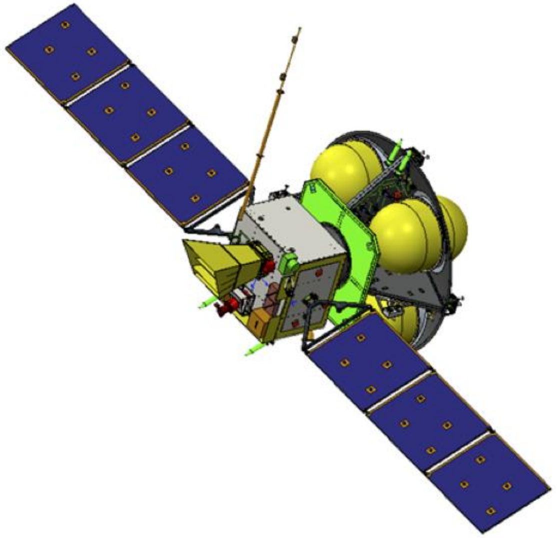
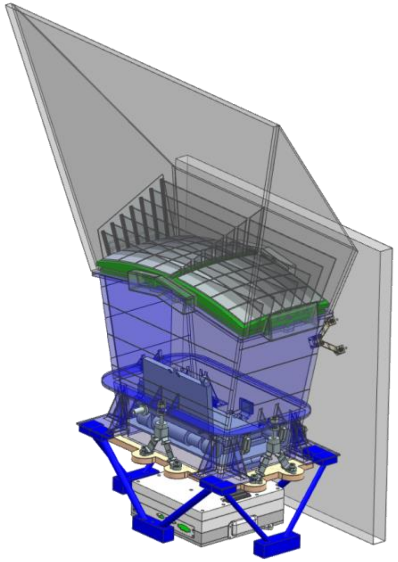
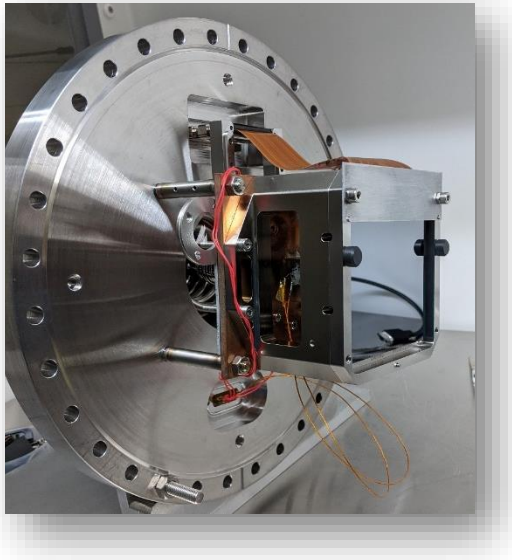
X-ray performance of a soft X-ray optimised charge-coupled device for astronomy



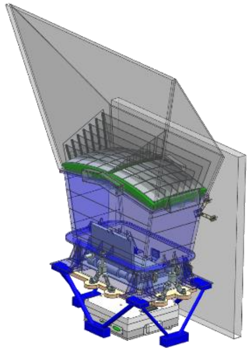


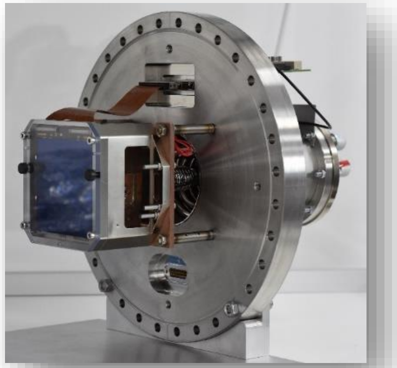


Tom Buggey – Position Sensitive Detectors 2023

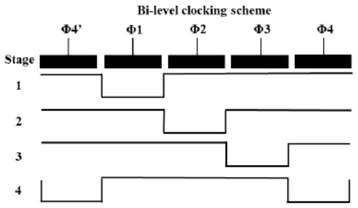
Summary

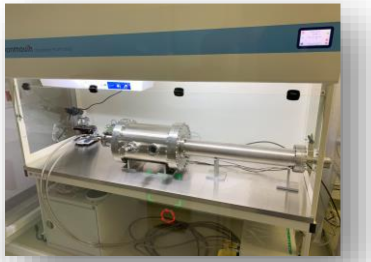
1) SMILE mission and the Soft X-ray Imager CCDs



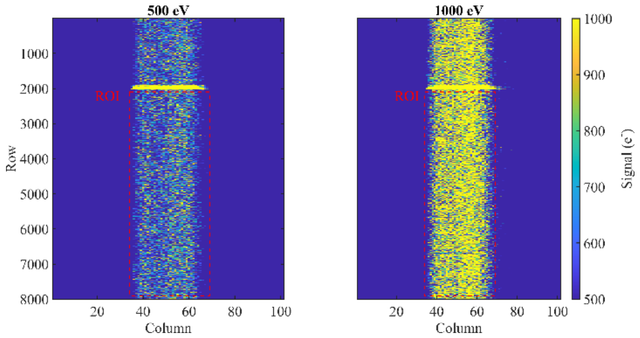


2) CCD principles and experimental activities

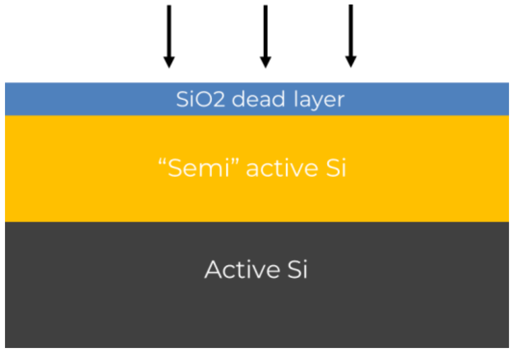


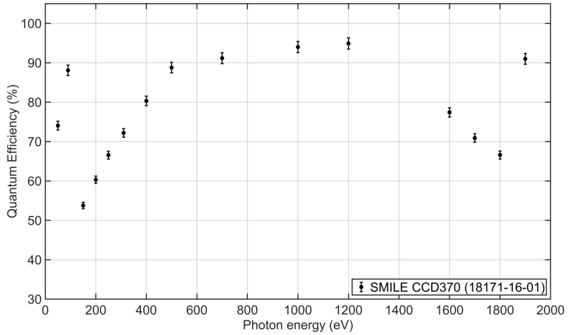


3) Experimental methods + techniques



4) Results, discussion and future work





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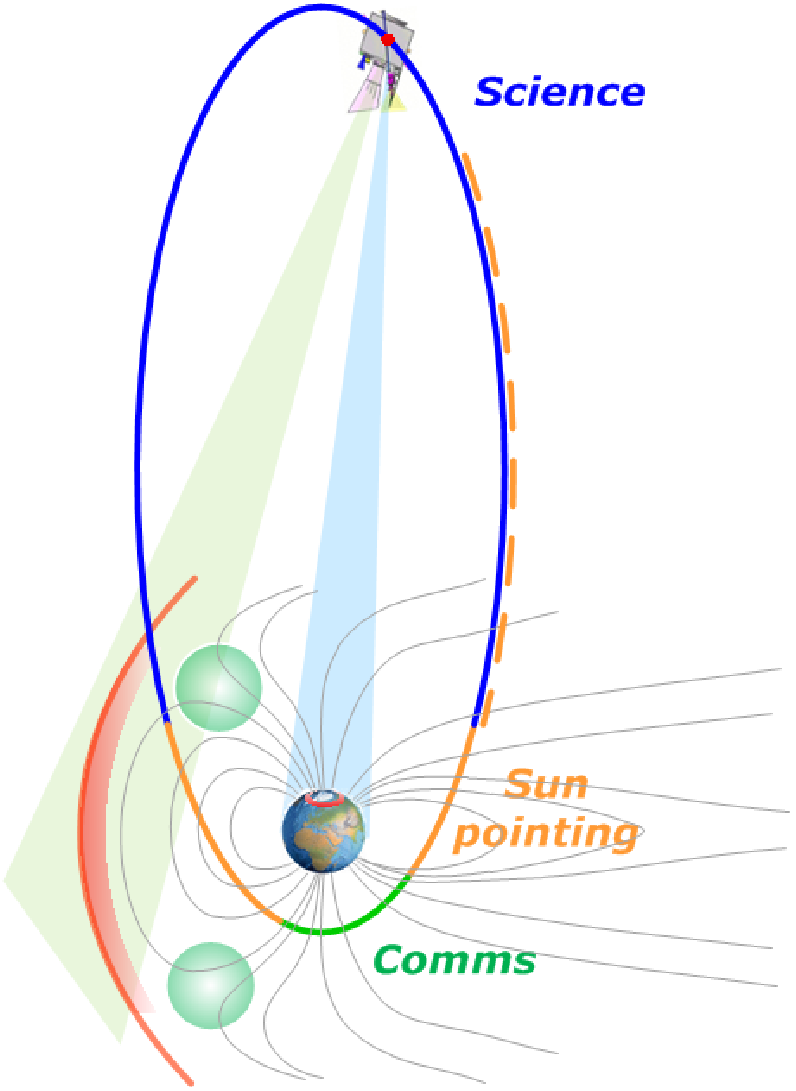
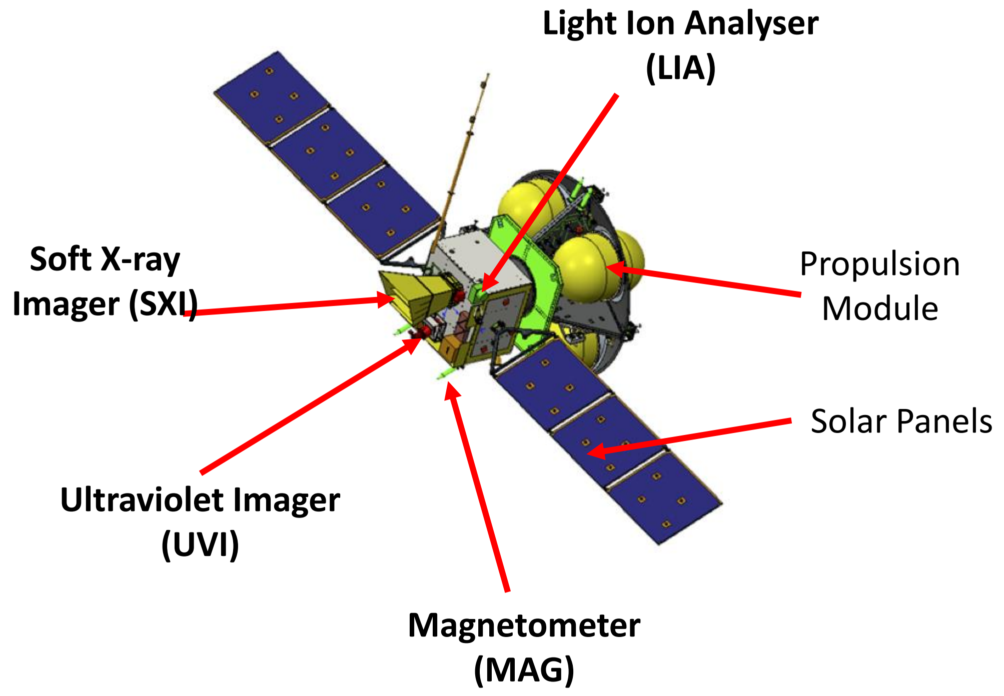
SMILE Mission Overview

