PSD12:
Applications in Astronomy, Planetary and Space Science

Andrew Holland

Talk Outline

1. Requirements for space imaging
2. Space Radiation Damage
3. CCDs vs CMOS
4. Optical Imaging
   1. CCD arrays – Euclid & Gaia
   2. EM CCDs – WFIRST/Roman
5. X-ray Photon Imaging with Spectroscopy
   1. CCD arrays – XMM & SMILE
   2. CMOS arrays - Theseus

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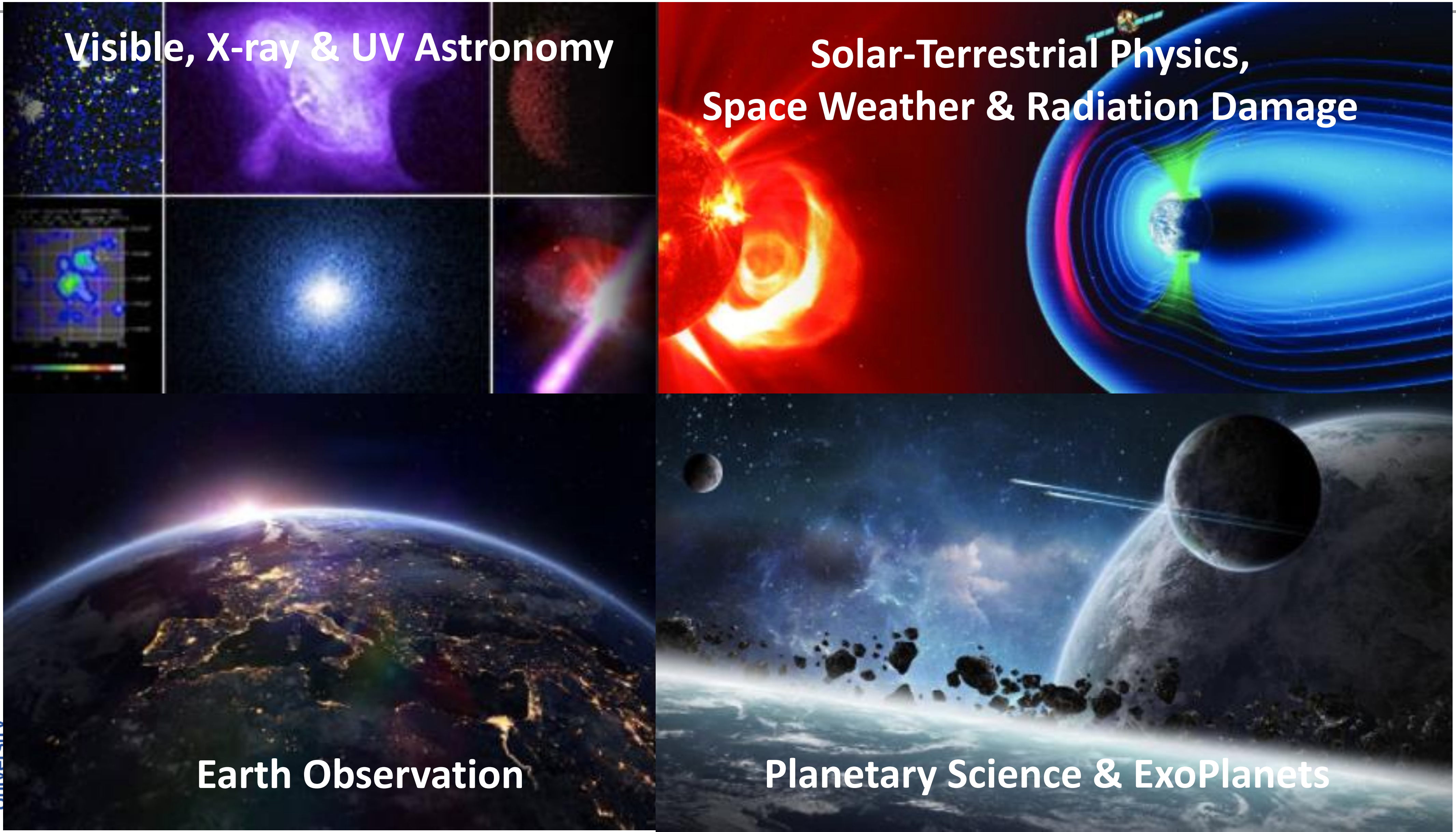
Space Science Themes



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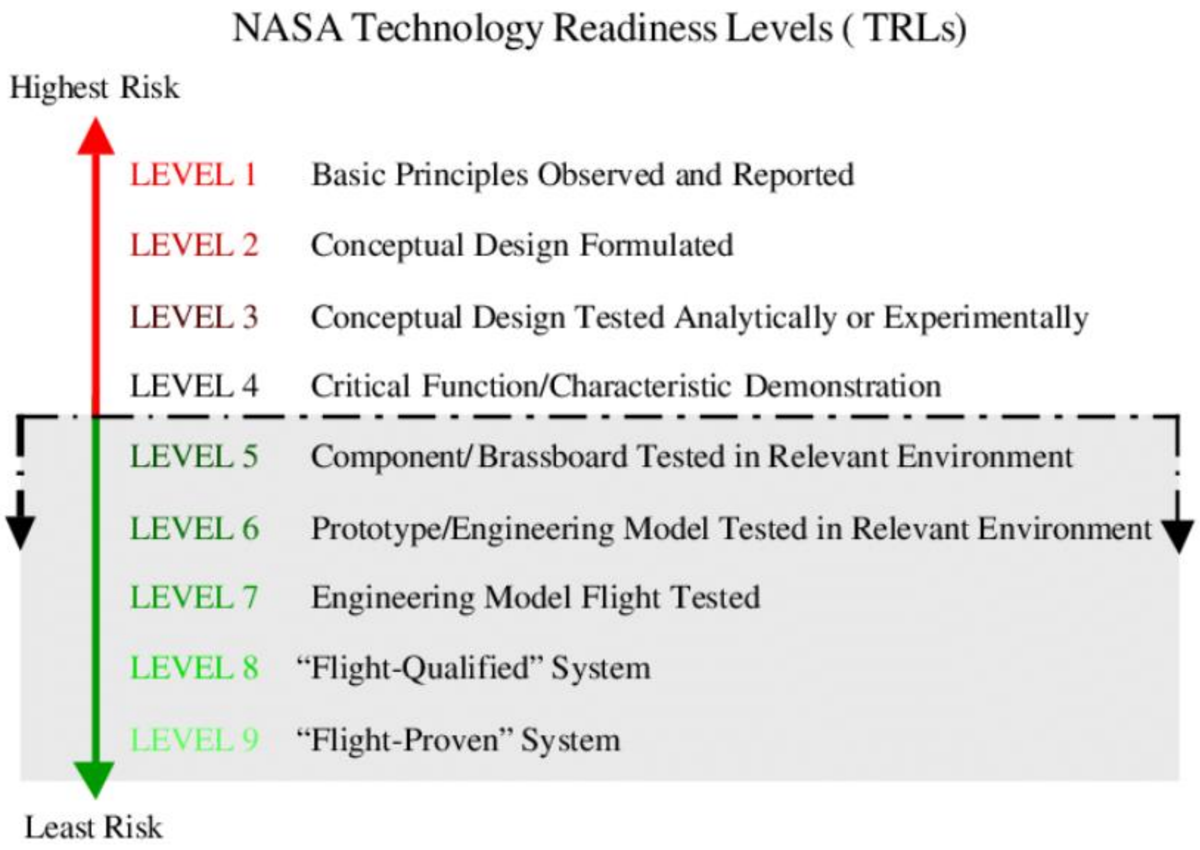
Detector Requirements for Space

1. Mission concepts often proposed with technology in the range TRL3-4
2. Should then get to TRL 5 or higher before mission adoption

3. Should withstand space environment
   1. Radiation impact on science performance
   2. Should withstand SEE
   3. (some applications – micrometeoroids)



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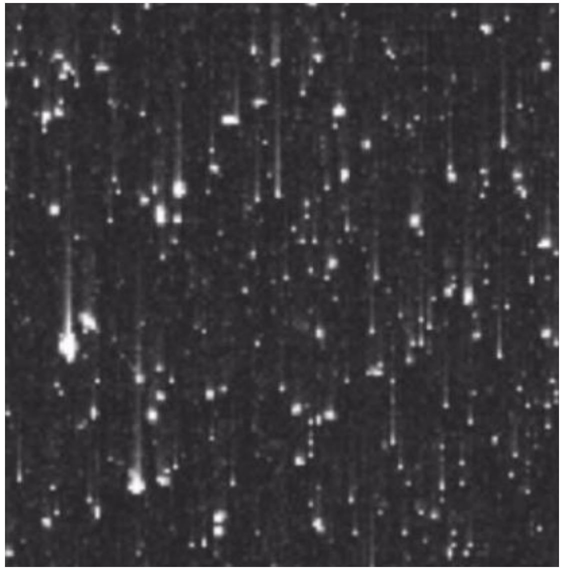
Timeline for XMM EPIC Developments

- 1987-1992 ESA funded various developments toward XMM,
  - significant performance enhancement
- 1989 ESA adopts XMM as a “Cornerstone” Mission for launch in 10 years
  - Radiation damage becomes “re-discovered”
- 1990 EPIC consortium created – Lead from Milan
- 1994 EOBB demonstrates the key performance characteristics of EPIC at Panter
- 1996 AH leaves the project…… (after essentially 10 years ..)
- 1999 Launch of XMM in December
- 2021 21 years of operation with resources for 20 more!

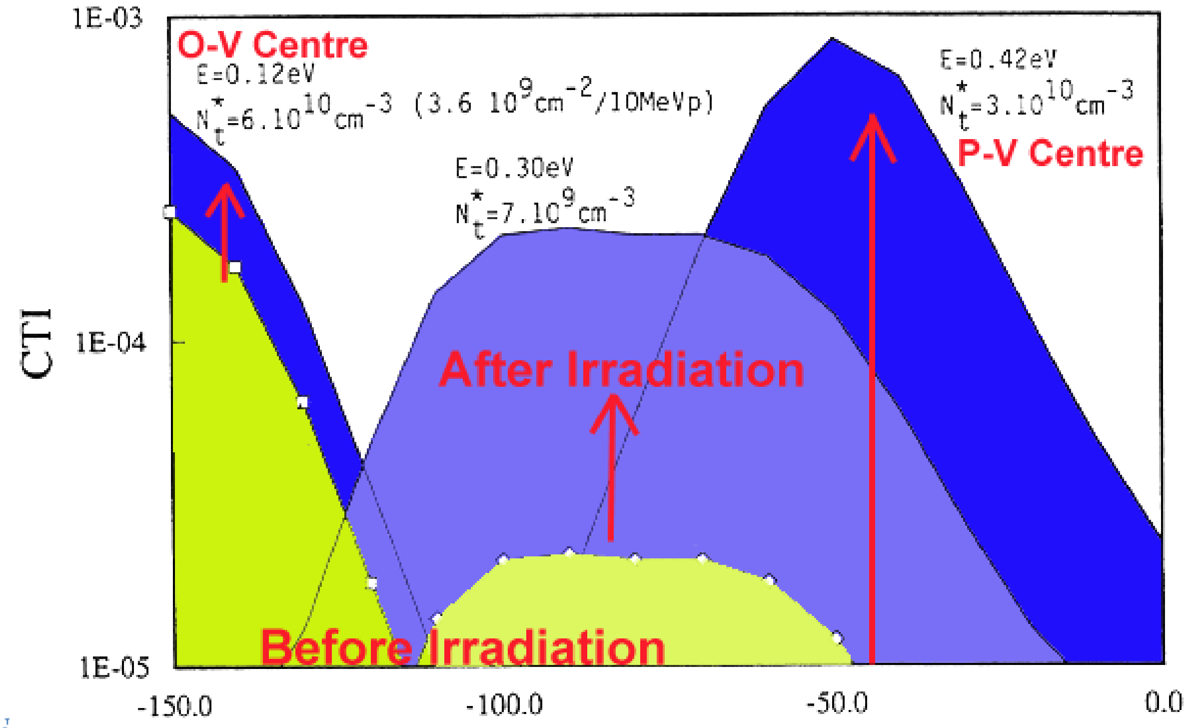


Quick Rush to the Birmingham Cyclotron

- Control room straight from Quatermass …

The work lead to models of trap species in the CCD

- Led to the identification of several key trap species
  - Deep/slow 0.42 eV P-V (V-V) complexes Parallel around -80°C
  - Mid-band 0.3 eV "Unknown defect" Parallel around -120°C
  - Shallow/Fast 0.12eV O-V complex Serial



