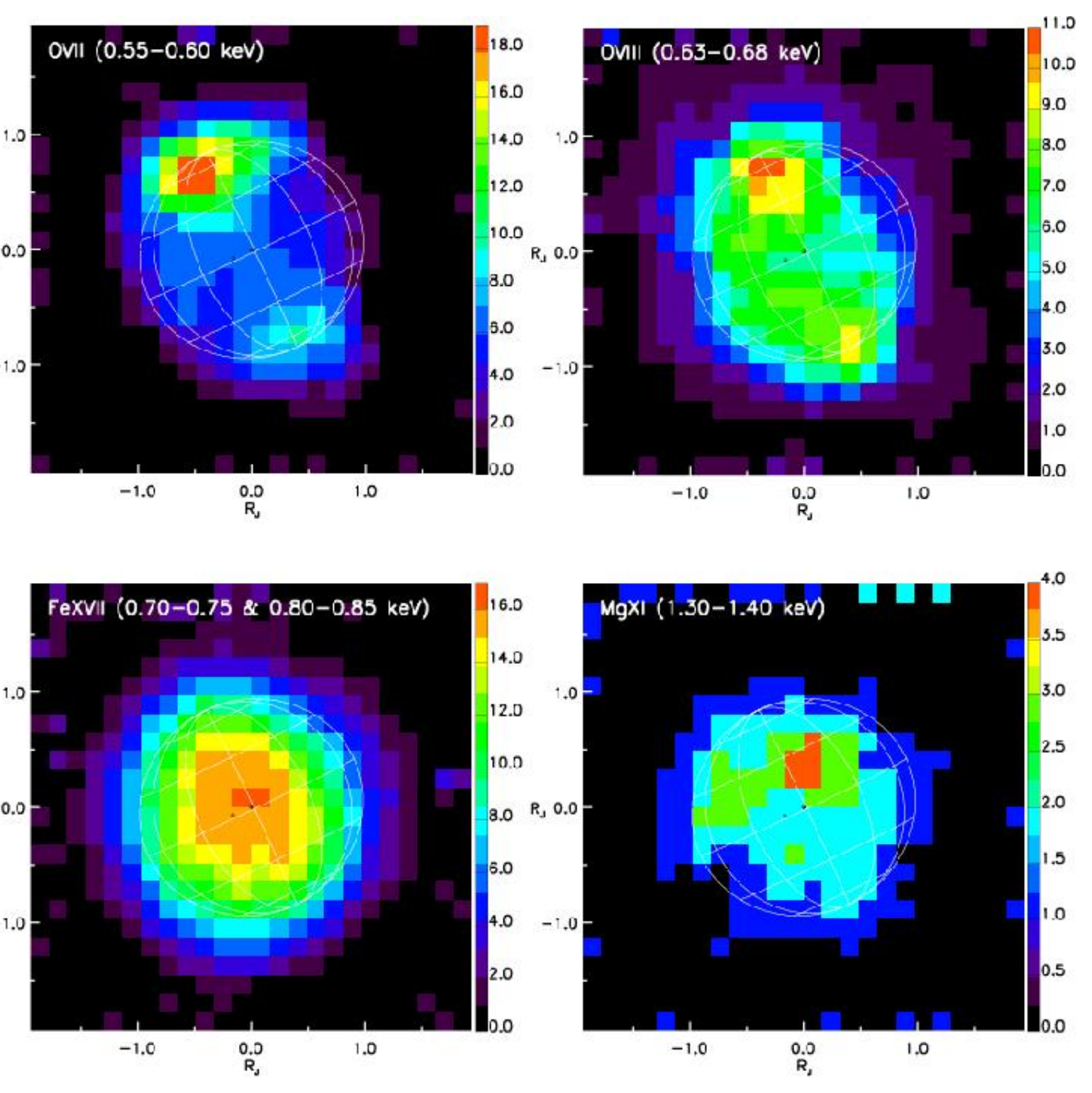
Monolithic CMOS detectors as X-ray Imaging Spectrometers for Planetary Missions

Kenter,A. Kraft,R. Murray,S.S. Fraser,G. Elvis,M. Garcia,M. Forman,W. Smith,R. McCoy,T. Branduardi-Ravmont,G. Rodiger,E. Watters,T.