- ESA mission with 4 instruments – 3 by China (CAS), and 1 ESA.
- Highly elliptical orbit will allow images of the entire Sun-Earth Magnetosphere interaction to be taken simultaneously, including in-situ measurements of Solar Wind strength and local magnetic field strength
- The Soft X-ray Imager (SXI) will observe X-rays produced in the cusps and Magnetopause boundary



SMILE spacecraft and SXI

SMILE Spacecraft



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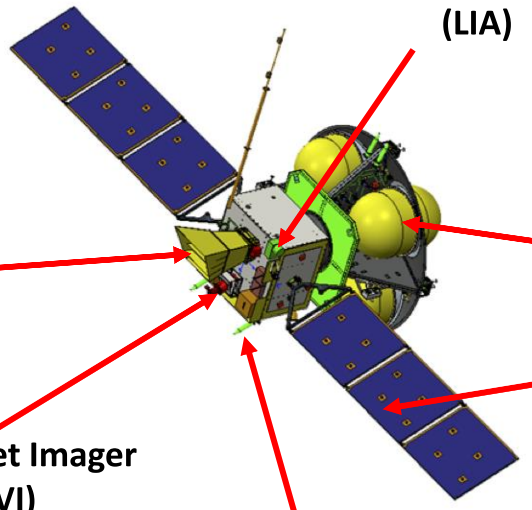
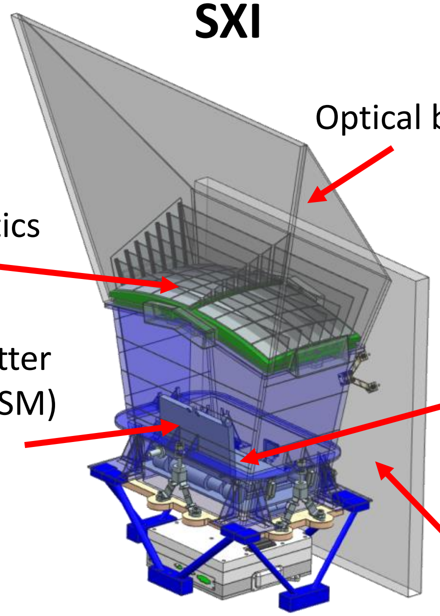


SXI



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SMILE

SMILE spacecraft and SXI

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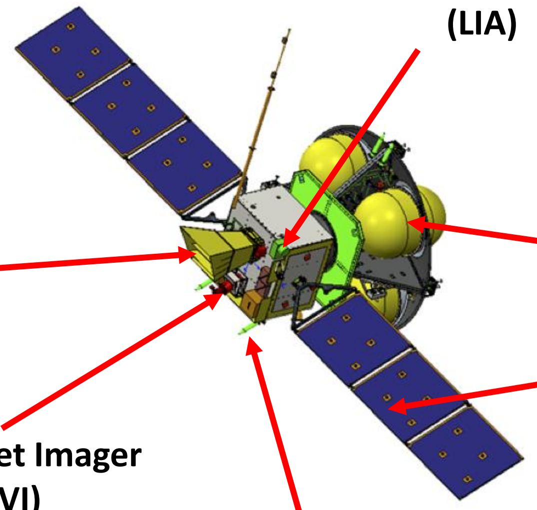

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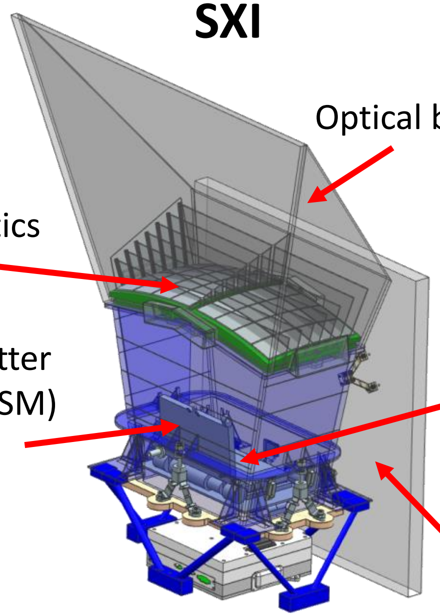
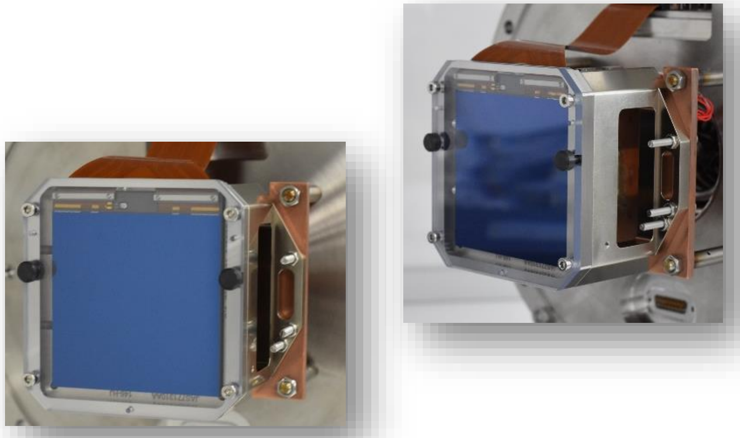
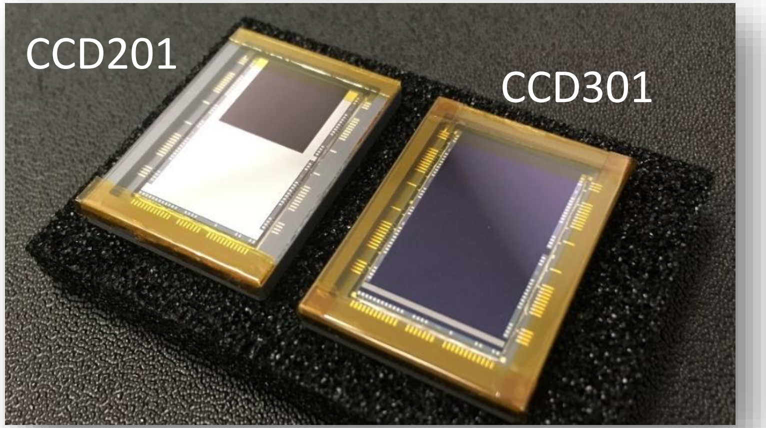


Focal plane – 2x CCD370s

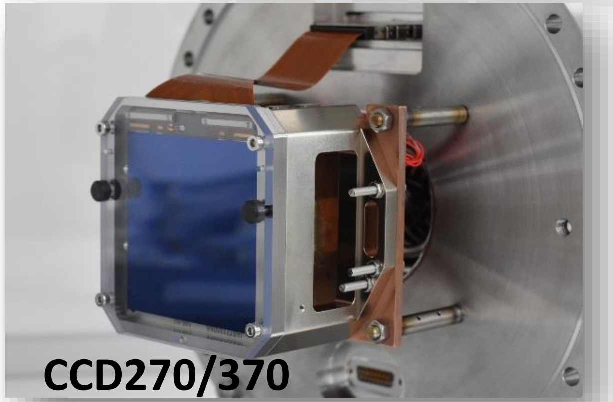


Charge-coupled devices (CCDs)

- The technology is comprised of an array of silicon pixels which make up the sensitive imaging region
- Readout of the image is performed via moving charge to and across the serial register



NASA RST



ESA SMILE/PLATO

ESA EUCLID

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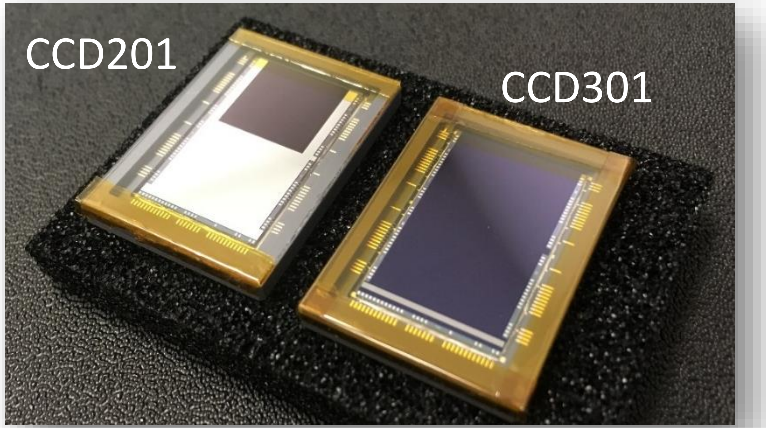

