X-ray CCD Detectors for Astronomy and Space Science

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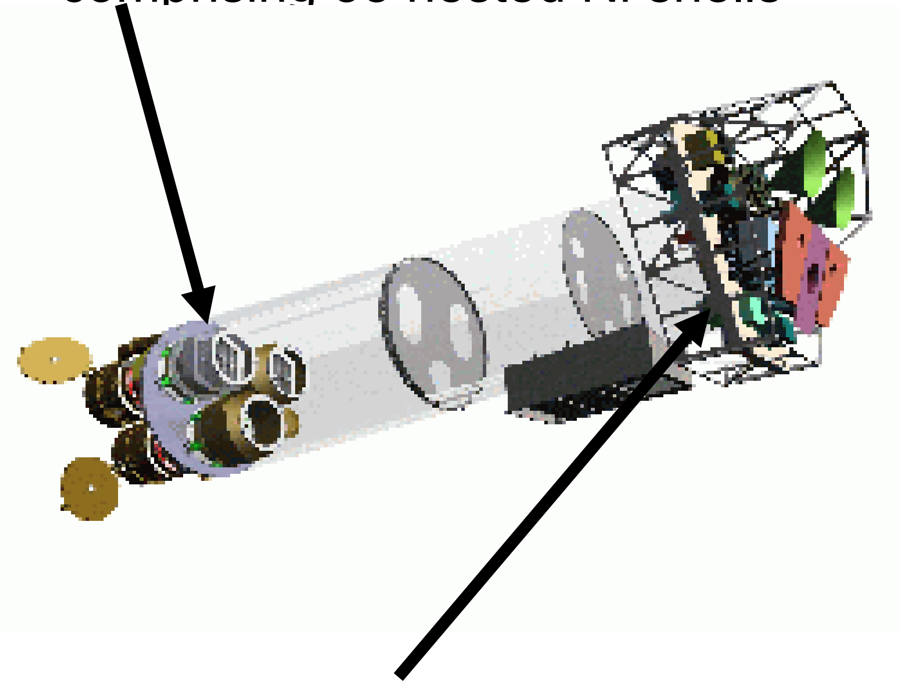
The Open University
e2v centre for electronic imaging

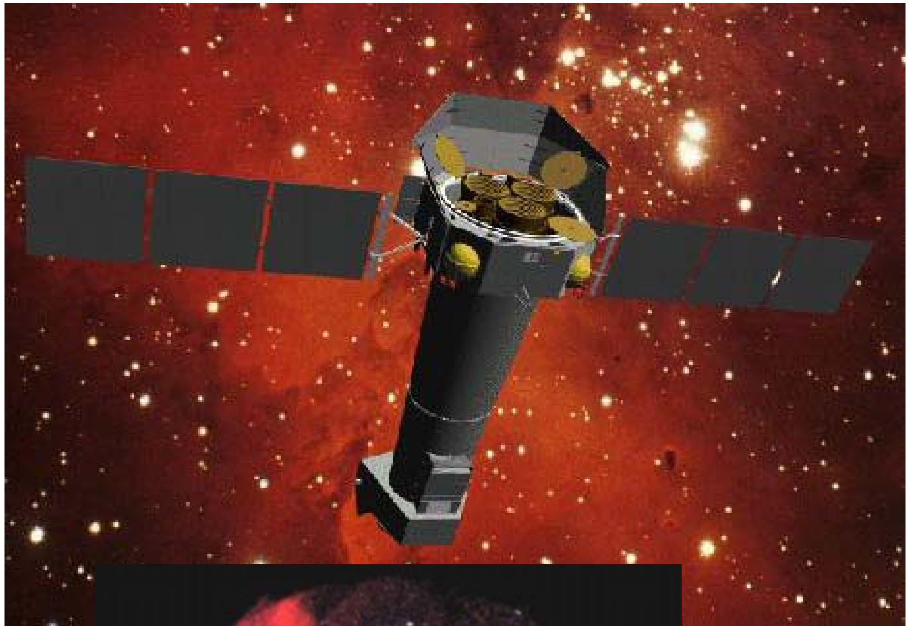
Focussed X-ray Imaging

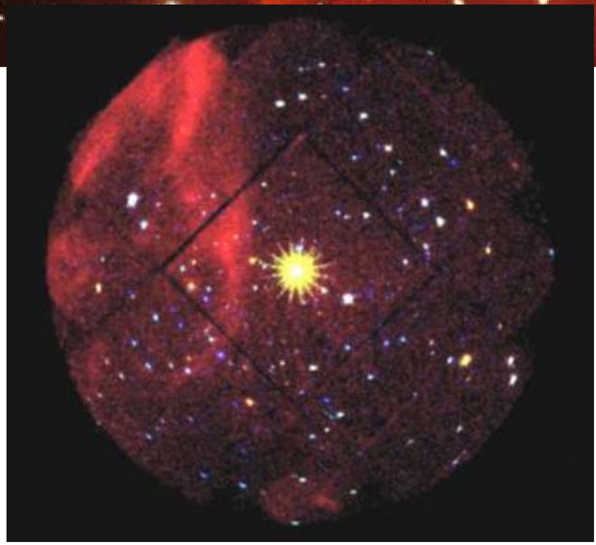
The ESA XMM/Newton Spacecraft

3 co-aligned optics, each comprising 58 nested Ni shells



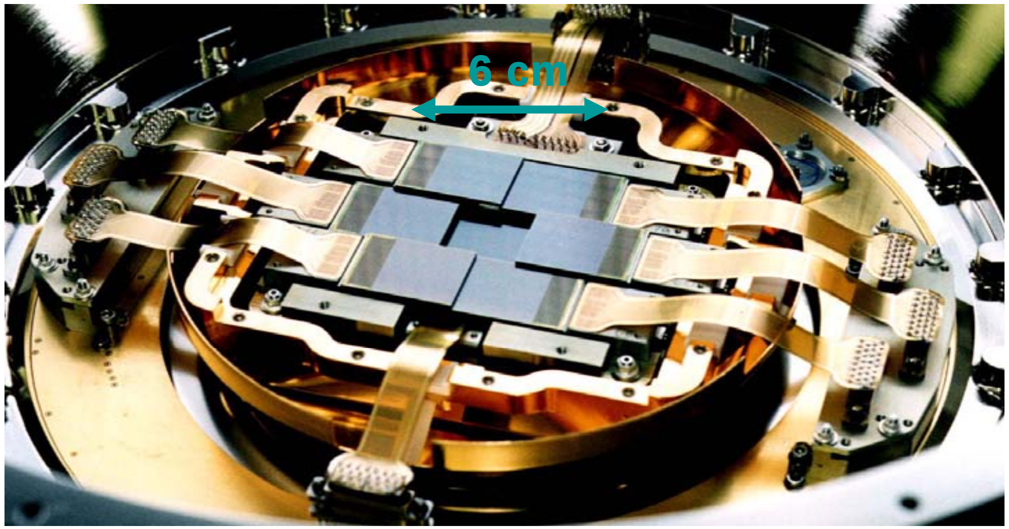
Focal plane detector arrays providing imaging and spectroscopy

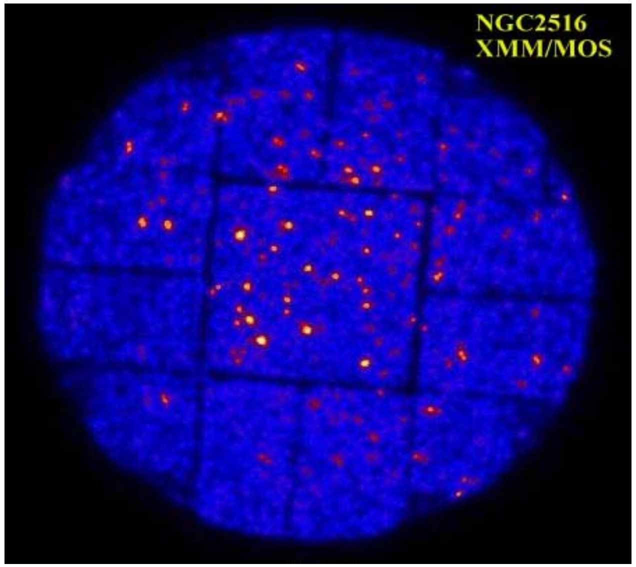




XMM EPIC MOS Cameras

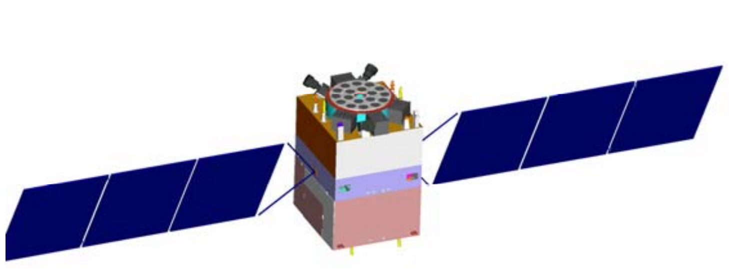
- 2 UK MOS cameras, having focal plane arrays of 7 CCDs
- Share their telescopes with the 2 RGS instruments
- Broad-band from 0.3-10 keV, ~35 μm depletion
- Increase in throughput, high energy QE and sub-keV resolution possible
- **Redundancy** comes from multiple detectors (and cameras)

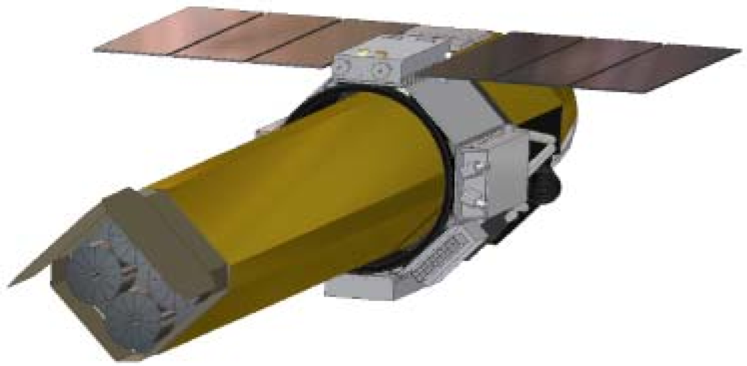


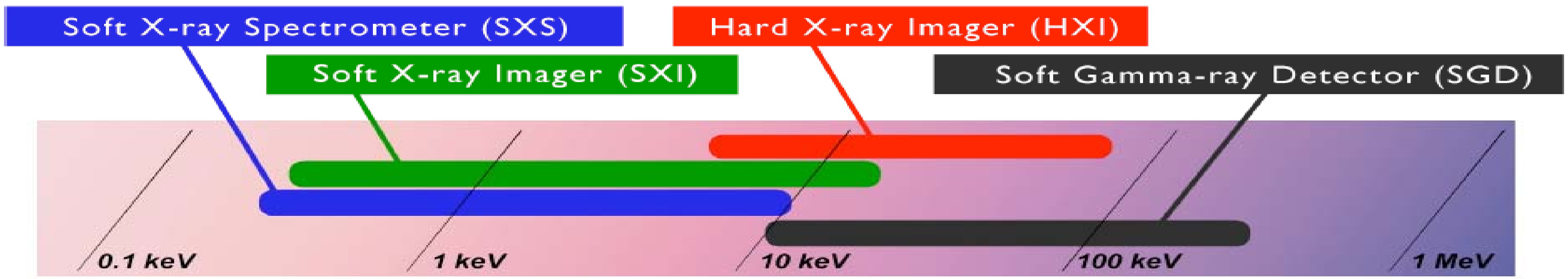


Future X-ray Astronomy Missions

- HXMT (China) ~2012
  - China's first X-ray astronomy mission
  - Collimated
- NeXT (Japan) ~2013
  - X-ray telescope
- IXO (ESA/NASA/Jaxa) ~2018
  - Merger of XEUS and Con-X

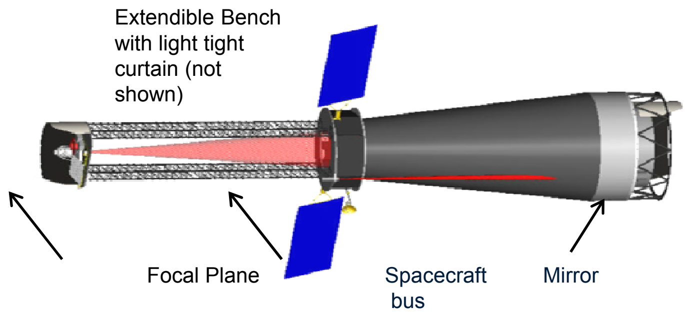




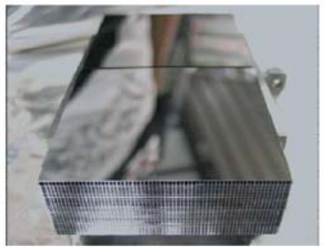


IXO baseline concept

- **"XEUS" becomes "IXO"**
- IXO science goals encompass all of XEUS and Con-X core science.
- L2 halo orbit
- Baseline is one spacecraft with an extensible optical bench instead of two spacecraft in formation-flying configuration
  - – requires the provision of a focal plane instrument interchange mechanism
- ESA Si-pore optics remain in the baseline for IXO, but US will study slumped-glass alternative in parallel
  - – NB parallel ESA study of slumped glass was already anticipated for XEUS.