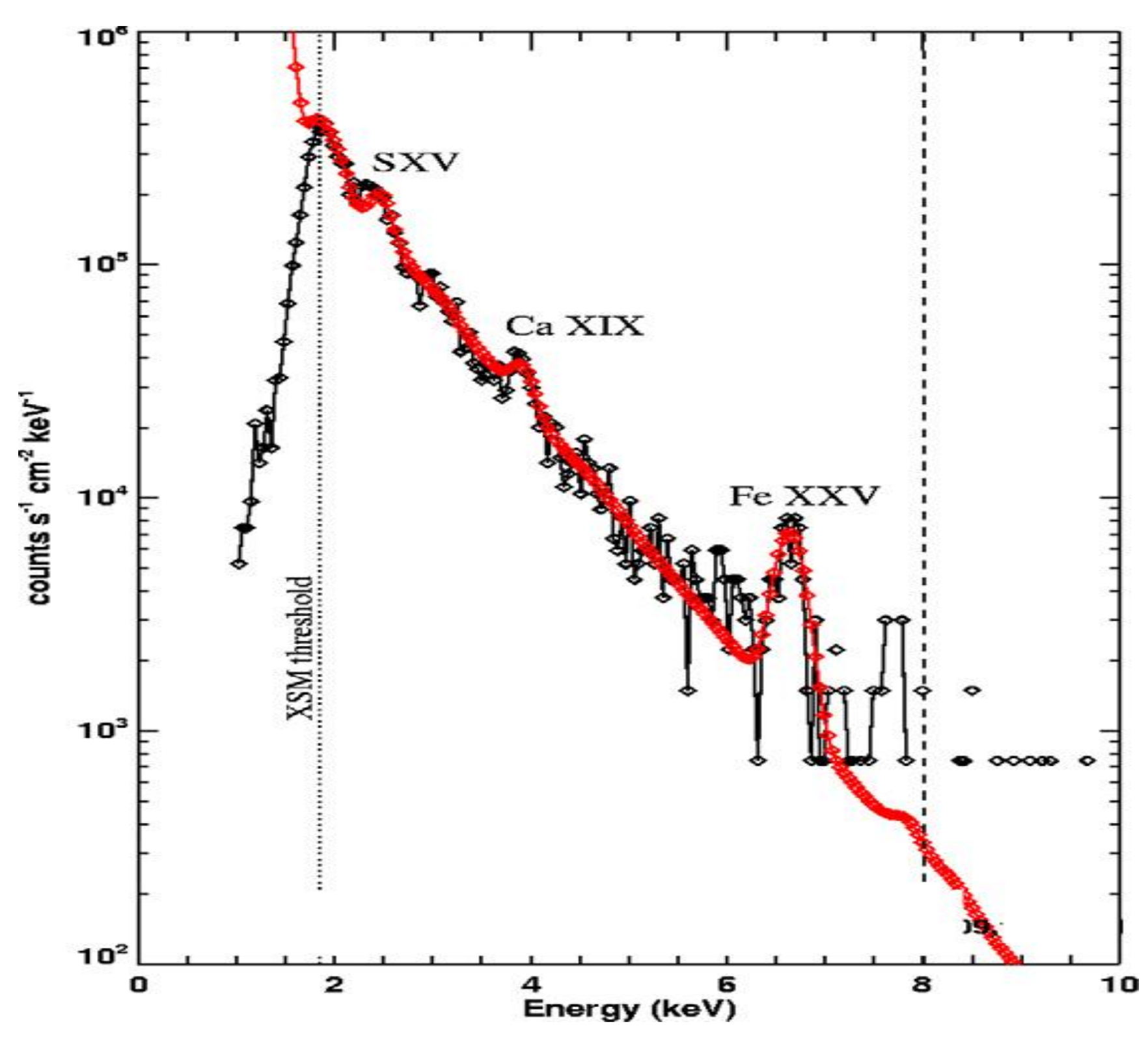
CMOS imaging detectors have replaced CCDs in commercial and consumer applications. The historical shortcomings of CMOS imaging detectors have recently been resolved and CMOS is now being used in the most demanding scientific applications such as single photon X-ray imaging spectroscopy where signals are small and low noise performance is mandatory.

Scientific CMOS performance now rivals CCDs in regards to read noise, Fixed Pattern Noise (FPN) and linearity. CMOS has the added advantage of:
•Very high radiation tolerance >100x that of CCD (Mrad vs krad); ideal for long duration space missions, or missions in high radiation environments.
•Very high read rates with low power consumption, provide temporal resolution, eliminate photon pile-up, and enable no or minimal cooling operation
CMOS large scale on-chip integration provides compact implementation, reliability and tremendous device level functionality.

The Smithsonian Astrophysical observatory (SAO) in collaboration with SRI/Sarnoff have developed scientific grade monolithic CMOS detectors optimized as x-ray single photon counting x-ray imaging spectrometers. These back thinned Monolithic CMOS imaging x-ray detectors provide high speed readout and Fano limited energy resolution (ΔE=36eV @ 500eV, ΔE=120eV at 6kev) over the entire soft energy (0.2-10keV) band. Such a detector coupled, to a focusing x-ray MicroChannel Plate Optic (MCPO) with ~arcmin type resolution would provide unprecedented capability to study the x-ray emission from a variety of solar system objects particularly at energies <500eV.



