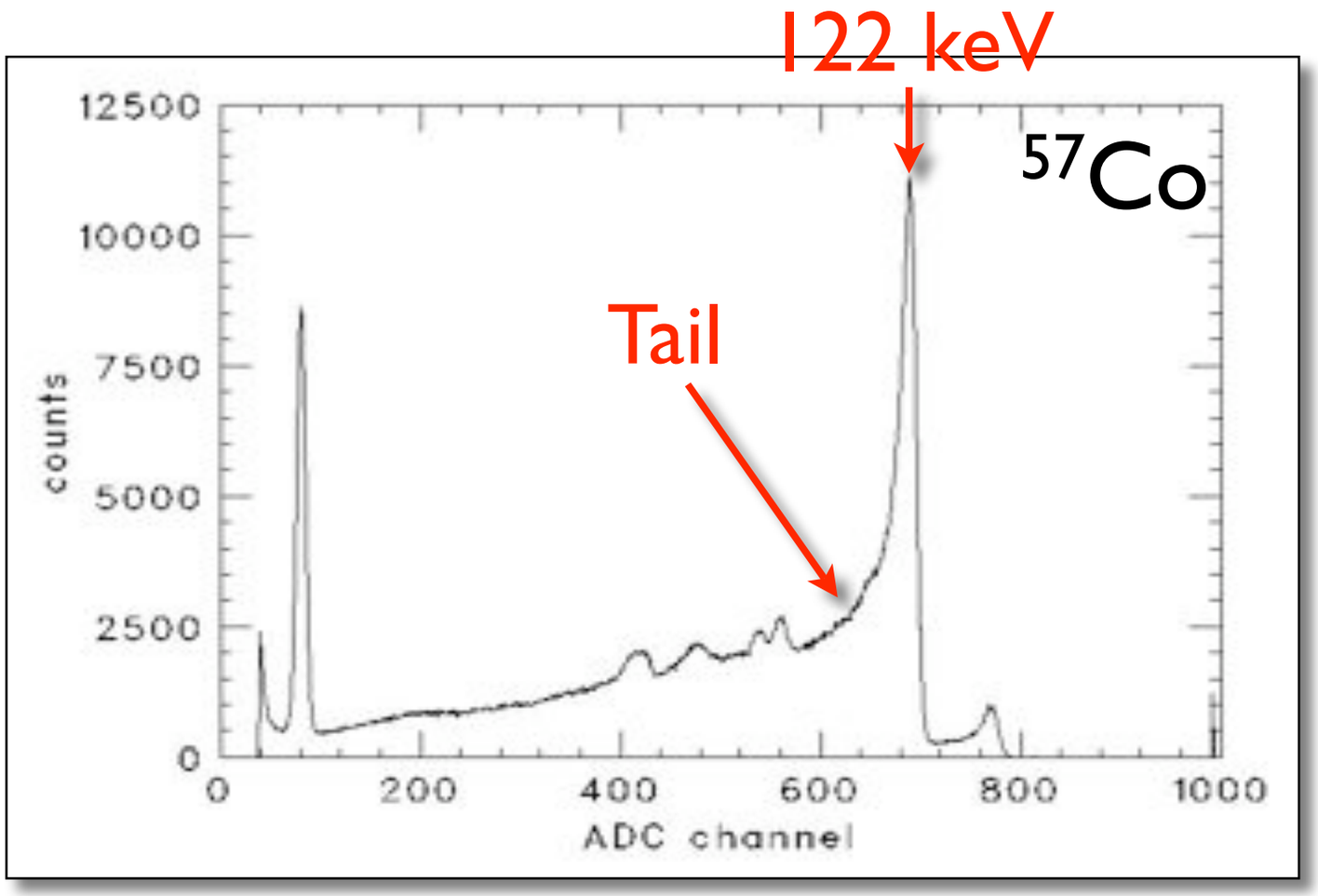
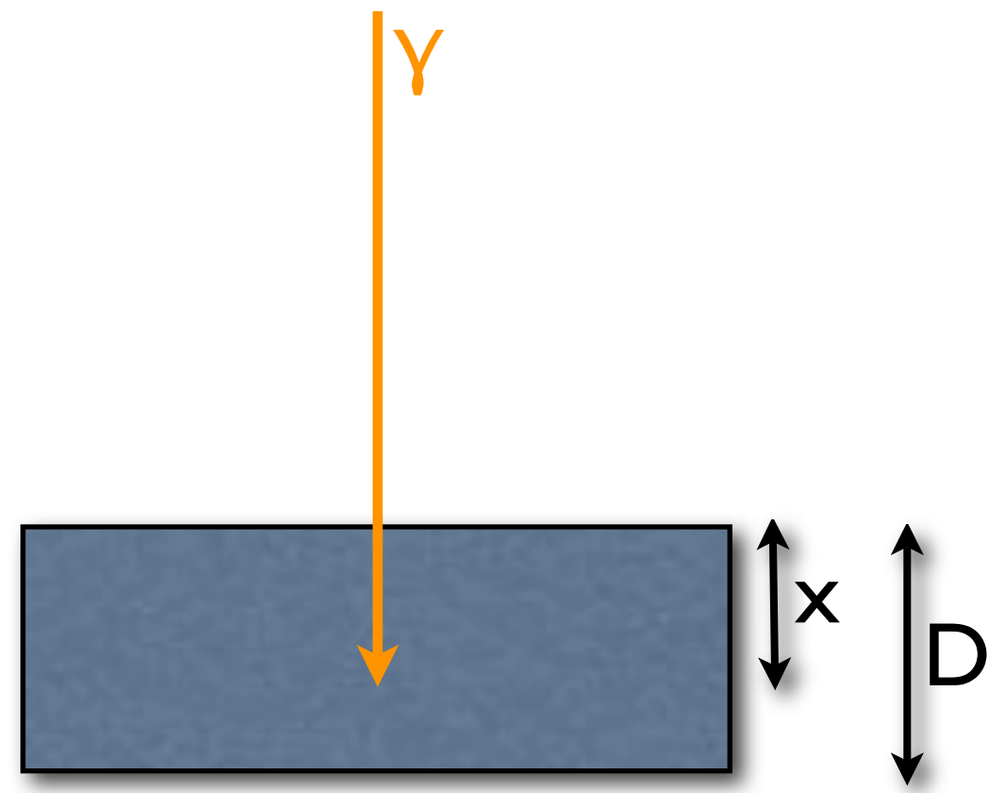
Sufficiently High E (Bias Voltage) up to μτE >> D

To Improve Energy Resolution...





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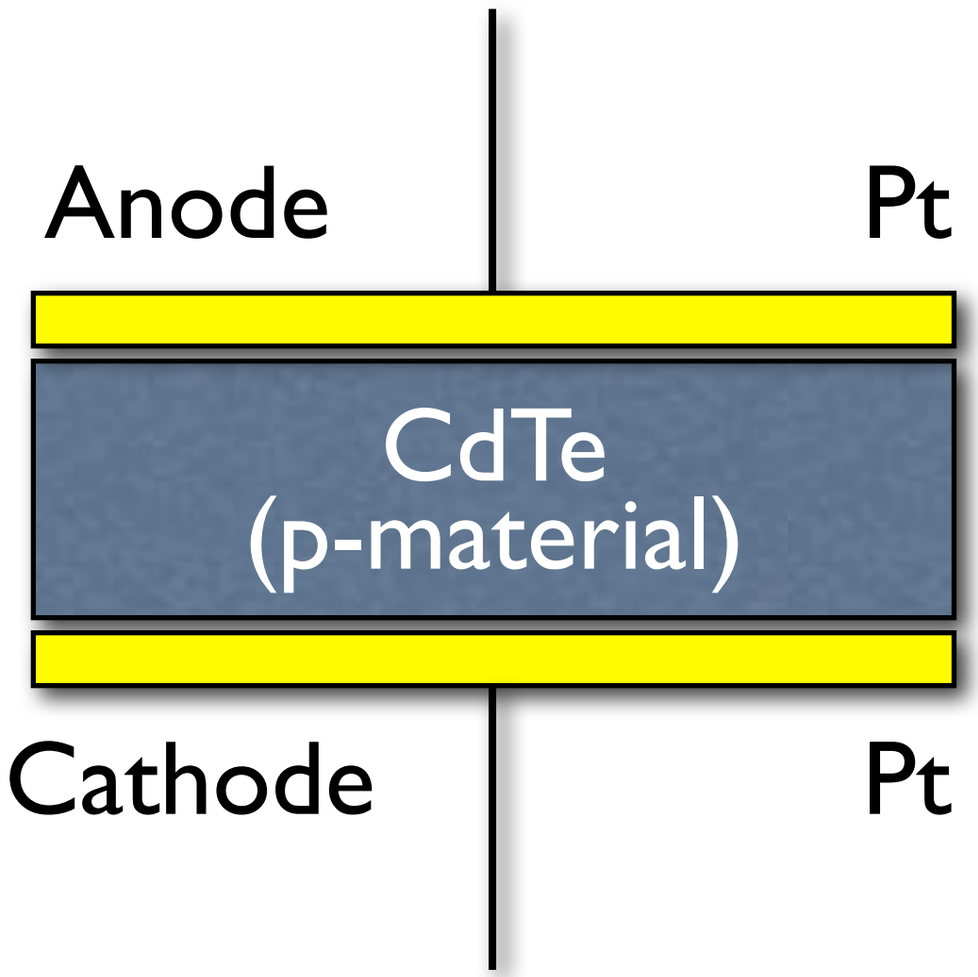
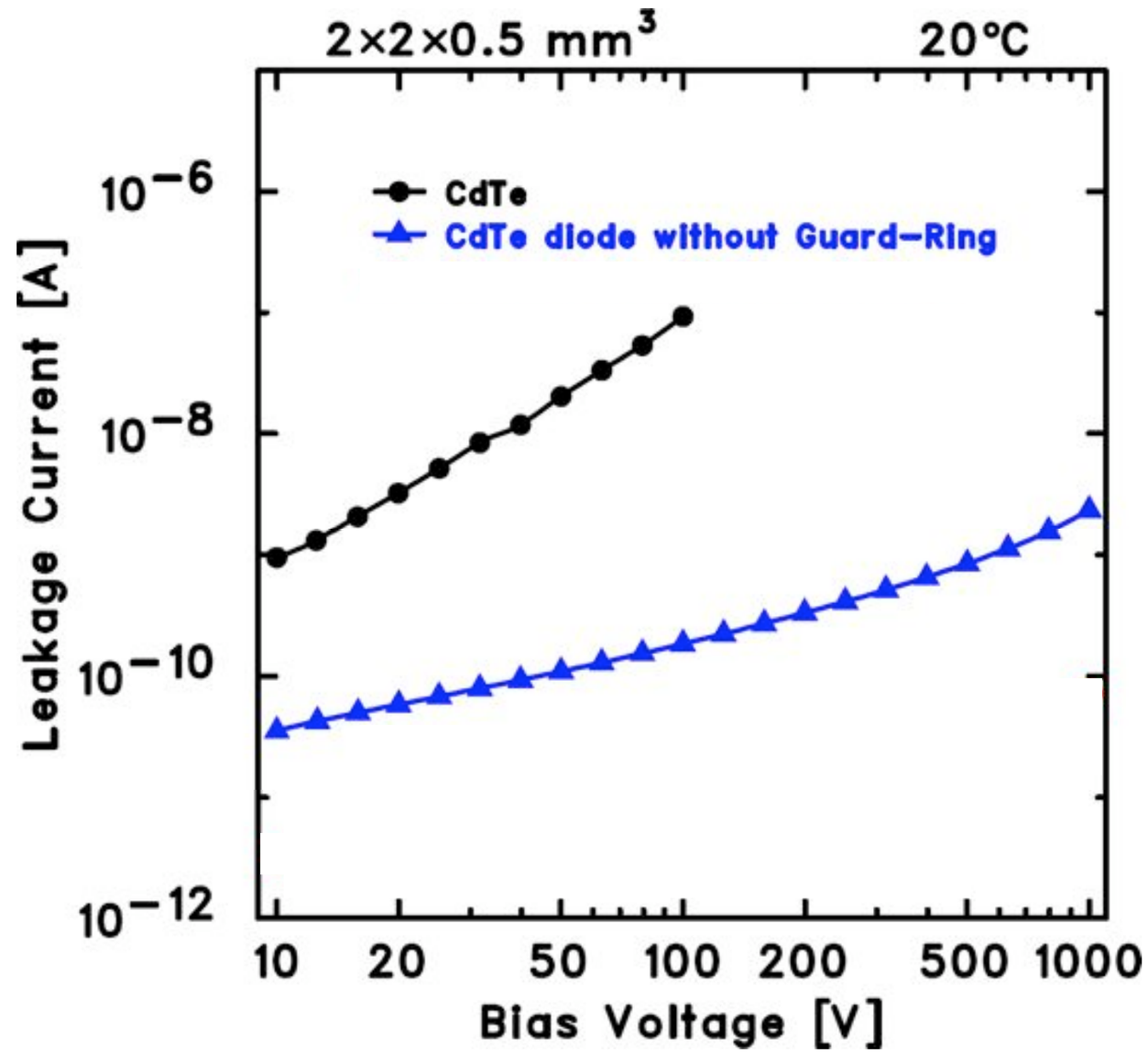
Sufficiently High E (Bias Voltage) up to μτE >> D

However, Low Leakage Current is Essential for Good ΔE

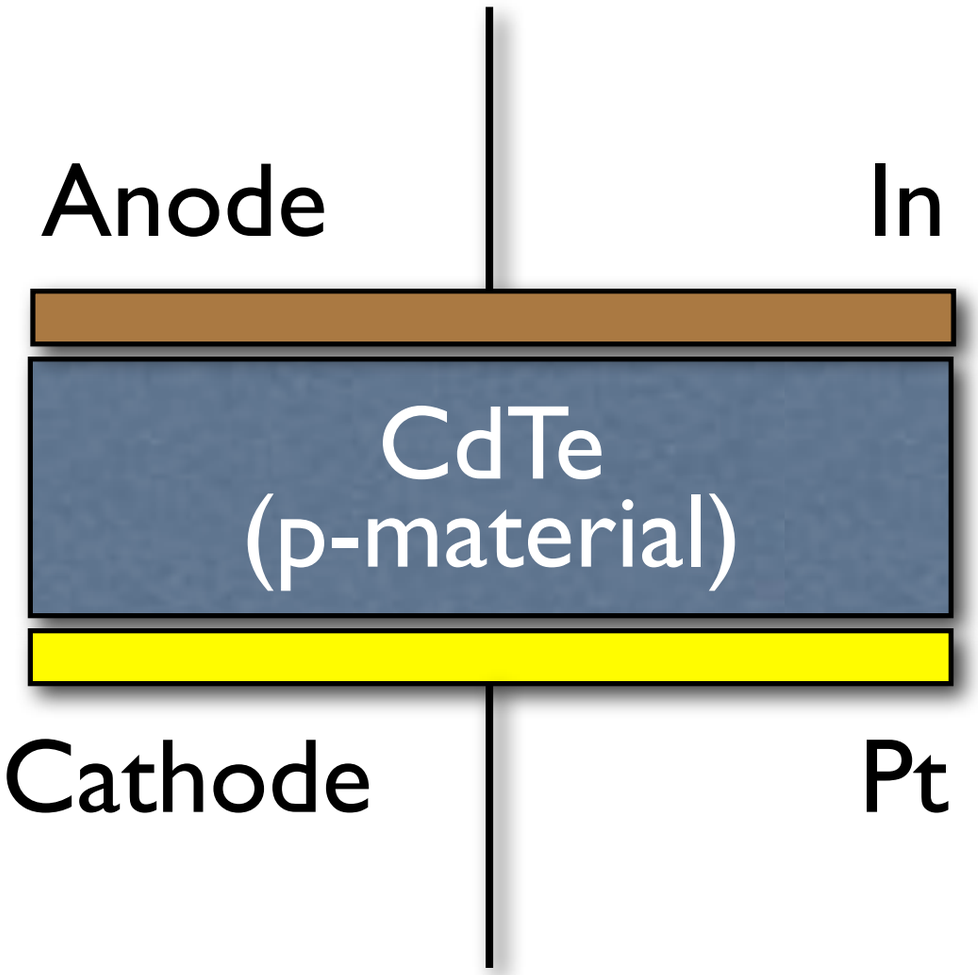
CdTe Schottky Diode

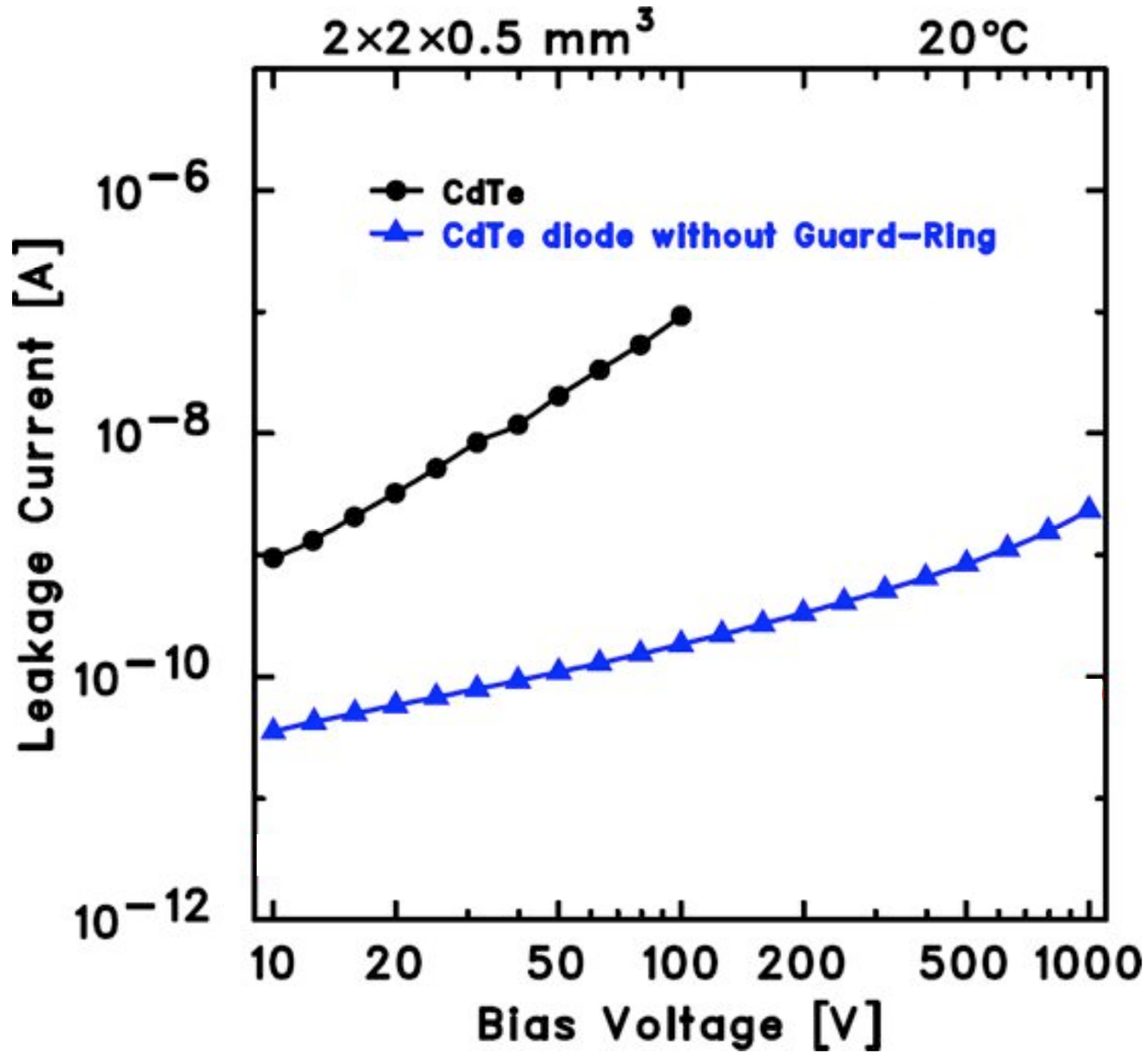




Use Indium (small work function) as the anode
→ Schottky barrier
Low Leakage Current