Silicon



Glass

IXO baseline concept

- Focal length is now 20-25m instead of 35m for XEUS
  - implications for the effective area as a function of energy and the instrument fields of view.
- Key requirements:
  - affective area ~3 m^2 @ 1.25 keV; ~1 m^2 @ 6 keV
  - angular resolution ≤ 5 arcsec
- Single optic with design optimized to minimize mass and maximize the collecting area ~3.4m diameter

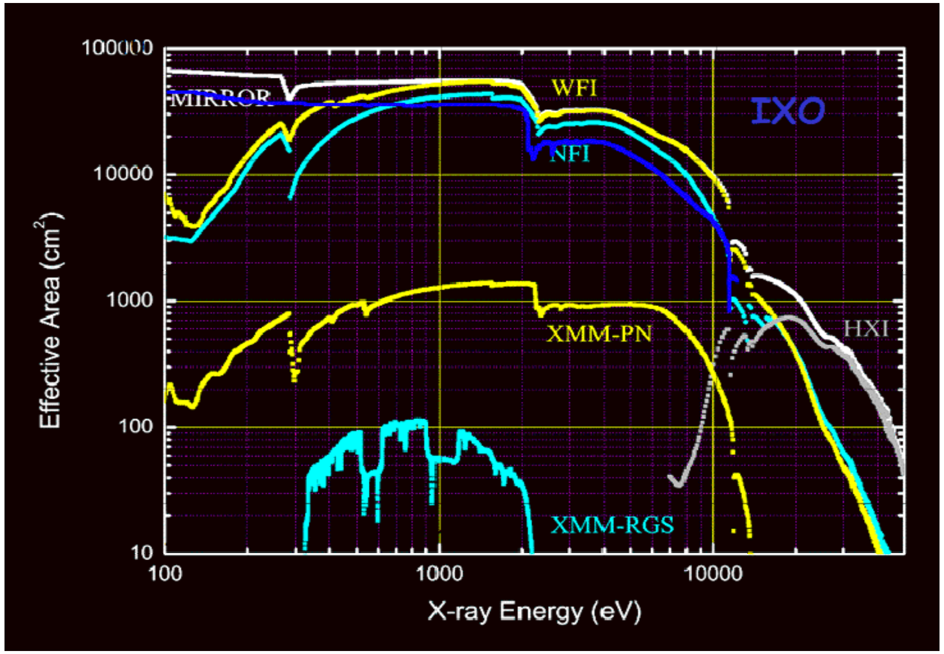
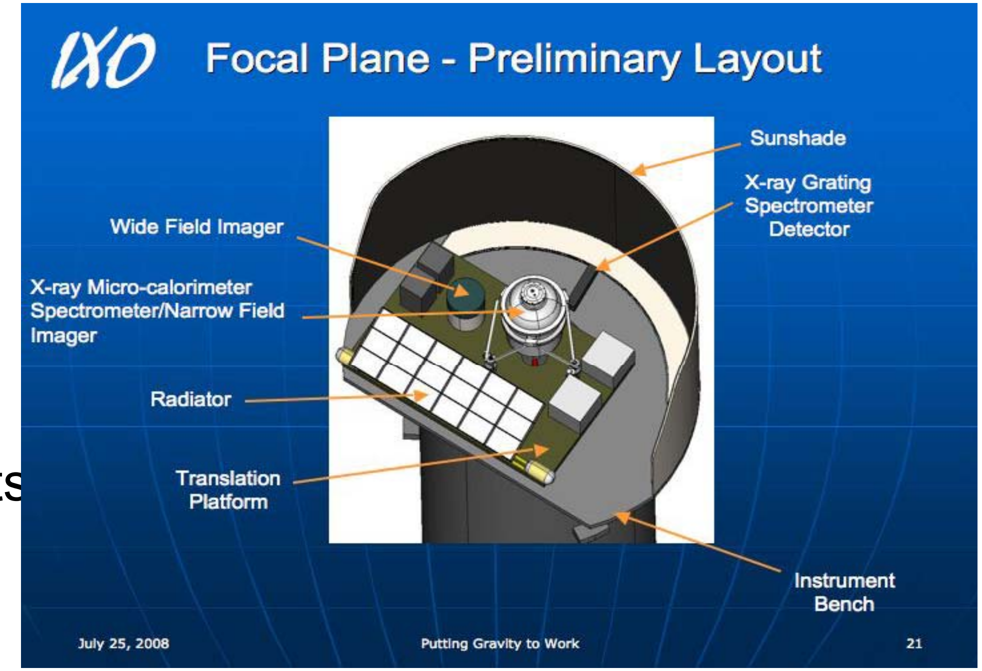


figure courtesy Günther Hasinger

IXO baseline concept

- Baseline instruments are:
  - **an X-ray wide field imaging spectrometer (=XEUS WFI)**
  - a high spectral resolution non-dispersive X-ray spectrometer (=XEUS NFI, Con-X XCS)
  - an X-ray grating spectrometer (=Con-X XGS)
  - “allocation for further payload elements with modest resource demands”
- Potential fields of view:
  - WFI: 12 arcmin
  - NFI: 5 arcmin



Key Reasons to Continue MOS Activity

- **Complementary technology to DEPFET**
  - **Reduces Technical Risk**
  - **Instrument Background**
    - Instrument background IS lower in the XMM MOS CCDs
  - **Redundancy**
    - Key unknown risk of micrometeorite hit killing FPA
    - 2 separate WFI sub-systems virtually remove risk of catastrophic failure
- **Hope to re-introduce increased FOV for WFI**

Key Technical MOS Developments

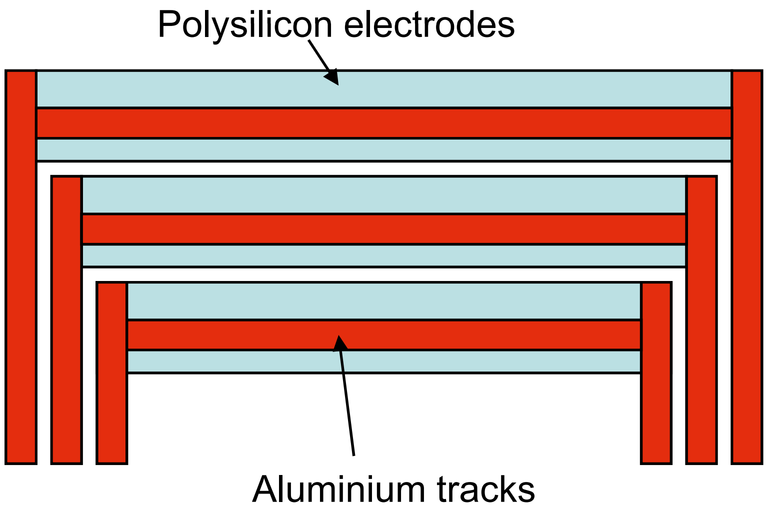
Development Item	Current Position	Goal	Funding Source
Increased Efficiency Deep depletion for higher >5 keV QE	300 µm	300 µm (achieved)	e2v PV
High speed readout ASIC Charge Transfer Speed	RAL design, 4 chan, 7 e- rms. ~10 µs/row	<5 e- rms. ~100ns/row	STFC + e2v PV Test current examples
Radiation Hardness Charge Injection and p-channel	~10 e- rms. injection noise 2kx4k samples	3 e- rms. ~3x improvement over n-channel	e2v PV + RG case
Low energy resolution	80 eV at 500eV	40 eV	Already have first test devices

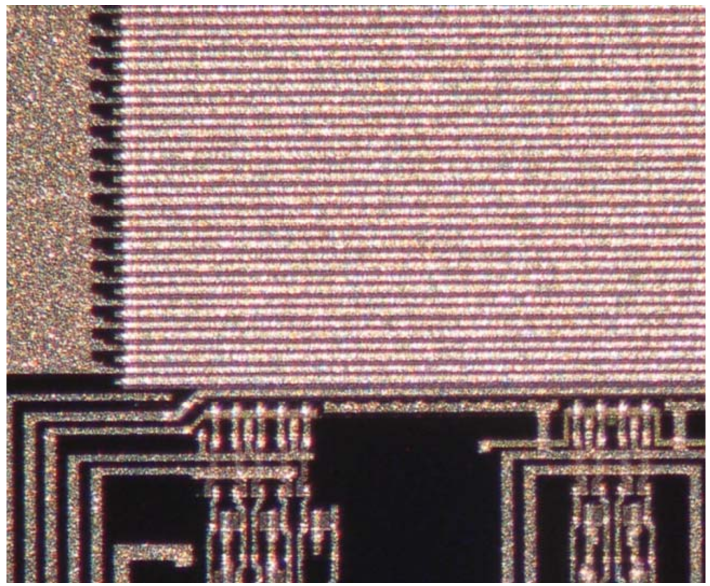
Key Developments Beyond XMM/EPIC

- Key DEPFET Alternative Technology Required
  - Charge Transfer Speed increase
- Key E-WFI Developments Required
  - Baffle and Straylight analysis
- Common Development Requirements
  - High throughput using a low noise multi channel ASICs
  - Improved high energy QE
  - High Sensitivity (low background)
  - Improved spectroscopic resolution at low energies
  - Radiation hard

Increased Transfer Speed

- A >30x increase in the throughput for the IXO optic can be achieved by
  - Fewer pixels (1/3)
  - An increase in readout speed (3x)
  - An increase in number of output nodes (8x)
- For a 2x1" format detector, frame time is 30 ms
- To retain >100:1 integration:transfer time – Frame transfer time should be <300 μs
- Line transfer time <<0.5 μs
- This requires the new technique of metal buttressing over the polysilicon electrodes to reduce resistance
- This technique has been developed for the CPCCD for LHC at e2v