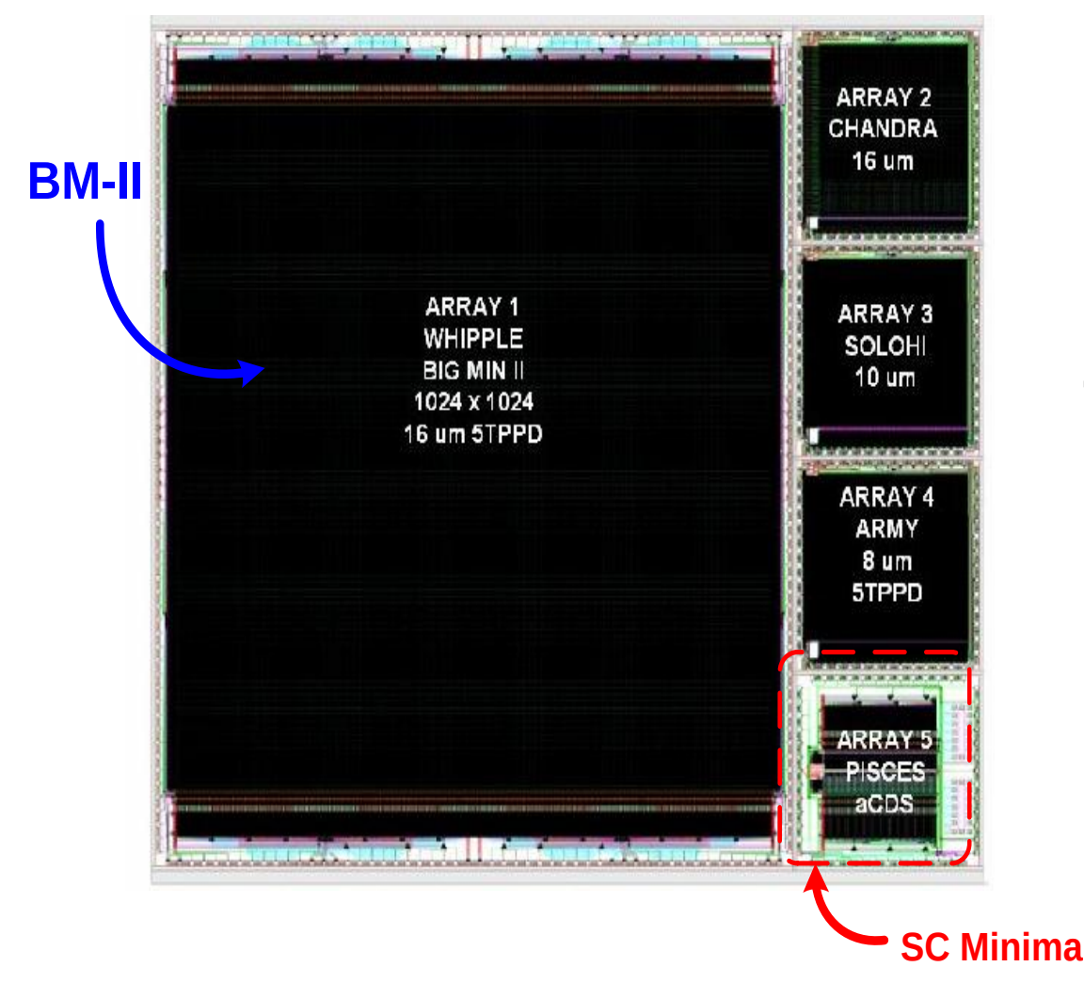
Observations of x-ray emission from the magnetosphere of Jupiter (Branduardi-Raymont et al., 2007).. Emission is due to the interaction of solar wind/solar x-rays with the atmospheres and magnetospheres of planets. The disk emission is due to Solar x-rays scattering and causing fluorescence in the Jovian atmosphere. The auroral emission is due to ions undergoing Charge Exchange (CX) In the polar regions. The origin of the ions is believe to be from the Solar wind and/or from Io. Previous observations of these phenomena have been limited since they have been performed by earth orbiting satellites such as Chandra and XMM. As part of a planetary mission, even a modestly sized CMOS/MCP-optic combination could spectrally, spatially, and temporally resolve this highly variable process in much greater detail and with much better statistics.



X-Ray Fluorescence (XRF) spectrum of lunar surface By the Chanrayaan-1 CIXS instrument (Narendranath *et al 2010*) using mechanical collimation and a Silicon Swept Charge Device (SCD).

Remote XRF spectroscopy (XRF) has been used to determine the surface composition of the moon and other atmosphere-less bodies since the Apollo era. The primary mechanism for producing x-ray fluorescence is excitation by x-rays from the Solar corona, and to a lesser extent excitation by charged particles. XRF observations have been performed on asteroids Itokawa and 433 Eros (Hayabusa mission Okada *et al* 2006) (NEAR-Shoemaker Trombka *et al*, 2001). The goal of these missions has been to measure and map the abundances and relative abundances of Fe,Ti,Ca,Mg,Al, Si. In some cases, radiation damage of the SCD/CCD detectors accumulated in transit, has resulted in loss of performance and calibration (D-CIXS on SMART-1 Grande et al,2007).The MIXS instrument (Fraser et al) to be launched on Beppi Columbo will perform XRF mapping of the surface of Mercury using an imaging Microchannel Plate optic with ~arcmin resolution and a Si DEPFET detector.

The Fano limited performance of monolithic our CMOS x-ray imaging spectrometers at energies below 500eV would allow us to further measure the abundances of light elements such as C,N,O,P. Since CMOS is inherently radiation "hard", instrument performance would not appreciably degrade from accumulated dose over the lifetime of any mission.



