Application of CdTe/CdZnTe Pixels to X-ray and Gamma-ray Astrophysics

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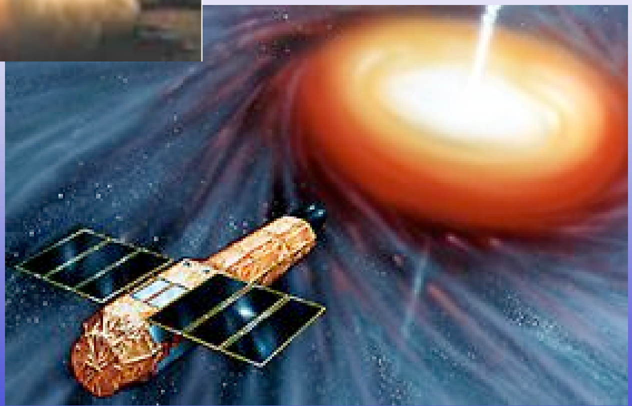
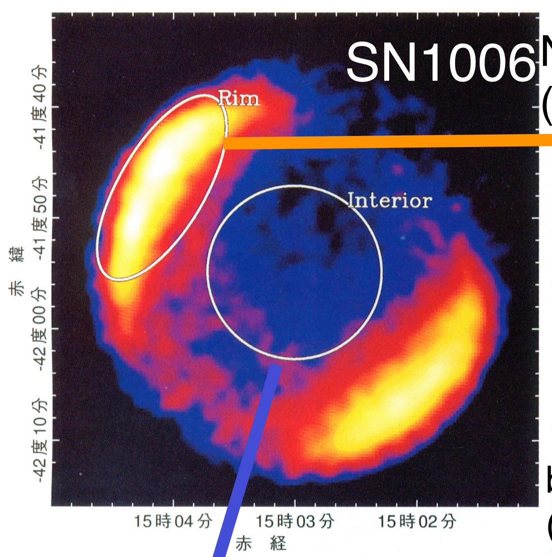


1. X-ray Astronomy
2. X-ray & Hard X-ray Optics
3. CdTe/CZT
4. CdTe/CZT Pixels & Hybridization
5. (Gamma-ray Detectors)
6. Summary

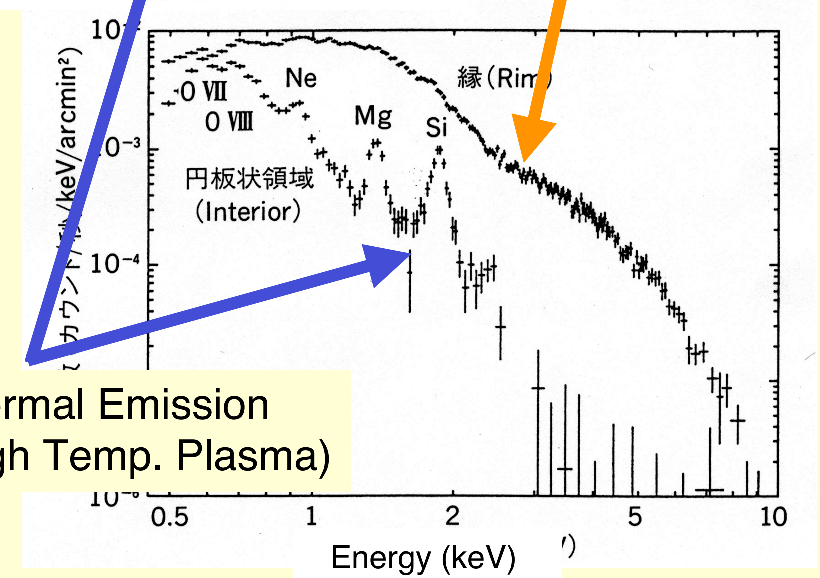
X-ray Astronomy



Non-Thermal Emission
(Particle Acceleration)

TeV Gamma-ray
Detected

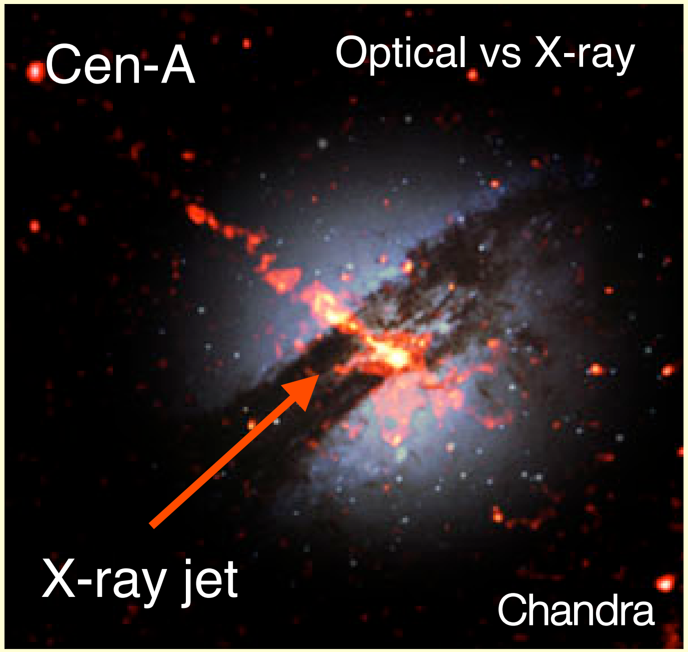
by Ozaki & Koyama
(ASCA Satellite)



Thermal Emission
(High Temp. Plasma)

- Extreme Universe
  - Super Novae/SNR
  - Black Holes / Neutron Star
  - Cluster of Galaxies
    “Particle Acceleration”

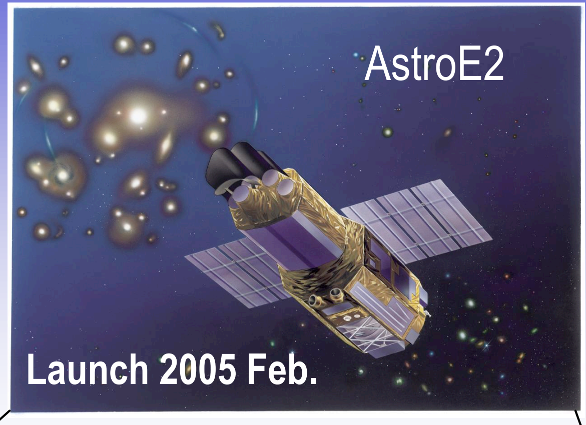
Huge Black Hole in
AGN and Jets



X-ray Space Observatories in the New Millennium

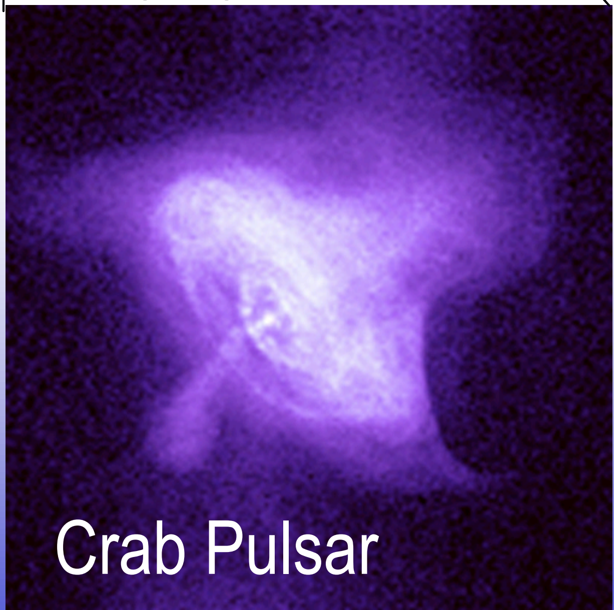
NASA

ESA (Europe)



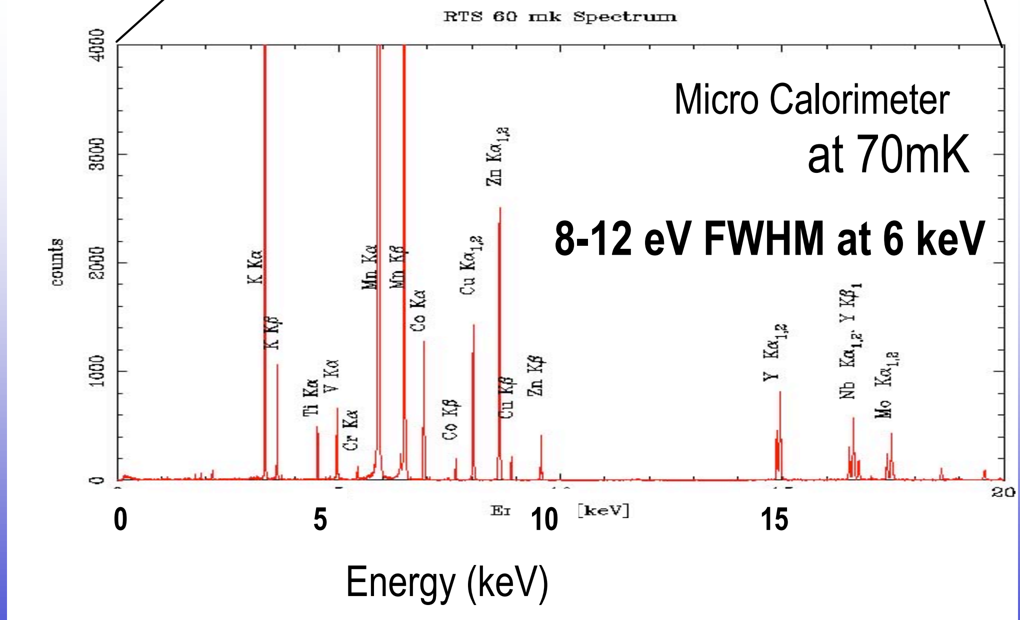
ISAS (Japan/US)