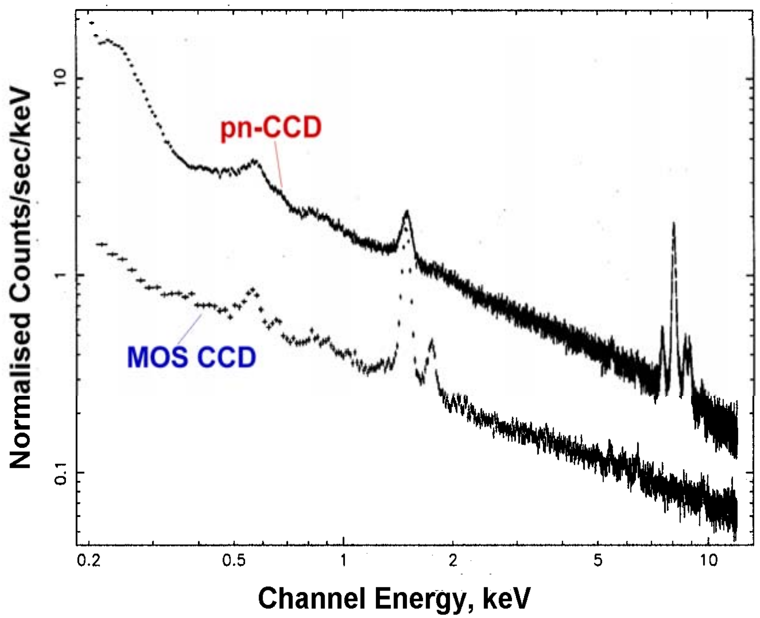




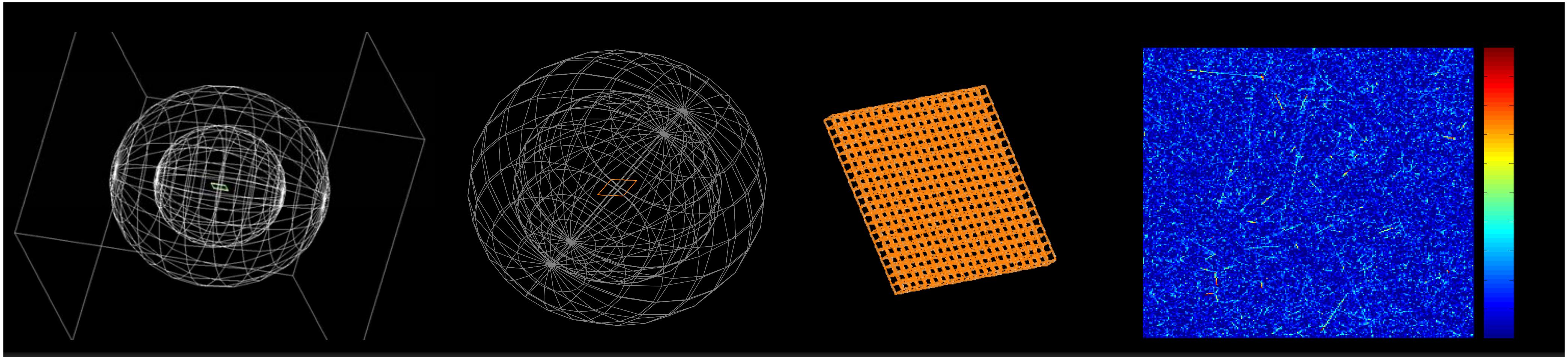
Low Background Detectors for E-WFI

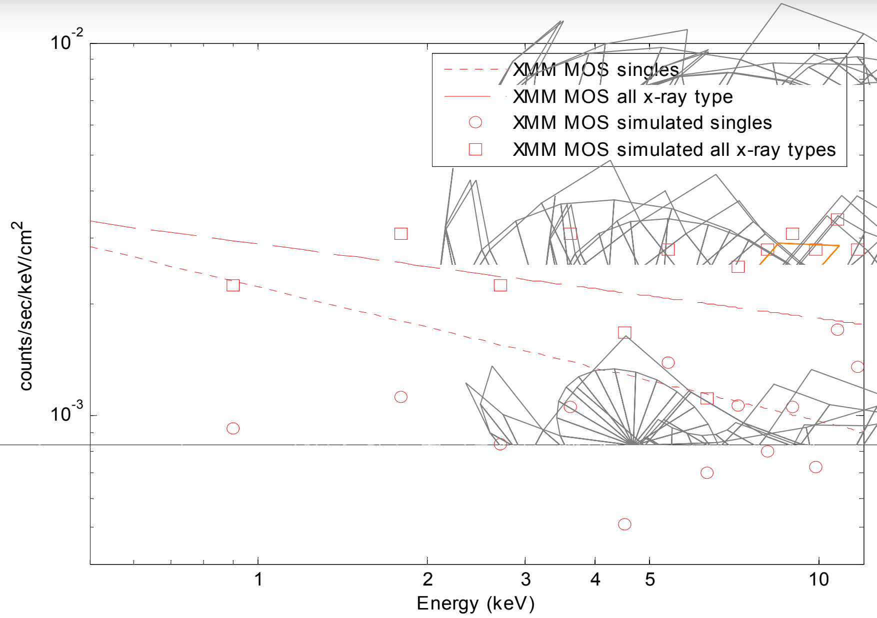
- Optimal sensitivity combines
  - Expected source spectrum
  - Mirror efficiency (basically <2 keV)
  - Detector QE
  - Detector background
- XMM detectors sensitive to
  - Single or double sided detection (+100%)
  - Thickness of "Entrance window" (+50%)
  - Pixel size (~10-20%)
- We are performing a study to maximise instrument sensitivity
- Warning against using many elements in the baffle/camera

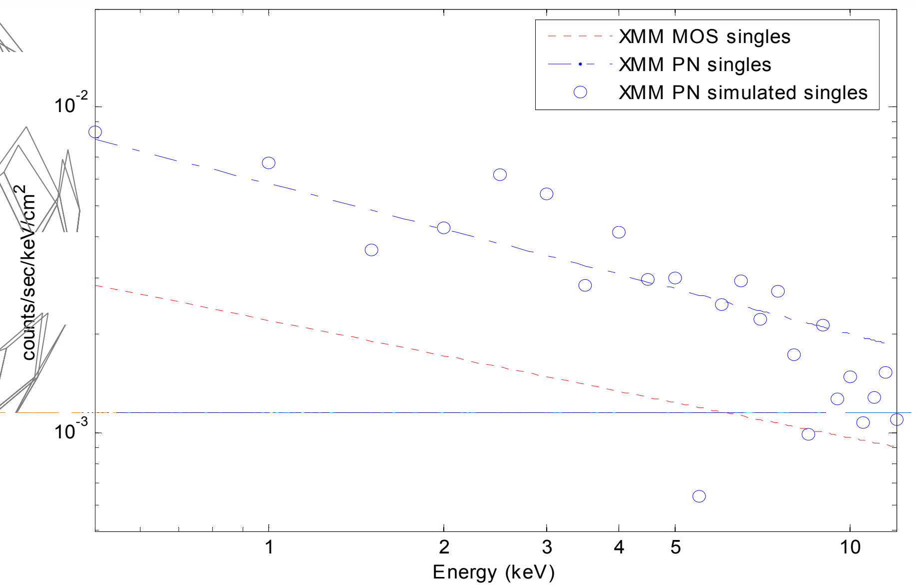
Out of field background (D.Lumb report)



Geant4 Model and Results







Instrument Background Study

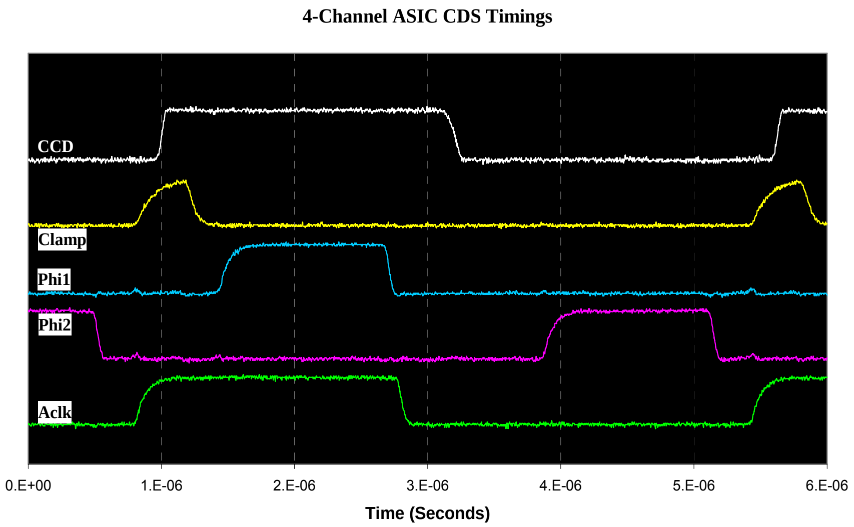
- Extensive study performed using Geant-4 comparing to EPIC MOS+pn, Suzaku and Swift instruments
- For XMM EPIC the dominant background is LE electrons from the camera
  - EPIC array averaged area to primary protons ~14 cm^2, ~50/s, >99.9% penetrating particles rejected
  - Residual background from soft electrons from surroundings plus Compton electrons internal to sensor
  - With scintillator veto shield, averaged area >300 cm^2, ~ 1200/s, would add to dead time, high-Z would also create more gamma background
- FI MOS CCDs inherently lower sensitivity to these than fully depleted BI structures
- Need to perform study into reducing the electron component off the shield
- Further Geant-4 model development to be undertaken

- Concerns over high-Z active shields impacting Si background + coatings
  - EPIC used Al shielding specifically to minimise background

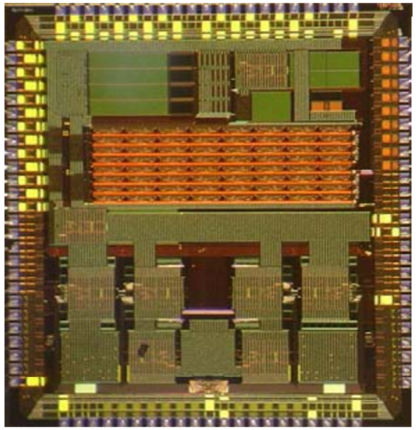
High Speed Readout

- High throughput required to minimise pile-up
- System noise specification of 5 e- rms.
- XMM/EPIC 1 node at 160 kHz
- XEUS minimum requirement : 8 nodes at 1 MHz
  - 30 x faster than XMM/EPIC
- Initial development with RAL (1 and 4 channel, 6-10 e- noise)
- Aim to develop a full 8 channel design