**Monolithic CMOS allows one to include almost anything on the device.
(pixel, amp, ADC….)**

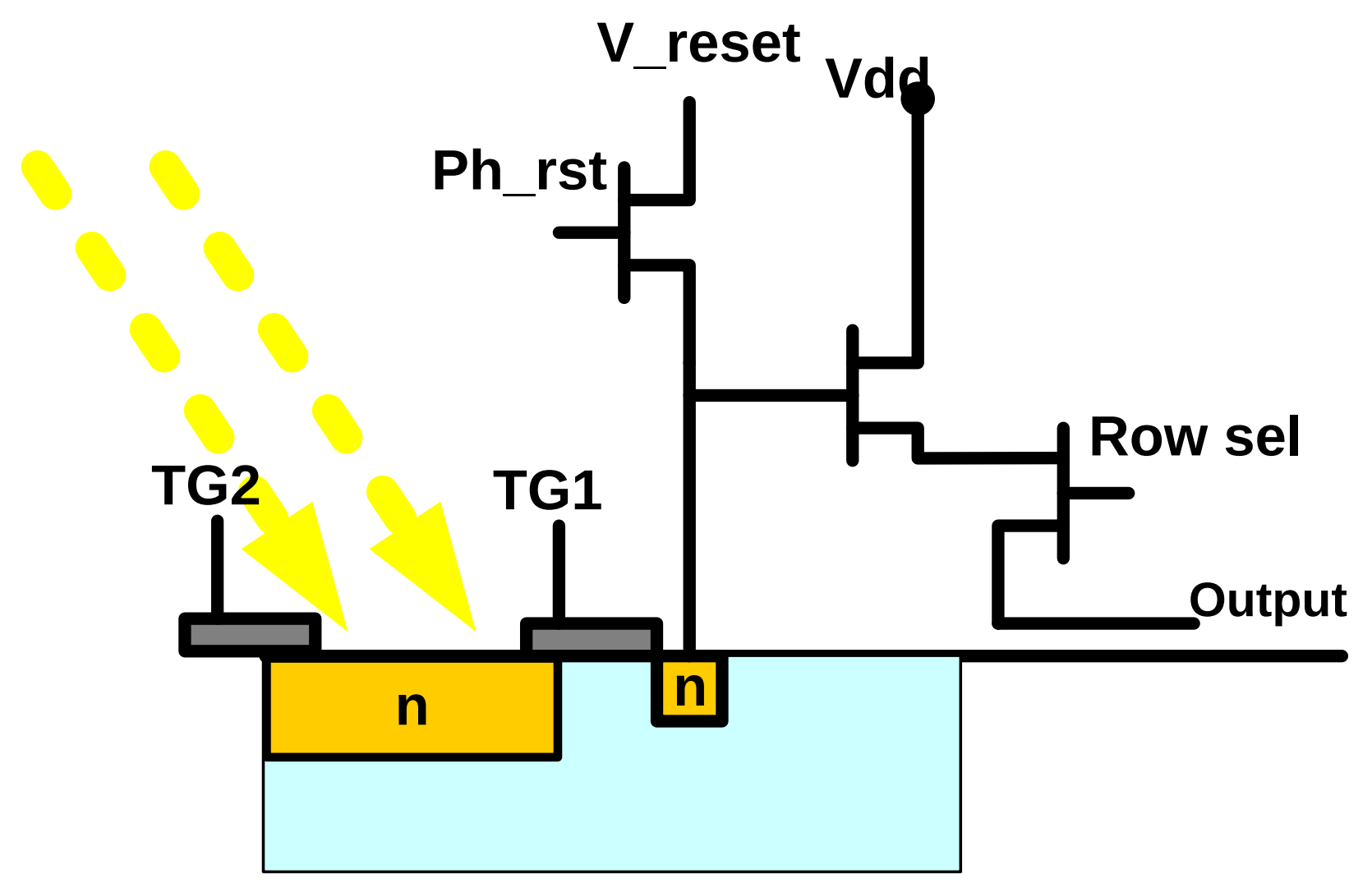
Optimize design for X-ray:

**Combine:
1) very high gain, low noise versatile 16µm pixel with:
2) highly parallel Signal Chain.**

→Fano limited at low energies and at high rates.