Imaging

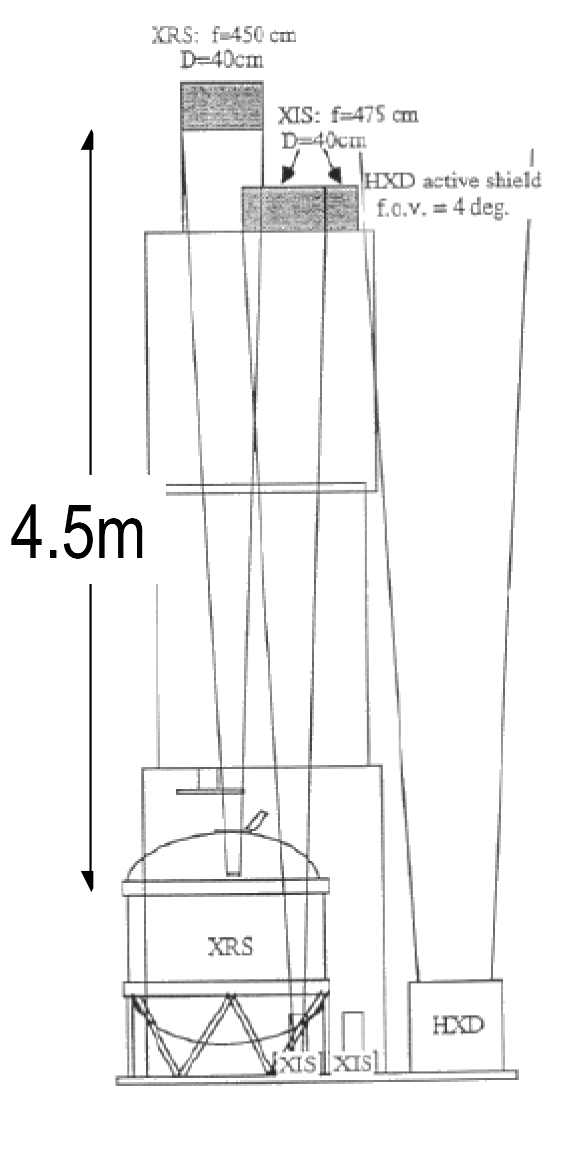


X-ray CCD

Spectroscopy



Astro-E2 X-ray Mirror



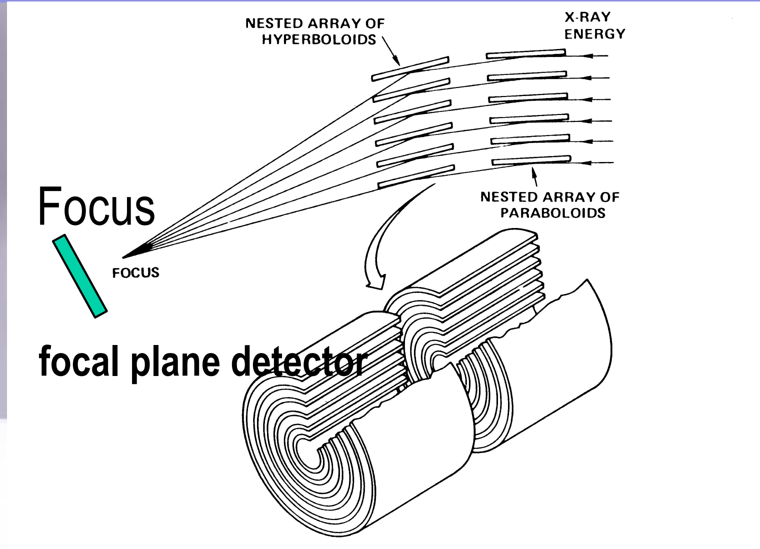
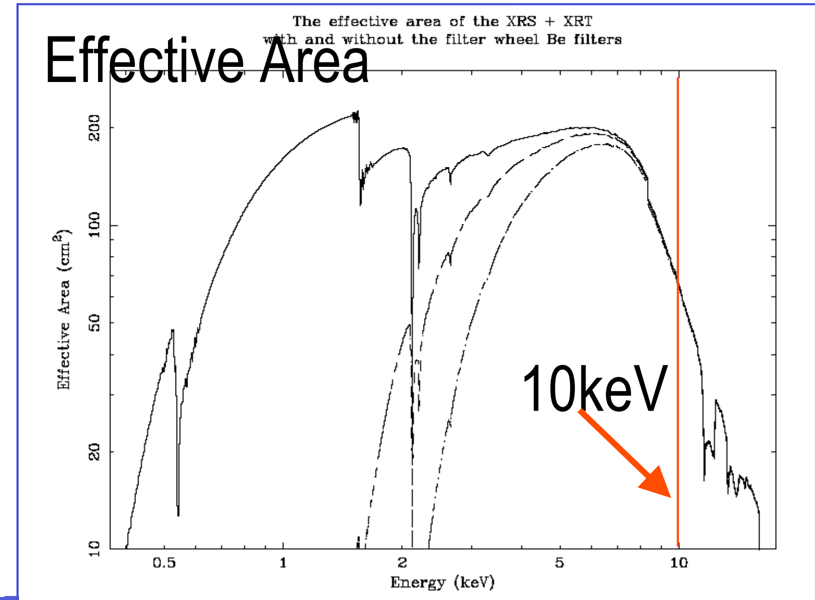
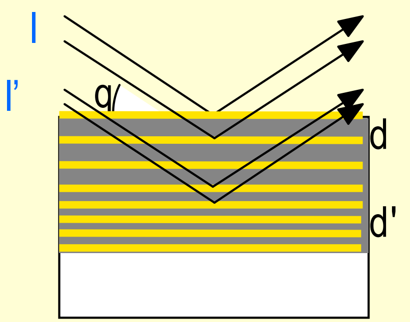


diagram of a grazing incidence X-ray telescope.
, now Hughes–Danbury Optical Systems.)



Hard X-ray optics for future missions

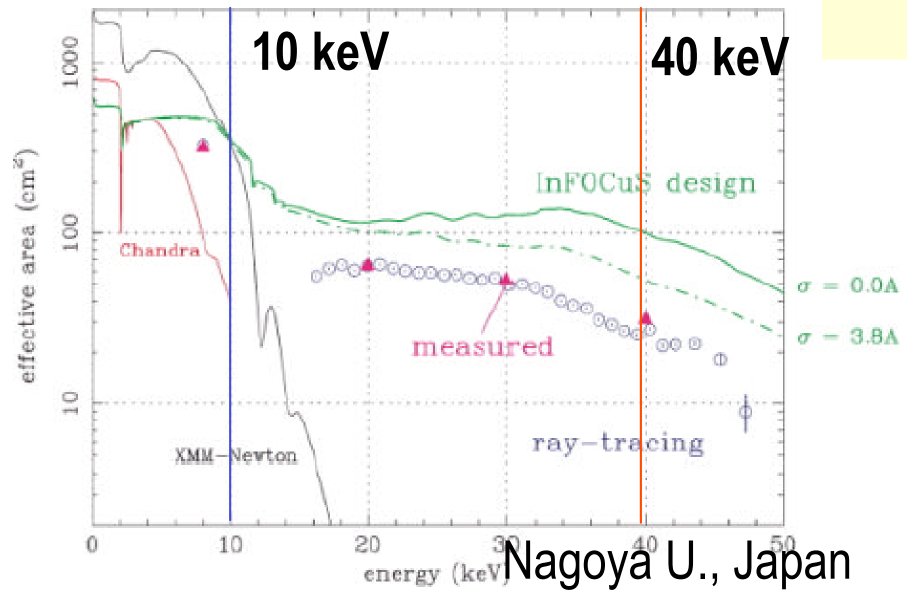


Pt/C 2d=5 - 10 nm

N ≤ 70 layer pairs

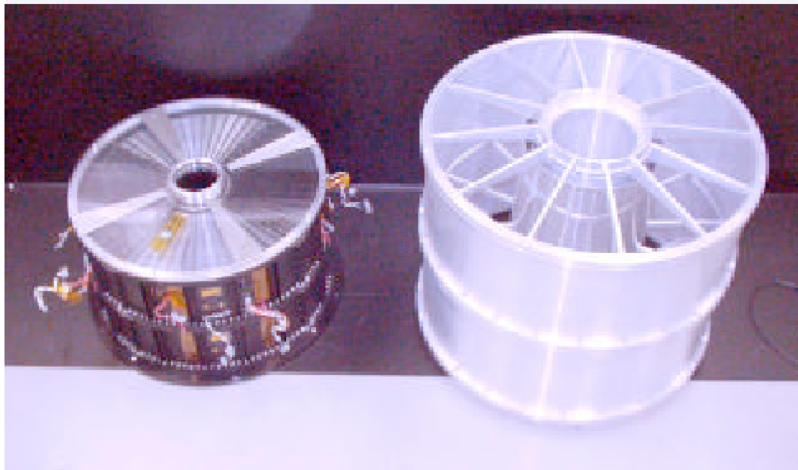
Lateral graded d-spacing multilaye

= Supermirror



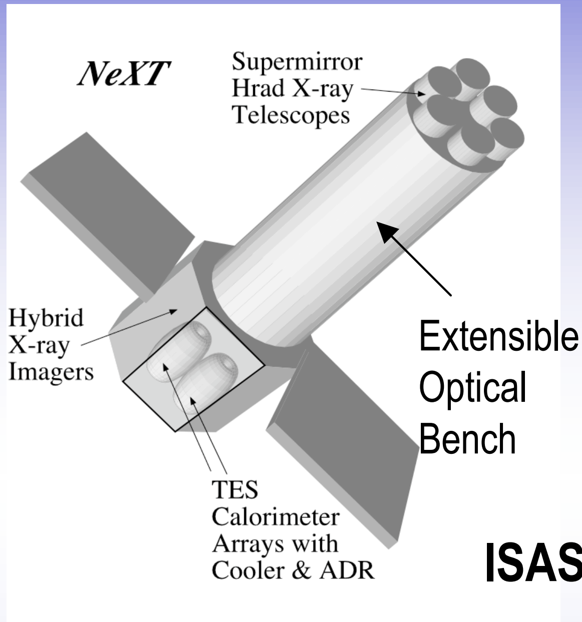
Nagoya U., Japan

- A multi-layer, grazing incidence hard X-ray telescope (super mirror)
  - Nagoya Univ. (Japan)
  - Columbia Univ. (US) and others
- Future Missions (~2010)
  - NeXT (Japan)
  - Constellation X (US)