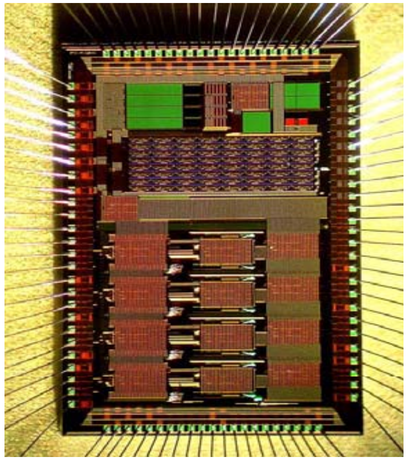
Clock timing diagram



2-channel CDS ASIC



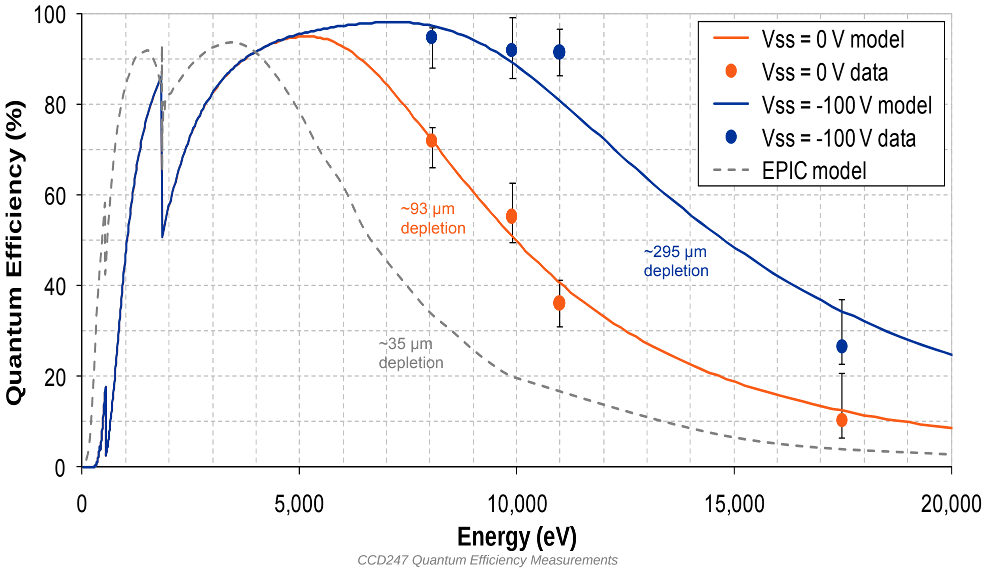
4 Channel ASIC



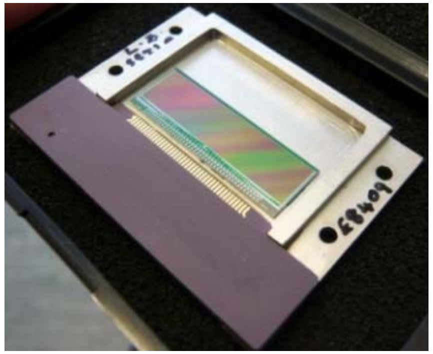
Increased Detection Efficiency

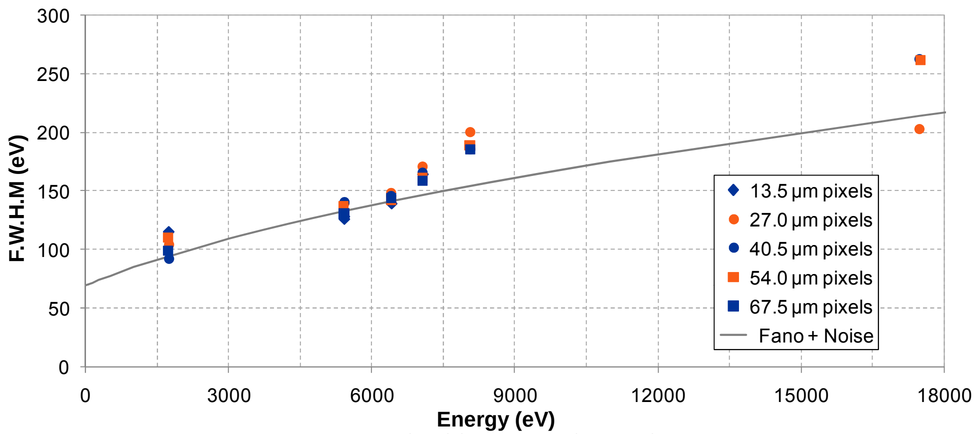
(see poster by Murray)

- Use of high purity bulk (FZ) material can increase depletion depth
- De-coupling rear substrate from that local to FET can enable increased bias
- 300 µm depletion for -100V on substrate
- 2nd generation devices tested using 512x2048 format – 13.5µm pixels
- Used on-chip binning to explore FWHM resolution vs. pixel size



CCD247 Quantum Efficiency Measurements

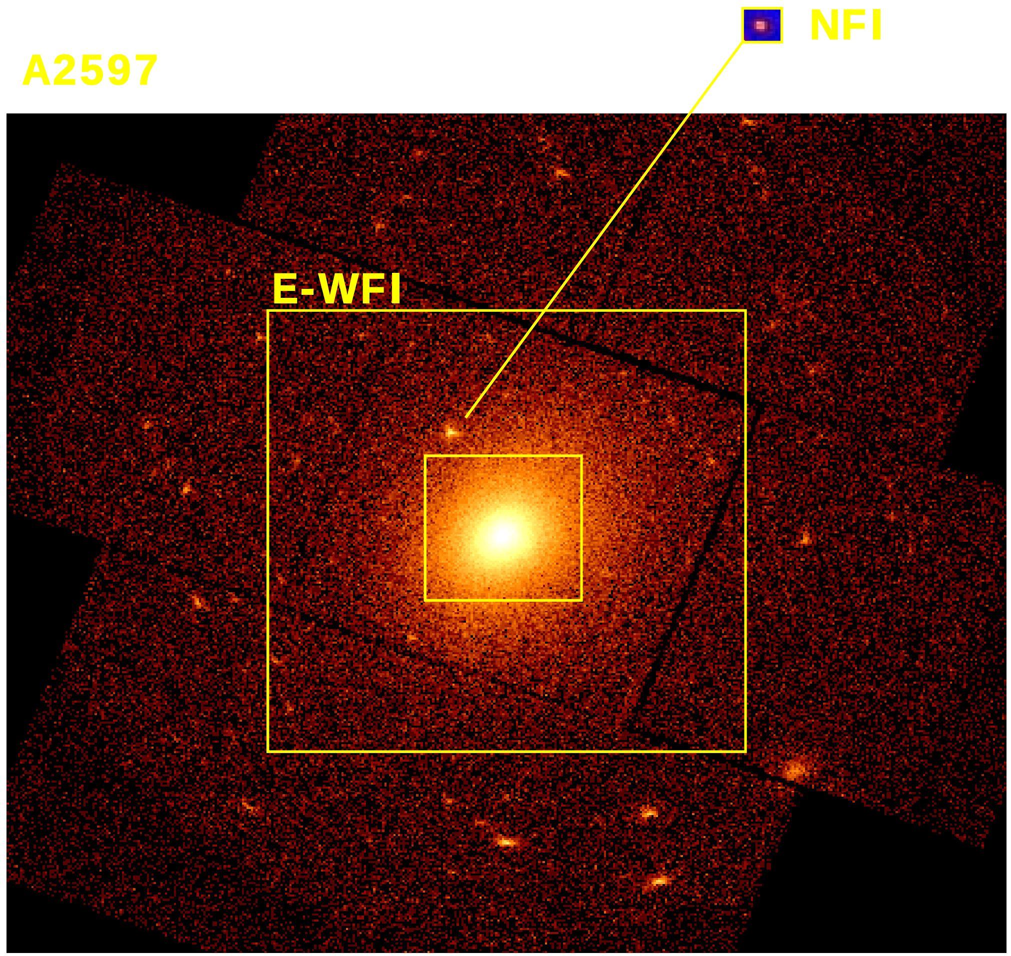




CCD247 Spectral Resolution Measurements (V_{SS} = -100 V)

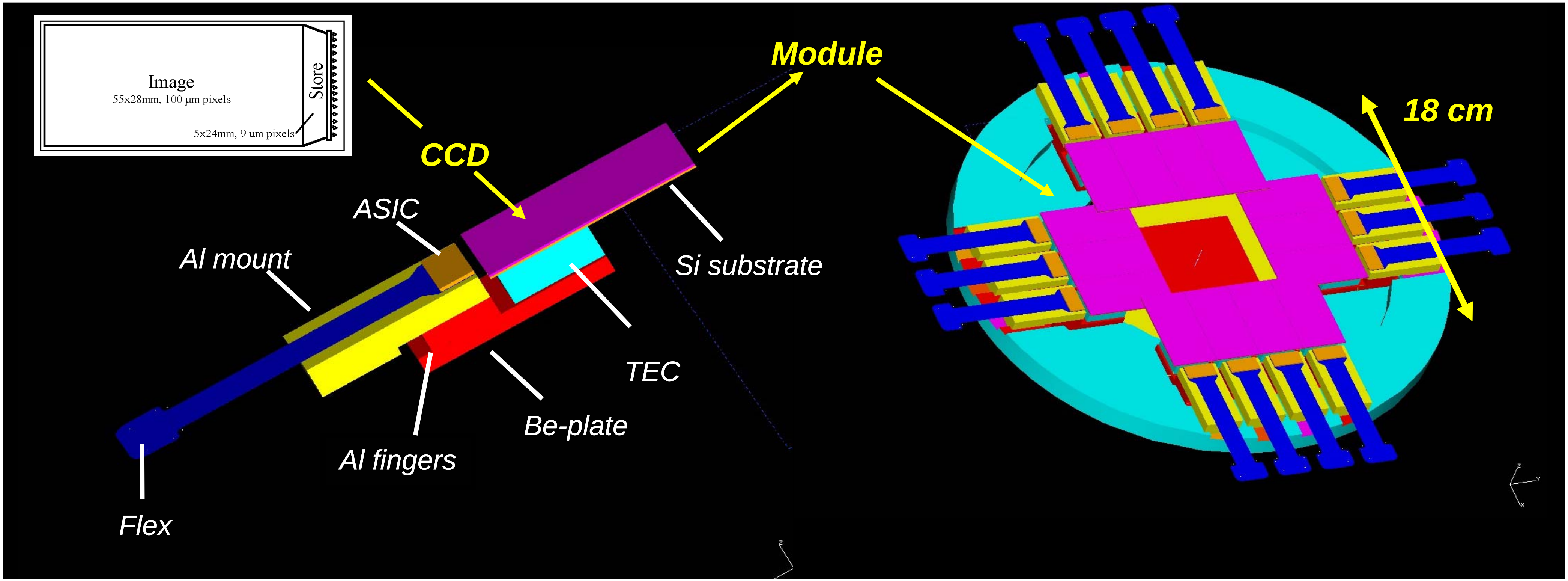
Increase in Science from the E-WFI

- IXO optic has 3.5x the focal length of XMM
- Useable field to 20 arcmin and **limited by detector size**
- Needs a very large focal plane array
- Survey & find first black hole requires use of all of field
- Proposing the DEPFET for the central field
- MOS CCDs to enhance field coverage by 9x
- Gives access to much more data



The XEUS E-WFI

- An X-ray camera for XEUS : dual technology to cover the target and serendipetous science
- Much larger array than XMM EPIC
- High rate DEPFET central array, surrounded by a CCD outer ring
- Only one possible CCD construction shown



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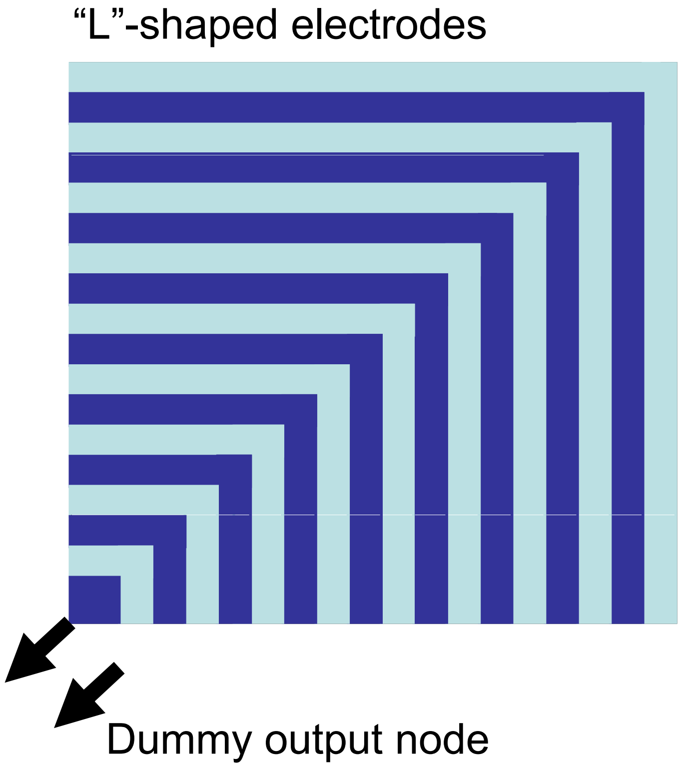
The Swept Charge Device

- Non-imaging CCD-based sensor for XRF
- Developed under the UK Impact programme ~1998
- New generation of devices designed in 2007

The New Family of SCDs

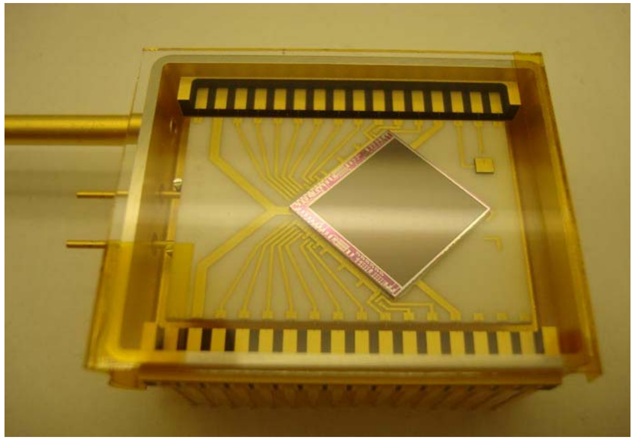
- **Non-imaging CCD technology for XRF**
- New design provides improvements to:
  - Radiation hardness
  - Readout speed
  - Operating temperature
- 2 phase operation with 100 µm pitch