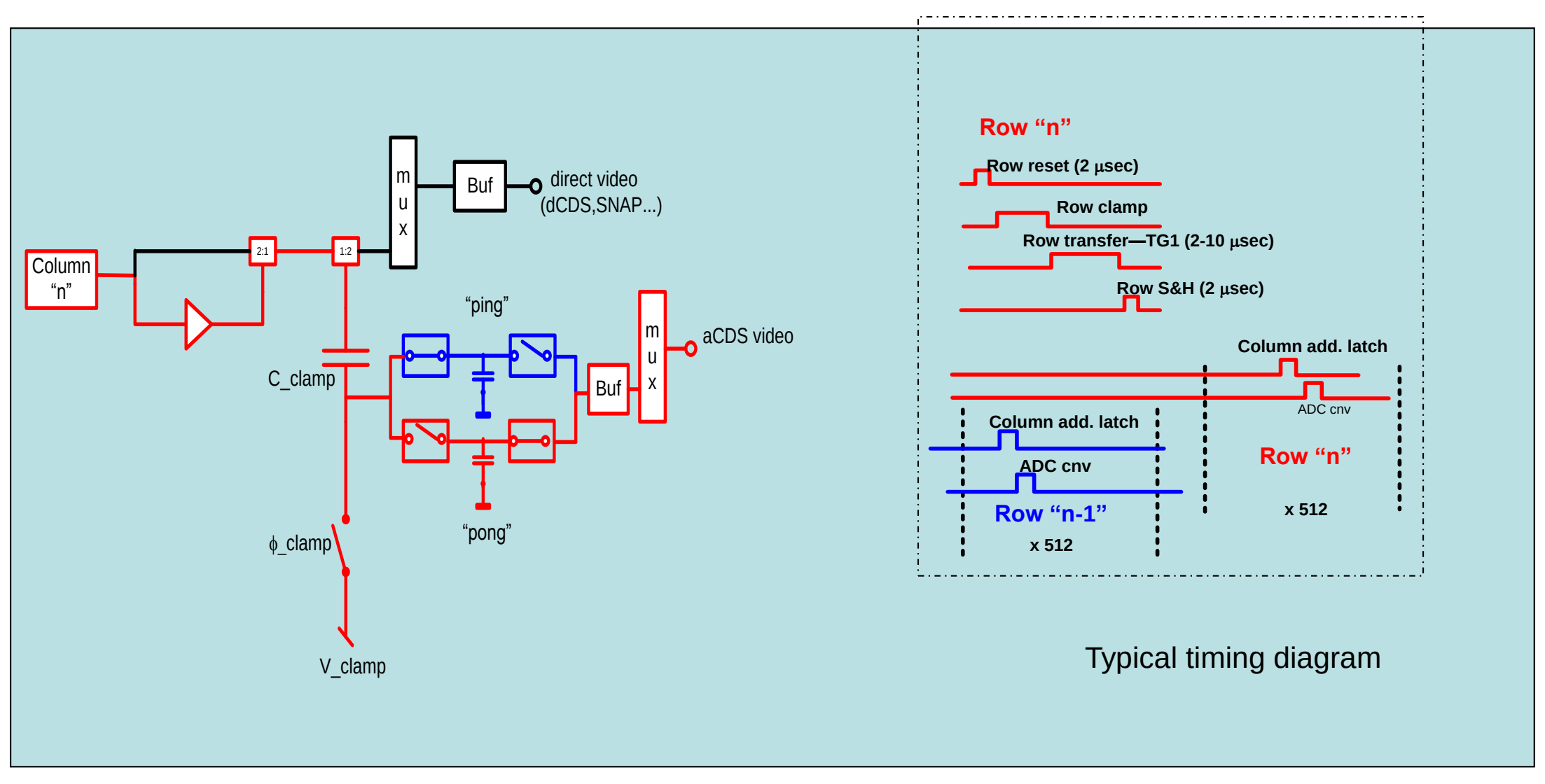
(CCDs may be Fano limited but not at high rates)

**SAO in collaboration with Sarnoff/SRI has been developing and optimizing monolithic CMOS detectors as x-ray imaging spectrometers. The monolithic process allows us to capitalize on the extensive abilities and infrastructure of the integrated circuit industry; devices can be made with tremendous on chip integration which results in great functionality and reliability. Our devices our made from high resistivity Silicon (30,000Ω-cm), and the device pixel and the highly parallel signal chain has been designed to provide low noise, high QE and very high read rate capability. Devices have been irradiated to levels of >1Mrad with
60MeV protons and show little degradation. New designs incorporating p-pixel technology have even higher radiation Tolerance (>10Mrad).**



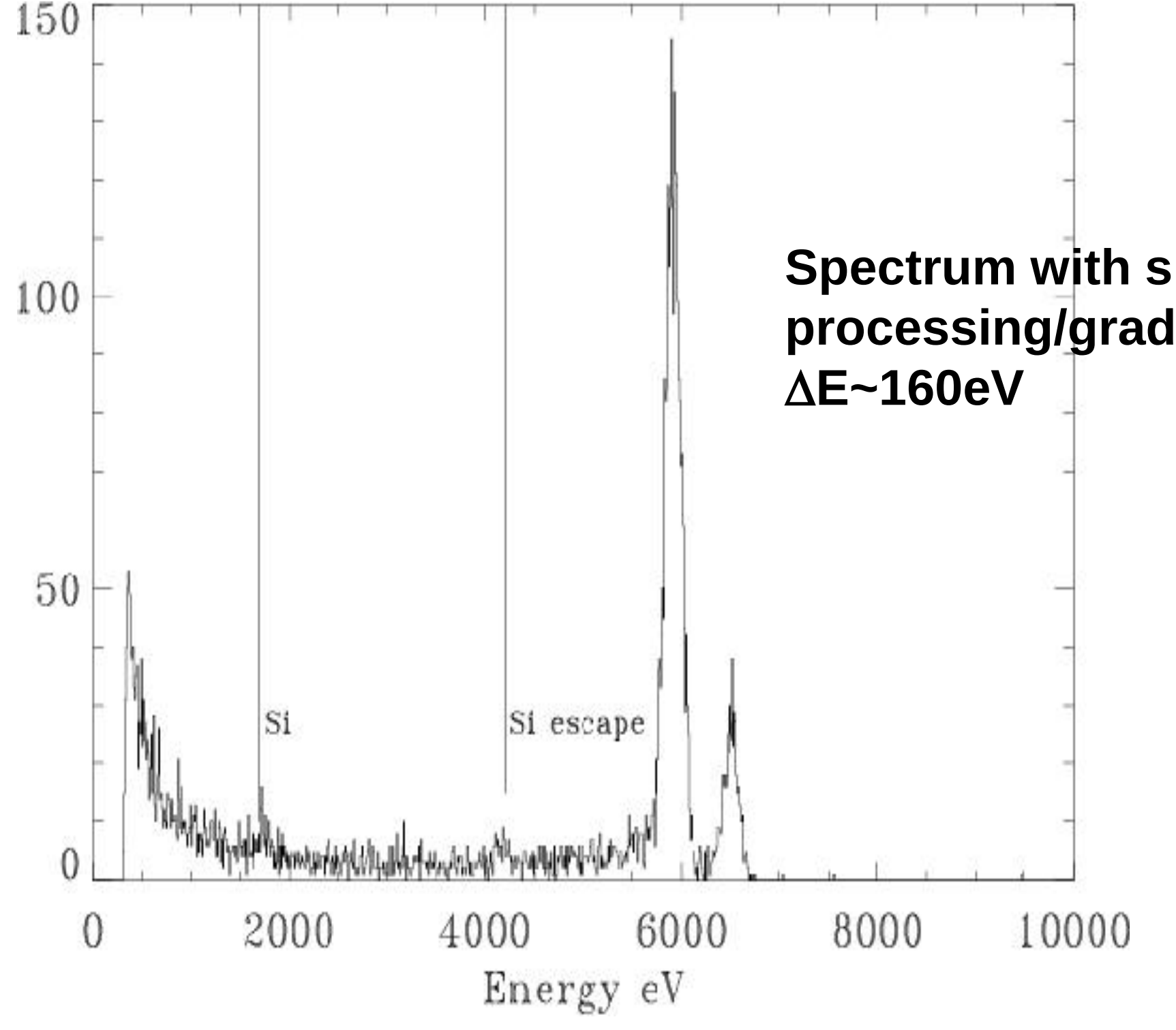
**High gain pixel with separate Photo-node and sense node with one charge transfer makes it possible to have:
•Very high gain (100µV/e).
•Very low read noise (~2erms; noise varies ~1/gain))
•analog CDS (aCDS)
•High radiation tolerance ("rad-hard")**