CdTe Schottky Diode





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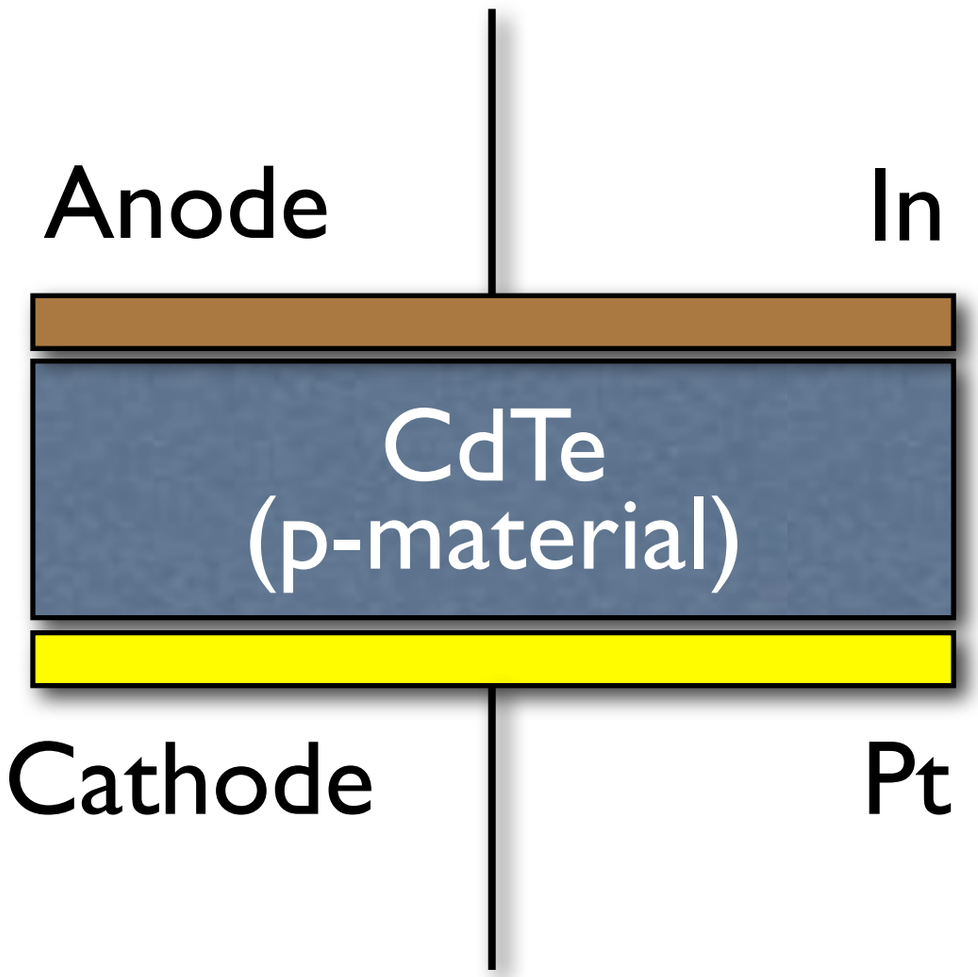
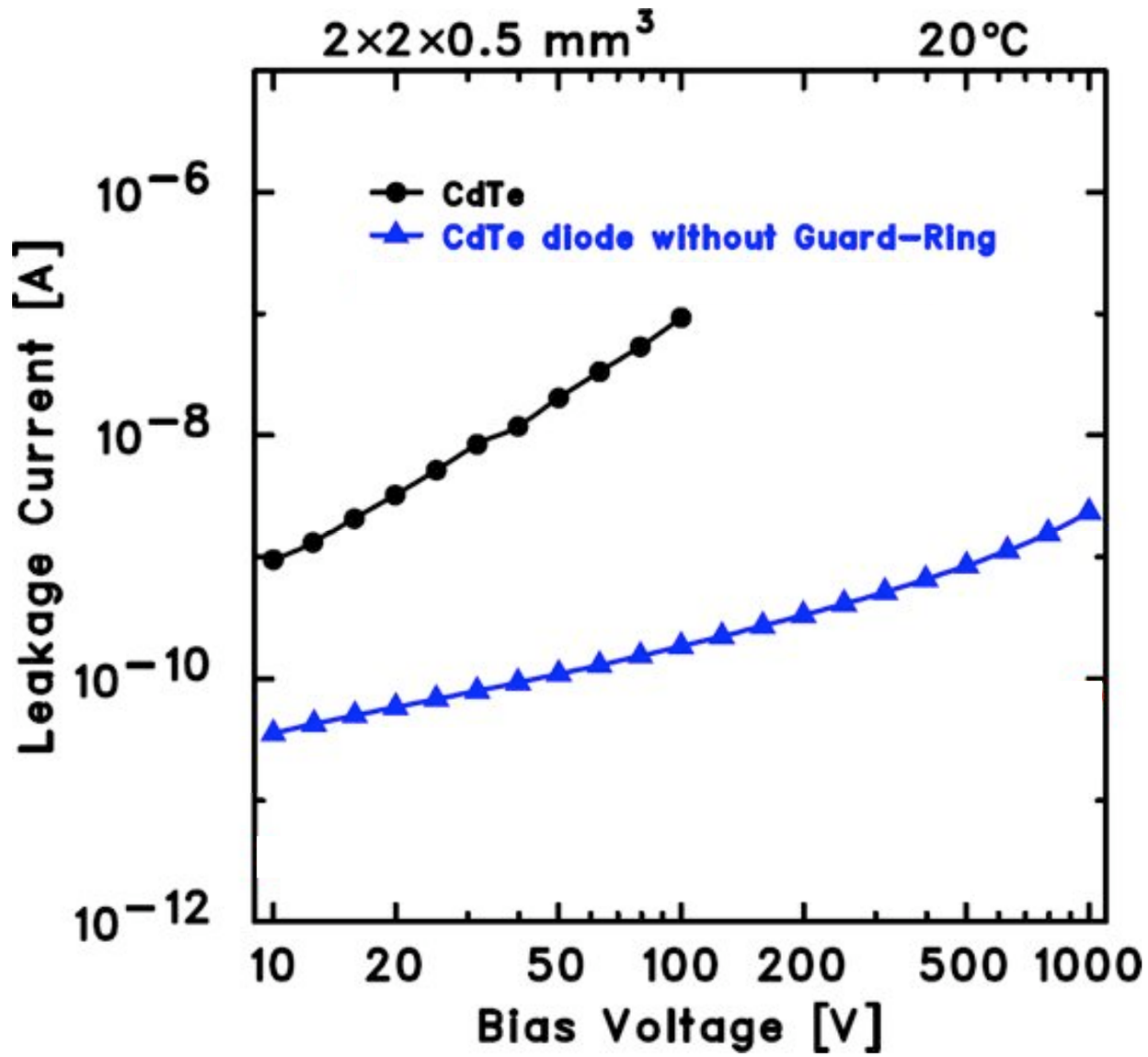
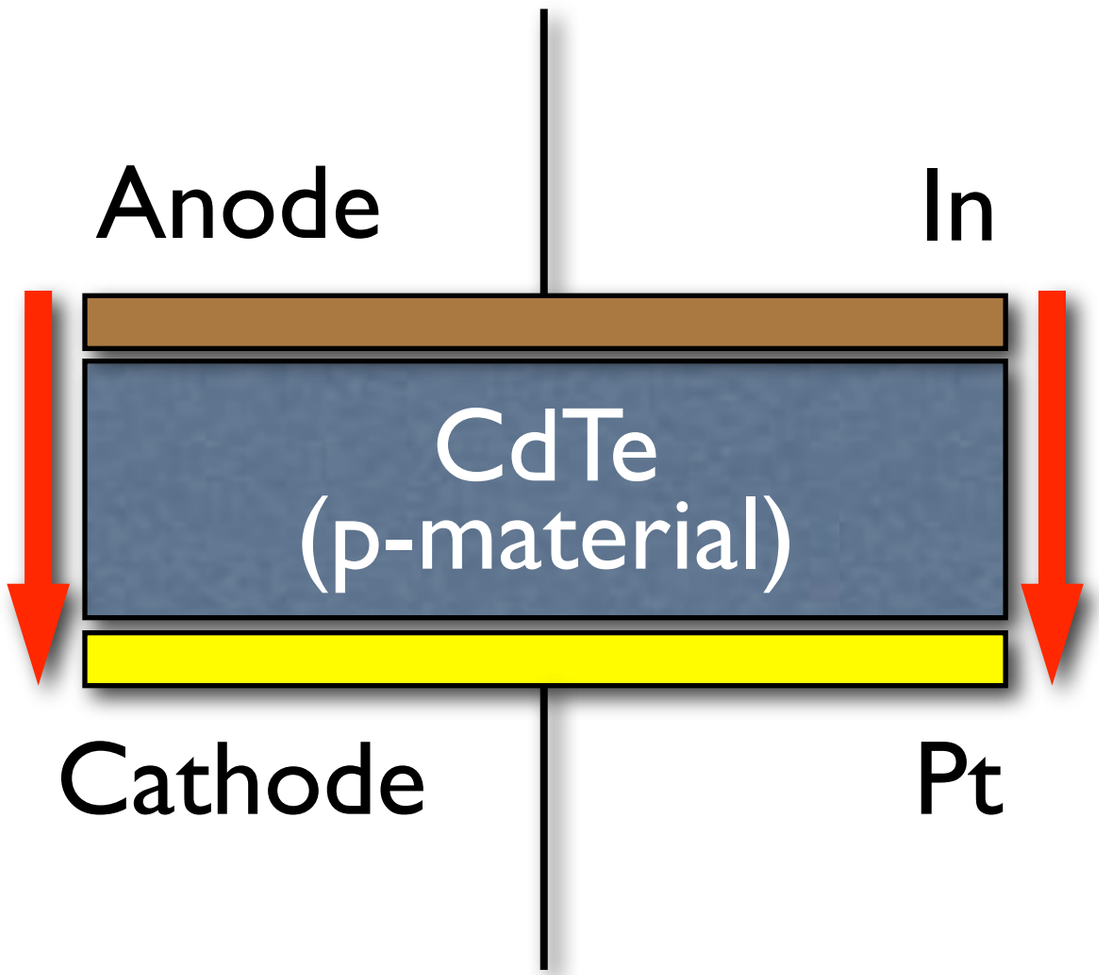
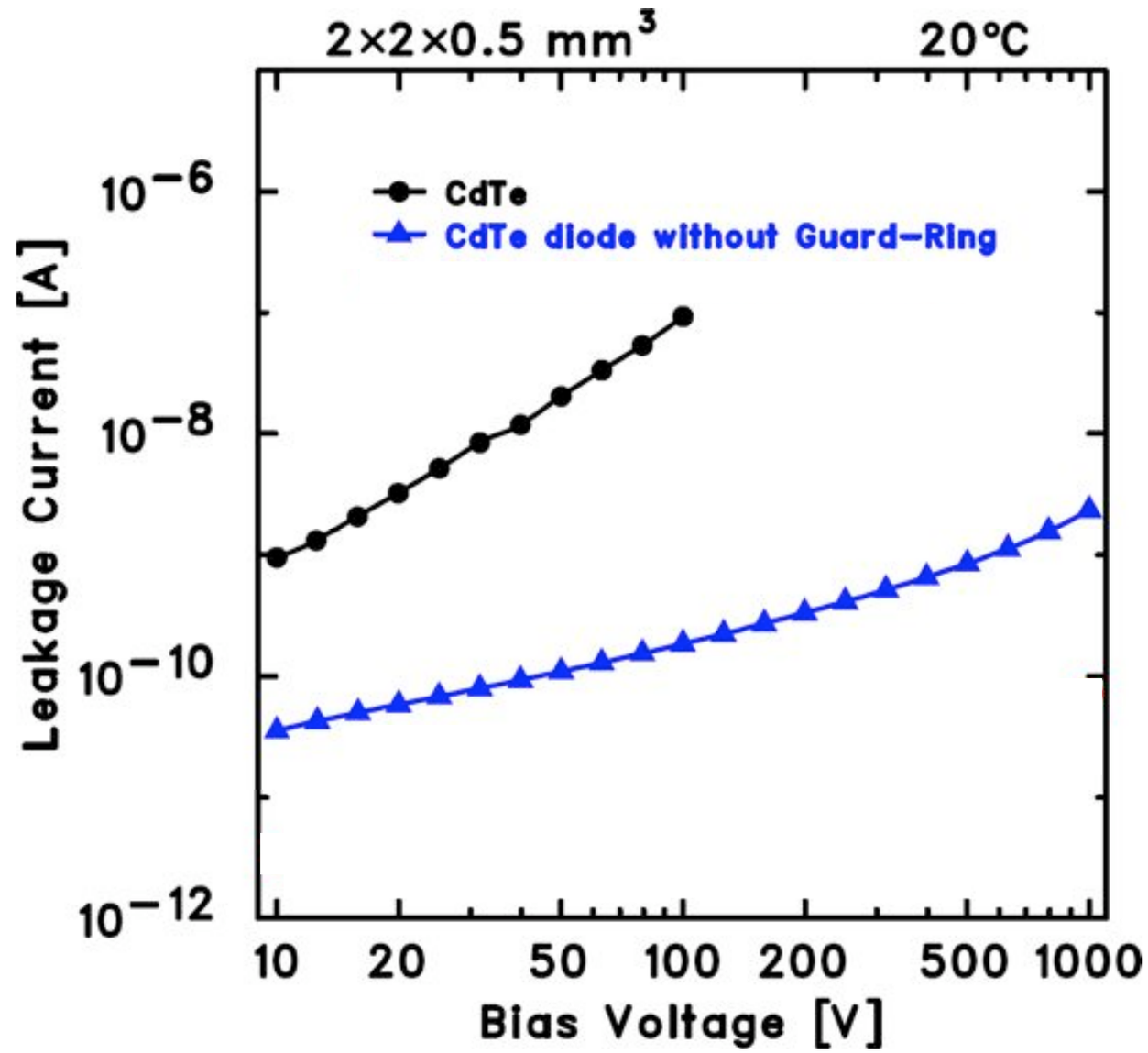