Designation	"Pixels"	Area
CCD235	20	5 mm^2
CCD234	200	100 mm^2
CCD236	200	420 mm^2

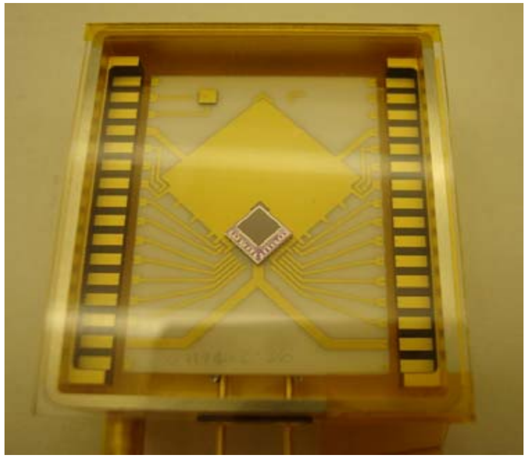


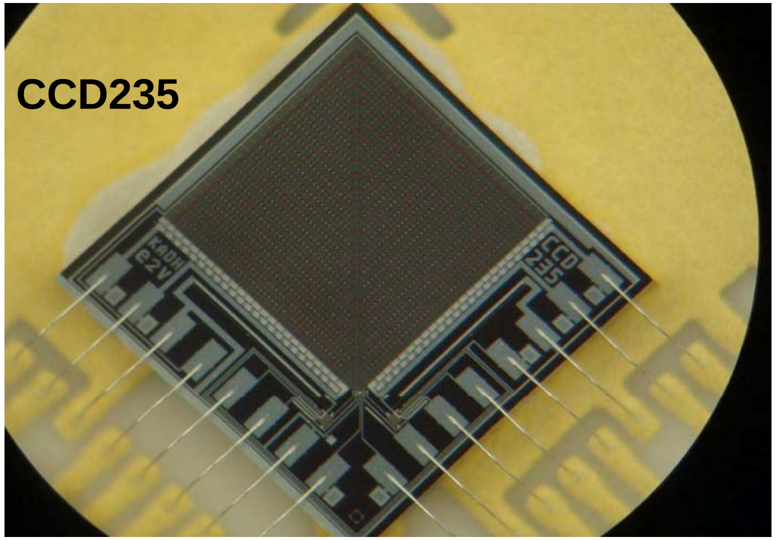
CCD234 and CCD235

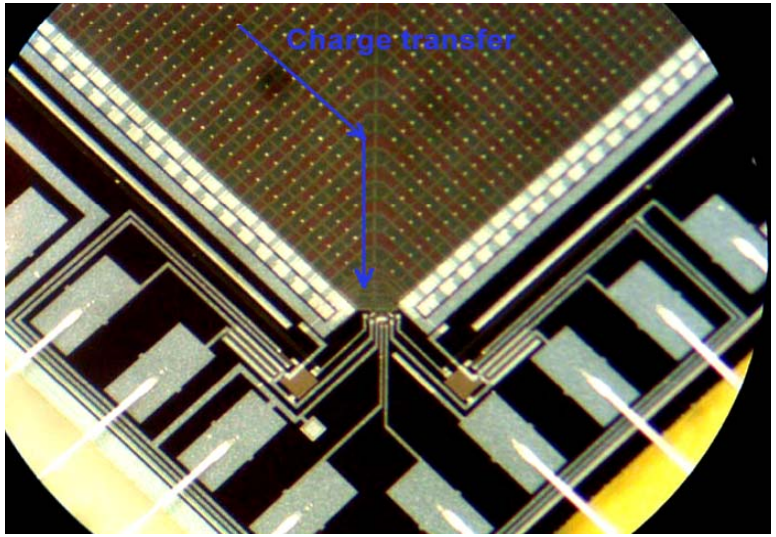
- CCD234 – Area = 100 mm^2



- CCD235 – Area = 5 mm^2

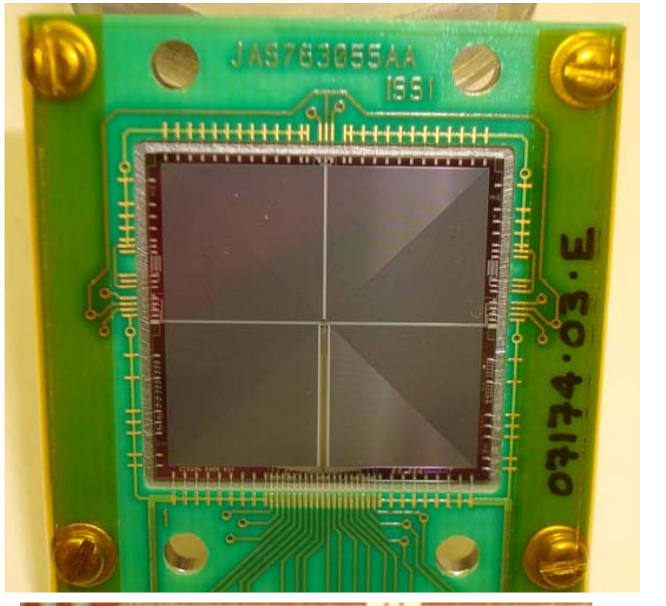




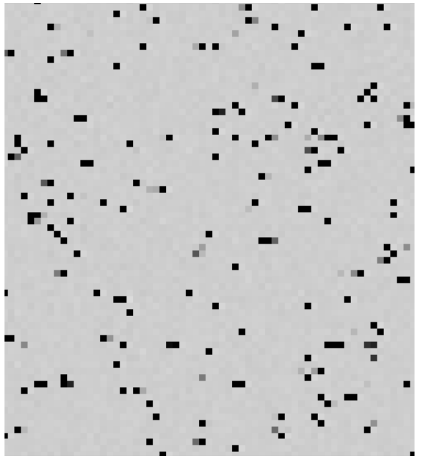


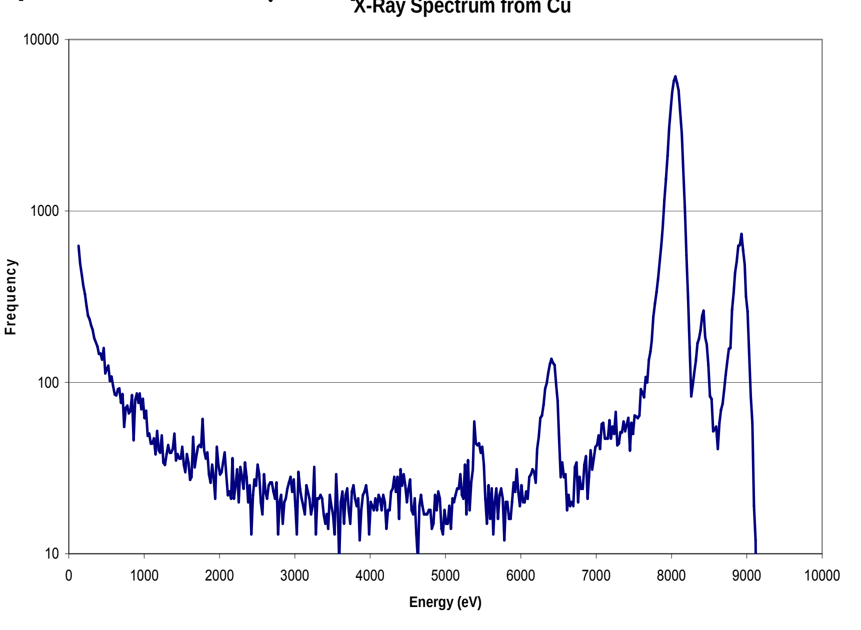
Large Pixels (100 μm)

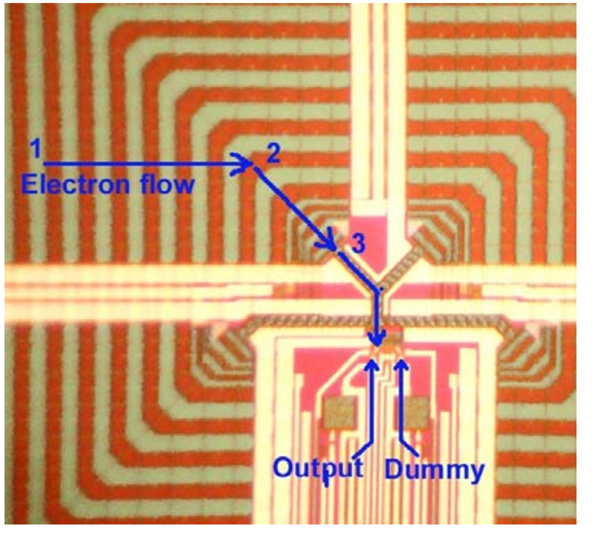
- X-ray optic PSF is ~1mm in diameter
- Fewer/larger pixels promote an increase in frame rate
- New CCDs tested with 100 μm pixel pitch for HXMT
- Large pixels demonstrating high charge collection and good CTE for X-ray spectroscopy
- Improved radiation hardness due to charge confinement – needs verification by tests
- CCD236 shown – 2 phase, 100 μm pitch