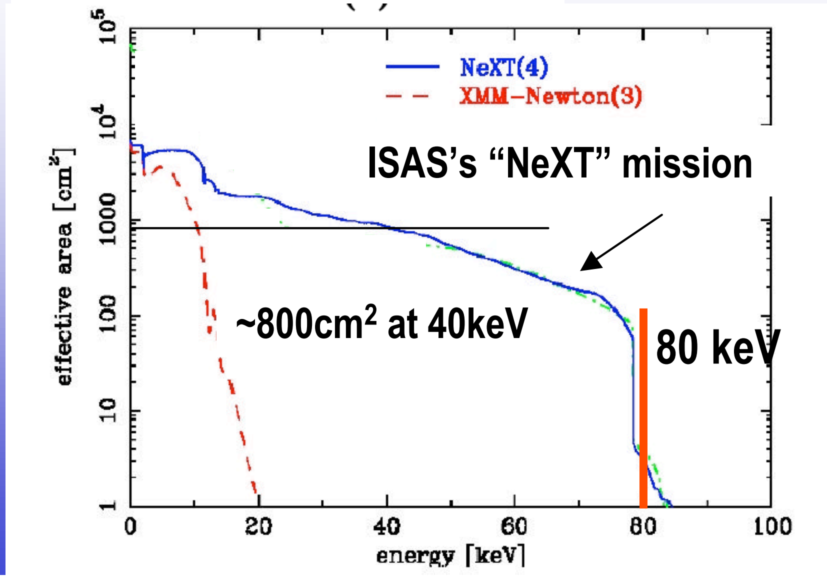


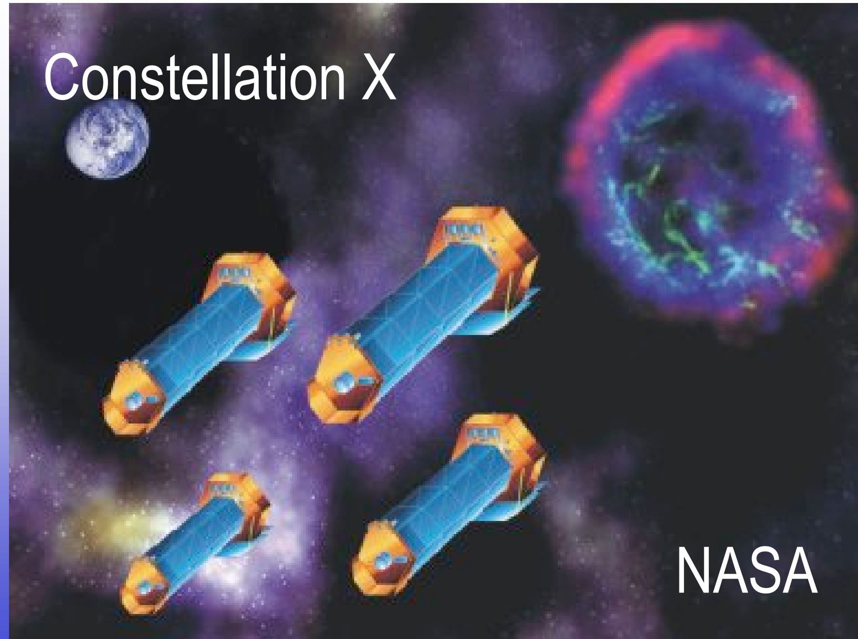
Future Mission
-- Focusing Hard X-ray Experiments --

Focusing Telescope is
not only for the equipment to take pictures
but also for the key to achieve high sensitivity.
Because,
a mirror concentrates the incoming flux onto a small spot of the detector, greatly reducing background due to particle interactions in the detector



ISAS, Japan





Focal Plane PIXEL Detector

- <u>Development of an imager which is sensitive up to 100 keV is crucial.</u> (X-ray CCD and Gas Chamber become transparent)

GOAL

pixel size

200 μm x 200μm for arcmin res.

(20μm x 20μm for arcsec res. if we have a good mirror)

detector size 5 cmx5 cm

max rate 100 cnts/pixel

time resolution 10 μs

energy resolution 500 eV (FWHM)

in 1-100 keV

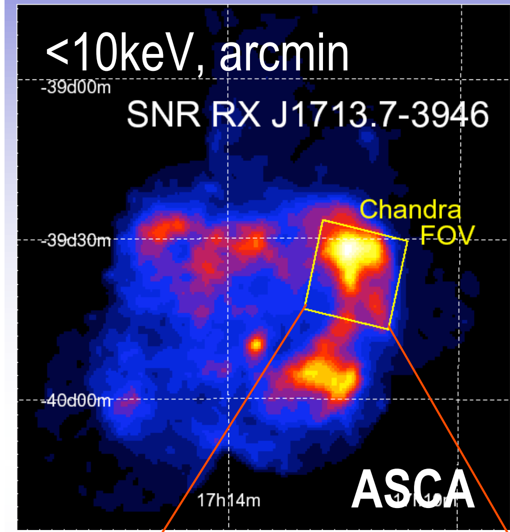
Example.

Accelerator in Super-Nova Remnants (SNR)

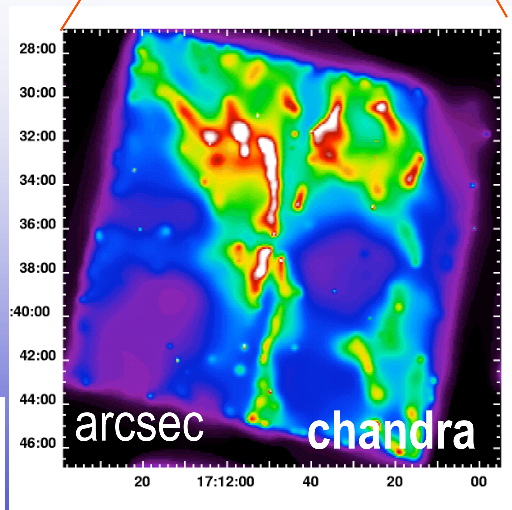
•Non-thermal X-ray

•TeV Gamma-ray detected

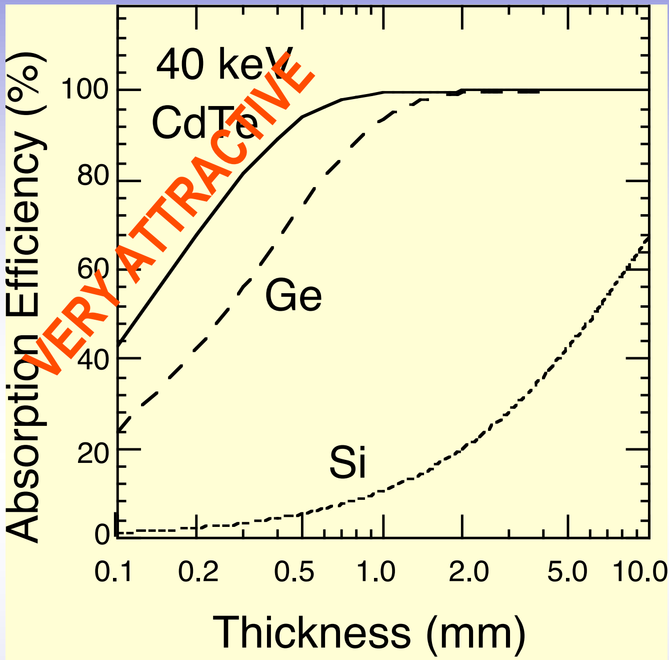
To study the physics of particle acceleration, we really need to go up to higher energy



Uchiyama, Aharonian, Takahashi, 2002 →



CdTe/CZT detectors



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

- Wide band gap (Eg ~ 1.5 eV)

⇒ Allows room temperature operation

High resistivity ~ **$10^{9\text{-}11}$ Ωcm**

⇒ With "ohmic" contacts, the detector can be operated as a simple "solid ionization chamber".