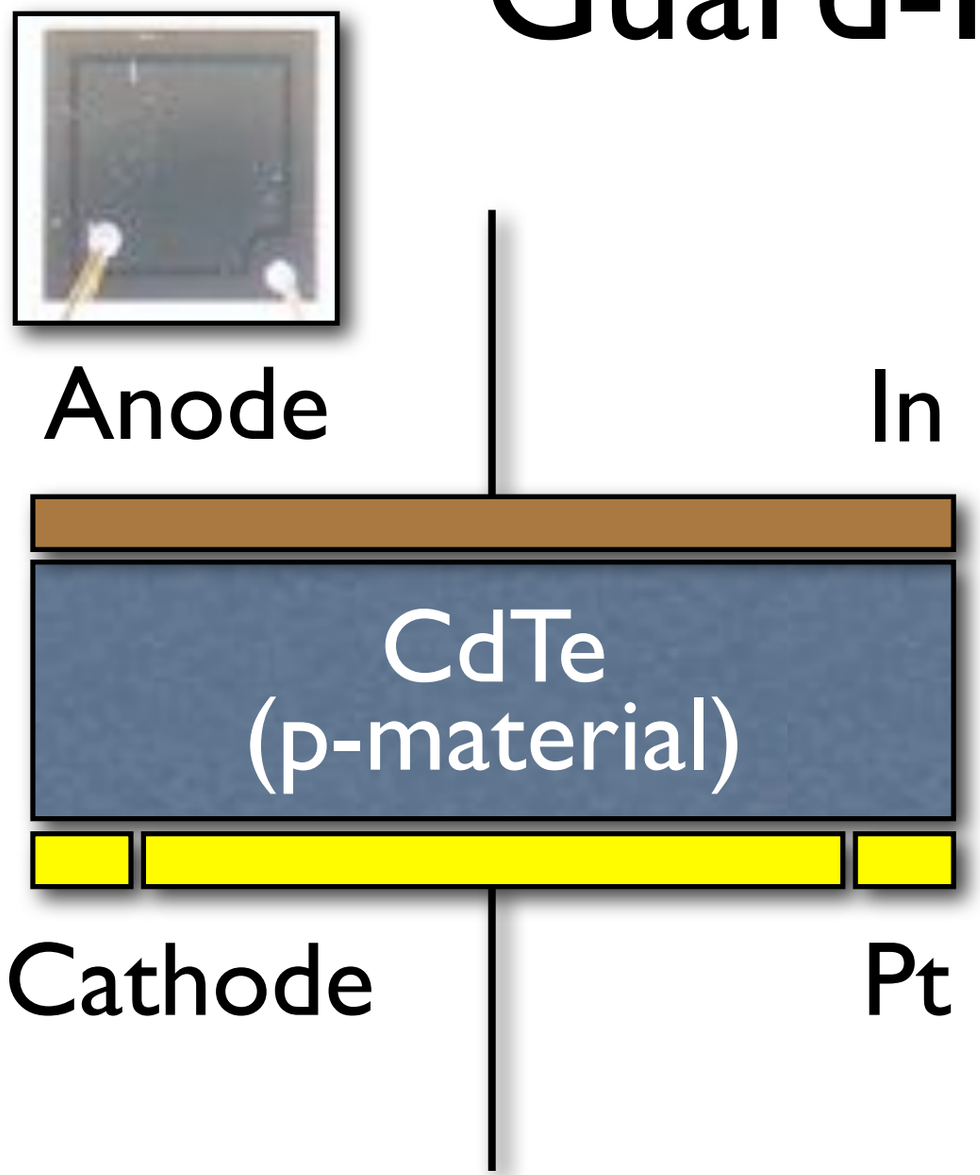
CdTe Schottky Diode

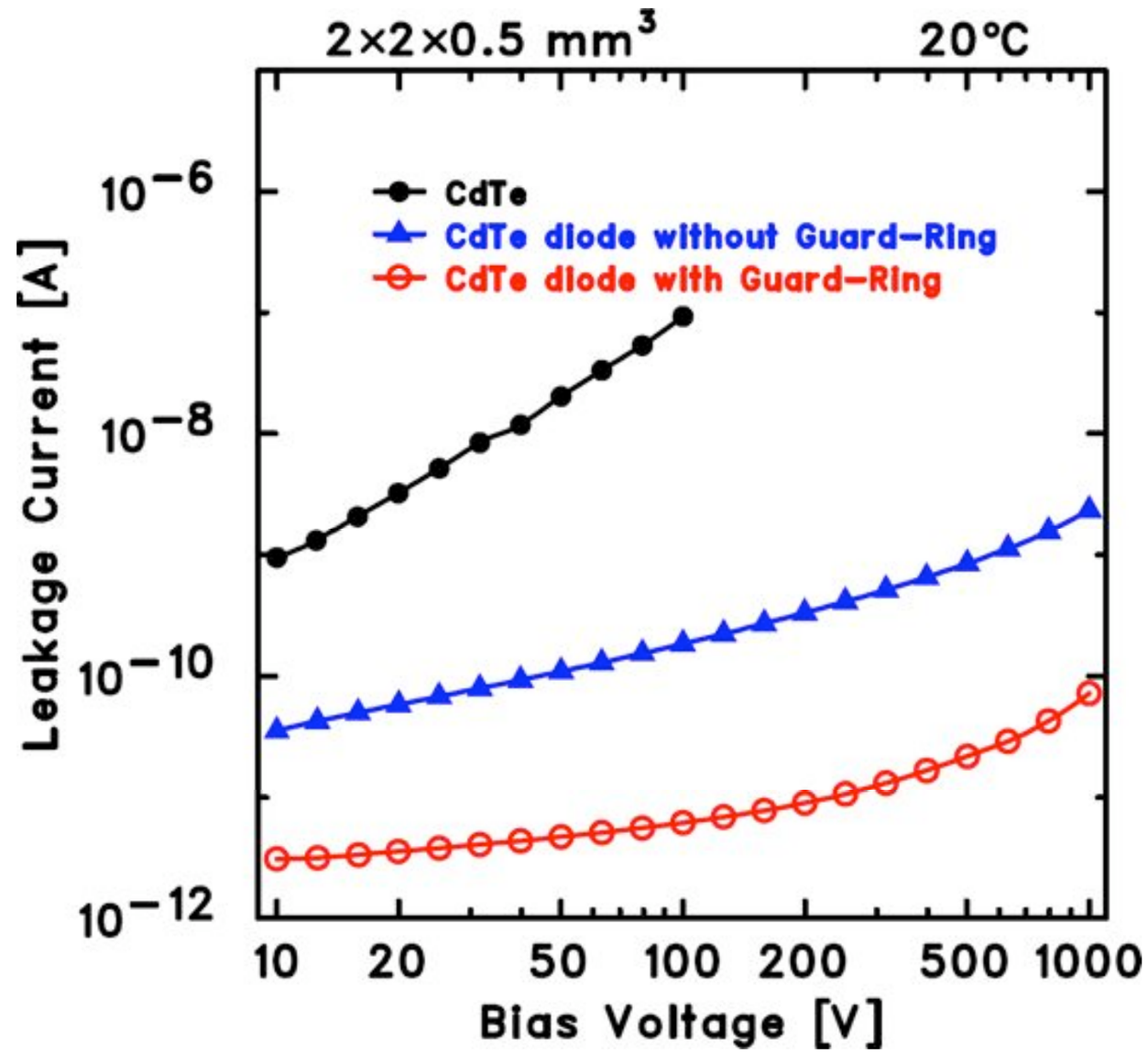




Most of the Leakage Current Flows through the Edges of the Device

Guard-Ring Structure

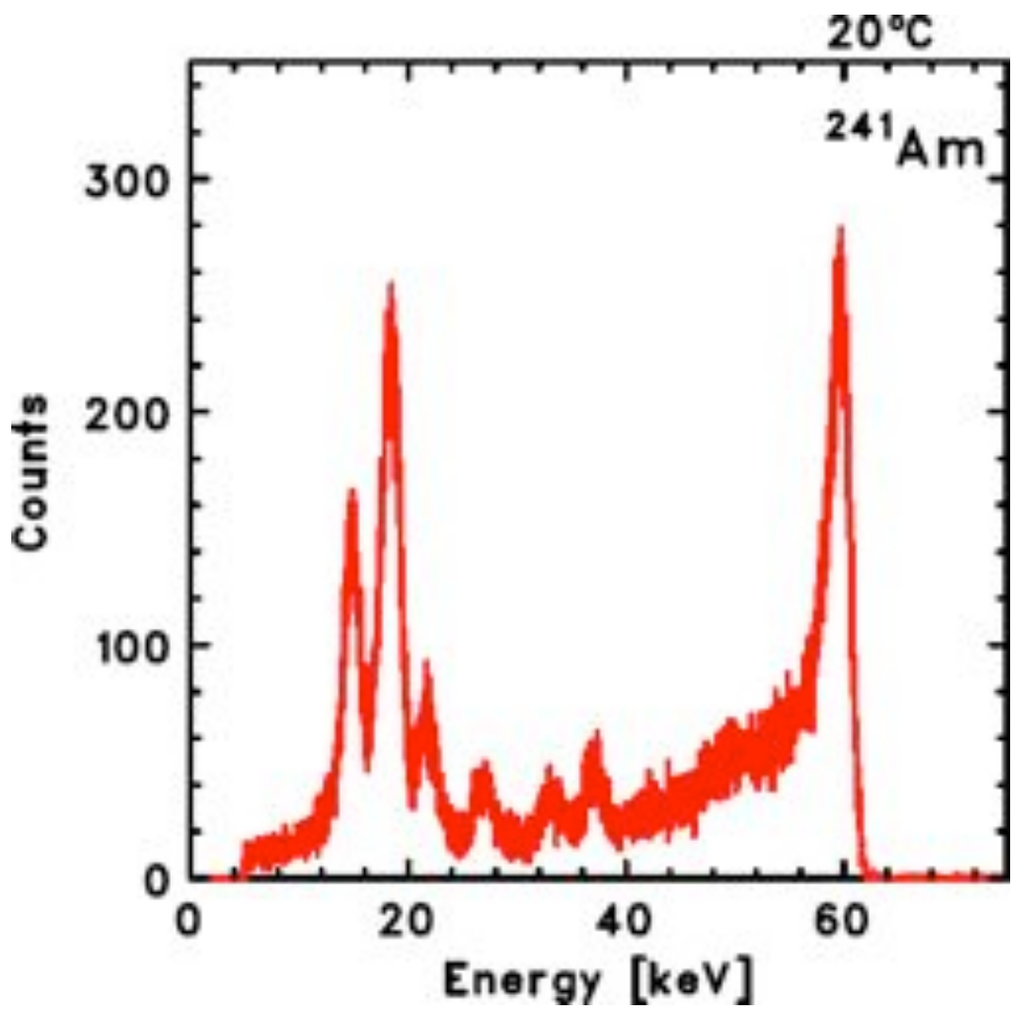




Extremely Low Leakage Current
→ Bias Voltage of 800 V for a 0.5 mm Thick Device
at Room Temperature

Spectral Performance of CdTe Diodes

Non-Diode



Spectral Performance of CdTe Diodes

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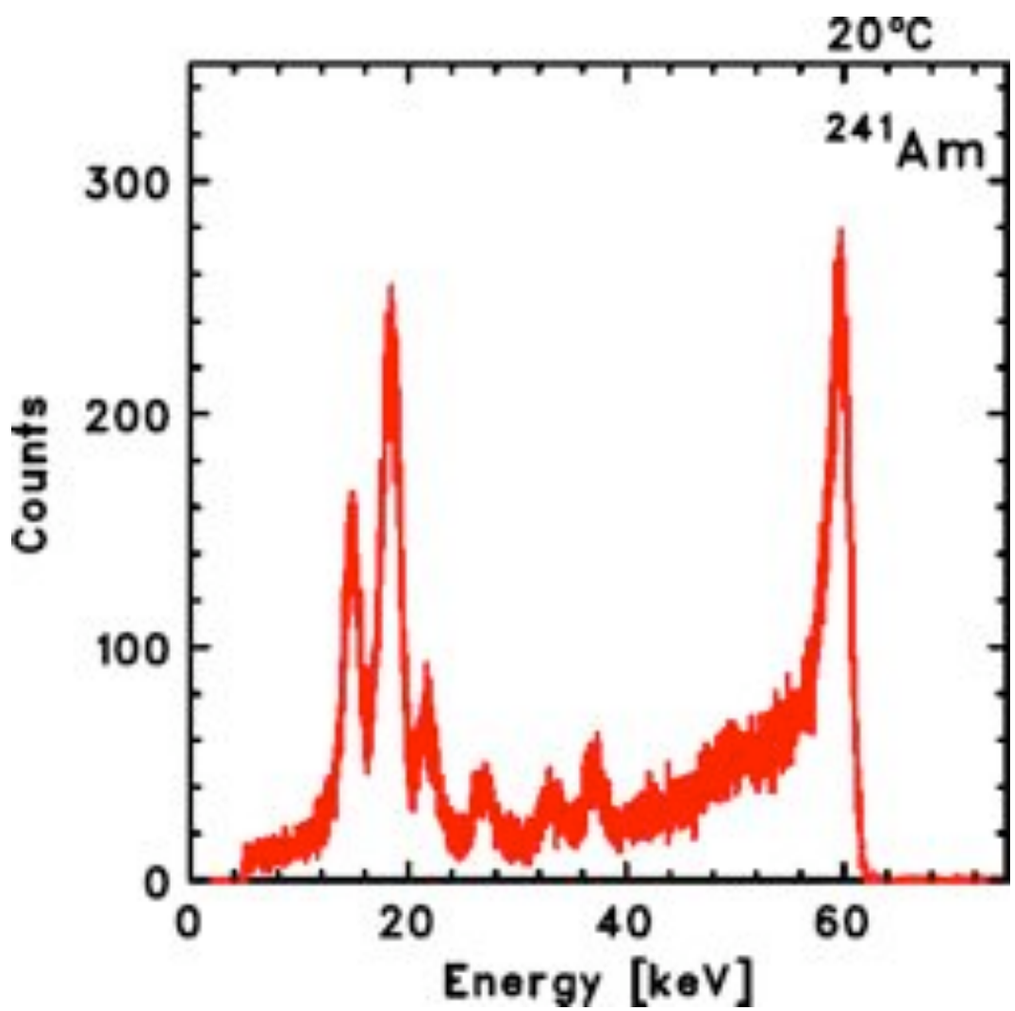
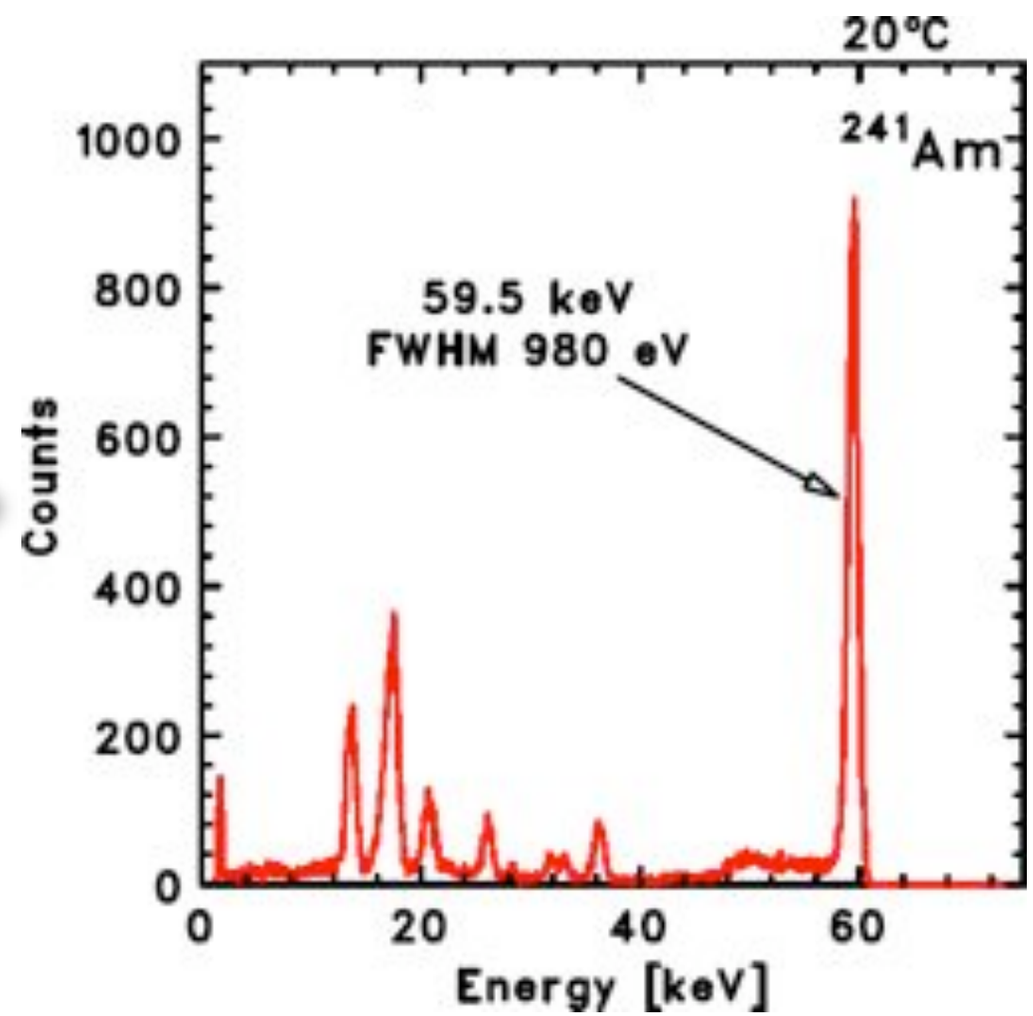
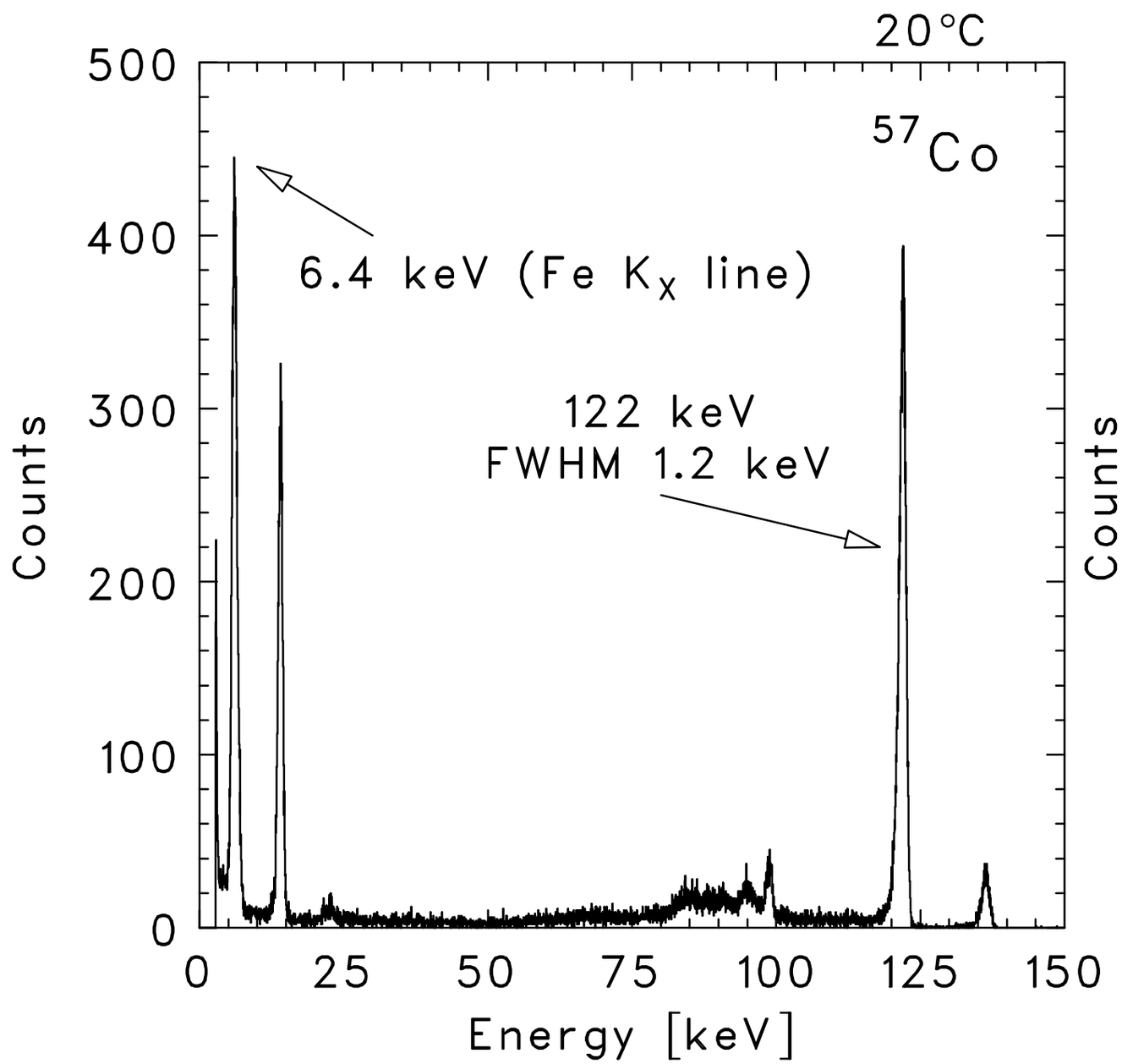


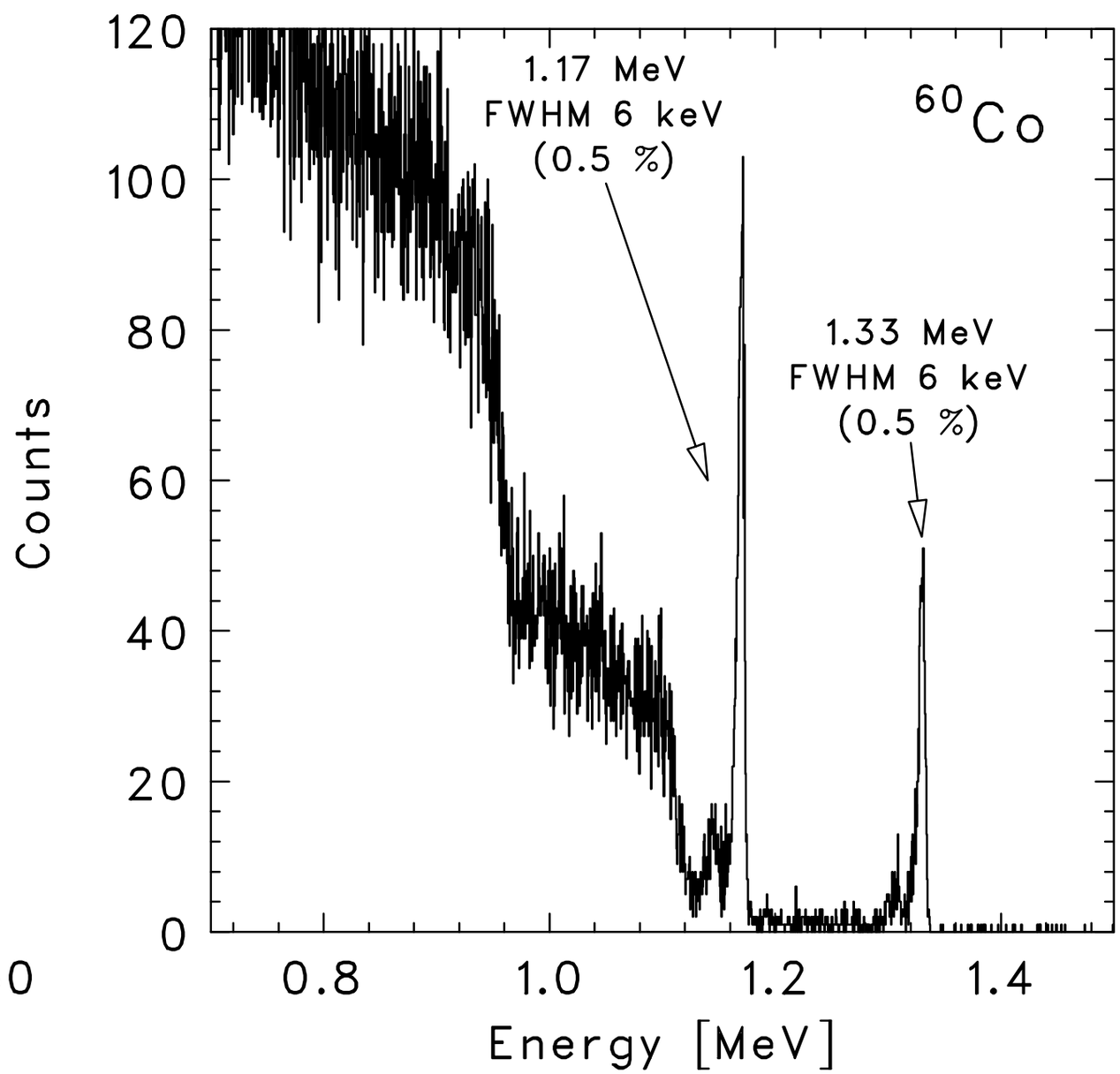
Diode



High Bias Voltage
→ Full Charge Collection (No Tail)!!