Cu-K in CCD235

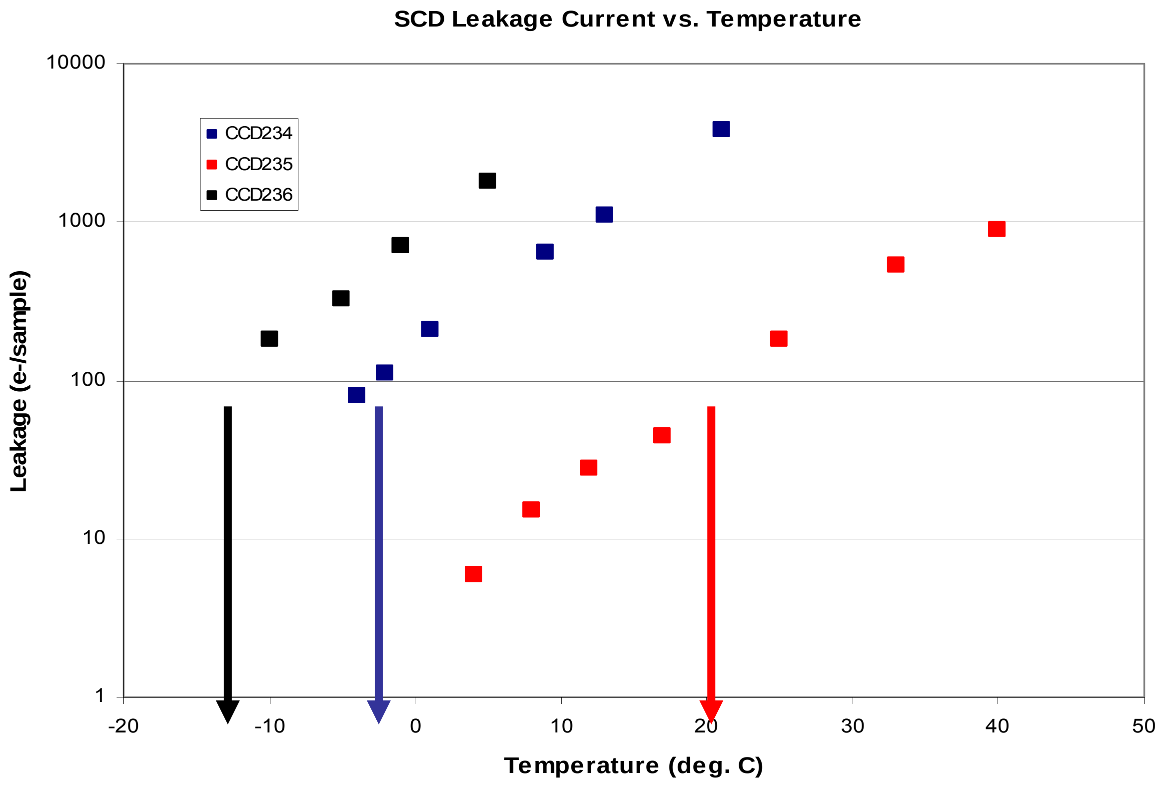


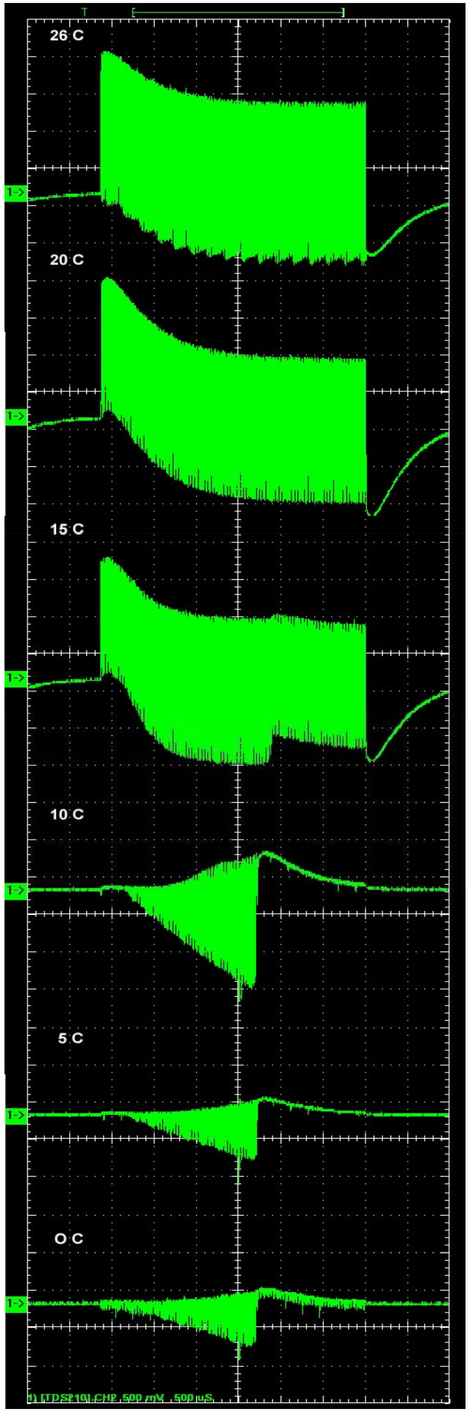




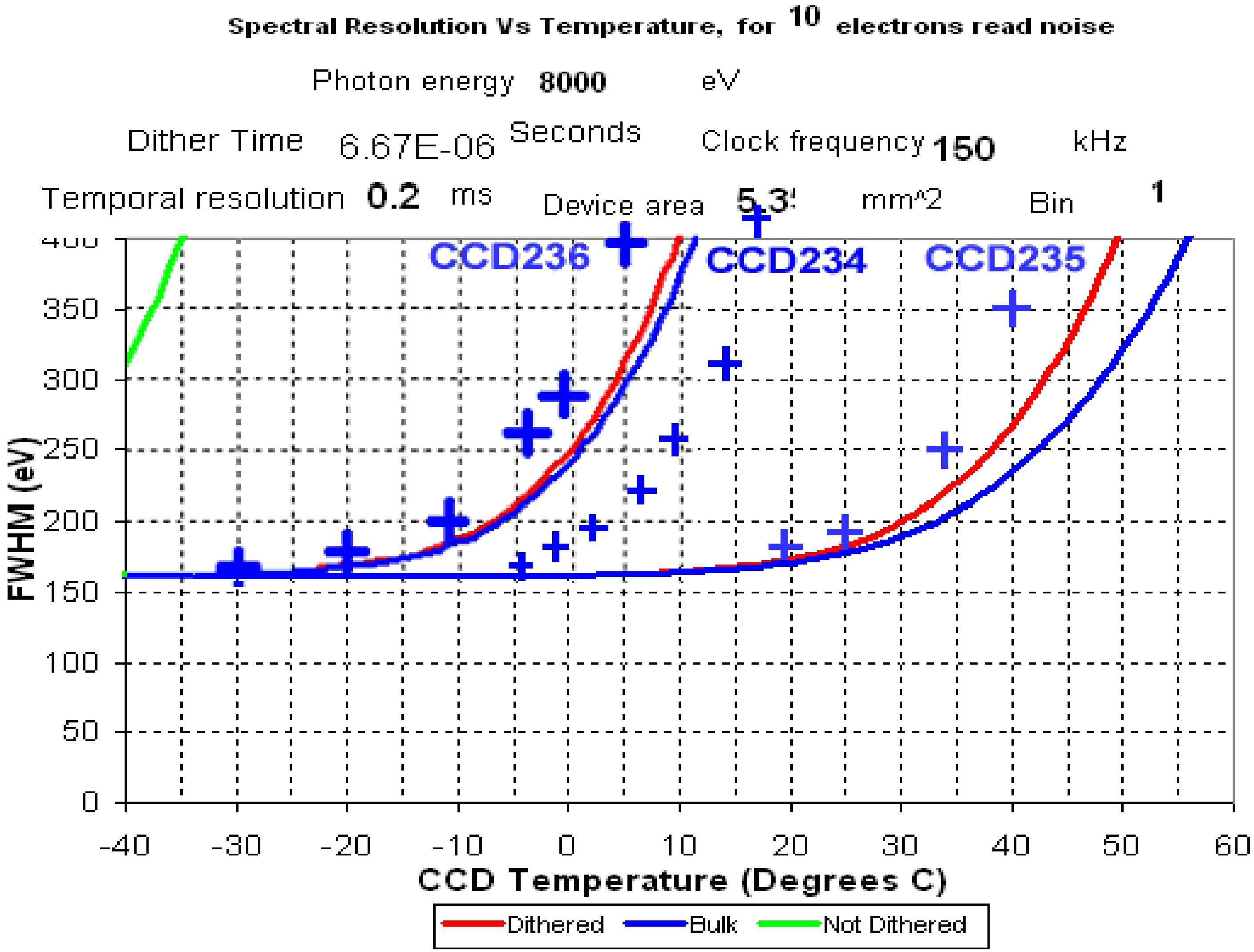
Leakage Current

- Devices only designed for small signal handling, <10k e^-
- CCD236 leakage saturates device at room temperature
- Leakage current measured at 100 kHz readout rate



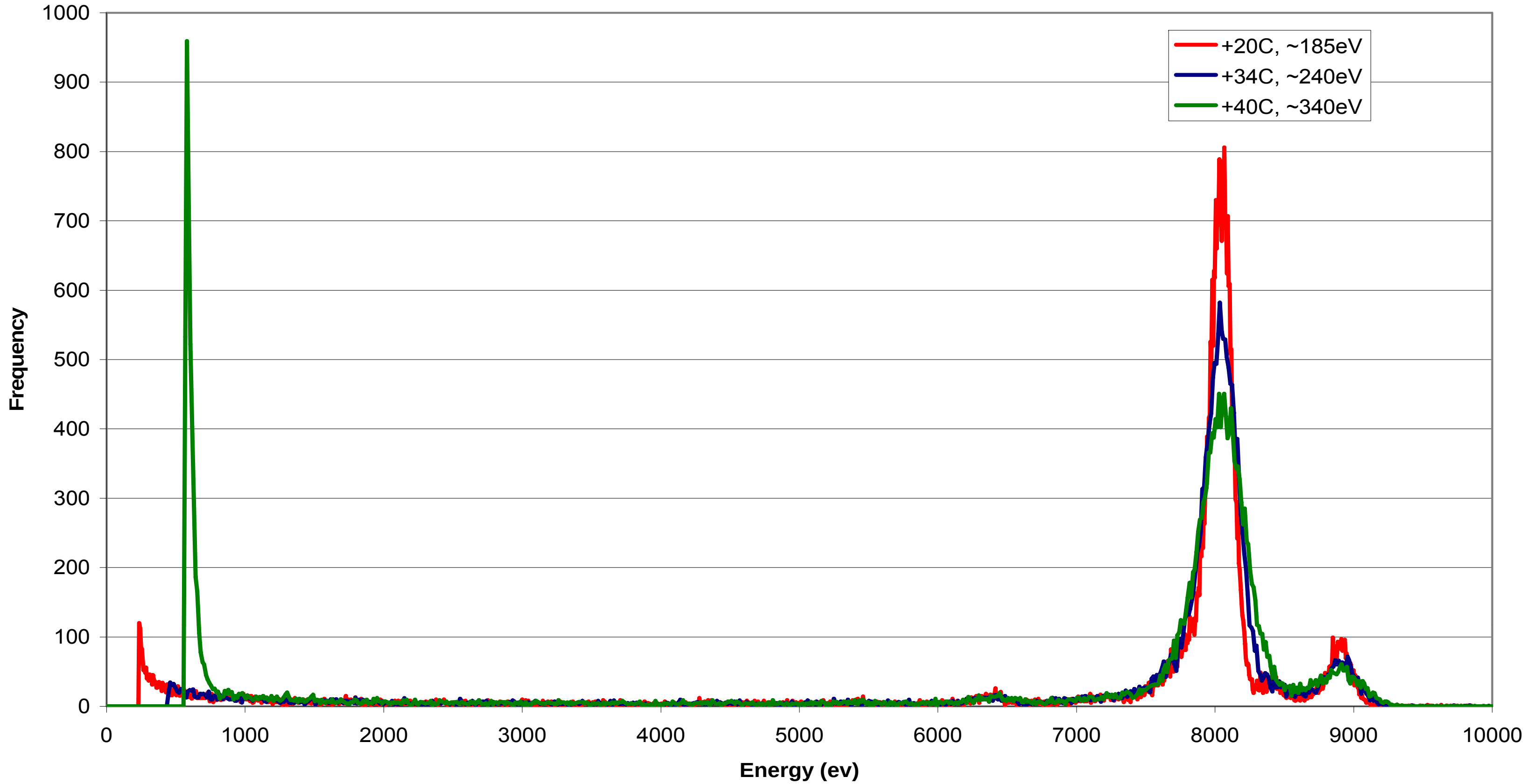


SCD Energy Resolution

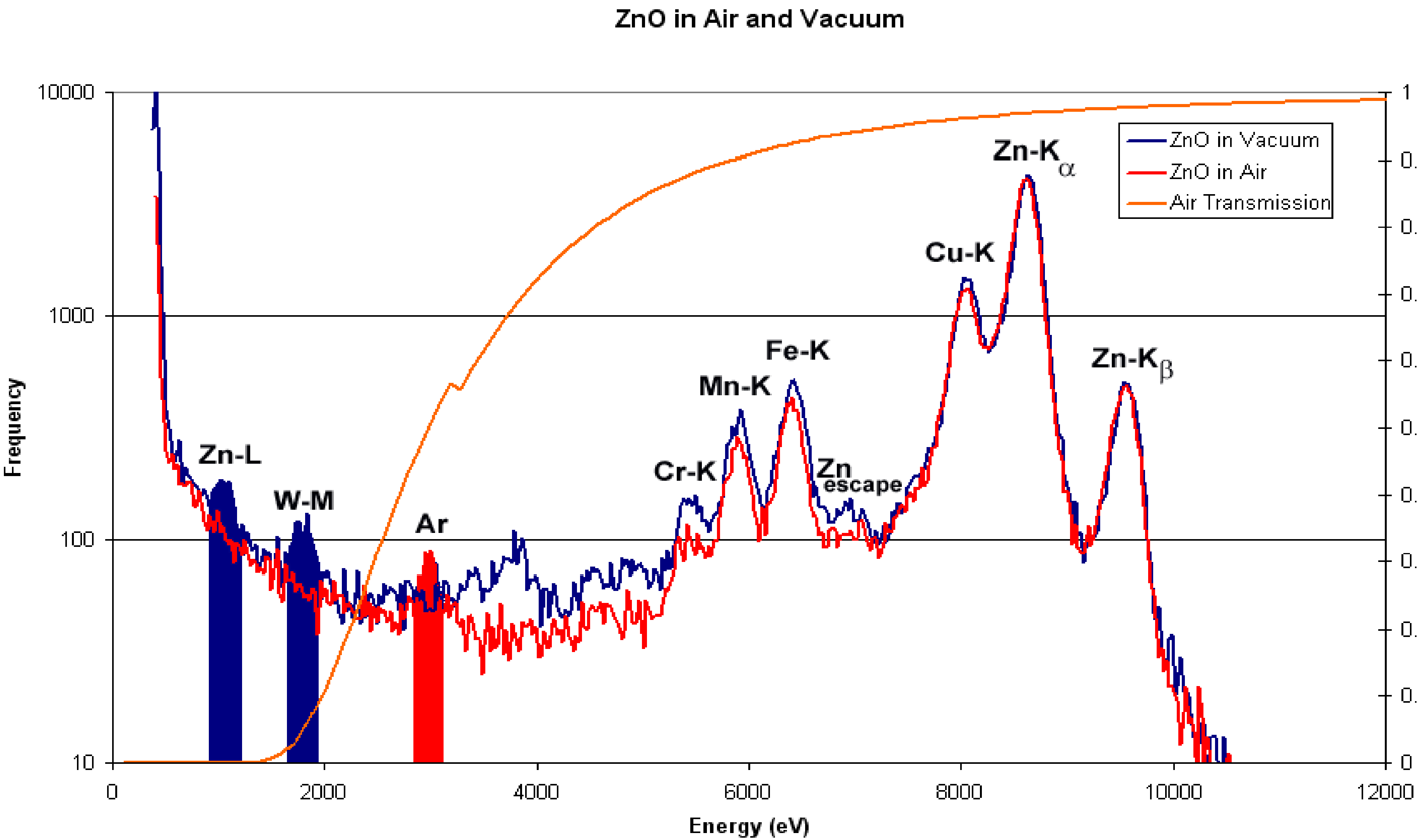


CCD235 Resolution at Elevated Temperatures

- Cu-K spectra in the CCD235 operated at 100 kHz above room temperature
- Is this a record for resolution vs. temperature?
- Note that the leakage contribution can be reduced by running faster
- Elemental identification at +50°C is possible