⇒ Diode Structure is possible to make

•Poor charge-carriers transport properties (recombination and trapping)

Low mobility(**μ**) and short life time (*t*) for holes

•Crystal NON-Uniformity and Size

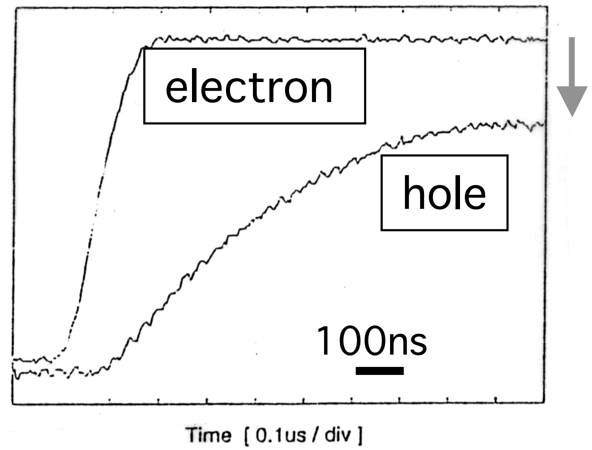
-> Significant Progress in 1990's

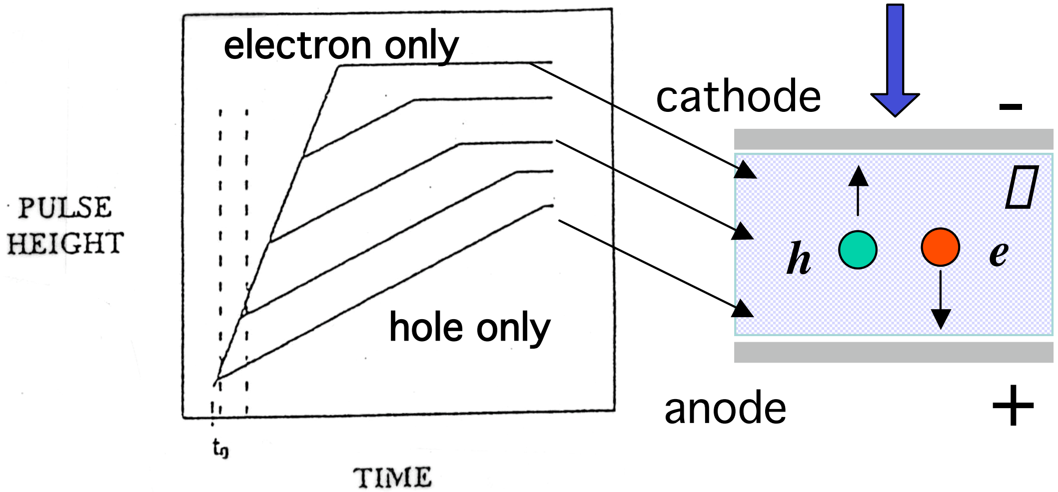
(see review by Takahashi & Watanabe, IEEE NS48, 4, 950, 2001)

Poor charge-carriers transport properties (recombination and trapping)

Low mobility(μ) and short life time (τ) for holes

Rise time & pulse height





mean drift path = μτE

E : internal electric field

μτ products

electron : 3×10^{-3} cm^2/V

hole

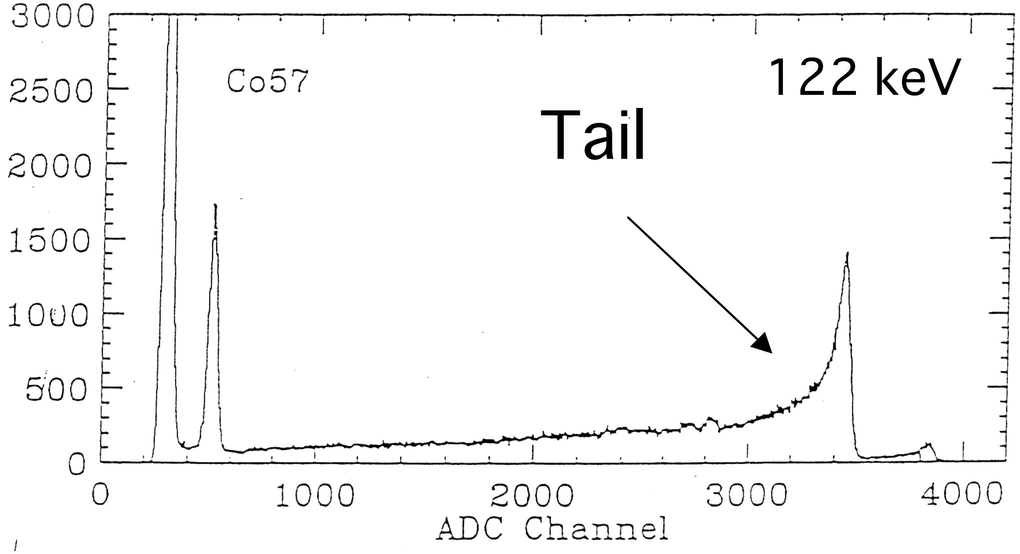
THM-CdTe : 3×10^{-4} cm^2/V

HPB-CdZnTe: ~0.5×10^{-4} cm^2/V

Si : 0.42(*e*), 0.22(*h*) cm^2/V

our measurements with recent CdTe/CZT

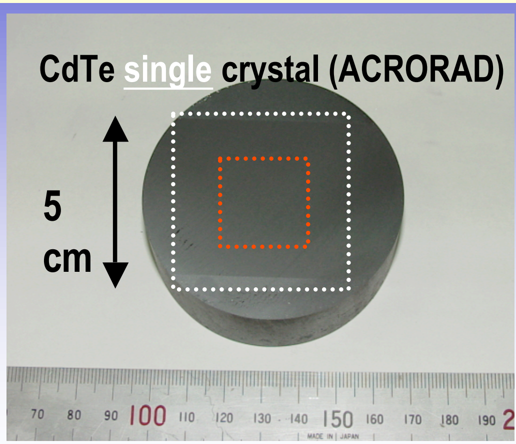
Pulse height depends on the interaction depth



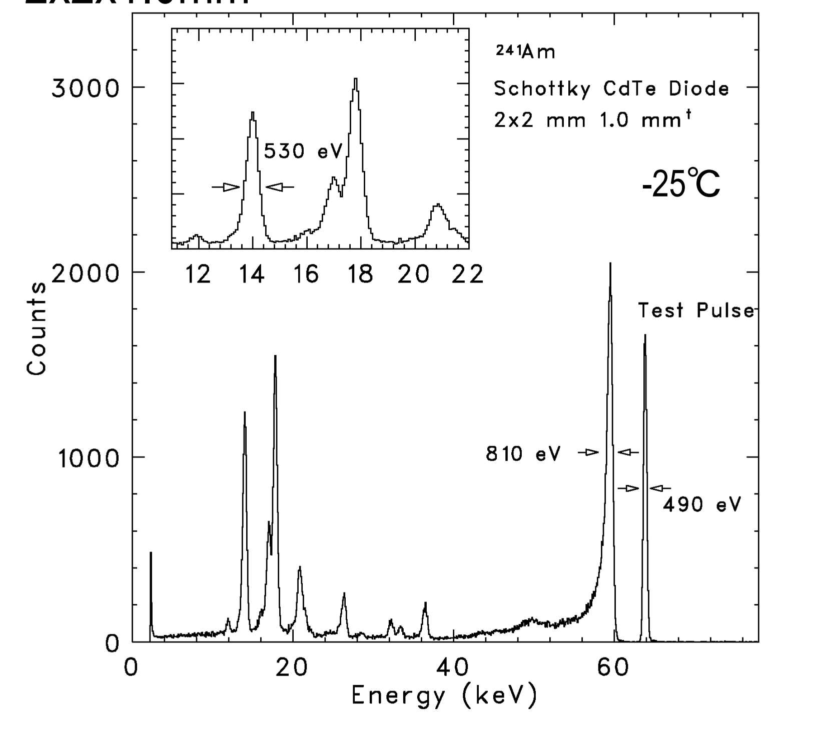
High Resolution CdTe detector (ISAS & ACRORAD)

- CdTe single crystal   (by ACRORAD)
- Schottky CdTe Diode (In/CdTe/Pt)
- Relatively thin device to apply high bias voltage for full charge collection

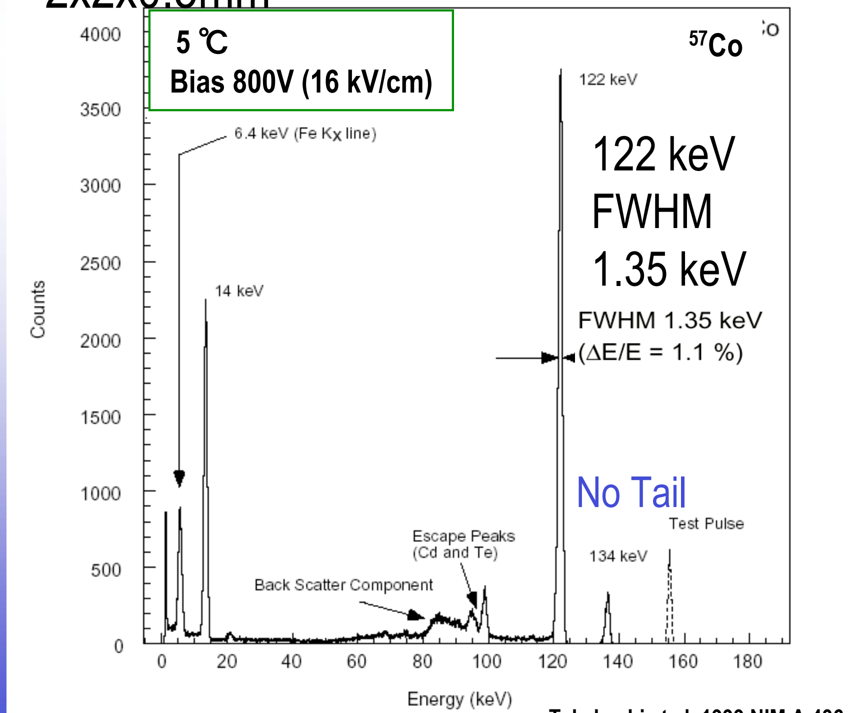
(see e.g. Takahashi et al. IEEE NS 2002, June)