Note: figure shows Front Illumination (FI). Final devices are thinned and Back Illuminated (BI)



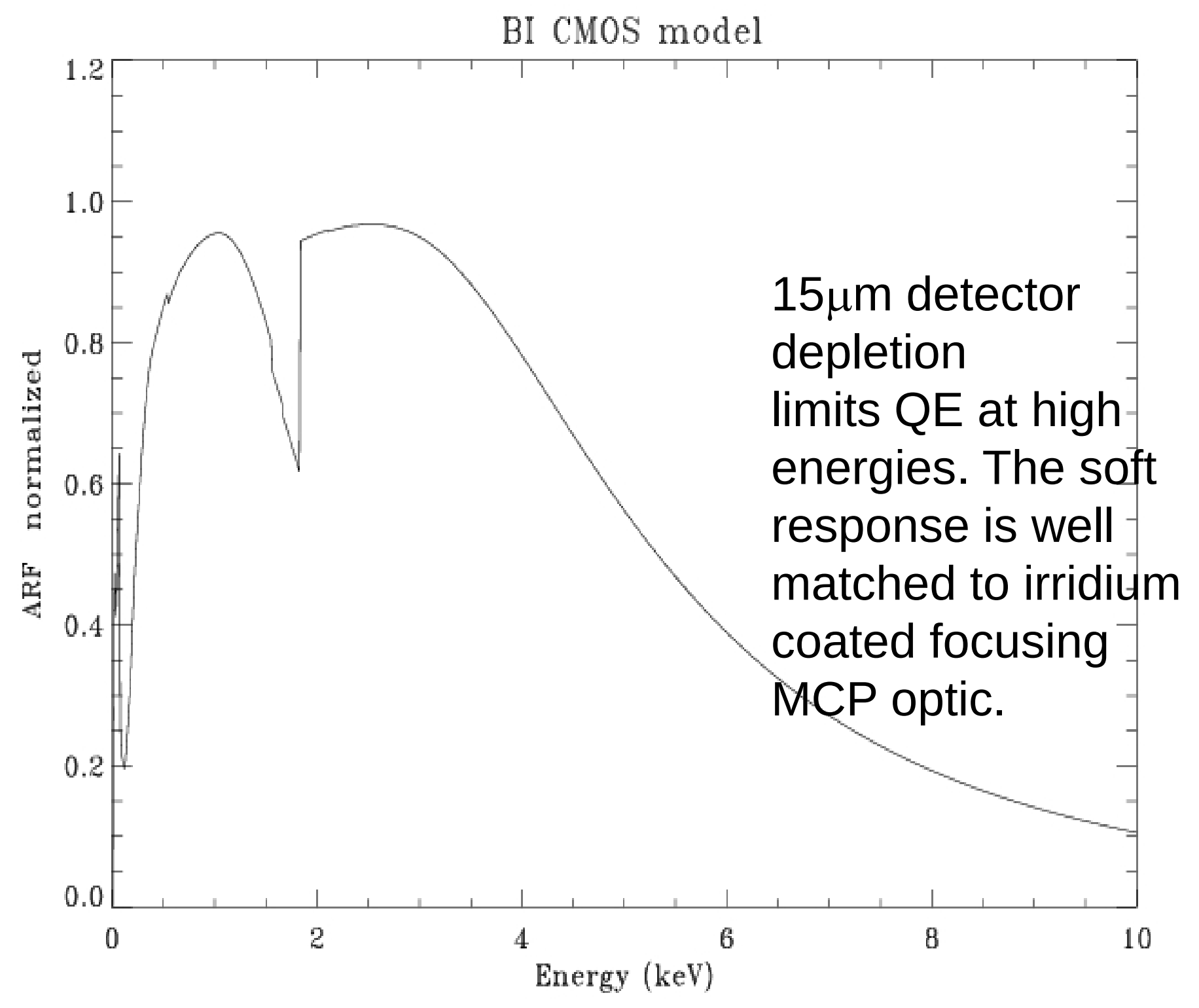
A separate Clamp and sample Analog Correlated Double Sampler (CDS) with "pin-pong" sample buffer is included in every column. CDS is performed for entire row at time. "Ping-pong" buffer ensures zero "overhead" time. Pixels can be read from sample & holds at high rate with no "white noise" penalty. Detector remains Fano limited even at very high read rates. High read rate/short integration times minimize dark current and allow warm operation which mitigates detector icing and loss of soft x-ray QE. Fast parallel signal chain and various modes of addressing pixels provide ~10µsec temporal resolution.