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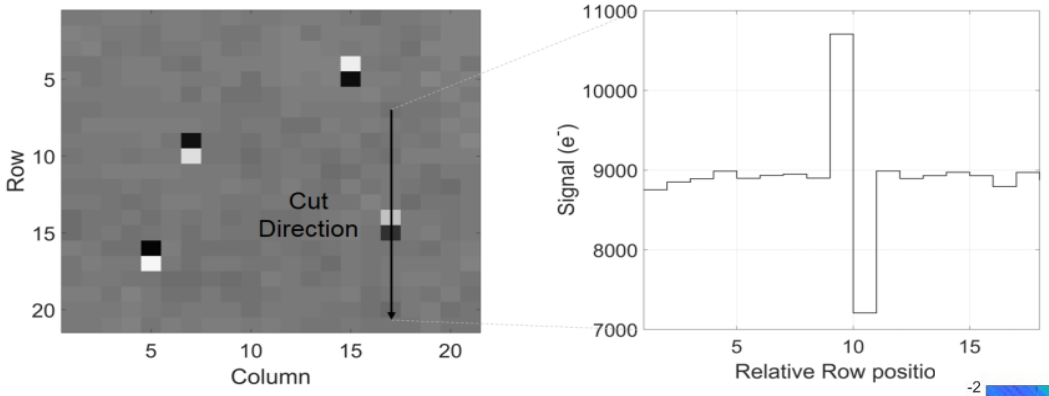
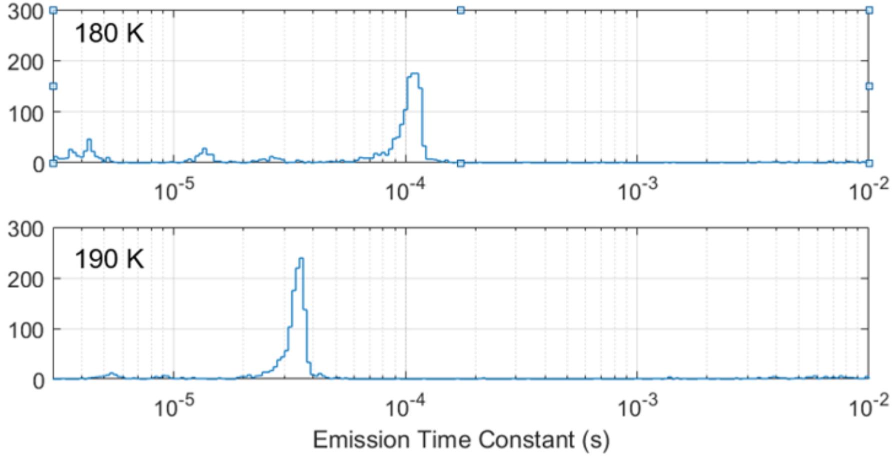
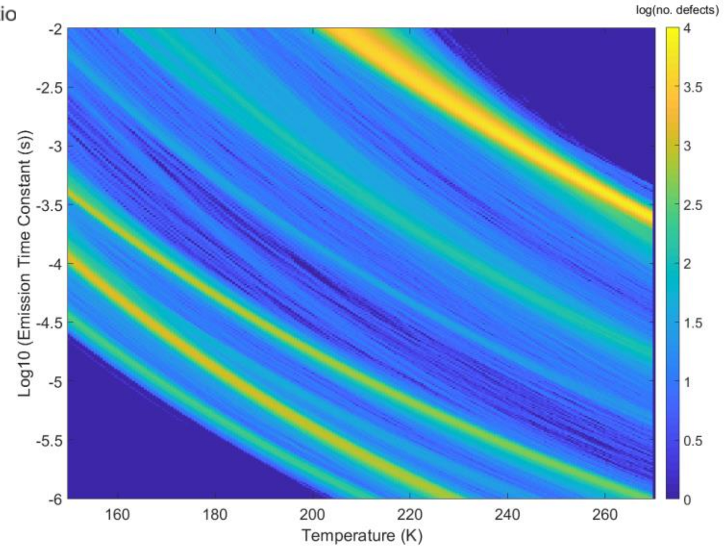
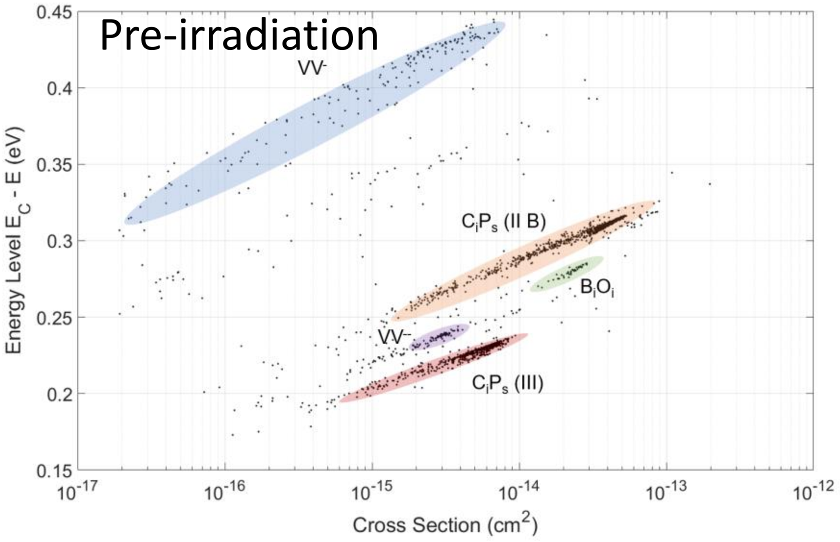
Proton-induced Traps using Pocket Pumping

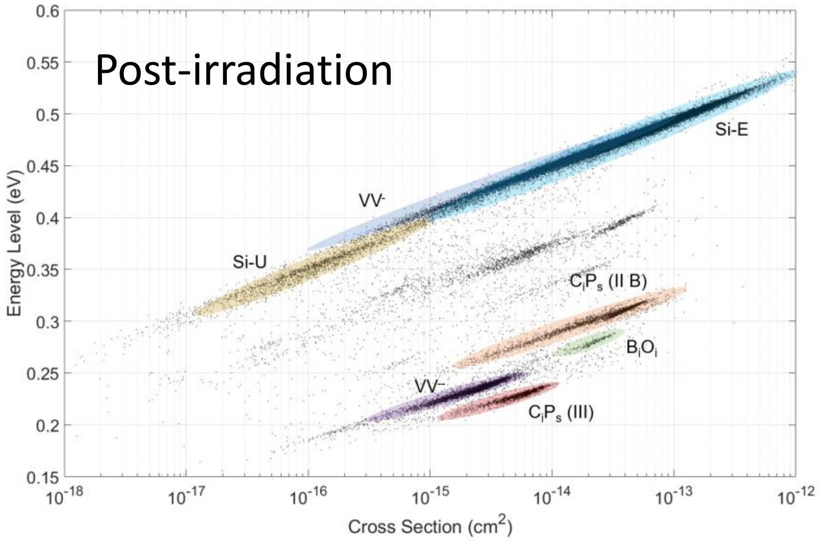
1. Using “pocket-pumping” to identify traps in pixels (developed for WFIRST)
2. Sweeping vs. clocking time and temperature
3. Can identify trap species in exquisite detail and precision
4. **Technique is being used in next-generation missions for CTI correction**





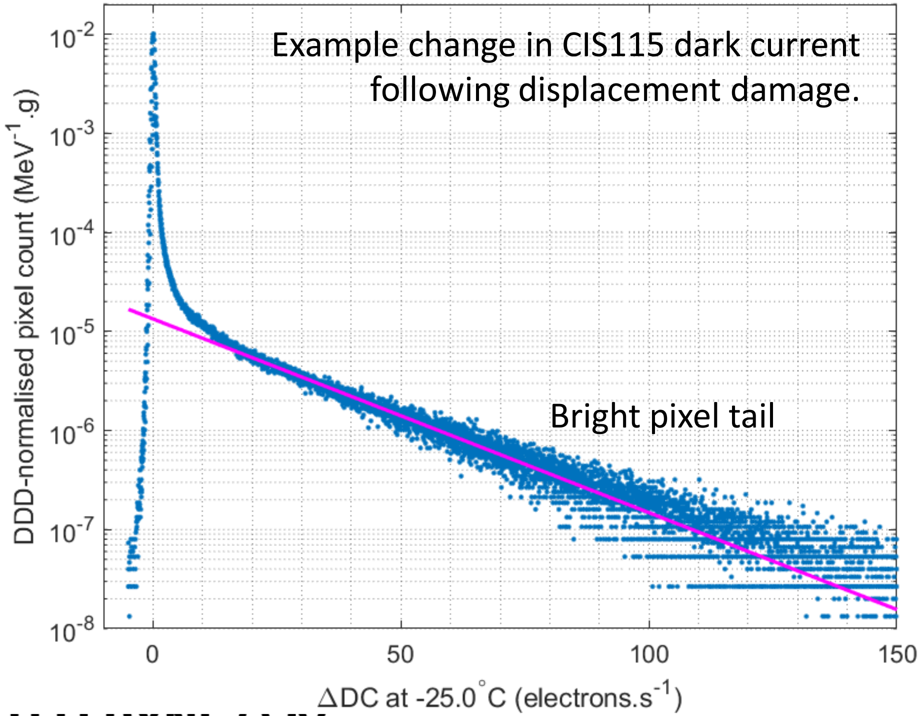




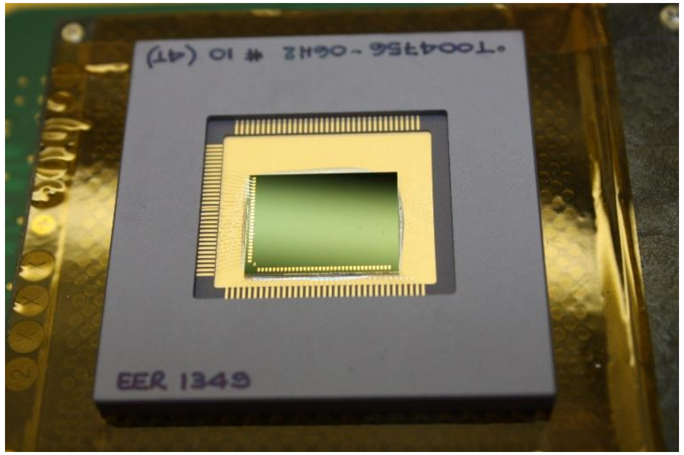


Proton-induced dark current behaviour

- CEI funded the development of the CIS115 for the JANUS camera on ESA's JUICE mission
- Driver for operational temperature is from the bright pixel defects produced by Displacement Damage Dose (DDD)



CIS115:
7 μm pixel
5 e rms. readout noise
4T pixel with pinned photodiode
10±1 μm thickness, ~4 μm depletion
Higher resistivity silicon
Tower-Jazz manufacture, Teledyne-e2v back thinned



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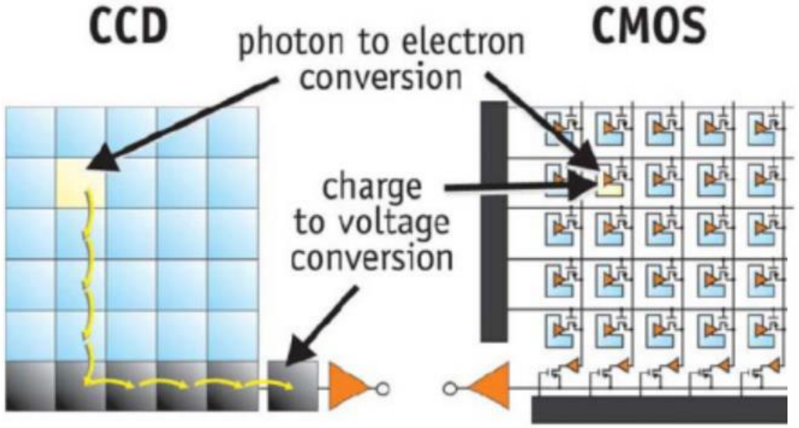
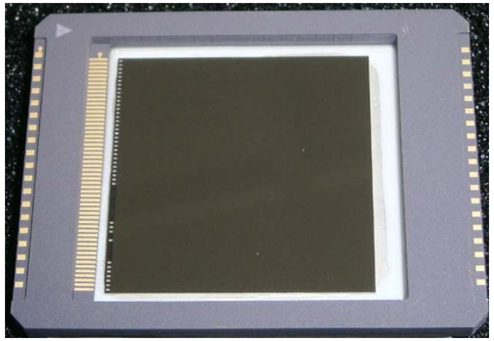
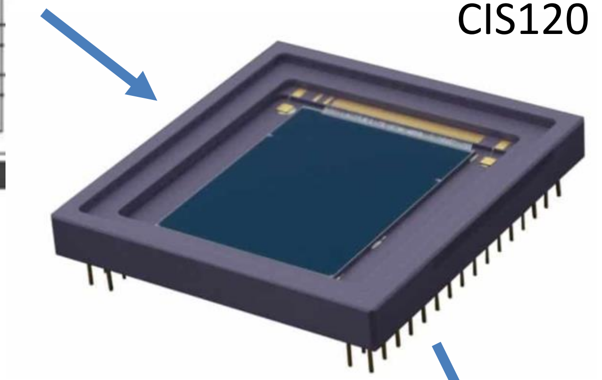
CCDs and CMOS Imagers