$2x2x1.0mm^3$

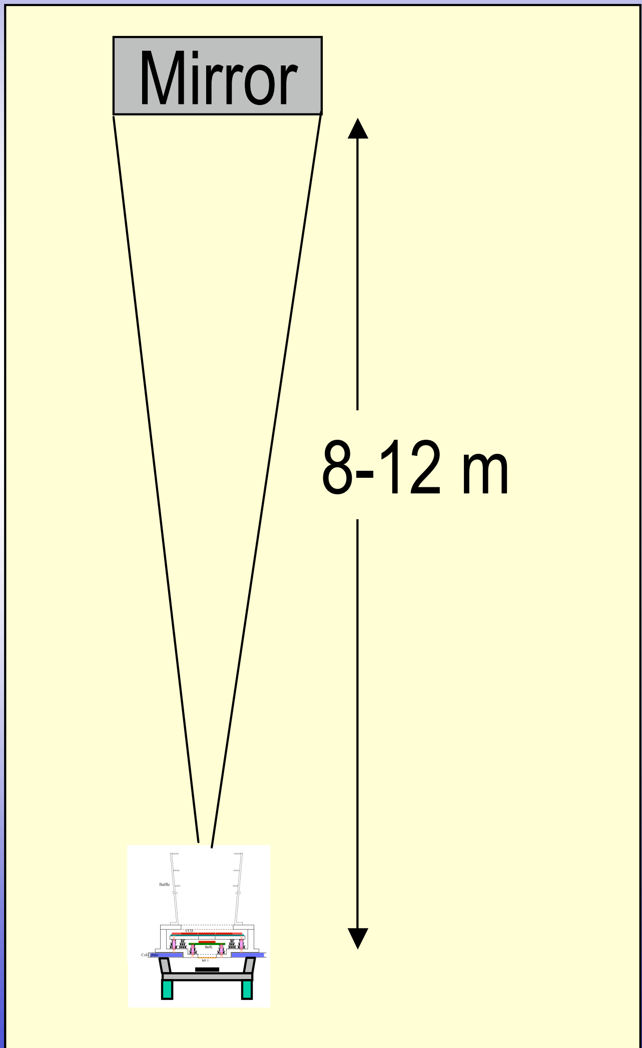


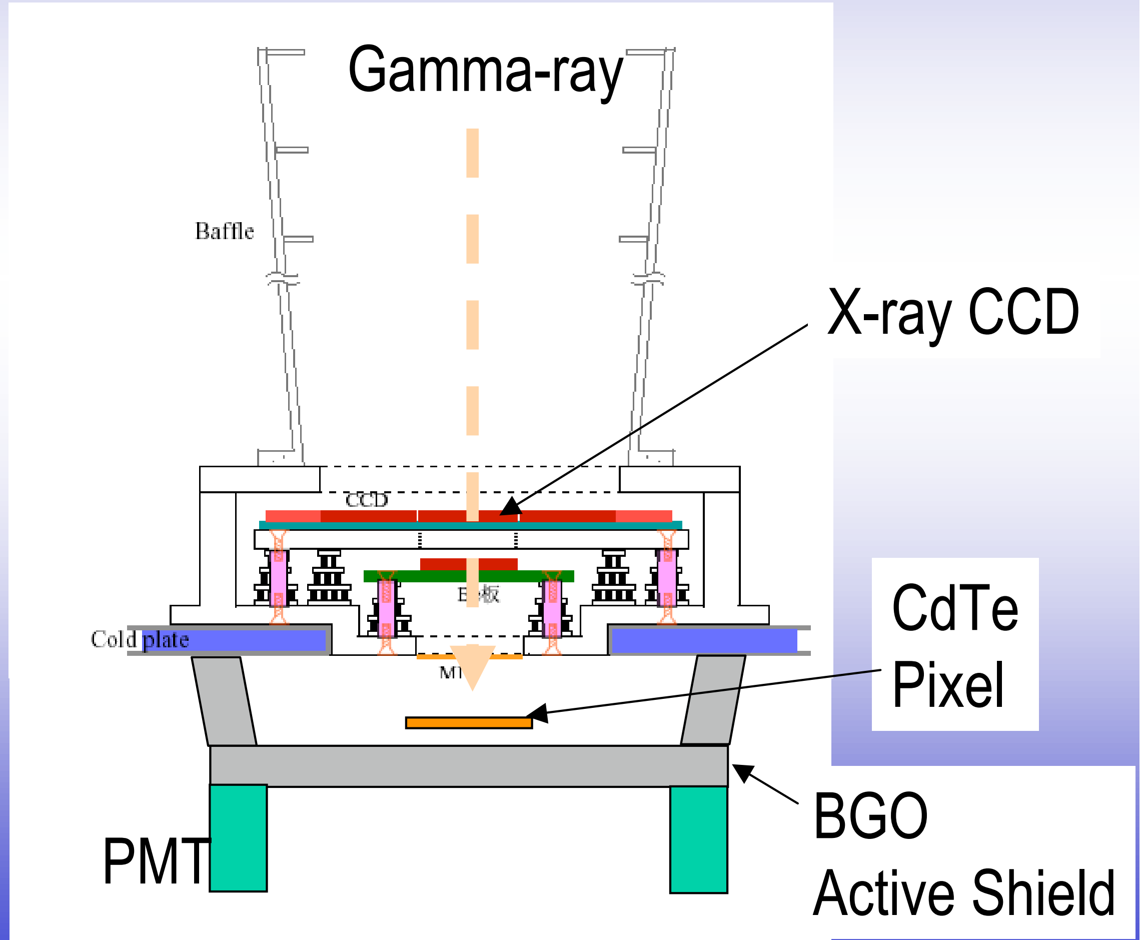
$2x2x0.5mm^3$



Takahashi et al. 1999 NIM A 436

Detector for the NeXT Mission

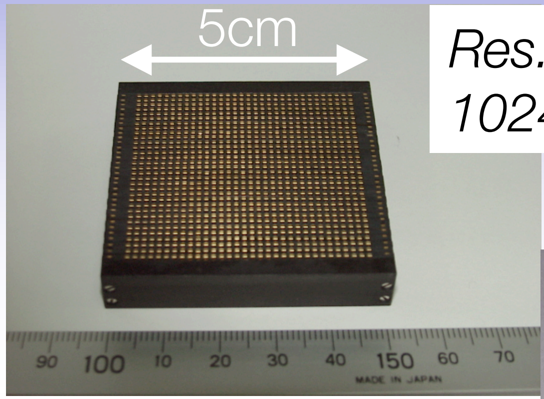




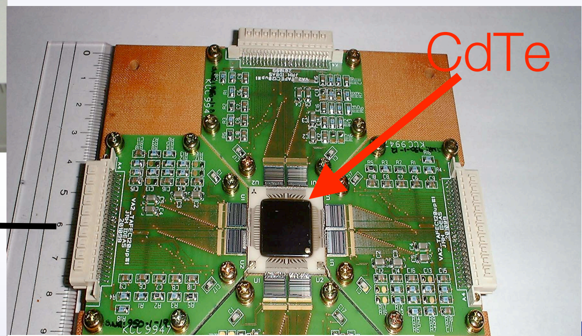
Imager development in ISAS

Key Technology for CdTe/CZT

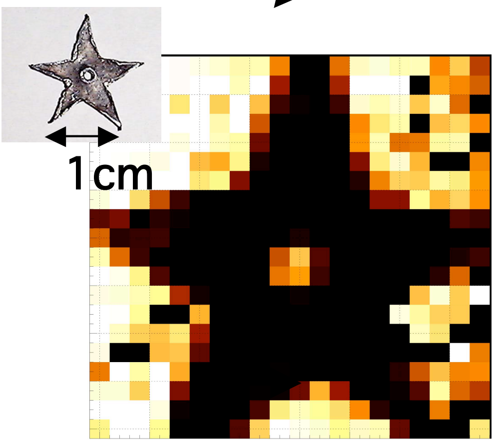
- Crystal (uniformity)
- Electrode on the crystal (Ohmic/Barrier)
- Wire bonding /Bump bonding
- Low noise (<30 electrons) ASICs