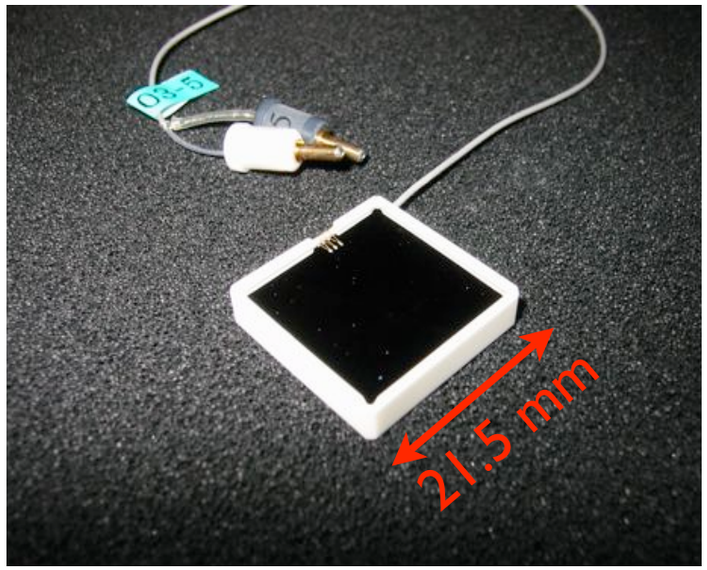
Spectral Performance of CdTe Diodes



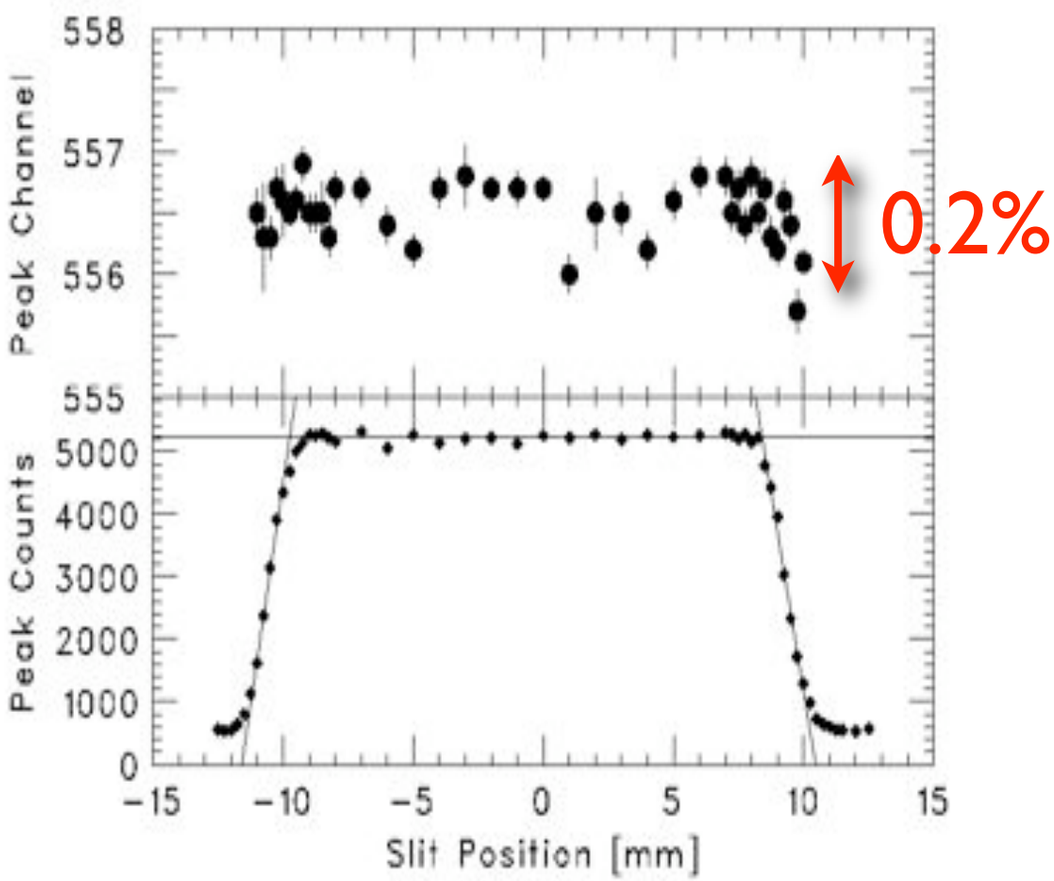


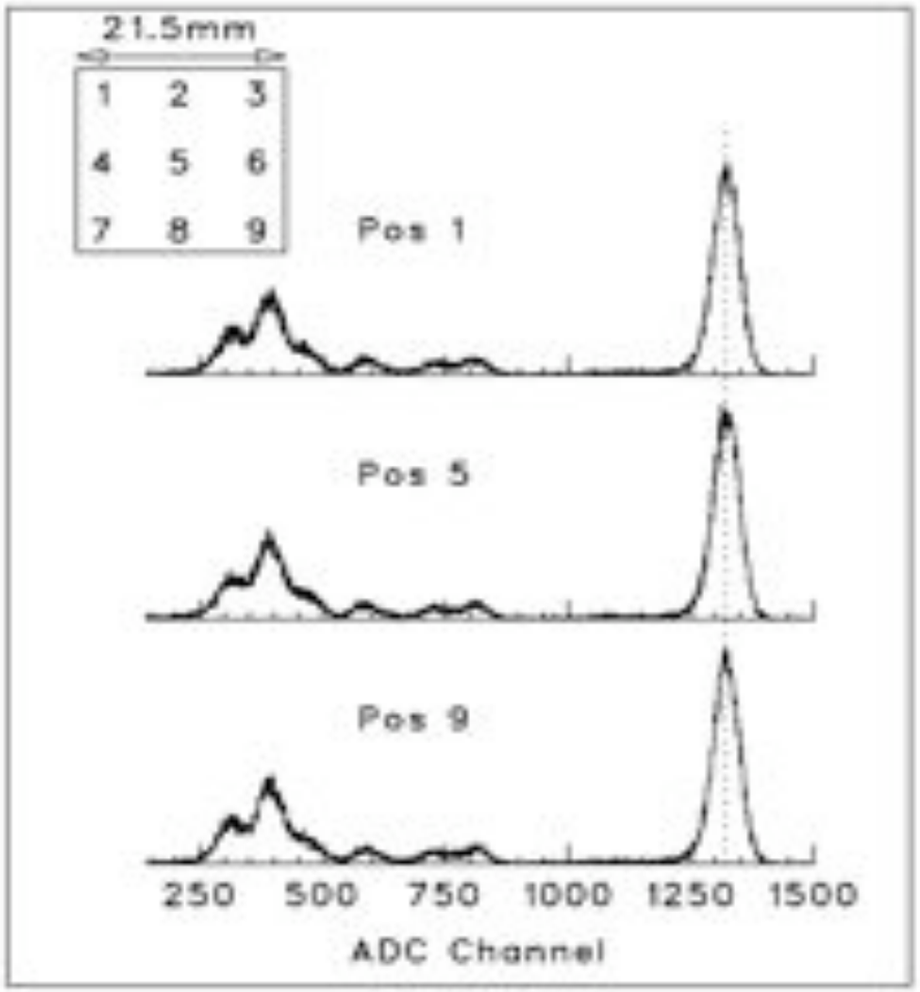
High Uniformity

Important Property for Imagers



High Uniformity was verified with our large-area device





Development of CdTe Pixel Detectors

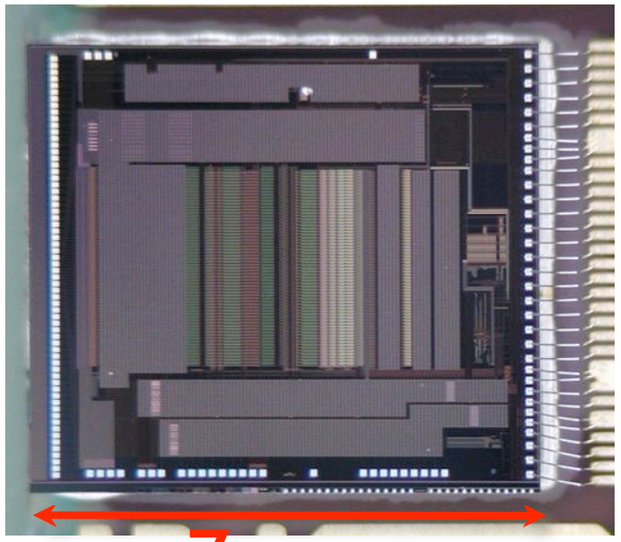
Pixel Detectors

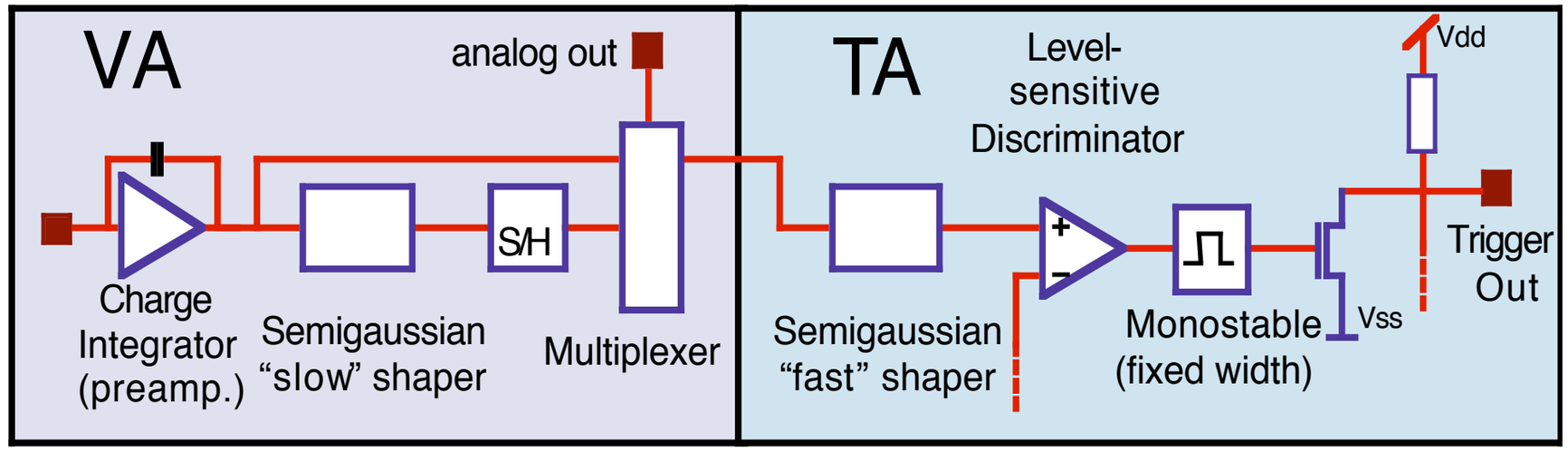
Key Technologies

- CdTe Devices with Good Energy Resolution and High Uniformity
- Analog ASICs
- Bump Bonding

Readout Analog ASIC

VA64TA: Development with IDEAS ASA, Norway



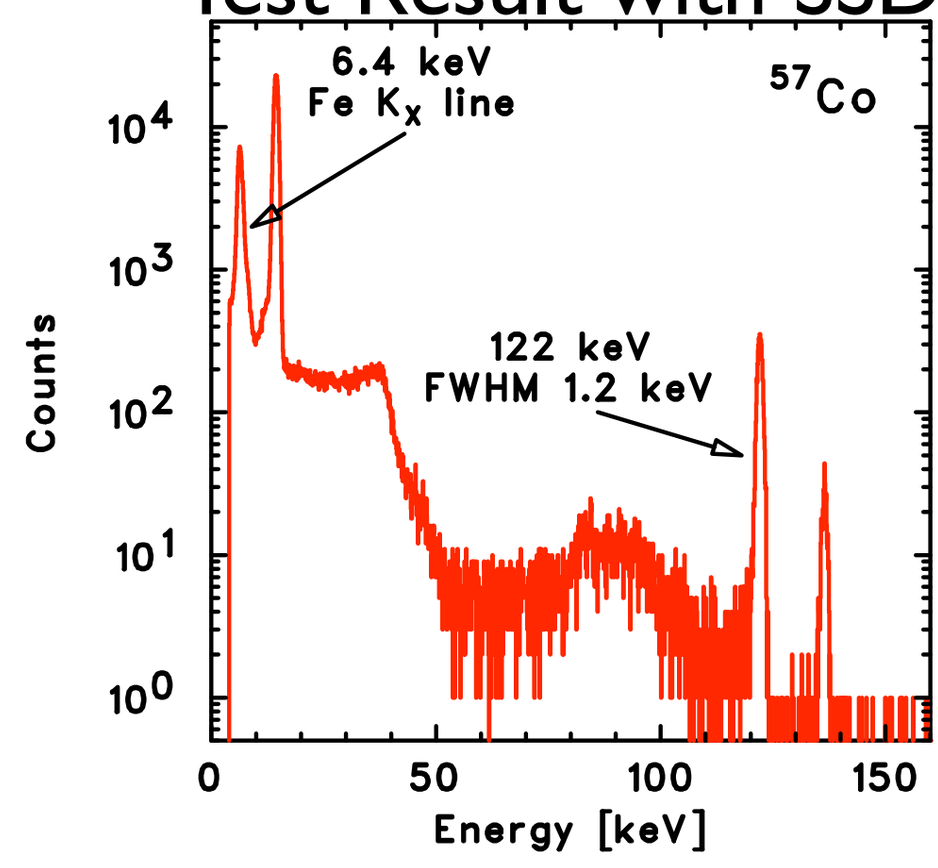


Peaking Time = 3–5 μs

Peaking Time = 600 ns

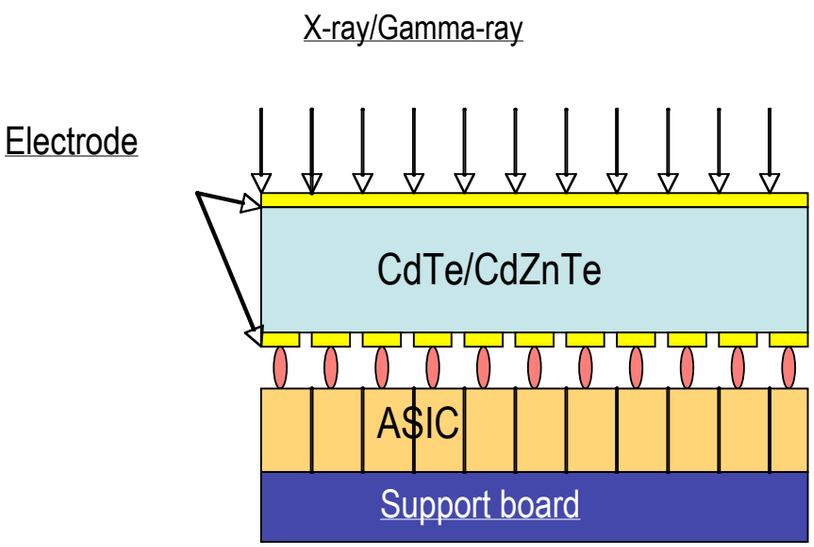
- Self Trigger Capability
- Good Noise Performance ($50e^-$ (RMS) @ 0pF)
- Low Power Dissipation (0.2 mW/channel)