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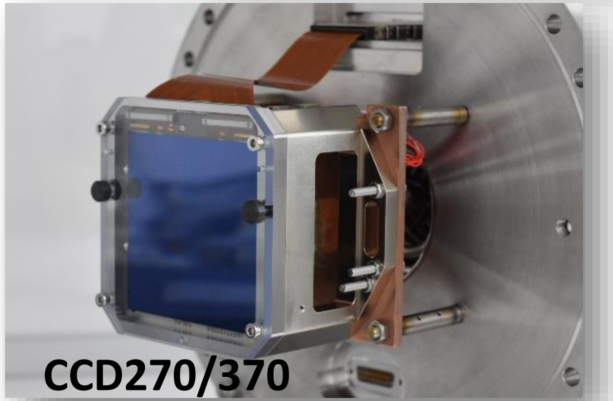

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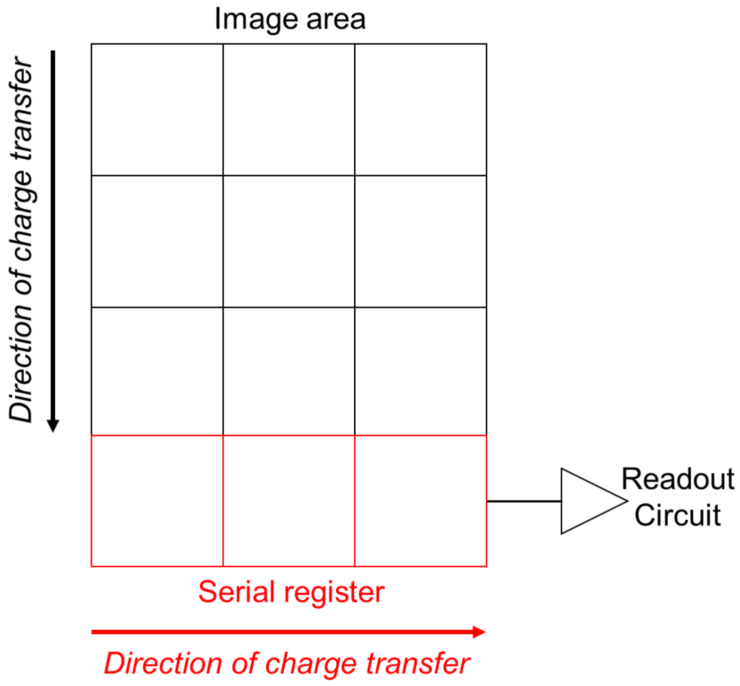

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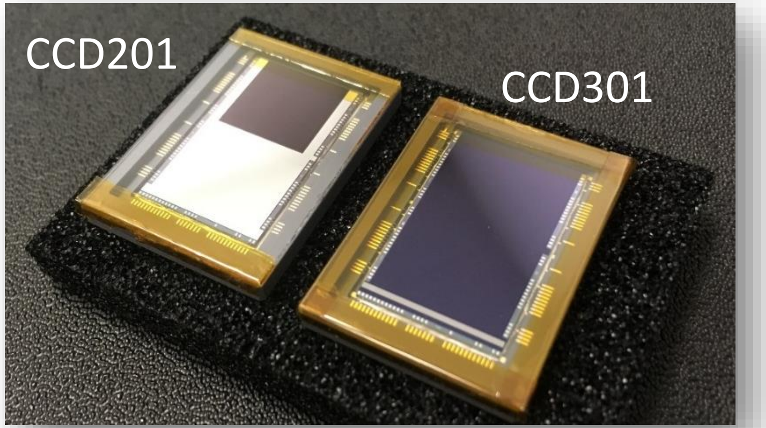

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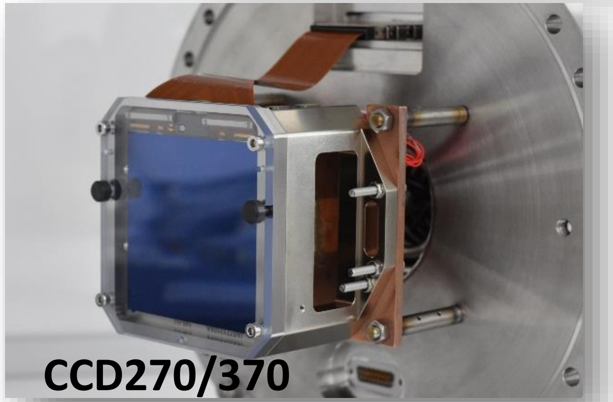

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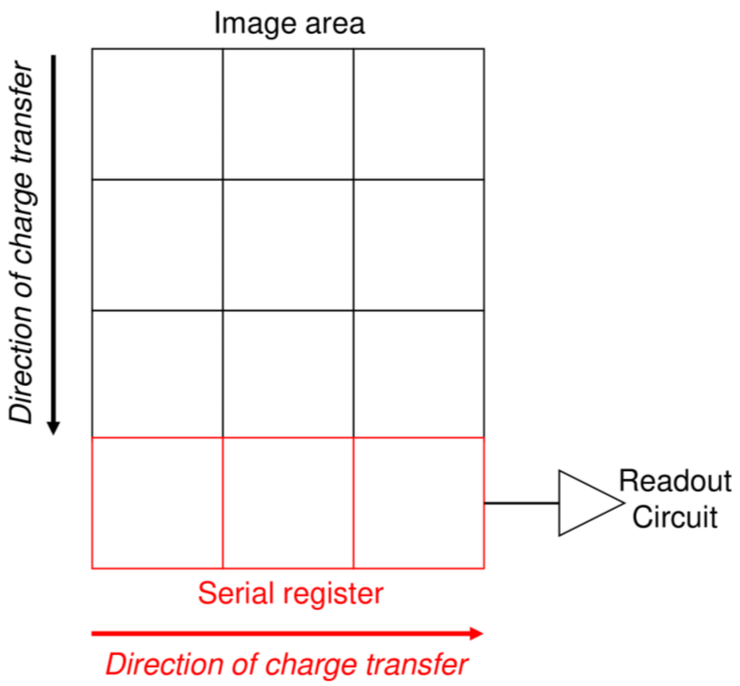

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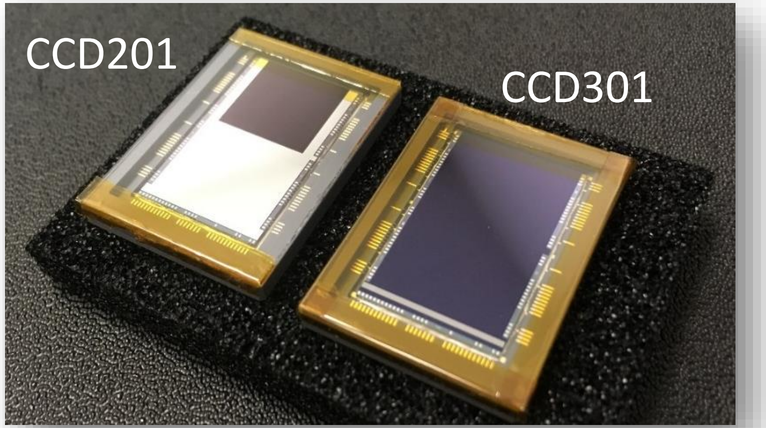

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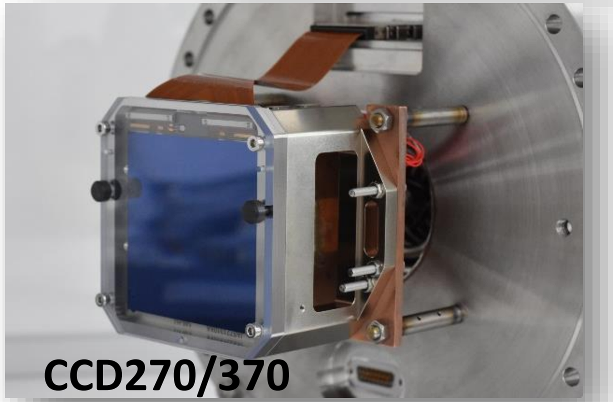

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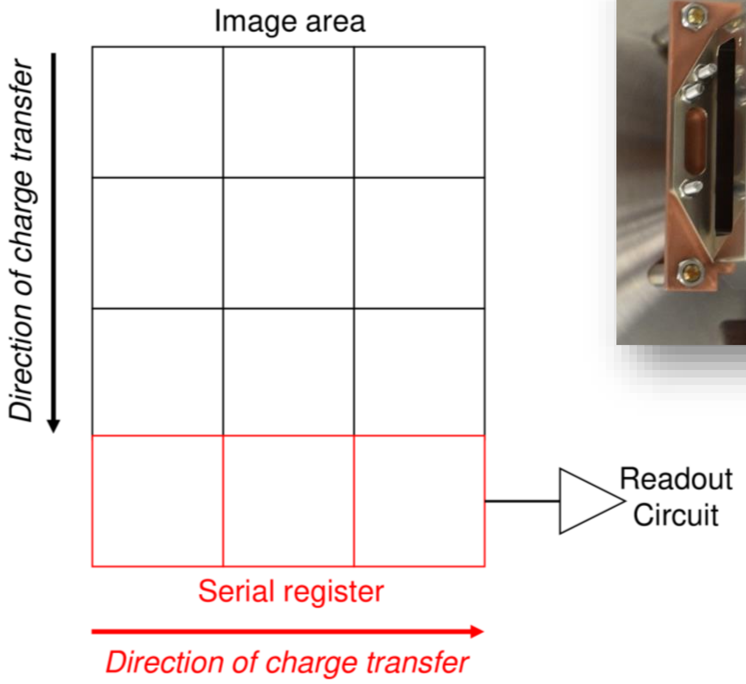