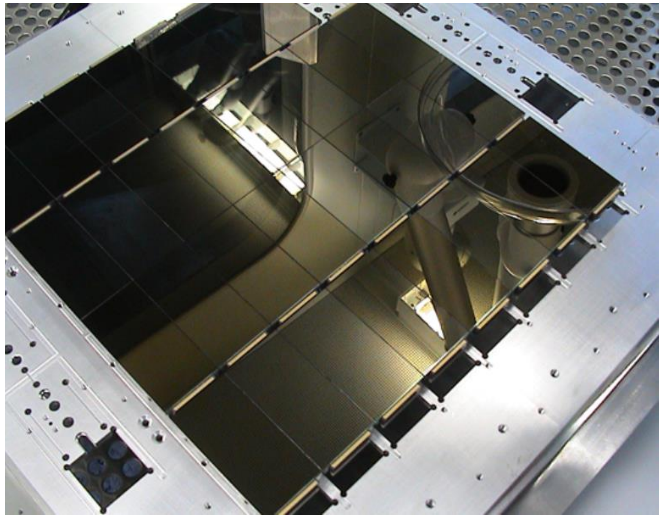
CCD42



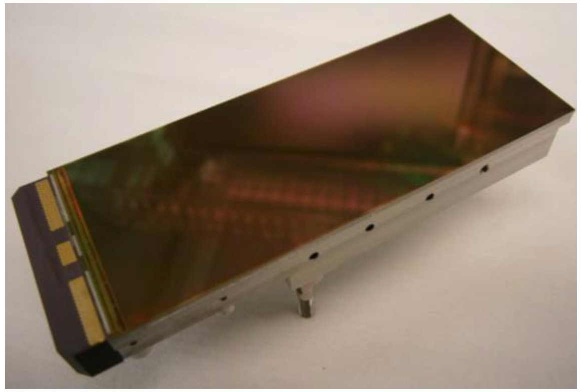
CIS120



CCD44-82



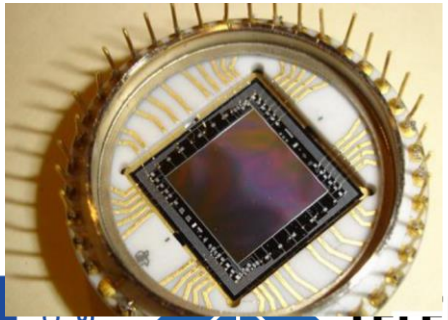
CIS113

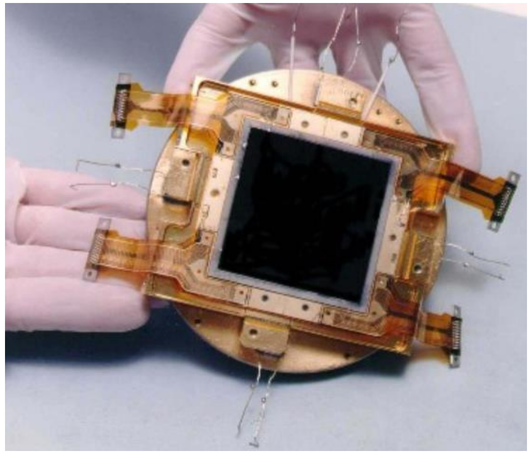


e2v Everywhereyoulook™

Hubble

- Launched December 1990
- Original WFPC imager only 800x800 pixels
- Upgrade to WFPC3 in 2009 using e2v CCD43 with 2051 x 4096





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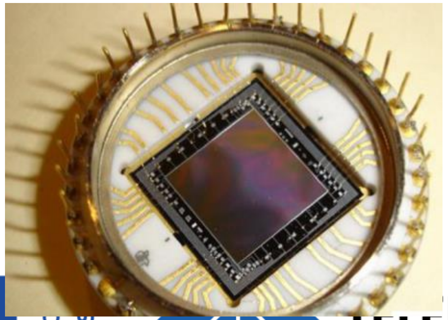
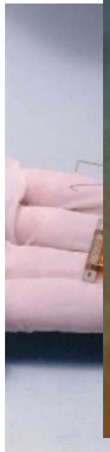
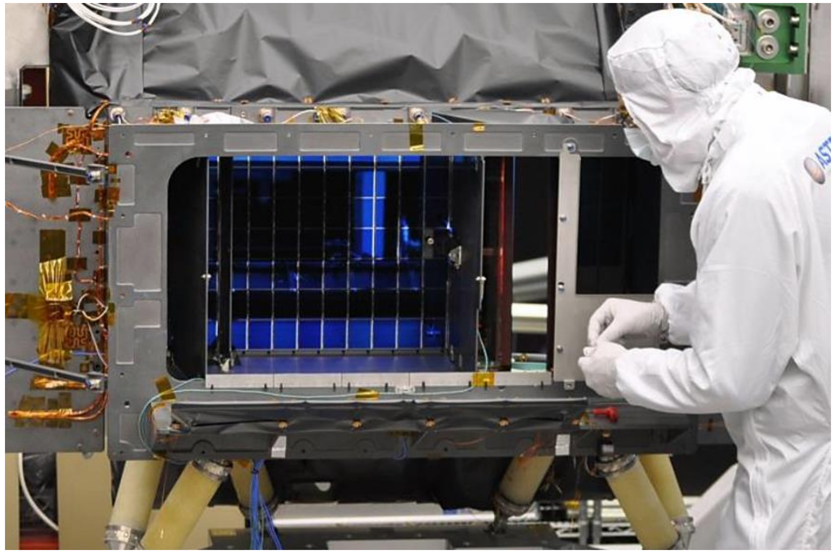




Gaia

1. Launched December 2013 to L2
2. To measure galactic shear due to gravitational microlensing
3. Custom 2k x 4.5k CCD sensors
4. 10x30 μm^2 pixels



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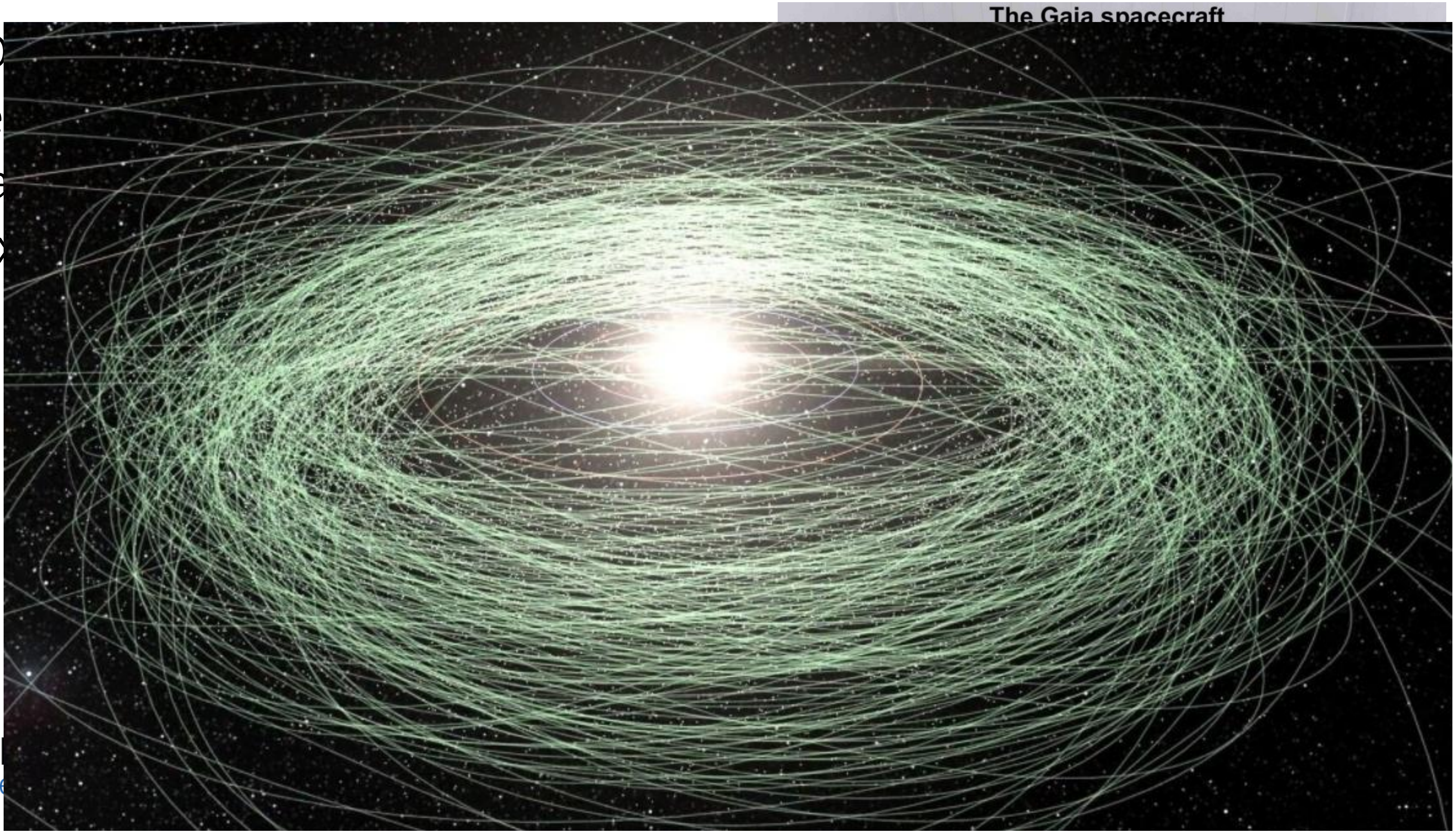
Gaia

- Launched D
- To measure
  gravitationa
- Custom 2k x
- 10x30 μm²



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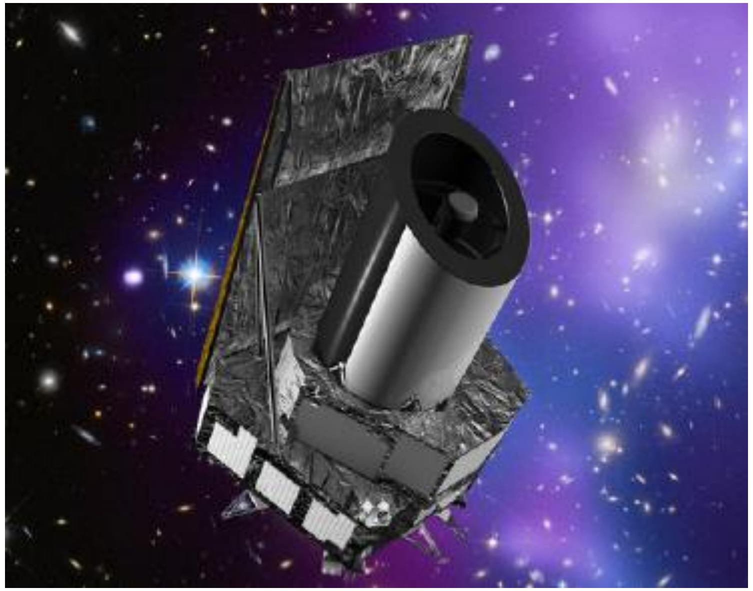
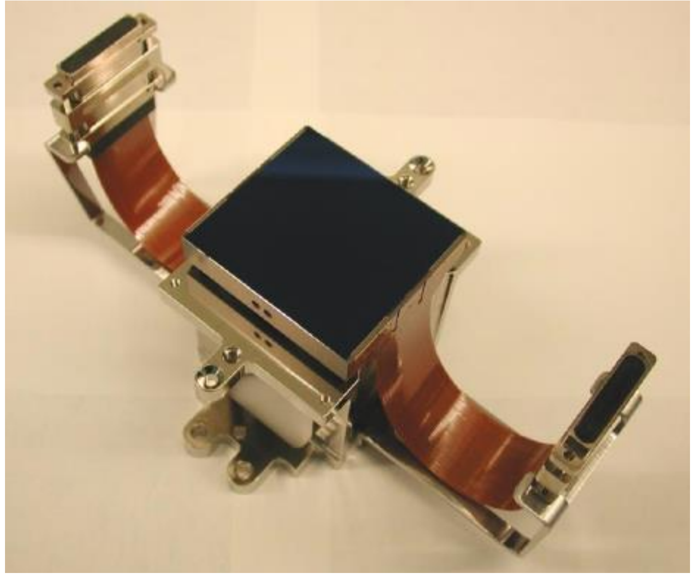
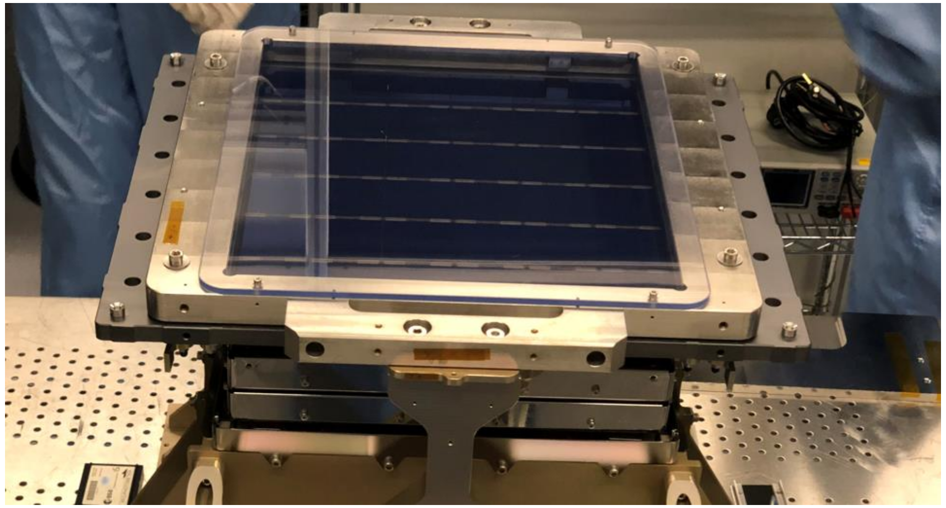
TE
Eve

Euclid

- Launch data Dec. 2022
- To measure galactic shear due to gravitational microlensing
- Custom 4k x 4k CCD sensors
- Radiation damage is still a concern