Test Result with SSD

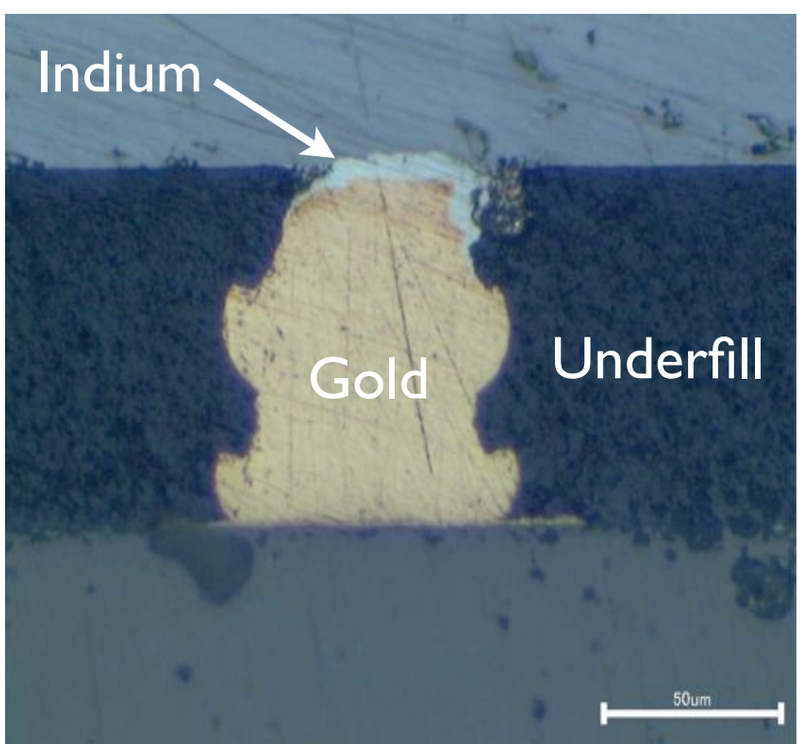


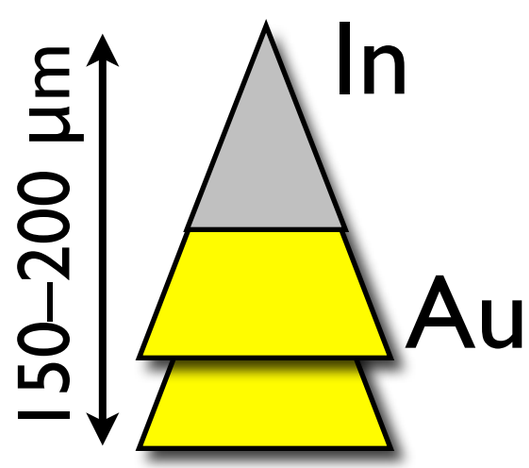
Bump Bonding

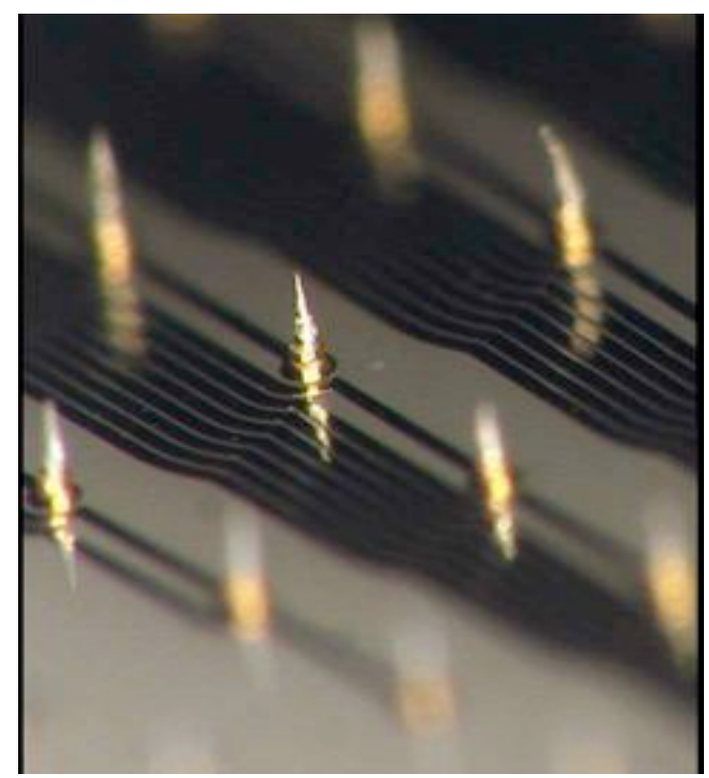
CdTe: Fragile against High Compression and High Temperature
Co-planarity is 2 μm at Most



Using Soft Metals:
Double Gold Studs with an Indium Topping

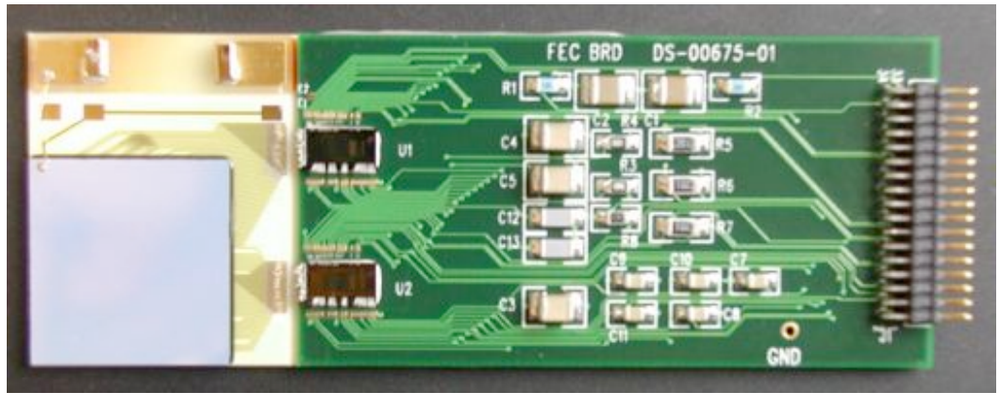




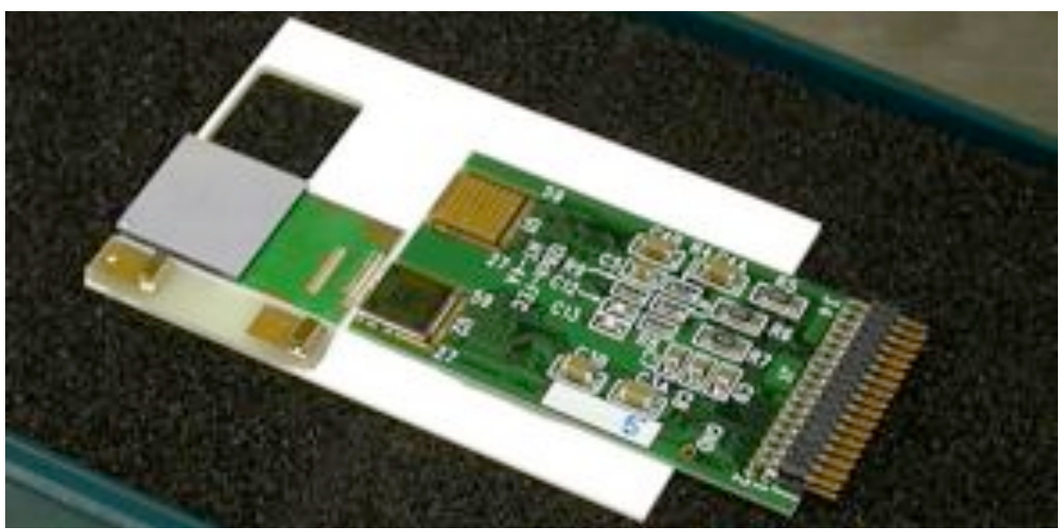


CdTe Pixel Detectors

8×8 Pixel Modules



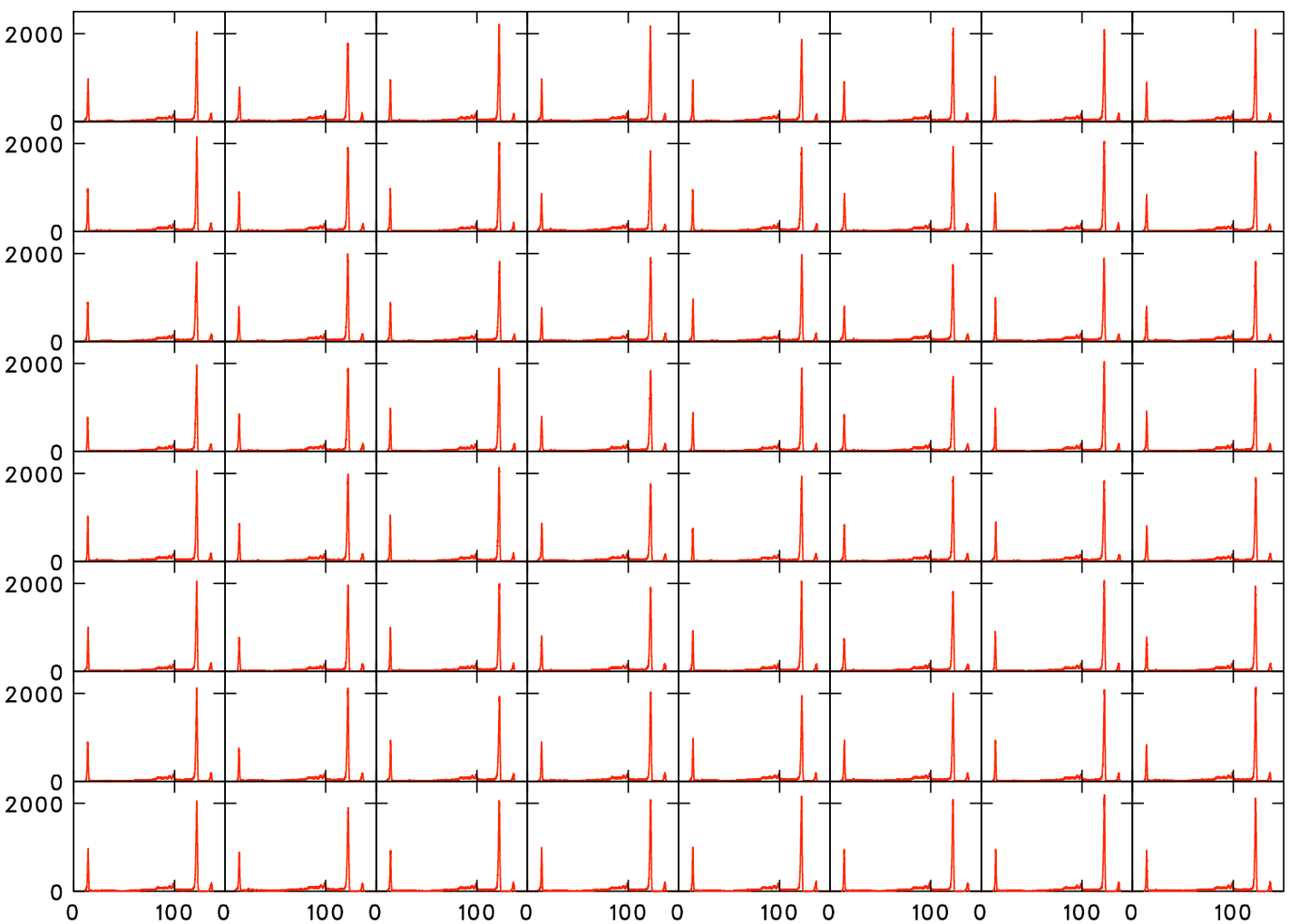
area: 18 × 18 mm^2
thickness: 0.5 mm
pixel size: 2 × 2 mm^2,
64 ch, cathode side
guard ring: 1 mm width

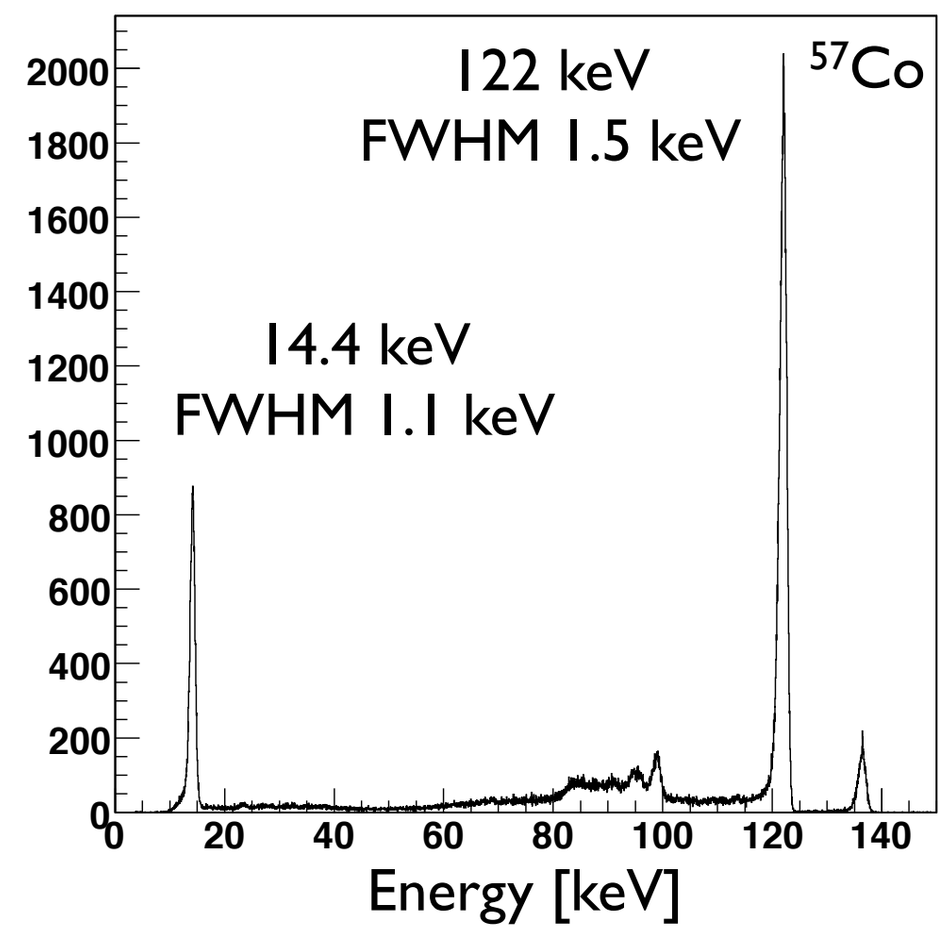


area: 11.2 × 11.2 mm^2,
thickness: 0.75 mm
pixel size: 1.35 × 1.35 mm^2,
64 ch, cathode side

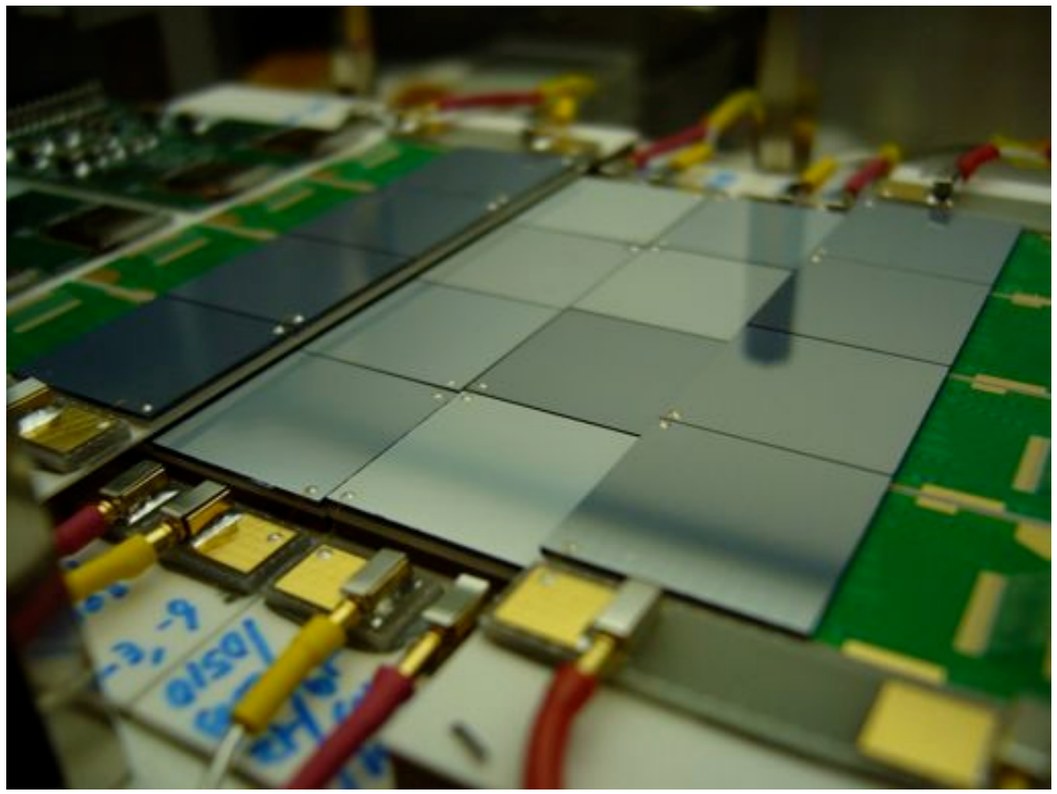
Spectral Performance

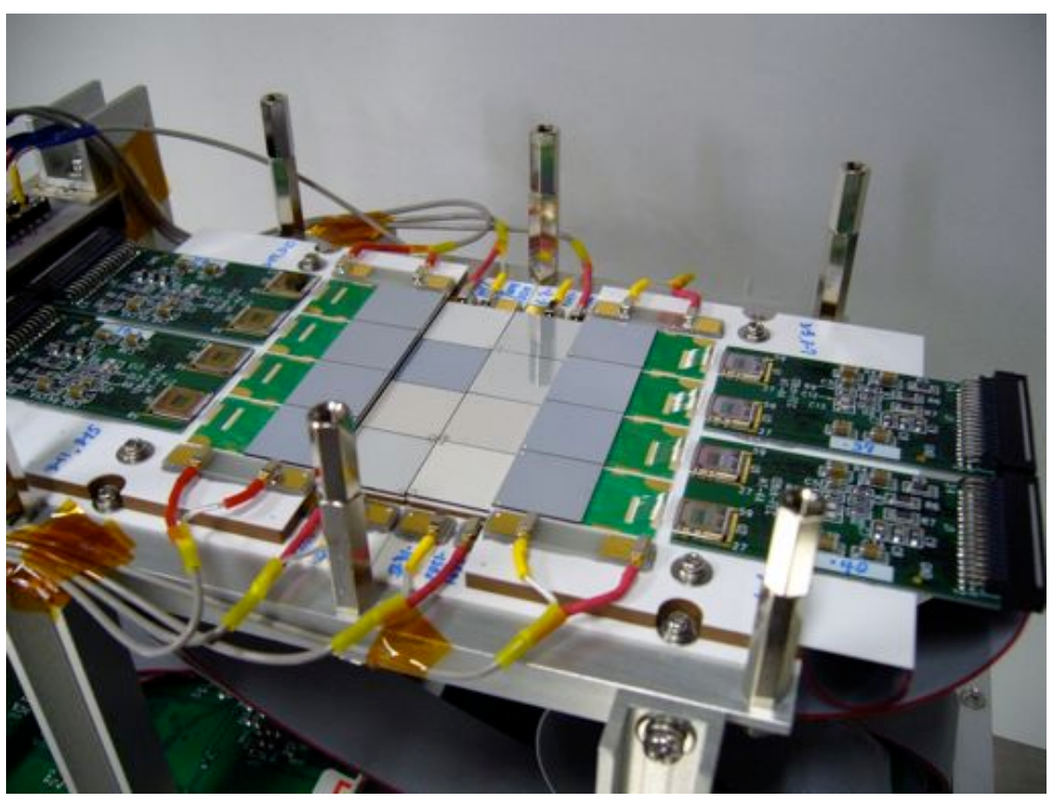
Good Energy Resolution
&
High Uniformity