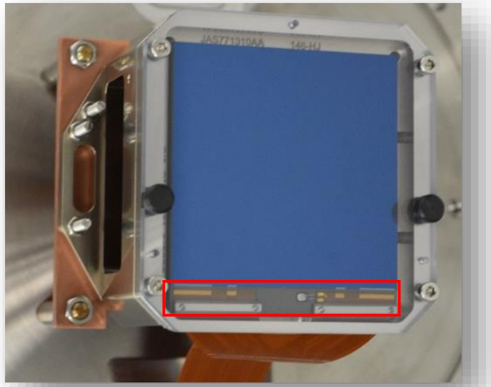

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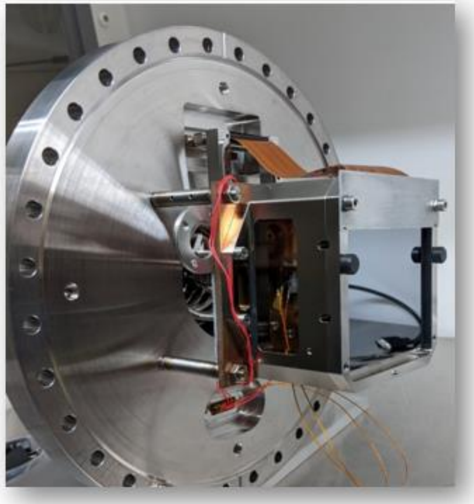
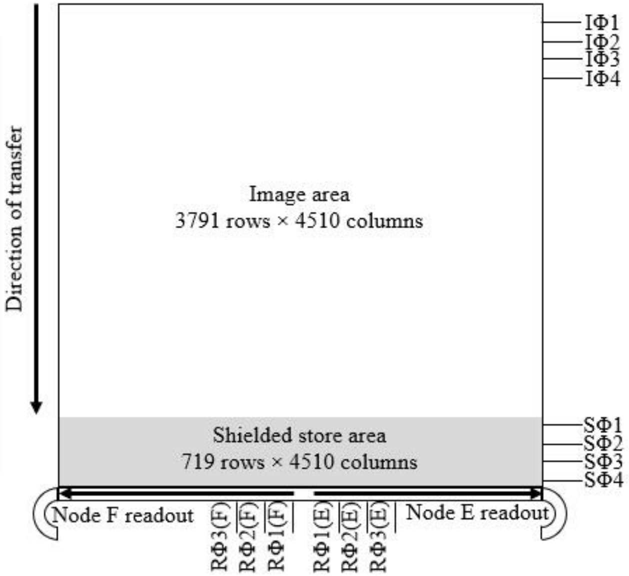
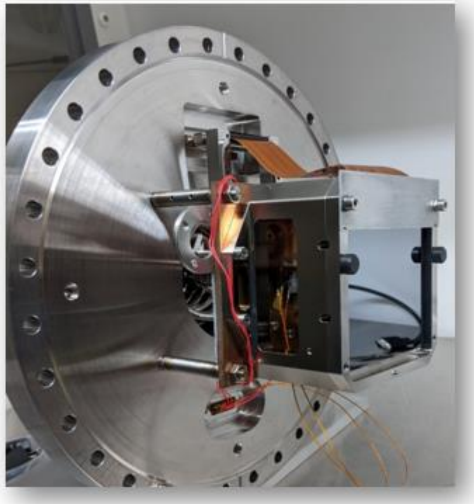
SMILE CCD370s

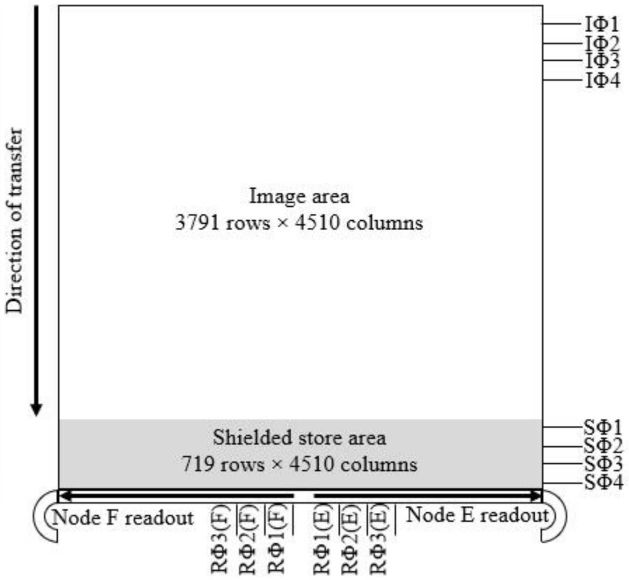


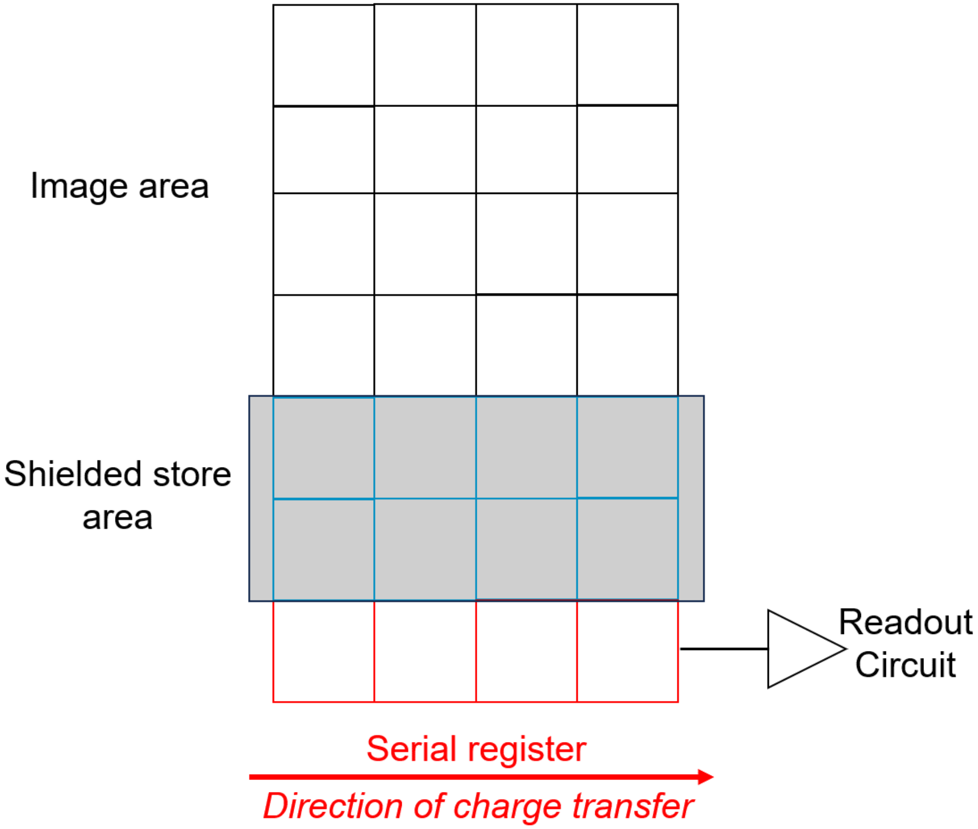


- Key quantities:
  - 18 µm square pixels
  - 16 µm thick silicon
  - 2 output nodes
  - Frame transfer operation mode with **6x6** on-chip binning – Excellent for energy resolution

SMILE CCD370s







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SMILE CCD370s – Modifications

Radiation hardness

- Supplementary buried channel – Smaller signals are confined to a smaller volume of silicon -> Less radiation induced defects encountered

S. Parsons *et al.*, (2022) *JINST* **17** P10025.

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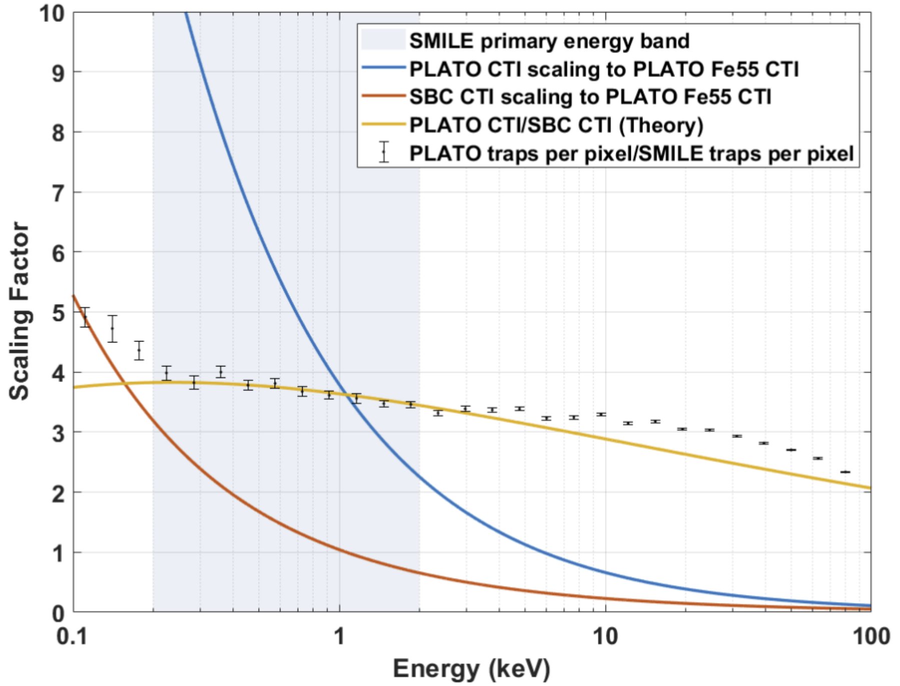