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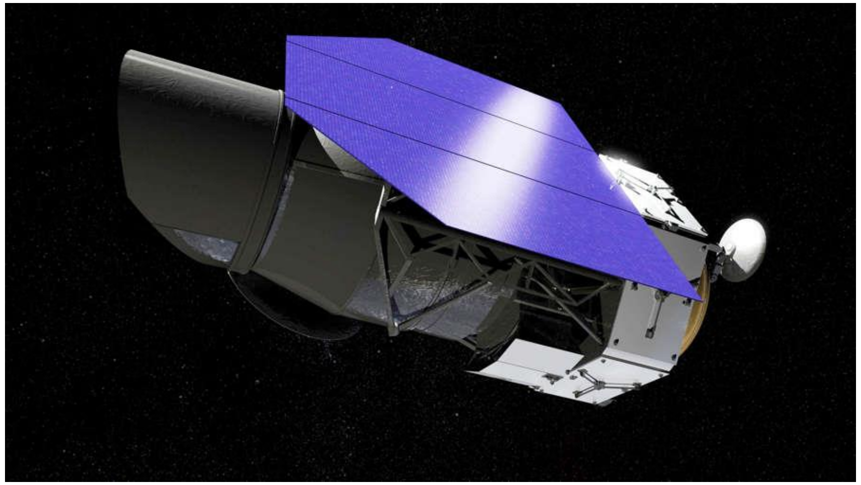
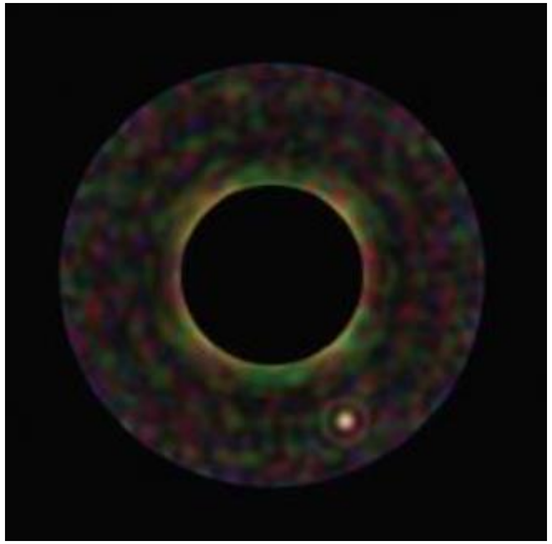
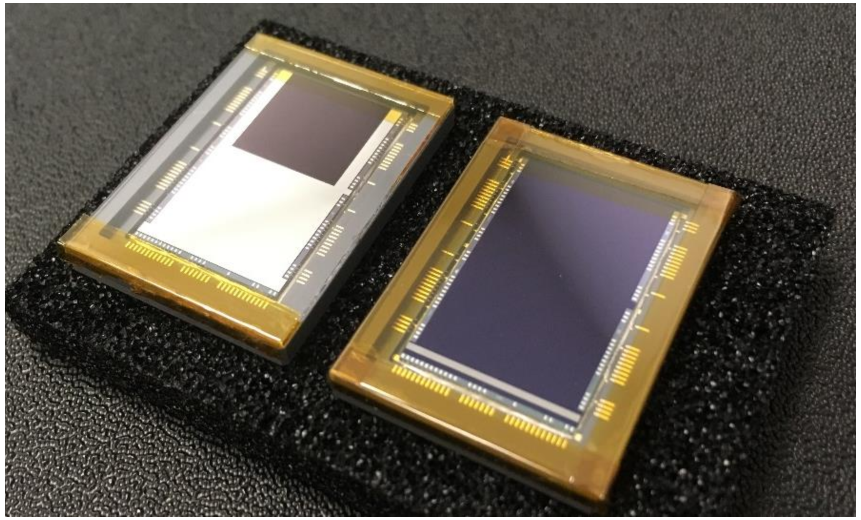
EM CCDs for the Roman (WFIRST) CGI

- Still many applications for single sensors
- EM CCDs being used for the coronagraph instrument on Roman
- Goal is to suppress light from the star and to directly image exoplanets







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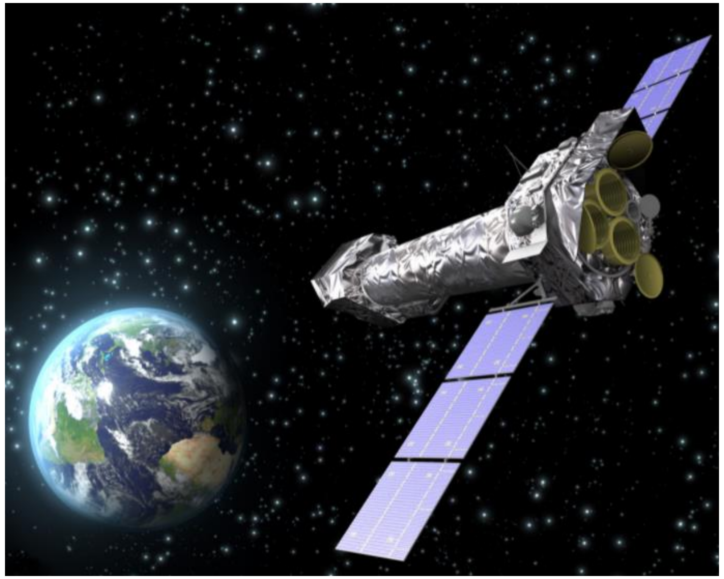
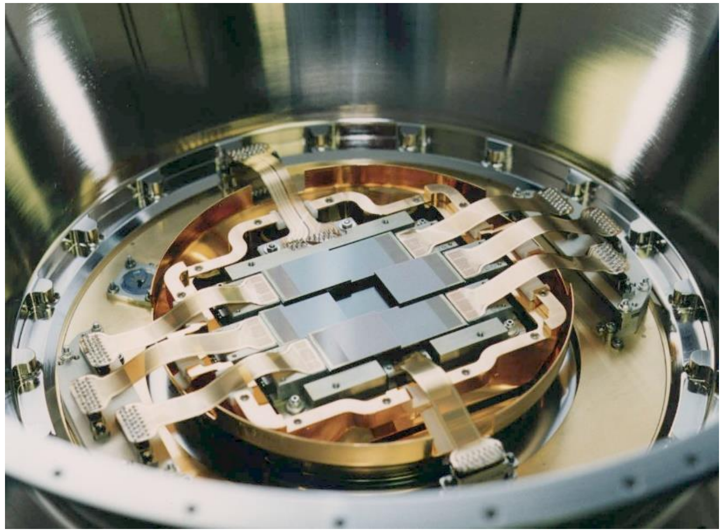
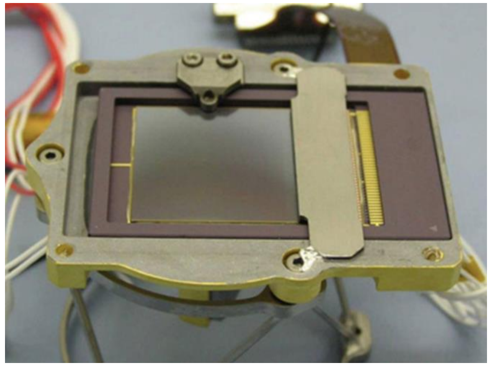
XMM Newton

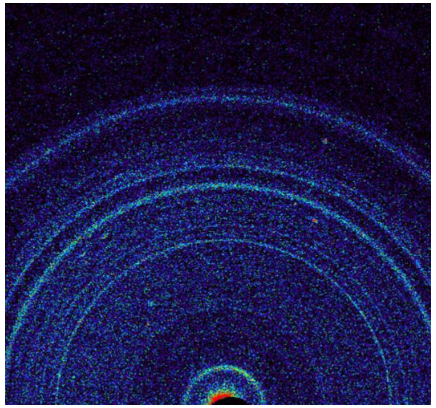
- Launched December 1999
- 2 EPIC-MOS cameras
- Each FPA having 7 CCD22s

- The CCD22 later re-used for Chemin on the Curiosity Rover









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ESA CCD Developments for XMM

- ESA funded a series of activities under it's TRP programme to support the two X-ray instruments
  - EPIC The imaging camera 0.3-12 keV, R~30, Imaging
  - RGS Dispersed X-ray grating 0.3-2keV, R~300, Non-Imaging
- Technical Development Activities

Parameter	State of Art	Target	Technology
Noise	~10e- rms.	<5 e- rms.	Lower node capacitance
Area	~1x1 cm^2	2x3 cm^2	Developing "stitching"
Depletion (QE)	5 μm	>30μm	High resistivity epi
Dead Layer	~1 mm	50 nm	Back-illumination
Serial CTE	0.99998	>0.99999	SBC (also helps with radiation)

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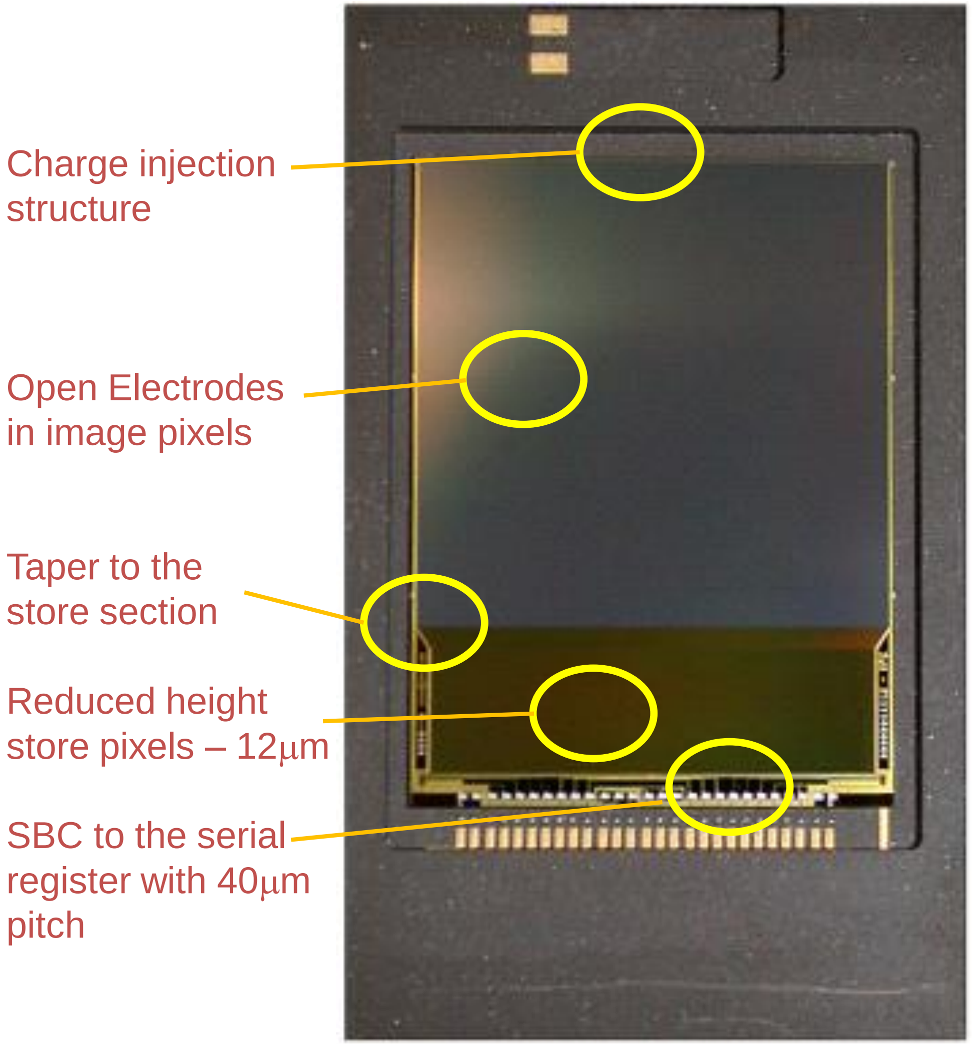
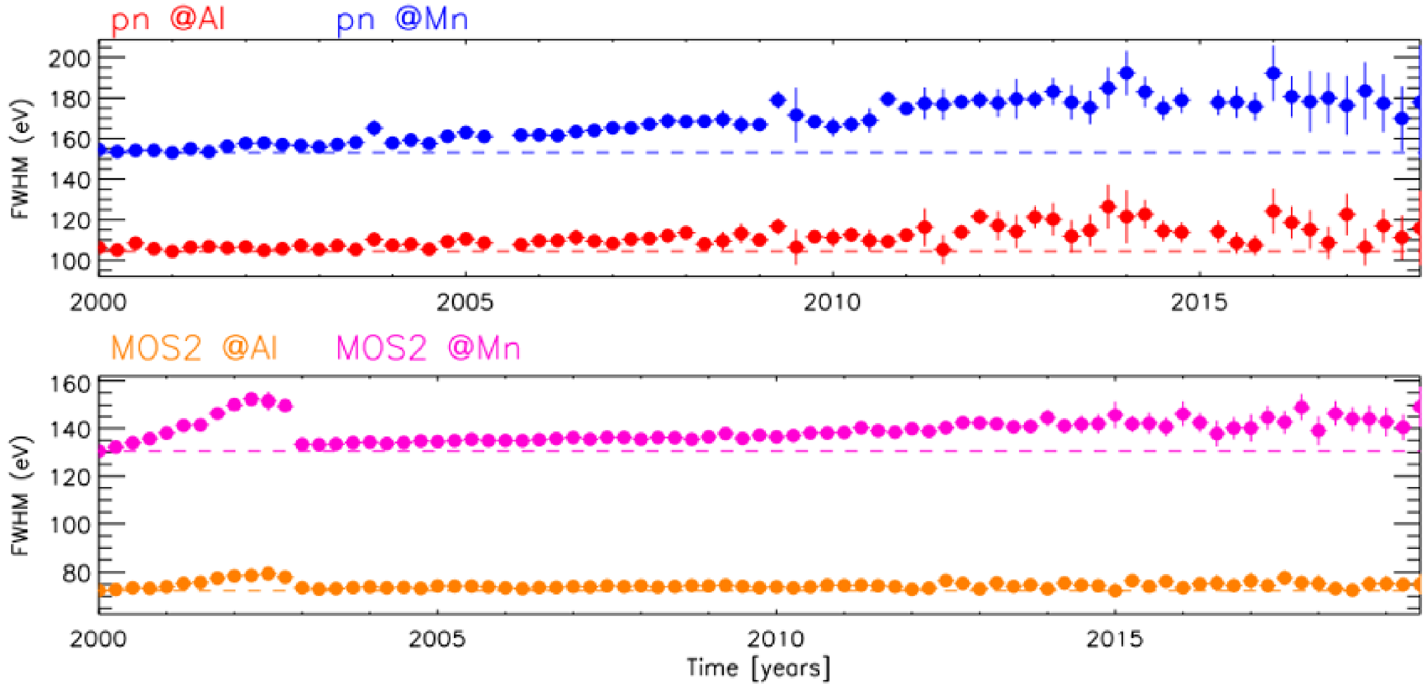
New Design Features in the CCD22 – TRL??