Large Area Imager

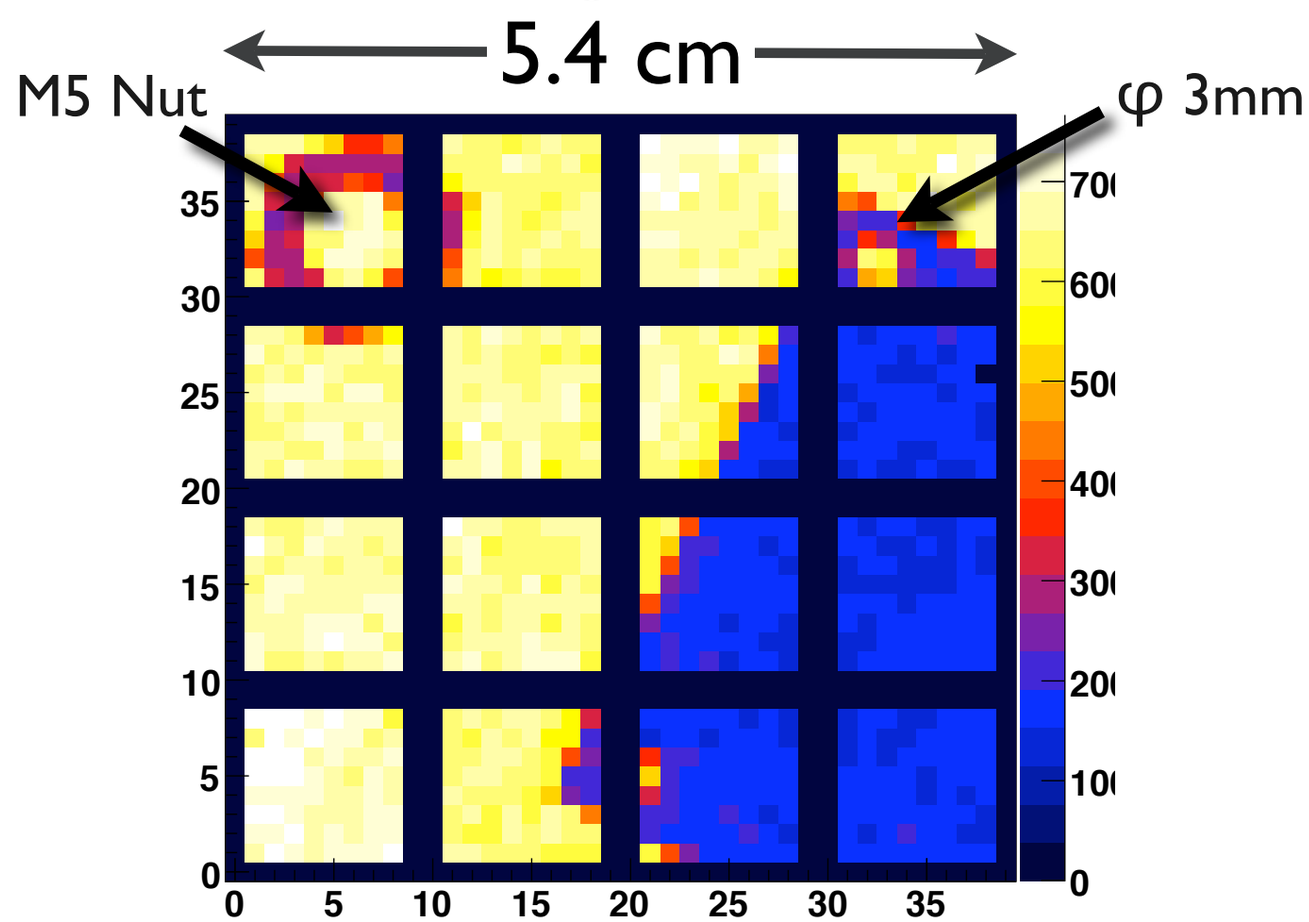




4×4 = 16 CdTe Pixel Modules

5.4 cm × 5.4 cm Large Area Imager

Shadow Image 30–150 keV

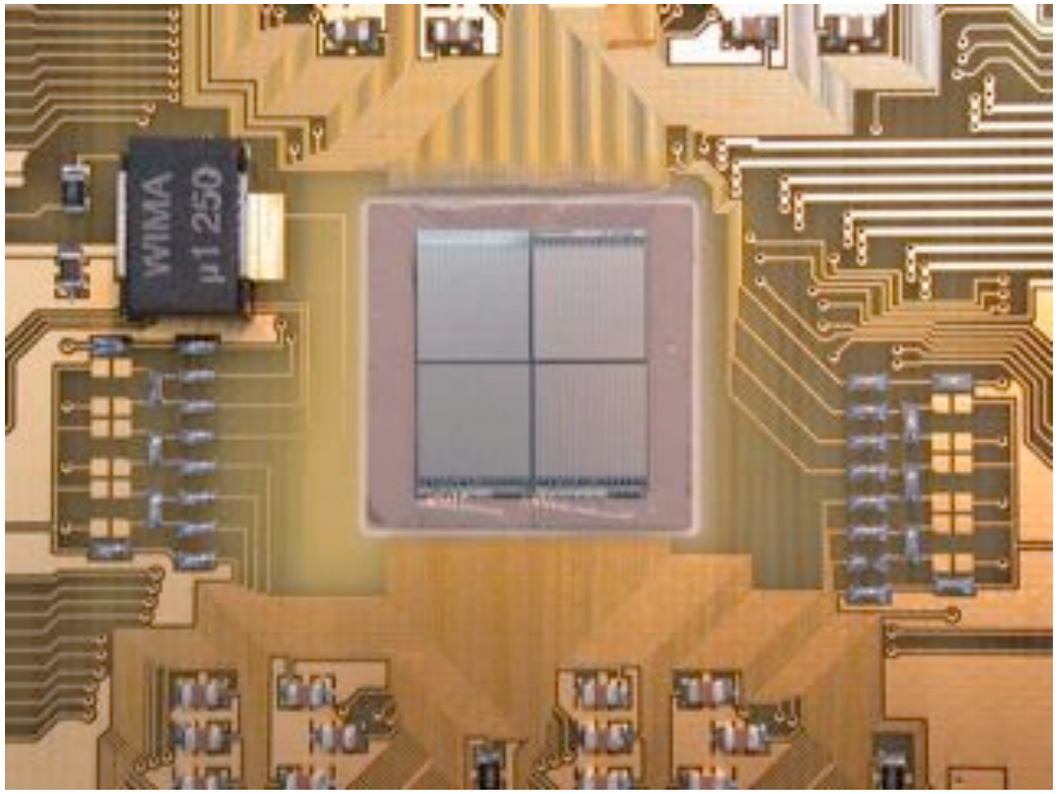


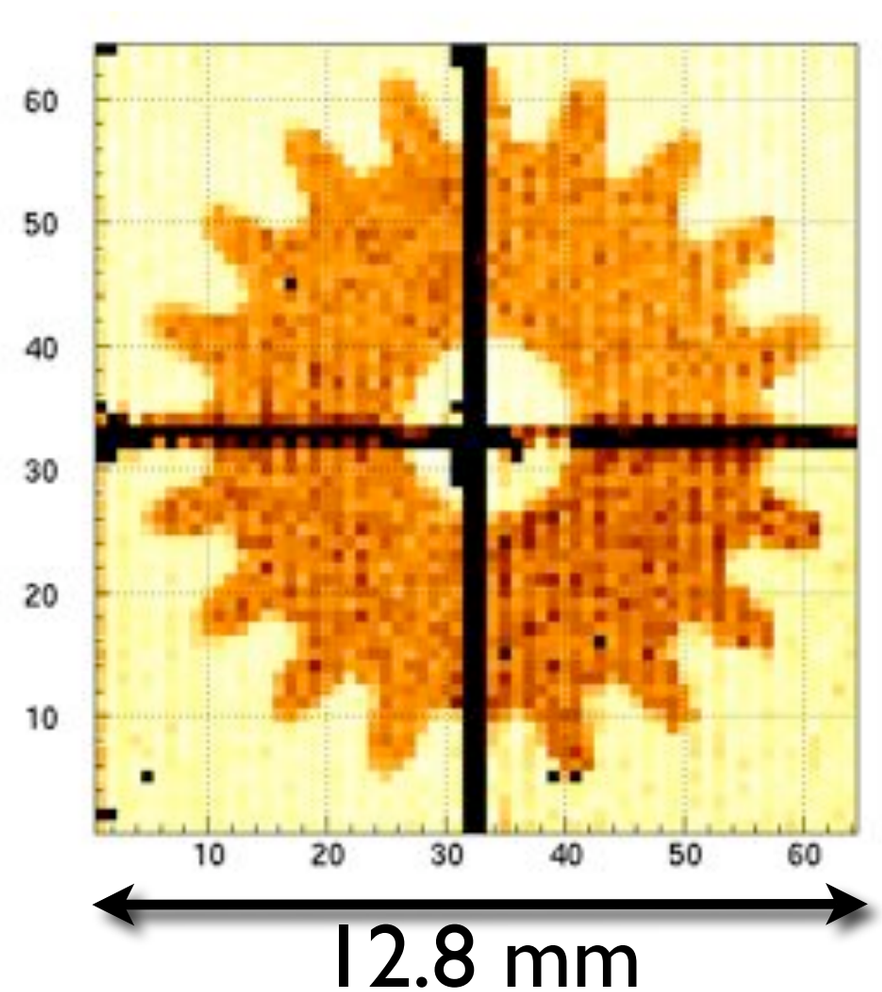
Fine Pixel Detector

Developments of Fine Pixel (200–500 μm) are on-going

Example

Collaboration with Bonn University (MPEC chip)
Photon Counting Chip
High-Resolution (200 μm) Image !!