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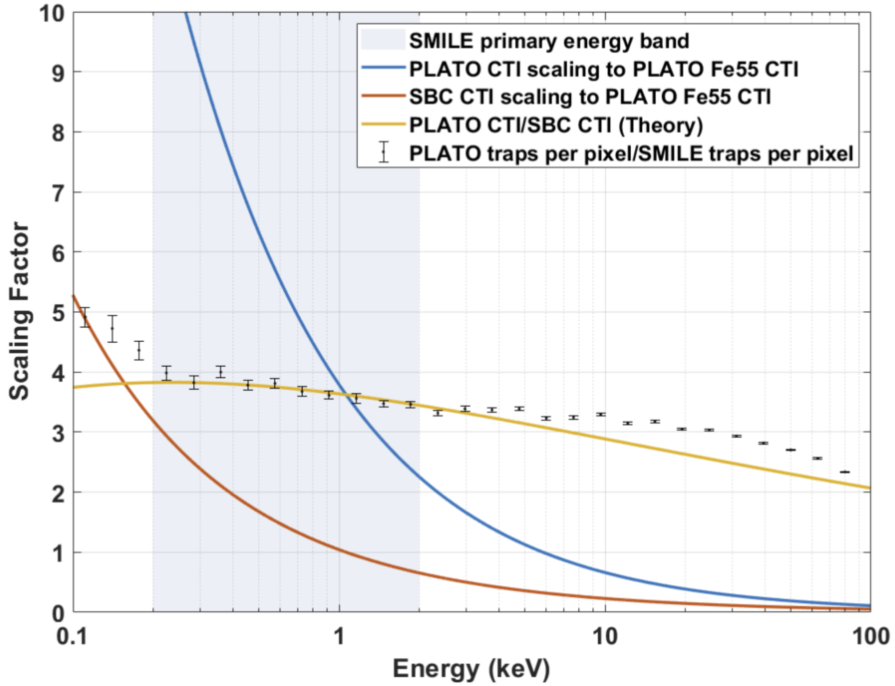

X-ray performance

- Enhanced backside passivation process offered by Te2v – P+ implant at the back surface with a built-in potential is etched away

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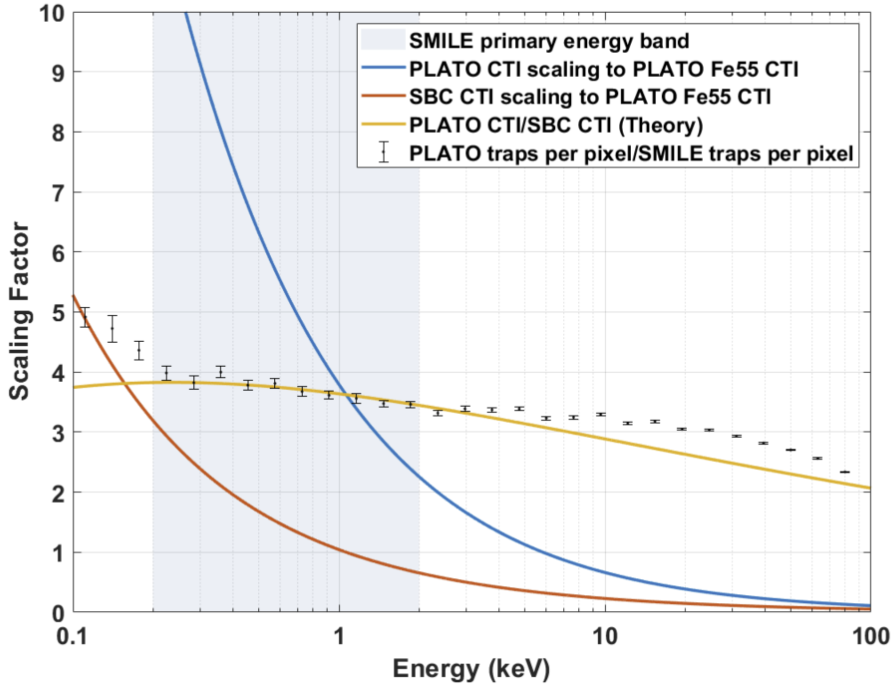

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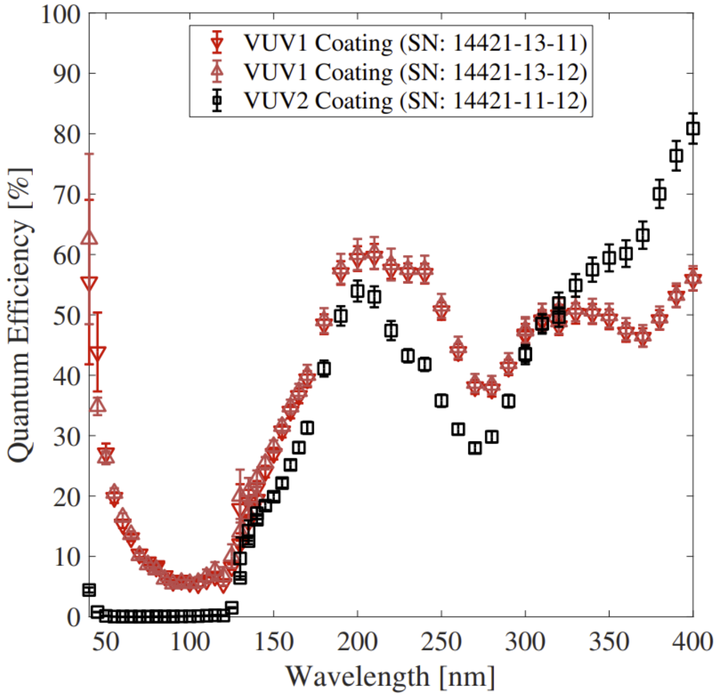

J. Heymes *et al.*, (2020) *SPIE*
S. Parsons *et al.*, (2022) *JINST* **17** P10025.

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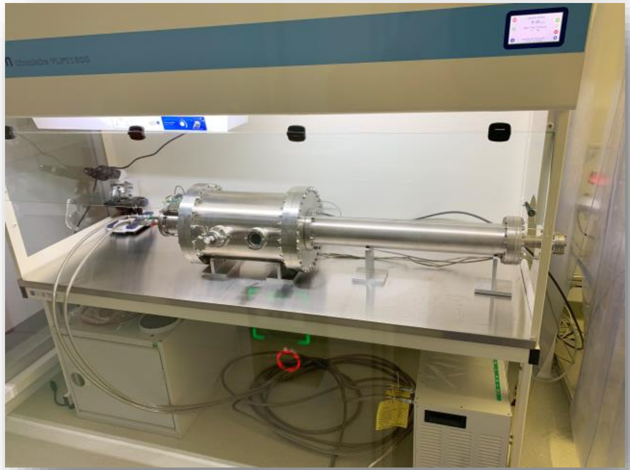
SMILE CCD characterisation campaigns

- Main experimental campaigns:
  - 3 irradiation campaigns, 1 more incoming
  - FM characterisation campaign
  - **BESSY Synchrotron soft X-ray QE/RMF campaign**

Birmingham irradiation setup

Harwell irradiation setup

Iso class 4 clean room – FM characterisation



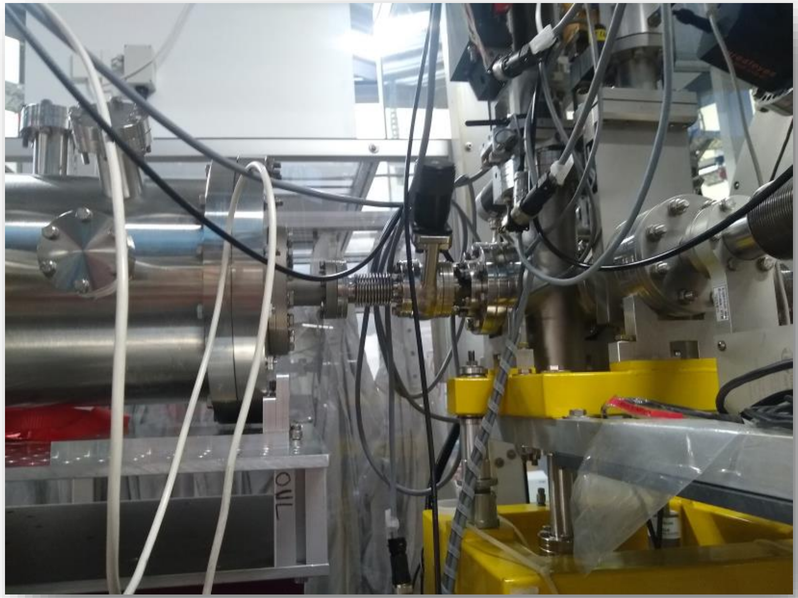
X-ray test campaign

Beamline	Photon Energy [eV]	Photon flux [s^{-1}]	Beam size [mm^2]
B1	50 – 1,900	10^{11} (TBC)	0.3 x 1.0

Chamber setup

Full-setup with beamline

Beamline-chamber interface



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QE measurements

- Integral charge method used (Moody 2017) -> Assuming the pixel/ADC is not saturated the total charge deposited in an area/unit time can be compared to the reference flux level

- Detector readout in binned time-delay integration mode:
  - 1 parallel shift
  - Serial register readout
  - Repeat 8000 times

I. Moody *et al.*, (2017)

Integral charge measurement method

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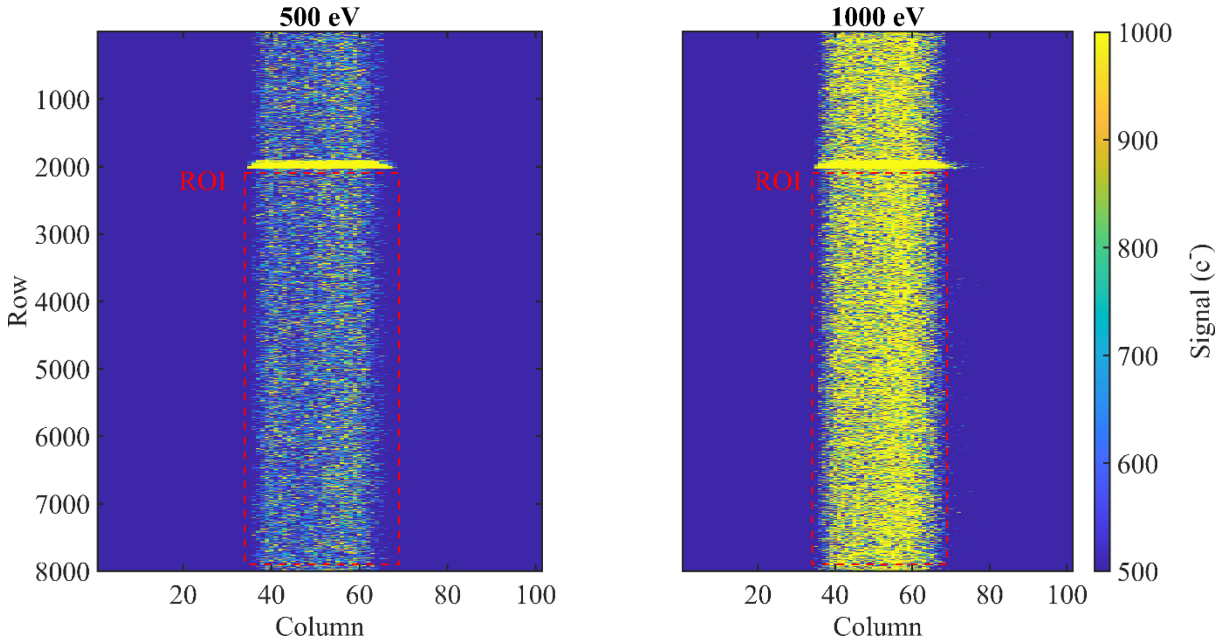
  - Repeat 8000 times
- BESSY provide a calibrated photodiode for absolute charge measurement values