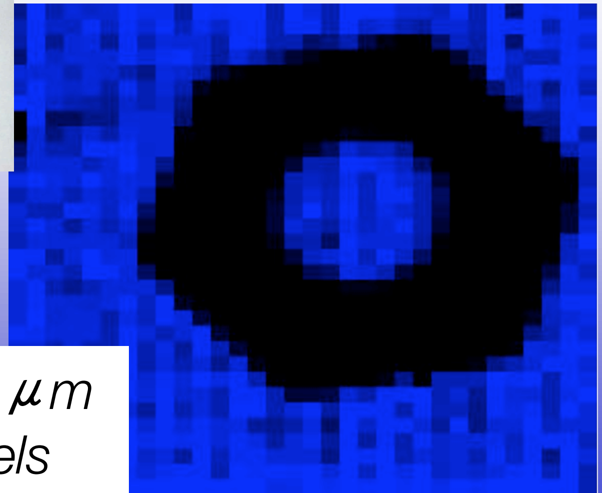


Res. 1.2mm
1024 pixels



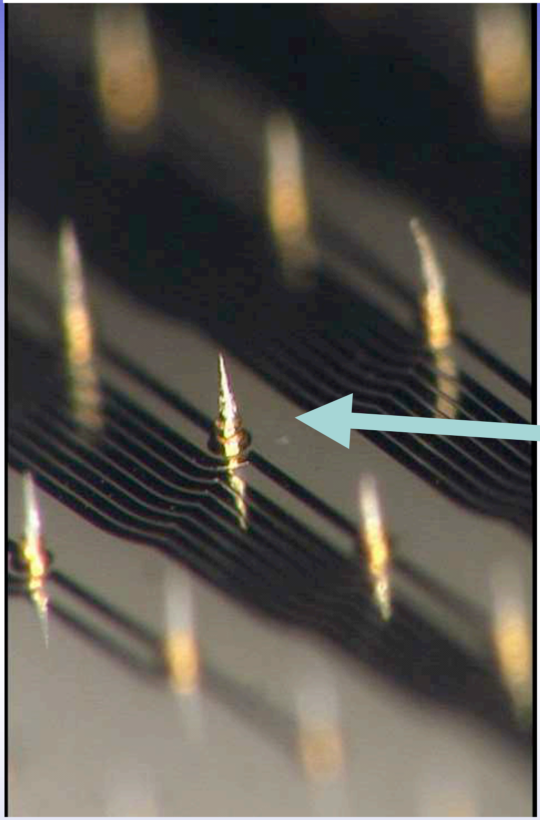
Res. 670 μm
400 pixels



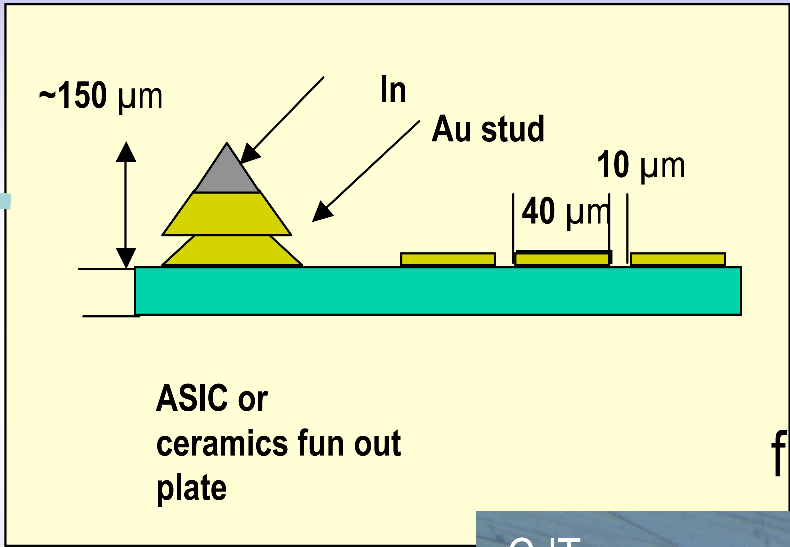


Res. 200 μm
1024 pixels

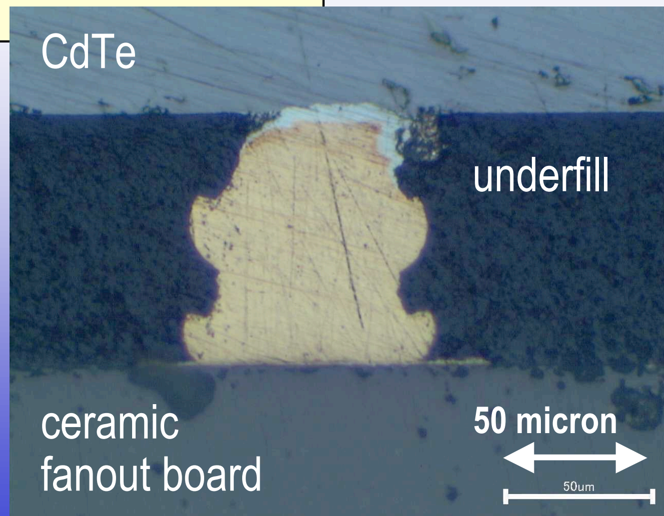
Gold-stud bump bonding for CdTe pixels



1. CdTe surface is very fragile (very soft)
2. Temperature should be kept low (Max 170℃ 10sec)
3. Planarity of CdTe wafer is ~ several micron (not so good)



flip chip bonds



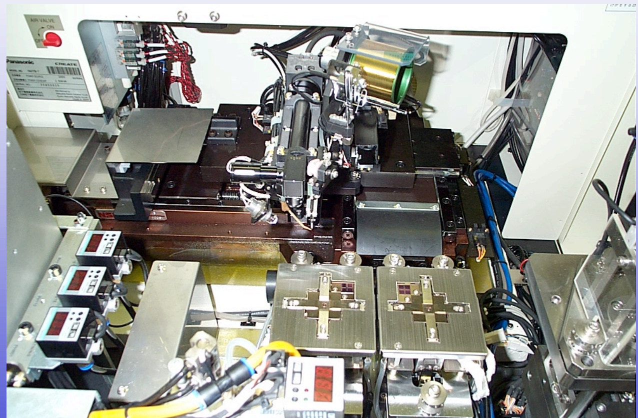
1. A stud consists of two stages of gold stud
2. Indium is printed on the top of the stud
3. Stud are placed on the ASIC (or the fun-out board)
4. Pressed together with 20 g of compression per pixel
5. Epoxy glue with low viscosity is filled in between the detector and the ASIC from the side (underfill)

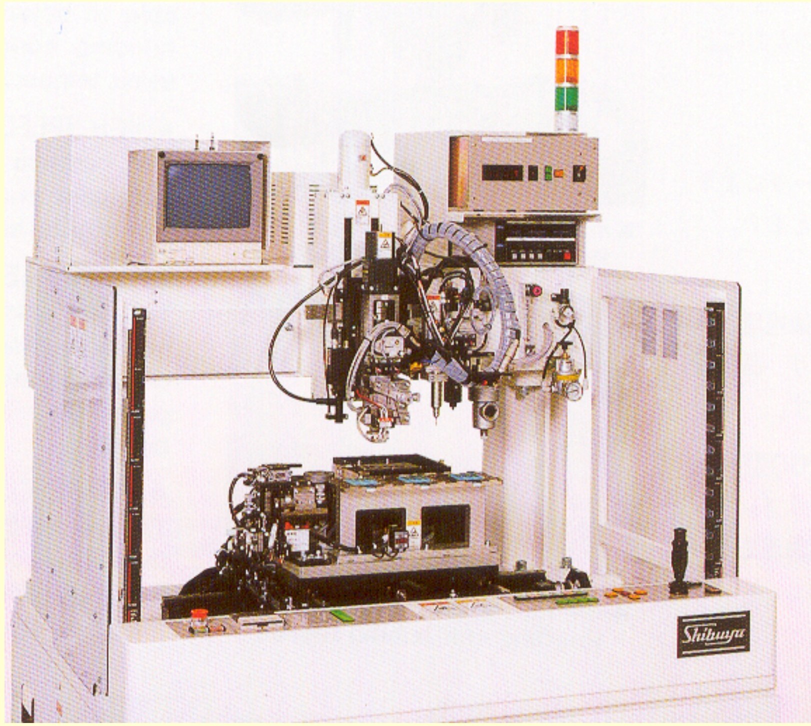
Bump Bonding

ball bonder

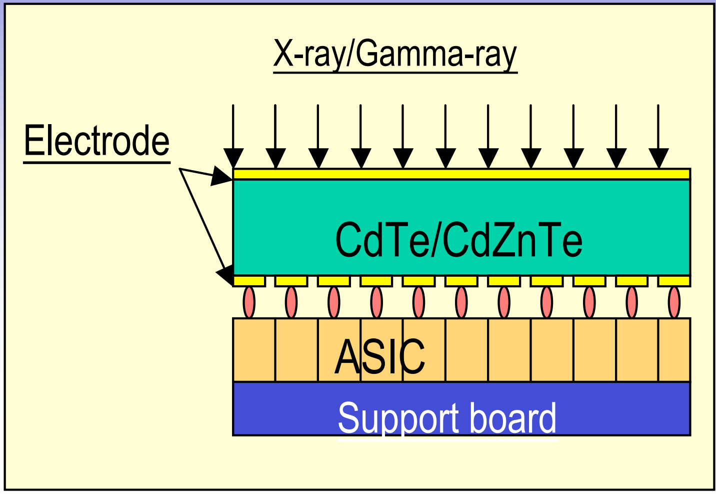
(put Au Stud on an ASIC or a fun out board)

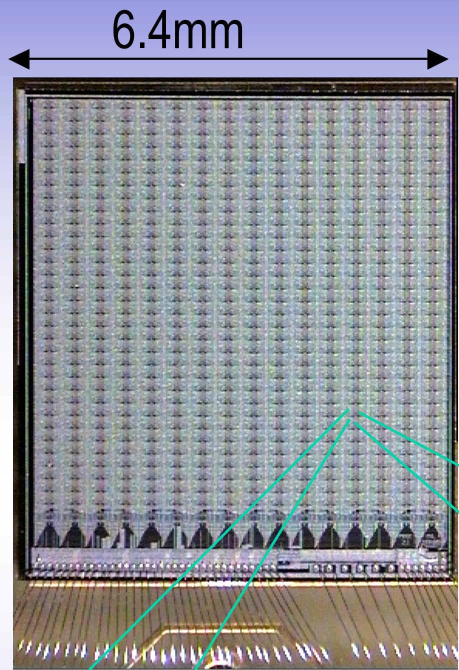
flip chip bonder
(Connect ASIC to CdTe)



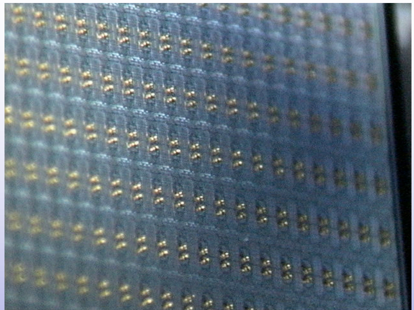


1024 pixel (200 μm x 200 μm) CdTe pixel detector with MPEC 2 chip (ISAS & Bonn Univ. project)