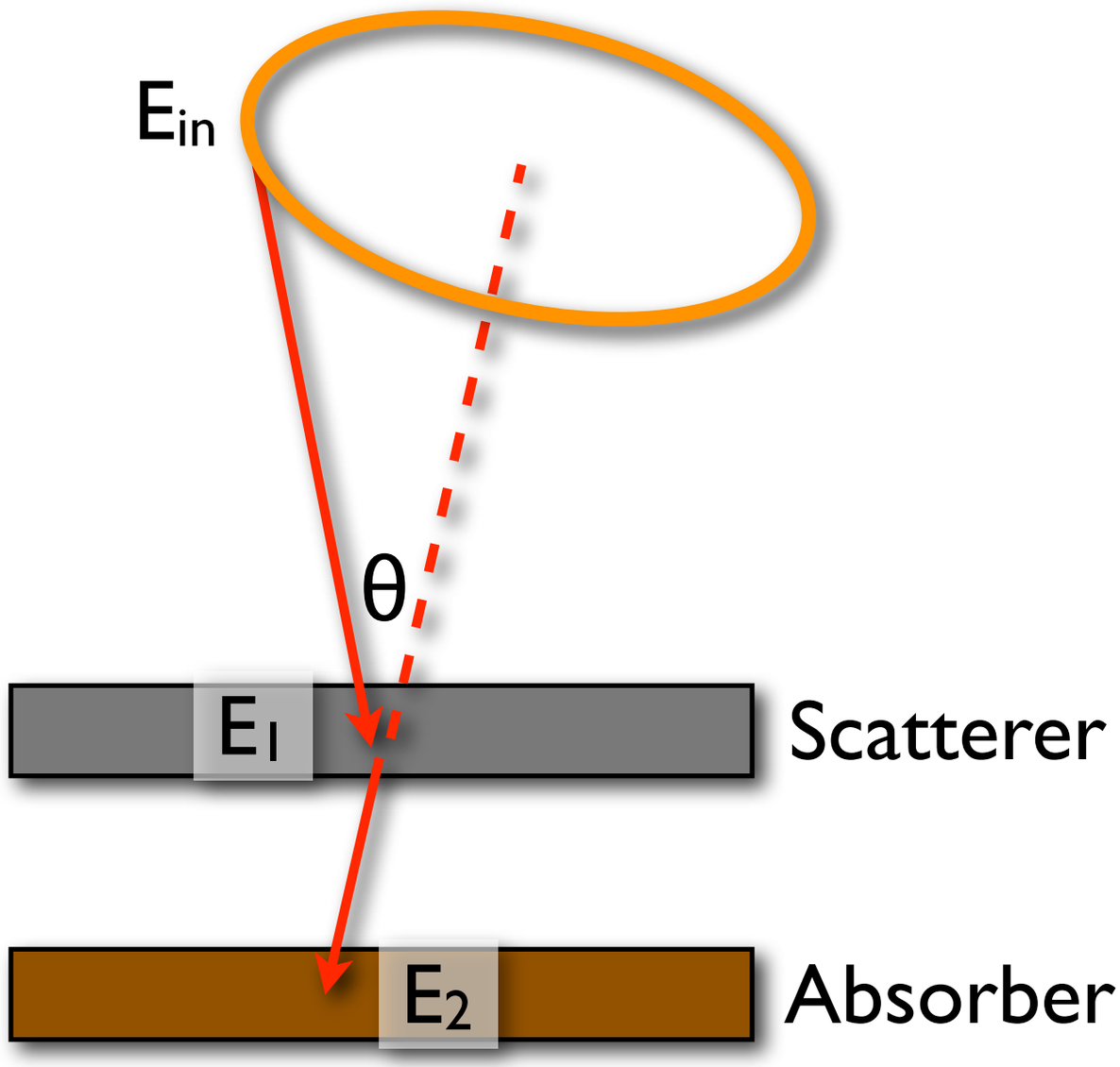


Example of Applications

Application to Compton Telescope

10–80 keV: CdTe Pixel Detectors + Hard X-ray Optics

80 keV–MeV: Compton Telescope



Compton Kinematics

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

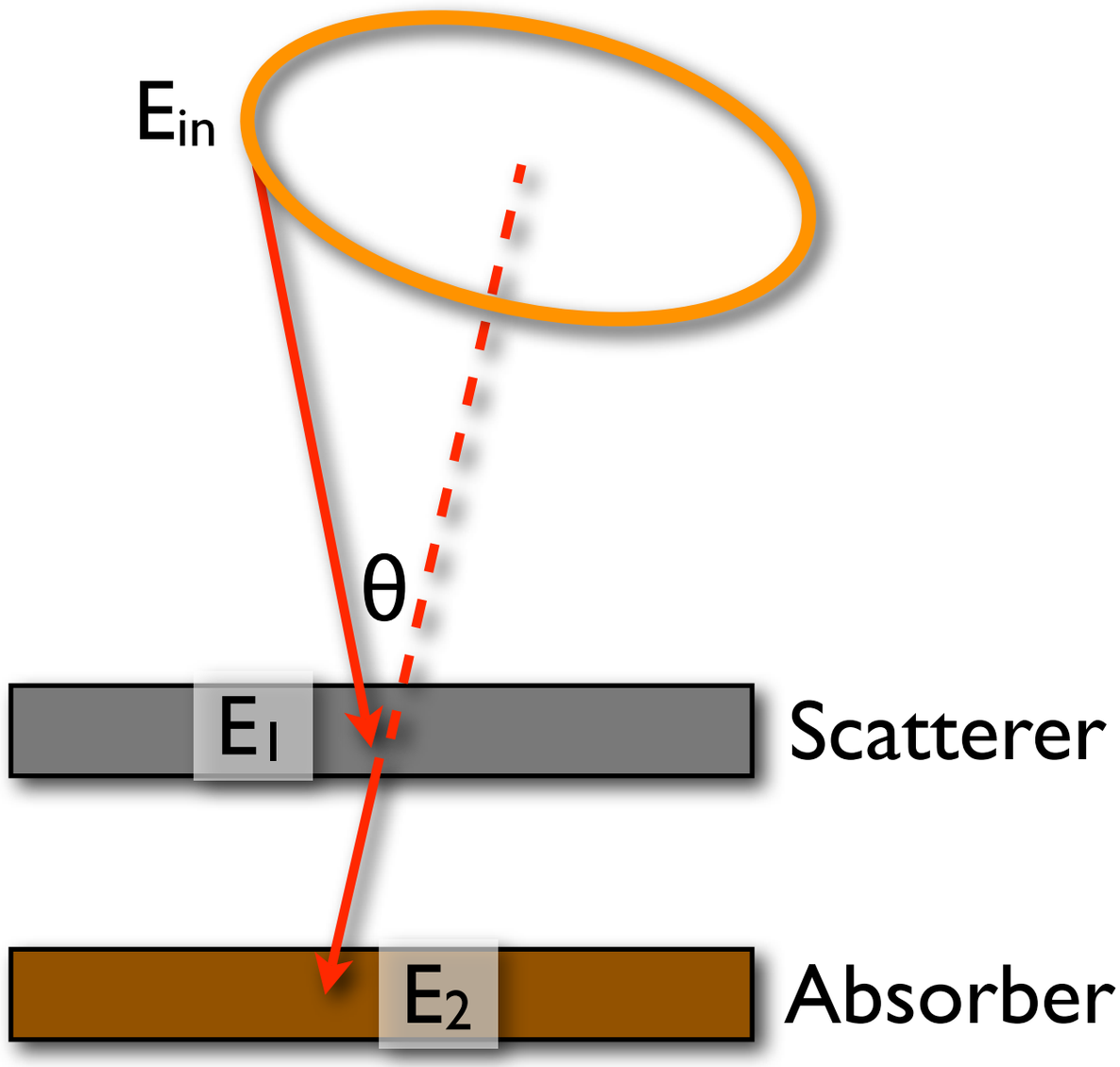
$$E_{\rm in} = E_1 + E_2$$

Compton Telescope with Semiconductors → Good Δθ & ΔE

Application to Compton Telescope

10–80 keV: CdTe Pixel Detectors + Hard X-ray Optics

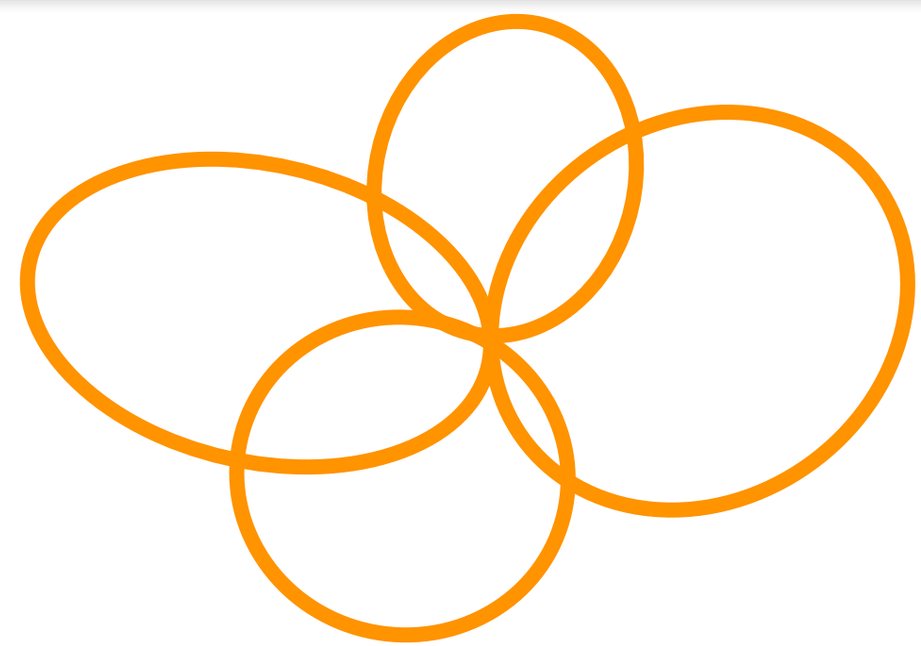
80 keV–MeV: Compton Telescope



Compton Kinematics

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

$$E_{\rm in} = E_1 + E_2$$

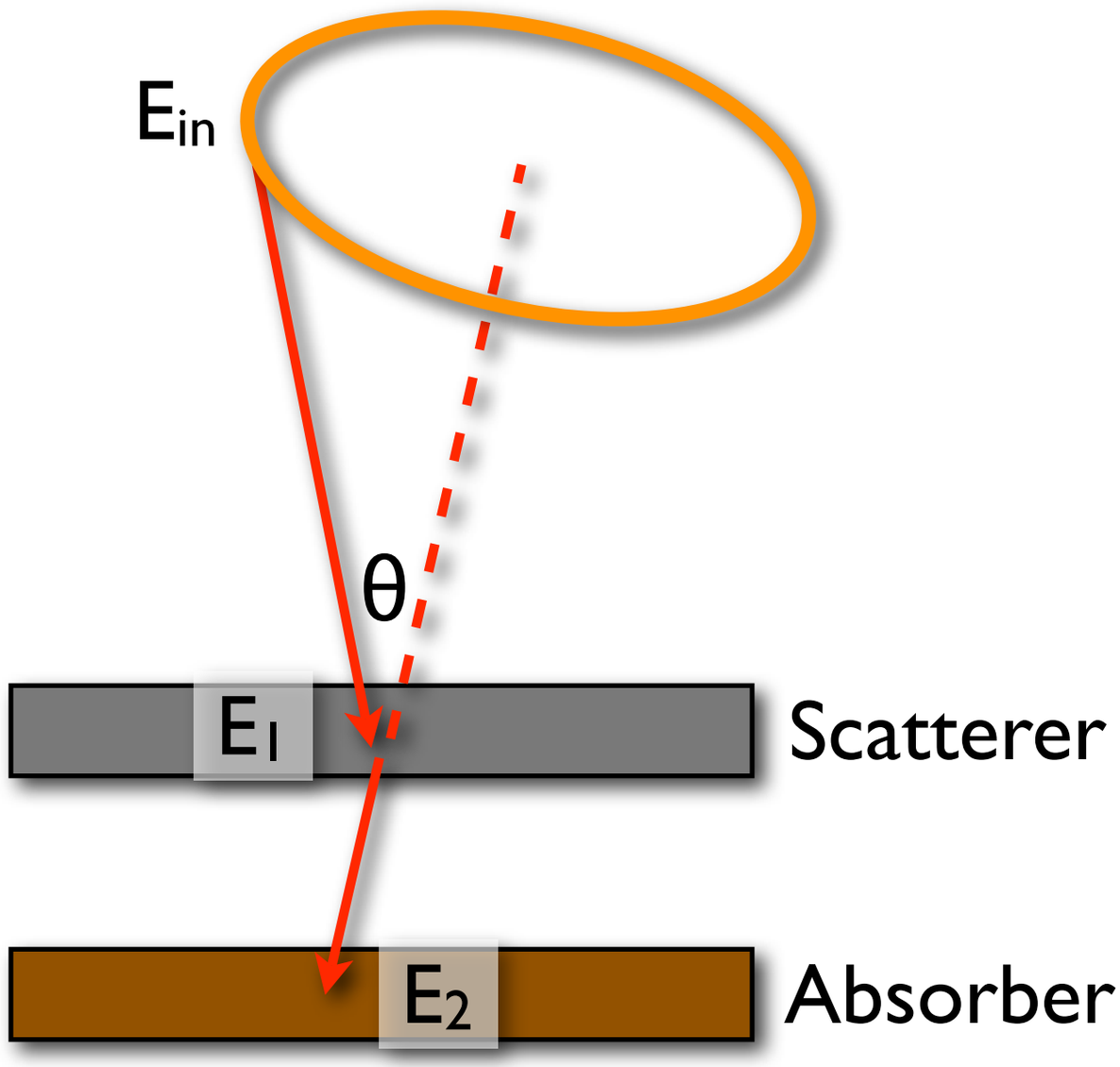


Compton Telescope with Semiconductors → Good Δθ & ΔE

Application to Compton Telescope

10–80 keV: CdTe Pixel Detectors + Hard X-ray Optics

80 keV–MeV: Compton Telescope



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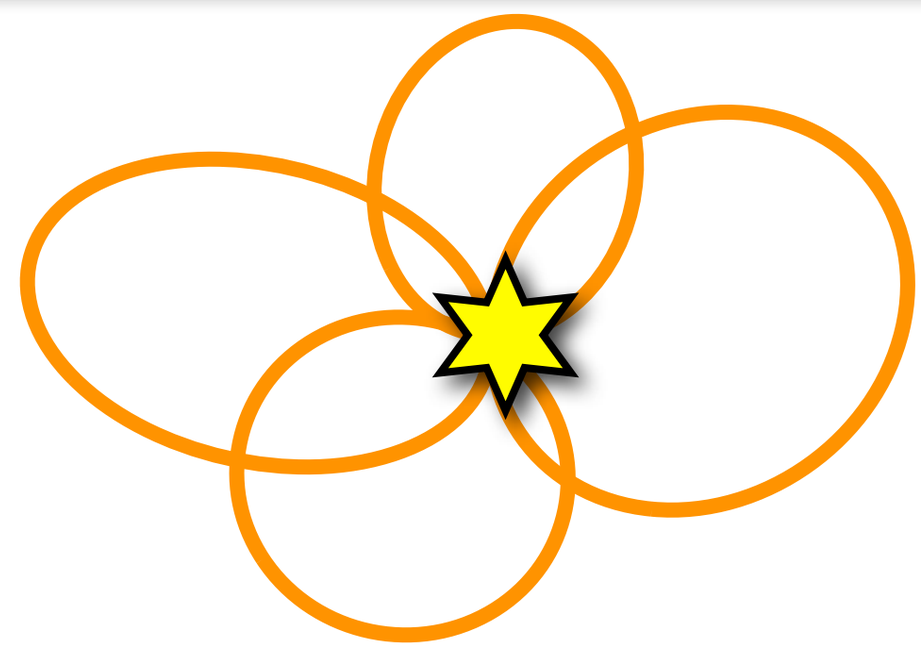
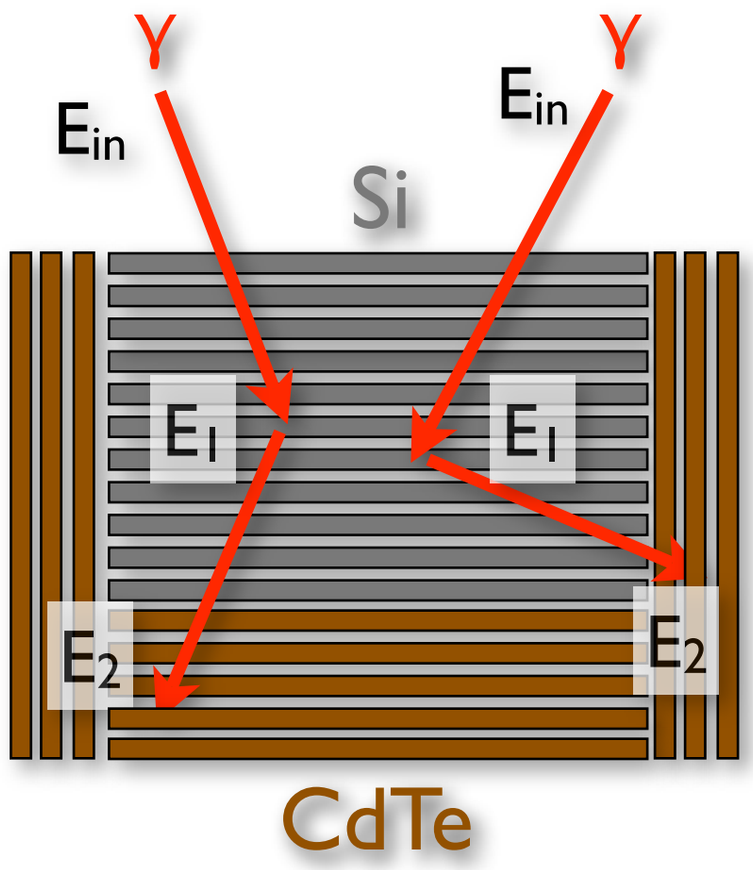


Compton Telescope with Semiconductors → Good Δθ & ΔE

Si/CdTe Compton Telescope



Semiconductor
(Scatterer & Absorber)

good energy & position resolution

→ Good Angular Resolution
Good Energy Resolution
Compact Design

Si: Scatterers
CdTe: Absorbers

Good from several 10 keV to MeV

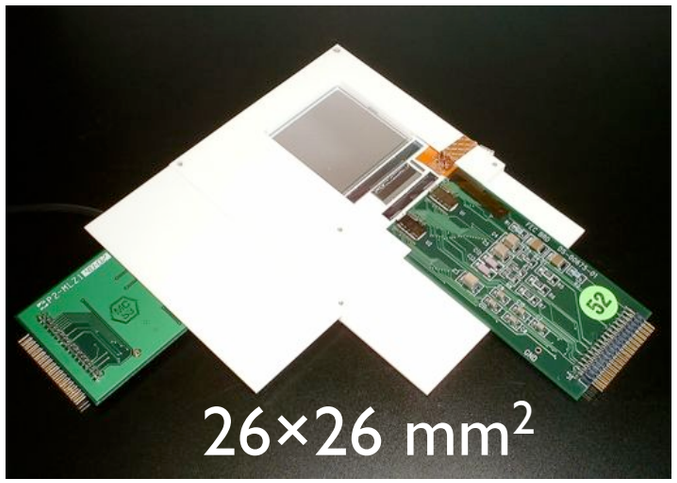
Si: High Compton Efficiency
Low Photo Abs. Efficiency

CdTe: High Abs. Efficiency

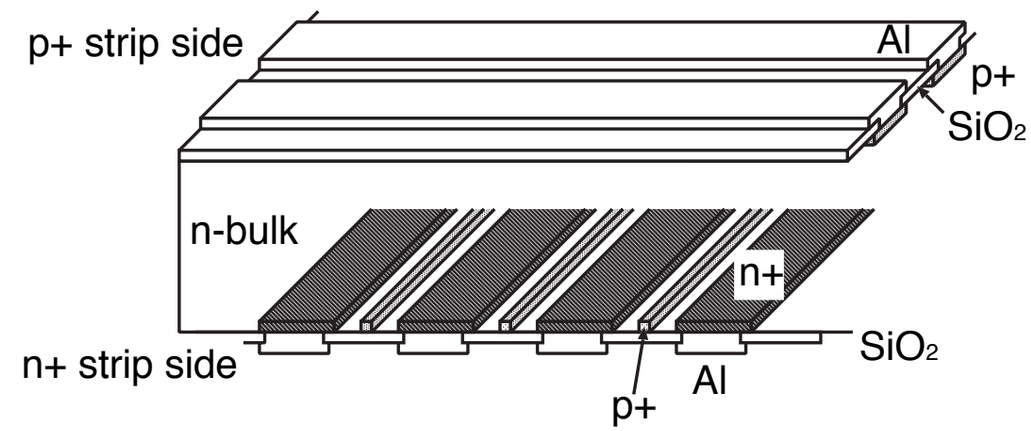
Goal: Angular Resolution ~ 1° @ 1 MeV
Detection Efficiency ~ 1–10 %

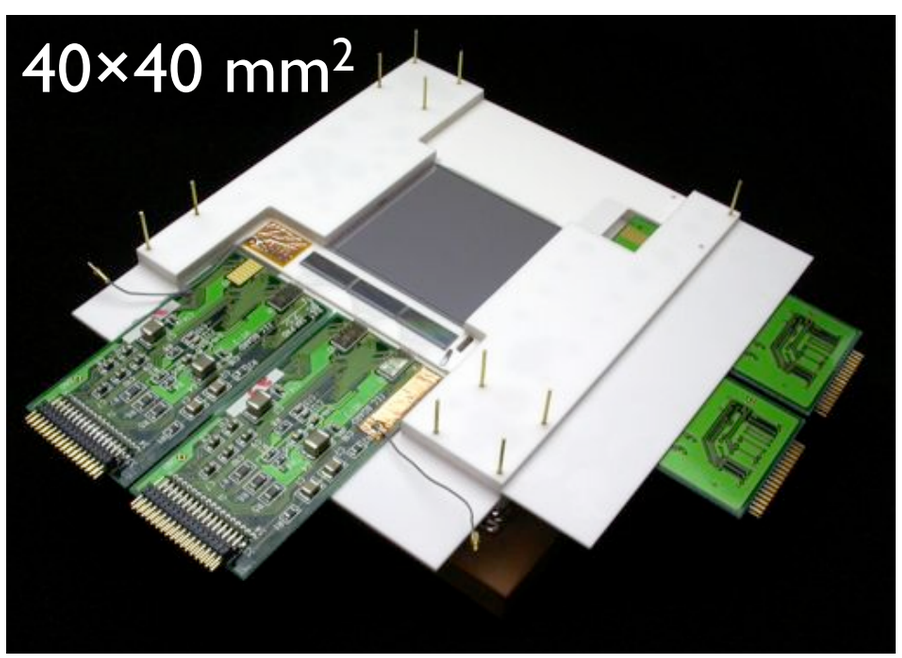
Double-sided Silicon Strip Detector (DSSD)

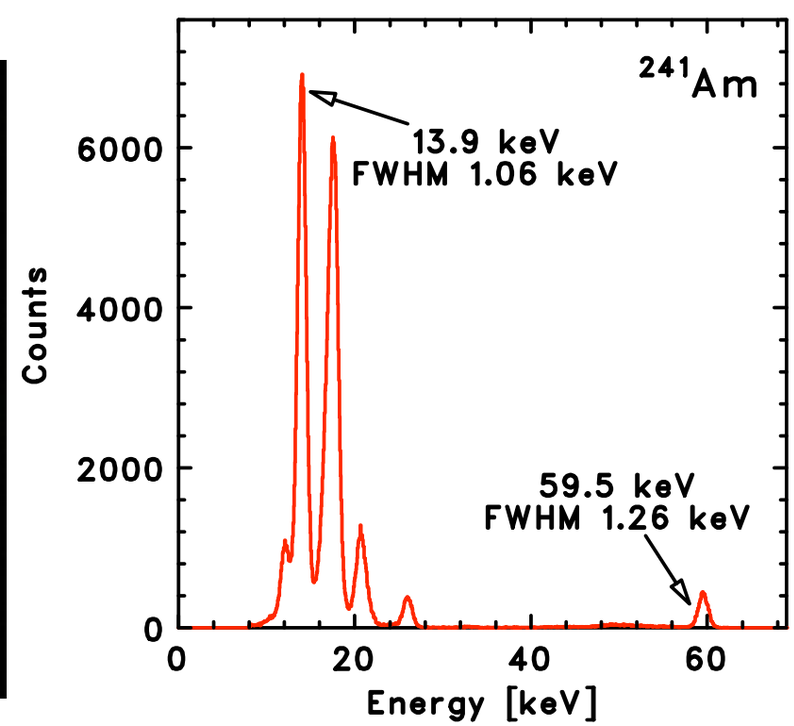
Another Key to our Compton Telescope Development with HAMAMATSU

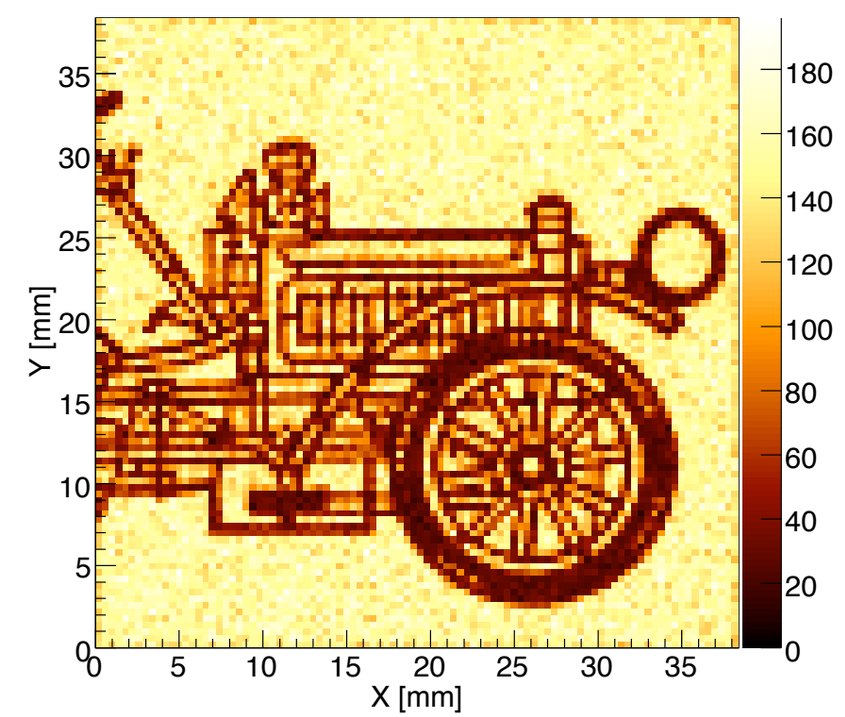


area: 26×26 – 38×38 mm²
thickness: 300–500 μm
pitch: 100–400 μm
64–128 strips on each side