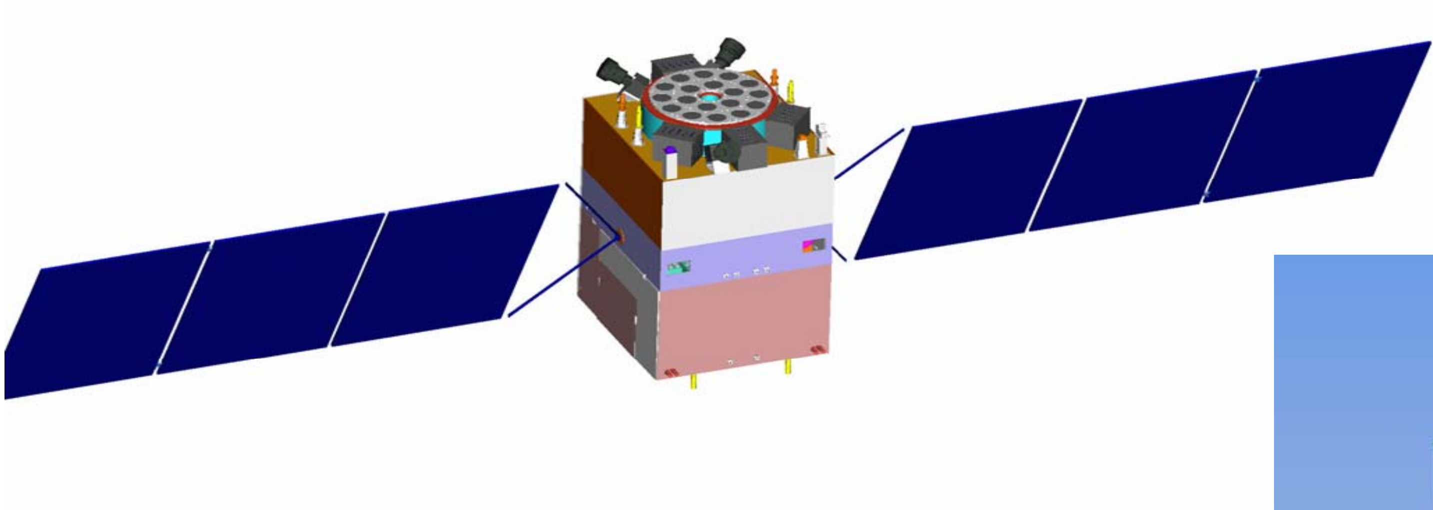


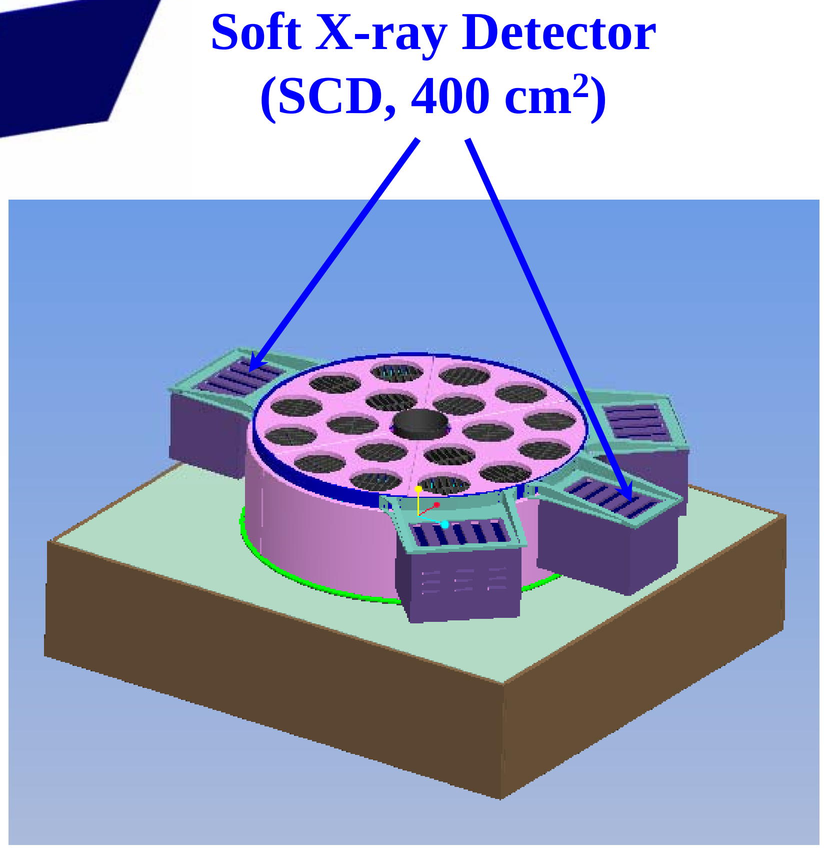
ZnO in Air and Vacuum – CCD235



SXI on HXMT

- Working with IHEP in Beijing to use an array of CCD236 SCDs for to soft X-ray imager on HXMT





Main Characteristics of HXMT Instruments

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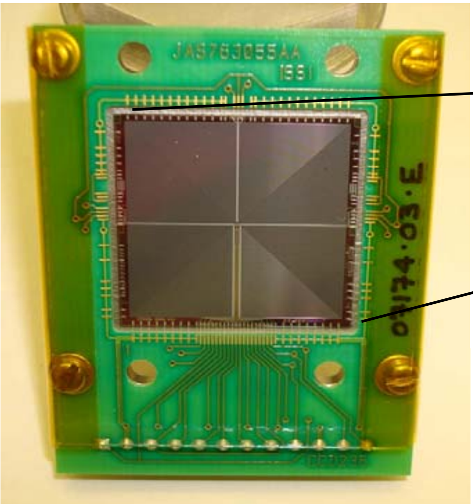
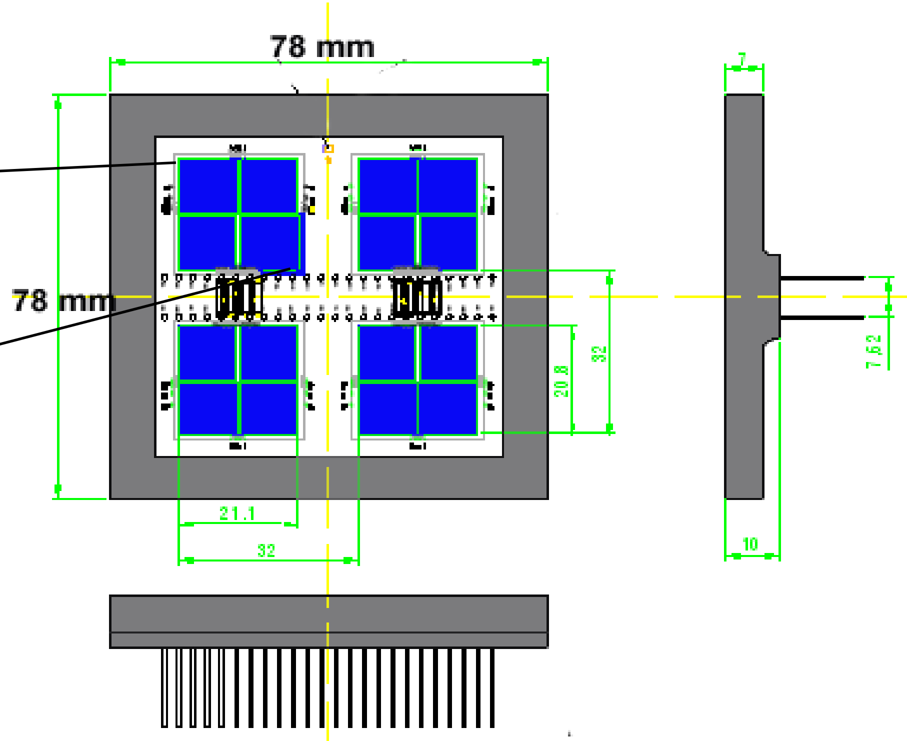
- Main Detector NaI(Tl)/CsI(Na) Phoswich
  - Total Detect Area ~5000 cm^2
  - Energy Range 20～250 keV
  - Energy Resolution ~19% (@60keV)
  - Field of View 5.7° x 5.7° （FWHM）
  - Source Location ≤1 arcmin(20σ)
  - Angular Resolution ≤5 arcmin(20σ)
- Secondary Instruments IEXD (7-30 keV, SiPIN, 1000 cm^2), **SXD ((1-15 keV, SCD, 400 cm^2)**
- Mass ~2500 kg (payload ~1100 kg)
- Dimension 2.0×2.0×2.8 m^3 (L×W×H)
- Nominal Mission lifetime 2—3 years
- Orbit Altitude 550km， Inclination 43°
- Attitude Three-axis stabilized

HXMT SCD Modules

- Aim to construct a detector array behind an X-ray collimator system
- Target of 320 cm^2 detection area
- Design concept includes 4 CCD236 devices on a ceramic module
- Collecting area is built up using a mosaic of these modules



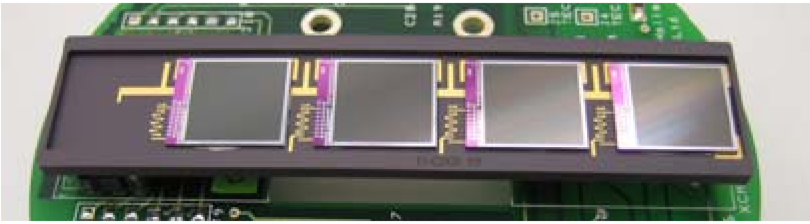


SCDs for Lunar Mapping

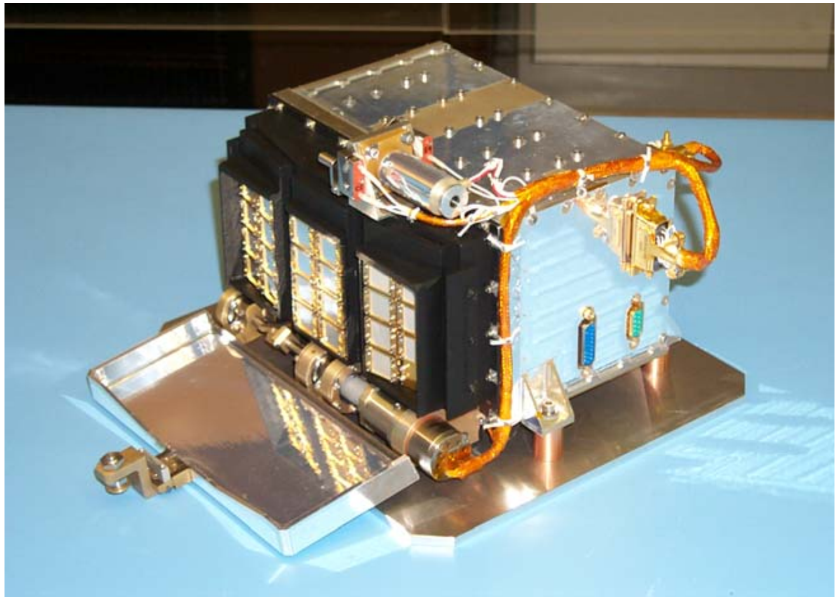
talk by D. Smith

- SCDs used in the D-CIXS instrument on ESA's Smart-1 lunar orbiter
  - Detectors heavily radiation damaged during the long transit to the moon
- Also to be flown on the C1XS spectrometer on ISRO's Chandrayaan-1 lunar orbiter
  - Improved instrument design to meet science goals over 2 year mission duration
- Both instruments use an array of SCDs in a 4x1 array package
- 6 such packages used per instrument, providing 24 sensors