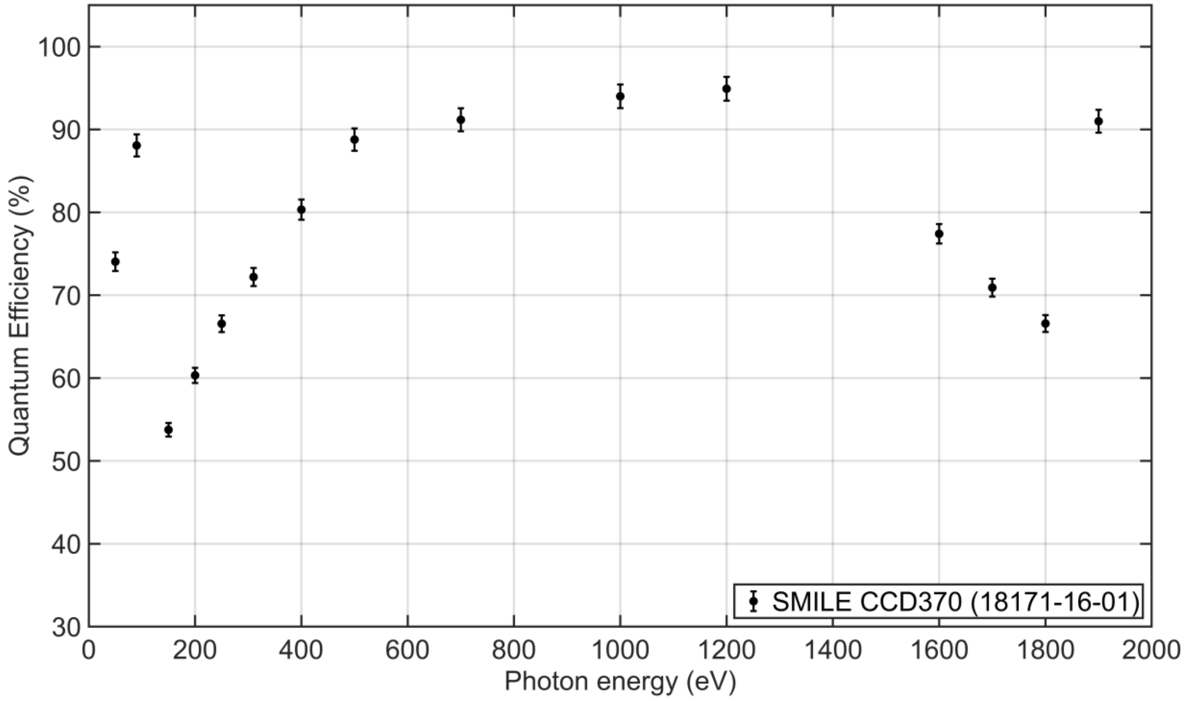
I. Moody *et al.*, (2017)

QE data: 50 eV – 1900 eV

- QE shown with error bars computed from the standard deviation of the signal deposited in each row

- QE at these energies has a distinct shape, with 2 significant drops in QE at ~100 eV and 1800 eV attributed to the known absorption edges

- What should the theoretical QE be across these energies?
  – Simple transmission QE model
  – Model based upon the layers in the pixel



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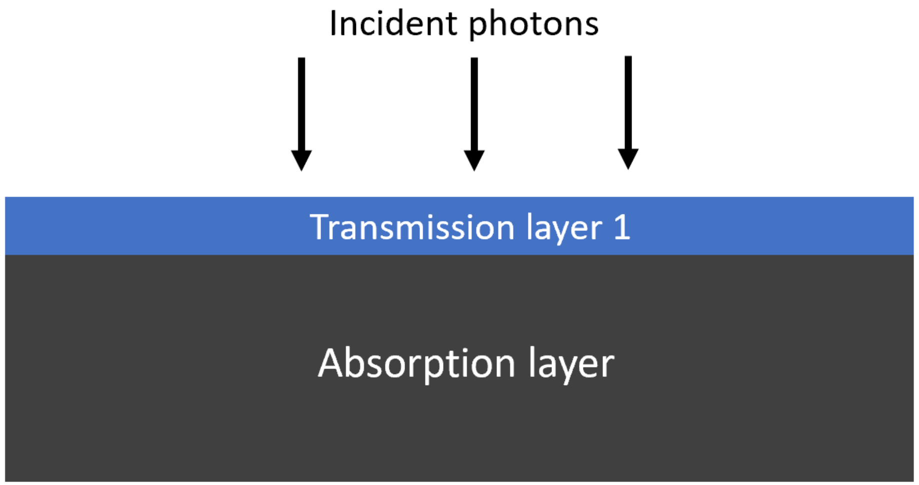
Transmission model

- Intensity equation – Based upon attenuation length in silicon
  - I_0 = Initial intensity
  - λ(E) = Attenuation length as a function of energy
  - t = thickness, summed over layers i

$$I = I_0 e^{\sum_i \frac{-t}{\lambda(E)}}$$

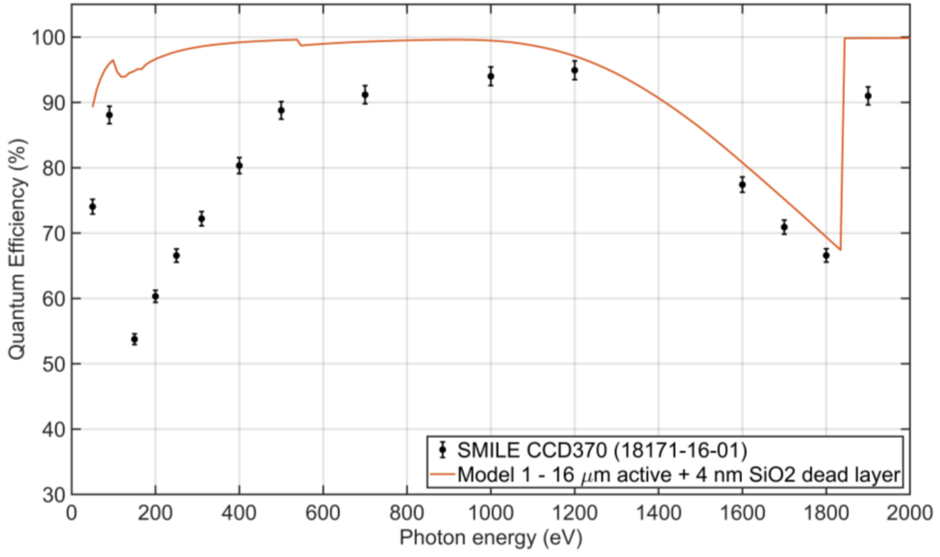
- For a photon to be absorbed, it must transmit through the non-sensitive layers

- Compute intensity through a given number of layers/materials, which make up the pixel architecture



QE data + model

- Initial model is the active silicon (16 microns), and a 4 nm dead layer of oxide – Poor match at lower energies



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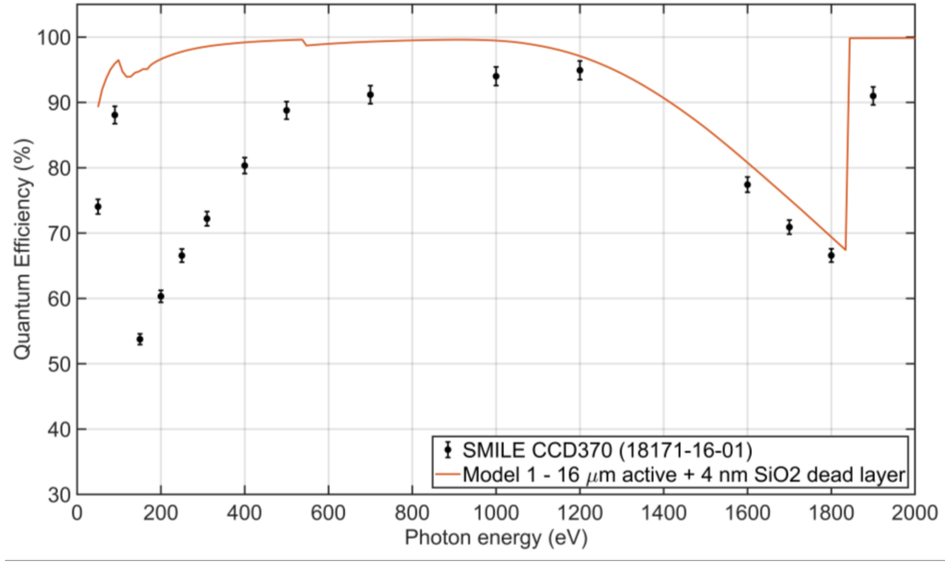