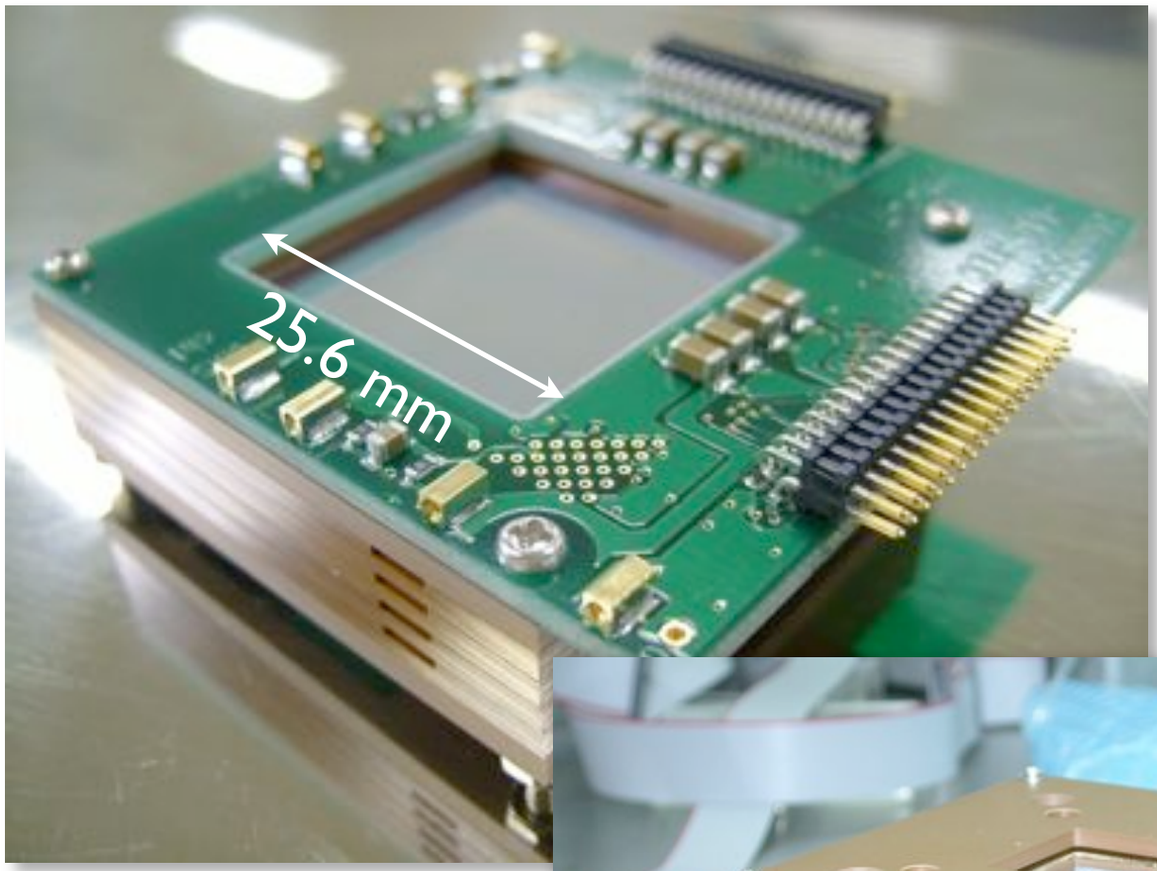




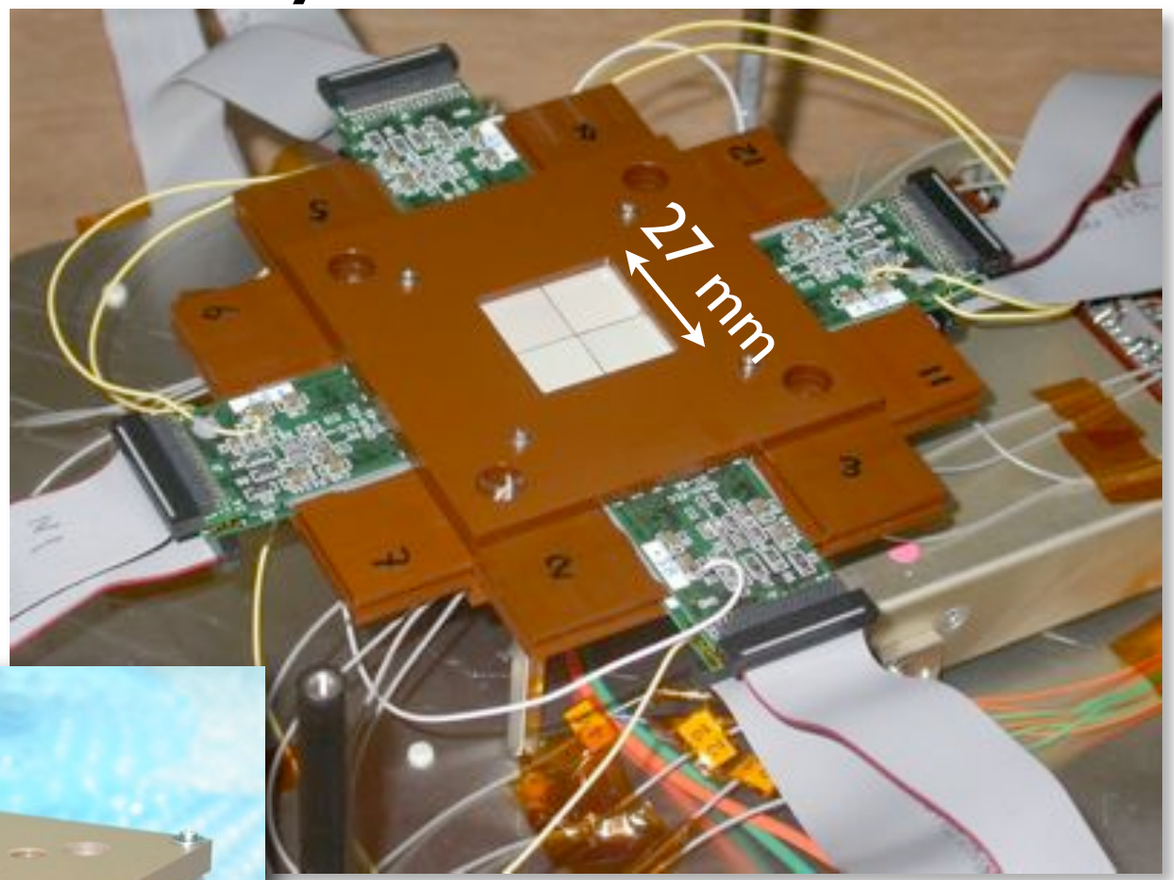


Compact Modules for Compton Telescope

4-layer DSSD module

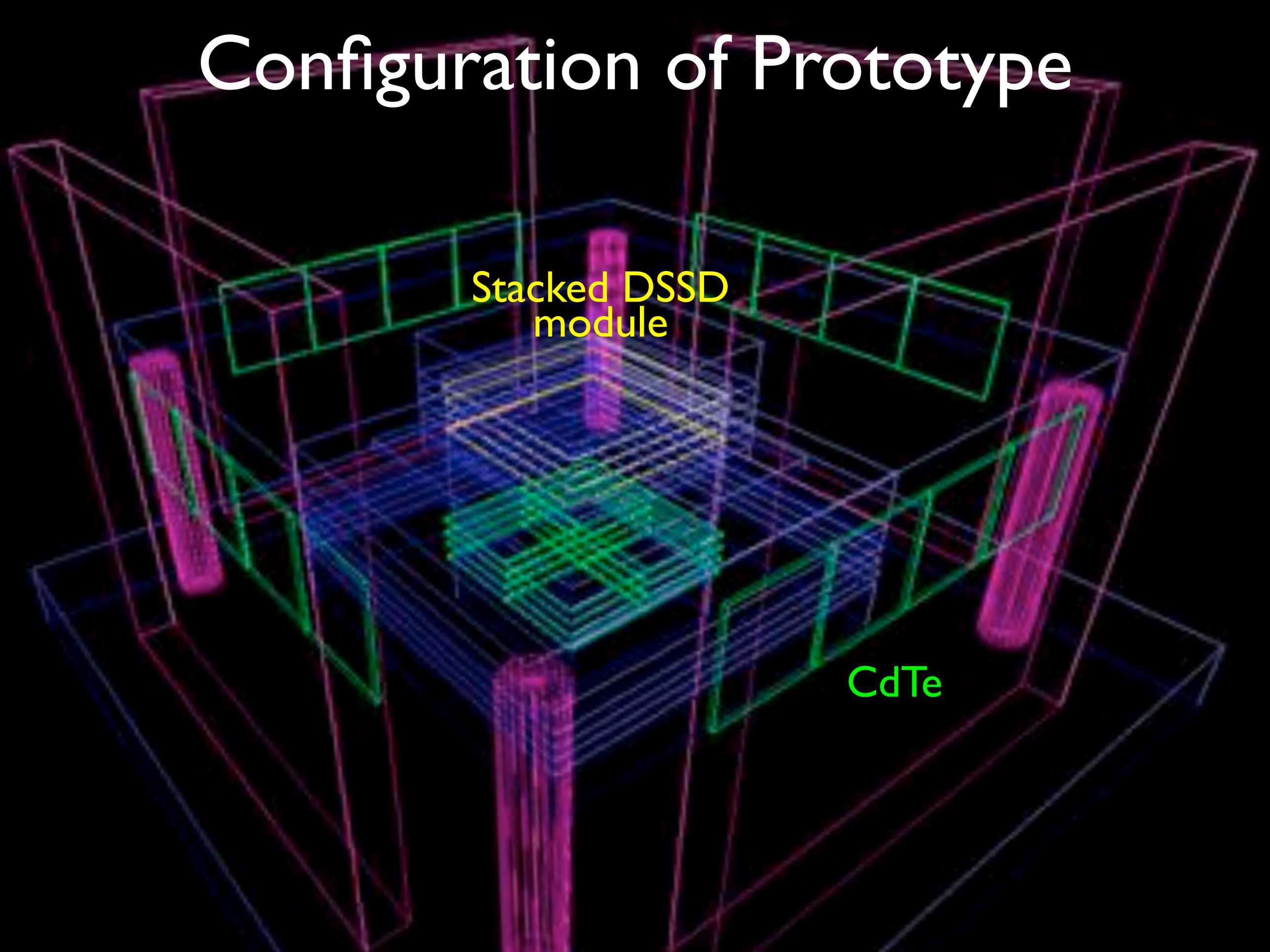


4-layer CdTe module

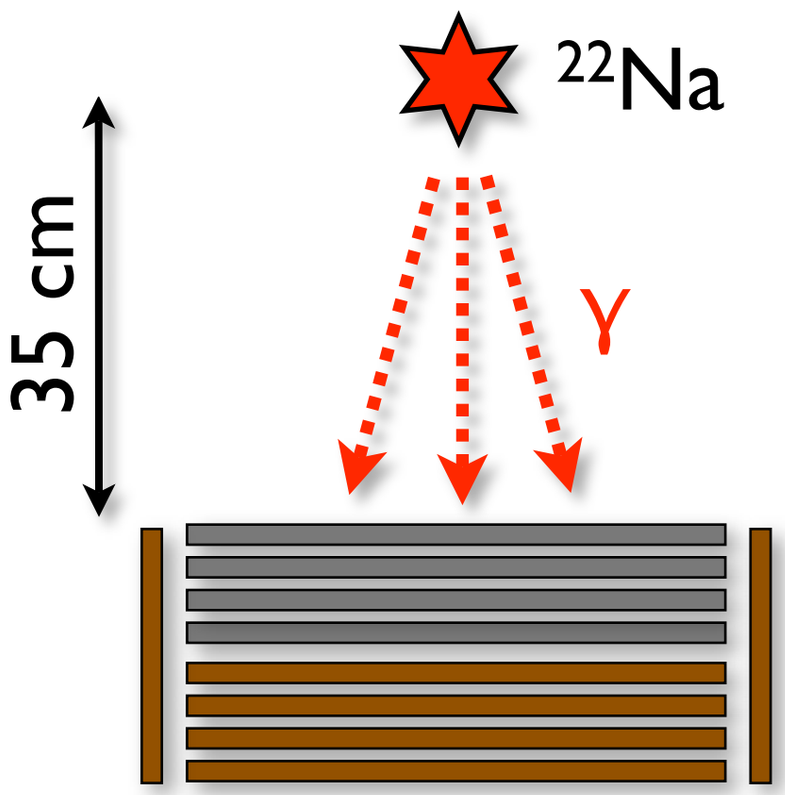


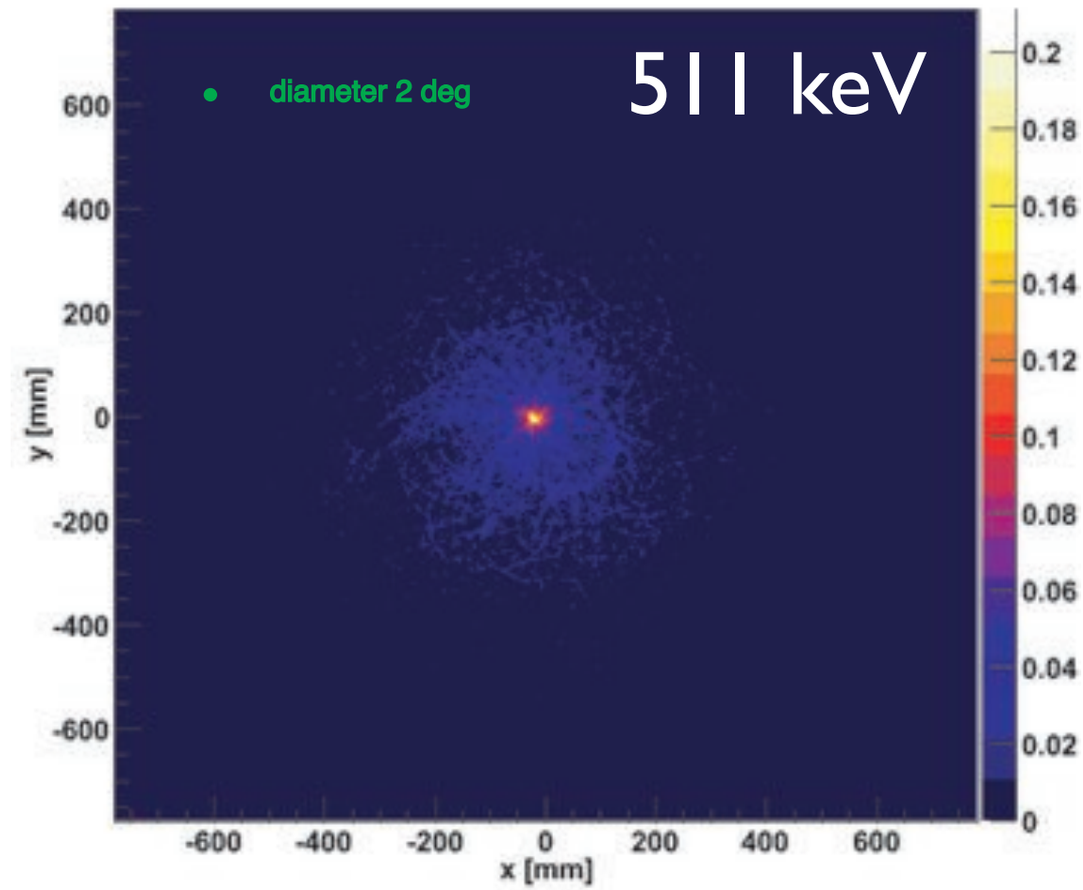
Prototype Compton Telescope

Configuration of Prototype



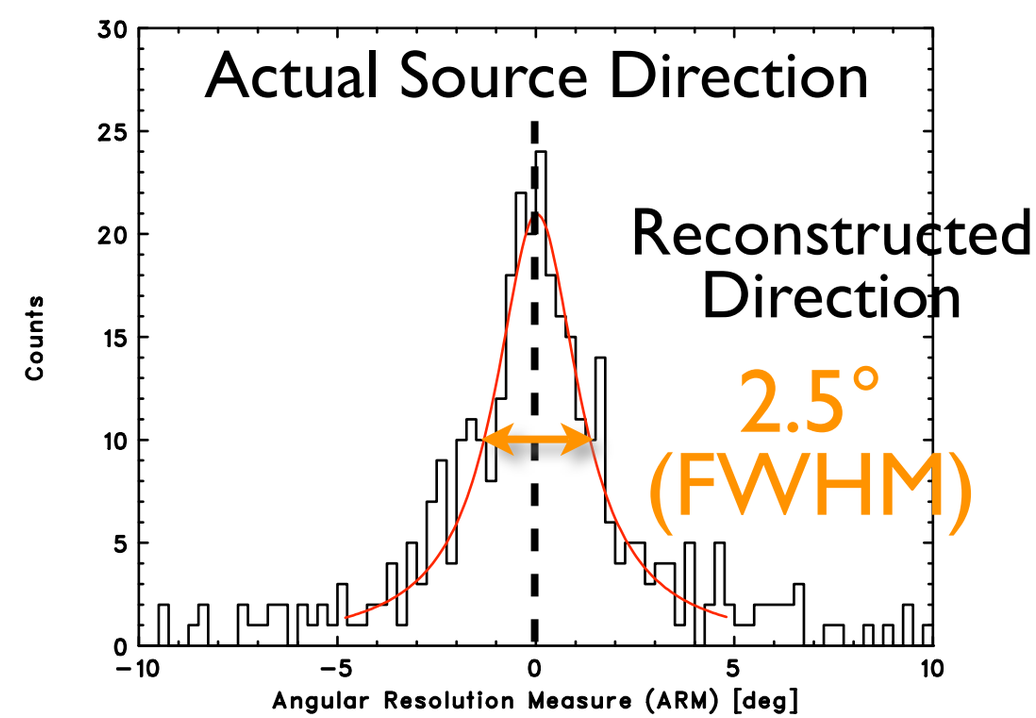
Reconstructed Image



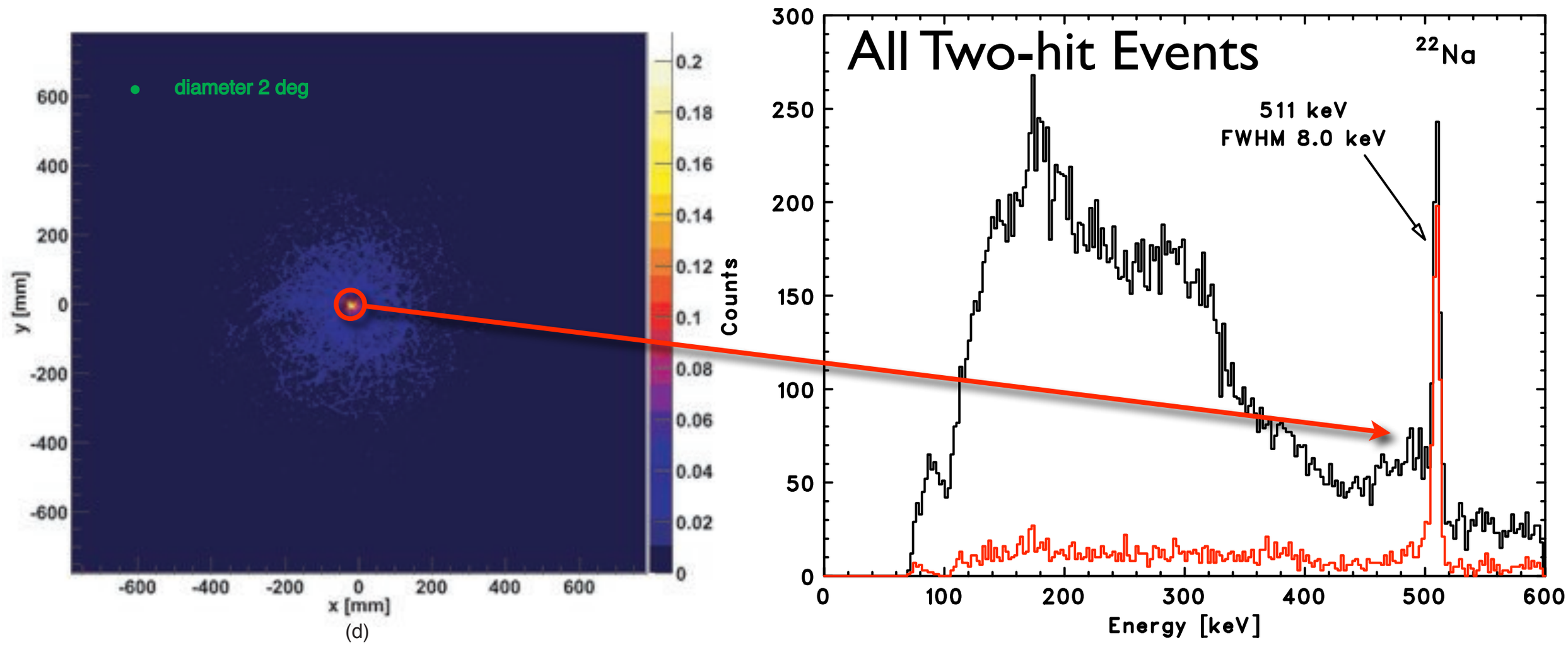


Succeeded in Compton Reconstruction from 60 keV to 700 keV

Good Angular Resolution
↑ Good ΔE of Our Detectors



Reconstructed Spectrum



Background Rejection by Compton Kinematics

Energy Resolution: 8.0 keV (FWHM) @ 511 keV

Summary

- CdTe is an attractive material for hard X-ray or soft gamma-ray detection
- We developed CdTe Schottky diode detector which features good energy resolution
- Our CdTe pixel detectors show good energy resolution & high uniformity
- We demonstrated imaging with fine-pixel sensors
- Application to Compton telescope is successful