^{55}Fe x-ray spectrum. T=300K



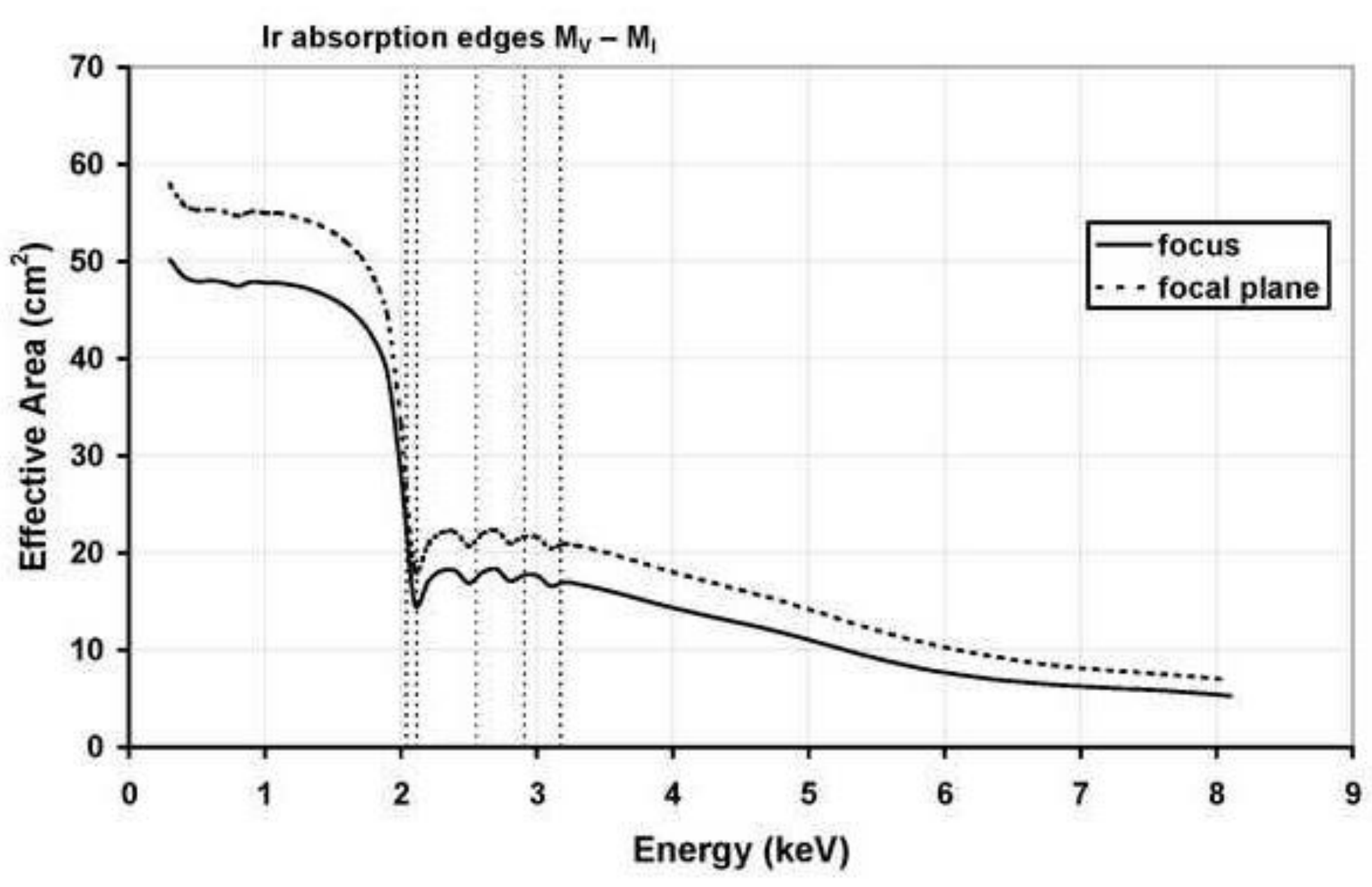
Spectrum with simple event processing/grade selection. ΔE~160eV

Room temperature ^{55}Fe x-ray spectrum for sample device. The spectral performance/read-noise does not depend on read rate due to the parallel output signal chain; this allows our devices to operate with minimal or no cooling. Maximum pixel rate is ~10MHz