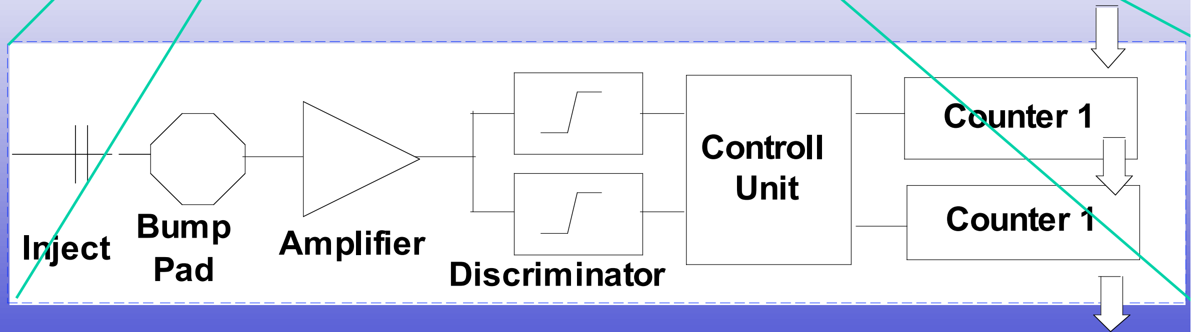




Every pixel contains complete read-out electronics with two discriminators and counters (MPEC2 chip by Bonn. U group)



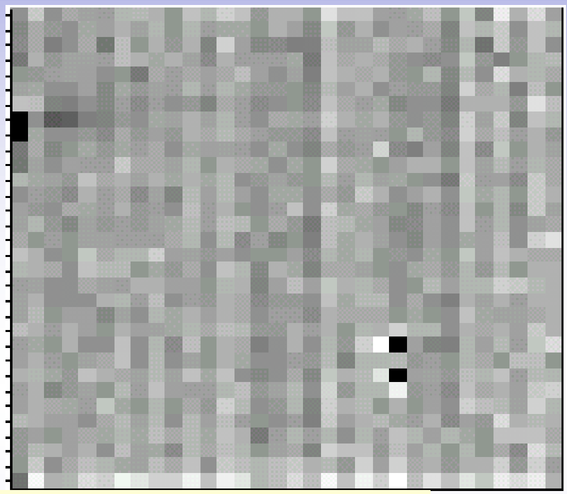
stud bumps



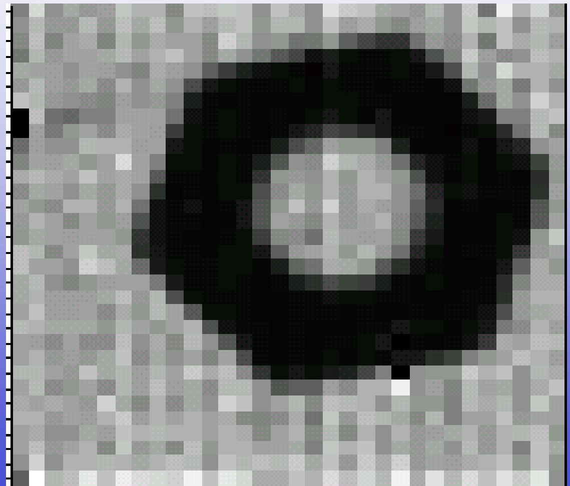
P.Fischer et al. IEEE NS 2001

CdTe+MPEC2 (ISAS & Bonn U. Project)

Flat Image (by 60 keV)

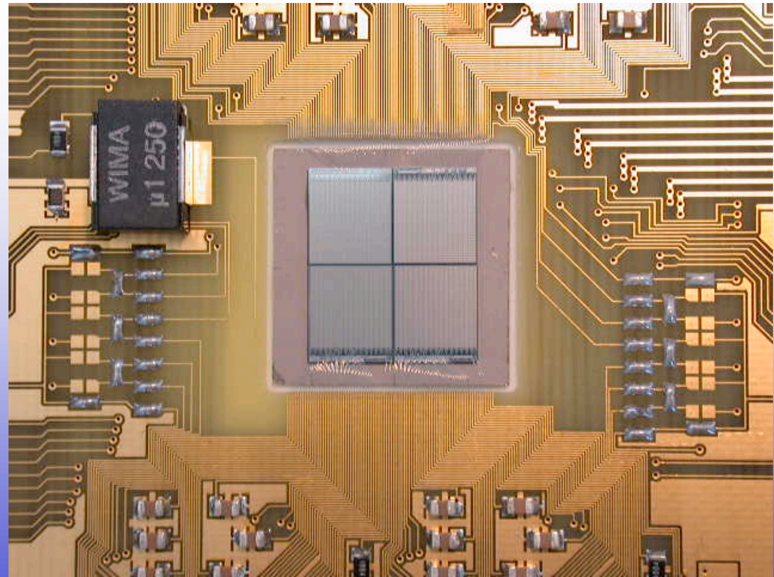


M3 nut (by 60 keV)



bump yield is high (>99.5%)

2nd Project
2x2detector

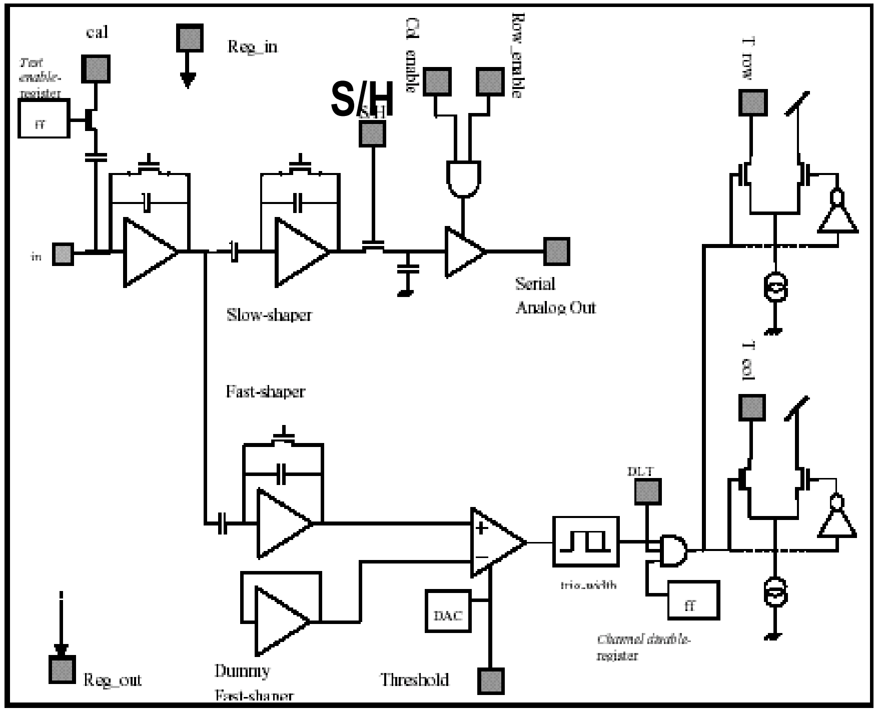


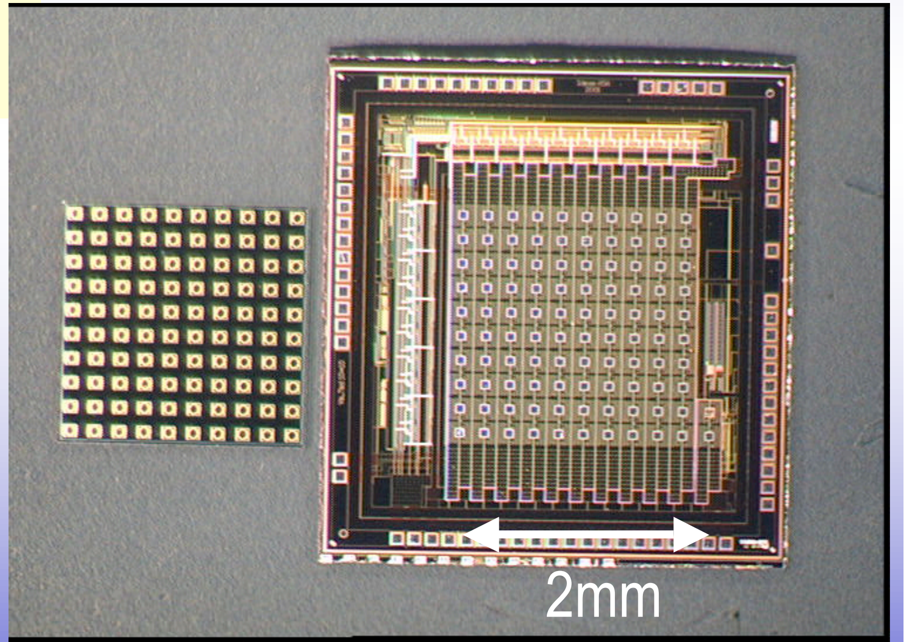
Pilot Chips (ISAS/IDEAS)

Fast Readout Chip for 100 pixels
(X trigger and Y trigger: read out only triggered pixel and its adjacent pixels)

200µmx200µm pixel, Typ. 0.5mW/pixel
0.35micron rule, double-poly, tripple metal with epitaxial layer
Goal : 50 electron @2µs 100fC