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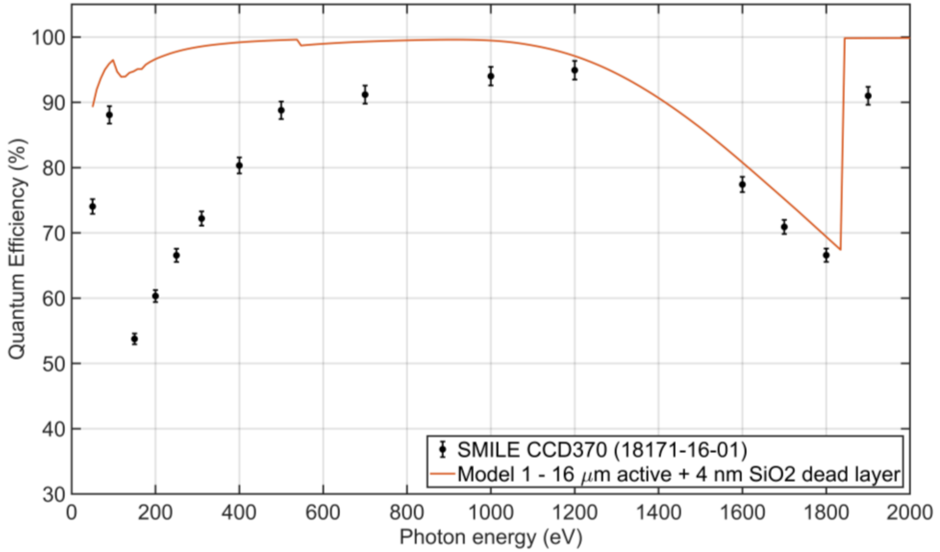

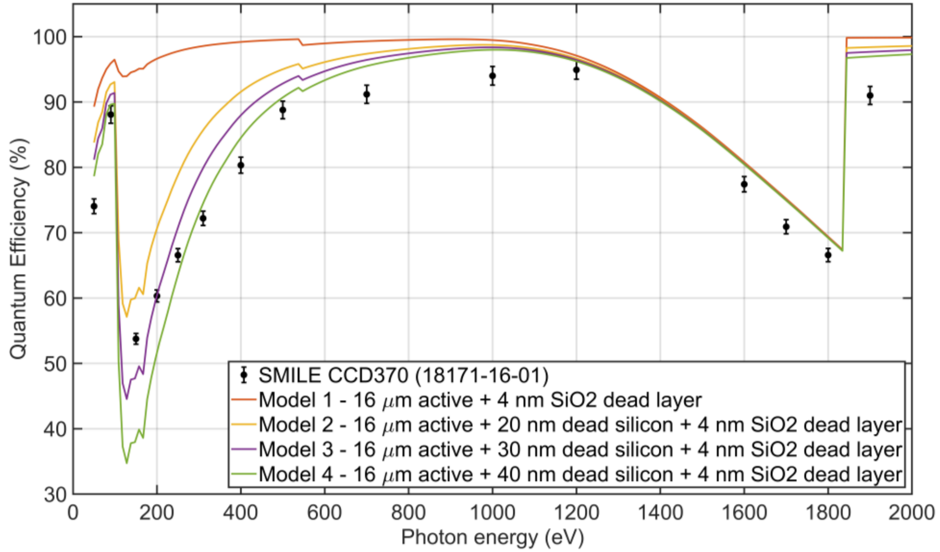

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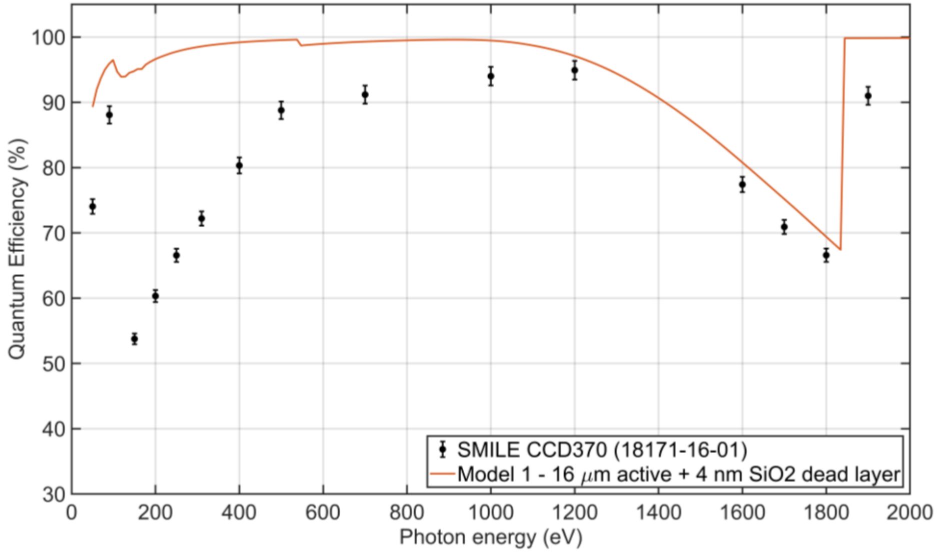
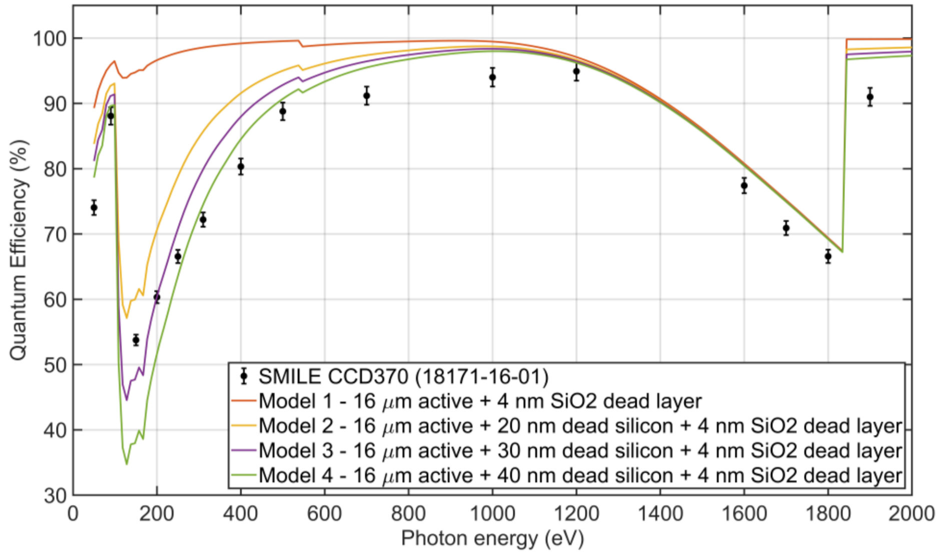
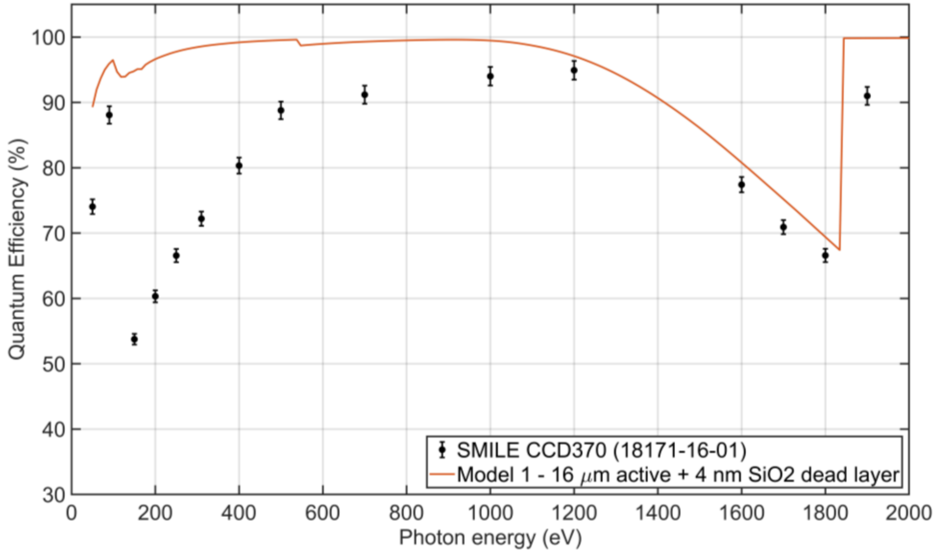
- But what physics does this represent, is it correct?

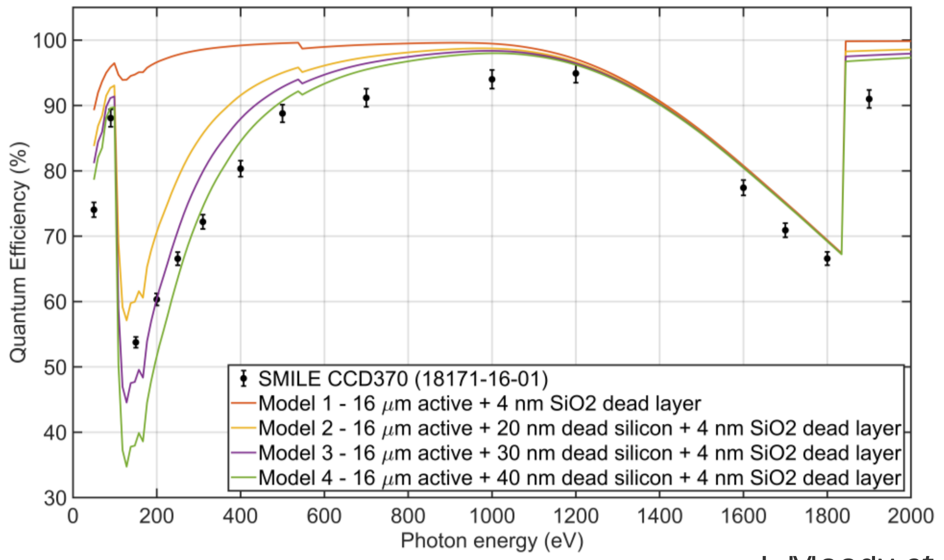




Back surface charge losses

- Moody paper suggested that X-rays interacting close to the p+ implant could reduce the effectiveness of the back surface passivation.
  - The mechanism would be the potential of the charge cloud being momentarily higher than the P+ built-in potential – This would lead to some charge losses to the back surface