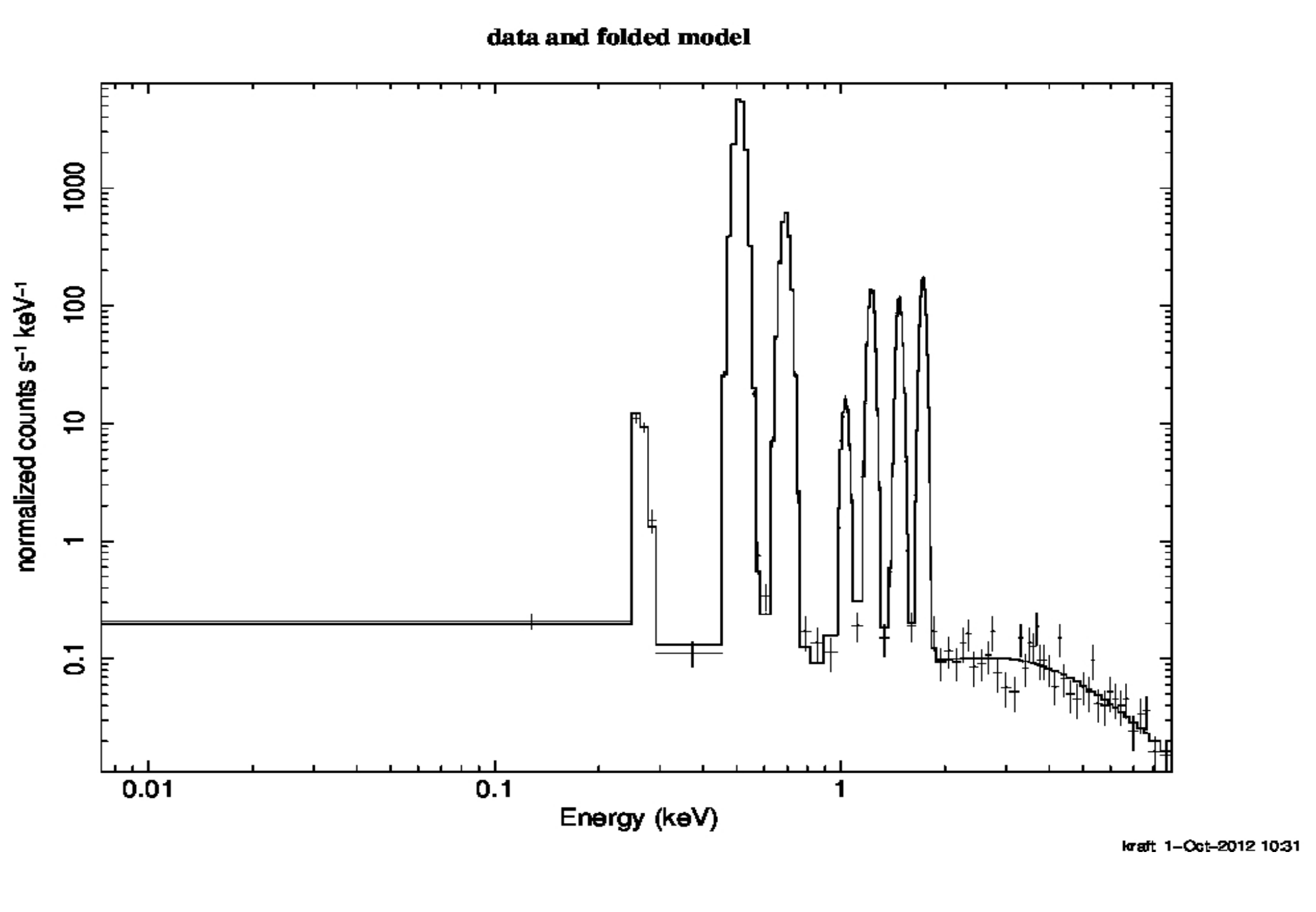


15µm detector depletion limits QE at high energies. The soft response is well matched to irridium coated focusing MCP optic.

We have created an Ancillary Response File (ARF) and a Redistribution Matrix Function (RMF) for our detector. The ARF assumes a 1000 Angstrom aluminum Optical Blocking Filter (OBF) directly deposited on the Si without using a free standing plastic substrate; this eliminates constituent (carbon/oxygen/nitrogen) absorption and enhances soft x-ray (<0.5keV) QE.



The Effective Area (EA) of the MIXS Microchannel Plate optic (MCP) (Fraser *et al* 2010). The EA is well matched to the response of our BI monolithic CMOS x-ray imaging detector. We are proposing to increase the TRL of our detectors/cameras by building a flight like CMOS camera with the intention of testing it with a MIXS type optic under the NASA MATISSE (Maturation of Instruments for Solar System Exploration) AO.



A simulated X-ray fluorescence emission line spectrum of a NEO at a distance of 1 AU as would be detected by our detector. This spectra includes a particle induced continuum background based on observed rates from the Suzaku mission. We have simulated a 100 s observation from a bright Solar flare. Similar signal to noise ratios could be obtained in lower flux Solar states by longer integrations. The C line has been added simply to show that it can clearly be resolved from from the other lines and the background. The strength of the line would be an order of magnitude higher for a carbonaceous asteroid.

Conclusion:

Monolithic CMOS x-ray imaging spectrometers now provide performance rivaling that of the best CCDS, with the added benefit of high read rates, low power consumption and very high radiation tolerance. Such a device, incorporated with a focusing optic would make an ideal detector to study x-ray emission within our Solar System. The high read rates and low power consumption require no or modest cooling. The radiation tolerance of CMOS will also maximize the useful lifetime of any mission.