- Several new design features were brought together into the single design
- This approach would now be deemed highly risky under the TRL approach
- “let someone who knows what they are doing get on with it”?



EPIC MOS Camera Radiation Mitigation Measures

- >3cm Al **shielding** over 4π using forward baffle approach
- Filter wheel with **thick "blocking" filter** — *Became important for soft protons*
- Ability to **cool** the FPA down to operating temp of -130^{o}C
- **Supplementary buried channels**
- First use of **Charge Injection** structure — *Never used in practice*
- Ability to **anneal** P-V centre at +130^{o}C — *Never used in practice*



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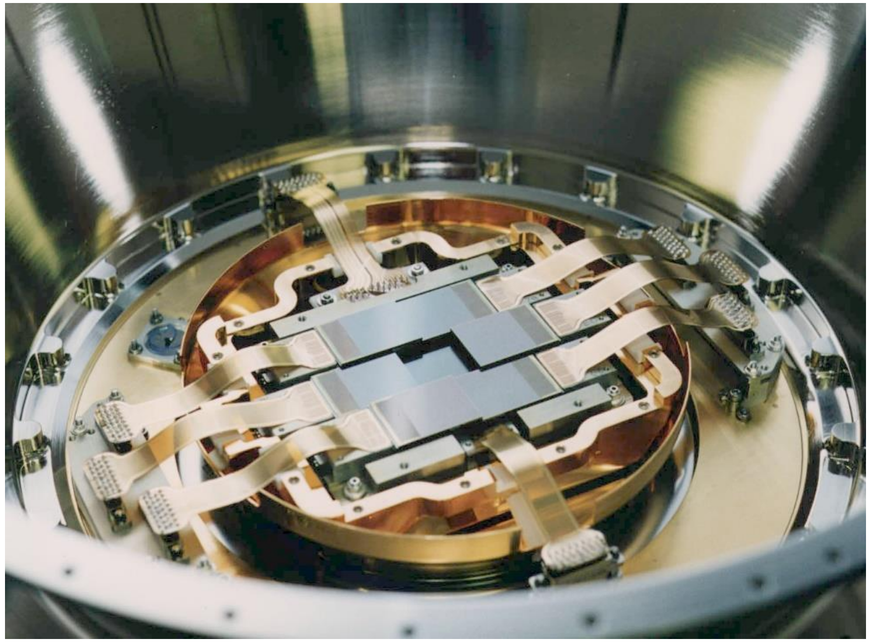
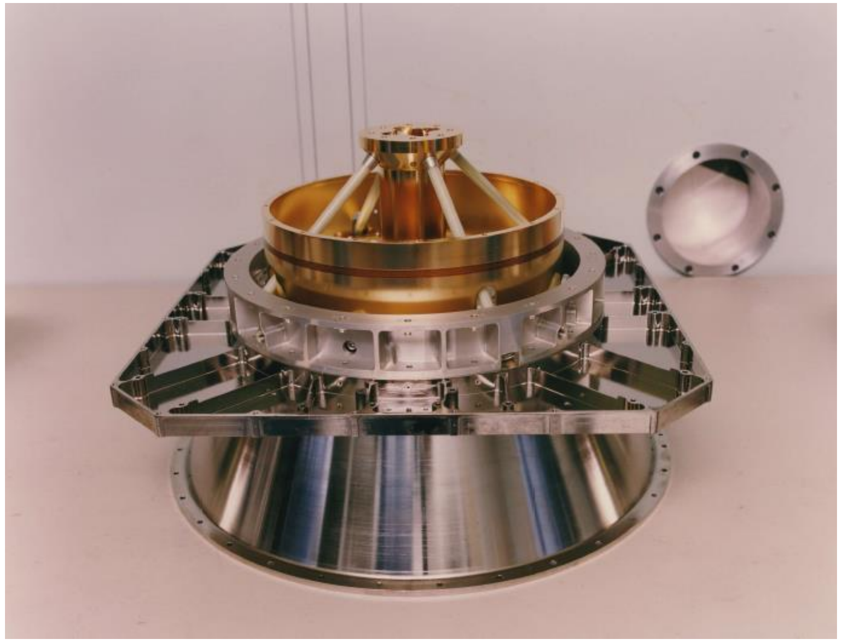
EPIC CCD Packaging and Focal Plane Array





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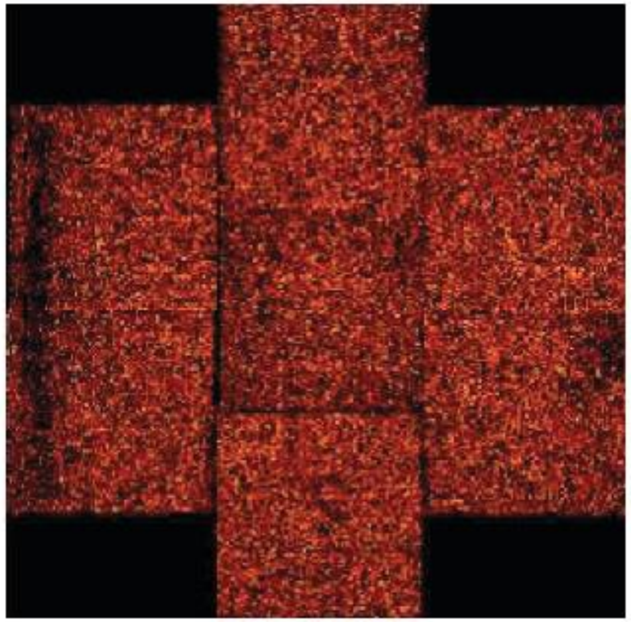
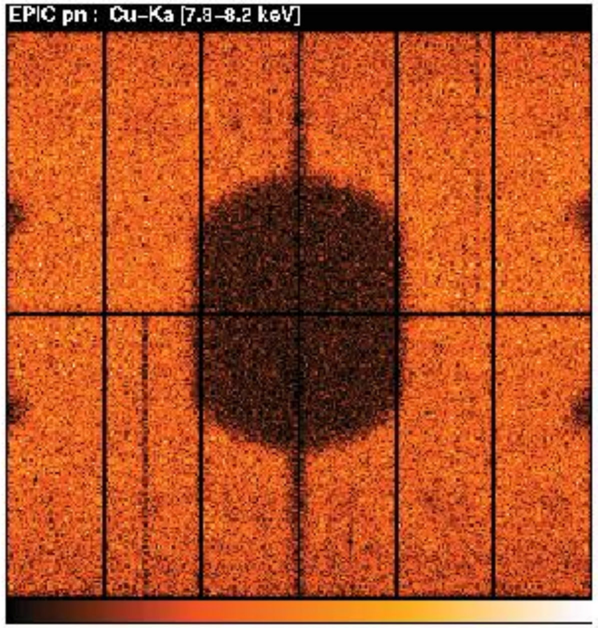
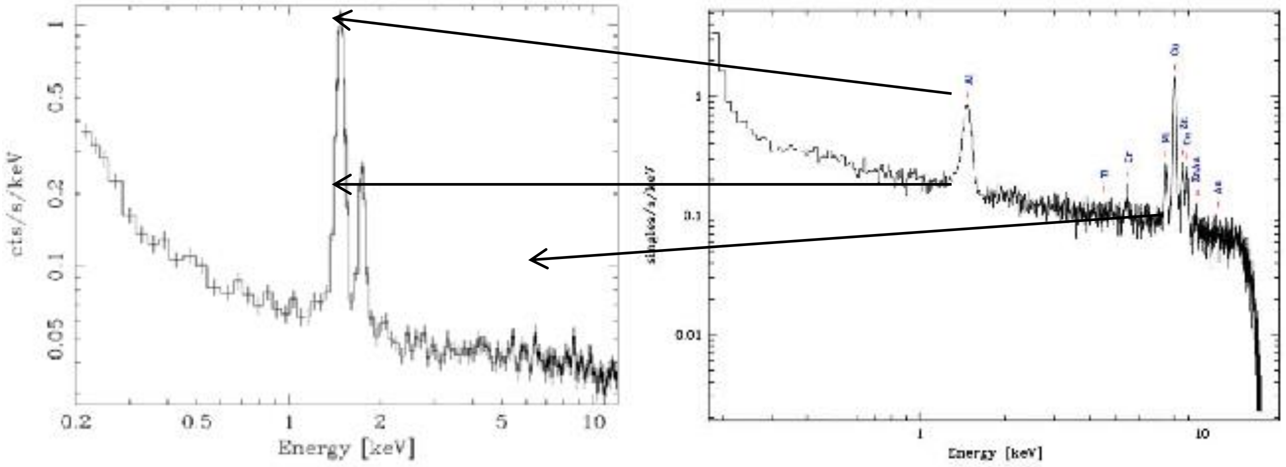
Instrumental Background in the EPIC Cameras

- X-ray background (protons)
- Fluorescence from the cryostat
- Now using significant development on low-background systems using GEANT-4







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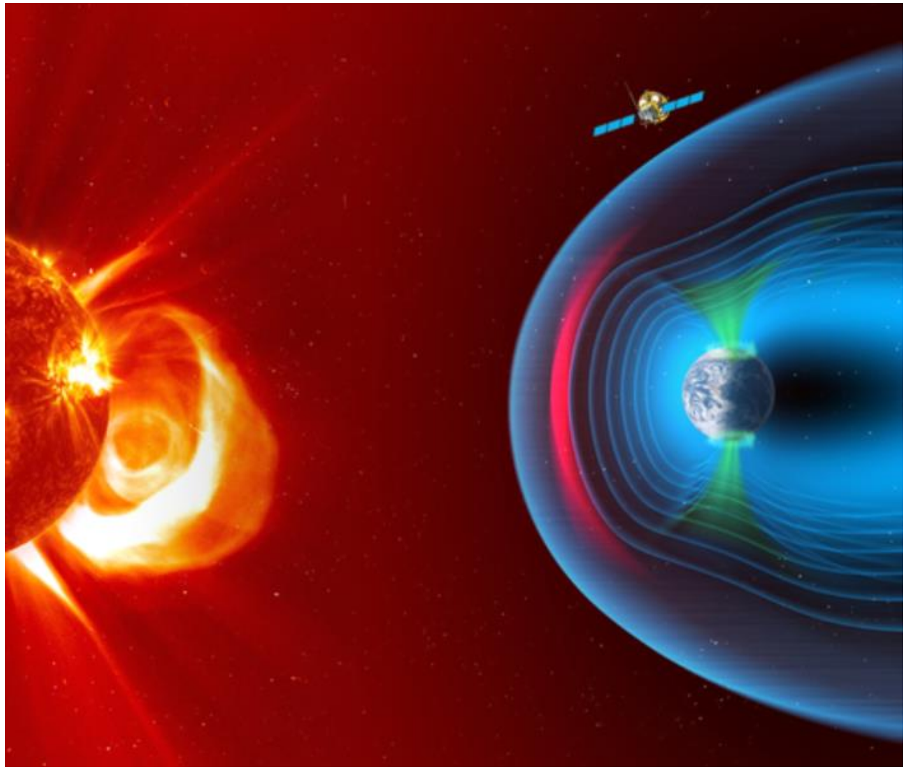
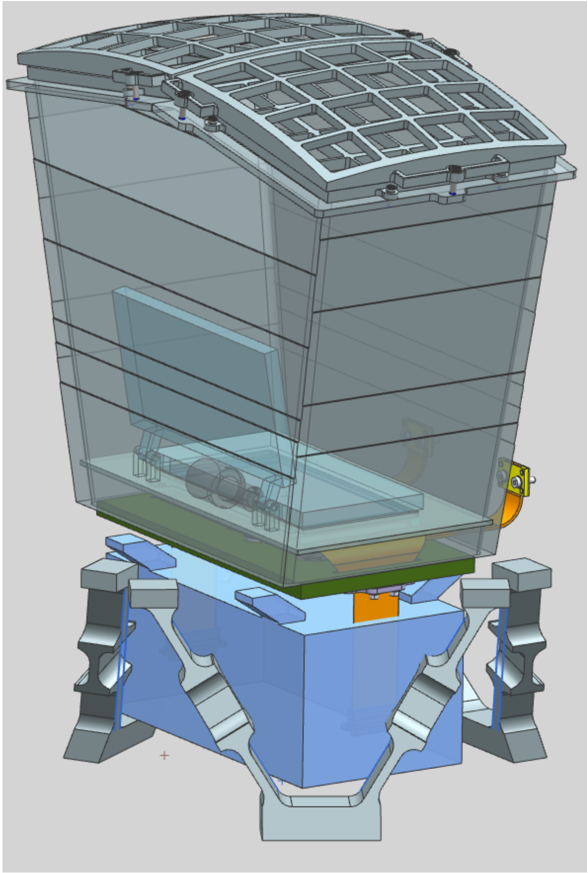
SMILE-SXI