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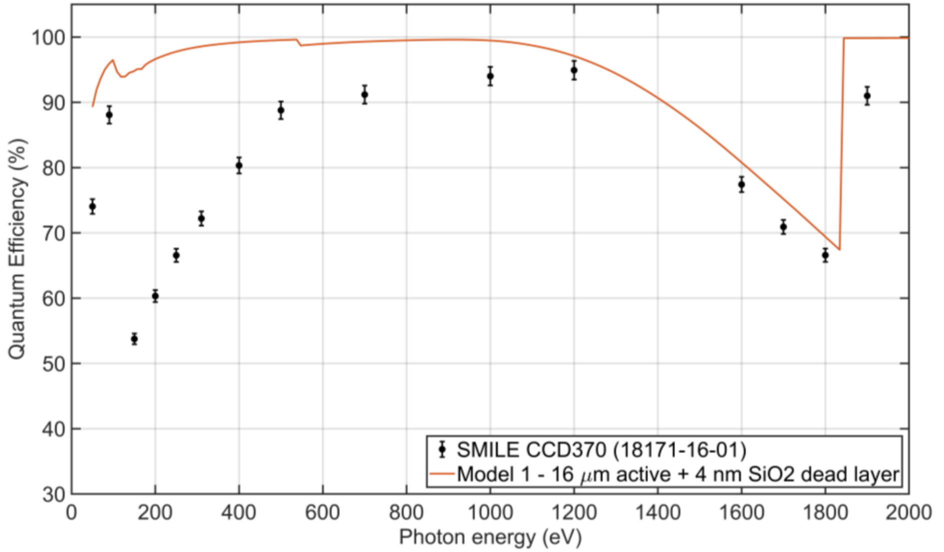
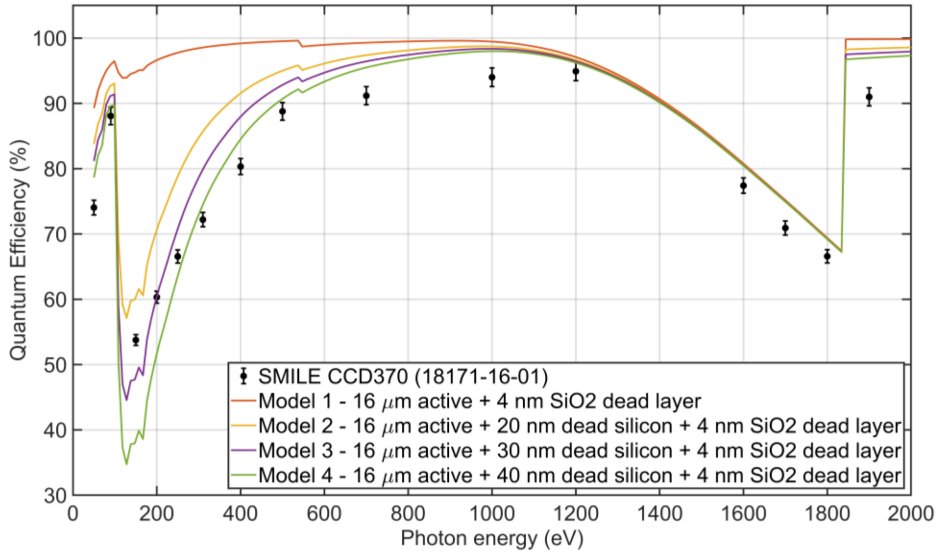
- This means the “dead” silicon layer implemented in the QE model, is more akin to a **semi-active layer** – A more physics-based model is required





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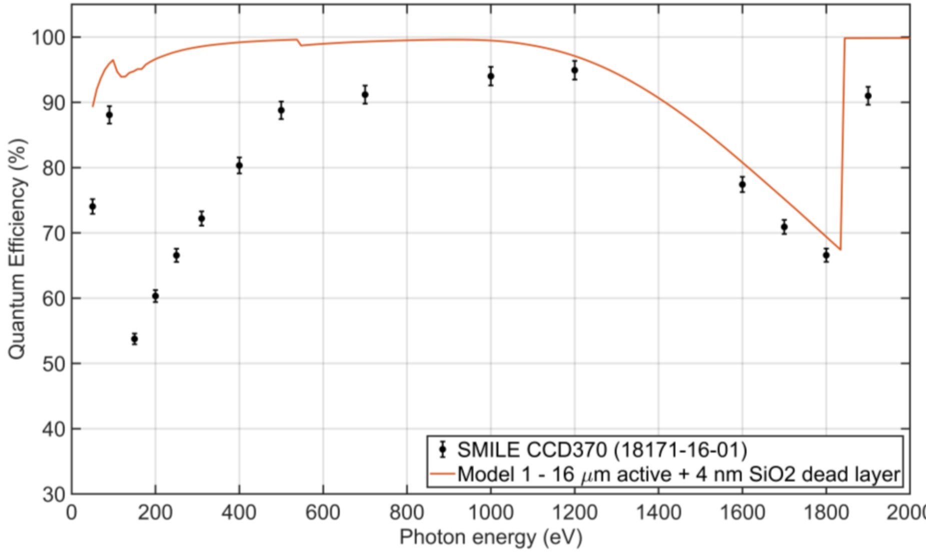
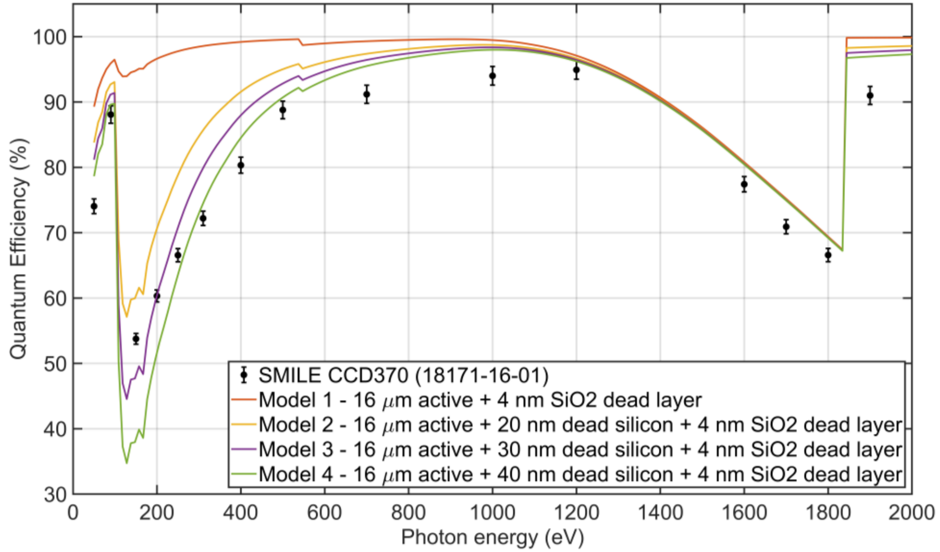
- PhD student working on X-ray physics in EMCCDs has been working on an analytical model for this – Results coming soon!





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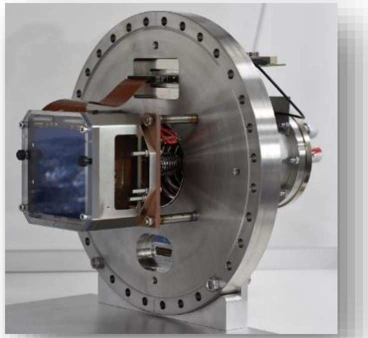
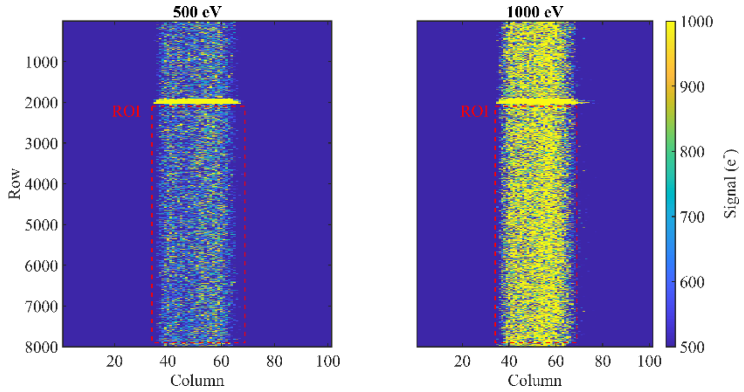
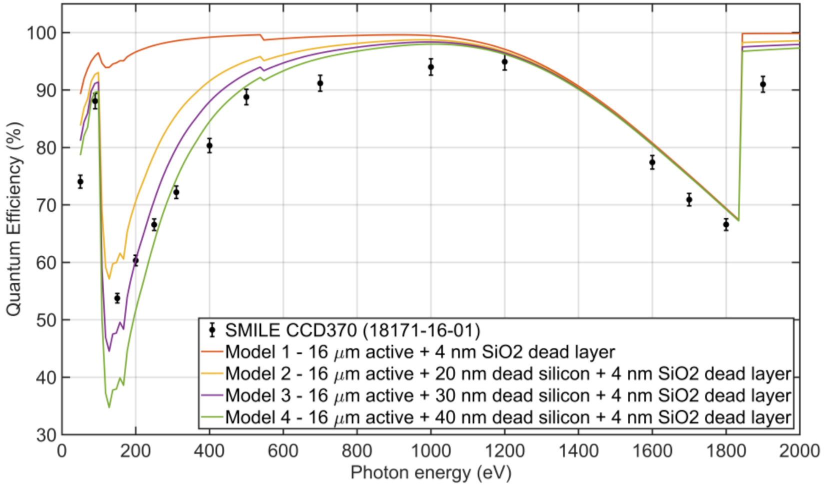
Conclusions

- A successful X-ray test campaign was carried out at the PTB beamline at BESSY
- The QE measured was close to the expected value and will be used as part of the SXI pipeline. This was also the first QE measurement on these devices so gives confidence to the manufacturing processes
- A transmission model was generated with an additional non-active Si layer, but some additional physics will be needed to improve the model-fit further







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