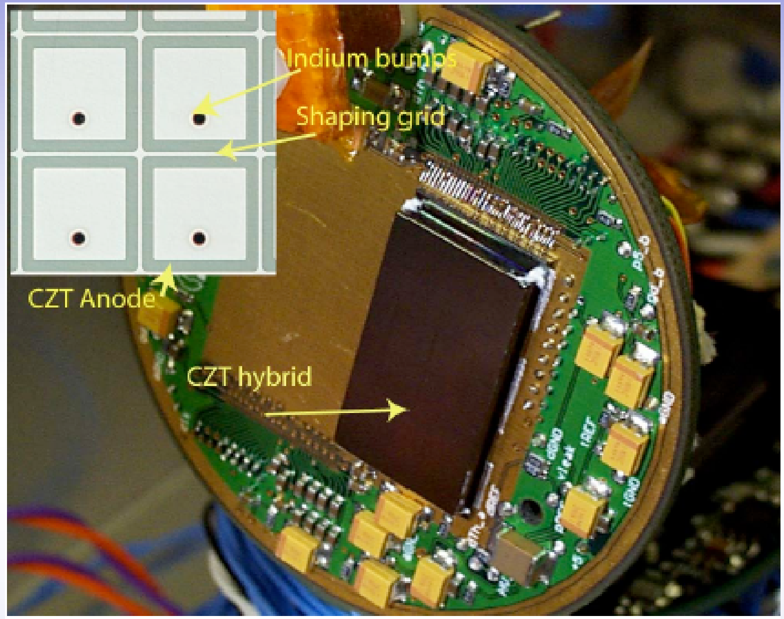
For the Space Application
- total dose 1krad/yr for LEO
- more severe in SEU/SEL
(we need very robust system)



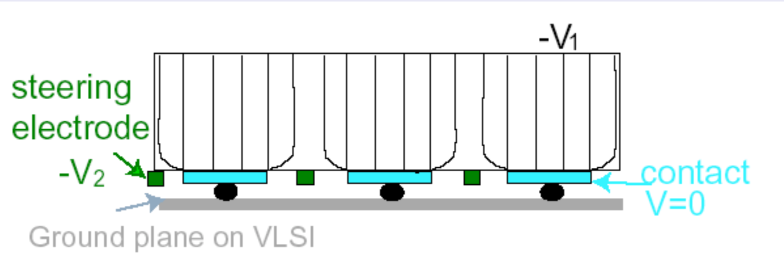


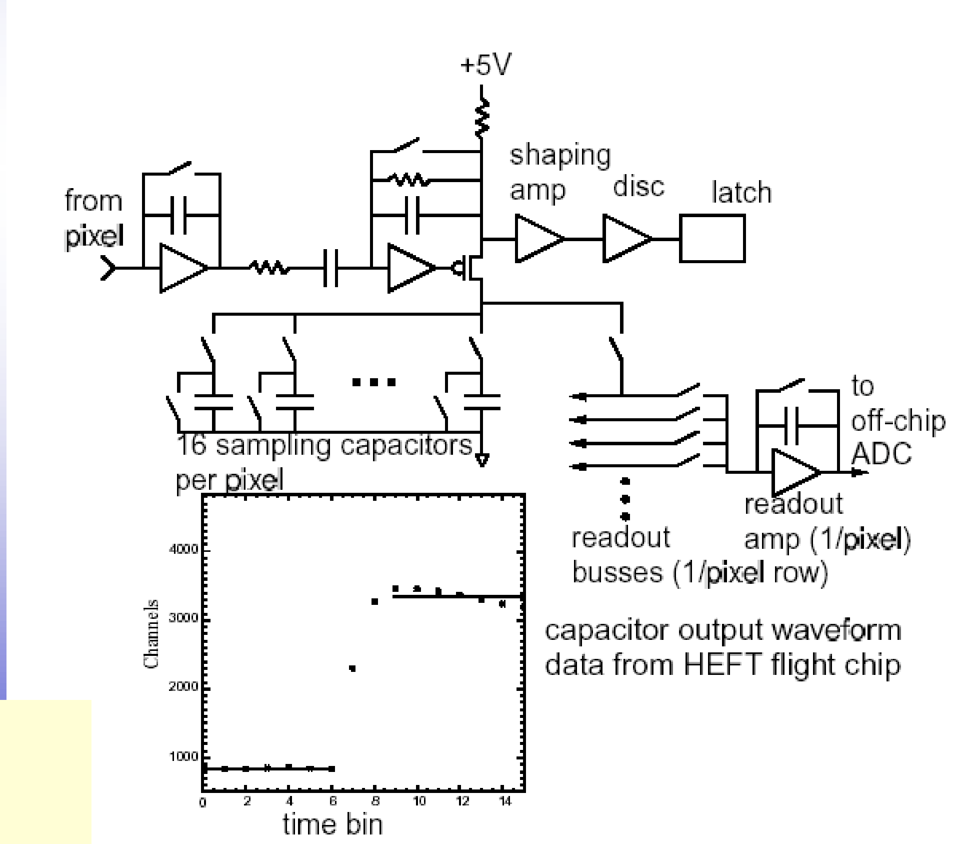
2dim ASIC (100pixel) for the pixel size of 200 micron by 200 micron

CZT imager at Caltech



pixel size: 580 μm x 580 μm
hybrid size : 1.3 cm x 2.5 cm
power : 50 μW/pixel



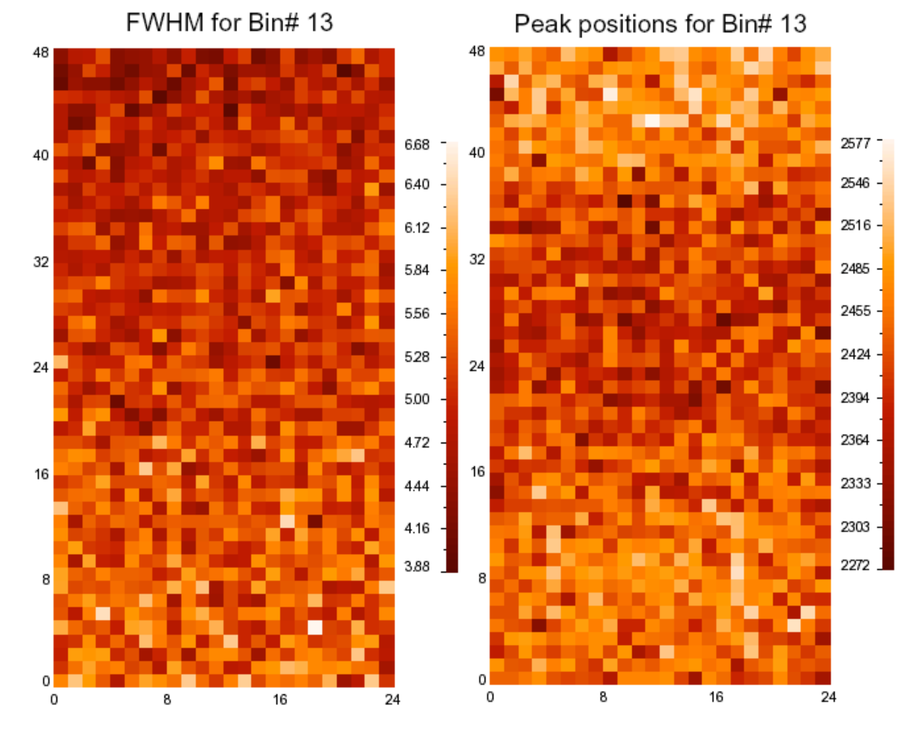


F.A. Harrison et al. SPIE, 2002

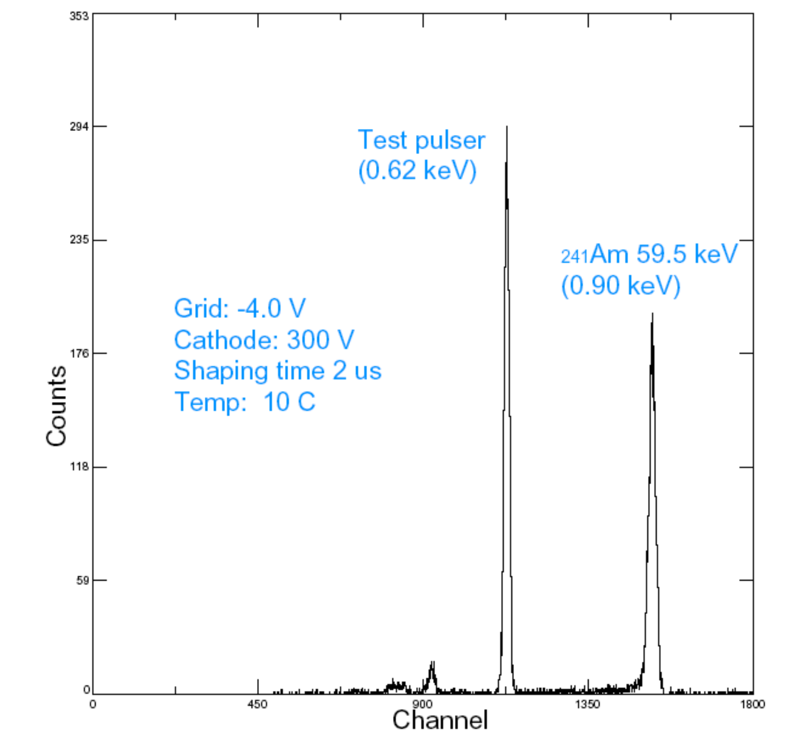
W.R. Cook et al. SPIE 3445, 1998

CZT imager at Caltech

ASIC performance by test pulse



Some Pixel attached



- New collaboration with ISAS will start to
  - Try highly-uniform CdTe single crystal
  - Try Au-Stud bump bonding to reduce capacitance

Summary

- Development of highly-sensitive imaging detector (PIXEL) in Hard X-ray (and in Gamma-ray) is crucial for the high-energy astro-physics mission planned in next 10 years.
- CdTe and CZT are most promising candidates for hard X-ray imager:
  - We have experienced significant progress in last 5-6 years, but still
    - We need to study more about materials
    - We need to establish more about hybridization issue
    - We need low noise ASICs (RMS noise < 50 electrons)