- Launch date ~2024
- Wide-angle observation (27° x 16°)
- Primary science is between 200 eV to 2000 eV
- UK-led consortium, with contributions from other ESA states
- Focal plane of 2 CCDs, being procured by ESA from Teledyne-e2v



Lobster-eye optics modules (U. of Leicester)

2x CCDs (OU), Front End Electronics (MSSL), Shielding door



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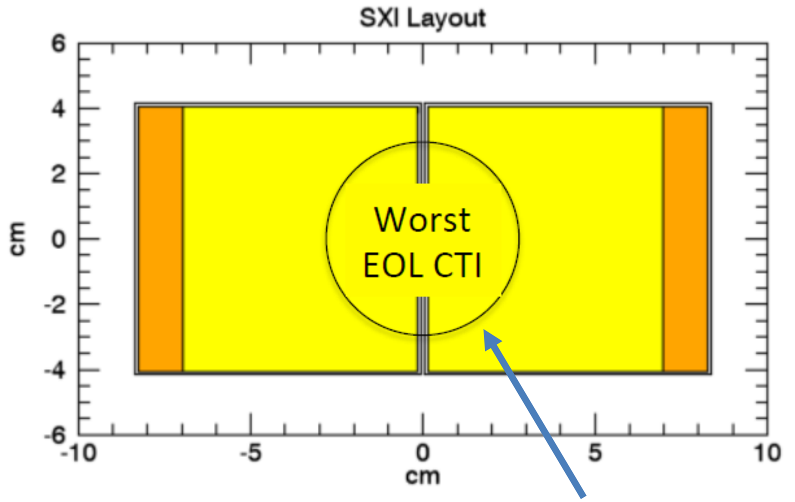
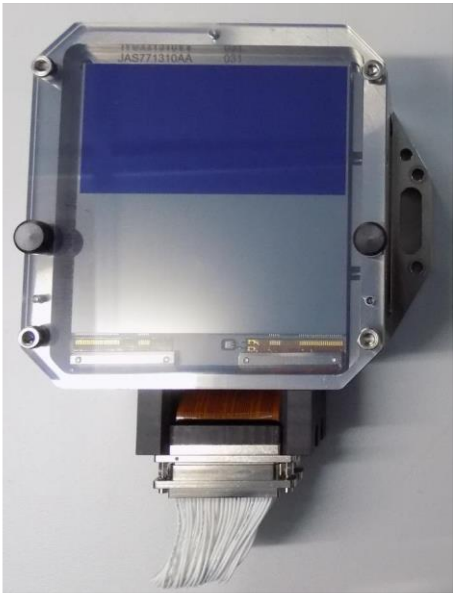
SMILE-SXI CCDs

- ESA procurement of CCDs from Teledyne-e2v optimising:
  - Soft X-ray performance
  - Schedule + cost
- CCD design is a modified PLATO detector (CCD270):
  - For TRL reasons
  - Utilising package qualification of PLATO
  - 4510 x 4510 native 18 μm square pixels
  - > 8.1 cm x 8.1 cm sensitive area
  - 16 μm thick silicon
  - Back-illuminated



Approximate size of the 7-CCD array for XMM EPIC



PLATO CCD270

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Detector thickness modelling for low background

Approximate modelling of detector thickness with GCR protons (L2 spectrum)

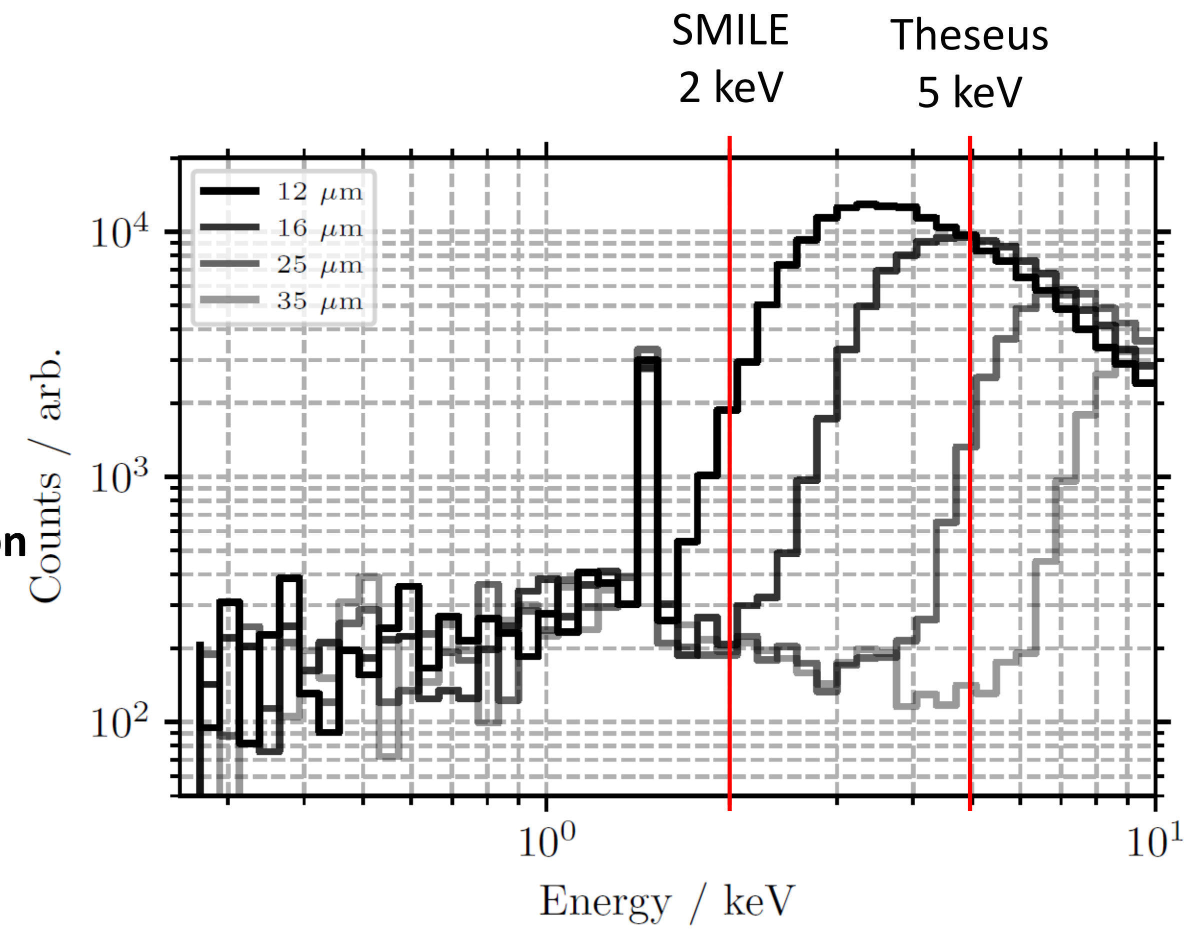
- Geometry is a 4 cm Al shield.
- Detector is a single slab of Silicon (no support wafer / optical filter)
- Pixels are 8 µm, to allow re-binning in the future.

For SMILE:

Increased active thickness from 12 to 16 µm

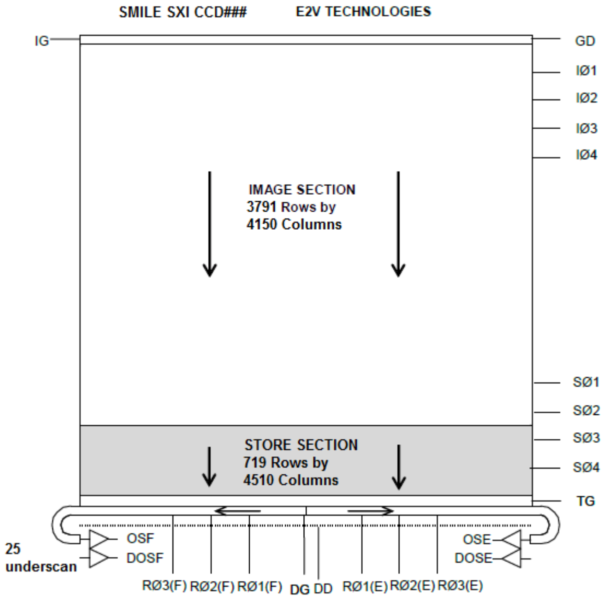
For Theseus:
Demonstrates off the shelf CIS120
will not have sensitivity >~1.5 keV

Requires thick devices of ~35 µm, BI, with full depletion

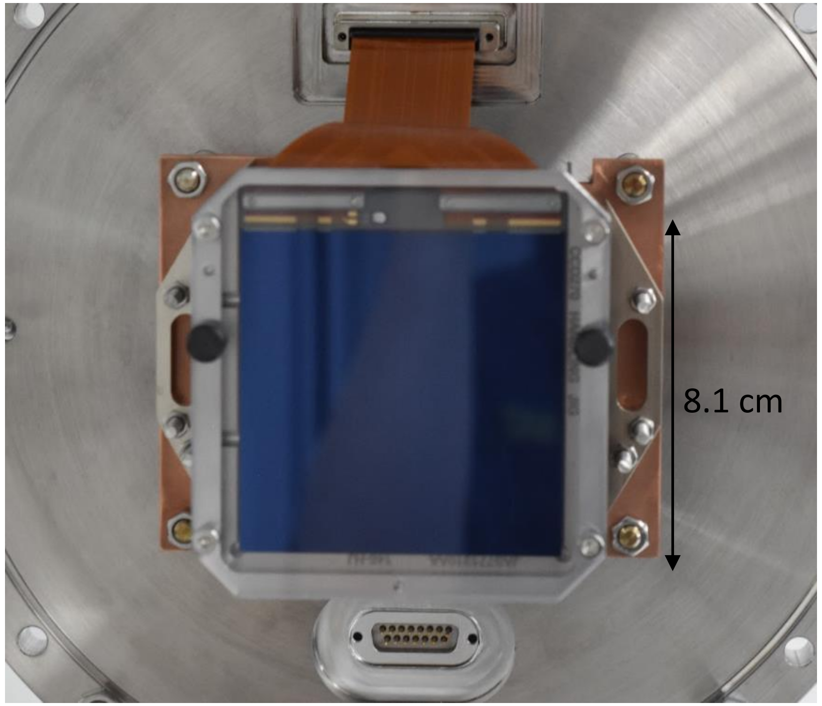


SMILE-SXI CCD modifications – CCD270 to CCD370

- For TRL reasons have modified the PLATO CCD270 design to become the SMILE CCD370
- Higher gain output amplifier to improve readout noise ~2 µV/e (PLATO-like) to ~7 µV/e (Euclid heritage)
- Supplementary buried channel in parallel image area (Gaia heritage)
- Narrow channel in serial register
- No anti-reflective coating, with e2v's enhanced BI passivation process

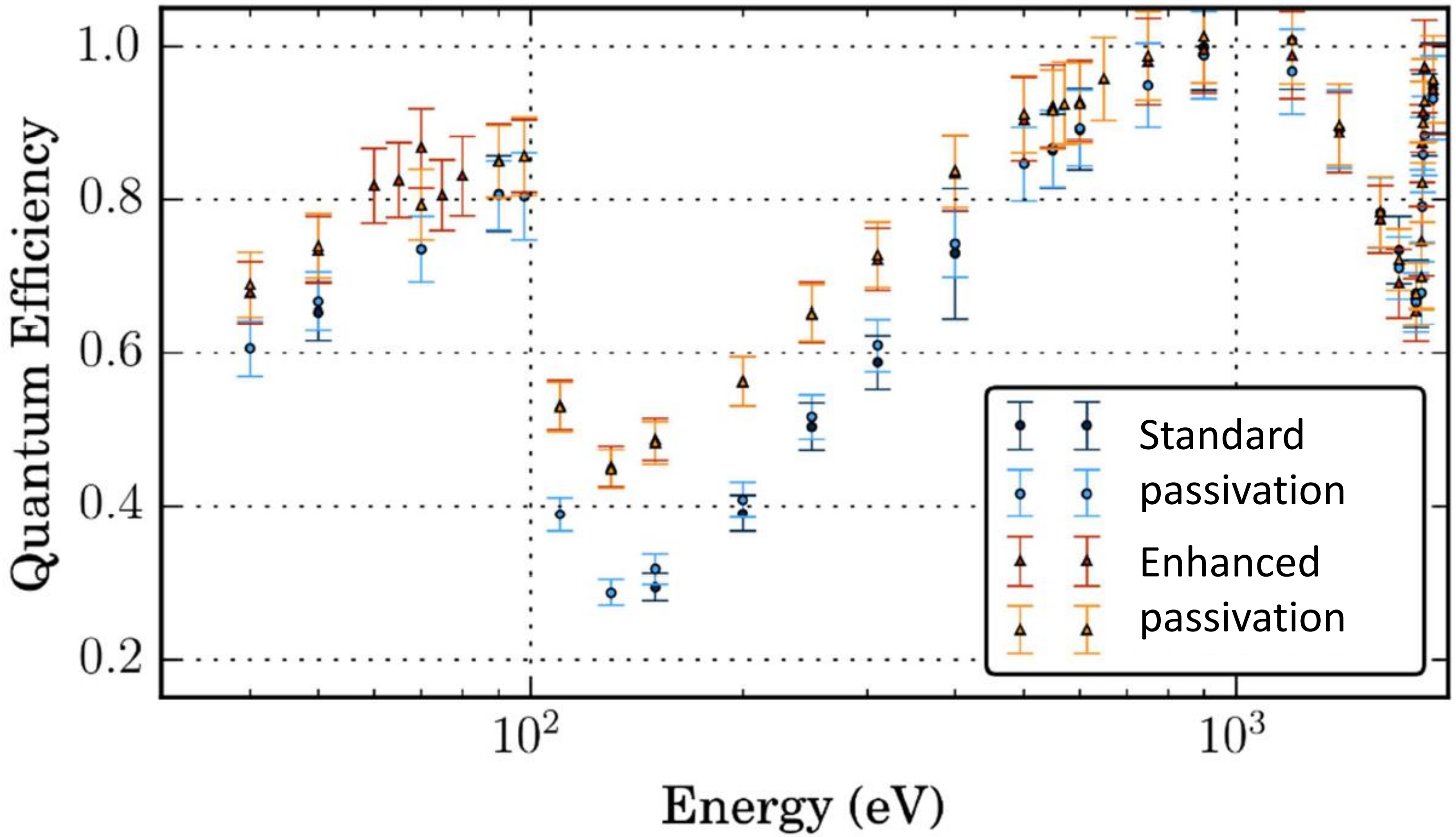


6:1 frame transfer ratio



Back-illuminated CCDs

Open University QE measurements at PTB beamline (BESSY II) in 2016:



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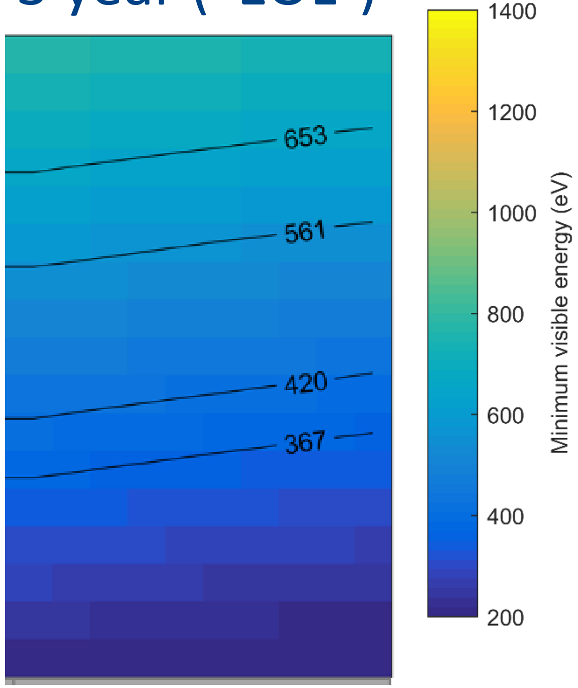
See poster by Jonathan Keelan

Modelling the SMILE spectrum

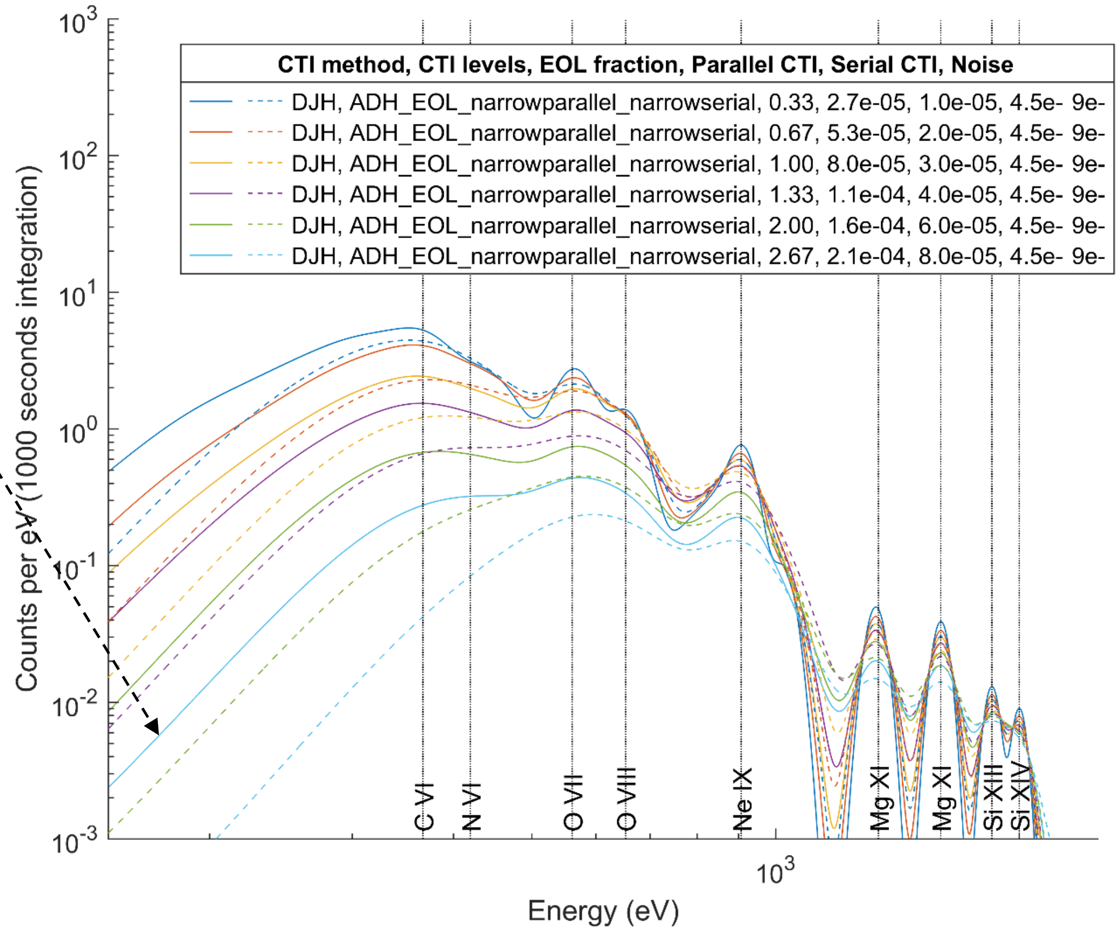
X-ray CTI simulation to understand instrument science output.

3 year (“EOL”)



Resolution and detection efficiency will degrade during mission lifetime

Ability to detect soft photons will be lost from the “top” of the array



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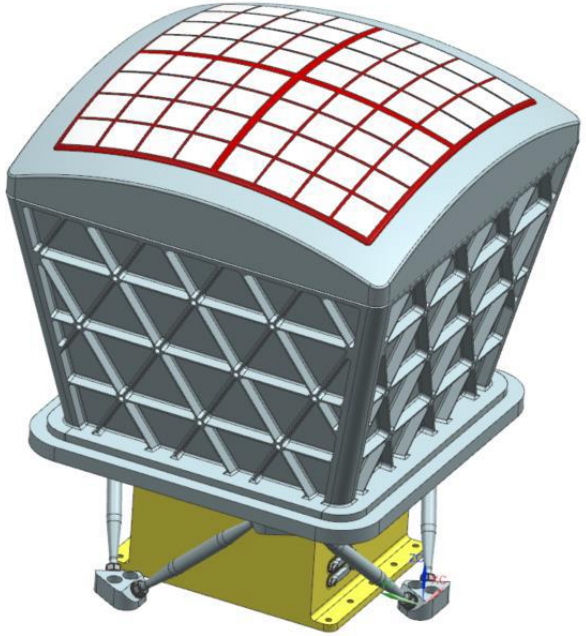
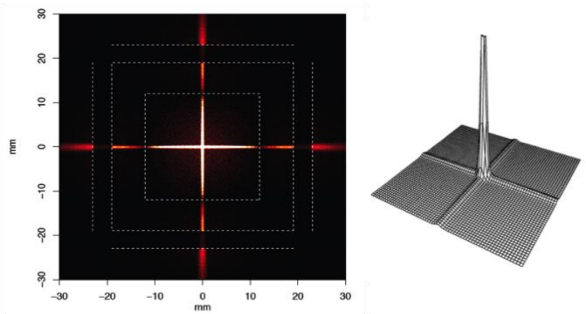
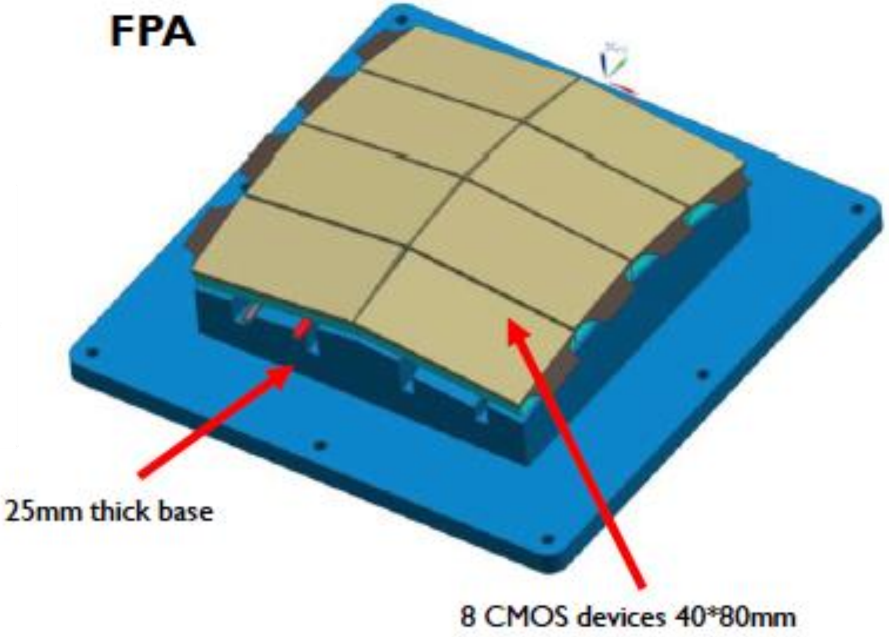
THESEUS Soft X-ray Imager (SXI)

- ESA M5 mission candidate for 2031 (unfortunately not selected for the M5 slot)
- 2 identical telescope modules observing in 0.3-5 keV band
- 8x8 array of MPOs provide FoV ~31 x 31 degree
- 2 modules FoV ~0.5 sr, with <2 arcmin locations
- Each module uses 8 large-format CMOS detectors

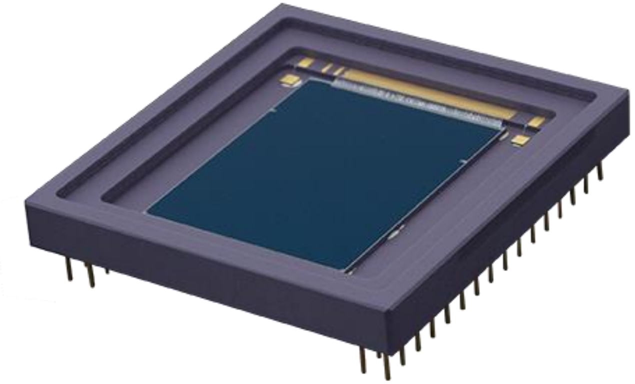


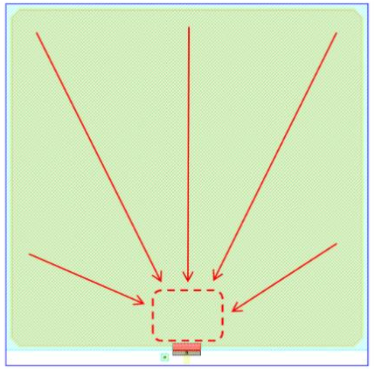


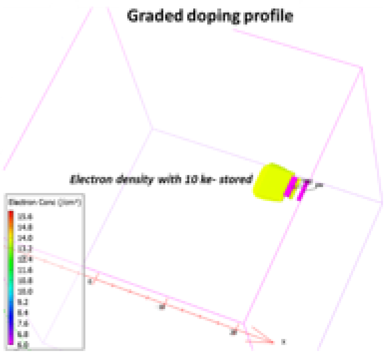


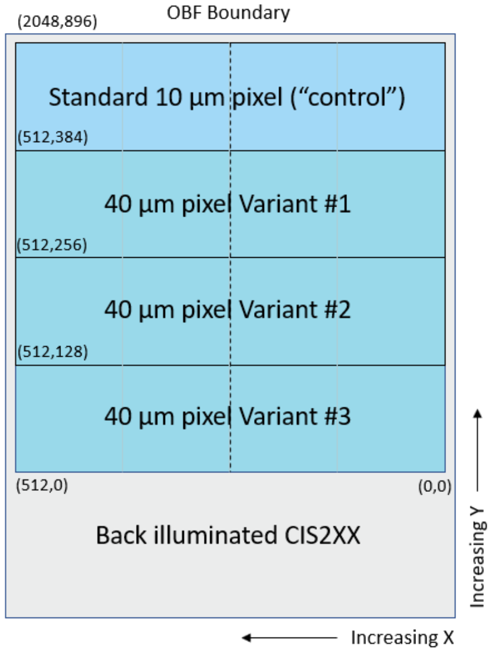
CIS221-X being developed under ESA TDE

- Device is based on Te2v's CMOS "digital platform"
- 2x2 cm^2 prototype detector
- Retains ¼ using the CIS120 10 μm pixels as controls
- Has 3 variants attempting to optimise the performance of the 40 μm pixel for Theseus
- With exception of the back-bias, all pins have identical function to the CIS120 package
- Integrated optical blocking filter (to be over the whole image area on half of the delivered devices)
- Key challenge is to design a pixel structure with efficient charge collection and transfer from the large CMOS pixel