- D-CIXS package shown below with 4 SCDs driven in parallel requiring only 12 connections

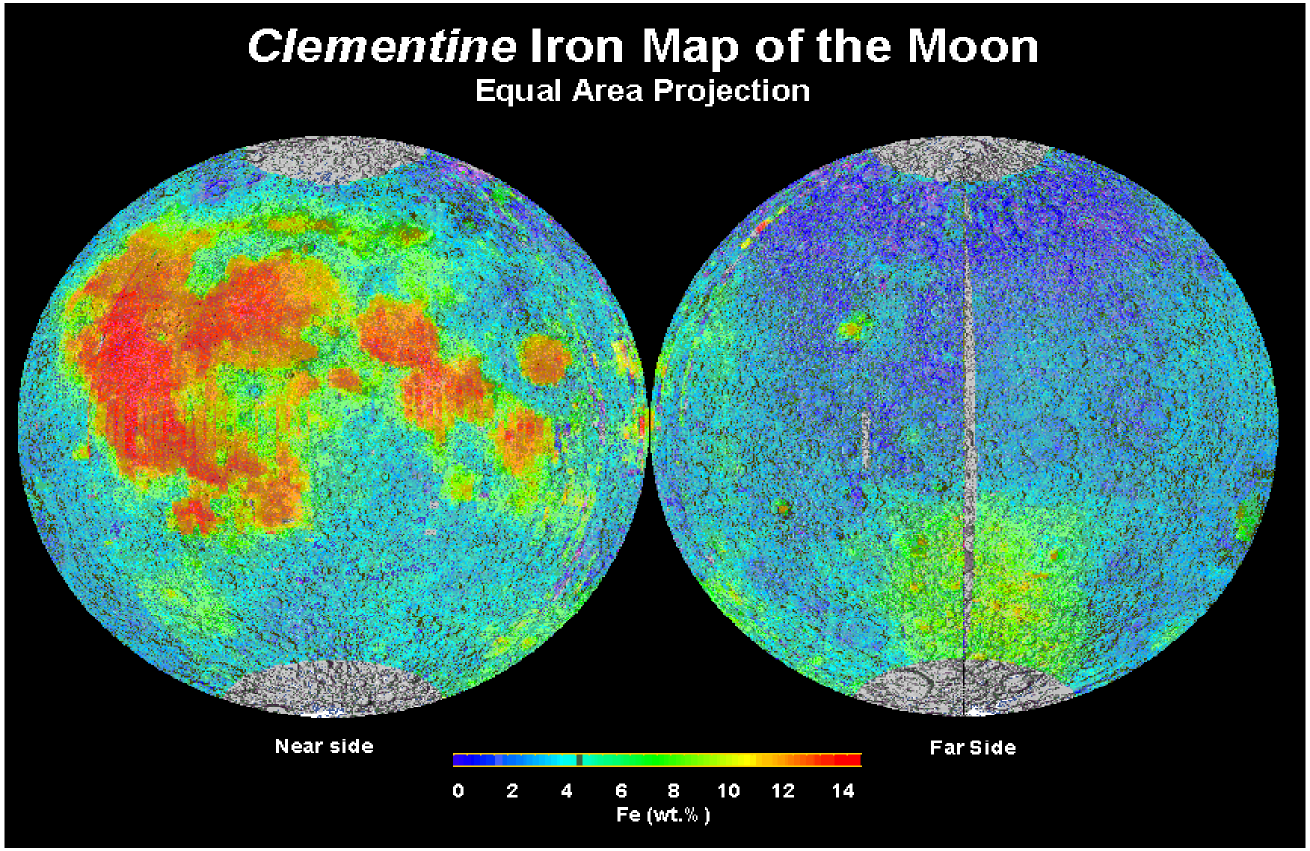


D-CIXS instrument (RAL)



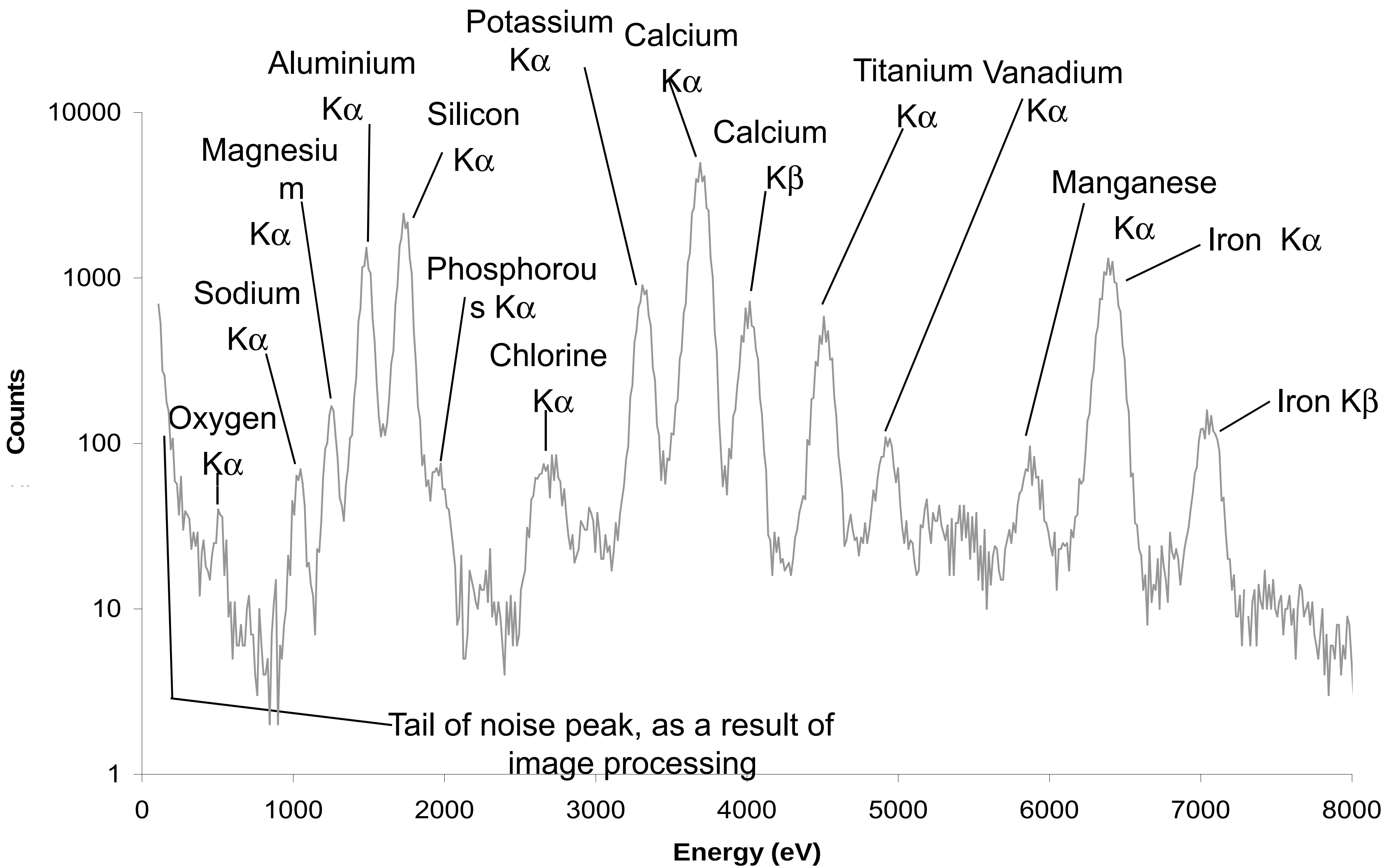
Elemental Mapping of the Moon

- **C1XS will produce elemental maps like the one shown from the NASA Clementine mission:**



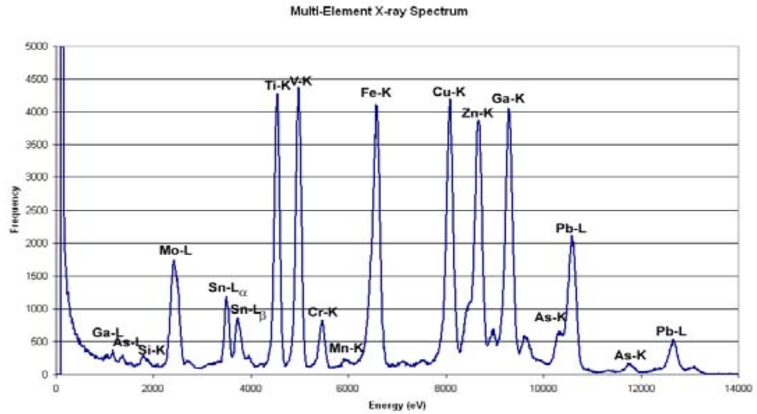
Etna Basalt

(Polished, 10 minute data collection)

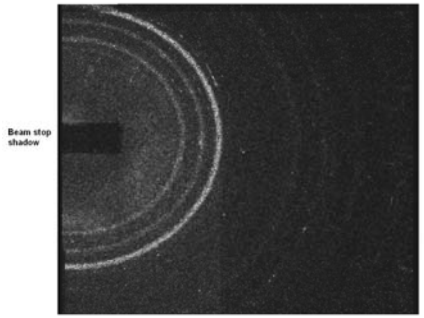


Spin-Off into other areas

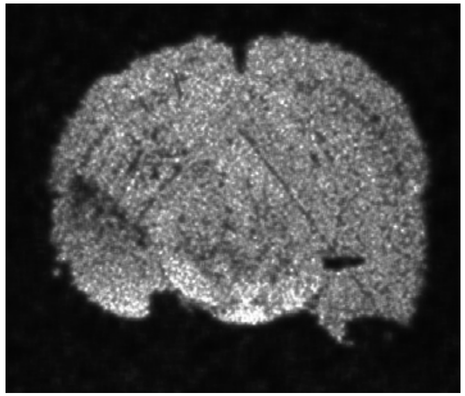
- Utilising the photon-counting mode of CCDs
- X-ray Fluorescence
  - Analysis of contaminants



- X-ray diffraction
  - Portable in-situ XRF/XRD for geology
  - www.inXitu.com



- Beta Autoradiography
  - Thin tissue imaging using 3H, 14C
  - www.xcam.co.uk



Conclusions

- MOS CCDs are being developed for future X-ray instruments in space science
- Over the next year the IXO baseline configuration is likely to change (watch this space…)
- Development of critical technology components is being addressed
  - Readout ASICs
  - Transfer time
  - Increased QE
  - Large pixels
- Currently no funding for a single demonstrator model incorporating all elements
- Modelling of instrument background is identifying the key contributors to aid their reduction in XEUS
- SCD technology is being applied to XRF for elemental mapping for Lunar science
- Spin-off is occurring into terrestrial XRF, XRD and Beta Autoradiography