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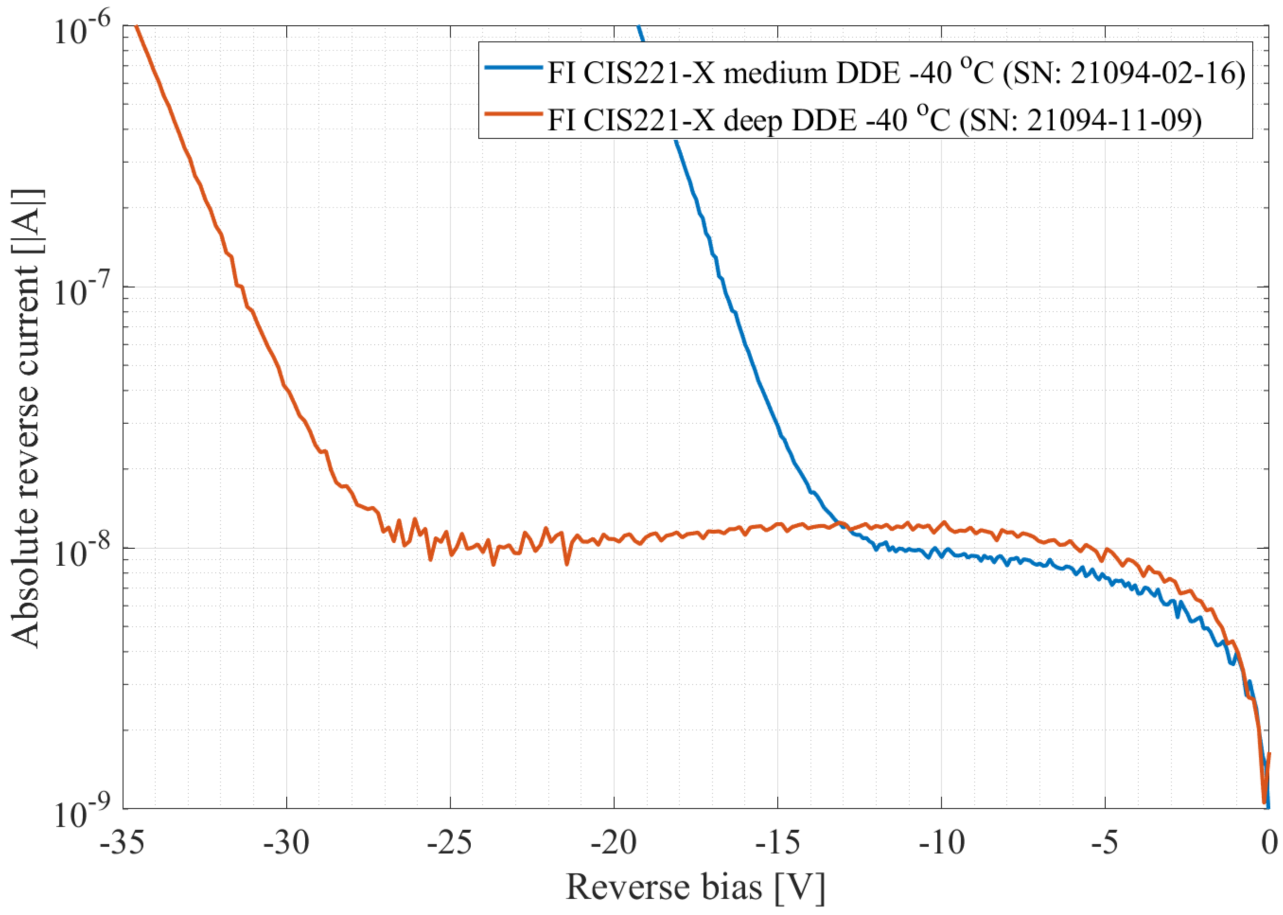
Initial Devices - Reverse current measurements

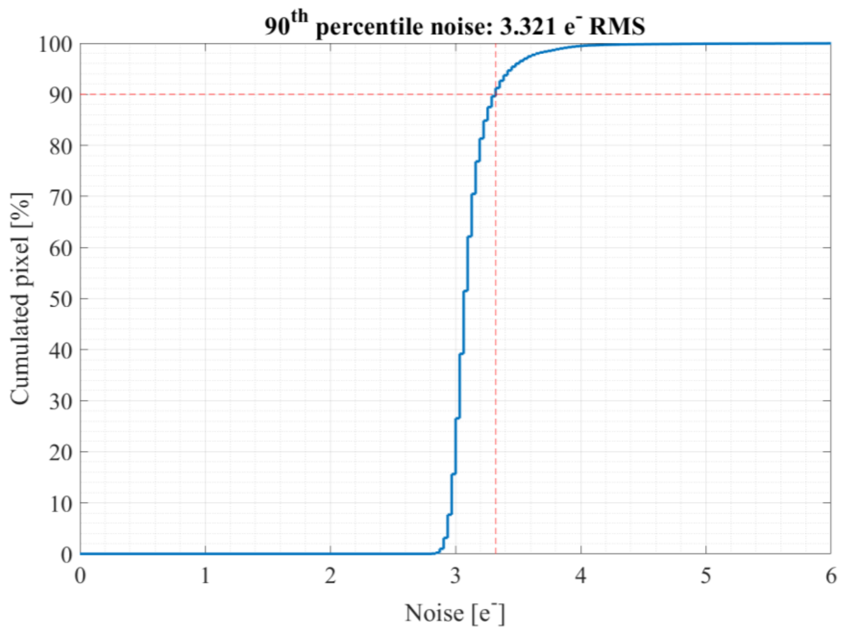
- **Manufactured on 50 μm-thick epitaxial silicon**
- **Current results on FI devices only**
- **BI devices anticipated toward end 2021**

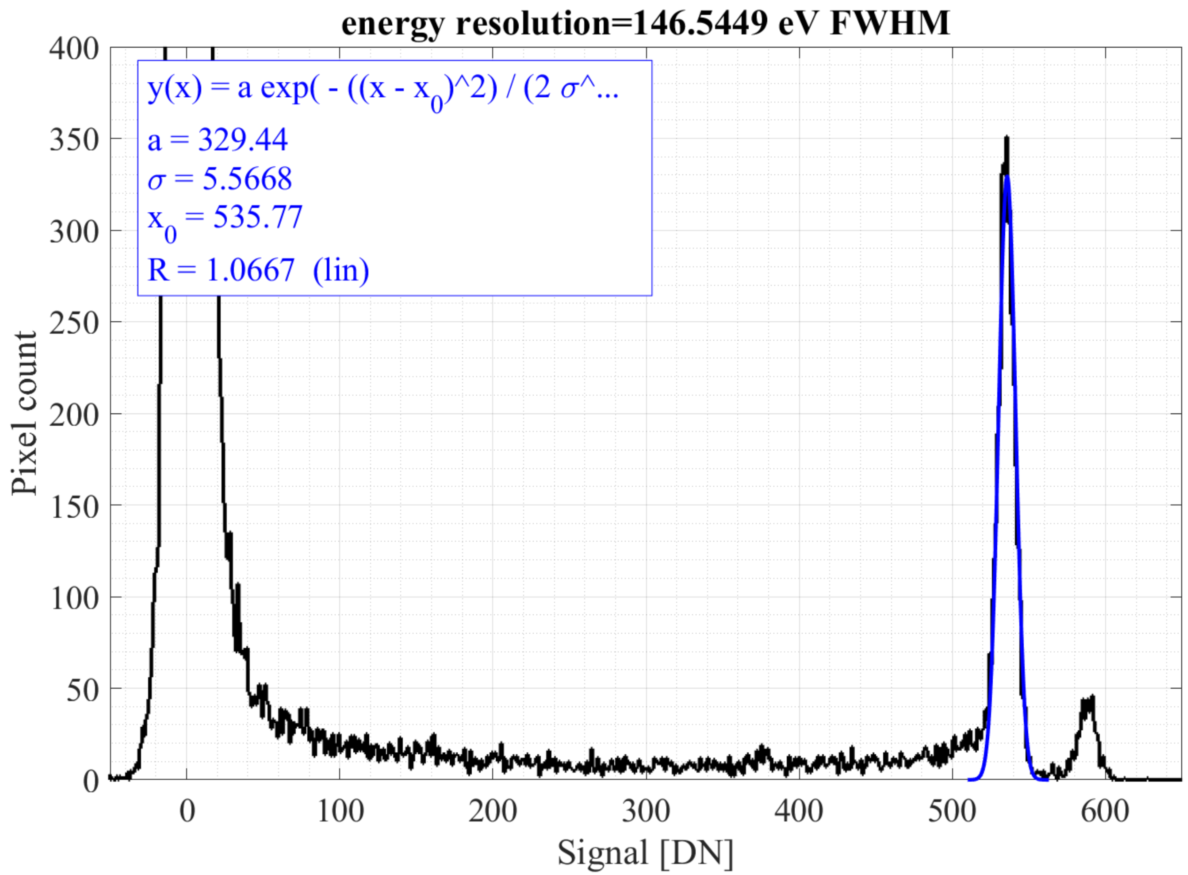
- **Measurements at -40 ºC**
- **Sensors biased**
- **Expected behaviours**
- **Based on only one device for each variant. Device to device variation to be expected.**



Initial X-ray performance

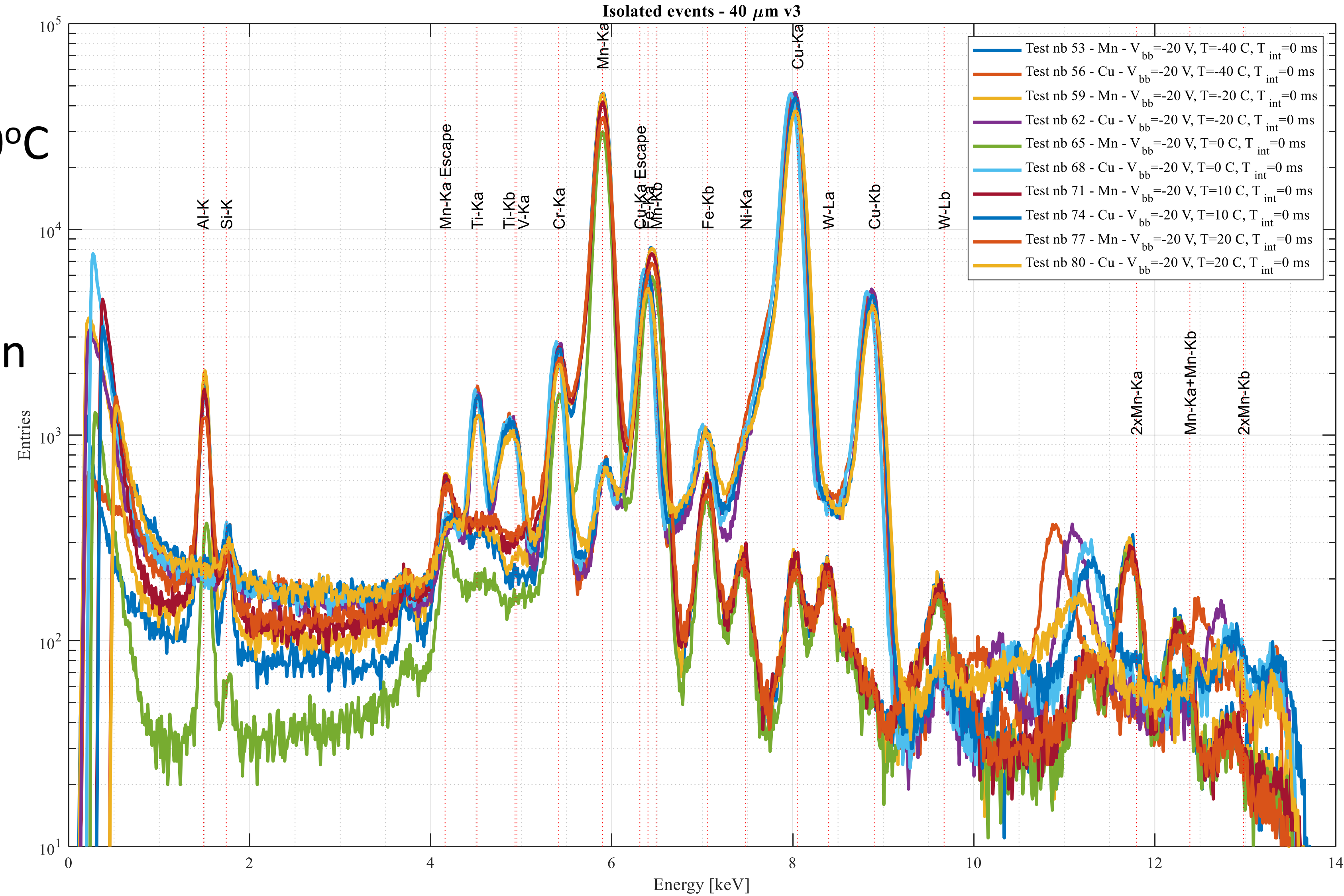
- **Noise ~3e- rms.**
- **Deep DDE variant**
- **Vbb=-20 V**
- **Cold (-40 C)**
- **All pixels plotted (no event detection)**





CIS221-X Isolated Event Spectra

- Operating temperatures over the range -40°C to +20°C
- Mn-K FWHM ~155eV without pixel gain correction
- With each variant covering ~1cm² represents possibly the best XRF spectra measured?



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Summary

- CCDs have been the workhorse detector for many visible and X-ray missions
  - However, radiation damage to CTI is becoming a limiting factor for some applications
- High performance, “scientific” CMOS image sensors are now growing in use
- Customised X-ray optimised CMOS sensors developed for Theseus are showing promise but with lower TRL
  - Fully digital devices, 3-sides buttable, large area, BI, etc.
  - Noise ~1.6 e- rms.
  - Full depletion up to 35 μm
- Development cost of custom CMOS image sensors is higher than CCDs & development times longer